Bilipschitz maps, analytic capacity, and the Cauchy integral

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Abstract

Let $\varphi : \mathbb{C} \to \mathbb{C}$ be a bilipschitz map. We prove that if $E \subset \mathbb{C}$ is compact, and $\gamma(E), \alpha(E)$ stand for its analytic and continuous analytic capacity respectively, then $C^{-1}\gamma(E) \leq \gamma(\varphi(E)) \leq C\gamma(E)$ and $C^{-1}\alpha(E) \leq \alpha(\varphi(E)) \leq C\alpha(E)$, where $C$ depends only on the bilipschitz constant of $\varphi$. Further, we show that if $\mu$ is a Radon measure on $\mathbb{C}$ and the Cauchy transform is bounded on $L^2(\mu)$, then the Cauchy transform is also bounded on $L^2(\varphi_*\mu)$, where $\varphi_*\mu$ is the image measure of $\mu$ by $\varphi$. To obtain these results, we estimate the curvature of $\varphi_*\mu$ by means of a corona type decomposition.

1. Introduction

A compact set $E \subset \mathbb{C}$ is said to be removable for bounded analytic functions if for any open set $\Omega$ containing $E$, every bounded function analytic on $\Omega \setminus E$ has an analytic extension to $\Omega$. In order to study removability, in the 1940’s Ahlfors [Ah] introduced the notion of analytic capacity. The analytic capacity of a compact set $E \subset \mathbb{C}$ is

$$\gamma(E) = \sup |f'(\infty)|,$$

where the supremum is taken over all analytic functions $f : \mathbb{C} \setminus E \to \mathbb{C}$ with $|f| \leq 1$ on $\mathbb{C} \setminus E$, and $f'(\infty) = \lim_{z \to \infty} z(f(z) - f(\infty))$.

In [Ah], Ahlfors proved that $E$ is removable for bounded analytic functions if and only if $\gamma(E) = 0$.

Painlevé’s problem consists of characterizing removable singularities for bounded analytic functions in a metric/geometric way. By Ahlfors’ result this is equivalent to describing compact sets with positive analytic capacity in metric/geometric terms.

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Vitushkin in the 1950’s and 1960’s showed that analytic capacity plays a central role in problems of uniform rational approximation on compact sets of the complex plane. Further, he introduced the continuous analytic capacity \( \alpha \), defined as
\[
\alpha(E) = \sup |f'(\infty)|,
\]
where the supremum is taken over all continuous functions \( f : \mathbb{C} \to \mathbb{C} \) which are analytic on \( \mathbb{C} \setminus E \), and uniformly bounded by 1 on \( \mathbb{C} \). Many results obtained by Vitushkin in connection with uniform rational approximation are stated in terms of \( \alpha \) and \( \gamma \). See [Vi], for example.

Until quite recently it was not known if removability is preserved by an affine map such as \( \varphi(x, y) = (x, 2y) \) (with \( x, y \in \mathbb{R} \)). From the results of [To3] (see Theorem A below) it easily follows that this is true even for \( C^{1+\varepsilon} \) diffeomorphisms. In the present paper we show that this also holds for bilipschitz maps. Remember that a map \( \varphi : \mathbb{C} \to \mathbb{C} \) is bilipschitz if it is bijective and there exists some constant \( L > 0 \) such that
\[
L^{-1}|z - w| \leq |\varphi(z) - \varphi(w)| \leq L|z - w|
\]
for all \( z, w \in \mathbb{C} \). The precise result that we will prove is the following.

**Theorem 1.1.** Let \( E \subset \mathbb{C} \) be a compact set and \( \varphi : \mathbb{C} \to \mathbb{C} \) a bilipschitz map. There exists a positive constant \( C \) depending only on \( \varphi \) such that
\[
(1.1) \quad C^{-1}\gamma(E) \leq \gamma(\varphi(E)) \leq C\gamma(E)
\]
and
\[
(1.2) \quad C^{-1}\alpha(E) \leq \alpha(\varphi(E)) \leq C\alpha(E).
\]

As far as we know, the question on the behaviour of analytic capacity under bilipschitz maps was first raised by Verdera [Ve1, p.435]. See also [Pa, p.113] for a more recent reference to the problem.

At first glance, the results stated in Theorem 1.1 may seem surprising, since \( f \) and \( f \circ \varphi \) are rarely both analytic simultaneously. However, by the results of G. David [Da1], it turns out that if \( E \) is compact with finite length (i.e. \( \mathcal{H}^1(E) < \infty \), where \( \mathcal{H}^1 \) stands for the 1-dimensional Hausdorff measure), then \( \gamma(E) > 0 \) if and only if \( \gamma(\varphi(E)) > 0 \). Moreover, Garnett and Verdera [GV] proved recently that \( \gamma(E) \) and \( \gamma(\varphi(E)) \) are comparable for a large class of Cantor sets \( E \) which may have non-\( \sigma \)-finite length.

Let us remark that the assumption that \( \varphi \) is bilipschitz in Theorem 1.1 is necessary for (1.1) or (1.2) to hold. The precise statement reads as follows.

**Proposition 1.2.** Let \( \varphi : \mathbb{C} \to \mathbb{C} \) be a homeomorphism such that either (1.1) holds for all compact sets \( E \subset \mathbb{C} \), or (1.2) holds for all compact sets \( E \subset \mathbb{C} \) (in both cases with \( C \) independent of \( E \)). Then \( \varphi \) is bilipschitz.
We introduce now some additional notation. A positive Radon measure \( \mu \) is said to have linear growth if there exists some constant \( C \) such that 
\[
\mu(B(x, r)) \leq C r
\]
for all \( x \in \mathbb{C}, \ r > 0 \). The linear density of \( \mu \) at \( x \in \mathbb{C} \) is (if it exists)
\[
\Theta_{\mu}(x) = \lim_{r \to 0} \frac{\mu(B(x, r))}{r}.
\]
Given three pairwise different points \( x, y, z \in \mathbb{C} \), their Menger curvature is
\[
c(x, y, z) = \frac{1}{R(x, y, z)},
\]
where \( R(x, y, z) \) is the radius of the circumference passing through \( x, y, z \) (with \( R(x, y, z) = \infty \), \( c(x, y, z) = 0 \) if \( x, y, z \) lie on a same line). If two among these points coincide, we set \( c(x, y, z) = 0 \). For a positive Radon measure \( \mu \), we define the curvature of \( \mu \) as
\[
c^2(\mu) = \int \int \int c(x, y, z)^2 \, d\mu(x) \, d\mu(y) \, d\mu(z).
\]
The notion of curvature of measures was introduced by Melnikov [Me] when he was studying a discrete version of analytic capacity, and it is one of the ideas which is responsible for the recent advances in connection with analytic capacity.

Given a complex Radon measure \( \nu \) on \( \mathbb{C} \), the Cauchy transform of \( \nu \) is
\[
C\nu(z) = \int \frac{1}{\xi - z} \, d\nu(\xi).
\]
This definition does not make sense, in general, for \( z \in \text{supp}(\nu) \), although one can easily see that the integral above is convergent at a.e. \( z \in \mathbb{C} \) (with respect to Lebesgue measure). This is the reason why one considers the \( \varepsilon \)-truncated Cauchy transform of \( \nu \), which is defined as
\[
C_{\varepsilon}\nu(z) = \int_{|\xi - z| > \varepsilon} \frac{1}{\xi - z} \, d\nu(\xi),
\]
for any \( \varepsilon > 0 \) and \( z \in \mathbb{C} \). Given a \( \mu \)-measurable function \( f \) on \( \mathbb{C} \) (where \( \mu \) is some fixed positive Radon measure on \( \mathbb{C} \)), we write \( C_\mu f \equiv C(f \, d\mu) \) and \( C_{\mu, \varepsilon} f \equiv C_\varepsilon(f \, d\mu) \) for any \( \varepsilon > 0 \). It is said that the Cauchy transform is bounded on \( L^2(\mu) \) if the operators \( C_{\mu, \varepsilon} \) are bounded on \( L^2(\mu) \) uniformly on \( \varepsilon > 0 \).

The relationship between the Cauchy transform and curvature of measures was found by Melnikov and Verdera [MV]. They proved that if \( \mu \) has linear growth, then
\[
\|C_{\varepsilon}\mu\|_{L^2(\mu)}^2 = \frac{1}{6} c^2_{\varepsilon}(\mu) + O(\mu(\mathbb{C})),
\]
where \( c^2_{\varepsilon}(\mu) \) is an \( \varepsilon \)-truncated version of \( c^2(\mu) \) (defined as in the right-hand side of (1.3), but with the triple integral over \( \{x, y, z \in \mathbb{C} : |x - y|, |y - z|, |x - z| > \varepsilon\} \)).
Moreover, there is also a strong connection (see [Pa]) between the notion of curvature of measures and the\( \beta \)'s from Jones' travelling salesman theorem [Jo]. The relationship with Favard length is an open problem (see Section 6 of the excellent survey paper [Matt], for example).

The proof of Theorem 1.1, as well as the one of the result of Garnett and Verdera [GV], use the following characterization of analytic capacity in terms of curvature of measures obtained recently by the author.

**Theorem A** ([To3]). For any compact \( E \subset \mathbb{C} \),
\[
\gamma(E) \simeq \sup \mu(E),
\]
where the supremum is taken over all Borel measures \( \mu \) supported on \( E \) such that \( \mu(B(x,r)) \leq r \) for all \( x \in E, r > 0 \) and \( c^2(\mu) \leq \mu(E) \).

The notation \( A \simeq B \) in the theorem means that there exists an absolute constant \( C > 0 \) such that
\[
C^{-1}A \leq B \leq CA.
\]

The corresponding result for \( \alpha \) is the following.

**Theorem B** ([To4]). For any compact \( E \subset \mathbb{C} \),
\[
\alpha(E) \simeq \sup \mu(E),
\]
where the supremum is taken over the Borel measures \( \mu \) supported on \( E \) such that \( \Theta\mu(x) = 0 \) for all \( x \in E \), \( \mu(B(x,r)) \leq r \) for all \( x \in E, r > 0 \), and \( c^2(\mu) \leq \mu(E) \).

Although the notion of curvature of a measure has a definite geometric flavor, it is not clear if the characterizations of \( \gamma \) and \( \alpha \) in Theorems A and B can be considered as purely metric/geometric. Nevertheless, Theorem 1.1 asserts that \( \gamma \) and \( \alpha \) have a metric nature, in a sense.

Theorem 1.1 is a direct consequence of the next result and of Theorems A and B.

**Theorem 1.3.** Let \( \mu \) be a Radon measure supported on a compact \( E \subset \mathbb{C} \), such that \( \mu(B(x,r)) \leq r \) for all \( x \in E, r > 0 \) and \( c^2(\mu) < \infty \). Let \( \varphi : \mathbb{C} \to \mathbb{C} \) be a bilipschitz mapping. There exists a positive constant \( C \) depending only on \( \varphi \) such that
\[
c^2(\varphi_\#\mu) \leq C(\mu(E) + c^2(\mu)).
\]

In the inequality above, \( \varphi_\#\mu \) stands for the image measure of \( \mu \) by \( \varphi \). That is to say, \( \varphi_\#\mu(A) = \mu(\varphi^{-1}(A)) \) for \( A \subset \mathbb{C} \).

We will prove Theorem 1.3 using a corona type decomposition, analogous to the one used by David and Semmes in [DS1] and [DS2] for AD regular sets (i.e. for sets \( E \) such that \( \mathcal{H}^1(E \cap B(x,r)) \simeq r \) for all \( x \in E, r > 0 \)). The ideas go back to Carleson’s corona construction. See [AHMTT] for a recent survey.
on similar techniques. In our situation, the measures \( \mu \) that we will consider do not satisfy any doubling or homogeneity condition. This fact is responsible for most of the technical difficulties that appear in the proof of Theorem 1.3.

By the relationship (1.4) between curvature and the Cauchy integral, the results in [To1] (or in [NTV]), and Theorem 1.3, we also deduce the next result.

**Theorem 1.4.** Let \( \varphi : \mathbb{C} \to \mathbb{C} \) be a bilipschitz map and \( \mu \) a Radon measure on \( \mathbb{C} \) without atoms. Set \( \sigma = \varphi_\# \mu \). If \( C_\mu \) is bounded on \( L^2(\mu) \), then \( C_\sigma \) is bounded on \( L^2(\sigma) \).

Notice that the theorem by Coifman, McIntosh and Meyer [CMM] concerning the \( L^2 \) boundedness of the Cauchy transform on Lipschitz graphs (with respect to arc length measure) can be considered as a particular case of Theorem 1.4. Indeed, if \( x \mapsto A(x) \) defines a Lipschitz graph on \( \mathbb{C} \), then the map \( \varphi(x, y) = (x, y + A(x)) \) is bilipschitz. Since \( \varphi \) sends the real line to the Lipschitz graph defined by \( A \) and the Cauchy transform is bounded on \( L^2(dx) \) on the real line (because it coincides with the Hilbert transform), from Theorem 1.4 we infer that it is also bounded on the Lipschitz graph.

The plan of the paper is the following. In Section 2 we prove (the easy) Proposition 1.2 and introduce additional notation and definitions. The rest of the paper is devoted to the proof of Theorem 1.3, which we have split into two main lemmas. The first one, Main Lemma 3.1, deals with the construction of a suitable corona type decomposition of \( E \), and it is proved in Sections 3–7. The second one, Main Lemma 8.1, is proved in Section 8, and it shows how one can estimate the curvature of a measure by means of a corona type decomposition. So the proof of Theorem 1.3 works as follows. In Main Lemma 3.1 we construct a corona type decomposition of \( E \), which is stable under bilipschitz maps.

That is to say, \( \varphi \) sends the corona decomposition of \( E \) (perhaps we should say of the pair \( (E, \mu) \)) to another corona decomposition of \( \varphi(E) \) (i.e. of the pair \( (\varphi(E), \varphi_\# \mu) \)). Then, Main Lemma 8.1 yields the required estimates for \( C_\#(\varphi_\# \mu) \).

2. Preliminaries

2.1. **Proof of Proposition 1.2.** Let \( \varphi : \mathbb{C} \to \mathbb{C} \) be a homeomorphism and suppose that \( \gamma(\varphi(E)) \simeq \gamma(E) \) for all compact sets \( E \subset \mathbb{C} \). Given \( x, y \in \mathbb{C} \), consider the segment \( E = [x, y] \). Then \( \varphi(E) \) is a curve and its analytic capacity is comparable to its diameter. Thus,

\[
|\varphi(x) - \varphi(y)| \leq \text{diam}(\varphi(E)) \simeq \gamma(\varphi(E)) \simeq \gamma(E) \simeq |x - y|.
\]

The converse inequality, \( |x - y| \lesssim |\varphi(x) - \varphi(y)| \), follows by application of the previous argument to \( \varphi^{-1} \).
If instead of \( \gamma(\varphi(E)) \simeq \gamma(E) \) we assume now that with \( \alpha(\varphi(E)) \simeq \alpha(E) \) for all compact sets \( E \), a similar argument works. For example, given \( x, y \in \mathbb{C} \), one can take \( E \) to be the closed ball centered at \( x \) with radius \( 2|x - y| \), and then one can argue as above.

### 2.2. Two remarks.
There are bijections \( \varphi : \mathbb{C} \to \mathbb{C} \) such that \( \gamma(\varphi(E)) \simeq \gamma(E) \) and \( \alpha(\varphi(E)) \simeq \alpha(E) \), for any compact \( E \subseteq \mathbb{C} \), which are not homeomorphisms. For example, set \( \varphi(z) = z \) if \( \Re(z) \geq 0 \) and \( \varphi(z) = z + i \) if \( \Re(z) < 0 \). Using the semiadditivity of \( \gamma \) and \( \alpha \) one easily sees that \( \gamma(\varphi(E)) \simeq \gamma(E) \) and \( \alpha(\varphi(E)) \simeq \alpha(E) \).

If the map \( \varphi : \mathbb{C} \to \mathbb{C} \) is assumed to be only Lipschitz, then none of the inequalities \( \gamma(\varphi(E)) \gtrsim \gamma(E) \) or \( \gamma(\varphi(E)) \lesssim \gamma(E) \) holds, in general. To check this, for the first inequality consider a constant map and \( E \) arbitrary with \( \gamma(E) > 0 \). For the second inequality, one only has to take into account that there are purely unrectifiable sets with finite length which project orthogonally onto a segment (with positive length) in some direction.

### 2.3. Additional notation and definitions.
An Ahlfors-David regular curve (or AD regular curve) is a curve \( \Gamma \) such that \( H^1(\Gamma \cap B(x, r)) \leq C_3 r^2 \) for all \( x \in \Gamma, r > 0 \), and some fixed \( C_3 > 0 \). If we want to specify the constant \( C_3 \), we will say that \( \Gamma \) is “\( C_3 \)-AD regular”.

In connection with the definition of \( c^2(\mu) \), we also set

\[
c^2_\mu(x) = \int \int c(x, y, z)^2 \, d\mu(y) \, d\mu(z).
\]

Thus, \( c^2(\mu) = \int c^2_\mu(x) \, d\mu(x) \). If \( A \subseteq \mathbb{C} \) is \( \mu \)-measurable,

\[
c^2_\mu(x, y, A) = \int_A c(x, y, z)^2 \, d\mu(z), \quad x, y \in \mathbb{C},
\]

and, if \( A, B, C \subseteq \mathbb{C} \) are \( \mu \)-measurable,

\[
c^2_\mu(x, A, B) = \int_A \int_B c(x, y, z)^2 \, d\mu(y) \, d\mu(z), \quad x \in \mathbb{C},
\]

and

\[
c^2_\mu(A, B, C) = \int_A \int_B \int_C c(x, y, z)^2 \, d\mu(x) \, d\mu(y) \, d\mu(z).
\]

The curvature operator \( K_\mu \) is

\[
K_\mu(f)(x) = \int k_\mu(x, y) f(y) \, d\mu(y), \quad x \in \mathbb{C}, f \in L^1_{\text{loc}}(\mu),
\]

where \( k_\mu(x, y) \) is the kernel

\[
k_\mu(x, y) = \int c(x, y, z)^2 \, d\mu(z) = c^2_\mu(x, y, \mathbb{C}), \quad x, y \in \mathbb{C}.
\]
For \( j \in \mathbb{Z} \), the truncated operators \( K_{\mu,j} \), \( j \in \mathbb{Z} \), are defined as

\[
K_{\mu,j} f(x) = \int_{|x-y|>2^{-j}} k_{\mu}(x,y) f(y) \, d\mu(y), \quad x \in \mathbb{C}, f \in L^1_{\text{loc}}(\mu).
\]

In this paper, by a square we mean a square with sides parallel to the axes. Moreover, we assume the squares to be half closed - half open. The side length of a square \( Q \) is denoted by \( \ell(Q) \). Given a square \( Q \) and \( a > 0 \), \( aQ \) denotes the square concentric with \( Q \) with side length \( a \ell(Q) \). The average (linear) density of a Radon measure \( \mu \) on \( Q \) is

\[
\theta_\mu(Q) := \frac{\mu(Q)}{\ell(Q)}.
\]  

A square \( Q \subset \mathbb{C} \) is called 4-dyadic if it is of the form \([j2^{-n}, (j+4)2^{-n}) \times [k2^{-n}, (k+4)2^{-n})\), with \( j, k, n \in \mathbb{Z} \). So a 4-dyadic square with side length \( 4 \cdot 2^{-n} \) is made up of 16 dyadic squares with side length \( 2^{-n} \). We will work quite often with 4-dyadic squares. All our arguments would also work with other variants of this type of square, such as squares \( 5Q \) with \( Q \) dyadic, say. However, our choice of 4-dyadic squares has some advantages. For example, if \( Q \) is 4-dyadic, \( \frac{1}{2}Q \) is another square made up of 4 dyadic squares, and some calculations may be a little simpler.

Given a square \( Q \) (which may be nondyadic) with side length \( 2^{-n} \), we denote \( J(Q) := n \). Given \( a, b > 1 \), we say that \( Q \) is \((a, b)\)-doubling if \( \mu(aQ) \leq b\mu(Q) \). If we do not want to specify the constant \( b \), we say that \( Q \) is \( a \)-doubling.

**Remark 2.1.** If \( b > a^2 \), then it easily follows that for \( \mu \)-a.e. \( x \in \mathbb{C} \) there exists a sequence of \((a, b)\)-doubling squares \( \{Q_n\}_n \) centered at \( x \) with \( \ell(Q_n) \to 0 \) (and with \( \ell(Q_n) = 2^{-k_n} \) for some \( k_n \in \mathbb{Z} \) if necessary).

As usual, in this paper the letter ‘\( C \)’ stands for an absolute constant which may change its value at different occurrences. On the other hand, constants with subscripts, such as \( C_1 \), retain their value at different occurrences. The notation \( A \lesssim B \) means that there is a positive absolute constant \( C \) such that \( A \leq CB \). So \( A \simeq B \) is equivalent to \( A \lesssim B \lesssim A \).

### 3. The corona decomposition

This section deals with the corona construction. In the next lemma we will introduce a family \( \text{Top}(E) \) of 4-dyadic squares (the top squares) satisfying some precise properties. Given any square \( Q \in \text{Top}(E) \), we denote by \( \text{Stop}(Q) \) the subfamily of the squares \( P \in \text{Top}(E) \) satisfying

(a) \( P \cap 3Q \neq \emptyset \),

(b) \( \ell(P) \leq \frac{1}{5} \ell(Q) \),

...
(c) $P$ is maximal, in the sense that there does not exist another square $P' \in \text{Top}(E)$ satisfying (a) and (b) which contains $P$.

We also denote by $Z(\mu)$ the set of points $x \in \mathbb{C}$ such that there does not exist a sequence of $(70, 5000)$-doubling squares $\{Q_n\}_n$ centered at $x$ with $\ell(Q_n) \to 0$ as $n \to \infty$, so that moreover $\ell(Q_n) = 2^{-k_n}$ for some $k_n \in \mathbb{Z}$. By the preceding remark we have $\mu(Z(\mu)) = 0$.

The set of good points for $Q$ is defined as

$$G(Q) := 3Q \cap \text{supp}(\mu) \setminus \left[ Z(\mu) \cup \bigcup_{P \in \text{Stop}(Q)} P \right].$$

Given two squares $Q \subset R$, we set

$$\delta_\mu(Q, R) := \int_{R \setminus Q} \frac{1}{|y - x_Q|} \, d\mu(y),$$

where $x_Q$ stands for the center of $Q$, and $R_Q$ is the smallest square concentric with $Q$ that contains $R$.

**Main Lemma 3.1** (The corona decomposition). Let $\mu$ be a Radon measure supported on $E \subset \mathbb{C}$ such that $\mu(B(x, r)) \leq C_0 r$ for all $x \in \mathbb{C}$, $r > 0$ and $c^2(\mu) < \infty$. There exists a family $\text{Top}(E)$ of $4$-dyadic $(16, 5000)$-doubling squares (called top squares) which satisfy the packing condition

$$\sum_{Q \in \text{Top}(E)} \theta_\mu(Q)^2 \mu(Q) \leq C(\mu(E) + c^2(\mu)),$$

and such that for each square $Q \in \text{Top}(E)$ there exists a $C_3$-AD regular curve $\Gamma_Q$ such that:

(a) $G(Q) \subset \Gamma_Q$.

(b) For each $P \in \text{Stop}(Q)$ there exists some square $\bar{P}$ containing $P$ such that $\delta_\mu(P, \bar{P}) \leq C\theta_\mu(Q)$ and $\bar{P} \cap \Gamma_Q \neq \emptyset$.

(c) If $P$ is a square with $\ell(P) \leq \ell(Q)$ such that either $P \cap G(Q) \neq \emptyset$ or there is another square $P' \in \text{Stop}(Q)$ such that $P \cap P' \neq \emptyset$ and $\ell(P') \leq \ell(P)$, then $\mu(P) \leq C \theta_\mu(Q) \ell(P)$.

Moreover, $\text{Top}(E)$ contains some $4$-dyadic square $R_0$ such that $E \subset R_0$.

Notice that the AD regularity constant of the curves $\Gamma_Q$ in the lemma is uniformly bounded above by the constant $C_3$.

In Subsections 3.1, 3.2 and 3.3 we explain how the $4$-dyadic squares in $\text{Top}(E)$ are chosen. Section 4 deals with the construction of the curves $\Gamma_Q$. The packing condition (3.1) is proved in Sections 5–7.
The squares in Top(E) are obtained by stopping-time arguments. The first step consists of choosing a family Top₀(E) which is a kind of pre-selection of the 4-dyadic squares which are candidates to be in Top(E). In the second step, some unnecessary squares in Top₀(E) are eliminated. The remaining family of squares is Top(E).

3.1. Pre-selection of the top squares. To prove the Main Lemma 3.1, we will assume that E is contained in a dyadic square with side length comparable to diam(E). It easy to check that the lemma follows from this particular case.

All the squares in Top₀(E) will be chosen to be (16, 5000)-doubling. We define the family Top₀(E) by induction. Let R₀ be a 4-dyadic square with ℓ(R₀) ≃ diam(E) such that E is contained in one of the four dyadic squares in 1/2R₀ with side length ℓ(R₀)/4. Then, we set R₀ ∈ Top₀(E). Suppose now that we have already decided that some squares belong to Top₀(E). If Q is one of them, then it generates a (finite or countable) family of “bad” (16, 5000)-doubling 4-dyadic squares, called Bad(Q). We will explain precisely below how this family is constructed. For the moment, let us say that if P ∈ Bad(Q), then P ⊂ 4Q and ℓ(P) ≤ ℓ(Q)/8. One should think that, in a sense, supp(µ|₃Q) can be well approximated by a “nice” curve Γₚ up to the scale of the squares in Bad(Q). All the squares in Bad(Q) become also elements of the family Top₀(E).

In other words, we start the construction of Top₀(E) by R₀. The next squares that we choose as elements of Top₀(E) are the squares from the family Bad(R₀). And the following ones are those generated as bad squares of some square which is already in Bad(R₀), and so on. The family Top₀(E) is at most countable. Moreover, in this process of generation of squares of Top₀(E), a priori, it may happen that some bad square P is generated by two different squares Q₁, Q₂ ∈ Top₀(E) (i.e. P ∈ Bad(Q₁) ∩ Bad(Q₂)). We do not care about this fact.

3.2. The family Bad(R). Let R be some fixed (16, 5000)-doubling 4-dyadic square. We will show now how we construct Bad(R). Roughly speaking, a square Q with center in 3R and ℓ(Q) ≤ ℓ(R)/32 is not good (we prefer to reserve the terminology “bad” for the final choice) for the approximation of µ|₃R by an Ahlfors regular curve Γₚ if either:

(a) θₚ(Q) ≫ θₚ(R) (i.e. too high density), or

(b) Kₚ,J(Q)+₁₀χₚ(x) - Kₚ,J(R)-₅χₚ(x) is too big for “many” points x ∈ Q (i.e. too high curvature), or

(c) θₚ(Q) ≪ θₚ(R) (i.e. too low density).

A first attempt to construct Bad(R) might consist of choosing some kind of maximal family of squares satisfying (a), (b) or (c). However, we want the
squares from $\text{Bad}(R)$ to be doubling, and so the arguments for the construction will become somewhat more involved.

Let $A > 0$ be some big constant (to be chosen below, in Subsection 5.2), $\delta > 0$ be some small constant (which will be fixed in Section 7, depending on $A$, besides other things), and $\varepsilon_0 > 0$ be another small constant (to be chosen also in Section 7, depending on $A$ and $\delta$). Let $Q$ be some $(70, 5000)$-doubling square centered at some point in $3R \cap \text{supp}(\mu)$, with $\ell(Q) = 2^{-n}\ell(R)$, $n \geq 5$. We introduce the following notation:

- If $\theta_\mu(Q) \geq A\theta_\mu(R)$, then we write $Q \in \text{HD}_{c,0}(R)$ (high density).
- If $Q \not\in \text{HD}_{c,0}(R)$ and
  \[ \mu \{ x \in Q : K_{\mu,j(Q)+10}\chi_E(x) - K_{\mu,j(R)-4}\chi_E(x) \geq \varepsilon_0\theta_\mu(R)^2 \} \geq \frac{1}{2} \mu(Q), \]
  then $Q \in \text{HC}_{c,0}(R)$ (high curvature).
- If $Q \not\in \text{HD}_{c,0}(R) \cup \text{HC}_{c,0}(R)$ and there exists some square $S_Q$ such that $Q \subset \frac{1}{100}S_Q$, with $\ell(S_Q) \leq \ell(R)/8$ and $\theta_\mu(S_Q) \leq \delta \theta_\mu(R)$, then we set $Q \in \text{LD}_{c,0}(R)$ (low density).

The subindex $c$ in $\text{HD}_{c,0}$, $\text{LD}_{c,0}$, and $\text{HC}_{c,0}$ refers to the fact that these families contain squares whose centers belong to $\text{supp}(\mu)$.

For each point $x \in 3R \cap \text{supp}(\mu)$ which belongs to some square from $\text{HD}_{c,0}(R) \cup \text{HC}_{c,0}(R) \cup \text{LD}_{c,0}(R)$ consider the largest square $Q_x \in \text{HD}_{c,0}(R) \cup \text{HC}_{c,0}(R) \cup \text{LD}_{c,0}(R)$ which contains $x$. Let $\hat{Q}_x$ be a 4-dyadic square with side length $4\ell(Q_x)$ such that $Q_x \subset \frac{1}{2}\hat{Q}_x$. Now we apply Besicovitch’s covering theorem to the family $\{\hat{Q}_x\}_x$ (notice that this theorem can be applied because $x \in \frac{1}{2}\hat{Q}_x$), and we obtain a family of 4-dyadic squares $\{\hat{Q}_x\}_i$ with finite overlap such that the union of the squares from $\text{HD}_{c,0}(R) \cup \text{HC}_{c,0}(R) \cup \text{LD}_{c,0}(R)$ is contained (as a set in $\mathbb{C}$) in $\bigcup_i \hat{Q}_x$. We define

\[ \text{Bad}(R) := \{\hat{Q}_x\}_i. \]

If $Q_{x_i} \in \text{HD}_{c,0}(R)$, then we write $\hat{Q}_{x_i} \in \text{HD}_0(R)$, and analogously with $\text{HC}_{c,0}(R)$, $\text{LD}_{c,0}(R)$ and $\text{HC}_0(R)$, $\text{LD}_0(R)$.

Remark 3.2. The constants that we denote by $C$ (with or without subindex) in the rest of the proof of Main Lemma 3.1 do not depend on $A$, $\delta$, or $\varepsilon_0$, unless stated otherwise.

In the next two lemmas we show some properties fulfilled by the family $\text{Bad}(R)$.

Lemma 3.3. Given $R \in \text{Top}_0(E)$, the following properties hold for every $Q \in \text{Bad}(R)$:
BILIPSCHITZ MAPS, ANALYTIC CAPACITY, AND THE CAUCHY INTEGRAL

(b) If \( Q \in \text{HD}_0(R) \), then \( \theta_\mu(Q) \gtrsim A \theta_\mu(R) \).

(c) If \( Q \in \text{HC}_0(R) \), then
\[
\mu\{x \in \frac{1}{2} Q : K_{\mu,J(Q)+12} \chi_E(x) - K_{\mu,J(R)-4} \chi_E(x) \geq C^{-1} \varepsilon_0 \theta_\mu(R)^2\} \gtrsim \frac{1}{2} \mu(Q).
\]

(d) If \( Q \in \text{LD}_0(R) \), then there exists some square \( S_Q \) such that
\[
Q \subset \frac{1}{20} S_Q, \quad \ell(S_Q) \leq \ell(R)/8, \quad \text{with} \quad \theta_\mu(S_Q) \lesssim \delta \theta_\mu(R).
\]

Proof. The doubling properties of \( Q \) and \( \frac{1}{2} Q \) follow easily. Let \( x \in 3R \cap \text{supp}(\mu) \) be such that \( Q = \hat{Q}_x \), by the notation above. Since \( \frac{1}{2} \hat{Q}_x \supset Q_x \), \( Q_x \) is \((70,5000)\)-doubling, and \( 70Q_x \supset 16 \hat{Q}_x \), we get
\[
\mu(\hat{Q}_x) \geq \mu(\frac{1}{2} \hat{Q}_x) \geq \mu(Q_x) \geq \frac{1}{5000} \mu(70Q_x) \geq \frac{1}{5000} \mu(16 \hat{Q}_x).
\]
The statements (b), (c) and (d) are a direct consequence of the definitions and of the fact that \( \theta_\mu(Q_x) \simeq \theta_\mu(\hat{Q}_x) \).

Lemma 3.4. Given \( R \in \text{Top}_0(E) \), the following properties hold for every \( Q \in \text{Bad}(R) \):

(a) If \( P \) is a square such that \( P \cap Q \neq \emptyset \) and \( \ell(Q) \leq \ell(P) \leq \ell(R) \), then
\[
\mu(P) \leq C_4 \theta_\mu(R) \ell(P).
\]

(b) If \( P \) is a square concentric with \( Q \), \( \ell(P) \leq \ell(R)/8 \), and \( \delta_\mu(Q,P) \geq C_5 A \theta_\mu(R) \) (where \( C_5 > 0 \) is big enough), then
\[
\mu(P) \geq \delta \theta_\mu(R) \ell(P)
\]

and
\[
K_{\mu,J(P)+12} \chi_E(x) - K_{\mu,J(R)-2} \chi_E(x) \lesssim A^2 \theta_\mu(R)^2 \quad \text{for all} \quad x \in P.
\]

Before proving the lemma we recall the following result, whose proof follows by standard arguments (see [To1, Lemma 2.4]).

Lemma 3.5. Let \( x, y, z \in \mathbb{C} \) be three pairwise different points, and let \( x' \in \mathbb{C} \) be such that \( C_6^{-1}|x - y| \leq |x' - y| \leq C_6|x - y| \). Then,
\[
|c(x, y, z) - c(x', y, z)| \leq (4 + 2C_6) \frac{|x - x'|}{|x - y||x - z|}.
\]
Proof of Lemma 3.4. Let \( x \in 3R \cap \text{supp}(\mu) \) be such that \( Q = \hat{Q}_x \), by the notation above.

Let us prove (a). If \( \ell(R)/8 < \ell(P) \leq \ell(R) \), then
\[
\mu(P) \leq \mu(5R) \lesssim \mu(R) = \theta_\mu(R) \ell(R) \lesssim \theta_\mu(R) \ell(P).
\]
If \( P \) is of the form \( 2^nQ_x \), \( n \geq 1 \), with \( \ell(P) \leq \ell(R)/8 \), and \( P \) is \((70,5000)\)-doubling, then
\[
\mu(2^nQ_x) = \theta_\mu(2^nQ_x) \ell(2^nQ_x) \leq A\theta_\mu(R) \ell(2^nQ_x),
\]
by the definition of \( Q_x \). If \( P \) is of the same type but it is not doubling, then we take the smallest \((70,5000)\)-doubling square \( \tilde{P} := 2^mQ_x \) such that \( P \subseteq \tilde{P} \) and \( \ell(P) \leq \ell(R)/8 \), in case that it exists. If all the squares \( 2^nQ_x \) containing \( P \) with \( \ell(2^nQ) \leq \ell(R)/8 \) are non-\((70,5000)\)-doubling, we set \( \tilde{P} := 2^mQ_x \), with \( m \) such that \( \ell(P) = \ell(R)/8 \). In any case we have
\[
\theta_\mu(P) \leq \theta_\mu(2P) \leq \theta_\mu(2^2P) \leq \cdots \leq \theta_\mu(\tilde{P}) \leq CA\theta_\mu(R).
\]
The statement (a) for an arbitrary square \( P \) such that \( P \cap \hat{Q}_x \neq \emptyset \) and \( \ell(\hat{Q}_x) \leq \ell(P) \leq \ell(R) \) follows easily from the preceding instances.

Now we turn our attention to (b). Let \( P \supset Q \) be a square concentric with \( Q \) such that \( \ell(P) \leq \ell(R)/8 \) and \( \delta_\mu(Q,P) \geq C_5A\theta_\mu(R) \). It is easy to check (by estimates analogous to the ones of [To2, Lemma 2.1]) that if \( C_5 \) is chosen big enough, then there exists some \((70,5000)\)-doubling square \( 2^nQ_x \) such that \( 2Q \subset 2^nQ_x \subset \frac{1}{10^{10}}P \). Then \( 2^nQ_x \notin LD_{c,0}(R) \), and by construction \( \theta_\mu(P) \geq \delta\theta_\mu(R) \).

On the other hand, also by construction, there exists some \( y \in 2^nQ_x \) such that
\[
K_{\mu,J(P)+12}(x) - K_{\mu,J(R)-2}(y) \leq K_{\mu,J(2^nQ_x)+12}(x) - K_{\mu,J(R)-4}(y) \leq \varepsilon_0\theta_\mu(R)^2.
\]
Then, for any \( x \in P \),
\[
(3.4) \quad K_{\mu,J(P)+12}(x) - K_{\mu,J(R)-2}(y)
\]
\[
= \int_{2^{-12}(\ell(P)<|x-t|\leq4\ell(R))} c(x,t,z)^2 \, d\mu(t) d\mu(z) - \int_{2^{-12}(\ell(P)<|x-t|\leq4\ell(R))} c(y,t,z)^2 \, d\mu(t) d\mu(z)
\]
\[
\leq 2 \int_{2^{-12}(\ell(P)<|x-t|\leq4\ell(R))} c(y,t,z)^2 \, d\mu(t) d\mu(z)
\]
\[
+2 \int_{2^{-12}(\ell(P)<|x-t|\leq4\ell(R))} \left[ c(x,t,z) - c(y,t,z) \right]^2 \, d\mu(t) d\mu(z)
\]
\[
=: 2I_1 + 2I_2.
\]
We have
\[
I_1 = K_{\mu,J(P)+12}(y) - K_{\mu,J(R)-2}(y) \leq \varepsilon_0\theta_\mu(R)^2.
\]
To estimate $I_2$, notice that by Lemma 3.5,

$$\left[ c(x, t, z) - c(y, t, z) \right]^2 \lesssim \max \left( \frac{1}{\ell(P)^2}, \frac{\ell(2^nQ_x)^2}{|x - t|^2 |x - z|^2} \right).$$

Integrating this inequality over $\{(t, z) \in \mathbb{C}^2 : 2^{-12} \ell(P) < |x - t| \leq 4 \ell(R)\}$ (dividing $\mathbb{C}$ into annuli, for example), one easily gets

$$I_2 \leq \left( \sup_{\lambda > 1} \frac{\mu(\lambda P \cap 16R)}{\ell(\lambda P)} \right)^2 \lesssim A^2 \theta_\mu(R)^2.$$

Summing the estimates for $I_1$ and $I_2$, we see that (3.3) follows.

### 3.3. Elimination of unnecessary squares from Top$_0(E)$.

Some of the bad squares generated by each square $R \in \text{Top}_0(E)$ may not be contained in $R$. This fact may cause troubles when we try to prove a packing condition such as (3.1) (because of the possible superposition of squares coming from different $R$’s in Top$_0(E)$). The class Top($E$) that we are going to construct will be a refined version of Top$_0(E)$, where some unnecessary squares will be eliminated.

Let us introduce some notation first. We say that a square $Q \in \text{Top}_0(E)$ is a descendant of another square $R \in \text{Top}_0(E)$ if there is a chain $R = Q_1, Q_2, \ldots, Q_n = Q$, with $Q_i \in \text{Top}_0(E)$ such that $Q_{i+1} \in \text{Bad}(Q_i)$ for each $i$. Observe that, in principle, some square $Q$ may be a descendant of more than one square $R$. Then, in the algorithm of elimination below, $Q$ must be counted with multiplicity (so that $Q$ is completely eliminated if it has been eliminated $m$ times, where $m$ is the multiplicity of $Q$, etc.)

Let us describe the algorithm for constructing Top($E$). We have to decide when any square in Top$_0(E)$ belongs to Top($E$). We follow an induction procedure of elimination. A square in Top$_0(E)$ that (during the algorithm we decide belongs to Top($E$)) is said to be “chosen for Top($E$)”. If we decide that it will not belong to Top($E$) (i.e. we eliminate it), we say that it is “unnecessary”. If we have not decided already if it is either chosen for Top($E$) or unnecessary, we say that it is “available”. We start with all the squares in Top$_0(E)$ being available, and at each step of the algorithm, some squares are chosen for Top($E$) and others become unnecessary.

Let $R_0$ be the 4-dyadic square containing $E$ defined at the beginning of Subsection 3.1. We start by choosing $R_0$ for Top($E$). Let $R_1$ be (one of) the squares from Bad($R_0$) with maximal side length. We choose $R_1$ for Top($E$) too. Next, we choose for Top($E$) (one of) the available square(s) $R_2 \in \text{Top}_0(E)$ with maximal side length. At this point, some available squares in Top$_0(E)$ may become unnecessary. First, these are the squares $Q$ with $Q \in \text{Bad}(R)$ for some $R \in \text{Top}_0(E)$ such that $Q \subset R_2$ and $\ell(R_2) \leq \ell(R)/8$ (notice that this implies that either $R = R_0$ or $R = R_1$). Also, all the squares which are descendants of unnecessary squares become unnecessary.
Suppose now that we have chosen $R_0, R_1, \ldots, R_{k-1}$ for $\text{Top}(E)$, with
\[ \ell(R_0) \geq \ell(R_1) \geq \cdots \geq \ell(R_{k-1}), \]
and that the available squares in $\text{Top}_0(E)$ have side length $\leq \ell(R_{k-1})$. Let $R_k$ be (one of) the available square(s) in $\text{Top}_0(E)$ with maximal side length. We choose $R_k$ for $\text{Top}(E)$. The squares that become unnecessary are those available squares $Q$ such that $Q \in \text{Bad}(R)$ for some $R \in \text{Top}_0(E)$ with $Q \subset R_k$ and $\ell(R_k) \leq \ell(R)/8$ (this implies that $R$ coincides with one of the squares $R_1, \ldots, R_{k-1}$). Again, all the squares which are descendants of unnecessary squares become unnecessary too.

It is easily seen that following this algorithm one will decide if any square in $\text{Top}_0(E)$ is unnecessary or chosen for $\text{Top}(E)$. Notice that the squares $Q \in \text{Bad}(R)$ which are eliminated after choosing $R_k$ are the ones such that $R_k$ becomes an “intermediate” square (in a sense) between $Q$ and its generator $R$ (i.e. the square $R \in \text{Top}_0(E)$ such that $Q \in \text{Bad}(R)$), as well as descendants of already eliminated squares. Moreover, if a square $Q$ has been eliminated but its generator $R$ has been chosen for $\text{Top}(E)$, it means that there is another chosen square $Q' \in \text{Top}(E)$ which contains $Q$, with $\ell(Q') \leq \ell(R)/8$. Thus, if $R \in \text{Top}(E)$, then

\[ \bigcup_{Q \in \text{Bad}(R)} Q \subset \bigcup_{Q' \in \text{Stop}(R)} Q', \]

where the union on the right side is over the squares $Q' \in \text{Top}(E)$ such that there exists $Q \in \text{Bad}(R)$ contained in $Q'$ and $\ell(Q') \leq \ell(R)/8$.

Remember the definition of $\text{Stop}(R)$, for $R \in \text{Top}(E)$, given at the beginning of Section 3. Notice that $\text{Bad}(R) \cap \text{Top}(E) \subset \text{Stop}(R)$. Of course, the opposite inclusion is false in general. By (3.5), we also have

\[ \bigcup_{Q \in \text{Bad}(R)} Q \subset \bigcup_{Q' \in \text{Stop}(R)} Q'. \]

Given $R \in \text{Top}(E)$ and $Q \in \text{Stop}(R)$, we write $Q \in \text{HD}(R)$ if there exists some $R' \in \text{Top}(E)$ such that $Q \in \text{Bad}(R') \cap \text{HD}(R')$ analogously with $\text{LD}(R)$ and $\text{HC}(R)$.

**Remark 3.6.** Let us insist again on the following fact: for any $R \in \text{Top}(E)$, if $Q \in \text{Bad}(R)$, then either $Q \in \text{Stop}(R)$ or otherwise there is some $Q' \in \text{Stop}(R)$ such that $Q' \supset Q$.

**Remark 3.7.** Changing constants if necessary, the properties (a) and (b) of Lemma 3.4 also hold if instead of assuming $Q \in \text{Bad}(R)$, we suppose that $Q \in \text{Stop}(R)$. This is due to the fact that, with the new assumption $Q \in \text{Stop}(R)$, the squares $P$ considered in Lemma 3.4 (a), (b) will be, roughly speaking, a subset of the corresponding squares $P$ with the assumption $Q \in \text{Bad}(R)$, because of the preceding remark.
On the other hand, in principle, (b), (c) and (d) in Lemma 3.3 may fail. Nevertheless, we will see in Lemma 5.3 below that they still do hold in some special cases.

4. Construction of the curves $\Gamma_R$, $R \in \text{Top}(E)$

4.1. P. Jones’ travelling salesman theorem. To construct the curves $\Gamma_R$ for $R \in \text{Top}(E)$, we will apply P. Jones’ techniques. Before stating the precise result that we will use, we need to introduce some notation. Given a set $K \subset \mathbb{C}$ and a square $Q$, let $V_Q$ be an infinite strip (or line in the degenerate case) of smallest possible width which contains $K \cap 3Q$, and let $w(V_Q)$ denote the width of $V_Q$. Then we set

$$\beta_K(Q) = \frac{w(V_Q)}{\ell(Q)}.$$

We will use the following version of Jones’ travelling salesman theorem [Jo]:

**Theorem C** (P. Jones). A set $K \subset \mathbb{C}$ is contained in an AD regular curve if and only if there exists some constant $C_7$ such that for every dyadic square $Q$

$$\sum_{P \in D, P \subset Q} \beta_K(P)^2 \ell(P) \leq C_7 \ell(Q).$$

The AD regularity constant of the curve depends on $C_7$.

Let us mention that in [MMV], using an $L^2$ version of Jones’ theorem due to David and Semmes [DS2], the authors showed that if $\mu$ is a measure such that $\mu(B(x,r)) \approx r$ and $c^2(\mu|_{B(x,r)}) \leq C\mu(B(x,r))$ for all $x \in \text{supp}(\mu)$, $0 < r \leq \text{diam}(\text{supp}(\mu))$, then $\text{supp}(\mu)$ is contained in an AD regular curve. In our case, the measure $\mu|_R$ does not satisfy these conditions. However, in a sense, they do hold for “big” balls $B(x,r)$, at scales sufficiently above the stopping squares.

In order to apply Jones’ result, we will construct a set $K$ which approximates $\text{supp}(\mu) \cap 3R$ at some level above the stopping squares and then, using Theorem C, we will show that there exists a curve $\Gamma_R$ which contains $K$. We have not been able to extend the arguments in [MMV] to our situation. Instead, our approach is based on another idea of Jones which shows how one can estimate the $\beta$ numbers of an AD regular set in terms of the curvature of a measure (see [Pa, Th. 38]).

4.2. Balanced squares. Before constructing the appropriate set $K$ which approximates $\text{supp}(\mu)$ we need to show the existence of some squares that will be called balanced squares, which will be essential for our calculations.
Given \(a, b > 0\), we say that a square \(Q\) is balanced with parameters \(a, b\) (or \((a, b)\)-balanced) with respect to \(\mu\) if there exist two squares \(Q_1, Q_2 \subset Q\) such that

- \(\text{dist}(Q_1, Q_2) \geq a \ell(Q)\),
- \(\ell(Q_i) \leq \frac{a}{10} \ell(Q)\) for \(i = 1, 2\), and
- \(\mu(Q_i) \geq b \mu(Q)\) for \(i = 1, 2\).

We write \(Q \in \text{Bal}_\mu(a, b)\).

The next lemmas deal with the existence of balanced squares.

**Lemma 4.1.** Let \(a = 1/40\). If \(Q \notin \text{Bal}_\mu(a, b)\), then there exists a square \(P \subset Q\) with \(\ell(P) \leq \ell(Q)/10\) such that \(\mu(P) \geq (1 - 2 \cdot 10^5 b) \mu(Q)\).

**Proof.** We set \(N := 400\). We split \(Q\) into \(N^2\) squares \(Q_k\), \(k = 1, \ldots, N^2\), of side length \(\ell(Q)/N = a \ell(Q)/10\). We put

\[
G = \{Q_k : 1 \leq k \leq N^2, \mu(Q_k) \geq b \mu(Q)\}.
\]

Since \(Q \notin \text{Bal}_\mu(a, b)\), given any pair of squares \(Q_j, Q_k\), \(1 \leq j, k \leq N^2\) such that \(\text{dist}(Q_j, Q_k) \geq a \ell(Q)\), it turns out that one of the two squares, say \(Q_j\), satisfies \(\mu(Q_j) \leq b \mu(Q)\). Therefore, all the squares from \(G\) are contained in a ball \(B_0\) of radius \(2a \ell(Q)\), since

\[
\left(\frac{2a}{10} + a\right)2^{1/2}\ell(Q) \leq 2a \ell(Q).
\]

Thus,

\[
\sum_{k:Q_k \in G} \mu(Q_k) \leq \mu(B_0 \cap Q).
\]

Also,

\[
\sum_{k:Q_k \notin G} \mu(Q_k) \leq b \sum_{k:Q_k \notin G} \mu(Q) \leq b N^2 \mu(Q) = \frac{100b}{a^2} \mu(Q).
\]

Then we have

\[
\mu(Q) \leq \mu(B_0 \cap Q) + \frac{100b}{a^2} \mu(Q).
\]

Thus,

\[
\mu(B_0 \cap Q) \geq \left(1 - \frac{100b}{a^2}\right) \mu(Q) \geq (1 - 2 \cdot 10^5 b) \mu(Q).
\]

Since the radius of \(B_0\) equals \(2a \ell(Q) = \ell(Q)/20\), there exists some square \(P \subset Q\) with side length \(\ell(Q)/10\) which contains \(B_0 \cap Q\), and we are done. \(\square\)
Lemma 4.2. Let $Q$ be a square such that $2Q \notin \text{Bal}_\mu(1/40, b)$, and suppose that $\theta_\mu(2Q) \leq C_4 A \theta_\mu(R)$ and $\theta_\mu(\frac{1}{2}Q) \geq C_4^{-1} \delta \theta_\mu(R)$ (with $C_4$ given by Lemma 3.4 (a)). If $b \ll \delta/A$, then

$$\mu(2Q \setminus Q) \leq \frac{1}{10} \mu(Q).$$

Proof. By Lemma 4.1 there exists a square $P \subset 2Q$ with $\ell(P) \leq \ell(2Q)/10$ such that $\mu(P) \geq (1 - 2 \cdot 10^5 b) \mu(2Q)$. If $P \not\subset Q$, then $P \subset 2Q \setminus \frac{1}{2}Q$, and so

$$\mu(2Q \setminus \frac{1}{2}Q) \geq \mu(P) \geq (1 - 2 \cdot 10^5 b) \mu(2Q).$$

Thus, $\mu(\frac{1}{2}Q) \leq 2 \cdot 10^5 b \mu(2Q)$. If $b \ll \delta/A$, then we derive $\theta_\mu(\frac{1}{2}Q) < C_4^{-2} \delta A^{-1} \theta_\mu(2Q)$, which is a contradiction. Therefore, $P \subset Q$, and then

$$\mu(2Q \setminus Q) \leq \mu(2Q \setminus P) \leq 2 \cdot 10^5 b \mu(2Q) \leq \frac{1}{10} \mu(\frac{1}{2}Q),$$

since $b \ll \delta/A$. \hfill \Box

Remark 4.3. From now on, we assume that $a = 1/40$, and moreover that $b = b(A, \delta) \ll \delta/A$, so that the preceding lemma holds. For these precise values of $a$ and $b$ we write $\text{Bal}(\mu) := \text{Bal}_\mu(a, b)$.

Lemma 4.4. Let $Q$ be a square whose center lies on $3R$ and is such that $\ell(Q) \leq C_8^{-1} A^{-2} \ell(R)$ and

$$\delta \theta_\mu(R) \lesssim \theta_\mu(2^n Q) \lesssim A \theta_\mu(R)$$

for all $n \geq 0$ with $\ell(2^n Q) \leq 8 \ell(R)$. If $C_8$ is big enough, then there exists some square $Q \in \text{Bal}(\mu)$ concentric with $Q$ such that $2 \ell(Q) \leq \ell(Q) \leq 8 \ell(R)$ and also $\ell(Q) \leq C_0(A, \delta) \ell(Q)$.

Proof. If $2^n Q \not\subset \text{Bal}(\mu)$ for $n = 1, \ldots, N$, with $\ell(2^n Q) \leq 8 \ell(R)$, then

$$\mu(2^n Q \setminus 2^{n-1} Q) \leq \frac{1}{10} \mu(2^{n-1} Q) \quad \text{for } n = 1, \ldots, N.$$

Thus, $\mu(2^n Q) \leq 1.1 \mu(2^{n-1} Q)$ for $n = 1, \ldots, N$, and so

$$\mu(2^N Q) \leq 1.1^N \mu(Q) \leq 2^{N/2} \mu(Q) \leq C A \theta_\mu(R) 2^{N/2} \ell(Q) = C A \theta_\mu(R) 2^{-N/2} \ell(2^N Q).$$

Therefore,

(4.2) \hspace{1cm} \theta_\mu(2^N Q) \leq C A 2^{-N/2} \theta_\mu(R).

Suppose that $N$ is such that $\ell(2^N Q) = 8 \ell(R)$. Then we have $\theta_\mu(R) \simeq \theta_\mu(2^N Q)$, and by (4.2) we get $C A 2^{-N/2} \geq 1$, and so

$$\ell(R) = \frac{1}{8} \ell(2^N Q) \leq C A^2 \ell(Q) =: \frac{C_8 A^2}{2} \ell(Q),$$

which contradicts the assumptions of the lemma.
We infer that there is a square $2^nQ \in \text{Bal}(\mu)$ with $n \geq 1$ and $\ell(2^nQ) \leq 8\ell(R)$. Let $\tilde{Q}$ be the smallest one. Let $N$ be such that $2^NQ = \frac{1}{2} \tilde{Q}$. From (4.2), since $\theta_\mu(2^NQ) \geq \delta_\mu(R)$, we deduce $C A \delta^{-1}2^{-N/2} \geq 1$, and then $\ell(\tilde{Q}) \leq CA^2 \delta^{-2} \ell(Q)$. \hfill \square

4.3. Construction of $K$. From Lemma 3.4 (b) it easily follows that for any square $Q \in \text{Bad}(R)$ there exists another square $\tilde{Q}$ concentric with $Q$ satisfying $2\ell(Q) \leq \ell(\tilde{Q}) \leq 8\ell(R)$ and $\delta_\mu(Q,\tilde{Q}) \lesssim A\theta_\mu(R)$, such that

$$\text{(4.3) if } n \geq -1 \text{ and } \ell(2^n\tilde{Q}) \leq 8\ell(R), \text{ then } \delta_\mu(Q,2^n\tilde{Q}) \lesssim A\theta_\mu(R)$$

and moreover

$$\text{(4.4) } \int_{\{y,z \in 3R \atop 2^{-12}\ell(\tilde{Q}) < |x-y| \leq 4\ell(R)\}} c(x,y,z)^2 \, d\mu(y)d\mu(z) \leq K_{\mu,J(\tilde{Q})+12}(x) - K_{\mu,J(\tilde{Q})-2}(x) \lesssim A^2\theta_\mu(R)^2$$

for all $x \in \tilde{Q}$.

As explained in Remark 3.7, the same holds if $Q \in \text{Stop}(R)$ (instead of $\text{Bad}(R)$). Further, we can take the squares $\tilde{Q}$ to be 4-dyadic (in this way, some of the calculations below will become simpler). That is to say, given $Q \in \text{Stop}(R)$ there exists a 4-dyadic square $\tilde{Q}$ such that $Q \subset \frac{1}{2} \tilde{Q}$ (we cannot assume $Q$ and $\tilde{Q}$ to be concentric) with $2\ell(Q) \leq \ell(\tilde{Q}) \leq 8\ell(R)$ and $\delta_\mu(Q,\tilde{Q}) \lesssim A\theta_\mu(R)$ which satisfies (4.3) and (4.4). We denote by $Q_{\text{stp}}(R)$ the family of squares $\tilde{Q}$, with $Q \in \text{Stop}(R)$, and we say that $\tilde{Q}$ is a quasi-stopping square of $R$.

We intend to construct some set $K$ containing $G(R)$ (remember that $G(R)$ is the set of good points of $R$) such that, besides other properties, for each $Q \in Q_{\text{stp}}(R)$ there exists some point $a_Q \in K$ with $\text{dist}(a_Q, Q) \leq C\ell(Q)$. In the next subsection, we will show that $K$ verifies (4.1), and thus $K$ will be contained in an AD regular curve $\Gamma_R$. This curve will fulfill the required properties in Main Lemma 3.1.

In the next lemma we deal with the details of the construction of $K$ and selection of the points $a_Q$, $Q \in Q_{\text{stp}}(R)$. Most difficulties are due to the fact that the squares $Q \in Q_{\text{stp}}(R)$ are not disjoint, in general.

**Lemma 4.5.** Let $\eta > 3$ be some fixed constant to be chosen below. For each $x \in 3R$,

$$\ell_x := \inf_{Q \in Q_{\text{stp}}(R)} \left( \ell(Q) + \frac{1}{40} \text{dist}(x,Q), \frac{1}{40} \text{dist}(x,G(R)) \right).$$

There exists a family of points $\{a_Q\}_{Q \in Q_{\text{stp}}(E)}$ such that if $K := G(R) \cup \{a_Q\}_{Q \in Q_{\text{stp}}(R)}$,

the following properties hold:
(a) For each $Q \in \text{Qstp}(R)$, $\text{dist}(a_Q, Q) \leq C\ell(Q)$.

(b) There exists $C > 0$ such that for all $x \in K$, $K \cap B(x, C^{-1}\ell_x) = \{x\}$.

(c) If $x \in K$ and $\ell_x > 0$, then

$$c_{\mu(B(x,\ell_x)\setminus B(x,\ell_x)]}^2(x) \leq \frac{C(A,\delta)}{\mu(B(x,\ell_x))} \iint_{y,z,t \in B(x,C\eta(\ell_x))} c(y,z,t)^2 d\mu(y)d\mu(z)d\mu(t).$$

We note that the lemma is understood better if we think about the points in $G(R)$ as degenerate quasi-stopping squares with zero side length. In our construction some points $a_Q$ may coincide for different squares $Q \in \text{Qstp}(R)$.

We also remark that if (b) were not required in the lemma, then its proof would be much simpler.

**Proof.** First we explain the algorithm for assigning a point $a_Q$ to each square $Q \in \text{Qstp}(R)$. Finally we will show that (a), (b) and (c) hold for our construction.

Take a fixed square $Q \in \text{Qstp}(R)$. Since $\ell_x$ is a continuous (and Lipschitz) function of $x$, there exists some $z_0 \in \overline{10Q}$ such that $\ell_x$ attains its minimum over $10Q$ at $z_0$. If $\ell_{z_0} = 0$, $a_Q := z_0$.

Suppose now that $\ell_{z_0} > 0$. Assume first that there exists a sequence of squares $\{P_n\}_n \subset \text{Qstp}(R)$ with $\ell(P_n) \to 0$ or points $p_n \in G(R)$ such that

$$\ell(P_n) + \frac{1}{40} \text{dist}(z_0, P_n) \to \ell_{z_0} \quad (4.6)$$

(we identify a point $p_n$ with a square $P_n$ with $\ell(P_n) = 0$). Since $\ell_{z_0} \leq \ell(Q)$ (because if $x \in Q$, then $\ell_x \leq \ell(Q)$ and $\ell_{z_0} \leq \ell_x$), we may assume $P_n \subset B(z_0, 4\ell(Q)) \subset \overline{90Q}$. Thus, there exists some point $z_1 \in \overline{90Q}$ such that a subsequence $\{P_{n_k}\}_k$ accumulates on $z_1$. We set $a_Q := z_1$. Observe that $\ell_{a_Q} = 0$ in this case.

Assume now that $\ell_{z_1} > 0$ and that a sequence $\{P_n\}_n$ as above does not exist. This implies that the infimum which defines $\ell_{z_0}$ (in (4.5) replacing $x$ by $z_0$) is attained over a subfamily of squares $P \in \text{Qstp}(R)$ with $\ell(P) \geq \delta$, for some fixed $\delta > 0$, which further satisfy $\text{dist}(P, Q) \leq 41\ell(Q)$ (because $\ell_{z_0} \leq \ell(Q)$). Then it turns out that such a subfamily of squares must be finite, because we are dealing with 4-dyadic squares. Thus the infimum in (4.5) (with $x$ replaced by $z_0$) is indeed a minimum (attained by only a finite number of squares in $\text{Qstp}(R)$). Among the squares where the minimum is attained, let $P_Q$ be one with minimal side length.

Let us apply Vitali’s covering theorem to the family of squares $P_Q$ obtained above. Then there exists a countable (or finite) subfamily of pairwise disjoint squares $P_i$ (which are of the type $P_Q$) such that

$$\bigcup_i P_i \subset \bigcup_i 5P_i.$$
where the union on the left side is over all the squares \( P_Q \) which arise in the algorithm above when one considers all the squares \( Q \in \text{Qstp}(R) \).

Now, for each \( i \) we choose a “good” point \( a_i \in \frac{1}{2} P_i \cap \text{supp}(\mu) \), so that

\[
(4.7) \int_{\{x, y \in 2\eta P_i : |a_i - y| \geq \ell(P_i)\}} c(a_i, y, z)^2 d\mu(y) d\mu(z) \leq \frac{1}{\mu(\frac{1}{2} P_i)} \int_{\{x, y \in 2\eta P_i : |x - y| \geq \ell(P_i)\}} c(x, y, z)^2 d\mu(x) d\mu(y) d\mu(z).
\]

We claim that for each square \( Q \in \text{Qstp}(R) \) for which \( a_Q \) has not been chosen yet (which means \( \ell_{z_0} > 0 \) and there is no sequence \( \{P_n\}_n \subset \text{Qstp}(R) \) with \( \ell(P_n) \to 0 \) satisfying (4.6)), there exists some \( a_i \) such that \( \text{dist}(a_i, Q) \leq C \ell(Q) \). Then we set \( a_Q := a_i \).

Before proving our claim, we show that if \( Q \in \text{Qstp}(R) \) is such that \( Q \cap 5 P_i \neq \emptyset \) for some \( i \), then \( \ell(Q) \geq \ell(P_i) \). Indeed, if \( \ell(Q) \leq \ell(P_i)/2 \) (remember that \( Q \) and \( P_i \) are 4-dyadic squares), then \( Q \subset 10 P_i \), and so it easily follows that for any \( y \in C \) we have

\[
(4.8) \quad \frac{1}{40} \text{dist}(y, P_i) \geq \ell(Q) = \frac{1}{40} \text{dist}(y, Q),
\]

which is not possible because of our construction (remember that there exists some \( z_0 \) such that the infimum defining \( \ell_{z_0} \) is attained by \( P_i \)).

Let us prove the claim now. By our construction, there exists some square \( P_Q \) with \( \ell(P_Q) \leq \ell(Q) \) such that \( \text{dist}(P_Q, Q) \leq C \ell(Q) \). Let \( P_i \) be such that \( 5 P_i \cap P_Q \neq \emptyset \). Since \( \ell(P_Q) \geq \ell(P_i) \),

\[
\text{dist}(a_i, Q) \leq \text{dist}(a_i, P_Q) + 2^{1/2} \ell(P_Q) + \text{dist}(P_Q, Q) \leq C \ell(P_Q) + 2^{1/2} \ell(P_Q) + C \ell(Q) \leq C \ell(Q).
\]

Let us consider the statement (b). If \( \ell_x = 0 \), there is nothing to prove. The only points such that \( \ell_x > 0 \) are the \( a_i \)’s. Notice that \( \ell_{a_i} \leq \ell(P_i) \) because \( a_i \in P_i \). On the other hand, we also have \( \ell_{a_i} \geq \frac{1}{40} \ell(P_i) \). Otherwise, it is easily seen that there exists some \( P \in \text{Qstp}(R) \) such that \( P \cap 5 P_i \neq \emptyset \) and \( \ell(P) \leq \ell(P_i)/2 \), which is not possible as shown above (in the paragraph of (4.8)). Thus (b) follows from the fact that \( a_i \in \frac{1}{2} P_i \), the squares \( P_i \) are disjoint, \( \ell(P_i) \approx \ell_{a_i} \), etc.

Finally (c) follows easily from (4.7) and the fact that \( B(a_i, \eta \ell_{a_i}) \subset 2 \eta P_i \subset B(a_i, C \eta \ell_{a_i}) \), for some \( C > 0 \).

4.4. **Estimate of** \( \sum_{P \in \mathcal{D}, P \subset Q} \beta_K(P)^2 \ell(P) \). We will need the following result.

**Lemma 4.6.** There exists some \( \lambda > 4 \) depending on \( A \) and \( \delta \) such that, given any \( Q \in \text{Qstp}(R) \), for each \( n \geq 1 \) with \( \lambda^{n+1} \ell(Q) \leq \ell(R) \) there exist two squares \( Q_n^a \) and \( Q_n^b \) fulfilling the following properties:
(a) \( Q_n^a, Q_n^b \subset \frac{\lambda^{n+1}}{2} Q \setminus \lambda^n Q \),
(b) \( \text{dist}(Q_n^a, Q_n^b) \gtrsim \lambda^n \ell(Q) \),
(c) \( \lambda^n \ell(Q) \lesssim \ell(Q_n^i) \lesssim \lambda^{n+1} \ell(Q), \) for \( i = a, b \),
(d) \( C(A, \delta)^{-1} \theta(\mu)(R) \lesssim \theta(\mu)(Q_n^i) \lesssim A \theta(\mu)(R), \) for \( i = a, b \).

Proof. The lemma follows easily from the existence of balanced squares (see Lemma 4.4). Indeed, if \( Q \in \text{Bal}(\mu) \), then there are two squares \( Q_1, Q_2 \subset Q \) fulfilling the properties stated just above Lemma 4.1. Since \( \text{dist}(Q_1, Q_2) \gtrsim \frac{1}{2^{10}} \ell(Q) \), one of the squares \( Q_i \) is contained in \( Q \setminus 2^{-7}Q \). From this fact one can easily deduce the existence of some constant \( \lambda_0 > 2 \) (depending on \( A, \delta, C, \ldots \)) such that for each \( n \geq 1 \) with \( \lambda_0^{n+1} \ell(Q) \leq \ell(R) \) there exists some square \( P_n \subset \frac{1}{2} \lambda_0^{n+1} Q \setminus \lambda_0^n Q \) satisfying \( \ell(P_n) \approx \lambda_0^{n+1} \ell(Q) \) and \( \theta(\mu)(P_n) \gtrsim C(A, \delta)^{-1} \theta(\mu)(R) \). If we set \( \lambda := \lambda_0^2, Q_n^a := P_{2n}, \) and \( Q_n^b := P_{2n+1} \), the lemma follows.

Remark 4.7. The lemma above also holds for \( x \in G(R) \) (interchanged with the square \( Q \in \text{Qstp}(R) \) in the lemma) and for \( x \) such that \( \ell_x = 0 \). That is to say, increasing \( \lambda \) if necessary, for each \( n \geq 1 \) we have squares \( Q_n^a, Q_n^b \subset B(x, \frac{1}{2} \lambda^{-n} \ell(R)) \setminus B(x, \lambda^{-n-1} \ell(R)) \) which satisfy properties analogous to (b), (c) and (d).

In the following lemma we show a version of (4.4) which involves the curvature \( c^2(\mu) \) truncated by the function \( \ell_x \).

**Lemma 4.8.** Let \( C_{10} > 0 \) be a fixed constant. For all \( x \in 3R \),

\[
\int_{y, z \in 3R} \int_{|x - y| \geq C_{10} \ell_x} c(x, y, z)^2 d\mu(y) d\mu(z) \leq C_{11} A^2 \theta(\mu)(R)^2,
\]

where \( C_{11} \) depends on \( C_{10} \).

The proof of the preceding estimate follows easily from (3.3) and Lemma 3.5 (as in (3.4)). We will not go through the details.

Proof of (4.1). We follow quite closely Jones’ ideas (see [Pa, pp. 39–44]).

It is enough to show that (4.1) holds for dyadic squares \( Q \) with \( \ell(Q) \leq (C_{12} \lambda)^{-1} \ell(R) \) (with \( \lambda \) given by Lemma 4.6 and \( C_{12} \) to be fixed below). So we assume \( \ell(Q) \leq (C_{12} \lambda)^{-1} \ell(R) \). Also, the sum (4.1) can be restricted to those squares \( P \in \mathcal{D} \) such that \( P \cap K \neq \emptyset \). That is, it suffices to prove that

\[
\sum_{P \in \mathcal{D}, P \subset Q, P \cap K \neq \emptyset} \beta_K(P)^2 \ell(P) \leq C(A, \delta) \ell(Q).
\]
The main step of the proof of (4.9) consists of estimating \( \beta_K(P) \) for some \( P \) as in the sum above in terms of \( \varphi^2(\mu) \). By standard arguments, if \( \beta(P) \neq 0 \), there are three pairwise different points \( z_0, z_1, z_2 \in K \cap 3P \) such that

\[
\beta_K(P) \simeq \frac{w(z_0, z_1, z_2)}{\ell(P)},
\]

where \( w(z_0, z_1, z_2) \) stands for the width of the thinnest infinite strip containing \( z_0, z_1, z_2 \). By (b) of Lemma 4.5, \( \ell_{z_0} \leq C|z_0 - z_1| \leq C\ell(P) \). So either \( \ell_{z_0} = 0 \) or there is some \( P_0 \in \text{Qstp}(R) \) with \( \ell(P_0) + \frac{1}{40} \text{dist}(z_0, P_0) \leq C\ell(P) \). In any case, if \( C_{12} \) has been chosen big enough, there are “many” balanced squares \( \hat{P} \) which contain \( z_0, z_1, z_2 \) such that \( \ell(P) \leq \ell(\hat{P}) \leq C(A, \delta)\ell(P) \). Arguing as in Lemma 4.6, we deduce that there exist two squares \( S_a, S_b \) contained in \( C(A, \delta)P \setminus P \) satisfying the properties stated just above Lemma 4.1. For any \( x_0 \in S_a \) and \( y_0 \in S_b \),

\[
w(z_0, z_1, z_2) \lesssim \text{dist}(z_0, L_{x_0, y_0}) + \text{dist}(z_1, L_{x_0, y_0}) + \text{dist}(z_2, L_{x_0, y_0}),
\]

as it is easy to check. Integrating over \( x_0 \in S_a \) and \( y_0 \in S_b \) we get

\[
w(z_0, z_1, z_2) \lesssim \frac{1}{\mu(S_a)\mu(S_b)} \int \int_{x_0 \in S_a, y_0 \in S_b} [\text{dist}(z_0, L_{x_0, y_0}) + \text{dist}(z_1, L_{x_0, y_0}) + \text{dist}(z_2, L_{x_0, y_0})] \, d\mu(x_0)d\mu(y_0).
\]

Thus there exists some \( z_i \), say \( z_0 \), such that

\[
w(z_0, z_1, z_2) \lesssim \frac{1}{\mu(S_a)\mu(S_b)} \int \int_{x_0 \in S_a, y_0 \in S_b} \text{dist}(z_i, L_{x_0, y_0}) \, d\mu(x_0)d\mu(y_0).
\]

From Lemma 4.6 and the subsequent remark we deduce that there are two families of squares \( \{P_n^a\}_{n \geq 1}, \{P_n^b\}_{n \geq 1} \) which satisfy the following properties for any \( n \geq 1 \) such that \( \lambda^{n+1} \leq \ell(P)/\ell_{z_0} \):

(a) \( P_n^a, P_n^b \subset B(z_0, \frac{1}{2} \lambda^{-n}\ell(P)) \setminus B(z_0, \lambda^{-n-1}\ell(P)) \),

(b) \( \text{dist}(P_n^a, P_n^b) \gtrsim \lambda^{-n-1}\ell(P) \),

(c) \( \lambda^{-n-1}\ell(P) \lesssim \ell(P_i^a) \lesssim \lambda^{-n}\ell(P) \), for \( i = a, b \),

(d) \( C(A, \delta)^{-1}\theta_\mu(R) \lesssim \theta_\mu(P_n^a) \lesssim A\theta_\mu(R) \), for \( i = a, b \),

with \( \lambda > 4 \). We also set \( P_0^a := S_a \) and \( P_0^b := S_b \).

Let \( N \) be the biggest positive integer such that \( \lambda^{N+1} \leq \ell(P)/\ell_{z_0} \) (with \( N = \infty \) if \( \ell_{z_0} = 0 \)). We claim that for all points \( x_n \in P_n^a \) and \( y_n \in P_n^b \) we have

\[
\text{dist}(z_0, L_{x_n, y_n}) \leq C \sum_{n=0}^{N} \left[ \text{dist}(x_{n+1}, L_{x_n, y_n}) + \text{dist}(y_{n+1}, L_{x_n, y_n}) \right],
\]
where \( x_{N+1} = y_{N+1} = z_0 \) if \( N < \infty \), and \( C \) depends on \( A, \delta, \lambda \) (like all the following constants denoted by \( C \) in the rest of the proof of (4.9)).

Assuming the claim for the moment, from (4.12) we get

\[
\text{dist}(z_0, L_{x_0,y_0}) \lesssim \sum_{n=0}^{N} \left[ c(x_n, y_n, x_{n+1}) |x_n - x_{n+1}| |y_n - x_{n+1}| + c(x_n, y_n, y_{n+1}) |x_n - y_{n+1}| |y_n - y_{n+1}| \right] \lesssim \sum_{n=0}^{N} \left[ c(x_n, y_n, x_{n+1}) + c(x_n, y_n, y_{n+1}) \right] \lambda^{-2n} \ell(P)^2.
\]

From (4.11), taking the \( \mu \)-mean of the above inequality over \( x_0 \in P_0^a = S_a \) and \( y_0 \in P_0^b = S_b \), then over \( x_1 \in P_1^a \) and \( y_1 \in P_1^b \), over \( x_2 \in P_2^a \) and \( y_2 \in P_2^b \), and so on, we obtain

\[
(4.13)
\]

\[
w(z_0, z_1, z_2) \lesssim \ell(P)^2 \sum_{n=0}^{N-1} \lambda^{-2n} \left[ \frac{A_n}{\mu(P_n^a)\mu(P_n^b)\mu(P_{n+1}^a)} + \frac{B_n}{\mu(P_n^a)\mu(P_n^b)\mu(P_{n+1}^b)} \right] + \ell(z_0)\int_{x \in P_N^a} c(x, y_N, z_0) \, d\mu(x) \, d\mu(y_N),
\]

where

\[
A_n := \int_{x \in P_n^a} \int_{y \in P_n^b} \int_{x_{n+1} \in P_{n+1}^a} c(x, y, x_{n+1}) \, d\mu(x) \, d\mu(y) \, d\mu(x_{n+1})
\]

and

\[
B_n := \int_{x \in P_n^a} \int_{y \in P_n^b} \int_{y_{n+1} \in P_{n+1}^b} c(x, y, y_{n+1}) \, d\mu(x) \, d\mu(y) \, d\mu(y_{n+1}).
\]

Note that the last term in (4.13) (the one involving \( \ell(z_0) \)) only appears when \( N < \infty \) (i.e. when \( \ell(z_0) > 0 \)). By Hölder inequality, the estimates for the squares \( P_n^a \) below (4.11), and Lemma 4.5 (c) (with \( \eta \) big enough), we get

\[
w(z_0, z_1, z_2) \lesssim \ell(P)^2 \sum_{n=0}^{N-1} \lambda^{-2n} \left[ \frac{c_n^2(P_n^a, P_n^b, P_{n+1}^a)}{\mu(P_n^a)\mu(P_n^b)\mu(P_{n+1}^a)}^{1/2} \right] + \ell(P)^2 \lambda^{-2N} \frac{c_n^2(z_0, P_n^a, P_n^b)}{\mu(P_n^a)\mu(P_n^b)}^{1/2} + \ell(P)^2 \lambda^{-N/2} \sum_{n=0}^{N-1} \lambda^{-n/2} c_n^2(P_n^a, P_n^b, P_{n+1}^{a} \cup P_{n+1}^{b})^{1/2}
\]

\[
\lesssim \theta_\mu(R)^{-3/2} \ell(P)^{1/2} \sum_{n=0}^{N-1} \lambda^{-n/2} c_n^2(P_n^a, P_n^b, P_{n+1}^{a} \cup P_{n+1}^{b})^{1/2}
\]

\[
+ \lambda^{-N/2} \left( \int_{x,y,z \in B(z_0, C\eta\ell(z_0))} c(x, y, z)^2 \, d\mu(x) \, d\mu(y) \, d\mu(z) \right)^{1/2}.
\]
By (4.10) and Cauchy-Schwartz, we obtain
\[
\beta_K(P)^2 \lesssim \frac{1}{\theta_\mu(R)^3 \ell(P)} \left[ \sum_{n=0}^N \lambda^{-n/2} c^2_n (P^a_n, P^b_n, P^a_{n+1} \cup P^b_{n+1}) + \lambda^{-N/2} \iint_{|y-z| \geq \ell_n} c(x, y, z)^2 d\mu(x) d\mu(y) d\mu(z) \right].
\]

Notice that for every \(x_n \in P^a_n\), we have \(\ell_{x_n} \lesssim \lambda^{-n} \ell(P)\), because \(\ell_{x_0} \lesssim \lambda^{-n} \ell(P)\), dist\((x_n, z_0) \approx \lambda^{-n} \ell(P)\), and \(\ell_x\) is a Lipschitz function of \(x\). Analogously, if \(y_n \in P^b_n\), then \(\ell_{y_n} \lesssim \lambda^{-n} \ell(P)\). Moreover, since for each \(n\) there exists some dyadic square \(S \subset P\) such that \(P^a_n \cup P^b_n \cup P^a_{n+1} \cup P^b_{n+1}\) is contained in \(3S\), with \(\ell(S) \approx \lambda^{-n} \ell(P)\), we infer that
\[
\theta_\mu(R)^3 \beta_K(P)^2 \ell(P) \lesssim \sum_{S: S \subset P} \left( \frac{\ell(S)}{\ell(P)} \right)^{1/2} \iint_{(x, y, z) \in S^* \cap R^\ell} c(x, y, z)^2 d\mu(x) d\mu(y) d\mu(z),
\]
where \(S^*\) is the set of \((\xi_1, \xi_2, \xi_3) \in (3S)^3\) such that \(|\xi_2 - \xi_3| \geq C^{-1} \ell(S)\), and \(R^\ell\) is the set of \((\xi_1, \xi_2, \xi_3) \in (3R)^3\) such that \(|\xi_2 - \xi_3| \geq C^{-1} (\ell_{\xi_2} + \ell_{\xi_3})\).

Now, for a fixed dyadic square \(Q\) with \(\ell(Q) \leq (C_1 \lambda)^{-1} \ell(R)\), by Lemma 4.8, we get (with the sums over \(P\) and \(S\) only for dyadic squares)
\[
\theta_\mu(R)^3 \sum_{P: P \subset Q} \beta_K(P)^2 \ell(P) \lesssim \sum_{S: S \subset Q} \iint_{(x, y, z) \in S^* \cap R^\ell} c(x, y, z)^2 d\mu(x) d\mu(y) d\mu(z) \sum_{P: S \subset P \subset Q} \left( \frac{\ell(S)}{\ell(P)} \right)^{1/2}
\]
\[
\lesssim \sum_{S: S \subset Q} \iint_{(x, y, z) \in S^* \cap R^\ell} c(x, y, z)^2 d\mu(x) d\mu(y) d\mu(z)
\]
\[
\lesssim \iint_{(x, y, z) \in (3Q)^* \cap R^\ell} c(x, y, z)^2 d\mu(x) d\mu(y) d\mu(z)
\]
\[
\lesssim \theta_\mu(R)^2 \mu(3Q) \lesssim \theta_\mu(R)^3 \ell(Q).
\]

It only remains to prove (4.12). Indeed, suppose for simplicity that \(N < \infty\). We set \(a_{N+1} := z_0\), and for \(0 \leq n \leq N\), let \(a_n\) be the orthogonal projection of \(a_{n+1}\) onto \(L_{x_n, y_n}\). Then
\[
\text{dist}(z_0, L_{x_0, y_0}) \leq \sum_{n=0}^N \text{dist}(a_n, a_{n+1}).
\]

Let us check that \(a_n \in B(z_0, \lambda^{-n} \ell(R))\) for \(0 \leq n \leq N + 1\). We argue by (backward) induction. The statement is clearly true for \(a_{N+1}\). Suppose now that \(a_{n+1} \in B(z_0, \lambda^{-n-1} \ell(R))\). By construction, we have \(x_n, y_n \in B(z_0, \frac{1}{2} \lambda^{-n} \ell(R))\).
On the other hand, since we are assuming \( \lambda > 4 \), then \( a_{n+1} \in B(z_0, \frac{1}{2}\lambda^{-n}\ell(R)) \) too. Then, by elementary geometry,
\[
a_n \in B(z_0, 2^{-1/2}\lambda^{-n}\ell(R)) \subset B(z_0, \lambda^{-n}\ell(R)).
\]

Since \( a_{n+1}, x_{n+1}, y_{n+1} \in B(z_0, \lambda^{-n-1}\ell(R)) \), they are collinear, and
\[
|x_{n+1} - y_{n+1}| \gtrsim \lambda^{-n-1}\ell(R),
\]
we deduce
\[
dist(a_n, a_{n+1}) = dist(a_{n+1}, L_{x_n, y_n}) \lesssim dist(x_{n+1}, L_{x_n, y_n}) + \text{dist}(y_{n+1}, L_{x_n, y_n}).
\]
Thus (4.12) follows from (4.14). \( \square \)

5. The packing condition for the top squares

5.1. The family \( \text{Stop}_{\max}^{1/2}(R) \). In order to prove the packing condition
\[
\sum_{R \in \text{Top}(E)} \theta_\mu(R)^2 \mu(R) \leq C(\mu(E) + c^2(\mu))
\]
(with \( C \) depending on \( A, \delta, \varepsilon_0, \ldots \)), we need to introduce some auxiliary families of squares. Let \( \text{Stop}_{\max}^{1/2}(R) \) be the subfamily of those squares \( Q \in \text{Stop}(R) \) such that there does not exist another square \( Q' \in \text{Top}(E) \), with \( Q' \cap 3R \neq \emptyset \) and \( \ell(Q') \leq \ell(R)/8 \), such that \( Q \in \text{Stop}(Q') \). So \( \text{Stop}_{\max}^{1/2}(R) \) is a maximal subfamily of \( \text{Stop}(R) \) in a sense. Notice, in particular, that if \( Q \in \text{Stop}_{\max}^{1/2}(R) \), then \( Q \not\in \text{Stop}(Q') \) for any \( Q' \in \text{Stop}(R) \). We also denote by \( \text{Stop}_{\max}^{1/2}(R) \) the subfamily of the squares \( Q \in \text{Stop}_{\max}^{1/2}(R) \) such that \( 4Q \cap \frac{1}{2}R \neq \emptyset \).

**Lemma 5.1.** For every \( R \in \text{Top}(E) \), there is \( \sum_{Q \in \text{Stop}(R)} \chi_{\frac{1}{2}Q} \leq C \).

**Proof.** Suppose that \( \frac{1}{2}Q \cap \frac{1}{2}Q' \neq \emptyset \) for \( Q, Q' \in \text{Stop}(R) \). If \( \ell(Q') \leq \ell(Q)/4 \), then \( Q' \subset Q \), which contradicts the definition of \( \text{Stop}(R) \). Thus, \( \ell(Q') \geq \ell(Q)/2 \), and in an analogous way, we have \( \ell(Q) \geq \ell(Q')/2 \). The lemma follows from the fact that there is a bounded number of 4-dyadic squares \( Q' \) such that \( \ell(Q)/2 \leq \ell(Q') \leq 2\ell(Q) \) for \( Q \) fixed. \( \square \)

**Lemma 5.2.**

(a) Suppose that \( R_1, R_2 \in \text{Top}(E) \) and \( Q \in \text{Stop}_{\max}^{1/2}(R_1) \cap \text{Stop}_{\max}^{1/2}(R_2) \). Then,
\[
\ell(R_2)/4 \leq \ell(R_1) \leq 4\ell(R_2).
\]

(b) There exists an absolute constant \( N_0 \) such that for any \( Q \in \text{Top}(E) \)
\[
\#\{R \in \text{Top}(E) : Q \in \text{Stop}_{\max}^{1/2}(R)\} \leq N_0.
\]
(c) For $R \in \text{Top}(E)$,
\[ \bigcup_{P \in \text{Stop}(R)} P \subset \bigcup_{Q \in \text{Stop}_{\text{max}}(R)} 4Q, \]
and, more generally, if $P, R \in \text{Top}(E)$ are such that $P \cap 3R \neq \emptyset$ and $\ell(P) \leq \ell(R)/8$, then there exists some square $Q \in \text{Stop}_{\text{max}}(R)$ such that $P \subset 4Q$.

(d) For $R \in \text{Top}(E)$,
\[ G^{1/2}(R) := \left\{ x \in \frac{1}{2}R \setminus \bigcup_{Q \in \text{Stop}_{\text{max}}^{1/2}(R)} 4Q \right\}. \]
Then, for each $x \in E$,
\[ \#\{ R \in \text{Top}(E) : x \in G^{1/2}(R) \} \leq N_1, \]
where $N_1$ is an absolute constant.

(e) If $R_1, R_2 \in \text{Top}(E)$, $Q \in \text{Stop}_{\text{max}}^{1/2}(R_1) \cap \text{Bad}(R_2)$, then
\[ \ell(R_1)/4 \leq \ell(R_2) \leq 4\ell(R_1) \]
and $\theta_\mu(R_1) \simeq \theta_\mu(R_2)$.

**Proof.** First we show (a). If $Q \in \text{Stop}_{\text{max}}^{1/2}(R_1) \cap \text{Stop}_{\text{max}}^{1/2}(R_2)$, then

\[ (5.2) \quad 4Q \cap \frac{1}{2} R_1 \neq \emptyset \quad \text{and} \quad 4Q \cap \frac{1}{2} R_2 \neq \emptyset. \]

It is easily seen that if $\ell(R_2) \leq \ell(R_1)/4$, then (5.2) and the fact that $\ell(Q) \leq \min(\ell(R_1), \ell(R_2))/8$ imply that $R_2 \subset R_1$. As a consequence, if $\ell(R_2) \leq \ell(R_1)/8$, then $Q \subset R_2 \subset R_1$ and so, by definition, $Q \notin \text{Stop}(R_1)$.

The same happens if we reverse the roles of $R_1$ and $R_2$, and so (5.1) holds.

It is easy to check that (b) follows from (a). This is left for the reader.

The statement (c) of the lemma follows from the fact that if there is a sequence of squares $Q_1, Q_2, \ldots, Q_n = P$ with $Q_1 \in \text{Stop}_{\text{max}}(R)$ and $Q_{j+1} \in \text{Stop}(Q_j)$ for $j \geq 1$, then $Q_{j+1} \cap 3Q_j \neq \emptyset$ and $\ell(Q_{j+1}) \leq \ell(Q_j)/8$, and so
\[ \text{dist}_\infty(Q_1, Q_n) + \ell(Q_n) \leq \sum_{j=1}^{n-1} \left[ \text{dist}_\infty(Q_j, Q_{j+1}) + \ell(Q_{j+1}) \right] \]
\[ \leq \sum_{j=1}^{\infty} \left[ 8^{1-j} + 8^{-j} \right] \ell(Q_1) = \frac{9}{7} \ell(Q_1) \leq \frac{3}{2} \ell(Q_1), \]
which implies that $Q_n \subset 4Q_1$ (dist$_\infty$ stands for the distance induced by the norm $|| \cdot ||_\infty$).

Let us show (d) now. Let $R_1, R_2 \in \text{Top}(E)$ be such that $x \in G^{1/2}(R_1) \cap G^{1/2}(R_2)$. If $\ell(R_2) \leq \ell(R_1)/8$, then by (c), $R_2$ is contained in $4Q$ for some
\(Q \in \text{Stop}_{\max}(R_1).\) Since \(x \in \frac{1}{2}R_1 \cap \frac{1}{2}R_2,\) we have \(4Q \cap \frac{1}{2}R_1 \neq \emptyset,\) and so \(Q \in \text{Stop}_{\max}(R_1),\) which is a contradiction. Therefore, \(\ell(R_2) > \ell(R_1)/8.\) The same inequality holds interchanging \(R_1\) by \(R_2.\) Thus, \(\ell(R_2)/4 \leq \ell(R_1) \leq 4\ell(R_2).\)

That is, all the squares \(R \in \text{Top}(E)\) such that \(x \in G^{1/2}(R)\) have comparable sizes, which implies that the number of these squares \(R\) is bounded above by some absolute constant.

Finally we will prove \((e)\). Suppose that \(\ell(R_2) \leq \ell(R_1)/8.\) From

\[(5.3)\ 4Q \cap \frac{1}{2}R_1 \neq \emptyset\quad \text{and} \quad \ell(Q) \leq \ell(R_2)/8,
\]

we infer that \(R_2 \subset 3R_1,\) and so \(R_2 \in \text{Stop}(R_1).\) This implies that \(Q \not\in \text{Stop}_{\max}(R_1),\) which is a contradiction. Thus, \(\ell(R_2) \geq \ell(R_1)/4.\)

The inequality \(\ell(R_2) \leq 4\ell(R_1)\) also holds. Otherwise \(\ell(R_1) \leq \ell(R_2)/8\) and \(Q \subset R_1\) (by \((5.3)\)) imply that \(Q \not\in \text{Top}(E)\) (it should have been eliminated when constructing \(\text{Top}(E)\) from \(\text{Top}_0(E)\)).

The comparability between \(\theta_\mu(R_1)\) and \(\theta_\mu(R_2)\) follows from \(4R_1 \cap 4R_2 \neq \emptyset\) (since \(Q\) is contained in the intersection) and \(1/4 \leq \ell(R_1)/\ell(R_2) \leq 4.\) Indeed, one easily deduces that then \(R_1 \subset 16R_2\) and \(R_2 \subset 16R_1,\) and by the doubling properties of \(R_1\) and \(R_2,\) one gets \(\theta_\mu(R_1) \simeq \theta_\mu(R_2).\) \(\square\)

The next result is a consequence of Lemma 3.3 and the statement \((e)\) in the preceding lemma.

**Lemma 5.3.** If \(R \in \text{Top}(E)\) and \(Q \in \text{Stop}_{\max}^{1/2}(R),\) then:

(a) If \(Q \in \text{HD}(R),\) then \(\theta_\mu(Q) \gtrsim A\theta_\mu(R).\)

(b) If \(Q \in \text{HC}(R),\) then

\[(5.4)\quad \mu\{x \in \frac{1}{2}Q: K_{\mu,J(Q)+12\chi_E}(x) - K_{\mu,J(R)-6\chi_E}(x) \geq C^{-1}v_0\theta_\mu(R)^2\} \geq C_{13}^{-1}\mu(Q).
\]

(c) If \(Q \in \text{LD}(R),\) then there exists some square \(S_Q\) such that \(Q \subset 1/20S_Q,\) with \(\ell(S_Q) \leq \ell(R)/2,\) and \(\theta_\mu(S_Q) \leq C_{14}\delta_\theta(R).\) Also,

\[(5.5)\quad \mu\{x \in \frac{1}{2}Q: K_{\mu,J(Q)+12\chi_E}(x) - K_{\mu,J(R)-2\chi_E}(x) \leq C\varepsilon_0\theta_\mu(R)^2\} \geq C_{15}^{-1}\mu(Q).
\]

**Proof.** Let \(R_2 \in \text{Top}(E)\) be such that \(Q \in \text{Bad}(R_2).\)

If \(Q \in \text{HD}(R),\) then \(Q \in \text{HD}_0(R_2)\) by definition, and by (b) in Lemma 3.3 and \((e)\) in the preceding lemma, \(\theta_\mu(Q) \gtrsim A\theta_\mu(R_2) \simeq A\theta_\mu(R).\)

If \(Q \in \text{HC}(R),\) then \(Q \in \text{HC}_0(R_2).\) Inequality \((5.4)\) follows from Lemma 3.3 \((e),\) and the fact that \(\theta_\mu(R) \simeq \theta_\mu(R_2)\) and \(|J(R) - J(R_2)| \leq 2\) by \((e)\) in the preceding lemma.

The statement \((c)\) also follows easily from Lemma 5.2 \((e)\) and the definition of \(\text{LD}_0(R)\) and Lemma 3.3 \((d).\) \(\square\)
Notice that, since $\frac{1}{2}R$ is doubling,
\begin{equation}
\mu(R) \lesssim \mu\left(\frac{1}{2} R\right) \leq \mu\left(\bigcup_{Q \in \text{Stop}^{1/2}(R)} 4Q\right) + \mu\left(\frac{1}{2} R \setminus \bigcup_{Q \in \text{Stop}^{1/2}(R)} 4Q\right).
\end{equation}

We distinguish a special kind of square $R \in \text{Top}(E)$. We set $R \in \text{VC}(E)$ (and we say that $\mu$ is very concentrated on $R$) if
\begin{equation}
\mu\left(\bigcup_{Q \in \text{Stop}^{1/2}(R) \cap \text{HD}(R)} Q\right) > \frac{1}{2} \mu\left(\frac{1}{2} R\right).
\end{equation}

5.2. Squares with $\mu$ very concentrated. For $R \in \text{VC}(E)$, using the doubling properties of $\frac{1}{2}R$ and $Q \in \text{Stop}^{1/2}(R)$, we get
\begin{align*}
\mu(R) &\lesssim \mu\left(\frac{1}{2} R\right) \leq 2\mu\left(\bigcup_{Q \in \text{Stop}^{1/2}(R) \cap \text{HD}(R)} 4Q\right) \\
&\lesssim \sum_{Q \in \text{Stop}^{1/2}(R) \cap \text{HD}(R)} \mu(Q),
\end{align*}
and since $\theta_\mu(Q) \gtrsim A\theta_\mu(R)$ for $Q \in \text{Stop}^{1/2}(R) \cap \text{HD}(R)$,
\begin{align*}
\theta_\mu(R)^2 \mu(R) &\lesssim \frac{1}{A^2} \sum_{Q \in \text{Stop}^{1/2}(R) \cap \text{HD}(R)} \theta_\mu(Q)^2 \mu(Q) \\
&\lesssim \frac{1}{A^2} \sum_{Q \in \text{Stop}^{1/2}(R)} \theta_\mu(Q)^2 \mu(Q).
\end{align*}

Then by (b) of Lemma 5.2,
\begin{equation}
\sum_{R \in \text{Top}(E) \cap \text{VC}(E)} \theta_\mu(R)^2 \mu(R) \leq \frac{C}{A^2} \sum_{R \in \text{Top}(E)} \sum_{Q \in \text{Stop}^{1/2}(R)} \theta_\mu(Q)^2 \mu(Q) \\
\leq \frac{C_{16}N_0}{A^2} \sum_{Q \in \text{Top}(E)} \theta_\mu(Q)^2 \mu(Q).
\end{equation}

If we choose $A$ such that $C_{16}N_0/A^2 \leq 1/2$, we deduce (see Remark 5.4 below)
\begin{equation}
\sum_{R \in \text{Top}(E)} \theta_\mu(R)^2 \mu(R) \leq 2 \sum_{R \in \text{Top}(E) \setminus \text{VC}(E)} \theta_\mu(R)^2 \mu(R).
\end{equation}

5.3. Squares with $\mu$ not very concentrated. If $R \notin \text{VC}(E)$, then
\begin{equation}
\mu\left(\bigcup_{Q \in \text{Stop}^{1/2}(R) \cap \text{HD}(R)} 4Q\right) \leq \frac{1}{2} \mu\left(\frac{1}{2} R\right),
\end{equation}
and by (5.6) we get
\begin{equation}
\mu\left(\frac{1}{2} R\right) \leq 2\mu\left(\bigcup_{Q \in \text{Stop}^{1/2}(R) \setminus \text{HD}(R)} 4Q\right) + 2\mu\left(\frac{1}{2} R \setminus \bigcup_{Q \in \text{Stop}^{1/2}(R)} 4Q\right).
\end{equation}
Therefore,
\[(5.8) \quad \mu(R) \leq C_{17} \mu \left( \bigcup_{Q \in \text{Stop}_{\max}^{1/2}(R) \cap \text{LD}(R)} 4Q \right) + C_{17} \mu \left( \bigcup_{Q \in \text{Stop}_{\max}^{1/2}(R) \cap \text{HC}(R)} 4Q \right)
+ C_{17} \mu \left( \frac{1}{2} R \setminus \bigcup_{Q \in \text{Stop}_{\max}^{1/2}(R)} 4Q \right).\]

We will show in Section 7 below that
\[(5.9) \quad \mu \left( \bigcup_{Q \in \text{Stop}_{\max}^{1/2}(R) \cap \text{LD}(R)} 4Q \right) \leq \eta \mu(R),\]
with \(\eta \leq 1/(2C_{17})\), and with \(\delta\) and \(\varepsilon_0\) chosen appropriately. Thus,
\[(5.10) \quad \sum_{R \in \text{Top}(E) \setminus V_C(E)} \theta \mu(R)^2 \mu \left( \bigcup_{Q \in \text{Stop}_{\max}^{1/2}(R) \cap \text{LD}(R)} 4Q \right) \leq \eta \sum_{R \in \text{Top}(E) \setminus V_C(E)} \theta \mu(R)^2 \mu(R).\]

Also, in Section 6 we will prove that
\[(5.11) \quad \sum_{R \in \text{Top}(E)} \sum_{Q \in \text{Stop}_{\max}^{1/2}(R) \cap \text{HC}(R)} \theta \mu(R)^2 \mu(Q) \leq C_{18} c^2(\mu),\]
with \(C_{18}\) possibly depending on \(A\), \(\delta\), and \(\varepsilon_0\).

Now we deal with the term
\[\sum_{R \in \text{Top}(E)} \mu \left( \frac{1}{2} R \setminus \bigcup_{Q \in \text{Stop}_{\max}^{1/2}(R)} 4Q \right) = \sum_{R \in \text{Top}(E)} \mu(G^{1/2}(R)).\]

From (d) of Lemma 5.2 we deduce
\[\sum_{R \in \text{Top}(E)} \mu(G^{1/2}(R)) \leq N_1 \mu(E).\]

Therefore,
\[(5.12) \quad \sum_{R \in \text{Top}(E)} \theta \mu(R)^2 \mu \left( \frac{1}{2} R \setminus \bigcup_{Q \in \text{Stop}_{\max}^{1/2}(R)} 4Q \right) \leq C_0^2 N_1 \mu(E).\]

From (5.8), (5.10), (5.11) and (5.12), we get
\[\sum_{R \in \text{Top}(E) \setminus V_C(E)} \theta \mu(R)^2 \mu(R) \leq C_{17} \eta \sum_{R \in \text{Top}(E) \setminus V_C(E)} \theta \mu(R)^2 \mu(R)
+ C c^2(\mu) + C_{17} C_0^2 N_1 \mu(E).\]

Therefore, since \(\eta < 1/(2C_{17})\),
\[\sum_{R \in \text{Top}(E) \setminus V_C(E)} \theta \mu(R)^2 \mu(R) \leq C_{18} \left[ c^2(\mu) + \mu(E) \right],\]
where \(C_{18}\) depends on \(A\) and \(\varepsilon_0\) (see the remark below). So (3.1) follows from this estimate and (5.7).
Remark 5.4. The arguments above work if one assumes 

\[ \sum_{R \in \text{Top}(E)} \theta_{\mu}(R)^2 \mu(R) < \infty. \]

To circumvent this difficulty it is necessary to argue more carefully. For example, we can operate with finite subsets of \( \text{Top}(E) \). Let \( \text{Top}_n(E) \) be the subfamily of \( \text{Top}(E) \) of those squares with side length \( \geq 2^{-n} \); and let \( A_n(E) \) be the family

\[ \{ Q \in \text{Top}(E) \setminus \text{Top}_n(E) : \exists R \in \text{Top}_n(E) \text{ such that } Q \in \text{Stop}^{1/2 \max(R)} \}. \]

Then, it can be checked that a slight modification of the preceding estimates yields

\[ \sum_{R \in \text{Top}_n(E)} \theta_{\mu}(R)^2 \mu(R) \lesssim \left( \frac{1}{A^2} + \eta \right) \sum_{R \in \text{Top}_n(E)} \theta_{\mu}(R)^2 \mu(R) \]

\[ + \sum_{R \in A_n(E)} \theta_{\mu}(R)^2 \mu(R) + c^2(\mu) + \mu(E). \]

If we choose \( A \) big enough and \( \eta \) sufficiently small, we obtain

\[ \sum_{R \in \text{Top}_n(E)} \theta_{\mu}(R)^2 \mu(R) \lesssim \sum_{R \in A_n(E)} \theta_{\mu}(R)^2 \mu(R) + c^2(\mu) + \mu(E). \]

(5.13) It can be shown that \( \sum_{R \in A_n(E)} \chi \frac{1}{2} R \leq C \) (this is left for the reader). Then

\[ \sum_{R \in A_n(E)} \theta_{\mu}(R)^2 \mu(R) \leq C_0^2 \sum_{R \in A_n(E)} \mu \left( \frac{1}{2} R \right) \lesssim C \mu(E), \]

and from (5.13) we deduce

\[ \sum_{R \in \text{Top}_n(E)} \theta_{\mu}(R)^2 \mu(R) \lesssim c^2(\mu) + \mu(E), \]

uniformly on \( n \).

6. Estimates for the high curvature squares

6.1. The class \( \widehat{\text{Top}}(E) \). To prove (5.11) it will be simpler to use dyadic squares than 4-dyadic squares.

Lemma 6.1. Let \( R \in \text{Top}(E) \) and \( Q \in \text{Stop}^{1/2} \text{Top}(E) \cap \text{HC}(R) \). There exists a dyadic square \( \hat{Q} \subset \frac{1}{2} Q \), with \( \ell(\hat{Q}) = \ell(Q)/4 \), such that \( \mu(\hat{Q}) \geq C_{10}^{-1} \mu(Q) \) and

\[ \int_{\hat{Q}} (K_{\mu,J(\hat{Q})} + 10 \chi_{\text{E}} - K_{\mu,J(R)} - 6 \chi_{\text{E}}) d\mu \gtrsim \varepsilon_0 \theta_{\mu}(R)^2 \mu(\hat{Q}). \]
Proof. Let $P_1, \ldots, P_4$ be the disjoint dyadic squares with side length $\ell(Q)/4$ such that $\frac{1}{2}Q = \bigcup_{1 \leq i \leq 4} P_i$. Remember that 
\[
\mu\{x \in \frac{1}{2}Q: K_{\mu,J(Q)} + 12 \chi_E(x) - K_{\mu,J(R) - 6} \chi_E(x) \geq C^{-1} \varepsilon_0 \theta_{\mu}(R)^2\} \geq C_{13}^{-1} \mu(Q).
\]
Let $\hat{Q}$ be the square $P_i$ such that
\[
\mu\{x \in P_i : K_{\mu,J(Q)} + 12 \chi_E(x) - K_{\mu,J(R) - 6} \chi_E(x) \geq C^{-1} \varepsilon_0 \theta_{\mu}(R)^2\}
\]
is maximal. Clearly, $\hat{Q}$ satisfies (6.1), and $\mu(\hat{Q}) \geq C_{13}^{-1} \mu(Q)/4$. \hfill \Box

For each square $Q \in \text{Stop}^{1/2}(R) \cap \text{HC}(R)$, with $R \in \text{Top}(E)$, we choose a dyadic subsquare $\hat{Q}$ of $Q$ as in the lemma. In the following Subsections 6.2 and 6.3 we denote by $\hat{\text{Top}}(E)$ the class made up of all the chosen subsquares $\hat{Q}$, and $\hat{R}_0$ (which is the dyadic subsquare of $\frac{1}{2}R_0$ with side length $\ell(R_0)/4$ which contains $E$). Notice that it may happen that $\# \hat{\text{Top}}(E) < \# \text{Top}(E)$, because not all the squares in $\text{Top}(E)$ are high curvature squares.

6.2. Decomposition of $c^2(\mu)$. We denote the class of all dyadic squares contained in $\hat{R}_0$ by $\Delta$, and the class of dyadic squares contained in $\hat{R}_0$ with side length $2^{-j}$, by $\Delta_j$.

Given $Q \in \hat{\text{Top}}(E)$, let $\hat{G}(Q)$ be the set of points $x \in Q$ which do not belong to any square $P \in \text{Top}(E)$, with $P \subseteq Q$. Let us denote by $\text{Term}(Q)$ the family of maximal dyadic squares $P \in \text{Top}(E)$, with $P \subseteq Q$. Finally, we let $\text{Tree}(Q)$ be the class of dyadic squares contained in $Q$, different from $Q$, which contain either a point $x \in \hat{G}(Q)$ or a square from $\text{Term}(Q)$. The squares in $\text{Term}(Q)$ are called terminal squares of the tree $\text{Tree}(Q)$, for obvious reasons.

Notice that we have
\[
\Delta = \{\hat{R}_0\} \cup \bigcup_{Q \in \hat{\text{Top}}(E)} \text{Tree}(Q),
\]
and that $\text{Tree}(Q) \cap \text{Tree}(R) = \emptyset$ if $Q \neq R$.

Given $Q \in \hat{\text{Top}}(E)$ with $Q \neq \hat{R}_0$, we denote by $\text{Root}(Q)$ the square $R$ such that $Q$ is a terminal square of $\text{Tree}(R)$.

We split the curvature $c^2(\mu)$ as follows:
\[
c^2(\mu) \geq \sum_{j} \sum_{Q \in \Delta_j} \int_{Q} (K_{\mu,J} + 10 \chi_E) d\mu
\]
\[
\geq \sum_{R \in \text{Top}(E)} \sum_{Q \in \text{Tree}(R)} \int_{Q} (K_{\mu,J(Q)} + 10 \chi_E - K_{\mu,J(Q)-11} \chi_E) d\mu.
\]

Observe that if $P \in \text{Term}(R)$ and $x \in P$, then
\[
\sum_{Q \in \text{Tree}(R)} \chi_Q(x) \left( K_{\mu,J(Q)} + 10 \chi_E(x) - K_{\mu,J(Q)-11} \chi_E(x) \right)
\]
\[
\geq K_{\mu,J(P)} + 10 \chi_E(x) - K_{\mu,J(R)-10} \chi_E(x).
\]
Therefore,

\[
(6.2) \quad c^2(\mu) \gtrsim \sum_{R \in \text{Top}(E)} \sum_{Q \in \text{Term}(R)} \int_Q \left( K_{\mu,J(Q)+10 \chi E} - K_{\mu,J(R)-10 \chi E} \right) d\mu
\]

\[
= \sum_{Q \in \text{Top}(E), Q \neq \hat{R}_0} \int_Q \left( K_{\mu,J(Q)+10 \chi E} - K_{\mu,J(\text{Root}(Q))-10 \chi E} \right) d\mu.
\]

6.3. **Proof of (5.11).** By Lemma 6.1 (we use the same notation as in the lemma), we have

\[
\sum_{R \in \text{Top}(E)} \sum_{Q \in \text{Stop}^{1/2}_\mu(R) \cap \text{HC}(R)} \theta_\mu(R)^2 \mu(Q) \leq N_0 \sum_{P \in \text{Top}(E), P \neq \hat{R}_0} \theta_\mu(R_P)^2 \mu(P),
\]

where \( N_0 \) is the constant appearing in (a) of Lemma 5.2, and \( R_P \in \text{Top}(E) \) is a square such that \( P = \hat{P}_1 \) and \( P_1 \in \text{Stop}^{1/2}_{\max}(R_P) \) for some \( P_1 \). The square \( R_P \) is not unique, but in any case remember that if \( P_1 \in \text{Stop}^{1/2}_{\max}(R_P) \cap \text{Stop}^{1/2}_{\max}(\hat{R}_P) \), then \( \theta_\mu(R_P^1) \approx \theta_\mu(R_P^2) \). By (6.1),

\[
(6.3) \quad \sum_{R \in \text{Top}(E)} \sum_{Q \in \text{Stop}^{1/2}_\mu(R) \cap \text{HC}(R)} \theta_\mu(R)^2 \mu(Q) \lesssim \varepsilon_0^{-1} \sum_{P \in \text{Top}(E), P \neq \hat{R}_0} \int_P \left( K_{\mu,J(P)+10 \chi E} - K_{\mu,J(\text{Root}(P))-6 \chi E} \right) d\mu.
\]

For every \( P \in \text{Top}(E) \) different from \( \hat{R}_0 \), we have \( \ell(R_P) \leq 16 \ell(\text{Root}(P)) \). This is clear if \( \text{Root}(P) = \hat{R}_0 \). For \( \text{Root}(P) \neq \hat{R}_0 \), let \( P_1, R_1 \in \text{Top}(E) \) be such that \( P = \hat{P}_1 \), \( \text{Root}(P) = \hat{R}_1 \). It is easily seen that \( P_1 \subseteq R_1 \). If \( \ell(R_P)/16 > \ell(\text{Root}(P)) = \ell(R_1)/4 \), then \( P_1 \not\in \text{Stop}(R_P) \), by the definition of the family \( \text{Stop}(\cdot) \) (since \( P_1 \subseteq R_1 \) and \( \ell(R_1) \leq \ell(R_P)/8 \)). Thus,

\[
J(R_P) \geq J(\text{Root}(P)) - 4,
\]

and so

\[
K_{\mu,J(P)+10 \chi E} - K_{\mu,J(\text{Root}(P))-6 \chi E} \leq \left( K_{\mu,J(P)+10 \chi E} - K_{\mu,J(\text{Root}(P))-10 \chi E} \right).
\]

From (6.3), (6.2), and the preceding estimate we get

\[
\sum_{R \in \text{Top}(E)} \sum_{Q \in \text{Stop}^{1/2}_\mu(R) \cap \text{HC}(R)} \theta_\mu(R)^2 \mu(Q) \lesssim \varepsilon_0^{-1} c^2(\mu). \quad \square
\]
7. Estimates for the low density squares

To prove the packing condition (3.1) it remains to show that

$$\mu\left(\bigcup_{Q \in \text{Stop}_{\max}^{1/2}(R) \cap \text{LD}(R)} 4Q\right) \leq \eta \mu(R),$$

with $\eta = 1/(2C_1\gamma)$ (notice that $\eta$ is an absolute constant and it does not depend either on $A$ or $\delta$).

7.1. The big and small squares $S_j$, $j \in I_{\text{LD}(R)}$. For each $x \in 4Q$, $Q \in \text{Stop}_{\max}^{1/2}(R) \cap \text{LD}(R)$, let $S_x$ be a square such that $x \in \frac{1}{5}S_x$, $\theta_\mu(S_x) \leq C_{14}\delta \theta_\mu(R)$, and $\ell(S_x) = 2^{-m}\ell(R)$ with $m \geq 1$ (this square exists because of (v) in Lemma 5.3). Moreover, we assume that $S_x$ has maximal side length among all the squares with these properties.

Let $\bigcup_{j \in I_{\text{LD}(R)}} S_j$ be a Besicovitch covering of $\bigcup_{Q \in \text{Stop}_{\max}^{1/2}(R) \cap \text{LD}(R)} 4Q$, with $S_j := S_{x_j}$ as explained above.

**Lemma 7.1.** There exist $n_0 \geq 4$ and $C_{20} > 0$ such that if $\ell(S_j) \leq C_{20}^{-1}\ell(R)$ for $j \in I_{\text{LD}(R)}$, then $\ell(64S_j) \leq \ell(2^{n_0}S_j) \leq \ell(R)$ and $\mu(2^{n_0}S_j) \geq 2\mu(S_j)$.

**Proof.** Given $n_0$ such that $\ell(64S_j) \leq \ell(2^{n_0}S_j) \leq \ell(R)$, we have

$$\mu(2^{n_0}S_j) \geq \delta \theta_\mu(R)\ell(2^{n_0}S_j) = 2^{n_0}\delta \theta_\mu(R)\ell(S_j) \geq 2^{n_0}\mu(S_j).$$

Thus, for $n_0$ big enough, we have $\mu(2^{n_0}S_j) \geq 2\mu(S_j)$. So the lemma follows if $C_{20}$ is big enough too (so that $\ell(2^{n_0}S_j) \leq \ell(R)$).

To prove (7.1) we will distinguish two types of squares $S_j$. If $S_j$, $j \in I_{\text{LD}(R)}$, satisfies

$$\ell(S_j) \geq \min\left(C_8^{-1}A^{-2}, C_{20}^{-1}\right)\ell(R),$$

where $C_8$ is as defined in Lemma 4.4, and $C_{20}$ in Lemma 7.1, then we write $j \in I_{\text{LD}(R)}^b$, and otherwise we set $j \in I_{\text{LD}(R)}^s$ (the superindices “b” and “s” stand for “big” and “small” respectively).

Next we estimate the measure $\mu$ of the family of the big squares $S_j$:

**Lemma 7.2.**

$$\mu\left(\bigcup_{j \in I_{\text{LD}(R)}^b} S_j\right) \lesssim A^4\delta \mu(R).$$

**Proof.** We set $C_{21} := \max(C_8, C_{20})$. Then each square $S_j$, $j \in I_{\text{LD}(R)}^b$, satisfies $\ell(S_j) \geq C_{21}^{-1}A^{-2}\ell(R)$. Since the family $\{S_j\}_{j \in I_{\text{LD}(R)}^b}$ has finite superposition we have

$$\#I_{\text{LD}(R)}^b \lesssim \left(\frac{\ell(R)}{\inf_{j \in I_{\text{LD}(R)}^b} \ell(S_j)}\right)^2 \lesssim A^4.$$
Therefore,
\[ \sum_{j \in I^{s}_{\text{LD}(R)}} \mu(S_j) \lesssim \sum_{j \in I^{s}_{\text{LD}(R)}} \delta \ell(S_j) \theta_{\mu}(R) \lesssim \delta \mu(R) \cdot \# I^{b}_{\text{LD}(R)} \lesssim A^{4} \delta \mu(R). \]

7.2. Estimates for the small squares $S_j$, $j \in I^{s}_{\text{LD}(R)}$. Now we turn our attention to the small squares $S_j$. For each $Q \in \text{Stop}_{\max}^{1/2}(R) \cap \text{LD}(R)$, let $W_Q$ be the set
\[ \{ x \in \frac{1}{2} Q \cap \text{supp}(\mu) : K_{\mu, j(Q) + 12 \chi_{E}(x)} - K_{\mu, j(Q) - 2 \chi_{E}(x)} \leq C \varepsilon_{0} \theta_{\mu}(R)^{2} \} \].
Remember that, by (5.5), $\mu(W_Q) \geq C^{-1} \mu(Q) \approx \mu(4Q)$, since $Q$ is 16-doubling.
For $j \in I_{\text{LD}(R)}$, we denote
\[ W_{j} := \bigcup_{Q \in \text{Stop}_{\max}^{1/2}(R) \cap \text{LD}(R)} W_{Q} \cap S_{j}. \]
Remember that the family $\{ S_{j} \}_{j \in I^{s}_{\text{LD}(R)}}$ was obtained by an application of the Besicovitch covering theorem. So $\{ S_{j} \}_{j \in I^{s}_{\text{LD}(R)}}$ can be split into $N_{B}$ subfamilies of pairwise disjoint squares $S_{j}$. Thus there exists a subfamily $\{ S_{j} \}_{j \in I^{s,0}_{\text{LD}(R)}}$, $I^{s,0}_{\text{LD}(R)} \subset I^{s}_{\text{LD}(R)}$, of pairwise disjoint squares such that
\[ \mu \left( \bigcup_{j \in I^{s,0}_{\text{LD}(R)}} W_{j} \right) \geq \frac{1}{N_{B}} \mu \left( \bigcup_{j \in I^{s}_{\text{LD}(R)}} W_{j} \right). \]
We set
\[ W := \bigcup_{j \in I^{s,0}_{\text{LD}(R)}} W_{j}. \]
By the preceding lemma and since $\sum_{Q \in \text{Stop}_{\max}^{1/2}(R) \cap \text{LD}(R)} \chi_{\frac{1}{2} Q} \leq C$ (see Lemma 5.1), we get
\[ (7.3) \quad \mu \left( \bigcup_{Q \in \text{Stop}_{\max}^{1/2}(R) \cap \text{LD}(R)} 4Q \right) \lesssim \sum_{Q \in \text{Stop}_{\max}^{1/2}(R) \cap \text{LD}(R)} \mu(4Q) \lesssim \sum_{Q \in \text{Stop}_{\max}^{1/2}(R) \cap \text{LD}(R)} \mu(W_Q) \lesssim \mu \left( \bigcup_{j \in I^{b}_{\text{LD}(R)}} W_{j} \right) + \mu \left( \bigcup_{j \in I^{s}_{\text{LD}(R)}} W_{j} \right) \lesssim A^{4} \delta \mu(R) + N_{B} \sum_{j \in I^{s,0}_{\text{LD}(R)}} \mu(W_{j}). \]

Remark 7.3. Another useful property of our construction of the squares $S_j$ is the following: If $Q \in \text{Stop}_{\max}^{1/2}(R) \cap \text{LD}(R)$ is such that $Q \cap S_{j} \neq \emptyset$ (for some $j \in I_{\text{LD}(R)}$), then $\ell(Q) \leq \ell(S_{j})$ and $Q \subset 3S_{j}$.
Indeed, suppose that $\ell(Q) > \ell(S_j)$. By Lemma 5.3 there exists some square $S_Q$ such that $Q \subset \frac{1}{2} S_Q$ with $\theta_\mu(S_Q) \leq C_{14}\delta \theta_\mu(R)$, and $\ell(S_Q) = 2^{-m} \ell(R)$ with $m \geq 1$. Then we have $S_j \subset 3Q \subset \frac{1}{2} S_Q$, which is not possible, because of the choice of $S_j$ with maximal size (besides other properties). The inclusion $Q \subset 3S_j$ is a direct consequence of the inequality $\ell(Q) \leq \ell(S_j)$ and the fact that $Q \cap S_j \neq \emptyset$.

Similar arguments show that, if $Q \in \text{Stop}^{1/2}_{\text{max}}(R) \cap \text{LD}(R)$, then
\[
\ell(Q) \leq \text{dist}(Q, S_j) + \ell(S_j).
\]

For $x \in W$, we set
\[
\ell_x := 2^{-12} \inf \{ \ell(Q) : Q \in \text{Stop}^{1/2}_{\text{max}}(R) \cap \text{LD}(R), x \in Q \}.
\]
Notice that, by the preceding remark, we have
\[
(7.4) \quad \ell_x \leq 2^{-12} \left( \text{dist}(x, S_j) + \ell(S_j) \right)
\]
for each $j \in I_{\text{LD}^{-\alpha}(R)}$. As a consequence, if $x \in S_j$, then $\ell_x \leq 2^{-12} \ell(S_j)$.

We consider the following truncated version of the curvature $c_\mu(x, 2R, 2R)$, for $x \in W$:
\[
c_{\text{tr}, \mu}^2(x, 2R, 2R) := \int_{|x-y| > \ell_x} c(x, y, z)^2 d\mu(y) d\mu(z).
\]

The next lemma follows easily from our construction.

**Lemma 7.4.** For every $x \in W$,
\[
c_{\text{tr}, \mu}^2(x, 2R, 2R) \lesssim \varepsilon_0 \theta_\mu(R)^2.
\]

**Proof.** Let $Q \in \text{Stop}^{1/2}_{\text{max}}(R) \cap \text{LD}(R)$ be such that $x \in W_Q$. By the definition of $W_Q$, we have
\[
c_{\text{tr}, \mu}^2(x, 2R, 2R) \leq \int_{2^{-12} \ell(Q) < |x-y| \leq \varepsilon_0 \ell(R)} c(x, y, z)^2 d\mu(y) d\mu(z)
= K_{\mu, j(Q)+12} \varepsilon_0 \theta_\mu(R)^2.
\]

For each $j \in I_{\text{LD}(R)}^{s, R}$, let $L_j$ be a segment of length $\mathcal{H}^1(L_j) = \ell(S_j)/8$ contained in $\frac{1}{2} S_j$. The exact position and orientation of $L_j$ will be fixed below. Let $\nu$ be the following measure
\[
d\nu = \sum_{j \in I_{\text{LD}(R)}^{s, R}} \frac{\mu(W_j)}{\mathcal{H}^1(L_j)} d\mathcal{H}^1_{|L_j|}.
\]

**Lemma 7.5.** The measure $\nu$ satisfies
\[
(7.5) \quad \nu(B(x, r)) \lesssim CA \theta_\mu(R)r \quad \text{for all } x \in \mathbb{C} \text{ and } r > 0,
\]
and if the position and orientation of each $L_j$ are chosen appropriately, also
\begin{equation}
(7.6) \quad c^2(\nu) \leq C(A, \delta)\varepsilon_0^{1/50} \theta_\mu(R)^2 \mu(R).
\end{equation}

We defer the proof of this lemma until Subsection 7.4. For the moment, we only remark that it follows from the estimate of $c^2_{\text{tr},\mu}(x, 2R, 2R)$ for $x \in W$ in Lemma 7.4, by comparison.

Now we recall David-Léger’s theorem [Lé] (the quantitative version in [Lé, Prop. 1.2]).

**Theorem D.** For any $c_0 > 0$, there exists some $\varepsilon_L > 0$ such that if $\tau$ is a Radon measure whose support is contained in a square $R$ and satisfies:

(a) $\tau(R) \geq \ell(R)$,

(b) $\tau(B(x, r)) \leq c_0 r$ for any $x \in \mathbb{C}$, $r > 0$, and

(c) $c^2(\tau) \leq \varepsilon_L \ell(R),$

then there exists a Lipschitz graph $\Gamma$ with slope $\leq 1/10$ (with respect to the appropriate axes) such that $\tau(\Gamma) \geq \frac{99}{100} \tau(R)$.

7.3. **Proof of (5.9).** Suppose that
\begin{equation}
(7.7) \quad \mu\left( \bigcup_{Q \in \text{Stop}^{1/2}_\mu(R) \cap \text{LD}(R)} 4Q \right) > \eta \mu(R).
\end{equation}

Remember that if $\delta$ is small enough, by (7.3),
\begin{equation}
(7.8) \quad \mu\left( \bigcup_{Q \in \text{Stop}^{1/2}_\mu(R) \cap \text{LD}(R)} 4Q \right) \leq \frac{\eta}{2} \mu(R) + CN_B \sum_{j \in \text{LD}^{s, 0}(R)} \mu(W_j).
\end{equation}

So we only have to estimate
\[ \sum_{j \in \text{LD}^{s, 0}(R)} \mu(W_j) = \nu(R). \]

From the assumption (7.7) and inequality (7.8) we deduce
\begin{equation}
(7.9) \quad \nu(R) \geq C^{-1} N_B^{-1} \frac{\eta}{2} \mu(R) =: C_{22}^{-1} \eta \mu(R).
\end{equation}

Considering the measure $\tau := \frac{C_{22}}{\eta \theta_\mu(R)} \nu$, we have
\[ \tau(R) \geq \frac{C_{22}}{\eta \theta_\mu(R)} C_{22}^{-1} \eta \mu(R) = \ell(R). \]

On the other hand, any ball $B(x, r)$ satisfies
\[ \tau(B(x, r)) \leq \frac{C_{22}}{\eta} CA r, \]
because of the estimate on the linear growth of $\nu$ in Lemma 7.5. Further, from the same lemma we also get the following estimate for $c^2(\tau)$:

$$c^2(\tau) = \frac{C_3^2}{\eta^3 \theta_\mu(R)^3} c^2(\nu) \leq \frac{C_3^2}{\eta^3 \theta_\mu(R)^3} C(A, \delta) \frac{1}{50} \theta_\mu(R)^2 \mu(R) = \frac{C_3^2 C(A, \delta)}{\eta^3} \frac{1}{50} \ell(R).$$

Therefore, by Theorem D, if $\varepsilon_0$ is small enough, there exists a Lipschitz graph $\Gamma$ with slope $\leq 1/10$ such that $\tau(\Gamma) \geq \frac{99}{100} \tau(R)$, which is equivalent to saying $\nu(\Gamma) \geq \frac{99}{100} \nu(R)$.

Let $J$ be the subset of indices $j \in I^s_{LD(R)}$ such that $L_j \cap \Gamma \neq \emptyset$. Notice that if $j \in J$, we have $\mathcal{H}^1(\Gamma \cap S_j) \geq \frac{1}{2} \ell(S_j)$ because $L_j$ is contained in $\frac{1}{2} S_j$. Thus, since the squares $S_j, j \in J$, are disjoint, we have

$$\sum_{j \in J} \ell(S_j) \leq 2 \mathcal{H}^1(\Gamma) \leq 10 \ell(R)$$

(of course, “10” is not the best constant here). Then we obtain

$$\nu(R) \leq \frac{100}{99} \sum_{j \in J} \nu(\Gamma \cap L_j) \leq \frac{100}{99} \sum_{j \in J} \nu(L_j) \leq \frac{100}{99} \sum_{j \in J} \mu(S_j) \leq \delta \mu(R) \sum_{j \in J} \ell(S_j) \lesssim \delta \mu(R) \ell(R) = \delta \mu(R).$$

Thus, if $\delta$ has been chosen small enough, we get a contradiction to (7.9). □

7.4. Proof of Lemma 7.5. To simplify notation, in this subsection we write $J_0 := I^s_{LD(R)}$.

The linear growth condition (7.5) follows easily from the fact that if $x \in S_j, j \in J_0$, then $\mu(B(x, r)) \lesssim A \theta_\mu(R) r$ for $r \geq \ell(S_j)$, and also

$$\frac{\mu(W_j)}{\mathcal{H}^1(L_j)} \lesssim \theta_\mu(S_j) \lesssim \theta_\mu(R).$$

The details are left for the reader.

The proof of (7.6) is more delicate. If, instead of choosing an appropriate orientation for each segment $L_j$, we assume all the $L_j$’s to be parallel to the $x$ axis, say, then instead of (7.6) we would get an estimate such as

$$c^2(\nu) \leq C_{23}(A, \delta) \theta_\mu(R)^2 \mu(R),$$

where $C_{23}(A, \delta)$ is a large constant. Unfortunately this estimate is not enough for our purposes, because for the application of Léger’s theorem to the measure $\tau$ in Subsection 7.3, we need $C_{23}(A, \delta) \leq \varepsilon_L$. 


The position and orientation of each segment $L_j$, $j \in J_0$, will be fixed with
the help of a balanced square $\tilde{S}_j$ concentric with $S_j$, with $S_j \subset \tilde{S}_j \subset C(A, \delta)S_j$.
We will show that $W_j$ is contained in a thin strip $V_j$ associated to $\tilde{S}_j$. The
segment $L_j$ will be a segment parallel to the strip $V_j$, with length $\ell(S_j)/8$, so
that the middle point of $L_j$ coincides with some point in $W_j \cap \frac{1}{6} S_j$.

7.4.1. Preliminary lemmas. For each $j \in J_0$, by Lemmas 4.4 and 7.1 there
exists a square $\tilde{S}_j$ concentric with $S_j$ satisfying

$$64\ell(S_j) \leq \ell(\tilde{S}_j) \leq \min(8\ell(R), C(A, \delta)) \ell(S_j),$$

such that $\tilde{S}_j \in \text{Bal}(\mu)$ and $\mu(\tilde{S}_j \setminus S_j) \geq \frac{1}{2} \mu(\tilde{S}_j)$.

**Lemma 7.6.** For each $j \in J_0$ there exist two squares $Q^1_j, Q^2_j \subset \tilde{S}_j$ and an
infinite strip $V_j$ of width $\leq \varepsilon_0^{1/6} \ell(S_j)$ which contains $10\varepsilon_0^{-1/50} S_j \cap W$ such that

(a) $\text{dist}(Q^1_j, Q^2_j) \geq a\ell(\tilde{S}_j)$,

(b) $\ell(Q^i_j) \leq \frac{a}{10} \ell(\tilde{S}_j)$ for $i = 1, 2$, and

(c) $\mu(Q^i_j \cap V_j) \geq \frac{b}{2} \mu(\tilde{S}_j)$ for $i = 1, 2$,

when $\varepsilon_0$ is small enough.

The constants $a$ and $b$ which appear in the lemma are the ones in Rem.

**Proof.** Since $\tilde{S}_j \in \text{Bal}(\mu)$, there are squares $Q^1_j, Q^2_j \subset \tilde{S}_j$ satisfying the
properties (a) and (b) and such that $\mu(Q^i_j) \geq b\mu(\tilde{S}_j)$, $i = 1, 2$. In order to
show the existence of the strip $V_j$, we will first prove that most of $\text{supp}(\mu) \cap \tilde{S}_j$
is very close to some line.

Let $x_0 \in W \cap \frac{1}{7} S_j$ ($x_0$ exists because of the construction of $S_j$). By (7.4),
for any $y \in \tilde{S}_j \setminus S_j$, we have $|y - x_0| > \ell_{x_0}$. Thus, by Lemma 7.4,

$$\int_{y \in \tilde{S}_j \cap S_j} \int_{z \in \tilde{S}_j} c(x_0, y, z)^2 d\mu(y) d\mu(z)$$

$$\leq \int_{y \in \tilde{S}_j \setminus S_j} \int_{|z - x_0| > \ell_{x_0}} c(x_0, y, z)^2 d\mu(y) d\mu(z) \leq \varepsilon_0 \theta_\mu(R)^2.$$ 

Therefore, there exists some $y_0 \in \tilde{S}_j \setminus S_j$ such that

$$\int_{z \in \tilde{S}_j} c(x_0, y_0, z)^2 d\mu(z) \leq \frac{\varepsilon_0 \theta_\mu(R)^2}{\mu(S_j \setminus S_j)} \leq \frac{2\varepsilon_0 \theta_\mu(R)^2}{\mu(\tilde{S_j})}.$$ 

By Tchebychev, we obtain
\[ \mu \{ z \in \hat{S}_i : \text{dist}(z, LX_{0,y_0}) > \varepsilon_0^{1/4} \ell(\hat{S}_i) \} \]
\[ \leq \frac{1}{4\varepsilon_0^2} \int_{\hat{S}_i} \left( \frac{2\text{dist}(z, LX_{0,y_0})}{\ell(\hat{S}_i)} \right)^2 \, d\mu(z) \]
\[ \leq \frac{\varepsilon(\hat{S}_i)}{\varepsilon_0^2} \int_{\hat{S}_i} \left( \frac{2\text{dist}(z, LX_{0,y_0})}{x_0-z \| z-y_0 \|} \right)^2 \, d\mu(z) = \frac{\varepsilon(\hat{S}_i)^2}{\varepsilon_0^{1/2}} \varepsilon_0^{1/2} \varepsilon_0^{1/2} \ell(x_0,y_0,\hat{S}_i) \]
\[ \leq 2\varepsilon_0^{1/2} \left( \frac{\theta_\mu(R)}{\theta_\mu(\hat{S}_i)} \right)^2 \mu(\hat{S}_i) \leq \frac{\varepsilon_0^{1/2}}{\delta^2} \mu(\hat{S}_i). \]

Let \( \tilde{V}_j \) be the infinite strip with axis \( LX_{0,y_0} \) and width \( 2\varepsilon_0^{1/4} \ell(\hat{S}_j) \). If \( \varepsilon_0 \) is small enough, we infer that

\[
(7.10) \quad \mu(\hat{S}_j \setminus \tilde{V}_j) \leq \frac{C\varepsilon_0^{1/2}}{\delta^2} \mu(\hat{S}_j) \leq \frac{1}{2} \mu(Q^i_j)
\]

for \( i = 1, 2, \) since \( \mu(Q^i_j) \geq b\mu(\hat{S}_j) \). Therefore, \( \mu(Q^i_j \cap \tilde{V}_j) \geq \frac{1}{2} \mu(Q^i_j) \) for each \( i \).

This will imply the statement (c) because we will construct \( V_j \) so that \( V_j \supset \tilde{V}_j \).

It remains to define \( V_j \) and to show that \( 10\varepsilon_0^{-1/50} \hat{S}_j \cap W \subset V_j \). Take \( y \in Q^i_j \cap \tilde{V}_j \) and \( z \in Q^2_j \cap V_j \). Since \( \text{dist}(y, z) \geq a\ell(\hat{S}_j) \) (with \( a = 1/40 \)), the segment \( L_{y,z} \cap 30\varepsilon_0^{-1/50} \hat{S}_j \) is contained in some strip with the same axis as \( \hat{V}_j \) and width \( C\varepsilon_0^{1/4} \ell(30\varepsilon_0^{-1/50} \hat{S}_j) \leq \varepsilon_0^{1/5} \ell(\hat{S}_j)/3 \) (assuming \( \varepsilon_0 \) small enough).

Let \( V_j \) be the strip with the same axis as \( \tilde{V}_j \) and width \( \varepsilon_0^{1/5} \ell(\hat{S}_j) \) (which is \( \leq \varepsilon_0^{1/6} \ell(\hat{S}_j) \) for \( \varepsilon_0 \) small). If \( x \in 10\varepsilon_0^{-1/50} \hat{S}_j \setminus V_j \), then \( \text{dist}(x, L_{y,z}) > \varepsilon_0^{1/5} \ell(\hat{S}_j)/3 \), and so

\[
c(x, y, z) \geq C^{-1} \varepsilon_0^{-1/5} \ell(\hat{S}_j) = C^{-1} \varepsilon_0^{-6/25} \ell(\hat{S}_j)^{-1}.
\]

Thus,

\[
c_\mu^2(x, Q^1_j, Q^2_j) \geq C^{-1} \varepsilon_0^{12/25} \ell(\hat{S}_j)^{-2} \mu(Q^1_j) \mu(Q^2_j) \geq C(A, \delta)^{-1} \varepsilon_0^{12/25} \theta_\mu(R)^2,
\]

which is larger than \( C\varepsilon_0^2 \theta_\mu(R)^2 \) as \( \varepsilon_0 \) has been taken small enough. Further, from (7.4) it easily follows that \( \ell_x \leq 2^{-12} \text{dist}(x, \hat{S}_j) + \ell(\hat{S}_j) \), and then either \( \ell_x \leq \text{dist}(x, Q^1_j) \) or \( \ell_x \leq \text{dist}(x, Q^2_j) \). As a consequence,

\[
\ell_{tr,\mu}^2(x, 2R, 2R) \geq c_\mu^2(x, Q^1_j, Q^2_j) > C\varepsilon_0^2 \theta_\mu(R)^2,
\]

and so \( x \notin W \). \( \square \)

The orientation of the segments \( L_j, j \in J_0 \), which support \( \nu \) is chosen so that each \( L_j \) is supported on the axis of \( V_j \). Remember also that \( L_j \) has length \( \ell(S_j)/8 \). We assume that its middle point coincides with some point in \( W \cap \frac{1}{2} S_j \) (for example, the point \( x_0 \) appearing in the proof of the preceding lemma). Notice that, in particular, we have \( L_j \subset \frac{1}{2} S_j \cap V_j \).
We denote \( \hat{S}_j := \varepsilon_0^{-1/50} \hat{S}_j \). Given two lines \( L \) and \( M \), \( \angle(L, M) \) stands for the angle between \( L \) and \( M \) (it does not matter which one of the two possible angles because we will always deal with its sinus). Also, given \( x, y, z \in \mathbb{C} \), we set \( \angle(x, y, z) := \angle(L_{xy}, L_{yz}) \).

slowly, in a sense.

**Lemma 7.7.** Let \( S_j, S_k, j, k \in J_0 \), be such that \( 3 \hat{S}_j \cap 3 \hat{S}_k \neq \emptyset \). Suppose that \( \ell(\hat{S}_j) \geq \ell(\hat{S}_k) \). Then, either \( \sin \angle(L_j, L_k) \leq C\varepsilon_0^{1/6} \) or \( \ell(S_k) \leq \varepsilon_0^{3/5} \ell(S_j) \). In any case, \( L_k \) is contained in a strip with the same axis as \( V_j \) and width \( \varepsilon_0^{1/8} \ell(S_j) \).

**Proof.** First we will show that either \( \sin \angle(L_j, L_k) \leq C\varepsilon_0^{1/6} \) or \( \ell(S_k) \leq \varepsilon_0^{3/5} \ell(S_j) \).

From the assumptions in the lemma we deduce that \( 3 \hat{S}_k \subset 9 \hat{S}_j \). By construction there exists some \( x \in W \cap L_k \). Consider the squares \( Q_j, Q_j^2 \subset \hat{S}_j \) mentioned in Lemma 7.6. Suppose that \( Q_j^1 \) is the one which is farther from \( x \), so that \( \text{dist}(x, Q_j^1) \geq C^{-1} \ell(\hat{S}_j) \). Take also the square \( Q_k^i, i = 1 \) or \( 2 \), which is farther from \( x \). Suppose this is \( Q_k^1 \), and so \( \text{dist}(x, Q_k^1) \geq C^{-1} \ell(\hat{S}_k) \). Take \( y \in Q_j^1 \cap V_j \) and \( z \in Q_k^1 \cap V_k \). Since \( x, y \in V_j \), clearly we have

\[
\sin \angle(L_j, x, y) \leq \frac{\text{width of } V_j}{|x - y|} \leq C\varepsilon_0^{1/6},
\]

and, analogously, since \( x \in V_k \), \( \sin \angle(L_k, x, z) \leq C\varepsilon_0^{1/6} \). So we infer that

\[
\sin \angle(L_j, L_k) \leq C \sin \angle(y, x, z) + C\varepsilon_0^{1/6}.
\]

Therefore,

\[
c(x, y, z) = \frac{2 \sin \angle(y, x, z)}{|y - z|} \geq C^{-1} \frac{\sin \angle(L_j, L_k) - C\varepsilon_0^{1/6}}{\ell(\hat{S}_j)}.
\]

Thus,

\[
\int_{y \in Q_j^i \cap V_j} \int_{z \in Q_k^i \cap V_k} c(x, y, z)^2 \, d\mu(y) \, d\mu(z)
\]

\[
geq C^{-1} \left( \sin \angle(L_j, L_k) - C\varepsilon_0^{1/6} \right)^2 \mu(Q_j^i \cap V_j) \mu(Q_k^i \cap V_k)
\]

\[
geq C(A, \delta)^{-1} \left( \sin \angle(L_j, L_k) - C\varepsilon_0^{1/6} \right)^2 \varepsilon_0^{-1/25} \ell(\hat{S}_j)^2 \mu(\hat{S}_j) \mu(\hat{S}_k)
\]

\[
geq C(A, \delta)^{-1} \left( \sin \angle(L_j, L_k) - C\varepsilon_0^{1/6} \right)^2 \varepsilon_0^{-1/25} \ell(\hat{S}_j) \theta_{\mu}(R)^2 \ell(\hat{S}_k).
\]
On the other hand, it is easily seen that
\[ e_{tr,\mu}^2(x, 2R, 2R) \geq \int_{y \in Q_j \cap V_j} c(x, y, z)^2 \, d\mu(y) \, d\mu(z). \]

Since \( x \in W \), we have \( e_{tr,\mu}^2(x, 2R, 2R) \leq \varepsilon_0 \theta_\mu(R)^2 \), and then we get
\[ \ell(\tilde{S}_k)(\sin \angle(L_j, L_k) - C_{24}\varepsilon_0^{1/6})^2 \leq C(A, \delta)\varepsilon_0^{24/25} \ell(\tilde{S}_j). \]

So we deduce that either \( \sin \angle(L_j, L_k) \leq 2C_{24}\varepsilon_0^{1/6} \), or otherwise,
\[ \ell(\tilde{S}_k) \leq C(A, \delta)\varepsilon_0^{24/25} \ell(\tilde{S}_j). \]

Thus,
\[ \ell(S_k) \leq C(A, \delta)\varepsilon_0^{47/75} \ell(\tilde{S}_j) \leq \varepsilon_0^{3/5} \ell(S_j), \]
assuming \( \varepsilon_0 \) small enough.

It remains to show that, in any case, \( L_k \) lies in a thin strip with the same axis as \( V_j \). Remember that \( x \in L_k \cap V_j \). If \( \ell(S_k) \leq \varepsilon_0^{3/5} \ell(S_j) \), then \( S_k \) (and thus \( L_k \)) is contained in a strip with the same axis as \( V_j \) and width
\[ \varepsilon_0^{1/6} \ell(S_j) + 2\varepsilon_0^{3/5} \ell(S_j) \leq \varepsilon_0^{1/8} \ell(S_j) \]
(for \( \varepsilon_0 \) small).

Supposing now that \( \sin \angle(L_j, L_k) \leq C\varepsilon_0^{1/6} \), we have
\[ \ell(S_k) \leq \ell(\tilde{S}_k) = \varepsilon_0^{1/50} \ell(\tilde{S}_k) \leq \varepsilon_0^{1/50} \ell(\tilde{S}_j) = \ell(\tilde{S}_j) \leq C(A, \delta)\ell(S_j). \]

We deduce that \( L_k \) is also contained in a strip with the same axis as \( V_j \) and width
\[ \varepsilon_0^{1/6} \ell(S_j) + 2\varepsilon_0^{3/5} \ell(S_j) \sin \angle(L_j, L_k) \leq \varepsilon_0^{1/6} \ell(S_j) + C(A, \delta)\varepsilon_0^{1/6} \ell(S_j) \leq \varepsilon_0^{1/8} \ell(S_j), \]
for \( \varepsilon_0 \) sufficiently small again.

**Lemma 7.8.** Given \( j \in J_0 \), let \( x \in L_j \), \( y, z \notin S_j \), \( x_1 \in Q_j^1 \cap V_j \), and \( x_2 \in Q_j^2 \cap V_j \). Then,
\[ c(x, y, z) \leq C(A, \delta) \left[ c(x_1, y, z) + c(x_2, y, z) \right] + \frac{C\varepsilon_0^{1/6} \ell(S_j)}{|x - y||x - z|}. \]

**Proof.** Let \( x' \) be the orthogonal projection of \( x \) onto the line \( L_{x_1, x_2} \). Since \( x_1, x_2 \in V_j \) and
\[ |x_1 - x_2| \geq \ell(\tilde{S}_j)/40 \gg \text{width of } V_j, \]
the segment \( L_{x_1, x_2} \cap S_j \) is contained in \( CV_j \), where \( CV_j \) stands for the strip with the same axis as \( V_j \) and width \( C \) times the one of \( V_j \). Remember also that \( L_j \) is a segment supported on the axis of \( V_j \). As a consequence,
\[ |x - x'| = \text{dist}(x, L_{x_1, x_2}) \leq C \text{ width of } V_j \leq C\varepsilon_0^{1/6} \ell(S_j). \]
By Lemma 3.5,

\[
(7.11) \quad c(x, y, z) \leq c(x', y, z) + \frac{C|x - x'|}{|x - y||x - z|},
\]

because \(x, x'\) are in \(S_j\) and far from \(\partial S_j\), while \(y, z \notin S_j\).

It can be shown that there exists some absolute constant \(C\) such that

\[
\text{dist}(x, L_{y, z}) \leq C(\text{dist}(x_1, L_{y, z}) + \text{dist}(x_2, L_{y, z})).
\]

This follows easily from the fact that \(x', x_1, x_2\) are collinear and \(|x_1 - x_2| \geq C^{-1}|x' - x_1|\). Notice also that, for \(i = 1, 2,\)

\[
|x_i - y| \leq C(A, \delta)|x' - y| \quad \text{and} \quad |x_i - z| \leq C(A, \delta)|x' - z|.
\]

In fact, the constants \(C(A, \delta)\) above depend on the ratio \(\ell(S_j)/\ell(S_j)\). We get

\[
c(x', y, z) = \frac{2\text{dist}(x, L_{y, z})}{|x - y||x - z|} \leq \frac{C(A, \delta)\text{dist}(x_1, L_{y, z})}{|x_1 - y||x_1 - z|} + \frac{C(A, \delta)\text{dist}(x_2, L_{y, z})}{|x_2 - y||x_2 - z|}
\]

\[
= C(A, \delta) \left[ c(x_1, y, z) + c(x_2, y, z) \right].
\]

From this estimate, (7.11), and the fact that \(|x - x'| \lesssim \varepsilon_0^{1/6}\ell(S_j)\), the lemma follows. \(\square\)

**Lemma 7.9.** Let \(M_{tr, \mu}\) be the following (truncated) maximal operator

\[
M_{tr, \mu}f(x) = \sup_{Q: x \in \frac{1}{2}Q \subset S_j} \frac{1}{\ell(Q)} \int_{Q \cap 2R} |f| \, d\mu,
\]

where \(S_x\) is the square \(S_j, j \in J_0\), which contains \(x\). Then, \(M_{tr, \mu}\) is bounded from \(L^2(\mu)\) into \(L^2(\nu)\), with norm depending on \(A\) and \(\delta\).

Notice that the notation “\(S_x\)” was also used at the beginning of Subsection 7.1, but with a different meaning.

**Proof.** We immediately check that \(M_{tr, \mu}\) is bounded from \(L^\infty(\mu)\) into \(L^\infty(\nu)\). So, by interpolation it is enough to show that it is also bounded from \(L^1(\mu)\) into \(L^{1, \infty}(\nu)\). Take a fixed \(\lambda > 0\). If \(M_{tr, \mu}f(x) > \lambda\) for some \(x \in \text{supp}(\nu)\), there is a square \(Q_x\) such that \(x \in \frac{1}{2}Q_x, \ell(Q_x) > 8\ell(S_x)\), and \(\int_{Q_x} |f| \, d\mu/\mu(Q_x) > \lambda\). By the Besicovitch covering theorem, there exists a family of points \(\{x_i\}_i \subset \text{supp}(\nu)\) so that the family of squares \(\{Q_x\}_i\) has finite overlap and \(\{x : M_{tr, \mu}f(x) > \lambda\} \subset \bigcup_i Q_{x_i}\). Since \(\ell(Q_{x_i}) > 8\ell(S_{x_i})\) and \(x_i \in \frac{1}{2}Q_{x_i}\), it is easy to check that there exists a square \(P\) concentric with \(S_{x_i}\), and with side length \(\ell(P) = \ell(Q_{x_i})/2\) such that \(S_{x_i} \subset P \subset Q_{x_i}\). Then,

\[
\nu(Q_{x_i}) \leq C A \theta_\mu(R) \ell(Q_{x_i}) = C A \theta_\mu(R) \ell(P) \leq C A \delta^{-1} \mu(P) \leq C(A, \delta) \mu(Q_{x_i}).
\]
Thus,
\[ \nu\{x : M_{r,\mu} f(x) > \lambda\} \leq \sum_i \nu(Q_{x_i}) \leq C(A, \delta) \sum_i \mu(Q_{x_i}) \]
\[ \leq \frac{C(A, \delta)}{\lambda} \sum_i \int_{Q_{x_i}} |f| \, d\mu \leq \frac{C(A, \delta)}{\lambda} \int |f| \, d\mu. \]  

7.4.2. Proof of (7.6). As in the preceding lemma, for \( x \in \bigcup_{j \in J_0} S_j \), we denote by \( S_x \) be the square \( S_j, j \in J_0 \), which contains \( x \). Analogously, \( \hat{S}_x, \hat{\hat{S}}_x \), \( Q^1_x, Q^2_x \), and \( V_x \) stand for \( \hat{S}_j, \hat{\hat{S}}_j, Q^1_j, Q^2_j \), and \( V_j \) respectively.

We denote
\[ F_1 := \{(x, y, z) \in (\bigcup_{j \in J_0} S_j)^3 : S_x = S_y \neq S_z\}, \]
\[ F_2 := \{(x, y, z) \in (\bigcup_{j \in J_0} S_j)^3 : S_x \neq S_y \neq S_z \neq S_x\}, \]
\[ F_3 := \{(x, y, z) \in F_2 : 3\hat{\hat{S}}_y \cap 3\hat{\hat{S}}_z = \emptyset\}, \]
\[ F_4 := \{(x, y, z) \in F_2 : 3\hat{\hat{S}}_x \cap 3\hat{\hat{S}}_y \neq \emptyset, 3\hat{\hat{S}}_x \cap 3\hat{\hat{S}}_z \neq \emptyset, 3\hat{\hat{S}}_y \cap 3\hat{\hat{S}}_z \neq \emptyset\}. \]

Since \( c^2(\nu_{S_j}) = 0 \) for all \( j \in J_0 \),
\[ c^2(\nu) = \iiint (\bigcup_{j \in J_0} S_j)^3 c(x, y, z) d\nu(x) d\nu(y) d\nu(z) \]
\[ = 3 \iiint_{F_1} \cdots + \iiint_{F_2} \cdots \leq 3 \iiint_{F_1} \cdots + 3 \iiint_{F_1} \cdots + \iiint_{F_4} \cdots \]
\[ =: 3I_1 + 3I_3 + I_4. \]

- Estimates for \( I_3 \). If \( y' \in S_y \cap W \) and \( z' \in S_z \cap W \), by Lemma 3.5
\[ c(x, y, z) \leq c(x, y', z') + \frac{Cl(S_y)}{|y - x||y - z|} + \frac{Cl(S_z)}{|z - x||z - y|} \]
\[ =: c(x, y', z') + C[T_y(x, y, z) + T_z(x, y, z)]. \]

Then it easily follows that
\[ I_3 \leq 2 \iint_{y, z \in W} c(x, y, z)^2 \, d\nu(x) d\mu(y) d\mu(z) \]
\[ \frac{3\hat{\hat{S}}_y \cap 3\hat{\hat{S}}_z = \emptyset}{3\hat{\hat{S}}_y \cap 3\hat{\hat{S}}_z = \emptyset} + C \iint_{y, z \in W} [T_y(x, y, z)^2 + T_z(x, y, z)^2] \, d\nu(x) d\nu(y) d\nu(z) \]
\[ =: 2I_{3,1} + CI_{3,2}. \]

Although it is not written explicitly, all the integrals above are restricted to \((2R)^3\) (and the same for the rest of the proof of (7.6)).
First, dealing with the term \( I_{3,2} \), we have

\[
\iint_{[x, y, z] \in F_2} T_y(x, y, z)^2 \, d\nu(x) \, d\nu(y) \, d\nu(z) \leq \iint_{|y-z| > \ell(S_x) / 2} \cdots
\]

\[
\leq \int \left( \int_{|y-z| > \ell(S_x) / 2} \frac{\ell(S_y)}{|y-z|^2} \, d\nu(x) \right) \left( \int_{|y-z| > \ell(S_x) / 2} \frac{\ell(S_y)}{|y-z|^2} \, d\nu(z) \right) \, d\nu(y)
\]

\[
\leq C \left( A \theta(R) \right) \left( A \theta(R) \frac{\ell(S_y)}{\ell(S_y)} \right) \nu(C) \leq C A^2 \theta(R)^2 \, \varepsilon_0^{1/50} \, \mu(R).
\]

We have analogous estimates for the integral of \( T_z(\cdots)^2 \). Thus,

\[
I_{3,2} \leq C A^2 \theta(R)^2 \, \varepsilon_0^{1/50} \, \mu(R).
\]

Now we consider the term \( I_{3,1} \) in (7.14). By Lemma 7.8, for all \( x_1 \in Q_x^1 \cap V_x \) and \( x_2 \in Q_x^2 \cap V_x \) we have

\[
c(x, y, z) \leq C(A, \delta) \left[ c(x_1, y, z) + c(x_2, y, z) \right] + \frac{C \varepsilon_0^{1/6} \ell(S_x)}{|x-y||x-z|}
\]

Integrating over \( x_1 \in Q_x^1 \cap V_x \) and over \( x_2 \in Q_x^2 \cap V_x \) with respect to \( \mu \), we obtain

\[
c(x, y, z) \leq \frac{C(A, \delta)}{\mu(S_x)} \int_{x \in V_x \cap Q_x^1} c(x_1, y, z) \, d\mu(x_1) + \int_{x_2 \in V_x \cap Q_x^2} c(x_2, y, z) \, d\mu(x_2)
\]

\[
+ C \varepsilon_0^{1/6} T_x(x, y, z),
\]

where \( T_x(x, y, z) := \ell(S_x) / (|x-y||x-z|) \). Therefore,

\[
c(x, y, z) \leq \frac{C(A, \delta)}{\mu(S_x)} \int_{S_x} c(w, y, z) \, d\mu(w) + C \varepsilon_0^{1/6} T_x(x, y, z)
\]

\[
\leq C(A, \delta) M_{tr, \mu}[c(\cdot, y, z)](x) + C \varepsilon_0^{1/6} T_x(x, y, z).
\]

Thus,

\[
I_{3,1} \leq C(A, \delta) \int \int_{x \in V_x \cap Q_x^1} \left. M_{tr, \mu}[c(\cdot, y, z)](x) \right| d\nu(x) \, d\mu(y) \, d\mu(z)
\]

\[
+ C \varepsilon_0^{1/3} \int \int_{|x-y|, |x-z| \geq \ell(S_x) / 2} T_x(x, y, z)^2 \, d\nu(x) \, d\mu(y) \, d\mu(z).
\]

The last integral on the right side is estimated as follows:

\[
\int \int_{|x-y|, |x-z| \geq \ell(S_x) / 2} T_x(x, y, z)^2 \, d\nu(x) \, d\mu(y) \, d\mu(z)
\]

\[
\leq \int \left( \int_{|x-y| > \ell(S_x) / 2} \frac{1}{|x-y|^2} \, d\mu(y) \right)^2 \, d\nu(x) \leq C A^2 \theta(R)^2 \, \mu(R).
\]
On the other hand, by Lemma 7.9 we know that $M_{tr,\mu}$ is bounded from $L^2(\mu)$ into $L^2(\nu)$. So we have

$$I_{3,1} \leq C(A, \delta) \iint_{3\dd 
abla_2 \dd \delta = \emptyset} c(x, y, z)^2 d\mu(x) d\mu(y) d\mu(z) + \varepsilon_0^{1/3} A^2 \theta_\mu(R)^2 \mu(R).$$

It is easy to check that

$$\int_{3\dd \nabla_2 \dd \delta = \emptyset} c(x, y, z)^2 d\mu(x) d\mu(y) d\mu(z) \leq \int c_{tr,\mu}(y, 2R, 2R) d\mu(y) \leq C_0 \theta_\mu(R)^2 \mu(R).$$

From the preceding estimates for $I_{3,1}$ and $I_{3,2}$, we get

$$I_3 \leq C(A, \delta) \varepsilon_0^{1/50} \theta_\mu(R)^2 \mu(R).$$

**Estimates for $I_4$.** By Fubini, we have

$$I_4 \leq 3 \int \int \int_{(x, y, z) \in F_4, \ell(\dd \nabla_2 \dd \delta \geq \ell(\dd \nabla_2 \dd \delta) \geq \ell(\dd \nabla_2 \dd \delta)} c(x, y, z)^2 d\nu(x) d\nu(y) d\nu(z) =: 3I'_4.$$ 

Now we split $I'_4$ as follows:

$$I'_4 = \left( \int \int \int_{(x, y, z) \in F_4, \ell(\dd \nabla_2 \dd \delta \geq \ell(\dd \nabla_2 \dd \delta) \geq \ell(\dd \nabla_2 \dd \delta)} c(x, y, z)^2 d\nu(x) d\nu(y) d\nu(z) \right) \left( \int \int \int_{(x, y, z) \in F_4, \ell(\dd \nabla_2 \dd \delta \geq \ell(\dd \nabla_2 \dd \delta) \geq \ell(\dd \nabla_2 \dd \delta)} c(x, y, z)^2 d\nu(x) d\nu(y) d\nu(z) \right)$$

$$=: I_{4,1} + I_{4,2}.$$

First we will study $I_{4,1}$. For $(x, y, z)$ in the domain of integration of $I_{4,1}$ we have

$$|x - y| \geq \frac{\ell(\dd \nabla_2 \dd \delta)}{4} \geq \frac{\ell(\dd \nabla_2 \dd \delta)}{4} \quad \text{and} \quad |x - z| \geq \frac{\ell(\dd \nabla_2 \dd \delta)}{4} \geq \frac{\ell(\dd \nabla_2 \dd \delta)}{4}.$$ 

The estimates for $I_{4,1}$ are similar to the ones for $I_3$. Indeed, consider $y' \in S_y \cap W$ and $z' \in S_z \cap W$, so that (7.13) also holds in this case. Instead of (7.14) now we get

$$I_{4,1} \leq 2 \int \int \int_{(x, y, z) \in F_4, \ell(\dd \nabla_2 \dd \delta \geq \ell(\dd \nabla_2 \dd \delta) \geq \ell(\dd \nabla_2 \dd \delta)} c(x, y, z)^2 d\nu(x) d\nu(y) d\nu(z)$$

$$+ C \int \int \int_{(x, y, z) \in F_4, \ell(\dd \nabla_2 \dd \delta \geq \ell(\dd \nabla_2 \dd \delta) \geq \ell(\dd \nabla_2 \dd \delta)} [T_y(x, y, z)^2 + T_z(x, y, z)^2] d\nu(x) d\nu(y) d\nu(z).$$
We have
\[
\int\int\int_{x, y, z \in F_x} T_y(x, y, z)^2 \, d\nu(x) \, d\mu(y) \, d\mu(z) \leq \int\int\int_{|y-x| > \ell(\hat{S}_y)/4} \int\int\int_{|y-z| > \ell(\hat{S}_z)/4} \ell(\hat{S}_y) \, |y-x|^2 \, d\nu(x) \, \ell(\hat{S}_y) \, \ell(\hat{S}_z) \, \mu(y) \, d\mu(z) 
\]
\[
\leq C \left( A \theta(\mu(R)) \ell(\hat{S}_y) \right) \mu(R) \leq C A^2 \theta(\mu(R))^2 \varepsilon_0^{1/50} \mu(R). 
\]

Analogous estimates hold for the integral of $T_z(\cdots)^2$ since in the domain of integration we have $|x - z| \geq \ell(\hat{S}_z)/4$.

To estimate the integral
\[
\int\int\int_{x, y, z \in F_x} c(x, y, z)^2 \, d\nu(x) \, d\mu(y) \, d\mu(z) 
\]
in (7.15), the same arguments used for $I_{3.1}$ work in this case. Only some minor changes which are left for the reader are required.

Now we deal with $I_{4.2}$. Take $(x, y, z)$ in the domain of integration of $I_{4.2}$.

Since $\ell(\hat{S}_x) \geq \ell(\hat{S}_y) \geq \ell(\hat{S}_z)$, $3\hat{S}_x \cap 3\hat{S}_y \neq \emptyset$, and $3\hat{S}_x \cap 3\hat{S}_z \neq \emptyset$, we have $3\hat{S}_y, 3\hat{S}_z \subset 9\hat{S}_x$. Remember that, by Lemma 7.7, the segments $L_y, L_z$ (and thus $y$ and $z$) are contained in a strip with the same axis as $V_x$ and width $\varepsilon_0^{1/8} \ell(S_x)$. Therefore,
\[
\sin \angle(L_x, \hat{x}y) \leq \frac{\varepsilon_0^{1/8} \ell(S_x)}{|x-y|} \leq \frac{\varepsilon_0^{1/8} \ell(S_x)}{C^{-1} \ell(S_x)} \leq C \varepsilon_0^{1/8},
\]
and, in the same way, $\sin \angle(L_x, \hat{x}z) \leq C \varepsilon_0^{1/8}$. Thus, we get
\[
\sin \angle(y, x, z) \leq C \left( \sin \angle(L_x, \hat{x}y) + \sin \angle(L_x, \hat{x}z) \right) \leq C \varepsilon_0^{1/8}. 
\]
Therefore, since $\ell(S_x) < \ell(\hat{S}_y)$,
\[
c(x, y, z) = \frac{2 \sin \angle(y, x, z)}{|y-z|} \leq \frac{C \varepsilon_0^{1/8} \ell(S_x)}{\ell(S_y)} \leq \frac{C(A, \delta) \varepsilon_0^{1/8}}{\varepsilon_0^{1/50} \ell(S_y)} \leq \frac{C(A, \delta) \varepsilon_0^{21/200}}{\ell(S_x)},
\]
and so
\[
I_{4.2} \leq \int_{x \in 2R} \left( \int_{y, z \in 9\hat{S}_x} C(A, \delta) \varepsilon_0^{21/100} \frac{\ell(S_y)^2}{\ell(S_x)^2} \, d\mu(y) \, d\mu(z) \right) \, d\mu(x) 
\]
\[
\leq C(A, \delta) \varepsilon_0^{21/100} \varepsilon_0^{-1/25} \theta(\mu(R))^2 \mu(R) = C(A, \delta) \varepsilon_0^{17/100} \theta(\mu(R))^2 \mu(R). 
\]

Gathering the estimates for $I_{4.1}$ and $I_{4.2}$, we obtain
\[
I \leq C(A, \delta) \left( \varepsilon_0^{1/50} + \varepsilon_0^{17/100} \right) \theta(\mu(R))^2 \mu(R) \leq C(A, \delta) \varepsilon_0^{1/50} \theta(\mu(R))^2 \mu(R). 
\]
• Estimates for $I_1$. We have

$$I_1 = \int \int \int_{x \in \text{supp}(\nu), \ y \in L_x, \ z \not\in \hat{S}_x} c(x, y, z)^2 \, d\nu(x) \, d\nu(y) \, d\nu(z)$$

$$+ \int \int \int_{y \in L_x, \ z \in \hat{S}_x \setminus S_x} c(x, y, z)^2 \, d\nu(x) \, d\nu(y) \, d\nu(z) =: I_{1.1} + I_{1.2}.$$ 

The term $I_{1.1}$ is estimated as follows:

$$I_{1.1} \leq \int \int_{x \in \text{supp}(\nu), \ |x-z| > \frac{1}{8}\frac{\ell(\hat{S}_x)}{4}} \frac{1}{|x-z|^2} \, d\nu(x) \, d\nu(y) \, d\nu(z)$$

$$\leq \int \int_{x \in \text{supp}(\nu)} \frac{C \theta_\mu(R)\nu(L_x)}{\ell(\hat{S}_x)} \, d\nu(x) \leq C \theta_\mu(R)^3 \varepsilon_{0}^{1/50} \mu(R),$$

since $\nu(L_x)/\ell(\hat{S}_x) \leq C \theta_\mu(R)\ell(S_x)/\ell(\hat{S}_x) \leq C \theta_\mu(R)\varepsilon_{0}^{1/50}$ and $\nu(\mathbb{C}) \leq C \mu(R)$.

Finally we turn our attention to $I_{1.2}$. Consider $(x, y, z)$ in the domain of integration of $I_{1.2}$. Clearly, in this case we have $\hat{S}_x \cap \hat{S}_z \neq \emptyset$. If $\ell(\hat{S}_x) \leq \ell(\hat{S}_z)$, by Lemma 7.7, $z$ is contained in a strip with the same axis as $V_x$ and width $\varepsilon_0^{1/8}\ell(S_x)$.

Suppose now that $\ell(\hat{S}_z) > \ell(\hat{S}_x)$. Then, again by Lemma 7.7, either $\sin \angle(L_x, L_z) \leq C \varepsilon_{0}^{1/6}$ or $\ell(S_x) \leq \varepsilon_{0}^{3/5}\ell(S_x)$. However, the latter inequality cannot hold because it implies

$$|x-z| \geq \ell(S_x)/4 \geq \varepsilon_{0}^{-3/5}\ell(S_x)/4 \gg \ell(\hat{S}_x),$$

and so $z \not\in \hat{S}_x$. Then the condition $\sin \angle(L_x, L_z) \leq C \varepsilon_{0}^{1/6}$ holds. Further, we have $\ell(S_x) \leq 2\ell(\hat{S}_x)$ because $z \in \hat{S}_x$. As a consequence, we easily infer that $z$ lies in a thin strip with the same axis as $V_x$ and width

$$\varepsilon_0^{1/6}\ell(S_x) + C \varepsilon_0^{1/6}\ell(\hat{S}_x) \leq C(A, \delta)\varepsilon_{0}^{1/6-1/50}\ell(S_x) \leq \varepsilon_{0}^{2/15}\ell(S_x),$$

for $\varepsilon_0$ small enough.

So in any case $z$ is contained in the strip with the same axis as $V_x$ and width $\varepsilon_{0}^{2/15}\ell(S_x)$. As a consequence, we deduce

$$\sin \angle(x, y, z) \lesssim \frac{\varepsilon_{0}^{2/15}\ell(S_x)}{|y-z|} \lesssim \varepsilon_{0}^{2/15}.$$

Thus, $c(x, y, z) \lesssim \varepsilon_{0}^{2/15}/|x-z| \lesssim \varepsilon_{0}^{2/15}/\ell(S_x)$, and so

$$I_{1.2} \lesssim \int \int \int_{x \in \text{supp}(\nu)} \frac{A \varepsilon_0^{4/15}}{\ell(S_x)^2} \theta_\mu(R)^2 \ell(\hat{S}_x)\ell(S_x) \, d\nu(x)$$

$$\lesssim C(A, \delta)\varepsilon_{0}^{4/15-1/50} \theta_\mu(R)^2 \mu(R) = C(A, \delta)\varepsilon_{0}^{37/150} \theta_\mu(R)^2 \mu(R).$$
End of the proof. By the estimates obtained for $I_1$, $I_3$ and $I_4$, we get
\[ c^2(\nu) \leq C(A, \delta) \theta_\mu(R)^2 \varepsilon_0^{1/50} \mu(R). \]

8. The curvature of $\varphi_2 \mu$

In this section we denote $\sigma := \varphi_2 \mu$ and $F := \varphi(E)$.

Given a square $Q$, we say that $\varphi(Q)$ is a $\varphi$-square. If $x_Q$ is the center of $Q$, then we call $\varphi(x_Q)$ the center of $\varphi(Q)$. We also set $\ell(\varphi(Q)) := \ell(Q)$. Since $\varphi$ is bilipschitz, we have $\ell(\varphi(Q)) \simeq \text{diam}(\varphi(Q))$. We will often use the letters $P, Q, R$ to denote $\varphi$-squares too. If $Q$ is a dyadic (or 4-dyadic) square, we say that $\varphi(Q)$ is a dyadic (or 4-dyadic) $\varphi$-square.

If $Q = \varphi(Q_0)$ is a $\varphi$-square, we let $\lambda Q = \varphi(\lambda Q_0)$, for $\lambda > 0$. Then $Q$ is $\lambda$-doubling if $\sigma(\lambda Q) \leq C \sigma(Q)$ for some $C \geq 1$. We also set
\[ \theta_\sigma(Q) := \frac{2^{1/2} \sigma(Q)}{\text{diam}(Q)} \]
(the number $2^{1/2}$ is due to aesthetic reasons; if $\varphi$ is the identity, then the definition coincides with (2.1)) and if $R$ is another $\varphi$-square which contains $Q$, we put
\[ \delta_\sigma(Q, R) := \int_{R_\sigma \setminus Q} \frac{1}{|y - x_Q|} \, d\sigma(y), \]
where $x_Q$ stands for the center of $Q$ and $R_\sigma$ is the smallest $\varphi$-square concentric with $Q$ that contains $R$.

Given a family $\text{Top}(F)$ of 4-dyadic $\varphi$-squares and a fixed $Q \in \text{Top}(F)$, we denote by $\text{Stop}(Q)$ the subfamily of $\varphi$-squares which satisfy the properties (a), (b), (c) stated at the beginning of Section 3 (with squares replaced by $\varphi$-squares). The set $G(Q)$ is also defined as in Section 3, with $\varphi$-squares instead of squares.

Main Lemma 8.1. Let $\sigma$ be a Radon measure supported on a compact $F \subset \mathbb{C}$. Suppose that $\sigma(B(x, r)) \leq C_0 r$ for all $x \in \mathbb{C}$, $r > 0$. Let $\text{Top}(F)$ be a family of 4-dyadic 16-doubling $\varphi$-squares (called top $\varphi$-squares) which contains some 4-dyadic $\varphi$-square $R_0$ such that $F \subset R_0$, and such that for each $Q \in \text{Top}(F)$ there exists a $C_{25}$-AD regular curve $\Gamma_Q$ satisfying:

(a) $\sigma$-almost every point in $G(Q)$ belongs to $\Gamma_Q$.

(b) For each $P \in \text{Stop}(Q)$ there exists some $\varphi$-square $\widetilde{P}$ containing $P$ such that $\delta_\sigma(P, P') \leq C \theta_\sigma(Q)$ and $P \cap \Gamma_Q \neq \emptyset$.

(c) If $P$ is a $\varphi$-square with $\ell(P) \leq \ell(Q)$ such that either $P \cap G(Q) \neq \emptyset$ or there is another $\varphi$-square $P' \in \text{Stop}(Q)$ such that $P \cap P' \neq \emptyset$ and $\ell(P') \leq \ell(P)$, then $\sigma(P) \leq C \theta_\sigma(Q) \ell(P)$. 

Then,
\[ c^2(\sigma) \leq C \sum_{Q \in \text{Top}(F)} \theta_{\sigma}(Q)^2 \sigma(Q). \]

We will prove this lemma in Subsections 8.2–8.8.

8.1. Proof of Theorem 1.3. This is an easy consequence of Main Lemmas 3.1 and 8.1. Indeed, if \( c^2(\mu) < \infty \), then we have the corona decomposition given by Main Lemma 3.1. Applying the bilipschitz map \( \varphi \), we obtain another corona decomposition for \( F = \varphi(E) \) like the one required in Main Lemma 8.1. In particular, notice that \( \varphi \) sends AD regular curves to AD regular curves, and also if \( Q, R \) are squares such that \( Q \subset R \), then
\[ \delta_{\sigma}(\varphi(Q), R) \leq \int_{R \setminus Q} \frac{1}{|y - x_Q|} d\mu(y) \]
with \( C \) depending on \( \varphi \). So, by Main Lemma 8.1, \( c^2(\sigma) \lesssim (\mu(E) + c^2(\mu)) \). □

8.2. Decomposition of \( c^2(\sigma) \). We start the proof of Main Lemma 8.1. Observe that
\[ c^2(\sigma) \leq \int \int \int_{|x - y| \geq |x - z|, |y - z|} c(x, y, z)^2 d\sigma(x) d\sigma(y) d\sigma(z). \]
We now introduce a variant of the curvature operator \( K_{\sigma} \). Consider the kernel
\[ \hat{k}_{\sigma}(x, y) = \int_{z: |x - y| \geq |x - z|, |y - z|} c(x, y, z)^2 d\sigma(z), \]
and set
\[ \hat{K}_{\sigma} f(x) = \int \hat{k}_{\sigma}(x, y) f(y) d\sigma(y), \quad x \in \mathbb{C}, f \in L^1_{\text{loc}}(\sigma) \]
(compare with the definition of \( k_{\mu}(x, y) \) and \( K_{\mu} \) in Section 2). We have
\[ \int_{F} \hat{K}_{\sigma} \chi F(x) d\sigma(x) \leq c^2(\sigma) \leq 3 \int_{F} \hat{K}_{\sigma} \chi F(x) d\sigma(x). \]
The truncated operator \( \hat{K}_{\sigma,j}, j \in \mathbb{Z}, \) is
\[ \hat{K}_{\sigma,j} f(x) = \int_{|x - y| > L^{-1}2^{-j}} \hat{k}_{\sigma}(x, y) f(y) d\sigma(y), \quad x \in \mathbb{C}, f \in L^1_{\text{loc}}(\sigma), \]
where \( L \) is the bilipschitz constant of \( \varphi \). We say that a \( \varphi \)-square \( Q \in \text{Top}(F) \) is a descendant of another \( \varphi \)-square \( R \in \text{Top}(F) \) if there is a chain \( R = \)
$Q_1, Q_2, \ldots, Q_n = Q$, with $Q_i \in \text{Top}(F)$ such that $Q_{i+1} \in \text{Stop}(Q_i)$ for each $i$. Only the $\varphi$-squares from $\text{Top}(F)$ which are descendants of $R_0$ will be relevant to estimate $c^2(\sigma)$. So we assume that all the $\varphi$-squares in $\text{Top}(F)$ are of this type.

To decompose $c^2(\sigma)$, we prefer to use dyadic $\varphi$-squares instead of 4-dyadic $\varphi$-squares. A $\varphi$-square $Q$ belongs to the family $\text{Top}_{\text{dy}}(F)$ if there exists some $R \in \text{Top}(F)$ such that $Q$ is one of the 16 dyadic $\varphi$-squares contained in $R$ with side length $\ell(R)/4$.

Note that if $Q \in \text{Top}_{\text{dy}}(F)$, then $Q$ is contained in a 4-dyadic $\varphi$-square $R$ such that $Q \subset R \subset 7Q \subset 3R$. Moreover, since each 4-dyadic $\varphi$-square $R \in \text{Top}(F)$ is made up of 16 dyadic $\varphi$-squares $Q \in \text{Top}_{\text{dy}}(F)$, we get (using the doubling properties of the $\varphi$-squares in $\text{Top}(F)$)

\begin{equation}
\sum_{Q \in \text{Top}_{\text{dy}}(F)} \theta_\sigma(7Q)^2 \sigma(7Q) \lesssim \sum_{R \in \text{Top}(F)} \theta_\sigma(R)^2 \sigma(R).
\end{equation}

Given $Q \in \text{Top}(F)$ or $Q \in \text{Top}_{\text{dy}}(F)$, we denote by $\text{Term}(Q)$ the family of maximal dyadic (and thus disjoint) $\varphi$-squares $P \in \text{Top}_{\text{dy}}(F)$, with $P \subset Q$. Finally, we let $\text{Tree}(Q)$ be the class of dyadic $\varphi$-squares contained in $Q$, different from $Q$, which are not proper $\varphi$-subsquares of any $P \in \text{Term}(Q)$.

We denote by $\varphi\Delta$ the class of dyadic $\varphi$-squares contained in $R_0$, and by $\varphi\Delta_j$ those $\varphi$-squares in $\varphi\Delta$ with side length $2^{-j}$. We have

$$\varphi\Delta = \{ Q \in \varphi\Delta : \ell(Q) \geq \ell(R_0)/4 \} \cup \bigcup_{Q \in \text{Top}_{\text{dy}}(F)} \text{Tree}(Q).$$

Observe that the $\varphi$-squares $Q \in \varphi\Delta$ such that $\ell(Q) \geq \ell(R_0)/4$ are the only $\varphi$-squares in $\text{Top}_{\text{dy}}(F)$ which may not belong to any $\text{Tree}(R)$, $R \in \text{Top}_{\text{dy}}(F)$. Notice also that $\text{Tree}(Q) \cap \text{Tree}(R) = \emptyset$ if $Q \not= R$.

We split the curvature $c^2(\sigma)$ as follows:

$$c^2(\sigma) \simeq \sum_j \sum_{Q \in \varphi\Delta_j} \int_Q (\tilde{K}_{\sigma,j+1} \chi_F - \tilde{K}_{\sigma,j} \chi_F) \, d\sigma + \int_F \tilde{K}_{\sigma,j}(R_0) + 2 \chi_F \, d\sigma$$

$$= \sum_{R \in \text{Top}_{\text{dy}}(F)} \sum_{Q \in \text{Tree}(R)} \int_Q (\tilde{K}_{\sigma,j}(Q) + 1 \chi_F - \tilde{K}_{\sigma,j}(Q) \chi_F) \, d\sigma$$

$$+ \int_F \tilde{K}_{\sigma,j}(R_0) + 2 \chi_F \, d\sigma,$$

where $J(Q)$ stands for the integer $j$ such that $Q \in \varphi\Delta_j$. Since

$$\int_F \tilde{K}_{\sigma,j}(R_0) + 2 \chi_F \, d\sigma \lesssim \theta_\sigma(R_0)^2 \sigma(F),$$
to prove Main Lemma 8.1 it is enough to show that
\[
(8.2) \quad \sum_{Q \in \text{Tree}(R)} \int_Q (\tilde{K}_{\sigma,J(Q)} + 1) \chi_F - \tilde{K}_{\sigma,J(Q)} \chi_F \, d\sigma \lesssim \theta_\sigma(7R)^2 \sigma(7R),
\]
for every \( R \in \text{Top}_d(F) \), by (8.1).

8.3. Regularization of the stopping \( \varphi \)-squares. Given a fixed \( R \in \text{Top}_d(F) \), let \( R_1 \) be a 4-dyadic \( \varphi \)-square \( R_1 \in \text{Top}(F) \) such that \( R \subset R_1 \subset 7R \) (it does not matter which \( R_1 \) if it is not unique). Let \( \Gamma_R := \Gamma_{R_1} \) be the AD regular curve satisfying (a) and (b) in Main Lemma 8.1.

It seems that after defining \( \text{Top}_d(F) \) we should introduce the family \( \text{Stop}_d(R) \) analogously. However, for technical reasons, it is better to introduce a regularized version of \( \text{Stop}_d(R) \) (it does not matter what \( \text{Stop}_d(R) \) means precisely), that we will denote by \( \text{Reg}_d(R) \). First we set
\[
d_R(x) := \inf_{Q \in \text{Stop}(R_1)} \{ \text{dist}(x, Q) + \ell(Q), \text{dist}(x, G(R_1)) \}.
\]
For each \( x \in 3R \cap \text{supp}(\sigma) \setminus [G(R_1) \cup Z(\sigma)] \) (recall that \( Z(\sigma) \) is a set of zero \( \sigma \)-measure, defined similarly to \( Z(\mu) \) at the beginning of Section 3), let \( Q_x \) be a dyadic \( \varphi \)-square containing \( x \) such that
\[
(8.3) \quad \frac{d_R(x)}{20L} < \ell(Q_x) \leq \frac{d_R(x)}{10L}.
\]
Remember that \( L \) is the bilipschitz constant of \( \varphi \). Then, \( \text{Reg}_d(R) \) is a maximal (and thus disjoint) subfamily of \( \{Q_x\}_{x \in 3R \cap \text{supp}(\sigma) \setminus [G(R_1) \cup Z(\sigma)]} \).

**Lemma 8.2.** (a) If \( P, Q \in \text{Reg}_d(R) \) and \( 2P \cap 2Q \neq \emptyset \), then \( \ell(Q)/2 \leq \ell(P) \leq 2\ell(Q) \).

(b) If \( Q \in \text{Reg}_d(R) \) and \( x \in Q, r \geq \ell(Q) \), then \( \sigma(B(x,r) \cap 4R) \leq C\theta_\sigma(R_1)r \).

(c) For each \( Q \in \text{Reg}_d(R) \), there exist some \( \varphi \)-square \( \tilde{Q} \) which contains \( Q \) such that \( \delta_\sigma(Q, \tilde{Q}) \leq C\theta_\sigma(R_1) \) and \( \frac{1}{2} \tilde{Q} \cap \Gamma_R \neq \emptyset \).

**Proof.** (a) Consider \( P, Q \in \text{Reg}_d(R) \) such that \( 2P \cap 2Q \neq \emptyset \). By construction, there exist some \( x \in P \) and some \( \varphi \)-square \( P_0 \in \text{Stop}(R_1) \) or point \( P_0 \in G(R_1) \) (for convenience, in this proof we identify points in \( G(R_1) \) with stopping squares in \( \text{Stop}(R_1) \) with zero side length) such that \( \ell(P) \geq d_R(x)/20L \) and
\[
\text{dist}(x, P_0) + \ell(P_0) \leq 1.1d_R(x) \leq 22L\ell(P).
\]
Thus, for any \( y \in Q \),
\[
\text{dist}(y, P_0) + \ell(P_0) \leq \text{diam}(2Q) + \text{diam}(2P) + \text{dist}(x, P_0) + \ell(P_0)
\leq 3\ell(Q) + 3\ell(P) + 22L\ell(P),
\]
since \( \text{diam}(2Q) \leq L \text{diam}(\varphi^{-1}(2Q)) = L8^{1/2}\ell(Q) \leq 3L\ell(Q) \). So \( d_R(y) \leq 3\ell(Q) + 25L\ell(P) \) for all \( y \in Q \). Therefore,

\[
\ell(Q) \leq \frac{1}{10L}(3L\ell(Q) + 25L\ell(P)),
\]

which yields \( \ell(Q) \leq \frac{25}{7}\ell(P) < 4\ell(P) \). This implies \( \ell(Q) \leq 2\ell(P) \), because \( P \) and \( Q \) are \( \varphi \)-dyadic squares.

The inequality \( \ell(P) \leq 2\ell(Q) \) is proved in an analogous way.

(b) Take now \( Q \in \text{Reg}_d(R) \) and \( x \in Q, r \geq \ell(Q) \). There exists some \( y \in Q \) and some \( \varphi \)-square \( P_0 \in \text{Stop}(R_1) \) such that \( d_R(y)/20L < \ell(Q) \leq d_R(y)/10 \) and

\[
\text{dist}(y, P_0) + \ell(P_0) \leq 1.1d_R(y) \leq 22L\ell(Q).
\]

Thus \( B(x, r) \) is contained in some \( \varphi \)-square of the form \( \frac{C\ell(P_0)}{\ell(P_0)}P_0 \), with \( \frac{C\ell(P_0)}{\ell(P_0)} \geq 1 \) and \( C \) depending on \( L \). Then,

\[
\sigma(B(x, r) \cap 4R) \leq \sigma\left(\frac{C\ell(P_0)}{\ell(P_0)}P_0 \cap 4R\right) \leq C\sigma(R_1)r.
\]

(c) We continue with the same notation as in (b). Let \( \tilde{P}_0 \) be a \( \varphi \)-square containing \( P_0 \) such that \( \delta_\sigma(P_0, \tilde{P}_0) \leq C\theta_\sigma(R_1) \) and \( \frac{1}{2}\tilde{P}_0 \cap \Gamma_R \neq \emptyset \) (given by (c) of Main Lemma 8.1). It is easily checked that there exists some absolute constant \( C_{26} \geq 1 \) such that \( C_{26}\tilde{P}_0 \) contains \( Q \). We set \( \tilde{Q} := C_{26}\tilde{P}_0 \).

Given \( R \in \text{Top}_d(F) \), we denote by \( \text{Tree}^\text{Reg}(R) \) the tree of dyadic \( \varphi \)-squares whose top \( \varphi \)-square is \( R \) and whose terminal \( \varphi \)-squares are the \( \varphi \)-squares \( Q_1 \in \text{Reg}_d(R) \) which are contained in \( R \) (this is the same definition as the one for \( \text{Tree}(R) \) in Subsection 8.2, but with \( \text{Term}(R) \) replaced by \( \text{Reg}_d(R) \)).

**Lemma 8.3.** Given any \( R \in \text{Top}_d(F) \), if \( Q \in \text{Tree}(R) \) and \( \sigma(Q) > 0 \), then \( Q \in \text{Tree}^\text{Reg}(R) \).

Roughly speaking, the lemma asserts that if we do not care about squares with vanishing \( \sigma \)-measure, then \( \text{Tree}(R) \subset \text{Tree}^\text{Reg}(R) \), and so we always stop later in \( \text{Tree}^\text{Reg}(R) \) than in \( \text{Tree}(R) \).

**Proof.** Let \( R_1 \) be the 4-dyadic \( \varphi \)-square \( R_1 \in \text{Top}(F) \) such that \( R \subset R_1 \subset 7R \) is as in the definition of \( \text{Reg}_d(R) \).

Let \( Q_0 \in \text{Tree}(R) \) be such that \( \sigma(Q_0) > 0 \). To see that \( Q_0 \in \text{Tree}^\text{Reg}(R) \), it is enough to show that \( Q_0 \) is not contained in any square \( Q_x \) like the ones appearing in (8.3), with \( x \in 3R \cap \text{supp}(\sigma) \setminus [G(R_1) \cup Z(\sigma)] \). Suppose that this is not the case, so that \( Q_0 \subset Q_x \) for some \( Q_x \) as above. Since

\[
R \cap \text{supp}(\sigma) \subset \bigcup_{P \in \text{Stop}(R_1)} P \cup G(R_1) \cup Z(\sigma)
\]
and \( \sigma(Q_0) \neq 0 \), by the definition of Tree\((R)\), either there exists some square \( P \in \text{Stop}(R_1) \) such that one of the 16 dyadic squares which form \( P \) (which is 4-dyadic) is contained in \( P \), or there exists some \( y_0 \in G(R_1) \cap Q_0 \). In any case, we deduce (identifying \( y_0 \) with a square \( P \) with \( \ell(P) = 0 \) in the latter case) that for any \( y \in Q_x \)

\[
d_R(y) \leq \ell(P) + 2^{1/2}L\ell(Q_x) \leq (4 + 2^{1/2}L)\ell(Q_x).
\]

In particular, this holds for \( x = y \), and so

\[
\ell(Q_x) \leq \frac{1}{10L}d_R(x) \leq \frac{4 + 2^{1/2}}{10}\ell(Q_x) \leq \frac{3}{5}\ell(Q_x).
\]

Thus \( \ell(Q_x) = 0 \), which is a contradiction. \( \square \)

8.4. Construction of the approximating measure on \( \Gamma_R \). In this subsection we denote \( \text{Reg}_{dy}(R) = \{ Q_i \}_{i \geq 1} \). For each \( i \), let \( \tilde{Q}_i \) be a \( \varphi \)-square containing \( P_i \) such that \( \delta_x(Q_i, \tilde{Q}_i) \leq C\theta_{\sigma}(R_1) \approx \theta_{\sigma}(7R) \) and \( \frac{1}{2}\tilde{Q}_i \cap \Gamma_R \neq \varnothing \). We may also suppose that \( \text{diam}(\Gamma_R) \geq 10\ell(R) \), since we can always extend \( \Gamma_R \) if necessary.

**Lemma 8.4.** For each \( i \geq 1 \) there exists some function \( g_i \geq 0 \) supported on \( \Gamma_R \cap \tilde{Q}_i \) such that

\[
\int_{\Gamma_R} g_i \, dH^1 = \sigma(Q_i),
\]

(8.4)

\[
\sum_{i} g_i \lesssim \theta_{\sigma}(R_1),
\]

(8.5)

and

\[
\|g_i\|_{\infty} \ell(\tilde{Q}_i) \lesssim \sigma(Q_i).
\]

(8.6)

**Proof.** The arguments are inspired by the Calderón-Zygmund decomposition of [To2, Lemma 7.3].

We assume first that the family \( \text{Reg}_{dy}(R) = \{ Q_i \}_{i \geq 1} \) is finite. We also suppose that \( \ell(\tilde{Q}_i) \leq \ell(\tilde{Q}_{i+1}) \) for all \( i \). The functions \( g_i \) that we will construct will be of the form \( g_i = \alpha_i\chi_{A_i} \), with \( \alpha_i \geq 0 \) and \( A_i \subset \tilde{Q}_i \). We set \( \alpha_1 := \sigma(Q_1)/\mathcal{H}^1(\tilde{Q}_1 \cap \Gamma_R) \) and \( A_1 := \tilde{Q}_1 \cap \Gamma_R \), so that \( \int_{\Gamma_R} g_1 \, dH^1 = \sigma(Q_1) \). Notice by the way that \( \|g_1\|_{\infty} \leq C\sigma(Q_1)/\ell(\tilde{Q}_1) \leq C\theta_{\sigma}(R_1) \).

To define \( g_k \), \( k \geq 2 \), we argue by induction. Suppose that \( g_1, \ldots, g_{k-1} \) have been constructed, satisfy (8.4) and \( \sum_{i=1}^{k-1} g_i \leq B\theta_{\sigma}(R_1) \), where \( B \) is some constant which will be chosen below. Let \( \tilde{Q}_{s_1}, \ldots, \tilde{Q}_{s_m} \) be the subfamily of \( \tilde{Q}_1, \ldots, \tilde{Q}_{k-1} \) such that \( \tilde{Q}_{s_j} \cap \tilde{Q}_k \neq \varnothing \). Since \( \ell(\tilde{Q}_{s_j}) \leq \ell(\tilde{Q}_k) \) (because of the nondecreasing sizes of the \( \tilde{Q}_i \)'s), we have \( \tilde{Q}_{s_j} \subset 3\tilde{Q}_k \). Using (8.4) for \( i = s_j \),
we get $$\sum_j \int_{\Gamma_R} g_{s_j} \, d\mathcal{H}^1 \leq \sum_j \sigma(Q_{s_j})$$

$$\leq \sigma(3\bar{Q}_k) \leq C\theta_\sigma(R_1)\ell(\bar{Q}_k) \leq C_{27}\theta_\sigma(R_1)\mathcal{H}^1(\Gamma_R \cap \bar{Q}_k).$$

Therefore, $$\mathcal{H}^1\left(\Gamma_R \cap \left\{ \sum_j g_{s_j} > 2C_{27}\theta_\sigma(R_1) \right\} \right) \leq \frac{1}{2}\mathcal{H}^1(\Gamma_R \cap \bar{Q}_k).$$

So we set

$$A_k := \Gamma_R \cap \bar{Q}_k \cap \left\{ \sum_j g_{s_j} \leq 2C_{27}\theta_\sigma(R_1) \right\},$$

and then $\mathcal{H}^1(A_k) \geq \mathcal{H}^1(\Gamma_R \cap \bar{Q}_k)/2$. Also, we put $\alpha_k := \frac{\sigma(Q_k)}{\mathcal{H}^1(A_k)}$, so that $\int_{\Gamma_R} g_k \, d\mathcal{H}^1 = \sigma(Q_k)$. Then,

$$\alpha_k \leq \frac{2\sigma(Q_k)}{\mathcal{H}^1(\Gamma_R \cap \bar{Q}_k)} \leq \frac{C\sigma(Q_k)}{\ell(\bar{Q}_k)} \leq C_{28}\theta_\sigma(R_1). \tag{8.7}$$

Thus,

$$g_k + \sum_j g_{s_j} \leq (2C_{27} + C_{28})\theta_\sigma(R_1).$$

We choose $B := 2C_{27} + C_{28}$ and (8.5) follows. Notice that (8.6) is proved in (8.7).

Suppose now that $\{Q_i\}$ is not finite. For each fixed $N$ we consider a family of squares $\{Q_i\}_{1 \leq i \leq N}$. As above, we construct functions $g_1^N, \ldots, g_N^N$ with supp($g_i^N$) $\subset Q_i \cap \Gamma_R$

$$\int_{\Gamma_R} g_i^N \, d\mathcal{H}^1 = \sigma(Q_i), \quad \sum_{i=1}^N g_i^N \leq B\theta_\sigma(R_1), \quad \text{and} \quad ||g_i^N||_{\infty, \ell(\bar{Q}_i)} \leq C\sigma(Q_i).$$

Then there is a subsequence $\{g_{i_k}^k\}_{k \in I_1}$, which is convergent in the weak * topology of $L^\infty(\mathcal{H}^1_{\Gamma_R})$ to some function $g_1 \in L^\infty(\mathcal{H}^1_{\Gamma_R})$. Now we take another subsequence $\{g_{i_k}^k\}_{k \in I_2}$, $I_2 \subset I_1$, convergent in the weak * topology of $L^\infty(\mathcal{H}^1_{\Gamma_R})$ to another function $g_2 \in L^\infty(\mathcal{H}^1_{\Gamma_R})$, etc. We have supp($g_i$) $\subset \bar{Q}_i$. Further, (8.4), (8.5) and (8.6) also hold, because of the weak * convergence. \qed

8.5. A symmetrization lemma. Recall that by Lemma 8.3, Tree(R) $\subset$ Tree^{Reg}(R). As a consequence,

$$\sum_{Q \in \text{Tree}(R)} \int_Q \left( \tilde{K}_{\sigma,J(Q)+1} \chi_F - \tilde{K}_{\sigma,J(Q)} \chi_F \right) \, d\sigma \leq \sum_{Q \in \text{Tree}^{\text{Reg}}(R)} \int_Q \ldots \, d\sigma.$$

Observe also that if $x \in Q_i$, then
This question is solved in the next lemma.

The lack of symmetry with respect to \( x, y, z \) in the truncation of the integrals that appear in (8.8) might cause some difficulties in our estimates. This question is solved in the next lemma.

For any \( y \in 3R \), we denote \( \ell_y := \ell(Q_i) \) if \( y \in Q_i \), and \( \ell_y := 0 \) if \( y \in 3R \setminus \bigcup_i Q_i \).

**Lemma 8.5.** (a) If \( |x - y| \geq C_{29}^{-1} \ell_x \), then \( |x - y| \geq C_{30}^{-1} \ell_y \), with \( C_{30} \) depending only on \( C_{29} \) and \( L \).

(b) There exists a sufficiently small constant \( \varepsilon > 0 \) such that

\[
(8.9) \sum_{Q \in \text{Tree}^{\text{res}}(R)} \chi_Q(x)(\tilde{K}_{\sigma,J(Q)} + \chi_F(x) - \tilde{K}_{\sigma,J(Q)} \chi_F(x)) \leq c^2_{\sigma|2R}(x).
\]

Proof. First we show (a). Suppose \( \ell_x \neq 0 \), \( \ell_y \neq 0 \). Take \( Q_i, Q_j \in \text{Reg}_0(Q) \) such that \( x \in Q_i \), and \( y \in Q_j \). So \( \ell_x = \ell(Q_i) \) and \( \ell_y = \ell(Q_j) \). If \( |x - y| \leq \ell(Q_j)/(2L) \), then \( x \in 2Q_j \). Thus \( Q_i \cap 2Q_j \neq \emptyset \), and then \( \ell(Q_i) \geq \ell(Q_j)/2 \), which yields

\[
|x - y| \geq C_{29}^{-1} \ell(Q_i) \geq \frac{C_{29}^{-1}}{2} \ell(Q_j).
\]

So in any case we have

\[
|x - y| \geq \min\left(\frac{1}{2L}, \frac{C_{29}^{-1}}{2}\right) \ell(Q_j).
\]

If \( \ell_x = 0 \) or \( \ell_y = 0 \) the arguments above also work, with the convention \( Q_i \equiv \{x\} \) or \( Q_j \equiv \{y\} \).
Let us prove (b) now. We put
\[
\int \int \int_{x, y, z \in 2R} c(x, y, z)^2 d\sigma(x) d\sigma(y) d\sigma(z)
\]
First we deal with the term \(A\). Thus, \(A\) and we get
\[
|A| \leq \int \int \int_{x, y, z \in 2R} c(x, y, z)^2 d\sigma(x) d\sigma(y) d\sigma(z)
\]
First we deal with the term \(A\). By (a) we deduce that if \(|x - y| \geq \frac{1}{2} \ell_x\), then \(|x - y| \geq C^{-1} \ell_y\), and so \(|x - y| \geq \varepsilon (\ell_x + \ell_y)\). If moreover \(|x - y| \geq |x - z| \geq |y - z|\), then \(|x - z| \geq \frac{1}{2}|x - y| \geq \frac{1}{4} \ell_x\). Thus, \(|x - z| \geq C^{-1} \ell_x\) by (a), and so \(|x - z| \geq \varepsilon (\ell_x + \ell_z)\). We obtain
\[
A \leq \int \int \int_{x, y, z \in 2R} c(x, y, z)^2 d\sigma(x) d\sigma(y) d\sigma(z)
\]
To estimate \(A_1\) we apply (a) again. Indeed, if \(|y - z| > \ell_y\), then \(|y - z| \geq C^{-1} \ell_z\), and we get \(|y - z| \geq \varepsilon (\ell_y + \ell_z)\). Therefore,
\[
A_1 \leq \int \int \int_{x, y, z \in 2R} c(x, y, z)^2 d\sigma(x) d\sigma(y) d\sigma(z).
\]
Now we deal with \(A_2\). For each \(y \in 2R\) we have
\[
\int_{x \in 2R} c(x, y, z)^2 d\sigma(x) d\sigma(z) \leq \int_{x \in 2R} \frac{C}{|x - y|^2} d\sigma(x) d\sigma(z)
\]
\[
\leq C \sigma(B(y, \ell_y)) \int_{x-y \geq \varepsilon \ell_y} \frac{1}{|x - y|^2} d\sigma(x) \leq C \varepsilon^{-1} \theta_\sigma(R_1)^2.
\]
Therefore,
\[
A_2 \leq C \varepsilon^{-1} \theta_\sigma(R_1)^2 \sigma(R_1).
\]
Thus, \(A\) is bounded above by the right-hand side of (8.10).

The term \(B\) is estimated similarly to \(A\). We will not go through the details. Then we obtain
\[ \int \int \int_{x, y, z \in 2R} c(x, y, z)^2 d\sigma(x) d\sigma(y) d\sigma(z) \]

\[ \leq C \theta_\sigma(R_1)^2 \sigma(R_1) + 2 \int \int \int_{x, y, z \in 2R} c(x, y, z)^2 d\sigma(x) d\sigma(y) d\sigma(z), \]

The reader may check that the ‘2’ preceding the integral on the right-hand side can be eliminated if one argues a little more carefully (although this fact will be not needed for the estimates below).

We denote

\[ c_t^2(\sigma_{2R}) := \int \int \int_{x, y, z \in 2R} c(x, y, z)^2 d\sigma(x) d\sigma(y) d\sigma(z). \]

We also set

\[ c_{t, \sigma_{2R}}^2(x) := \int \int \int_{y, z \in 2R} c(x, y, z)^2 d\sigma(y) d\sigma(z), \]

and

\[ c_{t, \sigma}^2(A, B, C) := \int \int \int_{x \in A, y \in B, z \in C} c(x, y, z)^2 d\sigma(x) d\sigma(y) d\sigma(z). \]

Notice that \( c_{t, \sigma}^2(A, B, C) \) is symmetric with respect to \( A, B, C \).

By (8.8), (8.9) and Lemma 8.5, to prove (8.2) it is enough to show that

\[ (8.11) \quad c_t^2(\sigma_{2R}) \leq C \theta_\sigma(R_1)^2 \sigma(R_1). \]

We set

\[ G_R := 2R \setminus \bigcup_i Q_i. \]

Observe that \( \sigma \)-almost all \( G_R \) are contained in \( \Gamma_R \), by (a) of Lemma 8.1.

We split \( c_t^2(\sigma_{2R}) \) as follows:

\[ (8.12) \quad c_t^2(\sigma_{2R}) = c_{t, \sigma}^2(\bigcup_i Q_i, \bigcup_i Q_i, \bigcup_i Q_i) + 3c_{t, \sigma}^2(\bigcup_i Q_i, \bigcup_i Q_i, G_R) + 3c_{t, \sigma}^2(\bigcup_i Q_i, G_R, G_R) + c_{t}^2(G_R, G_R, G_R). \]

8.6. **Estimate of** \( c_{t}^2(G_R, G_R, G_R) \). The measure \( \sigma|_{G_R} \) coincides with \( f \, d\mathcal{H}^1_{\Gamma_R} \), where \( f \) is some function such that \( \|f\|_{\infty} \leq C \theta_\sigma(R_1) \). Since the
Cauchy transform is bounded on $L^2(\mathcal{H}^1_{\Gamma_R})$ (with $\|C\|_{L^2(\mathcal{H}^1_{\Gamma_R}),L^2(\mathcal{H}^1_{\Gamma_R})}$ bounded above by some absolute constant), we have
\[
\|f\|_\infty^2 \leq \theta_\sigma(R_1)^3 \mathcal{H}^1(\Gamma_R) \leq \theta_\sigma(R_1)^3 \text{diam}(R_1) = C\theta_\sigma(R_1)^2 \sigma(R_1).
\]

8.7. Estimate of $c^2_{\ell,\sigma}(\cup_i Q_i, \cup_i Q_i, \cup_i Q_i)$. We set
\[
(8.13) \quad c^2_{\ell,\sigma}(\cup_i Q_i, \cup_j Q_j, \cup_k Q_k) = \sum_{i,j,k} c^2_{\ell,\sigma}(Q_i, Q_j, Q_k).
\]
Now we put
\[
Q_i = \left[ Q_i \cap (6\tilde{Q}_j \cup 6\tilde{Q}_k) \right] \cup \left[ Q_i \setminus (6\tilde{Q}_j \cup 6\tilde{Q}_k) \right],
\]
\[
Q_j = \left[ Q_j \cap (6\tilde{Q}_i \cup 6\tilde{Q}_k) \right] \cup \left[ Q_j \setminus (6\tilde{Q}_i \cup 6\tilde{Q}_k) \right],
\]
\[
Q_k = \left[ Q_k \cap (6\tilde{Q}_i \cup 6\tilde{Q}_j) \right] \cup \left[ Q_k \setminus (6\tilde{Q}_i \cup 6\tilde{Q}_j) \right].
\]
We replace $Q_i$, $Q_j$, and $Q_k$ in (8.13) by the right-hand side of the identities above, and we get
\[
c^2_{\ell,\sigma}(\cup_i Q_i, \cup_j Q_j, \cup_k Q_k)
\leq \sum_{i,j,k} c^2_{\ell,\sigma}(Q_i \setminus (6\tilde{Q}_j \cup 6\tilde{Q}_k), Q_j \setminus (6\tilde{Q}_i \cup 6\tilde{Q}_k), Q_k \setminus (6\tilde{Q}_i \cup 6\tilde{Q}_j))
\]
\[+ \sum_{i,j,k} c^2_{\ell,\sigma}(Q_i \cap (6\tilde{Q}_j \cup 6\tilde{Q}_k), Q_j, Q_k)
\]
\[+ \sum_{i,j,k} c^2_{\ell,\sigma}(Q_i, Q_j \cap (6\tilde{Q}_i \cup 6\tilde{Q}_k), Q_k)
\]
\[+ \sum_{i,j,k} c^2_{\ell,\sigma}(Q_i, Q_j \cap (6\tilde{Q}_i \cup 6\tilde{Q}_j), Q_k)
\]
\[=: U + V_1 + V_2 + V_3.
\]
First we estimate $V_1$, $V_2$, $V_3$. By symmetry, $V_1 = V_2 = V_3$, and also
\[
V_1 \leq \sum_{i,j,k} c^2_{\ell,\sigma}(Q_i \cap 6\tilde{Q}_j, Q_j, Q_k)
\]
\[+ \sum_{i,j,k} c^2_{\ell,\sigma}(Q_i \cap 6\tilde{Q}_k, Q_j, Q_k)
\]
\[= 2 \sum_{i,j,k} c^2_{\ell,\sigma}(Q_i \cap 6\tilde{Q}_j, Q_j, Q_k)
\]
\[\leq 2 \sum_j c^2_{\ell,\sigma}(Q_j, 6\tilde{Q}_j, 2R)
\]
\[= 2 \sum_j c^2_{\ell,\sigma}(Q_j, 6\tilde{Q}_j, 6\tilde{Q}_j) + 2 \sum_j c^2_{\ell,\sigma}(Q_j, 6\tilde{Q}_j, 2R \setminus 6\tilde{Q}_j)
\]
\[=: V_{1,1} + V_{1,2}.
\]
Now we deal with $V_{1,1}$:

$$c^2_{r,\sigma}(Q_j, 6\tilde{Q}_j, 6\tilde{Q}_j) \leq 2 \iint_{x \in Q_j, y, z \in 6\tilde{Q}_j} c(x, y, z)^2 d\sigma(x) d\sigma(y) d\sigma(z)$$

$$\lesssim \iint_{x \in Q_j} \int_{y \in 6\tilde{Q}_j} \left( \int_{|x-z| \geq |x-y| \geq \epsilon Q_j} \frac{1}{|x-z|^2} d\sigma(z) \right) d\sigma(y) d\sigma(x)$$

$$\lesssim \int_{x \in Q_j} \int_{y \in 6\tilde{Q}_j} \frac{\theta_\sigma(R_1)}{|x-y|} d\sigma(y) d\sigma(x)$$

$$\lesssim \int_{x \in Q_j} \theta_\sigma(R_1)^2 d\sigma(x) = \theta_\sigma(R_1)^2 \sigma(Q_j).$$

Thus, $V_{1,1} \lesssim \theta_\sigma(R_1)^2 \sigma(R_1)$.

The term $V_{1,2}$ is estimated likewise:

$$c^2_{r,\sigma}(Q_j, 6\tilde{Q}_j, 2R \setminus 6\tilde{Q}_j)$$

$$\lesssim \int_{x \in Q_j} \int_{y \in 6\tilde{Q}_j} \left( \int_{|x-z| \geq \epsilon Q_j} \frac{1}{|x-z|^2} d\sigma(z) \right) d\sigma(y) d\sigma(x)$$

$$\lesssim \int_{x \in Q_j} \int_{y \in 6\tilde{Q}_j} \frac{\theta_\sigma(R_1)}{|x-y|} d\sigma(y) d\sigma(x)$$

$$\lesssim \theta_\sigma(R_1)^2 \sigma(Q_j),$$

and so $V_{1,2} \leq C\theta_\sigma(R_1)^2 \sigma(R_1)$.

It only remains to estimate $U$. Notice that if

$$(8.14) \quad Q_i \setminus 6\tilde{Q}_i \neq \emptyset \quad \text{and} \quad Q_j \setminus 6\tilde{Q}_j \neq \emptyset,$$

then $2\tilde{Q}_i \cap 2\tilde{Q}_j = \emptyset$. Otherwise, $2\tilde{Q}_i \cap 2\tilde{Q}_j \neq \emptyset$ implies that either $Q_i \subset 2\tilde{Q}_i \subset 6\tilde{Q}_j$ or $Q_j \subset 2\tilde{Q}_j \subset 6\tilde{Q}_i$, which contradicts (8.14). Thus,

$$U = \sum_{i,j,k} c^2_{r,\sigma}(Q_i \setminus (6\tilde{Q}_j \cup 6\tilde{Q}_k), Q_j \setminus (6\tilde{Q}_i \cup 6\tilde{Q}_k), Q_k \setminus (6\tilde{Q}_i \cup 6\tilde{Q}_j))$$

$$\leq \sum_{i,j,k: 2\tilde{Q}_i \cap 2\tilde{Q}_j = \emptyset, 2\tilde{Q}_j \cap 2\tilde{Q}_k = \emptyset, 2\tilde{Q}_i \cap 2\tilde{Q}_k = \emptyset} c^2_{r}(Q_i, Q_j, Q_k).$$

Next we wish to compare $c^2_{r}(Q_i, Q_j, Q_k)$ (for $Q_i, Q_j, Q_k$ as in the last sum) with the curvature $c^2_{\mathcal{H}^1}(g_i, g_j, g_k)$, where $g_i, g_j, g_k$ are the bounded functions constructed in Lemma 8.4, which are supported on $\tilde{Q}_i, \tilde{Q}_j, \tilde{Q}_k$ respectively. We set

$$c^2_{\mathcal{H}^1}(g_i, g_j, g_k) := \iint_{\mathcal{H}^1} c(x, y, z)^2 g_i(x) g_j(y) g_k(z) d\mathcal{H}^1(x) d\mathcal{H}^1(y) d\mathcal{H}^1(z).$$
If \( x, x' \in \tilde{Q}_i \), \( y, y' \in \tilde{Q}_j \) and \( z, z' \in \tilde{Q}_k \), then
\[
c(x, y, z)^2 \leq 2c(x', y', z')^2 + \frac{C\ell(\tilde{Q}_i)^2}{|x - y|^2|x - z|^2} + \frac{C\ell(\tilde{Q}_j)^2}{|y - x|^2|y - z|^2} + \frac{C\ell(\tilde{Q}_k)^2}{|z - x|^2|z - y|^2},
\]
by Lemma 3.5. If we integrate \( x \in Q_i, y \in Q_j, \) and \( z \in Q_k \) with respect to \( \sigma \), and also \( x' \in \tilde{Q}_j \) with respect to the measure \( g_i \, d\mathcal{H}^1_{\Gamma_R} \), \( y' \in \tilde{Q}_j \) with respect to \( g_j \, d\mathcal{H}^1_{\Gamma_R} \), and \( z' \in \tilde{Q}_k \) with respect to \( g_k \, d\mathcal{H}^1_{\Gamma_R} \), then we get
\[
c_{\sigma}^2(Q_i, Q_j, Q_k) \leq 2c_{\mathcal{H}^1_{\Gamma_R}}^2(g_i, g_j, g_k)
+ \iint_{x \in Q_i, y \in Q_j, z \in Q_k} \frac{C\ell(\tilde{Q}_i)^2}{|x - y|^2|x - z|^2} \, d\sigma(x) \, d\sigma(y) \, d\sigma(z)
+ \iint_{x \in Q_i, y \in Q_j, z \in Q_k} \frac{C\ell(\tilde{Q}_j)^2}{|y - x|^2|y - z|^2} \, d\sigma(x) \, d\sigma(y) \, d\sigma(z)
+ \iint_{x \in Q_i, y \in Q_j, z \in Q_k} \frac{C\ell(\tilde{Q}_k)^2}{|z - x|^2|z - y|^2} \, d\sigma(x) \, d\sigma(y) \, d\sigma(z).
\]
Therefore, by symmetry,
\[
(8.15) \quad U \leq 2 \sum_{i,j,k} c_{\mathcal{H}^1_{\Gamma_R}}^2(g_i, g_j, g_k)
+ 3 \sum_i \iint_{x \in Q_i, y \in Q_j, z \in Q_k} \frac{C\ell(\tilde{Q}_i)^2}{|x - y|^2|y - z|^2} \, d\sigma(x) \, d\sigma(y) \, d\sigma(z).
\]
By Lemma 8.4, \( g := \sum_i g_i \lesssim \theta_{\sigma}(R_1) \), and then
\[
(8.16) \quad \sum_{i,j,k} c_{\mathcal{H}^1_{\Gamma_R}}^2(g_i, g_j, g_k) = c^2(g \, d\mathcal{H}^1_{\Gamma_R}) \lesssim \theta_{\sigma}(R_1)^3 c^2(\mathcal{H}^1_{\Gamma_R})
\lesssim \theta_{\sigma}(R_1)^3 \mathcal{H}^1(\Gamma_R) \lesssim \theta_{\sigma}(R_1)^2 \sigma(R_1).
\]
The integral in (8.15) is estimated as follows:
\[
\iint_{x \in Q_i, y \in Q_j, z \in Q_k} \frac{C\ell(\tilde{Q}_i)^2}{|x - y|^2|y - z|^2} \, d\sigma(x) \, d\sigma(y) \, d\sigma(z)
= \ell(\tilde{Q}_i) \left( \int_{x \in Q_i} \left( \int_{|y - x| > C^{-1} \ell(\tilde{Q}_i)} \frac{1}{|y - x|^2} \, d\sigma(y) \right)^2 \, d\sigma(x) \right)
\lesssim \ell(\tilde{Q}_i) \left( \int_{x \in Q_i} \frac{\theta_{\sigma}(R_1)^2}{\ell(\tilde{Q}_i)^2} \, d\sigma(x) \right) = \theta_{\sigma}(R_1)^2 \sigma(Q_i).
\]
From (8.15), (8.16) and the preceding estimate we get
\[ U \lesssim \theta \sigma(R_1)^2 \sigma(R_1). \]
We are done.

8.8. Estimates of \( c_{\ell,\sigma}^2 \left( \bigcup_i Q_i, \bigcup_i Q_i, G_R \right) \) and \( c_{\ell,\sigma}^2 \left( \bigcup_i Q_i, G_R, G_R \right) \). We leave these estimates for the reader. The arguments are similar to the ones used for \( c_{\ell,\sigma}^2 \left( \bigcup_i Q_i, \bigcup_i Q_i, \bigcup_i Q_i \right) \). In fact, notice that if by convention one allows the squares \( Q_i \) to be points, then \( (\bigcup_i Q_i) \times (\bigcup_i Q_i) \times G_R \) and \( (\bigcup_i Q_i) \times G_R \times G_R \) are subsets of \( (\bigcup_i Q_i)^3 \).

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References

[Ah] L. Ahlfors, Bounded analytic functions, Duke Math. J. 14 (1947), 1–11.

[AHMTT] P. Auscher, S. Hofmann, C. Muscalu, T. Tao, and C. Thiele, Carleson measures, trees, extrapolation, and \( T(b) \) theorems, Publ. Mat. 46 (2002), 257–325.

[CMM] R. R. Coifman, A. McIntosh, and Y. Meyer, L’intégrale de Cauchy définit un opérateur borné sur \( L^2 \) pour les courbes lipschitziennes, Ann. of Math. 116 (1982), 361–387.

[Da1] G. David, Unrectifiable 1-sets have vanishing analytic capacity, Revista Mat. Iberoamericana 14 (1998), 369–479.

[Da2] ———, Analytic capacity, Calderón-Zygmund operators, and rectifiability, Publ. Mat. 43 (1999), 3–25.

[DS1] G. David and S. Semmes, Singular integrals and rectifiable sets in \( R_n \): Au-delà des graphes lipschitziens, Astérisque 193 (1991), 1–145.

[DS2] ———, Analysis of and on Uniformly Rectifiable Sets, Mathematical Surveys and Monographs 38, A. M. S., Providence, RI, 1993.

[GV] J. Garnett and J. Verdera, Analytic capacity, bilipschitz maps and Cantor sets, Math. Res. Lett. 10 (2003), 515–522.

[Jo] P. W. Jones, Rectifiable sets and the travelling salesman problem, Invent. Math. 102 (1990), 1–15.

[Lé] J. C. Léger, Menger curvature and rectifiability, Ann. of Math. 149 (1999), 831–869.

[Mat] P. Mattila, Hausdorff dimension, projections, and Fourier transform, Publ. Mat. 48 (2004), 3–48.
[MMV] P. Mattila, M. S. Melnikov, and J. Verdera, The Cauchy integral, analytic capacity, and uniform rectifiability, *Ann. of Math.* **144** (1996), 127–136.

[Me] M. S. Melnikov, Analytic capacity: a discrete approach and the curvature of a measure, *Sb. Math.* **186** (1995), 827–846.

[MV] M. S. Melnikov and J. Verdera, A geometric proof of the $L^2$ boundedness of the Cauchy integral on Lipschitz graphs, *Internat. Math. Res. Notices* **7** (1995), 325–331.

[NTV] F. Nazarov, S. Treil, and A. Volberg, Cauchy integral and Calderón-Zygmund operators on nonhomogeneous spaces, *Internat. Math. Res. Notices* **15** (1997), 703–726.

[Pa] H. Pajot, *Analytic Capacity, Rectifiability, Menger Curvature and the Cauchy Integral*, Lecture Notes in Math. **1799**, Springer-Verlag, New York (2002).

[Se] S. Semmes, Analysis vs. geometry on a class of rectifiable hypersurfaces in $\mathbb{R}^n$, *Indiana Univ. Math. J.* **39** (1990), 1005–1035.

[To1] X. Tolsa, $L^2$-boundedness of the Cauchy integral operator for continuous measures, *Duke Math. J.* **98** (1999), 269–304.

[To2] ———, BMO, $H^1$, and Calderón-Zygmund operators for nondoubling measures, *Math. Ann.* **319** (2001), 89–149.

[To3] ———, Painlevé’s problem and the semiadditivity of analytic capacity, *Acta Math.* **190** (2003), 105–149.

[To4] ———, The semiadditivity of continuous analytic capacity and the inner boundary conjecture, *Amer. J. Math.* **126** (2004), 523–567.

[Ve1] J. Verdera, Removability, capacity and approximation, in *Complex Potential Theory* (Montreal, PQ, 1993), *NATO Adv. Sci. Internat. Ser. C Math. Phys. Sci.* **439**, 419–473, Kluwer Academic Publ., Dordrecht (1994).

[Ve2] ———, On the $T(1)$-theorem for the Cauchy integral, *Arkiv Mat.* **38** (2000), 183–199.

[Vi] A. G. Vitushkin, The analytic capacity of sets in problems of approximation theory, *Uspeikhi Mat. Nauk.* **22** (1967), 141–199 (Russian); in *Russian Math. Surveys* **22** (1967), 139–200.

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