Towards a Measurement of $\Delta \alpha_{\text{Had}}^{(5)}(m_Z^2)$ using the Radiative Return at BaBar

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Abstract. We present progress towards a measurement of the quantity $\Delta \alpha_{\text{Had}}^{(5)}(m_Z^2)$, which represents the variation in the value of the electromagnetic coupling constant $\alpha$ between $q^2 = 0$ and $m_Z^2$ due to the effects of the 5 lightest quark flavors. This quantity is one of the leading uncertainties in the global electroweak fits performed at the Z pole, and thus on the indirect determination of the Higgs boson mass. We obtain this quantity from an integral of the cross section for $e^+e^- \to q\bar{q}\gamma$, where the photon originates from initial-state radiation (ISR).

1. Introduction
The global electroweak fits performed at the Z pole [1] provide important consistency checks of the Standard Model (SM) as well as an indirect determination of the Higgs boson mass. Among the inputs to these fits is the value $\alpha(m_Z^2)$ of the electromagnetic coupling constant at the Z mass. The difference $\Delta \alpha(m_Z^2)$ between this value and the measured value $\alpha(q^2 = 0)$ can be written as

$$\alpha(m_Z^2) = \frac{\alpha(0)}{1 - \Delta \alpha_{\text{Lep}}(m_Z^2) - \Delta \alpha_{\text{top}}^{\text{Had}}(m_Z^2) - \Delta \alpha_{\text{Had}}^{(5)}(m_Z^2)}$$

(1)

where $\Delta \alpha_{\text{Lep}}(m_Z^2) = 31.49768(6) \times 10^{-3}$, $\Delta \alpha_{\text{top}}^{\text{Had}}(m_Z^2) = (-7.0 \pm 0.5) \times 10^{-5}$ and $\Delta \alpha_{\text{Had}}^{(5)}(m_Z^2) = (27.58 \pm 0.35) \times 10^{-3}$ are the contribution from leptons, the top quark, and the remaining five quarks respectively [2, 3, 4]. The large error on $\Delta \alpha_{\text{Had}}^{(5)}(m_Z^2)$ is due to the fact that unlike the other two terms, it cannot be calculated from first principles. It can however be written as a dispersion relation involving the ratio

$$R_{\text{Had}}(s) = \frac{\sigma_{e^+e^- \to \text{hadrons}}(s)}{\sigma_{e^+e^- \to \mu^+\mu^-}(s)}$$

(2)

of the hadronic and Born-level dimuon cross-section in $e^+e^-$ collisions at center-of-mass (CM) energy $\sqrt{s}$. $R_{\text{Had}}(s)$ is traditionally obtained at $e^+e^-$ colliders using an energy scan technique [5, 6]. However the precision of these measurements is limited, particularly for higher-multiplicity modes: the detection efficiency is strongly dependent on the hadronization model; the energy scan technique also introduces point-to-point systematics between the scan points; and since no collider can measure $R_{\text{Had}}(s)$ over the entire range defined above, data from several measurements need to be combined. For these reasons, $R_{\text{Had}}(s)$ is known to a precision of about 6% in the range $s = 2 - 7$ GeV [4] (as shown in Fig. 1 (right)), and this value dominates the
overall error. Reducing this error to below 3% would have a significant impact on the uncertainty of SM fits. Another technique has been proposed in recent years [7, 8] to measure \( \Delta \alpha_{\text{Had}}^{(5)}(m_Z^2) \), using initial-state radiation (ISR) emission. The emission of the photon lowers the effective CM energy of the collision, which allows to effectively scan the hadronic spectrum below the nominal CM energy of the collider. The large data samples available at meson factories provide sufficient statistics to perform systematics-dominated measurements. The technique has already been extensively used at \( \text{Babar} \) to measure cross-sections in exclusive modes [9, 10, 11]. The inclusive technique described here is complementary to these measurements: the \( s' \) smearing effect described below preclude its use for the \( g-2 \) case, but its larger \( s' \) range make it well-suited to the measurement of the \( \Delta \alpha_{\text{Had}}^{(5)}(m_Z^2) \) integral, which gets roughly equal contributions from all \( s' \) regions. In terms of the ISR production cross-section of hadrons, we have [12]

\[
\Delta \alpha_{\text{Had}}^{(5)}(m_Z^2) = \frac{m_Z^2}{4\pi^2\alpha} \int_{4m_Z^2}^{\infty} \frac{d\sigma_{e^+e^-\to\gamma\text{hadrons}}(s')}{(m_Z^2 - s')\xi(s', s)},
\]

where \( s' \) is the reduced CM energy of the \( e^+e^- \) collision after ISR emission; \( \xi(s', s) \) is a radiator function that expresses the probability to radiate from \( s \) down to \( s' \), and can be obtained with per-mil precision from a Monte-Carlo (MC) generator (in this work we rely on KKMC [13]). The goal of the analysis is to obtain \( \Delta \alpha_{\text{Had}}^{(5)}(m_Z^2) \) by a measurement of \( d\sigma_{e^+e^-\to\gamma\text{hadrons}}(s')/ds' \). Since background from nonradiative events rises with \( s' \), this study focuses on the region \( s' < 36 \text{ GeV} \), and we report a measurement of the quantity \( \Delta \alpha_{\text{Had}}^{(5)}(m_Z^2, 36 \text{ GeV}^2) \) defined similarly to \( \Delta \alpha_{\text{Had}}^{(5)}(m_Z^2) \) but with an upper cutoff of 36 GeV² in the integral. To achieve the desired precision, we perform an inclusive analysis, requiring only the presence of the ISR photon an a loose selection on the recoiling \( qq \) system. Since we do not require the presence of the full hadronic event, the \( s' \) value is obtained from the photon energy. This introduces a smearing in the measured \( s' \) value, particularly for small \( s' \), which makes it impossible to measure \( \sigma_{e^+e^-\to\gamma\text{hadrons}}(s') \) itself; however, since the weight factor in the integral varies slowly with \( s' \) this does not spoil the measurement of the integral. Leading backgrounds sources are \( e^+e^- \to \gamma\gamma, e^+e^-\gamma, \mu^+\mu^-\gamma \) and \( \tau^+\tau^-\gamma \) production, as well as photons originating from hadronic decays (\( \pi^0, \eta \to \gamma\gamma \)) and misidentified neutral hadrons (\( \bar{n}, K^0 \)). In most cases, we apply vetos on

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Left: typical event as seen in the \((r, z)\) plane; right: experimental values of \( R_{\text{Had}} \) used to compute \( \Delta \alpha_{\text{Had}}^{(5)}(m_Z^2) \) in Ref. [4].}
\end{figure}

\[ Y_1 = \sqrt{s} \text{ in GeV} \]

\[ Y_2 = R_{\text{Had}} \]
identified background processes, and subtract the remainder from the final sample. The $\mu^+\mu^-\gamma$ and $\tau^+\tau^-\gamma$ modes cannot be easily separated from signal; they are therefore retained with high efficiency and subtracted.

2. Analysis Technique

The data used in this analysis consists of $208.5 \text{ fb}^{-1}$ of data obtained in $e^+e^-$ collisions on the $\Upsilon(4S)$ peak and the continuum immediately below it. The $e^+e^-$ collisions are asymmetric, with energies of 9 and 3.1 GeV for the $e^-$ and $e^+$ beams respectively. The BaBar detector has been described elsewhere [14]. The main background-fighting tool in this analysis is the presence of the ISR photon. We require that this photon be detected, with an energy $E^*_\gamma > 3.3$ GeV in the center-of-mass (CM) frame of the $e^+e^-$ collision, and $0.386 < \theta^*_{\gamma} < 2.109$ in the laboratory frame (corresponding to $|\cos \theta^*_{\gamma}| < 0.8$ in the CM frame). The lower cutoff on $E^*_\gamma$ corresponds to $\sqrt{s'} < 6.5$ GeV for the hadronic system. QED backgrounds such as $e^+e^- \rightarrow \gamma\gamma$ and $e^+e^- \rightarrow e^+e^-\gamma$ are the leading sources of background at low $s'$. They are suppressed by the following vetos:

- $\gamma\gamma$ veto: reject events with two back-to-back high-energy clusters (or reconstructed conversions) in the CM frame.
- Radiative Bhabha veto: reject events with an identified electron and one or less identified hadron.
- Low-multiplicity filter: reject QED-like events with one track or less.

Background levels after these selections are shown in Fig. 2 (left). The second principal source of background consists of non-radiative hadronic events in which either a real photon is emitted in a hadronic decay or a hadronic process is misidentified as a photon. About 80% of these events originate from high-momentum $\pi^0$ decays. We reject these backgrounds using the following techniques:

- We loop over all photons in the event and look for combinations with the ISR photon having a mass $100 < m_{\gamma\gamma} < 170$ MeV to veto $\pi^0 \rightarrow \gamma\gamma$, and similar selections for other resonances decaying to photons.
- We apply a selection on the shower shape of the ISR photon cluster, suppressing backgrounds from neutral hadrons and multiple-photon showers.
- We build a Fisher discriminant from event-shape variables, to separate $e^+e^- \rightarrow q\bar{q}$ events from ISR production on topological grounds.

Background levels with all selections applied are shown in Fig. 2 (right). The distributions of most of the quantities used in the analysis can be cross-checked using data. When significant disagreements are found between data and simulation, a correction is implemented. In particular, $\mu^+\mu^-\gamma$ events are used to cross-check photon properties and measure the photon detection efficiency.

3. Results

The final spectrum can be obtained by applying all selections, subtracting estimated backgrounds and applying an $s'$-dependent signal efficiency correction. The value of $\Delta \alpha_{\text{Had}}^{(5)}(m^2_Z, 36 \text{ GeV}^2)$ is then computed by a weighted sum of the spectrum bins, with the weights designed to correct the effects of the radiative kernel $\xi$ of Eq. 3 and other radiative corrections. Leading sources of systematic uncertainty are shown in the tables of Fig. 3. The total systematic errors on signal efficiency and background levels are 1.7% and 3.3% respectively. There is also a 1.1% uncertainty on the integrated luminosity of the data sample, and a 1.6% error from the signal-extraction procedure. A total systematic error of 4.4% is therefore expected for a preliminary result that
Figure 2. $s'$ distribution in simulation after QED vetos (left) and all selections (right). From bottom to top, the samples are $q\bar{q}\gamma$ signal (blue), $\gamma\gamma$ and $e^+e^-$ (light gray), $\mu^+\mu^-$ (green), $\tau^+\tau^-$ (yellow), and udsc$\tau$ production (red).

| Source               | Value   |
|----------------------|---------|
| MC Generator         | 0.1%    |
| $\gamma$ efficiency  | 0.8%    |
| Tracking & PID       | 0.01%   |
| Hadronic vetos       | 0.5%    |
| QED veto             | 1.4%    |
| MC Statistics        | 0.02%   |
| Total                | 1.7%    |

| Source               | Value   |
|----------------------|---------|
| udsc$\tau$b          | 0.5%    |
| $\gamma\gamma$       | 0.6%    |
| $e^+e^-$              | 1.9%    |
| $\mu^+\mu^-$         | 1.3%    |
| $\tau^+\tau^-$       | 0.3%    |
| Two-photon events    | 2.2%    |
| $\Upsilon$ decays     | 0.2%    |
| Stale Bhabha events  | 0.2%    |
| Total                | 3.3%    |

Figure 3. Systematics errors on photon efficiency (left) and background levels (right). The values are taken relative to the expected value of $\Delta\alpha^{(5)}_{Had}(m^2_Z, 36 \text{ GeV}^2)$.

should be published shortly. We expect to be able to decrease the uncertainties on two-photon background, using a better modelization of their properties; the uncertainty on the QED veto efficiency could also be lowered with an improved determination method. This could reduce the total error down to about 3.6% for the final result.

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