Resummation of clustering logarithms for non-global QCD observables

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Jets shapes are of vital importance for LHC studies:

- exploiting jet substructure for boosted heavy-particles studies
- testing and tuning Monte Carlos
- extracting and confirming QCD parameters (perturbative and non-perturbative)

Numerical MC estimates have been very handy, but analytical estimates also:

- predict dependence on jet algorithms (thus the concept of optimal jet algorithm and jet parameters)
- give confidence that higher-order effects are under control

Amongst the phenomenologically most important jet shapes is the invariant mass ($\rho$) of a high-$p_t$ jet.
Jets shapes at hadron colliders

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Analytical jet-shape distributions – the state of the art and problems

Event/Jet shapes received substantial progress:

- Perturbative aspects
  - up to $N^3$LL accuracy for resummation for global event shapes
  - matching up to to $N^3$LO fixed-order e.g. Abbate et al 2011, Chien et al 2010, Becher et al 2008,...

- Non-perturbative aspects see e.g. Dasgupta et al 2007, 2009
  - analytical computation of such effects
  - disentangling various components

but non-global jet shapes still suffer from problems:

- non-global logs only resummable numerically in the large-$N_c$ limit
  - Dasgupta and Salam 2002

- jet algorithms introduce “clustering logs”

We show here how to deal with clustering logs...
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Clustering logs

Some history

- First calculation of non-global logs with jet clustering ($k_t$ algorithm) in energy flow between gaps: effect of non-global logs reduced with $k_t$ clustering. Appleby and Seymour, 2002

- However extra primary-emission (clustering) logs emerge when clustering is imposed. These were resummed numerically. Banfi and Dasgupta, 2005

- Analytical resummation of clustering logs for away from jet energy flow was performed. Non-global logs recalculated and found significantly reduced. Delenda, Appleby, Dasgupta and Banfi, 2006

- Recently a flurry of papers in SCET interested in resumming clustering logs. e.g. Kelley, Walsh and Zubrei, 2012
Clustering logs in energy flows vs. jet shapes

Why bother when resummation for $E_t$ flow exists?

For energy flow into gaps between jets:
- collinear emissions to jets do not matter (to SL accuracy)
- thus no double logs, only single logs (SL)
- resummation resulted in a power series in $R$ in the exponent:
  fast convergence of the series
- sufficient to compute the first few terms in the $R$-series

For jet shapes
- collinear emissions change the jet mass! double logs present
- may not have the $R$-series as in the $E_t$ flow case (as we shall see)

How do different algorithms affect the jet mass distribution?

How does the dependence on the jet radius enter it?
Jet algorithms in the soft-gluon approximation

Sequential recombination algorithms

Iterate until all objects are removed

- define \( d_{ij} = \min\left(k_{ti}^p, k_{tj}^p\right) \left(\delta\eta_{ij}^2 + \delta\phi_{ij}^2\right); \quad d_{iB} = k_{ti}^p R^2 \).
- search for smallest of all distances, \( d_{\text{min}} \).
- if \( d_{\text{min}} = d_{iB} \), object \( i \) is a jet and is removed.
- if \( d_{\text{min}} = d_{ij} \), objects \( i \) and \( j \) are merged.

- \( p = -2 \) for anti-\( k_t \) algo \( \Rightarrow \) clustering starts with hardest.
- \( p = +2 \) for \( k_t \) algo \( \Rightarrow \) clustering starts with softest.
- \( p = 0 \) for Cambridge/Aachen algo \( \Rightarrow \) clustering starts with geometrically closest.
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Jet algorithms in the soft-gluon approximation

SISCone algorithm

- Search for all stable cones of radius $R$ (in a seedless way) [stable cone is one which points in same direction as 4-momentum of its contents].
- Resolve overlaps between jets with a split/merge procedure with overlap parameter $f$.

Clustering depends on split-merge procedure.
How do jet algorithms affect the jet shape?

Primary emissions

C.f. the primary emission of two gluons off the hard \((Q)\) initiating quark \((k_2 \ll k_1 \ll Q)\) with \(\theta_{12} < \theta_{2j} < R < \theta_{1j}\).

anti-\(k_t\): complete real-virtual cancellation
no clustering logs

Clustering logs exponentiate just like Sudakov-type logs.
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\(k_t, CA, SISCone\) algorithms: real-virtual mismatch

\[ \Rightarrow C_F^2 α_s^2 L^2 \] clustering logs

Clustering logs **exponentiate** just like Sudakov-type logs.
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Secondary non-global emissions

C.f. the secondary emission of a softest gluon $k_2$ off another soft one $k_1$ ($k_2 \ll k_1 \ll Q$) with $\theta_{12} < \theta_{2j} < R < \theta_{1j}$

Employing $k_t$, CA, SIScone algorithms reduces NG logs but introduces new Abelian $C_F^2$ logs (relative to anti-$k_t$)
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$k_t$, CA, SISCones: real-virtual cancellation
reduced non-global contribution

**Employing $k_t$, CA, SIScone algorithms reduces NG logs**

**but introduces new Abelian $C_F^2$ logs (relative to anti-$k_t$)**
How do jet algorithms affect the jet shape?

Optimal jet algorithms and jet radii

Current practice (in phenomenology community):

- avoid non-global logs by studying global event shapes
- use anti-$k_t$ to get rid of clustering logs for non-global shapes
  
  e.g. Kang et al 2013, Chien et al 2012

however we disfavour use of anti-$k_t$ algorithm: In the $k_t$ algorithm:

- non-global logs have a small impact for large jet radii.
- watch for contamination with NP effects: favour small jet radii [underlying event $\sim R^2$, hadronisation $\sim 1/R$].
  
  Dasgupta Magnea and Salam, 2008

- hadronisation effects smaller for $k_t$ than for anti-$k_t$ algorithm.
  
  Dasgupta and Delenda, 2009

- must tune for optimal jet radii to minimise both perturbative and non-perturbative uncertainties [moderate jet radii?]
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▶ must tune for optimal jet radii to minimise both perturbative
  and non-perturbative uncertainties $[\text{moderate jet radii}?]$.  

We choose the normalised invariant jet mass:

\[
\rho = \left( \frac{\sum_{j \in \text{jet}} p_j}{\sum_i E_i} \right)^2 / \left( \sum_{i} E_i \right)^2
\]

\(j\) over particles in the measured jet; \(i\) over all particles.

We study the normalised single inclusive jet mass integrated distribution:

\[
\Sigma(R^2/\rho) = \int_{\rho}^{1} \frac{1}{\sigma} \frac{d\sigma}{d\rho'} d\rho'
\]

\(R\): jet radius

For simplicity we consider \(e^+e^- \rightarrow 2\) jets. [work in progress for jet +Z and 2 jets at hadron colliders].

\(^1\)our work holds for other jet shapes
Jet mass distribution

Normalised invariant jet mass integrated distribution:

The NLL resummed integrated jet mass distribution is written as:

\[
\sum_{\text{algo}} = \sum_{\text{glob}} \cdot S_{\text{ng}} \cdot C_{\text{clus}}
\]

\(\sum_{\text{glob}}\) is the global part (algorithm-independent):

\[
\sum_{\text{glob}} = \exp \left[L g_1(\alpha_s L) + g_2(\alpha_s L)\right]
\]

- \(L g_1(\alpha_s L)\) resums leading (double) logs \(L = \ln \frac{R^2}{\rho}\).
- \(g_2(\alpha_s L)\) resums next to leading (single) logs.
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\sum_{\text{glob}} = \exp \left[ Lg_1(\alpha_s L) + g_2(\alpha_s L) \right]
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- \(Lg_1(\alpha_s L)\) resums leading (double) logs \([L = \ln \frac{R^2}{\rho}]\).
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\(S_{\text{ng, algo}}\) is the non-global part:

▶ resums non-Abelian non-global single-logs numerically in the large-\(N_c\) limit.

▶ depends on the jet algorithm in use.

▶ effect is maximum for anti-\(k_t\) algorithm

▶ impact is significantly reduced for \(k_t, CA, SISCone\) algorithms
  [good!- less uncertainties due to large-\(N_c\) approx.]
Jet mass distribution

Normalised invariant jet mass integrated distribution:

The NLL resummed integrated jet mass distribution is written as:

\[ \sum^{\text{algo}} = \sum^{\text{glob}} \cdot S_{\text{ng}}^{\text{algo}} \cdot C_{\text{clus}}^{\text{algo}} \]

\( C_{\text{clus}}^{\text{algo}} \) is the clustering-induced part:

\[ C_{\text{clus}}^{\text{algo}} = \exp \left[ \sum_{n \geq 2} \frac{1}{n!} F_{n}^{\text{algo}} (-2 C_F t)^n \right] \]

where \( t = -\frac{1}{4\pi\beta_0} \ln(1 - \alpha_s \beta_0 L), \quad L = \ln \frac{R^2}{\rho} \)

- resums Abelian clustering-induced logs
- **In the anti-\( \kappa_t \) algo:** no clustering logs: \( C_{\text{clus}}^{\text{anti-}\kappa_t} = 1 \)
Clustering-logs coefficients

The clustering-logs coefficients \( F_{n}^{\text{algo}} \) are algorithm-dependent. They are integrals over rapidity and azimuth with corresponding algorithm-dependent phase-space (\( \Xi_{n}^{\text{algo}} \)):

\[
F_{n}^{\text{algo}}(R) = \frac{1}{\pi^n} \int \prod_{i} d\eta_i d\phi_i \frac{1}{\cosh^2 \eta_i - \cos^2 \phi_i} \Xi_{n}^{\text{algo}}(k_1, k_2, \cdots, k_n)
\]

| \( R \) | 0.1 | 0.4 | 0.7 | 1.0 |
|---|---|---|---|---|
| \( F_{2}^{k_t,CA,SISCone} \) | 0.183 | 0.184 | 0.188 | 0.208 |
| \( F_{3}^{k_t} \) | -0.052 | -0.053 | -0.055 | -0.061 |
| \( F_{3}^{CA} \) | -0.028 | -0.029 | -0.029 | -0.030 |
| \( F_{3}^{SISCone} \) [preliminary] | 0.033 | 0.034 | 0.037 | 0.060 |
| \( F_{4}^{k_t} \) | 0.022 | 0.023 | 0.023 | 0.024 |
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Clustering logs resummed: analytical vs. Monte Carlo

Comparison of the clustering part $C^{k_t}_{\text{clus}}$ in the $k_t$ algorithm to MC

MC originally by Dasgupta and Salam, with modifications by Appleby, Seymour; and Banfi [private communication].

- small contribution of maximum order 5%
- largely dominated by $F_2^{k_t}$ term
- uncalculated higher-order coeffs $F_n^{k_t}$ have negligible impact
Non-global logs in $k_t$ vs. anti-$k_t$

Comparison of the non-global components in the $k_t$ and anti-$k_t$ algorithms

- **anti-$k_t$ algorithm**: coefficients of non-global logs are radius-independent – comparable to hemisphere mass in $e^+e^-$ [untrue for hh collisions! – Dasgupta et al, 2012]

- **$k_t$ algorithm**: non-global logs smaller in effect; and for $R \sim 1$ non-global logs significantly diminished.
Full distributions in MC

Comparison of the full distributions in the $k_t$ and anti-$k_t$ algorithms

![Graphs showing full distributions in MC for different values of R.]

Overall effect for $R = 1.0$:

- **$k_t$ algorithm**: clustering and non-global logs (all together) modify the global part by a small $O(7\%)$.

- **anti-$k_t$ algorithm**: non-global logs modify the global part by a huge $O(50\%)$. 
Conclusions and Outlook

- Analytical estimates of jet shapes are important (guide choice of $R$).
- Non-global logs are a significant effect in the anti-$k_t$ algorithm, but no clustering logs.
- Both non-global and clustering logs have a small contribution in $k_t$ algorithm.
- Resummation of clustering logs available both for $k_t$, CA and SISCones algorithms.
- Impact of clustering logs: SISCones < CA < $k_t$.
- Work in progress for jet shapes at hadron colliders ($hh \rightarrow Z$+jet and $\rightarrow 2$ jets).
- Implementation of, at least, CA and maybe SISCones in Monte Carlo code is a future task.
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