On hadronisation effects in QCD jets

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Work done in collaboration with Mrinal Dasgupta

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Outline

Jets at hadron colliders

Various algorithms are widely used to determine final-state jets:

- Sequential recombination: k_t, anti-k_t, Cambridge/Aachen, ... Catani et al '93, Ellis et al '93, Cacciari et al '08, Dokshitzer et al '97, Wobisch et al '99
- Cone algorithms: Mid-point, SISCone, ... Sterman & Weinberg 1977, ... , Salam & Soyer 2007

Jet-quantities are then computed for different purposes:

- Search for new physics: (Higgs, SUSY particles, ...)
- Improve previous measurements: (pdfs, α_s, ...)

Amongst the most important jet-quantities at the LHC is the transverse momentum (p_t) of a high-p_t jet.

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Challenge at the LHC

The LHC has many complications that cannot be dealt with using the current theoretical techniques (at hadron level):

- Perturbative aspects
  - Colour and geometry structure of a $\geq$ 4-jet hadronic event is not so simple
  - Non-global logs, super-leading logs
- Non-perturbative aspects
  - Underlying event
  - Pile-up (higher beam energy $\Rightarrow$ more of it)
  - Hadronisation

let alone the situation at jet-level

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Don't we have Monte Carlos (PYTHIA, HERWIG,...) to handle this kind trouble?

Yes, but:

Analytical studies complement Monte Carlos.

For instance analytical estimates give answers to:

How do non-perturbative effects depend on jet size?

Can we disentangle Underlying Event and Hadronisation?

for us to make **best choice of jet radius**. Dasgupta et al, 2007.

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Analytical estimates of non-perturbative corrections

DW renormalon model and event shapes at LEP and HERA

Hadronisation is familiar from LEP and HERA event-shape variables: Great success up to 3-jet level (FULL NLL + NLO + $1/Q$); Dasgupta et al '02, '03, Banfi et al '07

Thanks to renormalon model: Beneke 98', Dokshitzer et al '95,'96,'98

Source of hadronisation is a "gluer" with $k_t \sim \Lambda_{\rm QCD}$.

To parameterise such non-perturbative emission, assume a universal infrared-finite (measurable) coupling parameter:

$$\alpha_0 = \int_0^{\mu_I} \frac{dk_t}{\mu_I} \alpha_s(k_t),$$

Perform analytical estimates using this notion in one event-shape, and fit to data to extract α_0.

Use α_0 on another event-shape.

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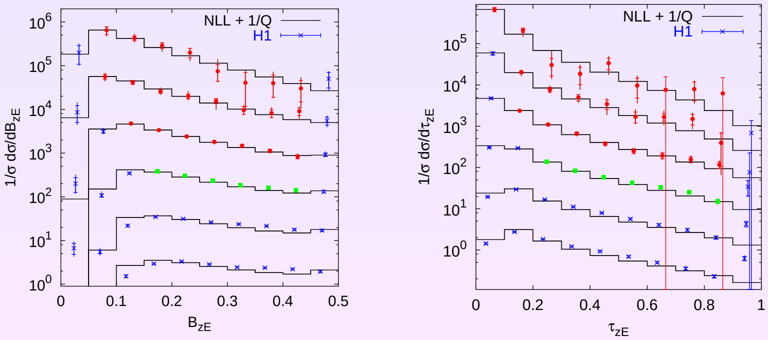
Event shape distributions at LEP and HERA

Dasgupta and Salam, 2003



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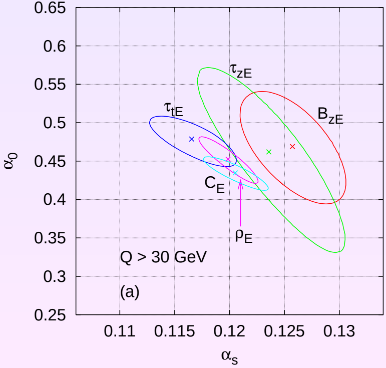
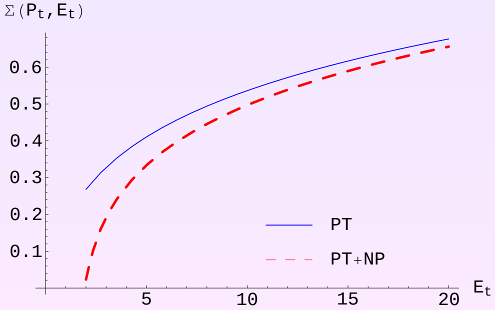


Analytical estimates of non-perturbative corrections

Now that the era of the LHC is due, we should apply what we learned from HERA/LEP

Recently we provided a first analytical estimate for the power corrections to away-from-jet energy flow in hadron-hadron collisions. Dasgupta and Delenda, 2007



Hadronisation, the underlying event and jets

Back to jets

An interesting result was obtained by Dasgupta et al (2007) for non-perturbative effects on QCD jets (δp_t of a jet due to NP effects in various jet algorithms):

- Underlying event scales as R^2 (feasible since the smaller the jet area the less it is polluted)
- Hadronisation scales as $1/R$ - manifestation of collinear singularity

Also universality of hadronisation corrections (coefficient of $1/R$) is maintained at single gluon level.

However two-loop effects are important. Nason & Seymour '95, Dokshitzer et al 98

We show here that this universality breaks at two-loop

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How does hadronisation affect the p_t of a jet?

The change in the p_t of a jet due to “gluer” emission

To leading-order in R, a jet changes it transverse momentum if it emits a gluon outside of it, thus:

$$\begin{aligned} \delta p_t &= \sum_{i \notin \text{jet}} k_{ti}, \\ &= k_{t1}\, \Xi_{\text{out}}(k_1) + k_{t2}\, \Xi_{\text{out}}(k_2) + \cdots \end{aligned}$$

The $\Xi_{\text{out}}(k_i)$ is the condition that gluon k_i ends up outside the hard jet after the application of the jet algorithm.

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Jet p_t in sequential recombination algorithms

Iterate until all objects are removed

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

$p = -2$ for anti-k_t algo $\Rightarrow$ clustering starts with hardest.
Gluon 1 ends up outside jet with:

$$\Xi_{\text{out}}(k_1) = \Theta_{\text{out}}(k_1)$$

$\Theta_{\text{out}}(k_i) = \Theta(\delta\eta_{ij}^2 + \delta\phi_{ij}^2 - R^2)$
(means gluon i is more than R away from the hard jet j).

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$p = +2$ for k_t algo $\Rightarrow$ clustering starts with softest.
Gluon 1 ends up outside jet with:

$$\begin{aligned}\Xi_{\rm out}(k_1) &= \Theta_{\rm out}(k_1)\left[1 - \Theta_{\rm out}(k_2)\Theta_{12}(k_1,k_2)\Theta_{\rm in}(k)\right] + \\ &+ \Theta_{\rm in}(k_1)\Theta_{\rm out}(k_2)\Theta_{12}(k_1,k_2)\Theta(d_{1j} - d_{12})\Theta_{\rm out}(k) + \\ &- \Theta_{\rm out}(k_1)\Theta_{\rm in}(k_2)\Theta_{12}(k_1,k_2)\Theta(d_{2j} - d_{12})\Theta_{\rm in}(k),\end{aligned}$$

$$\Theta_{12}(k_1,k_2) = \Theta(R^2 - \delta\eta_{12}^2 - \delta\phi_{12}^2),\ \Theta_{\rm in} = 1 - \Theta_{\rm out},\ k = k_1 + k_2$$

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- Search for smallest of all distances, $d_{\min}$.
- If $d_{\min} = d_{iB}$, object i is a jet and is removed.
- If $d_{\min} = d_{ij}$, objects i and j are merged.

$p = 0$ for Cambridge/Aachen algo $\Rightarrow$ clustering starts with closest.
Gluon 1 ends up outside jet with (preliminary):

$$\begin{aligned}
\Xi_{\rm out}(k_1) &= \Theta_{\rm out}(k_1)\left[1 - \Theta_{\rm out}(k_2)\Theta_{12}(k_1,k_2)\Theta_{\rm in}(k)\right] + \\
&+ \Theta_{\rm in}(k_1)\Theta_{\rm out}(k_2)\Theta_{12}(k_1,k_2)\Theta(d_{1j} - d_{12})\Theta_{\rm out}(k) + \\
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Jet p_t in cone algorithms

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.

Gluon 1 ends up outside the hard jet with (preliminary):

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& \qquad \times \Theta(-k_{t1} + f(k_{t1} + k_{t2}))\Theta(\theta_{1j}^2 - \theta_{12}^2) + \\
& - \Theta_{\rm in}(k_2)\Theta_{\rm out}(k_1)\Theta_{\rm out}(k)\Theta(R^2 - \theta_{1k}^2)\Theta(R^2 - \theta_{2k}^2) \times \\
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Results

Mean-value of change in p_t of a jet is:

$$\langle \delta p_t \rangle = \frac{C_F}{\pi} \int \frac{d^2 k_t}{\pi k_t^2} \frac{d\alpha}{\alpha} \left\{ \alpha_s(0) + 4\pi\chi(k_t^2) \right\} \delta p_t(k) + \\ + 4C_F \int \left(\frac{\alpha_s}{4\pi}\right)^2 d\Gamma_2 \frac{M^2}{2!} \delta p_t(k_1, k_2),$$

[α: angular variable, χ: 1-loop virtual correction, $d\Gamma_2$: 2-loop phase-space, $k = k_1 + k_2$ is parent gluon of mass $m^2 = 2k_1.k_2$.]

Results

Mean-value of change in p_t of a quark-jet due to hadronisation is:

$$\langle \delta p_t \rangle \approx -\frac{1}{R} \mathcal{M} \, 0.5 \, \mathrm{GeV},$$

[good approximation up to $R \sim 1$]
[for a gluon jet rescale this by $C_A/C_F = 9/4$]
where $\mathcal{M}$ is a rescaling factor:

Algorithm	Rescaling factor ($\mathcal{M}$)
anti-k_t	1.49 (a.k.a. Milan factor)
k_t	1.01
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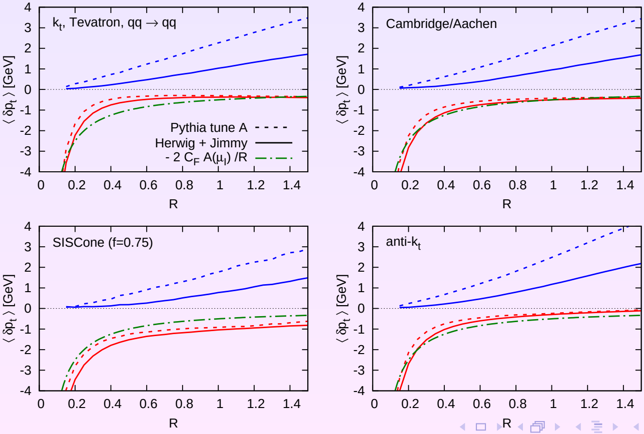
Comparison to Monte Carlos

Expect differences due to: rescaling factor, higher orders in R, and higher orders in α_s

Dasgupta et al, 2007



Conclusions and Outlook

- Analytical estimates of non-perturbative corrections are vital (guide choice of R).
- Hadronisation $\sim 1/R$, Underlying event $\sim R^2$.
- At one-gluon level, effect of hadronisation on p_t of jet is universal.
- This universality is broken at two-loop (significant effect). Result depends on algorithm case-by-case.
- Universality of α_0 is maintained.
- Hadronisation in k_t is 70% that in anti-k_t; and 90% that in Cambridge/Aachen.
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- This universality is broken at two-loop (significant effect). Result depends on algorithm case-by-case.
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