Soft QCD corrections to jets

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University of Manchester

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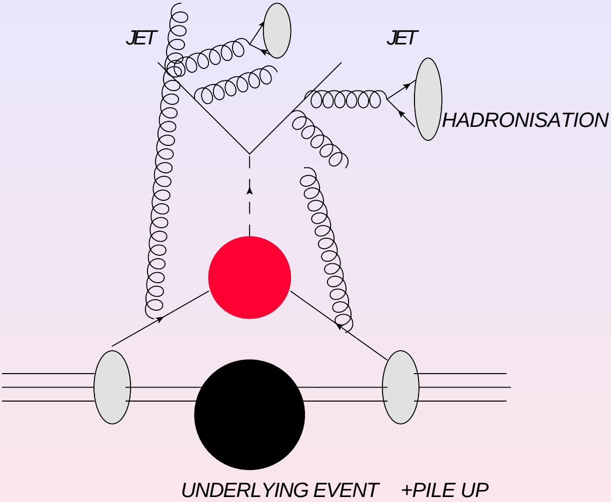
Soft QCD corrections to jets (without Monte Carlo)



How does a jet's energy or p_t relate to that of hard process partons?

Hard vs soft physics

Have to consider a plethora of effects. A loose classification can be

- Hard QCD corrections : Perturbative calculations, soft gluon resummation, parton showers.
- Soft corrections : everything else (hadronisation, underlying event etc)

Hadronisation has a natural scale Λ_{QCD}. For scales larger than this a perturbative approach can be used. Scale of UE is larger but an open question.

How well can we disentangle the various contributions? Do they have different dependence on various experimental parameters: e.g jet flavour, radius, p_t etc?

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A closer look at perturbation theory

Ignoring UE for now: QCD lagrangian consists of quark and gluon fields. Experimental observations are on bound states. What price do we pay for this? Depends on observable in question. For IRC safe observable one can write

$$R(Q^2) = \sum_n c_n \alpha_s^n(Q^2) + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{Q}\right)^p$$

Power suppressed corrections are price we pay. Can be numerically significant (comparable to NLO) e.g for LEP event shapes $Q \sim M_z$, $p = 1$. Moreover can depend on kinematics and be larger in some regions than others.

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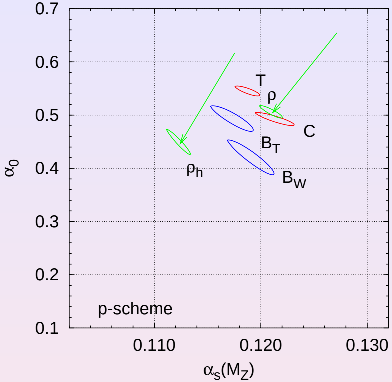
Non perturbative corrections with a perturbative approach

- Examine interface between “hard” PT and “soft” NP effects governed by $\Lambda_{\rm QCD}$. PT predictions break down when pushed too far. n! renormalon growth of PT coefficients for large n linked to power corrections.
- Thus study PT breakdown and use to estimate NP behaviour.

Dokshitzer-Webber model



Use a univeral IR finite α_s. Extend PT calculations into IR domain and see what happens.
Define

$$\mathcal{A}(\mu_I) = \frac{1}{\pi}\int_0^{\mu_I} dk_t\, \alpha_s(k_t).$$

Works well at LEP and HERA !

Jet physics at hadron colliders

Traditional approach restricted to MC event generators. BUT

- MC (many tunable parameters) does not reflect understanding of physics of hadronisation. Analytical models can.
- MC studies do not provide any detailed parametric understanding of NP effects. How much p_t from UE vs hadronisation? As a function of jet flavour, p_t, size?

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- Lack of parametric understanding leads to invalid statements and comparisons. E.g lack of awareness of R dependence led to comparions between cones with $R = 0.4$ to k_t with $R = 1.0$.
- MC hadronisation taken from hadron parton difference and added to NLO calculations often without cross-checks.

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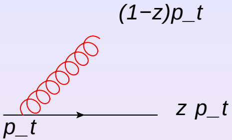
Jet p_t or energy scale analytically



Estimate perturbatively change in jet's p_t due to gluon radiation.
We have $\delta p_t = zp_t - p_t = -(1-z)p_t$.
Consider result in soft limit:

$$\langle p_t \rangle_q = -\frac{2C_F}{\pi}\int \alpha_s(p_t(1-z)\theta)\,(1-z)p_t\,\frac{dz}{1-z}\frac{d\theta}{\theta}\Theta(\theta - R)$$

At LO in PT can use $\alpha_s = \alpha_s(p_t)$ and carry out integral to get

$$\langle \delta p_t \rangle = 2C_F\frac{\alpha_s(p_t)}{\pi}p_t \ln R$$

PT result with running coupling actually diverges! Can use Dokshitzer Webber model to give meaning to the integral

Analytical calculation for hadronisation

Use DW prescription and proceed for the NP region.
Change variable to $k_t = p_t(1-z)\theta$

$$-\frac{2C_F}{\pi}\int_0^{\mu_I}\alpha_s(k_t)dk_t\int_R^1\frac{d\theta}{\theta^2}$$

This gives $-2C_F\frac{A}{R}$. Striking singular dependence on R.
Associated to scale of jet being RP_t.
Coefficent related to e^+e^- thrust. Prediction for quark jet
$\langle\delta p_t\rangle \sim -\frac{0.5\mathrm{GeV}}{R}$. Gluon jet gives $\sim \frac{-1\mathrm{GeV}}{R}$.

MD, Magnea and Salam 2008

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Jet masses

One can repeat the calculation for the jet mass in the same way:

$$\langle M_j^2 \rangle_q = \frac{C_F}{\pi} \int \alpha_s\left((1-z)p_t\theta\right) z(1-z) p_t^2 \theta^2 \frac{dz}{1-z} \frac{d\theta^2}{\theta^2}$$

Perturbative estimate is

$$\langle M_j^2 \rangle = C_F \frac{\alpha_s}{\pi} R^2 P_t^2$$

NP correction is

$$\langle M_j^2 \rangle_q = \frac{2C_F}{\pi} p_t \int \alpha_s(k_t) dk_t \int_0^R d\theta = 2C_F \mathcal{A} R P_t$$

$$\sim 0.5\,\mathrm{GeV} \times R P_t$$

Note that this is a small correction to perturbative estimate $R^2 P_t^2$ as long as $R P_t \gg \Lambda$.

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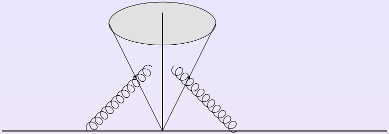
UE contribution

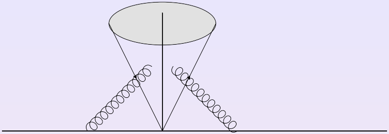


Contrast with underlying event contribution. Assume Λ_{UE} is energy per unit rapidity of soft UE particles.

$$\langle \delta p_t \rangle_{\mathrm{UE}} = \Lambda_{\mathrm{UE}} \int_{\eta^2+\phi^2<R^2} d\eta \frac{d\phi}{2\pi} = \Lambda_{\mathrm{UE}} \frac{R^2}{2}$$

Regular dependence on R (comes from jet area). For jet mass UE contribution goes as R^4. Similar effects from pile-up but order of magnitude larger at the LHC. A useful concept in assessing jets susceptability to UE and pile up is the jet area. This is only πR^2 for the anti-k_t algorithm. For more details see Cacciari, Soyez and Salam 2008

UE contribution



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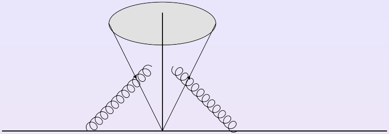

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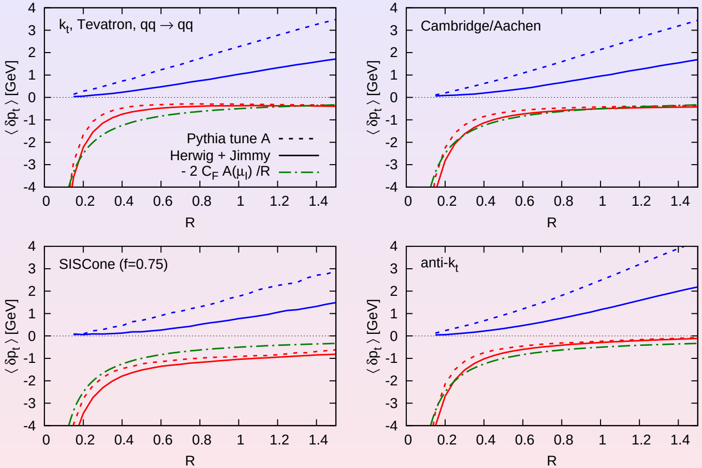
Comparison to MC models



Good agreement with analytical predictions. Same result for all algorithms. UE different between MC models.

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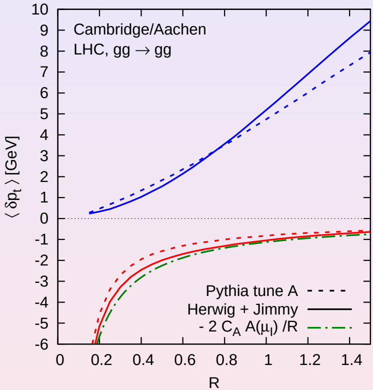

At LHC underlying event is an enormous effect.

Summary of findings

- Different algorithms show a similar sensitivity to hadronisation effects. Some differences in sensitivity to UE and pile up in more detailed studies.
- UE depends on collider energy and R and also on MC model !
- Hadronisation on jet colour factor and differently on R.
- $\Lambda_{\mathrm{UE}}(1.96\mathrm{TeV}) \approx 2-4\mathrm{GeV}$ and $\Lambda_{\mathrm{UE}}(14\mathrm{TeV}) \approx 10\mathrm{GeV}$
- More info in variable R analytical studies than fixed R MC studies.

Using jets

Let us study how we can put the analytics to good use. Knowing R dependence of various pieces gives rise to the question what is the optimal R for various physics studies?

To minimise radiative effects and UE is desirable for reconstructing mass peaks.

Take as crude estimate

$$\langle \delta p_t^2 \rangle = \langle \delta p_t \rangle_{\mathrm{h}}^2 + \langle \delta p_t \rangle_{\mathrm{UE}}^2 + \langle \delta p_t \rangle_{\mathrm{PT}}^2$$

Find minimum as a function of R. For pQCD studies minimise just UE and hadronisation. Gives

$$R = \sqrt{2}\left(\frac{C_i \mathcal{A}(\mu_I)}{\Lambda}\right)^{1/3}$$

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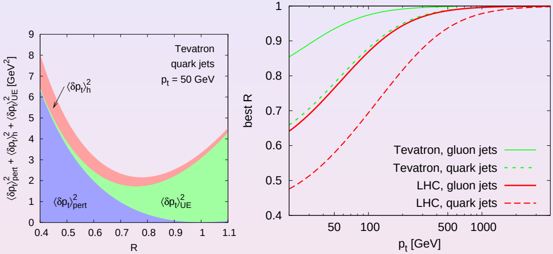
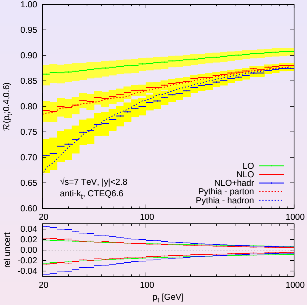
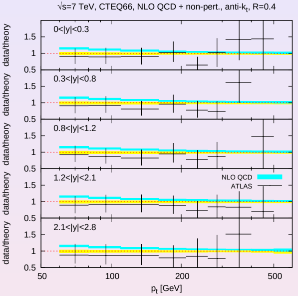
Optimal *R*



At high p_t one should use a larger R -minimises perturbative effect. Likewise for gluon jets a larger R is suggested. For LHC smaller R values than Tevatron.

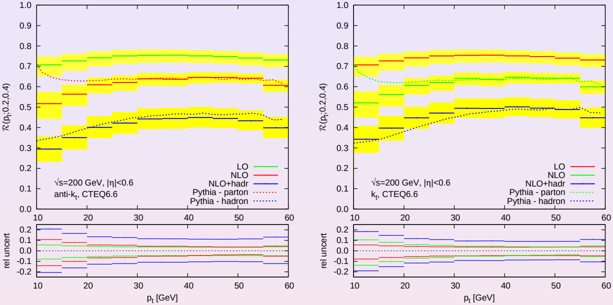
Comparisons to data





$$\mathcal{R} = \frac{\frac{d\sigma}{dp_t}(R_1)}{\frac{d\sigma}{dp_t}(R_2)}$$

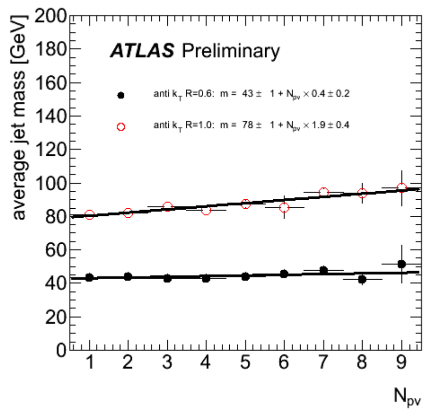
Soyez 2010



At RHIC smaller *R* means more visible role for hadronisation.

Soyez 2010

R dependence of jet masses



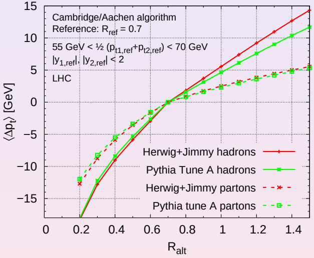
Ratio of slopes $R = 4.58 \sim (1.0/0.6)^3$ The R^3 scaling is because

$$\delta m = \sqrt{m^2 + \delta m^2} - m \approx \frac{\delta m^2}{2m}.$$

Since δm^2 scales as R^4 and m as R (note that $43/78 \approx 0.55$) one gets an R^3 behaviour.

Summary: Future measurements and some open questions

Already seen some applications to data. One further idea could be to directly extract the scale of UE from data. Study e.g δp_t by using a reference and alternative jet



$$\langle \delta p_t \rangle = \langle \delta p_t \rangle_{\mathrm{NLO}} - 2\langle C_i \rangle \left(\frac{1}{R_{\mathrm{alt}}} - \frac{1}{R_{\mathrm{ref}}}\right) \mathcal{A}(\mu_I)$$

$$+ (R_{\mathrm{alt}} J_1(R_{\mathrm{alt}}) - R_{\mathrm{ref}} J_1 (R_{\mathrm{ref}}) \Lambda_{\mathrm{UE}}$$

Summary (contd.)

- Simple theory estimates add much information to pure MC studies. Open question : how far can we expoilt these findings in practice? Specifically
  - Optimal R has been shown to be theoretically very valuable. Can the idea be exploited in practice given experimental limitations?
  - Currently we have ATLAS with anti-k_t algorithm and $R = 0.4$ and $R = 0.6$. CMS have $R = 0.5$ and $R = 0.7$. At least one value in common would have been useful? Do these values cover sufficient range given that optimal R in some cases has $R > 1$.
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