Non perturbative QCD of jets at hadron colliders

Mrinal Dasgupta

University of Manchester

with L. Magnea, G.P. Salam (2008) and Y. Delenda (2009)

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Outline

- Introduction.
- Non-perturbative effects at hadron colliders.
- Analytical studies of hadronisation contribution to jet energy.
- Monte Carlo studies.
- Two-loop enhancement factor for k_t jets.
- Tests and future studies

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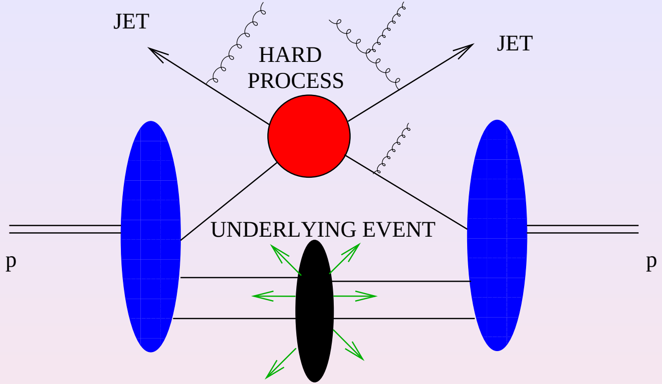
Tools for jet physics at hadron colliders



- PT tools
  - Fixed order calculations $\sigma = \sigma_0 \left(1 + c_1\alpha_s + c_2\alpha_s^2 + \cdots\right)$.
  - Resummation for corners of phase space $\sum \alpha_s^n L^m$.
  - Parton Showers.
- NP tools (since jets are hadron jets !)
  - MC models (HERWIG, PYTHIA)

PT tools developing steadily. NP improvement restricted to MC.

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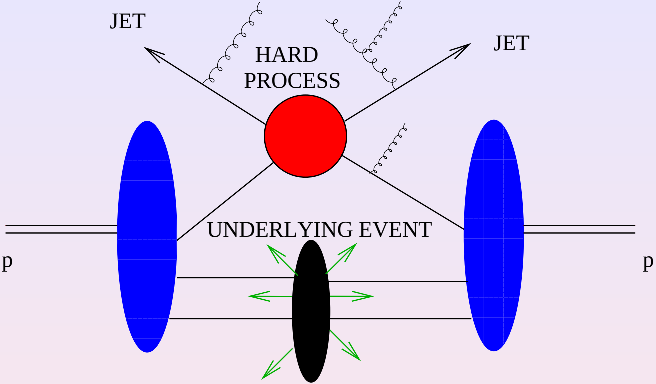

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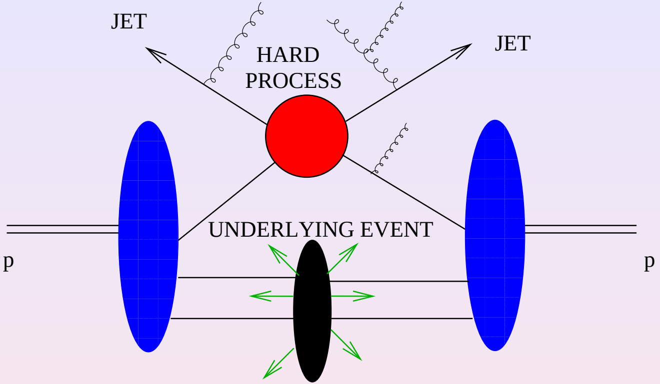

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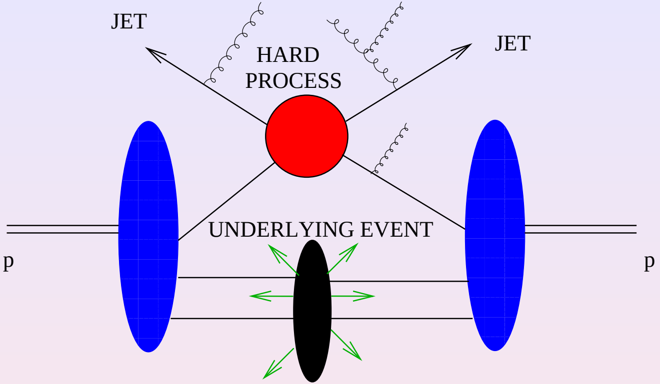

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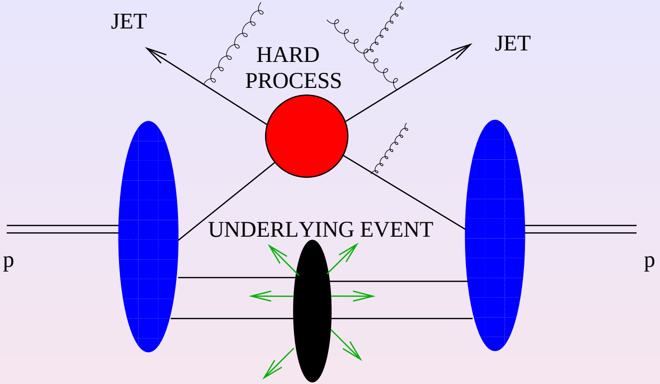

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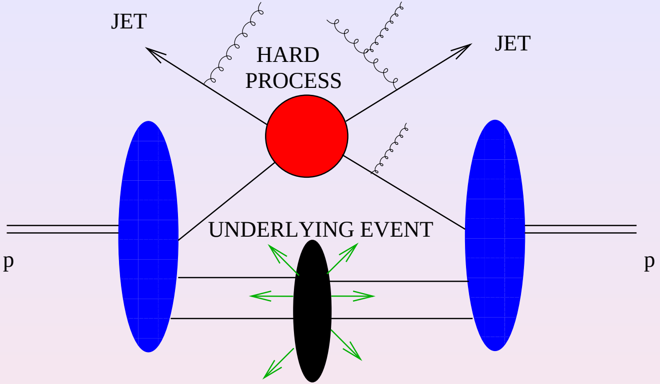

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Non-perturbative contributions

At hadron colliders two distinct NP effects contribute:

- hadronisation (ubiquitous, familiar from LEP , HERA.)
- underlying event (UE,specific to hadron colliders, messy, large at the LHC)

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Why bother when we have MC ?

- MC (many tunable parameters) does not reflect understanding of physics of hadronisation. Analytical studies 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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- MC hadronisation taken from difference between hadron level and parton shower , then added to NLO sometimes without cross-checks.

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Renormalon inspired techniques : Infrared region of dressed Feynman Graphs $\Longrightarrow$ NP effects.

Most succesful phenomenology for event shapes in DW model.

- NP corrections associated to hadronisation are triggered by a soft gluon $k_t \sim \Lambda_{\mathrm{QCD}}$.
- Such an emission is ill-defined in PT. Force it to have a meaning $\alpha_s^{\mathrm{PT}}(k_t) \to \alpha_s(k_t)$.

Assume universal IR finite QCD coupling. Only a single NP parameter enters

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

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Dokshitzer and Webber 1995, Dokshitzer, Khoze and Troyan 1996

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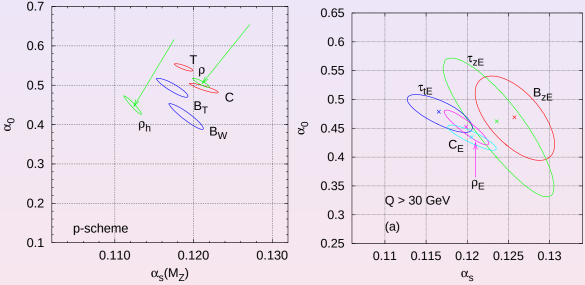
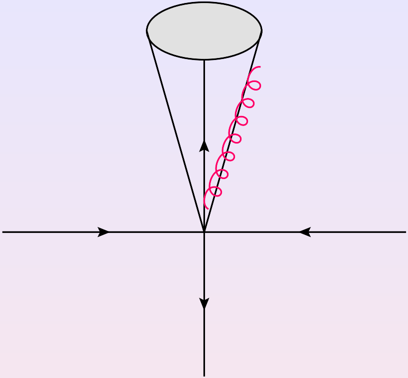
Universality

Observed to generally work well at LEP and HERA



Can we take over to hadron collider jets ?

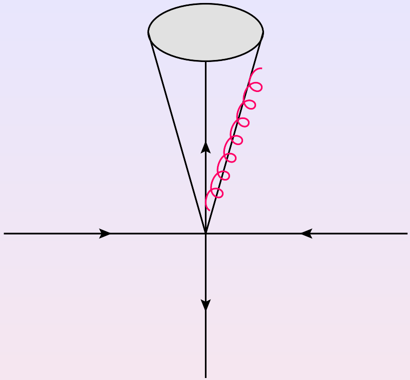
Jet transverse momenta



To work out average shift in jet p_t due to hadronisation:

First compute change in p_t due to gluon emission. E.g. for dijet production near threshold in hadron collisions

$$\delta p_t = p_t - \frac{\sqrt{s}}{2} = -\left(\frac{M_j^2}{\sqrt{s}} + \frac{M_r^2}{\sqrt{s}}\right) = \delta p_t^+ + \delta p_t^-$$



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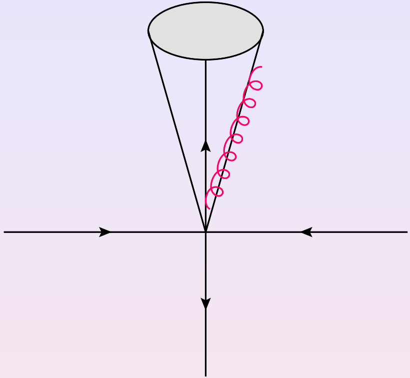

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Now average over soft gluon emission probability One has

$$\langle \delta p_t \rangle = \sum_{ij} C_{ij} I_{ij}$$

$$I_{ij} = I_{ij}^{+} + I_{ij}^{-}$$

$$I^{\pm}(R) \equiv \int_{\pm} d\eta \frac{d\phi}{2\pi} d\kappa_T^{(ij)} \, \delta\alpha_s \left(\kappa_T^{(ij)}\right) k_T \left| \frac{\partial k_T}{\partial \kappa_T^{(ij)}} \right| \frac{p_i \cdot p_j}{p_i \cdot k \, p_j \cdot k} \, \delta p_t^{\pm} \,,$$

with

$$\left(\kappa_T^{(ij)}\right)^2 = \frac{2 \, p_i \cdot k \, p_j \cdot k}{p_i \cdot p_j} \,,$$

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Results

Our results are

$$\langle \delta p_t \rangle^h = -C_i \frac{2}{R} A(\mu_I) + \mathcal{O}(R)$$

Value for $2C_F A(\mu_I) \approx 0.5$ GeV from e^+e^- event shapes.
Testable prediction (more cleanly at HERA).

$$\langle \delta p_t \rangle^{\mathrm{UE}} = \frac{\Lambda_{\mathrm{UE}}}{2} R J_1(R) = \frac{\Lambda_{\mathrm{UE}}}{2} \left(R^2 - \frac{R^4}{8} + \mathcal{O}(R^6) \right)$$

No handle on Λ_{UE} except MC studies.

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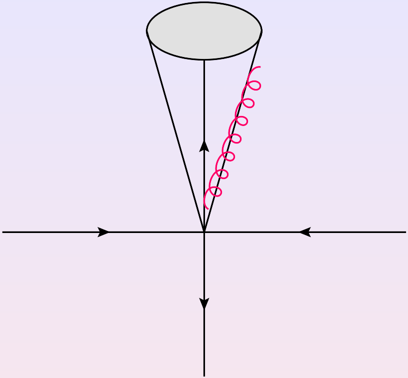
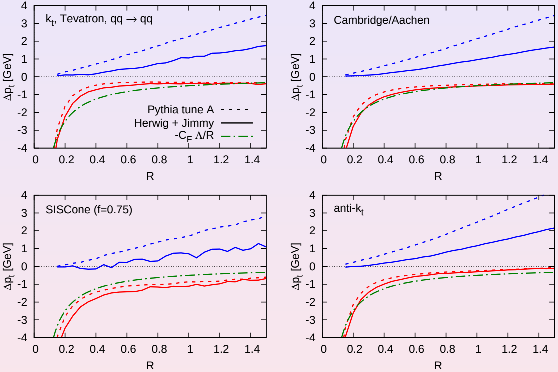
Origin and generality of $1/R$



The $1/R$ piece comes from collinear singularity associated to gluon emission from massless partons:

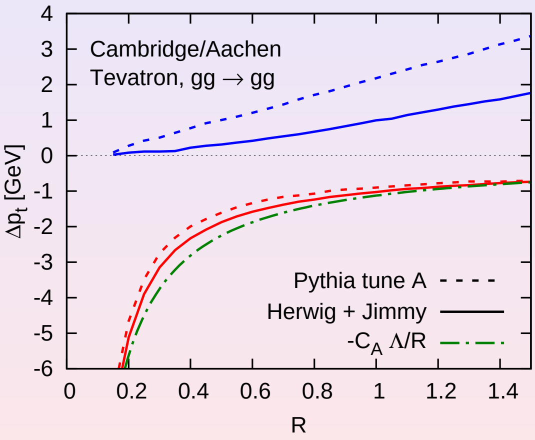
$$\langle \delta p_t \rangle = C_i \int dk_t \frac{\alpha_s(k_t)}{2\pi} \frac{\omega d\omega}{\omega} \int_{R^2}^{1} \frac{d\theta^2}{\theta^2} \delta\left(\omega\theta - k_t\right)$$

Comparisons to Monte Carlo



Similar behaviour for all algorithms. Differences in UE between MC's.

Comparisons to Monte Carlo models (contd.)



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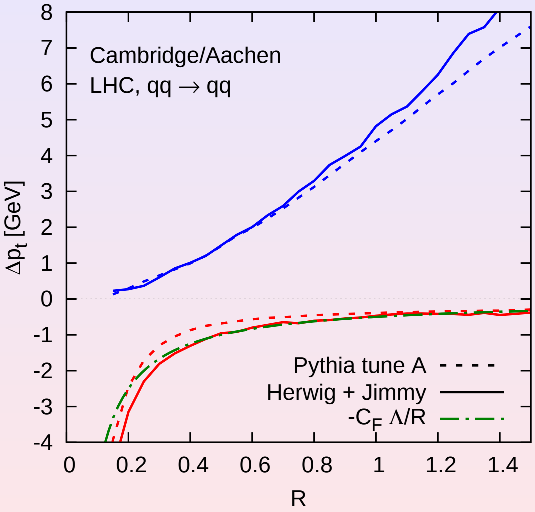

LHC underlying event is enormous effect.

Summary of findings

- Different algorithms show a similar sensitivity to NP effects.
- UE depends on collider energy and MC model as well as R.
- Hadronization on jet "colour factor" and differently on R.
- $\Lambda_{\mathrm{UE}}(1.96\mathrm{TeV}) \approx 2-4$ GeV and $\Lambda_{\mathrm{UE}}(14\mathrm{TeV}) \approx 10$ GeV. Large scale at LHC order of magnitude bigger than hadronisation.
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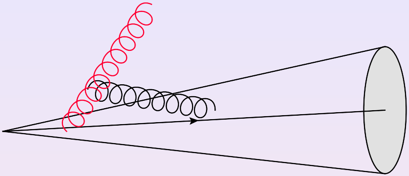
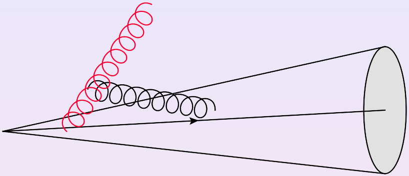
Calculations beyond one-loop



A significant problem plagues the previous estimates. We used $\alpha_s(k_t)$ in single gluon calc. However running of coupling only emerges when one considers gluon decay.

For many observables not inclusive over gluon decay cannot simply absorb gluon branching into running coupling ! Also the case for LEP and HERA event shapes. Nason and Seymour 1995

BUT one-loop numbers explain data beautifully !



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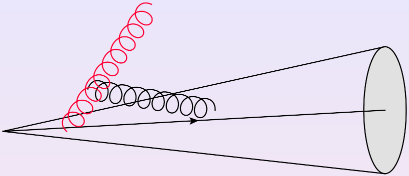

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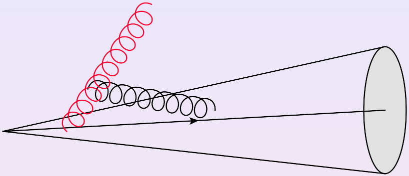

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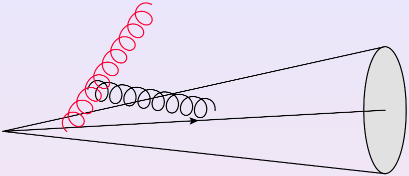
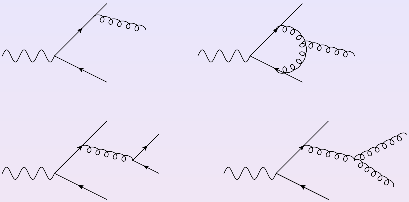


A significant problem plagues the previous estimates. We used $\alpha_s(k_t)$ in single gluon calc. However running of coupling only emerges when one considers gluon decay.

For many observables not inclusive over gluon decay cannot simply absorb gluon branching into running coupling ! Also the case for LEP and HERA event shapes. Nason and Seymour 1995

BUT one-loop numbers explain data beautifully !

The Milan factor



$$\langle \delta p_t \rangle = \frac{C_F}{\pi} \int \frac{d^2 k_t}{\pi k_t^2} \left\{ \alpha_s(0) + 4\pi\chi(k_t^2) \right\} \delta p_t(k) + $$

$$+ 4C_F \int \left(\frac{\alpha_s}{4\pi} \right)^2 d\Gamma_2 \frac{M^2}{2!} \delta p_t(k_1, k_2)$$

For event shape variables a two-loop analysis was carried out.

Dokshitzer, Marchesini, Lucenti and Salam 1997,1998

The Milan Factor

A remarkable result emerged :

$$\delta v^{\mathrm{NP},2} = M\, \delta v^{\mathrm{NP},1}$$

$$\frac{\delta v_2^{\mathrm{NP},2}}{\delta v_1^{\mathrm{NP},2}} = \frac{(\delta v_2)^{\mathrm{NP},1}}{(\delta v_1)^{\mathrm{NP},1}}$$

Linear dependence of event shape on soft particle transverse momenta crucial :

$$v = \sum_i k_{ti} f(\eta_i)$$

Value of $M = 1.49$ (Universal Milan factor) also for eP event shapes, and σ_L in e^+e^- annihilation.

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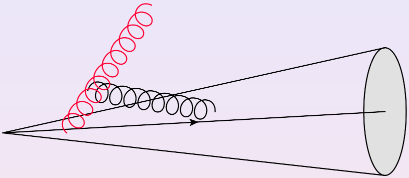
Jet algorithms and non-linearity



Non-linearity in emitted transverse momenta introduced by clustering and/or split-merge procedures. No successful calculations for such observables. Threatens universality. Cannot obtain correct normalisation of result till two-loop results are obtained.

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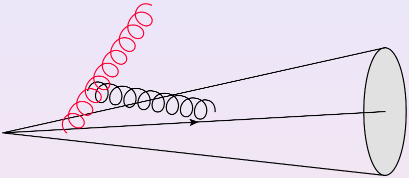

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Kinematic dependence on offspring partons in different algorithms

- k_t algorithm

$$\delta p_t(k_1,k_2) = \delta p_t(k_1)\Xi_{\rm out}(k_1) + \delta p_t(k_2)\Xi_{\rm out}(k_2)$$

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

$$\Theta_{\rm out}(k_1) = \theta\left(\delta\eta^2 - \delta\phi^2 - R^2\right)$$

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- The anti-k_t algorithm:

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

where

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Non-linear dependence on gluon emission in k_t algorithm. In contrast anti-k_t algorithm like a perfect cone.

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Two-loop enhancement factor for δp_t

Non-linearity of k_t algorithm breaks universality of M factor !

A new factor emerges $M_{\mathrm{k_t}} = 1.01$ to be compared to 1.49 for event shapes.

Dasgupta and Delenda 2009

The universal M factor emerges for jets in anti-k_t.

$$\frac{\delta p_t^{k_t}}{\delta p_t^{\mathrm{anti-k_t}}} = \frac{1.01}{1.49}$$

Hadronisation in the k_t algorithm 70 percent that of the anti-k_t. Also emerges in MC studies. We have for the first time a calculation of power-corrections to a non-linear observable. Result should be of theoretical interest too.

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Extensions to other algorithms (SISCONE, Cambridge/Aachen) is in progress.

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Applications

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- The ideas presented here can be directly tested in measurement.

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Optimal R

For studies reconstructing e.g. mass-peaks want to minimse dispersion

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

Perturbative R dependence is $\ln R$ at small R (dominant effect). For pQCD studies just total NP (UE and hadronisation) :

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

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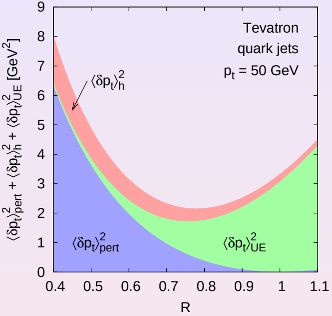

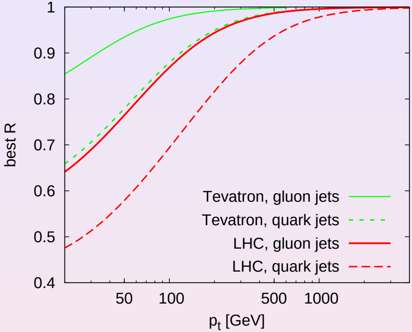

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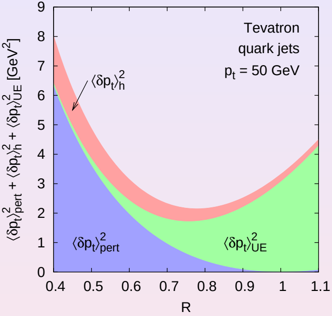

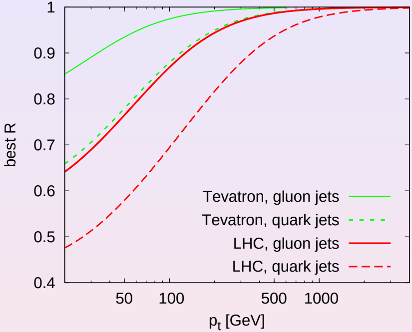

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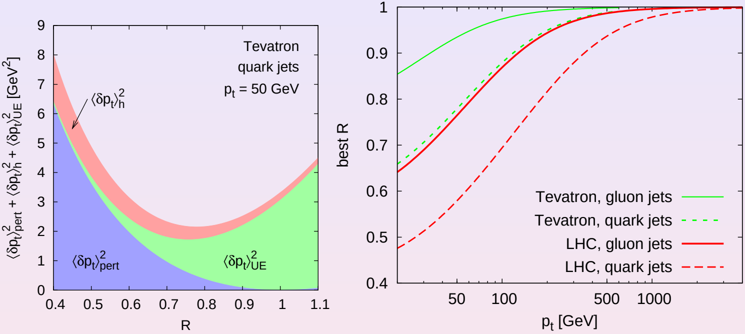

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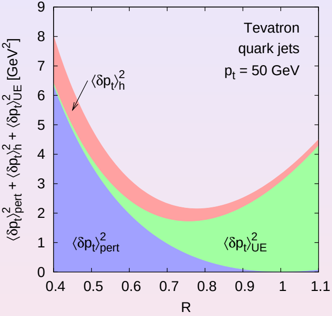

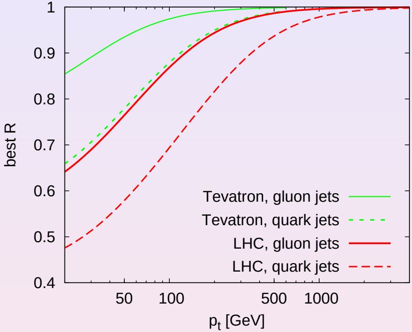

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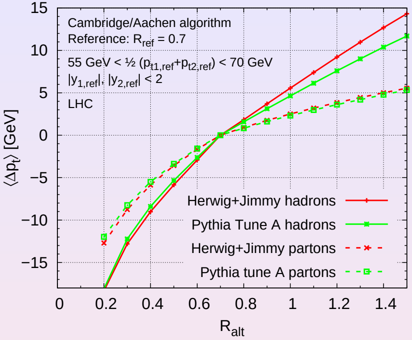
Direct tests



Direct experimental measurements of $\delta p_t(R)$. Can be compared to NLO + NP corrected results. Used to extract $\Lambda_{\rm UE}$ directly ?

Apply results to single-inclusive jet p_t spectra.

$$\frac{d\sigma}{dp_t} = \frac{d\sigma}{dp_t}_{\rm pert} (p_t - < \delta p_t >_{\rm NP})$$

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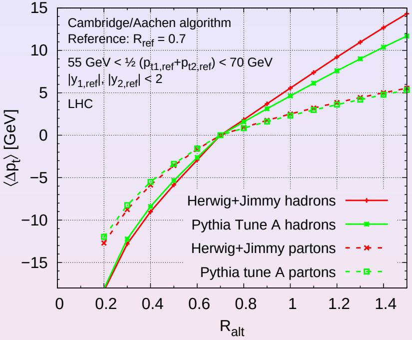

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MD, Magnea, Salam 2007

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- Features of jet algorithms being analytically and systematically understood. Radius dependence an important aspect of NP effects.
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