Issues with jets

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Outline

- Jets and IRC safety
- Non-perturbative effects at hadron colliders.
- Analytical studies of hadronistion contribution to jet energy.
- Monte Carlo studies.
- Possible tests and future measurements.

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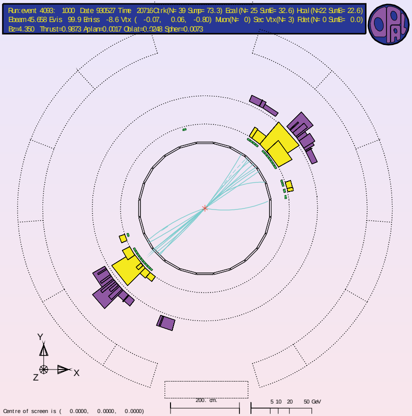
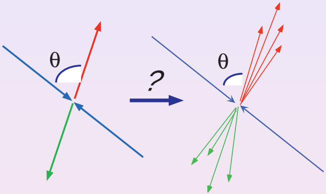
Prehistory - Birth of jet algorithms



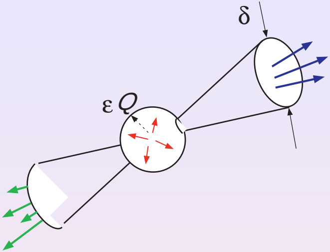
Experiments observe sprays of hadrons. What does theory say ?

Theory fails unless...



Beyond parton model one obtains divergent results for three and more particle production. Need to introduce energy resolution (like in QED) but also angular resolution.

Jet definition cures problem



A jet algorithm is an agreement ! Given this one can predict jet observables such as rates and distributions :

$$f_2 = 1 - 8C_F \frac{\alpha_s}{2\pi}\left(\ln\frac{1}{\delta}\left[\ln\left(\frac{1}{2\epsilon}-1\right)-\frac{3}{4}+3\epsilon\right] + \frac{\pi^2}{12}-\frac{7}{16}-\epsilon+\frac{3}{2}\epsilon^2+\mathcal{O}\left(\delta^2\ln\epsilon\right)\right)$$

$$f_3 = 1 - f_2$$

Back to the present

Things are much more sophisticated. Jet algorithms fall into two main categories

- Sequential recombination algorthms (k_t, Cambridge/Aachen). Cluster particles repeatedly according to some distance measure with some stopping criterion. IRC safe.
- Cone type algorithms (seeded,seedless). Look for energy flow into limited angular regions given by stable cones. Stable cone is one whose axis is centre of momentum of particles in it. Seeded cones are IRC unsafe. Salam and Soyez 2007

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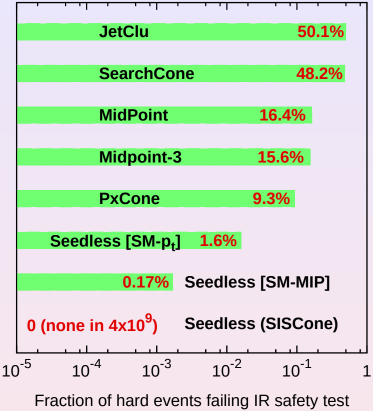
Unsafe algorithms commonly used



Discussion ongoing since 1990s ! Various fixes proposed e.g midpoint. Adopted for Tevatron run 2. However still IRC unsafe ! New fast practical seedless algorithm on the market SISCONE. Salam and Soyez 2007.

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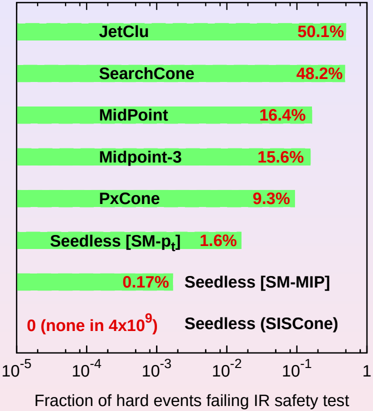

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Non-perturbative contributions

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)

Significant progress in understanding of hadronisation at LEP, HERA. Can we use it for jets at hadron colliders ?

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Hadronisation from LEP and HERA

Learnt a fair amount from studies of event shapes. Related to flow of energy-momentum in final state –linear in momenta. The summary of LEP and HERA experience : Event shapes receive large hadronisation corrections $\propto 1/Q$. Associated to hadronisation. BUT possible to analytically estimate size of these effects. Experimentally popular is DW approach . Extends perturbation theory into infrared with infrared finite universal coupling.

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Hadronisation from LEP and HERA

Power corrections linked to soft gluon emission with $k_t \sim \Lambda_{\mathrm{QCD}}$.

Soft gluons modify event shapes as

$$\delta V^{\mathrm{NP}} = \frac{k_t}{Q} f_V(\eta)$$

Change to event shape mean values is

$$\int_0^{\mu_I} \frac{dk_t}{k_t} \delta\alpha_s(k_t) \frac{k_t}{Q} d\eta f_V(\eta) = A(\mu_I) \frac{C_V}{Q}$$

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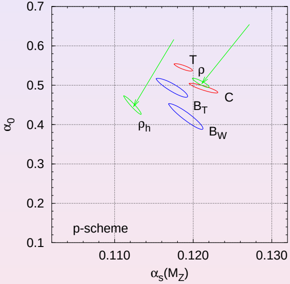
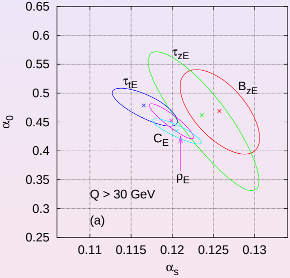
Universality

Observed to generally work well at LEP and HERA





Can we take over to hadron collider jets ?

Why bother when we have MC ?

- MC does not reflect understanding of physics of hadronisation. Analytical studies do.
- MC studies do not provide any detailed parametric understanding of NP effects or insight on how to separate hadronisation from UE.
- Lack of parametric understanding leads to myths: e.g. cone jets said to suffer from large hadronisation while k_t jets from UE. But $R_{\mathrm{cone}} = 0.4$ wheras $R_{k_t} = 1$.
- MC hadronisation taken from difference between hadron level and parton shower , then added to NLO sometimes without cross-checks.

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Jet transverse energy scale

Important ingredient of experimental jet studies.

Let's focus on this. Use LEP and HERA methods + universality to try to estimate hadronisation. Consider effects of soft emission and relate to IR universal coupling.

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One gluon calculation

Work with dijets near threshold. At Born level

$$\begin{aligned} p_1 &= \frac{\sqrt{s}}{2}(1,0,0,1) \\ p_2 &= \frac{\sqrt{s}}{2}(1,0,0,-1) \\ p_j &= p_t(1,1,0,0) \\ p_r &= p_t(1,-1,0,0) \end{aligned}$$

$$p_t = \frac{\sqrt{s}}{2}$$

Then we need one gluon correction. Two possibilites:

- Gluon recombined into jet.
- Gluon outside jet.

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Soft gluon contribution

Gluon + initiating parton = massive jet

$$\begin{aligned} p_1 &= \frac{\sqrt{s}}{2}(1,0,0,1) \\ p_2 &= \frac{\sqrt{s}}{2}(1,0,0,-1) \\ p_j &= (\sqrt{p_t^2 + M_j^2}, p_t, 0, 0) \\ p_r &= (p_t, -p_t, 0, 0) \end{aligned}$$

This leads to

$$p_t = \frac{\sqrt{s}}{2}\left(1 - \frac{M_j^2}{s}\right) \rightarrow \delta p_t^+ = \frac{-M_j^2}{2\sqrt{s}} = \frac{-p_j.k}{\sqrt{s}}$$

Similarly when gluon is not recombined, recoil system is massive :

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Integrating the one gluon contribution

2 → 2 process means several dipoles are involved in the antenna pattern for emission of soft gluon. Several copies of e^+e^-. 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

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Results

Different dipoles have different qualitative behaviour :

- In-In dipole

$$\begin{aligned} I_{12}(R) &= 2\,\mathcal{A}(\mu_I) \int_{\eta^2+\phi^2<R^2} d\eta\,\frac{d\phi}{2\pi}\,\cos\phi \\ &= 2\,\mathcal{A}(\mu_I)\,R\,J_1(R) \\ &= 2\,\mathcal{A}(\mu_I)\left(\frac{1}{2}R^2 - \frac{1}{16}R^4 + \frac{1}{384}R^6 + \mathcal{O}\left(R^8\right)\right) . \end{aligned}$$

- In-Recoil dipole

$$I_{1R}(R) = -\mathcal{A}(\mu_I)\left(\frac{1}{8}R^2 - \frac{9}{512}R^4 + \frac{73}{24576}R^6 + \mathcal{O}\left(R^8\right)\right) .$$

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Singular R dependence

In dipoles involving the triggered jet - collinear enhancement of integrand reflected in a linear power correction at jet boundary.

- Incoming-Jet dipole

$$I_{1J}(R) = \mathcal{A}(\mu_I)\left(-\frac{2}{R} + \frac{5}{8}R - \frac{23}{1536}R^3 - \frac{95}{73728}R^5 + \mathcal{O}\left(R^7\right)\right),$$

- Recoil-Jet dipole

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Parametric separation from underlying event

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).

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

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No handle on Λ_{UE} except MC studies.

Parametric separation from underlying event

Our results are

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

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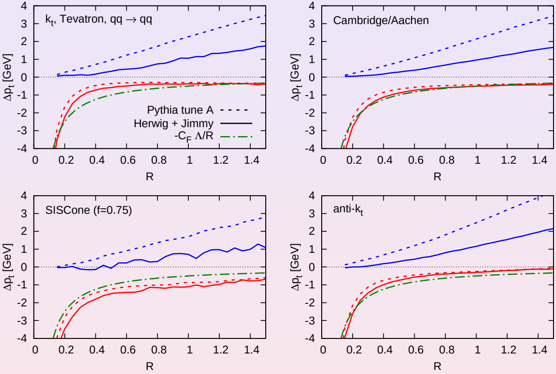
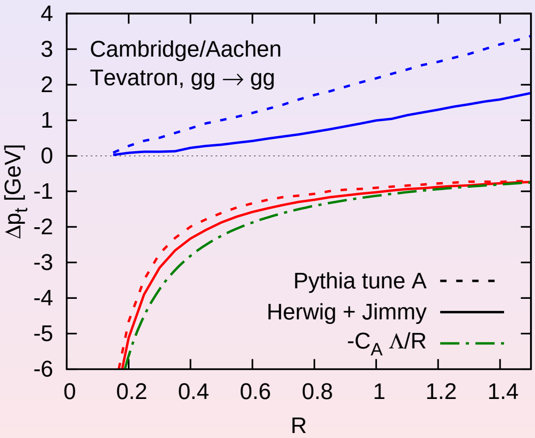
Comparisons to Monte Carlo



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

Comparisons to Monte Carlo models (contd.)



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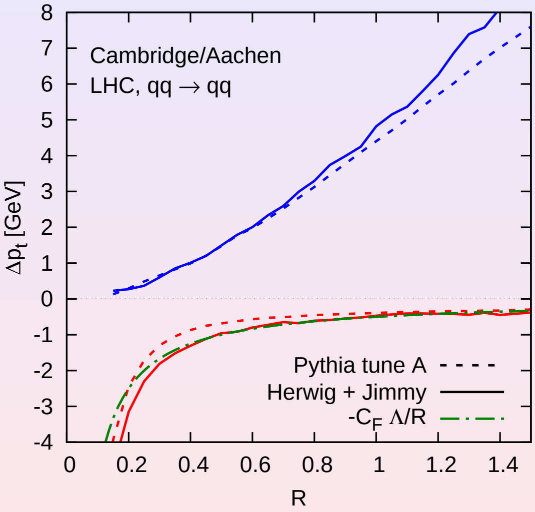

LHC underlying event is enormous effect.

Summary of findings

- Different algorithms show a similar sensitivity to NP effects (contradicts folklore)
- 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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Experimental considerations

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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) :

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

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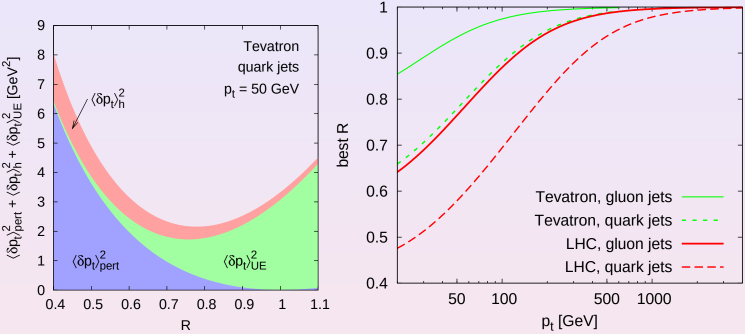

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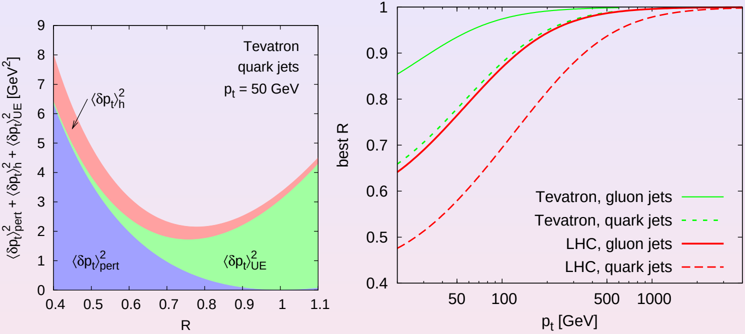

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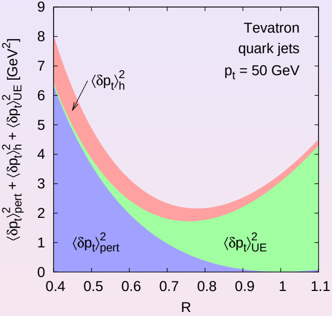

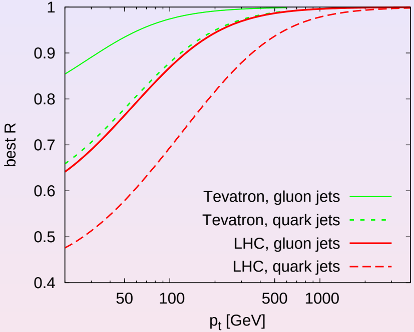

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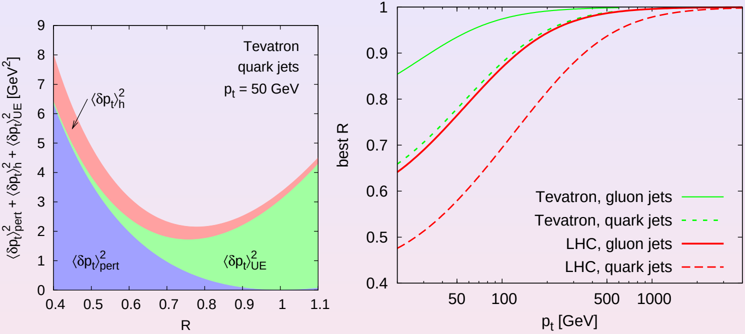

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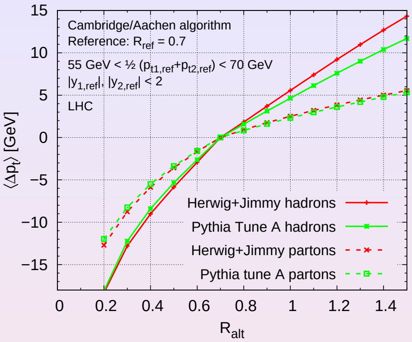

Direct experimental measurements of $\delta p_t(R)$. Can be compared to NLO + NP corrected results. Used to extract $\Lambda_{\rm UE}$ directly ?

Apply results to single-inclusive jet p_t spectra.

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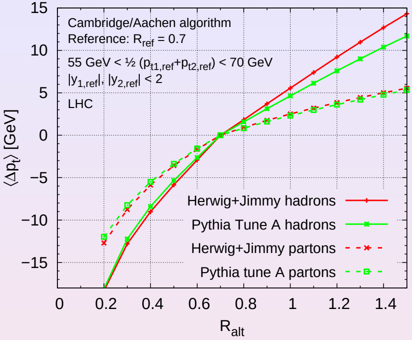

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MD, Magnea, Salam 2007

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