Non-perturbative effects for QCD jets at hadron colliders

Lorenzo Magnea

Università di Torino – INFN, Sezione di Torino

Work in collaboration with M. Dasgupta and G. Salam.

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Outline

Jets at Tevatron and LHC

- Jets are *ubiquitous* at hadron colliders

  $\longrightarrow$ the most common high-p_t final state

- Jets *need to be understood* in detail

  $\longrightarrow$ top mass, Higgs searches, QCD studies, new particle cascades

- Jets *at LHC* will be *numerous* and *complicated*

  $\longrightarrow t\bar{t}H \rightarrow 8\,\text{jets}$ ... , underlying event, pileup ...

- Jets are *inherently ambiguous* in QCD

  $\longrightarrow$ no unique link hard parton $\rightarrow$ jet

- Jets are *theoretically interesting*

  $\longrightarrow$ IR/C safety, resummations, hadronization ...

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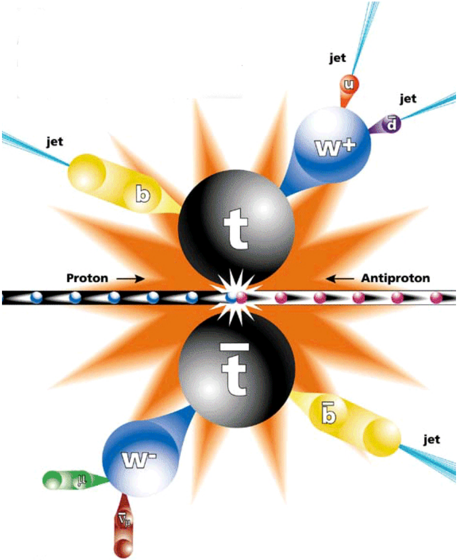
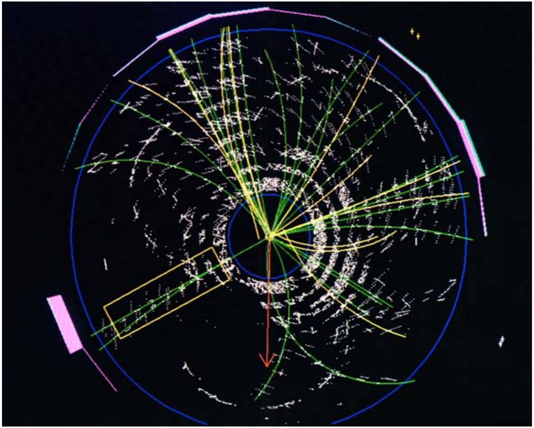
$t\bar{t} \to 4\,\text{jets} + \text{lepton} + \not{E}_t$: a cartoon



$t\bar{t} \rightarrow 4\,\text{jets} + \text{lepton} + \not{E}_t$: real life at CDF



From hard partons to jets

Hard scattering provides us with high-p_t partons *initiating* the jets. Jet momenta receive *several* PT and NP corrections.

- *Perturbative* radiation + parton *showering*

  $\longrightarrow$ expensive: $5 \cdot 10^2 \, \mathrm{m} \cdot \mathrm{y} \sim \$ \, 5 \cdot 10^7$ at NNLO ...

- Universal *hadronization*, induced by *soft radiation*

  $\longrightarrow$ from hard scattering, as in DIS, e^+e^-

- *Underlying event*, colored *fragments* from proton remnants

  $\longrightarrow$ no perturbative control, large at LHC

- *Pileup*, multiple proton scatterings per *bunch crossing*

  $\longrightarrow$ experimental issue, up to $10^2 \, \mathrm{GeV}$ per unit rapidity at LHC

Jet algorithms

- **Requirements.** IR/C *safe*, for theoretical stability; *fast*, for implementation; limited *hadronization corrections*
- **Algorithm structures.**
  - *Cone*. Top-down, intuitive, Sterman-Weinberg inspired.

    $\longrightarrow$ IR/C safety issues $\longrightarrow$ SISCone
  - *Sequential recombination*. Bottom-up, clustering, from e^+e^-.

$$\textit{Metric: } d_{ij}^{(p)} \equiv \min\left(k_{t,i}^{2p}, k_{t,j}^{2p}\right) \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2}\,, \quad d_{iB}^{(p)} \equiv k_{t,i}^{2p}\,,$$

Choices: $p = 1$: k_t, $p = 0$: *Cambridge*, $p = -1$: *Anti-k_t*

- **Recent progress.**
  - G. Salam *et al.*: FastJet, SISCone, Anti-k_t, Jet Area, Jet Flavor
  - Also S. Ellis *et al.*: SpartyJet

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Nonperturbative effects at TeV colliders

Why bother?

- Do power corrections *matter* for TeV jets?

  $$\Lambda/Q \sim 10^{-3} \longrightarrow \text{true asymptotics?}$$

- Precision measurements require precise *jet energy scale*

  $$1\% \text{ uncertainty} \longleftrightarrow \Delta M_{\rm top} \sim 1 \text{GeV}/c^2$$

- Steeply falling distributions *magnify* power corrections

  power corrections *necessary* to fit Tevatron data

- Hadronization and underlying event: *different* physics

  $\longrightarrow$ disentangle computable effects

- QCD dynamics *in full colors*.

  $\longrightarrow$ color correlations in hadronization

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Determining the jet energy scale

CDF, hep-ex/0510047

- *Precision* for the jet energy scale E_T is *important*

$$\Delta E_T/E_T = 10^{-2} \longrightarrow \Delta\sigma_{\rm jet}/\sigma_{\rm jet}|_{\rm 500GeV} = 10^{-1}$$

- *Determining* the jet energy scale is experimentally *difficult*

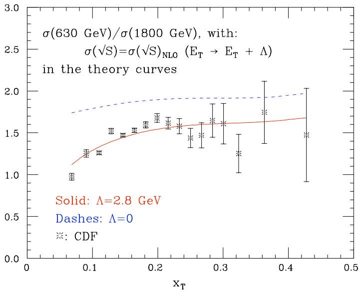
$$p_T^{\rm parton} = \left(p_T^{\rm jet} \times C_\eta - C_{\rm MI}\right) \times C_{\rm ABS} - C_{\rm UE} + C_{\rm OOC}$$

- Experimental *issues*: C_η , $C_{\rm MI}$, $C_{\rm ABS}$
  - Calorimeter and detector efficiencies
  - Multiple interactions
- Theoretical *input*: $C_{\rm UE}$, $C_{\rm OOC}$
  - Underlying event, hadronization, out-of-cone radiation
  - Models, Monte-Carlo, analytic results?

Fitting jet distributions at Tevatron

M.L. Mangano, hep-ph/9911256

The *ratio* of single-inclusive jet E_T distributions at different $\sqrt{S}$ should *scale* up to logarithms.



- Cross section ratio should *scale* up to *PDF* ad α_s effects.
- Data can be fitted with *shift* in distribution.
- *Small* Λ has impact at *high* E_T.
- $\sigma(E_T) \sim E_T^{-n} \to \frac{\delta\sigma}{\sigma} \sim -n\,\delta E_T$
- *Several* sources of energy flow *in* and *out* of jets.

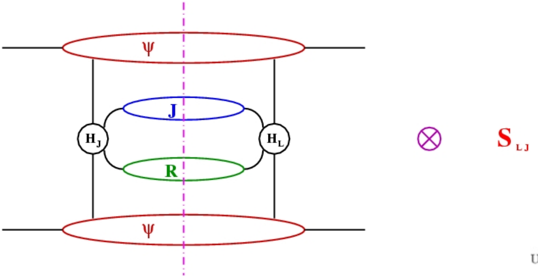
Discriminating power corrections

- *Sources* of power corrections at hadron colliders
  - Soft radiation from *hard antenna* $\Rightarrow$ *hadronization*.
    - ∗ *Accessible* with perturbative QCD.
    - ∗ Partially *localized* in phase space.
    - ∗ Tools: *resummations*, *dispersive techniques*.
  - *Background* soft radiation $\Rightarrow$ *underlying event*.
    - ∗ *Not calculable* in perturbative QCD.
    - ∗ *Fills* phase space (*minijets?*).
    - ∗ Tools: *models*, *Monte-Carlo*.
- Experimental *issues* impact on theory.
  - Phase space *cuts* $\longrightarrow$ *non-global* logarithms.
  - *Pileup* subtraction $\longrightarrow$ *jet areas*.

Factorization and resummation

Consider *inclusive* production of a *jet* with momentum p_J^μ in *hadron-hadron* collisions, near *partonic threshold*.

- *Partonic threshold*: $s_4 \equiv s + t + u \to 0$
  $\longrightarrow \alpha_s^n \left[\log^{2n-1}(s_4)/s_4\right]_+$ in the distribution.
- Sudakov logs arise from *collinear* and *soft* gluons, which *factorize*, with nontrivial *color mixing*



NLL jet E_T distribution

G. Sterman, N. Kidonakis, J. Owens ...

Factorization leads to *resummation*. For $q\bar{q}$ collisions

$$E_J \frac{d^3\sigma}{d^3 p_J} = \frac{1}{s} \exp\left[\mathcal{E}_{\mathrm{F}} + \mathcal{E}_{\mathrm{IN}} + \mathcal{E}_{\mathrm{OUT}}\right] \cdot \mathrm{Tr}\,\left[HS\right] \, .$$

Incoming partons build up a *Drell-Yan* structure

$$\mathcal{E}_{\mathrm{IN}} = - \sum_{i=1}^{2} \int_0^1 dz \frac{z^{N_i - 1} - 1}{1 - z} \left\{ \frac{1}{2} \nu_q \left[\alpha_s \left((1-z)^2 Q_i^2\right)\right] + \int_{(1-z)^2}^{1} \frac{d\xi}{\xi} A_q \left[\alpha_s \left(\xi Q_i^2\right)\right] \right\} \, .$$

Note: $N_1 = N(-u/s)\,,\; N_2 = N(-t/s)\,,\; Q_1 = -u/\sqrt{s}\,,\; Q_2 = -t/\sqrt{s}$

Outgoing partons near threshold cluster in *two jets*

$$\mathcal{E}_{\mathrm{OUT}} = - \sum_{i=J,R} \int_0^1 dz \frac{z^{N-1} - 1}{1 - z} \left\{ B_i \left[\alpha_s \left((1-z) p_T^2\right)\right] + C_i \left[\alpha_s \left((1-z)^2 p_T^2\right)\right] + \int_{(1-z)^2}^{1-z} \frac{d\xi}{\xi} A_i \left[\alpha_s \left(\xi p_T^2\right)\right] \right\} \, .$$

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Color exchange near threshold

Soft gluons change the *color structure* of the hard scattering.

- *Choose a basis* in color configuration space

$$c^{(1)}_{\{r_i\}} = \delta_{r_1 r_3} \delta_{r_2 r_4} \quad , \quad c^{(2)}_{\{r_i\}} = \left(T_A\right)_{r_3 r_1} \left(T^A\right)_{r_2 r_4} = \frac{1}{2} \left(\delta_{r_1 r_2} \delta_{r_3 r_4} - \frac{1}{N_c} \delta_{r_1 r_3} \delta_{r_2 r_4} \right)$$

- At *tree level*, for $q\bar{q}$ collisions

$$\mathcal{M}_{\{r_i\}} = \mathcal{M}_1 \, c^{(1)}_{\{r_i\}} + \mathcal{M}_2 \, c^{(2)}_{\{r_i\}} \rightarrow |\mathcal{M}|^2 = \mathcal{M}_I \mathcal{M}^*_J \ \mathrm{tr} \left[c^{(I)}_{\{r_i\}} \left(c^{(J)}_{\{r_i\}} \right)^\dagger \right] \equiv \mathrm{Tr} \ [HS]_0$$

- *Renormalization group* resums *soft* logarithms

$$\mathrm{Tr} \ [HS] \equiv H_{AB} \left(\alpha_s(\mu^2) \right) S^{AB} \left(\frac{p_T}{N\mu}, \alpha_s(\mu^2) \right) =$$

$$H \left(\alpha_s(p_T^2) \right) \cdot \overline{P} \exp \left(\int_{p_T}^{\frac{p_T}{N}} \frac{d\mu}{\mu} \Gamma_S^\dagger \left(\alpha_s(\mu^2) \right) \right) \cdot S \left(1, \alpha_s \left(\frac{p_T^2}{N^2} \right) \right) \cdot P \exp \left(\int_{p_T}^{\frac{p_T}{N}} \frac{d\mu}{\mu} \Gamma_S \left(\alpha_s(\mu^2) \right) \right)$$

- Note: $\left[\Gamma_S^{q\bar{q}} \right]^{(1)}_{11} = 2 C_F \log \left(-t/s \right) + \mathrm{i}\pi \ \ldots$

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Issues of globalness and jet algorithms

Resummations in hadron-hadron collisions *require* a precise definition of the observable.

- Precisely defining *threshold*
  - For *dijet distributions*: $M_{12} = (p_1 + p_2)^2$ *differs* from $M_{12} = 2p_1 \cdot p_2$ at *LL* level.
  - For *single inclusive* distributions: *fixed* and *integrated* rapidity differ ($N_i \to N$).
- Precisely defining the *observable*
  - Jet *algorithm*: IR safety *a must*.
  - Jet *momentum*: four-momentum recombination

    $p_\perp = \sum_i E_i \sin\theta_i$ vs. $p_\perp = \sum_i E_i \cdot \sin\theta_{\rm eff}$.
- Beware of *nonglobal* logarithms
  - Pick *global* observable: satisfied by x_T distribution.
  - *Minimize* impact of nonglobal logs: $k_\perp$ algorithm for energy flows; *joint* distributions.

Soft gluons in dipoles

Y. Dokshitzer, G. Marchesini

- Given *hard antenna*, define *eikonal* soft gluon *current*.

$$j^{\mu,b}(k) = \sum_{i=1}^{N_p} \frac{\omega\, p_i^{\mu}}{(k \cdot p_i)} T_i^b \, ; \qquad \sum_{i=1}^{N_p} T_i^b = 0 .$$

- Eikonal *cross section* is built by *dipoles*.

$$j^2(k) = 2 \sum_{i>j} T_i \cdot T_j \, \frac{\omega^2\,(p_i \cdot p_j)}{(k \cdot p_i)(k \cdot p_j)} \equiv 2 \sum_{i>j} T_i \cdot T_j \; w_{ij}(k),$$

- By *color conservation*, up to *three* hard emitters have *no color mixing* (unique *representation content*).
    - $-2T_1 \cdot T_2 = T_1^2 + T_2^2 = 2C_F \, ; \qquad -2T_1 \cdot T_2 = T_1^2 + T_2^2 - T_3^2 \, ,$
    - $-j^2(k) = T_1^2 \cdot W_{23}^{(1)}(k) + T_2^2 \cdot W_{13}^{(2)}(k) + T_3^2 \cdot W_{12}^{(3)}(k) \, ,$
    - $W_{23}^{(1)} = w_{12} + w_{13} - w_{23} \, .$

- Note: $W_{jk}^{(i)}$ isolates *collinear* singularity along i.

Soft gluons in dipoles

Beyond three emitters *different* color *representations* contribute.

- The *eikonal cross section* acquires *noncommuting* dipole combinations

$$-j^2(k) = T_1^2\, W_{34}^{(1)}(k) + T_2^2\, W_{34}^{(2)}(k) + T_3^2\, W_{12}^{(3)}(k) + T_4^2\, W_{12}^{(4)}(k) + T_t^2 \cdot A_t(k) + T_u^2 \cdot A_u(k)\,.$$

  with *nonCasimir* color factors

$$T_t^2 = (T_3 + T_1)^2 = (T_2 + T_4)^2, \qquad T_u^2 = (T_4 + T_1)^2 = (T_2 + T_3)^2.$$

- The resulting *distributions* are *collinear safe*

$$A_t = w_{12} + w_{34} - w_{13} - w_{24}\,, \qquad A_u = w_{12} + w_{34} - w_{14} - w_{23}\,,$$

- *Angular integrals* yield *momentum dependence* of radiators

$$\int \frac{d\Omega}{4\pi}\, A_t(k) = -2 \ln \frac{-t}{s}\,; \qquad \int \frac{d\Omega}{4\pi}\, A_u(k) = -2 \ln \frac{-u}{s}\,.$$

- Dipole approach *practical* for power corrections.

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Power corrections by dipoles

- *Consider* the single inclusive distribution for a jet observable $O(y, p_t, R)$, with *jet radius* $R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$.
- *Measure* the effect of *single soft gluon* emission on the distribution, as done in e^+e^- and DIS, but *dipole by dipole*.
- *Define* R-dependent power correction

$$\Delta O_{ij}^{\pm}(R) \equiv \int_{\pm} d\eta \frac{d\phi}{2\pi} \int_{\mu_c}^{\mu_f} d\kappa_t^{(ij)} \;\; \delta\alpha_s \left(\kappa_t^{(ij)}\right) k_t \left| \frac{\partial k_t}{\partial \kappa_t^{(ij)}} \right| \frac{p_i \cdot p_j}{p_i \cdot k \, p_j \cdot k} \, \delta O^{\pm} \left(k_t, \eta, \phi\right) \; .$$

- *Compute* in-cone and out-of-cone contributions

$$\Delta O_{ij}(R) = \Delta O_{ij}^{+}(R) + \Delta O_{ij}^{-}(R) = \Delta O_{ij}^{+}(R) + \Delta O_{ij}^{-\,\mathrm{all}}(R) - \Delta O_{ij}^{-\,\mathrm{in}}(R) \, .$$

- *Express* leading power R dependence in terms of (*universal?*) moment of the *non-perturbative* coupling, $\mathcal{A}(\mu_f)$

$$\mathcal{A}\left(\mu_f\right) = \frac{1}{\pi} \int_0^{\mu_{\mathrm{f}}} d\kappa_{\perp} \, \delta\alpha_s(\kappa_{\perp})$$

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Radius dependence: p_T distribution

Let $O = \xi_T \equiv 1 - 2p_T/\sqrt{S}$. In this case

- *In-In dipole*

$$\Delta\xi_{T,12}(R) = \frac{-4}{\sqrt{S}}\mathcal{A}(\mu_f)\, R\, J_1(R) = -\frac{4}{\sqrt{S}}\mathcal{A}(\mu_f)\left(\frac{R^2}{2} - \frac{R^4}{16} + \dots\right).$$

- *In-Jet dipoles*

$$\begin{aligned}\Delta\xi_{T,1j}(R) &= -\sqrt{\frac{2}{S}}\int_{\eta^2+\phi^2<R^2} d\eta \frac{d\phi}{2\pi}\alpha_s(\kappa_t)\frac{d\kappa_t}{\kappa_t}\kappa_t \frac{\cos\phi\, e^{\frac{3\eta}{2}}}{(\cosh\eta - \cos\phi)^{\frac{3}{2}}} \\ &= \frac{2}{\sqrt{S}}\mathcal{A}(\mu_f)\left(\frac{2}{R} - \frac{5}{8}R + \frac{23}{1536}R^3 + \dots\right)\end{aligned}$$

- *Jet-Recoil dipole*

$$\Delta\xi_{T,jr}(R) = \frac{2}{\sqrt{S}}\mathcal{A}(\mu_f)\left(\frac{2}{R} + \frac{1}{2}R + \frac{1}{96}R^3 + \dots\right)$$

- *In-Recoil dipoles*

$$\Delta\xi_{T,1r}(R) = -\frac{2}{\sqrt{S}}\mathcal{A}(\mu_f)\left(\frac{1}{8}R^2 - \frac{9}{512}R^4 - \frac{73}{24576}R^6 + \dots\right)$$

Radius dependence: mass distribution

For comparison, let $O = \nu_J \equiv M_J^2/S$. Now only gluons *recombined* with the jet contribute, and one finds *nonsingular* R dependence.

- *In-In dipole*

$$\Delta\nu_{J,12}(R) = \frac{1}{\sqrt{S}}\mathcal{A}(\mu_f)\left(\frac{1}{4}R^4 + \frac{1}{4608}R^8 + \mathcal{O}\left(R^{12}\right)\right) ,$$

- *In-Jet dipoles*

$$\Delta\nu_{J,1j}(R) = \frac{1}{\sqrt{S}}\mathcal{A}(\mu_f)\left(R + \frac{3}{16}R^3 + \frac{125}{9216}R^5 + \frac{7}{16384}R^7 + \mathcal{O}\left(R^9\right)\right) ,$$

- *Jet-Recoil dipole*

$$\Delta\nu_{J,jr}(R) = \frac{1}{\sqrt{S}}\mathcal{A}(\mu_f)\left(R + \frac{5}{576}R^5 + \mathcal{O}\left(R^9\right)\right) ,$$

- *In-Recoil dipoles*

$$\Delta\nu_{J,1r}(R) = \frac{1}{\sqrt{S}}\mathcal{A}(\mu_f)\left(\frac{1}{32}R^4 + \frac{3}{256}R^6 + \frac{169}{589824}R^8 + \mathcal{O}\left(R^{10}\right)\right) .$$

Combining dipoles

Example: *leading power* shift in p_t after *dipole recombination* for $\mathrm{qq'} \to \mathrm{qq'}$ parton process, at *central rapidity*.

$$\Delta p_t(R)|_{\mathrm{qq'}\to\mathrm{qq'}} = \mathcal{A}(\mu_f)\left[-\frac{2}{R}\,C_F + \frac{1}{8}\,R\left(5\,C_F - \frac{9}{N_c}\right) + \mathcal{O}\left(R^2\right)\right] \, .$$

- *Hadronization* has a *singular* R dependence. $1/R$ has a *collinear origin*, like the $\log R$ behavior of PT.
- The *color structure* at $1/R$ level is *abelian*, with the hard parton *color charge*. For *gluon jets*, $C_F \to C_A$.
- Possible *universality*: $\mathcal{A}(\mu_f)$ is the *same* as defined for *event shapes* in e^+e^- and DIS.
- Universality *generically broken* by *nonlinear effects* in jet algorithm, *except* for Anti-k_t.
- At $\mathcal{O}(R^2)$ hadronization is *overtaken* by *underlying event*, entering with a *new scale* Λ_{UE}.

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Power corrections by MonteCarlo

The *analytical* estimate of power corrections provided by resummation is valid *near threshold*. It can be compared with *numerical* estimates from QCD-inspired *MonteCarlo models* of hadronization.

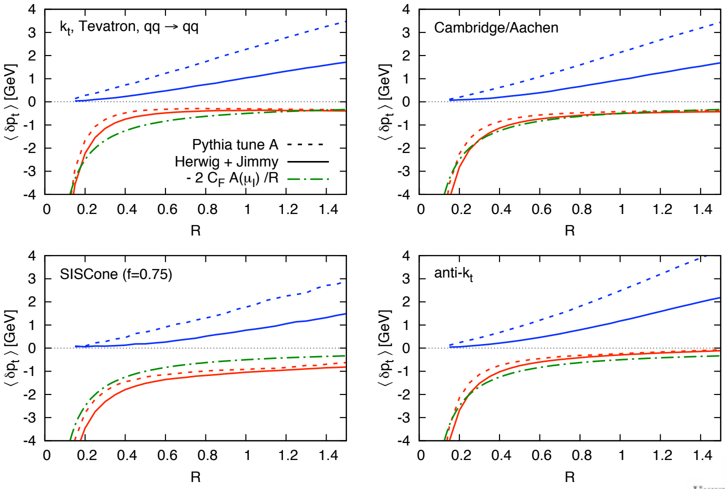
- *Run* MC at *parton level* (p), *hadron level without UE* (h) and finally *with UE* (u)
- *Select* events with hardest jet in chosen p_T range, *identify* two hardest jets, *define* for each hadron level

$$\Delta p_T^{(h/u)} = \frac{1}{2}\left(p_{T,1}^{(h/u)} + p_{T,2}^{(h/u)} - p_{T,1}^{(p)} - p_{T,2}^{(p)}\right) .$$

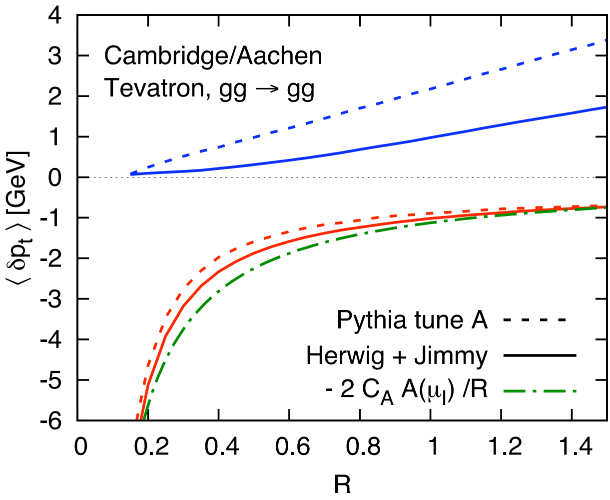
$$\Delta p_T^{(u-h)} = \Delta p_T^{(u)} - \Delta p_T^{(h)} .$$

- *Compare* results for different *jet algorithms*, *hadronization models*, *parton channels*.

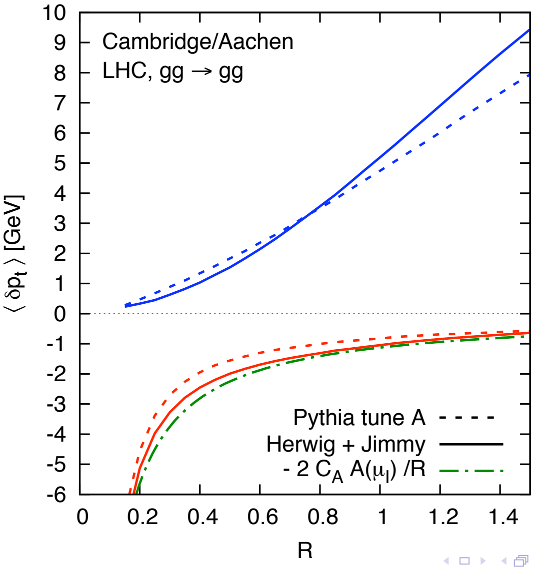
Quark scattering at Tevatron: comparing jet algorithms



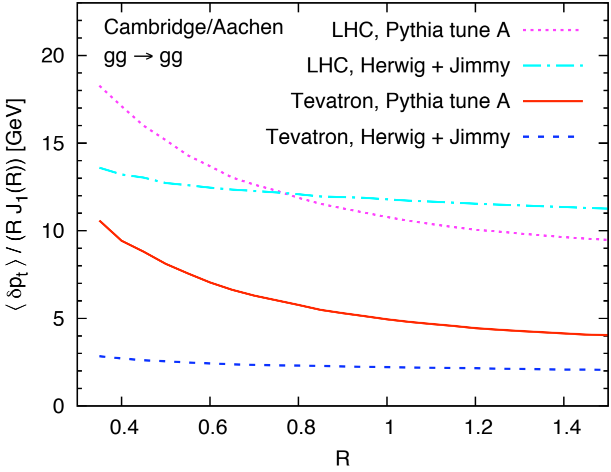
Gluon scattering at Tevatron



Gluon scattering at LHC



Underlying event, scaled



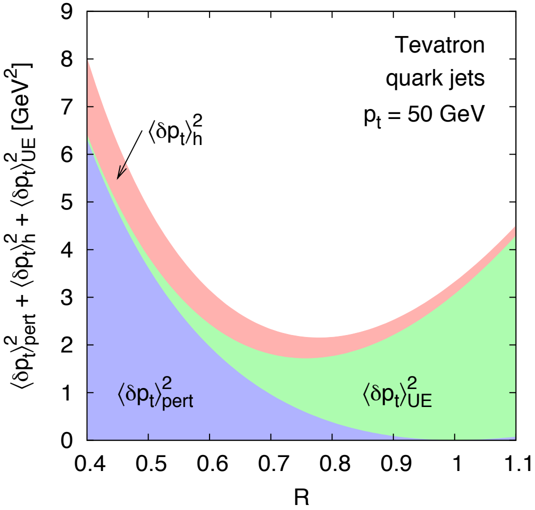
Jetography

The change in p_t from the *hard parton* to the *hadronic jet* has *several sources*, each with its own *scale* and radius, energy and color dependence.

	Dependence of jet Δp_t on			
	scale	*colour factor*	R	$\sqrt{s}$
PT	$\alpha_s(p_t)\, p_t$	C_i	$\ln R + \mathcal{O}(1)$	–
H	$\mathcal{A}(\mu_f)$	C_i	$-1/R + \mathcal{O}(R)$	–
UE	Λ_{UE}	–	$R^2 + \mathcal{O}(R^4)$	s^ω

- Jet *algorithm* dependence is *weak* at this level
- Parameters *tunable to optimize* specific physics searches
- *Radius* dependence usable to *disentangle* p_t sources.

Looking for the best R



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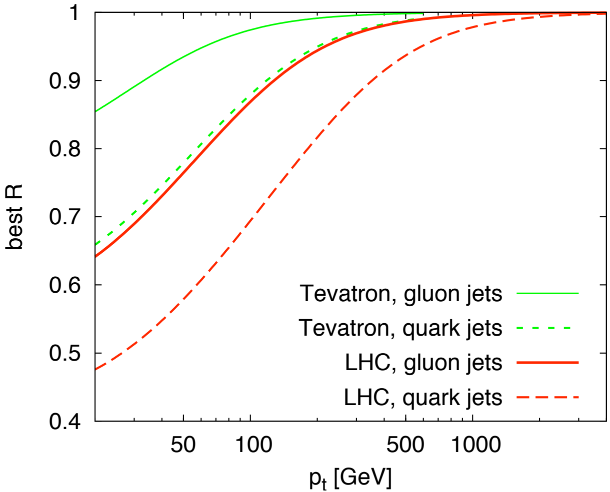
Looking for the best R



Perspective on hadronization

- Single inclusive jet distributions have Λ/p_T power corrections *from hadronization*.
- *Hadronization* corrections are *distinguishable* from *underlying event* effects because of *singular* R dependence.
- In a *"dispersive model"* the size of leading power corrections can be *related* to parameters *determined* in e^+e^- annihilation.
- Power corrections *near partonic threshold* are qualitatively compatible with *Monte Carlo* results.
- Work *in progress*.
  - Study *rapidity* dependence.
  - Investigate role of *jet algorithms*.
  - Combine with *resummation* to go *beyond shift*.

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Perspective

- In recent years: great progress in theoretical jets studies
  - Several *IR/C safe* jet algorithms available; *fast* implementation
  - Operational definitions of *jet area*, *jet flavor*
  - Progress in PT, *shower*, *resummation*, *hadronization*
- Progress will be necessary for complex LHC environment (multi-jet, large UE, pileup, ...)
  - To *take advantage* of available tools: *flexibility*
  - Use *different* (safe) *algorithms*, vary *parameters*
- QCD is now precision physics
  - *New frontiers* in quantum field theory
  - *Useful* for *new physics* studies
  - *Necessary* for *precision* studies

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