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 colliders

- The making and usage of jets
- Jet energy scale studies

Analytic study

- Soft gluons in dipoles
- Jet size dependence

MonteCarlo results

- Modeling power correction
- Comparing jet algorithms
- Comparing parton channels and energies

Optimizing R

- Varying jet parameters
- Looking for the best R

Perspective

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*

  $\longrightarrow t\bar{t}H \to 8\,\mathrm{jets}$ ... , underlying event, pileup ...

- Jets are *inherently ambiguous* in QCD

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

- Jets are *theoretically interesting*

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

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?

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

- Precision measurements require precise *jet energy scale*

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

- 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*

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

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

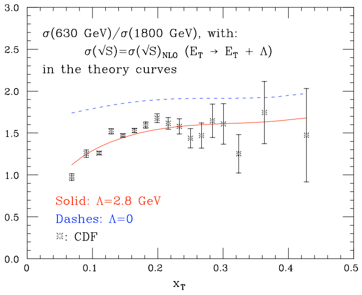
$$p_T^{\rm parton} = \left(p_T^{\rm jet} \times C_\eta - C_{\rm MI} \right) \times C_{\rm ABS} - C_{\rm UE} + C_{\rm OOC}$$

- 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.

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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.

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

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

- *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, $\mathcal{A}(\mu_f)$

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

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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*

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

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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}.

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*.

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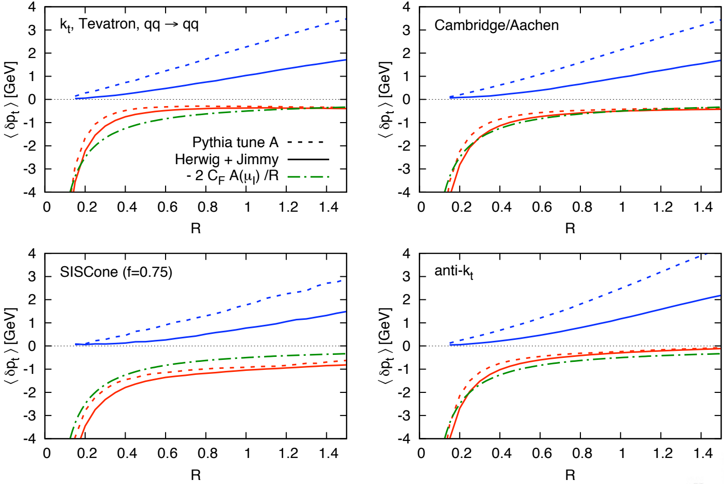
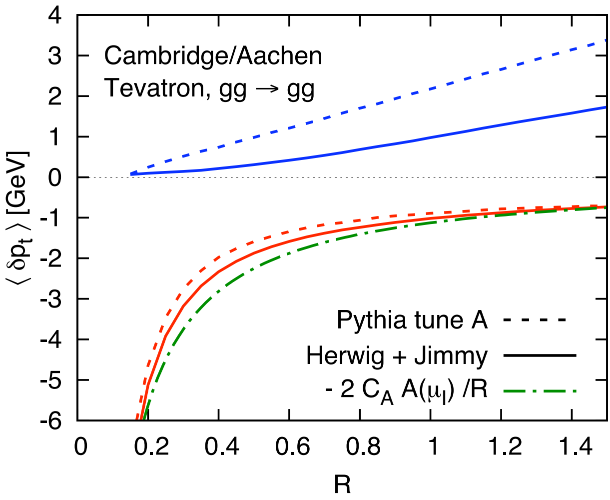
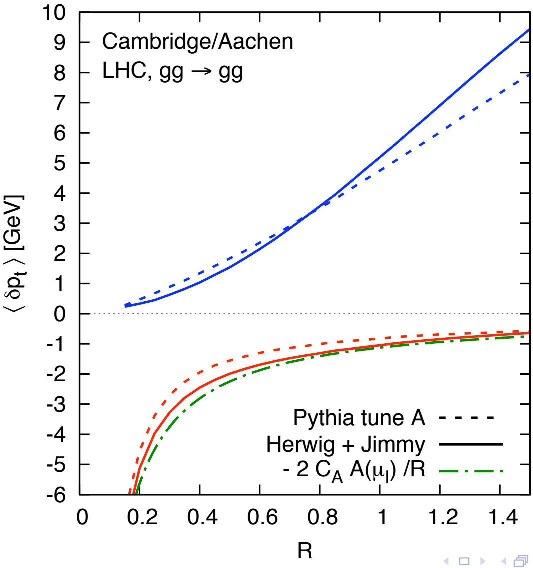
Quark scattering at Tevatron: comparing jet algorithms



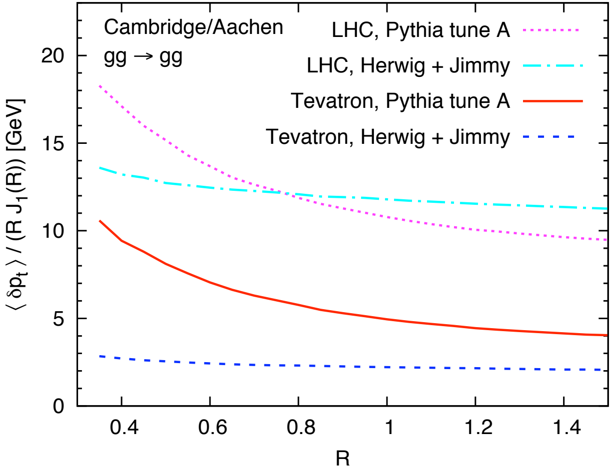
Gluon scattering at Tevatron



Gluon scattering at LHC



Underlying event, scaled



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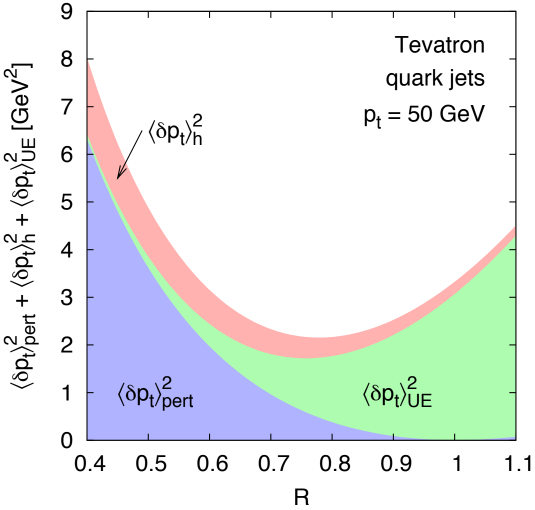
Jetography

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.

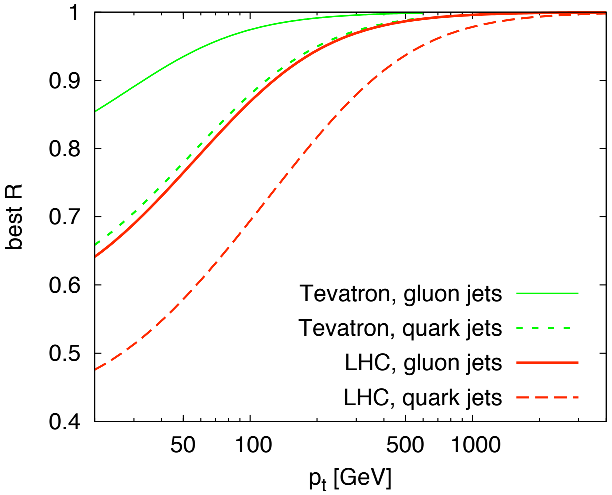
	Dependence of jet Δp_t on			
	scale	*colour factor*	R	$\sqrt{s}$
PT	$\alpha_s(p_t)\,p_t$	C_i	$\ln R + \mathcal{O}(1)$	–
H	$\mathcal{A}(\mu_f)$	C_i	$-1/R + \mathcal{O}(R)$	–
UE	Λ_{UE}	–	$R^2 + \mathcal{O}(R^4)$	s^ω

- 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



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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