Power corrections to jet distributions at hadron colliders

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Outline

Introduction

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- Jet energy scale studies
- Discriminating power corrections

Resummation

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- Resummed jet p_T distribution

Power corrections

- Dipole resummation
- Jet size dependence

MonteCarlo results

- Comparing algorithms
- Comparing parton channels

Perspective

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

- 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*.

  $\longrightarrow$ beauty from gauge invariance

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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?

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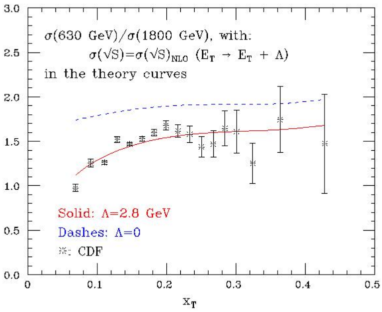
Fitting jet distributions at Tevatron

M.L. Mangano, hep-ph/9911256

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



Fit of CDF data with NLO QCD assuming

E_T-independent shift Λ in jet energy.

- 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.
- $\sigma(E_T) \sim E_T^{-n} \rightarrow \frac{\delta\sigma}{\sigma} \sim -n\delta E_T$
- *Several* sources of energy flow *in* and *out* of jets.

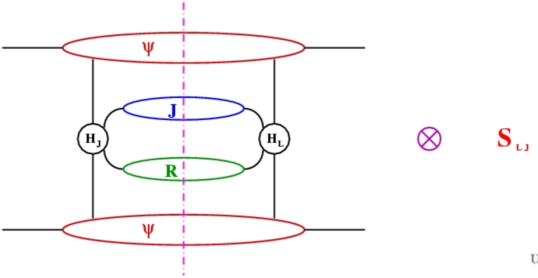
Discriminating power corrections

- *Sources* of power corrections at hadron colliders
  - Soft radiation from *hard antenna* ⇒ *hadronization*.
    - ∗ *Calculable* in perturbative QCD.
    - ∗ Partially *localized* in phase space.
    - ∗ Tools: *resummations*, *dispersive techniques*.
  - *Background* soft radiation ⇒ *underlying event*.
    - ∗ *Not calculable* in perturbative QCD.
    - ∗ *Fills* phase space (*minijets?*).
    - ∗ Tools: *models*, *Monte-Carlo*.
- Experimental *issues* impact on theory.
  - Detector *coverage* and phase space *cuts*.
  - *Jet* algorithms, *non-global* logarithms.

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*



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NLL jet E_T distribution

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

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

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

Incoming partons build up a *Drell-Yan* structure

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

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*

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

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

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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

- 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.

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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 an effective *jet radius* $R = \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.
- *Measure* effect of *single soft gluon* emission on the distribution *dipole by dipole* at power accuracy.
- *Define* R-dependent power correction

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

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

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

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

$$\mathcal{A}\left(\mu_f\right) = \int_0^{\mu_f} \frac{dk_\perp}{k_\perp} \alpha_s(k_\perp) \cdot k_\perp$$

Radius dependence: p_T distribution

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

- *In-In dipole*

$$\Delta\xi_{T,12}(R) = \frac{-4}{\sqrt{S}} \int_{+} d\eta \frac{d\phi}{2\pi} \alpha_s(k_t) \frac{dk_t}{k_t} k_t \cos\phi = -\frac{4}{\sqrt{S}} \mathcal{A}(\mu_f) \left(\frac{R^2}{2} - \frac{R^4}{16} + \frac{R^6}{384} + \ldots \right).$$

- *In-Jet dipoles*

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

- *Jet-Recoil dipole*

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

- *In-Recoil dipoles*

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

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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*

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

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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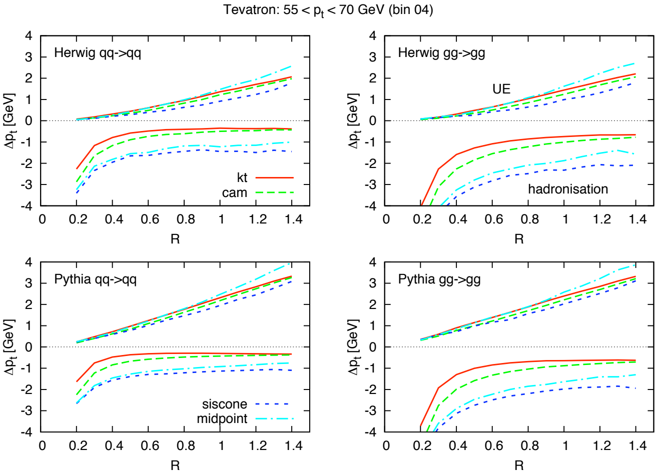
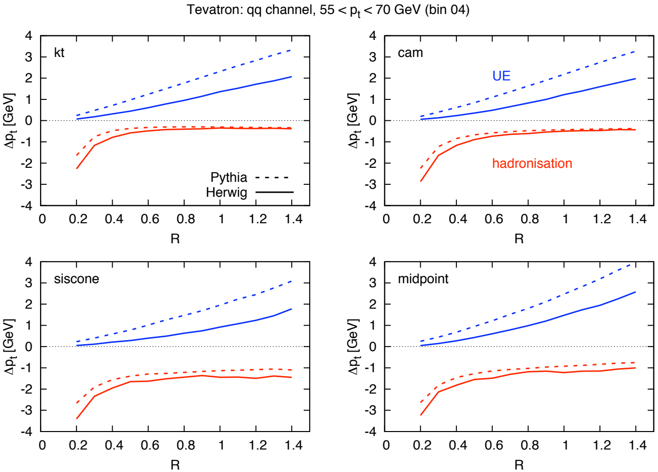
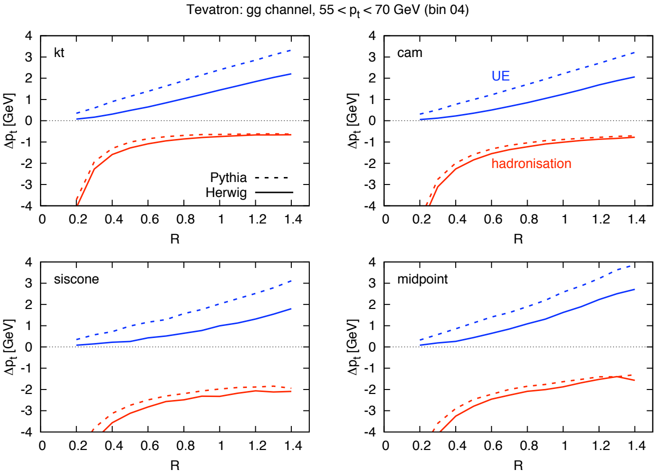
MC power corrections: comparing jet algorithms



MC power corrections: quark channel

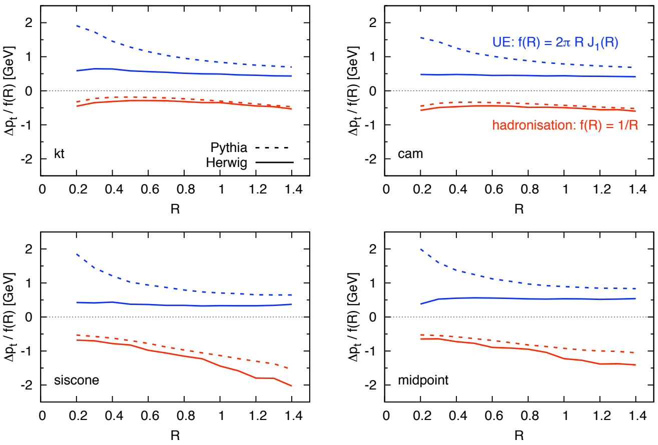


MC power corrections: gluon channel

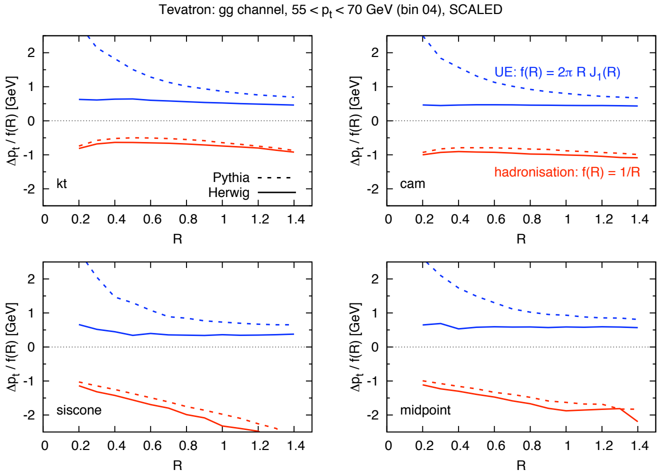


MC power corrections: quark channel, scaled

Tevatron: qq channel, $55 < p_t < 70$ GeV (bin 04), SCALED



MC power corrections: gluon channel, scaled



Disentangling 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 models of *underlying event*.

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Perspective

- *Resummation* and *power correction* studies at hadron colliders are interesting: the full power of *nonabelian gauge invariance* is displayed.
- *Resummation* and *power correction* studies at hadron colliders are relevant: precision phenomenology *requires* reliable modeling of *hadronization* and *underlying event*.
- Refined *QCD tools* are available: nonabelian *exponentiation*, *dispersive* methods, MonteCarlo *simulations*.
- *Disentangling hadronization* and *underlying event* is useful: different *physics* requires different *tools*.
- *Disentangling hadronization* and *underlying event* is possible: jet-size dependence is a (first) *handle*.
- *Phenomenology* of power corrections at hadron colliders is a realistic prospect.

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