QCD Matrix Elements and Truncated Showers

[based on Höche, Krauss, S., Siegert JHEP **0905** (2009) 053]

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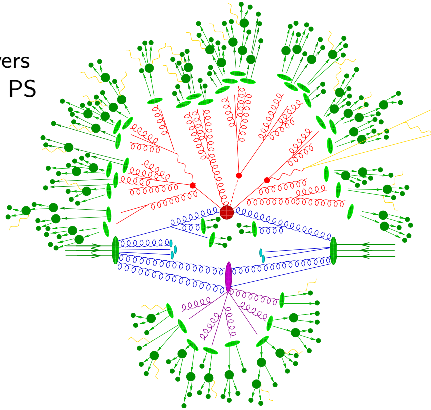
Hamburg 11/11/09

Multijet Events at Hadron Colliders

1. The physics case
2. Theoretical modelling
   - QCD Matrix Elements & Parton Showers
   - A new formalism for combining ME & PS
3. Application: Z^0 + jets @ Tevatron
4. Summary/Outlook

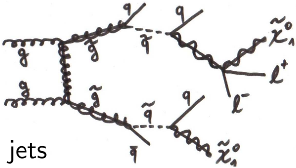


Searches for New Physics

- large cross sections for producing new colored states
- subsequent decays into SM final states + X
- generic signals: #-leptons + #-jets + $\not{E}_T$

$\rightsquigarrow$ new physics encoded in energies, flavors, edges

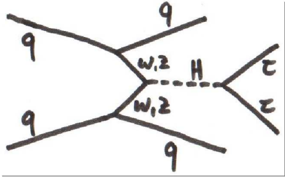
$\rightsquigarrow$ SM backgrounds: V+jets, VV+jets, $t\bar{t}$+jets, QCD jets



Measurements sensitive to QCD radiation

- veto on extra jets
- cuts on QCD affected observables

$\rightsquigarrow$ acceptances & cut efficiencies



Detailed understanding of QCD jet production needed!

Theoretical Modelling

Matrix Elements (hard interaction)

$$\sigma_{pp\to N}(Q^2) = \sum_{a,b} \int \mathrm{d}x_1 \mathrm{d}x_2 \; g_1(x_1, Q^2) g_2(x_2, Q^2) \, |\mathcal{M}_{12\to N}|^2 \, \mathrm{d}\Phi_N$$

+ $|\mathcal{M}_{12\to N}|^2$ encodes fundamental physics, interferences, off-shell effects
+ accounts for high-p_T, well separated partons
– poor for log-enhanced phase-space regions, few-parton final states only

Parton Showers (QCD evolution)

$$\frac{\partial}{\partial \log(t/\mu^2)} \frac{g_a(z,t)}{\Delta_a(\mu^2,t)} = \frac{1}{\Delta_a(\mu^2,t)} \int_z^{\zeta_{\max}} \frac{\mathrm{d}\zeta}{\zeta} \sum_{b=q,g} \mathcal{K}_{ba}(\zeta,t) \, g_b(\frac{z}{\zeta}, t)$$

$\mathcal{K}_{ba}(\zeta, t)$ - evolution kernels of the scheme e.g. DGLAP kernels $\alpha_s/2\pi \; P_{ba}(\zeta)$

ζ, t - splitting, evolution variable

+ accounts for multiple soft/collinear QCD emissions
+ resummation of large kinematical logarithms
– lacks hard/large angle emissions

To sensibly simulate *full events* we must combine the two !

Catani–Seymour dipole factorisation based Shower

Catani–Seymour local subtraction term

$$\int_{m+1} d\sigma^{A} = \sum_{\text{dipoles}} \int_{m} d\sigma^{B} \otimes \int_{1} dV_{\text{dipole}}$$

spin- & color correlation $\longleftarrow$ $\longrightarrow$ universal dipole term

[Catani, Seymour Nucl. Phys. B **485** (1997) 291]

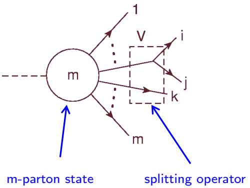
[Catani, Dittmaier, Seymour, Trocsanyi Nucl. Phys. B **627** (2002) 189]

Ansatz: Complete factorisation through

- projection onto leading term in $1/N_c$
- spin averaged dipole terms $V_{\text{dipole}} \rightarrow \langle V_{\text{dipole}} \rangle$

Shower Algorithm [Krauss, S. JHEP **0803** (2008) 038]

- color connected emitter–spectator 'dipoles'
- subsequent branchings of type II, IF, FI, FF
- exact momentum mappings
- emissions ordered in $k_\perp^2$



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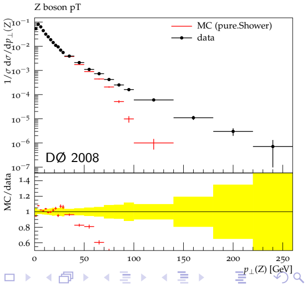


Combining ME & PS

Problem: QCD MEs and PS deal with the same physics!

- double counting of phase-space configurations
- unpopulated phase-space regions

Aim: Consistent description of real QCD emissions!

- proper description of soft/collinear *and* hard emissions
- combine QCD matrix elements of different parton multiplicity with showers

  [CKKW: Catani et. al '01, MLM: Mangano et. al '01, CKKW-L: Lönnblad '01]

Construction criteria:

- describe few hardest emissions through full matrix elements

$$\mathcal{K}_{ba}(z,t) \to \frac{1}{\mathrm{d}\hat{\sigma}_a^{(N)}(\Phi_N)} \frac{\mathrm{d}\hat{\sigma}_b^{(N+1)}(z,t;\Phi_N)}{\mathrm{d}\log(t/\mu^2)\,\mathrm{d}z}$$

- preserve shower-evolution equation i.e. logarithmic accuracy
- avoid double counting or empty phase-space regions

⇝ $\boxed{\textbf{slice emission phase space by parton-separation criterion } \mathbf{Q_{ba}(z,t)}}$

Solution part 1: Slicing the phase space

Phase-space separation

$$\mathcal{K}^{\rm PS}_{ba}(z,t) = \ \mathcal{K}_{ba}(z,t)\ \Theta\left[Q_{\rm cut} - Q_{ba}(z,t)\right] \quad \leftarrow \text{shower regime}$$

$$\mathcal{K}^{\rm ME}_{ba}(z,t) = \ \mathcal{K}_{ba}(z,t)\ \Theta\left[Q_{ba}(z,t) - Q_{\rm cut}\right] \quad \leftarrow \text{matrix-element regime}$$

$\Rightarrow$ $Q_{ba}(z,t)$ has to identify logarithmically enhanced phase-space regions

Consequences

Sudakov form factor and shower no-branch probabilities factorize

$$\Delta_a(\mu^2,t) = \Delta^{\rm PS}_a(\mu^2,t)\ \Delta^{\rm ME}_a(\mu^2,t)$$

$$\rightsquigarrow \mathcal{P}^{(B)}_{{\rm no},\,a}(t,t') = \mathcal{P}^{(B)\,{\rm PS}}_{{\rm no},\,a}(t,t')\ \mathcal{P}^{(B)\,{\rm ME}}_{{\rm no},\,a}(t,t') = \frac{\Delta^{\rm PS}_a(\mu^2,t')\,g_a(z,t)}{\Delta^{\rm PS}_a(\mu^2,t)\,g_a(z,t')}\,\frac{\Delta^{\rm ME}_a(\mu^2,t')}{\Delta^{\rm ME}_a(\mu^2,t)}$$

$\rightsquigarrow$ need to constrain shower emissions to $Q < Q_{\rm cut}$

$\rightsquigarrow$ matrix elements need to be reweighted [made exclusive quantities]

$\hookrightarrow$ think of ME's as predetermined shower emissions, truncated shower

Solution part 1: Slicing the phase space

The proposed measure [example final-state splitting]

$$Q_{ij}^2 \;=\; 2\,p_i p_j \,\min_{k\neq i,j} \frac{2}{C_{i,j}^k + C_{j,i}^k}\,; \qquad C_{i,j}^k \;=\; \begin{cases} \dfrac{p_i p_k}{(p_i+p_k)p_j} - \dfrac{m_i^2}{2\,p_i p_j} & \text{if } j = g \\ 1 & \text{else} \end{cases}$$

$\hookrightarrow$ minimize over color partners k

IR limitae

soft limit: $\mathbf{p_j = \lambda q,\ \lambda \longrightarrow 0}$

$$\frac{1}{Q_{ij}^2} \to \frac{1}{2\,\lambda^2}\,\frac{1}{2\,p_i\,q}\,\max_{k\neq i,j}\left[\frac{p_i p_k}{(p_i+p_k)\,q} - \frac{m_i^2}{2\,p_i\,q}\right]$$

quasi-collinear limit: $\mathbf{k_\perp \longrightarrow \lambda k_\perp,\ m \longrightarrow \lambda m}$

$$\frac{1}{Q_{ij}^2} \to \frac{1}{2\,\lambda^2}\,\frac{1}{p_{ij}^2 - m_i^2 - m_j^2}\left(\widetilde{C}_{i,j} + \widetilde{C}_{j,i}\right)\,; \qquad \widetilde{C}_{i,j} = \begin{cases} \dfrac{z}{1-z} - \dfrac{m_i^2}{2\,p_i p_j} & \text{if } j = g \\ 1 & \text{else} \end{cases}$$

$\rightsquigarrow$ **measure correctly identifies enhanced phase-space regions**

Solution part 2: Defining PS histories

Interpret ME as if produced by PS

- Identify most likely splitting acc. to PS branching probability
- Combine partons into mother parton acc. to inverse PS kinematics
- Continue until $2 \rightarrow 2$ core process

$\rightsquigarrow$ shower-specific cluster algorithm

$\rightsquigarrow$ predetermined shower emissions

PS starts at core process

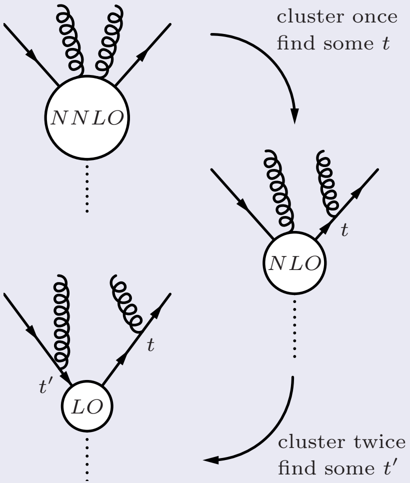
can radiate "between" ME emissions

ME branchings must be respected

evolution-, splitting- & angular variable preserved

$\rightsquigarrow$ truncated shower

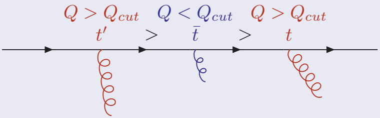
Example branching history



Solution part 3: Truncated shower

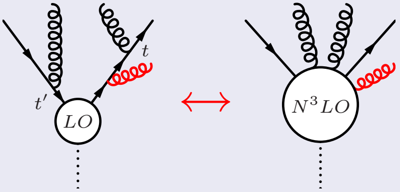
Assume ME splittings at t and $t' > t$

Shower emission below $Q_{\rm cut}$



- $\rightsquigarrow$ emission accepted
- $\rightsquigarrow$ large-angle soft emissions
- $\rightsquigarrow$ soft color coherence
- $\rightsquigarrow$ approx. in CKKW only [Nason 2004]

Shower emission above $Q_{\rm cut}$

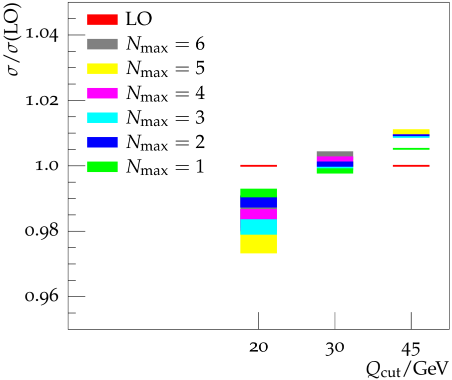


- $\rightsquigarrow$ entire event is rejected
- $\rightsquigarrow$ Sudakov suppression $\mathcal{P}^{\rm ME}_{{\rm no},\,a}(t, t')$
- $\rightsquigarrow$ to be described by ME instead
- $\rightsquigarrow$ $\sigma_{\rm tot}$ preserved at LO

Application: DY total cross section

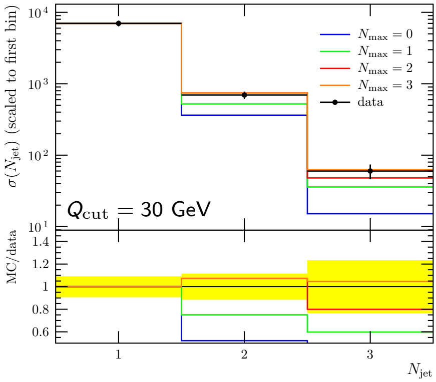
Q_{cut} and/or N_{max} variation should affect σ_{tot} only beyond (N)LL

Example: DY-pair production $\sigma_{\rm tot}$ @ Tevatron



Jet rates and -spectra improved compared to pure PS simulation
due to exact real emission ME's

Example: DY-pair production $\sigma_{\mathrm{e^+e^-+N_{jet}}}$ CDF Data: PRL **100** (2008) 102001

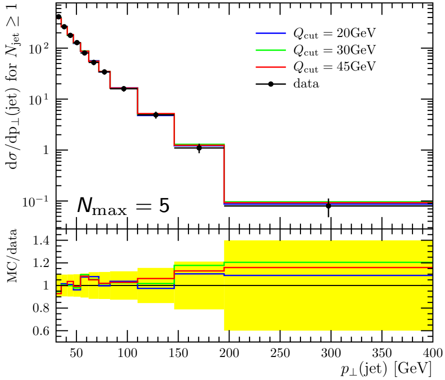


Application: Jet spectra

Variation of Q_{cut} should affect distributions only beyond (N)LL

But Q_{cut} must be in range where PS approximation is valid!

Example: All-jets p_T in DY-pair production CDF Data: PRL **100** (2008) 102001

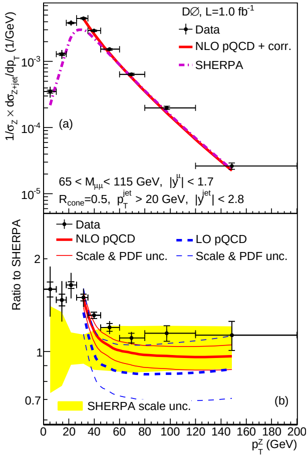


Application: Z/γ^* transverse momentum

Comparison to Sherpa's CKKW implementation in v1.1.3

Example: DY-p_T in Z/γ^*+jet+X events DØ Data: Phys. Lett. B **669** (2008) 278

Sherpa v1.1.3



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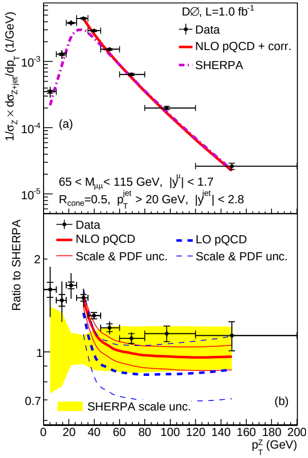
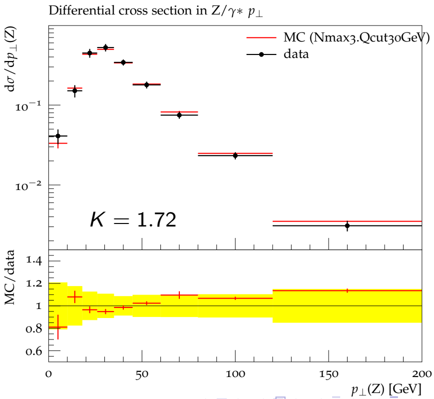


Sherpa v1.2



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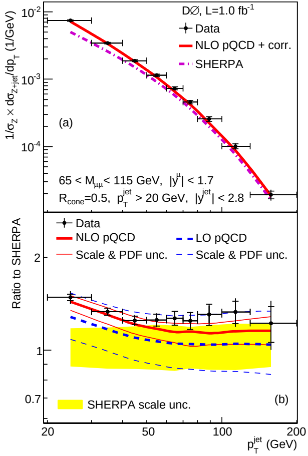

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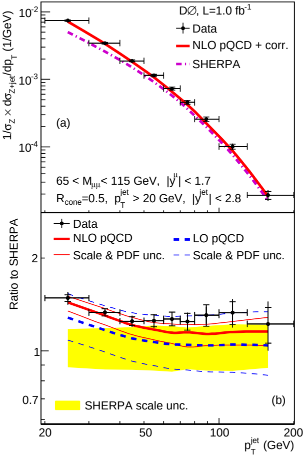
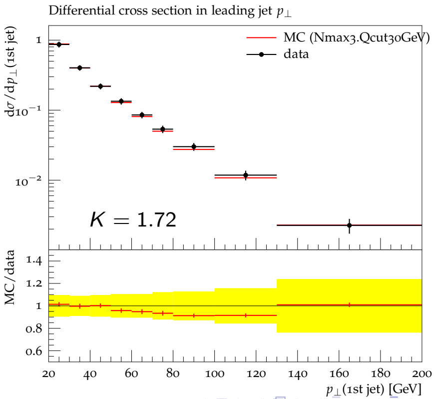


Sherpa v1.2



Summary/Outlook

Summary

- Multijet ME-PS merging sustainable approach to describe multijet events
- Virtues of two complementary approaches combined
  - hard emissions through exact (tree-level) matrix elements
  - (intra) jet evolution through QCD parton showers
- New formalism relying on truncated shower
  - MEs from Comix [Höche, Gleisberg JHEP **0812** (2008) 039]
  - dipole subtraction based shower
  - largely reduced merging systematics
  - available within Sherpa-v1.2

Outlook

- Application to Deep Inelastic Scattering
  - crossing invariant recoil strategy
  - modified FI & IF splitting kernels [positive definite]
- Interleaved QCD$\oplus$QED evolution
- New Physics production processes