QCD matrix elements and truncated showers

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IOP HEPP 2009, 6-8th April 2009, Oxford

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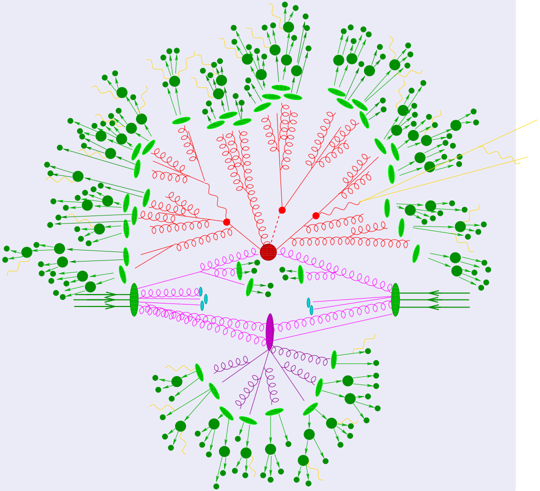
Monte-Carlo event generation

PERTURBATIVE PHYSICS

- Initial state parton shower (QCD)
- Signal process
- Final state parton shower (QCD)
- Underlying event

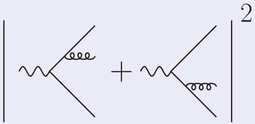
SOFT PHYSICS

- Fragmentation
- Hadron decays
- QED radiation

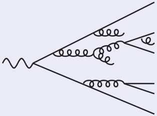


Two approaches

Matrix Elements



Parton Showers



- \+ Exact to fixed order
- \+ Include all interferences
- \+ $N_C = 3$ (summed or sampled)
- – Perturbation breaks down due to large logarithms
- – Only low FS multiplicity

- \+ Resum logarithmically enhanced contributions to all orders
- \+ Produce high-multiplicity final state
- – Only approximation to ME for splitting
- – No interference effects
- – Large N_C limit only

$\Downarrow$

Goal: Combine advantages

- Describe **particular final state** by **ME** (hard QCD radiation)
- Don't spoil the **inclusive picture** provided by the **PS** (intrajet evolution)

Ellis, Stirling, Webber: QCD and Collider Physics

Evolution equation in terms of Sudakov form factor Δ

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

$$\Delta_a(\mu^2,t) \;=\; \exp\left\{ -\int_{\mu^2}^{t} \frac{\mathrm{d}\bar{t}}{\bar{t}} \int \mathrm{d}\zeta \sum_{b=q,g} \frac{1}{2}\, \mathcal{K}_{ab}(\zeta,\bar{t}) \right\}$$

- Kernel describes parton splitting: $\mathcal{K}_{ab}(z,t) \to \frac{1}{\mathrm{d}\sigma_a^{(N)}(\Phi_N)} \frac{\mathrm{d}\sigma_b^{(N+1)}(z,t;\Phi_N)}{\mathrm{d}\log(t/\mu^2)\,\mathrm{d}z}$
- Solution: Probability for no (final state) shower branching between two scales

$$\mathcal{P}^{(F)}_{\text{no},\,a}(t,t') = \frac{\Delta_a(\mu^2,t')}{\Delta_a(\mu^2,t)} \stackrel{!}{=} \mathcal{R}$$

$\Rightarrow$ **MC method** for dicing successive branching scales using random number $\mathcal{R} \in [0,1]$

Preparation for ME/PS merging

Use different splitting kernels in different regions in phase space, but:
Preserve total evolution equation!

Preparation: Slicing the phase space

Emission phase space divided by parton separation criterion $Q_{ab}(z,t)$

$$\mathcal{K}_{ab}^{\mathrm{PS}}(z,t) = \mathcal{K}_{ab}(z,t)\,\Theta\left[Q_{\mathrm{cut}} - Q_{ab}(z,t)\right] \quad \text{and} \quad \mathcal{K}_{ab}^{\mathrm{ME}}(z,t) = \mathcal{K}_{ab}(z,t)\,\Theta\left[Q_{ab}(z,t) - Q_{\mathrm{cut}}\right]$$

- $Q_{ab}(z,t)$ has to identify logarithmically enhanced phase space regions
- Similar to a jet measure

Evolution factorises

- Sudakov form factor:

$$\Delta_a(\mu^2,t) = \Delta_a^{\mathrm{PS}}(\mu^2,t')\,\Delta_a^{\mathrm{ME}}(\mu^2,t')$$

- No-branching probability:

$$\mathcal{P}^{(F)}_{\mathrm{no},\,a}(t,t') = \mathcal{P}^{(F)\,\mathrm{PS}}_{\mathrm{no},\,a}(t,t')\,\mathcal{P}^{(F)\,\mathrm{ME}}_{\mathrm{no},\,a}(t,t')$$

Simple rules so far for each regime:

- **Independent evolution** according to no-branching probabilities (e.g. by MC-method)
- **Veto** emissions below/above Q_{cut}

Want to use exact matrix elements in ME regime

- Seems trivial: Use exact matrix elements as kernel, instead of approximation
- But: Integration in terms of shower variables unfeasible for high multiplicity
- Alternative Idea: Start from ME generated event, where the integration can be optimised

Some intermediate steps are necessary . . .

- (Generate ME event above Q_{cut} according to σ and $d\sigma$)
- Determine most probable **branching history** leading to ME final state
- Make ME radiation **exclusive**
- **Truncated showering** at each internal line between its production and decay scale
- (Normal showering for external lines down to hadronisation scale with Q_{cut} veto)

$\Downarrow$

Shower runs unimpaired in PS regime.
Correct evolution is recovered in ME regime.

Connecting fixed-order to resummation: Branching histories

Previous Slide:

Need intermediate shower evolution scales for weights and to start the shower

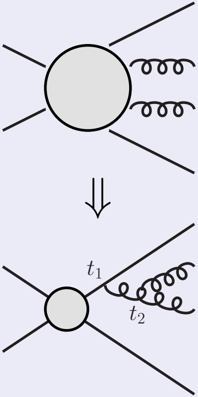
Problem: ME only gives final state, no history
Solution: Backward-clustering (running the shower reversed)

1. Take N-particle final state
2. Identify most probable splitting (lowest shower measure)
3. Recombine partons using inverted shower kinematics
   → N-1 particles + splitting variables for one node
4. Repeat 2 and 3 until core process

⇓

Most probable branching history a la shower.

Now let's use it ...



ME regime

- **Radiation in ME regime fixed, but inclusive (below μ_F)**

  $\Downarrow$

  A posteriori reweighting with no-branching probability

$$\mathcal{P}^{(F)\,\mathrm{ME}}_{\mathrm{no},\,a}(t,t') = \frac{\Delta^{\mathrm{ME}}(\mu^2,t')}{\Delta^{\mathrm{ME}}(\mu^2,t)}$$

  with t' (production scale) and t (decay scale) for each internal line

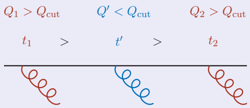
  $\Downarrow$

  Correct exclusive radiation in the ME regime

- α_s reweighting using branching scales

Shower regime

- **Some splittings are pre-determined** by ME
  $\Rightarrow$ "Truncated" shower necessary
  - Q_{cut}-vetoed shower between production and decay scale
  - Then insert pre-determined node
  - Restart evolution from there

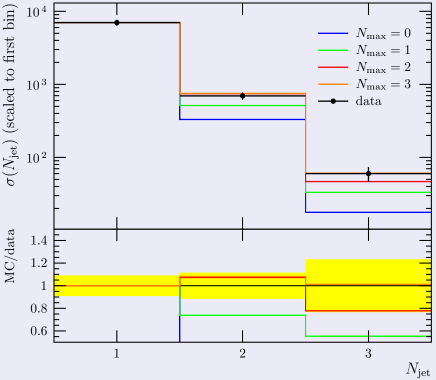


Is it useful? Results for $p\bar{p} \to e^+e^- + \text{jets}$ at $\sqrt{s} = 1960\,\text{GeV}$ PRL 100,102001 arXiv:0711.3717 [hep-ex]

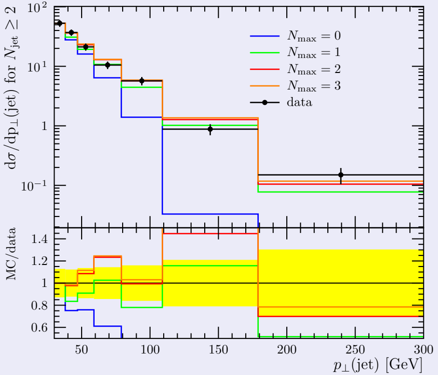
Algorithm implemented in SHERPA framework

CSSHOWER++	Shower based on Catani-Seymour subtraction
COMIX	Matrix elements based on Berends-Giele recursion

Jet multiplicity



$p_\perp$(jet) in $N_{\text{jet}} \geq 2$ events

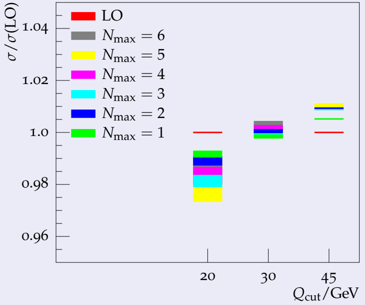


Is it consistent? Results for $p\bar{p} \to e^+e^- + \text{jets}$ at $\sqrt{s} = 1960\,\text{GeV}$

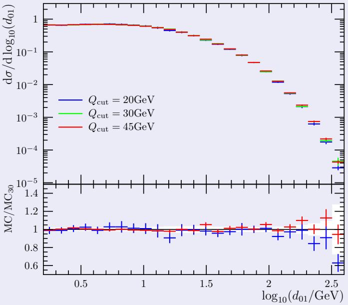
Consistency tests

- Total LO cross section stable?
- Observables independent from “unphysical” merging cut?

Total cross sections



$1 \to 0$ jet resolution ($k_\perp$)



Conclusions

- Method allows to add higher order matrix element corrections to parton showers
- Preserves shower evolution (its logarithmic accuracy)
- Necessary to describe experimental data
- Small systematic deviations, good consistency

Outlook

- Fully implemented in SHERPA, will be released as version 1.2 in the near future
- Testing in more processes, phenomenology
- Start thinking about how to include full NLO matrix elements

Backup: Parton separation criterion

Reminder

$$\mathcal{K}^{\mathrm{PS}}_{ab}(z,t) = \mathcal{K}_{ab}(z,t)\,\Theta\left[Q_{\mathrm{cut}} - Q_{ab}(z,t)\right] \quad \text{and} \quad \mathcal{K}^{\mathrm{ME}}_{ab}(z,t) = \mathcal{K}_{ab}(z,t)\,\Theta\left[Q_{ab}(z,t) - Q_{\mathrm{cut}}\right]$$

- Has to regularise MEs (like a jetfinder)
- Otherwise completely arbitrary until now

$$Q^2_{ij} = 2\,p_i p_j \min_{k\neq i,j} \frac{2}{C^k_{i,j} + C^k_{j,i}}$$

Final state partons $(ij) \to i,\, j$

$$C^k_{i,j} = \begin{cases} \dfrac{p_i p_k}{(p_i+p_k)p_j} - \dfrac{m_i^2}{2\,p_i p_j} & \text{if } j = g \\ 1 & \text{else} \end{cases}$$

Initial state parton $a \to (aj)\,j$

$$C^k_{a,j} = C^k_{(aj),\,j}$$

with $p_{aj} = p_a - p_j$

- The minimum is over all possible colour partners k of parton (ij)
- Identifies regions of soft ($E_g \to 0$) and/or (quasi-)collinear ($\approx k_\perp^2 \to 0$) enhancements
- Similar to jet finder (e.g. Durham in e^+e^- case), but with flavour information