New $p_\perp$-ordered showers
and
Interleaved Multiple Interactions

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Transverse-momentum-ordered showers

1) Define
\[ p_{\perp\text{evol}}^2 = z(1 - z)Q^2 = z(1 - z)M^2 \] for FSR
\[ p_{\perp\text{evol}}^2 = (1 - z)Q^2 = (1 - z)(-M^2) \] for ISR

2) Evolve all partons downwards in \( p_{\perp\text{evol}} \) from common \( p_{\perp\text{max}} \)

\[
dP_a = \frac{dp_{\perp\text{evol}}^2}{p_{\perp\text{evol}}^2} \frac{\alpha_s(p_{\perp\text{evol}}^2)}{2\pi} \frac{\alpha_s(p_{\perp\text{evol}}^2)}{p_{\perp\text{evol}}^2} P_{a\rightarrow bc}(z) \, dz \, \exp \left( -\int p_{\perp\text{max}}^2 \, \ldots \right)
\]

\[
dP_b = \frac{dp_{\perp\text{evol}}^2}{p_{\perp\text{evol}}^2} \frac{\alpha_s(p_{\perp\text{evol}}^2)}{2\pi} x' f_a(x', p_{\perp\text{evol}}^2) \frac{\alpha_s(p_{\perp\text{evol}}^2)}{x f_b(x, p_{\perp\text{evol}}^2)} P_{a\rightarrow bc}(z) \, dz \, \exp ( - \ldots )
\]

Pick the one with largest \( p_{\perp\text{evol}} \) to undergo branching; also gives \( z \).

3) Kinematics: Derive \( Q^2 = \pm M^2 \) by inversion of 1), but then interpret \( z \) as energy fraction (not lightcone) in “dipole” rest frame, so that Lorentz invariant and matched to matrix elements.
Assume yet unbranched partons on-shell and shuffle \((E, p)\) inside dipole.

4) Iterate \( \Rightarrow \) combined sequence \( p_{\perp\text{max}} > p_{\perp 1} > p_{\perp 2} > \ldots > p_{\perp\text{min}} \).
Interleaved Multiple Interactions

$p_{\perp}$

$p_{\perp \text{max}}$

$p_{\perp 1}$

ISR

$p_{\perp 2}$

ISR

$p_{\perp 3}$

ISR

$p_{\perp 4}$

ISR

$p_{\perp \text{min}}$

1 2 3 4

interaction number

$p_{\perp \text{max}}$

$p_{\perp 1}$

ISR

$p_{\perp 2}$

ISR

$p_{\perp 3}$

ISR

$p_{\perp 4}$

ISR

ISR
• **Competition:** (for PDF and phase space)

\[
\frac{d\mathcal{P}}{dp_{\perp}} = \left( \frac{d\mathcal{P}_{\text{MI}}}{dp_{\perp}} + \sum \frac{d\mathcal{P}_{\text{ISR}}}{dp_{\perp}} \right) \exp \left( - \int_{p_{\perp}}^{p_{\perp,i-1}} \left( \frac{d\mathcal{P}_{\text{MI}}}{dp'_{\perp}} + \sum \frac{d\mathcal{P}_{\text{ISR}}}{dp'_{\perp}} \right) dp'_{\perp} \right)
\]

\( \Rightarrow \) one interleaved sequence of MI and ISR

FSR: no competition so not required (but nice for ME merging)

• **Regularization procedure:**

\[
\alpha_s(p_{\perp}^2) \frac{dp_{\perp}^2}{p_{\perp}^2} \rightarrow \alpha_s(p_{\perp,0}^2 + p_{\perp}^2) \frac{dp_{\perp}^2}{p_{\perp,0}^2 + p_{\perp}^2}
\]

common for MI (quadratically) and ISR by colour neutralization

\( p_{\perp,0} \approx 2–3 \text{ GeV energy-dependent (Tune A)} \)

• **Availability:**

in **PYTHIA 6.312** on [www.thep.lu.se/~torbjorn/Pythia.html](http://www.thep.lu.se/~torbjorn/Pythia.html)

**but** **pp/\bar{p}p only** (technical + physics reasons)

• **Data comparisons:**

usually comparable with Tune A (for better or worse), but still in need of good tuning and detailed tests, and ...
\[ \langle p_{\perp} \rangle (n_{\text{ch}}) \] problematical

Tevatron Run II: \[ \langle p_{\perp} \rangle (n_{\text{ch}}) \]

- Tune A
- Rap
- Sharp ISR
- Low FSR
- High FSR

\[ \Rightarrow \text{how are final-state colours correlated?} \]

- **Next steps:**
  - test and tune, especially colour flow
  - intertwine FSR
  - intertwine = \((3 \rightarrow 3) + 2\) interacting partons with same ancestry