Merging Matrix Elements with Interleaved Showers

Stefan Prestel\textsuperscript{a}

(Lund University)

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Fixed order calculations

Calculate transition cross section order by order:

\[
F_1 \left| \begin{array}{c}
\Phi^2_d \\
\Phi_1^2
\end{array} \right| d\Phi_1 + \\
F_2 \left| \begin{array}{c}
\Phi^2_d + F_2 \\
\Phi_2^2 + F_2
\end{array} \right| d\Phi_2 + h.c. + \\
F_1 \left| \begin{array}{c}
\Phi^2_d \\
\Phi_1^2
\end{array} \right|^\dagger d\Phi_1 + h.c. + \ldots
\]

Fixed order calculations of transition probabilities are exact to a given order in the coupling. Validity of Born-level approximation breaks down in collinear regions.
Collinear factorization

In the collinear region, we have

\[ d\sigma_n(p, p_i) \approx \frac{\alpha_s}{2\pi} \int \frac{dk_{\perp}^2}{k_{\perp}^2} \int dzP(z) d\sigma_{n-1} \]

\[ = \frac{\alpha_s}{2\pi} \log \left( \frac{k_{\perp,\text{max}}^2}{k_{\perp,\text{min}}^2} \right) \int dzP(z) d\sigma_{n-1} + \text{non-logarithmic} \]

And for two independent, strongly ordered emissions, we get

\[ \frac{\alpha_s}{2\pi} \int \frac{Q^2}{m^2} \frac{dk_{\perp,1}^2}{k_{\perp,1}^2} \int \frac{|k_{\perp,1}^2|}{m^2} \frac{dk_{\perp,2}^2}{k_{\perp,2}^2} = \frac{1}{2} \left[ \frac{\alpha_s}{2\pi} \log \left( \frac{Q^2}{m^2} \right) \right]^2 \]
But there’s more... 

Can these approximations be compared to data?
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→ Describe an exclusive event in detail:
  • Hard interaction (e.g. by fixed order)
  • Soft + collinear radiation (e.g. by all-order)
  • Multiple interactions between the colliding particles
  • Conversion of partons into hadrons
  • . . .

→ Multi purpose event generators: At heart resummation programs, but there’s a lot more to them.
Combining fixed order MCs and Event Generators

The approaches are complementary. Can we retain the features of both in one setup?

\[ F_2 \]

\[ \begin{align*}
F_2 & \quad d\Phi_2 \\
\bar{d} & \quad W^+ \\
g & \quad \bar{u}
\end{align*} \]

\[ \begin{align*}
F_2 & \quad F_1 \frac{F_1}{F_2} \\
\Delta_u & \quad \Delta_d \\
\bar{d} & \quad W^+ \\
g & \quad P_{gg}/\rho^2 \quad \bar{u}
\end{align*} \]

⇒ Yes: Use different approaches to fill different regions of phasespace
⇒ Use ME+PS merging algorithms to get a more complete description.
CKKW-L ME PS merging

- Get the state $S_{+n}$ (with all partons above a cut $t_{\text{MS}}$) from a matrix element generator
CKKW-L ME PS merging

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- Start shower from last reconstructed scale, then
  - If $n$ is the highest multiplicity, continue;
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- Combine histograms for all ME multiplicities to get distributions for ME+PS merging.
But there’s more...

In **Pythia8**, MI are interleaved with spacelike showers.

If $\rho_{\text{ISR}} > \rho_{\text{MI}}$, **Pythia8** interprets this as
Combining merging and MI

Philosophy: Do exactly as Pythia8 does, except that the hardest jets from the hard interaction should be described by the tree-level ME.
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Hard jets from multiple interactions should be described by the shower.

Hard jets from the ME should not reduce the probability of high-$p_T$ MI.

$\Rightarrow$ Keep no-MI probabilities
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Hard jets from the ME should not reduce the probability of high-$p_\perp$ MI.

⇒ Keep no-MI probabilities

Change the trial shower steps:

- When trial showering off reclustered state, just treat MI identical to radiation.
- When trial showering off the ME state, only veto if QCD radiation from the hard interaction was above $k_{\perp MS}$.

...see arXiv:1109.4829 [hep-ph]
Figure: Left panel: Durham jet resolution $3 \rightarrow 2$, at LEP, for three merging scales. Right panel: The $p_{\perp}$ of a $W$ boson for $E_{CM} = 7000$ GeV in $pp$ collisions, for three merging scales.
pp → W + jets

Figure: Jet multiplicity and $p_\perp$ of the second jet for $E_{CM} = 7000$ GeV, $t_{MS} = 30$ GeV in $pp \to W$ events.
pp $\rightarrow W + \text{jets MI treatment}$

Does the MI treatment make a large difference?
pp→ W + jets MI treatment

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not really
**pp → W + jets MI treatment**

Does the MI treatment make a large difference?

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**Figure:** $\Delta R_{12}$ between hardest/second hardest jet (in $p_\perp$, $p_\perp jet > 11$ GeV) for $E_{CM} = 7000$ GeV, $t_{MS} = 10$ GeV in $pp \rightarrow Z$ events.
...moving on: Di-bosons and di-jets

Figure: Left panel: Di-jet invariant mass in di-boson events

\( p\bar{p} \rightarrow W^+Z \rightarrow e^+\nu_ejj \) for \( E_{CM} = 1960 \text{ GeV}, \ t_{MS} = 30 \text{ GeV} \). Right panel: Differential jet shape in pure QCD events, for \( E_{CM} = 1960 \text{ GeV}, \ t_{MS} = 30 \text{ GeV} \).
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• The implementation has been checked extensively. A closer look at Di-boson/Di-jet predictions could be fun.
Conclusions

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• Both can be consistently be combined in CKKW(-L) merging
• The implementation of CKKW-L merging in \texttt{PYTHIA8} makes the inclusion of multiple interactions conceptually straight-forward.
• The implementation has been checked extensively. A closer look at Di-boson/Di-jet predictions could be fun.
• A inbuild CKKW-L merging will be shipped with the next public \texttt{PYTHIA8} version. Before that: Ask me!
Thank you.