Matching and merging Matrix Elements with Parton Showers I

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Outline of Lectures

- Lecture I: Introduction, Tree-level ME, NLO, PS, ordering, basic strategies, ...
- Lecture II: Tree-level ME merging with PS, CKKW(-L), Pseudo Shower, MLM, e^+e^- comparison, ...
- Lecture III: ME+PS merging in *pp*, NLO matching with PS, MC@NLO, POWHEG, NL^3, ...

Outline

The Problem

- We want to study processes with several hard jets.
- These are important backgrounds to new physics.
- We can calculate processes with several hard partons.
- But a parton is not a jet.

- We want to study processes with one or two extra jets.
- These are important to obtain high precision cross sections.
- We can calculate processes with one or two hard partons to NLO.
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- We want to study processes with one or two extra jets.
- These are important to obtain high precision cross sections.
- We can calculate processes with one or two hard partons to NLO.
- But a parton is not a jet.
- A jet is not a jet is not a jet.

- Parton vs. partonic jets vs. hadronic jets vs. detector jet.
- A single parton will always radiate due to soft and collinear poles.
- In addition at LHC the phase space for parton radiation is very large - Partons will radiate because they can.
- Partons will give rise to hadrons.
- [The detector we will hopefully understand. . .]

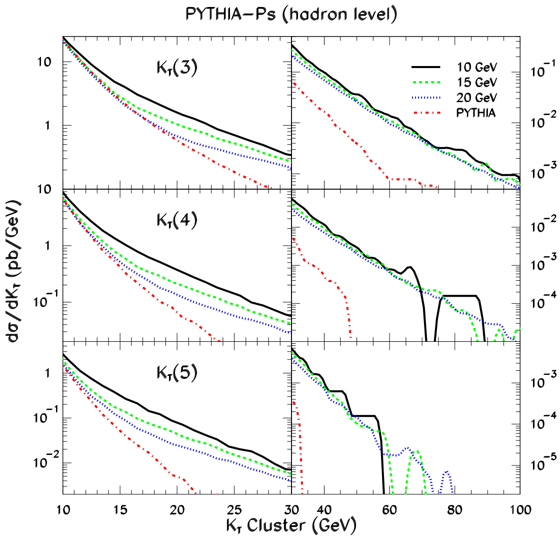
- QCD has been around since the 70's, but it is still not completely understood.
- Precision is still lacking. Typically above 1-10%
- Perturbation theory is difficult when phase space increases – large logarithms, $\sim \log Q^2$ and/or $\sim \log x$, accompany every order in α_s.
- Non-perturbative region can only be handled by models.
- When studying backgrounds to rare processes, we need to understand very rare QCD processes.

- We need to understand how partons turn into jets: parton→parton cascade→hadrons.
- We need to understand the fluctuations in this process.
- We need to have hadronization models - these rely on the proper modeling of soft and collinear partons.
- We therefore need parton showers.

But we cannot rely on parton showers alone.

- Parton showers are only approximate
  sometimes we need NLO to get good precision
- Parton showers describe rare (hard) fluctuations badly
  sometimes we need proper ME calculations of several hard partons.

In the best of all worlds we should just be able to combine them.


PYTHIA−Ps (hadron level)
$K_T(3)$
$K_T(4)$
$K_T(5)$
10 GeV
15 GeV
20 GeV
PYTHIA
$d\sigma/dK_T$ (pb/GeV)
K_T Cluster (GeV)

W+3,4,5 jets

The Tree-level ME strategy

This is basically straight forward, but can be cumbersome

- Select a jet multiplicity
- Draw all possible Feynman diagrams
- Calculate the corresponding amplitudes
- Sum and square
- Generate phase space points and weight with the cross section
- (un-weight if you need properly sampled events)

This can be automated (MADGRAPH, COMPHEP, ...) but:

- Difficult to get more than ~6 final state particles
- There are soft and collinear poles so we need a cut μ
- It can become extremely difficult to sample the phase space

$$
\begin{aligned}
d\sigma_0 &= C_0^{\mathrm{ME}}(\boldsymbol{p}_{1..m};\mu)d\Phi_m \\
d\sigma_{+1}(\mu) &= \alpha_s C_1^{\mathrm{ME}}(\boldsymbol{p}_{1..m},\boldsymbol{q}_1;\mu)d\Phi_{m+1} \\
d\sigma_{+2}(\mu) &= \alpha_s^2 C_2^{\mathrm{ME}}(\boldsymbol{p}_{1..m},\boldsymbol{q}_1,\boldsymbol{q}_2;\mu)d\Phi_{m+2} \\
&\vdots
\end{aligned}
$$

- Matrix elements are **inclusive**:
  σ_{+1} is the cross section for *at least* one extra partons which includes σ_{+2}.
- We cannot simply add ME's with different jet multiplicities.

The NLO strategy

$$
\begin{aligned}
d\sigma_{+n}(\mu) &= \Big[\alpha_s^n C_n^{\mathrm{ME}}(\boldsymbol{p}_{1..m},\boldsymbol{q}_{1..n};\mu) + \alpha_s^{n+1} C_n^{\mathrm{loop}}(\boldsymbol{p}_{1..m},\boldsymbol{q}_{1..n};\mu) \\
&\quad + \alpha_s^{n+1}\int^{\mu} d^3q' C_{n+1}^{\mathrm{ME}}(\boldsymbol{p}_{1..m},\boldsymbol{q}_{1..n};\mu,\boldsymbol{q'})\Big] d\Phi_{m+n} \\
d\sigma_{+n+1}(\mu) &= \alpha_s^{n+1} C_{n+1}^{\mathrm{ME}}(\boldsymbol{p}_{1..m},\boldsymbol{q}_{1..n},\boldsymbol{q'};\mu) d\Phi_{m+n+1}
\end{aligned}
$$

- $\int^{\mu} C_{n+1}^{\mathrm{ME}} d^3q'$ is the integral below the jet cutoff μ and it is divergent.
- But the divergency is canceled by the infinity in C_n^{loop} and the sum is finite (although not always positive).

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$$d\sigma_{+n+1}(\mu) = \alpha_s^{n+1} C_{n+1}^{\mathrm{ME}}(\boldsymbol{p}_{1..m}, \boldsymbol{q}_{1..n}, \boldsymbol{q}'; \mu) d\Phi_{m+n+1}$$

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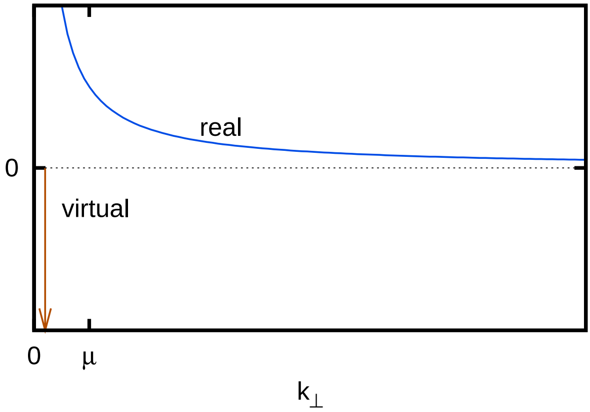
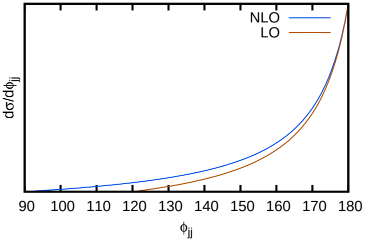
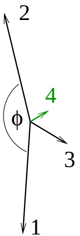

real
0
virtual
0
µ
$k_\perp$

- We can use this to generate both events with n and $n + 1$ parton events and the result is correct to α_s^{n+1}
- If μ is small the n cross section will become very negative, however, for a soft and collinearly safe observable the sum will be positive and finite.
- Note that the result will only be NLO if the leading (first non-zero) order result for the observable is α_s^n.
- A “NLO” generator will not always give NLO results. It depends on the observable.

Di-jet decorrelation





Measure the azimuthal angle between the two hardest jets. Clearly the 2-jet matrix element will only give back-to back jets, so the three-jet matrix element will give the leading order. And an NLO 3-jet generator (α_s^4) will give us NLO.

But for $\phi_{jj} < 120^\circ$, the two hardest jets needs at least *two* softer jets to balance. So the NLO becomes LO here.

The Parton Shower strategy

Rather than calculating a few terms in the α_s expansion exactly, we can try to approximate all terms.

$$
\begin{aligned}
d\sigma_0(\mu) &= \left[C_0^{\mathrm{ME}}(\boldsymbol{p}_{1..m};\mu) + \alpha_s C_{0,1}^{\mathrm{PS}}(\boldsymbol{p}_{1..m};\mu) + \alpha_s^2 C_{0,2}^{\mathrm{PS}}(\boldsymbol{p}_{1..m};\mu) + \ldots\right] d\Phi_m \\
d\sigma_{+1}(\mu) &= \left[\alpha_s C_1^{\mathrm{PS}}(\boldsymbol{p}_{1..m},\boldsymbol{q}_1;\mu) + \alpha_s^2 C_{1,1}^{\mathrm{PS}}(\boldsymbol{p}_{1..m},\boldsymbol{q}_1;\mu) + \ldots\right] d\Phi_{m+1} \\
d\sigma_{+2}(\mu) &= \left[\alpha_s^2 C_2^{\mathrm{PS}}(\boldsymbol{p}_{1..m},\boldsymbol{q}_1,\boldsymbol{q}_2;\mu) + \alpha_s^3 C_{2,1}^{\mathrm{PS}}(\boldsymbol{p}_{1..m},\boldsymbol{q}_1,\boldsymbol{q}_2;\mu) + \ldots\right] d\Phi_{m+2} \\
&\vdots
\end{aligned}
$$

The tree-level terms

$$C_n^{\mathrm{PS}} = C_0^{\mathrm{ME}} \times \text{[splitting functions]} \approx C_n^{\mathrm{ME}}$$

are good approximations in the soft and collinear limits when the successive splittings are strongly ordered.

The loop terms $C_{n,l}^{\mathrm{PS}}$ are also good approximations in this limit and exponentiate

$$d\sigma_0 = C_0^{\mathrm{ME}}(\boldsymbol{p}_{1..m};\mu) \times \exp\left(-\int_\mu \alpha_s \frac{C_1^{\mathrm{PS}}(\boldsymbol{p}_{1..m},\boldsymbol{q}_1;\mu)}{C_0^{\mathrm{ME}}(\boldsymbol{p}_{1..m};\mu)} d^3q_1\right) d\Phi_m$$

This is the Sudakov form factor which can be interpreted as a no-emission probability in the phase space integrated over.

$$
\begin{aligned}
d\sigma_0 &= C_0^{\mathrm{ME}}(\boldsymbol{p}_{1..m};\mu) \times \Delta_{S0}(\rho_0,\rho_c;\mu) d\Phi_m \\
d\sigma_{+1}(\mu) &= \alpha_{\mathrm{s}} C_1^{\mathrm{PS}}(\boldsymbol{p}_{1..m},\rho_1,\boldsymbol{x}_1;\mu) \times \\
&\quad \Delta_{S0}(\rho_0,\rho_1;\mu)\Delta_{S1}(\boldsymbol{p}_{1..m},\rho_1,\rho_c;\mu) d\Phi_{m+1} \\
d\sigma_{+2}(\mu) &= \alpha_{\mathrm{s}}^2 C_2^{\mathrm{PS}}(\boldsymbol{p}_{1..m},\rho_1,\boldsymbol{x}_1,\rho_2,\boldsymbol{x}_2;\mu) \times \\
&\quad \Delta_{S0}(\rho_0,\rho_1;\mu)\Delta_{S1}(\rho_1,\rho_2;\mu)\Delta_{S2}(\rho_2,\rho_c;\mu) d\Phi_{m+2} \\
&\vdots
\end{aligned}
$$

The shower is ordered in ρ ($= p_\perp$, virtuality, angle) so that
$\rho_{\max} = \rho_0 > \rho_1 > \rho_2 > \ldots > \rho_c$
$\boldsymbol{x}_i$ are auxiliary variables needed to specify a splitting (energy fraction, azimuth, rapidity, …)

- The parton shower does not change the leading order cross section $\sum_{n=0}^{\infty} \sigma_{+n}^{\mathrm{PS}}(\mu) = \sigma_{0}^{\mathrm{ME}}(\mu)$.
- The parton shower uses a coupling which is running with the $p_{\perp}$ of each emission: $\alpha_{\mathrm{s}}^{2} \rightarrow \alpha_{\mathrm{s}}(p_{\perp 1})\alpha_{\mathrm{s}}(p_{\perp 2})$
- The choice of ordering variable will turn out to be important.

Ordering Variables

How do we choose the evolution variable, ρ?

The most natural choice is to choose a variable which isolates both the soft and collinear poles in the splitting kernel. This is the case for $\rho = p_\perp^2$ as used in eg. ARIADNE.

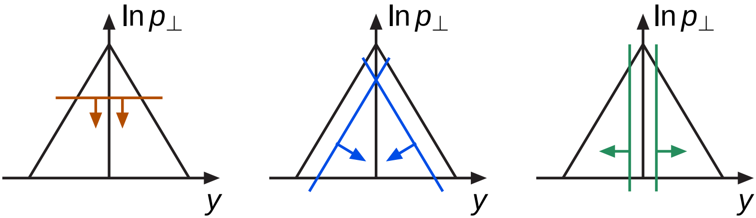
In old versions of PYTHIA and SHERPA the evolution variable is the virtuality Q^2 which in principle is fine except that $\alpha_s(p_\perp^2)$ may diverge for any given Q^2. Also angular ordering needs to be imposed in separately.

In HERWIG the ordering is in angle, which ensures angular ordering, but does not isolate the soft pole, and an additional cutoff is needed.

Transverse momentum $\rho = p_\perp^2$

Virtuality $\rho = Q^2 \sim \frac{p_\perp^2}{z(1-z)}$

Angle $\rho \sim E^2\theta^2 \sim \frac{p_\perp^2}{z^2(1-z)^2}$



Pros and Cons

	ME	NLO	PS
cutoff-independence	$-$	$+$	$+$
observable-independent	$+$	$-$	$+$
several multiplicities	$-$	$(+)$	$+$
exact (to given α_s order)	$+$	$+$	$-$
correct cross section	$(+)$	$+$	$-$
unit or positive weight events	$+$	$-$	$+$

Pros and Cons

	ME	NLO	PS	?
cutoff-independence	−	+	+	+
observable-independent	+	−	+	+
several multiplicities	−	(+)	+	+
exact (to given α_s order)	+	+	−	+
correct cross section	(+)	+	−	+
unit or positive weight events	+	−	+	+

How to combine ME and/or NLO with PS?

- Start with ME/NLO and add PS
- Use PS and modify emissions according to ME and/or NLO (reweighting)
- Use standard ME/NLO generator and add modified PS.
- Use modified ME/NLO generator and add plain PS. (matching)
- Use modified ME/NLO generator and add modified PS.
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$$\vdots$$

- Start with PS
- Modify with tree-level ME
- Modify with NLO

$$d\sigma_0 = \left[C_0^{\mathrm{ME}}(\boldsymbol{p}_{1..m};\mu) + \alpha_s C_{0,1}^{\mathrm{PS}}(\boldsymbol{p}_{1..m};\mu) + \alpha_s^2 C_{0,2}^{\mathrm{PS}}(\boldsymbol{p}_{1..m};\mu) + \dots\right] d\Phi_m$$

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$$

- Start with PS
- Modify with tree-level ME
- Modify with NLO

Reweighting of first emission in PS

In many cases the first (or hardest) splitting function can be corrected to reproduce the first order tree-level ME.

$$P^{\mathrm{PS}}(\rho, \boldsymbol{x}) \rightarrow P^{\mathrm{ME}}(\boldsymbol{p}_{1..m}, \rho, \boldsymbol{x}) = \frac{C_1^{\mathrm{ME}}(\boldsymbol{p}_{1..m}, \rho, \boldsymbol{x})}{C_0^{\mathrm{ME}}(\boldsymbol{p}_{1..m})}$$

Doing this for higher orders is much more difficult.

This is done in PYTHIA for many processes.
(also for some subsequent emissions ignoring previous emissions)

This is fairly easy to do in the Veto-algorithm:

- Generate an emission, $(\rho, \boldsymbol{x})$, using $c \cdot P^{\mathrm{PS}}(\rho, \boldsymbol{x})$ which is larger than $P^{\mathrm{ME}}(\boldsymbol{p}_{1..m}, \rho, \boldsymbol{x})$ everywhere.
- Keep the emission with probability $P^{\mathrm{ME}}/c \cdot P^{\mathrm{PS}}$, and continue cascade with standard splitting functions.
- If vetoed, generate new emission with ρ as maximum.

- The corrected splitting function is properly exponentiated
- We get part of the NLO term correct as well
- But the loop term is not correct and, as for the general PS, the cross section is only correct to LO

We can introduce a K-factor

$$C_0^{\mathrm{ME}}(\boldsymbol{p}_{1..m}) \to \frac{\sigma^{\mathrm{NLO}}}{\sigma_0} C_0^{\mathrm{ME}}(\boldsymbol{p}_{1..m})$$

But the NLO shape $(\boldsymbol{p}_{1..m})$ will not be correct.
(although it often looks quite good)

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Matching

Based on the NLO subtraction method.

$$
\begin{aligned}
d\sigma_0 &= \left[C_0^{\mathrm{ME}}(\boldsymbol{p}_{1..m}) + \alpha_s C_0^{\mathrm{loop}}(\boldsymbol{p}_{1..m}) \right. \\
&\qquad \left. + \alpha_s \int d^3q' C_1^{\mathrm{PS}}(\boldsymbol{p}_{1..m}, \boldsymbol{q'})\right] d\Phi_m \\
d\sigma_{+1} &= \alpha_s \left[C_1^{\mathrm{ME}}(\boldsymbol{p}_{1..m}, \boldsymbol{q'}) - C_1^{\mathrm{PS}}(\boldsymbol{p}_{1..m}, \boldsymbol{q'})\right] d\Phi_{m+1}
\end{aligned}
$$

- Use the first parton shower splitting as subtraction term.
- Add PS to the σ_0 term (undoing the integral)
- Add PS to the σ_1 term

- Correct cross section
- If C_0^{ME} does not need cutoff, it is not needed at all.
- We have to worry about ordering of the PS
- Event weights may be negative

Merging

$$\begin{aligned} d\sigma_0 &= C_0^{\mathrm{ME}}(\boldsymbol{p}_{1..m};\mu)d\Phi_m \\ d\sigma_{+1}(\mu) &= \alpha_s C_1^{\mathrm{ME}}(\boldsymbol{p}_{1..m},\rho_1,\boldsymbol{x}_1;\mu)d\Phi_{m+1} \\ d\sigma_{+2}(\mu) &= \alpha_s^2 C_2^{\mathrm{ME}}(\boldsymbol{p}_{1..m},\rho_1,\boldsymbol{x}_1,\rho_2,\boldsymbol{x}_2;\mu)d\Phi_{m+2} \\ &\vdots \end{aligned}$$

- Start out with ME generated *n*-jet states.
- Reweight with Sudakov form factors to get exclusive states.
- (also reweight with running α_s)
- Add PS below cutoff, μ.

Merging

$$
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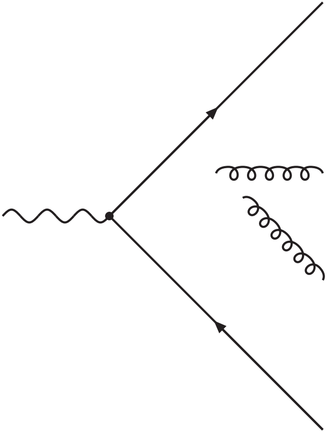
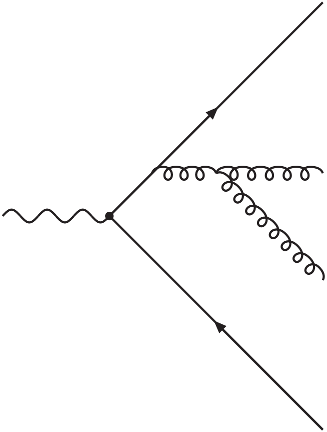


We don't know where the partons come from.

We do “know” their colour connections.

$$P_{C_i} = \frac{|A_{C_i}|^2}{\sum_j |A_{C_j}|^2}$$



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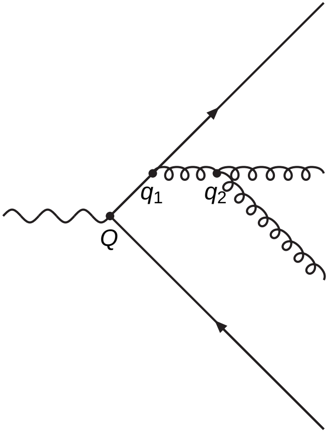

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- We can go as high in jet multiplicity as the ME generator allows.
- We always need a cutoff μ.
- How do we construct the emission scales, ρ.
- Do these scales need be the same as in the PS? (we have to worry about ordering)
- Avoid double-counting.
- Avoid under counting.

The general procedure

(We will here assume $\mathrm{e^+e^-}$ and introduce *pp* collisions later)

Assuming you have a ME generator producing LO order events and up to N extra partons using some jet cutoff μ.

1. Choose a parton multiplicity $n \leq N$ according to the integrated cross sections and generate a corresponding state.
2. Construct a series of emission scales $q_1, \ldots, q_n$.
3. Reweight event with running coupling $\prod_i^n \frac{\alpha_{\mathrm{s}}(q_i)}{\alpha_{\mathrm{s}}^{\mathrm{ME}}}$.
4. Model the Sudakov form factors and reweight.
5. Add a parton shower, but veto any emission with a jet-scale above μ, except if $n = N$: veto above q_N.

Several procedures have been proposed, and they differ in

- Different jet-algorithms defining the cutoff.
- Different ways of constructing the emission scales.
- Different modeling of the Sudakov form factors
- Different ways of adding the Shower (starting scales).
- Different veto strategies in the Shower.

In all cases the reweighting can be fixed so that all weights are less than unity, and can be replaced by a veto to give unit-weight events.

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