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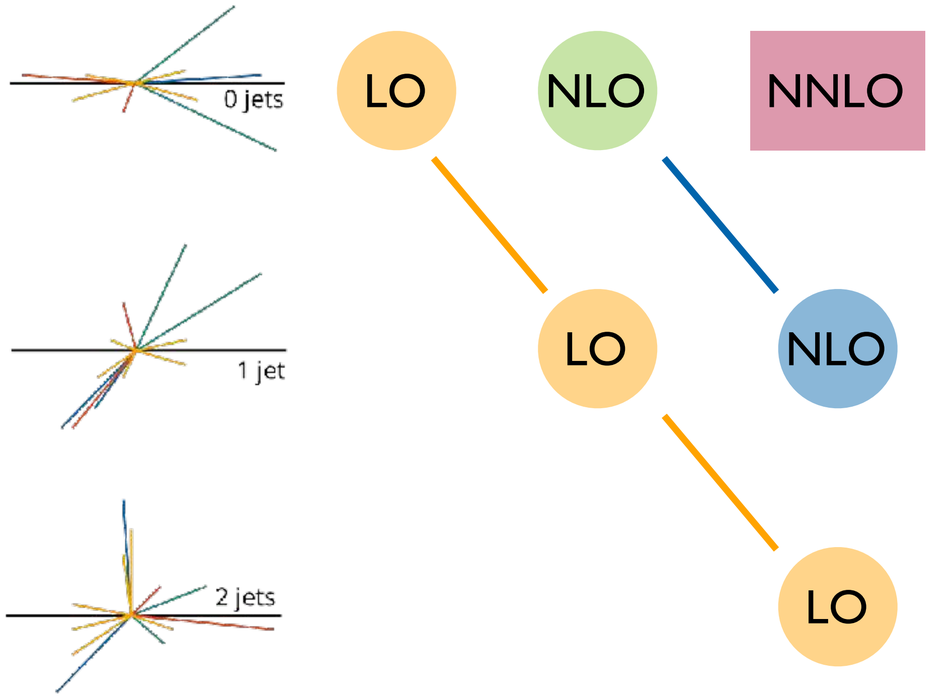
# Matching & Merging




Simon Plätzer
Particle Physics — University of Graz / University of Vienna

At the
CTEQ/MCnet School 2021
Dresden/Online | 8 September 2021

LO merging
NLO matching
NLO merging

# Outline/Goals

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**Part I**

Fixed Order Basics
NLO Matching

**Part II**

(N)LO Multijet Merging
Combination with NNLO
~~Outlook on shower development~~

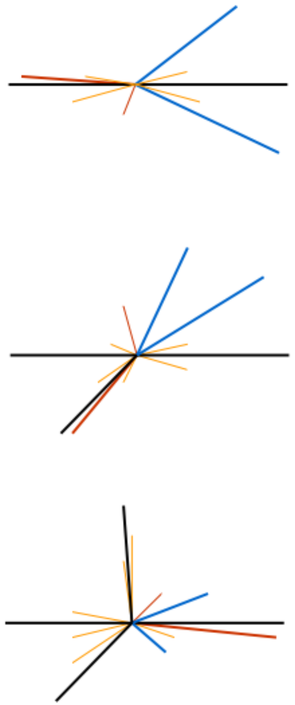
# LO Merging

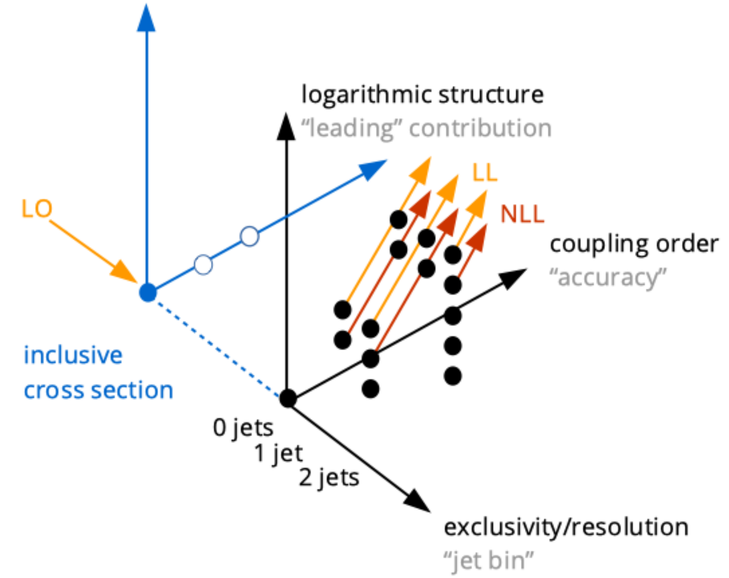


Generalize matrix element corrections to higher multiplicities.

As for matrix element corrections, we cannot guarantee anything about the inclusive cross section.

Using pure matrix elements for the first hand full of hard emissions is generally problematic: efficiency, resonances, …






$$d\sigma_{m+1}(\phi_{m+1}) \simeq d\sigma_m(\Phi_m(\phi_{m+1})) \times V(q,z,\phi_m) \left|\frac{\partial \Phi_{m+1}(q,z,\phi_m)}{\partial(q,z,\phi_m)}\right| dq\, dz \qquad V \sim \frac{|M_{m+1}|^2}{|M_m|^2}$$

# Starting Point: Multiple Shower Emissions

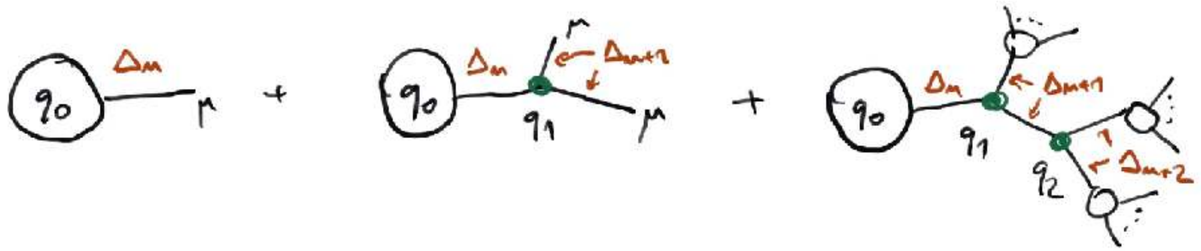


Distinguish between shower domain and matrix element domain for each parton multiplicity.

If phase space reachable by shower in matrix element domain, replace by exact cross section.

Otherwise keep shower.

$$
\begin{aligned}
&d\sigma(\Phi_n)\, PS_{q_0}[u(\Phi_n)] \\
&= d\sigma(\Phi_n)\, \Delta_n(\mu|q_0) + d\sigma(\Phi_n) P(\Phi_{n+1}|q_1) \frac{d\Phi_{n+1}}{d\Phi_n} \Delta_n(q_1|q_0)\, PS[u(\Phi_{n+1})] \\
&= d\sigma(\Phi_n)\, \Delta_n(\mu|q_0) \\
&+ d\sigma(\Phi_n) P(\Phi_{n+1}|q_1) \frac{d\Phi_{n+1}}{d\Phi_n} \Delta_{n+1}(\mu|q_1)\, \Delta_n(q_1|q_0) \\
&+ d\sigma(\Phi_n) P(\Phi_{n+1}|q_2) P(\Phi_n|q_1) \frac{d\Phi_{n+2}}{d\Phi_n} \Delta_{n+1}(q_2|q_1)\, \Delta_n(q_1|q_0)\, PS[u(\Phi_{n+2})]
\end{aligned}
$$




$$d\sigma(\Phi_n) P(\Phi_{n+1}|q_1) \frac{d\Phi_{n+1}}{d\Phi_n} \longrightarrow d\sigma_{n+1}$$

**if $q_1 > \rho$**

$$d\sigma(\Phi_n) P(\Phi_{n+1}|q_2) P(\Phi_n|q_1) \frac{d\Phi_{n+2}}{d\Phi_n} \longrightarrow d\sigma_{n+2}$$

**if $q_2 > \rho$**

# Clustering & Reweighting

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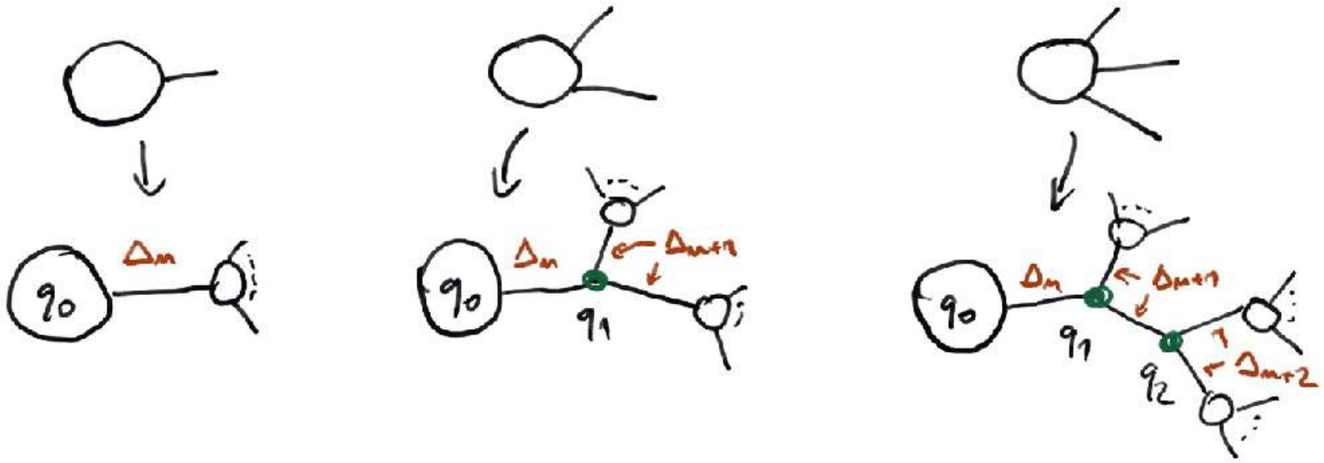
Reinterpret hard matrix elements in shower histories.

- Among the available histories select one with a particular weight.
- Reweight to account for the running coupling, and PDF in backward evolution.



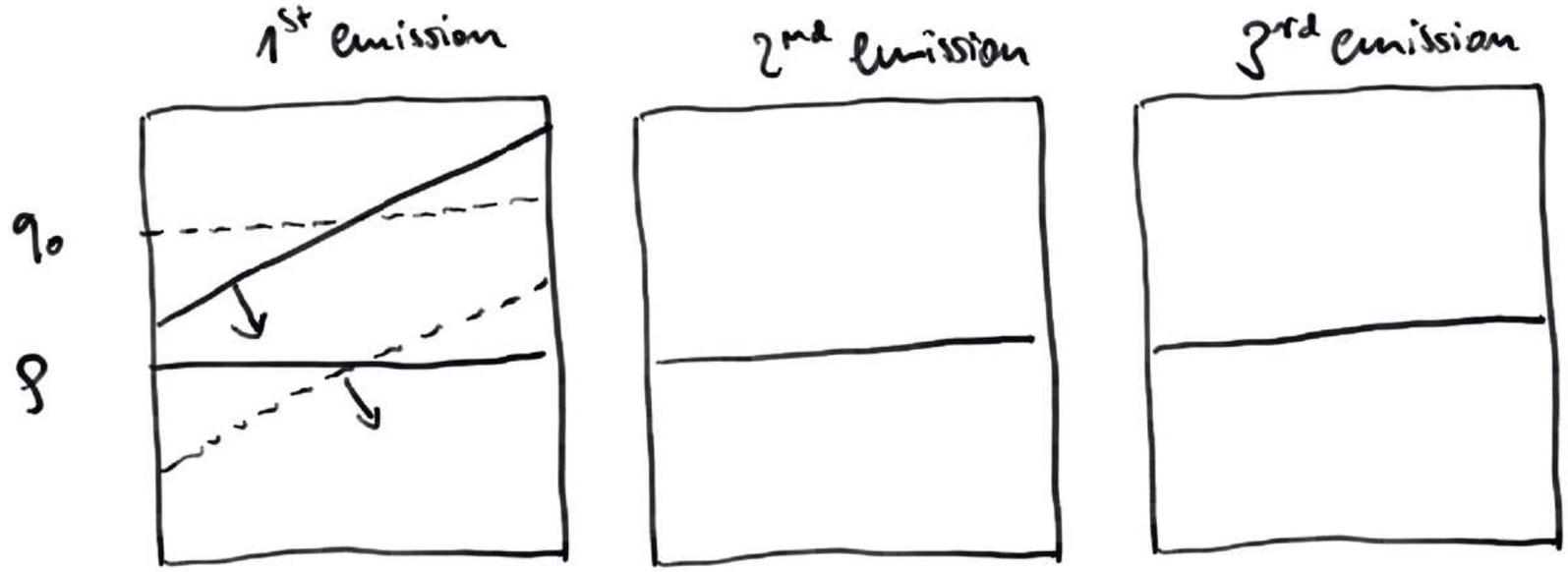

The final step is to reweight by the Sudakov factors for each clustered line, and each hard parton down to the scale which separates matrix element from shower domain.

The first algorithms achieved this by numerical weights, newer versions do this by vetoed showers which automatically exponentiate the wanted contributions.

[Catani, Krauss, Kuhn, Webber] [Lönnblad]

# Ordering & Phase Space

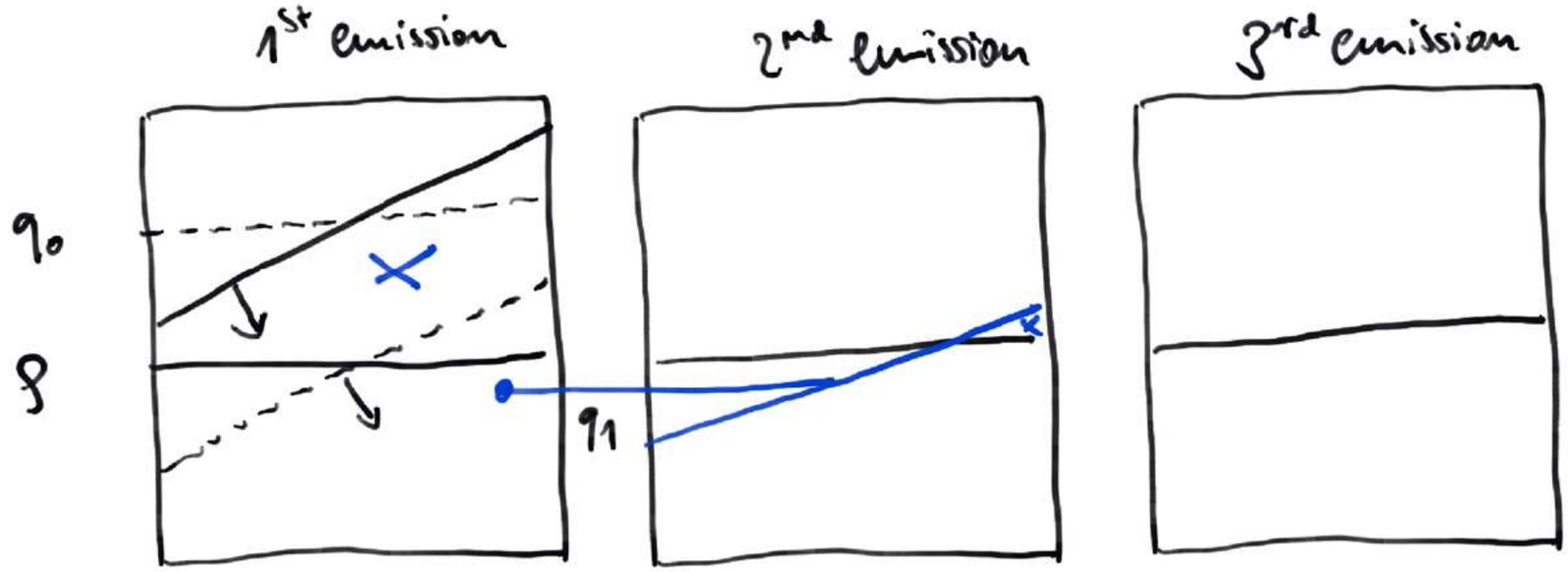





Mind differences in phase space boundaries.
Diagonal: Shower evolution boundary — horizontal: Matrix element boundary.
Not all phase space might be available to shower: add extra hard process.

# Ordering & Phase Space

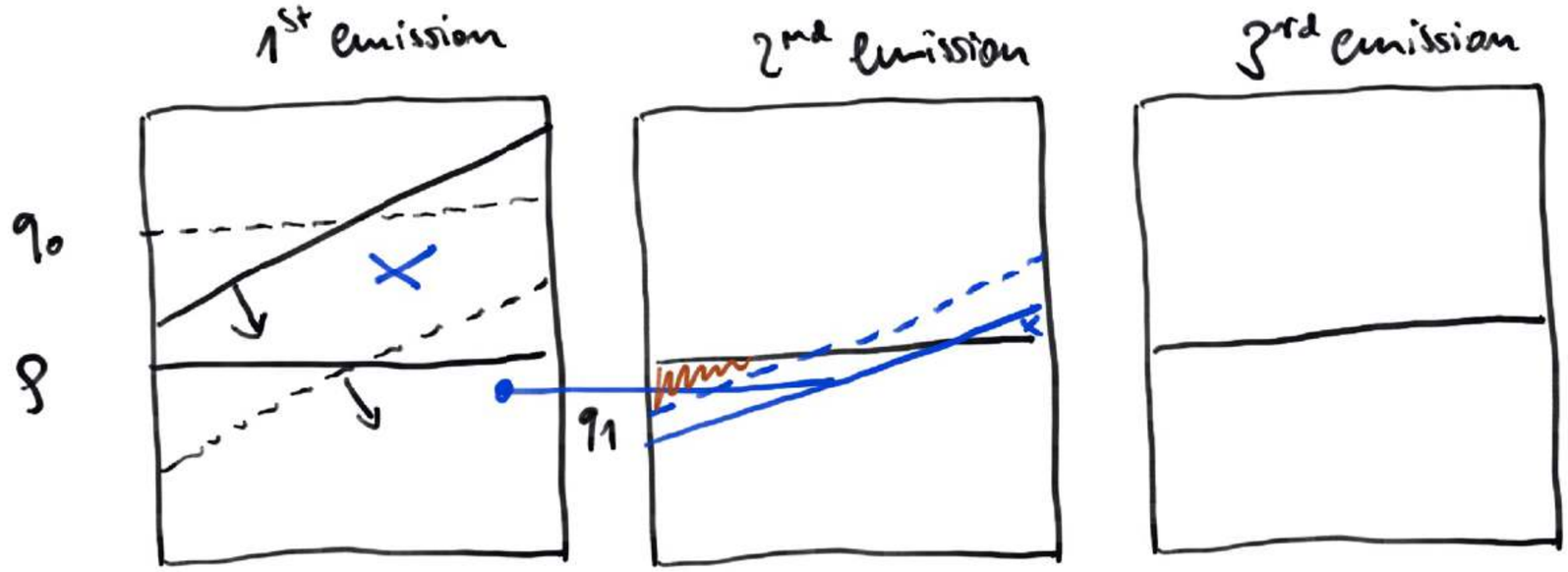





Veto shower in matrix element region.
Naively starting at merging scale might leave out phase space.

# Ordering & Phase Space

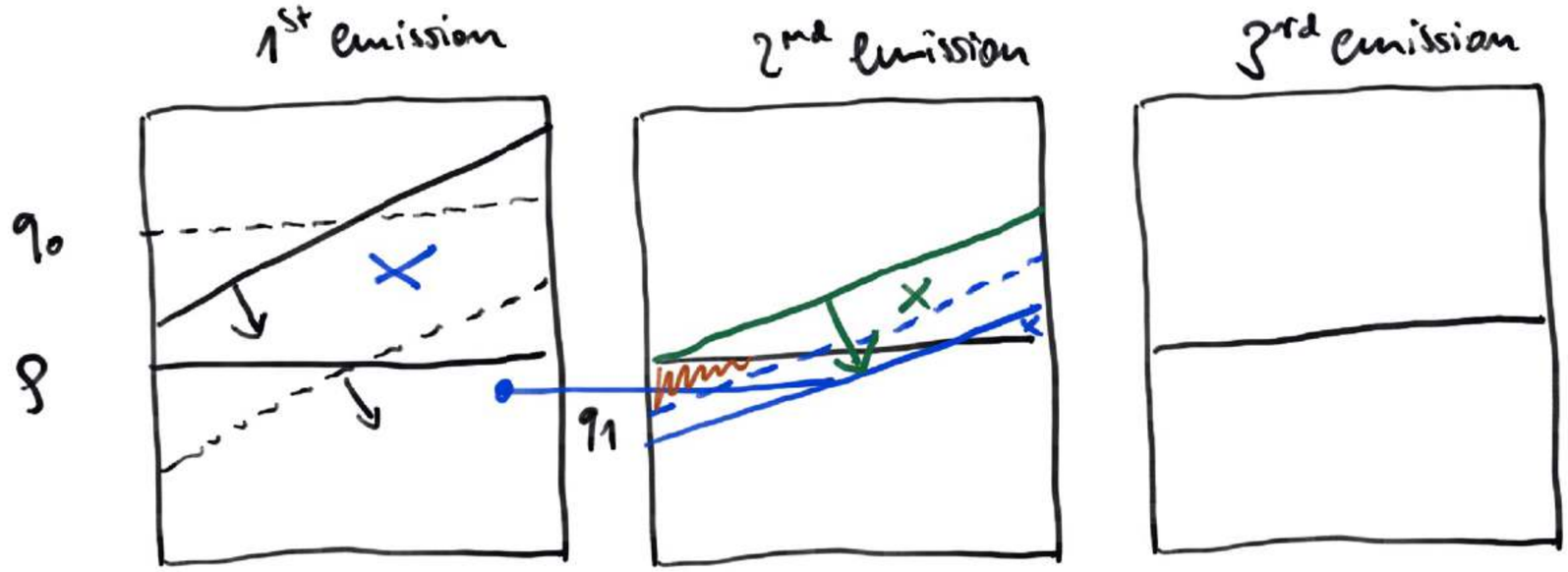





Veto for secondary emissions.
Incompatibility of resolutions might leave further holes in phase space.

# Ordering & Phase Space

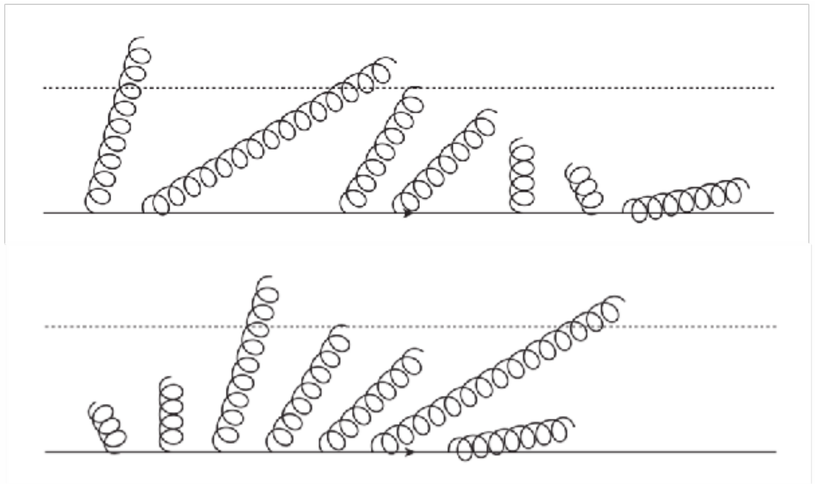




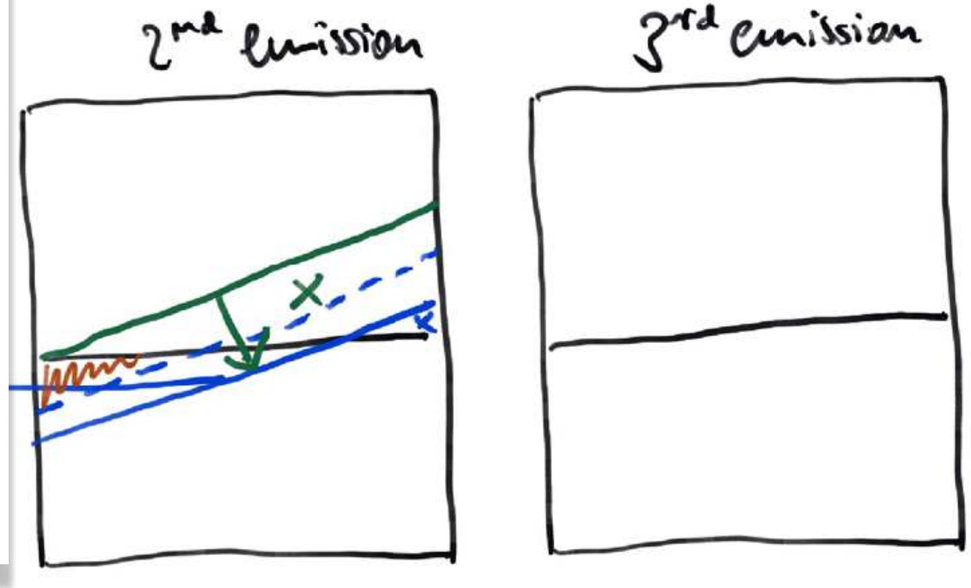

Add a truncated vetoed shower to account for mismatch.

# Ordering & Phase Space





in the context of merging:
[Richardson, Hamilton, Tully]
[Höche, Krauss, Schumann, Siegert]

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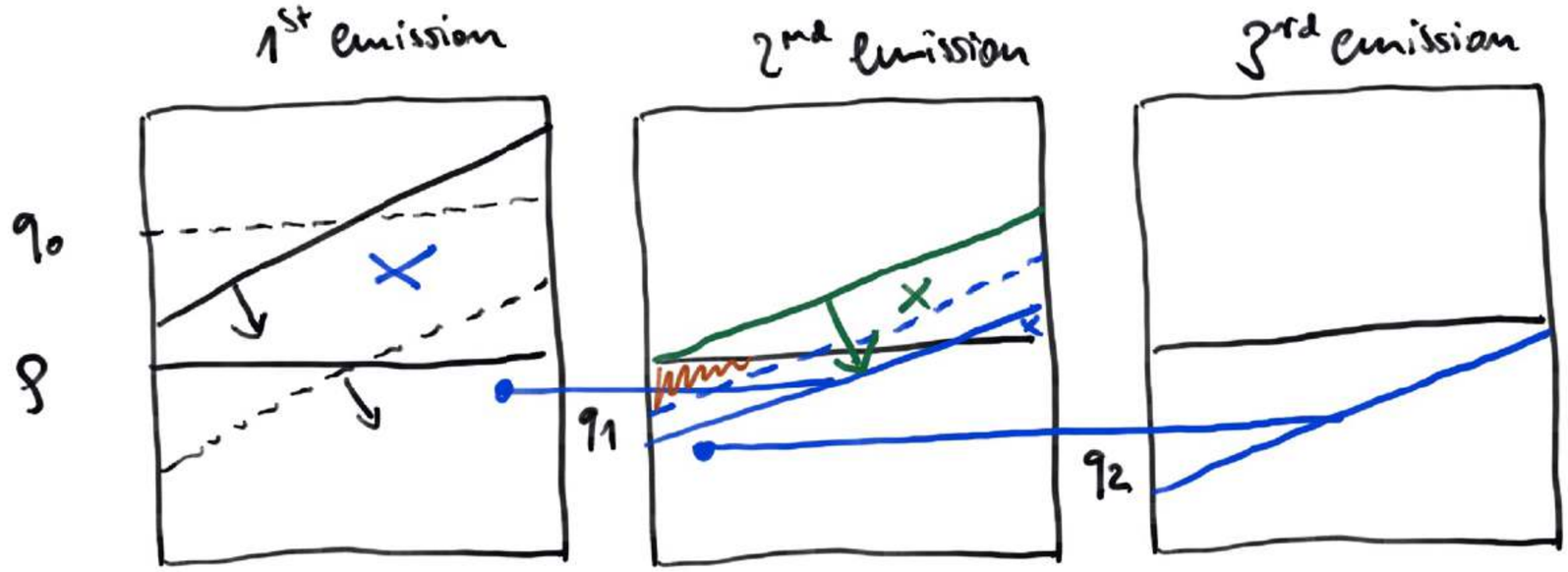
# Ordering & Phase Space






Continue normal showering if no further complications can happen.

# Inclusive & Exclusive Cross Sections

Cross sections generated by the shower:

$$= n \text{ jets}: \quad d\sigma(\Phi_0)\frac{d\Phi_n}{d\Phi_0}P(\Phi_0,q_0)\cdots P(\Phi_n,q_n)\,\Delta_n(q|q_n|\cdots|q_0)$$

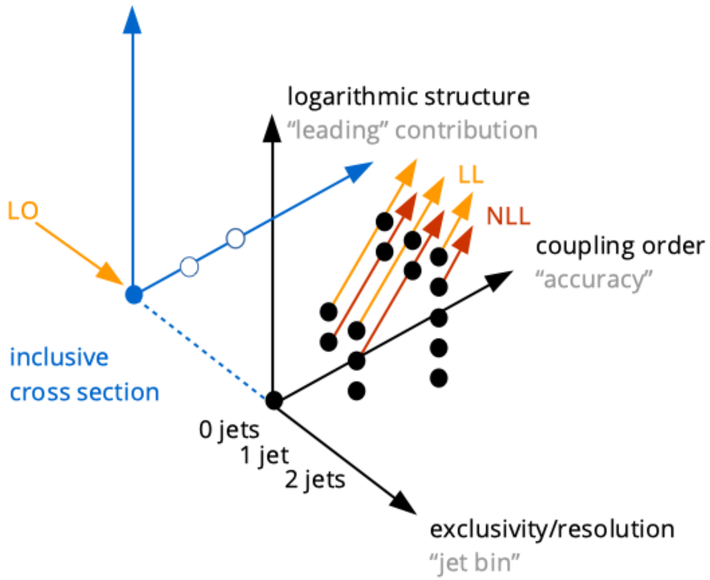
$$\geq n \text{ jets}: \quad d\sigma(\Phi_0)\frac{d\Phi_n}{d\Phi_0}P(\Phi_0,q_0)\cdots P(\Phi_n,q_n)\,\Delta_{n+1}(q_{n+1}|\cdots|q_0)$$

Cross sections after merging:

$$= n: \quad d\sigma_n(\Phi_n)\,\Delta_n(q|q_n|\cdots|q_0)$$

$$\geq n: \quad d\sigma_n(\Phi_n)\,\Delta_{n+1}(q_{n+1}|\cdots|q_0) + \int_q^{q_n} dq_{n+1}\left(\frac{d\sigma(\Phi_{n+1})}{dq_{n+1}} - \frac{d\Phi_{n+1}}{d\Phi_n dq_{n+1}}P(\Phi_n,q_{n+1})\,d\sigma(\Phi_n)\right)\times\Delta_n(q_{n+1}|\cdots|q_0)$$

At tree level this is not logarithmically enhanced.



# NLO Merging

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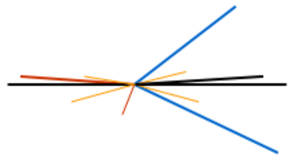
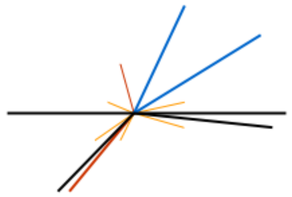
NLO matching condition:

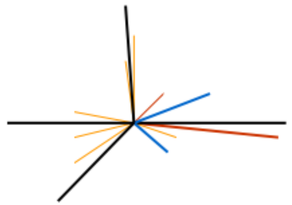
$$PS[d\sigma_{NLO}^{matched}] = d\sigma_{NLO} + \mathcal{O}(\alpha_s^{n+2})$$

$$\int PS[d\sigma_{NLO}^{matched}] = \sigma_{NLO}$$

$$d\sigma_{NLO}^{matched} = d\sigma_{NLO} - PS[d\sigma_{LO}]|_{\mathcal{O}(\alpha_s)}$$

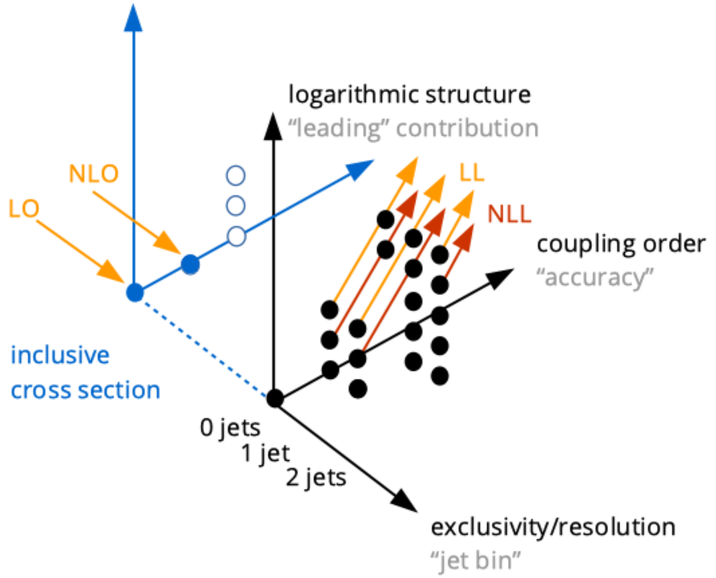






Merging condition: Preserve exclusive cross sections in ME region

$$d\sigma_n(\Phi_n)\,\Delta_n(q|q_n|\cdots|q_0)$$




Can we combine the two?

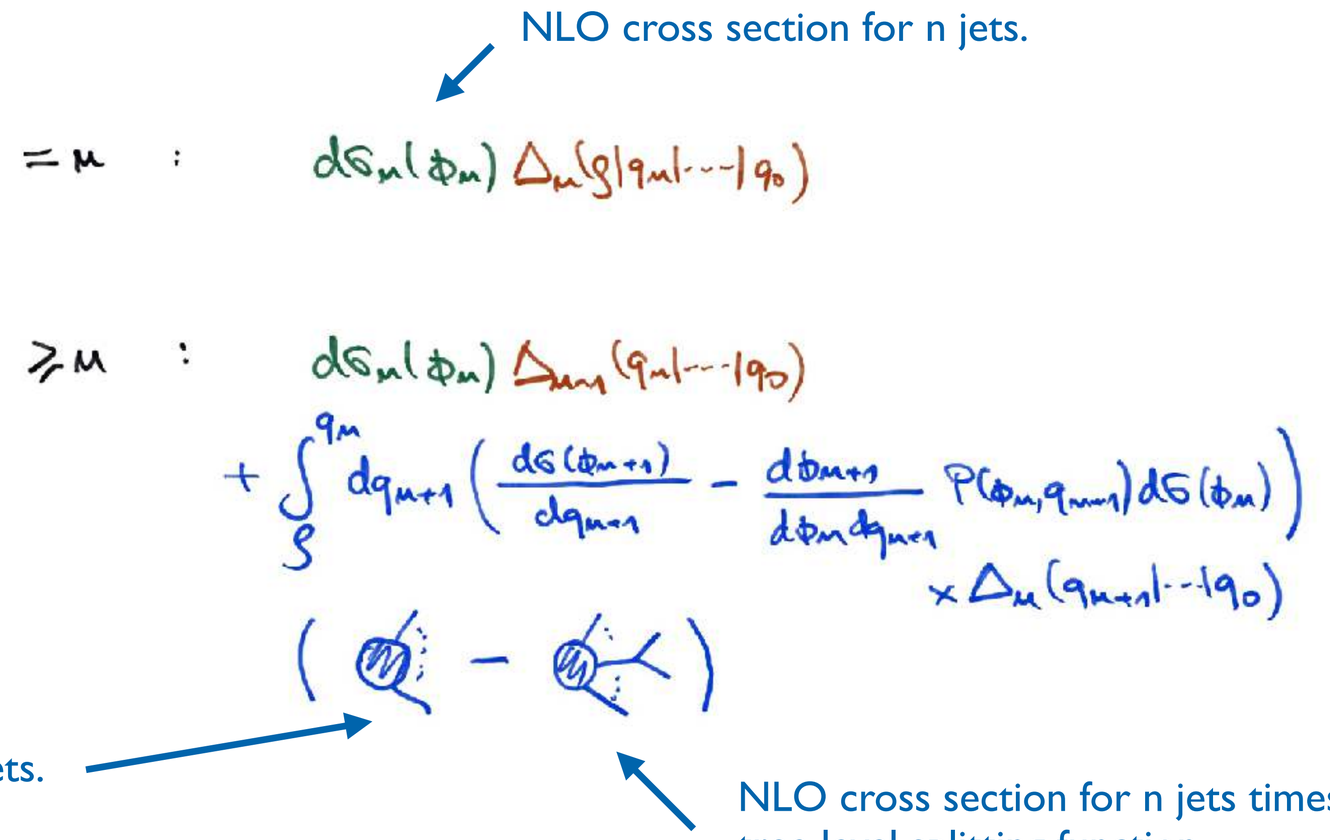
→ Preserve exclusive cross sections in ME region up to NLO

→ Possibly preserve cross sections in shower region up to NLO

# Unitarization

Exclusive cross sections are now NLO accurate by virtue of the merging condition.

The mismatch in inclusive cross section is now disturbing: Logarithmic enhancement of difference is same parametric size as the NLO corrections for lowest jet multiplicity.



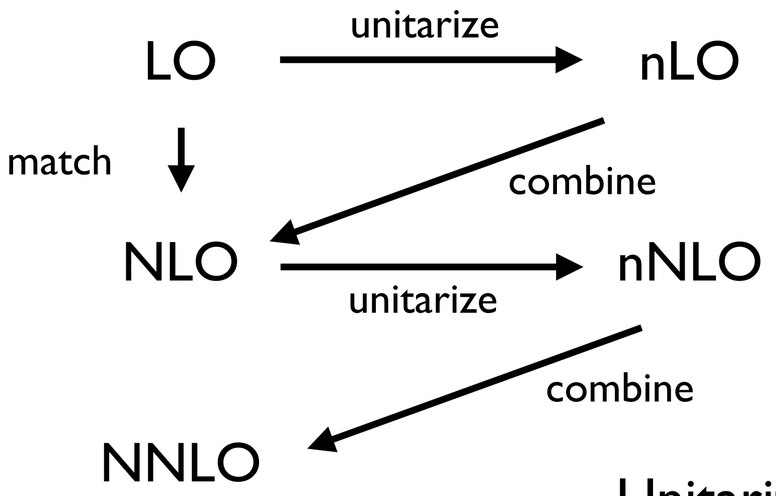

At this level we could subtract this effect from the lower jet multiplicity and enforce to preserve *inclusive* cross sections.

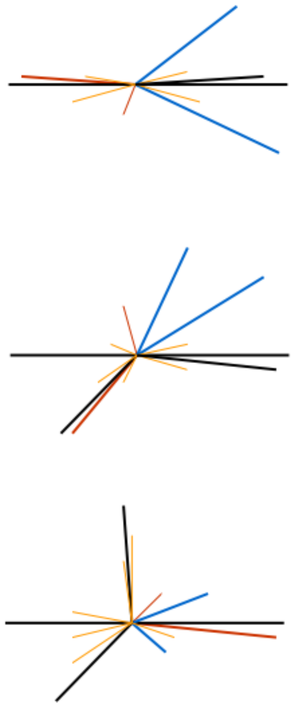
[Lönnblad, Prestel] [Plätzer]

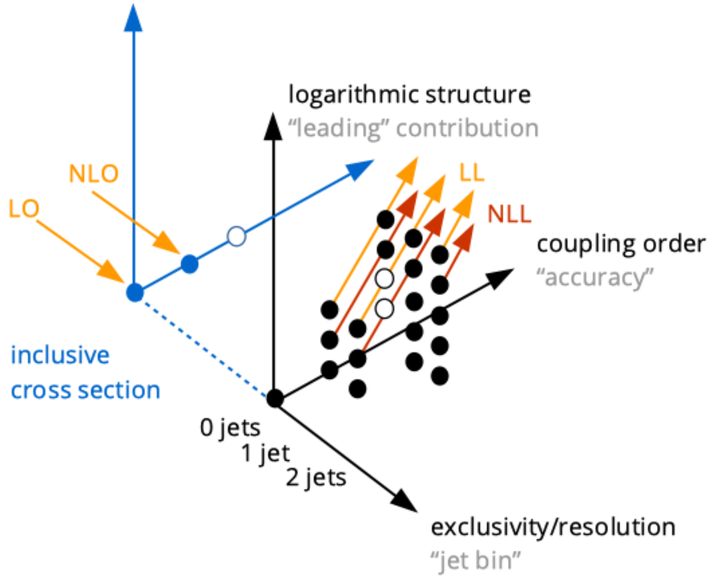
# Combination with NNLO

A higher order shower evolution would not have suffered from the problem above.

We could also have used such a shower to truly match to NNLO, which would have contained NLO for the zero and first jet bin.






Unitarization well suited for combination with NNLO. [Höche, Prestel]

Similar considerations underpin the MiNNLO method. [Hamilton, Nason, Zanderighi …]

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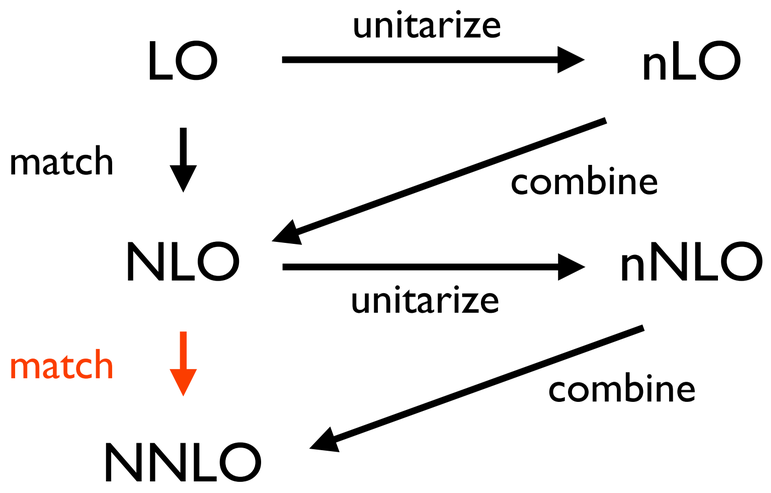
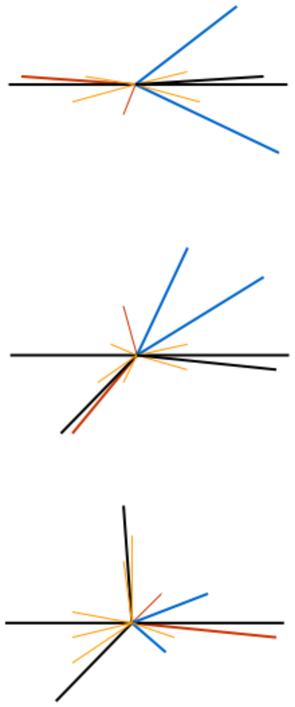
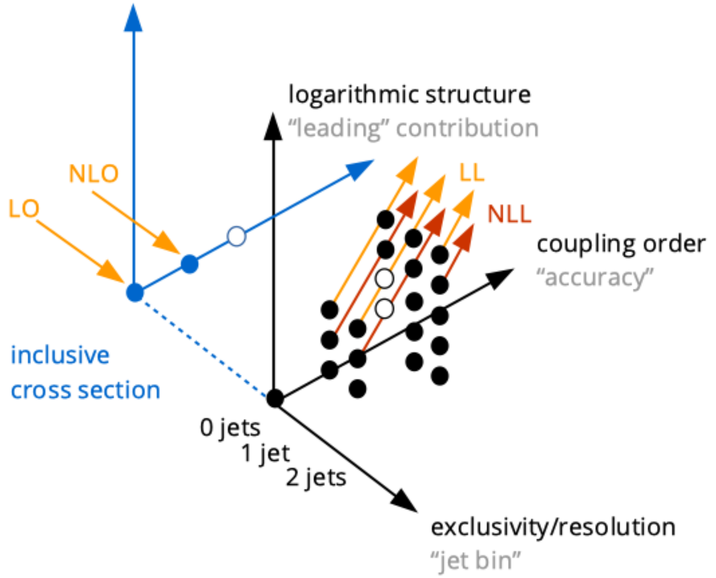
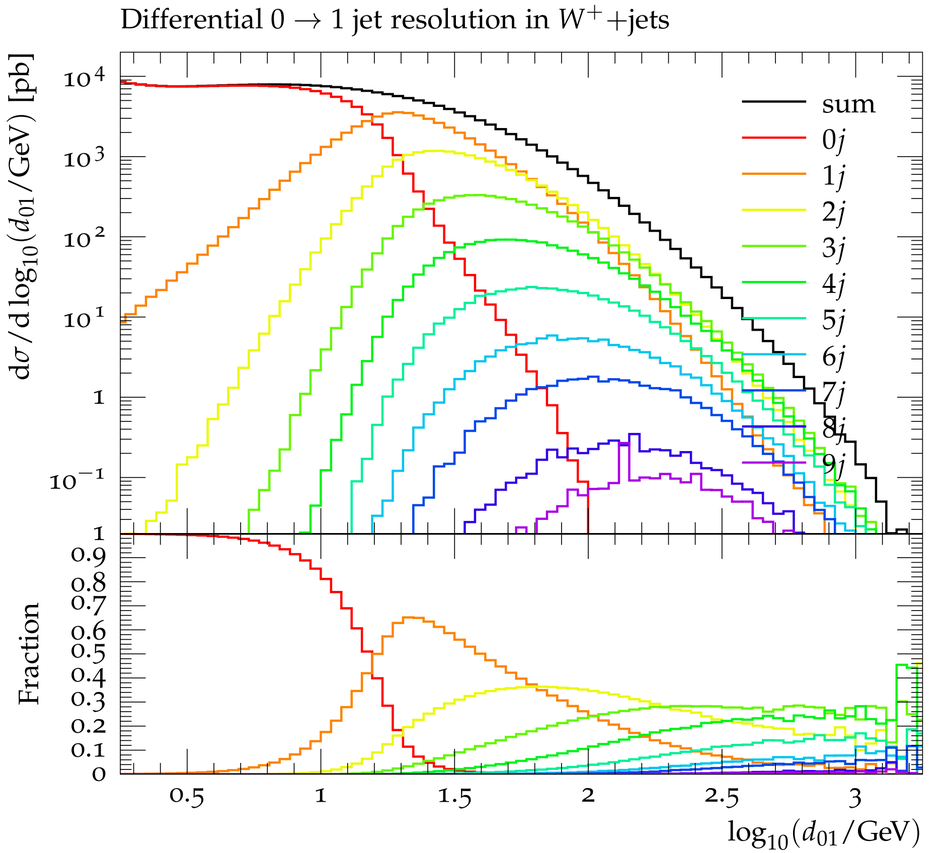


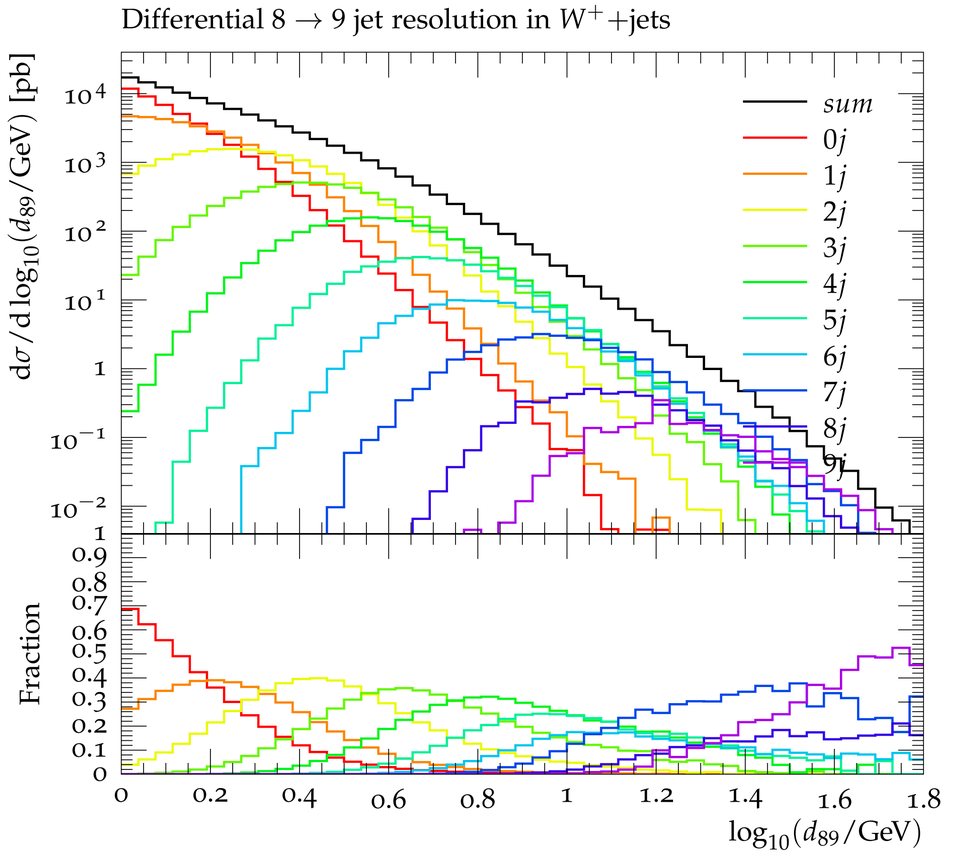






Matching to NNLO is more desirable, and requires better parton showers.

# Examples




[Sherpa — 1905.05120]

# Multi-purpose Event Generators

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| | Current release series | Hard matrix elements | Shower algorithms | NLO Matching | Multijet merging | MPI | Hadronization | Shower variations |
|---|---|---|---|---|---|---|---|---|
| H7 | Herwig 7 | Internal, libraries, event files | QTilde, Dipoles | Internally automated | Internally automated | Eikonal | Clusters, (Strings) | Yes |
|  | Pythia 8 | Internal, event files | Pt ordered, DIRE,VINCIA | External | Internal, ME via event files | Interleaved | Strings | Yes |
|  | Sherpa 2 | Internal, libraries | CSShower, DIRE | Internally automated | Internally automated | Eikonal | Clusters, Strings | Yes |

All now offer unitarized merging.

# Thank you!

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