Matching & Merging
In Parton Shower Event Generators

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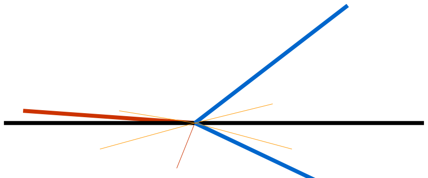
Part I
Basics & NLO Matching

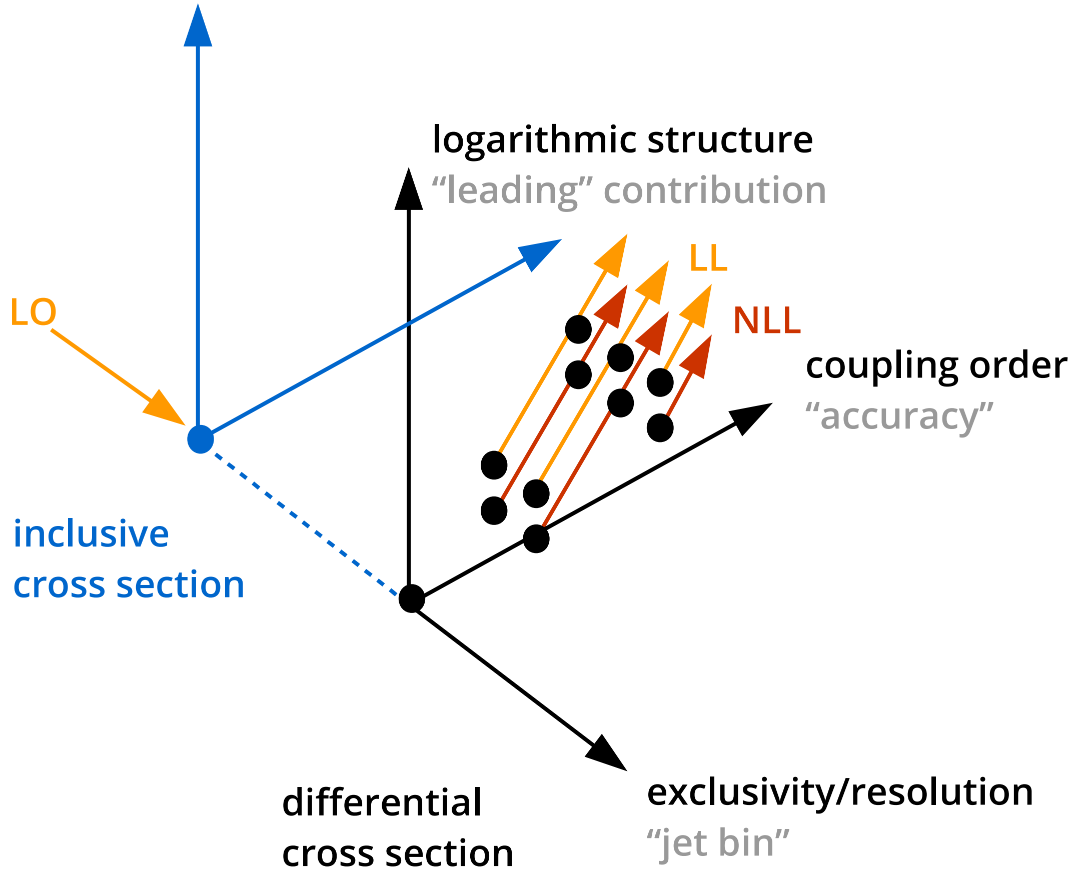
Part II
(N)LO multijet merging & combining with NNLO

Warning

This will be very pictorial, as most of the formulae underlying the actual algorithms rapidly become very complicated.

LO Multijet Merging





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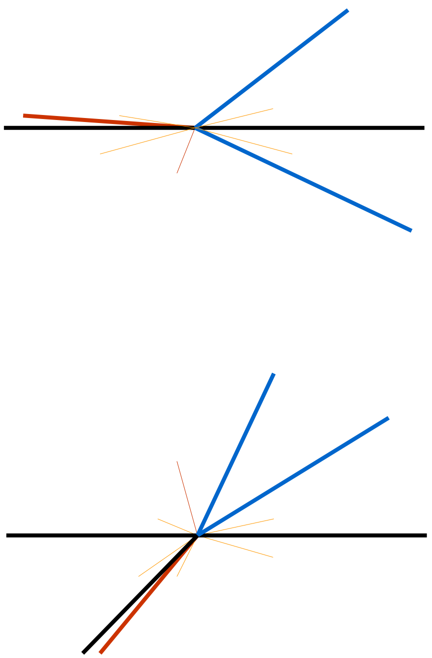

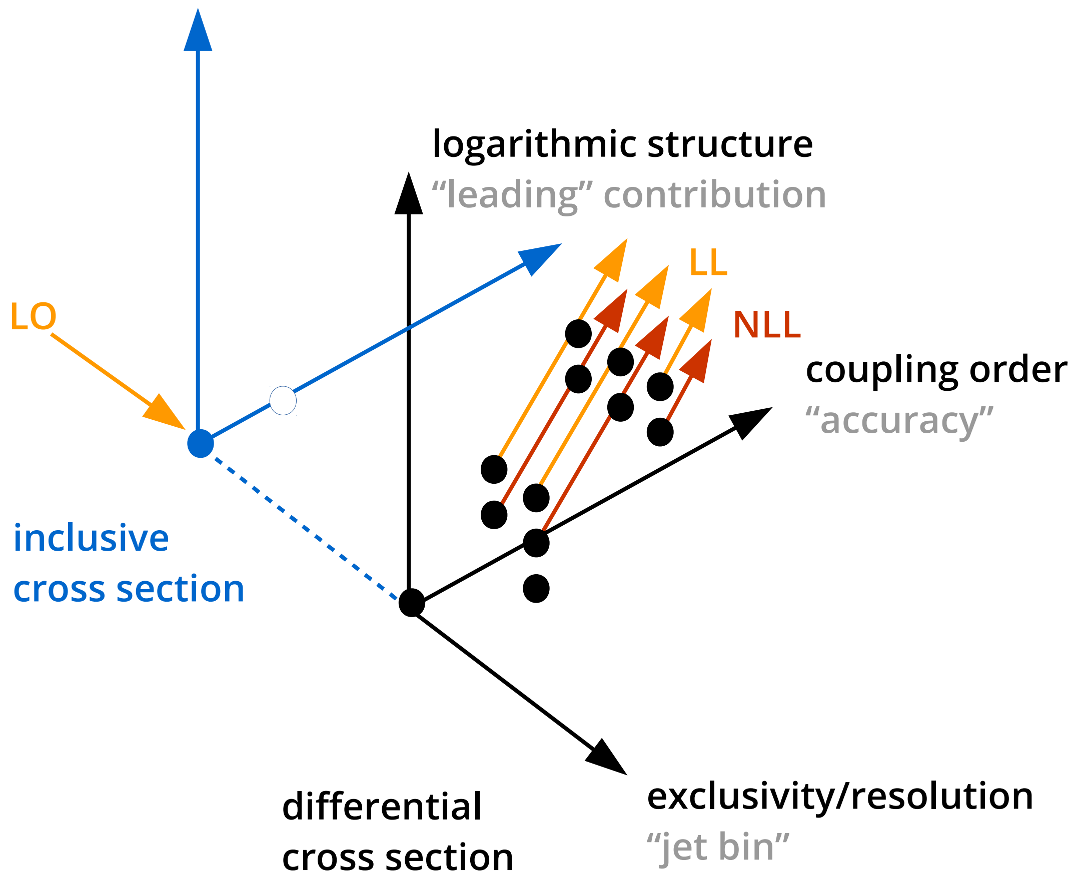

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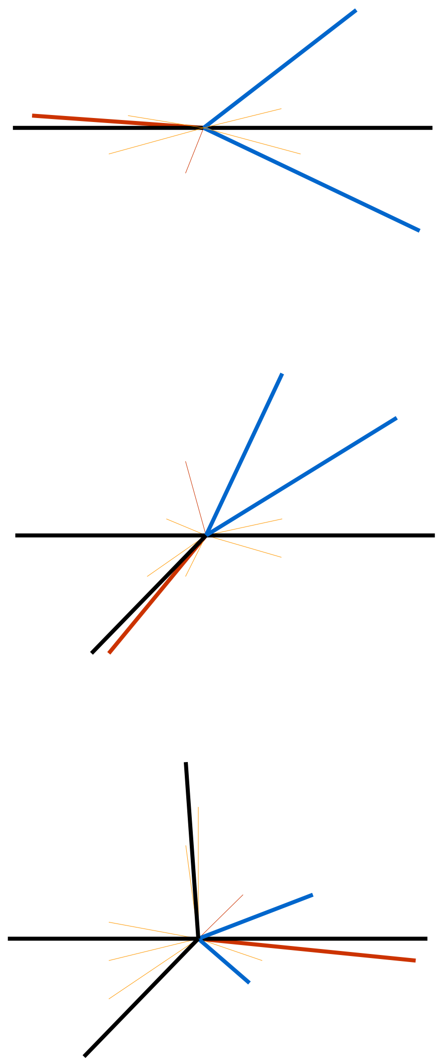
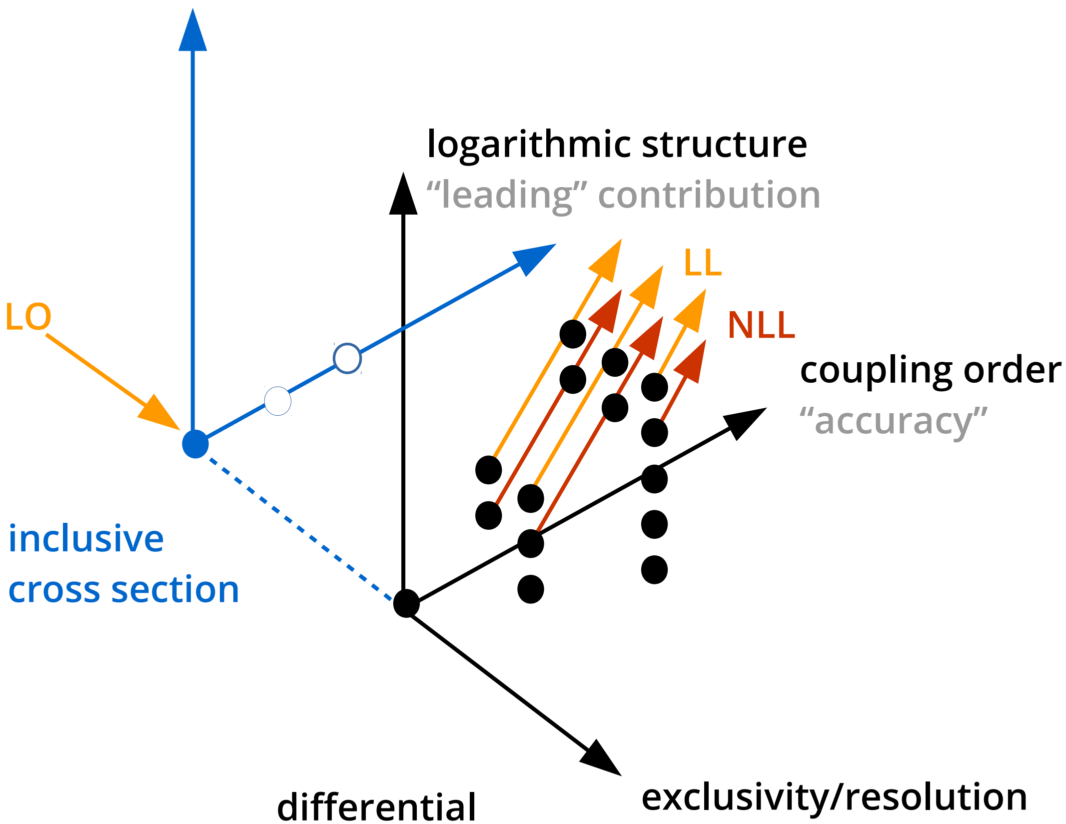
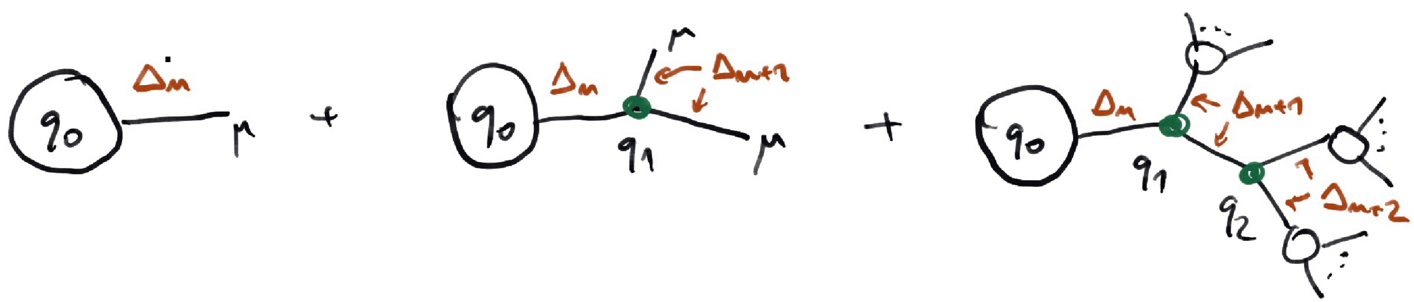




Motivation: Multiple Shower Emissions

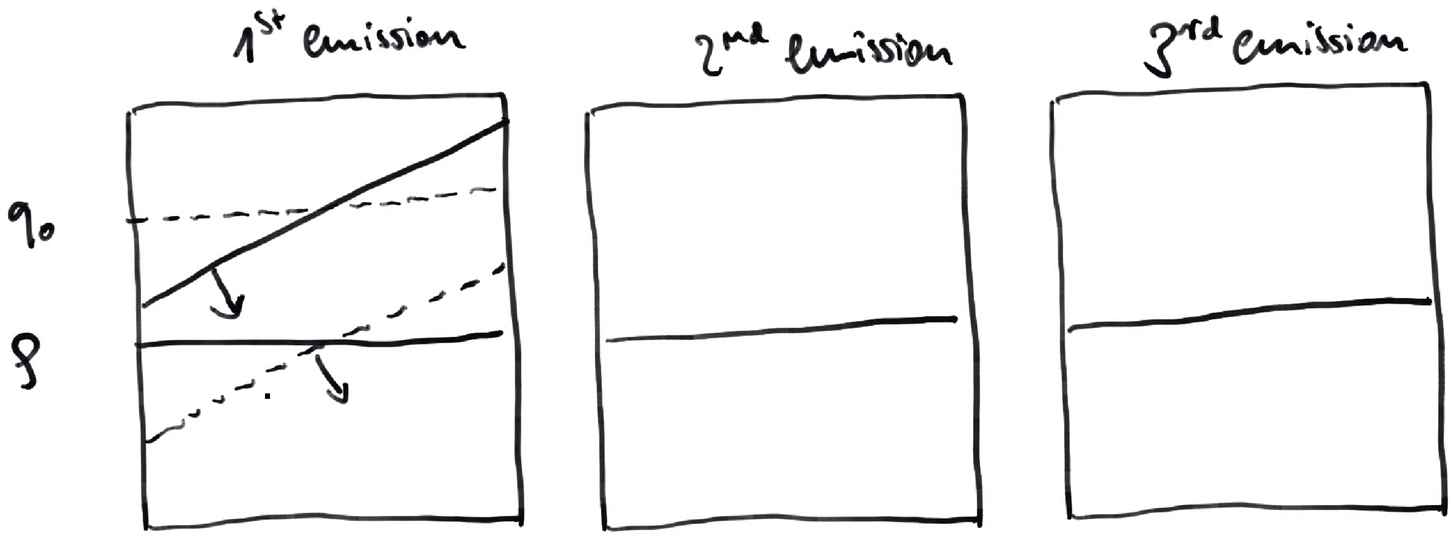
$$
\begin{aligned}
d\sigma(\Phi_n)\, PS_{q_0}[u(\Phi_n)]
&= d\sigma(\Phi_n)\, \Delta_n(\mu|q_0) + d\sigma(\Phi_n)\, P(\Phi_n, q_1)\, \frac{d\Phi_{n+1}}{d\Phi_n}\, \Delta_n(q_1|q_0)\, PS[u(\Phi_{n+1})] \\
&= d\sigma(\Phi_n)\, \Delta_n(\mu|q_0) \\
&\quad + d\sigma(\Phi_n)\, P(\Phi_n, q_1)\, \frac{d\Phi_{n+1}}{d\Phi_n}\,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



Basic idea: replace approximate matrix elements with exact ones, but keep Sudakov factors which regularize divergences.

LO Merging – Phase Space Considerations

Cut phase space into matrix element and parton shower populated regions.



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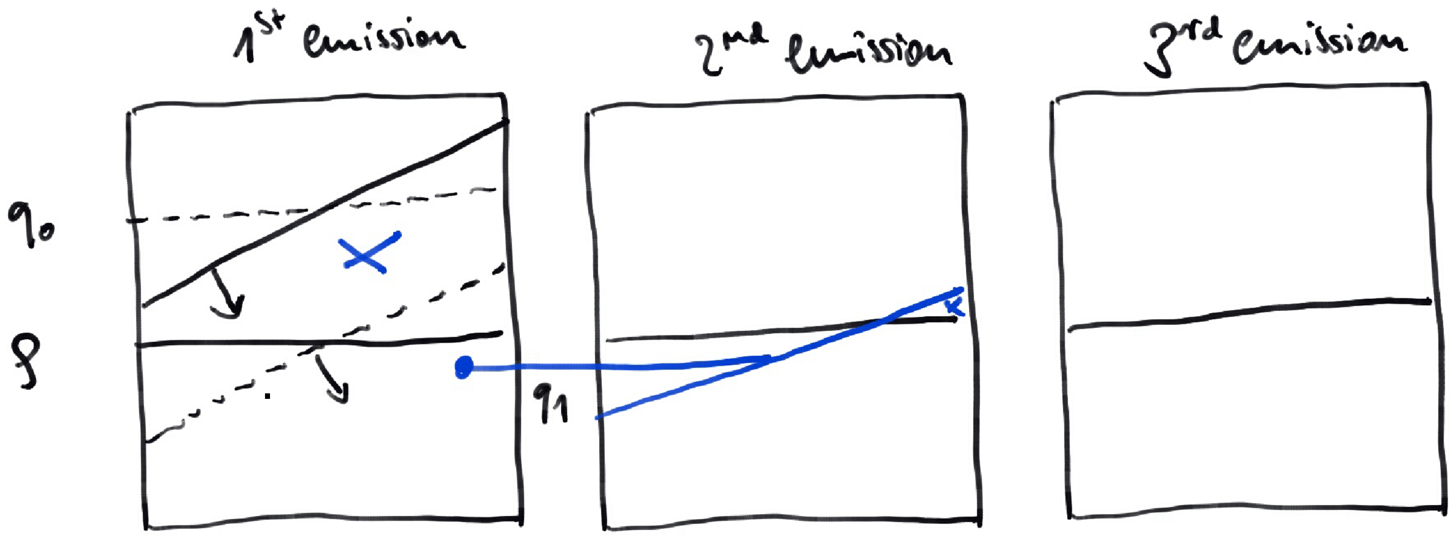

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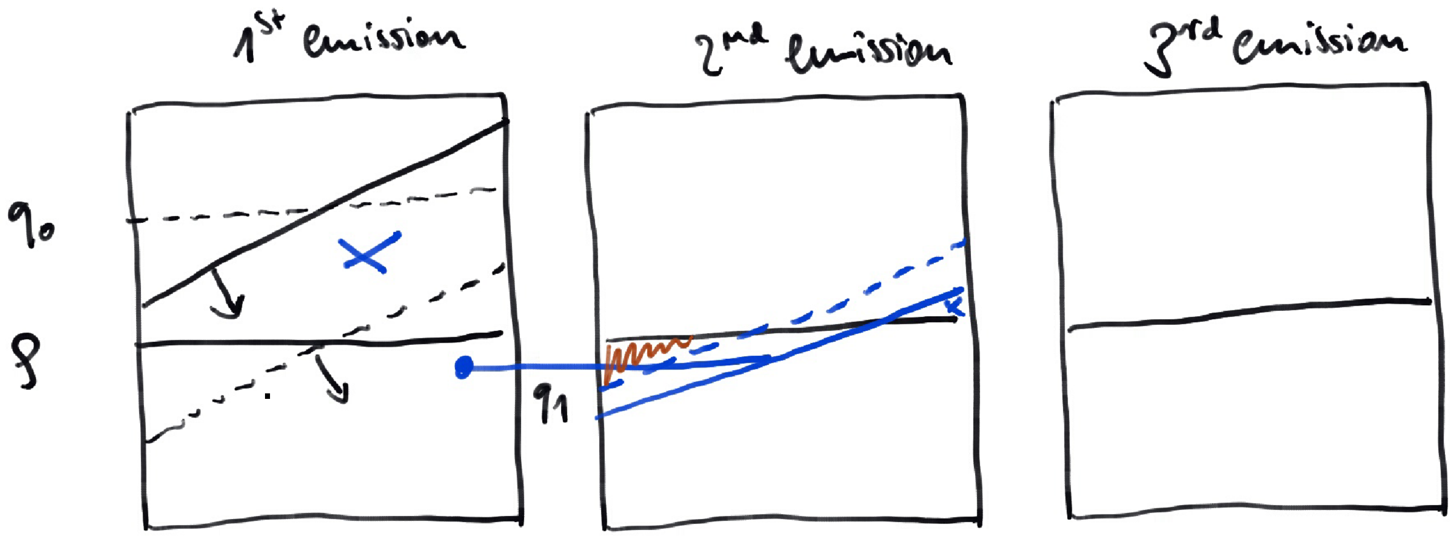

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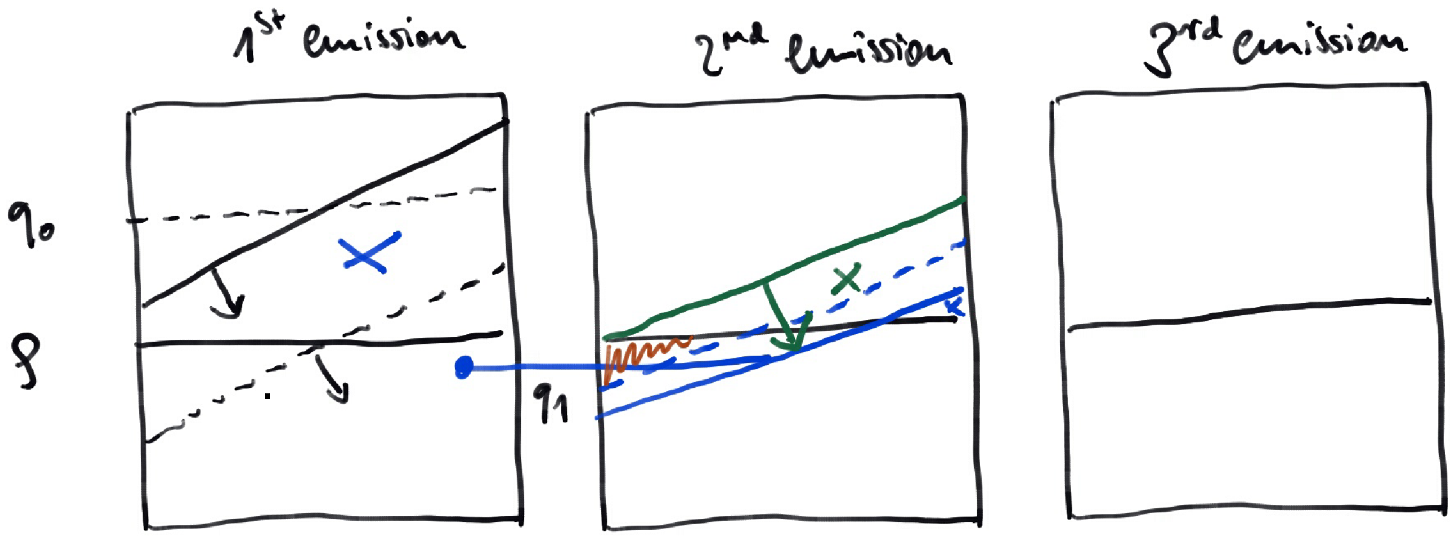

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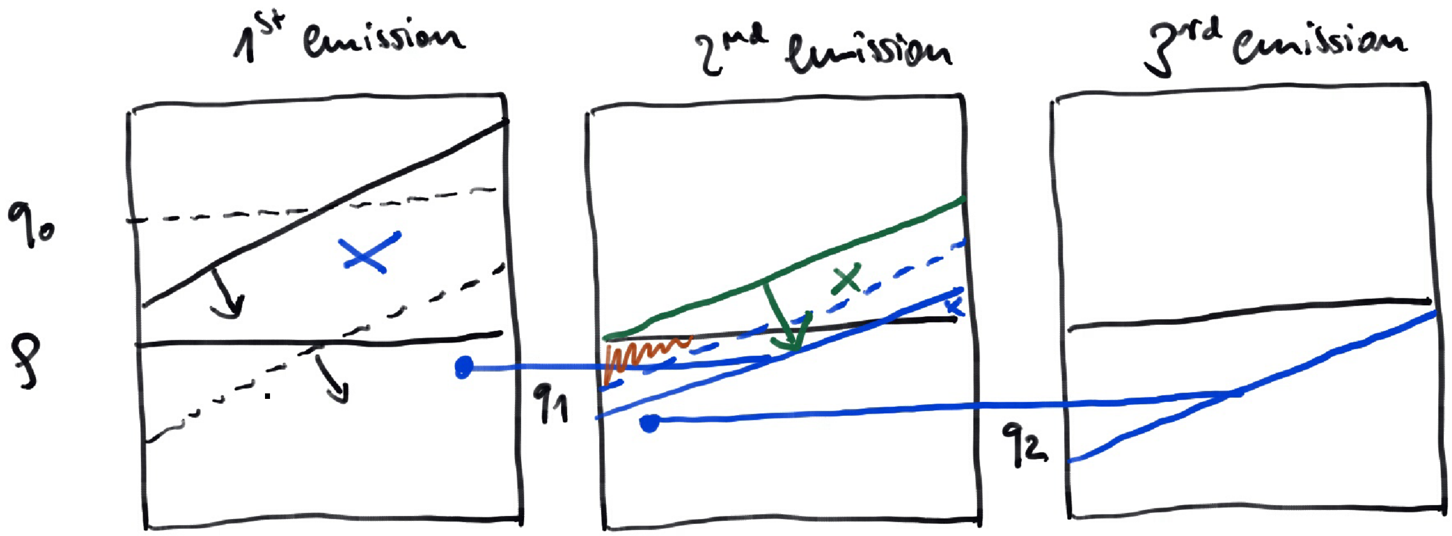
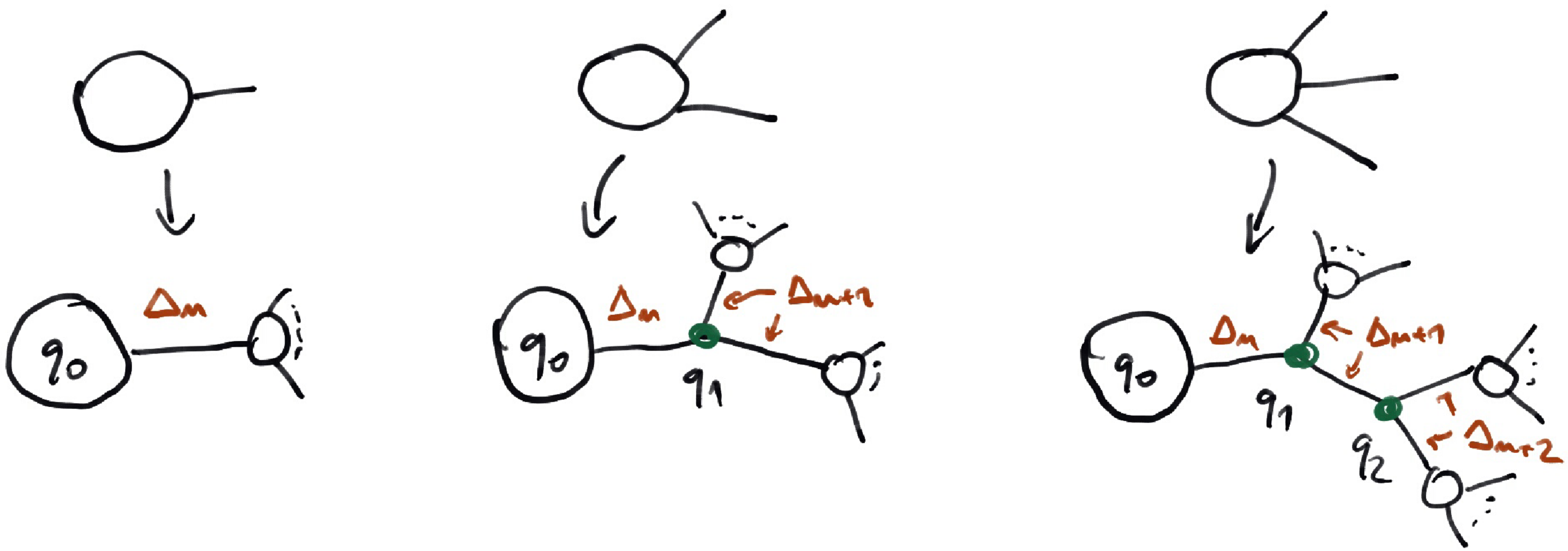


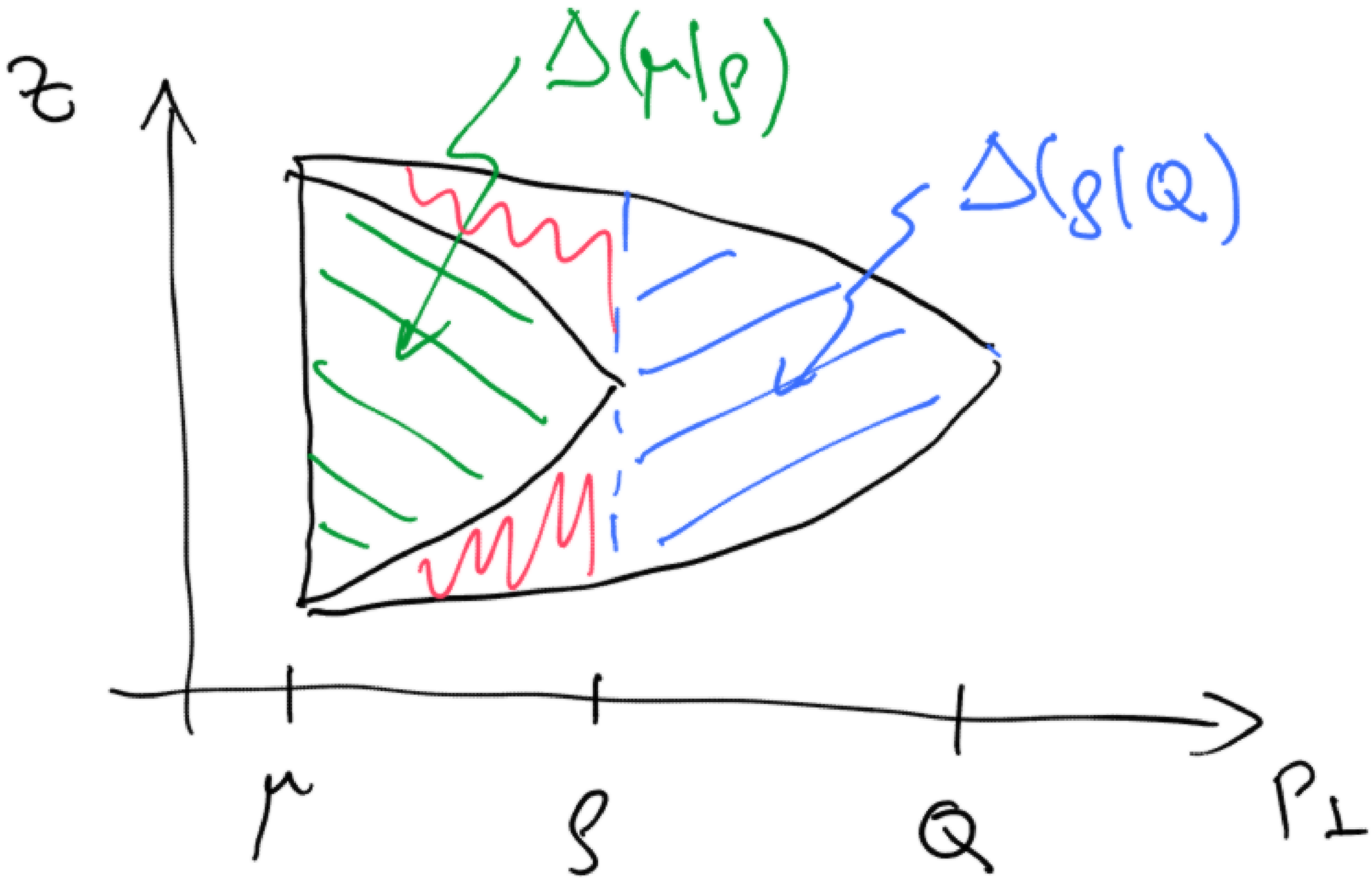
Traditional LO Merging Algorithms



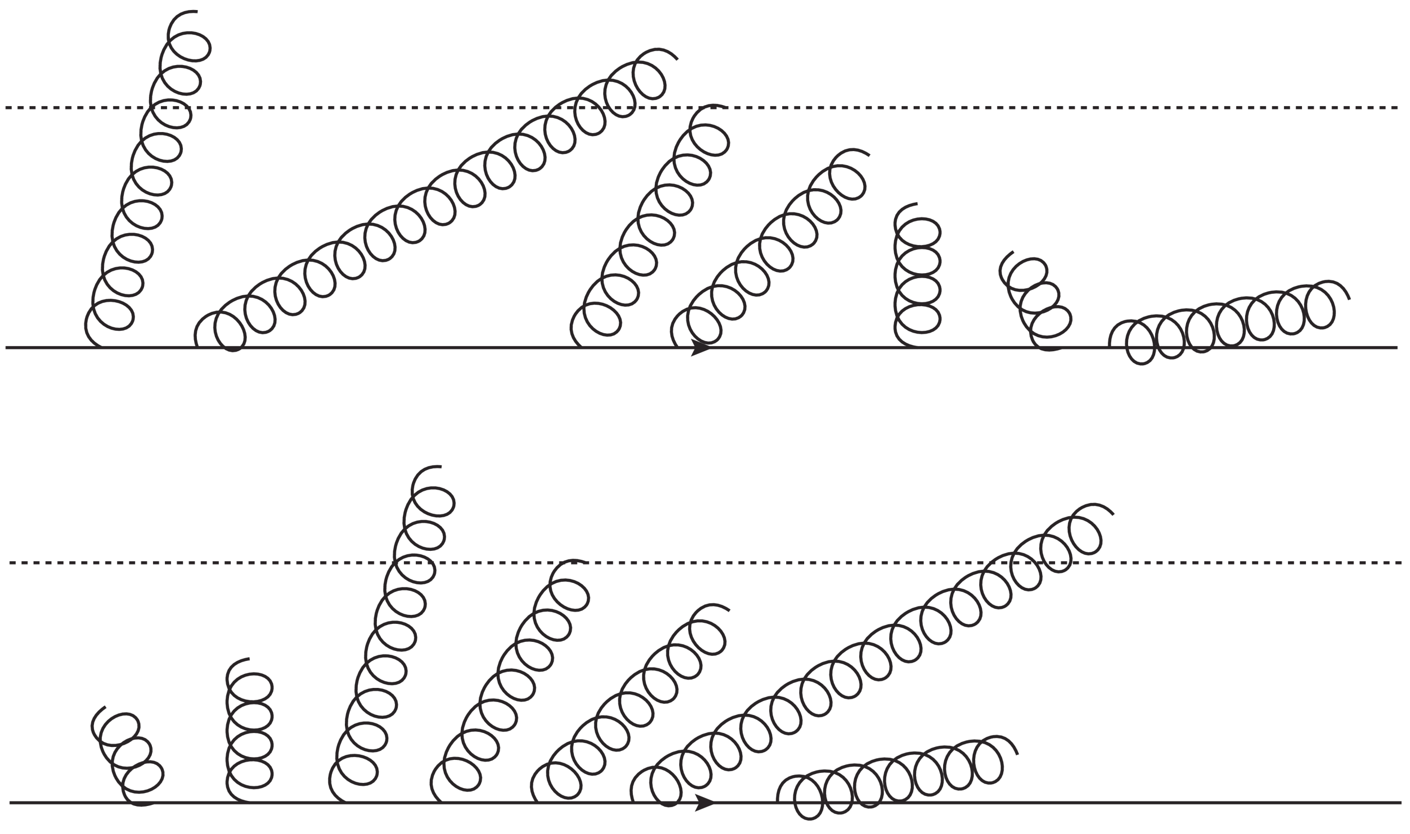
1) Generate matrix element configurations
2) Cluster back into a parton shower history
3) Apply Sudakov weights
4) Add vetoed (possibly truncated) showers

[Catani, Krauss, Kuhn Webber 2001 + Lönnblad 2002]

Vetoed Showers and Sudakov Form Factors

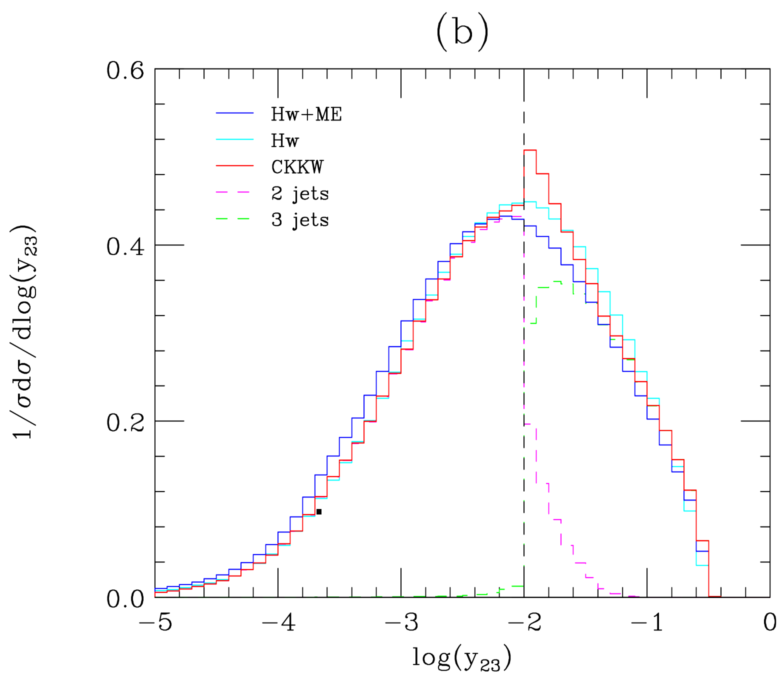


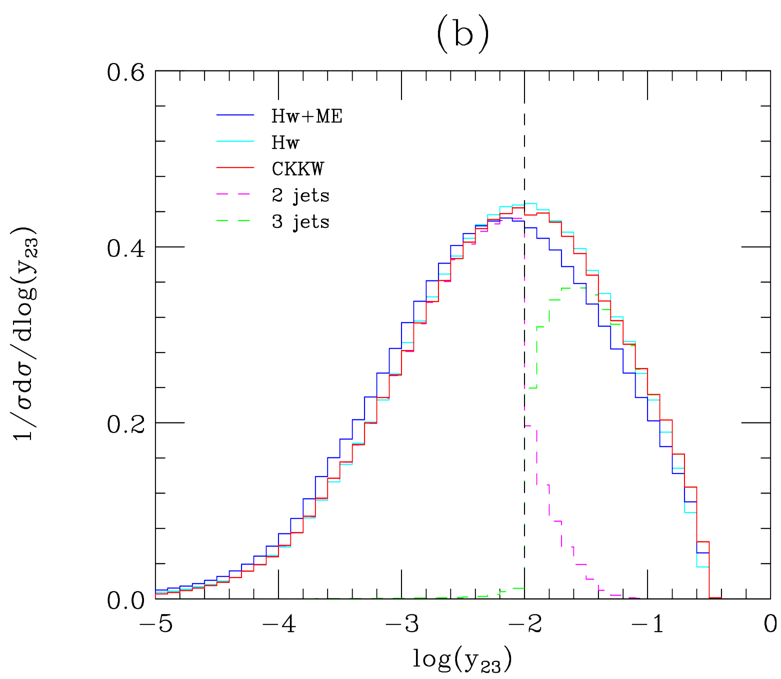
Truncated Showers



[Hamilton, Richardson, Tully 2009 + Höche, Krauss, Schumann, Siegert 2009]

Truncated Showers – Do they matter?





[Hamilton, Richardson, Tully 2009]

Exclusive and Inclusive Jet Cross Sections

Expectations from the shower:

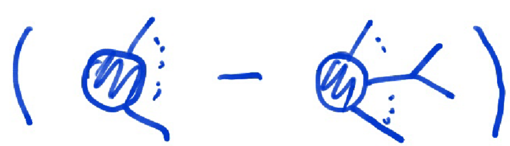
$= n$ jets: $$d\sigma(\Phi_0)\,\frac{d\Phi_n}{d\Phi_0}\,P(\Phi_0,q_0)\cdots P(\Phi_n,q_n)\,\Delta_n(\rho|q_n|\cdots|q_0)$$

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

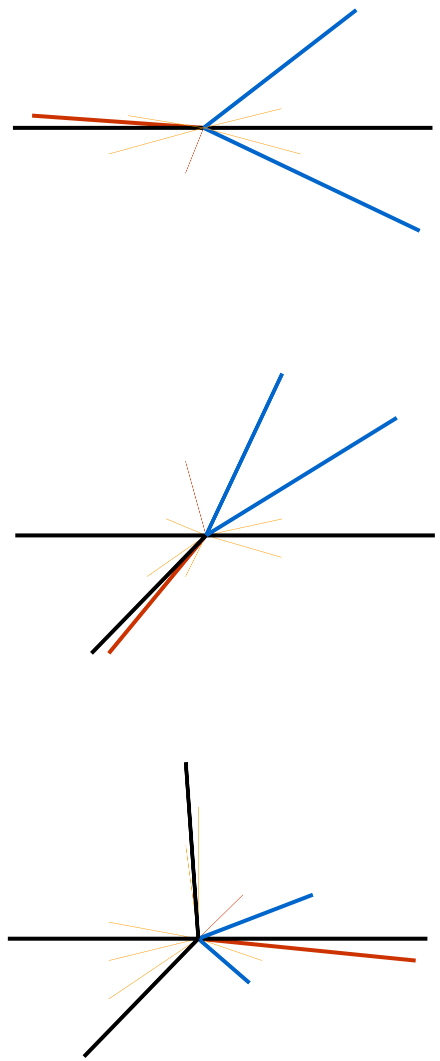
With merging:

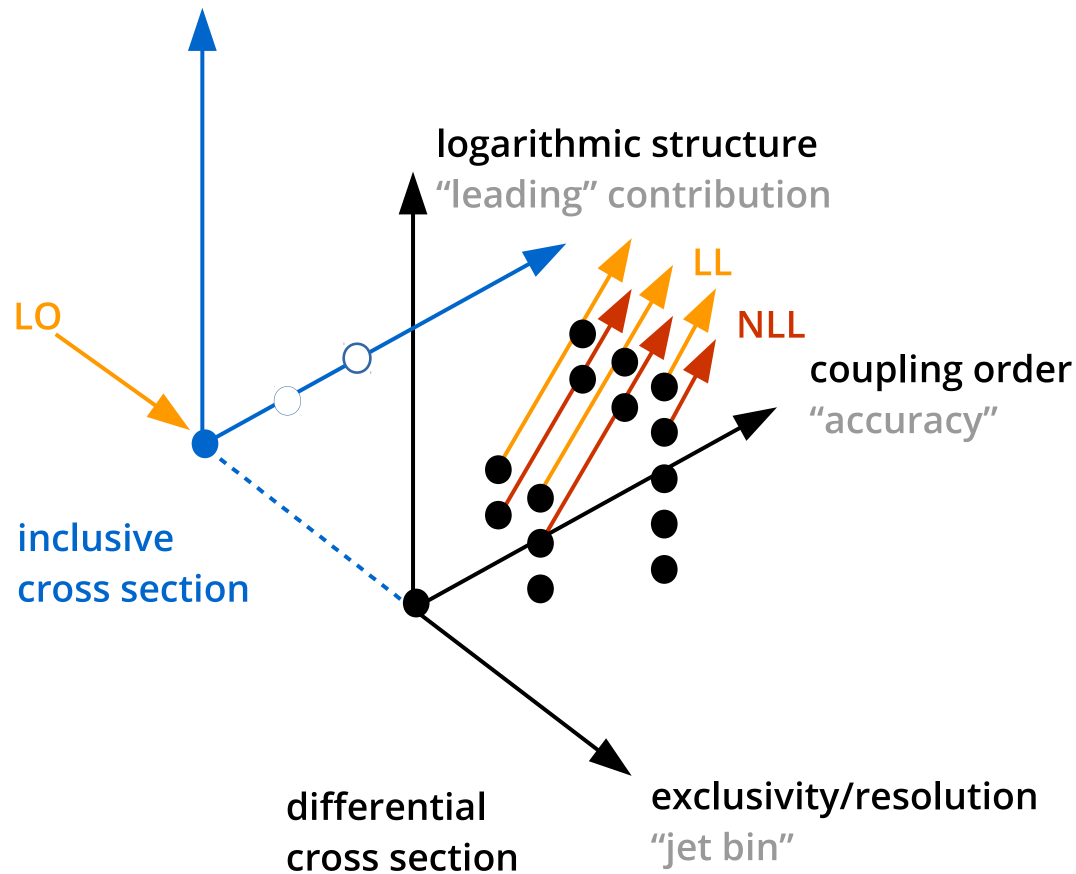
$= n$: $$d\sigma_n(\Phi_n)\,\Delta_n(\rho|q_n|\cdots|q_0)$$

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



NLO Multijet Merging





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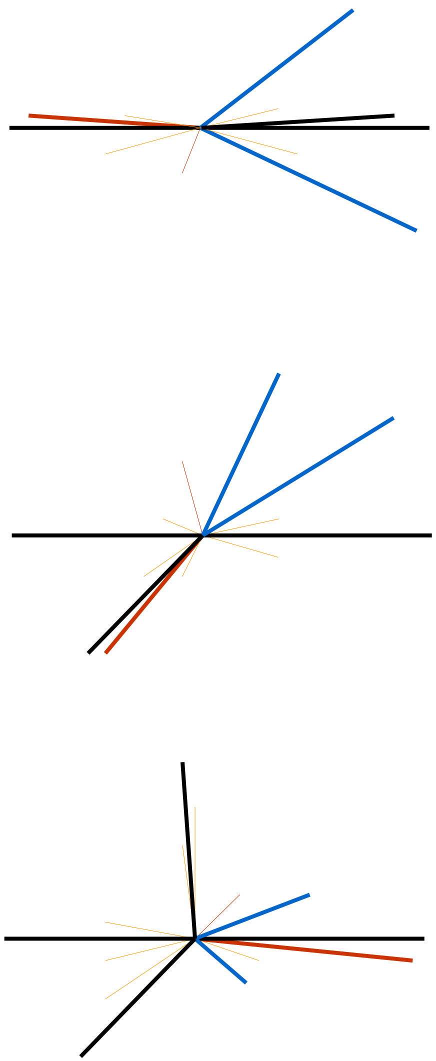
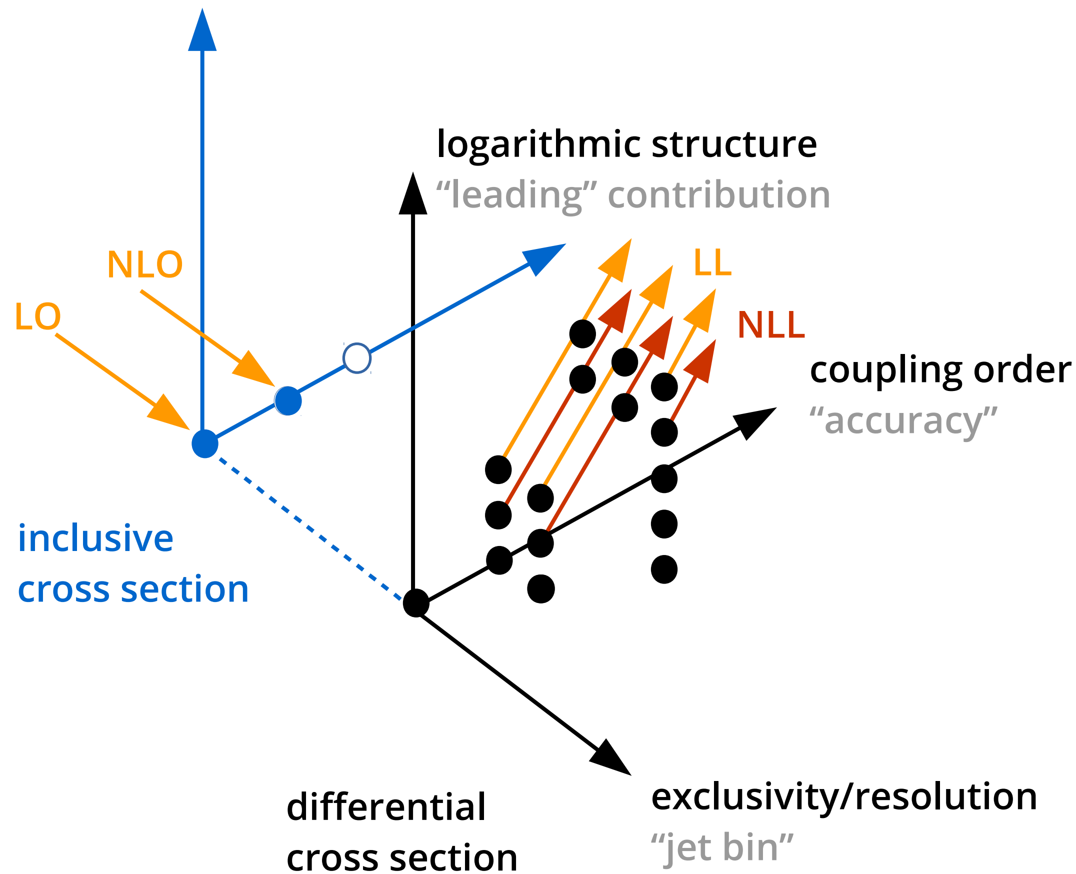
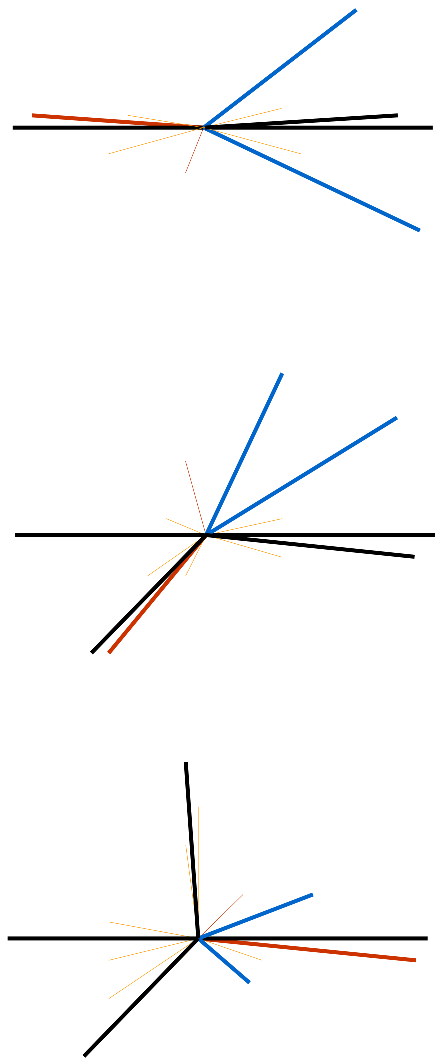
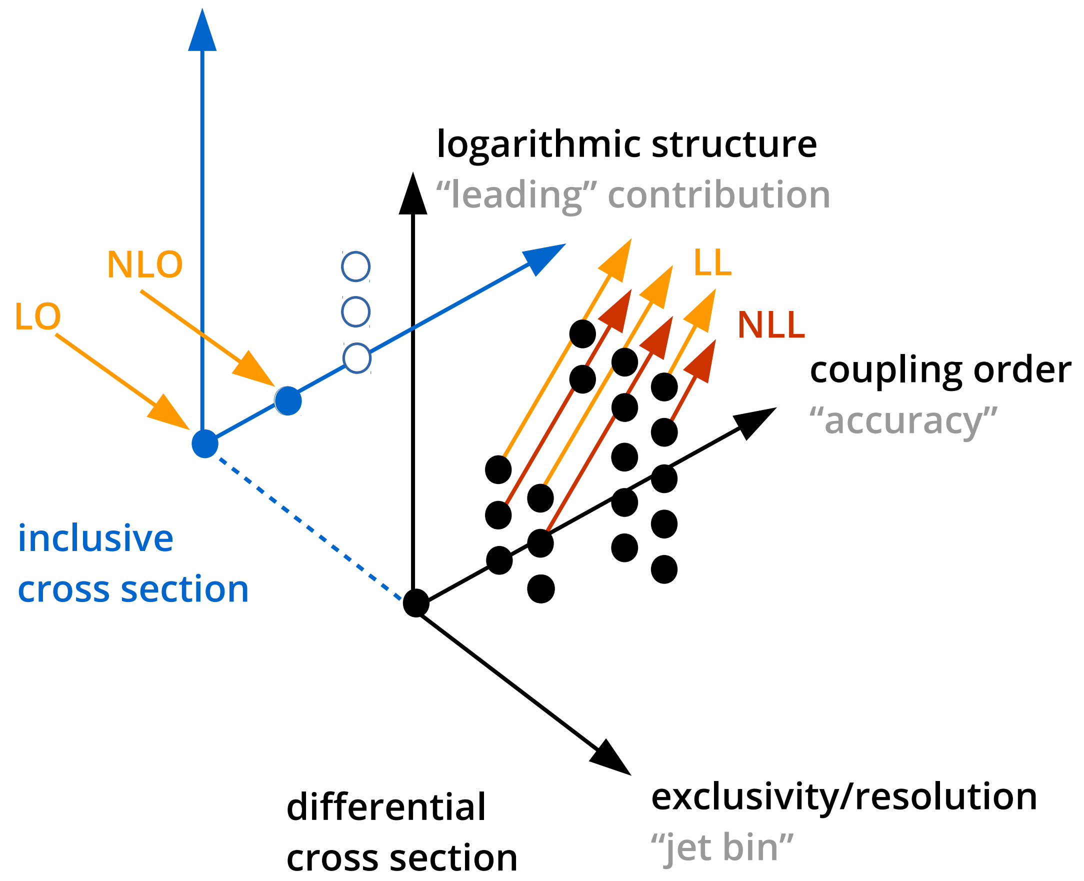




NLO Multijet Merging





Matching – worse in NLO Merging ...

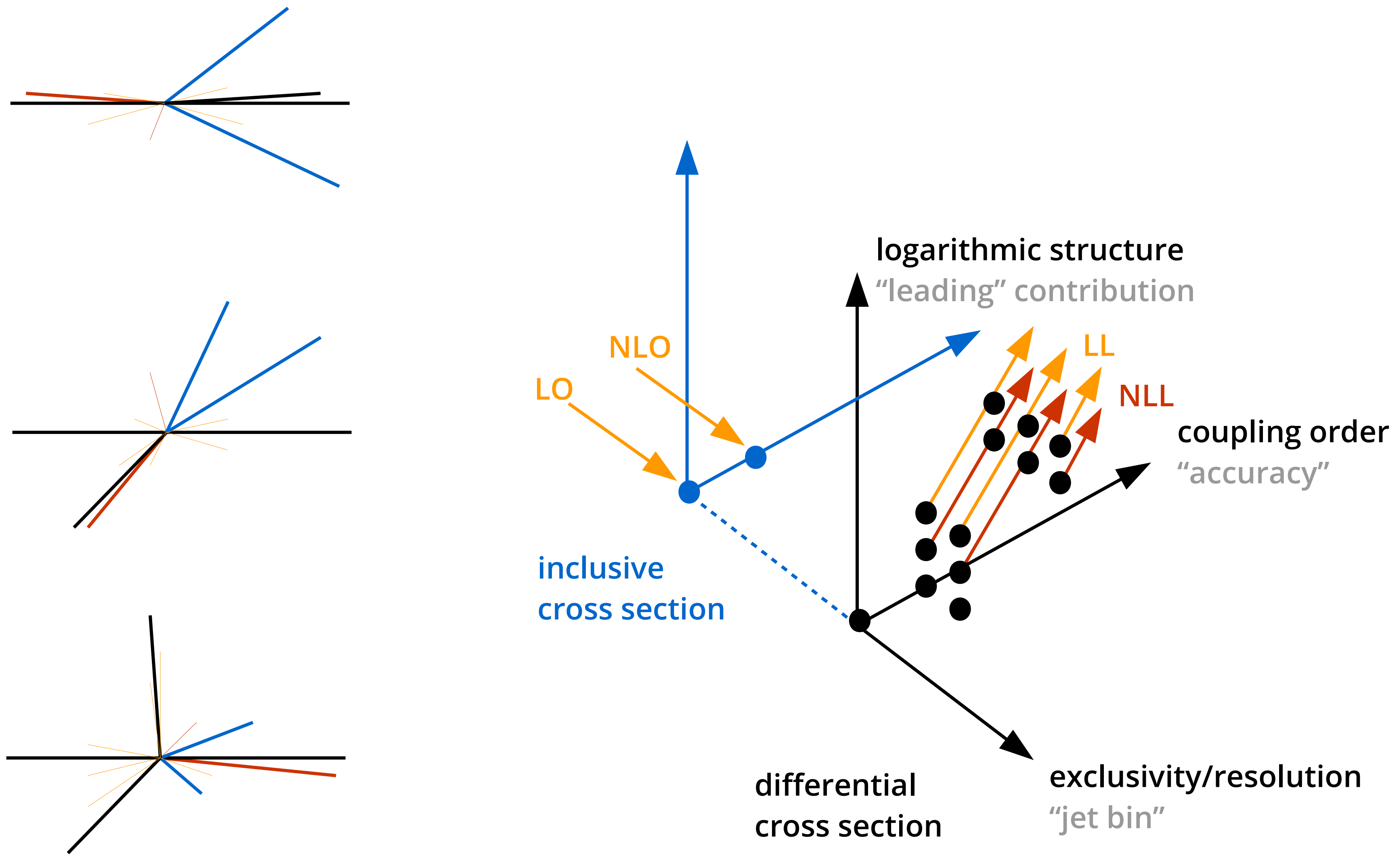
Basic motivation is similar to LO merging, but now use exclusive NLO cross sections instead on exclusive LO cross sections as input to clustering.

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

Double counting subtraction more involved:
Expand merged cross sections including Sudakov factors.

$$PS_v\left[d\sigma_{NLO}^{merged}\,\Delta_n(g|q_n|\cdots|q_0)\right] = \ldots$$

Paving the way to combine with NNLO



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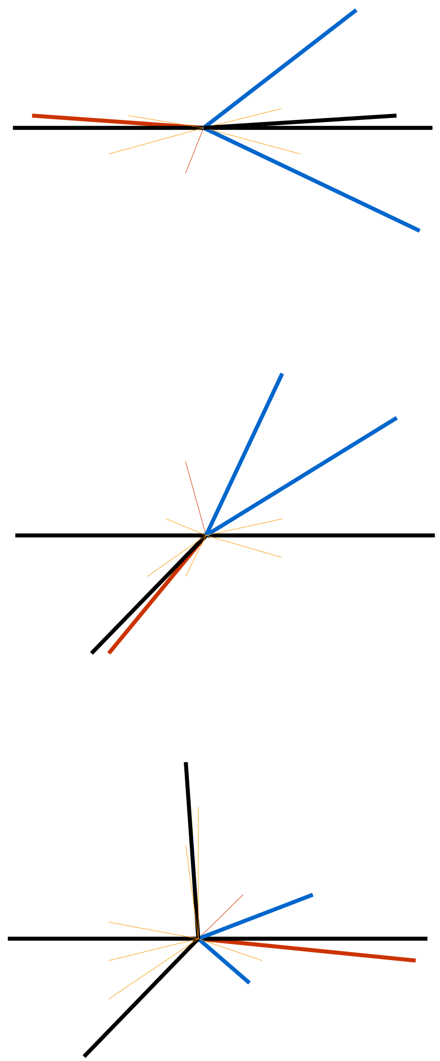

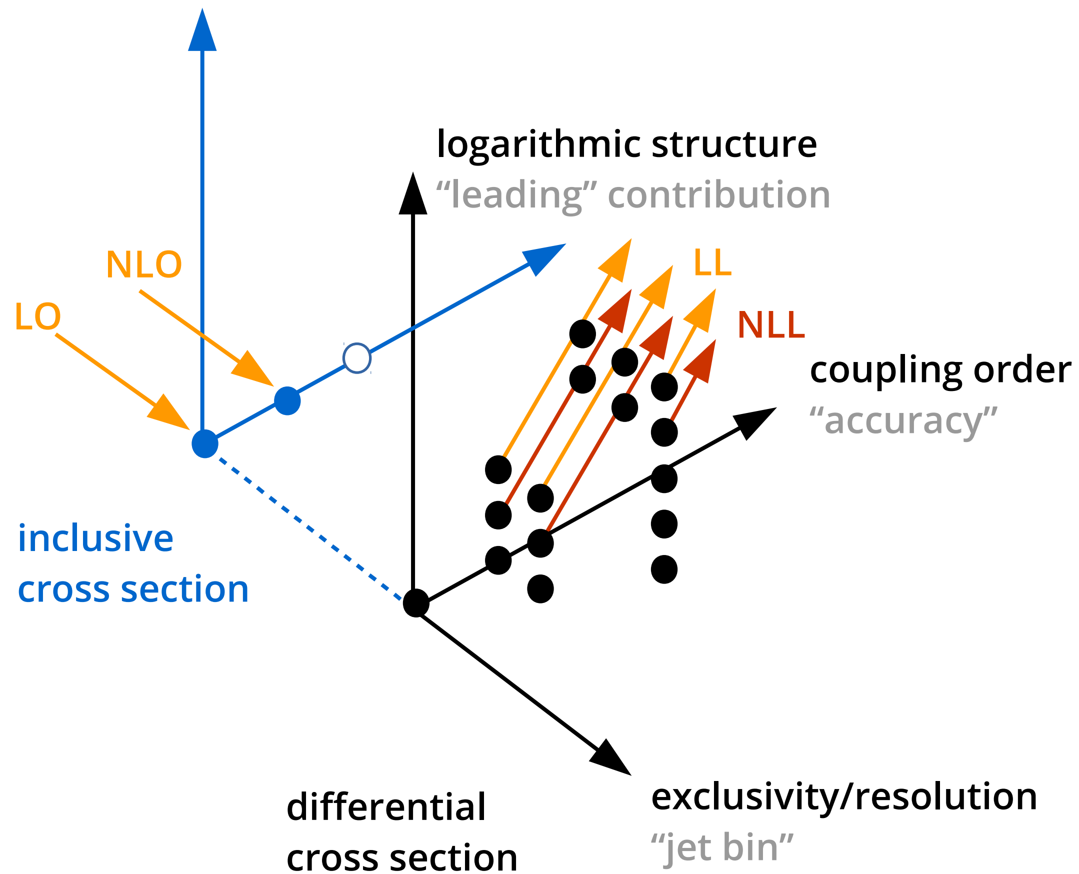

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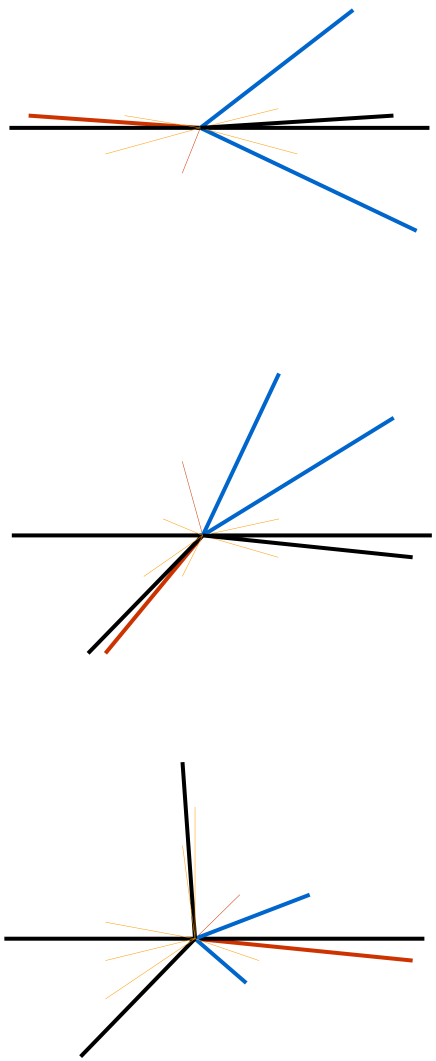

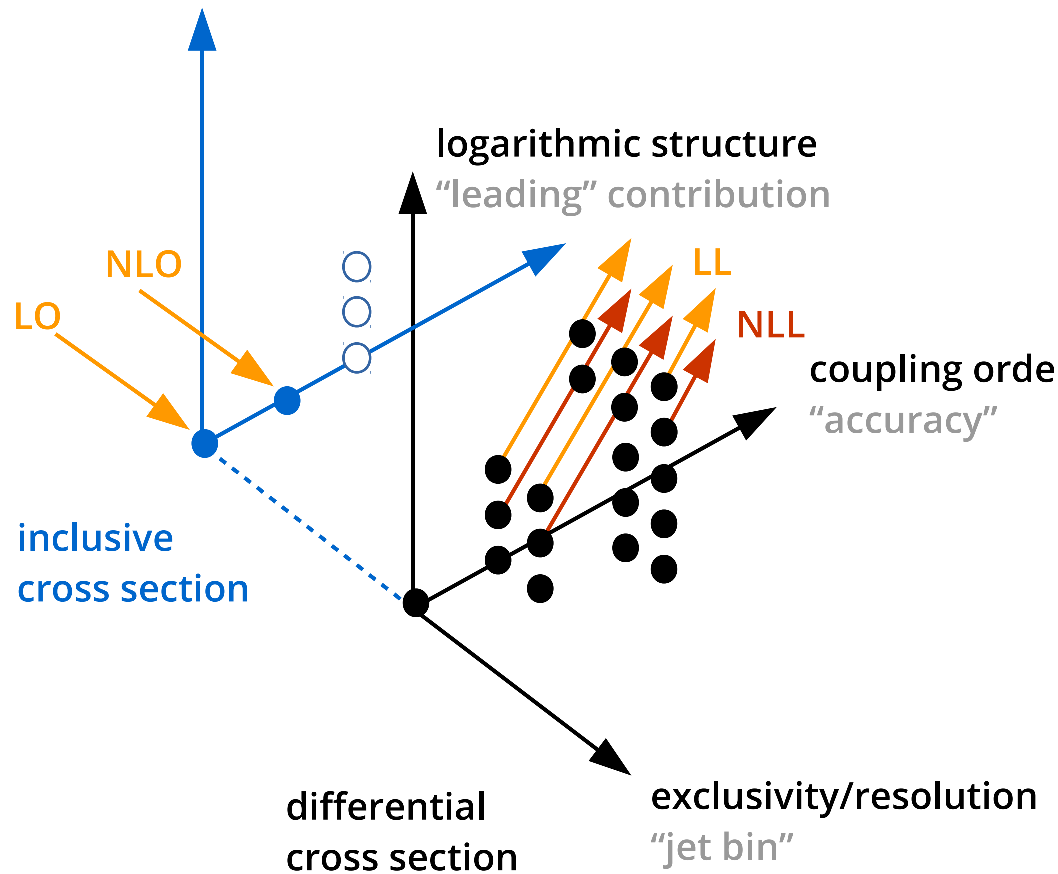

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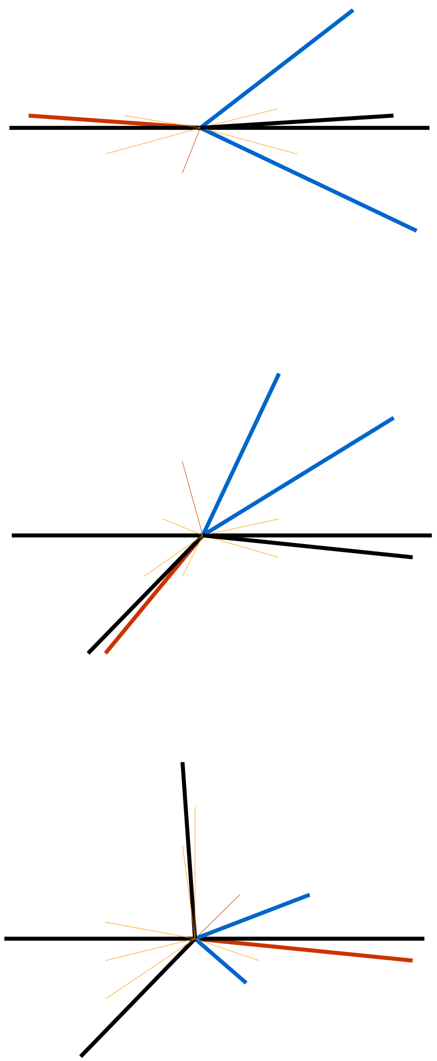
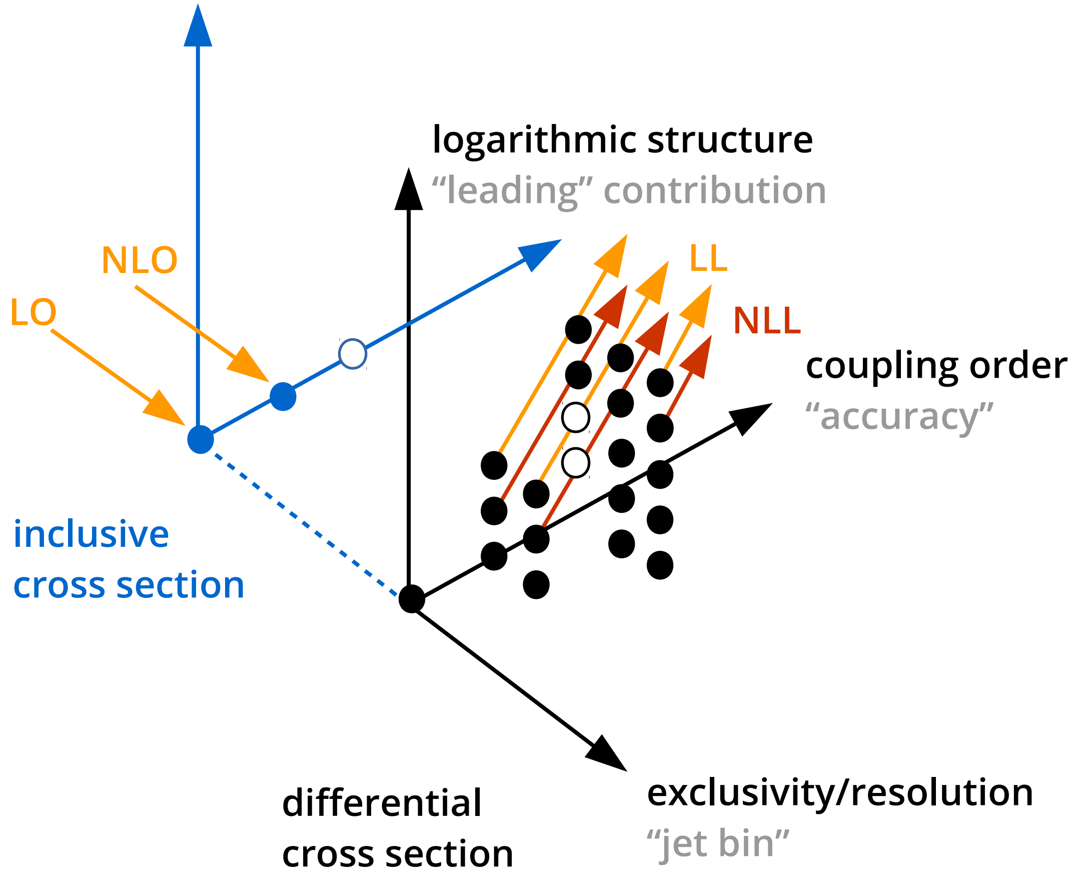


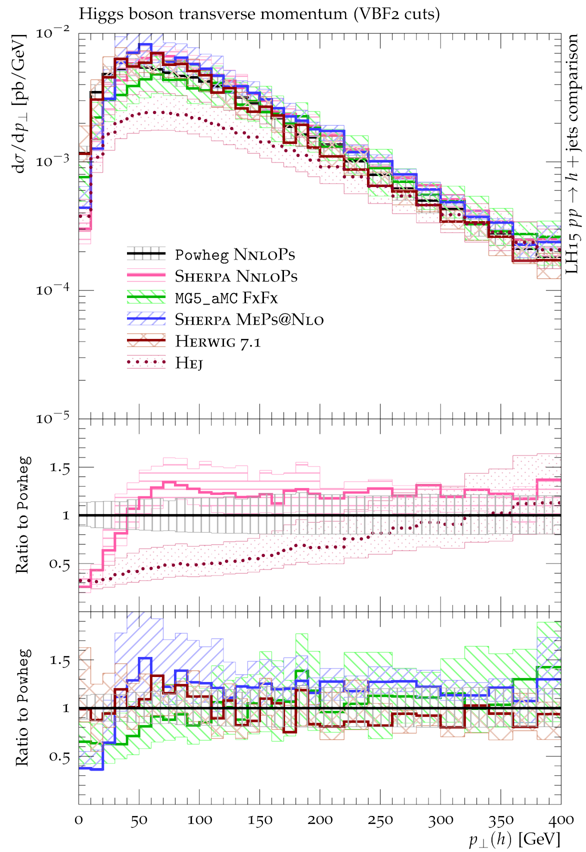


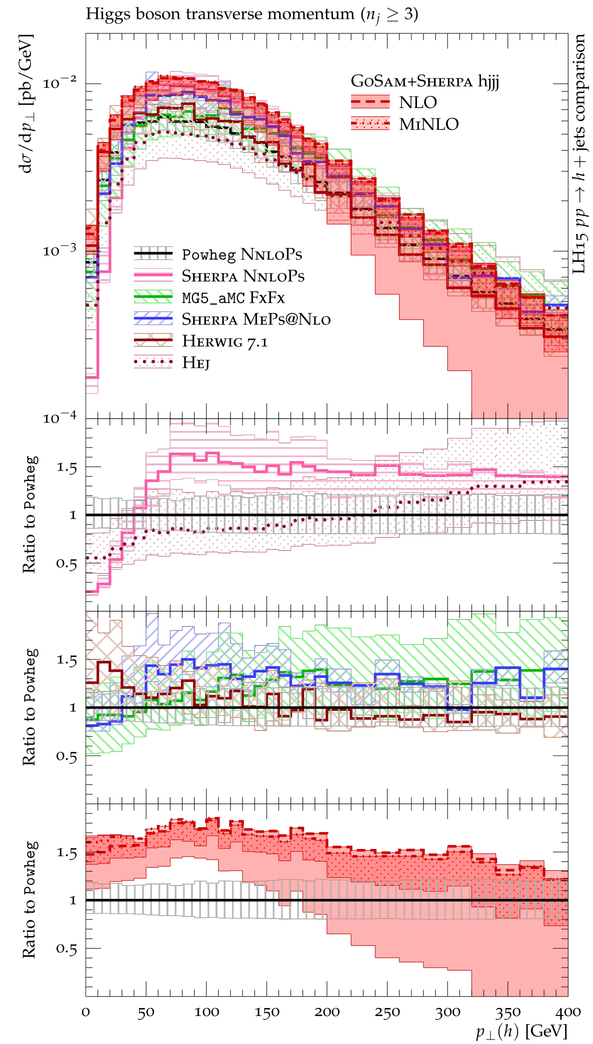
Available Multi-purpose Frameworks

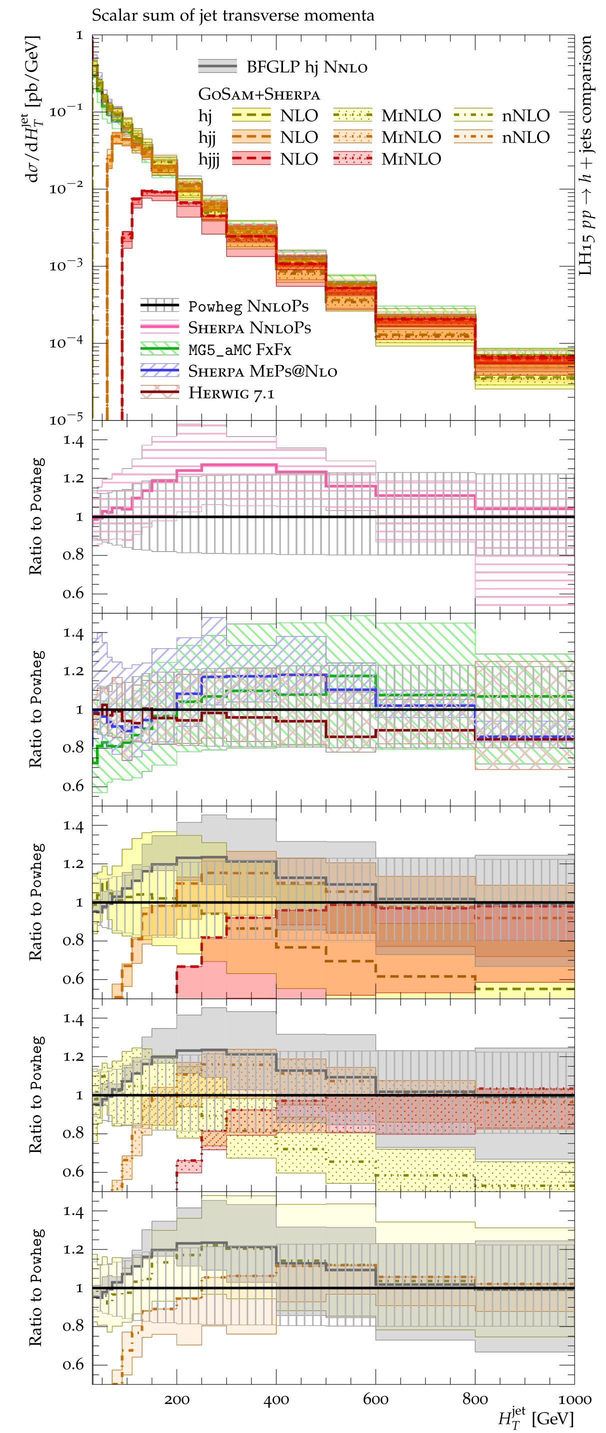
Acronym	Xsec	Shower	NNLO combined
NL3	event files	Ariadne, Pythia 8	no
		[Lavesson, Lönnblad – 2008] [Lönnblad, Prestel – 2012]	
MINLO / MINLO'	internal/BLHA	any, Pythia in practice	yes
		[Hamilton, Zanderighi et al. – 2012]	
MEPS@NLO	internal/BLHA	Sherpa CSS	no
		[Höche, Krauss, Schönherr, Siegert + Gehrmann – 2012]	
FxFx	internal	Herwig6/++, Pythia 6/8	no
		[Frederix, Frixione – 2012]	
Vincia	internal	Vincia (FS)	no
		[Skands et al. – 2012]	
UNLOPS/Pythia	event files	Pythia 8	no
UNLOPS/Sherpa	internal/BLHA	Sherpa CSS	yes
UNLOPS/Herwig	internal/BLHA	Herwig 7 Dipoles	no
[Lönnblad, Prestel – 2012] [Plätzer 2012] [Höche,Li,Prestel – 2014] [Bellm, Gieseke, Plätzer – 2015]			
Geneva	internal/resum	any, Pythia in practice	yes
		[Alioli, Tackmann et al. – 2012]	

State of the Art Predictions for H+Jets

Les Houches 2015







Summary & Outlook – Part II

LO merging is established technology.

→ As for NLO matching, all major generators provide it.

Multitude of NLO multijet tools.

→ Different algorithms, need to be addressed in detail.

NLO multijet merging allows for *combination* with NNLO.

→ Matching requires showers to be pushed to higher orders.