

Matching & Merging

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

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

Part I

Fixed Order Basics
NLO Matching

Part II

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

I will limit myself to QCD.

$$d\sigma = d\sigma^{\text{LO}} + \alpha_S(Q) d\sigma^{\text{NLO}}(Q) + \alpha_S^2(Q) d\sigma^{\text{NNLO}}(Q) + \dots$$

Fixed Order Calculations

Expand cross sections to a fixed order in the strong coupling: **virtual** (loop) corrections and **real emission** contributions enter in different phase space dependence.

$$\int |\mu_{\text{Lo}}|^2 u(\phi_n) d\phi_n + \int 2\text{Re}(\mu_{\text{Lo}}^* \mu_{\text{virt}}) u(\phi_n) d\phi_n \\ + \int |\mu_{\text{real}}|^2 u(\phi_{n+1}) d\phi_{n+1} + \mathcal{O}(\alpha_s^2)$$

$$\mu_{\text{Lo}} = \text{diagram} + \dots$$

$$\mu_{\text{virt}} = \text{diagram} + \dots \quad \mu_{\text{real}} = \text{diagram} + \dots$$

For suitable **observables**, infrared divergencies cancel between real emission and virtual corrections.
UV divergencies in the virtual corrections will be removed.

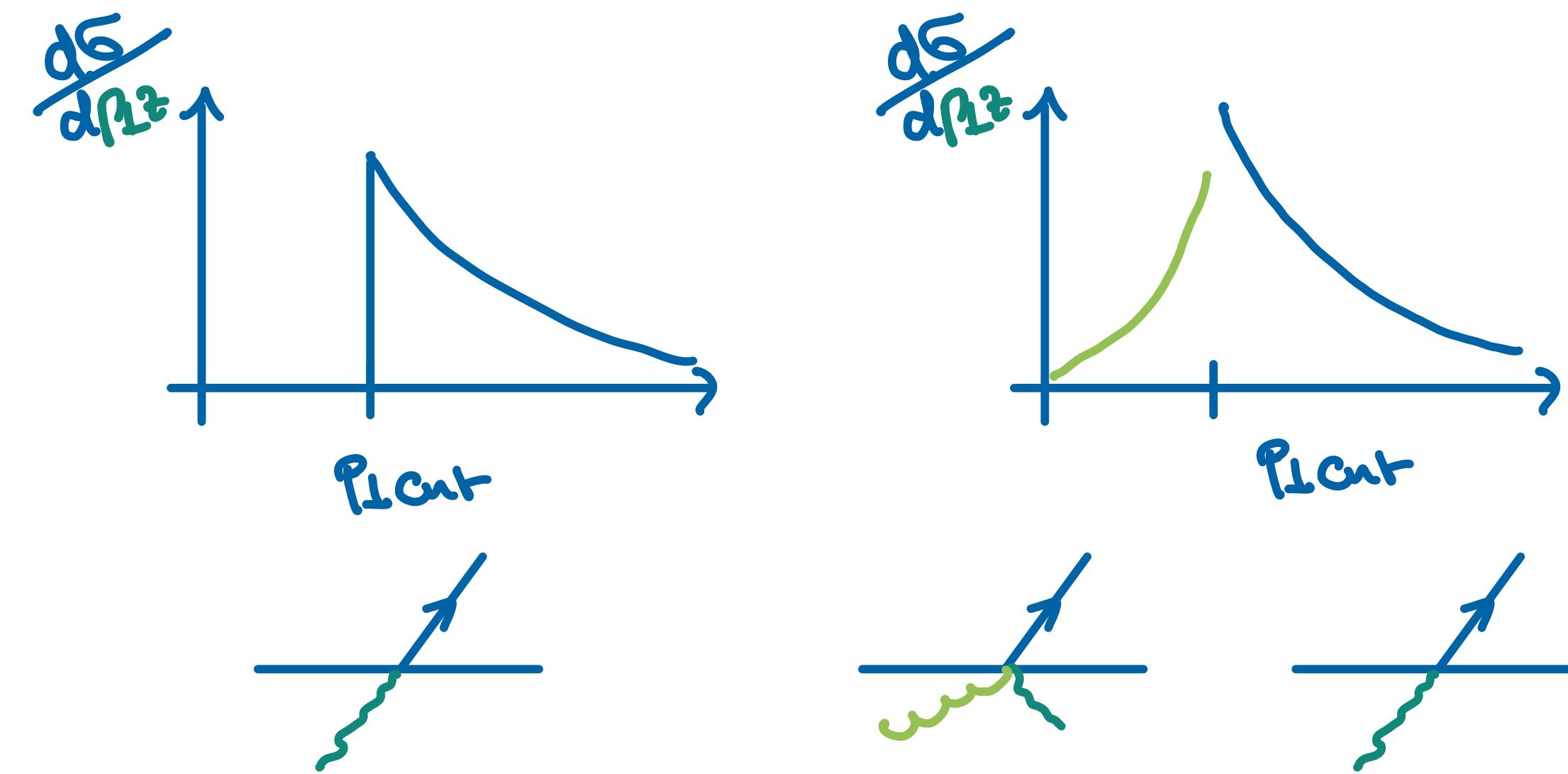
Accuracy of Fixed Order Calculations

Fixed order calculations can describe jet cross sections, or cross sections with identified hadrons in the initial or final state, which require the introduction of parton distribution or fragmentation functions.

$$\alpha_s(\xi \mu_R) = \alpha_s(\mu_R) - \alpha_s^2(\mu_R) (\beta_0 \ln \xi + \mathcal{O}(\alpha_s^3))$$

$$2\text{Re}(\mu_{\text{lo}}^* \mu_{\text{virt}}) \sim 1/\mu_{\text{lo}} l^2 \alpha_s(\mu_R) \beta_0 \ln \frac{\mu_R}{Q} + \dots$$

For an $N^k\text{LO}$ observable, the dependence on the unphysical renormalisation and factorisation scales is postponed to an $N^{k+1}\text{LO}$ contribution: use their variation as an estimate of higher order corrections.



Some comment is needed

The Subtraction Formalism

Renormalized **virtual** corrections in dimensional regularization:

Poles in ϵ due to loop momenta soft and/or collinear to external momenta.

Real contributions divergent for soft/collinear emission:

Poles in ϵ after integration over phase space.

$$\begin{aligned} & \int [2\text{Re}(\mu_{\text{lo}}^* \mu_{\text{virt}}) + \int \mu_{\text{lo}}^\alpha V_{\alpha\beta} \mu_{\text{lo}}^{*\beta} d\Phi_1]_{\Sigma=0} u(\Phi_n) d\Phi_m \\ & + \left[[\mu_{\text{real}}|^2 u(\Phi_{n+1}) - \mu_{\text{lo}}^\alpha V_{\alpha\beta} \mu_{\text{lo}}^{*\beta} u(\Xi_n(\Phi_{n+1}))] d\Phi_{m+1} \right]_{\Sigma=0} \end{aligned}$$

Use **subtraction** terms to handle divergencies.

Cannot generate ‘events’ from fixed-order cross sections — real emission and subtraction term contributions highly correlated.

Use subtraction terms to handle divergencies.

$$\int [2\operatorname{Re}(\mu_{\text{real}}^* \mu_{\text{virt}}) + \int \mu_{\text{real}}^\alpha \nabla_\beta \mu_{\text{real}}^{*\beta} d\Phi_1]_{\Sigma=0} u(\phi_n) d\Phi_n \\ + \left[[\mu_{\text{real}}|^2 u(\phi_{n+1}) - \mu_{\text{real}}^\alpha \nabla_\beta \mu_{\text{real}}^{*\beta} u(\Phi_n(\phi_{n+1}))] d\Phi_{n+1} \right]_{\Sigma=\infty}$$

Subtracted cross sections only finite for infrared safe observables:

$$u(\phi_{n+1}) \rightarrow u(\phi_n)$$

$$E_g \ll Q \text{ or } \cos \theta_{gi} \rightarrow 1$$

$$\Phi_n(\phi_{n+1}) \rightarrow \Phi_n$$

No collinear divergence for massive cartons, but enhancement possible.

Subtraction at Work

Let us illustrate the technique with a toy model.

$$|\mu_{\text{lo}}|^2 u(\phi_{\text{lo}}) = \alpha_0 u(0)$$

$$\begin{aligned} u_{\text{virt}} &= -\alpha_0 \mu_{\text{lo}} \int_0^\infty \frac{dx}{x^{1-\varepsilon}} (\beta_0 \Theta(x-\mu) + \kappa \Theta(\mu-x)) \\ &= \left(\alpha_0 \beta_0 \frac{1}{\varepsilon} \mu^\varepsilon - \alpha_0 \kappa \frac{1}{\varepsilon} \mu^\varepsilon \right) \mu_{\text{lo}} \end{aligned}$$

$$|\mu_{\text{real}}|^2 u(\phi_{\text{real}}) d\phi_{\mu+1} = \alpha_0 \frac{\kappa + c x}{x^{1-\varepsilon}} u(x) \Theta(\mu-x)$$

$$\mu_{\text{lo}}^* V_{\alpha\beta} \mu_{\text{lo}}^* u(\Xi_{\mu}(\phi_{\mu+1})) d\phi_{\mu+1} = \alpha_0 \frac{1}{x^{1-\varepsilon}} \kappa u(0) \Theta(\mu-x)$$

Subtracted real emission contribution
is (integrable) finite in four dimensions:

Bare coupling will be renormalised and provides counter term for the UV divergence:

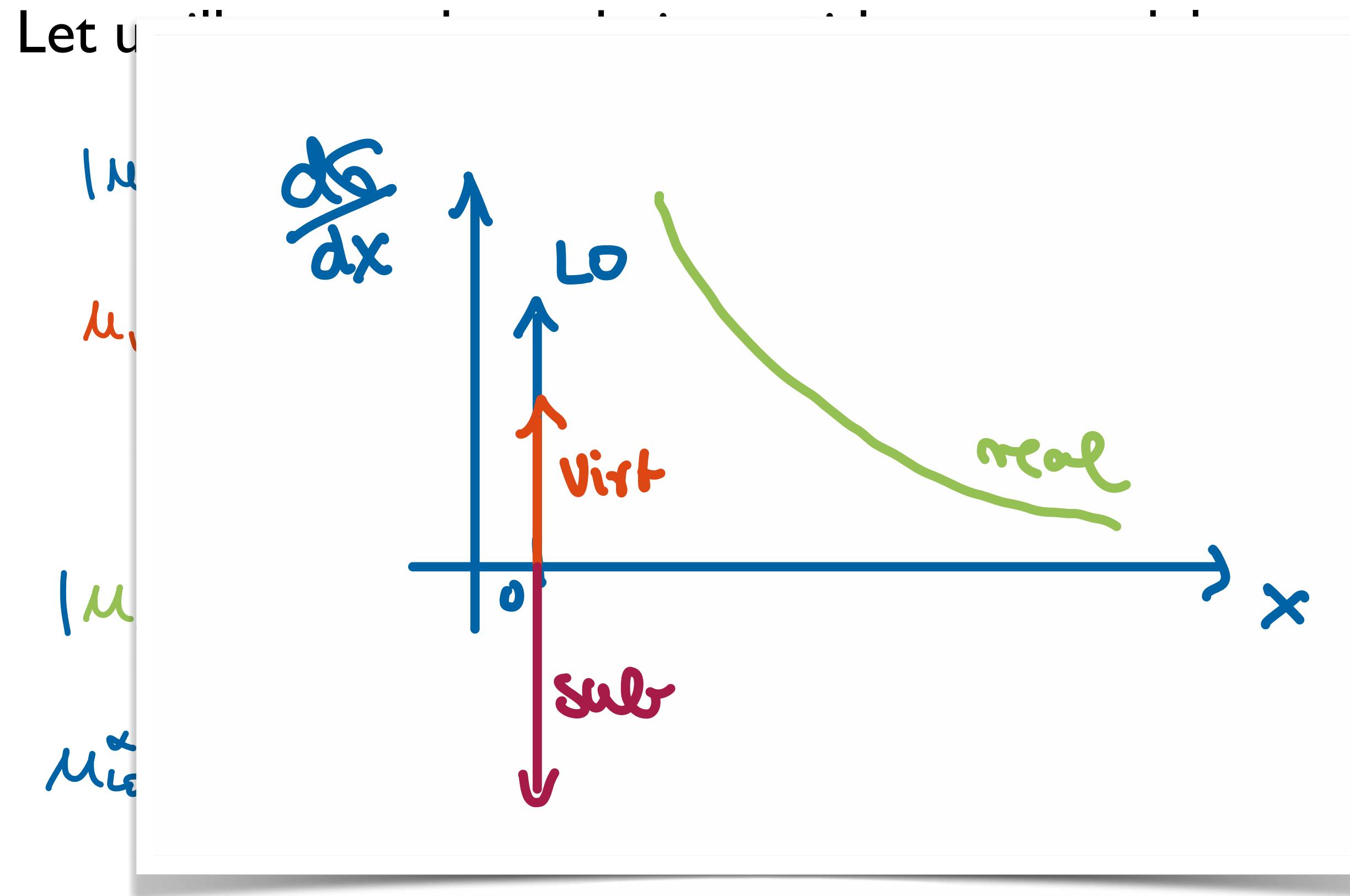
$$\alpha_0 = \alpha_s(\mu_R) \left(\frac{\mu_R}{\mu} \right)^\varepsilon \left(1 - \frac{\beta_0}{\varepsilon} \alpha_s(\mu_R) + \mathcal{O}(\alpha_s(\mu_R^2)) \right)$$

Real emission and subtraction terms:
integral of the subtraction term will
cancel the IR divergence

$$(|\mu_{\text{real}}|^2 u(\phi_{\text{real}}) - \mu_{\text{lo}}^* V_{\alpha\beta} \mu_{\text{lo}}^* u(\Xi_{\mu}(\phi_{\mu+1}))) d\phi_{\mu+1}$$

$$\underset{\varepsilon \rightarrow 0}{\sim} \alpha_s(\mu) \left(c u(x) + \frac{\kappa}{x} (u(x) - u(0)) \right) + \mathcal{O}(\alpha_s^2(\mu))$$

Subtraction at Work



Subtracted real emission contribution is (integrable) finite in four dimensions:

Bare coupling will be renormalised and provides counter term for the UV divergence:

$$\alpha_0 = \alpha_s(\mu_R) \left(\frac{\mu_R}{\mu} \right)^\varepsilon \left(1 - \frac{\beta_0}{\Sigma} \alpha_s(\mu_R) + \mathcal{O}(\alpha_s(\mu^3)) \right)$$

Real emission and subtraction terms: integral of the subtraction term will cancel the IR divergence

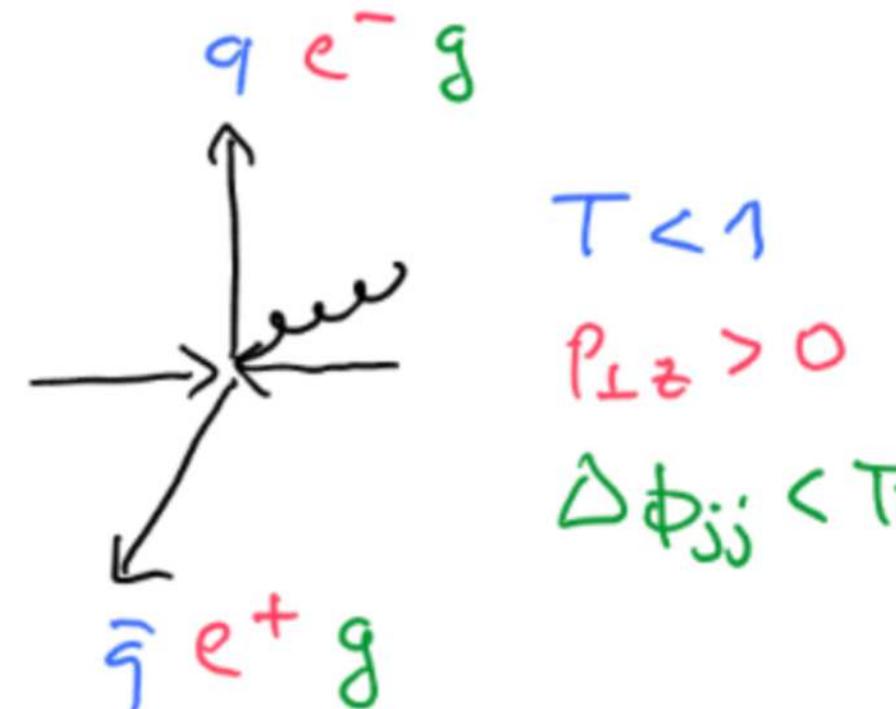
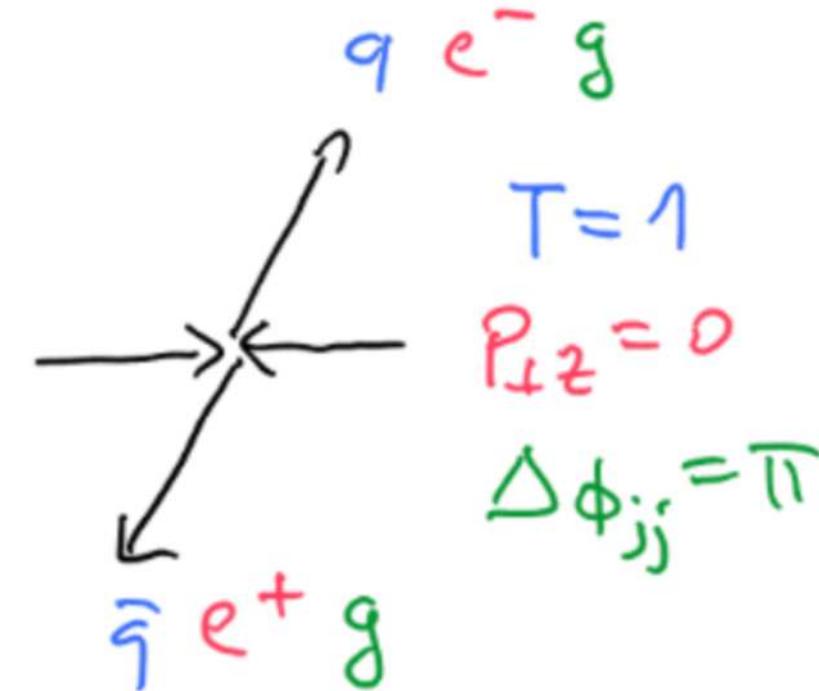
$$\left(|\mu_{\text{real}}|^2 u(\phi_{\mu}) - \mu_\infty^\varepsilon V_{\phi\phi} \mu_\infty^{\beta} u(\Xi_\mu(\phi_{\mu})) \right) d\phi_{\mu+1}$$
$$\underset{\varepsilon \rightarrow 0}{\sim} \alpha_s(\mu_R) \left(C u(x) + \frac{K}{x} (u(x) - u(0)) \right) + \mathcal{O}(\alpha_s^2(\mu_R))$$

Infrared Sensitive Observables

Event generators aim at highly exclusive observables:
Perturbative, high-multiplicity final states — convoluted with phenomenological models.

Require (recursive) infrared safety of these observables, but most of them are infrared sensitive: Measure deviation from an ideal n-jet topology, and require a minimum amount of radiation to acquire non-trivial values.

At any fixed order in perturbation theory they will diverge when the requirement of additional radiation is relaxed.



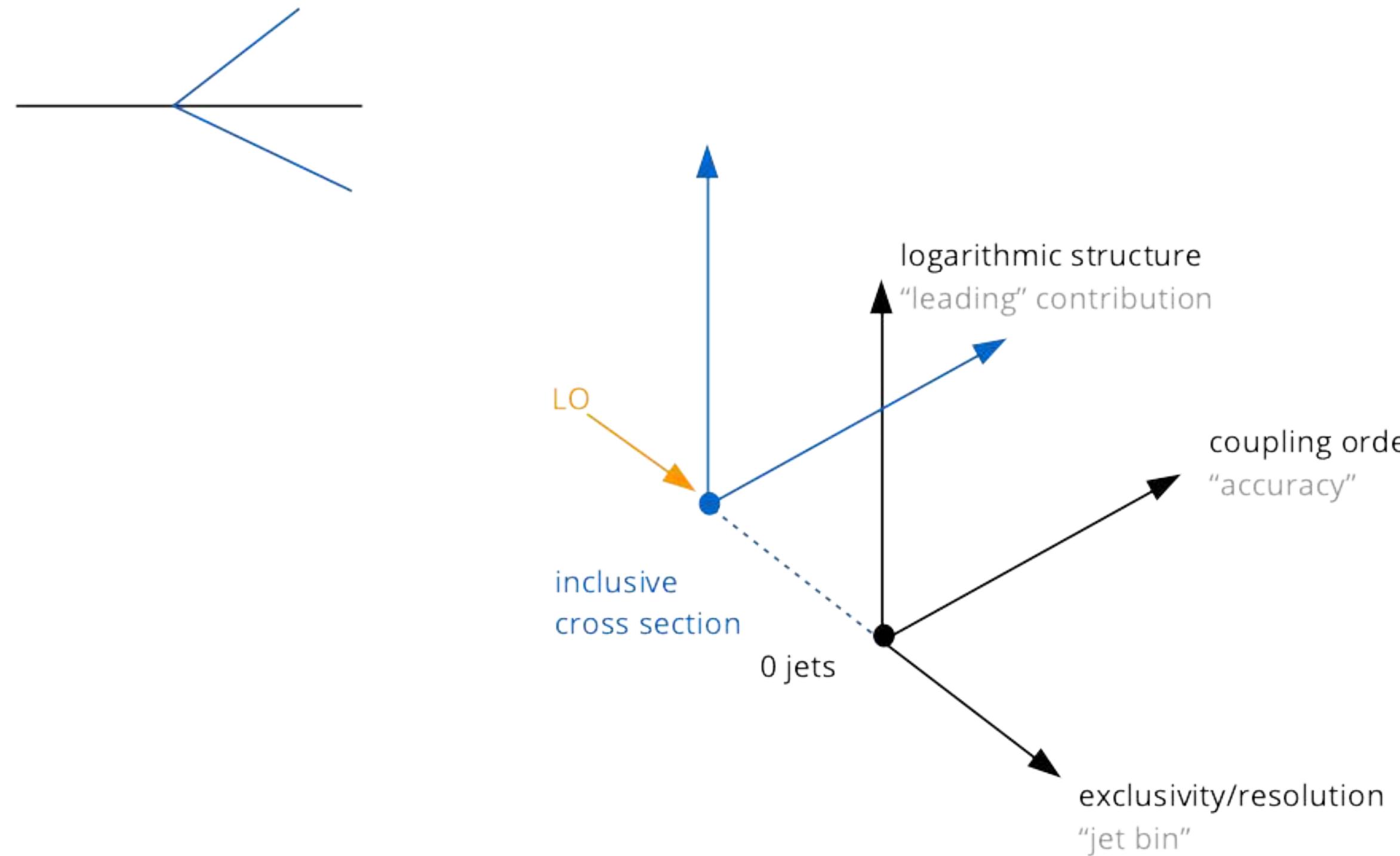
$$\sigma(n \text{ jets}, \tau) \sim \sum_k \sum_{l \leq 2k} c_{nkl} \alpha_s^k(Q) \ln^l \frac{1}{\tau}$$

Landscape of Infrared Sensitive Observables

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ



universität
wien



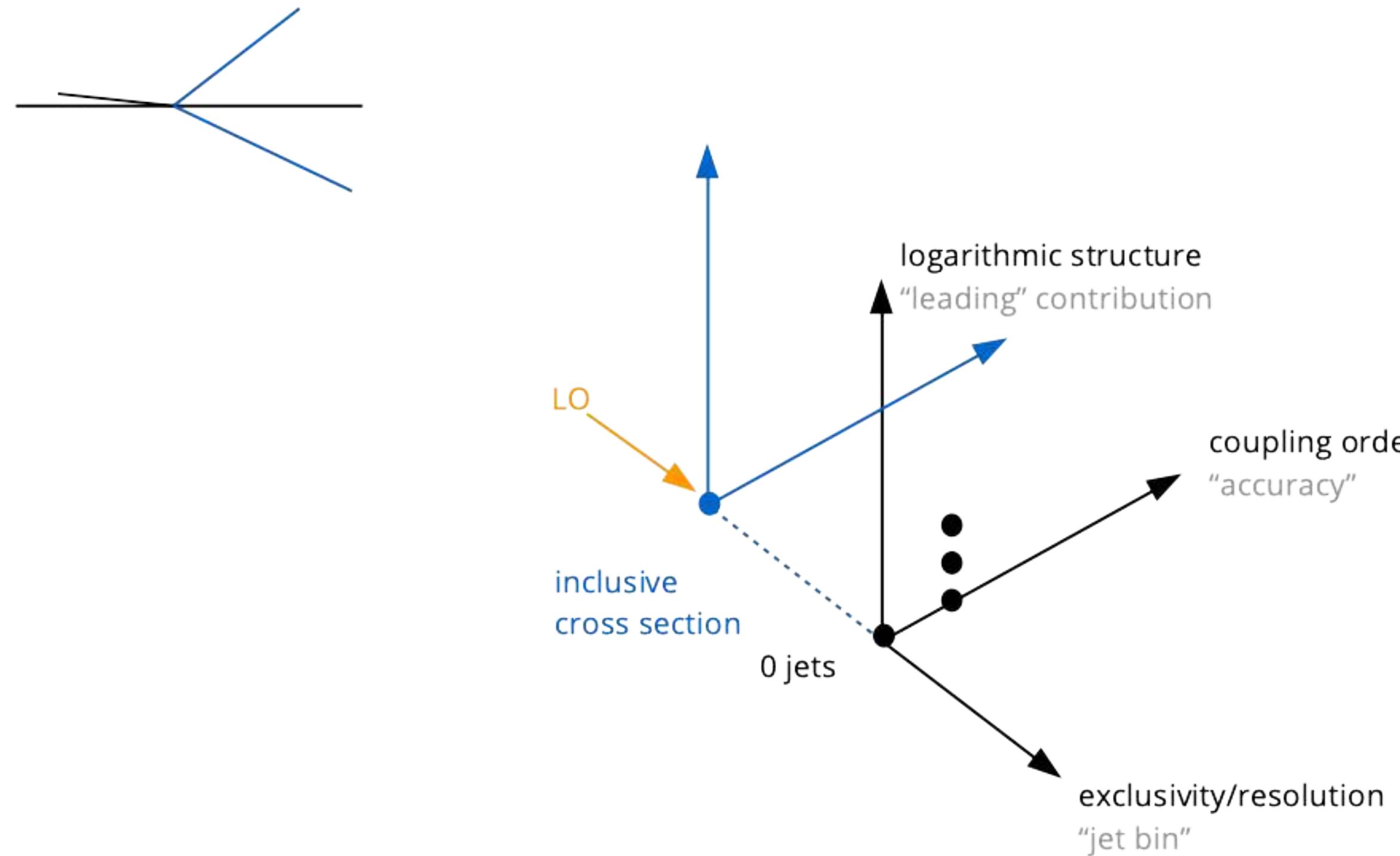
$$\sigma(n \text{ jets}, \tau) \sim \sum_k \sum_{l \leq 2k} c_{nkl} \alpha_s^k(Q) \ln^l \frac{1}{\tau}$$

Landscape of Infrared Sensitive Observables

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ



universität
wien



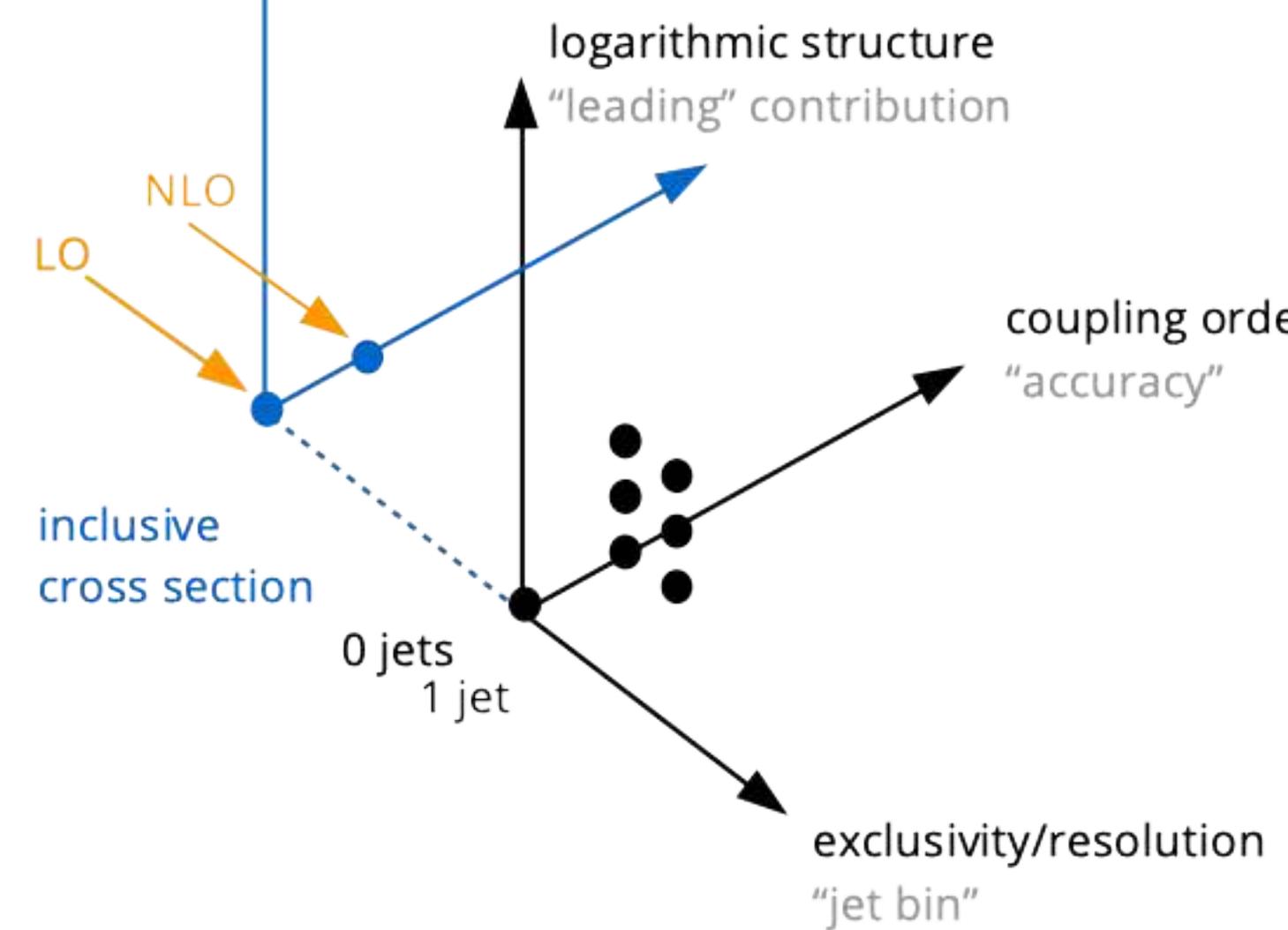
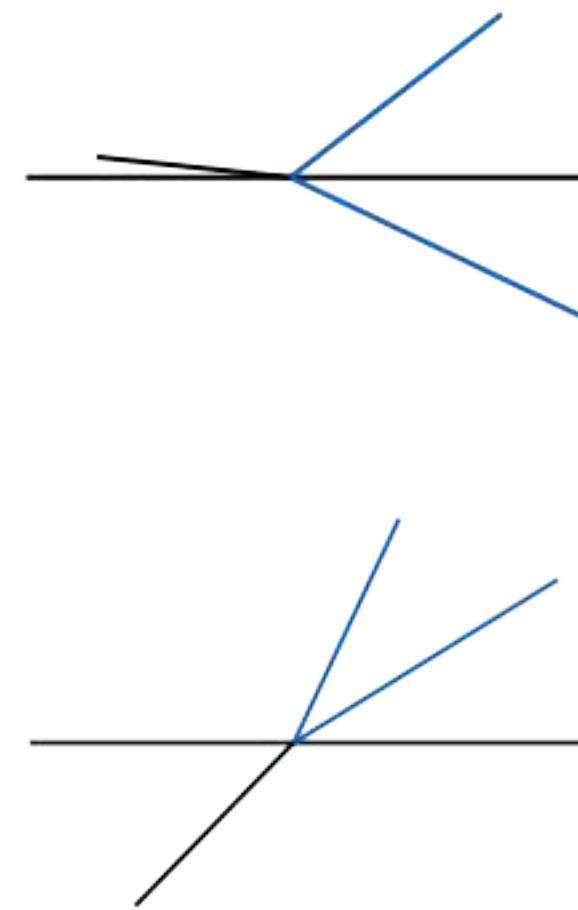
$$\sigma(n \text{ jets}, \tau) \sim \sum_k \sum_{l \leq 2k} c_{nkl} \alpha_s^k(Q) \ln^l \frac{1}{\tau}$$

Landscape of Infrared Sensitive Observables

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ



universität
wien



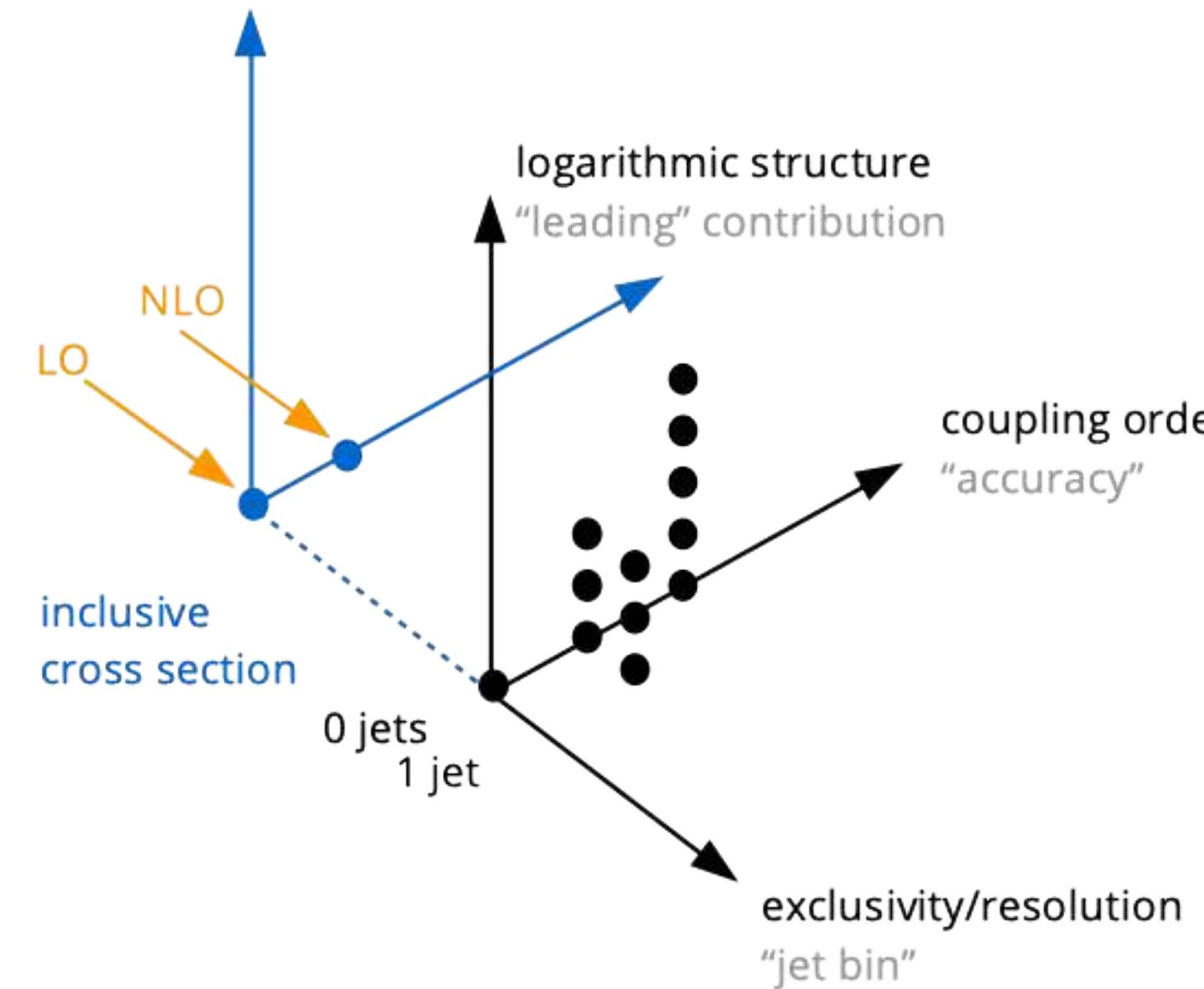
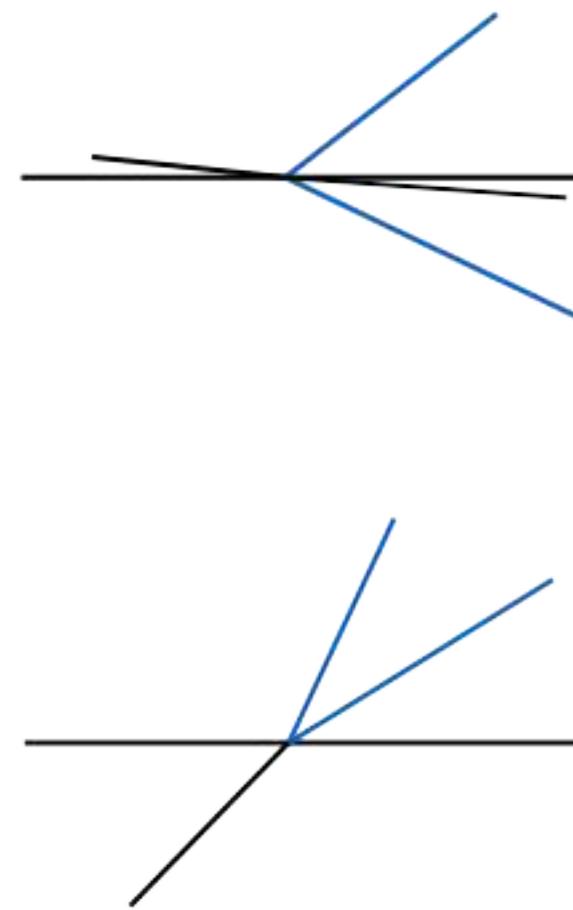
$$\sigma(n \text{ jets}, \tau) \sim \sum_k \sum_{l \leq 2k} c_{nkl} \alpha_s^k(Q) \ln^l \frac{1}{\tau}$$

Landscape of Infrared Sensitive Observables

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ



universität
wien



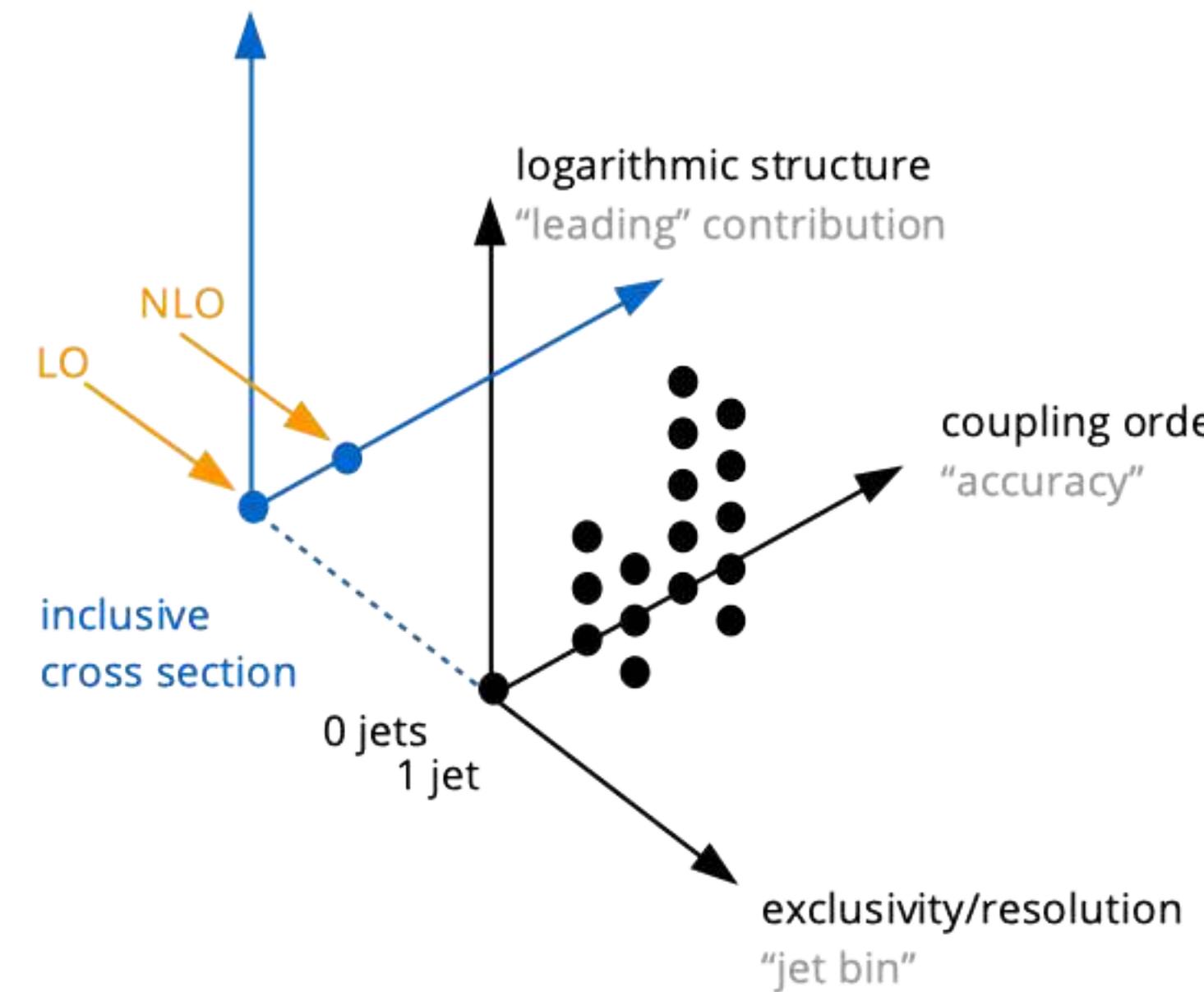
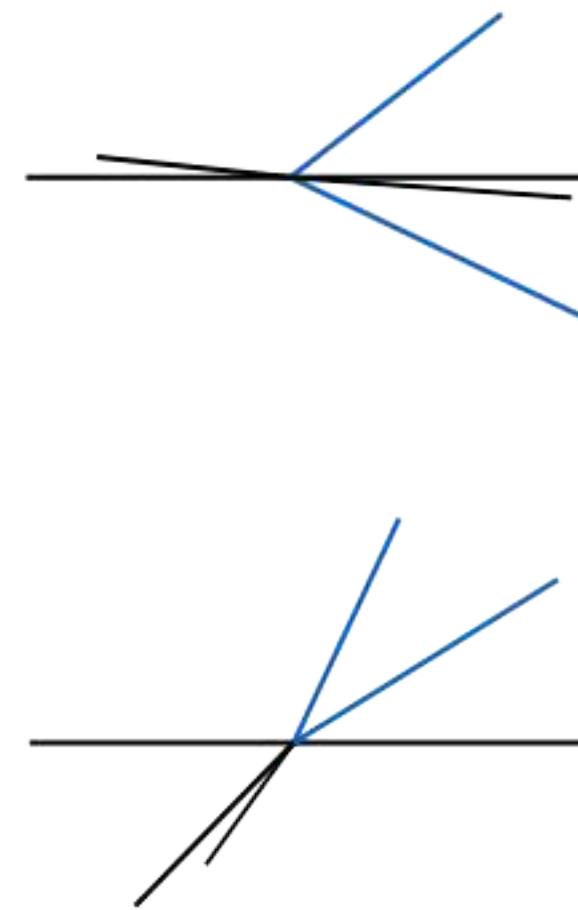
$$\sigma(n \text{ jets}, \tau) \sim \sum_k \sum_{l \leq 2k} c_{nkl} \alpha_s^k(Q) \ln^l \frac{1}{\tau}$$

Landscape of Infrared Sensitive Observables

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ



universität
wien



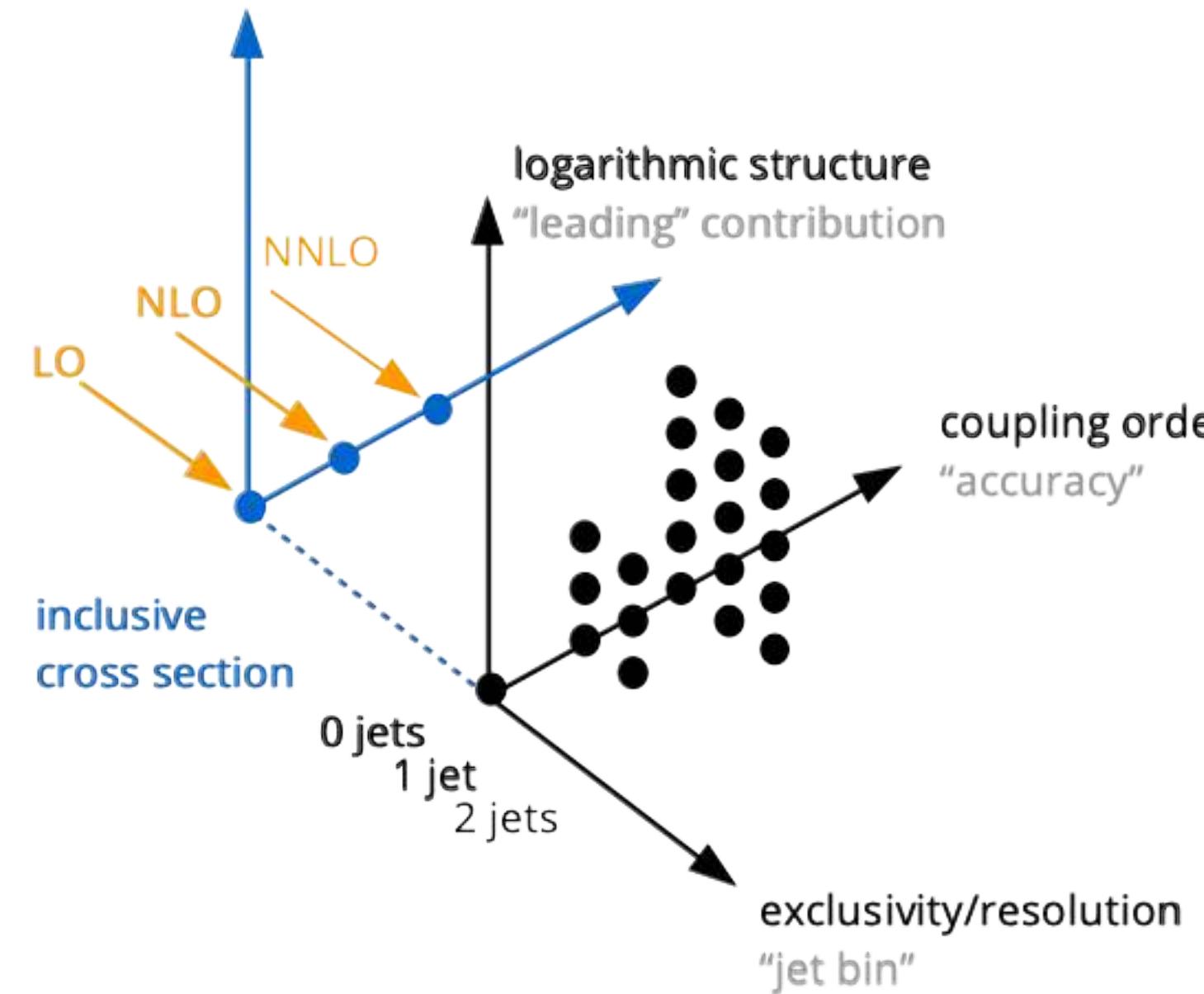
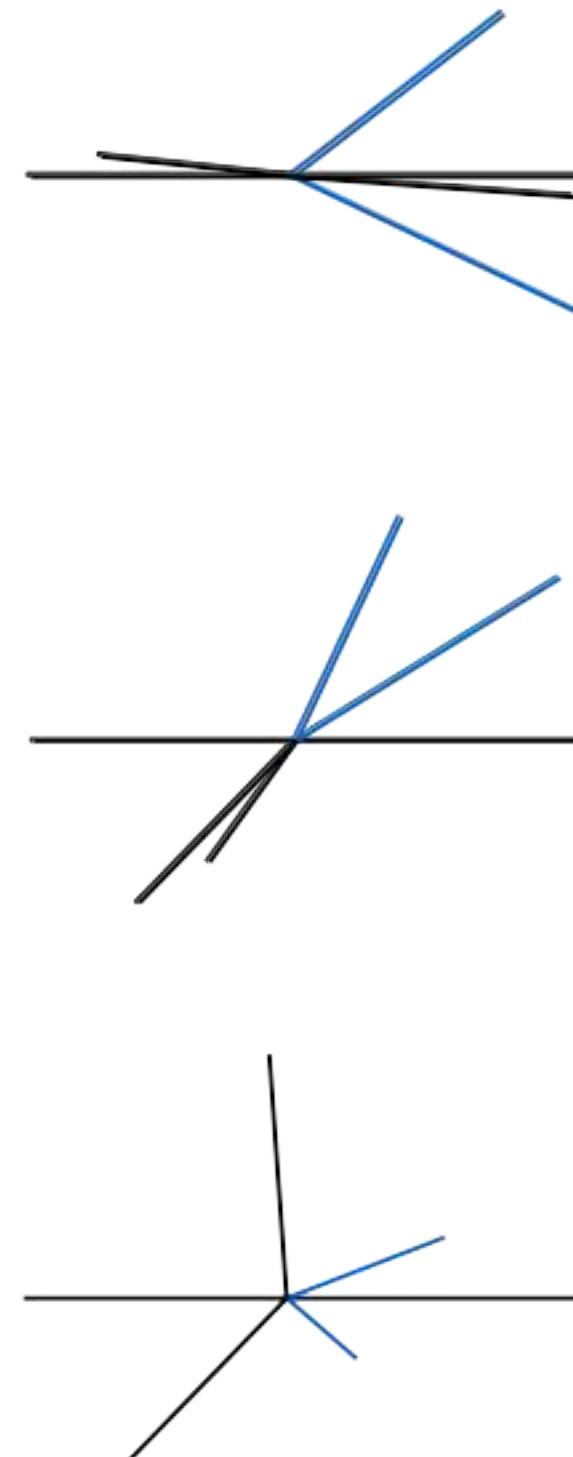
$$\sigma(n \text{ jets}, \tau) \sim \sum_k \sum_{l \leq 2k} c_{nkl} \alpha_s^k(Q) \ln^l \frac{1}{\tau}$$

Landscape of Infrared Sensitive Observables

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ



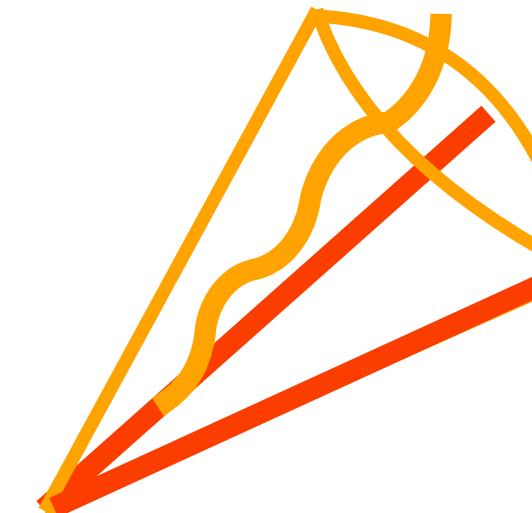
universität
wien



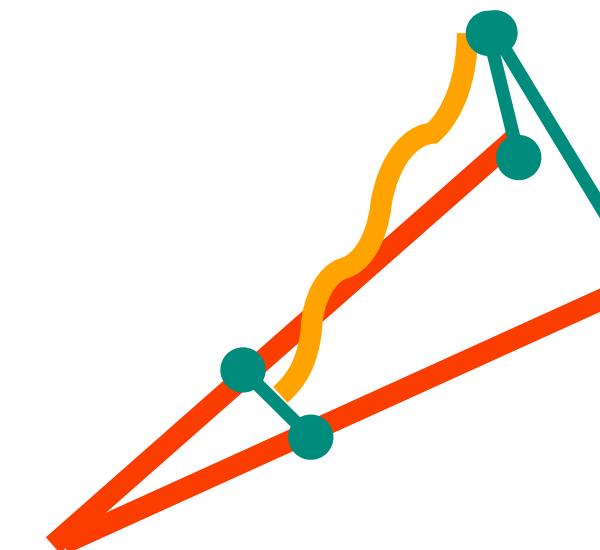
$$\sigma(n \text{ jets}, \tau) \sim \sum_k \sum_{l \leq 2k} c_{nkl} \alpha_s^k(Q) \ln^l \frac{1}{\tau}$$

Probabilistic sequences of emissions from universal splitting kernels. Interference approximate.

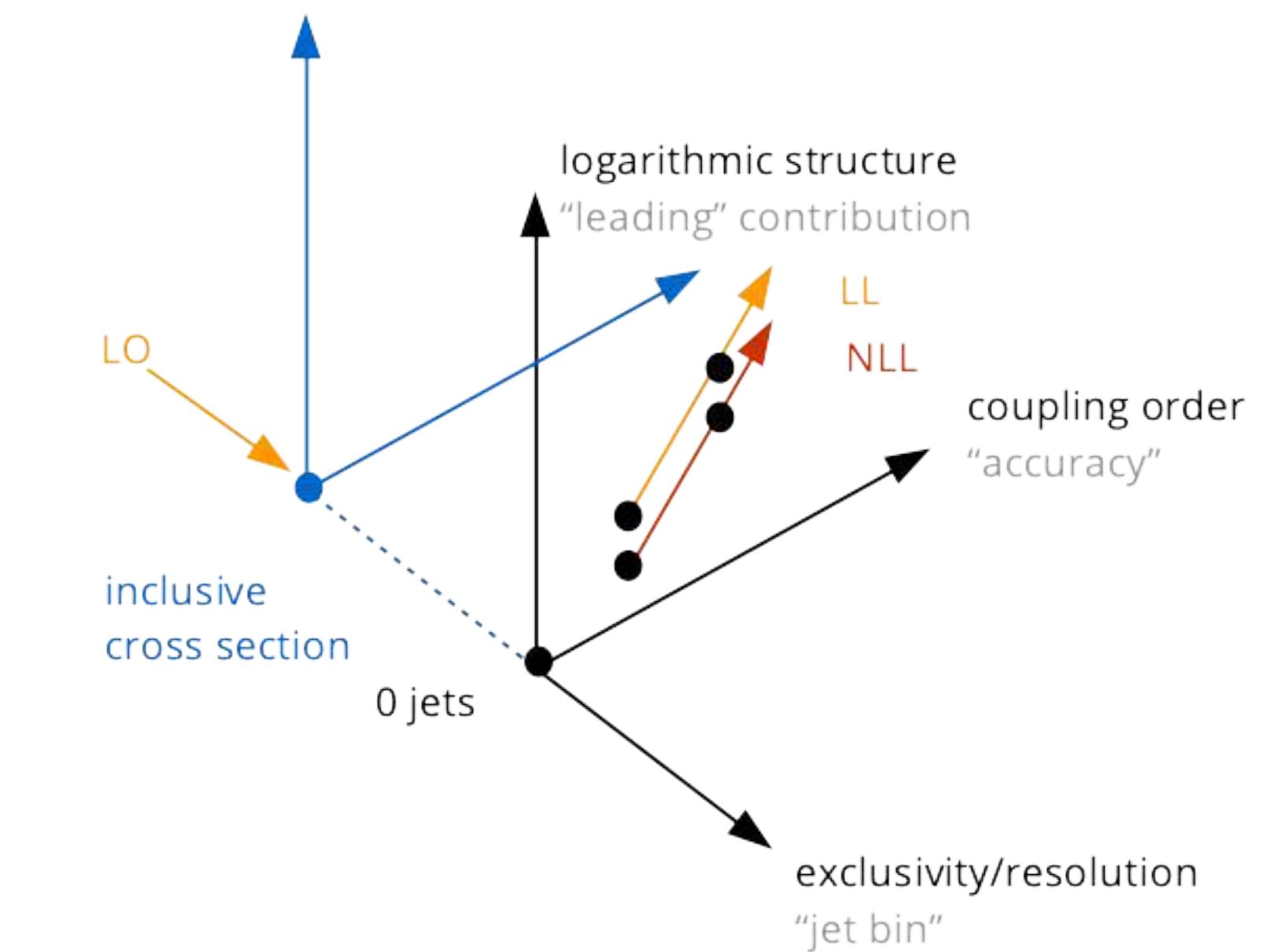
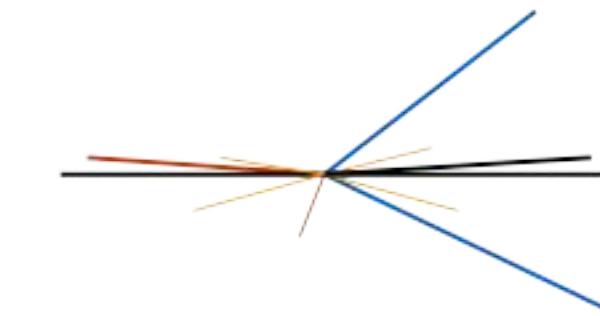
$$d\sigma_{n+1} = \frac{\alpha_s}{2\pi} \frac{dq}{q} dz P(z, q) d\sigma_n$$



Parton branchings order in angle.



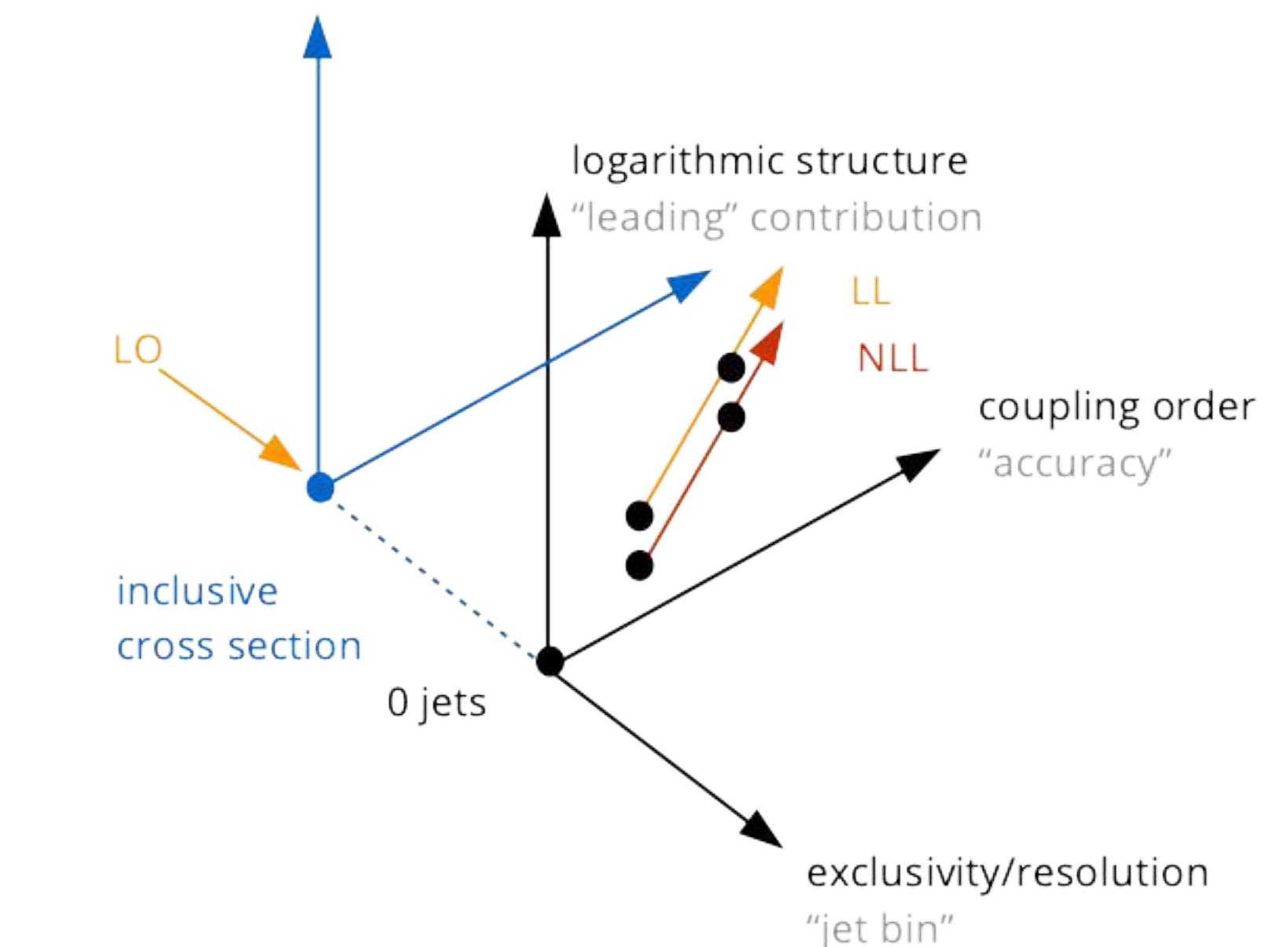
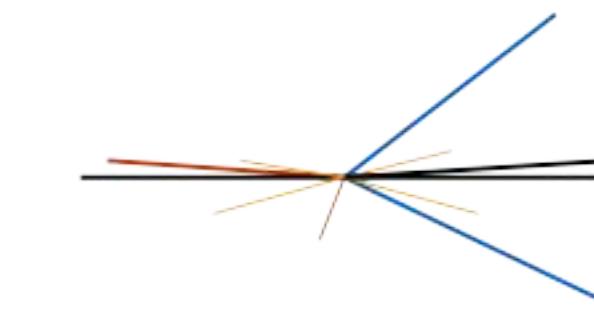
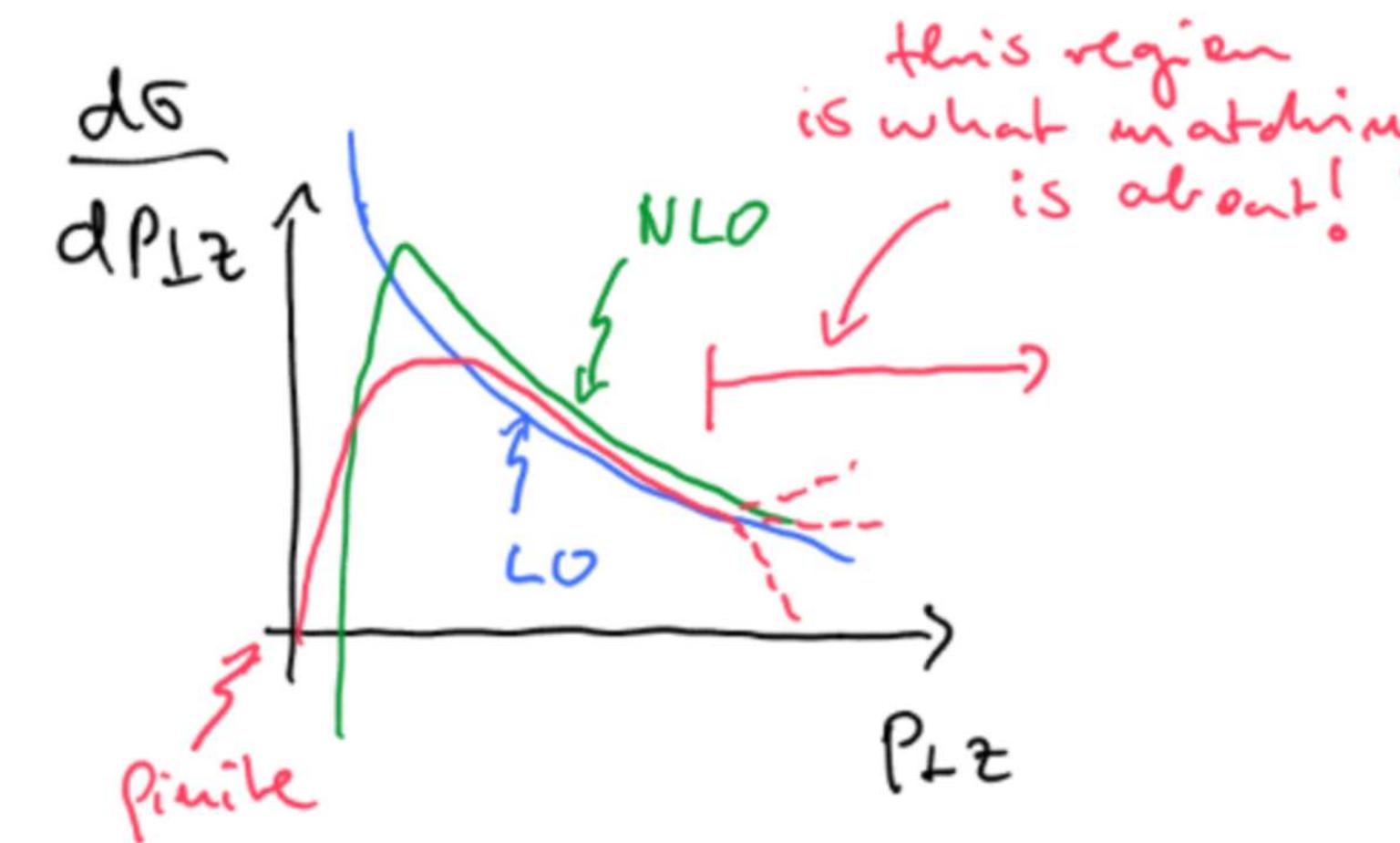
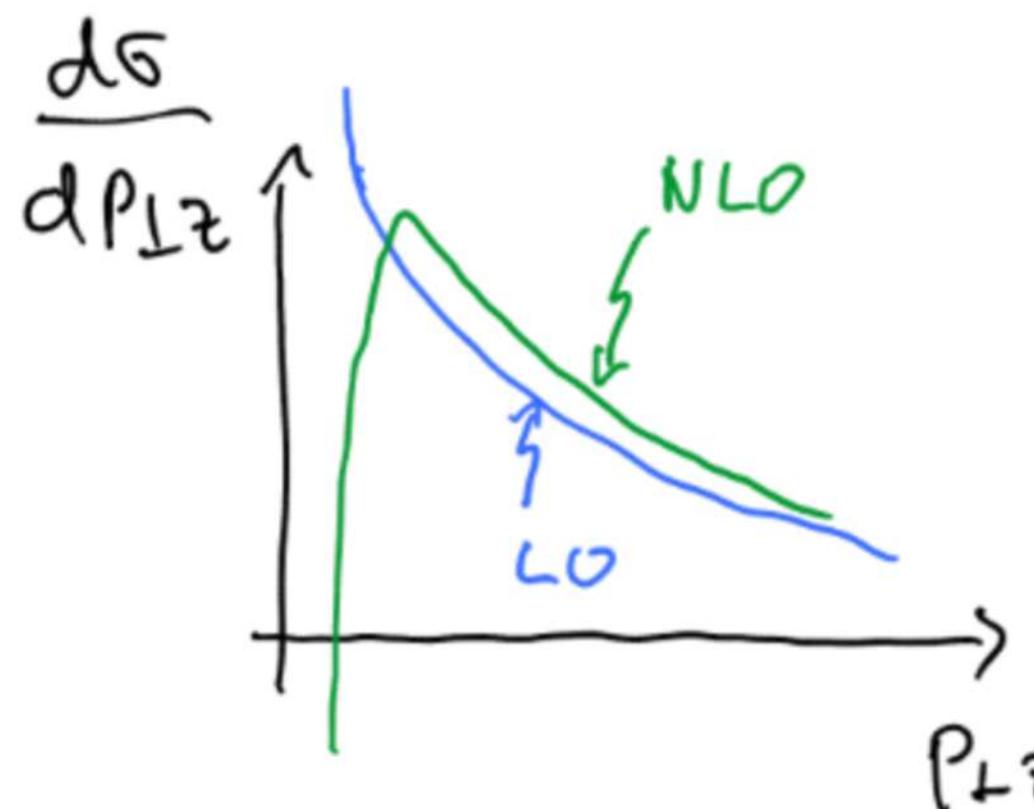
Dipole branchings order in transverse momentum.



$$\sigma(n \text{ jets}, \tau) \sim \sum_k \sum_{l \leq 2k} c_{nkl} \alpha_s^k(Q) \ln^l \frac{1}{\tau}$$

Probabilistic sequences of emissions from universal splitting kernels. Interference approximate.

Physical behaviour of cross sections in regions of soft/collinear radiation.



$$\sigma(n \text{ jets}, \tau) \sim \sum_k \sum_{l \leq 2k} c_{nkl} \alpha_s^k(Q) \ln^l \frac{1}{\tau}$$

Contain **real emission** and **virtual** contributions in no-emission probability:

Iterative procedure

$$\text{PS}_\mu^Q[u](\phi_n) = \Delta(\mu, Q, \phi_n) u(\phi_n) + \sum_{i=1}^n \int_\mu^Q \frac{dq}{q} \int dz V^{(i)}(q, z, \phi_n) \Delta(q, Q, \phi_n) \text{PS}_\mu^q[u](\Phi_{n+1}^{(i)}(\phi_n, q, z))$$

no-emission probability
ordering!emission kernelkinematic mapping

Preserve total inclusive cross section — unitary evolution:

$$1 = \text{PS}_\mu^Q[1] = \Delta(\mu, Q, \phi_n) + \int_\mu^Q \frac{dq}{q} \int dz V(q, z, \phi_n) \Delta(q, Q, \phi_n)$$

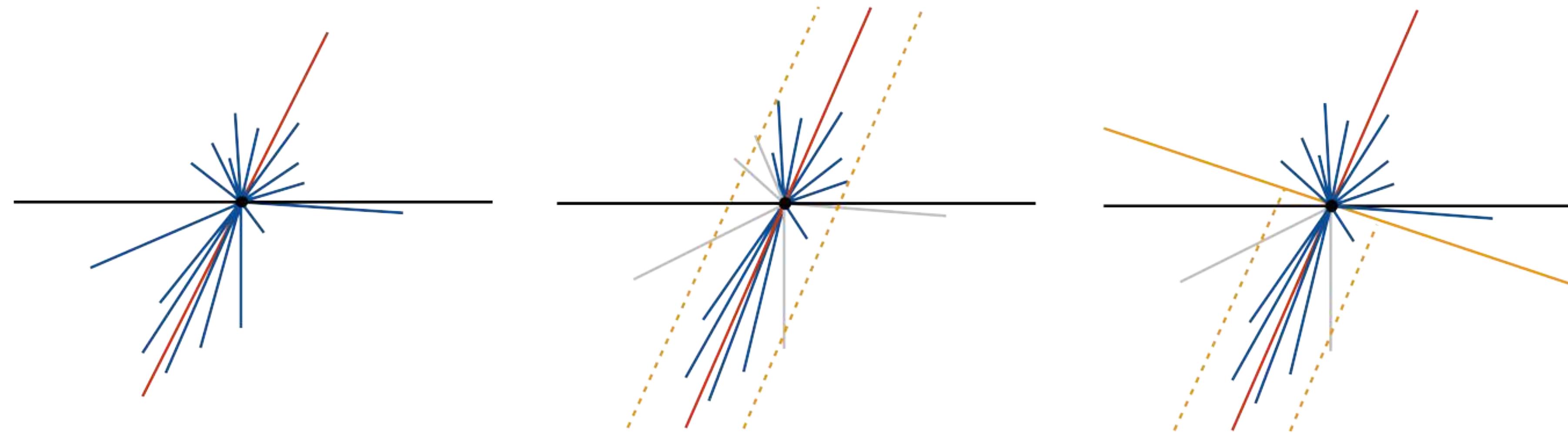
inclusive measurement function

Accuracy of Parton Showers

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ



universität
wien

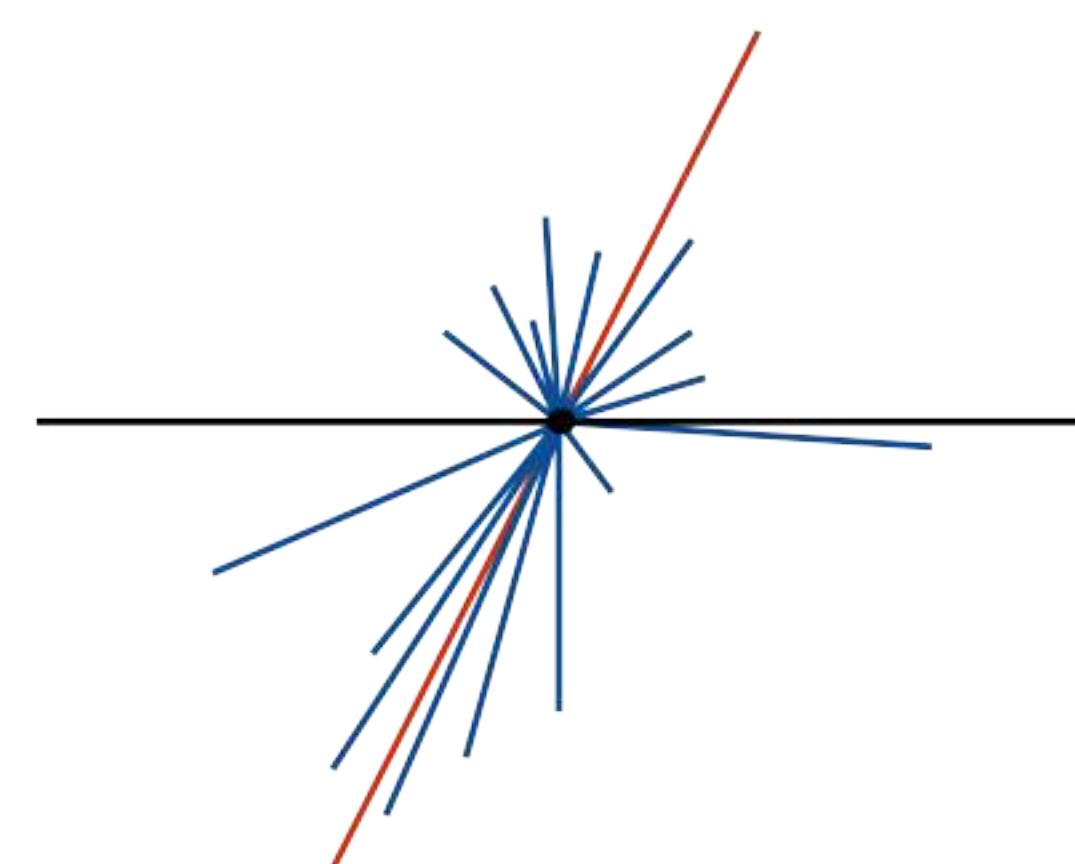


Tailored as resummation algorithms for different classes of observables.

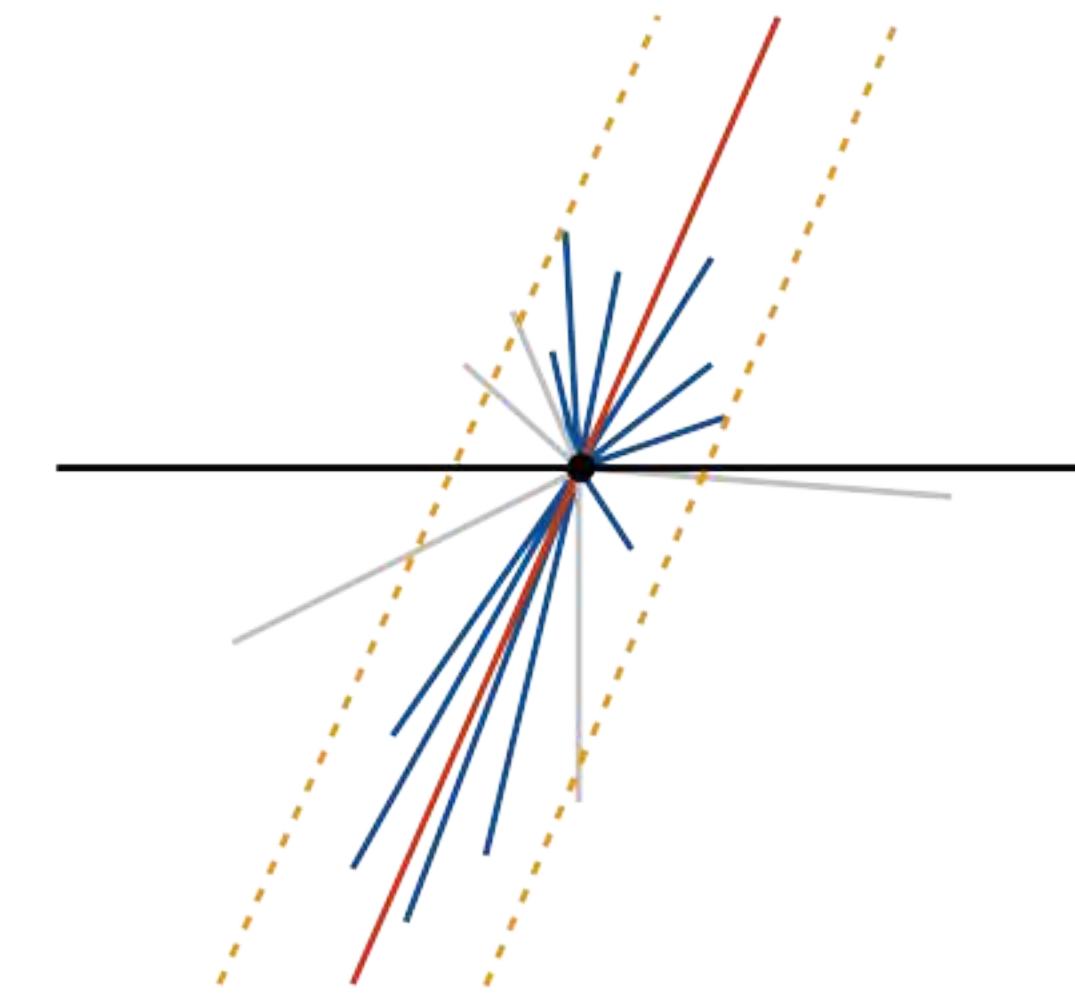
Colour and spin correlations present in factorisation of emissions, but algorithmically hidden in use of QCD coherence or the large-N limit.

$$\sum_i \text{---} \left. \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \vdots \\ \text{---} \end{array} \right\} q_L = \text{---} + \mathcal{O}\left(\frac{q^2}{\alpha_s}\right)$$

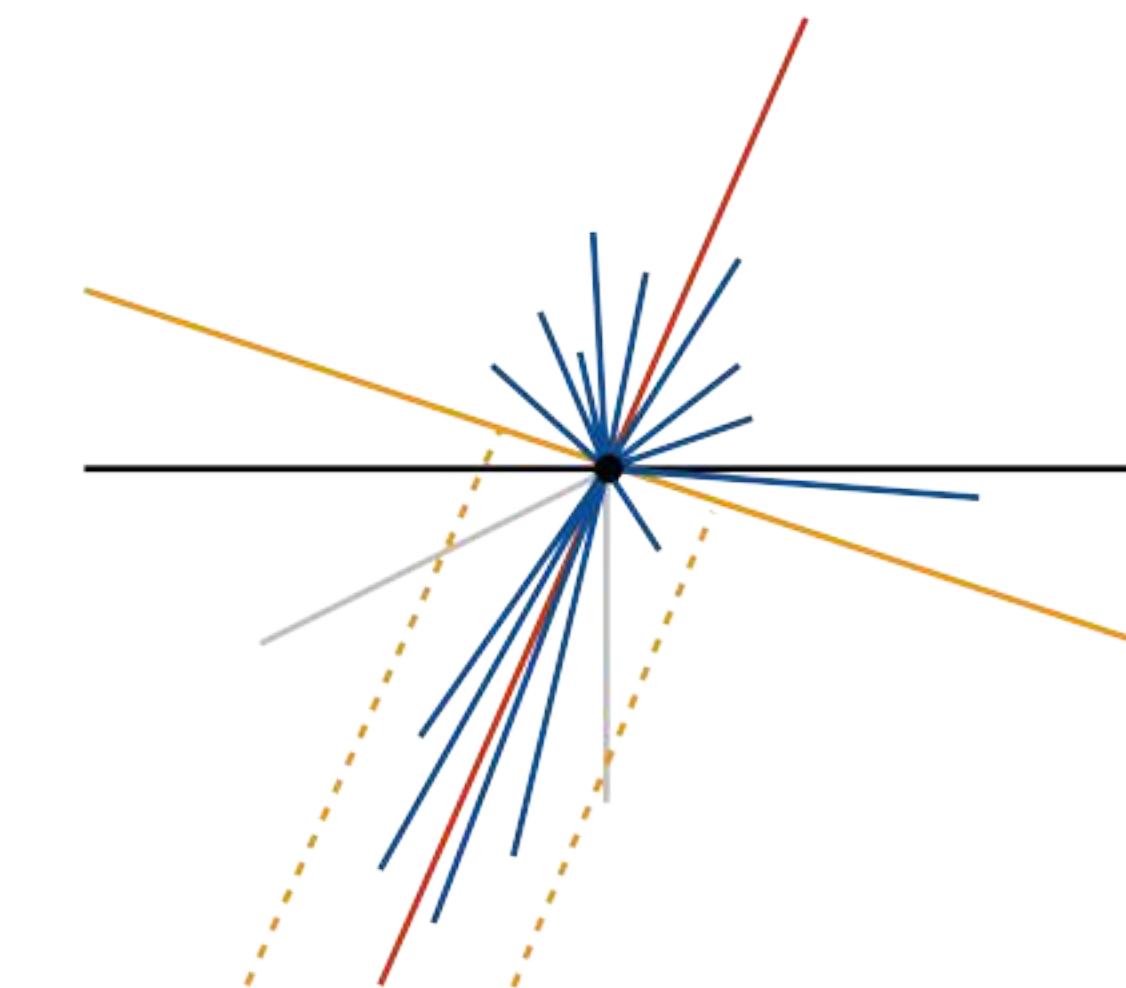
Pressing issues in parton showers



NLO with matching



NLL with coherent branching
Issues in dipole showers

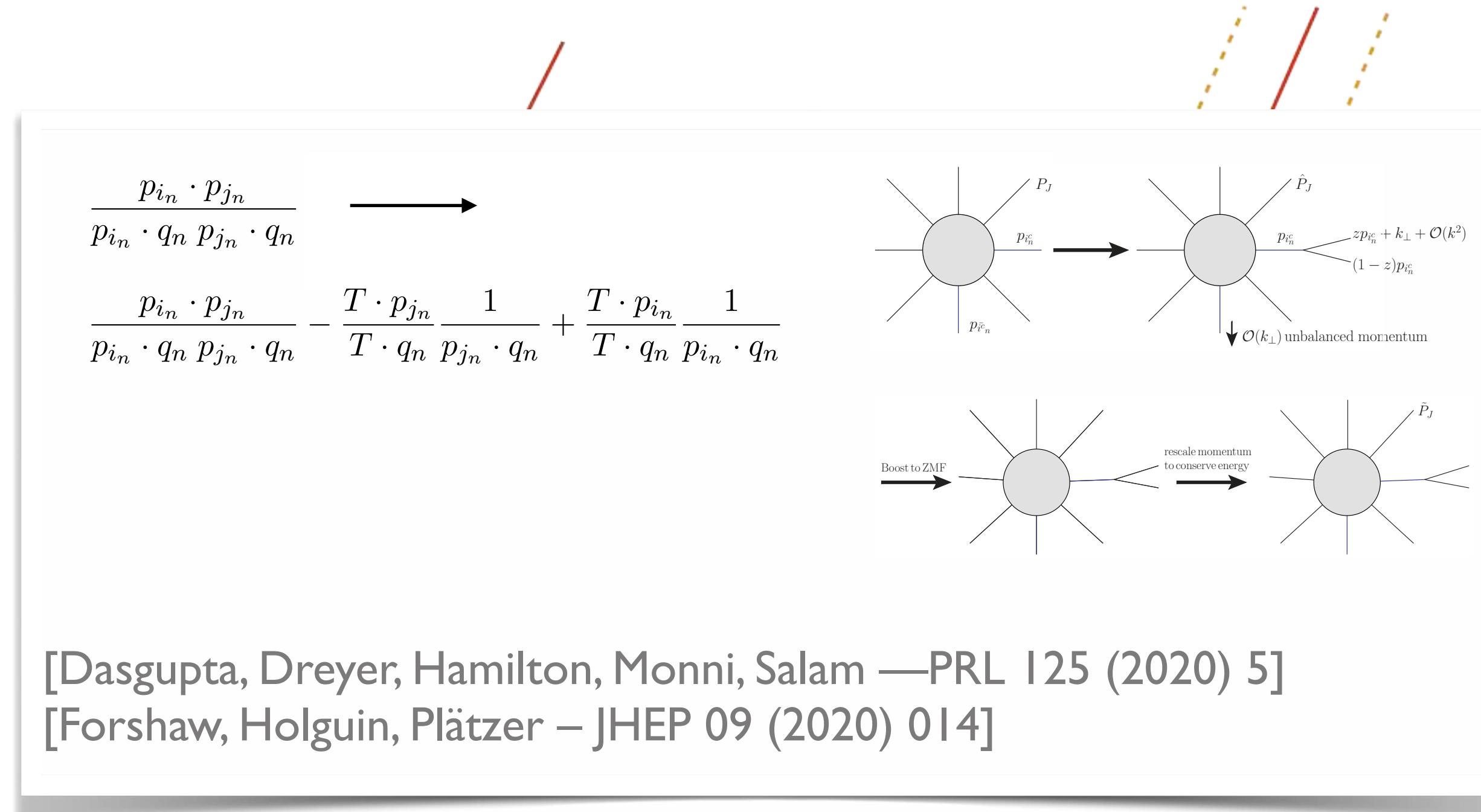


Issues in coherent branching
LL with dipole showers

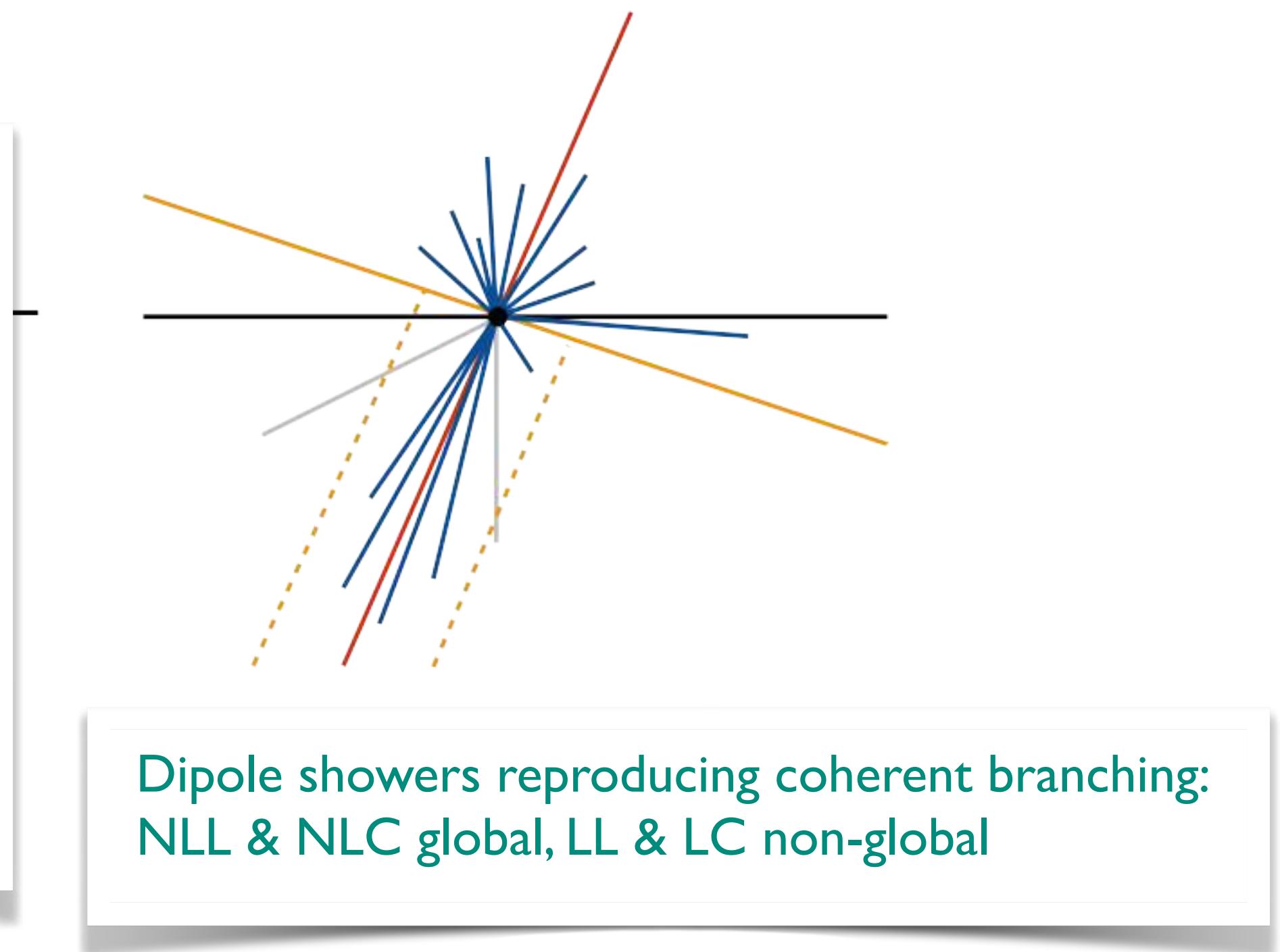
[Dasgupta, Dreyer, Hamilton, Monni, Salam et al.— JHEP 09 (2018) 033, ...]
[Hoang, Plätzer, Samitz — JHEP 1810 (2018) 200]
[Bewick, Ferrario, Richardson, Seymour — JHEP 04 (2020) 019]

$$\sigma(n \text{ jets}, \tau) \sim \sum_k \sum_{l \leq 2k} c_{nkl} \alpha_s^k(Q) \ln^l \frac{1}{\tau}$$

Pressing issues in parton showers



[Dasgupta, Dreyer, Hamilton, Monni, Salam — PRL 125 (2020) 5]
 [Forshaw, Holguin, Plätzer — JHEP 09 (2020) 014]



[Dasgupta, Dreyer, Hamilton, Monni, Salam et al. — JHEP 09 (2018) 033, ...]
 [Hoang, Plätzer, Samitz — JHEP 1810 (2018) 200]
 [Bewick, Ferrario, Richardson, Seymour — JHEP 04 (2020) 019]

$$\sigma(n \text{ jets}, \tau) \sim \sum_k \sum_{l \leq 2k} c_{nkl} \ \alpha_s^k(Q) \ \ln^l \frac{1}{\tau}$$

Matching and Merging

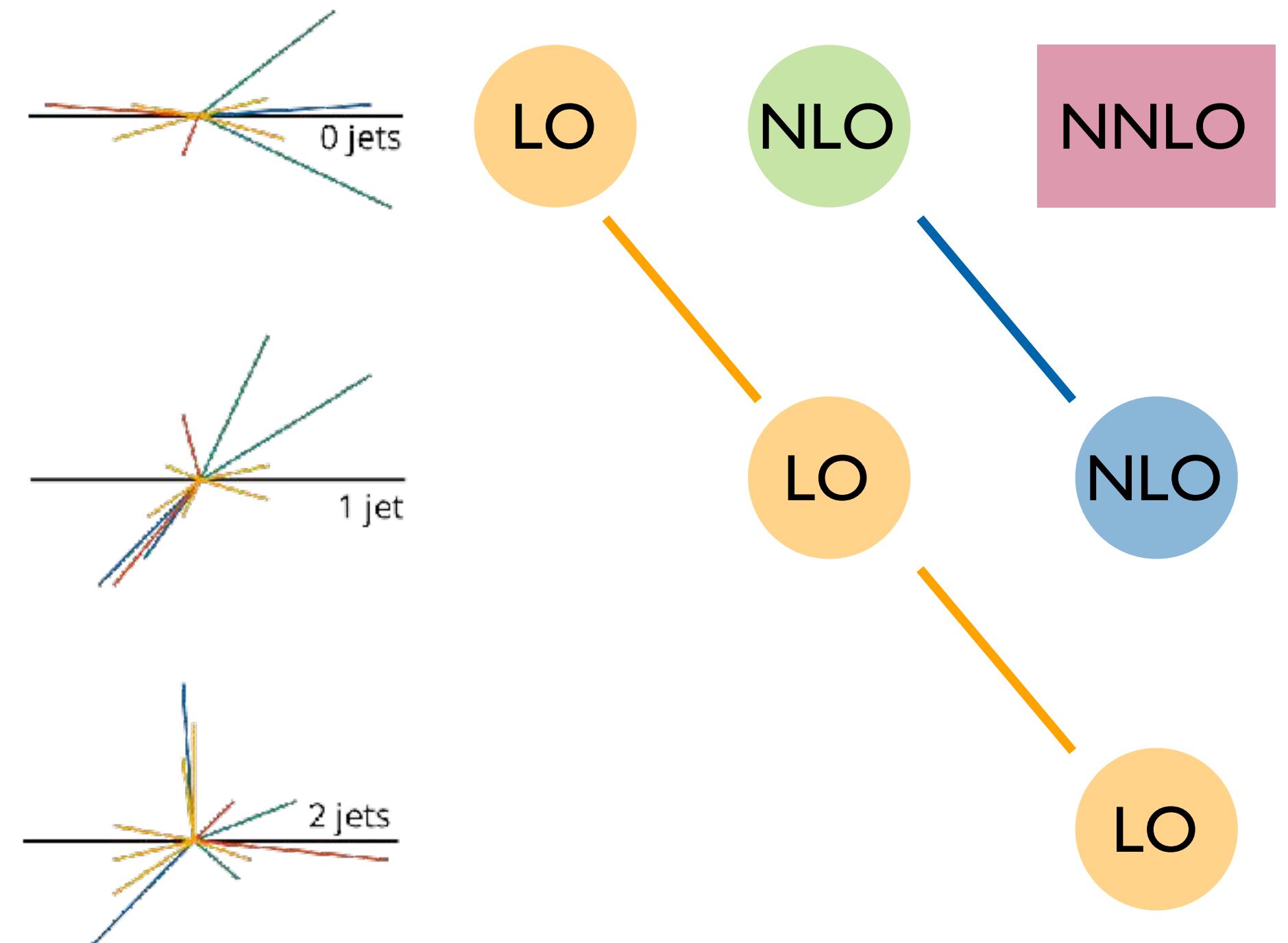
Egal — “Hauptsache Higher Orders”

Matching:

- Combine resummation with fixed order.
- Here: combine a parton shower with an NLO calculation.
- Applicable only where the fixed order calculation is reliable, not the lower jet bin.

Merging:

- Combine calculations of different jet multiplicity with a parton shower.
- Applicable across jet bins.
- At low scales only shower predictions.



LO merging
NLO matching
NLO merging

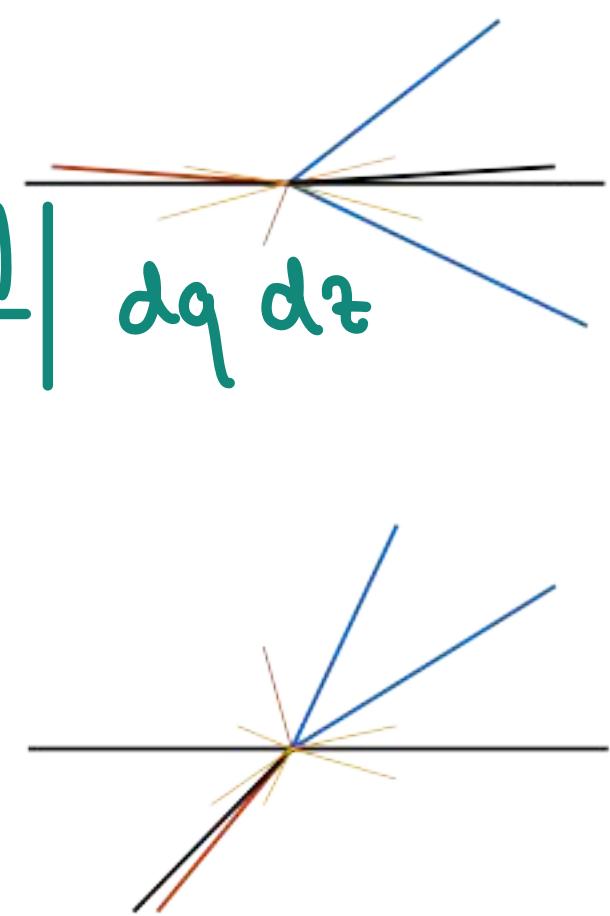
Matrix Element Corrections

[Sjöstrand, Seymour ...]

Invert the approximation as far as possible:

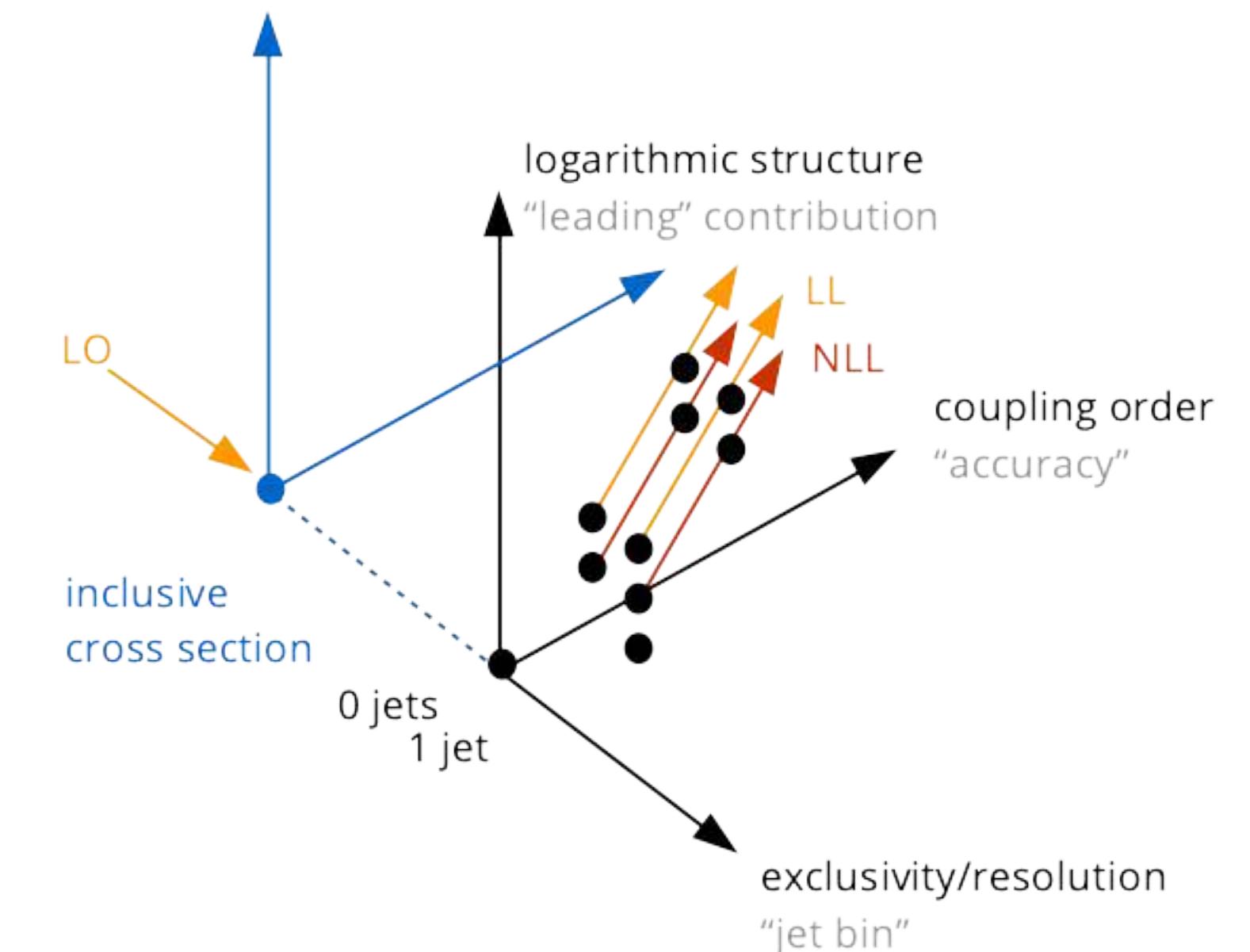
$$d\sigma_{\text{inel}}(\phi_{n+1}) \simeq d\sigma_n(\Sigma_n(\phi_n)) \\ \times V(q, z, \phi_n) \left| \frac{\partial \Sigma_n(q, z, \phi_n)}{\partial (q, z, \phi_n)} \right| dq dz$$

Might help to restore non-trivial correlations upon fixed-order expansion.



Mind that we calculate virtual corrections only from unitarity: improvement is only seen in shapes.

$$d\sigma_n(\phi_n) \underset{\mu}{\text{PS}}^Q [u(\phi_n)] \\ = d\sigma_n(\phi_n) \left(1 - \int_0^\infty dh dz \int_m V(h, z, \phi_n) u(h) \right) u(\phi_n) \\ + |M_u|^2 (\Phi_n(\phi_n)) V(\phi_{n+1}) \\ \Theta(Q - q(\phi_{n+1})) \Theta(q(\phi_{n+1}) - \mu) d\phi_{n+1} u(\phi_{n+1}) + \mathcal{O}(x_s^2)$$



Matrix Element Corrections

[Sjöstrand, Seymour ...]

Invert the approximation as far as possible:

$$d\sigma_{n+1}(\phi_{n+1}) \simeq d\sigma_n(\Xi_n(\phi_n)) \times V(\phi_n)$$

E.g. colour correlations:

$$d\sigma_{n+1} \sim |\mathcal{M}_{n+1}|^2 = \langle \mathcal{M}_{n+1} | \mathcal{M}_{n+1} \rangle \sim P d\sigma_n$$

Might help to restore non-trivial correlations upon fixed-order calculations.

$$\rightarrow \frac{\text{Tr} [|\mathcal{M}_n\rangle\langle \mathcal{M}_n|P]}{|\mathcal{M}_n|^2 P} P d\sigma_n$$

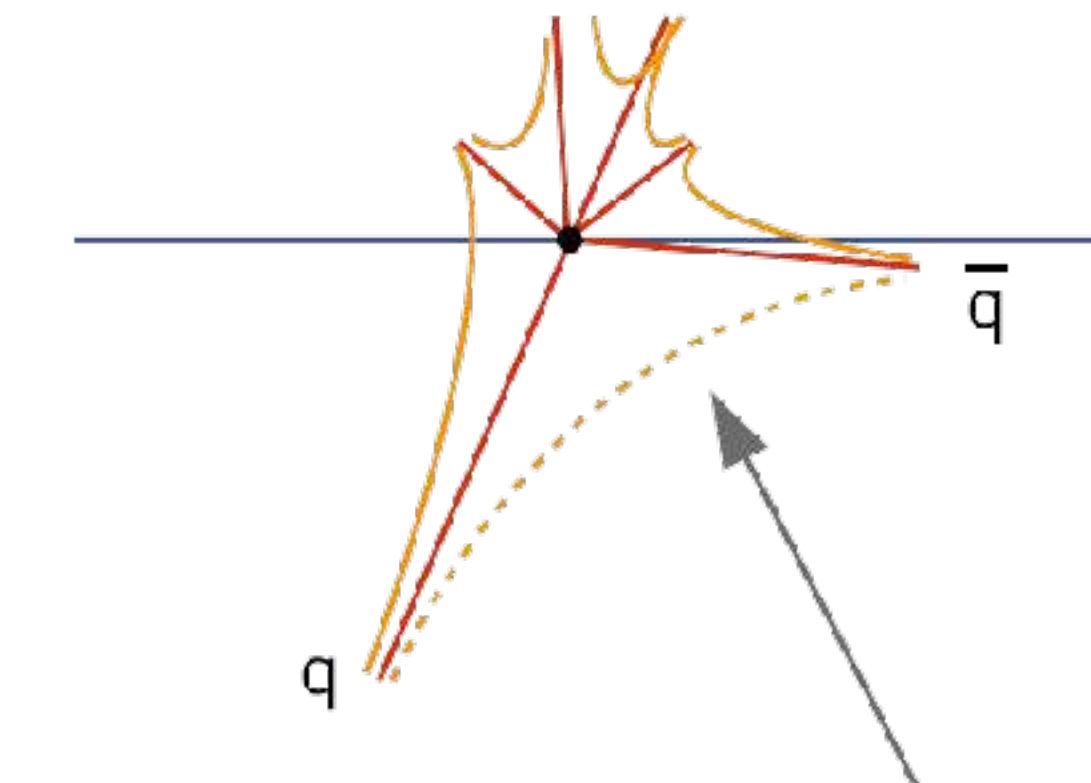
Mind that we calculate virtual corrections only from unitarity: improvements seen in shapes.

$$d\sigma_n(\phi_n) \stackrel{PS}{=} \int_0^\infty d\mu d\tau J_n V(\mu, \tau, \phi_n) u(\phi_n)$$

$$+ |\mathcal{M}_n|^2(\Xi_n(\phi_n)) V(\phi_{n+1}) \\ \Theta(Q - q(\phi_{n+1})) \Theta(q(\phi_{n+1}) - \mu) d\phi_{n+1} u(\phi_{n+1}) + \mathcal{O}(\alpha_s^2)$$

[Plätzer, Sjödahl — 2012-2018]

[Höche, Reichelt — 2019]



Some subleading-N corrections can be restored.

NLO Matching

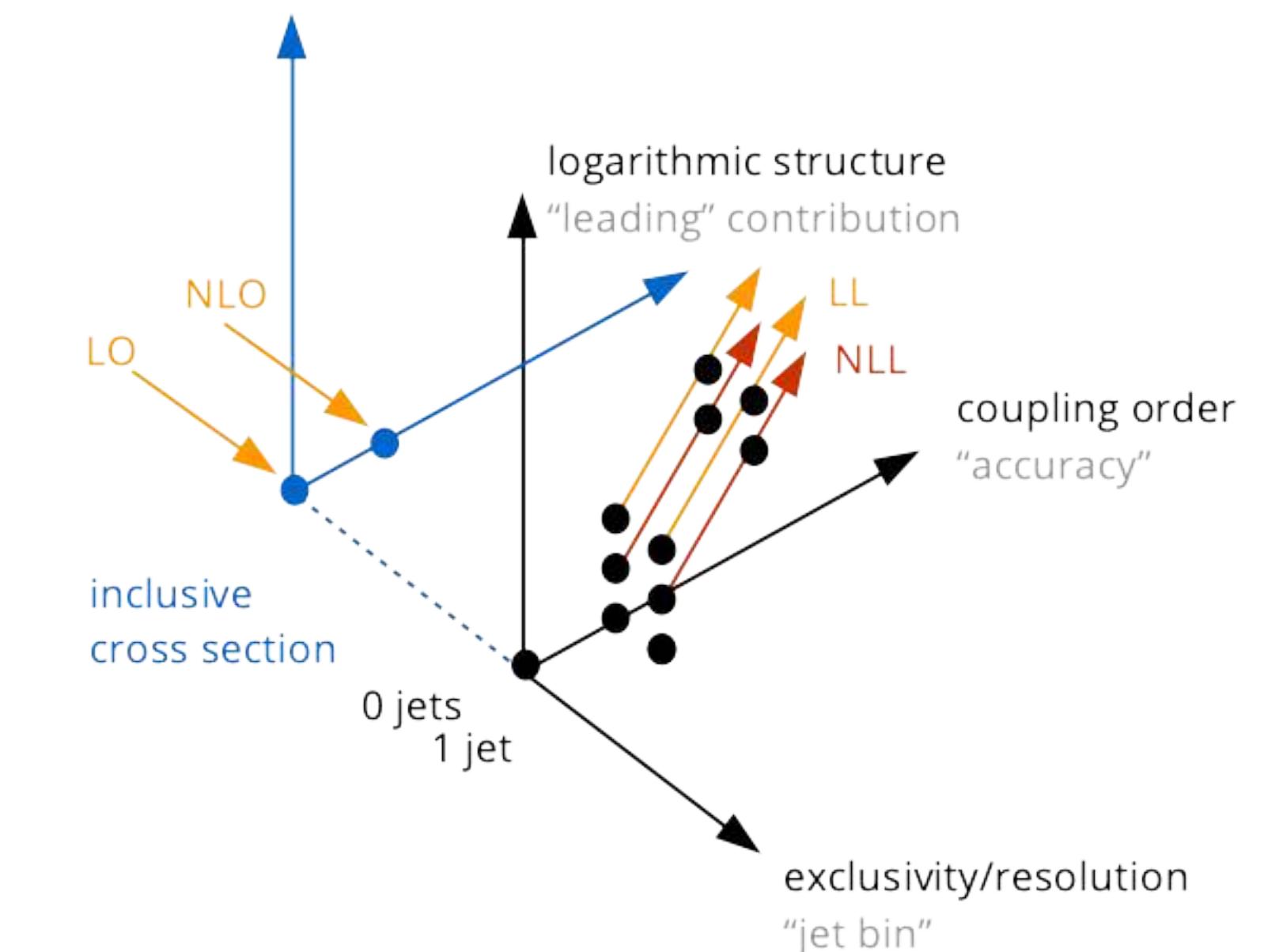
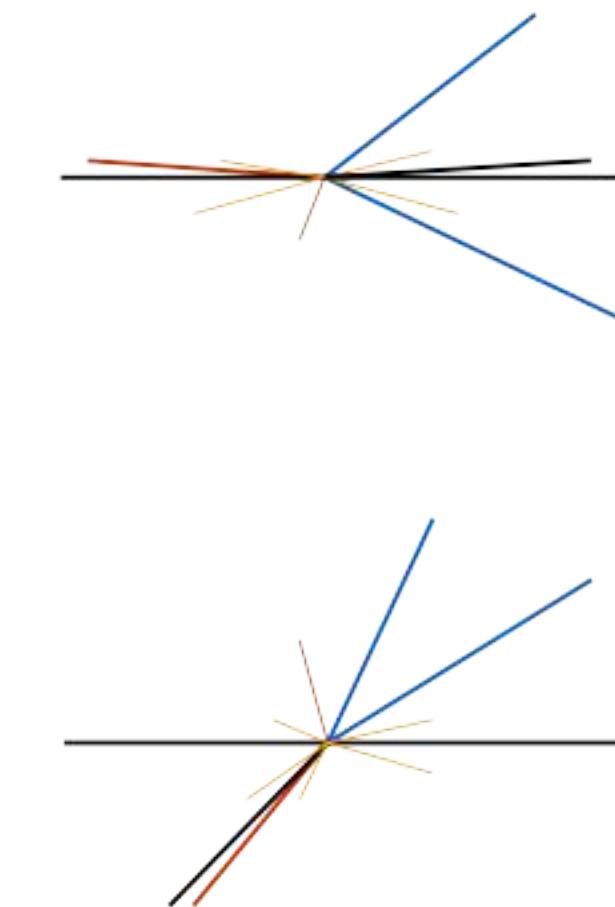
[Frixione, Webber ...]

$$\begin{aligned}
 & d\sigma_n(\phi_n) \text{PS}_\mu^Q [u(\phi_n)] \\
 &= d\sigma_n(\phi_n) \left(1 - \int_0^\alpha dh dz J_n V(h, z, \phi_n) \right) u(\phi_n) \\
 &+ | \mu u'(\Phi_n(\phi_{n+1})) V(\Phi_{n+1}) \\
 &\Theta(Q - q(\phi_{n+1})) \Theta(q(\phi_{n+1}) - \mu) d\phi_{n+1} u(\phi_{n+1}) + \mathcal{O}(\alpha_s^2)
 \end{aligned}$$

Once we control the expansion we can demand a matching condition:

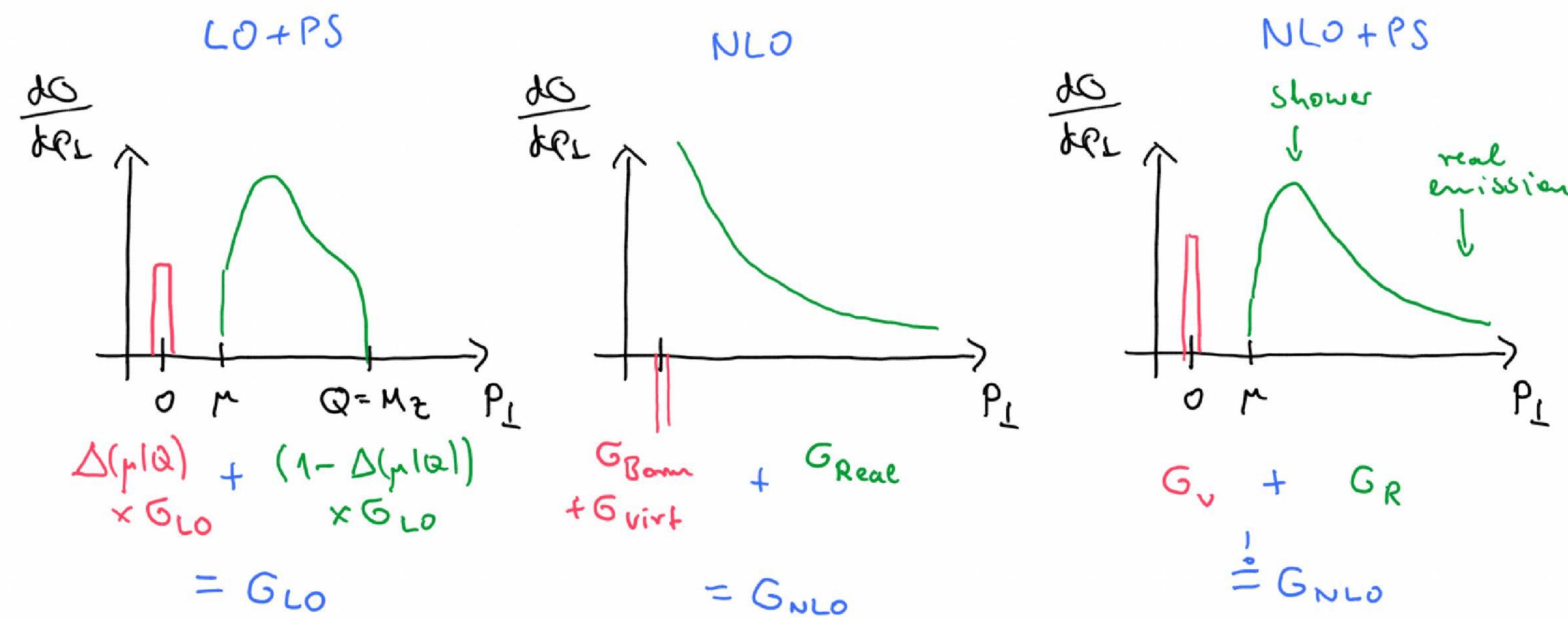
$$\text{PS}[d\sigma_{\text{NLO}}^{\text{matched}}] = d\sigma_{\text{NLO}} + \mathcal{O}(\alpha_s^{n+2})$$

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



In a nutshell:

- Inclusive cross section reproduces NLO result (in case we can define an inclusive cross section)
- First additional jet described at LO from NLO real emission
- 1 to 0 jet limit exhibits proper Sudakov suppression.

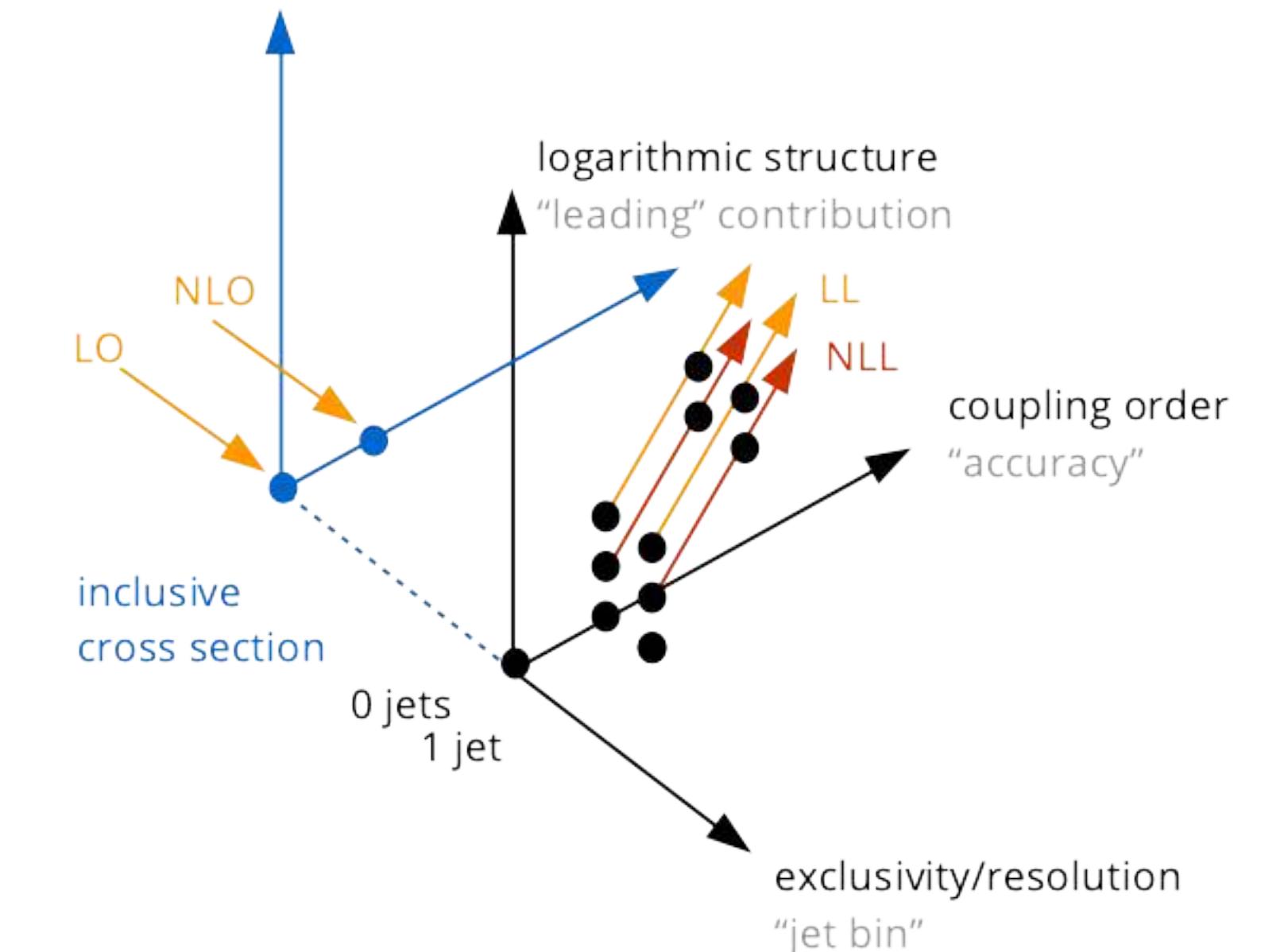


Shower expansion:

$$\begin{aligned}
 d\sigma_n(\phi_n) & \stackrel{\text{PS}_\mu^Q}{=} u(\phi_n) \\
 & = d\sigma_n(\phi_n) \left(1 - \int_r^\infty dh dz J_n V(h, z, \phi_n) \right) u(\phi_n) \\
 & + |\lambda_n|^2 (\Phi_n(\phi_{n+1})) V(\phi_{n+1}) \\
 & \Theta(Q - q(\phi_{n+1})) \Theta(q(\phi_{n+1}) - \mu) d\phi_{n+1} u(\phi_{n+1}) + \mathcal{O}(\alpha_s^2)
 \end{aligned}$$

Subtracted NLO correction:

$$\begin{aligned}
 & \int [2 \operatorname{Re}(\mu_{\text{lo}}^* \mu_{\text{virt}}) + \int \mu_{\text{lo}}^* V_{\alpha\beta} \mu_{\text{lo}}^{*\beta} d\phi_1]_{\varepsilon=0} u(\phi_n) d\phi_n \\
 & + \int [\mu_{\text{real}} |^2 u(\phi_{n+1}) - \mu_{\text{lo}}^* V_{\alpha\beta} \mu_{\text{lo}}^{*\beta} u(\Phi_n(\phi_{n+1}))] d\phi_{n+1}]_{\varepsilon=0}
 \end{aligned}$$



Solving the matching condition

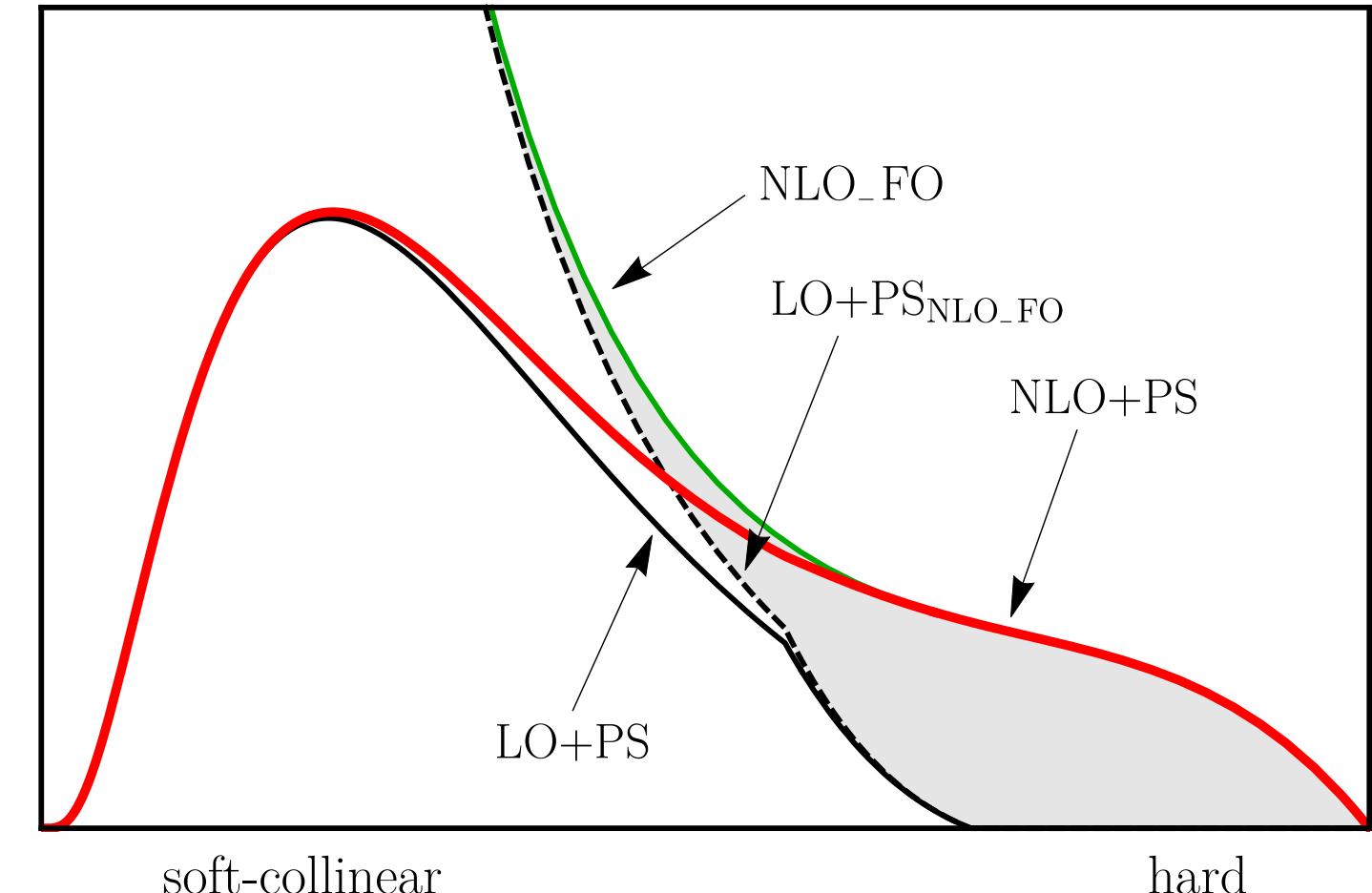
$$\int [|\mu_{\text{real}}|^2 u(\phi_{n+1}) - \mu_\text{lo}^2 V_{\alpha\beta} \mu_\text{lo}^{*\beta} u(\Xi_n(\phi_{n+1}))] d\phi_{n+1}$$

$$|\mu_\text{lo}|^2(\Xi_n(\phi_{n+1})) V(\phi_{n+1}) \Theta(q(\phi_{n+1}) - \mu) \Theta(Q - q(\phi_{n+1}))$$

$$(u(\phi_{n+1}) - u(\Xi_n(\phi_{n+1}))) d\phi_{n+1}$$

subtraction mapping

shower mapping

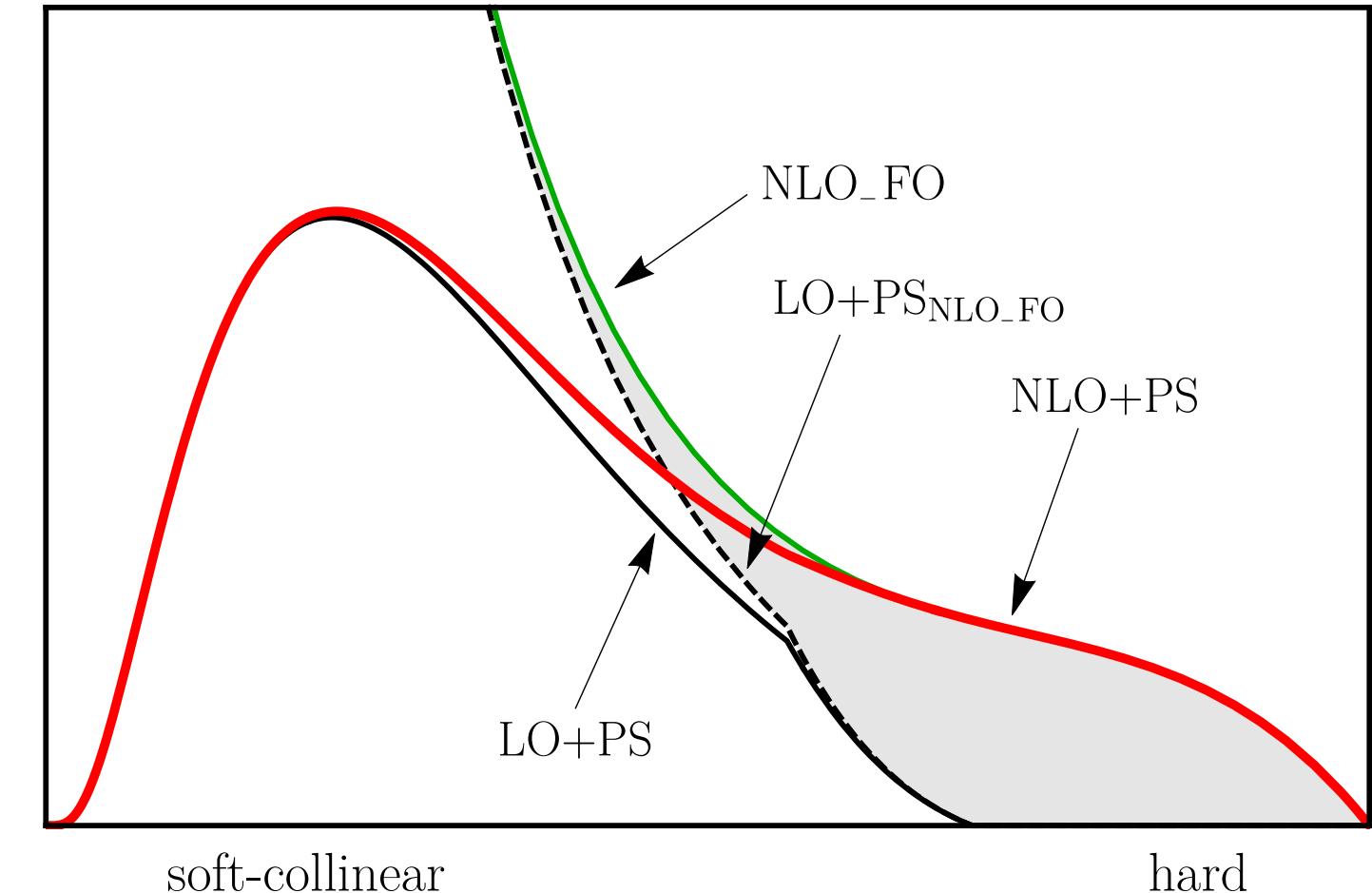


Matching with Matrix Element Corrections

What if we derived all emission cross sections from the real emission matrix element?

$$\int [|\mathcal{M}_{\text{real}}|^2 u(\phi_{n+1}) - \mathcal{M}_{\text{LO}}^* V_{\alpha\beta} \mathcal{M}_{\text{LO}}^{*\beta} u(\Phi_n(\phi_{n+1}))] d\phi_{n+1}$$

$$|\mathcal{M}_{\text{LO}}^*(\Phi_n(\phi_{n+1})) V(\phi_{n+1}) \Theta(q(\phi_{n+1}) - \mu) \Theta(Q - q(\phi_{n+1})) \\ (u(\phi_{n+1}) - u(\Phi_n(\phi_{n+1})))| d\phi_{n+1}$$

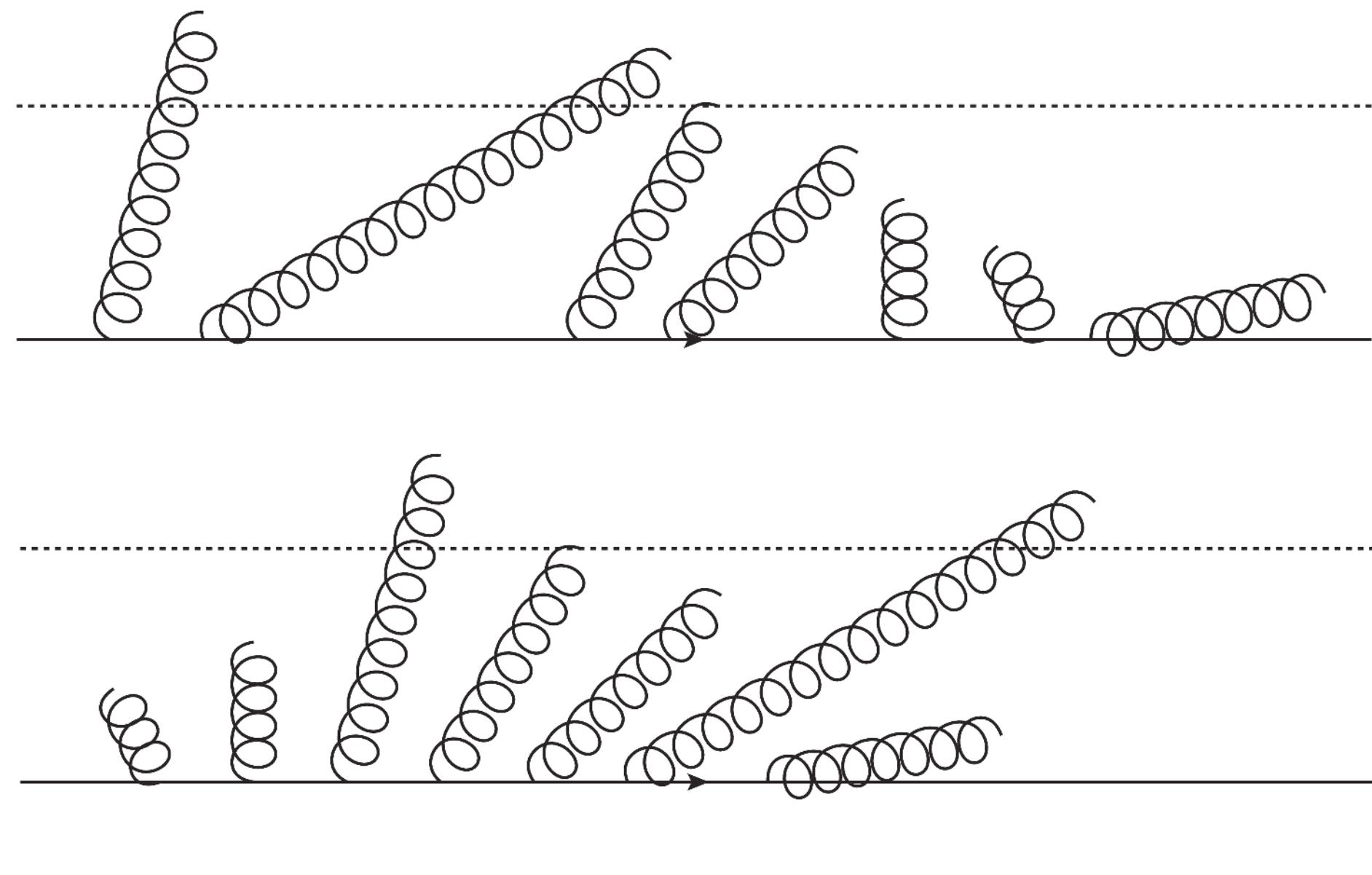


$$\int [|\mathcal{M}_{\text{real}}|^2 u(\phi_{n+1}) - \mathcal{M}_{\text{LO}}^* V_{\alpha\beta} \mathcal{M}_{\text{LO}}^{*\beta} u(\Phi_n(\phi_{n+1}))] d\phi_{n+1} \\ - |\mathcal{M}_{\text{real}}|^2 \Theta(Q - q(\phi_{n+1})) \\ (u(\phi_{n+1}) - u(\Phi_n(\phi_{n+1}))) d\phi_{n+1}$$

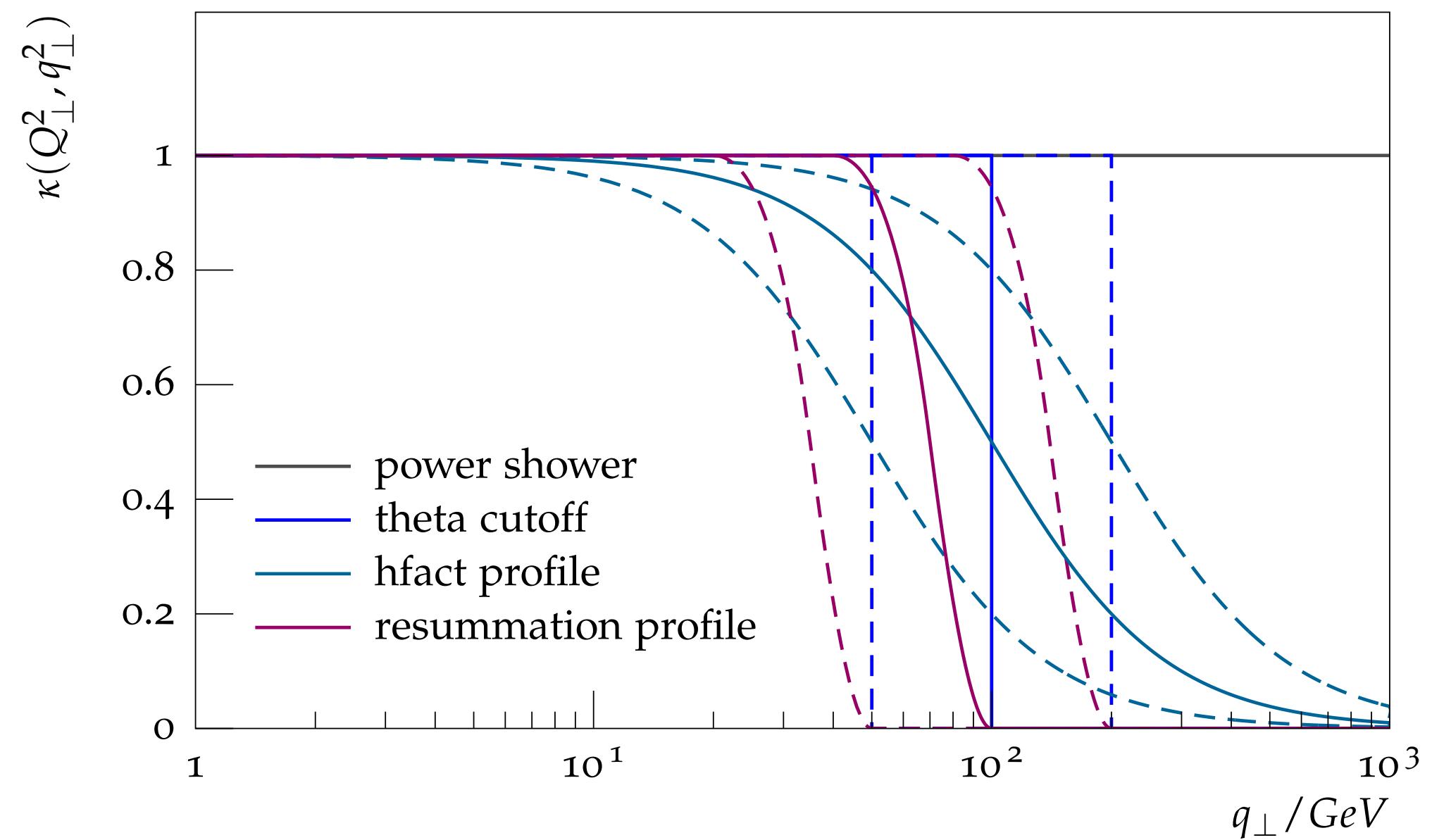
This is the Powheg method in its simplest form — [Nason,Frixione]

The Hard Scale & Truncated Showers

Q limits the hard radiation produced by the parton shower — it might not coincide with the evolution variable.



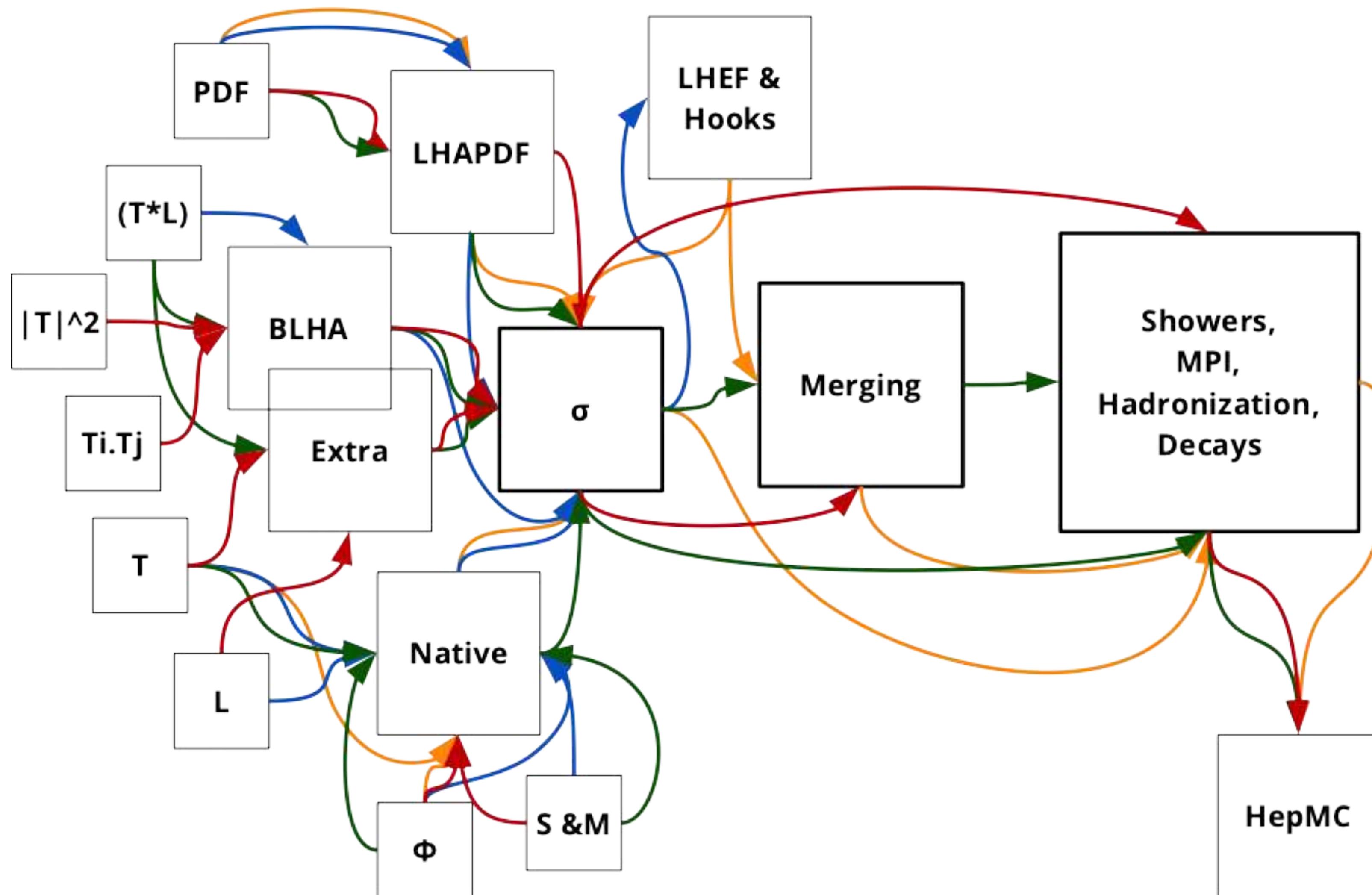
A step of NNLO size might appear if we cut hard, but smearing needs to be done very carefully:



Truncated showers are needed otherwise.

[Nason — more when we discuss merging]

[Bellm, Nail, Plätzer, Schichtel, Siodmok – EPJ C76 (2016) 665]
also Hdamp/hfact in Powheg



Mixture of C++ and FORTRAN, run-time interfaces, event file interfaces.

Central:

- LHAPDF
- External (loop) ME providers
- LHE files

Multi-purpose Event Generators

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ



Current release series	Hard matrix elements	Shower algorithms	NLO Matching	Multijet merging	MPI	Hadronization	Shower variations
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

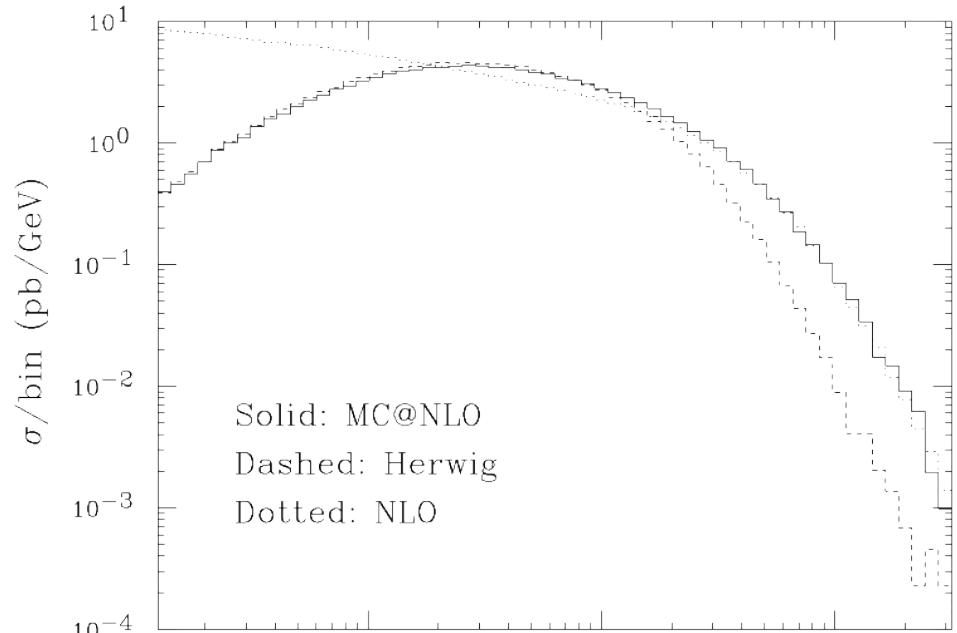
Multi-purpose Event Generators



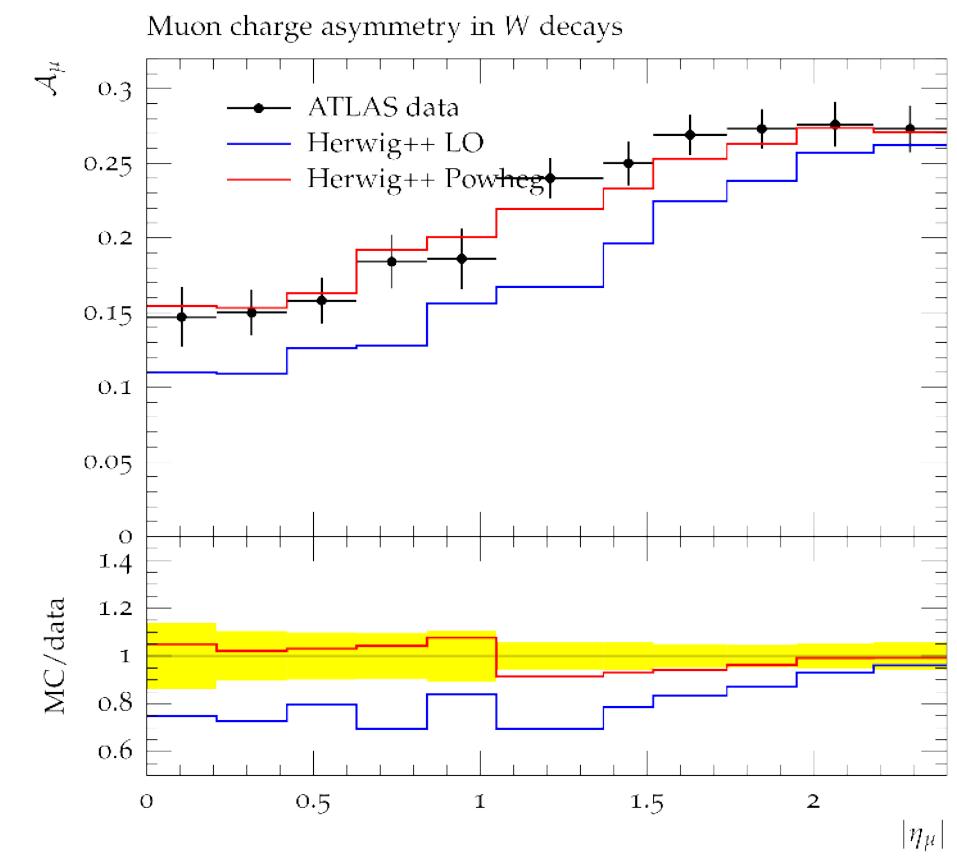
Current release series	Hard matrix elements	Shower algorithms	NLO Matching	Multijet merging	MPI	Hadronization	Shower variations
Herwig 7	Internal, libraries, event files	QTilde, Dipoles	Internally automated	Internally automated	Eikonal	Clusters, (Strings)	Yes
Pythia 8	Internal, event files	Pt ordered, 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

Use Cases

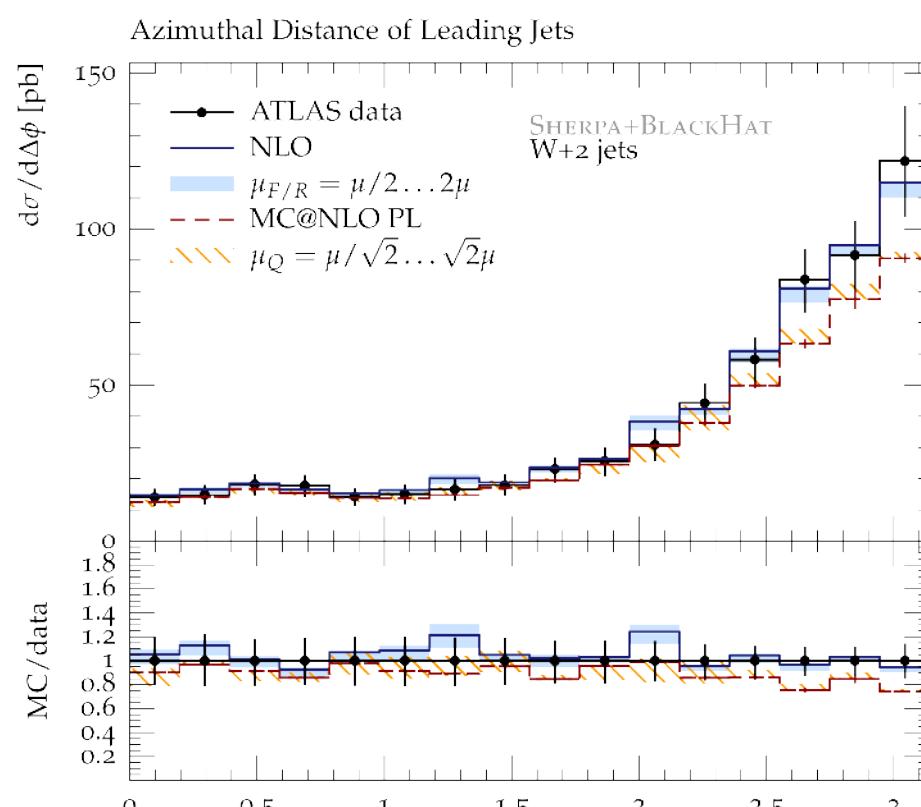
Historic examples of developing NLO matching



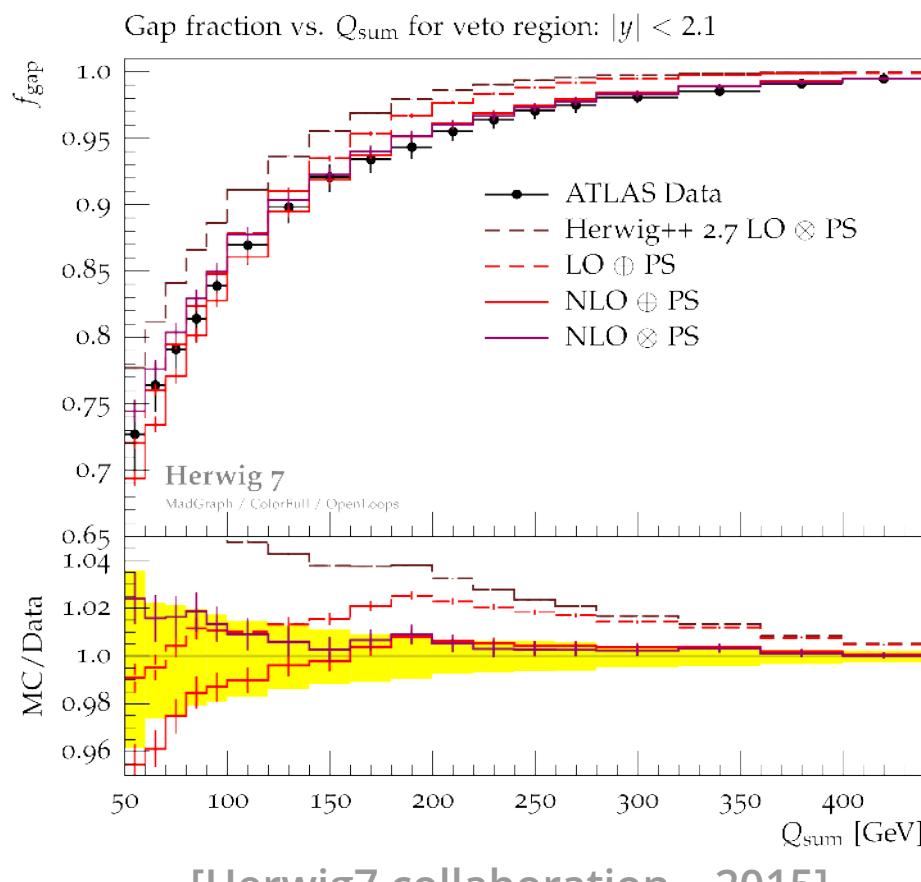
[Frixione, Webber – 2002]



[Hamilton, Richardson, Tully – 2009]

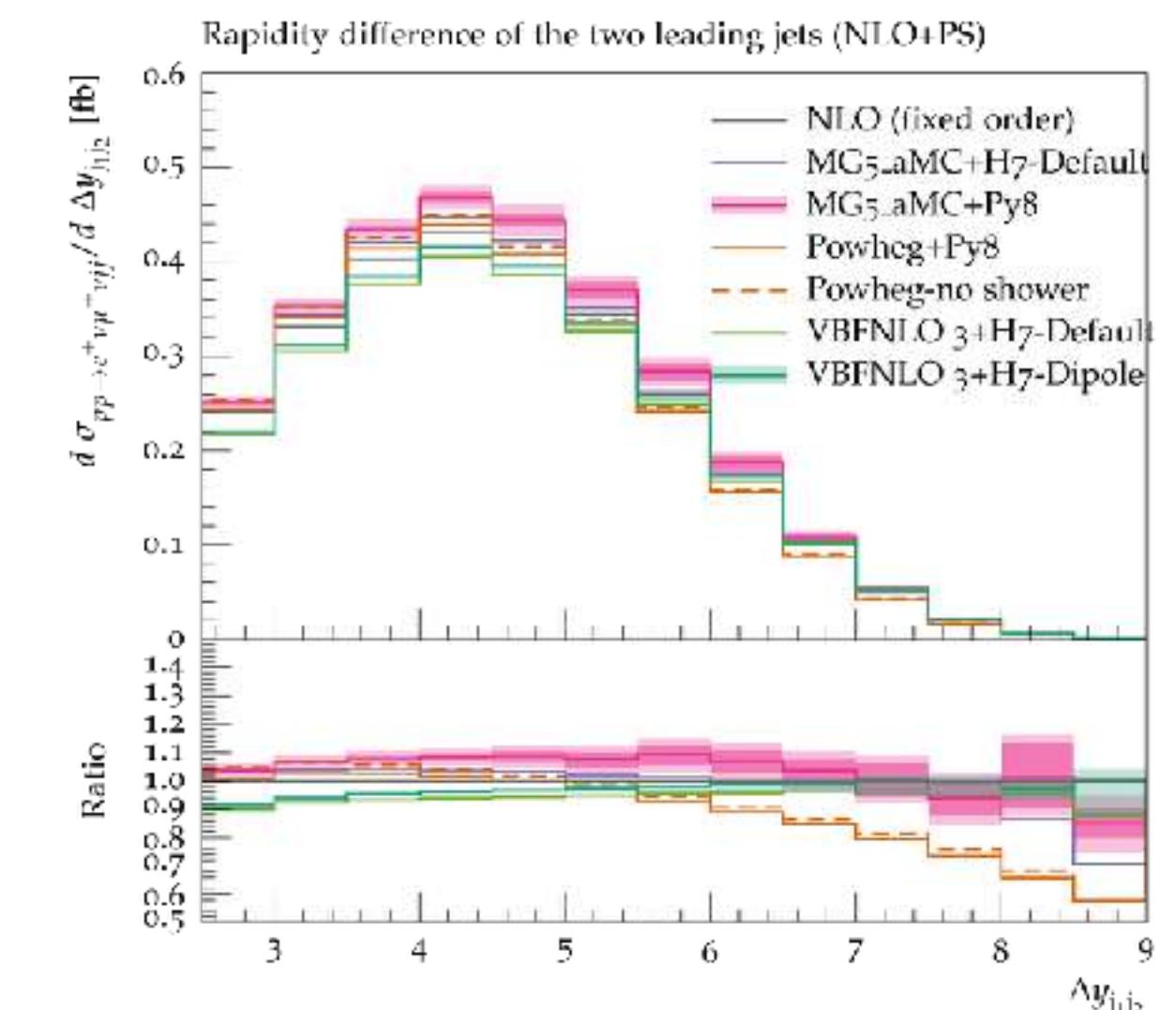
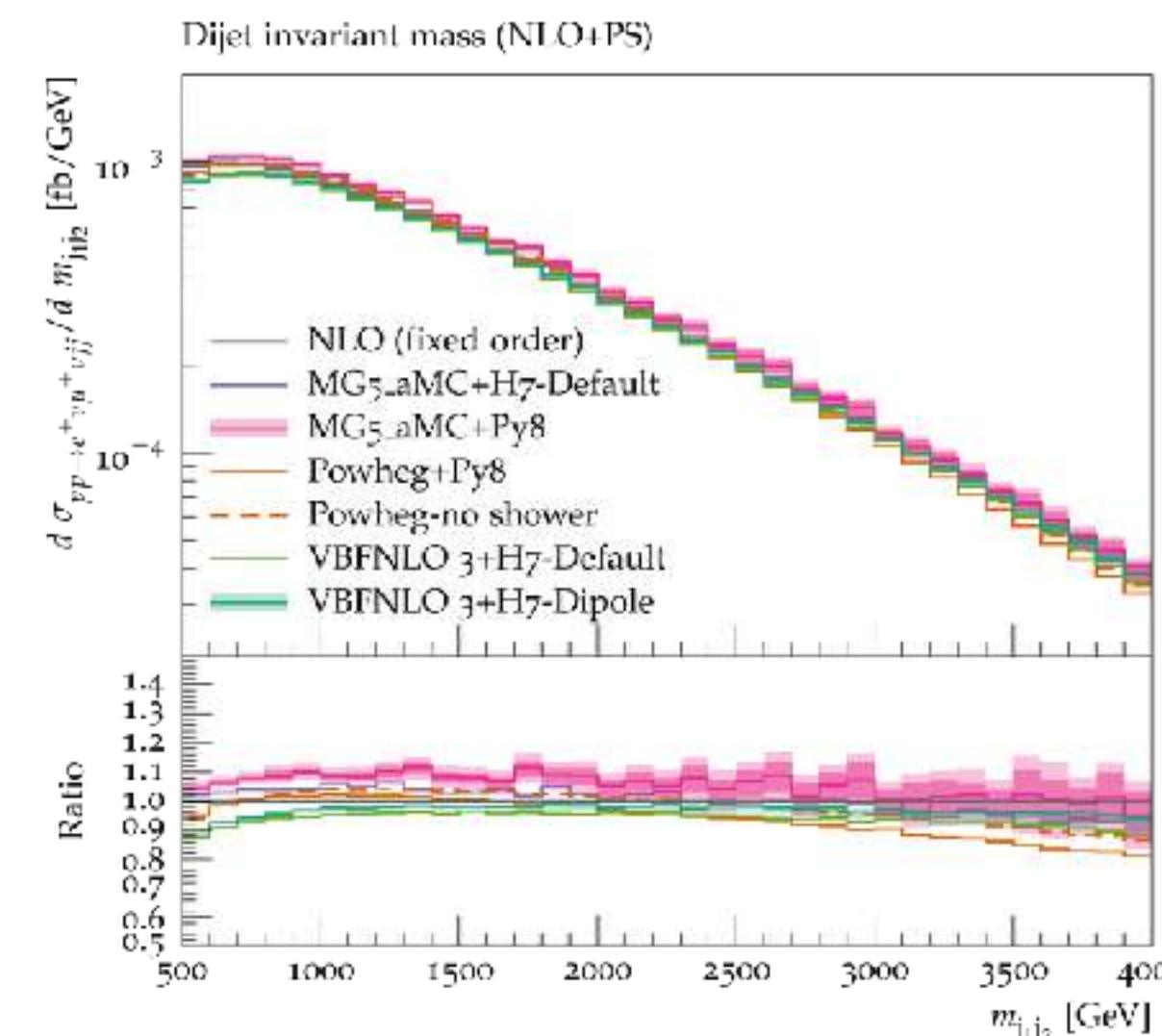


[Höche, Krauss, Schönherr, Siegert – 2012]



[Herwig7 collaboration – 2015]

Nowadays combined with shower and matching variations to evaluate perturbative uncertainties:



[Rauch et al. For VBSCAN study – EPJ C78 (2018) 671]

Comparisons across a wide range of tools and methods is still mandatory!

Thank you!

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ



universität
wien