MC challenges for future ee colliders

Simon Plätzer
Institute of Physics — NAWI, University of Graz
Particle Physics — University of Vienna

At the
FCC Physics Workshop
Krakau | 25 January 2023

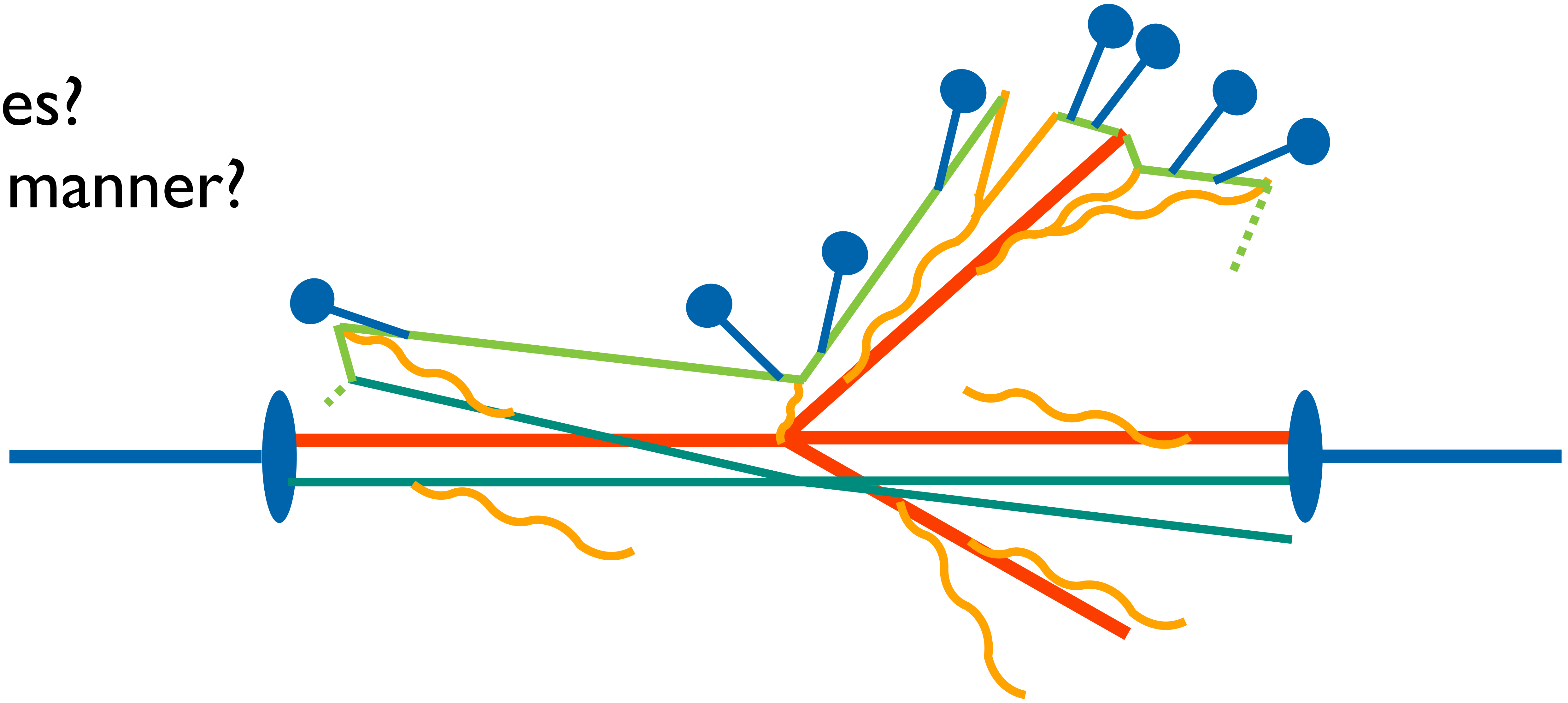
Main challenges

How do we accurately describe details of final states?
How do we quantify precision in a comprehensive manner?

Matching beyond NLO QCD?
Solve shower bottlenecks first?

How to benchmark precision of QCD algorithms?
How to accurately include EW and QED?

How to constrain hadronization models?
What is their response to perturbative variations?



$$\mathrm{d}\sigma \sim \mathrm{L} \times \mathrm{d}\sigma_H(Q) \times \mathrm{PS}(Q \to \mu) \times \mathrm{MPI} \times \mathrm{Had}(\mu \to \Lambda) \times \ldots$$

Main challenges

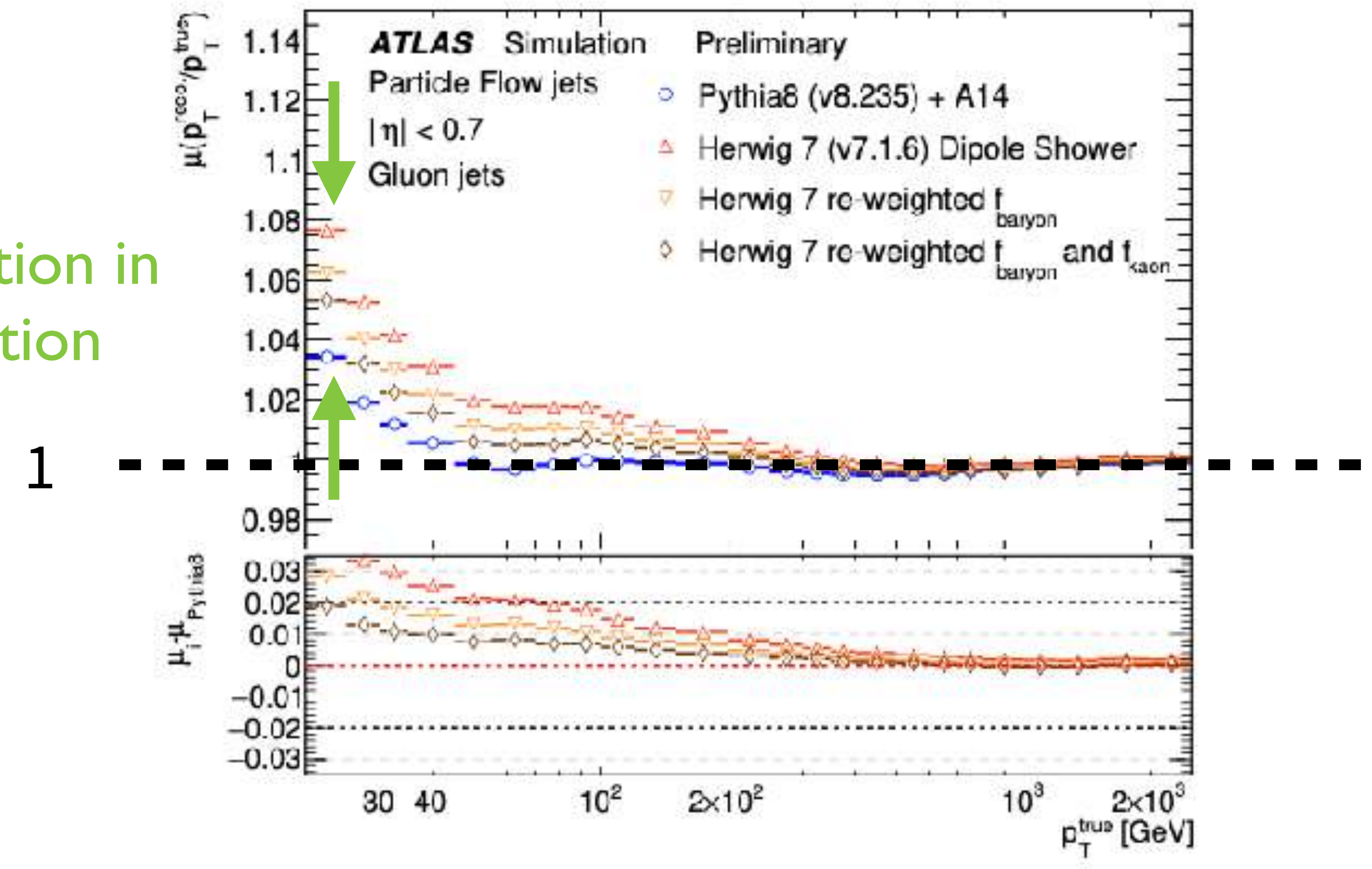
Perturbative precision is far from the last word:

E.g. lack of understanding of baryon production is limiting the power of q/g discrimination.

[see also Siodmok’s talk]

Personal selection of some recent topics:
Parton showers, hadronization and their interface.
And new algorithms.

deviation of reconstructed pt



simulated pt

[ATLAS-PUB-2022-021]

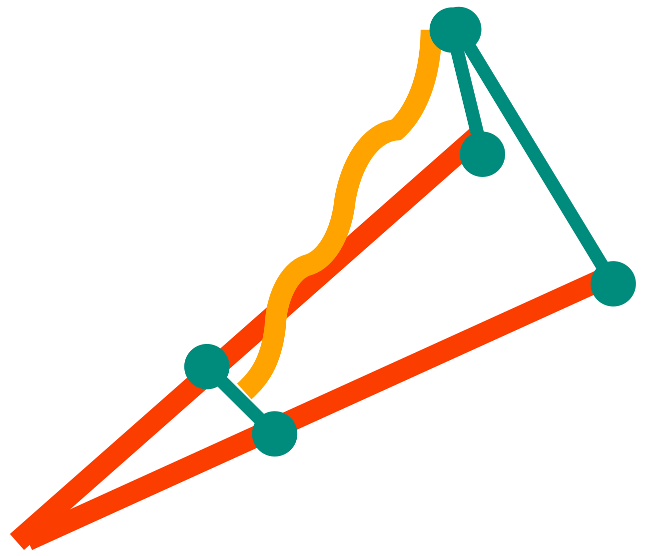
$$\mathrm{d}\sigma \sim \mathrm{L} \times \mathrm{d}\sigma_H(Q) \times \mathrm{PS}(Q \to \mu) \times \mathrm{MPI} \times \mathrm{Had}(\mu \to \Lambda) \times \ldots$$

Shower & Parton Branching Paradigms

Parton branchings
order in angle.

- Driven by QCD coherence
- Recoil global
- Links to analytic use of coherent branching

Herwig 7

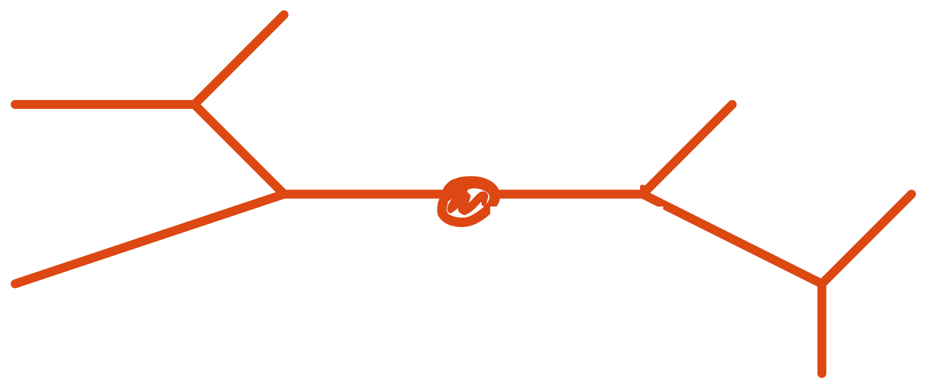


Dipole branchings order
in transverse momentum.

- Driven by large-N dipole pattern and colour flows
- Momentum conservation for each emission
- Advantageous for matching & merging

Herwig 7, Pythia 8, Sherpa, PanScales, Deductor

Sequences of emission scales and momentum fractions as Markov process.
Restore momentum conservation per emissions or at end of evolution.



$$\mathrm{d}S = \frac{\alpha_s}{2\pi}\frac{\mathrm{d}\tilde{q}_i^2}{\tilde{q}_i^2}\mathrm{d}z P(z_i) \exp\left(-\int_{\tilde{q}_i^2}^{Q^2}\frac{\mathrm{d}q^2}{q^2}\int_{z_-(k^2)}^{z_+(k^2)}\mathrm{d}\xi\frac{\alpha_s}{2\pi}P(z)\right)$$

emission rate

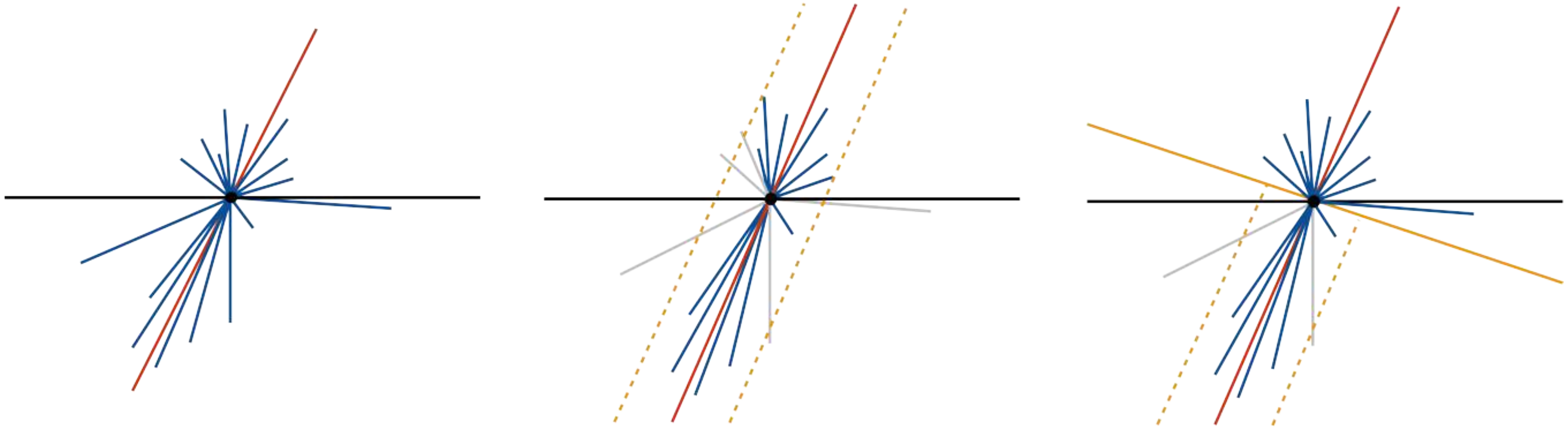
no emission probability

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

LHC-age Working Horses

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

Accuracy of Parton Showers



Global event shapes from coherent branching

$$H(\alpha_s) \times \exp\left(\boxed{Lg_1(\alpha_s L)} + \boxed{g_2(\alpha_s L)} + \boxed{\alpha_s g_3(\alpha_s L)} + \ldots\right)$$

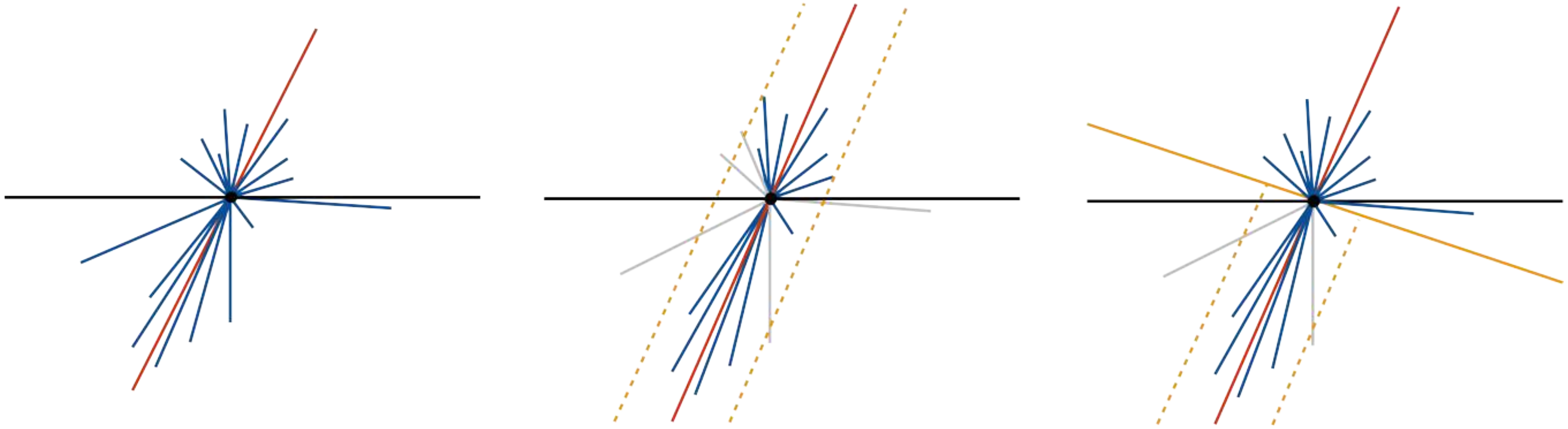
LL — qualitative

NLL — quantitative

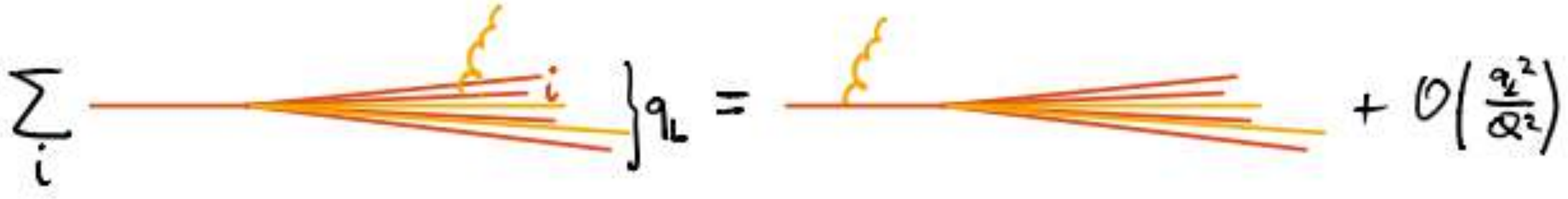
NNLL — precision

$\alpha_s L \sim 1$

Accuracy of Parton Showers



Global event shapes from coherent branching, subject to appropriate initial conditions:



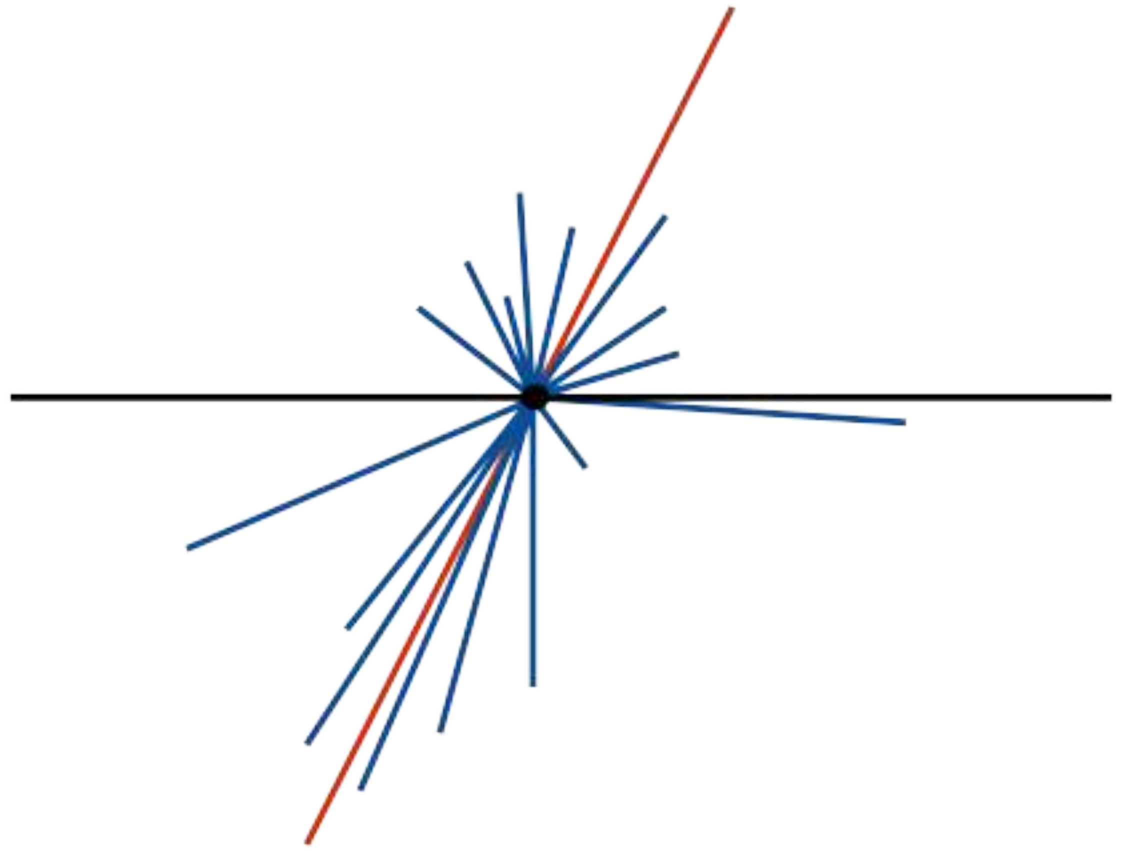
Non-global observables in the large-N limit from dipole branching

$$\frac{\partial G_{ab}(t)}{\partial t} = -\int_{\text{in}} \frac{\mathrm{d}\Omega_k}{4\pi}\omega_{ab}(k)G_{ab}(t) + \int_{\text{out}} \frac{\mathrm{d}\Omega_k}{4\pi}\omega_{ab}(k)\Big[G_{ak}(t)G_{kb}(t) - G_{ab}(t)\Big]$$

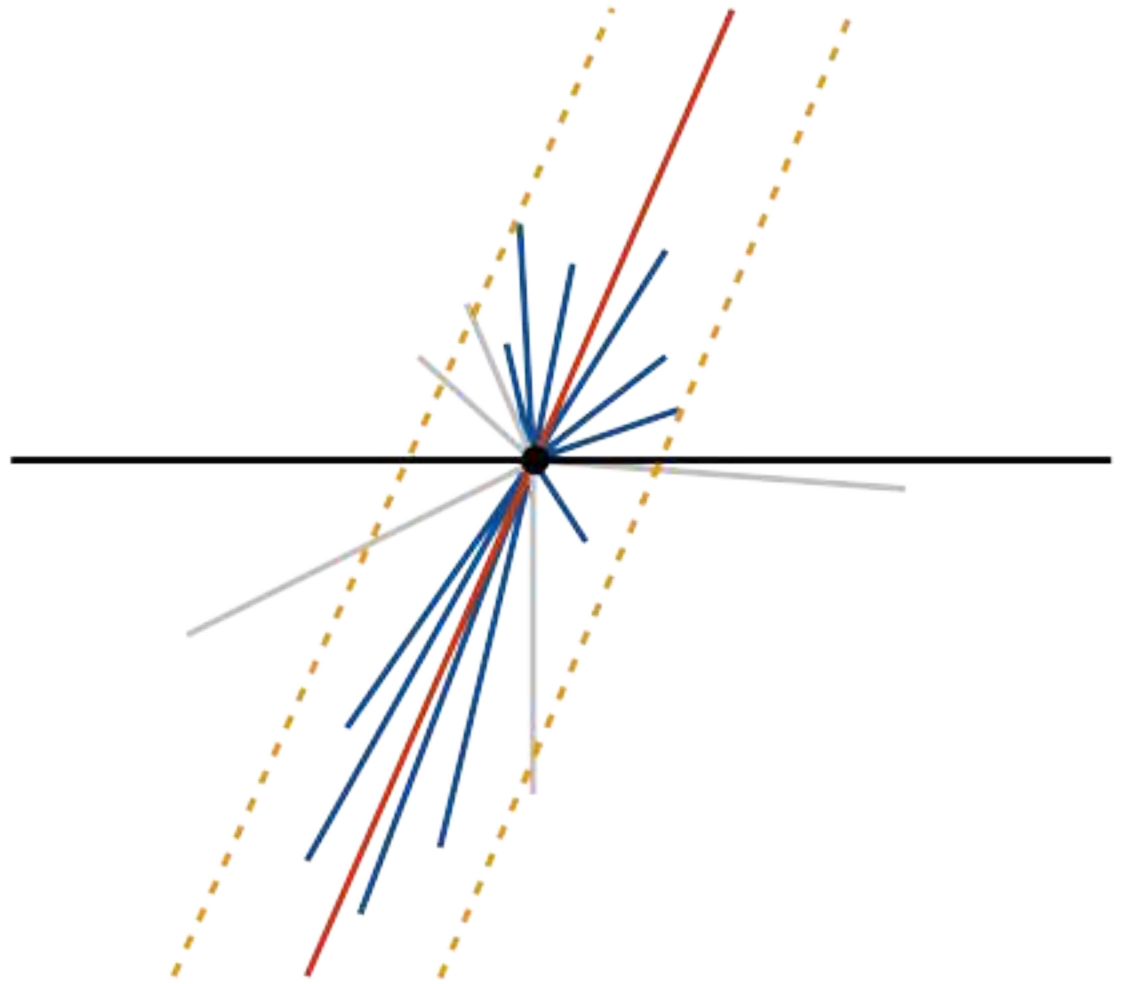
[Catani, Trentadue, Webber, Marchesini ….]

[Banfi, Marchesini, Smye — JHEP 08 (2002) 006]

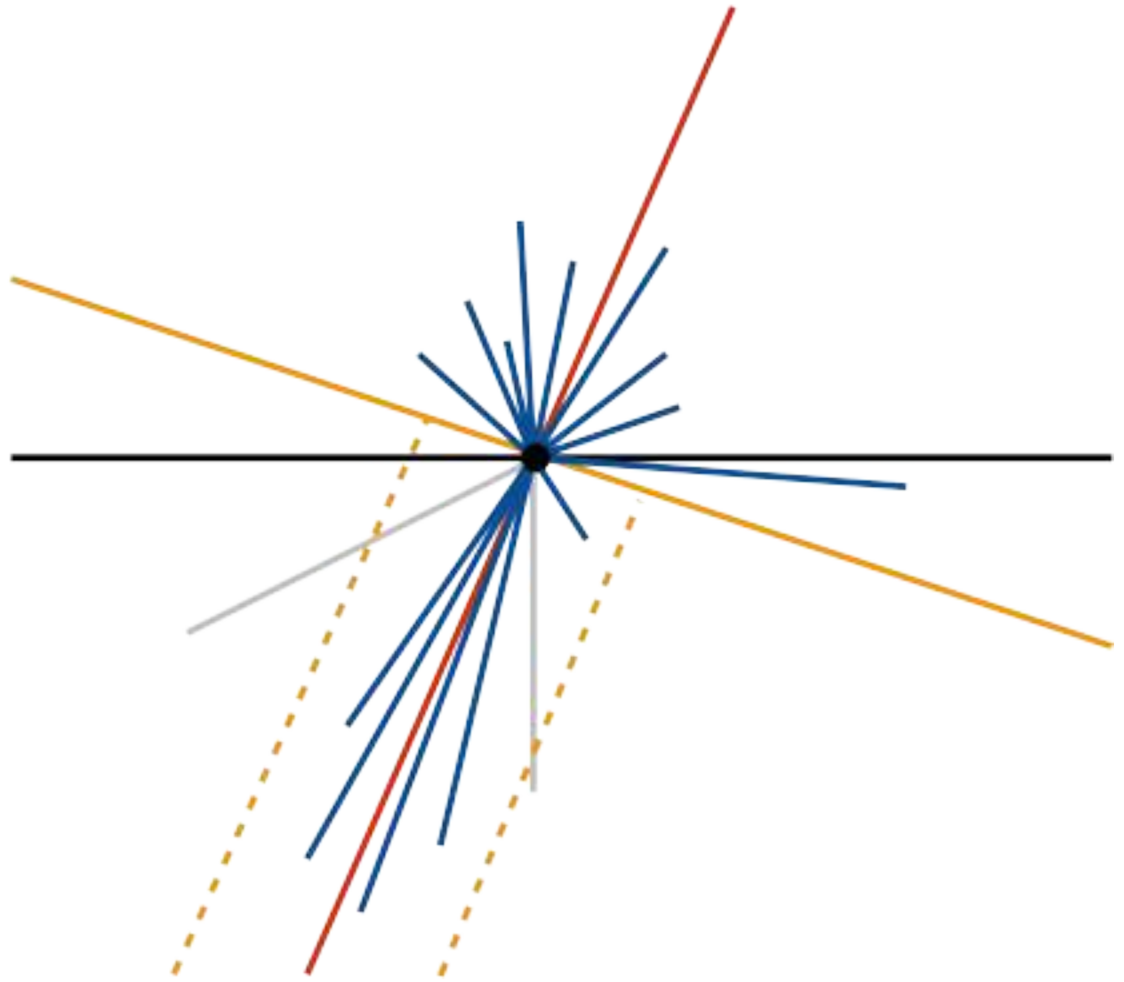
Accuracy of Parton Showers



(N)NLO with matching



NLL with coherent branching
Issues in dipole showers

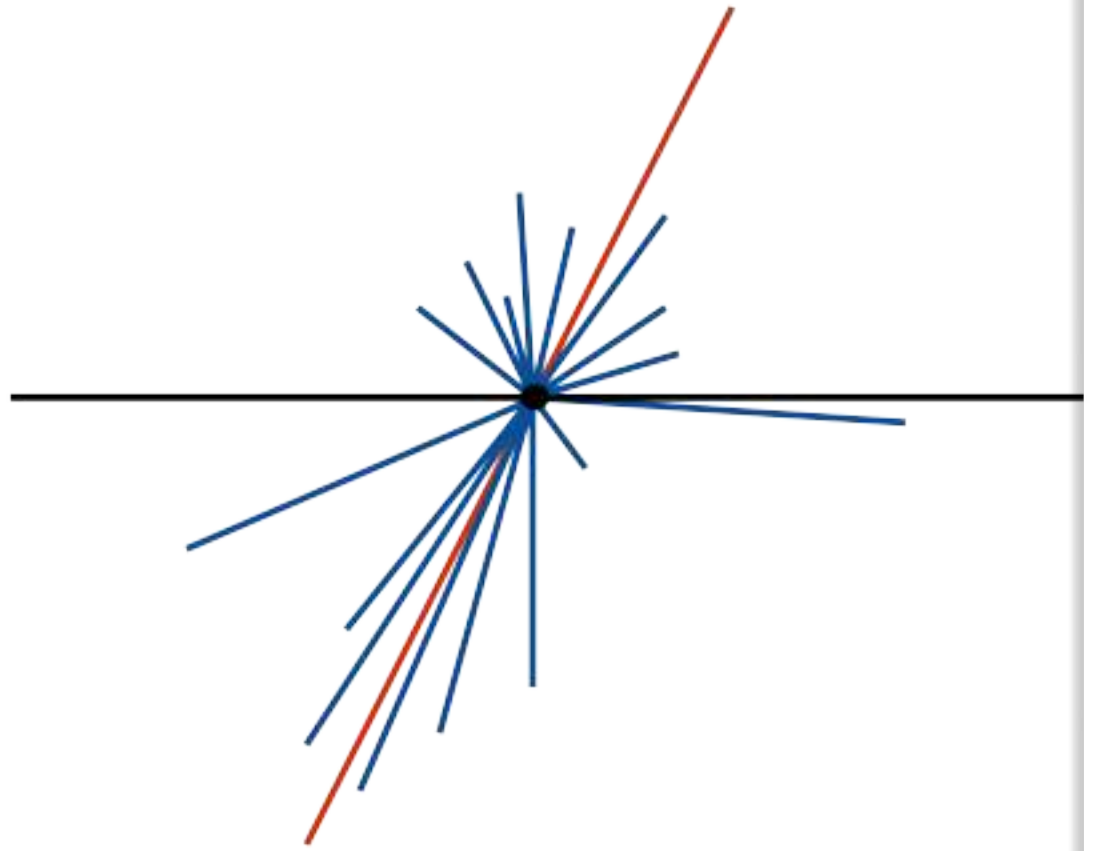


Issues in coherent branching
LL with dipole showers

Can we push this to NLL$_{\text{global}}$ / LL$_{\text{non-global}}$ in one (dipole) algorithm?

$$\alpha_s L \sim 1 \qquad \alpha_s N^2 \sim 1$$

Accuracy of Parton Showers



(N)NLO with matching

Demonstrate NLL accurate evolution:

- PanScales — numerical

[PanScales — Dasgupta, Monni, Salam, Soyez + ….]

- Deductor — numerical/analytical

[Nagy, Soper]

- Forshaw/Holguin/Plätzer — analytical

[aim at improving Herwig 7 dipole shower]

- Sherpa — numerical/analytical

[Herren, Höche, Krauss, Reichelt, Schönherr]

} Based on amplitude evolution.

Can we push this to NLL$_{\text{global}}$ / LL$_{\text{non-global}}$ in one (dipole) algorithm?

$$\alpha_s L \sim 1 \qquad \alpha_s N^2 \sim 1$$

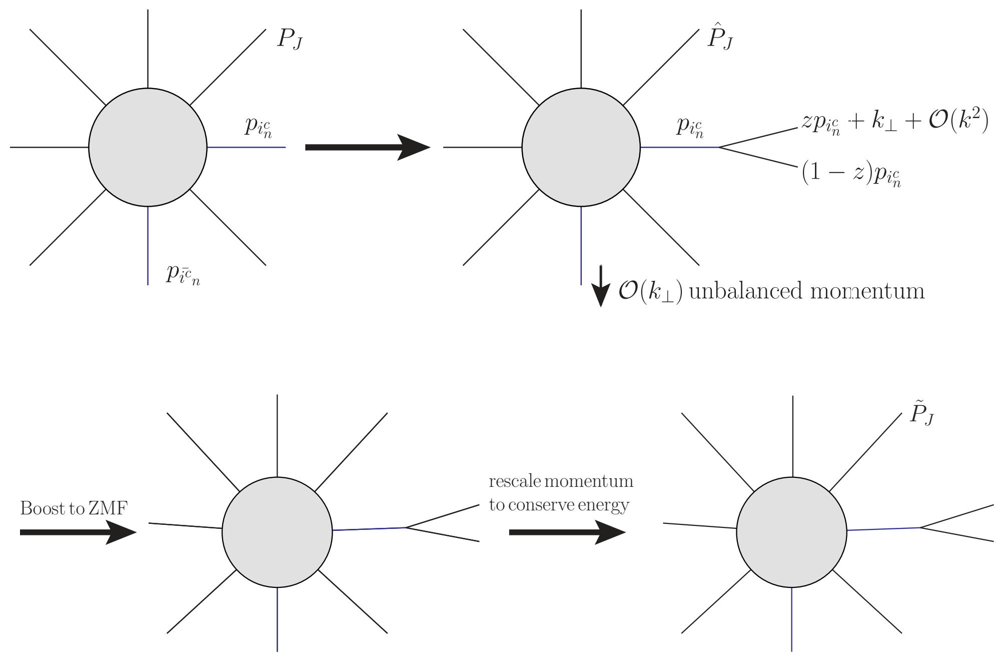
NLL$_{\text{global}}$/LL$_{\text{non-global}}$ showers

Two main ingredients in intricate interplay with ordering variable:

$$\frac{p_{i_n}\cdot p_{j_n}}{p_{i_n}\cdot q_n\; p_{j_n}\cdot q_n} \longrightarrow$$

$$\frac{p_{i_n}\cdot p_{j_n}}{p_{i_n}\cdot q_n\; p_{j_n}\cdot q_n} - \frac{T\cdot p_{j_n}}{T\cdot q_n}\frac{1}{p_{j_n}\cdot q_n} + \frac{T\cdot p_{i_n}}{T\cdot q_n}\frac{1}{p_{i_n}\cdot q_n}$$

Partition of soft radiation



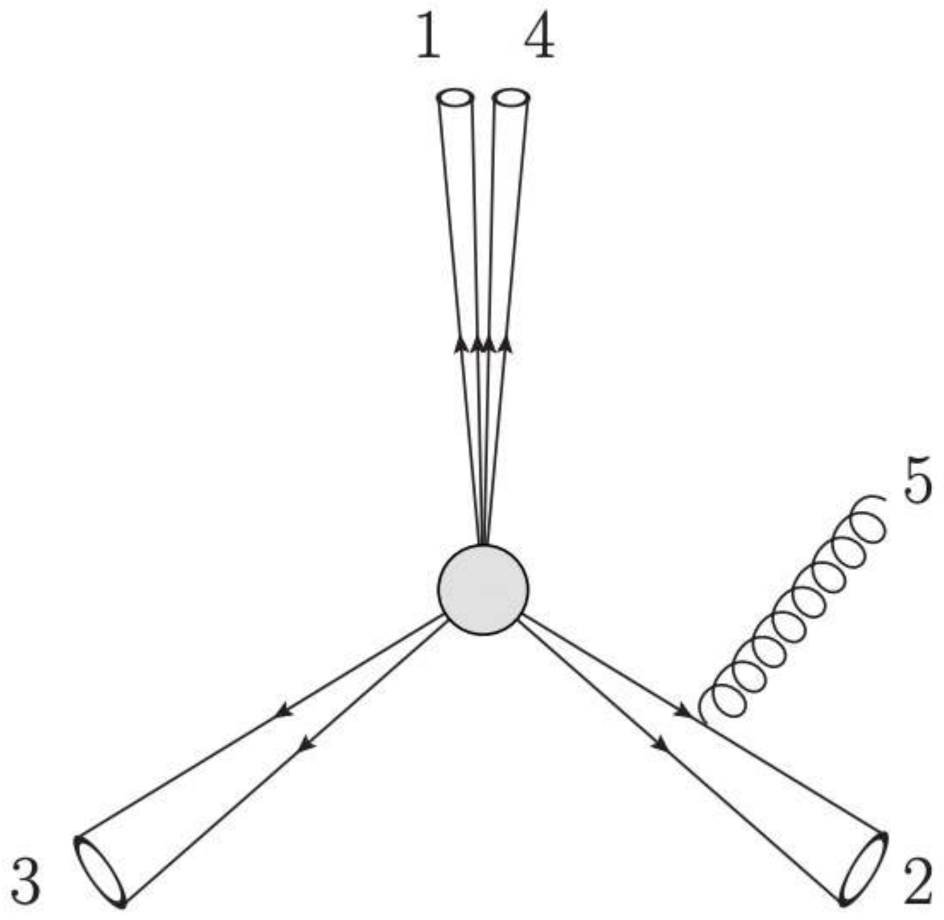
Recoil

Implementations now in Deductor, Herwig, PanScales, Sherpa

Not only present in dipole showers, can even affect coherent branching.

[Bewick, Ferrario, Richardson, Seymour —JHEP 04 (2020) 019]

Can extent this to three jet topologies:



[Holguin, Forshaw, Plätzer — JHEP 05 (2022) 190]

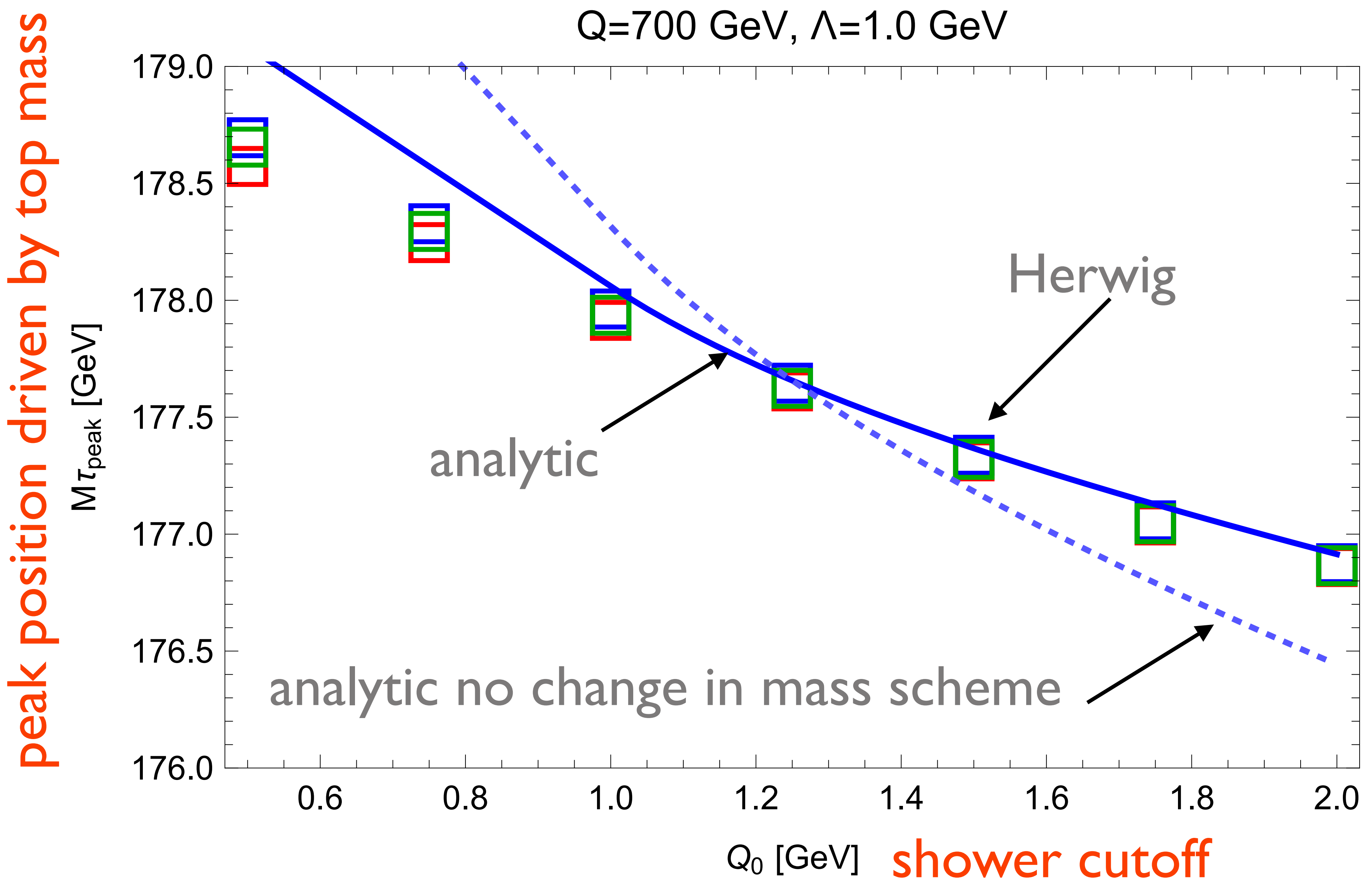
Where it (also) matters

Coherent branching jet mass including mass effects:

$$z\,(1-z)\,\tilde{q}^2 = -m^2_{\widetilde{ij}} + \frac{m_i^2}{z} + \frac{m_j^2}{1-z} - \frac{p_\perp^2}{z\,(1-z)}$$

using [Gieseke, Stephens, Webber – JHEP 0312 (2003) 045]

NLL accurate for global observables with massive quarks.



peak position driven by top mass

shower cutoff

Top mass definition from coherent branching.

[Hoang, Plätzer, Samitz — JHEP 1810 (2018) 200]

$$m_t^{\rm MC} = m_t^{\rm pole} + \Delta_m^{\rm pert} + \Delta_m^{\rm non\text{-}pert}$$

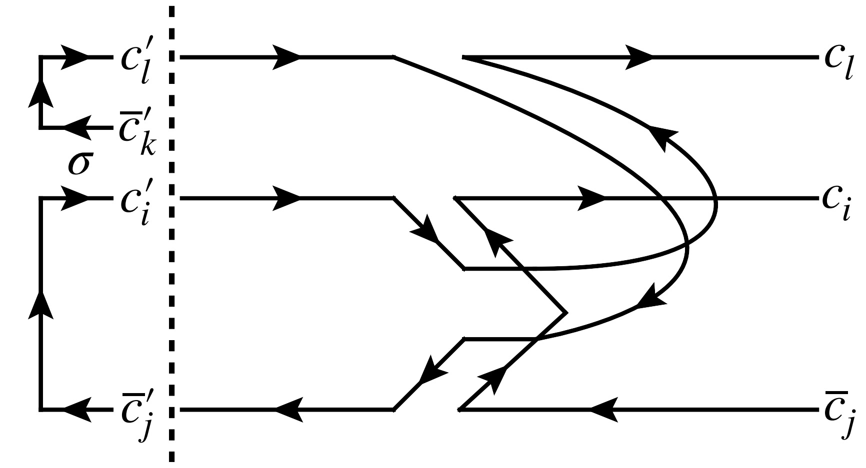
$$m_t^{\rm CB}(Q_0) = m_t^{\rm pole} - \frac{2}{3} Q_0\ \alpha_s(Q_0) + \mathcal{O}(\alpha_s^2)$$

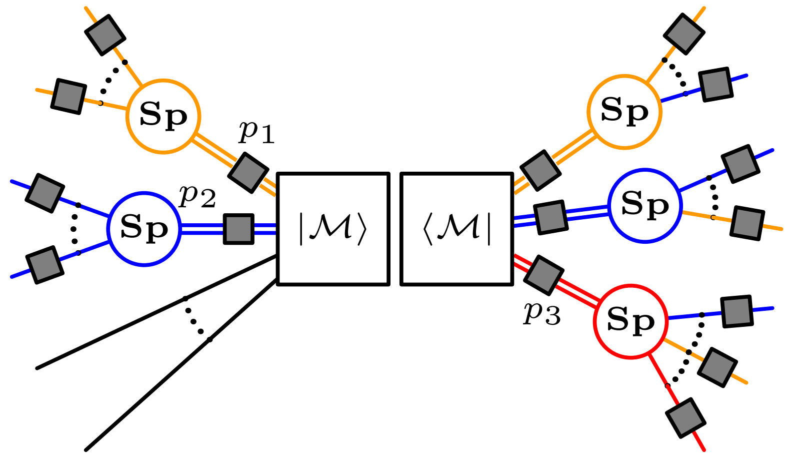
Take home message: hadronization and mass scheme compensate for shower cutoff dependence.

Showers at higher orders

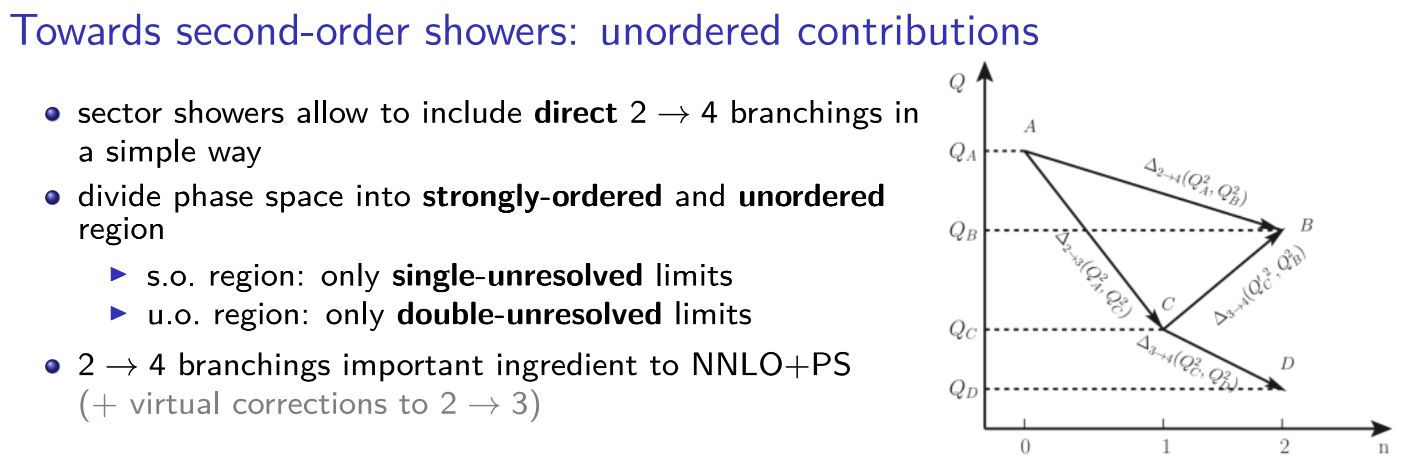
Identifying algorithms for higher order parton shower kernels is an active field.

- How to remove iterated pieces?
- How is the large-N limit working?
- How to combine soft and collinear regions?





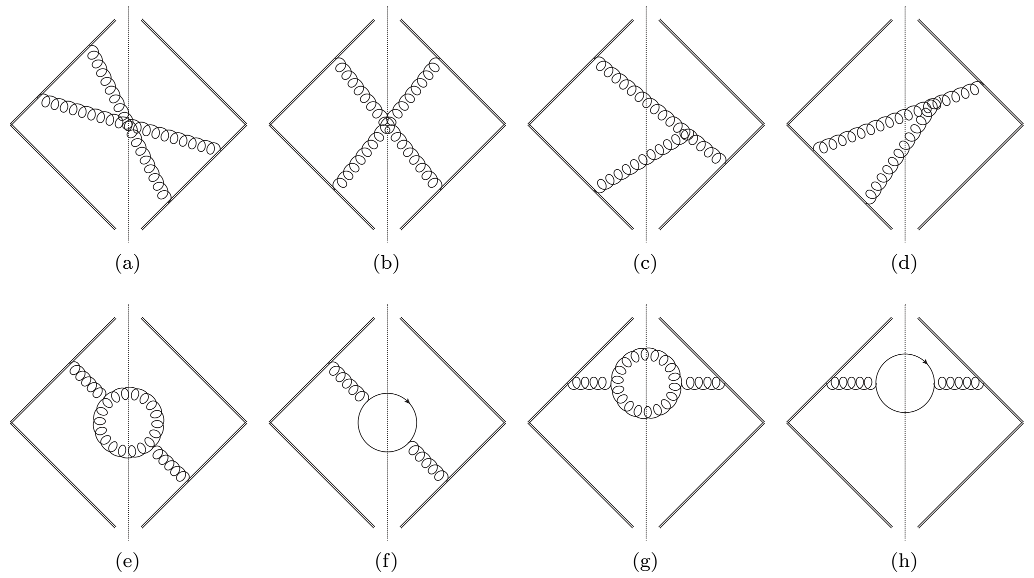
[Plätzer, Ruffa — JHEP 06 (2021) 007]
[Löschner, Plätzer, Simpson — arXiv:2112.14454]



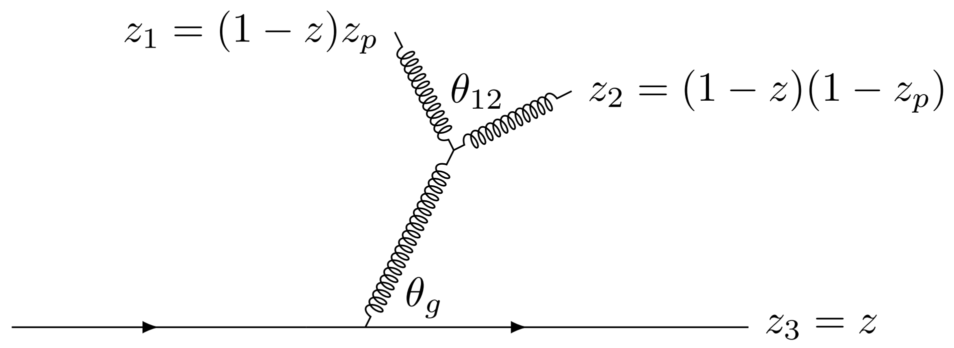
Towards second-order showers: unordered contributions

- sector showers allow to include **direct** 2 → 4 branchings in a simple way
- divide phase space into **strongly-ordered** and **unordered** region
  - s.o. region: only **single-unresolved** limits
  - u.o. region: only **double-unresolved** limits
- 2 → 4 branchings important ingredient to NNLO+PS (+ virtual corrections to 2 → 3)

[C. Preuss for Vincia — PSR 21]



[Dulat, Höche, Prestel — Phys.Rev.D 98 (2018) 7]
[Gellersen, Höche, Prestel — Phys.Rev.D 105 (2022) 11]



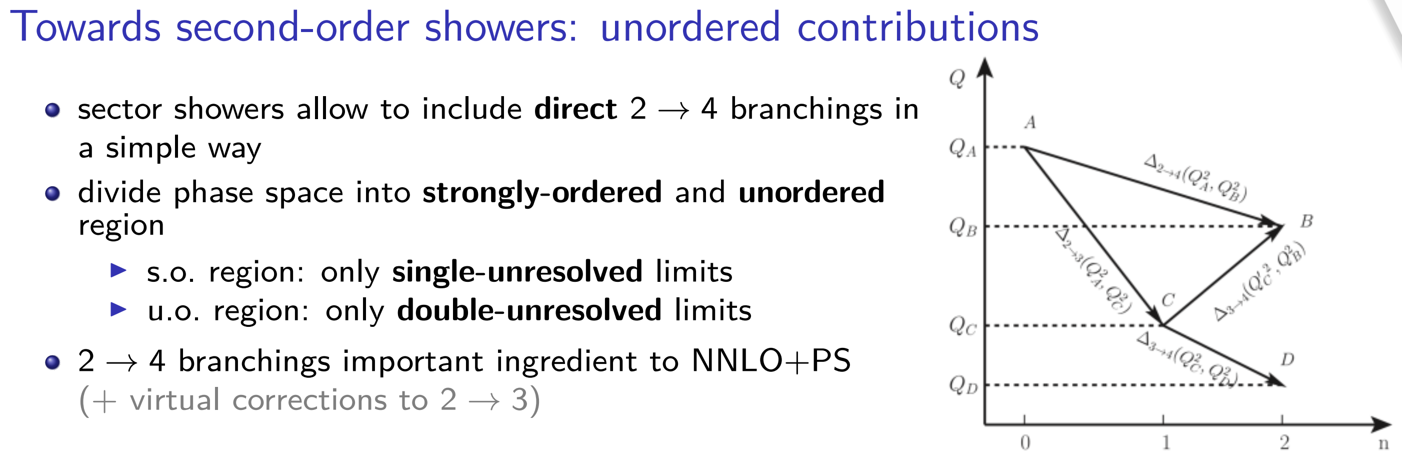
[Dasgupta, El-Menoufi — JHEP 12 (2021) 158]

Showers at higher orders

Identifying algorithms for higher order parton shower active field.

- How to remove iterated pieces?
- How is the large-N limit working?
- How to combine soft and c

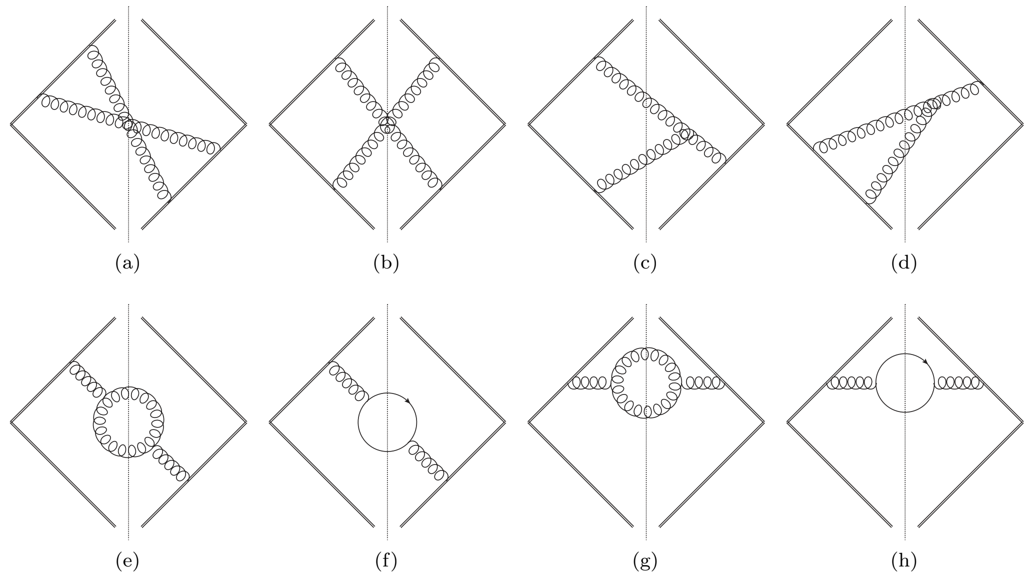
Higher accuracy/order of building blocks is necessary but not sufficient to achieve more accurate algorithms.



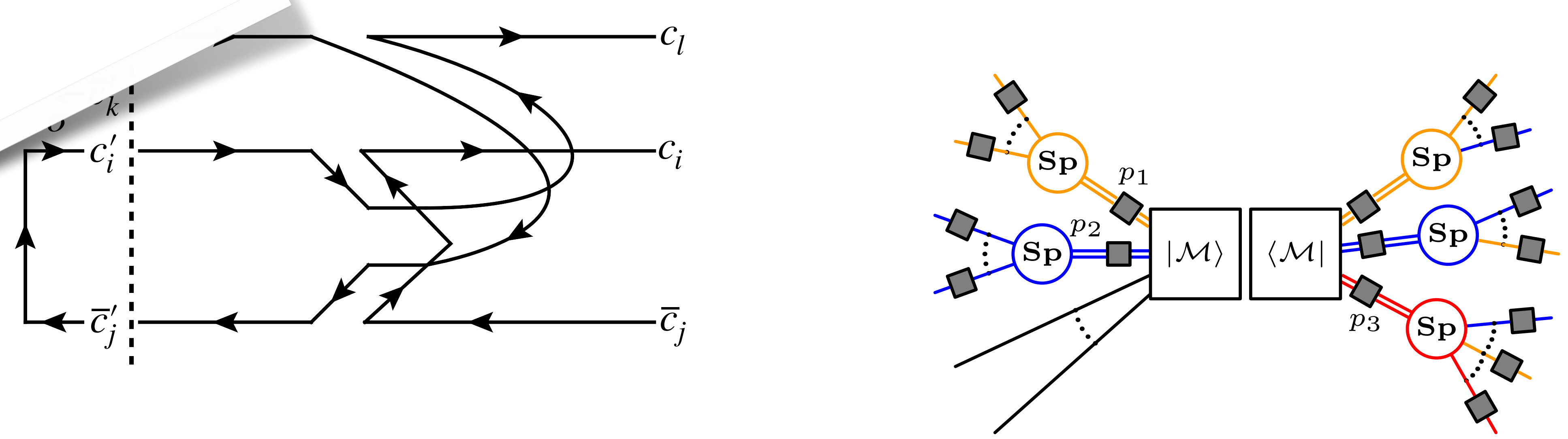
Towards second-order showers: unordered contributions

- sector showers allow to include **direct** 2 → 4 branchings in a simple way
- divide phase space into **strongly-ordered** and **unordered** region
  - s.o. region: only **single-unresolved** limits
  - u.o. region: only **double-unresolved** limits
- 2 → 4 branchings important ingredient to NNLO+PS (+ virtual corrections to 2 → 3)

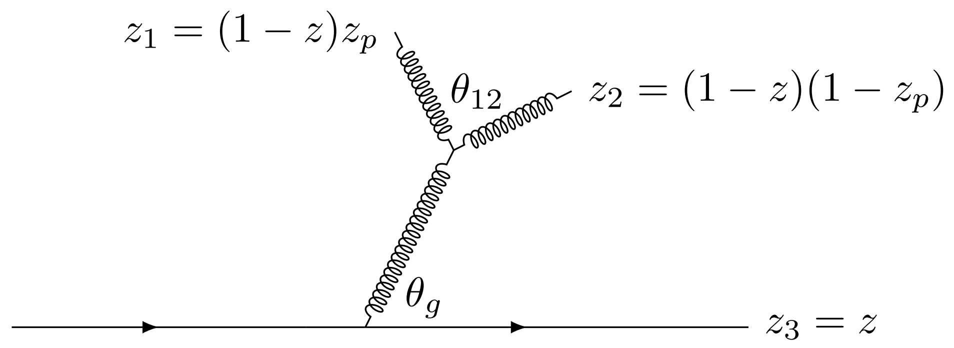
[C. Preuss for Vincia — PSR 21]



[Dulat, Höche, Prestel — Phys.Rev.D 98 (2018) 7]
[Gellersen, Höche, Prestel — Phys.Rev.D 105 (2022) 11]



[Plätzer, Ruffa — JHEP 06 (2021) 007]
[Löschner, Plätzer, Simpson — arXiv:2112.14454]



[Dasgupta, El-Menoufi — JHEP 12 (2021) 158]

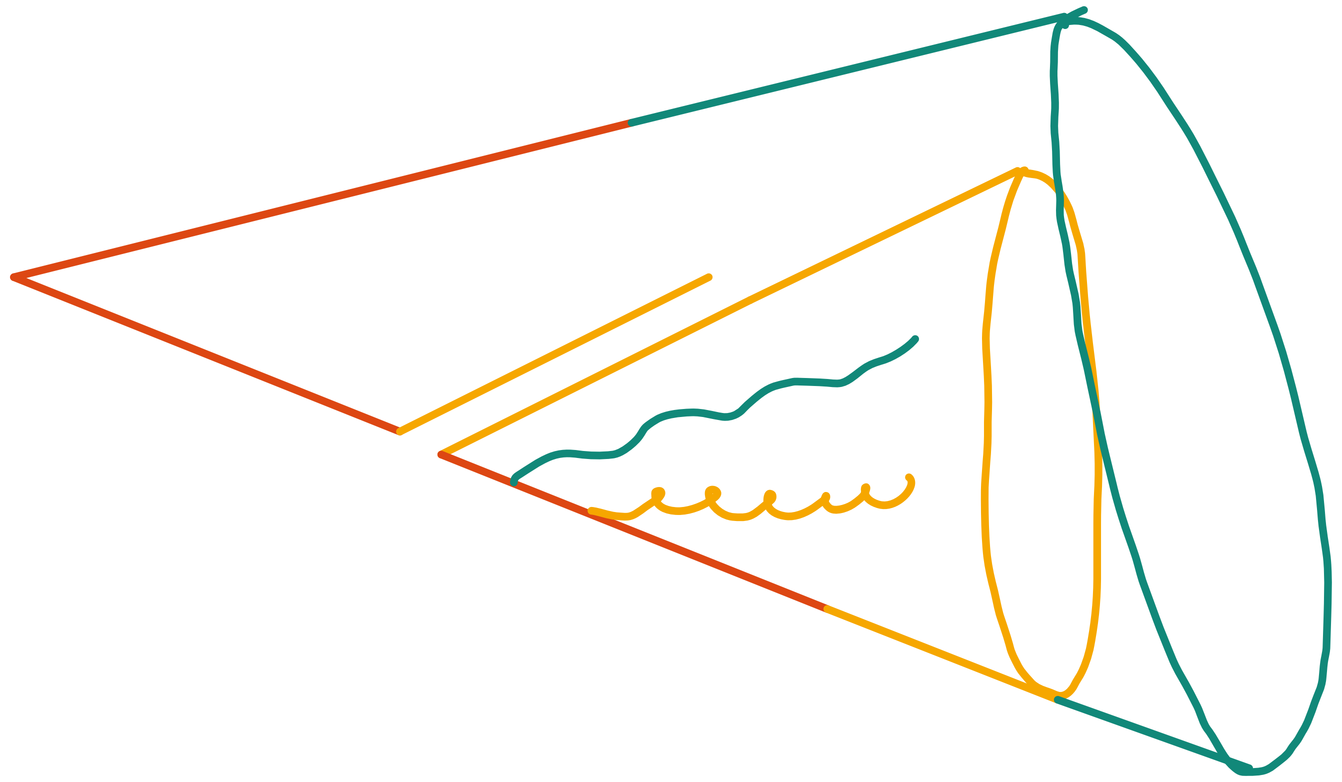
Showering beyond QCD

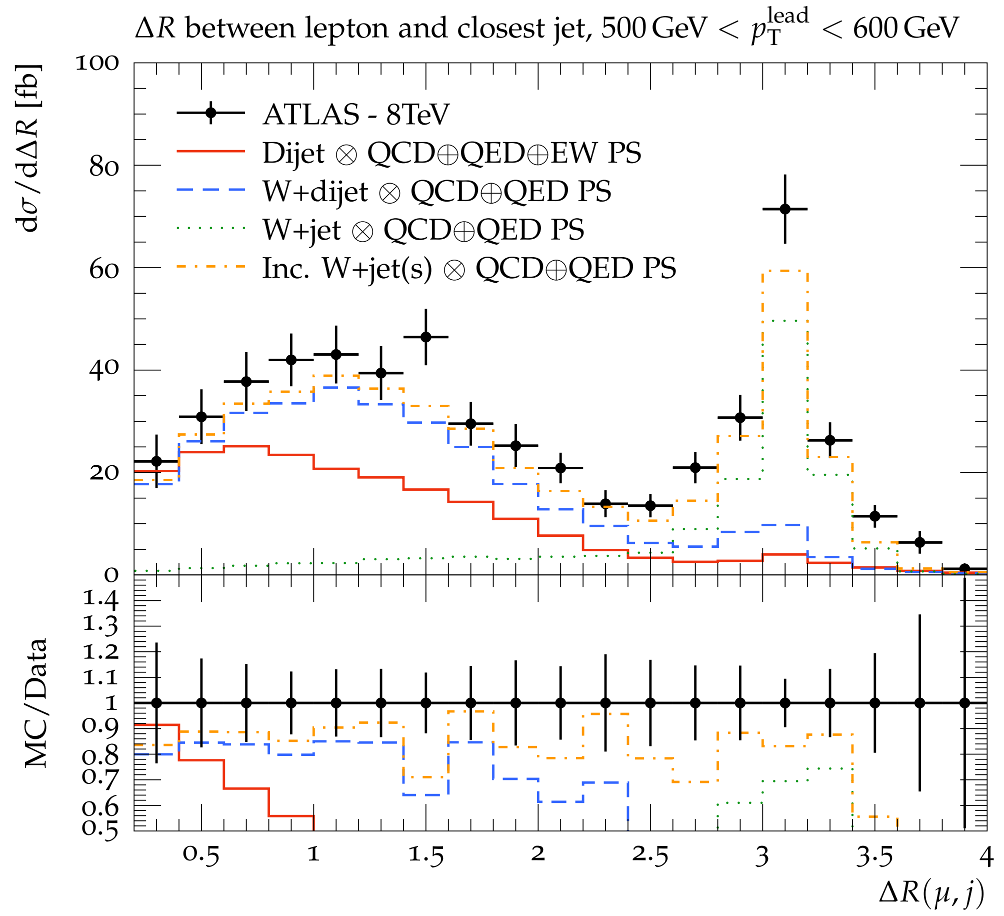
First steps to extend showers from QCD to other interactions: [Herwig, Pythia, Sherpa provide QED and (some) EWK]

- Angular ordered shower in quasi-collinear limit rather straightforward.
- Relation to large-angle soft pattern and initial conditions still need investigation

Work ongoing, e.g. [Plätzer, Sjödahl — arXiv:2204.03258]

Different charges require different angular ordering cones:
one evolution variable per interaction.

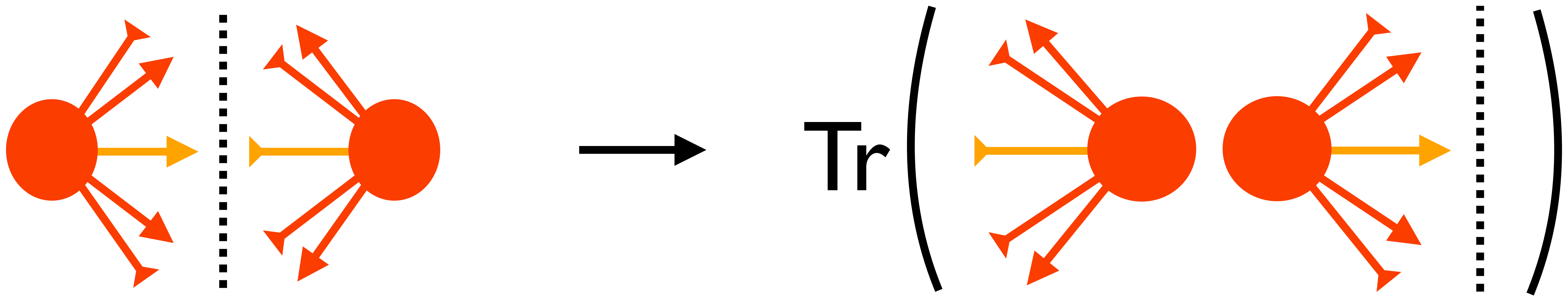




[Masouminia, Richardson — JHEP 04 (2022) 112]

How do we lift this to the same level of cornering QCD showers (and matching)?

Amplitude evolution

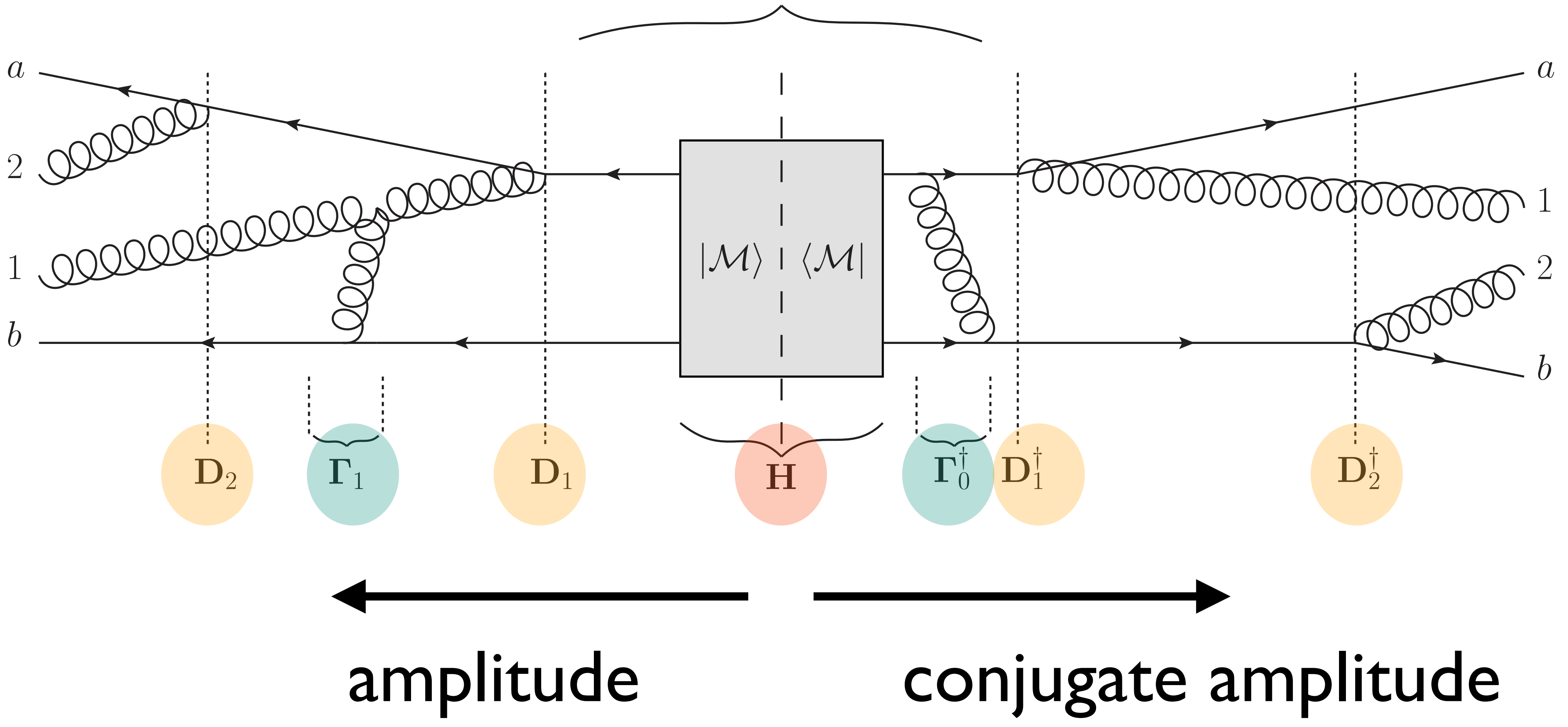


$$\mathbf{A}_n(q) = \int_q^Q \frac{\mathrm{d}k}{k}\, \mathrm{P}e^{-\int_q^k \frac{\mathrm{d}k'}{k'}\mathbf{\Gamma}(k')}\, \mathbf{D}_n(k)\, \mathbf{A}_{n-1}(k)\, \mathbf{D}_n^\dagger(k)\, \overline{\mathrm{P}}e^{-\int_q^k \frac{\mathrm{d}k'}{k'}\mathbf{\Gamma}^\dagger(k')}$$

Markovian algorithm at the amplitude level:
Iterate gluon exchanges and emission.

Different histories in amplitude and conjugate amplitude needed to include interference.

[Angeles, De Angelis, Forshaw, Plätzer, Seymour – JHEP 05 (2018) 044]
[Forshaw, Holguin, Plätzer – JHEP 1908 (2019) 145, …]
[Nagy, Soper — PRD 98 (2018) 1, …]

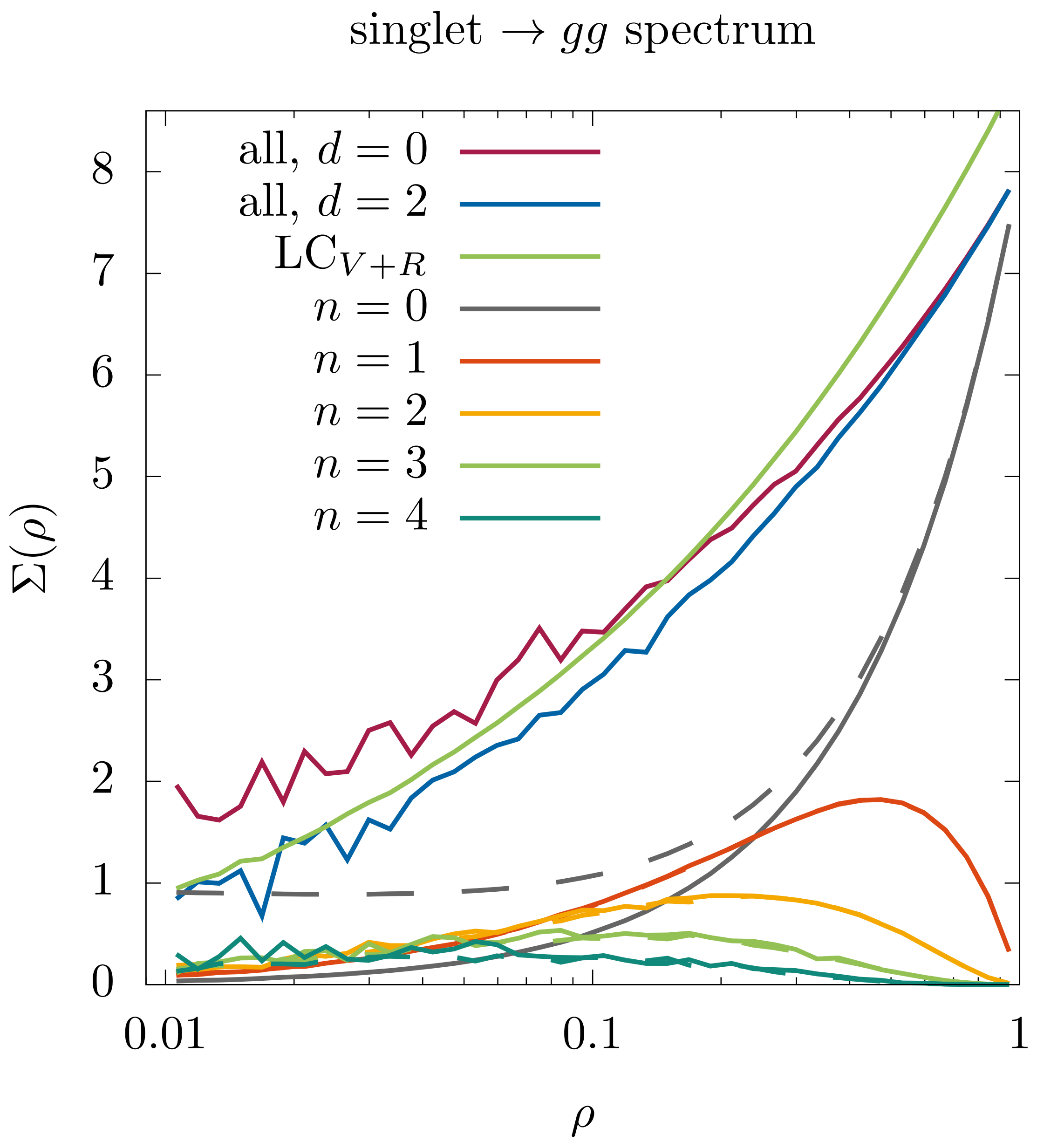


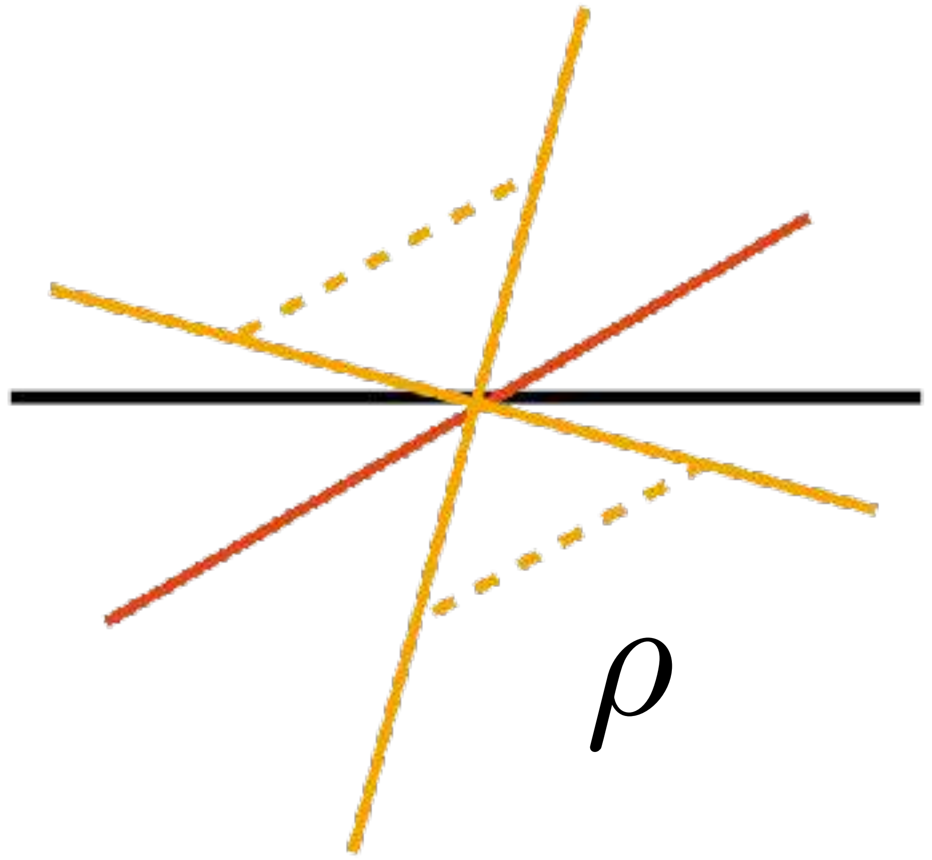
Simulations beyond leading colour

CVolver solves evolution equations in colour flow space

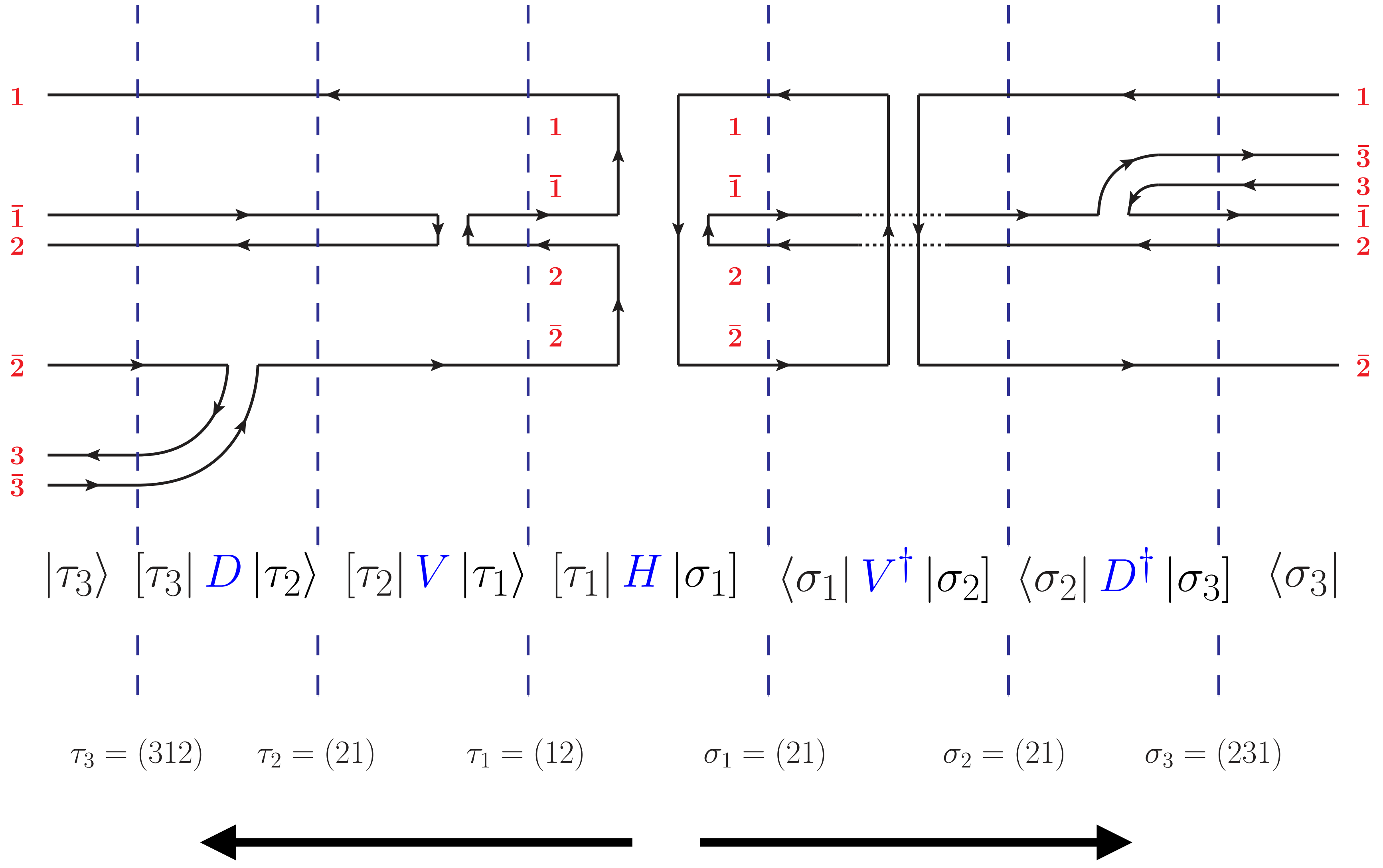
[De Angelis, Forshaw, Plätzer — PRL 126 (2021) 11]
[Plätzer – EPJ C 74 (2014) 2907]

$$\mathbf{A}_n(q) = \int_q^Q \frac{\mathrm{d}k}{k}\, \mathrm{P}e^{-\int_q^k \frac{\mathrm{d}k'}{k'}\boldsymbol{\Gamma}(k')}\, \mathbf{D}_n(k)\, \mathbf{A}_{n-1}(k)\, \mathbf{D}_n^\dagger(k)\, \overline{\mathrm{P}}e^{-\int_q^k \frac{\mathrm{d}k'}{k'}\boldsymbol{\Gamma}^\dagger(k')}$$





$$\Sigma(\rho) = \sum_n \int \mathrm{d}\sigma(\{p_i\}) \prod_i \theta_{\mathrm{in}}(\rho - E_i)$$



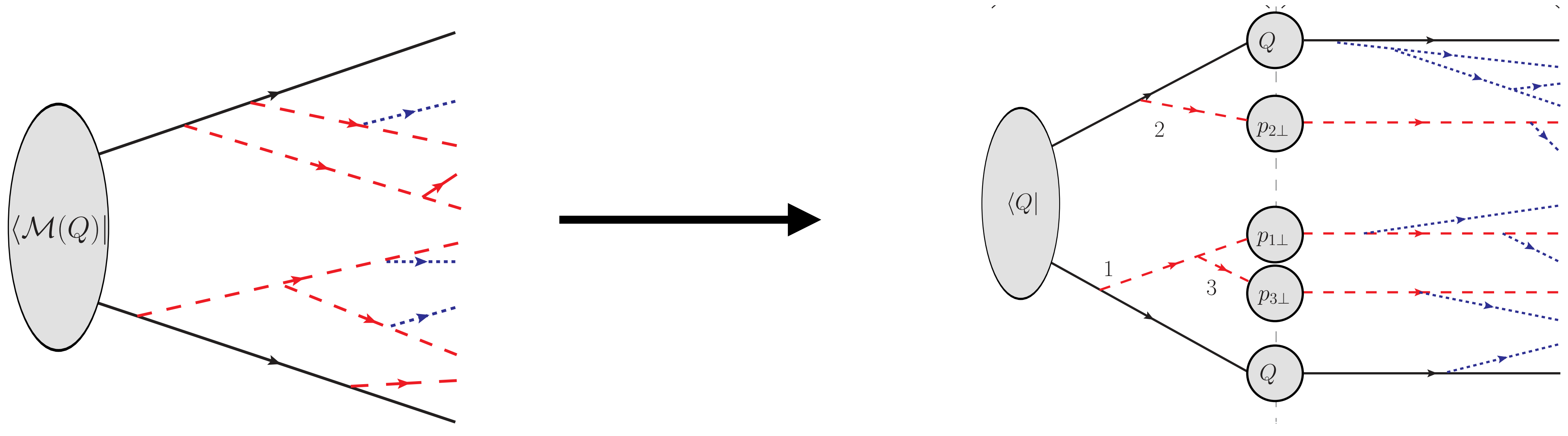
amplitude　　conjugate amplitude

Agrees with [Hatta et al. — Nucl.Phys.B 962 (2021) 115273] using equivalent Langevin formulation.

Advancing amplitude evolution

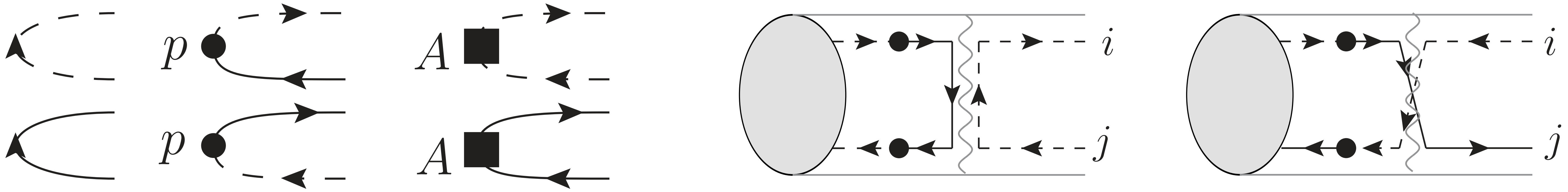
Amplitude evolution rapidly evolving:

- Inclusion of hard collinear contributions?
- Electroweak and QED effects?
- Higher order contributions?
- Hadronization?



Re-arrange soft and collinear evolution
[Forshaw, Holguin, Plätzer – JHEP 1908 (2019) 145, …]

Electroweak evolution requires isospin and chirality flows, and better handling of kinematics.

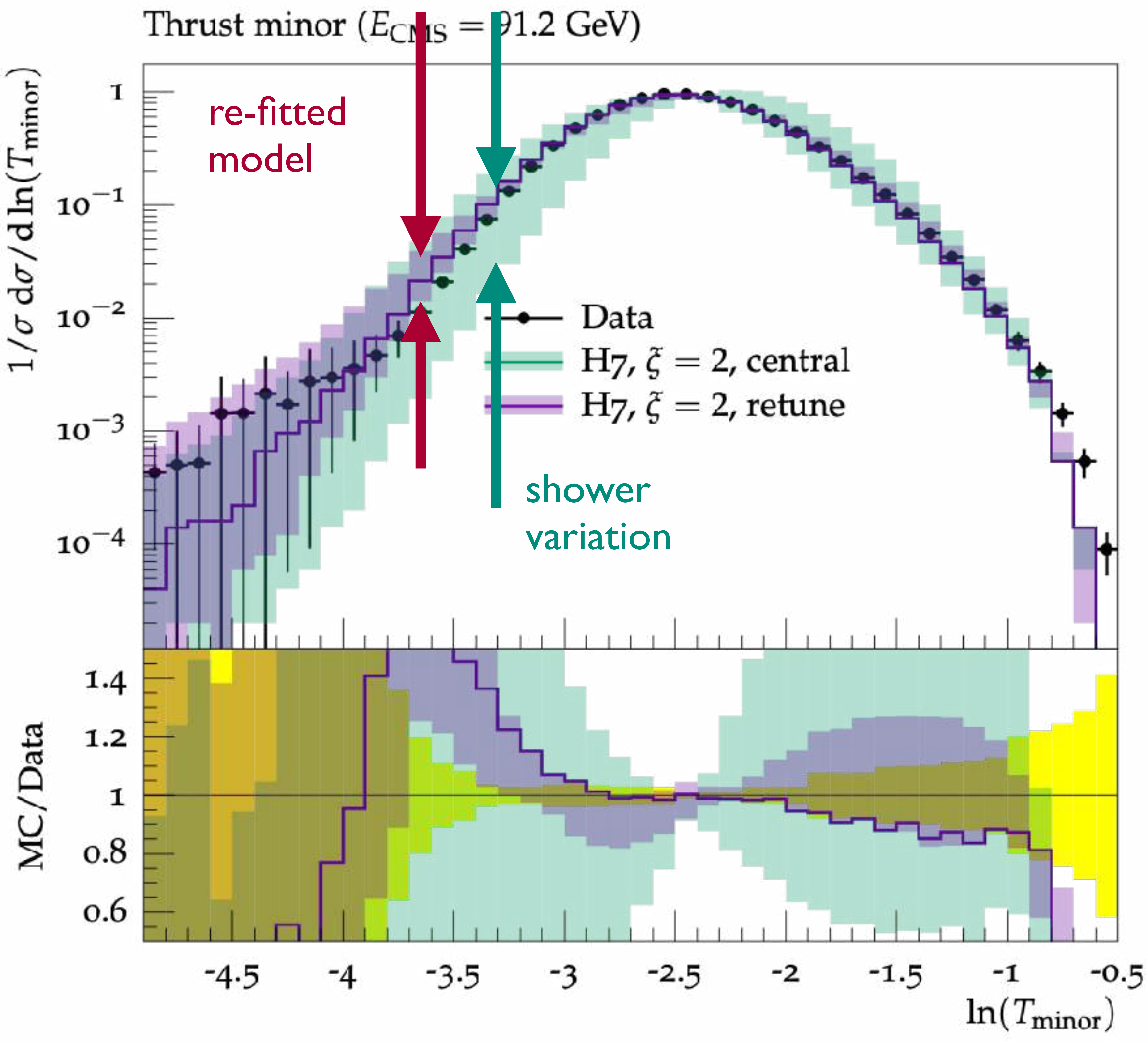


[Plätzer, Sjödahl — arXiv:2204.03258]

Leverage both as a theory tool to construct showers as well as algorithms in their own right.
Only approach to consistently combine interference terms in the hard process with showering.

The interface to hadronization

[Bellm, Lönnblad, Plätzer, Prestel, Samitz, Siodmok, Hoang — Les Houches 2017]



re-fitted model

shower variation

The interface to hadronization

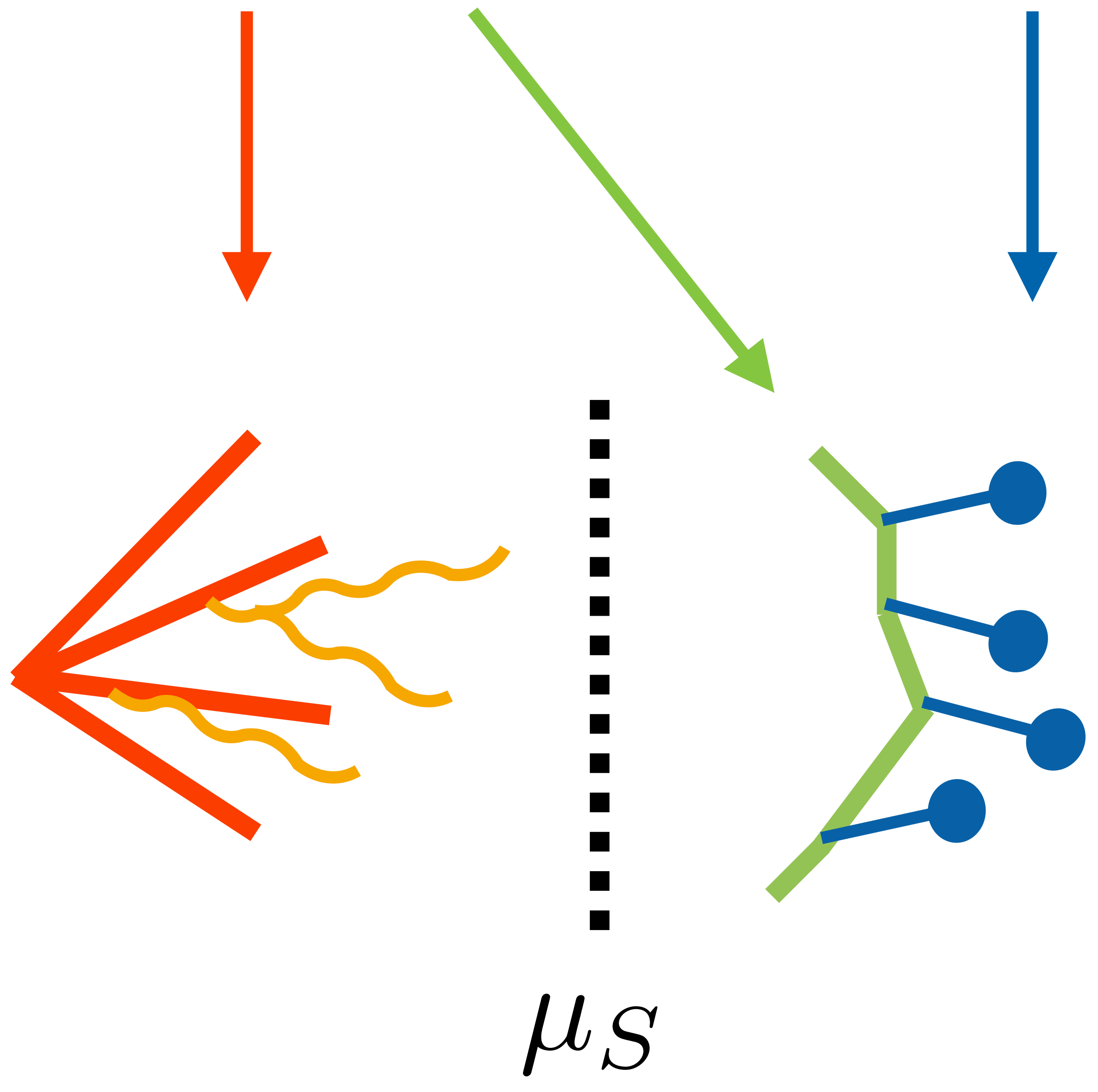
How do we consistently hadronize in light of (improved) shower algorithms?

How to do this at subleading N and higher order shower evolution?

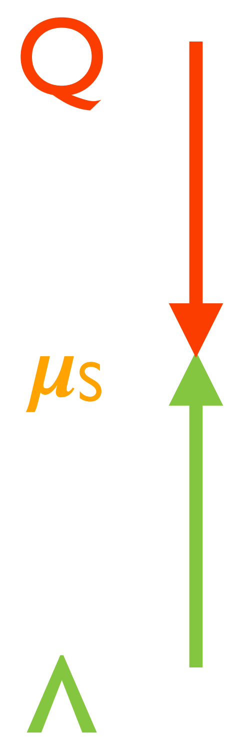
[Plätzer – arXiv:2204.06956]

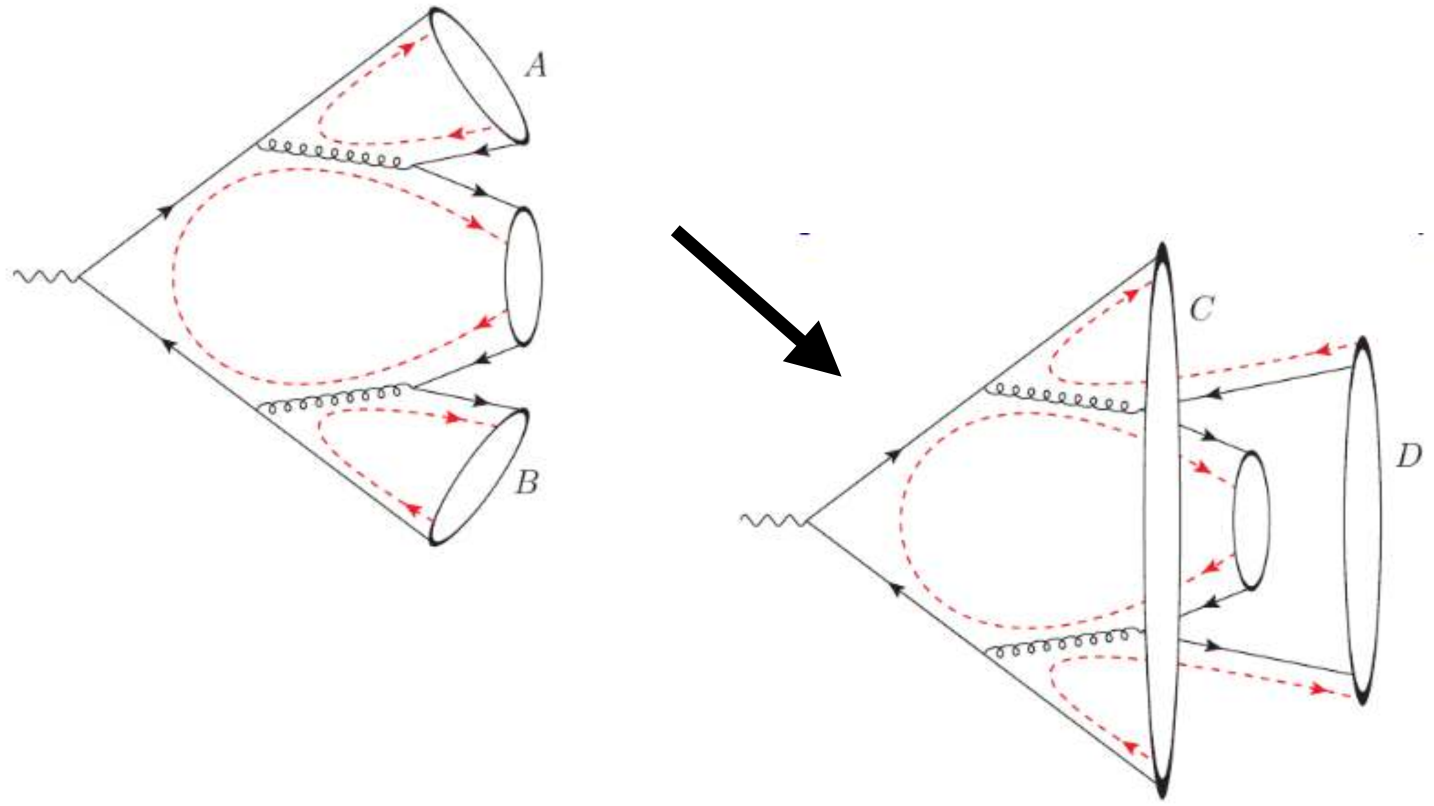
$$\sigma = \sum_{n,m} \int \int \mathrm{Tr}_n \left[\mathbf{M}_n \mathbf{U}_{nm}\right] \mathrm{d}\phi_m u(\phi_m)$$

$$0 = \frac{\mathrm{d}}{\mathrm{d}\mu_S}$$



Implies evolution equations for both shower (amplitude) evolution as well as for a hadronization model.

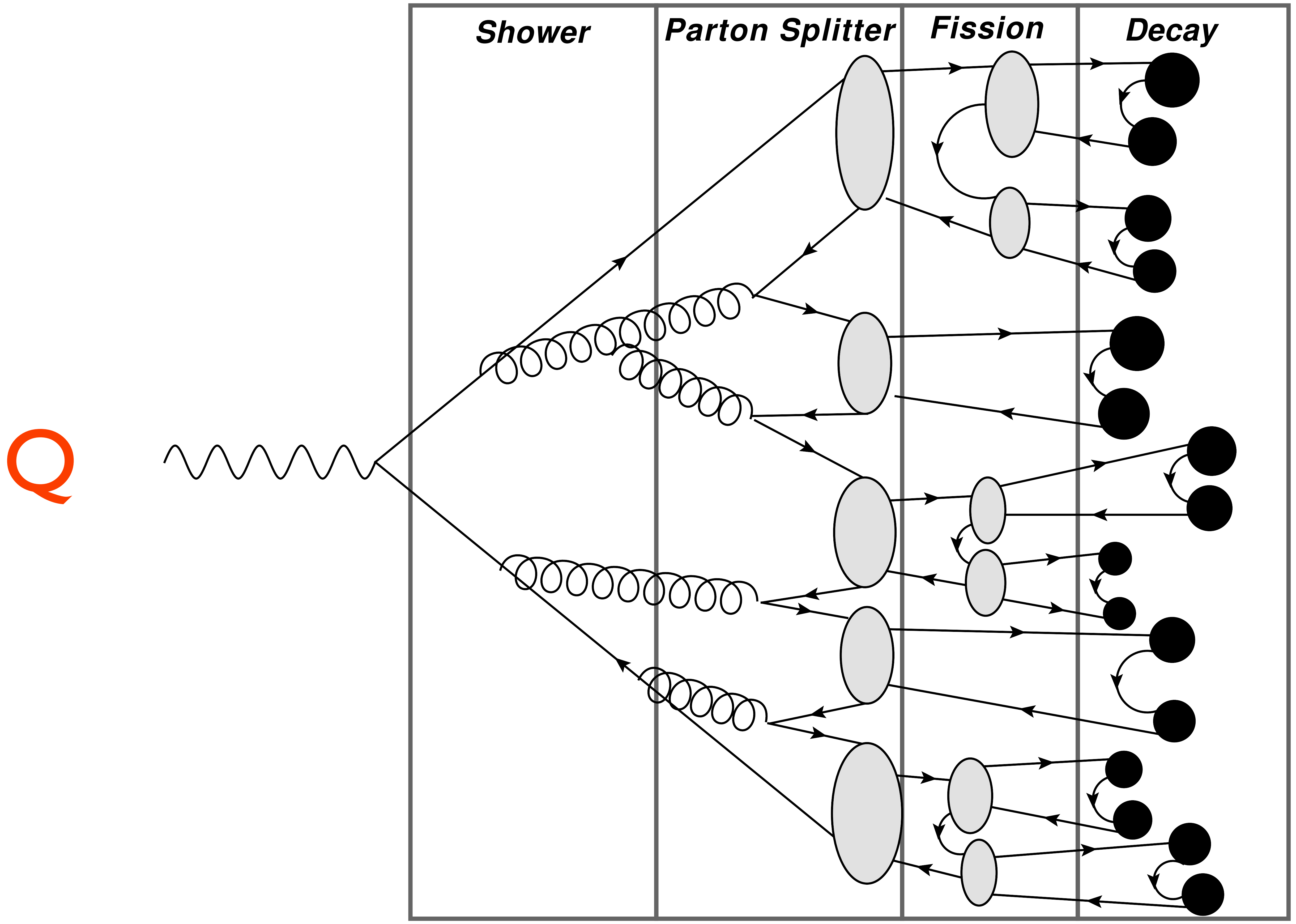


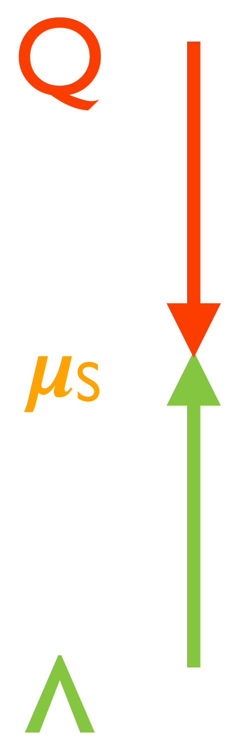


e.g. colour reconnection *implied* just as observed in
[Gieseke, Kirchgaesser, Plätzer – EPJ C 78 (2018) 99]
[Gieseke, Kirchgaesser, Plätzer, Siodmok – JHEP 11 (2018) 149]

The interface to hadronization

[Plätzer – arXiv:2204.06956]
plus work in progress



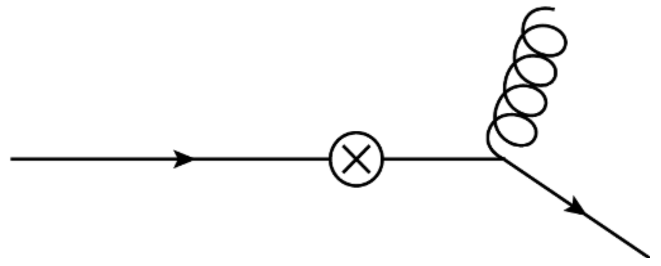
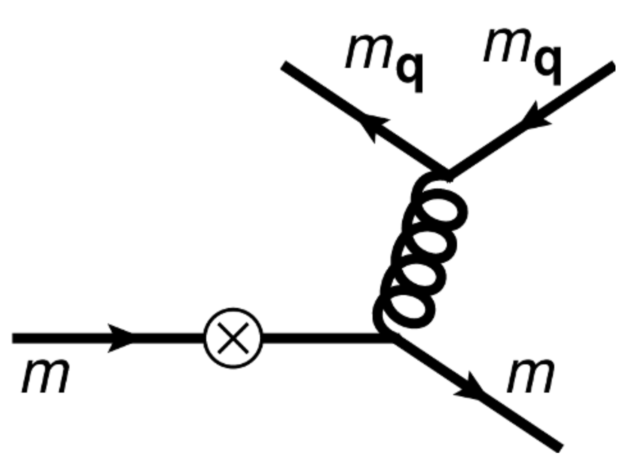
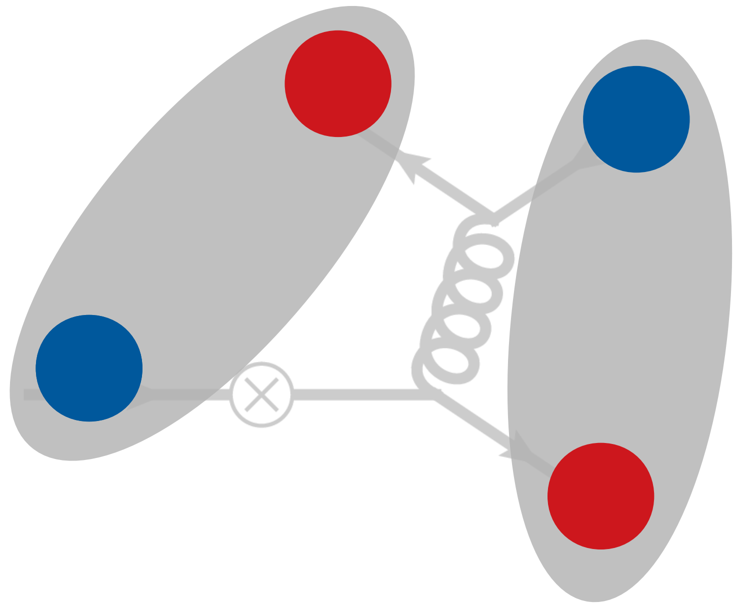
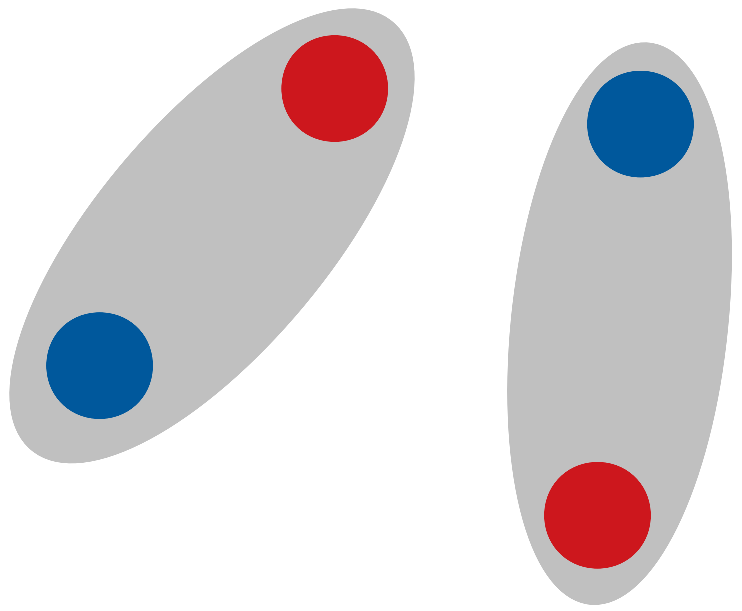
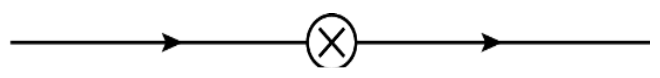
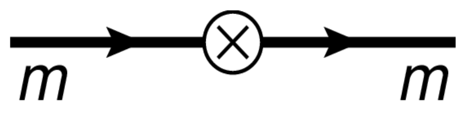
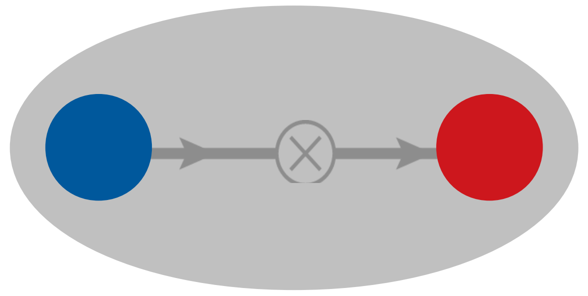
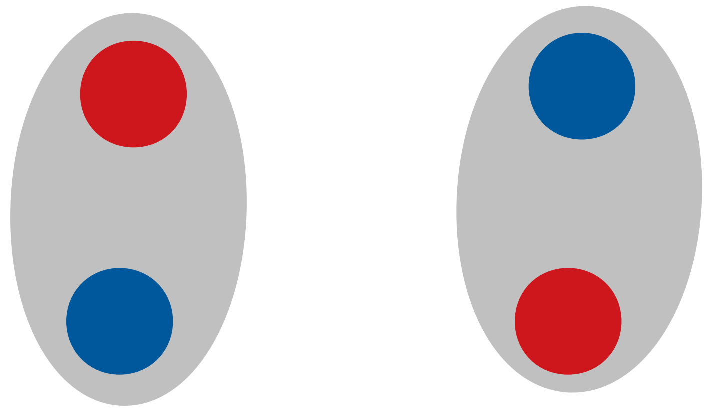


construct by cutoff response

constrain by tuning

Stepping stone: match clusters to shower

UV limit of hadronization needs to reproduce soft limit of (angular ordered) shower.

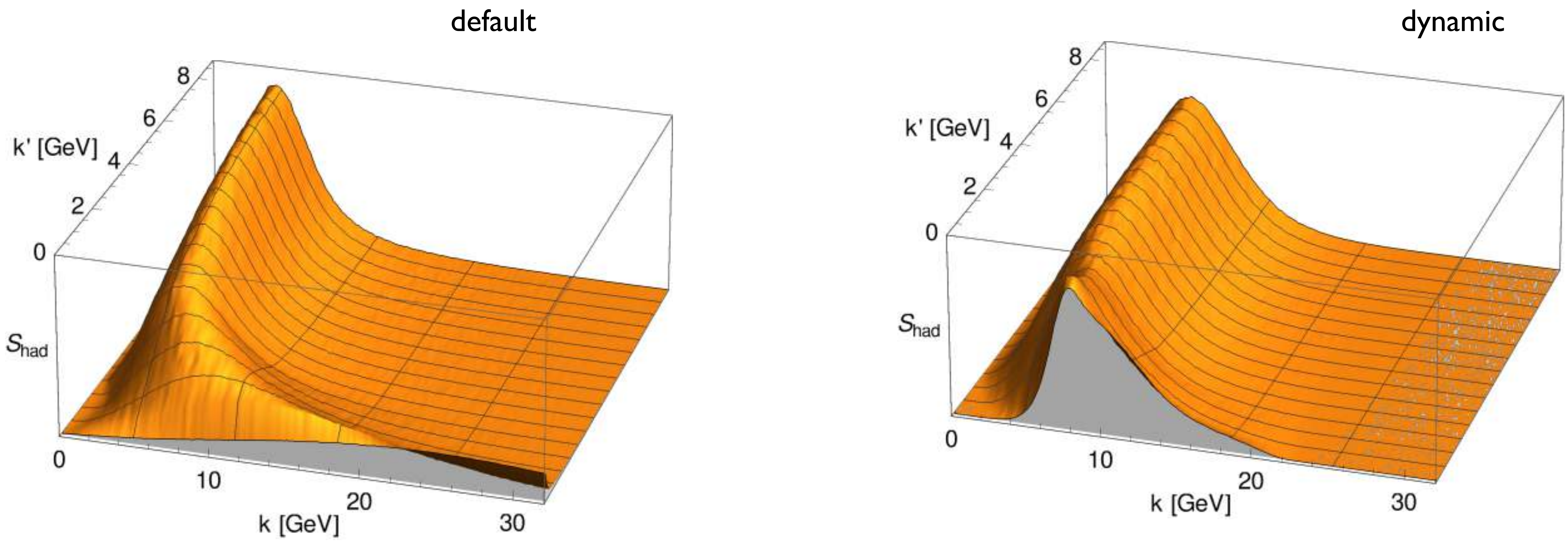
parton shower	forced splitting and constituent masses	cluster formation	cluster fission
			
			

figures by Daniel Samitz

[Hoang, Plätzer, Samitz — in progress]
[Kiebacher, Plätzer, Priedigkeit — in progress]

Tuning and hadronization corrections

Significantly different shapes of hadronization corrections (extracted bin by bin from Herwig)



default

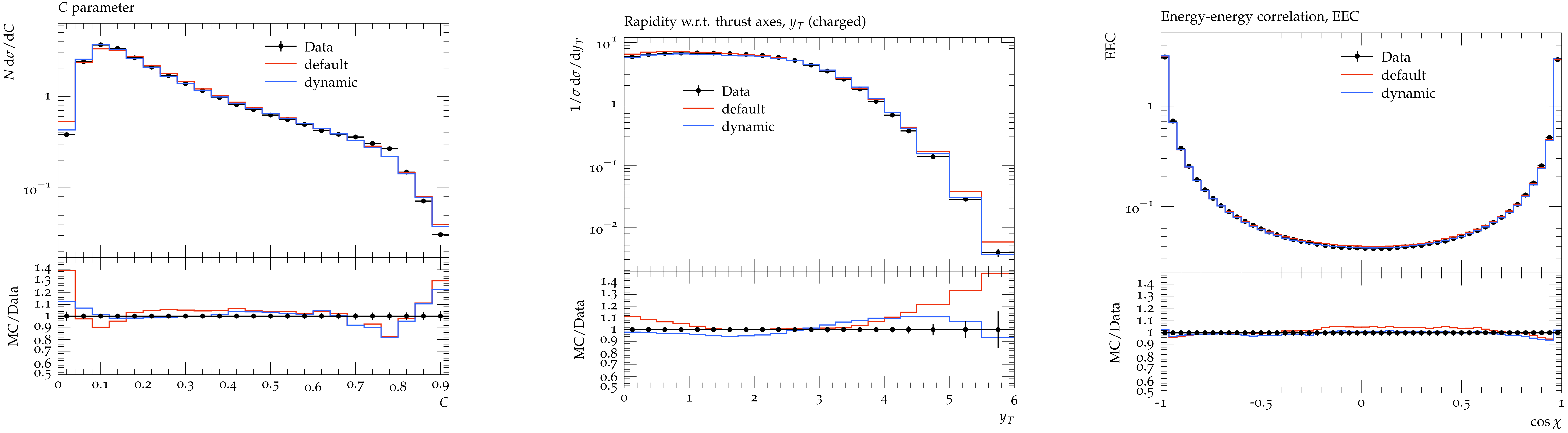
dynamic

C parameter parton versus hadron level

[Hoang, Plätzer, Samitz — in progress]

Tuning and hadronization corrections

Significantly different shapes of hadronization corrections (extracted bin by bin from Herwig)



C parameter

rapidity wrt thrust

EEC

C parameter parton versus hadron level

[Hoang, Plätzer, Samitz — in progress]

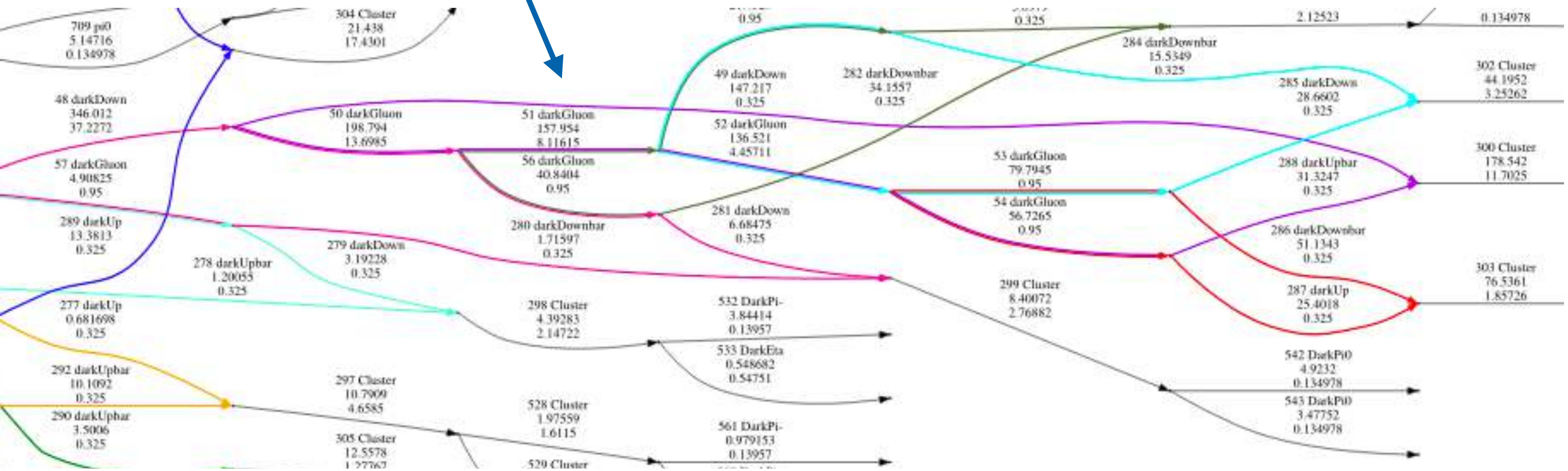
Hidden valley hadronization

Hidden valley angular ordered shower, based on new shower interactions framework

[Masouminia, Richardson]

More flexible cluster hadronization

[Plätzer, Stafford]



[Kulkarni, Masouminia, Papaefstathiou, Plätzer, Siodmok, Stafford — in progress]

Herwig package complementing Pythia's hidden valley model.

Blindly relying on validity of coherence and quasi-collinear limit … among many other questions.

Algorithms & Efficiency

Sudakov-type densities central to Showers

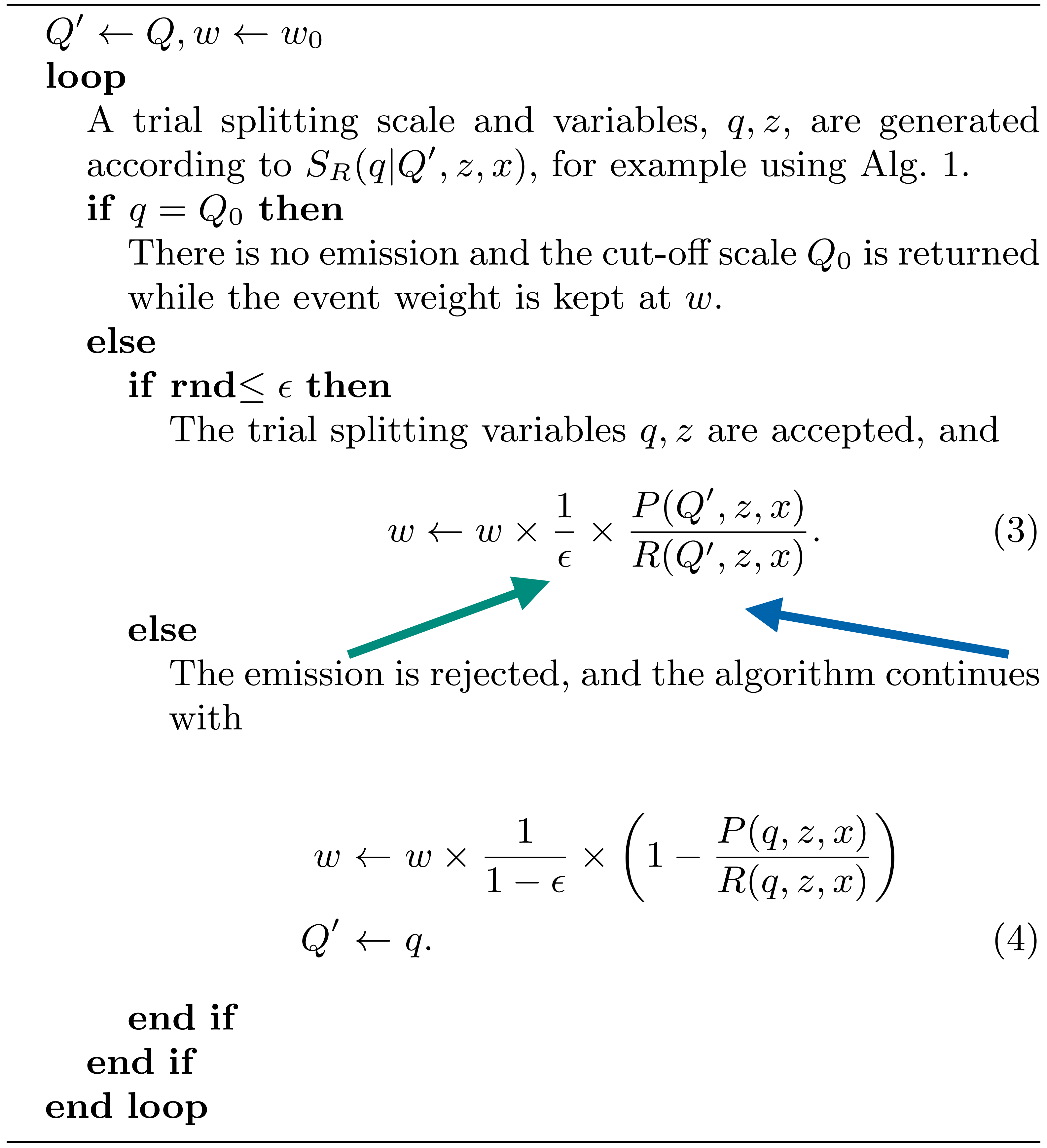
[Olsson, Plätzer, Sjödahl — EPJC 80 (2020) 10]
[Plätzer, Sjödahl — EPJ Plus 127 (2012) 26]

no emission

$$\frac{\mathrm{d}S_P(q|Q,z,x)}{\mathrm{d}q\ \mathrm{d}z} = \Delta_P(Q_0|Q,x)\delta(q-Q_0)\delta(z-z_0)$$
$$+\Delta_P(q|Q,x)P(q,z,x)\theta(Q-q)\theta(q-Q_0)$$

emission

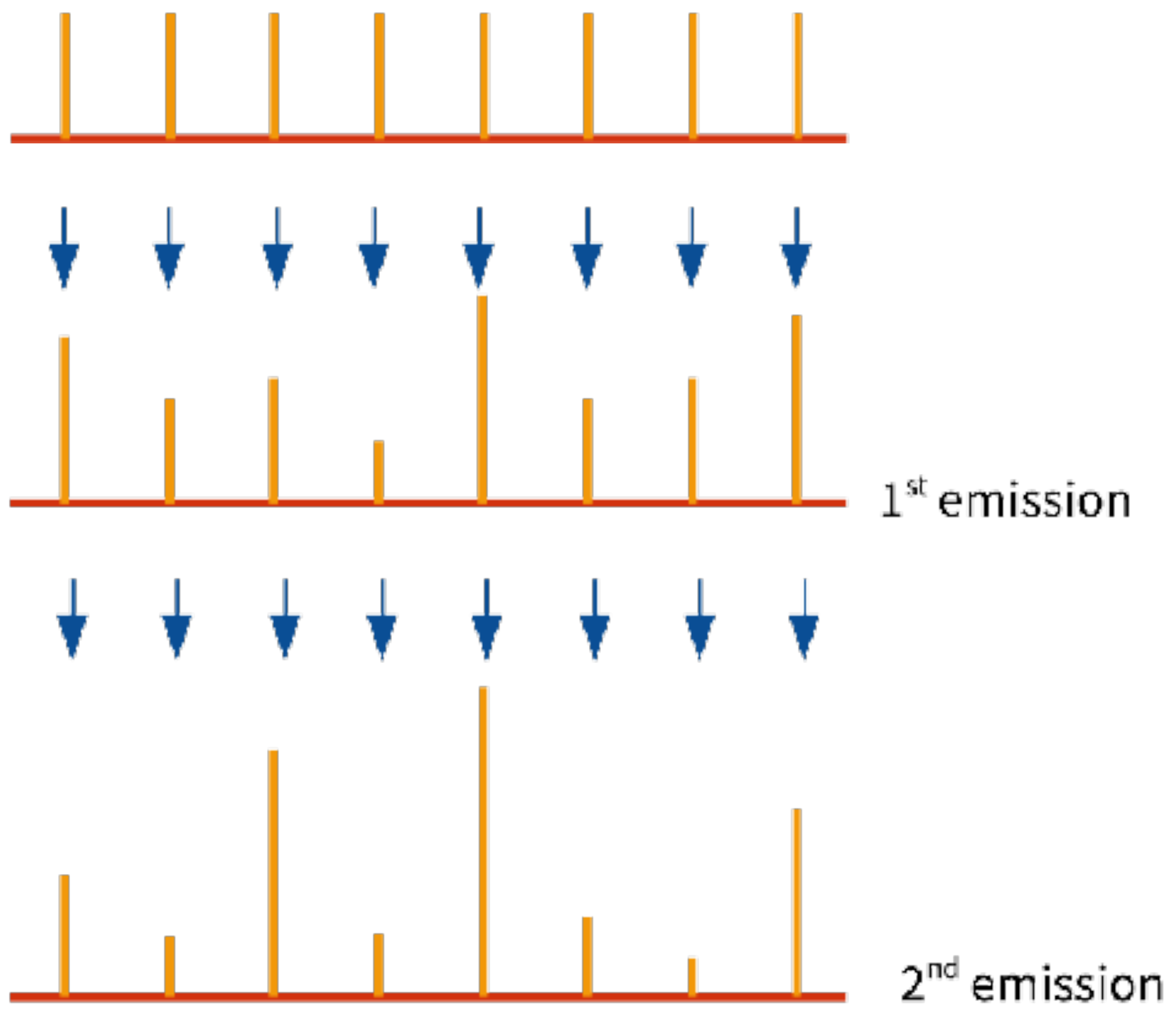
Negative P or unknown overestimate requires weighted veto algorithm, with in principle arbitrary proposal kernel and veto probability.

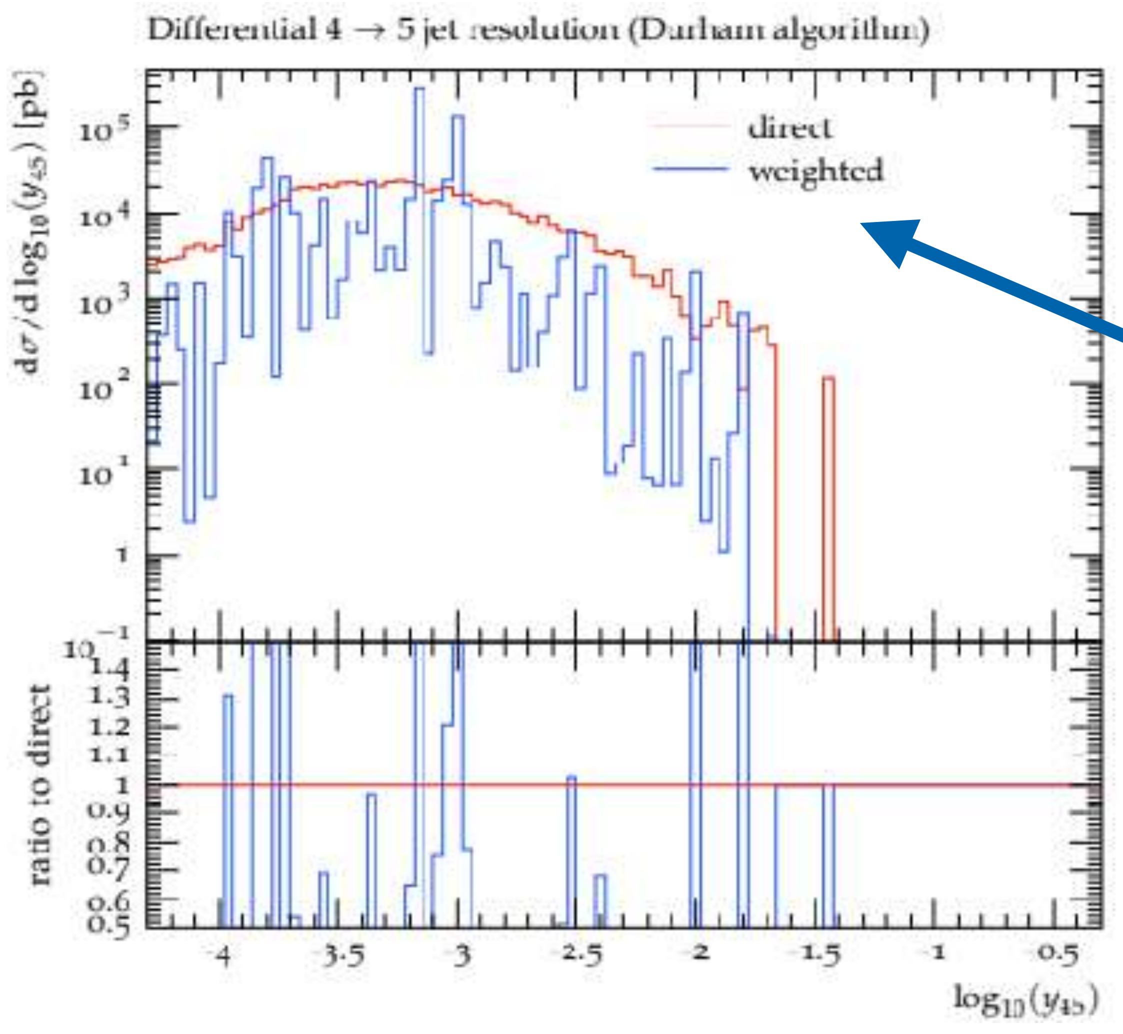


```
$Q' \leftarrow Q, w \leftarrow w_0$
loop
  A trial splitting scale and variables, $q, z$, are generated according to $S_R(q|Q',z,x)$, for example using Alg. 1.
  if $q = Q_0$ then
    There is no emission and the cut-off scale $Q_0$ is returned while the event weight is kept at $w$.
  else
    if rnd$\leq \epsilon$ then
      The trial splitting variables $q, z$ are accepted, and
          $w \leftarrow w \times \frac{1}{\epsilon} \times \frac{P(Q',z,x)}{R(Q',z,x)}.$      (3)
    else
      The emission is rejected, and the algorithm continues with
          $w \leftarrow w \times \frac{1}{1-\epsilon} \times \left(1 - \frac{P(q,z,x)}{R(q,z,x)}\right)$
          $Q' \leftarrow q.$      (4)
    end if
  end if
end loop
```

Weighted Veto Algorithms & Resampling

[Olsson, Plätzer, Sjödahl — EPJ C80 (2020) 10, 934]





Weighted branching algorithms exhibit prohibitive weight distributions & convergence issues.

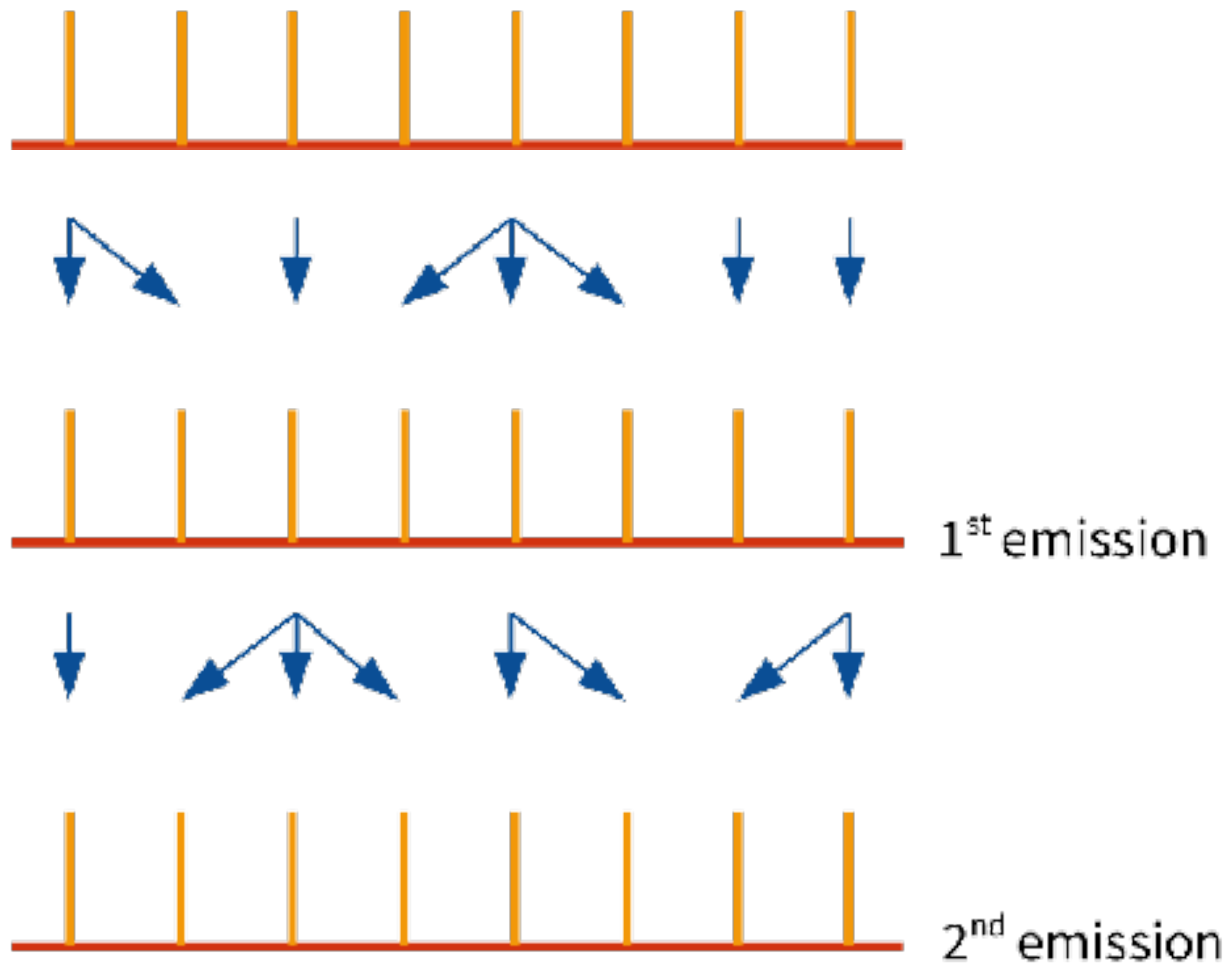
Result without resampling

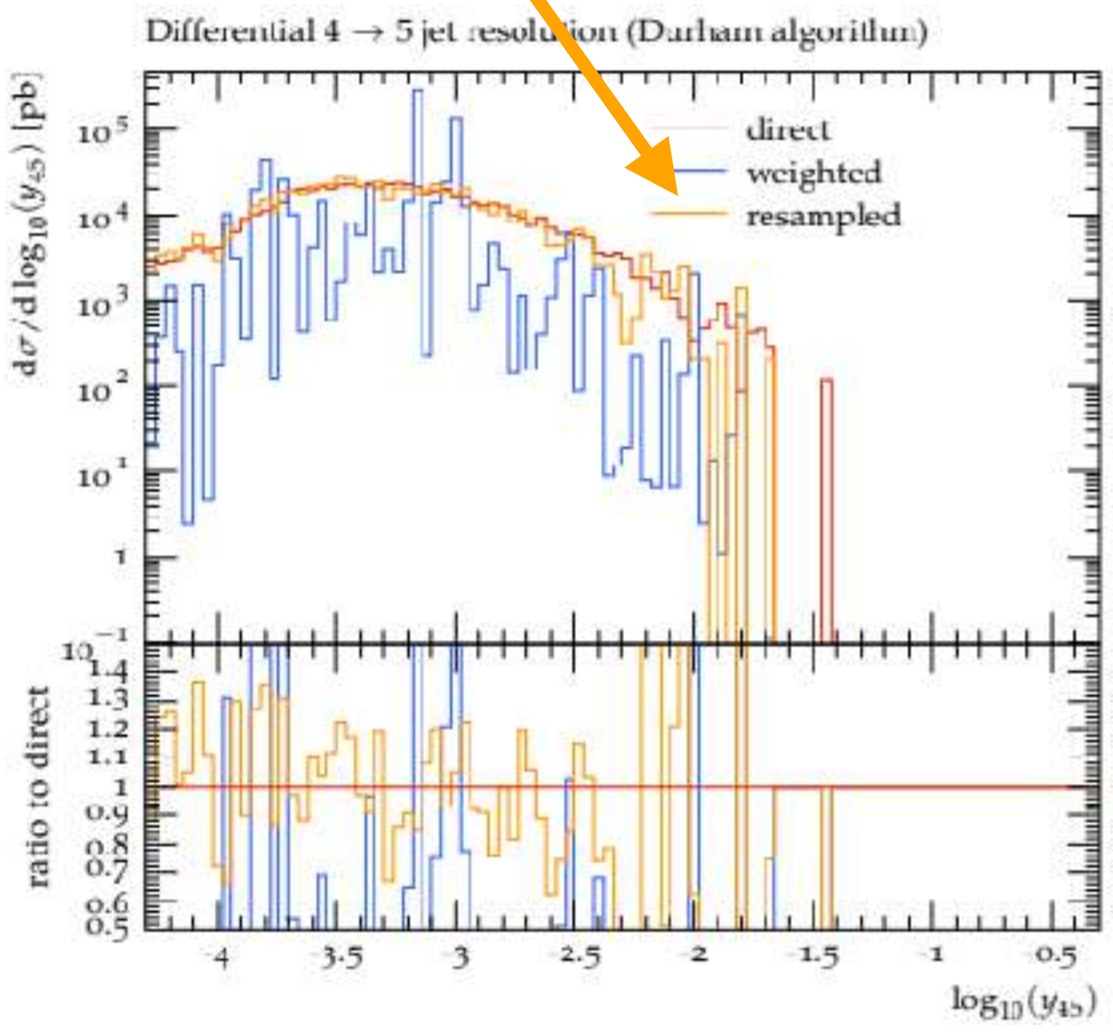
Result with resampling

Resampling algorithms can compress weight distributions at intermediate steps.

Different resampling method developed as event generator after-burner.

[Andersen, Gütschow, Maier, Prestel — EPJ C 80 (2020) 11]





Some words on matching

Matching is important and challenging.
NLO Matching & merging well established, can *combine* with NNLO and beyond using unitarized merging algorithms.

[Plätzer — JHEP 08 (2013) 114] [Lönnblad, Prestel — JHEP 02 (2013) 049]
e.g. N3LO — [Prestel — JHEP 11 (2021) 041]

True *matching* beyond NLO and including QED/EW needs much more progress on showers first.

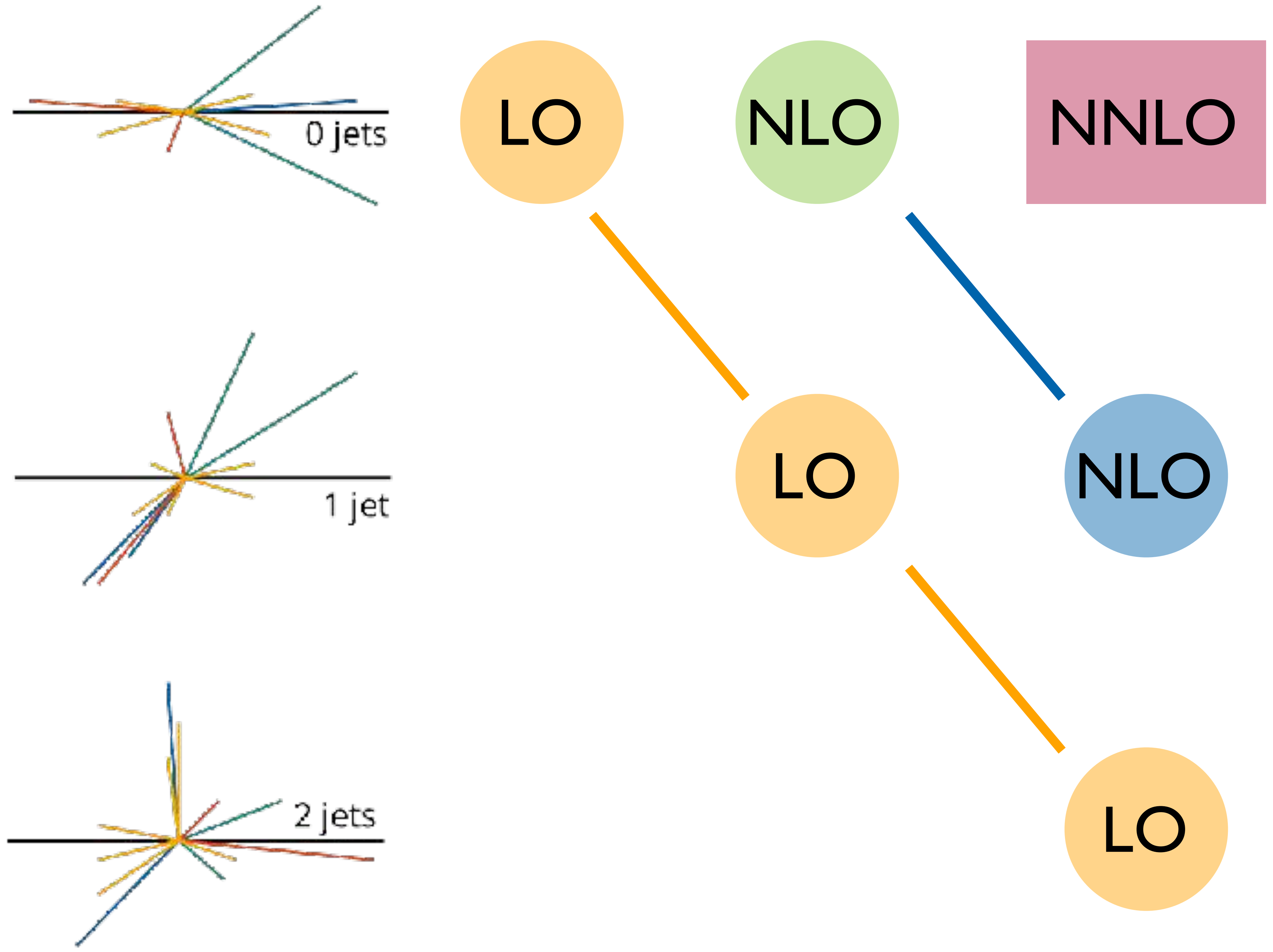
Some progress towards NNLO by correcting showers.

[Campbell, Höche, Li, Preuss, Skands — arXiv:2108.07133]

Showers need to demonstrate that their construction yields double emission kernels which read

(2 correlated, ordered emissions) - (1x1 ordered emissions)
+ (2 correlated, un-ordered emissions)

[Plätzer – arXiv:2204.06956]



- De-facto standard in multi-purpose event generators
- Tweaks still possible

[Nason, Salam — JHEP 01 (2022) 067]

Herwig 7/Matchbox & KrkNLO, MG5_aMC@NLO, PowhegBox, Sherpa

Summary & Outlook

Multi-purpose event generators can start to do FCC physics, but a face a significant number of challenges.
Matching & merging has been focus of last decade.

As we aim to use more and more of the complex structures, shower accuracy becomes the bottleneck.
Also for matching to more than NNLO QCD.

The understanding of hadronization effects and models, and their interplay with parton showers will be one of the main topics in the future, not only in light of measuring fundamental parameters.

Amplitude level evolution can serve as theoretical framework and algorithm in its own right.

Need to explore subleading colour and other effects which are inaccessible to probabilistic algorithms:
We cannot argue that these effects are small if we do not have a tool to explicitly check.

Thank you.

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ

UNI GRAZ

universität wien