UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ

Accidents happen :-(
Last-minute recycled slides —
think of this as complementing Stefan Hoeche’s summary at HP2 …

Showers and all that

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

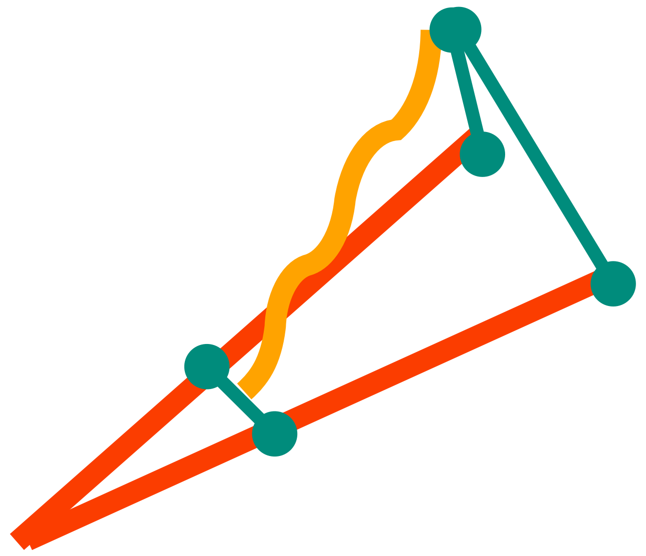
At the
MCnet meeting
Graz/Online | 22 September 2022

Shower & Parton Branching Paradigms

Parton branchings order in angle.

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

Herwig 7

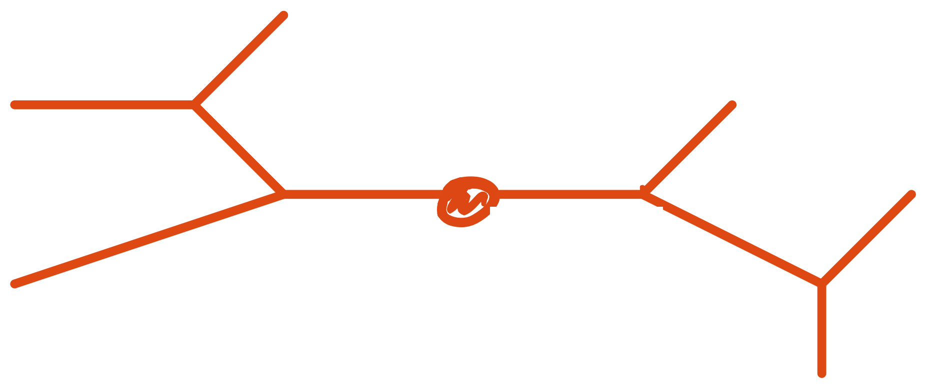


Dipole branchings order in transverse momentum.

- 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.



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

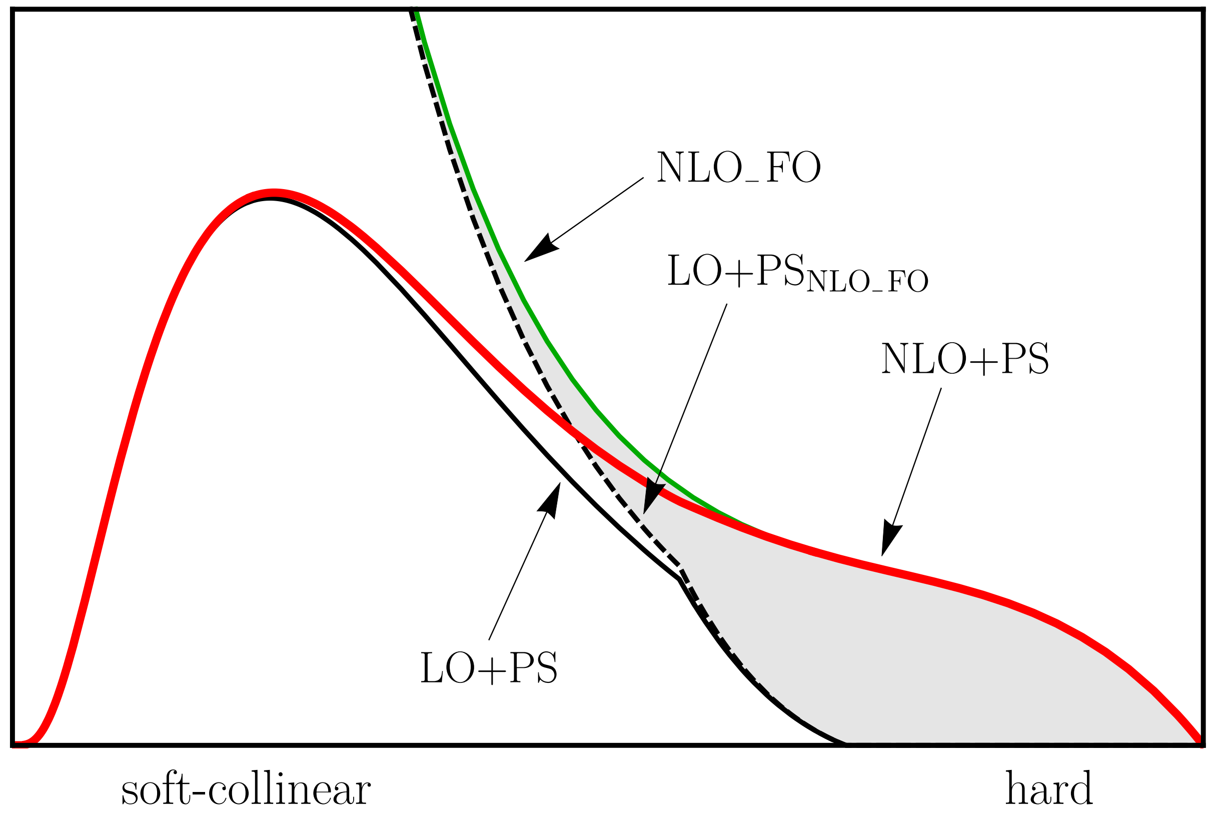
emission rate

no emission probability

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

Matching & Merging

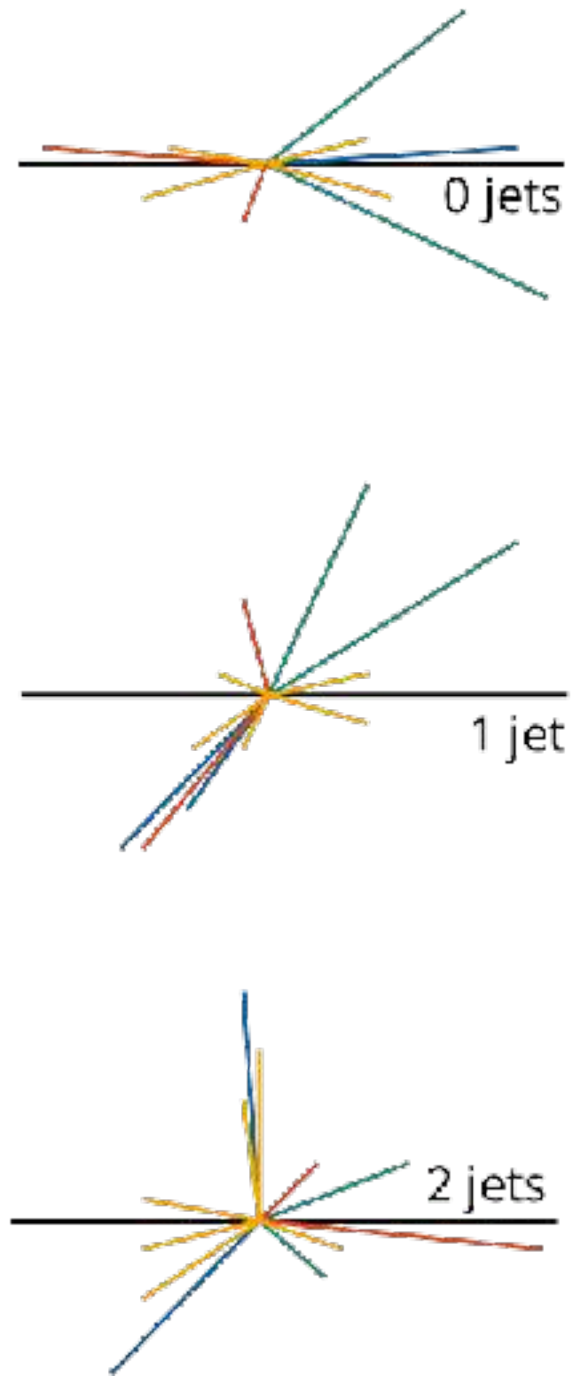
Matching determined by expanding shower to fixed order, and subtracting it from fixed-order cross section.

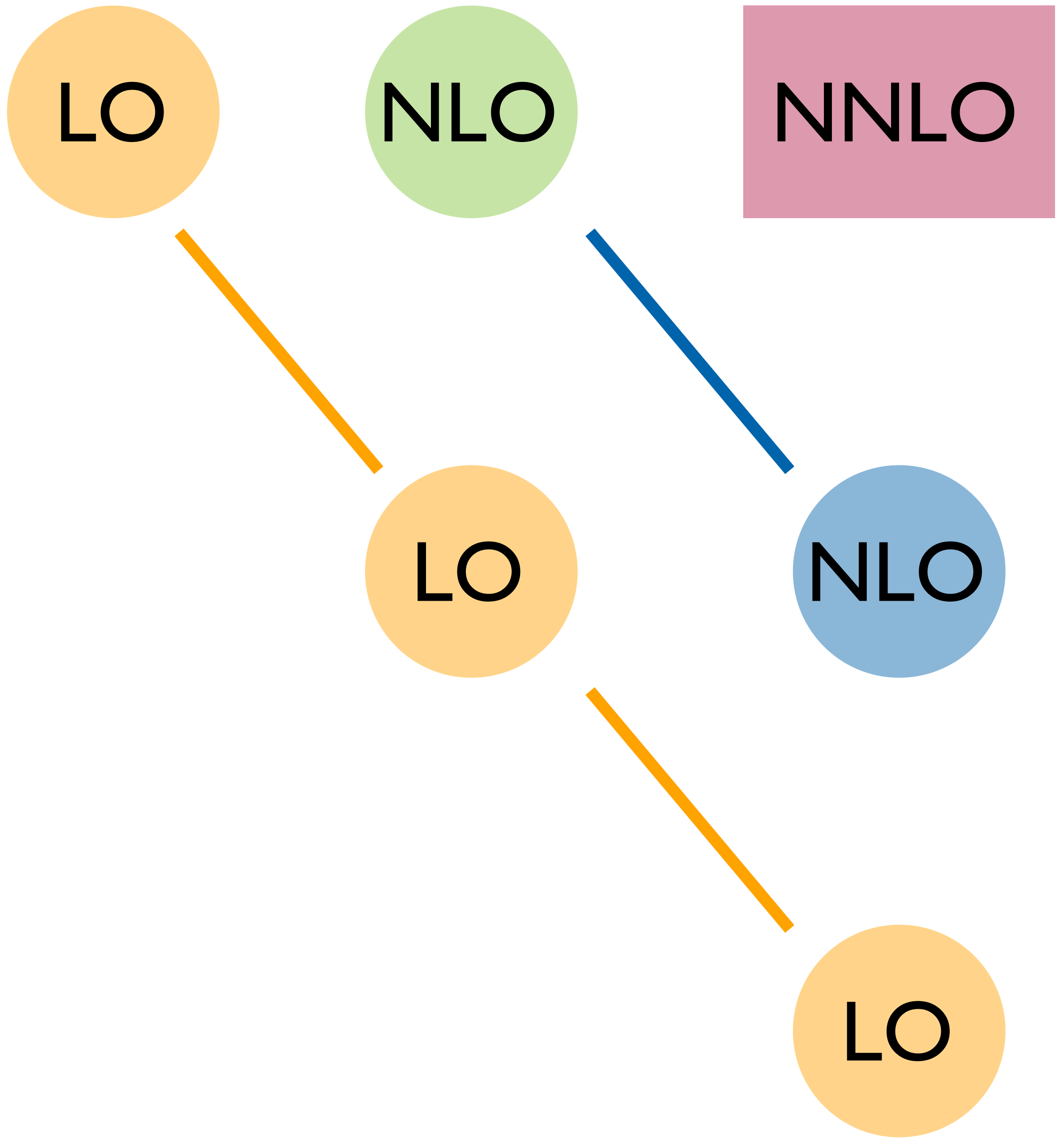


- De-facto standard in multi-purpose event generators
- Tweaks still possible

[Nason, Salam — JHEP 01 (2022) 067]

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





Unitartized merging algorithms are state of the art.

[Plätzer — JHEP 08 (2013) 114] [Lönnblad, Prestel — JHEP 02 (2013) 049]
[Bellm, Gieseke, Plätzer — EPJ C78 (2018) 244]

Allow for combination with higher orders

e.g. [Prestel — JHEP 11 (2021) 041]

Matching at NNLO explored, but requires better showers.

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

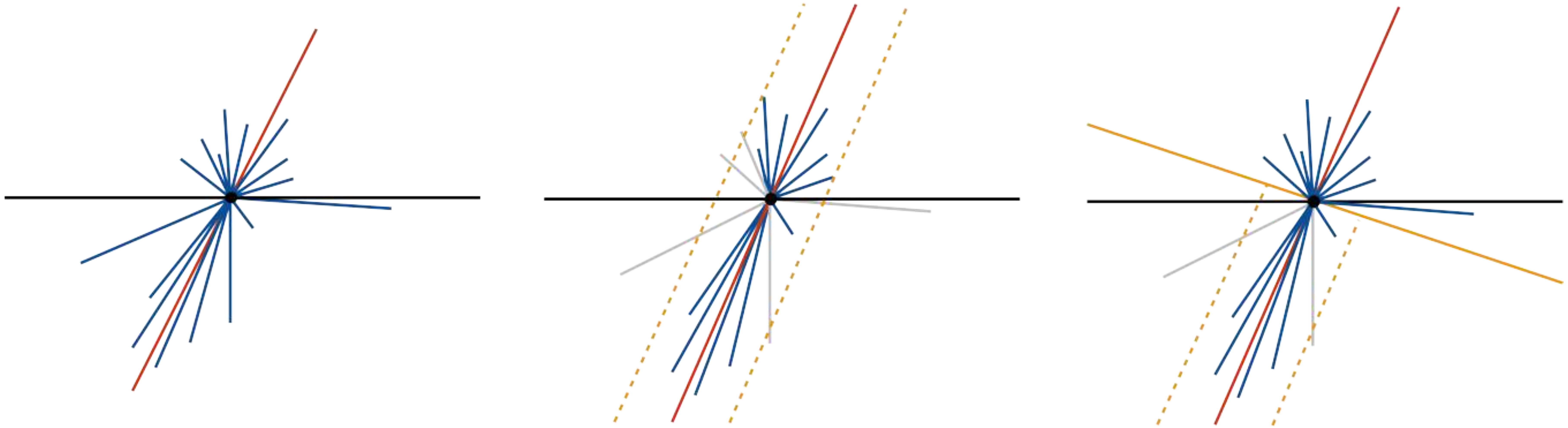
Merging & matching
NLO merging
Matching at NNLO?

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

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ



Global event shapes from coherent branching

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

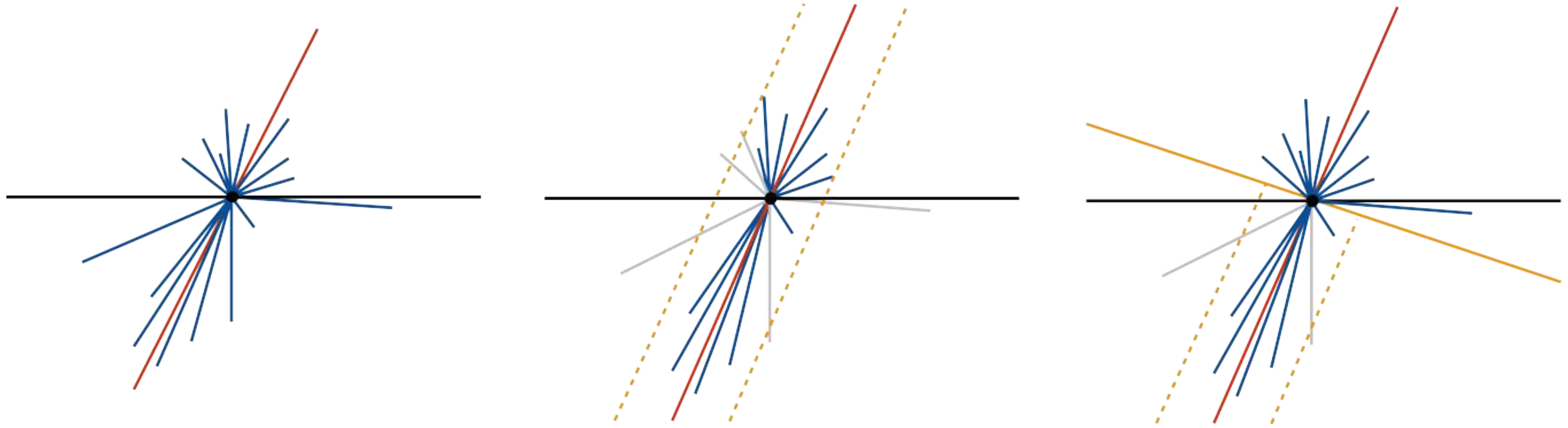
LL — qualitative NLL — quantitative NNLL — precision

$\alpha_s L \sim 1$

Accuracy of Parton Showers

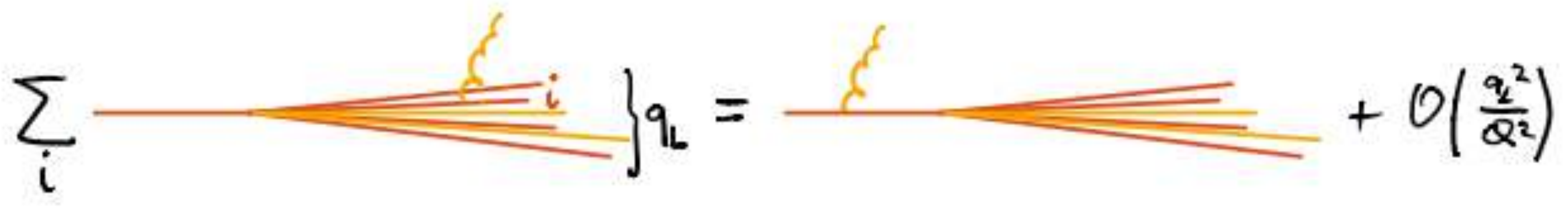
UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ

universität wien



Global event shapes from coherent branching

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

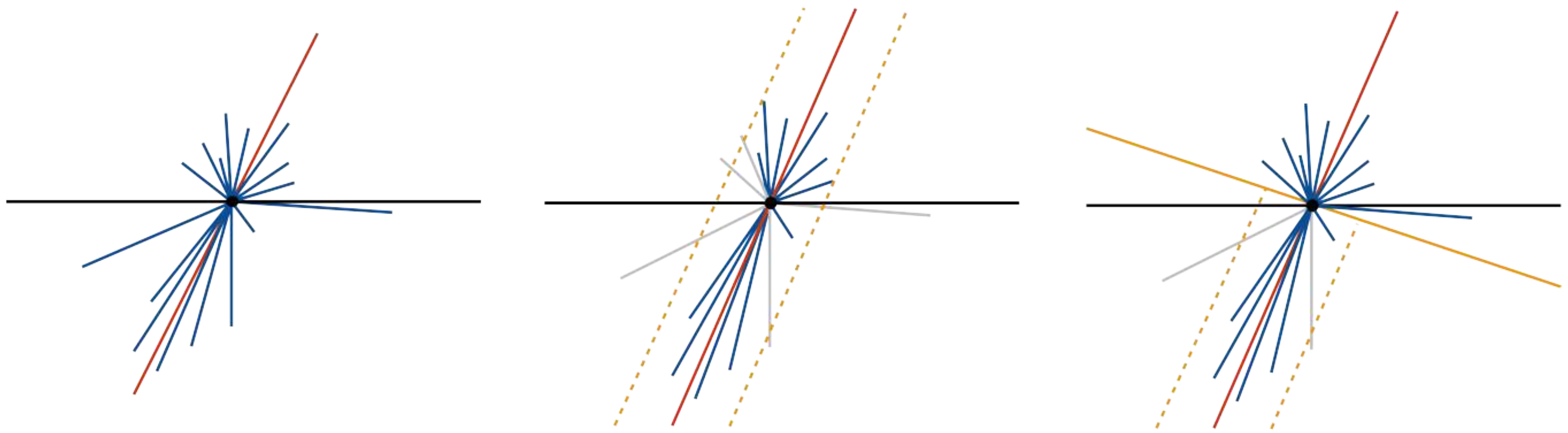


$$\frac{\partial G_{ab}(t)}{\partial t} = -\int_{\text{in}} \frac{\mathrm{d}\Omega_k}{4\pi} \omega_{ab}(k) G_{ab}(t) + \int_{\text{out}} \frac{\mathrm{d}\Omega_k}{4\pi} \omega_{ab}(k) \Big[G_{ak}(t) G_{kb}(t) - G_{ab}(t) \Big]$$

[Catani, Trentadue, Webber, Marchesini ….]

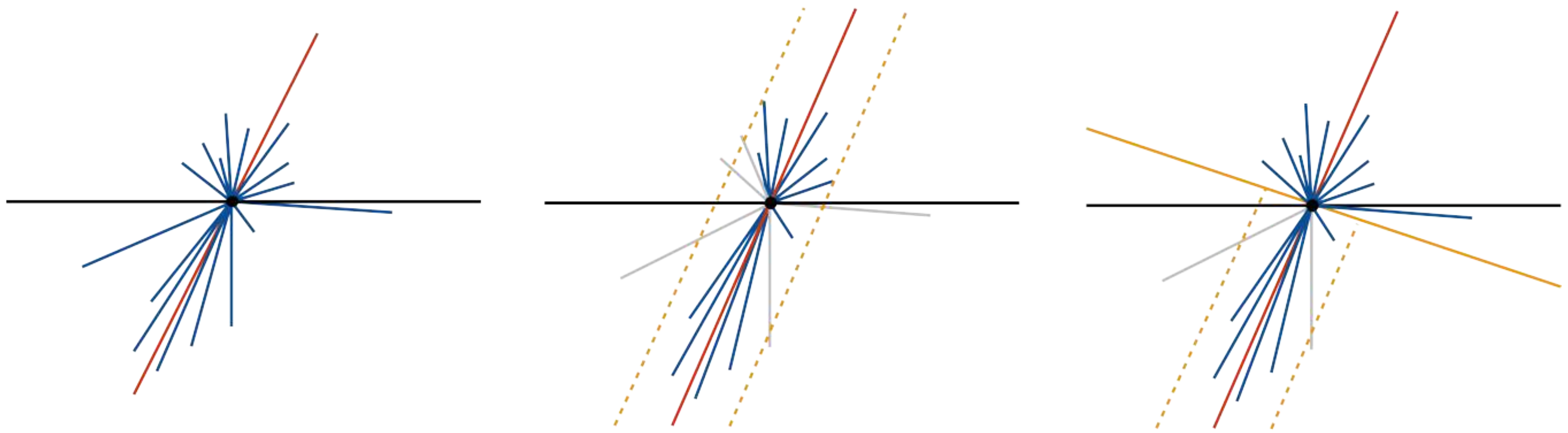
[Banfi, Marchesini, Smye — JHEP 08 (2002) 006]
even at NLL: [Banfi, Dreyer, Monti — JHEP 10 (2021) 006]

Accuracy of Parton Showers



Accuracy of Parton Showers

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ
universität wien



NLO with matching

NLL with coherent branching
Issues in dipole showers

Issues in coherent branching
LL with dipole showers

Understand and decide on accuracy of (existing) parton shower algorithms, take as a starting point for incremental improvements.

$$H(\alpha_s) \times \exp\left(L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots\right)$$

$\alpha_s L \sim 1$ LL NLL NNLL

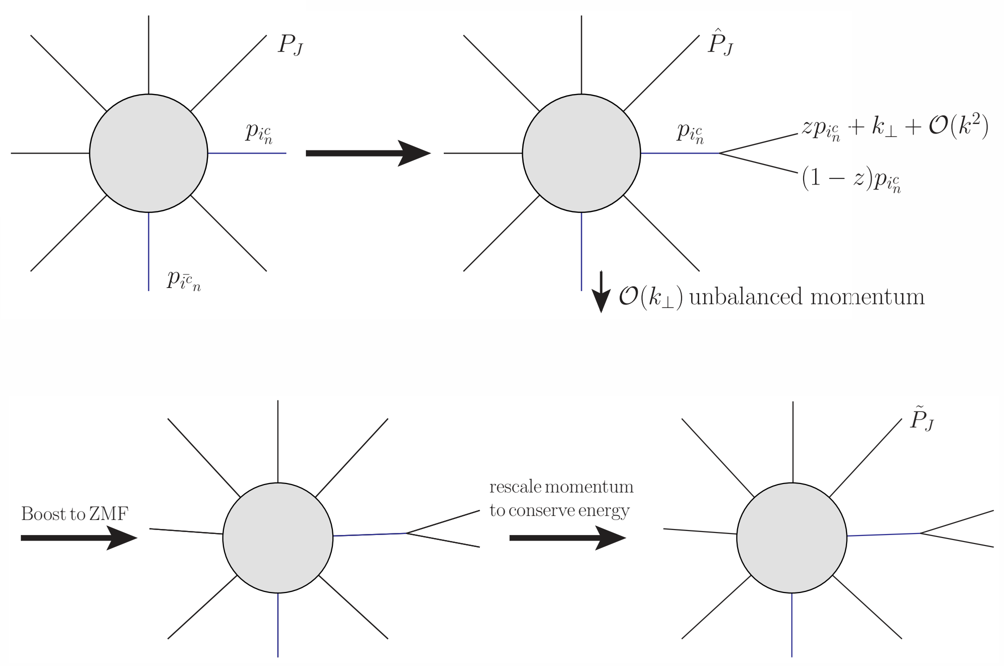
[Dasgupta, Dreyer, Hamilton, Monni, Salam et al. — JHEP 09 (2018) 033, …]
[Hoang, Plätzer, Samitz — JHEP 1810 (2018) 200]
[Bewick, Ferrario, Richardson, Seymour — JHEP 04 (2020) 019]

Accuracy of Parton Showers

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

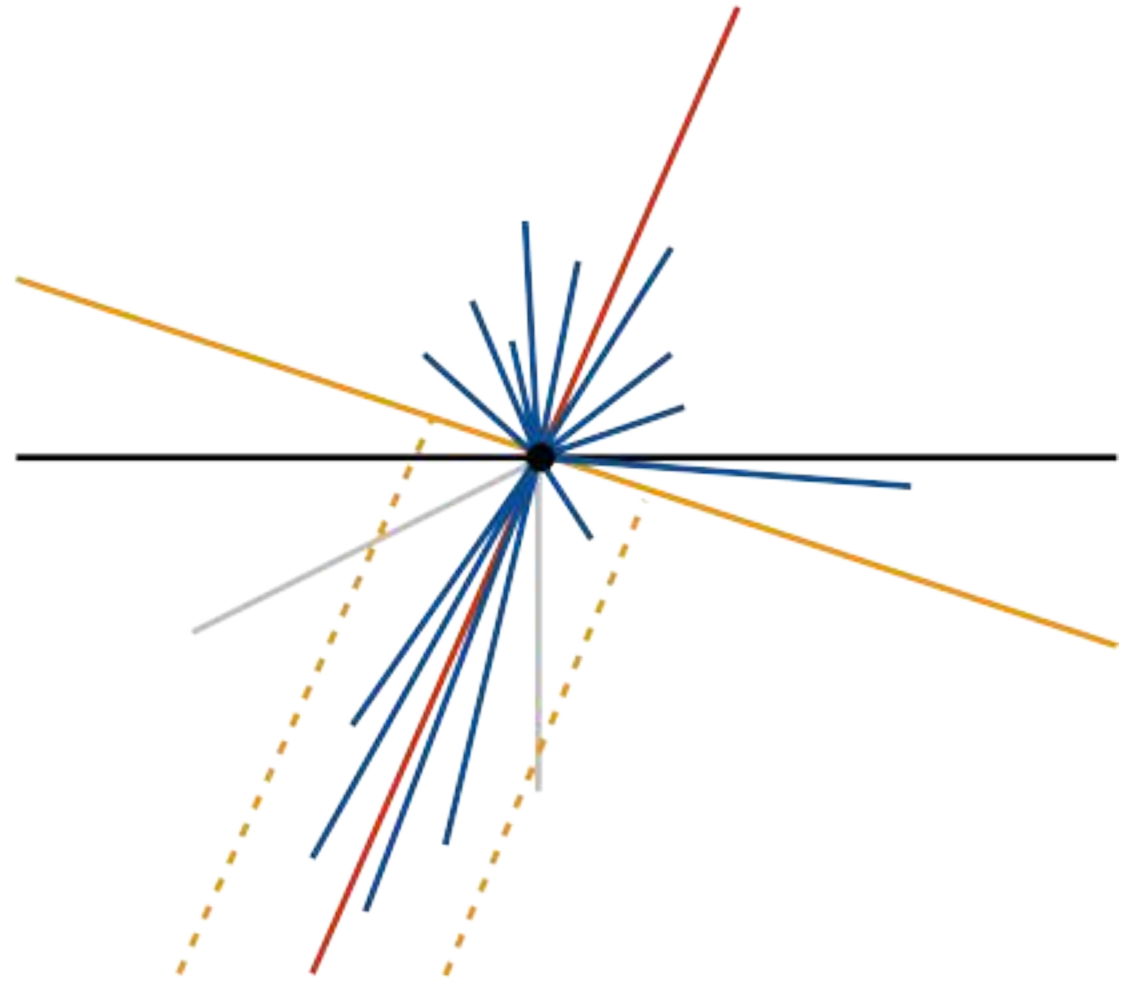
$$\frac{p_{i_n}\cdot p_{j_n}}{p_{i_n}\cdot q_n\; p_{j_n}\cdot q_n} - \frac{T\cdot p_{j_n}}{T\cdot q_n}\frac{1}{p_{j_n}\cdot q_n} + \frac{T\cdot p_{i_n}}{T\cdot q_n}\frac{1}{p_{i_n}\cdot q_n}$$

Partition of soft radiation



Recoil

[Dasgupta, Dreyer, Hamilton, Monni, Salam —PRL 125 (2020) 5]
[Forshaw, Holguin, Plätzer – JHEP 09 (2020) 014 & EPC C81 (2021) 4]



Dipole showers reproducing coherent branching:
NLL & NLC global, LL & LC non-global

Understand and decide on accuracy of (existing) parton shower algorithms,
take as a starting point for incremental improvements.

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

$\alpha_s L\sim 1$ LL NLL NNLL

[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]

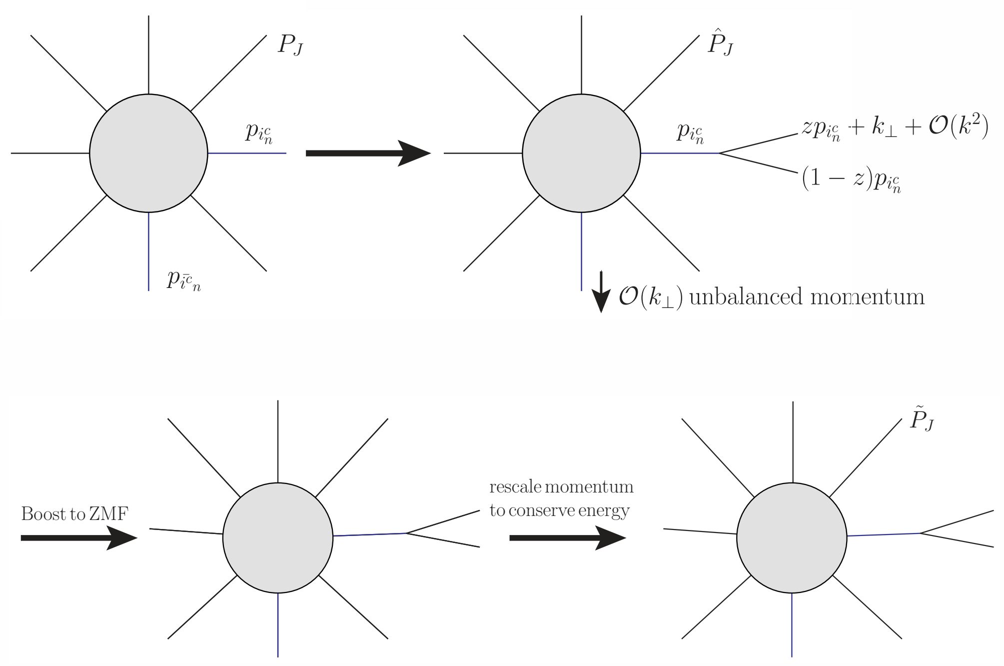
Accuracy of Parton Showers

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ

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

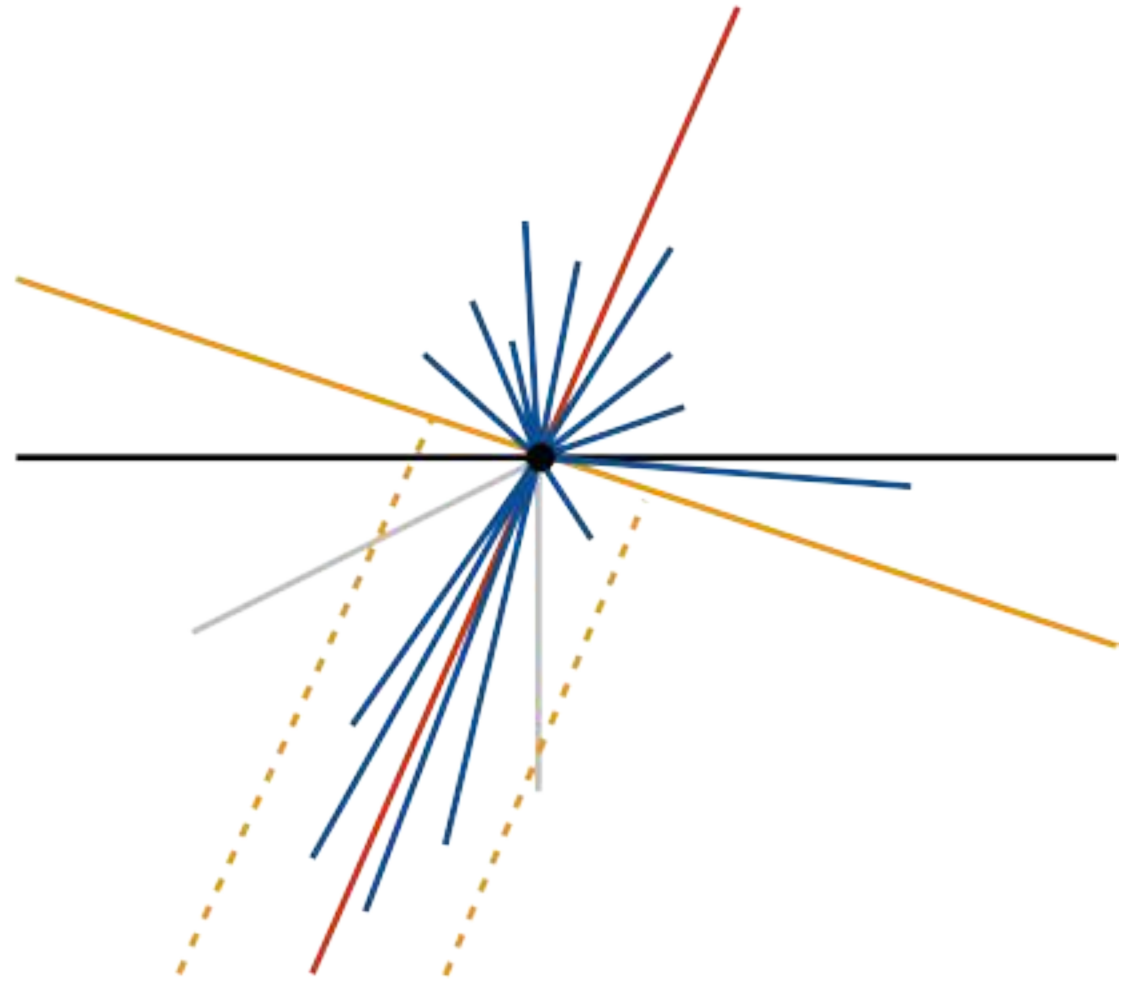
$$\frac{p_{i_n}\cdot p_{j_n}}{p_{i_n}\cdot q_n \; p_{j_n}\cdot q_n} - \frac{T\cdot p_{j_n}}{T\cdot q_n}\frac{1}{p_{j_n}\cdot q_n} + \frac{T\cdot p_{i_n}}{T\cdot q_n}\frac{1}{p_{i_n}\cdot q_n}$$

Partition of soft radiation



Recoil

[Dasgupta, Dreyer, Hamilton, Monni, Salam —PRL 125 (2020) 5]
[Forshaw, Holguin, Plätzer – JHEP 09 (2020) 014 & EPC C81 (2021) 4]



Dipole showers reproducing coherent branching:
NLL & NLC global, LL & LC non-global

Understand and decide on accuracy of (existing) pa
take as a starting point for incremental improvements.

Another issue is the large-N limit: $\alpha_s N^2 \sim 1$

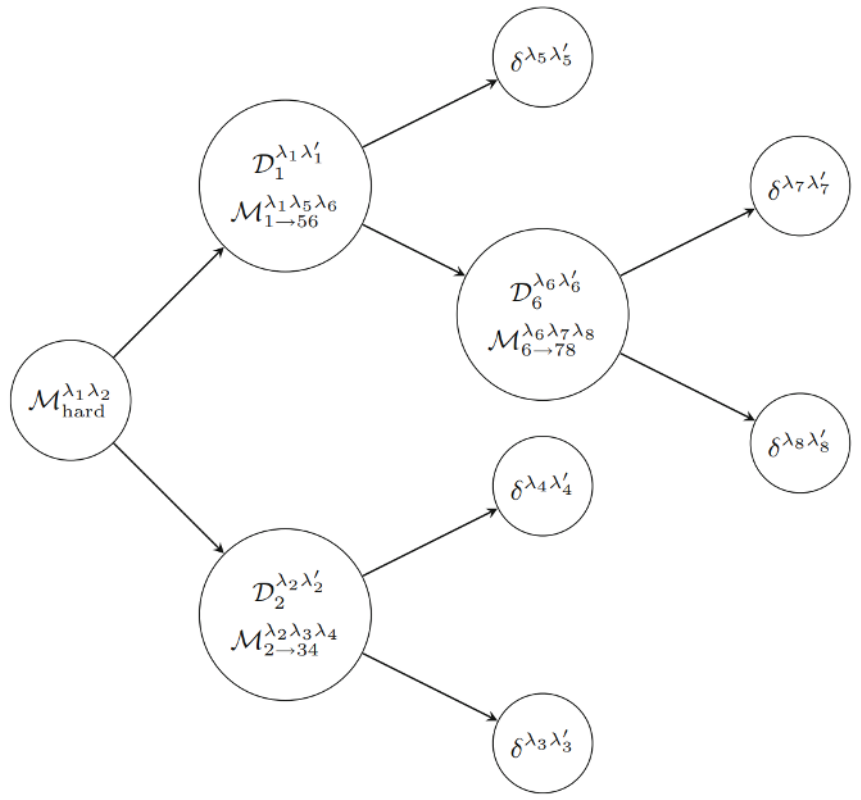
$$H(\alpha_s) \times \exp\left(Lg_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots\right)$$

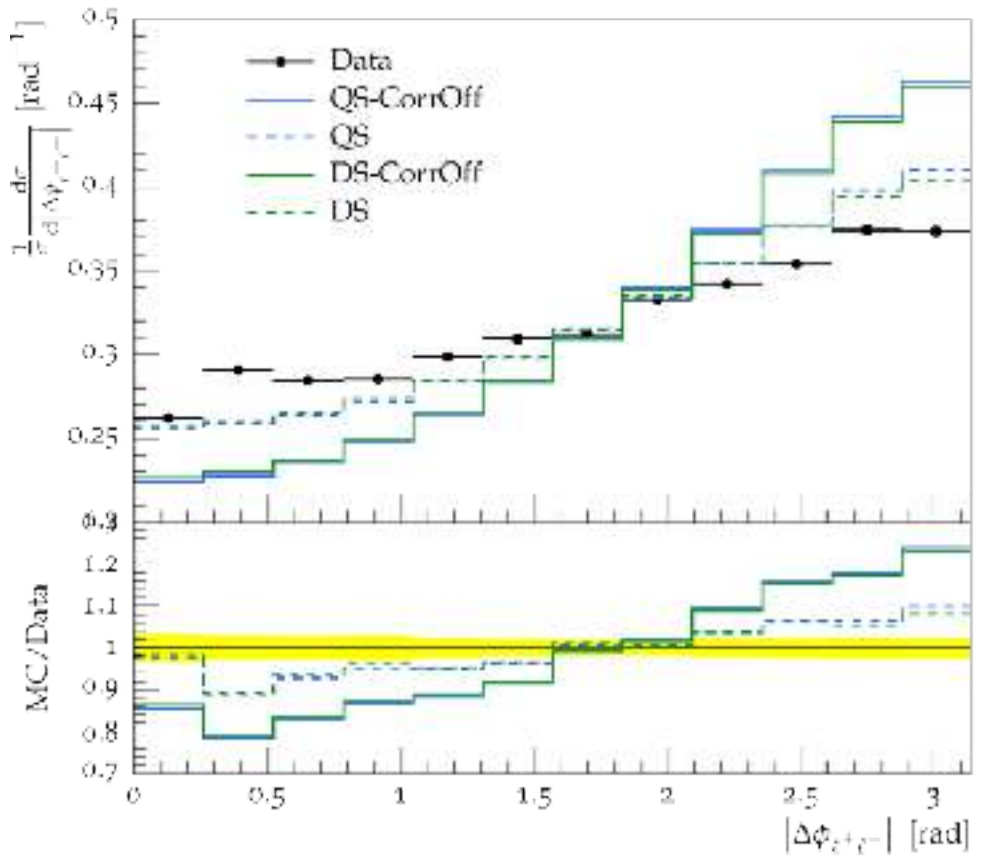
$\alpha_s L \sim 1$ LL NLL NNLL

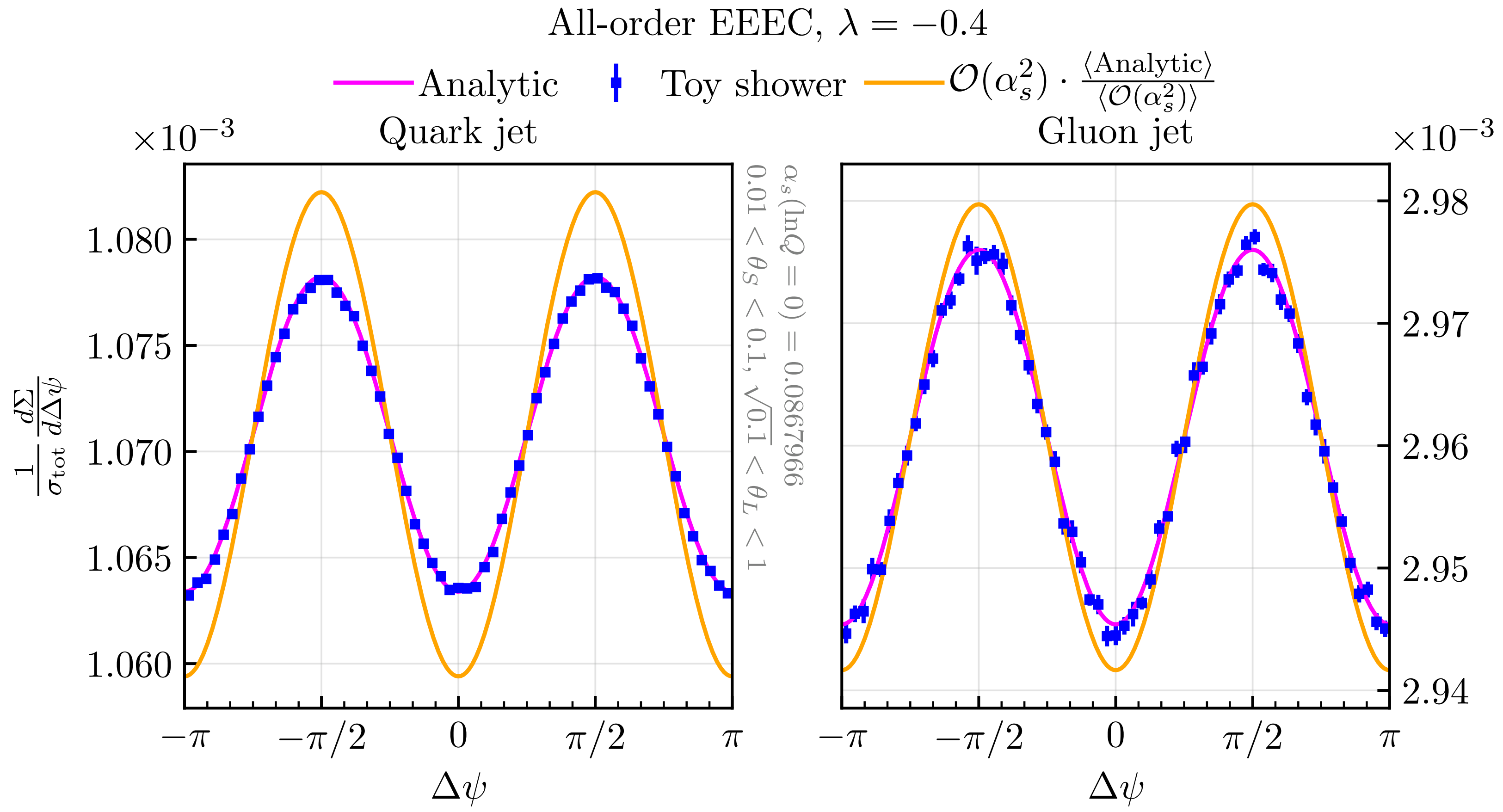
[Dasgupta, Dreyer, Hamilton, Monni, Salam et al. — JHEP 09 (2018) 033, …]
[Hoang, Plätzer, Samitz — JHEP 1810 (2018) 200]
[Bewick, Ferrario, Richardson, Seymour — JHEP 04 (2020) 019]

Spin & Colour Correlations Matter

Spin correlations building on Collins-Knowles algorithm







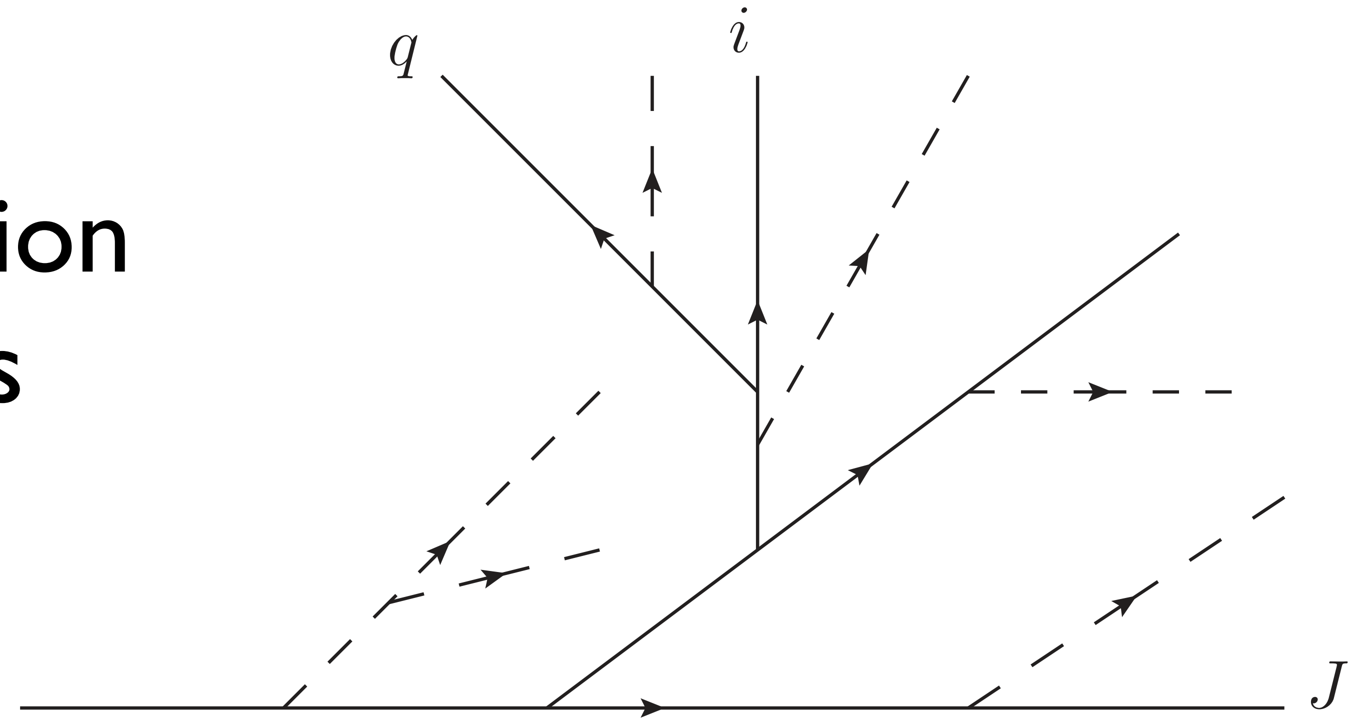
[Webster, Richardson - Eur.Phys.J.C 80 (2020) 2]

[Karlberg, Salam, Scyboz, Verheyen — Eur.Phys.J.C 81 (2021) 8, 681]

Dynamic colour factors in dipole showers

$$\mathcal{C}_{iJ}(\theta_{iq},\theta_{LJ}) = \left(C_F\delta_i^{(q)} + \frac{C_A}{2}\delta_i^{(g)}\right)\theta(\theta_{iq} < \theta_{LJ}) + \left(\frac{C_A}{2}\delta_J^{(g)} + C_F\delta_J^{(q)}\right)\theta(\theta_{iq} > \theta_{LJ})$$

Track angular extent of evolution to reproduce colour factors as dictated by coherence.



[Forshaw, Holguin, Plätzer — EPJ C81 (2021) 4]

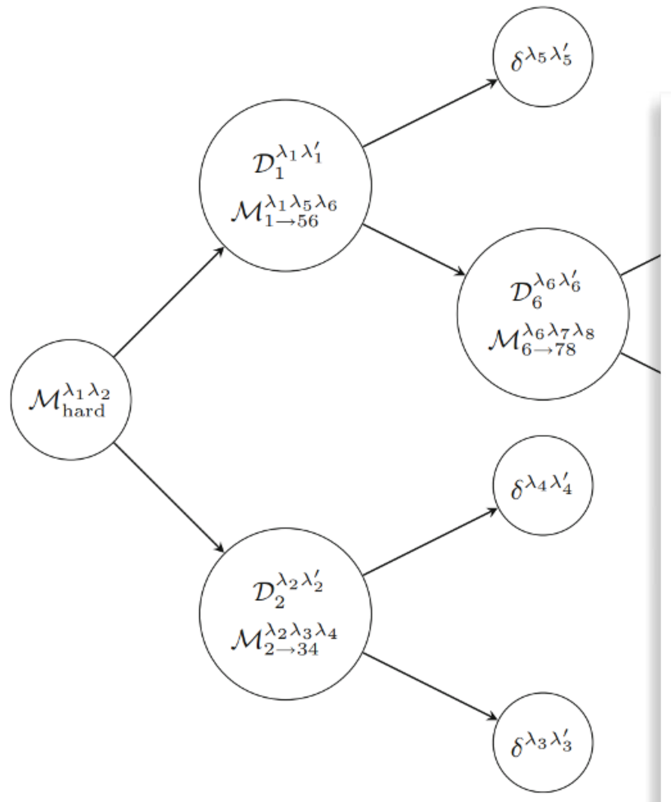
[Hamilton, Medves, Salam, Scyboz, Soyez — JHEP 03 (2021) 041

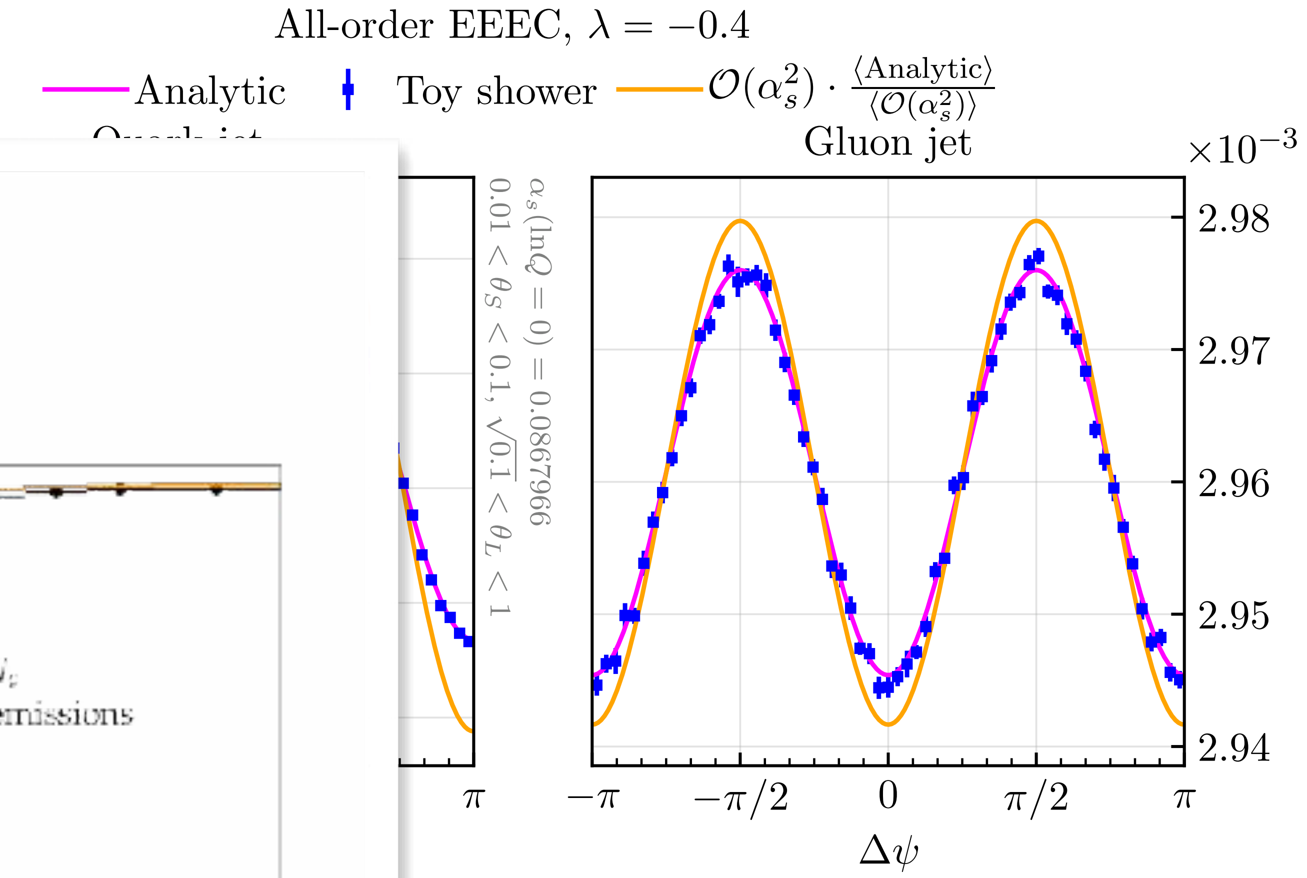
Spin & Colour Correlations Matter

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ

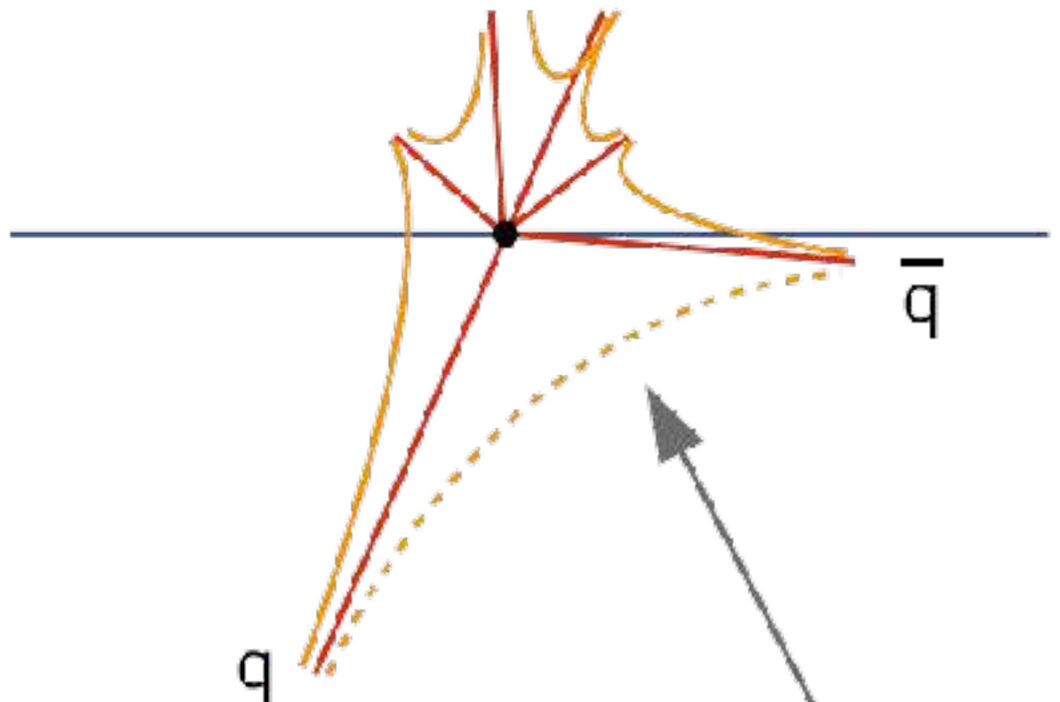
universität wien

Spin correlations building on Collins-Knowles algorithm

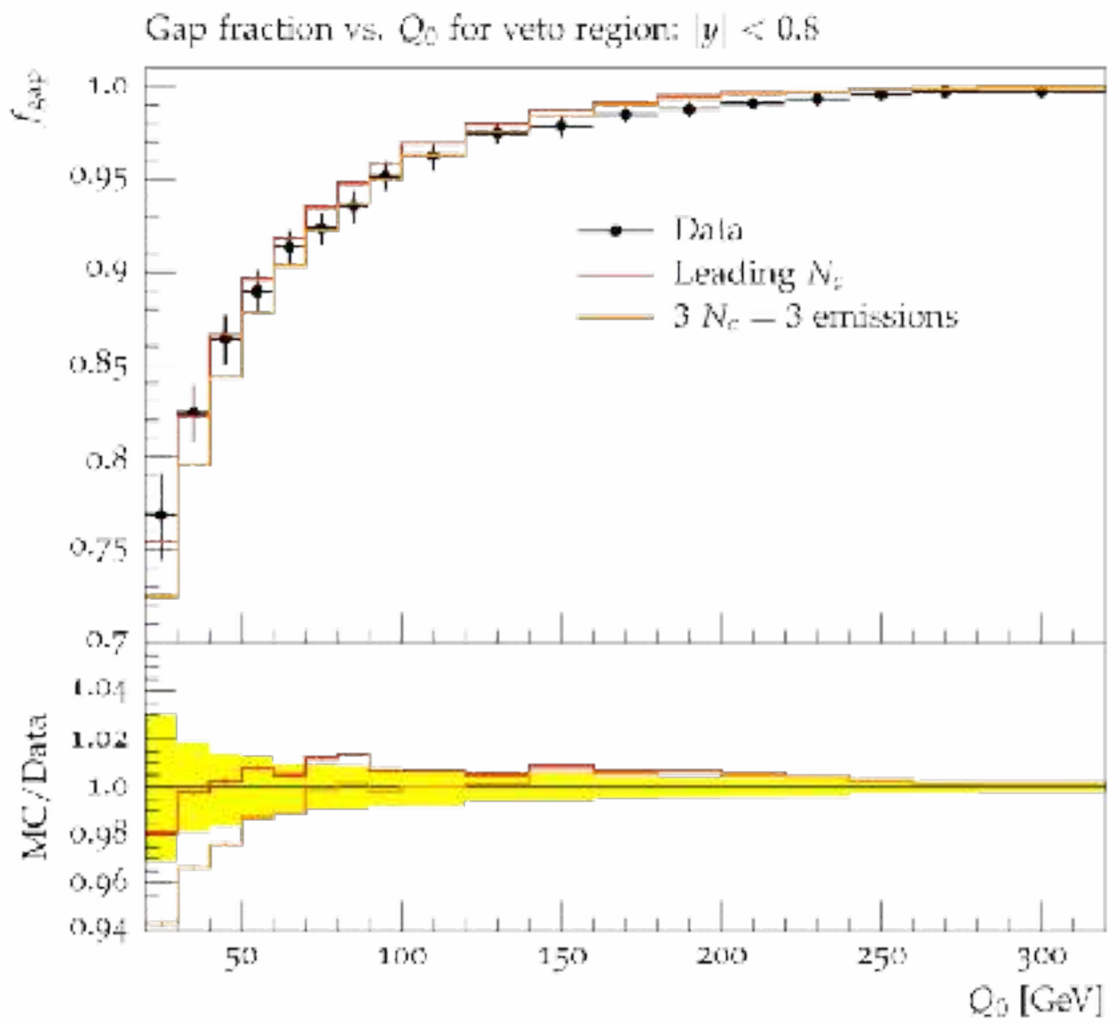




Some further colour correlations can be restored



Some subleading-N corrections can be restored.



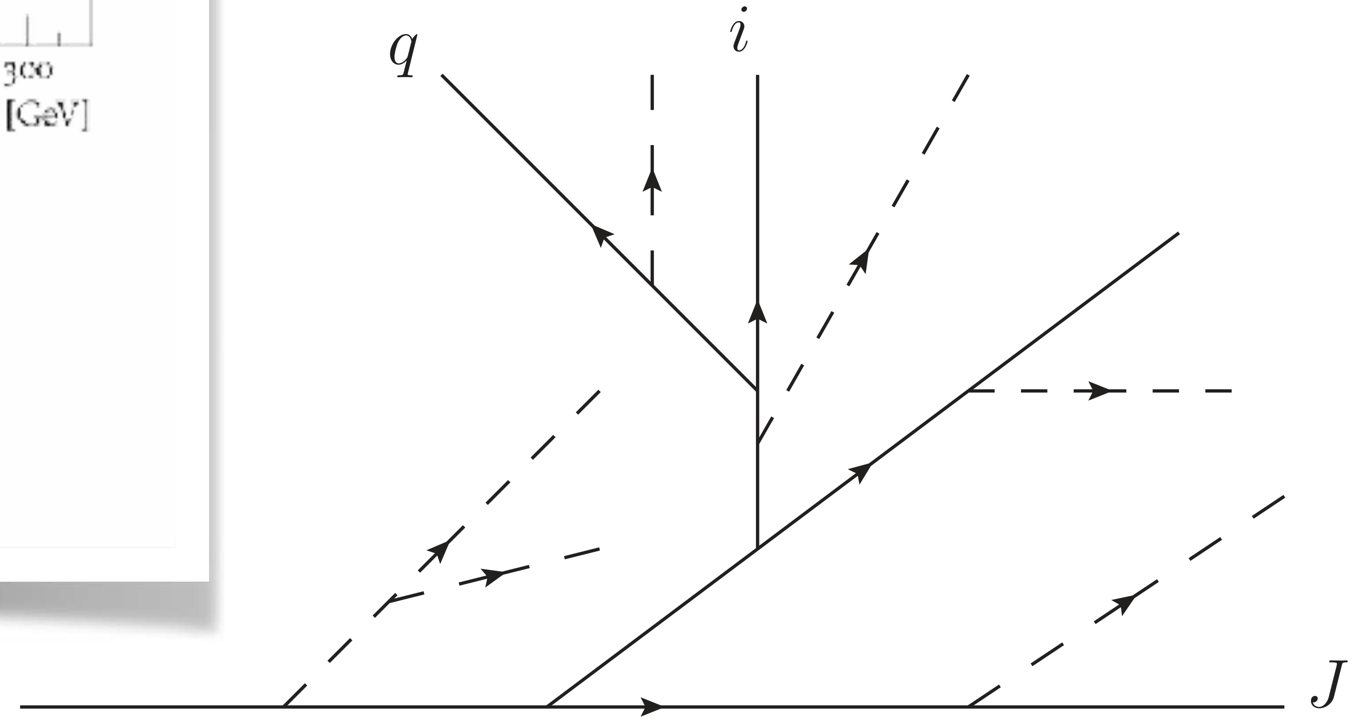
[Plätzer, Sjödahl – JHEP 1207 (2012) 042]
[Plätzer, Sjödahl, Thoren – JHEP 11 (2018) 009]
[Höche, Reichelt — Phys.Rev.D 104 (2021) 3, 034006]

yen — Eur.Phys.J.C 81 (2021) 8, 681]

Dynamic colour f

$$\mathcal{C}_{iJ}(\theta_{iq},\theta_{LJ}) = \Big(C_F \delta_i^{(q)}$$

$$+ \Big(\frac{C_A}{2}$$



[Forshaw, Holguin, Plätzer — EPJ C81 (2021) 4]
[Hamilton, Medves, Salam, Scyboz, Soyez — JHEP 03 (2021) 041

Improving Shower Accuracy

Demonstrate NLL accurate evolution:

[PanScales]

- PanScales — numerical

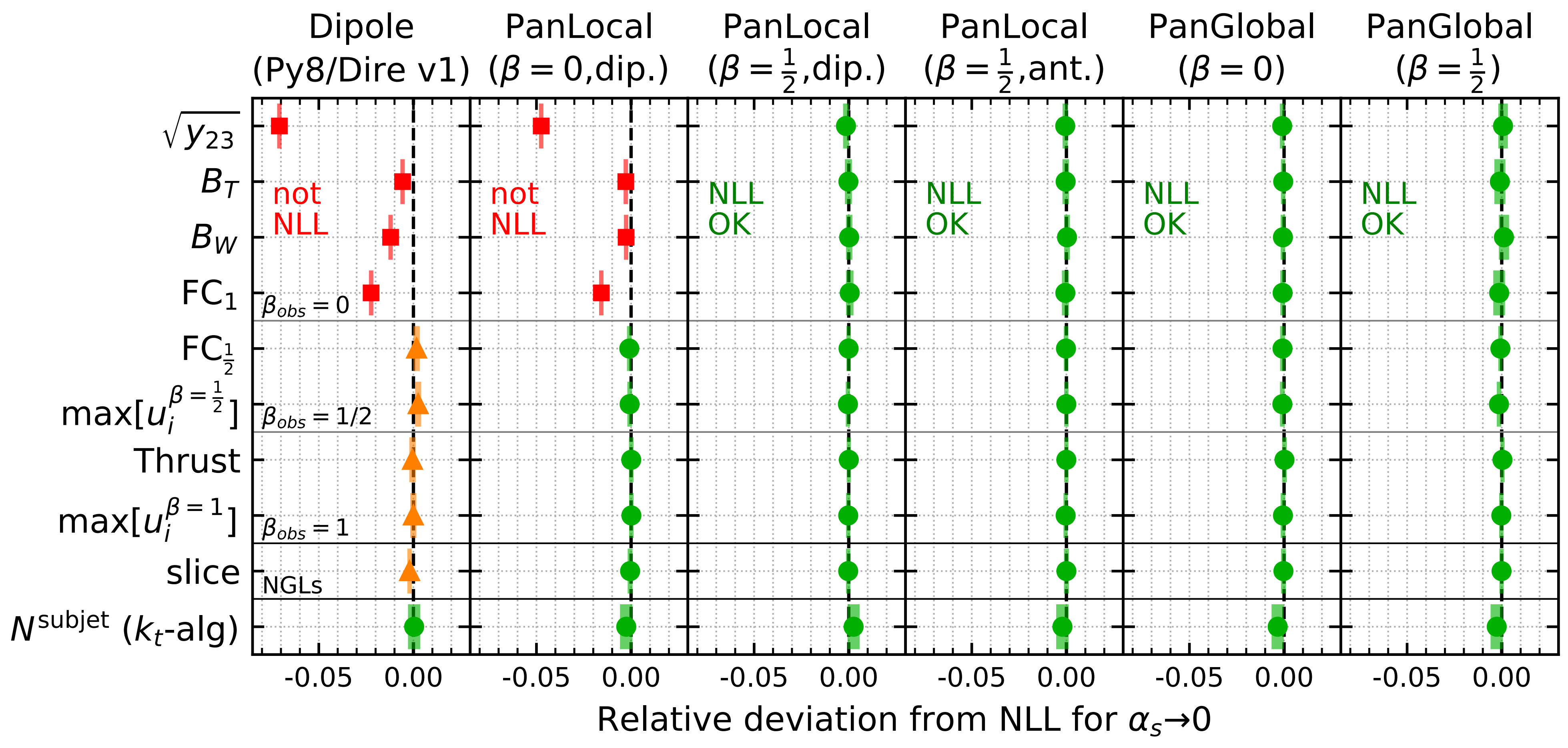
  [Dasgupta, Monni, Salam, Soyez + …]
- Deductor — numerical/analytical

  [Nagy, Soper]
- Forshaw/Holguin/Plätzer — analytical

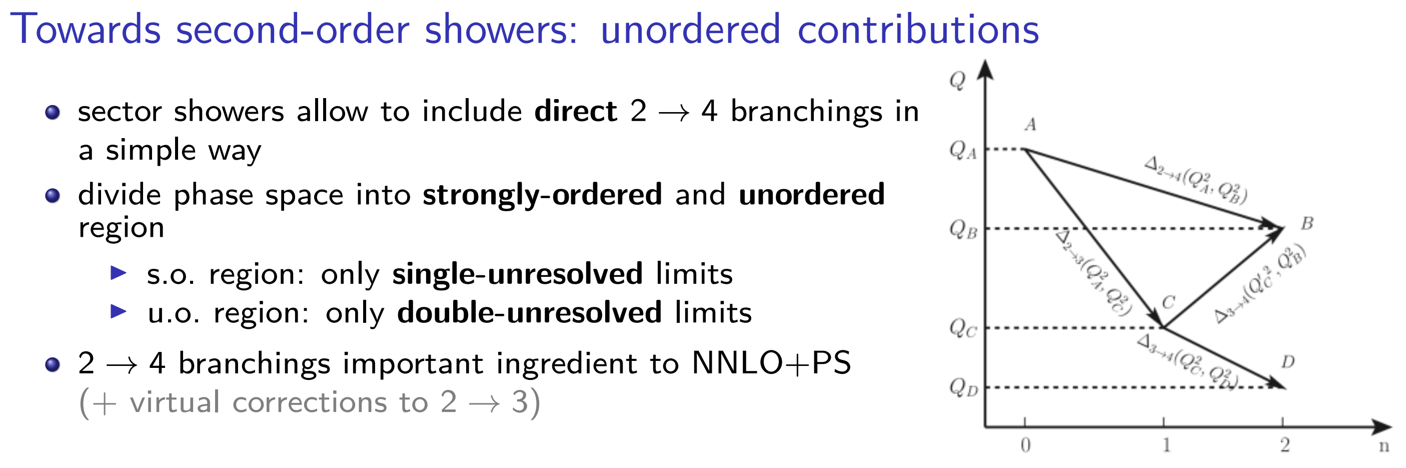
  [aim at improving Herwig 7 dipole shower]
- Sherpa — numerical/analytical

  [Herren, Höche, Krauss, Reichelt, Schönherr]

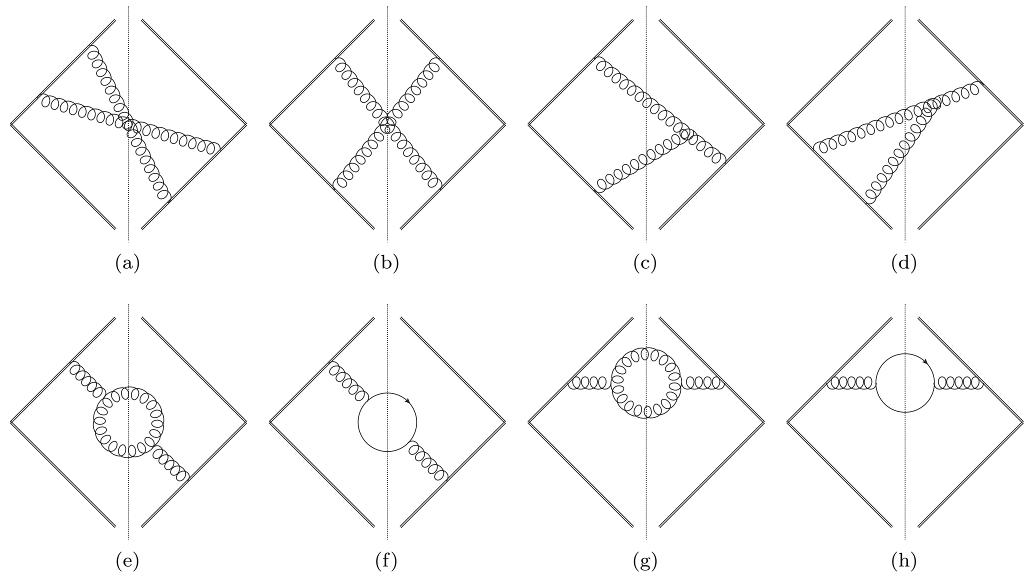
} Based on amplitude evolution.



Provide higher order building blocks beyond single emissions

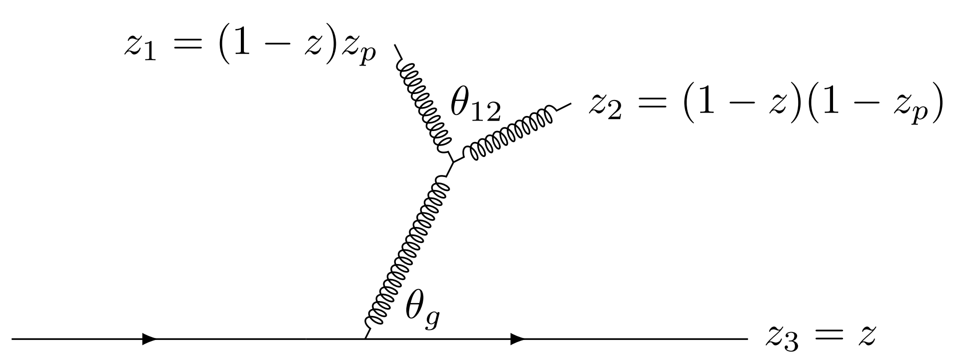


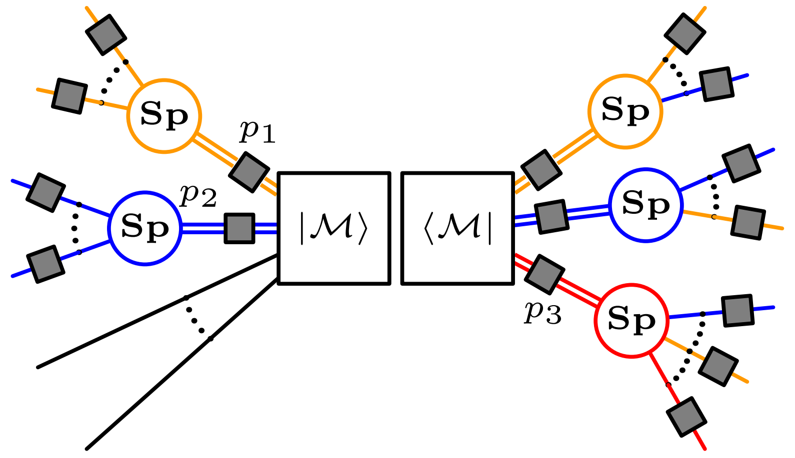
[C. Preuss for Vincia — PSR 21]



[Dulat, Höche, Prestel — Phys.Rev.D 98 (2018) 7]
[Gellersen, Höche, Prestel — arXiv:2110.05964]

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





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

Improving Shower Accuracy

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ

universität wien

Demonstrate NLL accurate evolution:

[PanScales]

- PanScales — numerical

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

- Deductor — numerical/analytical

  [Nagy, Soper]

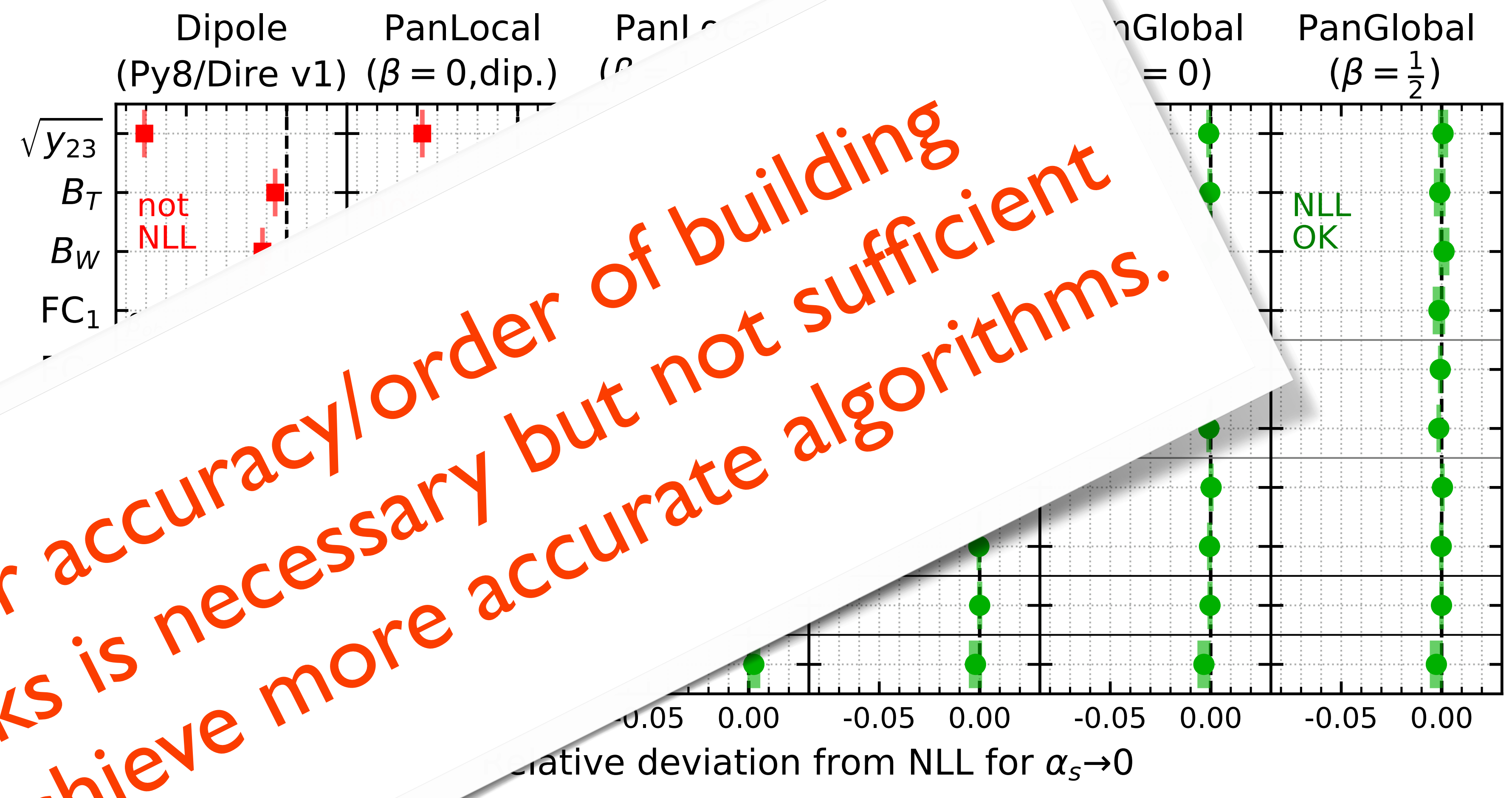
- Forshaw/Holguin/Plätzer — analytical

  [aim at improving Herwig 7 dipole shower]

- Sherpa — numerical/analytical

  [Herren, Höche, Krauss, Reichelt, Schönherr]

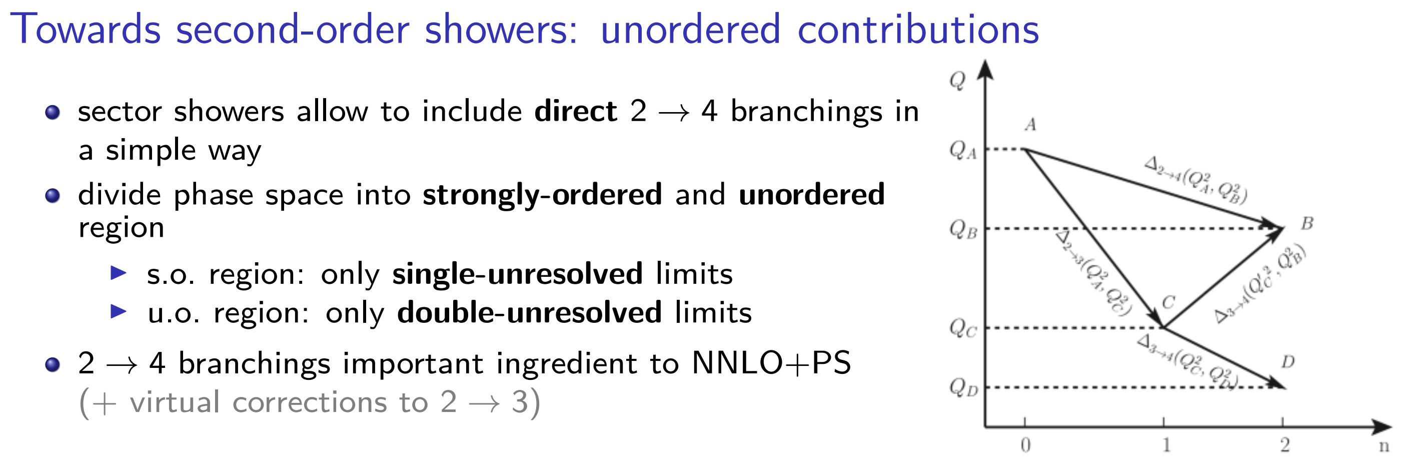
} Based on amplitude evolution.



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

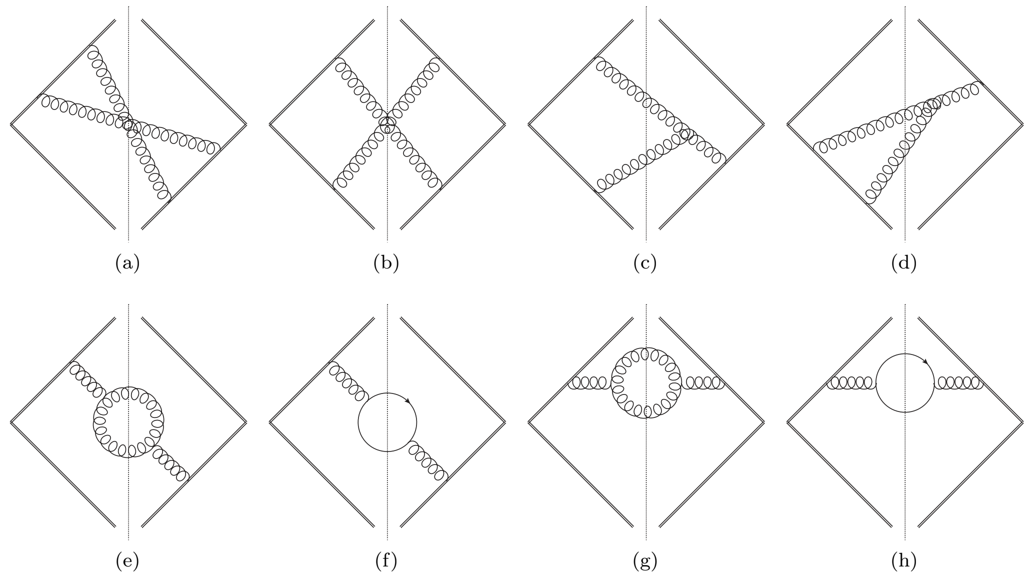
[Plätzer, Ruffa — JHEP 06 (2021) 007]
[Löschner, Plätzer, Simpson — arXiv:2112.14454]

Provide higher order building blocks beyond single emissions

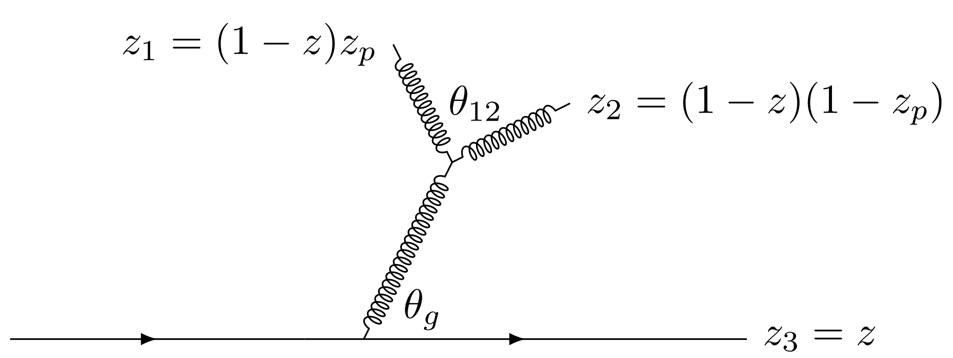

Towards second-order showers: unordered contributions

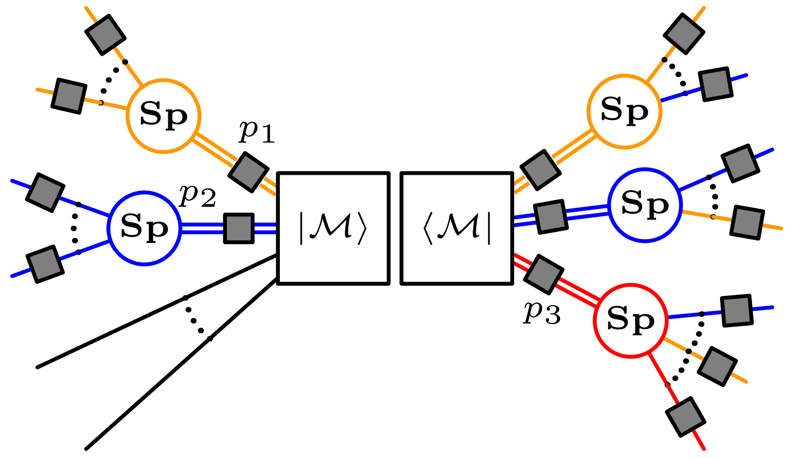
- sector showers allow to include **direct** $2 \to 4$ branchings in a simple way
- divide phase space into **strongly-ordered** and **unordered** region
  - s.o. region: only **single-unresolved** limits
  - u.o. region: only **double-unresolved** limits
- $2 \to 4$ branchings important ingredient to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

[C. Preuss for Vincia — PSR 21]



[Dulat, Höche, Prestel — Phys.Rev.D 98 (2018) 7]
[Gellersen, Höche, Prestel — arXiv:2110.05964]





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

Accuracy for massive event shapes

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ

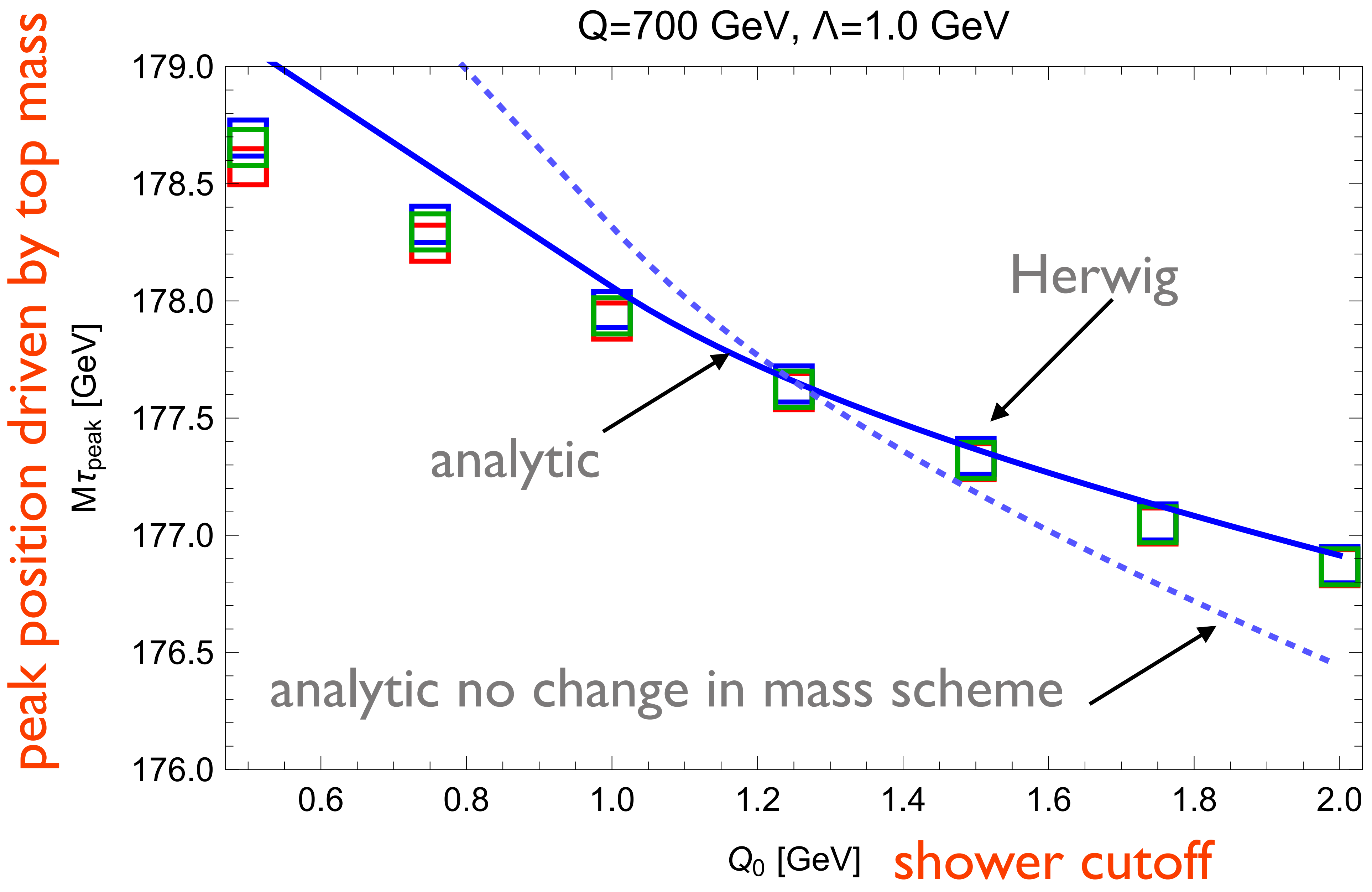
universität wien

Coherent branching jet mass distribution including mass effects

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

$$P_{q\to qg} = \frac{C_F}{1-z}\left[1 + z^2 - \frac{2m_q^2}{z\tilde{q}^2}\right]$$

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



NLL accurate for global observables with massive quarks.

Analytically calculate perturbative correction to the top mass as predicted by parton branching algorithms

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

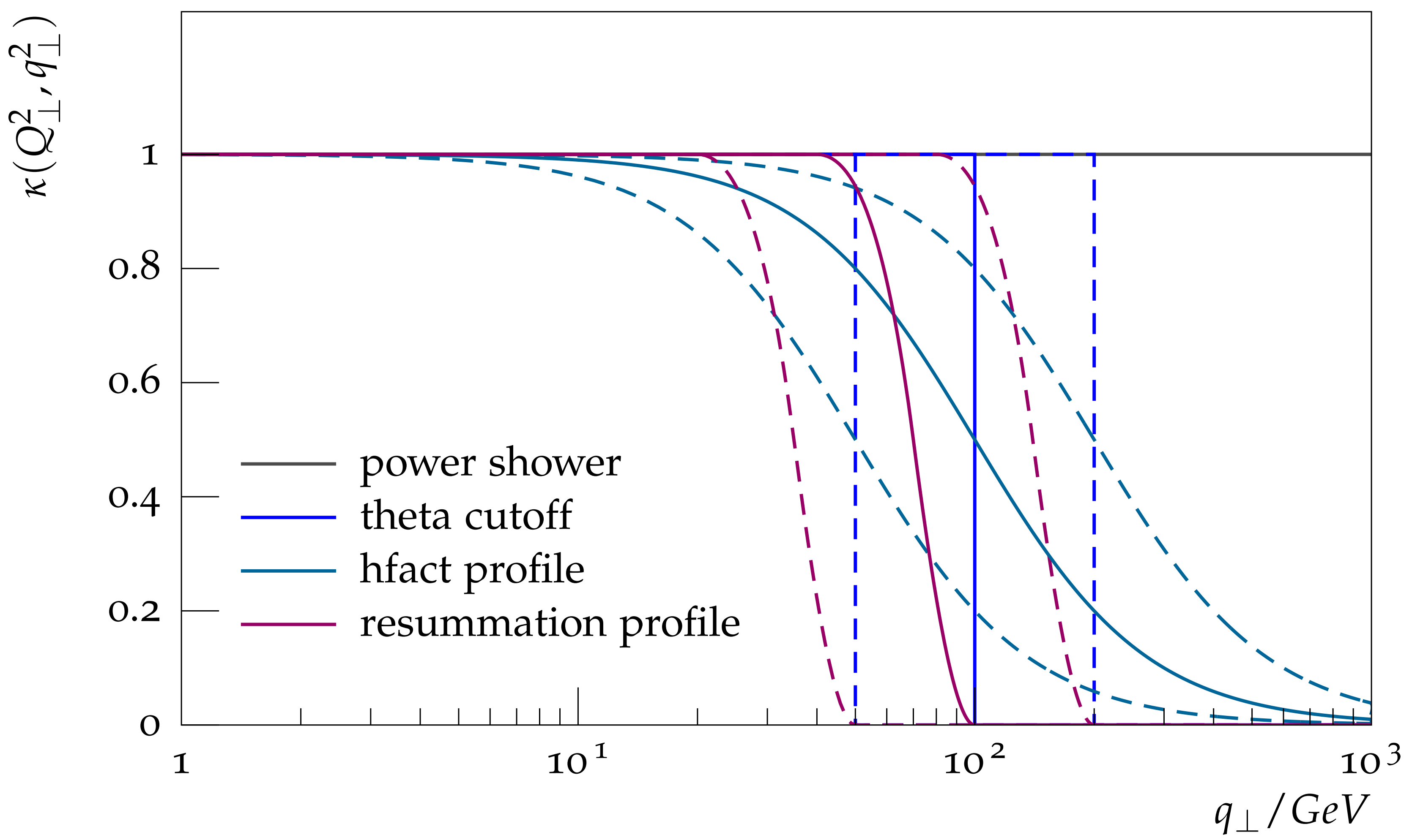
$$m_t^{\rm CB}(Q_0) = m_t^{\rm pole} - \frac{2}{3} Q_0\, \alpha_s(Q_0) + \mathcal{O}(\alpha_s^2)$$

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

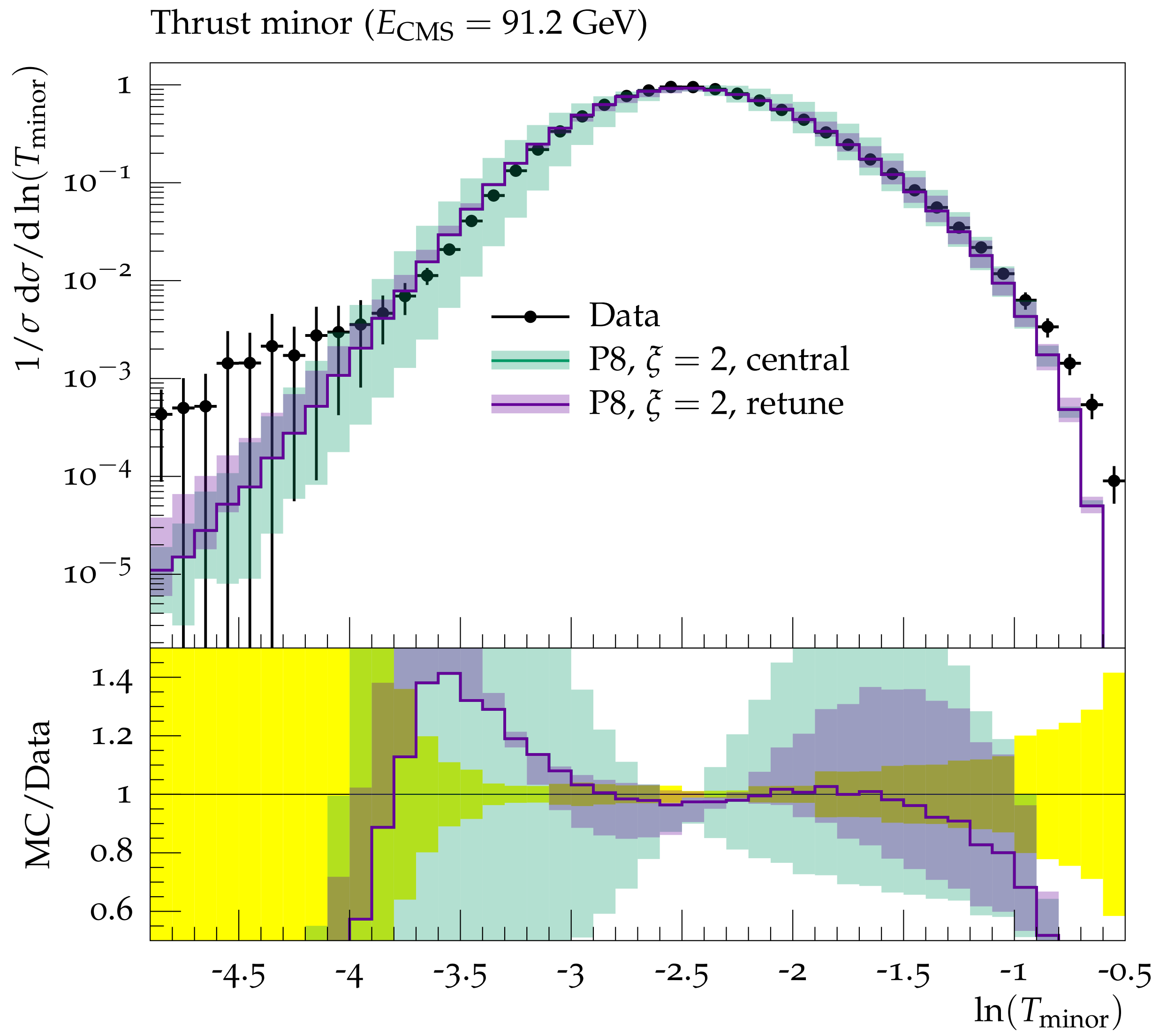
See Silvia's talk for related discussions.

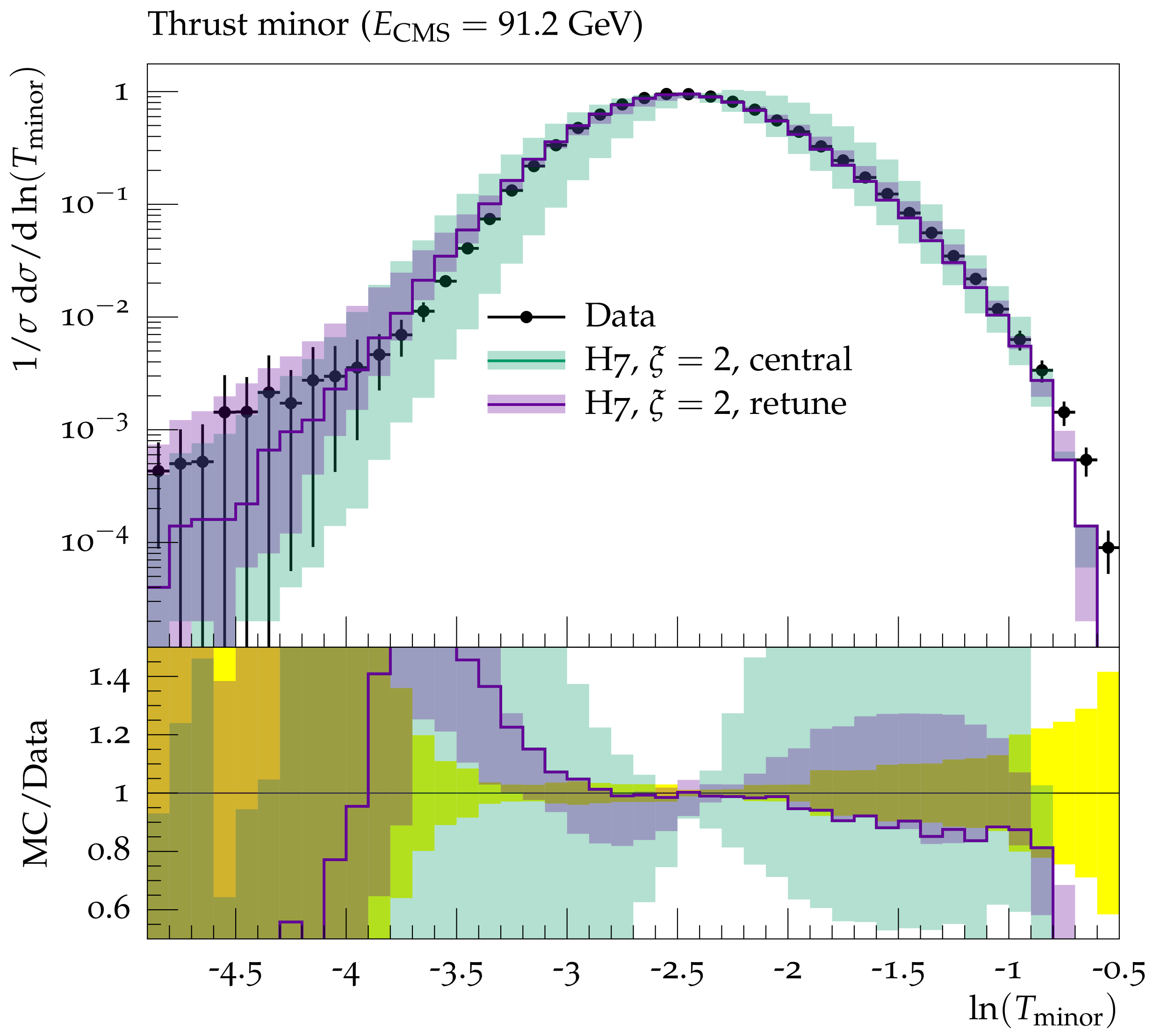
Hadronization & perturbative variations

Start to gain control of perturbative variations in the shower, and since long on the impact of matching, e.g. by dependence on hard shower scale.



[Bellm, Nail, Plätzer, Schichtel, Siodmok – EPJ C76 (2016) 665]

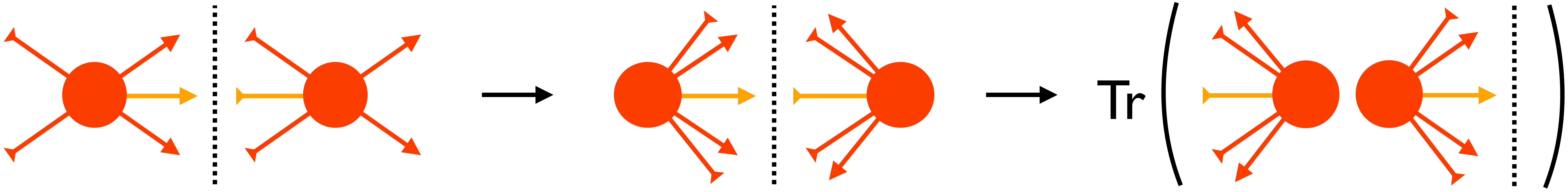




But how do these variations conspire with soft physics? What is the uncertainty budget of an event generator, comprehensively? E.g. check how variations of α_S are absorbed by re-tuning hadronization (more in a couple of minutes).

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

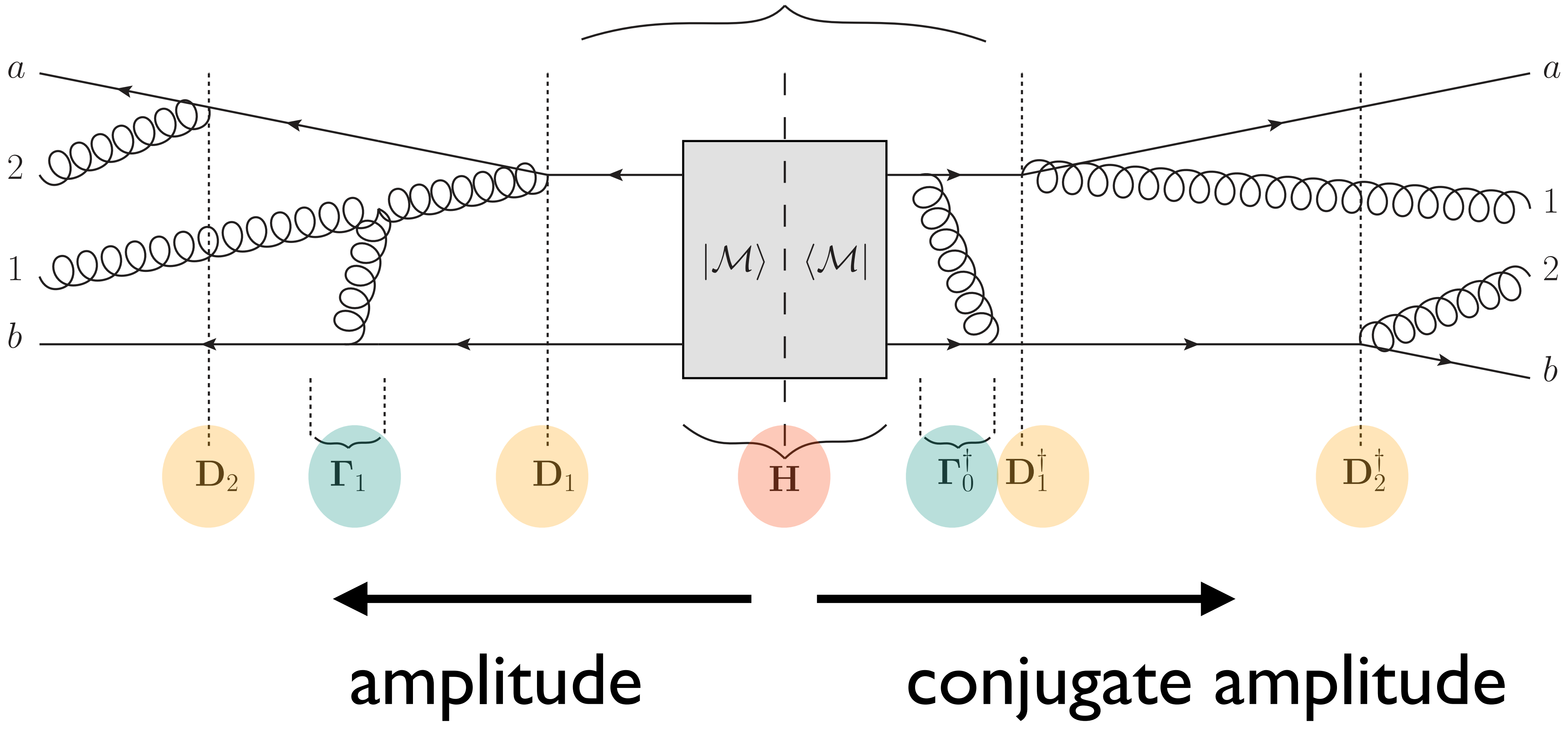
Amplitude evolution



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

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]

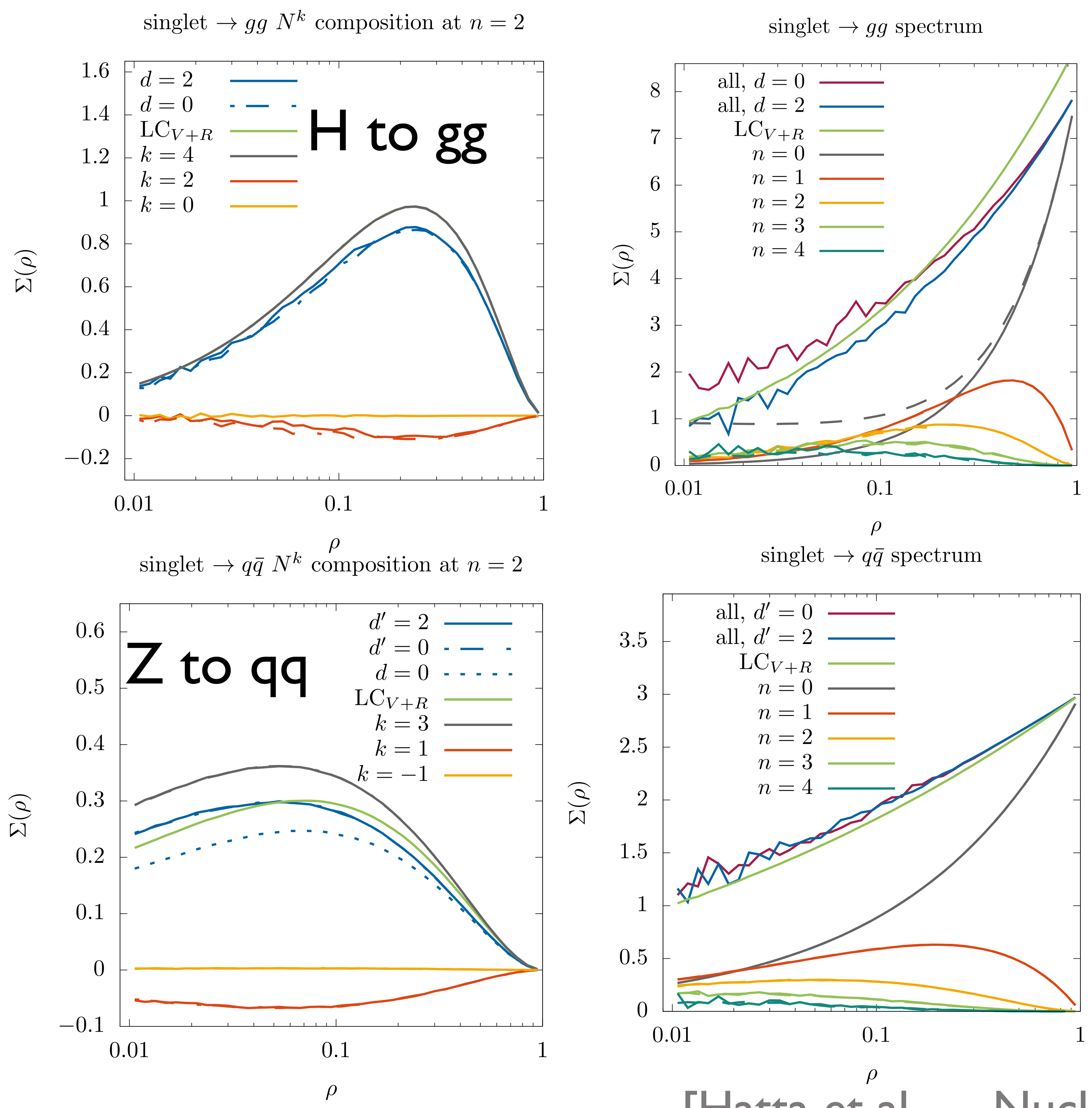
Beyond Leading Colour

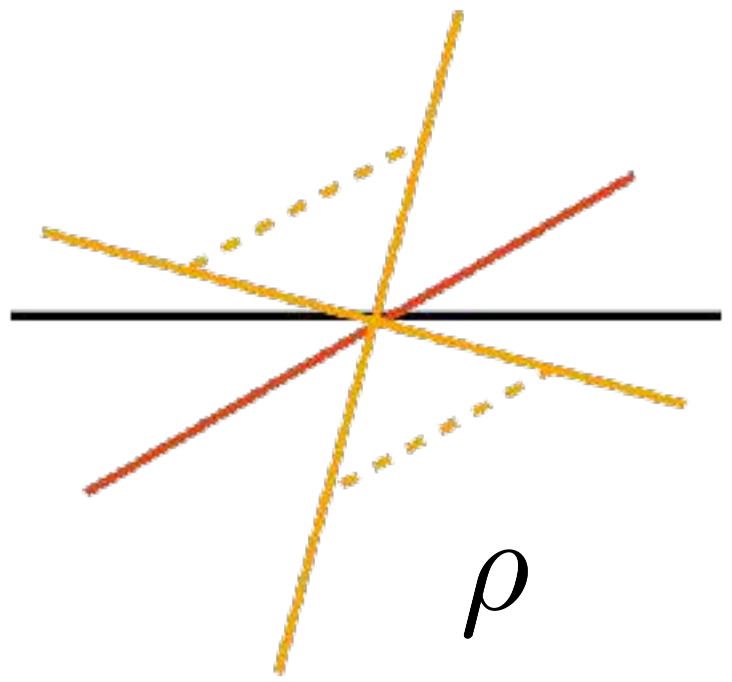
CVolver library implements numerical evolution in colour space.

origins in [Plätzer – EPJ C 74 (2014) 2907]

[De Angelis, Forshaw, Plätzer — PRL 126 (2021) 11]

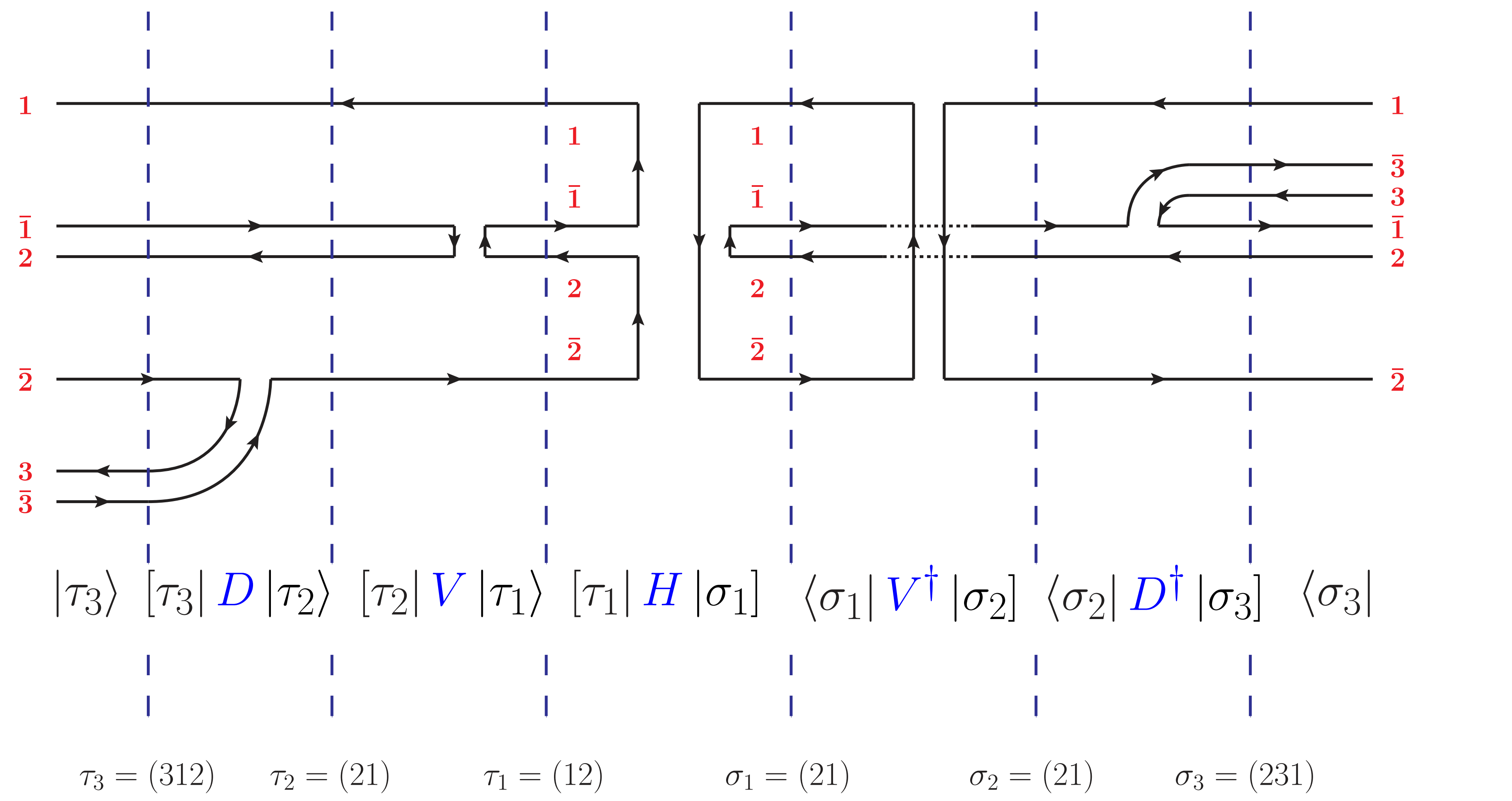
Resummation of non-global logarithms at full colour:

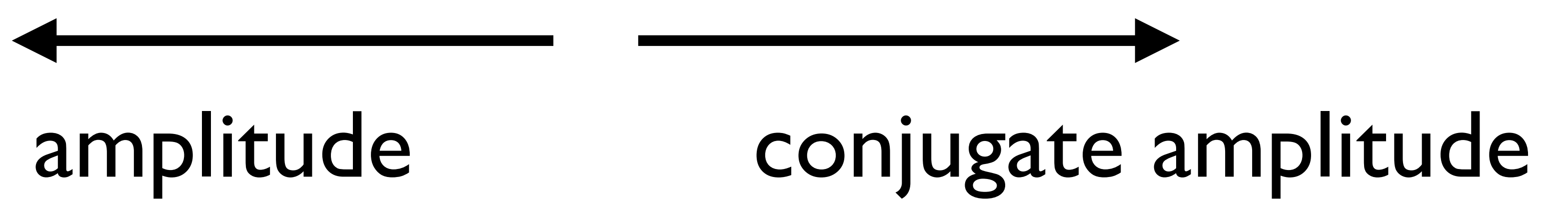




$$\Sigma(\rho) = \sum_n \int d\sigma(\{p_i\}) \prod_i \theta_{\rm in}(\rho - E_i)$$

[Hatta et al. — Nucl.Phys.B 962 (2021) 115273]

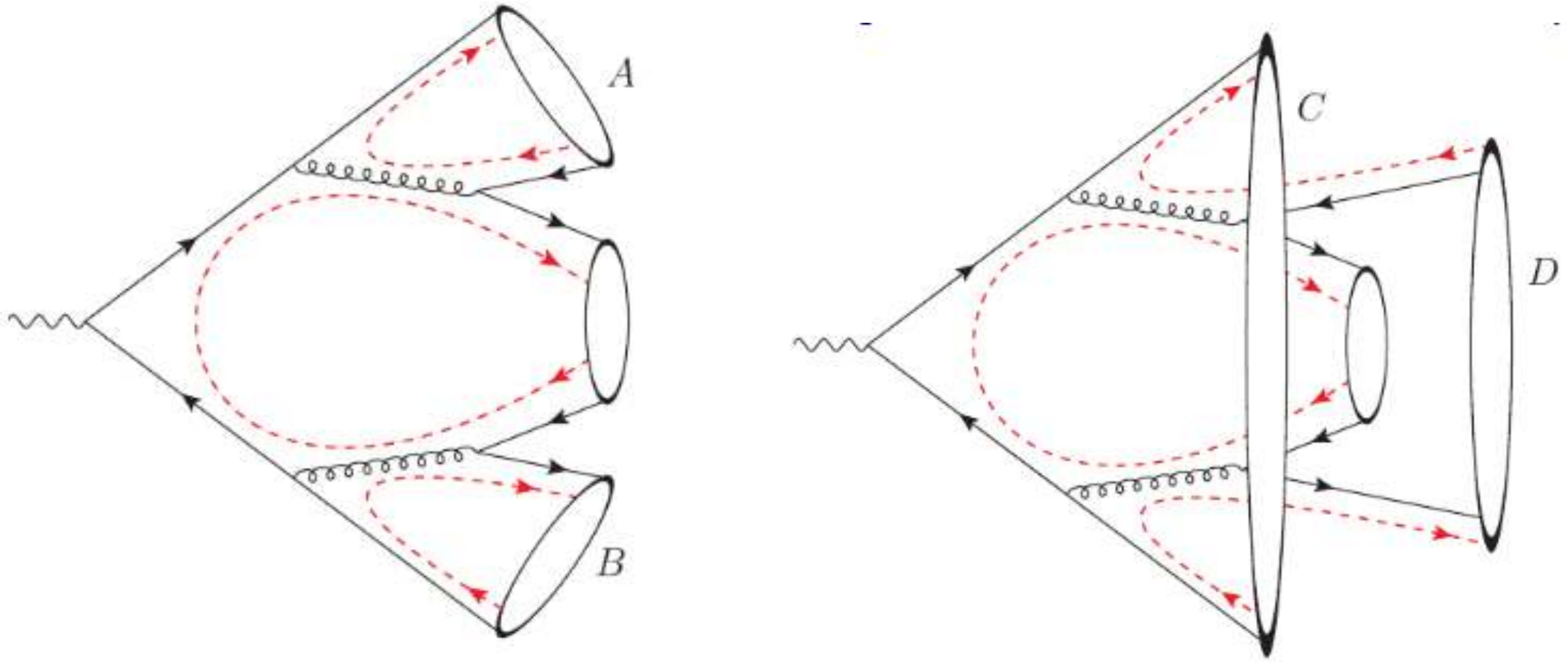


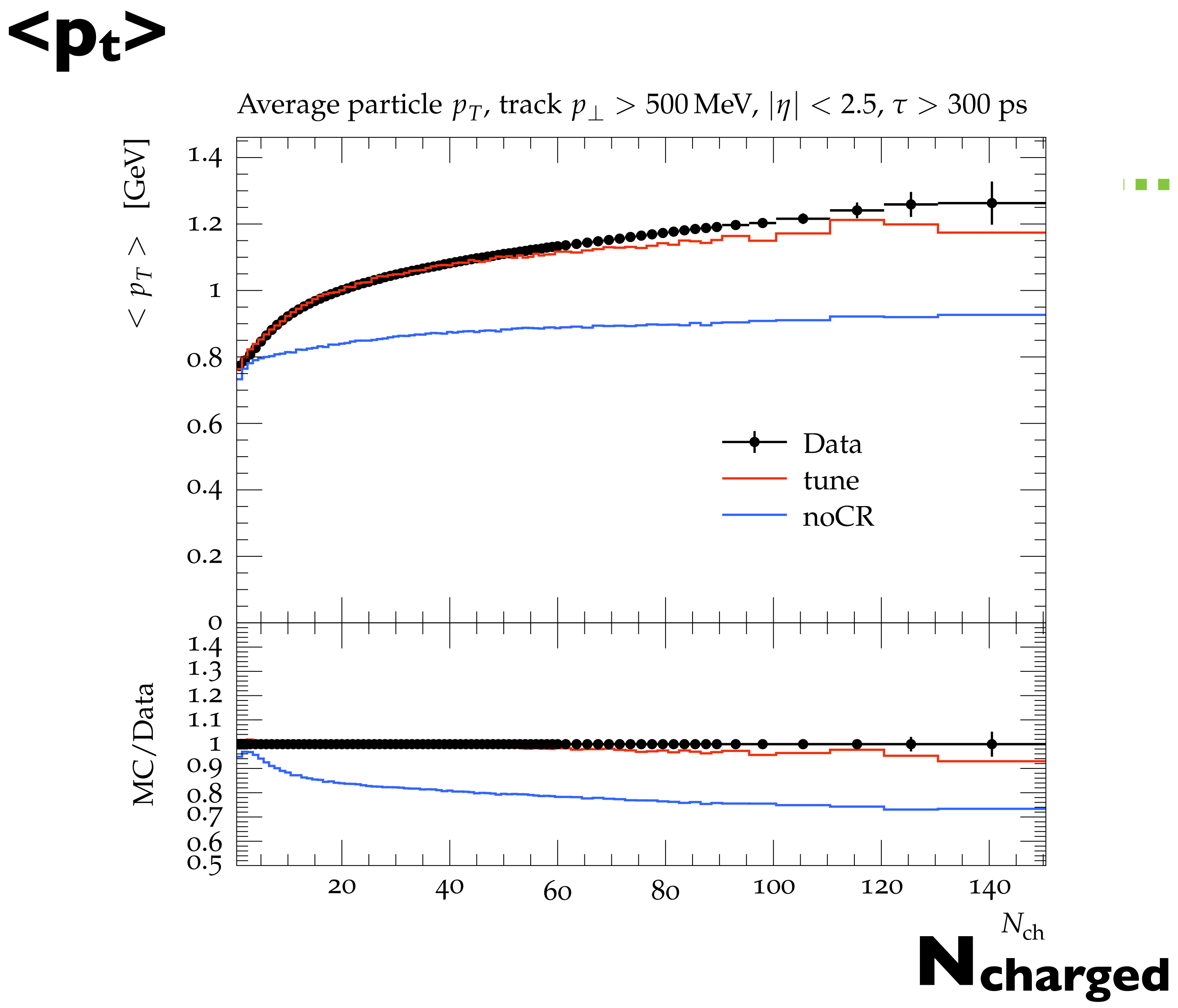


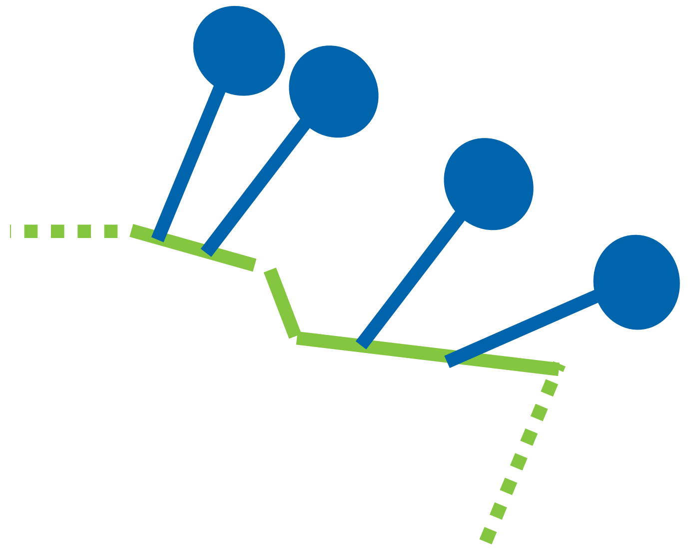
Avoid complexity which grows with colour space dimensionality:

- Monte Carlo over colour flows,
- events at intermediate steps carry complex weights.

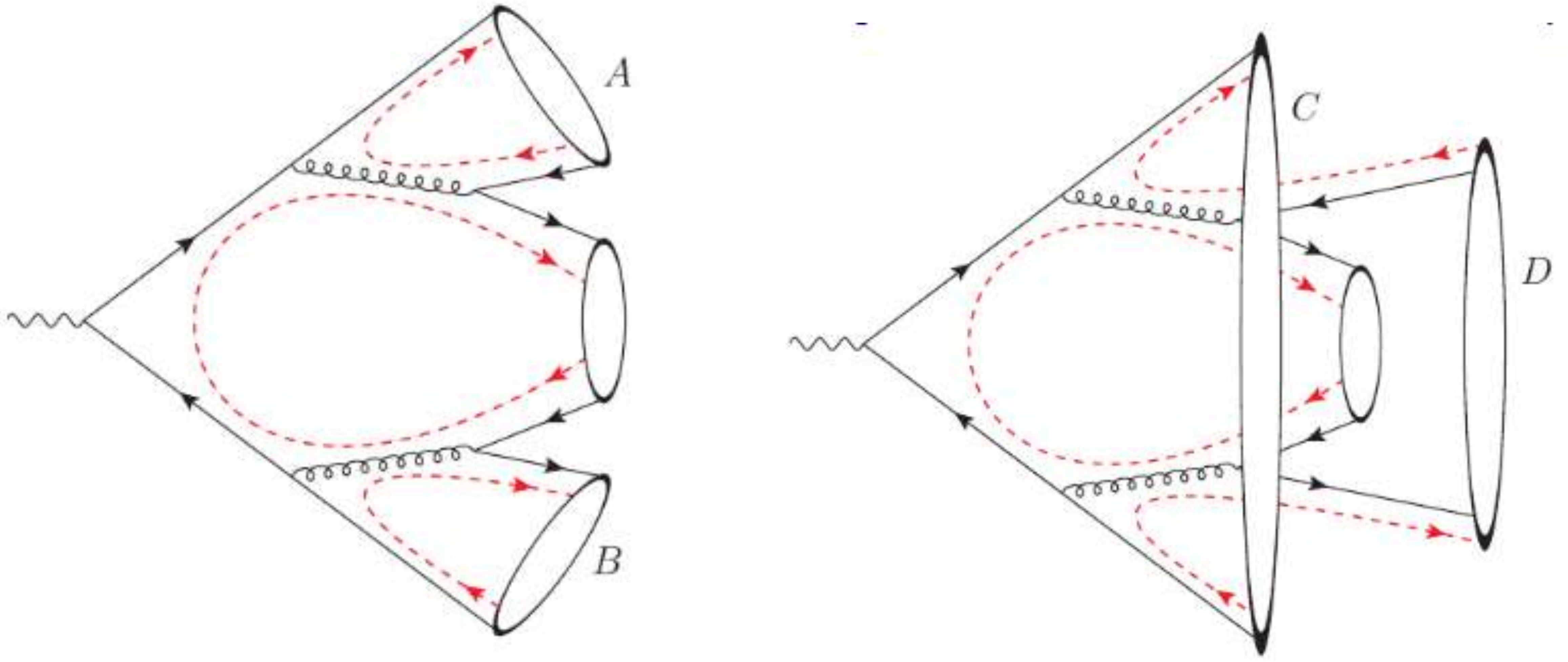
Would subleading-N matter?

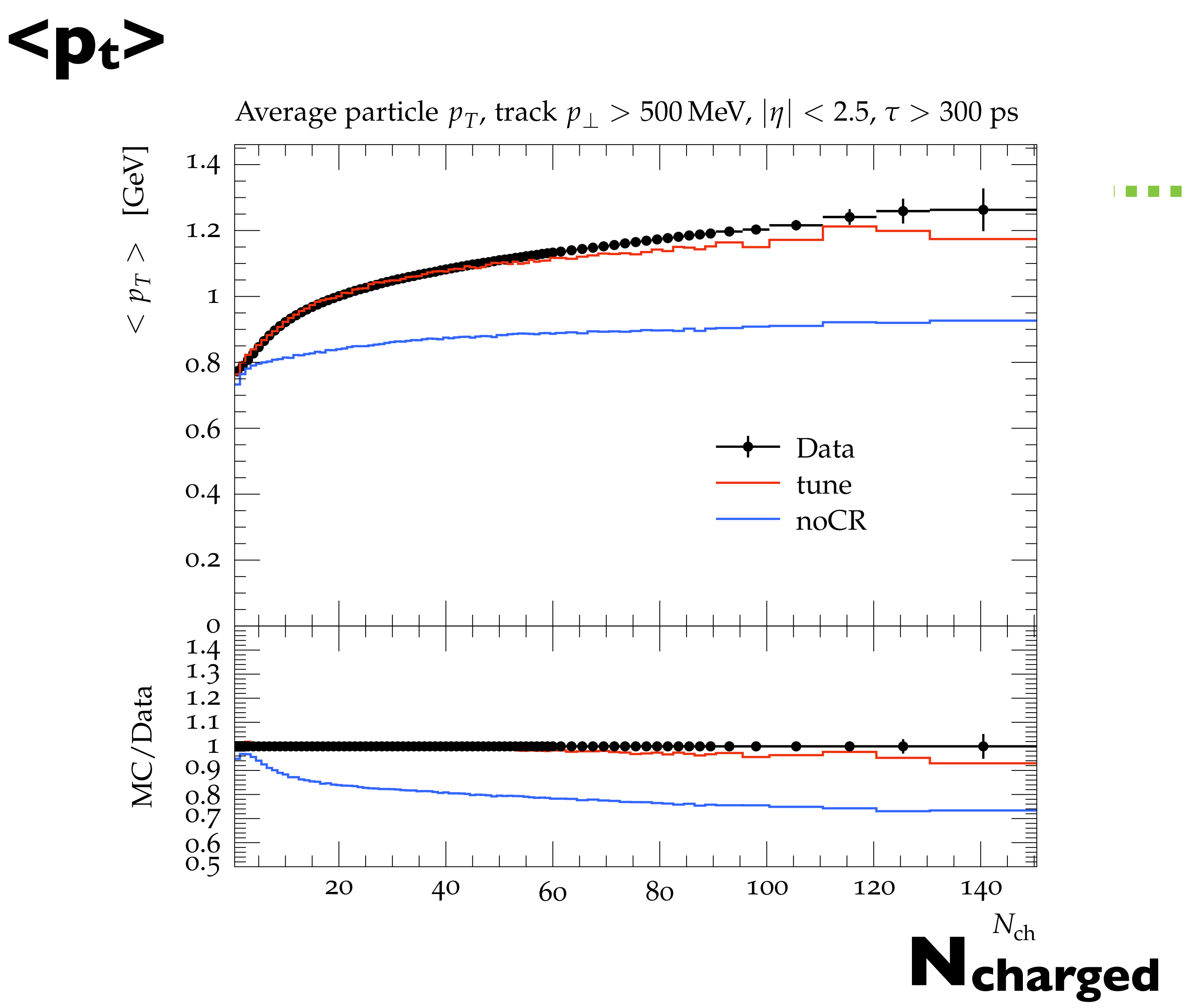


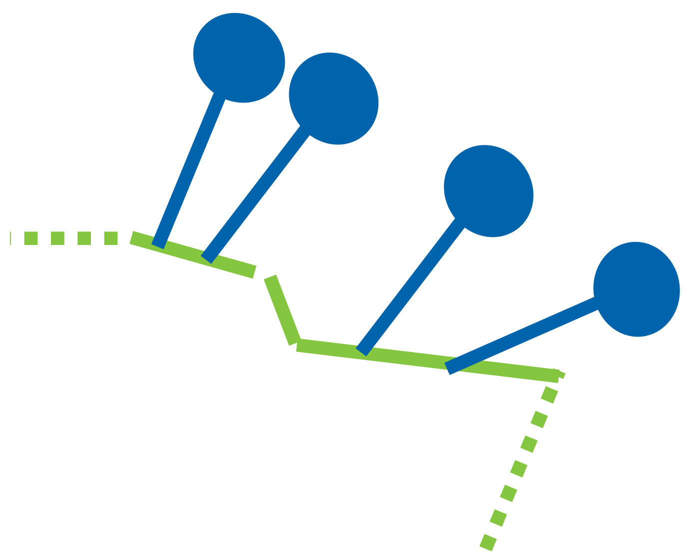




Would subleading-N matter?







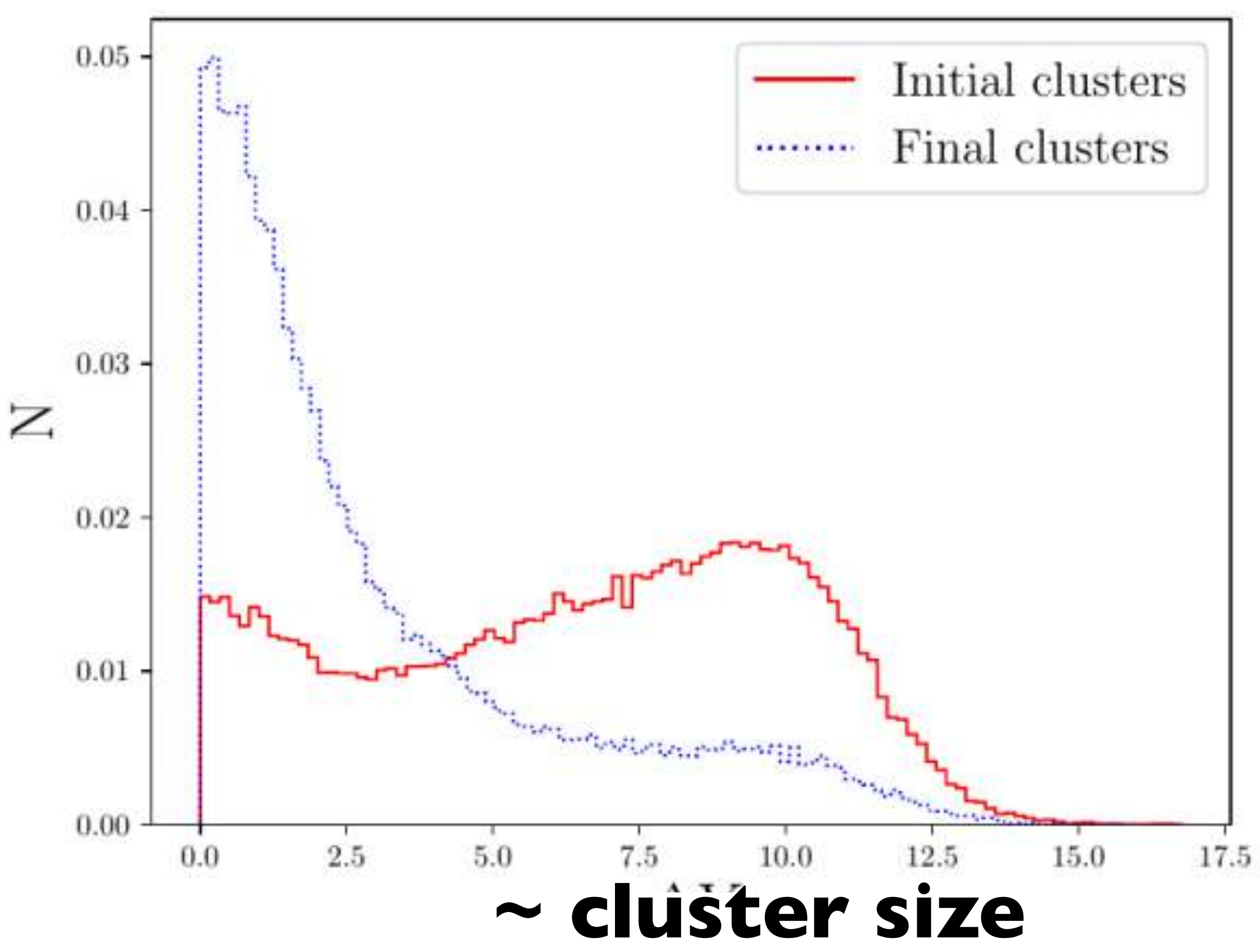
Approach colour reconnection from colour evolution: perturbative component?

Reconnection amplitude

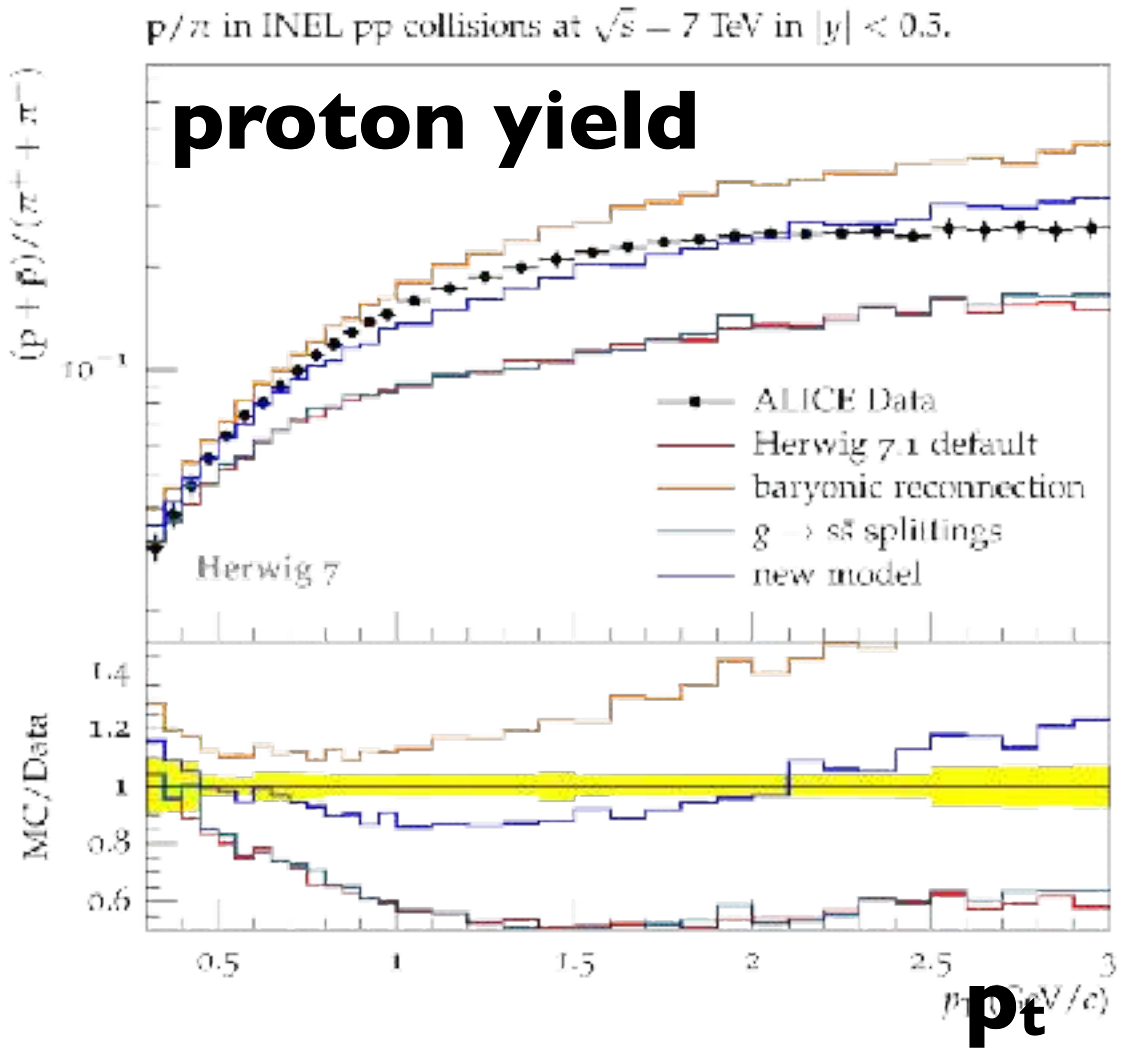
$$\mathrm{P}e^{-\int_q^k \frac{\mathrm{d}k'}{k'}\mathbf{\Gamma}(k')}$$

$$\mathcal{A}_{\tau\to\sigma} = \langle\sigma|\mathbf{U}\left(\{p\},\mu^2,\{M_{ij}^2\}\right)|\tau\rangle$$

[Gieseke, Kirchgaesser, Plätzer – EPJ C 78 (2018) 99]
[Gieseke, Kirchgaesser, Plätzer, Siodmok – JHEP 11 (2018) 149]

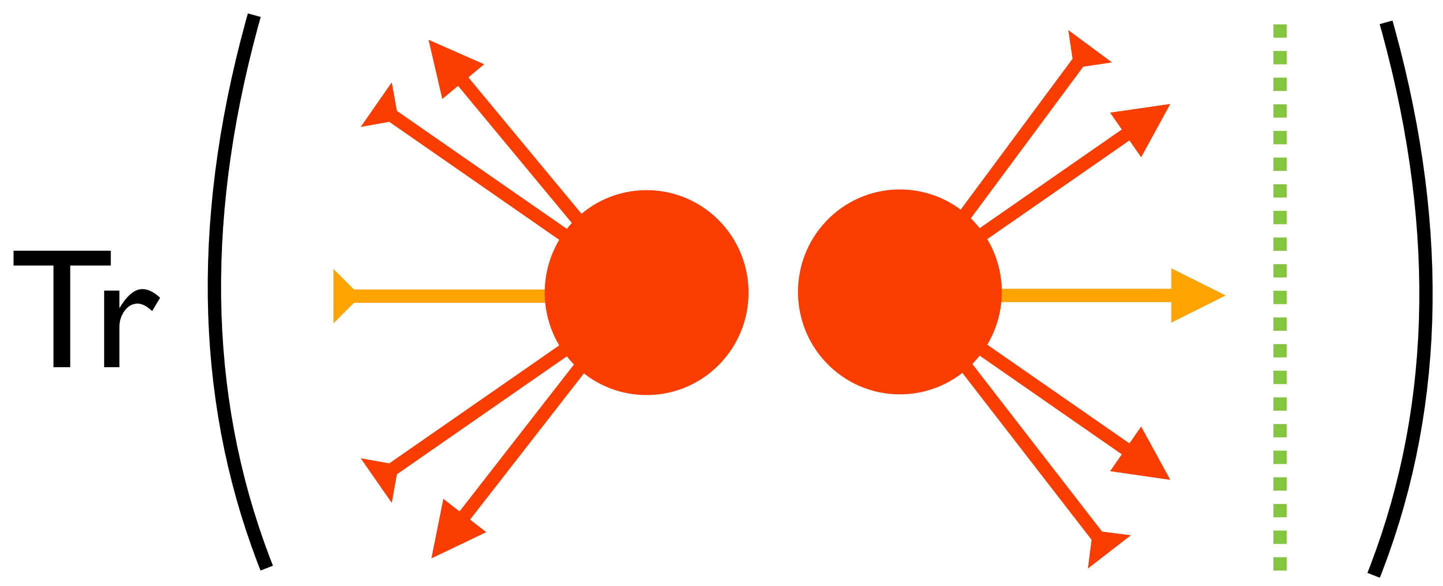


=



Amplitude evolution & hadronization

Generalize amplitude evolution paradigm to a fully exclusive observable.



Not a rigorously proven factorisation theorem, but certainly the form in which we expect a hadronization model to enter the calculation.

$$\sigma[\mathbf{U}] = \sum_n \int \alpha_0^n \, \mathrm{Tr}\left[\mathbf{M}_n(Q;p_1,...,p_n)\mathbf{U}_n(Q;p_1,...,p_n)\right] \mathrm{d}\phi(Q) \prod_{i=1}^{n} (4\pi\mu^2)^\epsilon [\mathrm{d}p_i]\tilde{\delta}(p_i)$$

Rely on factorisation properties of amplitudes to isolate divergent contributions.
Physical cross section finite: resort to RGE methodology.

[Plätzer – arXiv:2204.06956]

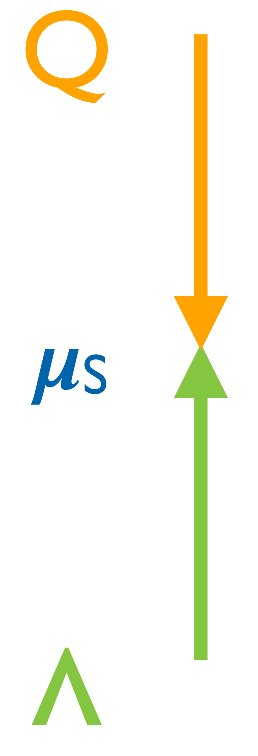
Evolution equations

[Plätzer – arXiv:2204.06956]

We can now obtain the evolution equations we asked for:

$$\partial_S \mathbf{A}_n = \mathbf{\Gamma}_{n,S}\mathbf{A}_n + \mathbf{A}_n \mathbf{\Gamma}^\dagger_{n,S} - \sum_{s\geq 1} \alpha_S^s \mathbf{R}^{(s)}_{S,n} \mathbf{A}_{n-s} \mathbf{R}^{(s)\dagger}_{S,n}$$

$$\partial_S \equiv \partial / \partial \log \mu_S$$



$$\partial_S \mathbf{S}_n = -\tilde{\mathbf{\Gamma}}^\dagger_{S,n}\mathbf{S}_n - \mathbf{S}_n \tilde{\mathbf{\Gamma}}_{S,n} + \sum_{s\geq 1} \alpha_S^s \int \tilde{\mathbf{R}}^{(s)\dagger}_{S,n+s} \mathbf{S}_{n+s} \tilde{\mathbf{R}}^{(s)}_{S,n+s} \prod_{i=n+1}^{n+s} [\mathrm{d}p_i] \tilde{\delta}(p_i)$$

Coupled system of evolution equations: For each resolution we have chosen, we get one.
Directions of evolution are different in scale and multiplicity.

α_s corrections to tower of logarithms present in A

soft evolution ~ hadronization model

$$\sigma[\mathbf{U}_n] = \sum_n \int \alpha_S^n \ \mathrm{Tr}\left[(\mathbf{A}_n + \mathbf{\Delta}_n)\mathbf{S}_n\right] \mathrm{d}\phi(Q) \prod_{i=1}^{n} \mu_R^{2\epsilon} [\mathrm{d}p_i] \tilde{\delta}(p_i)$$

dressing of hard process ~ parton shower

Evolution equations

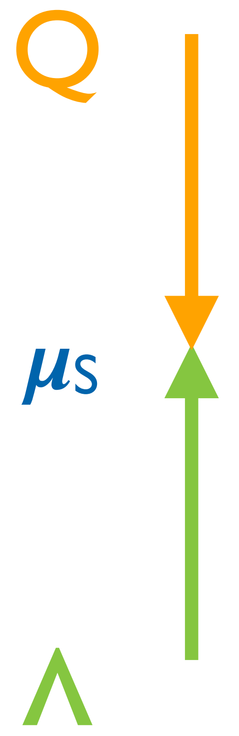
[Plätzer – arXiv:2204.06956]

We can now obtain the evolution equations we asked for:

$$\partial_S \mathbf{A}_n = \mathbf{\Gamma}_{n,S}\mathbf{A}_n + \mathbf{A}_n\mathbf{\Gamma}^\dagger_{n,S} - \sum_{s\geq 1}\alpha_S^s \mathbf{R}^{(s)}_{S,n}\mathbf{A}_{n-s}\mathbf{R}^{(s)\dagger}_{S,n}$$

$$\partial_S \equiv \partial/\partial\log\mu_S$$

$$\partial_S \mathbf{S}_n = -\tilde{\mathbf{\Gamma}}^\dagger_{S,n}\mathbf{S}_n - \mathbf{S}_n\tilde{\mathbf{\Gamma}}_{S,n} + \sum_{s\geq 1}\alpha_S^s\int \tilde{\mathbf{R}}^{(s)\dagger}_{S,n+s}\mathbf{S}_{n+s}\tilde{\mathbf{R}}^{(s)}_{S,n+s}\prod_{i=n+1}^{n+s}[\mathrm{d}p_i]\tilde{\delta}(p_i)$$



$$\begin{aligned}\mathbf{R}_n^{(2,0)}\circ\mathbf{R}_n^{(2,0)\dagger} &= \hat{\mathbf{D}}_n^{(2,0)}\circ\hat{\mathbf{D}}_n^{(2,0)\dagger}\partial_S\Theta_{n,2}\\ &- \hat{\mathbf{D}}_n^{(1,0)}\hat{\mathbf{D}}_{n-1}^{(1,0)}\circ\hat{\mathbf{D}}_{n-1}^{(1,0)\dagger}\hat{\mathbf{D}}_n^{(1,0)\dagger}(1-\Theta_{n-1,1})\partial_S\Theta_{n,1}\end{aligned}$$

At second order subtract the iterated kernel from the order limit, and include un-ordered separately.

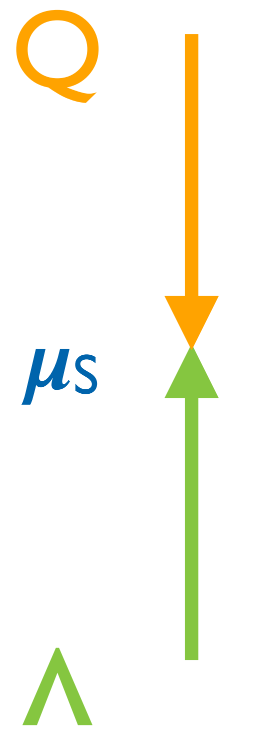
$$\begin{aligned}\mathbf{R}_n^{(2,0)}\circ\mathbf{R}_n^{(2,0)\dagger} = &\left(\hat{\mathbf{D}}_n^{(0,2)}\circ\hat{\mathbf{D}}_n^{(0,2)\dagger}\hat{\Theta}_{n,2} - \hat{\mathbf{D}}_n^{(0,1)}\hat{\mathbf{D}}_{n-1}^{(0,1)}\circ\hat{\mathbf{D}}_{n-1}^{(0,1)\dagger}\hat{\mathbf{D}}_n^{(0,1)\dagger}\hat{\Theta}_{n-1,1}\hat{\Theta}_{n,1}\right)\\ &\times\theta(E_{n-1}-\mu_S)\delta(E_n-\mu_s)\\ &+\hat{\mathbf{D}}_n^{(0,2)}\circ\hat{\mathbf{D}}_n^{(0,2)\dagger}\hat{\Theta}_{n,2}\theta(E_n-\mu_S)\delta(E_{n-1}-\mu_S)\ ,\end{aligned}$$

Hadronization models

We can now obtain the evolution equations we asked for:

$$\partial_S \mathbf{A}_n = \mathbf{\Gamma}_{n,S}\mathbf{A}_n + \mathbf{A}_n\mathbf{\Gamma}^{\dagger}_{n,S} - \sum_{s\geq 1} \alpha_S^s \mathbf{R}^{(s)}_{S,n}\mathbf{A}_{n-s}\mathbf{R}^{(s)\dagger}_{S,n}$$

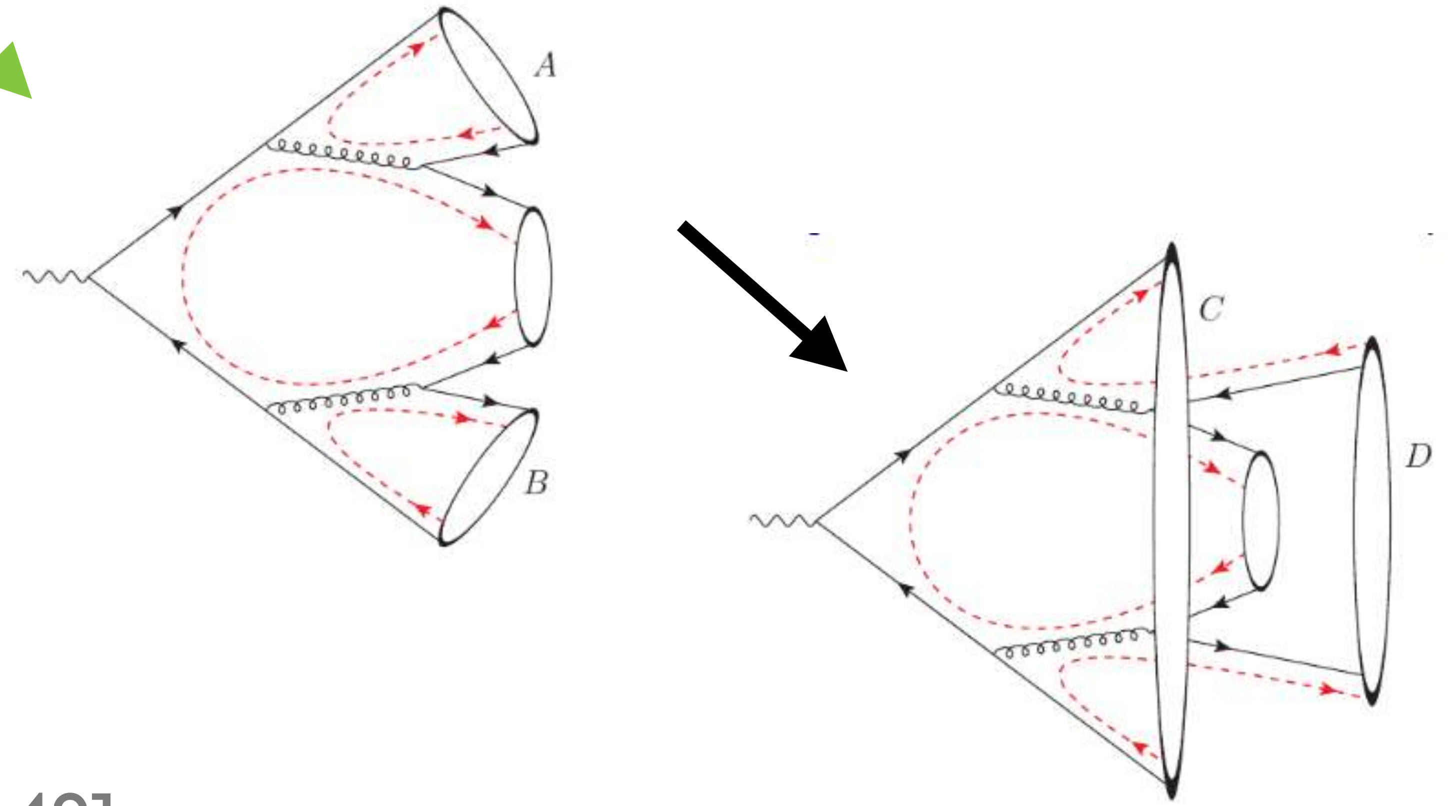
$$\partial_S \equiv \partial/\partial \log \mu_S$$

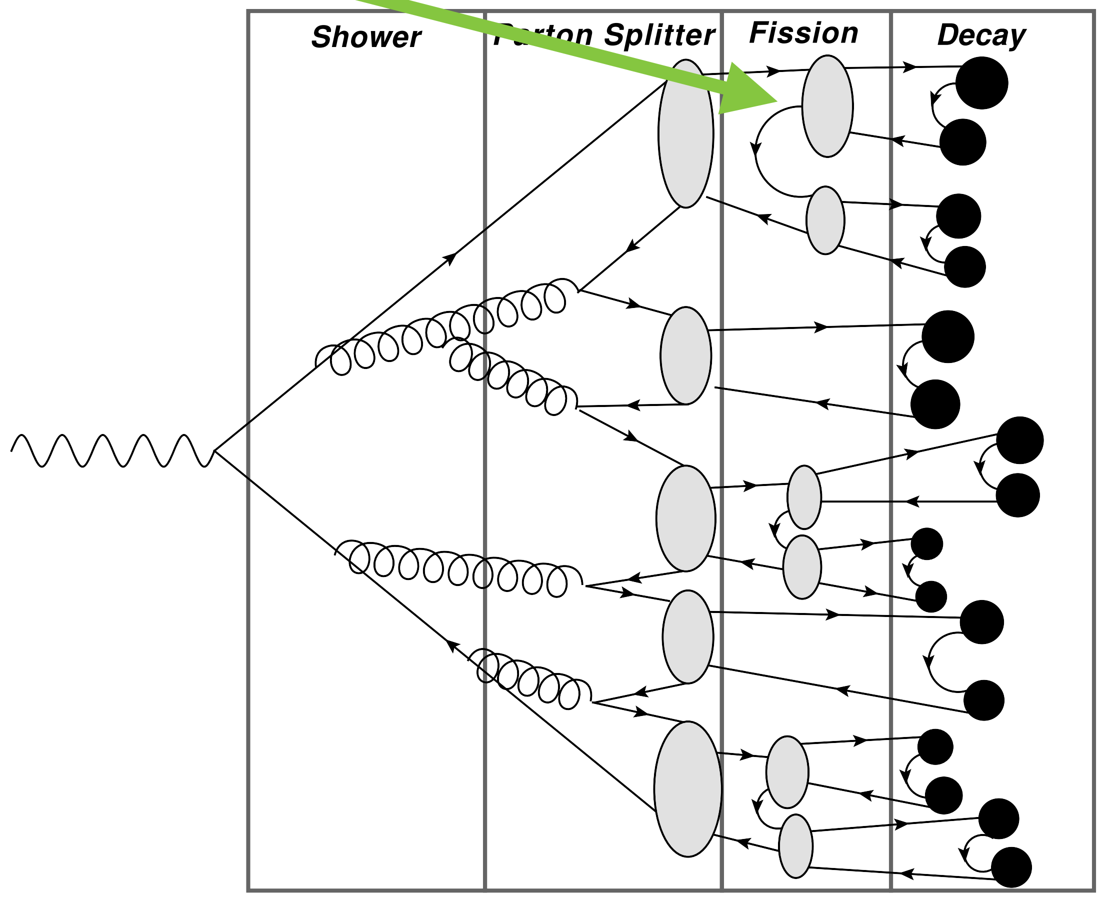


$$\partial_S \mathbf{S}_n = -\tilde{\mathbf{\Gamma}}^{\dagger}_{S,n}\mathbf{S}_n - \mathbf{S}_n\tilde{\mathbf{\Gamma}}_{S,n} + \sum_{s\geq 1} \alpha_S^s \int \tilde{\mathbf{R}}^{(s)\dagger}_{S,n+s}\mathbf{S}_{n+s}\tilde{\mathbf{R}}^{(s)}_{S,n+s} \prod_{i=n+1}^{n+s} [\mathrm{d}p_i]\tilde{\delta}(p_i)$$

Evolution equation for a hadronization model!

Features which relate to the high-energy dynamics of the Herwig cluster model.





[Gieseke, Kirchgaesser, Plätzer, Siodmok – JHEP 11 (2018) 149]

Algorithms & Efficiency

Sudakov-type densities central to Showers

[Olsson, Plätzer, Sjödahl — EPJC 80 (2020) 10]
[Plätzer, Sjödahl — EPJ Plus 127 (2012) 26]
Also cf. shower variations e.g.
[Bellm, Plätzer, et al. — Phys.Rev.D 94 (2016) 3, 034028]

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

$Q' \leftarrow Q, w \leftarrow w_0$
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

$$w \leftarrow w \times \frac{1}{\epsilon} \times \frac{P(Q',z,x)}{R(Q',z,x)}. \qquad (3)$$

else
The emission is rejected, and the algorithm continues with

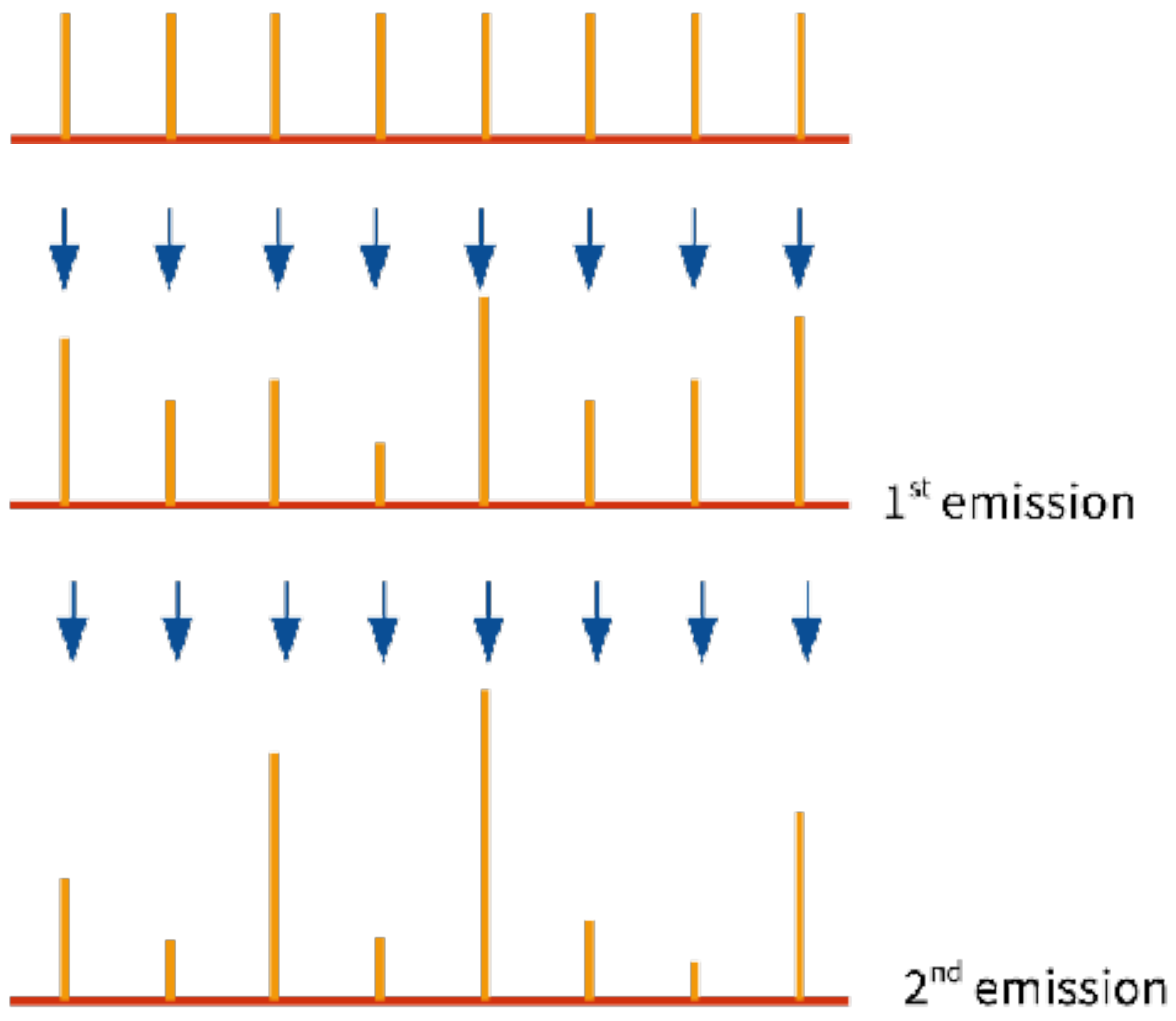
$$w \leftarrow w \times \frac{1}{1-\epsilon} \times \left(1 - \frac{P(q,z,x)}{R(q,z,x)}\right)$$
$$Q' \leftarrow q. \qquad (4)$$

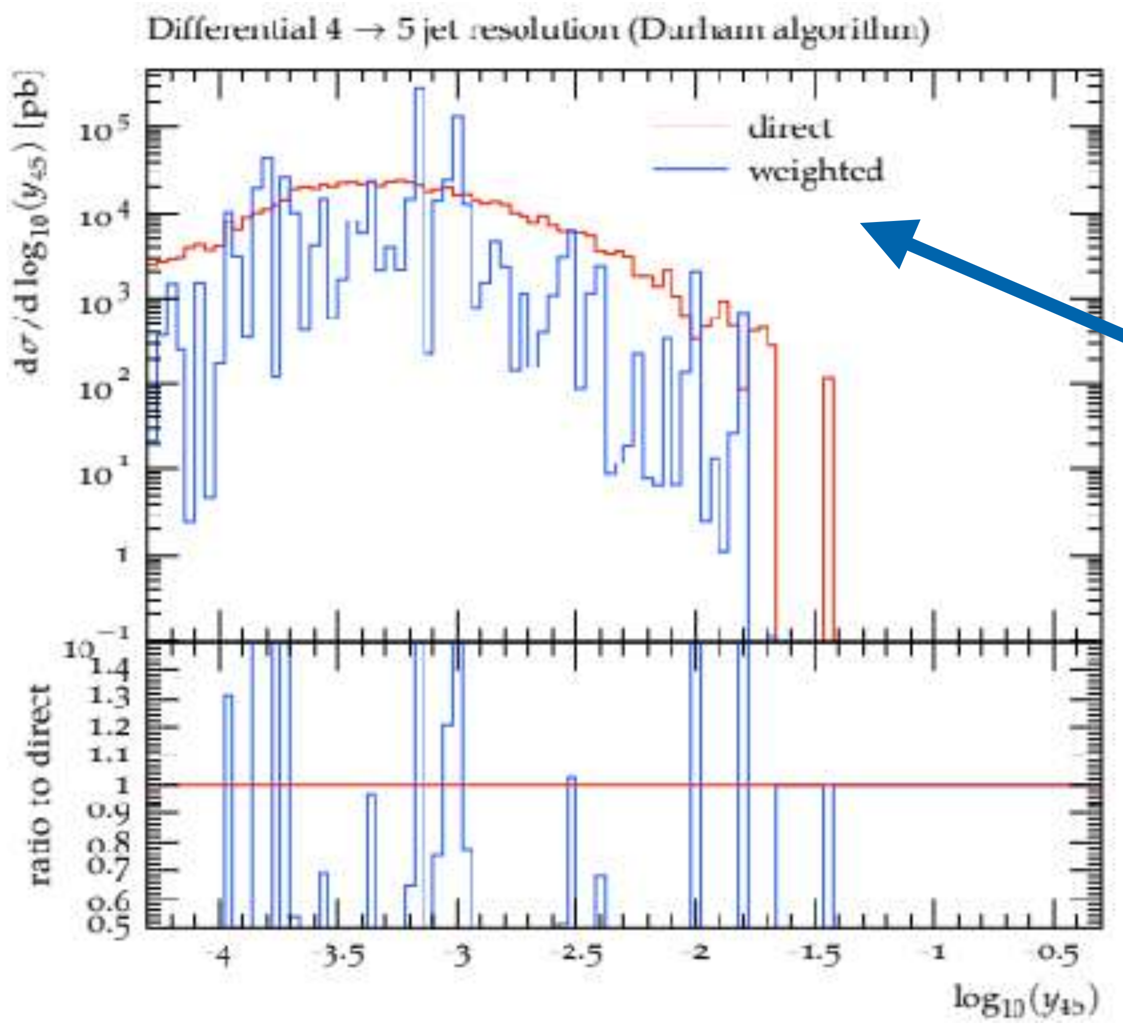
end if
end if
end loop

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

Weighted Veto Algorithms & Resampling

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





Weighted branching algorithms exhibit prohibitive weight distributions & convergence issues.

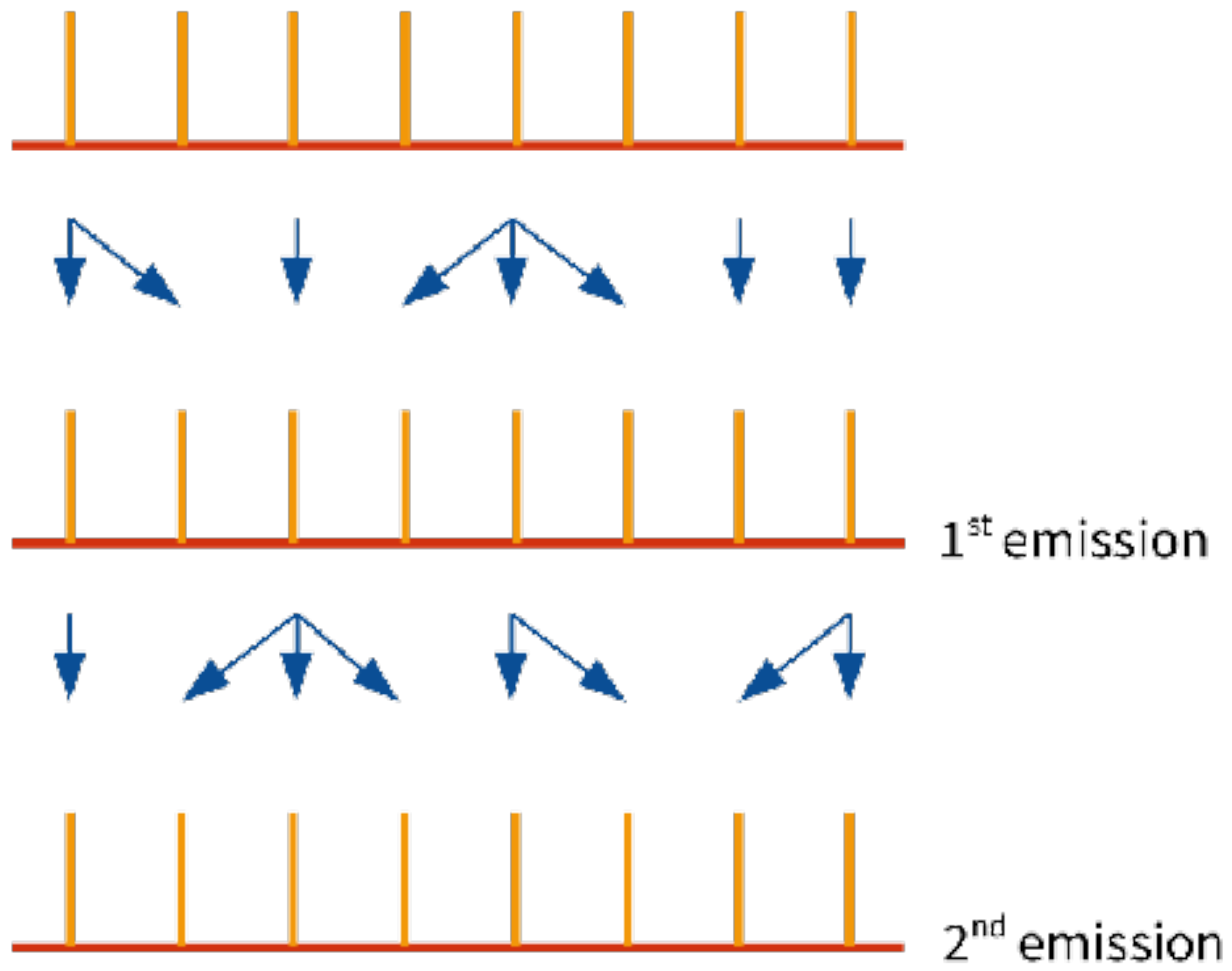
Result without resampling

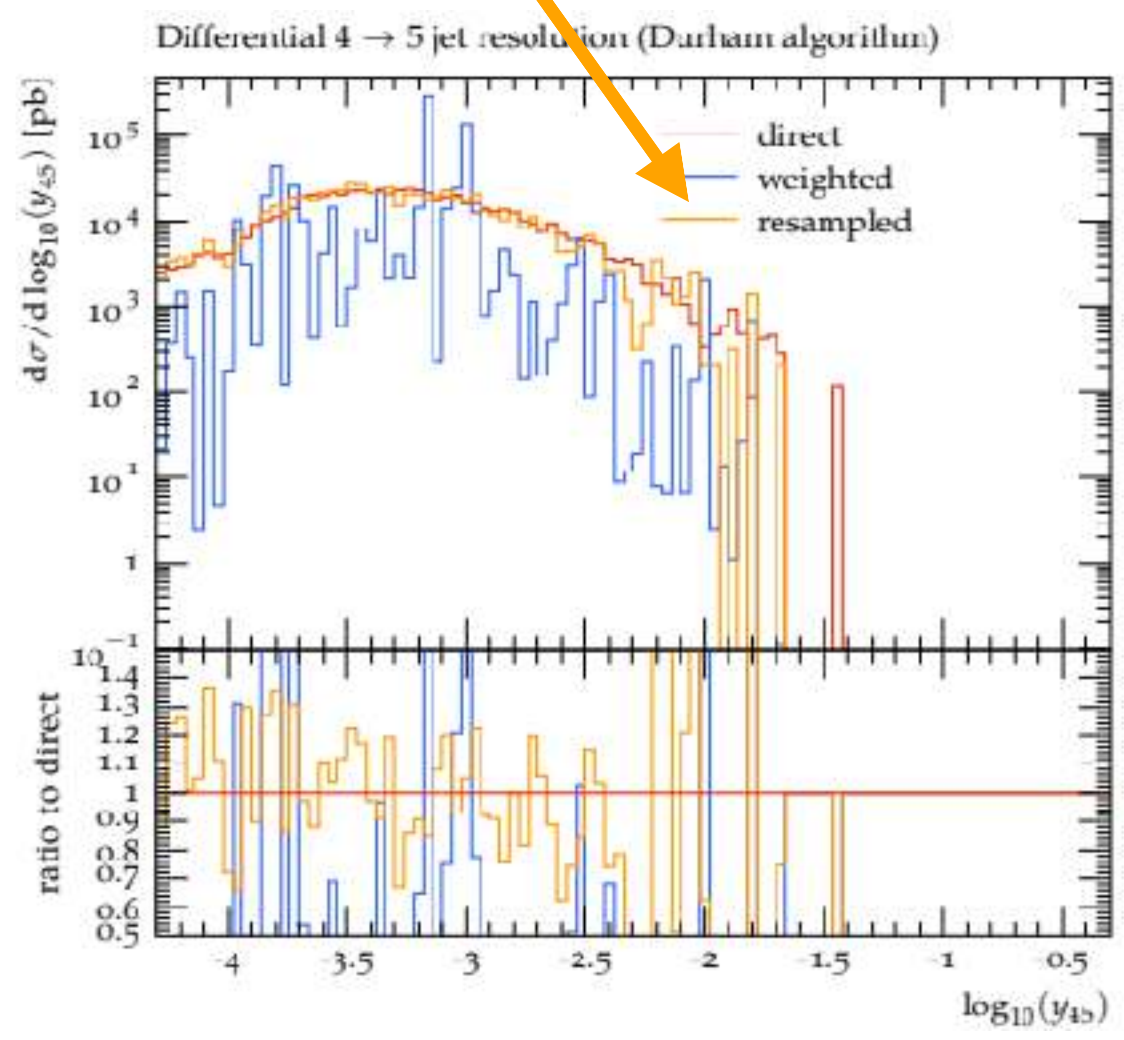
Result with resampling

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]



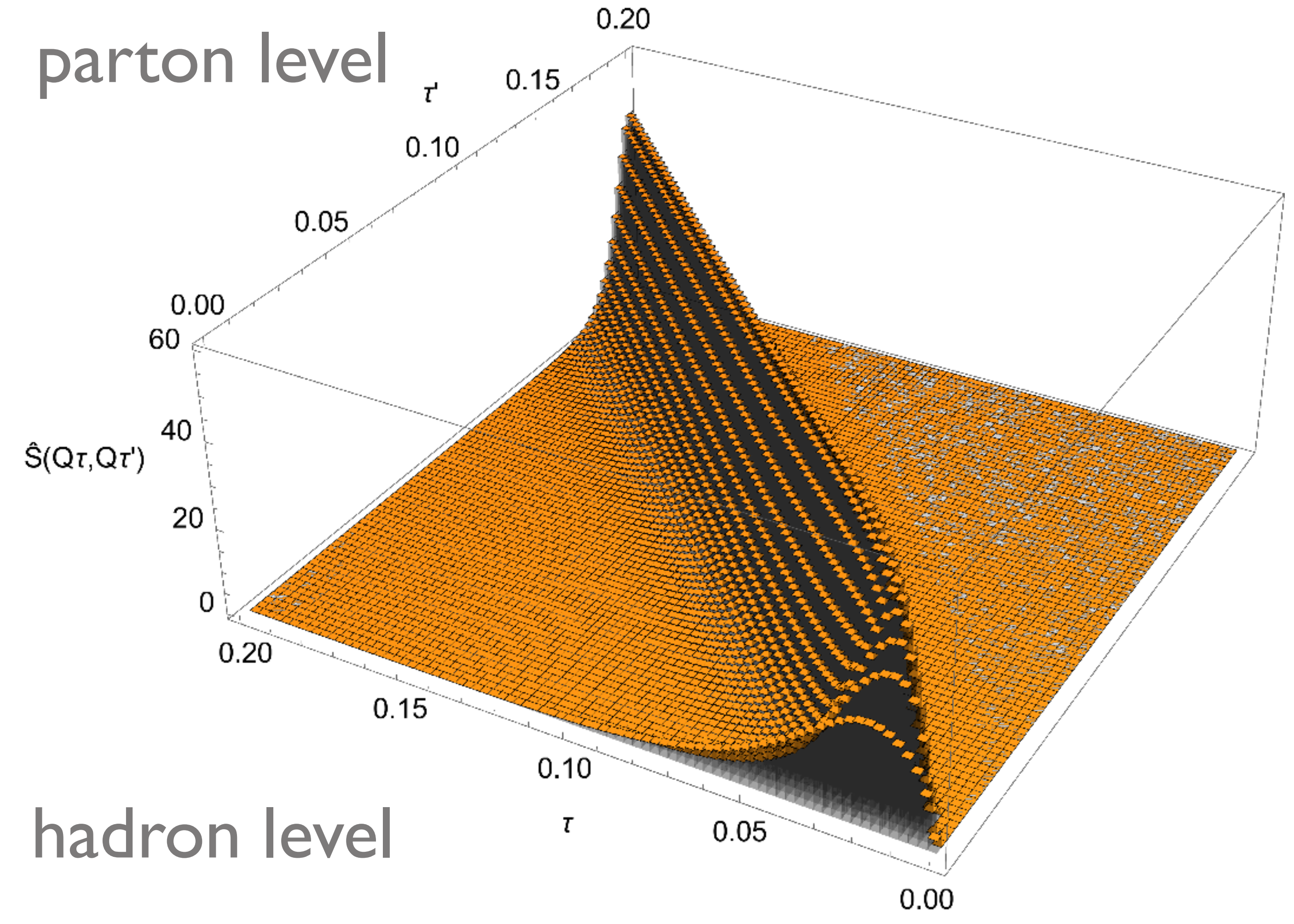


Summary

Multi-purpose event generators well established for all FCC options.
Matching & merging has been focus of last decade.

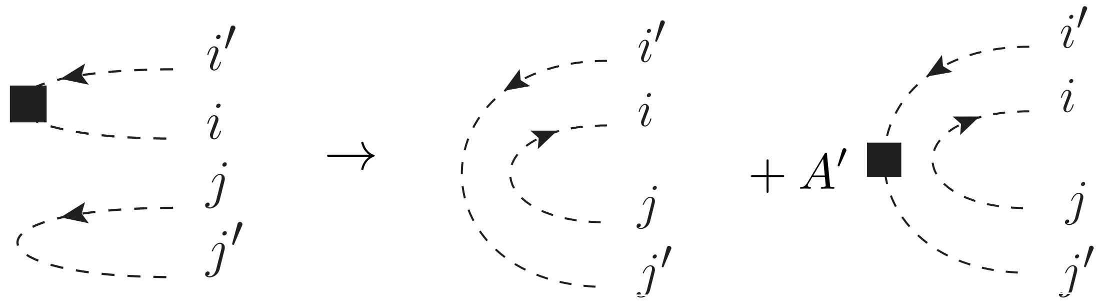
As we aim to use more and more of the complex structures, shower accuracy becomes the bottleneck. Also for matching to more than NNLO QCD.

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.

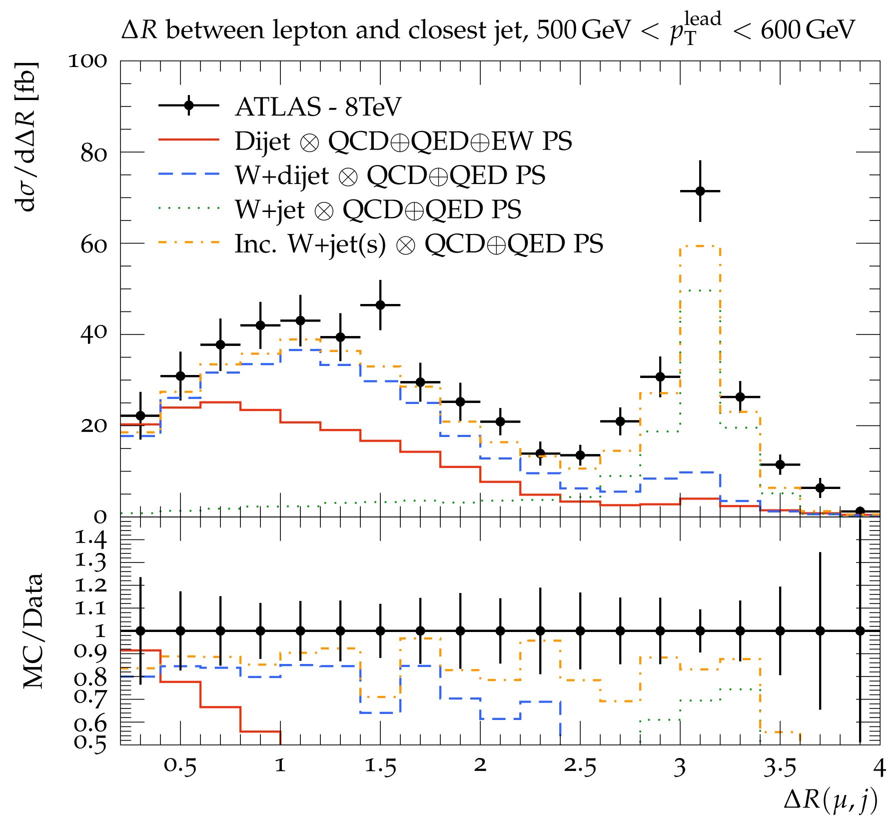


[Hoang, Plätzer, Samitz — in progress]

Electroweak being addressed, but only at the start to understand amplitude level effects and "soft" region.



[Plätzer, Sjödahl — arXiv:2204.03258]



[Masouminia, Richardson — arXiv:2108.10817]

[Christiansen, Sjöstrand, Bauer, Webber, Brooks, Verheyen, Skands ….]

Thanks!