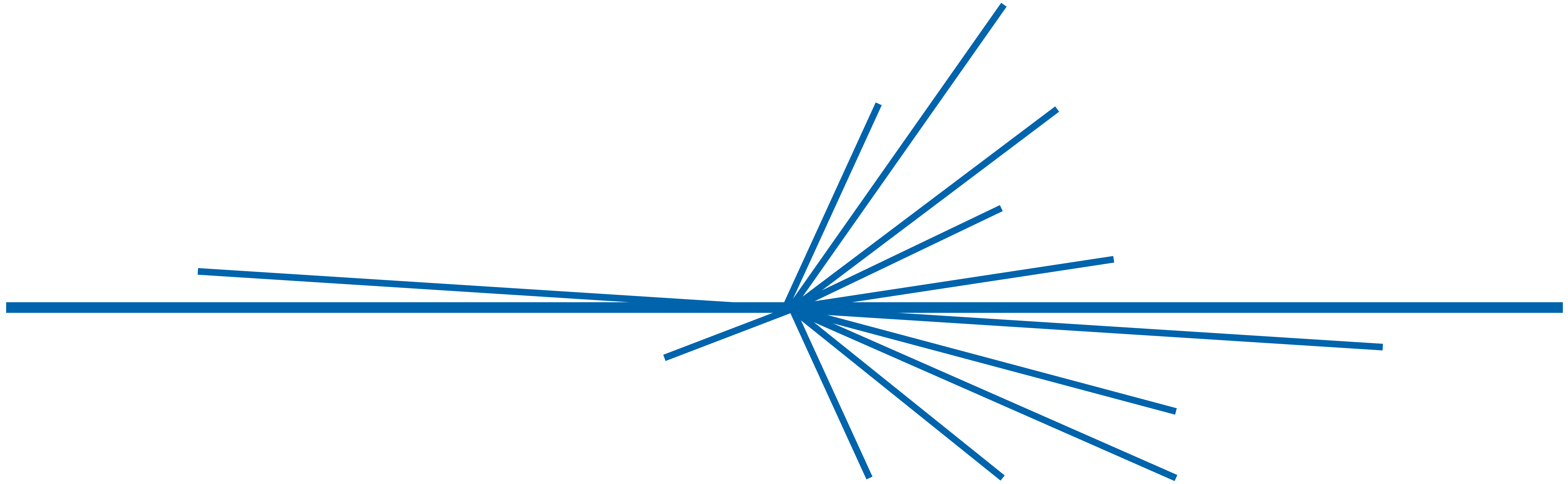
UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ

Event Generators & Parton Showers

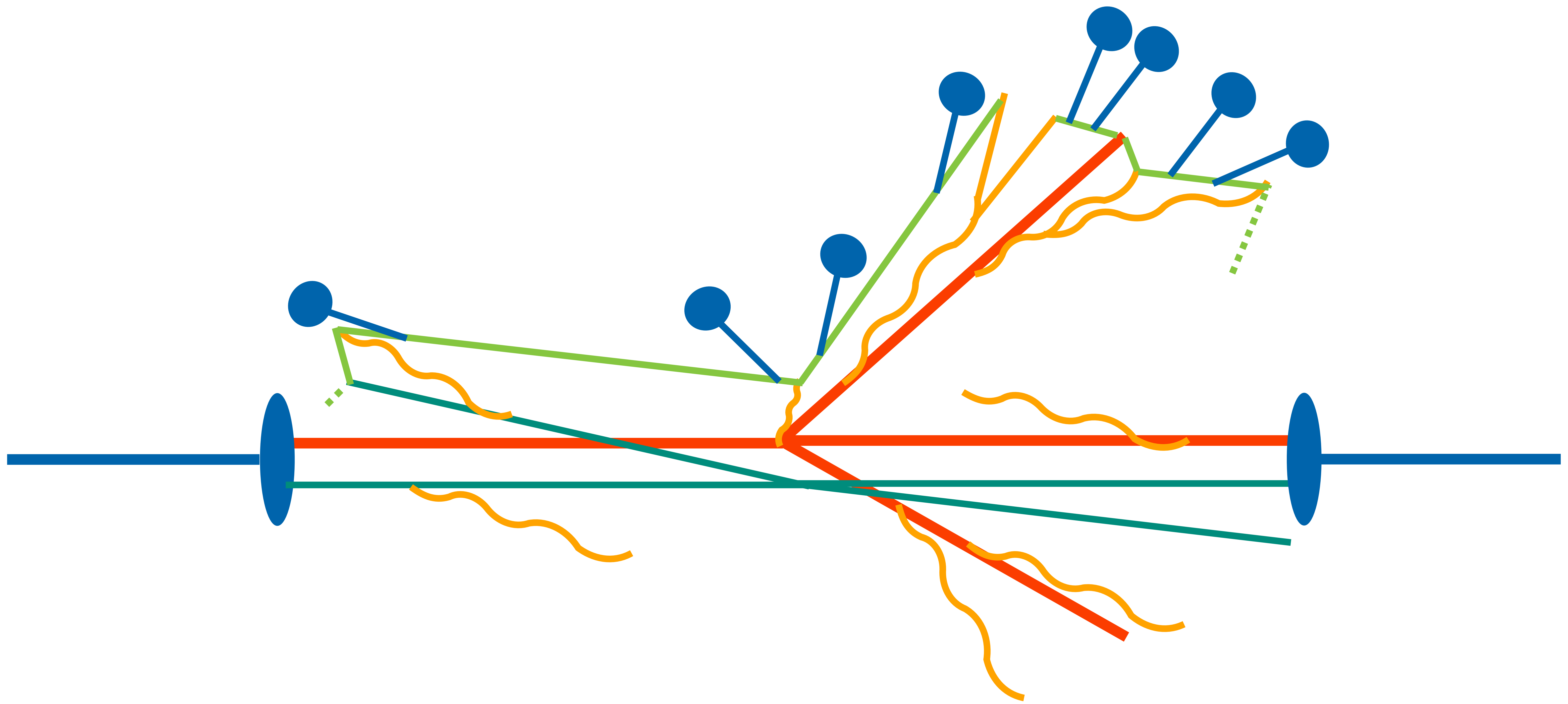
Simon Plätzer
Institute of Physics — NAWI, University of Graz
Particle Physics — University of Vienna

At the
FCC Physics Workshop
Liverpool/Online | 7 February 2022

Complexity at Colliders

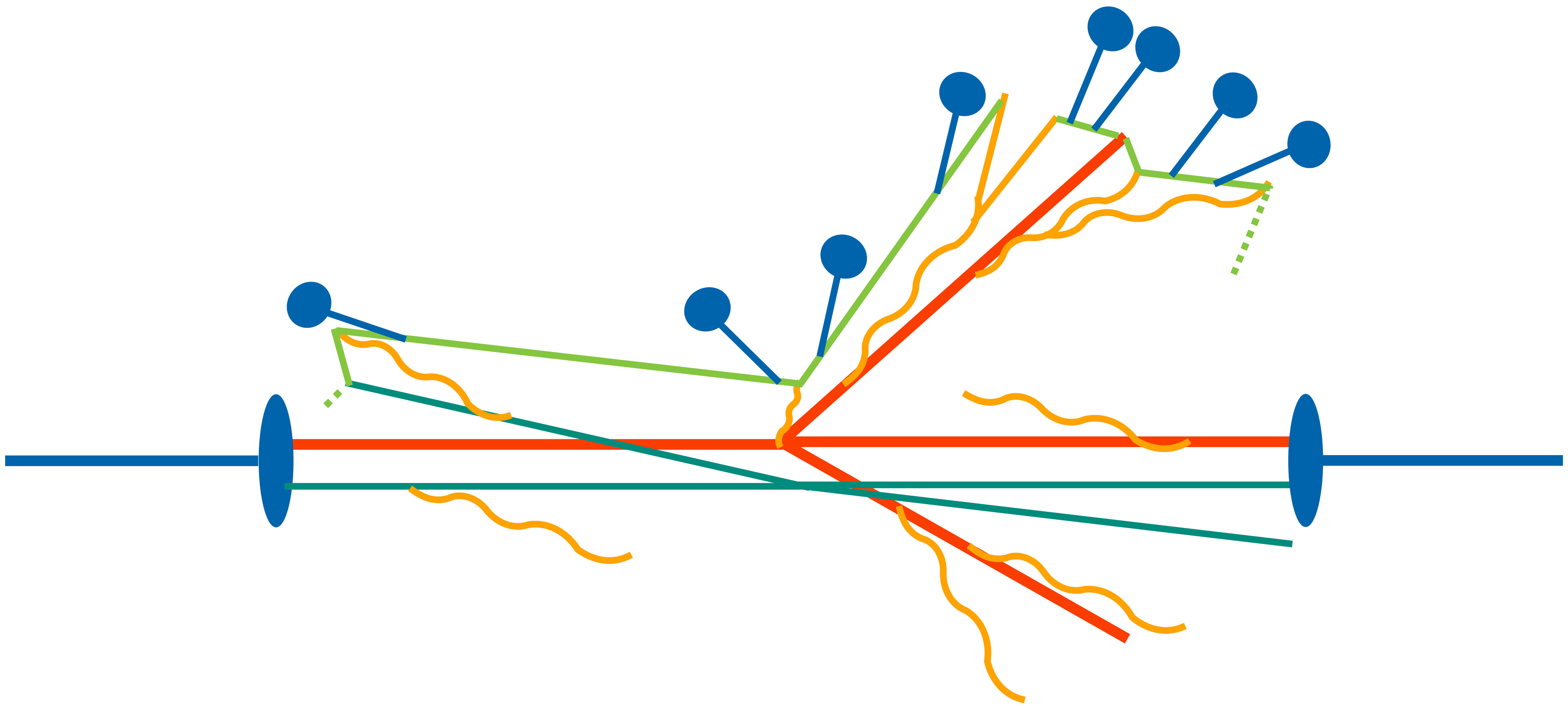


Complexity, factorized.



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

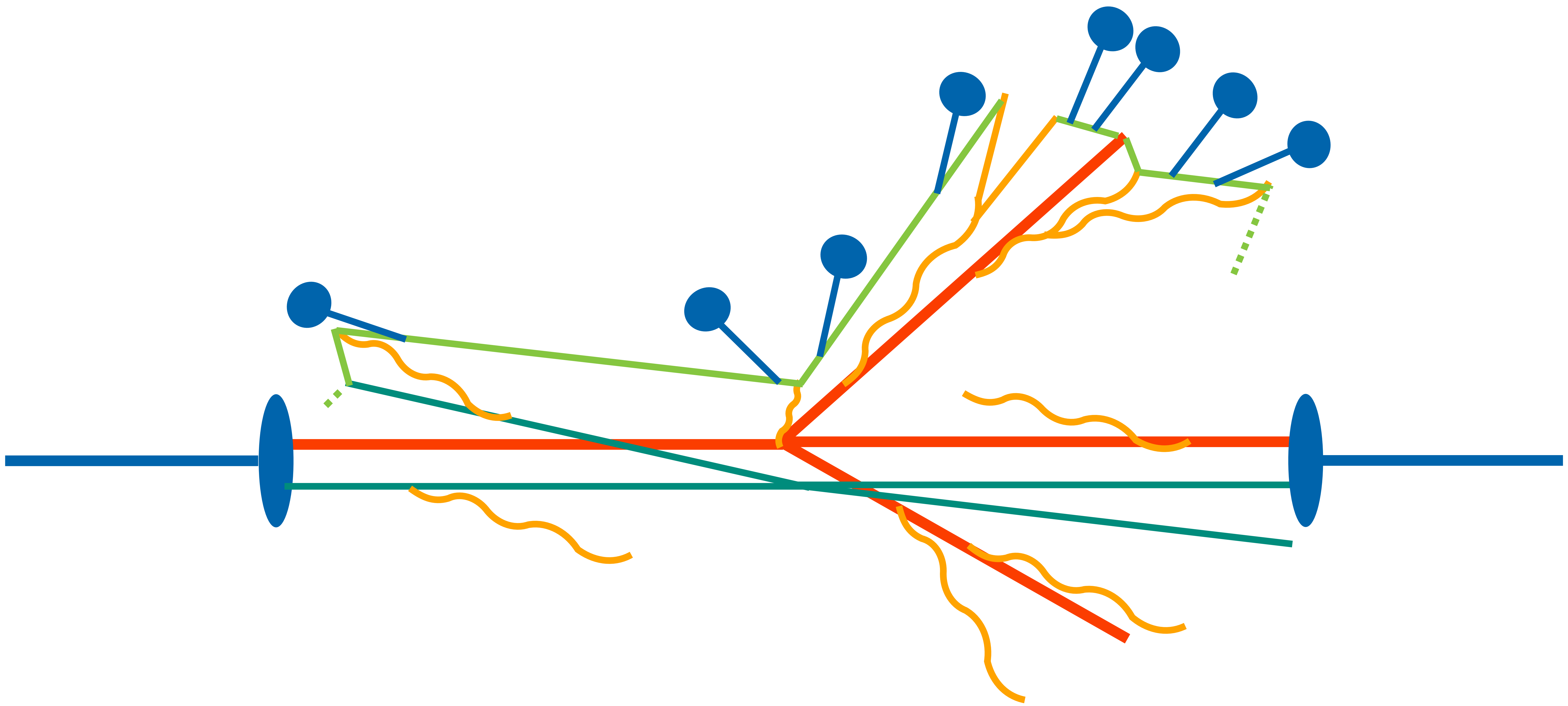
Complexity, factorized.



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

100's of GeV

Complexity, factorized.

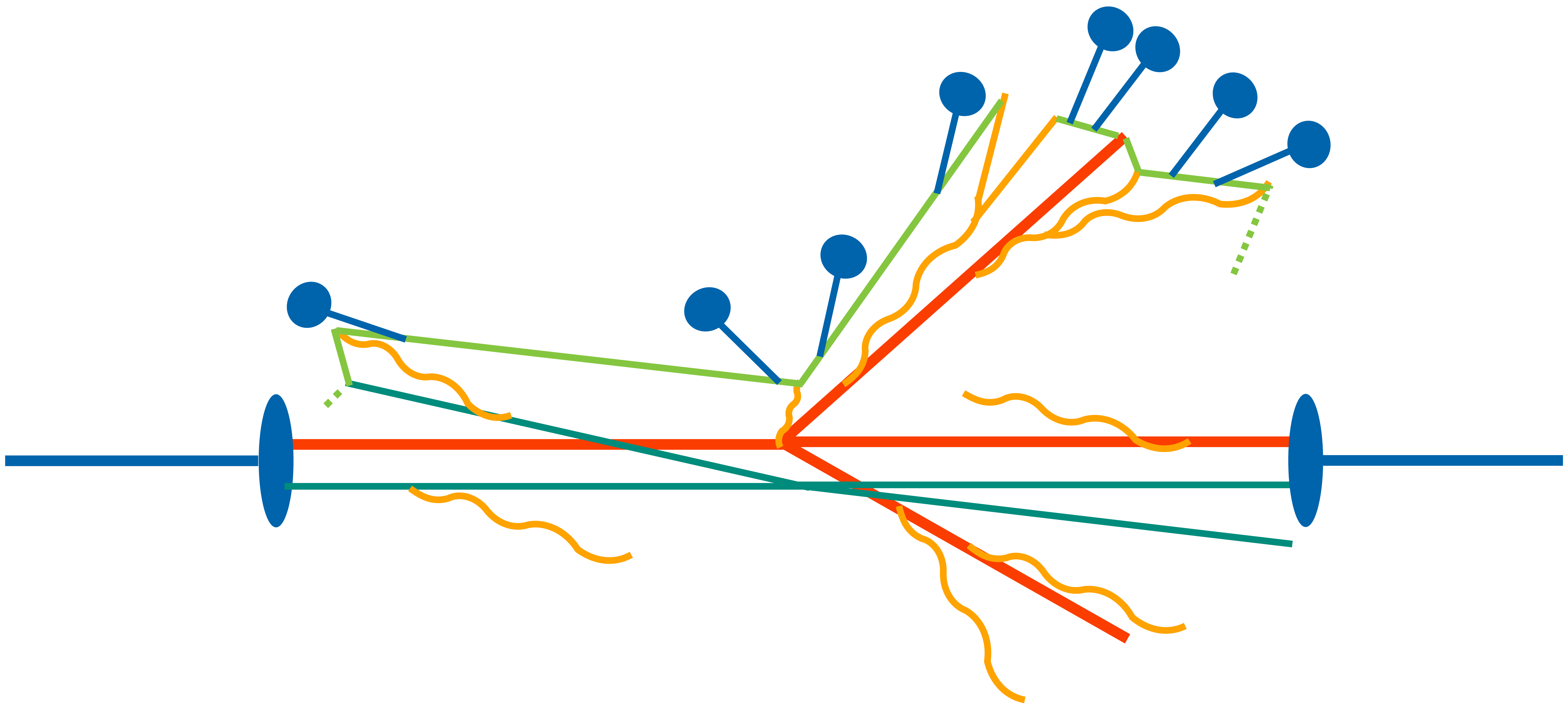


$$\mathrm{d}\sigma \sim \mathrm{L} \times \mathrm{d}\sigma_H(Q) \times \mathrm{PS}(Q \to \mu) \times \mathrm{MPI} \times \mathrm{Had}(\mu \to \Lambda) \times \ldots$$

100's of GeV

1-2 GeV

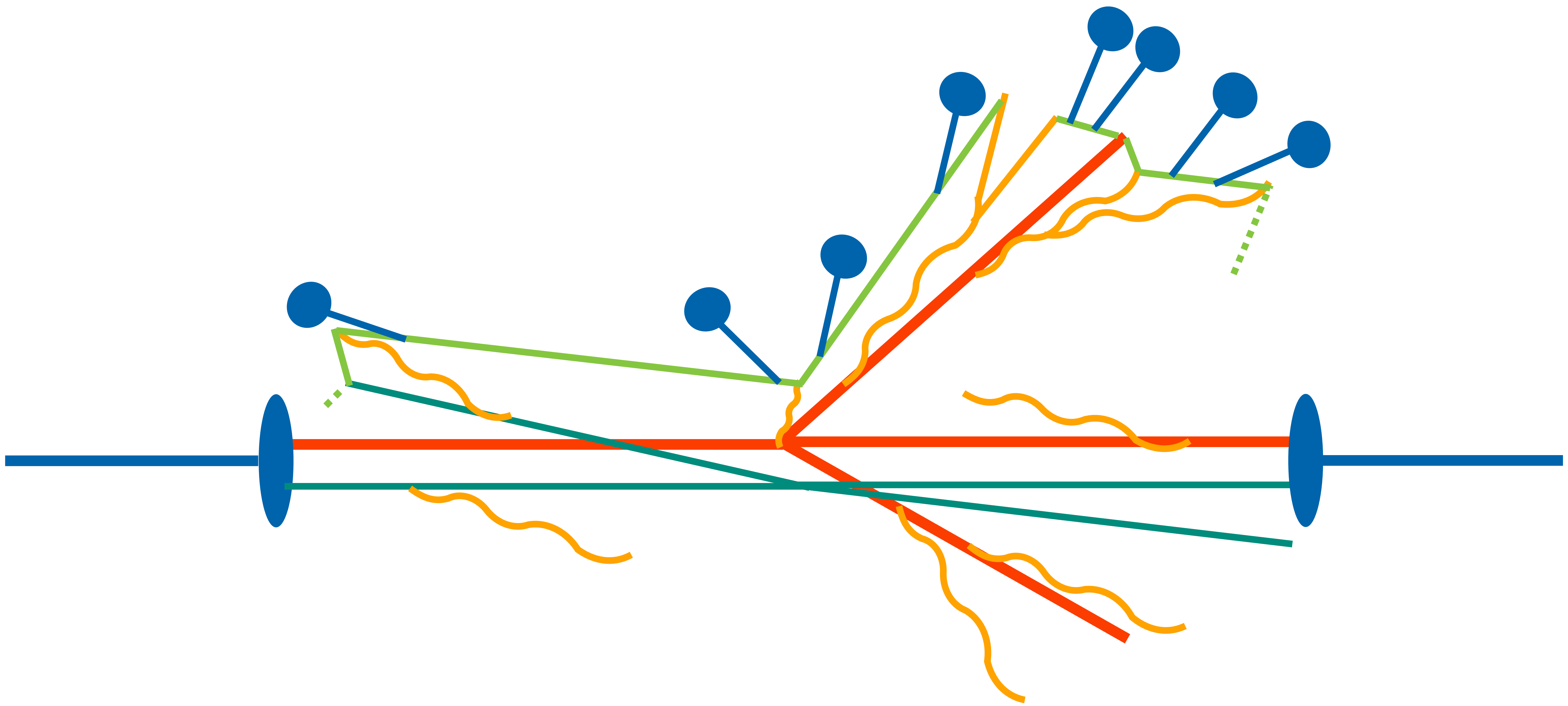
Complexity, factorized.



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

100's of GeV 1-2 GeV few 100's MeV

Complexity, factorized.



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

100's of GeV 1-2 GeV 1-10 GeV few 100's MeV

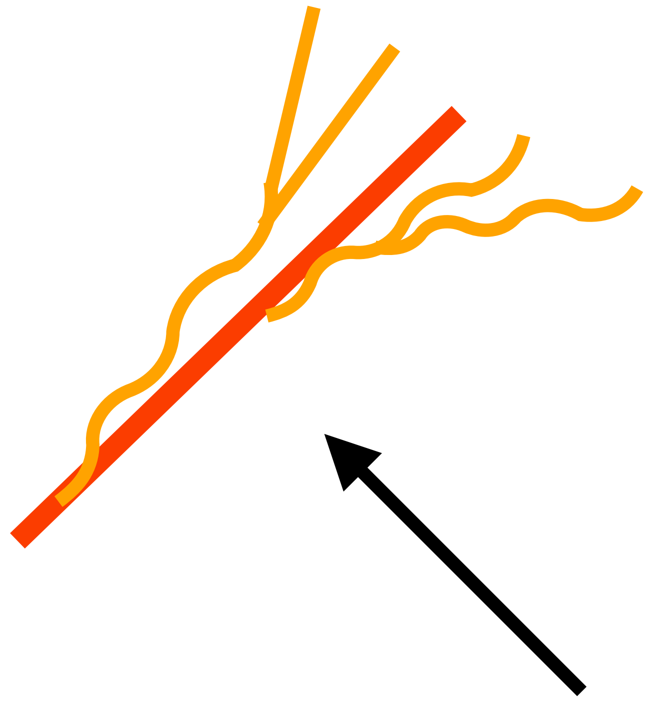
QCD & Event Generators

QCD description of collider reactions:
Complexity challenges precision.

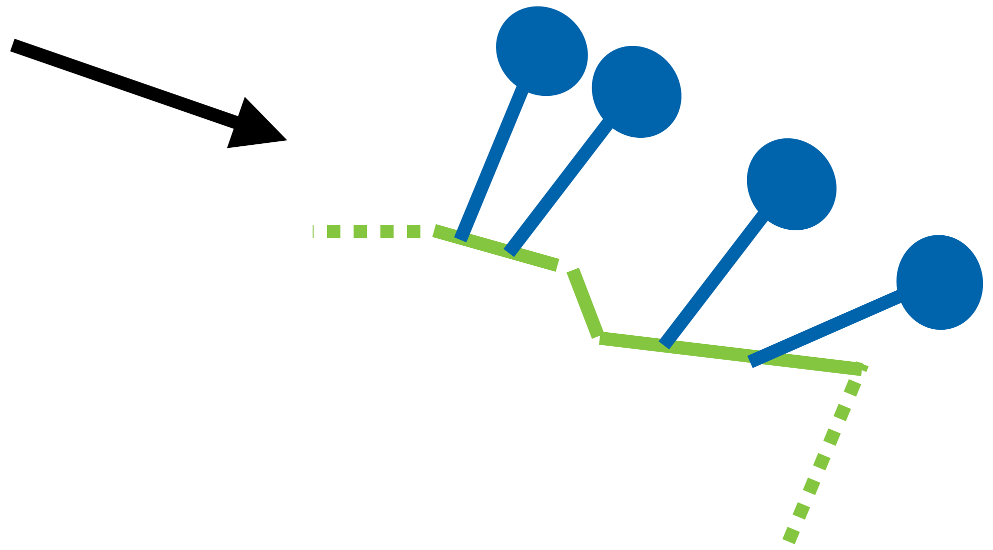
Hard partonic scattering:
NLO QCD routinely

Jet evolution — parton branching:
NLL sometimes, mostly unclear

Multi-parton interactions
Hadronization — the unknown?



This talk, i.e. mostly a focus on FCC-ee



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

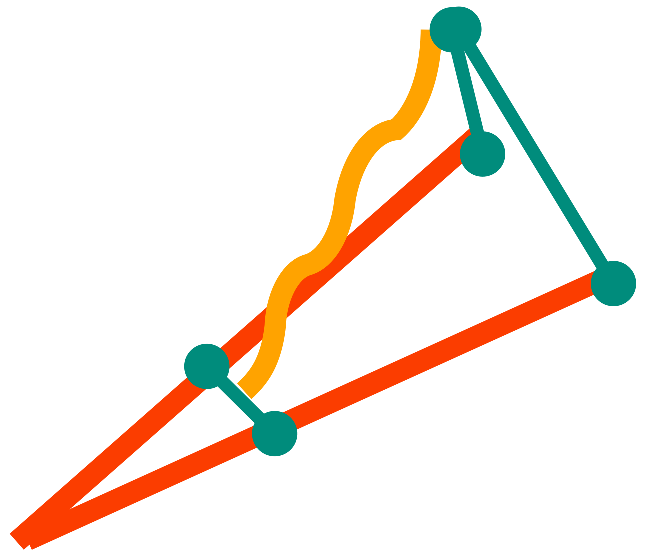
Shower & Parton Branching Paradigms

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ
universität wien

Parton branchings order in angle.

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

Herwig 7

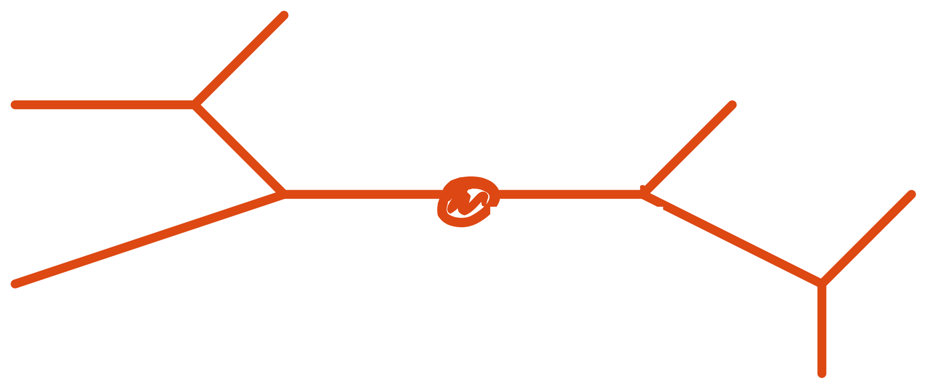


Dipole branchings order in transverse momentum.

- 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.



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

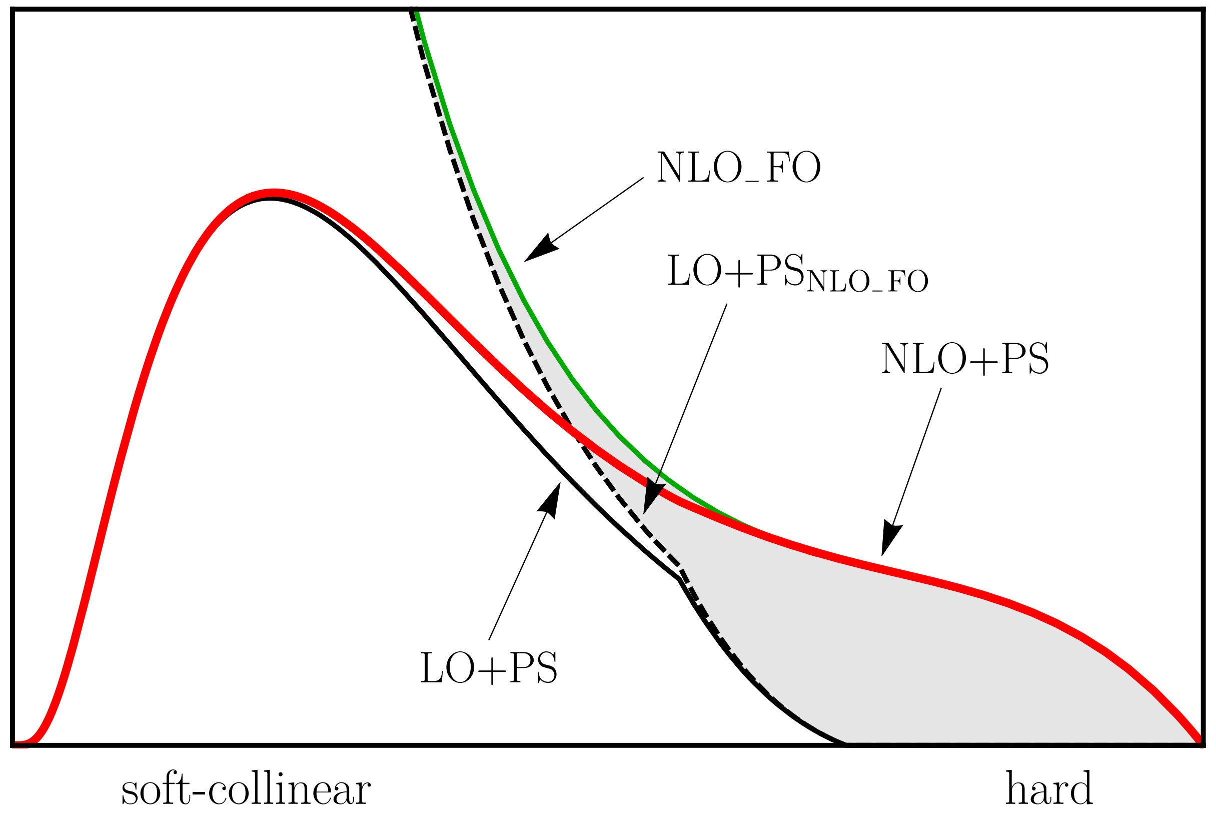
emission rate

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

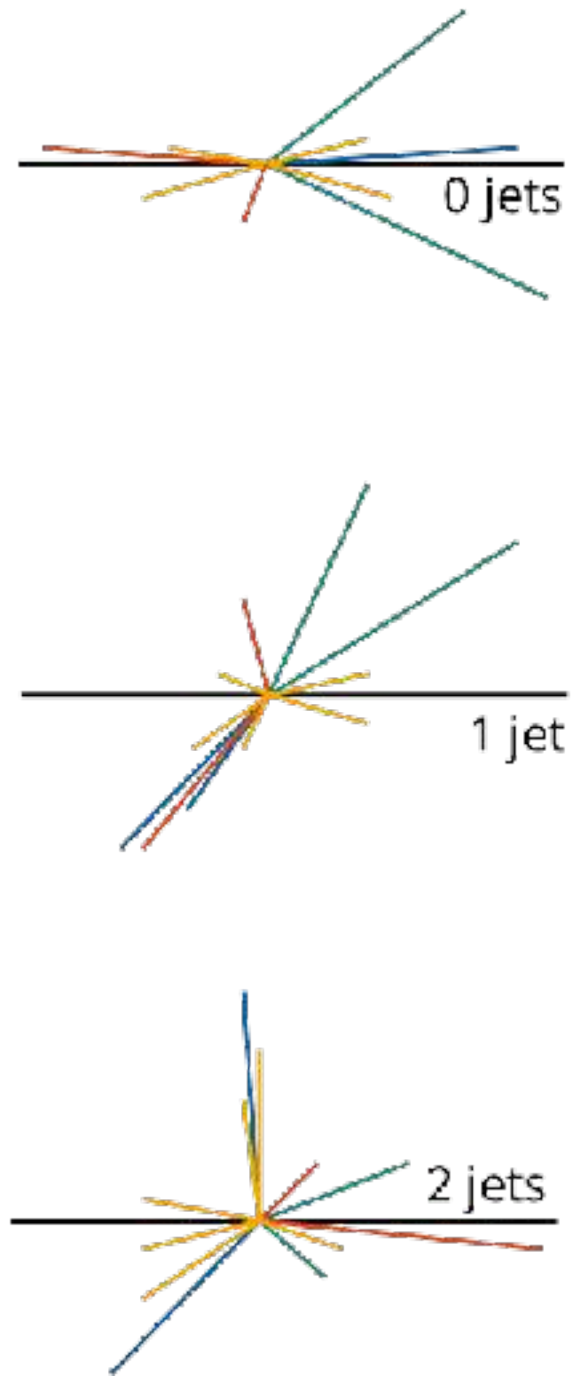
Matching determined by expanding shower to fixed order, and subtracting it from fixed-order cross section.

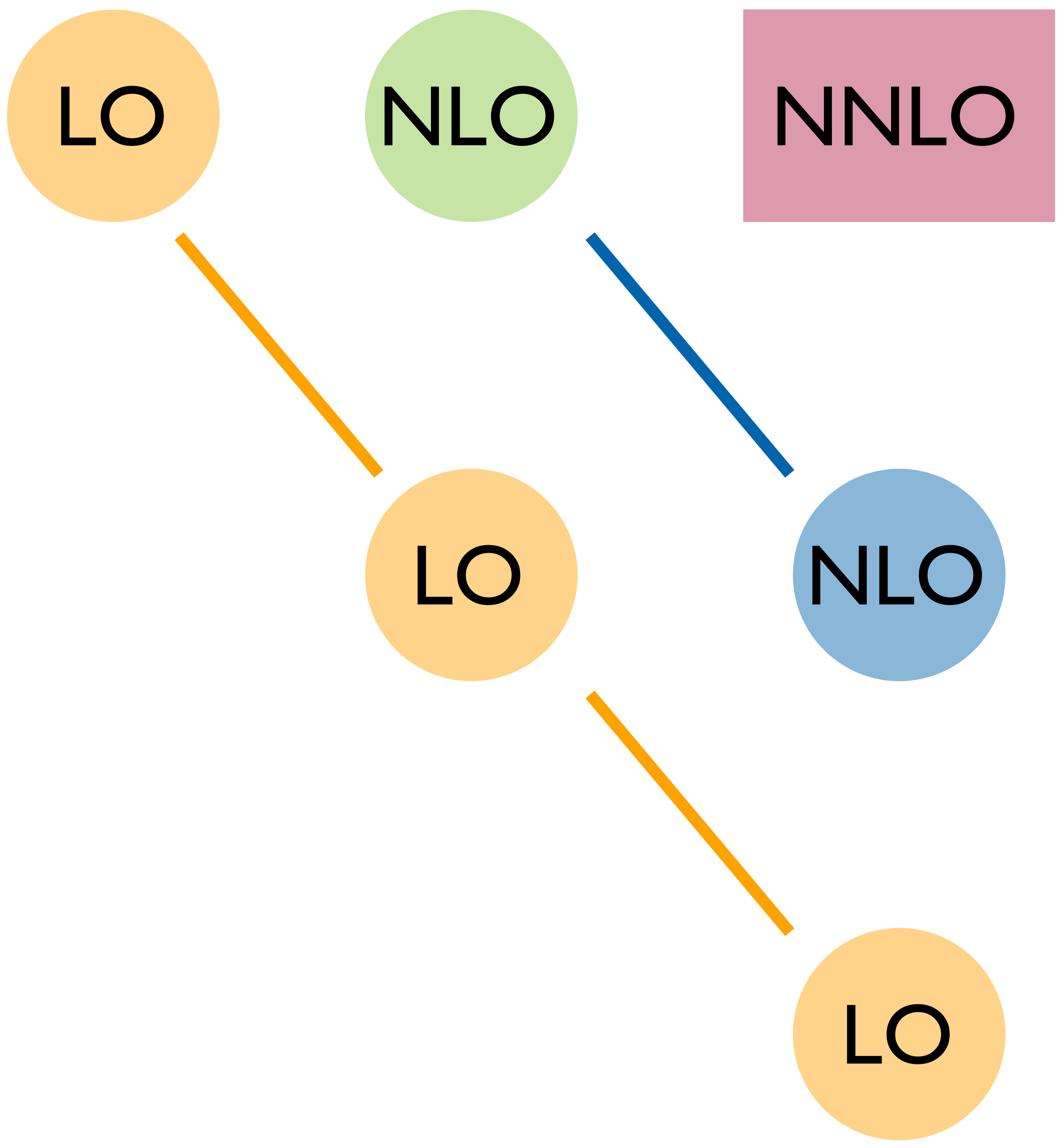


- De-facto standard in multi-purpose event generators
- Tweaks still possible

[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

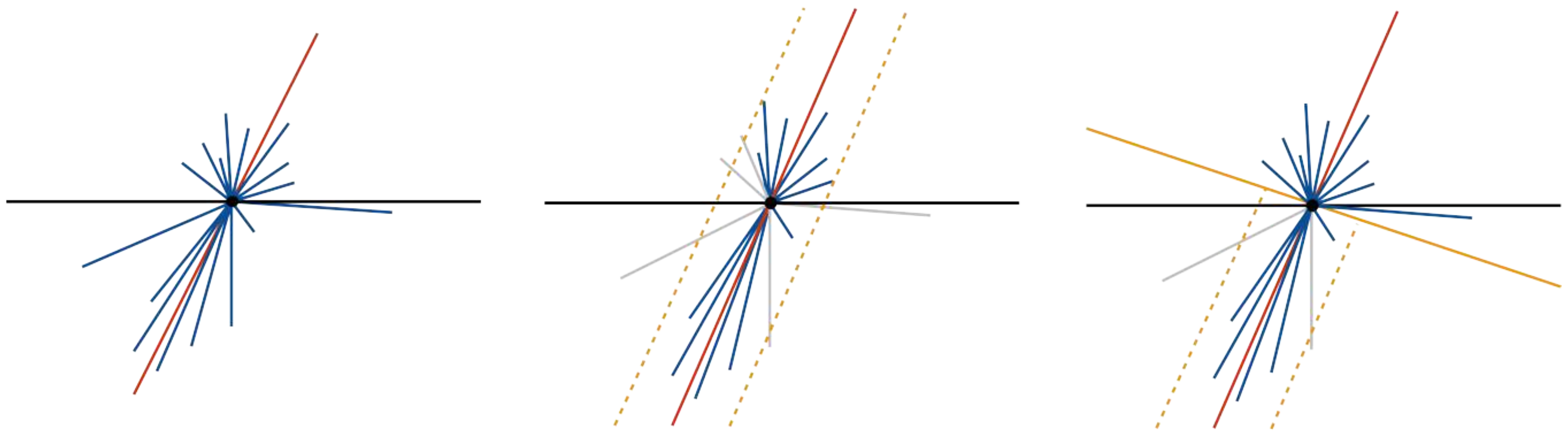
LHC-age Working Horses

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ
UNI GRAZ
universität wien

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	

General purpose — ready for FCC-xx

Accuracy of Parton Showers



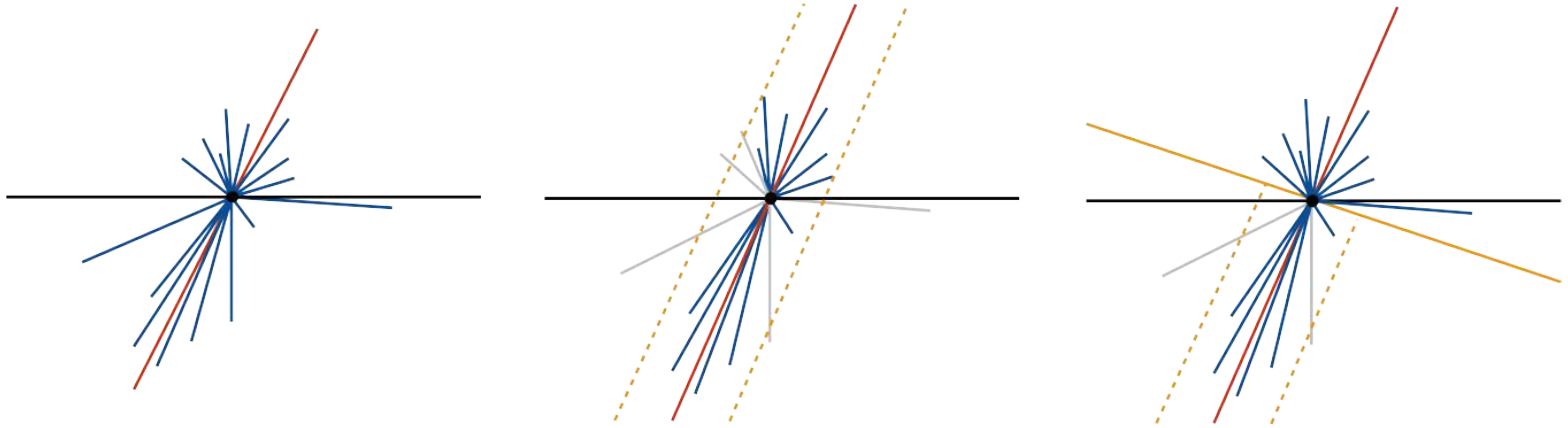
Global event shapes from coherent branching

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

LL — qualitative NLL — quantitative NNLL — precision

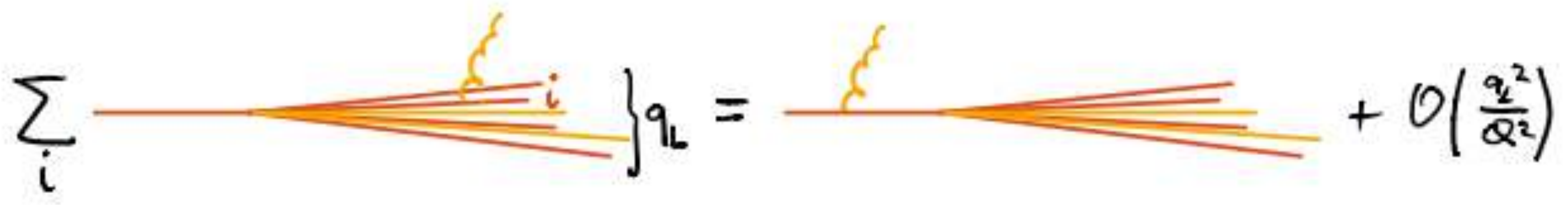
$\alpha_s L \sim 1$

Accuracy of Parton Showers



Global event shapes from coherent branching

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



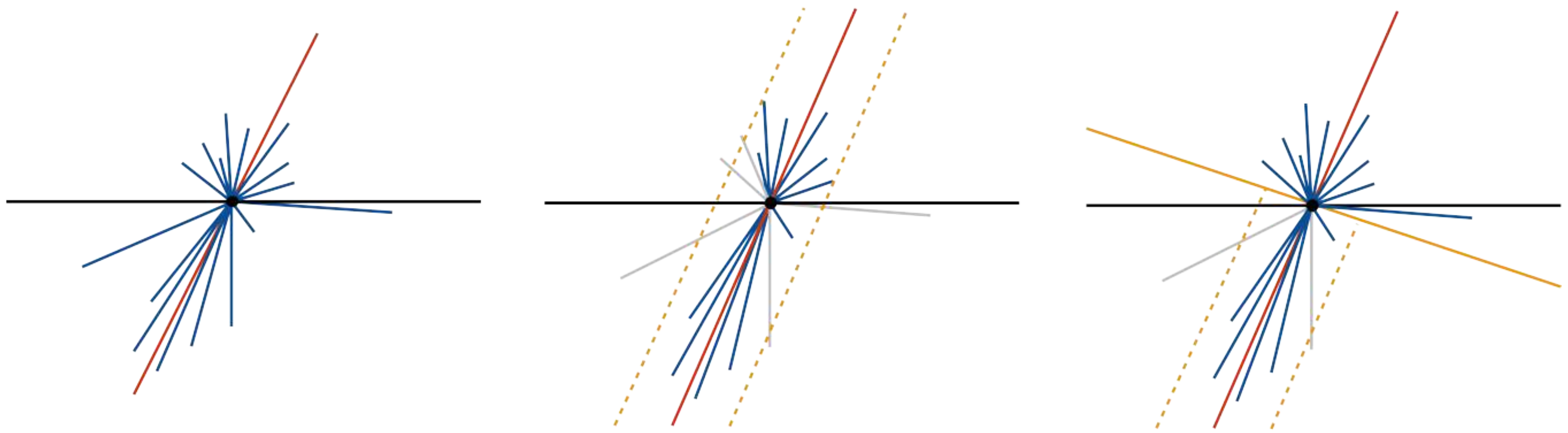
$$\frac{\partial G_{ab}(t)}{\partial t} = -\int_{\text{in}} \frac{d\Omega_k}{4\pi}\omega_{ab}(k)G_{ab}(t) + \int_{\text{out}} \frac{d\Omega_k}{4\pi}\omega_{ab}(k)\Big[G_{ak}(t)G_{kb}(t) - G_{ab}(t)\Big]$$

[Catani, Trentadue, Webber, Marchesini ….]

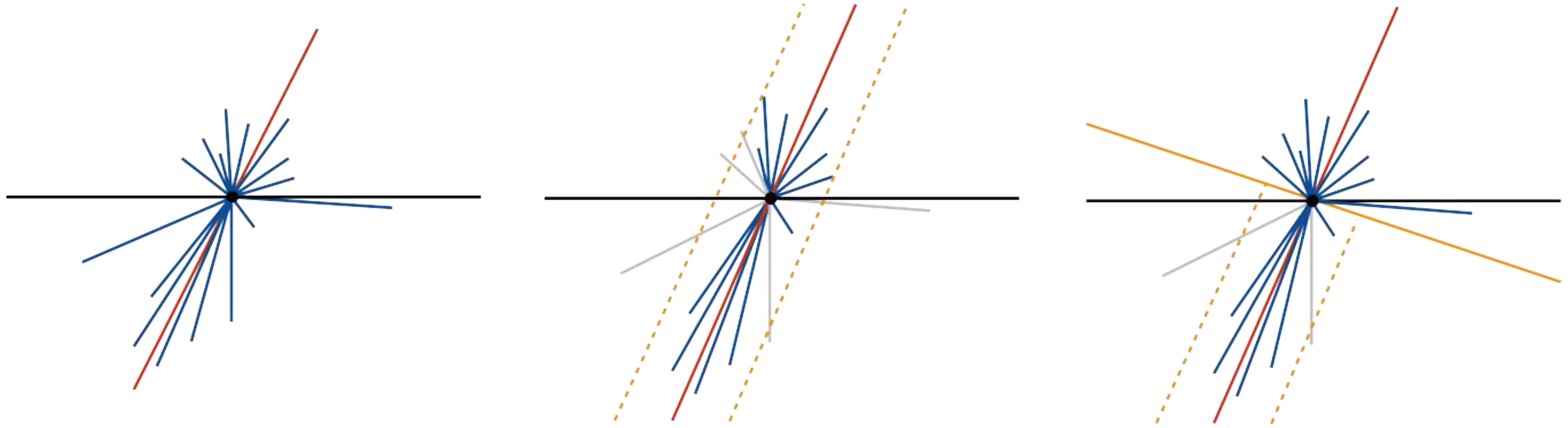
[Banfi, Marchesini, Smye — JHEP 08 (2002) 006]
even at NLL: [Banfi, Dreyer, Monti — JHEP 10 (2021) 006]

Accuracy of Parton Showers

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ



Accuracy of Parton Showers



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

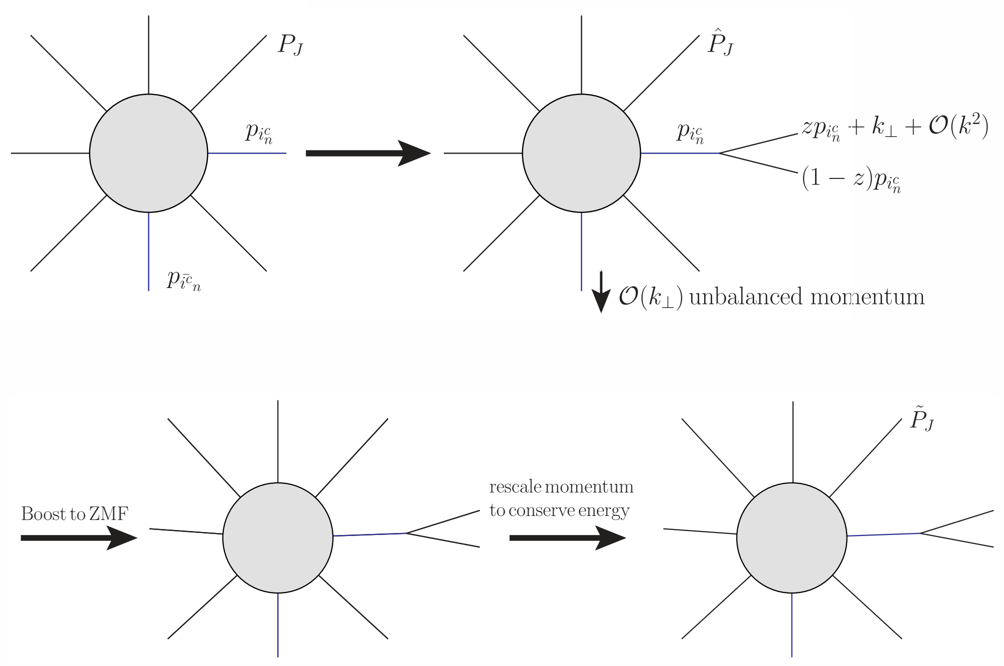
[Dasgupta, Dreyer, Hamilton, Monni, Salam et al. — JHEP 09 (2018) 033, …]
[Hoang, Plätzer, Samitz — JHEP 1810 (2018) 200]
[Bewick, Ferrario, Richardson, Seymour — JHEP 04 (2020) 019]

Accuracy of Parton Showers

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

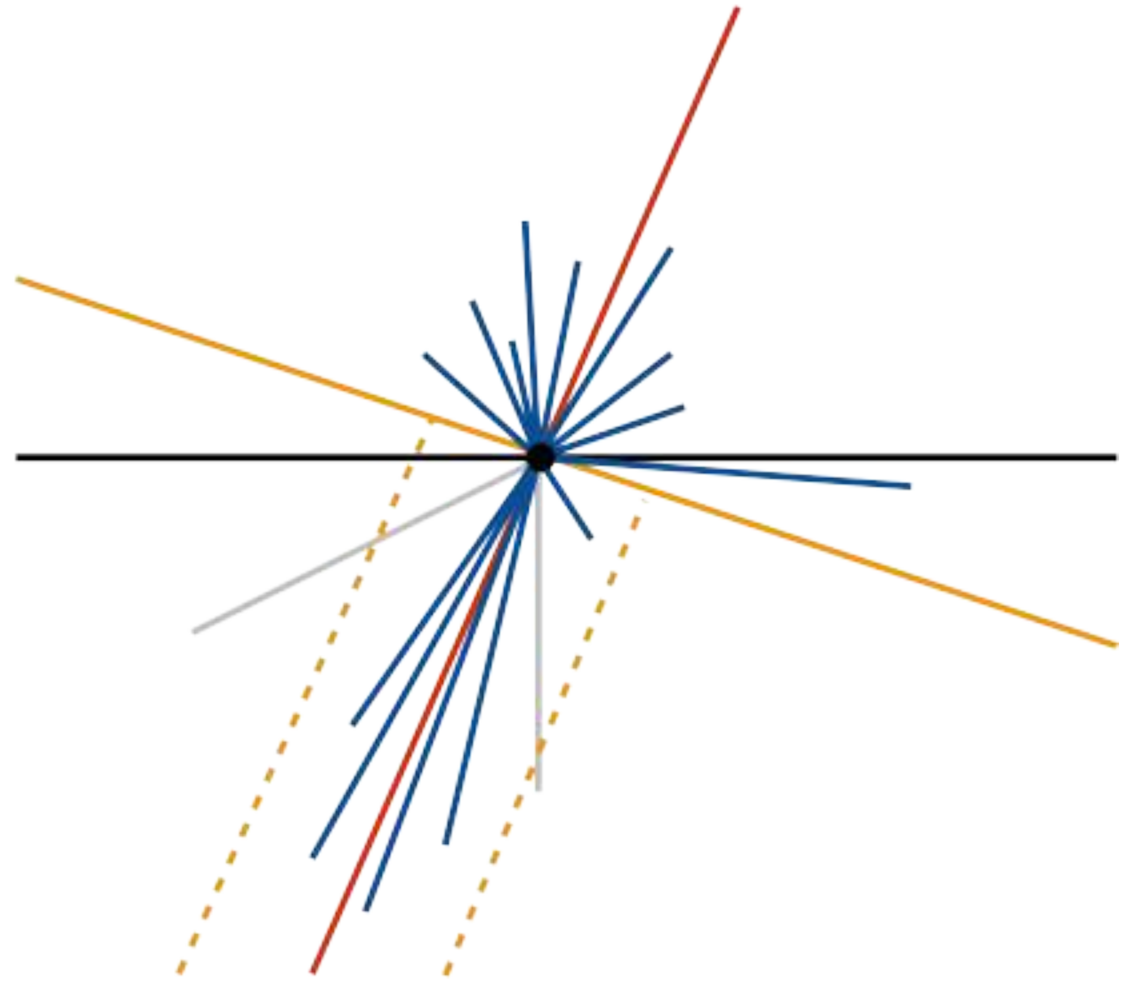
$$\frac{p_{i_n} \cdot p_{j_n}}{p_{i_n} \cdot q_n \, p_{j_n} \cdot q_n} - \frac{T \cdot p_{j_n}}{T \cdot q_n} \frac{1}{p_{j_n} \cdot q_n} + \frac{T \cdot p_{i_n}}{T \cdot q_n} \frac{1}{p_{i_n} \cdot q_n}$$

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.

[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]

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

$\alpha_s L \sim 1$ LL NLL NNLL

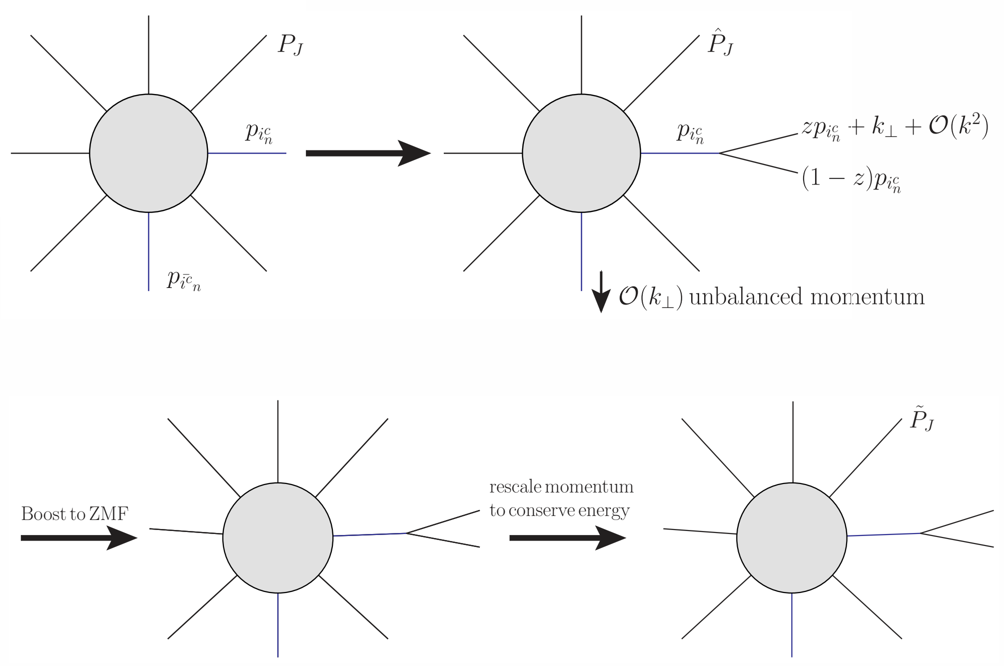
Accuracy of Parton Showers

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ

universität wien

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

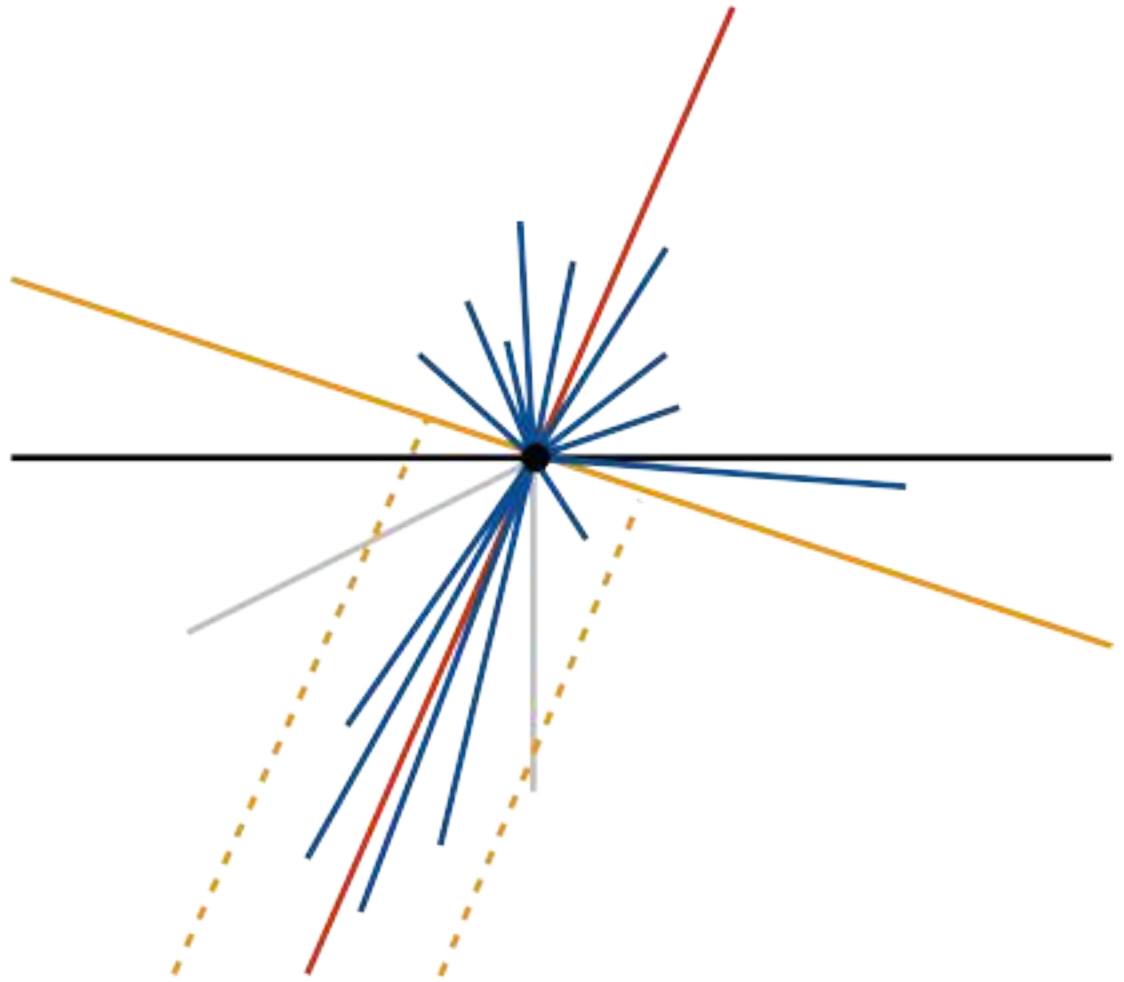
$$\frac{p_{i_n}\cdot p_{j_n}}{p_{i_n}\cdot q_n\; p_{j_n}\cdot q_n} - \frac{T\cdot p_{j_n}}{T\cdot q_n}\frac{1}{p_{j_n}\cdot q_n} + \frac{T\cdot p_{i_n}}{T\cdot q_n}\frac{1}{p_{i_n}\cdot q_n}$$



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: $\alpha_s N^2 \sim 1$

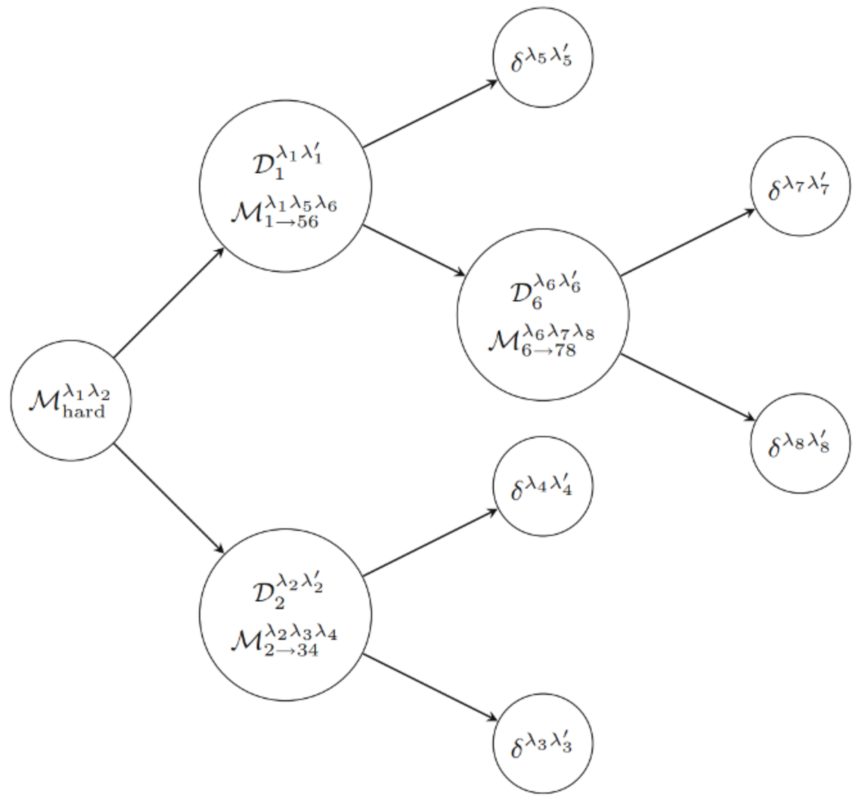
$$H(\alpha_s)\times\exp\left(Lg_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots\right)$$

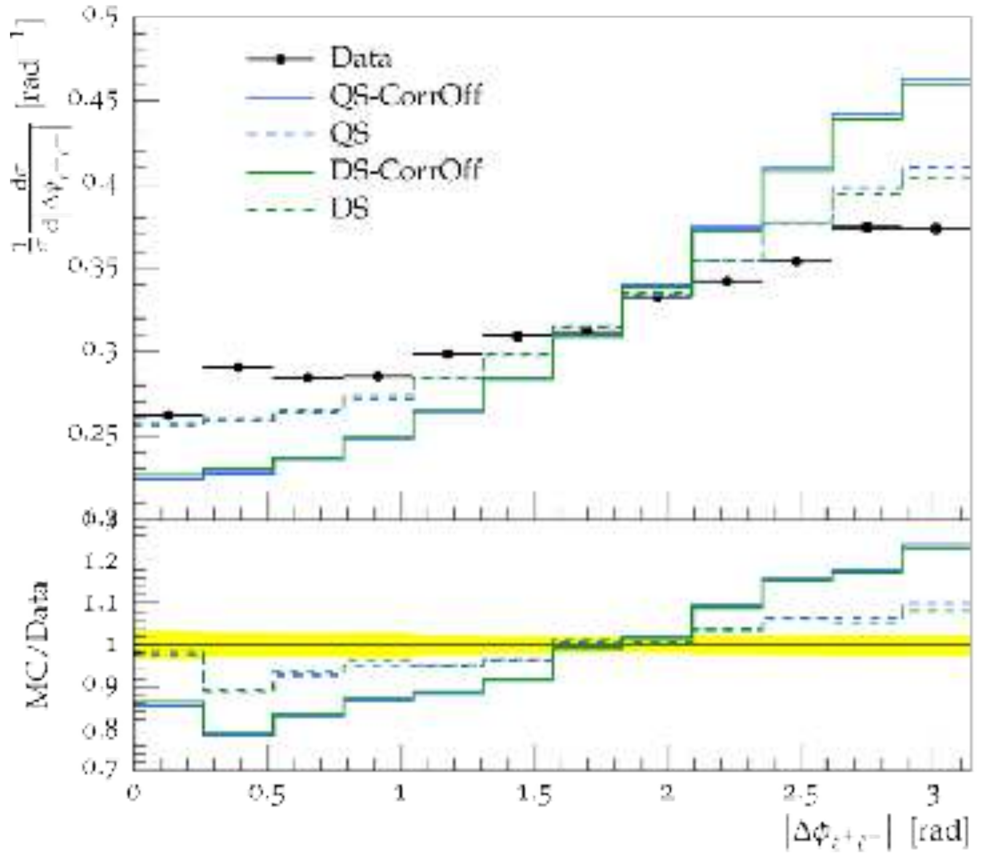
$\alpha_s L \sim 1$ LL NLL NNLL

[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]

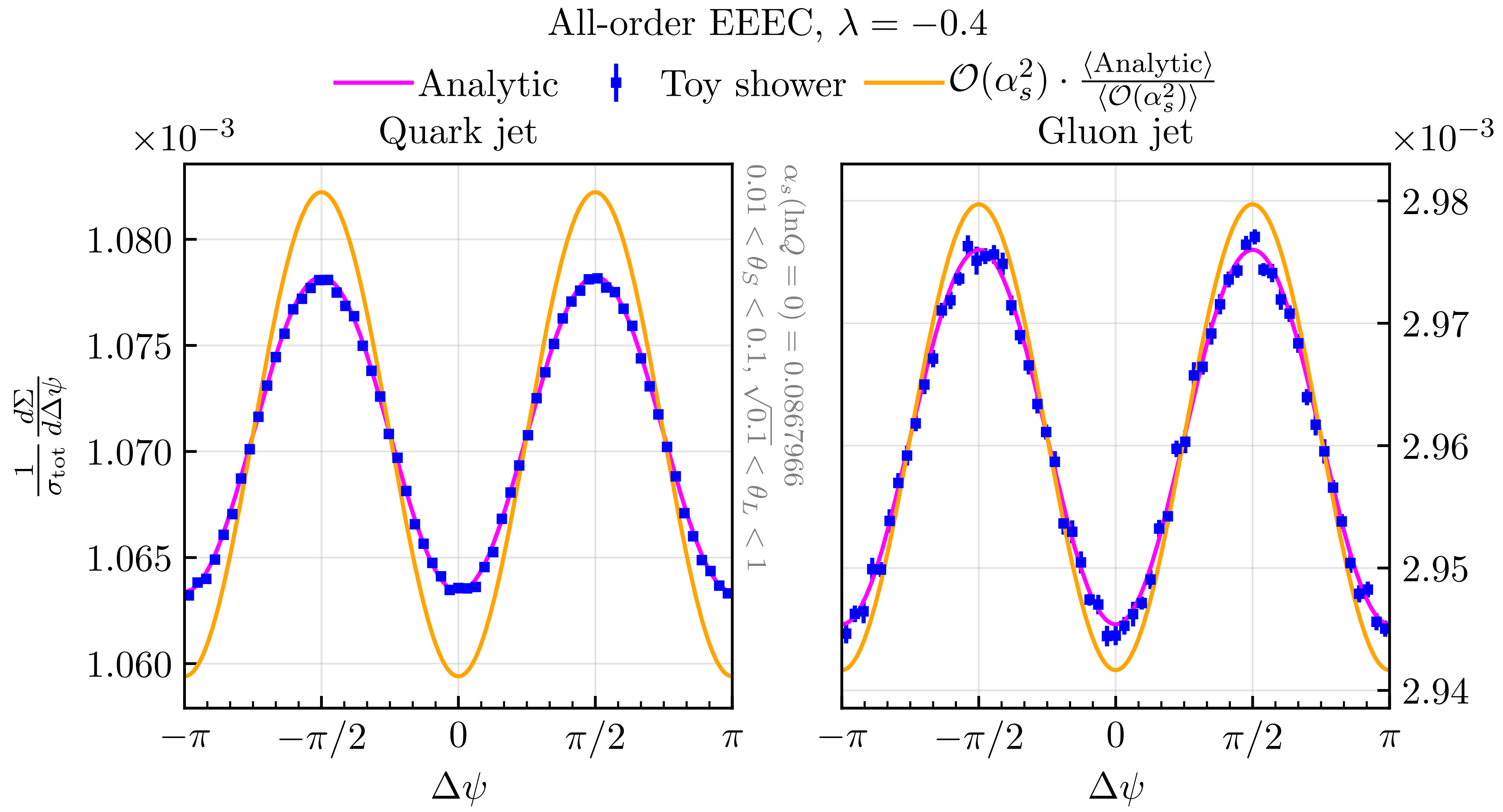
Spin & Colour Correlations Matter

Spin correlations building on Collins-Knowles algorithm





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

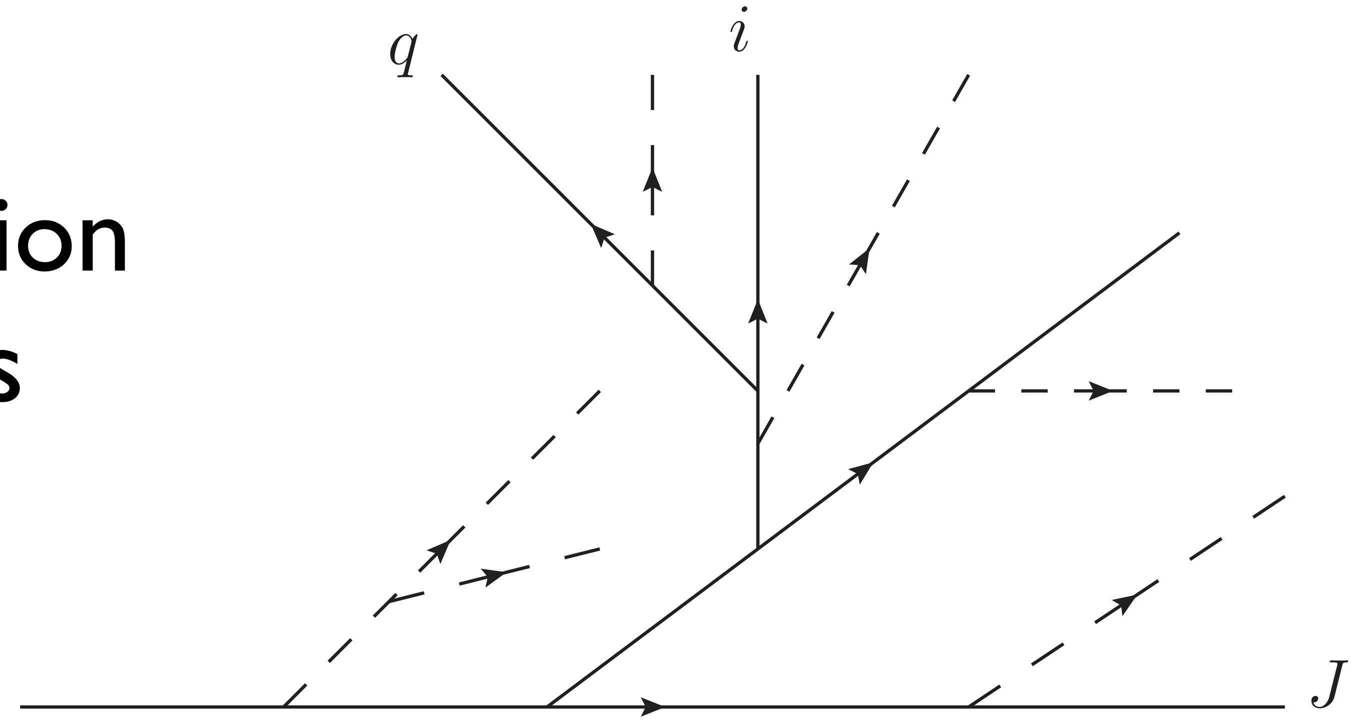


[Karlberg, Salam, Scyboz, Verheyen — Eur.Phys.J.C 81 (2021) 8, 681]

Dynamic colour factors in dipole showers

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

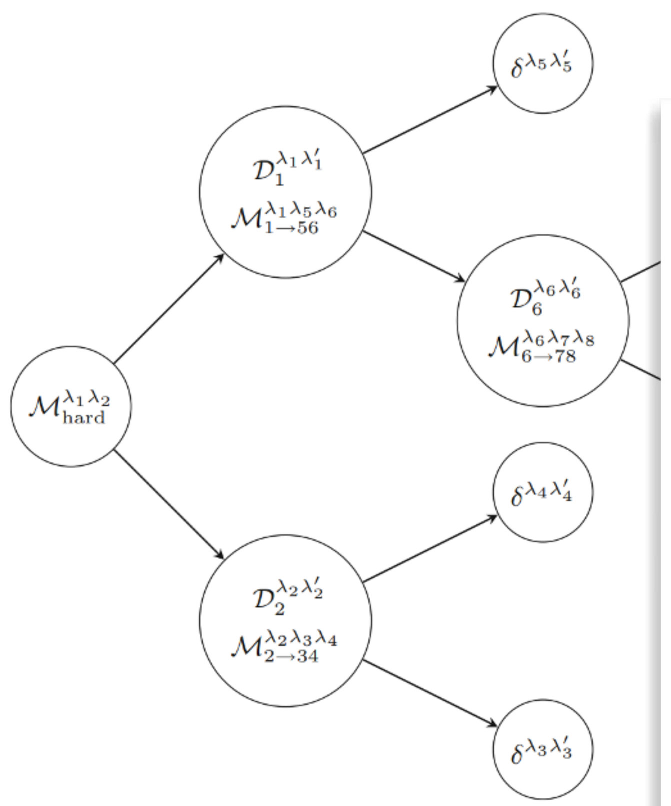
Track angular extent of evolution to reproduce colour factors as dictated by coherence.

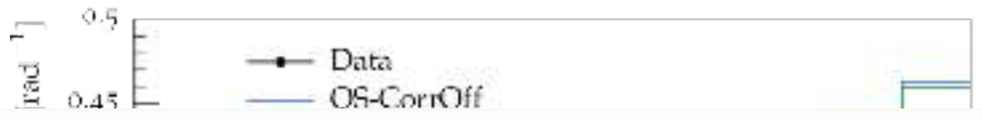


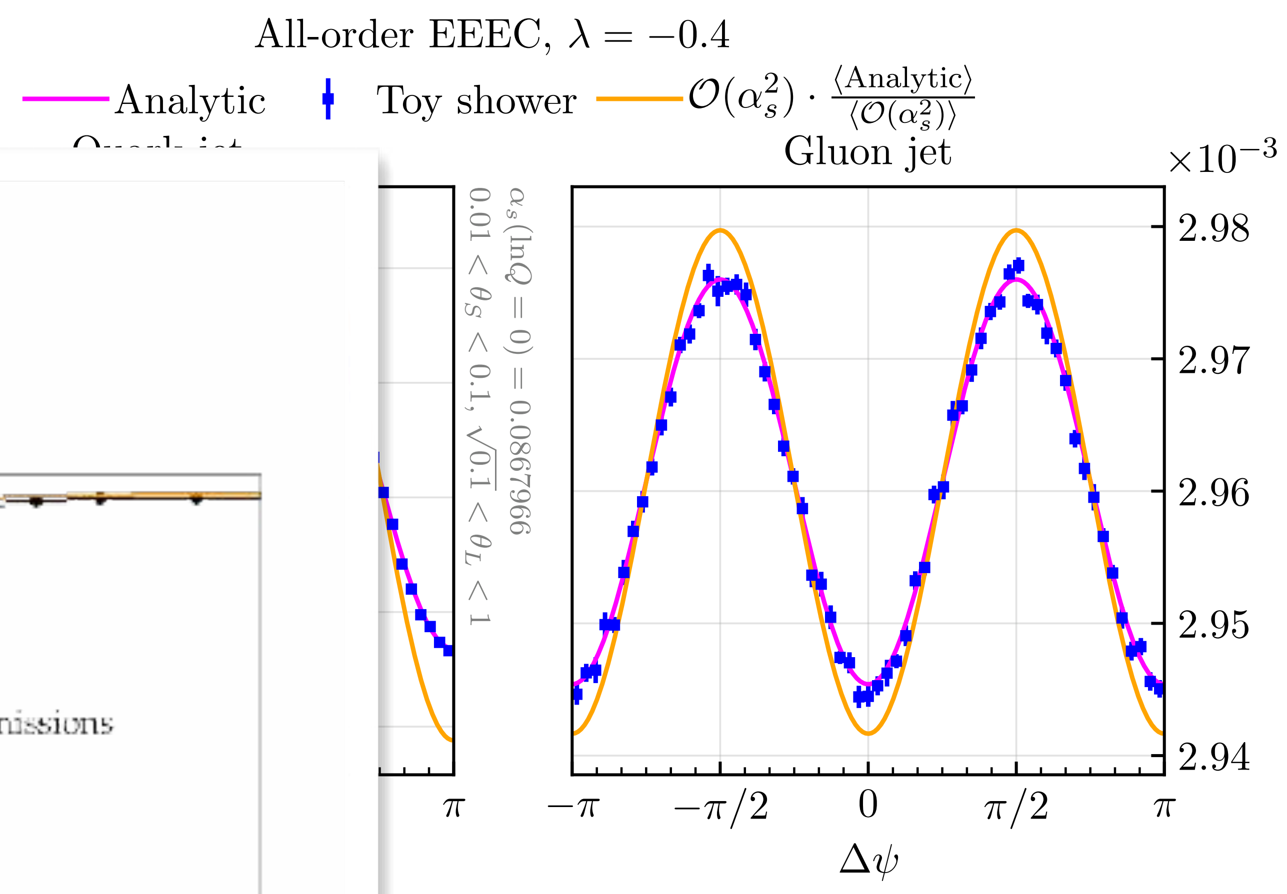
[Forshaw, Holguin, Plätzer — EPJ C81 (2021) 4]
[Hamilton, Medves, Salam, Scyboz, Soyez — JHEP 03 (2021) 041]

Spin & Colour Correlations Matter

Spin correlations building on Collins-Knowles algorithm





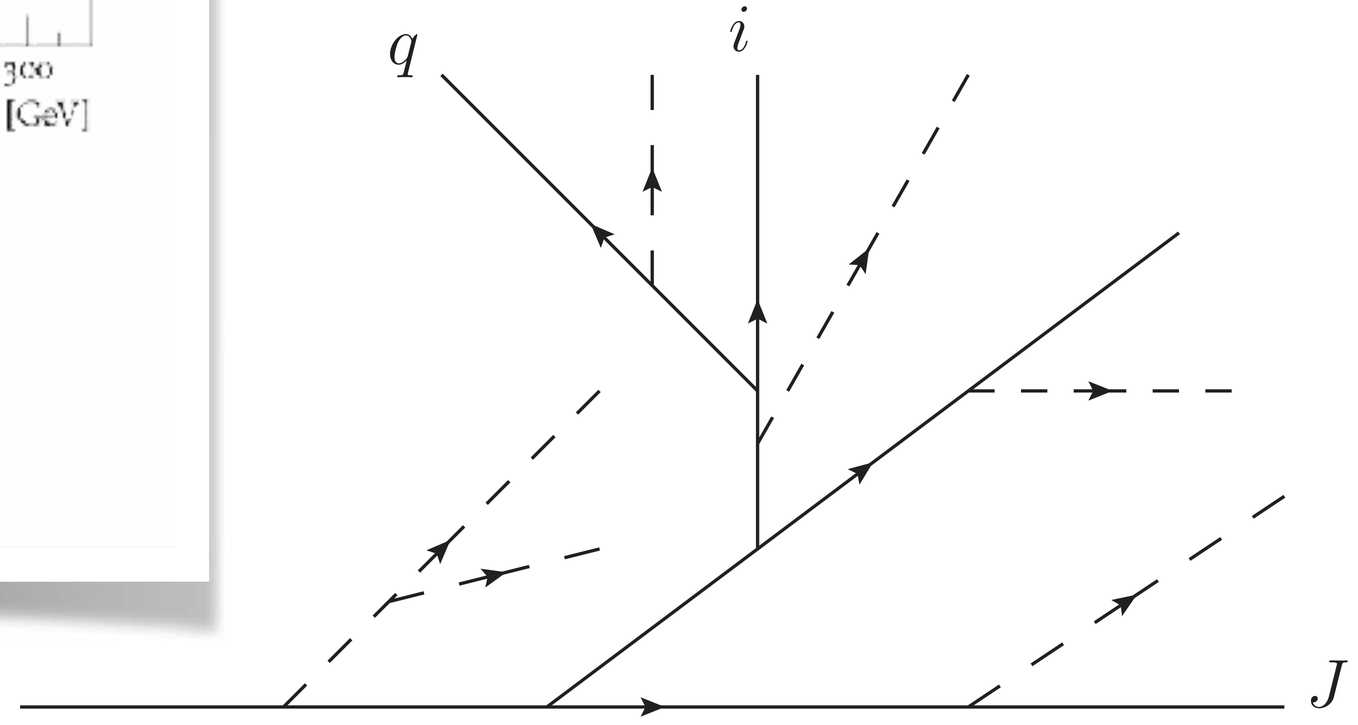


yen — Eur.Phys.J.C 81 (2021) 8, 681]

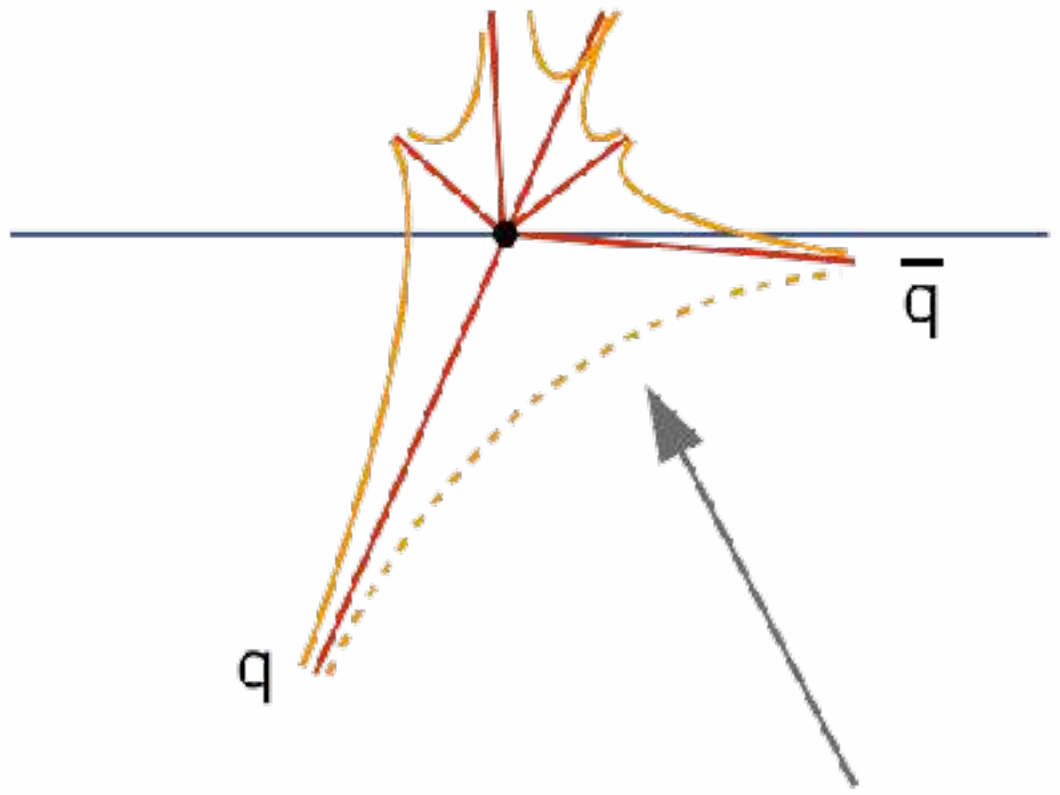
Dynamic colour f

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

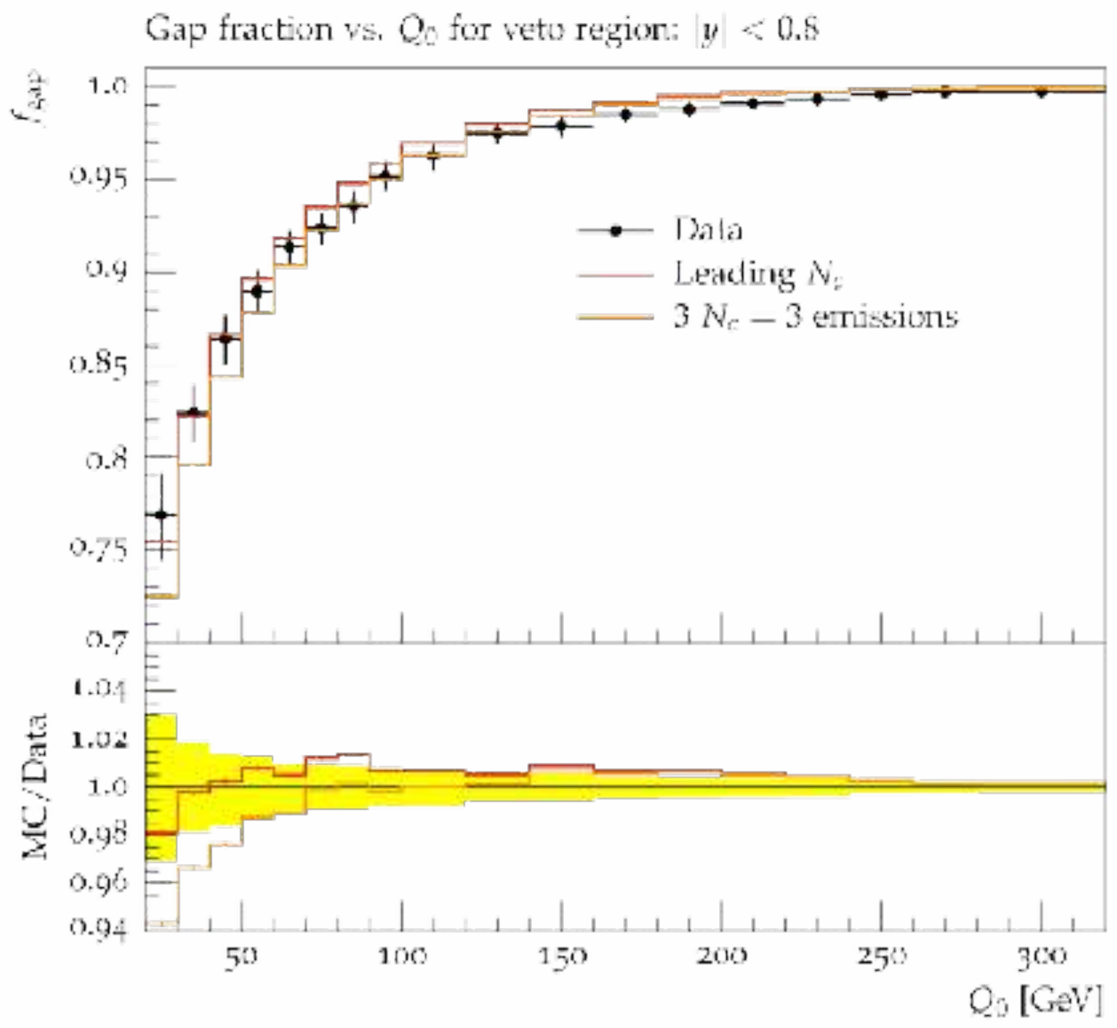
$$+ \Big(\frac{C_A}{2}$$



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]

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

Improving Shower Accuracy

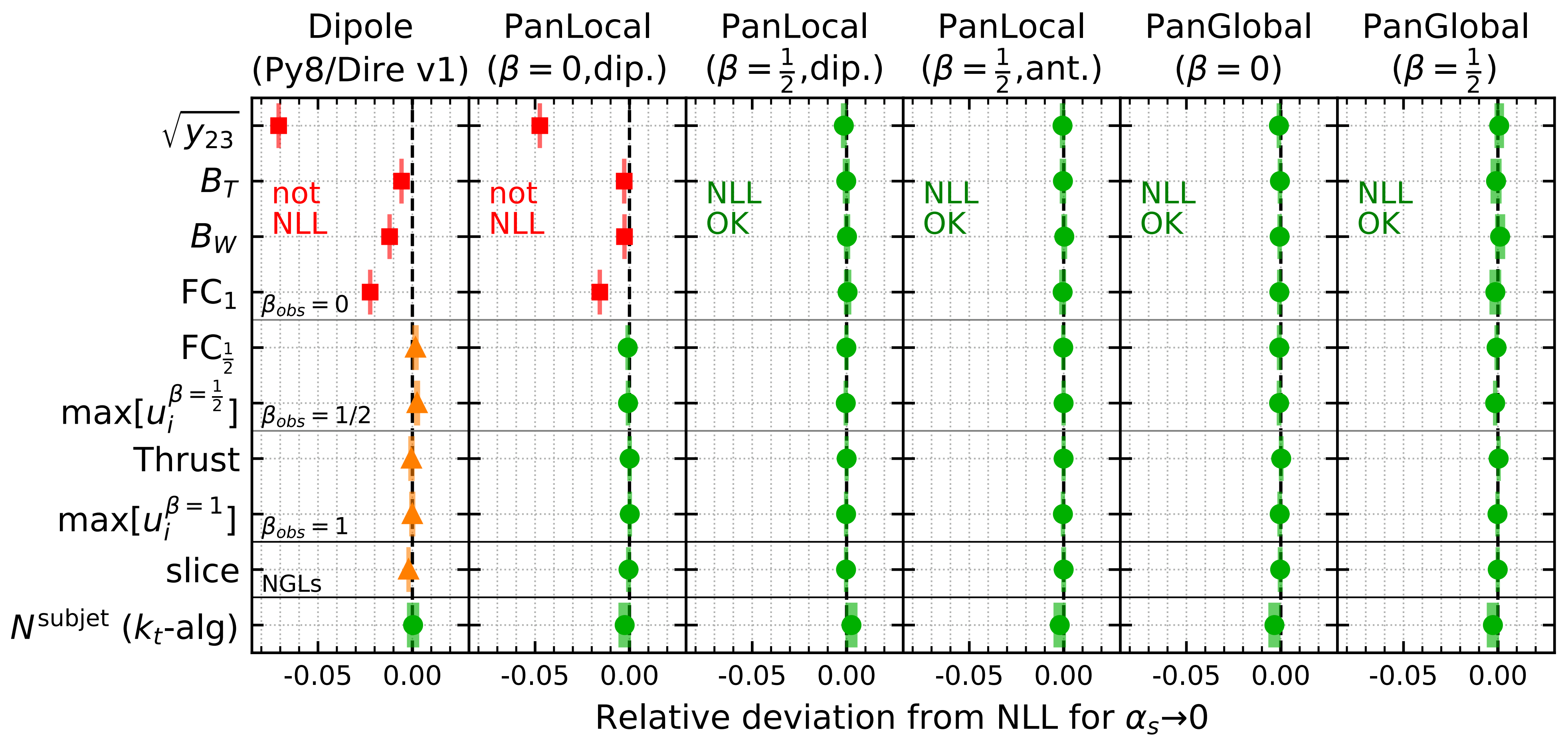
UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ
universität wien

Demonstrate NLL accurate evolution:

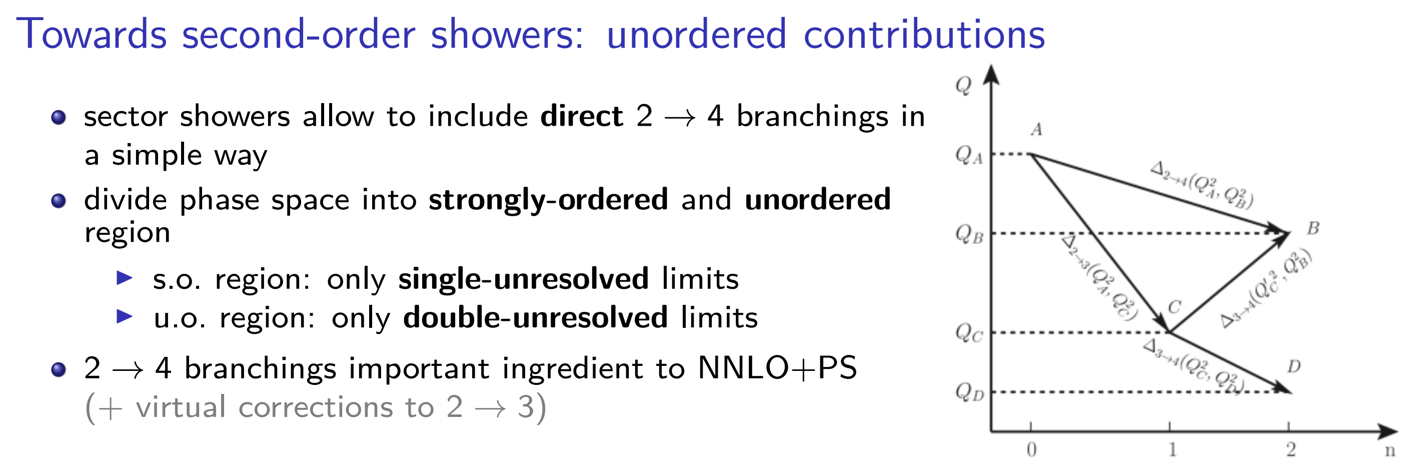
- PanScales — numerical
  [Dasgupta, Monni, Salam, Soyez + ….]
- Deductor — numerical/analytical
  [Nagy, Soper]
- Forshaw/Holguin/Plätzer — analytical
  [aim at improving Herwig 7 dipole shower]

} Based on amplitude evolution.

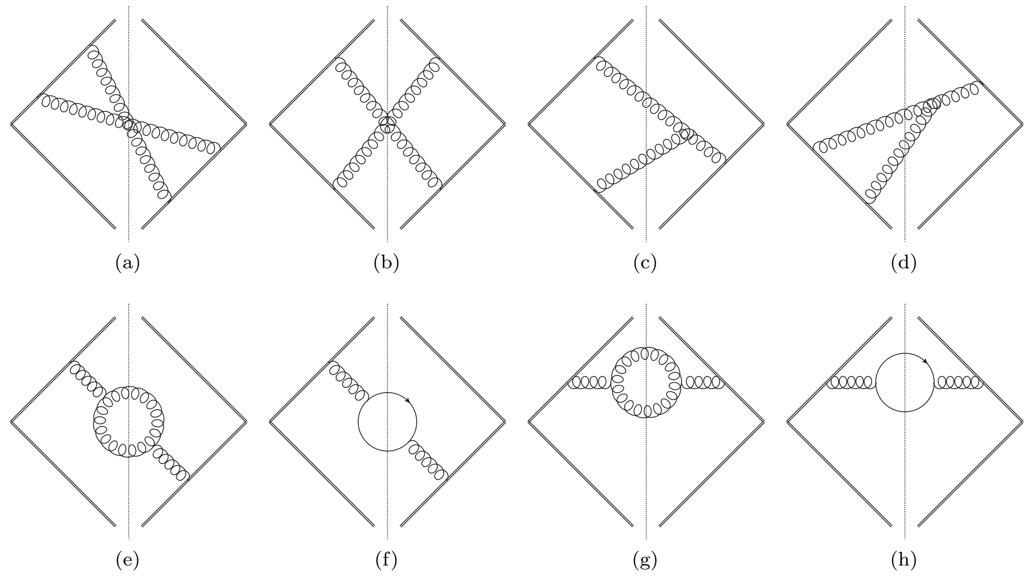
[PanScales]



Provide higher order building blocks beyond single emissions

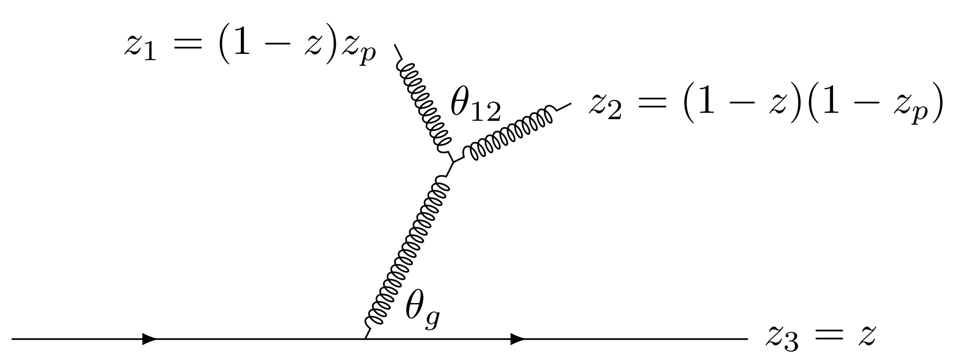


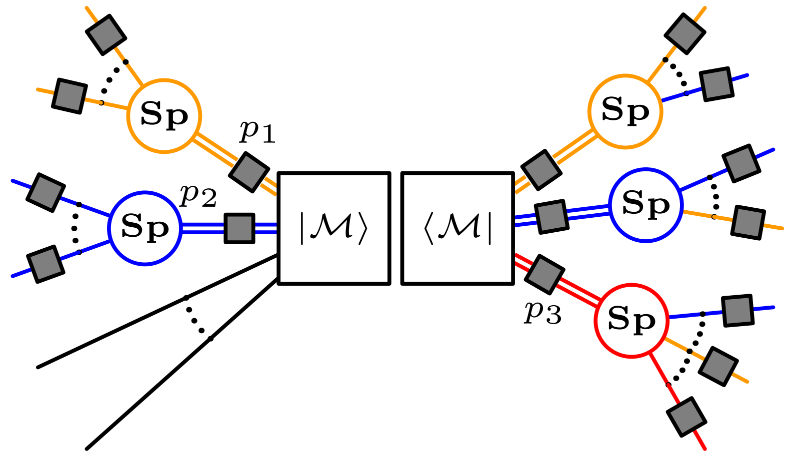
[C. Preuss for Vincia — PSR 21]



[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]

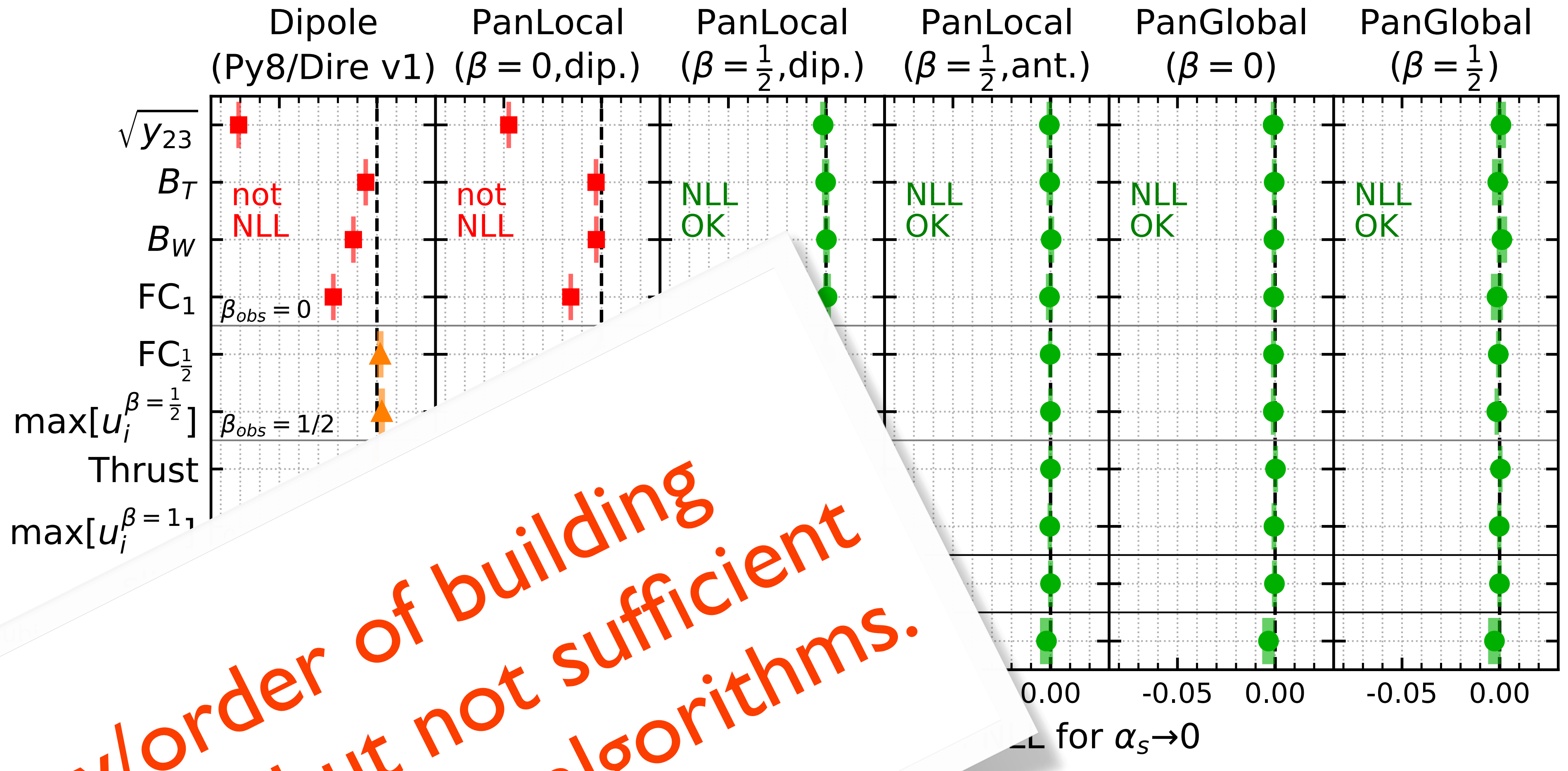
Improving Shower Accuracy

[PanScales]

Demonstrate NLL accurate evolution:

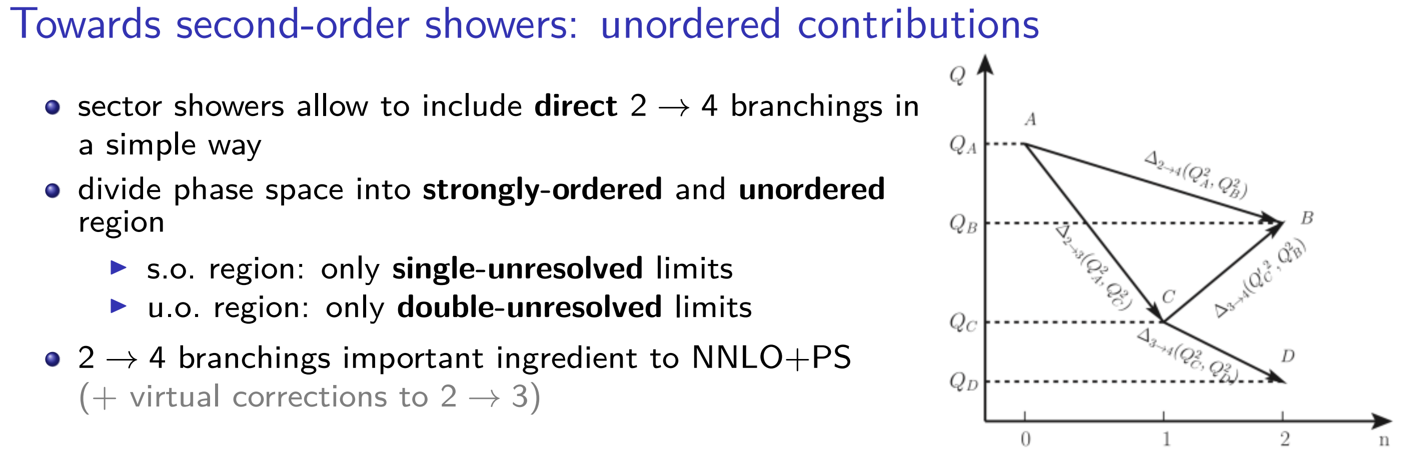
- PanScales — numerical
  [Dasgupta, Monni, Salam, Soyez + ….]
- Deductor — numerical/analytical
  [Nagy, Soper]
- Forshaw/Holguin/Plätzer — analytical
  [aim at improving Herwig 7 dipole shower]

} Based on amplitude evolution.

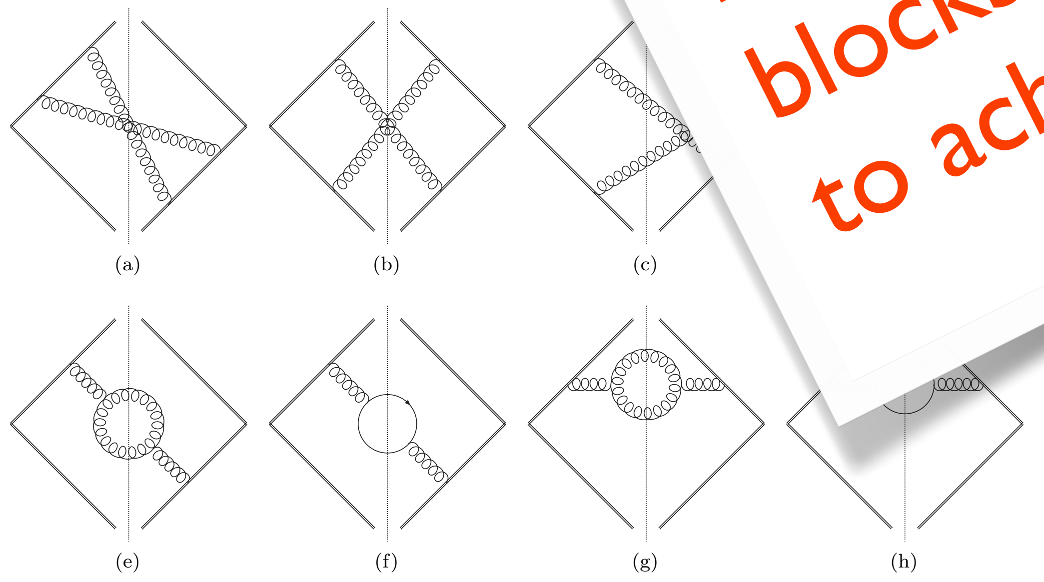


Higher accuracy/order of building blocks is necessary but not sufficient to achieve more accurate algorithms.

Provide higher order building blocks beyond singl

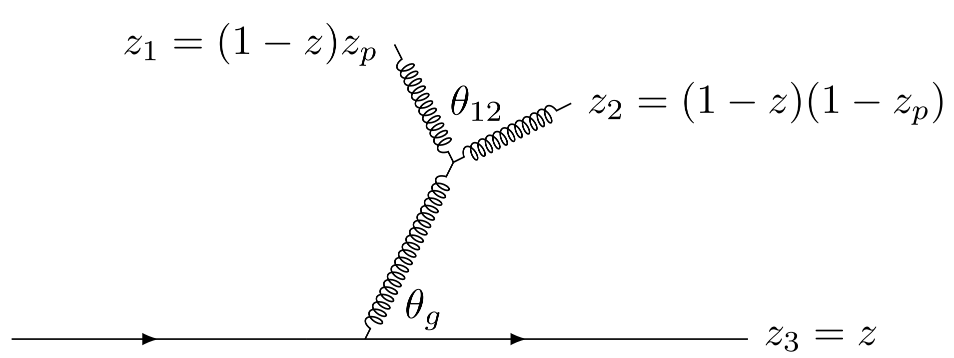


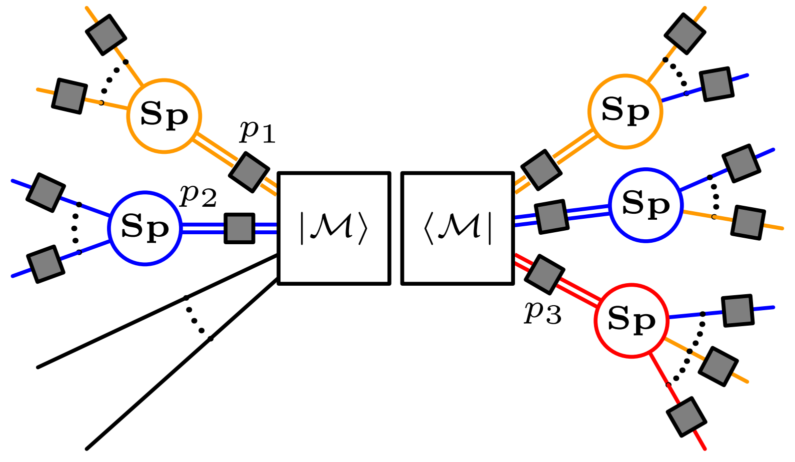
[C. Preuss for Vincia — PSR 21]



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

…ia — JHEP 06 (2021) 007]
…ner, Plätzer, Simpson — arXiv:2112.14454]





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

Accuracy for massive event shapes

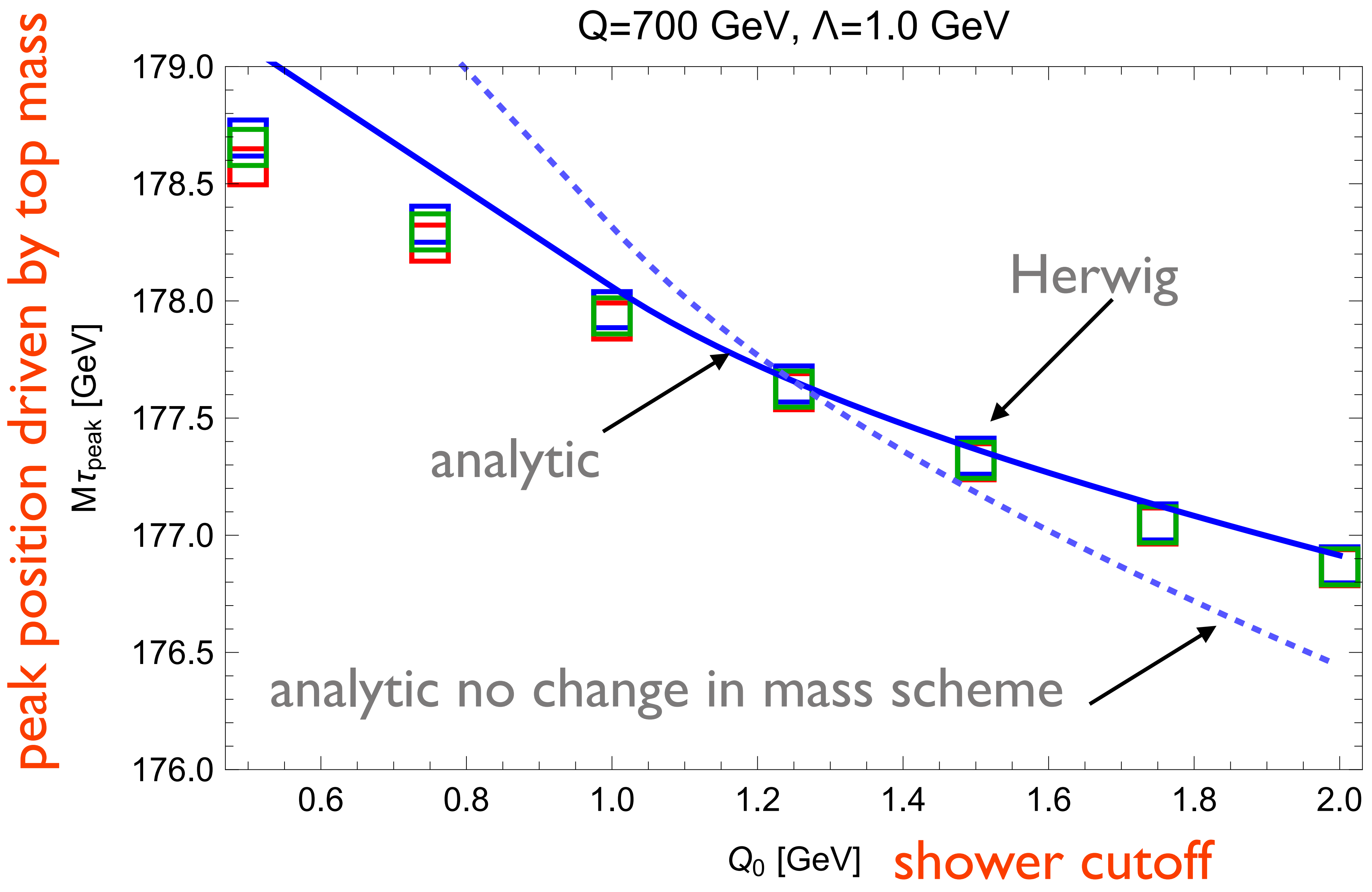
UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ
universität wien

Coherent branching jet mass distribution including mass effects

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

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

[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

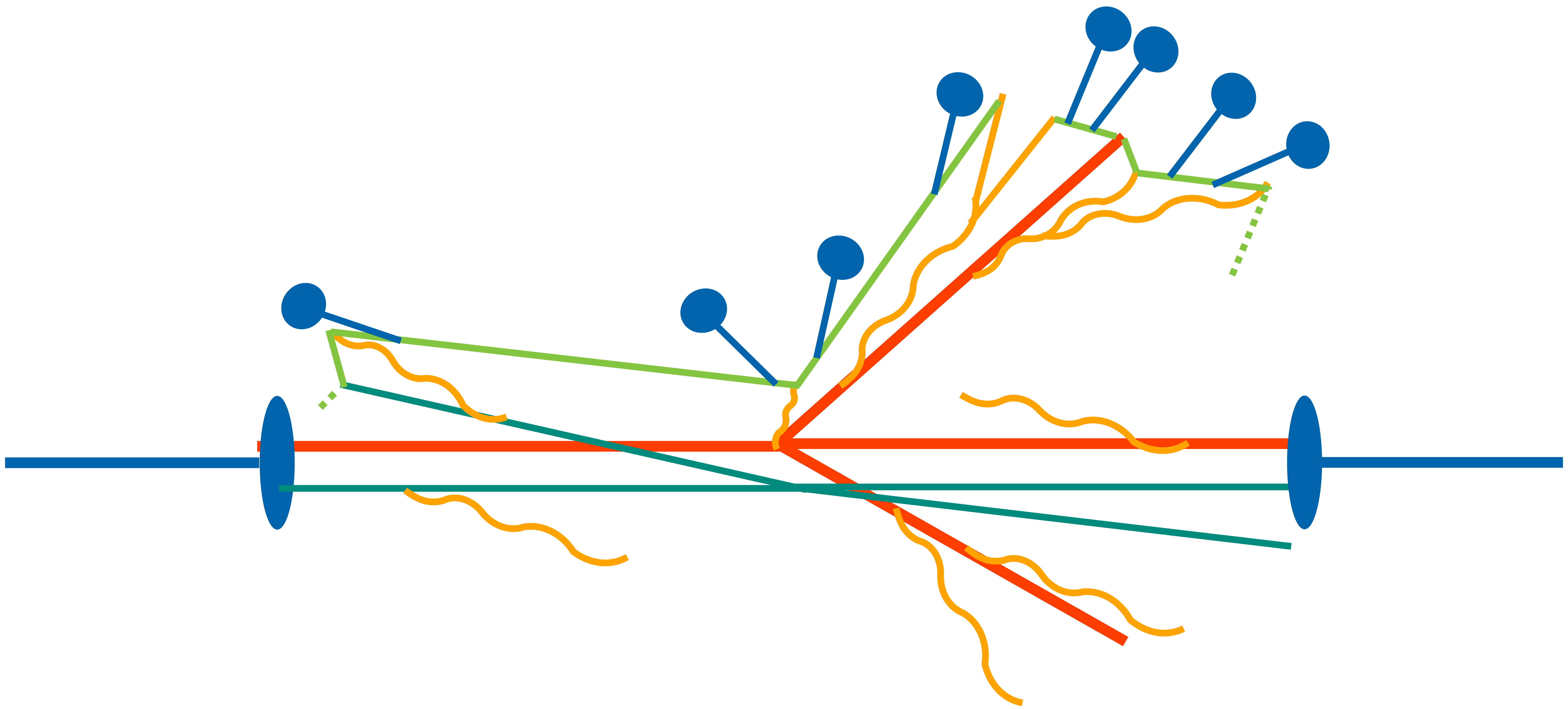
$$m_t^{\rm MC} = m_t^{\rm pole} + \Delta_m^{\rm pert} + \Delta_m^{\rm non\text{-}pert} + \Delta_m^{\rm MC}$$

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

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

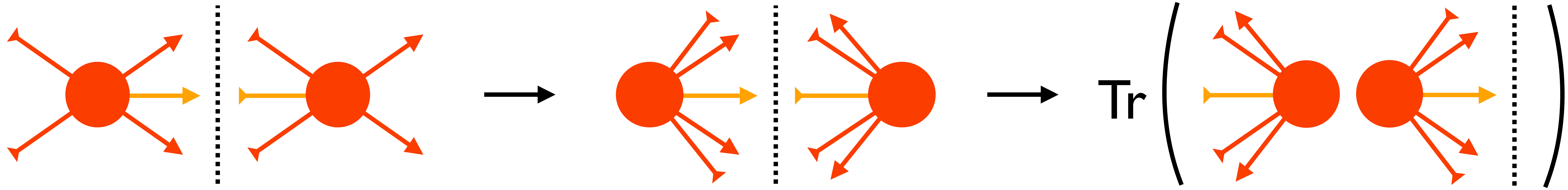
See Silvia's talk for related discussions.

Complexity factorized?



$$\mathrm{d}\sigma \sim \mathrm{Tr}\left[\mathbf{PS}(Q \to \mu)\mathrm{d}\mathbf{H}(Q)\mathbf{PS}^\dagger(Q \to \mu)\mathbf{Had}(\mu \to \Lambda)\right]$$

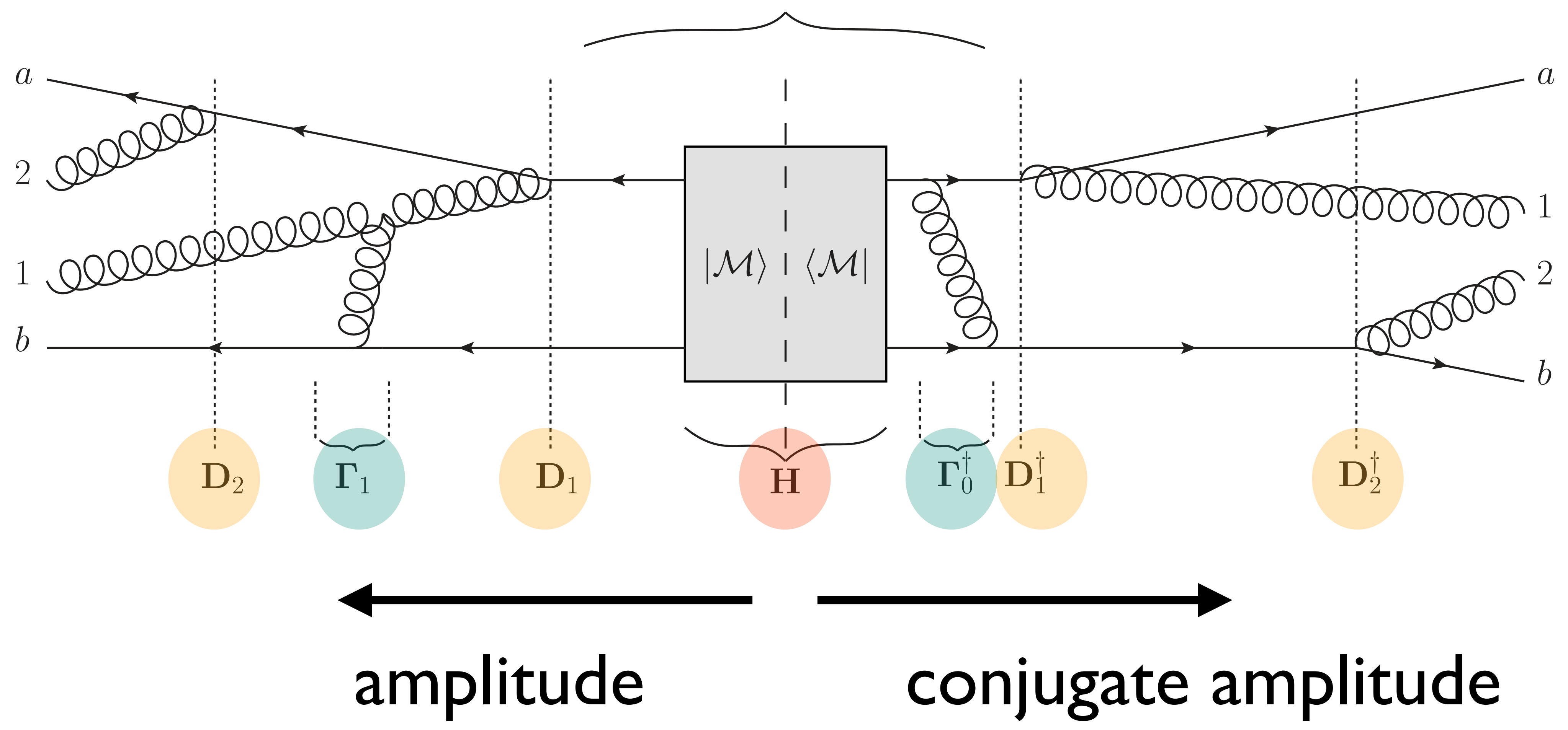
Amplitude evolution



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

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

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



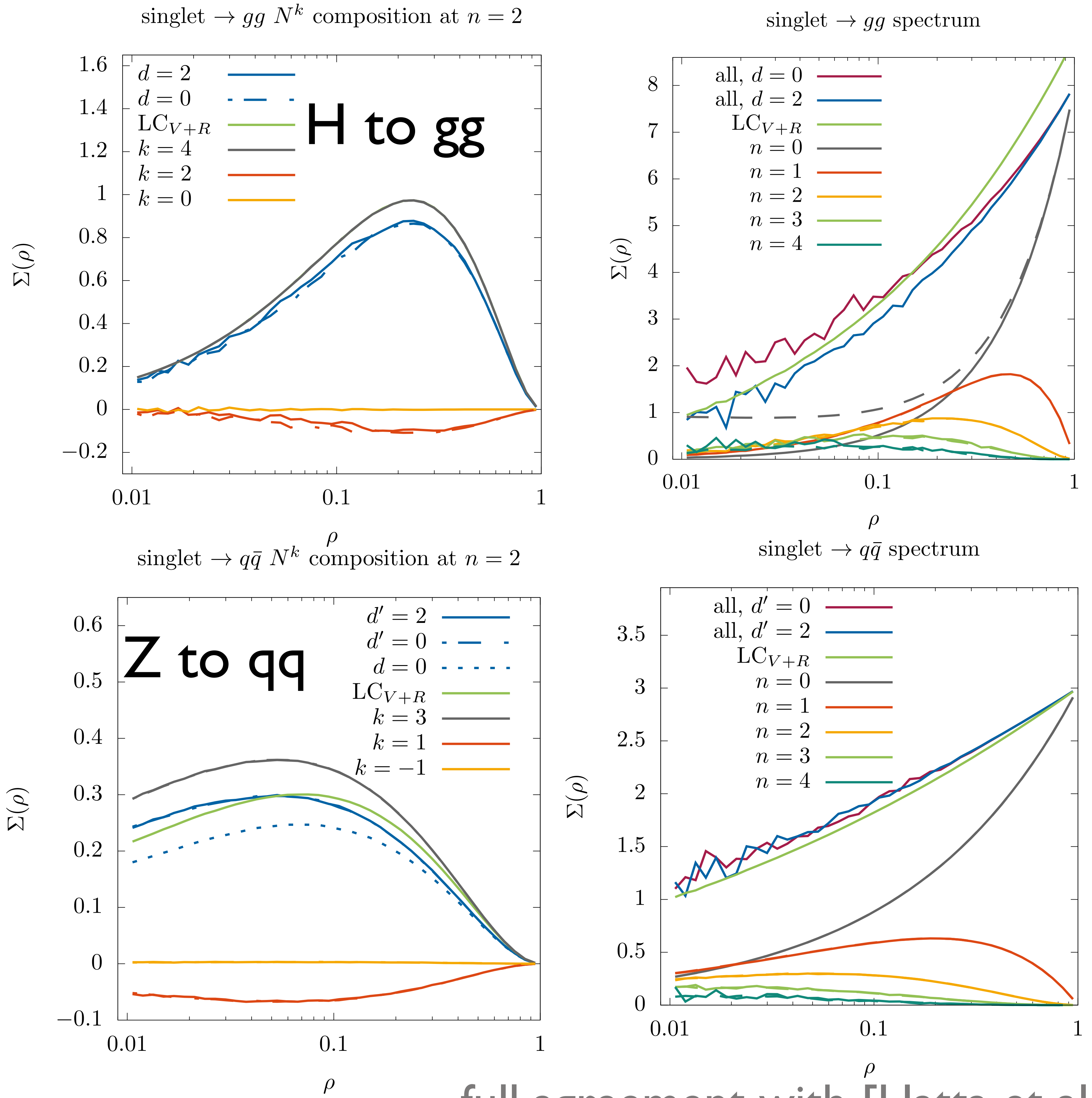
[Angeles, De Angelis, Forshaw, Plätzer, Seymour – JHEP 05 (2018) 044]
[Forshaw, Holguin, Plätzer – JHEP 1908 (2019) 145, …]
[Nagy, Soper — JHEP 06 (2014) 097 & PRD 98 (2018) 1, …]

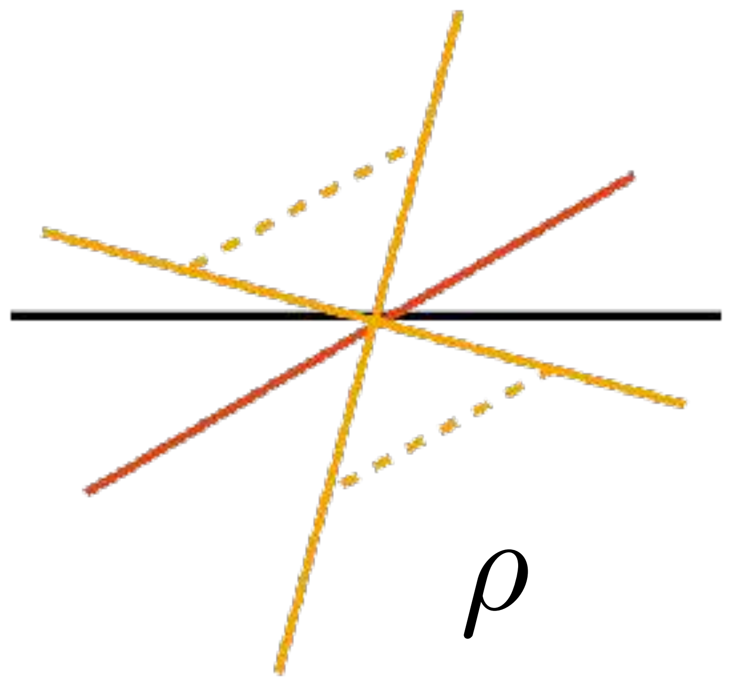
Beyond Leading Colour

CVolver library implements numerical evolution in colour space.

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

Resummation of non-global logarithms at full colour:

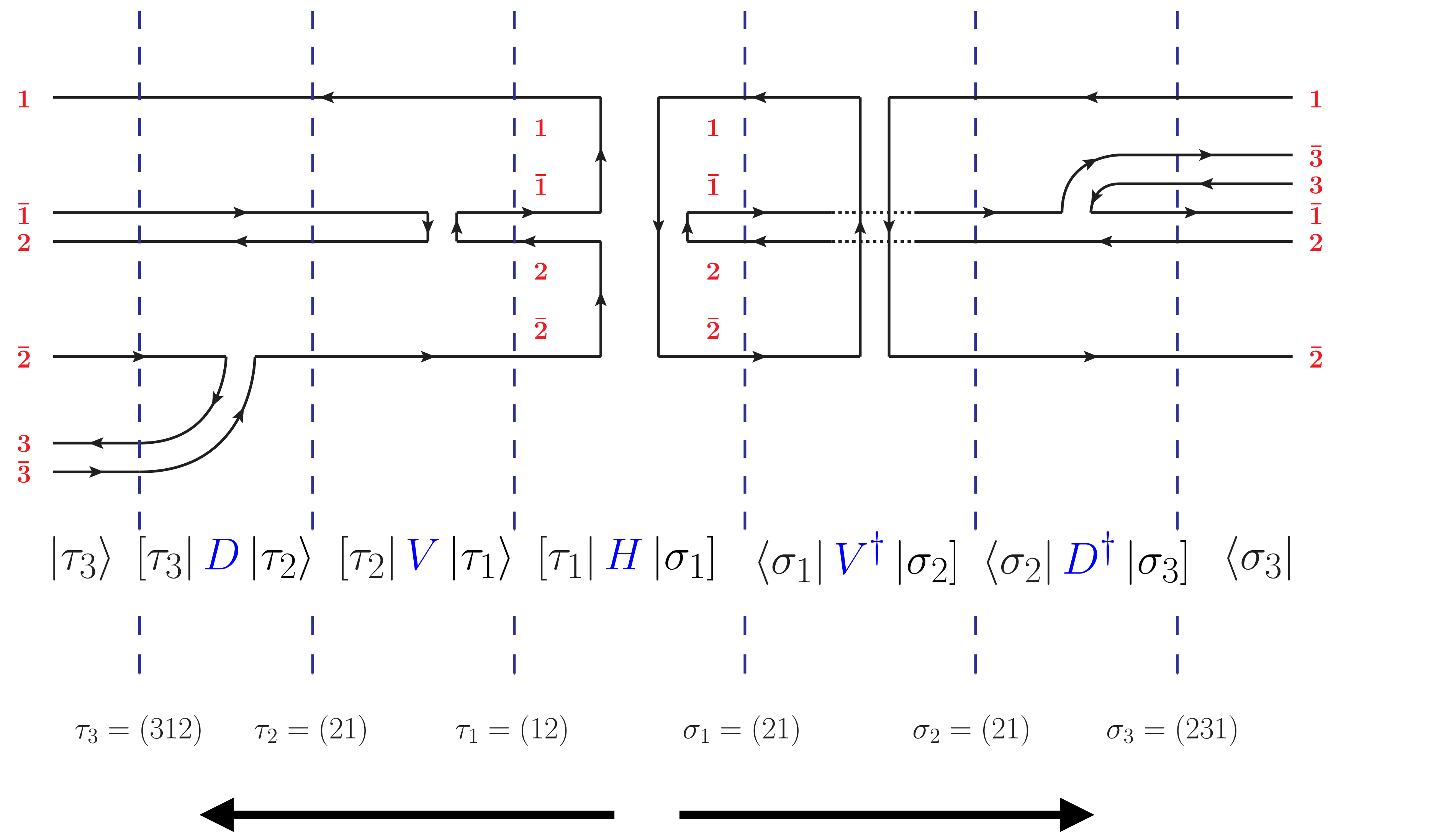




$$\Sigma(\rho) = \sum_n \int \mathrm{d}\sigma(\{p_i\}) \prod_i \theta_{\mathrm{in}}(\rho - E_i)$$

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

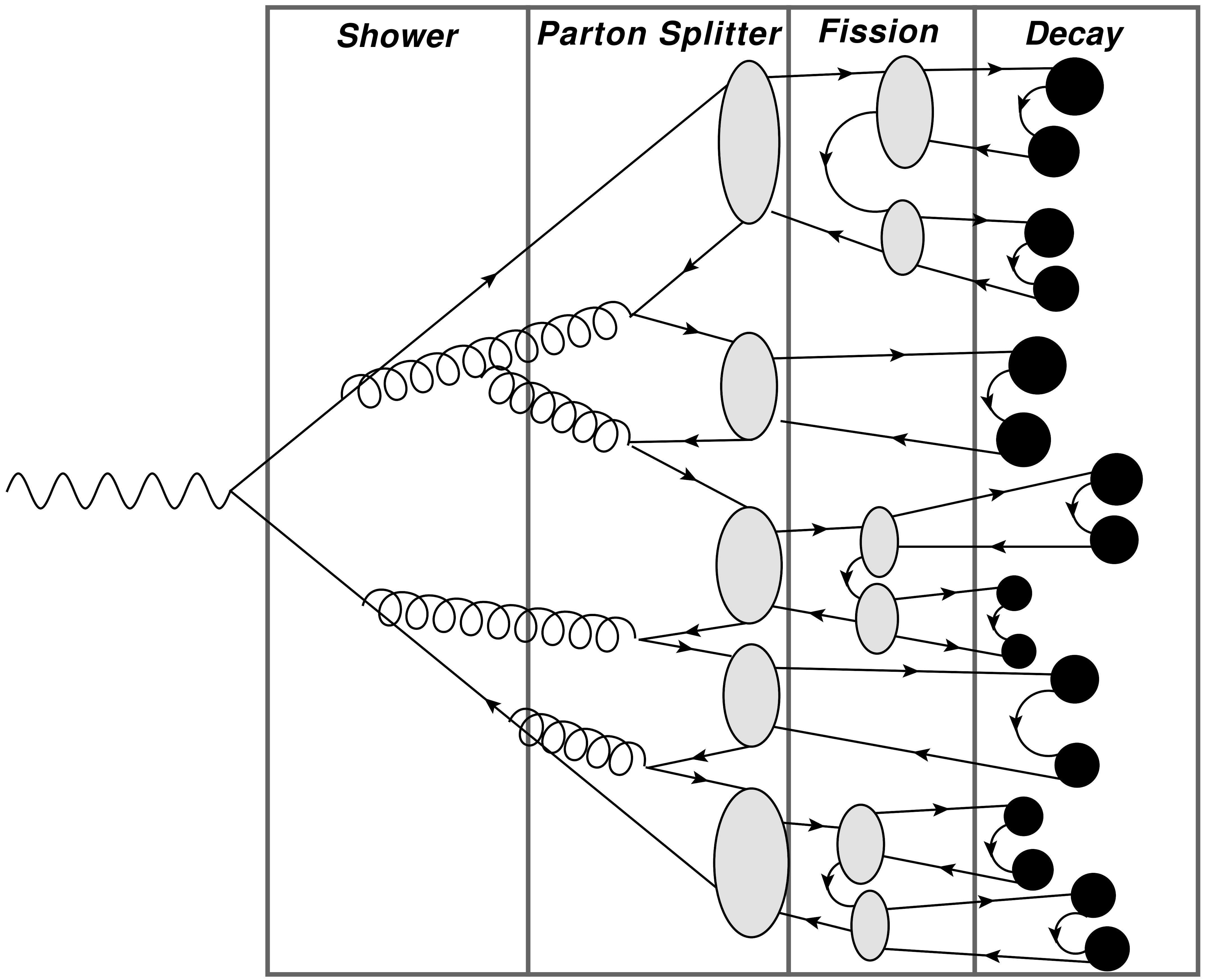
[De Angelis, Forshaw, Plätzer — PRL 126 (2021) 11]

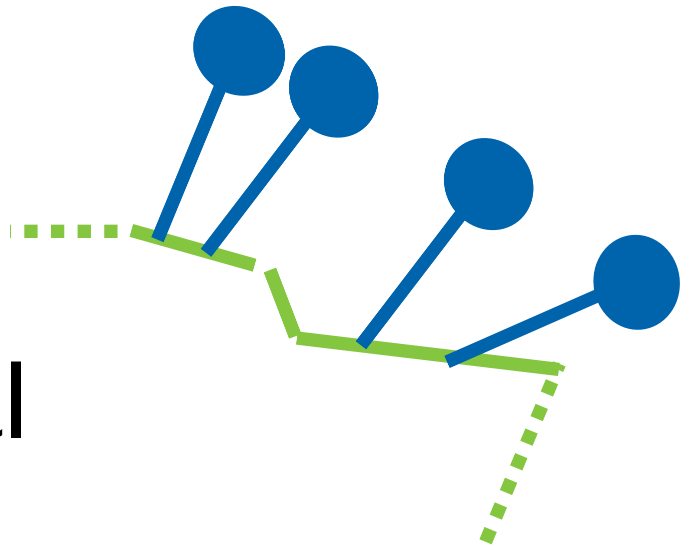


Avoid complexity which grows with colour space dimensionality:

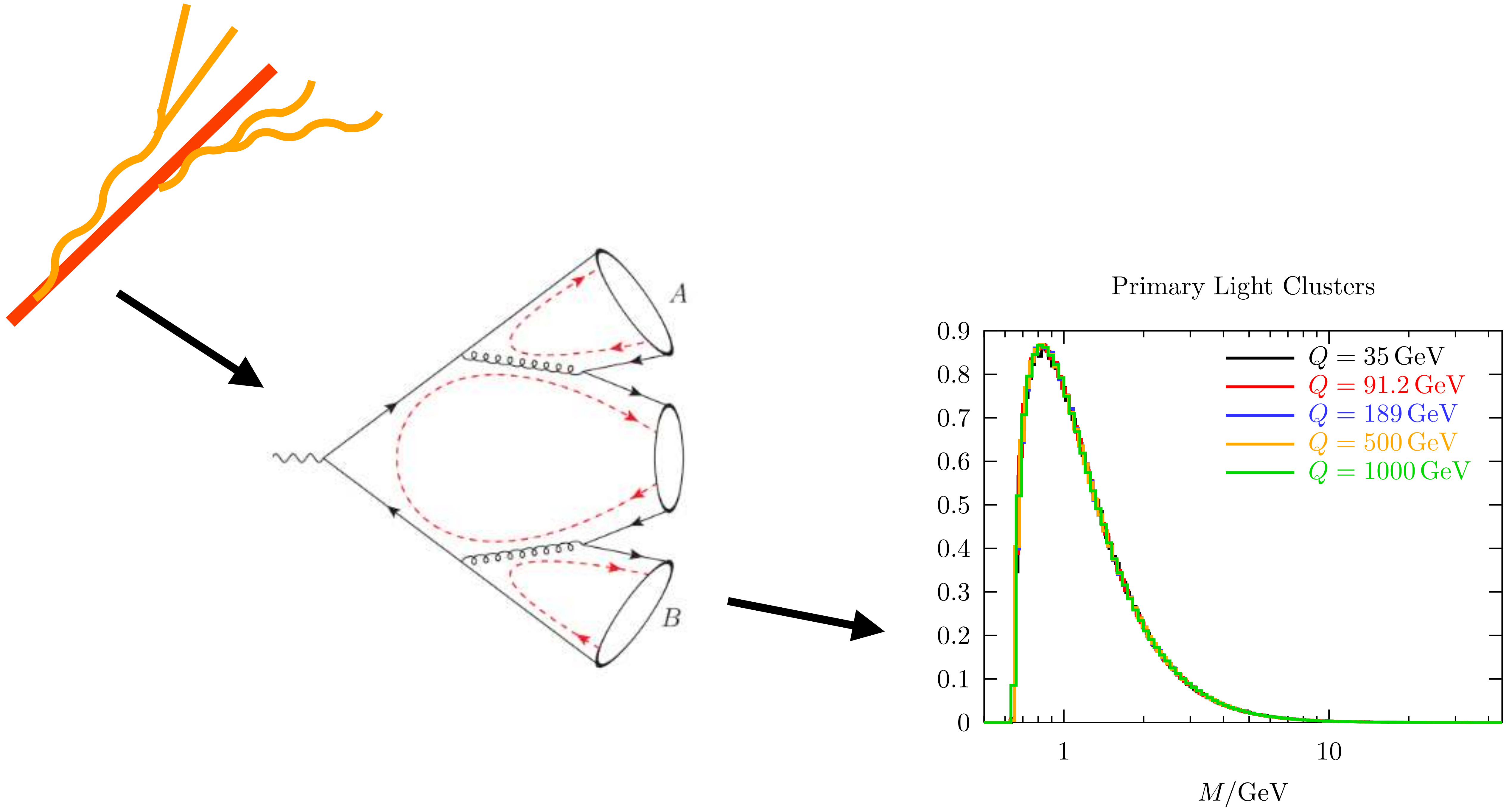
- Monte Carlo over colour flows,
- events at intermediate steps carry complex weights.

Perturbative Implications for Hadronization





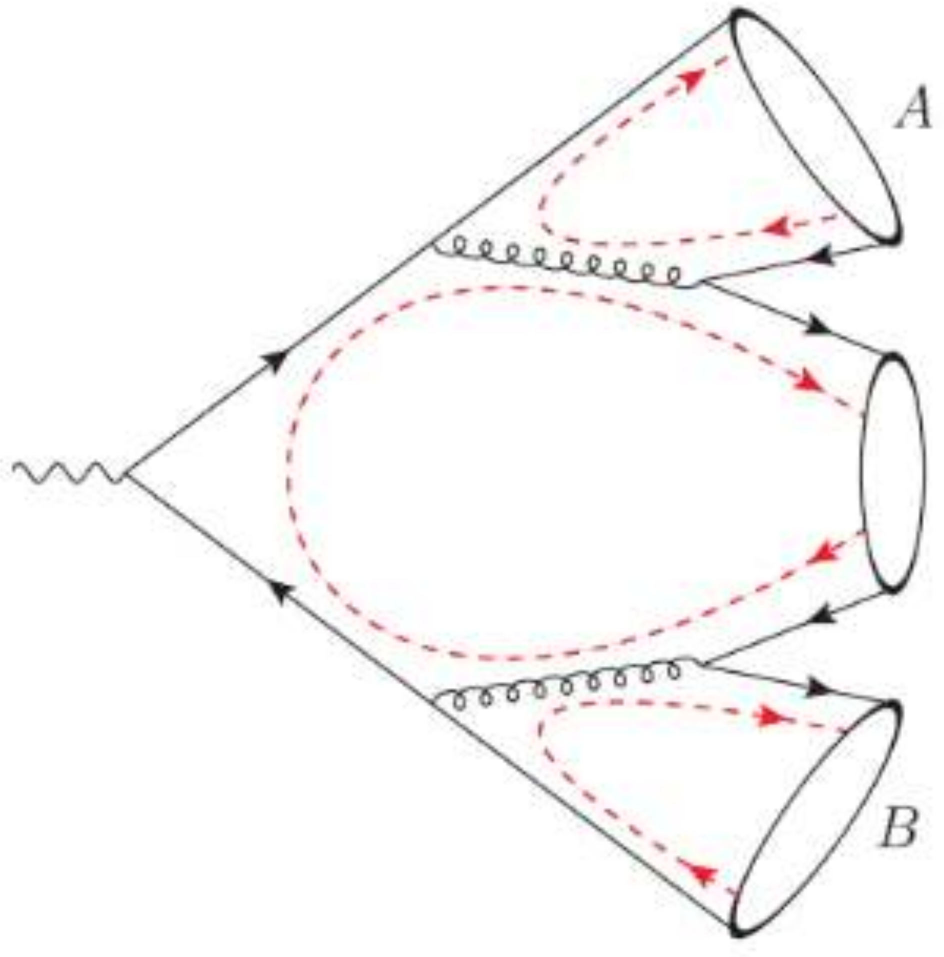
Coherent shower evolution triggers universal cluster spectrum: pre-confinement.

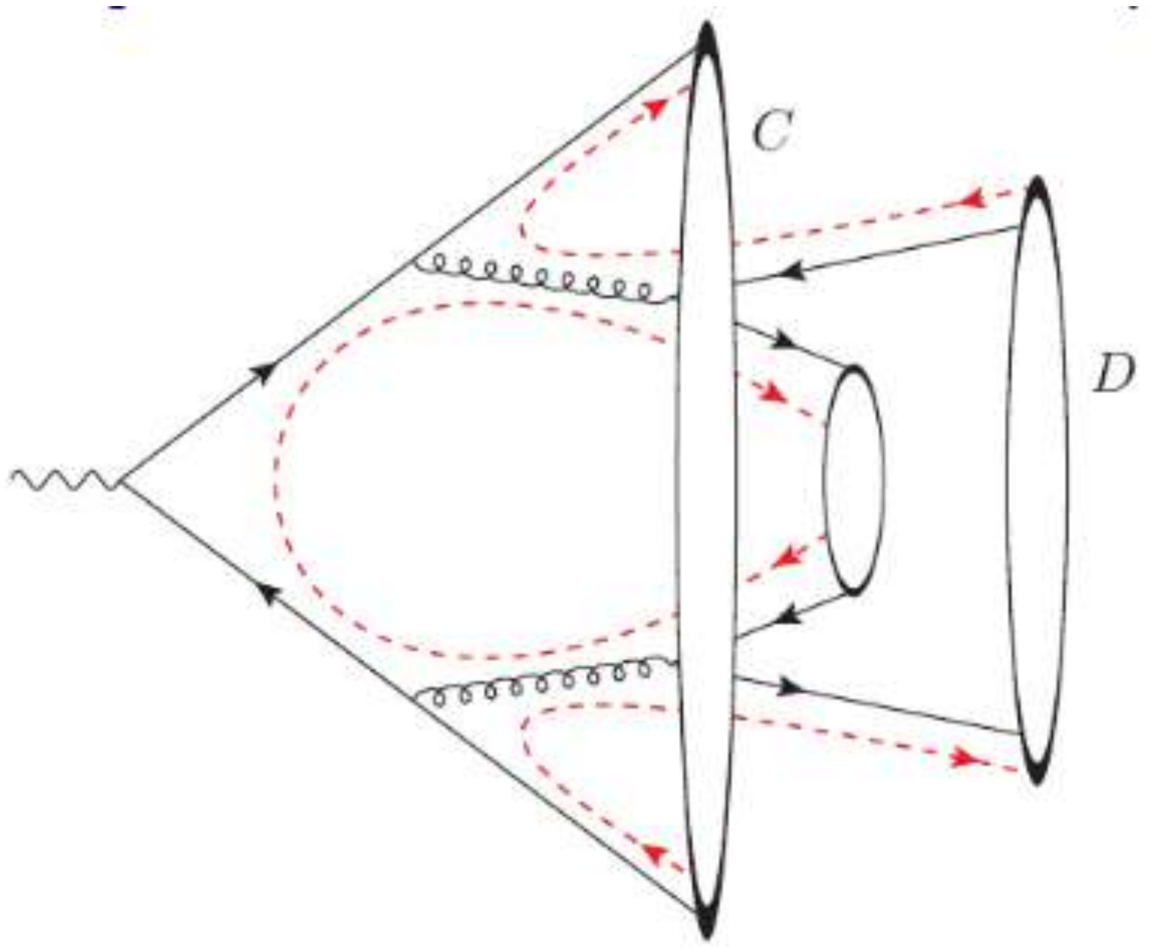


[Figure by Patrick Kirchgaesser]

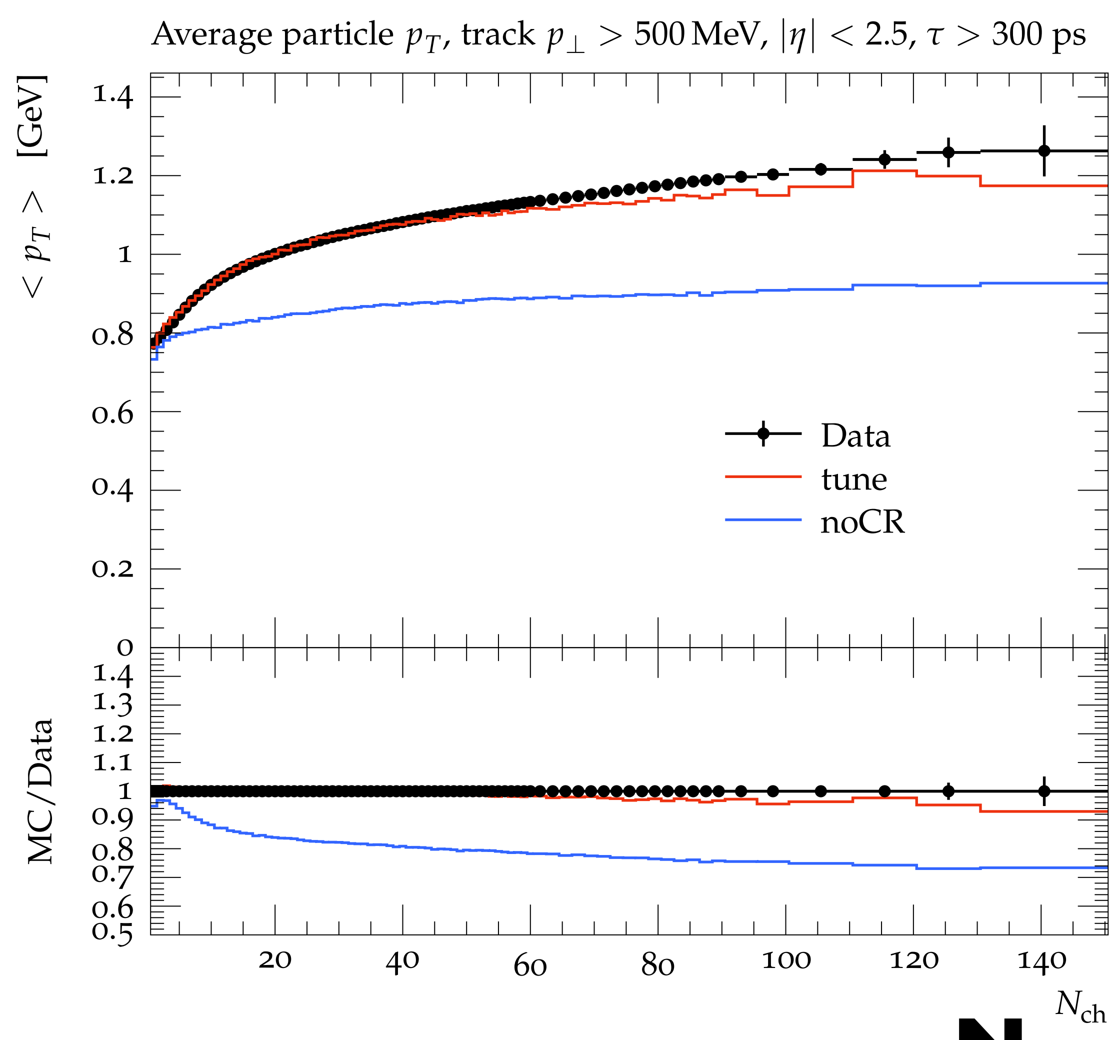
[Herwig++ 1.0 release — Gieseke et al. JHEP 02 (2004) 005]

Would subleading-N matter?

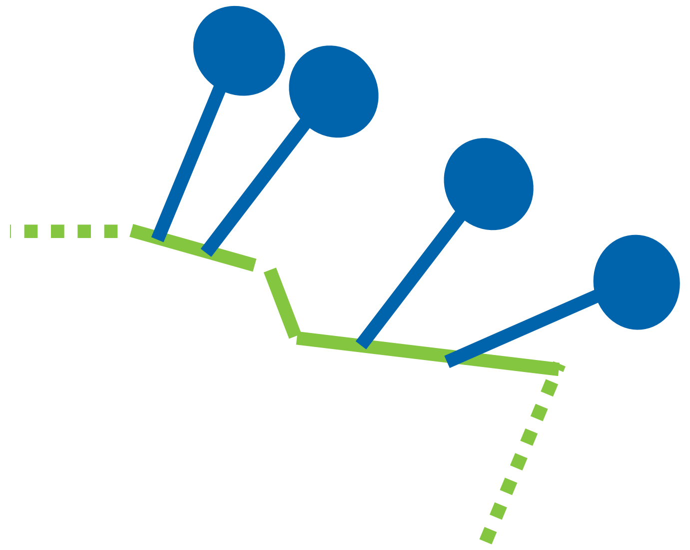




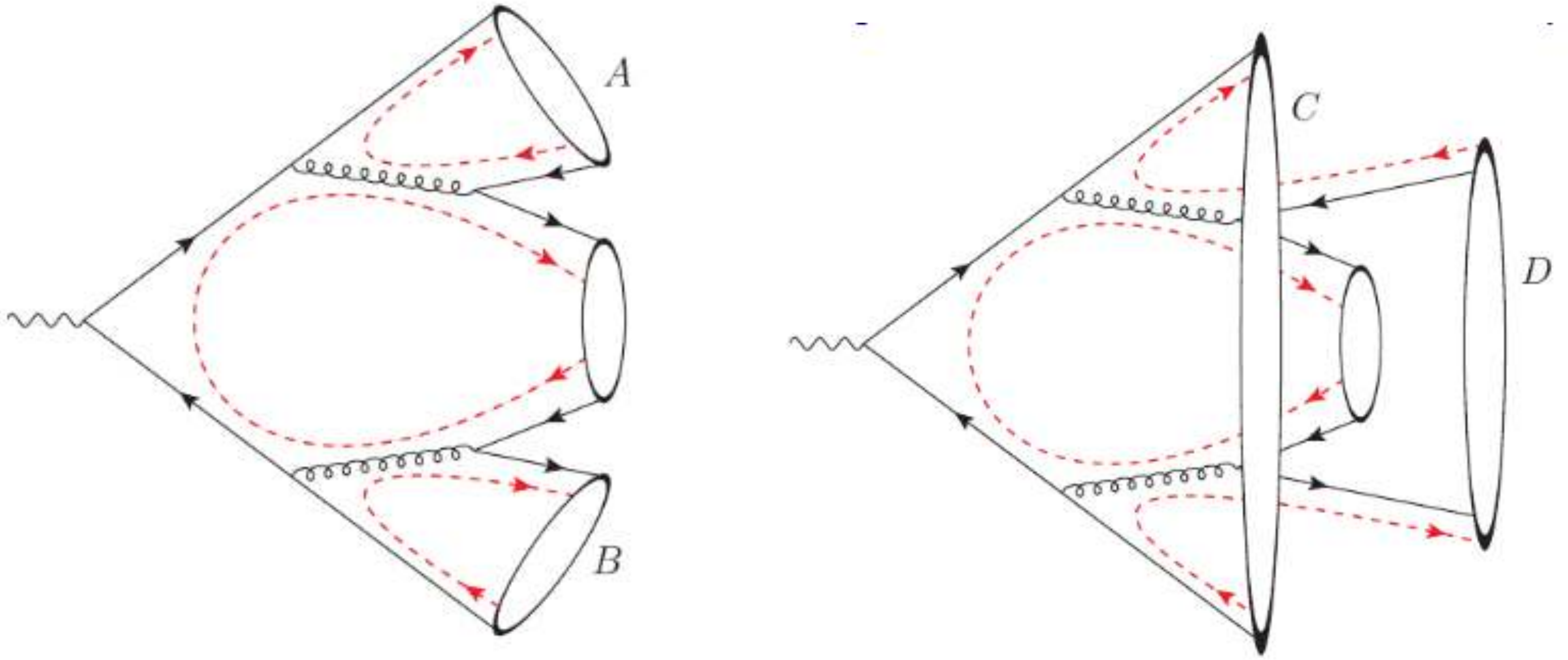
<pt>

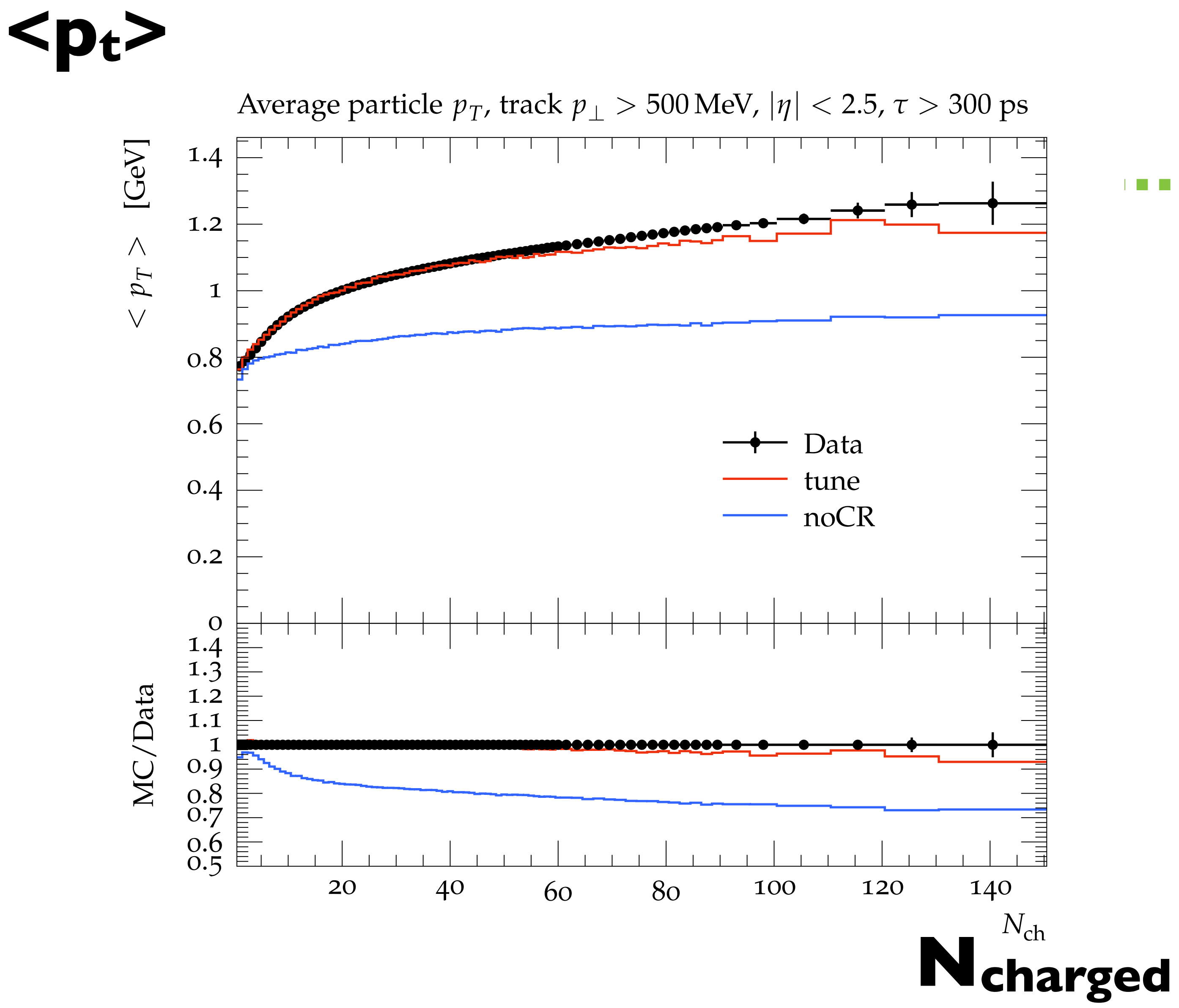


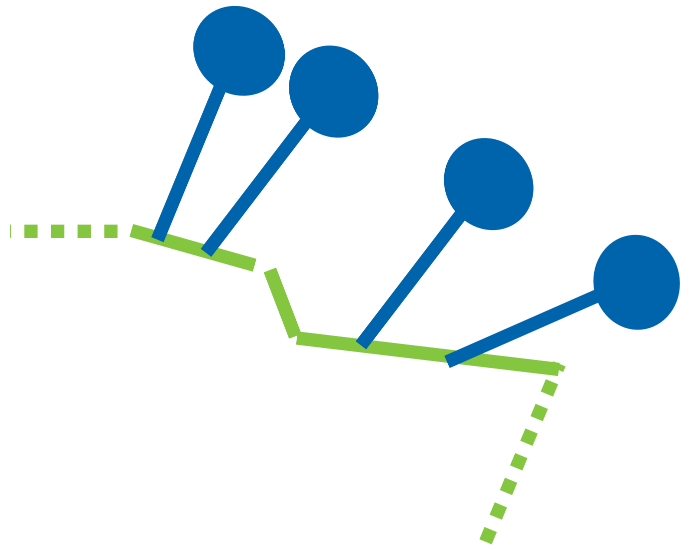
$N_{charged}$



Would subleading-N matter?







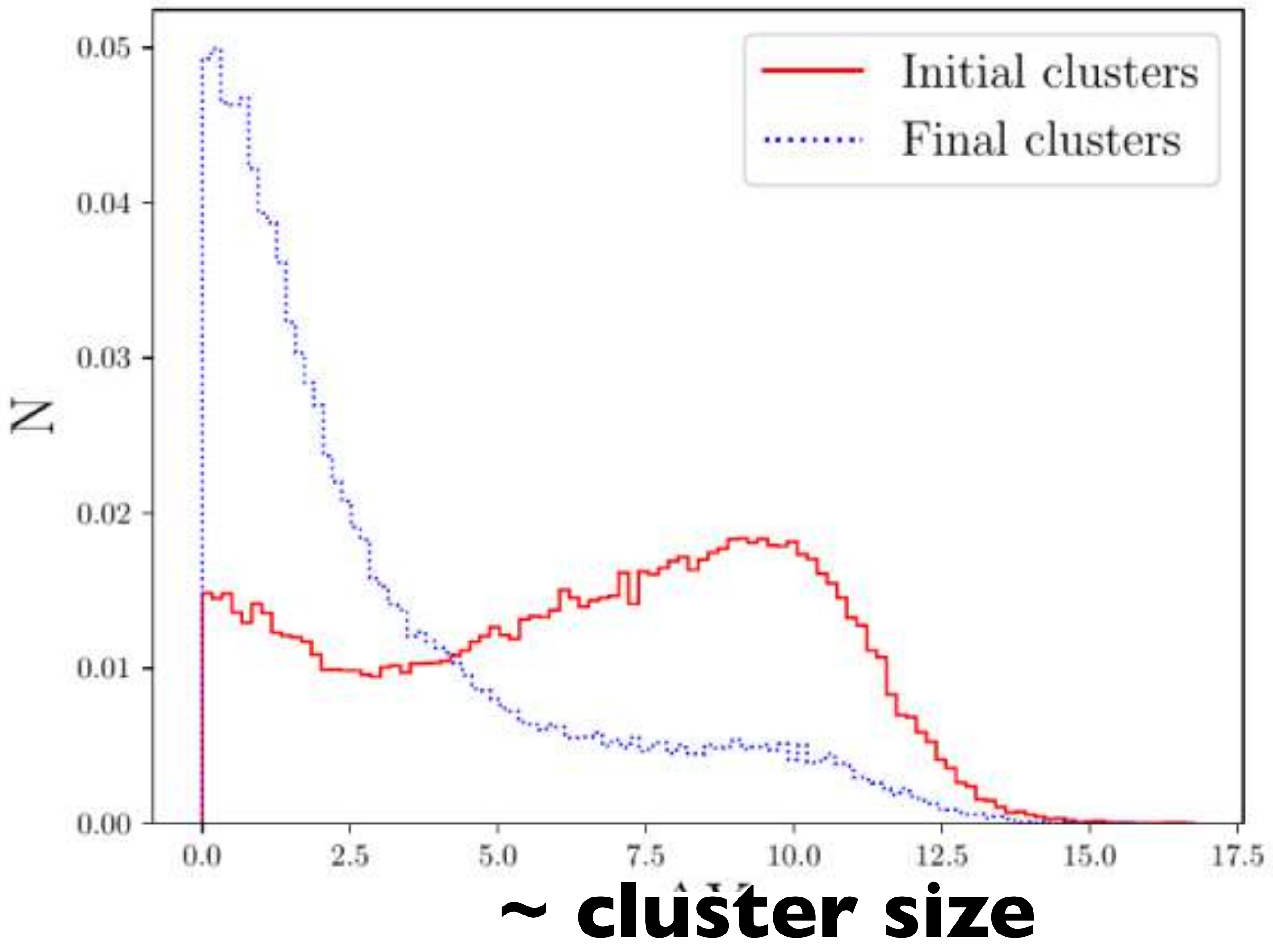
Approach colour reconnection from colour evolution: perturbative component?

Reconnection amplitude

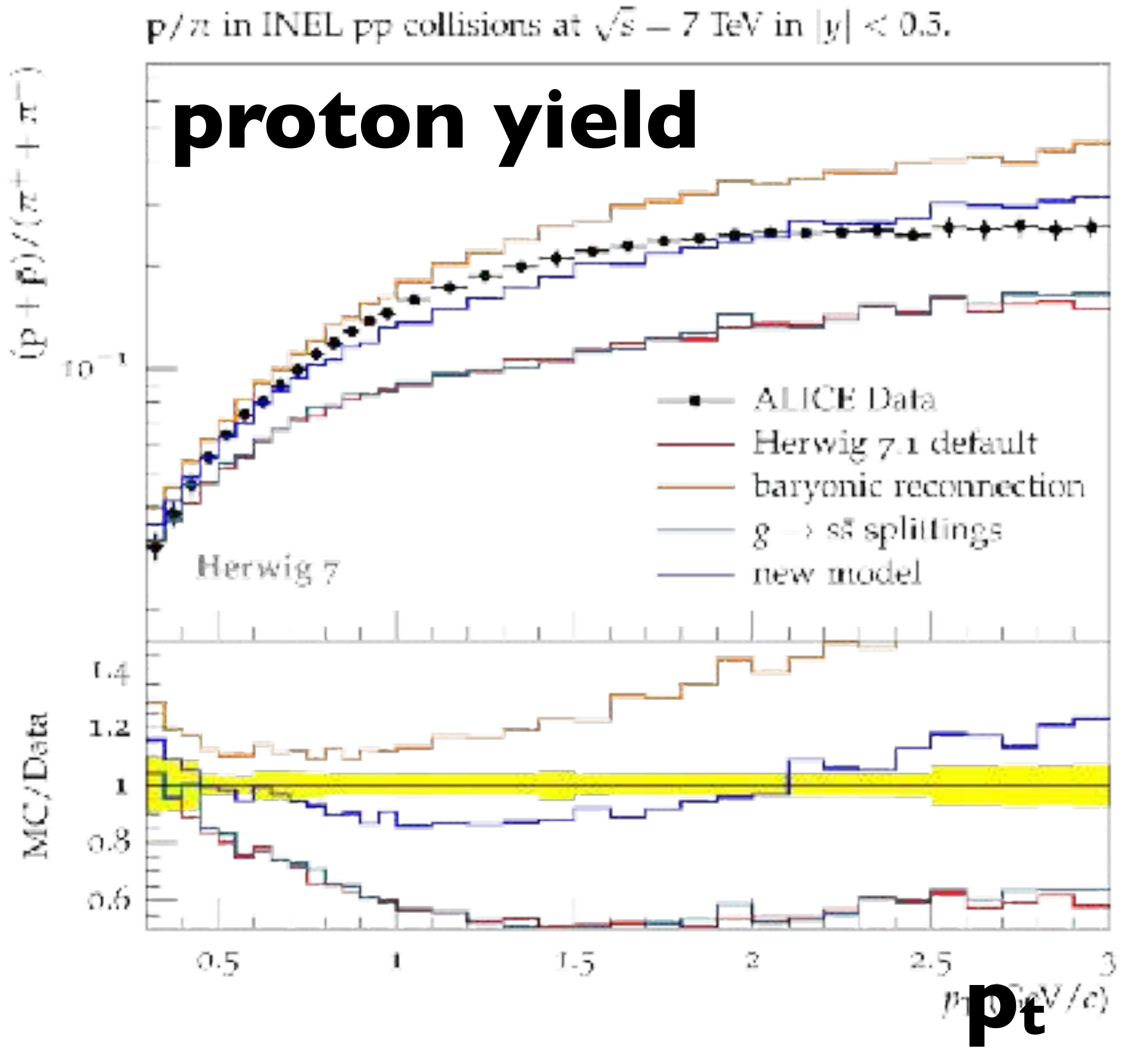
$$\mathrm{P}e^{-\int_q^k \frac{\mathrm{d}k'}{k'}\boldsymbol{\Gamma}(k')}$$

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

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



=



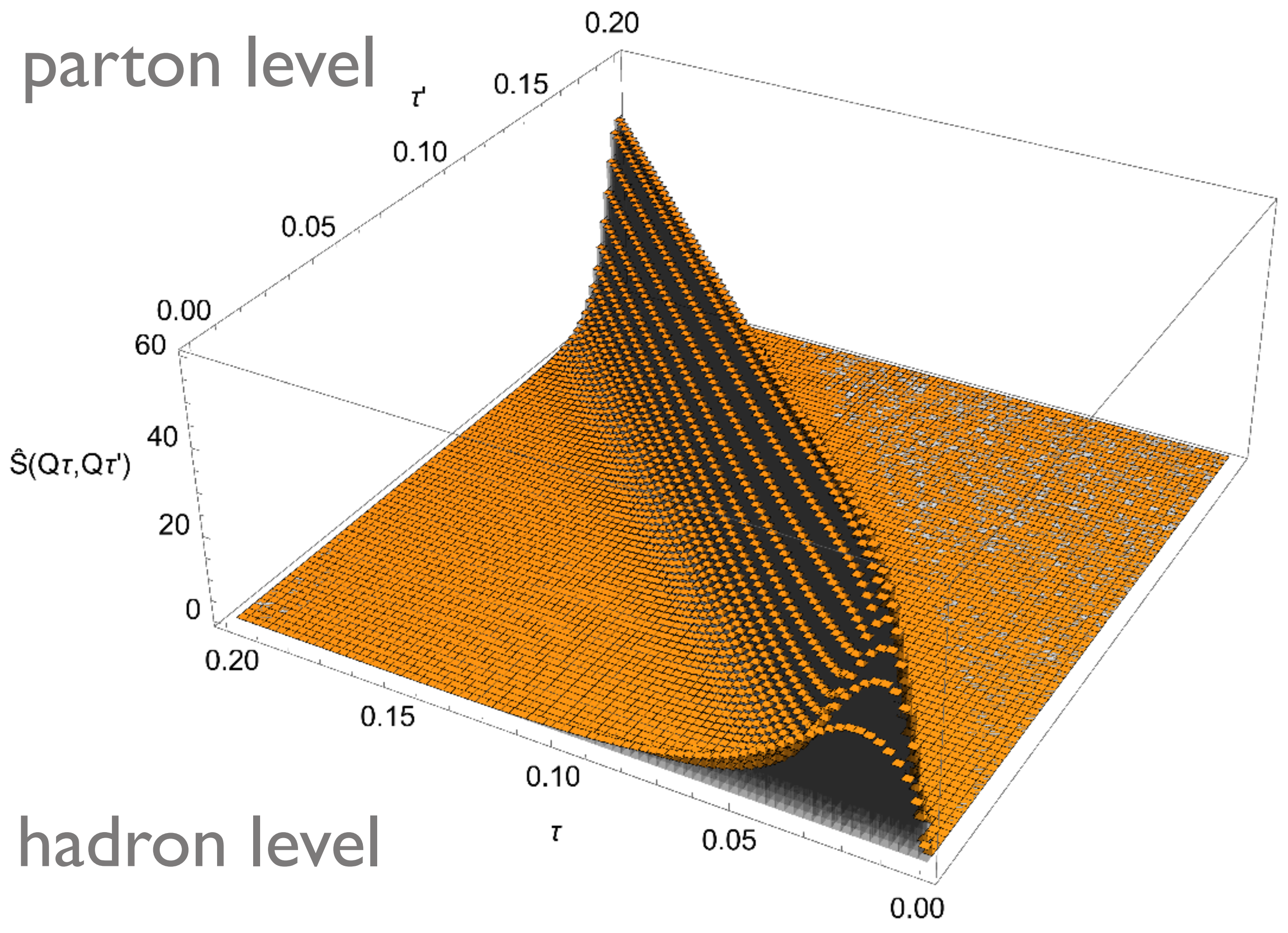
Summary & Outlook

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

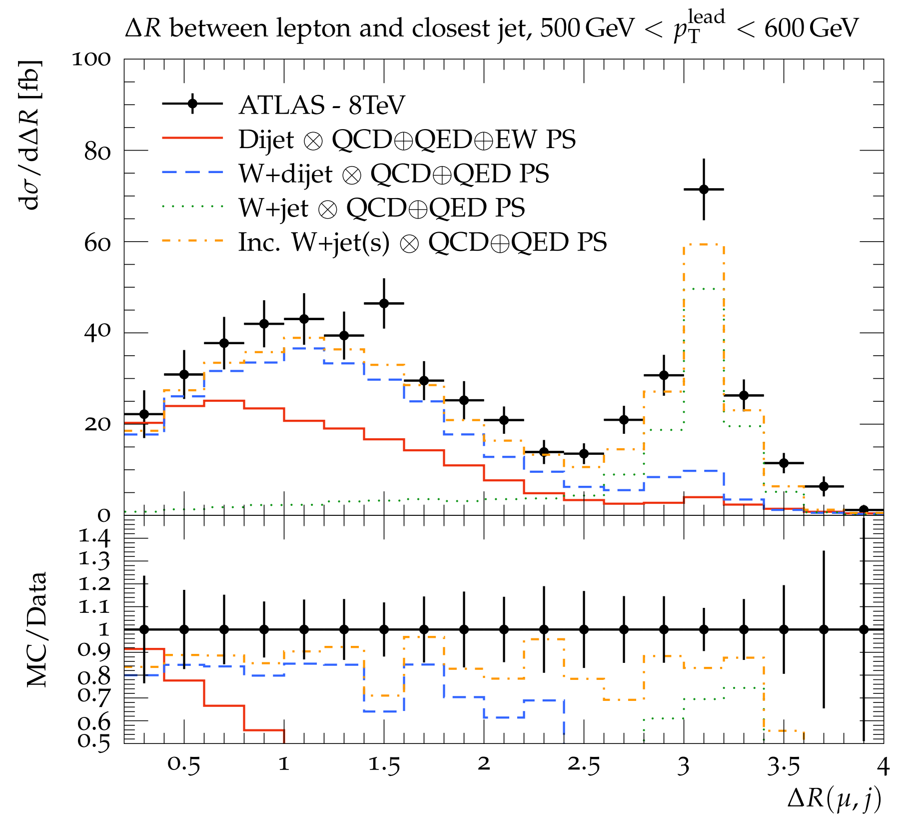
As we aim to use more and more of the complex structures, shower accuracy becomes the bottleneck. Also for matching to more than NNLO QCD.

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.

There is much more beyond this:
electroweak effects, BSM, …



[Hoang, Plätzer, Samitz — in progress]



[Masouminia, Richardson — arXiv:2108.10817]

Thank you!