News on Herwig

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

At
LHC Top Working Group
Online | 30 November 2023

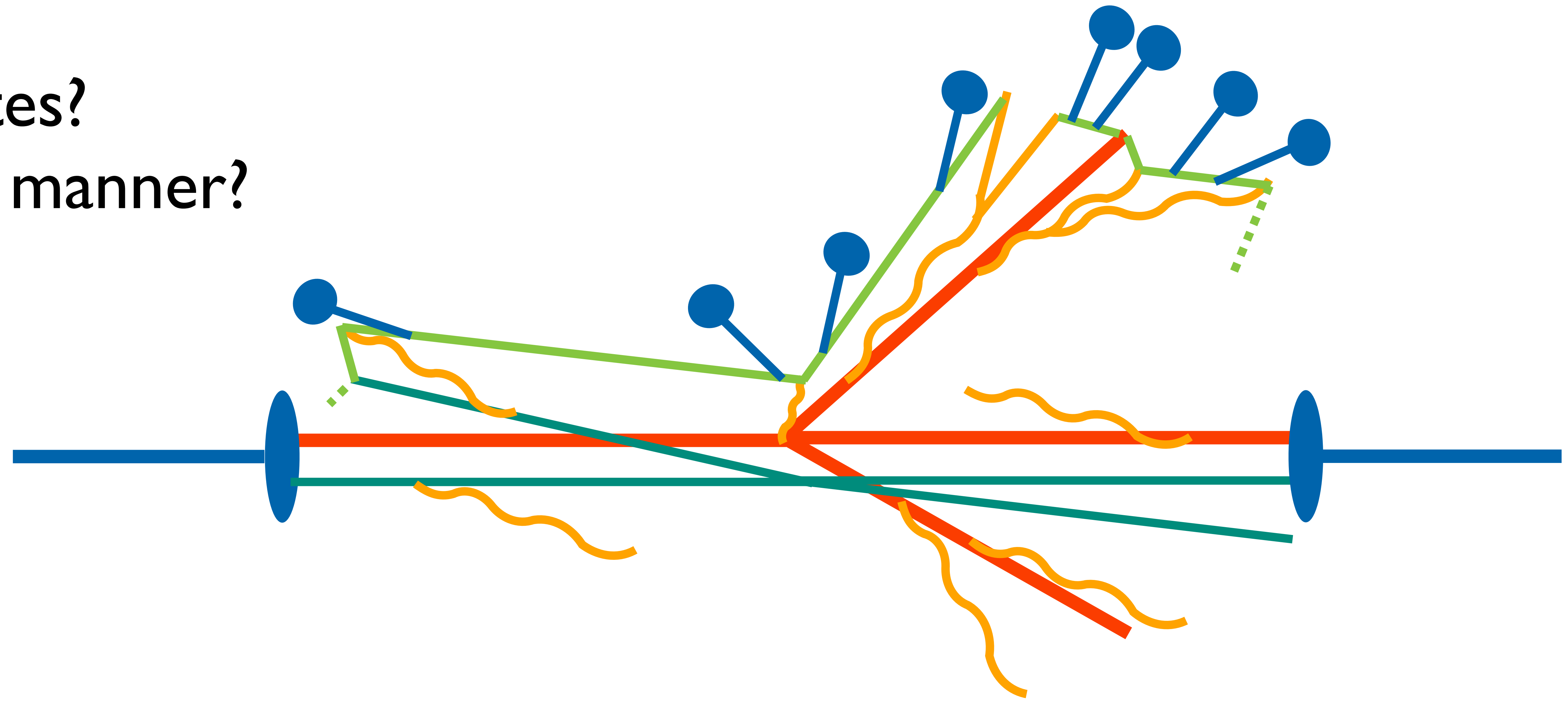
Current challenges for event generators

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?



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

Herwig 7 Overview

[Herwig collaboration – Eur.Phys.J. C76 (2016) 665]

Two shower modules: angular ordered and dipole-type.

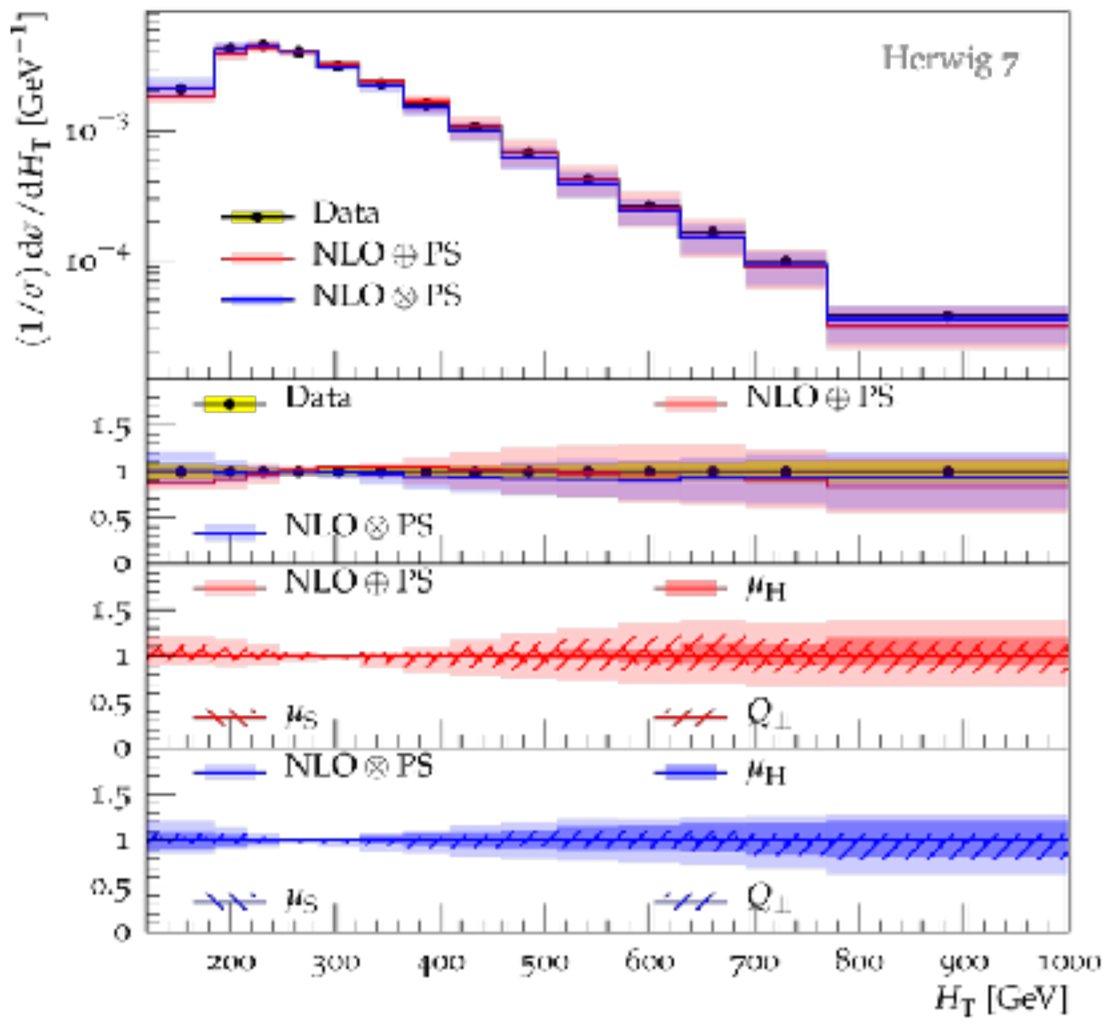
[Gieseke, Stephens, Webber – JHEP 0312 (2003) 045]
[Plätzer, Gieseke – JHEP 1101 (2011) 024]

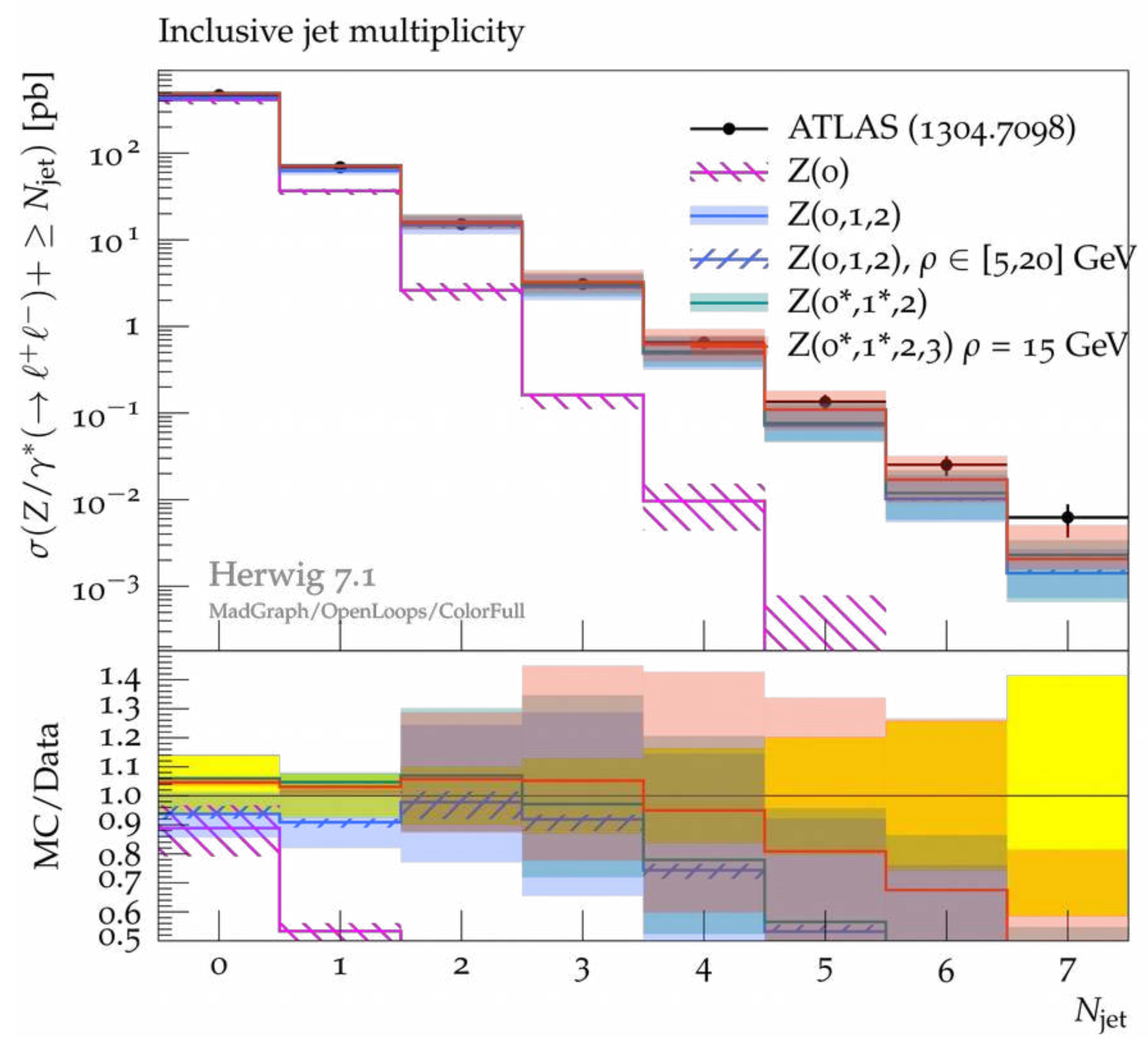
[Plätzer, Gieseke – EPJ C72 (2012) 2187]
[Plätzer — JHEP 1308 (2013) 114]
[Bellm, Gieseke, Plätzer — EPJ C78 (2018) 244]

Automated NLO matching and multi jet merging.

Automated BSM simulations using UFO model files.

[Gigg, Richardson — EPJ C51 (2007) 989]
[Richardson, Wilcock — EPJ C74 (2014) 2713]

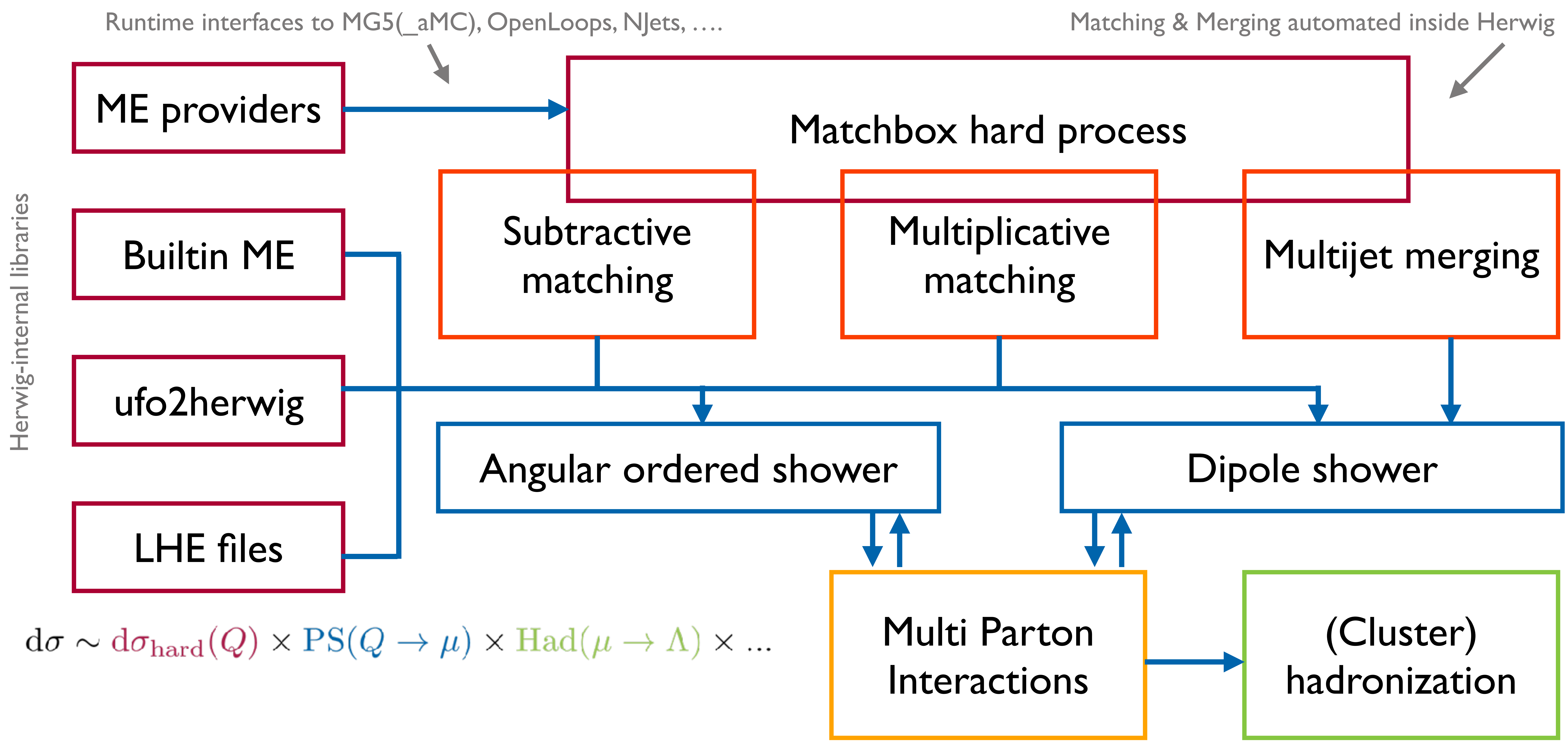




Cluster hadronization model

Eikonal MPI model

Under the Hood



$$\mathrm{d}\sigma \sim \mathrm{d}\sigma_{\mathrm{hard}}(Q) \times \mathrm{PS}(Q \to \mu) \times \mathrm{Had}(\mu \to \Lambda) \times \ldots$$

BSM Simulation

- Most of the work over the last 10 years has focused on simulation of Standard Model processes.
- Still a number of BSM improvements:
  - Handling of colour sextets;
  - More BSM models;
  - full correlations (i.e. including in shower);
  - use τ decay currents for nearly degenerate BSM decays.
- Major improvement with the ability to use models in the UFO format
  - python ufo2herwig program converts UFO to C++ code implementing the model.
  - can then be used like an internal model with simulation of production, decay and QCD radiation from the BSM particles.
- Herwig 7.2, handling of general Lorentz structures for the vertices and more colour structures.
- Next minor release 7.2.3 will include suppрt for python3 although many issues as most UFO models still in python2.

We have released 7.3!

[Gigg, Richardson — EPJ C51 (2007) 989]
[Richardson, Wilcock — EPJ C74 (2014) 2713]

- Model with:
  - spin-$\frac{3}{2}$ particles;
  - complicated Dirac structures;
  - $\epsilon^{\alpha\beta\gamma\delta}$ in many vertices;
- Tough test for automatic parsing of the vertices.
- Excellent agreement with MC5-aMCNLO.

[Richardson for Tools 2020]

Process	σ/pb Hw 7	σ/pb Mad	Ratio	Fractional Difference	χ
$gu \to \tilde{u}_1 gld$	$(27.20200 \pm 0.0040) \times 10^{-1}$	$(27.21160 \pm 0.0079) \times 10^{-1}$	0.9996	-0.0002	-1.0852
$gu \to \tilde{u}_1 grv$	$(18.53800 \pm 0.0030) \times 10^{-1}$	$(18.53830 \pm 0.0044) \times 10^{-1}$	1.0000	-0.0000	-0.0564
$gu \to \tilde{u}_4 gld$	$(28.13400 \pm 0.0040) \times 10^{-1}$	$(28.13260 \pm 0.0085) \times 10^{-1}$	1.0000	0.0000	0.1495
$gu \to \tilde{u}_4 grv$	$(19.48900 \pm 0.0030) \times 10^{-1}$	$(19.49400 \pm 0.0048) \times 10^{-1}$	0.9997	-0.0001	-0.8891
$gs \to \tilde{d}_2 gld$	$(1.11250 \pm 0.0002) \times 10^{-1}$	$(1.11264 \pm 0.0003) \times 10^{-1}$	0.9999	-0.0001	-0.4102
$gs \to \tilde{d}_2 grv$	$(1.08280 \pm 0.0002) \times 10^{-1}$	$(1.08255 \pm 0.0003) \times 10^{-1}$	1.0002	0.0001	0.7631
$gs \to \tilde{d}_5 gld$	$(1.22070 \pm 0.0002) \times 10^{-1}$	$(1.22098 \pm 0.0003) \times 10^{-1}$	0.9998	-0.0001	-0.7607
$gs \to \tilde{d}_5 grv$	$(1.22890 \pm 0.0002) \times 10^{-1}$	$(1.22904 \pm 0.0003) \times 10^{-1}$	0.9999	-0.0001	-0.4333
$gc \to \tilde{u}_2 gld$	$(7.69000 \pm 0.0010) \times 10^{-2}$	$(7.68954 \pm 0.0020) \times 10^{-2}$	1.0001	0.0000	0.2080
$gc \to \tilde{u}_2 grv$	$(7.61300 \pm 0.0010) \times 10^{-2}$	$(7.61320 \pm 0.0017) \times 10^{-2}$	1.0000	-0.0000	-0.1001
$gc \to \tilde{u}_5 gld$	$(8.06500 \pm 0.0010) \times 10^{-2}$	$(8.06697 \pm 0.0021) \times 10^{-2}$	0.9998	-0.0001	-0.8579
$gc \to \tilde{u}_5 grv$	$(8.12600 \pm 0.0010) \times 10^{-2}$	$(8.12763 \pm 0.0018) \times 10^{-2}$	0.9998	-0.0001	-0.7919
$gb \to \tilde{d}_3 gld$	$(5.65120 \pm 0.0008) \times 10^{-2}$	$(5.64113 \pm 0.0014) \times 10^{-2}$	1.0018	0.0009	6.2993
$gb \to \tilde{d}_3 grv$	$(6.21400 \pm 0.0010) \times 10^{-2}$	$(6.20548 \pm 0.0013) \times 10^{-2}$	1.0014	0.0007	5.1251
$gb \to \tilde{d}_6 gld$	$(4.94500 \pm 0.0008) \times 10^{-2}$	$(4.95255 \pm 0.0012) \times 10^{-2}$	0.9985	-0.0008	-5.1105
$gb \to \tilde{d}_6 grv$	$(5.20610 \pm 0.0008) \times 10^{-2}$	$(5.21305 \pm 0.0012) \times 10^{-2}$	0.9987	-0.0007	-4.8722
$g\bar{d} \to \tilde{d}_1^* gld$	$(2.12470 \pm 0.0003) \times 10^{-1}$	$(2.12507 \pm 0.0005) \times 10^{-1}$	0.9998	-0.0001	-0.5958
$g\bar{d} \to \tilde{d}_1^* grv$	$(2.01050 \pm 0.0003) \times 10^{-1}$	$(2.01034 \pm 0.0005) \times 10^{-1}$	1.0001	0.0000	0.2877
$g\bar{d} \to \tilde{d}_4^* gld$	$(2.32600 \pm 0.0004) \times 10^{-1}$	$(2.32610 \pm 0.0006) \times 10^{-1}$	1.0000	-0.0000	-0.1367
$g\bar{d} \to \tilde{d}_4^* grv$	$(2.27300 \pm 0.0004) \times 10^{-1}$	$(2.27331 \pm 0.0005) \times 10^{-1}$	0.9999	-0.0001	-0.4704
$g\bar{u} \to \tilde{u}_1^* gld$	$(1.71460 \pm 0.0003) \times 10^{-1}$	$(1.71493 \pm 0.0004) \times 10^{-1}$	0.9998	-0.0001	-0.6189
$g\bar{u} \to \tilde{u}_1^* grv$	$(1.65060 \pm 0.0003) \times 10^{-1}$	$(1.65038 \pm 0.0004) \times 10^{-1}$	1.0001	0.0001	0.4498
$g\bar{u} \to \tilde{u}_4^* gld$	$(1.79670 \pm 0.0003) \times 10^{-1}$	$(1.79669 \pm 0.0004) \times 10^{-1}$	1.0000	0.0000	0.0188
$g\bar{u} \to \tilde{u}_4^* grv$	$(1.75910 \pm 0.0003) \times 10^{-1}$	$(1.75882 \pm 0.0004) \times 10^{-1}$	1.0002	0.0001	0.5742
$g\bar{s} \to \tilde{d}_2^* gld$	$(9.70200 \pm 0.0010) \times 10^{-2}$	$(9.70334 \pm 0.0024) \times 10^{-2}$	0.9999	-0.0001	-0.5159
$g\bar{s} \to \tilde{d}_2^* grv$	$(9.59600 \pm 0.0010) \times 10^{-2}$	$(9.59757 \pm 0.0022) \times 10^{-2}$	0.9998	-0.0001	-0.6553
$g\bar{s} \to \tilde{d}_5^* gld$	$(1.06630 \pm 0.0002) \times 10^{-1}$	$(1.06679 \pm 0.0003) \times 10^{-1}$	0.9995	-0.0002	-1.4664
$g\bar{s} \to \tilde{d}_5^* grv$	$(1.09190 \pm 0.0002) \times 10^{-1}$	$(1.09190 \pm 0.0002) \times 10^{-1}$	1.0000	-0.0000	-0.0032
$g\bar{c} \to \tilde{u}_2^* gld$	$(7.69000 \pm 0.0010) \times 10^{-2}$	$(7.68954 \pm 0.0020) \times 10^{-2}$	1.0001	0.0000	0.2080
$g\bar{c} \to \tilde{u}_2^* grv$	$(7.61300 \pm 0.0010) \times 10^{-2}$	$(7.61320 \pm 0.0017) \times 10^{-2}$	1.0000	-0.0000	-0.1001
$g\bar{c} \to \tilde{u}_5^* gld$	$(8.06500 \pm 0.0010) \times 10^{-2}$	$(8.06697 \pm 0.0021) \times 10^{-2}$	0.9998	-0.0001	-0.8579
$g\bar{c} \to \tilde{u}_5^* grv$	$(8.12600 \pm 0.0010) \times 10^{-2}$	$(8.12763 \pm 0.0018) \times 10^{-2}$	0.9998	-0.0001	-0.7919
$g\bar{b} \to \tilde{d}_3^* gld$	$(5.65120 \pm 0.0008) \times 10^{-2}$	$(5.64113 \pm 0.0014) \times 10^{-2}$	1.0018	0.0009	6.2993
$g\bar{b} \to \tilde{d}_3^* grv$	$(6.21400 \pm 0.0010) \times 10^{-2}$	$(6.20548 \pm 0.0013) \times 10^{-2}$	1.0014	0.0007	5.1251
$g\bar{b} \to \tilde{d}_6^* gld$	$(4.94500 \pm 0.0008) \times 10^{-2}$	$(4.95255 \pm 0.0012) \times 10^{-2}$	0.9985	-0.0008	-5.1105

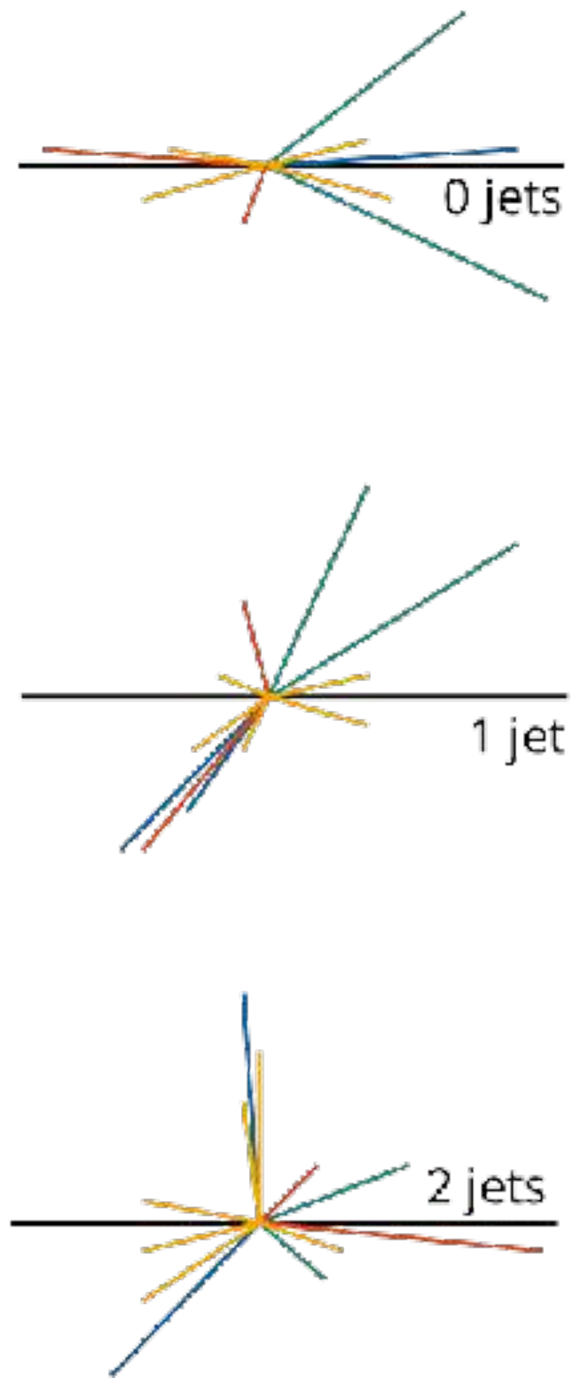
Matching & Merging

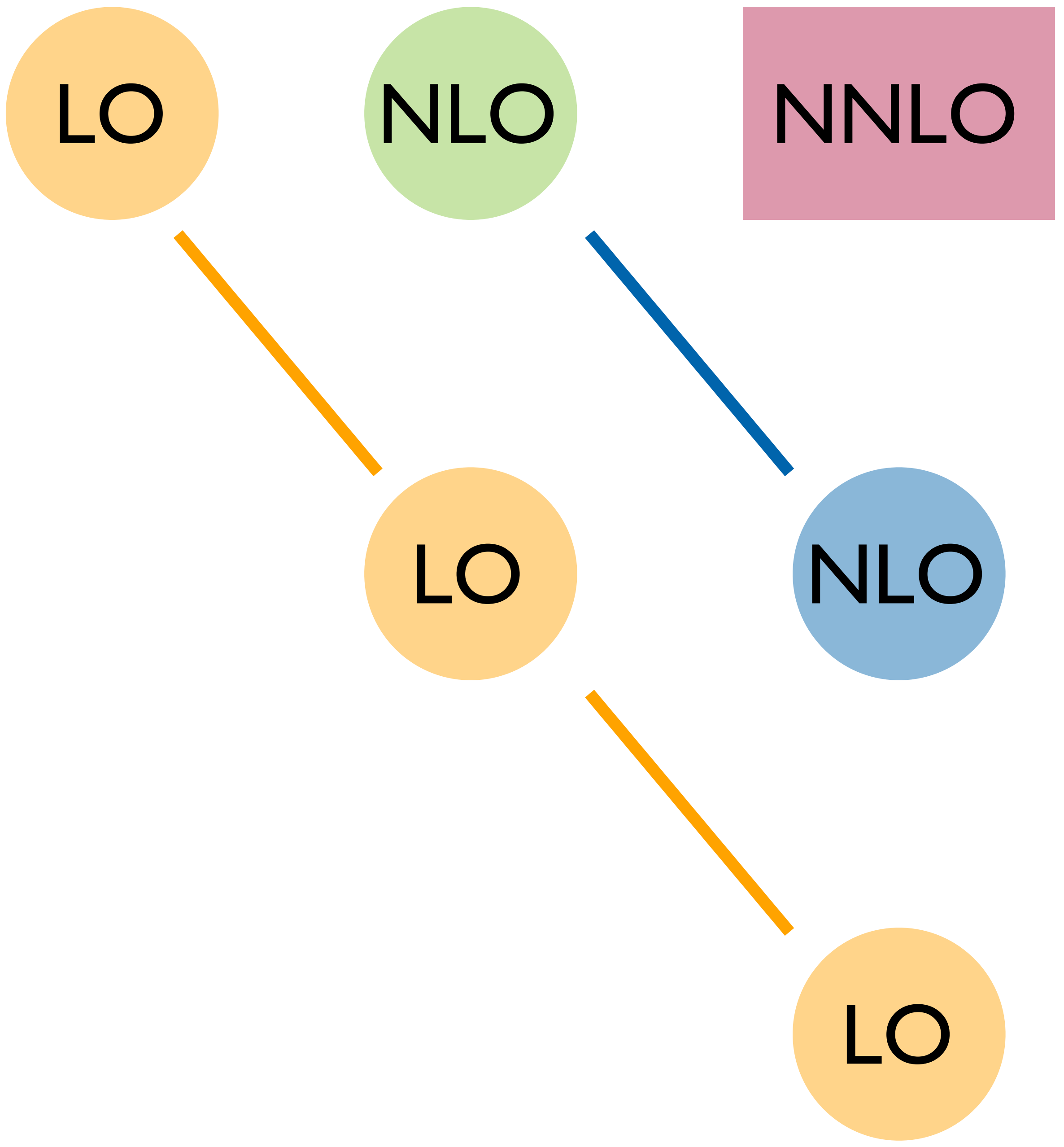
Matching & merging at NLO — works for general hard process.

[Plätzer, Gieseke – EPJ C72 (2012) 2187]

NLO matching also applied to decay chains

[Richardson, Wilcock — EPJ C74 (2014) 2713]





Merging & matching
Unitarized merging

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

Previous and ongoing development:

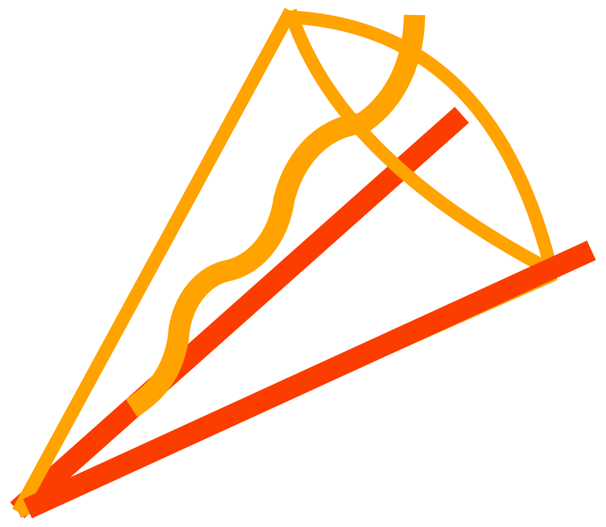
- More matching paradigms
- Reduction of negative weights
- Uncertainty estimates from cuts and resolution
- Consistent treatment of shower cutoff effects.

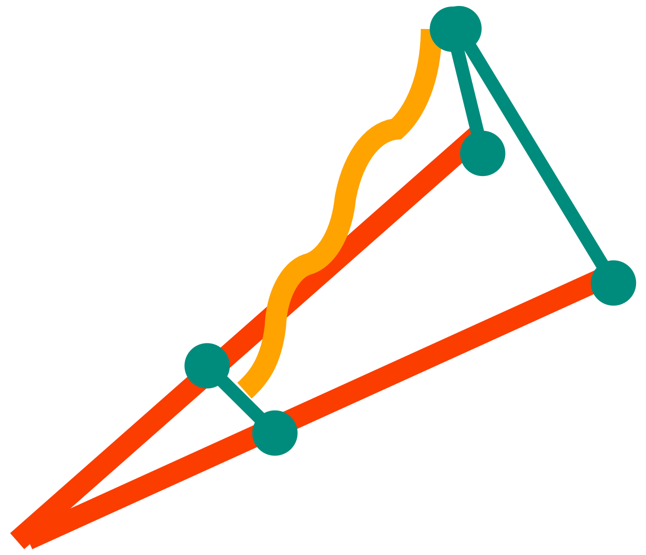
[Plätzer, Siodmok, Whitehead — in progress]

Internal treatment of NLO cross sections required.

The Herwig showers

Two complementary approaches, mostly similar in physics capabilities.





	Parton branchings order in angle.	Dipole branchings order in transverse momentum.
Full mass effects	✓	✓
Spin correlations	✓	✓
Colour ME corrections	✗	✓
Matching plugin	✓	✓
Multijet merging	✗	✓
QED radiation	✓	✗
Variation weights	✓	✓

Spin and colour correlations only possible with builtin matrix elements (handmade or Matchbox).
Will become an even closer tie in light of newer shower and matching algorithms.

Parton shower extras

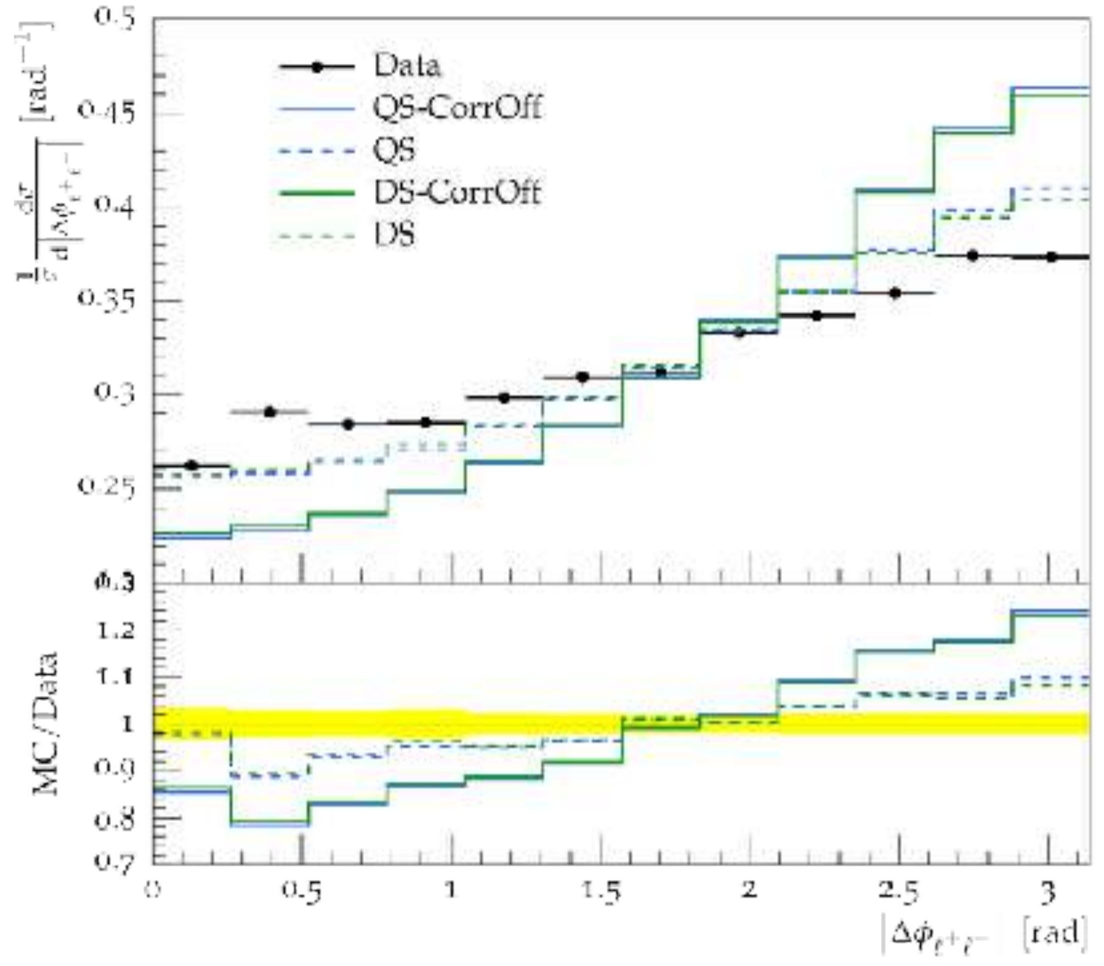
Several improvements on existing shower algorithms

- Spin correlations in both shower modules

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

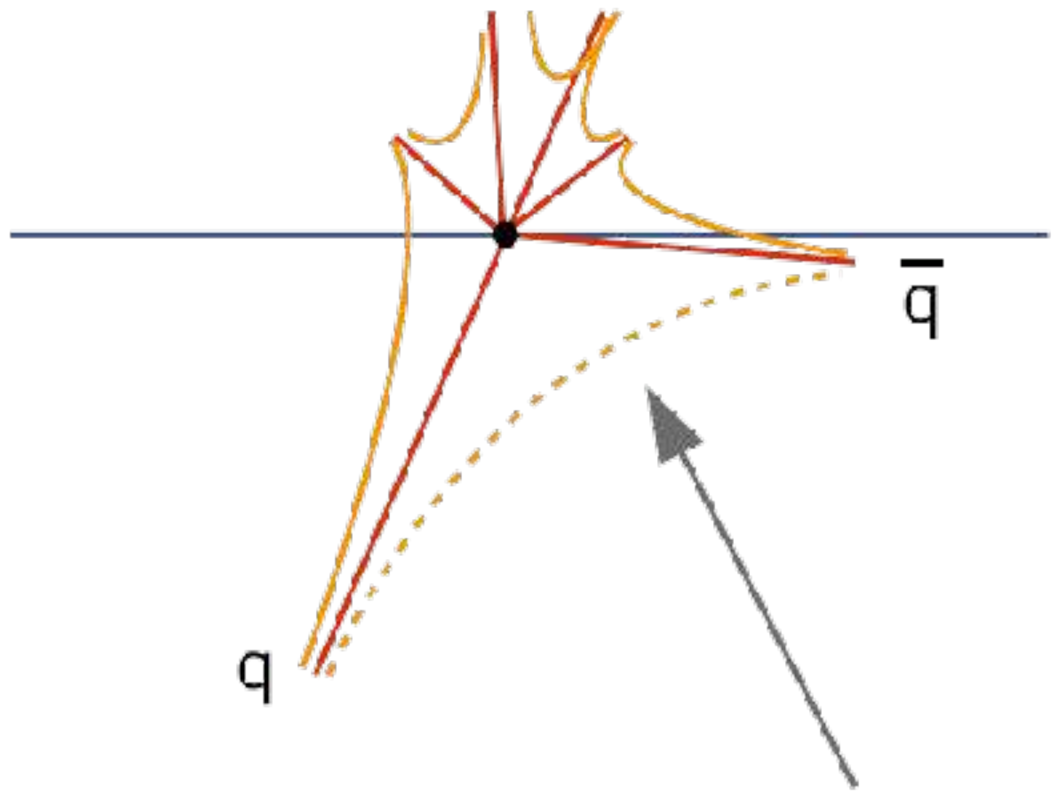
- QED radiation in angular ordered shower
- Shower reweighting algorithms encode some variations on-the-fly

[Bellm, Plätzer, Richardson, Siodmok, Webster – PRD 94 (2016) 3]

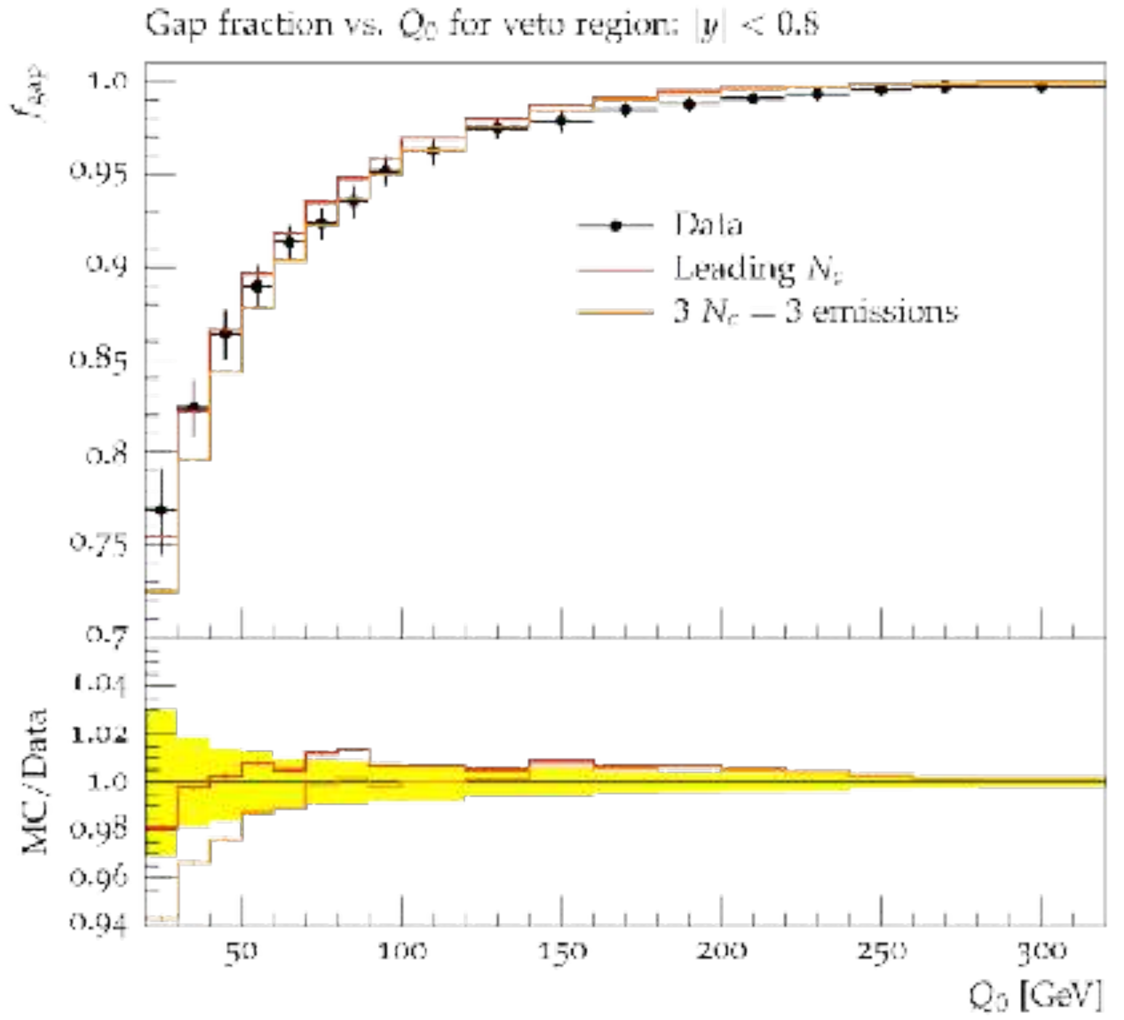


Colour matrix element corrections available in the dipole shower evolution: Restore subleading colour corrections in dipole showers.

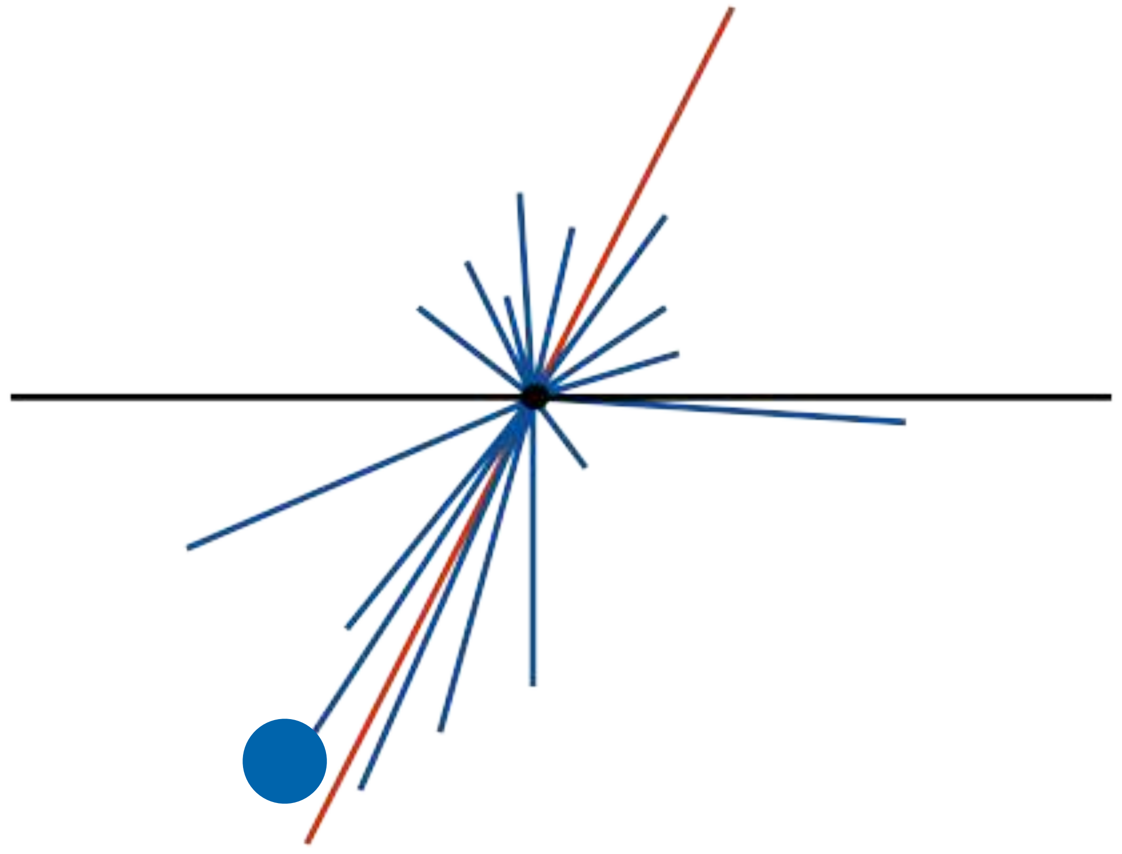
[Plätzer, Sjödahl – JHEP 1207 (2012) 042]
[Plätzer, Sjödahl, Thoren – JHEP 11 (2018) 009]



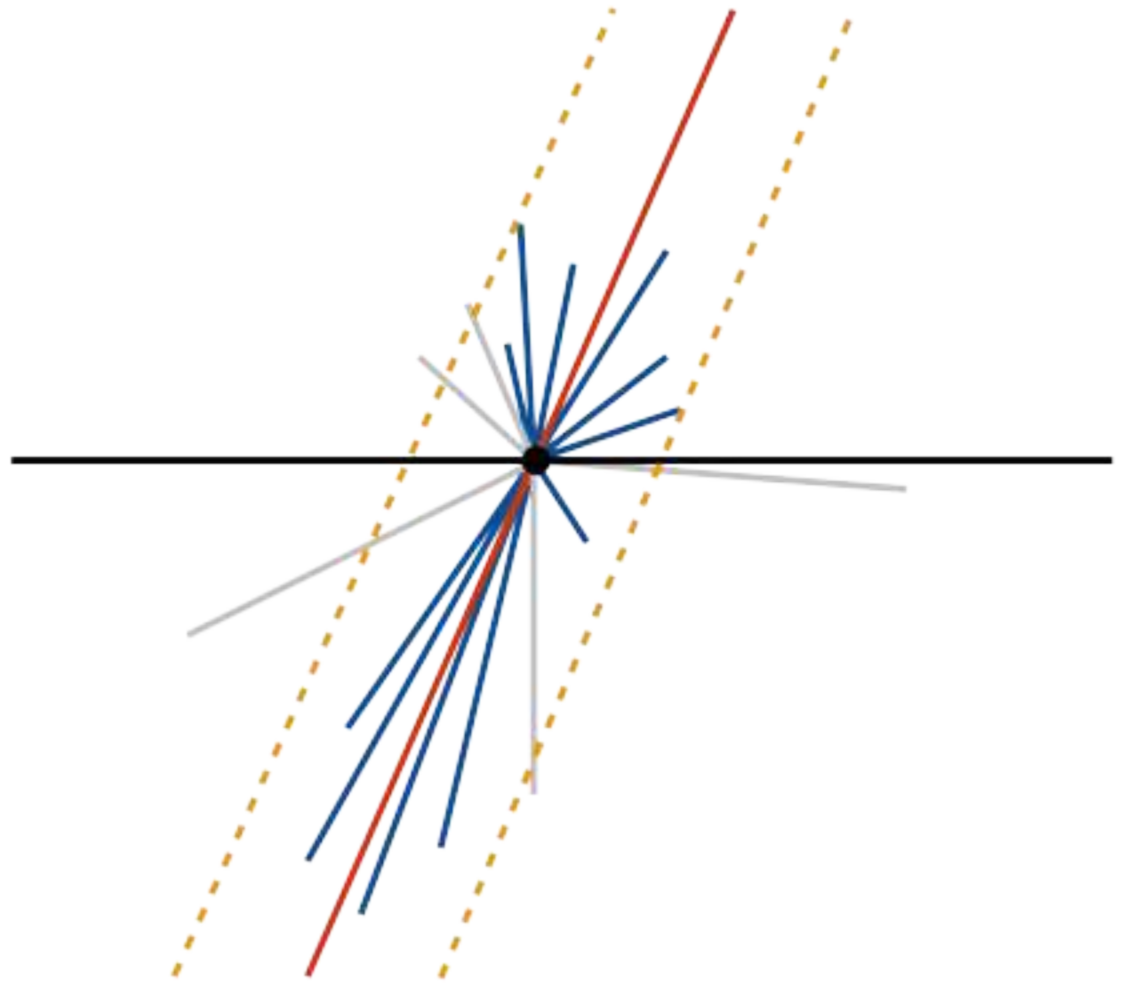
Some subleading-N corrections can be restored.



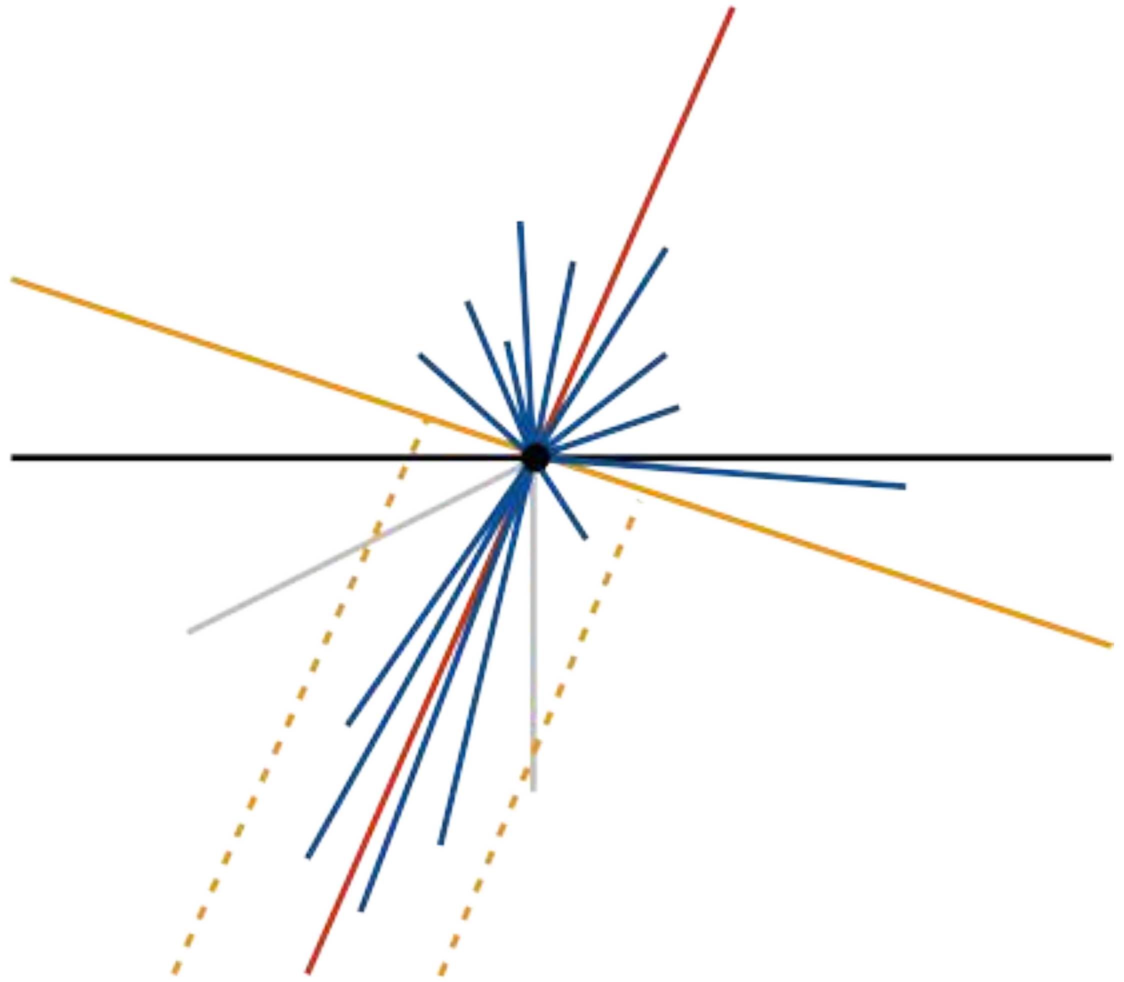
Event generator accuracy



(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 $\mathrm{NLL}_{\mathrm{global}}$ / $\mathrm{LL}_{\mathrm{non\text{-}global}}$ in one (dipole) algorithm?

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

Event generator accuracy

Progress in improving the PS accuracy

- **Assessing the logarithmic accuracy of a shower**
  Herwig [1904.11866, 2107.04051], Deductor [2011.04777], Forshaw, Holguin, Plätzer [2003.06400]
  PanScales [1805.09327, 2002.11114], Alaric [2110.05964], …

- **Triple collinear / double soft splittings**
  Dulat, Höche, Krauss, Gellersen, Prestel [1705.00982, 1705.00742, 1805.03757, 2110.05964]
  Li & Skands [1611.00013], Löschner, Plätzer, Simpson Dore [2112.14454], …

- Matching to fixed-order **see Alexander's talk**
  NLO; i.e. Frixione & Webber [0204244], Nason [0409146], …
  NNLO; i.e. UNNLOPS [1407.3773], MiNNLOps [1908.06987], Vincia [2108.07133], …
  NNNLO; Prestel [2106.03206], Bertone, Prestel [2202.01082]

- Colour (and spin) correlations **see Simon's talk**
  Forshaw, Holguin, Plätzer, Sjödahl [1201.0260, 1808.00332, 1905.08686, 2007.09648, 2011.15087]
  Deductor [0706.0017, 1401.6364, 1501.00778, 1902.02105], Herwig [1807.01955], Plätzer & Ruffa [2012.15215]
  PanScales [2011.10054, 2103.16526, 2111.01161], …

- Electroweak corrections
  Vincia [2002.09248, 2108.10786], Pythia [1401.5238], Herwig [2108.10817], …

Super-active field of research:
taken from Melissa van Bleekveld's talk at the CERN workshop on parton showers for future colliders.

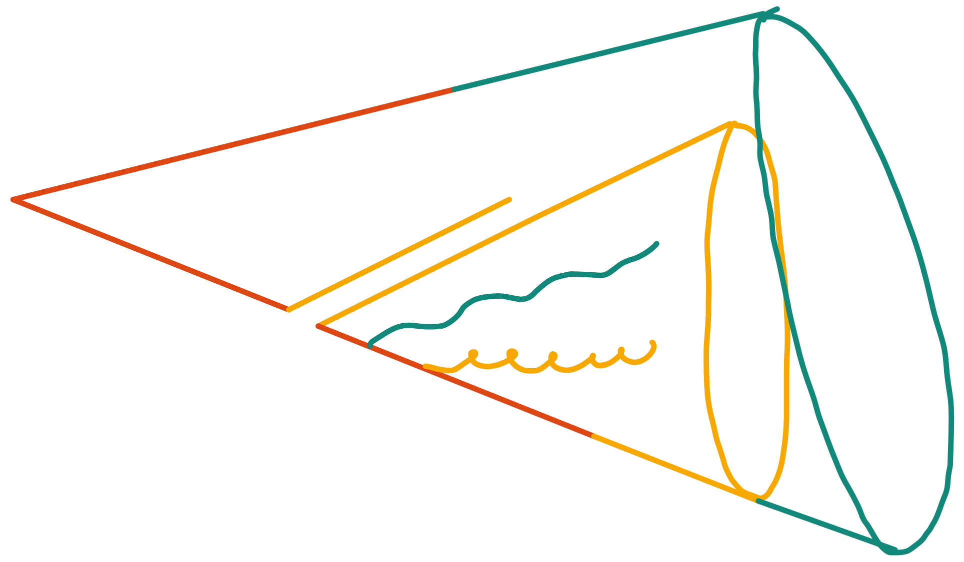
C … nching … vers

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

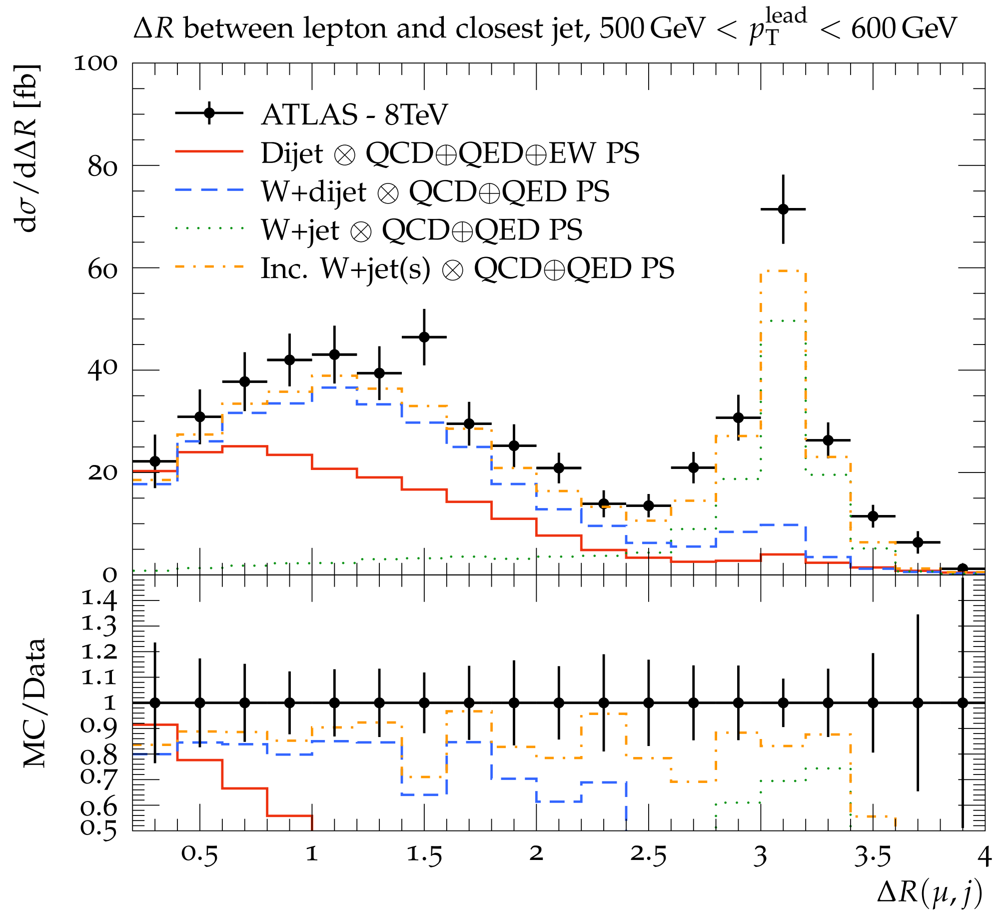
Parton showers

Heavily developed further:

- NLL accuracy for both angular ordered and dipole shower
- Colour and spin correlations
- Electroweak radiation and QED radiation



In place for QED, soon for electroweak and possibly beyond.



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

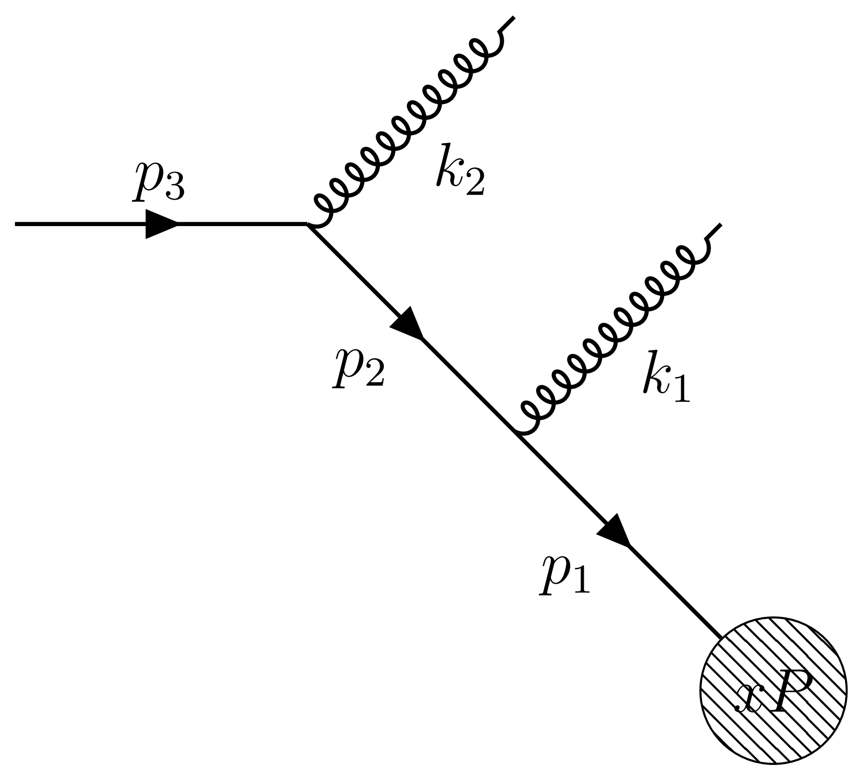
Complemented by analytic control and issues e.g. on the interpretation of the top quark mass.

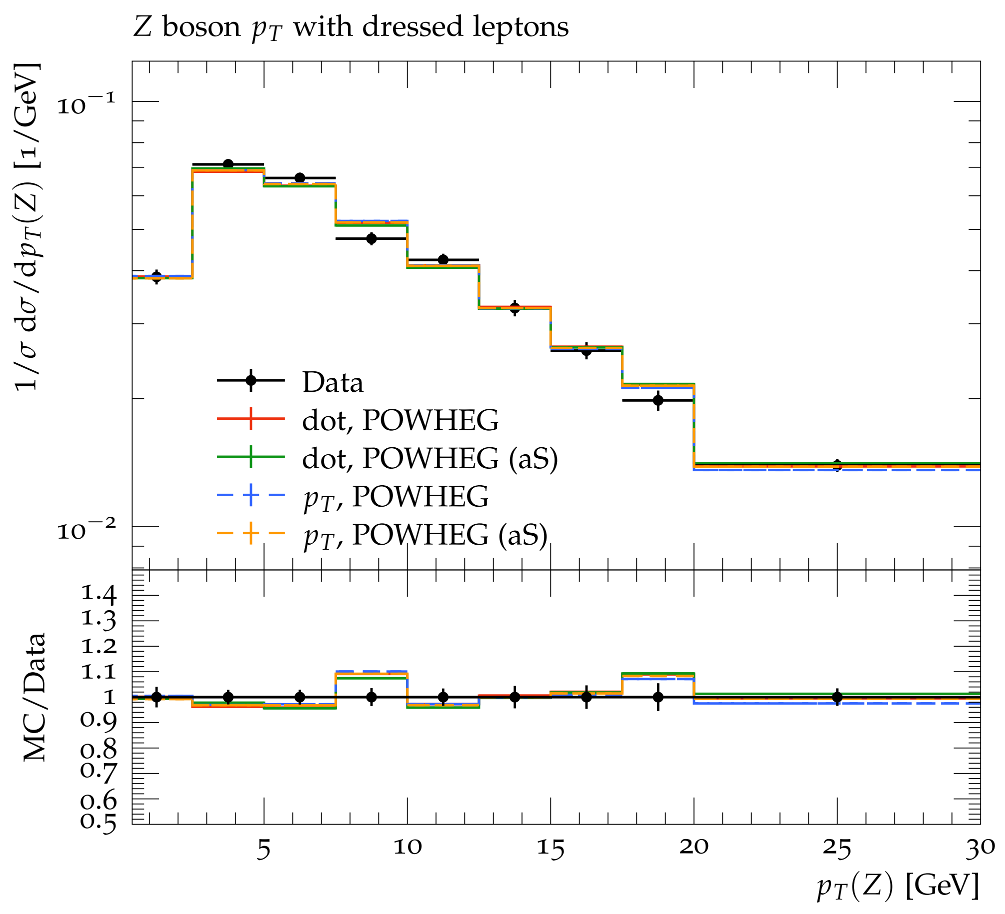
Matching is always central, and consistent variations of parton shower phase space and initial conditions (hard scale and profile) for systematics are synchronised automatically within Herwig/Matchbox.

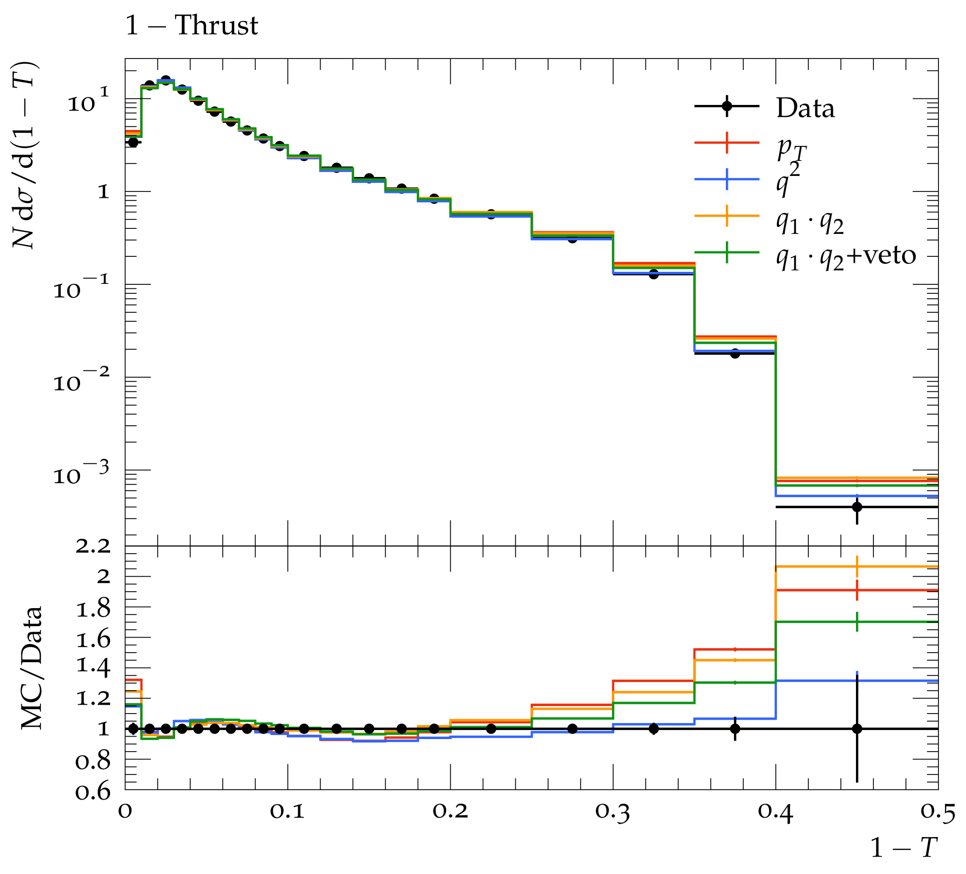
(Dipole) shower improvements: NLL accuracy

Problems not only present in dipole showers, can even screw up angular ordered ones:

[Bewick, Ferrario, Richardson, Seymour —JHEP 04 (2020) 019 & 01 (2022) 026]

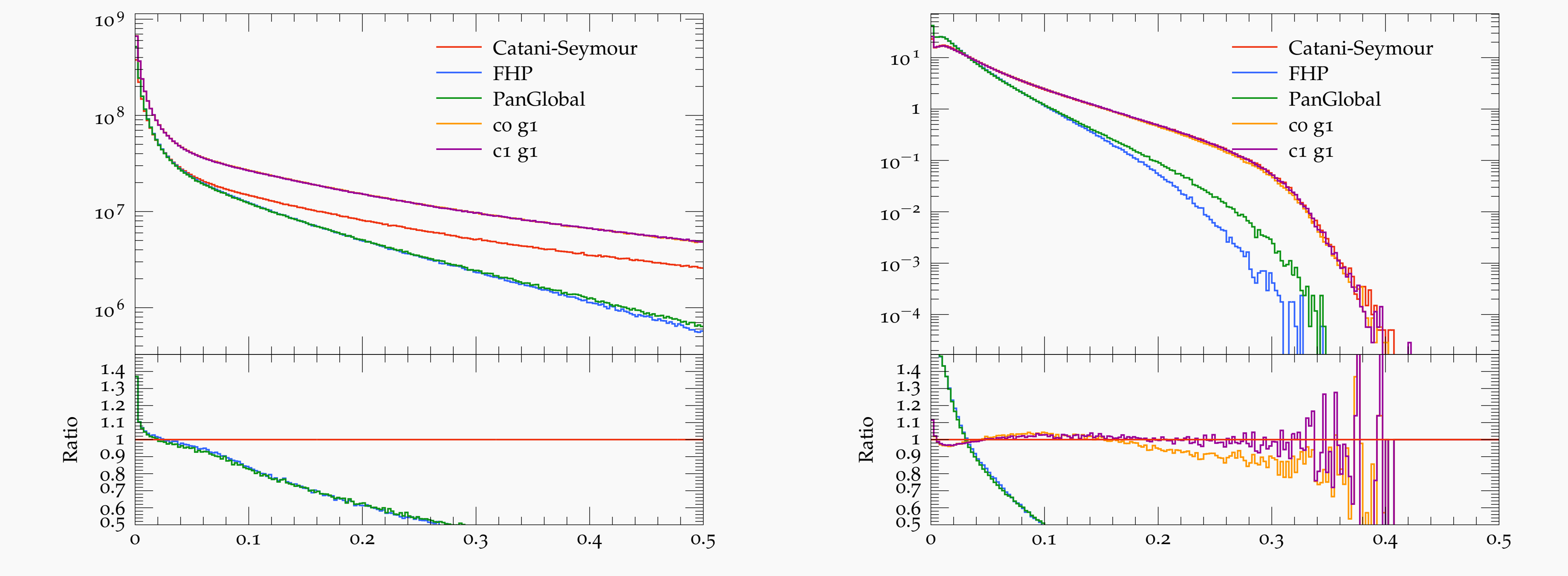






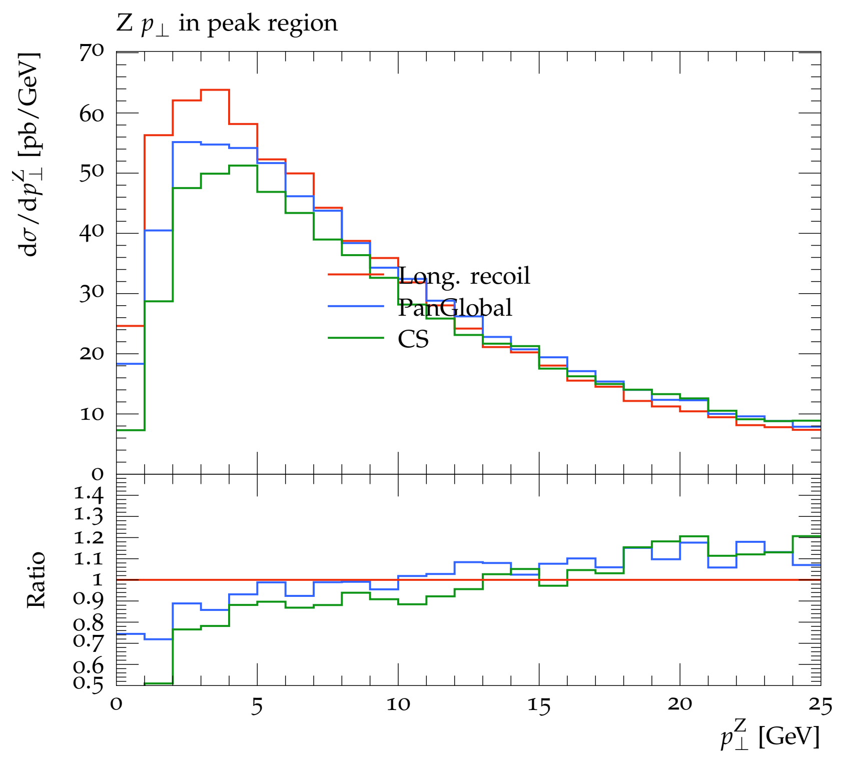
Need to allow building up high-mass events to not constrain shower evolution.

Herwig dipole shower is on track:



(e) C Parameter (f) Heavy Jet Mass

Investigating a large class of accurate kinematic mappings and issues in the initial state.



[Duncan, Holguin, Plätzer, Seymour, Sule — ongoing]

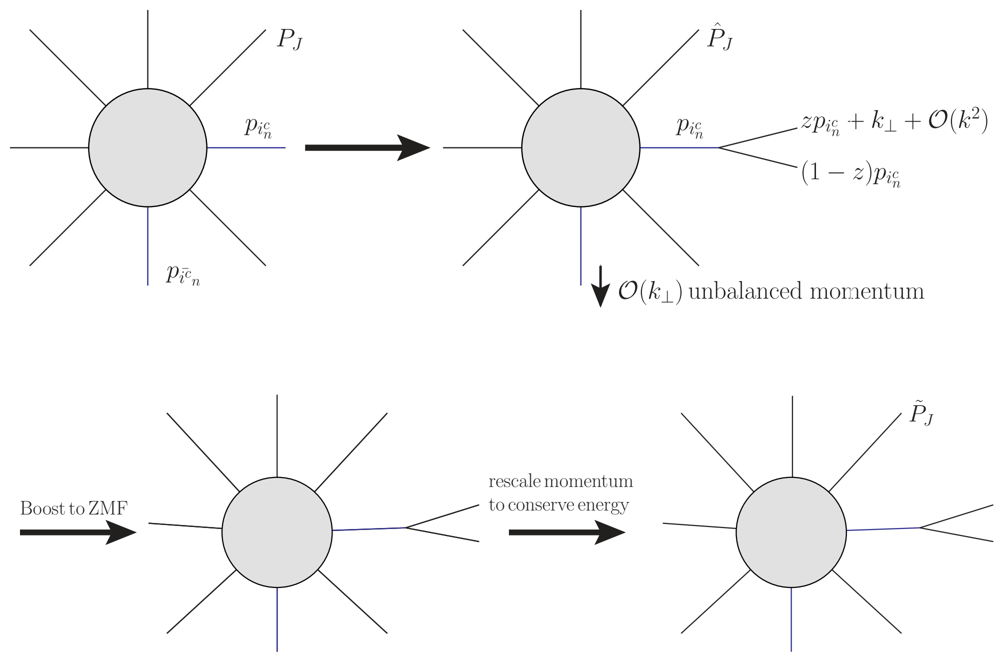
NLL$_{\text{global}}$/LL$_{\text{non-global}}$ showers

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



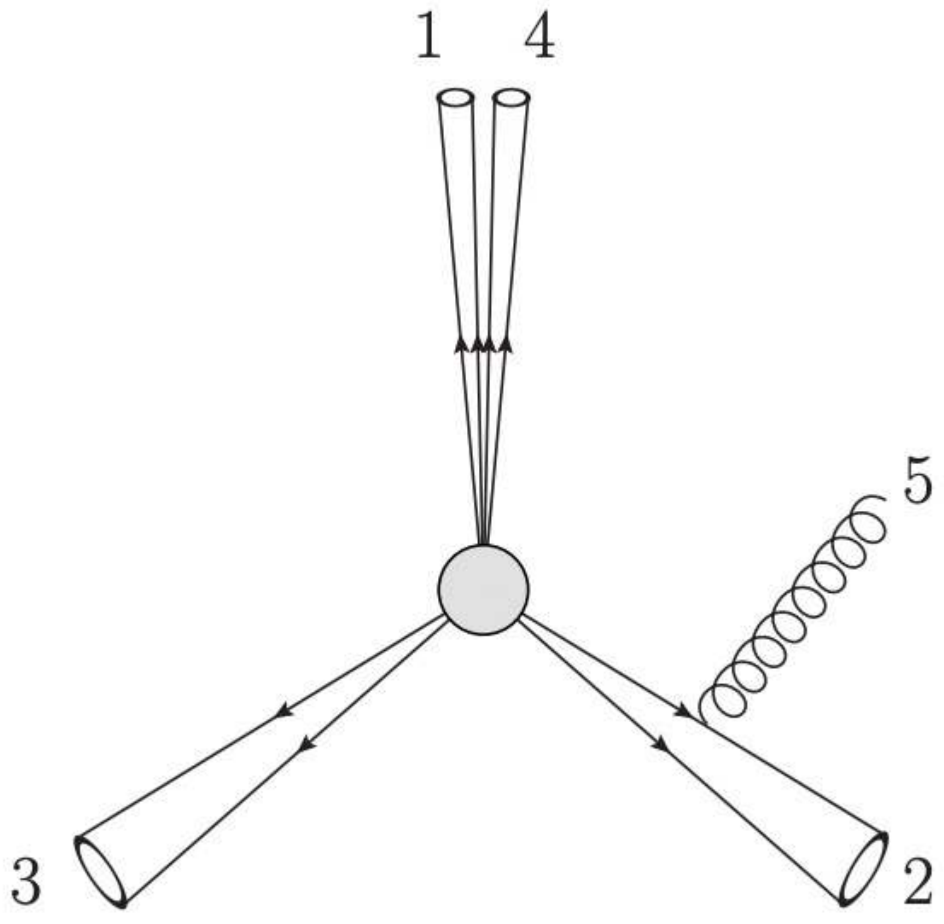
Recoil

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]

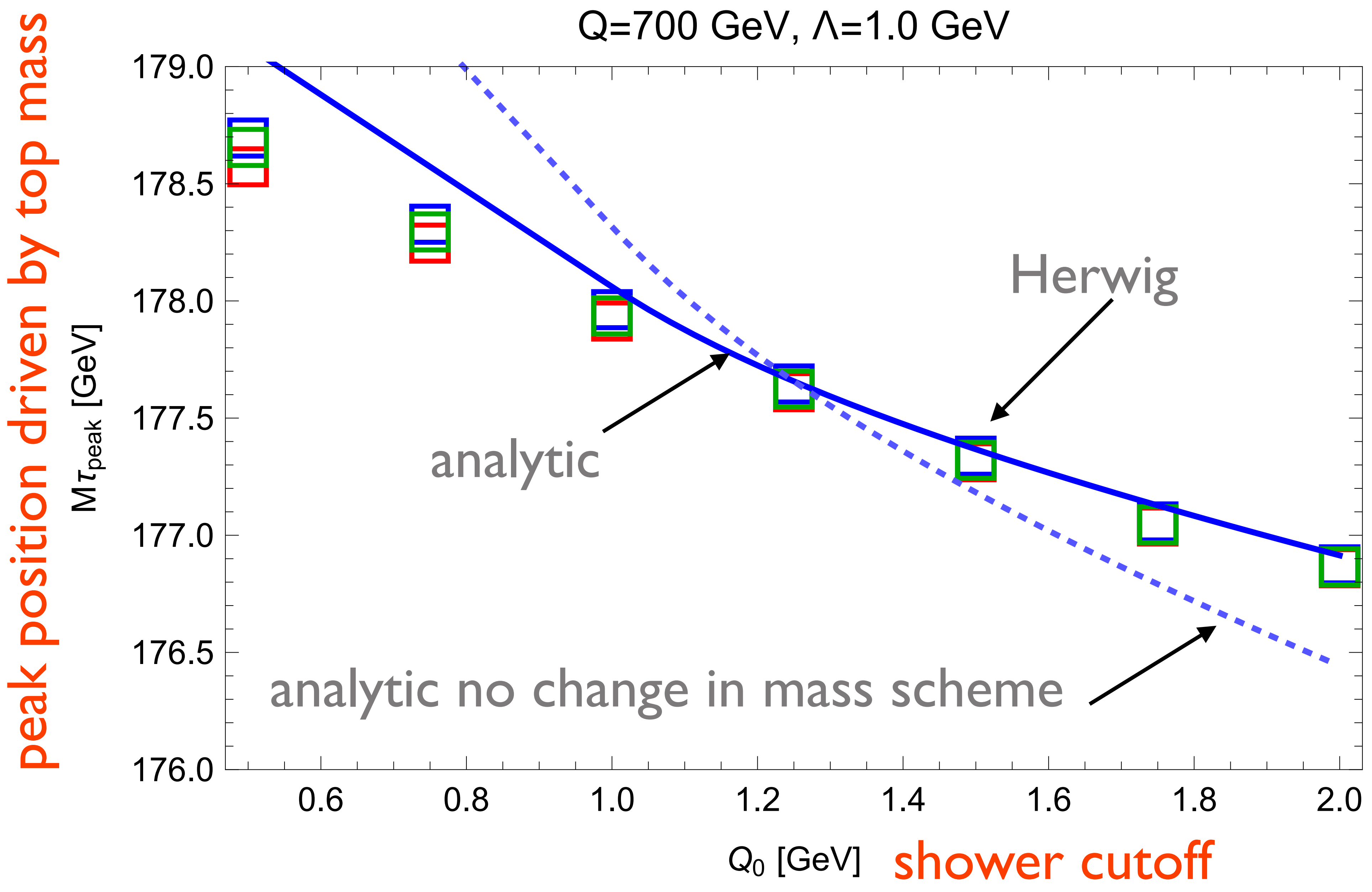
Where it (also) matters

Coherent branching jet mass including mass effects:

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

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

NLL accurate for global observables with massive quarks.



Top mass definition from coherent branching.

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

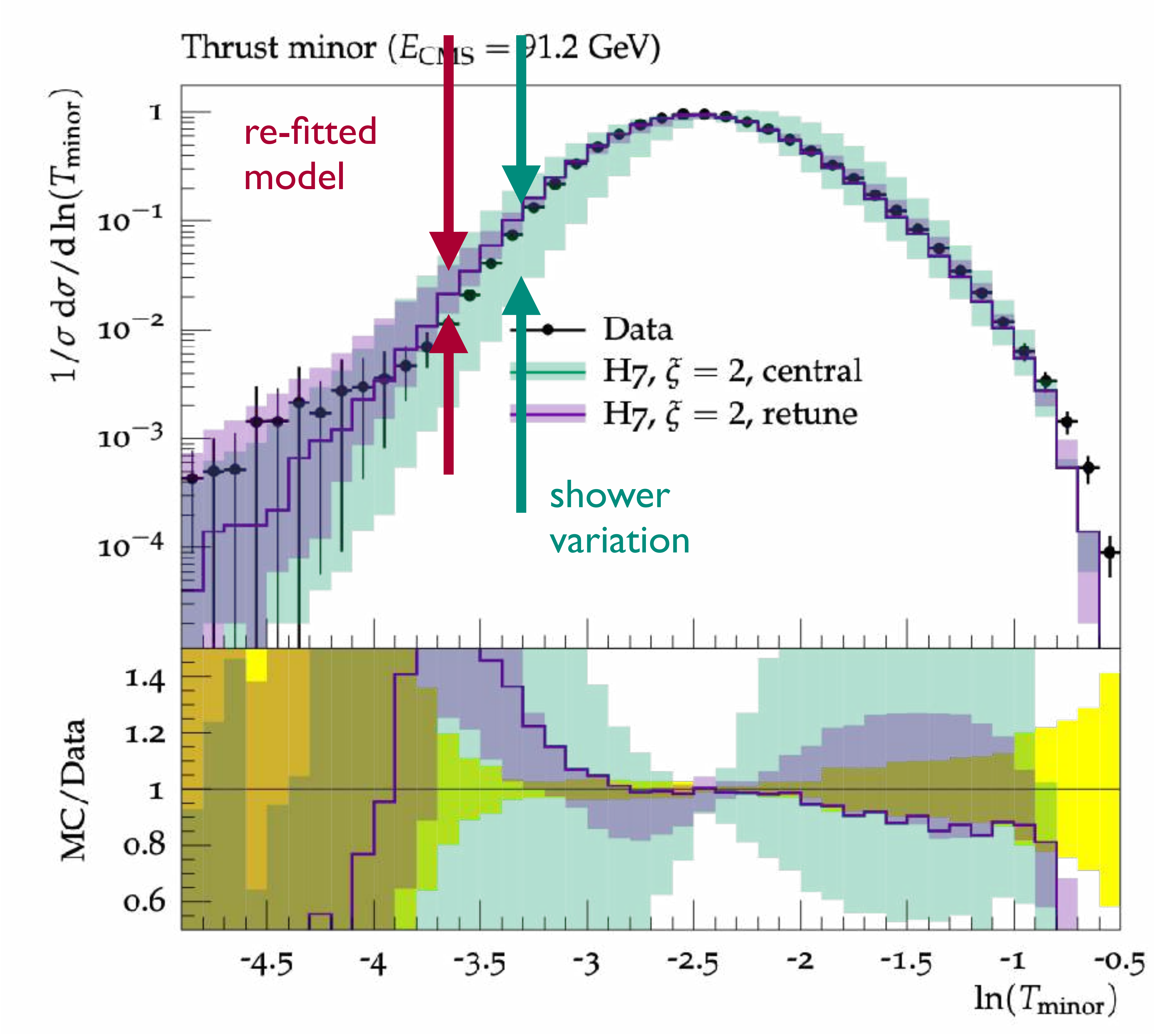
$$m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} + \Delta_m^{\mathrm{pert}} + \Delta_m^{\mathrm{non\text{-}pert}}$$

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

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

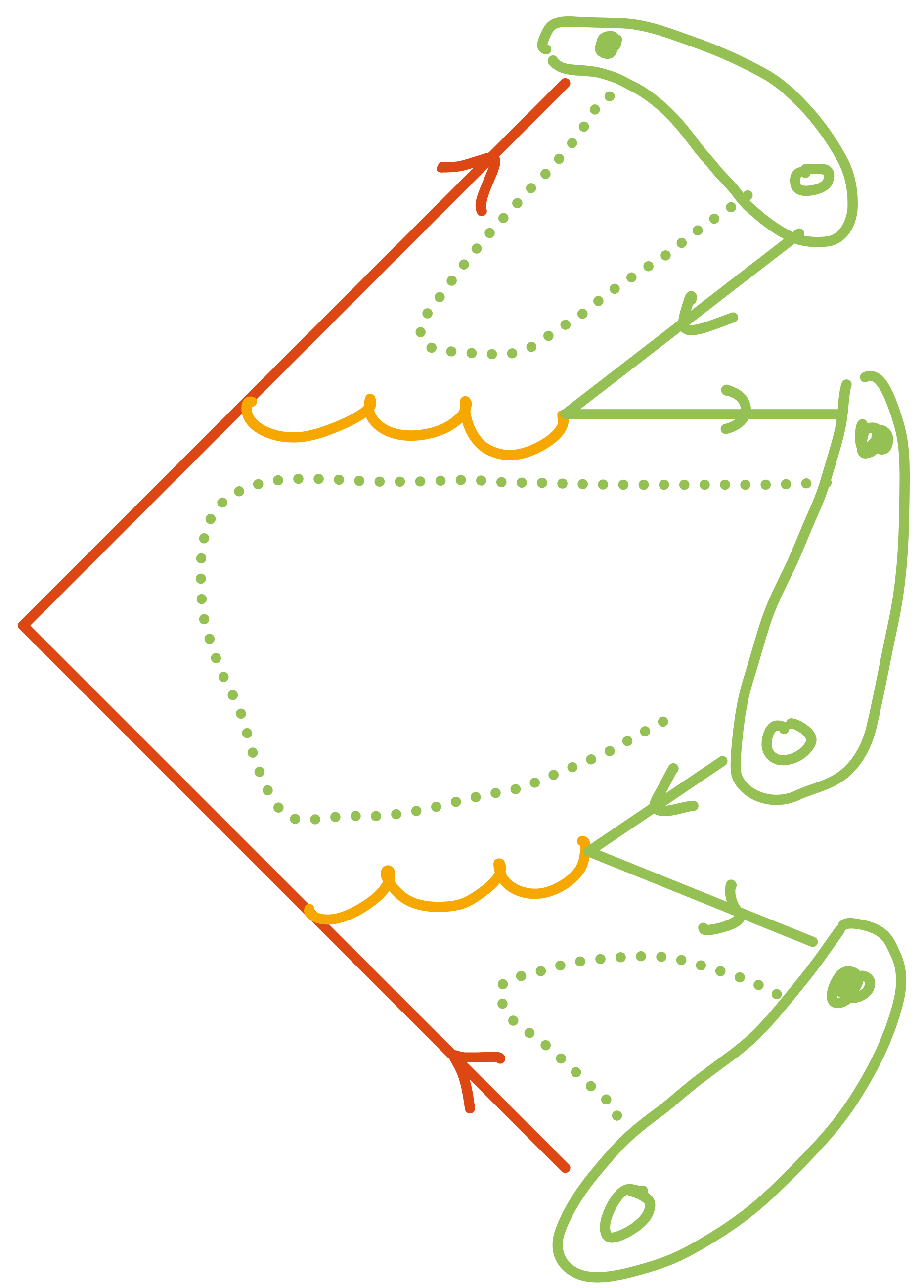
Hadronization?

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



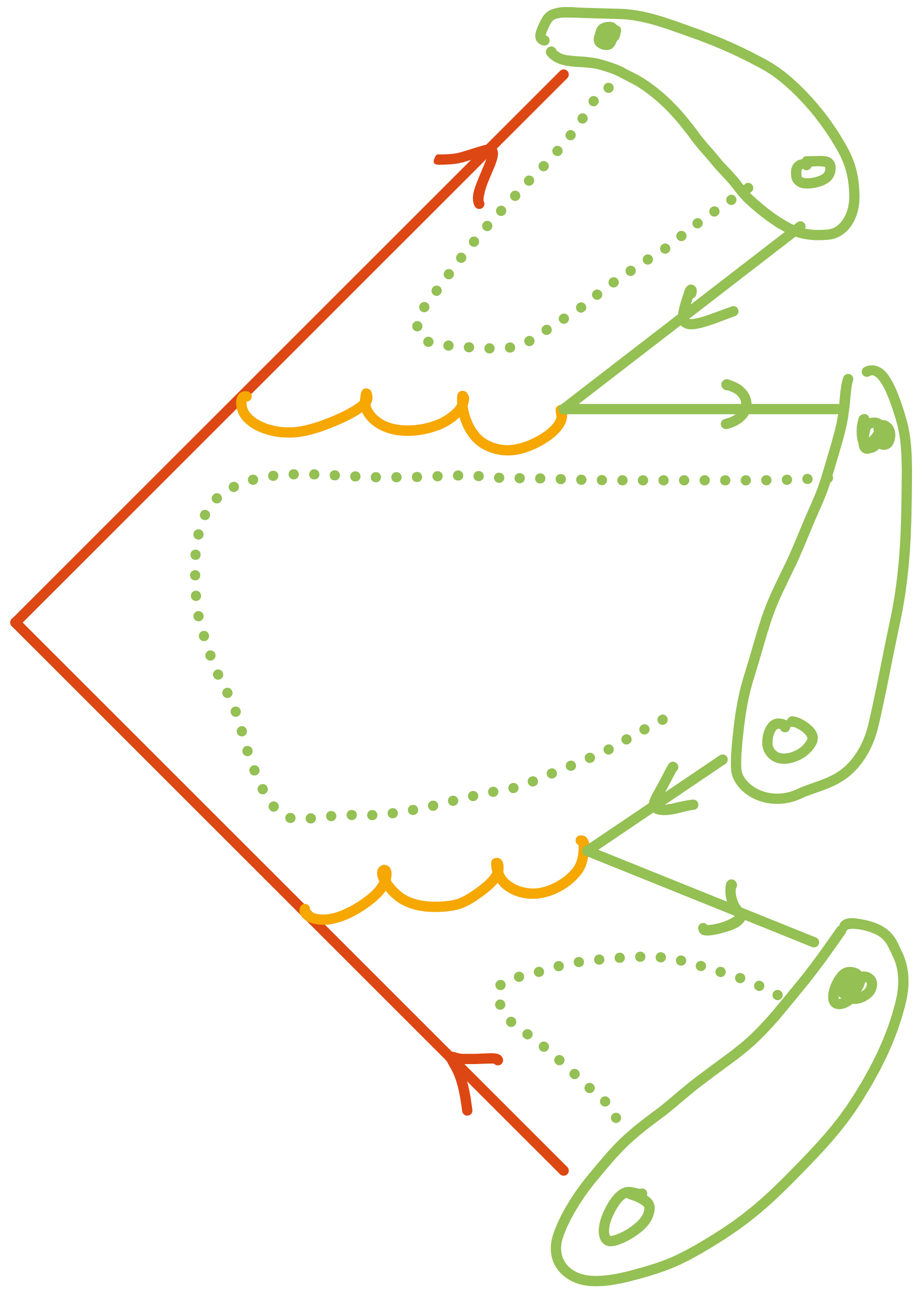
Hadronization

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

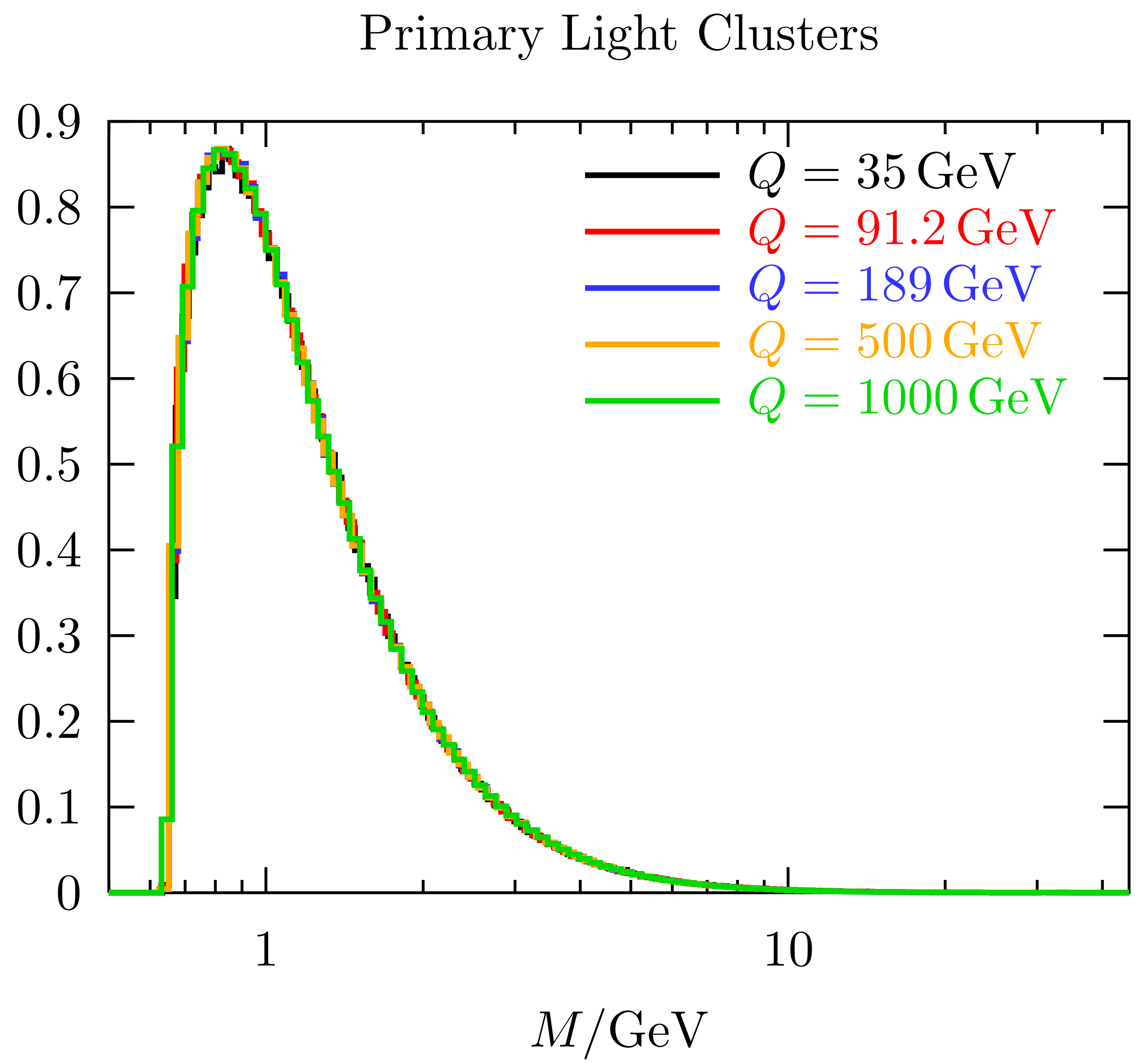


Hadronization

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



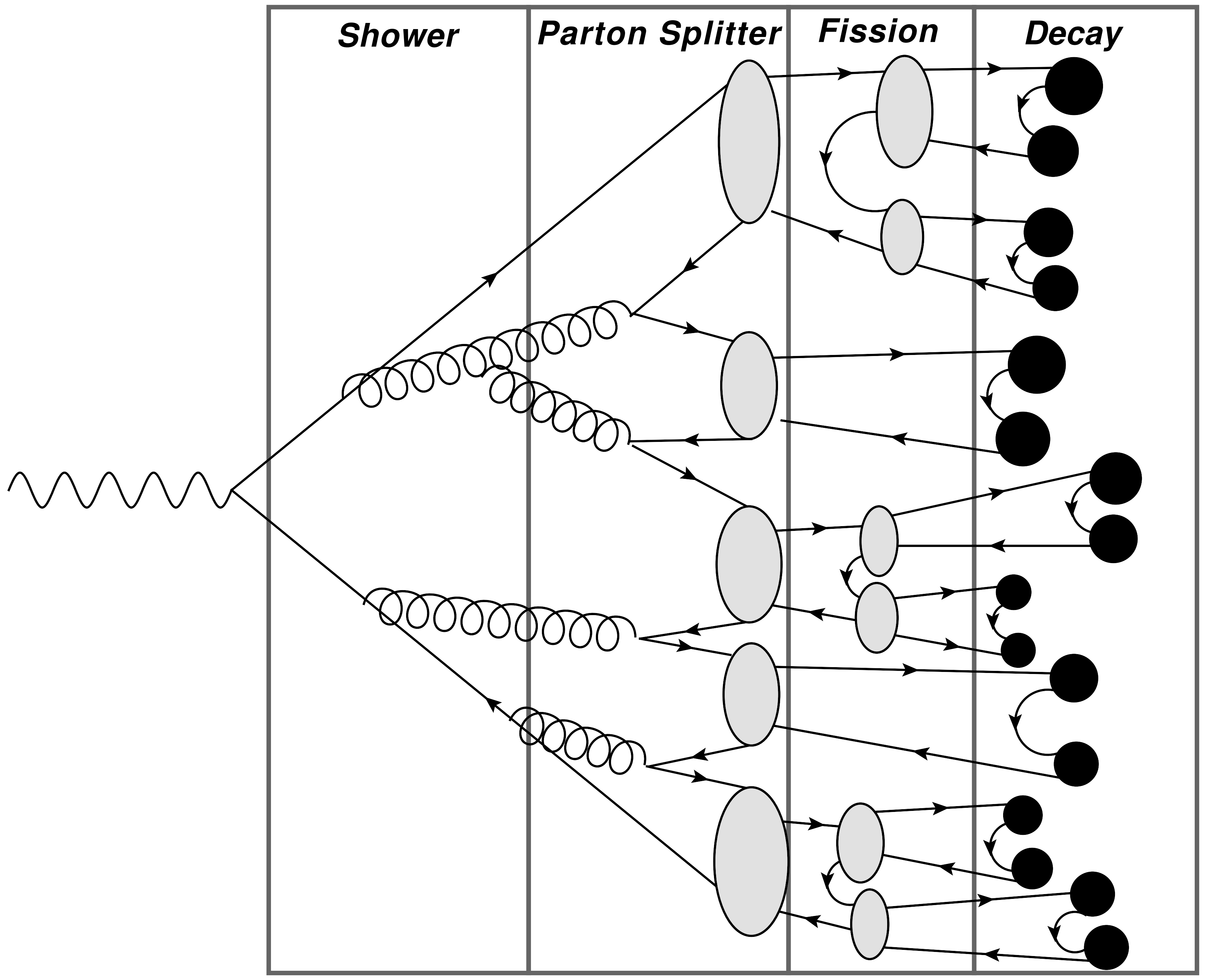
Universal cluster spectrum: pre-confinement.



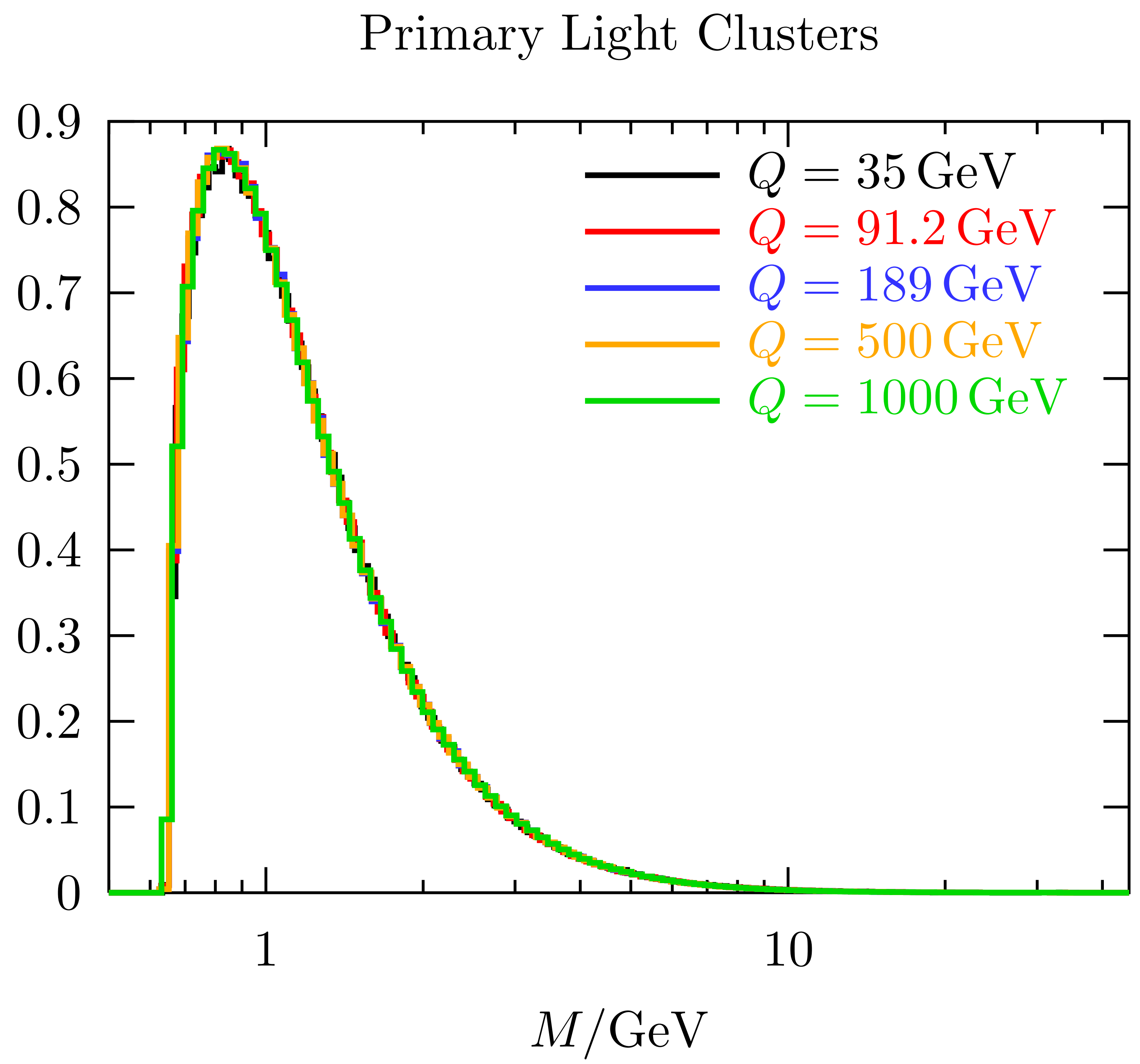
[Herwig++ 1.0 release — Gieseke et al. JHEP 02 (2004) 005]

Hadronization

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



Universal cluster spectrum: pre-confinement.



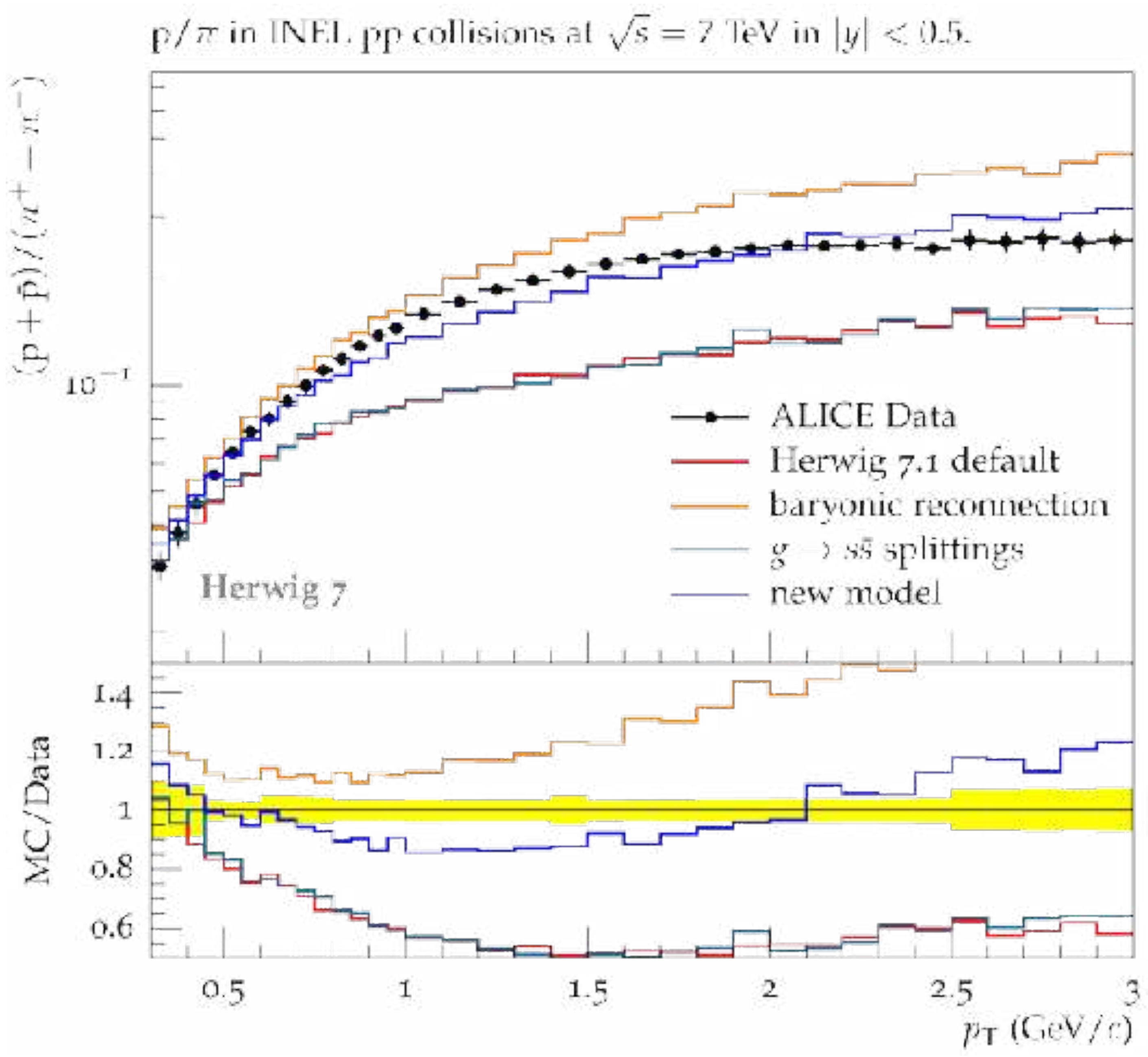
[Figure by Patrick Kirchgaesser]

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

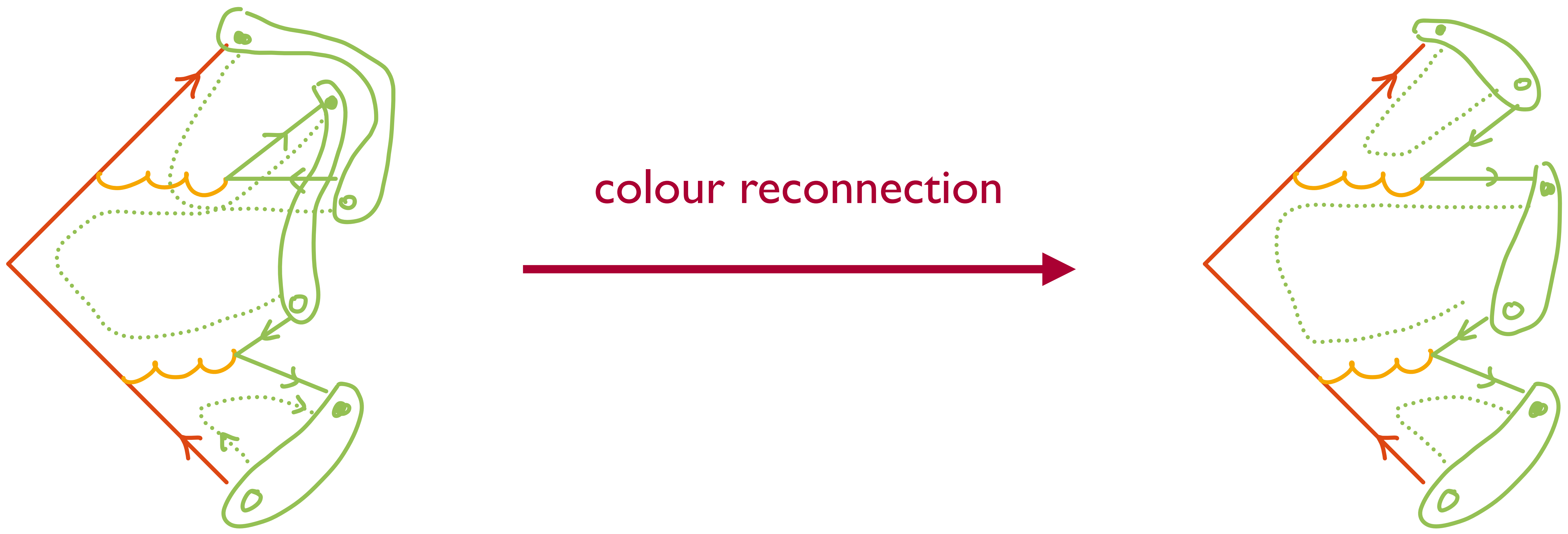
Colour Reconnection

Ignorance about colour correlations results in clusters which are too heavy.

proton yield



p_t



Most sophisticated algorithms in the cluster model now include baryons and non-trivial momentum information.

[Gieseke, Kirchgaesser, Plätzer – '18]
[Gieseke, Kirchgaesser, Plätzer, Siodmok – '18]

Factorisation and evolution

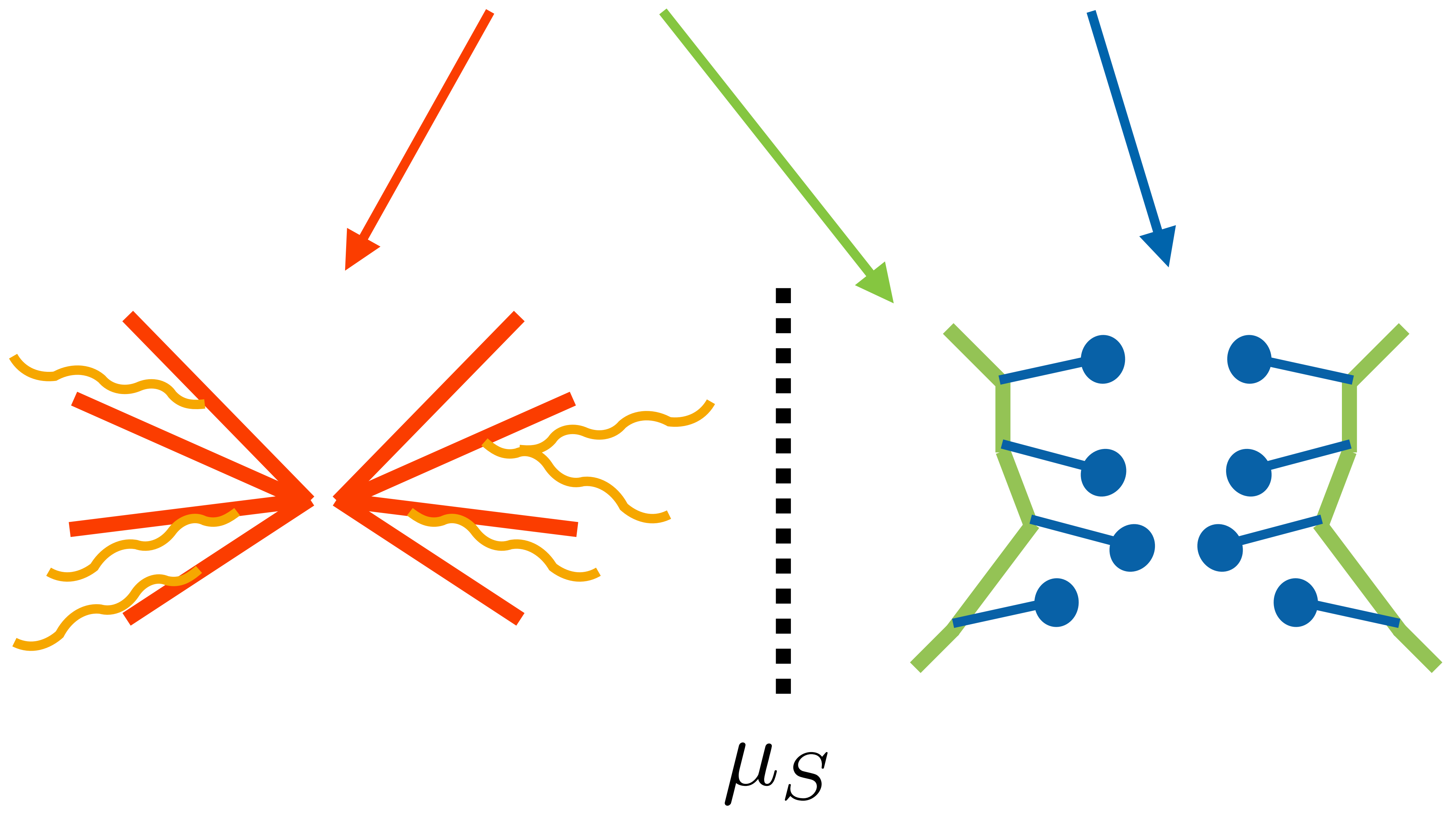
$$\sigma = \sum_{n,m} \int \int \mathrm{Tr}_n \left[\mathbf{M}_n \mathbf{U}_{nm}\right] \mathrm{d}\phi_m u(\phi_m)$$

[Plätzer – JHEP 07 (2023) 126]

Factorisation and evolution

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

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

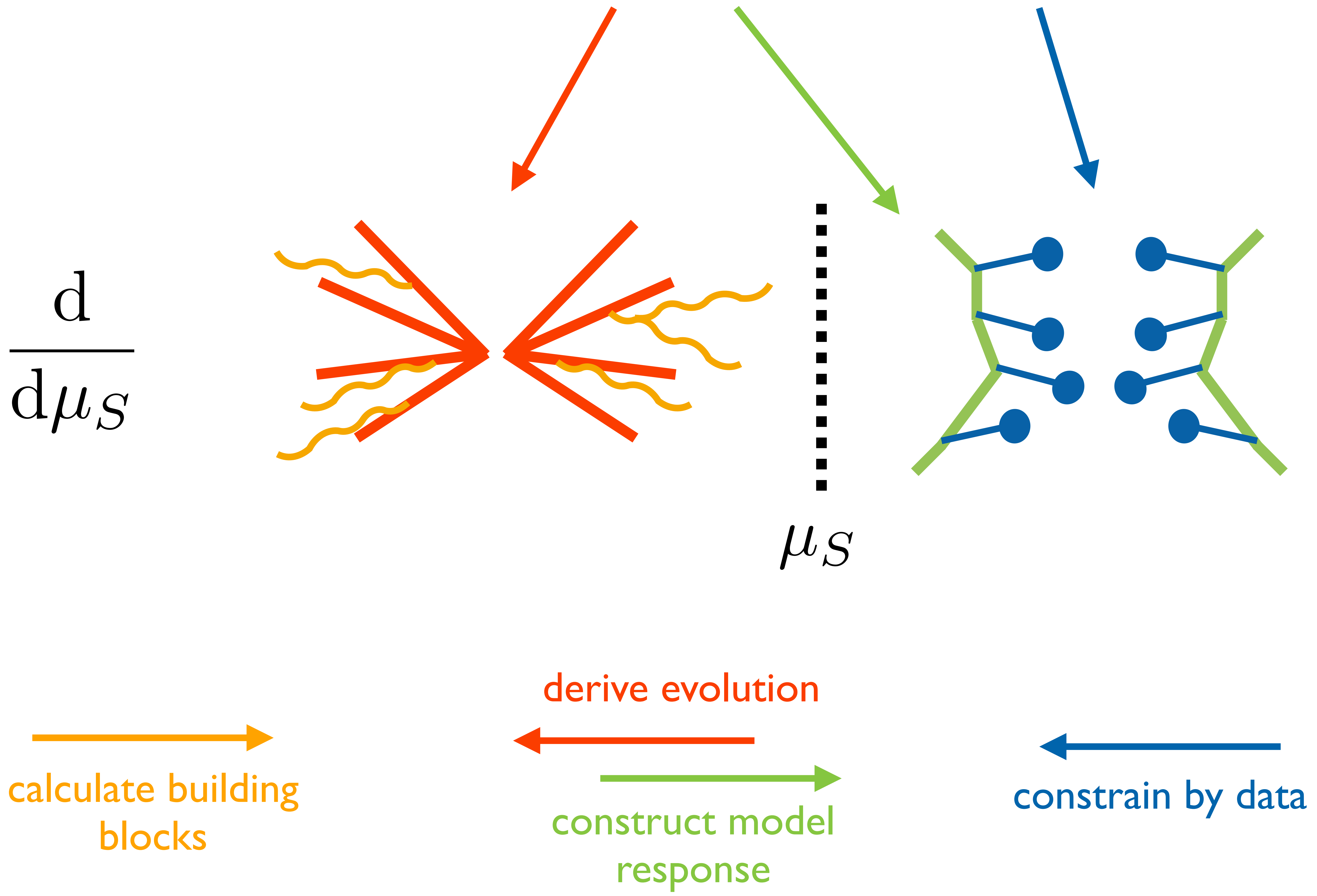


[Plätzer – JHEP 07 (2023) 126]

Factorisation and evolution

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

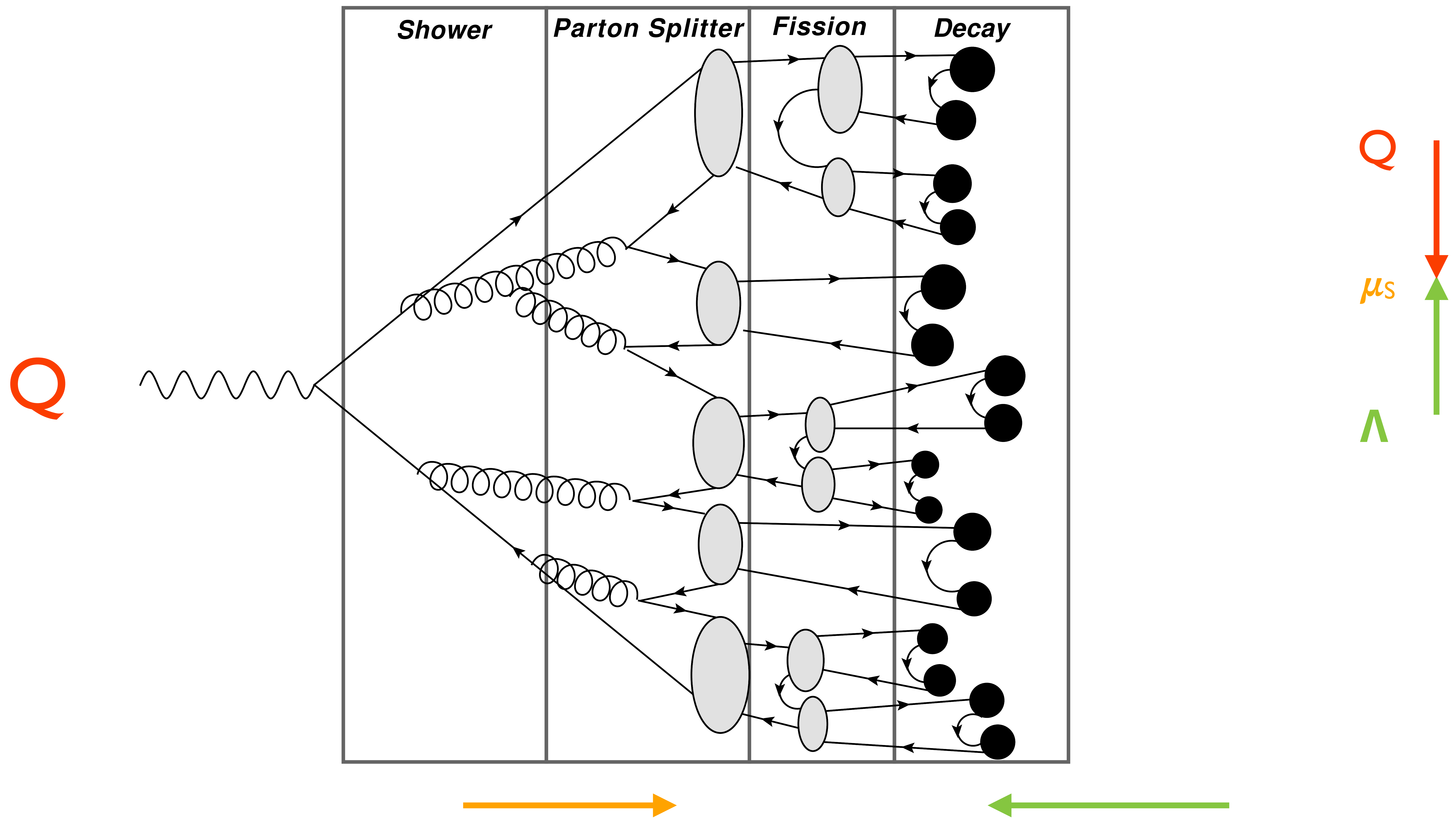
$$0 = \frac{\mathrm{d}}{\mathrm{d}\mu_S}$$



[Plätzer – JHEP 07 (2023) 126]

The interface to hadronization

[Plätzer – JHEP 07 (2023) 126]
[Hoang, Jin, Plätzer, Samitz — in preparation]

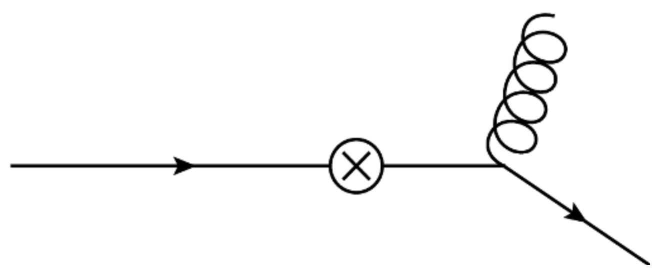
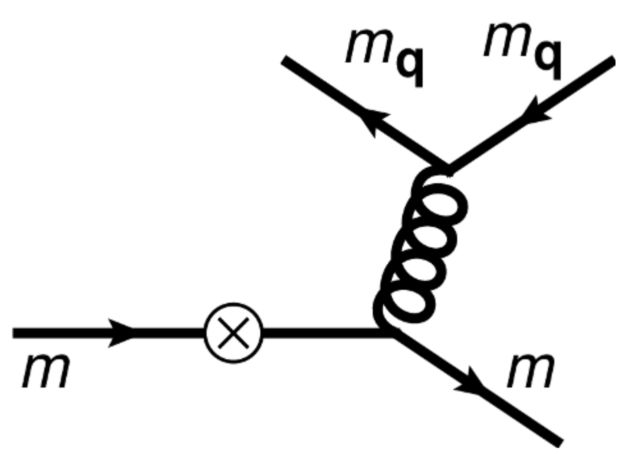
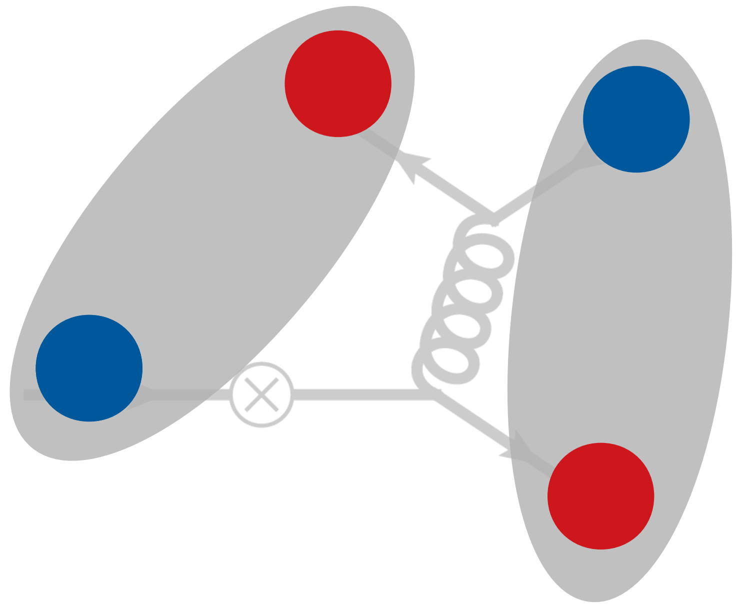
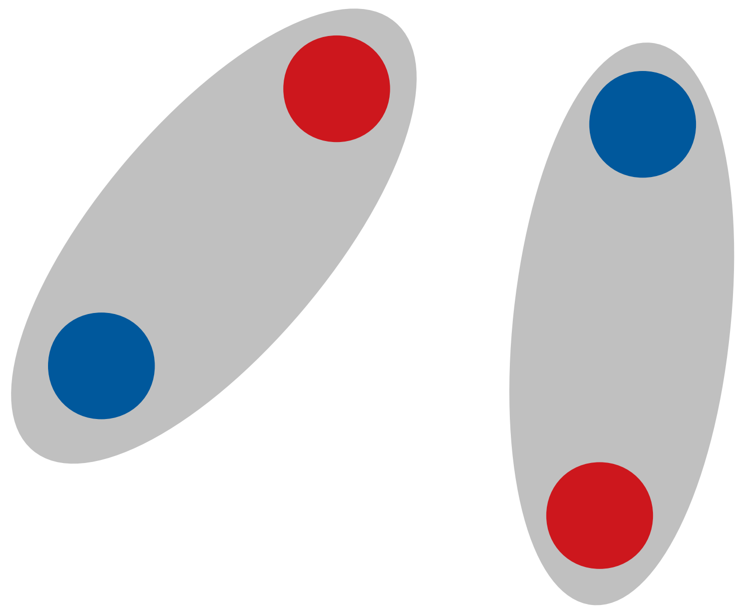
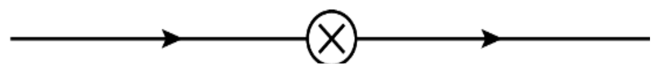
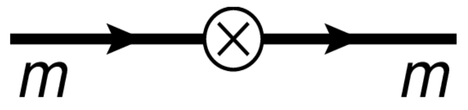
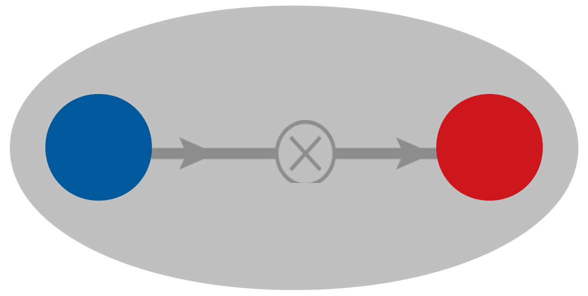
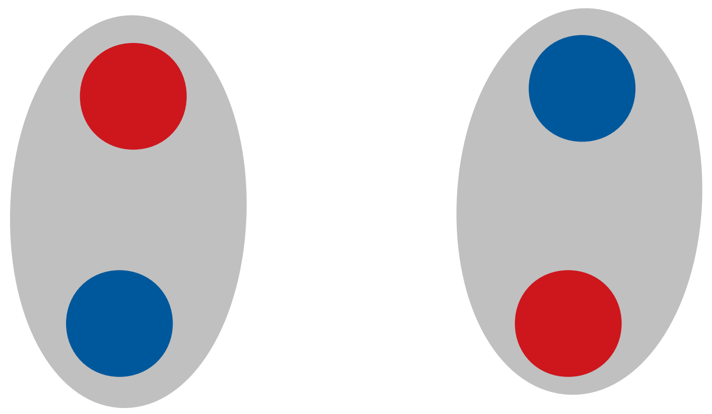


construct by cutoff response

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
			
			

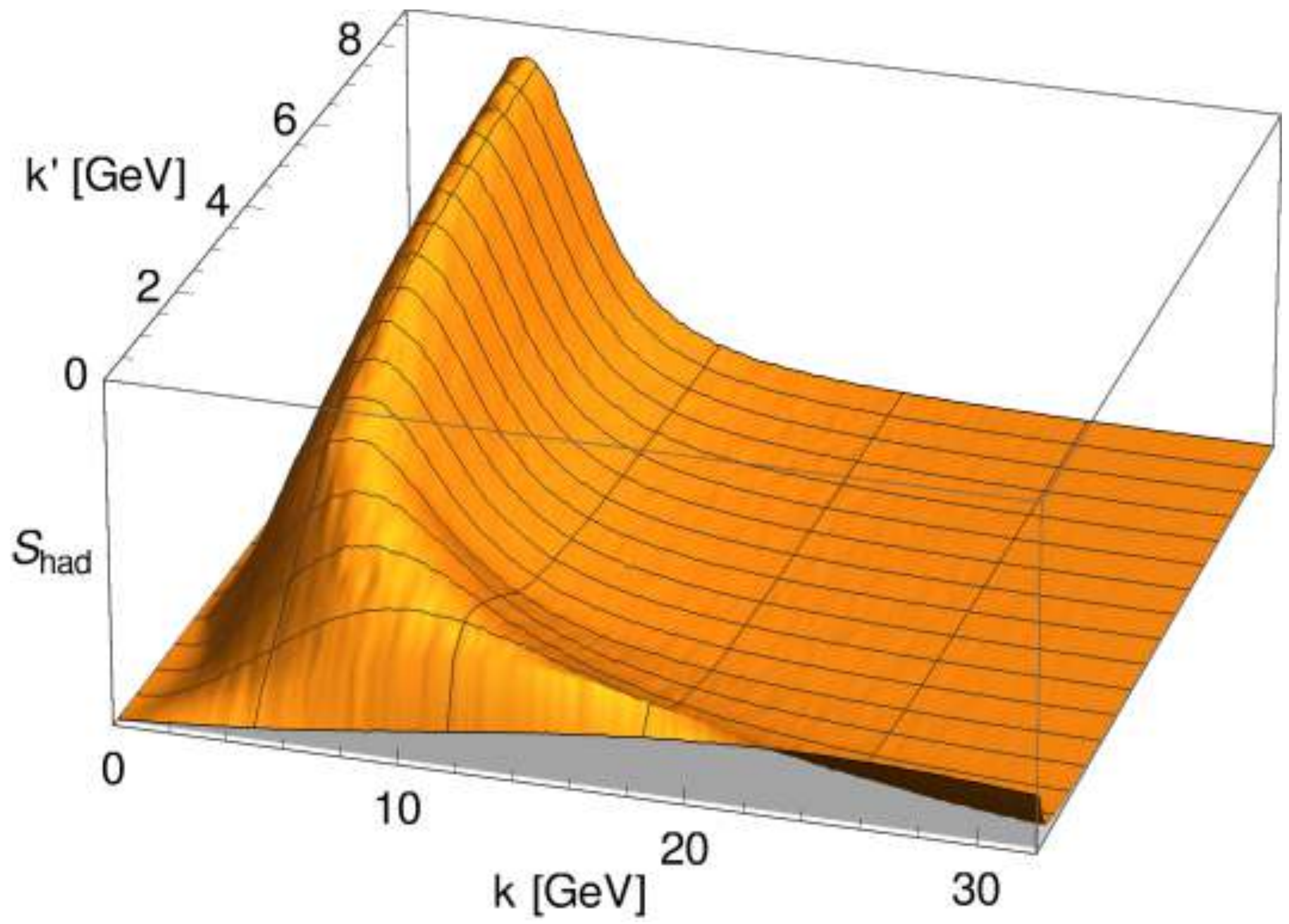
figures by Daniel Samitz

[Hoang, Jin, Plätzer, Samitz — in preparation]
[Gieseke, Kiebacher, Plätzer, Priedigkeit — in progress]

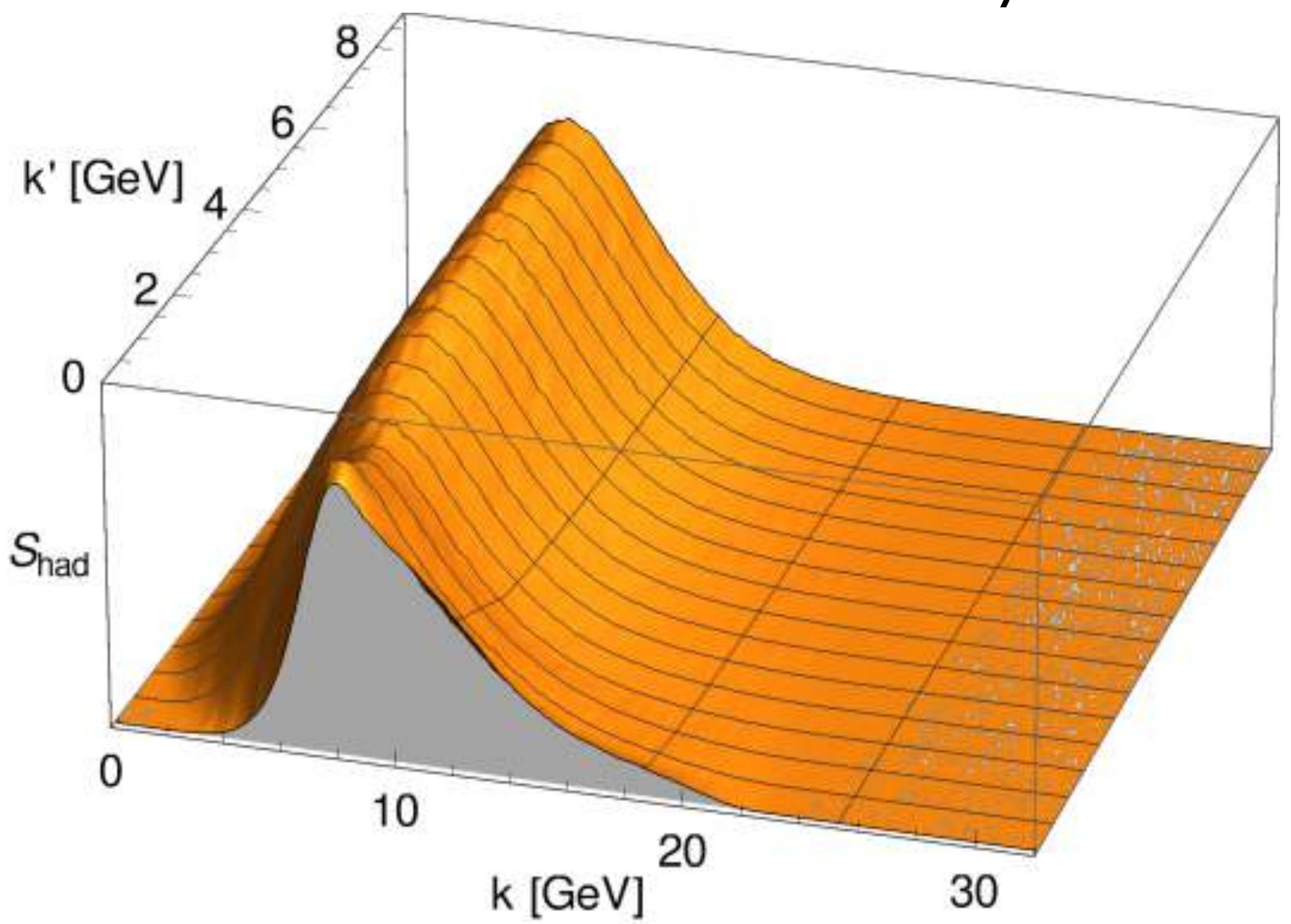
Tuning and hadronization corrections

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

default



dynamic



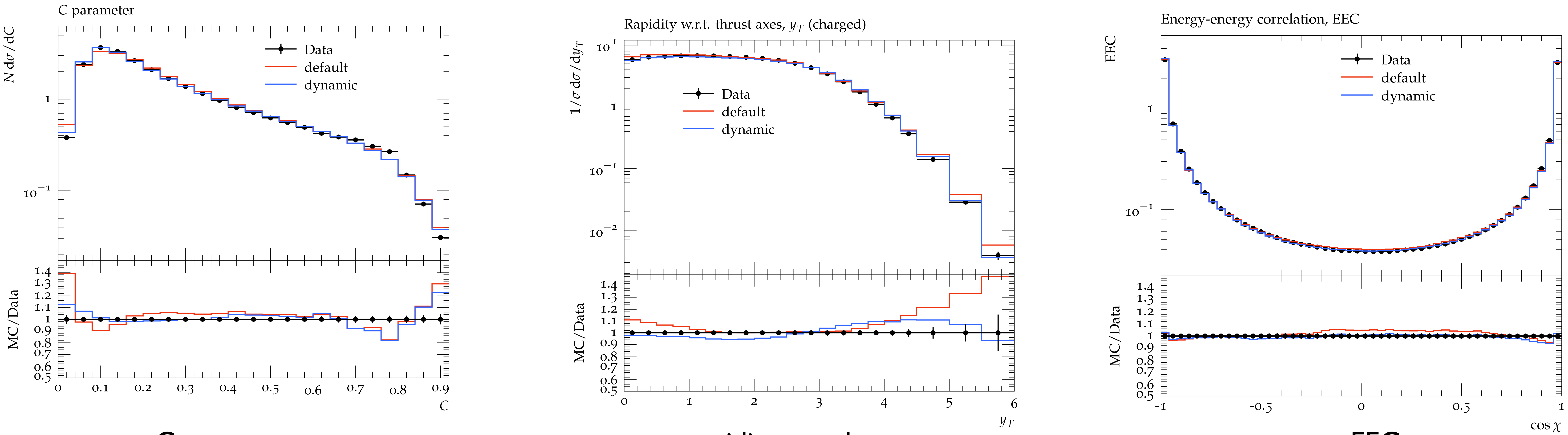
C parameter parton versus hadron level

[Hoang, Jin, Plätzer, Samitz — in preparation]

Tuning and hadronization corrections

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

Dedicated tunes show model improvement, general tunes comparable to old model.
In all tunes new dynamic model shows significantly reduced dependence on the infrared cutoff.



C parameter | rapidity wrt thrust | EEC

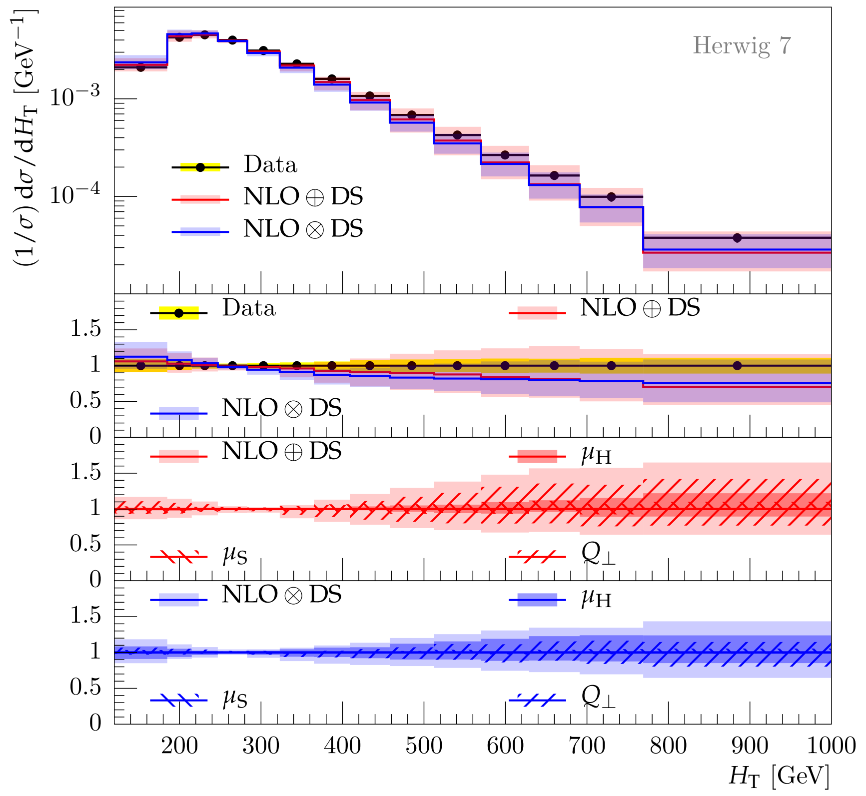
C parameter parton versus hadron level

[Hoang, Jin, Plätzer, Samitz — in preparation]

Summary

Herwig offers a significant amount of predicting top quark physics.

[Cormier, Plätzer, Reuschle, Richardson, Webster – Eur.Phys.J.C 79 (2019) 11]
[Richardson, Webster — Eur.Phys.J.C 80 (2020) 2]
[Plätzer, Sjödahl, Thoren – JHEP 11 (2018) 009]



Detailed control of matching with Matchbox is the backbone and working horse of consistent uncertainties with our showers.

(Further) developing shower accuracy, including massive quarks, is crucial for precision predictions. One of our main objectives, but cannot be looked at in isolation.

Second objective is hadronization, needed to seek a comprehensive and reliable uncertainty budget.

Impacts accurate and precise predictions, and interpretation of fundamental parameters. An understanding at amplitude level and subleading-N effects is unavoidable in this context.

Matching is also not out of focus, with many interesting developments regarding efficiency (negative weights) as well as systematics of matching and merging.

[Plätzer, Siodmok, Whitehead — in progress]

Thank you!

Herwig 7.3 just out — release note to appear

Please contact us at herwig@hepforge.org