UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ

Parton Showers

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

At the
QCD@LHC workshop
Freiburg | 7 October 2024

https://particle.uni-graz.at/en/event-generators-and-resummation/

UNIVERSITÄT GRAZ
UNIVERSITY OF GRAZ

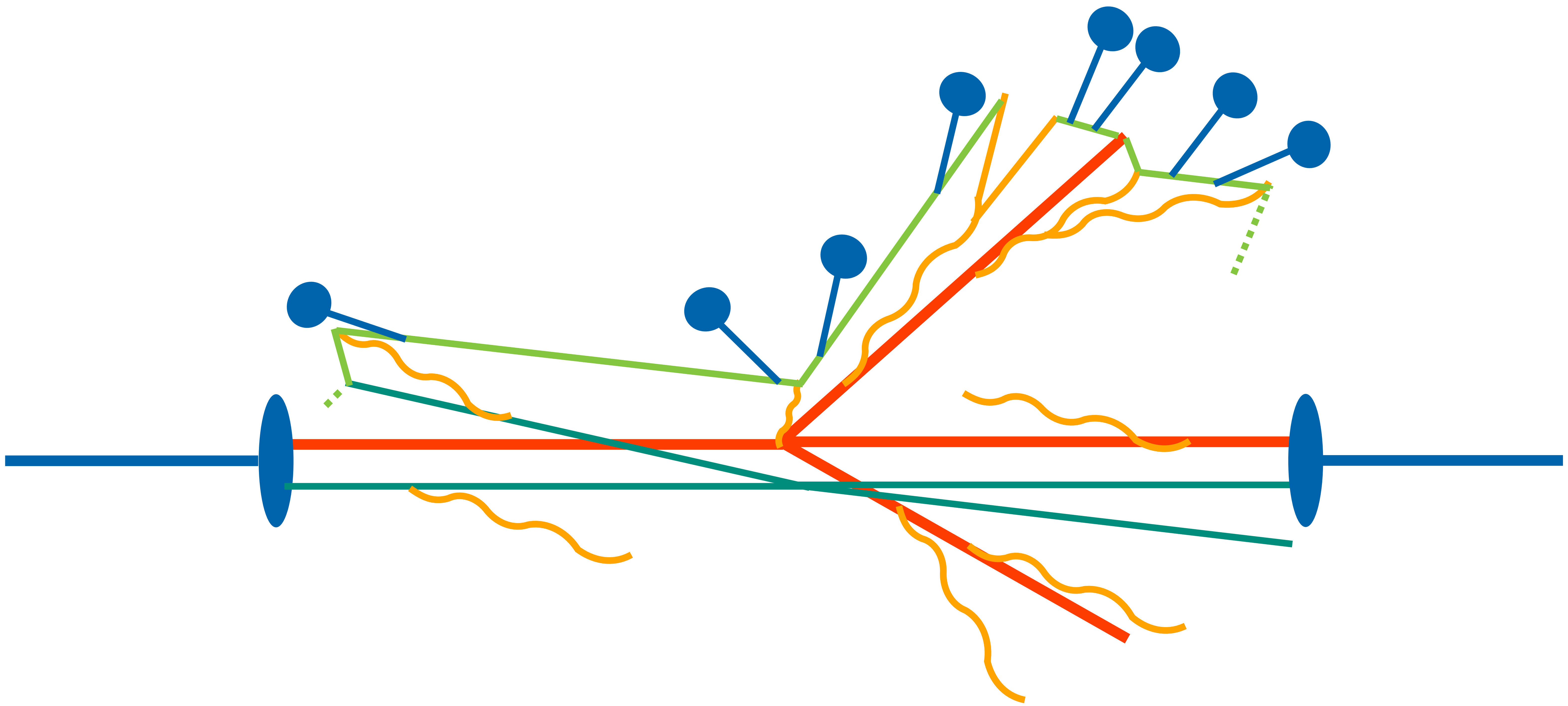
Parton Showers (& Hadronization)

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

At the
QCD@LHC workshop
Freiburg | 7 October 2024

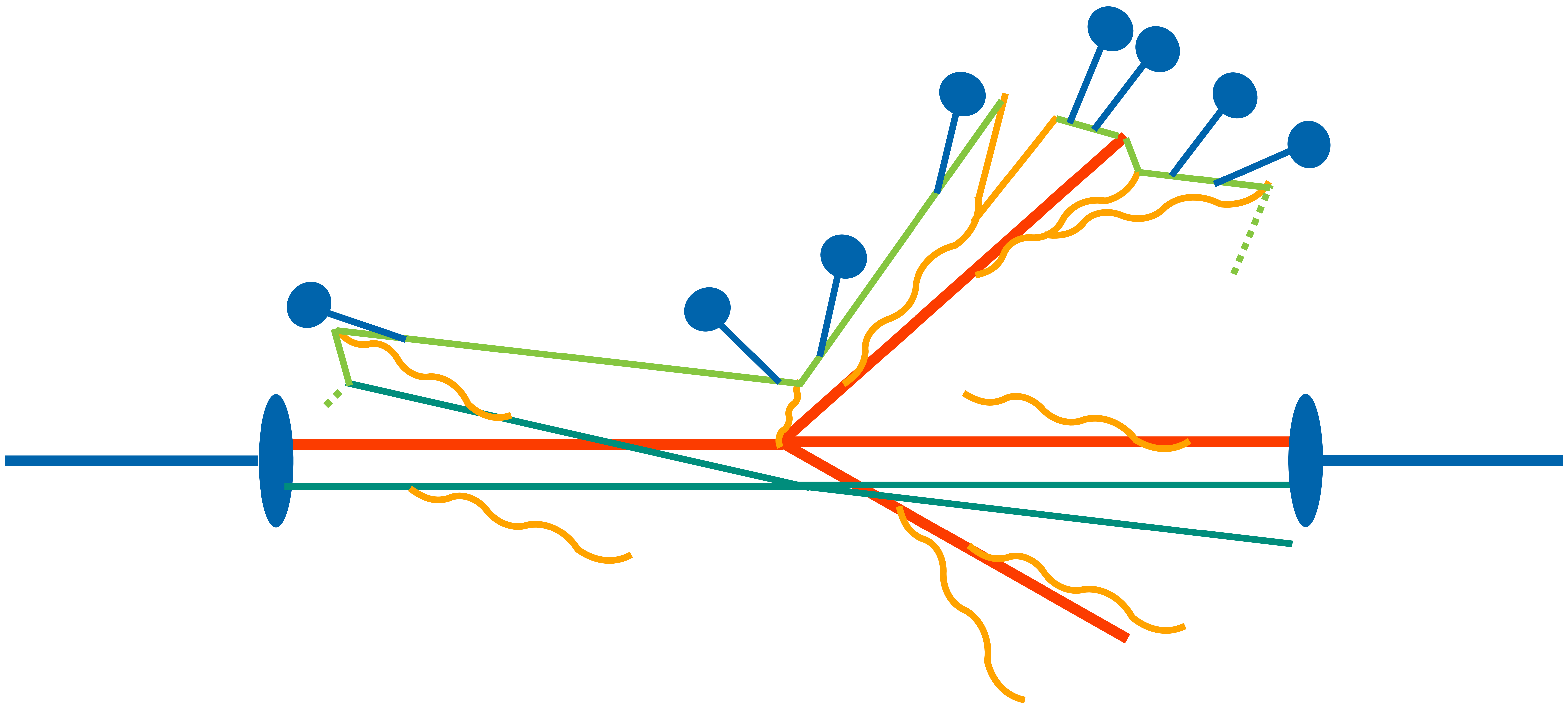
https://particle.uni-graz.at/en/event-generators-and-resummation/

Setting the scene



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

Setting the scene

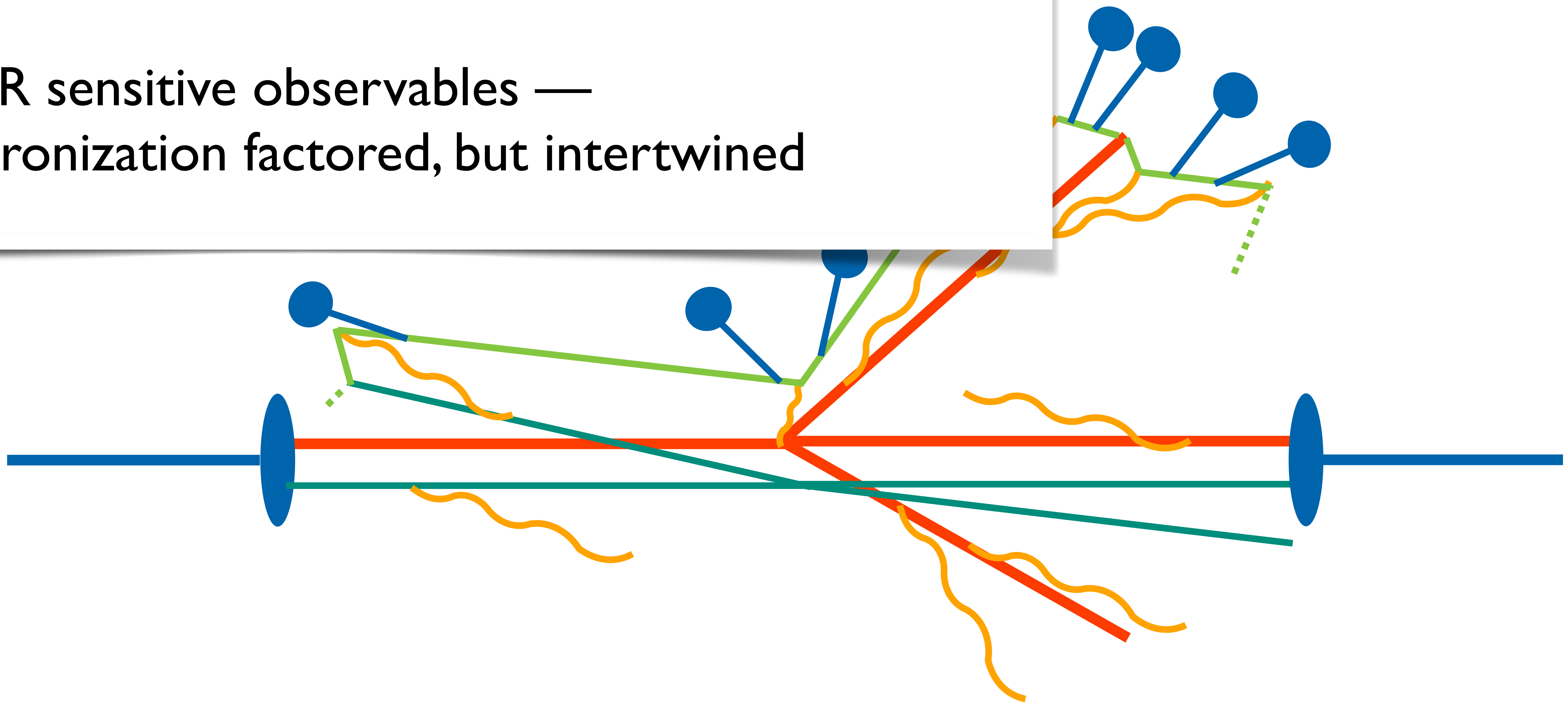


$$d\sigma \sim L \times d\sigma_H(Q) \times PS(Q \to \mu) \times MPI \times Had(\mu \to \Lambda) \times \ldots$$

Setting the scene

Central for realistic description of the observed complexity.

Description of IR sensitive observables —
shower and hadronization factored, but intertwined

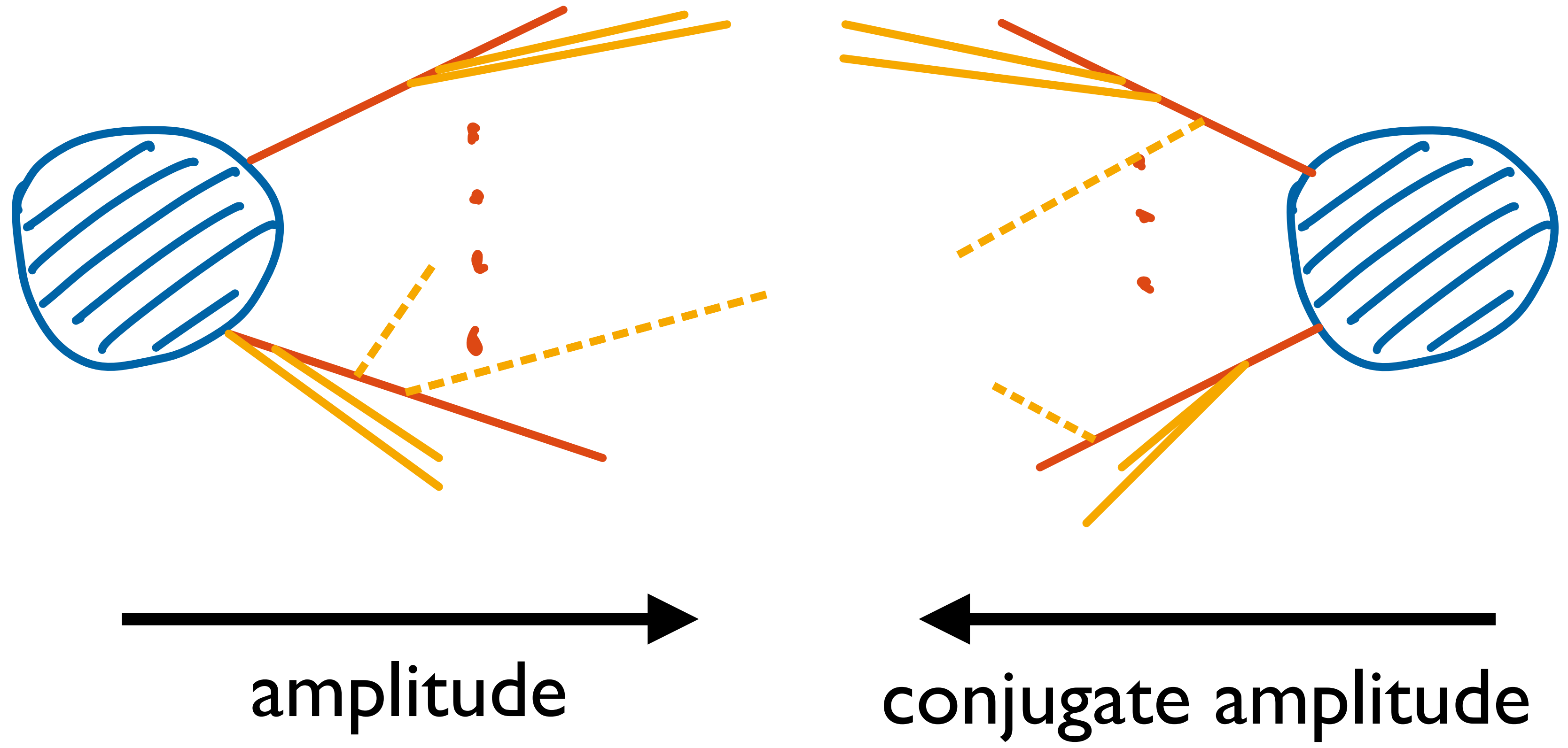


100's of GeV — 1-2 GeV — few 100's MeV

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

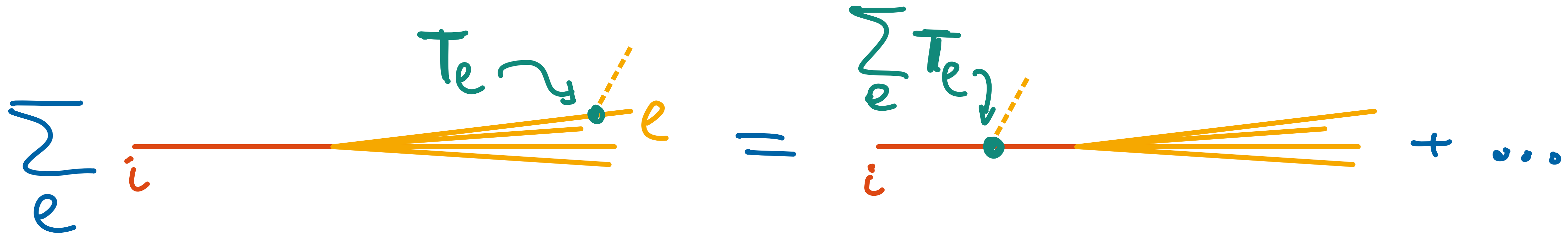
Probabilistic algorithms with QCD coherence or large-N limit

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



$$\sim \mathcal{M}_n^{+}(p_1,\ldots,p_n)\, \mathbf{T} \cdots \mathbf{T} \circ \mathbf{T} \cdots \mathbf{T}\, \mathcal{M}_n(p_1,\ldots,p_n)$$

Exploit QCD coherence:



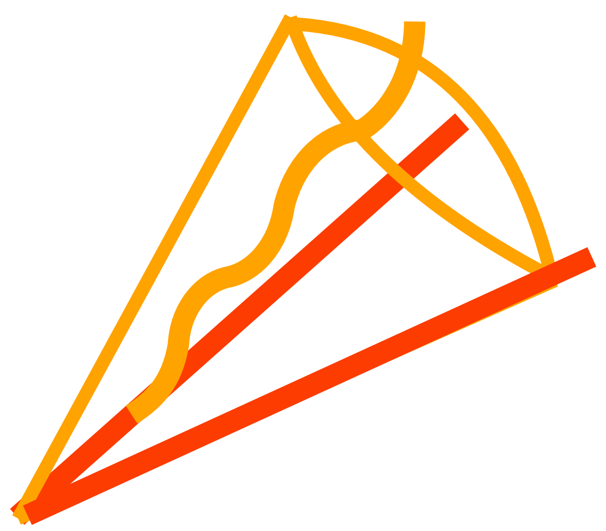
$$\mathrm{d}S = \frac{\alpha_s}{2\pi}\frac{\mathrm{d}\tilde{q}_i^2}{\tilde{q}_i^2}\mathrm{d}z P(z_i) \exp\left(-\int_{\tilde{q}_i^2}^{Q^2}\frac{\mathrm{d}q^2}{q^2}\int_{z_-(k^2)}^{z_+(k^2)}\mathrm{d}\xi\frac{\alpha_s}{2\pi}P(z)\right)$$

emission rate

no emission probability

All probabilistic algorithms determine the effect of gluon exchange and virtual corrections by unitarity.

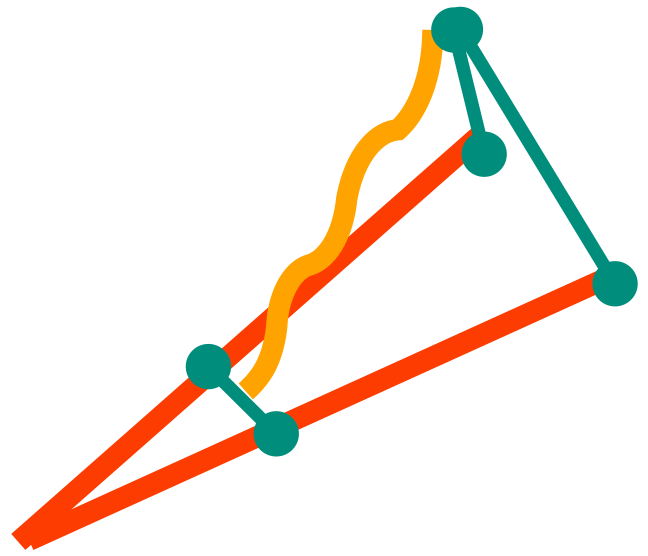
Favorite probabilistic algorithms



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

Current release	Hard matrix	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, ALARIC	Internally automated	Internally automated	Eikonal	Clusters, Strings	Yes

Plethora of approaches to compare — need to go beyond in understanding and controlling shower algorithms.

Main lines of current parton shower research

Shower development is a broad field, fortunately back on the agenda.
Hadronziation is not exactly shower development, but enters at a similar level,

See Schumann's talk. Always needs to accompany shower development.

Matching/Merging

Control and demonstration of perturbative accuracy.

(N)NLL accuracy

Description of electroweak effects and BSM scenarios.

Interactions beyond QCD

Amplitude evolution

Genuine quantum effects: not limited to subleading colour.

Hadronization

Comprehensive, factorized picture and construction of algorithms.

Remaining focus of this talk:

- Perturbative accuracy
- Beyond probabilistic algorithms.
- Factorisation and hadronization.

The struggle with QED, EW and other interactions

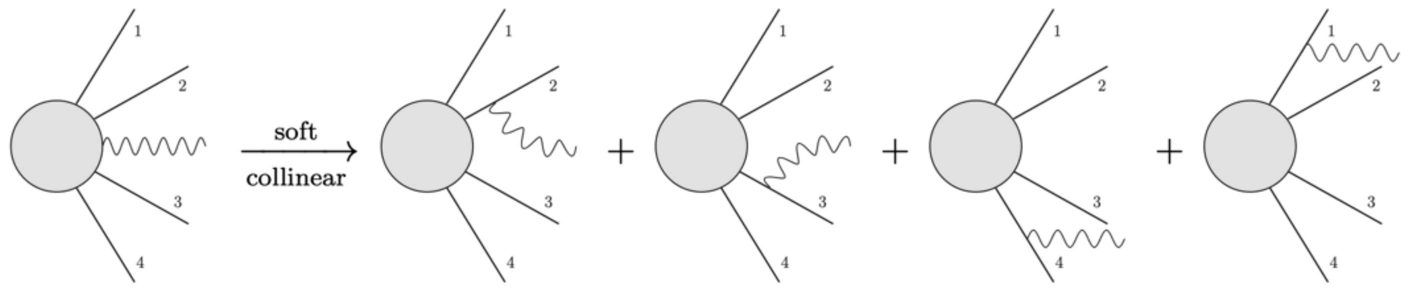
- The absence of a large-N limit forces us to question existing structures
- Accuracy from interleaving with QCD needs to be carefully addressed
- The inner workings and role of coherence is entirely unknown

Interactions beyond QCD

Halfway safe ground in the quasi-collinear limit, should be exploring these algorithms.
Spin correlations are vital — amplitude evolution will be crucial to build algorithms.

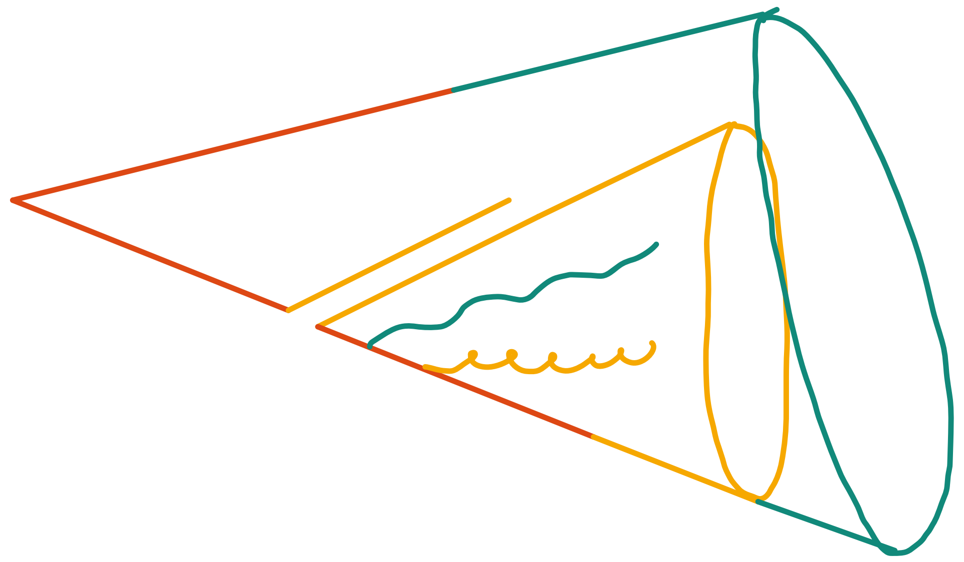
Recent examples:

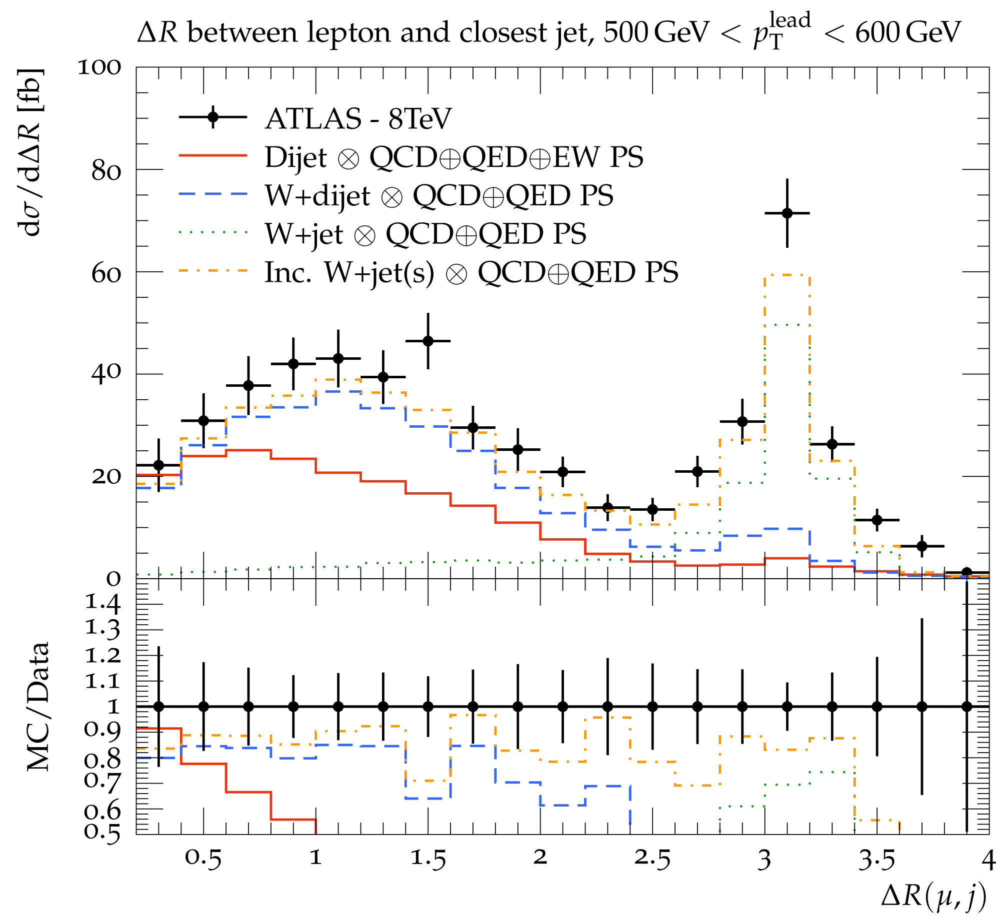
Sectorised QED multipoles and electroweak splittings in VINCIA



[Verheyen, Skands— '21]

Multiscale interleaved angular ordering in Herwig





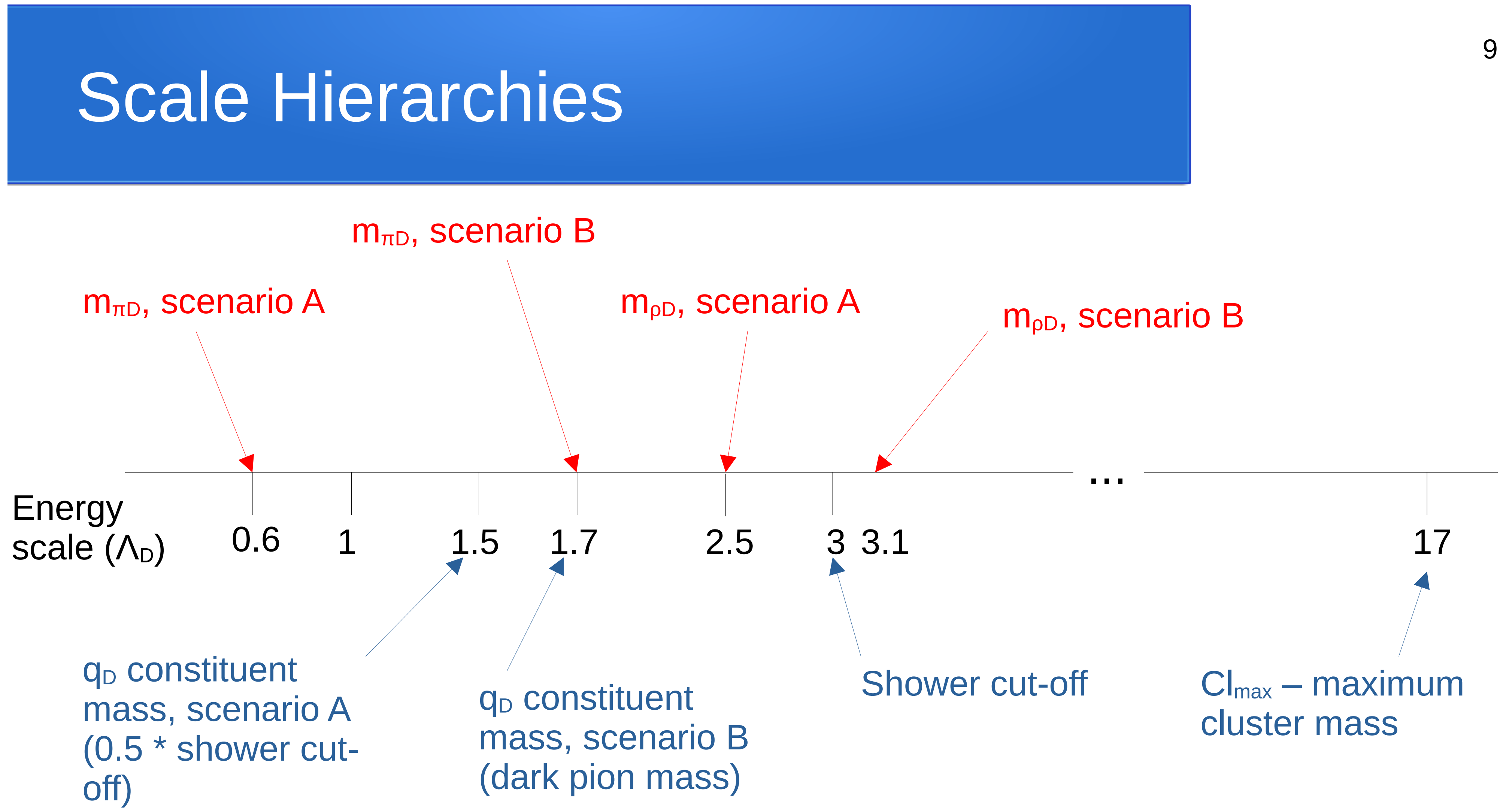
[Masouminia, Richardson — '21]

Dark sector showers

Interactions beyond QCD

QCD-like dark sectors can in principle build on existing QCD showering. Hadronization and scale hierarchy can differ significantly: no safe territory.

New in Herwig and the cluster model — more investigations and pheno to follow.

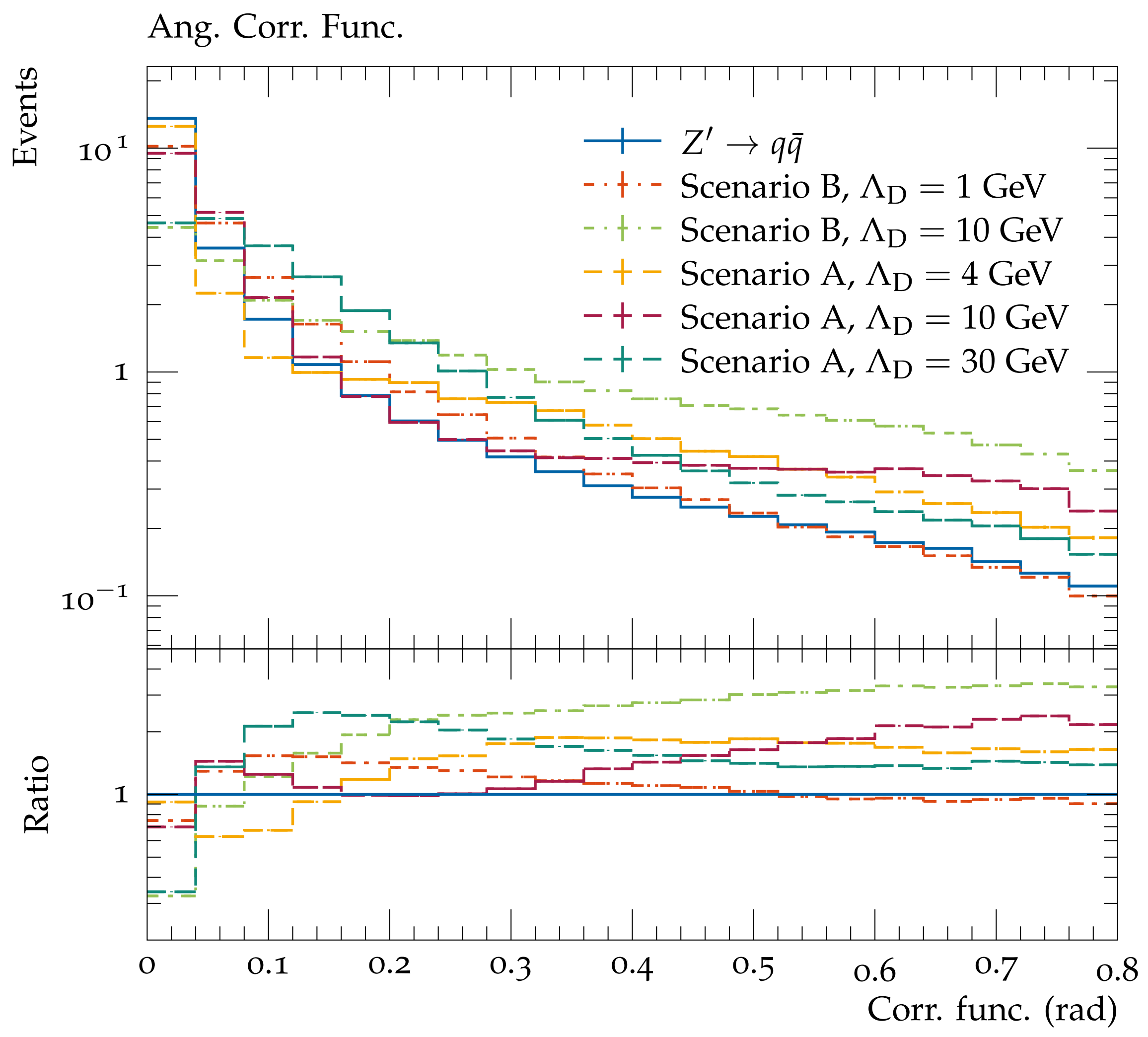


[Stafford at PSR ’24]

Angularities, correlations … extremely useful observables.

[See also recent Les Houches study (in progress) and Kiebacher @ PSR ’24].

$$EEC^{\gamma}(\rho) = \frac{1}{N_\gamma} \sum_{i<j\in \mathrm{jet}} (E_i E_j)^{\gamma} \delta(\Delta R_{ij} - \rho)$$



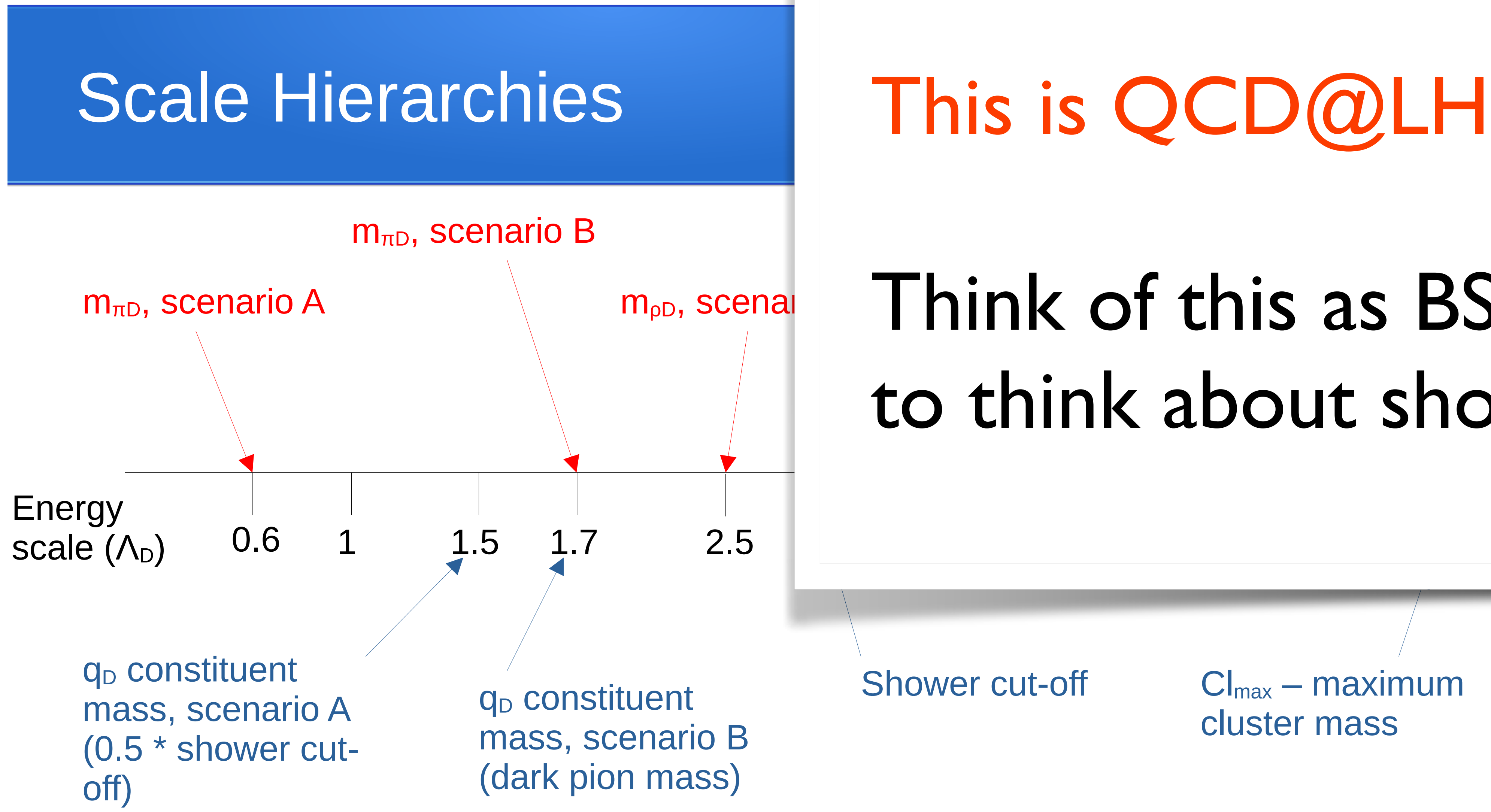
[Kulkarni, Masouminia, Plätzer, Stafford — ’24]

Dark sector showers

Interactions beyond QCD

QCD-like dark sectors can in principle build on existing QCD showering.
Hadronization and scale hierarchy can differ significantly: no safe territory.

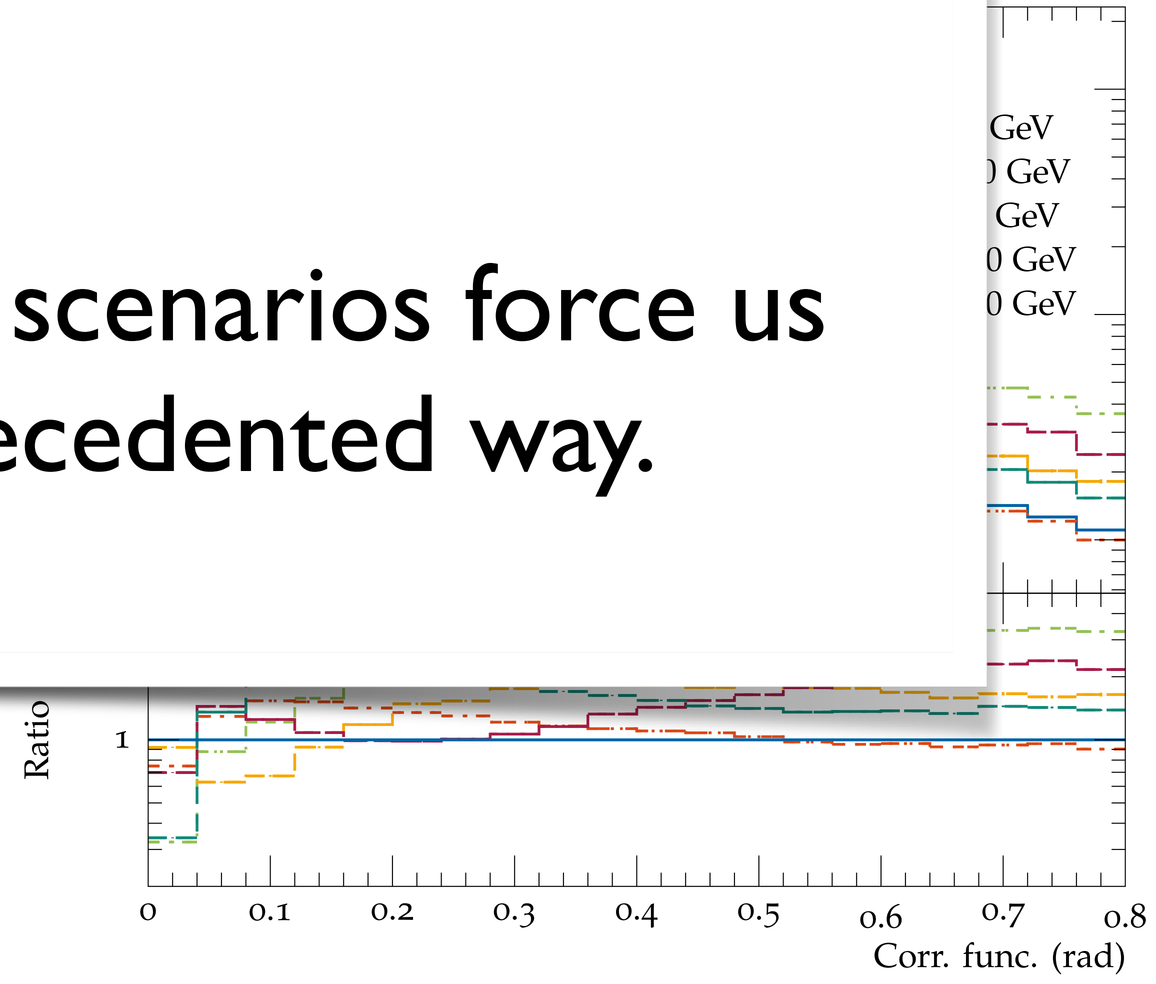
New in Herwig and the cluster model — more investigations and pheno to follow.



This is QCD@LHC — why bother?

Think of this as BSM4QCD: all of QED, EW and BSM scenarios force us to think about showers and hadronisation in an unprecedented way.

$$\frac{1}{N_\gamma} \sum_{i<j\in \mathrm{jet}} (E_i E_j)^\gamma \delta(\Delta R_{ij} - \rho)$$



[Stafford at PSR '24]

[Kulkarni, Masouminia, Plätzer, Stafford — '24]

Main lines of current parton shower research

Shower development is a broad field, fortunately back on the agenda.
Hadronziation is not exactly shower development, but enters at a similar level,

See Schumann's talk. Always needs to accompany shower development.

Matching/Merging

Control and demonstration of perturbative accuracy.

(N)NLL accuracy

Description of electroweak effects and BSM scenarios.

Interactions beyond QCD

Amplitude evolution

Genuine quantum effects: not limited to subleading colour.

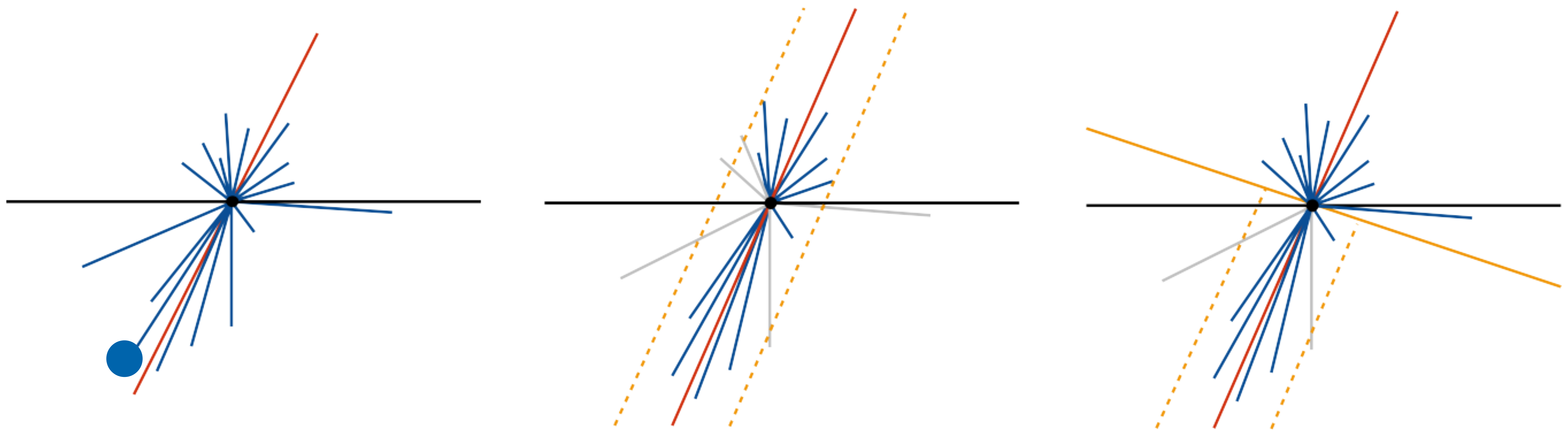
Hadronization

Comprehensive, factorized picture and construction of algorithms.

Remaining focus of this talk:

- Perturbative accuracy
- Beyond probabilistic algorithms.
- Factorisation and hadronization.

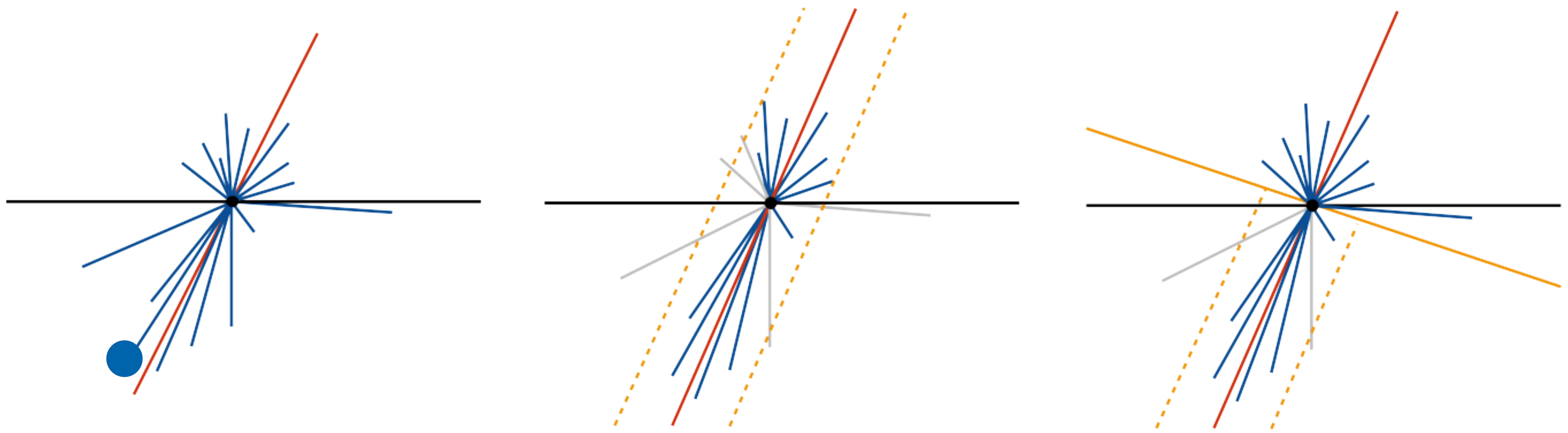
Accuracy of parton showers



Fragmentation is fine if we get collinear physics right.

Accuracy of Parton Showers

[Catani, Trentadue, Webber, Marchesini ….]



Fragmentation is fine if we get collinear physics right.

Global event shapes from coherent branching — for two jets.

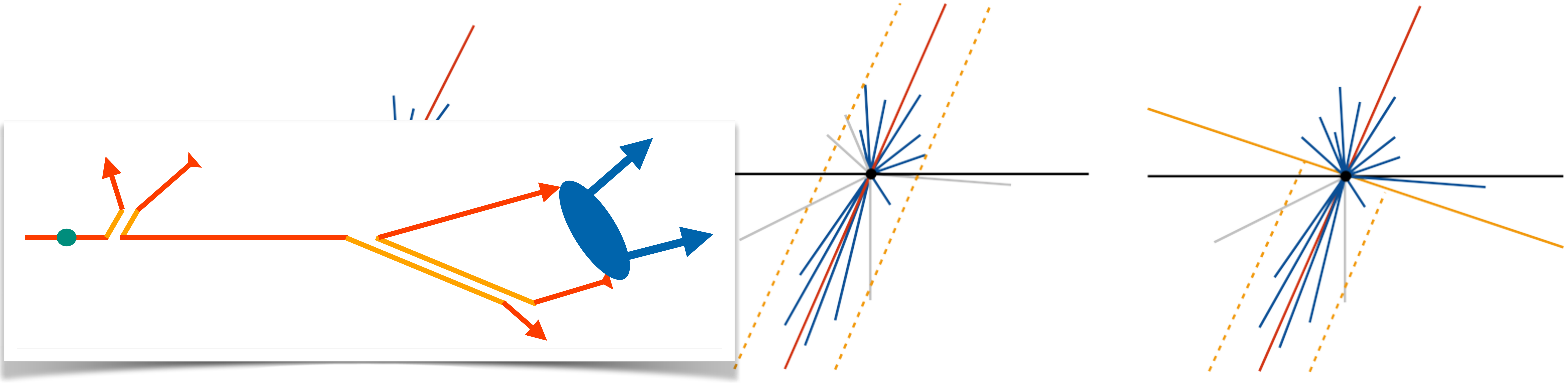
$$H(\alpha_s) \times \exp\left(Lg_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots\right)$$

LL — qualitative NLL — quantitative NNLL — precision

$$\alpha_s L \sim 1$$

Accuracy of Parton Showers

[Catani, Trentadue, Webber, Marchesini ….]



Fragmentation is fine if we get collinear physics right.

Global event shapes from coherent branching — for two jets.

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

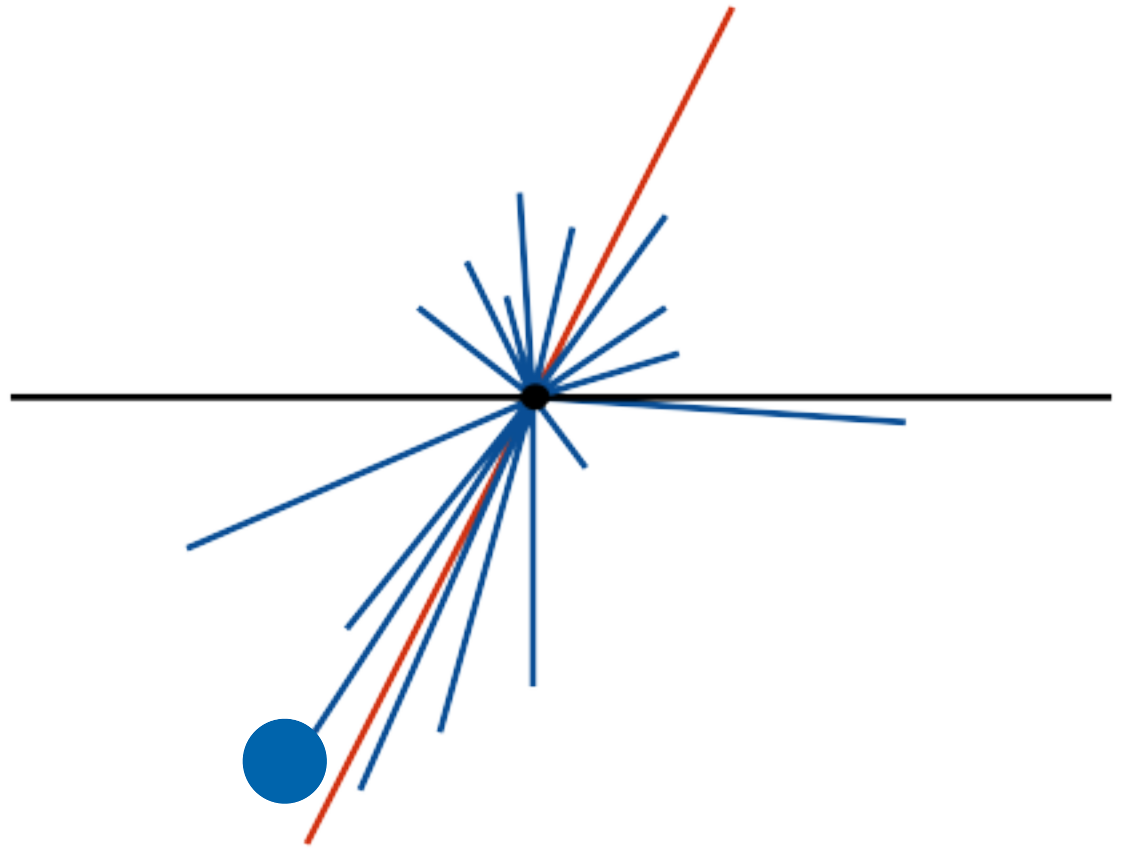
LL — qualitative

NLL — quantitative

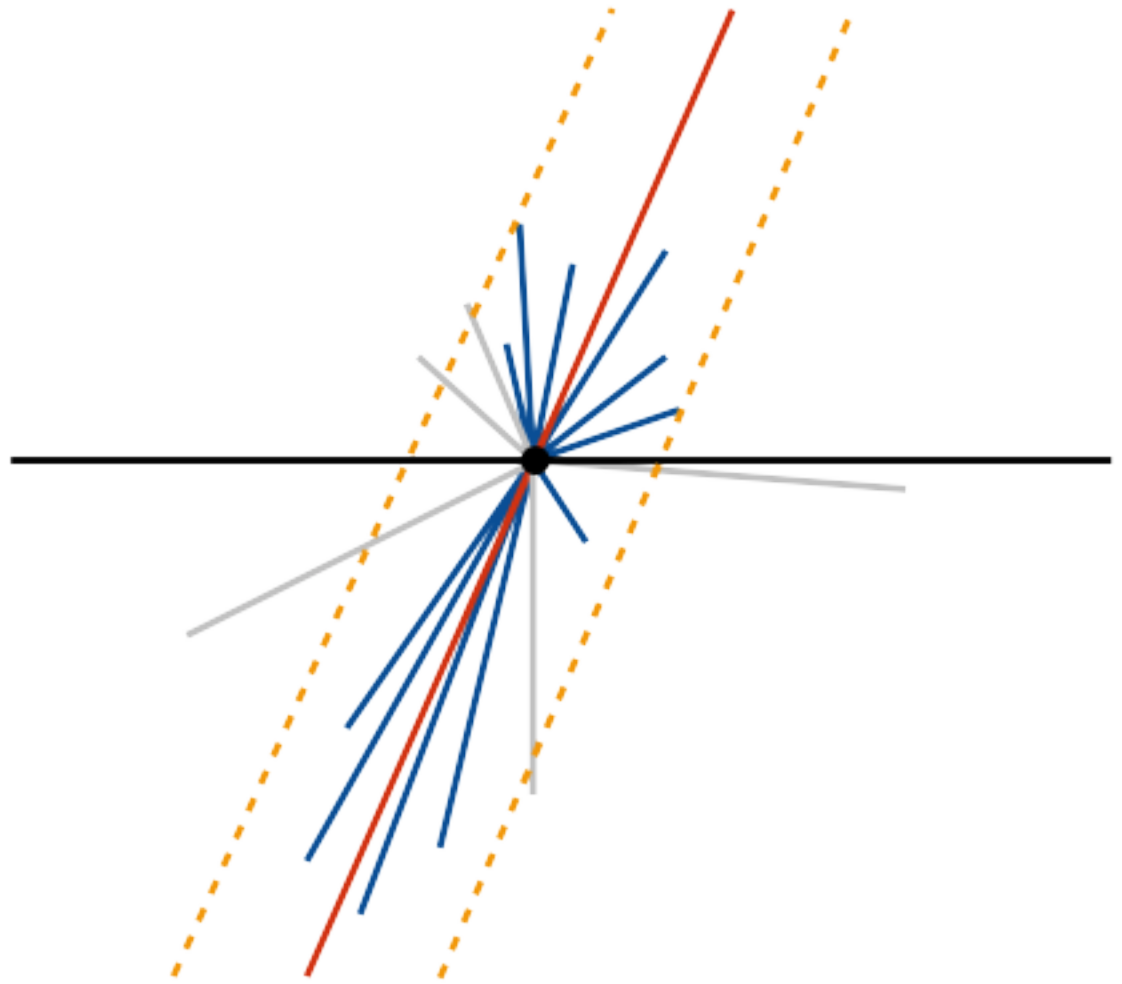
NNLL — precision

$\alpha_s L \sim 1$

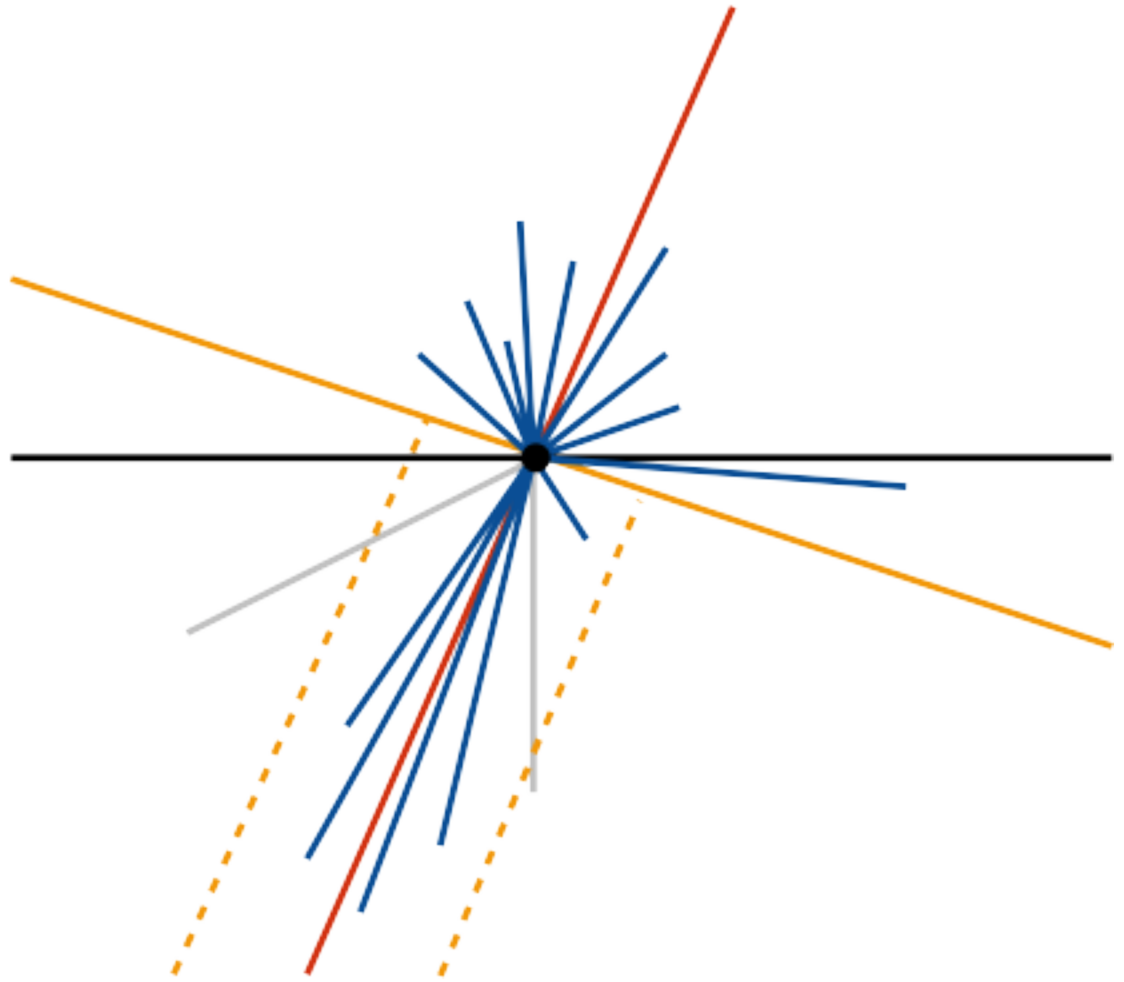
Accuracy of Parton Showers



Fragmentation is fine if we get collinear physics right.



Global event shapes from coherent branching — for two jets.



Coherence breaks down for non-global observables.

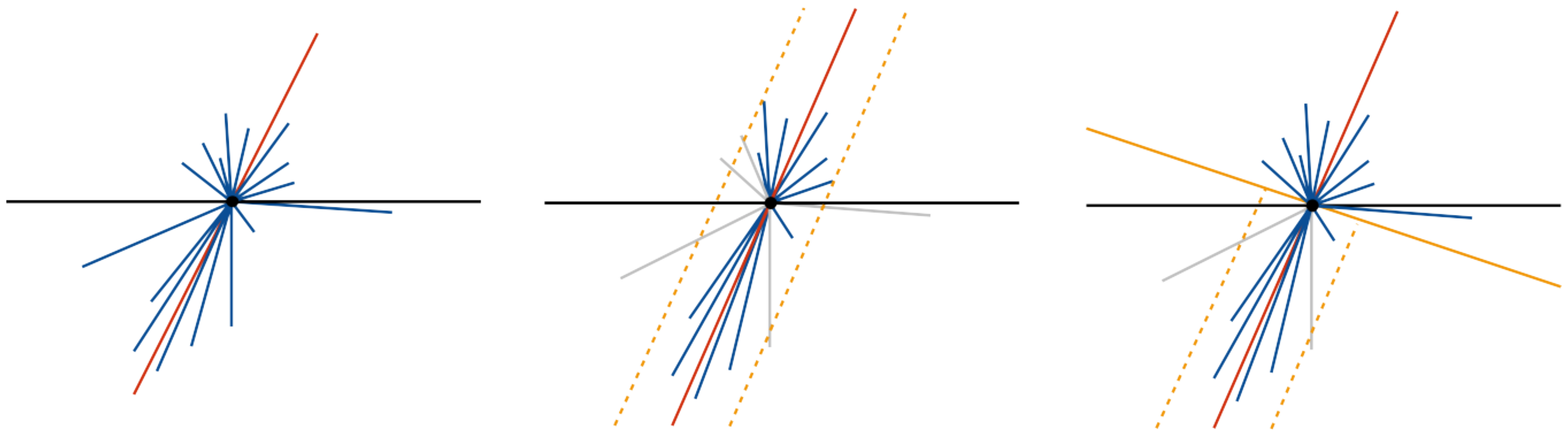
$T_k T_l T_i \cdot T_j T_m T_n$

large-N limit ↓

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

[Banfi, Marchesini, Smye '02]

The quest for NLL precision



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

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

The quest for NLL precision

Demonstrate NLL accurate evolution:

enormous progress

- PanScales — numerical
  [PanScales — Dasgupta, Monni, Salam, Soyez + ….]
- Forshaw/Holguin/Plätzer — analytical
  [aim at improving Herwig 7 dipole shower]
- Deductor — numerical/analytical
  [Nagy, Soper]
- Sherpa — numerical/analytical
  [Herren, Höche, Krauss, Reichelt, Schönherr]
- Apollo — numerical [Preuss]

Based on amplitude evolution.

‘18

‘20

‘22

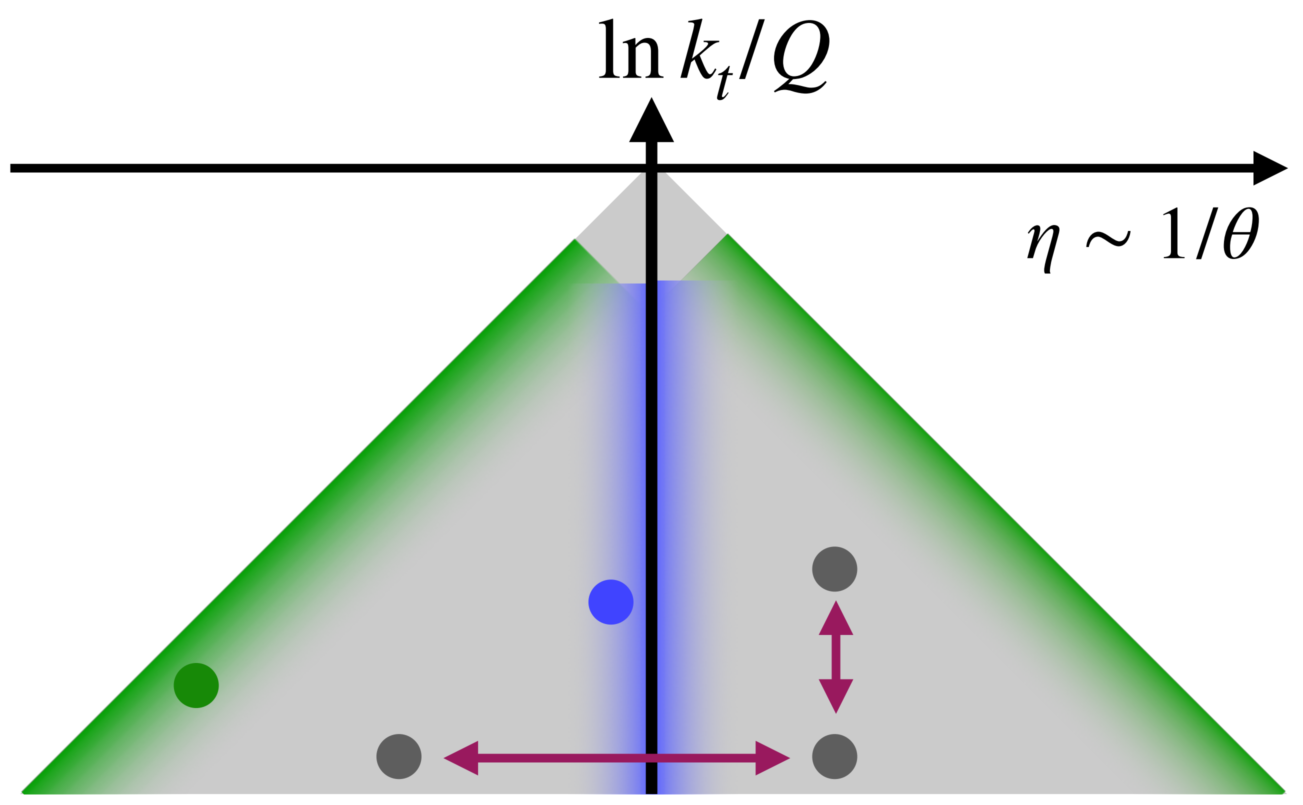
‘24

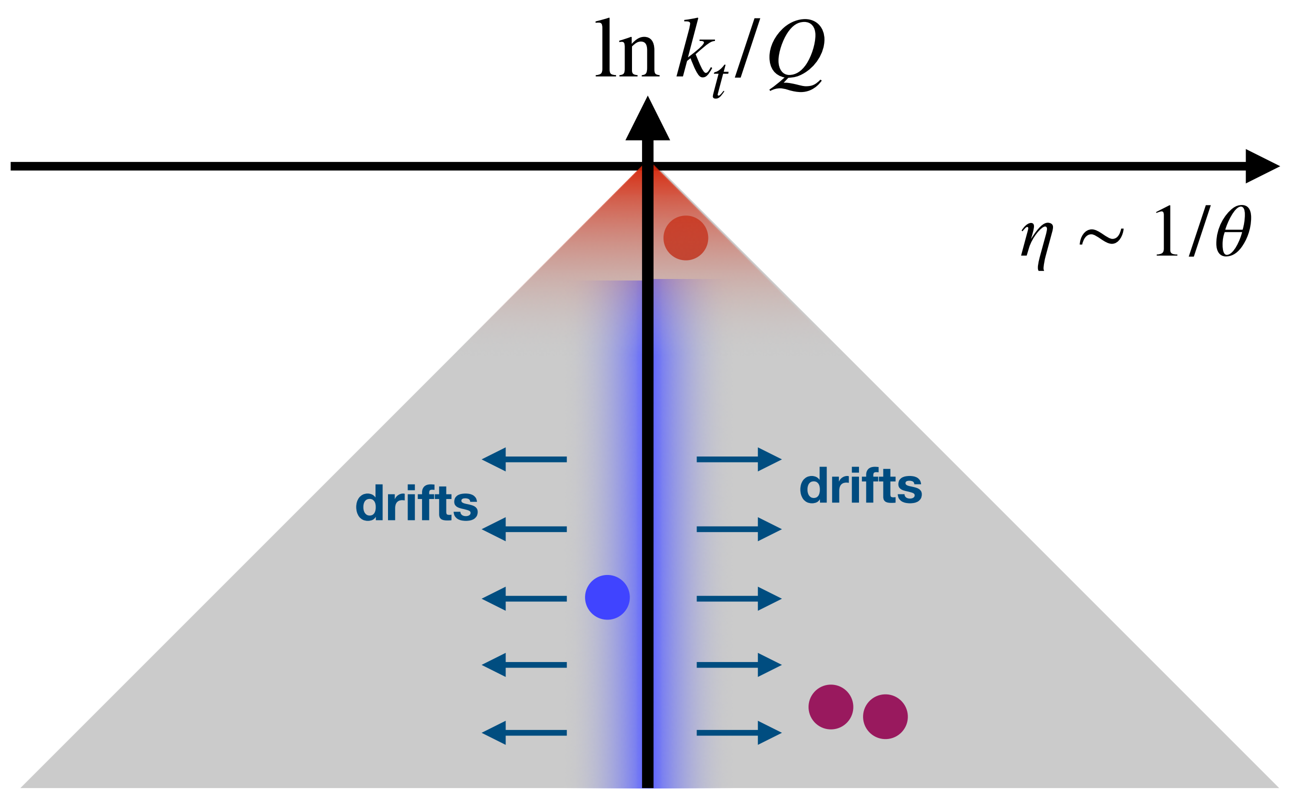
Can we push this to $\text{NLL}_{\text{global}}$ / $\text{LL}_{\text{non-global}}$ in one (dipole) algorithm?

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

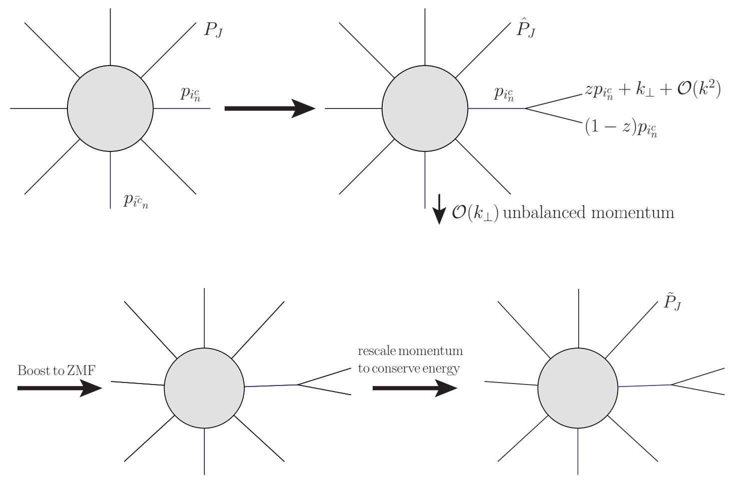
Improving Shower Accuracy — Tools

Lund plane as a tool

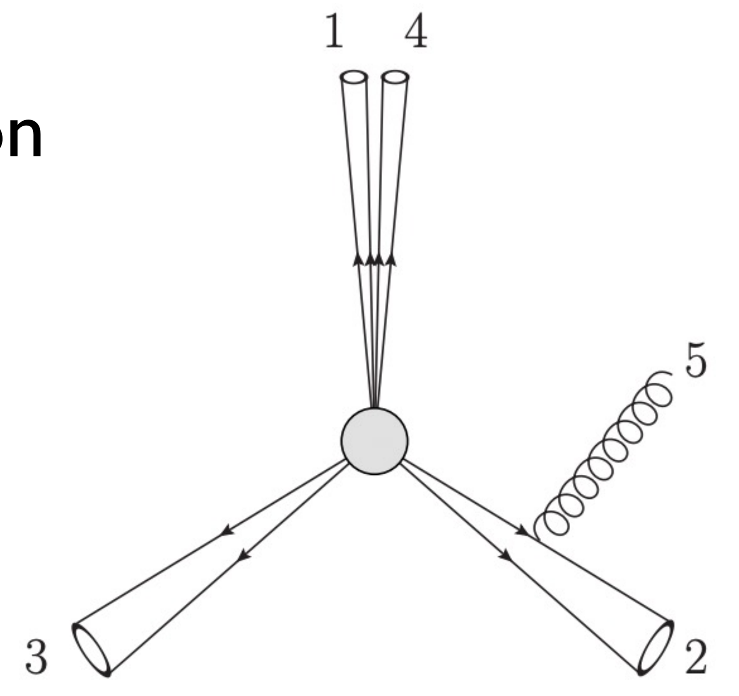




[van Bleekveld @ MBI '24]



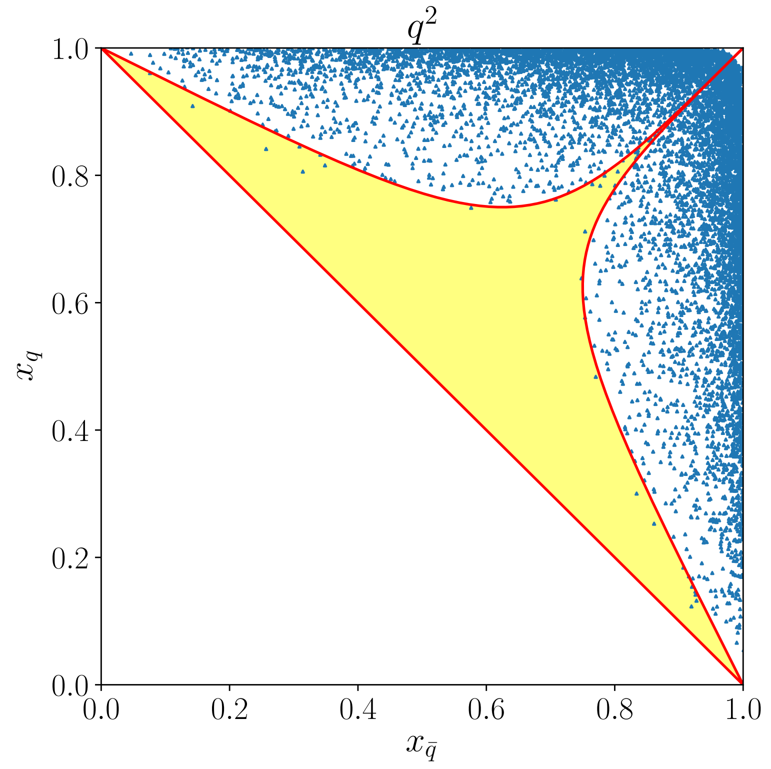
Analytic insight and amplitude evolution as a theoretical tool, extending probabilistic algorithms.



$$\delta\Sigma(L) \approx \frac{4\alpha_s^2 \mathcal{C}_F^2 \sigma_{n_H}}{\pi^2} \int_0^Q \frac{\mathrm{d}q_{1\perp}^{(a_1,b_1)}}{q_{1\perp}^{(a_1,b_1)}} \int_{-\ln Q/q_{1\perp}^{(a_1,b_1)}}^{\ln Q/q_{1\perp}^{(a_1,b_1)}} \mathrm{d}y_1 \int_0^{q_{1\perp}^{(a_1,b_1)}} \frac{\mathrm{d}q_{2\perp}^{(a_2,1_2)}}{q_{2\perp}^{(a_2,1_2)}} \int_{-\ln Q/q_{2\perp}^{(a_2,1_2)}}^{\ln Q/q_{2\perp}^{(a_2,1_2)}} \mathrm{d}y_2$$
$$\times \int_0^{2\pi} \frac{\mathrm{d}\phi_2}{2\pi} \left[\Theta\left(e^{-L} - V(\{p\}_2)\right) - \Theta\left(e^{-L} - V(\{p\}_{\mathrm{correct}})\right)\right].$$

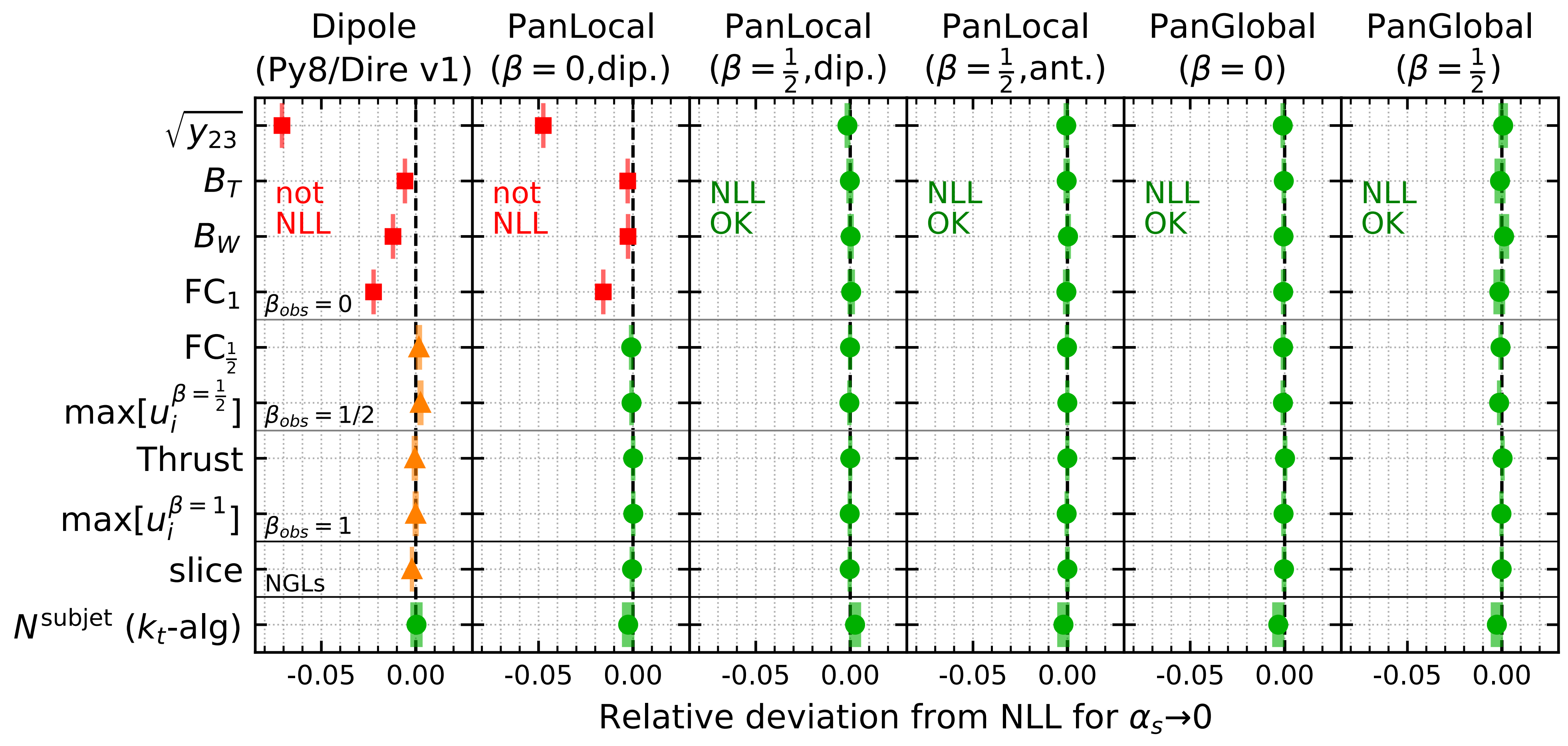
[Forshaw, Holguin, Plätzer —'21, '22]

Detailed analysis of coherent branching.



[Bewick, Ferrario, Richardson, Seymour — '19, '20]

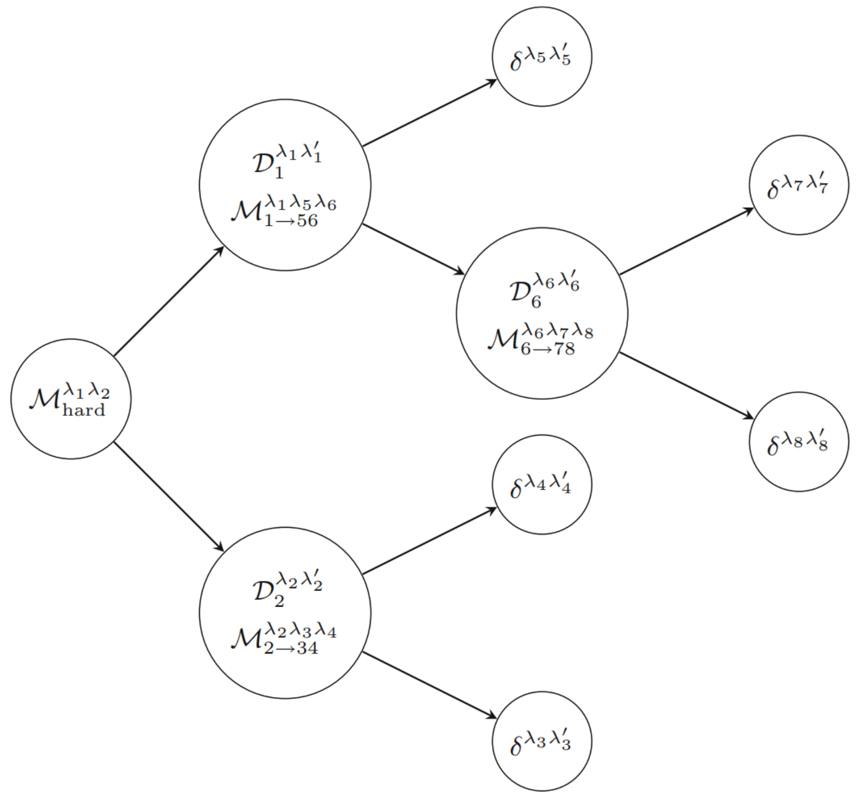
Detailed numerical checks against well-known benchmarks.

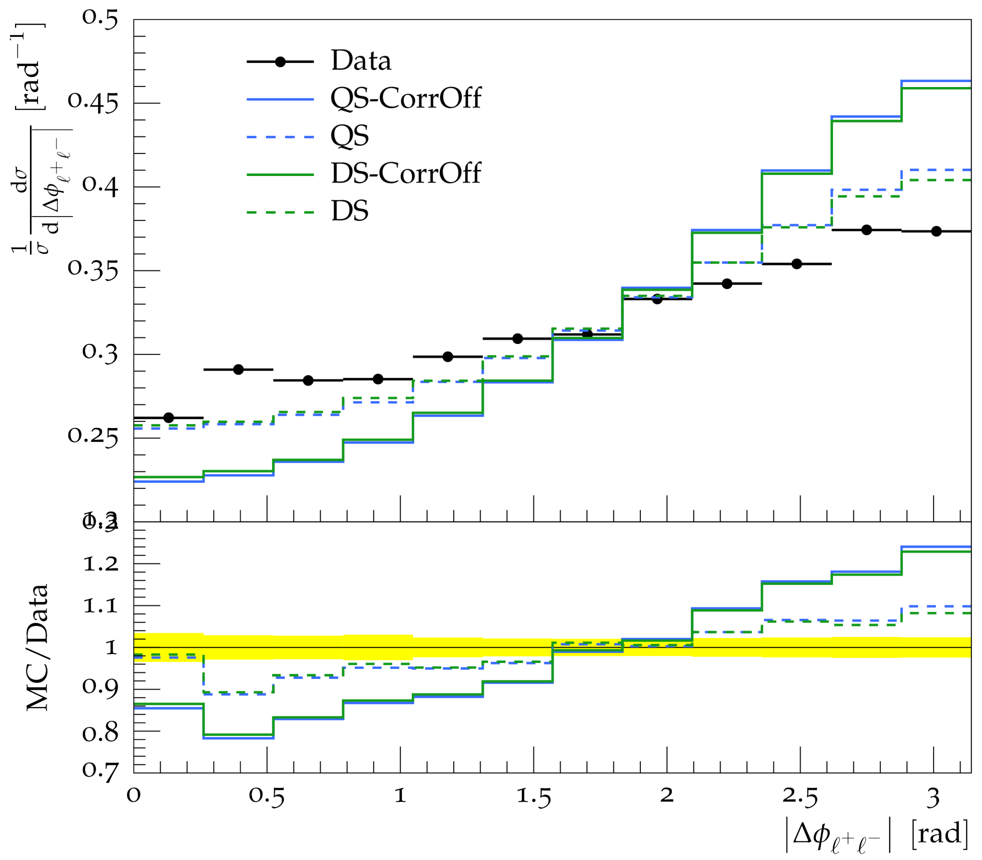


[PanScales]

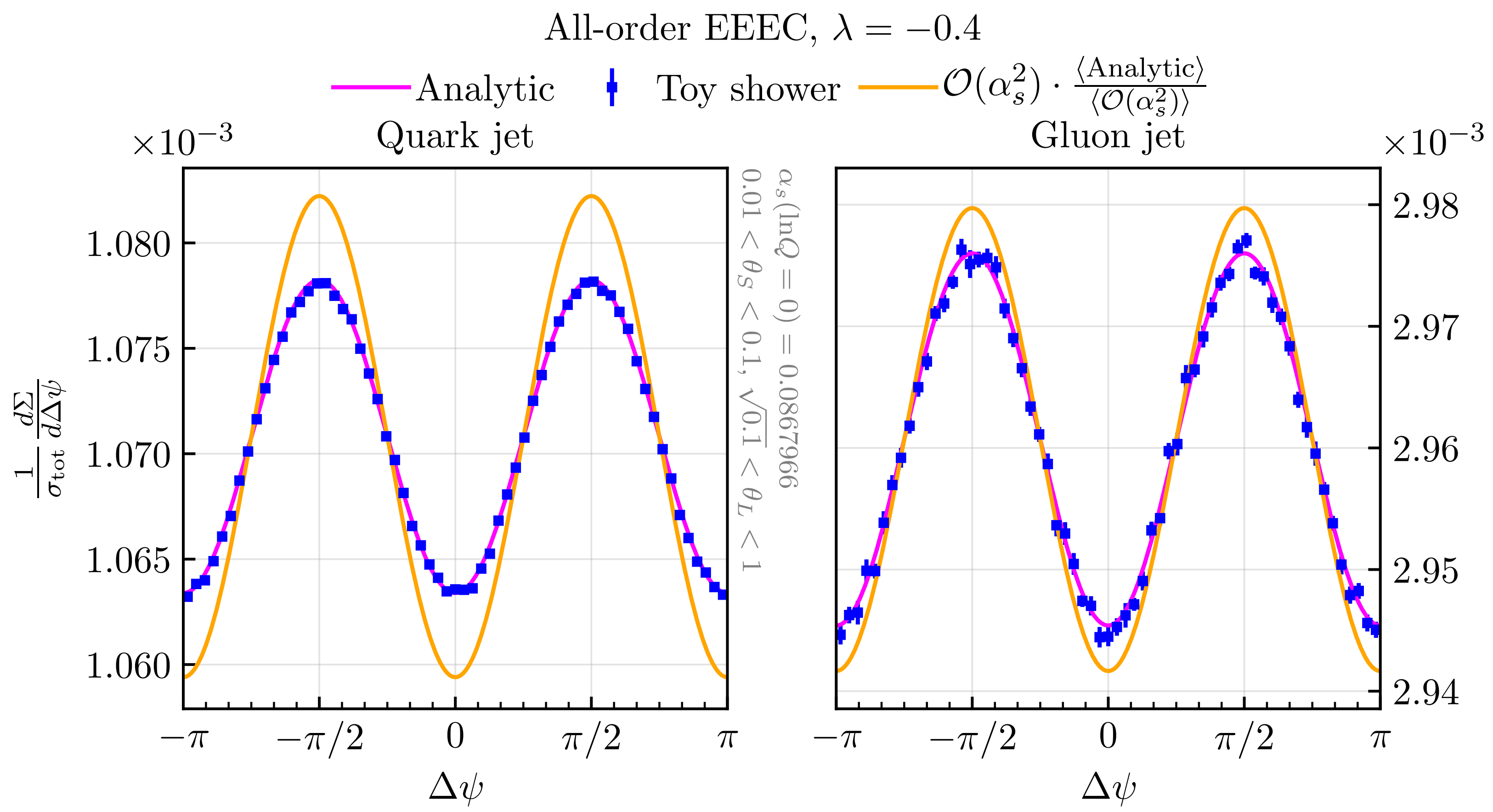
Improving Shower Accuracy — Spin & Colour Correlations

Spin correlations building on Collins-Knowles algorithm





[Webster, Richardson - ’20]



[Karlberg, Salam, Scyboz, Verheyen — ’21]

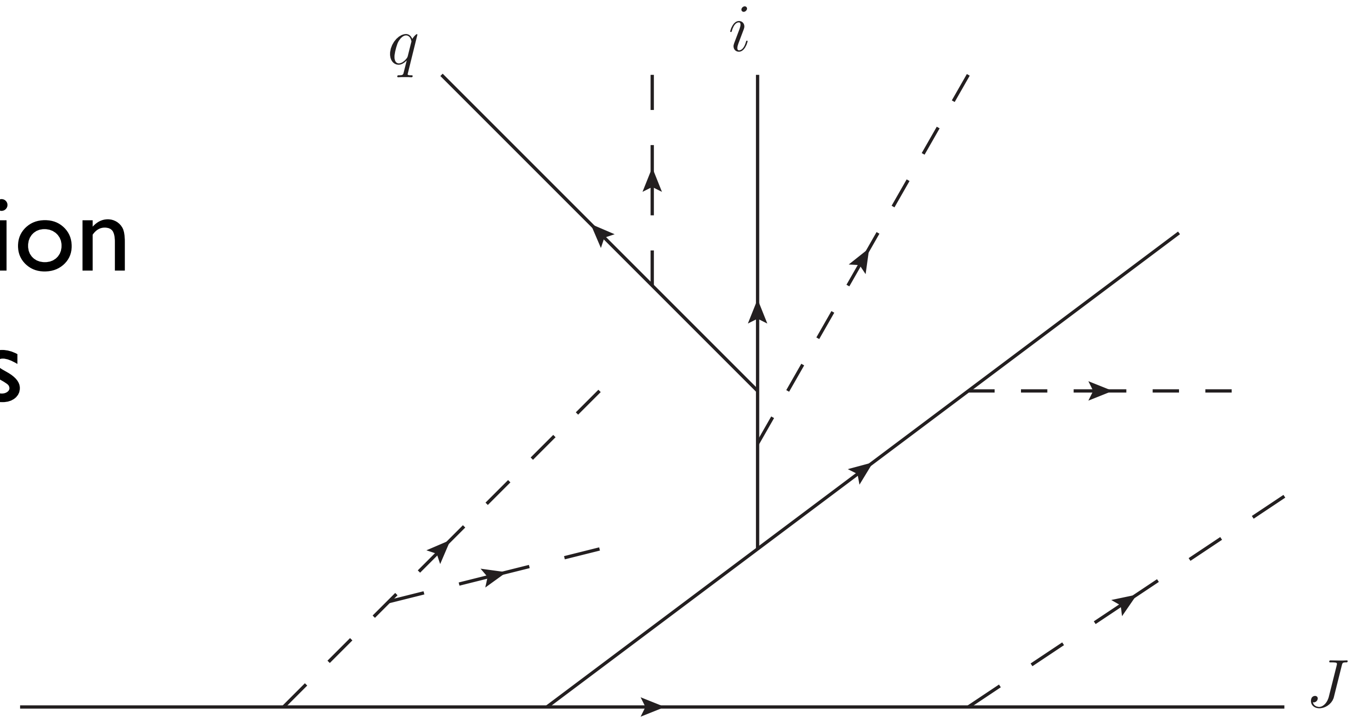
Dynamic colour factors in dipole showers

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

[Forshaw, Holguin, Plätzer — ’21]

[Hamilton, Medves, Salam, Scyboz, Soyez — ’21]

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



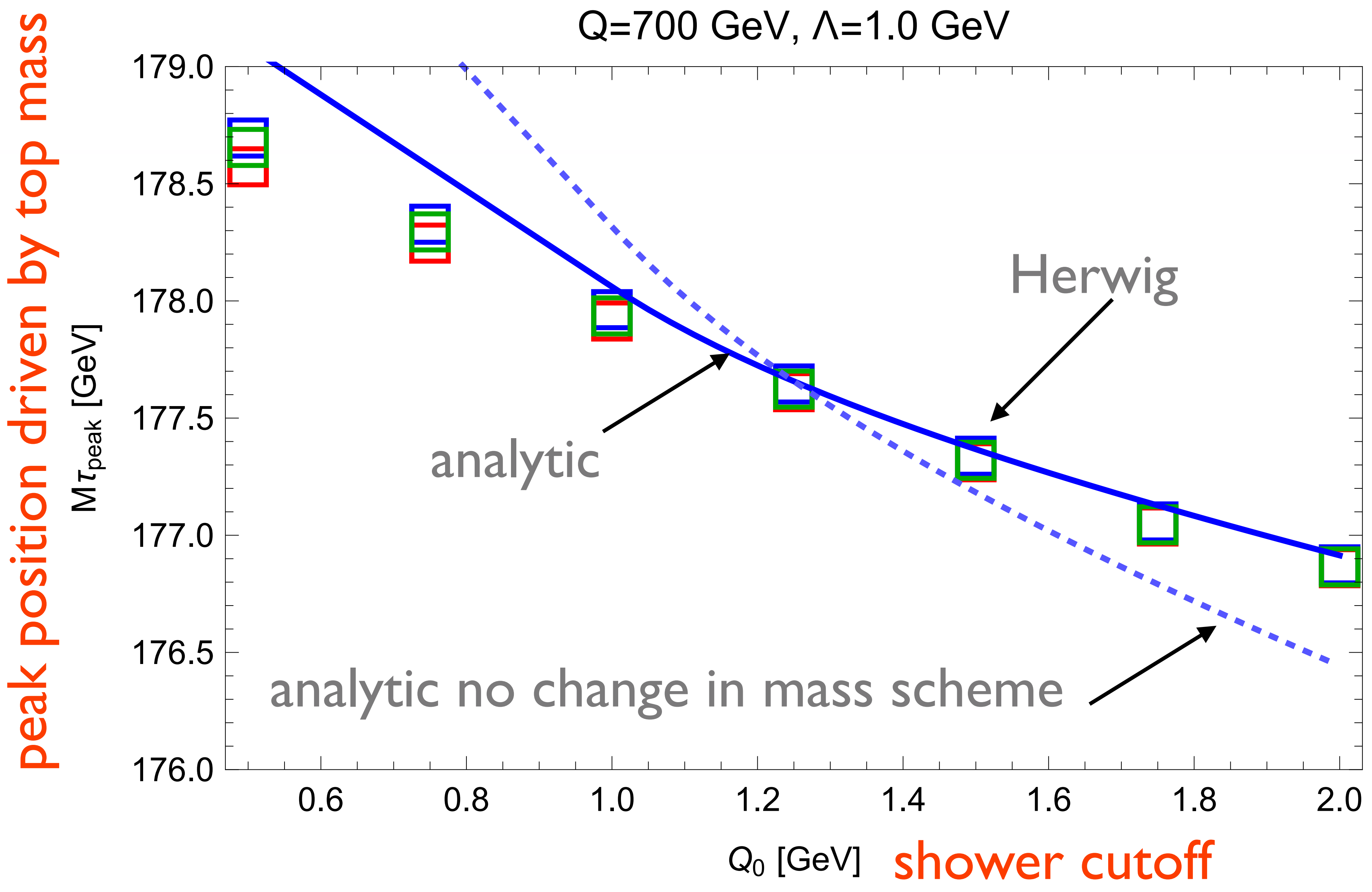
Where it (also) matters

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 – '03]

NLL accurate for global observables with massive quarks.



Top mass definition from coherent branching.

[Hoang, Plätzer, Samitz — '18]

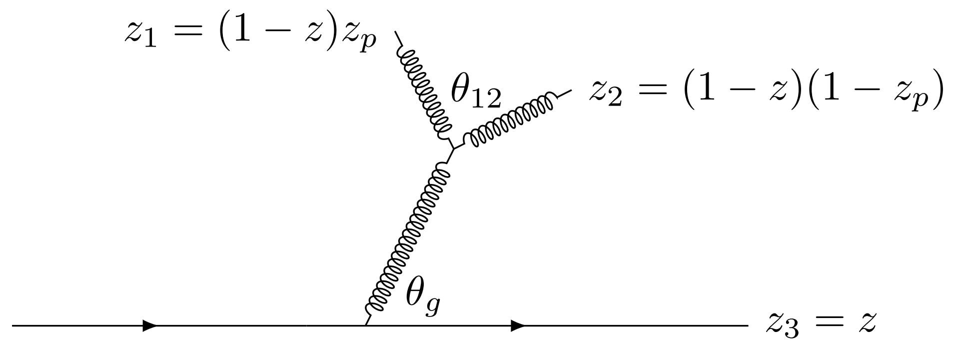
$$m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} + \Delta_m^{\mathrm{pert}} + \Delta_m^{\text{non-pert}}$$

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

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

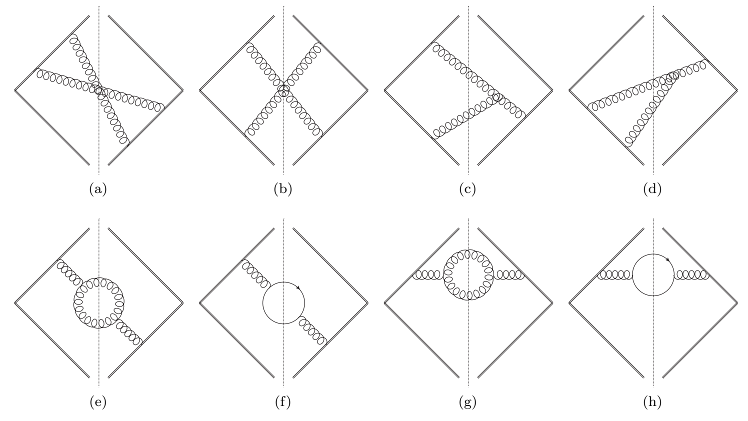
Beyond NLL$_{\text{global}}$ — more differential, NLL$_{\text{nonglobal}}$, NNLL$_{\text{global}}$, …

Structure of second order ingredients and dedicated resummations: uncover algorithms and benchmarks.

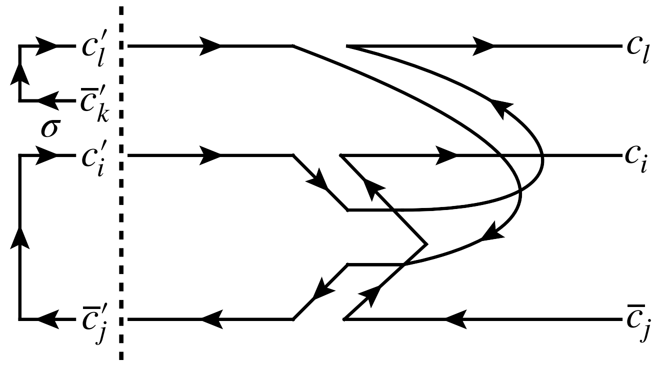


[Dasgupta, El-Menoufi — '21]

Kinematic and colour structure of emission kernels beyond LO



[Dulat, Höche, Prestel — '18]
[Gellersen, Höche, Prestel — '22]



[Plätzer, Ruffa — '21]

Effective couplings and collinear fragmentation

$$\frac{\alpha_s}{2\pi}K(z_g) = \frac{V_{q\bar q g}}{B_{q\bar q g}} - \frac{V_{q\bar q}}{B_{q\bar q}} + \int_0^{\tilde v_g} \frac{d\Phi_{q\bar q ij}}{d\Phi_{q\bar q g}}\frac{B_{q\bar q ij}}{B_{q\bar q g}} - \int_0^{v_g} \frac{d\Phi_{q\bar q g'}}{d\Phi_{q\bar q}}\frac{B_{q\bar q g'}}{B_{q\bar q}}$$

[Van Beekveld, Dasgupta, El-Menoufi, Halliwell, Karlberg, Monni — '24]

Building amplitude evolution at the second order.

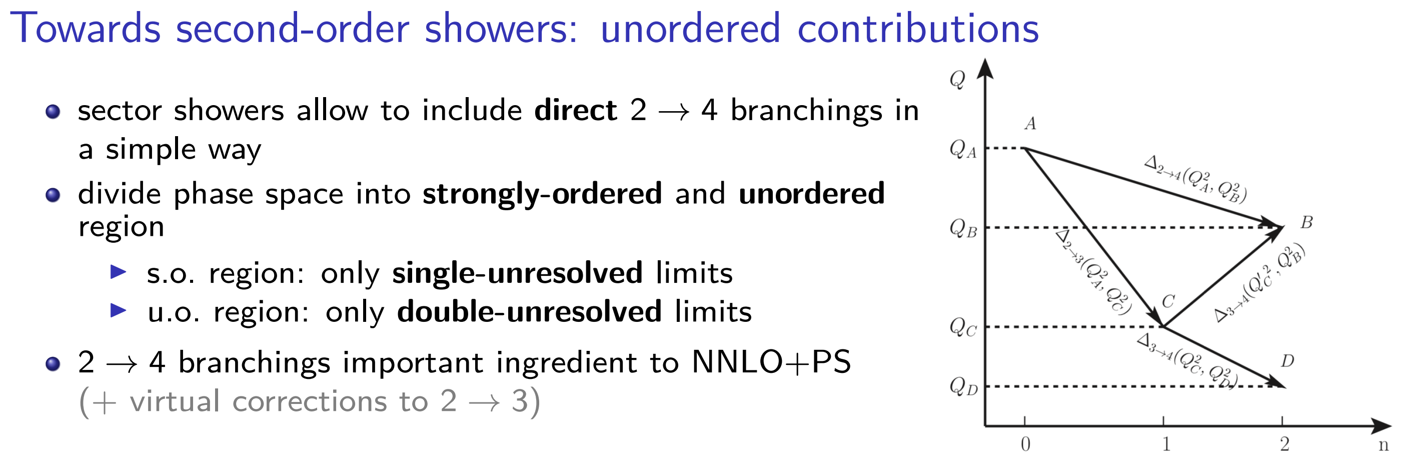
$$\mathbf{\Gamma}^{(2)}_{S,n} = -\hat{\mathbf{V}}^{(2)}_n\,[\partial_S \Xi_{n,2}] + \hat{\mathbf{V}}^{(1)}_n\,[\partial_S \Xi_{n,1}]\,\hat{\mathbf{V}}^{(1)}_n\,[1-\Xi_{n,1}]$$

$$\mathbf{R}^{(1,1)}_n \circ \mathbf{R}^{(1,0)\dagger}_n = \left(\hat{\mathbf{D}}^{(1,1)}_n\,[1-\Xi_{n,1}] - \hat{\mathbf{D}}^{(1,0)}_n \hat{\mathbf{V}}^{(1)}_{n-1}\,[1-\Xi_{n-1,1}]\right) \circ \hat{\mathbf{D}}^{(1,0)\dagger}_n \partial_S \Theta_{n,1} + \left(\hat{\mathbf{D}}^{(1,1)}_n\,[\partial_S \Xi_{n,1}] - \hat{\mathbf{V}}^{(1)}_n\,[\partial_S \Xi_{n,1}]\,\hat{\mathbf{D}}^{(1,0)}_n\right) \circ \hat{\mathbf{D}}^{(1,0)\dagger}_n (1-\Theta_{n,1})\,,$$

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

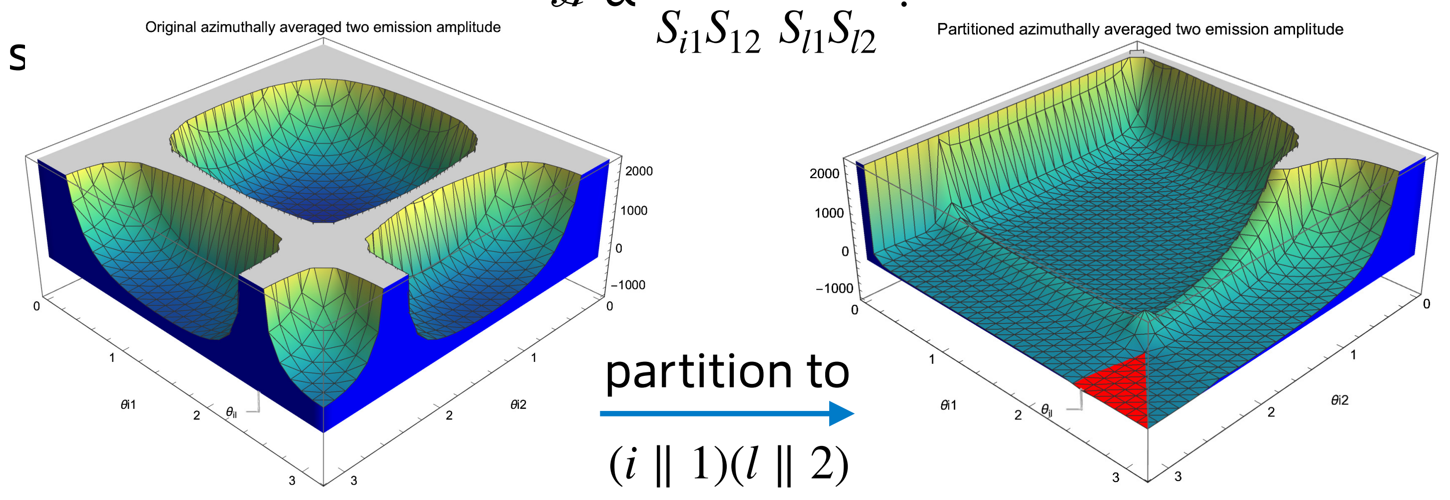
[Plätzer — '22]
[Nagy, Soper — PSR '24]

Double emission matrix element corrections



[C. Preuss for Vincia — PSR 21]
[PanScales double soft algorithms]

$$\mathscr{A} \propto \frac{1}{S_{i1}S_{12}}\,\frac{1}{S_{l1}S_{l2}}\,:$$



[Löschner — PSR '24]
[Löschner, Plätzer, Simpson — '21]

Beyond $\text{NLL}_{\text{global}}$ — more differential, $\text{NLL}_{\text{nonglobal}}$, $\text{NNLL}_{\text{global}}$, …

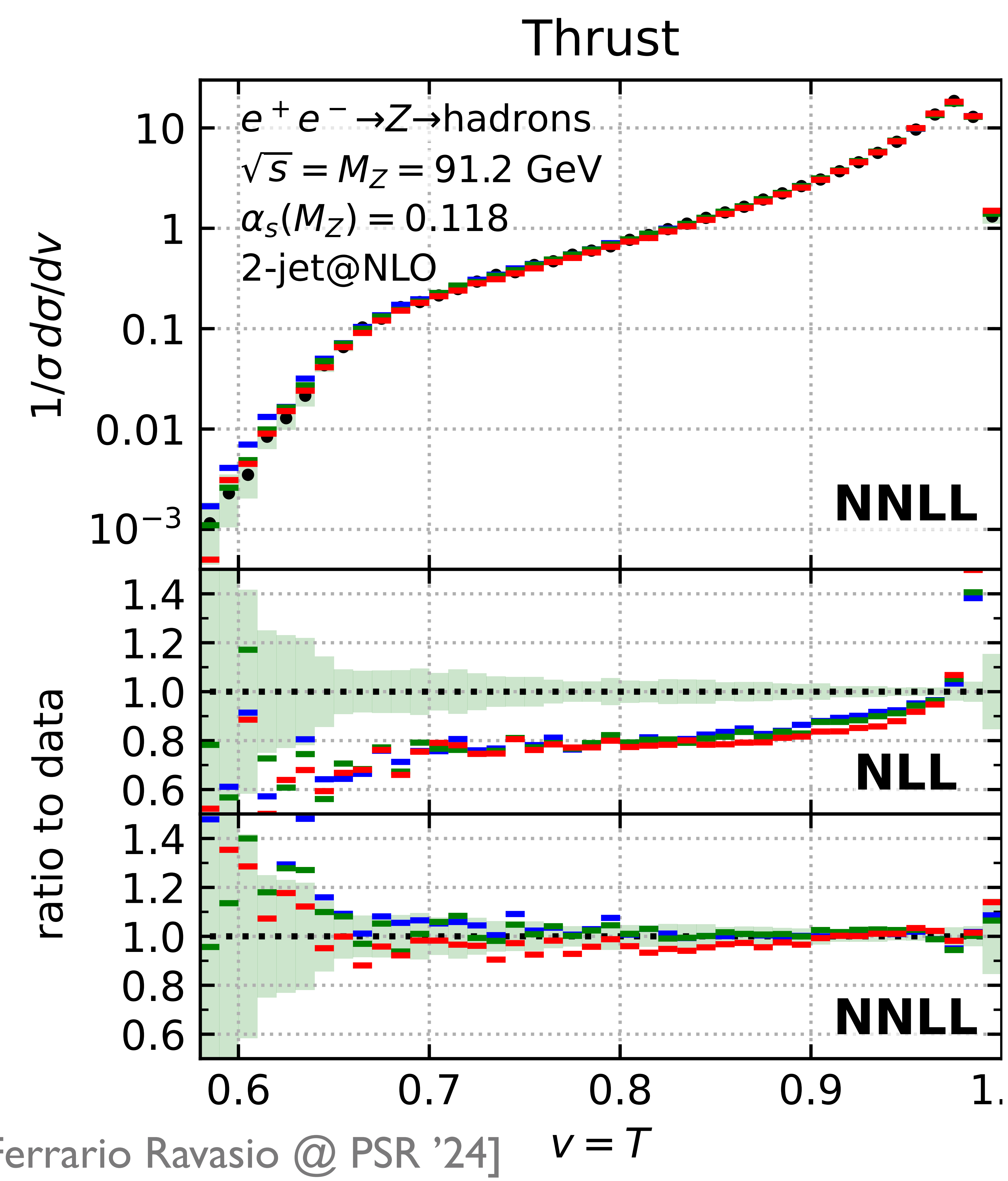
Algorithms are more than the sum of their ingredients.

Way forward is hard, but possible — we need to find systematic formulations.

Demonstrate accuracy for certain observables, but strive for most differential/flexible algorithms.

Role of data comparisons not always clear but encouraging.

See Karlberg's talk



[Ferrario Ravasio @ PSR '24]

Main lines of current parton shower research

Shower development is a broad field, fortunately back on the agenda.
Hadronziation is not exactly shower development, but enters at a similar level,

See Schumann's talk. Always needs to accompany shower development.

Matching/Merging

Control and demonstration of perturbative accuracy.

(N)NLL accuracy

Description of electroweak effects and BSM scenarios.

Interactions beyond QCD

Amplitude evolution

Genuine quantum effects: not limited to subleading colour.

Hadronization

Comprehensive, factorized picture and construction of algorithms.

Remaining focus of this talk:

- Perturbative accuracy
- Beyond probabilistic algorithms.
- Factorisation and hadronization.

Full colour and interferences are central to go beyond

Colour reconnection and hadronization is about subleading-N.
So are shower accuracy and interference terms.

Colour factor algorithms	Colour ME corrections	Full amplitude evolution
Coherent, NLL-accurate dipole showers	Colour-exact real emissions as far as possible	Colour-exact real and virtual corrections
[Gustafson] [PanScales '21] [Forshaw, Holguin, Plätzer '21]	[Plätzer, Sjödahl '12, '18] [Höche, Reichelt '20]	[Forshaw, Plätzer + … '13 …] [Nagy, Soper '07 …]

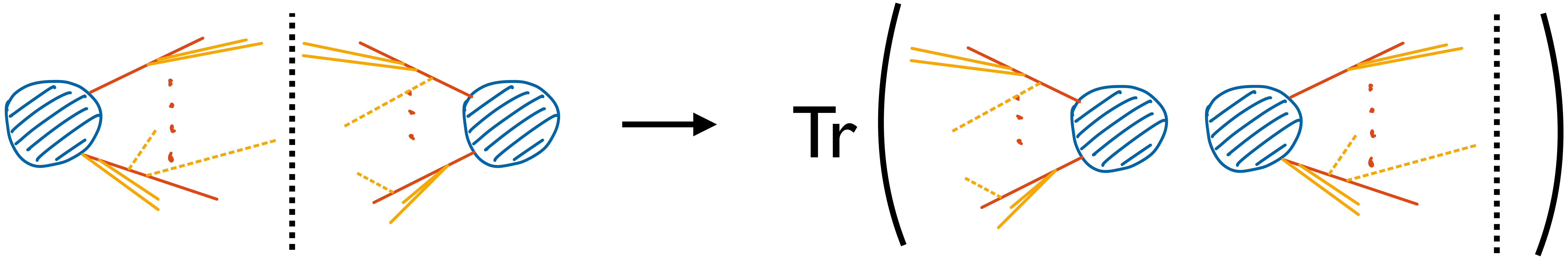
Full colour and interferences are central to go beyond

Colour reconnection and hadronization is about subleading-N.
So are shower accuracy and interference terms.

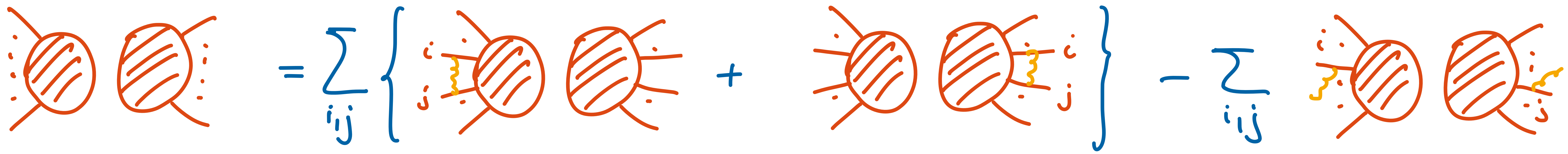
Colour factor algorithms	Colour ME corrections	Full amplitude evolution
Coherent, NLL-accurate dipole showers	Colour-exact real emissions as far as possible	Colour-exact real and virtual corrections
[Gustafson] [PanScales '21] [Forshaw, Holguin, Plätzer '21]	[Plätzer, Sjödahl '12, '18] [Höche, Reichelt '20]	[Forshaw, Plätzer + … '13 …] [Nagy, Soper '07 …]

The amplitude evolution equation

see Torre's talk

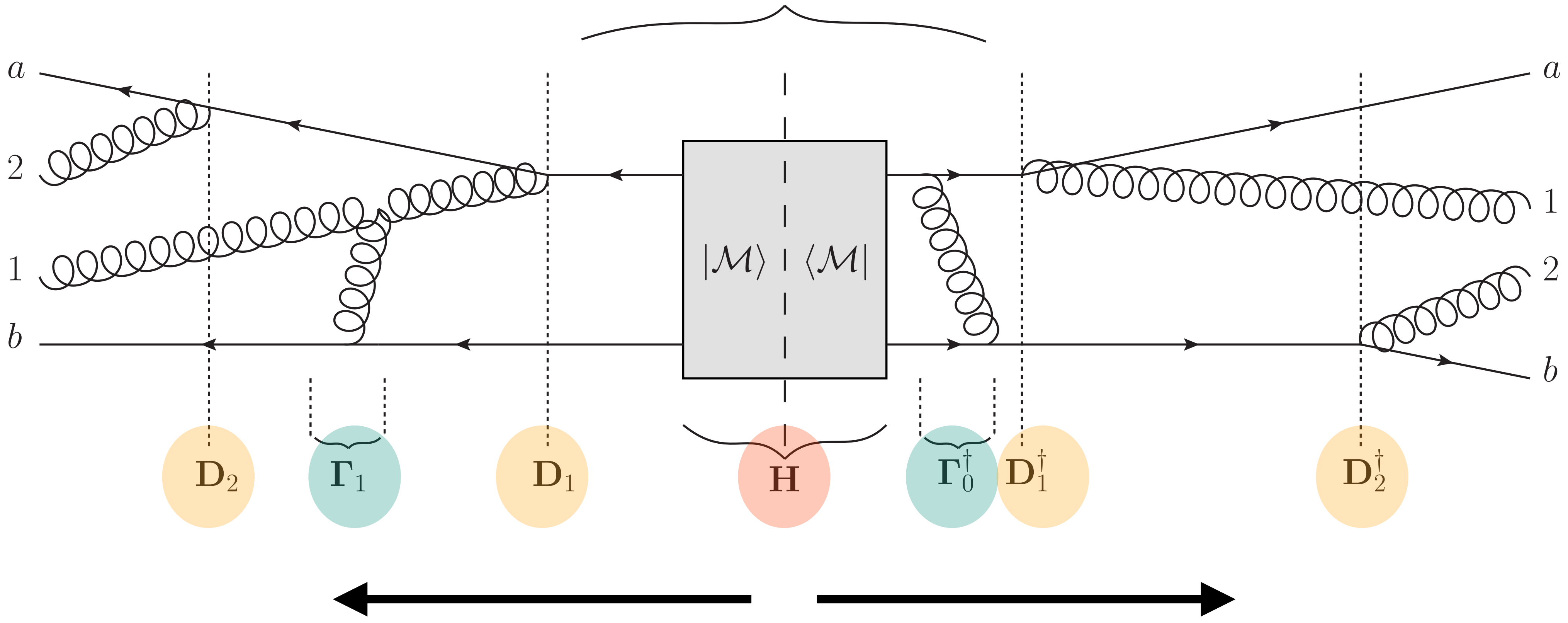


$$q\frac{\mathrm{d}}{\mathrm{d}q}$$



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

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

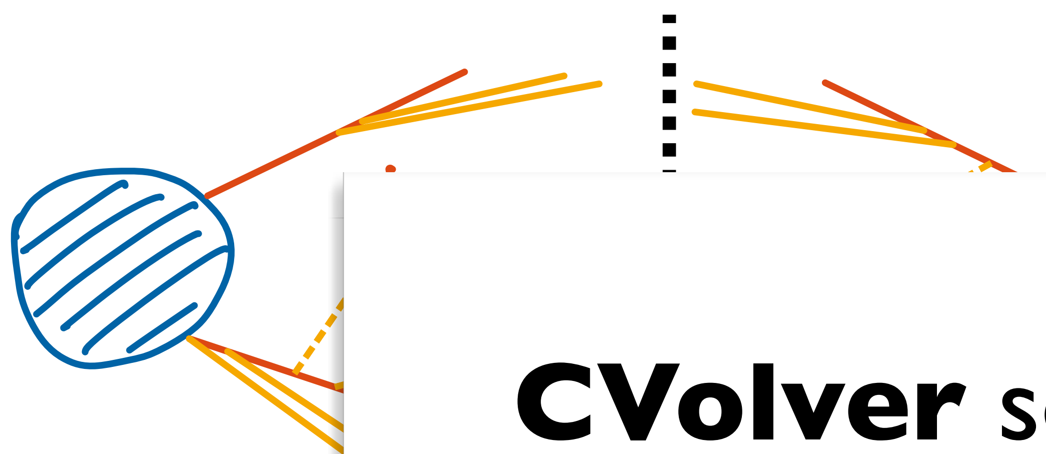


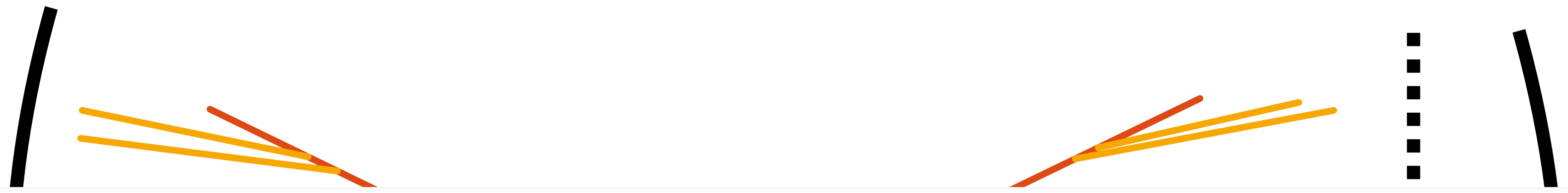
amplitude | conjugate amplitude

[Forshaw, Plätzer, De Angelis, Torre, … — '18 … '24]

The amplitude evolution equation

see Torre's talk





$$q\frac{\mathrm{d}}{\mathrm{d}q}$$

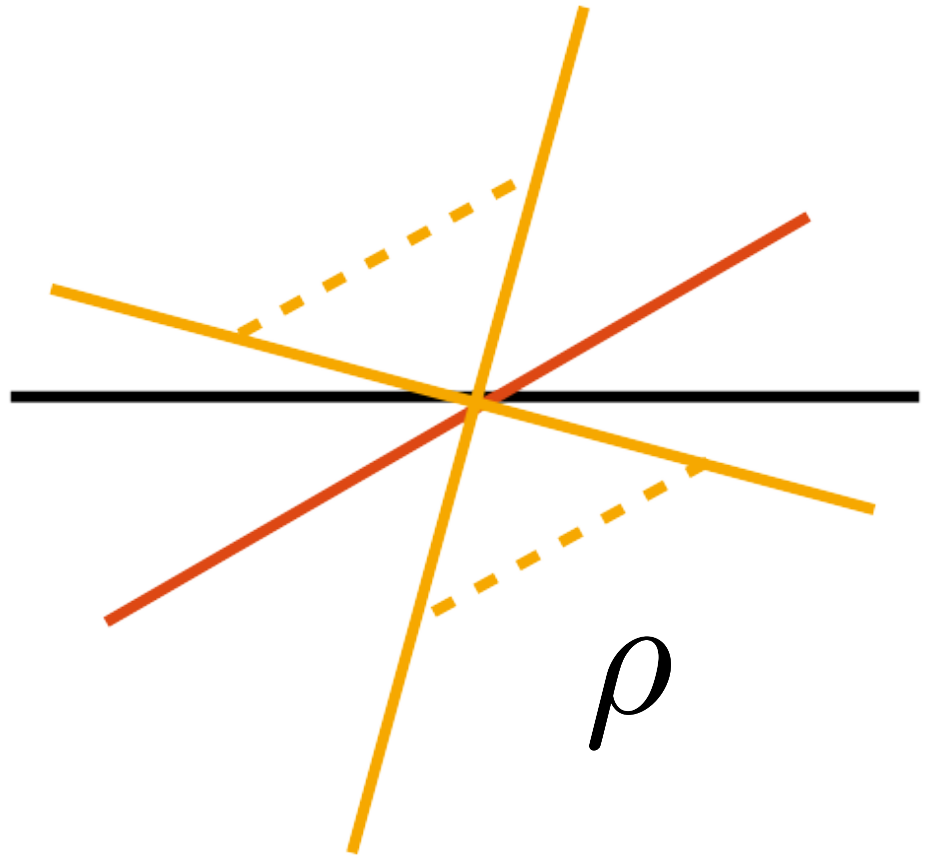
Markovian algorithm a
Iterate gluon exchang

Different histories in a
amplitude needed to i

[Forshaw, Plätzer, De Angelis, Torre, … — '18 … '24]

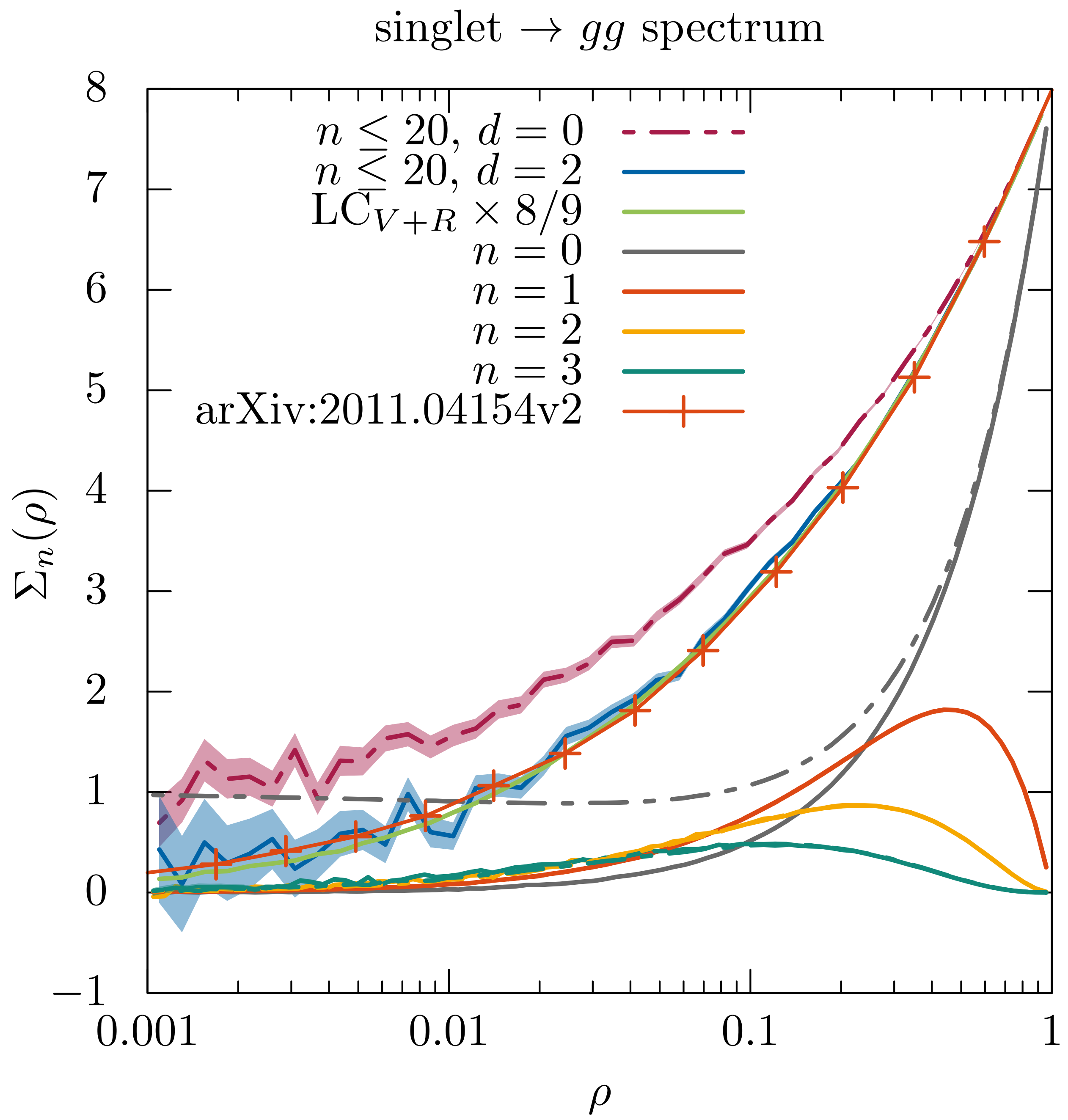
amplitude conjugate amplitude

CVolver solves evolution equations in colour flow space. Flexible for dedicated resummation and new parton showers.



Jet vetoes studied first — benchmarks available.

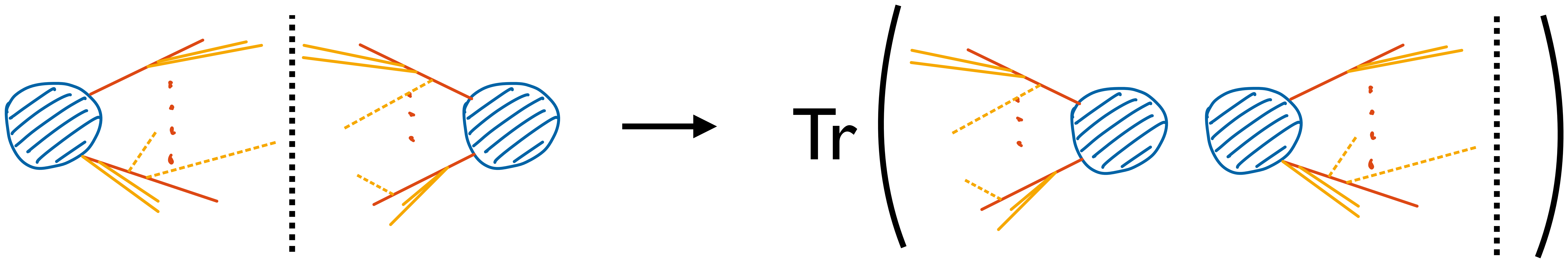
$$\Sigma(\rho) = \sum_n \int \mathrm{d}\sigma(\{p_i\}) \prod_i \theta_{\rm in}(\rho - E_i)$$

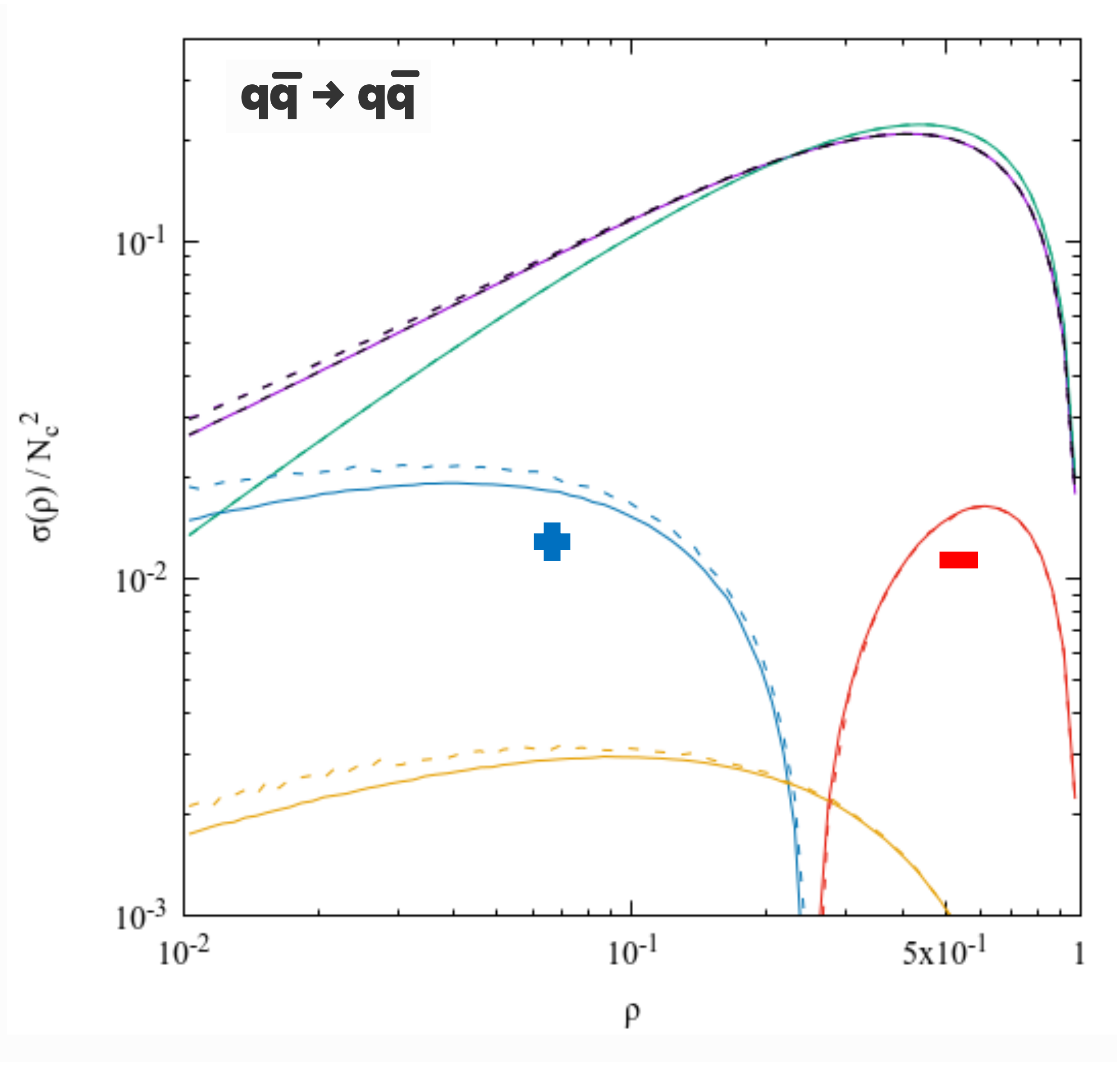


[Forshaw, Plätzer, DeAngelis, Torre …]

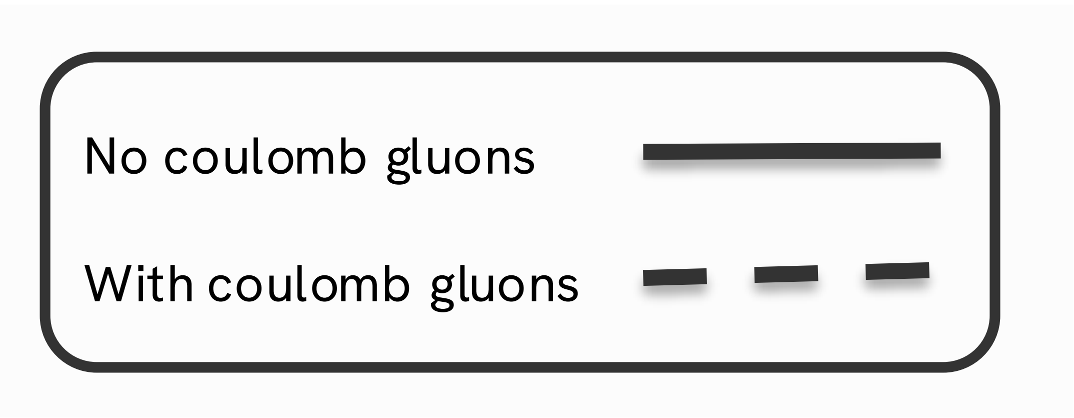
Amplitude evolution at hadron colliders

see Torre's talk

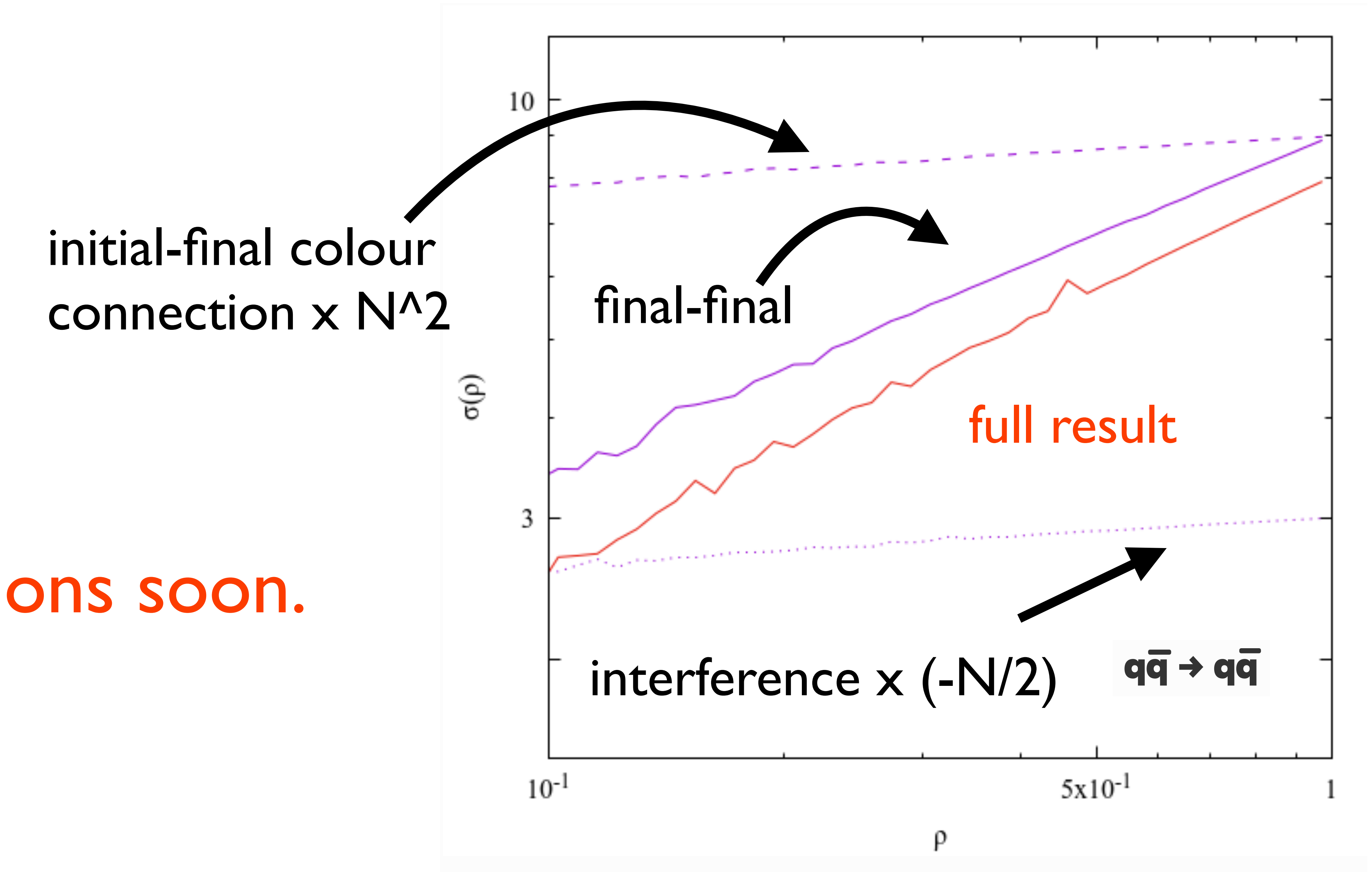




Impact of Coulomb modes



Showering of hard process interferences



Differential predictions soon.

[Forshaw, Plätzer, De Angelis, Torre, … — in progress]
Baseline jet veto cross sections in agreement with Hatta '20

Amplitude evolution and electroweak physics

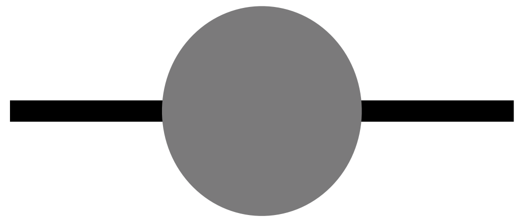
[Plätzer, Sjödahl — ’22]

Factorizing momentum mappings

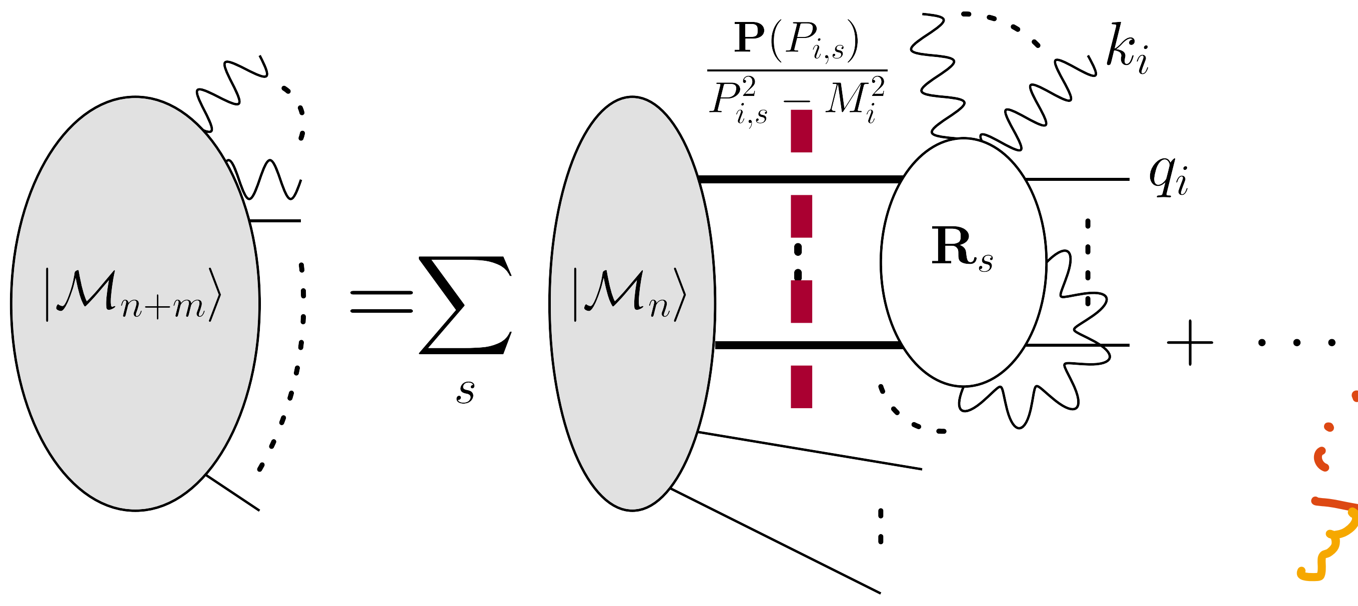
$$K^\mu_{i,s} = \Lambda^\mu{}_\nu \left(Q^\nu_{i,s} + \delta_{i,s}\, n^\nu_{i,s}\right)$$

$$q^\mu_i = \Lambda^\mu{}_\nu \left(\alpha p^\nu_i + \frac{(1-\alpha^2)M_i^2 + p_i\cdot Q_{i,s}}{2\alpha\, n_{i,s}\cdot p_i} n^\nu_{i,s}\right) - K^\mu_{i,s}$$

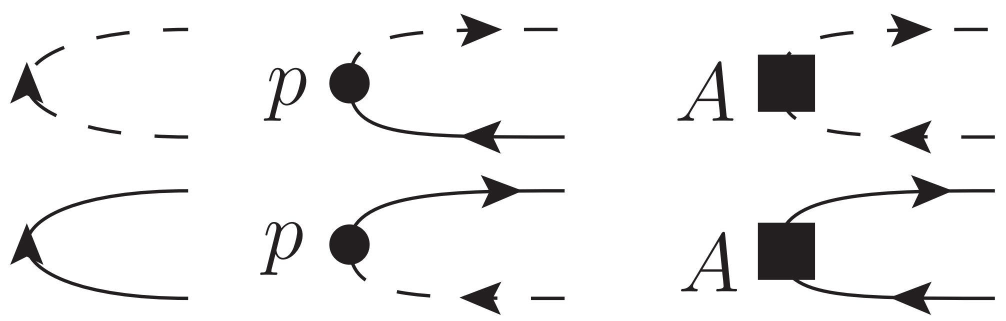
Momentum mappings to systematically factor renormalised matrix elements.

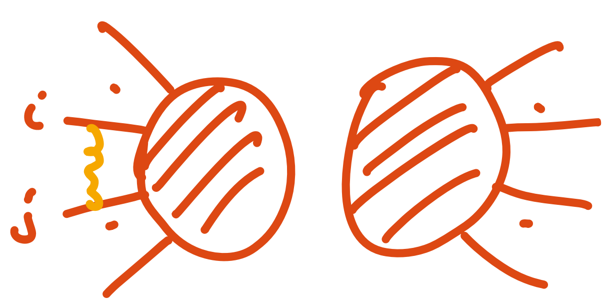


$$= \frac{1}{2p_i\cdot Q_{i,s}} \frac{\Psi(\Lambda p_i, M_i)\bar\Psi(\Lambda p_i, M_i)}{1-\Sigma'(M_i^2)} + \mathcal{O}(\lambda)$$

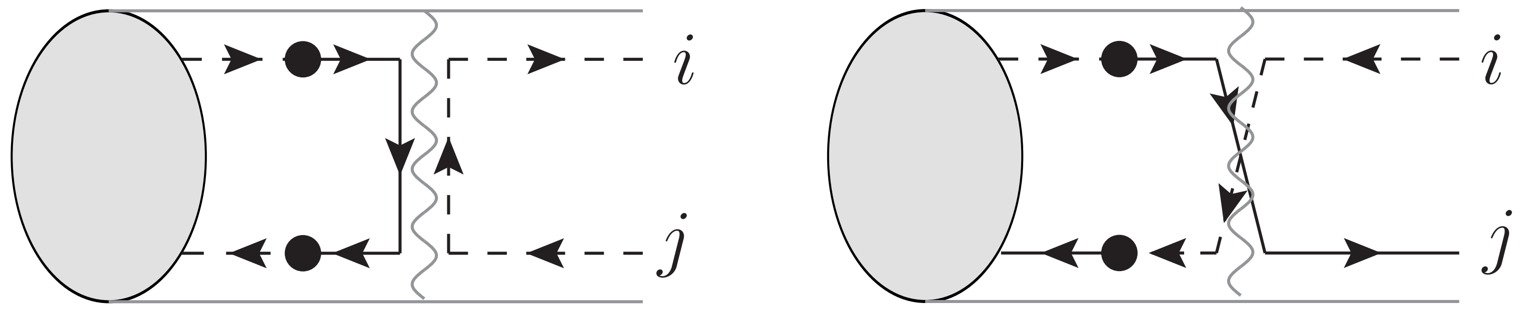


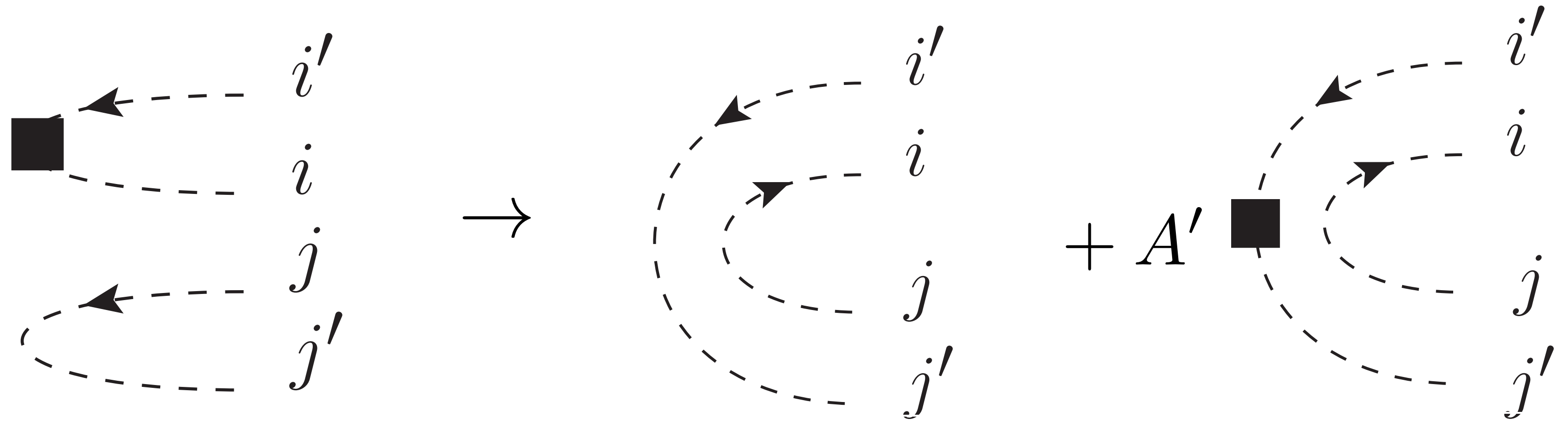
Find a basis of spin structures, together with isospin and colour.





Electroweak bosons now mix different chiral basis states.





Main lines of current parton shower research

Shower development is a broad field, fortunately back on the agenda.
Hadronziation is not exactly shower development, but enters at a similar level,

See Schumann's talk. Always needs to accompany shower development.

Matching/Merging

Control and demonstration of perturbative accuracy.

(N)NLL accuracy

Description of electroweak effects and BSM scenarios.

Interactions beyond QCD

Amplitude evolution

Genuine quantum effects: not limited to subleading colour.

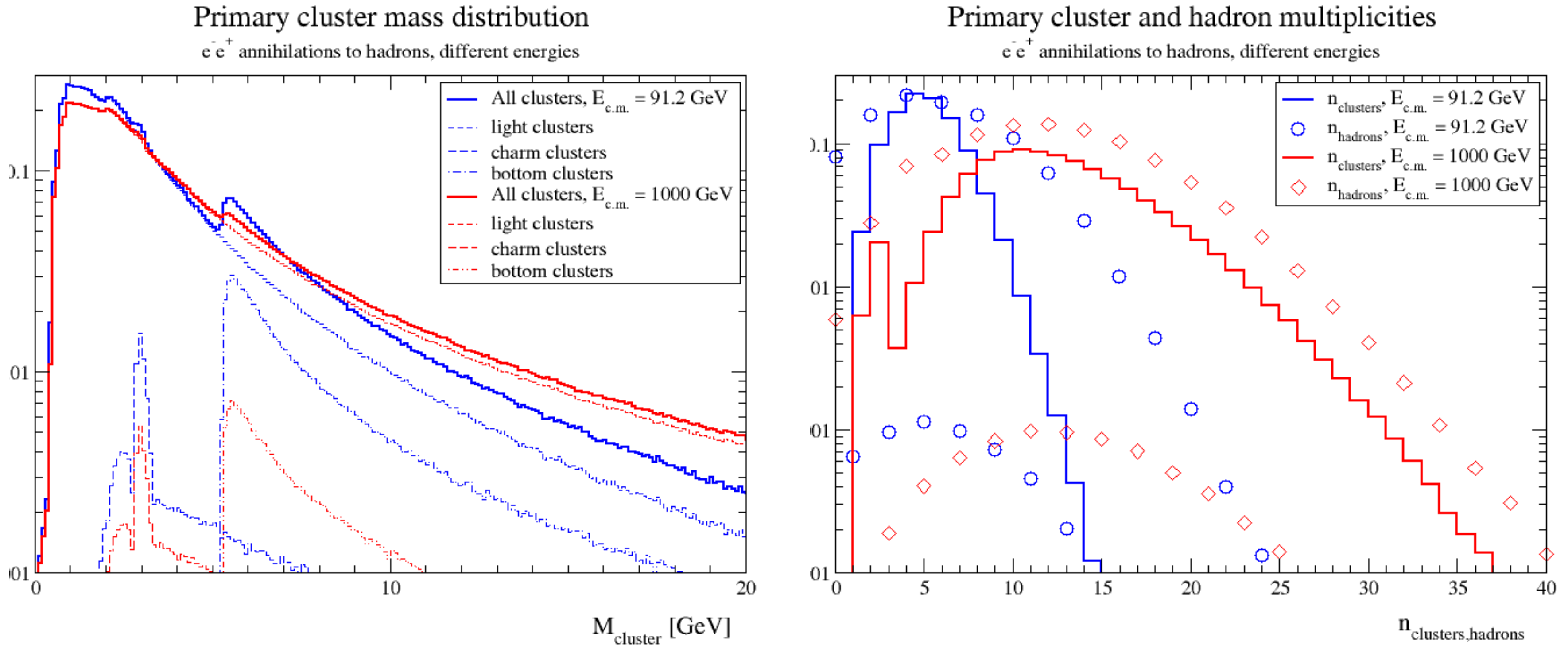
Hadronization

Comprehensive, factorized picture and construction of algorithms.

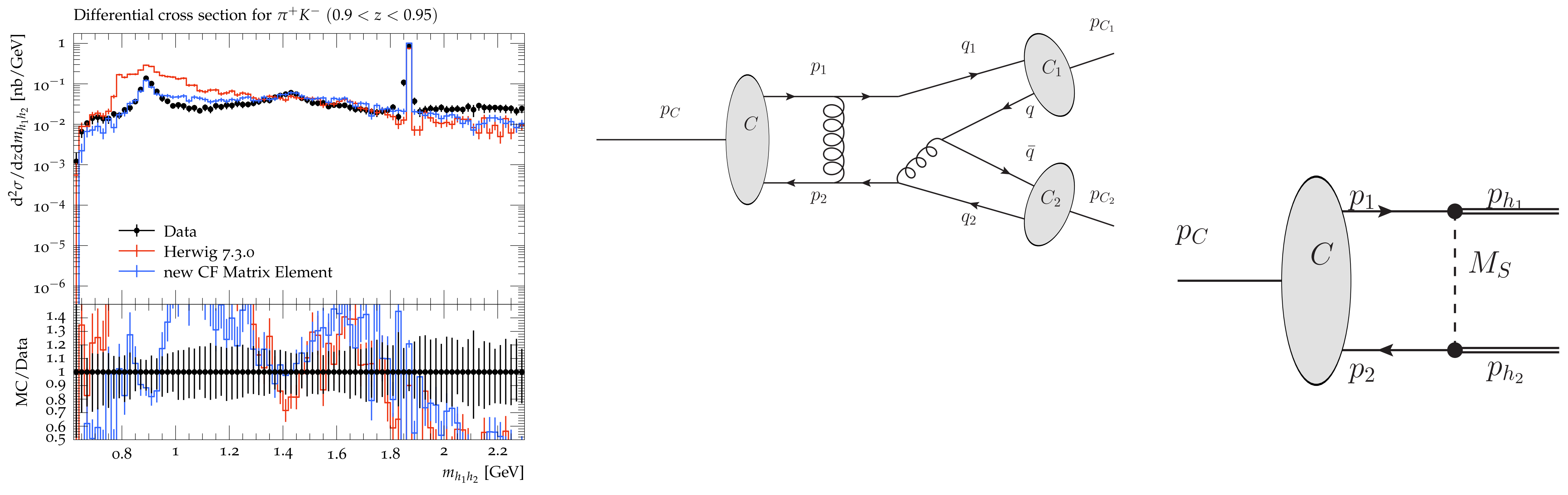
Remaining focus of this talk:

- Perturbative accuracy
- Beyond probabilistic algorithms.
- Factorisation and hadronization.

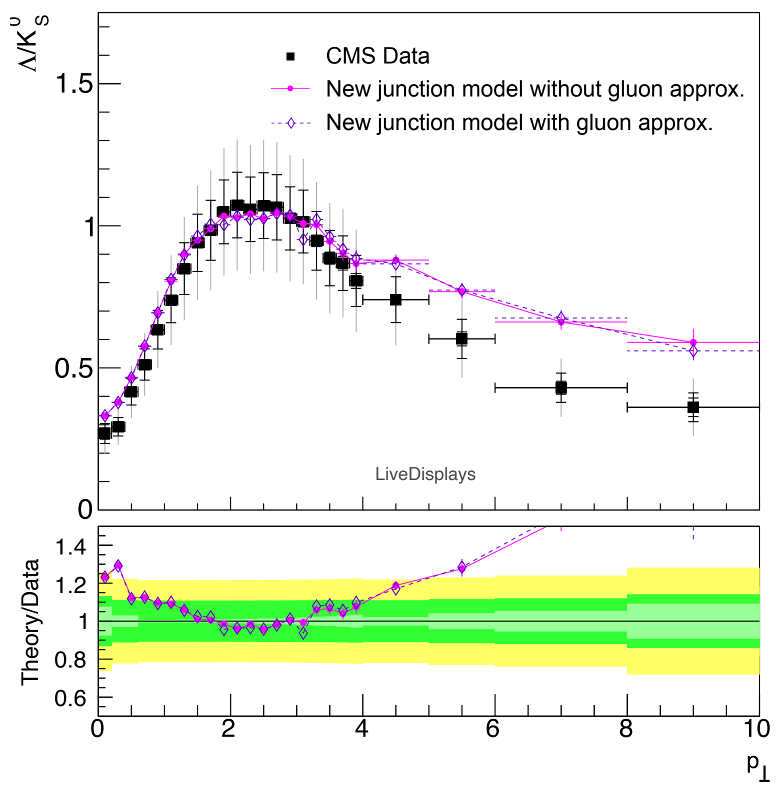
Hadronization in general purpose event generators



[Chahal, Krauss — '22]



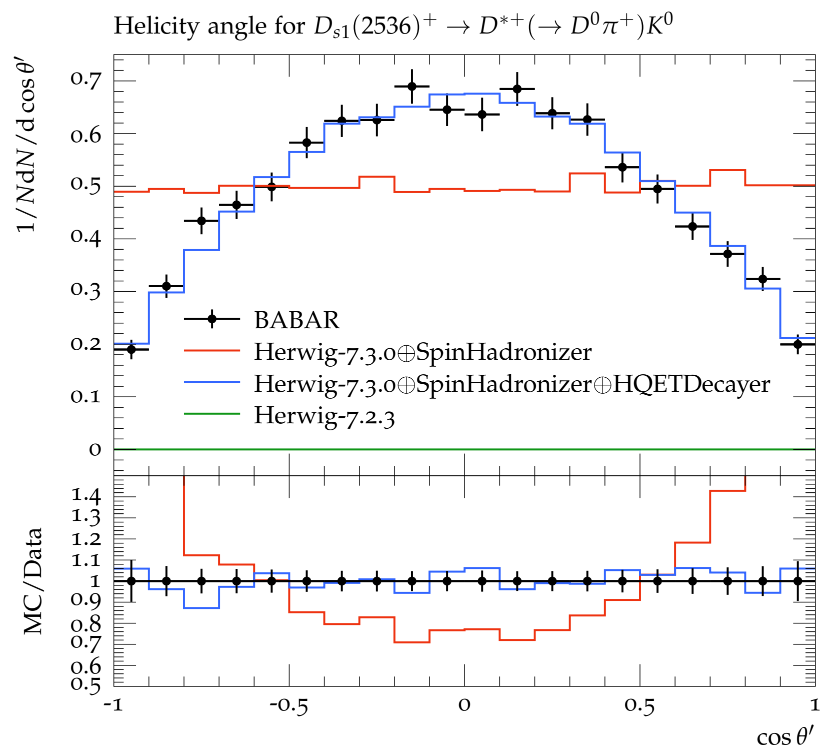
[Gieseke, Kiebacher, Plätzer, Priedigkeit — in progress]



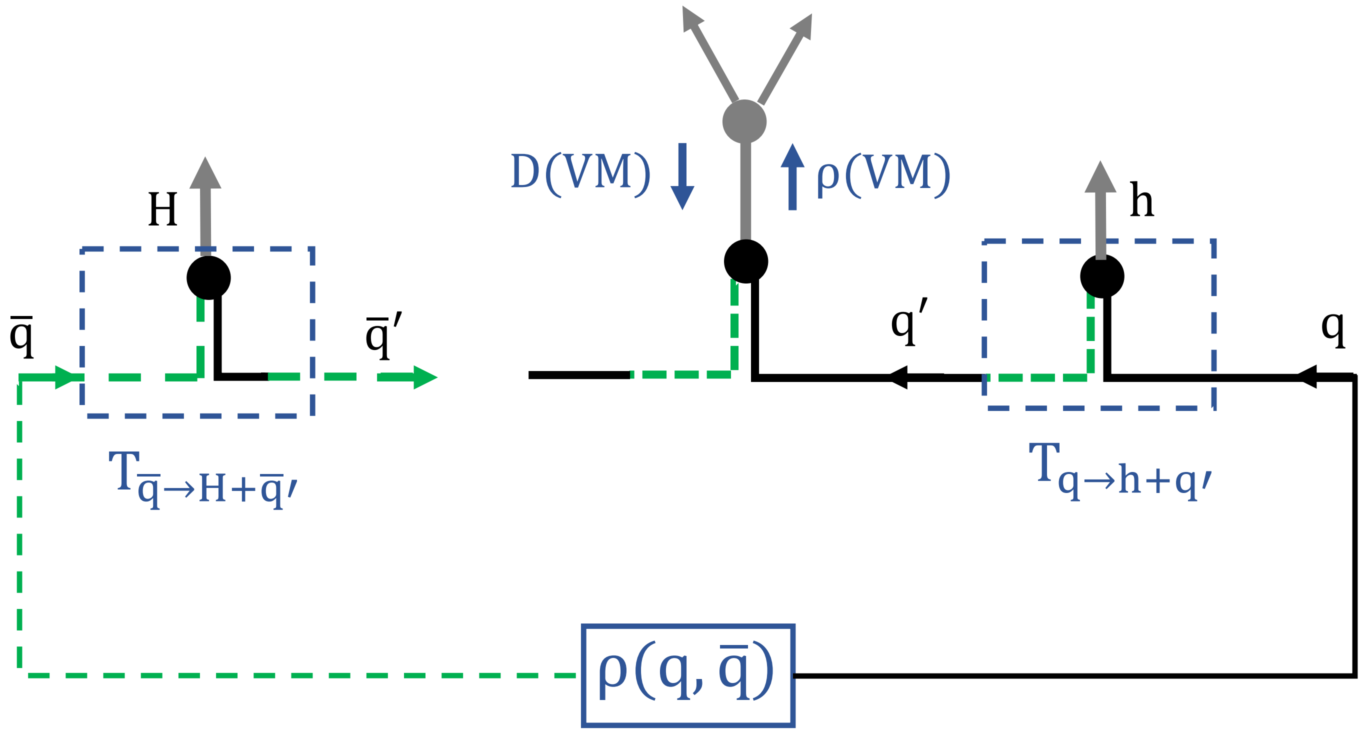
[Altmann, Skands — '24]

Back to an active field

- Colour reconnection
- Spin physics
- Kinematics and low energy hadronization



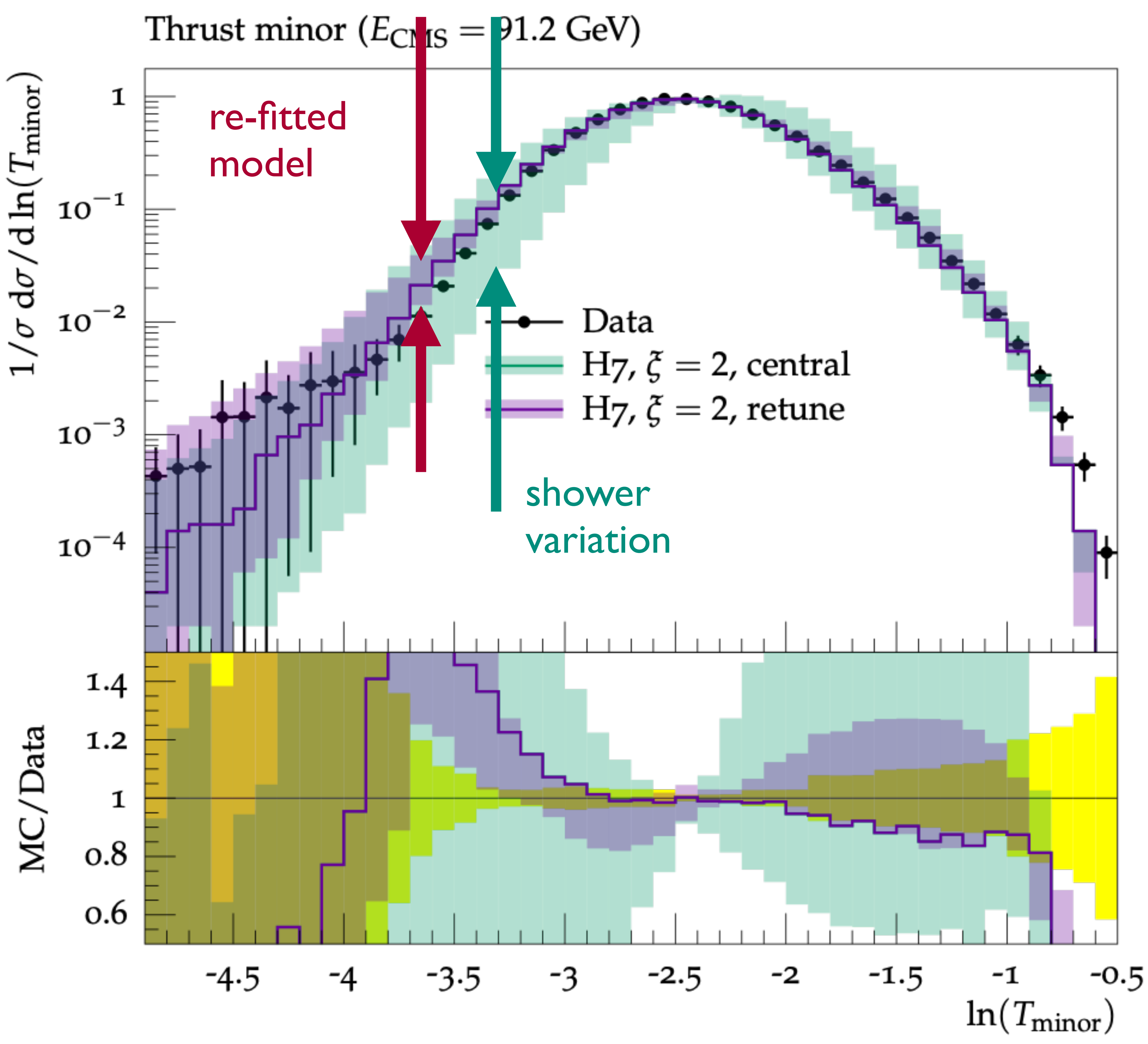
[Masouminia, Richardson — '23]



[Kerbizi, Lönnblad, Martin — '24]

Why we should worry about PS x Hadronization

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

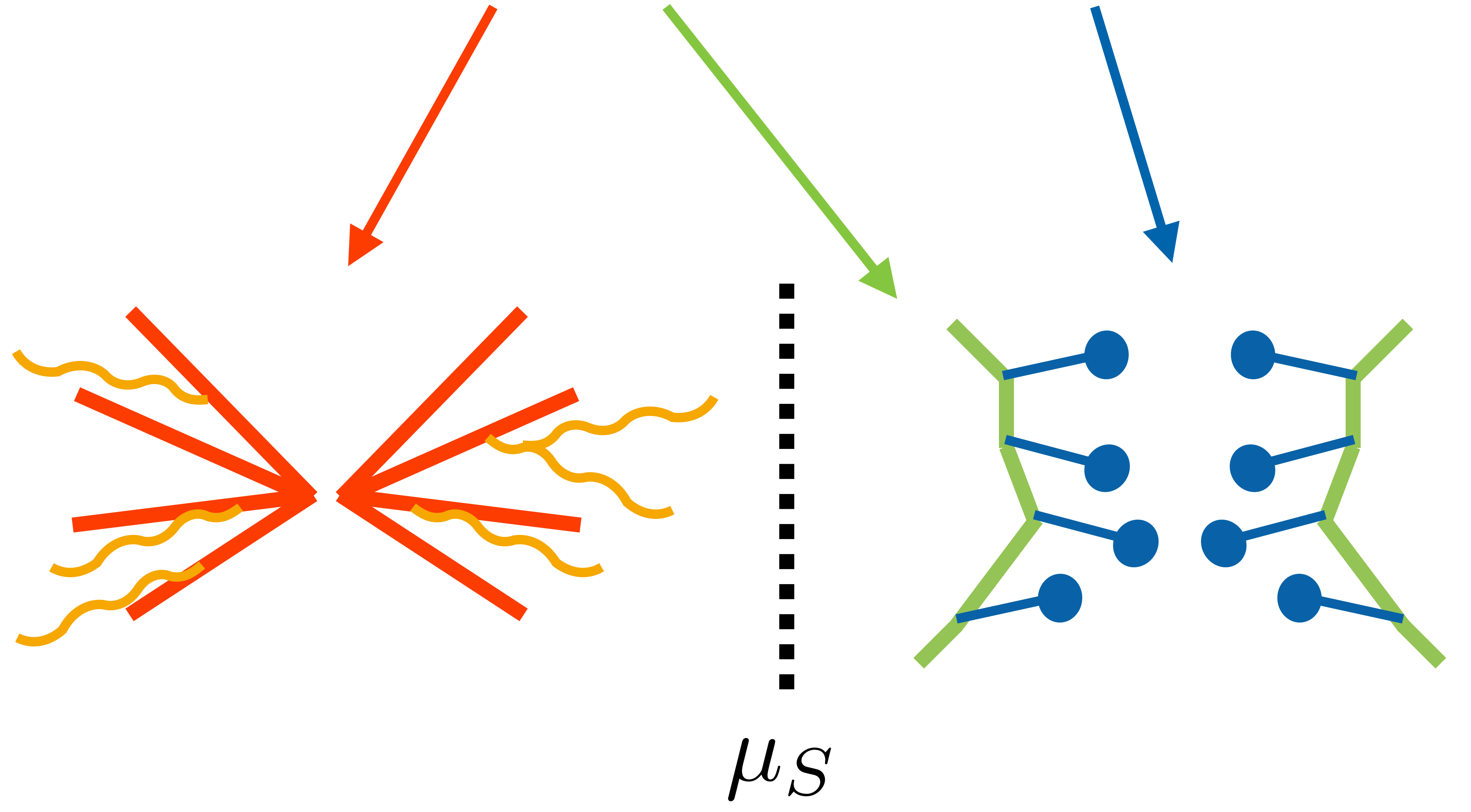


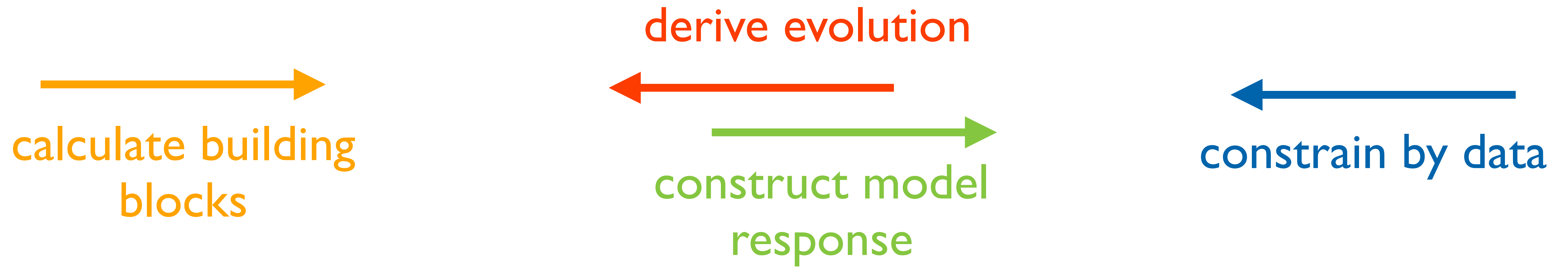
A factorised approach

[Plätzer — '22]

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

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



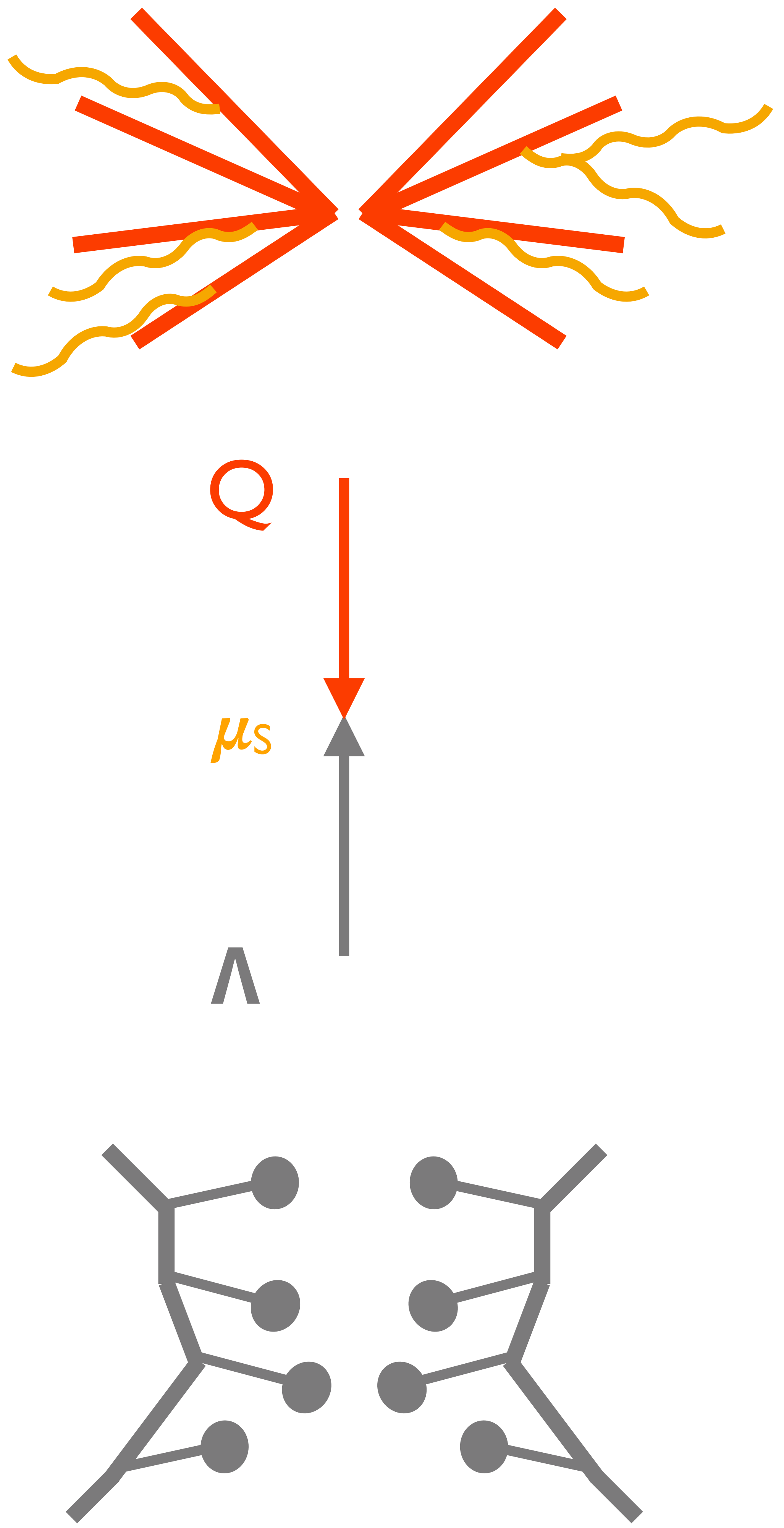


Shower cutoff has central role as factorisation scale:

- Shower/hadronization constrained by renormalisation group
- Formulated in amplitude level evolution, contains event generators in large-N limit.

A factorised approach

[Plätzer — '22]



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

Systematic construction of amplitude evolution algorithms.

Subtract IR divergencies
in unresolved regions

Re-arrange to resum
IR enhancements

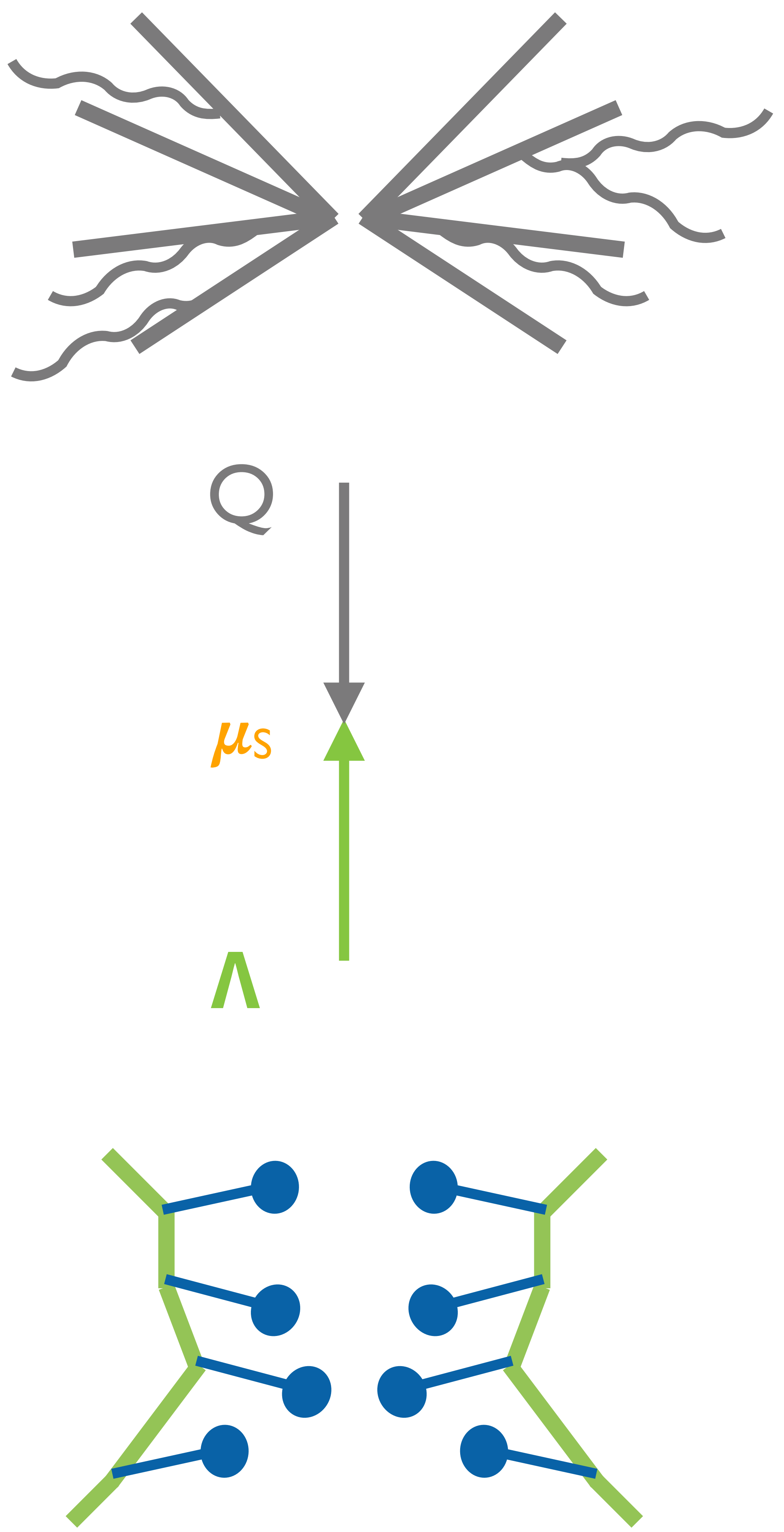
$$\mathbf{U}_n = \mathcal{X}_n \left[\mathbf{S}(\mu_S), \mu_S\right]$$

$$\sigma = \sum_n \alpha_S^n \int \mathrm{Tr}\left[\mathbf{A}_n(\mu_S) \mathbf{S}_n(\mu_S)\right] \mathrm{d}\phi_n$$

$$\mathbf{M}_n Z_g^n = \mathcal{Z}_n \left[\mathbf{A}(\mu_S), \mu_S\right]$$

A factorised approach

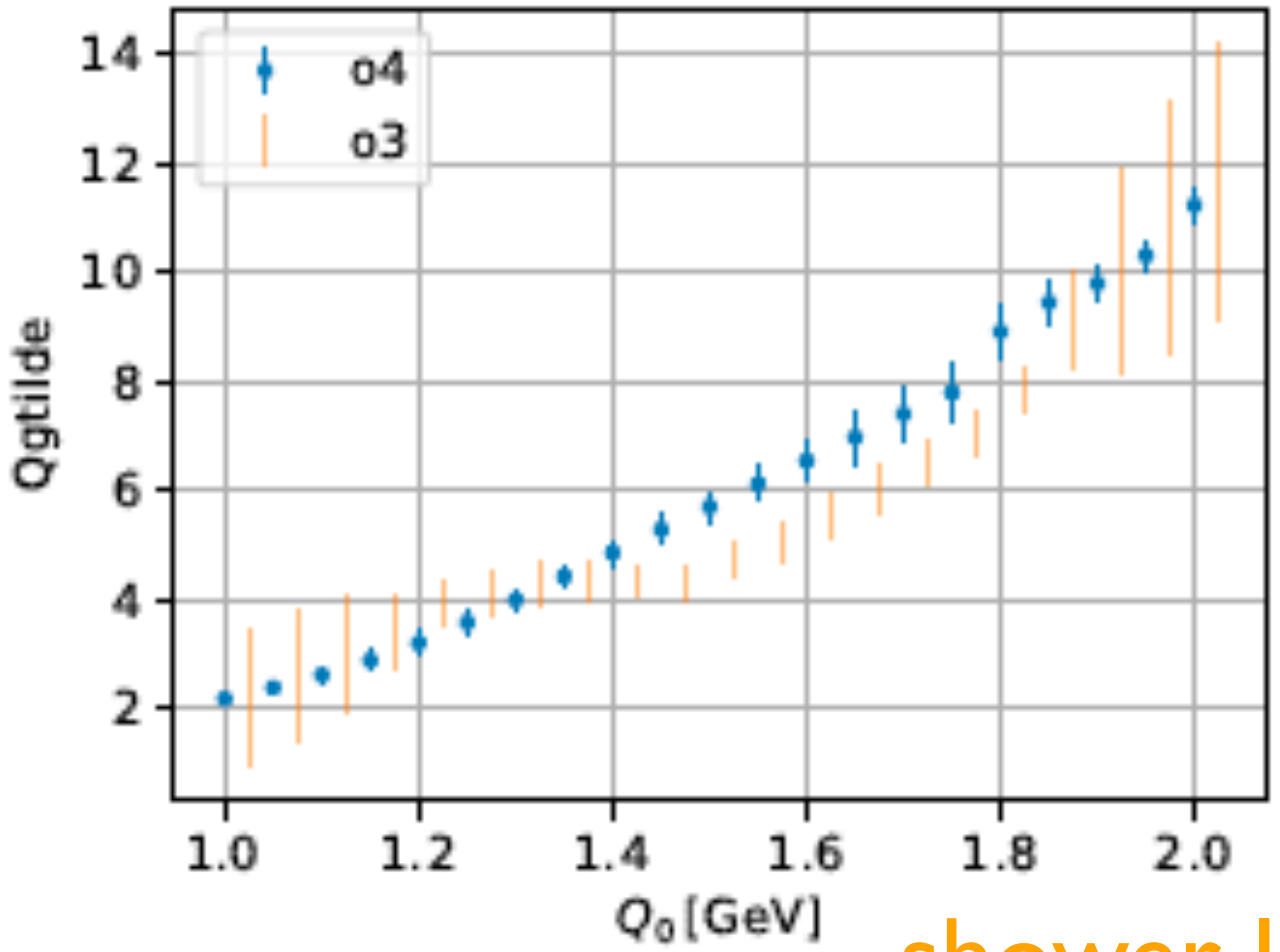
[Hoang, Jin, Plätzer, Samitz — '24]
[Gieseke, Kiebacher, Plätzer, Priedigkeit — in progress]



Leads to constructive prescription for "high energy" end of hadronization.

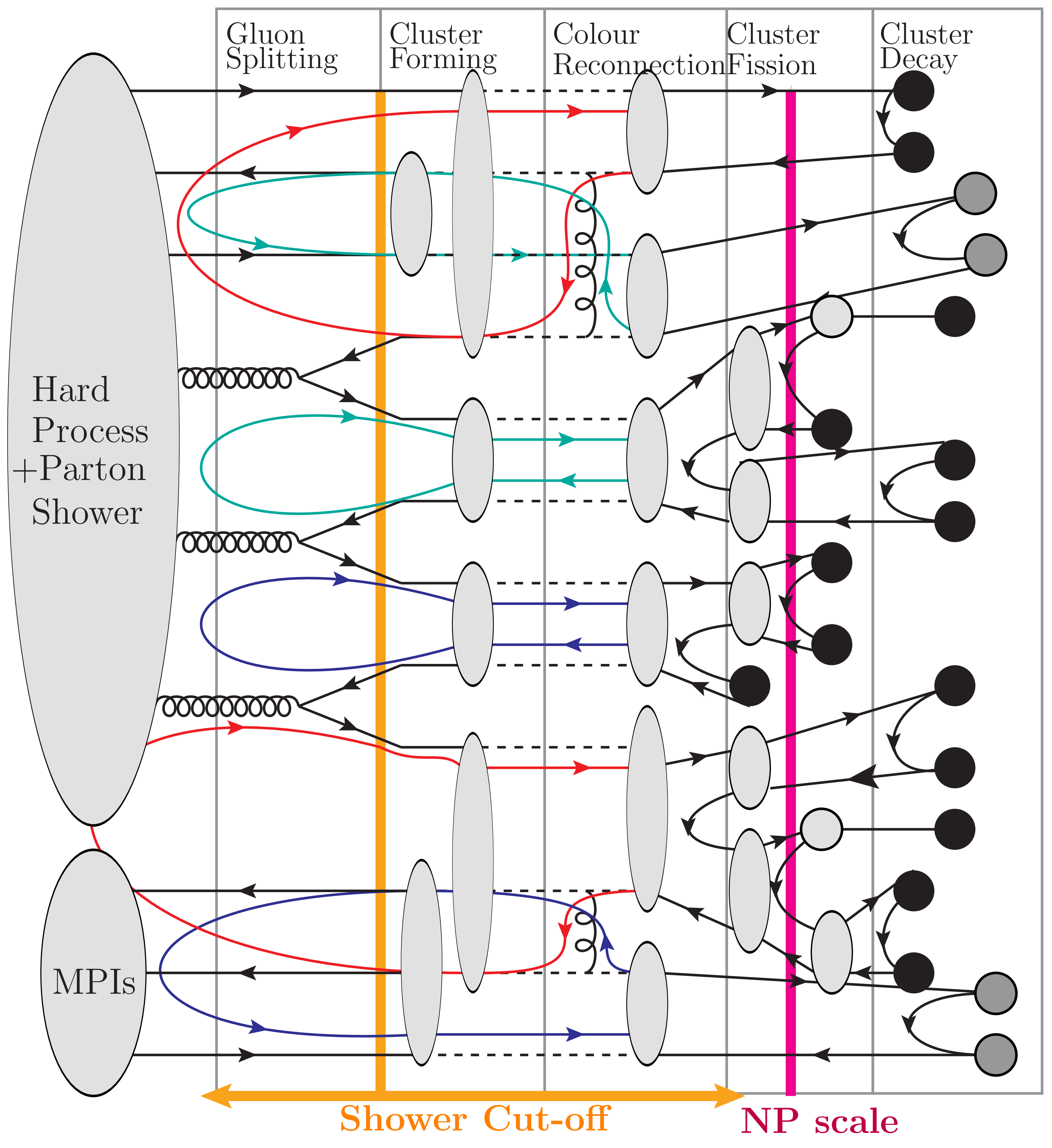
First steps demonstrated:

hadronization UV cutoff



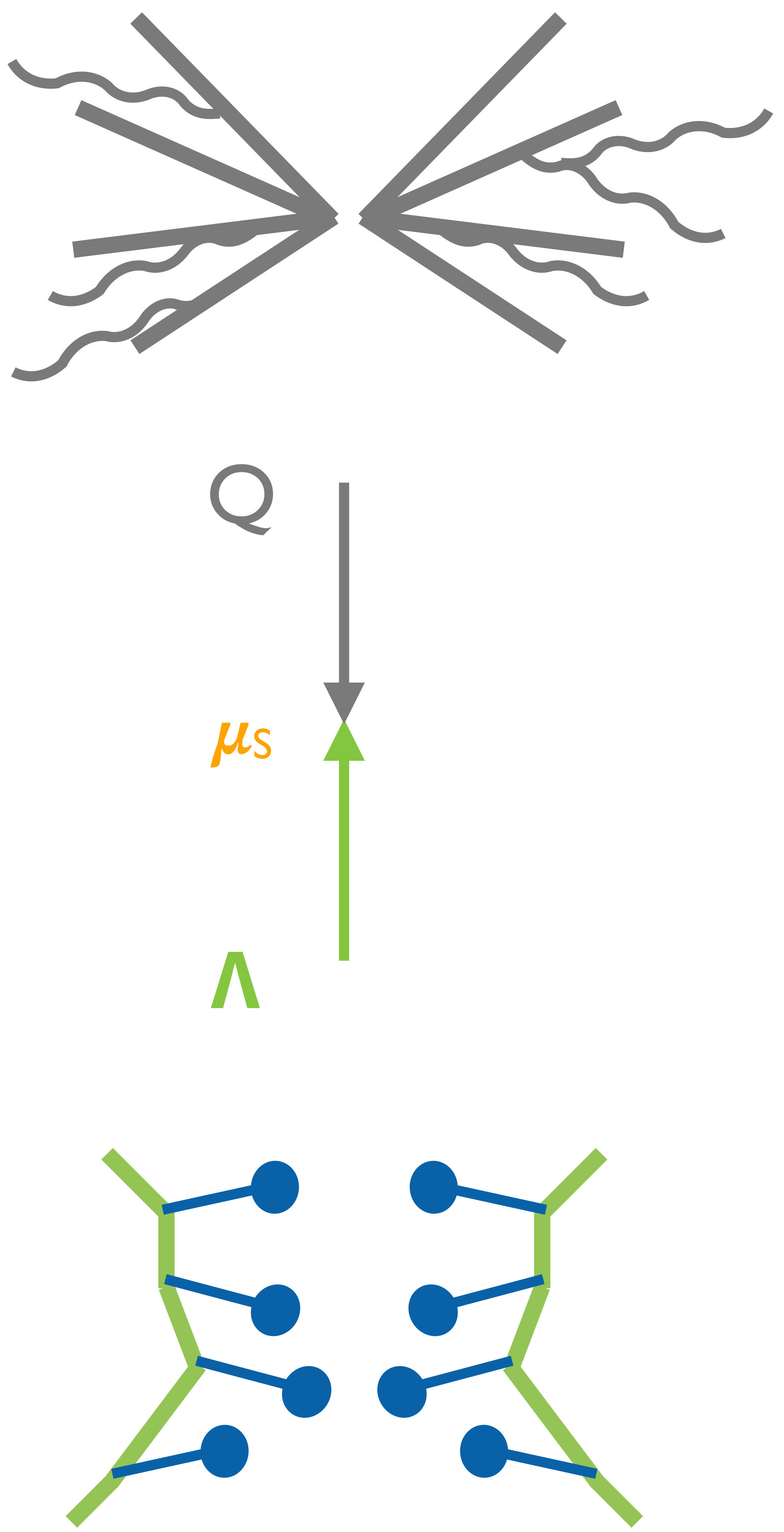
shower IR cutoff

Lower energy dynamics in the model not sensitive to cutoff anymore.



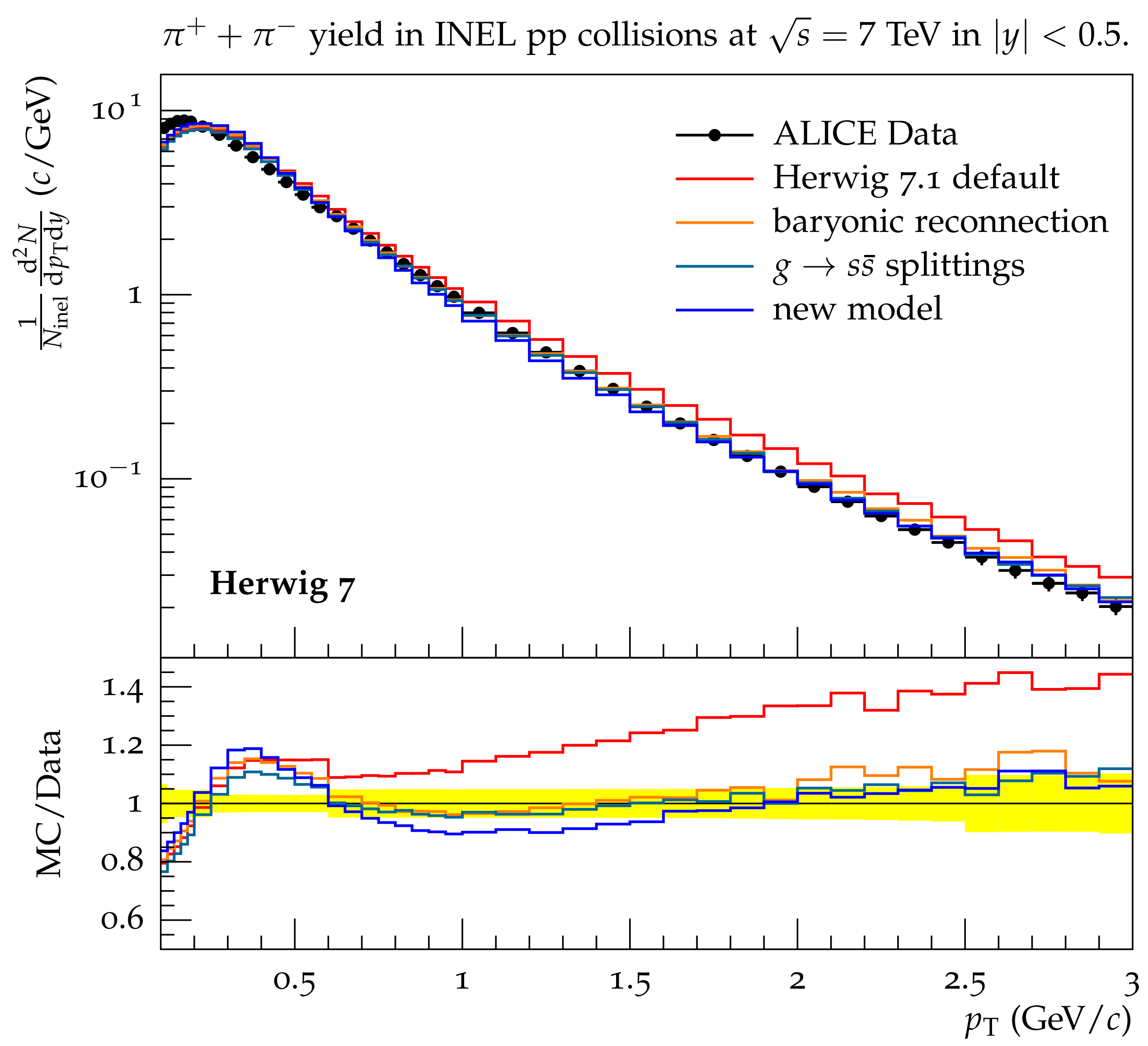
[Kiebacher @ PSR '24]

A factorised approach



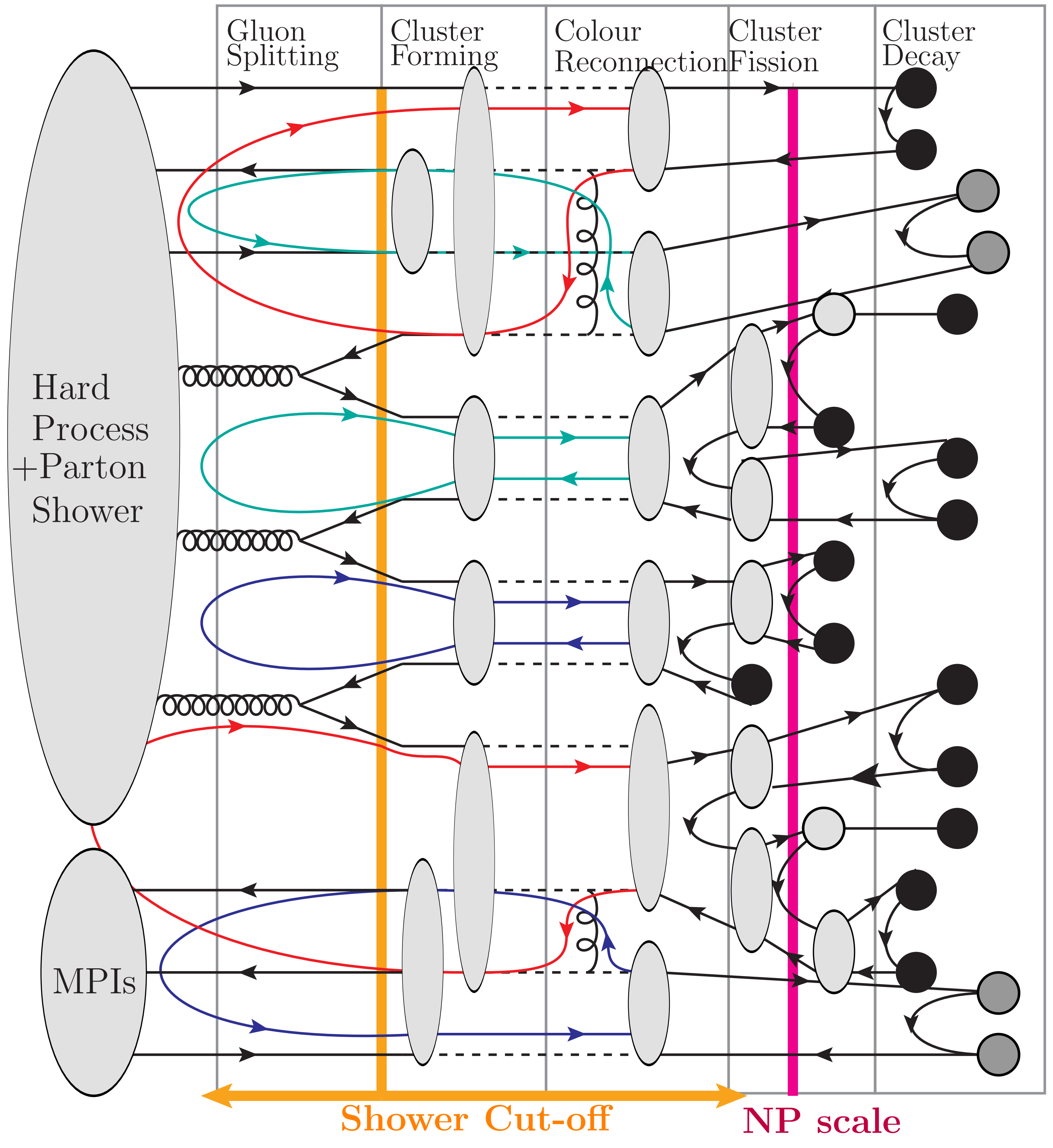
Leads to constructive prescription for "high energy" end of hadronization.

Colour reconnection dynamics implied from amplitude evolution structures:



[Gieseke, Kirchgaesser, Plätzer, Siodmok — '17, '18]

[Hoang, Jin, Plätzer, Samitz — '24]
[Gieseke, Kiebacher, Plätzer, Priedigkeit — in progress]



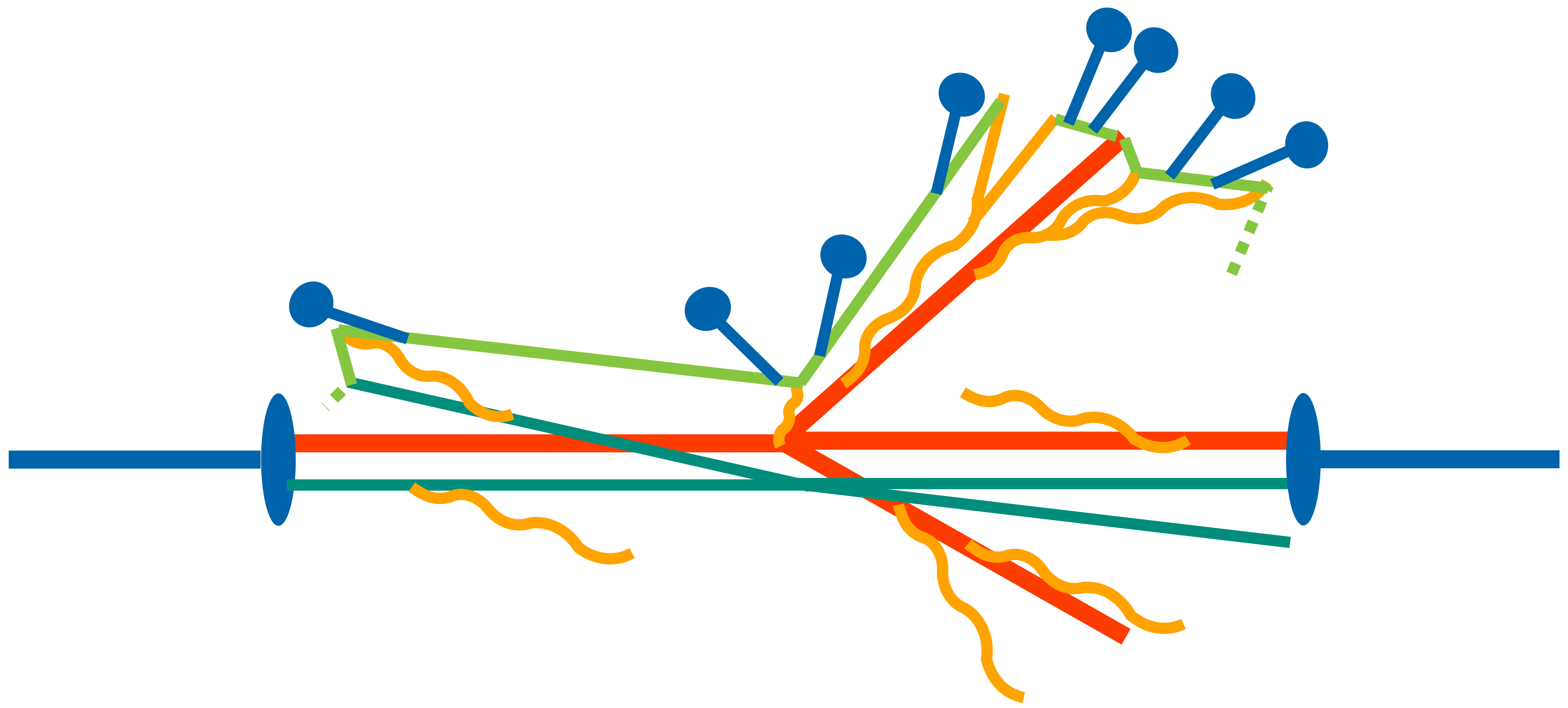
[Kiebacher @ PSR '24]

Summary

Parton showers are central to event generators.

I emphasise that we study shower *algorithms* rather than shower *models* — predict QCD effects in a hierarchy of strongly ordered energy scales.

We can, and need, to assess their accuracy and strive for underlying, well-defined, construction principles.



Infrared sensitive observables are of course the prime test bed — matching will do remaining aspects for jet observables. Hadronization can not be looked at in isolation but is intertwined with parton showering.

Amplitude evolution provides us with a new paradigm which we can use to construct parton showers, as a dedicated resummation tools and eventually to study the structure of amplitudes using simulation.

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

Summary

Many of the current developments happen at e+e- — that's a matter of fact, and we need to start simple.

But several of the current projects start to port algorithms to hadron colliders — stay tuned.

Parton showers are central to event generators.

I emphasise that we study shower *algorithms* rather than shower *models* — predict QCD effects in a hierarchy of strongly ordered energy scales.

We can, and need, to assess their accuracy and strive for underlying, well-defined, construction principles.

Infrared sensitive observables are of course the prime test bed — matching will do remain ... cts for jet observables. Hadronization can not be looked at in isolation but is intertwined with parton showering.

Amplitude evolution provides us with a new paradigm which we can use to construct parton showers, as a dedicated resummation tools and eventually to study the structure of amplitudes using simulation.

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

Thank you