MC Generators: Theoretical Progress

Simon Plätzer
Particle Physics — University of Vienna

at the
Physics at TeV Colliders 2021
Les Houches/digital | 16 June 2021

A biased, personal selection (no exhaustive reference lists), and based on discussions with Josh McFayden and Frank Siegert.

Overview

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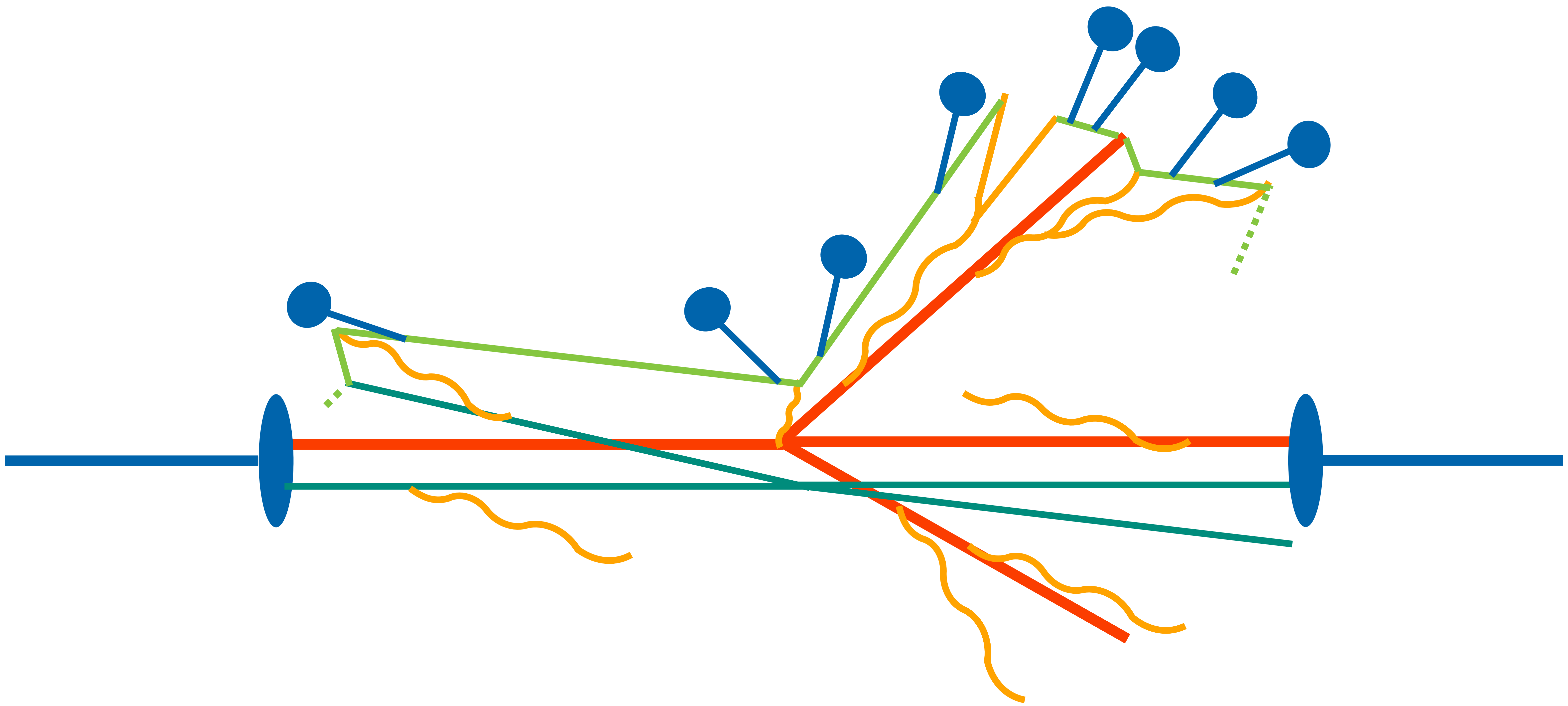


$$\mathrm{d}\sigma \sim \mathrm{L} \times \mathrm{d}\sigma_H(Q) \times \mathrm{PS}(Q \to \mu) \times \mathrm{MPI} \times \mathrm{Had}(\mu \to \Lambda) \times \ldots$$

Recent Questions & Development

Showers rule!

- Accuracy/Precision
- Spin & colour correlations
- New Paradigms
- Unstable particles
- Electroweak contributions
- **Non-perturbative interplay**

This shouldn't imply that we should not further explore the interplay of showers and matching/merging (see Alex's talk, as well).

14:00	Electroweak corrections and multijet merging	Enrico Bothmann	14:00 - 14:20
	The PanScale shower approach	Pier Francesco Monni	14:20 - 14:40
	Boosted Higgs Production in Vector Boson Fusion	Silvia Ferrario Ravasio	14:40 - 14:55
15:00	Parton-Shower Effects in Higgs Production via Vector-Boson Fusion	Johannes Scheller	14:55 - 15:10
	Spin correlations in the PanScales parton showers and jet observables	Rob Verheyen	15:10 - 15:25
	Break		15:25 - 15:40
	Sector showers with fixed-order corrections	Christian Preuss	15:40 - 16:00
16:00	Subleading colour effects in the PanScales parton showers and beyond	Ludovic Scyboz	16:00 - 16:15
	Improved dipole showers	Simon Platzer	16:15 - 16:35
	Subleading effect in parton showers	Davison Soper	16:35 - 16:55

PSR21 - Parton Showers and Resummation

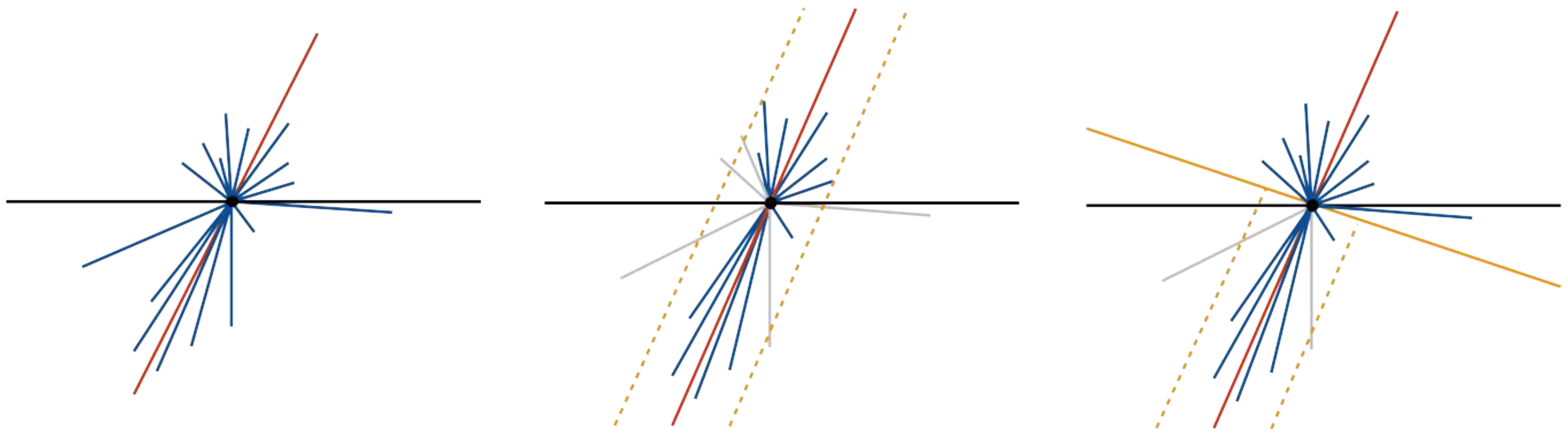
25-27 May 2021

Europe/Zurich timezone

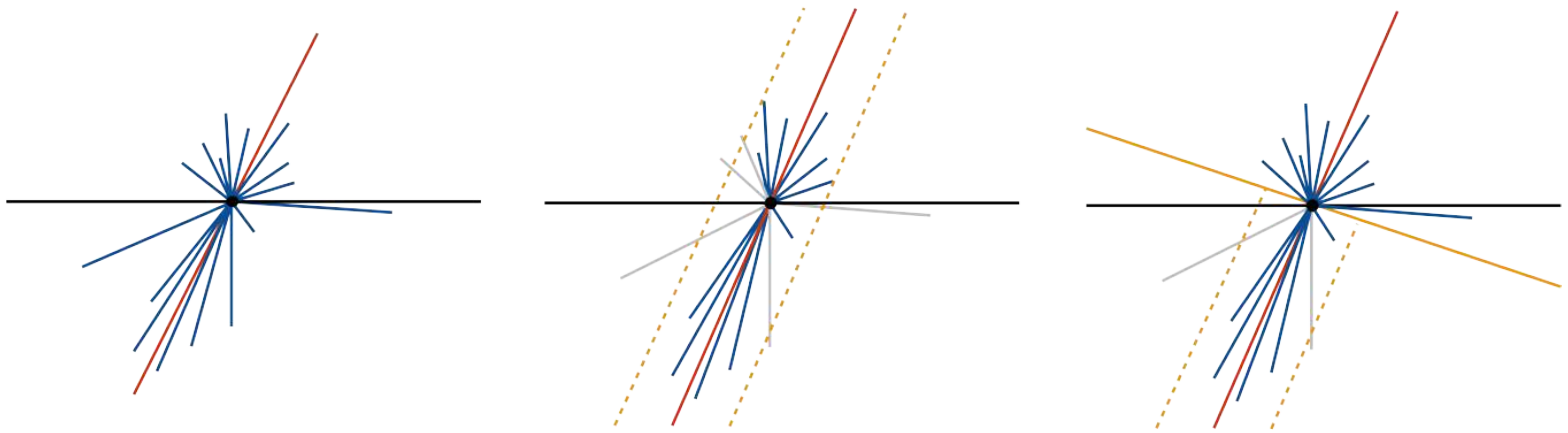
14:00	MC generator overview	Stefan Prestel et al.	14:00 - 14:45

https://indico.cern.ch/event/1018828/timetable/#20210525.detailed

Accuracy



Pressing issues in parton showers



NLO with matching

NLL with coherent branching
Issues in dipole showers

Issues in coherent branching
LL with dipole showers

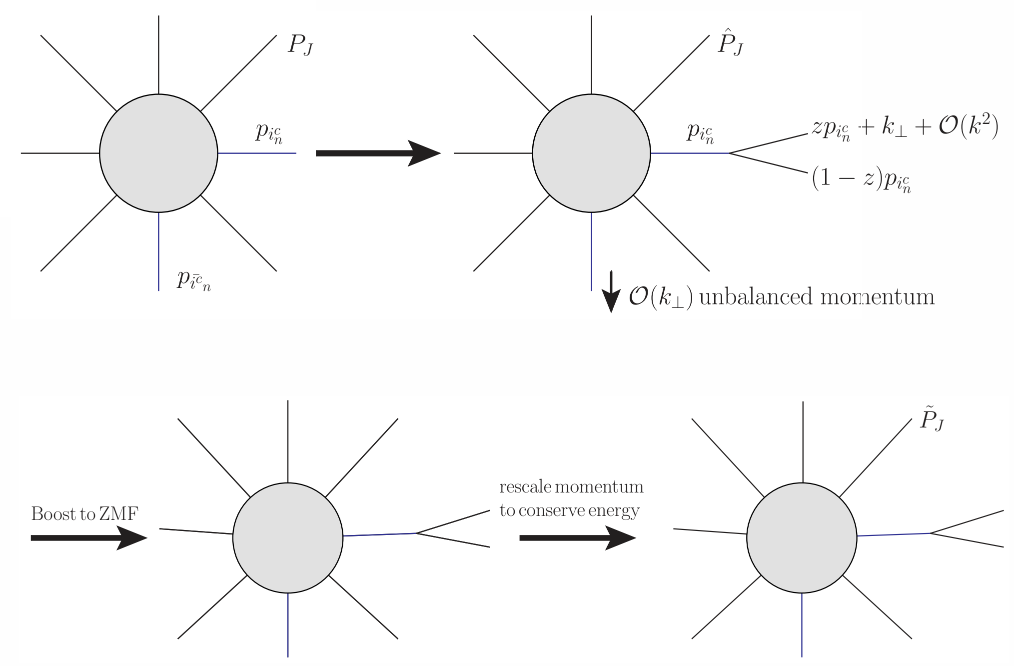
Understand and decide on accuracy of (existing) parton shower algorithms, take as a starting point for incremental improvements.

[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]

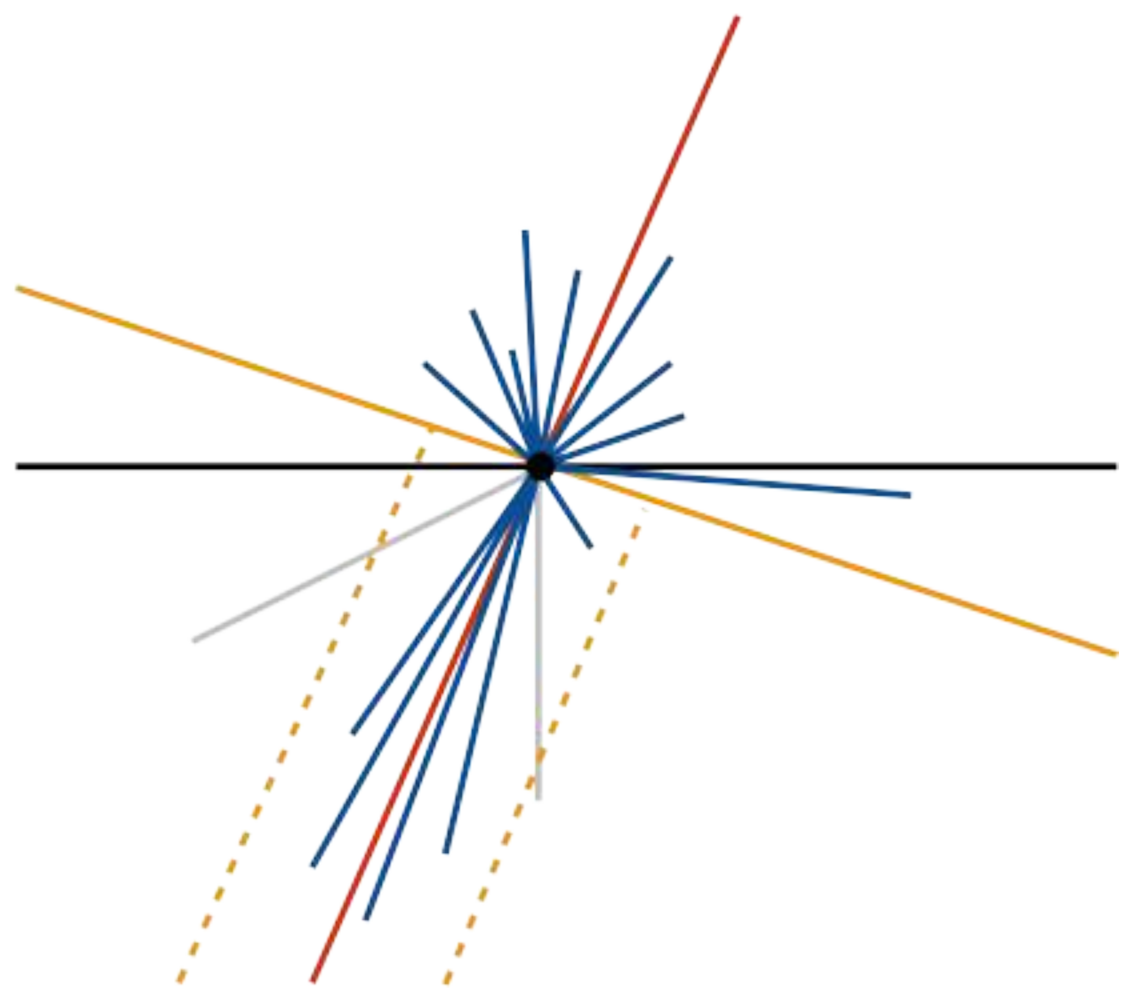
Pressing issues in parton showers

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

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



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



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]

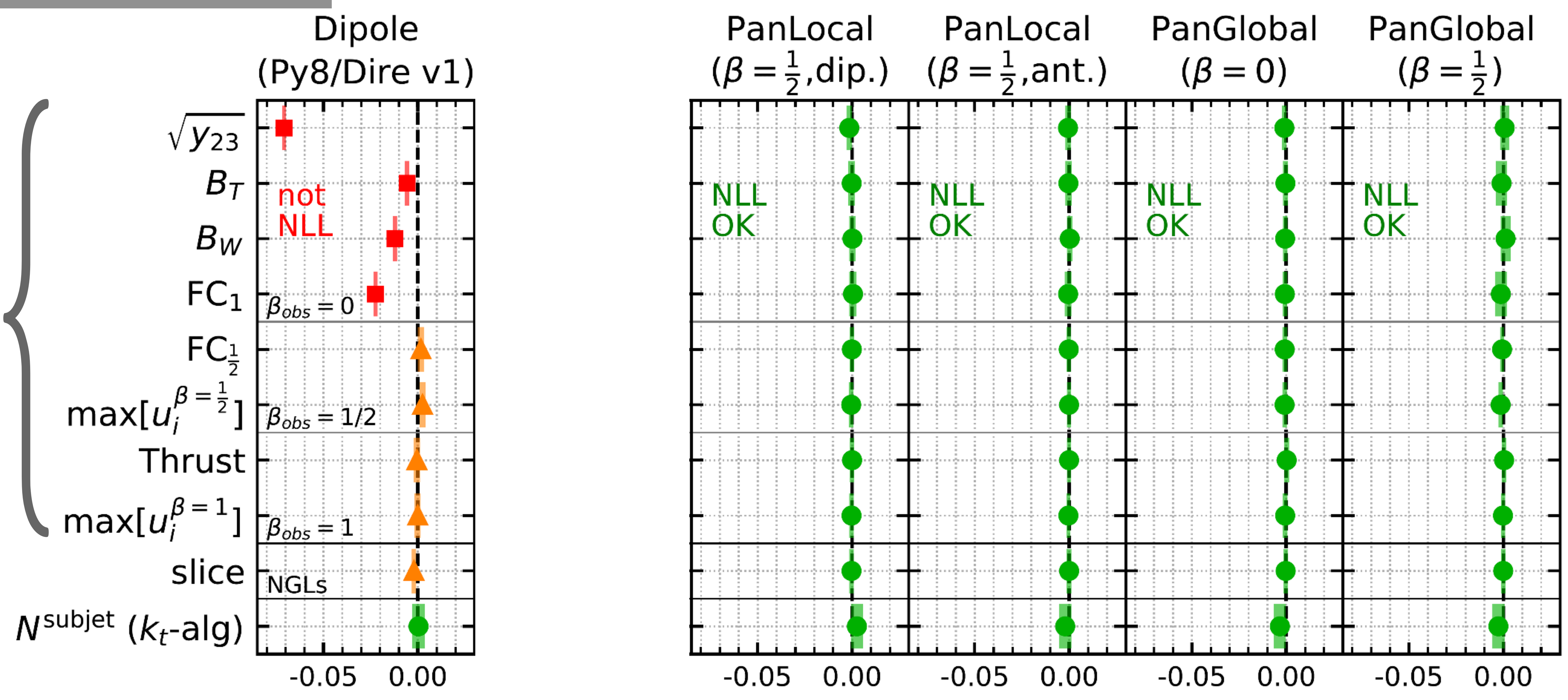
Accuracy

Accuracy across many observables

Plots: relative deviation from exact NLL [in $\alpha_s \to 0$ limit at fixed $\alpha_s L$]

[Sjostrand et al. '15]
[Hoeche, Prestel '15]

[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez '20]



Global observables: sensitive to strong η (θ) separation at NLL

e.g.

$$\mathrm{T} = \max_{\hat{n}} \frac{\sum_i |\mathbf{p}_i \cdot \hat{n}|}{\sum_i |\mathbf{p}_i|}$$

$$\mathrm{FC}_x = \sum_{i \neq j} \frac{E_i E_j}{(\sum_i E_i)^2} |\sin\theta_{ij}|^x (1 - |\cos\theta_{ij}|)^{1-x} \Theta((\mathbf{p}_i \cdot \hat{n})(\mathbf{p}_j \cdot \hat{n}))$$

$$\max\left[u_i^\beta\right] = \max_{\text{primary decl.}} \left\{k_{t1} e^{-\beta|\eta_1|}, \ldots, k_{tn} e^{-\beta|\eta_n|}\right\}$$

Orange triangles indicate spurious terms (either NLL or SLL) at fixed order, that become small when resummed

Accuracy

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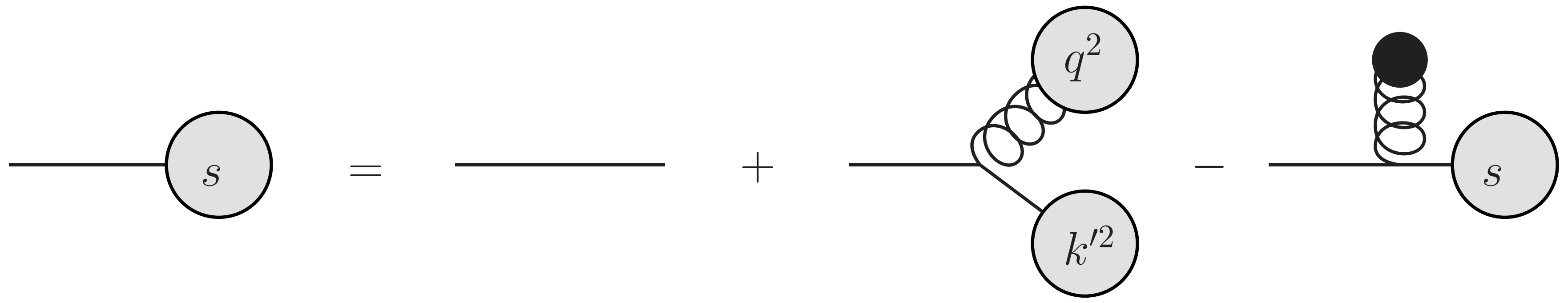
[Catani, Trentadue, Webber, Marchesini, …]

Evolution equations for coherent branching jet mass distribution

$$J(s,Q^2) = \delta(s) + \int_0^{Q^2} \frac{\mathrm{d}\tilde{q}^2}{\tilde{q}^2} \int_0^1 \mathrm{d}z\, P_{qq}\Big[\alpha_s\big(z(1-z)\tilde{q}\big), z\Big]$$
$$\times \left[\int_0^\infty \mathrm{d}k'^2 \int_0^\infty \mathrm{d}q^2 \delta\Big(s - \frac{k'^2}{z} - \frac{q^2}{1-z} - z(1-z)\tilde{q}^2\Big) J(k'^2, z^2\tilde{q}^2) J_g(q^2,(1-z)^2\tilde{q}^2) - J(s,\tilde{q}^2)\right]$$



NLL accurate for global observables with massive quarks, and if inclusive over secondary soft gluon emission.

$$\alpha_s \to \alpha_s\left(1 + K_g \frac{\alpha_s}{2\pi}\right)$$

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

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

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

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

Spin & Colour Correlations

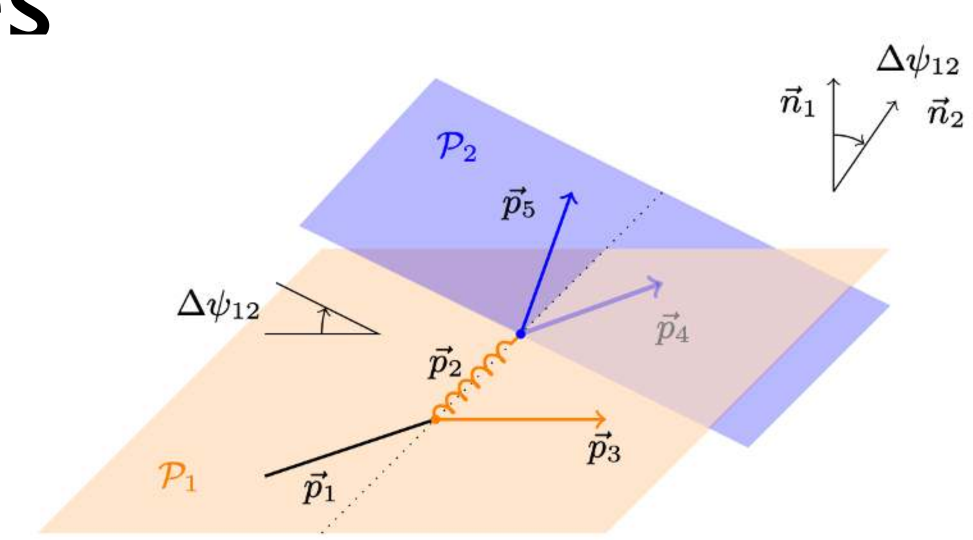
Several improvements on existing shower algorithms

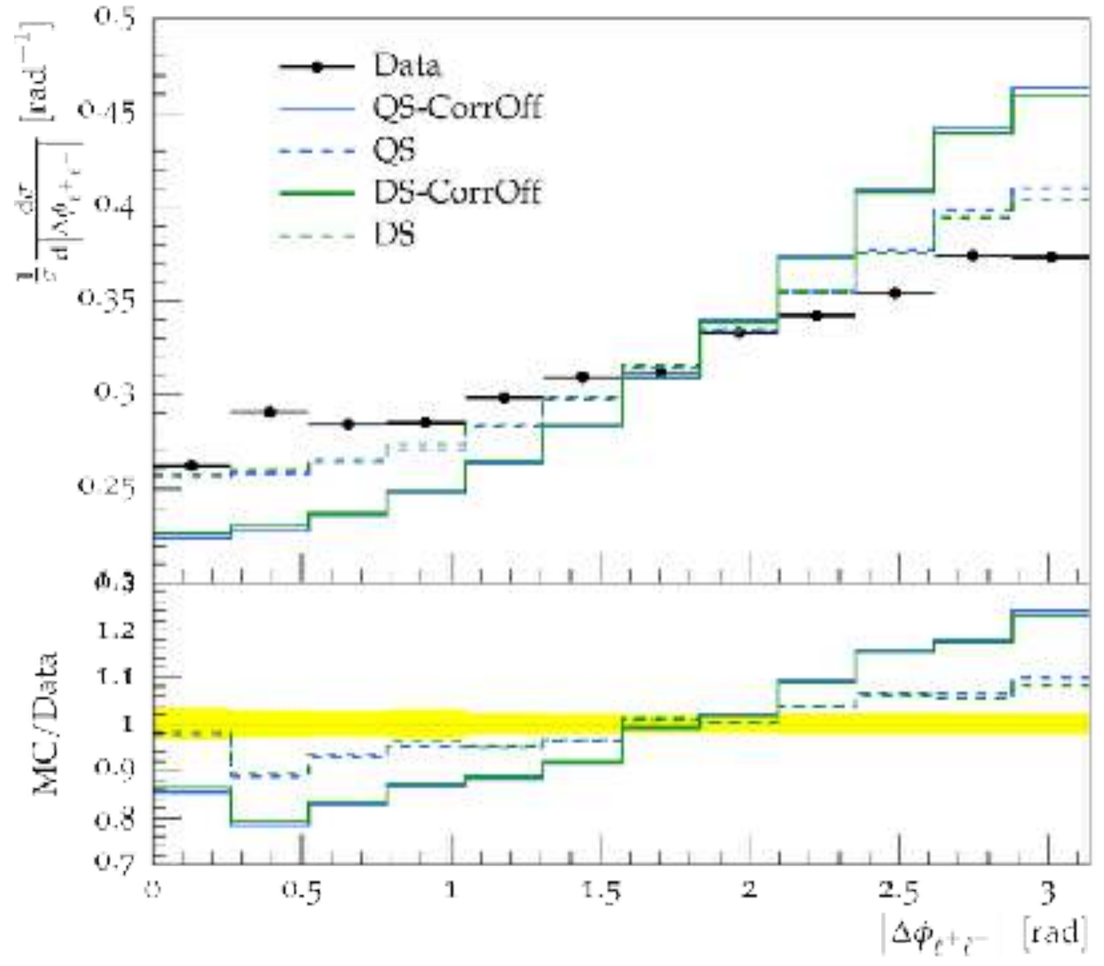
- Spin correlations in Herwig's shower modules

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

- Similar approach pursued by PanScales team

  [Karlberg, Salam, Scyboz, Verheyen — 2103.16526]

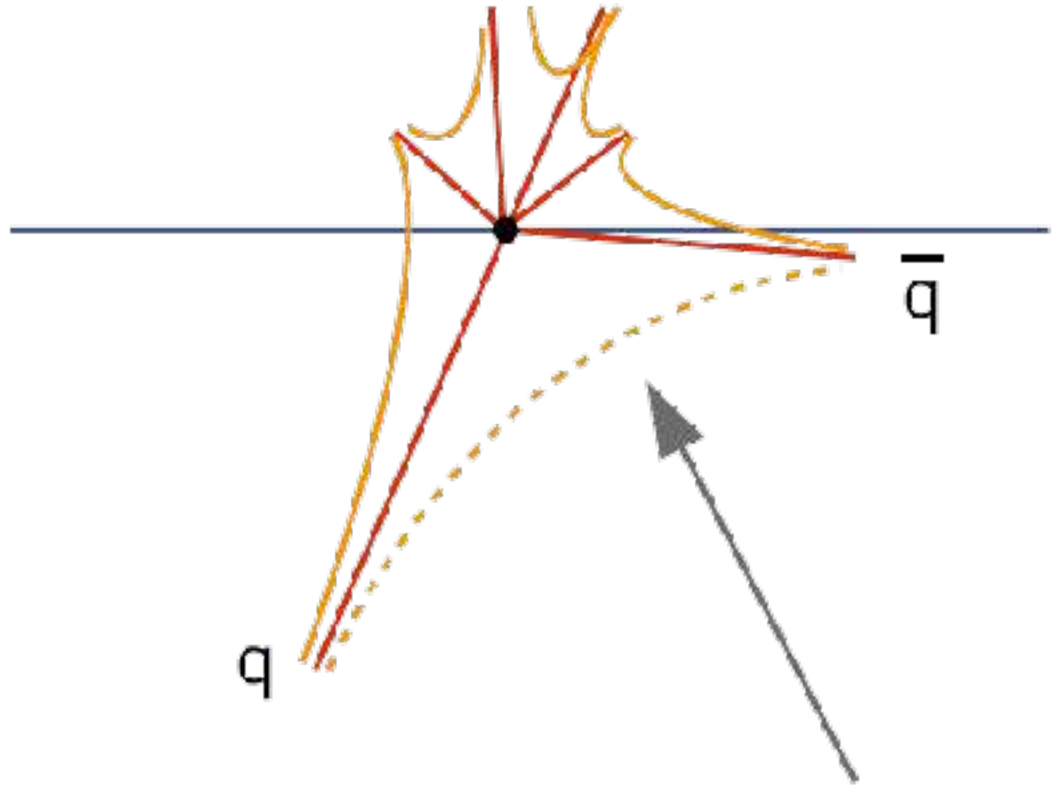




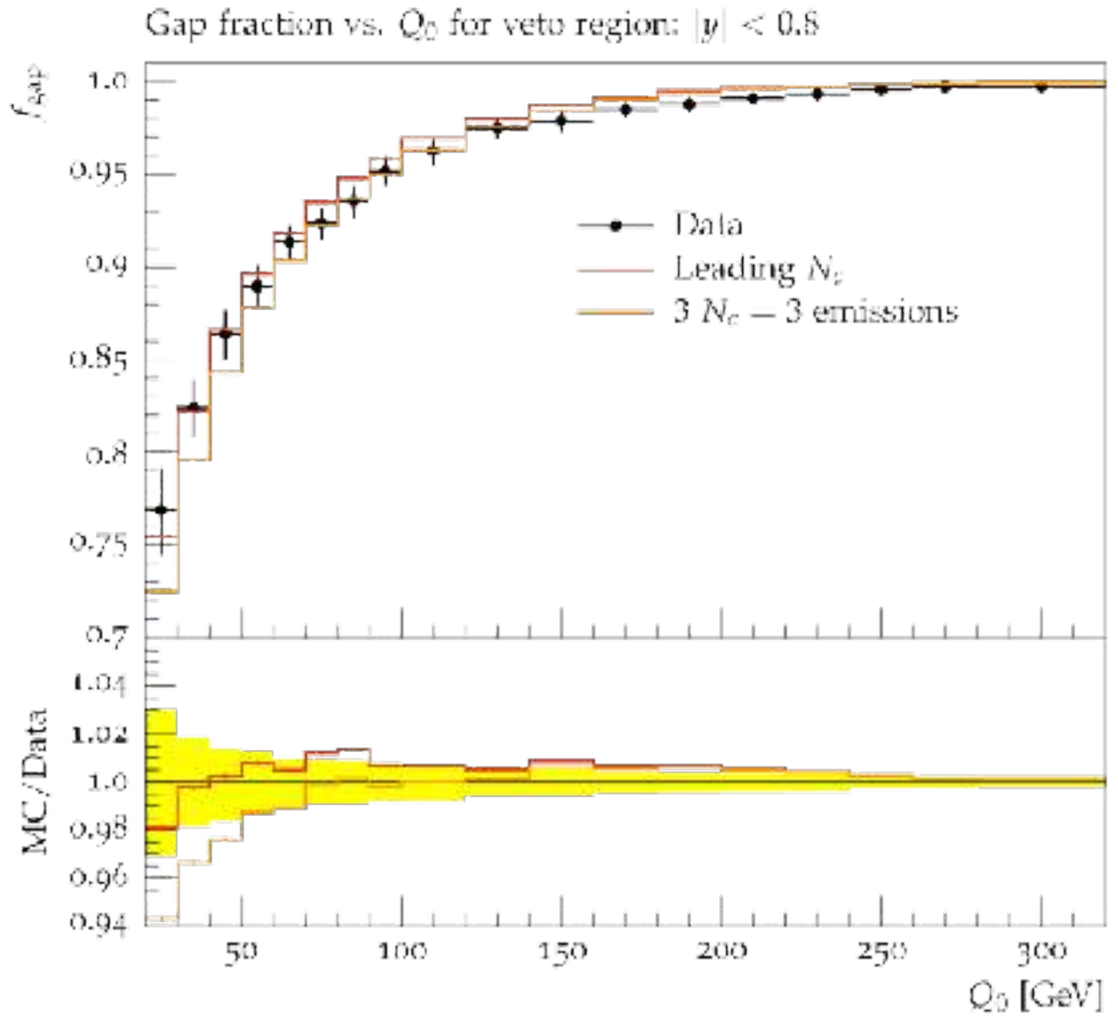
Colour matrix element corrections available in dipole-type showers:

Real improved, but virtual still by naive unitarity: not full colour.

[Plätzer, Sjödahl – JHEP 1207 (2012) 042]
[Plätzer, Sjödahl, Thoren – JHEP 11 (2018) 009]
[Höche, Reichelt — arXiv:2001.11492v2]



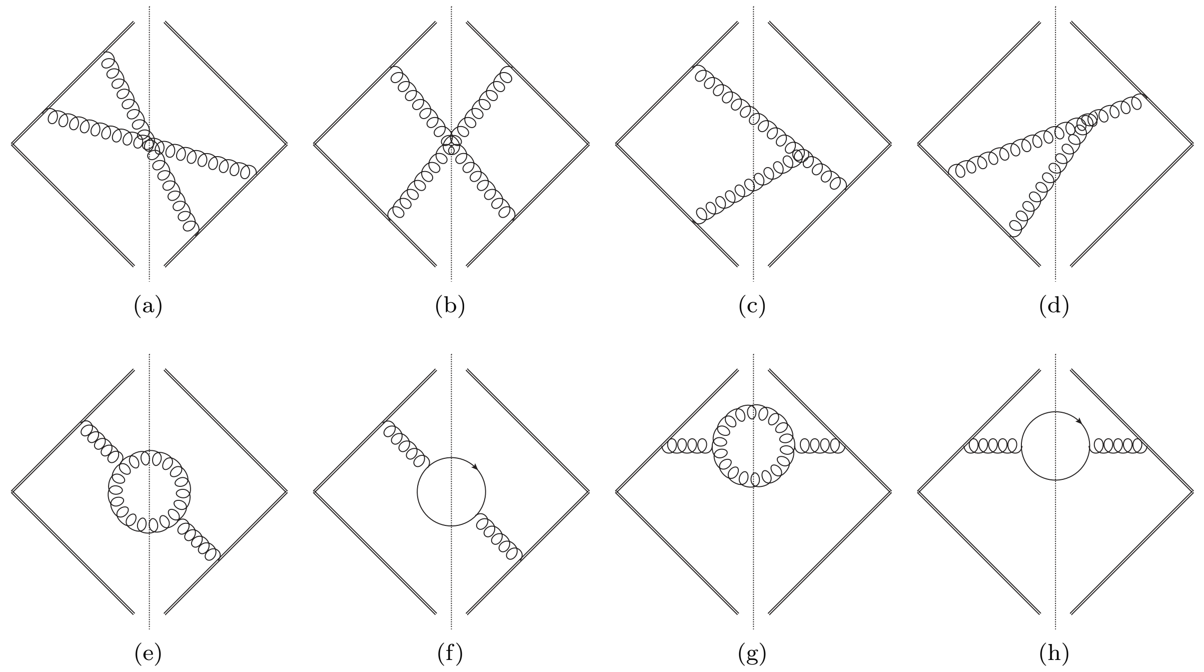
Some subleading-N corrections can be restored.



Roads to Precision

First steps to doubly unresolved emission kernels:

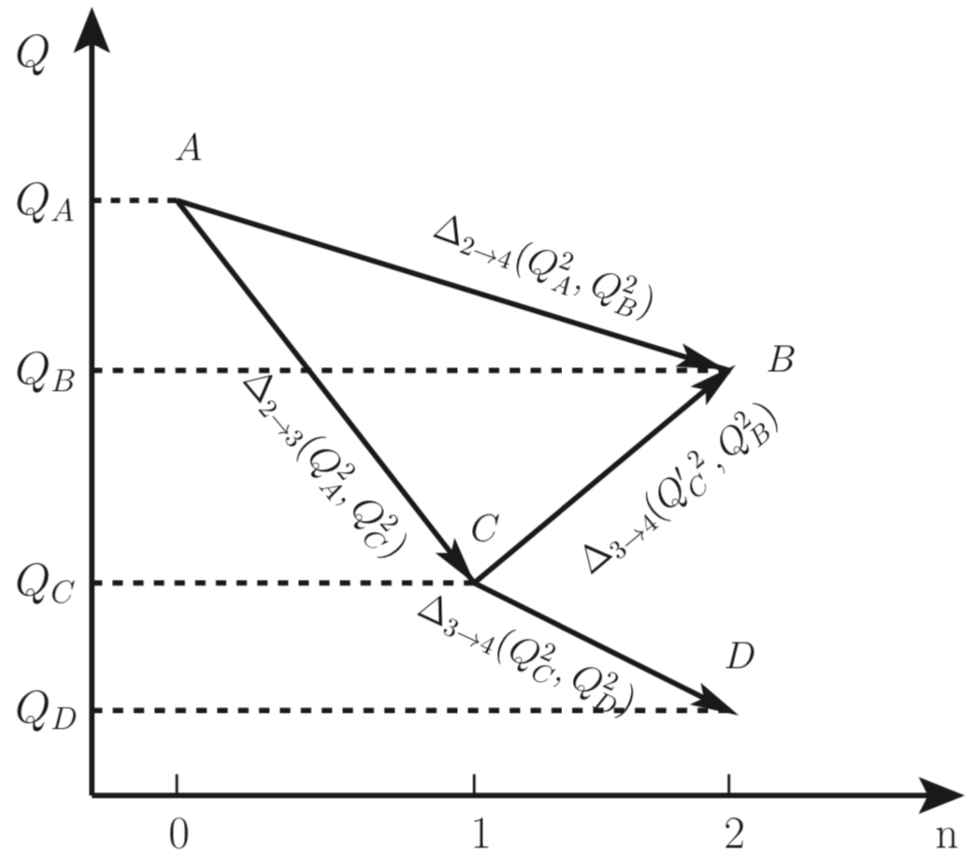
- Triple collinear splittings
- Double soft (inclusively included in CMW)
- Via antenna functions and matrix element corrections

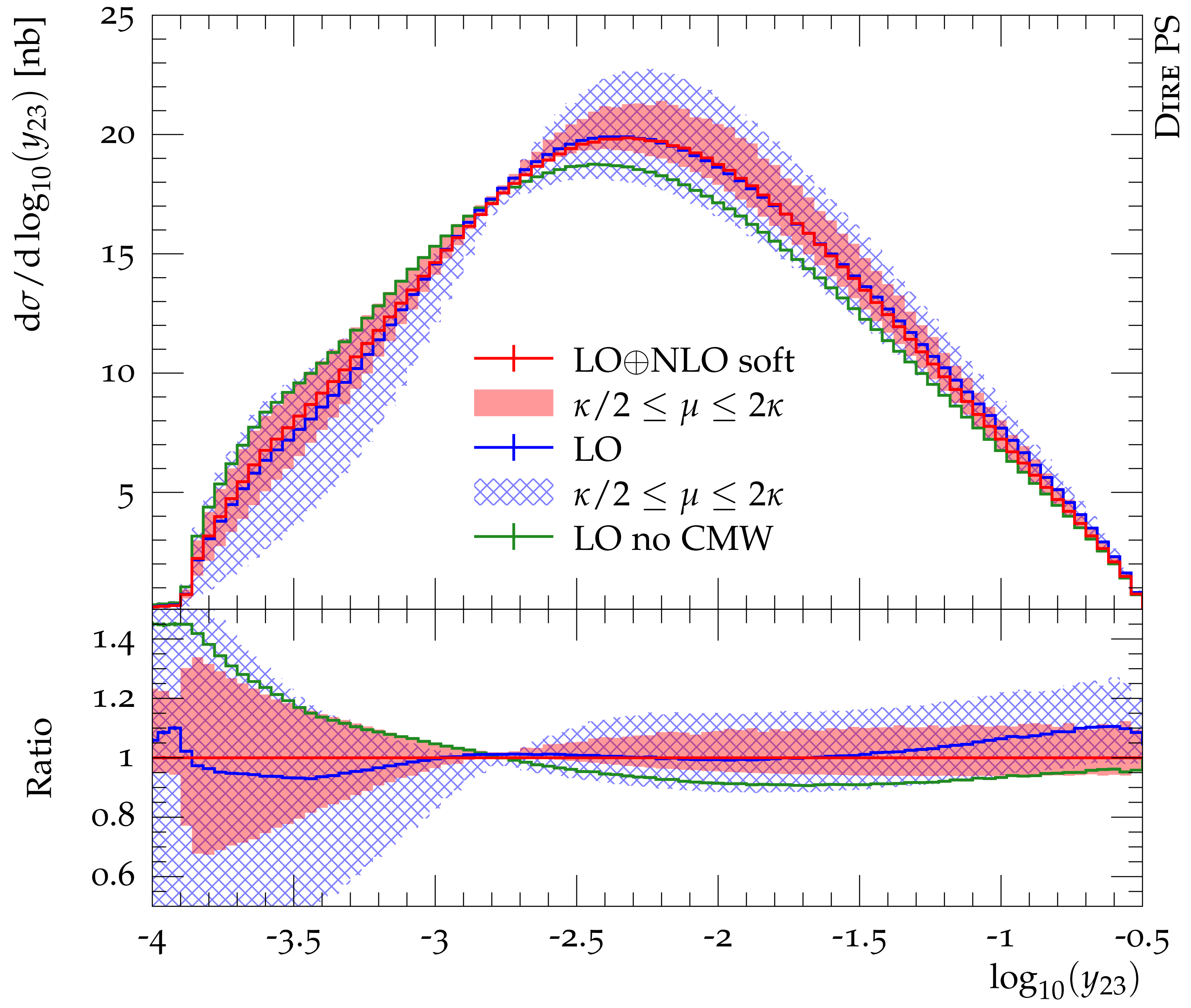


No unified approach known yet.

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 — PSR 21]

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

Roads to Precision

NLL evolution equation

Soft shower to resum NGL at NLL and LC

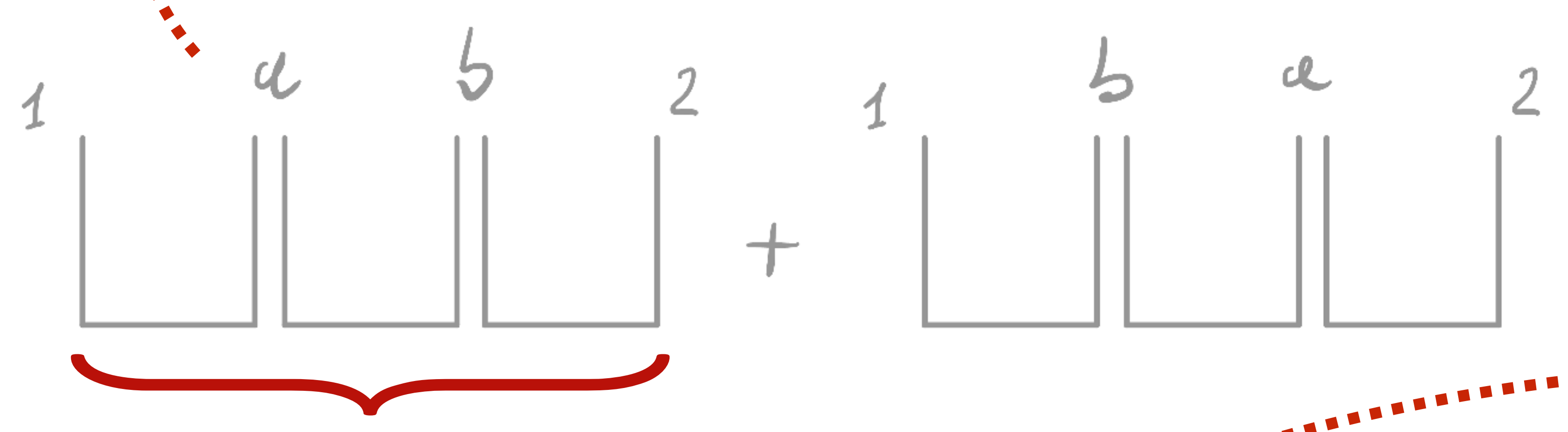
- Observable dependence disentangled in Laplace space

[Monni — PSR 21]
[Banfi, Dreyer, Monti — 2104.06416]

- e.g. real corr.$^{\text{ns}}$: contributions from two adjacent dipoles

$$\mathbb{K}^{\mathrm{RR}}[G[Q,u],u] := \int [dk_a] \int [dk_b]\, \bar{\alpha}^2(Q) Q \delta(Q - k_{t(ab)}) \Theta(k_{ta} - k_{tb})$$
$$\times \Big[\bar{w}_{12}^{(gg)}(k_b,k_a) G_{1b}[Q;u] G_{ba}[Q;u] G_{a2}[Q;u] u(k_a) u(k_b)$$
$$+ \bar{w}_{12}^{(gg)}(k_a,k_b) G_{1a}[Q;u] G_{ab}[Q;u] G_{b2}[Q;u] u(k_a) u(k_b)$$
$$- \left(\bar{w}_{12}^{(gg)}(k_b,k_a) + \bar{w}_{12}^{(gg)}(k_a,k_b) \right) G_{1(ab)}[Q;u] G_{(ab)2}[Q;u] u(k_{(ab)}) \Big]$$

Evolution variable must be adjusted (dipole k_t of the parent) to guarantee collinear safety for any u(k)



- Correct only for correlated contribution to squared amplitude (exponentiation of soft singularities)

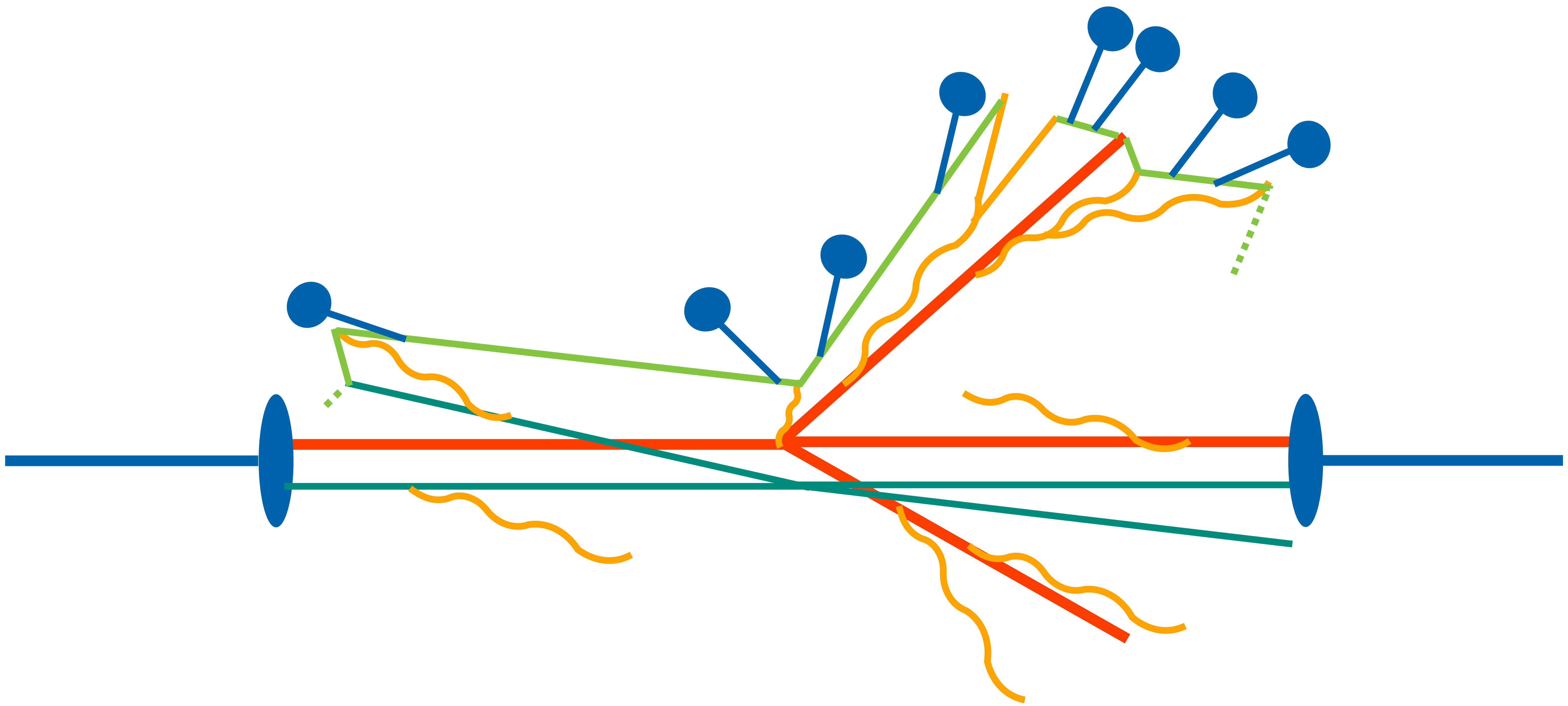
$$\tilde{w}_{12}^{(0)}(k_a,k_b) = \frac{1}{2} w_{12}^{(0)}(k_a) w_{12}^{(0)}(k_b) + \bar{w}_{12}^{(gg)}(k_a,k_b)$$

- Independent contribution correctly treated in LL kernel

Full-colour structures and kinematics of 2-loop virtual also known.

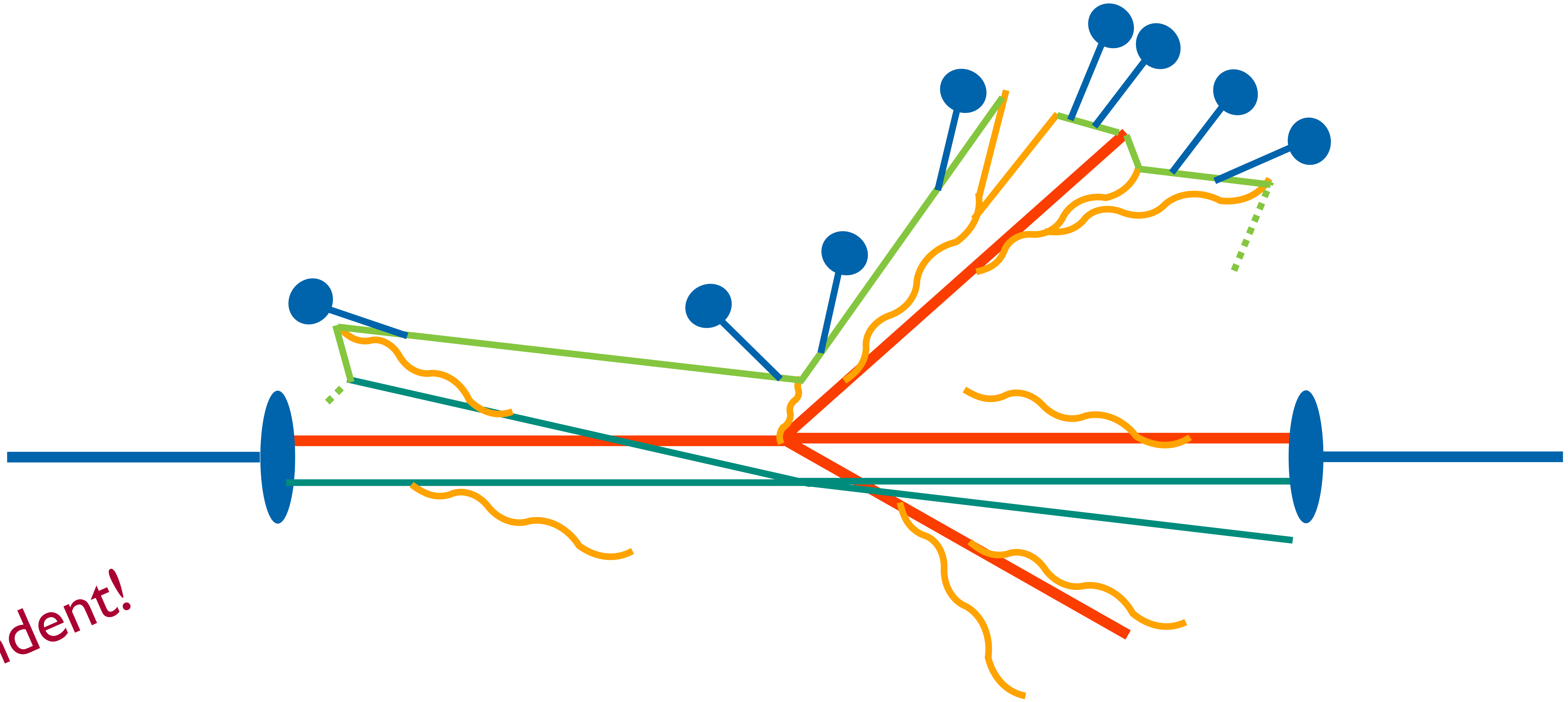
[Plätzer, Ruffa — JHEP 06 (2021) 007]

Beyond Current Paradigms



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

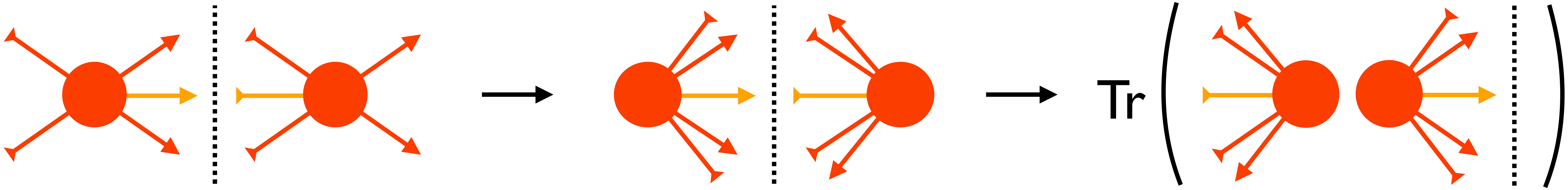
Beyond Current Paradigms



Large-N and/or observable dependent!

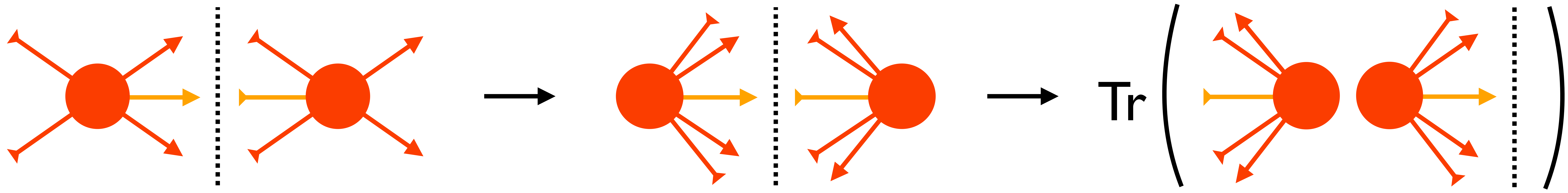
$$d\sigma \sim \mathrm{L} \times d\sigma_H(Q) \times \mathrm{PS}(Q \to \mu) \times \mathrm{MPI} \times \mathrm{Had}(\mu \to \Lambda) \times \ldots$$

Cross Sections and Amplitudes



[Nagy, Soper — …]
[De Angelis, Holguin, Forshaw, Plätzer, Ruffa — …]

Cross Sections and Amplitudes



$$\sigma[u] = \sum_n \int \mathrm{Tr}\left[\mathbf{A}_n\right] u(q_1, \ldots, q_n) \mathrm{d}\phi(q_1, \ldots, q_n)$$

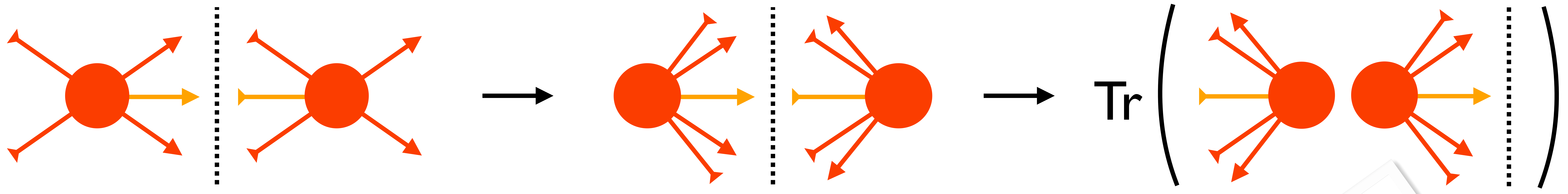
sum over emissions

'density operator' ~ amplitude amplitude⁺

observable and phase space

[Nagy, Soper — …]
[De Angelis, Holguin, Forshaw, Plätzer, Ruffa — …]

Cross Sections and Amplitudes



$$\sigma[u] = \sum_n \int \mathrm{Tr}\left[\mathbf{A}_n\right] u(q_1, \ldots, q_n) \mathrm{d}$$

sum over emissions

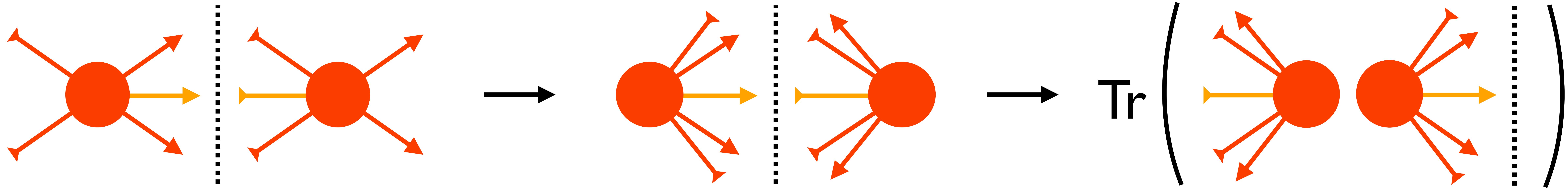
'density operator' ~ amplitude amplitude⁺

ervable and phase space

Theoretical starting point & algorithmic approach in its own right.

[Nagy, Soper — …]
[De Angelis, Holguin, Forshaw, Plätzer, Ruffa — …]

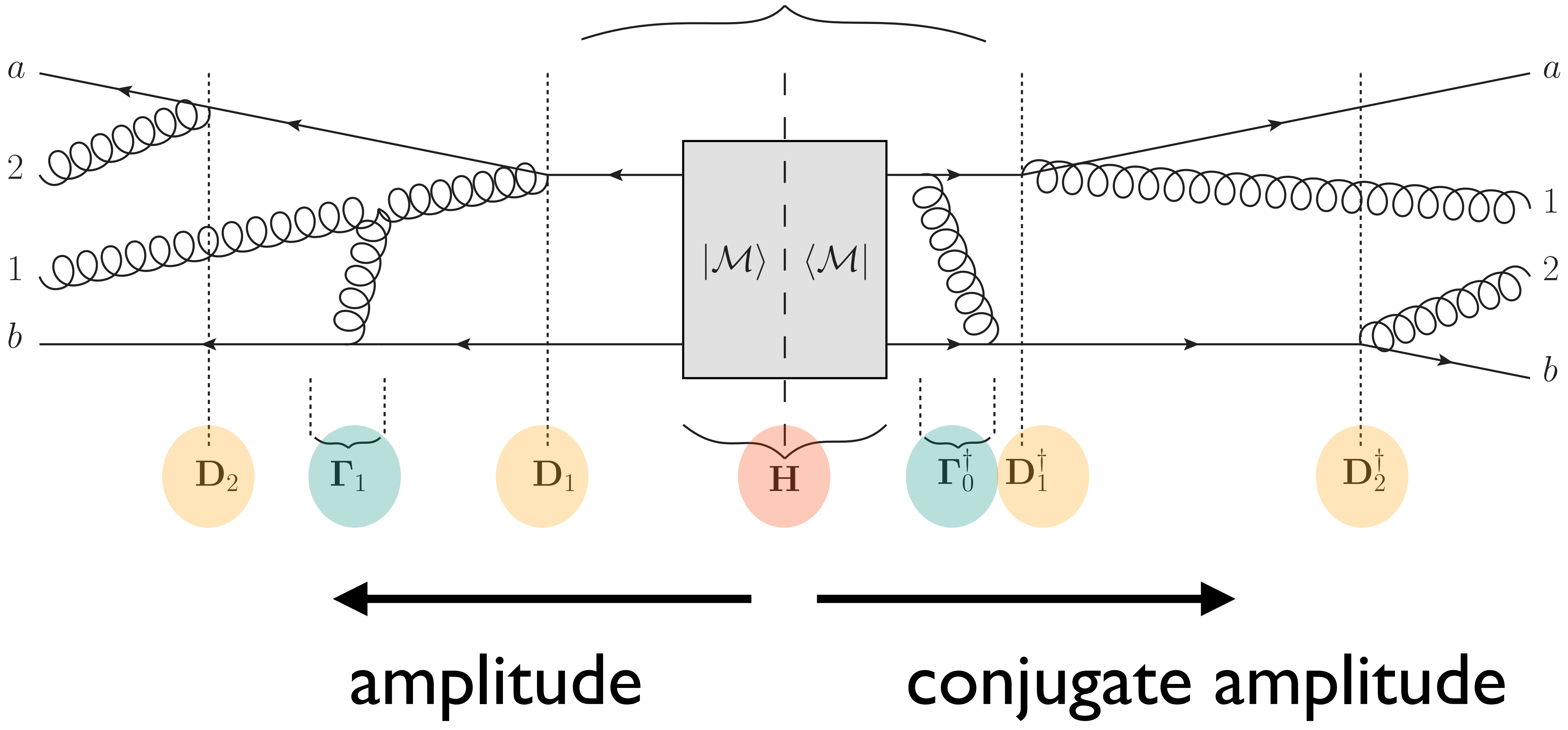
Cross Sections and Amplitudes



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

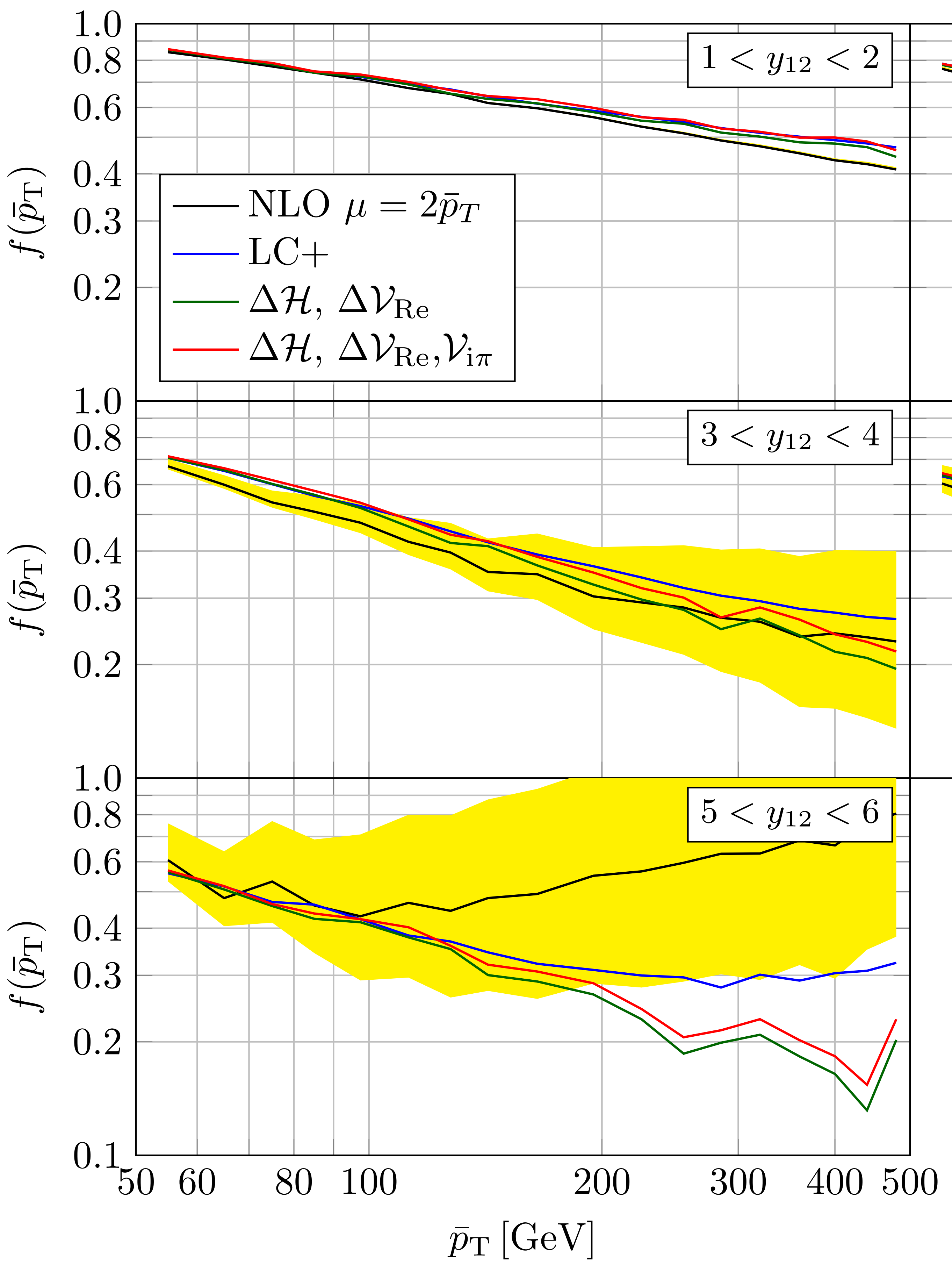
Markovian algorithm at the amplitude level:
Iterate gluon exchanges and emission.

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



[Nagy, Soper — …]
[De Angelis, Holguin, Forshaw, Plätzer, Ruffa — …]

Beyond Leading Colour



$E_{\rm cm} = 13\text{GeV}$

$|y| < 4.4$

$R = 0.4$

[Nagy, Soper — …]

LC+ Approximation

We insert a projection **only on the spectator side**

$$t_k^\dagger \big|\{c\}_m\big\rangle \longrightarrow C(l, m+1) t_k^\dagger \big|\{c\}_m\big\rangle$$
$$\big\langle\{c'\}_m\big| t_k \longrightarrow \big\langle\{c'\}_m\big| t_k C(l, m+1)^\dagger$$

The **operator** ***C(l, m+1)*** is defined by it action on the basis states:

$$C(l, m+1)\big|\{\hat{c}\}_{m+1}\big\rangle = \begin{cases} \big|\{\hat{c}\}_{m+1}\big\rangle & \text{if } l \text{ and } m+1 \text{ are color connected in } \{\hat{c}\}_{m+1} \\ 0 & \text{otherwise} \end{cases}$$

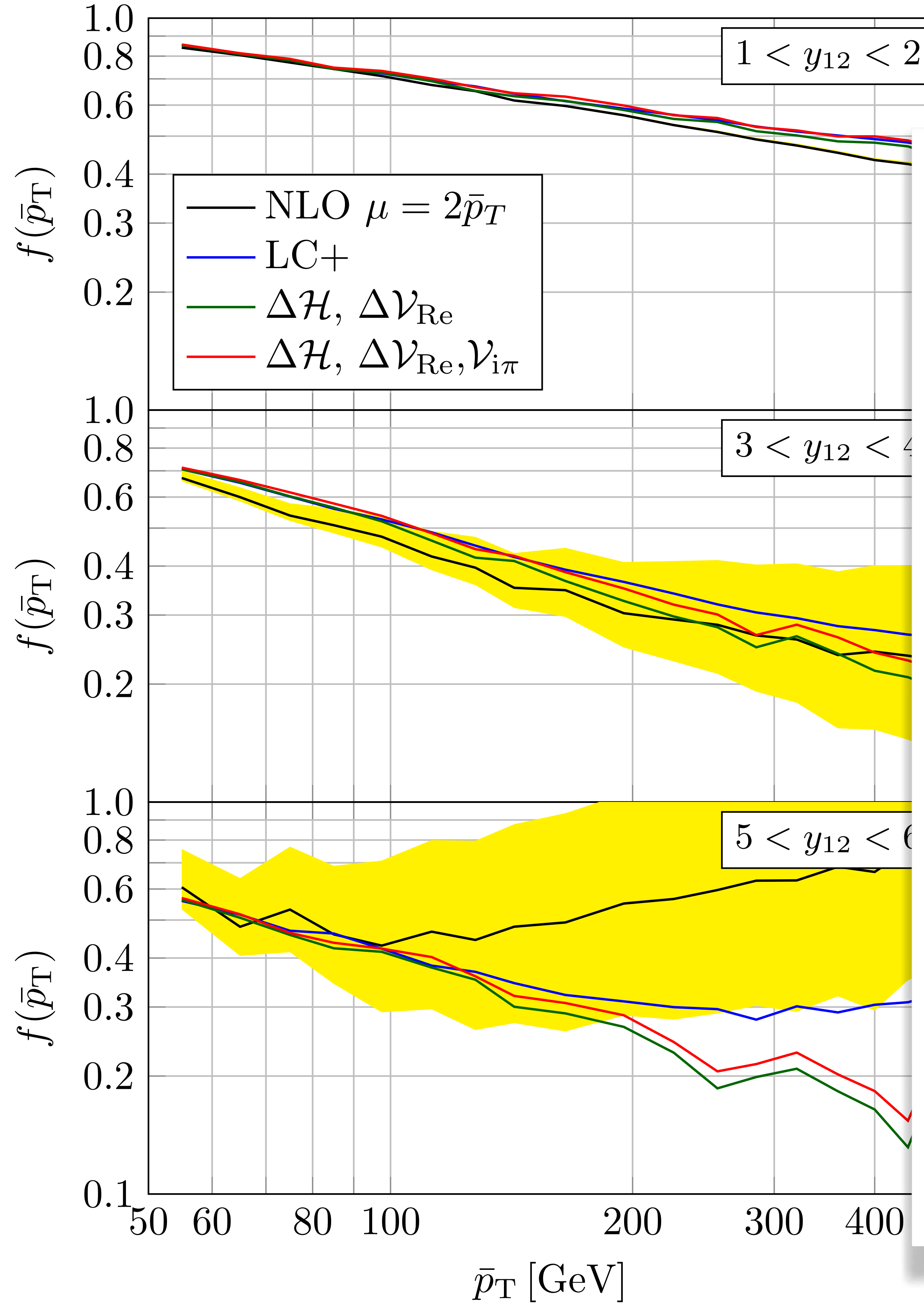
(In string basis l and m+1 are color connected when they are next to each other along the fermion line.)

In the inclusive splitting operator, the color simplifies a lot:

$$[t_l \cdot t_k^\dagger]\big|\{c\}_m\big\rangle \longrightarrow [t_l \cdot C(l, m+1) t_k^\dagger]\big|\{c\}_m\big\rangle = \big|\{c\}_m\big\rangle \frac{t_l^2}{1+\delta_{gf_l}}$$
$$\big\langle\{c'\}_m\big|[t_k \cdot t_l^\dagger] \longrightarrow \big\langle\{c'\}_m\big|[t_k C(l, m+1)^\dagger \cdot t_l^\dagger] = \frac{t_l^2}{1+\delta_{gf_l}}\big\langle\{c'\}_m\big|$$

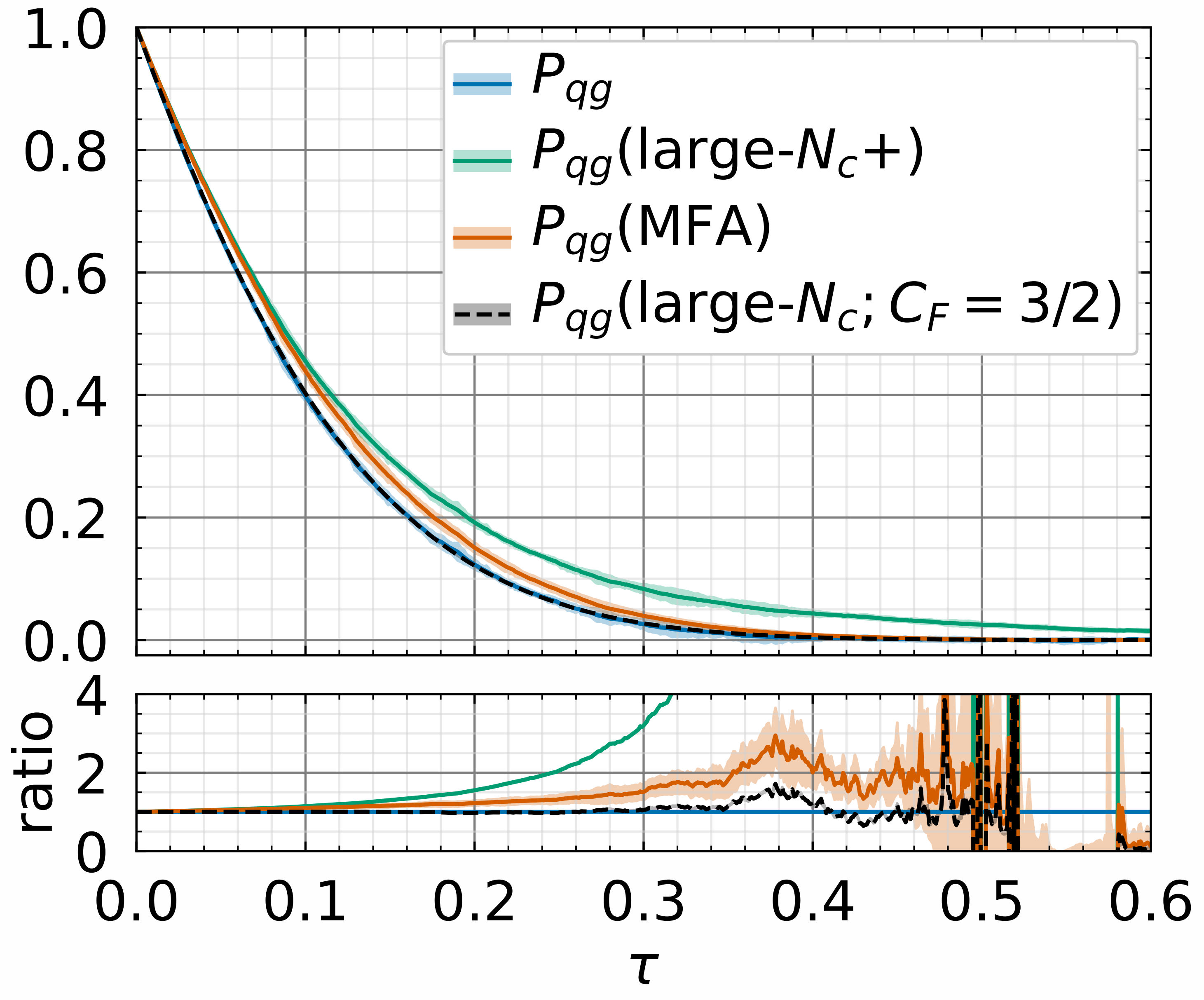
[Nagy — PSR 19]

Beyond Leading Colour



[Nagy, Soper — …]

LC+ Approximation



Jet veto in qg to qg scattering.

Uses a lattice inspired method from a Langevin formulation.

[Hatta, Ueda — …]

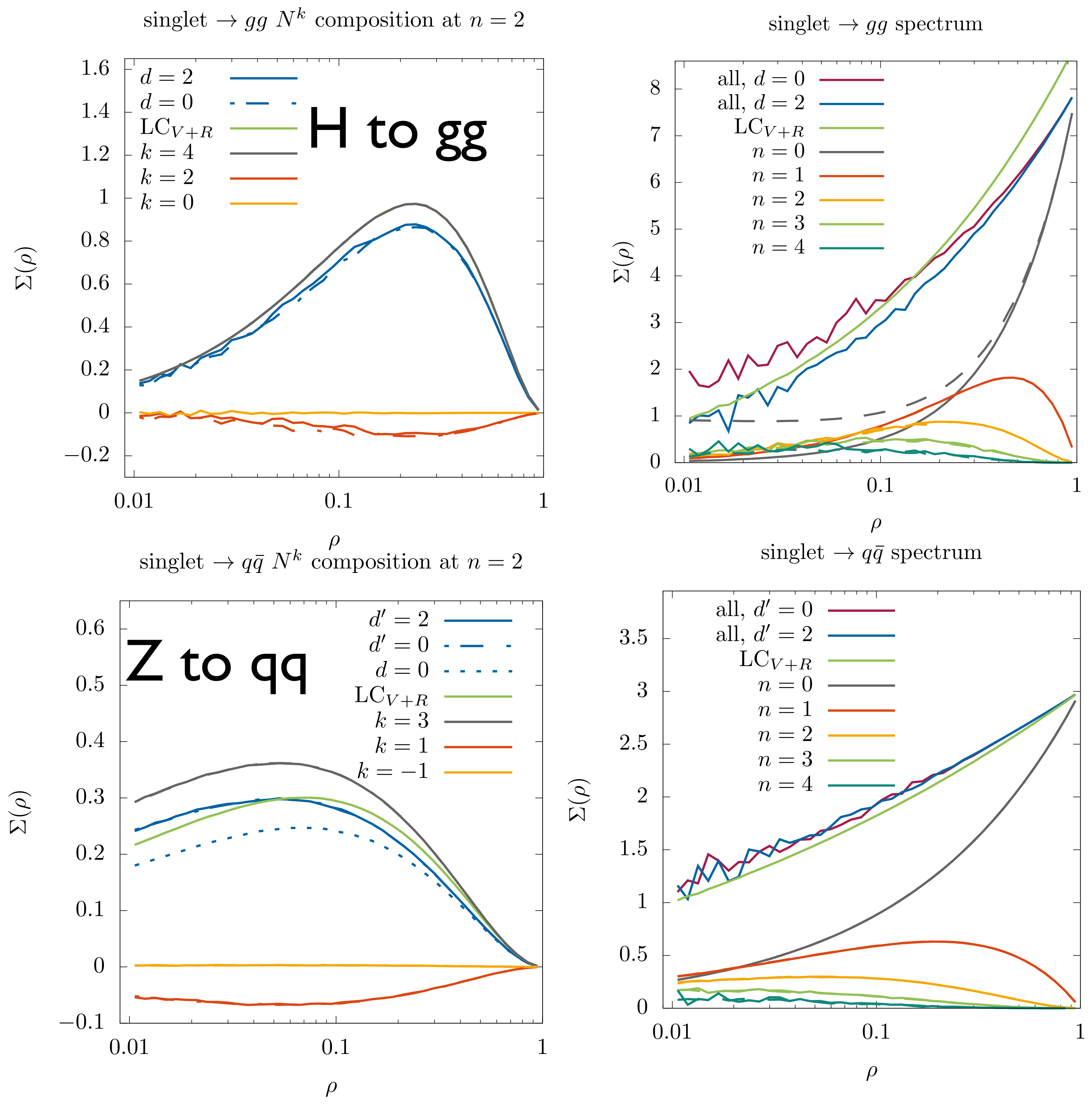
[Nagy — PSR 19]

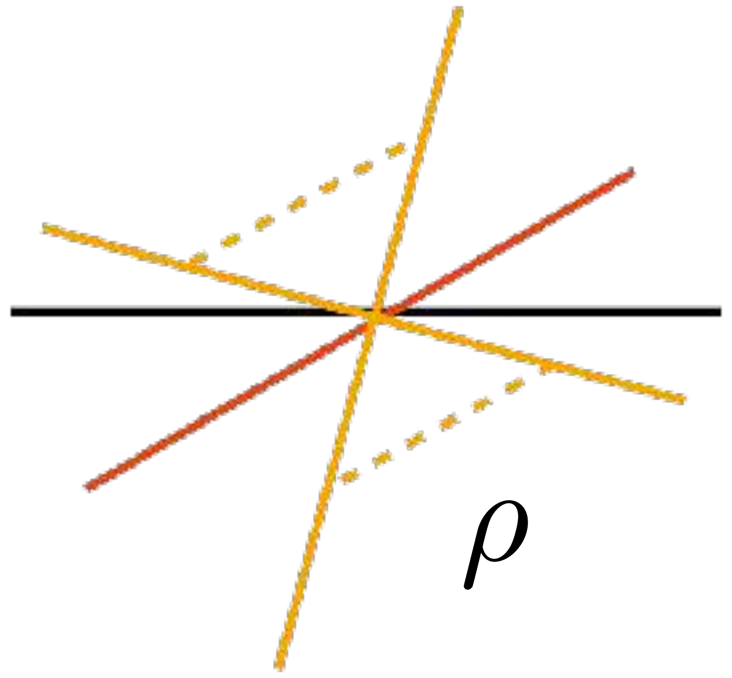
Beyond Leading Colour

CVolver library implements numerical evolution in colour space.

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

Resummation of non-global logarithms at full colour:

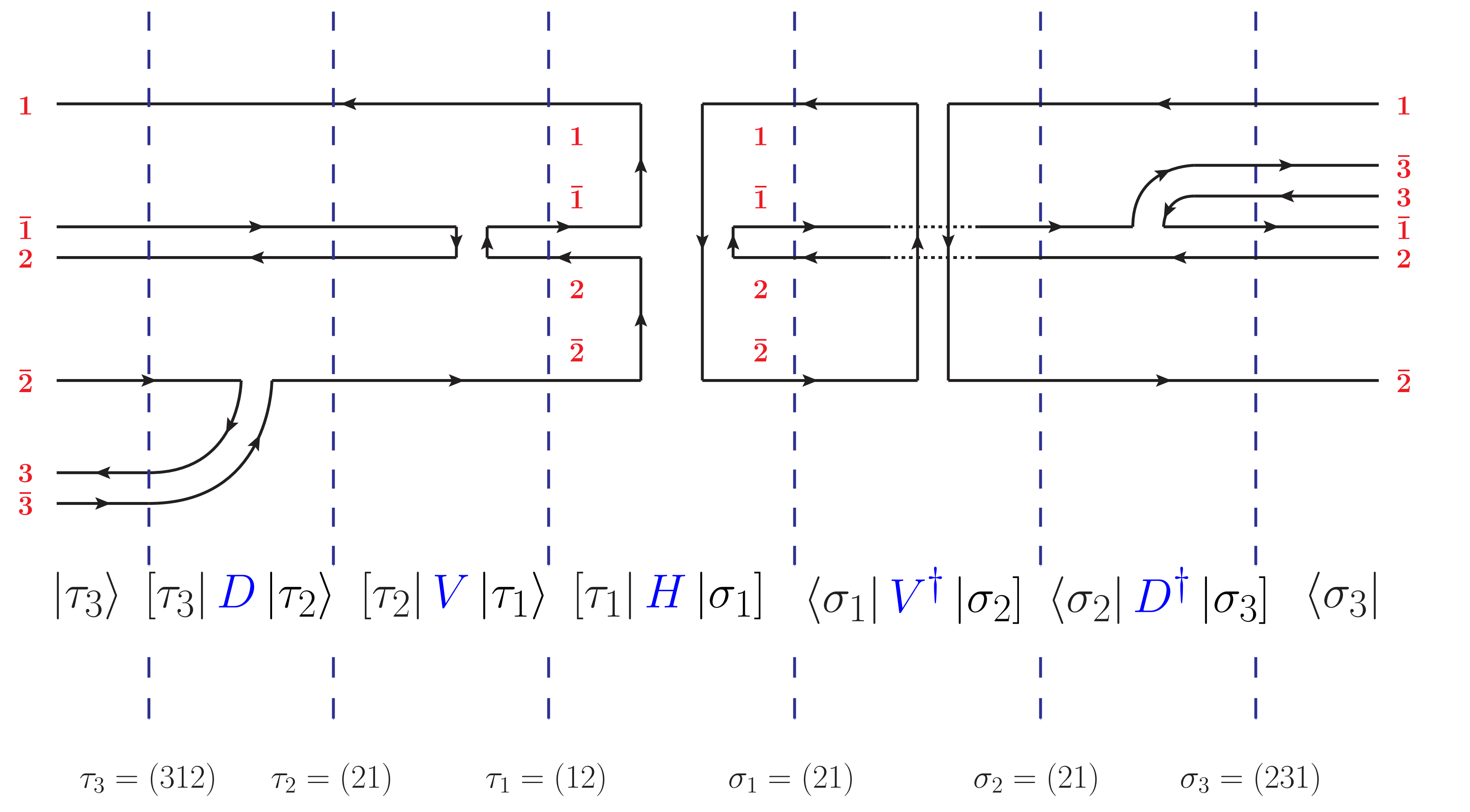




$$\Sigma(\rho) = \sum_n \int \mathrm{d}\sigma(\{p_i\}) \prod_i \theta_{\rm in}(\rho - E_i)$$

Full agreement with Hatta & Ueda.

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



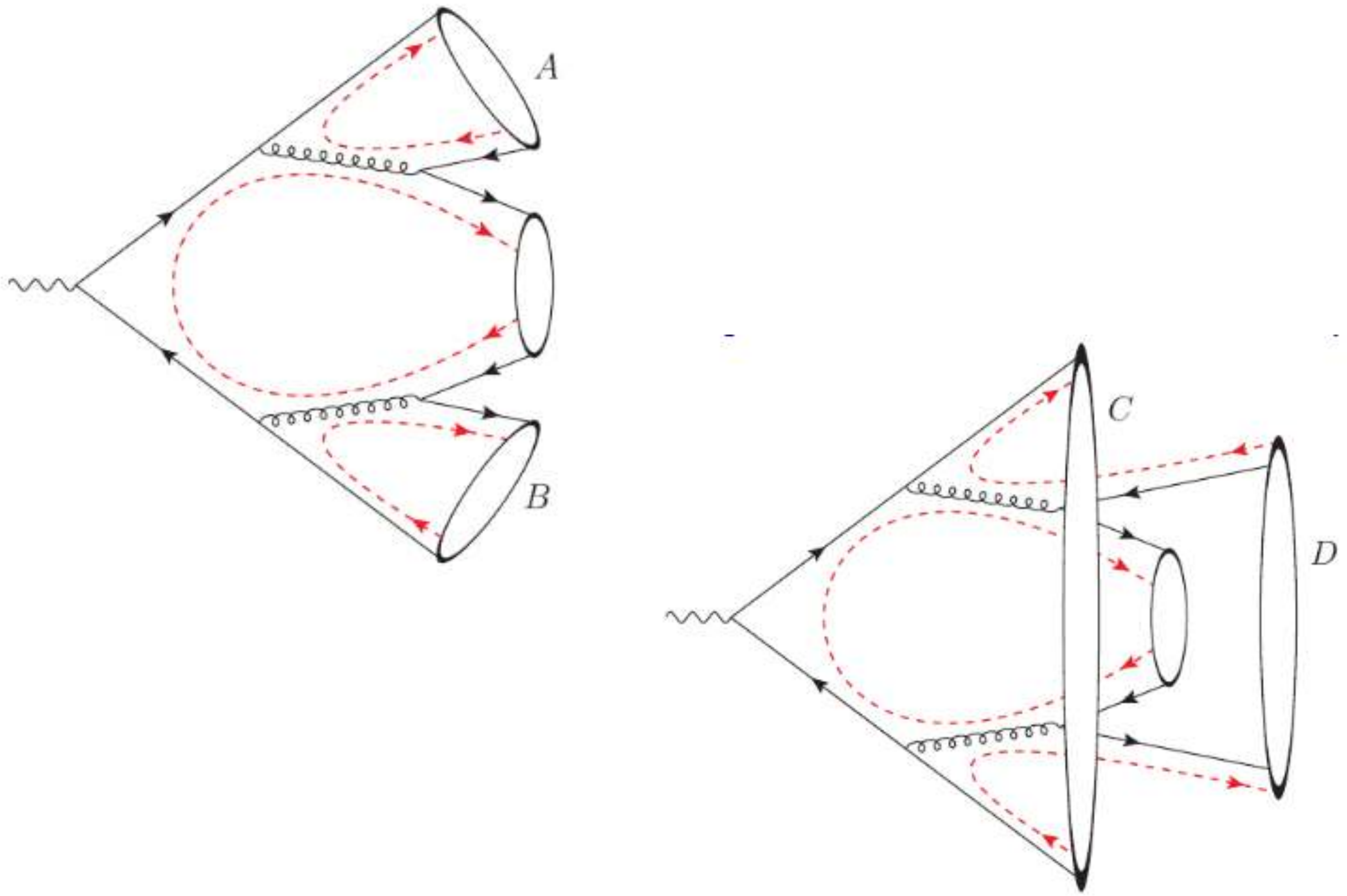
amplitude ← → conjugate amplitude

Avoid complexity which grows with colour space dimensionality:

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

Phenomenological Impact?

Project colour state on low-mass colour singlet systems.
Clusters = highly excited hadrons.



Colour reconnection: cluster swaps.

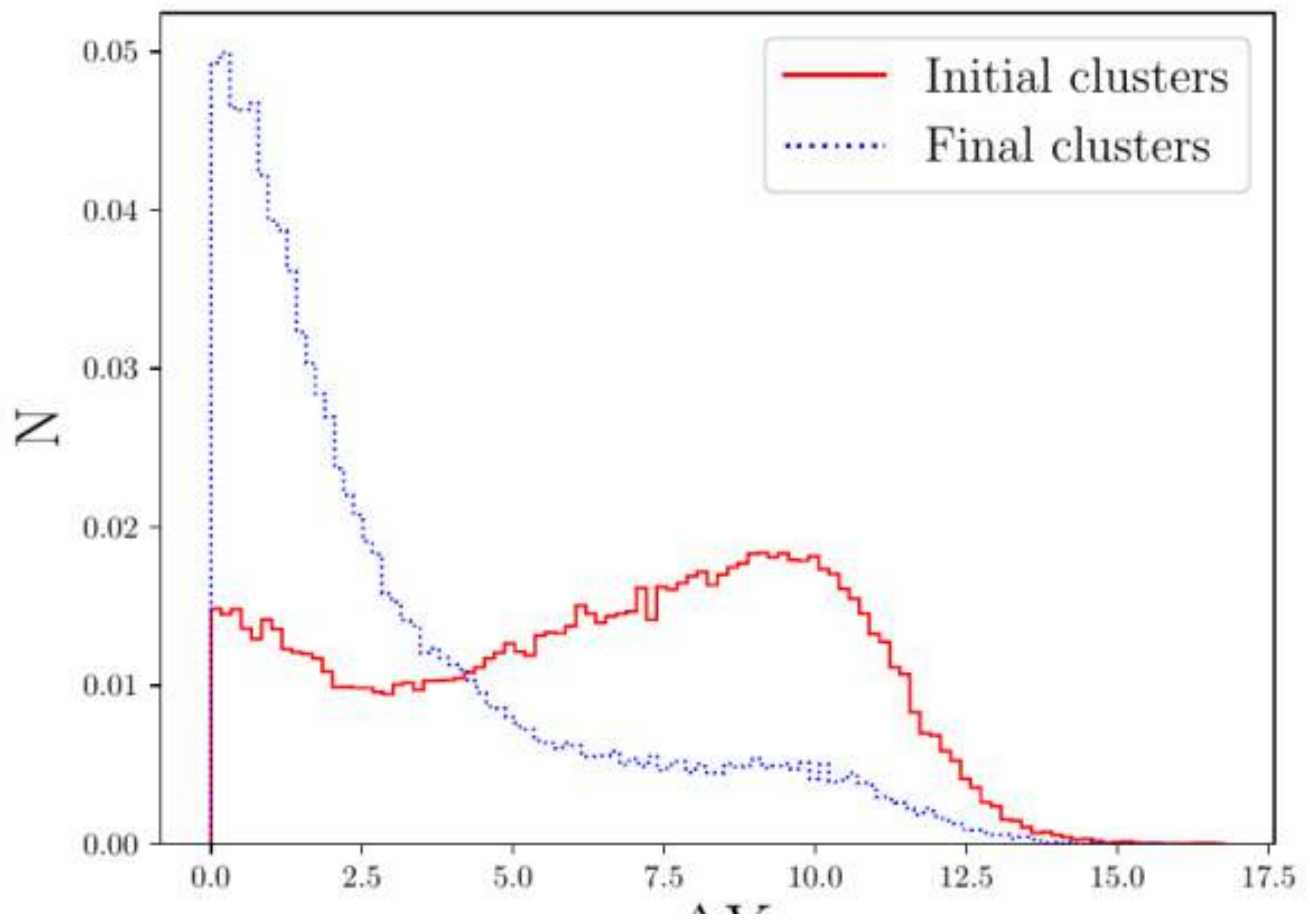
[Gieseke, Kirchgaesser, Plätzer – EPJ C 78 (2018) 99]

Approach colour reconnection from colour evolution: perturbative component?

Reconnection amplitude

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

Strong support for geometric models from colour evolution.



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

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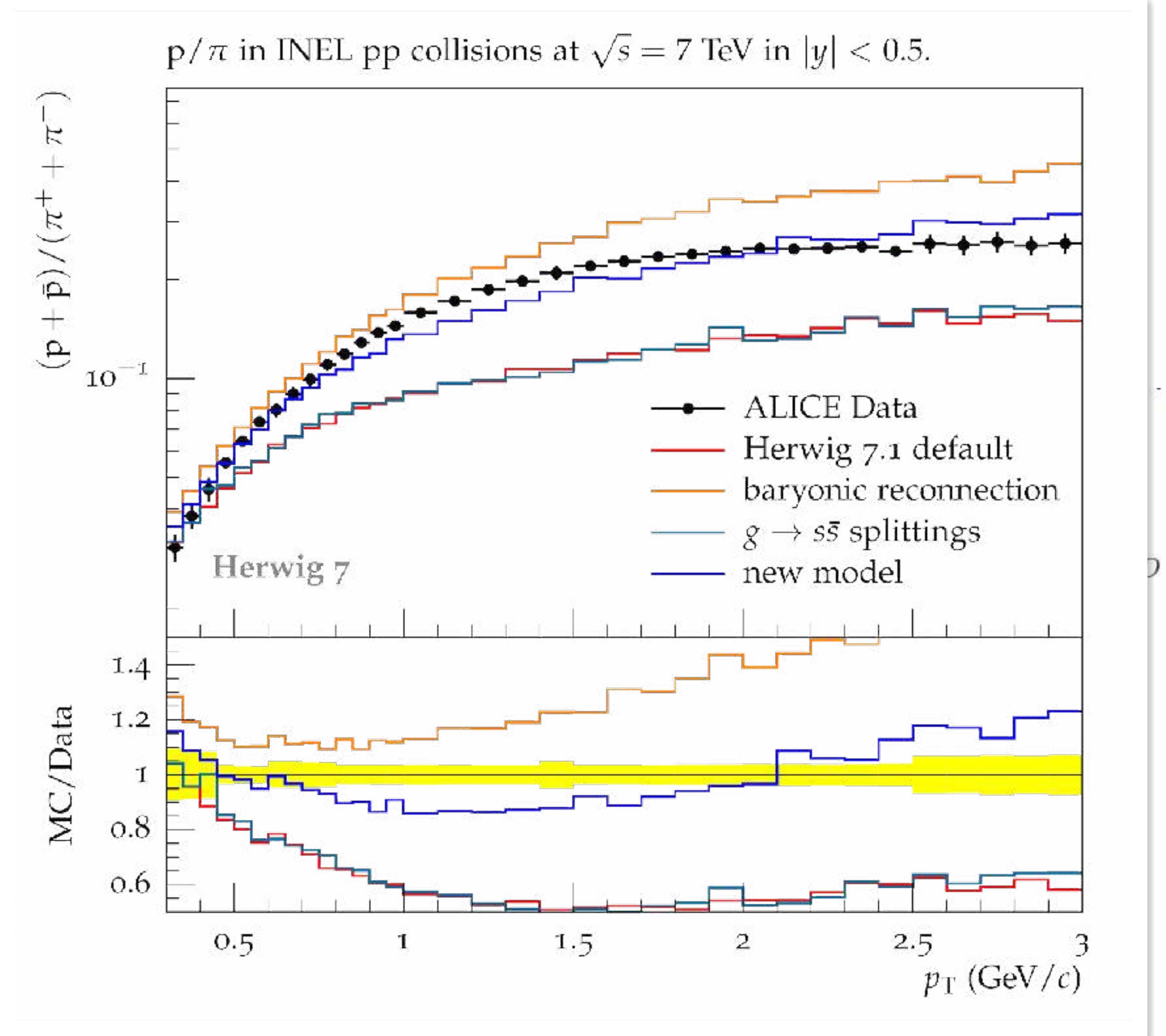

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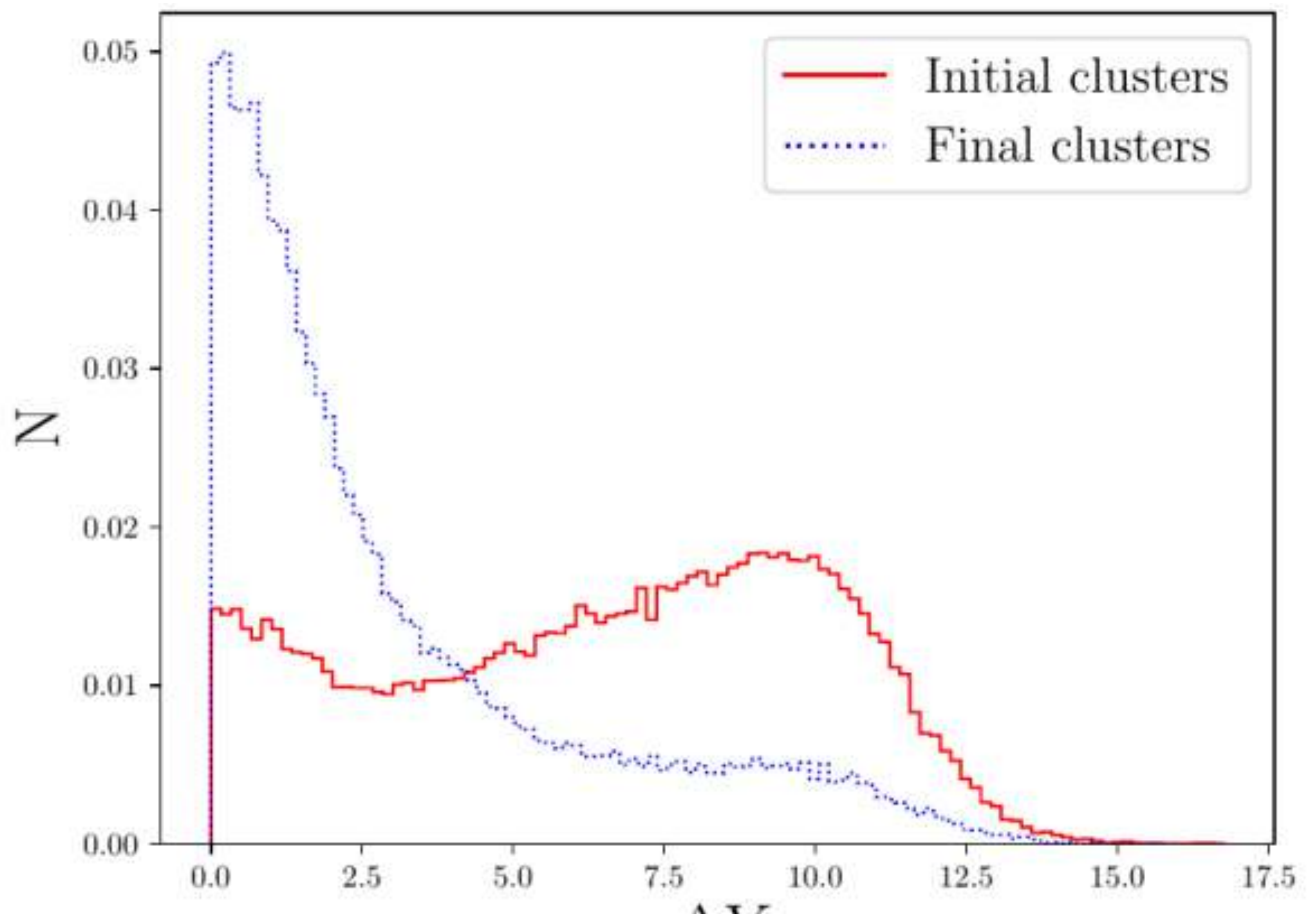
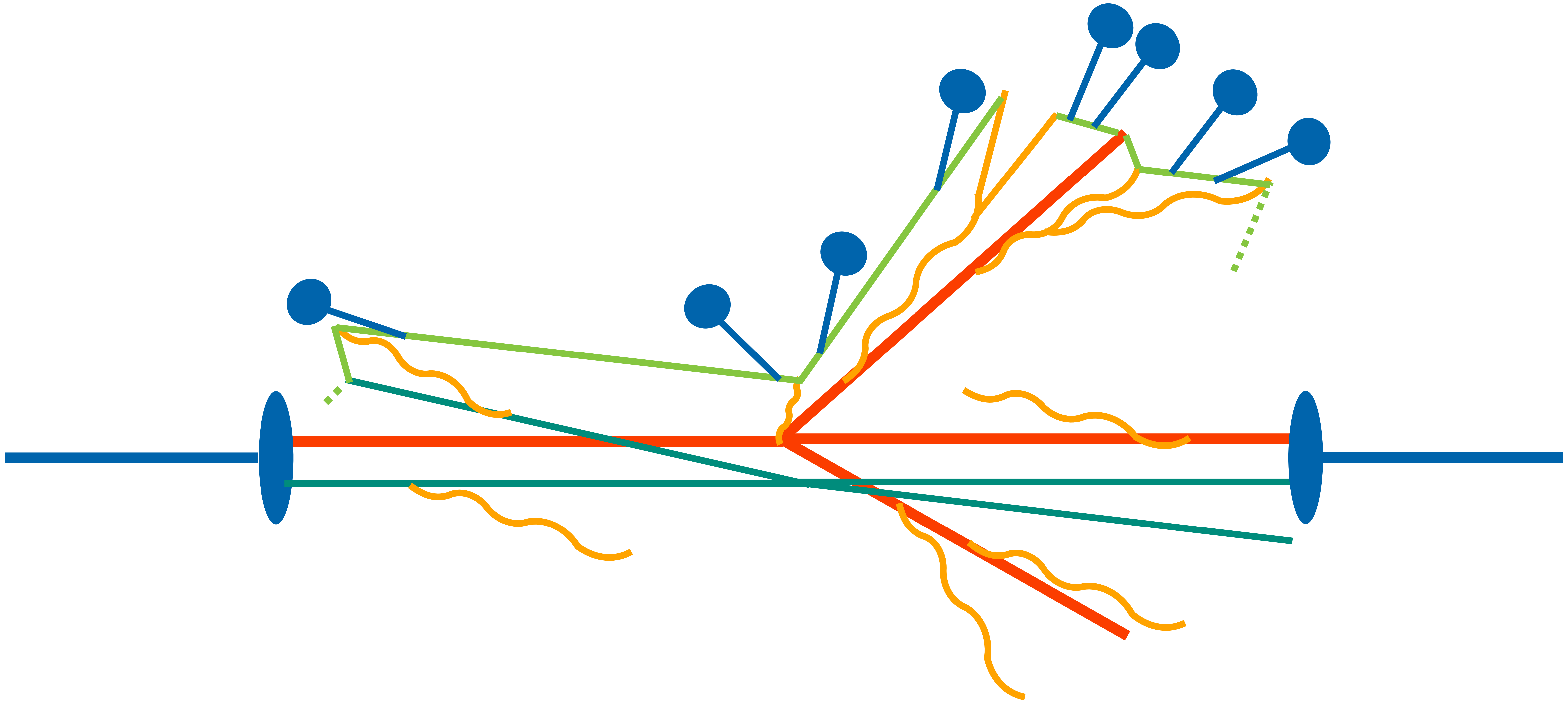


[Gieseke, Kirchgaesser, Plätzer, Siodmok – JHEP 11 (2018) 149]

Uncertainties — Perturbative & Non-perturbative



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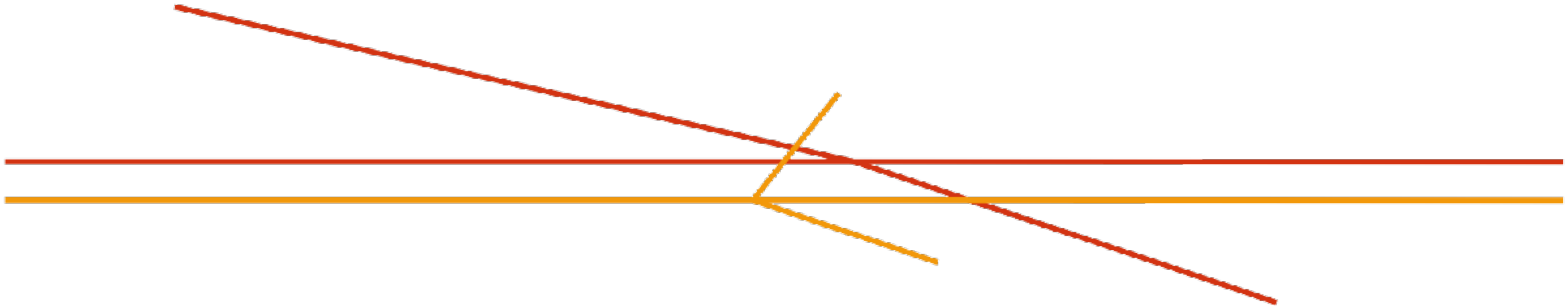
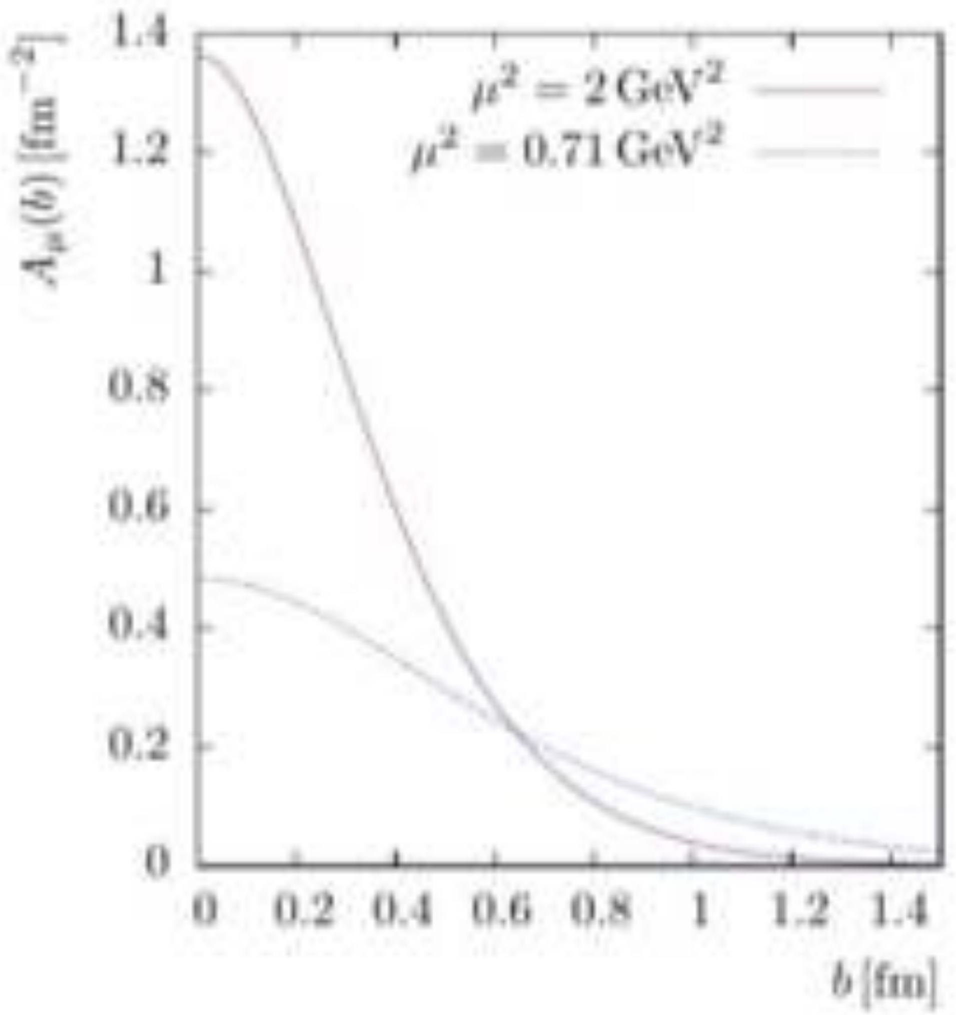
MPI & Colour Reconnection

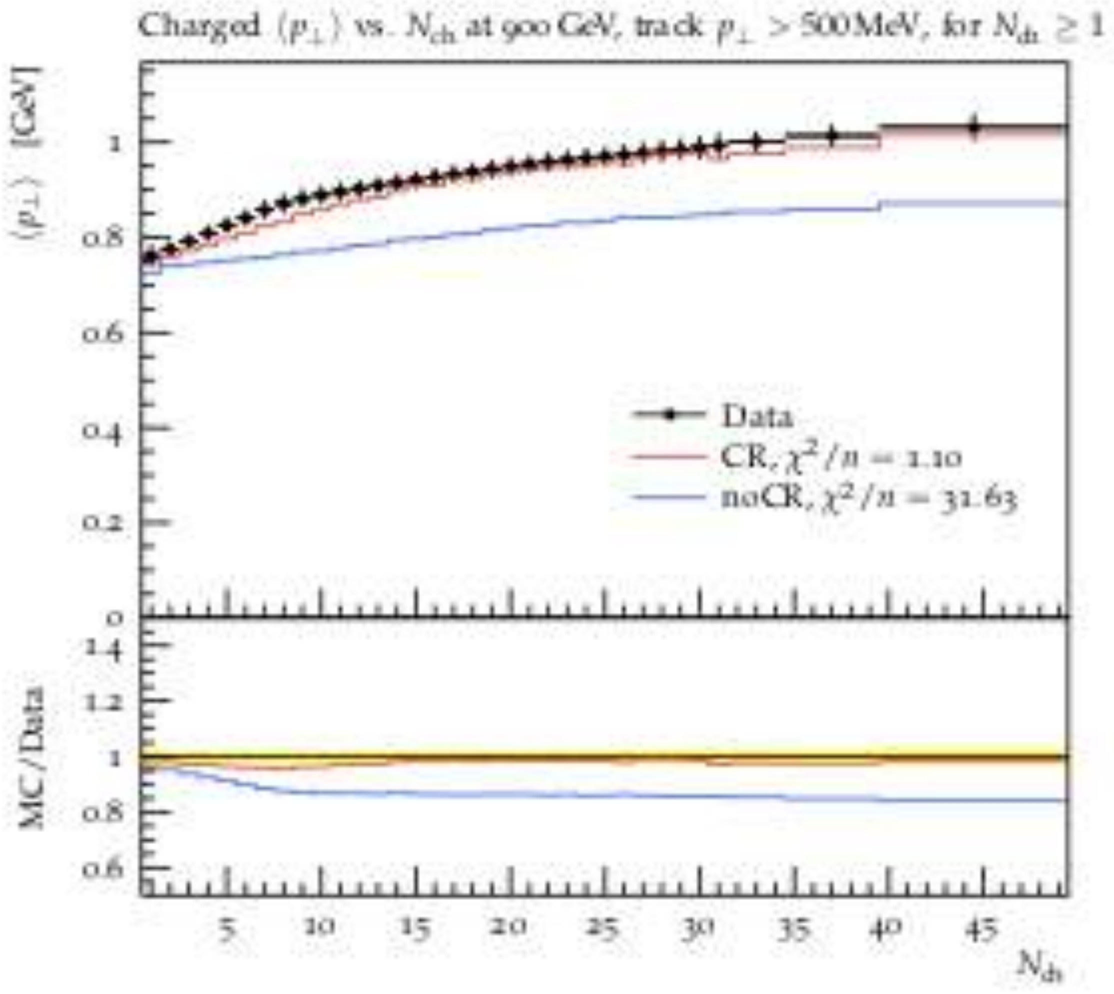


Assume some matter distribution in the proton, and effective multiplicity distribution of additional scatters.

Colour reconnection crucial to describe MinBias and UE data: lack of knowledge about colour correlations.

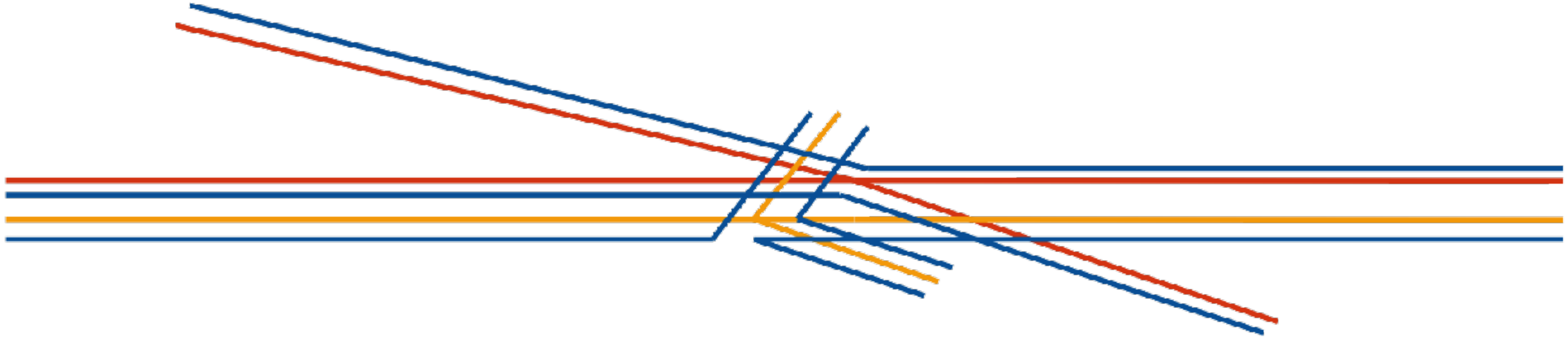


[Gieseke, Kirchgaesser, Plätzer – EPJ C 78 (2018) 99]



[Gieseke, Röhr, Siodmok – EPJ C 72 (2012) 2225]

MPI & Colour Reconnection



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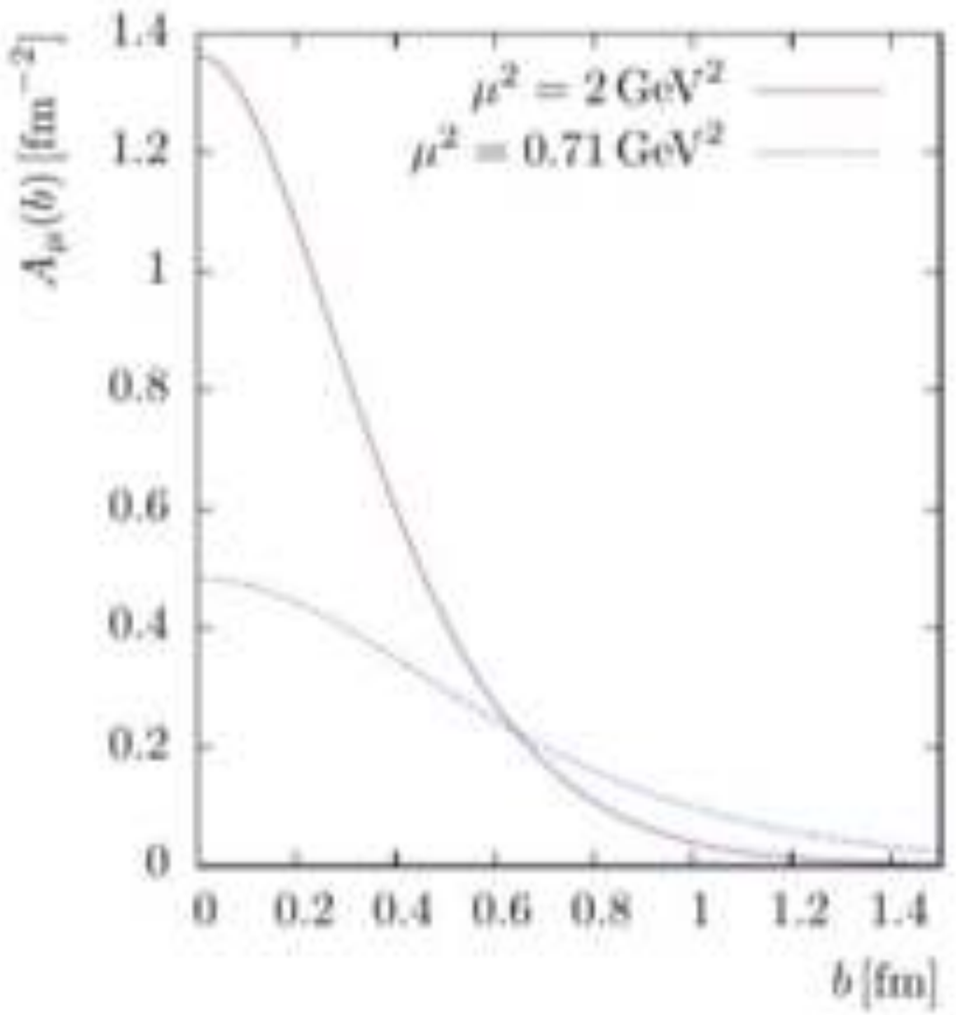

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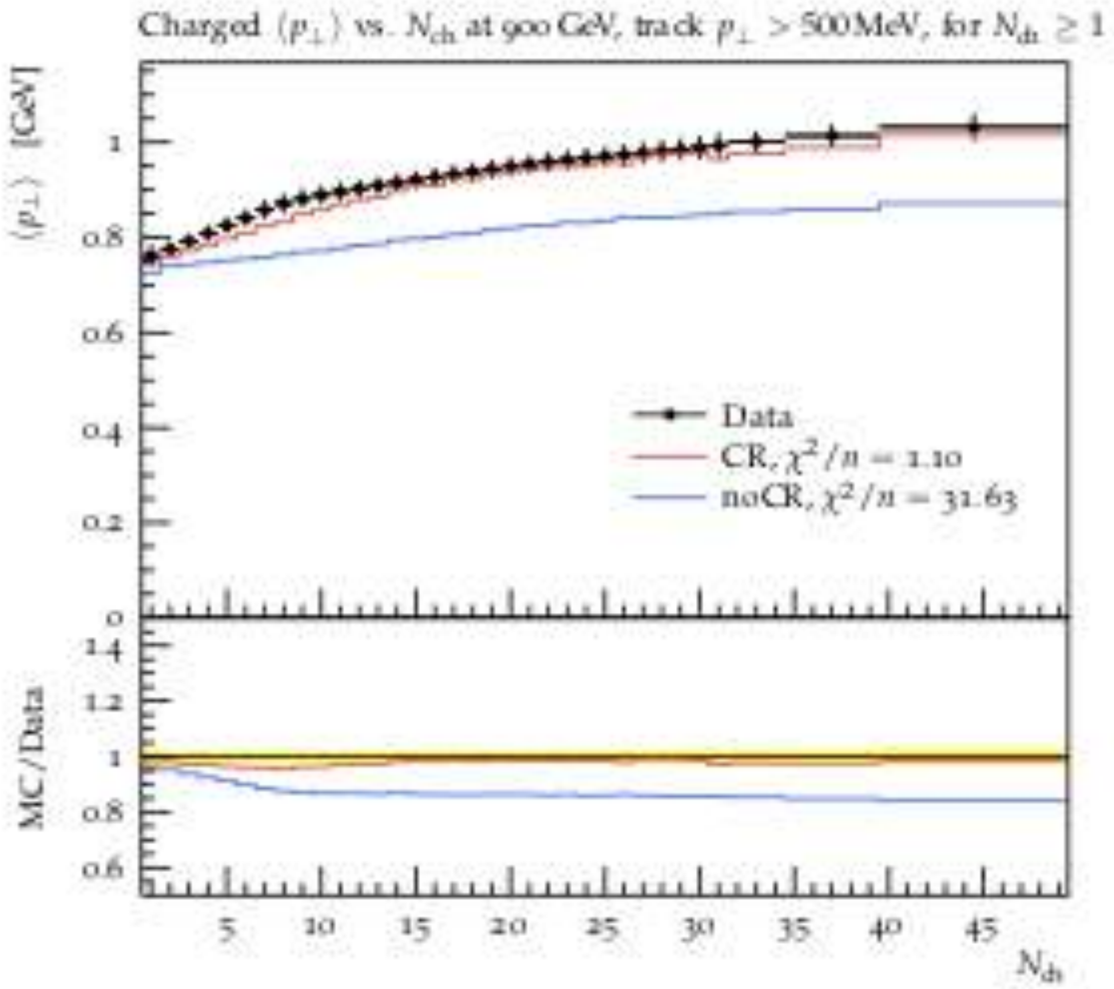

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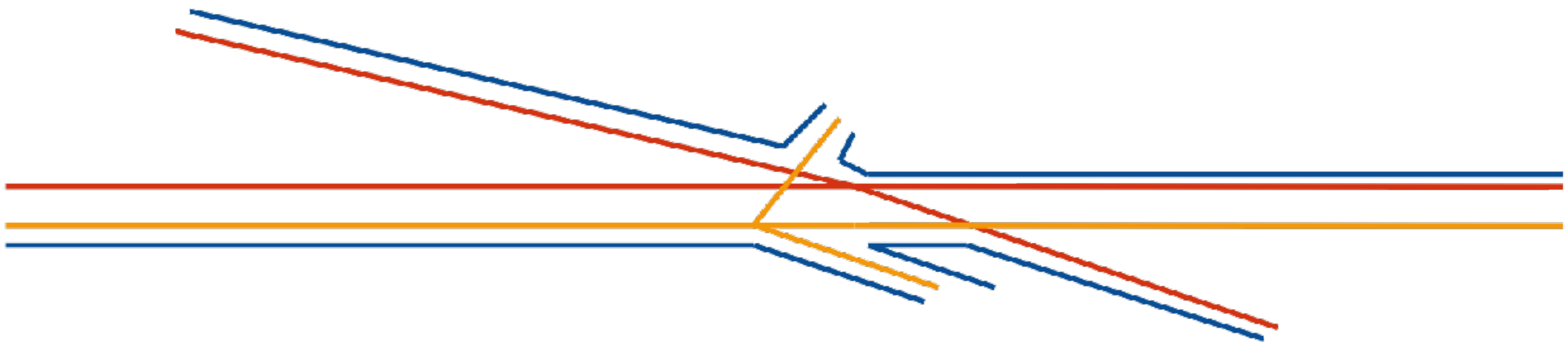

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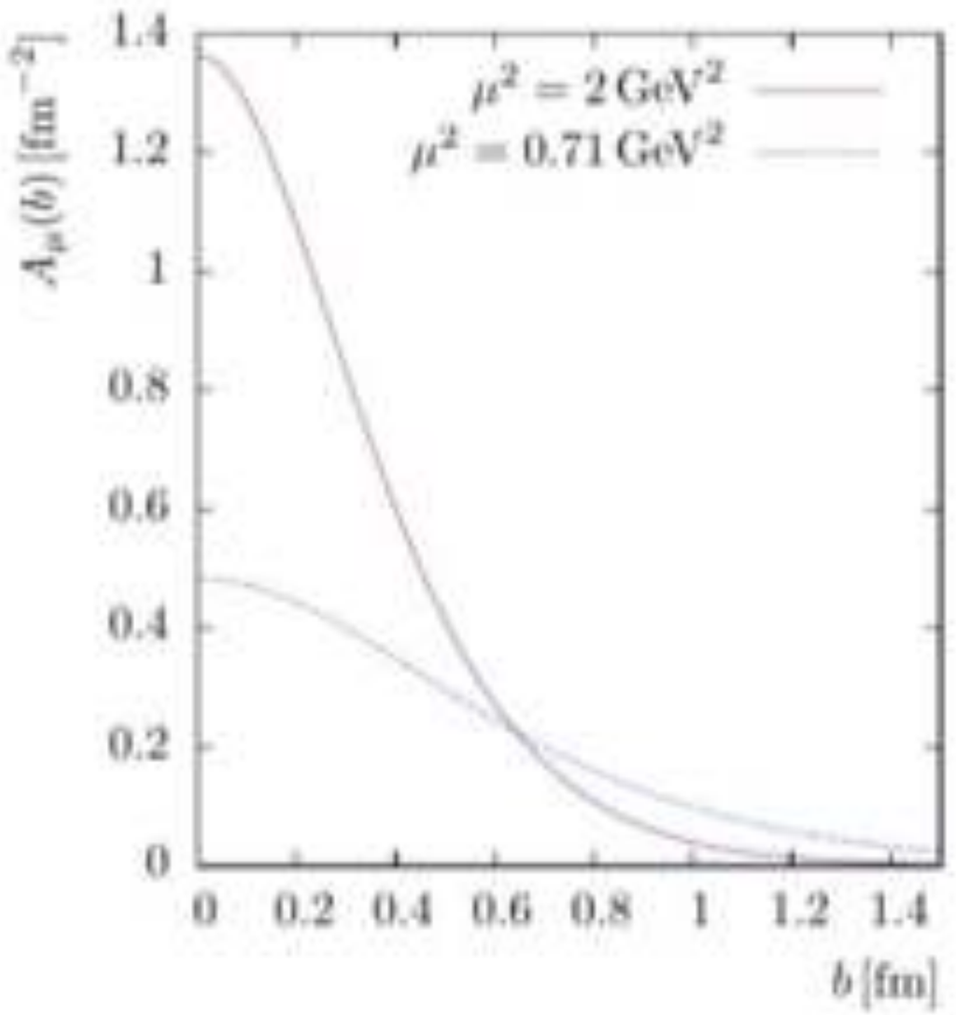

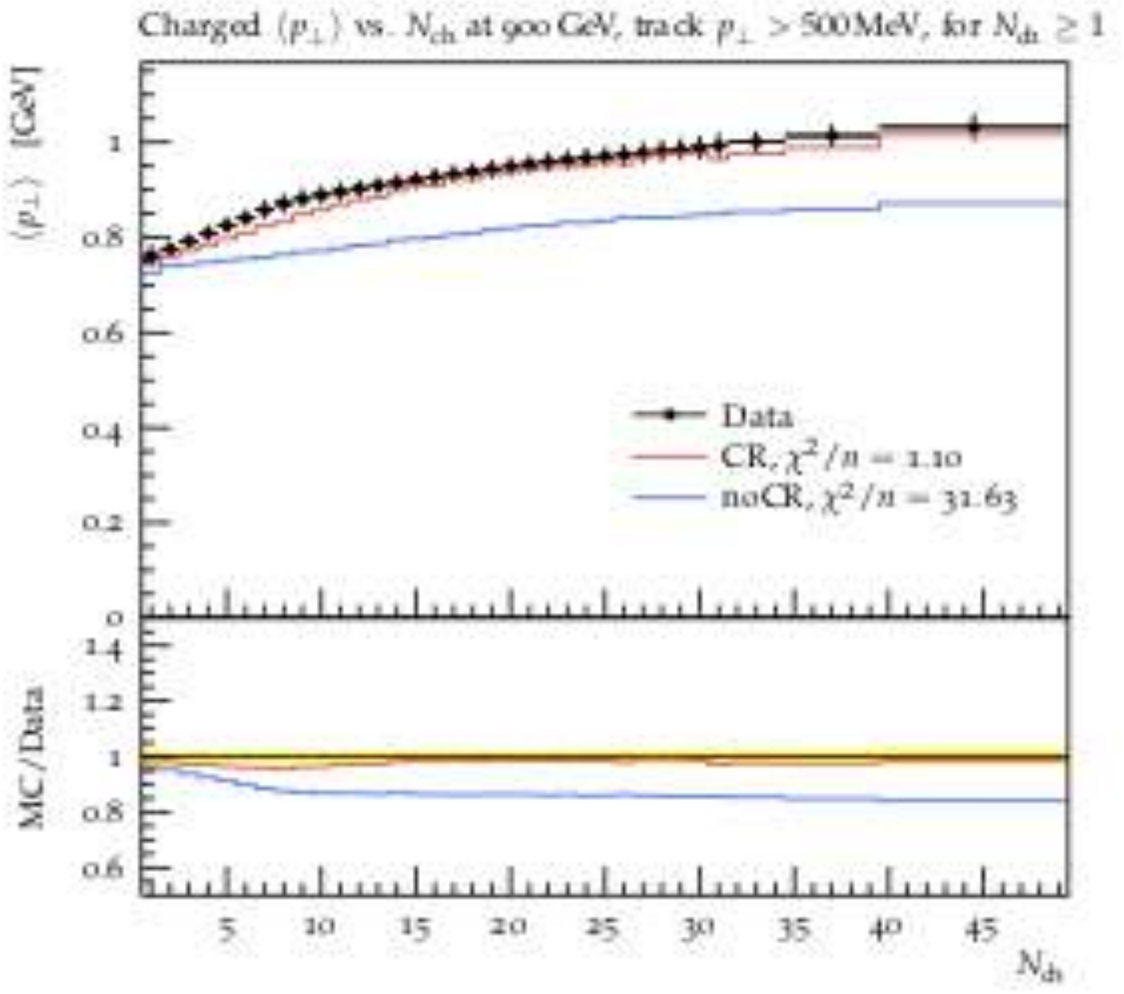

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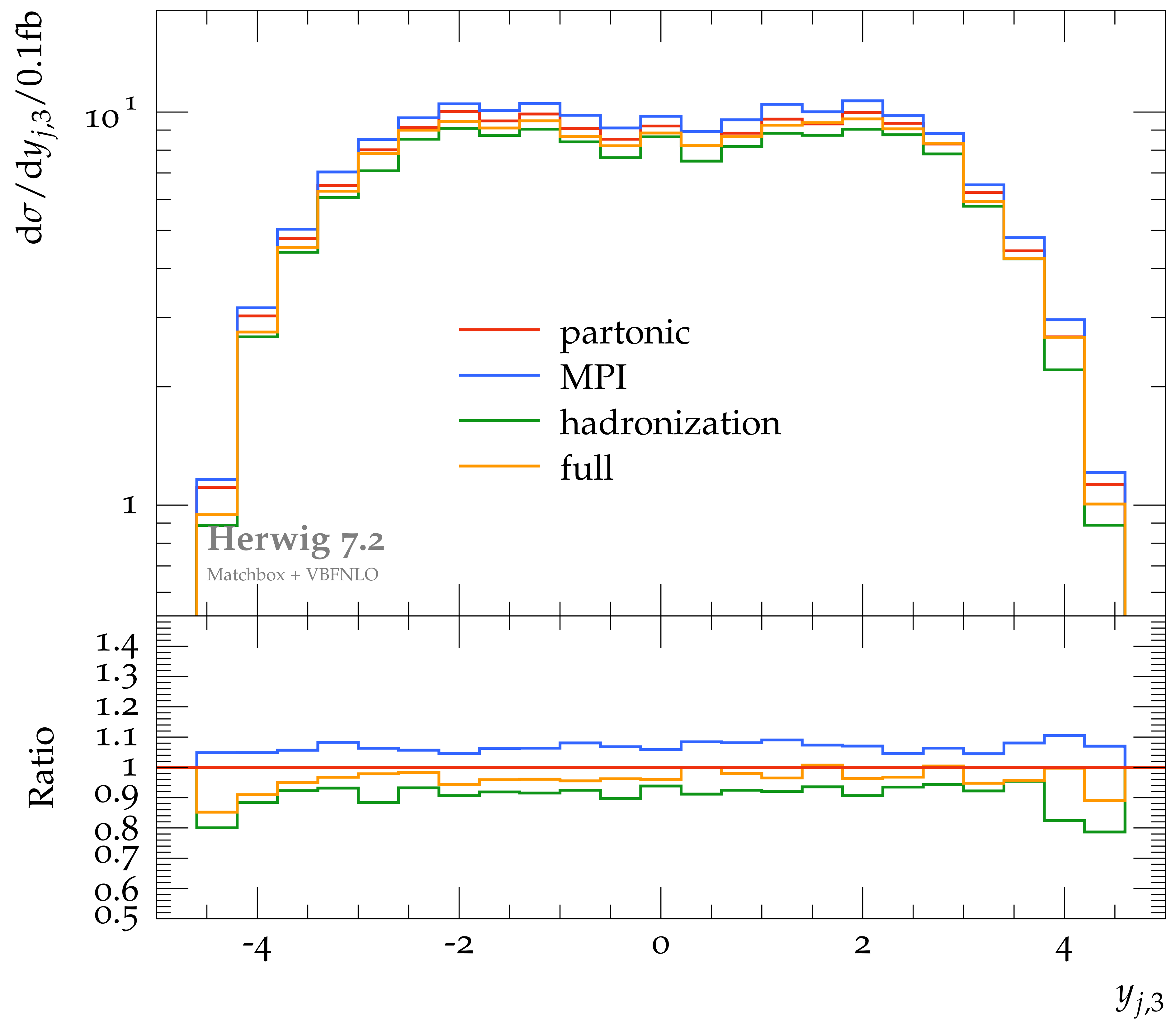
MPI & Colour Reconnection

[Bittrich, Kirchgaesser, Papaefstathiou, Plätzer, Todt — in preparation]

Soft QCD effects are not absent: significant impact on interjet activity and jet shapes.
On/off exercise will only hint at their relative importance.

Questions to be raised:

- Quantify impact (and how certain that is)
- Determine interplay with perturbative variations and models
- Watch out for lack of perturbative dynamics beyond current NLO+PS



Benchmark is VBF Z production, but findings should be ~ universal.

MPI & Colour Reconnection

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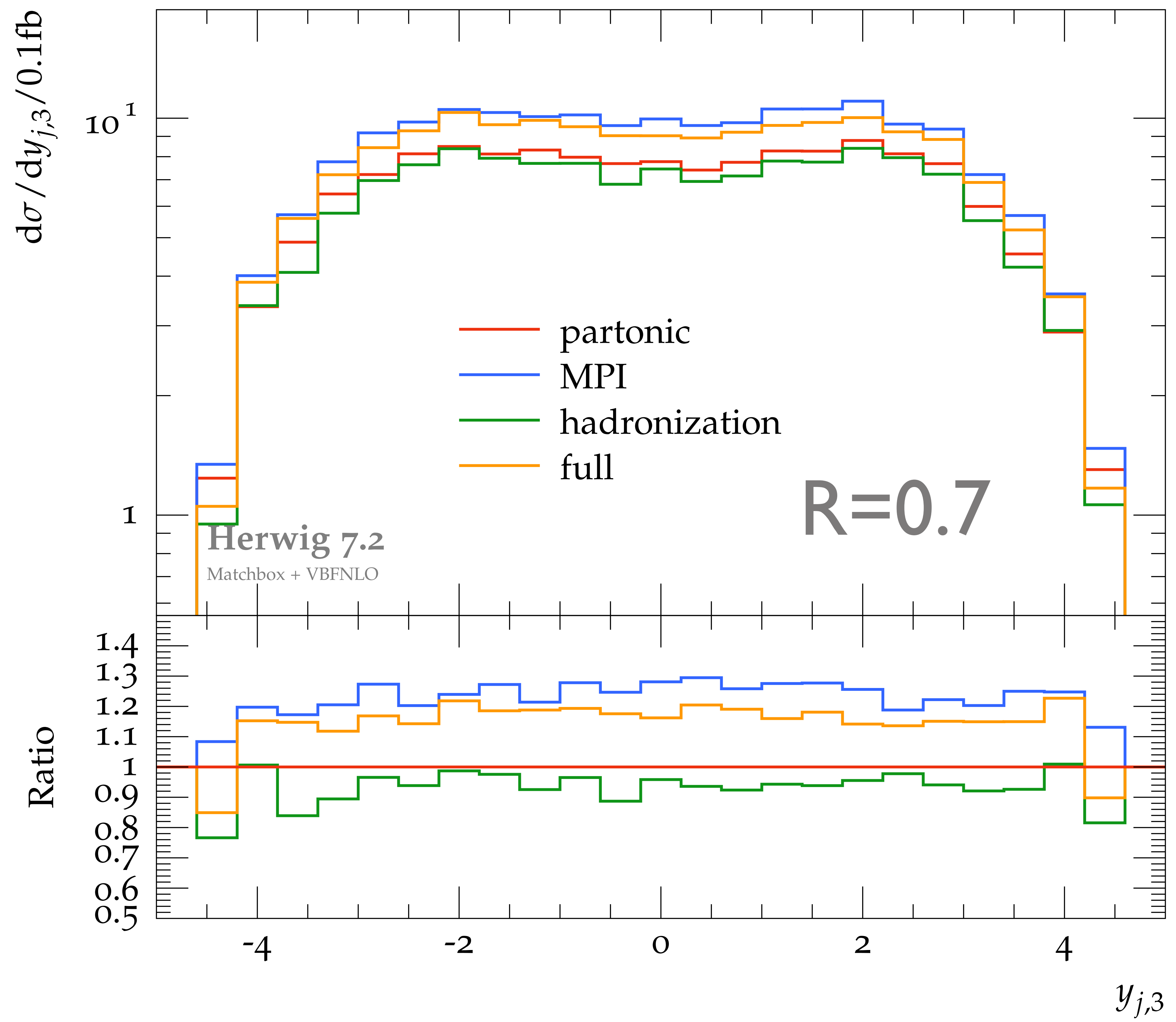

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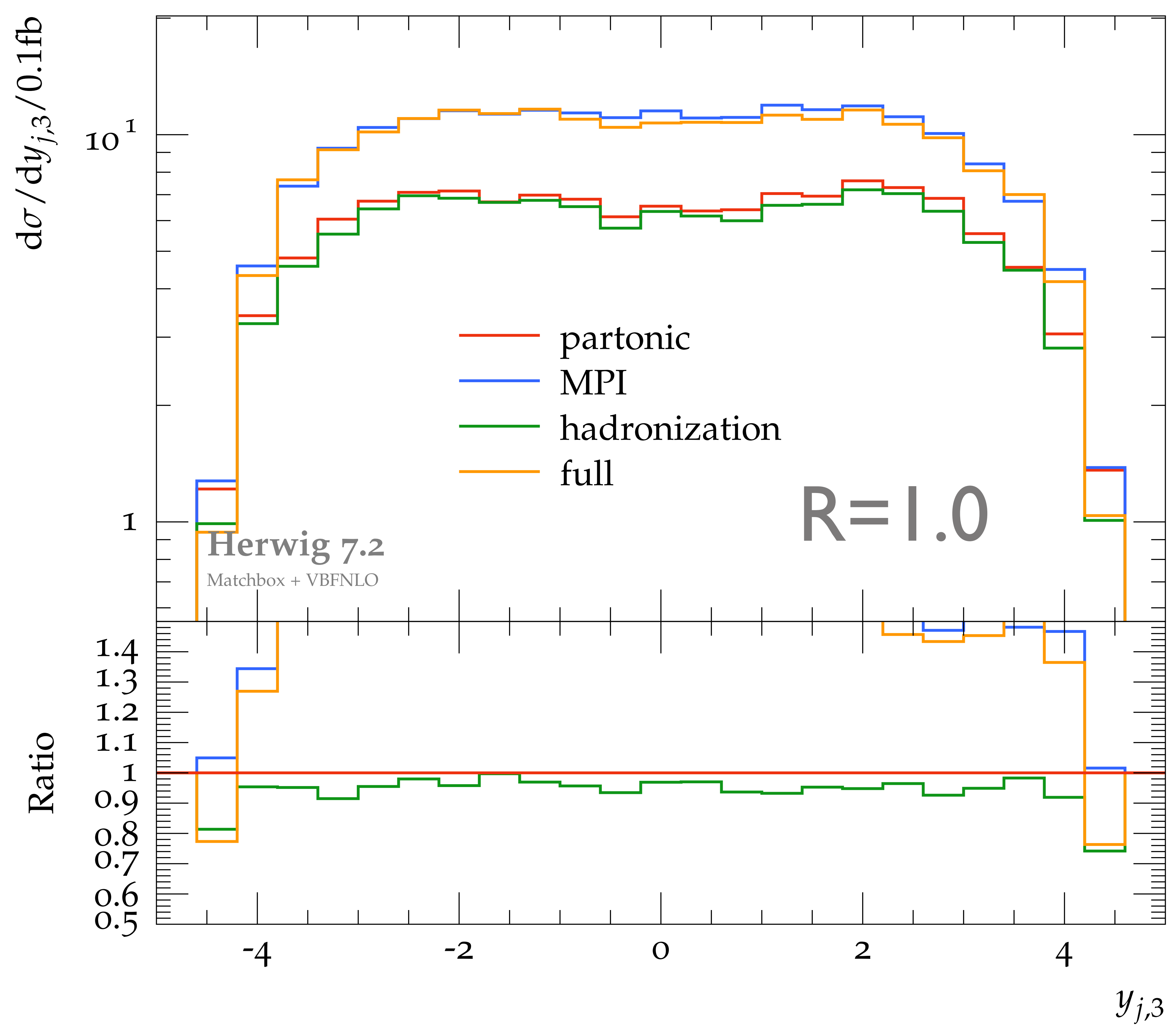

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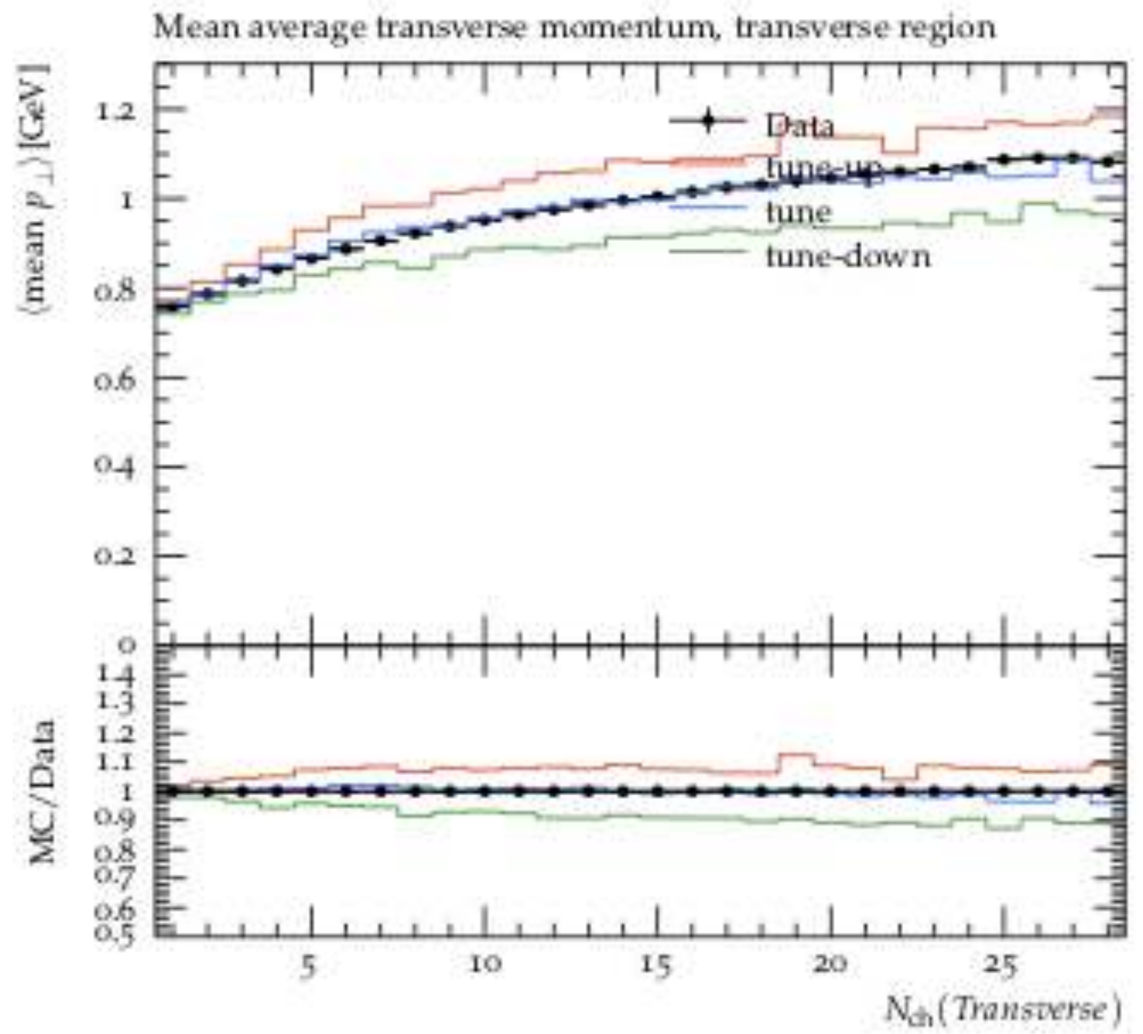
Model variations

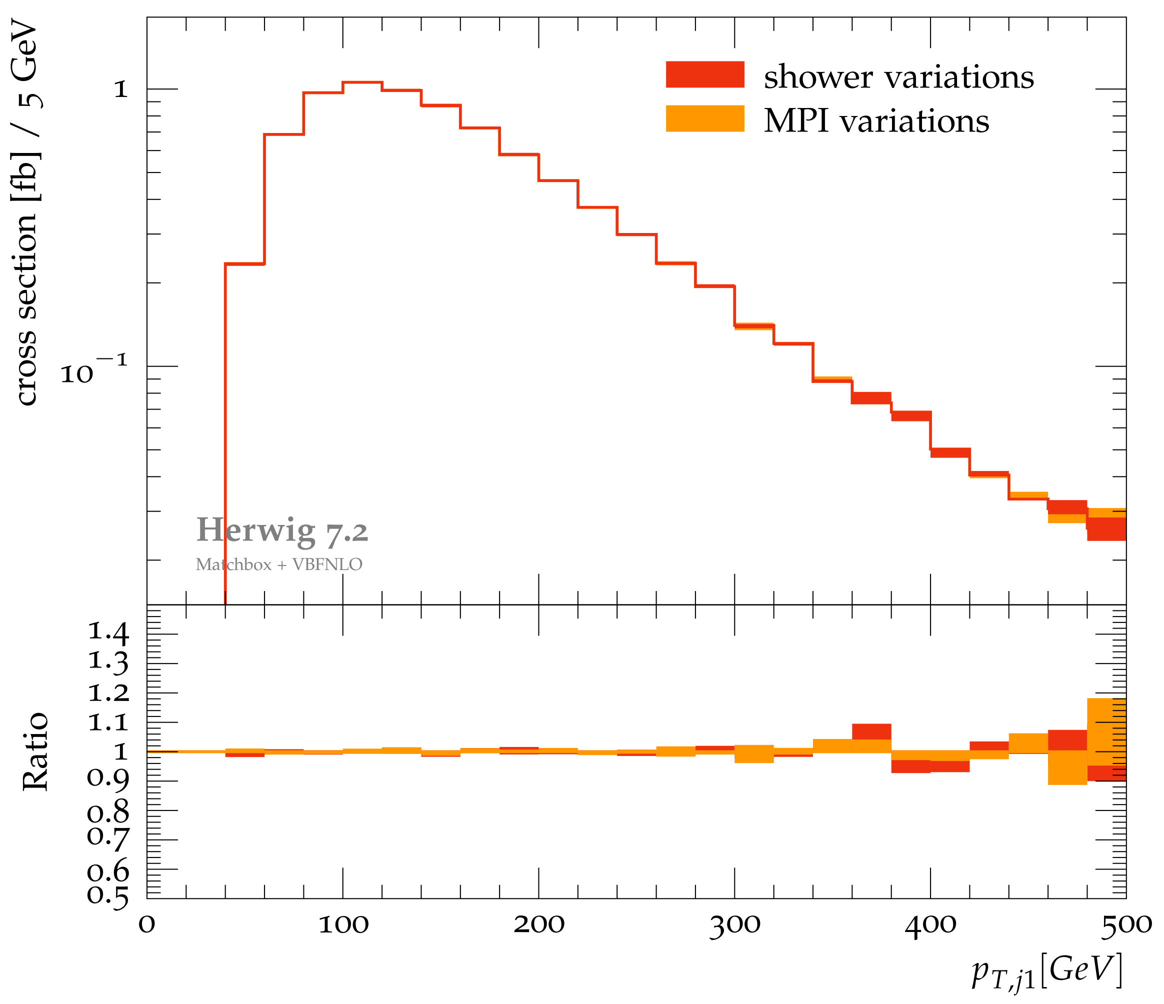
[Bittrich, Kirchgaesser, Papaefstathiou, Plätzer, Todt — in preparation]

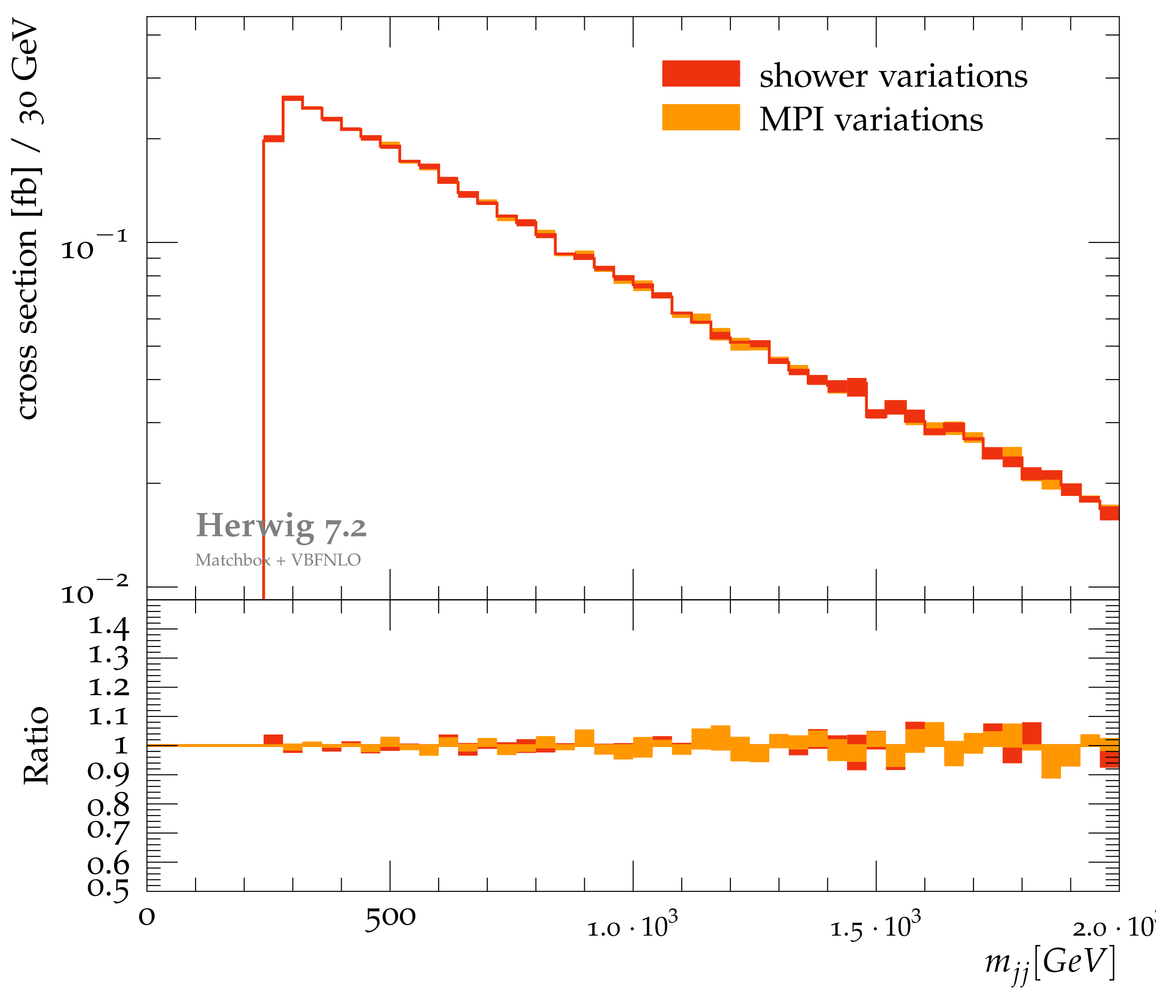
Strategy

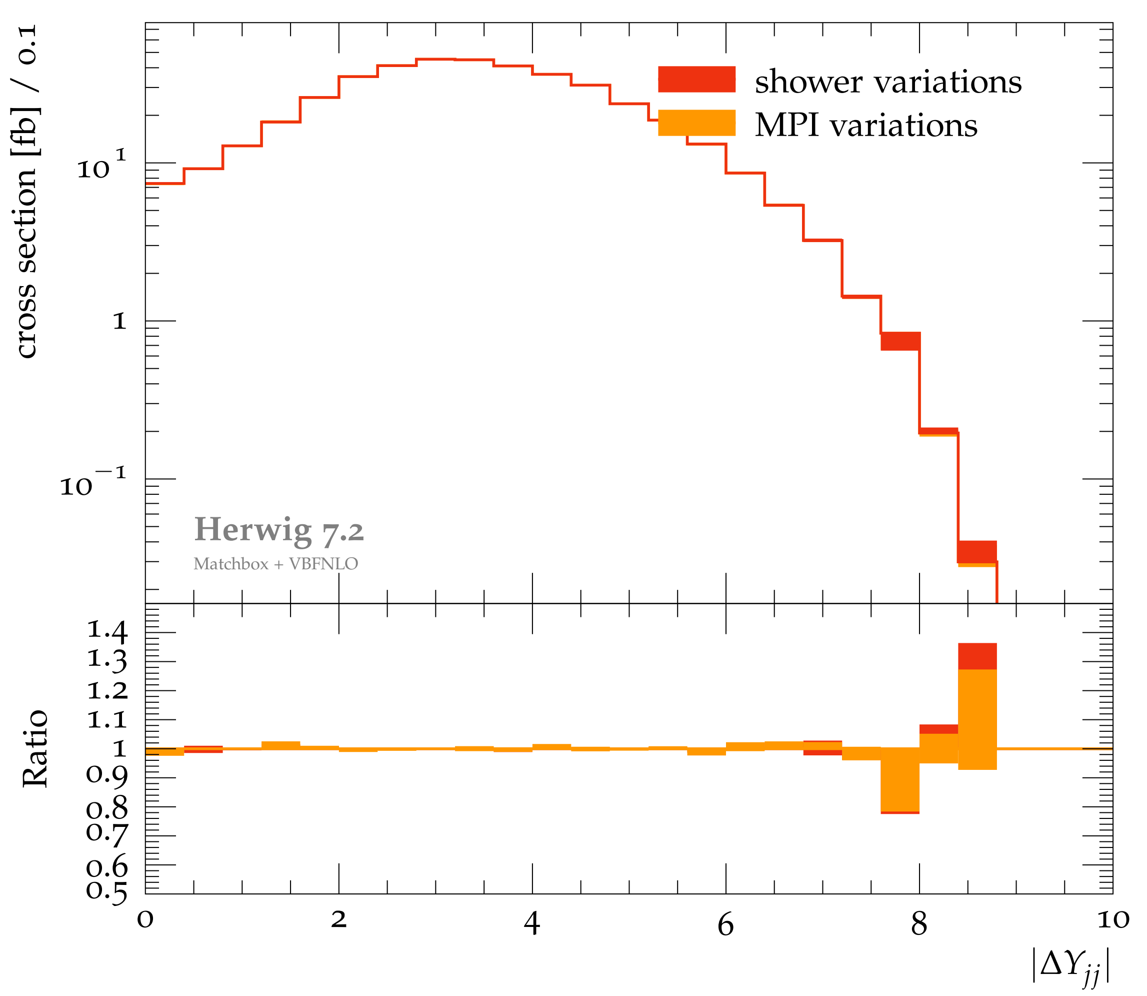
- Vary colour reconnection and MPI parameters to stay within ~ 10% agreement of typical tuning observables
- Vary perturbative scales, specifically shower hard scale
- Full NLO+PS study including shower variations



Tagging jet distributions mostly stable







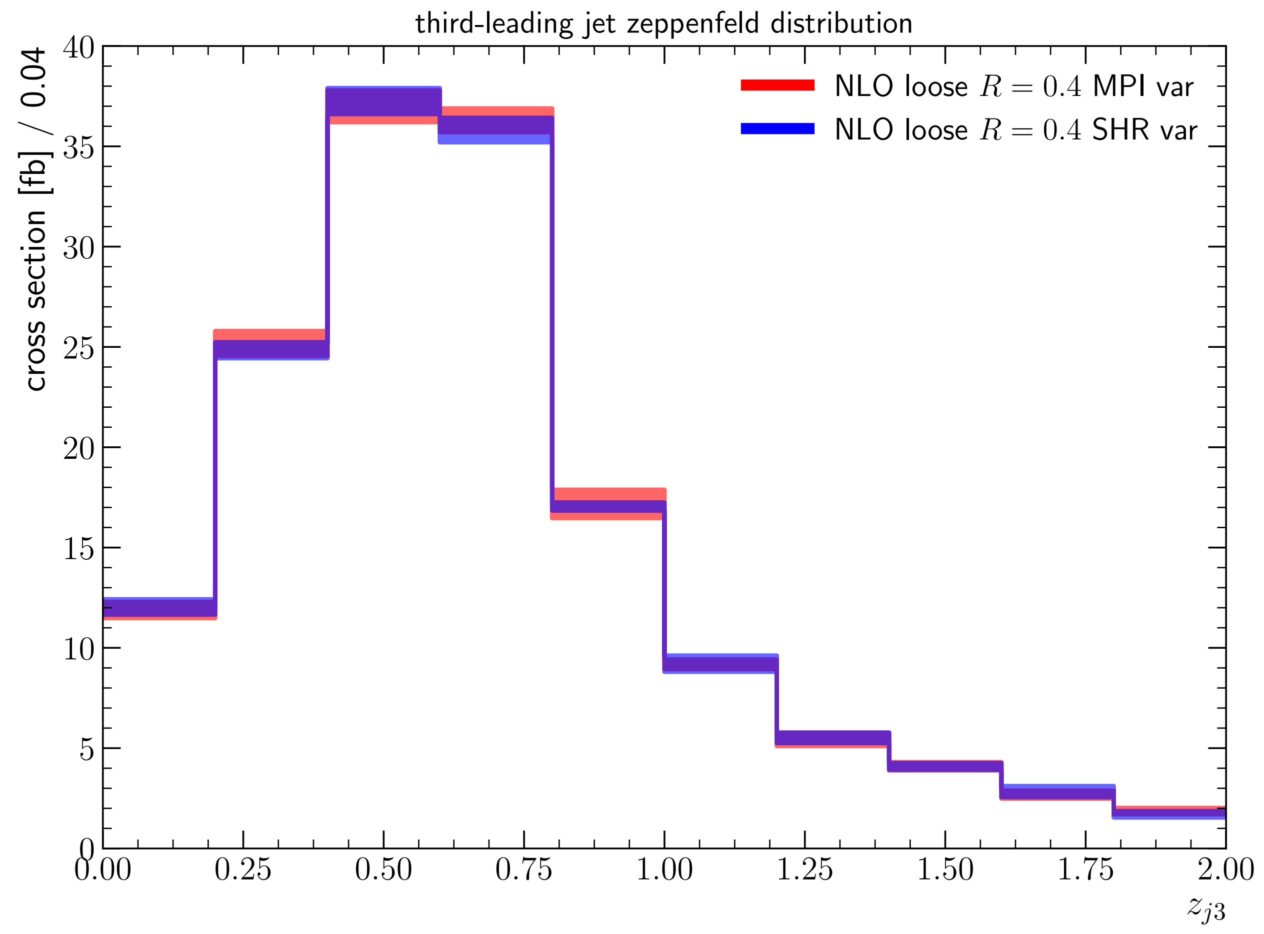
Model variations

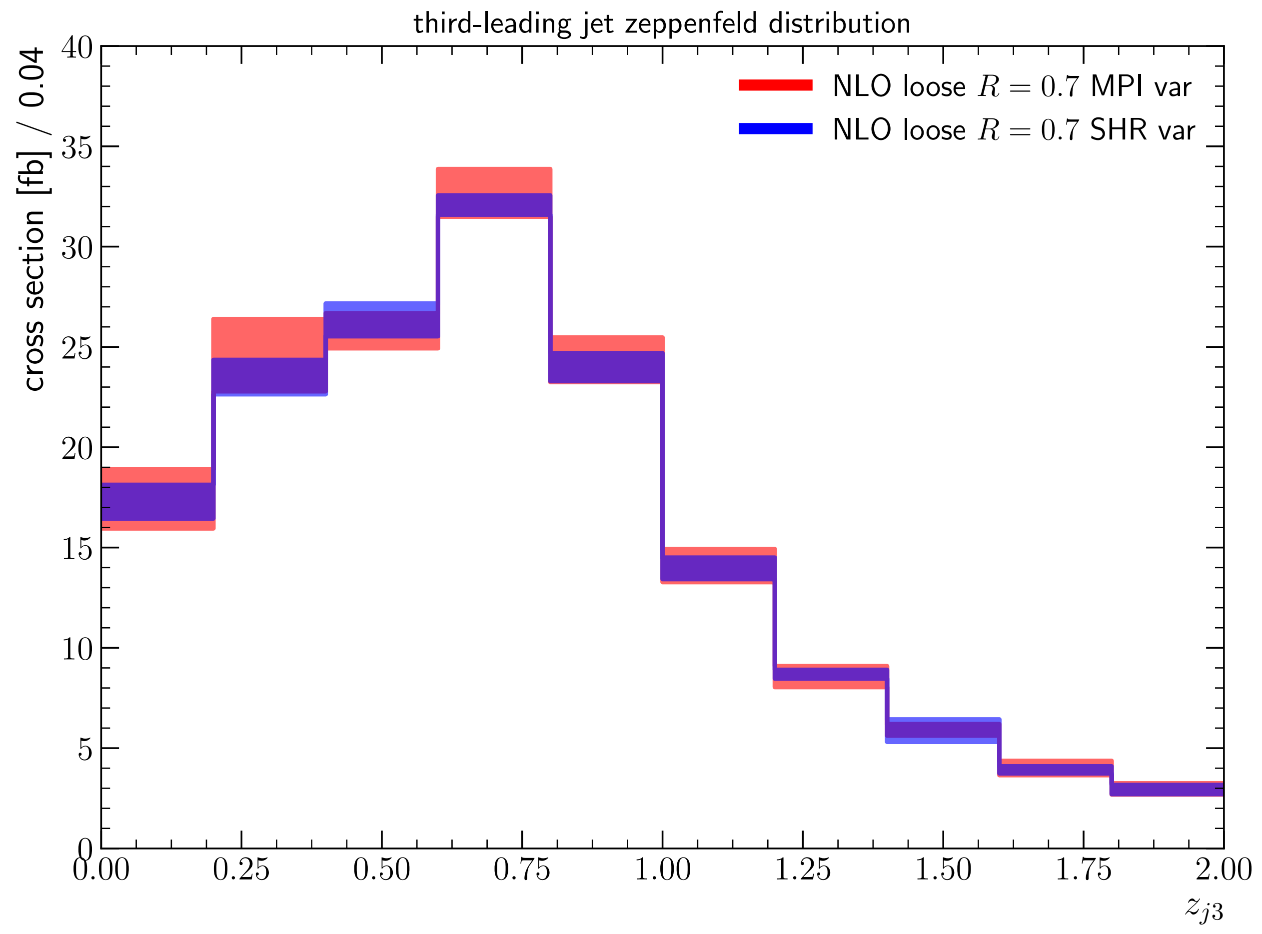
Third jet Zeppenfeld variable between perturbative and MPI variations.

R=0.4

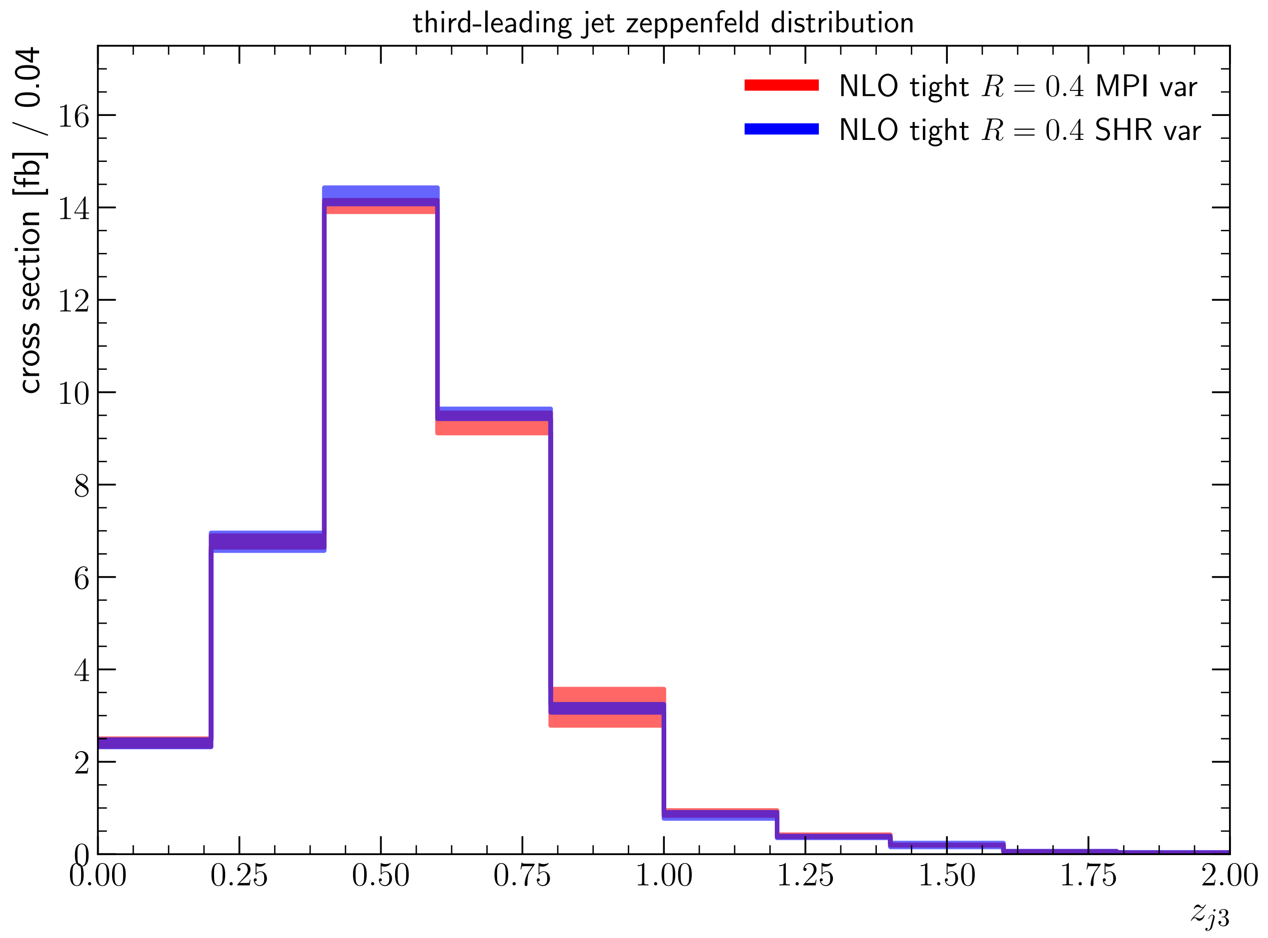
R=0.7

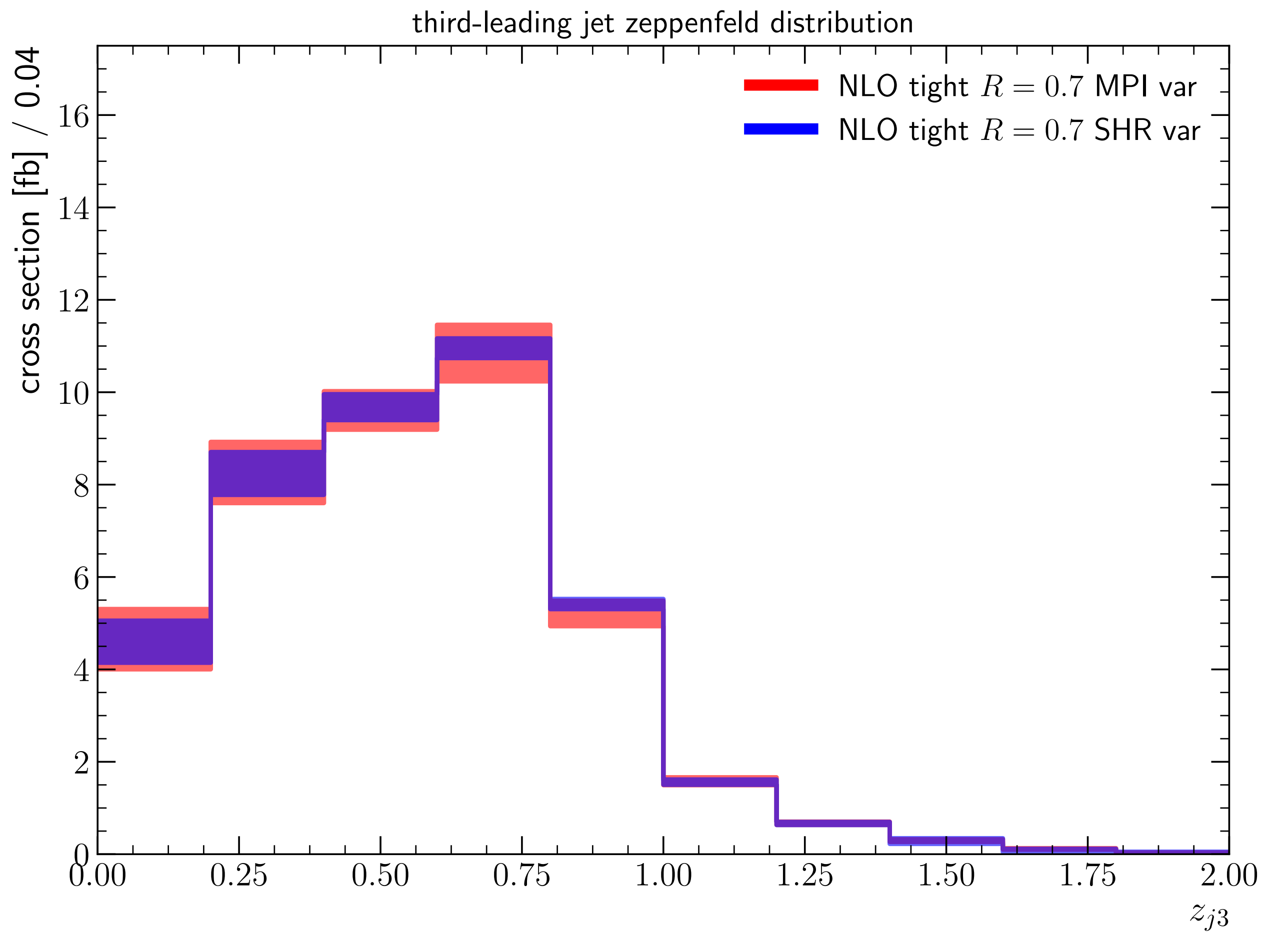
Loose selection





Tight selection





[Bittrich, Kirchgaesser, Papaefstathiou, Plätzer, Todt — in preparation]

Algorithms & Efficiency

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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

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

else
The emission is rejected, and the algorithm continues with

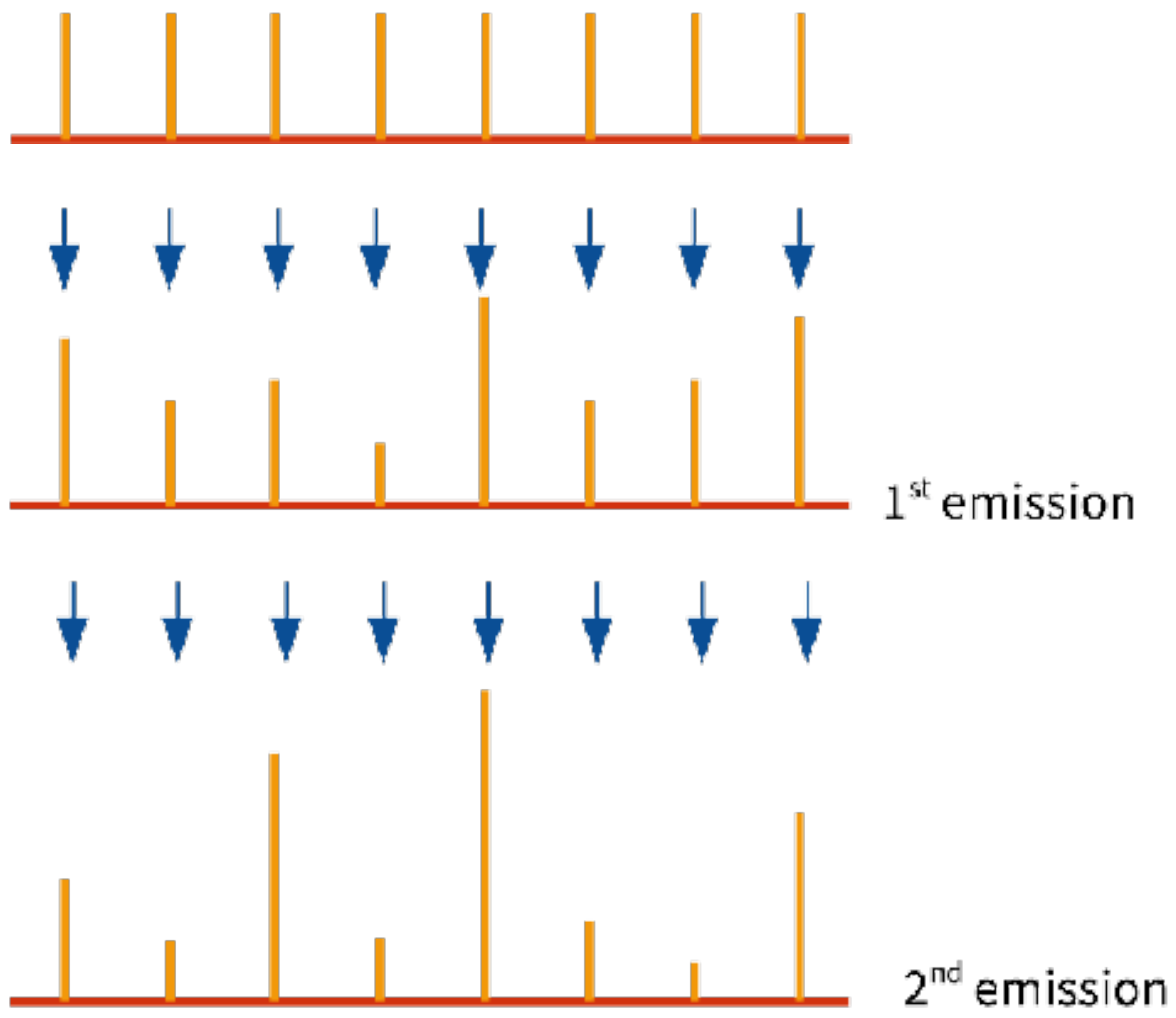
$$w \leftarrow w \times \frac{1}{1-\epsilon} \times \left(1 - \frac{P(q,z,x)}{R(q,z,x)}\right)$$
$$Q' \leftarrow q. \quad (4)$$

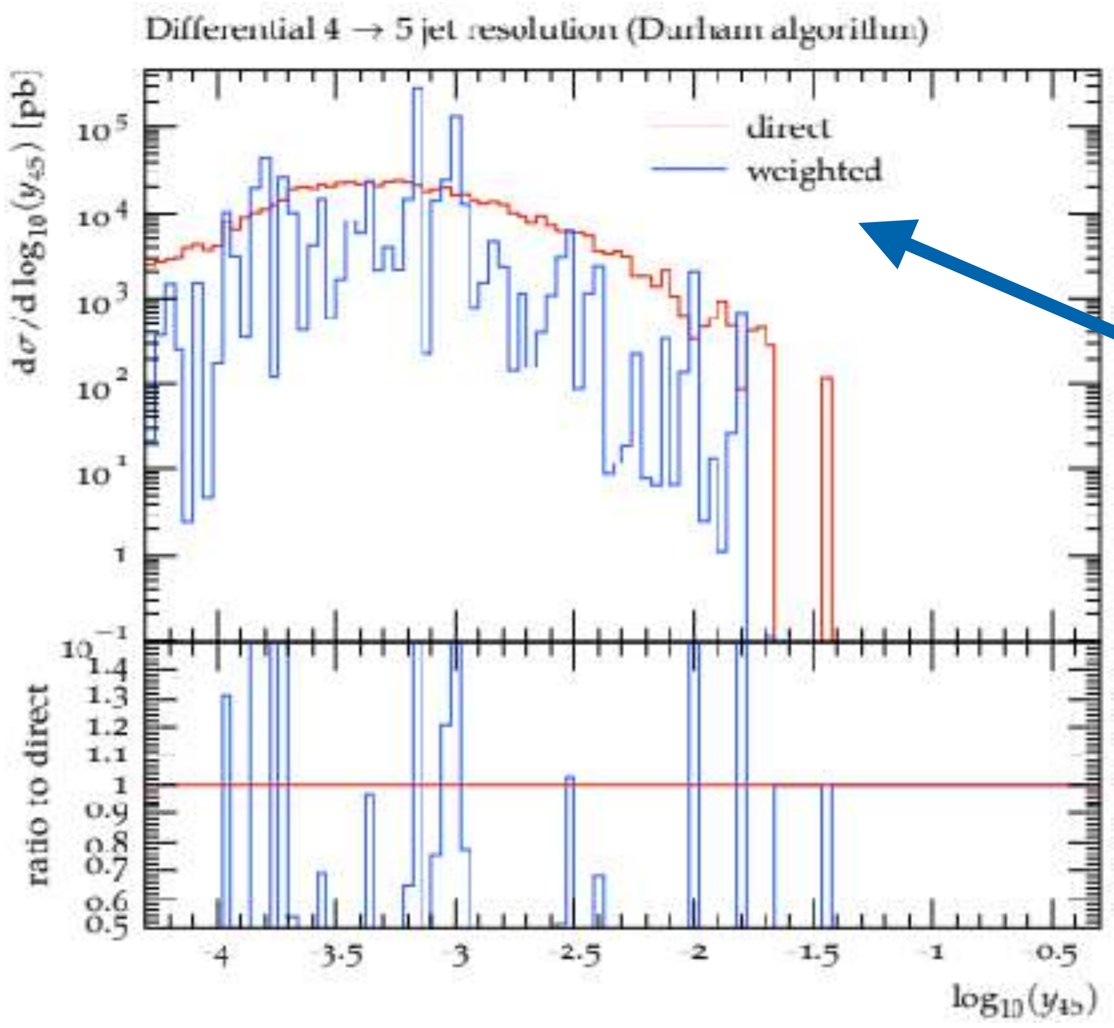
end if
end if
end loop

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]

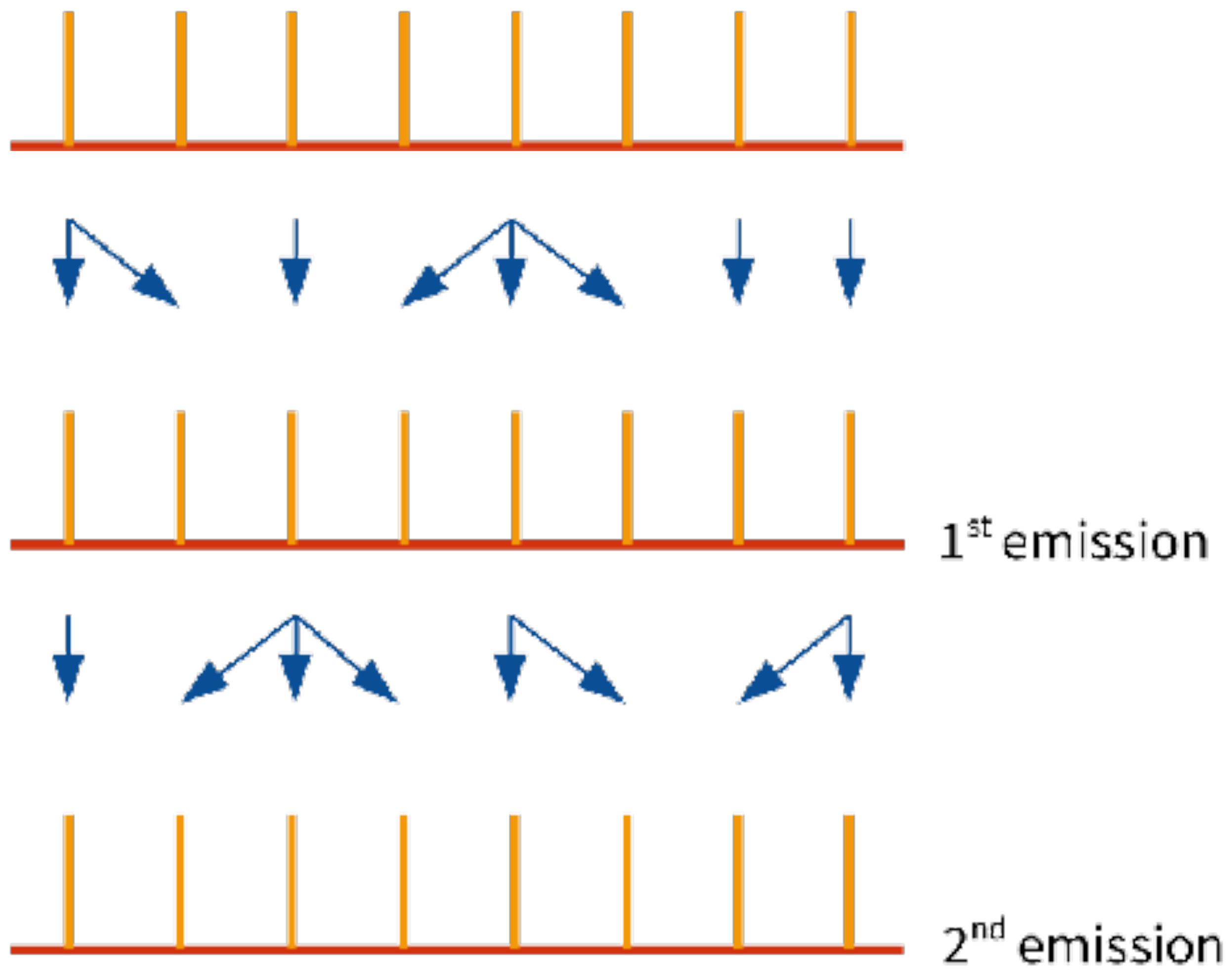


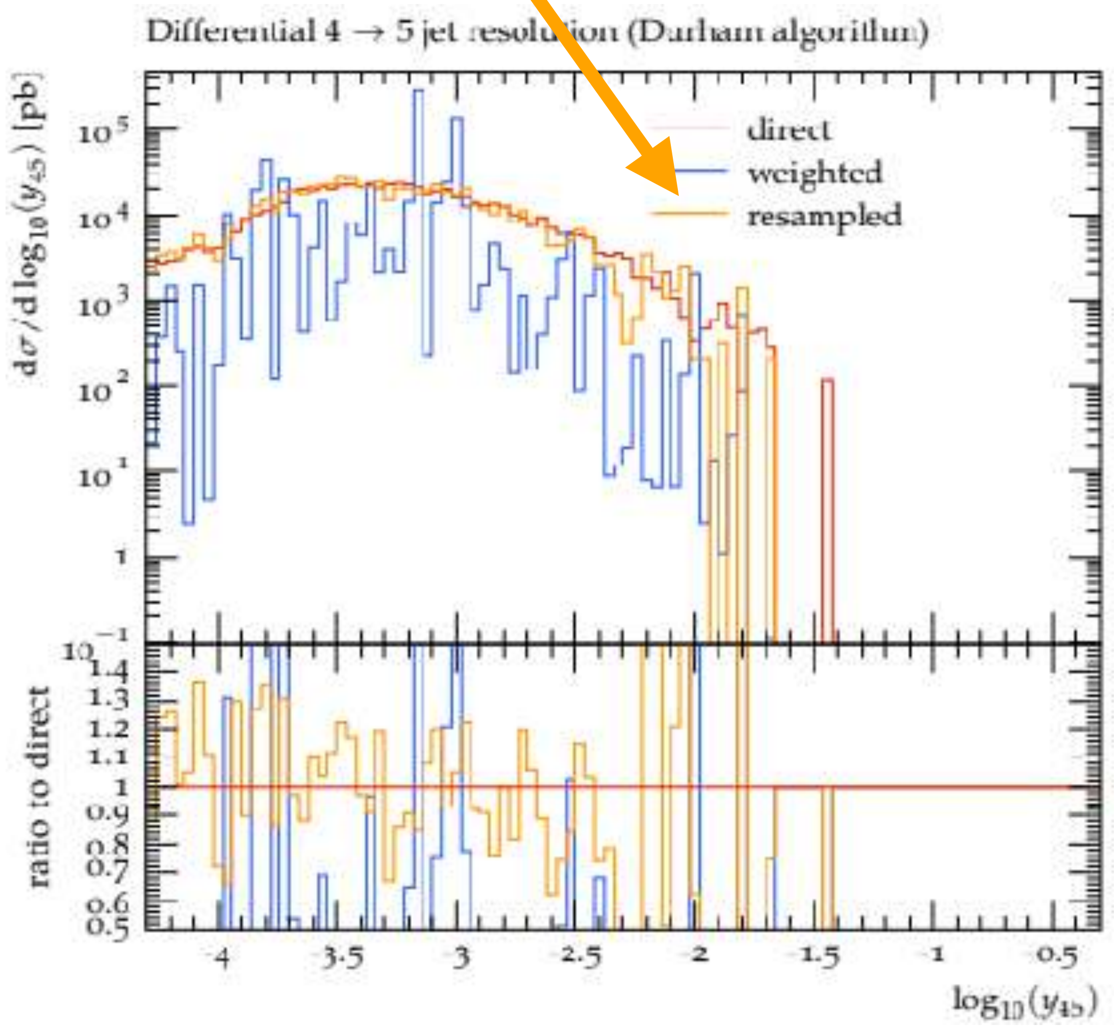


Weighted branching algorithms exhibit prohibitive weight distributions & convergence issues.

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]

Possible Topics of Activity

- Non-perturbative uncertainties
  - common hadronisation interface and variations
  - theoretical understanding
  - differences in tuned comparisons
  - pheno impact for certain classes of processes (e.g. VBF/VBS)
- Shower accuracy studies
  - comparing different schemes on higher orders, evaluate phenomenological impact
  - Subleading colour and interplay with colour reconnection
  - New sampling methods and algorithms versus machine learning techniques
  - Accuracy of merging resummed calculation versus ME+PS paradigms
- Photon physics, modelling of fragmentation
- Heavy flavour matching
  - review of existing measurements
  - Connecting precision calculation, fragmentation and decays
  - partons at 100 TeV
- Common LHC event bazaar
- Status and needs for electroweak corrections and radiation in shower algorithms
- Machine learning and adaptive Monte Carlo methods

[from LH wiki — Huston + McFayden / Siegert / Plätzer]

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What about accords?

[from LH wiki — Huston + McFayden / Siegert / Plätzer]

Revisit the Accords?

2009

THE TOOLS AND MONTE CARLO WORKING GROUP
Summary Report

I INTERFACES

2. A STANDARD FORMAT FOR LES HOUCHES EVENT FILES, VERSION 2

3. A DRAFT RUNTIME INTERFACE TO COMBINE PARTON SHOWERS AND NEXT-TO-LEADING ORDER QCD PROGRAMS

Matchbox's Low-level interface, later inserted BLHA as intermediate level

2011 & 2013

THE SM AND NLO MULTILEG AND SM MC WORKING GROUPS:
Summary Report

Les Houches 2013: Physics at TeV Colliders
Standard Model Working Group Report

I NLO automation and (N)NLO techniques
1 The first use case for BLHA2 extensions: NJET plus Herwig++/Matchbox[3] . . . .
2 GoSam plus Herwig++/Matchbox[4] . . . .

A proposal for a standard interface between Monte Carlo tools and one-loop programs

T. Binoth

The University of Edinburgh, Edinburgh EH9 3JZ, Scotland, United Kingdom

Binoth Les Houches Accord
LHEF Files

Update of the Binoth Les Houches Accord for a standard interface between Monte Carlo tools and one-loop programs

Do these still fit our needs?
New paradigms, new capabilities, efficient storage/generation …

Thanks!