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Simulation & pheno of instanton- and sphaleron-induced processes

Simon Plätzer

Particle Physics — University of Vienna

at

“Topological Effects in the Standard Model” TH Institute

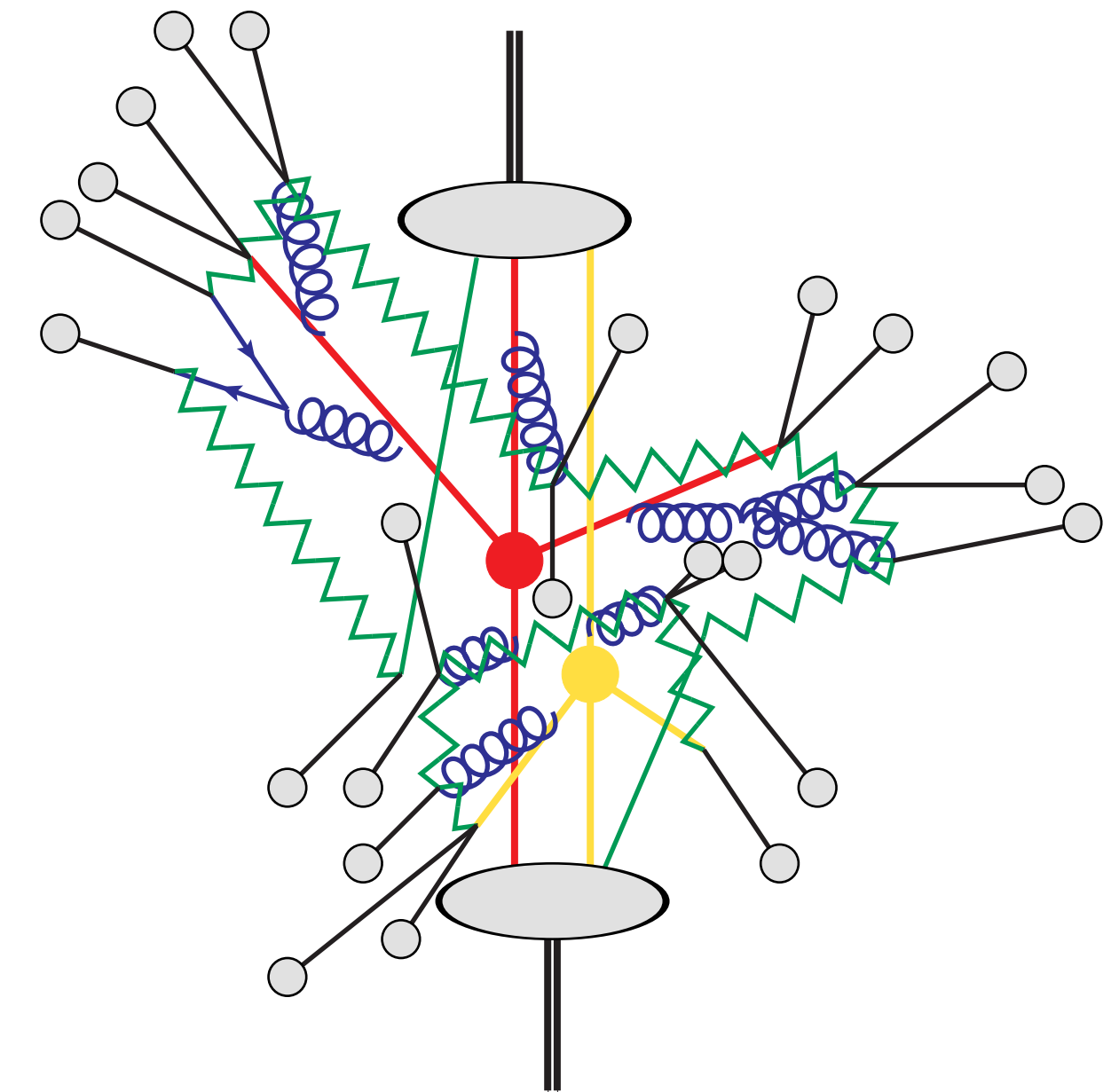
Digital | 18 December 2020

QCD description of collider reactions:
Complexity challenges precision.

Hard partonic scattering:
NLO QCD routinely

Jet evolution — parton showers:
NLL sometimes, mostly unclear

Multi-parton interactions
Hadronization



$$d\sigma \sim d\sigma_{\text{hard}}(Q) \times \text{PS}(Q \rightarrow \mu) \times \text{Had}(\mu \rightarrow \Lambda) \times \dots$$

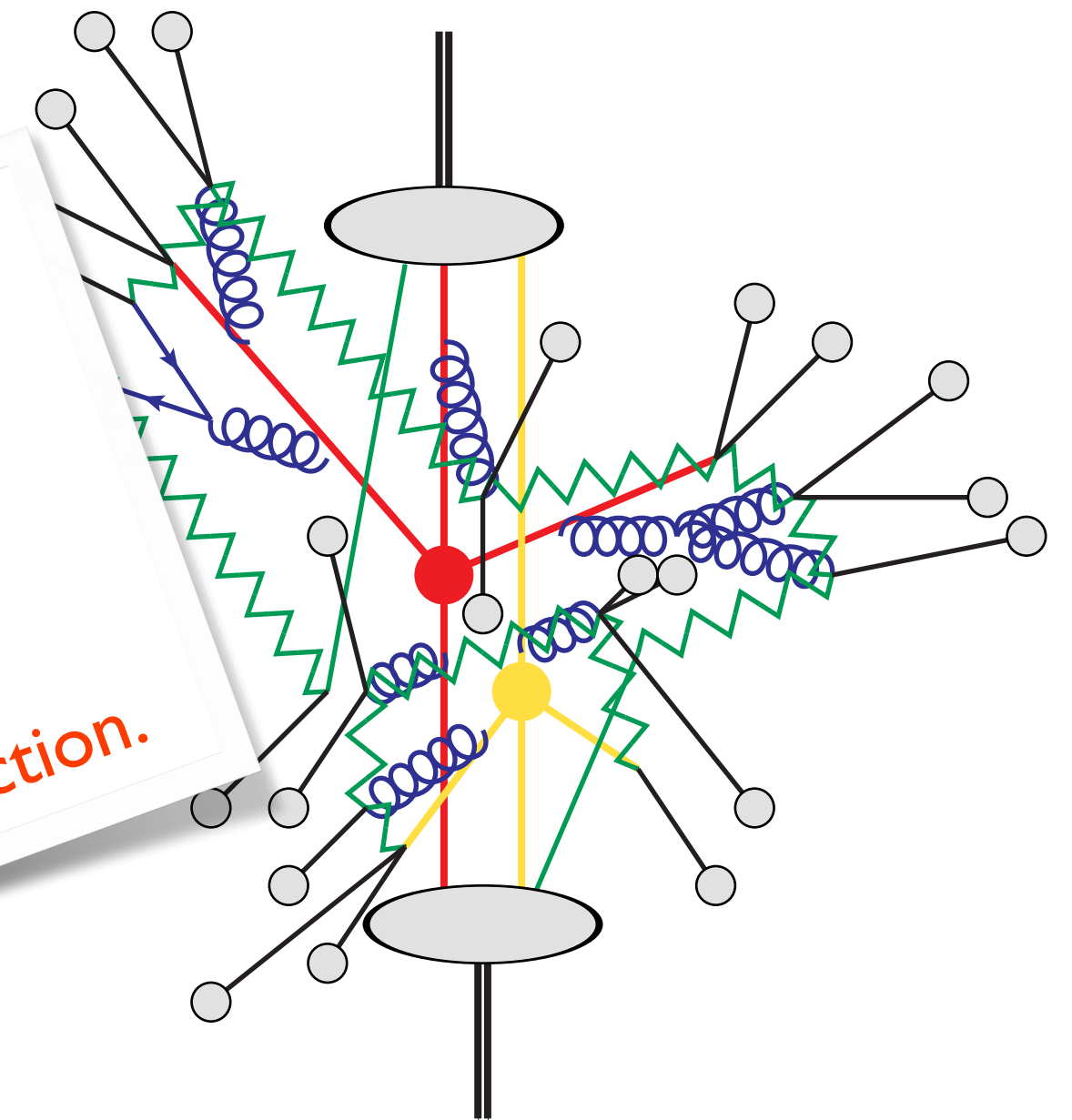
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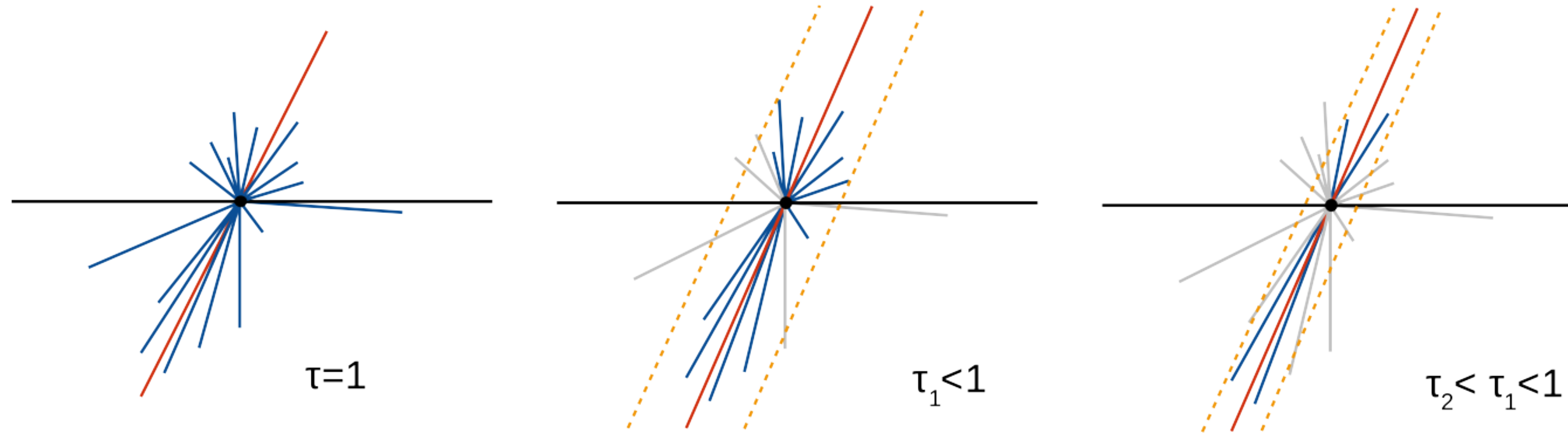
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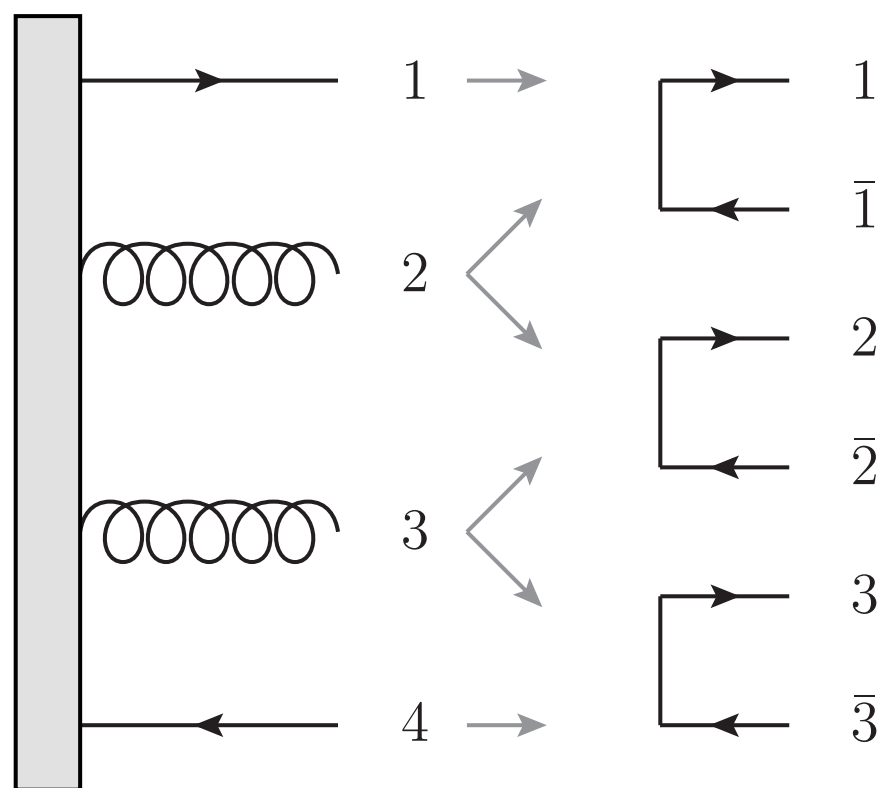
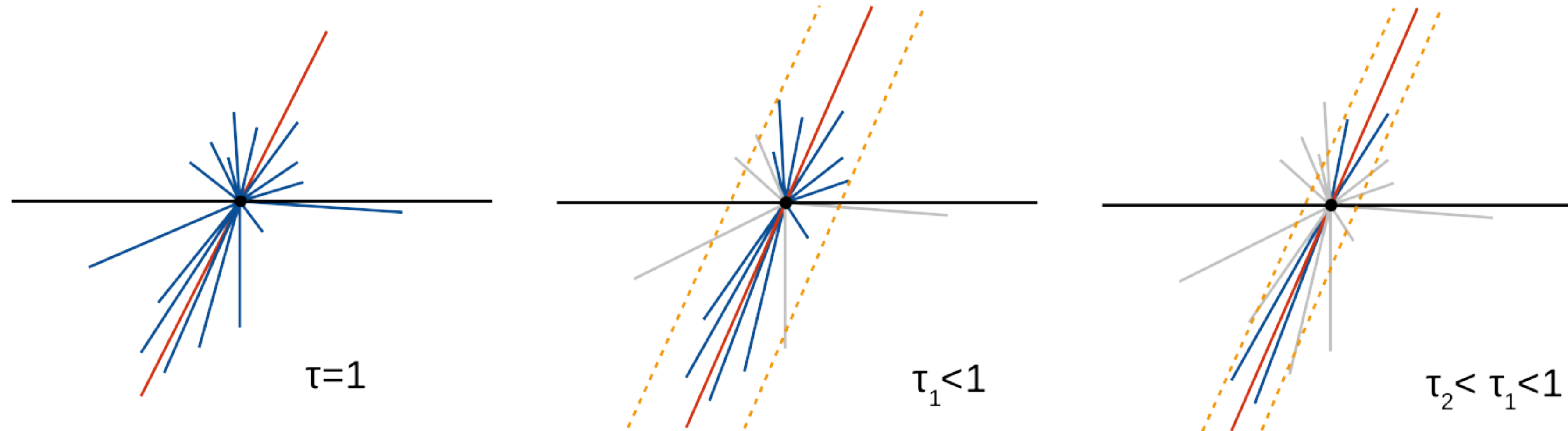
A guided tour of an event generator
and special considerations for
instantons and sphalerons.
Totally (Herwig) biased and personal selection.



$$d\sigma \sim d\sigma_{\text{hard}}(Q) \times PS(Q \rightarrow \mu) \times \text{Had}(\mu \rightarrow \Lambda) \times \dots$$



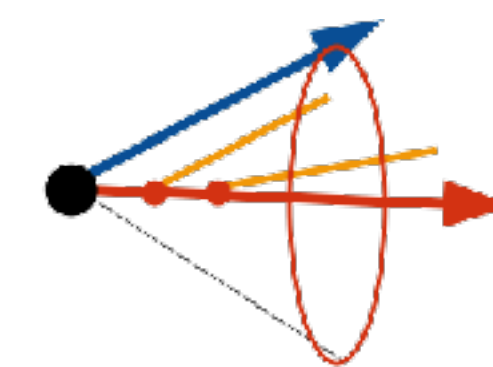
$$\sum_i \left\{ \text{diagram with wavy line and index } i \right\} q_L = \text{diagram with wavy line} + \mathcal{O}\left(\frac{q_L^2}{Q^2}\right)$$



$$\frac{d\tilde{q}^2}{\tilde{q}^2} dz \frac{2}{1-z} \sim \frac{n \cdot \bar{n}}{n \cdot q_i q_i \cdot n} \frac{d^3 k_i}{2E_i}$$

Pick a colour flow according to colour sub-amplitudes.

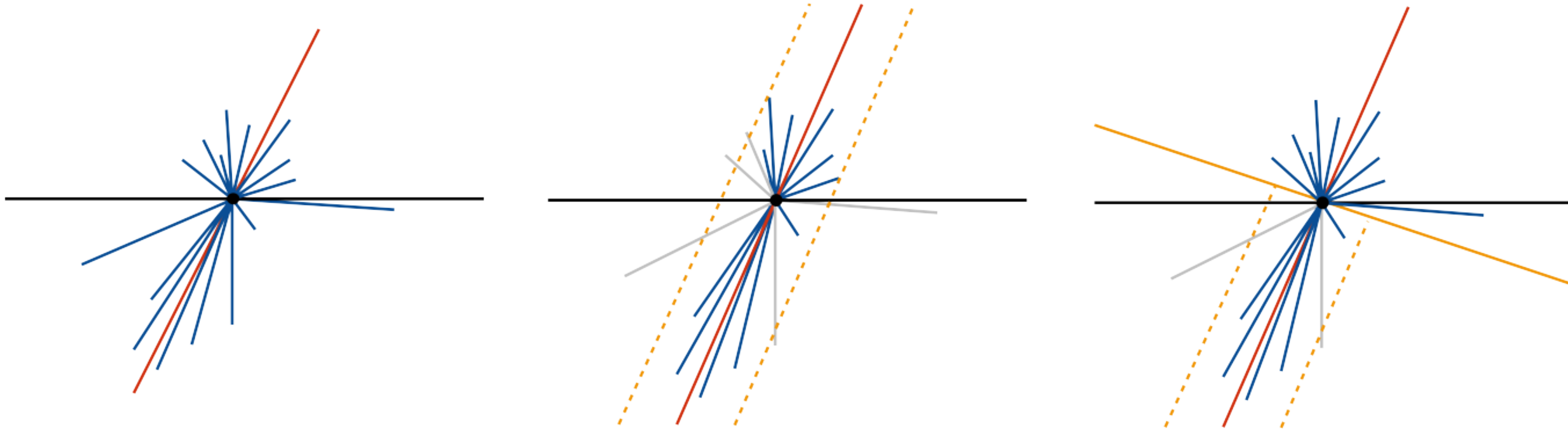
Soft radiation according to hard process legs.



branchings
order in \sim angle



dipoles
order in $\sim p_T$



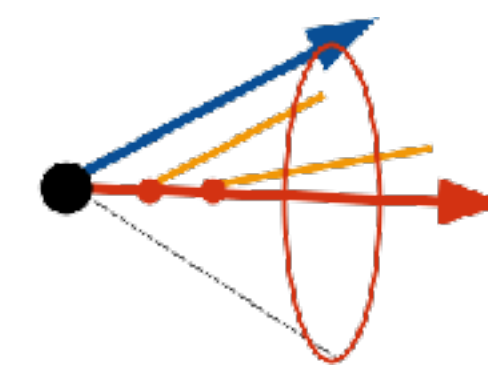
Coherence argument fails for most general observables,
perform accurate resummation using dipole showers.

Thorough analysis and improvements see e.g.

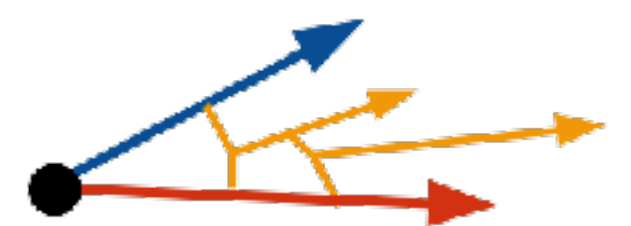
[Forshaw, Holguin, Plätzer – JHEP 1908 (2019) 145]

[Dasgupta, Dreyer, Hamilton, Monni, Salam —PRL 125 (2020) 5]

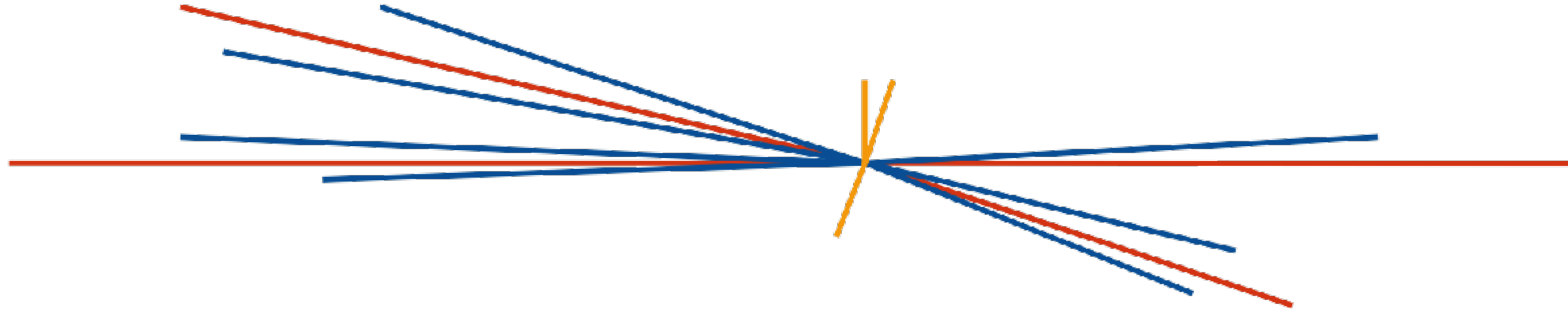
[Forshaw, Holguin, Plätzer – JHEP 09 (2020) 014]



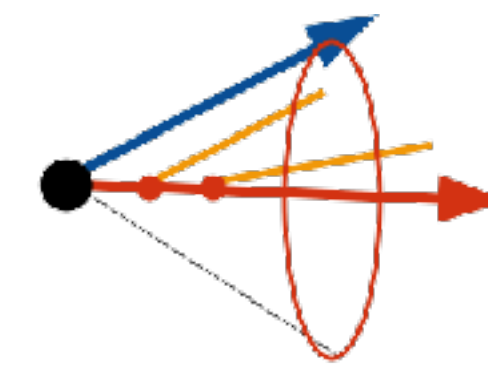
branchings
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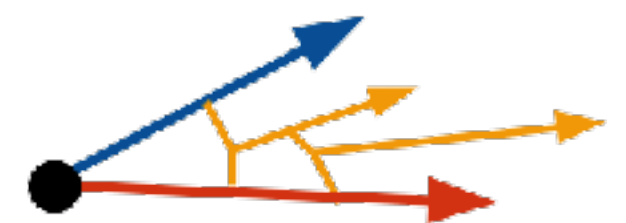
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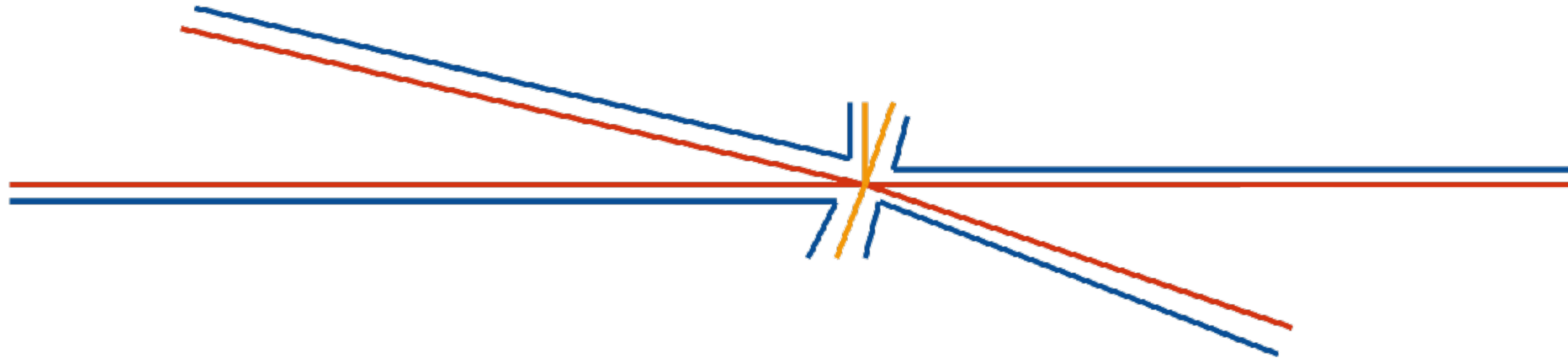
Large-angle soft gluons isolate colour charges in jets: relevant picture for hadronization.



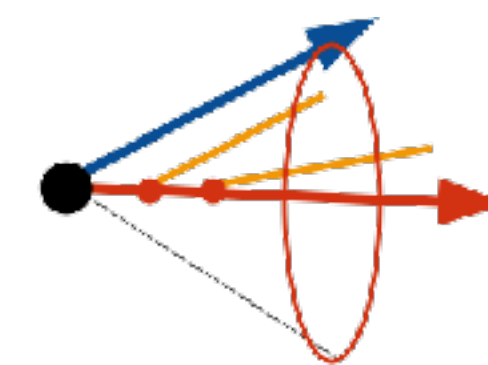
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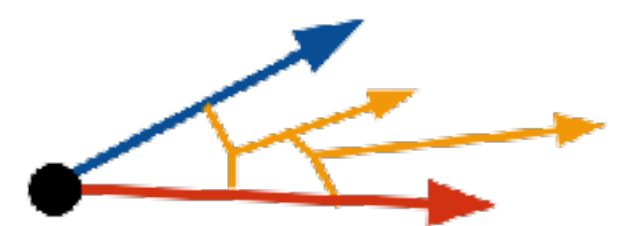
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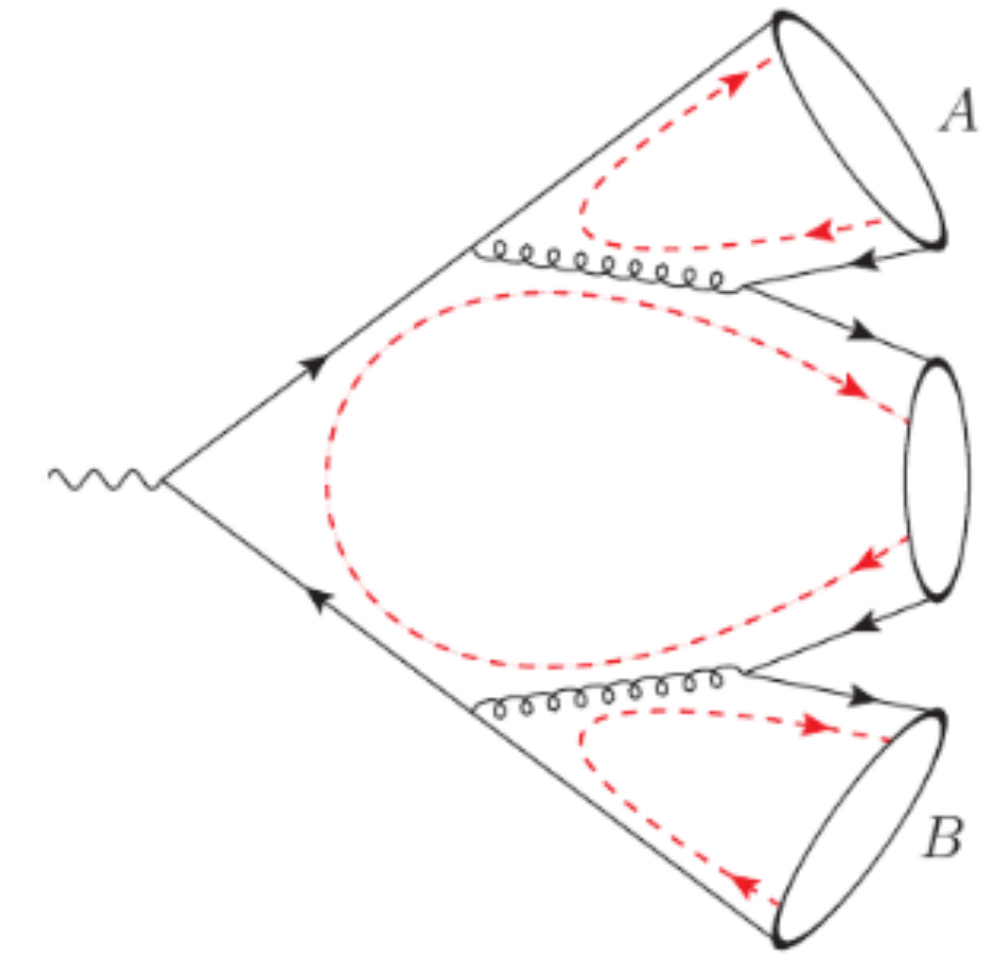
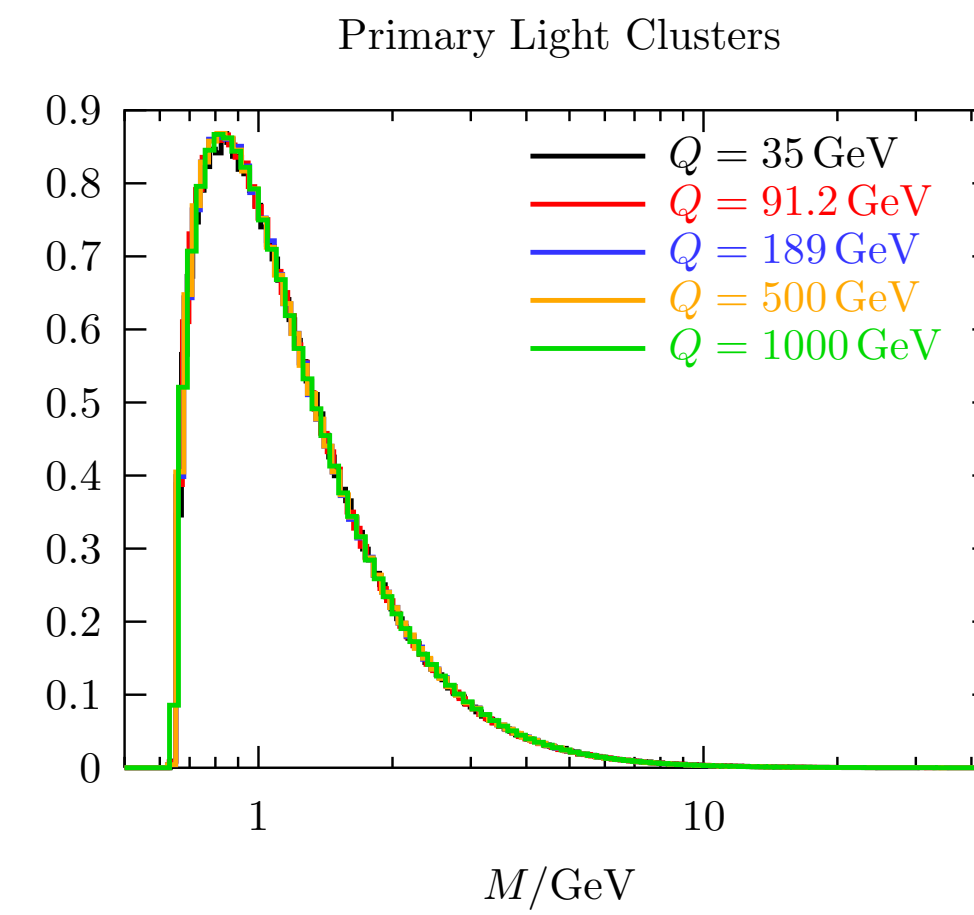
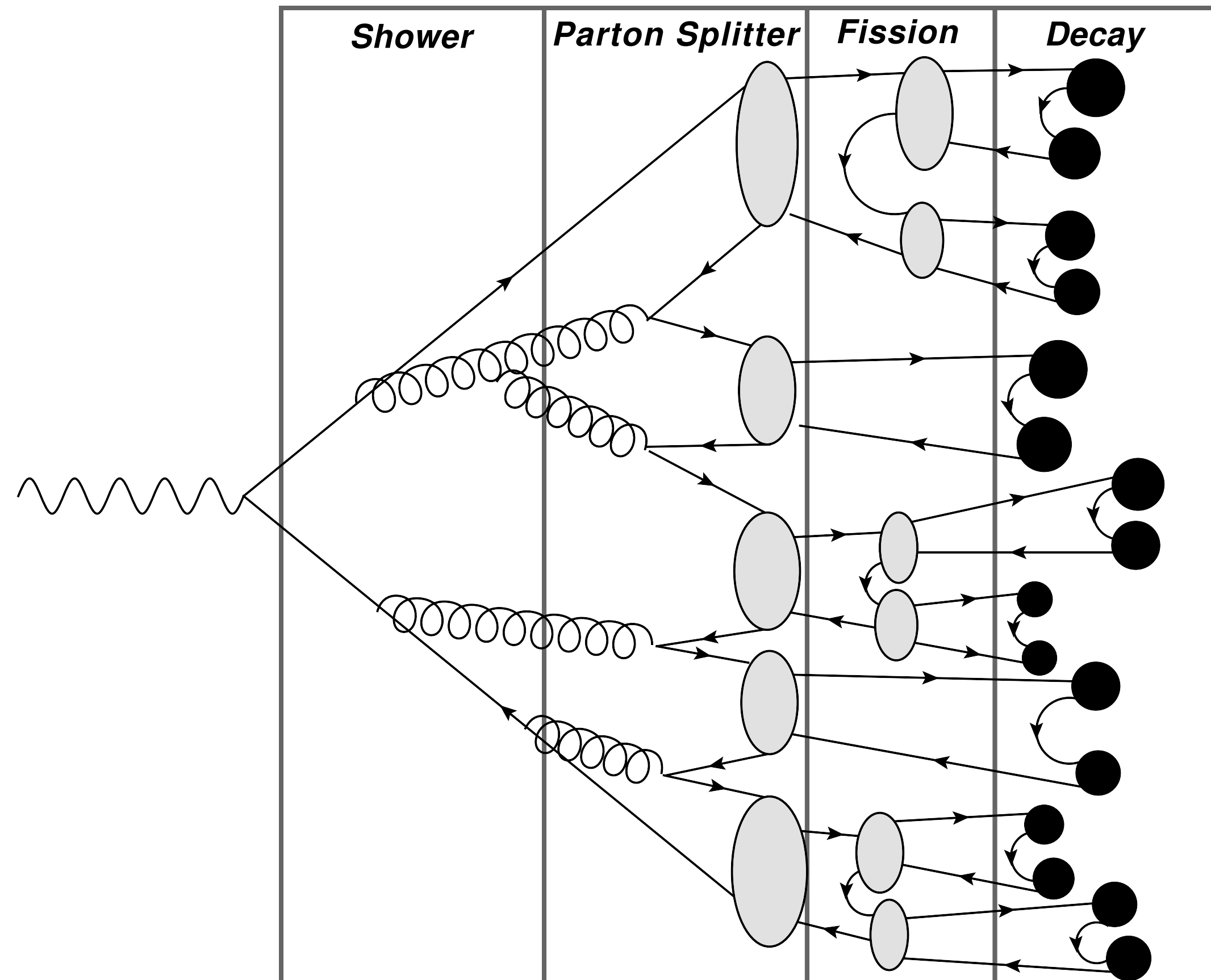
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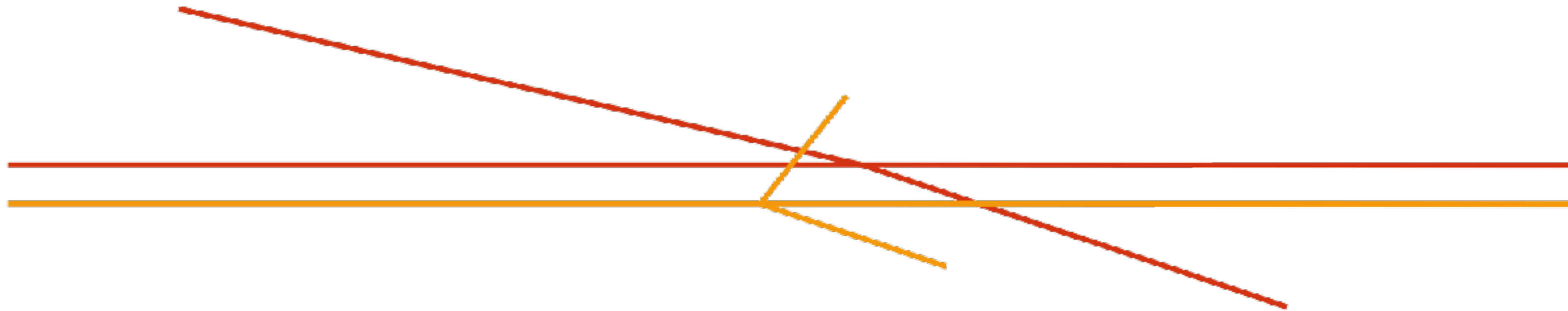
dipoles
order in $\sim p_T$



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

Universal spectrum of cluster masses:
highly excited hadronic states which
undergo decays to observed hadrons.

Multi-Parton Interactions

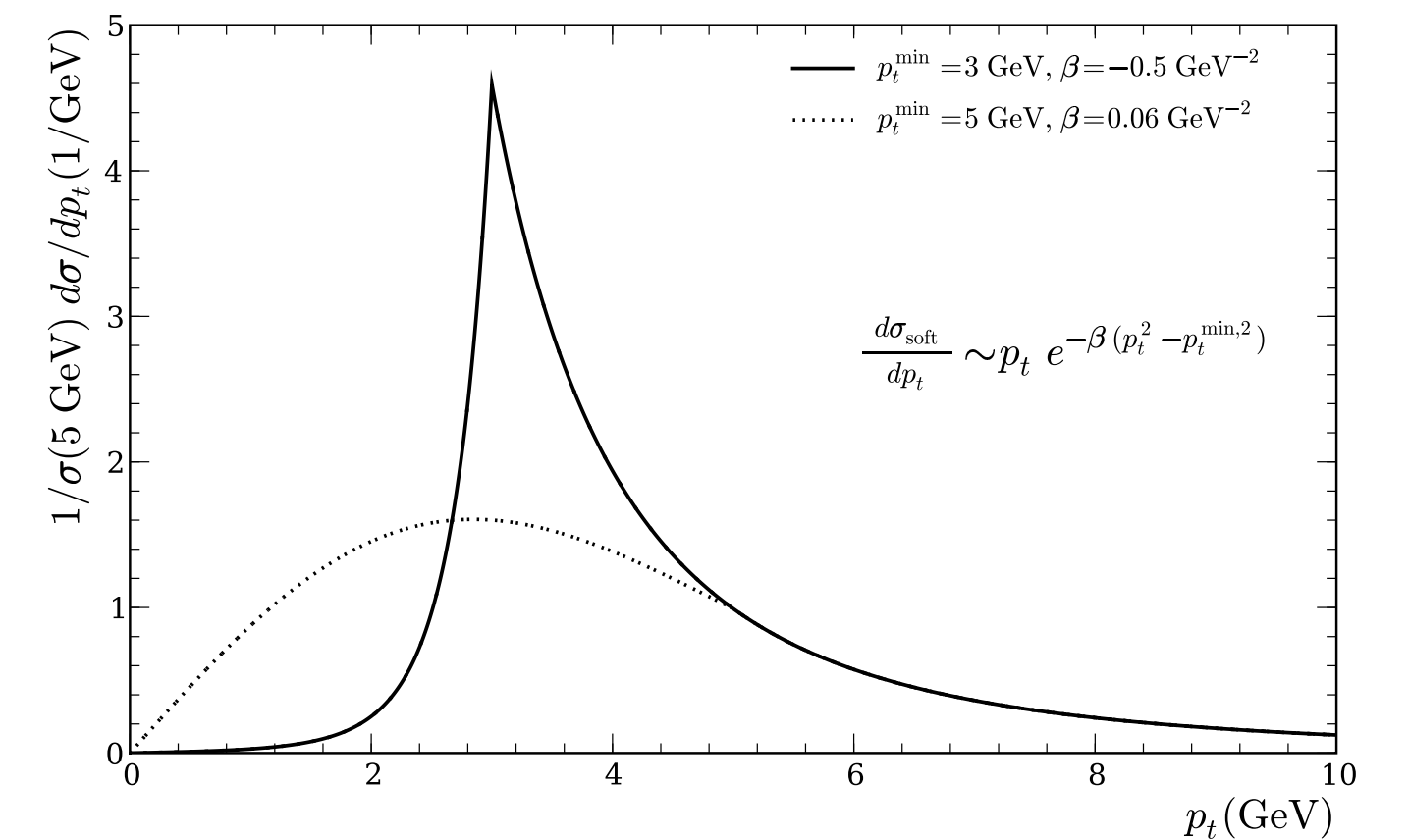
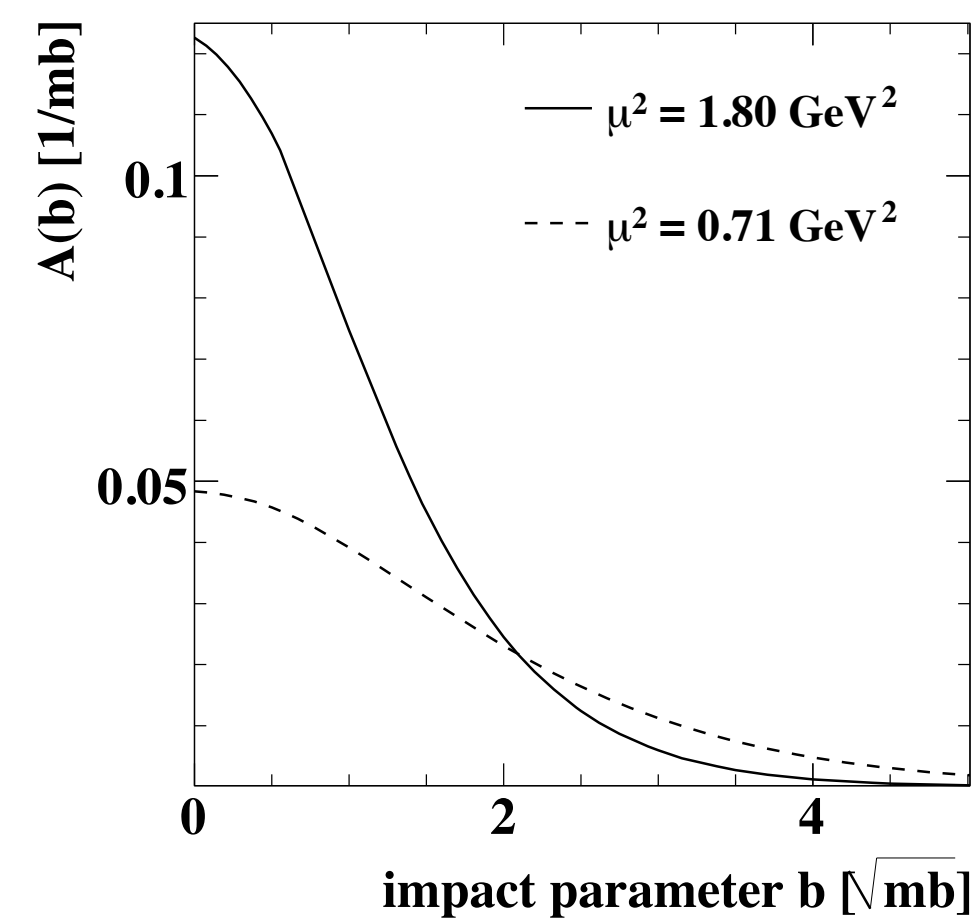


Matter distribution
in the proton.

Recent work in Herwig:

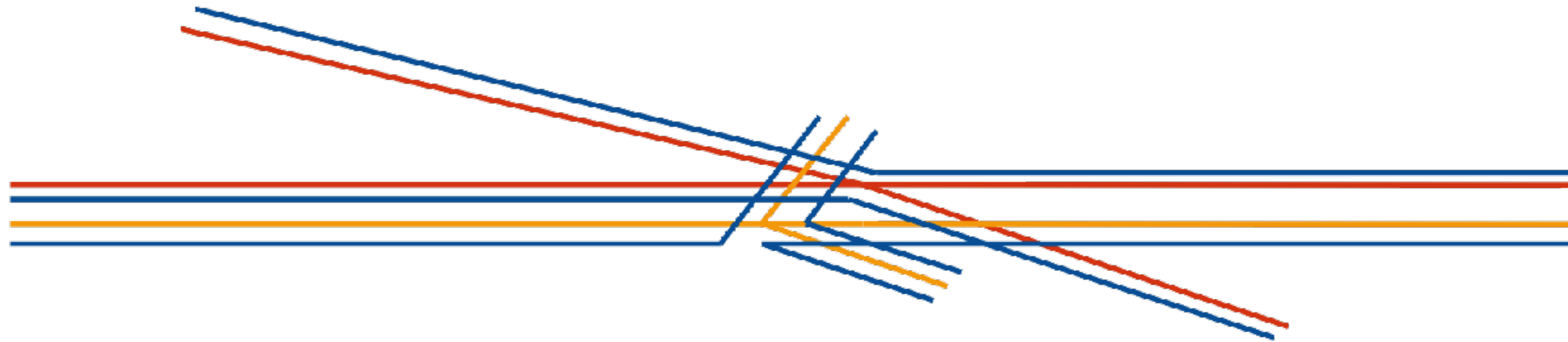
[Gieseke, Loshaj, Kirchgaesser — EPJ C77 (2017) 156]

[Bellm, Gieseke, Kirchgaesser — arXiv:1911.13149]



2 to 2 cross section.

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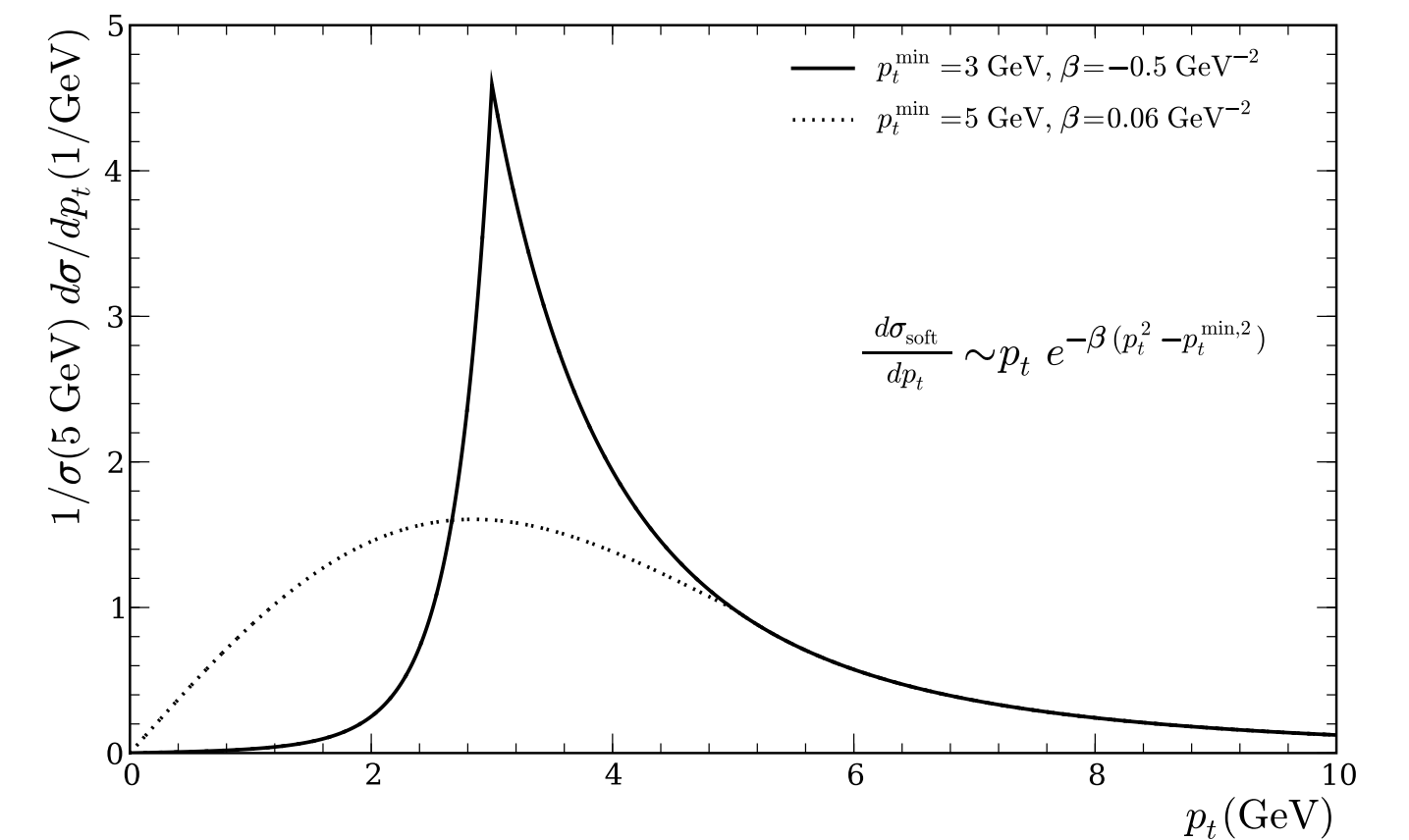
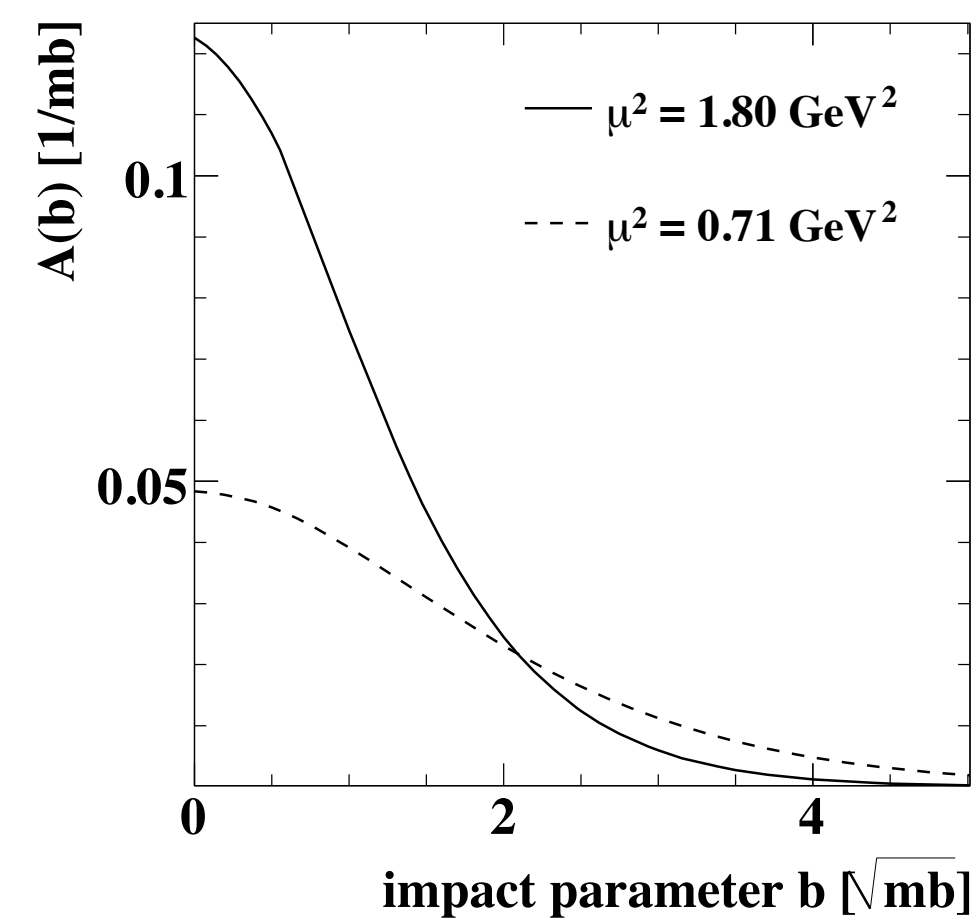


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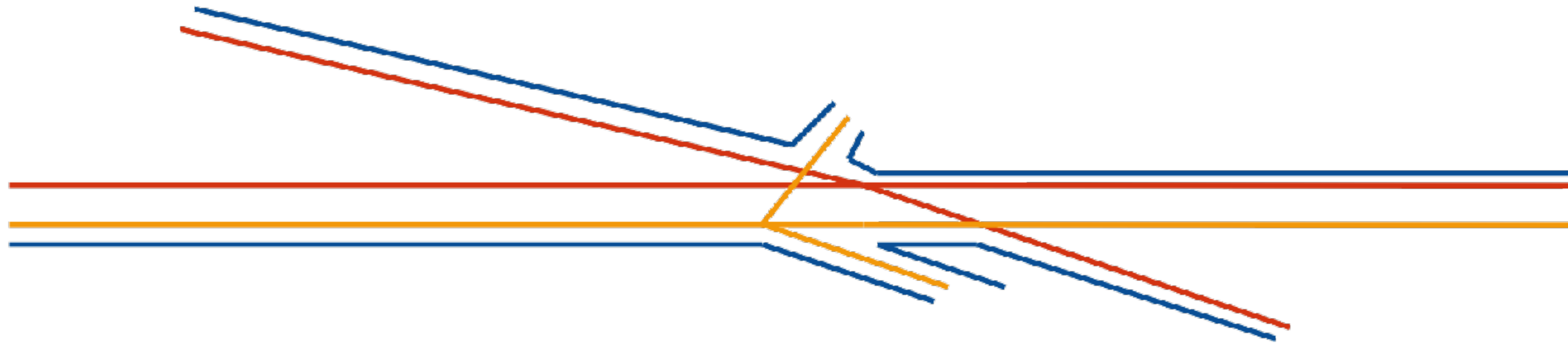
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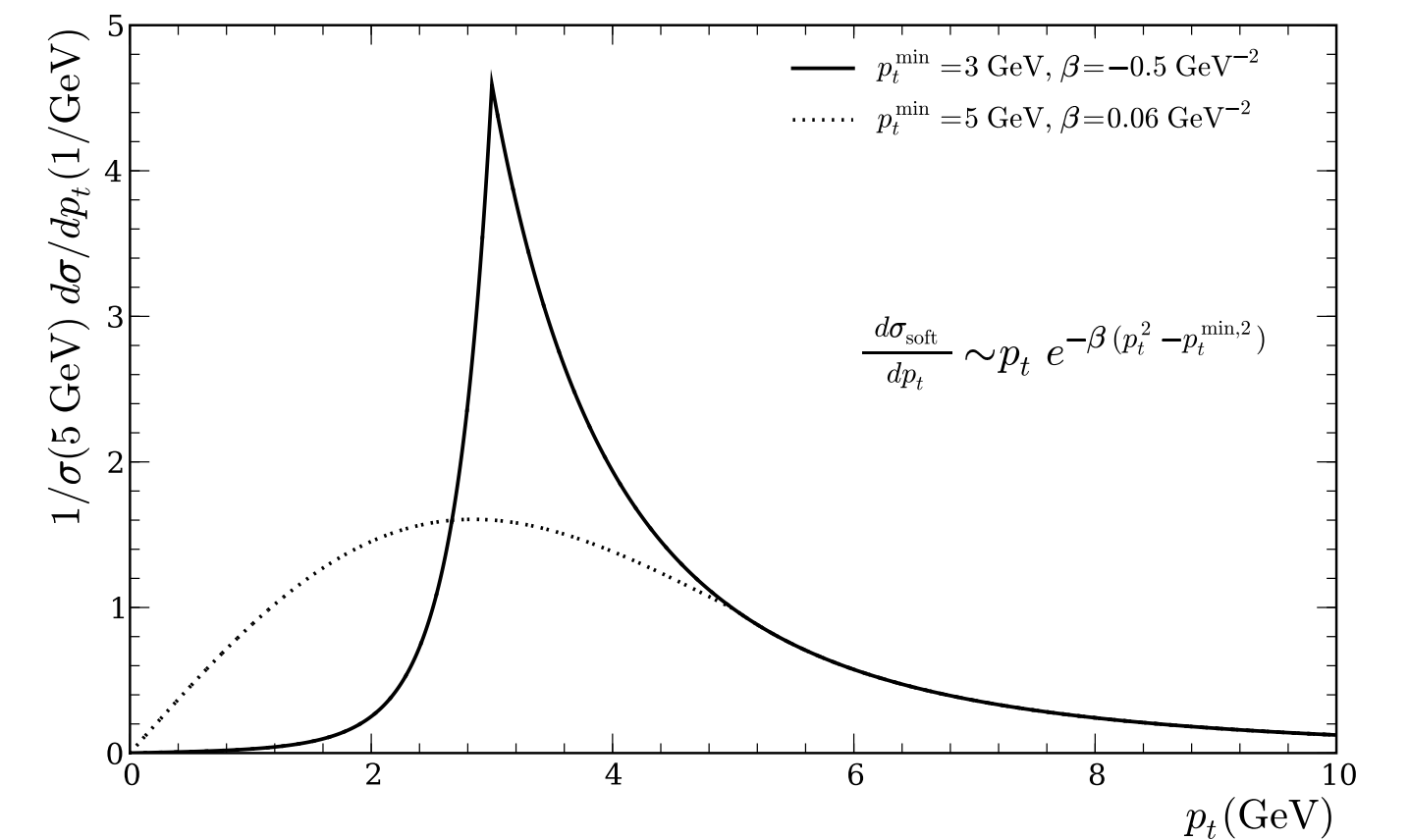
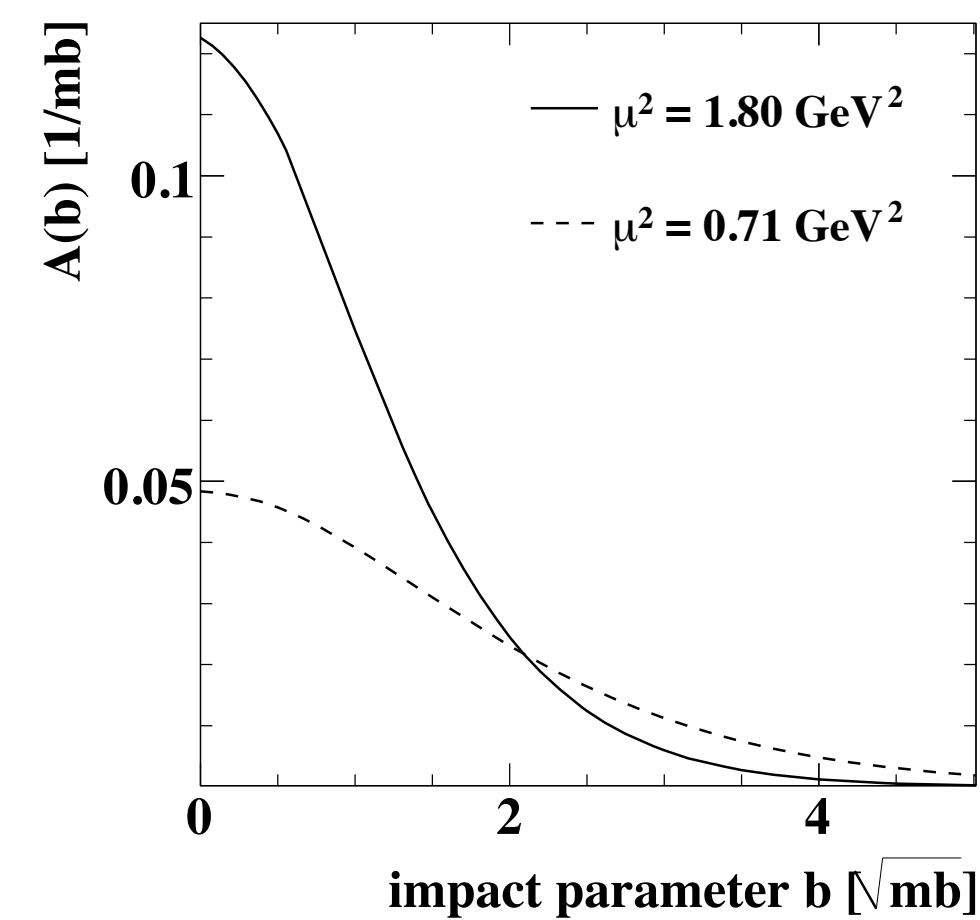


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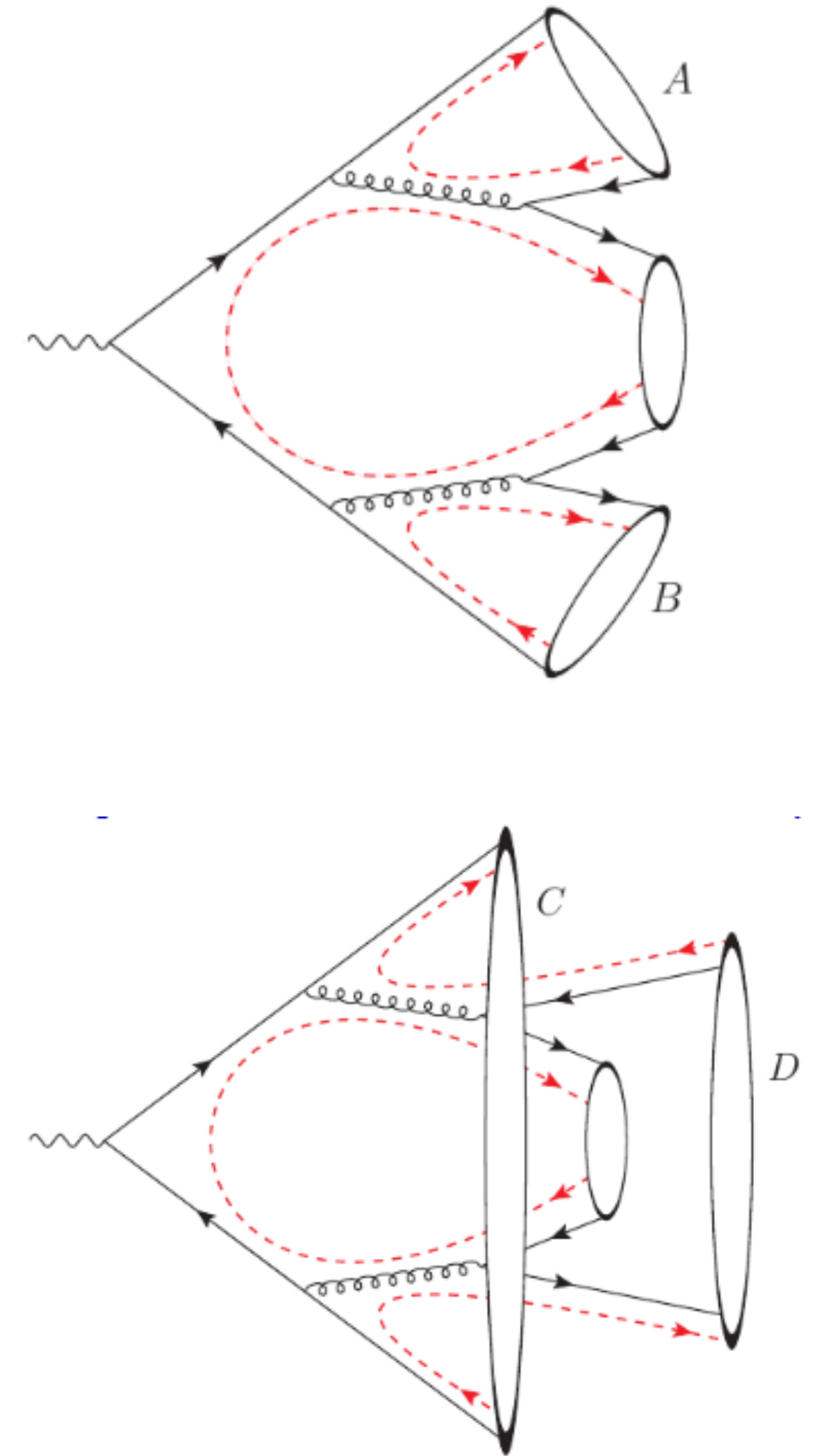
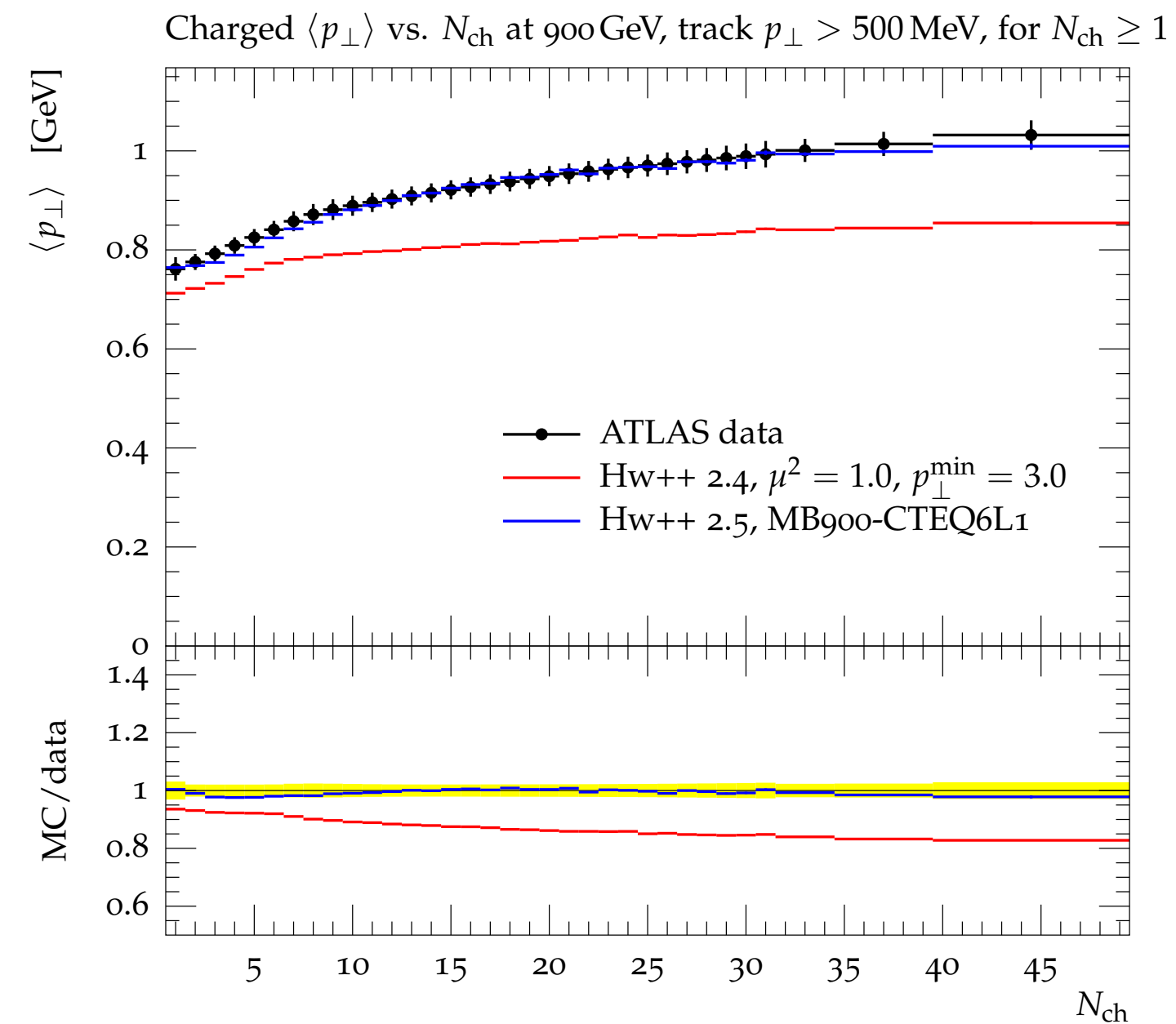
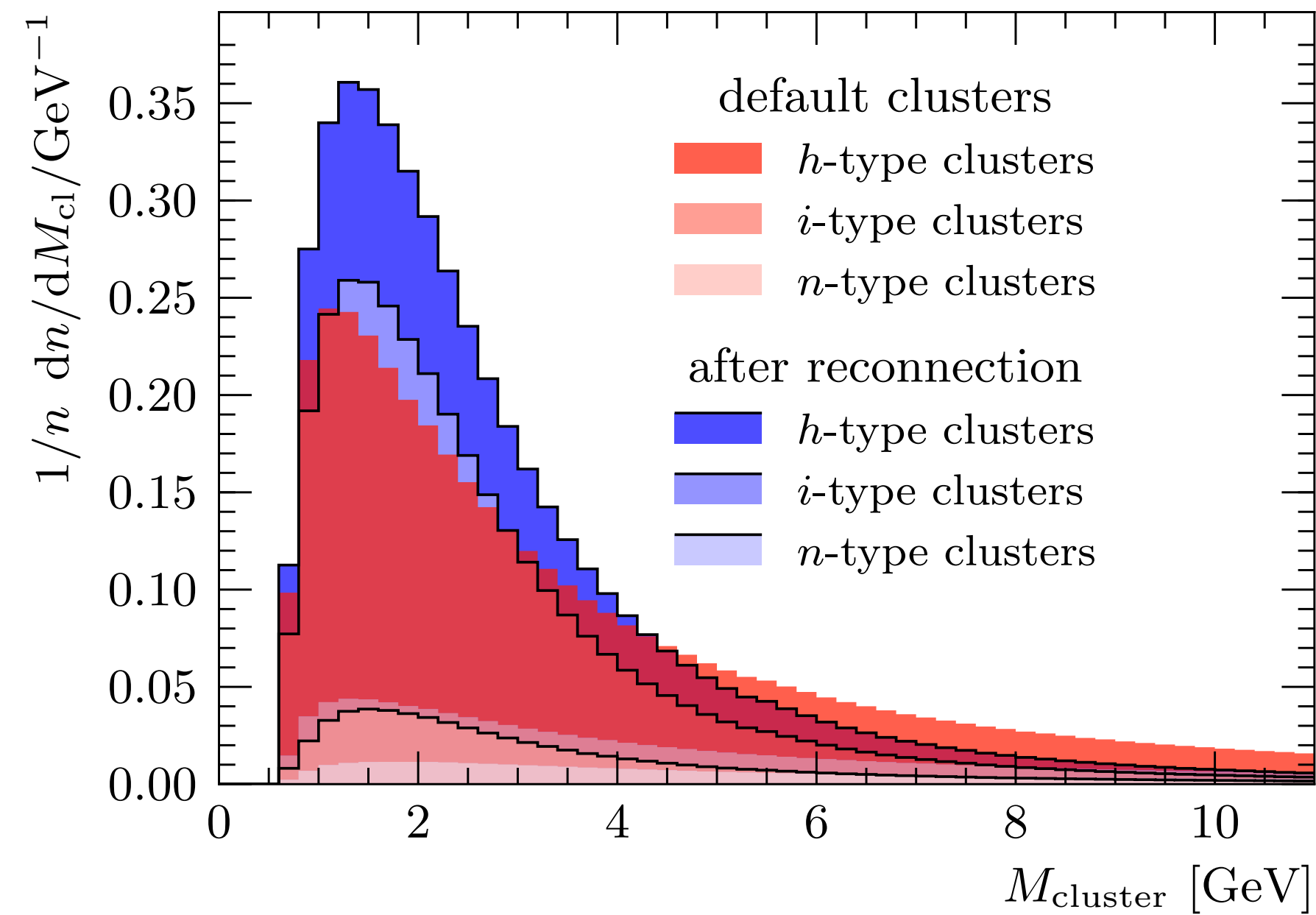
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[Gieseke, Röhr, Siodmok — EPJ C72 (2012) 2225]

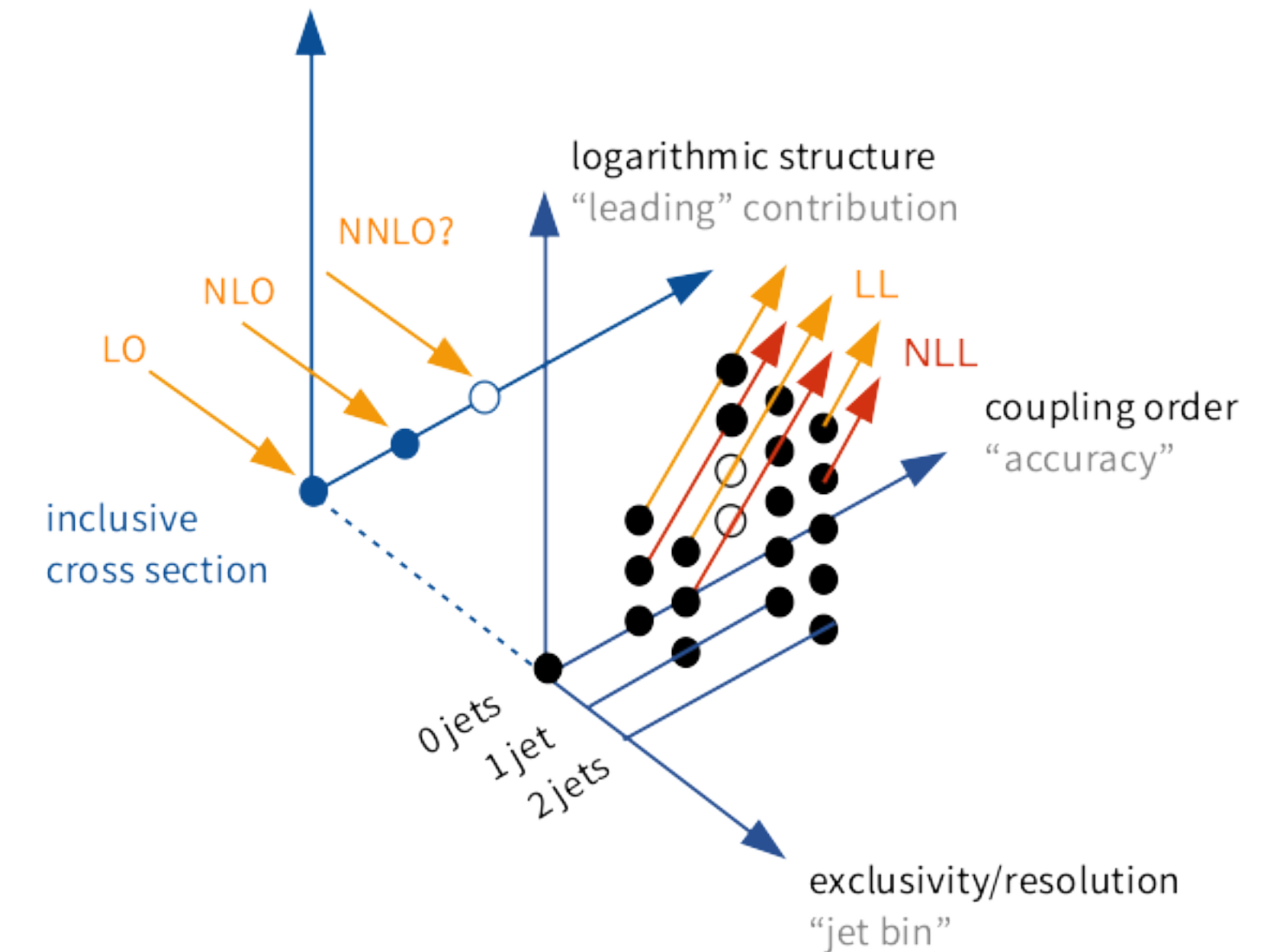
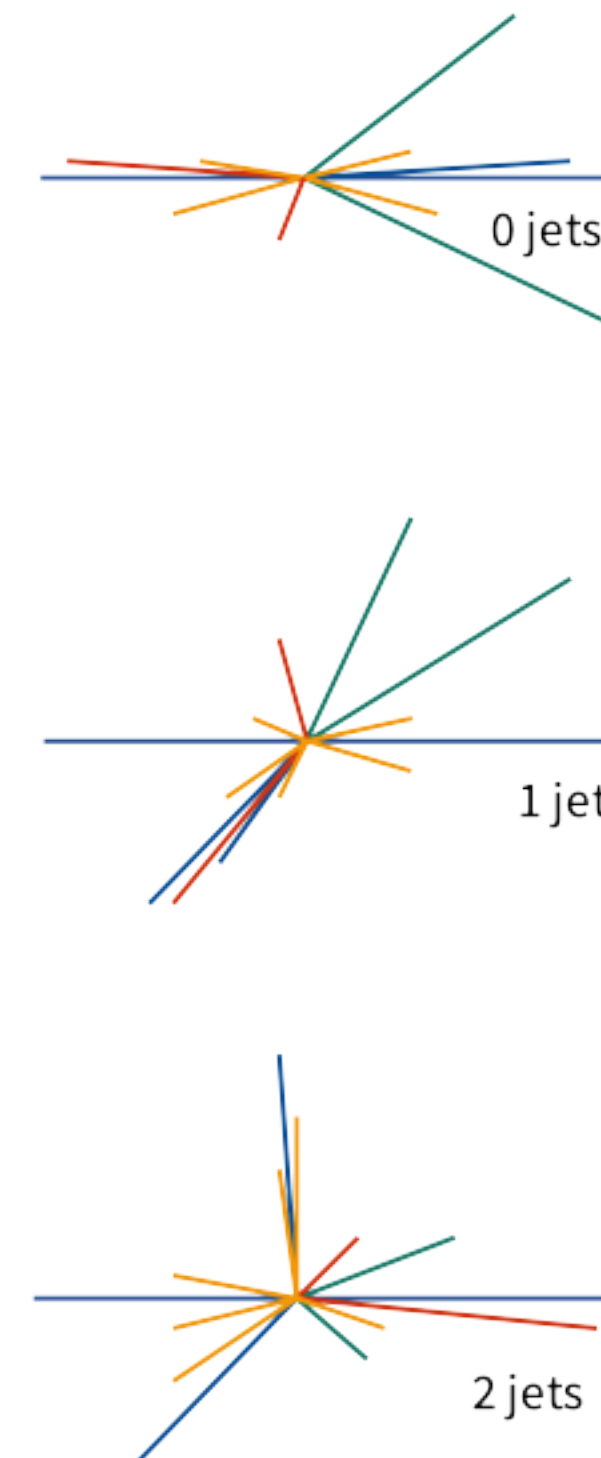
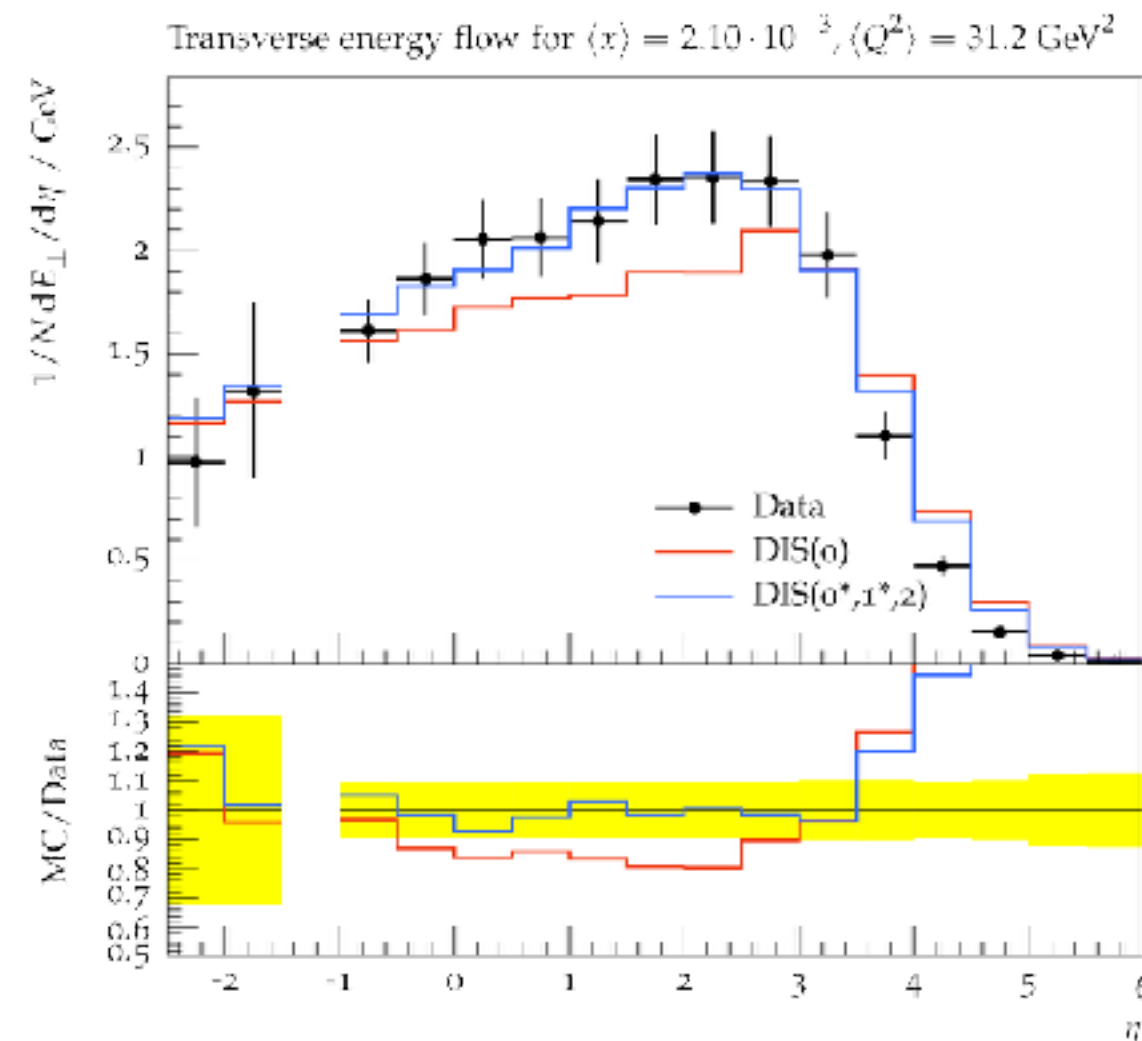
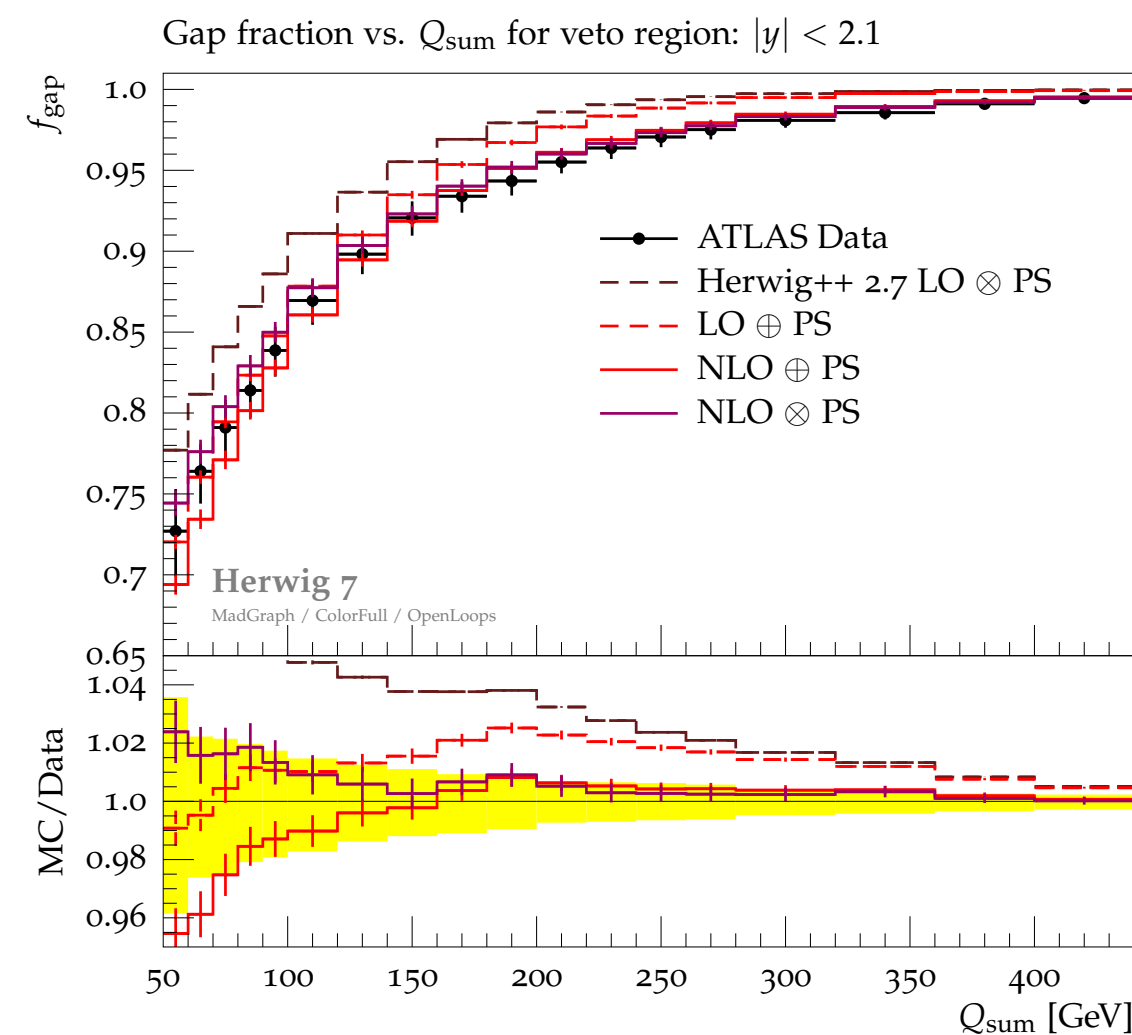
[Gieseke, Kirchgaesser, Plätzer – EPJ C 78 (2018) 99]

Hard QCD Backgrounds: NLO matching & merging

Matching:
Enforce NLO QCD accuracy at fixed order.

Merging:
Combine jet multiplicities, possibly at NLO.

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



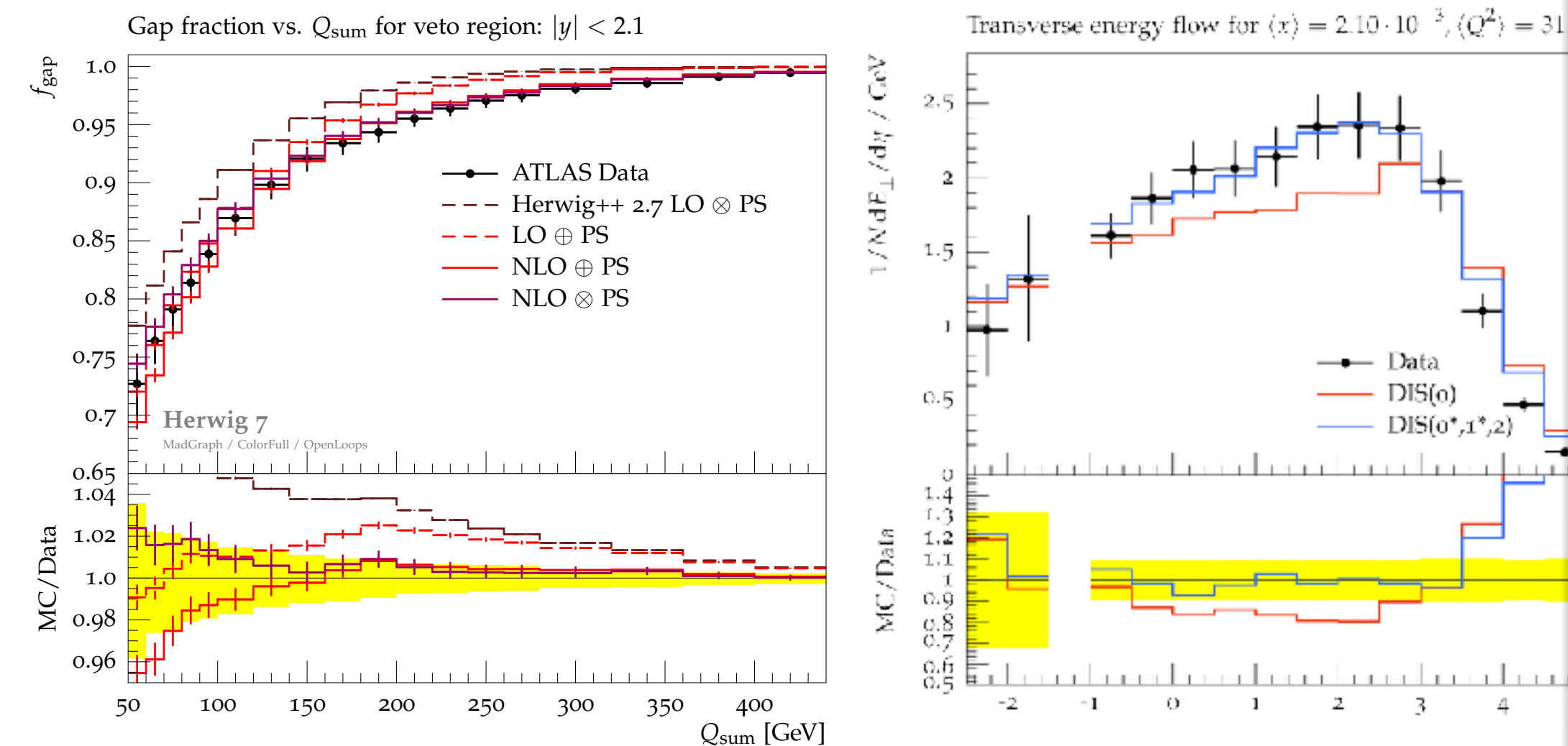
Matching and merging in Herwig:
[Plätzer, Gieseke – EPJ C72 (2012) 2187]
[Bellm, Gieseke, Plätzer — EPJ C78 (2018) 244]

Unitarized merging schemes:
[Plätzer — JHEP 1308 (2013) 114]
[Prestel, Lönnblad — JHEP 03 (2013) 166]

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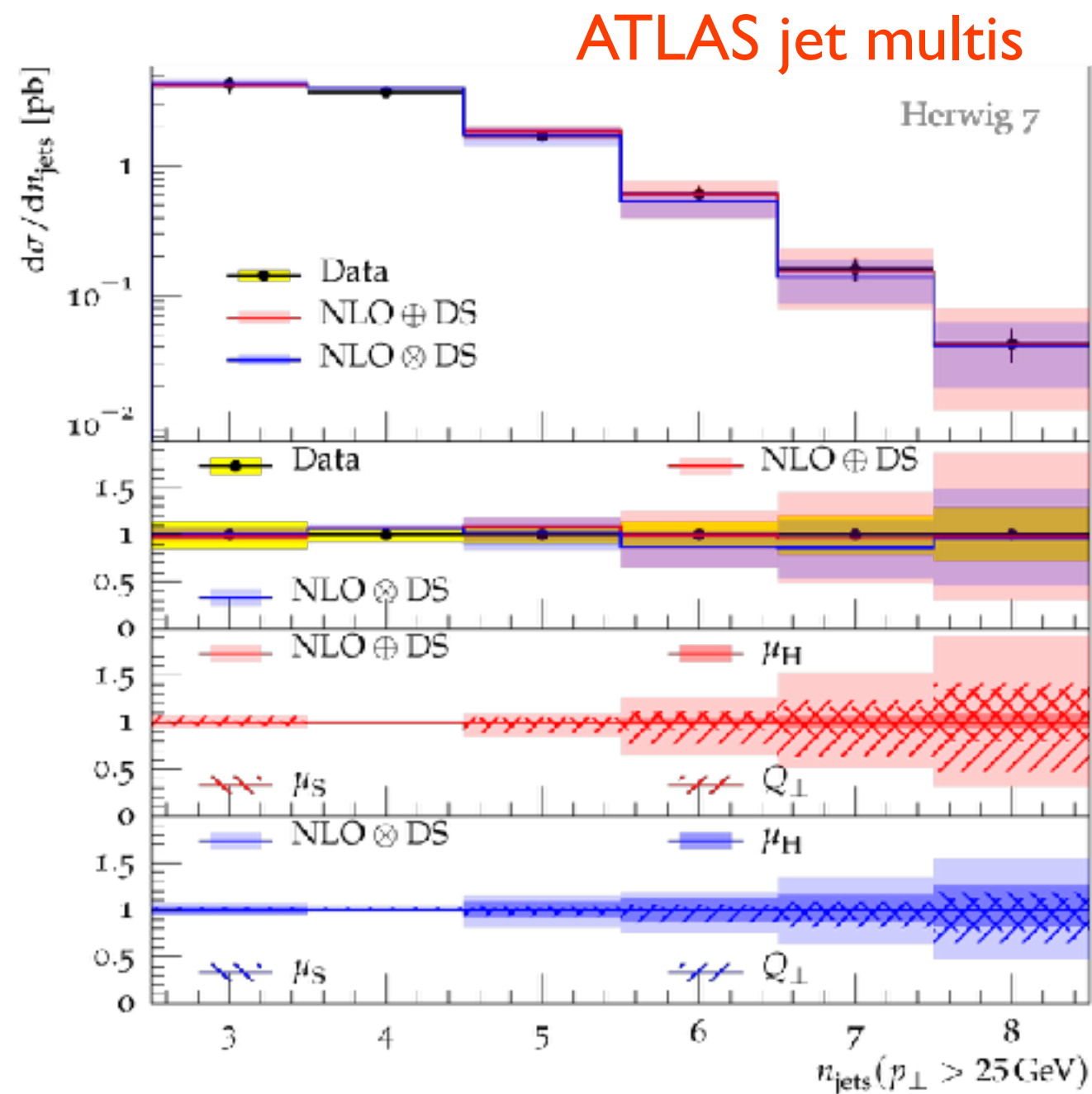


Matching and merging in Herwig:
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Perturbative aspects well under control.

Similar facilities
in Herwig, Pythia
& Sherpa.

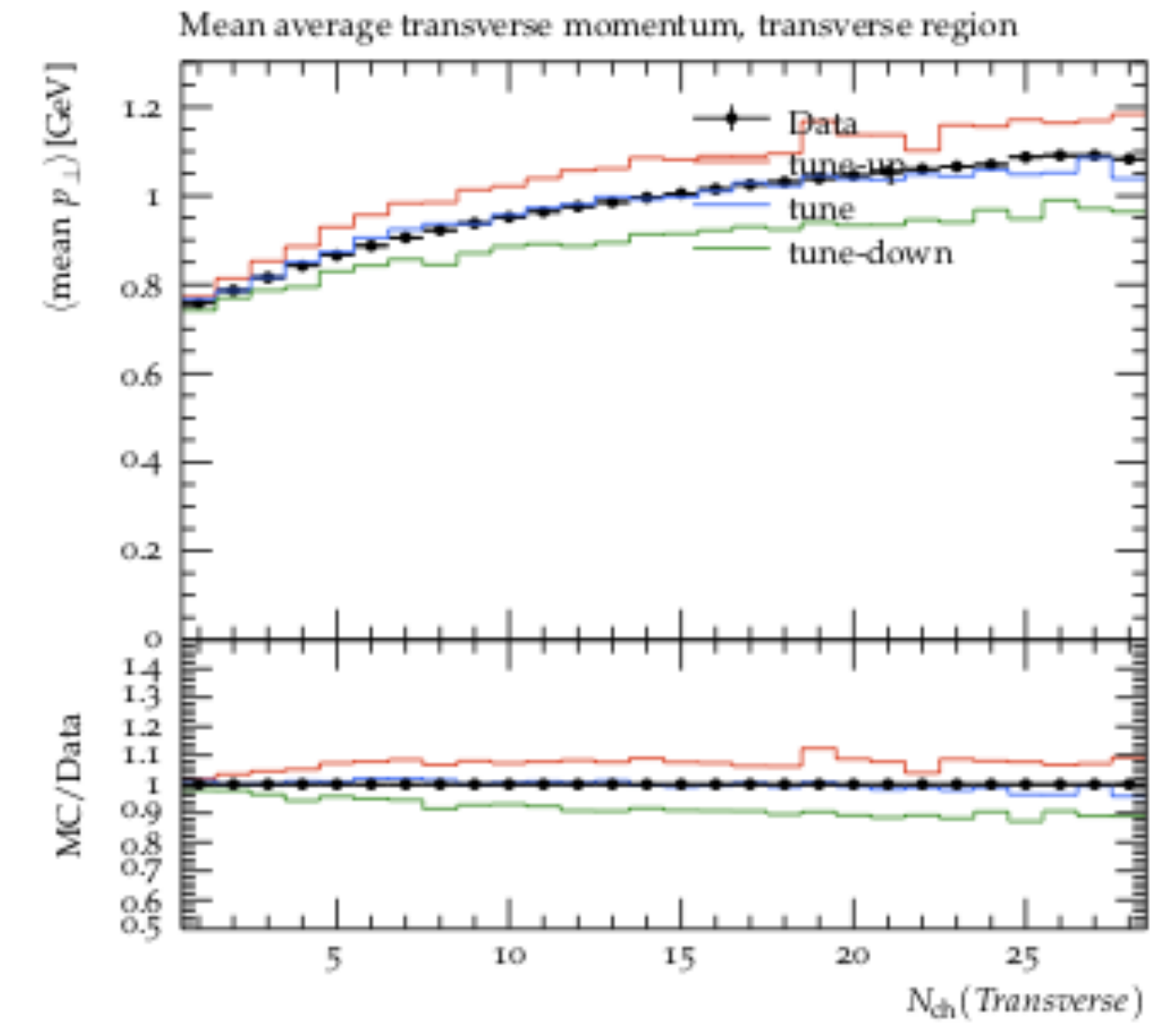
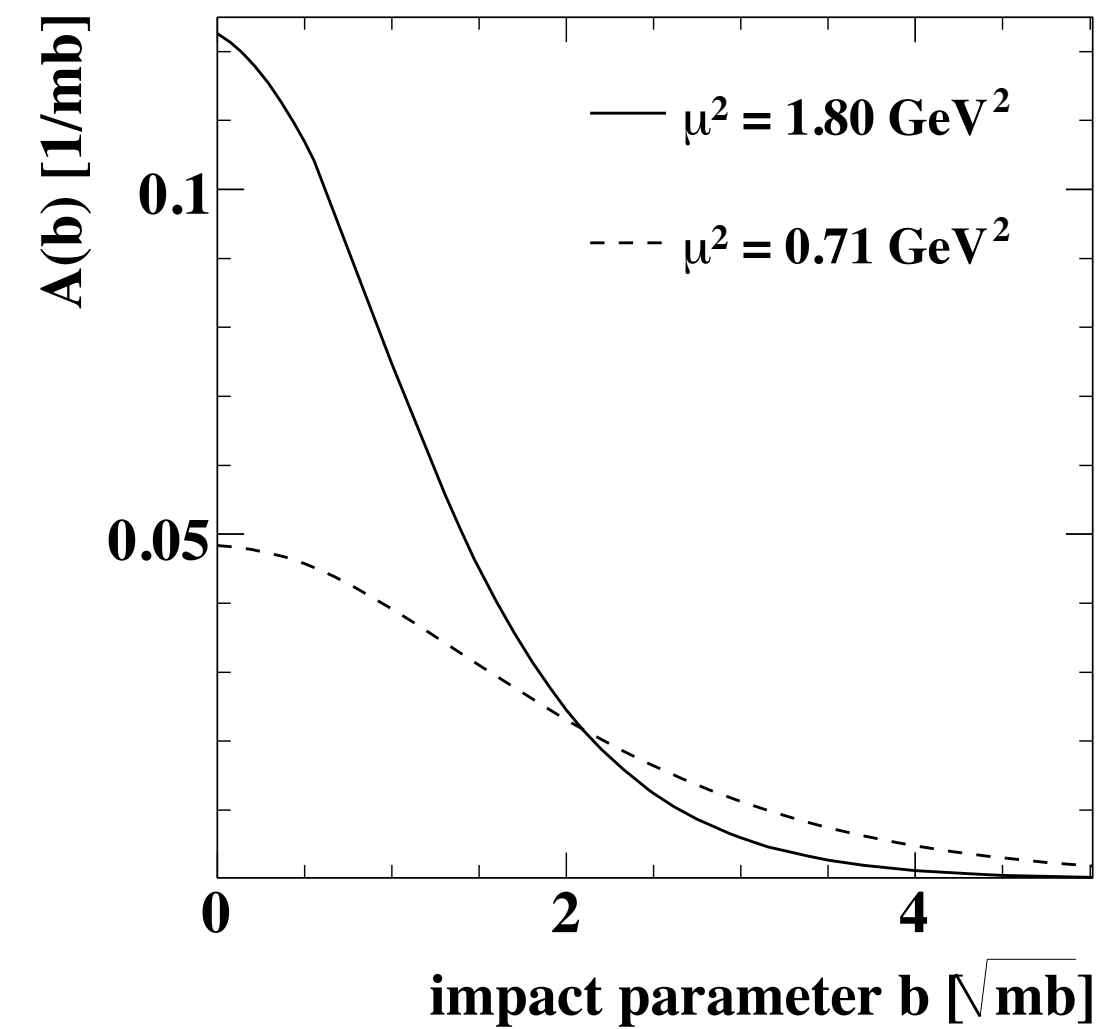
[Bellm, Nail, Plätzer, Schichtel, Siodmok – EPJ C76 (2016) 665]
[Cormier, Plätzer, Reuschle, Richardson, Webster — EPJ C79 (2019) 915]
[Prestel, Lönnblad — JHEP 03 (2013) 166]



Uncertainties in Tuning & Models

Precise data and accurate description of soft-QCD data after tuning does not imply anything about the models reliability/precision.

["Eigentunes" are only a measure of goodness-of-fit.]



Uncertainties in Tuning & Models

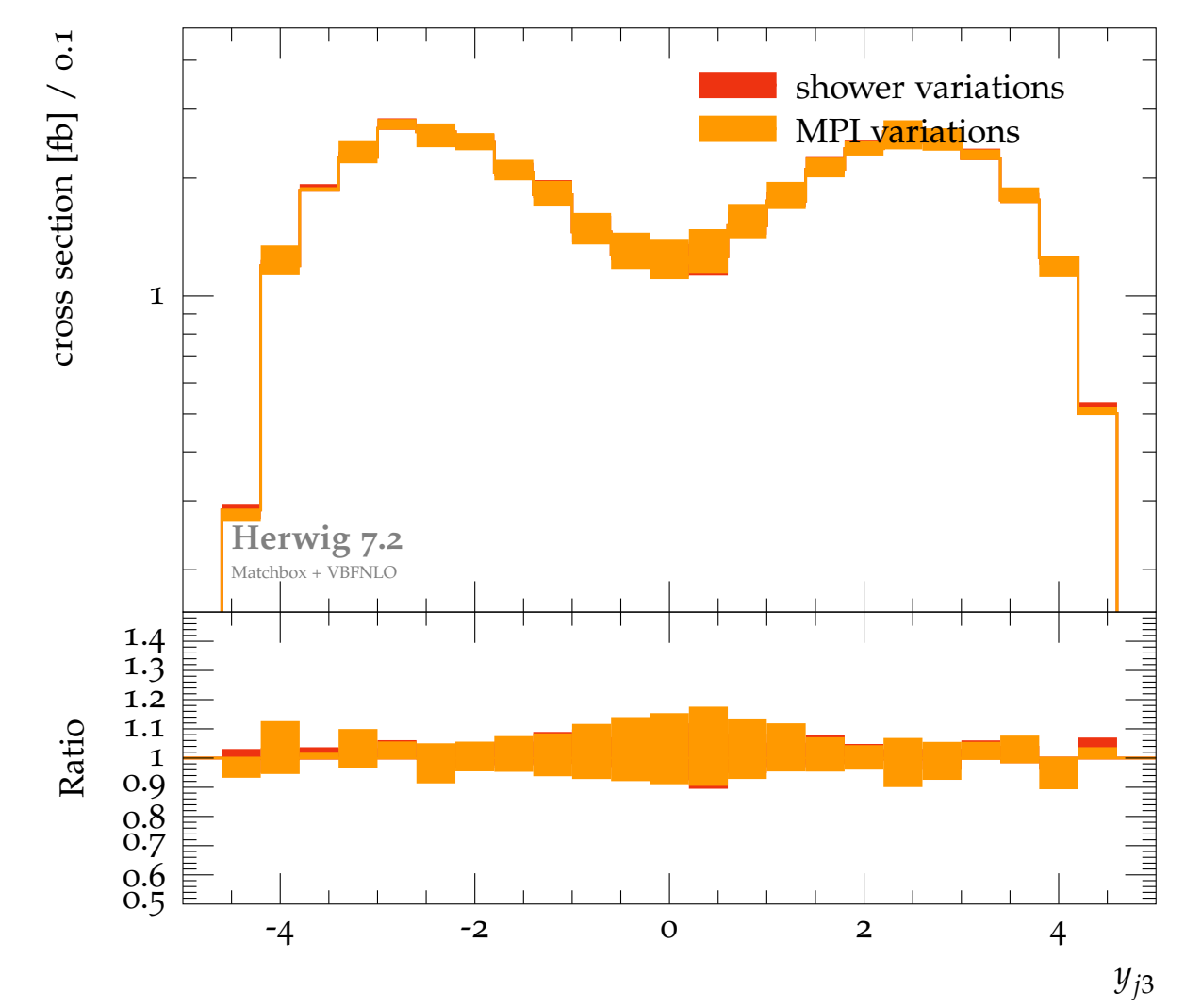
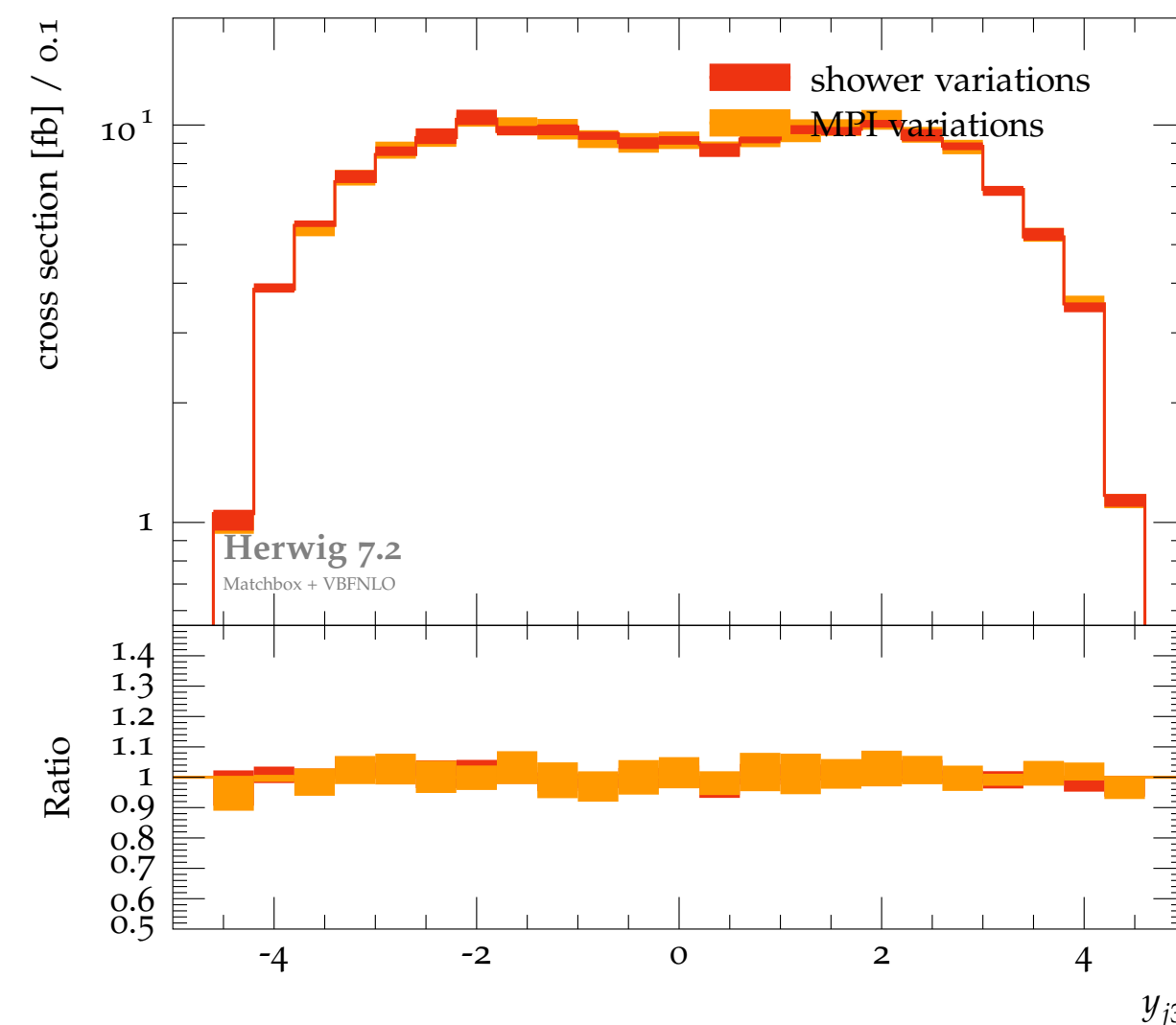
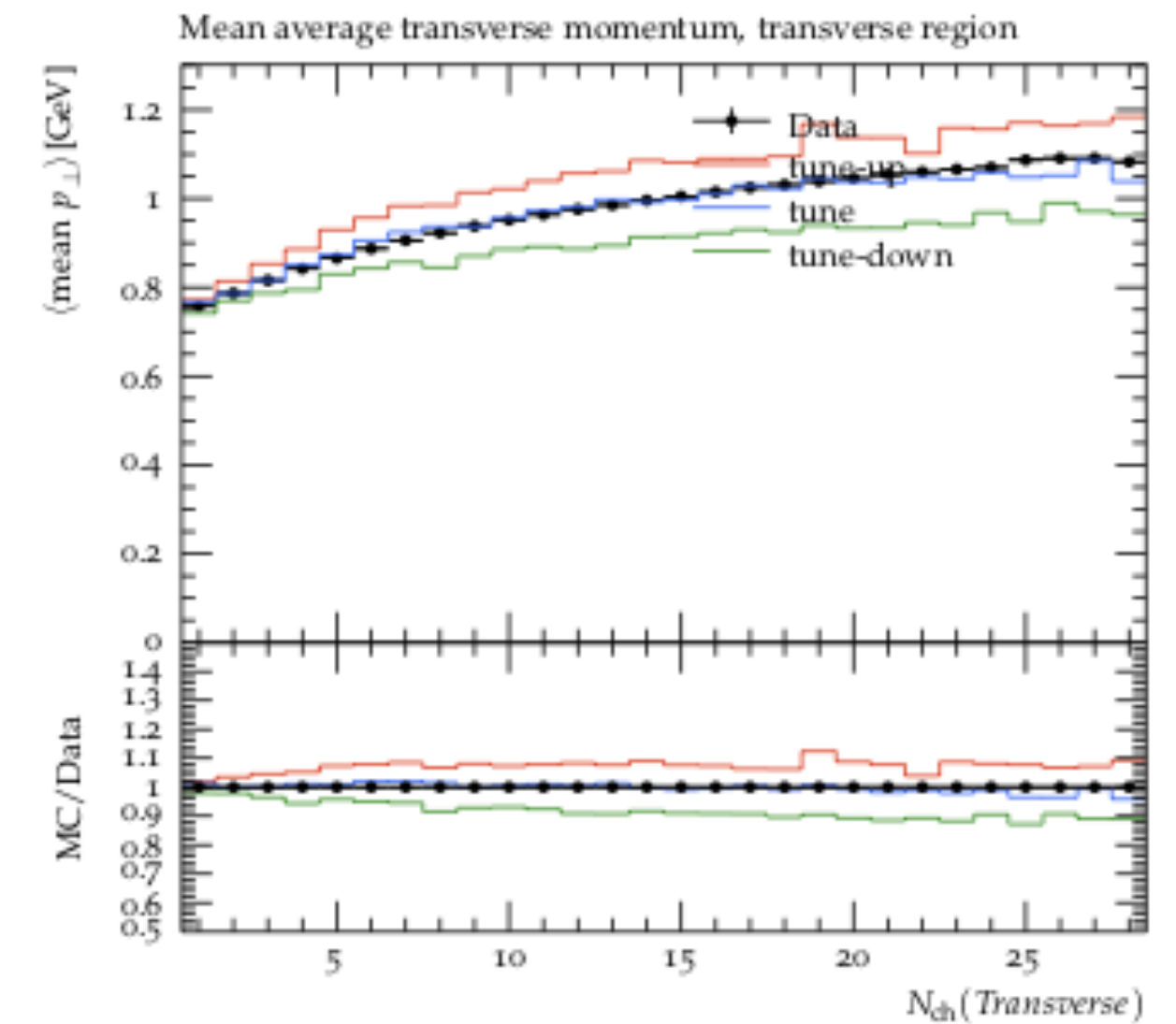
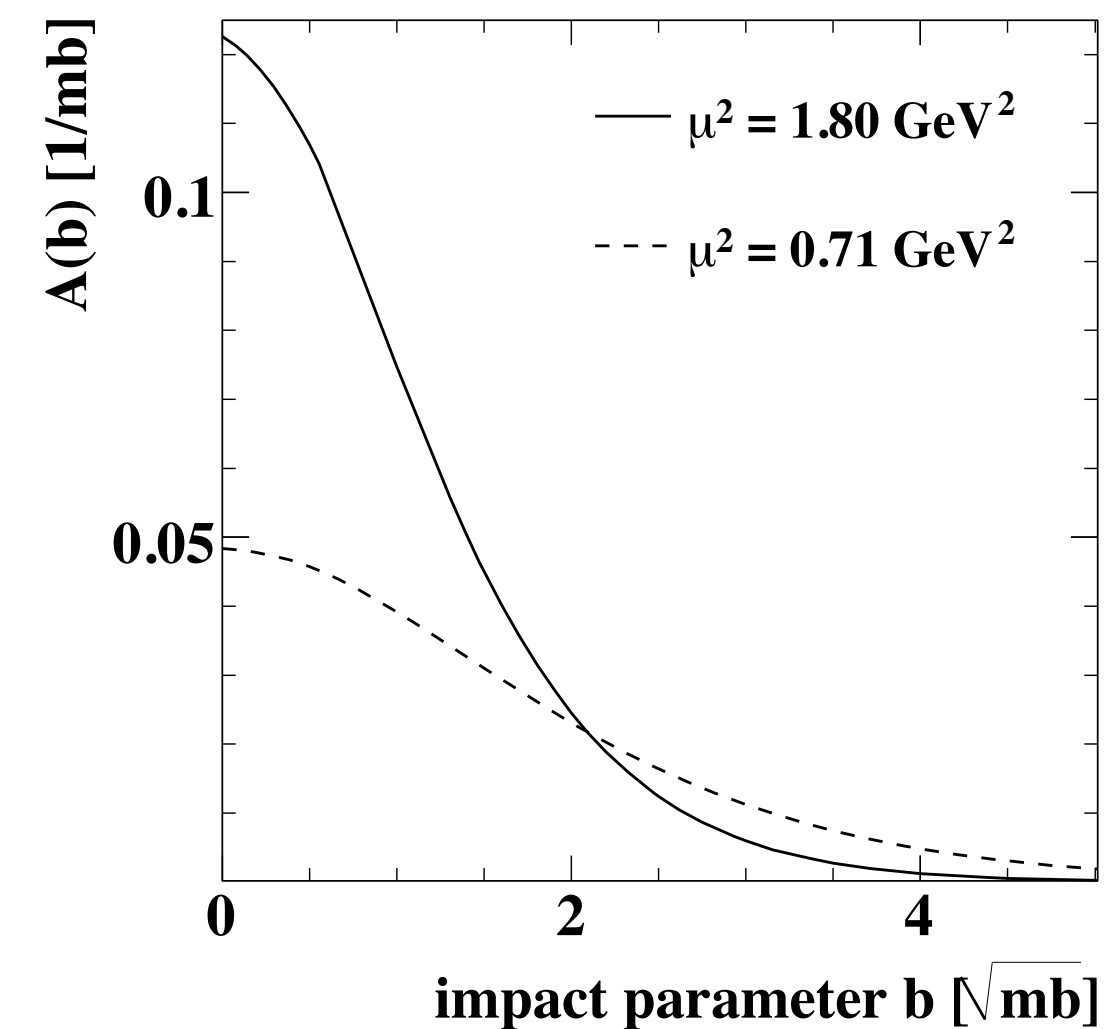
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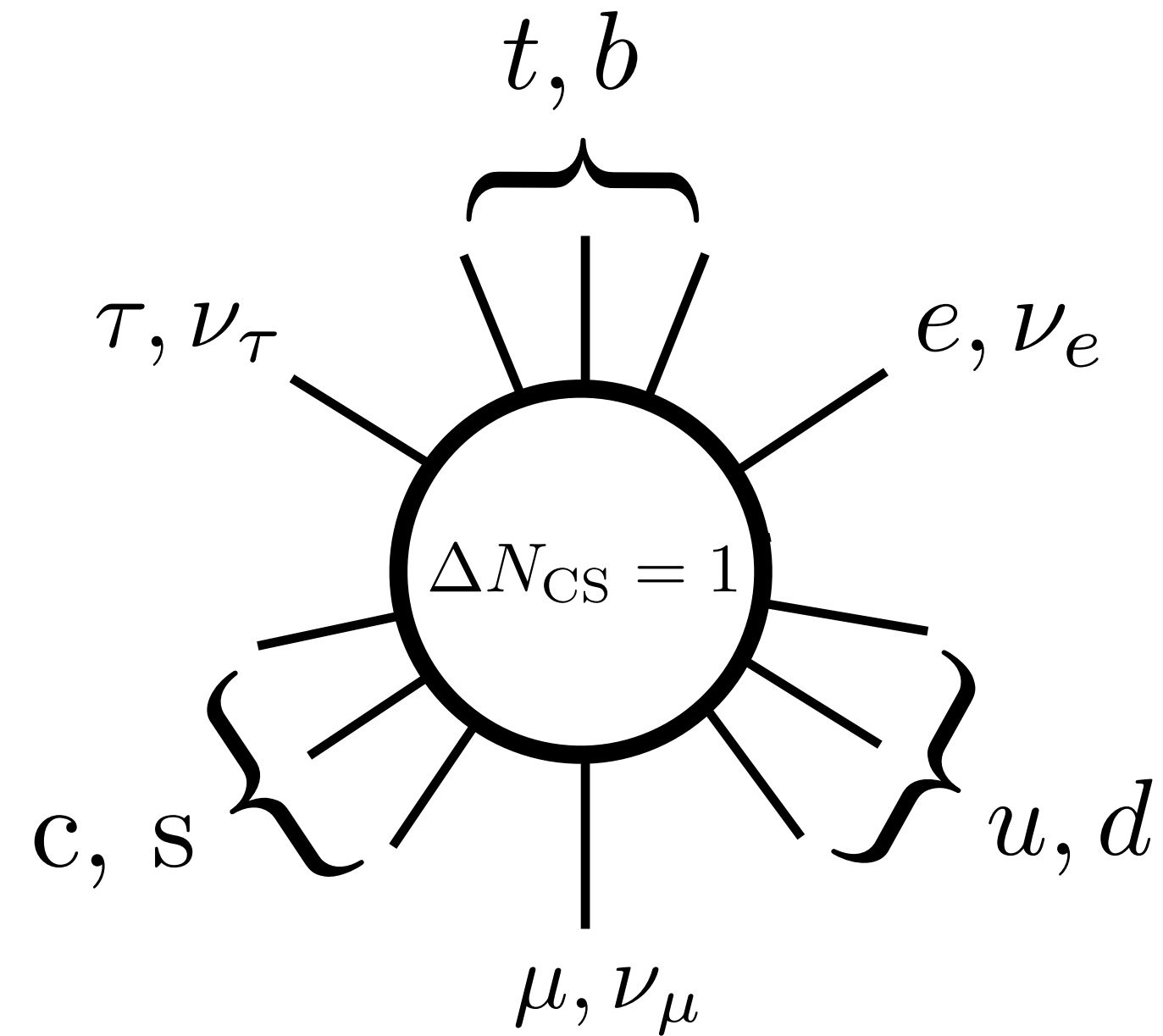
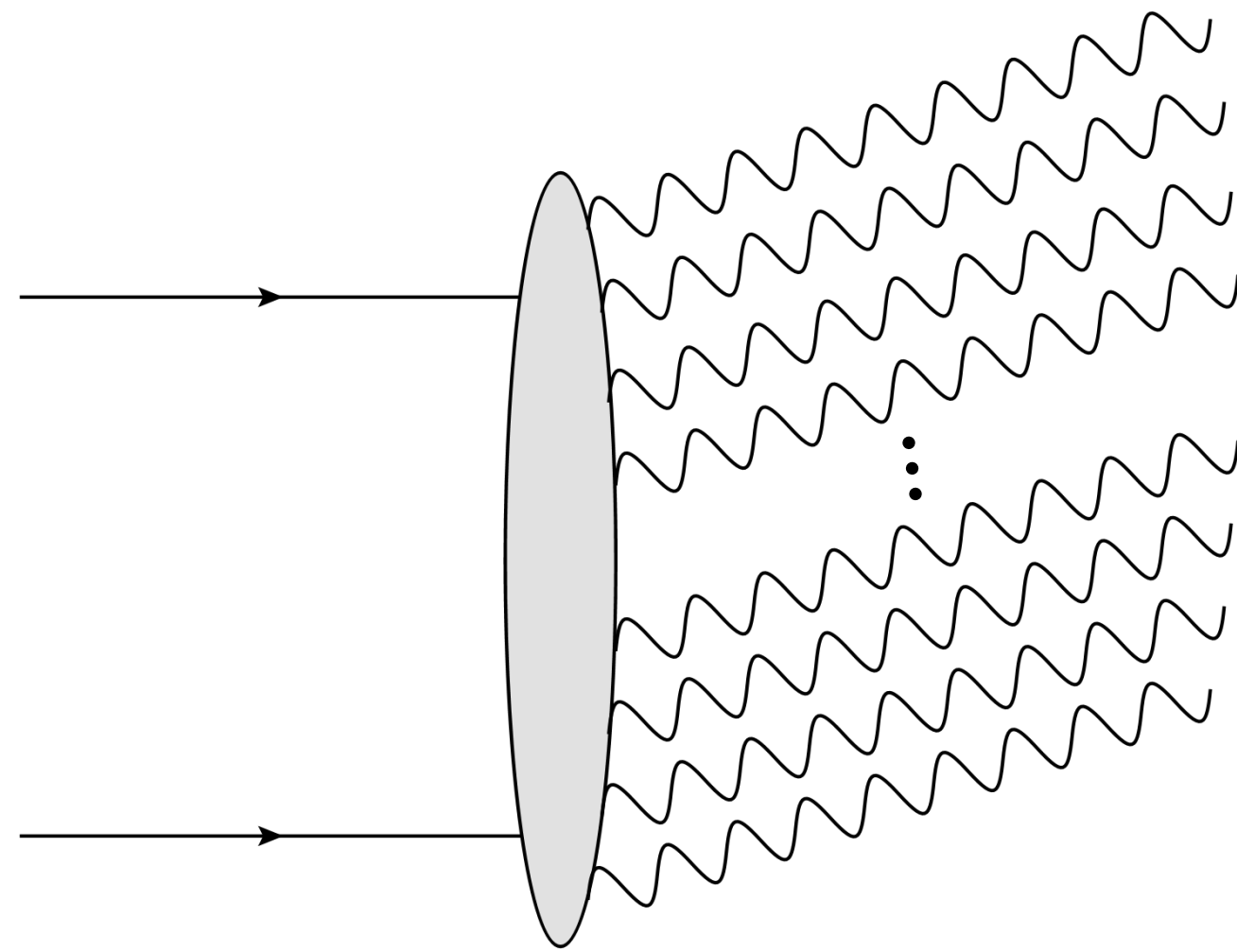
[“Eigentunes” are only a measure of goodness-of-fit.]

Surprises hide in MPI variations, e.g. for VBF/VBS processes.

Impact on instanton-induced signatures?

[Kirchgaesser, Papaefstathiou, Plätzer – in progress]





Challenges in integration in existing (NLO/multijet driven) structures:
Varying multiplicity, phase space coverage, colour, ...

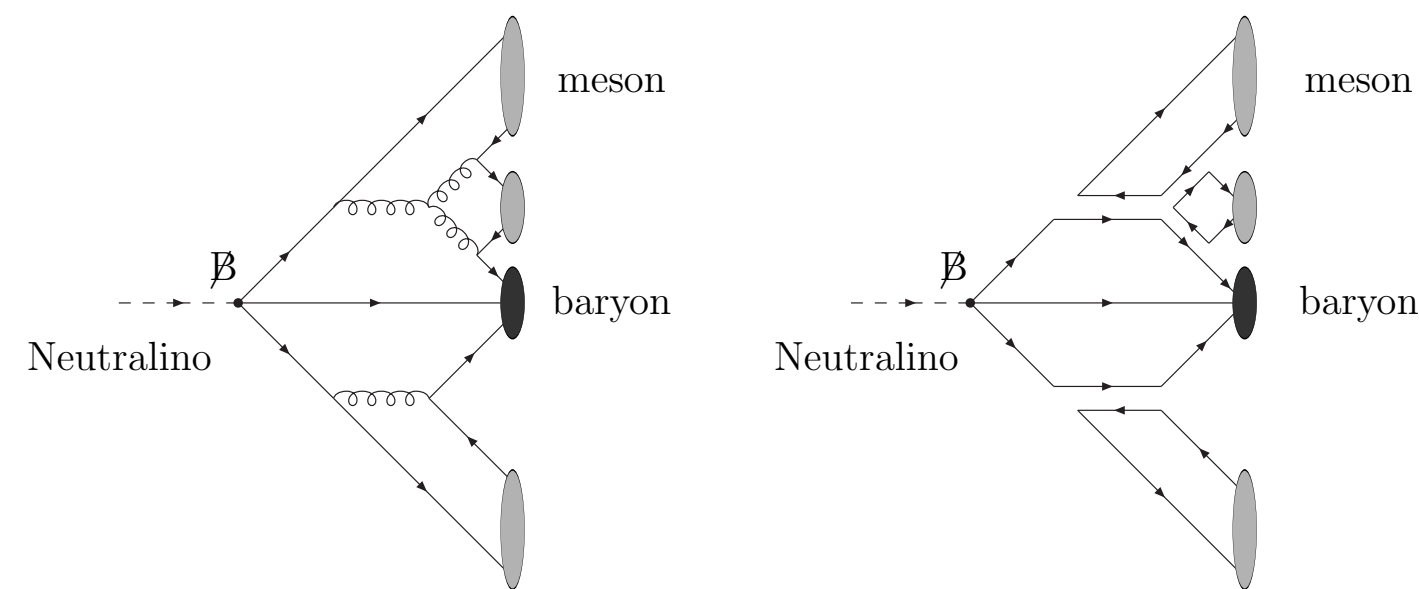
Flexible infrastructure in Herwig 7.

Sphalerons — [Papaefstathiou, Plätzer, Sakurai — JHEP 1912 (2019) 017]
Instantons — [Papaefstathiou, Plätzer — in progress]

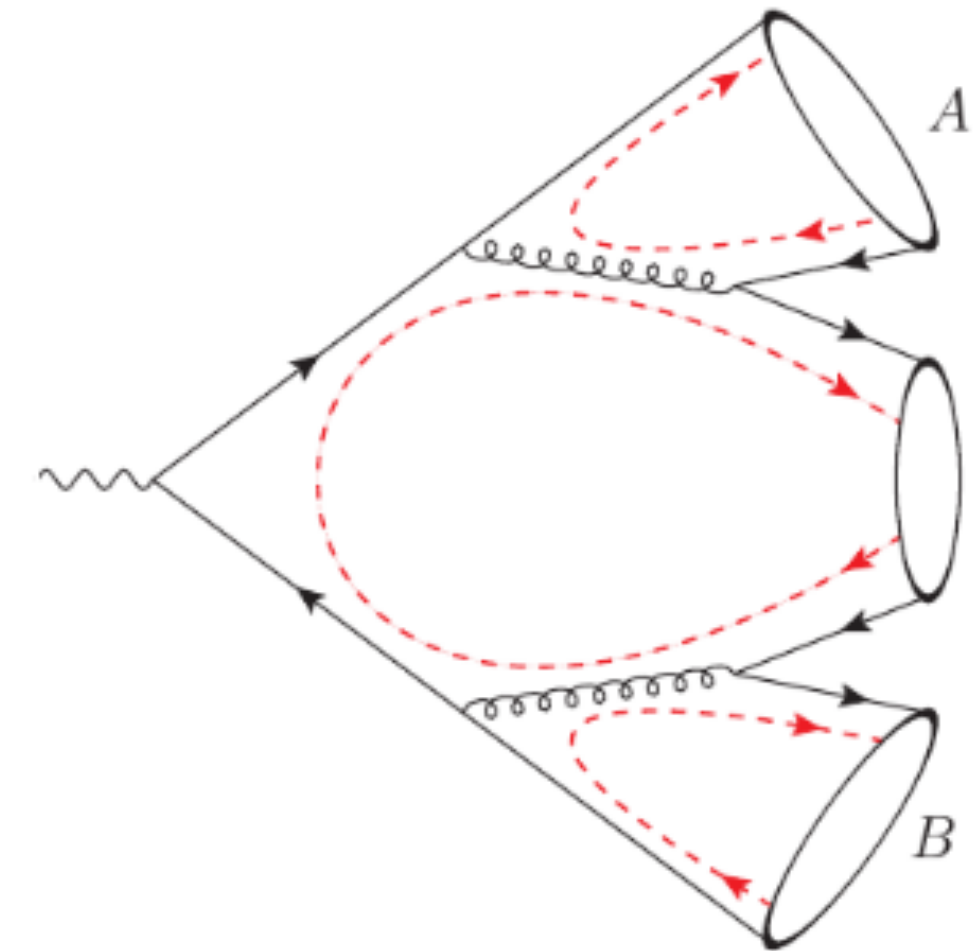
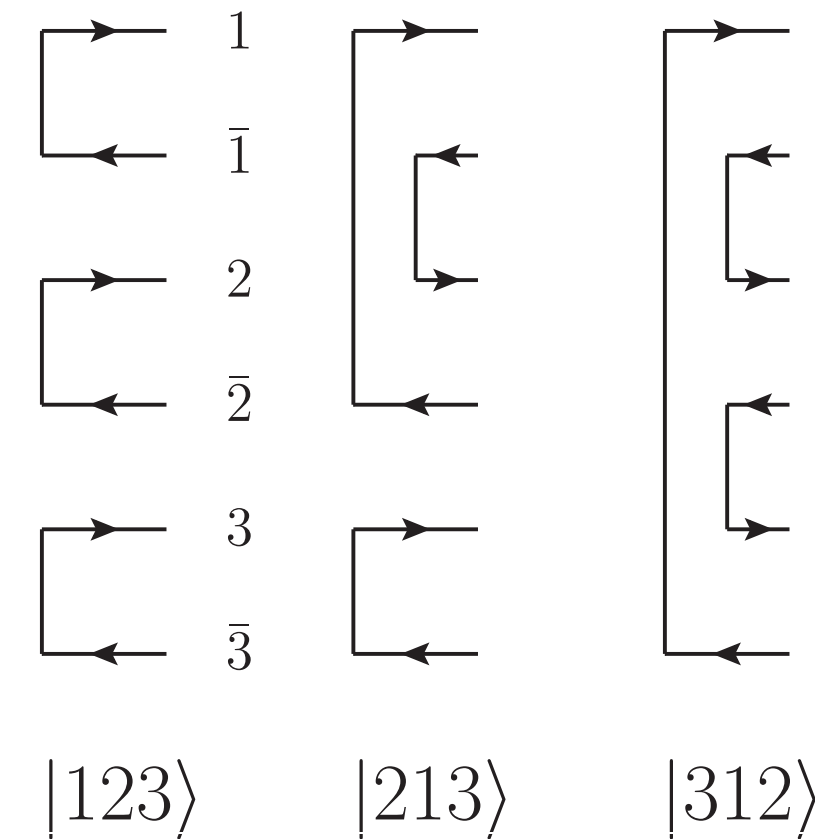
Baryons (and Baryon number violation)

Dipoles/clusters/string pieces:
Mesonic DOF, driven by LEP.
Baryons only from hadronization.

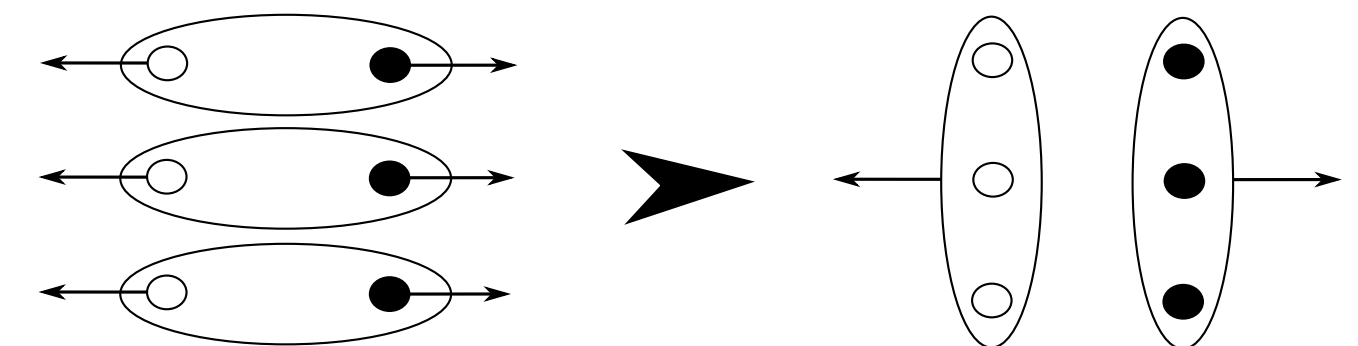
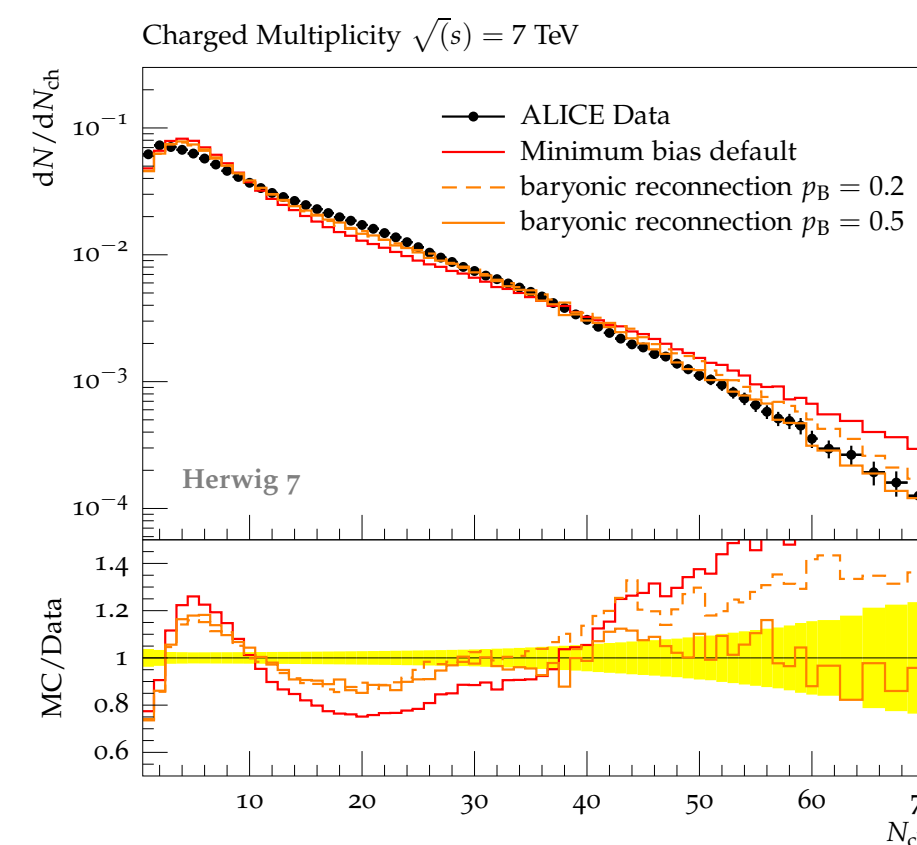
Some aspects of radiation &
hadronization from simulation of
RPV SUSY.



[Dreiner, Richardson, Seymour – JHEP 04 (2000) 008]



Colour reconnection into Baryonic clusters.



$$R_{q,qq} + R_{\bar{q},\bar{q}\bar{q}} < R_{q,\bar{q}} + R_{qq,\bar{q}\bar{q}}$$

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

Analysis of evolution in colour space needed to judge structure of (dipole) shower evolution.

[Plätzer — in progress] following [Angeles, De Angelis, Forshaw, Plätzer, Seymour – JHEP 05 (2018) 044]

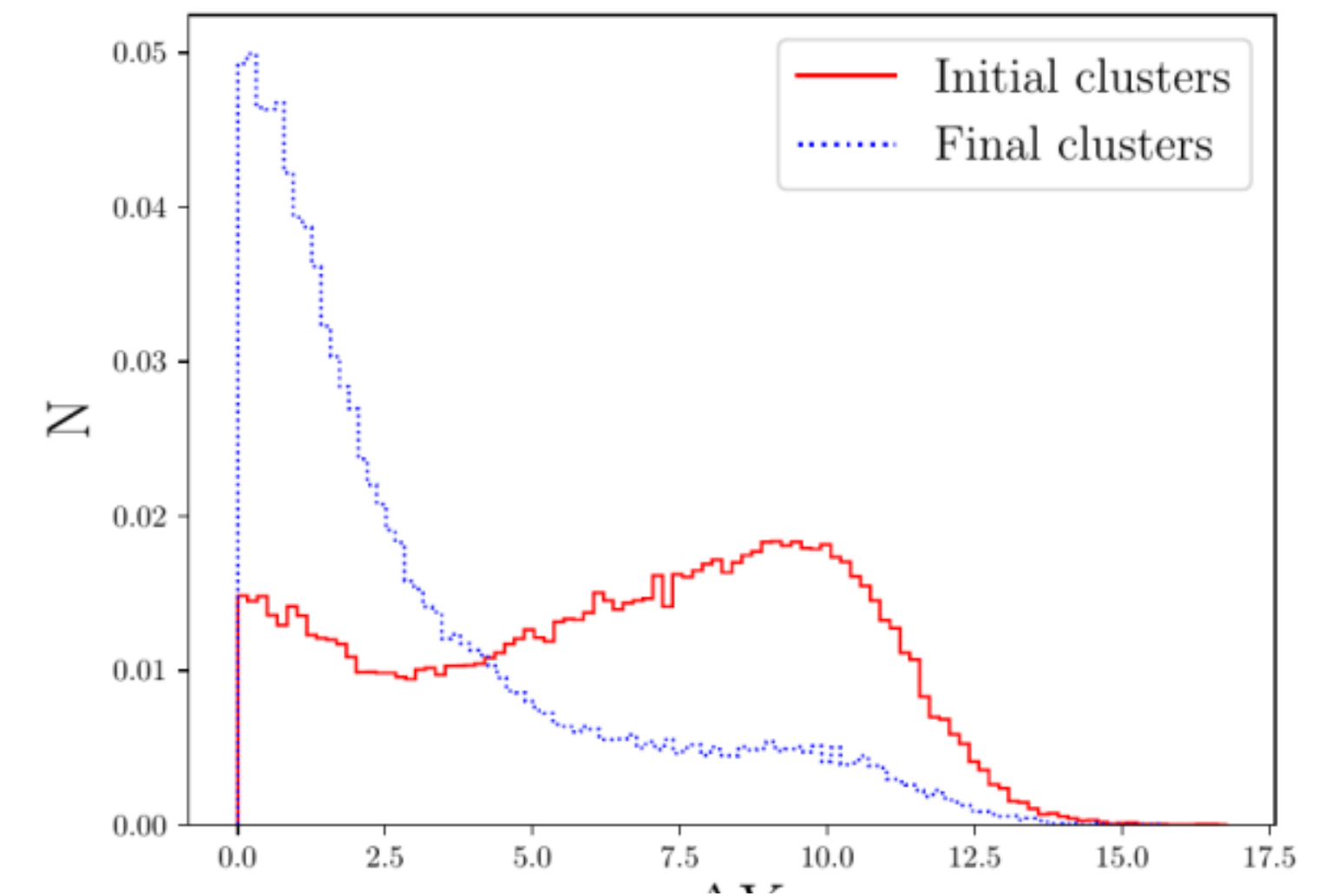
Colour reconnection amplitudes from soft gluon evolution can include (un-)connection of baryons.

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

$$\mathcal{A}_{\tau \rightarrow B_{ijk} \otimes \tilde{\sigma}_{ijk}} = \langle B_{ijk} | \otimes \langle \tilde{\sigma}_{ijk} | \mathbf{U}(\{p\}, \mu^2, \{M_{ij}^2\}) | \tau \rangle$$

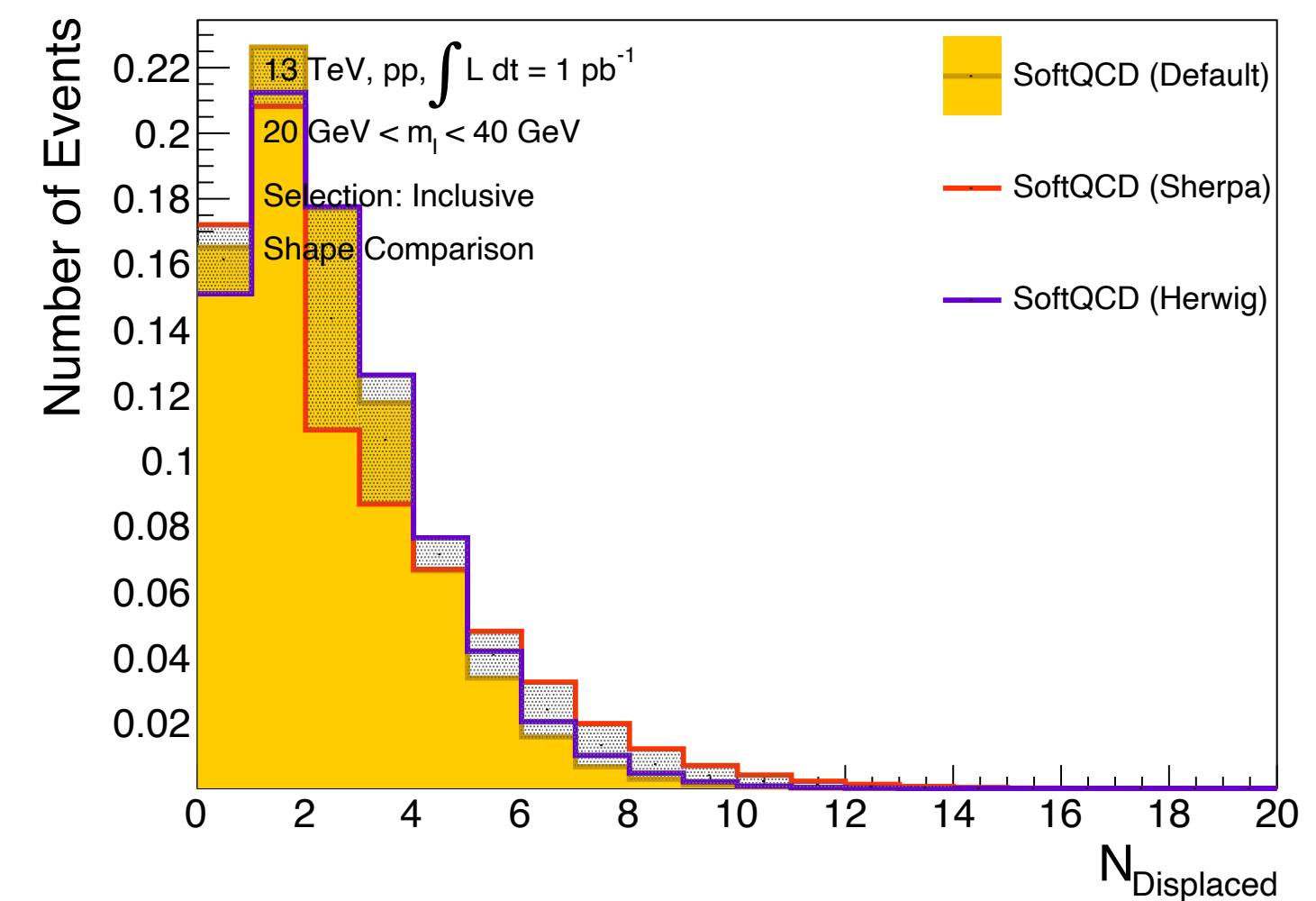
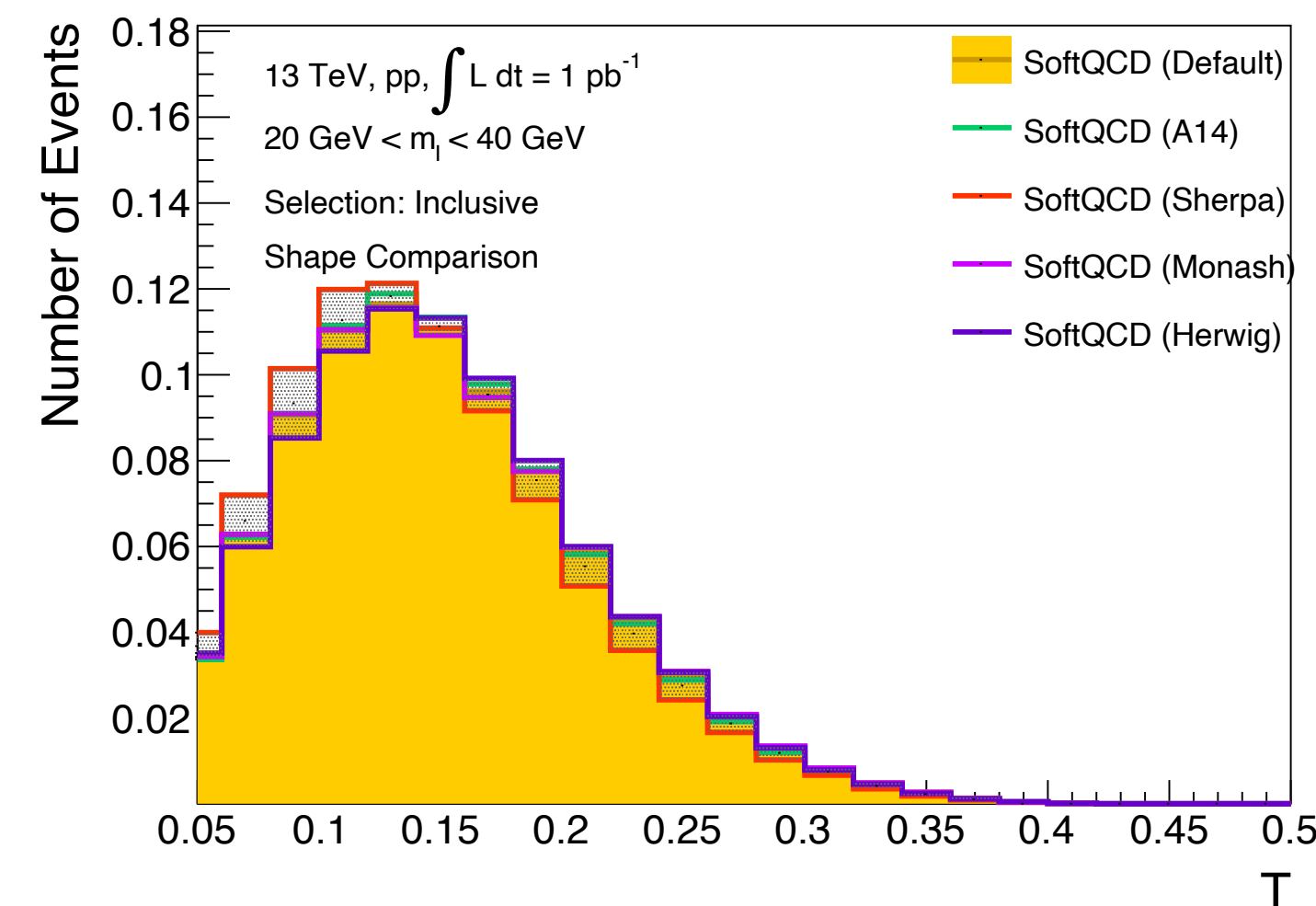
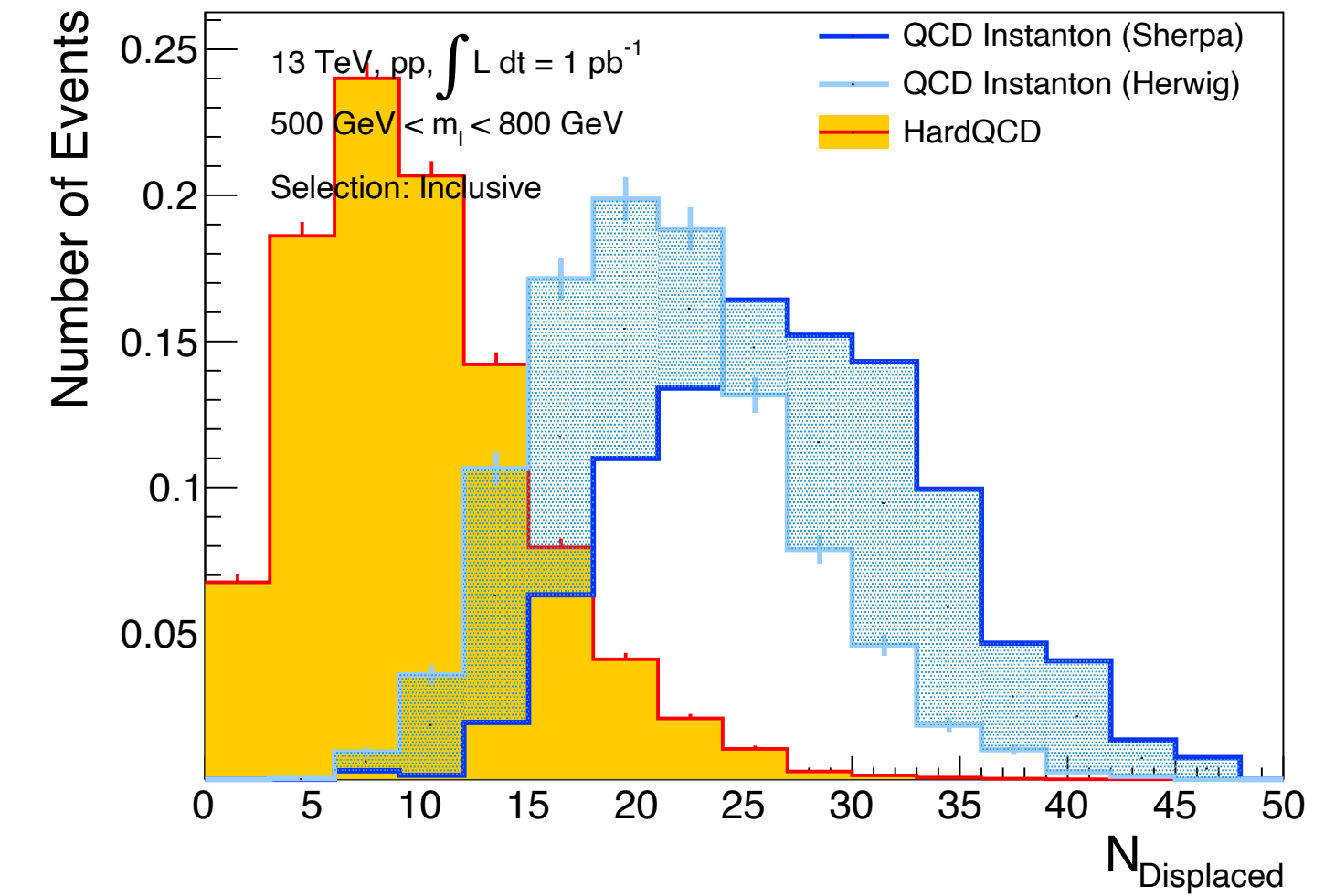
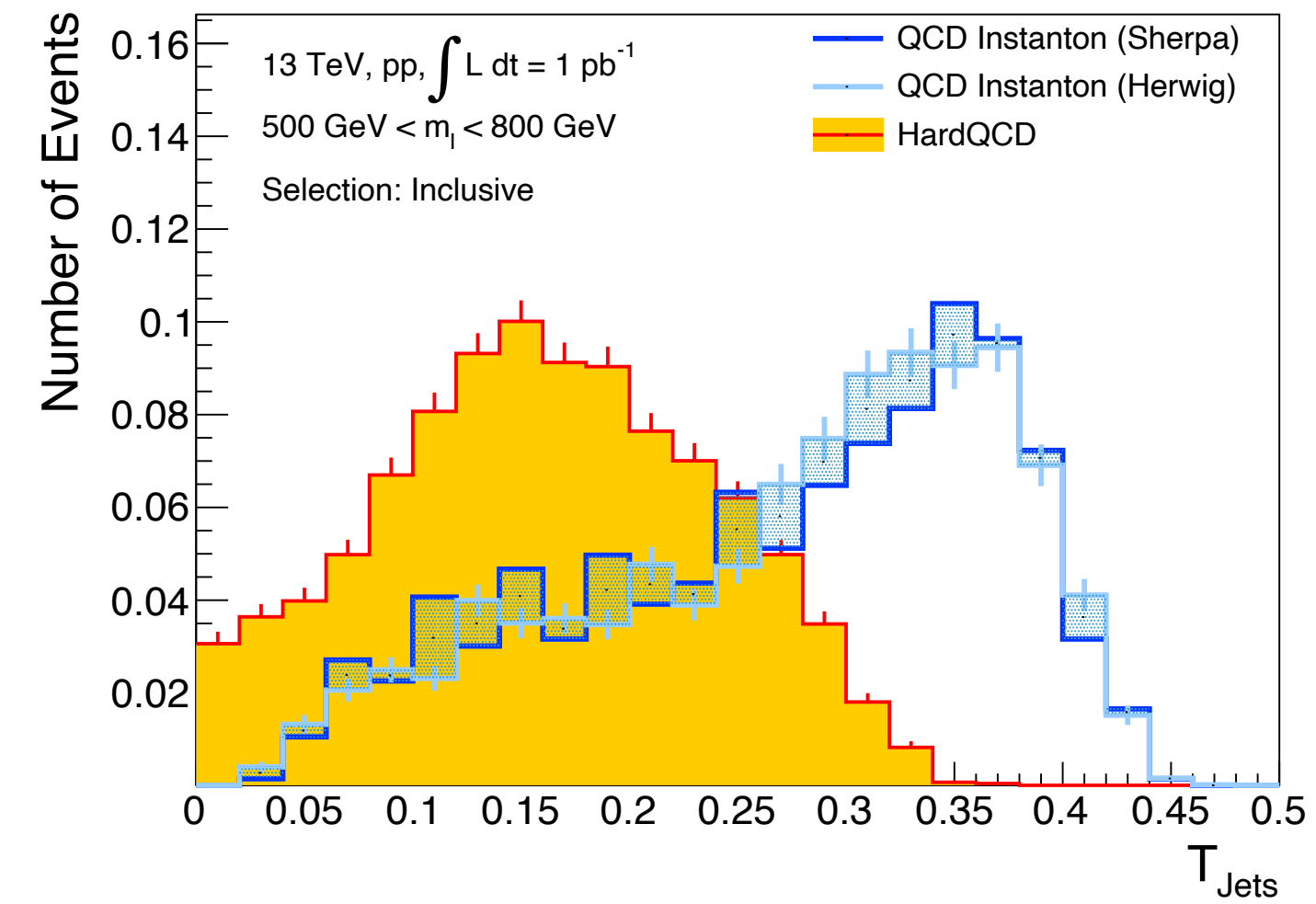
$$|B_{ijk}\rangle = \frac{1}{N_B} \epsilon^{ijk} \epsilon_{\bar{i}\bar{j}\bar{k}} =$$

$$\frac{1}{N_B} \left(\left| \begin{smallmatrix} i & j & k \\ \bar{i} & \bar{j} & \bar{k} \end{smallmatrix} \right\rangle + \left| \begin{smallmatrix} j & k & i \\ \bar{i} & \bar{j} & \bar{k} \end{smallmatrix} \right\rangle + \left| \begin{smallmatrix} k & i & j \\ \bar{i} & \bar{j} & \bar{k} \end{smallmatrix} \right\rangle - \left| \begin{smallmatrix} j & i & k \\ \bar{i} & \bar{j} & \bar{k} \end{smallmatrix} \right\rangle - \left| \begin{smallmatrix} i & k & j \\ \bar{i} & \bar{j} & \bar{k} \end{smallmatrix} \right\rangle - \left| \begin{smallmatrix} k & j & i \\ \bar{i} & \bar{j} & \bar{k} \end{smallmatrix} \right\rangle \right)$$



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

Stable predictions for event shapes.
Vast variation in tracks/vertices.



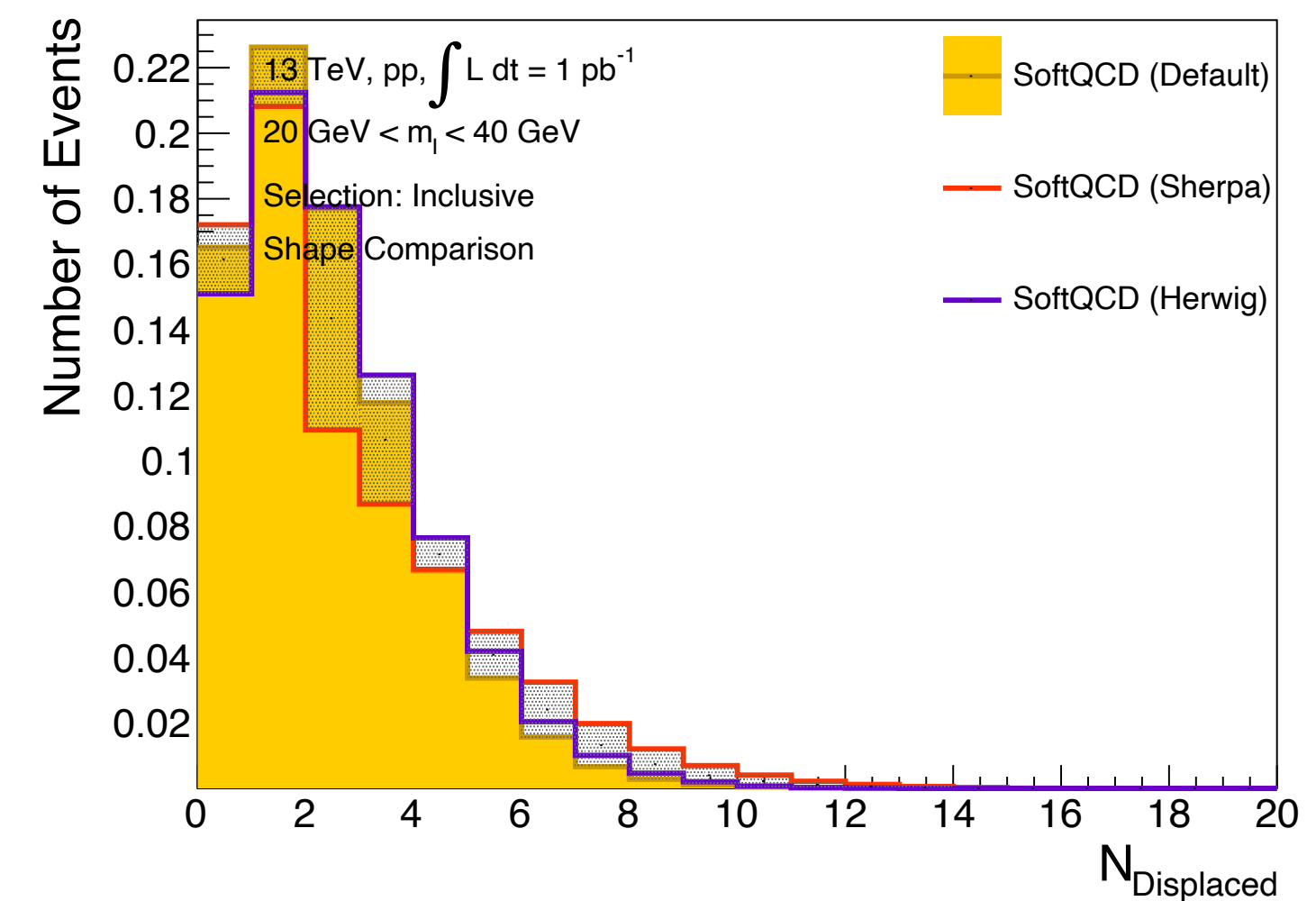
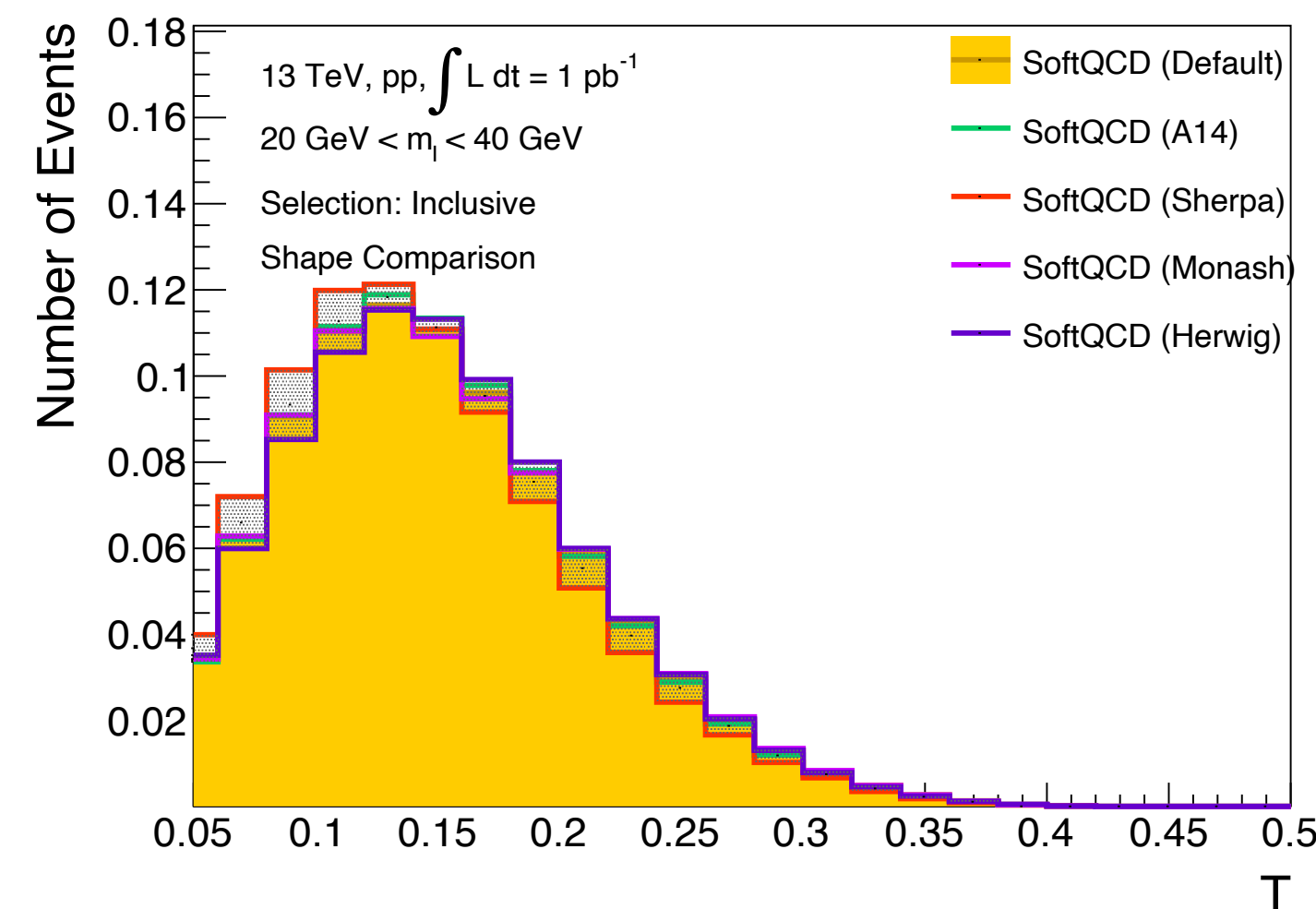
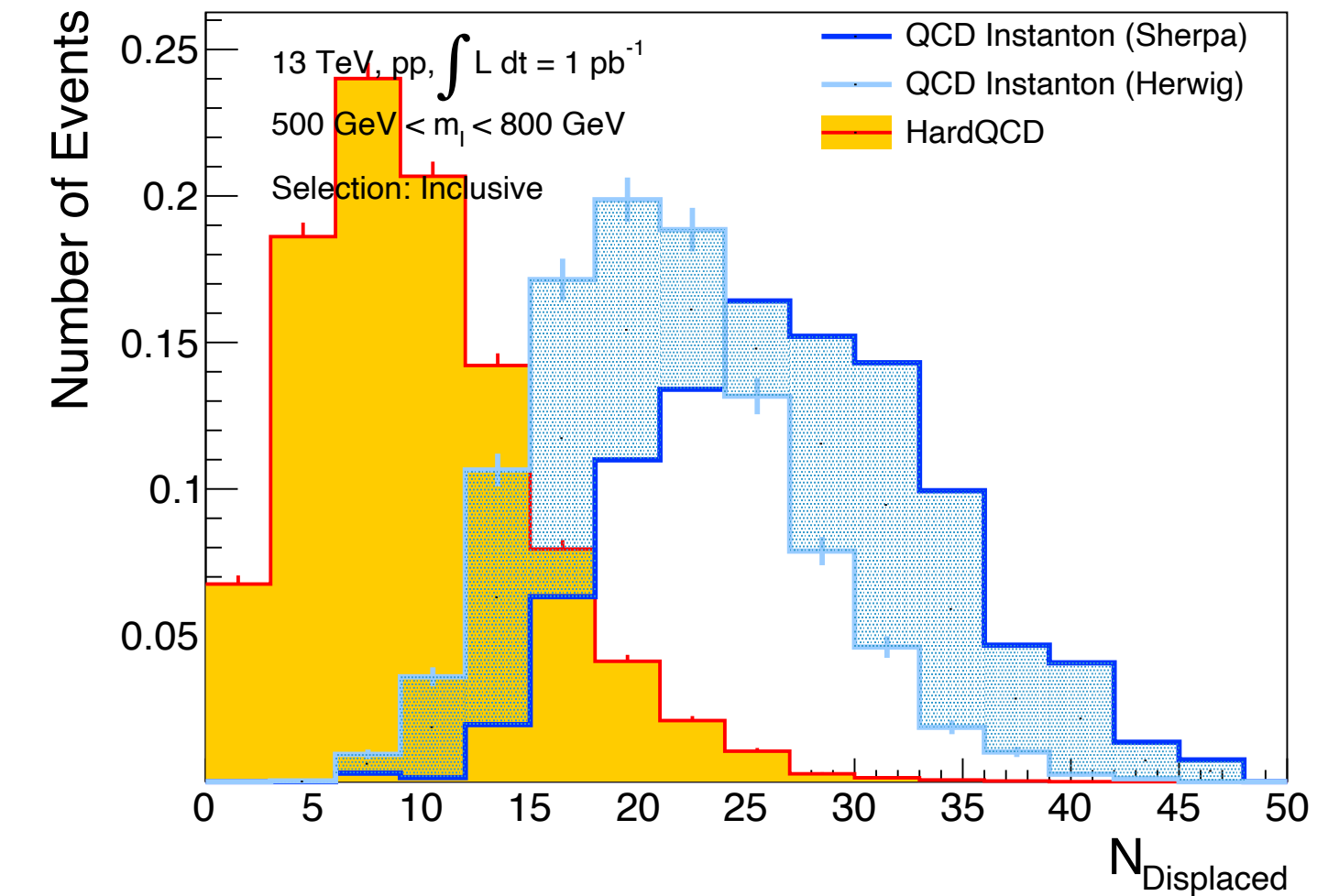
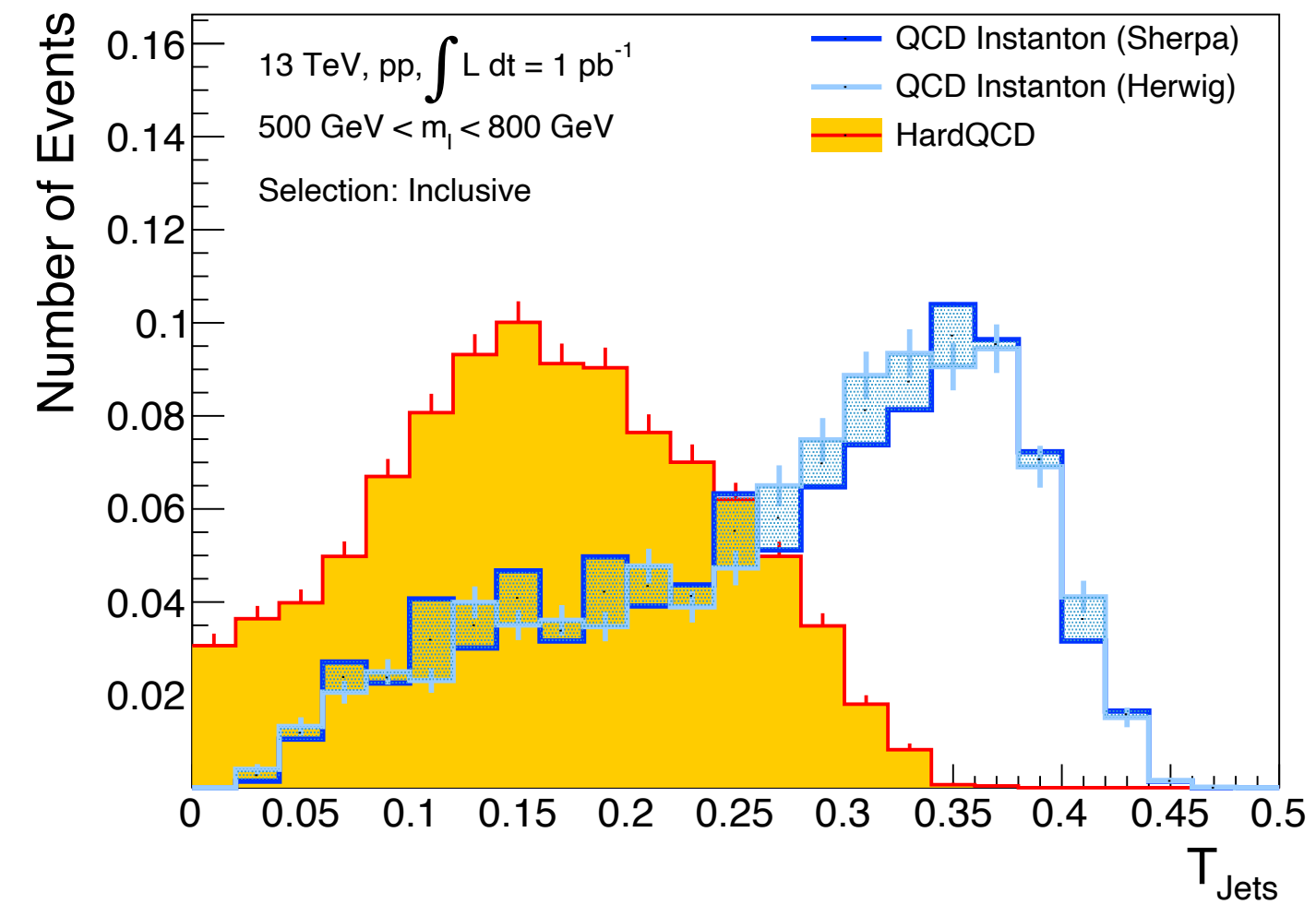
[Amoroso — based on Instanton simulation in Herwig 7]
[Papaefstathiou, Plätzer — unpublished]

Open questions & work in progress

Stable predictions for event shapes.
Vast variation in tracks/vertices.

Shower evolution, colour choices?
Tune variation/model uncertainties?

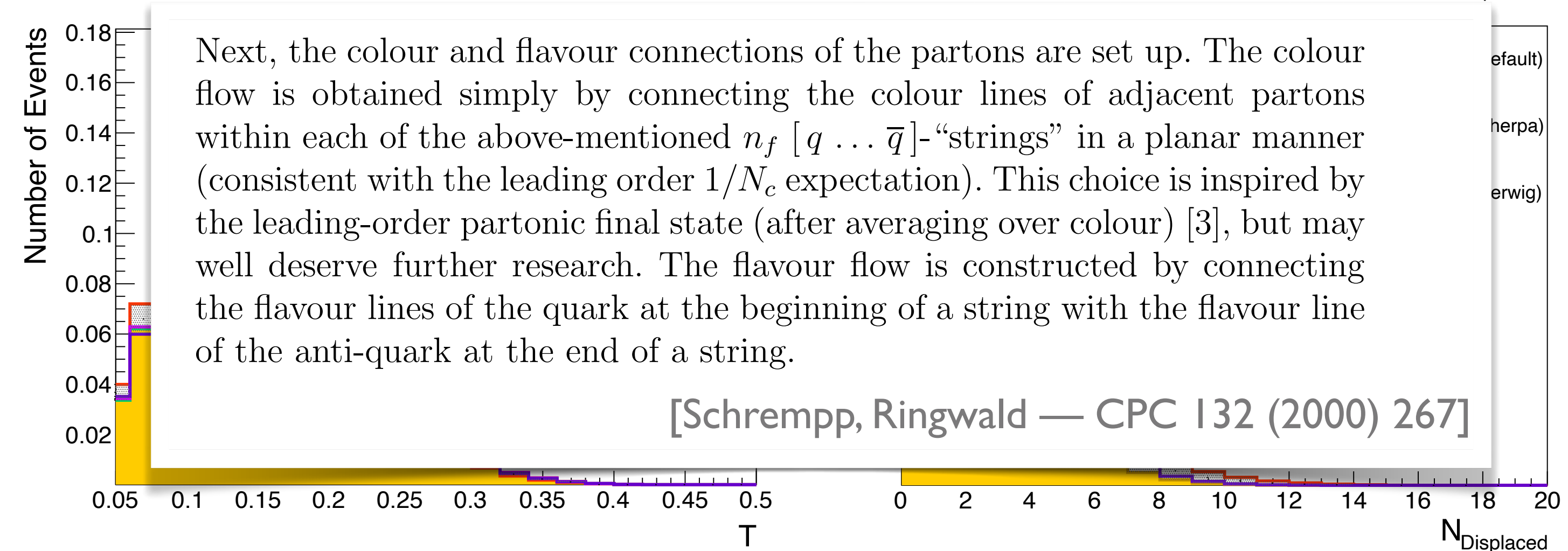
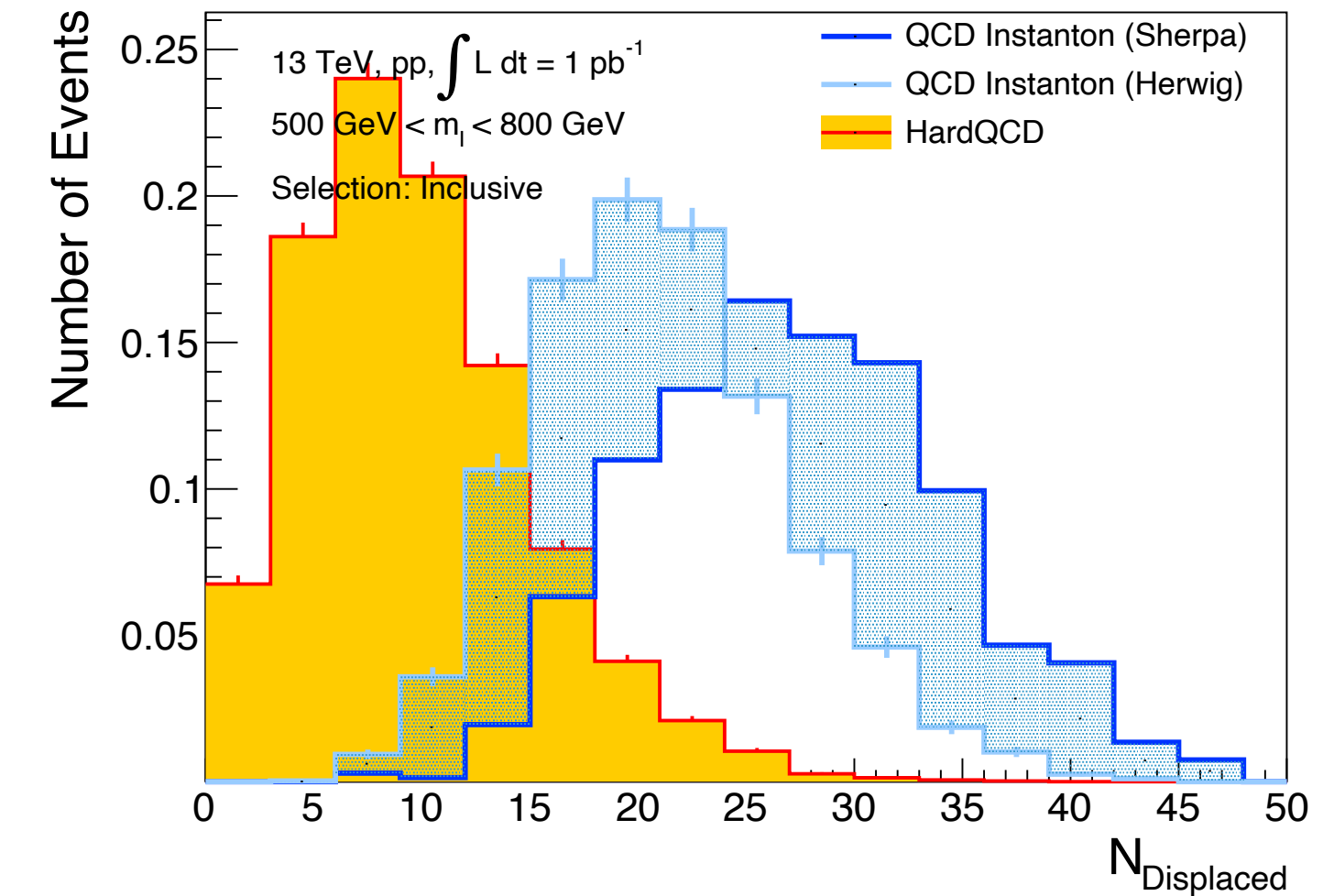
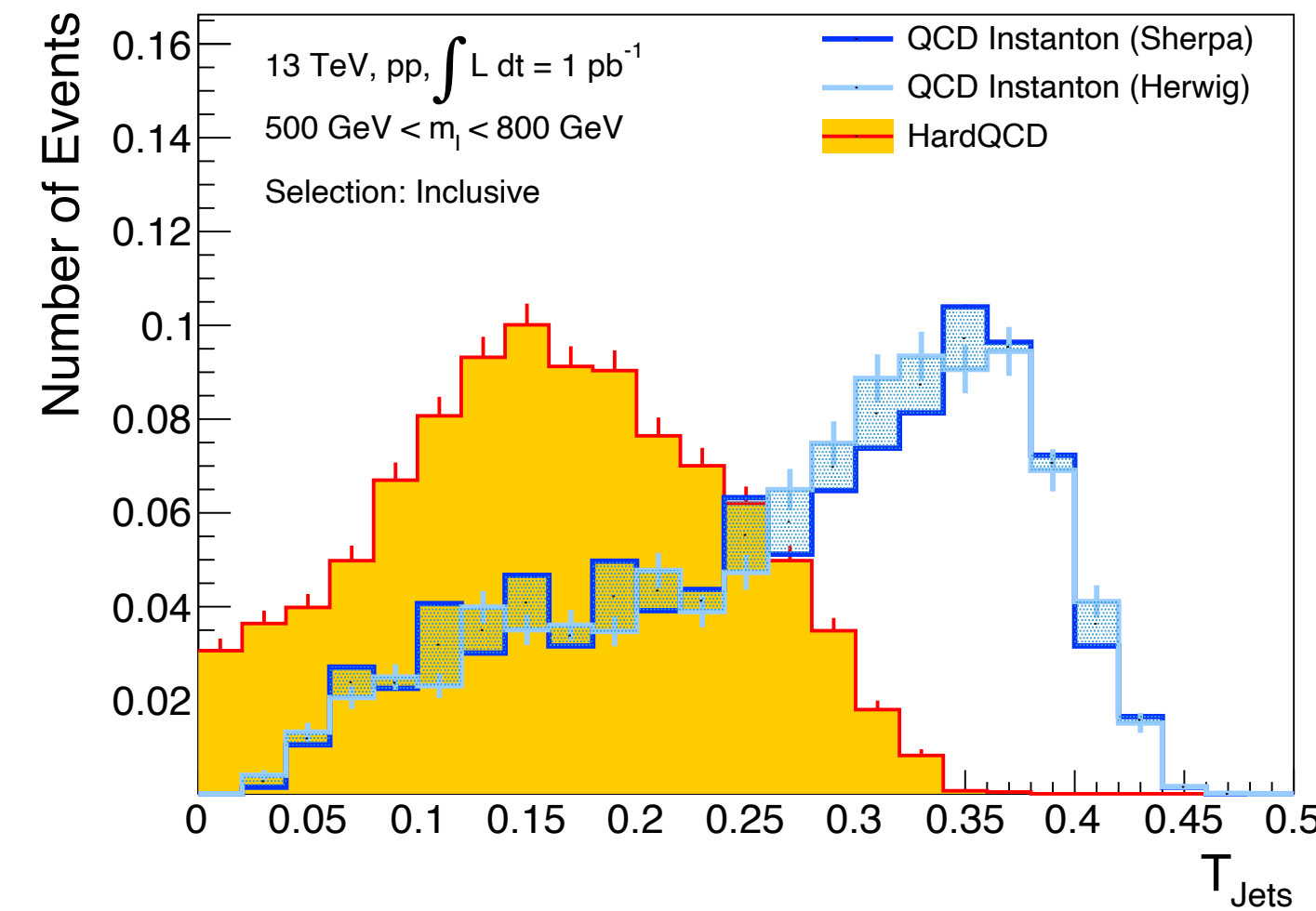
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Thank you!