Non-perturbative Modelling in MC event generators

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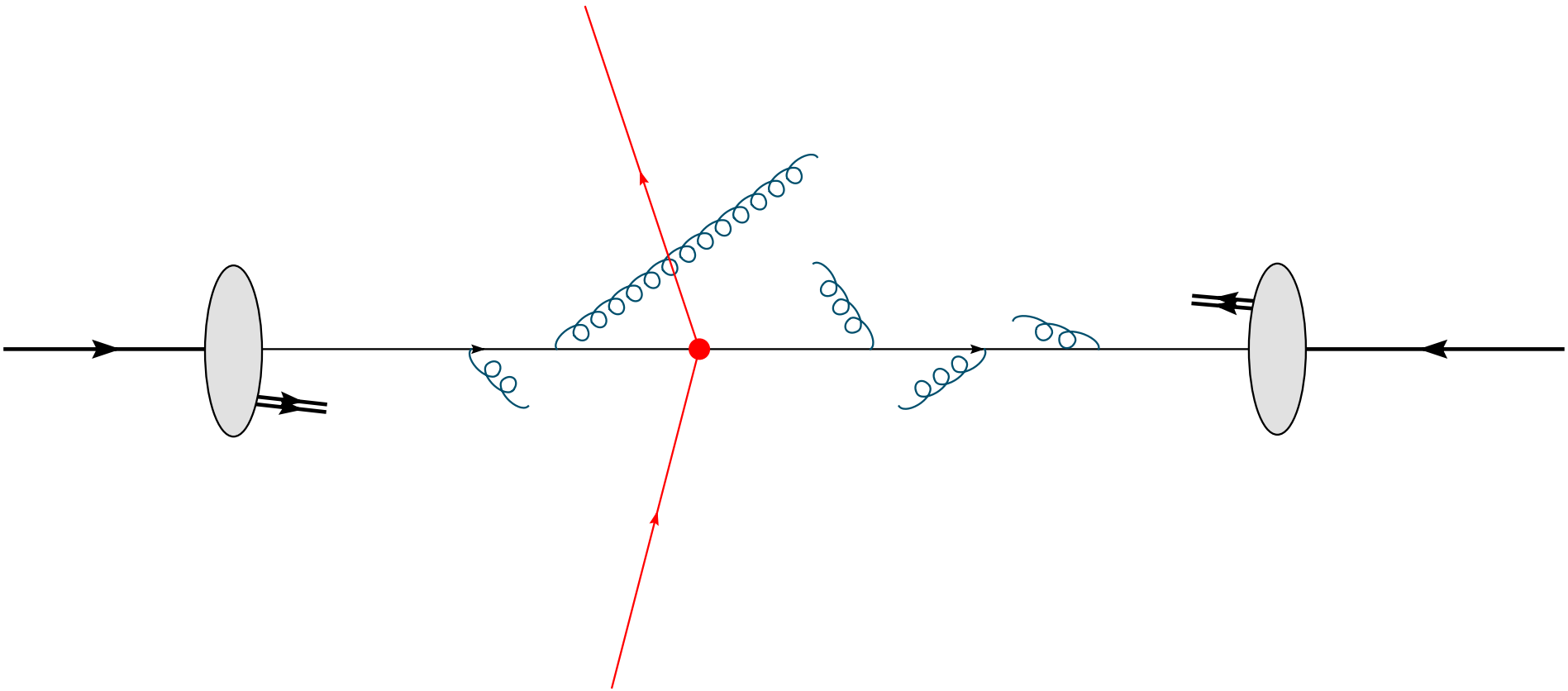
pp Event Generator



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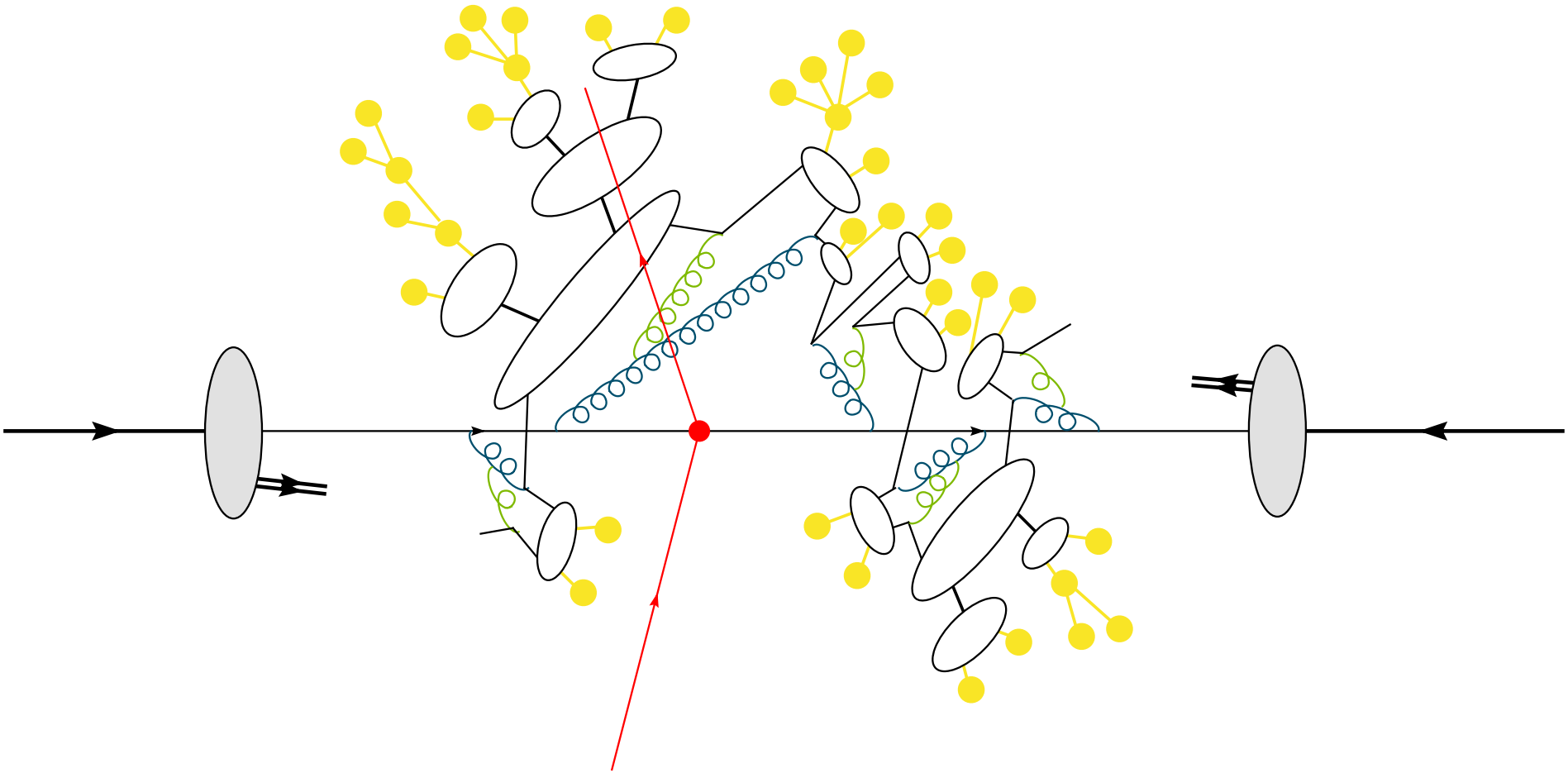

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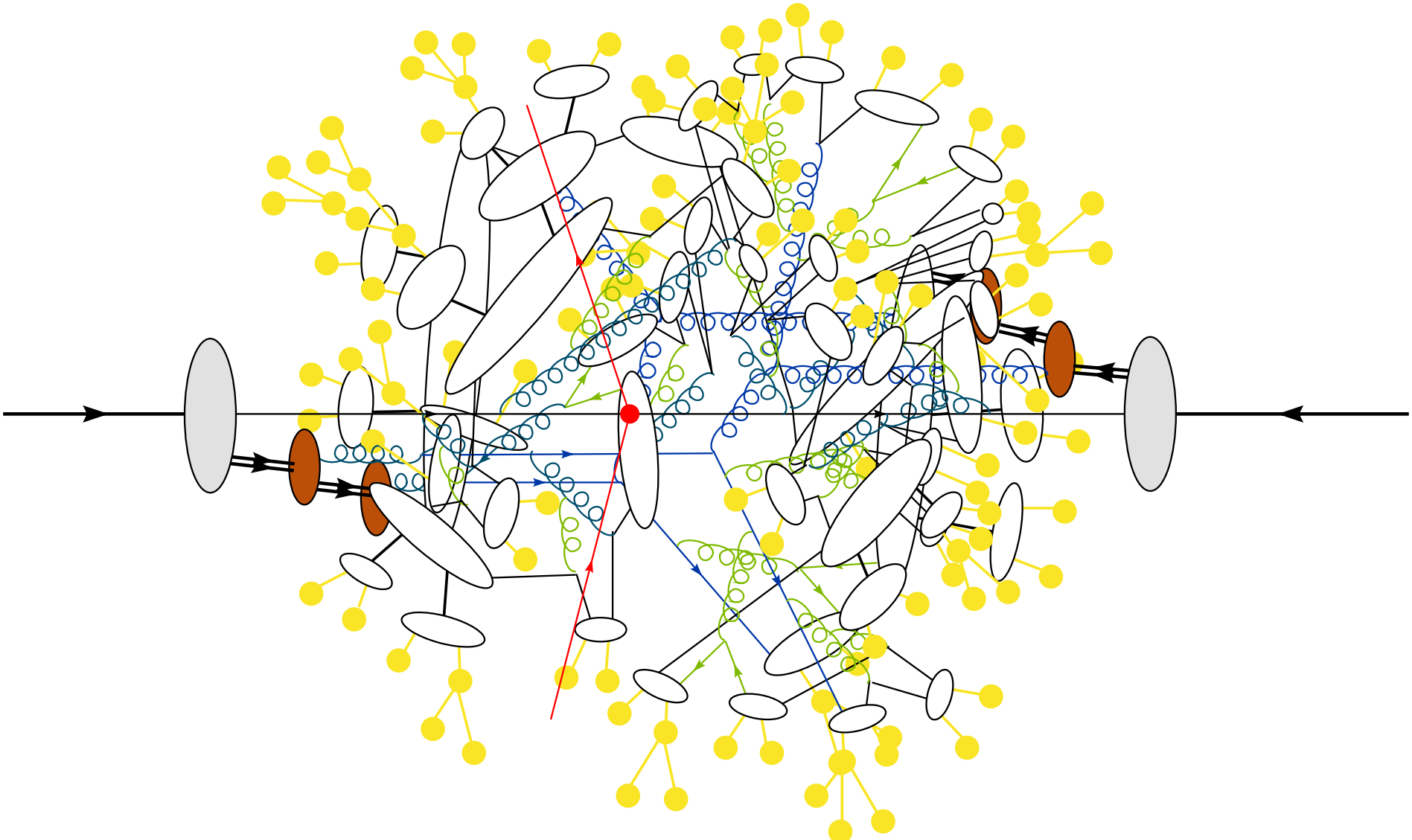


Outline

Brief recap of soft models in Herwig

Hadronization
Multiple partonic interactions
Colour reconnection

Some new developments/studies

NP corrections in dijets and Z+jet
Two particle correlations
Dynamics in cluster hadronizaion and Colour reconnection

Soft models

Where do soft models affect observables that are first and foremost determined perturbatively?

- Hadronization and Hadronic Decays
- Multiple Parton Interactions (MPI) Modelling
- Colour Reconnection
- (. . .)

All are in close *correspondence* with the parton shower.

Soft models

Observations at colliders that are affected

- "Corrections"
- Soft particles *always* add to jet activity
- Hadronization and MPI add/remove activity from jets
- Many soft or few hard particles share the partonic momentum flow?
- Few heavy particles or many light particles?

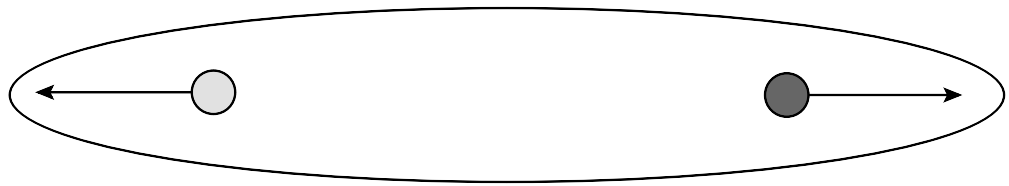
Precision goal — "MC error" often sizable

Soft models

More fundamental questions

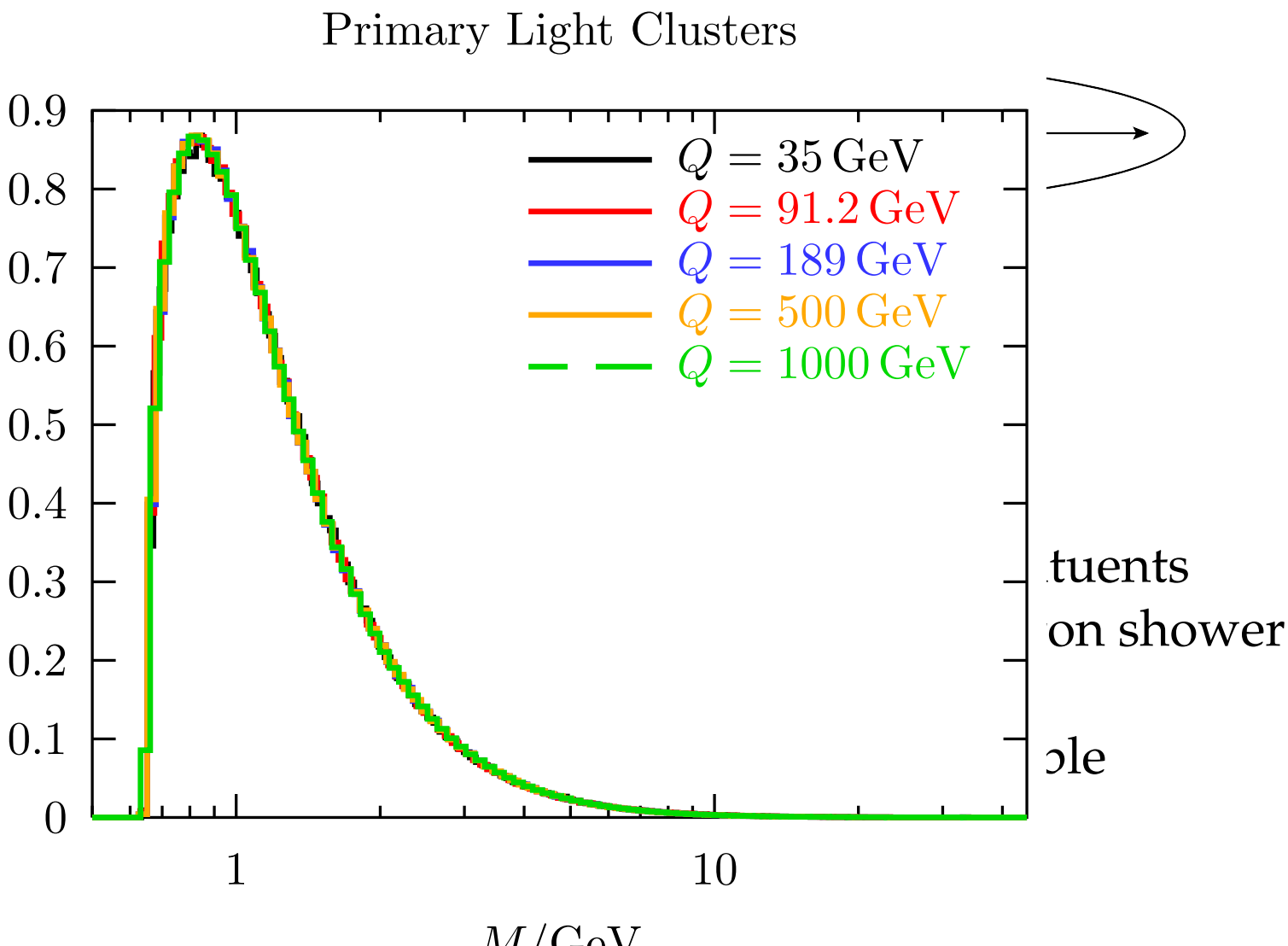
- "The ridge" (near side long range correlations in η)
- Dense, high multiplicity events
- Strangeness enhancement
- pp to heavy ions
- Microscopic modeling of medium effects
- Is "Pythia minus Herwig" good enough?
- More/better theory input in soft models?

Cluster Hadronization



Cluster carries net momentum of its constituents
Spectrum determined by final state of parton shower
Independent of hard scales
Tail of *heavy clusters*, still large scale available

Cluster Hadronization



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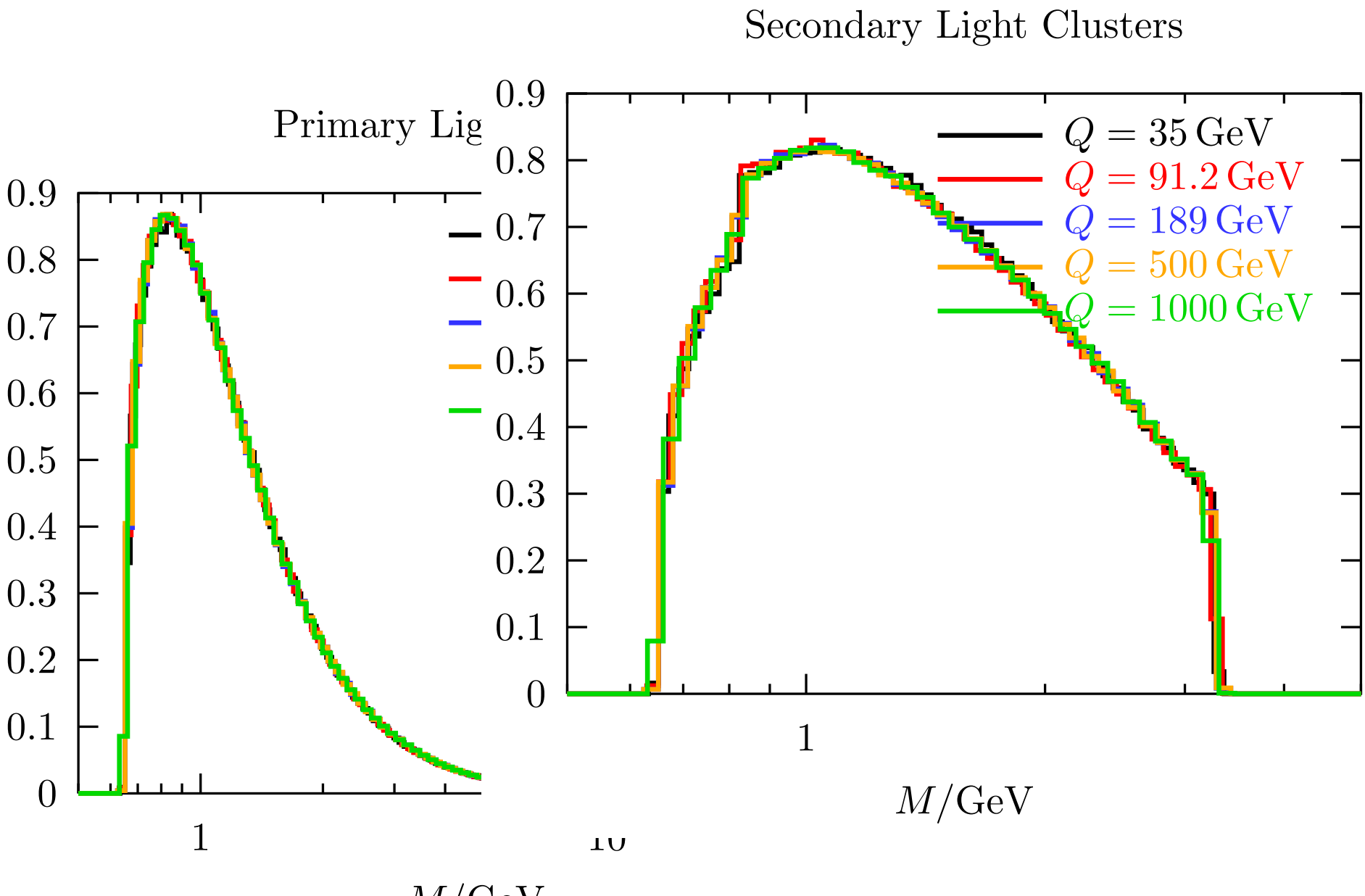

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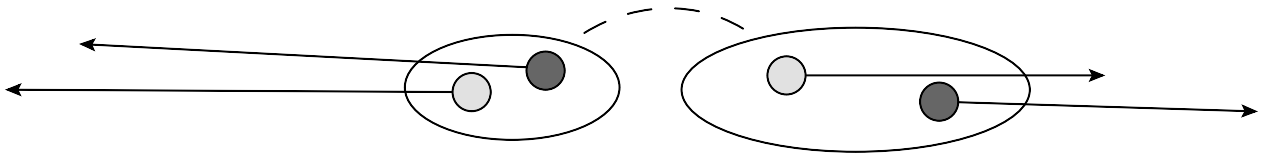
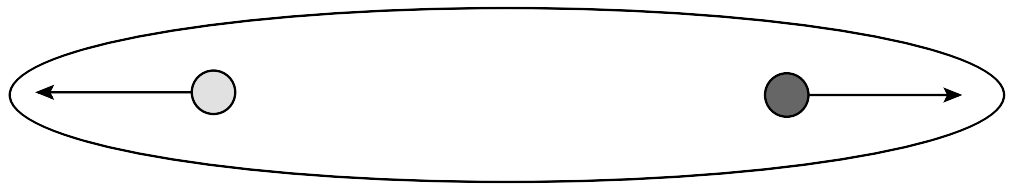


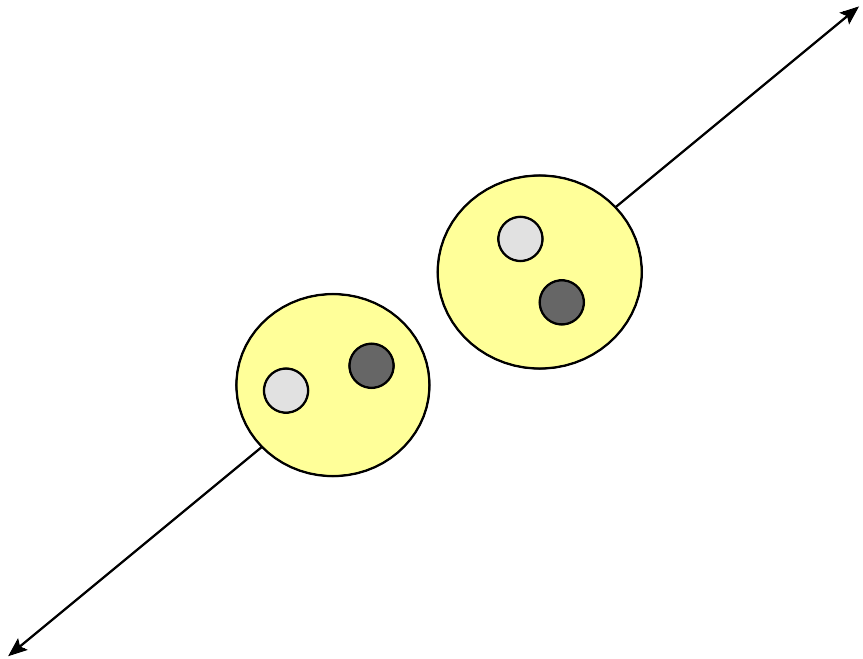
Binary fission along quarks' direction of motion
Flavour introduced in $q\bar{q}$ pairs
Baryons could be introduced via diquarks
Mass $\rightarrow$ multiplicity, momentum
Beam remnant clusters split off as very light clusters
$\rightarrow$ *Kinematic triangle*

Cluster Hadronization



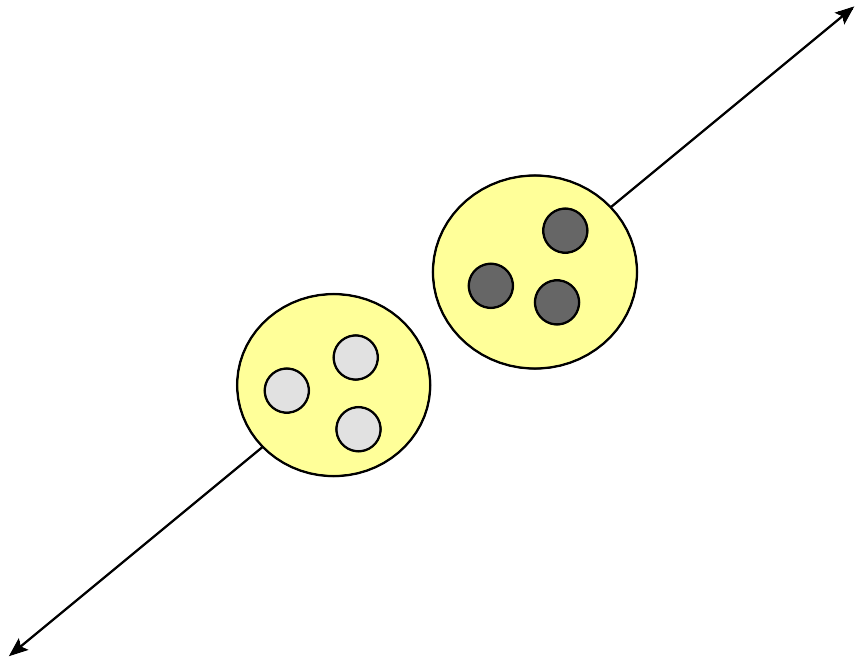
End up with fairly light clusters
too light? Decay into single hadron
Exchange momentum with neighbour

Cluster Hadronization



Decay isotropically into hadron pairs
Individual Hadrons get weight according to flavour multiplet, CM momentum, spin multiplicity etc.

Cluster Hadronization



Baryon pairs possible
usually appear from clusters with 1 or 2 diquarks
could also emerge in pairs from mesonic clusters

Hadronization

UV cutoff of hadronizaiton is IR cutoff of parton shower.
Some kind of factorization.

- Assignment of colour lines, leading $1/N_C$ expansion.
  First insight from colour evolution of soft gluons?
  More updates from parton showers at non-leading colour.
- Colour reconnection models alter the picture. See later.
- Gluon splitting, m_g-dependence (+kinematic details?)
- Fission dynamics, now binary. Choice of phase space.
  Non-binary, i.e. $2 \to N$ fission, relation to soft UE?
  Non-perturbative $p_\perp$.
- Choice of hadrons and masses in cluster decay

[Plätzer, JHEP 07 (2023) 126; Hoang, Plätzer, Samitz, JHEP 10 (2018) 200]

[SG, Hoang, Kiebacher, Plätzer, Samitz, *in progress*]

After tuning (ideal world):
$\approx$ independence of PS cutoff scale μ^2

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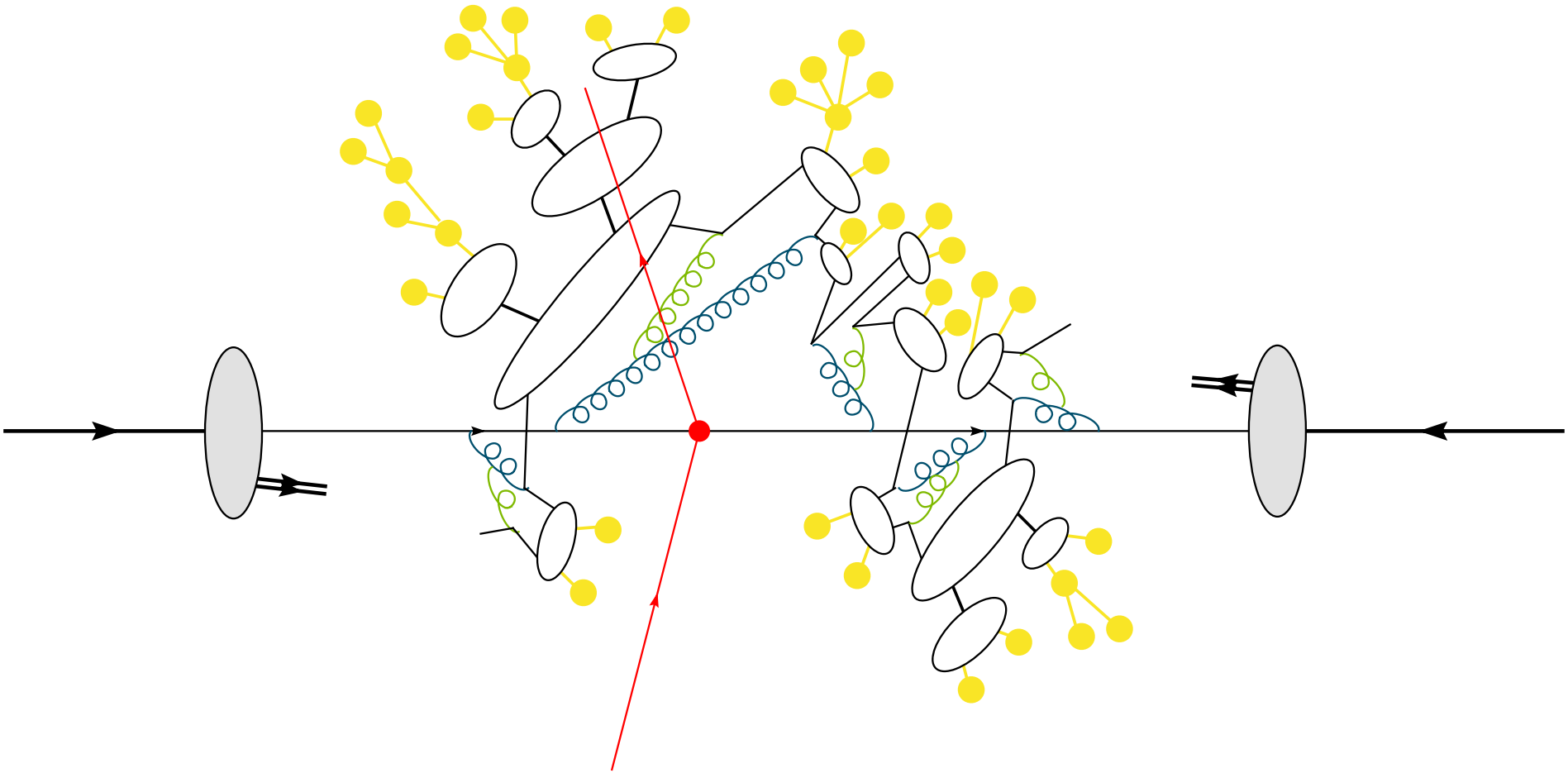

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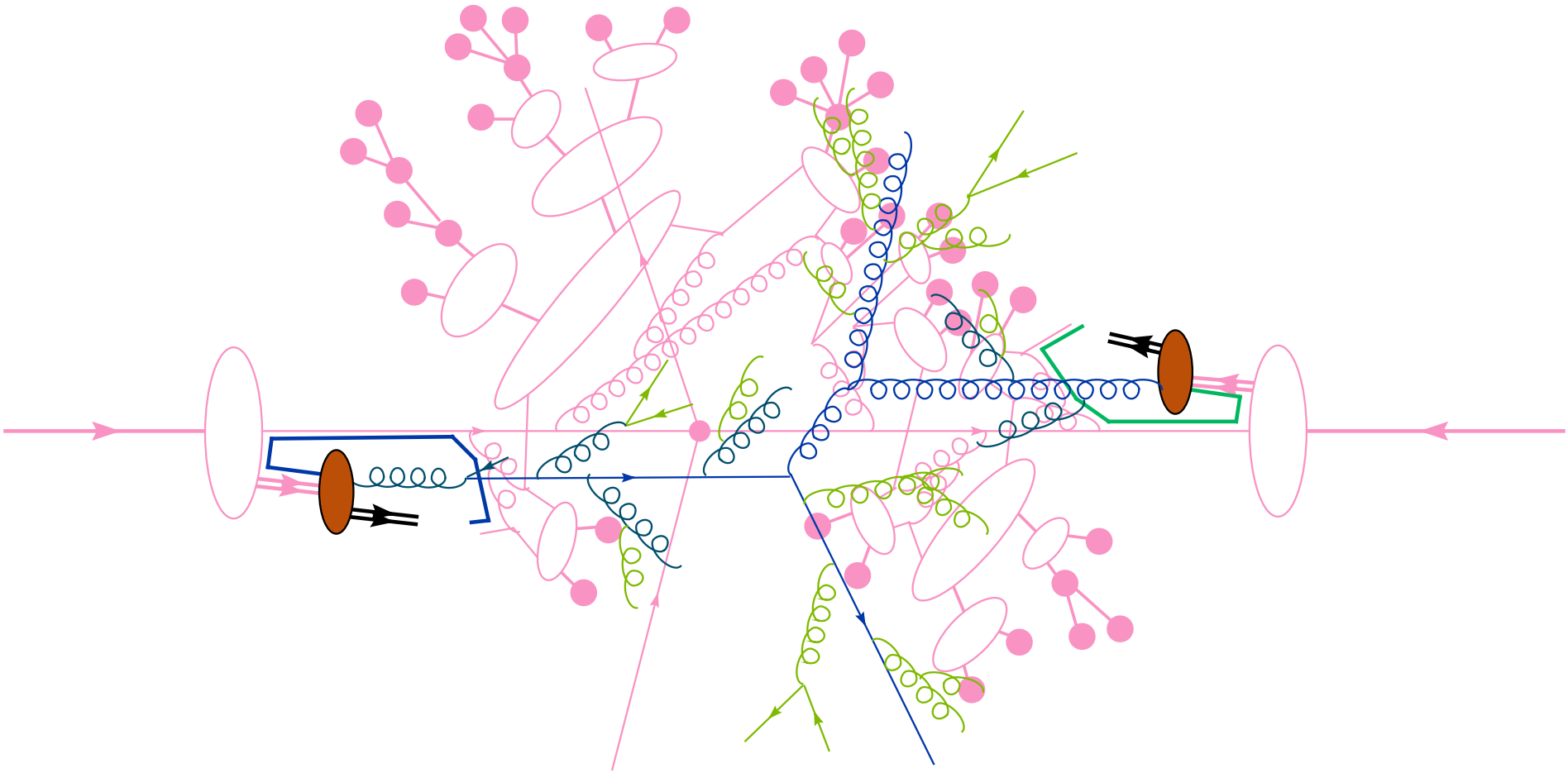

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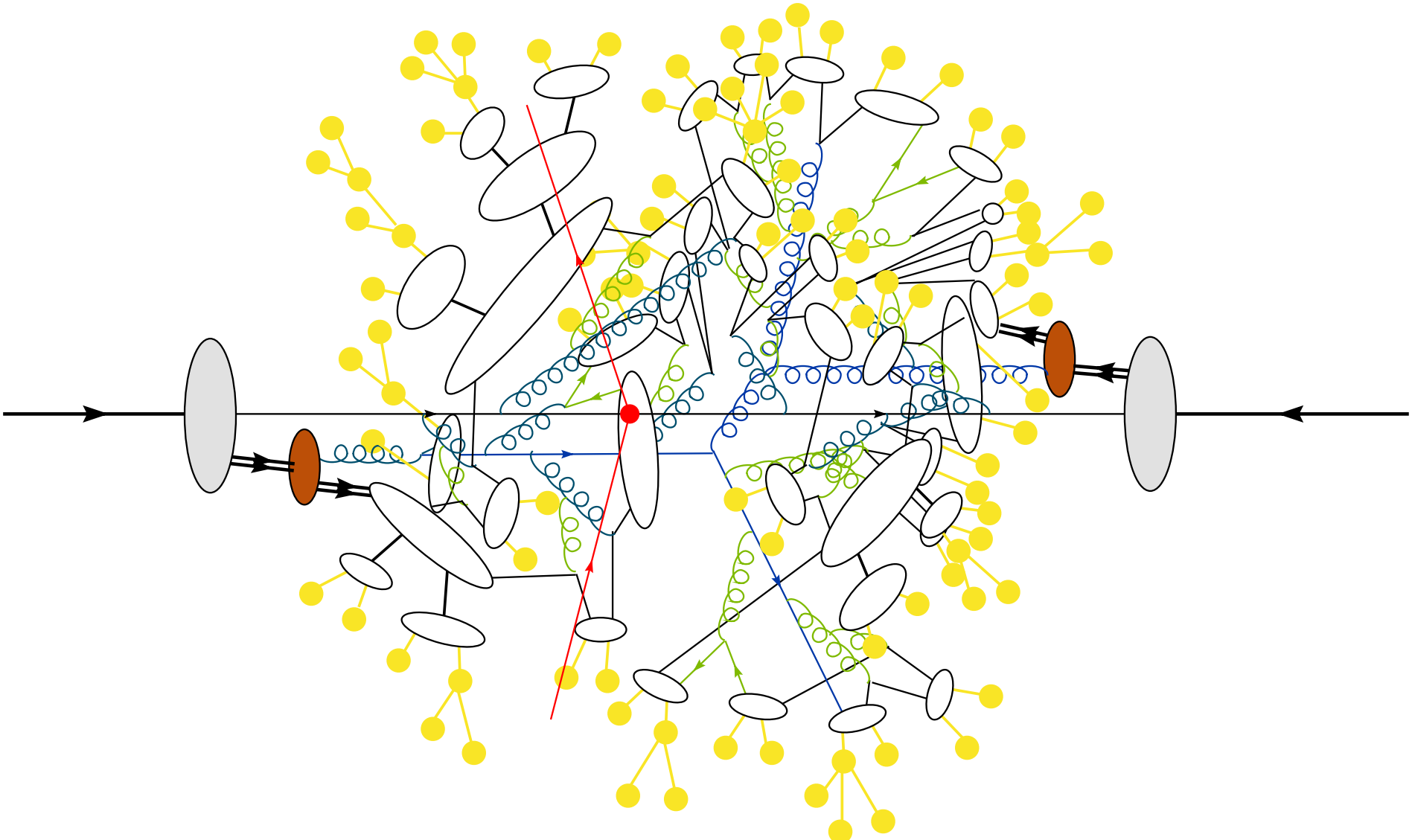

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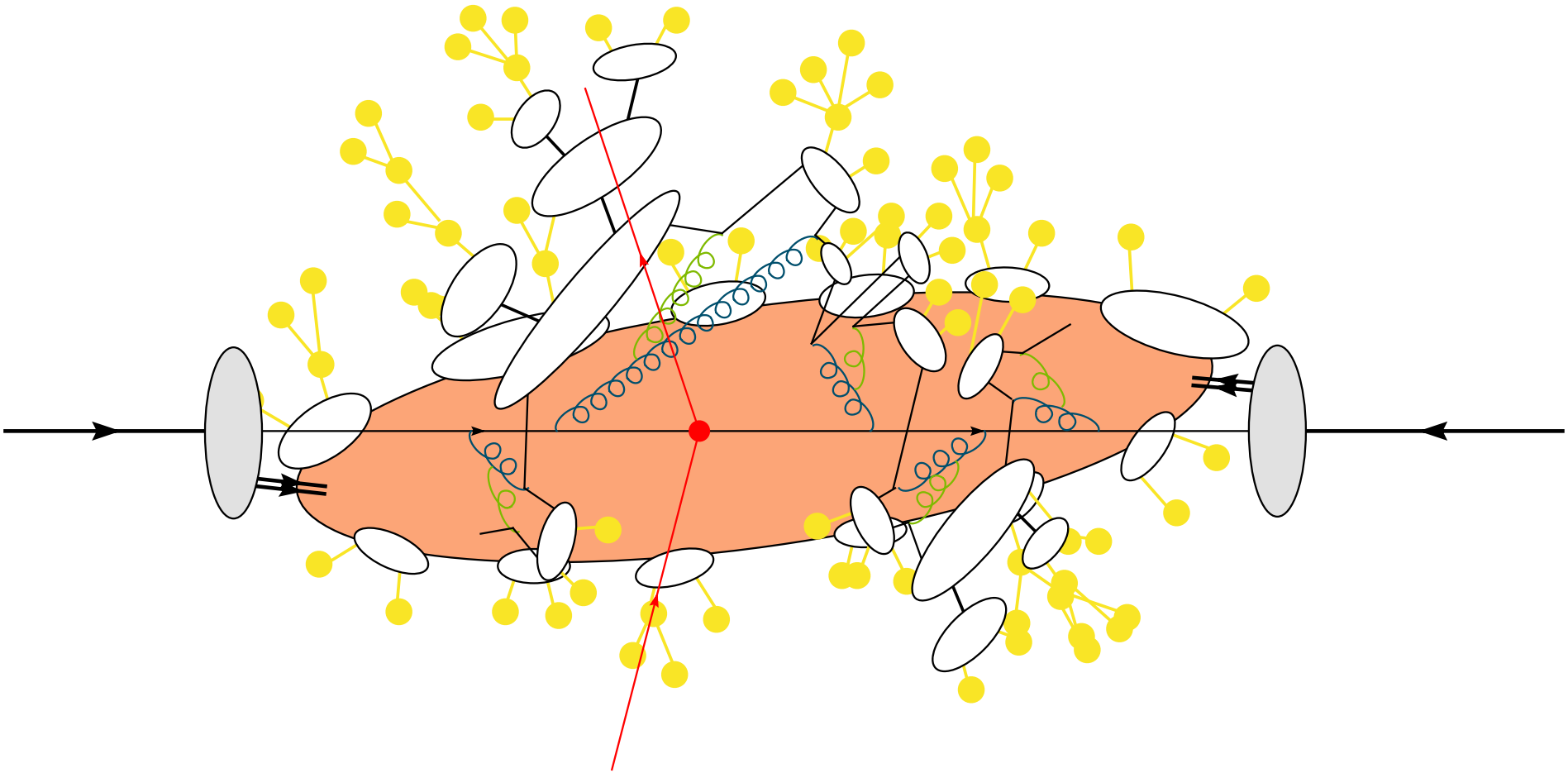
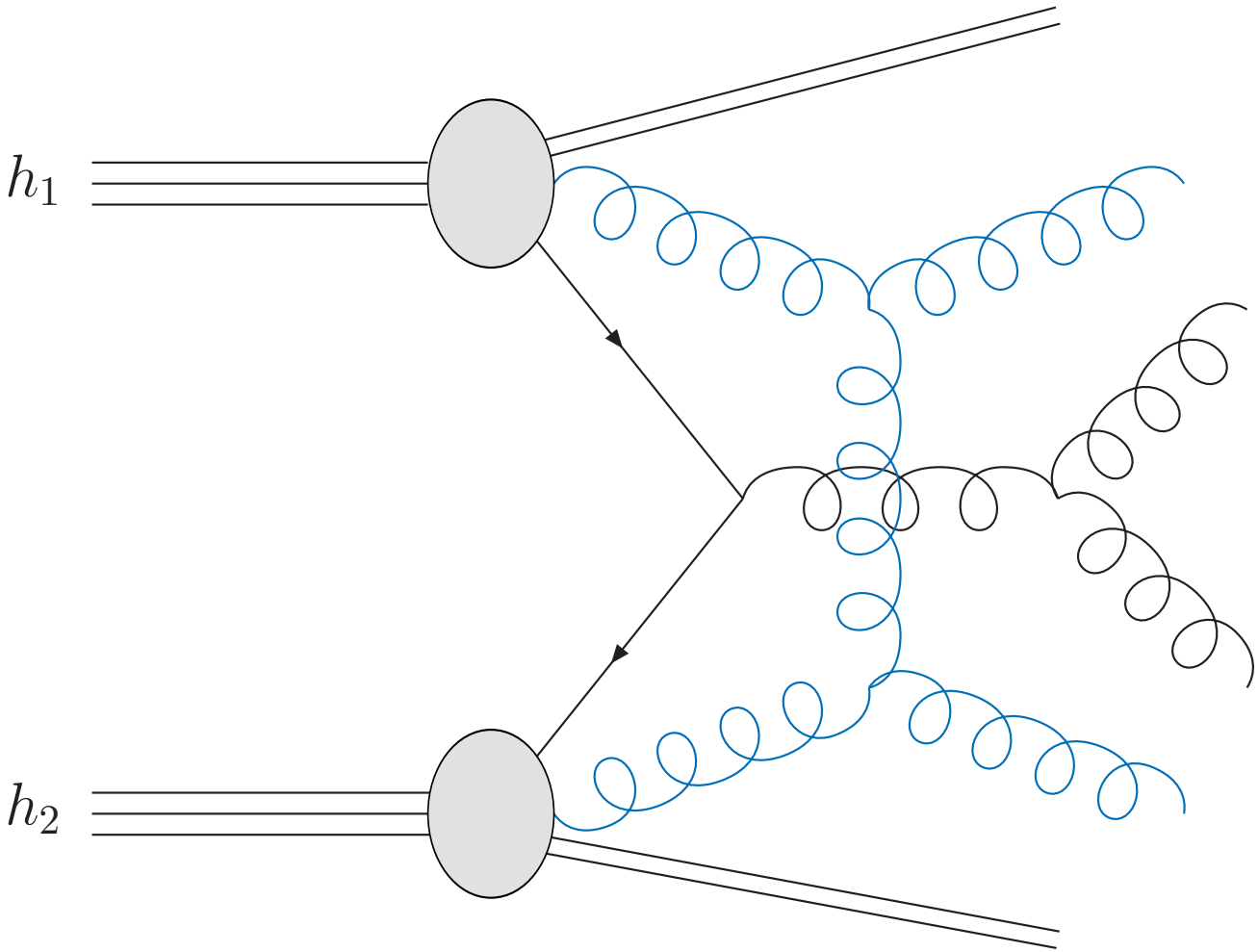
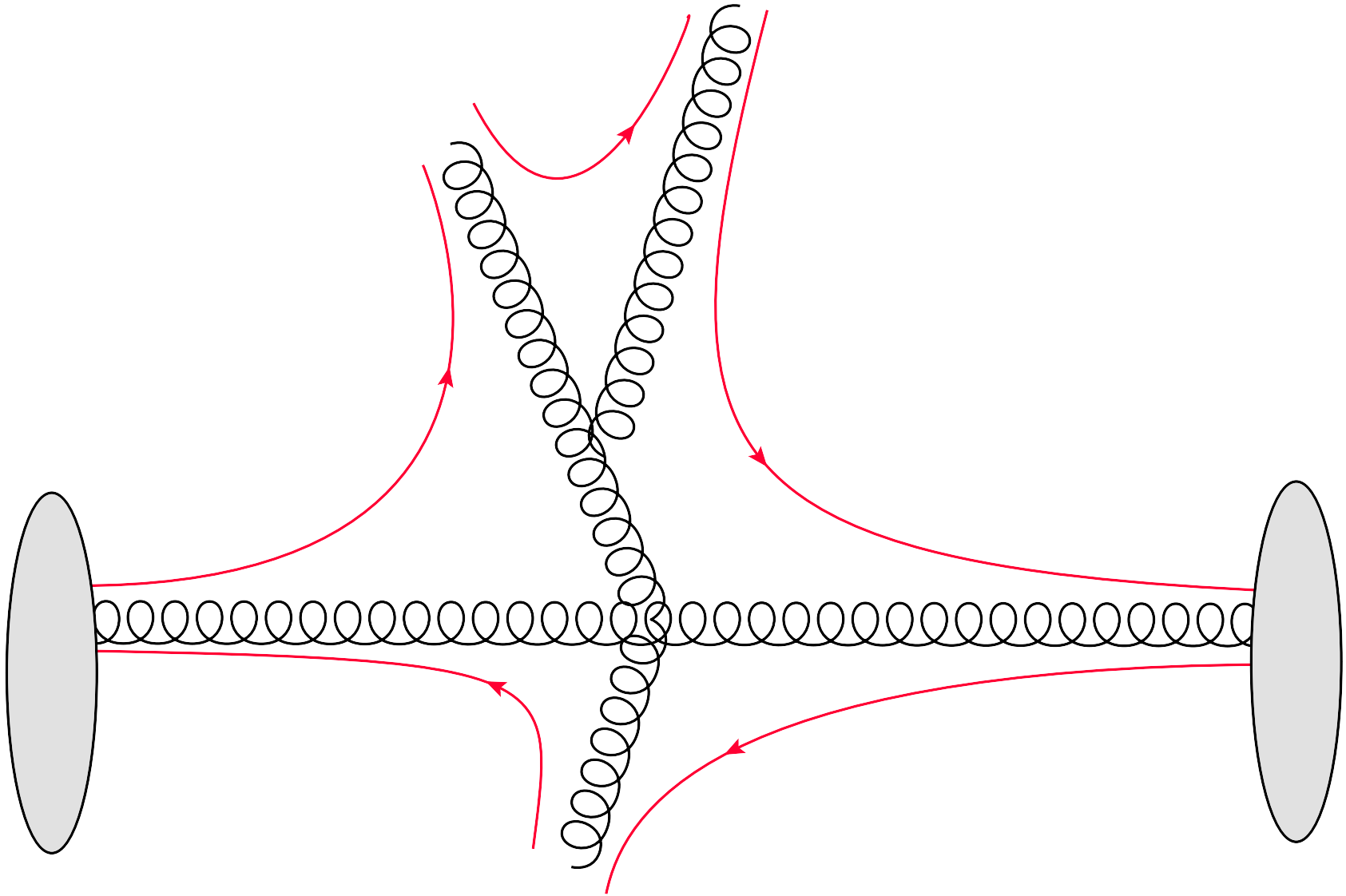


MPI/Eikonal model basics

Mulitple hard and soft interactions



Colour correlations in hadronic collisions



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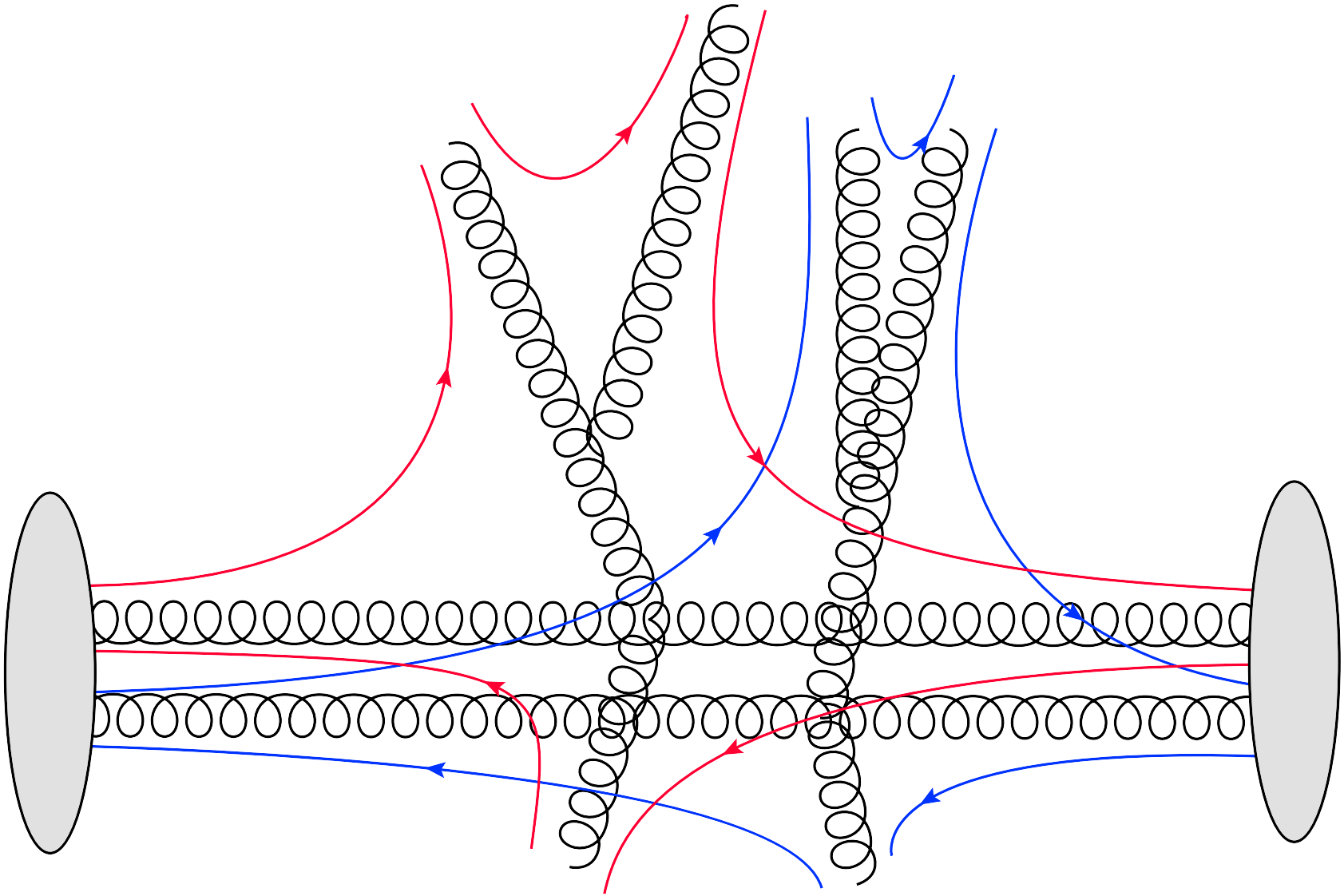

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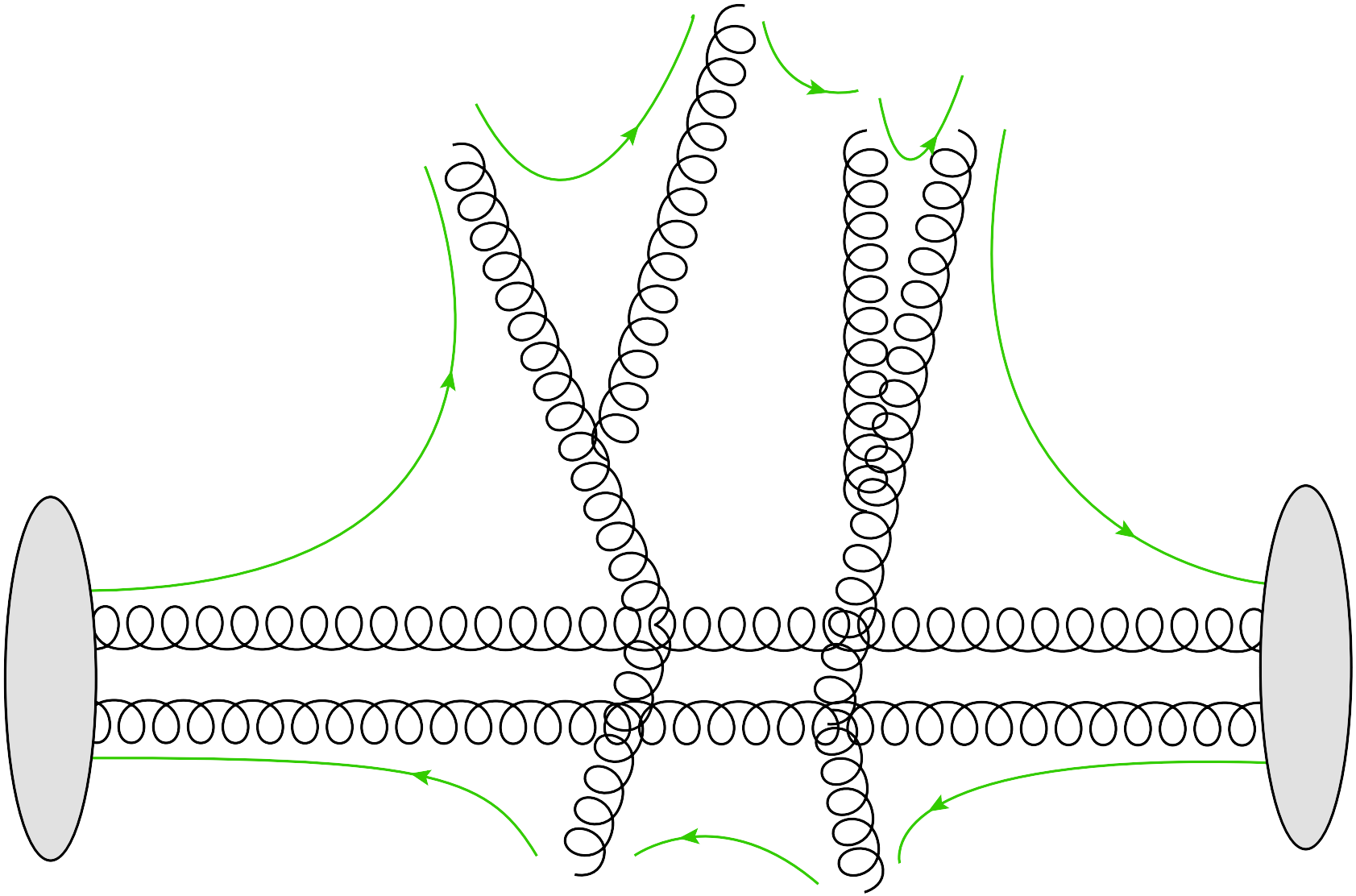
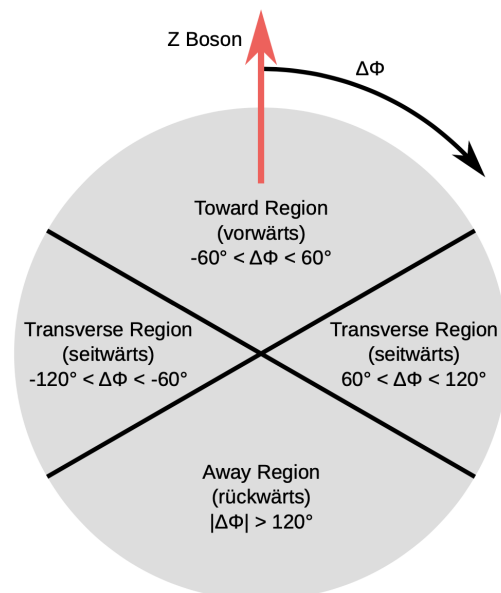


Example: Underlying event in Z+jets events

Toward region = Z boson
Away region = recoil jet
Transverse = UE, *but* also activity from additional jets
Trans-min/max = transverse with higher/lower $\Sigma E_{\perp}$

Sensitive to higher order corrections,
i.e. real emission of hard jets

How universal is the MPI description,
as normally tuned to jet events/Min Bias?



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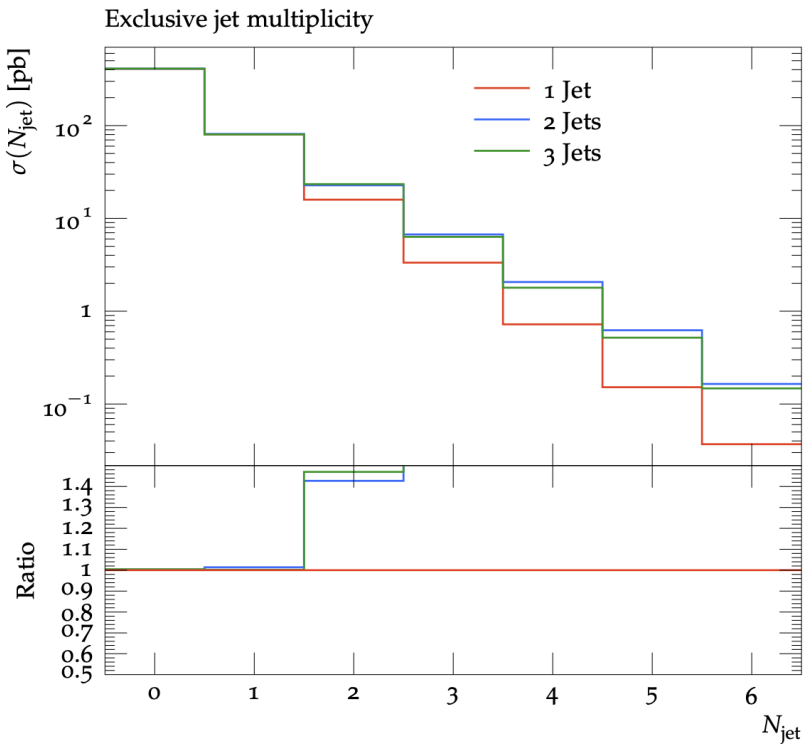
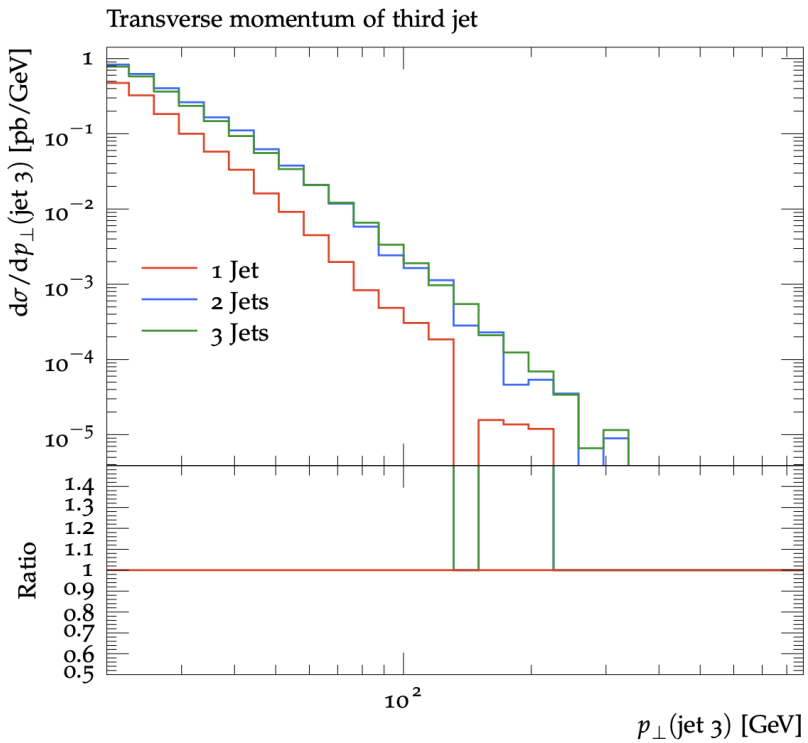


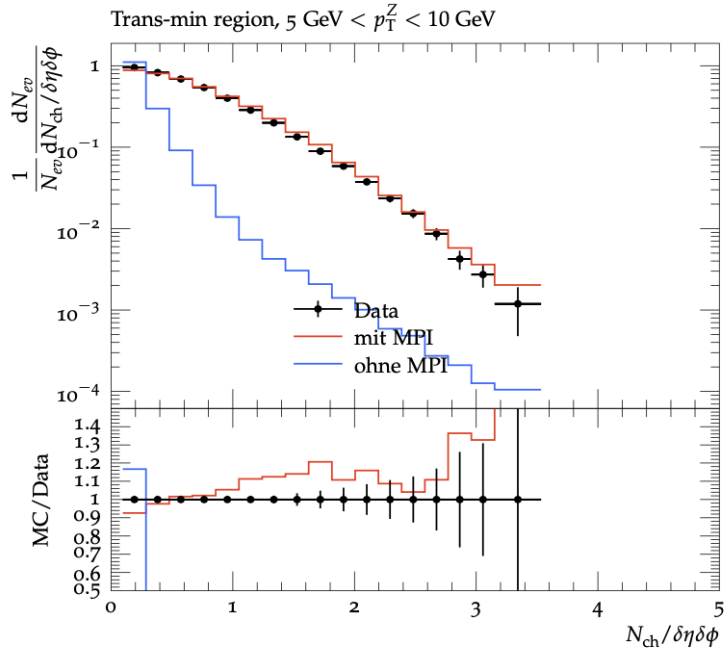


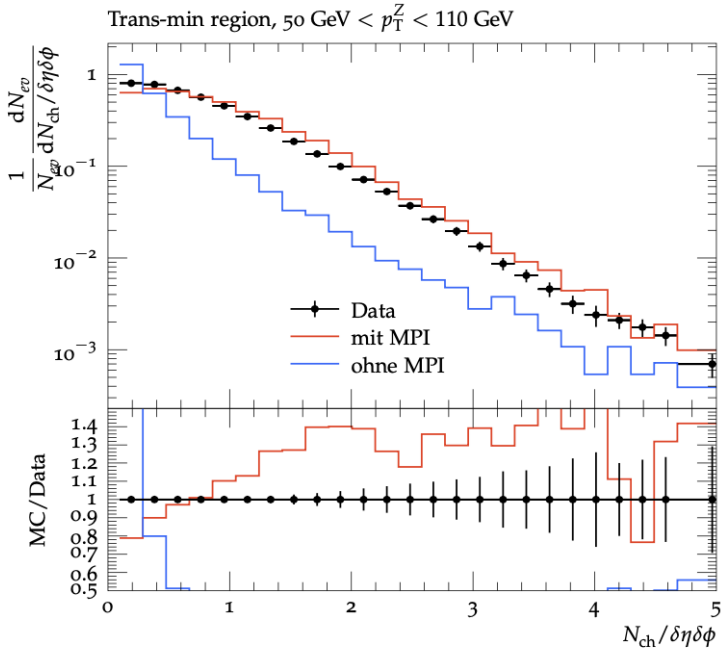
Merging important for jet observables

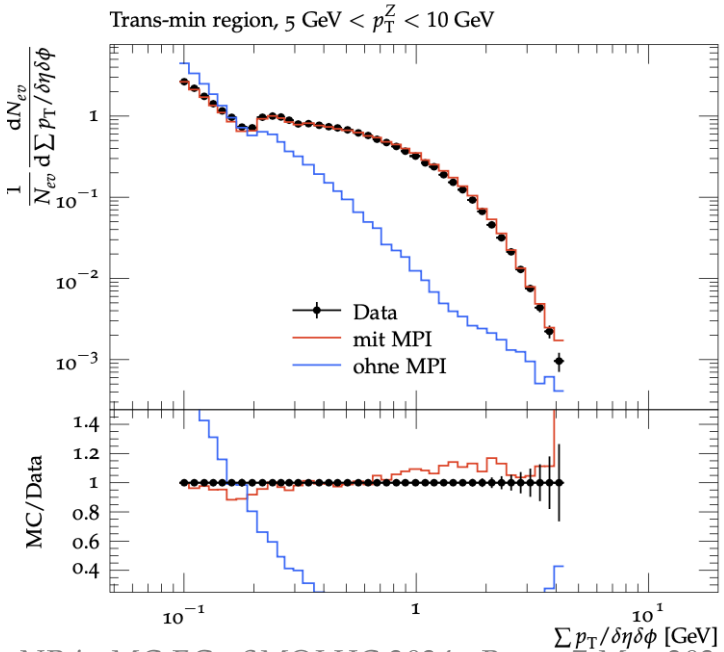
[K. Bartnick, B.Sc. thesis, KIT 2021]

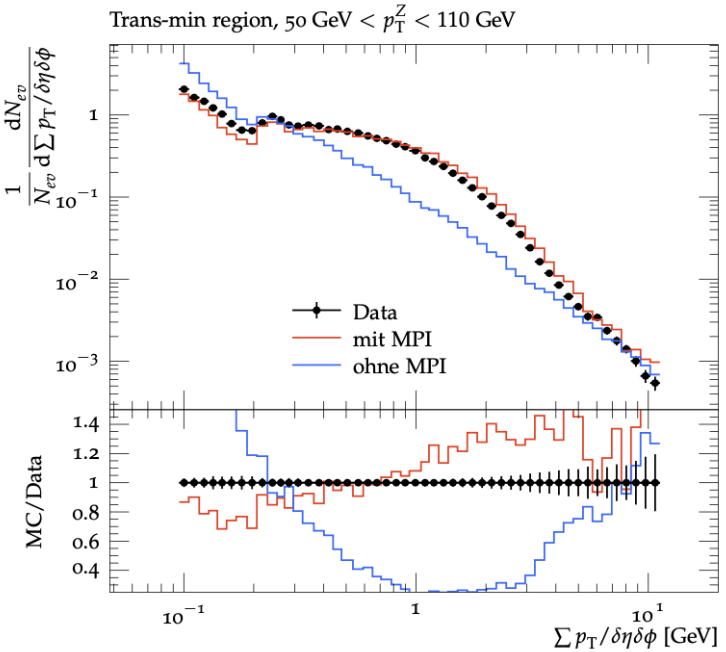
[ATLAS, EPJ C74 (12) 2014]

Example: Underlying event in Z+jets events









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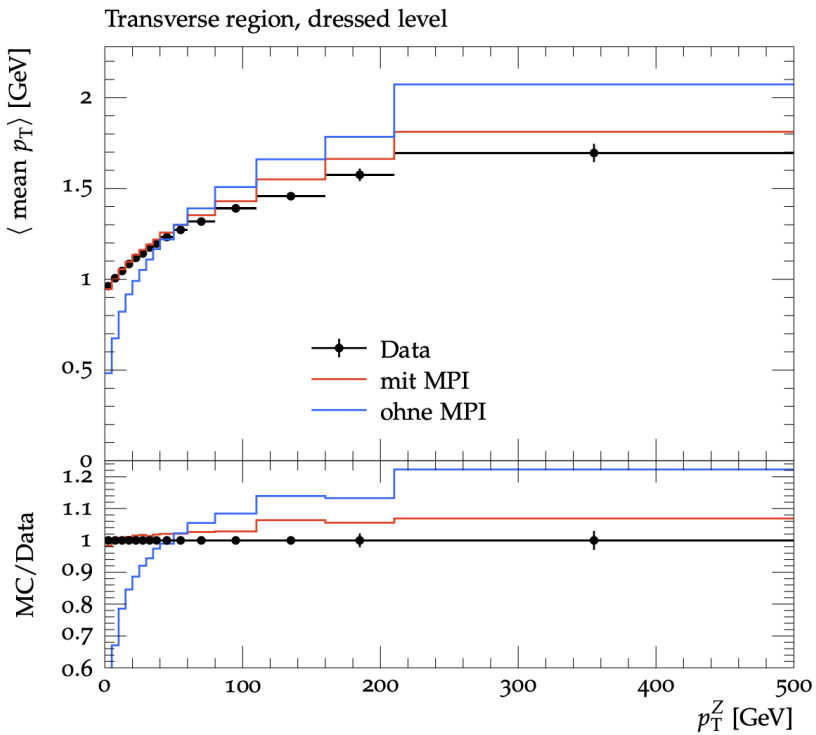

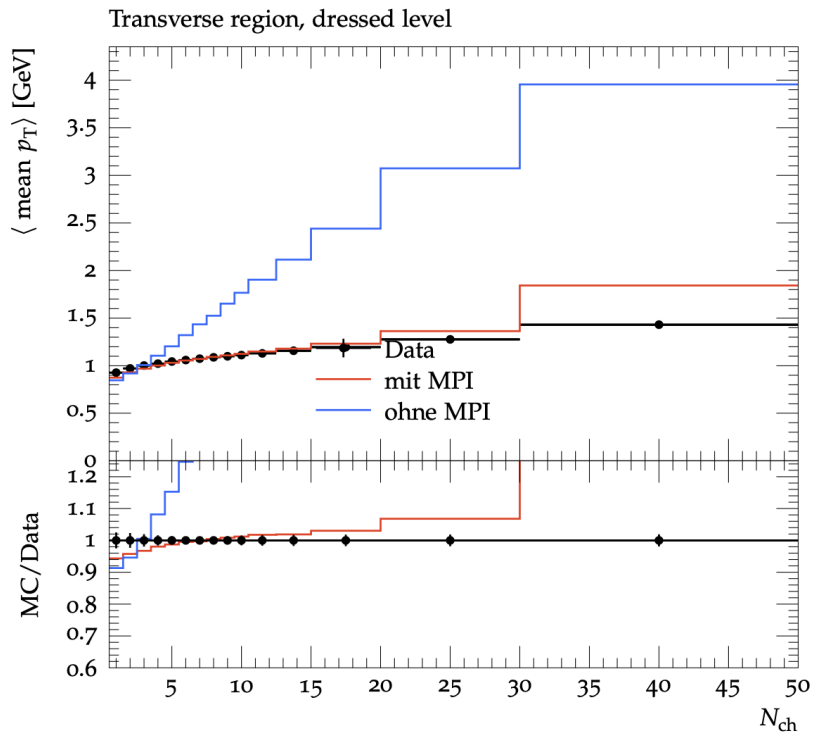

[K. Bartnick, B.Sc. thesis, KIT 2021]

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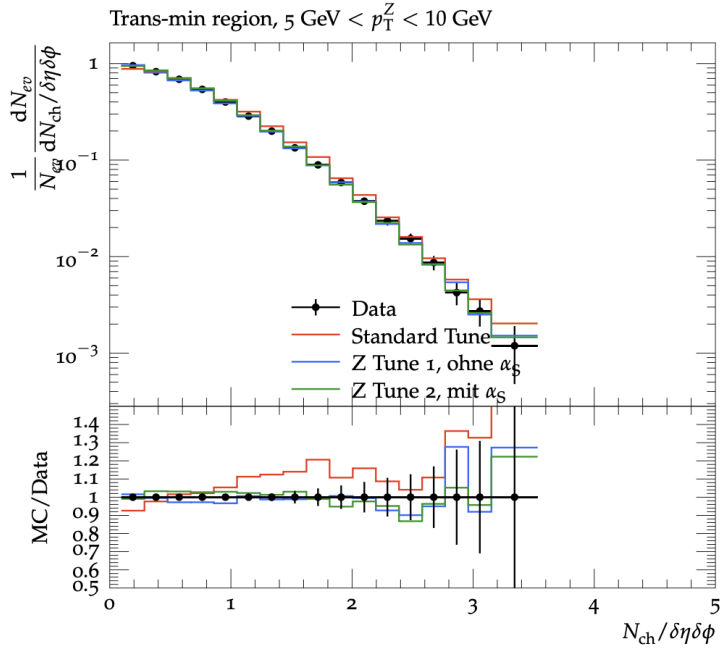

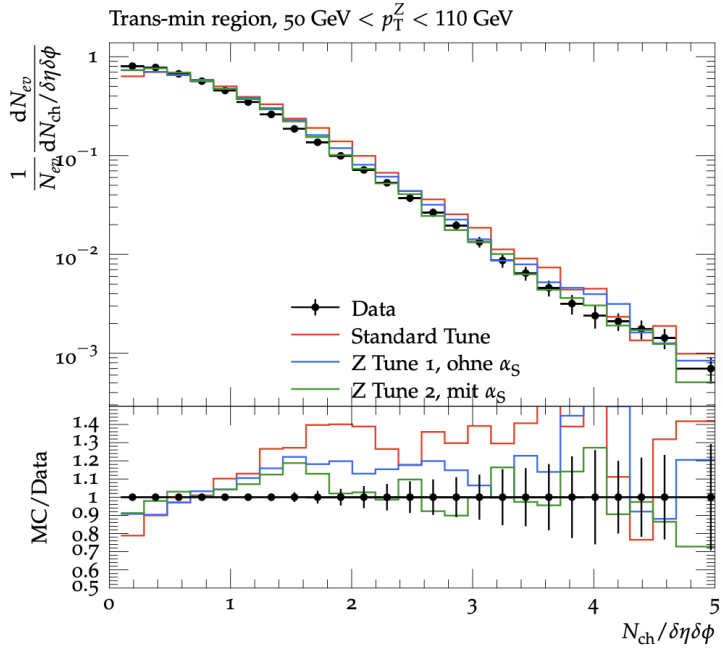

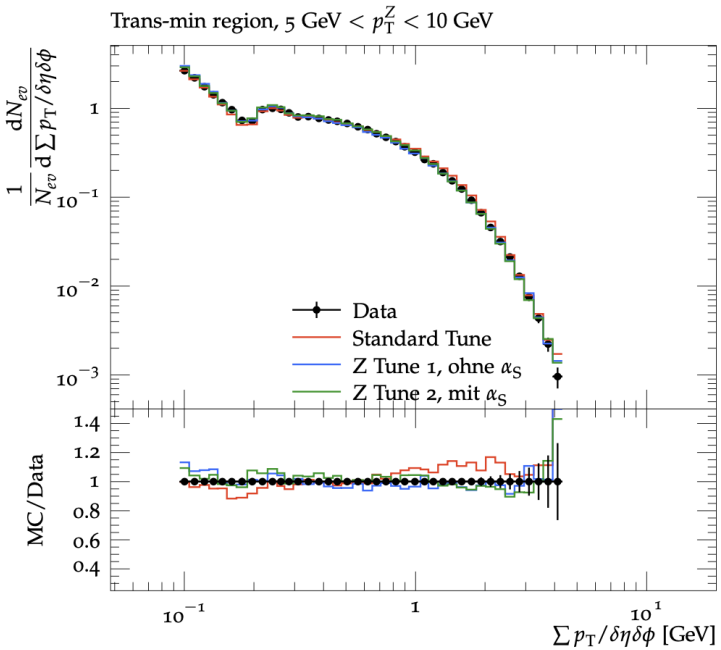

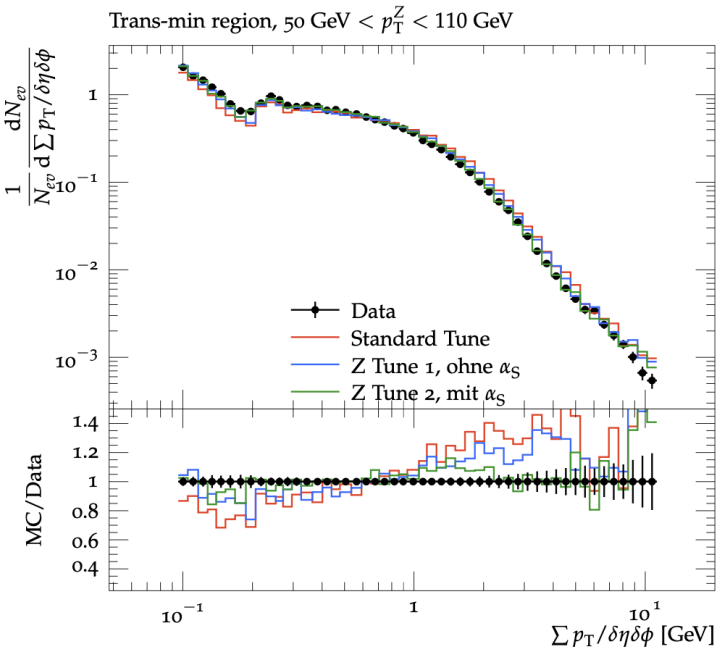

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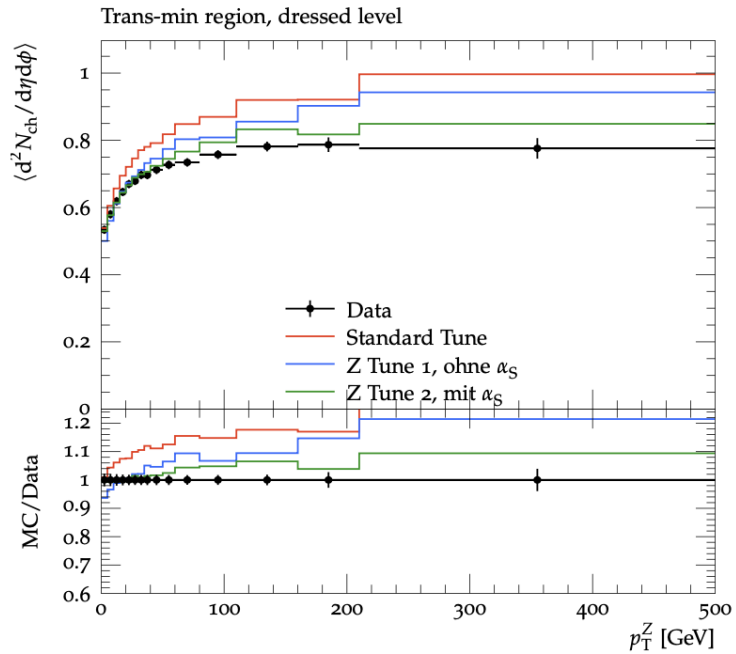
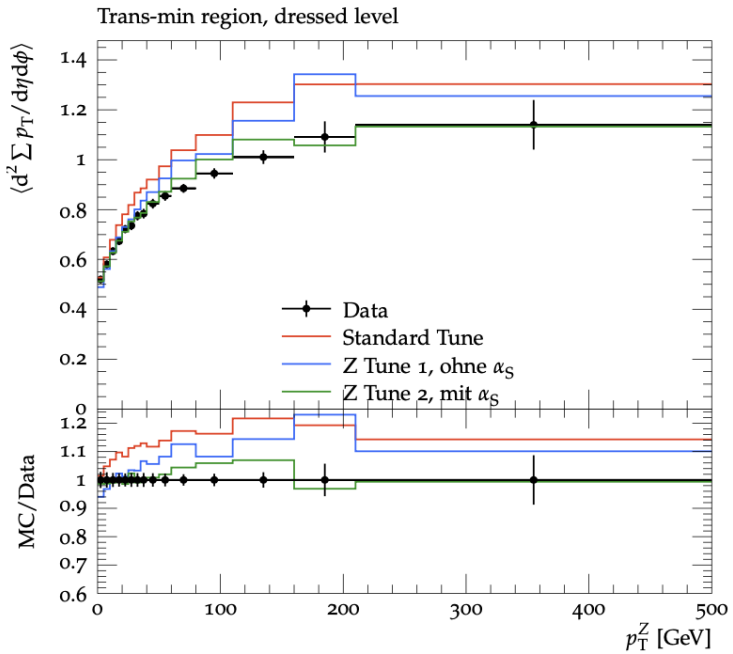
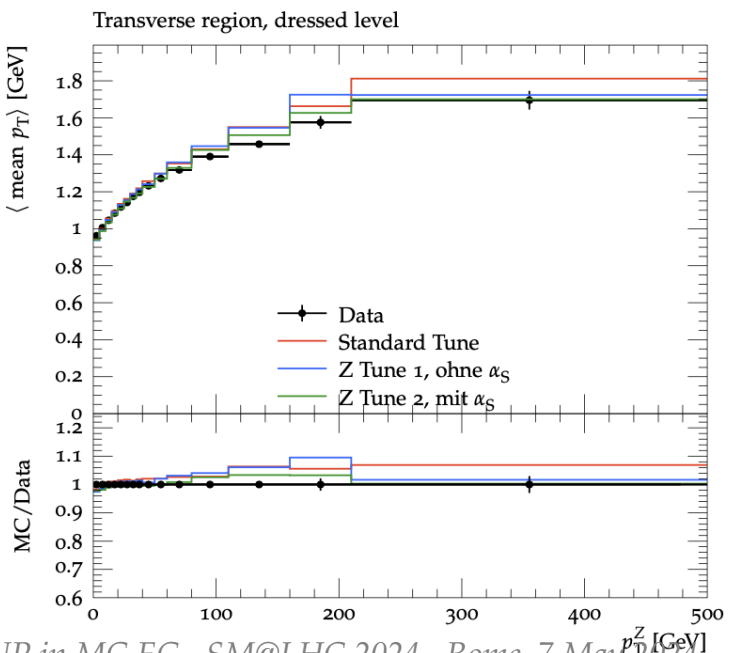
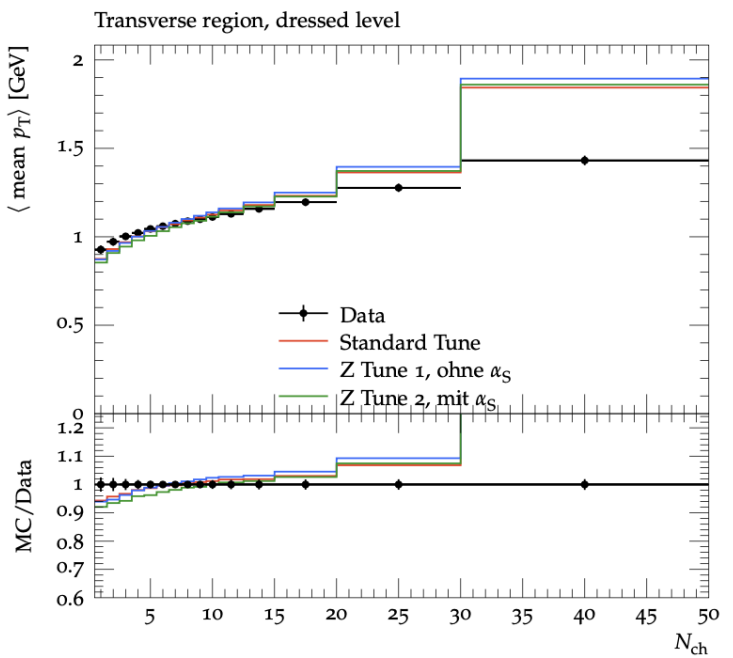








So far…

We find that for many observables we get a reasonable answer

Only looking at any *charged particles*

General activity from soft particles reflected

High $p_\perp$ observables decouple where expected (not shown)

How about more details?

Application in Physics Analysis

Consider precision prediction of differential cross section involving jets for observables that are not (very) sensitive to non-perturbative physics.

MC to determine non-perturbative bin-by-bin corrections.

Correction factor from simulation

$$C(\text{bin } i) = \frac{O(\text{PS+Had+MPI})}{O(\text{PS})}$$

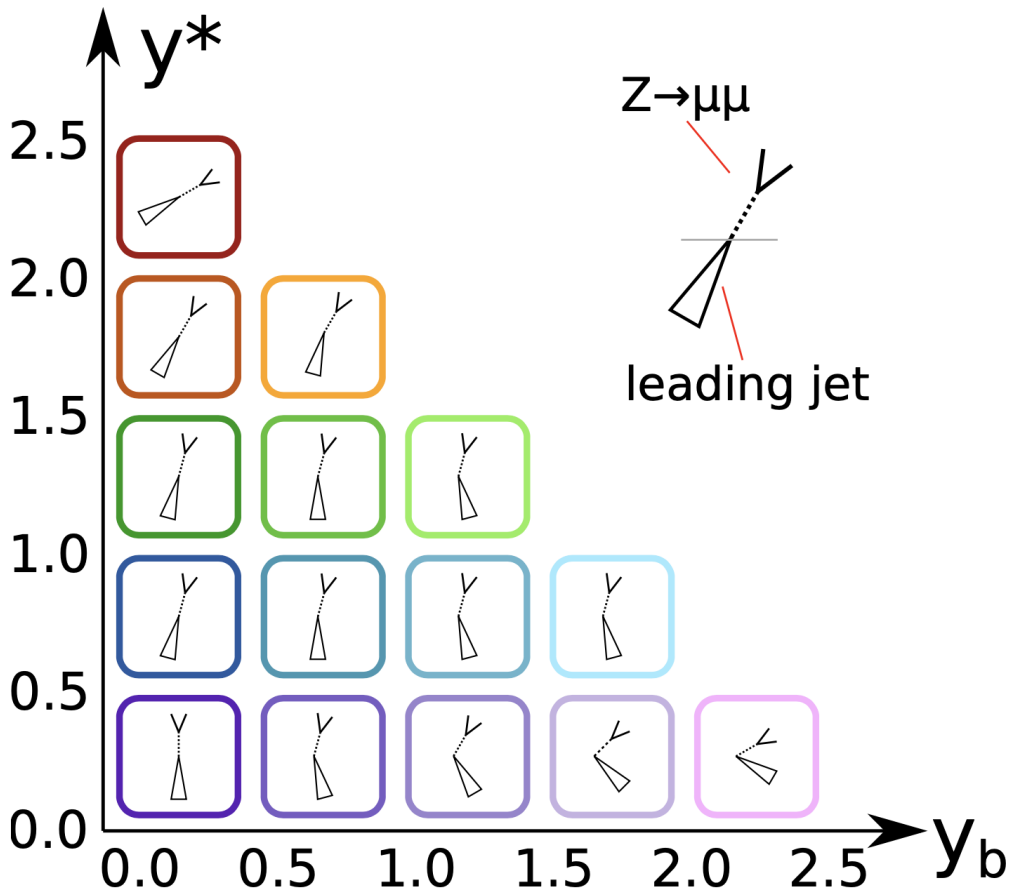
Compare dijets and Z+jets.

Use LO/NLO simulation with Herwig 7 (CH3 tune), Anti-kt jets with $R = 0.4, 0.8$ (AK4, AK8).

Triple differential dijet/Z+jet production

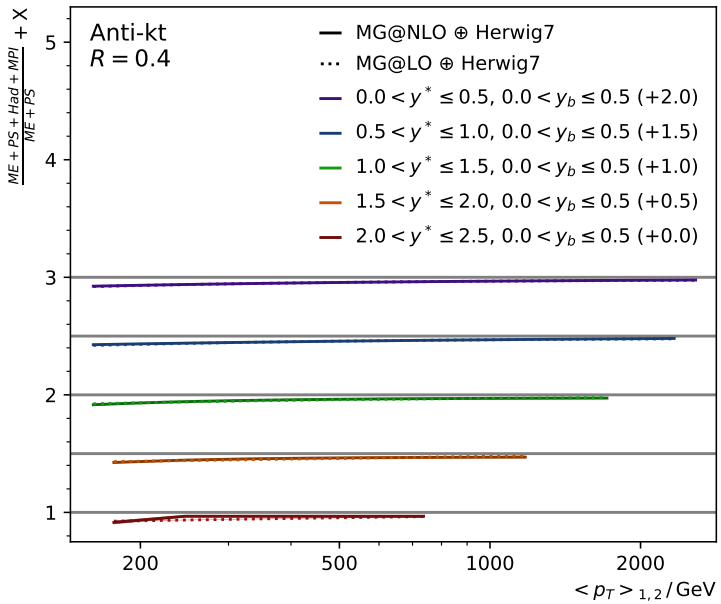
Expect: smallest NP effects in central region. Differences between large y_b and large y^*? "Spill-over" of extra activity?

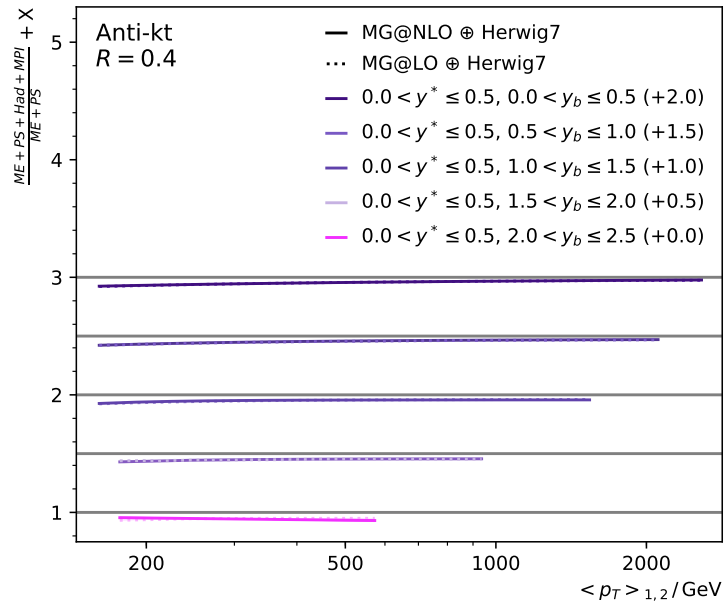
[SG, M. Horzela, M. Kaur, K. Rabbertz, A. Singla, C. Verstege]

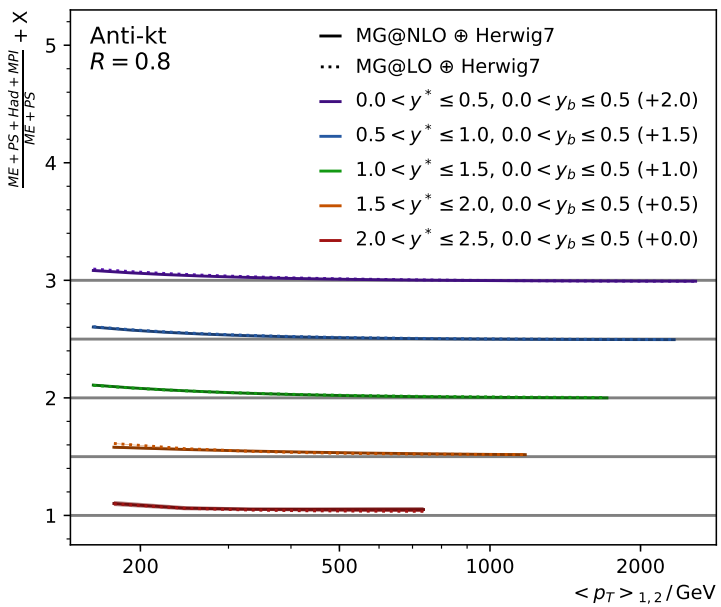


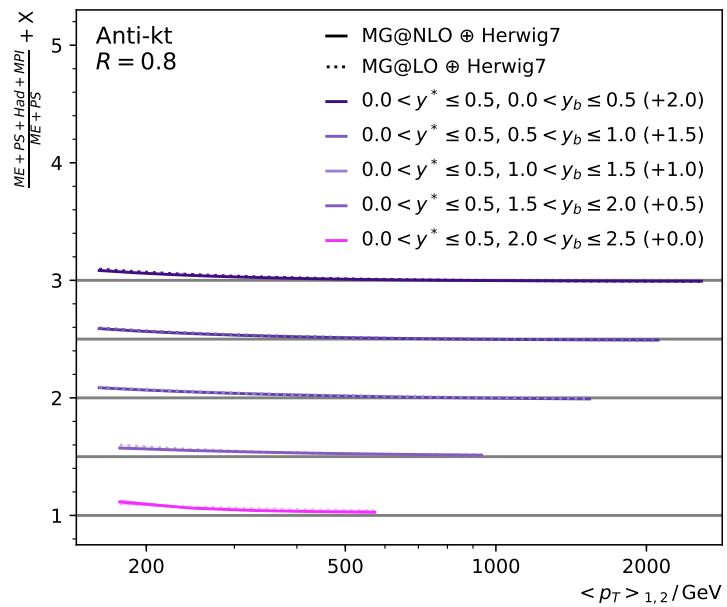
[Fig. from M.J. Schnepf, PhD thesis, KIT-ETP 2022.]

NP correction factors — Dijets Total

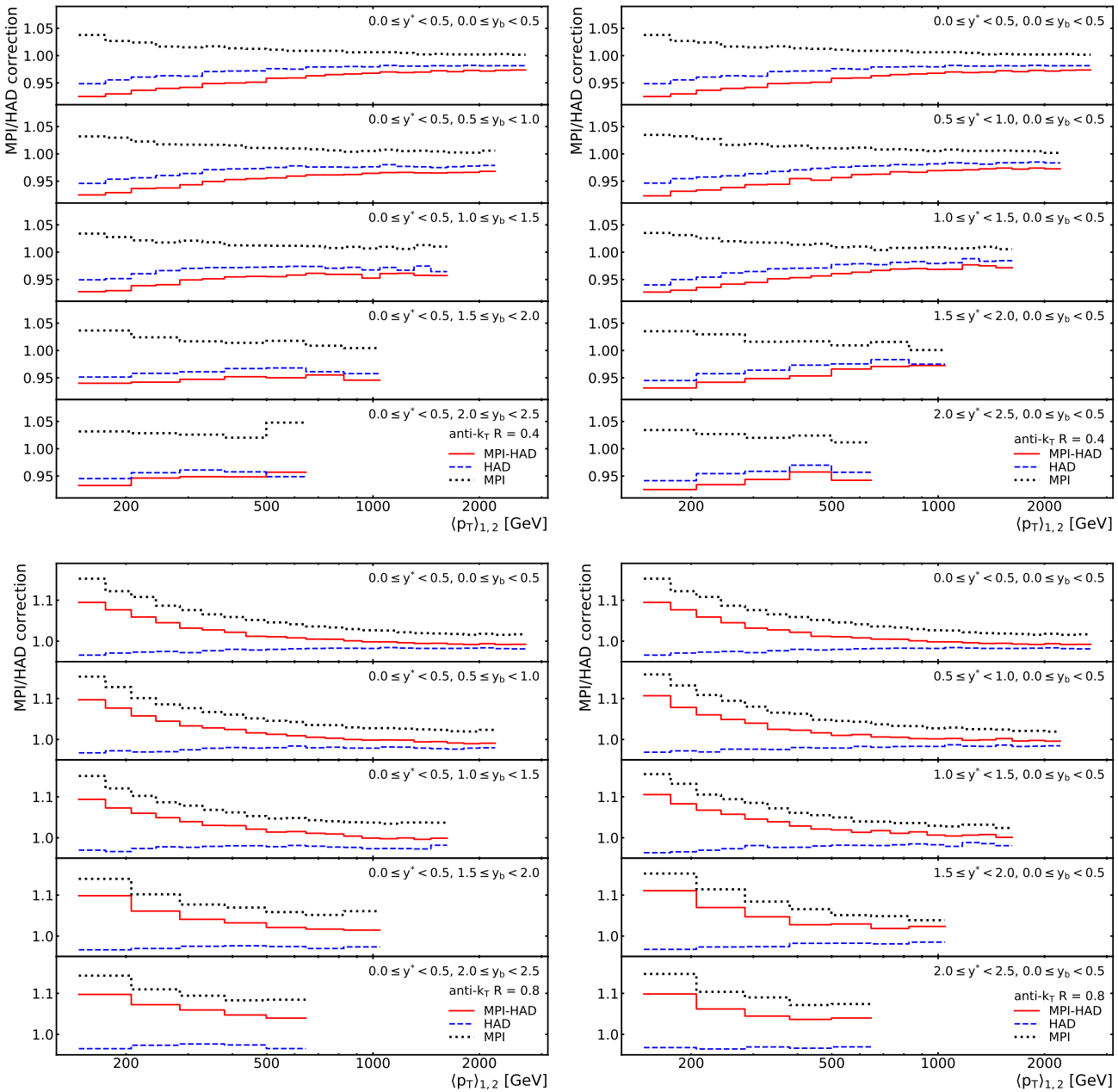




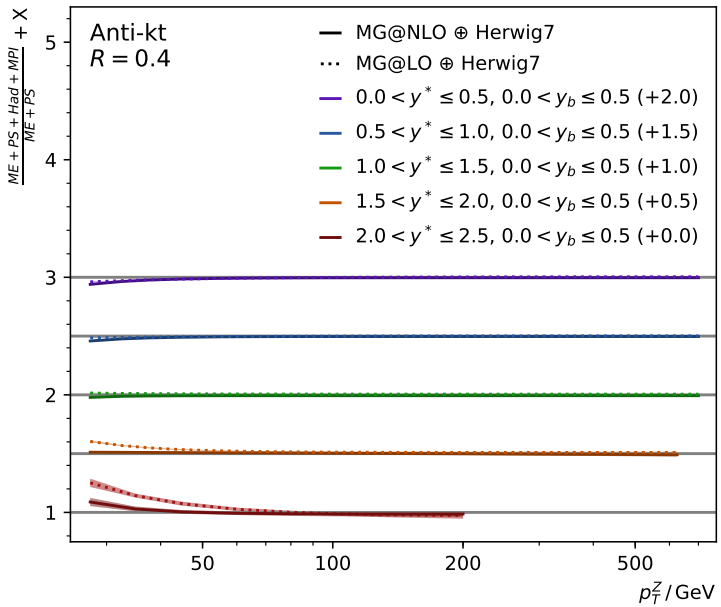


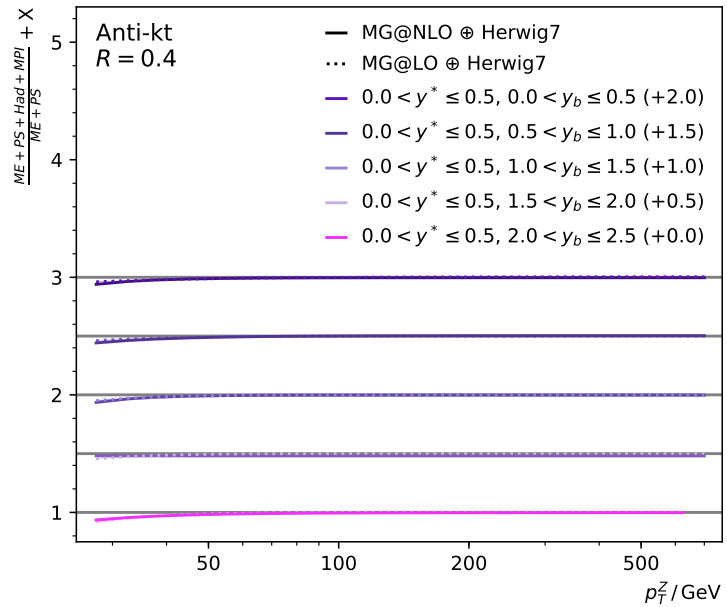


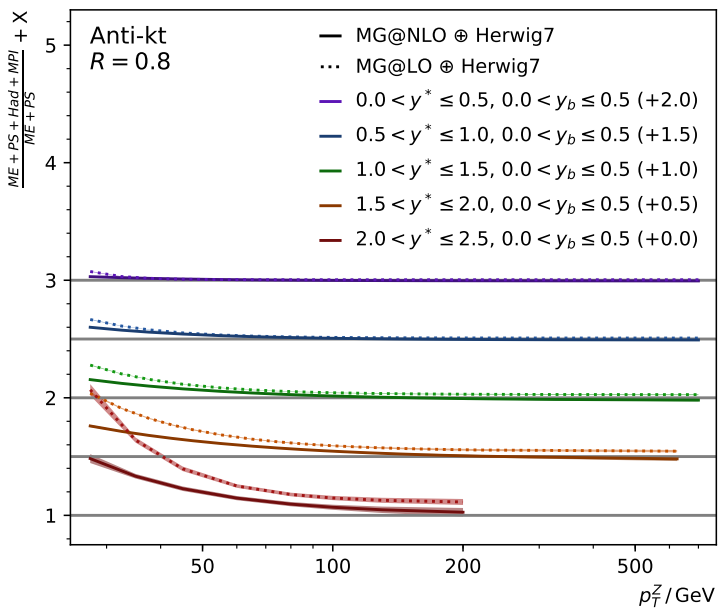
NP correction factors — Dijets MPI/Had

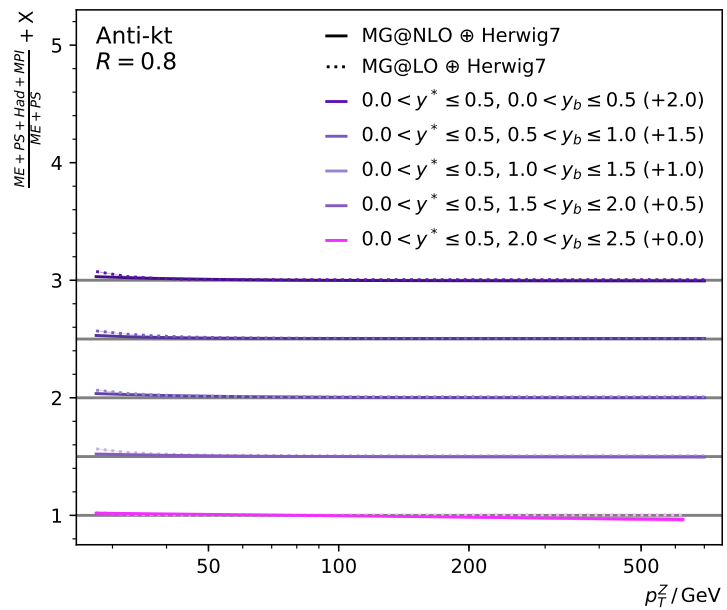


NP correction factors — Z+jet Total

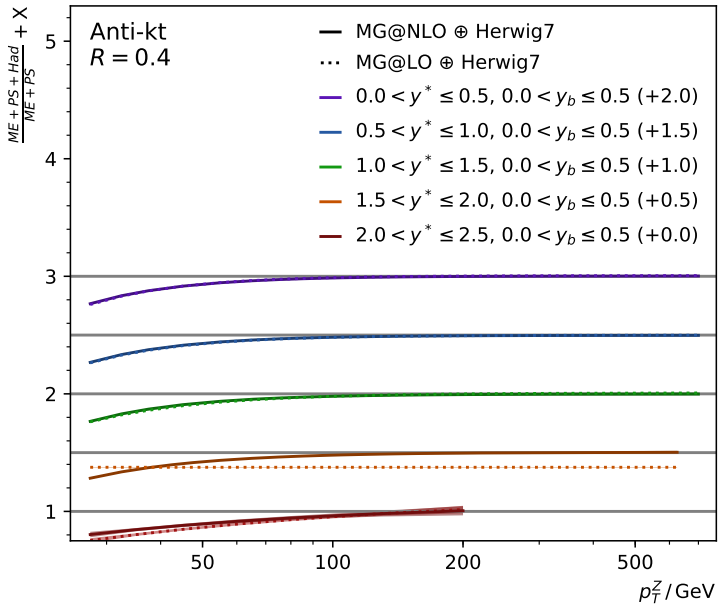


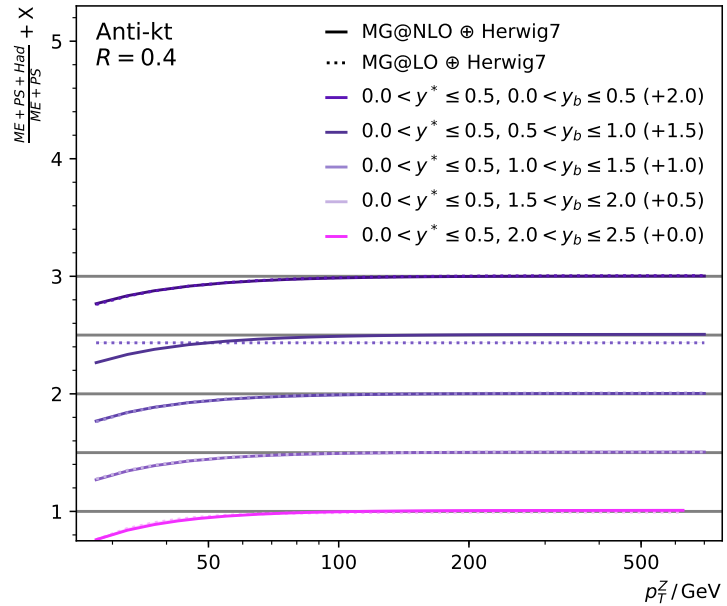


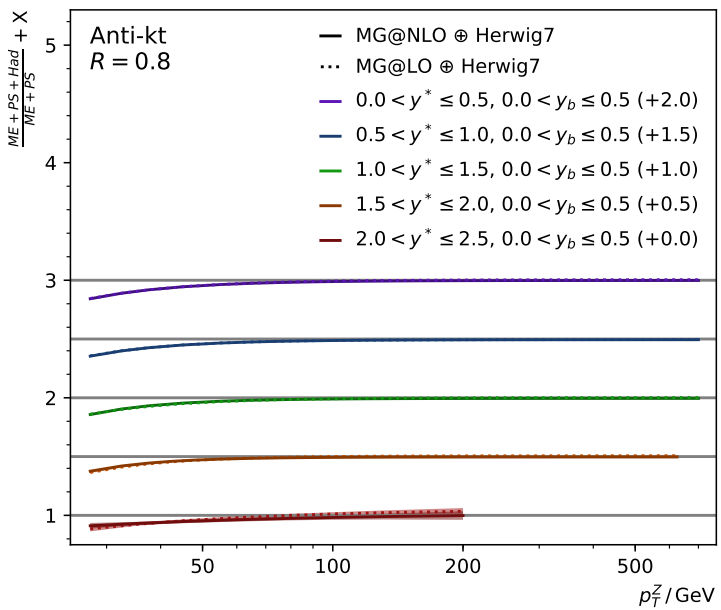


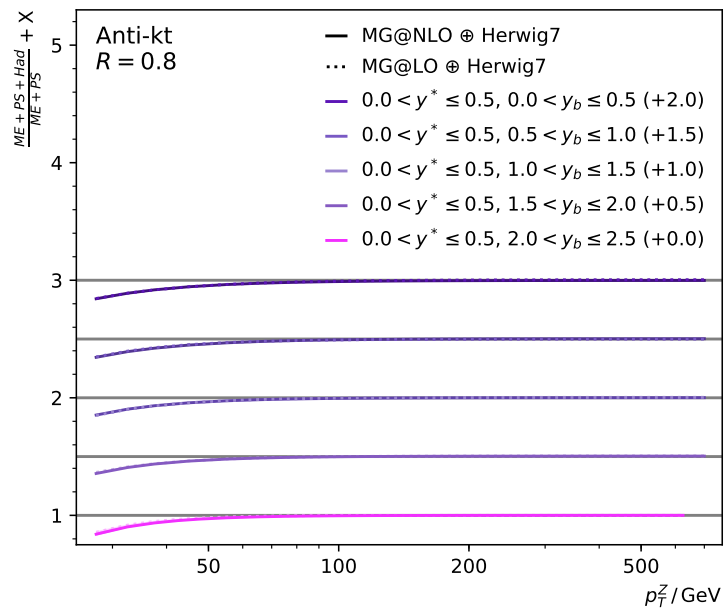


NP correction factors — Z+jet Hadronization

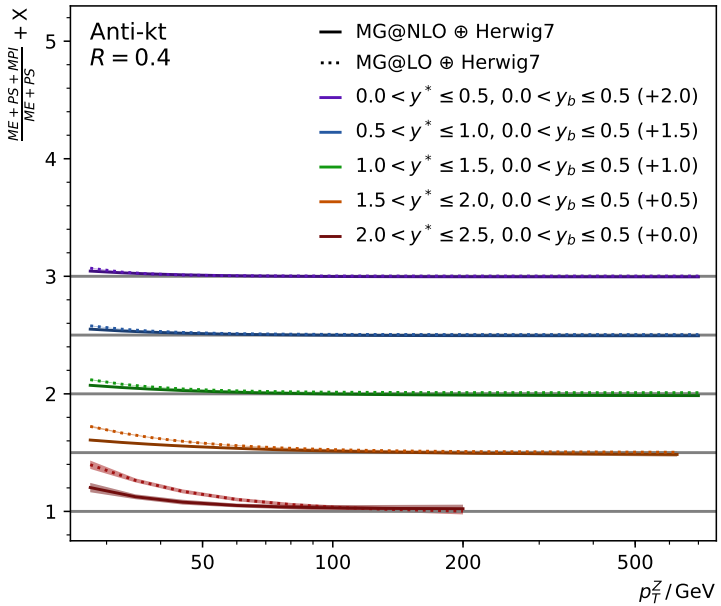


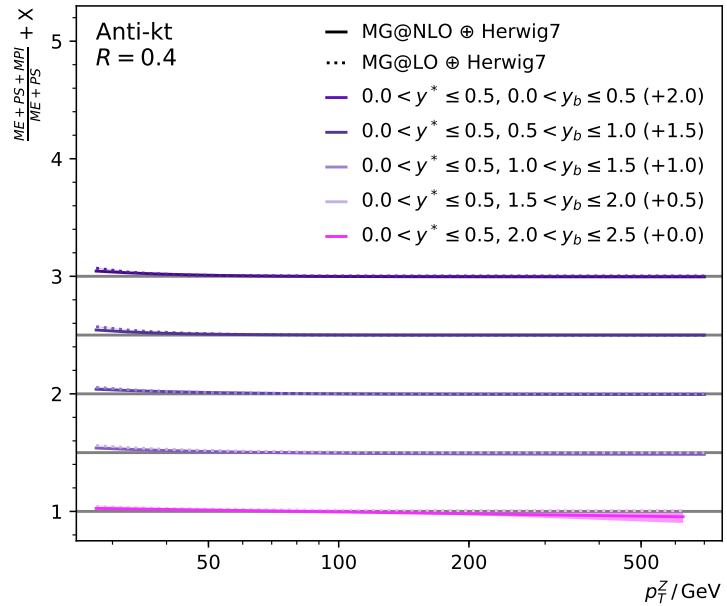


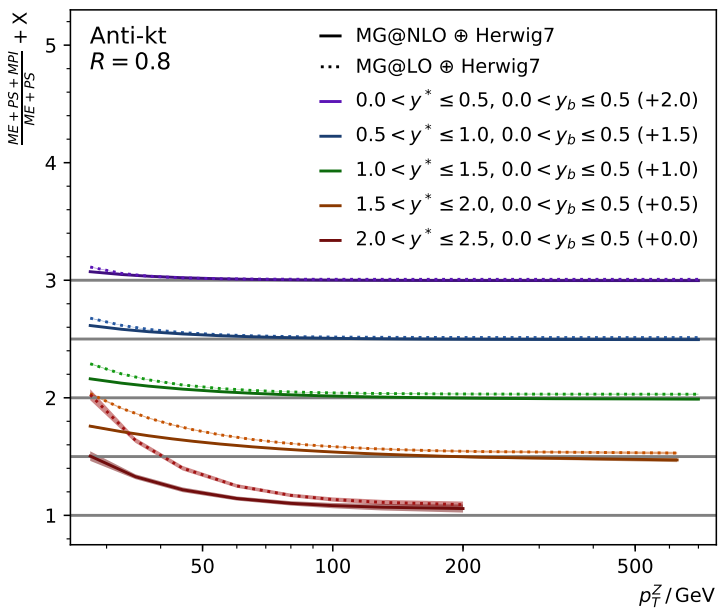


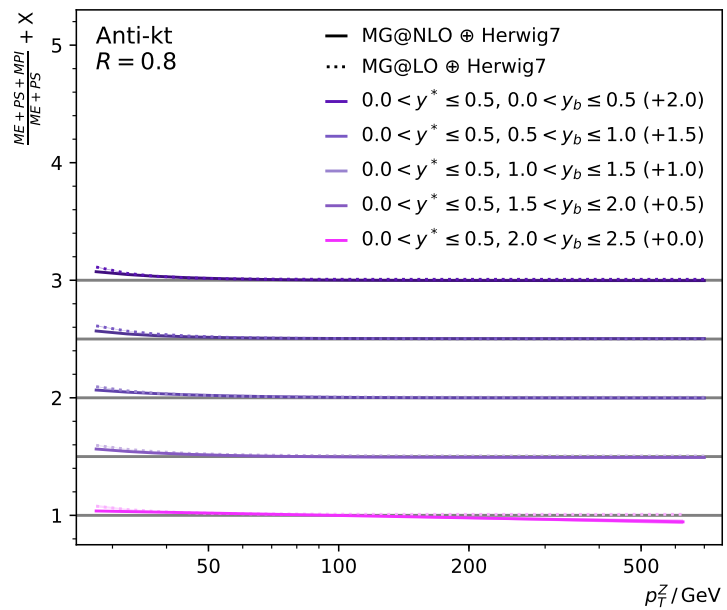


NP correction factors — Z+jet MPI

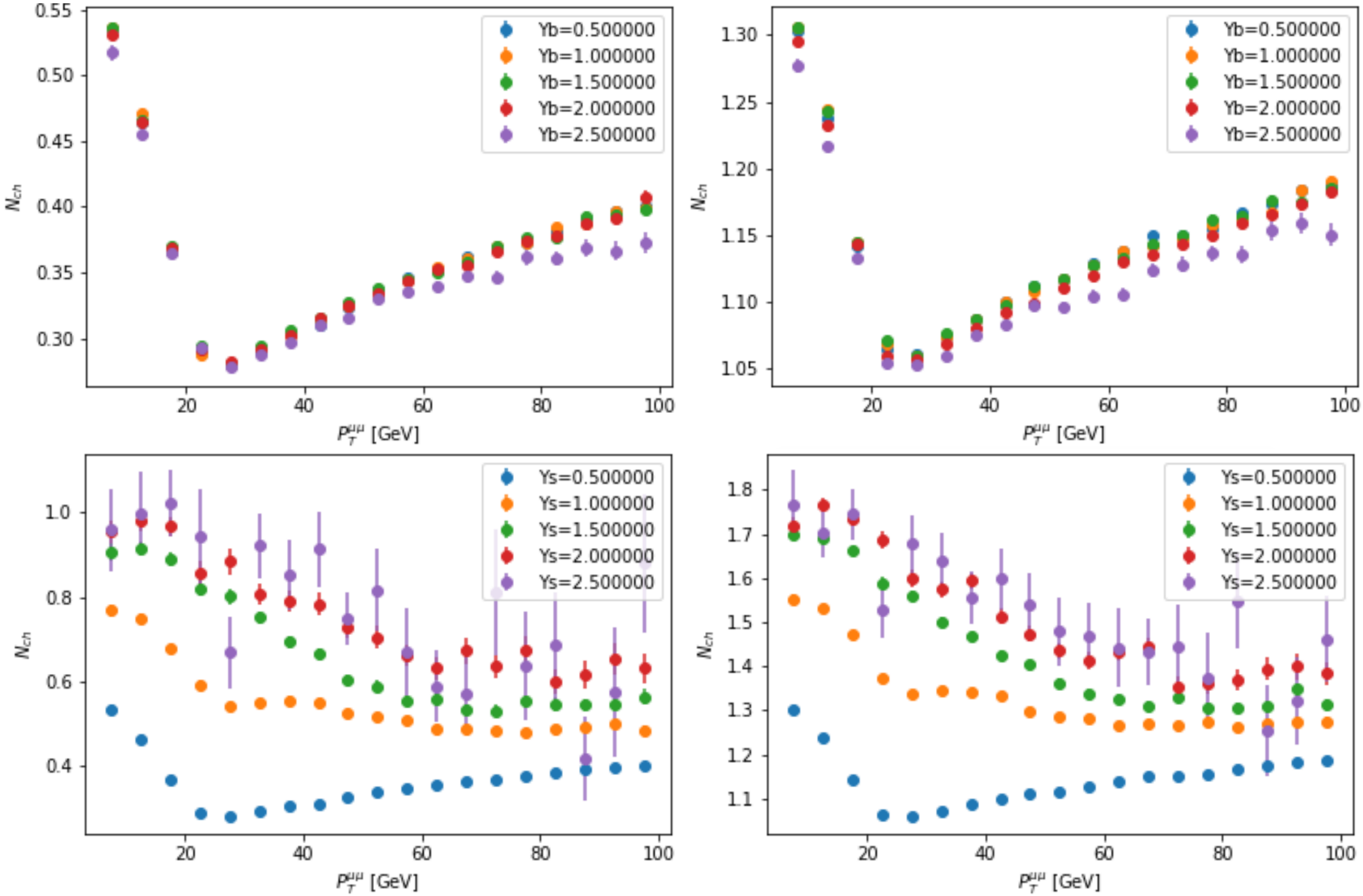








Z+jet "differential" UE



[D. Leonardi, B.Sc. thesis, KIT 2024]

MPI off/on

Observations

Correction factors from *interplay* of Hadronization and MPI

Larger at small $p_\perp$, as expected

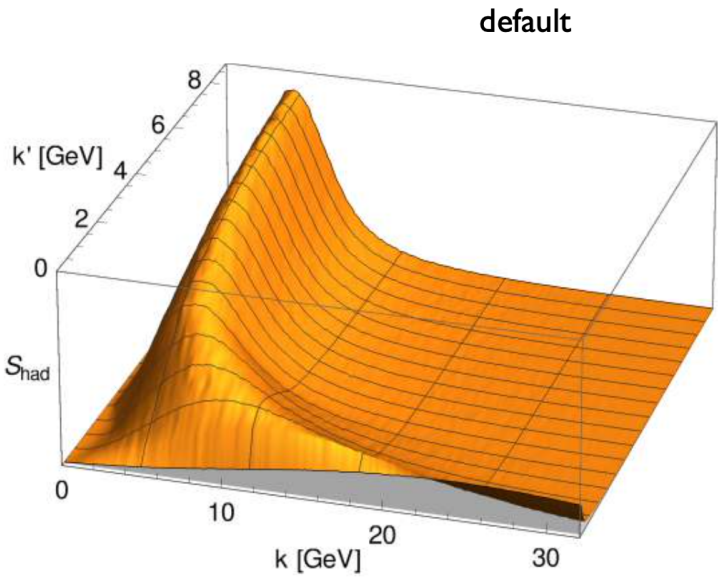
Hadronization tends to reduce cross section at low $p_\perp$ — energy get pulled out of the jet from cluster/string towards colour connected partner.

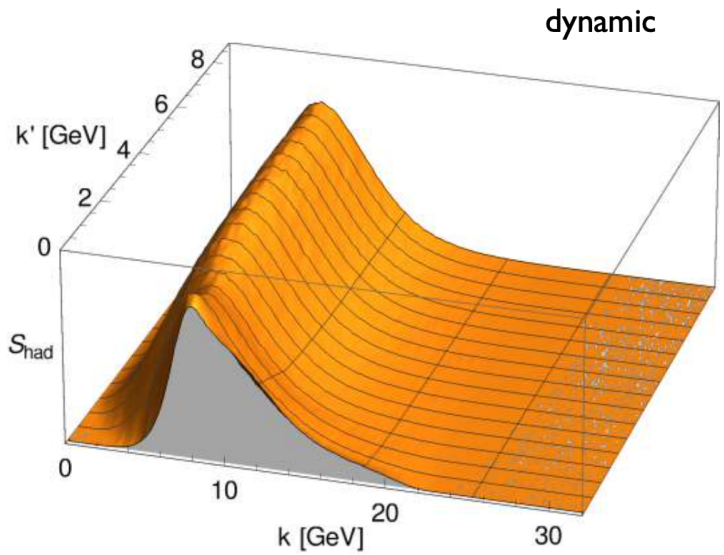
MPI enhances cross section due to extra activiy added

MPI effect gets very large (up to $2\times$) at low $p_\perp$

Dynamical Hadronization corrections

Use dynamical gluon mass and model for cluster splittings with smooth continuation of cluster dynamics from parton shower.

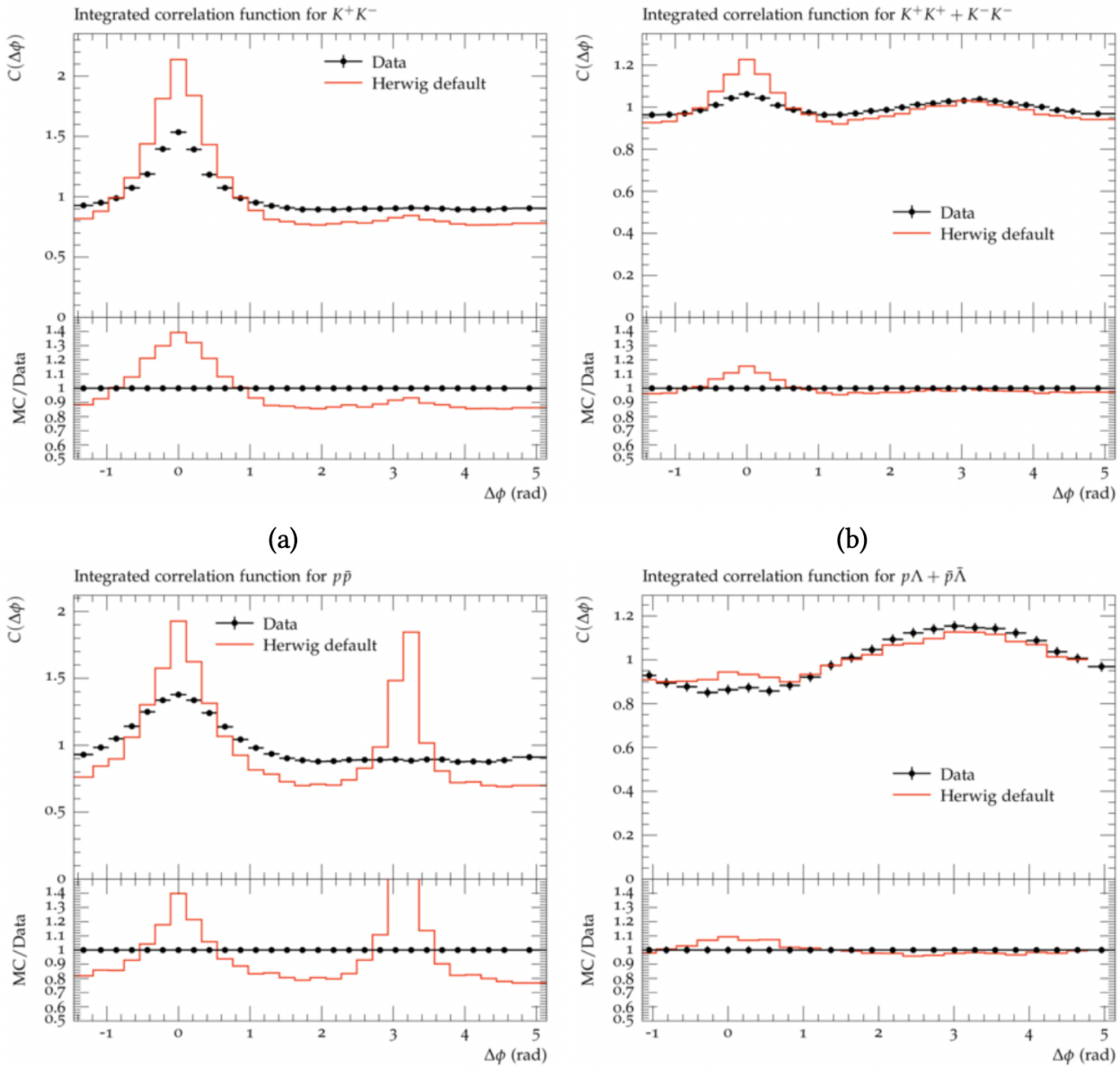




Hadronization corrections not picked up from hard parton scales anymore!

[Plätzer, Samitz]

Example: Two-particle correlations



[Ronja Zimmermann, M.Sc. thesis, KIT 2021; ALICE, EPJC77(2017)8,569]

Example: Two-particle correlations

Cluster model innherently introduces strong two particle correlations in cluster decay

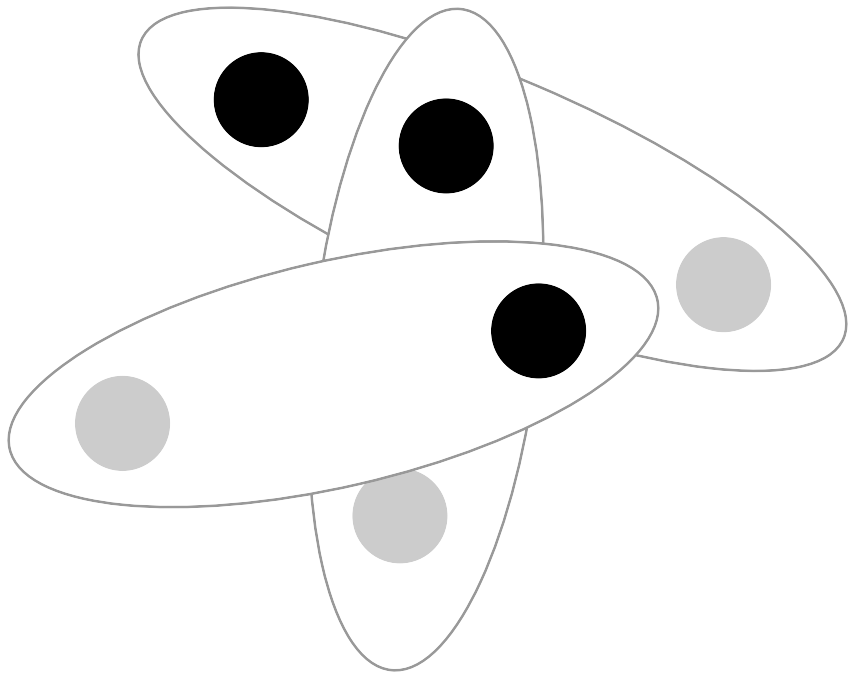
$$\text{cluster} \longrightarrow \text{hadron} + \text{hadron}$$

Simple model to overcome this strong correlation, rather than bookkeeping in hadronization do *post hadronization momentum swaps*

[Ronja Zimmermann, M.Sc. thesis, KIT 2021]

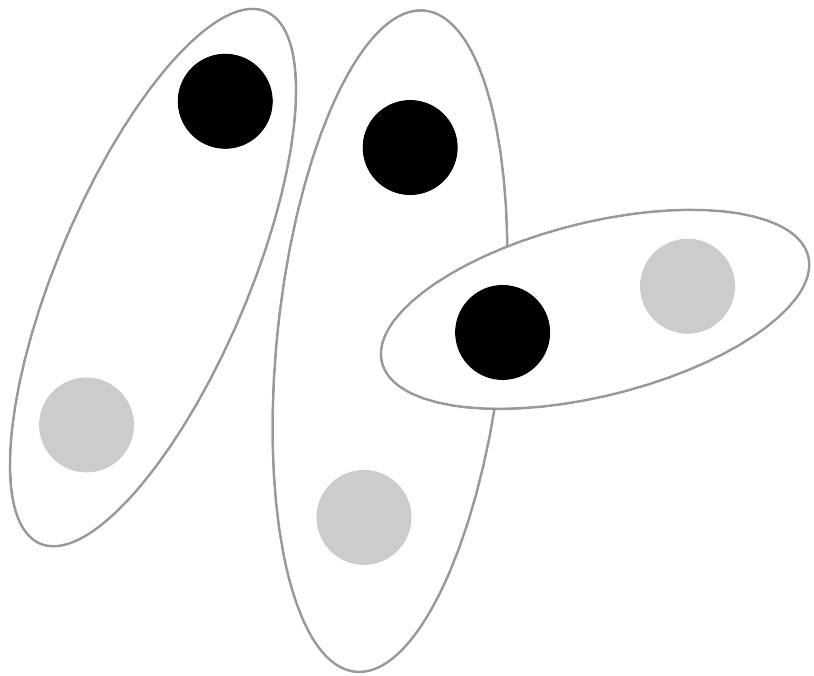
New modes of colour reconnection

Colour structure as it may result from parton shower



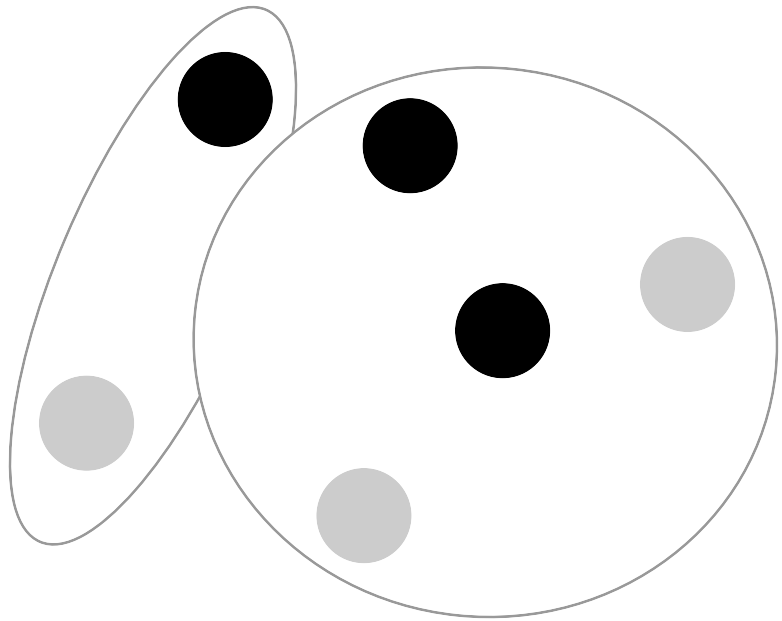
New modes of colour reconnection

After colour reconnection $MM \to MM$



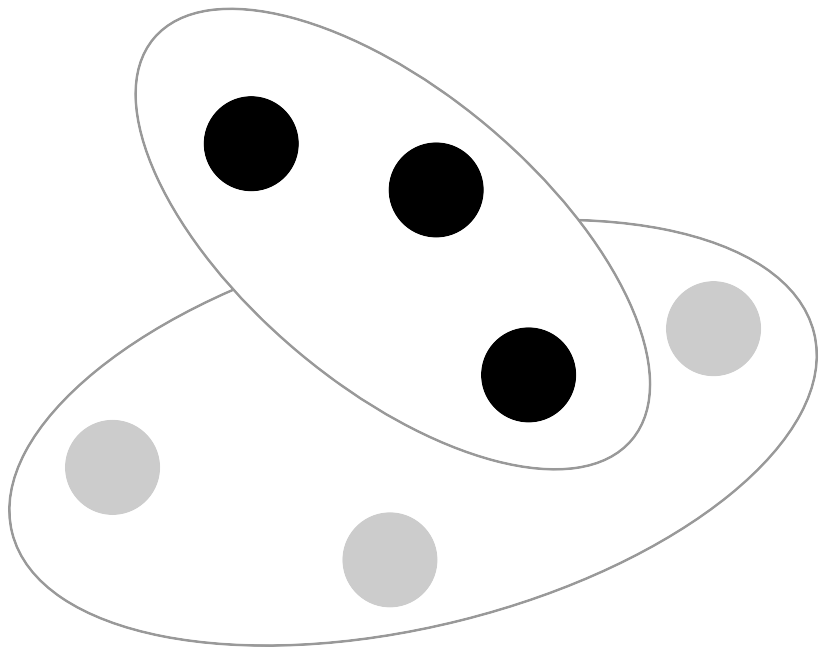
New modes of colour reconnection

$MM \to (qq) - (\bar{q}\bar{q})$



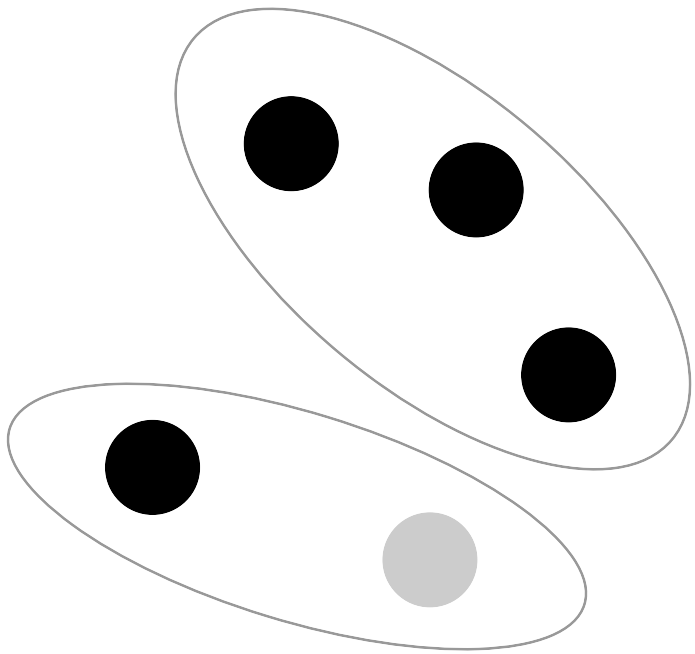
New modes of colour reconnection

Baryonic reconnection



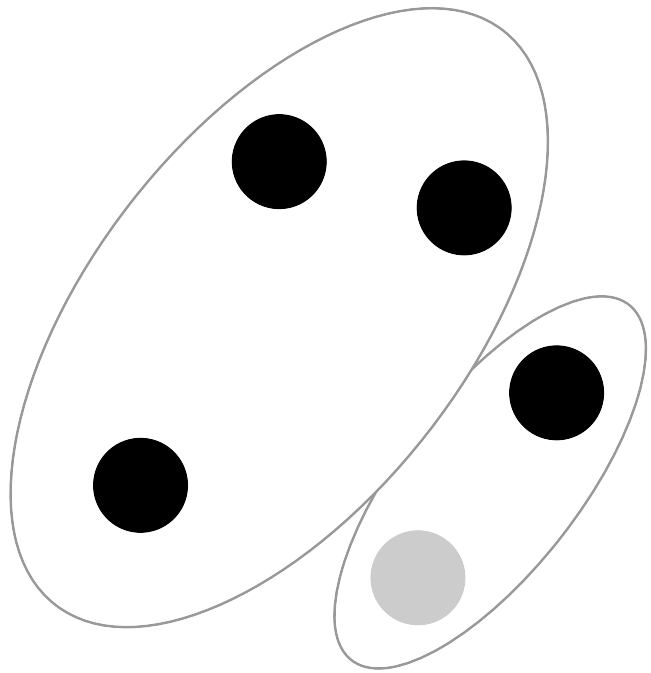
New modes of colour reconnection

Baryonic and mesonic cluster



New modes of colour reconnection

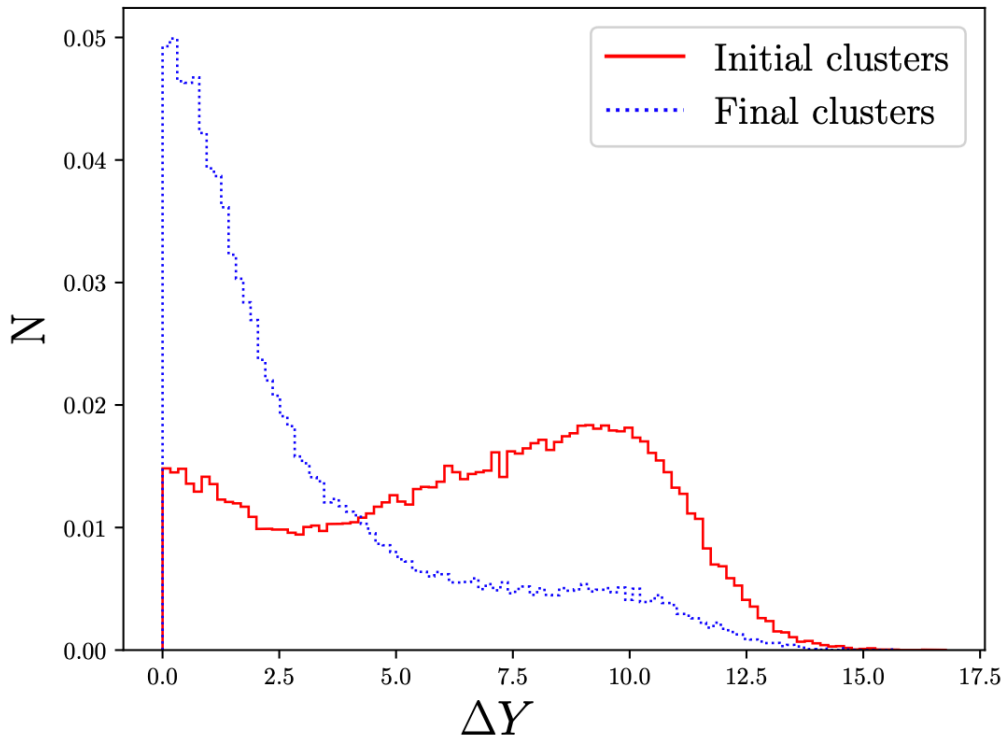
Baryonic and mesonic cluster



Colour reconnection from soft gluon evolution

CR could be initiated by soft gluon exchange = colour-anticolour exchange in the fundamental representation.

- Evolution of multiple clusters in colour space
- project on colour singlet states
- phase space dependent weights
- preconfinement evident



[SG, Kirchgaeßer, Plätzer, Siodmok, JHEP 11 (2018) 149]

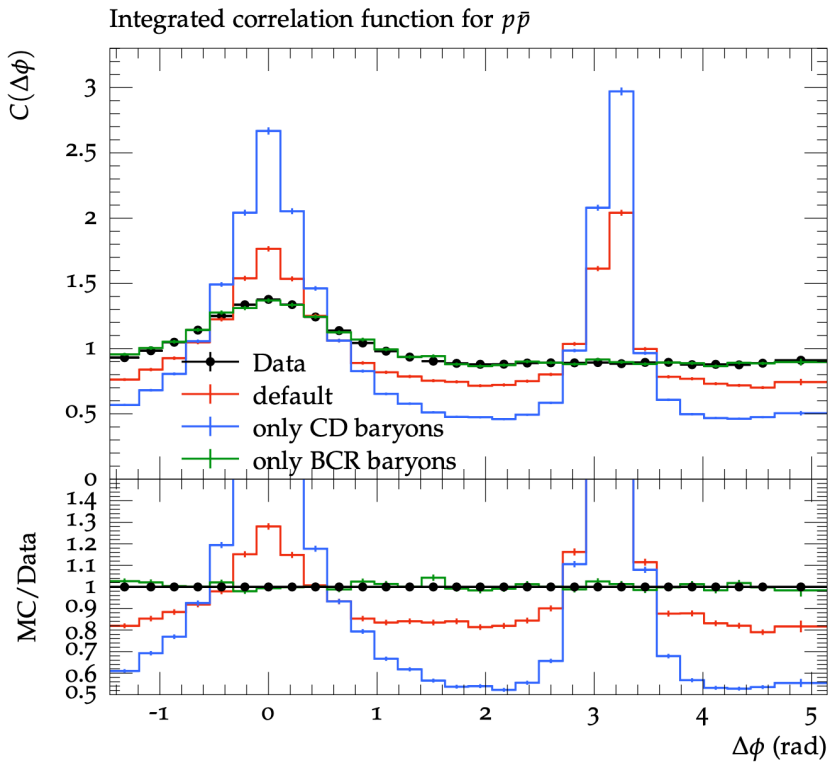
Cluster fission dynamics

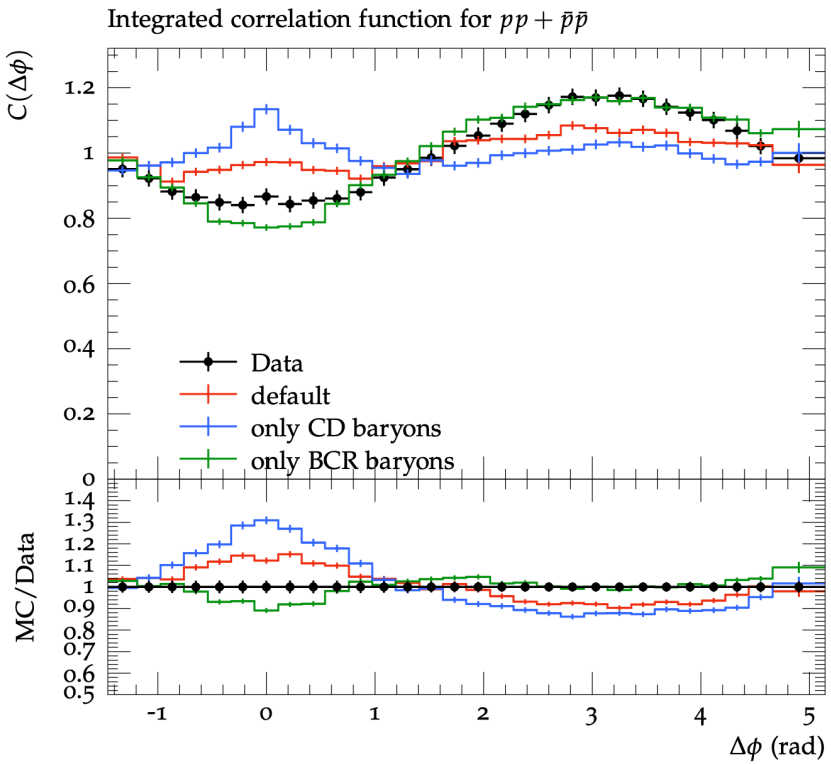
Still only longitudinal splitting in $C \to CC$ phase space.

Demand smooth connection to parton shower μ^2 = UV cutoff for hadronization $\to$ real sensitivity to "soft" regions in event shapes etc. [Plätzer, Samitz, *to appear*]

Demand smooth interpolation from perturbative to non-perturbative physics.
Currently under study [SG, S. Kiebacher, S. Plätzer, Priedigkeit, *in progress*]

First steps…



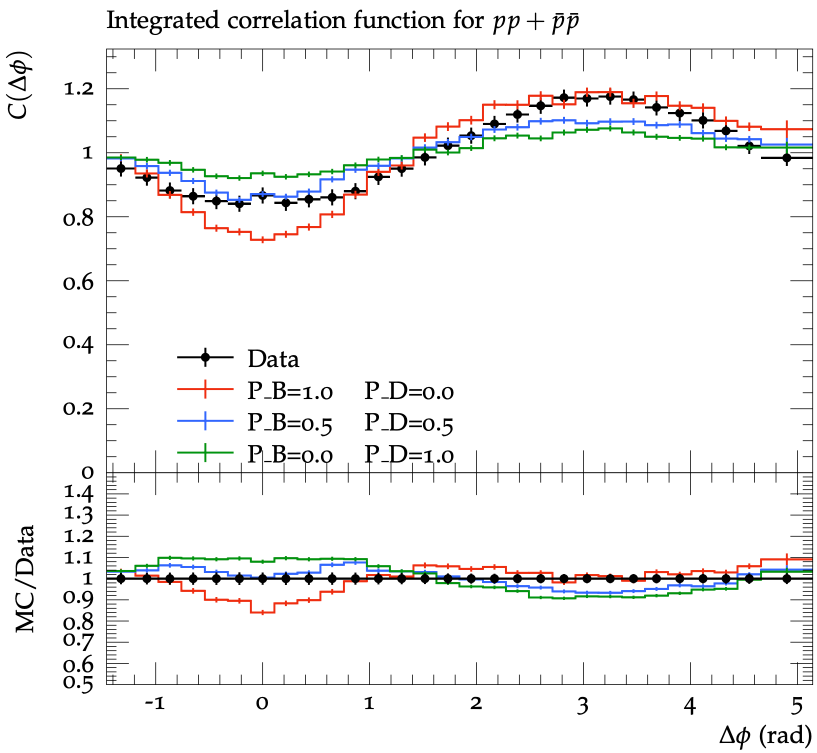


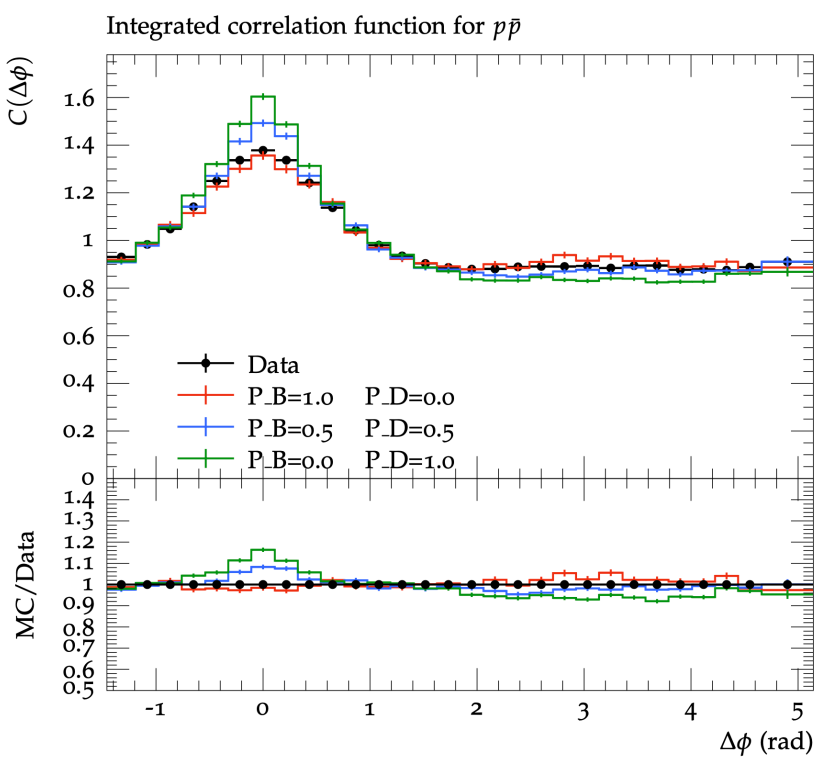
[SG, Kiebacher, Plätzer, Priedigkeit, in progress]

[Data from ALICE, EPJC77(2017)8,569]

Cluster Decay correlations as expected
No strong correlations from CR.

First steps…





[SG, Kiebacher, Plätzer, Priedigkeit, in progress]

[Data from ALICE, EPJC77(2017)8,569]

Balance of diquark-pair and baryonic clusters.

Summary and conclusion

Overview of hadronization and soft physics models

NP corrections can be quite large in forward region
How robust are the MPI models?
More data?

Ideas need to be tied together in a bigger context:

- parton showers beyond leading colour
- colour reconnection from soft gluon evolution
- hadronization is not “stand-alone”

Close links to high density phenomena, $\rightarrow$ heavy ions
$\rightarrow$ colour ropes in Lund string model

A fresh look at soft physics must tie many loose ends together