Herwig Overview (soft physics)

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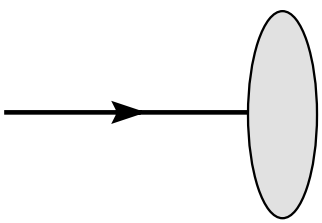

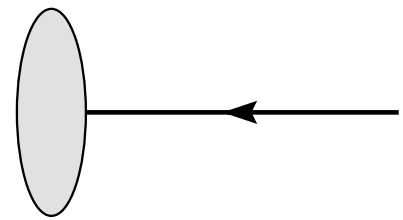

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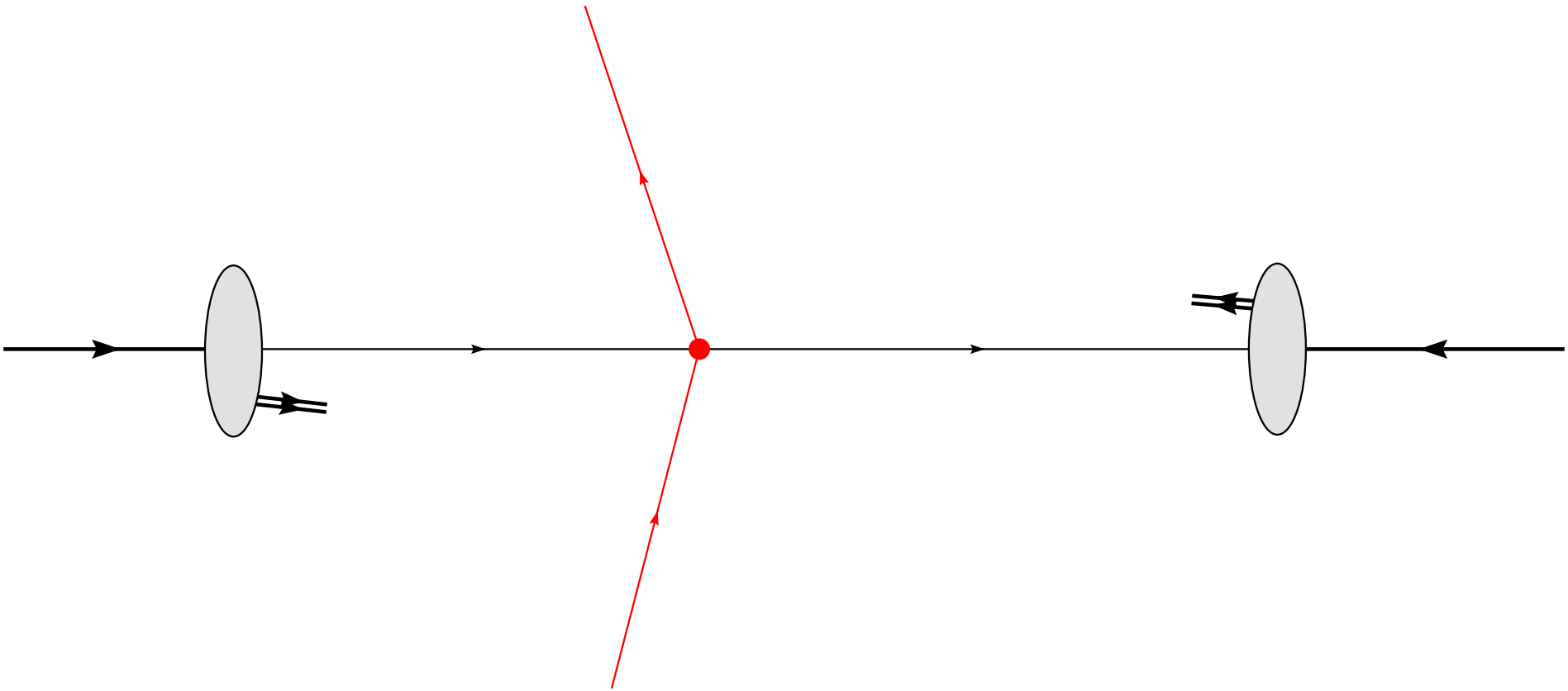

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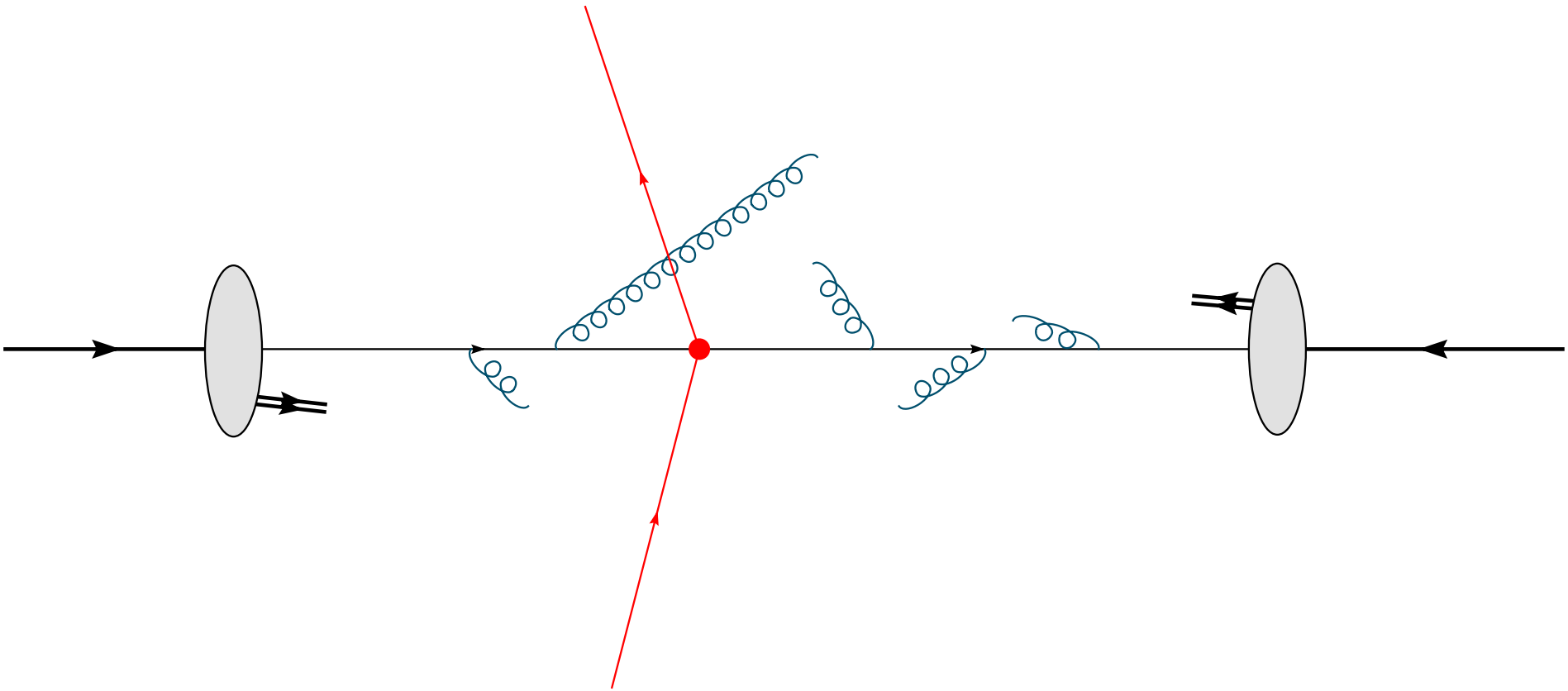

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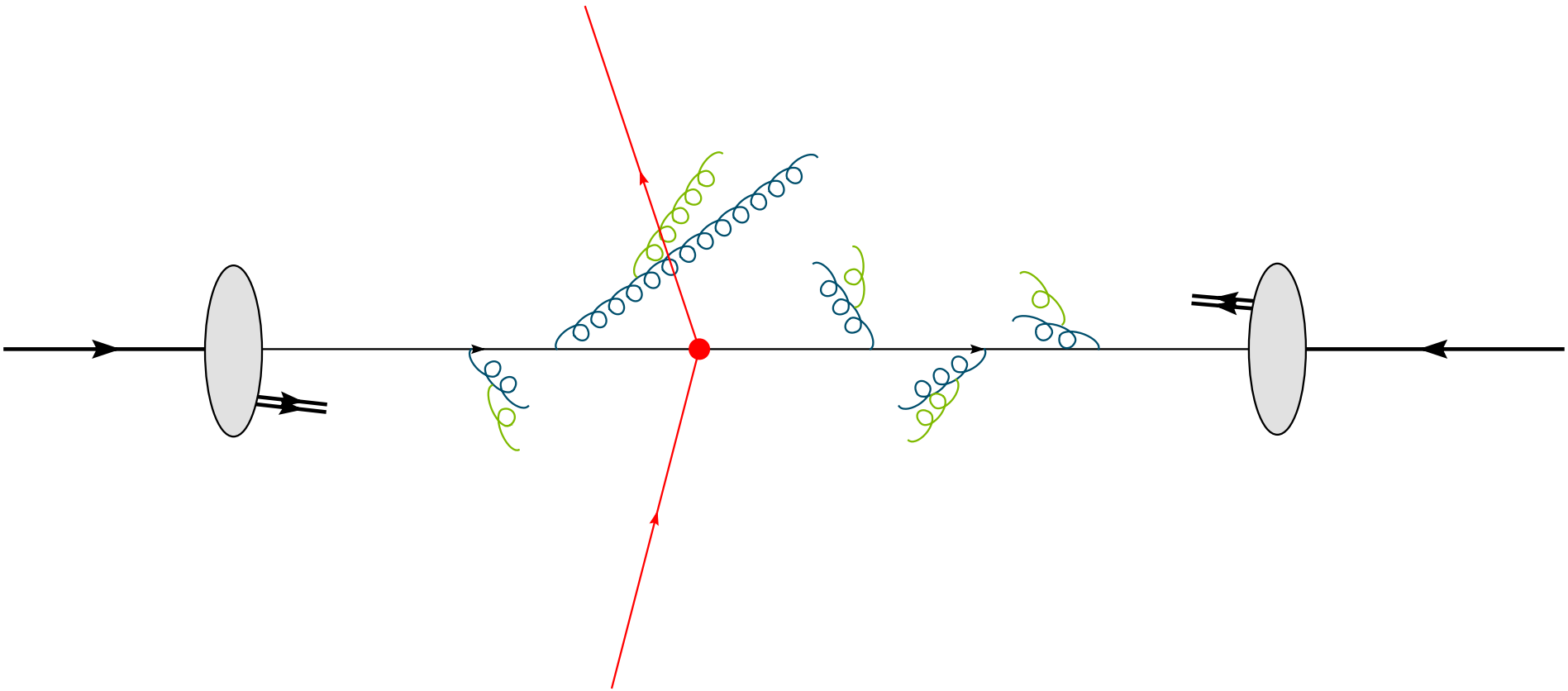

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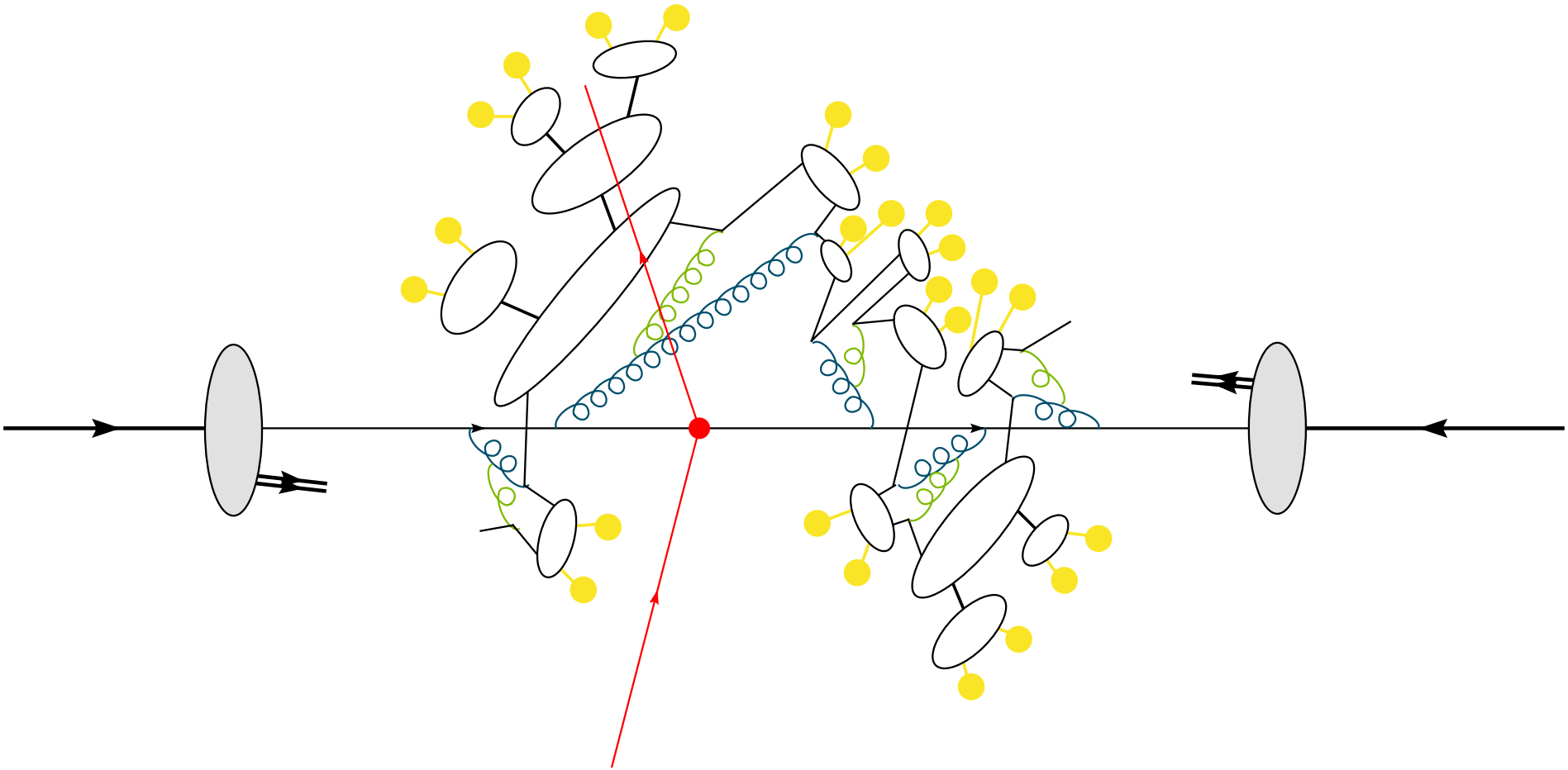

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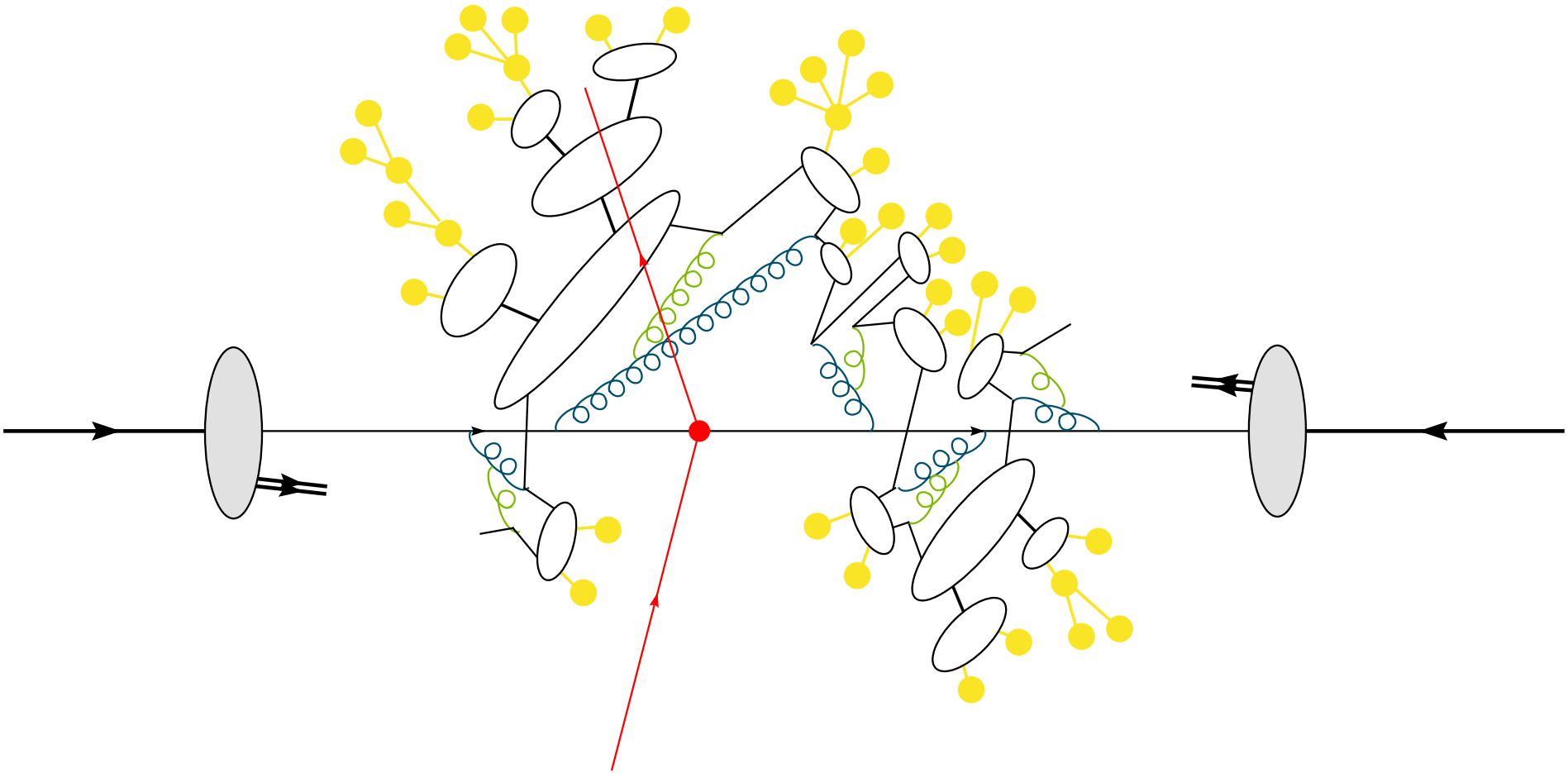

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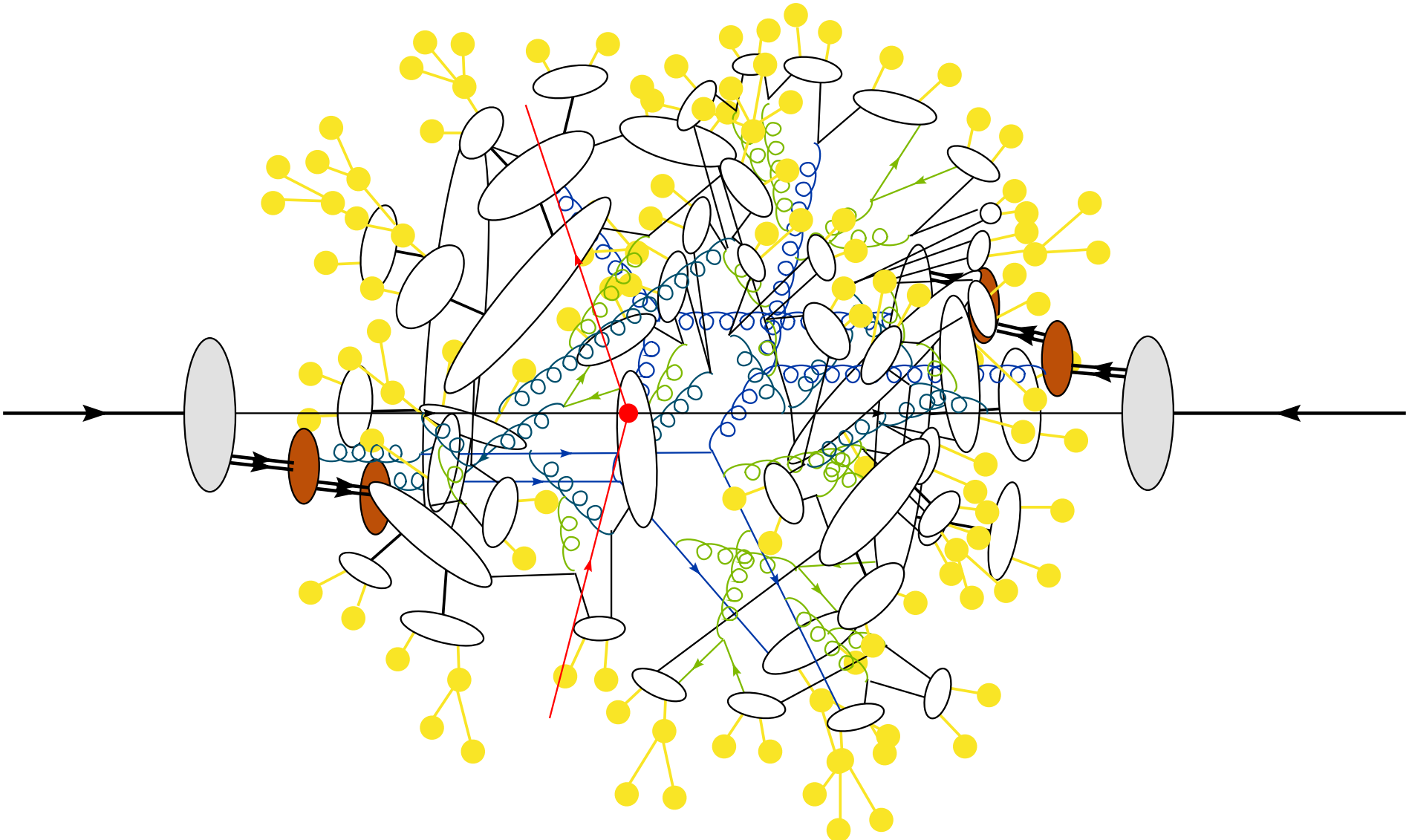


New Herwig Release 7.3 (out soon)

Some highlights

- EW branchings in AO parton shower [Masouminia, Richardson]
- Recoil schemes for angular ordered shower [Bewick, Ravasio, Richardson, Seymour]
- Decays of heavy mesons with HQET improvements [Masouminia, Richardson]
- Interface to String hadronization [Siodmok]
- Many optimizations and bug fixes

New infrastructure for further developments

- Refactoring of cluster fission and decay [Kiebacher, Plätzer, Samitz, Stafford]
- Colour reconnection [SG, Kiebacher, Plätzer]
- Generalized BSM showers [Lee, Masouminia, Seymour]
- Dark showers [Kulkarni, Masouminia, Plätzer, Stafford]
- Dark photons [Kling, Masouminia, Plätzer, Reimitz]

Outline

Brief recap of soft models in Herwig

Hadronization
Multiple partonic interactions
Colour reconnection

Some new developments

Heavy meson decays
Dynamics in cluster hadronizaion
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.

One obvious but important omission: pdfs

Soft models

Observations at colliders that are affected

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

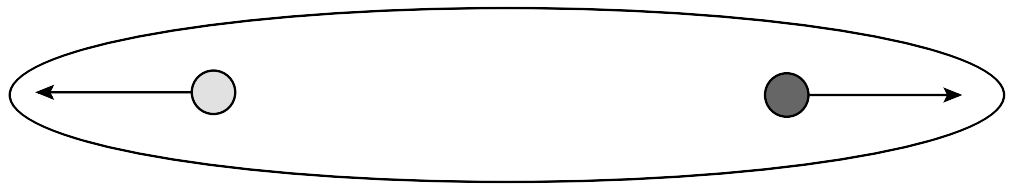
Precision goal — "MC error" often sizable

Soft models

More fundamental questions

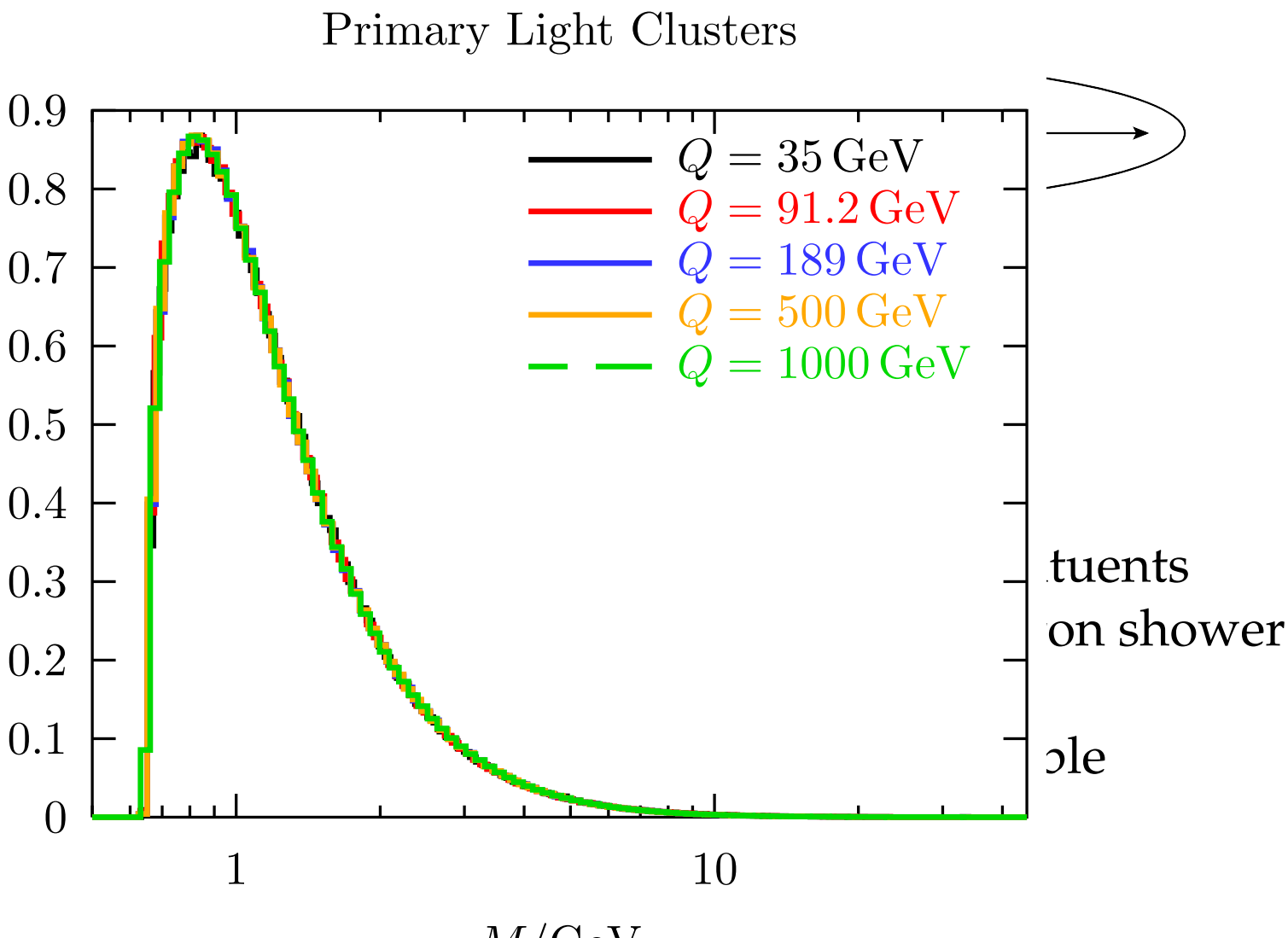
- "The ridge" (near side long range correlations in η)
- Dense, high multiplicity events
- Strangeness enhancement
- pp to heavy ions
- Microscopic modeling of medium effects
- Is "Pythia minus Herwig" good enough?
- More/better theory input in soft models?

Cluster Hadronization

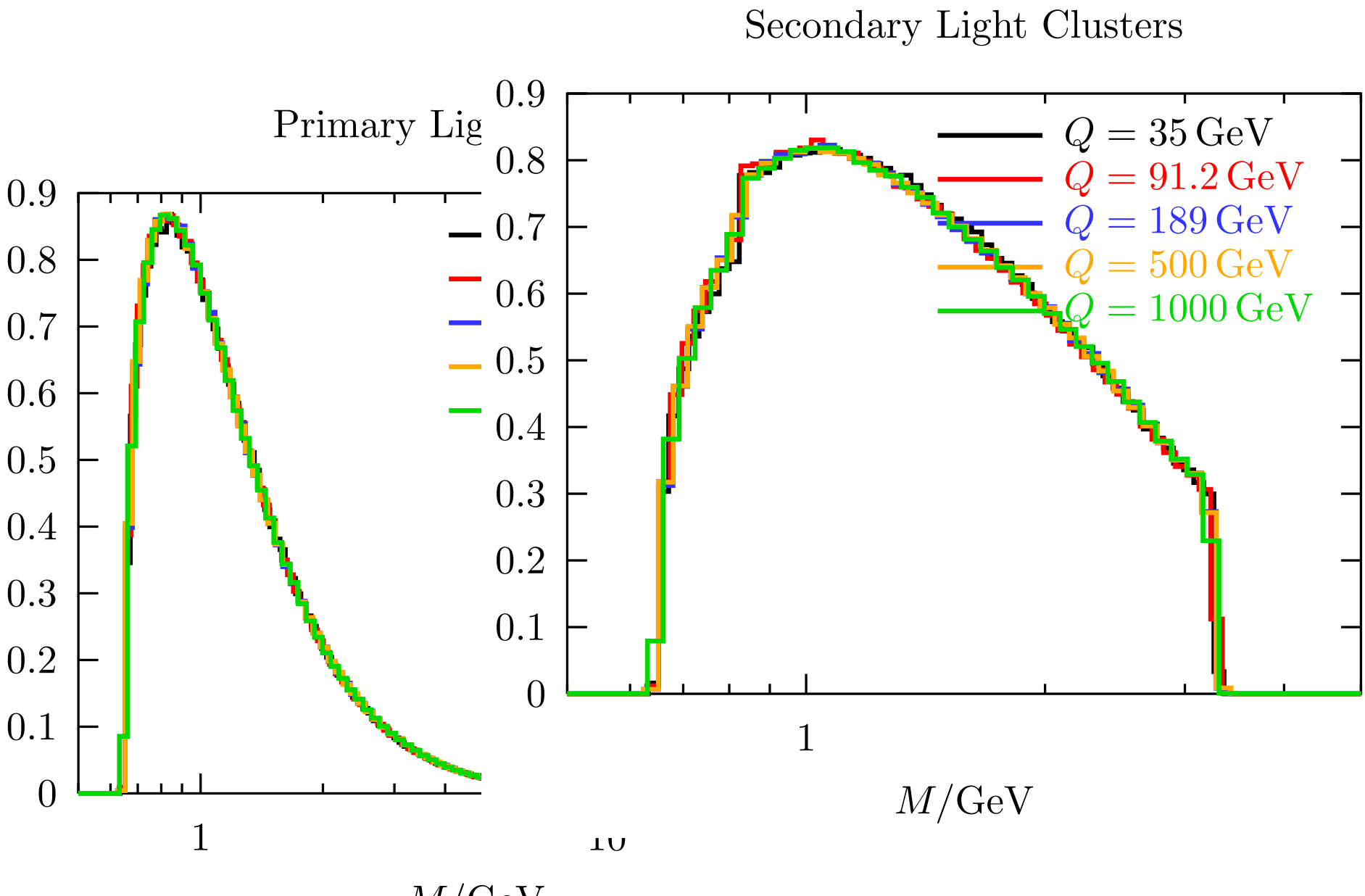


Cluster carries net momentum of its constituents
Spectrum determined by final state of parton shower
Independent of hard scales
Tail of *heavy clusters*, still large scale available

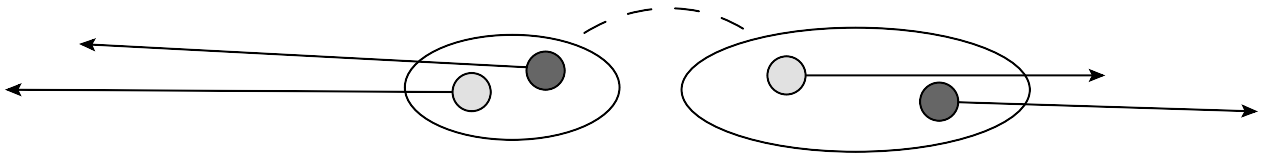
Cluster Hadronization



Cluster Hadronization

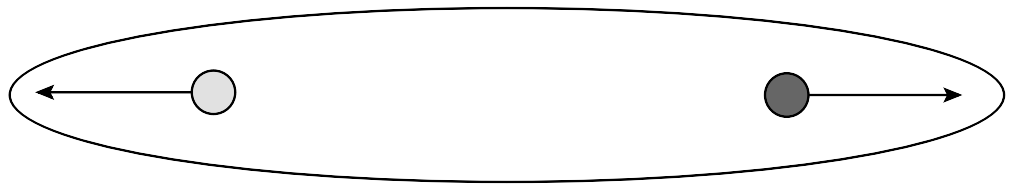


Cluster Hadronization



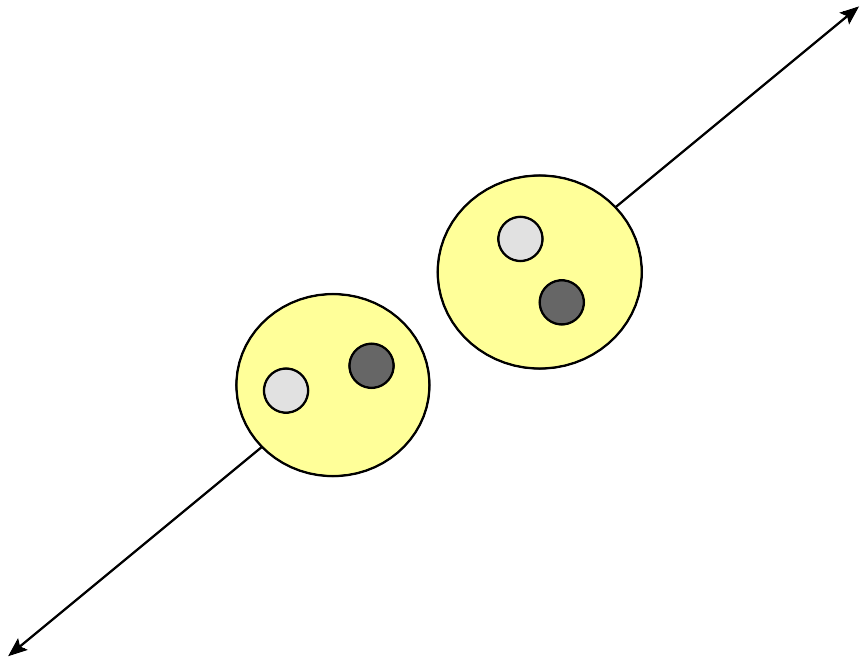
Binary fission along quarks' direction of motion
Flavour introduced in $q\bar{q}$ pairs
Baryons could be introduced via diquarks
Mass $\rightarrow$ multiplicity, momentum
Beam remnant clusters split off as very light clusters
$\rightarrow$ *Kinematic triangle*

Cluster Hadronization



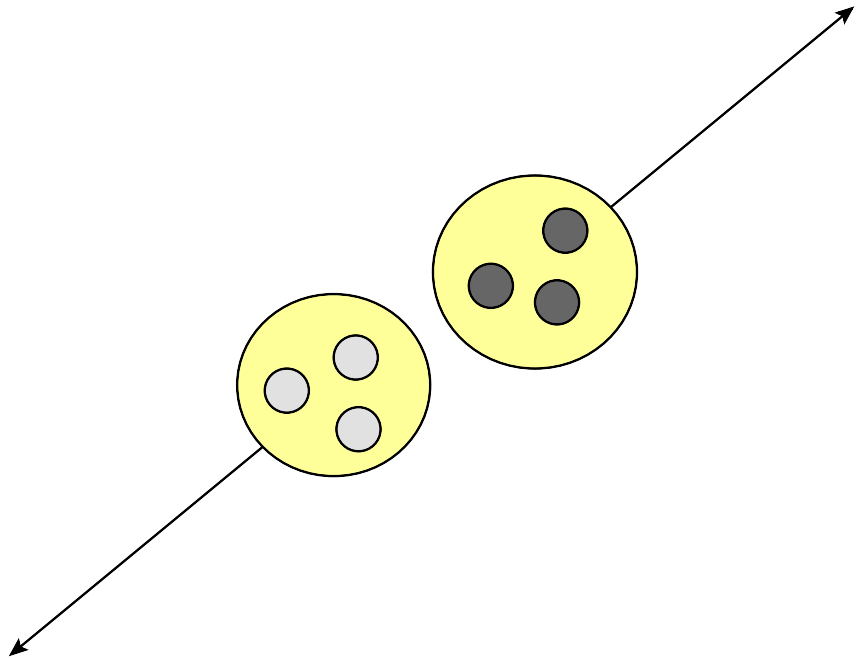
End up with fairly light clusters
too light? Decay into single hadron
Exchange momentum with neighbour

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.

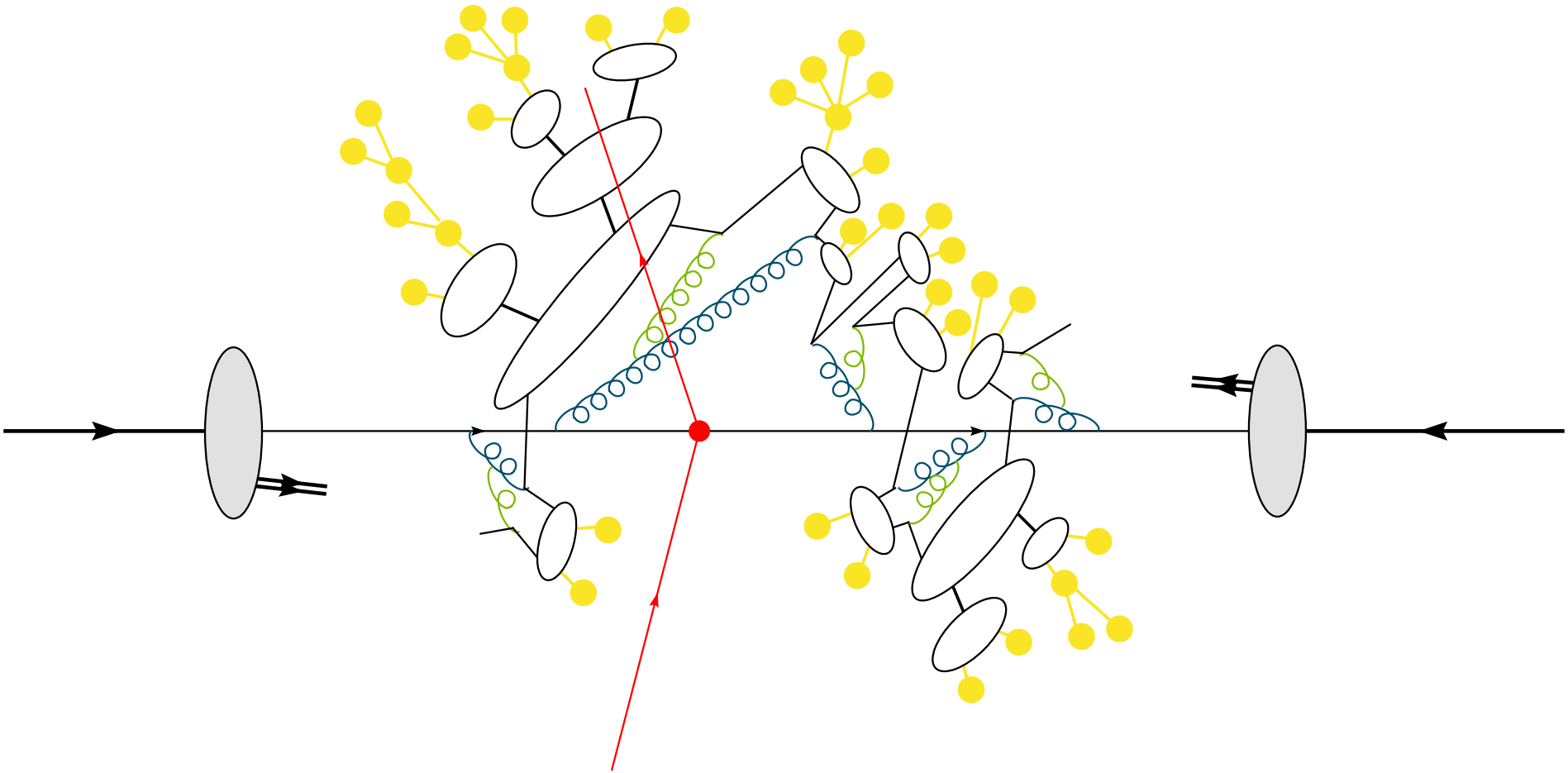
- Assignment of colour lines, leading $1/N_C$ expansion.
  First insight from colour evolution of soft gluons?
  More updates from parton showers at non-leading colour.
- Colour reconnection models alter the picture. See later.
- Gluon splitting, m_g-dependence (+kinematic details?)
- Fission dynamics, 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

pp Event Generator



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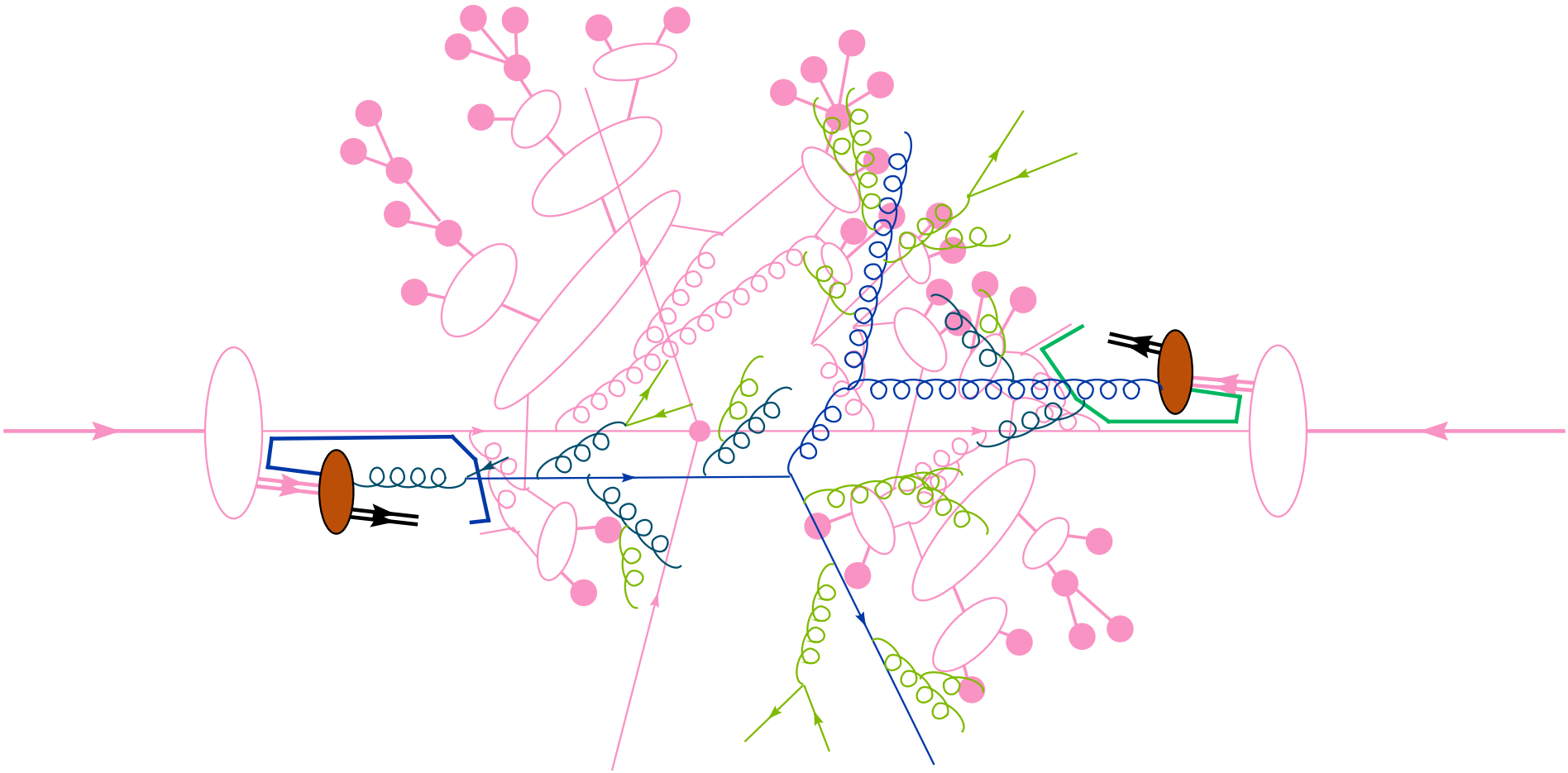

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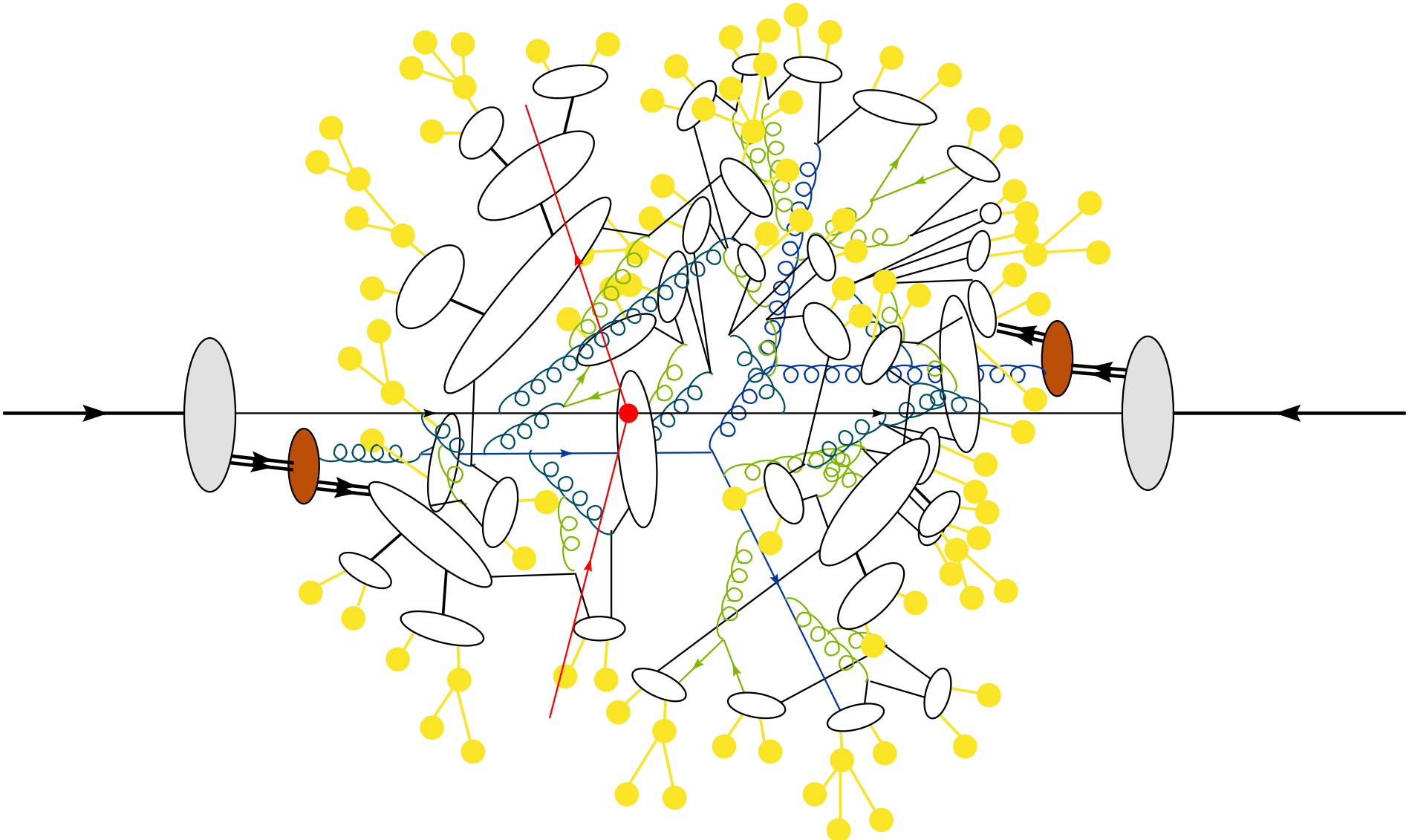

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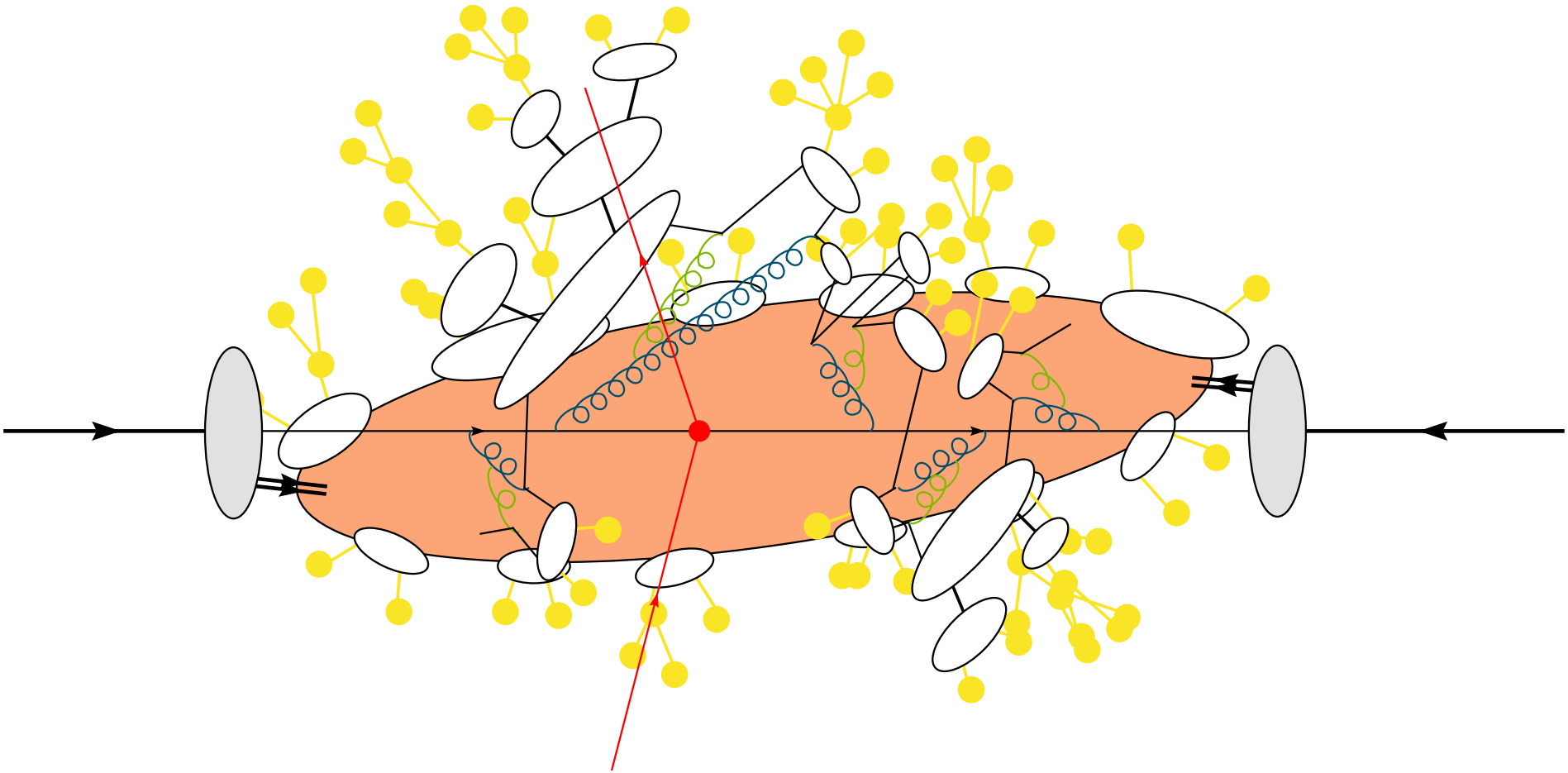
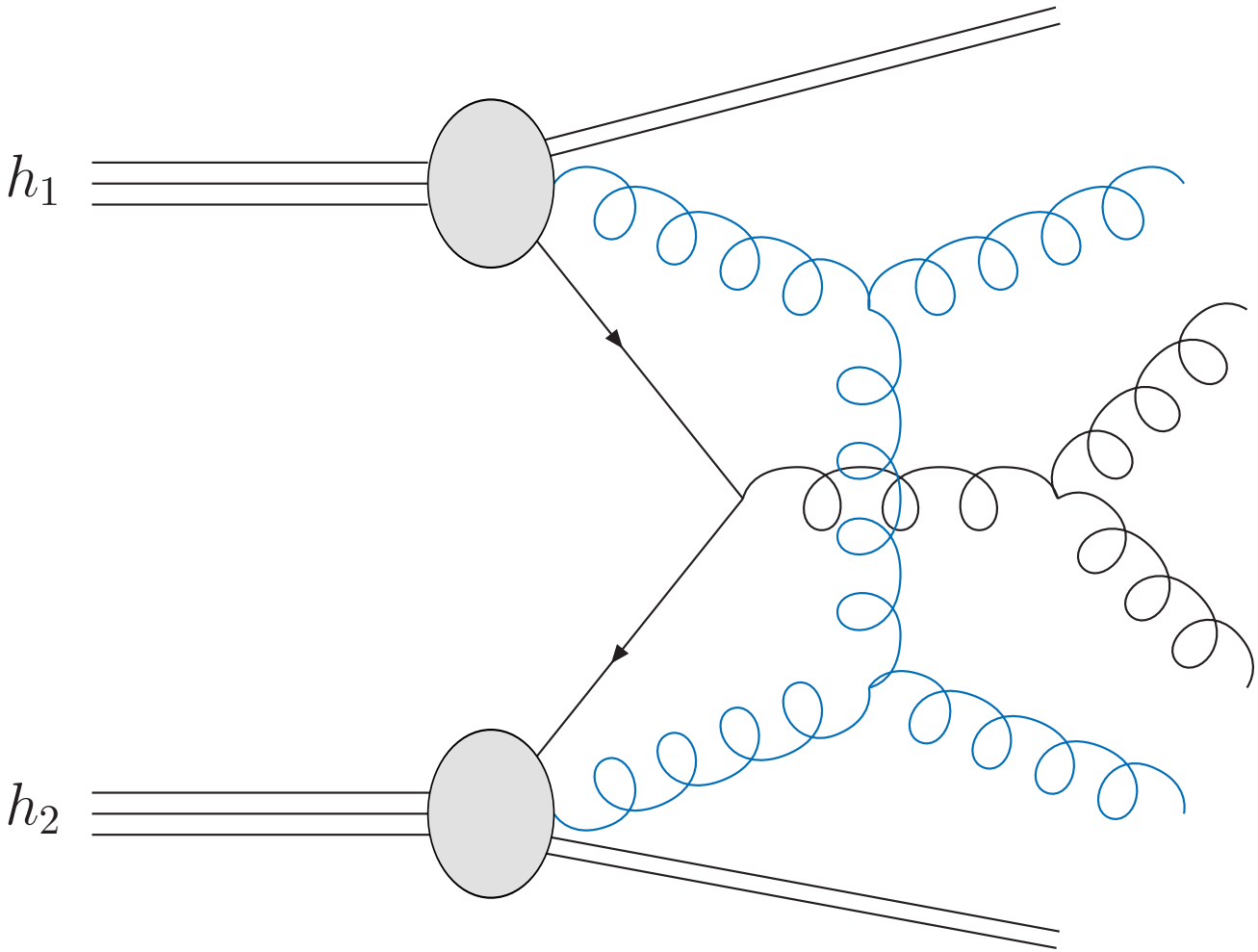


MPI/Eikonal model basics

Mulitple hard and soft interactions



Overlap function

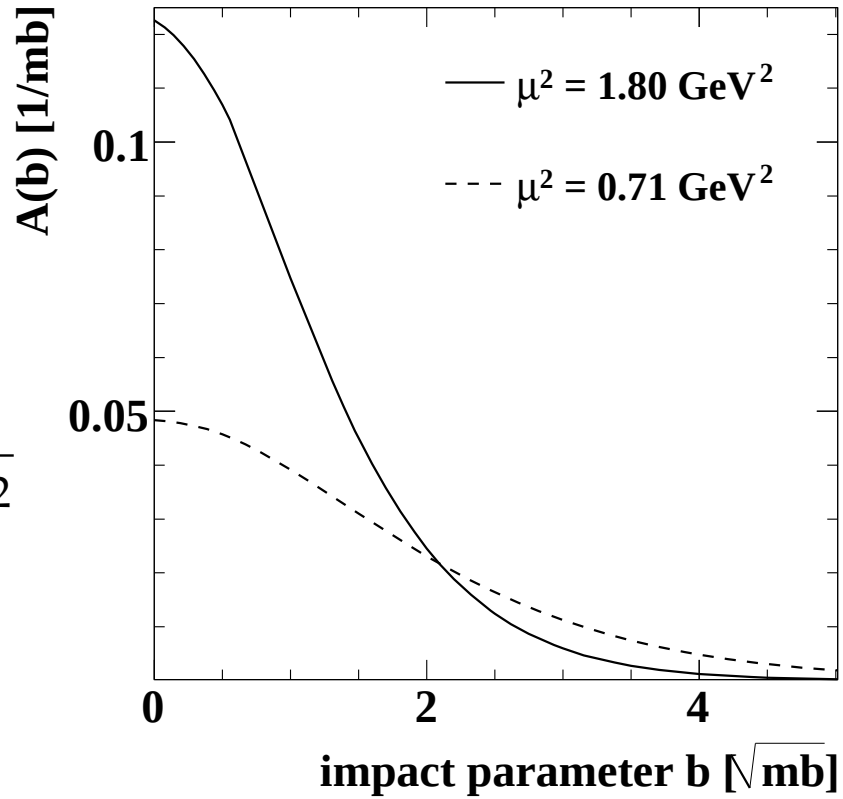
$$A(b) = \int \mathrm{d}^2\vec{b}' G_A(|\vec{b}'|) G_B(|\vec{b} - \vec{b}'|)$$

$G(\vec{b})$ from electromagnetic FF:

$$G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{\mathrm{d}^2\vec{k}}{(2\pi)^2} \frac{\mathrm{e}^{i\vec{k}\cdot\vec{b}}}{(1+\vec{k}^2/\mu^2)^2}$$

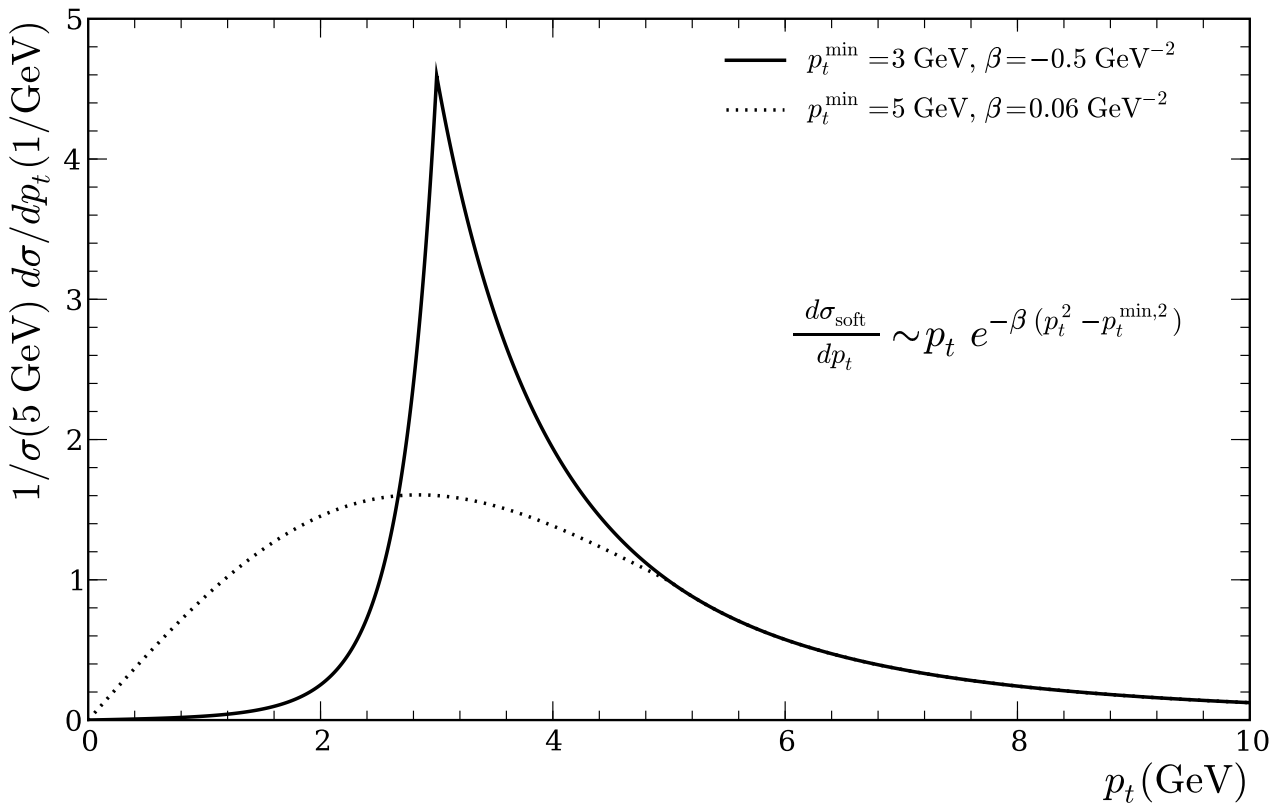
But μ^2 *not fixed* to the *electromagnetic* $0.71\,\mathrm{GeV}^2$.
Free for colour charges.

$\Rightarrow$ Two main parameters: $\mu^2, p_t^{\min}$.



Extending into the soft region

Continuation of the differential cross section into the soft region $p_t < p_t^{\min}$ (here: p_t integral kept fixed)

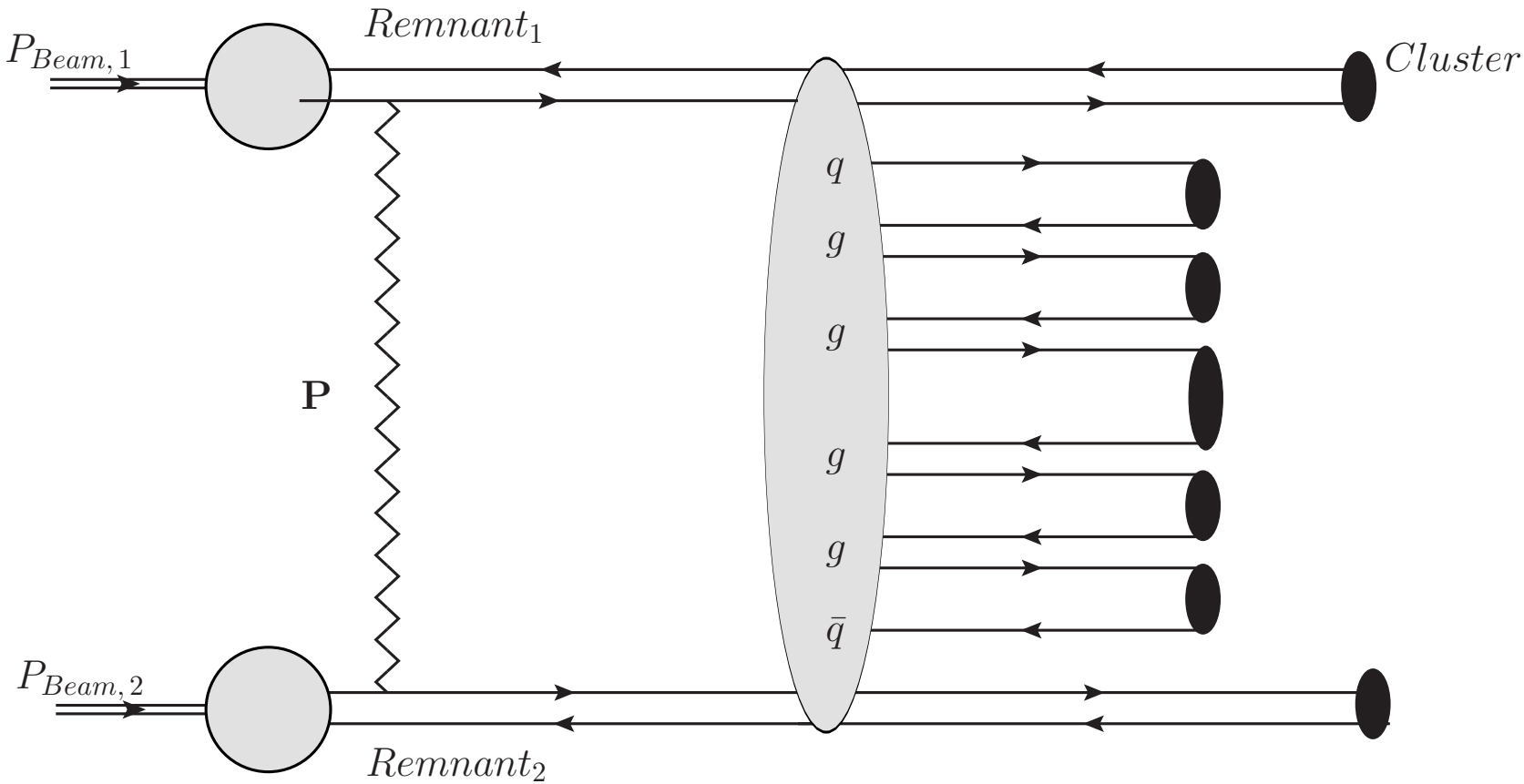


Extra parameters σ_{soft} and μ^2_{soft} fixed from data.

[M. Bähr, SG, M.H. Seymour, JHEP 0807 (2008) 076]

Soft particle production model in Herwig

Single soft ladder with MinBias initiating process.



Further hard/soft MPI scatters possible.

[SG, F. Loshaj, P. Kirchgaeßer, EPJ C77 (2017) 156]

[J. Bellm, SG, P. Kirchgaeßer, EPJ C80 (2020) 5, 469]

Diffractive final states

Strictly low mass diffraction only. Allow M^2 large nonetheless.

M^2 power-like, t exponential (Regge).

$$pp \to \text{(baryonic cluster)} + p \ .$$

Hadronic content from cluster fission/decay $C \to hh \ldots$
Cluster may be quite light. If very light, use directly

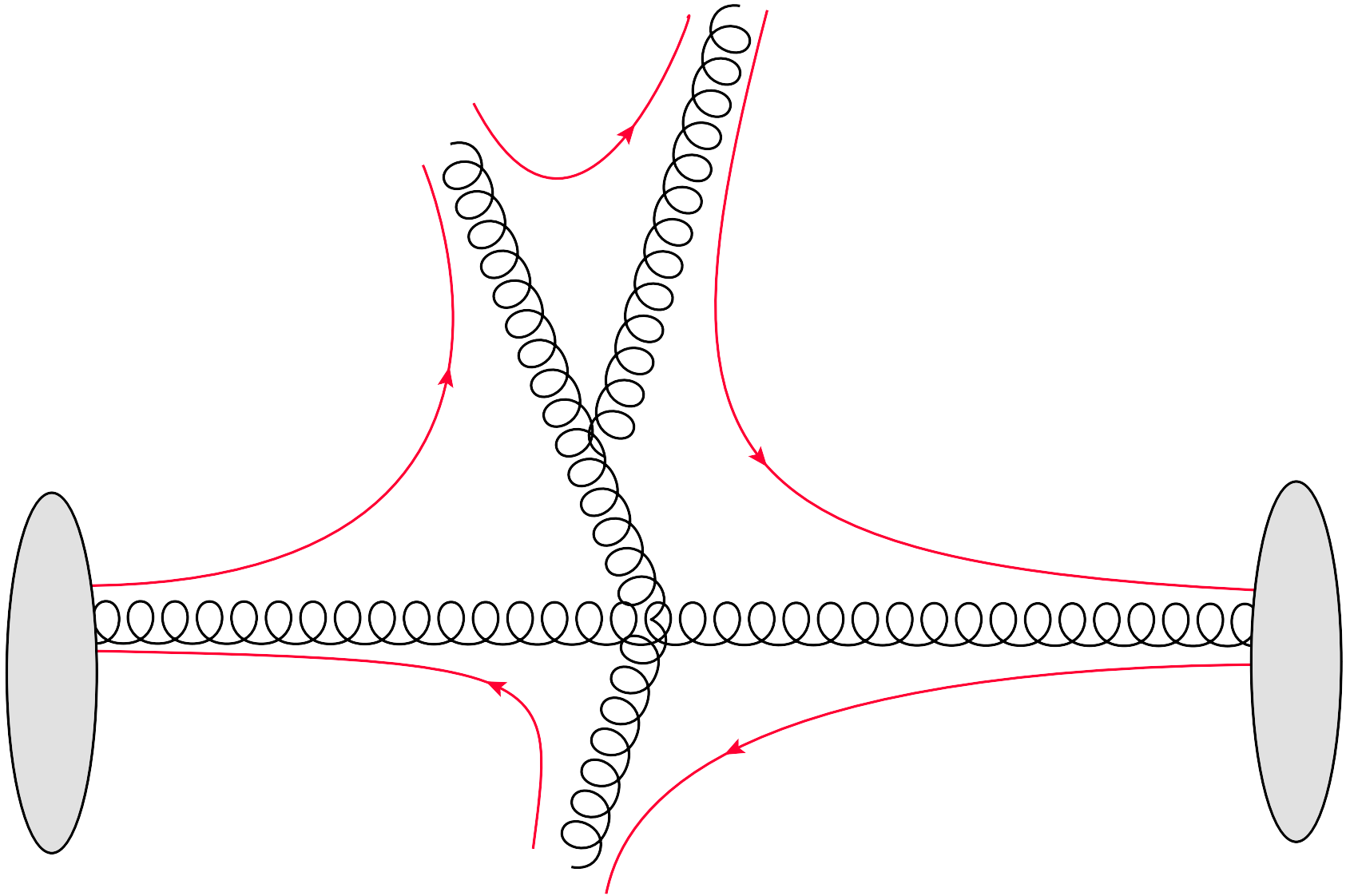
$$pp \to N^* + p \ .$$

Also double diffraction implemented.

$$pp \to (\text{cluster}) + (\text{cluster}) \qquad pp \to N^* + N^* \ .$$

Technically: simple MEs for diffractive processes set up.

Colour correlations in hadronic collisions



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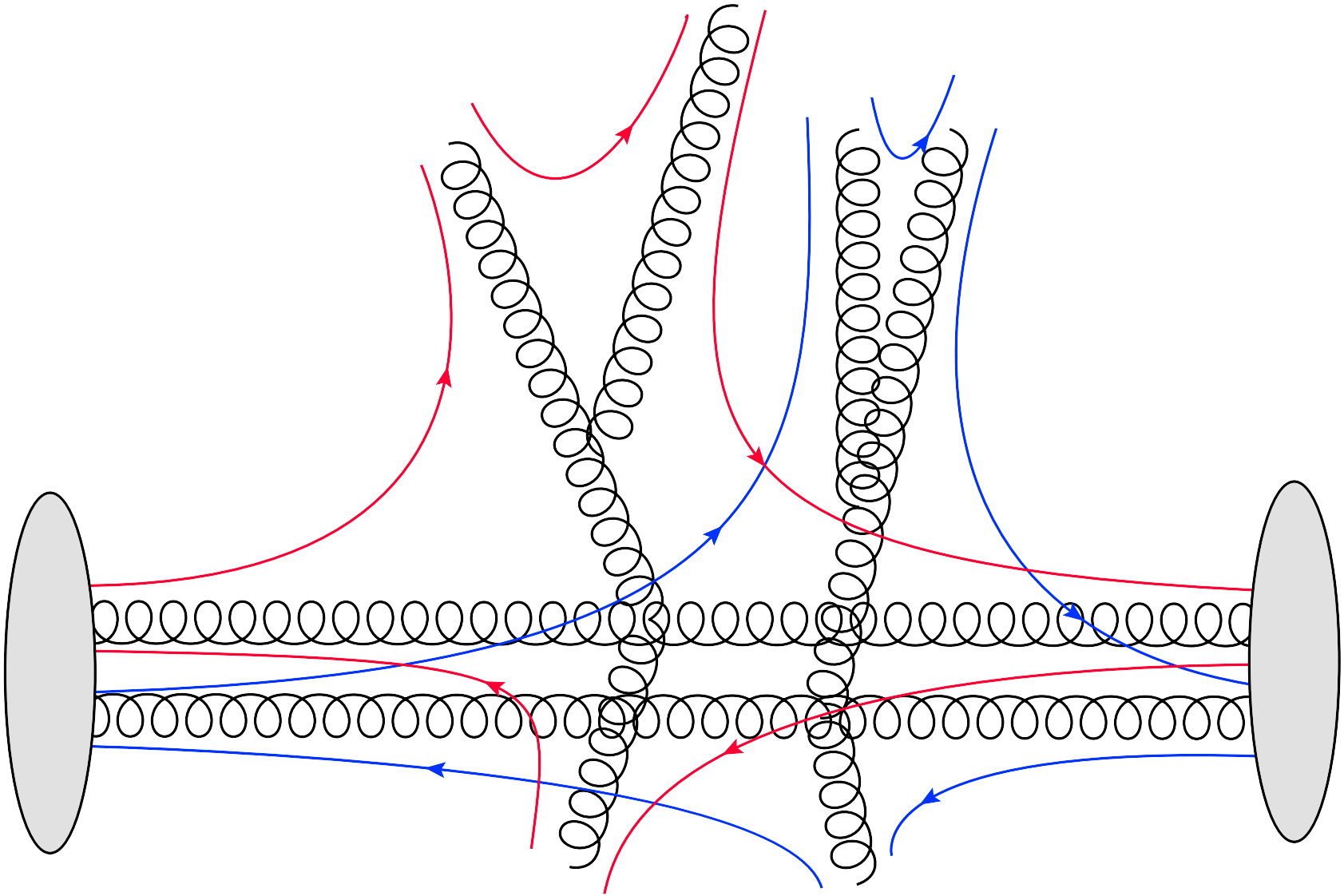

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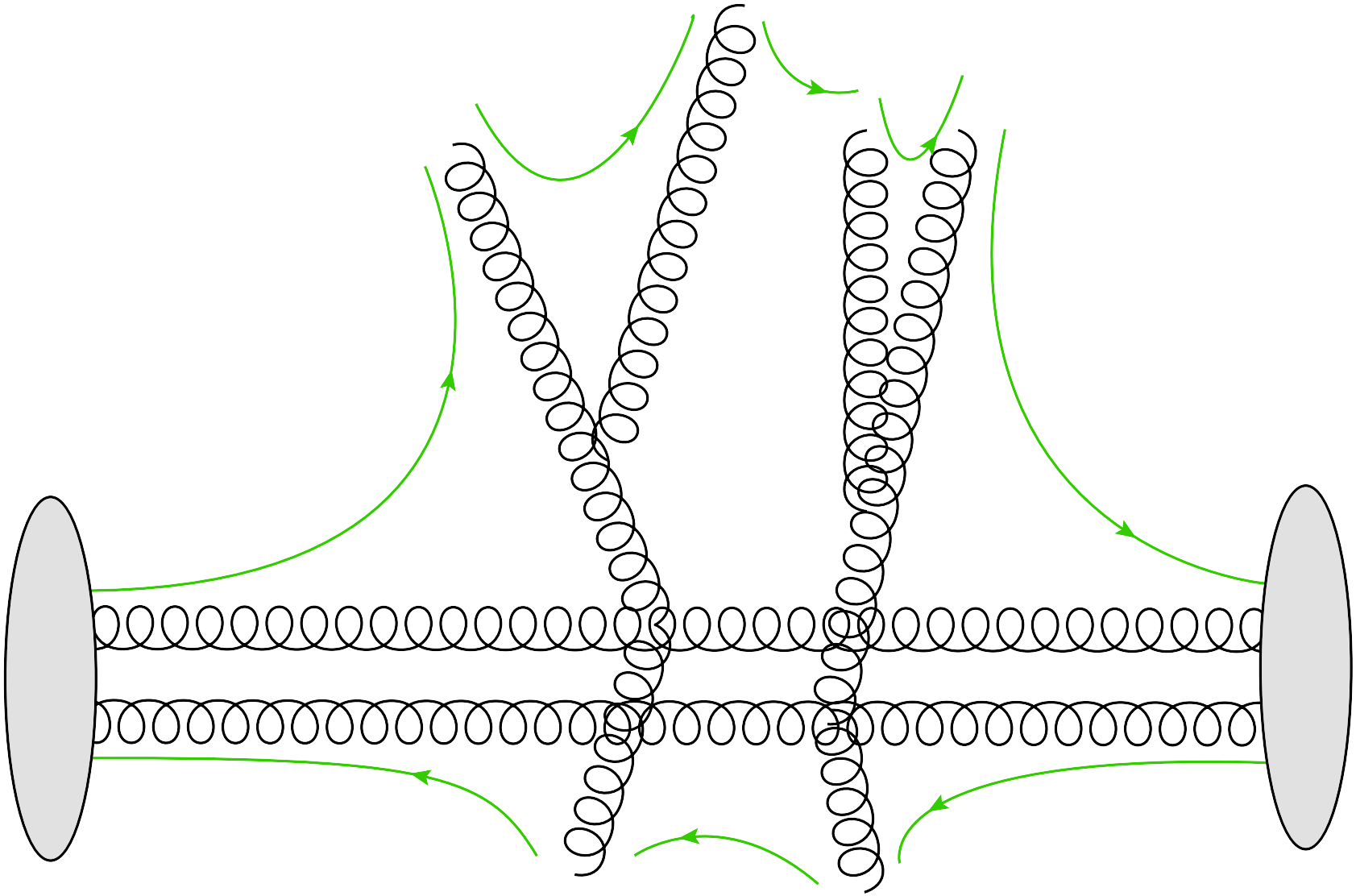
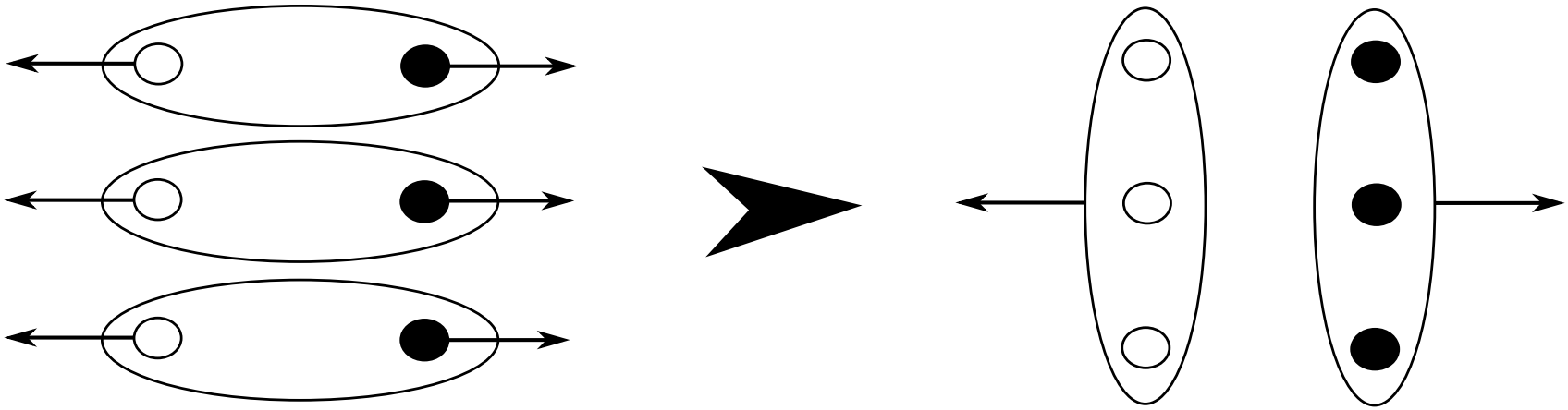


Rapididy based colour reconnection

Colour singlets not only from $q\bar{q}$ but also from qqq states



But, baryonic clusters would typically be much heavier

$$M_{ijk} + M_{lmn} > M_{il} + M_{jm} + M_{kn}$$

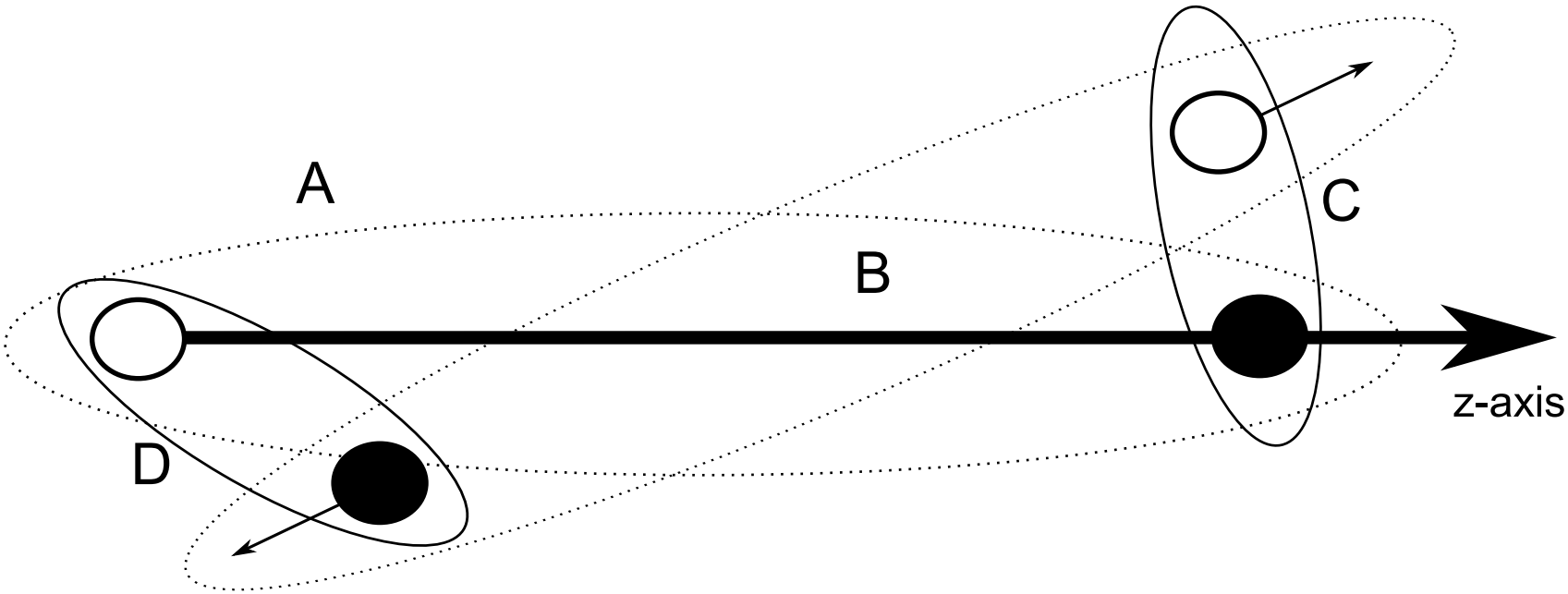
would always/often be reconnected into mesonic clusters.

[SG, C. Röhr, A. Siodmok, EPJC72 (2012) 2225]

[SG, P. Kirchgaeßer, S. Plätzer, EPJC78 (2018) 99]

Rapididy based colour reconnection

"Closeness" of quarks not based on invariant mass but on proximity in momentum space.



Consider other quarks' movement based on their rapidity in reference clusters' CM frame.

[SG, C. Röhr, A. Siodmok, EPJC72 (2012) 2225]

[SG, P. Kirchgaeßer, S. Plätzer, EPJC78 (2018) 99]

Parameters and tuning

Diffraction plus MPI incl new soft model.

Diffractive cross sections adjusted to data.

Tuning to Min Bias data: $\eta, p_\perp$ for various N_{ch}, $\langle p_\perp \rangle (N_{\text{ch}})$.

Usual MPI parameters

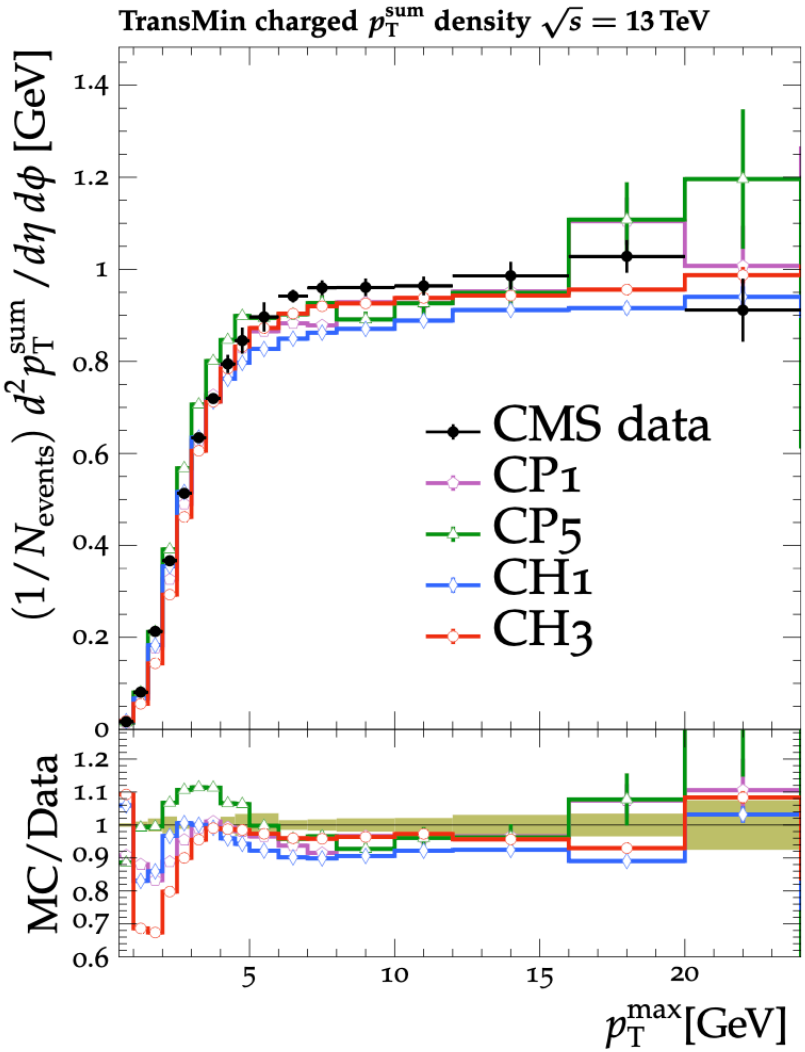
$$(p_{\perp,0}^{\min}, b) \to p_\perp^{\min}(\sqrt{s}), \quad \mu^2, \quad p_{\text{reco}} \ .$$

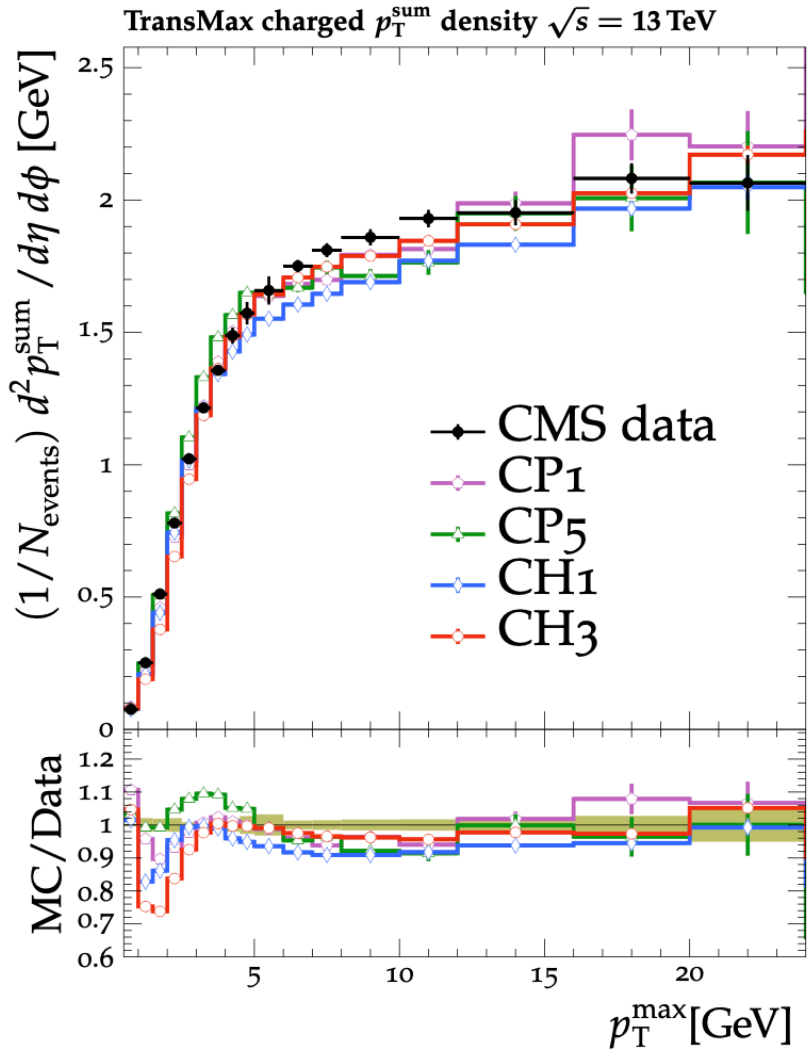
One additional parameter
("gluons per unit rapidity" in soft ladder)

$$n_{\text{ladder}} \ .$$

Colour reconnection probabilities.
Good description of most UE and Min Bias data

Underlying Event (CMS tunes)





[CMS H7 tunes, EPJC 81 (2021) 312]

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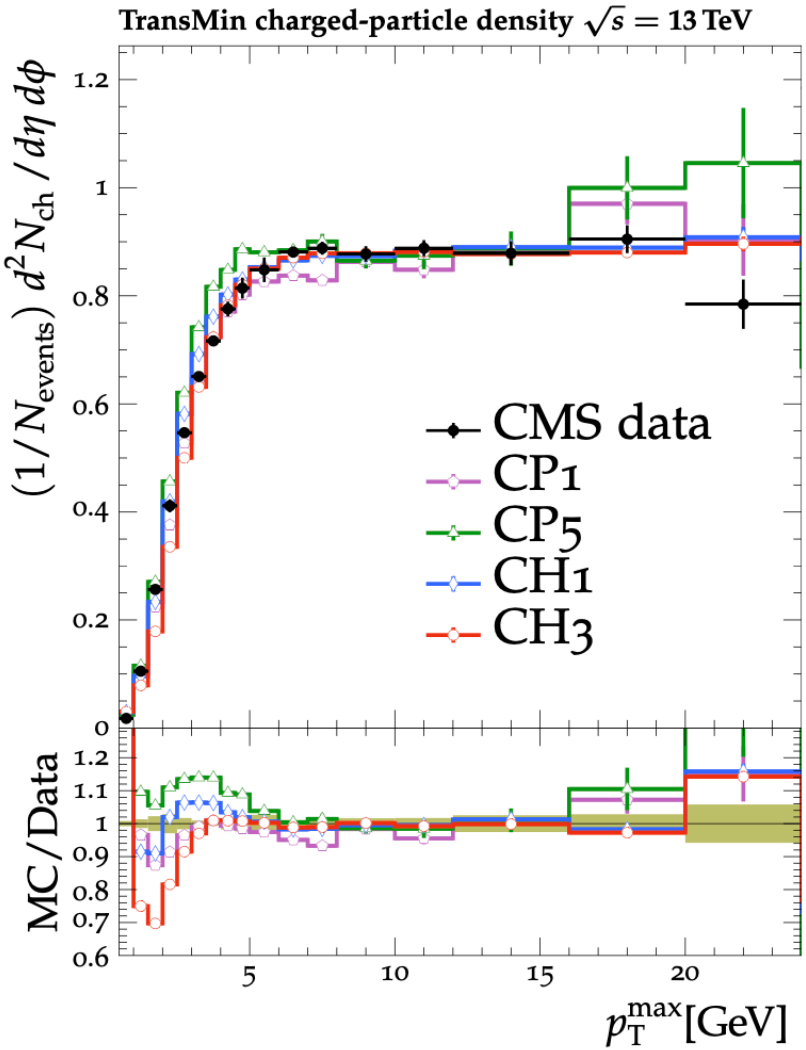

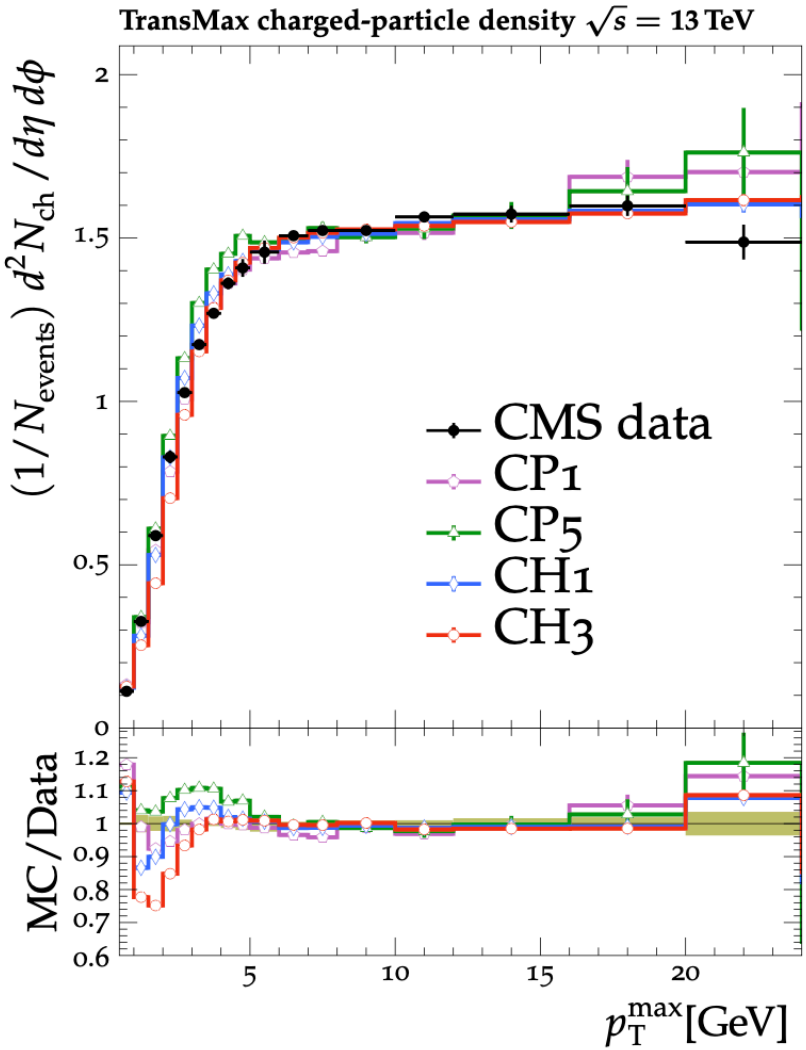

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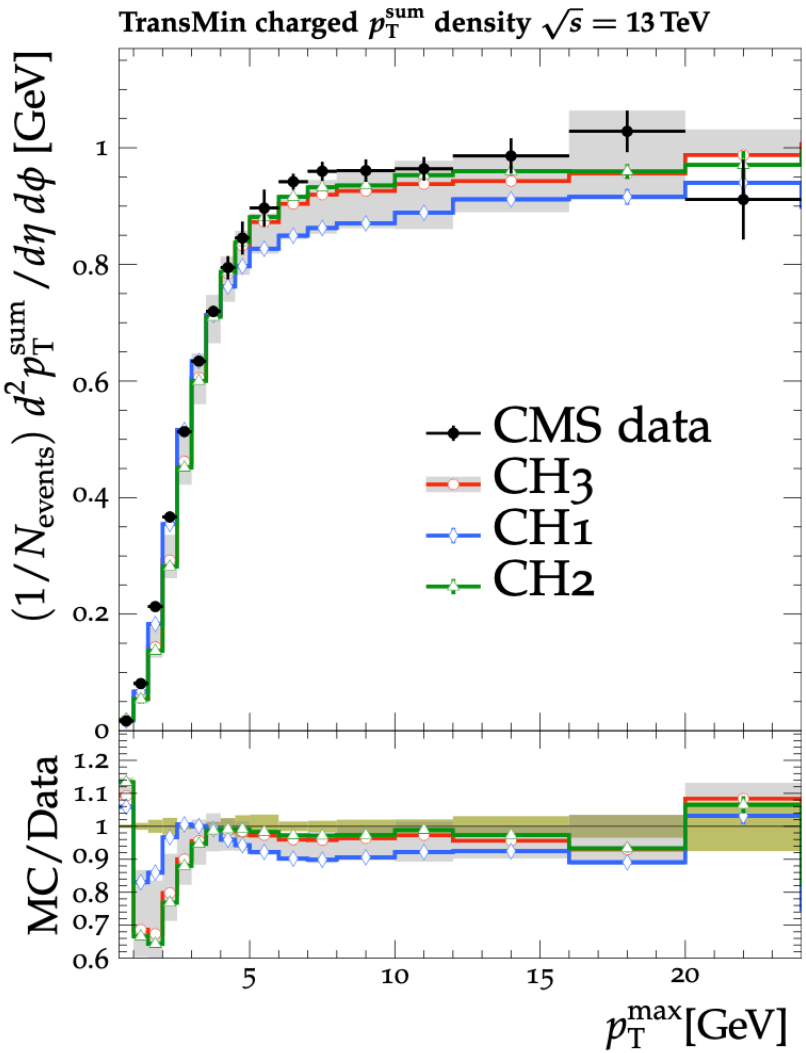
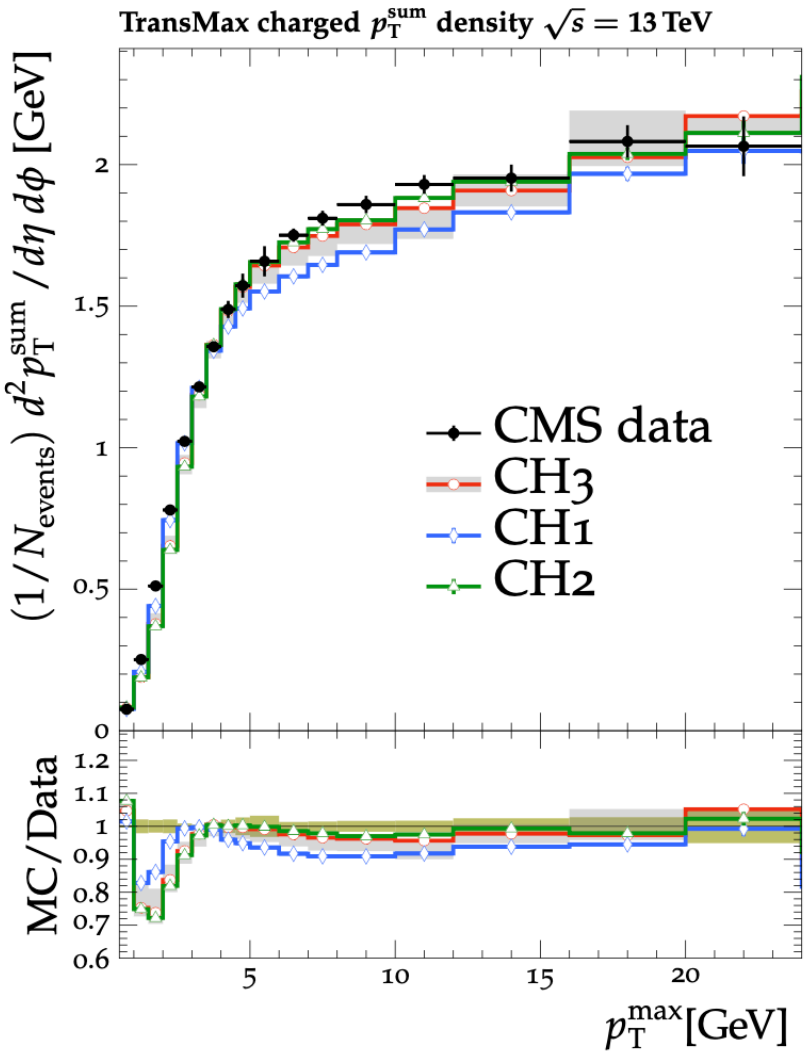
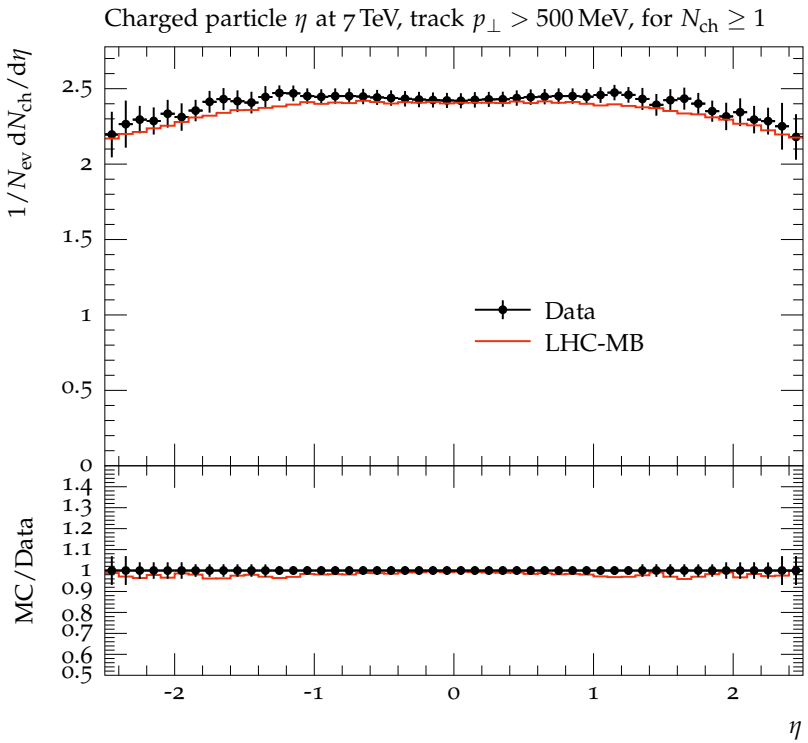
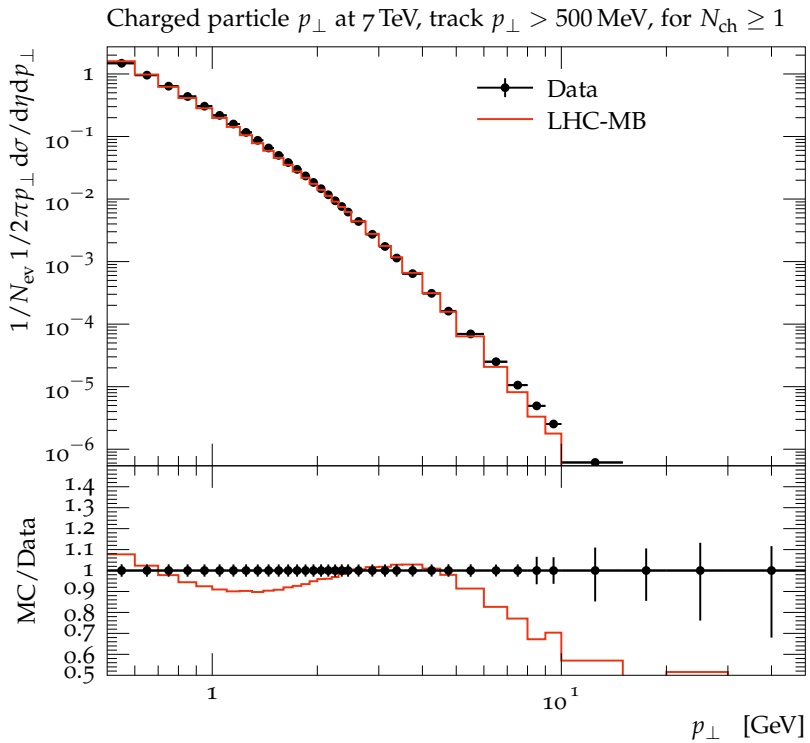




[CMS H7 tunes, EPJC 81 (2021) 312]

Example: Min Bias observables

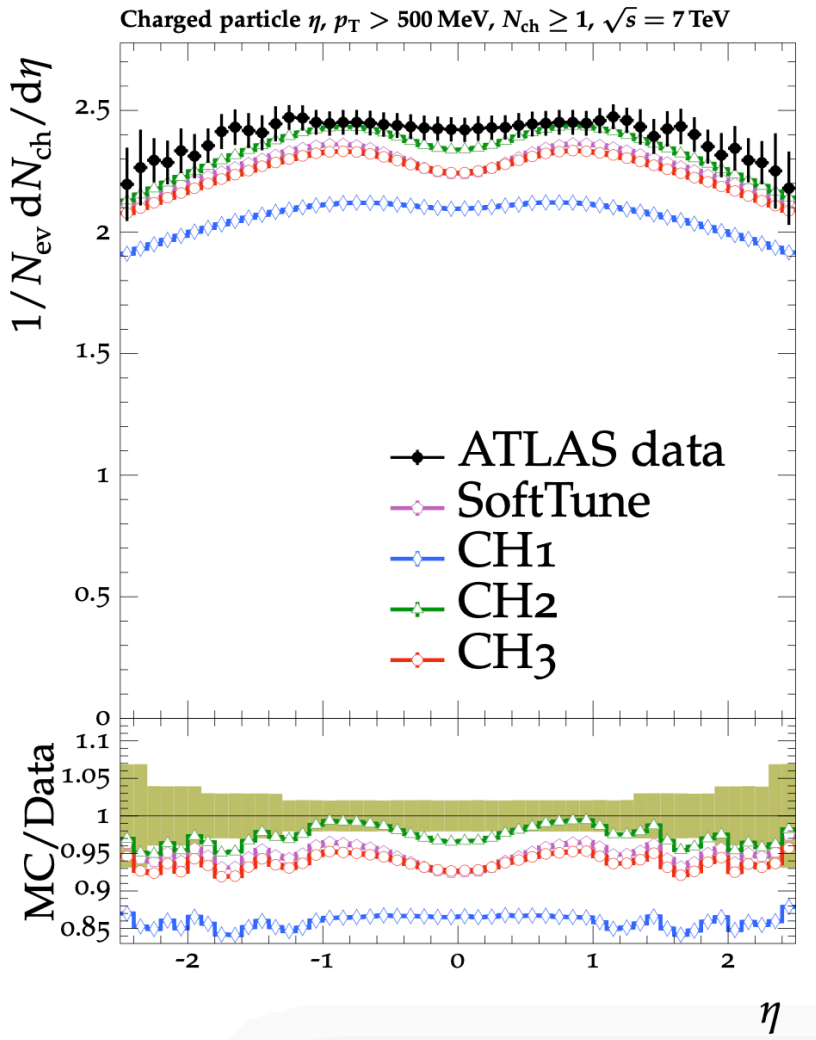


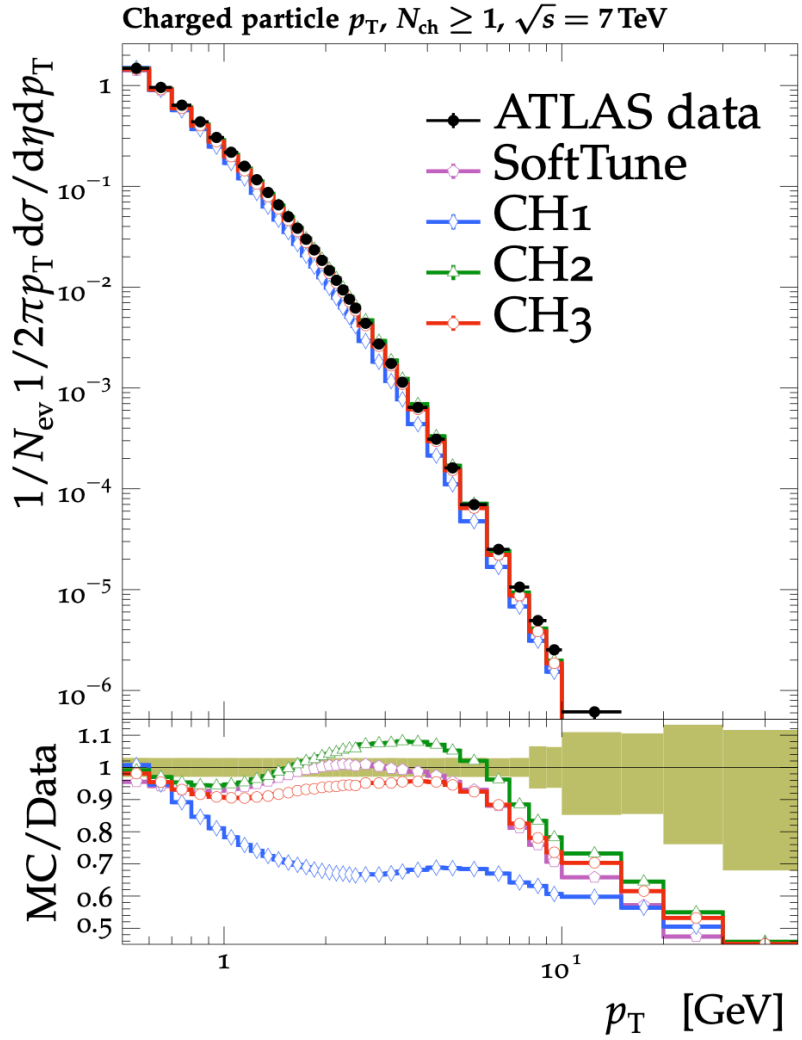


[ATLAS, New J.Phys. 13 (2011) 053033; Herwig 7.2.2]

Standard particle production observables
MPI and NP models tuned to these

Example: Min Bias observables

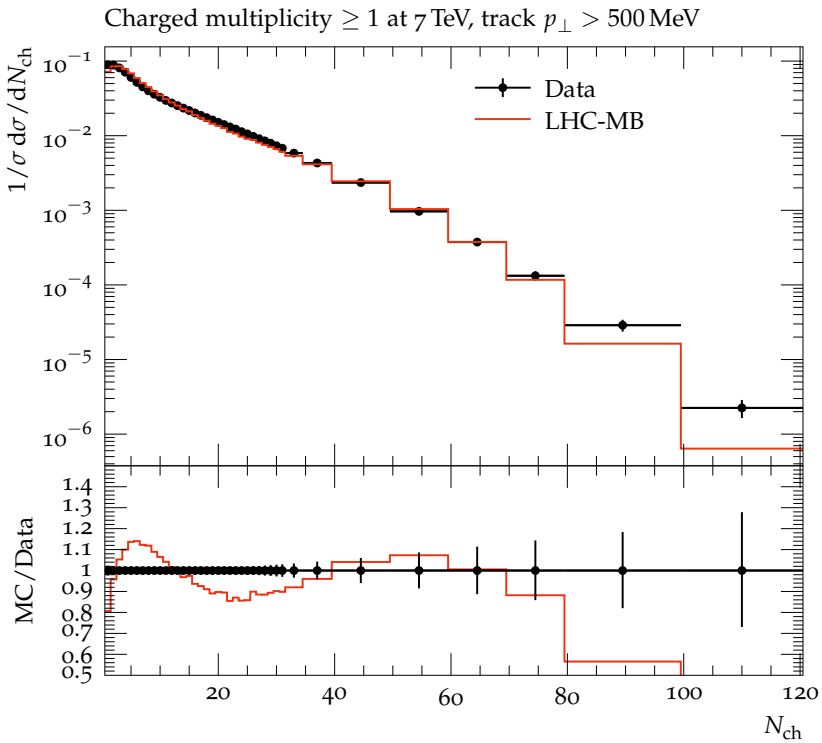


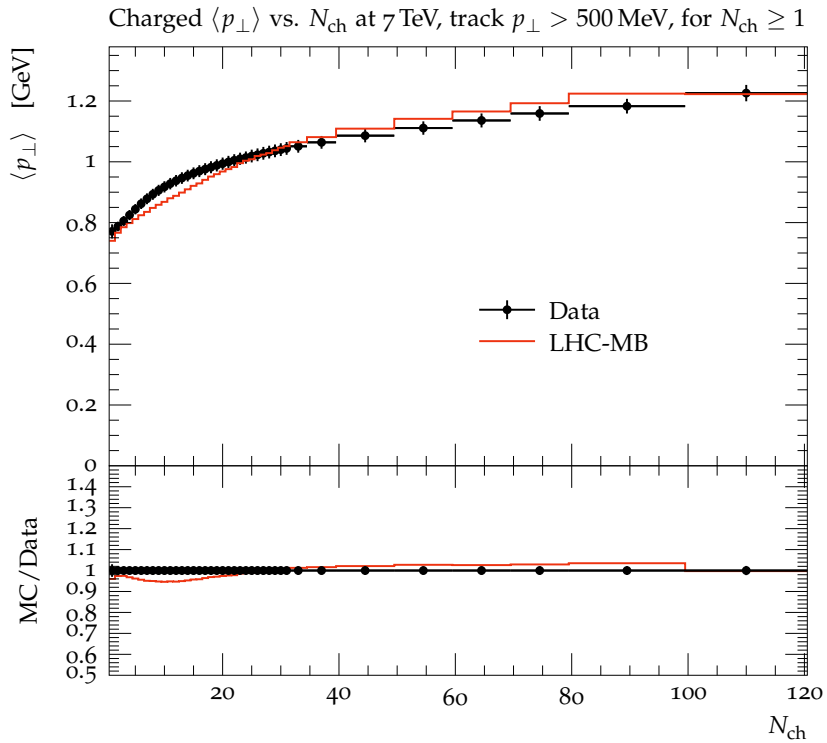


[Same data, CMS tune]

Standard particle production observables
MPI and NP models tuned to these

Example: Min Bias observables





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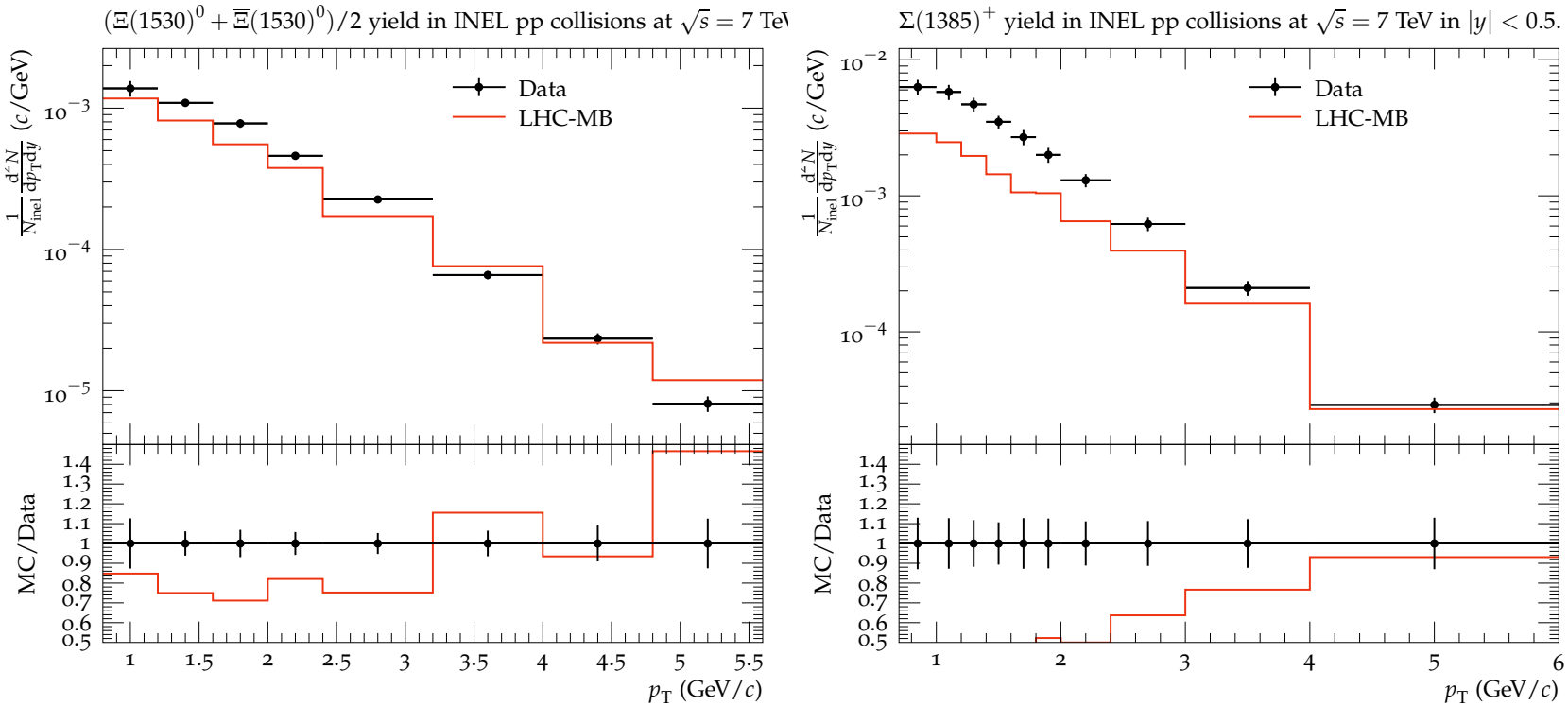


[ALICE, EPJ C75 (2015) 1,1; Herwig 7.2.2]

Identified particles, baryons in particular, harder to describe

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

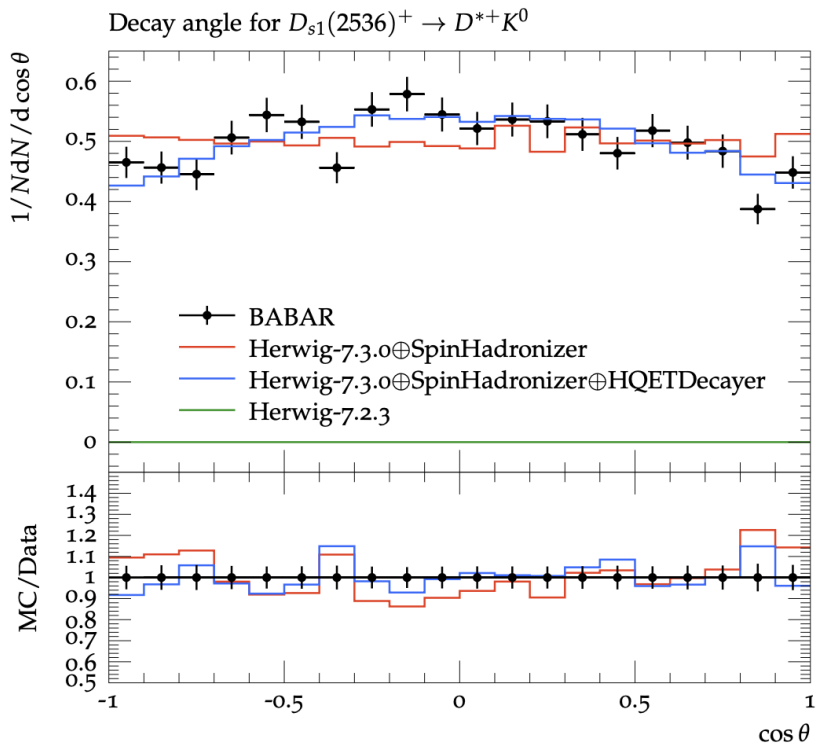
High $p_\perp$ observables decouple where expected (not shown)

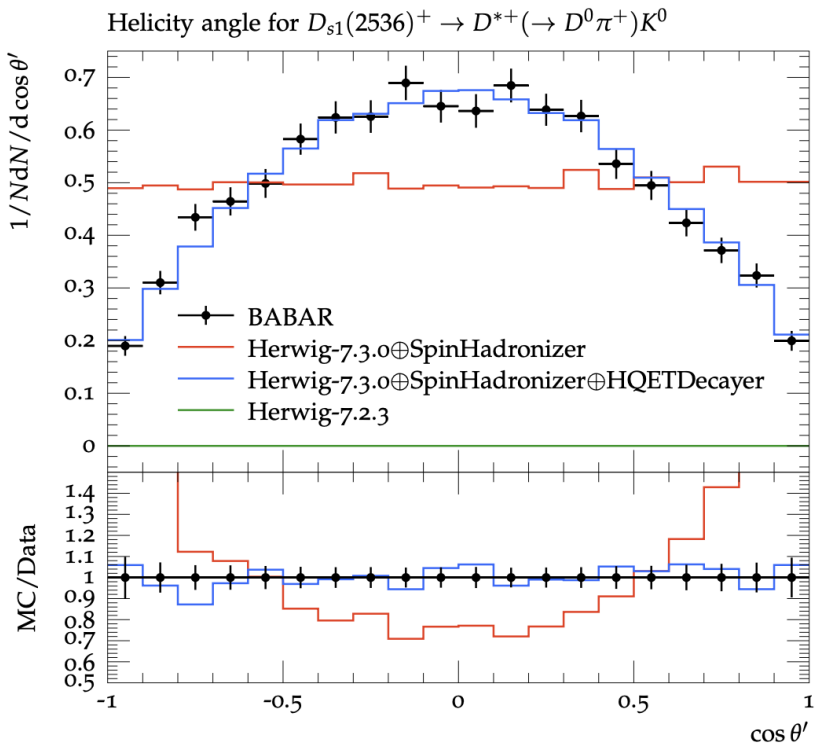
How about more details?

Some new developments

Decays of heavy mesons

Possibility to retain polarization information of heavy quark, use in hadronization and heavy meson decay.





[Masounimina, Richardson]

See talk by Aidin Masouminia!

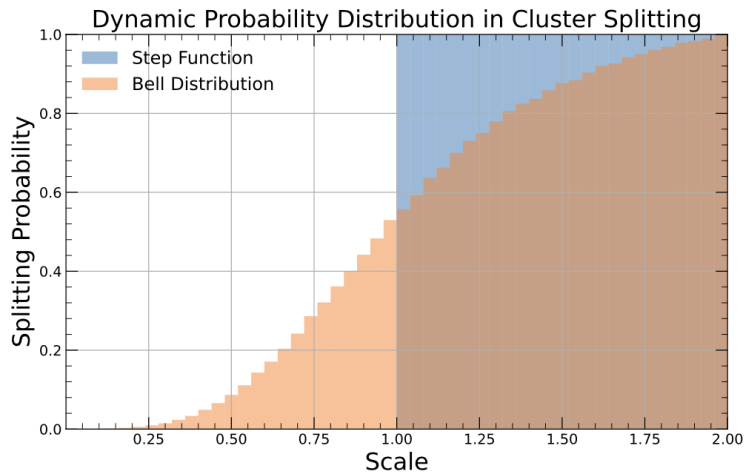
Threshold smearing in cluster fission

`Static` vs `Dynamic` kinematic thersholds in cluster splitting:

$$\texttt{Static}: \quad M > M_1 + M_2, \quad M_1 > m + m_1, \quad M_2 > m + m_2$$
$$\texttt{Dynamic}: \quad M^2 > M_1^2 + M_2^2, \quad M_1^2 > m^2 + m_1^2 + \delta_{\mathrm{th}}, \quad M_2^2 > m^2 + m_2^2 + \delta_{\mathrm{th}}$$

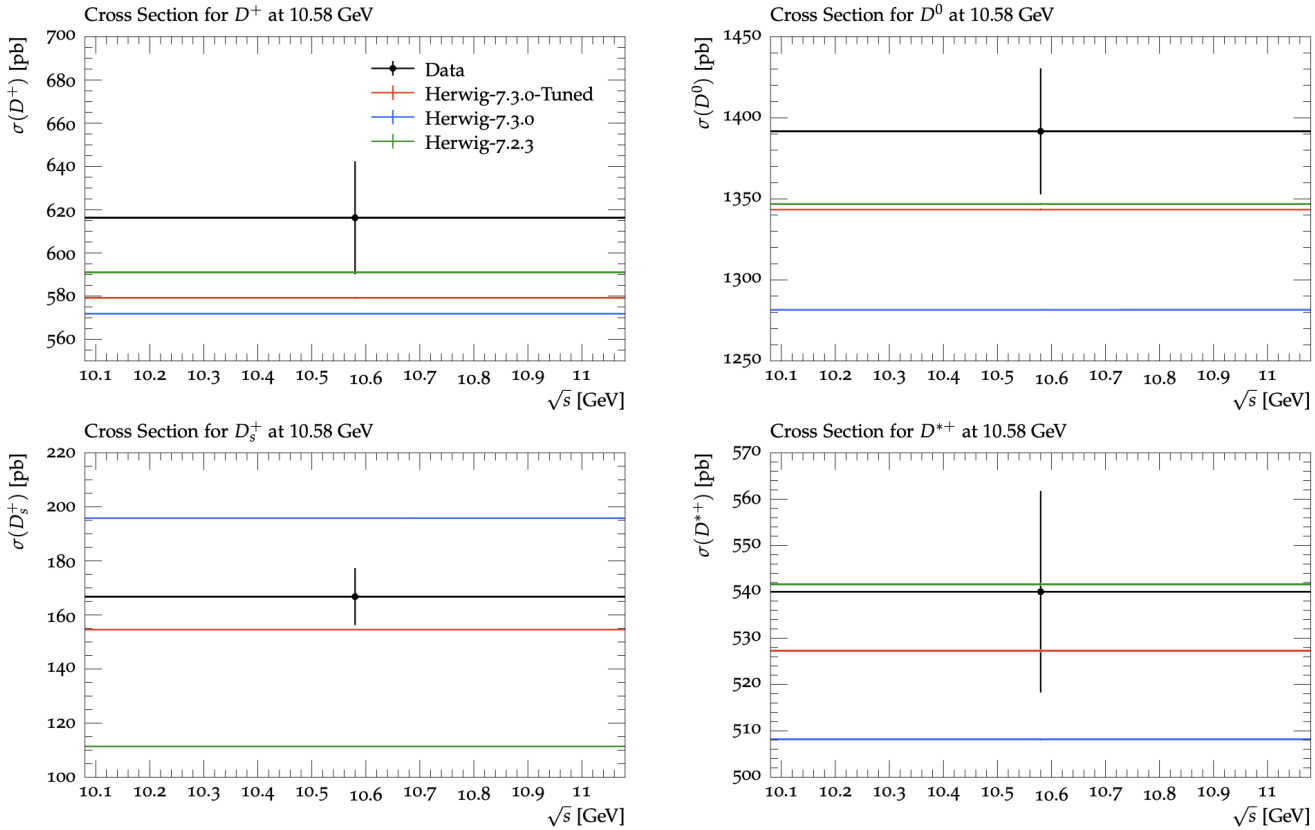
Probability of cluster splittings for heavy clusters:

$$P_{\mathrm{cluster}} = \frac{1}{1 + \left|\frac{M-\delta}{M_{\mathrm{th}}}\right|^r} > \mathrm{Rand}(0,1)$$



[Masounimina, Richardson]

Threshold smearing in cluster fission



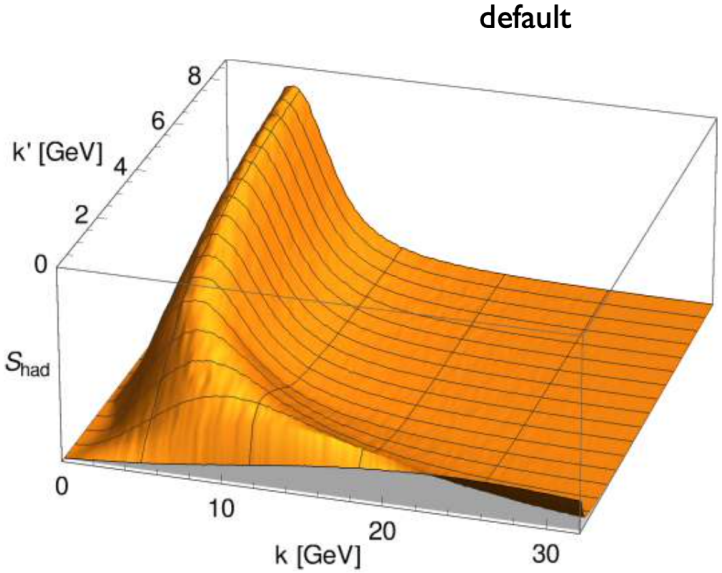
[Masounimina, Richardson]

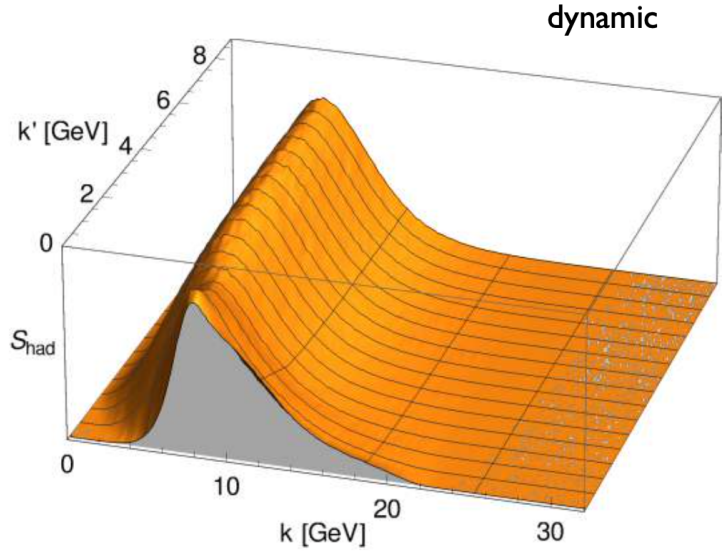
General tune of Herwig 7.3 with this improvement.

See talk by Aidin Masouminia!

Dynamical Hadronization corrections

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



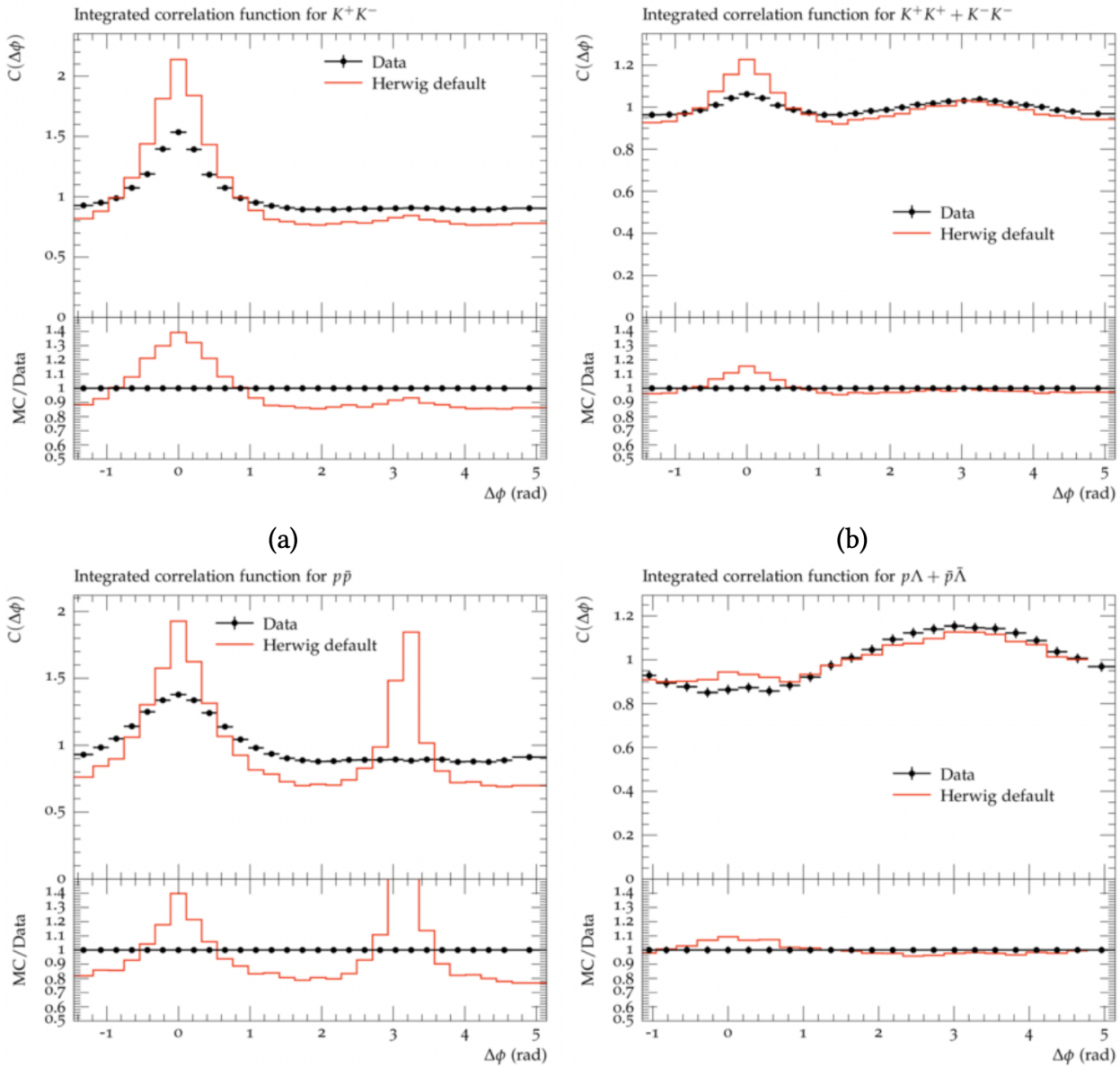


Hadronization corrections not picked up from hard parton scales anymore!

[Plätzer, Samitz]

See talk by Simon Plätzer!

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

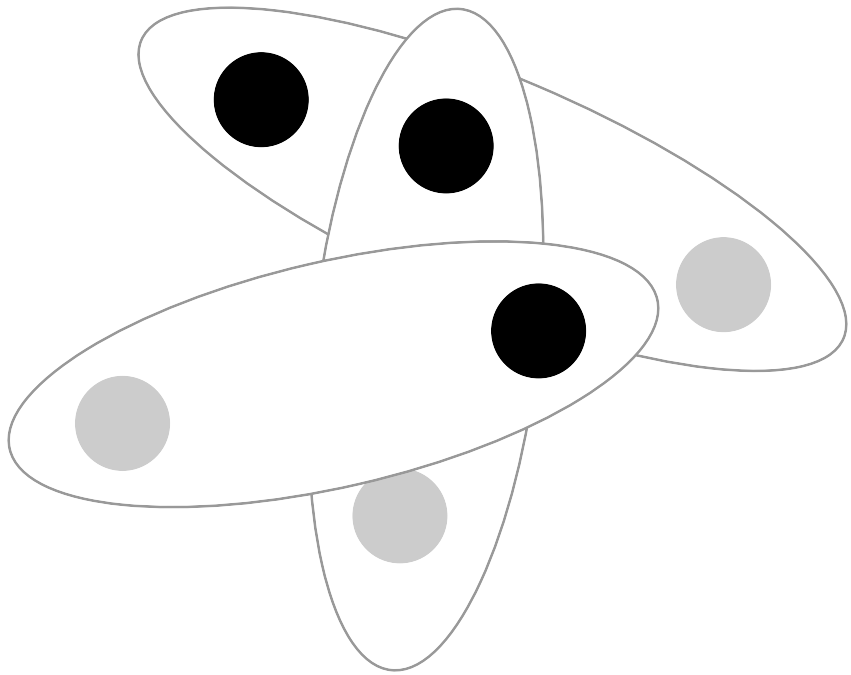
$$\text{cluster} \longrightarrow \text{hadron} + \text{hadron}$$

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

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

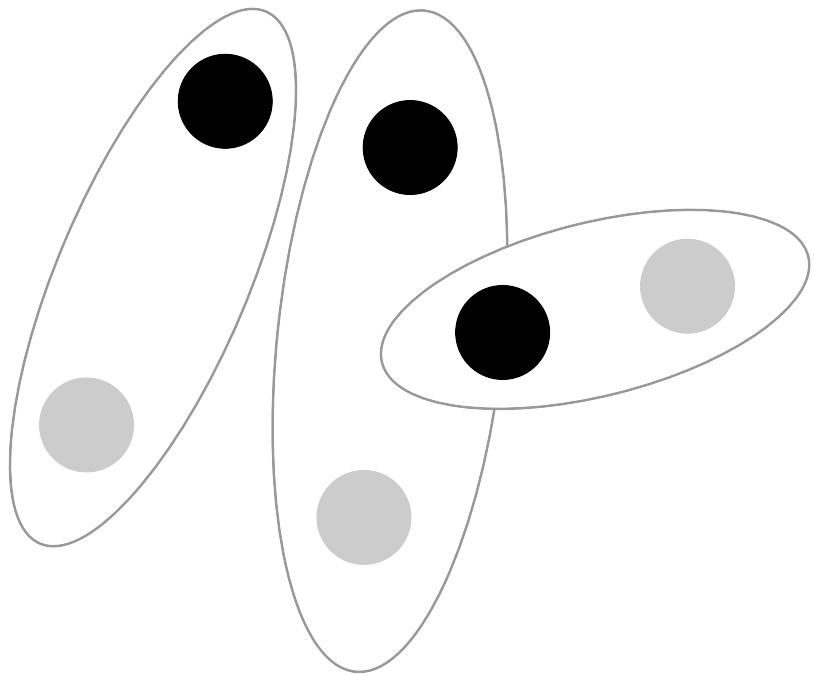
New modes of colour reconnection

Colour structure as it may result from parton shower



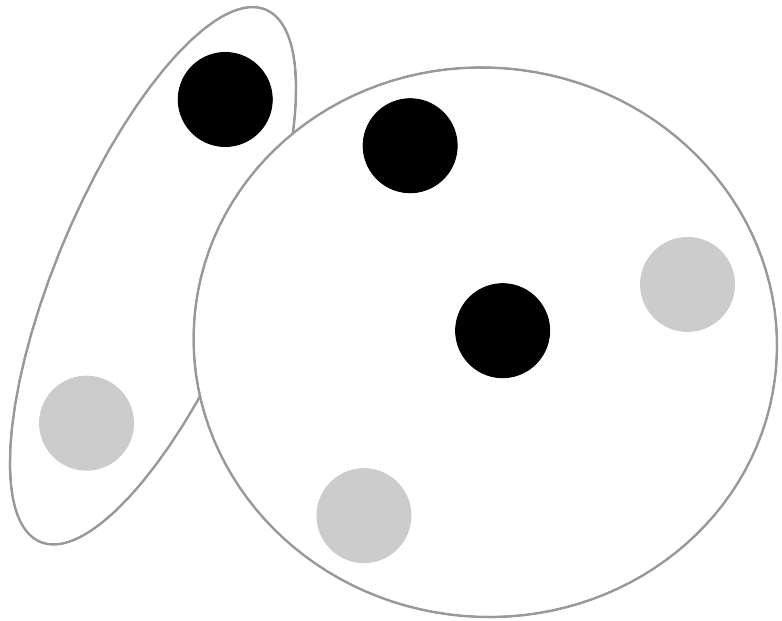
New modes of colour reconnection

After colour reconnection $MM \to MM$



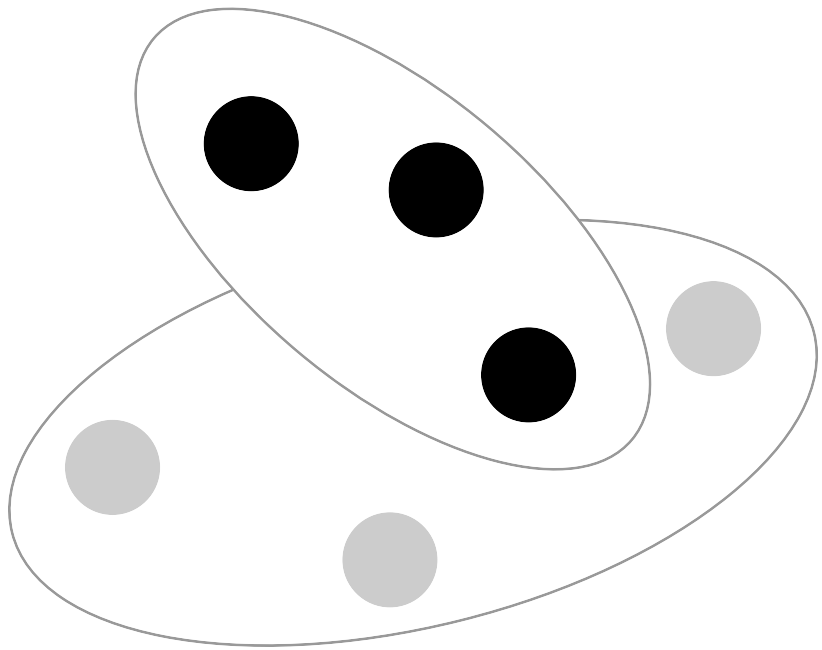
New modes of colour reconnection

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



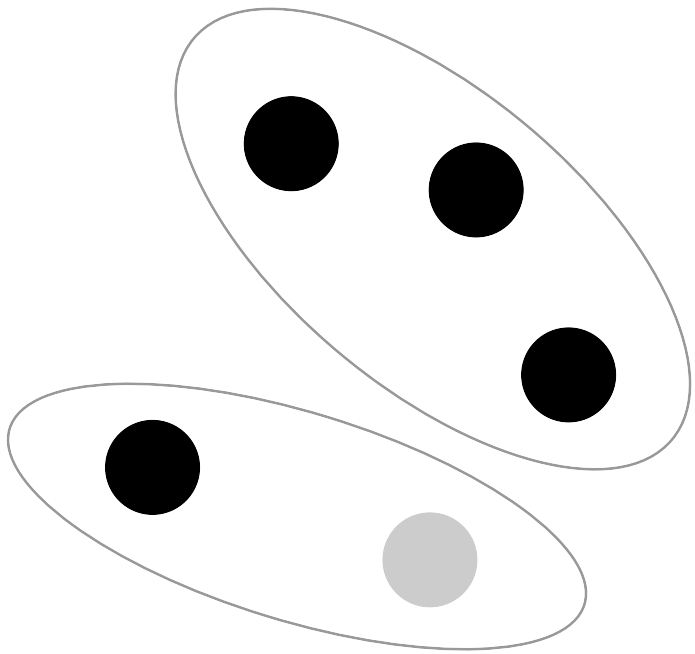
New modes of colour reconnection

Baryonic reconnection



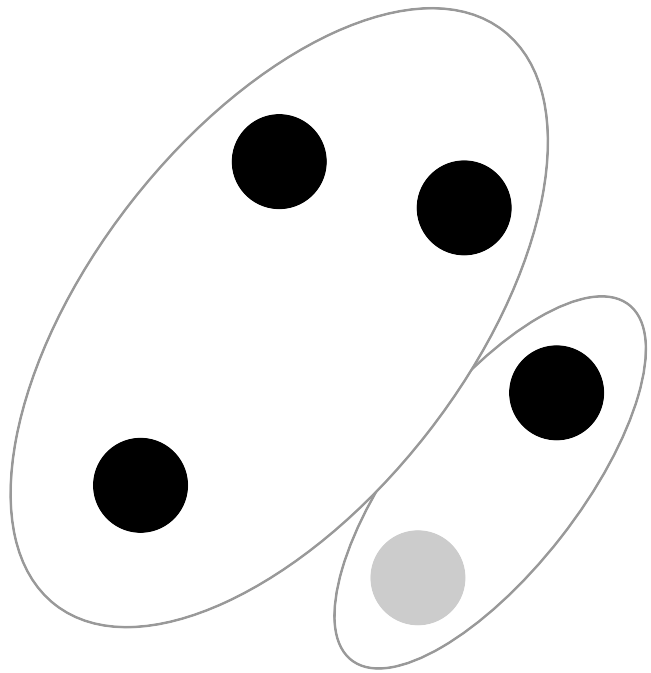
New modes of colour reconnection

Baryonic and mesonic cluster



New modes of colour reconnection

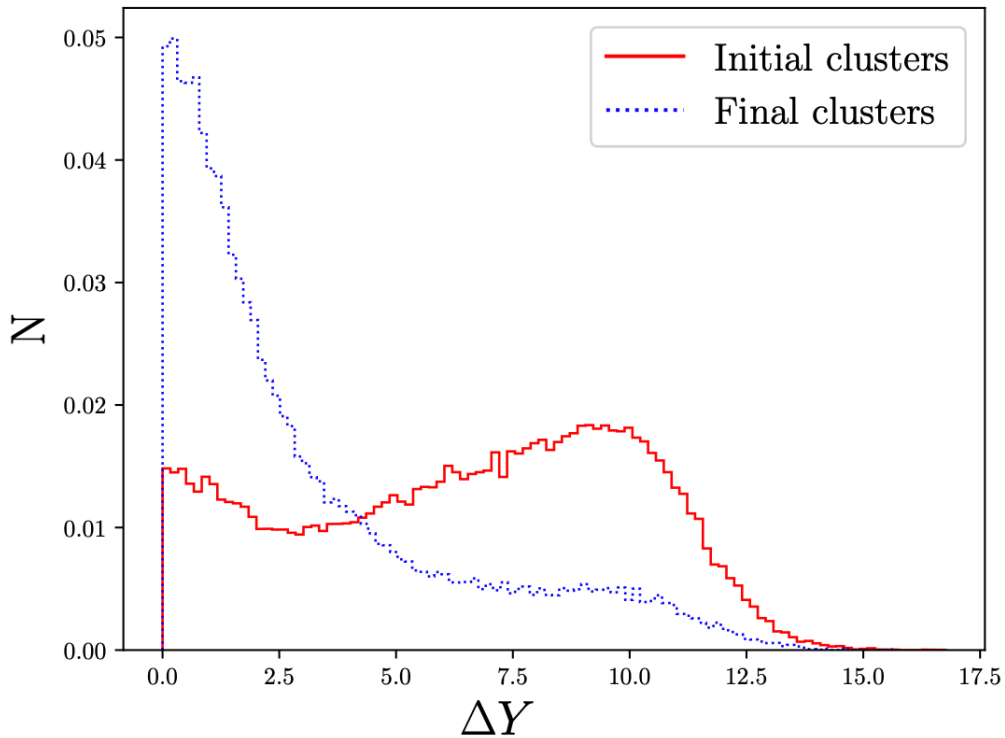
Baryonic and mesonic cluster



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]

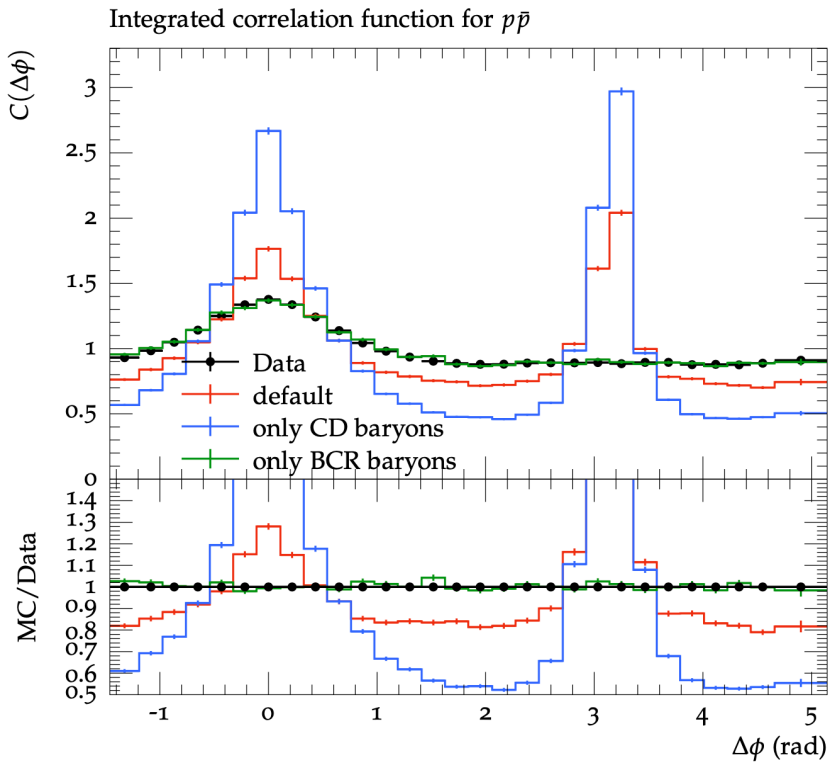
Cluster fission dynamics

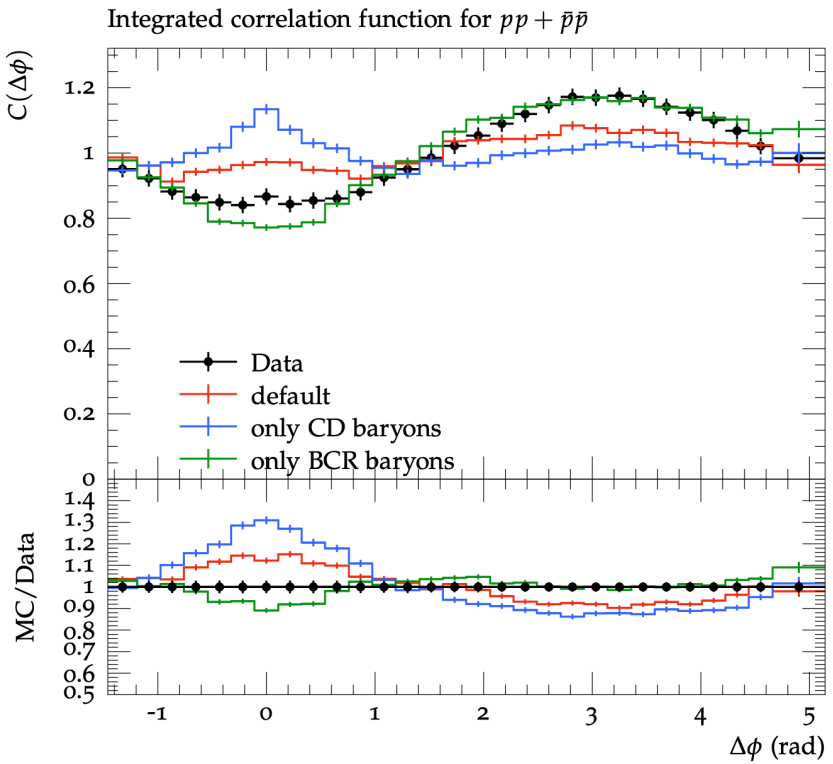
Still only longitudinal splitting in $C \to CC$ phase space.

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…



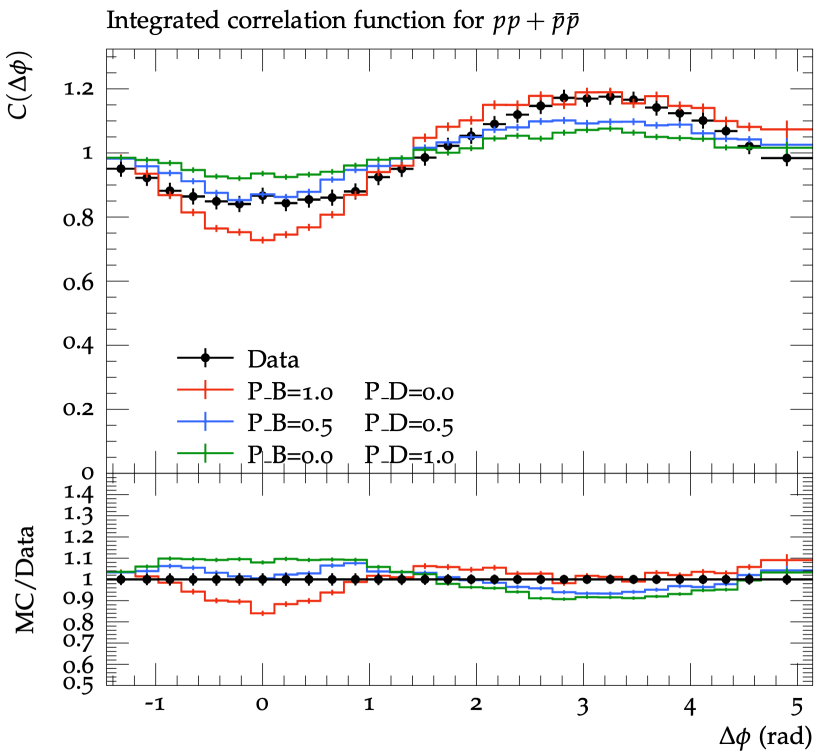


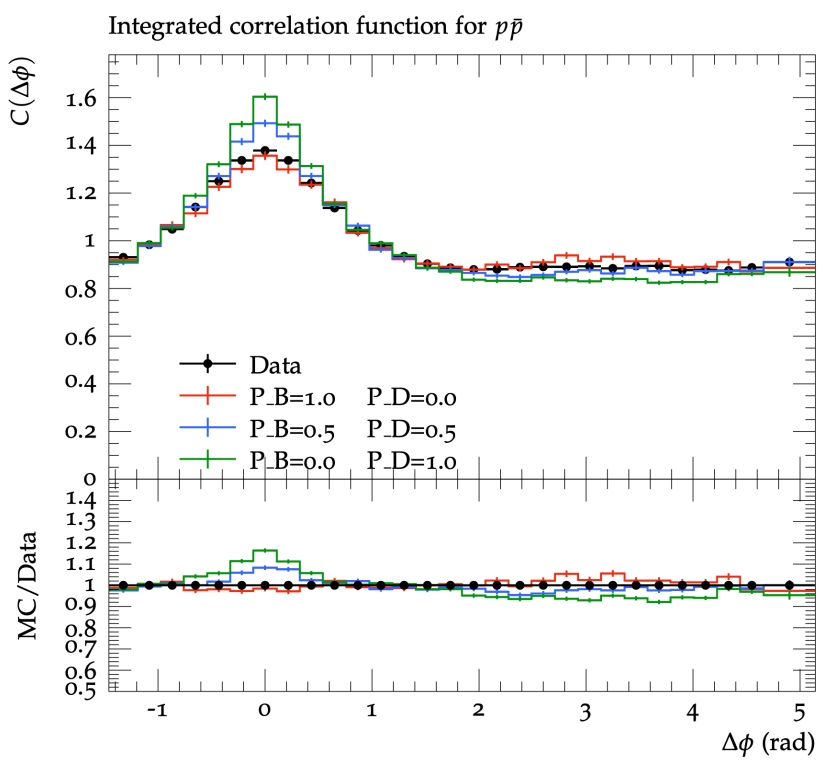
[SG, Kiebacher, Plätzer, Priedigkeit, in progress]

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

Cluster Decay correlations as expected
No strong correlations from CR.
See Stefan Kiebacher's talk

First steps…





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

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

Balance of diquark-pair and baryonic clusters.
See Stefan Kiebacher's talk

Summary and conclusion

Overview of hadronization and soft physics models

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

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