Soft Physics

Stefan Gieseke

Institut für Theoretische Physik
KIT

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TRR 257 - Particle Physics Phenomenology
after the Higgs Discovery

Soft models

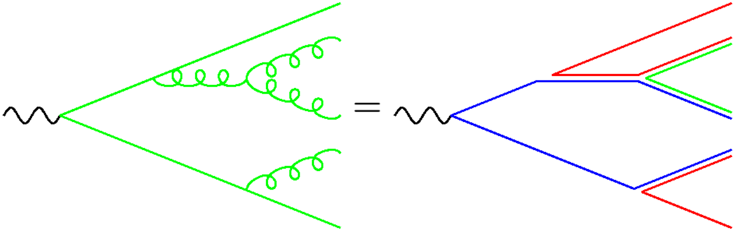
Where do soft models affect observables that are first and foremost determined perturbatively?

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

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

Colour preconfinement

Large N_C limit $\longrightarrow$ planar graphs dominate.
Gluon = colour — anticolour pair



Parton shower organises partons in colour space. Colour partners (=colour singlet pairs) end up close in phase space.

$\longrightarrow$ Input for hadronization model

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?)

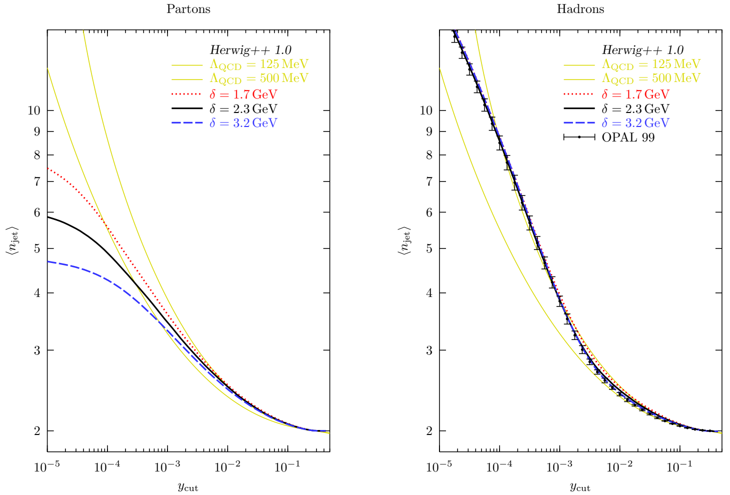
- Fission dynamics, now binary. Choice of phase space.
  Non-binary, i.e. $2 \to N$ fission, relation to soft UE?
  Non-perturbative $p_\perp$.

- Choice of hadrons and masses in cluster decay

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

μ^2-dependence (here: δ)

Smooth interplay between shower and hadronization.

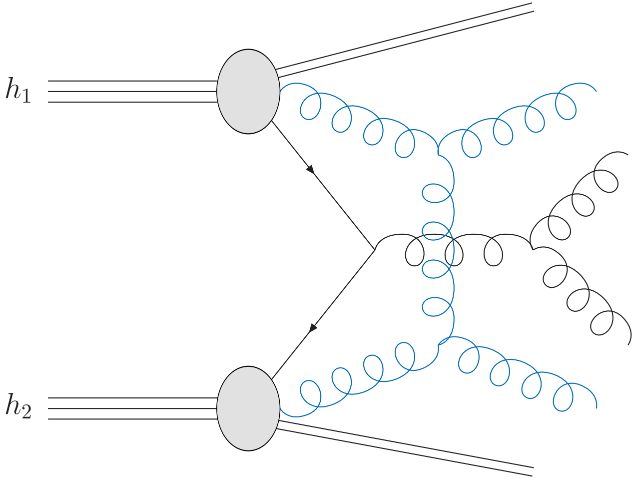


UV behaviour of Hadronization could be derived from PS.

[SG, A. Ribon, M. Seymour, P. Stephens, B.R. Webber, JHEP 0402 (2004) 005]

MPI/Eikonal model basics

Mulitple hard and soft interactions



Eikonal model basics

Use eikonal approximation (= independent scatters). Leads to Poisson distribution of number m of additional scatters,

$$P_m(\vec{b},s) = \frac{\bar{n}(\vec{b},s)^m}{m!} \mathrm{e}^{-\bar{n}(\vec{b},s)} \,.$$

Then we get σ_{inel}:

$$\sigma_{\mathrm{inel}} = \int \mathrm{d}^2\vec{b} \sum_{m=1}^{\infty} P_m(\vec{b},s) = \int \mathrm{d}^2\vec{b} \left(1 - \mathrm{e}^{-\bar{n}(\vec{b},s)}\right) \,.$$

Cf. σ_{inel} from scattering theory in eikonal approx. with scattering amplitude $a(\vec{b},s) = \frac{1}{2i}(\mathrm{e}^{-\chi(\vec{b},s)} - 1)$

$$\sigma_{\mathrm{inel}} = \int \mathrm{d}^2\vec{b} \left(1 - \mathrm{e}^{-2\chi(\vec{b},s)}\right) \qquad \Rightarrow \qquad \chi(\vec{b},s) = \frac{1}{2}\bar{n}(\vec{b},s) \,.$$

$\chi(\vec{b},s)$ is called *eikonal* function.

Eikonal model basics

Calculation of $\bar{n}(\vec{b},s)$ from parton model assumptions:

$$\bar{n}(\vec{b},s) = L_{\text{partons}}(x_1,x_2,\vec{b}) \otimes \sum_{ij} \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$

$$= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$

$$\times D_{i/A}(x_1,p_t^2,|\vec{b}'|) D_{j/B}(x_2,p_t^2,|\vec{b}-\vec{b}'|)$$

$$= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2}$$

$$\times f_{i/A}(x_1,p_t^2) G_A(|\vec{b}'|) f_{j/B}(x_2,p_t^2) G_B(|\vec{b}-\vec{b}'|)$$

$$= A(\vec{b}) \sigma^{\text{inc}}(s;p_t^{\text{min}}) \, .$$

$$\Rightarrow \quad \chi(\vec{b},s) = \tfrac{1}{2}\bar{n}(\vec{b},s) = \tfrac{1}{2}A(\vec{b})\sigma^{\text{inc}}(s;p_t^{\text{min}}) \, .$$

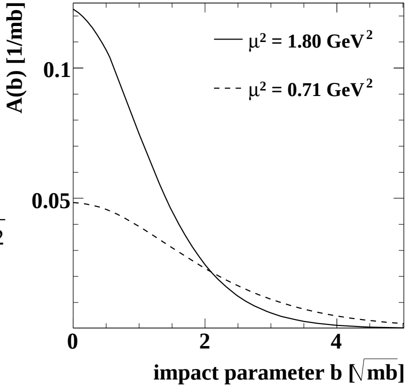
Overlap function

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

$G(\vec{b})$ 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: $\mu^2, p_t^{\min}$.

MPI at low $p_\perp$

Pythia: "freezing" of hard $\sim 1/p_\perp^4$ spectrum at low $p_\perp$ as model for soft MPI.

Herwig: transition from hard to soft MPI at $p_\perp^{\rm min}$.

Sherpa: BFKL ladders

Soft particle production model in Herwig

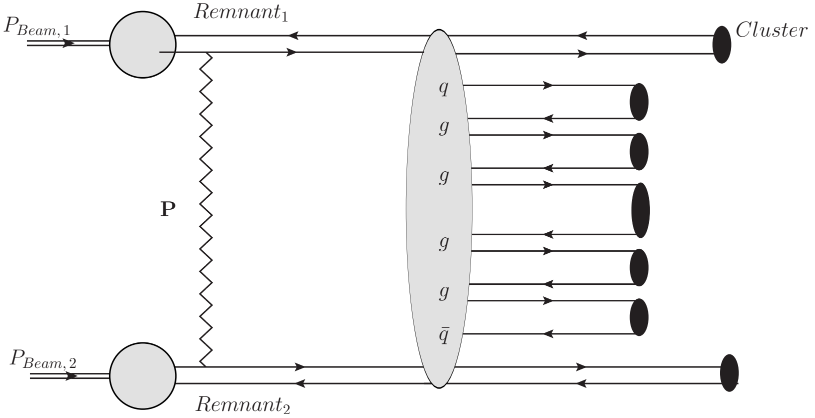
- #ladders = N_{soft} (MPI).
- N particles from Poissonian, width $\langle N \rangle$.
- $\sim$ flat in y
- $p_\perp$ from Gaussian acc to soft MPI model.
- particles are q, g, see figure.
  Symmetrically produced from both remnants.
- Colour connections between neighboured particles.

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

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

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]

Energy evolution

Some parameters $\sqrt{s}$ dependent.

$$p_\perp^{\min} = p_{\perp,0}^{\min}\left(\frac{\sqrt{s}+m_0}{E_0}\right)^b \qquad \longrightarrow \qquad p_{\perp,0}, b$$

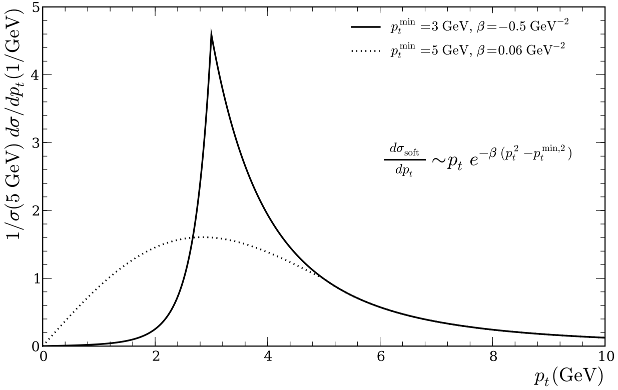
$p_{\perp,0} \sim 3.5\,\mathrm{GeV}$, $b \sim 0.4$.

$$\langle n_{\mathrm{ladder}}\rangle = N_0\left(\frac{s}{1\,\mathrm{TeV}^2}\right)^a \log\frac{s}{m_p^2} \qquad \longrightarrow \qquad N_0, a$$

$N_0 \sim 1$, $a \sim -0.08$.

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 $\sigma_{\rm soft}$ and $\mu^2_{\rm soft}$ fixed from data.

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

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: new MEs for diffractive processes set up.

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 $N_{\rm ch}$, $\langle p_\perp \rangle(N_{\rm ch})$.

Usual MPI parameters

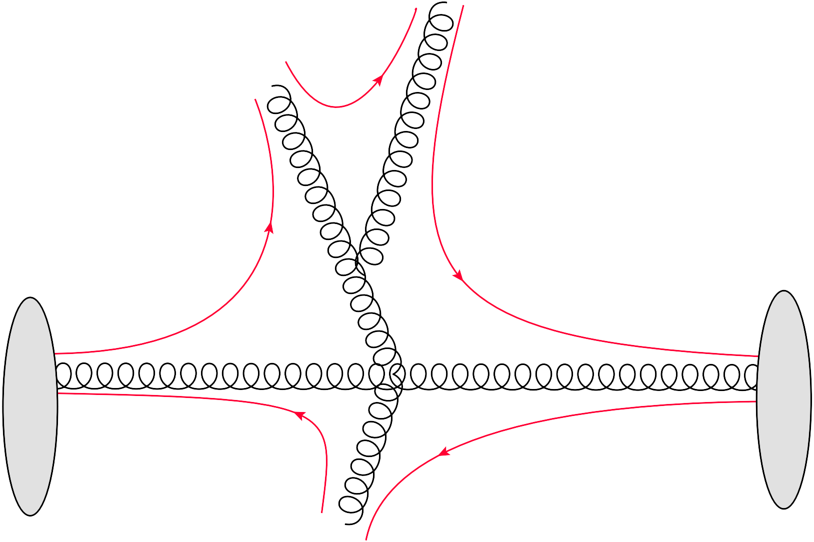
$$(p_{\perp,0}^{\rm min}, b) \to p_\perp^{\rm min}(\sqrt{s}), \quad \mu^2, \quad p_{\rm reco}\ .$$

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

$$n_{\rm ladder}\ .$$

Good description of most UE and Min Bias data
→ Hard Diffraction

Colour correlations in hadronic collisions



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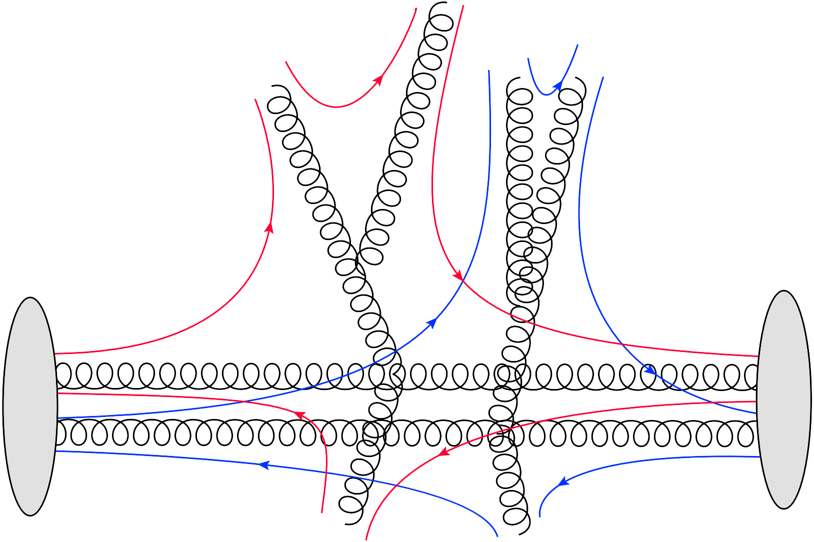

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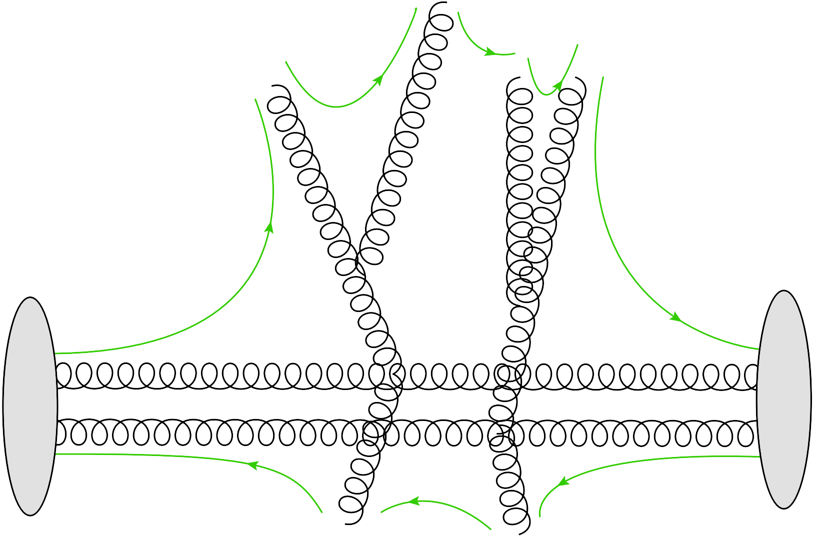
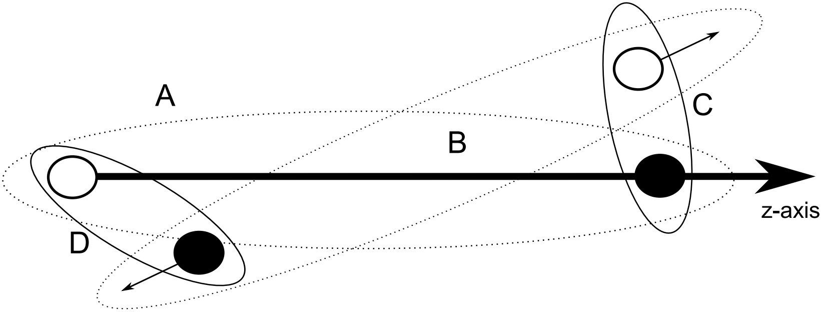


Rapididy based colour reconnection

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



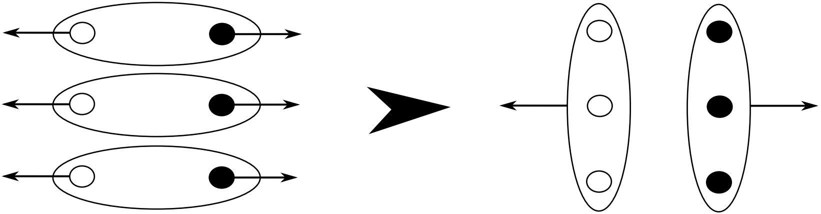
Consider other quarks' movement based on their rapidity in reference clusters' CM frame.

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

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

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]

Colour Reconnection

Different models for “colour distance”

- Δy, ΔR, also with transverse component

[Bellm, Duncan, SG, Myska, Siodmok, EPJC79 (2019) 12, 1003]

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

- Different models for minimization of colour distance, combinatiorial, Metropolis.

[Sandhoff, Skands, 2005]

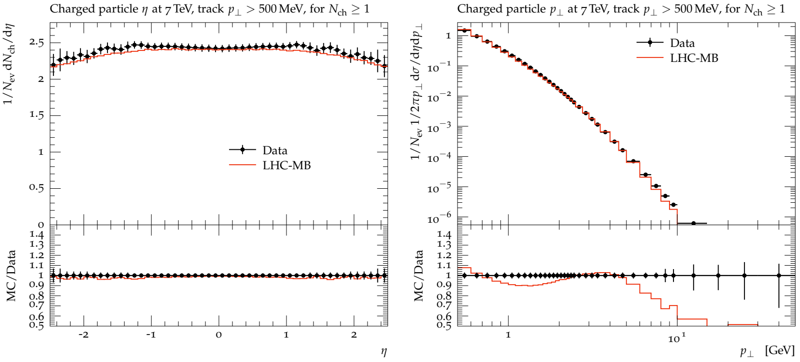
[SG, C. Röhr, A. Siodmok, EPJC72 (2012) 2225]

Perturbative support of phenomenological approach from soft gluons

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

Colour Reconnection, particularly with the formation of Baryons, seems to be key for our understanding of particle production and correlations.

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

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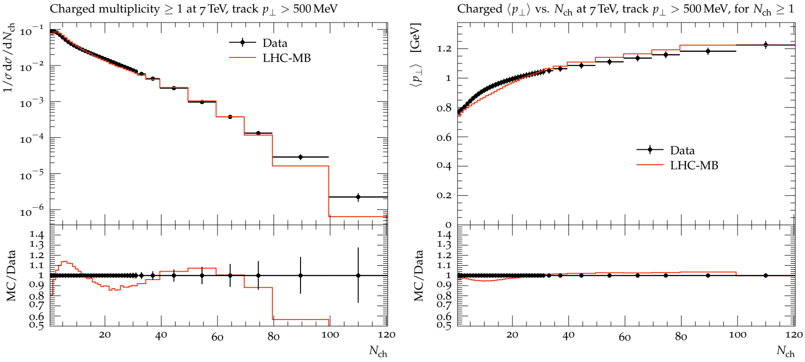

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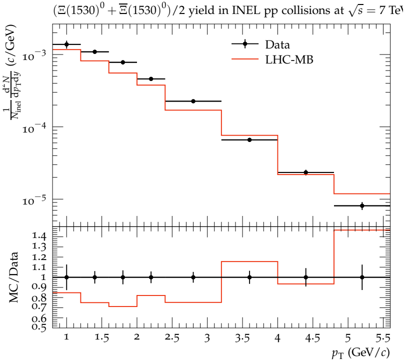
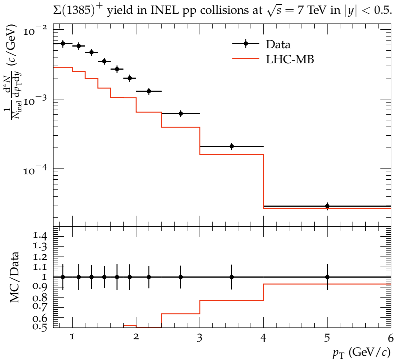




[ALICE, EPJ C75 (2015) 1,1; Herwig 7.2.2]

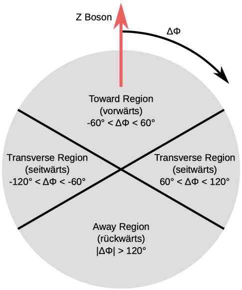
Identified particles, baryons in particular, harder to describe
$\rightarrow$ probably not "just" tuning?

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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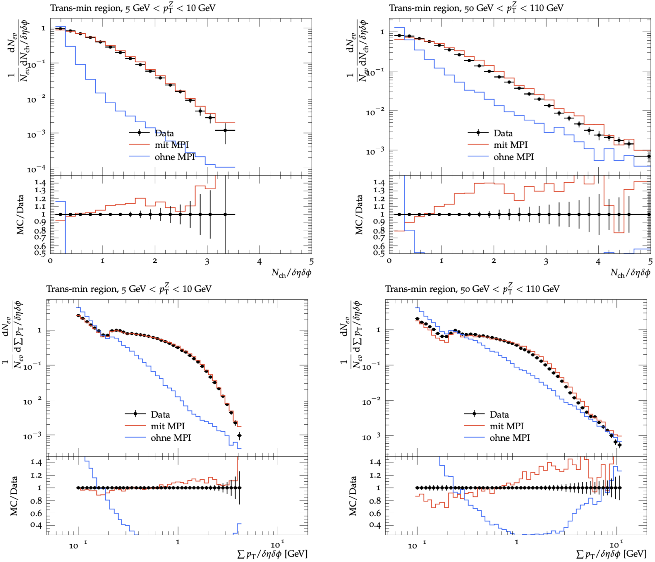

[K. Bartnick, B.Sc. thesis, KIT 2021]

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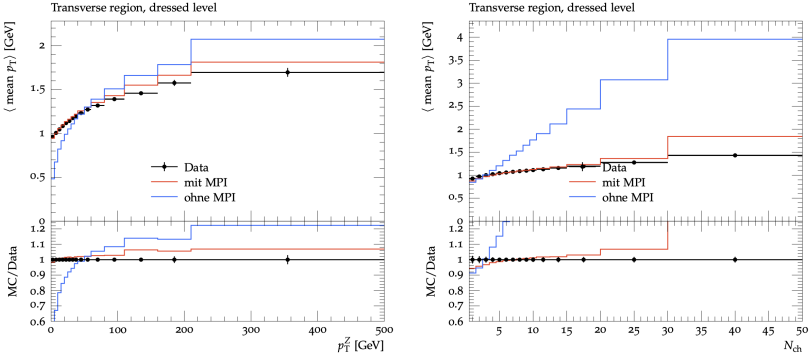

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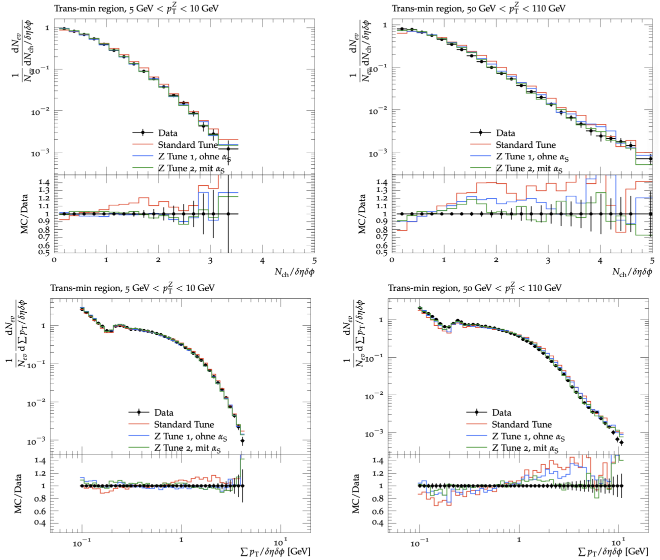

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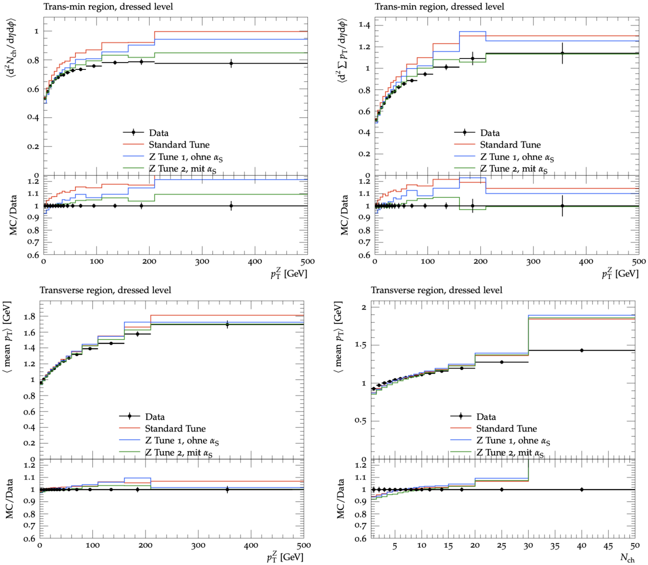
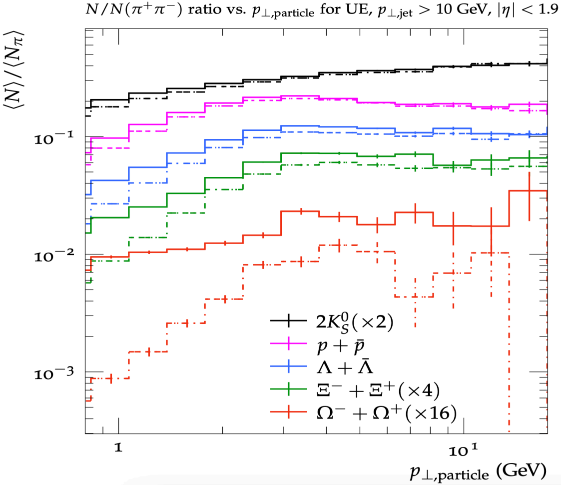


[K. Bartnick, B.Sc. thesis, KIT 2021]

Colour Ropes in string fragmentation

Idea: strings close → new colour configurations → higher string tension → enhancement of heavy particle production



[Bierlich, Chakraborty, Gustafson, Lönnblad, SciPost Phys. 13 (2022) 2, 023]

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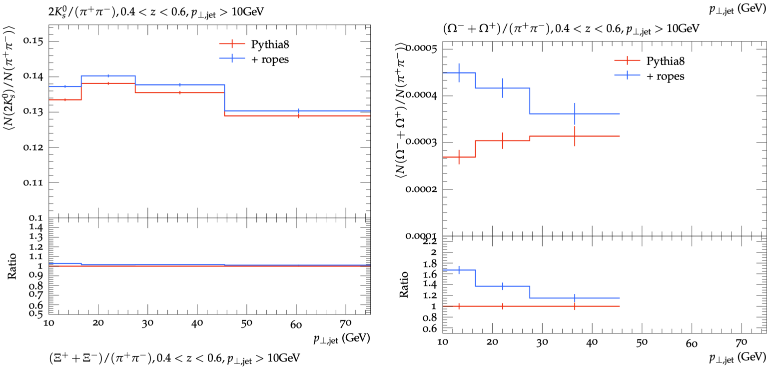

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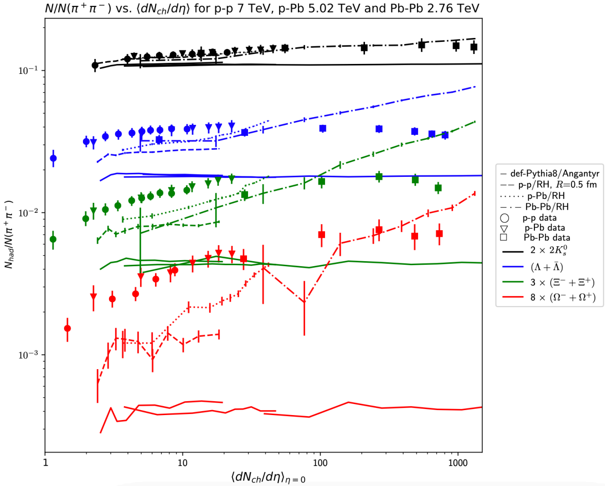
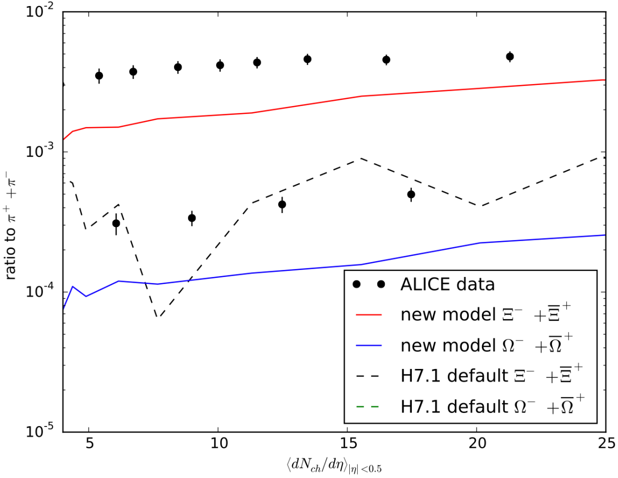


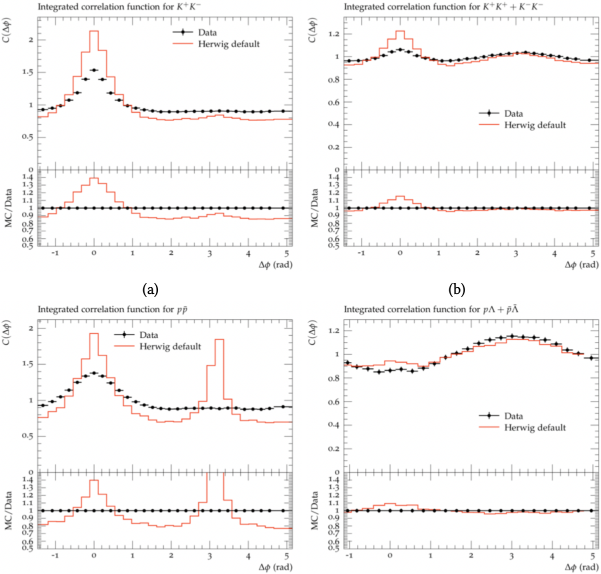
[Bierlich, Chakraborty, Gustafson, Lönnblad, 2205.11170]

Strange Baryons in Herwig



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

Example: Two-particle correlations



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

Example: Two-particle correlations

Cluster model innherently introduces strong two particle correlations in cluster decay

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

Somewhat lifted by baryonic colour reconnection

$$3M \to B\bar{B}$$

New reconnection modes, allowed by colour confinement?

$$BM \to B'M' \qquad B\bar{B} \to 3M \qquad 2B \to 2B'$$

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

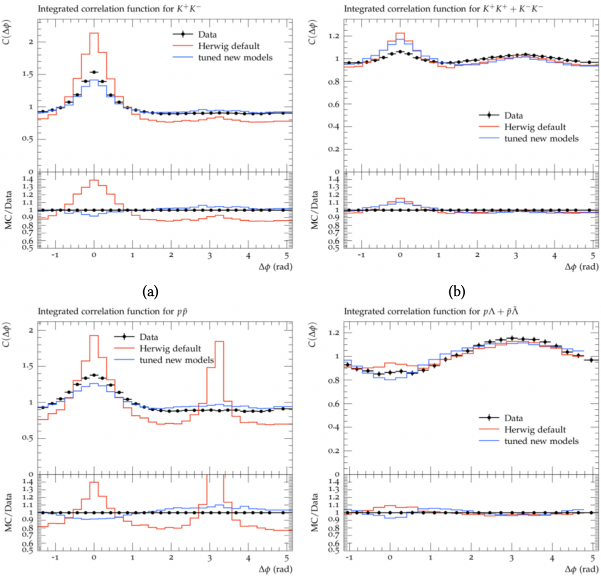
[D. Sudermann, Master's thesis KIT 2018]

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

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

[SG, Stefan Kiebacher, in progress]

Example: Two-particle correlations



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

Remarks on Colour Reconnection

Hints that more general colour reconnections are important for e.g. baryon production.

Baryons only from colour reconnection?

Tie together with high density, space-time picture

High density, heavy ions

Conclusion

- Non-perturbative models determine many details of particle production
- Many observables only look into averaged quantities
- Detailed observations demand refinements
- Models not always universal (re-tuning)
- Correlations improved with new modeling