Soft and hard multiple interactions in hadronic collisions

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pp Event Generator

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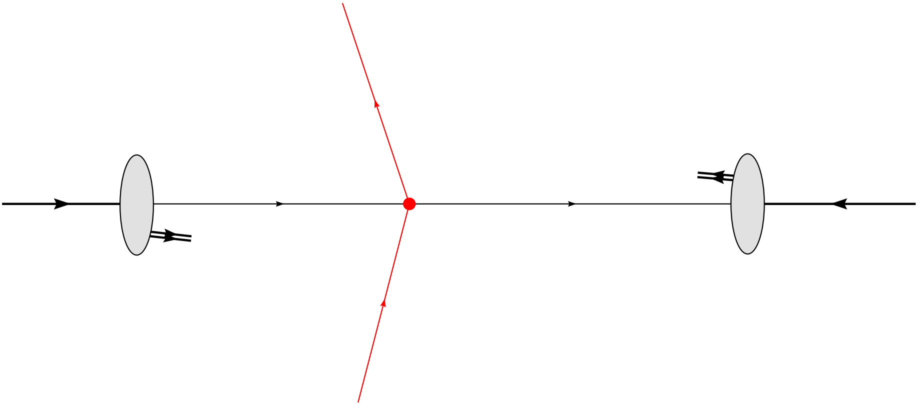

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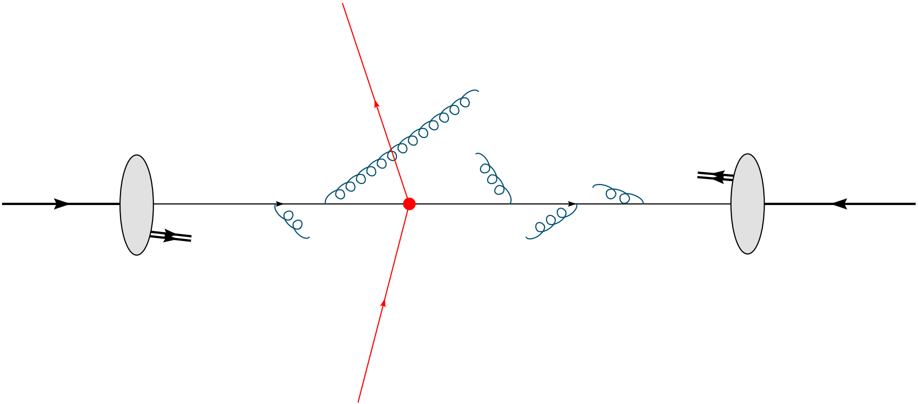

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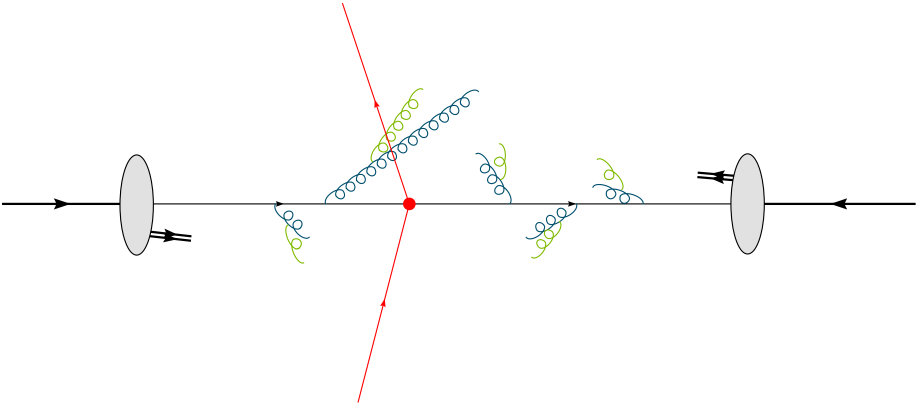

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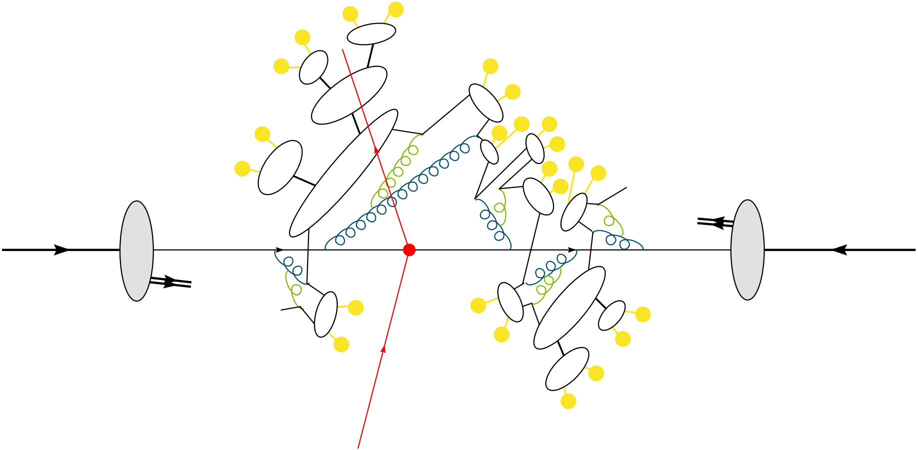

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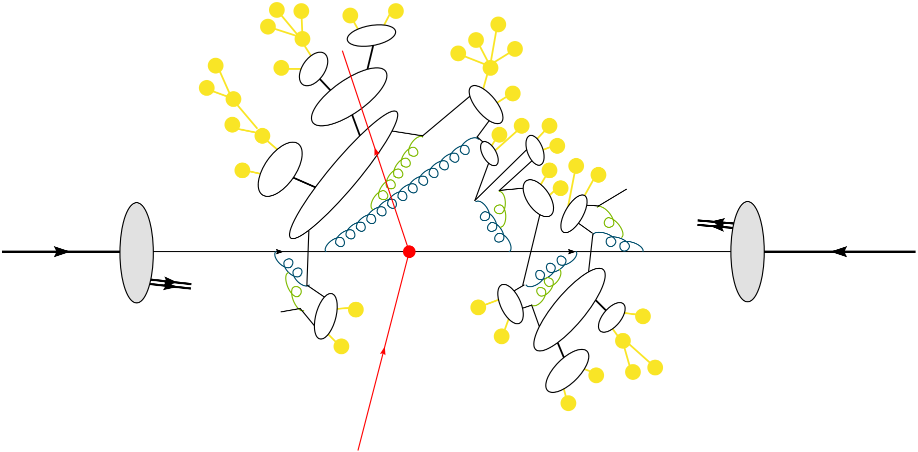

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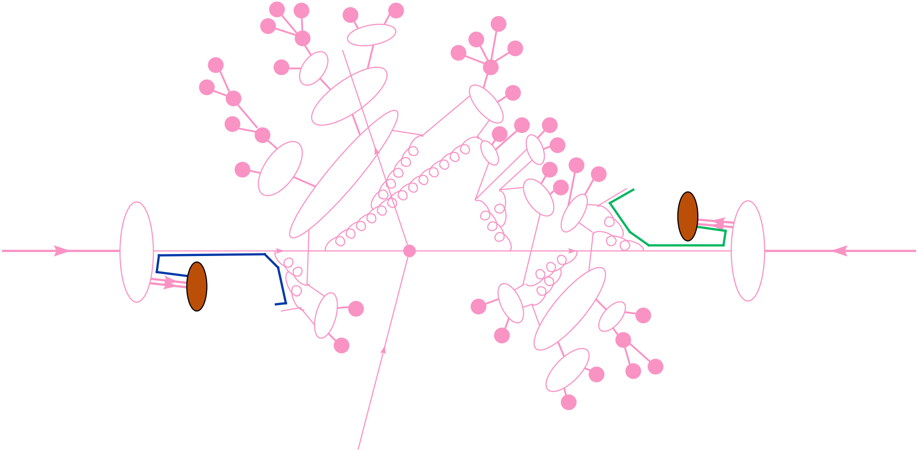

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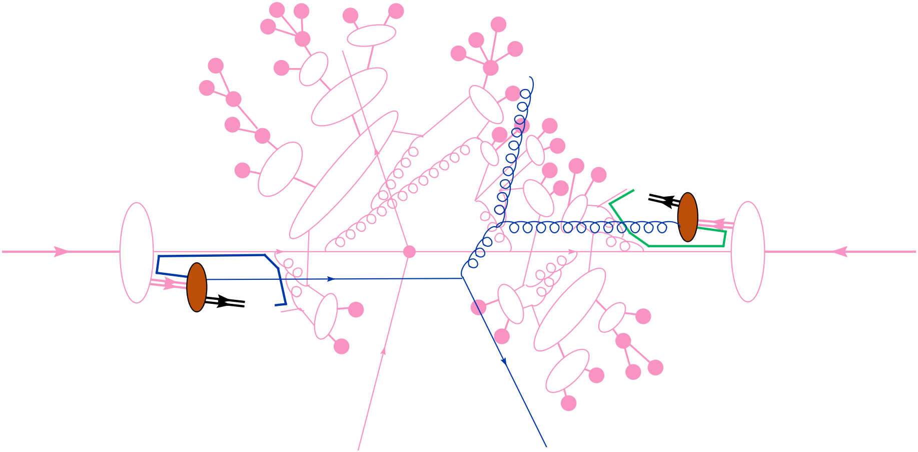

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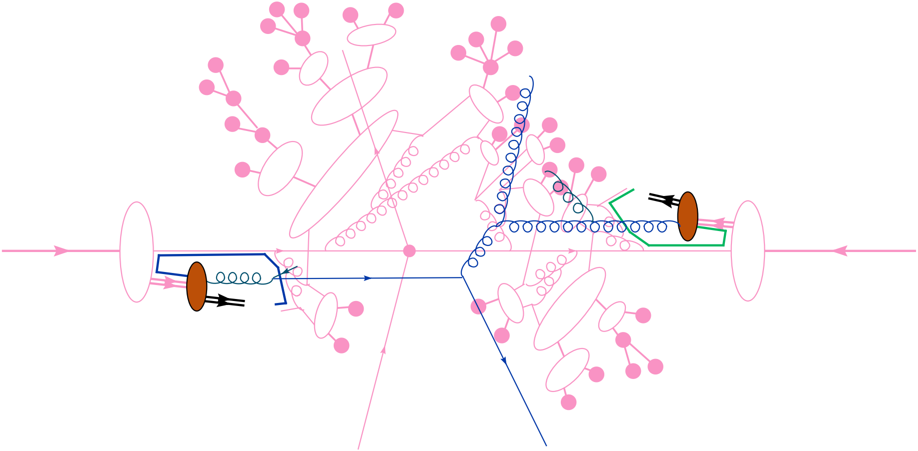

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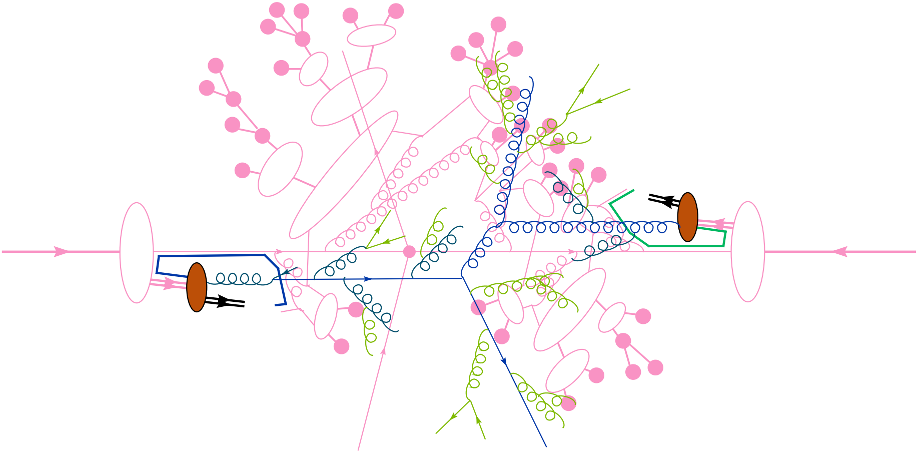

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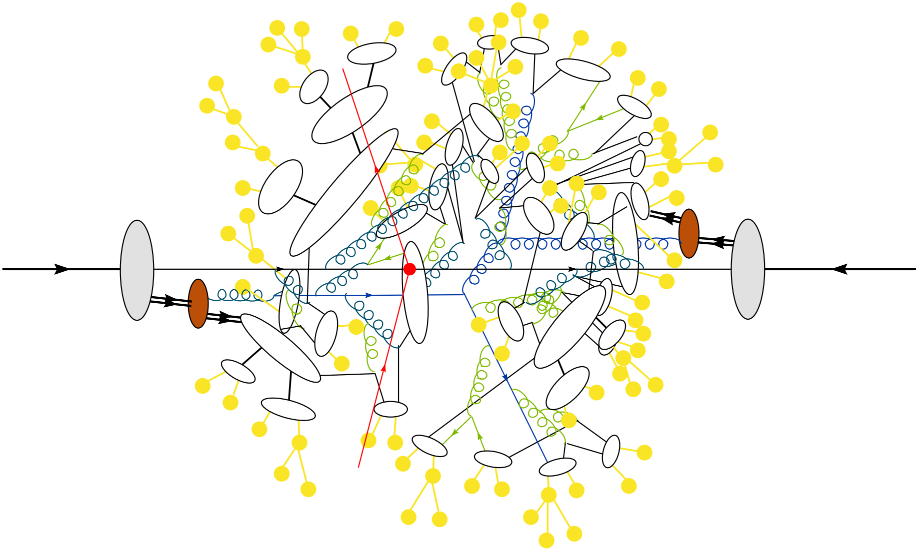

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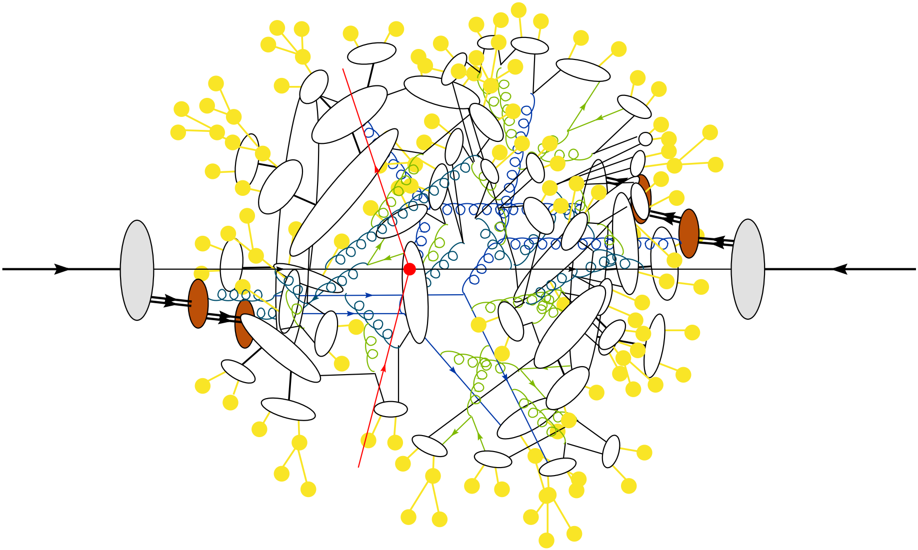


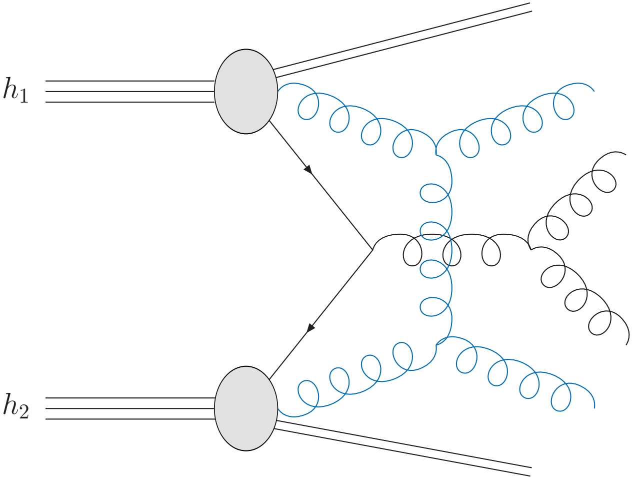
Outline

- Introduction to hard and soft MPI
  with Herwig as fairly generic example
- More recent developments
  - Soft scatters
  - Diffraction
  - Baryon production

Introduction: Multiple Partonic Interactions in Herwig

Eikonal model basics

Mulitple hard interactions (MPI)



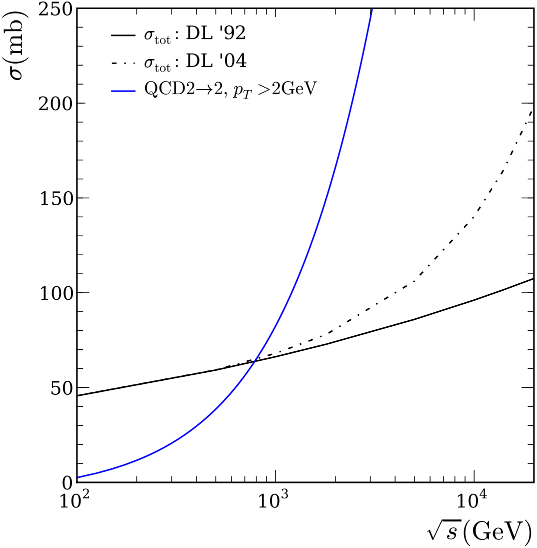
Eikonal model basics

Starting point: hard inclusive jet cross section.

$$\sigma^{\rm inc}(s;p_t^{\rm min}) = \sum_{i,j} \int_{p_t^{\rm min\,2}} {\rm d}p_t^2 f_{i/h_1}(x_1,\mu^2) \otimes \frac{{\rm d}\hat{\sigma}_{i,j}}{{\rm d}p_t^2} \otimes f_{j/h_2}(x_2,\mu^2)\,,$$

$\sigma^{\rm inc} > \sigma_{\rm tot}$ eventually (for moderately small $p_t^{\rm min}$).

Eikonal model basics



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$\sigma^{\rm inc} > \sigma_{\rm tot}$ eventually (for moderately small $p_t^{\rm min}$).

Interpretation: $\sigma^{\rm inc}$ counts *all* partonic scatters that happen during a single *pp* collision ⇒ more than a single interaction.

$$\sigma^{\rm inc} = \bar{n}\sigma_{\rm inel}.$$

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}:

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

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

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

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

Eikonal model basics

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

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

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

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

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

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

Eikonal model basics

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

$$
\begin{aligned}
\bar{n}(\vec{b},s) &= L_{\text{partons}}(x_1,x_2,\vec{b}) \otimes \sum_{ij} \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&\qquad \times D_{i/A}(x_1,p_t^2,|\vec{b}'|) D_{j/B}(x_2,p_t^2,|\vec{b}-\vec{b}'|) \\
&= \sum_{ij} \frac{1}{1+\delta_{ij}} \int \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}^2\vec{b}' \int \mathrm{d}p_t^2 \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}p_t^2} \\
&\qquad \times f_{i/A}(x_1,p_t^2) G_A(|\vec{b}'|) f_{j/B}(x_2,p_t^2) G_B(|\vec{b}-\vec{b}'|) \\
&= A(\vec{b}) \sigma^{\text{inc}}(s;p_t^{\text{min}}) \,.
\end{aligned}
$$

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

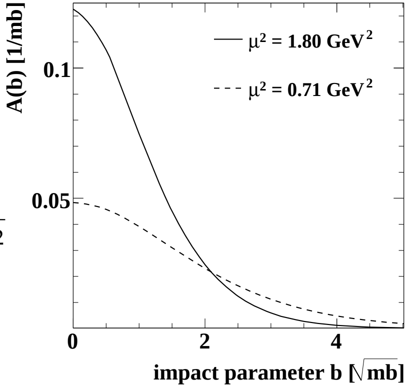
Overlap function

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

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

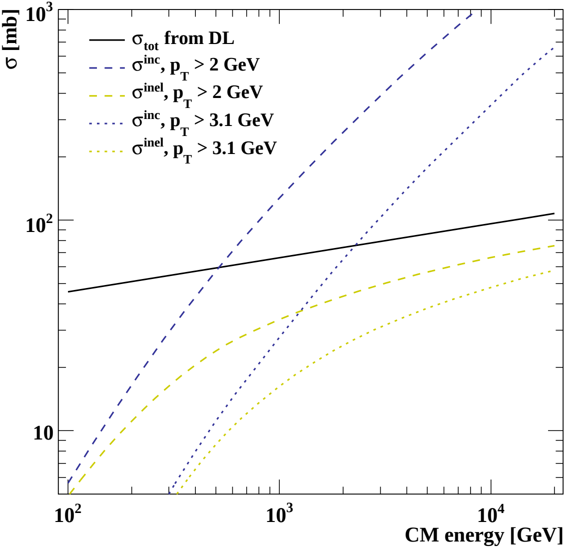
$$G_p(\vec{b}) = G_{\bar{p}}(\vec{b}) = \int \frac{\mathrm{d}^2\vec{k}}{(2\pi)^2} \frac{\mathrm{e}^{i\vec{k}\cdot\vec{b}}}{(1+\vec{k}^2/\mu^2)^2}$$

But μ^2 *not fixed* to the *electromagnetic* 0.71 GeV^2.
Free for colour charges.



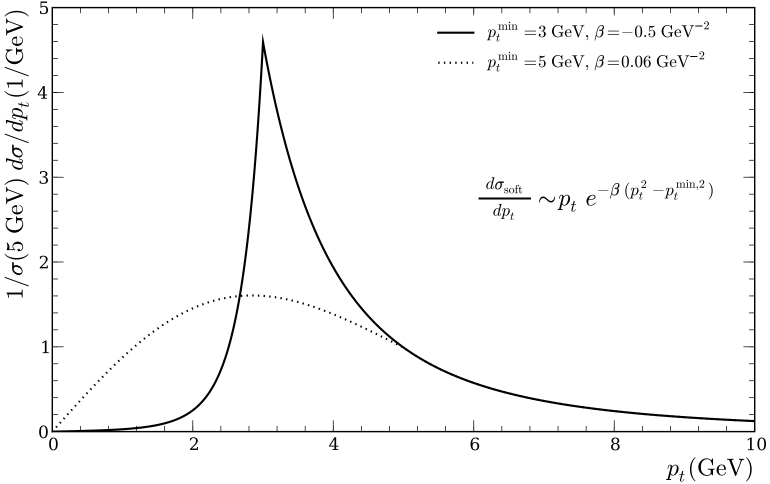
$\Rightarrow$ Two main parameters: $\mu^2, p_t^{\min}$.

Unitarized cross sections



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)



Hot Spot model

Fix the two parameters μ_{soft} and $\sigma_{\text{soft}}^{\text{inc}}$ in

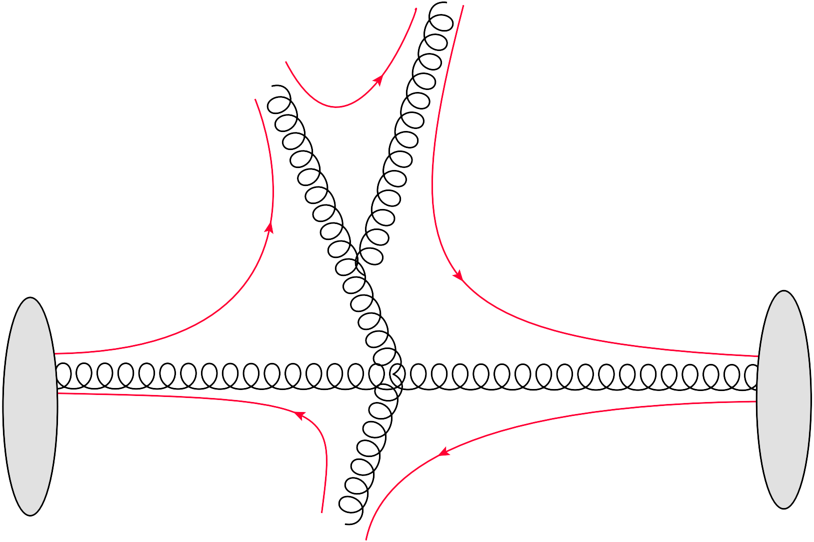
$$\chi_{\text{tot}}(\vec{b},s) = \frac{1}{2}\left(A(\vec{b};\mu)\sigma^{\text{inc}}\text{hard}(s;p_t^{\text{min}}) + A(\vec{b};\mu_{\text{soft}})\sigma_{\text{soft}}^{\text{inc}}\right)$$

from two constraints. Require simultaneous description of σ_{tot} and b_{el} (measured/well predicted),

$$\sigma_{\text{tot}}(s) \stackrel{!}{=} 2\int \mathrm{d}^2\vec{b}\left(1-\mathrm{e}^{-\chi_{\text{tot}}(\vec{b},s)}\right) ,$$

$$b_{\text{el}}(s) \stackrel{!}{=} \int \mathrm{d}^2\vec{b}\,\frac{b^2}{\sigma_{\text{tot}}}\left(1-\mathrm{e}^{-\chi_{\text{tot}}(\vec{b},s)}\right) .$$

Colour Reconnection — idea



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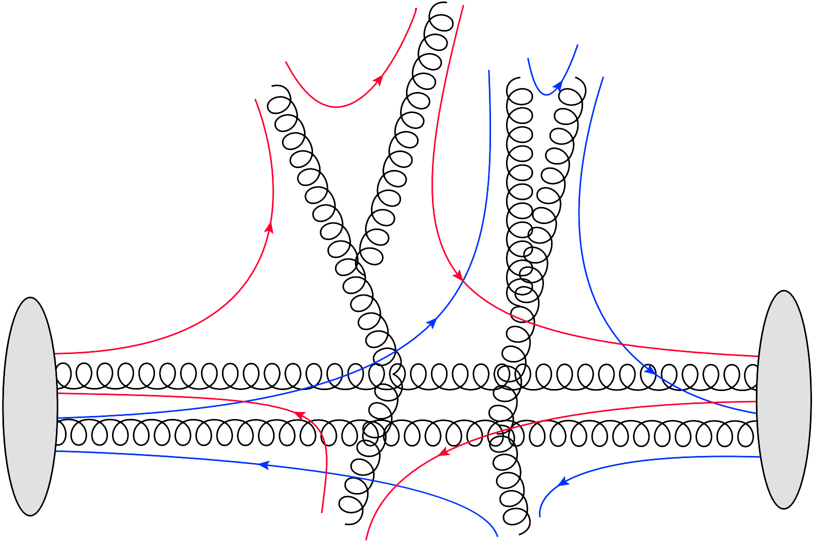

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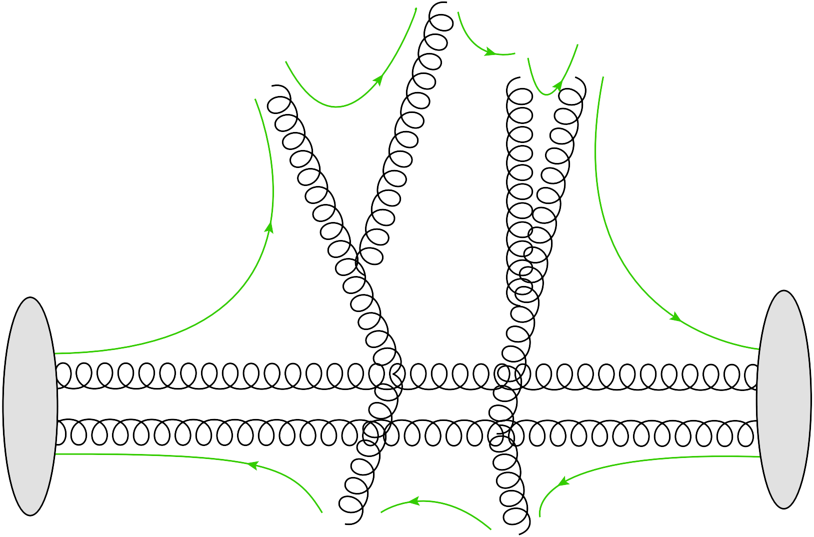
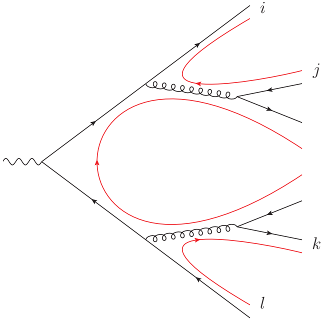


Colour reconnection (CR) in Herwig



Extend cluster hadronization:

- QCD parton showers provide *pre-confinement* ⇒ colour-anticolour pairs

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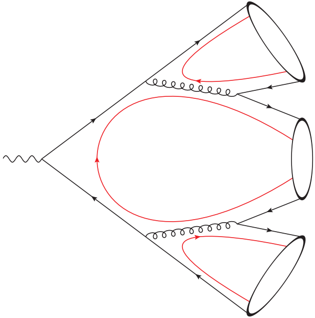

Extend cluster hadronization:

- QCD parton showers provide *pre-confinement* $\Rightarrow$ colour-anticolour pairs
- $\rightarrow$ *clusters*

[SG, C. Röhr, A. Siodmok, EPJ C72 (2012) 2225]

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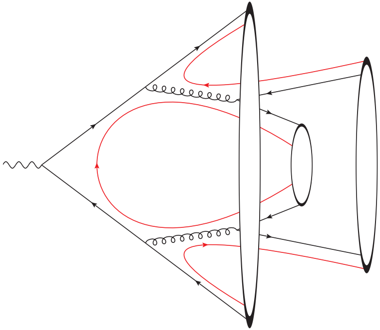

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- CR in the cluster hadronization model: allow *reformation* of clusters, *e.g.* $(il) + (jk)$

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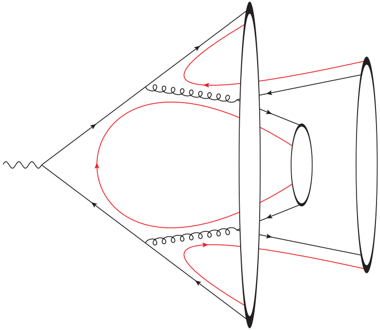

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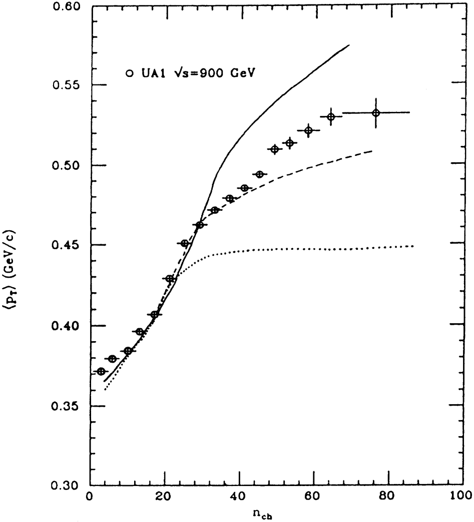
- Allow CR if the cluster mass decreases,

$$M_{il} + M_{kj} < M_{ij} + M_{kl},$$

- Accept alternative clustering with probability p_{reco} (model parameter) $\Rightarrow$ this allows to switch on CR smoothly
- Alternative *Statistical CR* (Metropolis)

[SG, C. Röhr, A. Siodmok, EPJ C72 (2012) 2225]

Colour reconnections



- Sensitivity to CR already known since UA1.
- (From Sjöstrand / van Zijl)

MPI in Herwig

Semihard MPI

- Default from Herwig++ 2.1. [Herwig++, 0711.3137]
- Multiple hard interactions, $p_t \geq p_t^{\min}$. [Bähr, SG, Seymour, JHEP 0807:076]
- pQCD $2 \to 2$.
- Similar to `JIMMY`.
- Good description of harder UE data ("plateau").

MPI in Herwig

Soft MPI

- Default from Herwig++ 2.3. [Herwig++, 0812.0529]
- Extension to soft interactions $p_t < p_t^{\min}$.
- Theoretical work with simplest possible extension. [Bähr, Butterworth, Seymour, JHEP 0901:065]
- "Hot Spot" model. [Bähr, Butterworth, SG, Seymour, 0905.4671]

Recent developments in Herwig

Old implementation of soft scattering

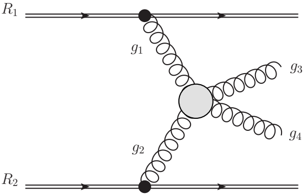
Soft gluon production with soft $p_t < p_t^{\min}$ spectrum.

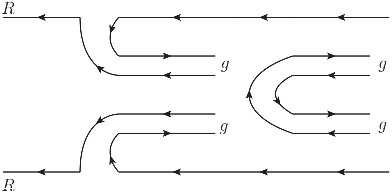
Colour structure important. Two extreme cases possible.

Sensitivity to parameter

$$\texttt{colourDisrupt} = P(\text{disrupt colour lines})$$

Long colour lines appear when swapping outgoing gluons.



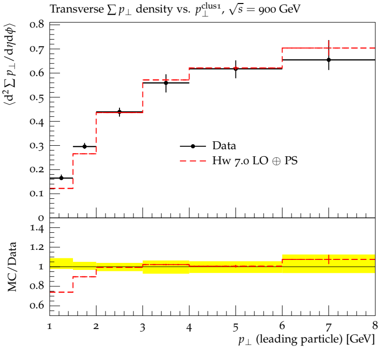


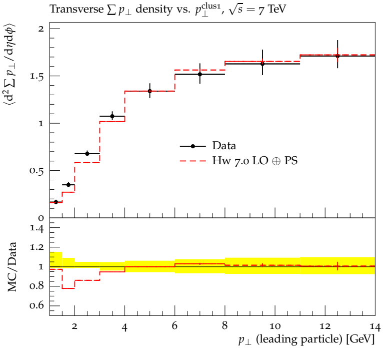
Colour reconnections applied!

So far at the LHC

Soft model is extension of MPI model for Underlying Event and *harder* aspects of Min Bias events.
Herwig 7.0 at 900 GeV and 7 TeV:

[ATLAS, Eur.Phys.J. C71 (2011) 1636]





Still reasonably well for moderately soft particles.

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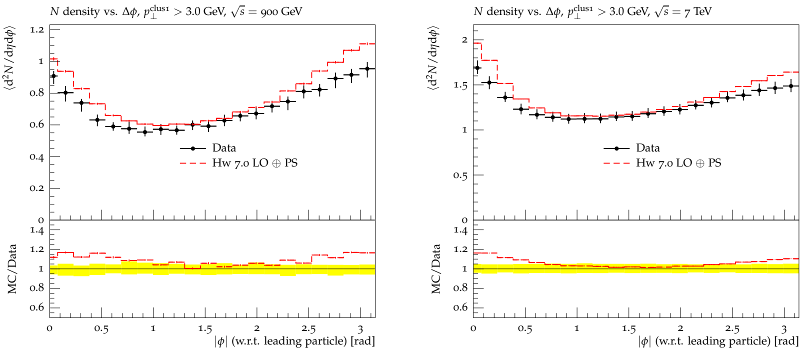
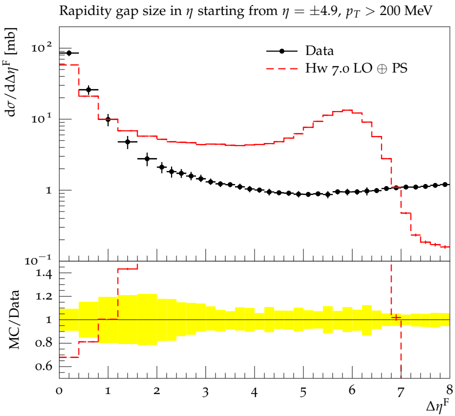


Still reasonably well for moderately soft particles.

The bump

A clear case of abusing a model for the hard UE in forward/diffractive final states…

[ATLAS, Eur.Phys.J. C72 (2012) 1926]



Bump is artefact. No Diffraction. Poor modeling of soft interactions. Colour assignment ad hoc.

Newer developments

Challenge accepted.

- Model for diffractive final states.
- Model for soft particle production.

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

- New baryon production mechanisms.

[SG, P. Kirchgaeßer, S. Plätzer, arXiv 10/2017]

Diffraction as part of minimum bias simulation

Diffractive final states directly modeled.

Not embedded in MPI approach via cuts through triple pomeron vertices. Therefore change in constraint

$$x\sigma_{\rm tot}(s) \stackrel{!}{=} 2\int {\rm d}^2\vec{b}\left(1-{\rm e}^{-\chi_{\rm tot}(\vec{b},s)}\right) \ ,$$

where

$$x \approx 1 - \frac{\sigma_{\rm diff}}{\sigma_{\rm tot}} \approx 75\% \ .$$

In min-bias simulation: every event is either

- diffractive, directly modeled from *pp* initial state.
- non-diffractive, modeled in the MPI picture, parton level.

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

$$pp \to \Delta + p \ .$$

Also double diffraction implemented.

$$pp \to (\text{cluster}) + (\text{cluster}) \qquad pp \to \Delta + \Delta \ .$$

Technically: new MEs for diffractive processes set up.

Model for soft particle production in Herwig

Reproduce core properties of soft particle production.

"flat in rapidity", "narrow in p_t".

Main idea: "soft interaction = cut pomeron = particle ladder".

N_{soft} from MPI model = #ladders.

Clusters produced via colour connected quarks and gluons.

Adopt to soft interactions in Herwig via remnant decays.

Multiperipheral kinematics

[Baker, Ter-Martirosyan 1976]

Average relative momentum fraction $\langle x \rangle$. Leads to flat rapidity distribution of emissions in a single ladder.

$$\Delta y \sim \ln \frac{1}{x} \ .$$

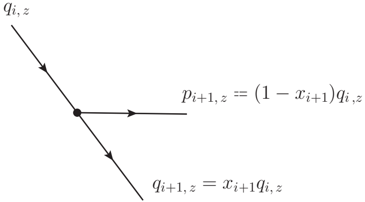
Choose some constant C, then

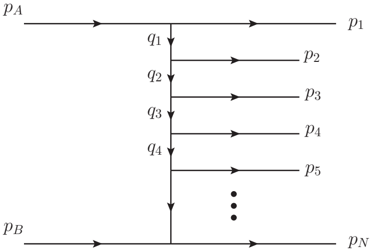
$$\langle x \rangle \sim 1/C \ .$$

$\langle N \rangle$ average number of emitted particles.

$$\langle N \rangle = \frac{1}{\ln C} \ln \frac{s}{m^2}$$

$p_\perp$ or $m_\perp$ moderate, unordered.



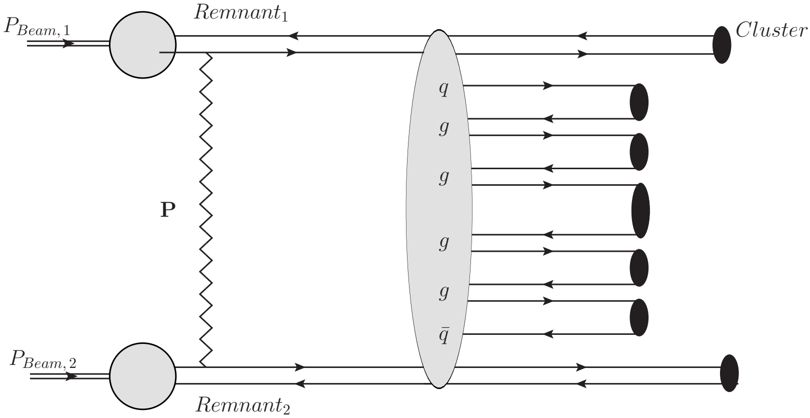


Soft particle production model in Herwig

- #ladders = N_{soft} (MPI).
- N particles from Poissonian, width $\langle N \rangle$.
  Model parameter $1/\ln C \equiv n_{\text{ladder}} \to$ tuned.
- x_i smeared around $\langle x \rangle$ (calculated).
- $p_\perp$ from Gaussian acc to soft MPI model.
- particles are q, g, see figure.
  Symmetrically produced from both remnants.
- Colour connections between neighboured particles.

Soft particle production model in Herwig

Single soft ladder with MinBias initiating process.



Further hard/soft MPI scatters possible.

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

Usual MPI parameters

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

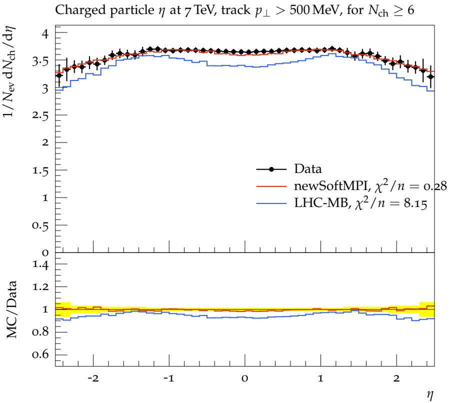
One additional parameter

$$n_{\mathrm{ladder}} \, .$$

Tuned results

ATLAS Min Bias 7 TeV.

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

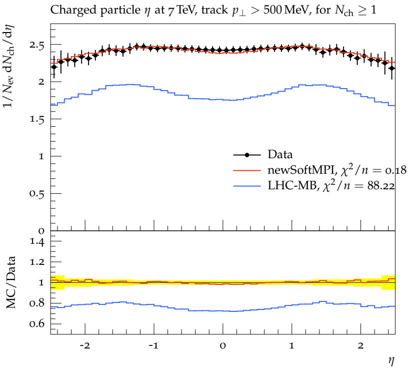


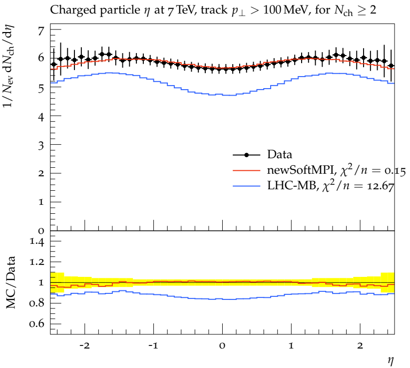
Similar to previous results, "harder part of Min Bias".

Tuned results

ATLAS Min Bias 7 TeV.

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



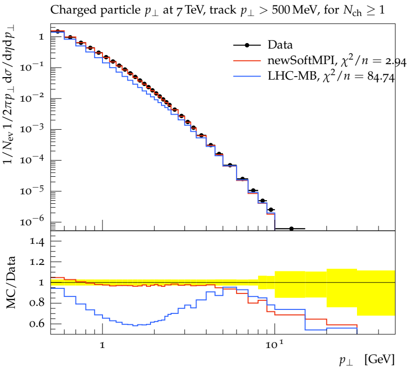


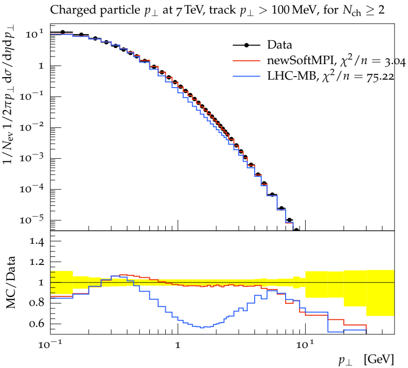
Also soft rates well described.

Tuned results

ATLAS Min Bias 7 TeV.

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



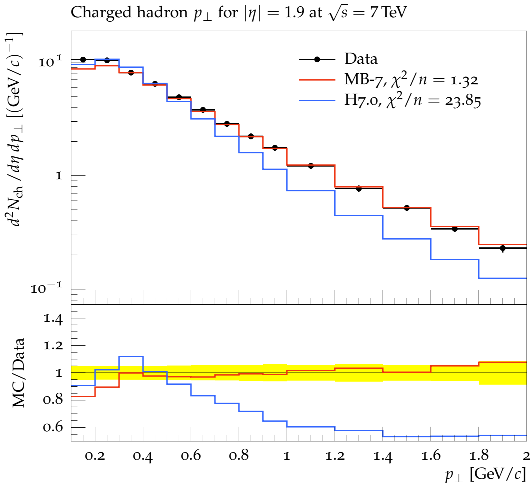


Tails? Still within 1σ.

More results

CMS, NSD analysis 7 TeV

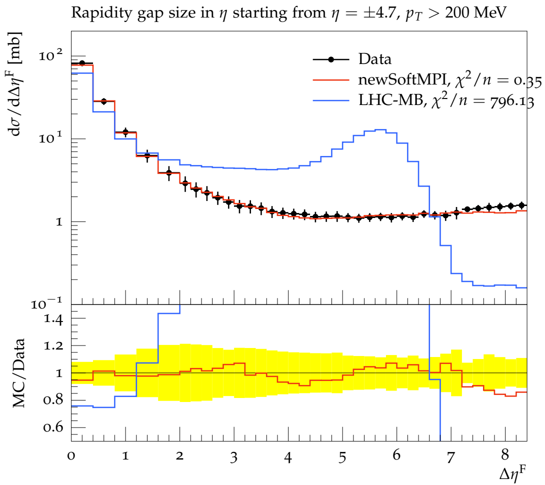
[CMS, PRL 105 (2010) 022002]



Lowest bin → potential to be tunable.

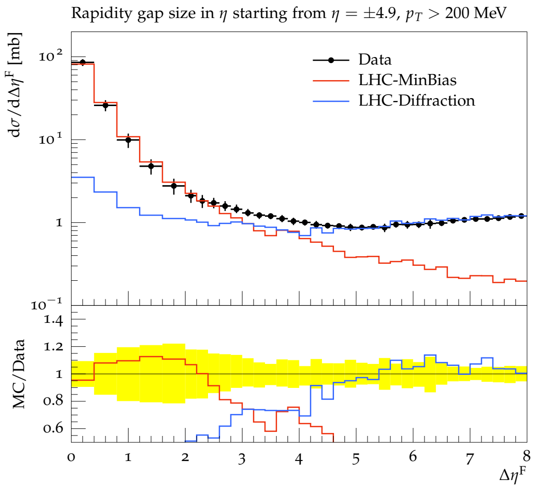
The bump plot, $\Delta\eta_F$

[CMS, PRD 92 (2015) 012003]



Individual contributions to $\Delta\eta_F$

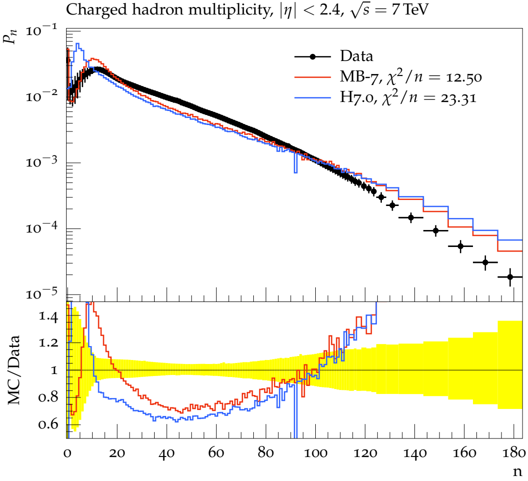
[ATLAS, Eur.Phys.J. C72 (2012) 1926]



Charged particle multiplicity

CMS, NSD analysis 7 TeV

[CMS, PRL 105 (2010) 022002]



Large discrepancies, tail in particular. Low $n \rightarrow$ “NSD”?

Baryons

[SG, P. Kirchgaeßer, S. Plätzer, 1710.10906]

Modelling of baryon production:

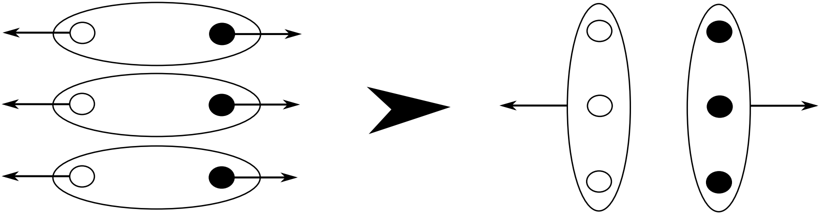
- Thus far, not considered in particular
- Take a lot of energy as mass, at once
- More baryons $\rightarrow$ less charge

Ideas for improvement:

- Colour reconnection
- non-perturbative $g \rightarrow s\bar{s}$ splitting in cluster formation, re-tune gluon mass vs strange mass (constituent masses).

Rapididy based colour reconnection

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



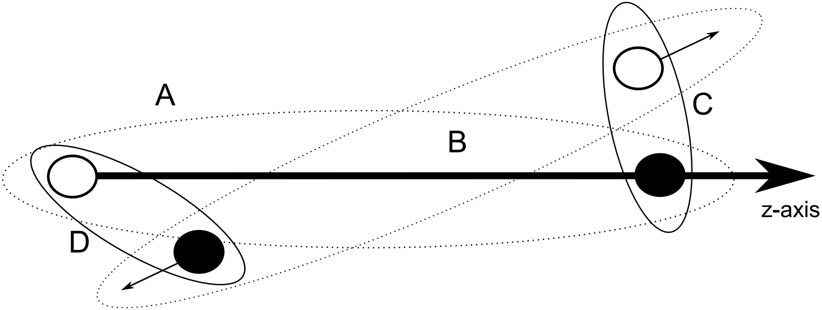
But, baryonic clusters would typically be much heavier

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

would always/often be reconnected into mesonic clusters.

Rapididy based colour reconnection

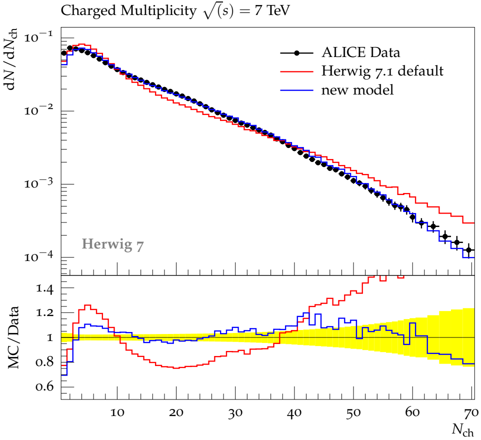
"Closeness" of quarks not based on invariant mass but on proximity in momentum space.



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

Results

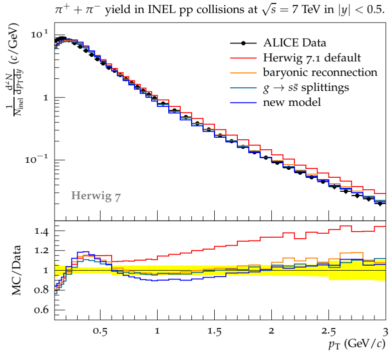
[ALICE, EPJ C75 (2015) 226]

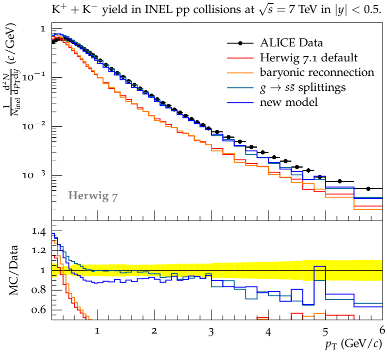


Idea seems to work.

Results

[ALICE, EPJ C75 (2015) 226]

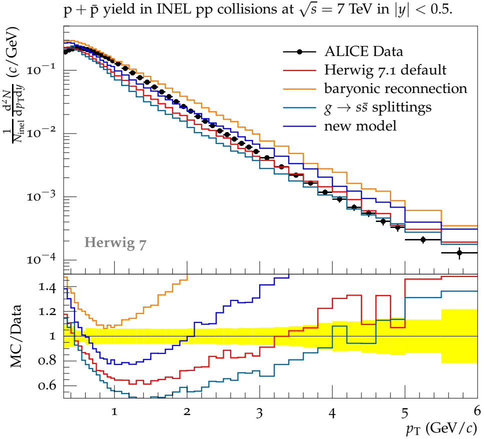




Strangeness difficult. $g \to s\bar{s}$ splitting.

Results

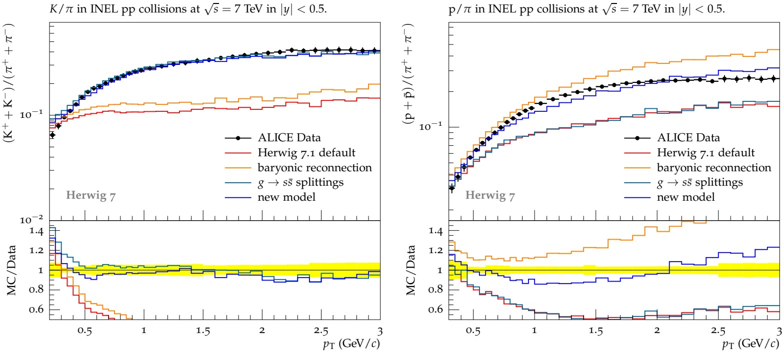
[ALICE, EPJ C75 (2015) 226]



Protons remain tough, much better though.

Results

[ALICE, EPJ C75 (2015) 226]



Ratios much improved.

Conclusions

- MPI integral part of modelling *pp* collisions.
- important for Min Bias *and* underlying event.
- New Min Bias scattering with diffraction and soft particle production.
- Baryon production improved.