

# Soft interactions in Herwig

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(with Stefan Gieseke and Frashër Loshaj)



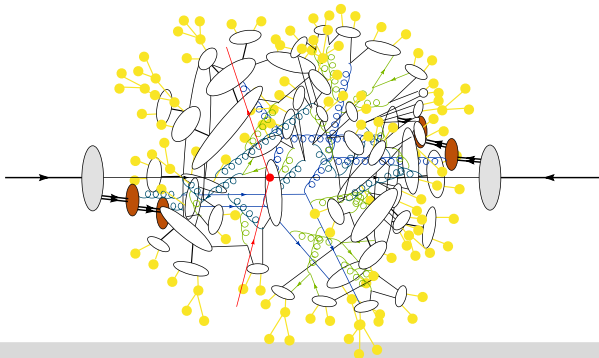
# A typical pp collision from Herwigs point of view

- Hard scattering
- MPI
- ISR/FSR
- Parton shower
- Hadronization
- Decays

Let's jump right in...

# A typical pp collision from Herwig's point of view

- ... and focus on the underlying event which accompanies the hard scattering of a pp collision.
- Underlying event modelled as MPI.



## Multiple parton interactions

- Hadrons are composite objects  $\rightarrow$  Probability of having more than one interaction.
- Default from Herwig++ 2.1.
- Interactions above a certain value  $p_{\perp}^{\min}$  simulated as QCD  $2 \rightarrow 2$  processes (*semi-hard* interactions). [Bähr, Gieseke, Seymour, JHEP 0807:076]
- Interactions below  $p_{\perp}^{\min}$  modelled as an elastic scattering among gluons (*soft* interactions).[Bähr, Butterworth, Seymour, JHEP 0901:065] [Bähr, Butterworth, Gieseke, Seymour, 0905.4671]

## Multiple parton interactions

- In Herwig based on the eikonal model.

$$\mathcal{P}_{h,s} = \frac{2\chi_{\text{hard}}(b, s)^h}{h!} \frac{2\chi_{\text{soft}}(b, s)^n}{n!} e^{-2\chi_{\text{tot}}(b,s)}$$

$$\chi_{\text{tot}}(b, s) = \frac{1}{2} (A(b, \mu) \sigma_{\text{hard}}^{\text{inc}}(s, p_{\perp}^{\text{min}}) + A(b, \mu_{\text{soft}}) \sigma_{\text{soft}}^{\text{inc}})$$

- Parameters of the soft model fixed to describe  $\sigma_{\text{tot}}$  and  $b_{\text{el}}$ .
- $p_{\perp}$  sampled from a distribution that is parameterised with a Gaussian distribution

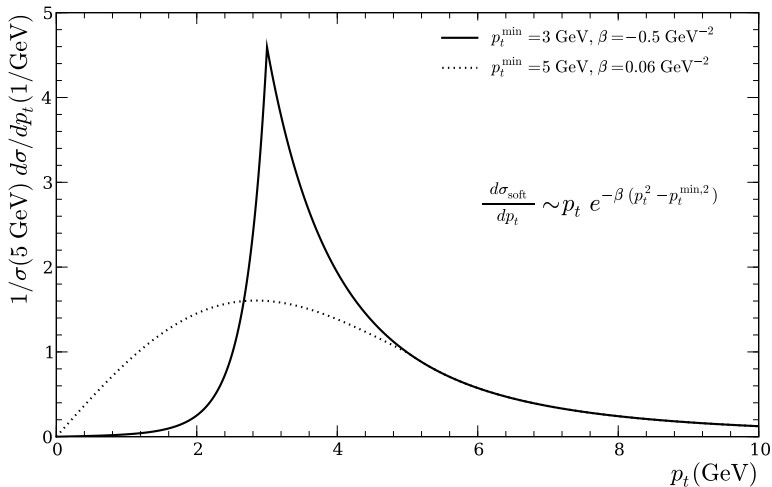
$$\frac{d\sigma_{\text{soft}}^{\text{inc}}}{dp_{\perp}} = A e^{-\beta p_{\perp}^2}.$$

- Then simulate  $h$  semi-hard interactions and  $n$  soft interactions.

# Sampling of transverse momentum

- Extension of the differential cross section into the soft region

$$p_t < p_t^{\min}$$

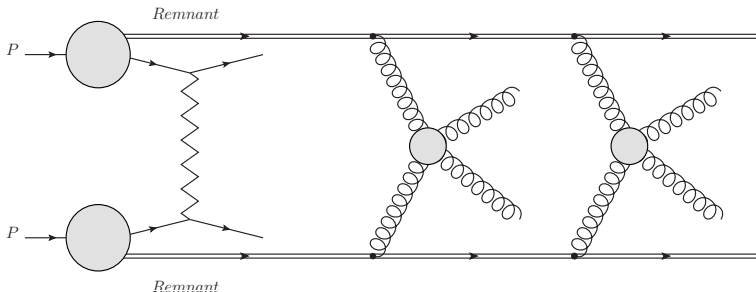


# Old model for soft interactions

- Number of soft interactions  $N_{\text{soft}}$  calculated in the eikonal model.

$$\sigma_{\text{tot}} = \sigma_{\text{hard}} + \sigma_{\text{soft}} + (\sigma_{\text{diffraction}})$$

- Modelled as elastic  $2 \rightarrow 2$  gluon scattering with  $p_{\perp} < p_{\perp}^{\text{min}}$ .

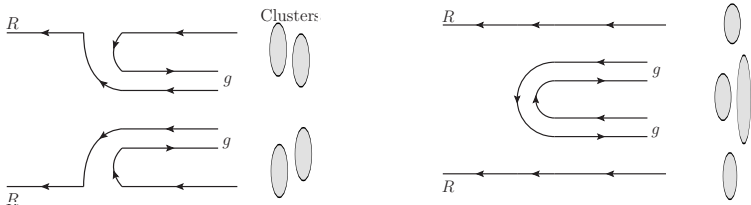


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- Possible colour connections between the gluons and the remnants.



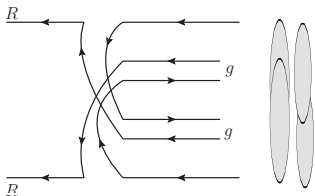


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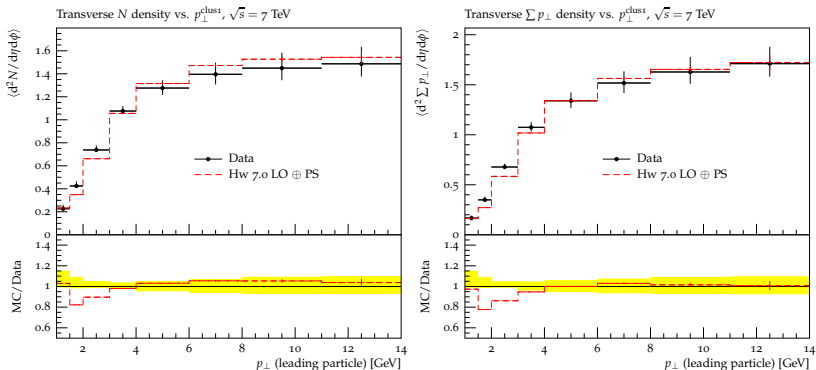
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- No real control over colour connections  $\rightarrow$  events with large rapidity gaps.

# Results of the old model

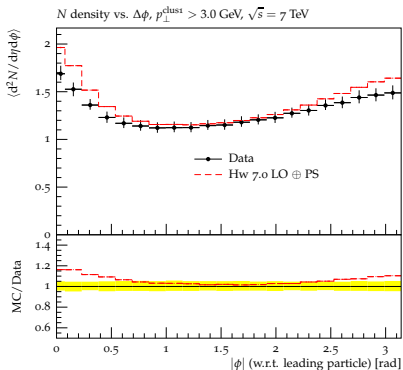
- Simplest possible extension of the hard MPI model in order to describe the soft part of the UE for low- $p_t$  jet production [Bähr, Butterworth, Gieseke, Seymour, 0905.4671]



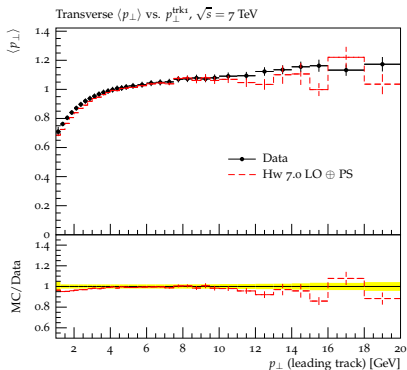
[Eur.Phys.J. C71 (2011) 1636]

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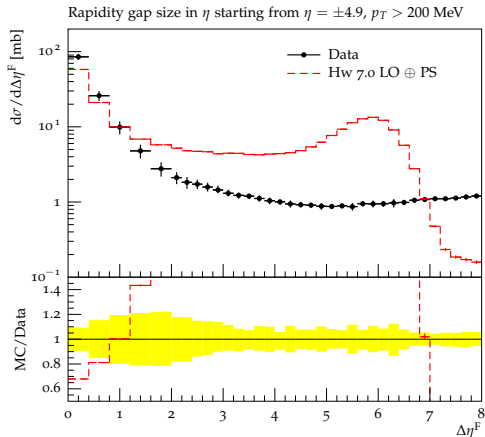
[Phys. Rev. D 83 (2011) 112001]

## Summary so far...

- Main focus on description of the UE.
- Hard MPI model does a good job.
- Soft MPI model as simplest possible extension to describe low- $p_t$  jets.
- No model for diffraction  $\rightarrow$  MB difficult
- Description of diffraction reduced MB data improves with CR [Gieseke, Röhr, Siodmok, *Eur.Phys.J. C72 (2012) 2225*].
- Model has to be looked at from every direction...

## ...The “Bump” problem

- Artifact of the model for soft MPI
- No diffraction  $\rightarrow$  expect close to none events with high  $\Delta\eta^F$



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

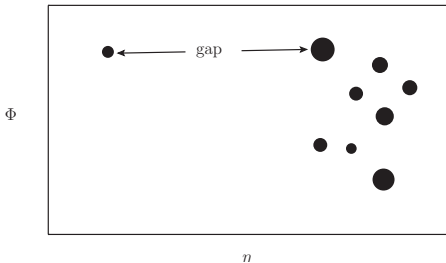
# Rapidity Gap

- Total cross section for hadronic collisions.

$$\sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{inel}}$$
$$\sigma_{\text{inel}} = \sigma_{\text{ND}} + \underbrace{\sigma_{\text{SD}} + \sigma_{\text{DD}}}_{\text{Diffraction}}$$

Diffraction events associated with colourless exchange  
→ large rapidity interval without any hadronic activity.

**(Pseudo-)rapidity gap**  $\Delta\eta$



# Behaviour

- ND contributions characterised by experimental observation that  $\langle \Delta\eta \rangle \approx 0.15 + \text{fluctuations due to hadronisation. (for a low } p_{\perp} \text{ cut)}$

$$\rightarrow \frac{d\sigma_{\text{ND}}}{d\Delta\eta} \sim e^{-a\Delta\eta}$$

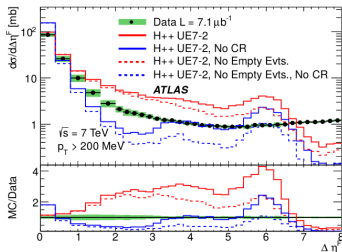
- D contributions dominated by events with large  $\Delta\eta$ .

$$\rightarrow \frac{d\sigma_{\text{D}}}{d\Delta\eta} \approx \text{const. (w.r.t } \Delta\eta)$$

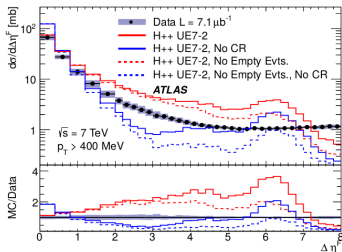
- Cross section measured differential to rapidity gap with different cuts on  $p_{\perp}$  by ATLAS and CMS.
- e.g  $p_{\perp} > 200 \text{ MeV}$ ,  $p_{\perp} > 500 \text{ MeV} \rightarrow$  minimum bias analyses.
- At high centre-of-mass energies dominated by MPI.

# The “Bump” problem

- $\Delta\eta^F$  is defined as the larger of two pseudorapidity regions without any hadronic activity.



(a)



(b)

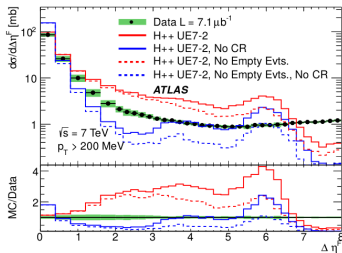
[Eur.Phys.J. C72 (2012) 1926]

- Herwig++: no model for diffraction  $\rightarrow \sim \exp(-a\Delta\eta)$  for low  $p_{\perp}$  cut.
- Extremely sensitive to colour connections in soft MPI.
- No connection topology could produce the required fall off [arXiv:1602.04690 [hep-ph]].

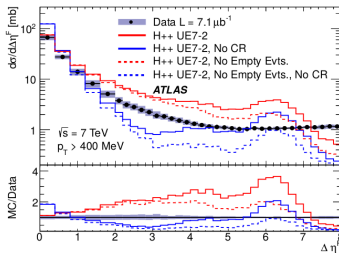


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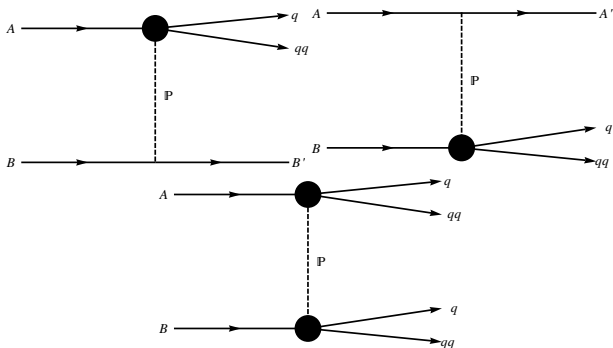
(b)

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

- Need model for diffraction!
- New model for soft MPI!

# Diffraction

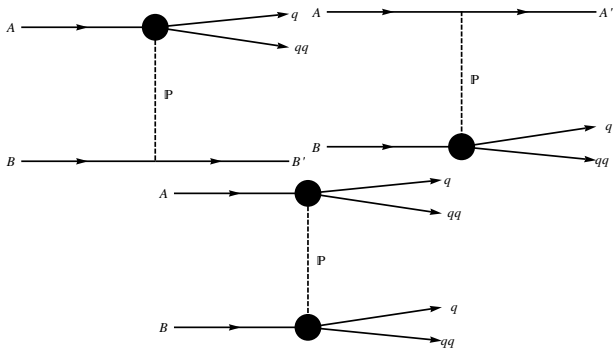
- Implemented by Frashër Loshaj for soft diffraction in Herwig by modelling it with the following matrix elements.



- Final state treated fully nonperturbatively - Quark ( $q$ ) and diquark ( $qq$ ) form a cluster with diffractive mass  $M$  and stretched along the direction of the dissociated proton.  $\rightarrow$  No crosstalk!
- For masses  $M$  below  $m_p + m_q + m_{qq}$ , we consider  $pp \rightarrow \Delta p$ .

# Diffraction

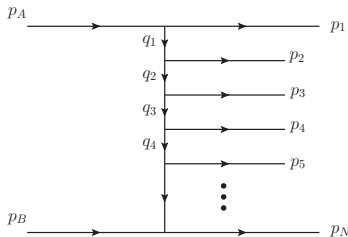
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- Final state treated fully nonperturbatively - Quark ( $q$ ) and diquark ( $qq$ ) form a cluster with diffractive mass  $M$  and stretched along the direction of the dissociated proton.  $\rightarrow$  No crosstalk!
- No central diffraction yet.

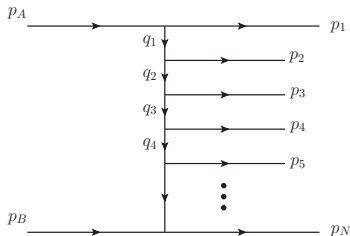
# New model for soft interactions

- Two constraints:
  - i) From MB data: Distribution should be approximately uniform in rapidity.
  - ii) Non-diffractive part of the cross section  $\sim e^{-a\Delta\eta}$ .
- Based on multiperipheral kinematics motivated by “cut Pomerons” [Baker, Ter-Martirosyan, Phys.Rept. 28 (1976) 1-143]
- Idea: Number of soft interactions from MPI model = cut pomerons = particle ladders

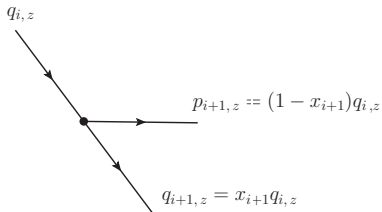


# Kinematics

## ■ Multiperipheral ladder:



$$\langle N \rangle \simeq \ln \frac{s}{m^2}$$

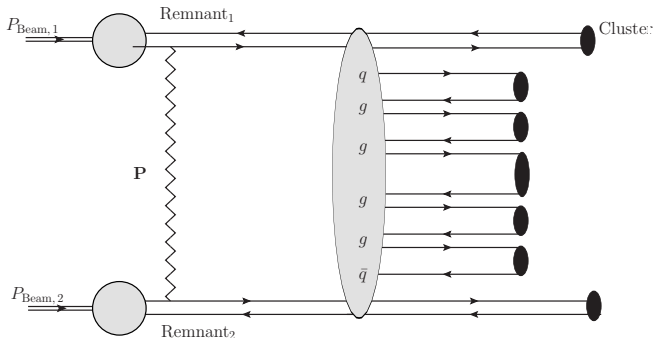


$$\Delta y \sim \ln \frac{1}{x}$$

## ■ $x_j \simeq x$ such that it gives uniform distribution in rapidity.

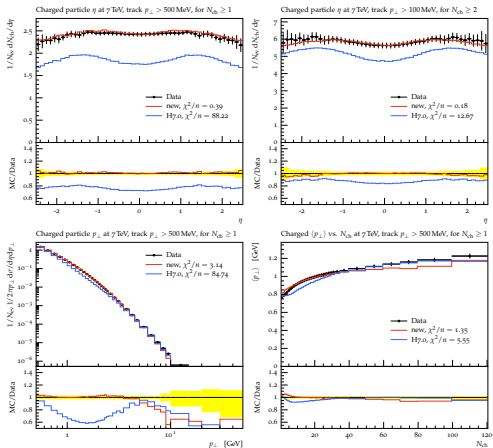
# Colour connections

- Particles in the ladder modeled as gluons.
- Emit one  $q\bar{q}$  pair in order to get the correct colour connections between the neighbours  $\rightarrow$  new model produces clusters ordered in rapidity. (Remnants are always anticoloured in Herwig)



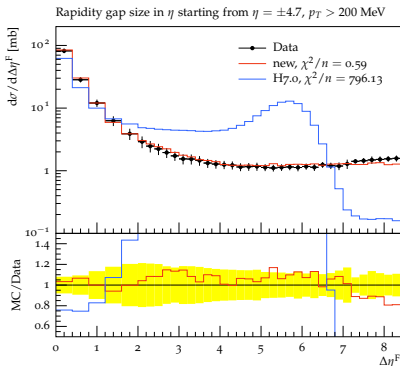
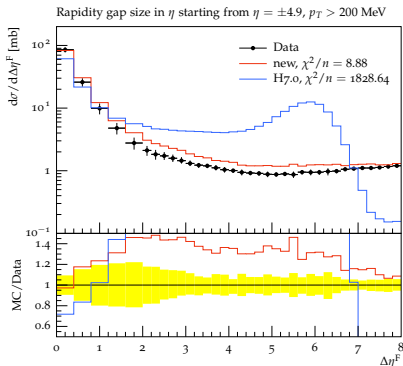
# Minimum Bias

- Tuned to MB data from ATLAS [New J.Phys.13:053033,2011] with PROFESSOR 2 [Eur.Phys.J. C65 (2010) 331-357].
- In combination with the model for diffraction Herwig is for the first time able to cover all aspects of MB analyses.



# Rapidity Gap

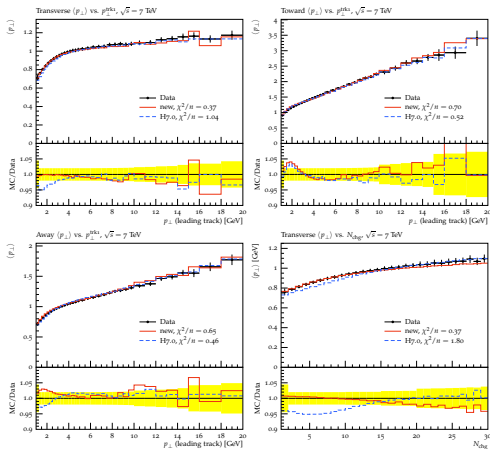
- Satisfying description of ATLAS [Eur.Phys.J. C72 (2012) 1926] and CMS [Phys.Rev. D92 (2015) no.1, 012003] data.





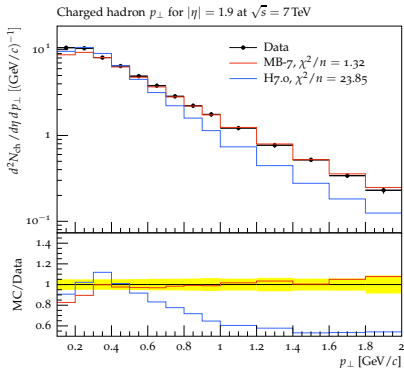
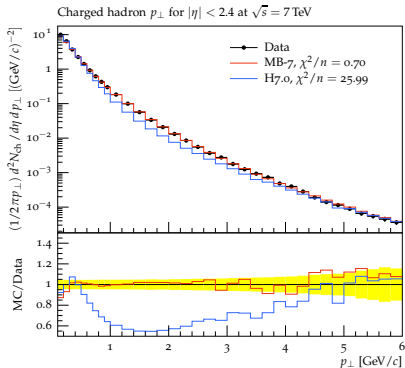
# Underlying event

- Look at activity in transverse, toward and away region.



# Non-single-diffractive analyses

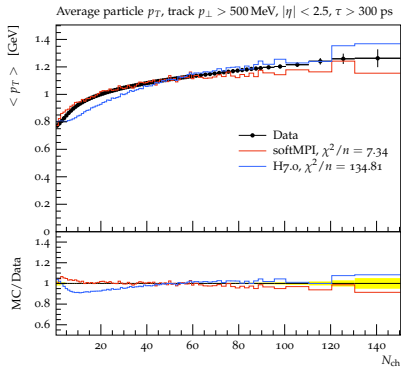
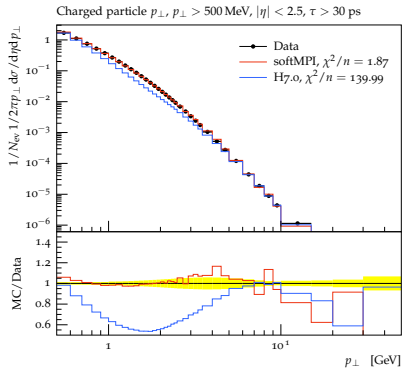
## ■ CMS: [Phys.Rev.Lett.105:022002,2010]



- Overall good description.
- For transverse momenta  $p_{\perp} < 0.3$  GeV difficult.

# Extrapolation to 13 TeV

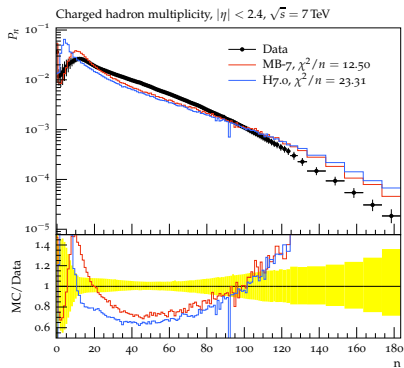
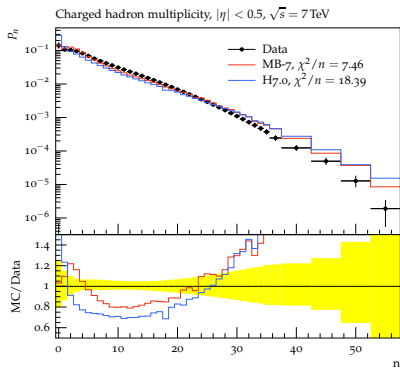
- ATLAS: [Physics Letters B (2016), Vol. 758, pp. 67-88]



- Need more 13 TeV MB/UE analyses!
- Supports 7 TeV tune.

# Non-single-diffractive analyses

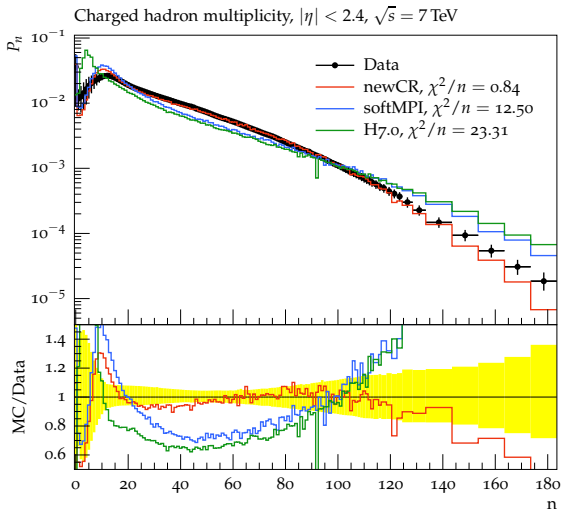
## ■ CMS: [J. High Energy Phys. 01 (2011) 079]



## ■ Overestimation of the high $n$ region $\rightarrow$ new model for CR.

# Outlook

- New model for CR with baryonic reconnection.



# Summary and Outlook

- Implemented model for soft interactions and diffraction.
- General improvement of all observables considered.
- Resolved the "bump" problem.
- High multiplicities remain very difficult.
- Ongoing studies of underlying event analyses with the new model.
- New model for CR in process.
- Baryon ratios.
- More details in [Gieseke, Loshaj, PK, 1612.04701].
- Will be released with Herwig 7.1.