QGSJET-III model: novel features

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- Wealth of relevant experimental data from LHC: precision era for MC generators of hadronic collisions
- $\Rightarrow$ improvements of existing models
  - notably, new approaches for missing interaction mechanisms
  - also fine-tuning of model parameters

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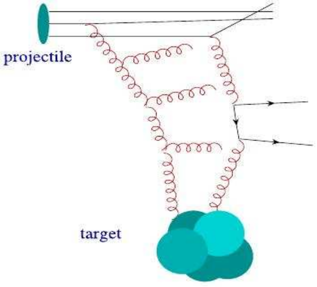
Here few selected topics will be discussed

- treatment of higher twist corrections to hard parton scattering
- Good-Walker approach for diffraction and 'color fluctuations'
- pion exchange process in pp scattering and LHCf data

Qualitative picture for hadronic MC event generators

- QCD-inspired: interaction mediated by parton cascades
- multiple scattering
  (many cascades in parallel)
- real cascades ⇒ particle production
- virtual cascades ⇒ elastic rescattering (momentum transfer)
- generally nonperturbative physics
  ⇒ phenomenological approaches



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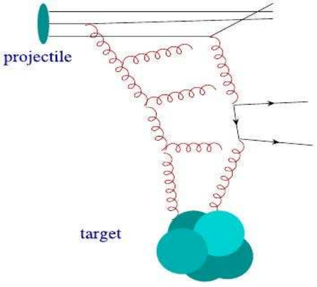

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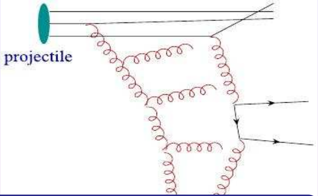
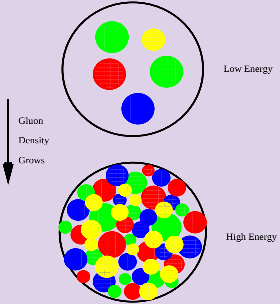


At very high energies, significant nonlinear effects expected

When parton density becomes high (high energy and/or small b):

- parton cascades strongly overlap and interact with each other
- ⇒ shadowing effects (slower rise of parton density)
- saturation: parton production compensated by fusion of partons



Parton saturation: a word of caution

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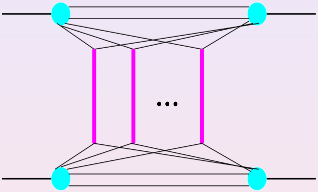
Observable are (hard) interactions of partons

- here same argument applies: not too many boxing pairs at the same ring
- but: one may have arbitrary many virtual boxers (= partons) at the ring, if they don't fight (no problem with observations/unitarity)

QGSJET(-II): Reggeon Field Theory (RFT) approach

- multiple scattering = multi-Pomeron exchanges (multiple parton cascades)
- allows to calculate: cross sections & partial probabilities of final states



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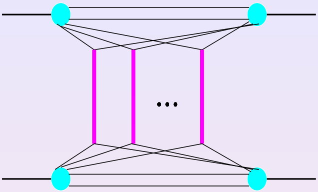
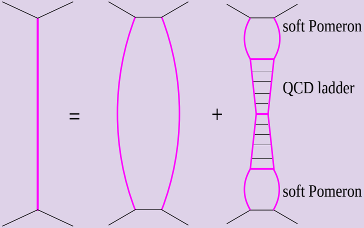


For hard processes: 'semihard Pomeron' approach
[Drescher, Hladik, SO, Pierog & Werner, 2001]

- soft Pomerons to describe soft (parts of) cascades ($p_t^2 < Q_0^2$)
  - ⇒ transverse expansion (finite Pomeron slope)
- DGLAP for hard cascades
- altogether: 'general Pomeron'



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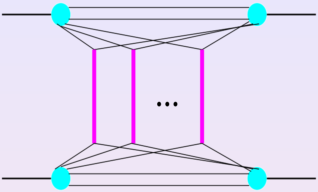

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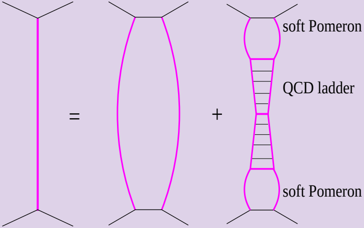

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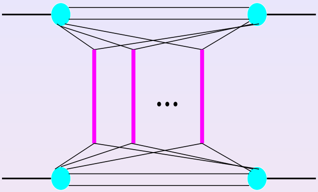

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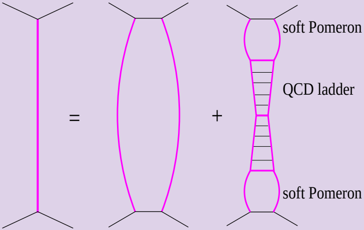

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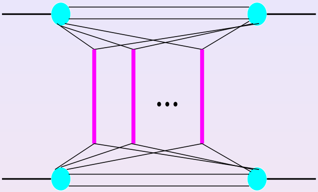
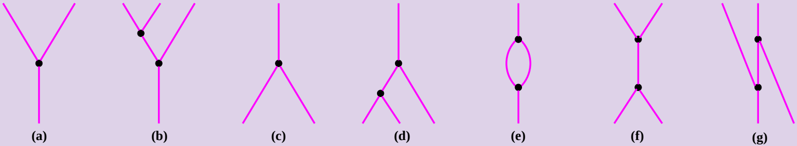


Nonlinear effects: Pomeron-Pomeron interactions (scattering of intermediate partons off the proj./target hadrons & off each other)



thick lines = Pomerons = 'elementary' parton cascades

QGSJET-III: treatment of higher twist (HT) effects

Any model should respect collinear factorization of pQCD

$$\sigma^{\text{jet}}_{pp}(s, p_{\text{t,cut}}) = \sum_{I,J=q,\bar{q},g} \int_{p_{\text{t}}>p_{\text{t,cut}}} dp_t^2 \int dx^+ \, dx^- \, \frac{d\sigma^{2\to 2}_{IJ}(x^+x^-s, p_t^2)}{dp_t^2} \times f_{I/p}(x^+, M_{\text{F}}^2)\, f_{J/p}(x^-, M_{\text{F}}^2)$$

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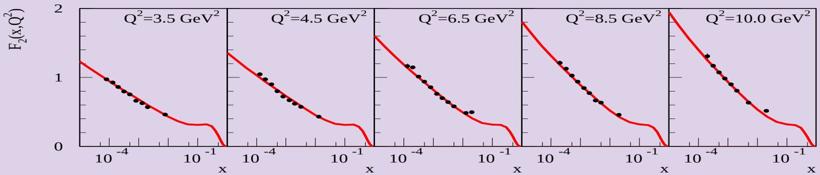
PDFs $f_{I/p}(x,Q^2)$: already constrained by HERA data $\Rightarrow$ no freedom for stronger parton saturation



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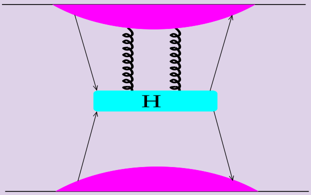
Collinear factorization: valid at leading twist (up to $1/Q^n$ terms)

- corrections due to parton rescattering on 'soft' ($x \simeq 0$) gluons *[Qiu & Vitev, 2004, 2006]*
  - hard scattering involves any number of additional gluon pairs
  - corrections suppressed as $1/(p_t^2)^n$



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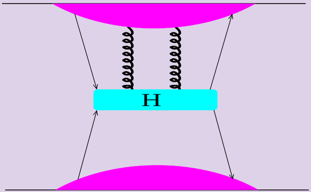


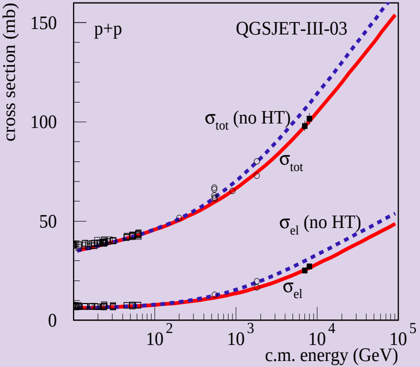
QGSJET-III: phenomenological implementation of the mechanism

- with HT effects: dependence on Q_0-cutoff strongly reduced (currently: $Q_0^2 = 2$ GeV^2)

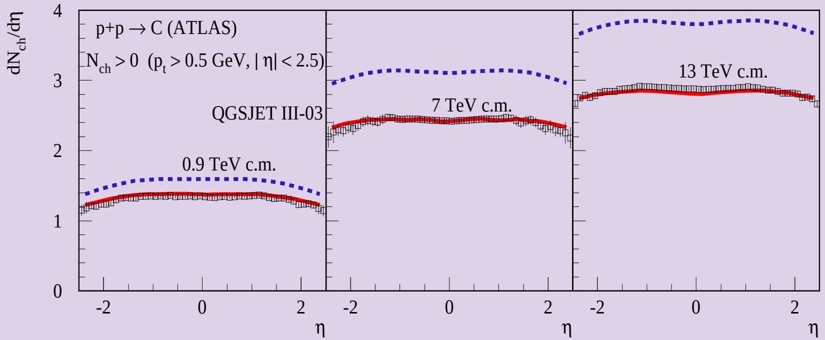
HT effects: impact on cross sections & particle production

Impact on $\sqrt{s}$-dependence of $\sigma_{pp}^{tot/el}$

- significant corrections for total/elastic cross sections
  - start to be important already at $\sqrt{s} \sim 1$ TeV



Impact on charged hadron multiplicity



- reduction of N_{ch}: stronger at higher energies (as expected)

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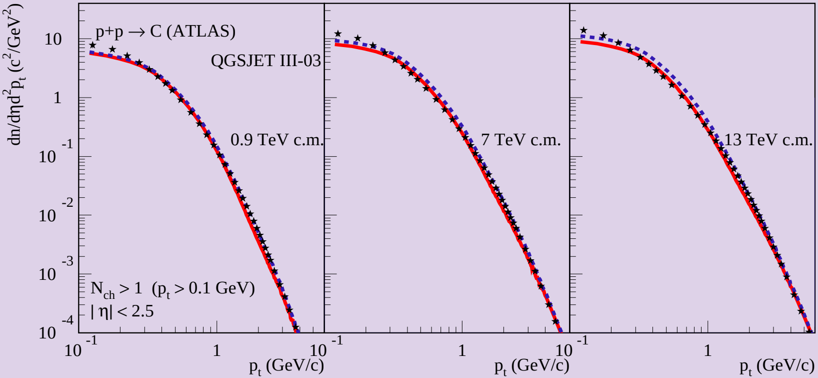
Impact on charged hadron p_t-spectra



- stronger effect at higher energies
- mostly for moderately small p_t:
  the effect fades away with increasing p_t $(\propto 1/p_t^2)$

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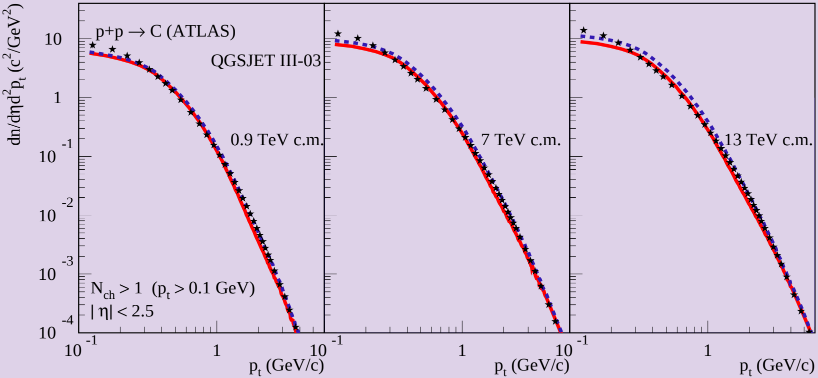
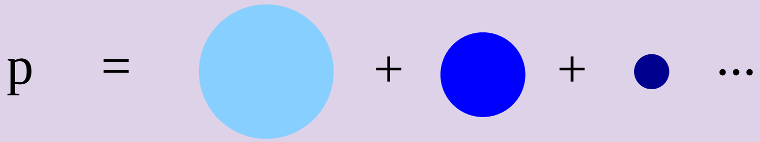


NB: qualitatively, the approach mimics an energy dependent p_t-cutoff for jet production

- suppresses emission of jets of moderately small p_t
- has no impact on PDFs ⇒ not related to parton saturation

Good-Walker approach for diffraction & 'color fluctuations'

Good-Walker approach: proton is a superposition of a number of elastic scattering eigenstates: $|p\rangle = \sum_i \sqrt{C_i}\,|i\rangle$



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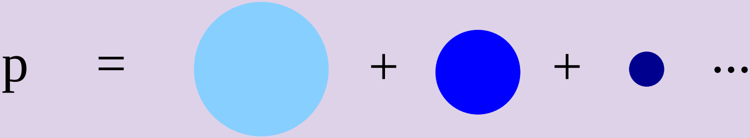

- in pp scattering, those states undergo different absorption: $|p\rangle = \sum_i \sqrt{C_i}\,|i\rangle \rightarrow \sum_i \sqrt{C_i'}\,|i\rangle = \alpha\,|p\rangle + \beta\,|p^*\rangle$
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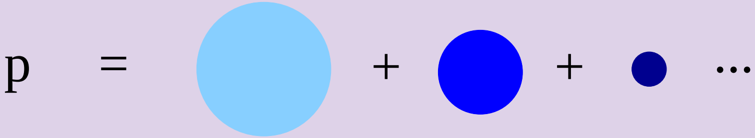

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- the treatment involves interaction eikonals $\chi^{\rm tot}_{pp(ij)}(s,b,Q_0^2)$ for different combinations of such states, e.g.

$$\sigma^{\rm inel}_{pp}(s,b) = \sum_{i,j} C_i\, C_j \int d^2b\, \left[1 - e^{-2\chi^{\rm tot}_{pp(ij)}(s,b)}\right]$$

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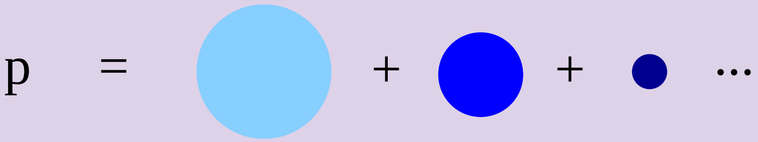

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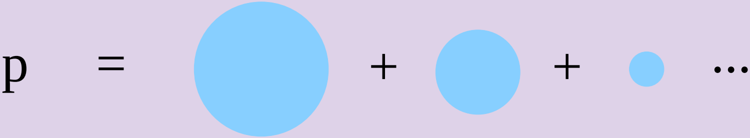
- for each state $|i\rangle$: its own size & parton density

Good-Walker approach for diffraction & 'color fluctuations'

'Color fluctuations approach' *[Frankfurt et al., 2008]*

- Pomeron coupling to state $|i\rangle \propto R_i^2$

  $\Rightarrow$ same 'soft parton density' for all the states:



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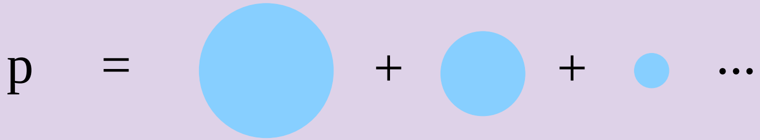
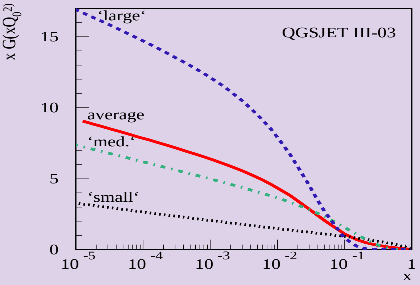


Momentum sum rule should be valid for each state $|i\rangle$

$$\sum_{I=q,\bar{q},g} \int dx\, x\, f_{I/p(i)}(x, Q^2) = 1$$

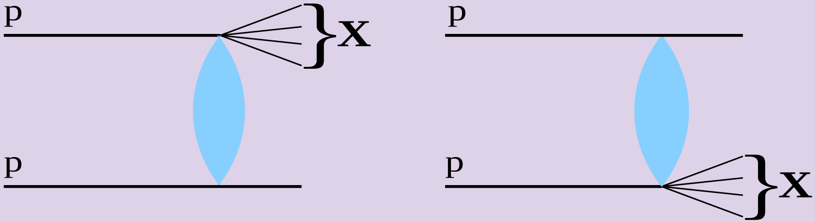
- $\Rightarrow$ harder gluon PDFs for smaller states



Good-Walker approach for diffraction & 'color fluctuations'

NB: inelastic diffraction vanishes in the 'black disk' limit

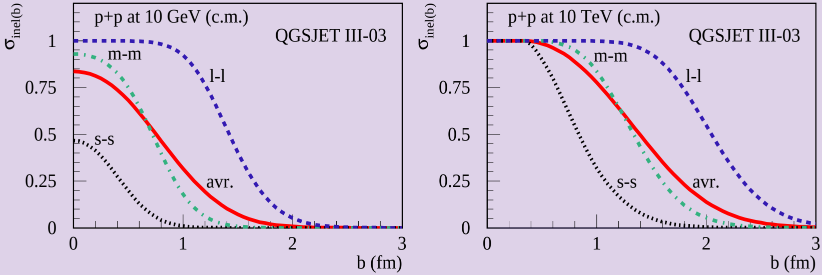
- i.e., when the probability for ND inelastic rescatterings approaches unity (for given b)



- the blue 'blob' – rapidity gap suppression factor (the probability not to have ND inelastic rescatterings)

Good-Walker approach for diffraction & 'color fluctuations'

Interaction profiles for different combinations of states



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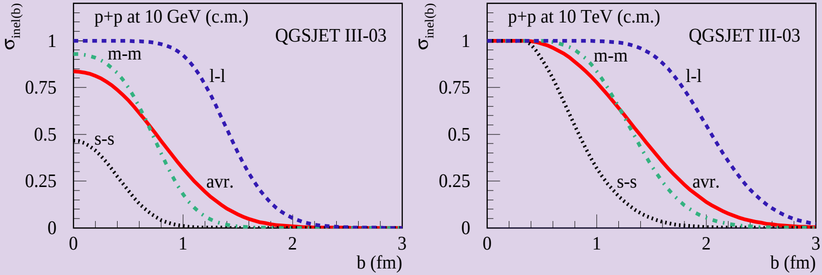

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  - $\Rightarrow$ wide kinematic range for diffraction

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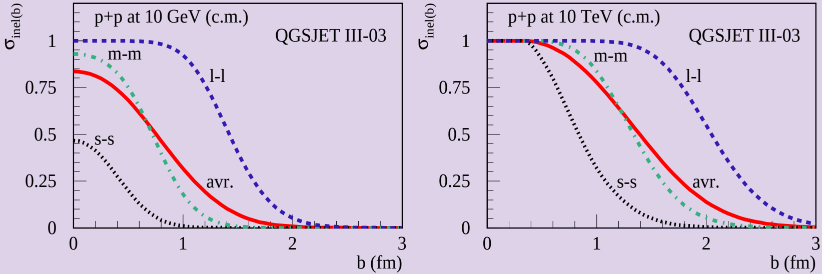

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- $\sqrt{s} = 10$ TeV: $\sigma_{pp}^{\rm inel}(b) \simeq 1$, at small b
  - $\Rightarrow$ diffraction only possible at large b

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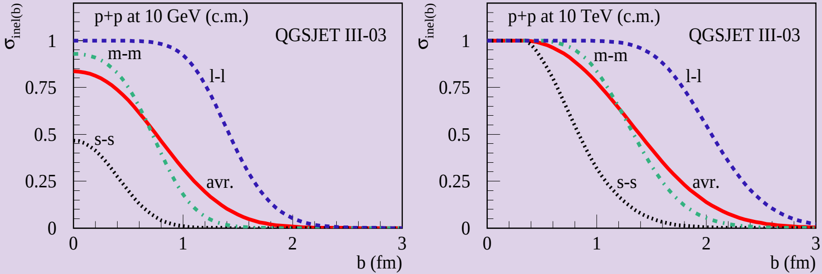

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Of importance to reduce low mass diffraction at high energies

- e.g. $\sigma_{pp}^{SD}(M_X < 3.4$ GeV$) = 3.3$ mb in QGSJET-III, compared to 2.62 ± 2.17 mb from TOTEM

π-exchange process in pp scattering & LHCf data

- forward hadron production in p-air & π-air interactions: high importance for EAS simulations
  - dominated by diffractive contributions
  - but: important role of special non-diffractive (ND) interactions: $\mathbb{RRP}$ contributions

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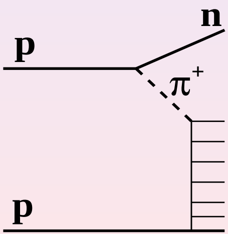
  - π-exchange process may be dominant (small pion mass)



π-exchange process in *pp* scattering & LHCf data

- forward hadron production in *p*-air & π-air interactions: high importance for EAS simulations
  - dominated by diffractive contributions
  - but: important role of special non-diffractive (ND) interactions: $\mathbb{RRP}$ contributions
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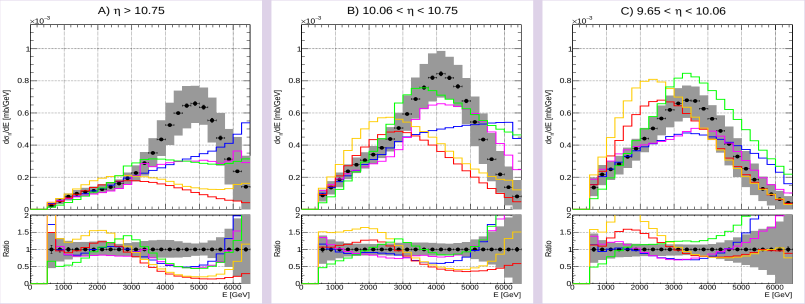
LHCf data on forward neutrons: pronounced π-exchange 'bump'?



- not described properly by all the models

π-exchange process in pp scattering & LHCf data

- cross section for π-exchange (e.g. Kaidalov et al., 2006):

$$\frac{d^2\sigma(pp \to nX)}{dx_n\, dt} = \frac{-t\, G^2_{\pi^+ pn}}{16\pi^2 (t - m_\pi^2)^2} F^2(t)\, \sigma^{tot}_{\pi p}(M_X^2)\, (1 - x_n)^{1-2\alpha_\pi(t)}$$

$\alpha_\pi(t) = \alpha'_\pi\,(t - m_\pi^2)$, $\alpha'_\pi \simeq 1$ GeV^{-2}; $F(t) \simeq e^{R_\pi^2\, t}$, $R_\pi^2 \simeq 0.3$ GeV^{-2}

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- NB: s^Δ $(\Delta = \alpha_{\mathbb{P}}(0) - 1 > 0)$ energy rise would violate unitarity
  - $\Rightarrow$ one has to account for absorptive effects

π-exchange process in pp scattering & LHCf data

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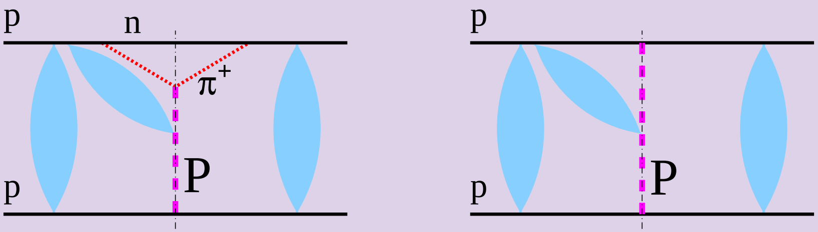

- eikonal rapidity gap suppression factor (to exclude additional inelastic rescatterings)
- enhanced diagrams (to exclude inelastic rescattering of intermediate partons in the Pomeron)

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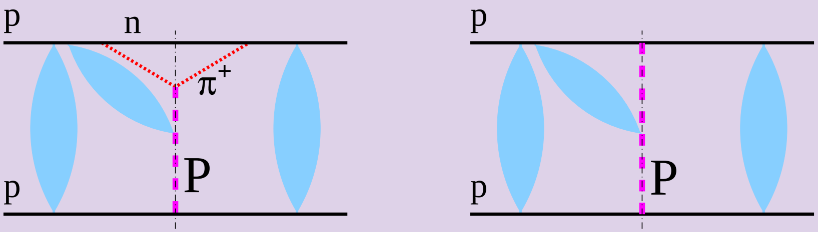
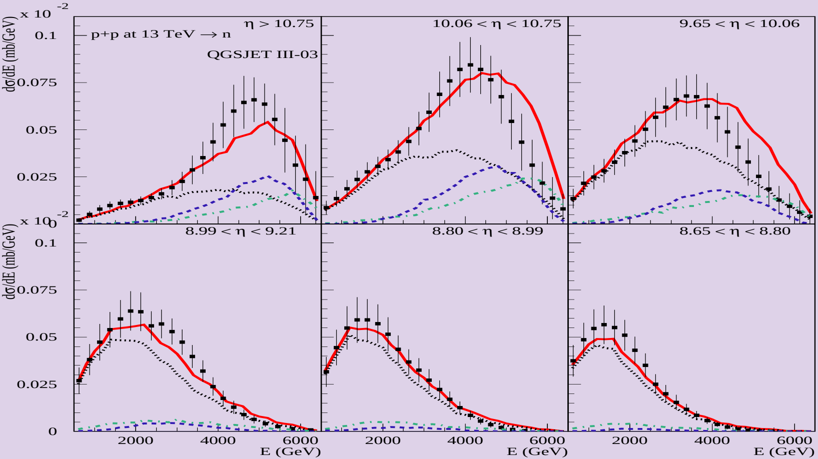


- eikonal rapidity gap suppression factor (to exclude additional inelastic rescatterings)
- enhanced diagrams (to exclude inelastic rescattering of intermediate partons in the Pomeron)
- $\Rightarrow$ treat π-exchange as a part (probability w_{π}) of $1\mathbb{P}$-exchange

Comparison to LHCf data at $\sqrt{s} = 13$ TeV ($w_\pi = 0.3$)



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- comparable contribution from inelastic diffraction

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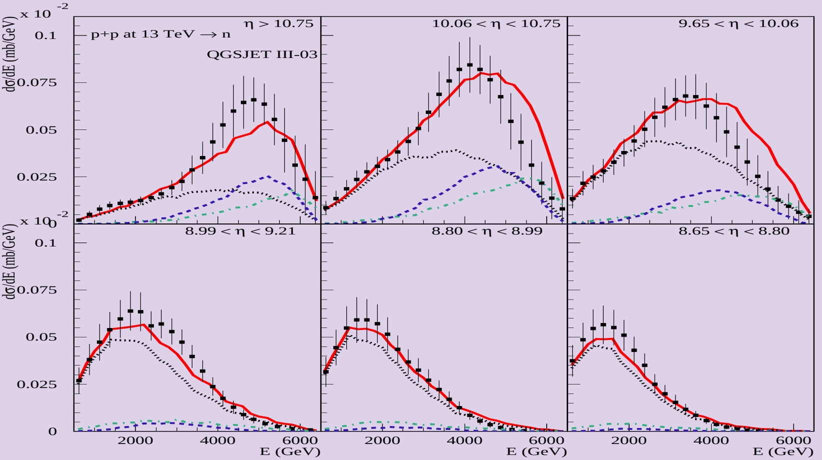

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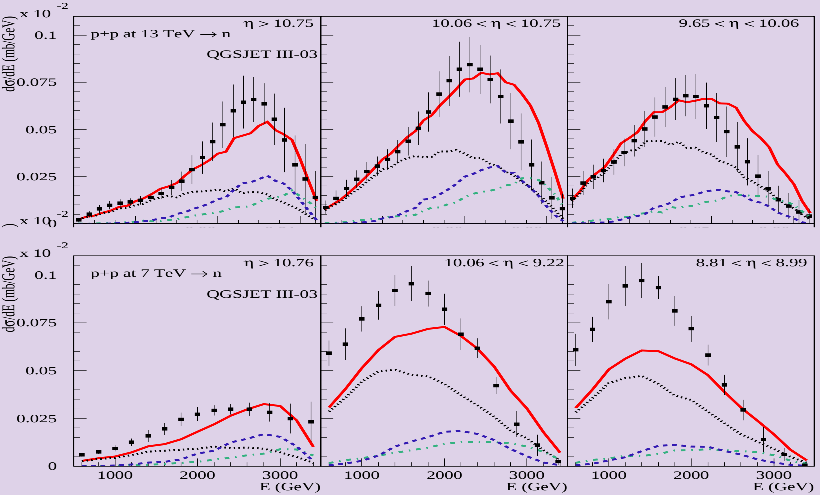

- $\sqrt{s} = 7$ TeV: smaller forward neutron yield than in the data
- more forward neutrons at $\sqrt{s} = 7$ TeV than at $\sqrt{s} = 13$ TeV?

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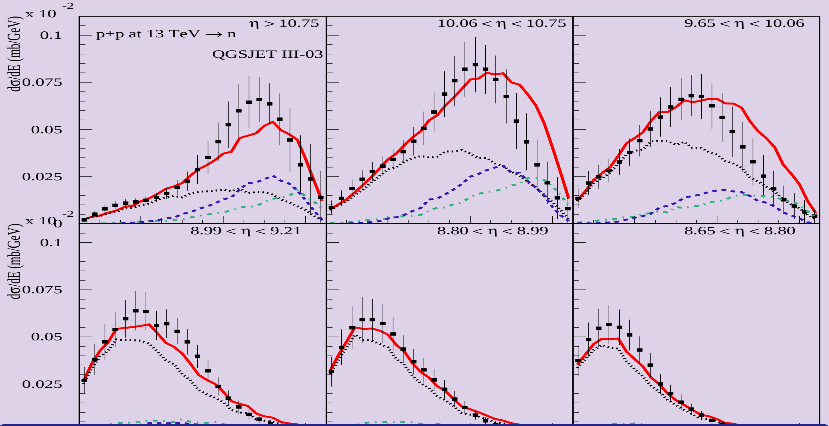

For EAS, more important is the π-exchange in π-air *[SO, 2013]*

- dominance of the π-exchange over the ρ-exchange $\Rightarrow$ enhancement of forward ρ^0 production & suppression of π^0
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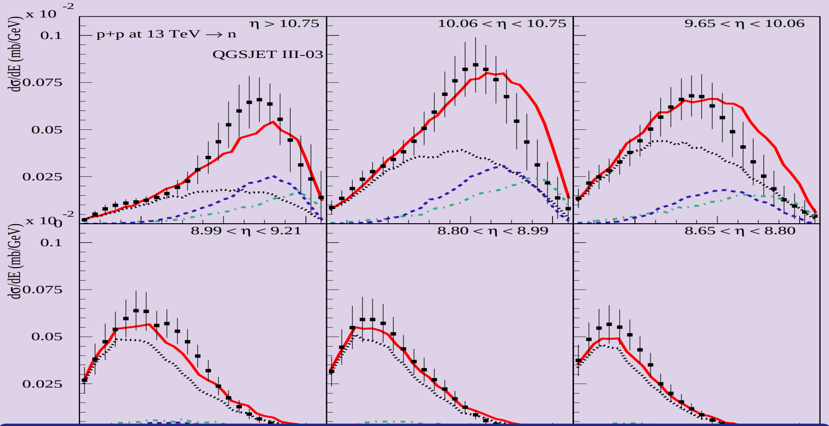

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