Performance and future evolution of QGSJET

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HAP Workshop on CR Composition

KIT, September 21-23, 2015

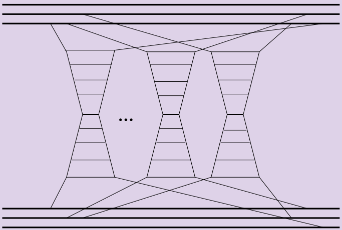
Outline of the talk

1. Overview of the model & recent udates
2. Forward ρ^0 production & π-exchange mechanism in πp collisions
3. Inelastic diffraction: model predictions, LHC data, and EAS characteristics
4. LHCf data on forward spectra of neutrons and π^0: model-based analysis
5. Summary

QGSJET: based on the Reggeon Field Theory approach

High energy collisions = multiple scattering processes

- many parton cascades in parallel
- typically small momentum transfer along the cascades



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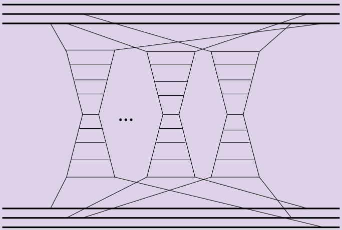
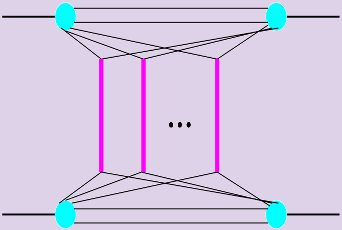


RFT: Pomerons = 'elementary' cascades

- e.g. elastic amplitude
- requires Pomeron amplitude & Pomeron-hadron vertices



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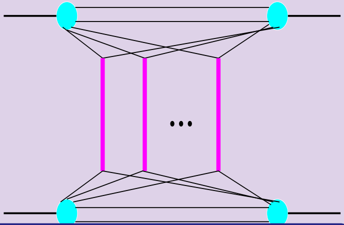
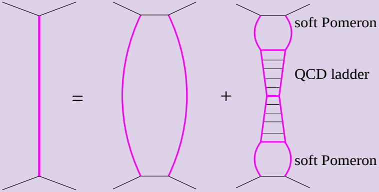


Hard processes included using the 'semihard Pomeron' approach

- soft Pomerons to describe soft (parts of) cascades ($p_t^2 < Q_0^2$)
  - $\Rightarrow$ transverse expansion governed by the Pomeron slope
- DGLAP for hard cascades
- taken together: 'general Pomeron'



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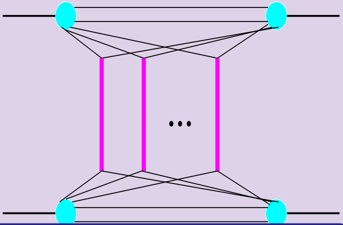

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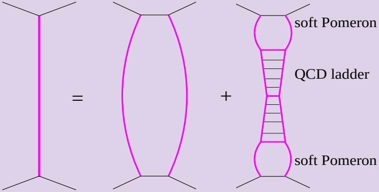

QGSJET-II-04: full resummation of $\mathbb{PP}$-interactions

[SO, PLB636 (2006) 40; PRD77 (2008) 034009; PRD83 (2011) 014018]

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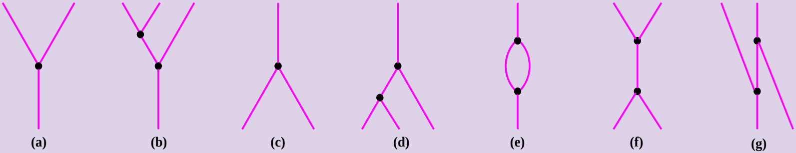

thick lines = Pomerons = 'elementary' parton cascades

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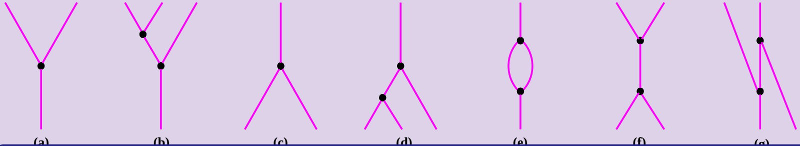
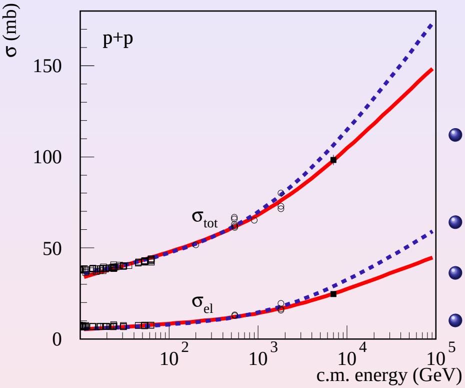


Coherent treatment of cross sections & particle production

- partial cross sections for various final states (including diffractive): from unitarity cuts of elastic diagrams
  - $\Rightarrow$ no additional free parameters (e.g. for diffraction)
- s-channel unitarity satisfied: $\sum_{\text{graphs,cuts}} \bar{\chi}^{\text{cut}} = 2\sum_{\text{graphs}} \chi^{\text{uncut}}$
- positive-definite cross sections for all final states $\Rightarrow$ MC generation
- no additional free parameters for hA & AA collisions

Most recent model update: also fine-tuning to LHC data



- most importantly: to TOTEM data on $\sigma_{pp}^{\mathrm{tot/el}}$
- implied slower rise of $\sigma_{pp}^{\mathrm{inel}}$
- $\Rightarrow$ same trend for $\sigma_{p-\mathrm{air}}^{\mathrm{inel}}$
- $\Rightarrow$ deeper shower maximum (at highest CR energies)

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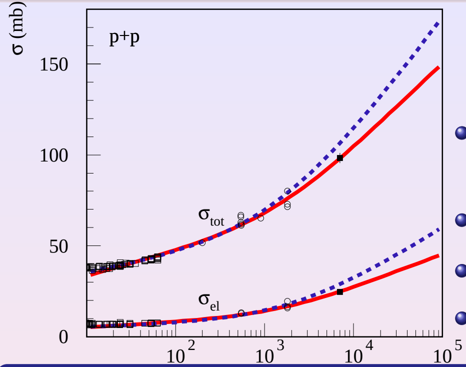

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Development of QGSJET-II completed

- full resummation of $\mathbb{PP}$ interaction graphs: no further improvements needed
- fine-tuning to LHC data had stronger effect on EAS characteristics than theoretical developments
- further: towards pQCD treatment of nonlinear effects

π-exchange dominance for neutral meson production in πp & πA collisions *[SO,EPJWC52 (2013) 02001]*

- the mechanism discussed at ISVHECRI-2012
- a bit simple-minded one
- yet important: strong impact on N_μ in EAS

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Experimental fact: $\sim 50\%$ of pions in πp - from resonance decays

- $\Rightarrow$ duality approach often used in models
  - resonances not treated explicitely
    (their contributions included in final pion spectra)
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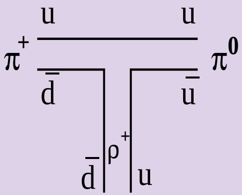
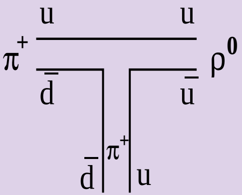
Forward ND production - governed by Reggeon exchanges ($\mathbb{RRP}$)





- e.g. leading π^0: ρ-trajectory
- for leading ρ^0: π-meson exchange

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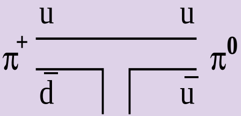

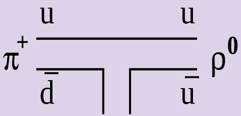

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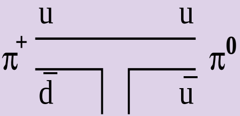
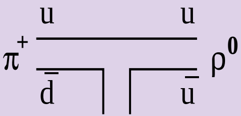
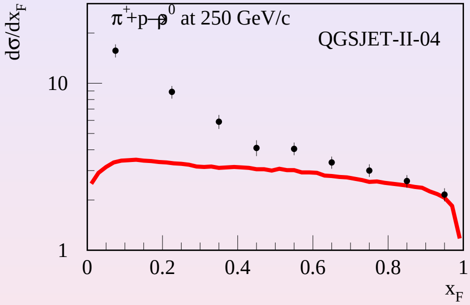




- e.g. leading π^0: ρ-trajectory

- $\Rightarrow$ generally both π^0 and ρ^0 expected as leading hadrons
- doesn't seem to be the case in exp. data

Charge exchange in πp collisions



- assuming pion exchange dominance for leading hadron production in πp
- reasonable description of forward ρ^0 production
- NB: central production of ρs not treated explicitely

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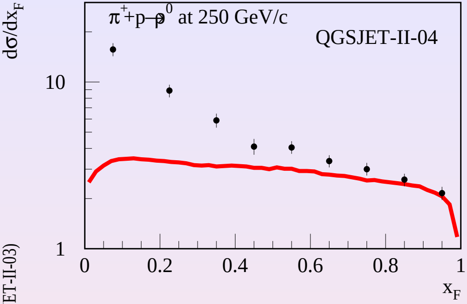

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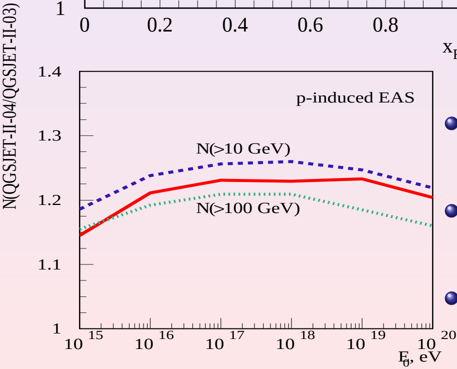

- $\sim 20\%$ higher N_μ $(> 1$ GeV) (relative to QGSJET-II-03)
- the enhancement weakly depends on E_0
- nearly same N_μ excess up to $E_\mu \sim 100$ GeV

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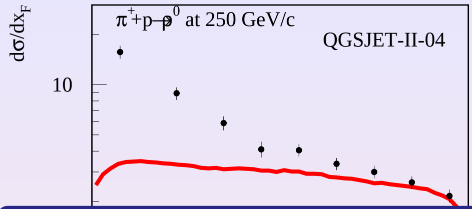

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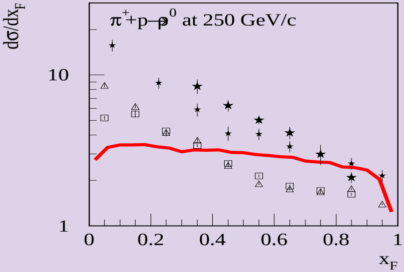
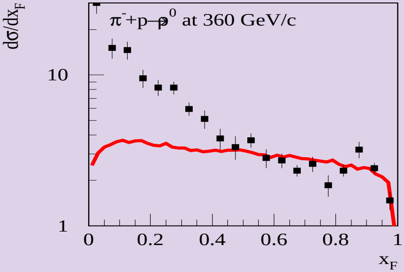
1st caveat: large spread in exp. data for ρ^0 production





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  - consistent with earlier measurements in πp

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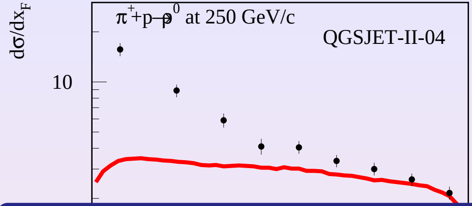

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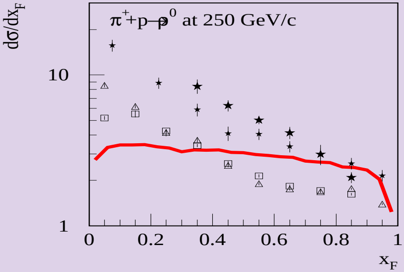

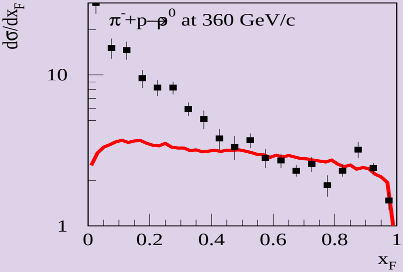

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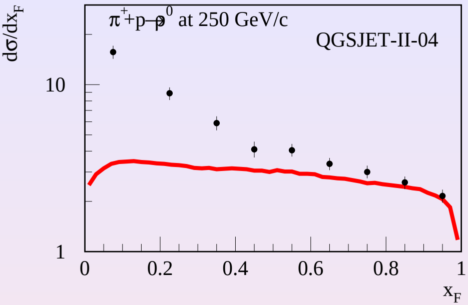

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2nd caveat: isospin invariance requires same mechanism for $\rho^\pm$

- experimental data: controvercial
- exchanges of other Reggeons potentially important
- NB: forward $\rho^\pm$ production instead of $\pi^\pm$ would channel more energy into e/m cascade
  - $\Rightarrow$ reduce N_μ in EAS
  - by how much?

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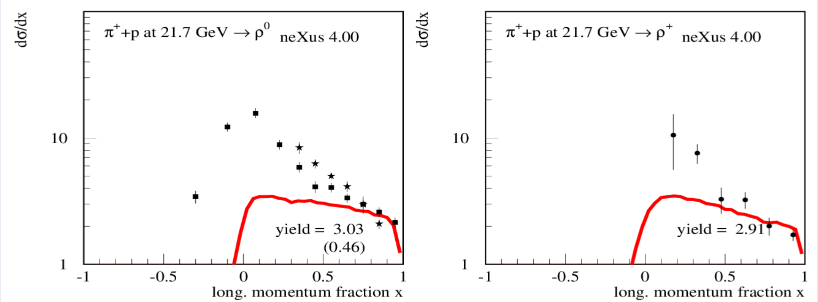

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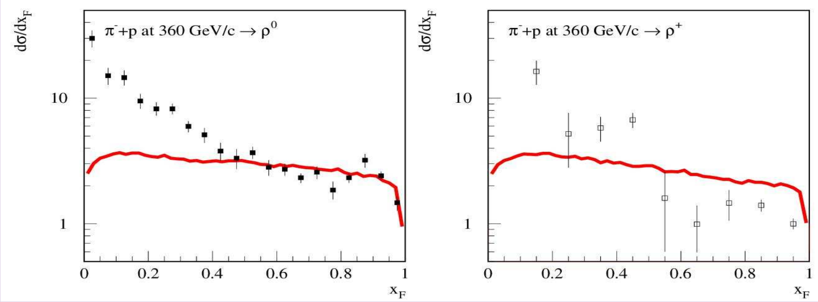
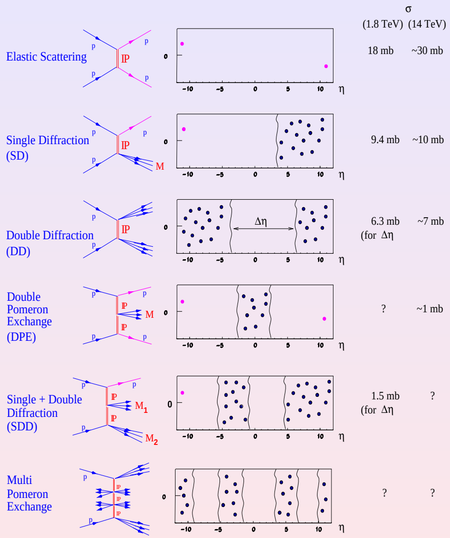


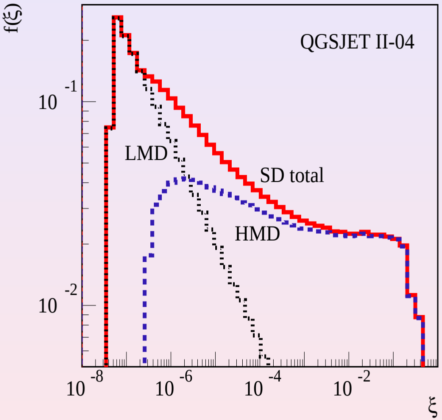
- and do EAS calculations...
- result: reduction of N_μ: $< 5\%$

Inelastic diffraction



- experimentally: formation of large rapidity gap not covered by secondaries
- challenge for MC models
- strong impact on EAS predictions (notably $X_{\max}$)

Modification of M_X-dependence for SD by absorption *[SO, PRD81 (2010) 114028, PLB703 (2011) 588]*



- nontrivial M_X-shape for HMD – due to absorptive effects ($\xi = M_X^2/s$)
- crucial - impact parameter dependence: stronger absorption (nonlinear effects) at smaller b

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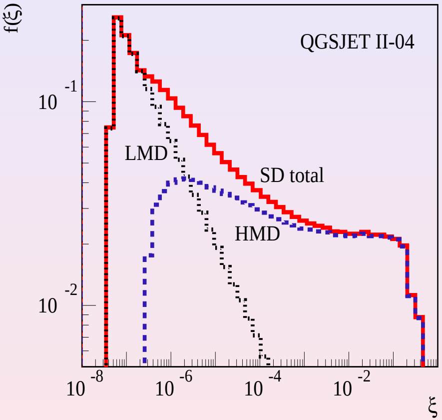

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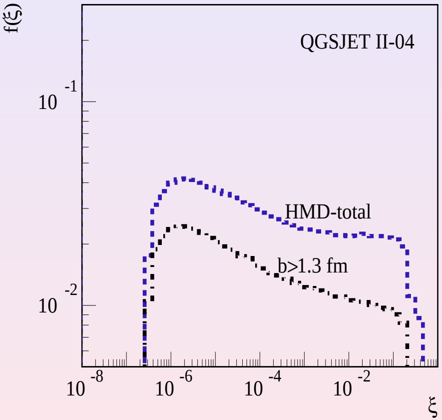

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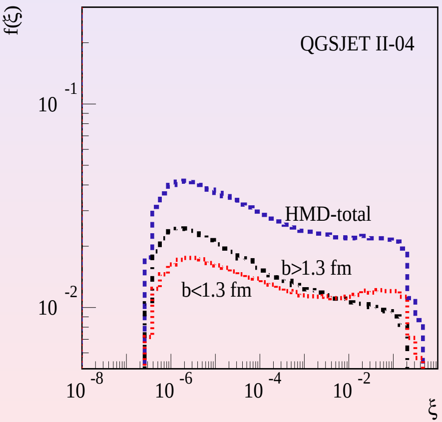

- nontrivial shape for HMD: due to absorptive effects
- steeper ξ-shape at large b: weaker absorptive effects
- flatter ξ-shape at smaller b: strong absorption
- peripheral contribution (steeper ξ-shape) dominates for small M_X
- for large M_X: 'central' and 'peripheral' contributions comparable

What do we see in LHC data?

Agreement of the predicted σ_{pp}^{SD} (M_X-shape and rate) with TOTEM

M_X range, GeV	< 3.4	$3.4 - 1100$	$3.4 - 7$	$7 - 350$	$350 - 1100$
TOTEM	2.62 ± 2.17	6.5 ± 1.3	$\simeq 1.8$	$\simeq 3.3$	$\simeq 1.4$
QGSJET-II-04	3.9	7.2	1.9	3.9	1.5

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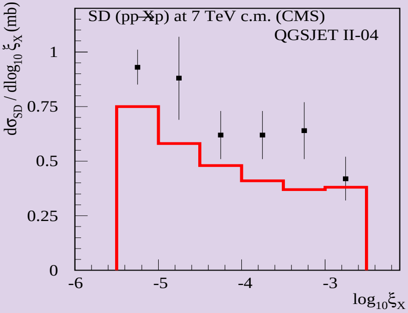

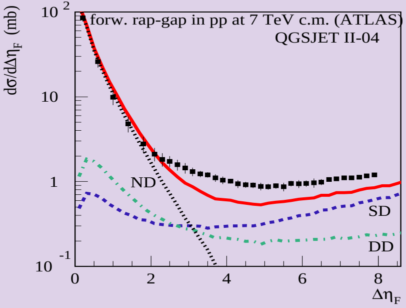

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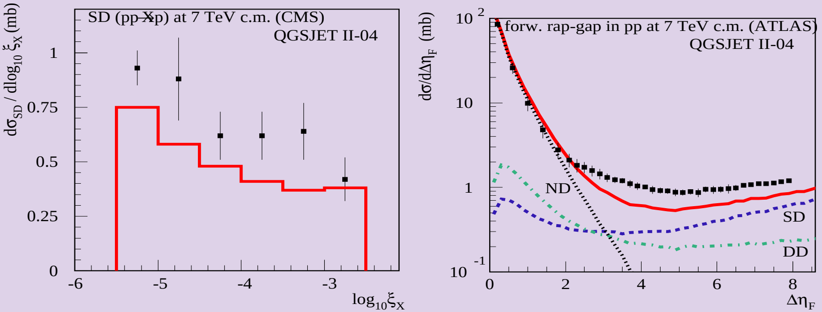
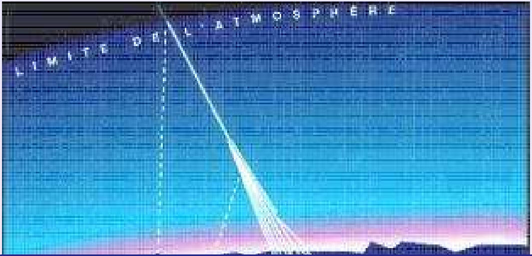


- rates of SD & rap-gaps: $30-40\%$ below CMS & ATLAS

Inelastic diffraction & cosmic ray composition studies



$X_{\max}$ – best suited for CR composition studies

- predictions for $X_{\max}$ depend on $\sigma^{\rm inel}_{p-{\rm air}}$, $\sigma^{\rm diffr}_{p-{\rm air}}$, $K^{\rm inel}_{p-{\rm air}}$, ...
  - $\sigma^{\rm tot/el}_{pp}$ can be reliably extrapolated thanks to LHC studies (notably by TOTEM, ATLAS)
  - $\sigma^{\rm diffr}_{pp}$ impacts recalculation from pp to pA (AA)
    - $\sigma^{\rm inel}_{p-{\rm air}}$ – due to inelastic screening (correlated with $\sigma^{\rm diffr}_{pp}$)
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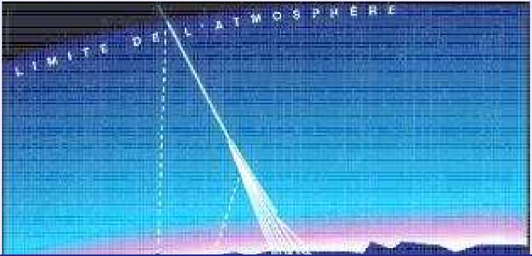

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Impact of uncertainties of $\sigma_{pp}^{\rm SD}$ on $X_{\max}$ *[SO, PRD89 (2014) 7, 074009]*

- Presently: serious tension between CMS & TOTEM concerning diffraction rate in pp

	TOTEM	CMS
M_X range, GeV	$7-350$	$12-394$
$\sigma_{pp}^{\rm SD}(\Delta M_X)$, mb	$\simeq 3.3$	4.3 ± 0.6
$\frac{d\sigma_{pp}^{\rm SD}}{dy_{\rm gap}}$, mb	0.42	0.62

- $\Rightarrow$ may be regarded as a characteristic uncertainty for $\sigma_{pp}^{\rm SD}$
  - impact on $X_{\max}$ & RMS($X_{\max}$)?

Impact of uncertainties of $\sigma_{pp}^{\rm SD}$ on $X_{\max}$ *[SO, PRD89 (2014) 7, 074009]*

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  – to approach CMS results
  - slightly smaller LMD – to soften disagreement with TOTEM
- SD-: smaller LMD (by 30%), same HMD
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Single diffraction: SD- agrees with TOTEM, SD+ o.k. with CMS

M_X range, GeV	< 3.4	$3.4 - 1100$	$3.4 - 7$	$7 - 350$	$350 - 1100$
TOTEM	2.62 ± 2.17	6.5 ± 1.3	$\simeq 1.8$	$\simeq 3.3$	$\simeq 1.4$
option SD+	3.2	8.2	1.8	4.7	1.7
option SD-	2.6	7.2	1.6	3.9	1.7

CMS ($M_X = 12 - 394$ GeV)	option SD+	option SD-
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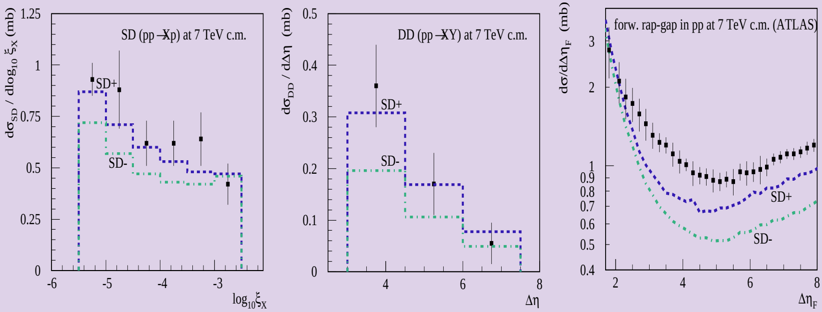
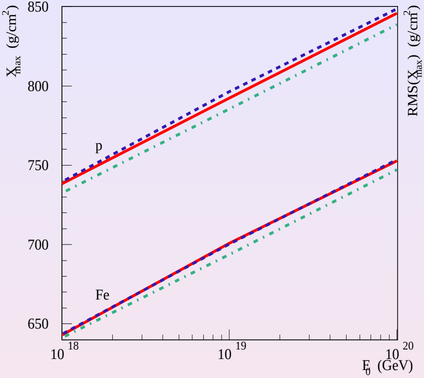
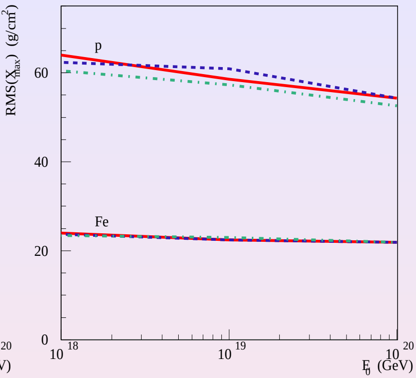
Comparison with differential SD & DD (CMS) & rap-gap (ATLAS)



Impact on X_{max} & RMS(X_{max})

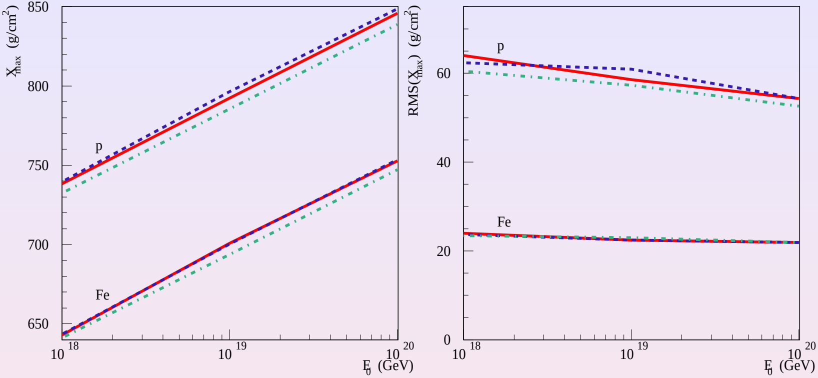




Option SD-: smaller low mass diffraction

- $\Rightarrow$ smaller inelastic screening $\Rightarrow$ larger $\sigma^{\rm inel}_{p-{\rm air}}$
- smaller diffraction for proton-air $\Rightarrow$ larger $K^{\rm inel}_{p-{\rm air}}$, $N^{\rm ch}_{p-{\rm air}}$
- $\Rightarrow$ smaller X_{max} (all effects work in the same direction): $\Delta X_{max} \simeq -10\,{\rm g/cm^2}$

Impact on X_{max} & RMS(X_{max})



Option SD+: larger high mass diffraction

- opposite effects
- but: minor impact on X_{max} ($\Delta X_{max} < 5\,\mathrm{g/cm^2}$)

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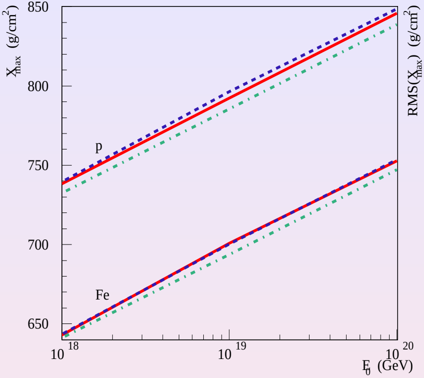

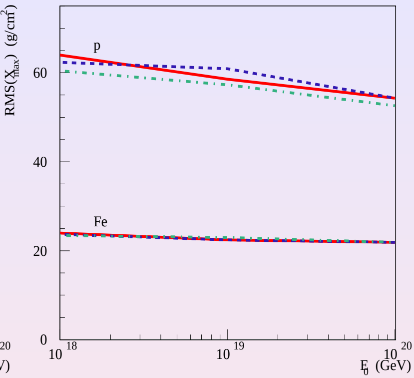

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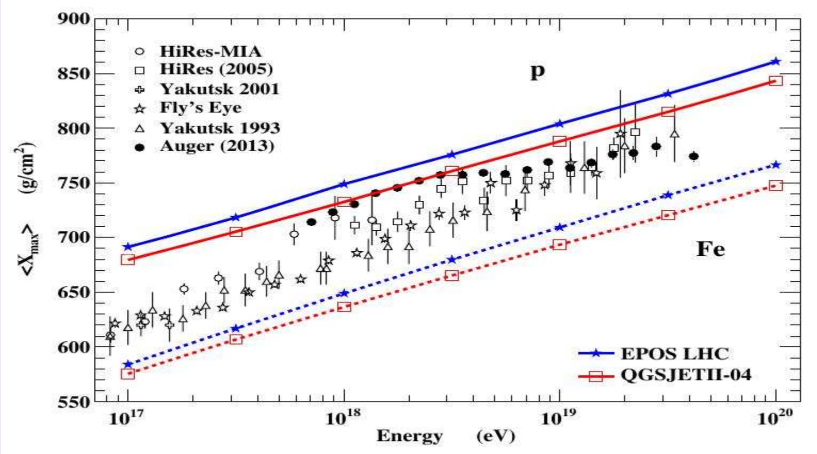
Impact on $X_{\max}$ & RMS($X_{\max}$)

Why larger $X_{\max}$ differences with other models (e.g. EPOS-LHC)?

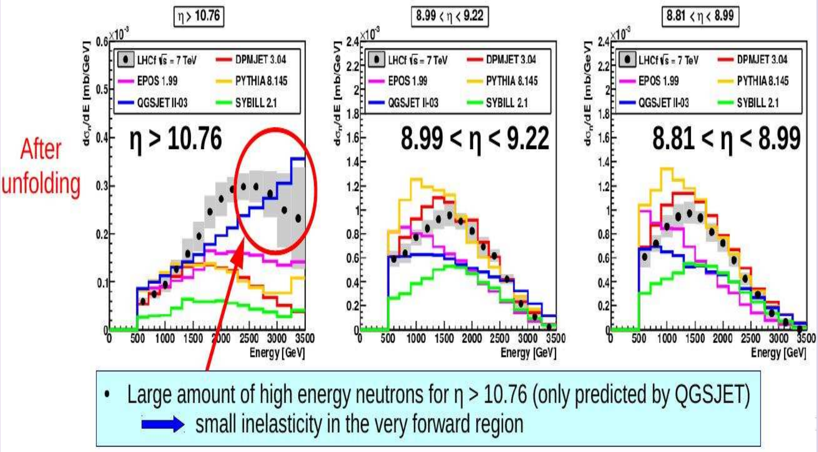


[plot from T. Pierog]

- to be discussed in the summary talk

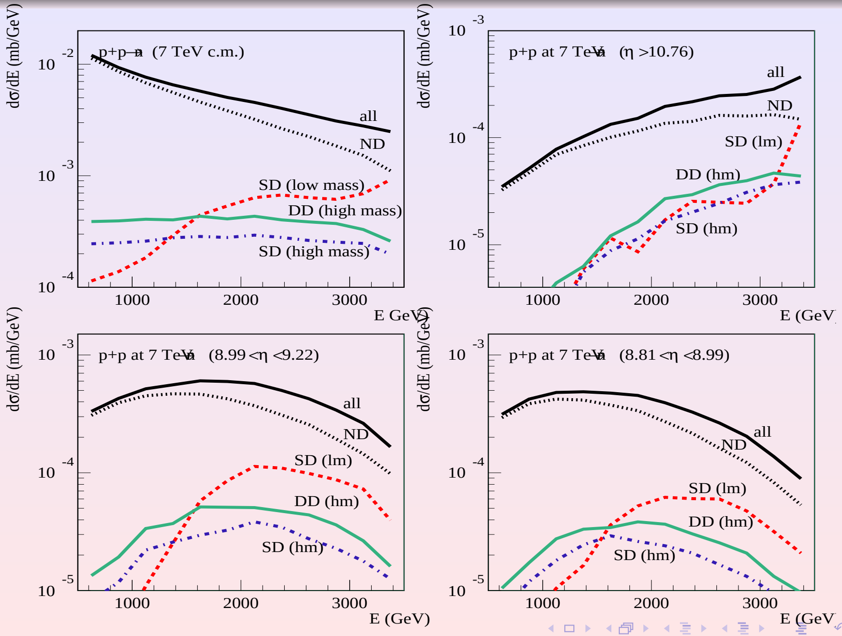
Forward production: neutrons

LHCf data at 7 TeV c.m. *[talk of A. Tiberio at HSZD-2015]*



How to understand the results?

Forward neutron spectra in LHCF: different contributions



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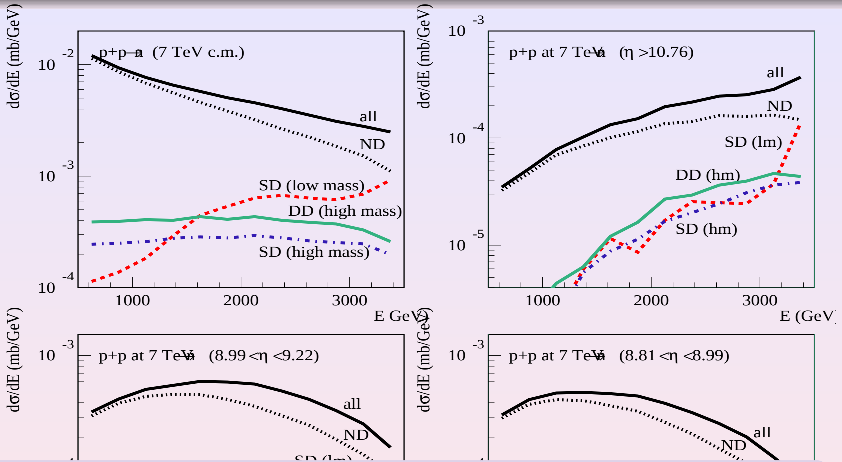

- low mass projectile diffr.: up to 50% contribution at $x_F \to 1$
- main contribution: nondiffractive collisions
  - for large x_F - dominated by pion exchange mechanism ($\mathbb{RRP}$-contribution) *[Kopeliovich et al., PRD91 (2015) 054030]*

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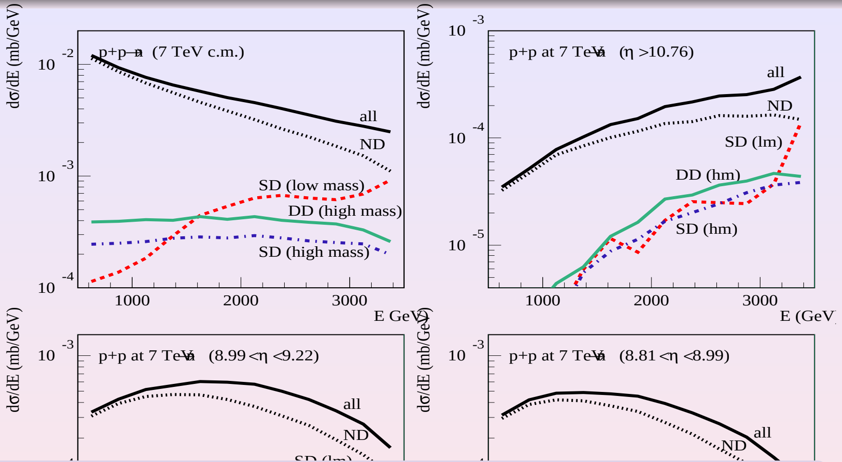

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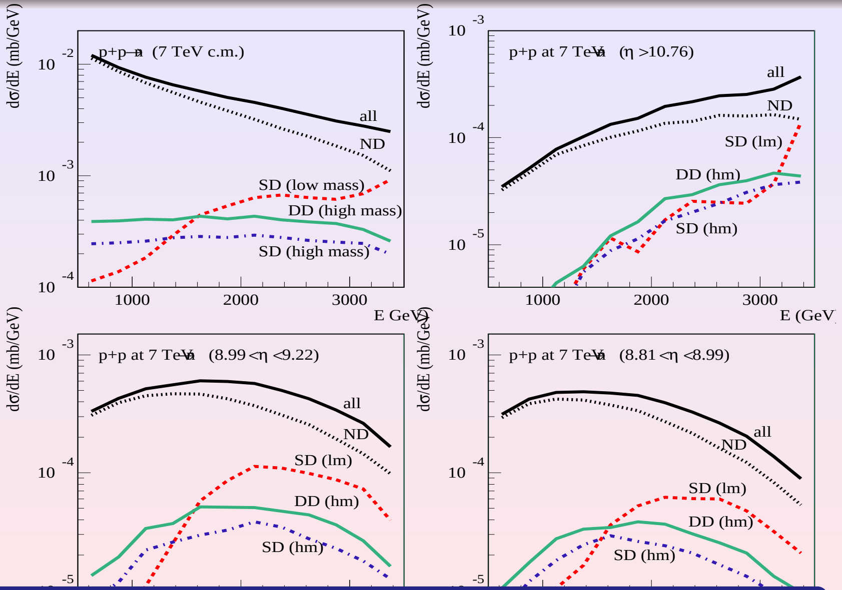
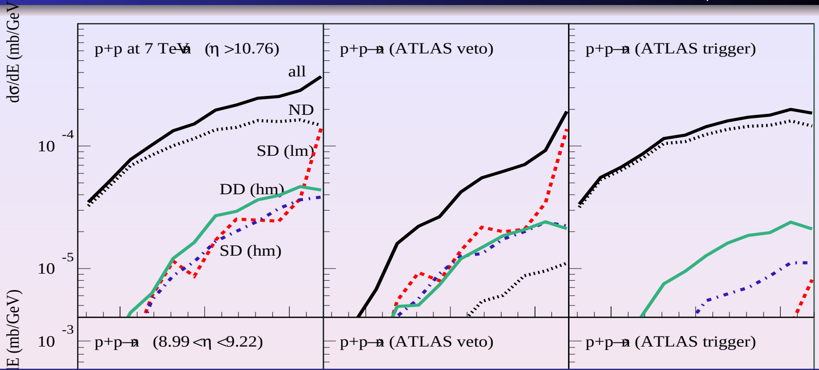


how to separate different contributions experimentally?

Forward neutron spectra: LHCF + ATLAS veto/trigger



ATLAS to veto/trigger charged particles ($p_t > 0.5$ GeV, $|\eta| < 2.5$)

- veto removes ND almost completely!
  - ⇒ allows a clean detection of low mass diffraction (impossible with other LHC detectors)
- triggering activity in ATLAS removes most of diffraction
  - ⇒ neutron spectra measurement in ND events

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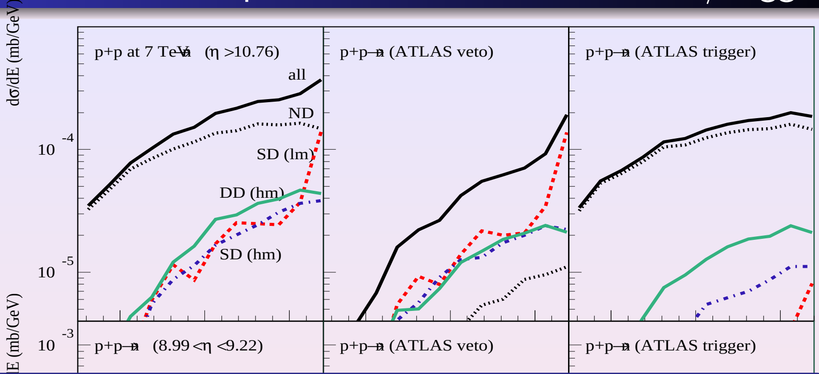

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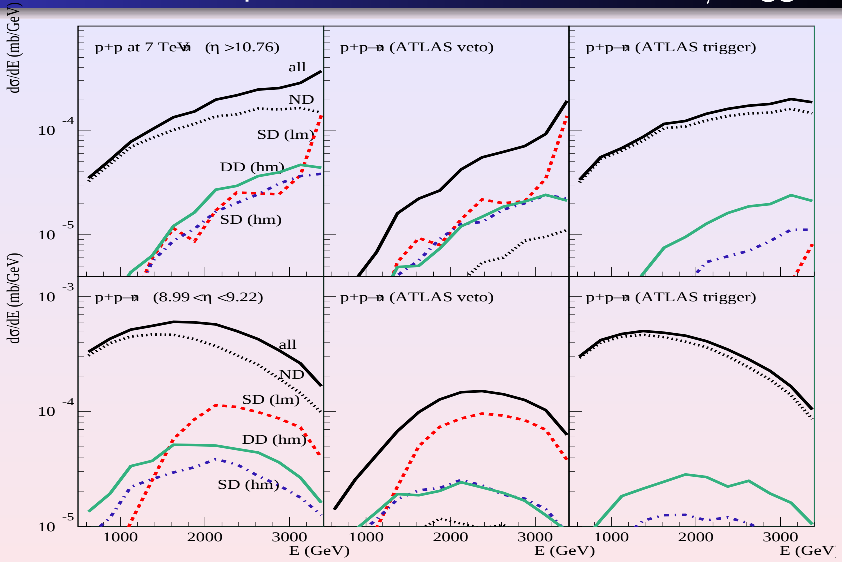
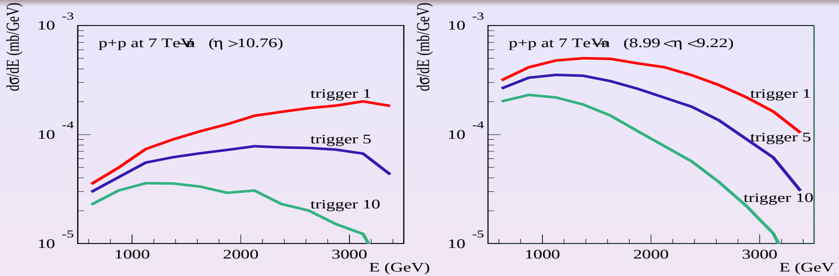


Combination of the 3 measurements ⇒ separation of the different components!

'Centrality' dependence in pp: test of pp to p-air transition



Require at least 1, 5, 10 charged particles in ATLAS ($p_t > 0.5$ GeV)

- enhanced multiple scattering
- $\Rightarrow$ strong suppression of forward neutron production
  - pion exchange goes away
  - higher energy loss by the 'remnant' state
- important test for CR applications:
  measure of the 'inelasticity' in ND collisions
- NB: ND $p-$air collision - like more 'central' pp interaction

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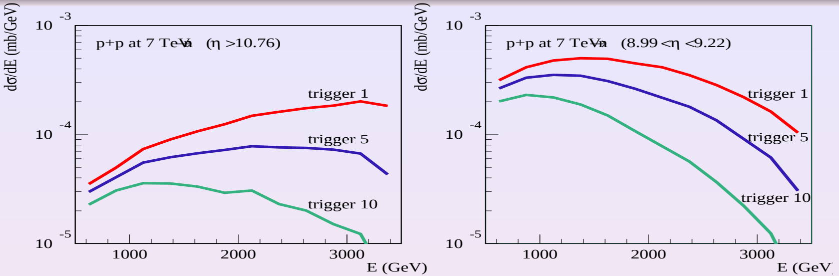

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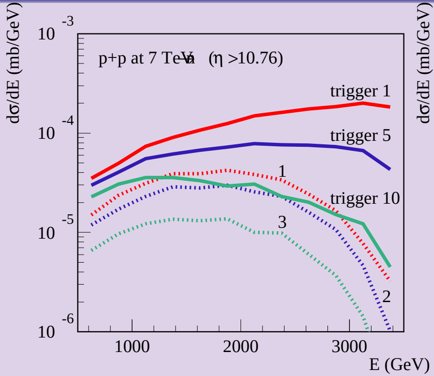
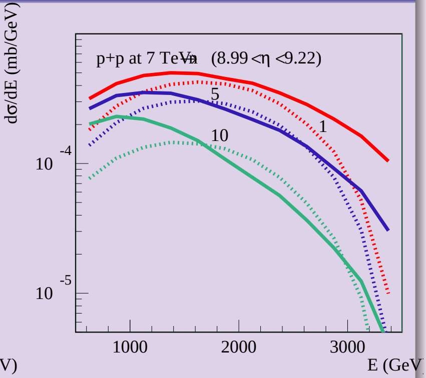
'Centrality' dependence in *pp*: test of *pp* to *p*-air transition

Compare QGSJET-II-04 (solid lines) to SIBYLL 2.1 (dotted)

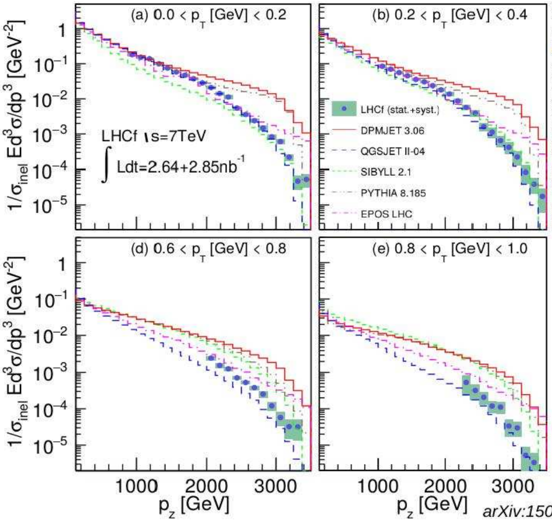




- order of magnitude differences
- nearly same spectral shape in SIBYLL for all the triggers! (forward spectra decoupled from central production)
- $\Rightarrow$ important discriminator between models

Forward production: π^0

LHCf data at 7 TeV c.m. *[talk of A. Tiberio at HSZD-2015]*



- Good agreement of QGSJET II-04
- EPOS-LHC harder at $P_z > 2$ TeV
- DPMJET and Pythia OK at $P_T < 0.2$ GeV and $P_z < 1.6$ TeV, harder at $P_z > 1.6$ TeV
- SIBYLL similar to DPMJET and PYTHIA increasing P_T, low yield at $P_T < 0.2$ GeV

arXiv:1507:08764v1 Submitted to PRD

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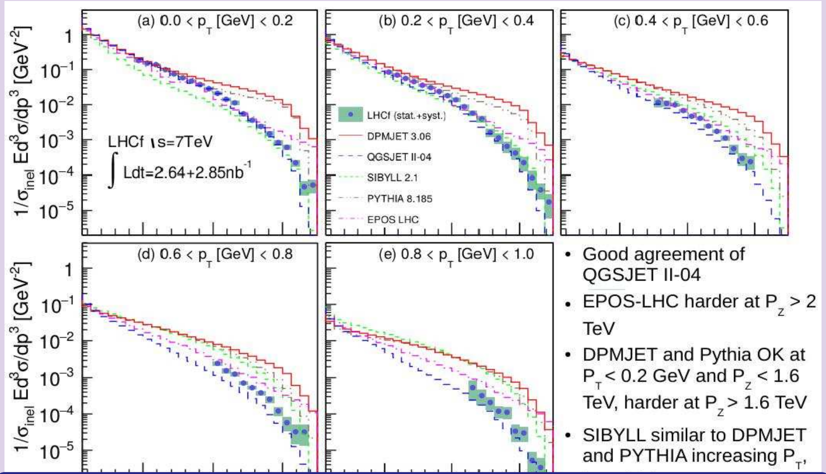
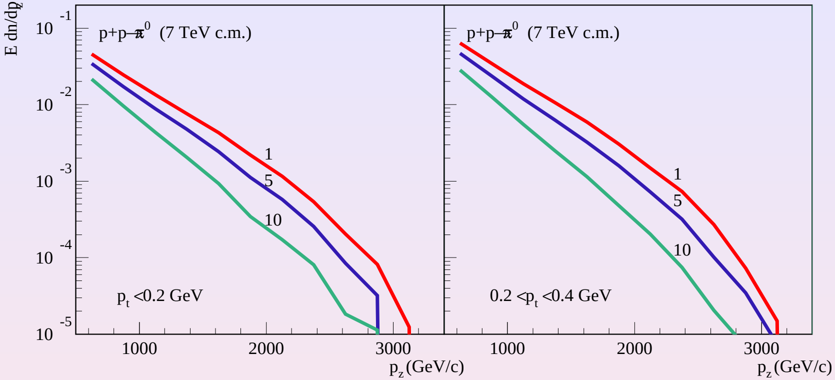


How the spectra should evolve from pp to p-air?

- NB: forward spectra of $\pi^{\pm}$ - of importance for $X_{\max}^{\mu}$!

'Centrality' dependence as a test for pp to p-air transition



- increasing 'centrality' of pp collisions by ATLAS triggers:
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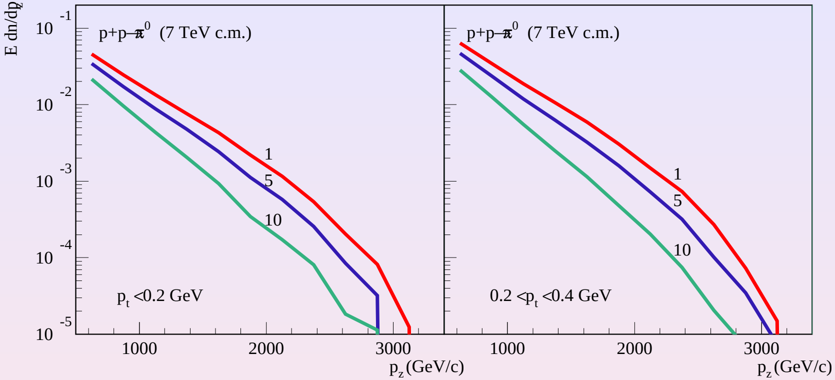

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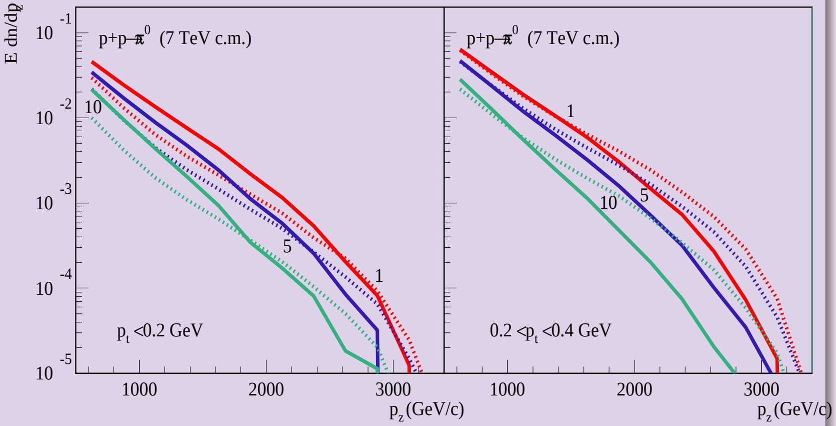

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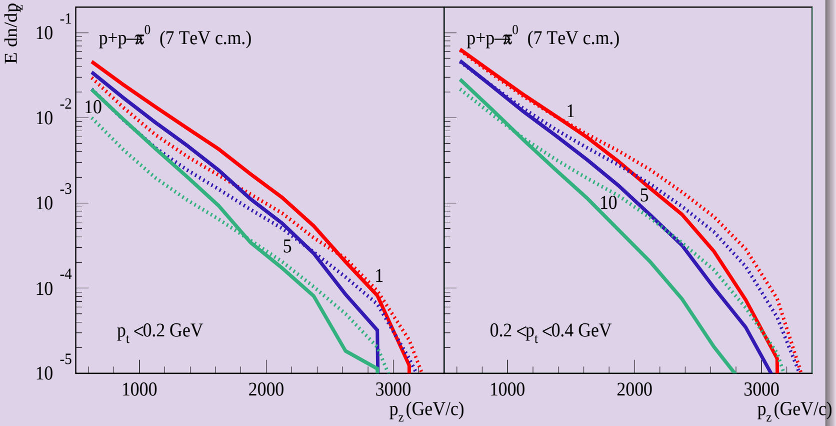

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   - treatment of all significant $\mathbb{P}\mathbb{P}$-interaction contributions
   - calibration to LHC data (notably to $\sigma_{pp}^{\mathrm{tot/el}}$ by TOTEM)
   - dominance of π-exchange for charge exchange in πp
2. Further: towards pQCD treatment of nonlinear effects
   - not a short-term project
3. LHC data generally support the approach of the model
   - however, indications in the data:
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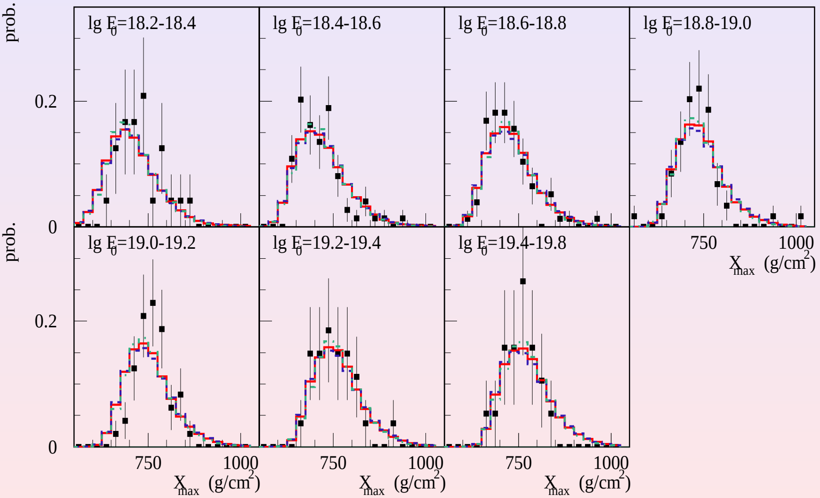
Extra slides

Potential impact of diffraction uncertainties on CR studies

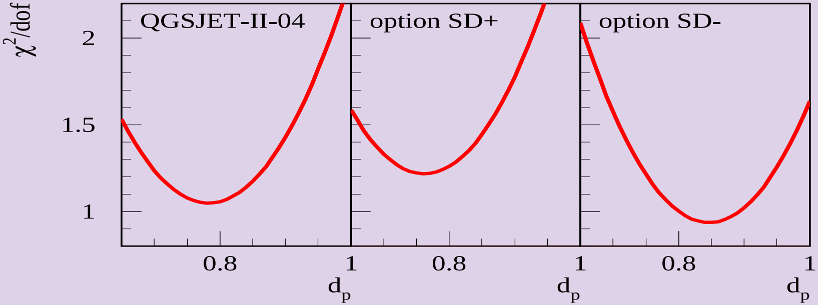
- Fit of Telescope Array data by p+Fe CR composition



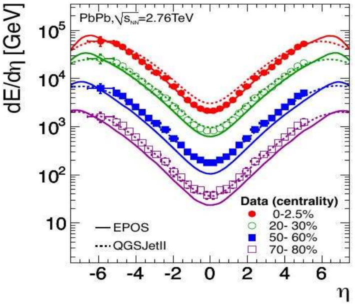
Potential impact of diffraction uncertainties on CR studies

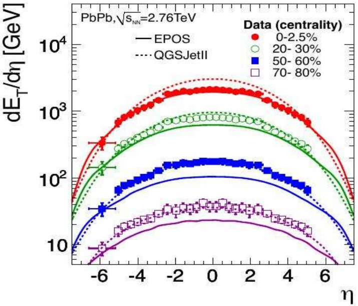
- Fit of Telescope Array data by p+Fe CR composition

Fit quality for different proton abundances d_p ($d_{\mathrm{Fe}} = 1 - d_p$)



- option SD+: pure proton composition excluded
- option SD-: almost pure proton composition is o.k. (astrophysically favorable scenario)





EPOS better for central collisions, QGSJET better for peripheral ones ?