Hadronic interactions in cosmic rays and at the LHC

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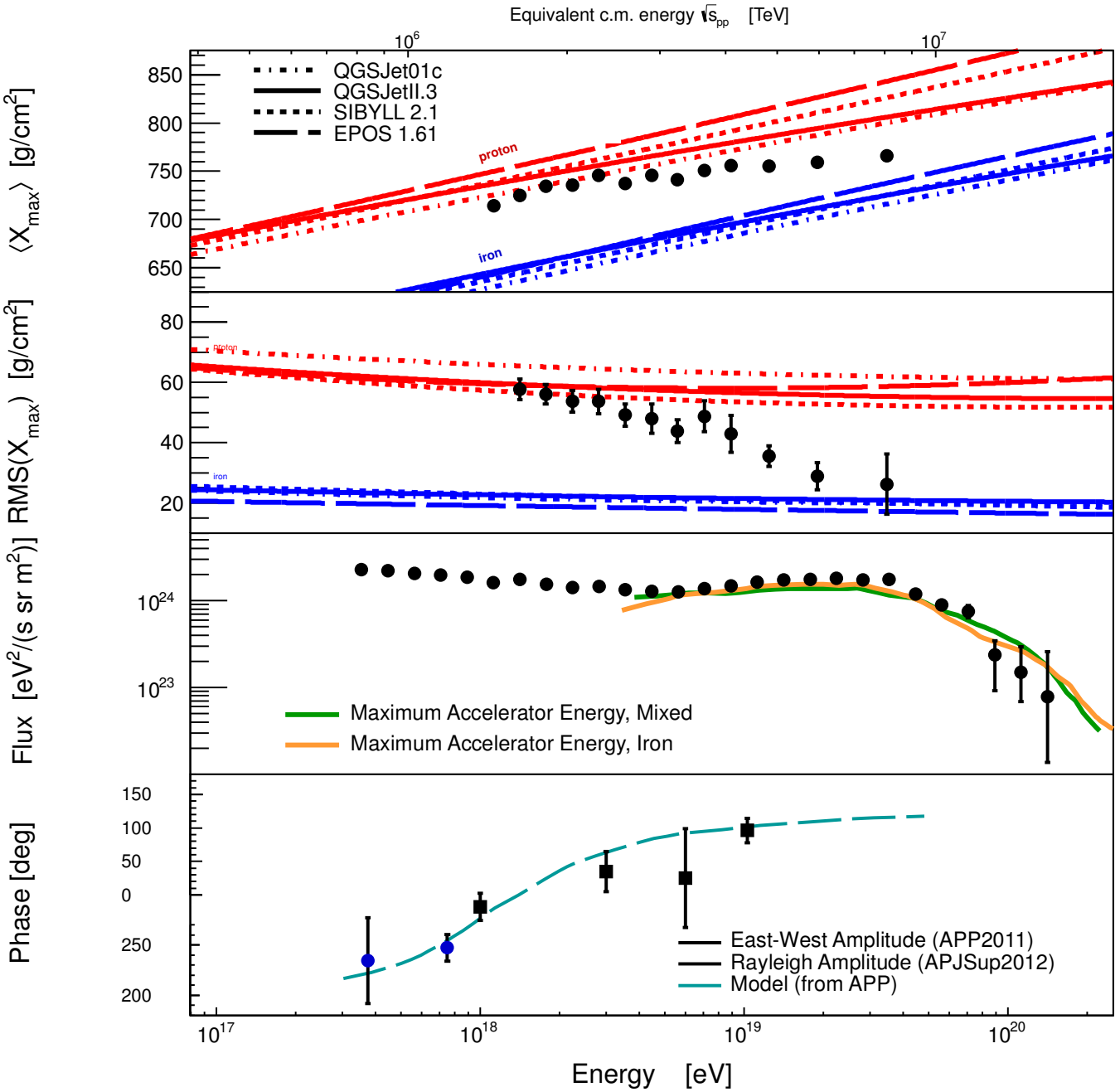
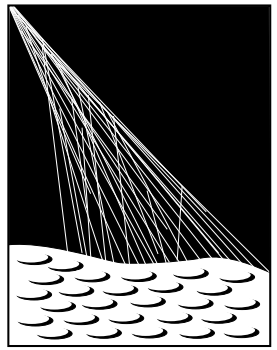
Karlsruhe Institute of Technology

CRIS, 16. September 2015, Gallipoli

UHECR, (Partial) Overview of Experimental Situation



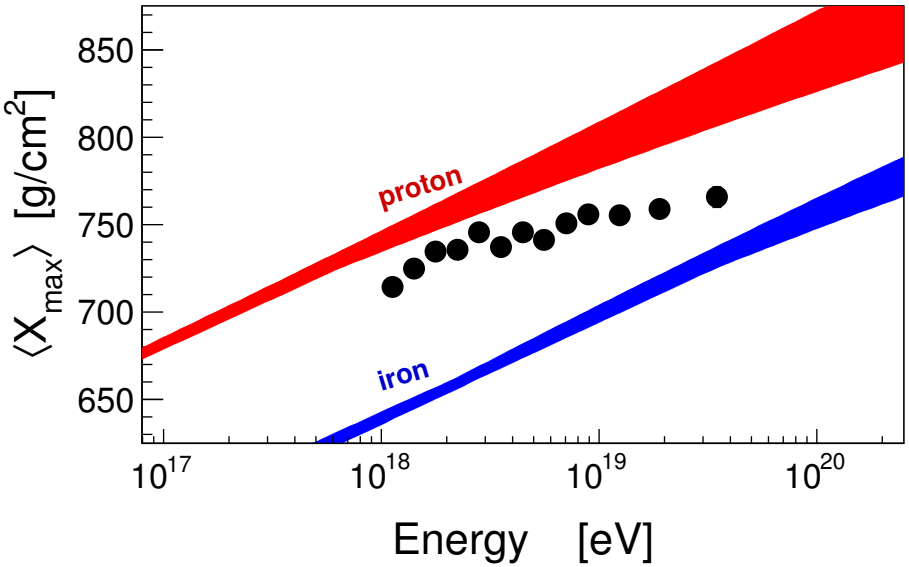


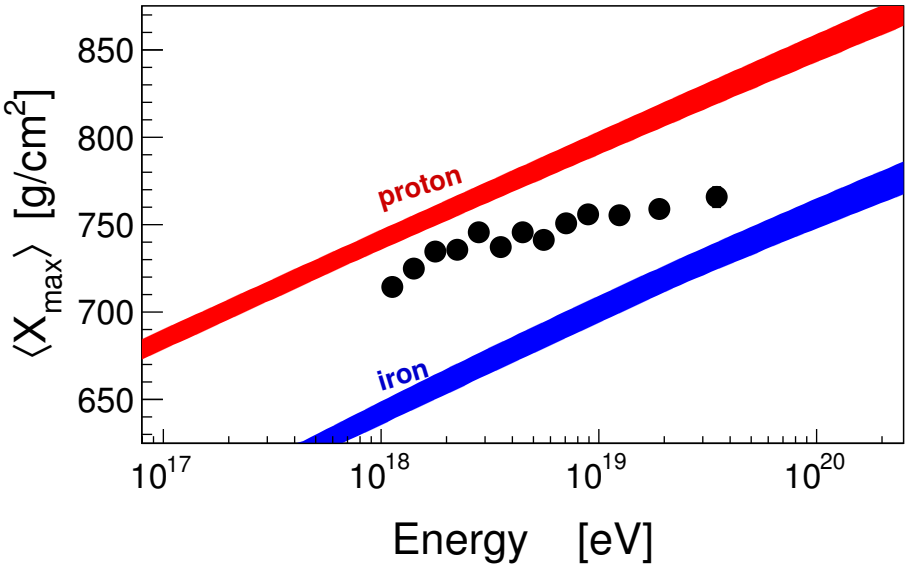
PIERRE AUGER OBSERVATORY

Model Tuning to LHC Data (at 7 TeV)

EPOS 1.99 → **EPOS LHC**

QGSJetII.3 → **QGSJetII.4**





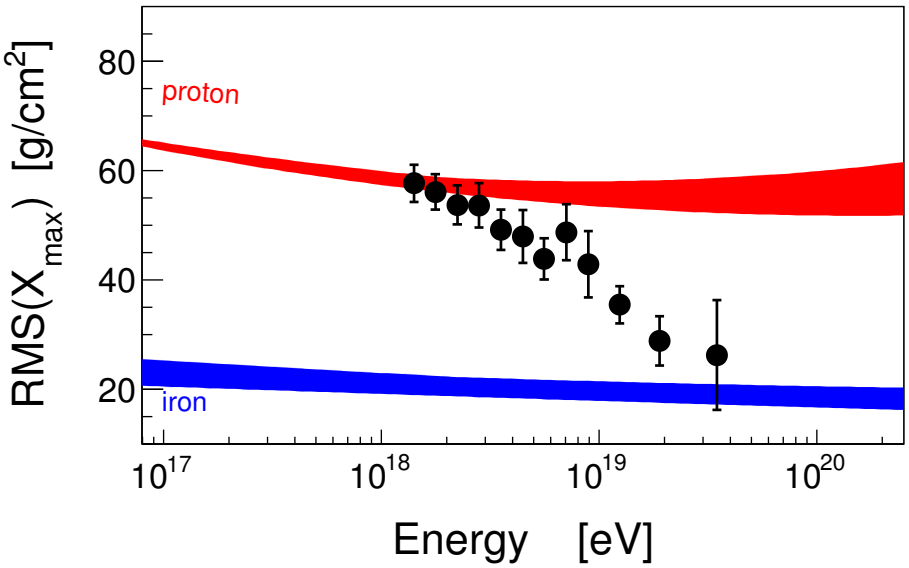
Caveats / Potential:

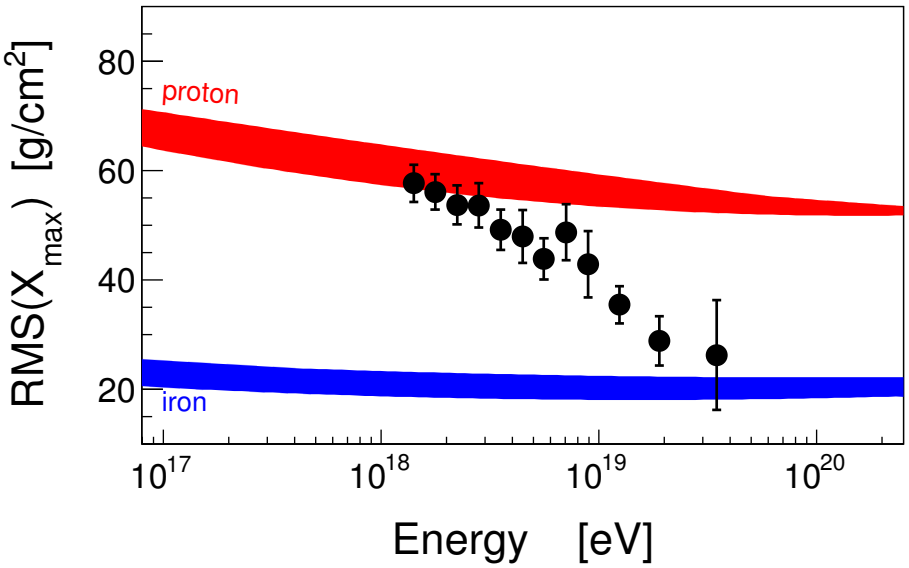
- Only central rapidities $|\eta| < 2$
- Not highest possible center-of-mass energies
- Mainly proton-proton data

Other Observables: Fluctuations

EPOS 1.99 → **EPOS LHC**

QGSJetII.3 → **QGSJetII.4**

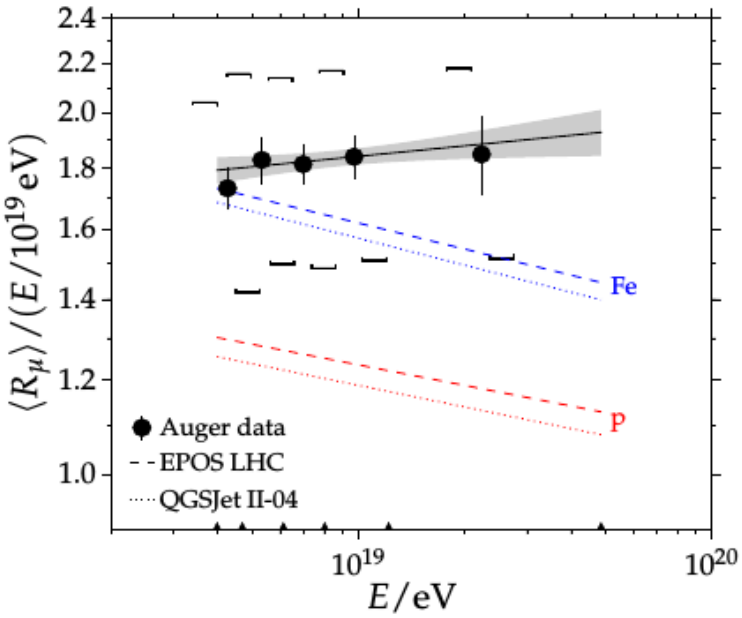


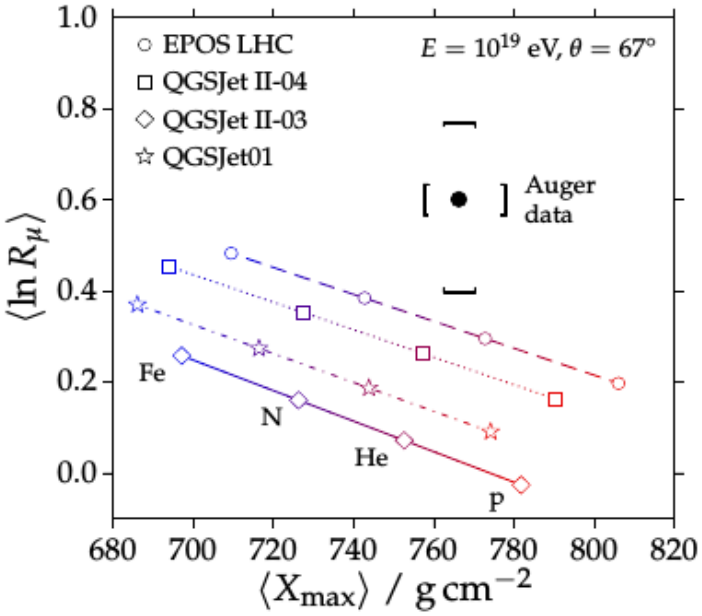


Caveats:

- Very different compared to $\langle X_{\max} \rangle$
- LHC tuning did improve the high energy end, but worsened the agreement at lower/medium energies

Muon Content at Ground Level





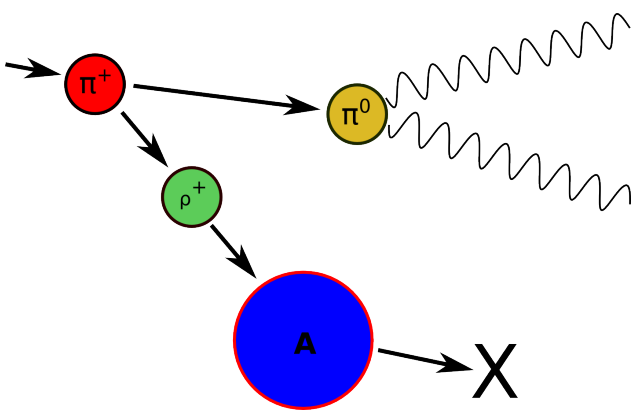
Auger, arXiv-1408.1421 [atro-ph]

- More muons in air shower data than expected
- No consistency between different observables can be achieved

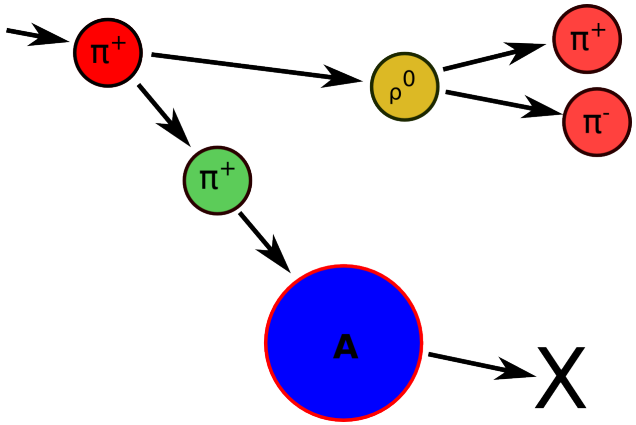
$\rightarrow$ Interaction physics in air showers models is not accurate

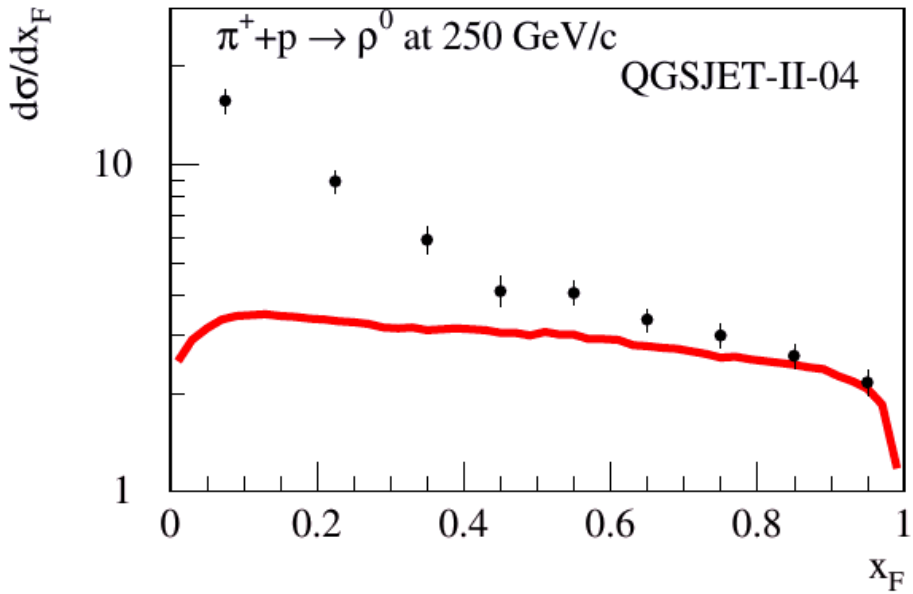
(Forward) ρ^0 Production, QGSJetII.3→QGSJetII.4

Charge Exchange, Leading π^0/ρ^0 production:



versus





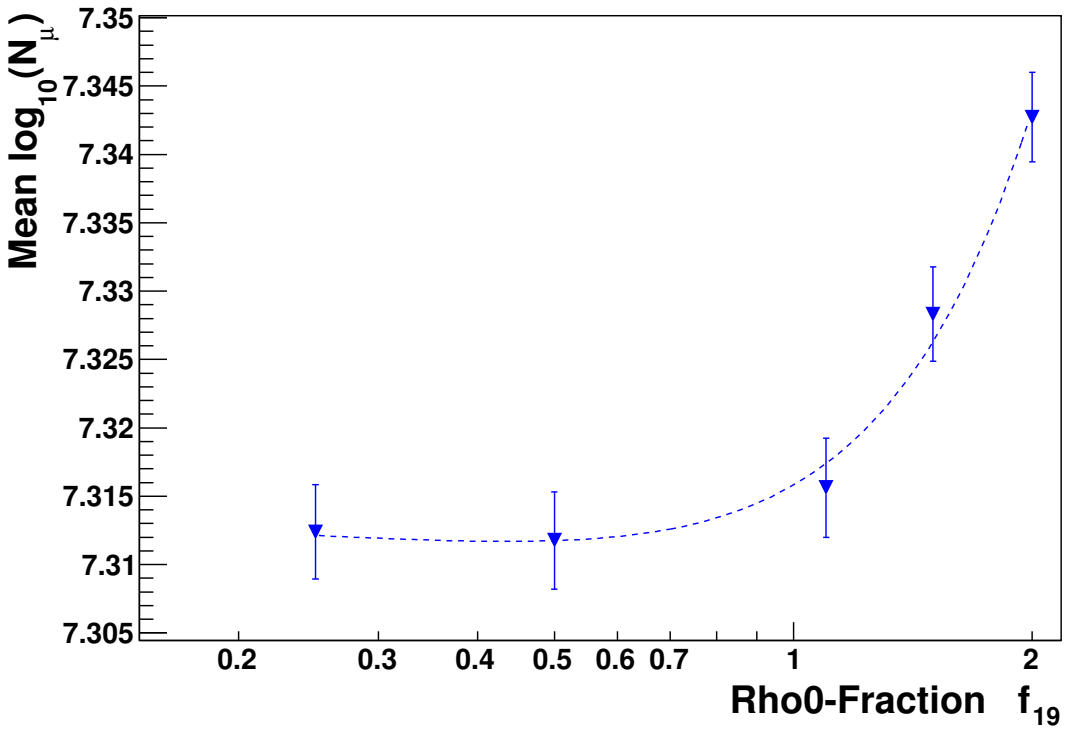
S. Ostapchenko, ISVHECRI 2012

Impact on Muons in Air Showers

Systematically change the leading π^0/ρ^0 ratio in CONEX:

(SIBYLL, proton, $10^{19.5}$ eV)

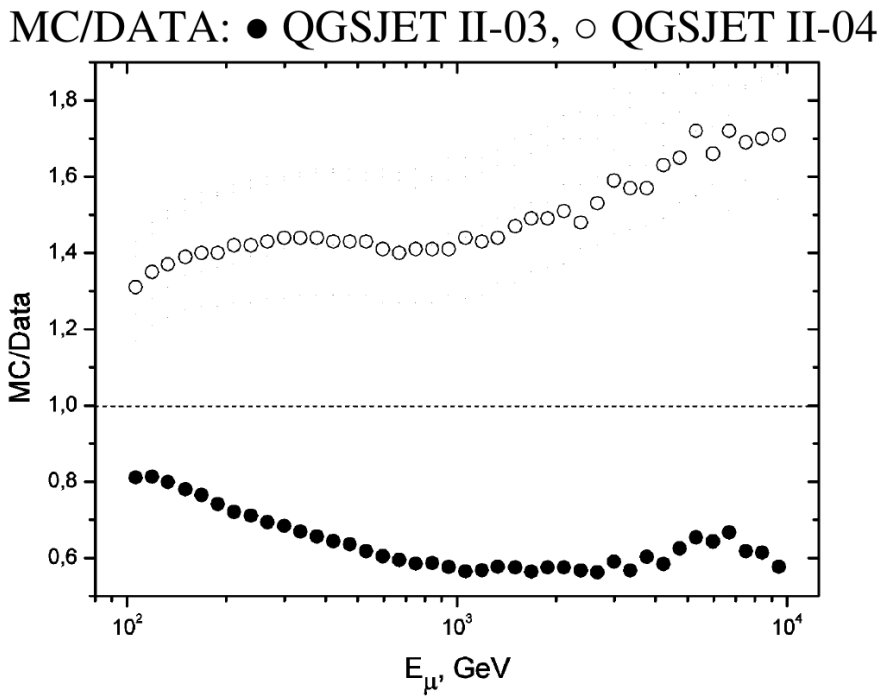
(f19 is the scaling factor for ratio at $10^{19}\,eV$, logarithmic energy dependence)



Ulrich, Engel, Baus, ISVHECRI 2014

Forward ρ^0 production, QGSJetII.4

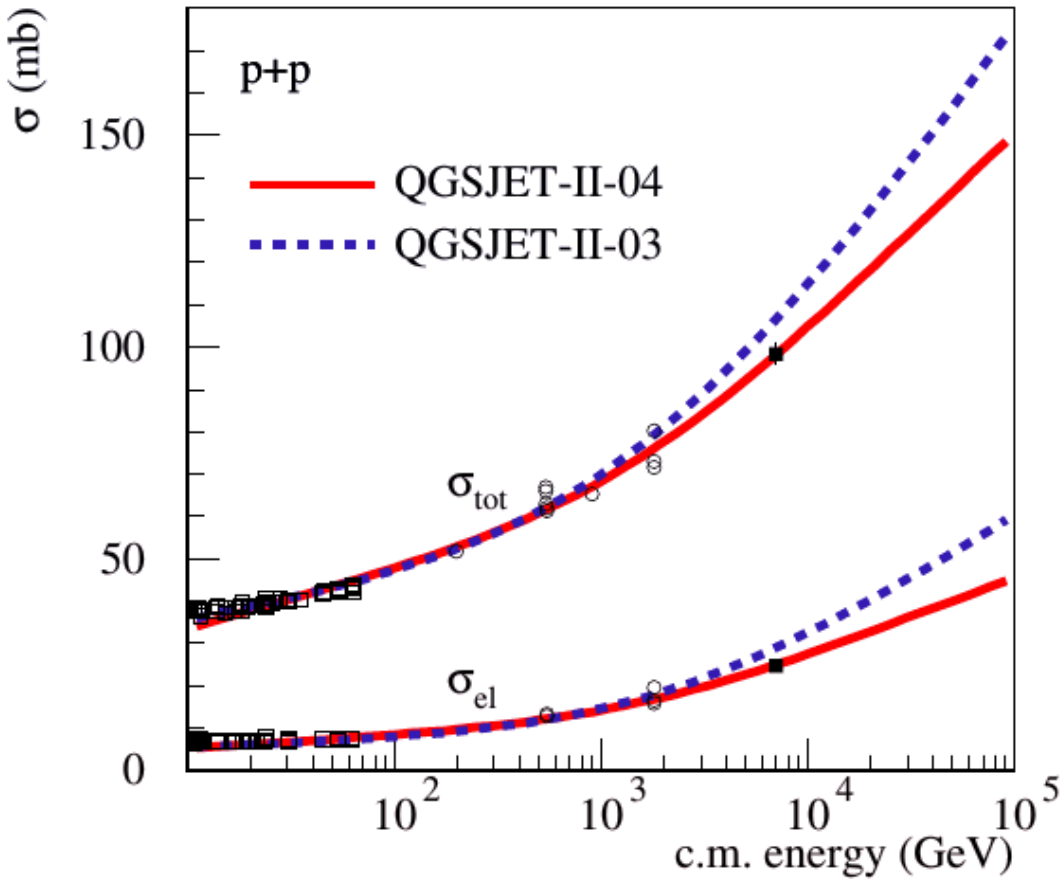
Prediction of inclusive athmospheric muon fluxes as a test of hadronic interaction models



A.V. Lukyashin, ISVHECRI 2014

$\Rightarrow$ Too many ρ^0 produced now?

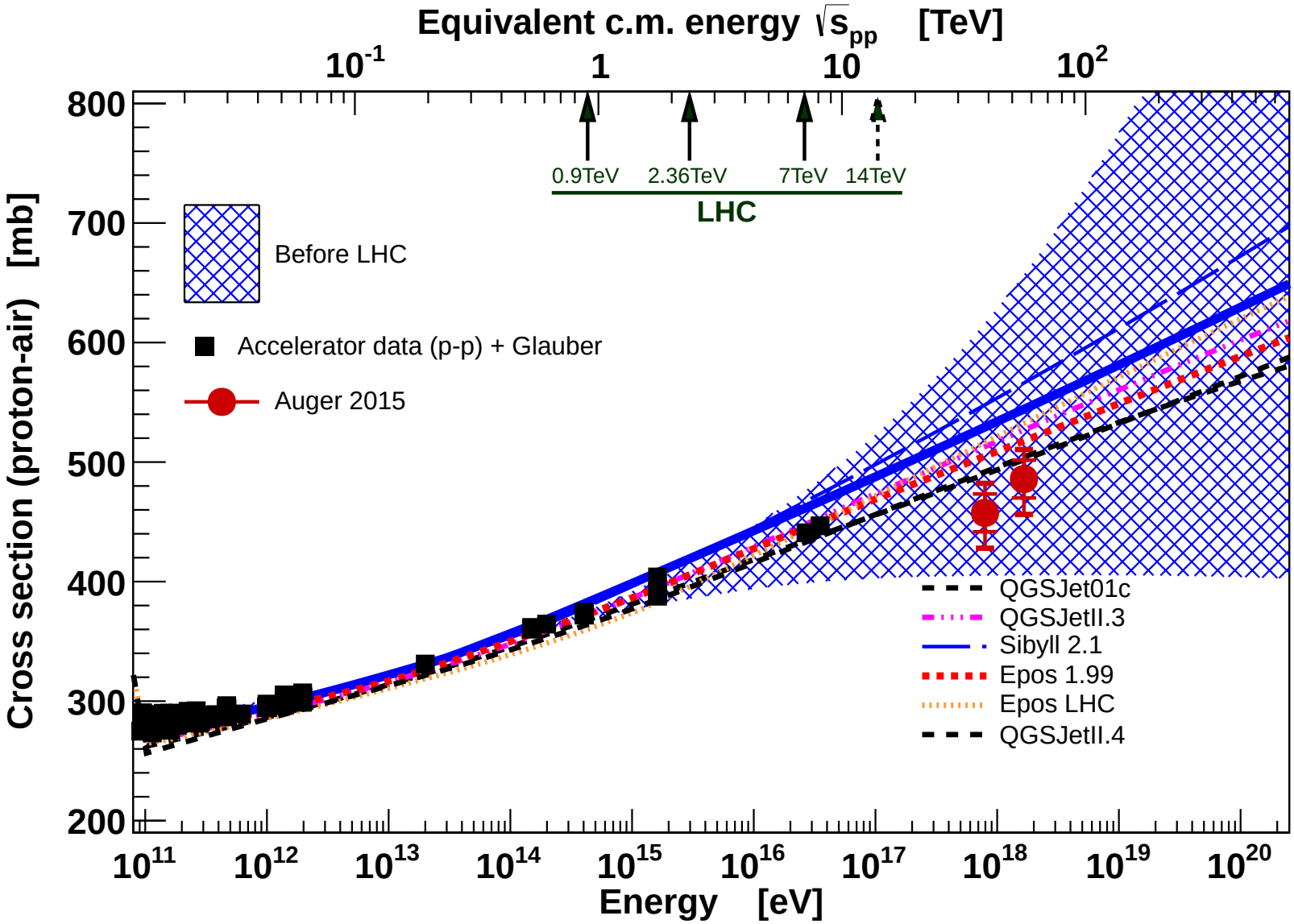
Cross section data



S. Ostapchenko, ISVHECRI 2014

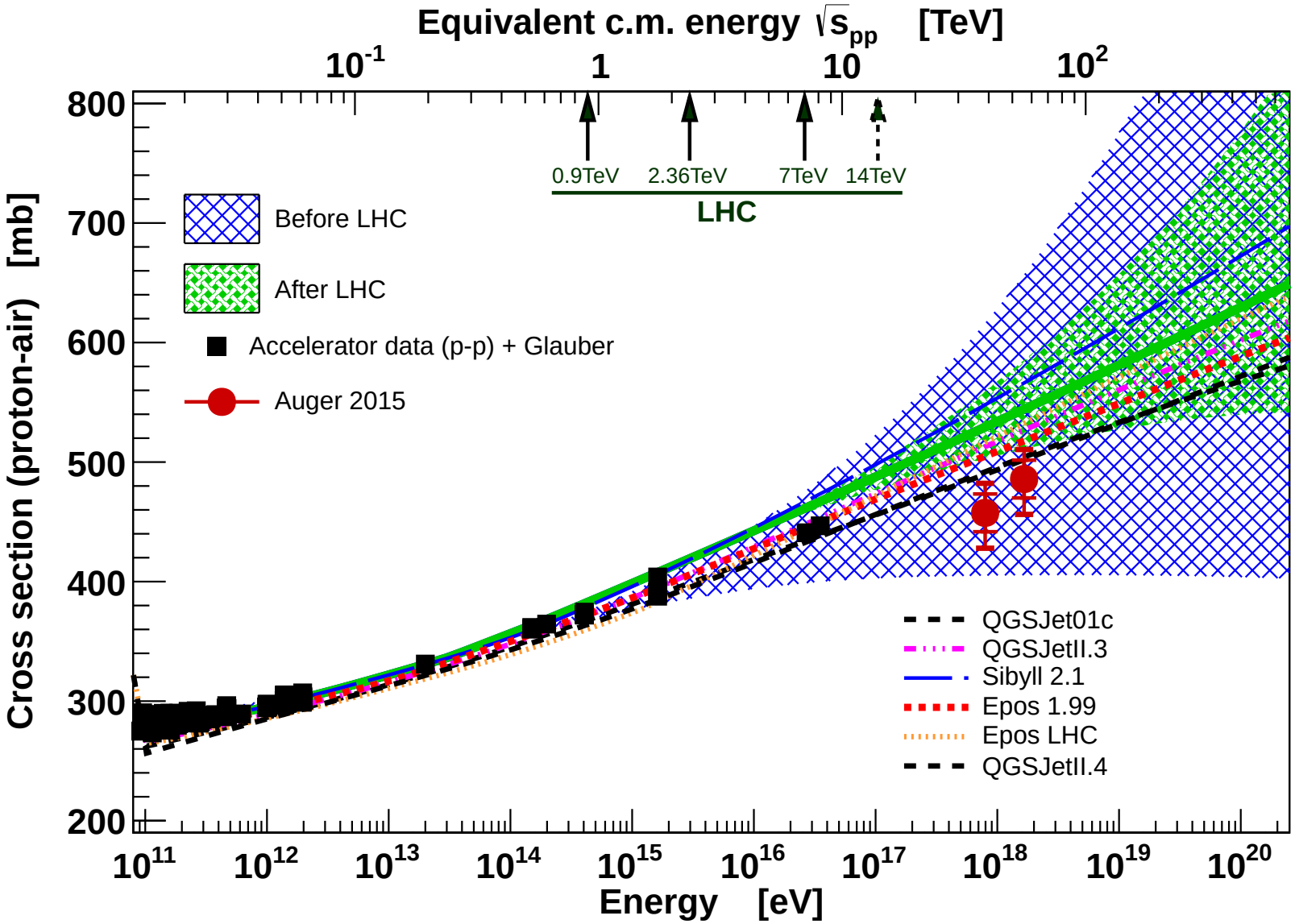
Proton-Air Cross Section is one of the most important quantities for air shower modeling

Proton-Proton → Proton-Air, With Tevatron Data

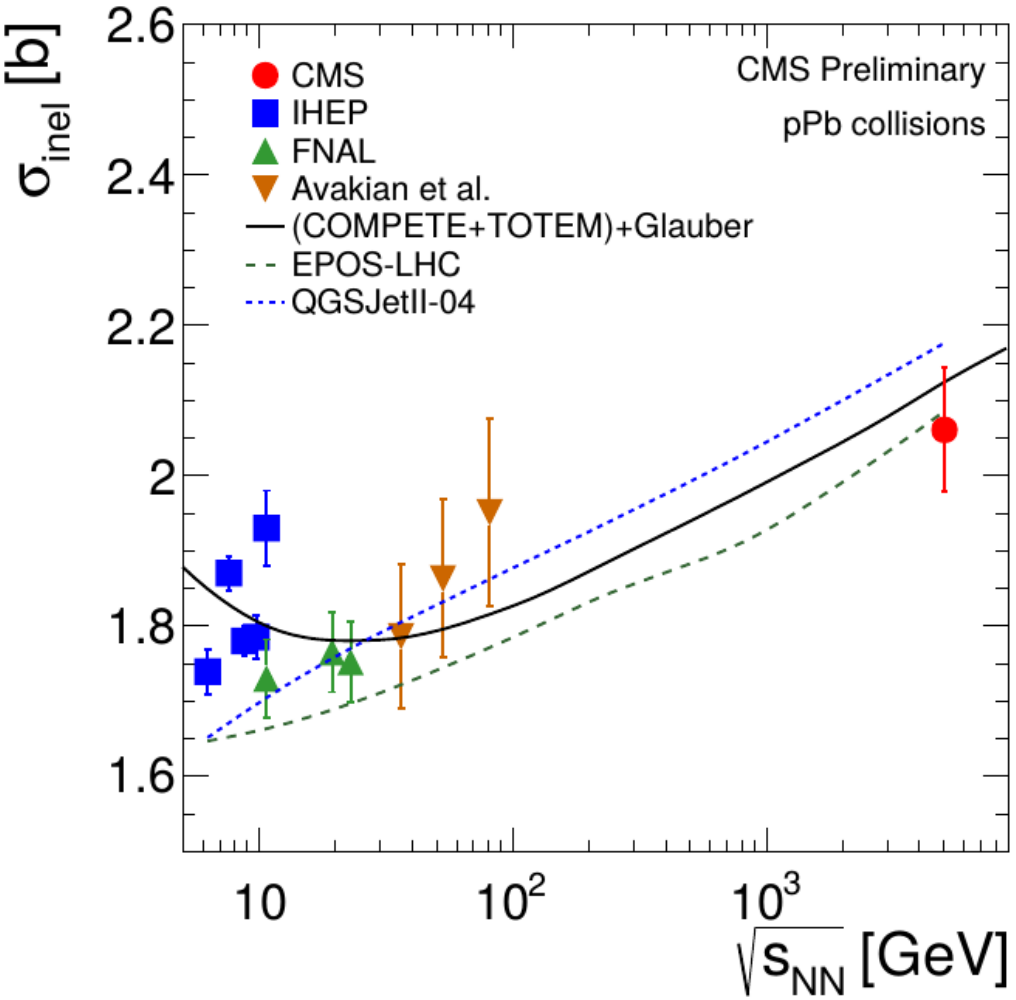


compare to Nucl.Phys.Proc.Suppl. 196 (2009) 335

Proton-Proton → Proton-Air, With LHC Data



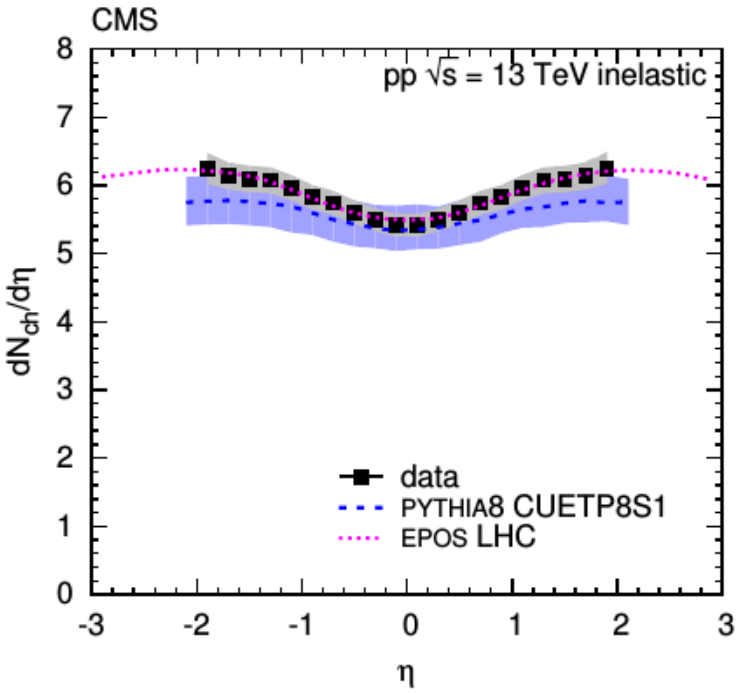
Inelastic Proton-Lead Cross Section at 5.02 TeV

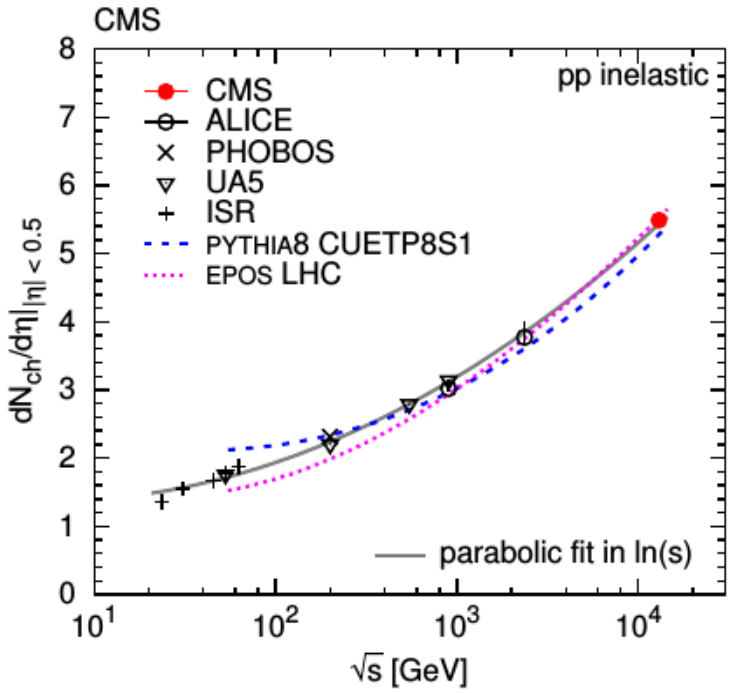


arXiv:1509.03893, submitted to PLB

- **Direct test of Glauber model and its extensions at LHC**

dN/dEta at 13 TeV

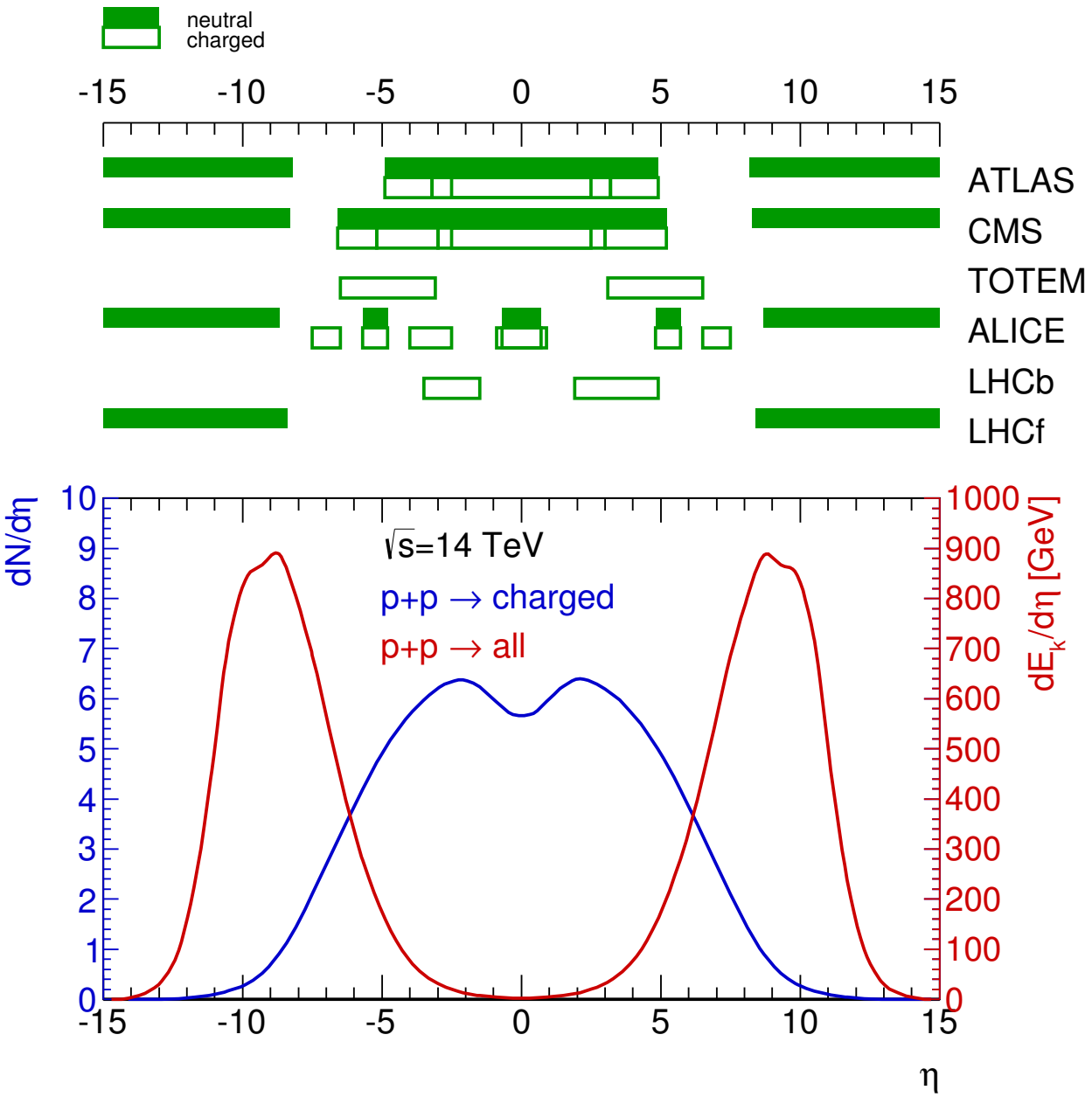




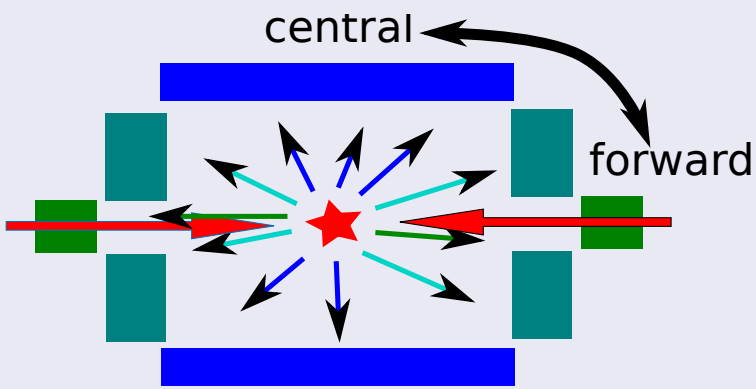
arXiv:1507.05915, submitted to PLB

- First LHC paper at 13 TeV, without CMS magnet
- EPOS-LHC makes an excellent first impression

Acceptance of LHC experiments



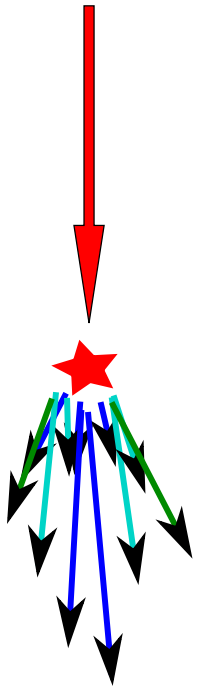
Relevance of Acceptace



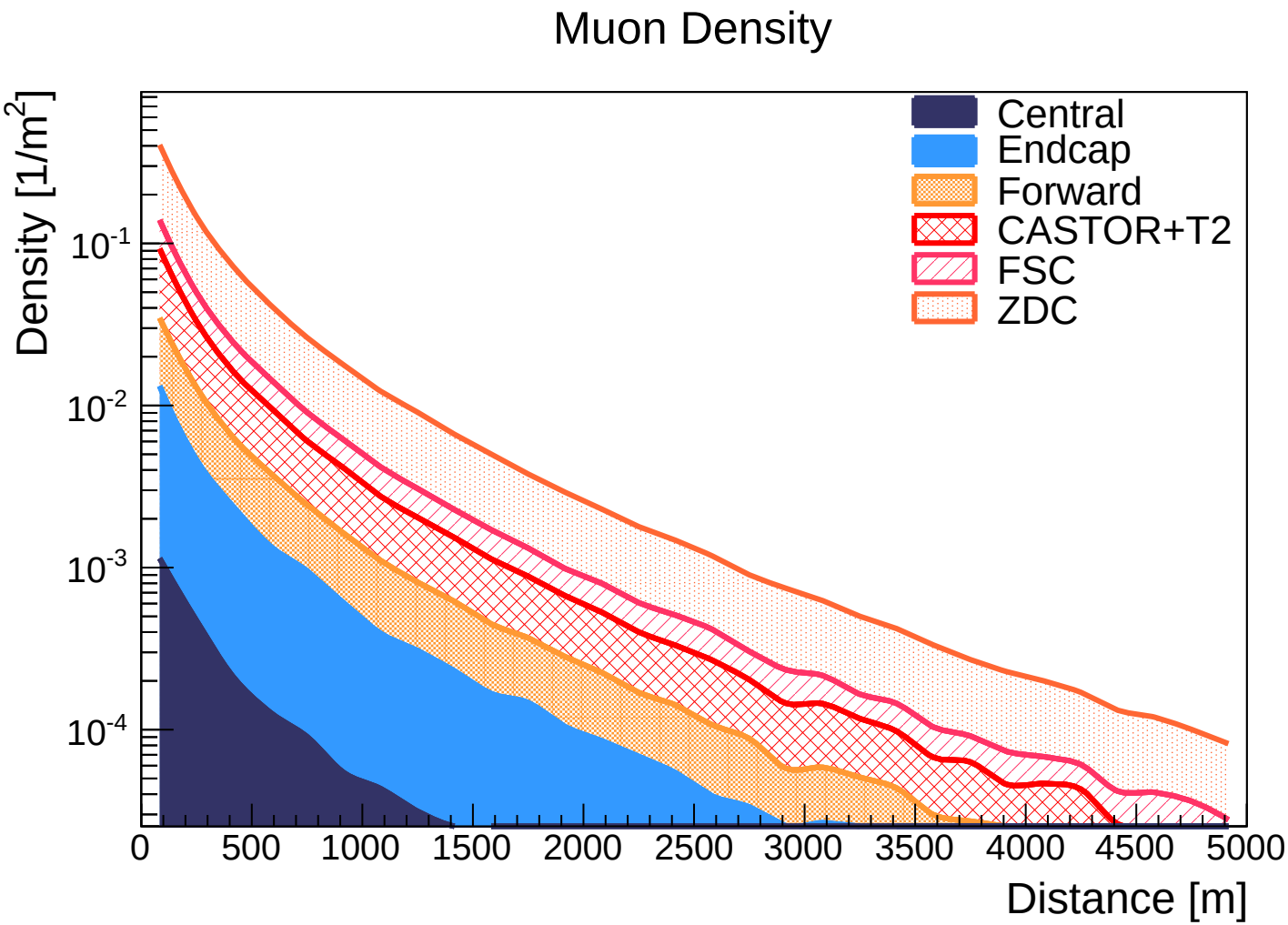
- Central ($|\eta| < 1$)
- Endcap ($1 < |\eta| < 3.5$)
- Forward ($3 < |\eta| < 5$), HF
- CASTOR+T2 ($5 < |\eta| < 6.6$)
- FSC ($6.6 < |\eta| < 8$)
- ZDC ($|\eta| > 8$), LHCf

- How relevant are specific detectors at LHC for air showers?

$\rightarrow$ Simulate parts of shower individually.

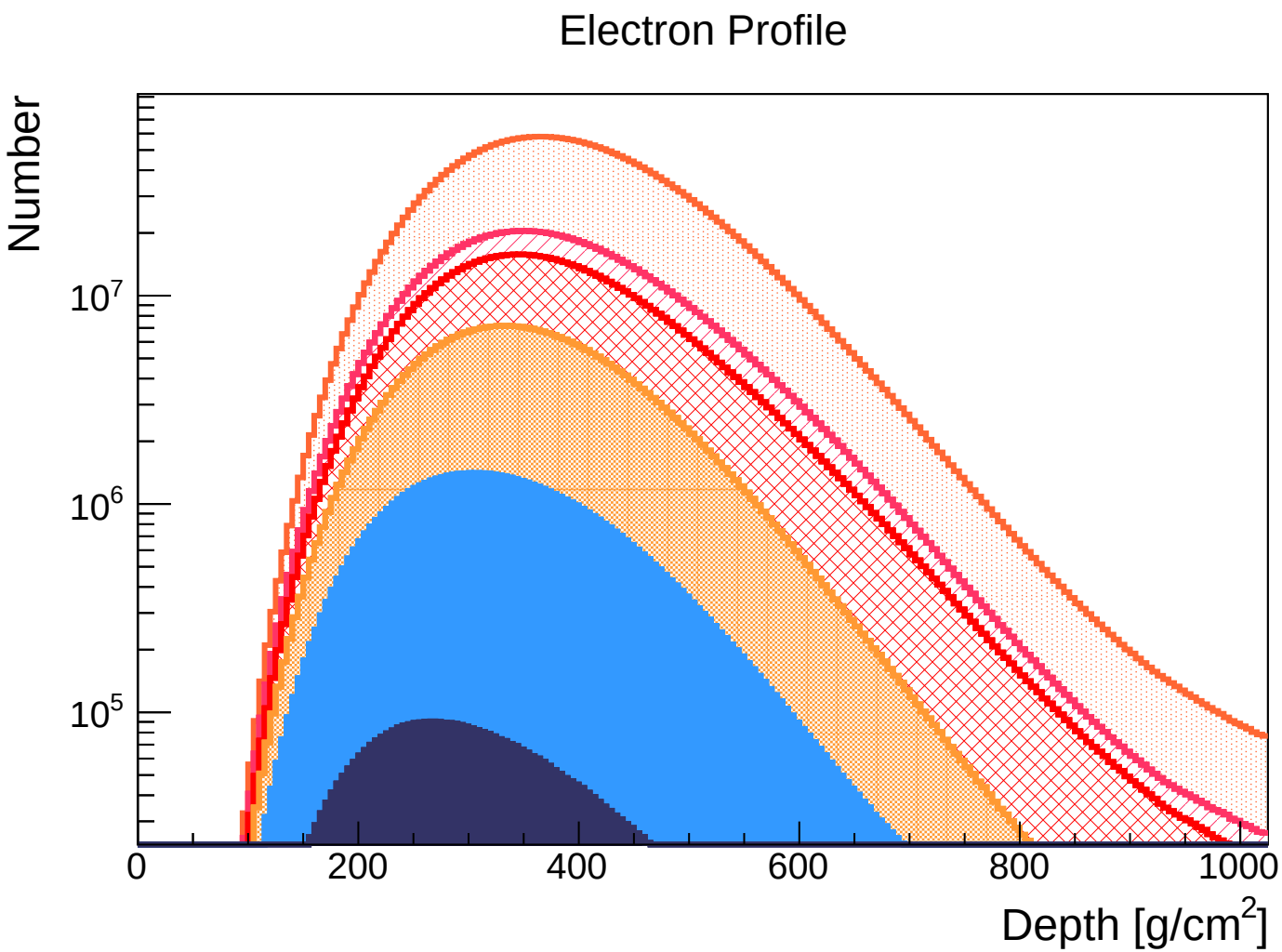


Lateral Particle Density on Ground Level



- Air shower models so far only tuned to about 10 % !
- Forward detectors are crucial.

Longitudinal Shower Development



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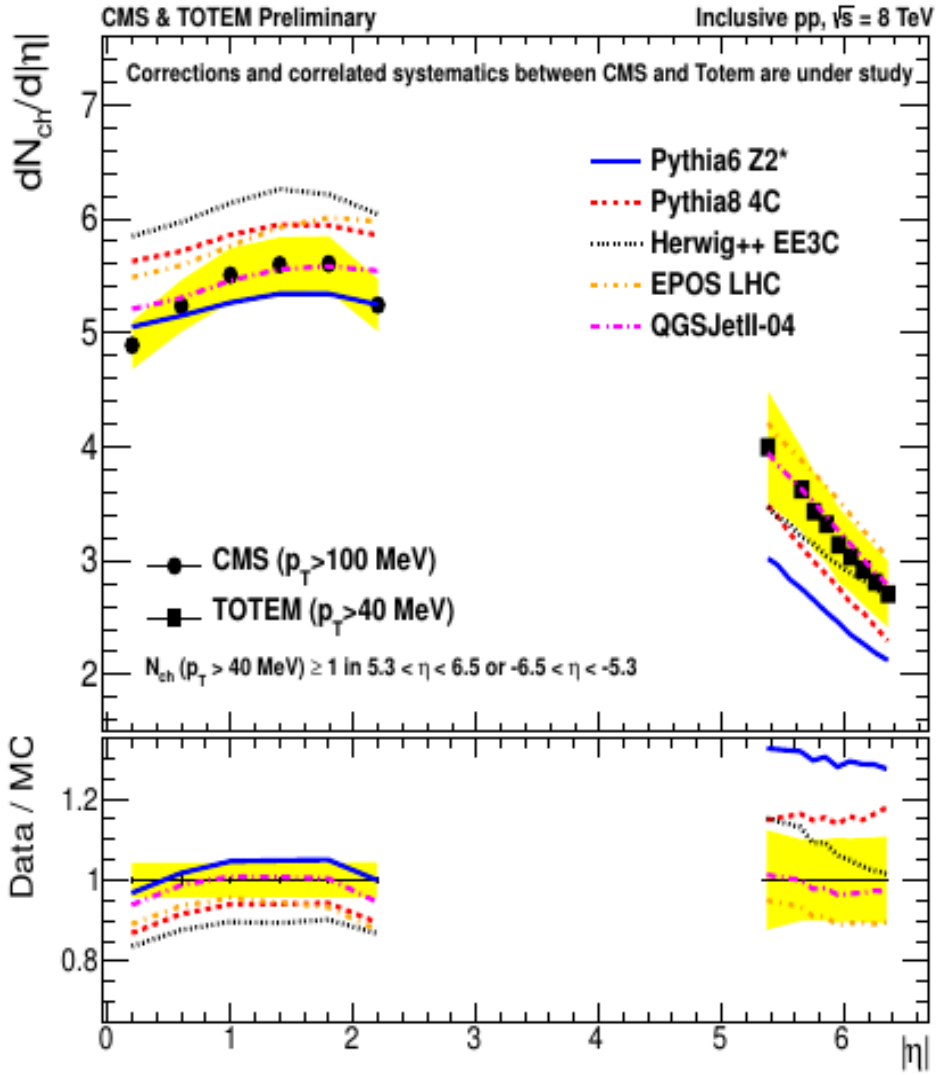
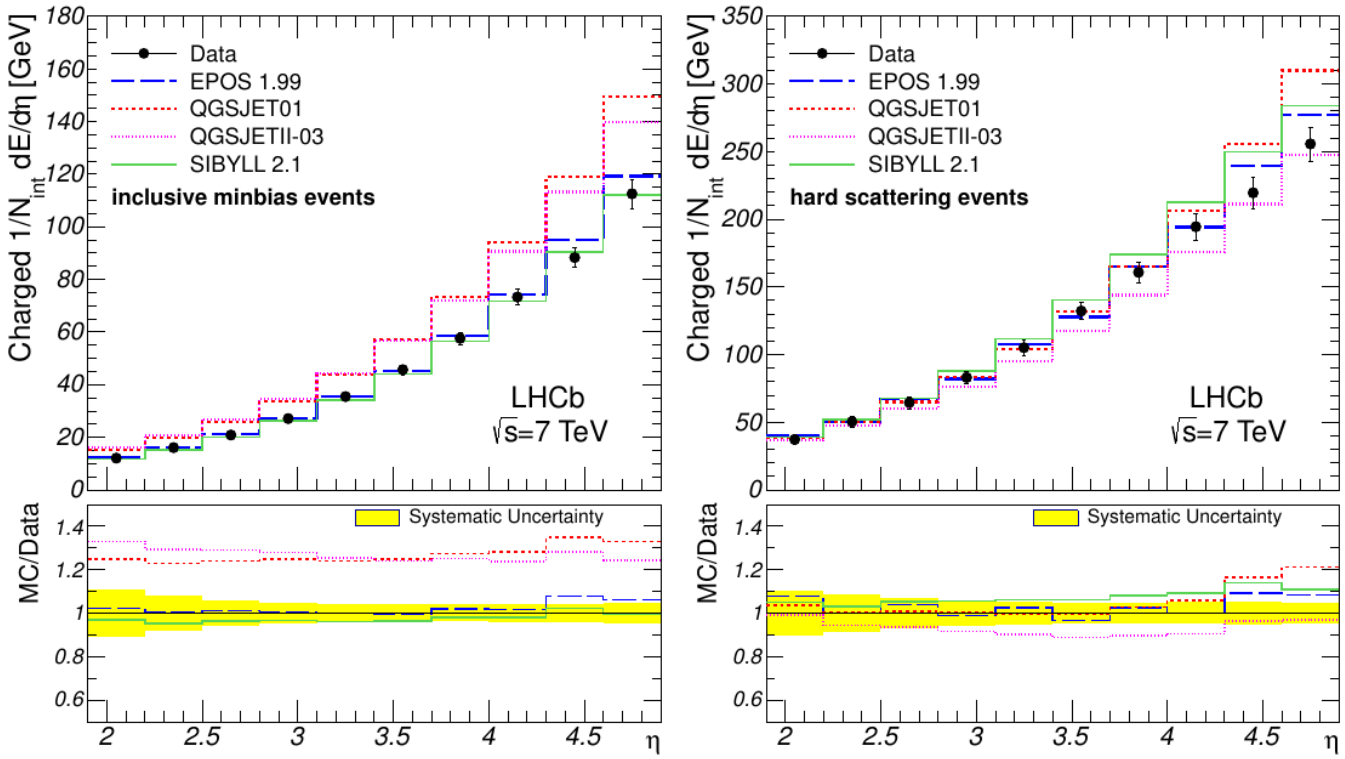
CMS+TOTEM forward multiplicities



Forward charged multiplicities: *Europhys.Lett. 98 (2012) 31002*

Cosmic Ray Models and forward energy: LHCb

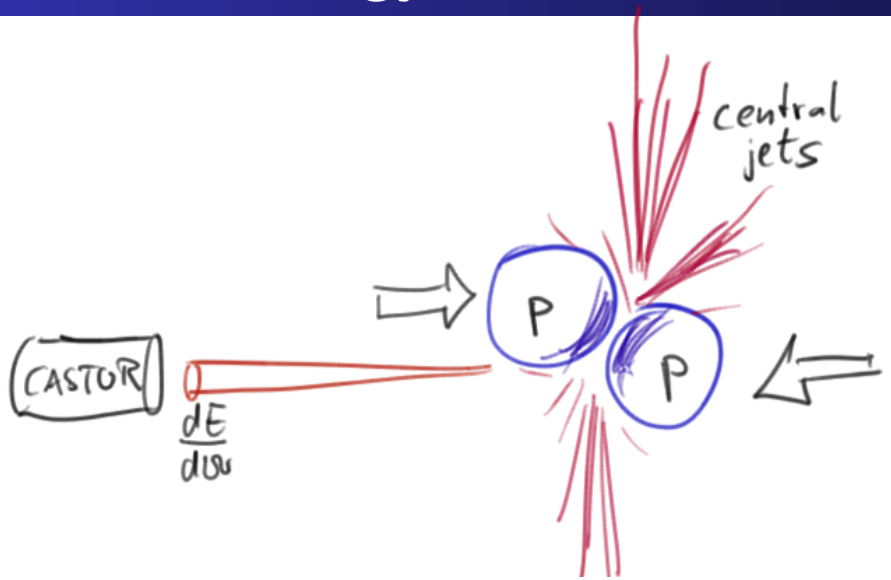


Eur.Phys.J. C73 (2013) 2421

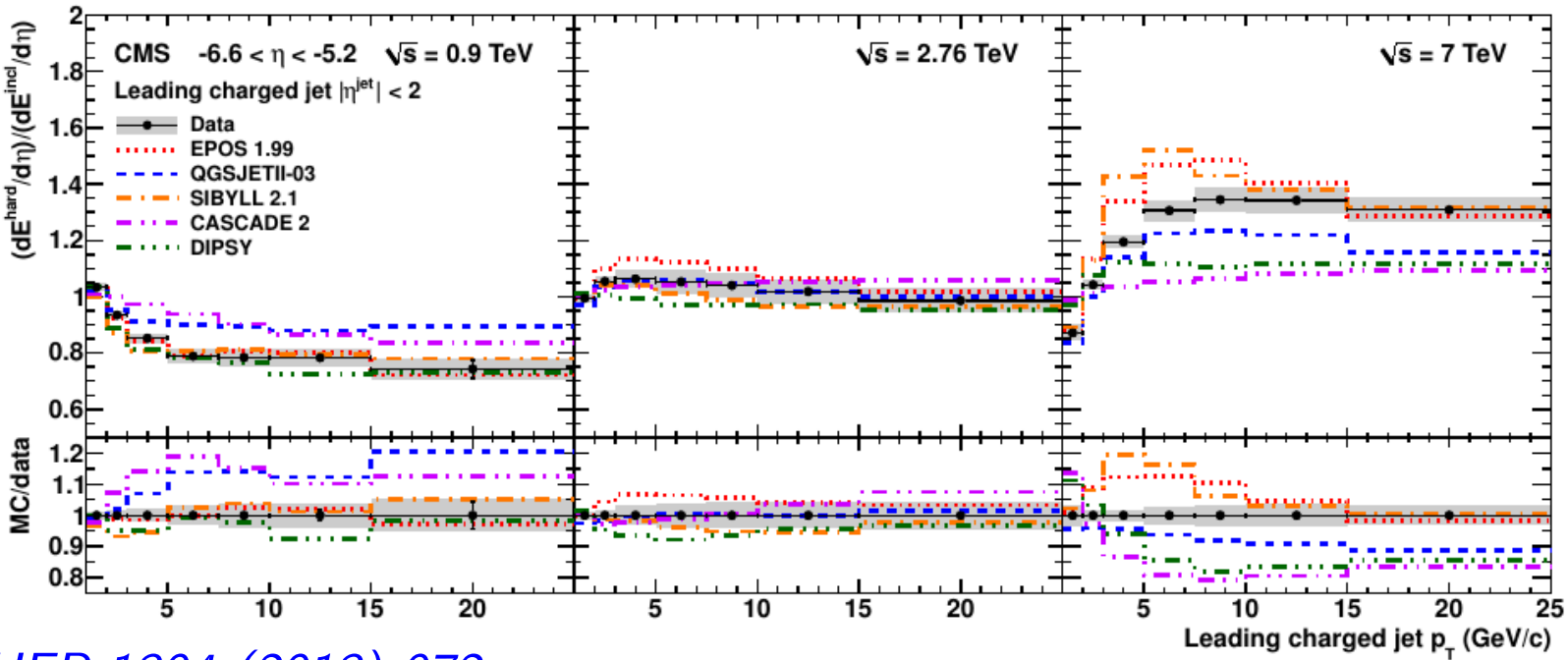
Comparison on event generator level:

- Forward energy flow
- SIBYLL 2.1 is excellent, but none of the models is perfect

Forward Energy as a Function of Central Activity

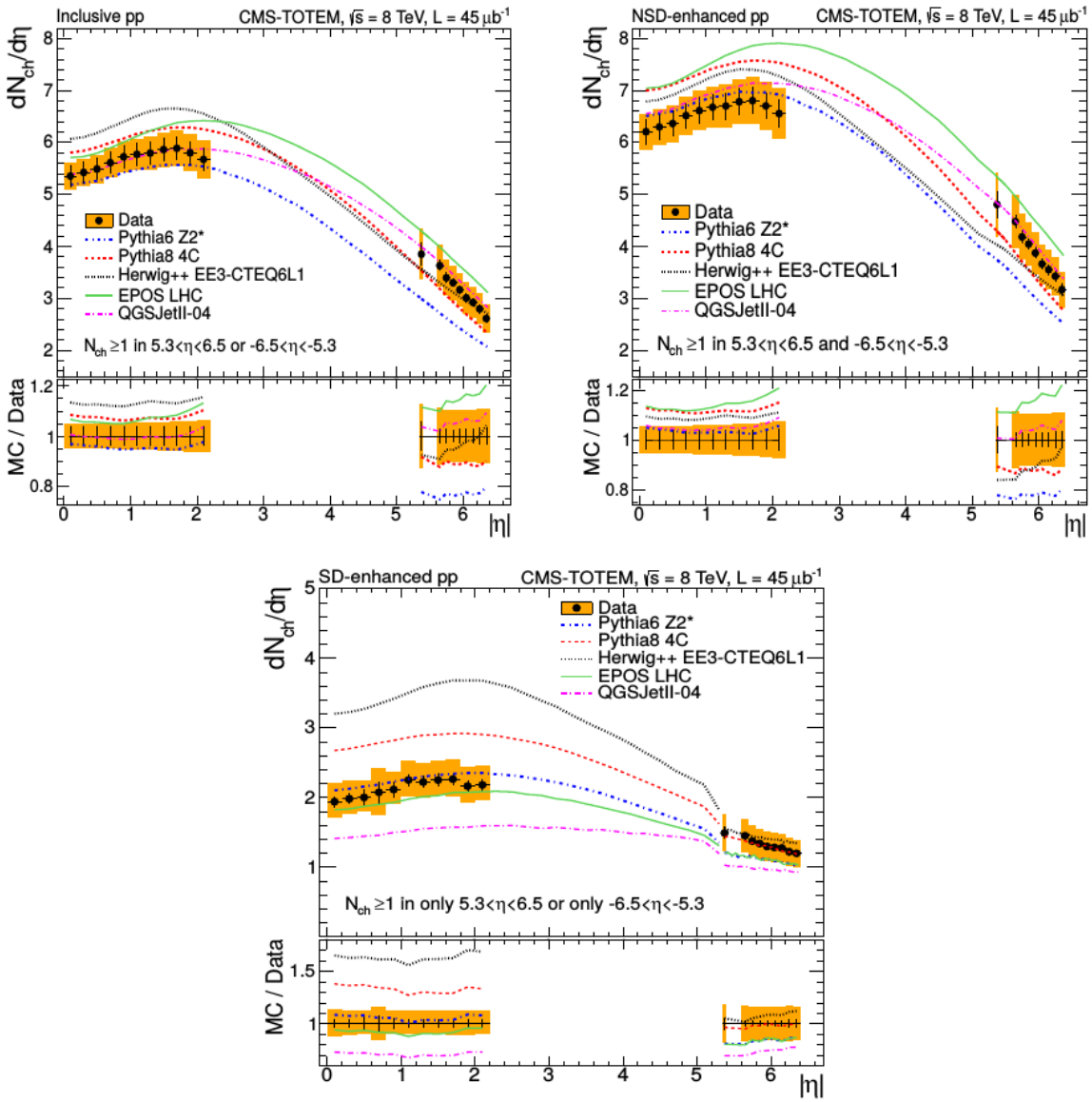


- **Forward energy** ∼ Remnant fragmentation
- **Central jets** ∼ String fragmentation
- "Underlying-Event" study in very forward direction



JHEP 1304 (2013) 072

CMS + TOTEM Combined Multiplicity Data (pp, 8 TeV)



The European Physical Journal C, Oct 2014, 74:3053

CMS Minijet Measurements (pp, 8 TeV)

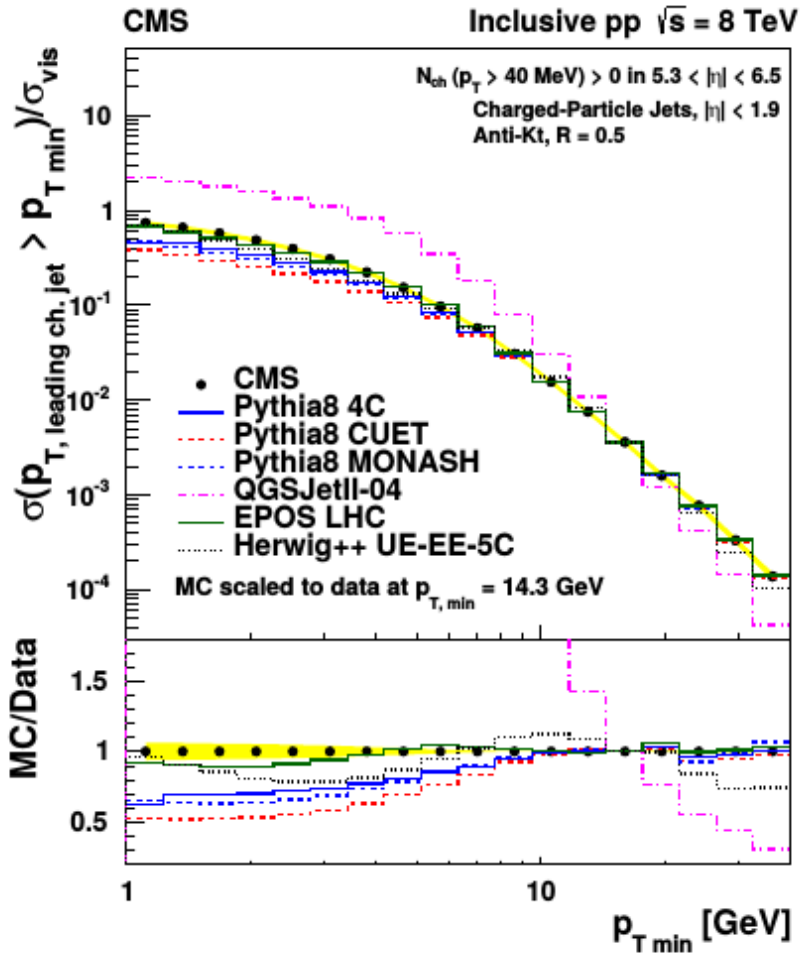
$$\sigma_{QCD}(s, p_{T,min}) = \int_{p_{T,min}}^{\sqrt{s}/2} dp_T \int_{4p_T^2/s}^{1} dx_1 \int_{4p_T^2/(x_1 s)}^{1} dx_2 \sum_{ijkl} f_{i,A}(x_1, p_T^2) f_{j,B}(x_2, p_T^2) \frac{d\hat{\sigma}_{ij}^{kl}(\hat{s})}{dp_T}$$

p_T - cut-off

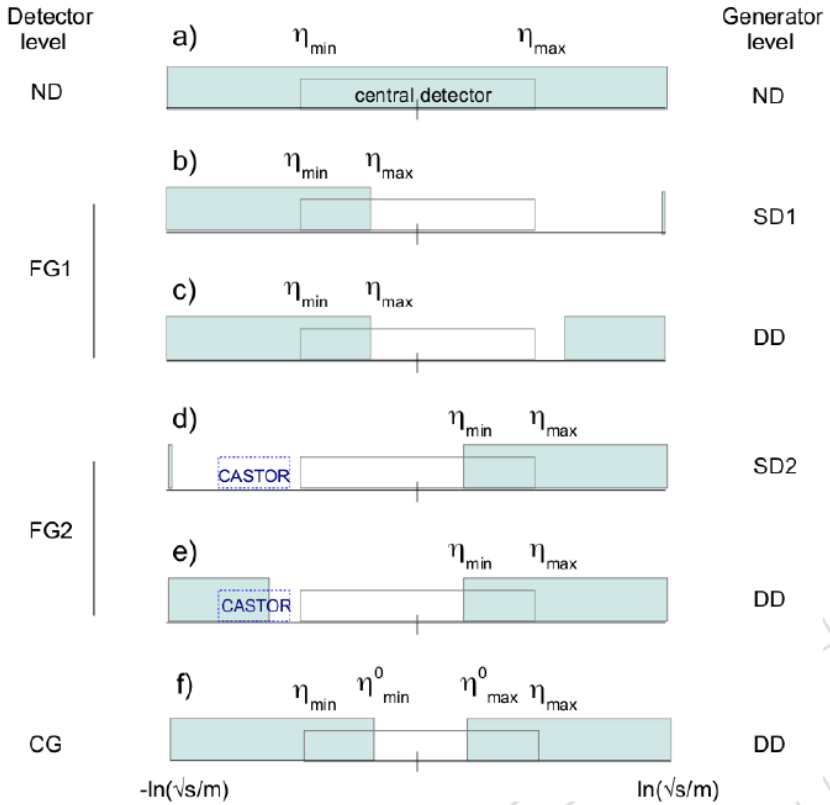
Parton distribution functions, PDFs

Minijet cross section

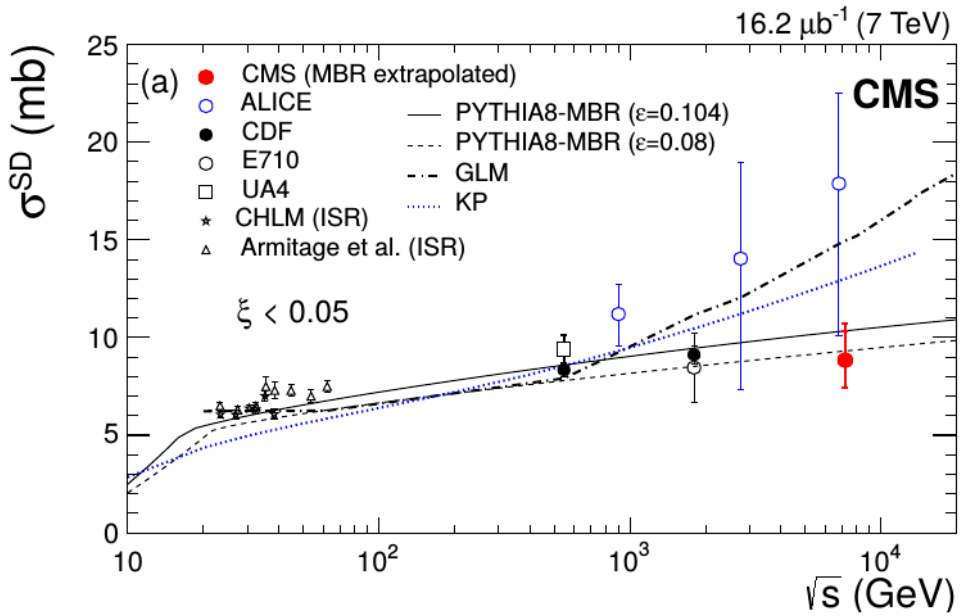
- Hadronization in string fragmentation, minijet production
- p_T threshold



CMS/CASTOR Low-Mass Single Diffraction (pp, 7 TeV)



(submitted to PRD)



Separation of single- and double-diffraction only possible with CASTOR detector.

Summary