Measurements at LHC an their relevance for air shower physics

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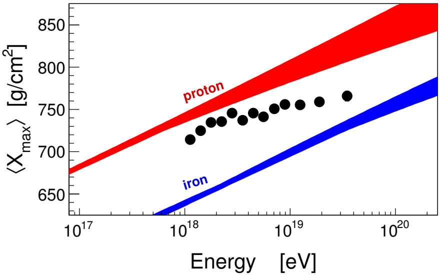
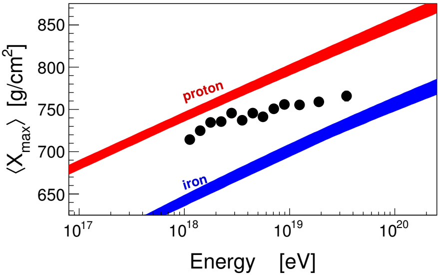
EPOS 1.99 → **EPOS LHC**
QGSJetII.3 → **QGSJetII.4**



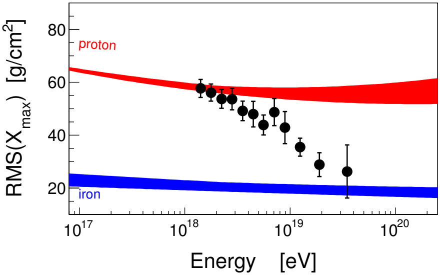


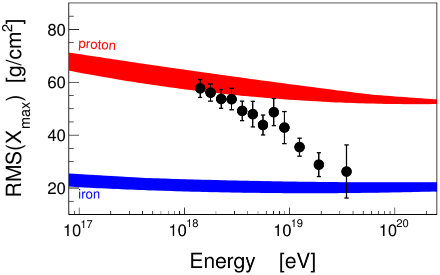
Tuning impact:

- Obvious apparent improved model predictions
- But is this really a quantitative indication of a better understanding?

Air Shower Fluctuations

EPOS 1.99	→	**EPOS LHC**
QGSJetII.3	→	**QGSJetII.4**

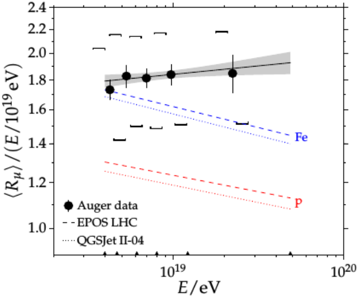


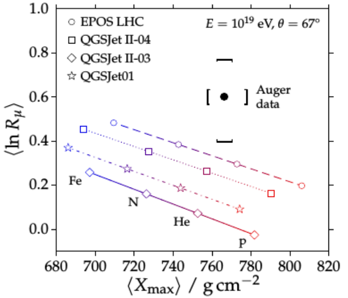


Caveats:

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

Muon Content at Ground Level





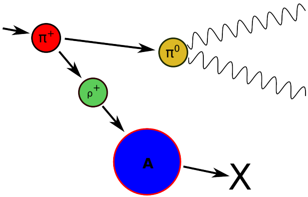
Auger, arXiv-1408.1421 [atro-ph]

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

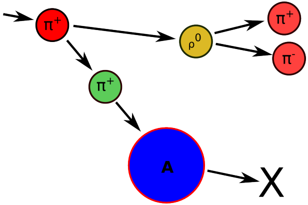
→ Interaction physics in air shower models still not accurate

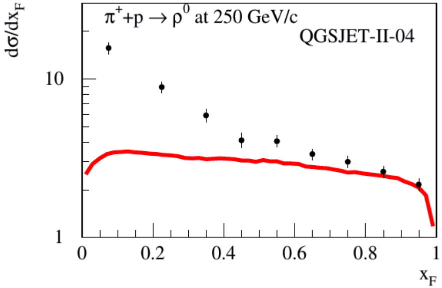
Forward ρ^0 Production, QGSJetII.3→QGSJetII.4

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



versus





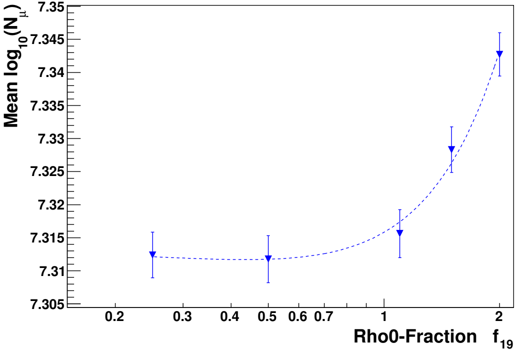
S. Ostapchenko, ISVHECRI 2012

Impact on Muons in Air Showers

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

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

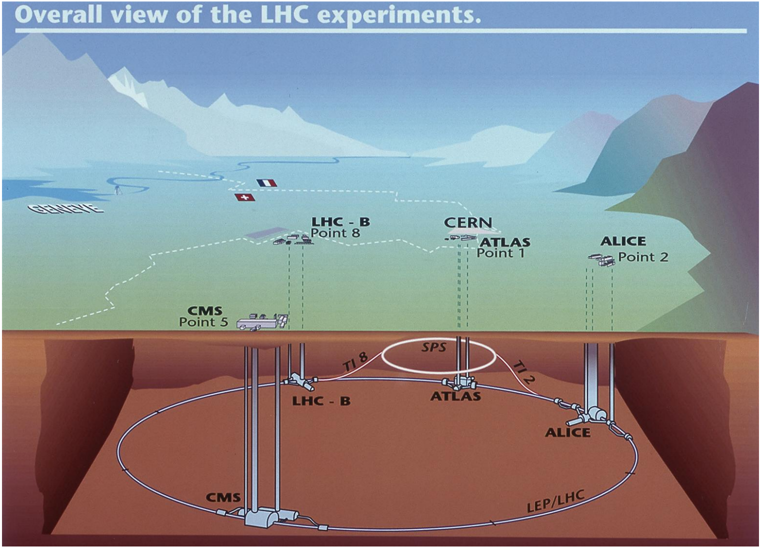
(f19 is the scaling factor for ratio at $10^{19}\,eV$, logarithmic energy dependence)



Ulrich, Engel, Baus, ISVHECRI 2014

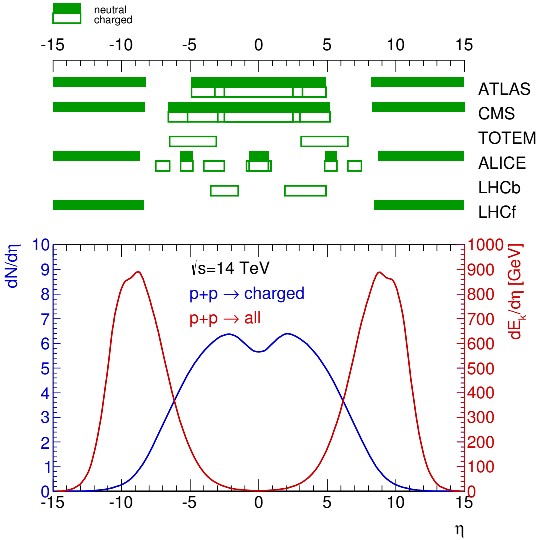
(Similar observation for baryon production in models)

Large Hadron Collider and Experiments



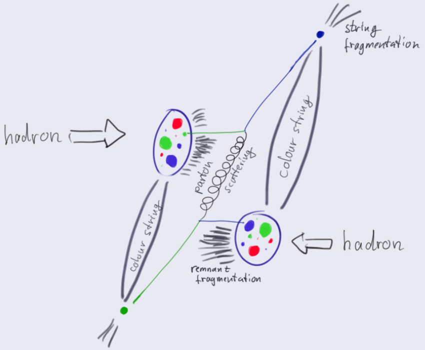
Angular acceptance of LHC experiments

Definition of *pseudorapidity*: $\eta = -0.5 \log \tan \theta/2$

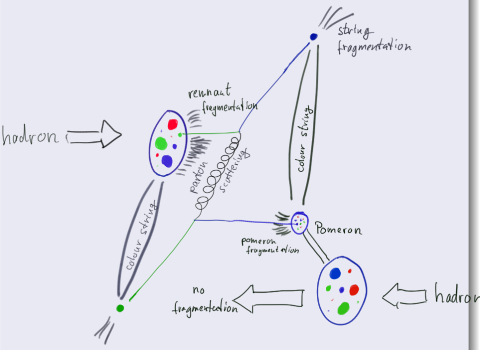


Hadronic Multi-Particle Production

Inelastic Collision



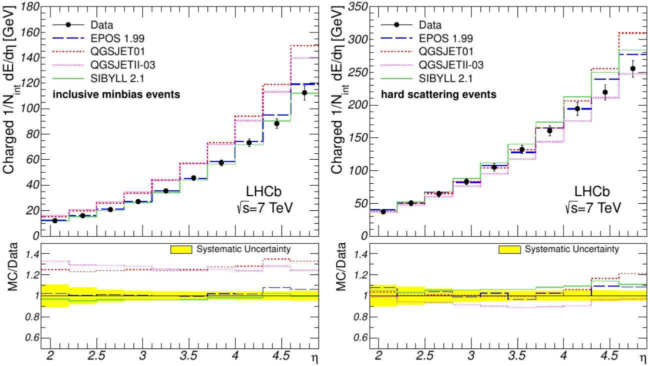
Diffraction



- Particle production via QCD confinement
- Many different model assumptions/parameters needed
- No calculations from first principles

$\Rightarrow$ **Precise measurements are of paramount importance**

Cosmic Ray Models and forward energy: LHCb

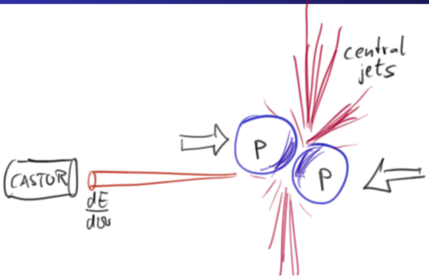


Eur.Phys.J. C73 (2013) 2421

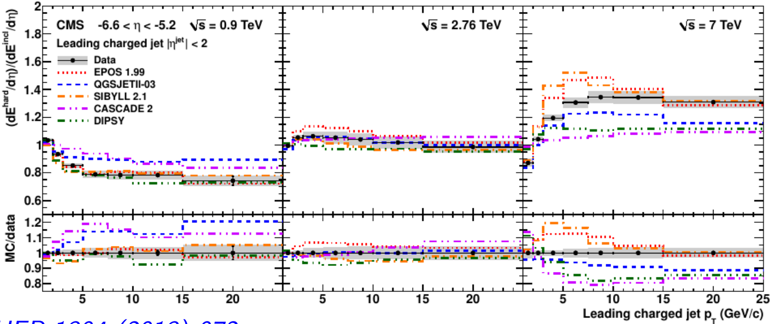
Comparison on event generator level:

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

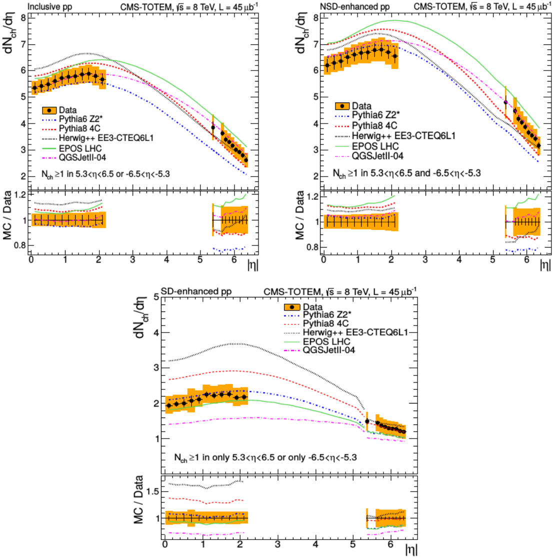
Forward Energy as a Function of Central Activity



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



JHEP 1304 (2013) 072



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

CMS Minijet Measurements (pp, 8 TeV)

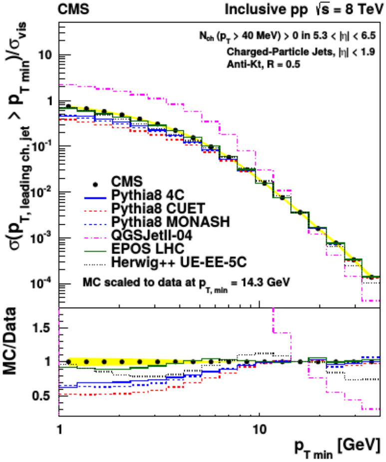
$$\sigma_{QCD}(s, p_{T,min}) = \int_{p_{T,min}}^{\sqrt{s}/2} dp_T \int_{4p_T^2/s}^{1} dx_1 \int_{4p_T^2/(x_1 s)}^{1} dx_2 \sum_{ijkl} f_{i,A}(x_1, p_T^2) f_{j,B}(x_2, p_T^2) \frac{d\hat{\sigma}_{ij}^{kl}(\hat{s})}{dp_T}$$

p_T-cutoff

Parton distribution functions, PDFs

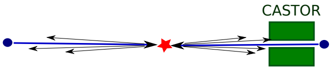
Minijet cross section

- Hadronization in string fragmentation, minijet production
- p_{T} threshold

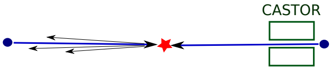


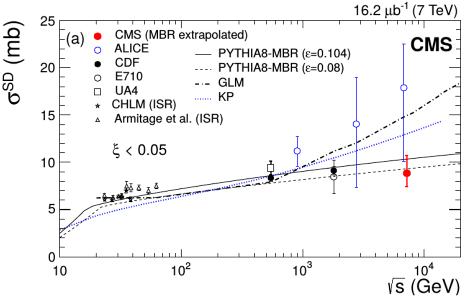
CMS/CASTOR Low-Mass Single Diffraction (pp, 7 TeV)

Double Diffraction



Single Diffraction

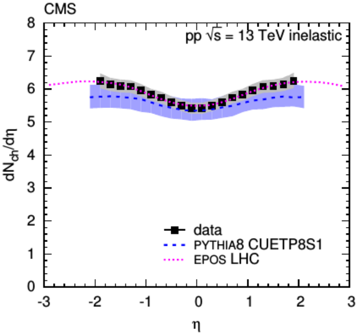


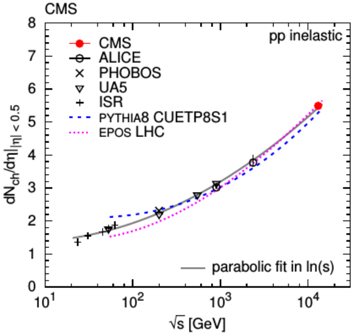


(submitted to PRD)

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

$dN_{ch,had}/d\eta$ at 13 TeV

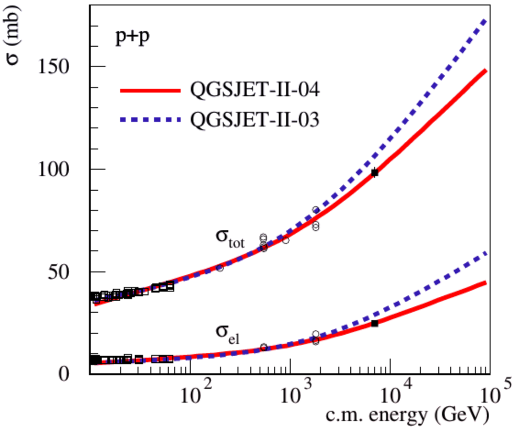




arXiv:1507.05915, submitted to PLB

- First LHC paper at 13 TeV (without CMS magnet→no p_T-cutoff)
- EPOS-LHC makes an excellent first impression

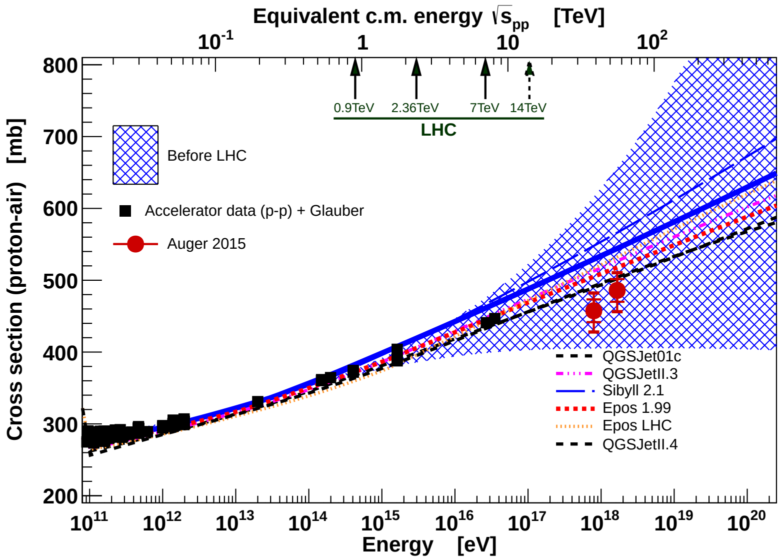
Cross section data



S. Ostapchenko, ISVHECRI 2014

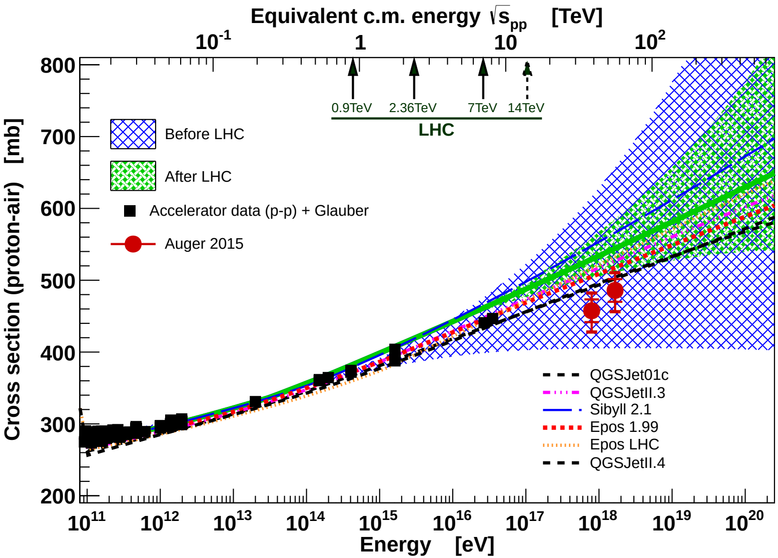
Proton-Air cross section is one of the most important quantities for air shower modeling

Proton-Air cross section, with Tevatron data



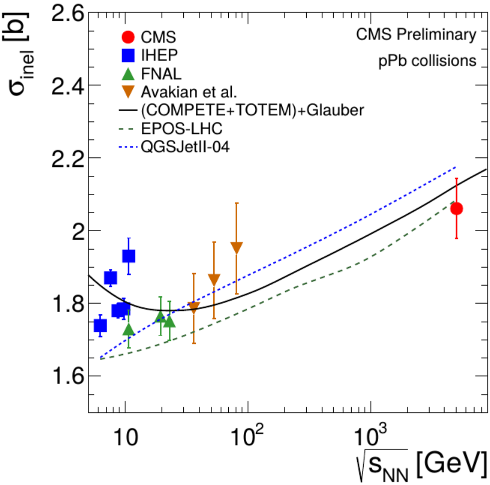
compare to Nucl.Phys.Proc.Suppl. 196 (2009) 335

Proton-Air cross section, with LHC data



$\Rightarrow$ Sign of a clear relevant improvement

Inelastic Proton-Lead Cross Section at 5.02 TeV

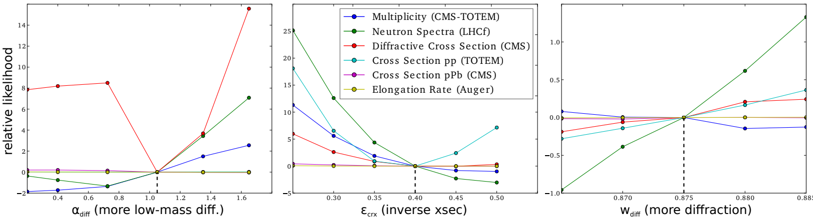


arXiv:1509.03893, submitted to PLB

- **Direct test of Glauber model (and extensions) at LHC**

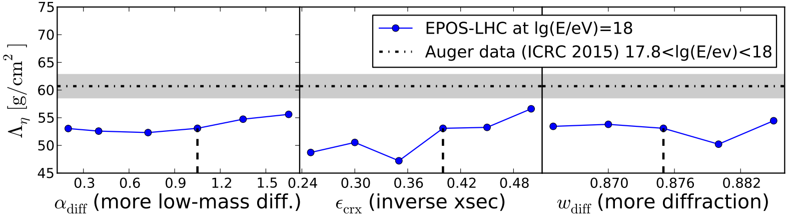
- Global likelihood: $\mathcal{L}_{\rm global} = \mathcal{L}_{\rm Accelerators} \cdot \mathcal{L}_{\rm CR}$
- Exploit sensitivity of various data on model features: *marginalize* model differences

→ New analysis framework to perform automated large scale simulation productions in many dimensions of accelerator as well as cosmic ray observables



C. Baus et al., ICRC 2015

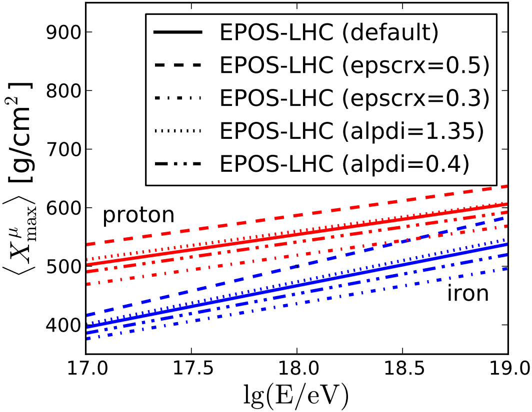
Example: Proton-air cross section, $X_{\rm max}$-slope Λ_η



- EPOS p-air cross section prediction is too large
- Most sensitive parameter: ϵ_{crx}
- Some limited effect also from other studied parameters

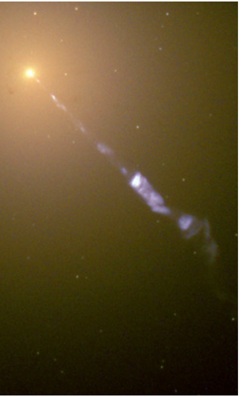
- Caveat: statistics not large enough
- Caveat: only EPOS so far
- Caveat: no systematic study of all relevant EPOS parameter-space

Example: Muon production (MPD)



- Still difficult to compare directly to data
- Very sensitive to model parameters

Summary



⇒ **LHC data extremely important**

⇒ **Not yet derived maximum information gain**

⇒ **Global approach could provide ultimate insight**