Karlsruhe Institute of Technology

Importance of dedicated LHC measurements for cosmic ray physics

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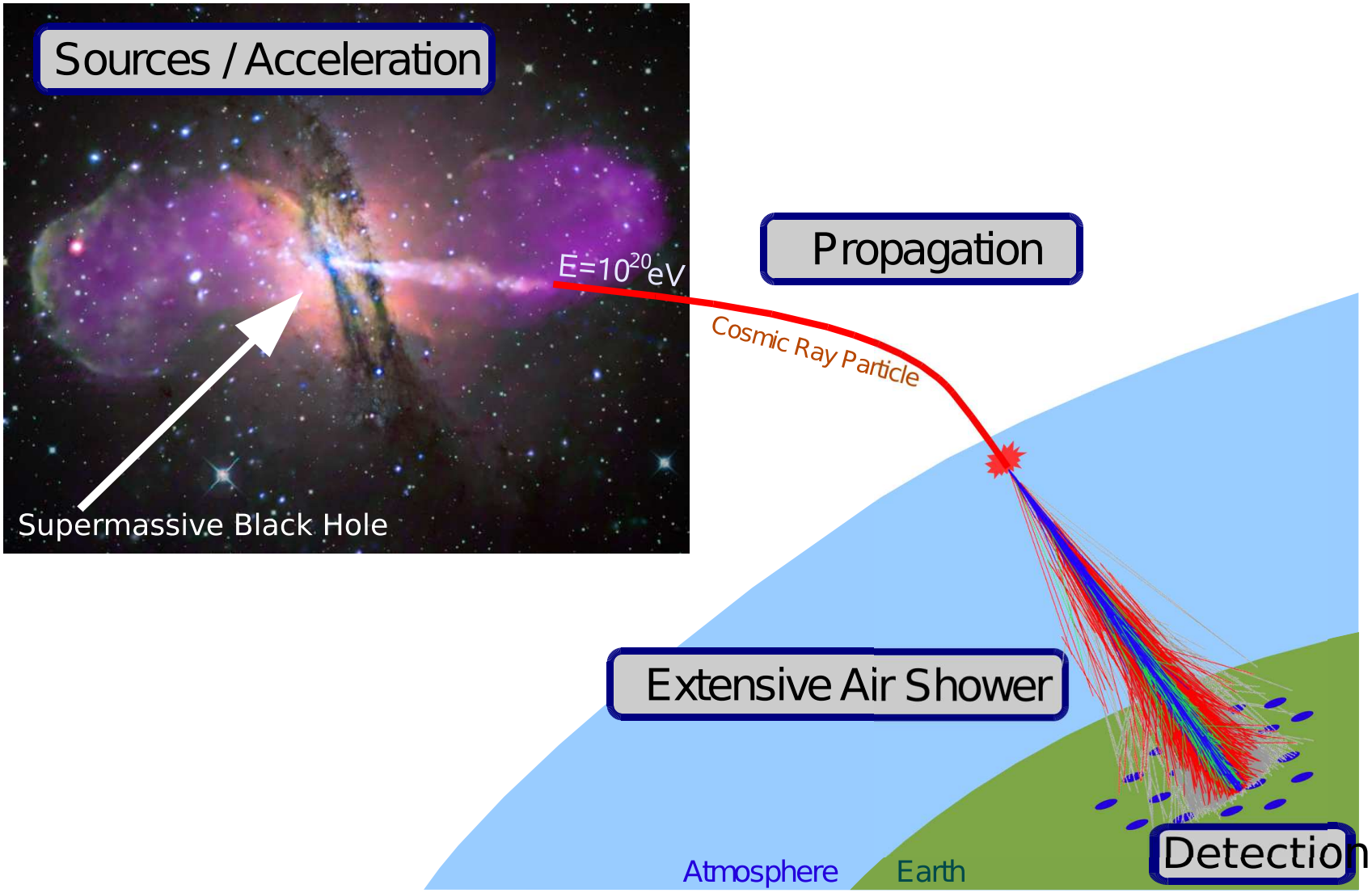
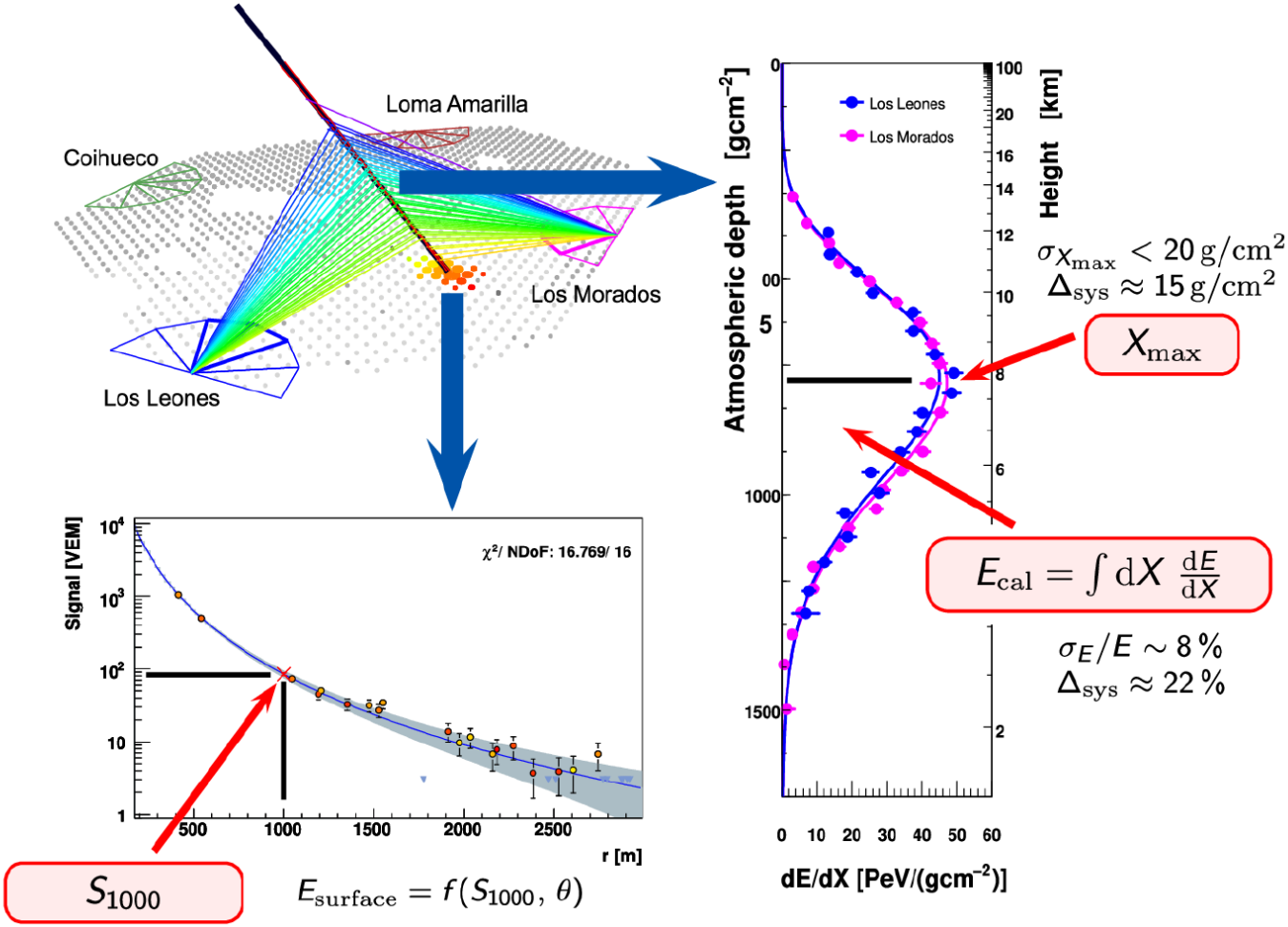
30. October 2019, Budapest

Cosmic rays at Earth



Messengers from violent places in our universe. **What are they? Where do they come from? How do they interact?**

Introduction of observables



The atmosphere as calorimeter

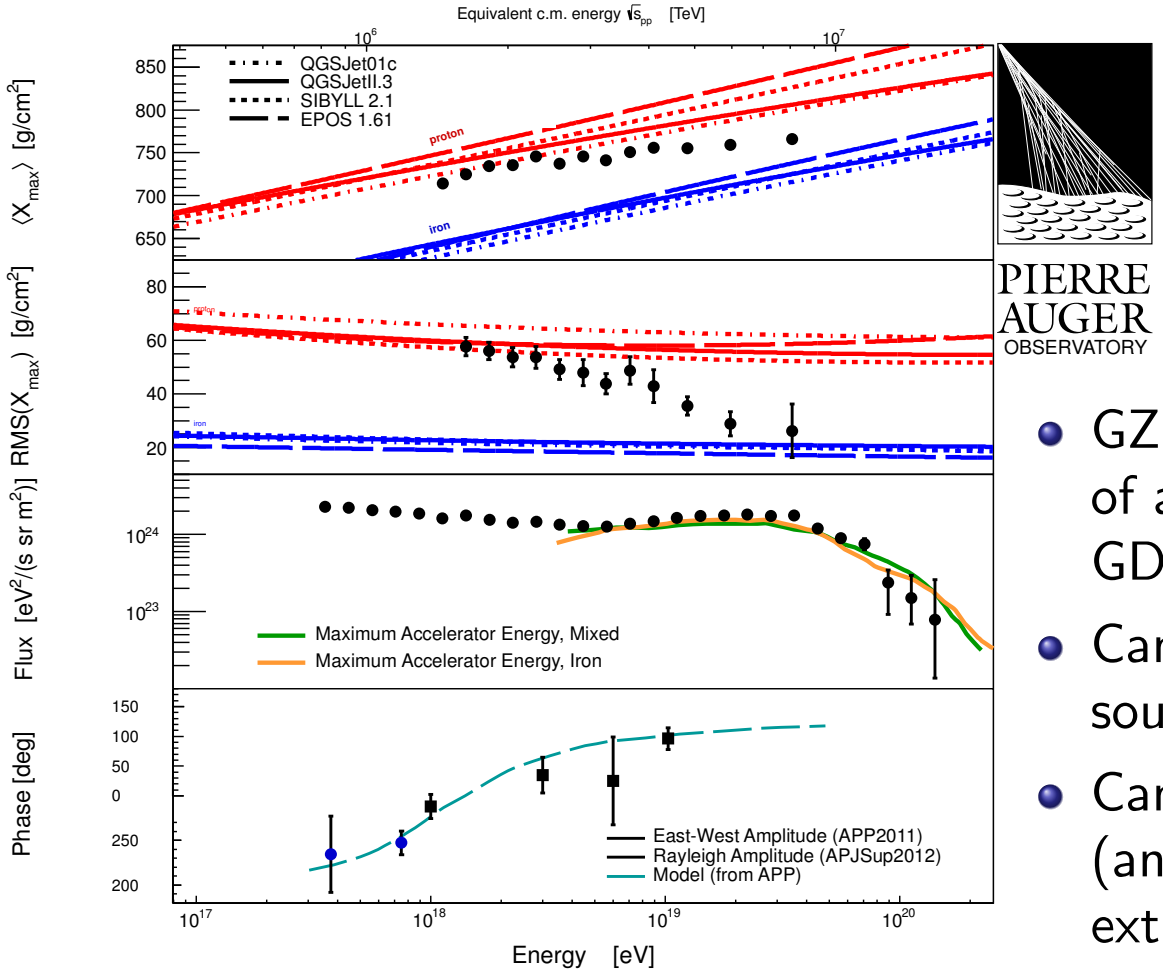
Telescopes measure dE/dX and timing.

Surface detectors measure particle fluxes and timing.

$$N_\mu \propto \left(\frac{E}{A}\right)^\beta$$
$$X_{\max} \propto \ln\left(\frac{E}{A}\right)$$
$$E_0 = E_{\mathrm{cal}} + E_{\mathrm{invisible}}$$
$$E_0 \propto S_{1000}$$

Ultra-high energy cosmic rays: experimental overview

What is the nature and the sources of the highest energy particles in the universe?



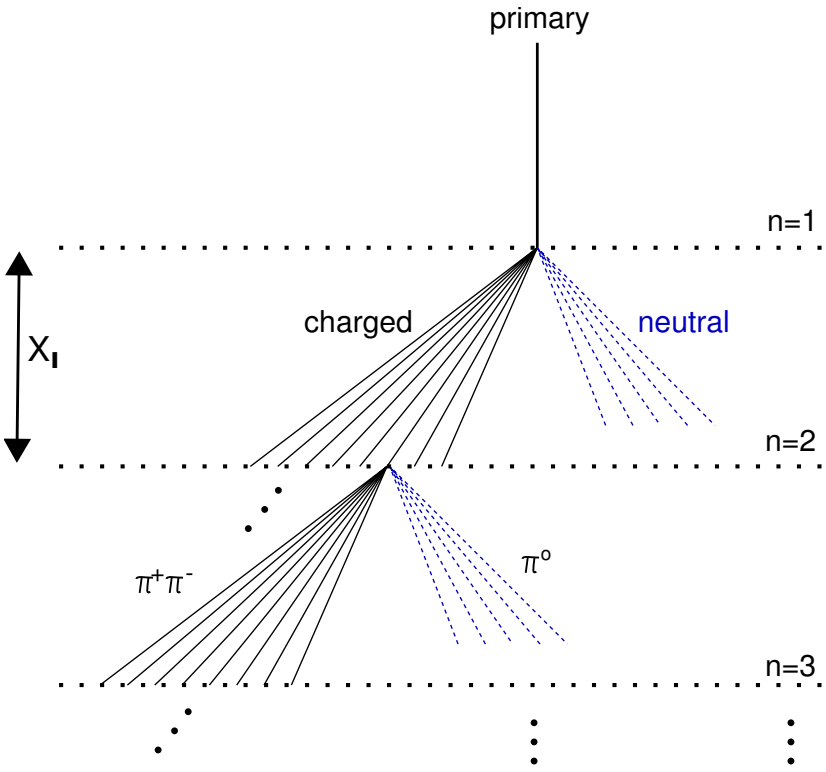
PIERRE AUGER OBSERVATORY

- GZK cutoff? Maximum energy of accelerators? GDR/dissociation?
- Can we find individual (point) sources?
- Can we identify a transition (anisotropy) from galactic to extragalactic?

→ **Mass composition main challenge to resolve questions!**

Air shower cascades

Extended Heitler Model:



Shower maximum

$$X_{\max} \approx \lambda_{\mathrm{I}} + X_0 \ln \frac{E_0}{N_{\mathrm{mult}}\, E_{\mathrm{crit}}^{\mathrm{e.m.}}}$$

Muon number at observation level

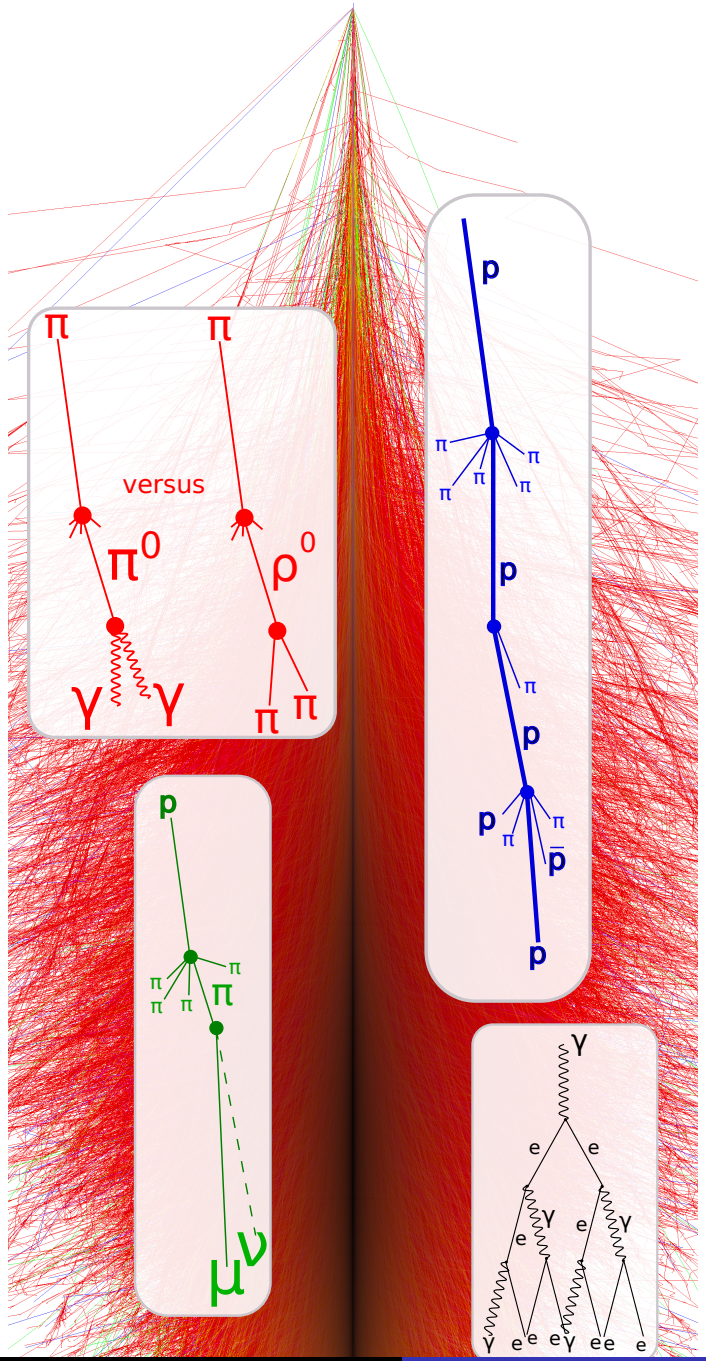
$$N_\mu = N_{\pi^\pm} = \left(\frac{E_0}{E_{\mathrm{crit}}^{\mathrm{I}}}\right)^\beta$$

where

$$\beta = \ln\left(\tfrac{2}{3}\, N_{\mathrm{mult}}\right) / \ln\left(N_{\mathrm{mult}}\right) \approx 0.9$$

(J. Matthews, APP 22 (2005) 387)

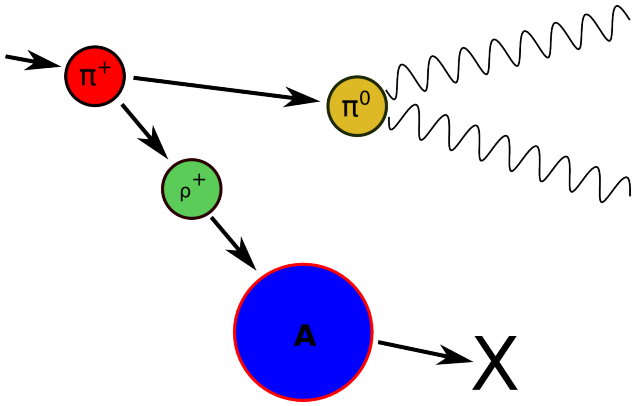
Ultra-high energy cosmic ray extensive air showers



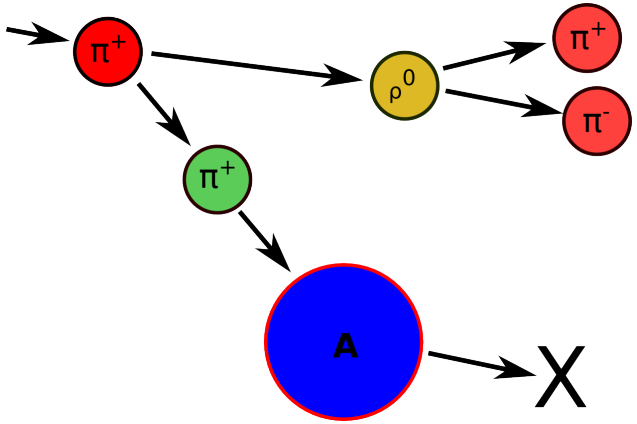
- Huge coupled cascading process
- Conversion of primary energy into
  - Electrons/ photons
  - Muons
  - Low energy hadrons
- Most relevant mass-sensitive observables are:
  - Depth of shower maximum
  - Muon content
- Precise modelling is mandatory for a cosmic ray mass measurement

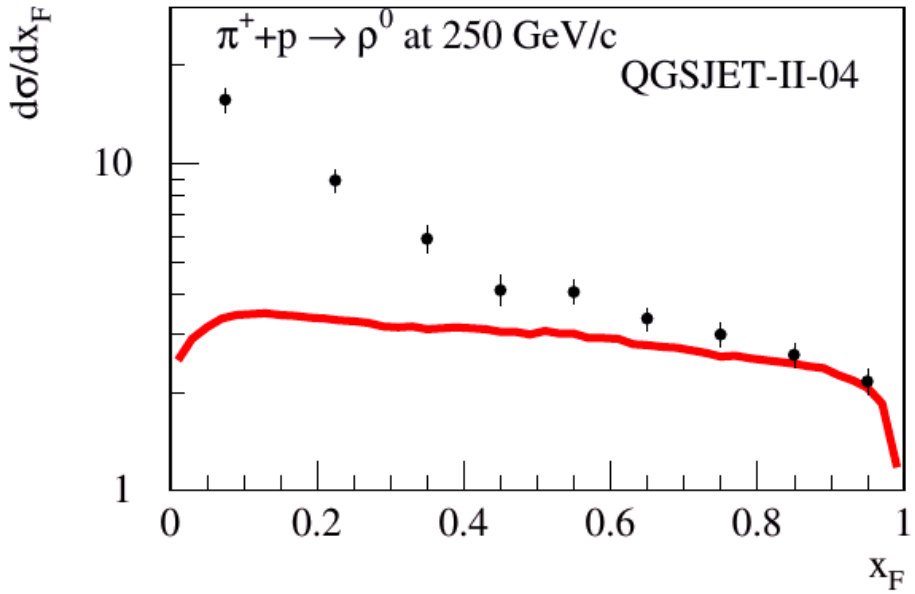
Forward ρ^0 Production, QGSJetII.3→QGSJetII.4

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



versus

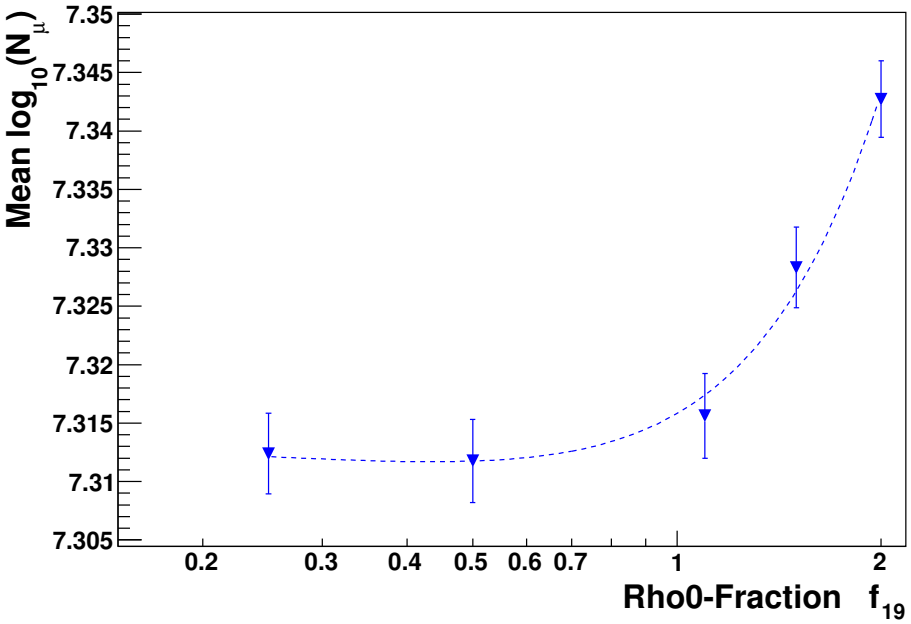




S. Ostapchenko, ISVHECRI 2012

Impact on muons in air showers

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



Ulrich, Engel, Baus, ISVHECRI 2014

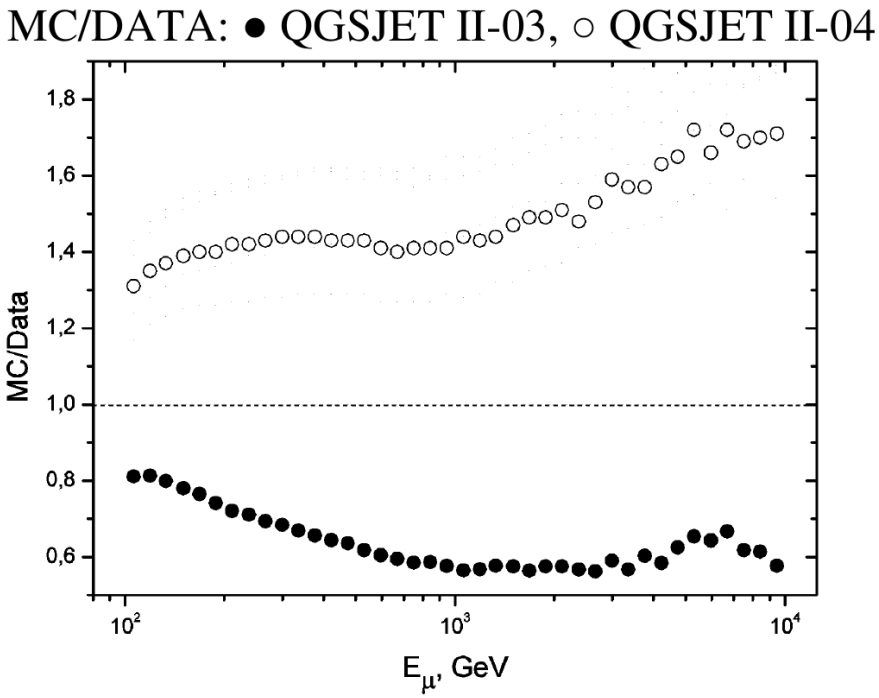
SIBYLL, protons, $10^{19.5}$ eV

Ad-hoc modifications (PRD 83 (2011) 054026): f19 is scaling factor for ρ^0 and baryons at $10^{19}\,eV$:

$$\alpha^{\mathrm{modified}}(\mathrm{E}) = \alpha^{\mathrm{orig}}(\mathrm{E}) \cdot \left(1 + (\mathrm{f}_{19} - 1) \cdot \frac{\lg_{10}(\mathrm{E}/\mathrm{E}_{\mathrm{thr}})}{\lg_{10}(10^{19}\,\mathrm{eV}/\mathrm{E}_{\mathrm{thr}})}\right) \quad \text{with } E_{\mathrm{thr}} = 10^{15}\,eV$$

Forward ρ^0 production, QGSJetII.4

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

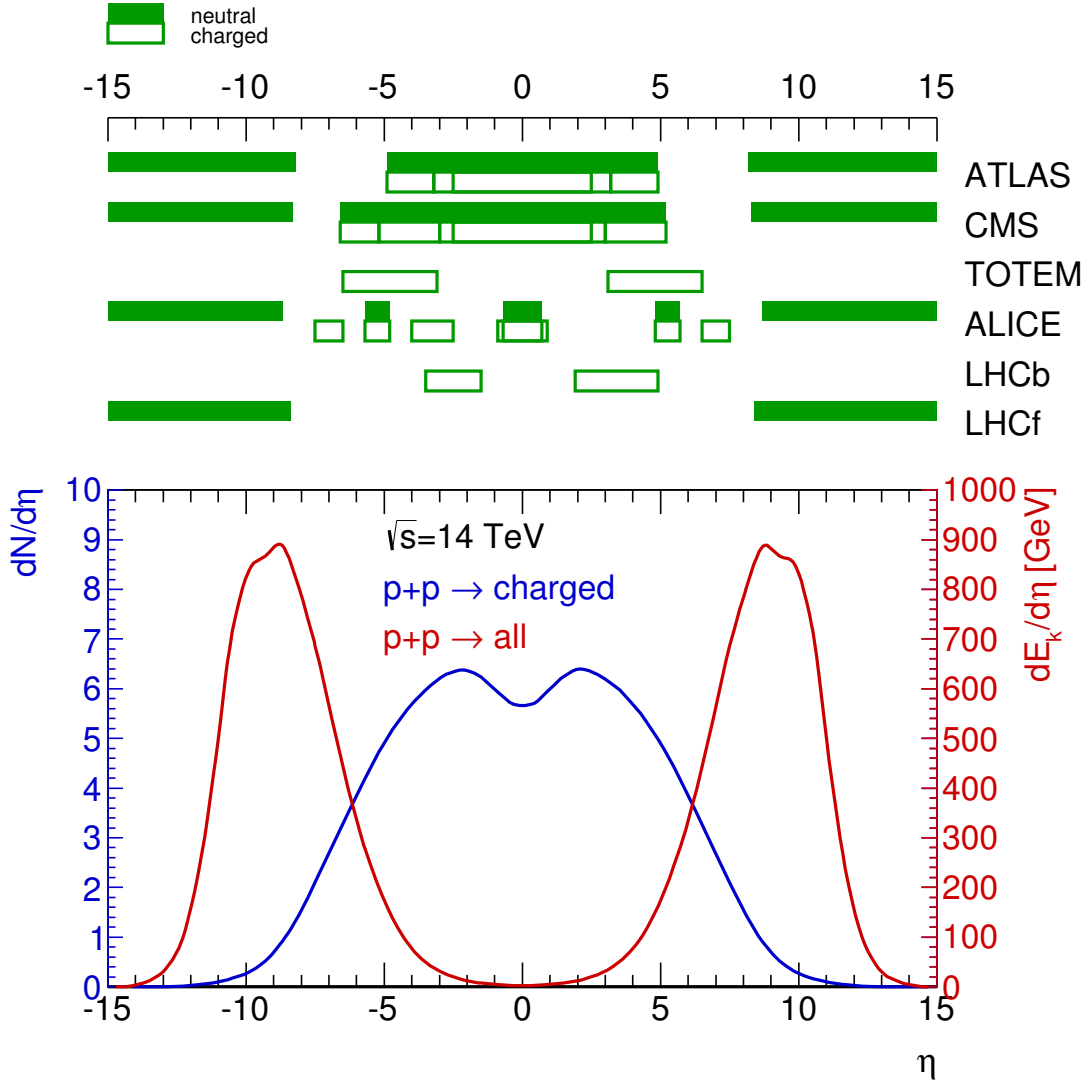


A.V. Lukyashin, ISVHECRI 2014

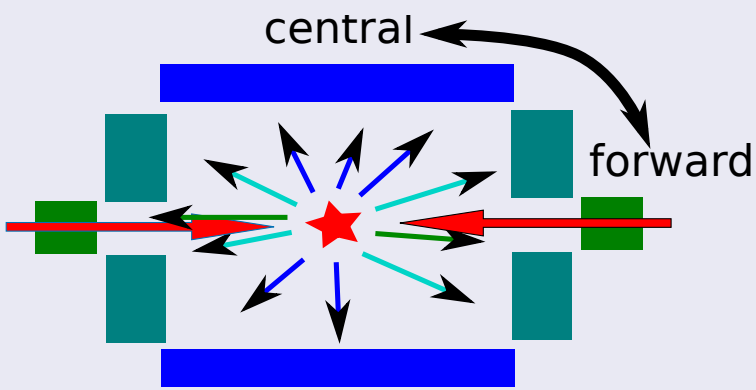
⇒ Too many muons at ∼ TeV
⇒ But: still not enough muons at ∼ GeV

Angular acceptance of LHC experiments

Definition of *pseudorapidity*: $\eta = -\log\tan(\theta/2)$
where θ is the angle wrt. to the beam



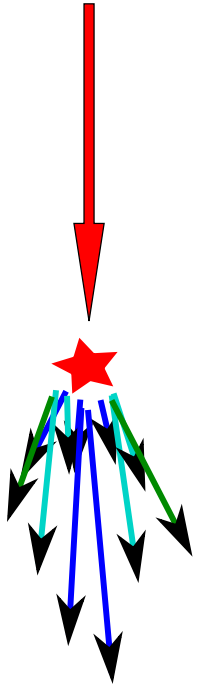
Phase-space coverage at LHC



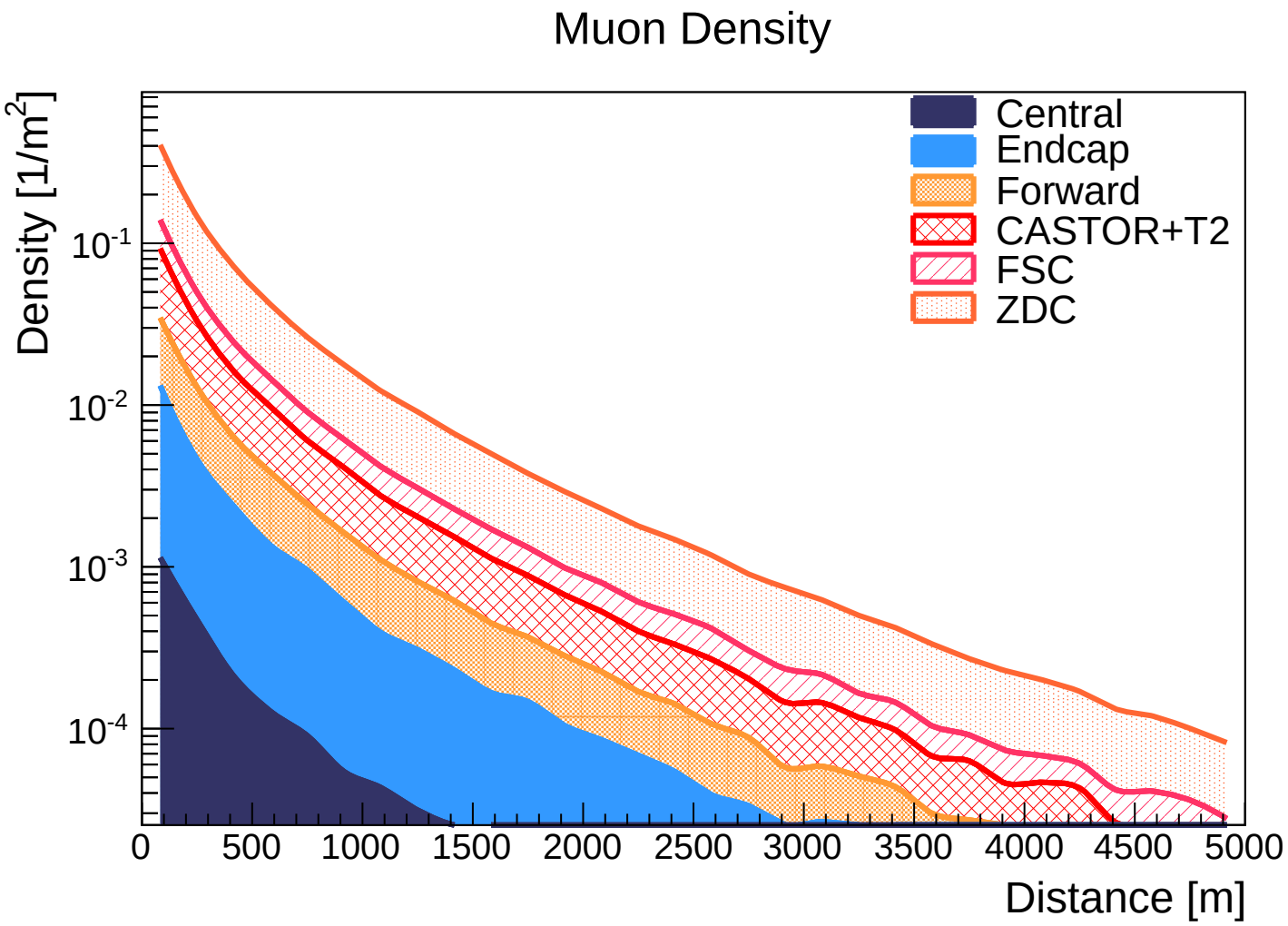
- Central ($|\eta| < 1$)
- Endcap ($1 < |\eta| < 3.5$)
- Forward ($3 < |\eta| < 5$), HF
- CASTOR+T2 ($5 < |\eta| < 6.6$)
- FSC ($6.6 < |\eta| < 8$)
- ZDC ($|\eta| > 8$), LHCf

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

$\rightarrow$ Simulate parts of shower individually.

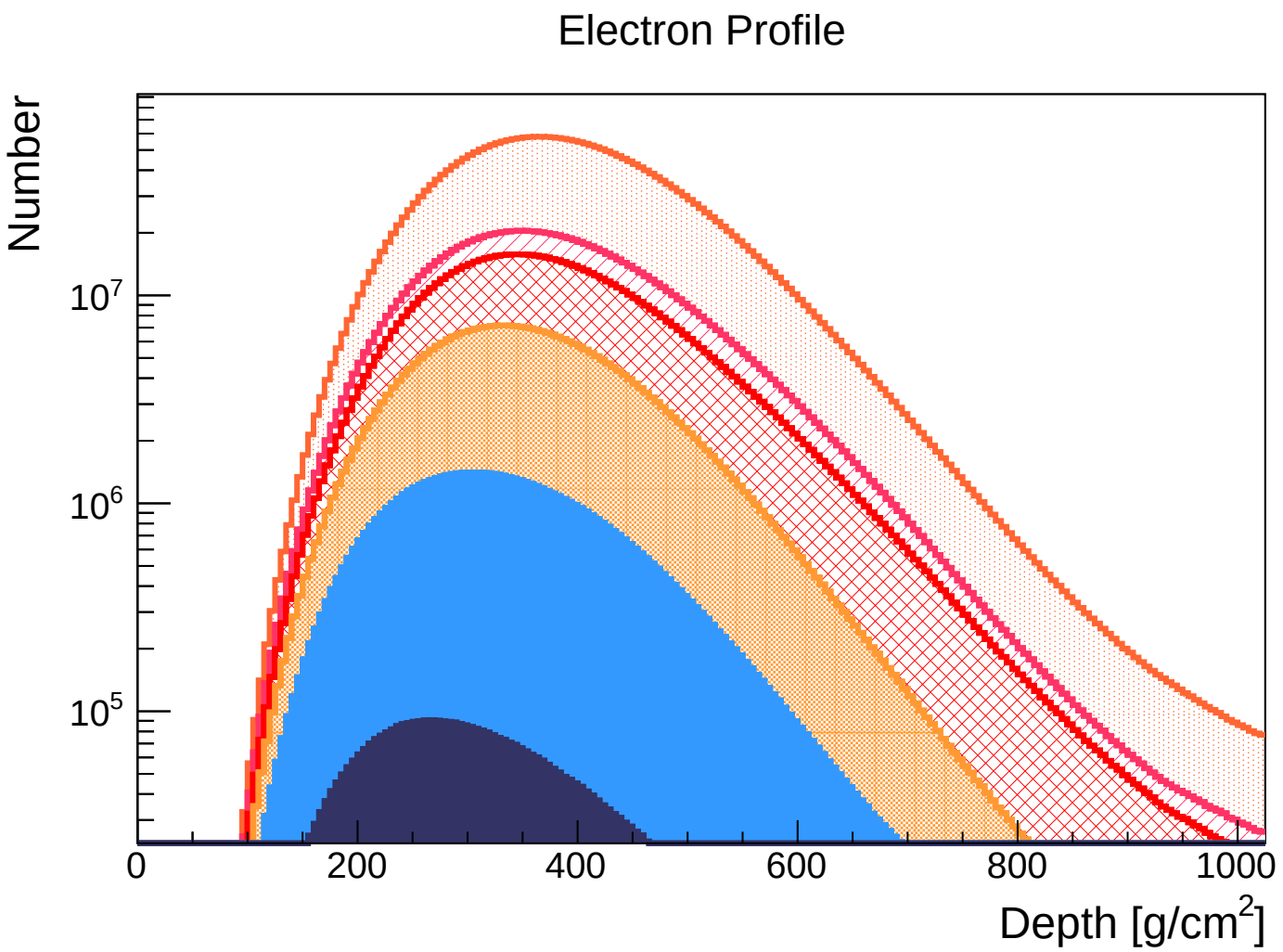


Lateral particle density on ground level



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

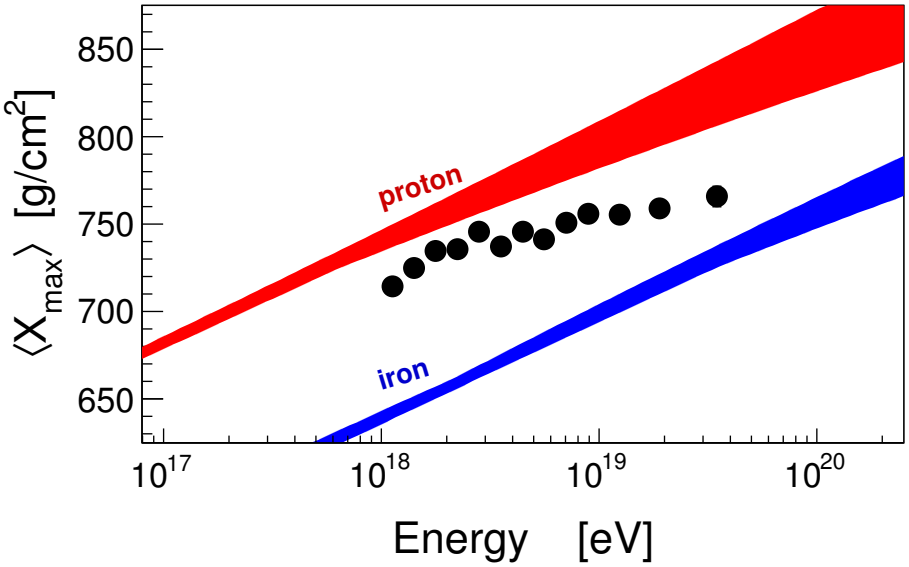
Longitudinal shower development

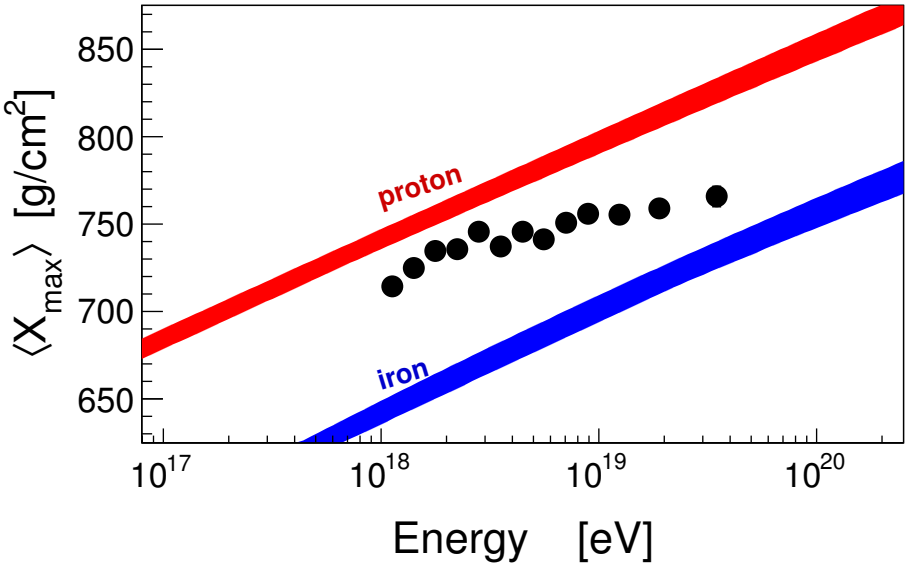


- Air shower models so far only tuned to about 10 % !
- Forward detectors are crucial.

Model tuning to LHC data and $\langle X_{\max} \rangle$ predictions

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

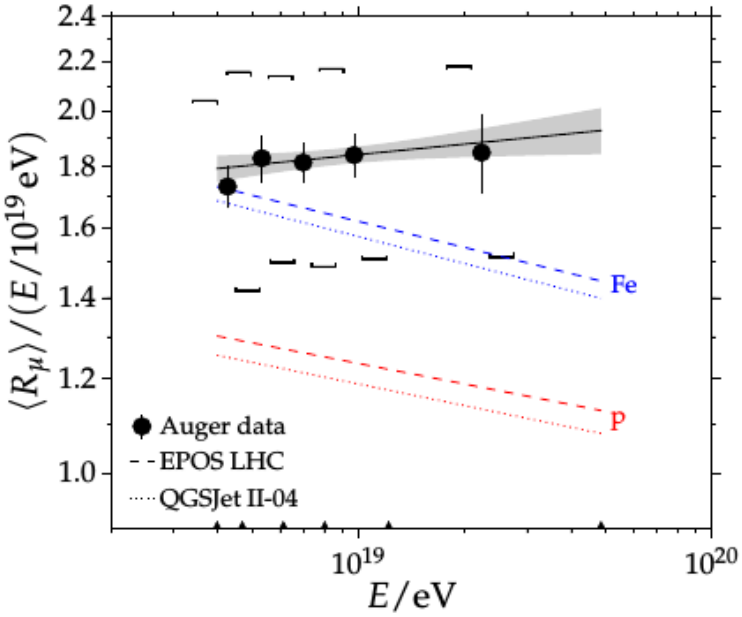


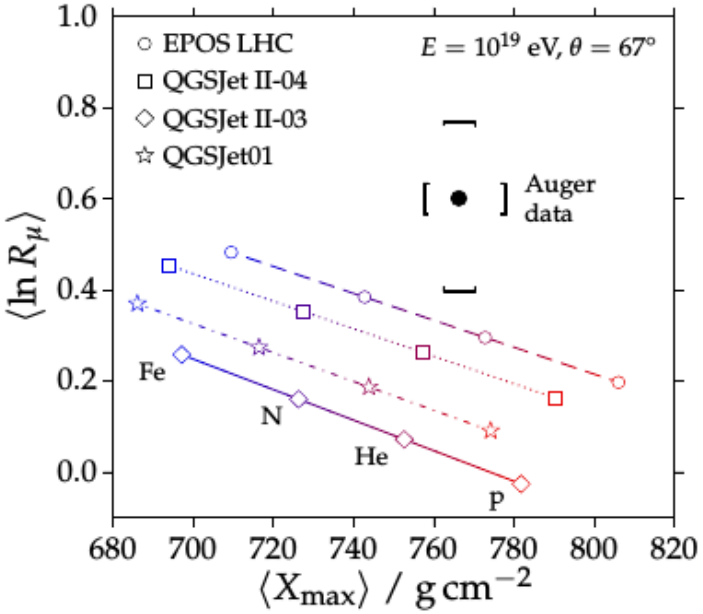


Tuning impact:

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

Muon content of air showers at ground level



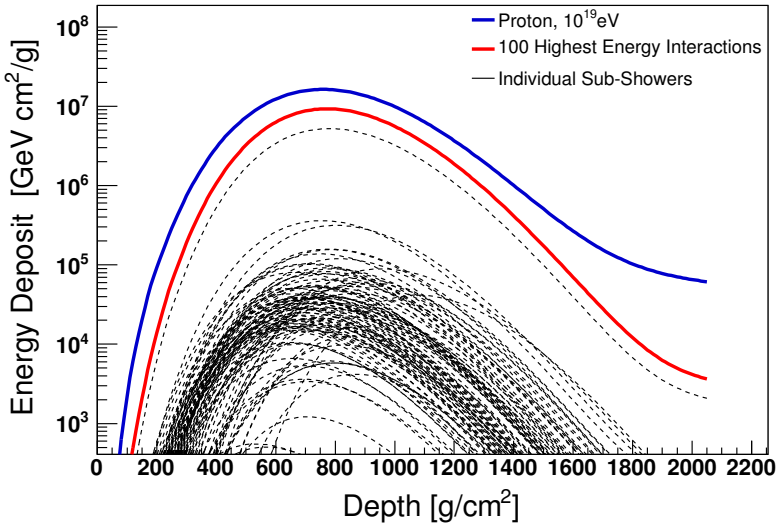


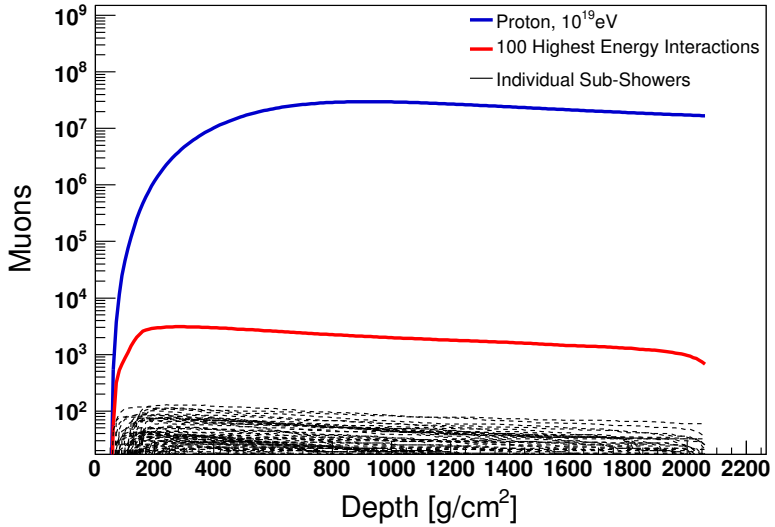
Auger, PRD 91 (2015) 032003

- 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

Sensitivity to interaction physics





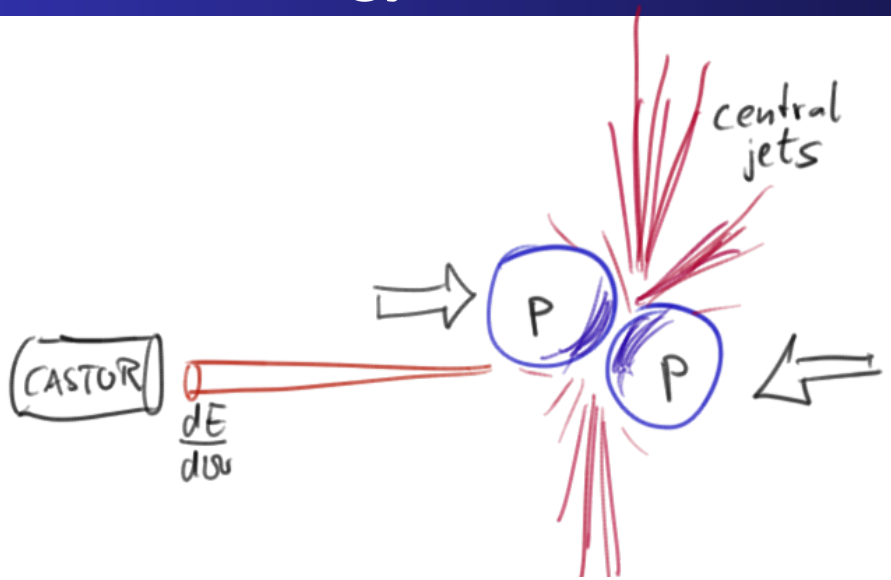
⇒ **Very different impact on different EAS observables:**

- Global shower properties and the shower maximum X_{max} are sensitive to the highest energy interactions
- Muons in air showers are sensitive to the hadronic cascade over all energies

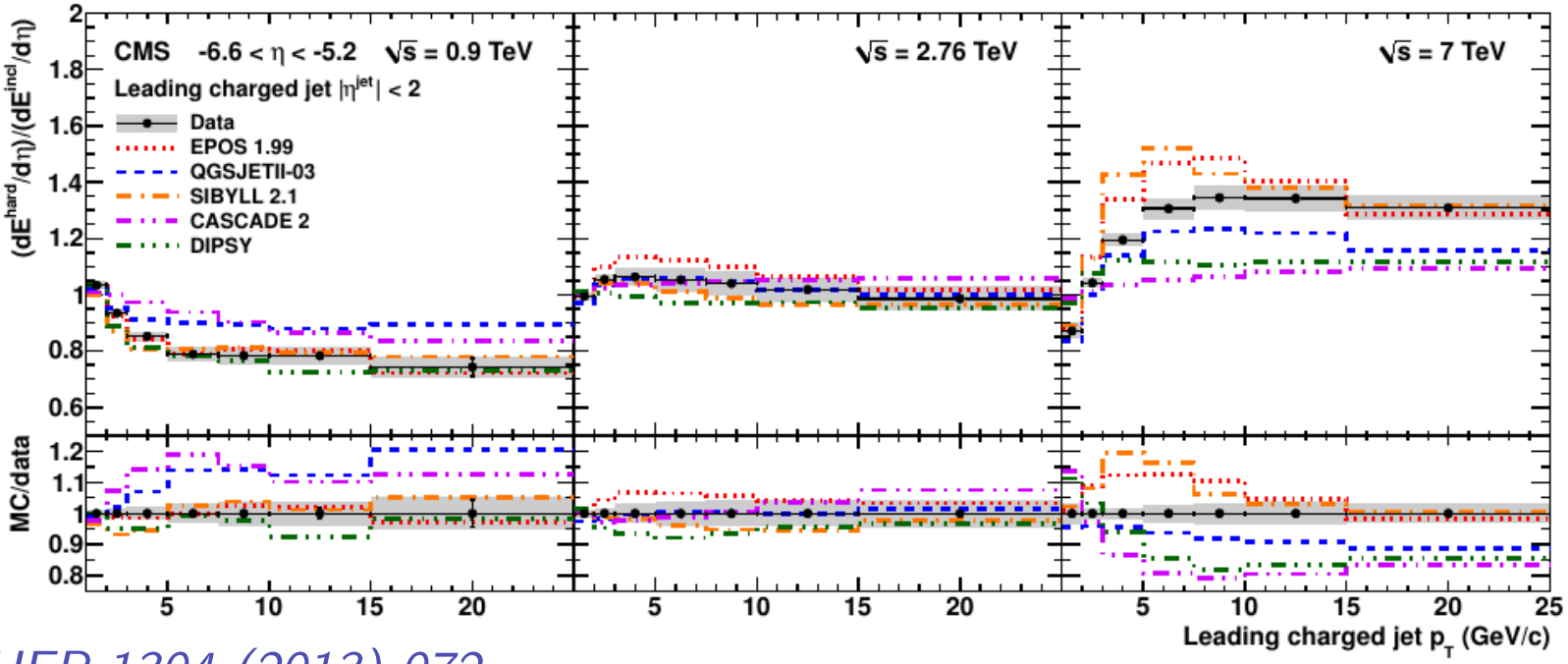
⇒ Large problem in predicting the overall muon number is small problem on the level of individual interactions

Example:
typical 8 had. generations, 5% effect in each → $1.05^8 \approx$50% total effect

Forward energy as a function of central activity (pp)



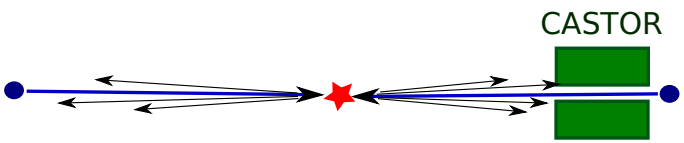
- **Forward energy** ∼ Remnant fragmentation
- **Central jets** ∼ String fragmentation
- "Underlying-Event" study in very forward direction



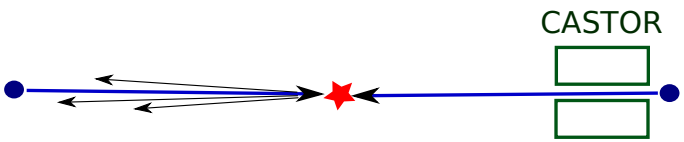
JHEP 1304 (2013) 072

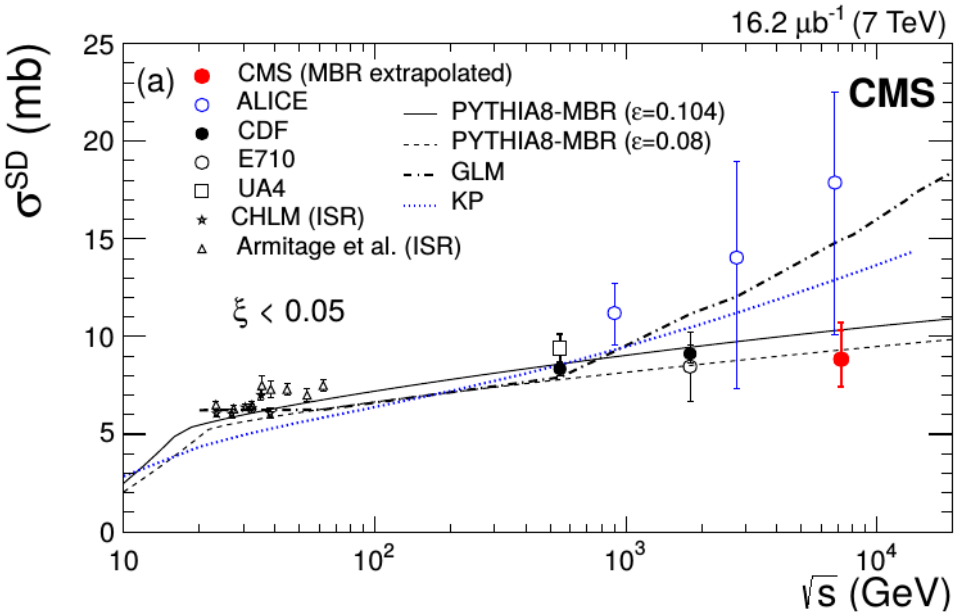
CMS/CASTOR low-mass single diffraction (pp, 7 TeV)

Double Diffraction



Single Diffraction

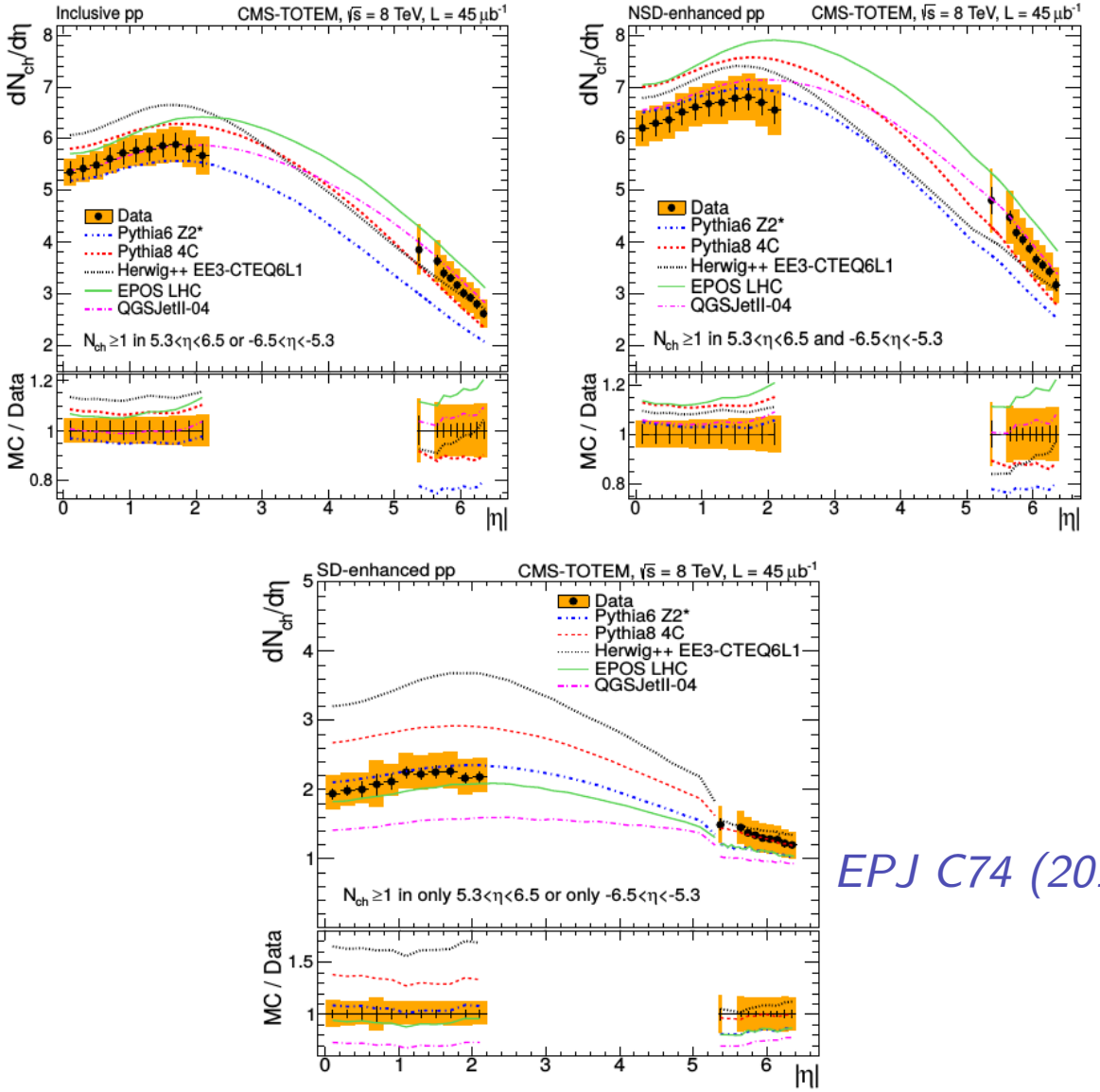




PRD 92 (2015) 012003

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

CMS + TOTEM combined multiplicity data (pp, 8 TeV)



EPJ C74 (2014) 3053

1) Very wide acceptance! 2) Correlations and final state selection!

CMS minijet measurements (pp, 8 TeV)

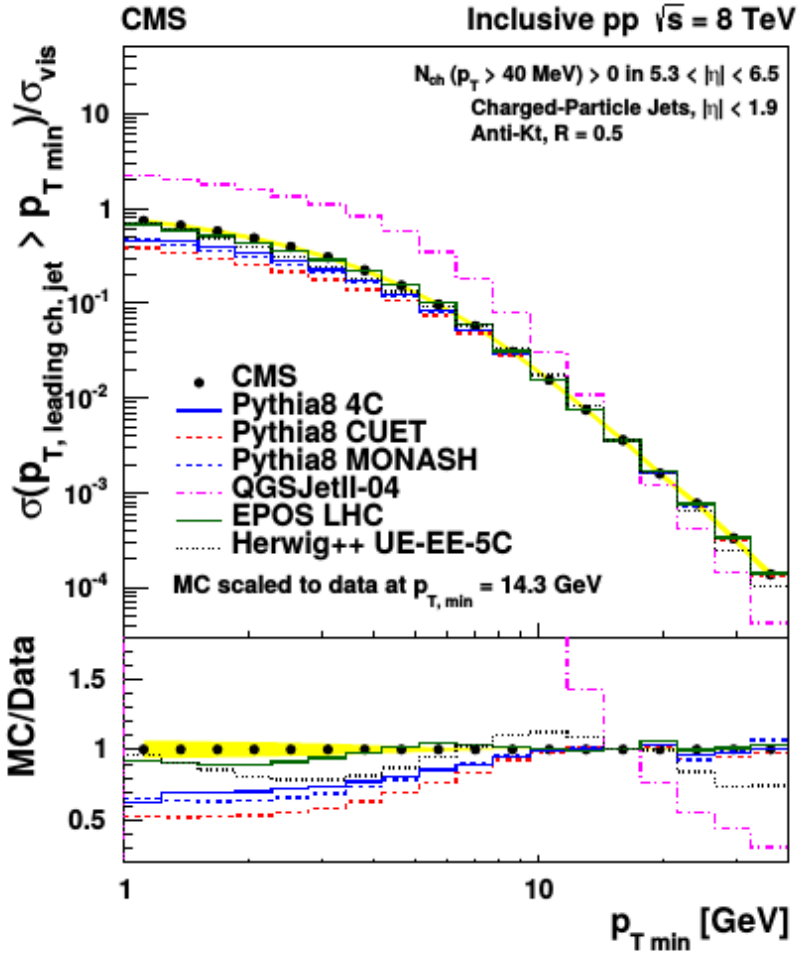
$$\sigma_{QCD}(s, p_{T,min}) = \int_{p_{T,min}}^{\sqrt{s}/2} dp_T \int_{4p_T^2/s}^{1} dx_1 \int_{4p_T^2/(x_1 s)}^{1} dx_2 \sum_{ijkl} f_{i,A}(x_1, p_T^2) f_{j,B}(x_2, p_T^2) \frac{d\hat{\sigma}_{ij}^{kl}(\hat{s})}{dp_T}$$

p_T-cutoff

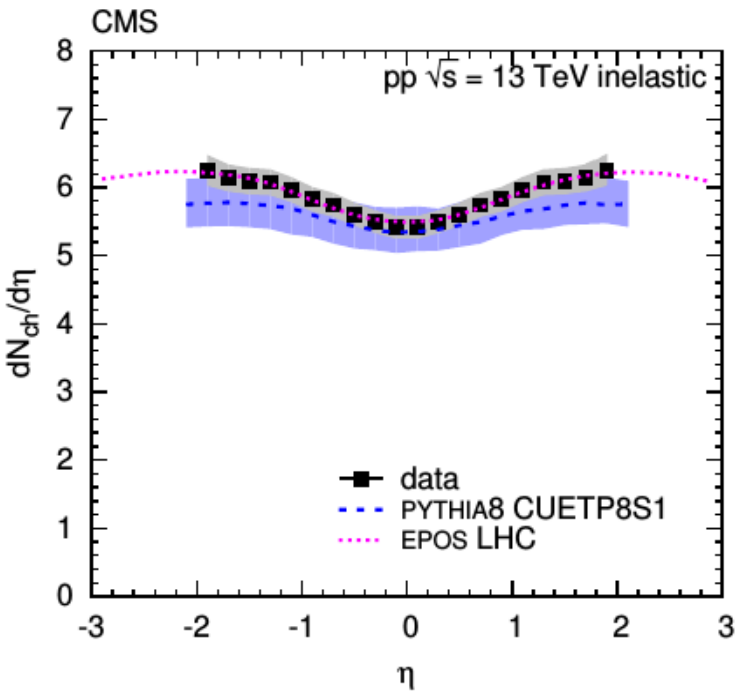
Parton distribution functions, PDFs

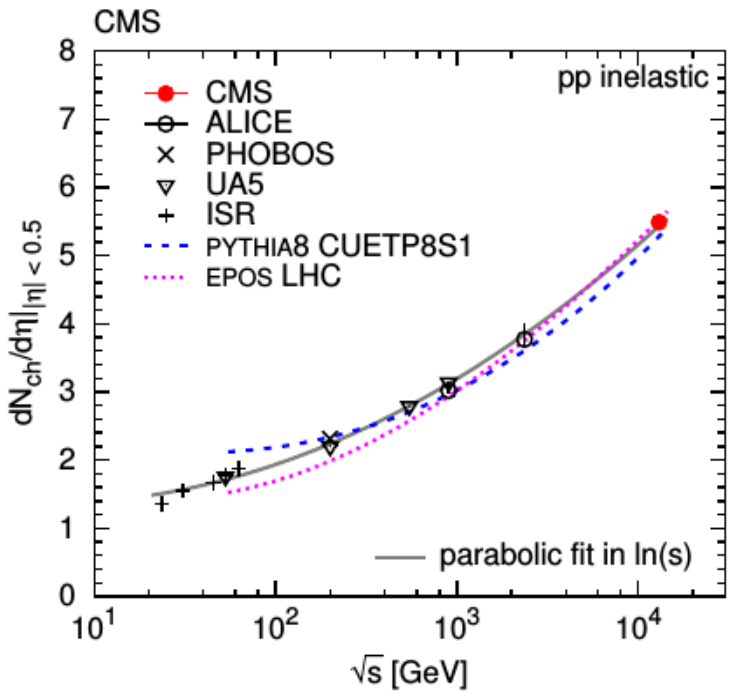
Minijet Cross section

- Hadronization in string fragmentation, minijet production
- p_T threshold



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



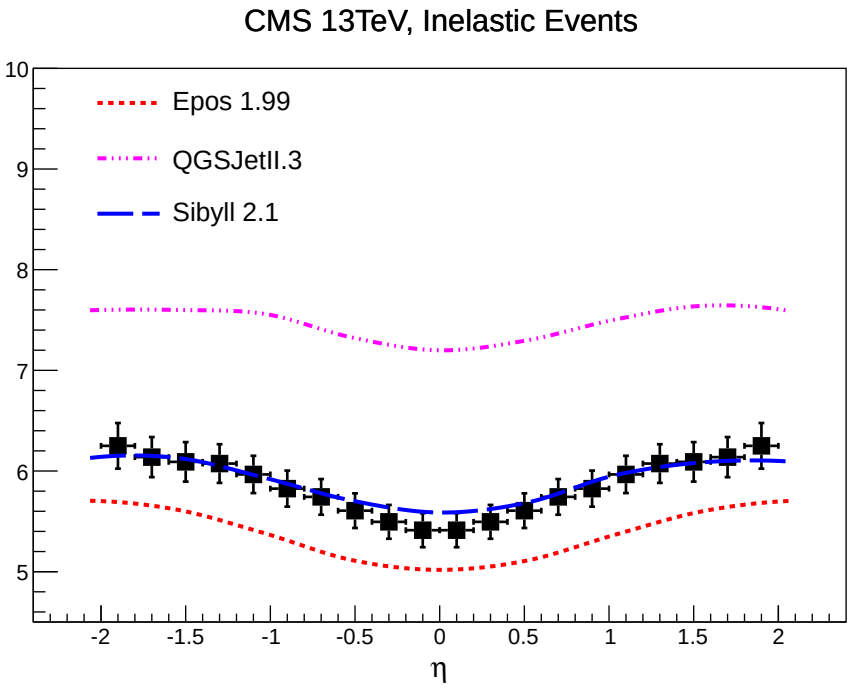


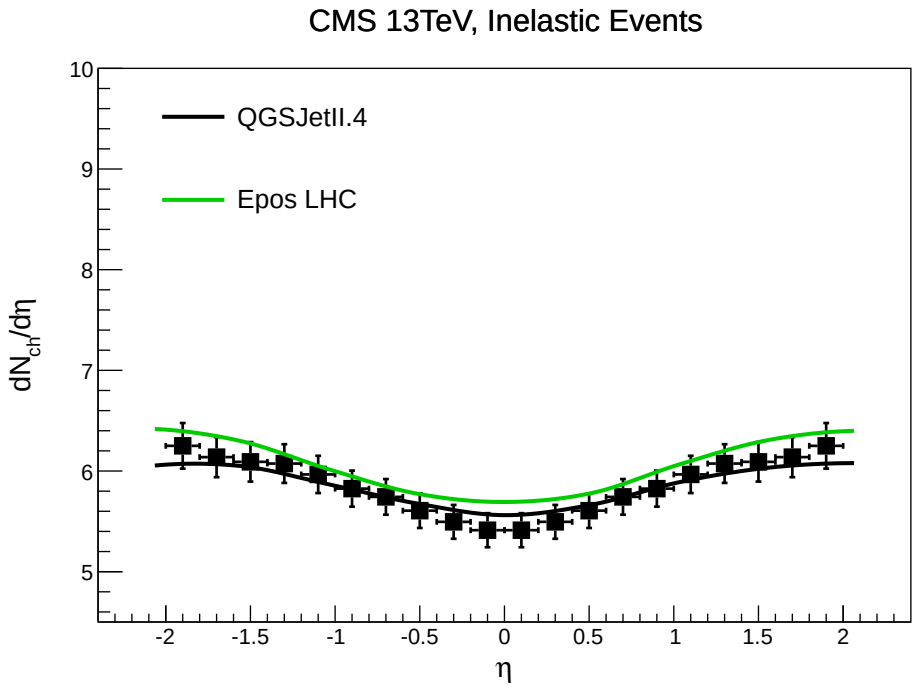
Phys.Lett. B 751 (2015) 143

- First LHC paper at 13 TeV (without CMS magnet→no p_T-cutoff)
- EPOS-LHC makes an excellent first impression
- And: analysis performed in Budapest!

Multiplicity measurements at 13 TeV

pre-LHC models → **Models tuned at 7 TeV**

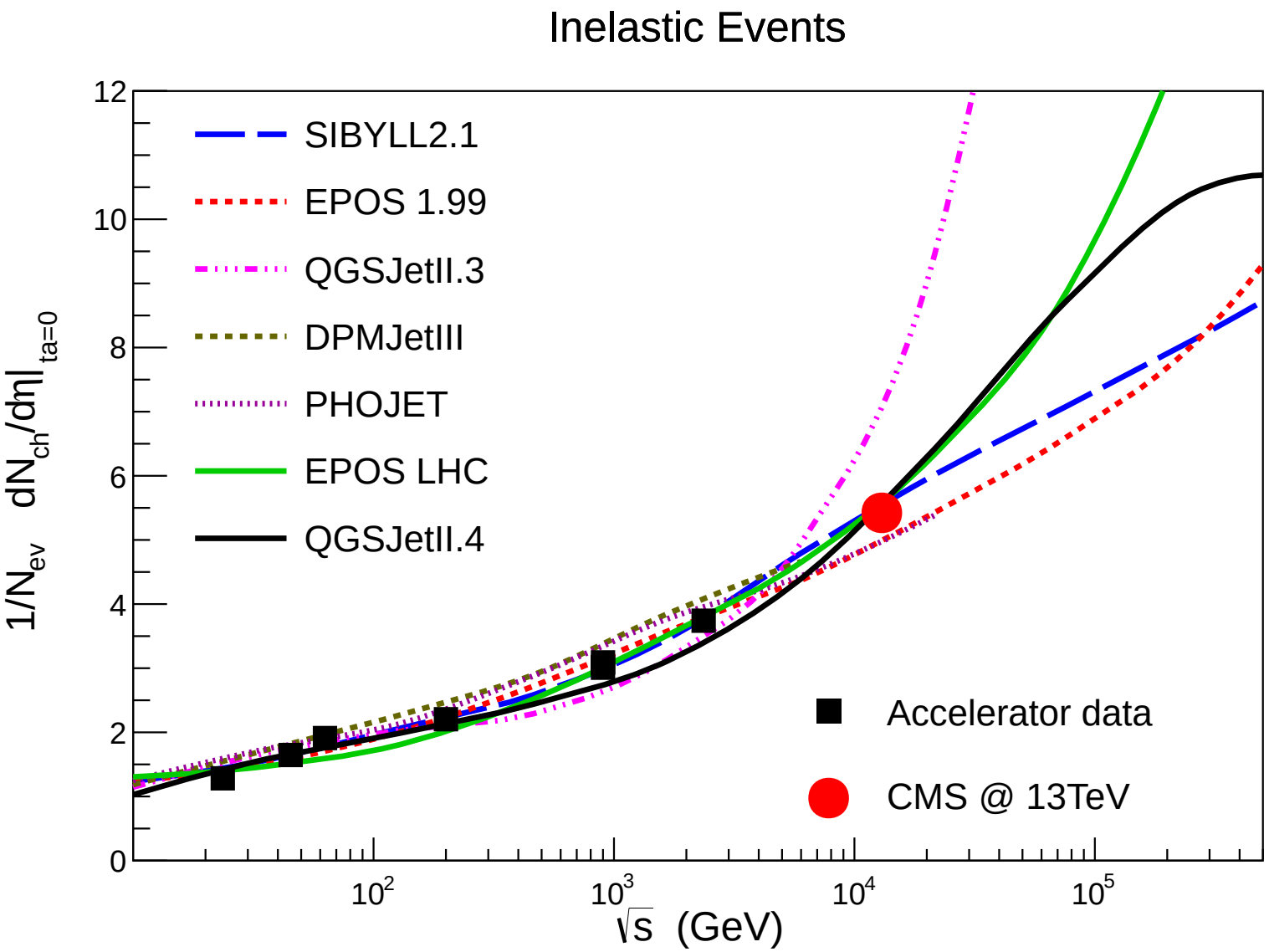




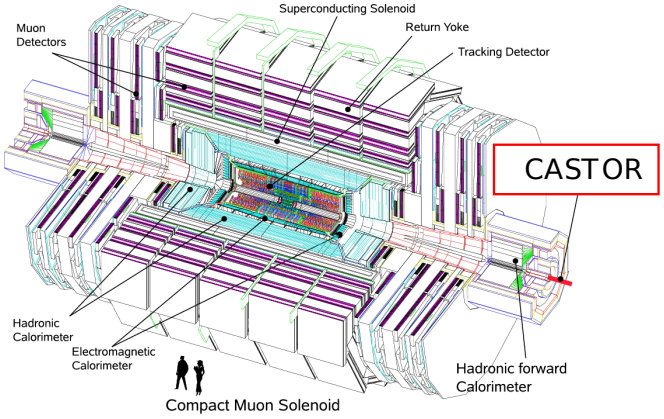
CMS: PLB 751 (2015) 143

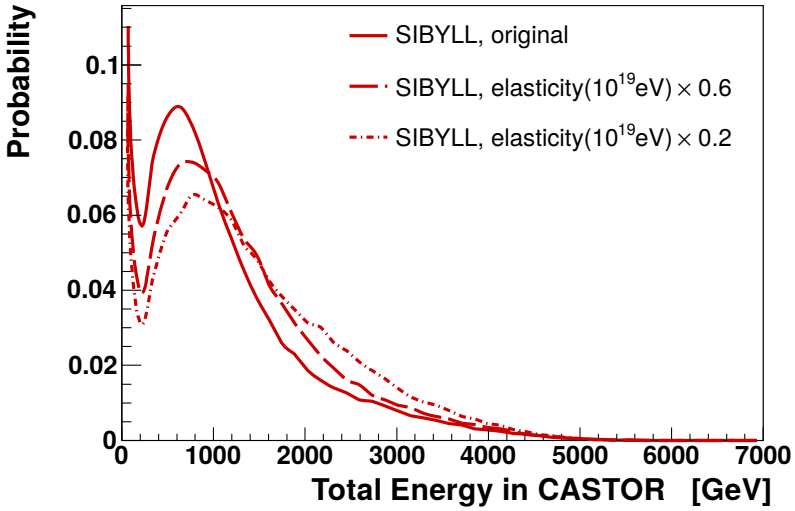
- Good extrapolation over factor ≈2 in $\sqrt{s}$
- Poorly constraint beyond factor > 10 in $\sqrt{s}$

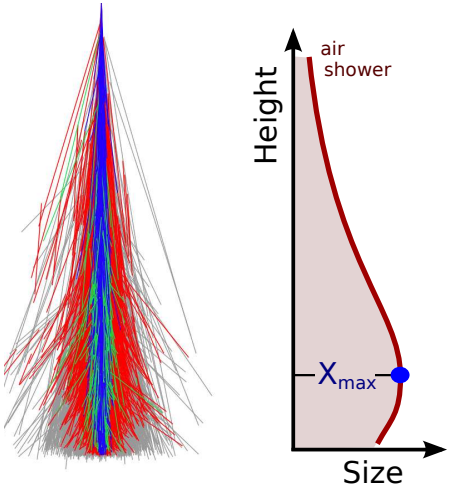
Extrapolation to ultra-high energies

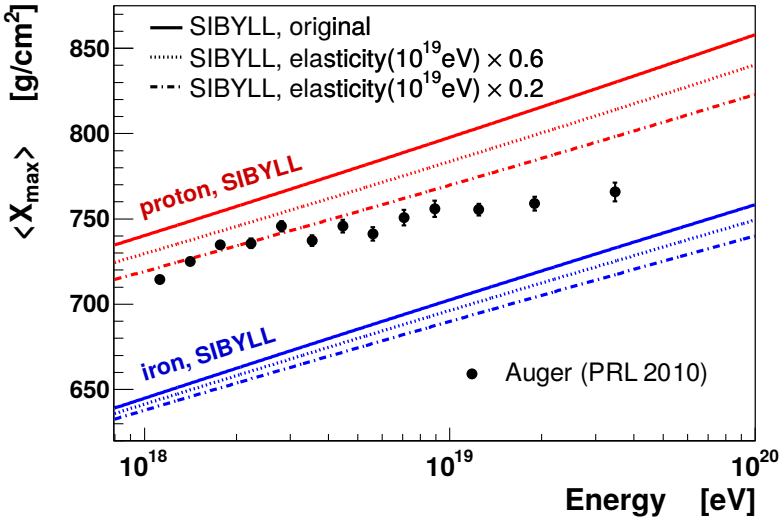


CASTOR and cosmic ray interpretation



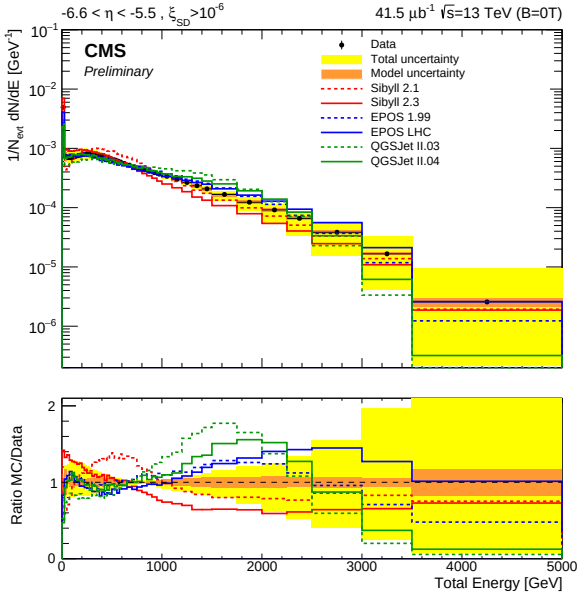




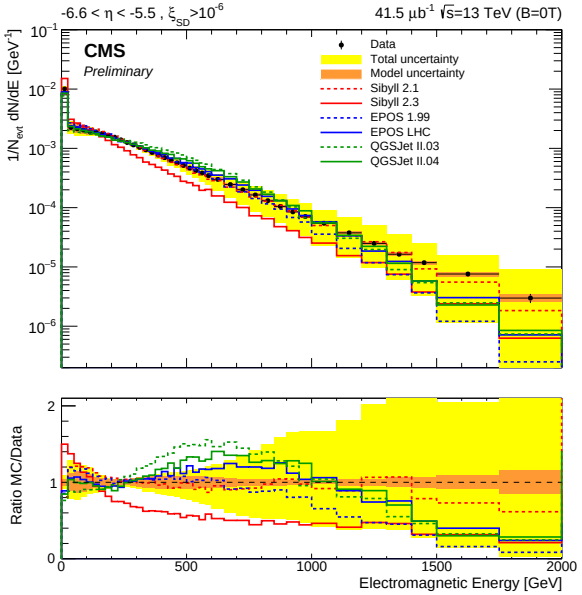


CASTOR at 13 TeV

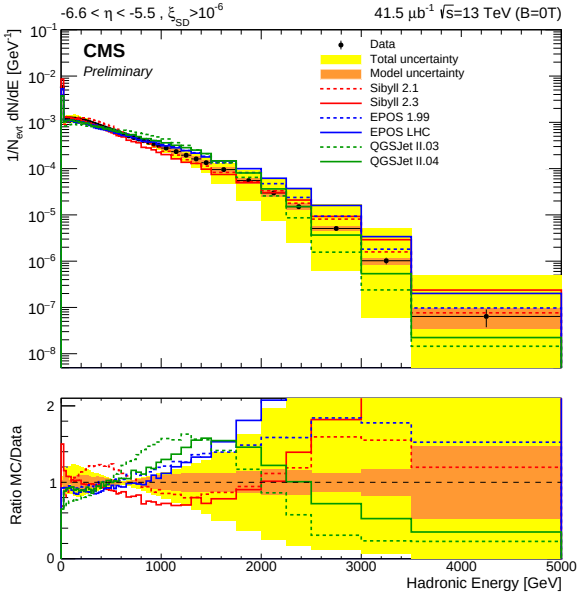
Total energy



Electromagnetic energy



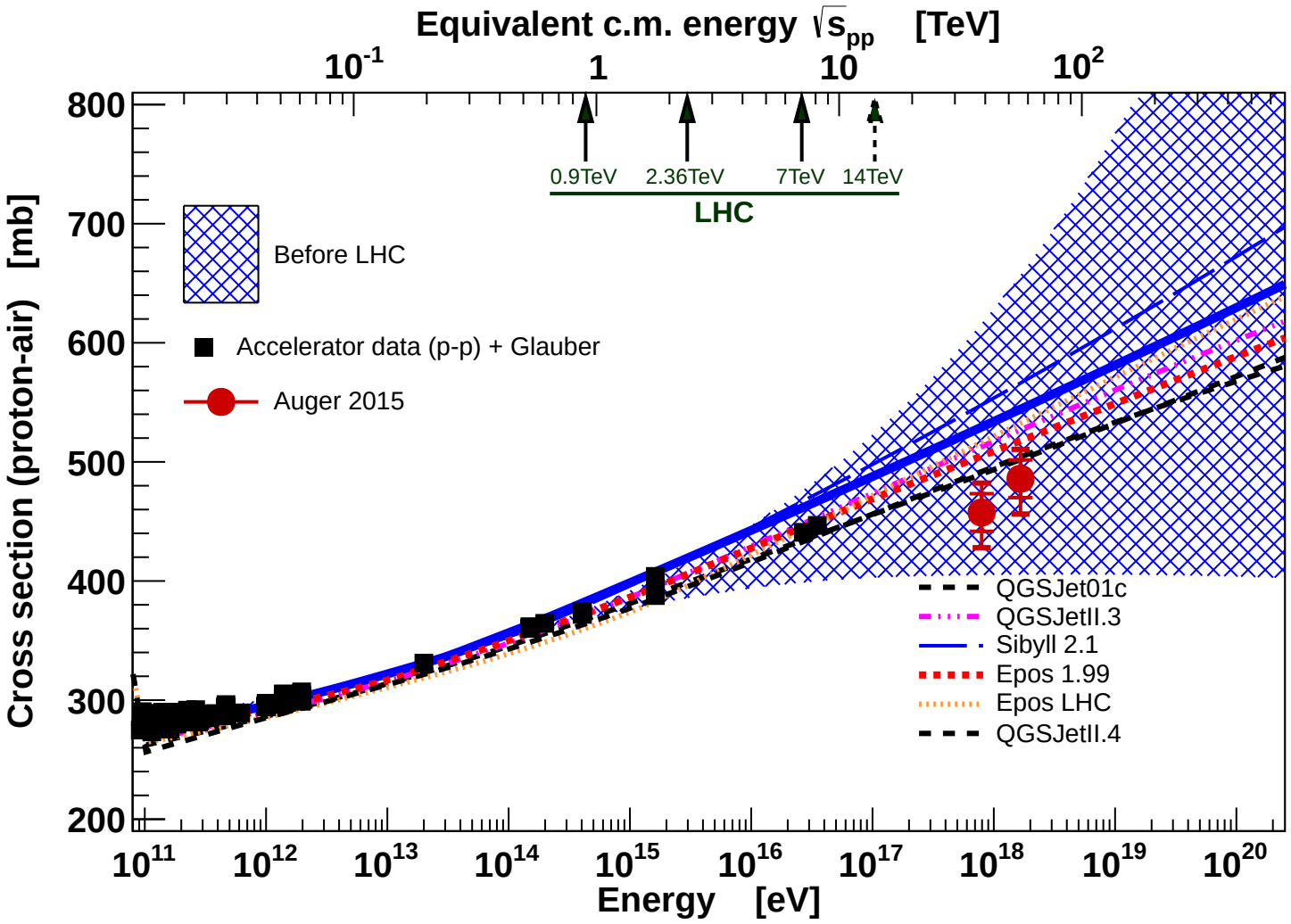
Hadronic energy



JHEP 08 (2017) 046

- Model performance tested in crucial phase-space domain
- Very sensitive to MPI, diffraction, low-x structure
- Represents a significant part of the overall energy-flow

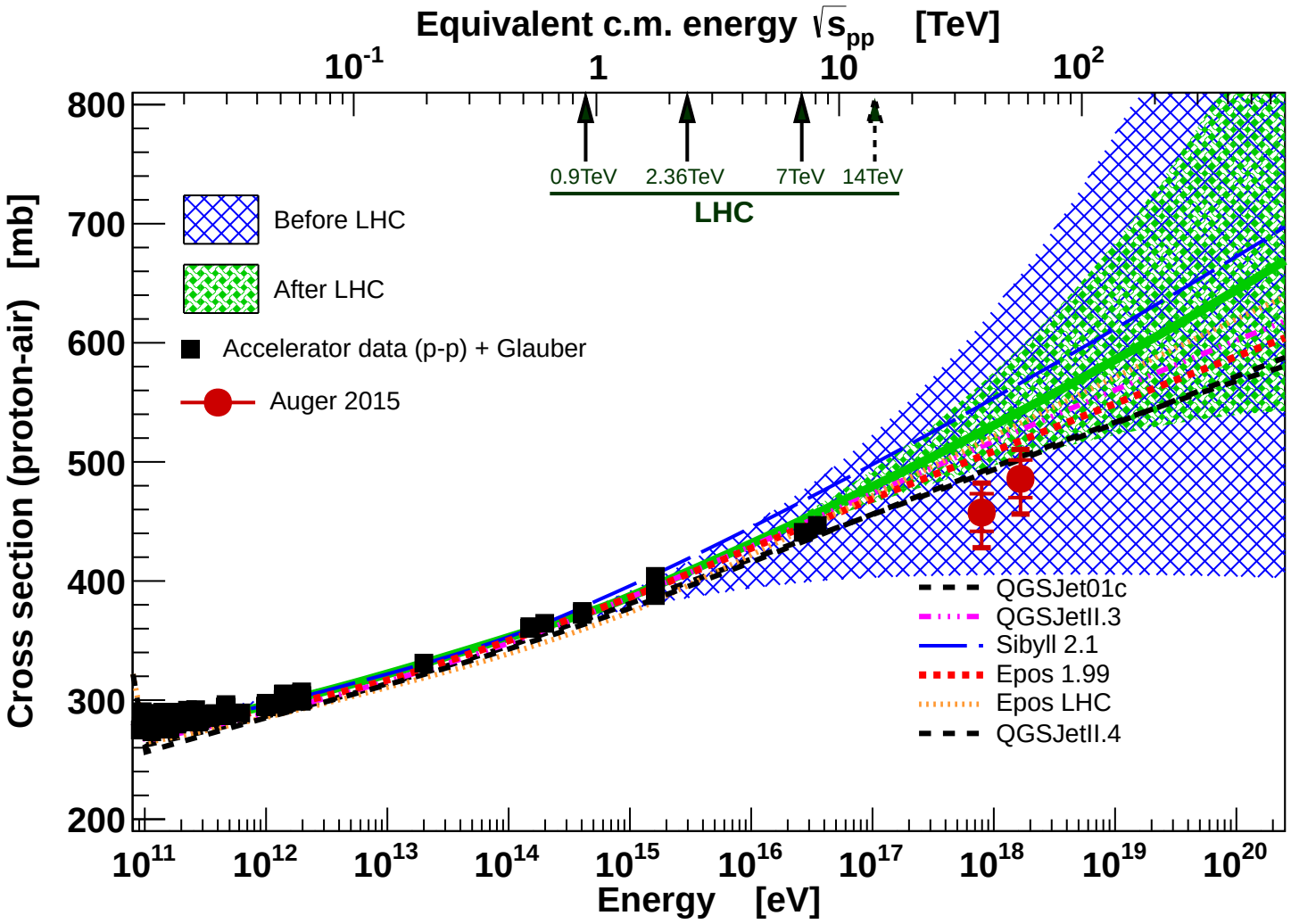
Proton-Air cross section, with Tevatron data



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

Large uncertainties due to nuclear effects from pp to p-air

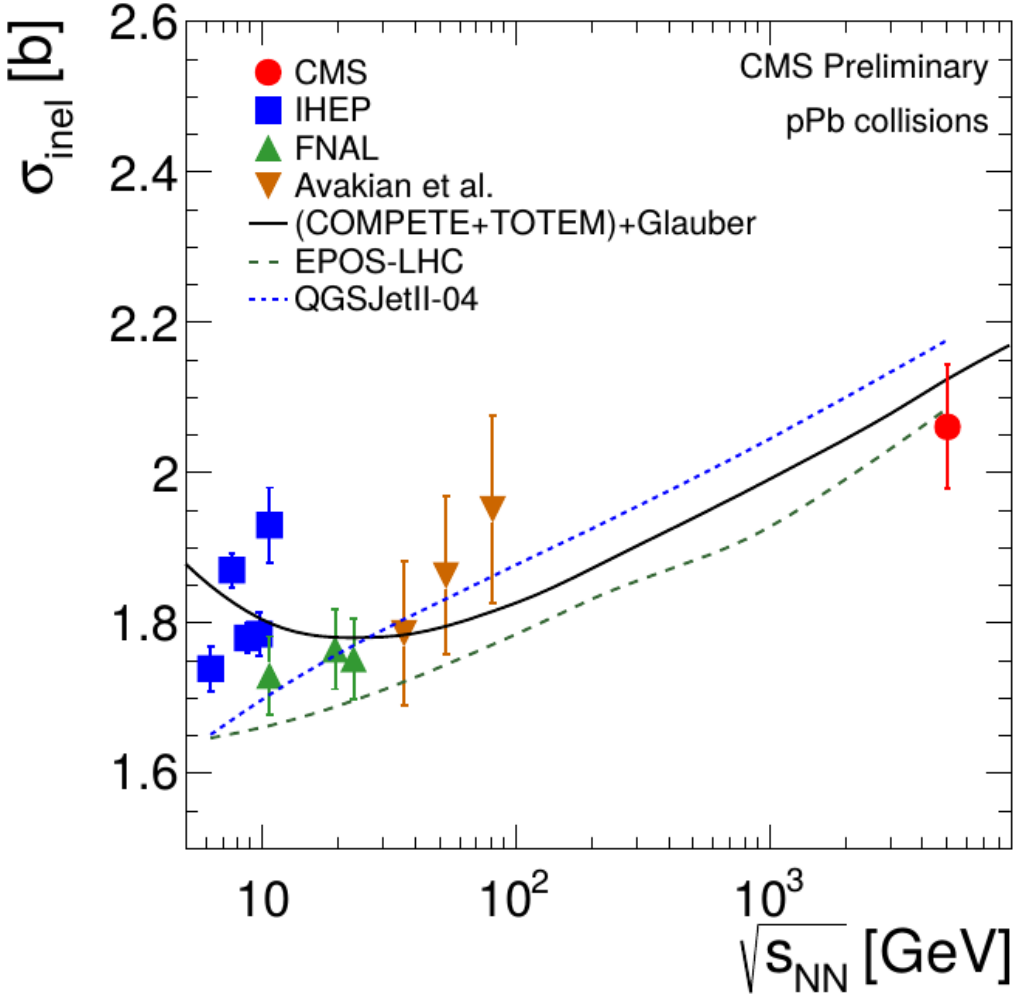
Proton-Air cross section, with LHC data



⇒ Sign of a clear relevant improvement

Large uncertainties due to nuclear effects from pp to p-air

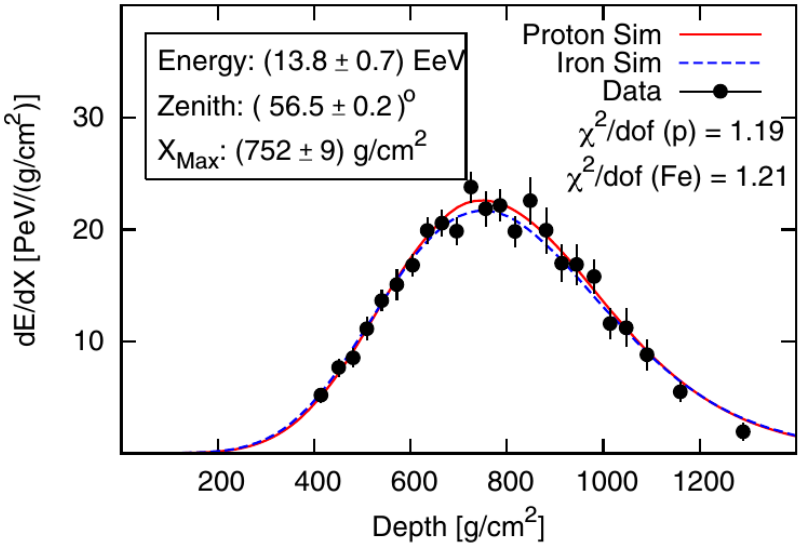
Inelastic proton-lead cross section at 5.02 TeV

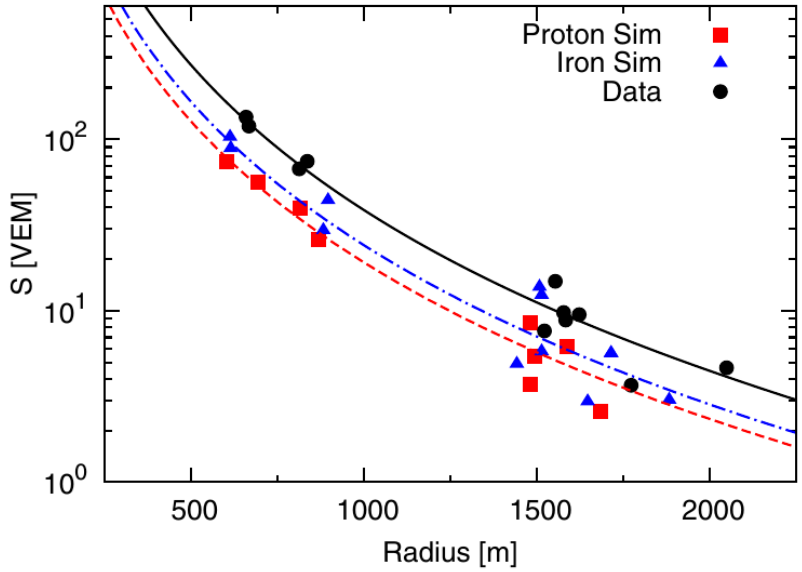


PLB 759 (2016) 641

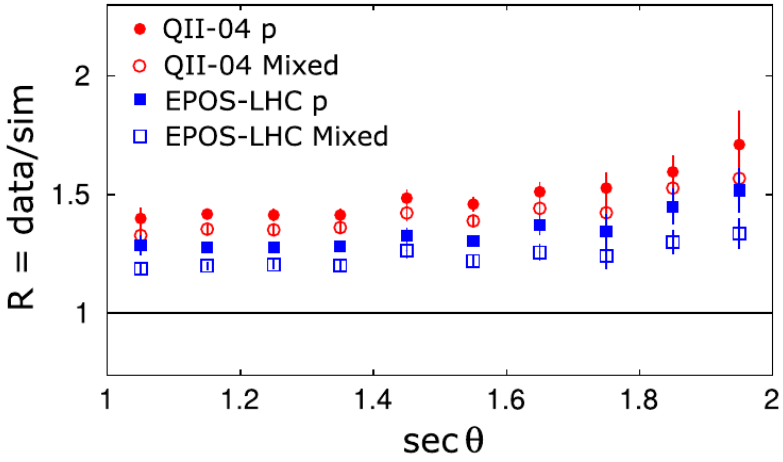
- **Direct test of Glauber model (and related physics) at LHC**
- **proton-oxygen will be much more powerful.**

Hadronic interactions, Auger



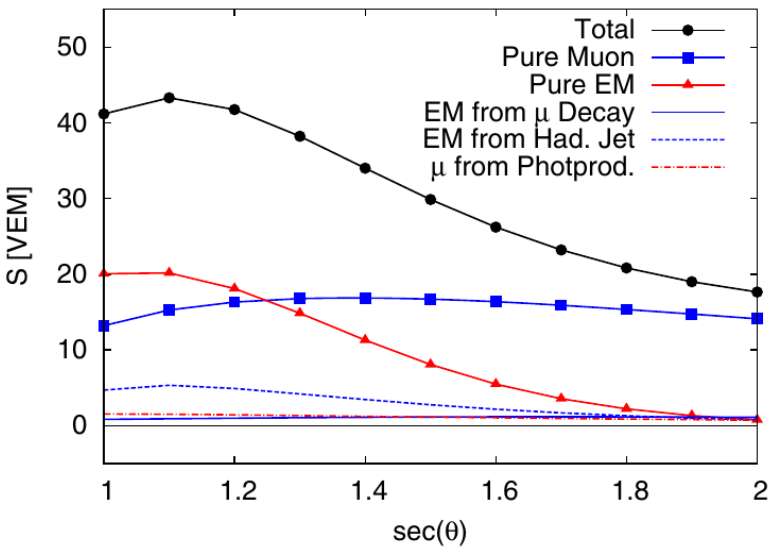


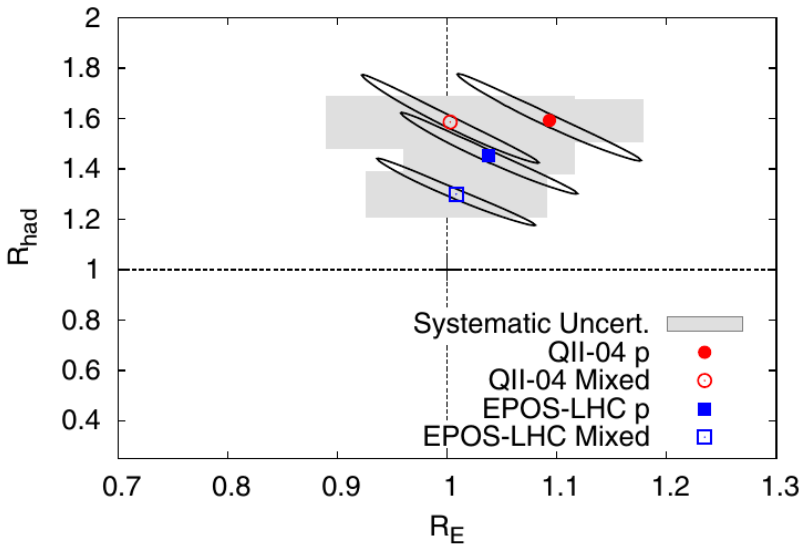
Attempt of consistent description of longitudinal and lateral shower data.



PRL 117, 192001 (2016)

Hadron/Muon component in data is too large





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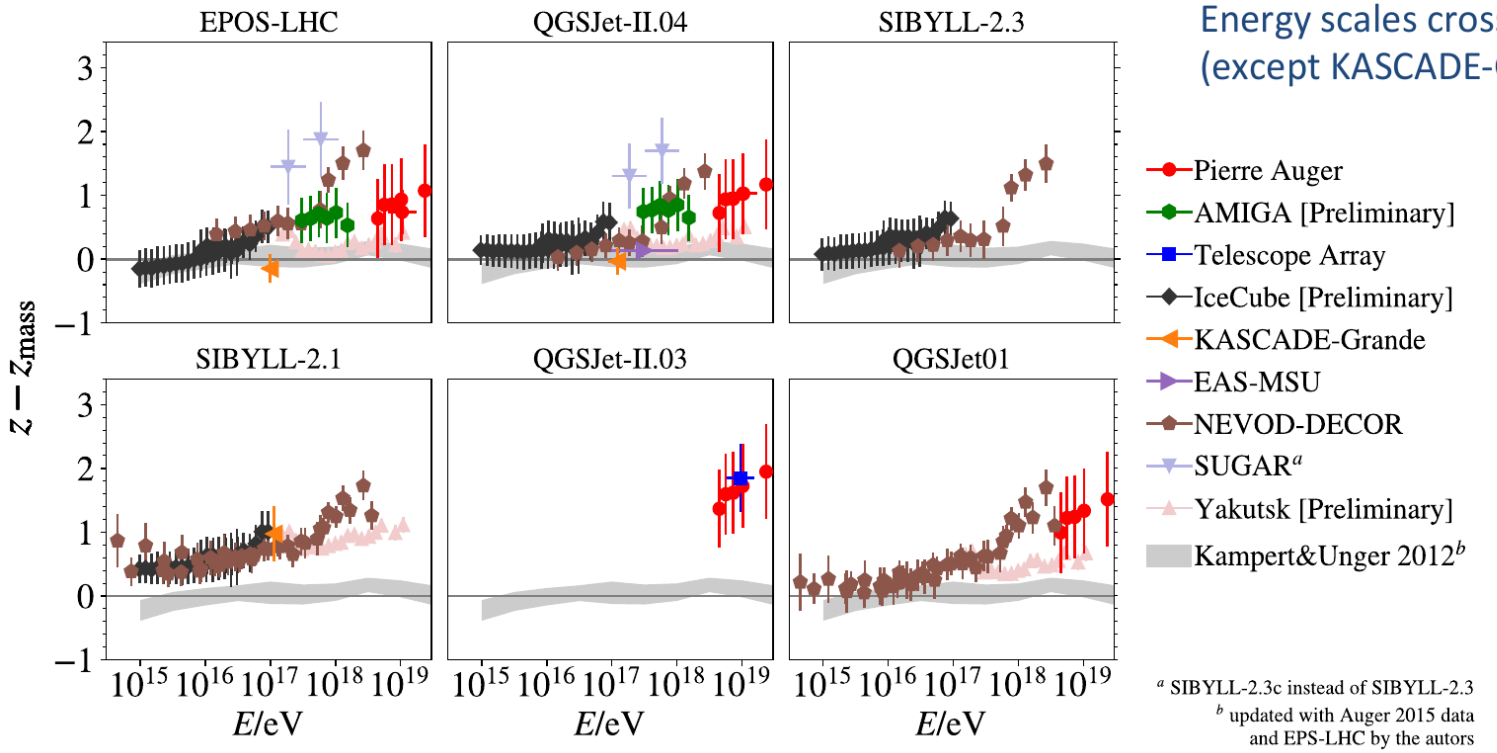
- Scale E.M. and had. part of MC showers with R_E and R_{had} to fit data:

$$S_{\mathrm{resc}}(R_{\mathrm{E}}, R_{\mathrm{had}}) = R_{\mathrm{E}} S_{\mathrm{EM}} + R_{\mathrm{had}} R_{\mathrm{E}}^{\alpha} S_{\mathrm{had}}$$

- While $R_E = 1$ is possible and mostly consistent with data
- R_{had} is significantly above 1
- None of the models/assumptions reproduces data

Compilation of muon measurements

- WHISP report at UHECR 2018 conference, Oct 8-12 2018
- Comprehensive compilation of muon measurements from air shower experiments



Energy scales cross-calibrated (except KASCADE-Grande, EAS-MSU)

Systematic discrepancies reported by majority of experiments starting around 5×10^{16} eV equiv. to $\mathbf{s^{1/2} = 10\ TeV}$

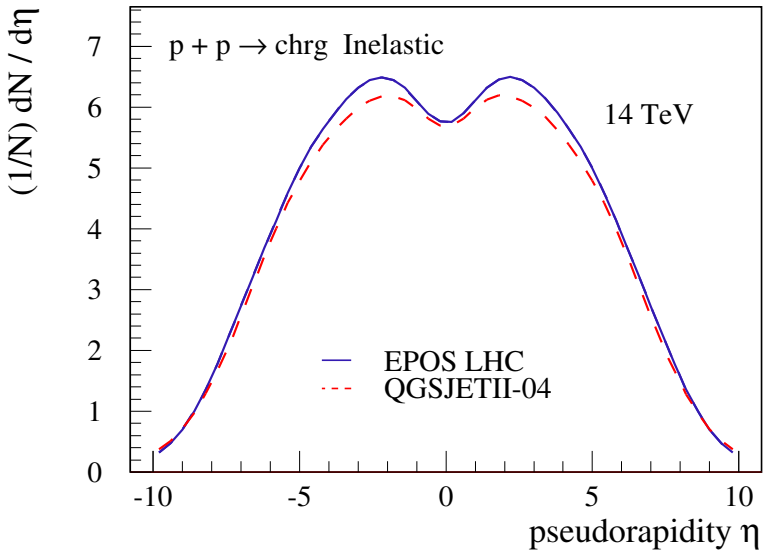
Apart from shower energy, possible dependence on shower age, lateral distance, muon energy threshold

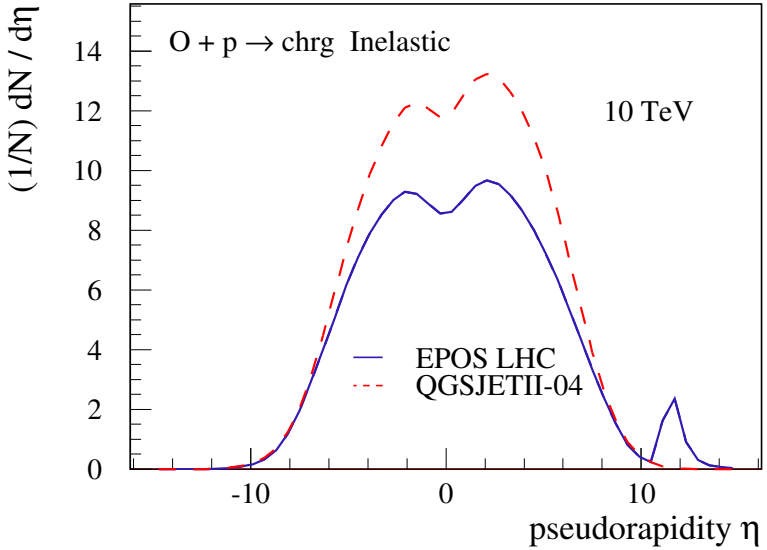
Not simple to fix:

- No simple key measurement
- Need to accurately know and extrapolate several features
- Focus on precise measurements of features in references systems, use models to predict interactions in unavailable target systems and phase space

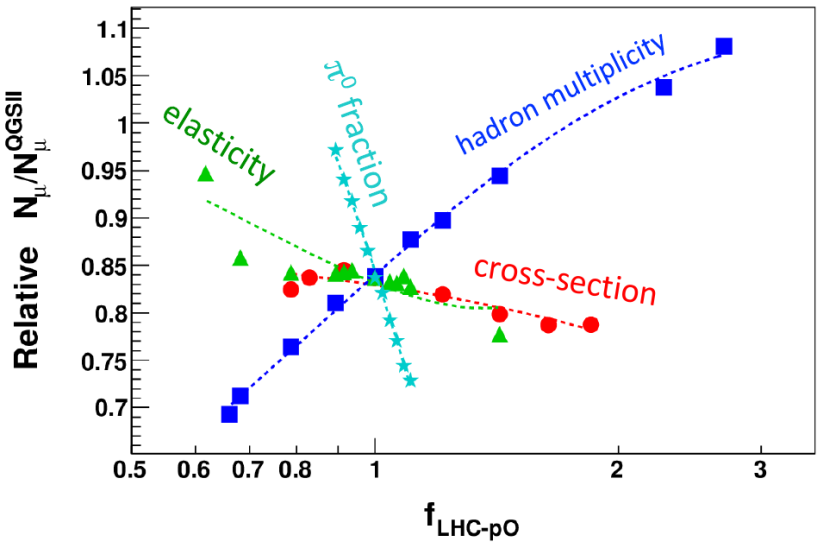
Proton-Oxygen Data at LHC: Very Relevant

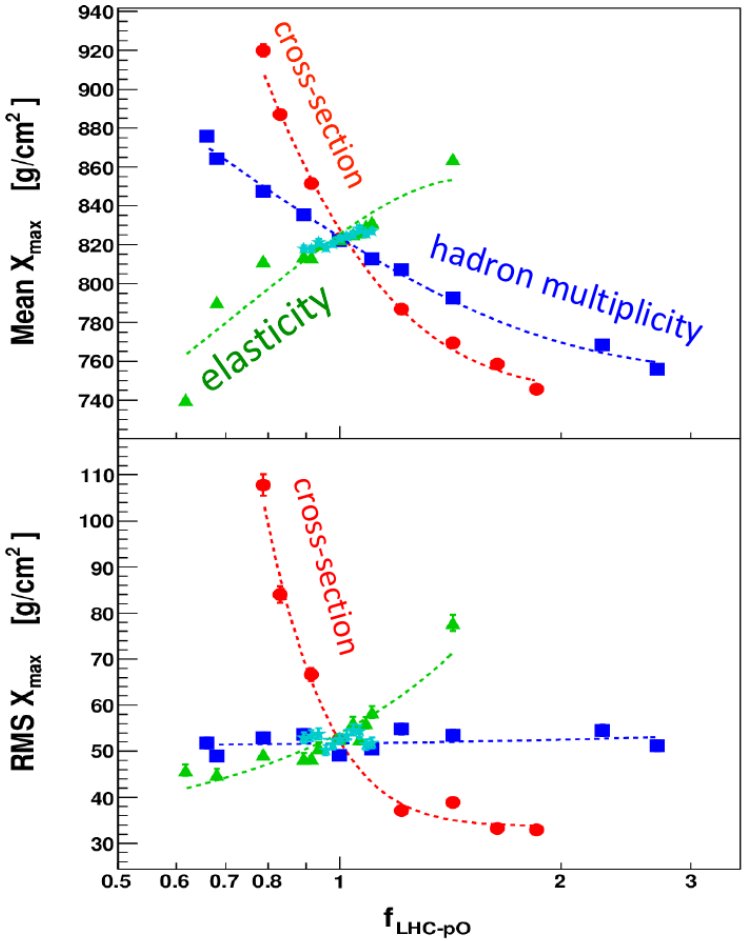
- Asymmetric heavy-ion run with proton-oxygen nuclei
- LHC Run3 $\sqrt{s_{\mathrm{NN}}^{\mathrm{pO}}} = 10\,\mathrm{TeV}$ (Proton beam at 7 TeV)
- Oxygen very close to atmospheric material of extensive air shower production (nitrogen)
- Impact on model predictions :





Potential of proton-oxygen data



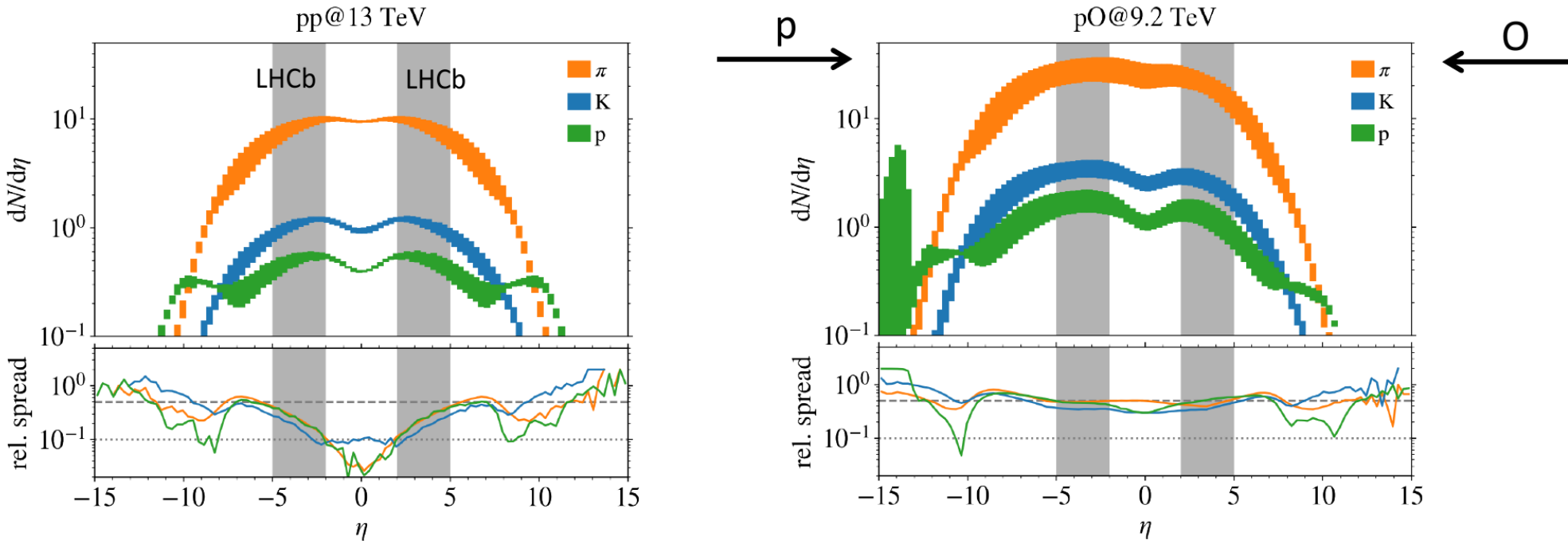


Remove uncertainties from nuclear effects.

Increase accuracy of air shower simualtions.

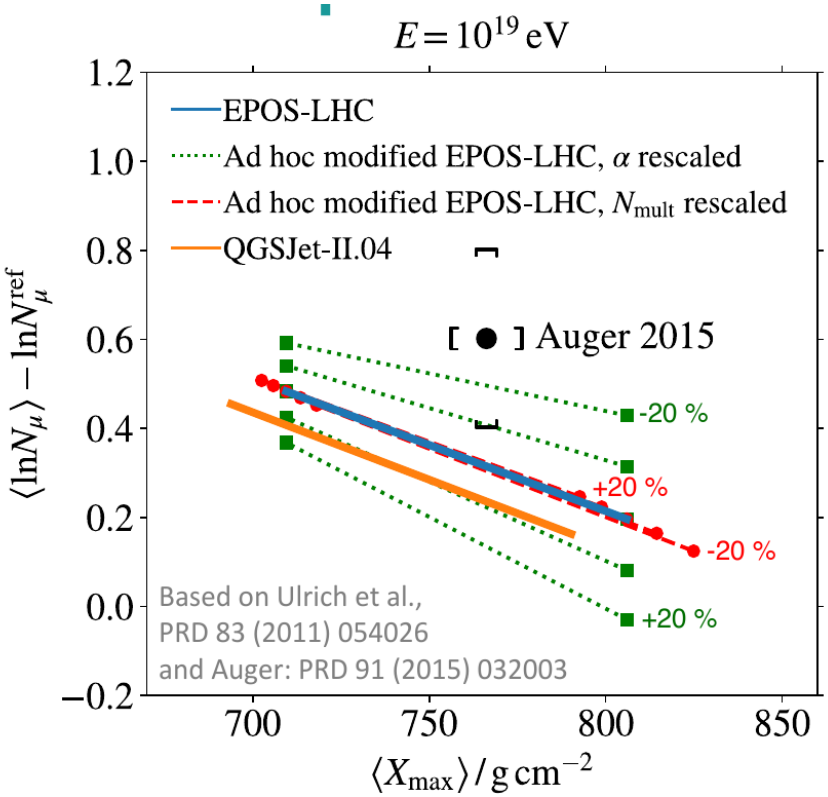
Extrapolation as one problem

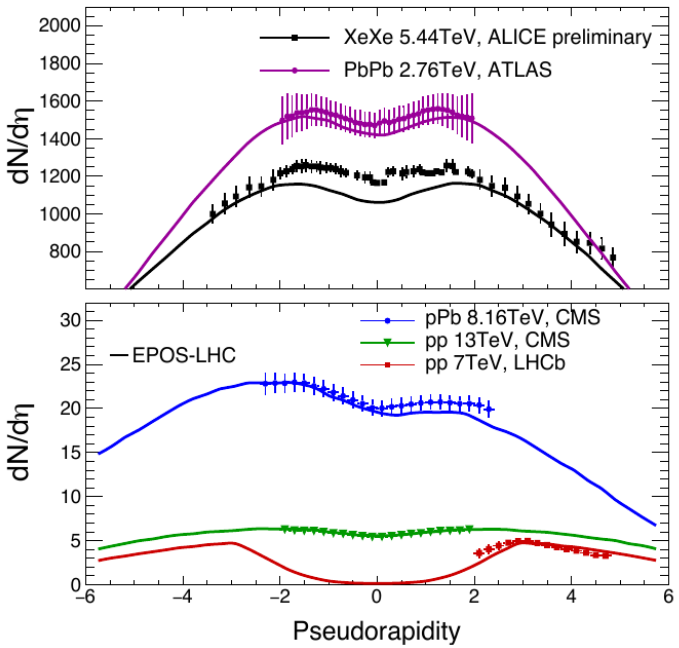
Shown is spread between: EPOS-LHC, QGSJetII.04, SIBYLL-2.3



Models mostly tuned to p+p data at |η| < 2: p+p 10 % model spread, **p+O 50 %** model spread

Impact of LHC measurements



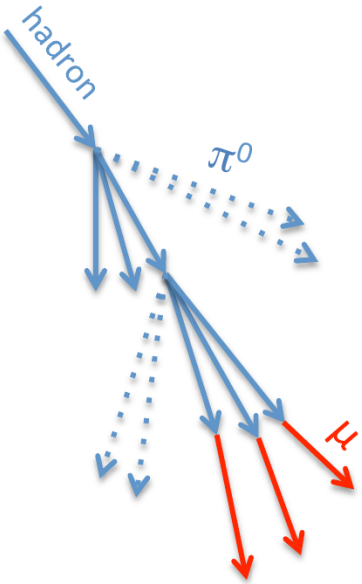


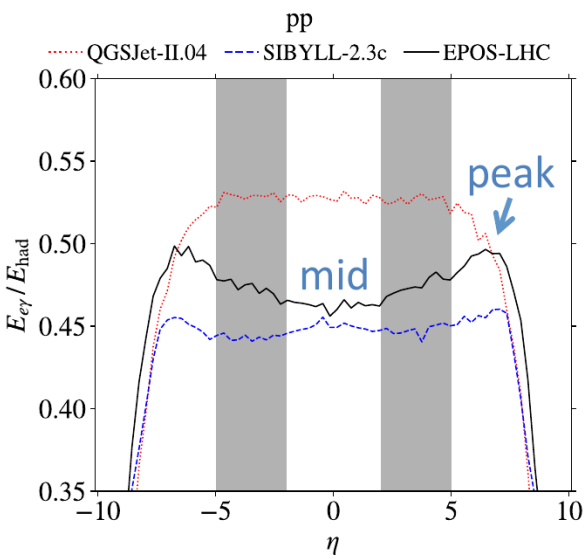
ALICE Xe-Xe arXiv:1807.09061; ATLAS Pb-Pb arXiv:1504.04337; CMS p-Pb arXiv:1710.09355v2; CMS p-p arXiv:1507.05915v2; LHCb p-p arXiv:1402.4430

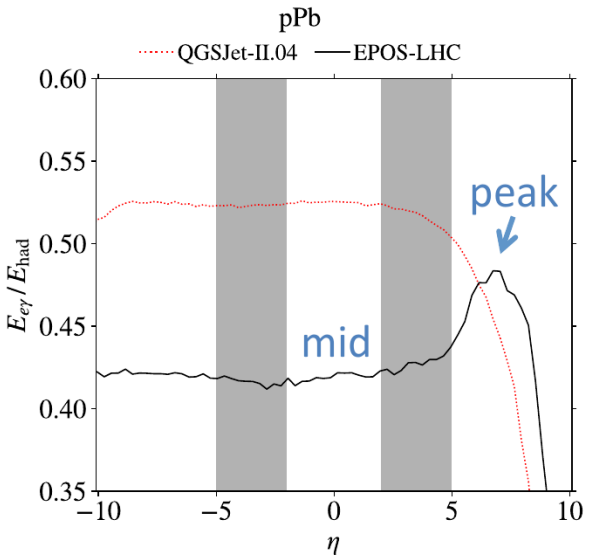
- X_{max} sensitive to: **inelastic cross-section**, hadron multiplicity
- N_μ sensitive to: **energy fraction lost to π^0**, hadron multiplicity
- **Nuclear modification in forward-produced hadrons** expected and important

Energy flow: e/γ vs. hadrons

- Hadronic energy "lost" to π^0s cannot produce muons in late shower
- "Energy loss" described by observable $E_{e\gamma}/E_{hadrons}$





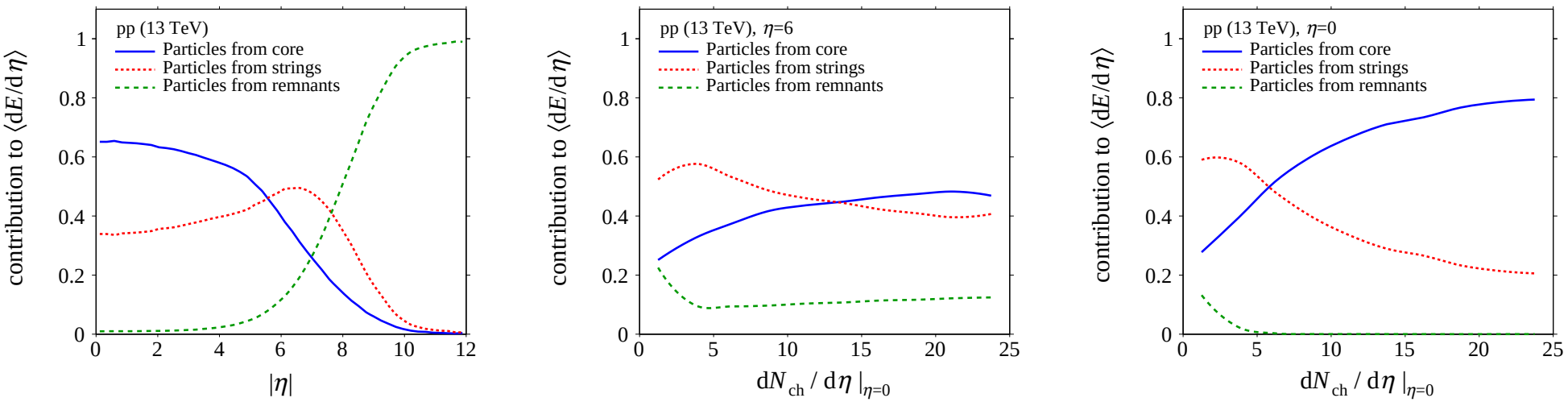


- Model predictions differ by **15 %** and in **shape**: only EPOS has forward peaks
- Translates to about **20 % shift in N_μ -> high impact on Muon Puzzle**

Mechanisms for different EM-ratios

Secondaries are produced in different mechanisms in different phase space regions:

vs η vs N_{mult} $(\eta = 0)$ vs N_{mult} $(\eta = 6)$

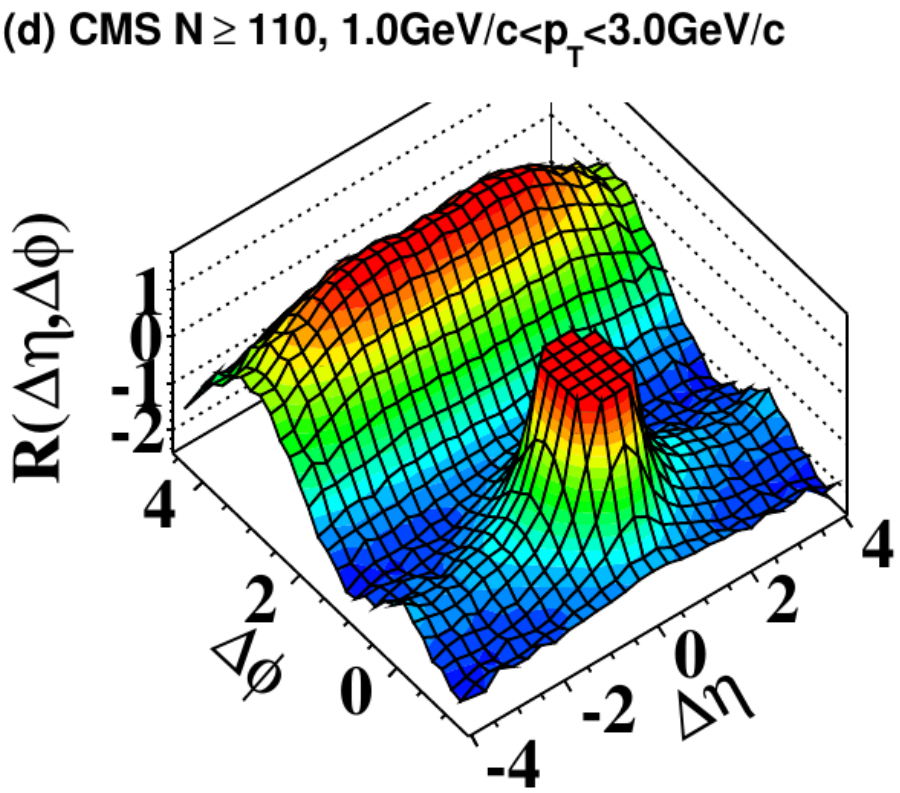


arXiv:1902.09265 [hep-ph]

And: each mechanism has its own EM-ratio ($R = E_{\mathrm{e.m.}}/E_{\mathrm{had}}$).

Collective effects in small systems

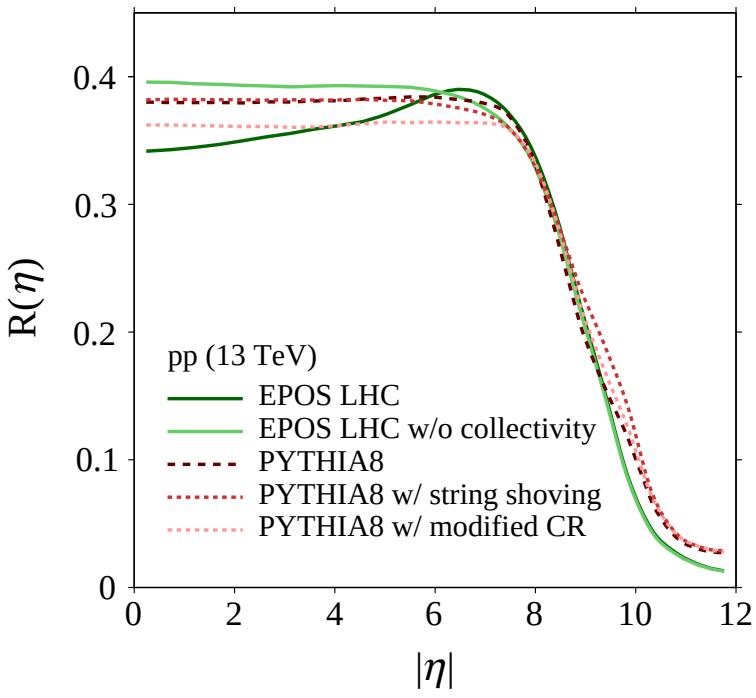
Observation of Long-Range, Near-Side Angular Correlations in Proton-Proton Collisions at the LHC:

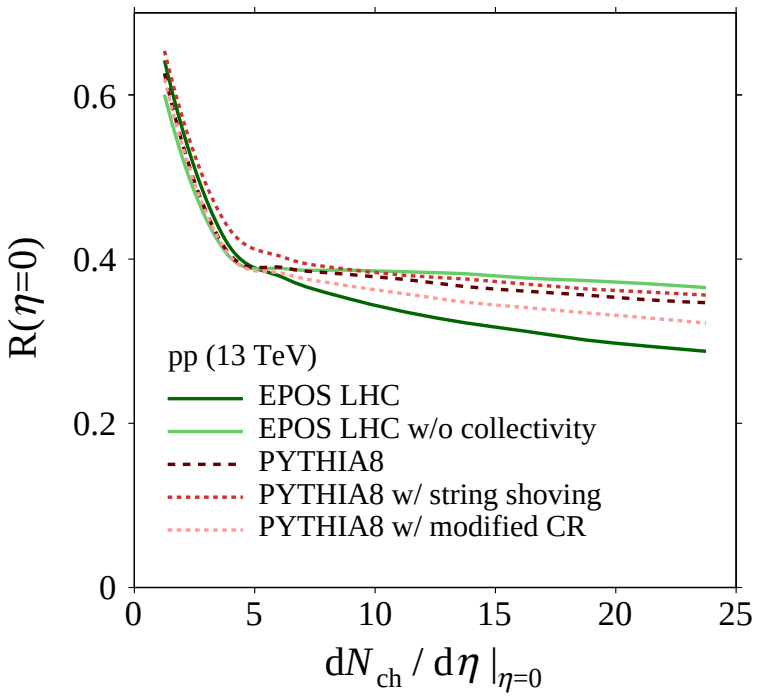


JHEP 09 (2010) 091

A rare discovery at LHC!

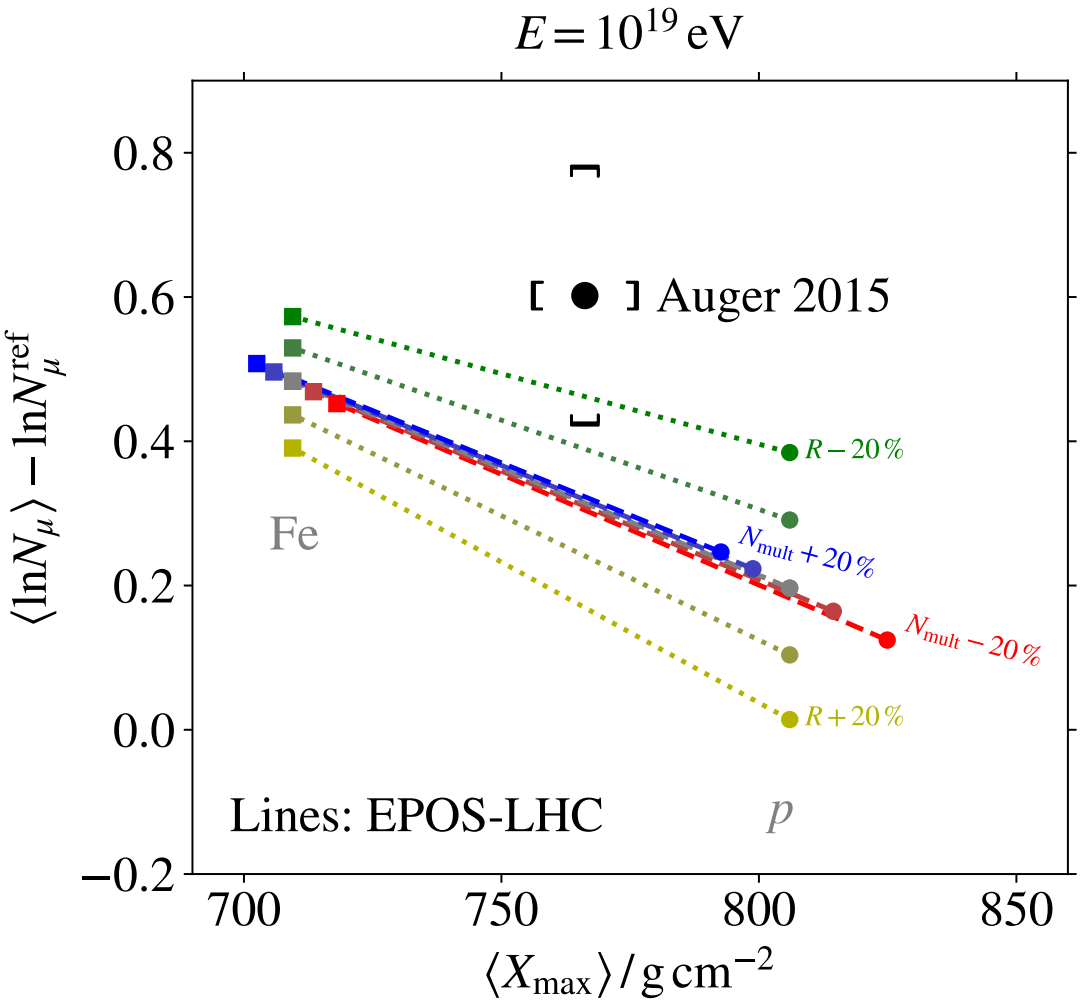
Potential (further) signatures at LHC





Could be measured at LHC → shape analyses

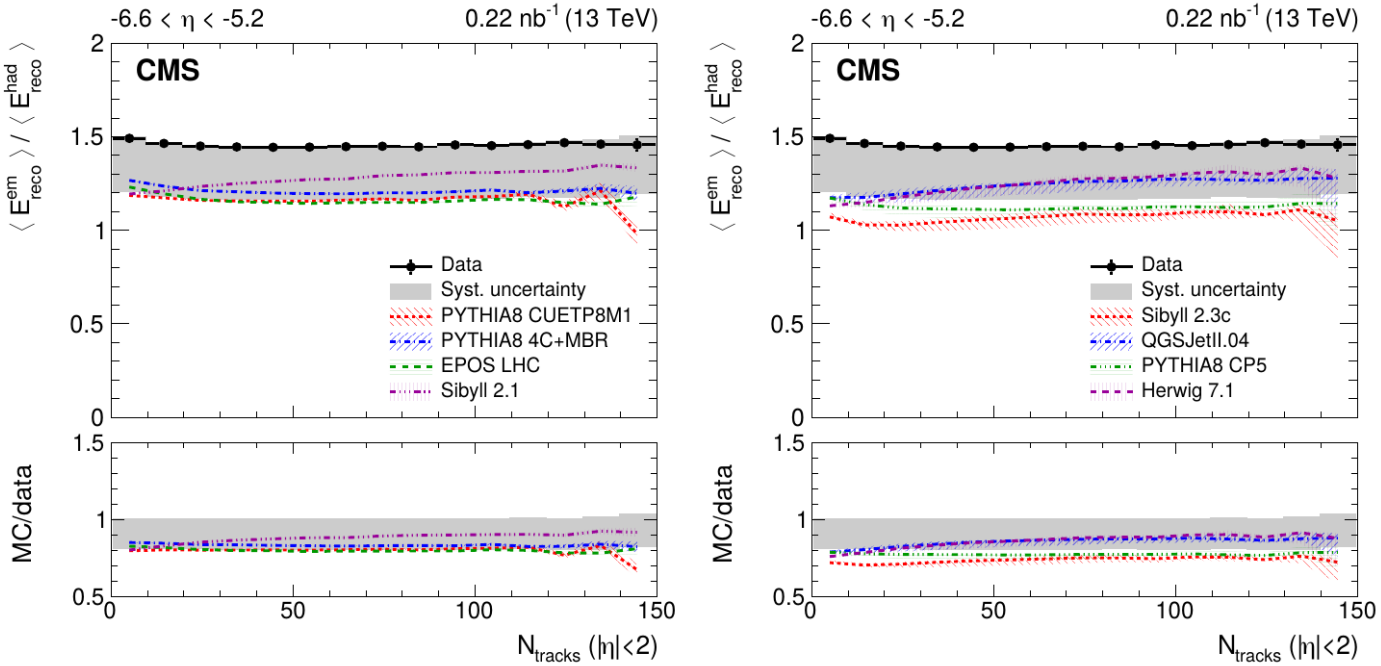
Relation to muon mystery



Orthogonal to many other effects → important for muon mystery

Measurement at CMS/CASTOR

Measurement of the average very forward energy as a function of the track multiplicity at central pseudorapidities in proton-proton collisions at 13 TeV:



CMS, arXiv:1908.01750 [hep-ex], submitted

LHC shopping list

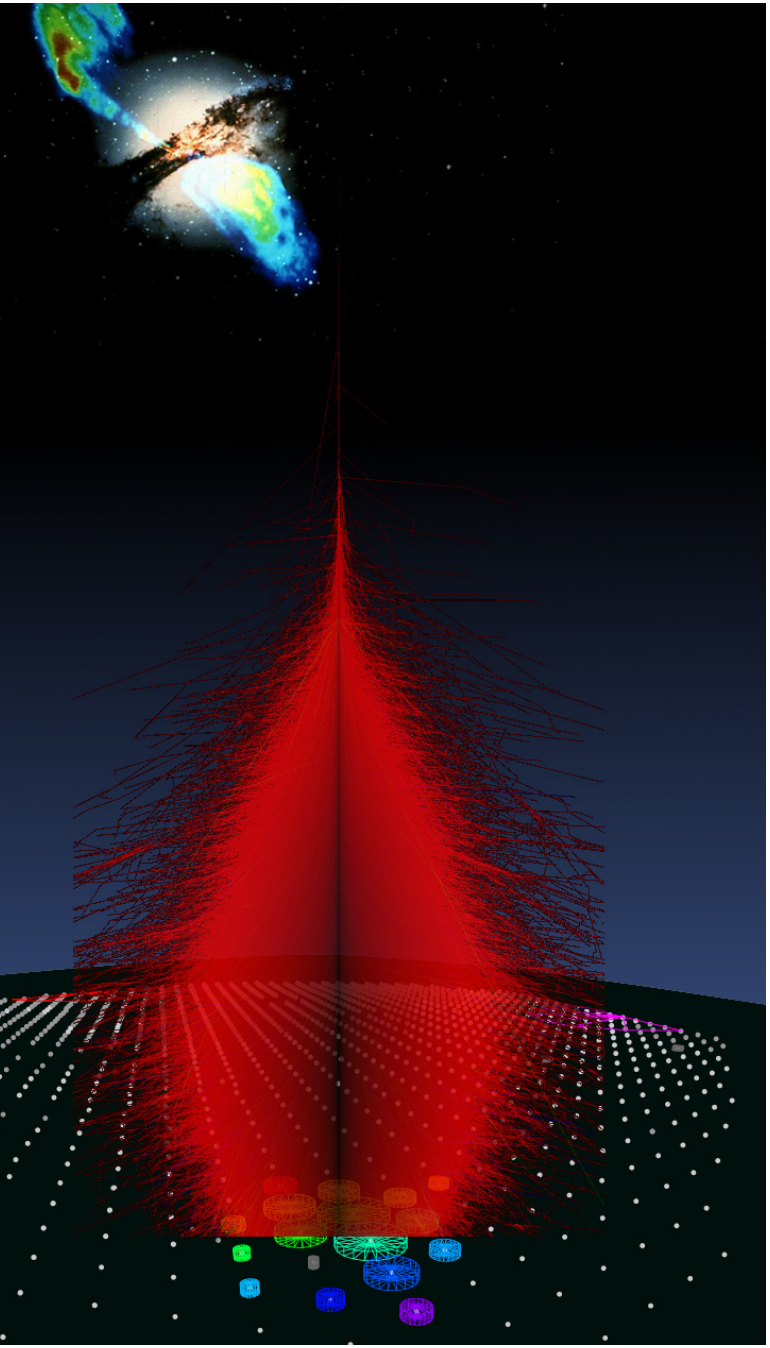
At 13 TeV

- Total and elastic cross section, elastic slope, imaginary to real part of amplitude (rho)
- Soft diffraction, rapidity gaps, characteristics of "pomeron" exchange
- Mini-jets, PID spectra, correlations
- PDF constraints ($W^{\pm}$, Z, ...)
- LHCf zero-degree π^0 and neutrons
- Underlying event with CASTOR, CMS+TOTEM $dN/d\eta$

Finally

- LHC energy scan: 0.9 GeV $\rightarrow$ large x_F-range
- Nuclear scan: proton-lead, proton-oxygen
- Maximum acceptance, dedicated detector components
- Pion as beam particle

Summary



LHC impact on UHECR interpretation

- Models are constraint much better
- Predictions tend to converge (overall)
- Different observables have very different sensitivity to interaction uncerainties
- Muon mystery may be related to a few percent of unaccounted physics per collision
- Models so far tuned at LHC roughly to a level of about 10 %
- Forward detectors ultimately of paramount importance
- Important for air showers: energy AND phase space !
- Nuclear effects are another important source of uncertainties. Need oxygen in LHC.