Karlsruhe Institute of Technology

PIERRE AUGER OBSERVATORY

CMS Compact Muon Solenoid

Ultra-High Energy Cosmic Rays and Hadronic Interaction Models

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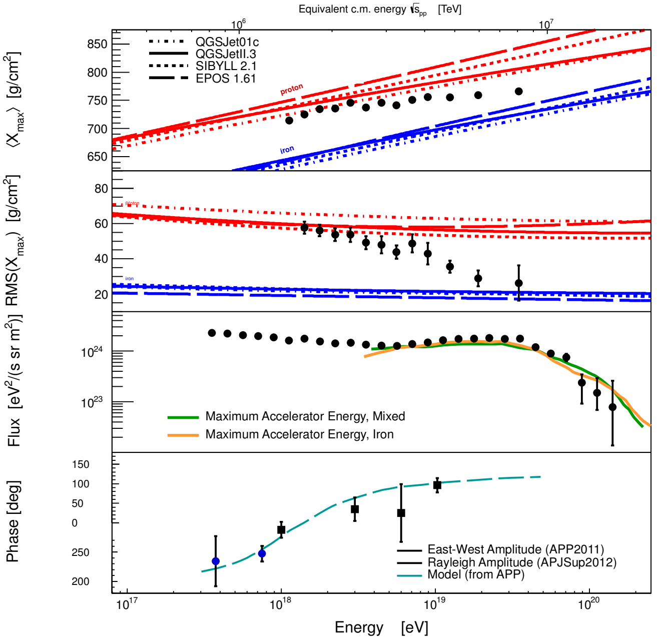
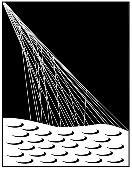
Karlsruhe Institute of Technology

PANIC, 27. August 2014 Hamburg

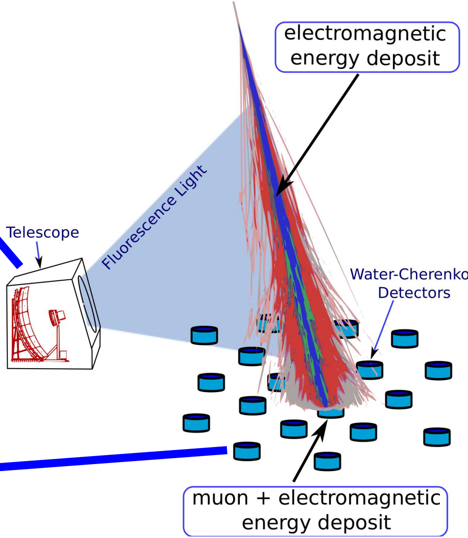
UHECR, Overview of Experimental Situation





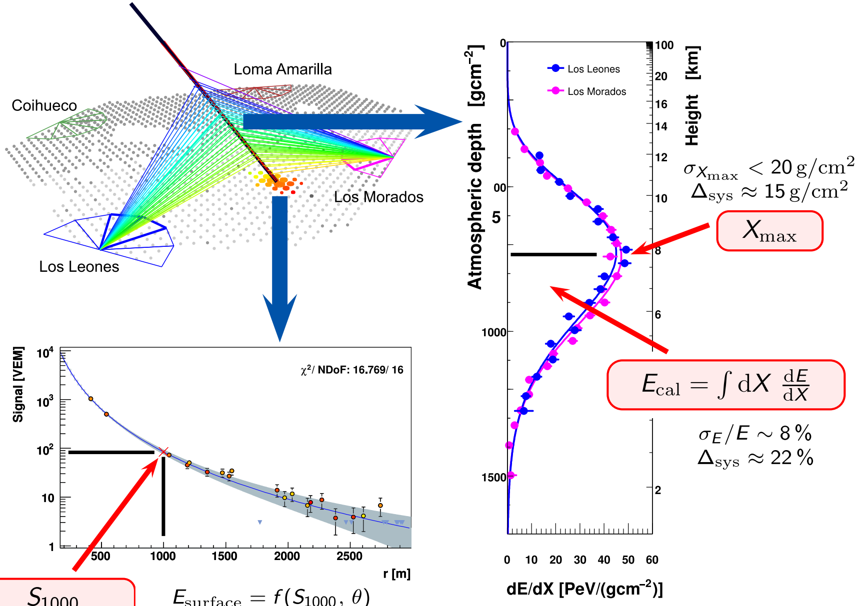
Experimental Techniques (Pierre Auger)

24 Telescopes, 4 Sites



1600 Water-Cherenkov Detectors, ≈3000 km^2

Data and Reconstruction



S_{1000}

$E_{\rm surface} = f(S_{1000},\, \theta)$

$X_{\rm max}$

$\sigma_{X_{\rm max}} < 20\,{\rm g/cm^2}$
$\Delta_{\rm sys} \approx 15\,{\rm g/cm^2}$

$E_{\rm cal} = \int {\rm d}X \, \frac{{\rm d}E}{{\rm d}X}$

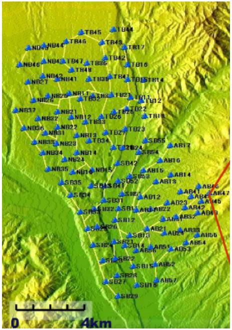
$\sigma_E/E \sim 8\,\%$
$\Delta_{\rm sys} \approx 22\,\%$

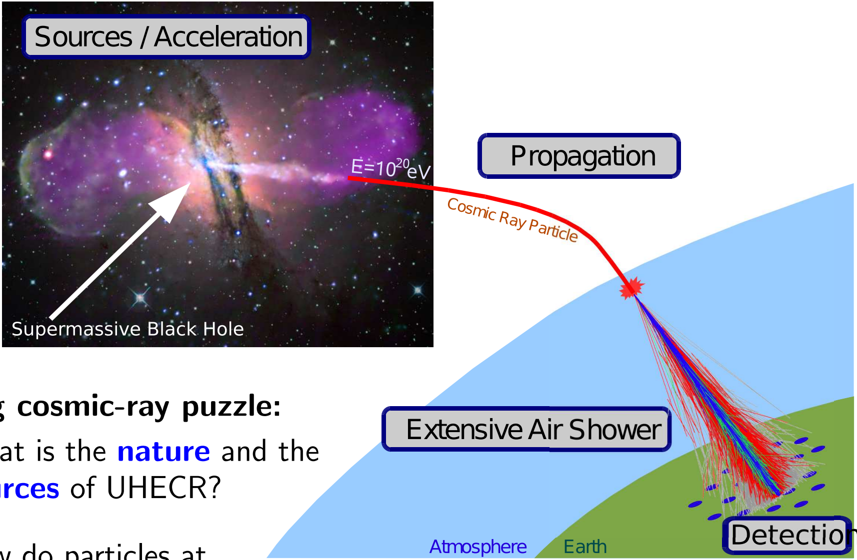
Other Ultra-High Energy Observatories

Telescope Array / HiRes

Yakutsk

AGASA

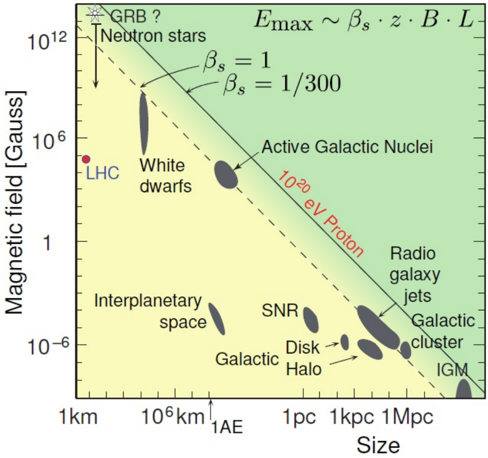




Solving cosmic-ray puzzle:

- What is the **nature** and the **sources** of UHECR?
- How do particles at ultra-high energies **interact**?

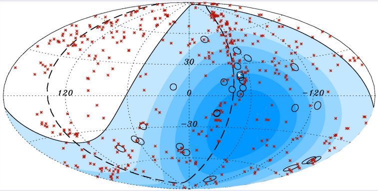
Potential Sources?



- $E_{\max} \propto \beta_s z B L$
- Due to energy losses, sources cannot be "far" away ($\sim \mathcal{O}$(10 Mpc))
- There are only few very powerful "good" source candidates...
- Iron easier to accelerate than proton
- Difficult to produce protons at $E > 10^{20}$ eV
- Unknown how useful directional information is (charge of particles? magnitude and structure of fields? distances?)

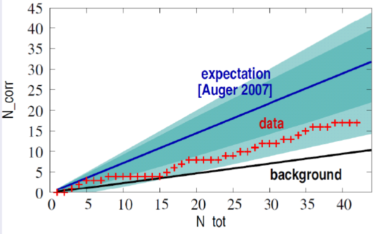
Anisotropies in North and South (at E>57 EeV)

Auger 2007

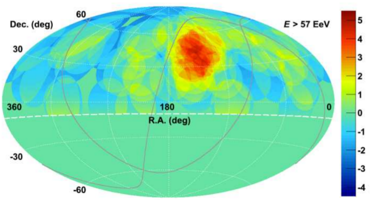


Science 318 (2007) 938

Telescope Array 2013



APJ 777 (2013) 88

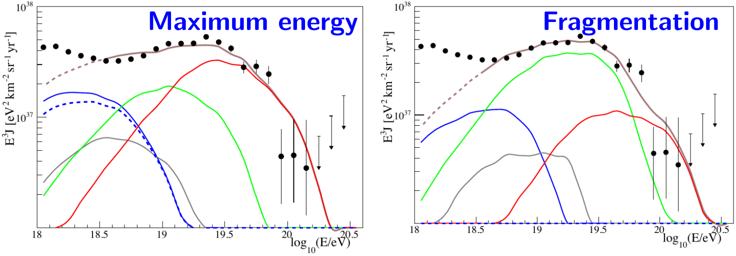


Astrophys.J. 790 (2014) L21

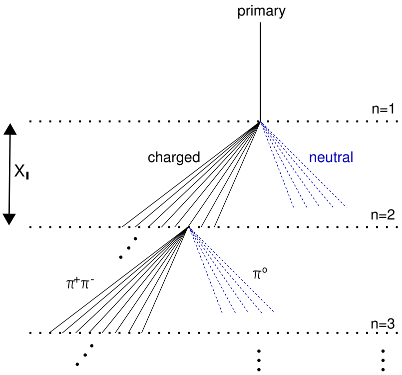
Any clear anisotropy signal indicates the presence of protons in UHECR.

- Data very precise over wide range in energy
- No simple model works
- Also composition sensitive data disfavours simple models

proton helium nitrogen iron



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

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

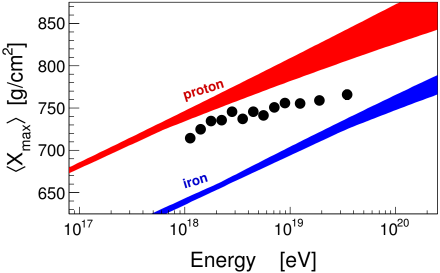
where

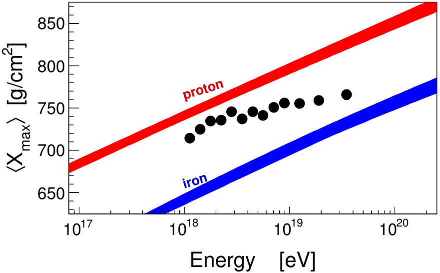
$$\beta = \ln\left(\tfrac{2}{3}\, N_{\mathrm{mult}}\right) / \ln\left(N_{\mathrm{mult}}\right) \approx 0.9$$

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

EPOS 1.99 → **EPOS LHC**

QGSJetII.3 → **QGSJetII.4**



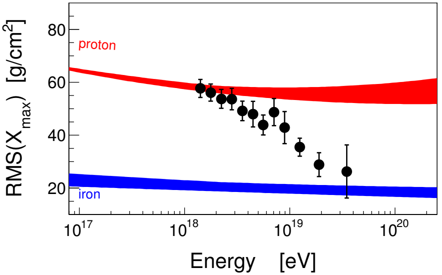


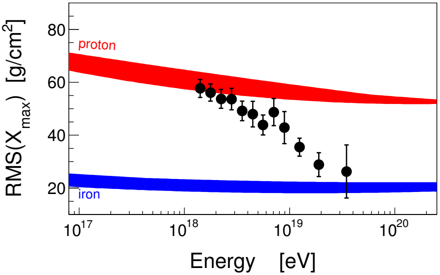
Caveats / Potential:

- 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**

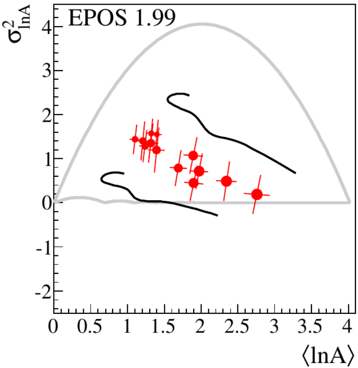


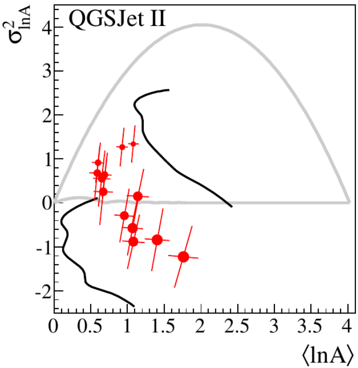


Caveats:

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

Correlations between Average and RMS

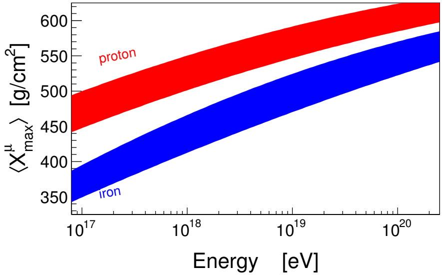




JCAP 02 (2013) 026

- All models compatible with a changing mass composition as a function of energy
- Some tension of a few models with the data

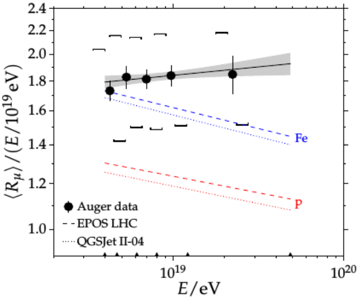
EPOS LHC
QGSJetII.4

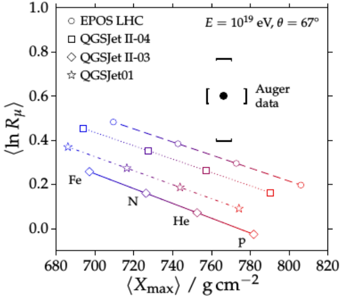


Status after tuning to 7 TeV:

- Spread of model predictions has not been improved
- Still very difficult to simulate muons
- No model is able to describe the muon content of air showers

Muon Content at Ground Level





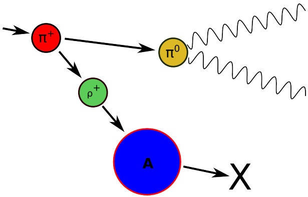
Auger, arXiv-1408.1421 [atro-ph]

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

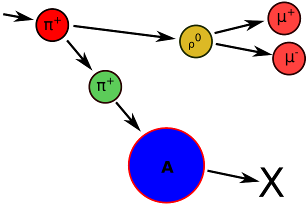
→ Possible cause: interaction physics in air showers models is not accurate

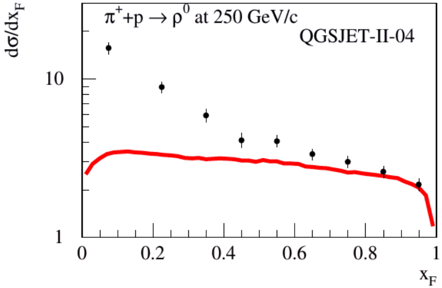
(Forward) ρ^0 Production, QGSJetII.3→QGSJetII.4

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



versus





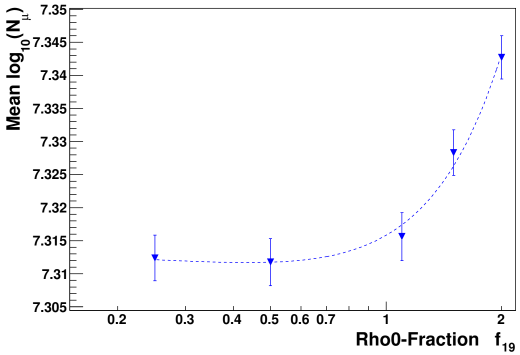
S. Ostapchenko, ISVHECRI 2012

Impact on Muons in Air Showers

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

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

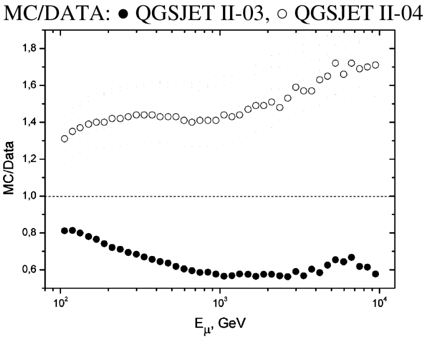
(f19 is the scaling factor for ratio at 10^{19} eV, logarithmic energy dependence)



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

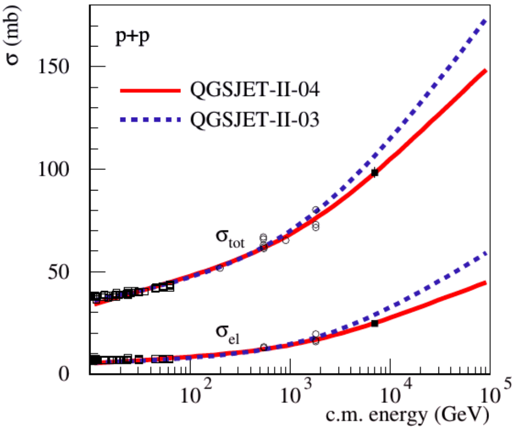
⇒ Too many ρ^0 produced now?

Problems: Acceptance and Extrapolations

⇒ **Reduce extrapolation uncertainties in interaction models**

- **Center-of-mass-energy**
  LHC, Central measurements plus **forward region**
- **Phase-space**
  - **Nuclear Effects**
    LHC: compare p-p, Pb-p and e.g. **p-O**
  - **high-x_F**
    Fixed Target Experiments at SPS, but also with **LHC beam**

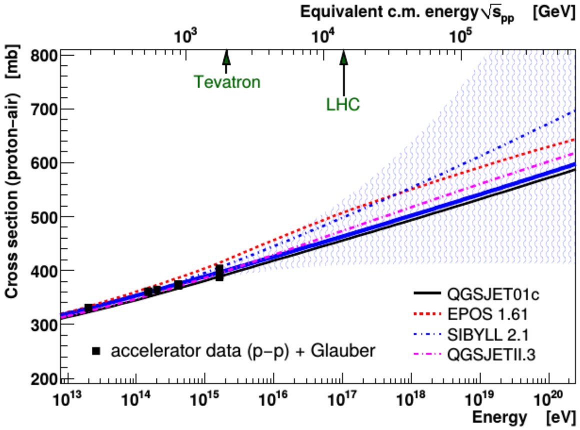
Model Tuning to LHC Data up to 7 TeV



S. Ostapchenko, ISVHECRI 2014

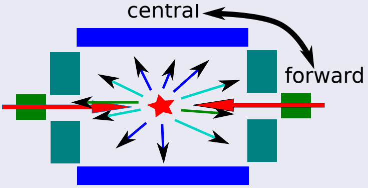
Proton-Air Cross Section is one of the most important quantities for air shower modeling

Proton-Proton → Proton-Air



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

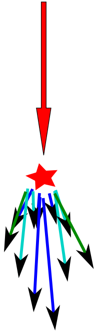
Large uncertainties due to nuclear effects from pp to p-air



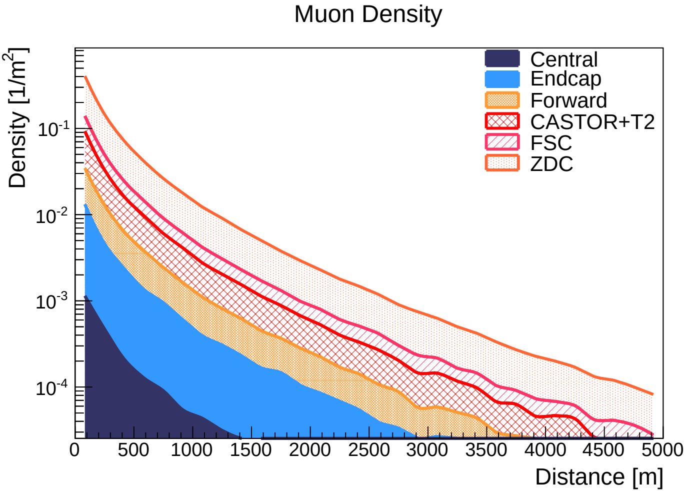
- Central ($|\eta| < 1$)
- Endcap ($1 < |\eta| < 3.5$)
- Forward ($3 < |\eta| < 5$), HF
- CASTOR+T2 ($5 < |\eta| < 6.6$)
- FSC ($6.6 < |\eta| < 8$)
- ZDC ($|\eta| > 8$), LHCf

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

$\rightarrow$ Simulate parts of shower individually.

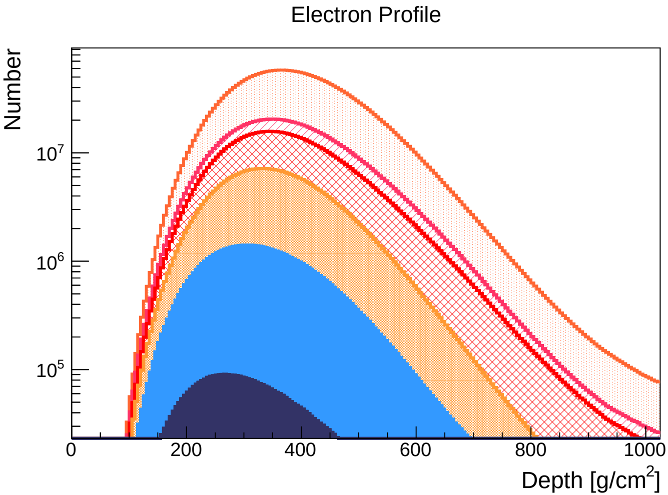


Lateral Particle Density on Ground Level



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

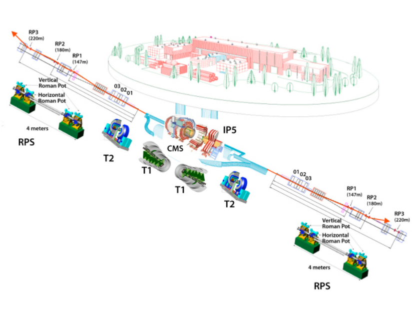
Longitudinal Shower Development



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

LHC Forward Detectors

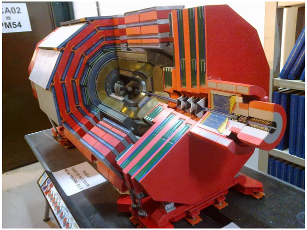
TOTEM

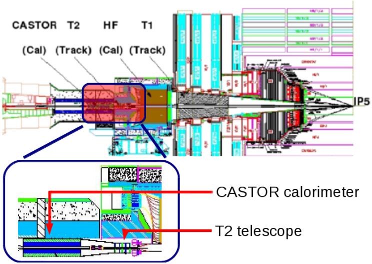


LHCf

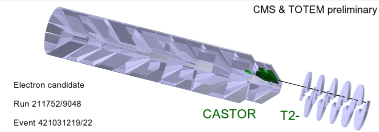
CASTOR

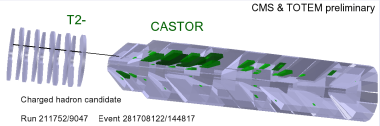
- TOTEM: Very forward particle production and elastic
- LHCf: Very forward photon, π^0, neutrons
- CASTOR: Very forward energy, diffraction





Particle Reconstruction





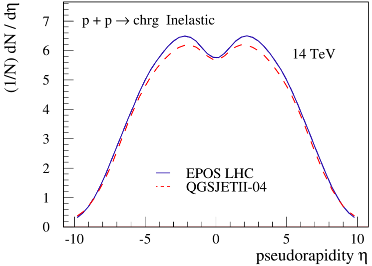
320 GeV at $\eta = -5.97$

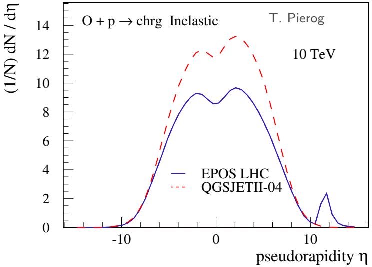
210 GeV at $\eta = -5.69$

Jets, leptons and resonances at η up to 6.6

Proton-Oxygen Data at LHC: **Very Relevant**

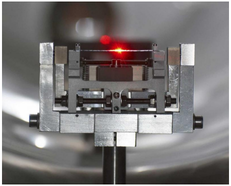
- Asymmetric heavy-ion run with proton-oxygen nuclei
- After LS1, $\sqrt{s_{\mathrm{NN}}^{\mathrm{pO}}} = 10\ TeV$ (Proton beam at 7 TeV)
- Oxygen very close to atmospheric material of extensive air shower production (nitrogen)
- Impact on model predictions :





Fixed Target with LHC Beam

Bent crystal, UA9:



e.g. PRL 87 (2001) 094802

A Fixed Target ExpeRiment at LHC

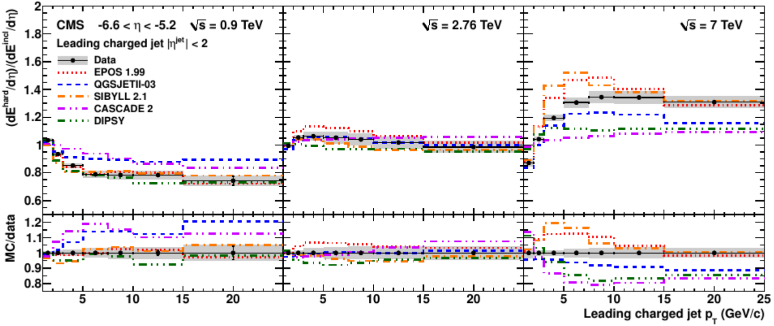
arXiv/hep-ph 1207.3507

- Precision QCD
- W/Z studies,
- Quarkonia physics
- Cosmic Rays, Neutrino Production

First steps

IDHEFIX Proposal in H2020, 1st AFTER week at CERN Nov/2014

Very forward underlying event:

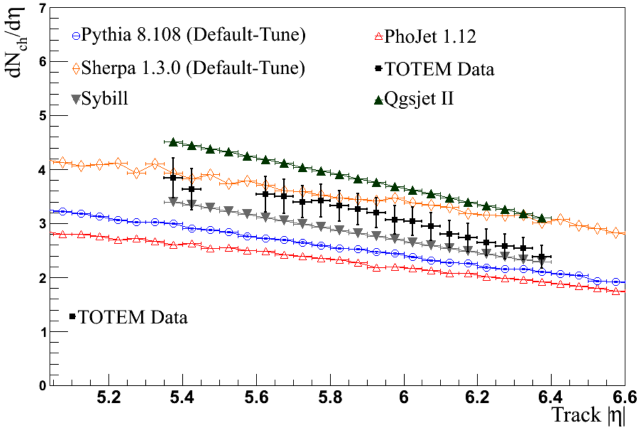


JHEP 1304 (2013) 072

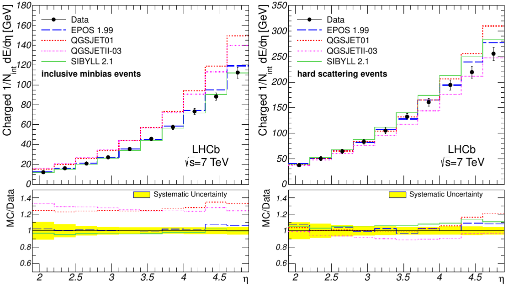
In CMS:

- Used for pPb and PbPb (and forward pp) detector studies and correction factors
- Where relevant, also event generator comparisons are performed

Cosmic Ray Models and Recent LHC Data: TOTEM



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

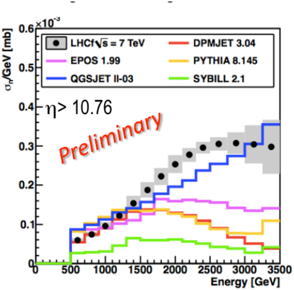


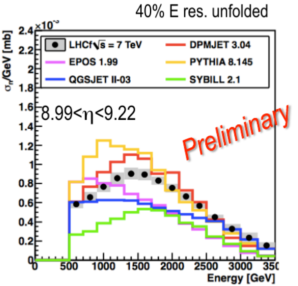
Eur.Phys.J. C73 (2013) 2421

Comparison on event generator level:

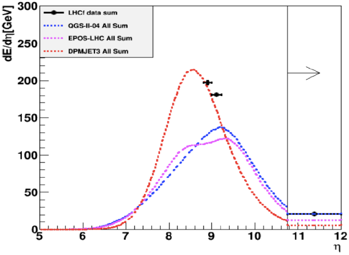
- Forward energy flow
- Forward Lambda production, strangeness
- More in preparation...

Cosmic Ray Models and Recent LHC Data: LHCf





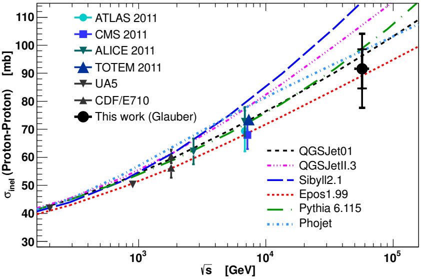
- Unique Collaboration/Experiment
- Very good phase-space to constrain cosmic-ray models
- Only caveat: limited to neutrals



Plot by N.Sakurai

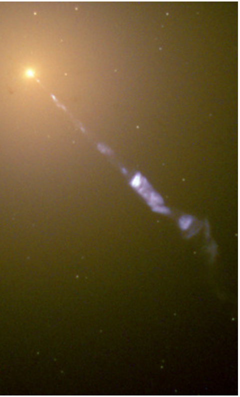
But also Cosmic Rays can add Information:

- Measure cross sections in extensive air showers from fluctuations (57 TeV)
- Measure muon content
- Cosmic Ray data constrains particle production over wide ranges of energies, including accelerators
- Exotic shower profiles can provide information on elasticity, diffraction, ...



Auger: *Phys. Rev. Lett. 109, 062002 (2012)*

Summary



$\Rightarrow$ **UHECR data becomes much more precise**

$\Rightarrow$ **Currently, no fully consitent picture of physics**

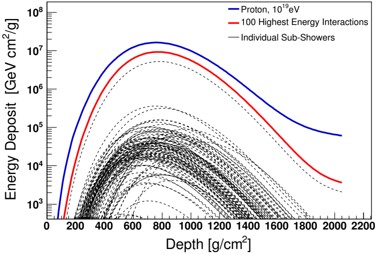
$\Rightarrow$ **Hadronic interactions play key role**

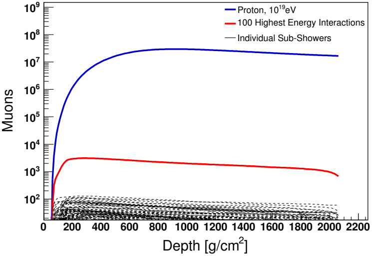
Sensitivity to Interaction Physics

- Wide range of energies, reaching beyond accelerators
- Uncertainty: extrapolation of hadronic interactions
  - Phase space (!)
  - Energy

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

X_{max} Very high energy interactions
Muons Low energy interactions

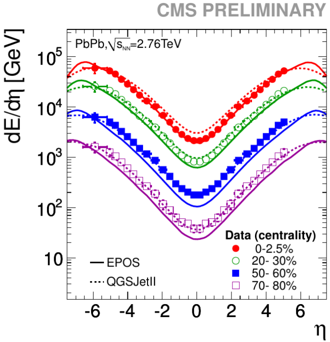


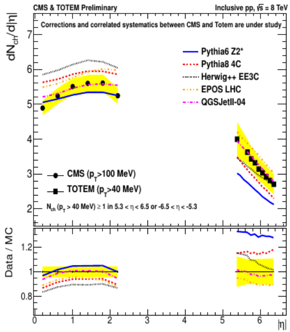


TOTEM, LHCf, TOTEM+CMS

- Total, elastic, inelastic, diffractive cross-sections
- Forward photon and neutron spectra.
- Diffraction
- Generell particle production characteristics

For example:





Deflection in Magnetic Fields