Karlsruhe Institute of Technology

Review of LHC Data

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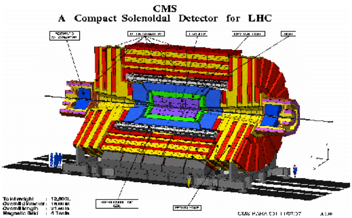
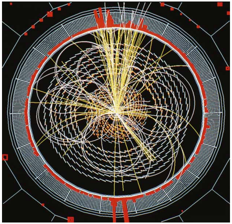
UHECR, 13. Oct 2014 Springdale

Interactions in EAS: Acceptance and Extrapolations

⇒ **Reduce uncertainties in interaction models with accelerator data**

- **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**





- **Pseudorapidity,** η

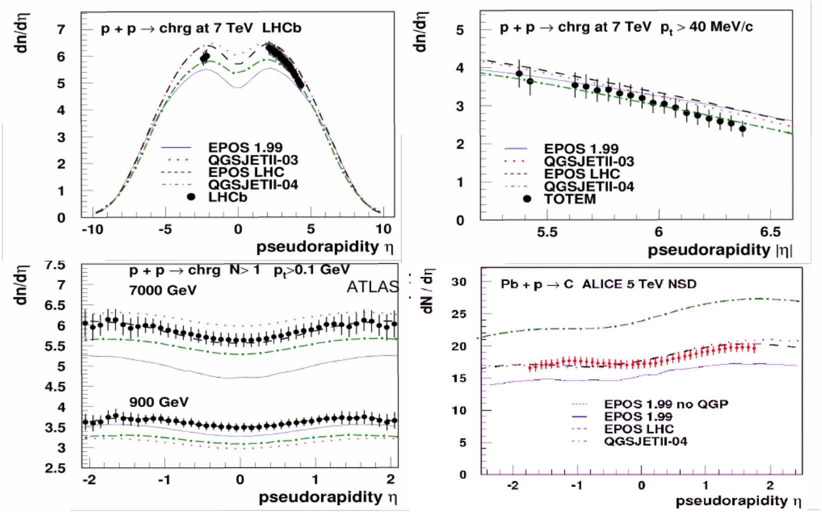
  $\eta = -0.5 \log \tan(\theta/2)$,

  where θ is the angle w.r.t. z-axis, which is beam direction

- **Magnetic Deflection and** p_T

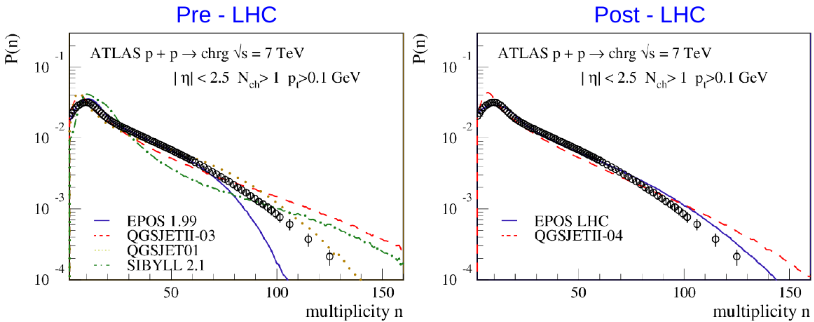
  Tracking: $p_\mathrm{T} > 100\,\mathrm{MeV}$
  Calorimetry: $p_\mathrm{T} > 1\,\mathrm{GeV}$

Pseudorapidity Densities After Tuning to LHC (7TeV)

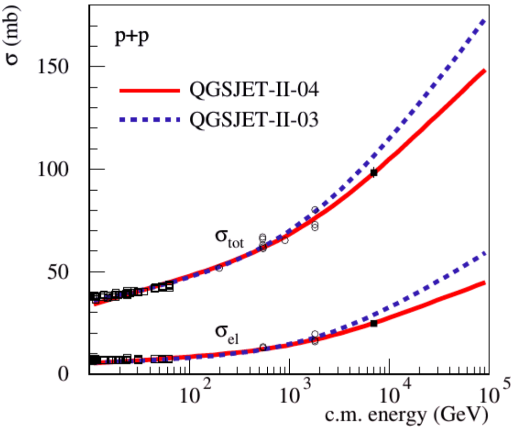


- Very good description of (central) data

Multiplicities After Tuning to LHC (7TeV)



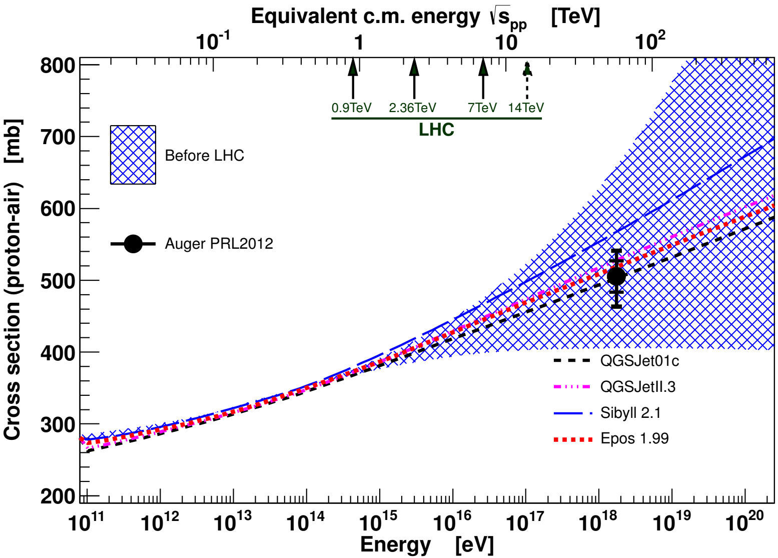
- Average better described
- Still differences in the shape
- Modelling of tail much better



S. Ostapchenko, ISVHECRI 2014

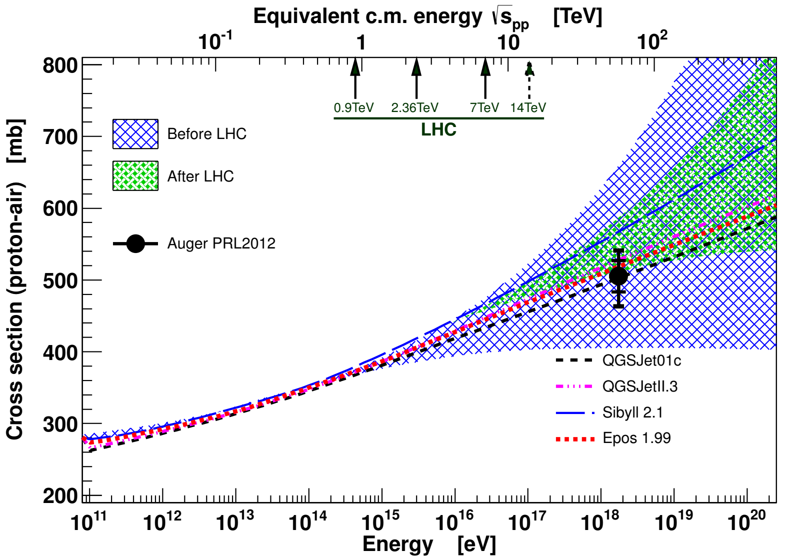
Proton-Air Cross Section is one of the most important quantities for air shower modeling

Proton-Proton → Proton-Air, With Tevatron Data



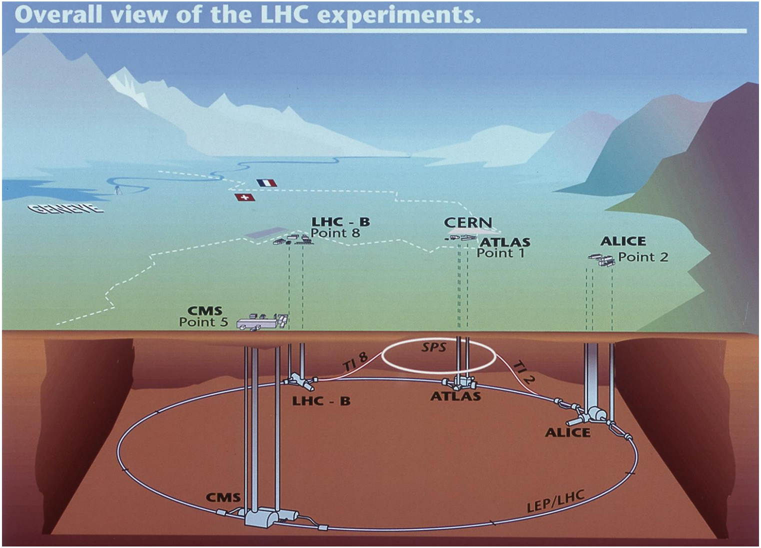
Nucl.Phys.Proc.Suppl. 196 (2009) 335

Proton-Proton → Proton-Air, With LHC Data

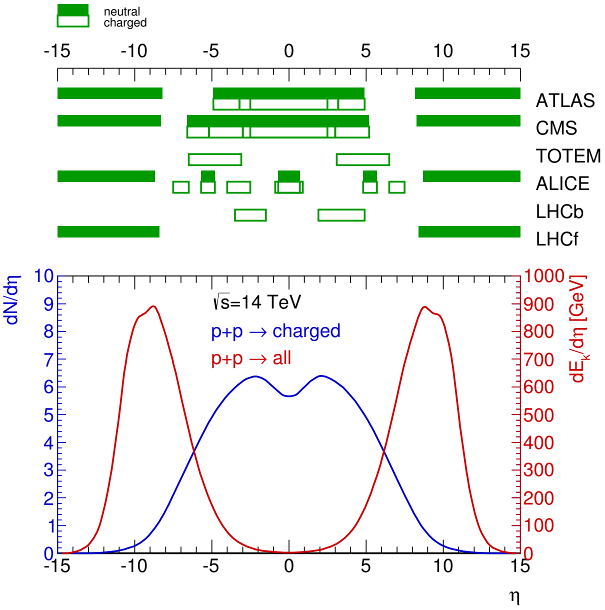


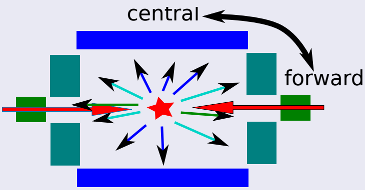
Update: ECRS 2014

Large Hadron Collider and Experiments



Large Hadron Collider and Experiment Acceptances

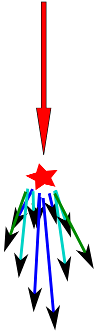




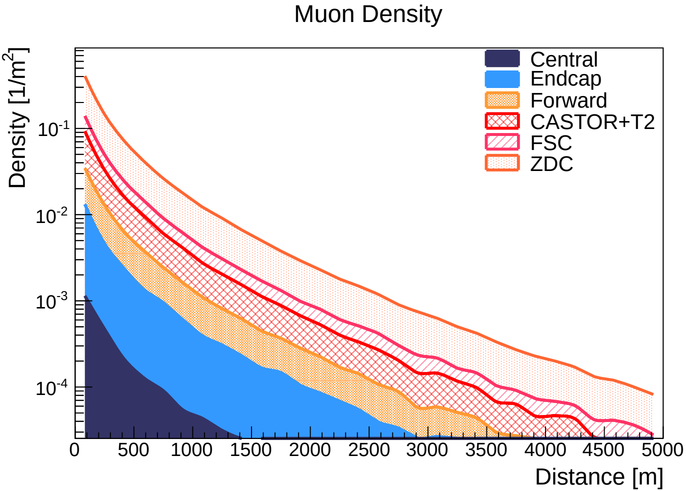
- Central ($|\eta| < 1$)
- Endcap ($1 < |\eta| < 3.5$)
- Forward ($3 < |\eta| < 5$), HF
- CASTOR+T2 ($5 < |\eta| < 6.6$)
- FSC ($6.6 < |\eta| < 8$)
- ZDC ($|\eta| > 8$), LHCf

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

$\rightarrow$ Simulate parts of shower individually.

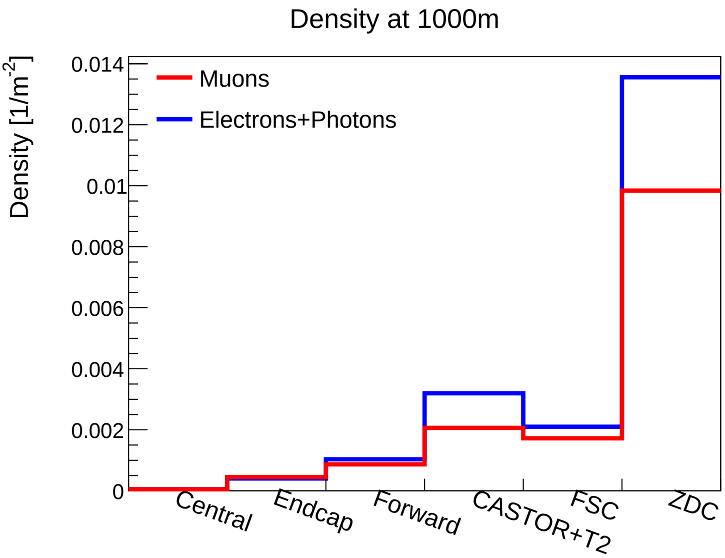


Lateral Particle Density on Ground Level

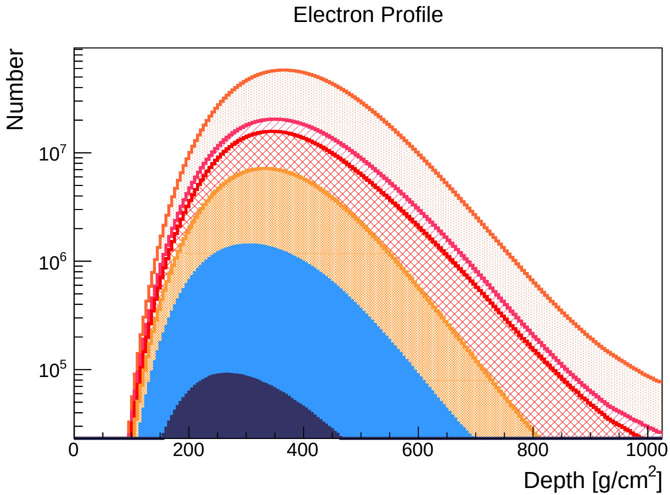


- Air shower models so far only tuned to about 10 % !
- Forward detectors are crucial.

Particle Densities at 1000 m From Shower Core



Only partly accessible to observation at LHC !



- Air shower models so far only tuned to about 10 % !
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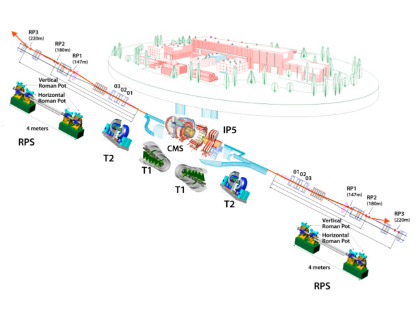
TOTEM

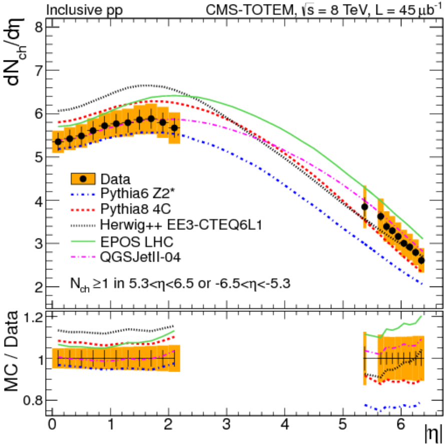


LHCf

CASTOR

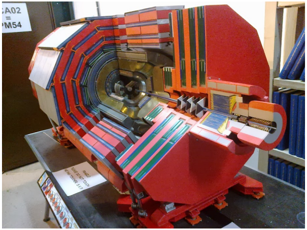
- TOTEM: Very forward particle production and elastic
- LHCf: Very forward photon, π^0, neutrons
- CASTOR: Very forward energy, diffraction

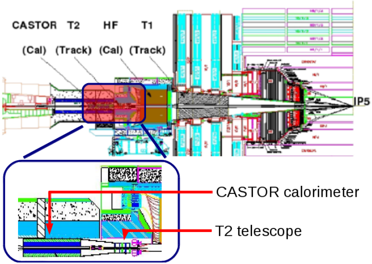
Maximal Acceptance: CMS+TOTEM at 8TeV



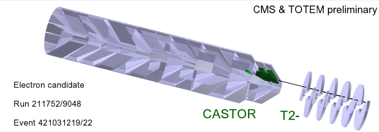
- New collaboration between CMS+TOTEM
- Models better in the center are worse forward, and vice versa
- QGSJetII.4 describes these data best

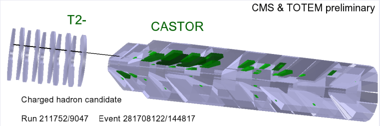
TOTEM/T2 + CMS/CASTOR





Particle Reconstruction



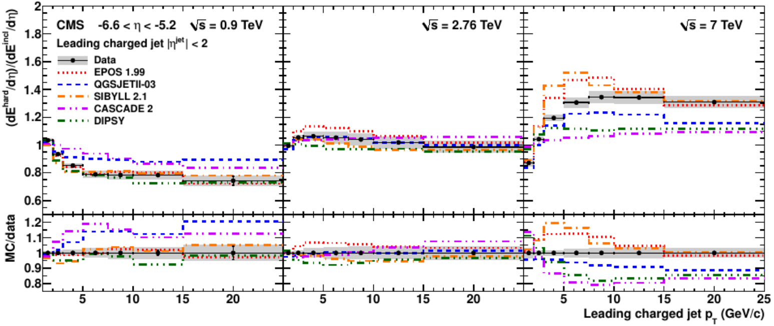


320 GeV at $\eta = -5.97$

210 GeV at $\eta = -5.69$

Jets, leptons and resonances at η up to 6.6

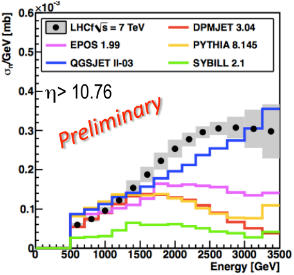
Energy in Very Forward Direction: CMS/CASTOR

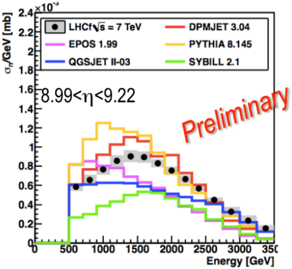


JHEP 1304 (2013) 072

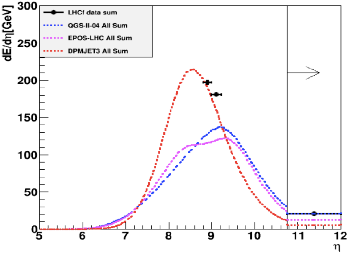
- Unique measurement at very forward phase-space
- Discrepancies become large for higher energies
- 13 TeV data will be very interesting to get

More: Nobuyuki Sakurai, this conference
Here: results shown at ISVHECRI 2014

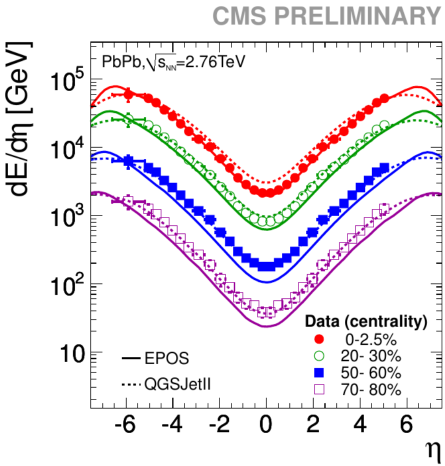




- Unique Collaboration/Experiment
- Very good phase-space to constrain cosmic-ray models
- Only caveat: limited to neutrals

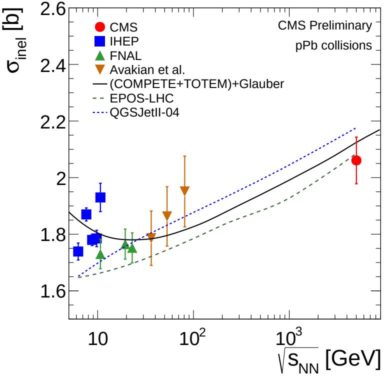


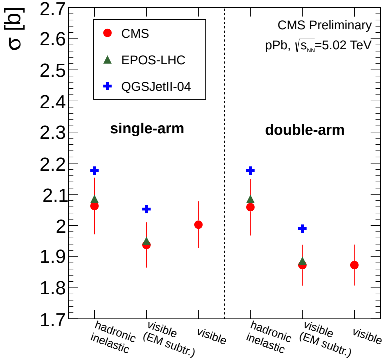
Plot by N.Sakurai



- Lead-Lead provides extreme scenario, however, peripheral collisions can be compared to the collision of light nuclei
- No model performs equally well going from very central to peripheral PbPb collisions

Nuclear Effects in the Cross Section (Proton-Lead)

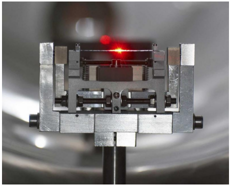




- Test of Glauber Model (pp and pPb) at LHC
- Standard Glauber Model performs well
- QGSJetII.4 slighlty too high

Fixed Target with LHC Beam

Bent crystal, UA9:



e.g. PRL 87 (2001) 094802

A Fixed Target ExpeRiment at LHC (AFTER@LHC)

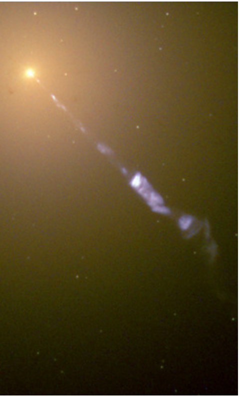
arXiv/hep-ph 1207.3507

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

First steps

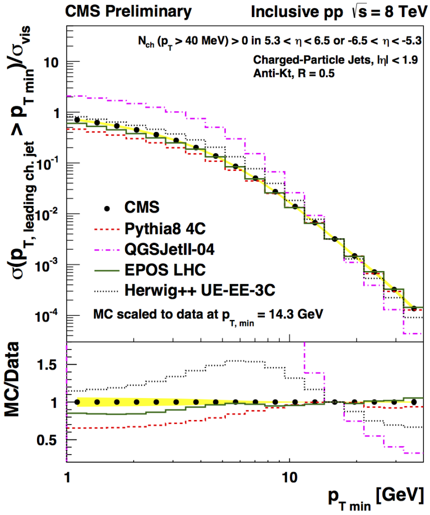
1st AFTER-week at CERN Nov/2014

Summary



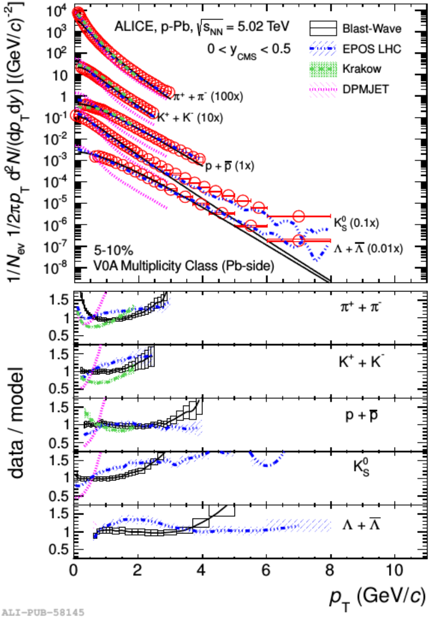
⇒ **Major impact of LHC data on cosmic ray models**
⇒ **Expect more from 13TeV collisions in 2015**
⇒ **Phase-space for tuning not yet fully exploited**

Additional Material



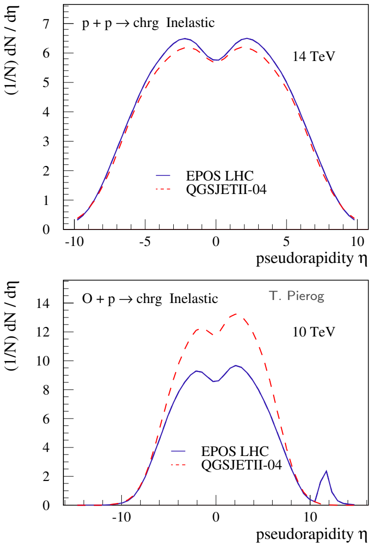
- Main origin of particle production in air showers
- Information on the multiple-scattering nature of collisions
- Cosmic ray models describe data better than e.g. PYTHIA

Nuclear Effects in Proton-Lead Collisions



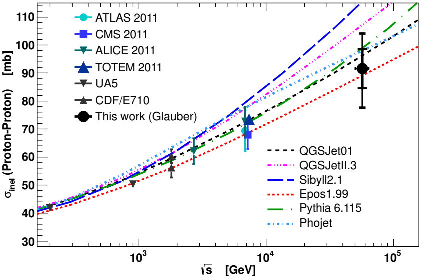
- Proton-Lead is a closer to the CR-Air system as compared to Lead-Lead
- EPOS performs very well for central collisions at central rapidity
- Results with identified particles provide additional information

- 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 :



Cosmic Rays also 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, ...



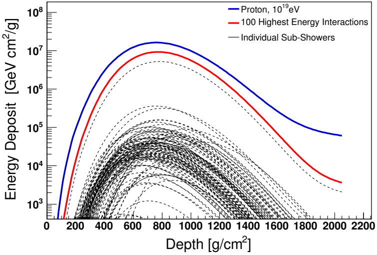
Auger: *Phys. Rev. Lett. 109, 062002 (2012)*

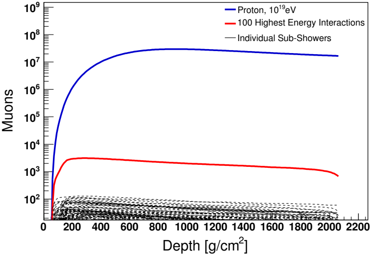
Sensitivity to Interaction Physics

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

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

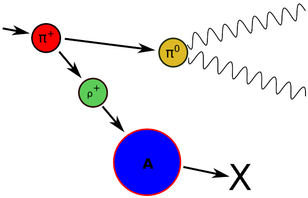
X_{max} Very high energy interactions
Muons Low energy interactions



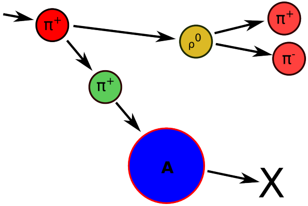


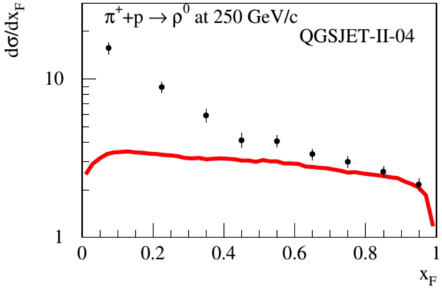
(Forward) ρ^0 Production, QGSJetII.3→QGSJetII.4

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



versus





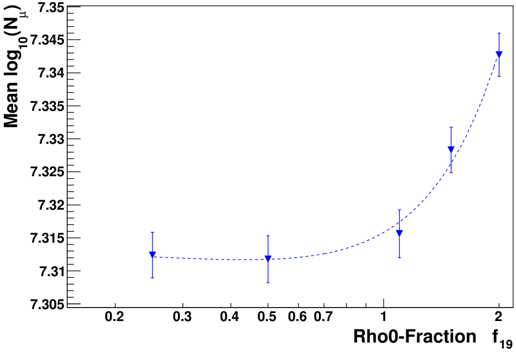
S. Ostapchenko, ISVHECRI 2012

Impact on Muons in Air Showers

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

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

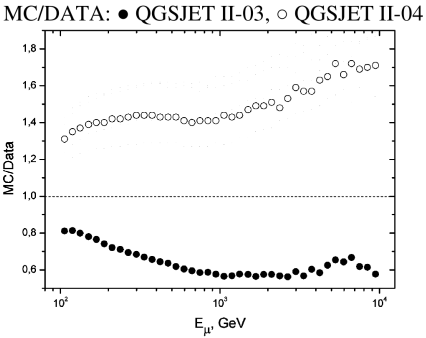
(f19 is the scaling factor for ratio at 10^{19} eV, logarithmic energy dependence)



Ulrich, Engel, Baus, ISVHECRI 2014

Forward ρ^0 production, QGSJetII.4

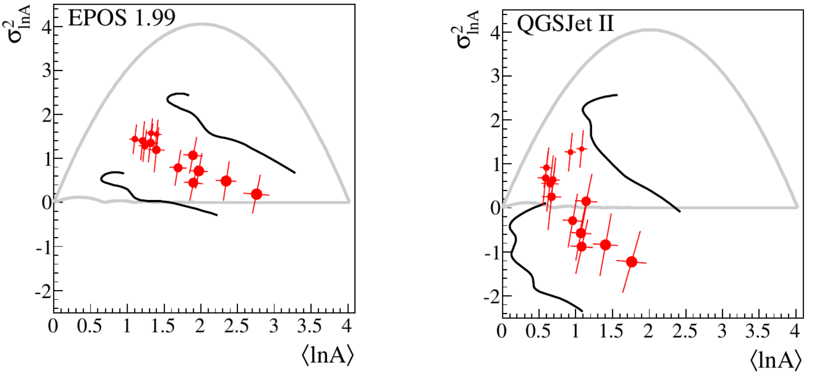
Prediction of inclusive athmospheric muon fluxes as a test of hadronic interaction models



A.V. Lukyashin, ISVHECRI 2014

⇒ Too many ρ^0 produced now?

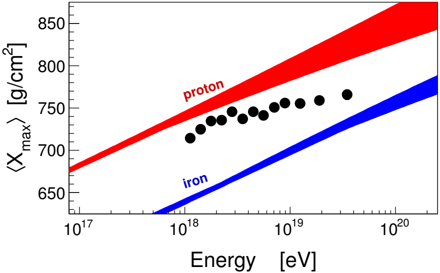
Correlations between Average and RMS

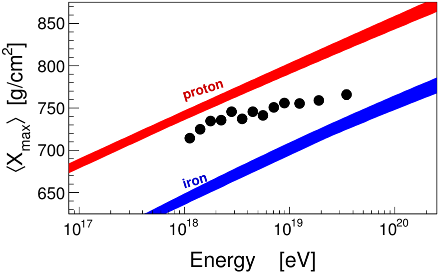


JCAP 02 (2013) 026

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

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

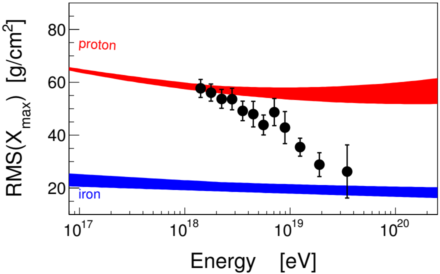


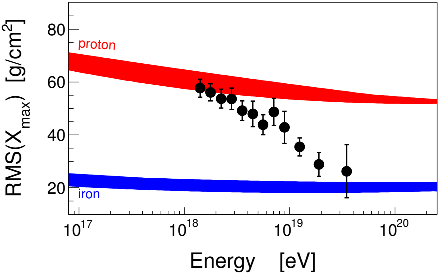


Caveats / Potential:

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

EPOS 1.99	$\rightarrow$	**EPOS LHC**
QGSJetII.3	$\rightarrow$	**QGSJetII.4**

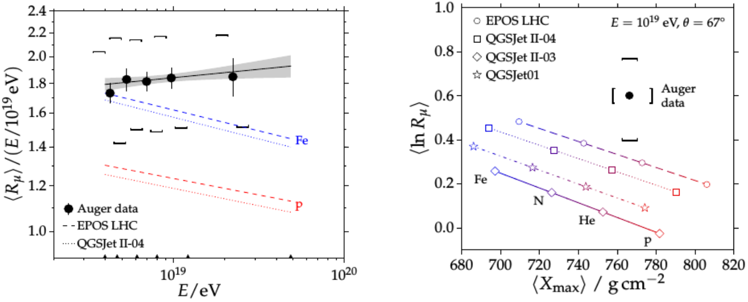




Caveats:

- 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

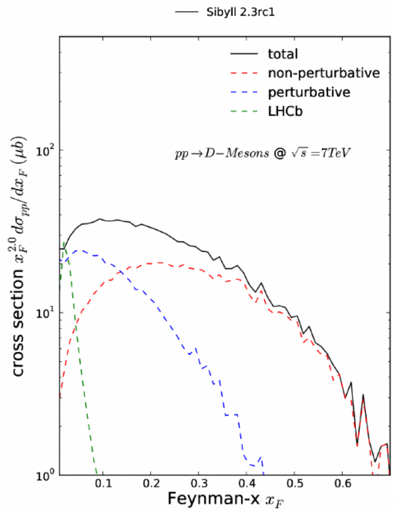


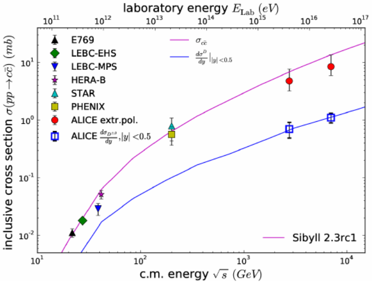
Auger, arXiv-1408.1421 [atro-ph]

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

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

Acceptance for Charm Production at LHC





F. Riehn, ISVHECRI 2014

LHCb: $\approx$7 % of total production observed