Karlsruhe Institute of Technology

PIERRE AUGER OBSERVATORY

CMS Compact Muon Solenoid

The Importance of Accelerator Measurements for the Interpretation of UHECR data

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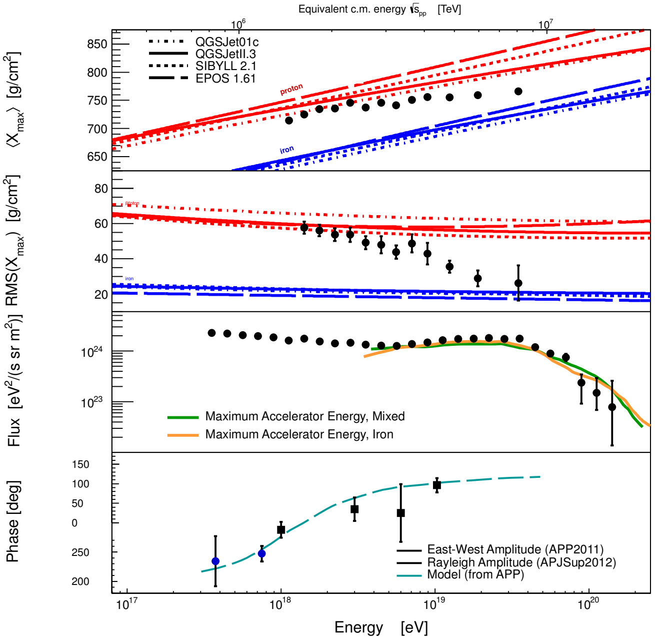
October 30th 2014, Rome

Ultra-High Energy Cosmic Rays, Data



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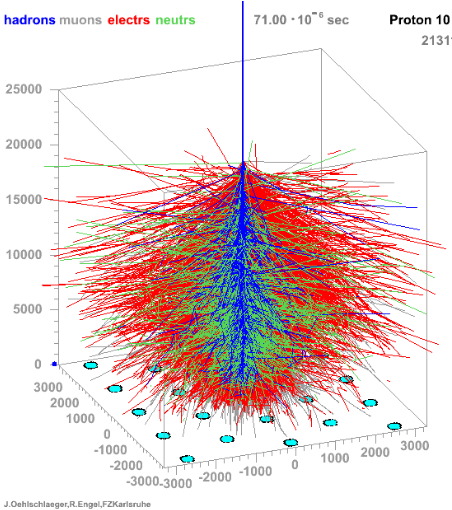
Extensive Air Showers



Air showers are very extended cascades and contain a huge number of particles
$N \sim E_0/(O(1\,GeV))$

Typical observables are:

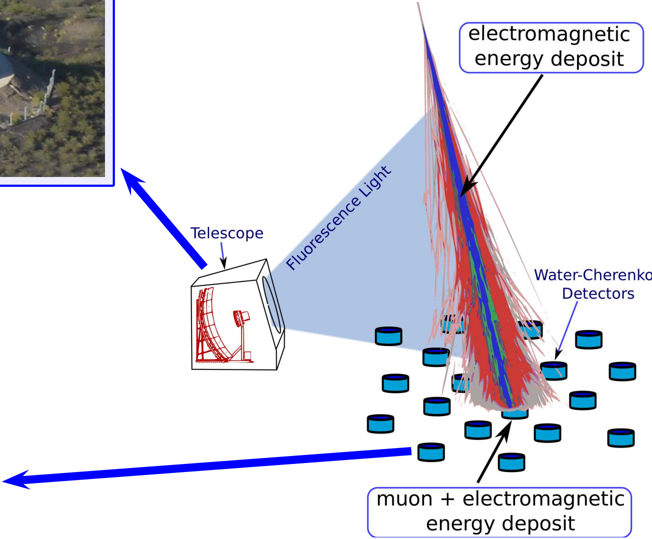
- $\mathbf{X_{max}}$ Slant depth of shower maximum
- $\mathbf{N_e}$ Number of electrons at ground level
- $\mathbf{N_\mu}$ Number of muons at ground level

At Ultra-High Energies

X_{max} most precisely measured N_μ most challenging to understand

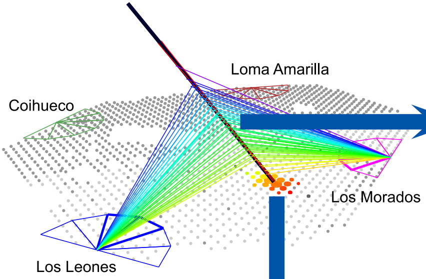
Ultra-High Energy Cosmic Rays, Experiments

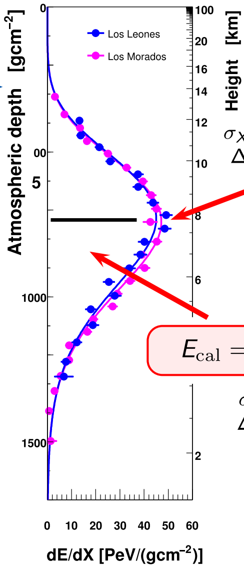
24 Telescopes, 4 Sites



1600 Water-Cherenkov Detectors, $\approx 3000\,\text{km}^2$

Data and Reconstruction



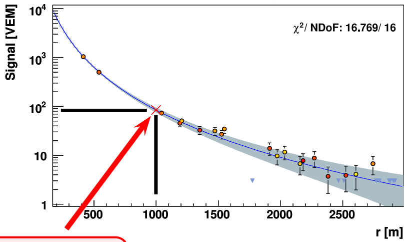


$\sigma_{X_{\max}} < 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \approx 15\,\mathrm{g/cm^2}$

$X_{\max}$

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

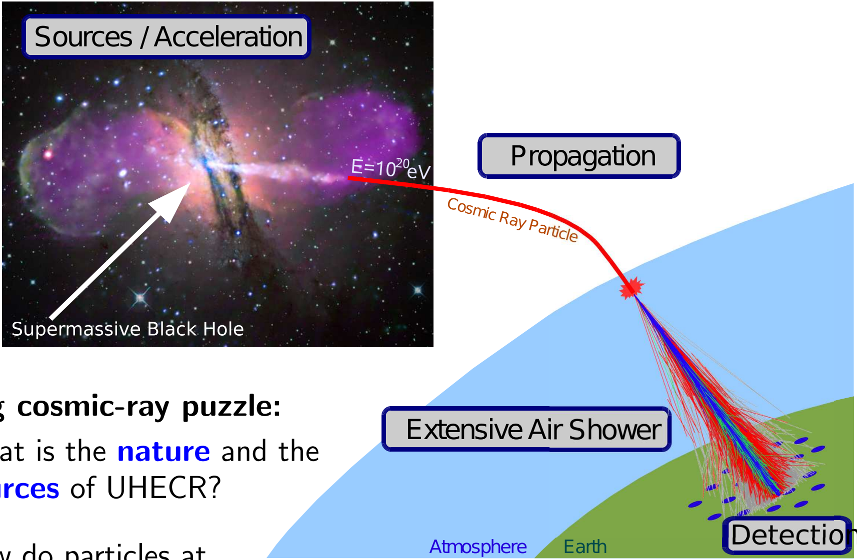
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 22\,\%$



S_{1000}

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

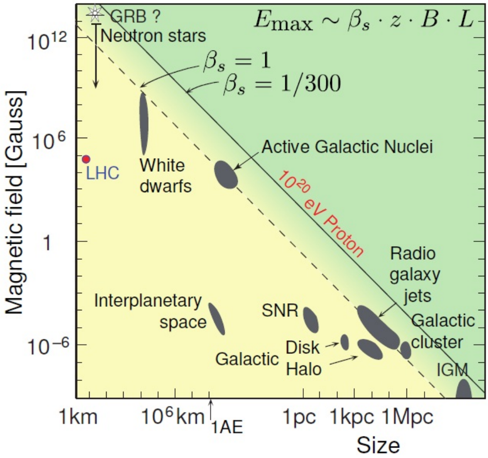
Ultra-High Energy Cosmic Rays, Questions



Solving cosmic-ray puzzle:

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

Sources?

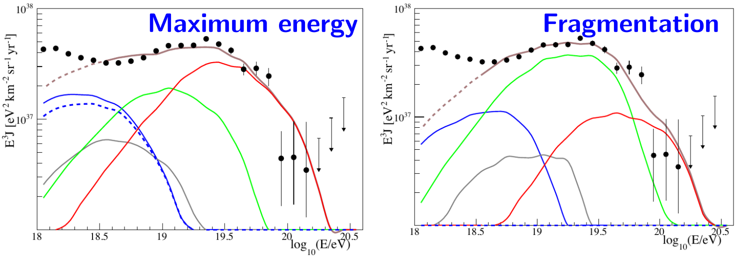


- $E_{\max} \propto \beta_s z B L$
- Due to energy losses, sources cannot be "far" away ($\sim \mathcal{O}$(10 Mpc))
- There are only few very powerful "good" source candidates...
- Iron easier to accelerate than proton
- Difficult to produce protons at $E > 10^{20}$ eV
- Unknown how useful directional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

Phenomenological Fits of the Energy Spectrum

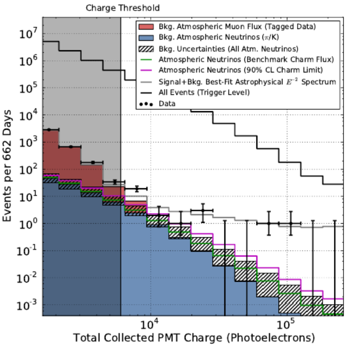
- Data very precise over wide range in energy
- No simple model works
- ⊕ Also composition sensitive data disfavours simple models

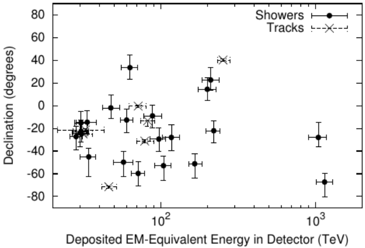
proton helium nitrogen iron

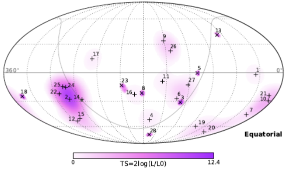


- The first real astrophysical neutrino candidates
- Up to PeV energies
- Atmospheric prompt charm production ?

IceCube





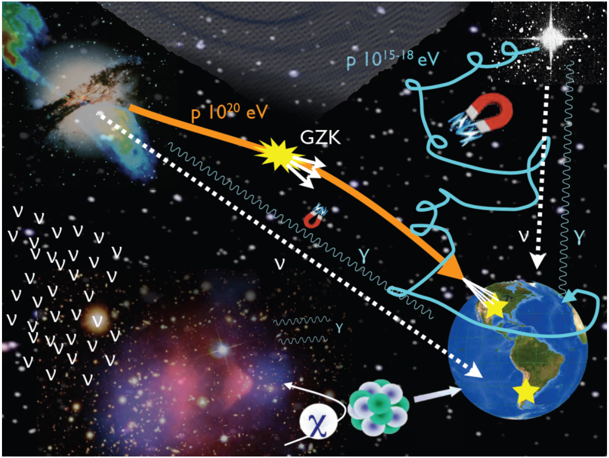


Science 342 (2013) 1242856

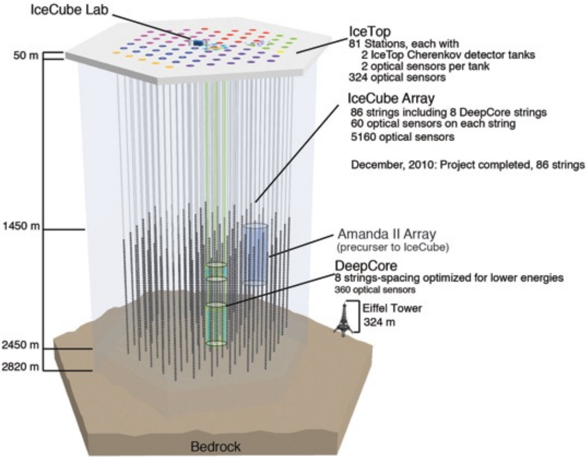
PRL 111, 021103 (2013)

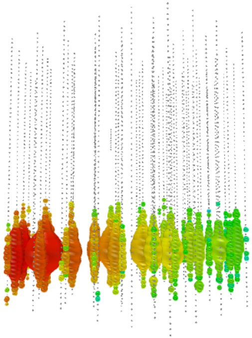
High Energy Neutrinos, Questions

- What is the physics of the **most violent astrophysical** events?
- Where are ultra-high neutrinos produced in the universe?
- Neutrinos from galactic Supernova.
- How do neutrinos interact with their environment.



High Energy Neutrinos, Experiments

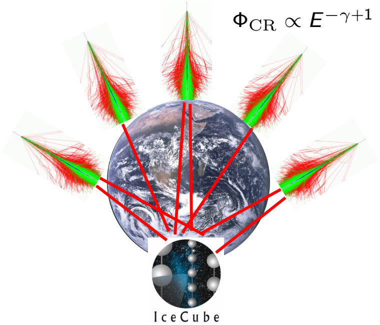




Upgrades: larger (huger), and more precise

High Energy Neutrino Production (Atmospheric)

$\Phi_{\mathrm{CR}} \propto E^{-\gamma+1}$



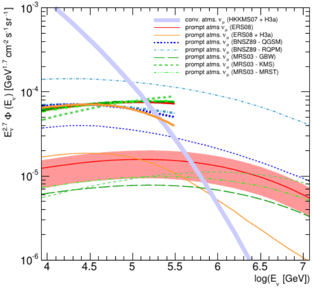
Spectrum-weighted moments:

$$Z = \int_0^1 x_{\mathrm{F}}^{\gamma} \cdot \frac{\mathrm{d}n}{\mathrm{d}x_{\mathrm{F}}} \mathrm{d}X_{\mathrm{F}}$$

Neutrino flux:

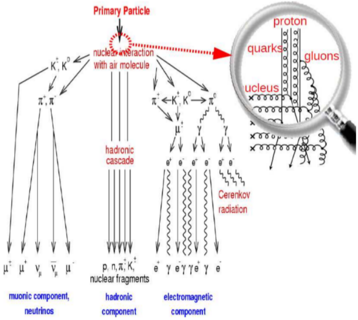
$\Phi_\nu \propto Z$

- Meson or muon decay, e.g. $\pi^+ \to \mu^+ \nu_\mu$
- In Extensive air showers: decay $\leftrightarrow$ interaction
- Pions, Kaons, Charmed Mesons



More details e.g.: arXiv:9505417/hep-ph

Interactions in Air Showers



Requirements and Problems:

- Interactions up to $\sqrt{s} \sim 500$ TeV
  $\rightarrow$ Far beyond accelerator energies...
- Mainly soft physics + diffraction: **forward region**
  $\rightarrow$ Difficult to instrument...
  $\rightarrow$ Only fixed target at lower energies...
- Target is **air**: p-air, π-air, K-air, A-air, ...
  $\rightarrow$ Typical target very different from **air**:
  Nuclear effects must be considered...

Ingredients:

- Theory: pQCD (hard) + Gribov-Regge (soft)
- A lot of phenomenology: Diffraction, String fragmentation, Saturation, Remnants, Nuclear effects, ...

Older models:

Glauber based, different mostly in remnants+diffraction, for example:
QGSJet01 *(Kalmykov, Ostapchenko)*
SIBYLL *(Engel, Gaisser, Lipari, Stanev)*

Recent models:

QGSJetII *(Ostapchenko)*
Theory++, Optimized for cosmic rays

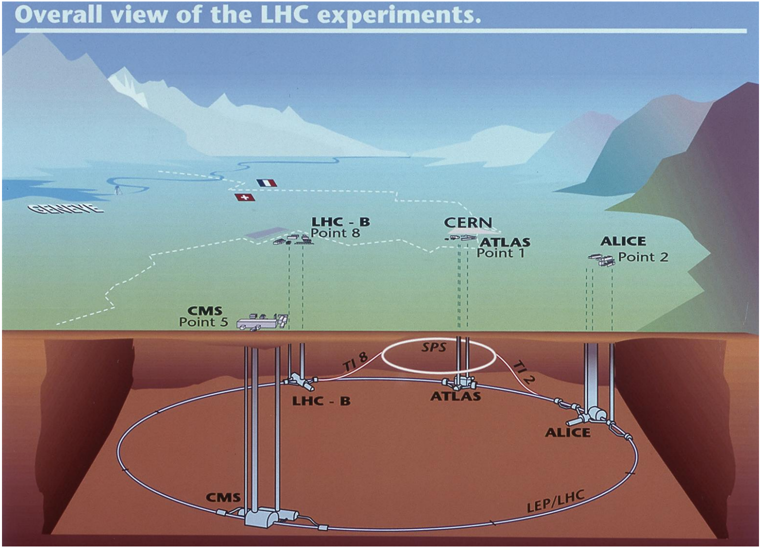
EPOS *(Werner, Pierog)*
Phenomenology++
Optimized for LHC, RHIC (and cosmic rays)

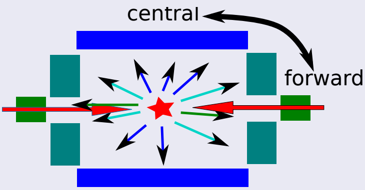
Problems: Acceptance and Extrapolations

⇒ **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**

Large Hadron Collider and Experiments

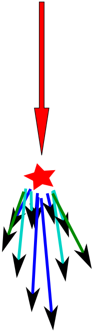




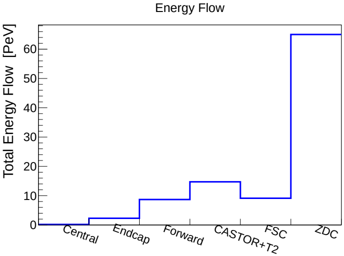
- Central ($|\eta| < 1$)
- Endcap ($1 < |\eta| < 3.5$)
- Forward ($3 < |\eta| < 5$), HF
- CASTOR+T2 ($5 < |\eta| < 6.6$)
- FSC ($6.6 < |\eta| < 8$)
- ZDC ($|\eta| > 8$), LHCf

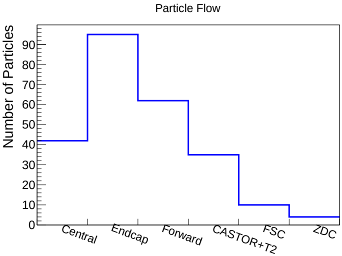
- How relevant are specific detectors at LHC for air showers?

$\rightarrow$ Simulate parts of shower individually.



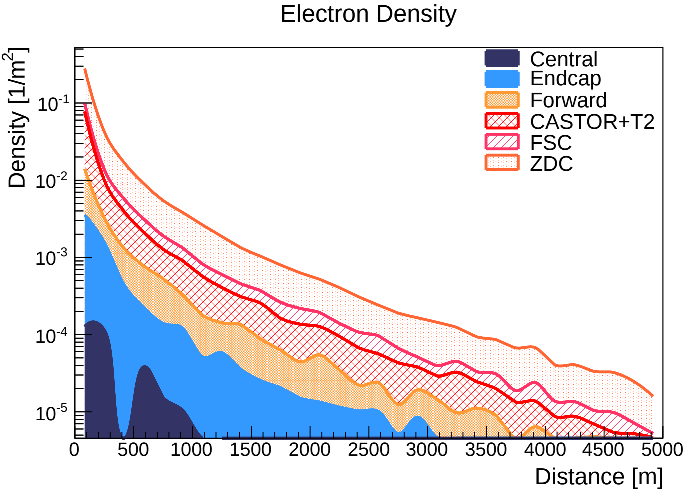
Secondaries of the first interaction in lab-system





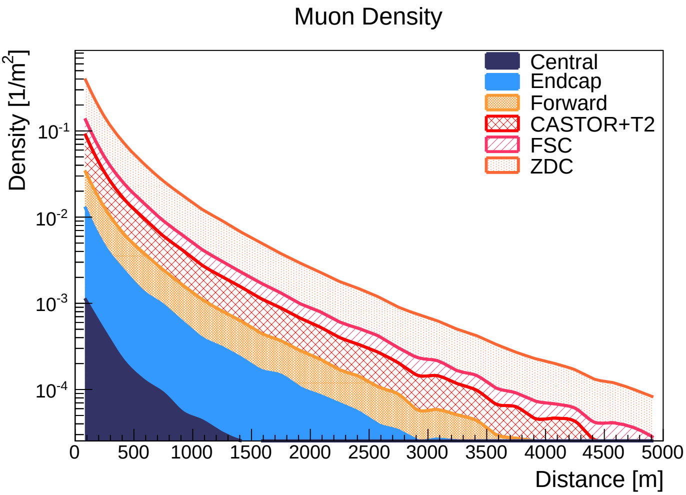
- Simulate first interaction with SIBYLL
- proton at 10^{17}eV $\rightarrow \sqrt{s_{NN}} = 14\,\text{TeV}$ (LHC)
- Histogram particle densities above threshold of (0.3GeV for muons+hadrons and 0.003GeV for E.M.)

Lateral Particle Density on Ground Level



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

Lateral Particle Density on Ground Level



- Air shower models so far only tuned to about 10 % !
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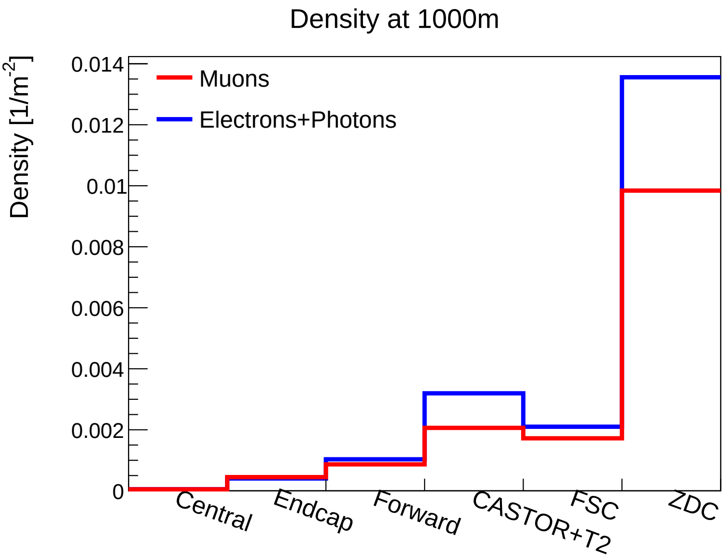
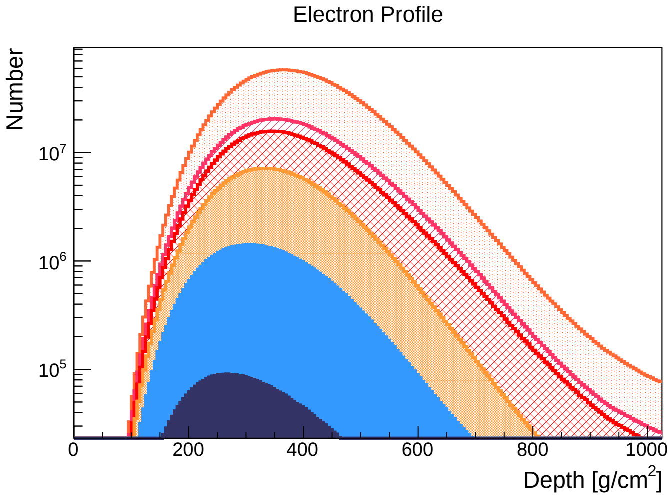
Particle Densities at 1000 m From Shower Core



Only partly accessible to observation at LHC !

Longitudinal Shower Development



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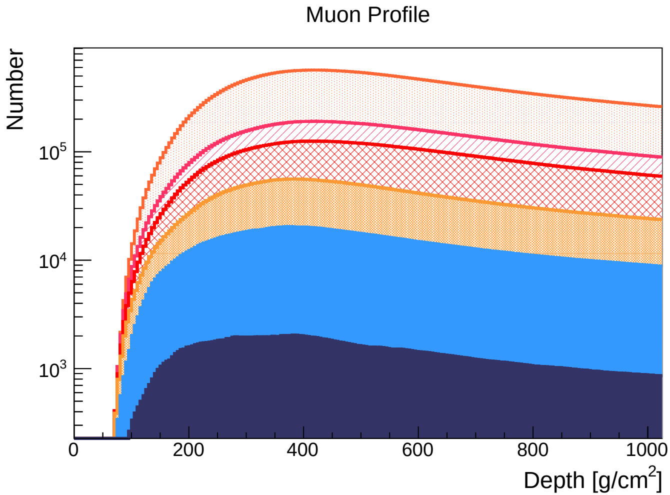
Longitudinal Shower Development



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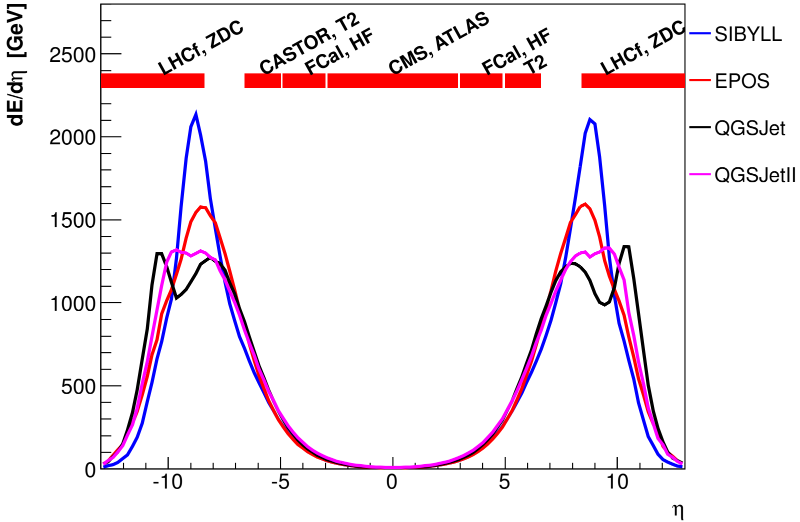
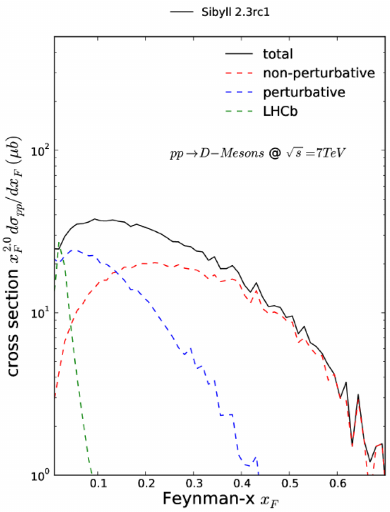
- Forward detectors are crucial.

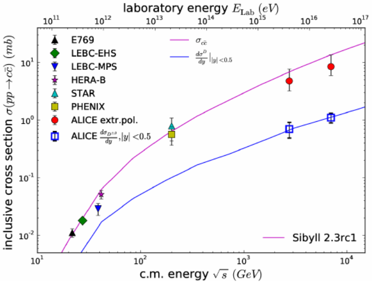
Energy Density per Pseudorapidity



Most energy is directed toward the forward region

Acceptance for Charm Production at LHC





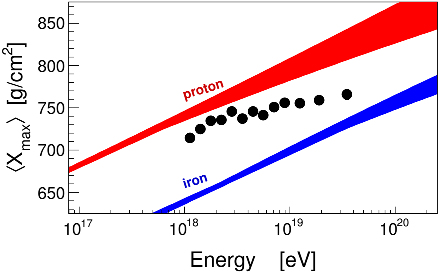
F. Riehn, ISVHECRI 2014

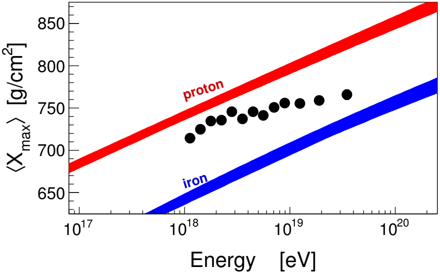
LHCb: $\approx$7 % of total production observed

Model Tuning to LHC Data (at 7 TeV) **Impact**

EPOS 1.99 → **EPOS LHC**

QGSJetII.3 → **QGSJetII.4**



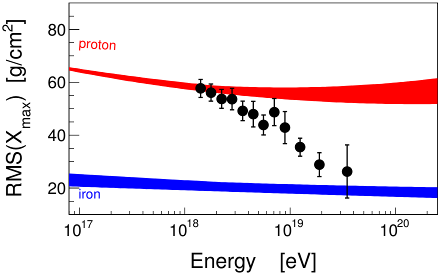


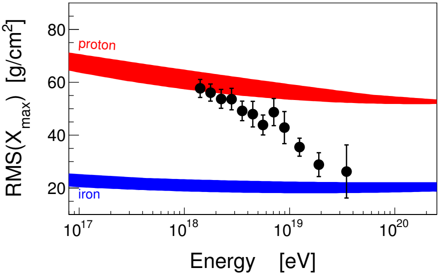
Caveats / Potential:

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

EPOS 1.99 → **EPOS LHC**

QGSJetII.3 → **QGSJetII.4**

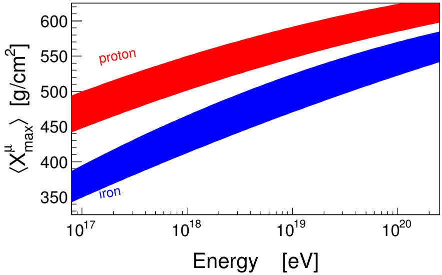




Caveats:

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

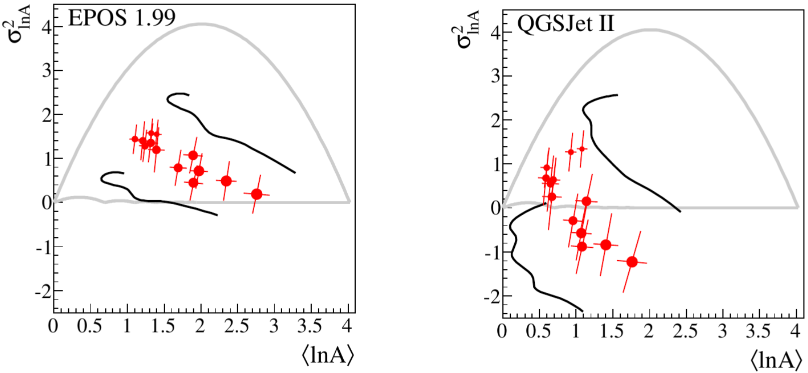
EPOS LHC
QGSJetII.4



Status after tuning to 7 TeV:

- General model performance after first LHC tuning better, but not yet sufficient
- More aspects and more data needs to be taken into account
- Partly iron is now on the same level of model uncertainty than protons $\rightarrow$ nuclear effects become more relevant!

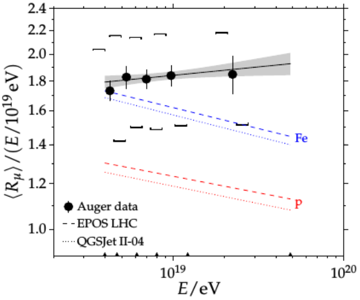
Correlations between Average and RMS

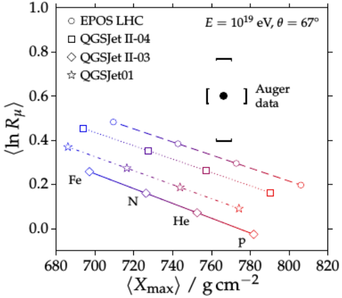


JCAP 02 (2013) 026

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

Muon Content at Ground Level





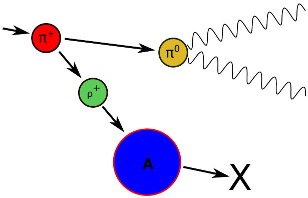
Auger, arXiv-1408.1421 [atro-ph]

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

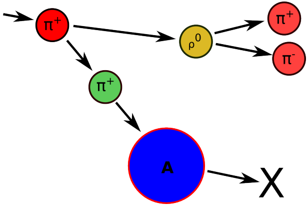
→ Possible cause: interaction physics in air showers models is not accurate

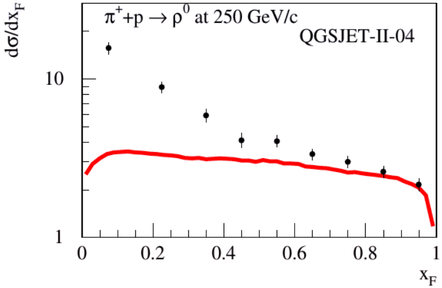
(Forward) ρ^0 Production, QGSJetII.3→QGSJetII.4

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



versus





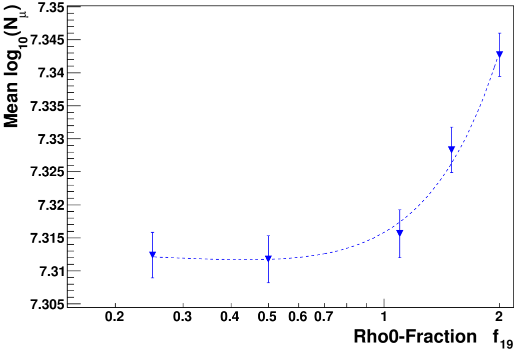
S. Ostapchenko, ISVHECRI 2012

Impact on Muons in Air Showers

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

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

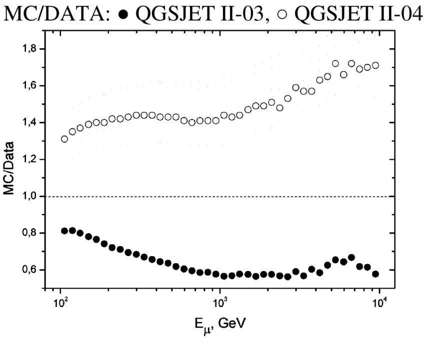
(f19 is the scaling factor for ratio at 10^{19} eV, logarithmic energy dependence)



Ulrich, Engel, Baus, ISVHECRI 2014

Forward ρ^0 production, QGSJetII.4

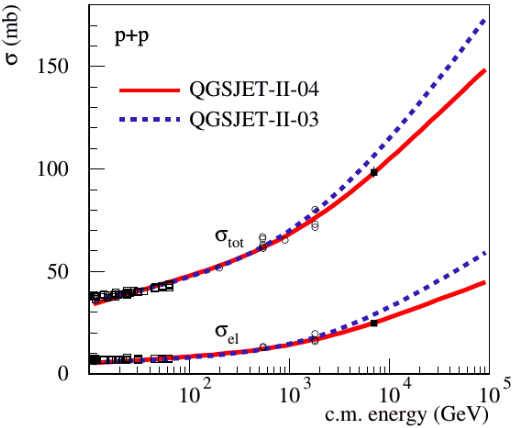
Prediction of inclusive athmospheric muon fluxes as a test of hadronic interaction models



A.V. Lukyashin, ISVHECRI 2014

⇒ Too many ρ^0 produced now?

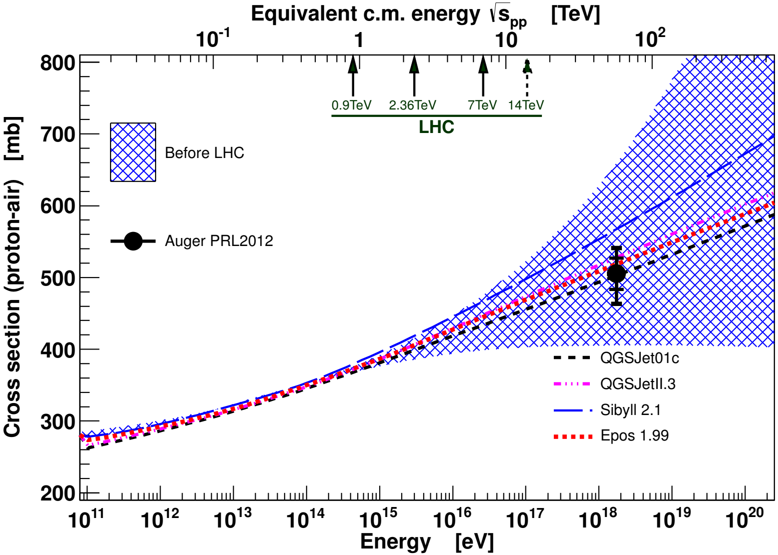
Model Tuning to LHC Data up to 7 TeV



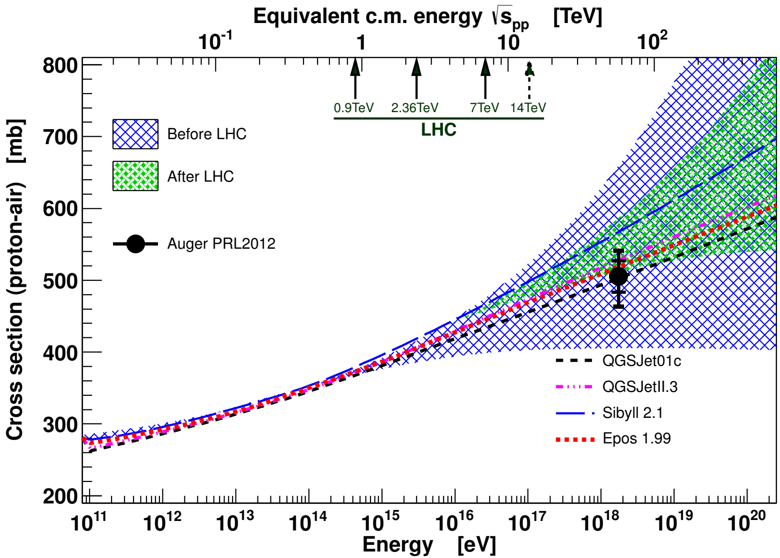
S. Ostapchenko, ISVHECRI 2014

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

Proton-Proton → Proton-Air, With Tevatron Data

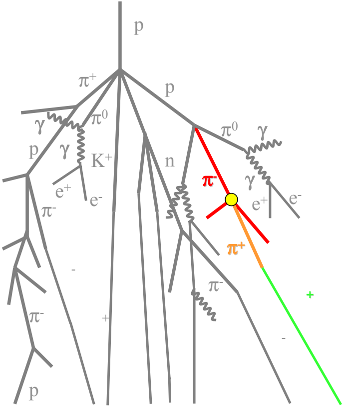


Nucl.Phys.Proc.Suppl. 196 (2009) 335



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

Muon Production in Extensive Air Showers



$A + air \rightarrow$ hadrons
$p + air \rightarrow$ hadrons
$\pi + air \rightarrow$ hadrons

$e^{\pm} \rightarrow e^{\pm} + \gamma$
$\gamma \rightarrow e^{+} + e^{-}$

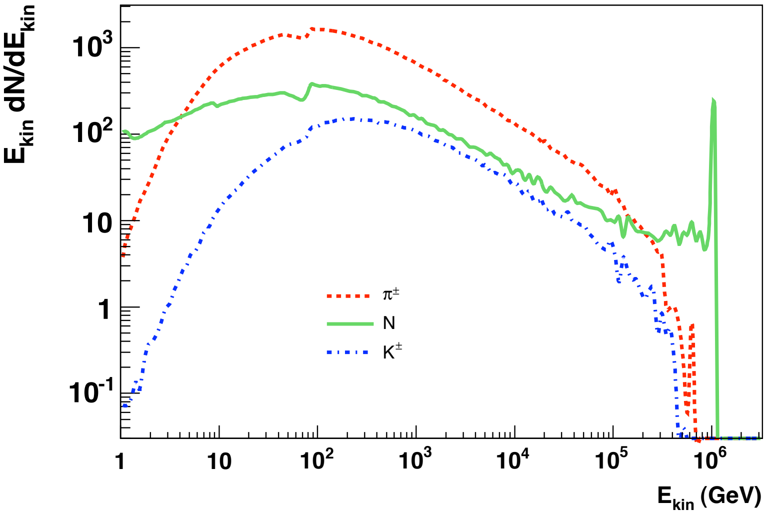
$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}/\bar{\nu_{\mu}}$

Important energies: **10 - 1000 GeV**

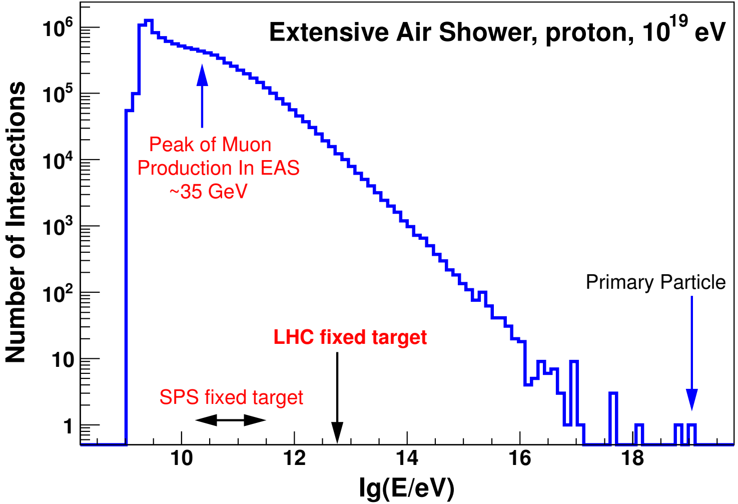
	beam particle	secondary
pion	**72.3 %**	**89.2 %**
nucleon	**20.9 %**	-
kaon	**6.5 %**	**10.5 %**

Air shower components: hadrons, electromagnetic, muons

Projectiles in air showers that lead to muon production



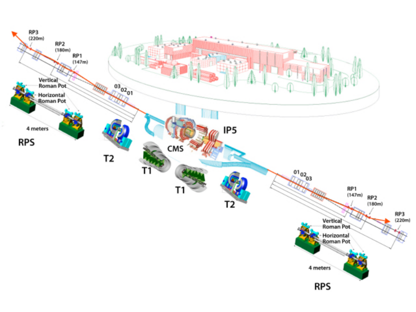
Hadronic Interactions in EAS



- Pion cascade in air
- Pions decay into muons with a peak around $\sim 35\,\text{GeV}$

Forward Detectors

TOTEM



LHCf

CASTOR

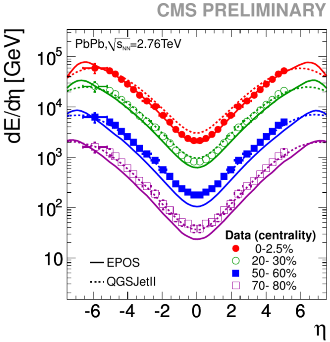
- TOTEM: Very forward particle production and elastic
- LHCf: Very forward photon, pi^0, neutrons
- CASTOR: Very forward energy, diffraction

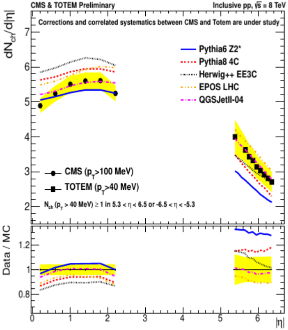
Relevant for Astroparticle Physics

TOTEM, LHCf, TOTEM+CMS

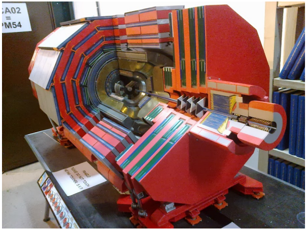
- Total, elastic, inelastic, diffractive cross-sections
- Forward photon and neutron spectra.
- Diffraction
- Generell particle production characteristics

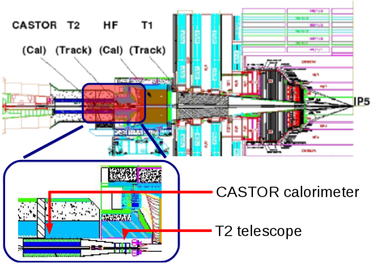
For example:



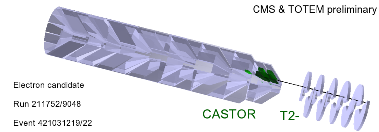


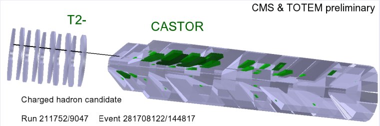
TOTEM/T2 + CMS/CASTOR





Particle Reconstruction





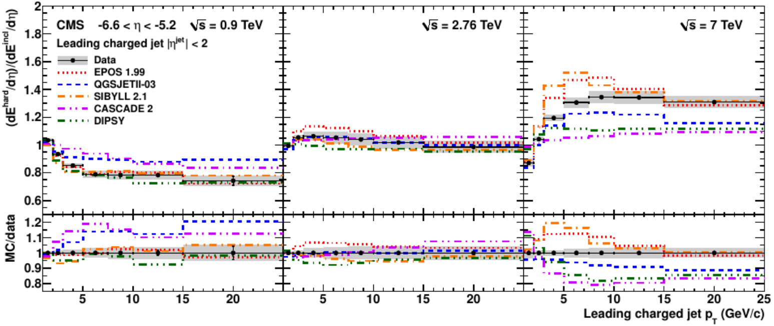
320 GeV at $\eta = -5.97$

210 GeV at $\eta = -5.69$

Jets, leptons and resonances at η up to 6.6

Cosmic Ray Models and Recent LHC Data: CMS

Very forward underlying event:

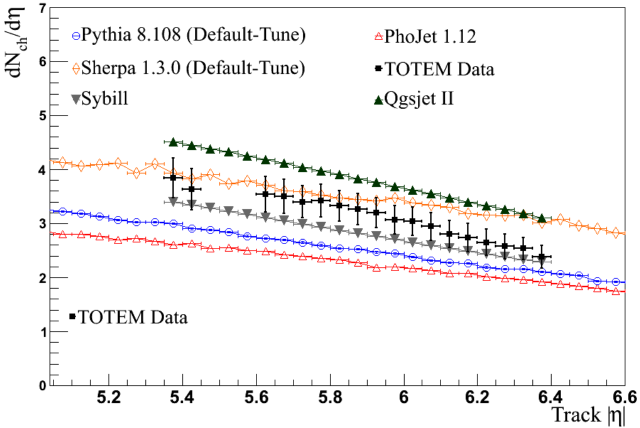


JHEP 1304 (2013) 072

In CMS:

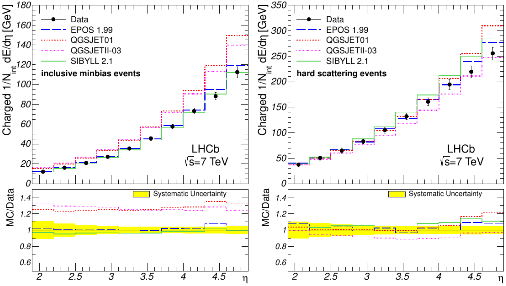
- Used for pPb and PbPb (and forward pp) detector studies and correction factors
- Where relevant, also event generator comparisons are performed

Cosmic Ray Models and Recent LHC Data: TOTEM



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

Cosmic Ray Models and Recent LHC Data: LHCb



Eur.Phys.J. C73 (2013) 2421

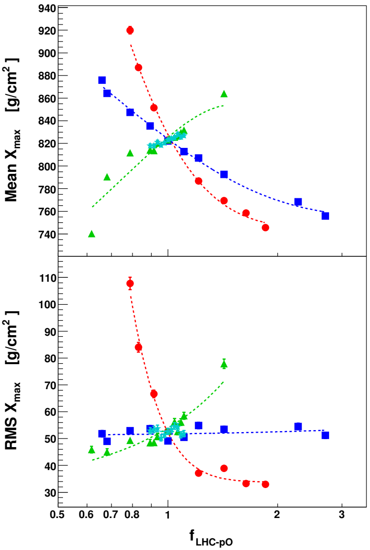
Comparison on event generator level:

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

Tool: **CRMC http://www.auger.de/∼rulrich/crmc.html**

Proton-Oxygen Data at LHC

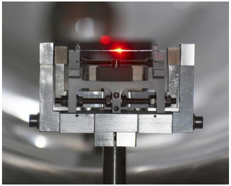
- Asymmetric heavy-ion run with proton-oxygen nuclei
- After LS1, $\sqrt{s} = 9\ TeV$ (Proton beam at 3.5 TeV)
- Oxygen very close to atmospheric material of extesive air shower production (nitrogen)



PRD 83 (2011) 054026

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 in Nov 2014

Air Shower Calibration Experiment

Note:

There is no simple experiment, for a precise and relevant measurement...

Scientific motivation:

How accurate is the modeling of shower development with CORSIKA? Both: Electromagnetic and Muon component.

Explore the origin of the air shower muon problem with p-C, π-C shower measurement?

Constrain the prompt charm high-energy muon production very precisely up to TeV energies.

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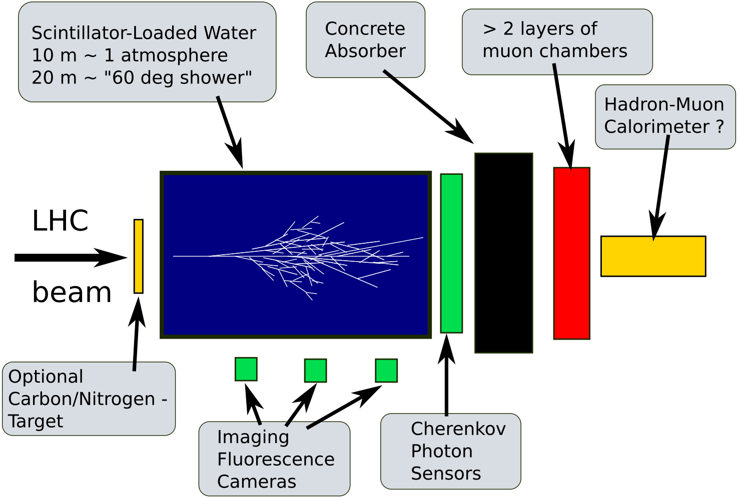
Possible Experimental Layout



Advantages and Challenges

Advantages:

- Directly test CORSIKA + hadronic models !
- Very obvious and clear connection to UHECR physics
- For the first time: end-to-end calibration of air shower development
- Detectors relatively simple and maybe can be partly reused from other experiments. At least the technology.
- Pierre Auger Software framework (Offline) can be used almost 1:1. Simulation, reconstruction and analysis almost identical to Auger.

Challenges:

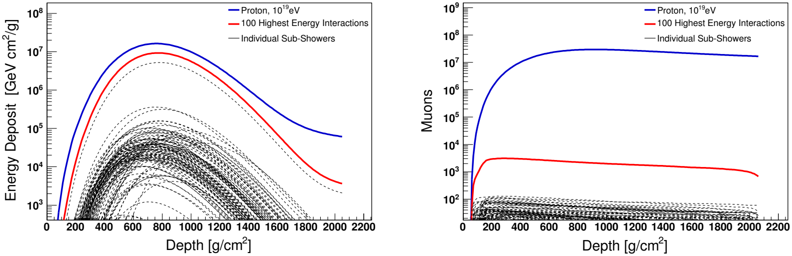
- Pion beam
- Calibration of detector systems. Best with pure electron and muon beams.

Sensitivity to Interaction Physics

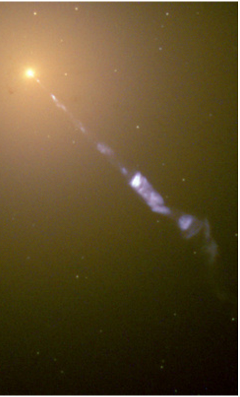
- Wide range of energies, reaching beyond accelerators
- Uncertainty: extrapolation of hadronic interactions
  - Phase space (!)
  - Energy

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

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



Summary



- ⇒ **Astrophysics at accelerators**
- ⇒ **Air Shower Muon Problem**
- ⇒ **Prompt-charm production, PeV neutrino**