Karlsruhe Institute of Technology

Impact of AFTER on Astroparticle Physics

Orsay, 20. October 2011

PIERRE AUGER OBSERVATORY

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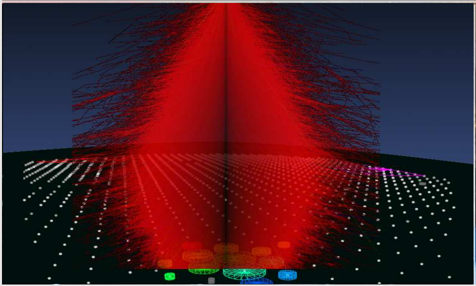
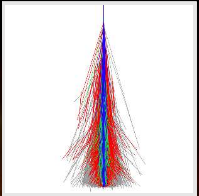
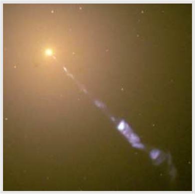


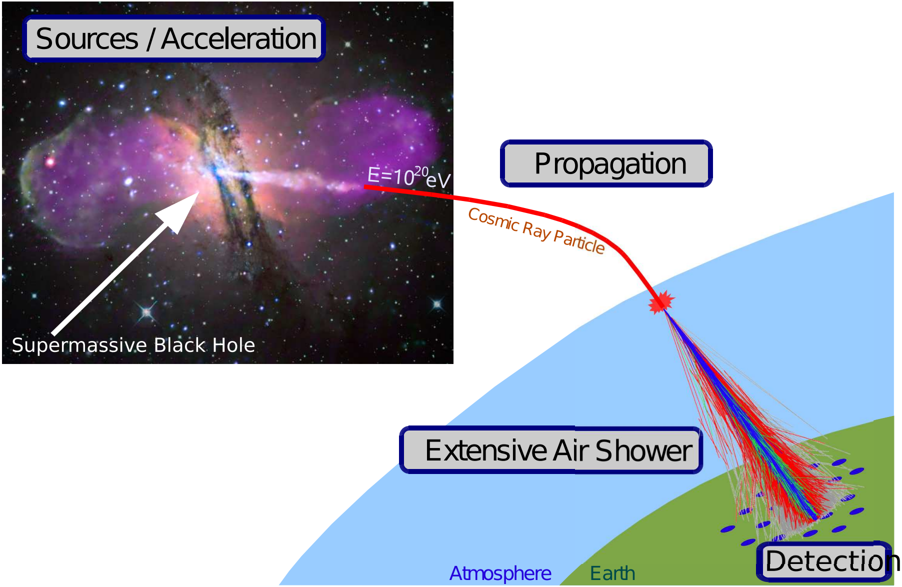
Connecting High Energy Particle Physics with Astrophysics





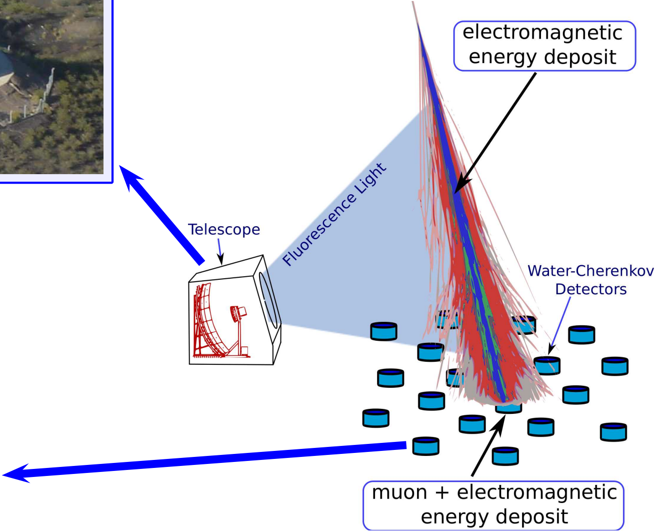
Extensive Air Showers (especially Muons), Atmospheric Neutrino Fluxes

Overview



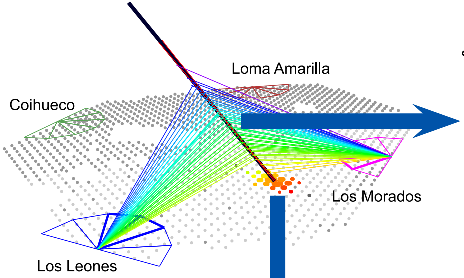
Sources / Acceleration
Supermassive Black Hole
$E=10^{20}$eV
Propagation
Cosmic Ray Particle
Extensive Air Shower
Atmosphere
Earth
Detection

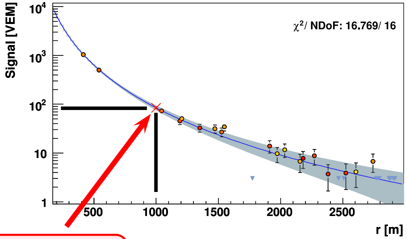
24 Telescopes, 4 Sites

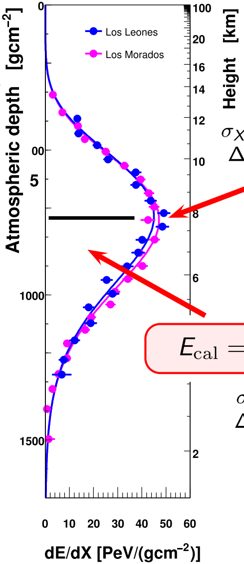


1600 Water-Cherenkov Detectors, $\approx$3000 km^2

Data and Reconstruction







S_{1000}

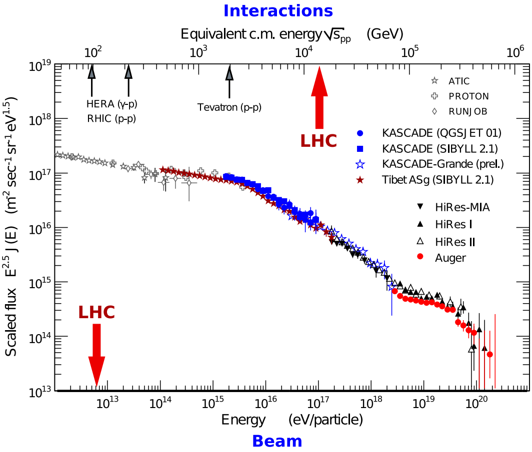
$E_{\mathrm{surface}} = f(S_{1000}, \theta)$

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

X_{max}

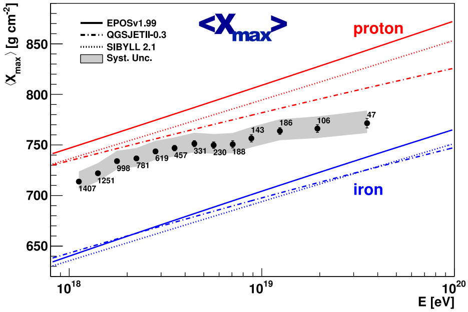
$E_{\mathrm{cal}} = \int \mathrm{d}X \, \frac{\mathrm{d}E}{\mathrm{d}X}$

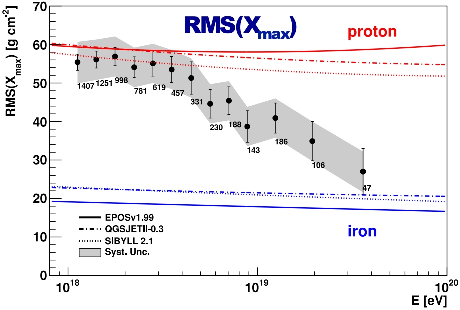
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 22\,\%$



- What is the origin of the high energy cutoff?
  - Photopion production: $p + \gamma_{\text{cmb}} \to N + \pi$
  - Giant-Dipole-Resonances: $A + \gamma_{\text{cmb}} \to (A-1) + N$
  - Maximal energy of accelerators
- Depends on cosmic ray composition!

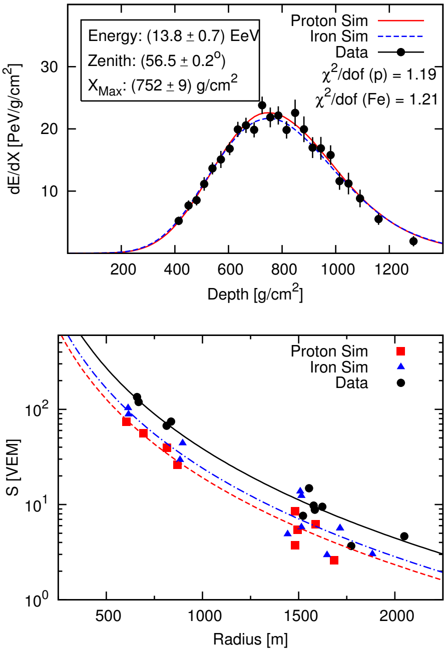
Depth of the Shower Maximum



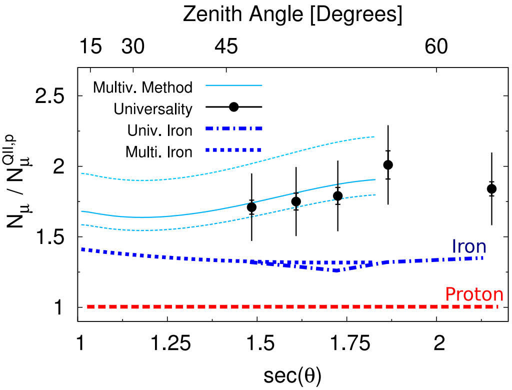


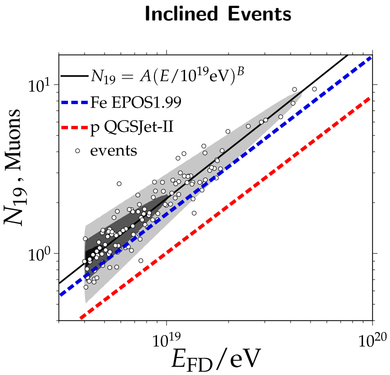
- One of the key observations of Auger
- Something fundamental is happening around 3×10^{18} eV
- Composition changes rapidly? Interaction physics?

Longitudinal and Surface-Array Data



Auger Muon Results



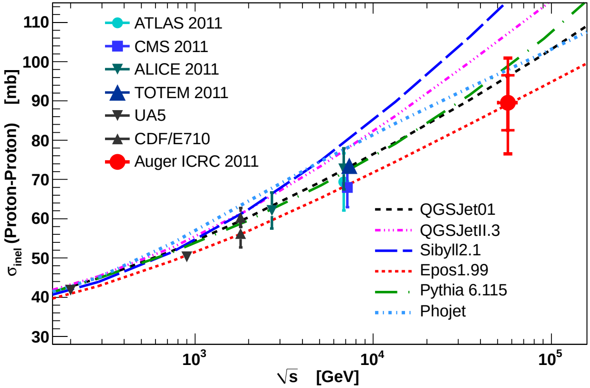


- Models significantly under-predict muons
- Muon deficit largest at high zenith angles ($N_\mu / N_\mu^{\mathrm{QII,p}} \sim 2$)

⇒ Not completely clear how to fix:
energy scale, GeV-TeV interactions, composition ...

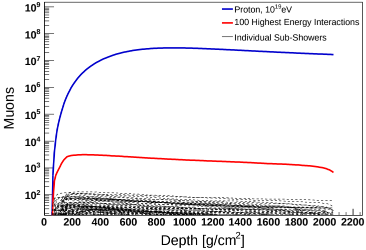
Inelastic Proton-Proton Cross-Section

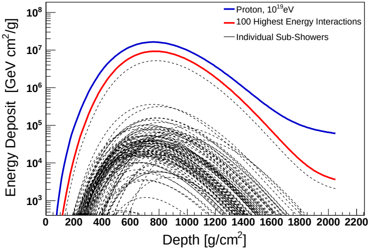
Based on X_{max} fluctuations ⇒ not sensitive to muon-related problems



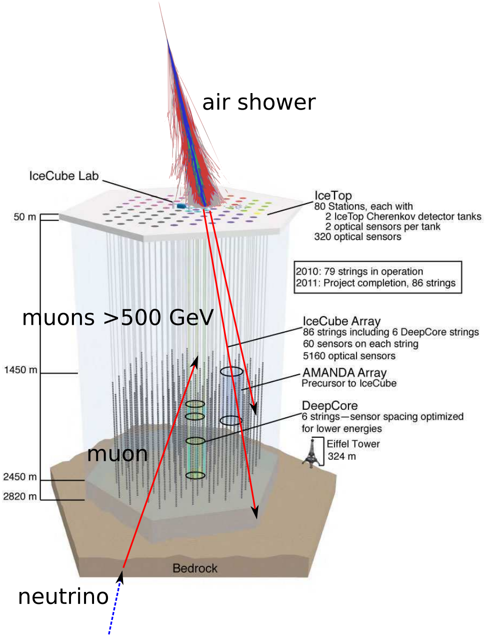
$$\sigma_{\mathbf{pp}}^{\mathbf{inel}} = \left[\mathbf{90} \ \pm \mathbf{7}_{\mathbf{stat}} \ \left({}^{+9}_{-11}\right)_{\mathbf{sys}} \ \pm \mathbf{1.5}_{\mathbf{Glauber}}\right] \ \mathbf{mb}$$

$$\sqrt{\mathbf{s_{pp}}} = [\mathbf{57} \ \pm \mathbf{0.3}_{\mathrm{stat}} \ \pm \mathbf{6}_{\mathrm{sys}}] \ \mathbf{TeV}$$

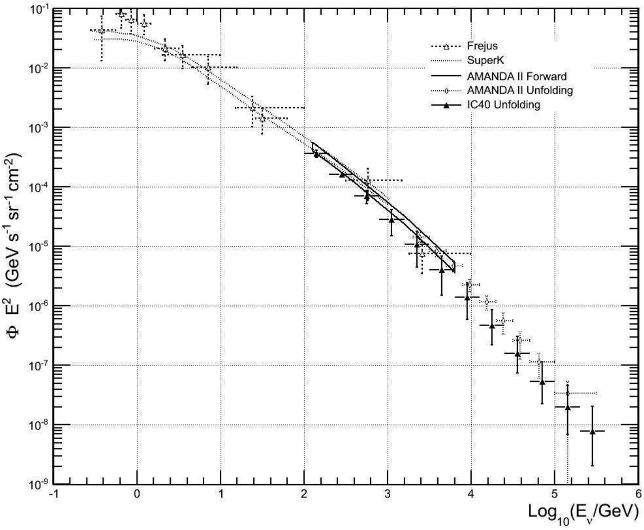




- Global shower properties and the **shower maximum** are sensitive to the highest energy interactions
- Muons in air showers sensitive to the hadronic cascade over all energies

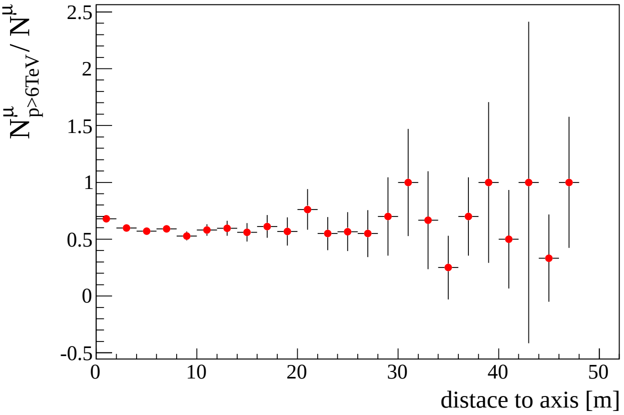

air shower
IceCube Lab
IceTop
80 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
320 optical sensors
2010: 79 strings in operation
2011: Project completion, 86 strings
50 m
muons >500 GeV
IceCube Array
86 strings including 6 DeepCore strings
60 sensors on each string
5160 optical sensors
1450 m
AMANDA Array
Precursor to IceCube
DeepCore
6 strings—sensor spacing optimized for lower energies
Eiffel Tower
324 m
muon
2450 m
2820 m
Bedrock
neutrino

Neutrino Spectrum

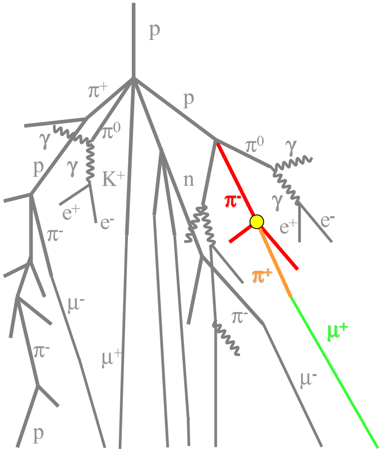


- Multi-TeV atmospheric muons+neutrino background

Production of High-Energy Muons



Extensive Air Showers



$$A + air \to \text{hadrons}$$
$$p + air \to \text{hadrons}$$
$$\pi + air \to \text{hadrons}$$

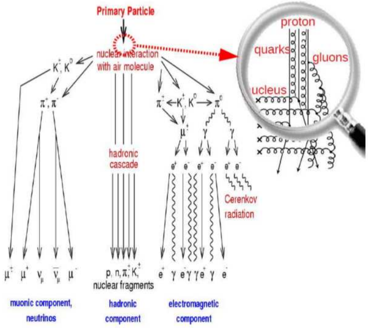
$$e^{\pm} \to e^{\pm} + \gamma$$
$$\gamma \to e^{+} + e^{-}$$

$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}/\bar{\nu}_{\mu}$$

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



Requirements and Problems:

- Interactions up to $\sqrt{s} \sim 500\,\text{TeV}$
  $\rightarrow$ 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:

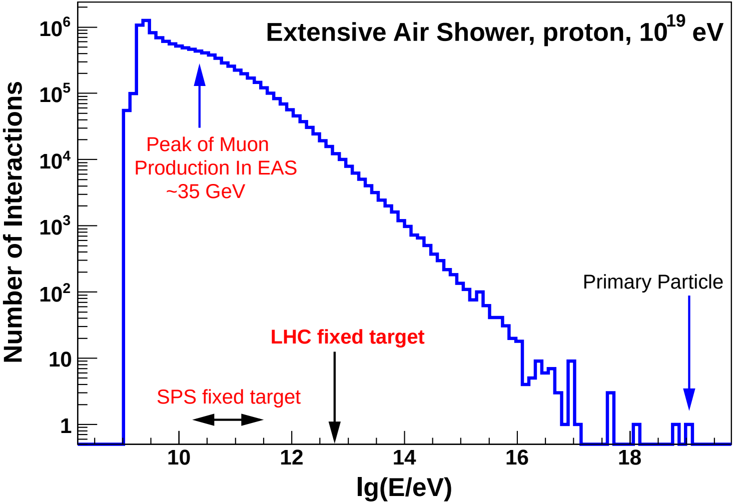
Glauber based, different mostly in remnants+diffraction, for example:
QGSJet01 *(Kalmykov, Ostapchenko)*
SIBYLL *(Engel, Gaisser, Lipari, Stanev)*

Recent models:

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

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

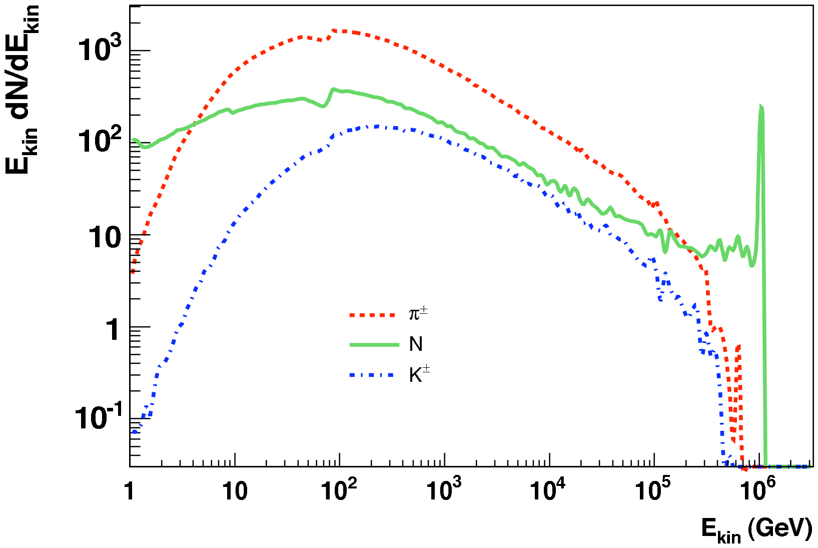
Hadronic Interactions in EAS



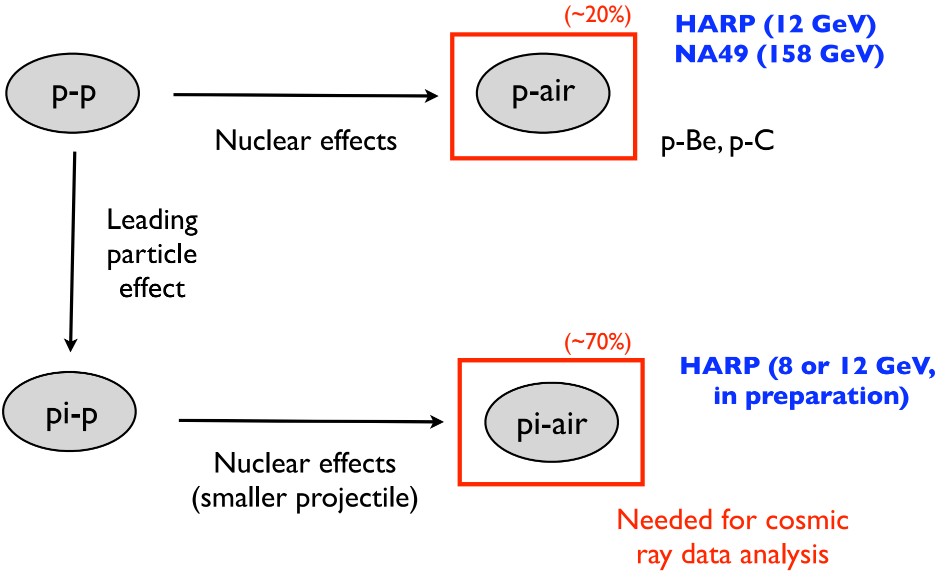
- Pion cascade in air
- Pions decay into muons with a peak around $\sim 35\,\text{GeV}$

Muon Production in EAS

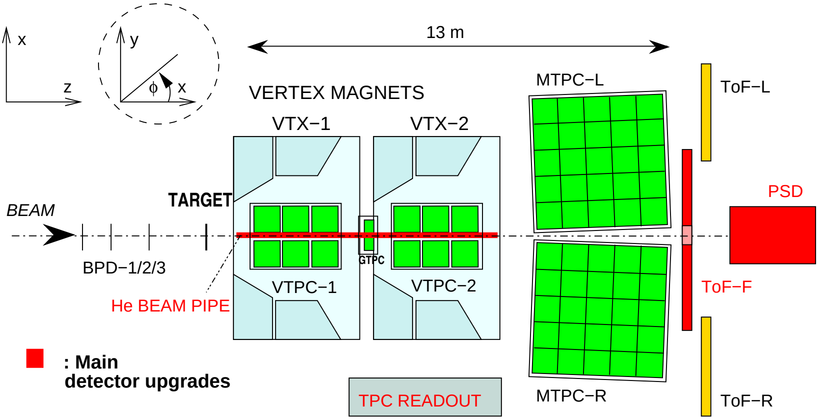
Projectiles in air showers that lead to muon production



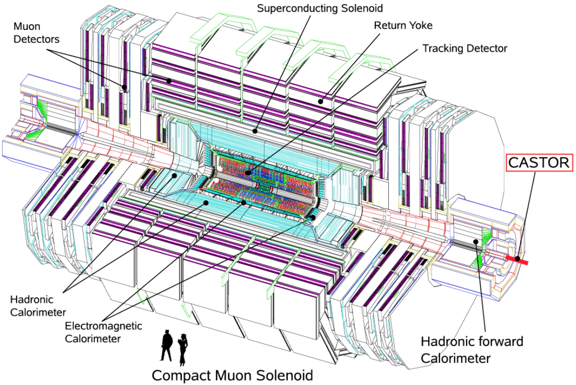
Relevant Target: Air (^{14}N, ^{16}O, . . .)



NA61, Fixed Target at SPS



- Active contribution from cosmic-ray group at KIT
- Ideal to study pion interactions that directly produce muons in air-showers



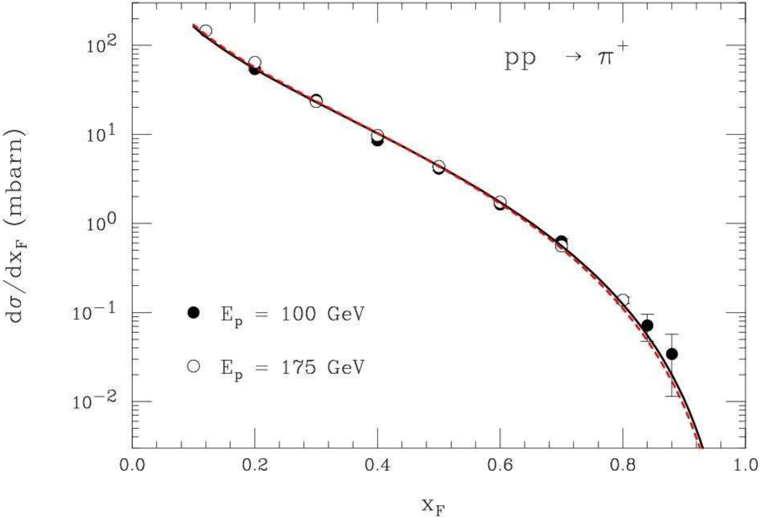
- Active contribution from group at KIT in CMS/CASTOR
- Improve understanding of early stages of air shower development
- QCD at high energies, high parton densities
- But:
  - Only p-p, Pb-Pb, p-Pb
  - Forward region difficult to instrument, miss $6.5 < \eta < 8.2$

LHC: Fixed Target

- Variety of (secondary) projectiles: p, pions, kaons, ...
- Different targets, including: C (solid), N_2 (liquid), O_2 (liquid), ...
- Measure forward particle production
- Good magnetic bending power

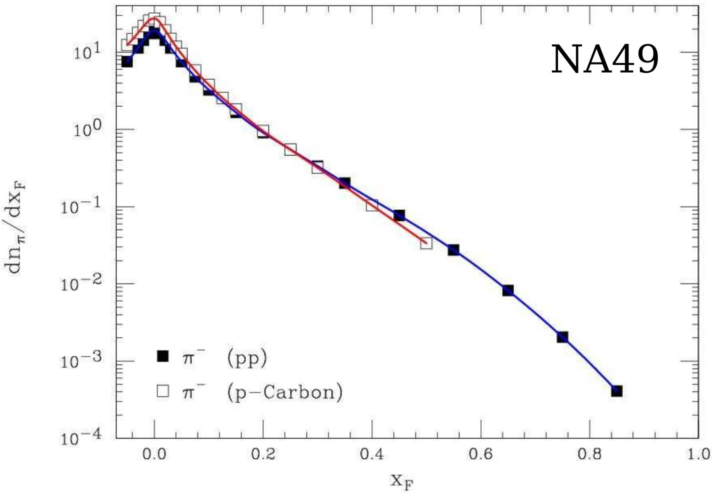
- Cross sections
- Elasticity (projectile energy/xf spectrum)
- e/m energy transfer (pi0 energy/xf spectrum)
- Multiplicity
- Forward baryon spectra

Phenomenological Evidence for Scaling

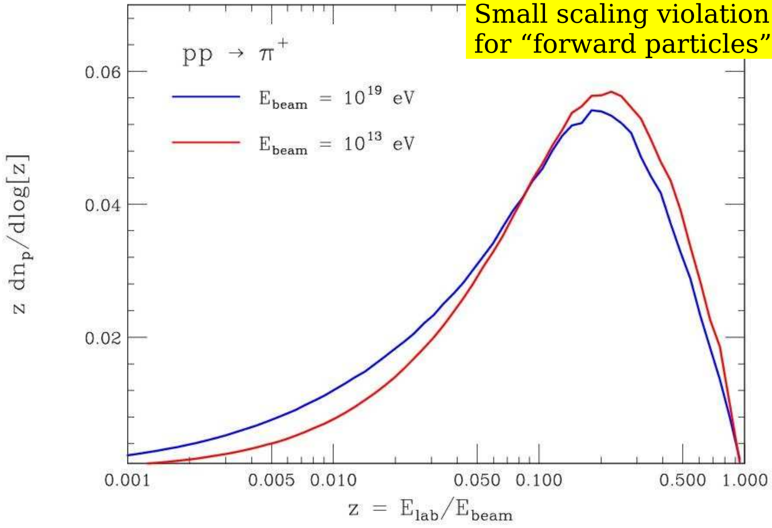


Fermilab pp, Brenner et al. 1982

Nuclear Effects

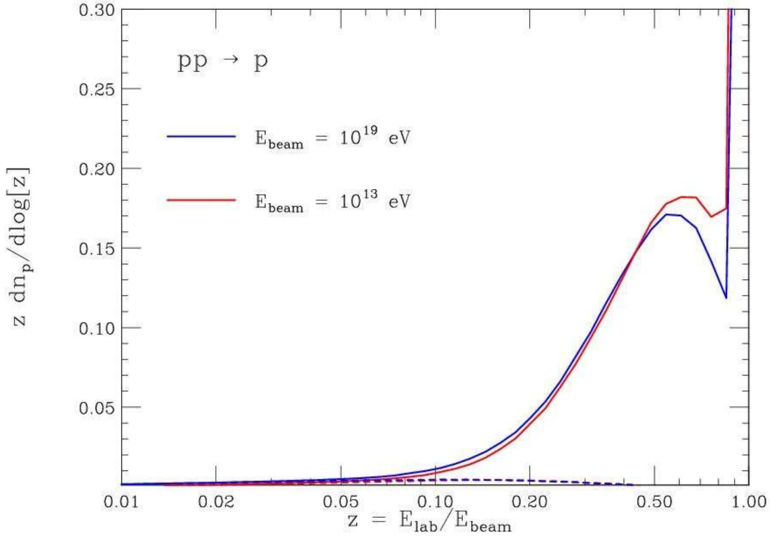


Extrapolation to Ultra-High Energies

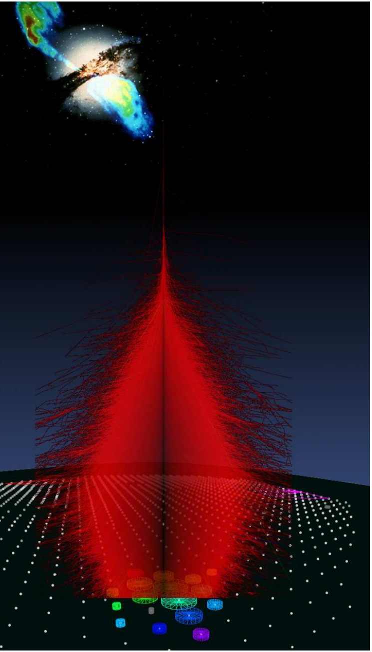


Small scaling violation [?]
for "forward particles"

Elasticity (e.g. pair→p) Spectra



Summary



Exciting connections between cosmic-ray and elementary particle physics

Muons in Air Showers

$\rightarrow$ Interactions GeV to EeV

- Significant deficit in simulations
- Have to learn much more about hadronic interactions at $\sim$TeV
- Fixed target at LHC could contribute significantly

The combination of LHC and Auger data in the next years can bring us much closer to solving the cosmic-ray puzzle