ULTRA-HIGH ENERGY COSMIC RAYS

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CLASHEP Arequipa, Perú - March 2013

Outline

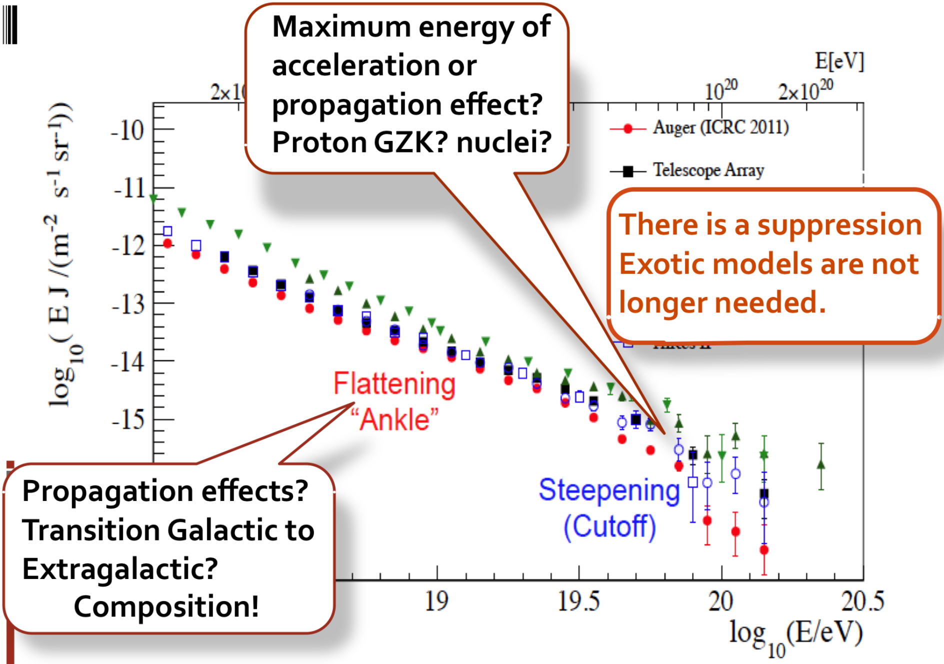
Lect. 1

- ✓ Historical Introduction
- ✓ Acceleration mechanisms
- ✓ Propagation
- ✓ Detection Techniques: SD, FD, Hybrid
- ✓ Energy Spectrum: is there an end?

Lect. 2

- ✓ Cosmic ray astronomy?
- ✓ EAS phenomenology
- ✓ Composition of UHECR
- ✓ Neutral messengers
- ✓ Hadronic interactions in EAS

TODAY



Maximum energy of acceleration or propagation effect? Proton GZK? nuclei?
There is a suppression
Exotic models are not longer needed.
Propagation effects? Transition Galactic to Extragalactic?
Composition!
Flattening
"Ankle"
Steepening
(Cutoff)
Auger (ICRC 2011)
Telescope Array
E[eV]
10^{20}
2×10^{20}
$\log_{10}(E\,J\,/(m^{-2}\ s^{-1}\ sr^{-1}))$
-10
-11
-12
-13
-14
-15
19
19.5
20
20.5
$\log_{10}(E/eV)$

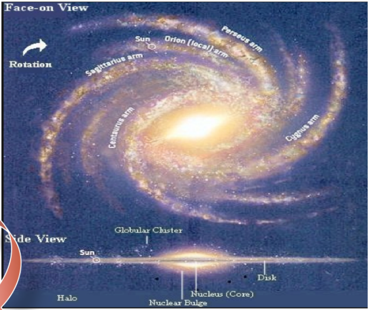
Local Universe is not strongly magnetized

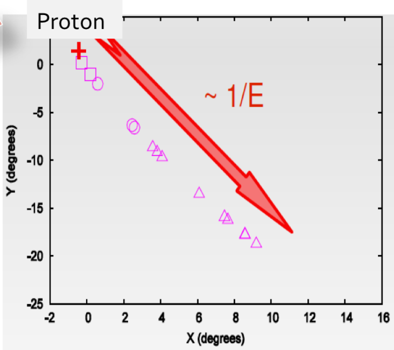
Galactic Magnetic Fields

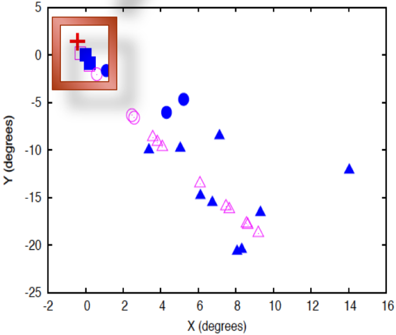
$$\theta_{\rm Gal} = \theta^{\rm regular}_{\rm Disk} + \theta^{\rm turbulent}_{\rm Disk} + \theta^{\rm regular}_{\rm Halo} + \theta^{\rm turbulent}_{\rm Halo}$$

$$\delta \simeq 8.1^\circ \frac{40\ {\rm EeV}}{E/Z} \left| \int_0^L \frac{\rm ds}{3\ {\rm kpc}} \times \frac{\mathbf{B}}{2\ \mu{\rm G}} \right|$$

$$\delta_{rms} \simeq 1.4^\circ \frac{40\ {\rm EeV}}{E/Z} \frac{B_{rms}}{4\ \mu{\rm G}} \sqrt{\frac{L}{3\ {\rm kpc}}} \sqrt{\frac{L_c}{50\ {\rm pc}}}$$

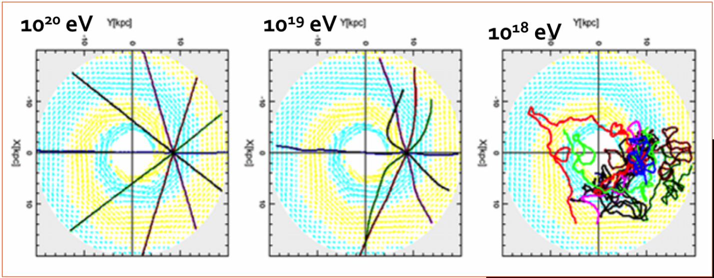






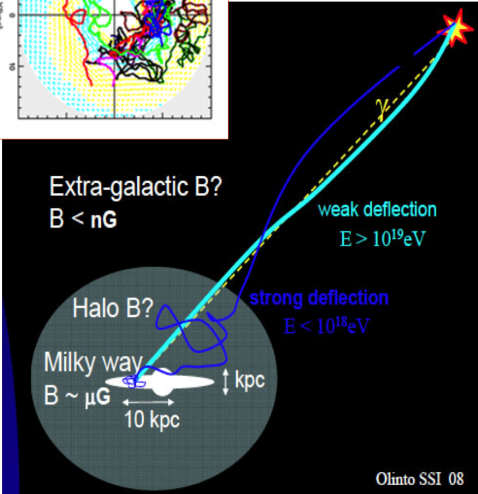
Giacinti, Derkx, Semikoz, JCAP1003,022 (2010)

Galactic and Extragalactic Magnetic Fields



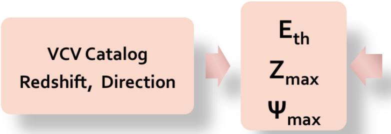
- High energy proton deflection angle: few degrees
- Iron deflection at 10^{19} eV: 50-70°
- Finding iron sources needs a better knowledge of GMF

Proton astronomy?



Anisotropies in the Sky Distribution

Auger (2007): VCV Catalogue (AGNs< 100Mpc)



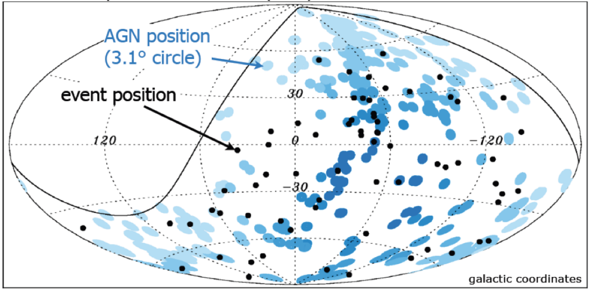
SD data, θ<60°, Angular resolution 0.9°

$$P = \sum_{j=k}^{N} \binom{N}{j} p_{iso}^{j} (1 - p_{iso})^{N-j}$$

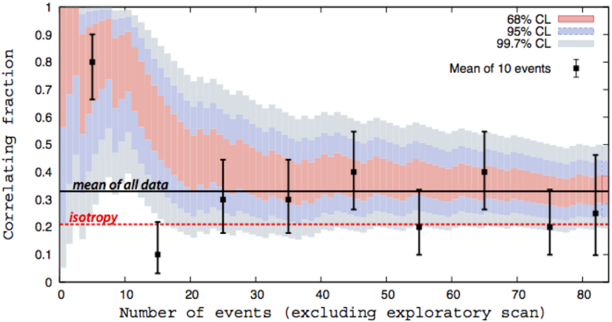
- E_{th}= 55 EeV , D_{max}= 75 Mpc (z_{max}= 0.016)
- ψ = 3.1° , 9/14 correlated.
- Independent sample→ 99% significance level for rejecting the hypothesis that the distribution of arrival directions is isotropic given the VCV AGN coverage of the sky.

Auger update with VCV catalog (2011)

First results reported in Science 318 (2007) 938

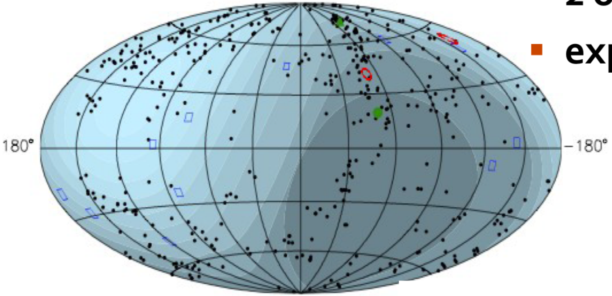


28 out of 84 correlate



- 33 ± 5%
- 21% isotropic hypothesis

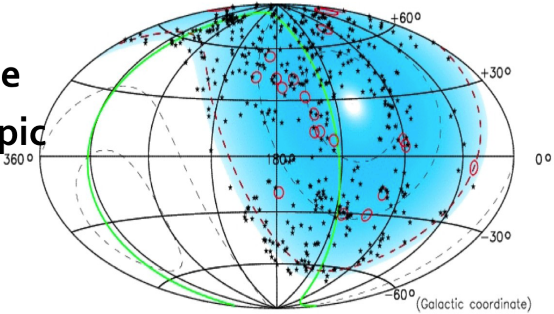
HiRes (2008)



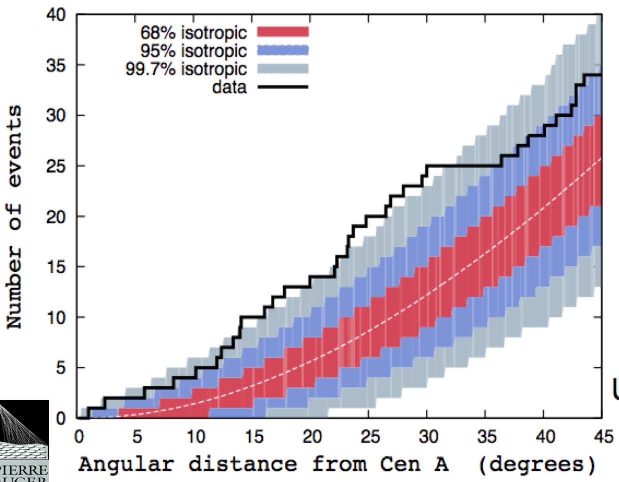
- 2 out of 13 correlate
- expect 3.2 if isotropic

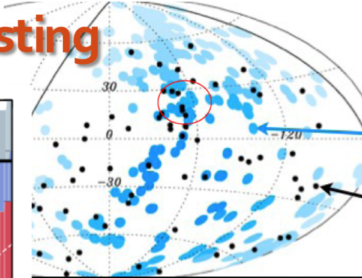
TA (2011)

- 8 out of 20 correlate
- expect 4.8 if isotropic



Centaurus A appears interesting

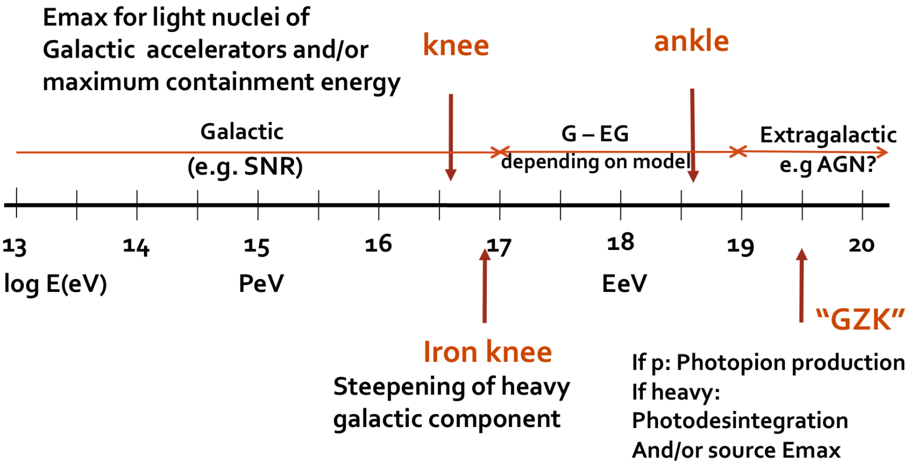




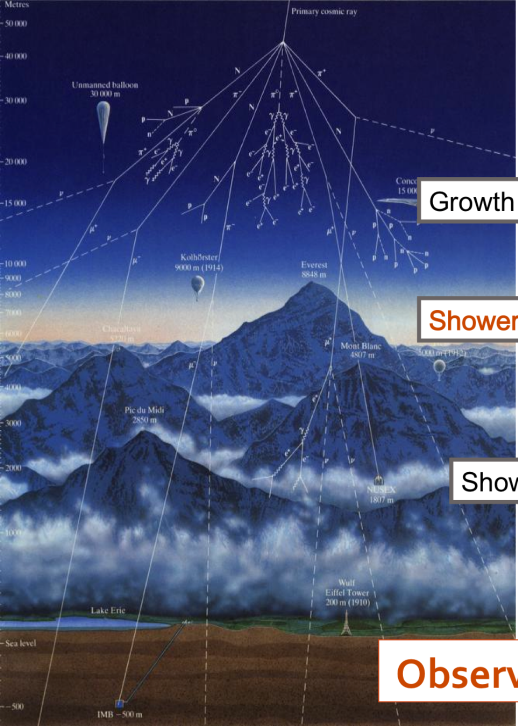
PIERRE AUGER OBSERVATORY

Closest radio-galaxy (3.8 Mpc) in the southern hemisphere.

Possible astrophysical interpretation



- Simple astrophysics models describe the observed spectrum
- Constraining models needs composition measurement
- Composition interpretation needs hadronic interactions models

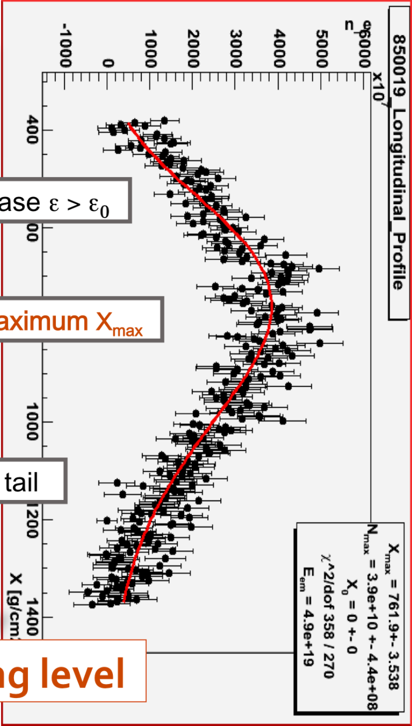


Growth phase $\varepsilon > \varepsilon_0$

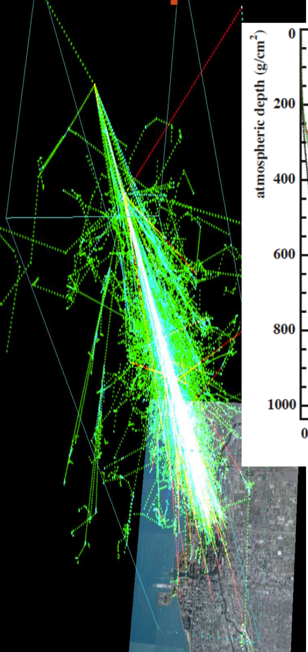
Shower maximum X_{max}

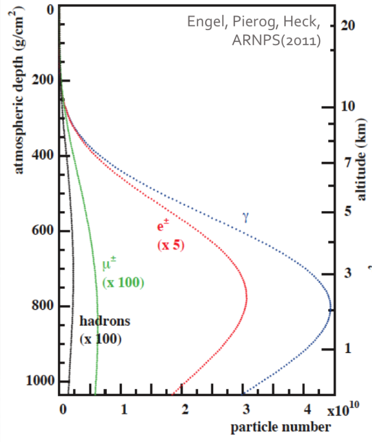
Shower tail

Observing level



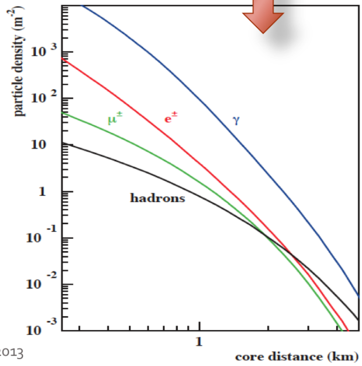
Components of the EAS





Longitudinal profiles

Lateral profiles



Heitler model

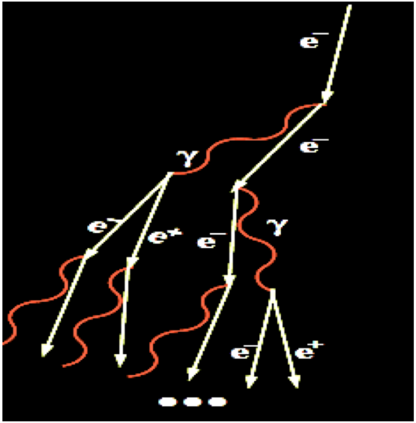
- After n generations

$$n = X/X_{\rm EM}$$

$$N \approx 2^n$$

- At the shower maximum

$$N_{\rm max} = E_0/\epsilon_0$$

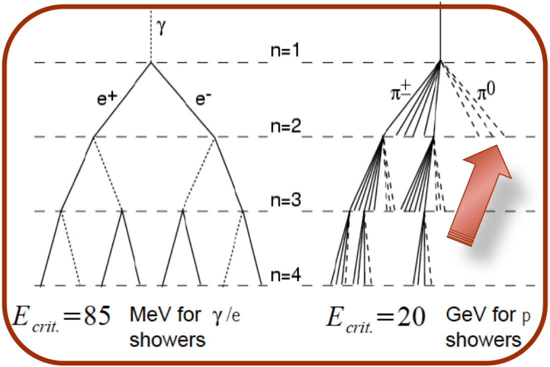


$$X_{\rm max} \approx X_{\rm EM} \frac{\ln(E_0/\epsilon_0)}{\ln 2}$$

The Elongation Rate

$$D_e = \frac{\delta X_{\rm max}}{\delta \ln E}$$

Baryon induced showers



$$\lambda_{p-\mathrm{air}} = X_0$$

$$\langle n(E)\rangle \rightarrow E/\langle n(E)\rangle$$

$$X_{\max}(E) \approx X_0 + X_{\mathrm{EM}} \ln[E/\langle n(E)\rangle]$$

$$\langle n(E)\rangle \approx n_0 E^{\Delta}$$

$$D_e = X_{\mathrm{EM}} \left[1 - \frac{\delta \ln\langle n(E)\rangle}{\delta \ln E} + \frac{X_0}{X_{\mathrm{EM}}} \frac{\delta \ln(X_0)}{\delta \ln E}\right] = X_{\mathrm{EM}}\,(1-B)$$

$$B \equiv \Delta - \frac{X_0}{X_{\mathrm{EM}}} \frac{\delta \ln X_0}{\delta \ln E}$$

Estimating the number of muons

$$N_\mu = (2N_\pi)^{n_c}$$

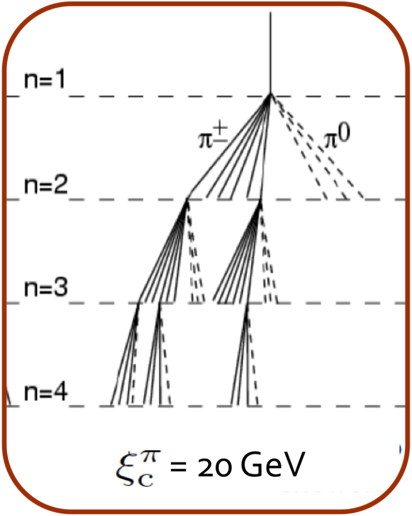
$$n_c = \ln(E_0/\xi_c^\pi)/\ln(3N_\pi)$$

$$\boxed{N_\mu = (E_0/\xi_c^\pi)^\beta}$$

$$\beta = \ln(2N_\pi)/\ln(3N_\pi)$$

$$N_\pi = 5,\ \beta = 0.85$$

From simulations β → 0.88-0.92



Matthews, Astropart. Phys. 22 (2005) 387

Nμ depends on the primary E, the air density and the charged and total multiplicity of the hadronic interactions.

Superposition model

A–induced shower of energy **E** ⇒ **A** proton-induced showers of energy **E/A**

$$X_{\max} \propto \ln(E_0/A)$$

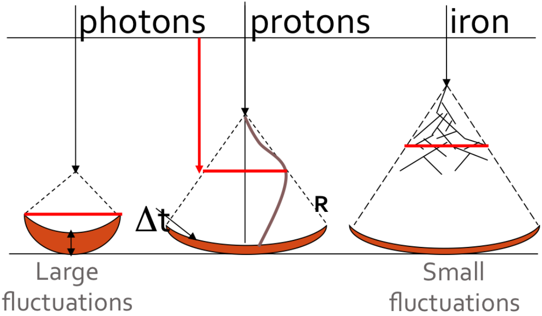
$$D_e = X_0\,(1-B)\left[1-\frac{\partial\langle \ln A\rangle}{\partial \ln E}\right]$$

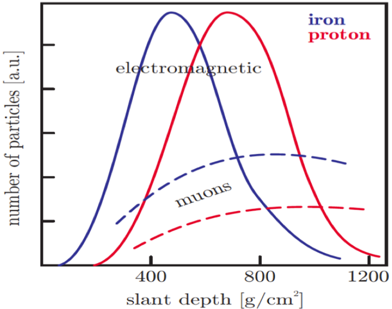
$$N_\mu^A \propto A(E_0/A)^\beta$$

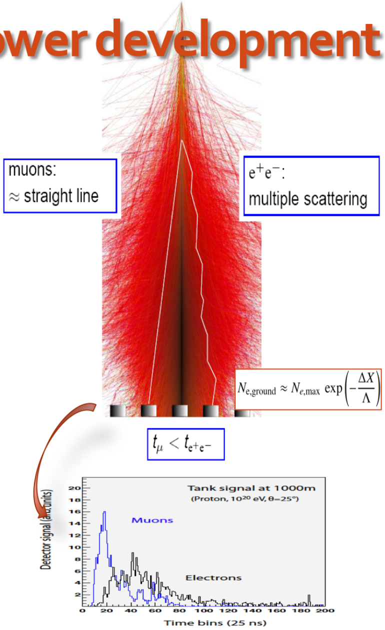
Nucleus-induced EAS

- ✓ reach their maxima earlier
- ✓ have more muons.

Primary species and shower development



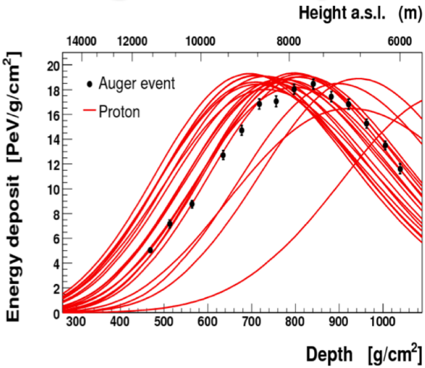


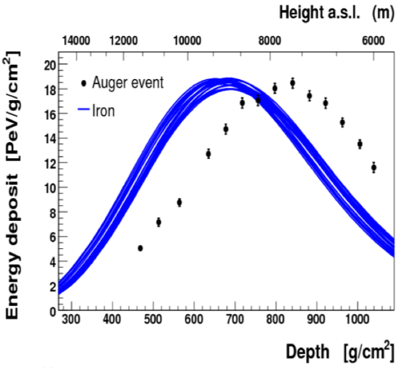


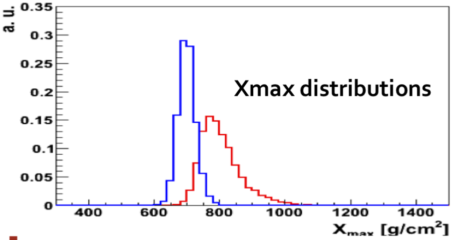
Small X_{max}
quick signal

Large X_{max}
slow signal

Longitudinal profile



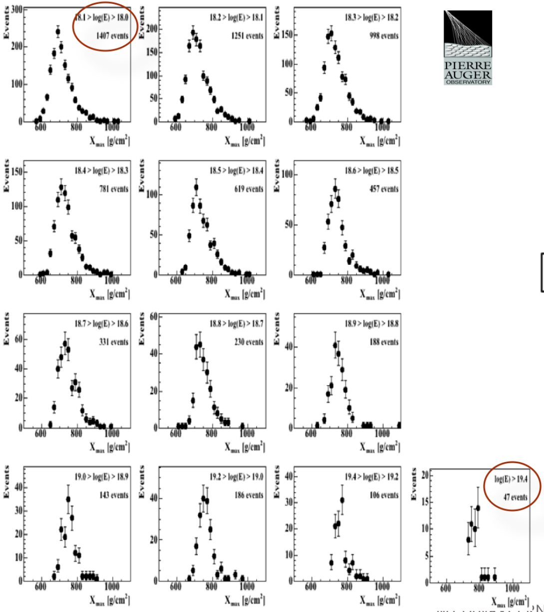


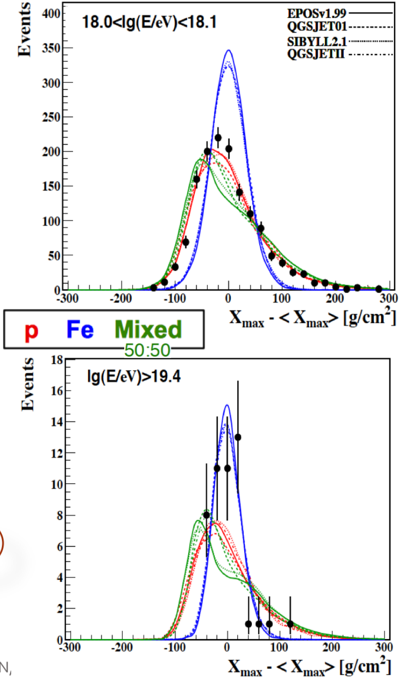


Mean X_{max} and $RMS(X_{max})$ are sensitive to mass

Pampa Amarilla, Mendoza, Argentina

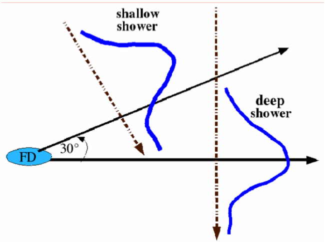
Xmax distributions

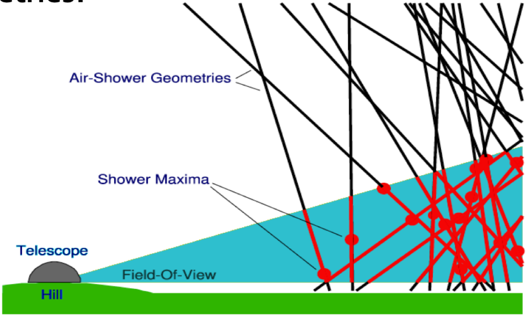




Field of view bias

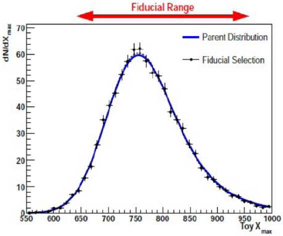
Field of view of FD telescopes does not cover full Xmax range for all shower geometries.



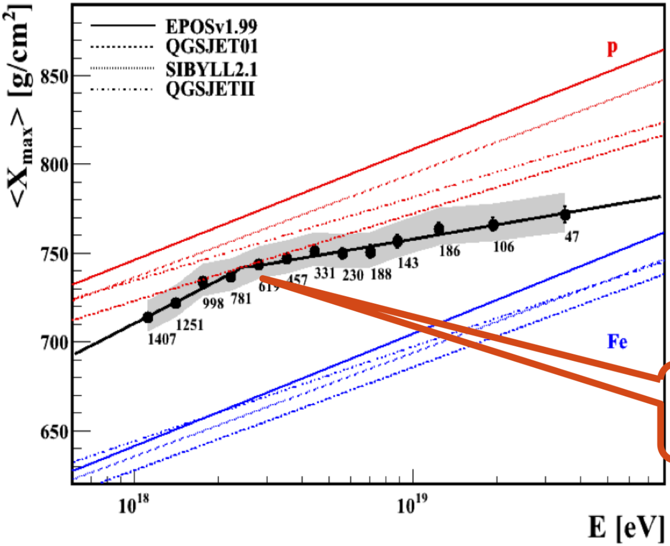


- Select only shower geometries that cover full Xmax range
- Compare measurement directly with generator-level prediction

Results are detector independent



Auger elongation rate



Low Energy

$D_{10} = 82^{+48}_{-8}$ g/cm²/decade

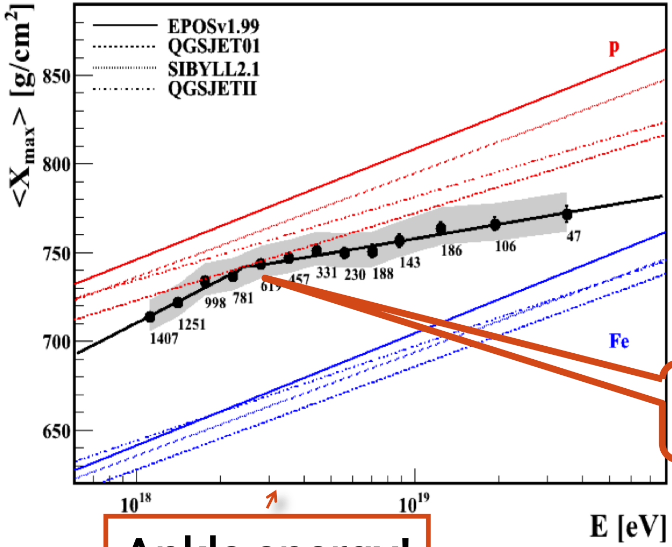
High Energy

$D_{10} = 27^{+3}_{-8}$ g/cm²/decade

Energy break

$\log(E_{break}/\mathrm{eV}) = 18.38^{+0.07}_{-0.17}$

Auger elongation rate



Low Energy

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$D_{10} = 27^{+3}_{-8}$ g/cm^2/decade

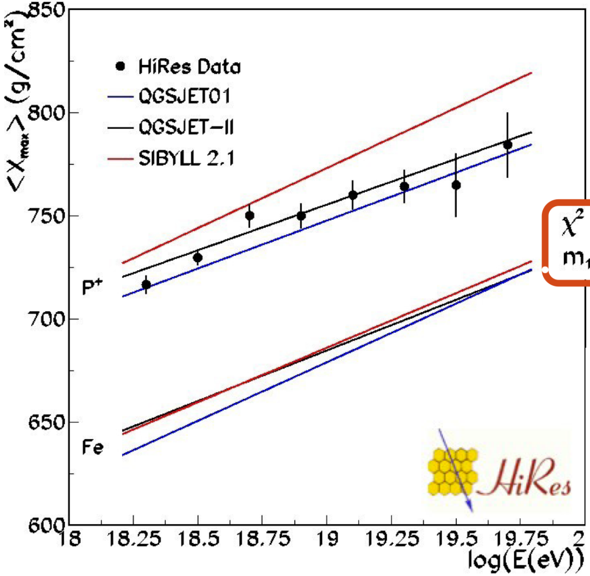
Energy break

$\log(E_{break}/\mathrm{eV}) = 18.38^{+0.07}_{-0.17}$

Ankle energy!

Utah desert, USA

HiRes: proton in 2 decades

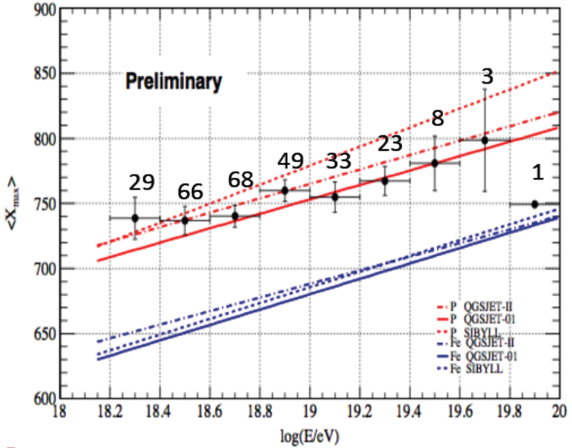


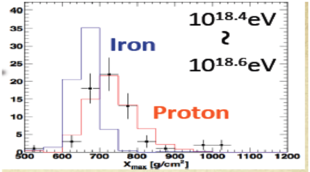
- Xmax acceptance bias in data and MC for HiRes and TA.

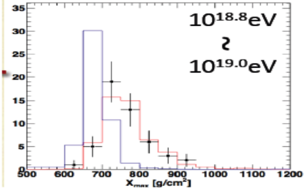
$\chi^2 = 5.2159/6$ d.o.f.
$m_1 = 47.8717 \pm 6.03218$

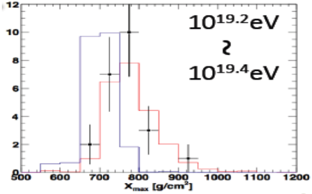
- Constant composition
- No evidence for galactic-to-extragalactic transition at ankle

TA: Pure proton?



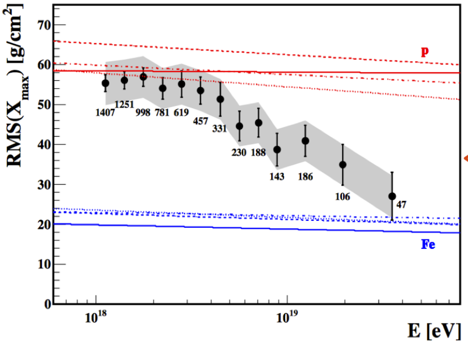






Ikeda Daisuke for the Telescope Array Collaboration, UHECR2012

RMS (X_{max}) vs Energy



AUGER: RMS(X_{max})

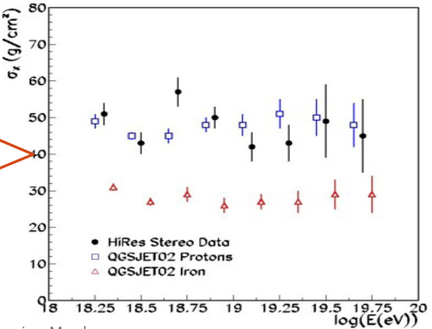
Resolution is subtracted from data.

27g/cm² →low energy

18g/cm²→high energy

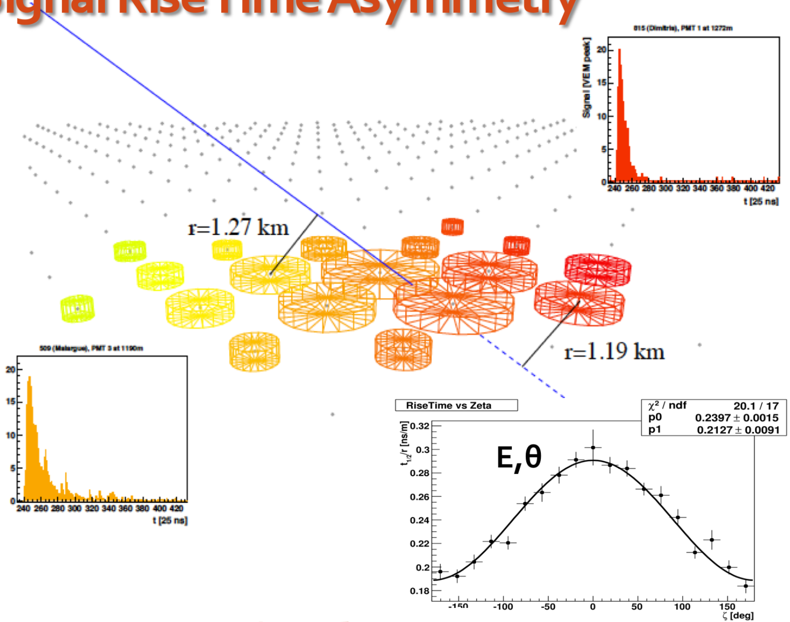
HiRes

Define width as σ of Gaussian truncated at 2xRMS, without correction for detector resolution



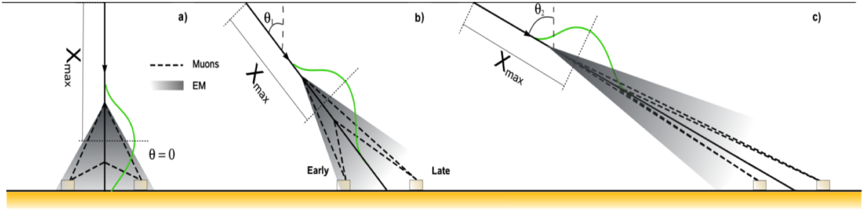
Signal Rise Time Asymmetry

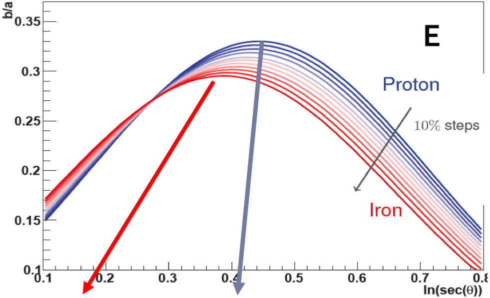
MTD et al, Astropart.Phys. 31 (2009), 312



$\langle t_{1/2}/r \rangle = a + b \cos \zeta$ → b/a: asymmetry factor

Asymmetry and shower evolution

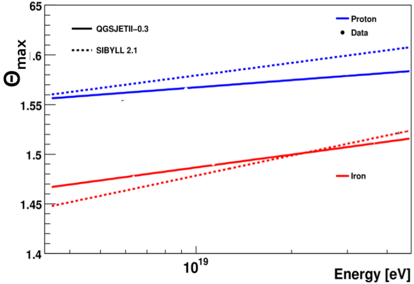




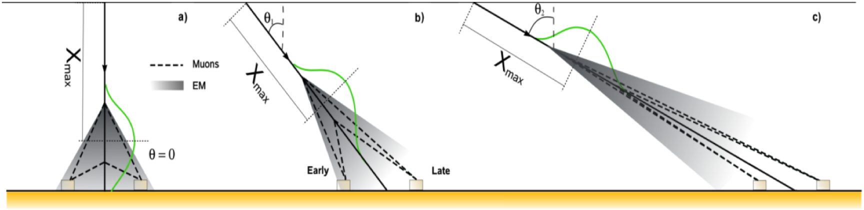
Θ_{max} (iron) Θ_{max} (proton)

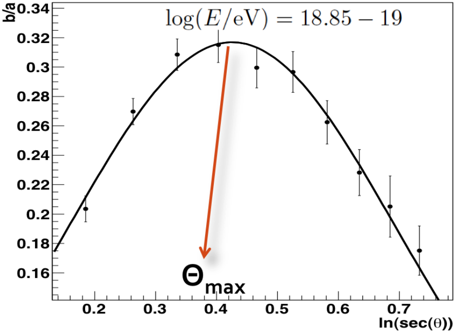
MTD et al, Astropart.Phys. 31 (2009), 312

Θ_{max}: Measure sec θ at which asymmetry b/a is maximal



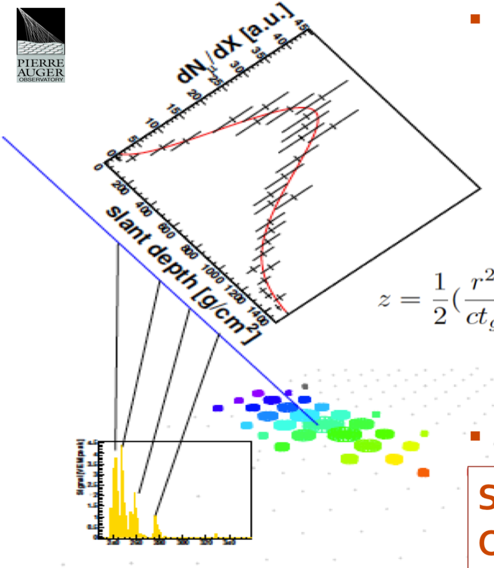
Asymmetry and shower evolution



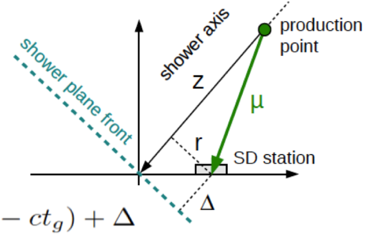


SD Mass Sensitive Observable of the Auger Observatory.

Muon Production Depth



- **Distribution of muon production heights**



$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$

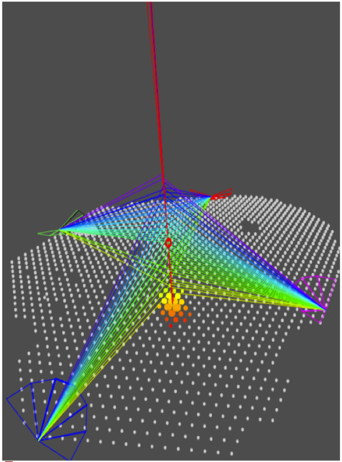
$$X^\mu = \int_z^\infty \rho(z')dz'$$

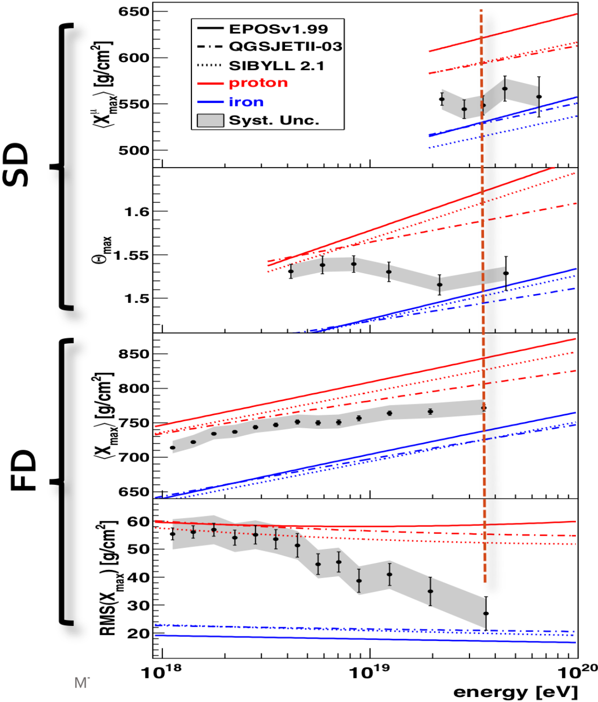
- **Maximum at X^μ_{max}**

SD Mass Sensitive Observable of the Auger Observatory.

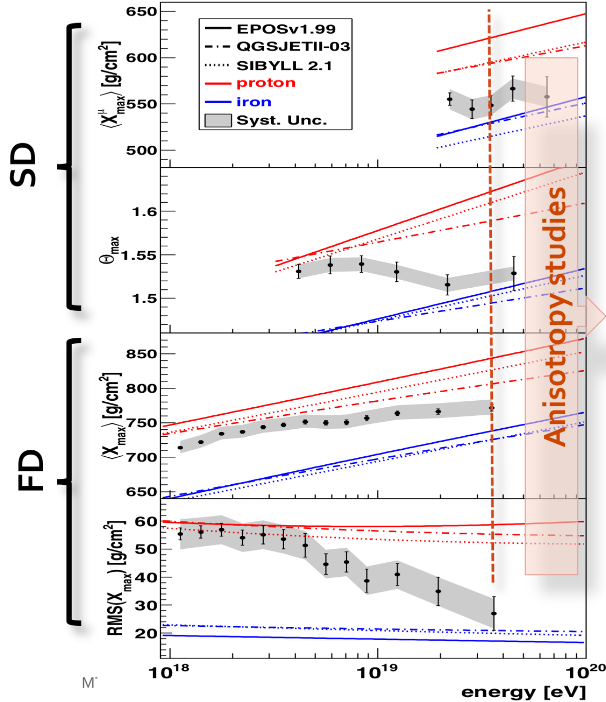
Cazon et al. *Astropart.* Phys 21, 71 (2004)
Astropart. Phys 23, 392 (2005)

Auger Composition





Auger Composition



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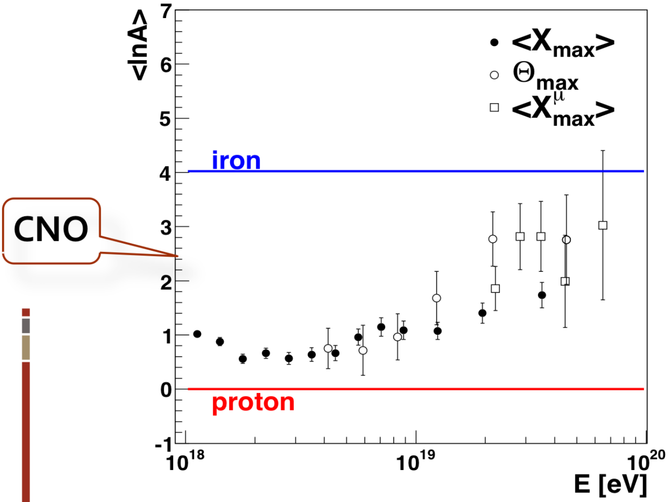
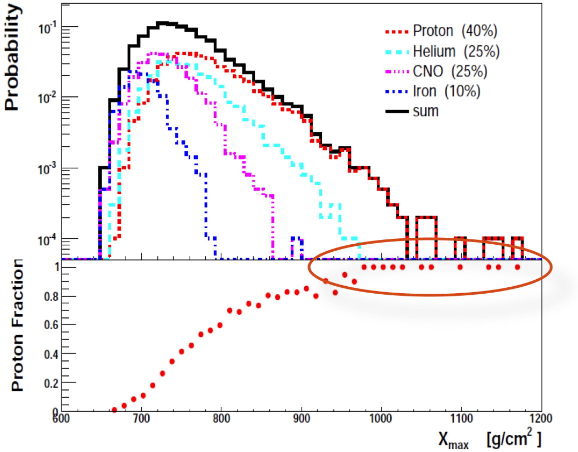
Simple exercise with QGSJETII and Auger published results



- Only statistical uncertainities
- Similar results with other hadronic models

MTD, D. García Pinto,
M. Unger, H. Walhberg

Fluctuations in Xmax distribution

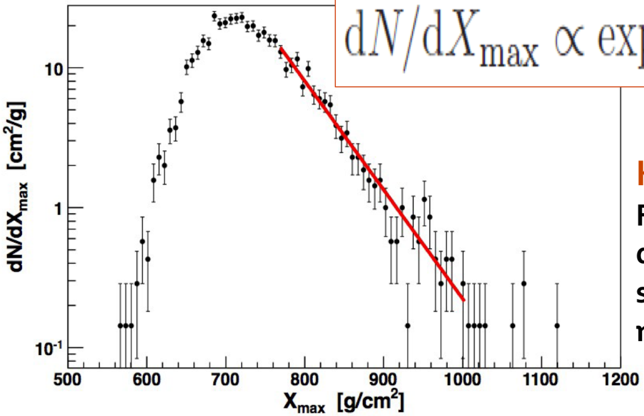


The tail of the X_{max} distribution populated by proton.

The tail is sensitive to p-air cross section

Ellworth et al. PRD 1982, Baltrusaitis et al. PRL 1984, etc..

p-air cross section measurement



$$dN/dX_{max} \propto \exp(-X_{max}/\Lambda_\eta)$$

Key parameter:

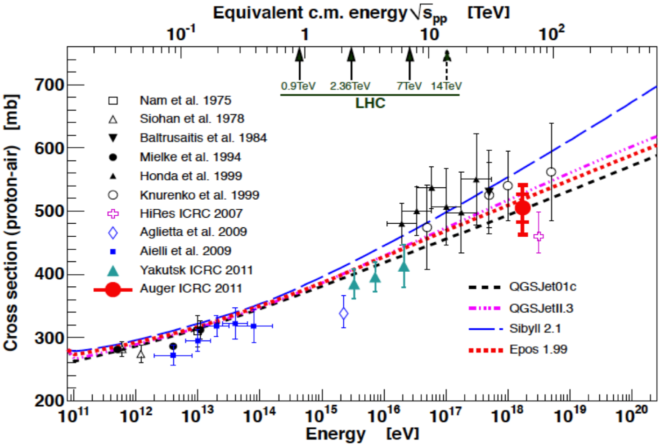
Fraction of the most deeply penetrating showers used.

$\eta = 0.2$

Average energy $10^{18.24}$ eV

$$\Lambda_\eta = [55.8 \pm 2.3(\text{stat}) \pm 1.6(\text{sys})]\ \text{g/cm}^2 \rightarrow \sigma_{\text{p-air}}$$

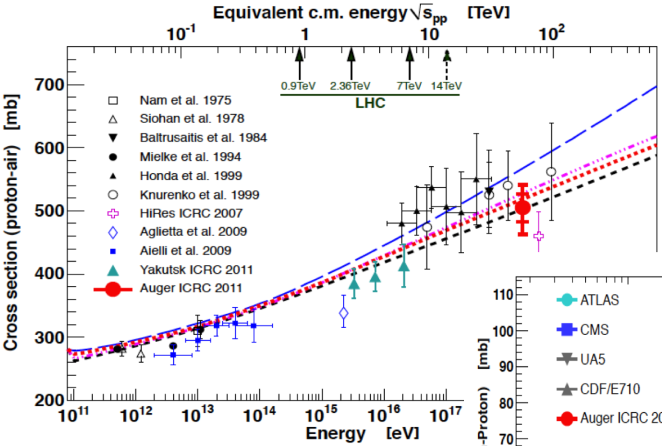
p-air cross section at 57 TeV



$$\sigma_{p\text{-air}}^{\text{prod}} = [505 \pm 22(\text{stat})\ ^{+28}_{-36}(\text{sys})]\ \text{mb}$$

- Helium bias potentially largest syst.

p-air cross section at 57 TeV

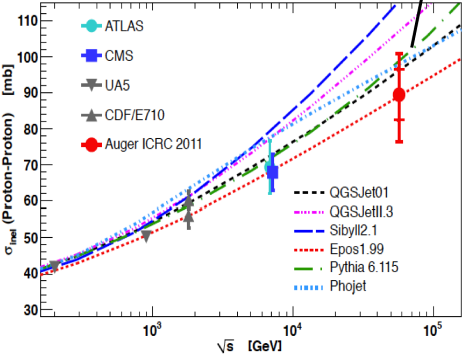


Glauber model

R. Ulrich et. al.
Nucl.Phys.PS. 196 (2009) 335340

$$\sigma_{pp}^{tot} = \left[129 \pm 13(\text{stat}) \,^{+17}_{-20}(\text{sys}) \pm 11(\text{Glauber})\right] \text{ mb}.$$

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



Neutral messengers

Production → At the UHECR sources
Production → Cosmogenics

PHOTONS

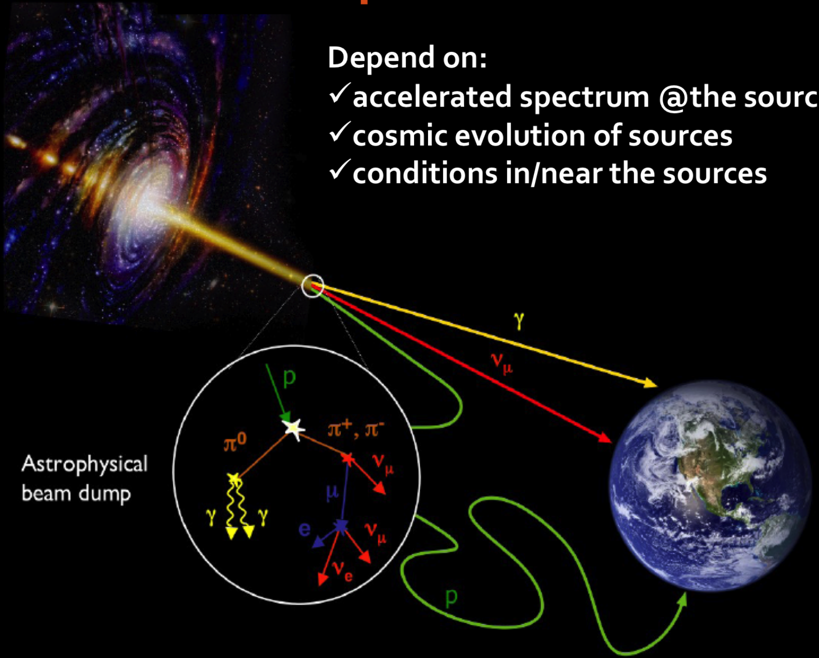
- Interactions in the sources.
- Absorbed on extragalactic backgrounds.

NEUTRINOS

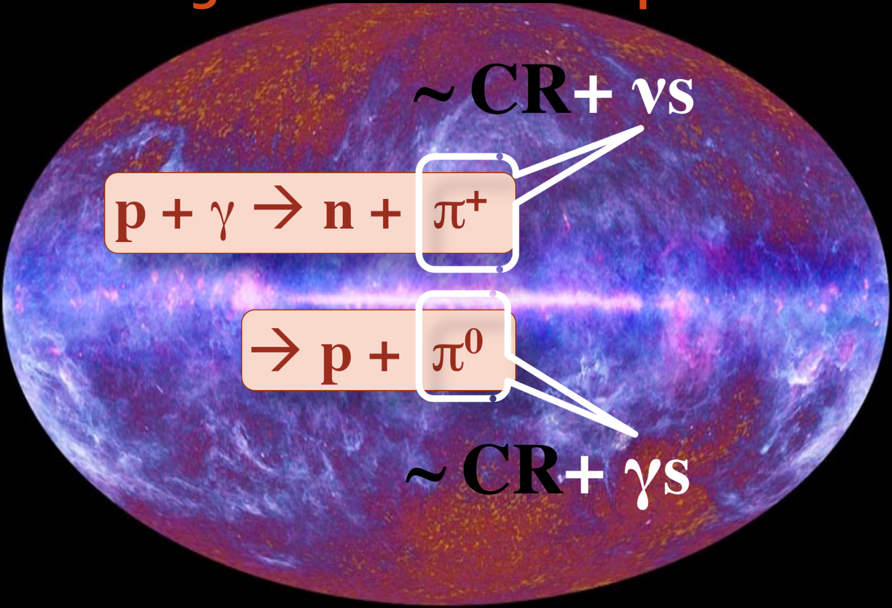
- No interactions in sources
- Propagate unabsorbed and without deflection.
- Difficult to detect.

neutrinos and photons at the source

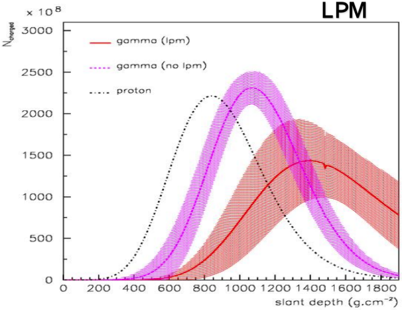
Depend on:
✓accelerated spectrum @the source
✓cosmic evolution of sources
✓conditions in/near the sources

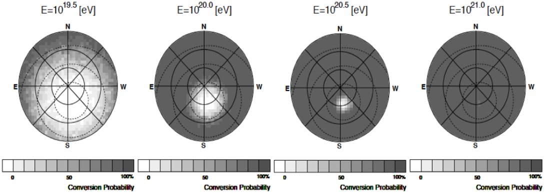


Cosmogenics neutrinos and photons



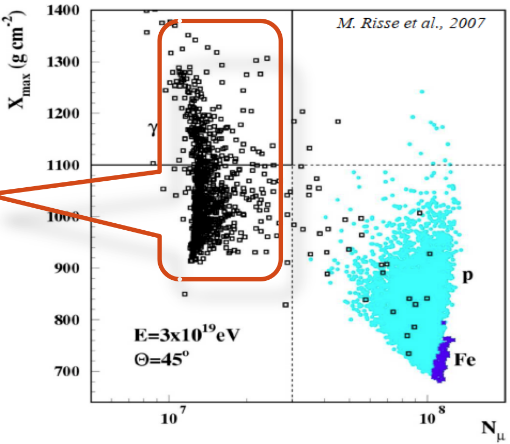
Photon EAS



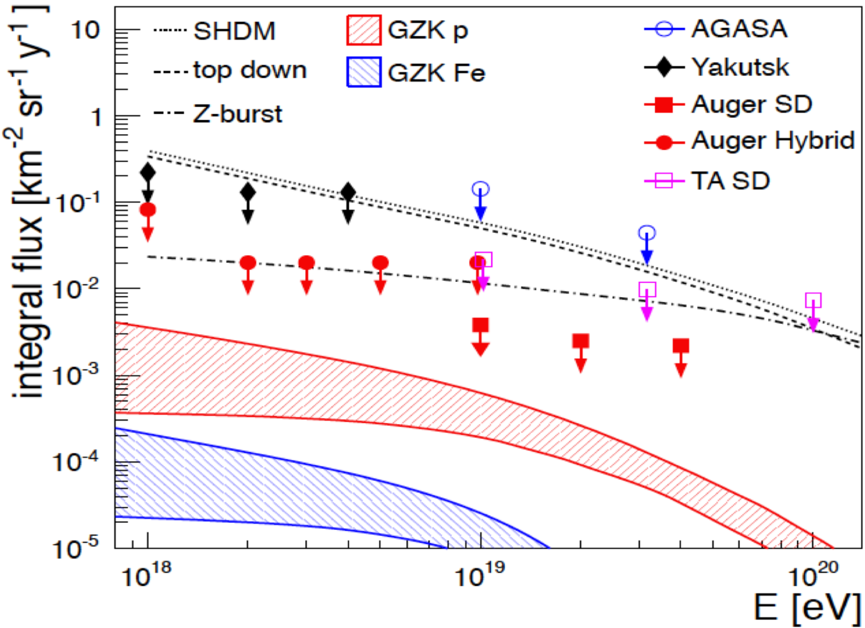


- ✓ Deeper Xmax
- ✓ Smaller muon content

- Steeper LDF
- Larger risetime

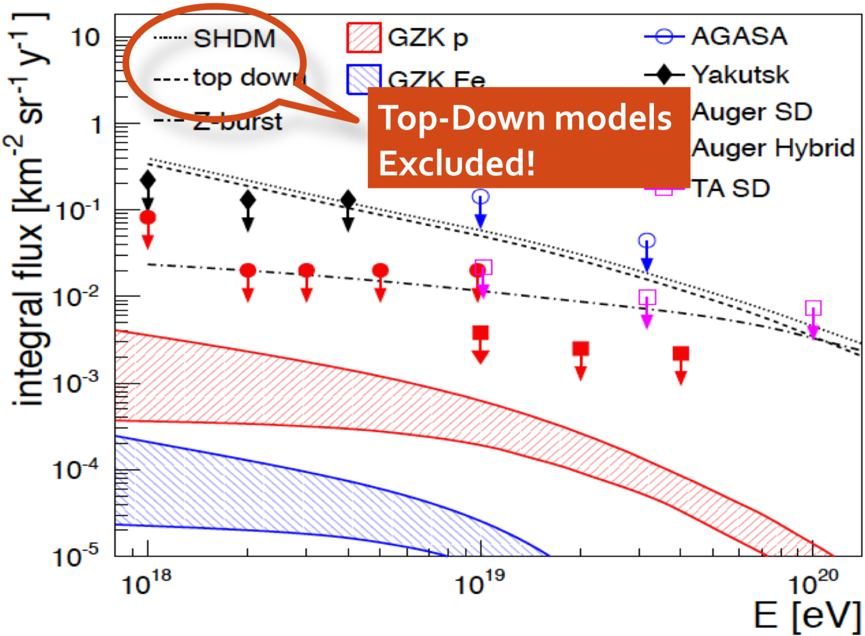


Upper limits on Photon Flux



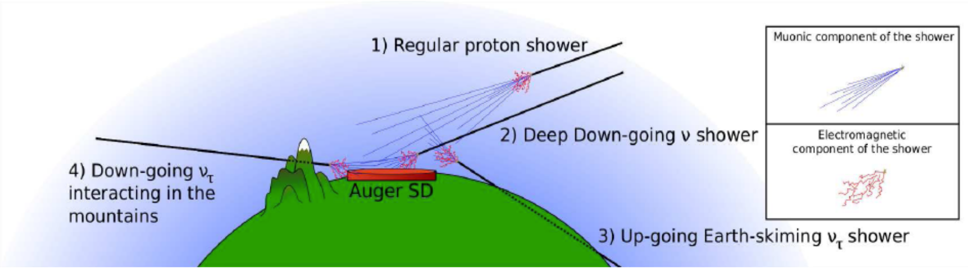
K-H Kampert, M.Unge, arXiv:1201.0018

Upper limits on Photon Flux

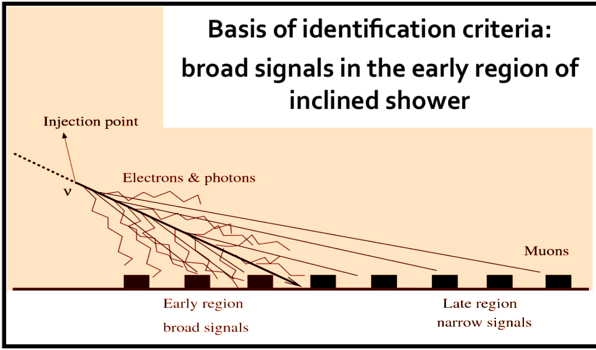


K-H Kampert, M.Unge, arXiv:1201.0018

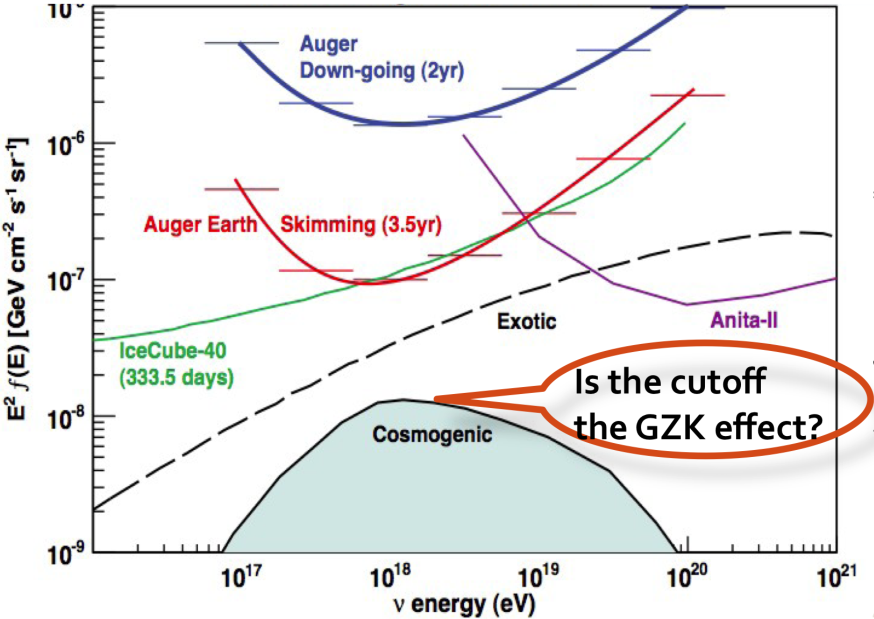
The Auger UHE neutrino observatory



"young" showers at very great atmospheric slant depth.

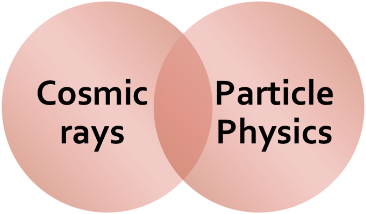


Neutrino flux upper limits



Y. Guardincerri for Pierre Auger Coll. ICRC2011

Hadronic interactions in EAS



$$X_{max} \sim \lambda_e \ln\left((1-k).\, E_0/(2.\mathrm{N}_{tot}.\, A)\right) + \lambda_{ine}$$

Matthews, APP. 22 (2005) 387

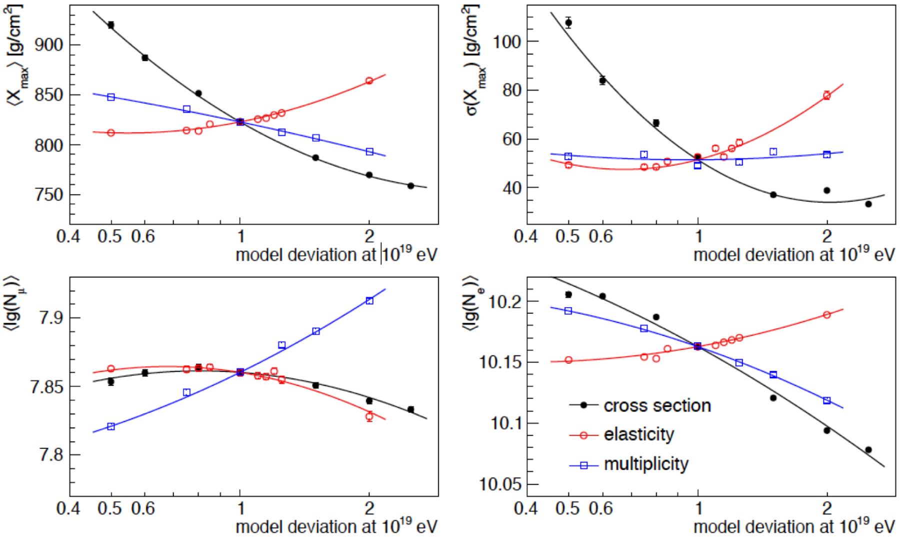
Model dependent parameters

k = elasticity

Ntot = total multiplicity

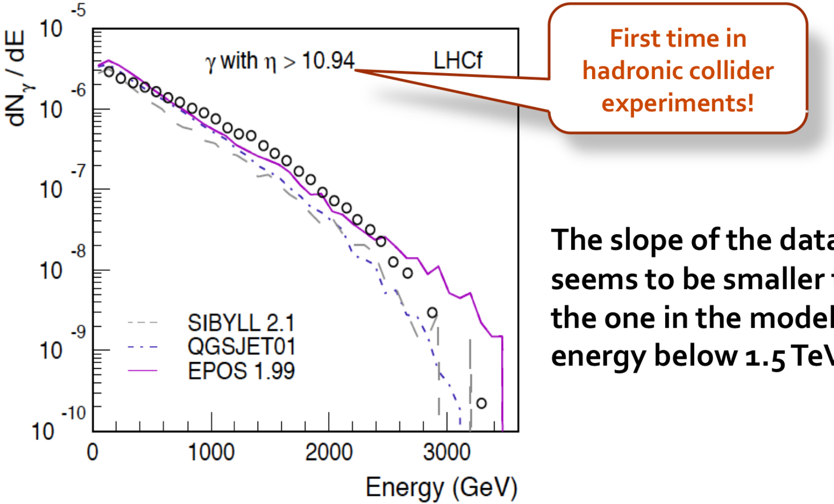
λine = hadronic mean free path (cross section)

Impact of model uncertainties on EAS



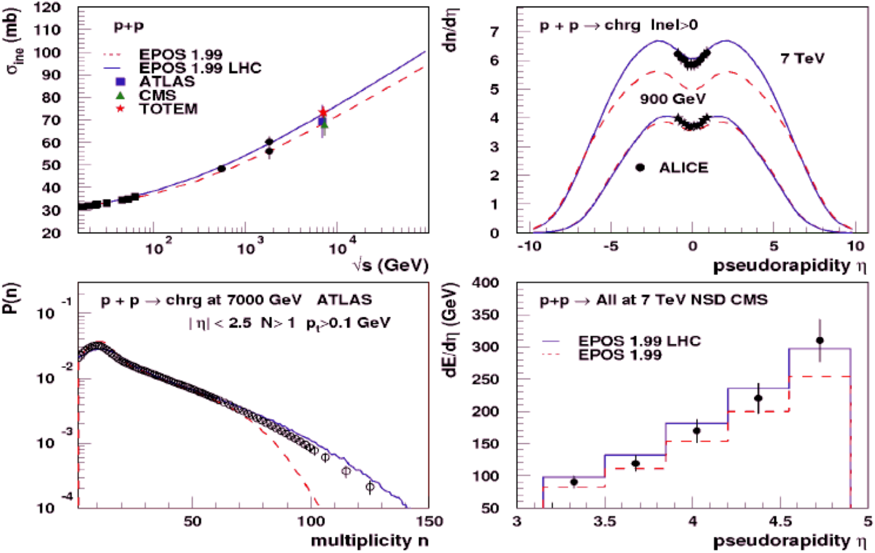
K-H Kampert, M.Unge, arXiv:1201.0018

Forward Energy Distribution



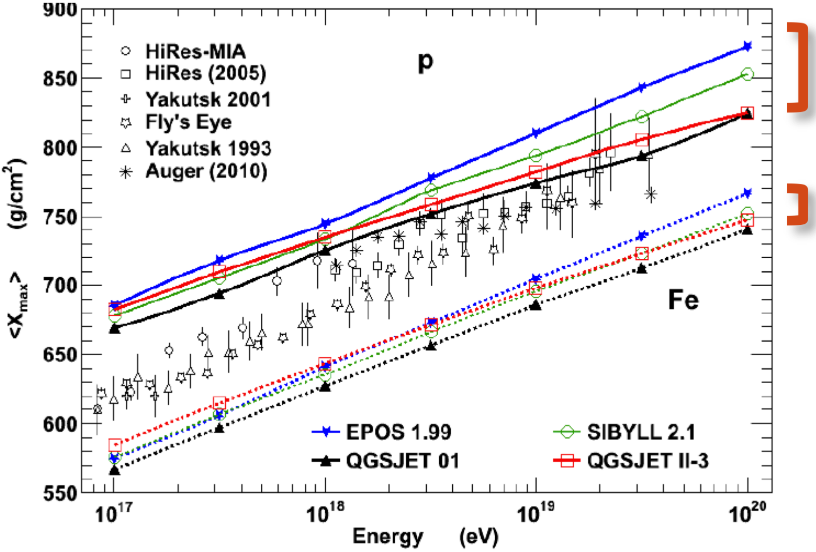
The slope of the data seems to be smaller than the one in the models for energy below 1.5 TeV.

EPOS 1.99 LHC (an example)

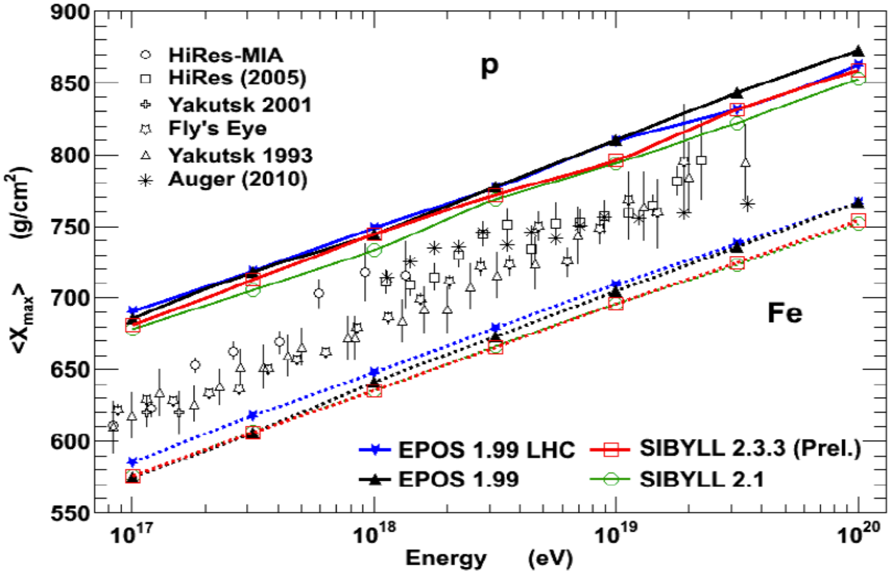


From T.Pierog, UHECR 2012

Xmax before LHC



Xmax after LHC



Pierog, UHECR 2012

Final remarks…

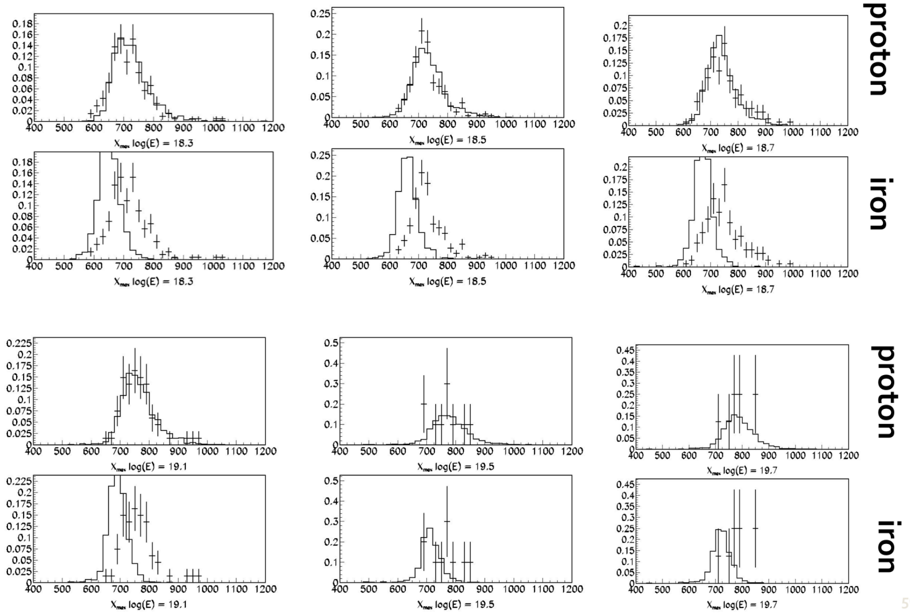
- Energy spectrum: There is a suppression (GZK?). Precise measurement of shape and energy scale of the ankle to discriminate models!
- Arrival directions: (an)isotropy above 55 EeV.

  Is Cen A the first UHECR observed source?
- Composition: some indications that CRs become heavier at higher energies.
- Limits on the flux of UHE photons and neutrinos disfavor exotic production scenarios (GZK?)

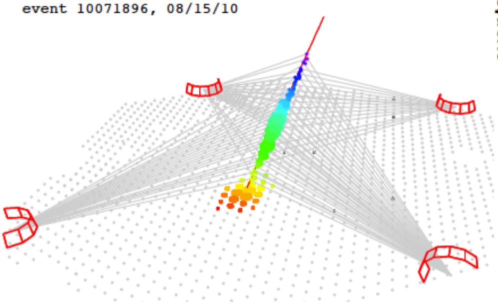
The End

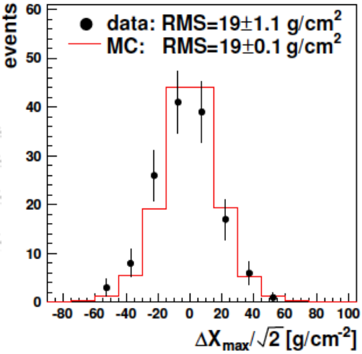
BACKUP SLIDES

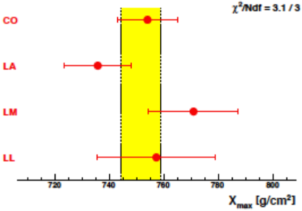
Xmax distributions: p and p and p

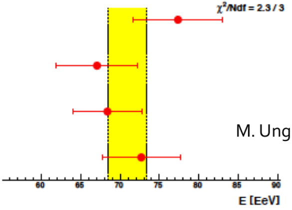


Cross checks with *Multi Eye* events









M. Unger for Pierre Auger coll, UHECR 2012,