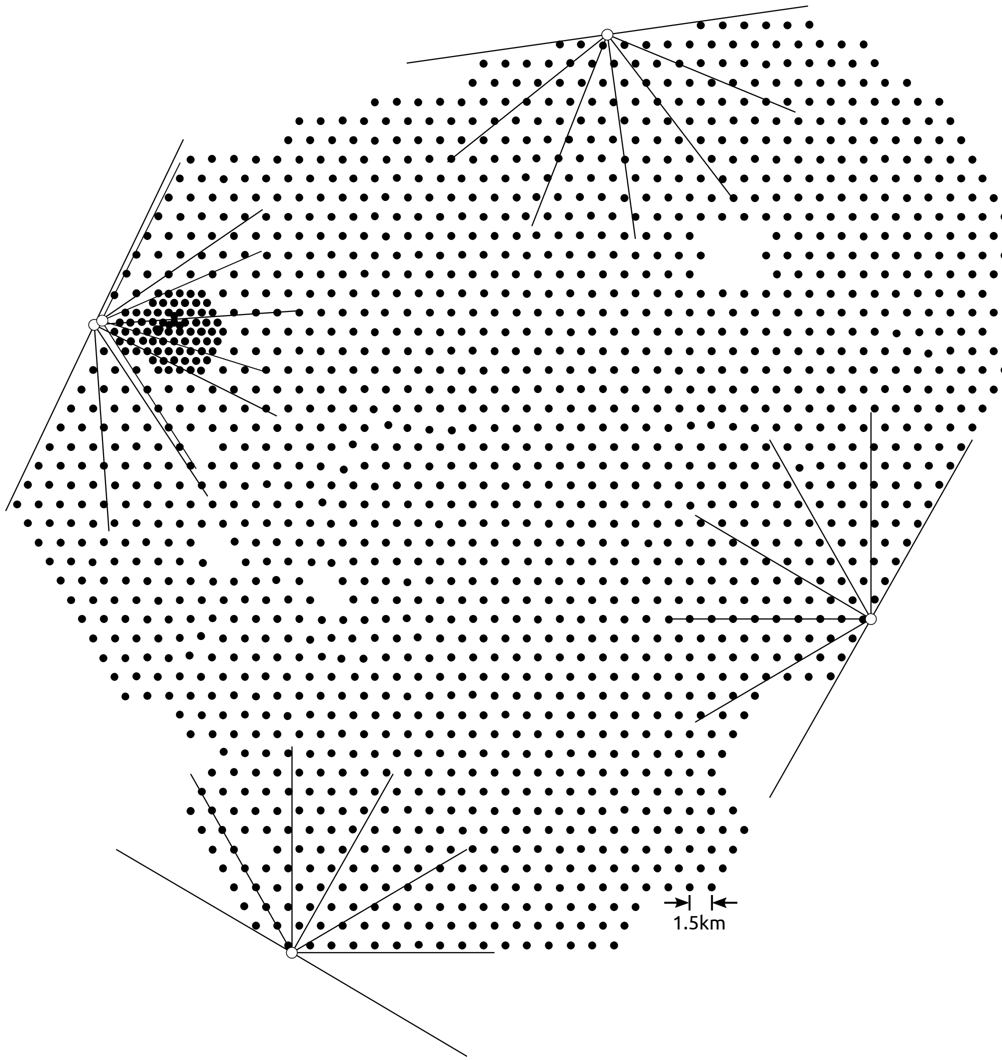


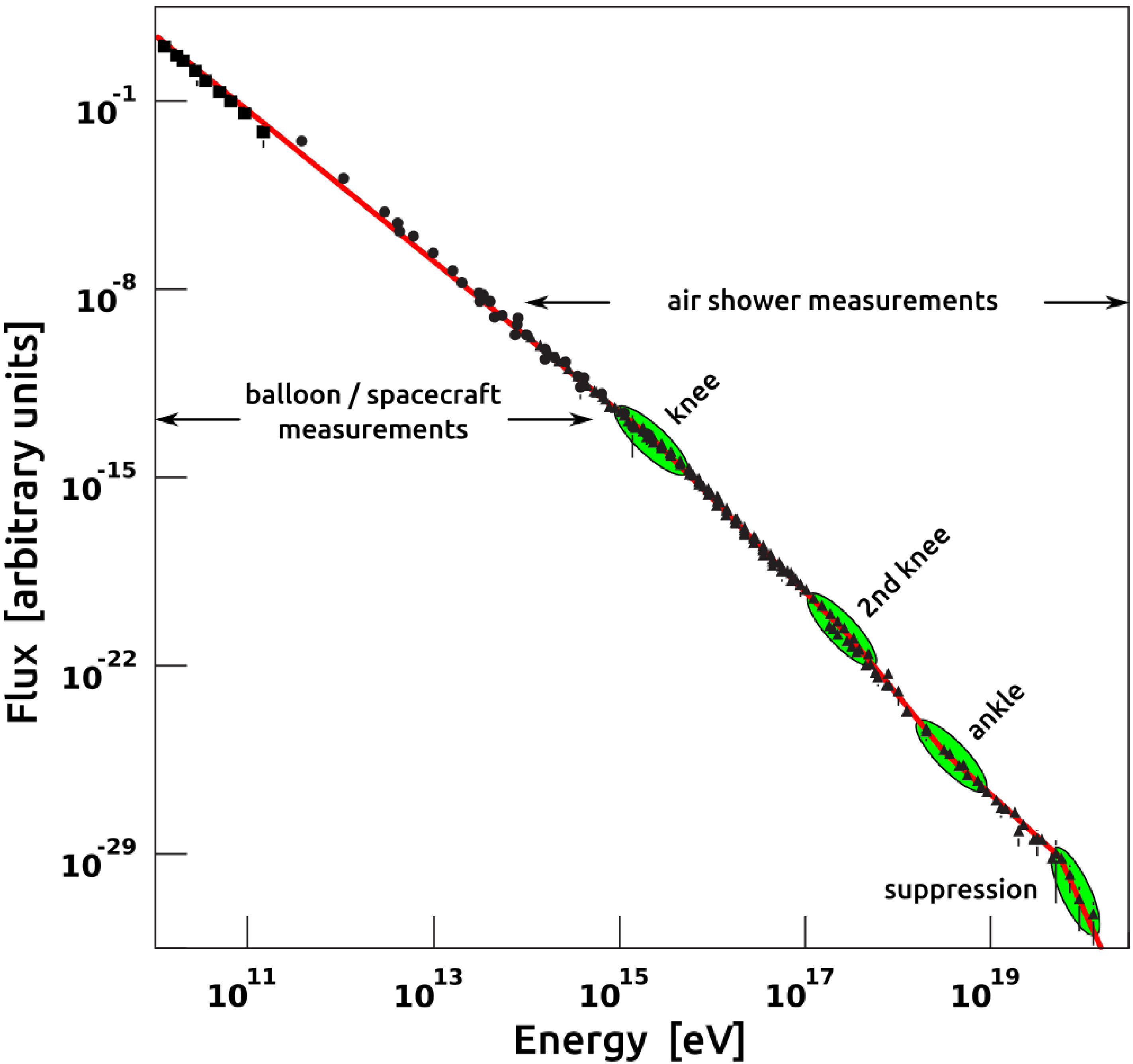
PIERRE AUGER OBSERVATORY

The Upgrade of the Pierre Auger Observatory

Darko Veberic
IKP, Karlsruhe Institute of Technology (KIT), Germany

for the Pierre Auger Collaboration
http://www.auger.org/archive/authors_2016_03.html

Spectrum of Cosmic Rays

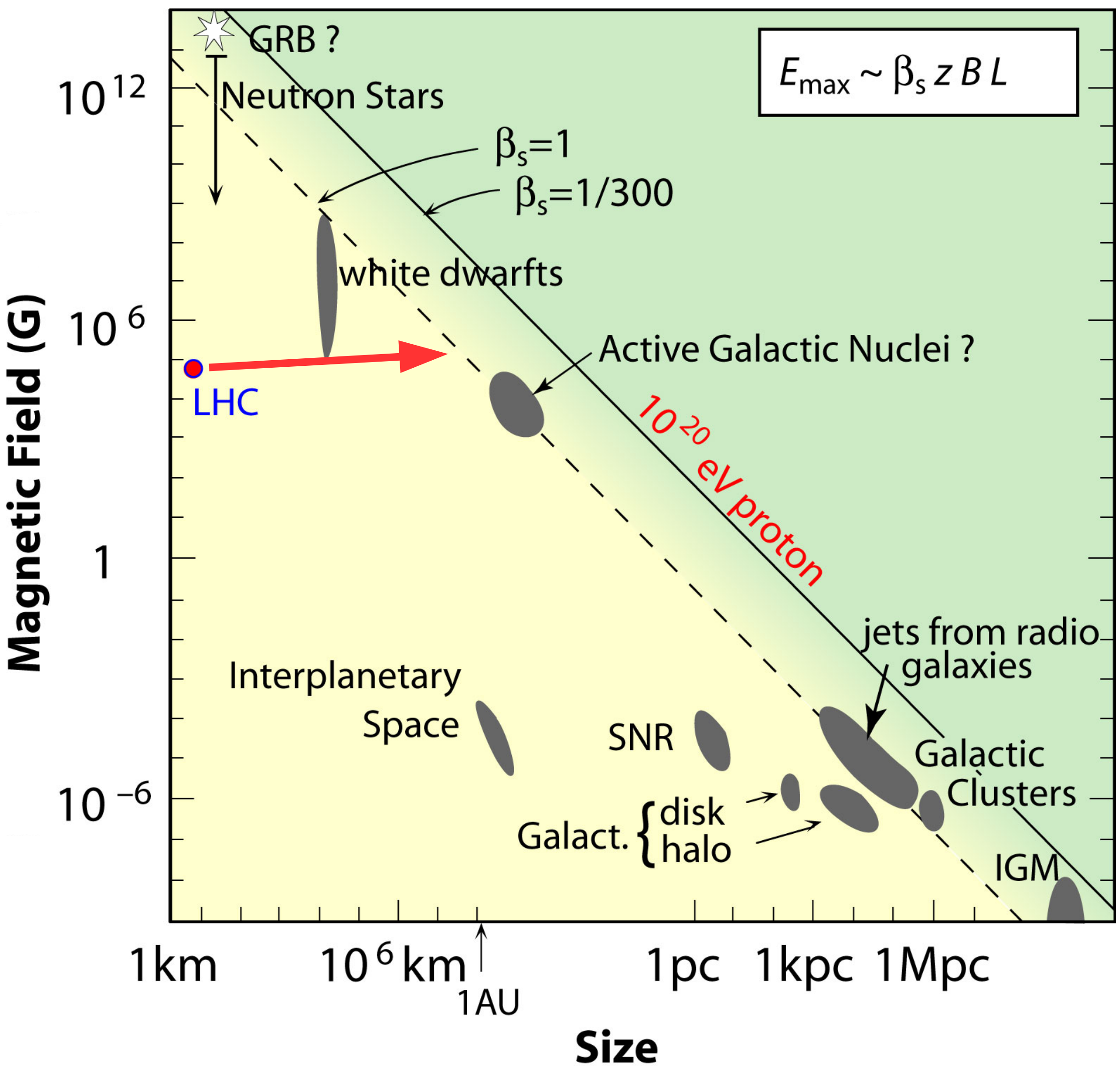


1 particle/m²/second

1 particle/m²/year

1 particle/km²/century

Cosmic Accelerators



10^{20} eV protons

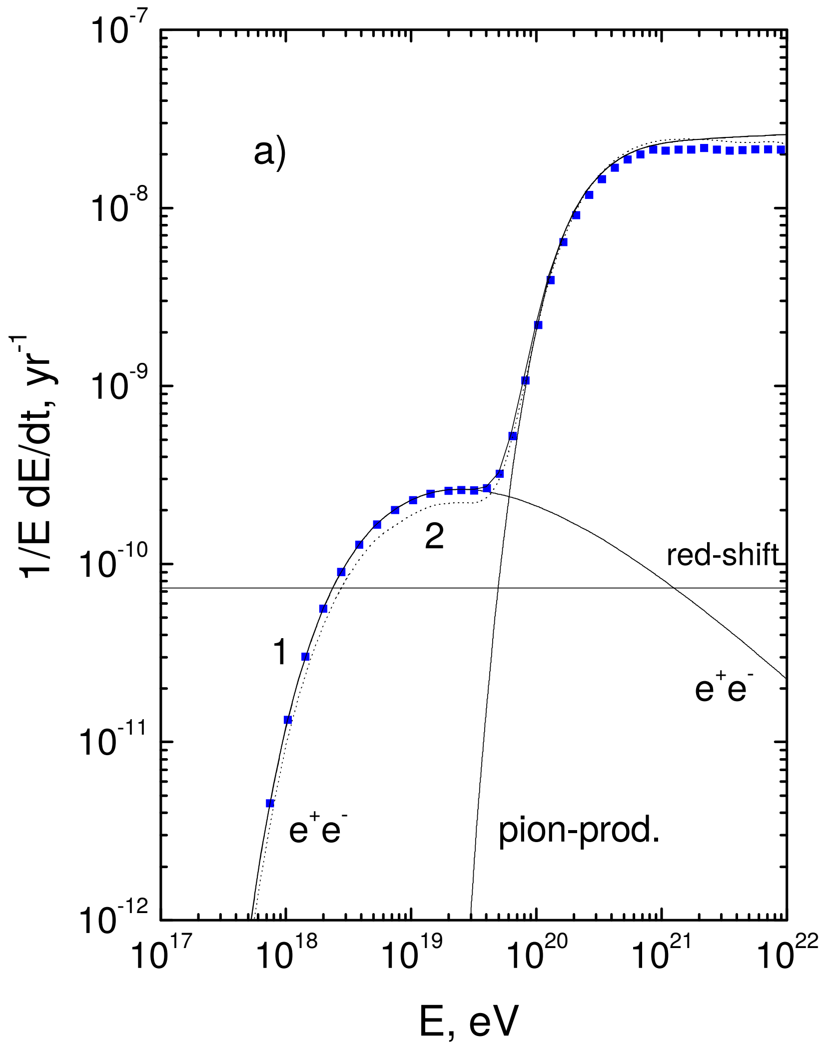
Mercury orbit

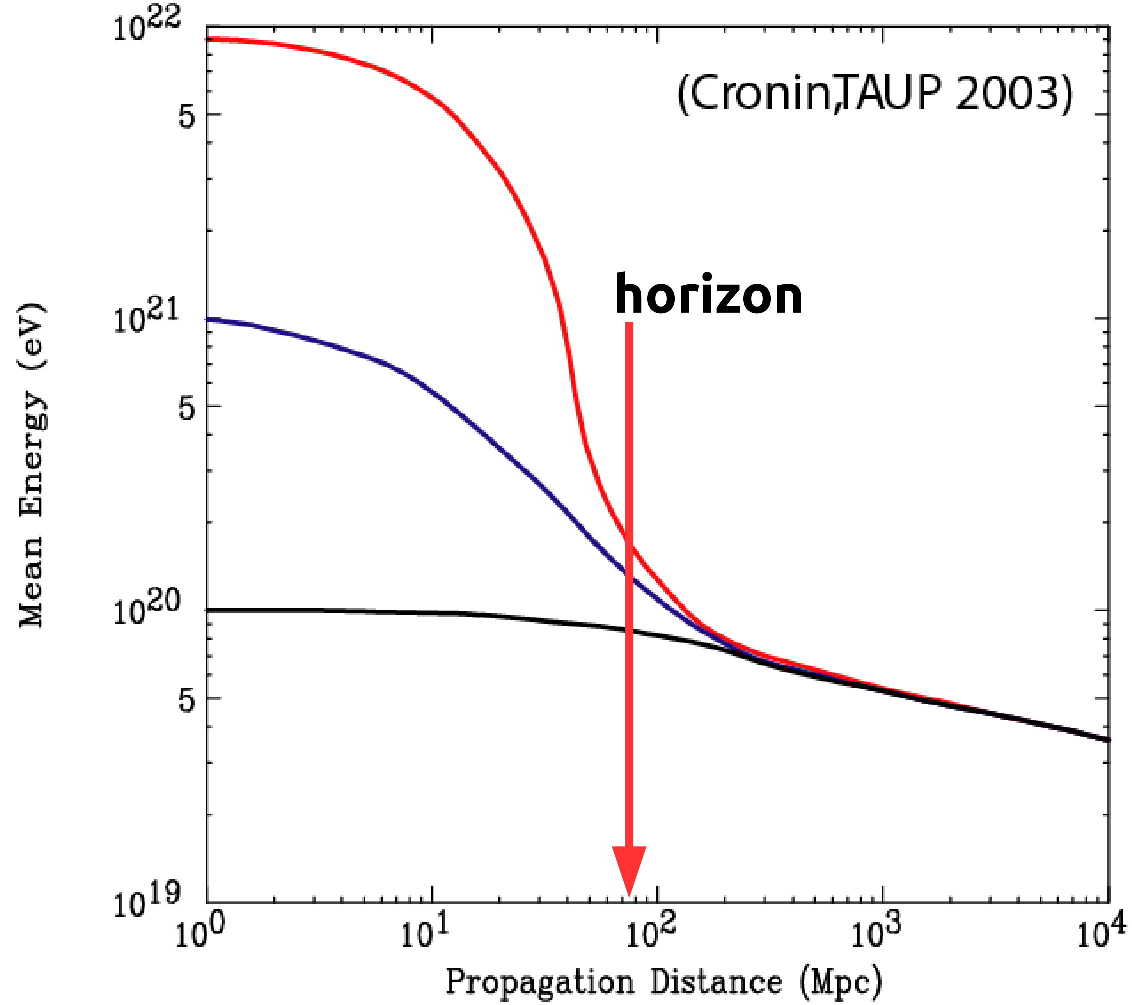
Clear, then Hazy and Foggy

energy loss through inelastic scattering on CMB

$$p + \gamma_{cmb} \to \Delta^+ \to p + \pi^\circ$$
$$\to n + \pi^+$$

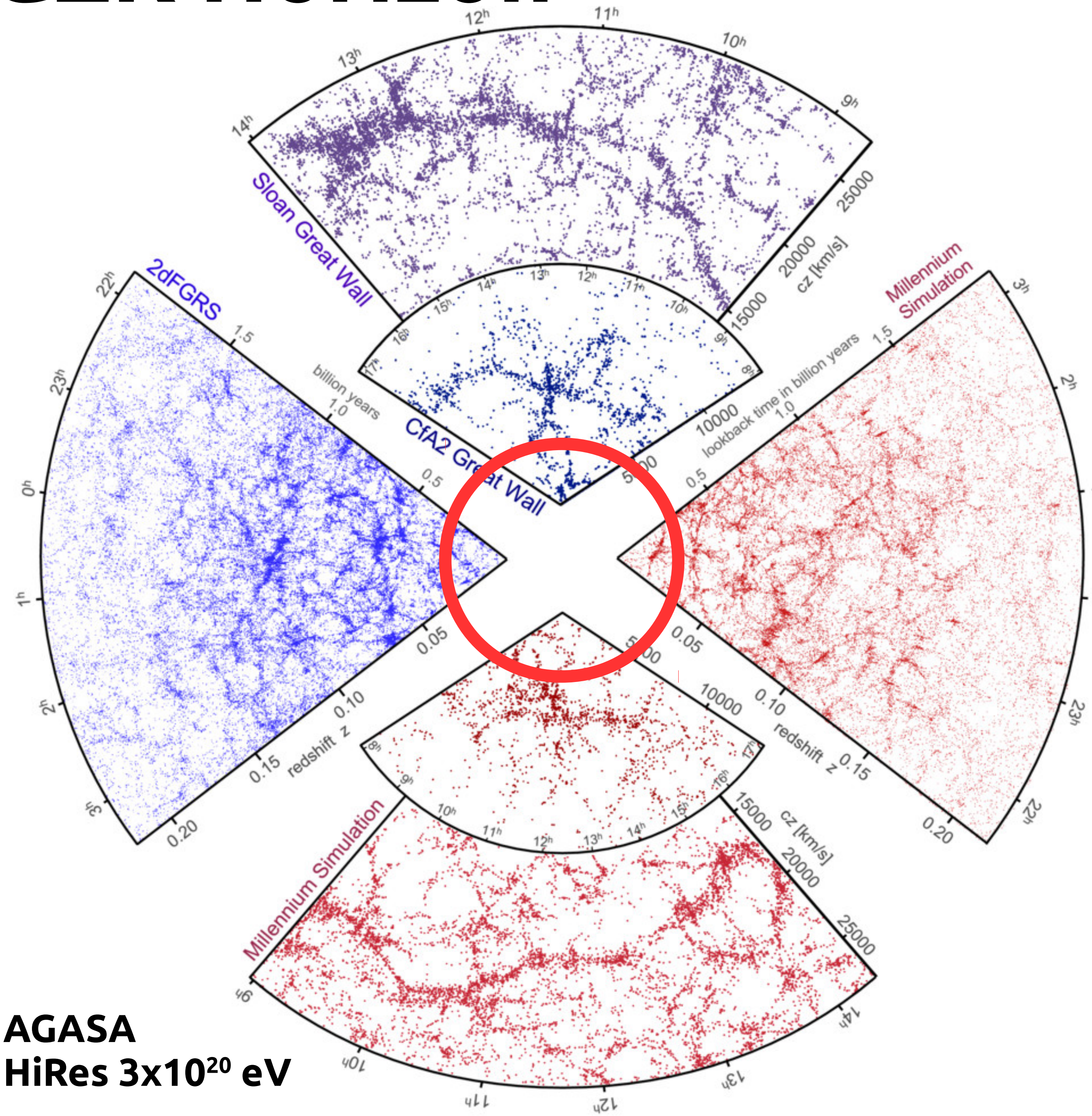
Greisen, PRL 16 (1966) 748.
Zatsepin, Kuz'min, JETP Lett. 4 (1966) 78.





GZK Horizon

GZK horizon:
~75 Mpc
~250 Mly
~0.02 redshift



AGASA
HiRes $3x10^{20}$ eV

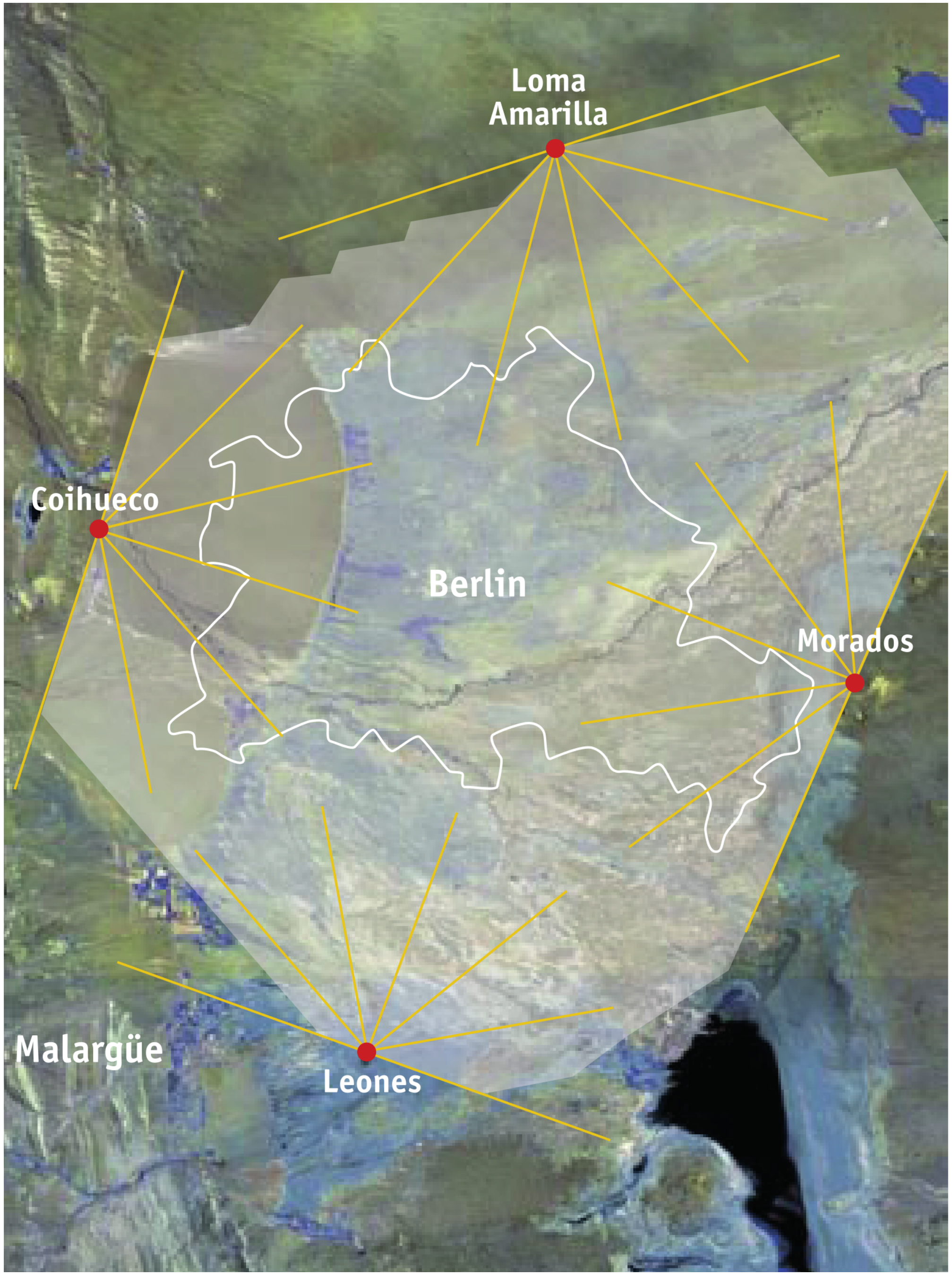
Pierre Auger Collaboration

16 countries, ~90 institutions, ~500 authors

Argentina
Australia
Brasil
Colombia*
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
USA

**associated*

Pierre Auger Observatory

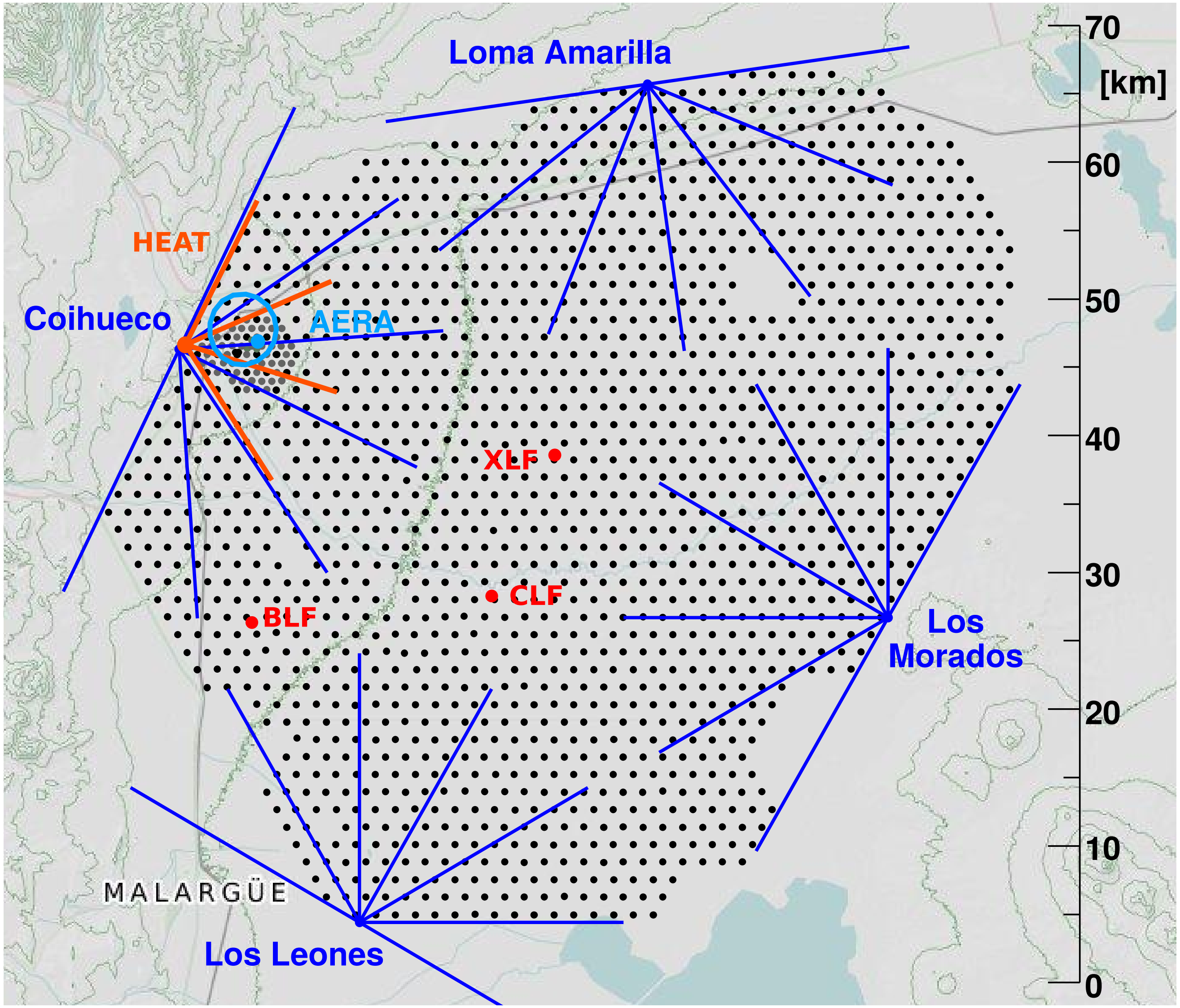


just east of Andes
Province of Mendoza, Argentina

area 3000 km² (4x Berlin)

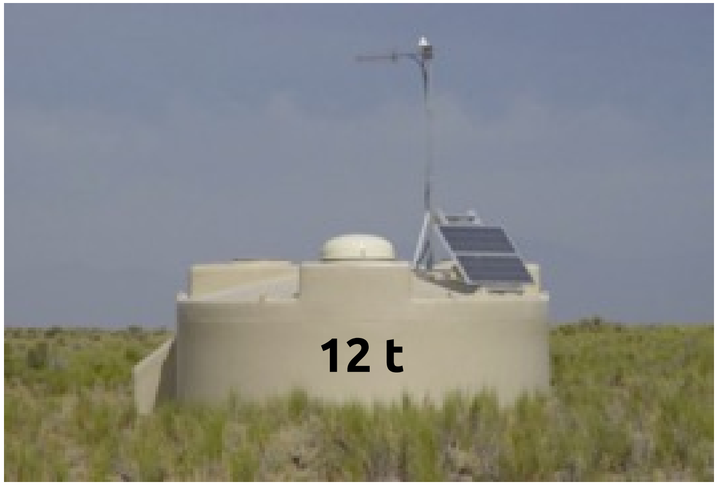
2000: Engineering Array
2004: start...
2008: end of construction

Detectors



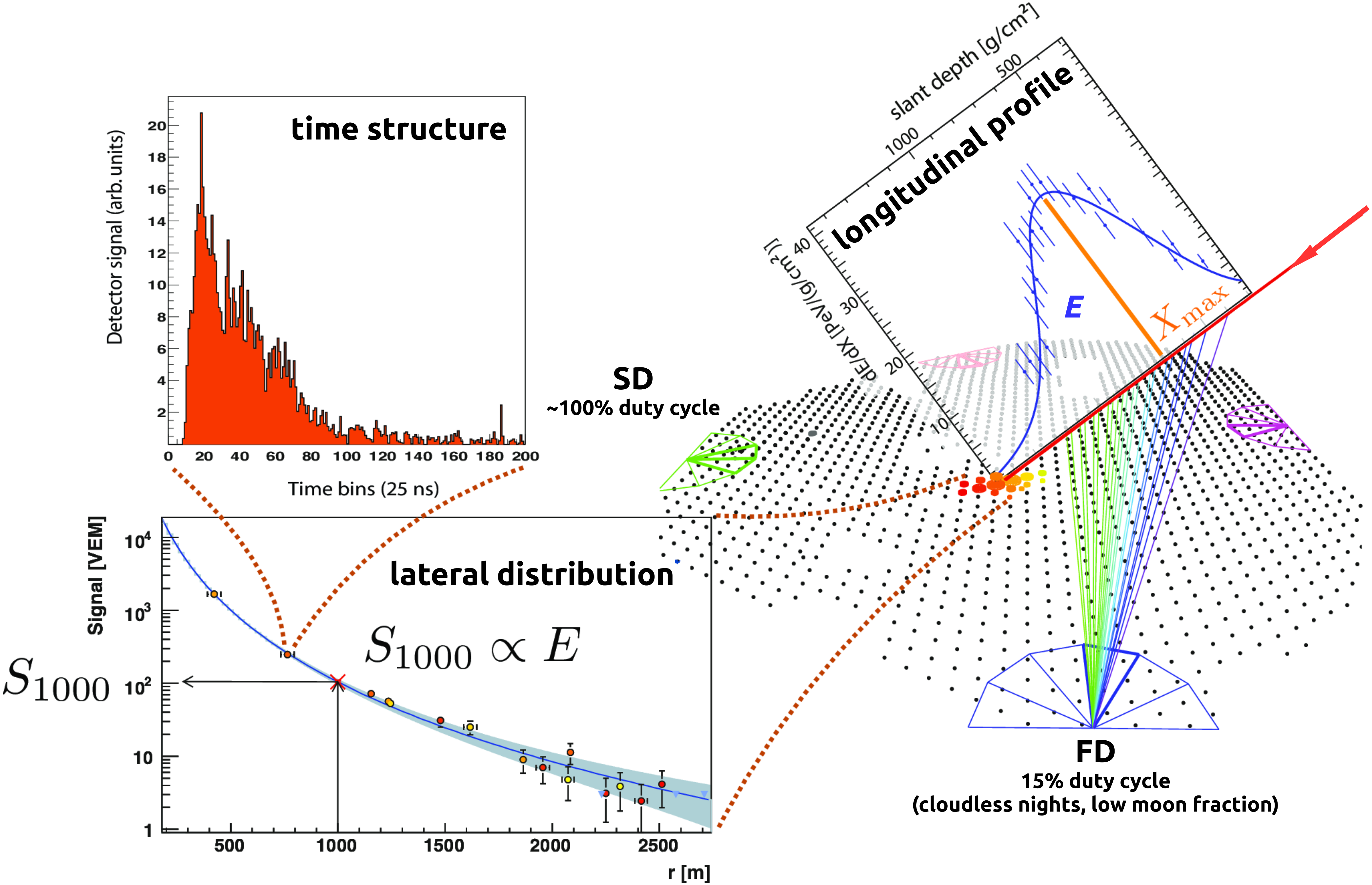
1.5 km spacing, 1660 SD stations; 27 FD telescopes
lidars, cloud monitoring, weather stations
$\langle h \rangle$ = 1450 m a.s.l., X_{vert} = 860 g/cm^2

fluorescence detector (FD)



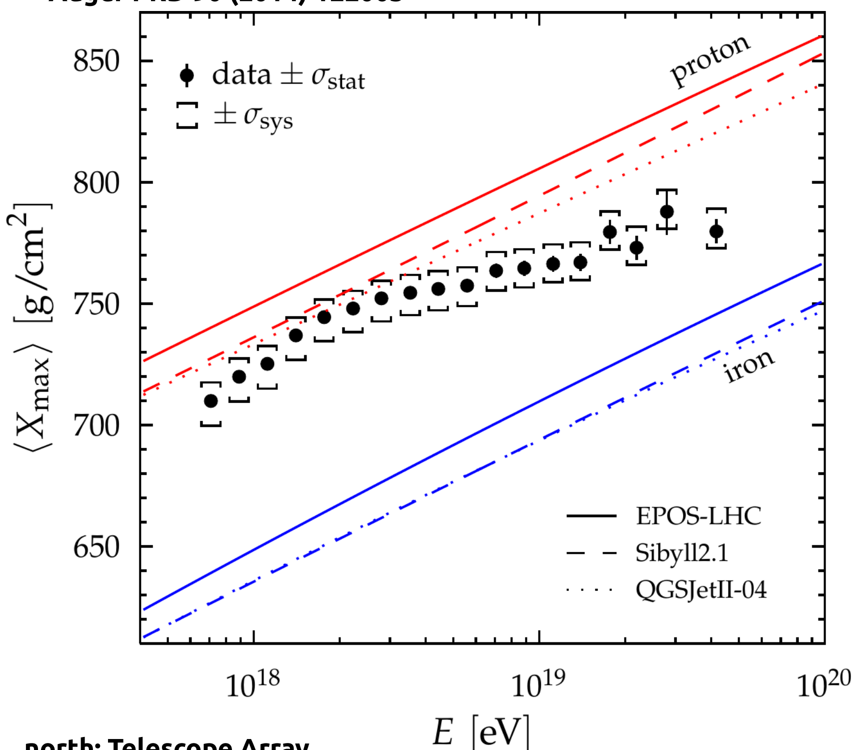
surface detector (SD)
water-Cherenkov technique

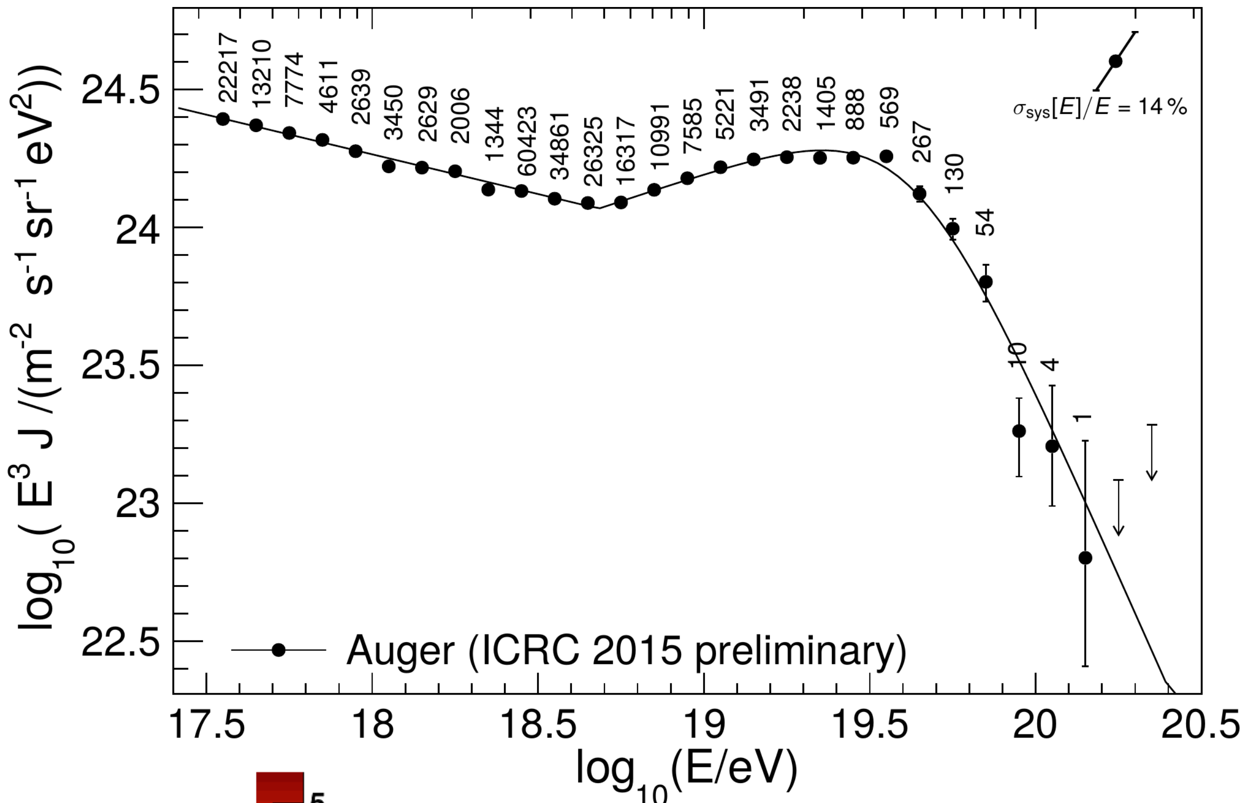
Shower Observables

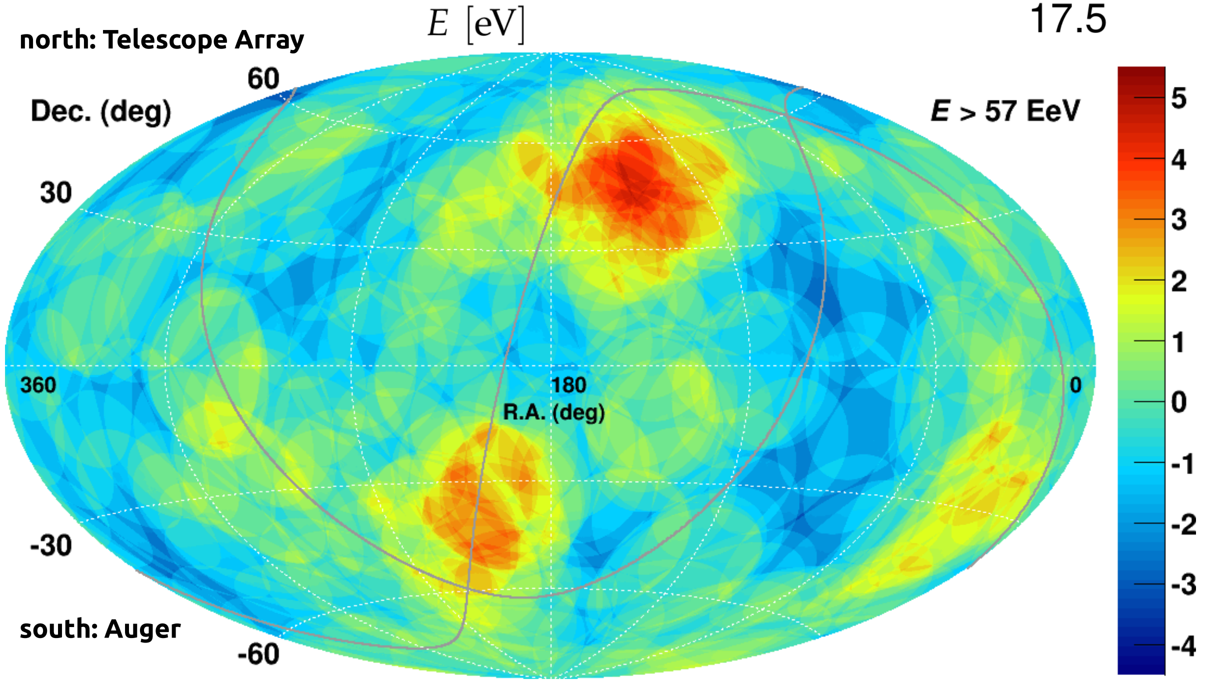


Main Results

Auger PRD 90 (2014) 122005







strong flux suppression

surprising composition change at $10^{18.5}$ eV

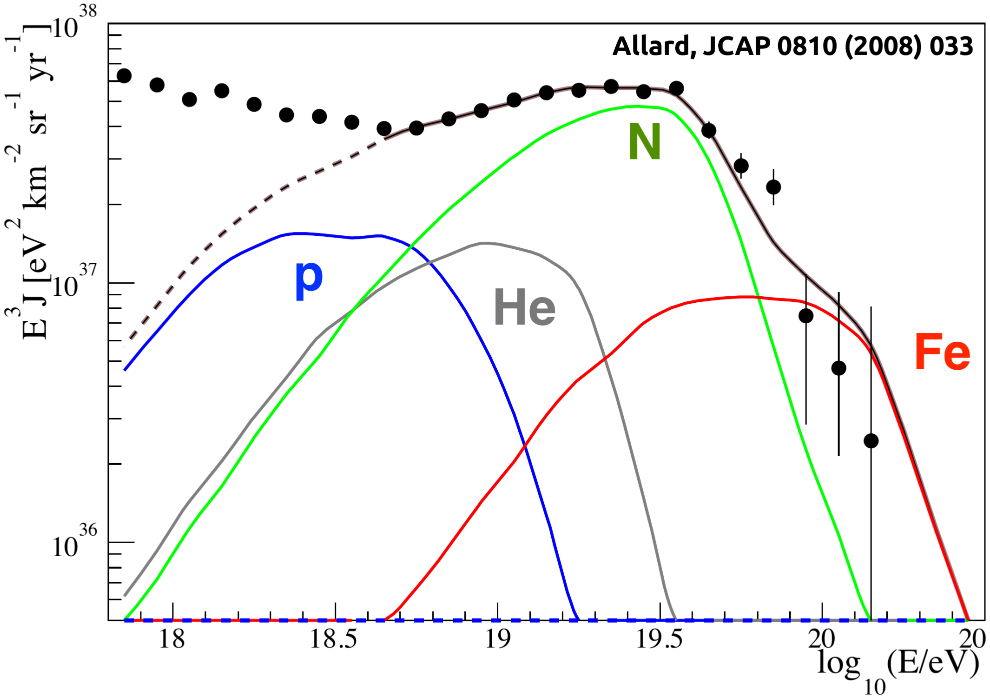
large number of muons

remarkably isotropic sky

~7% dipole

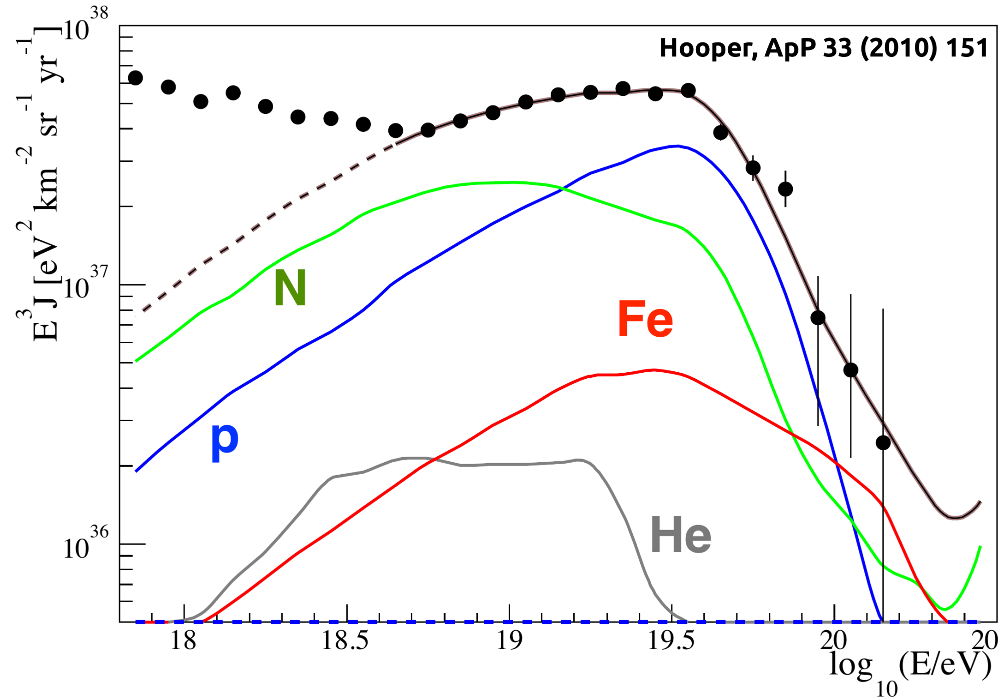
Two Suppression Scenarios

Scenario 1



- sources accelerate to maximum rigidity ("tired" sources)
- energies shifted up by *Z*
- heavy injection Si-Fe

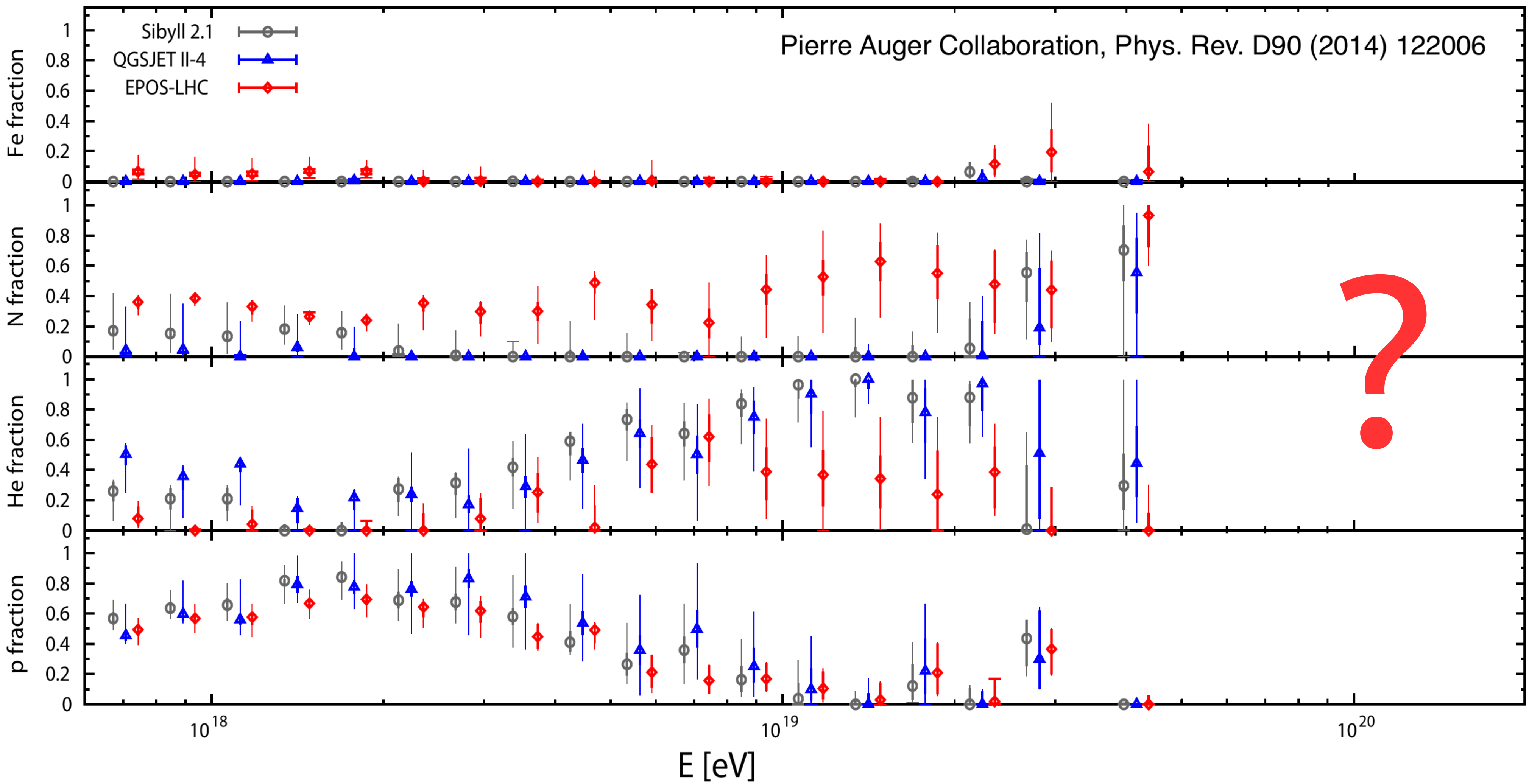
Scenario 2



- (mostly) photo-disintegration
- energies shifted down by *A*
- light elements come from heavy
- CR astronomy still possible

+ p-dominated "dip" scenario

Composition Fits to X_{max}



proton fraction at highest energies?

X_{max} from FD!

new particle physics?

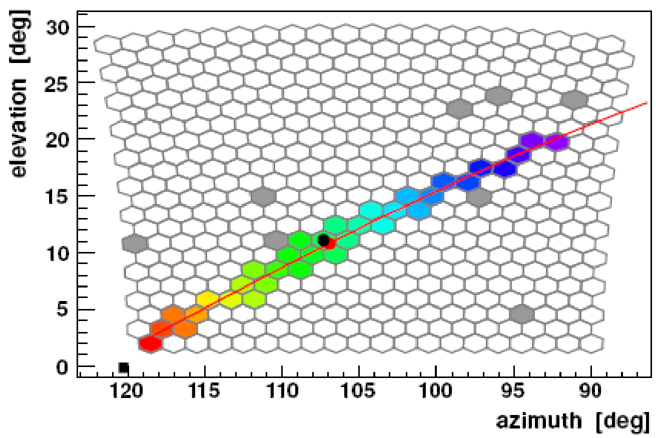
Increase of FD Duty Cycle

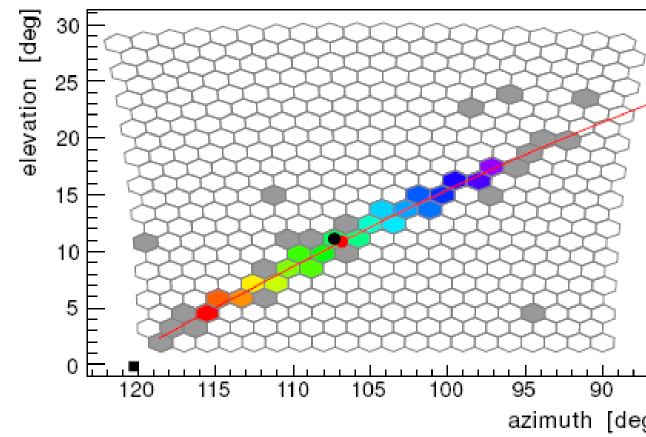
dark moonless nights →
moon fraction: 90%

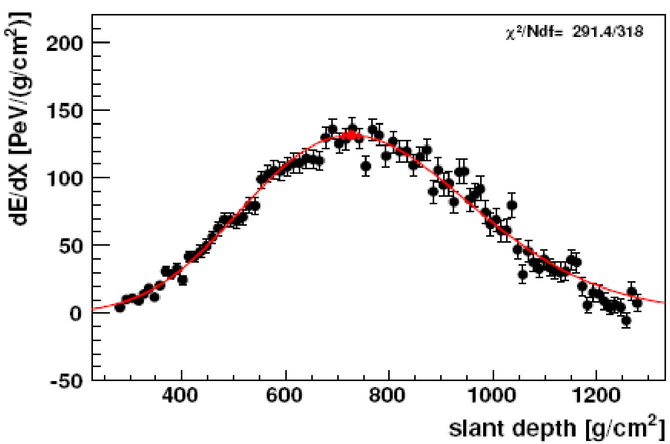
background 40x higher

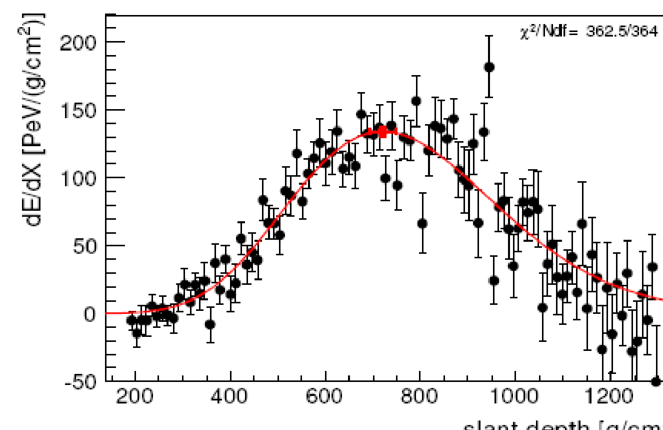
10x lower gain (aging!)

50% larger duty cycle

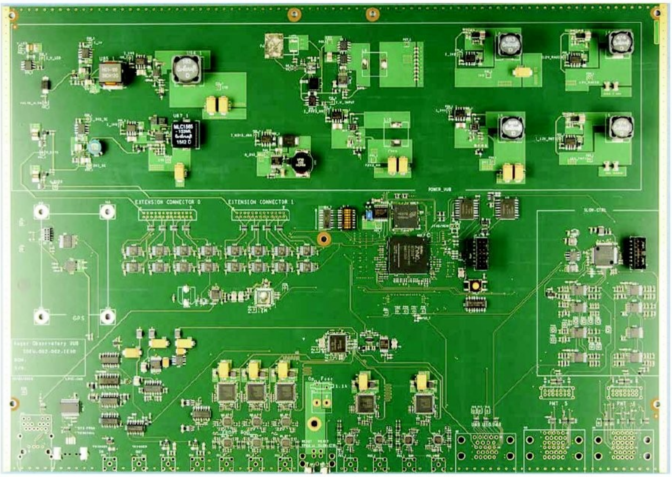




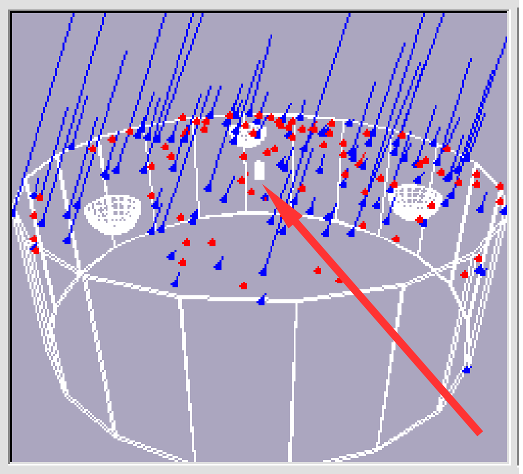




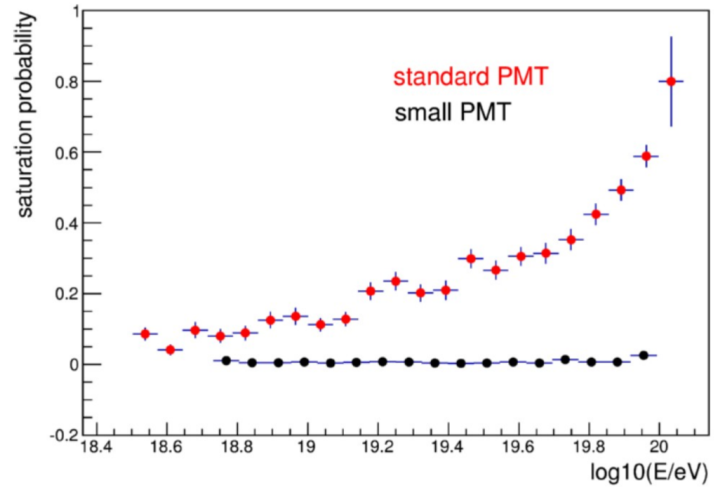
Enhancements



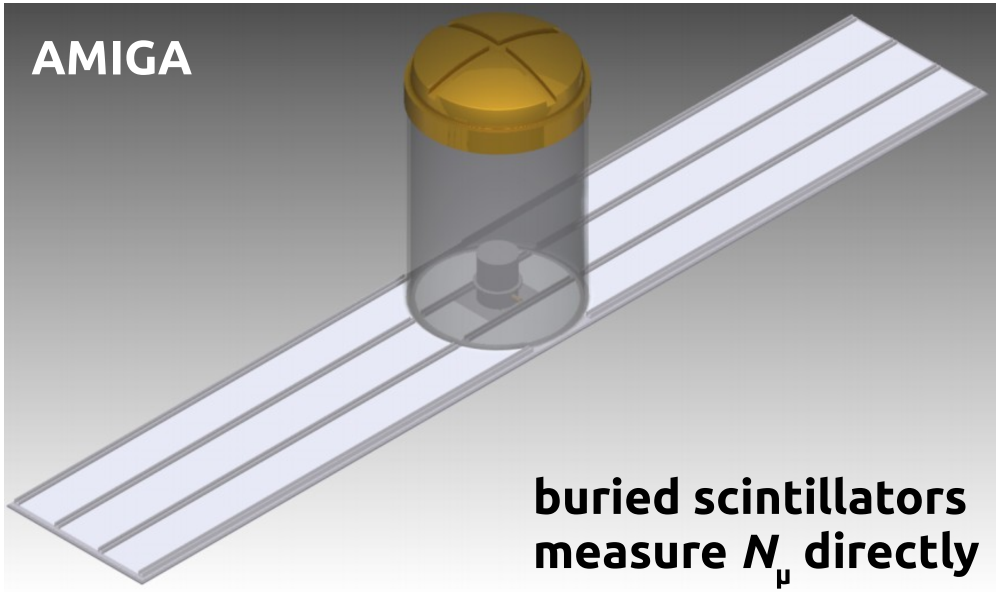
new electronics
40→120 MHz sampling
more channels, CPU



currently 3 large PMTs
+small PMT



station closest to core



buried scintillators
measure N_μ directly

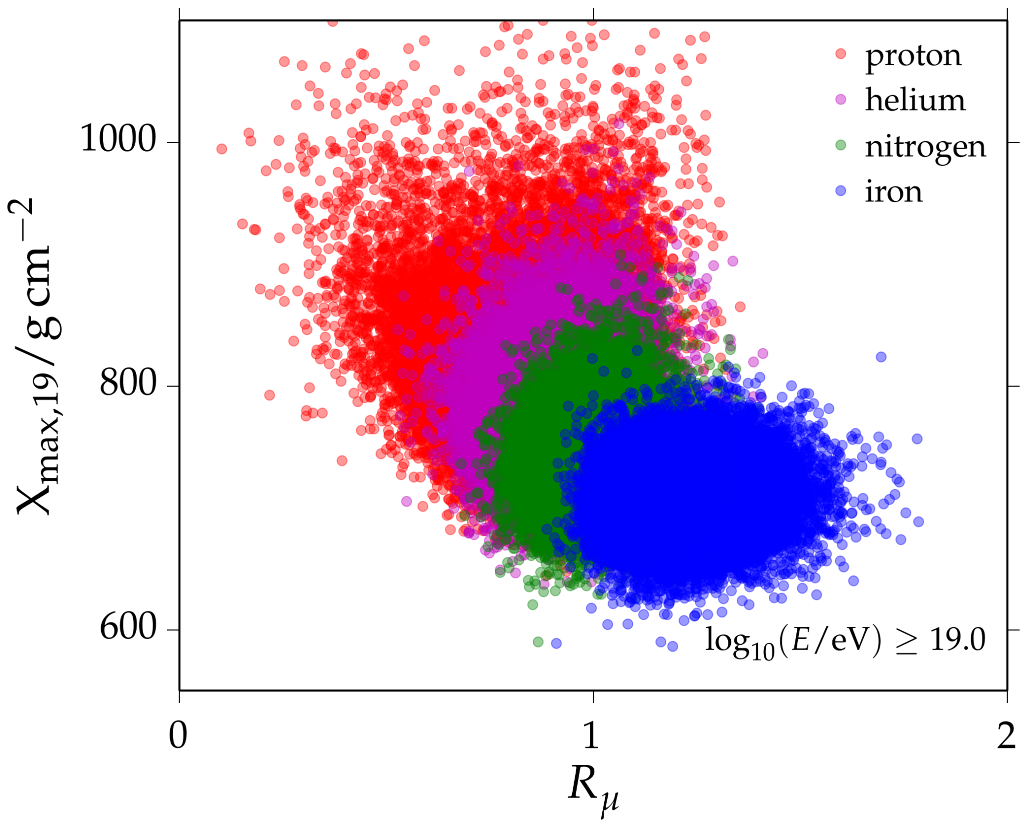
only infill area

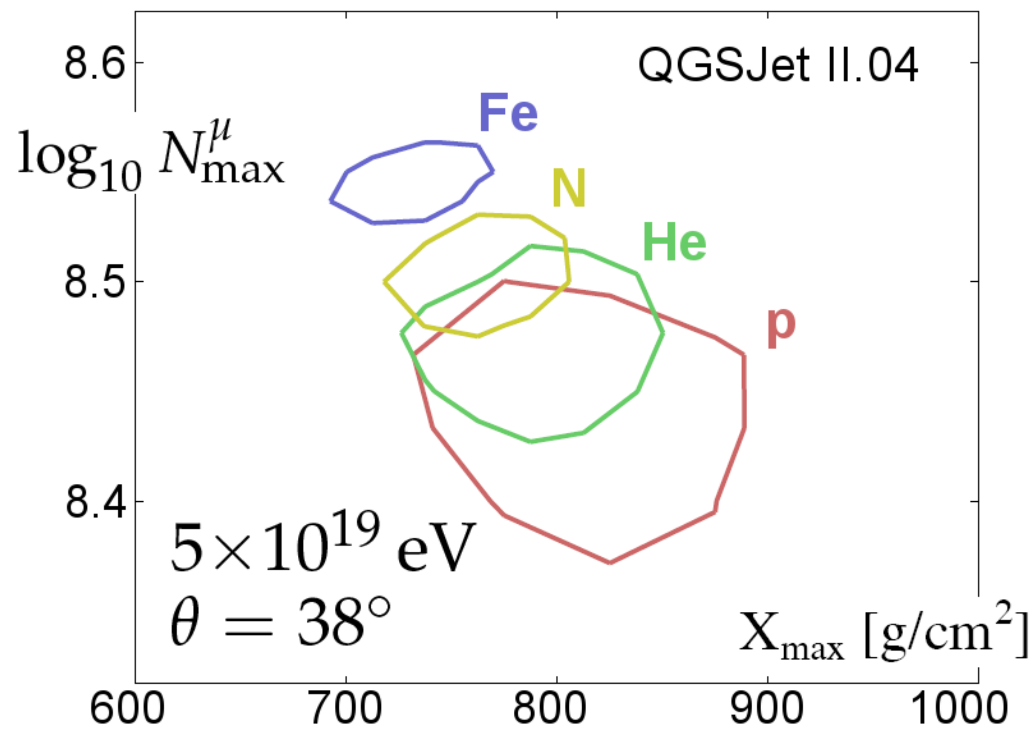
Increased Composition Sensitivity

with SD

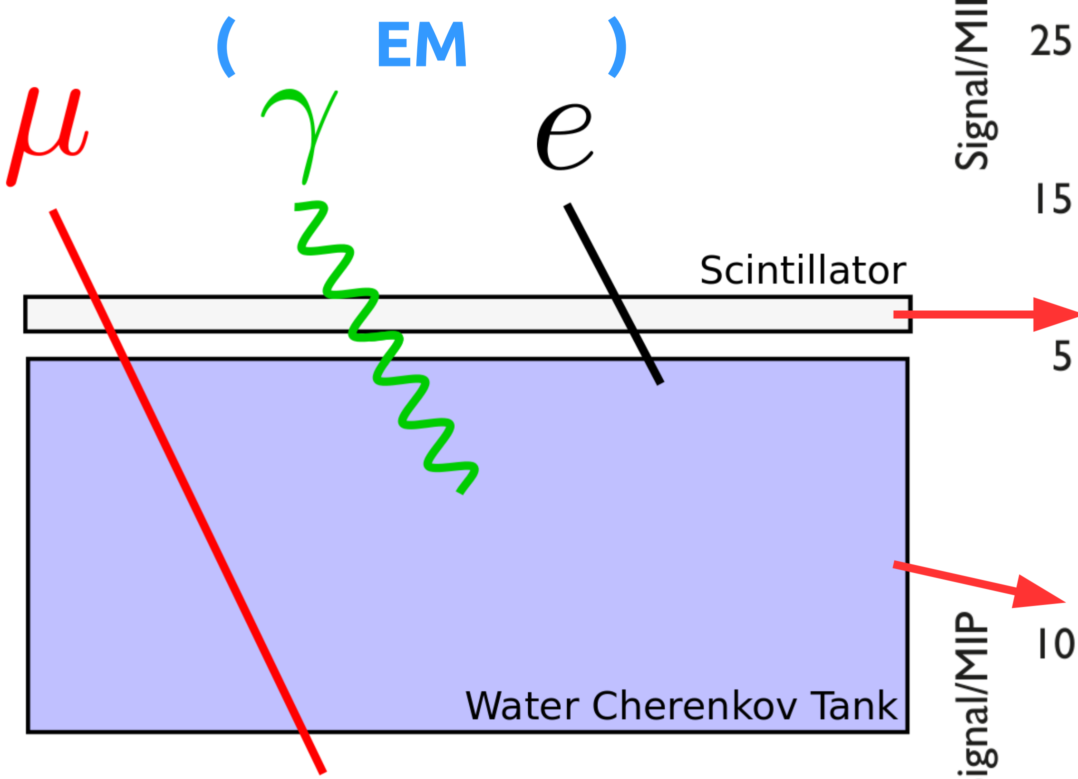
main goal!

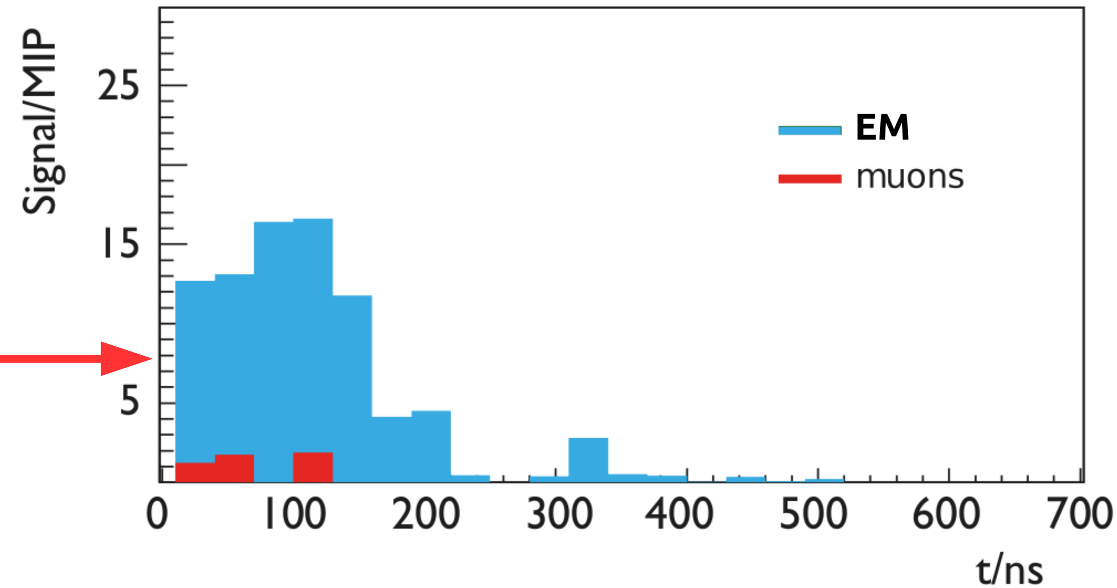
X_{max} and muons

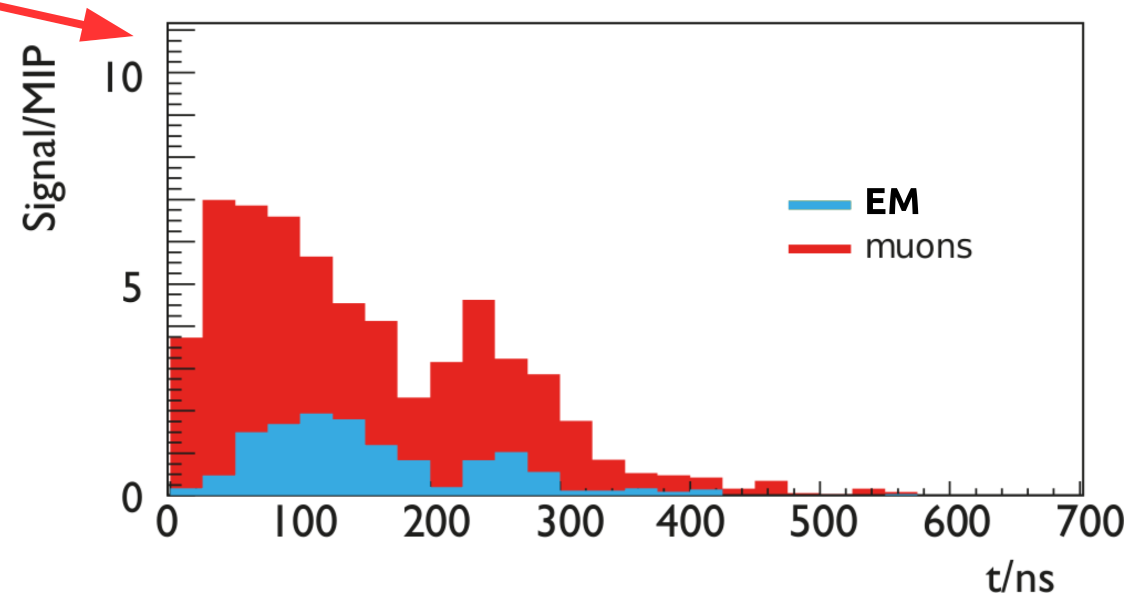




Complementary Response

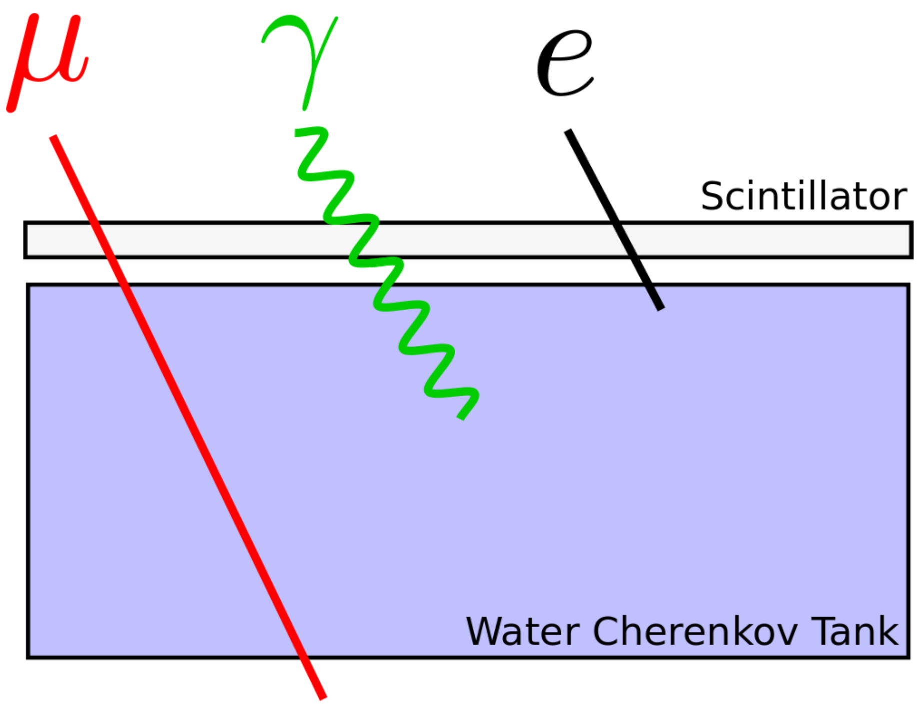


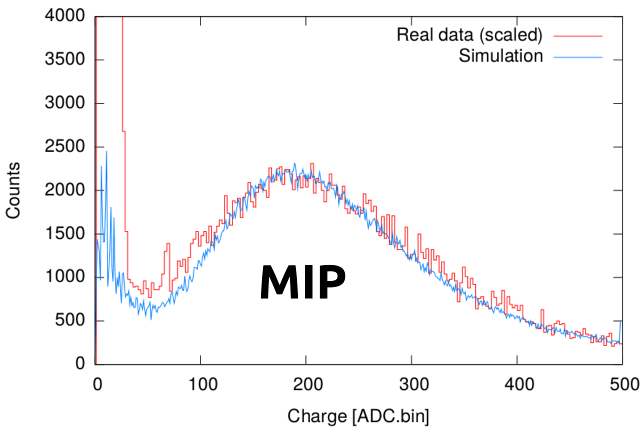




$$S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}$$

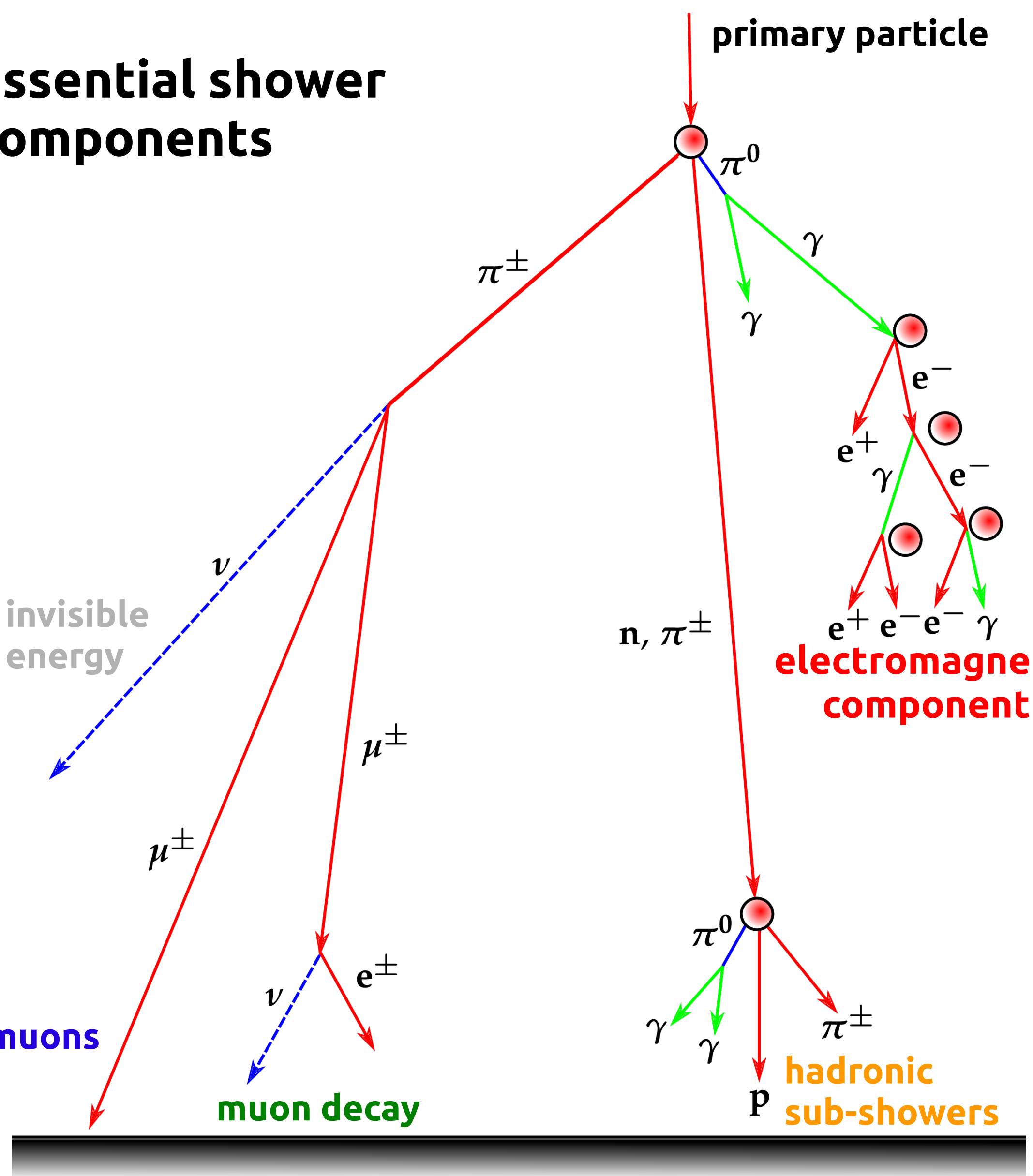
R&D Prototype

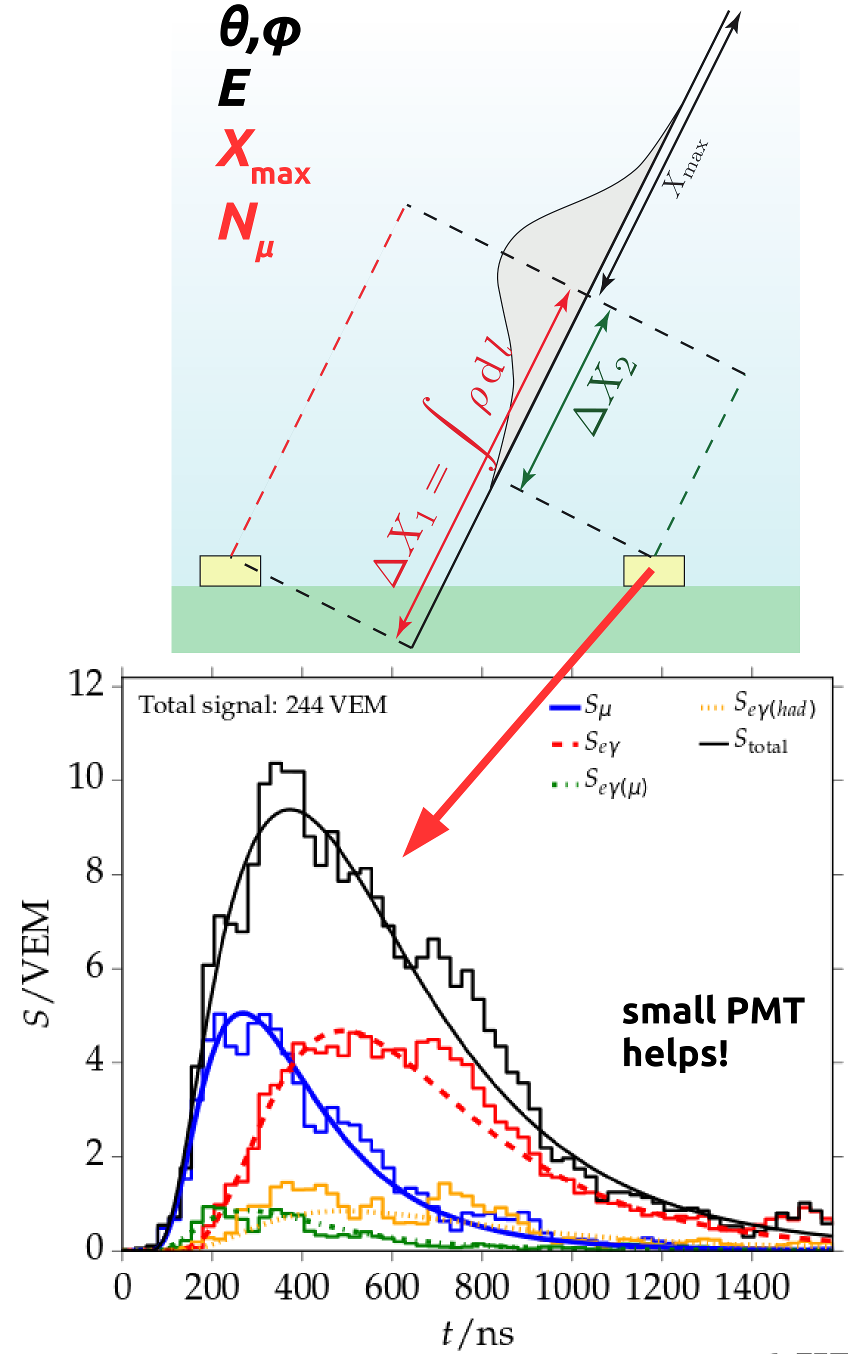




Universality

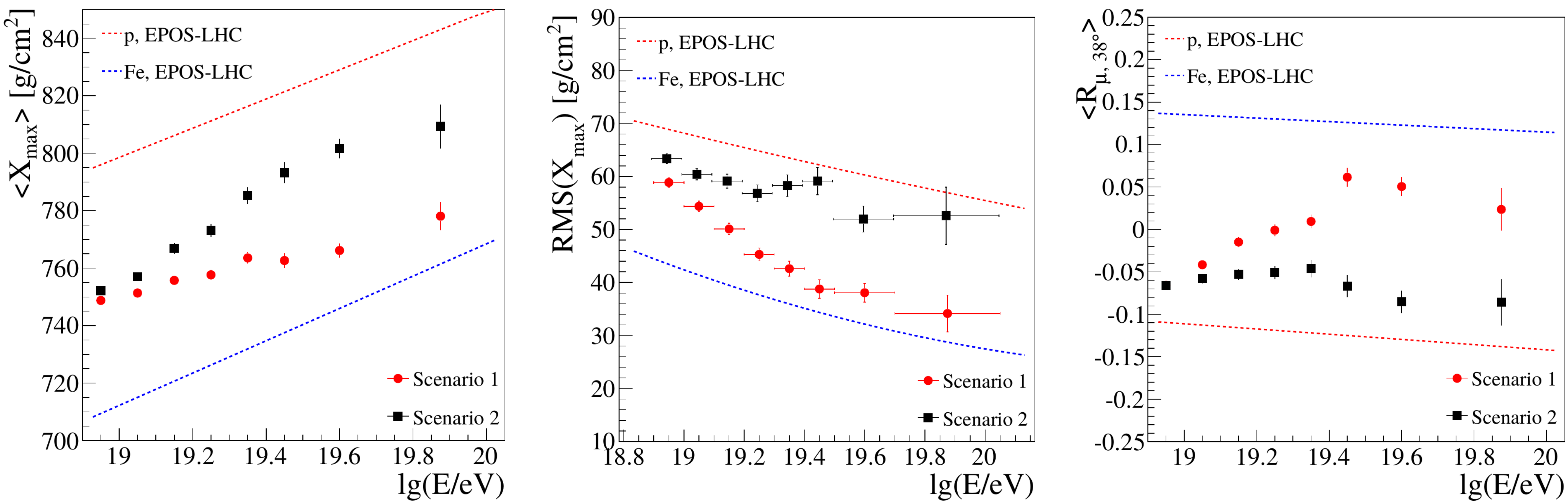
essential shower components



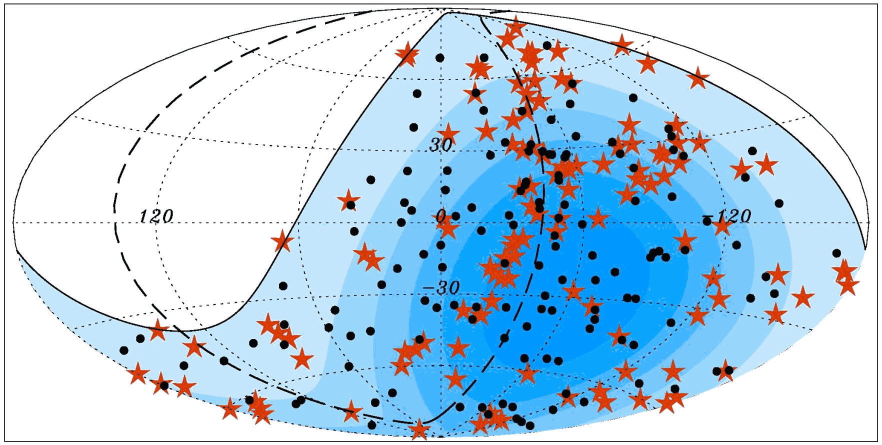


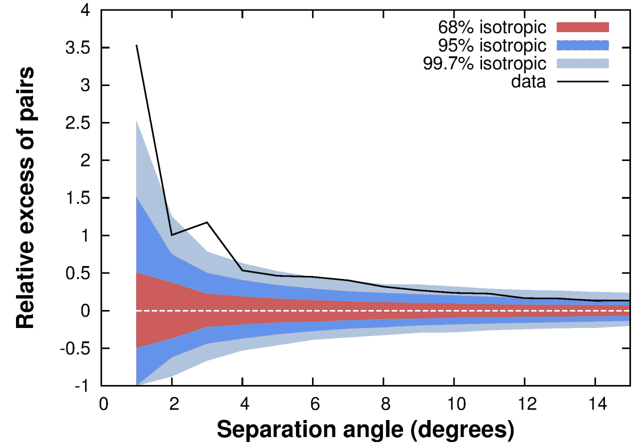
Different Consequences

$\langle X_{max} \rangle$ | $\sigma(X_{max})$ | muons



Composition-Enhanced Anisotropy

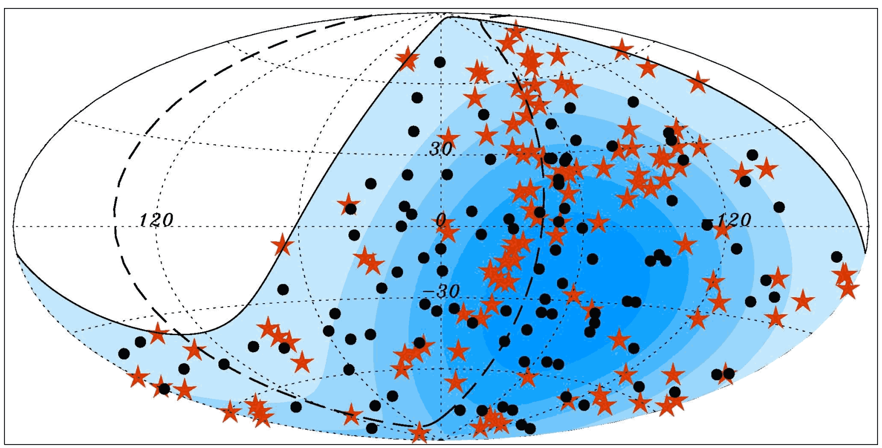


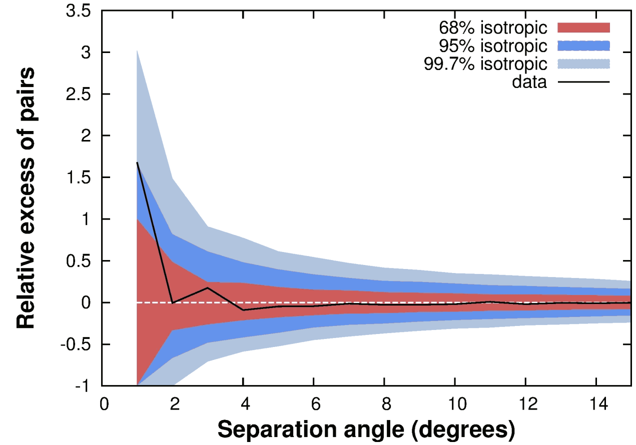


E > 5.5EeV events

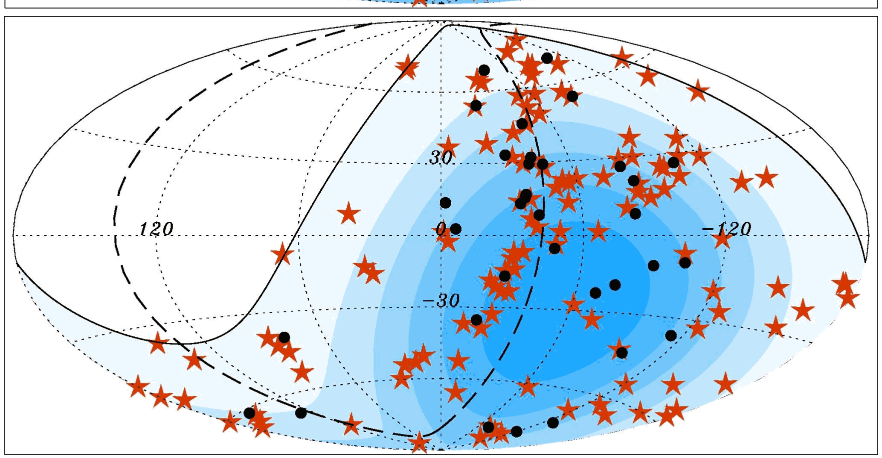
X_{max} from max. rigidity scenario

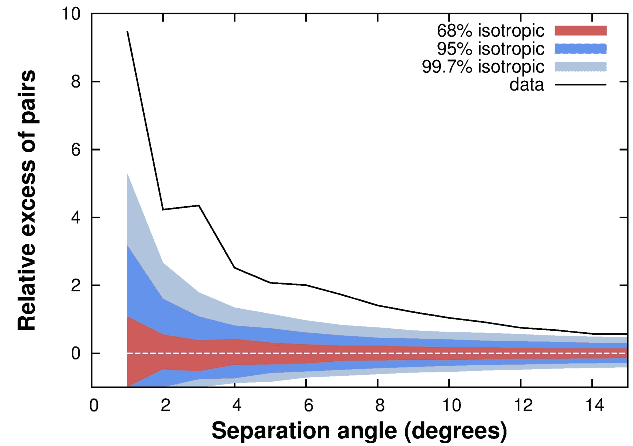
10% p added





p-depleted





p-enhanced

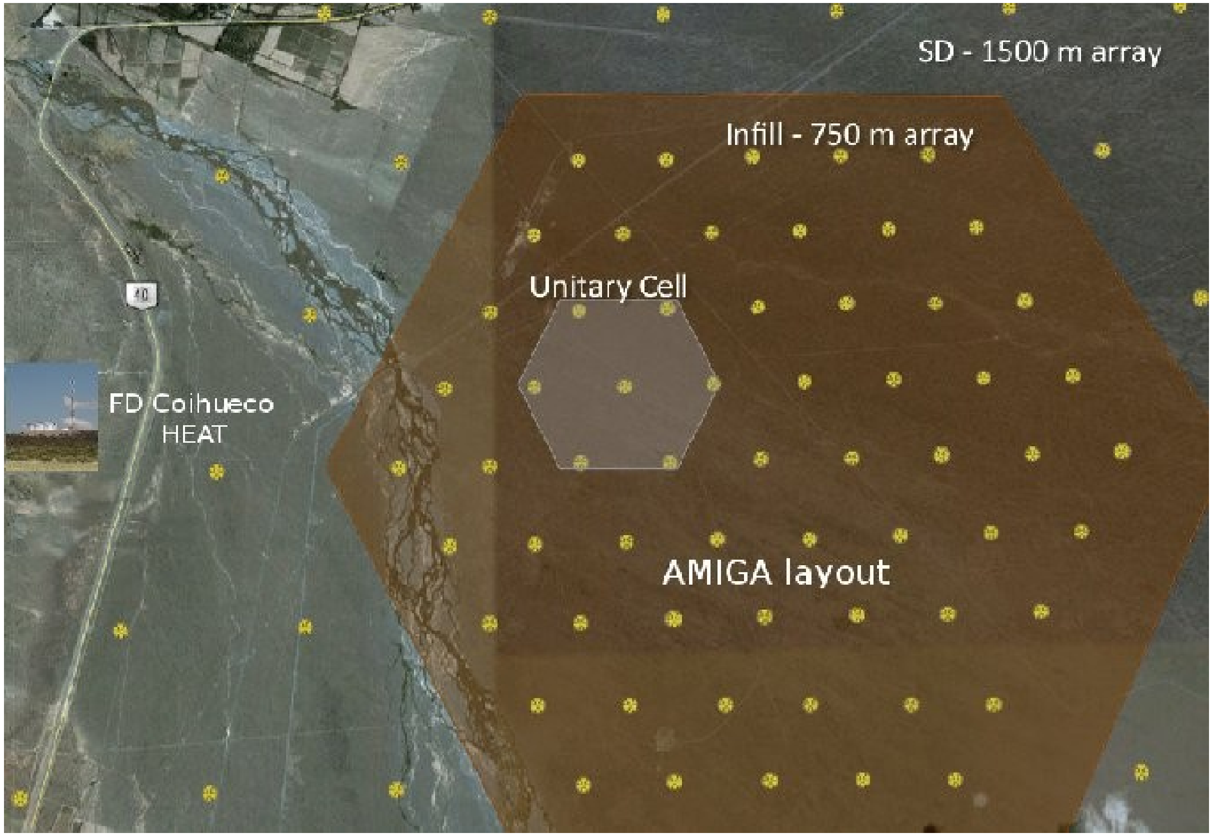
Timeline

July 2016: Engineering Array, 12 stations equipped with scintillators → SSD

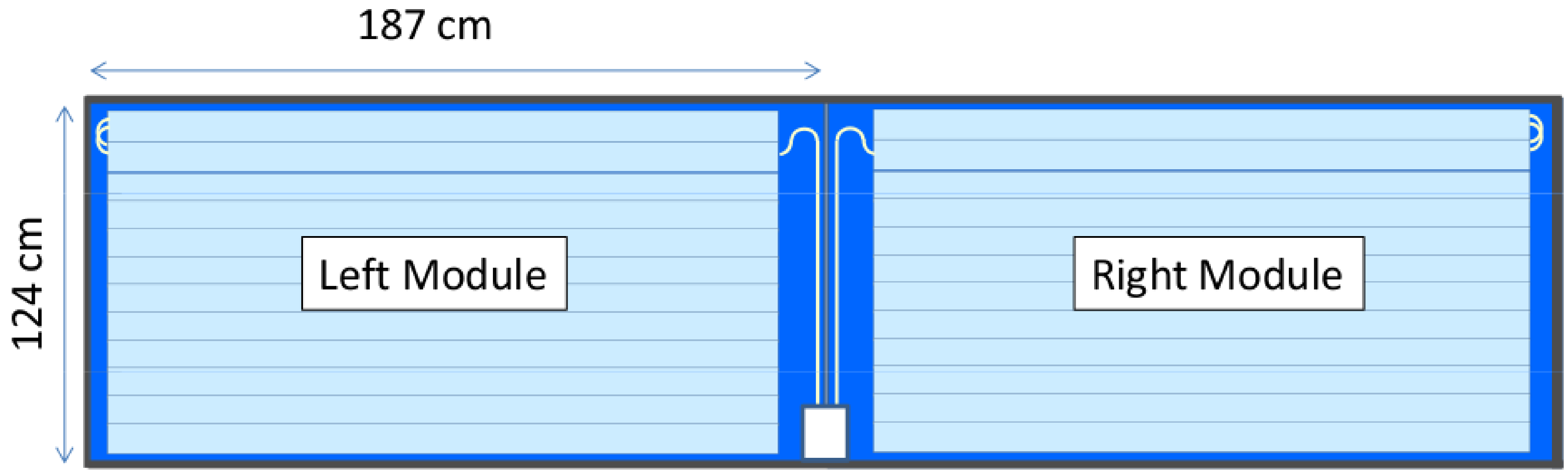
end of 2016: evaluation

2017-2018: deployment of 1600 SSD

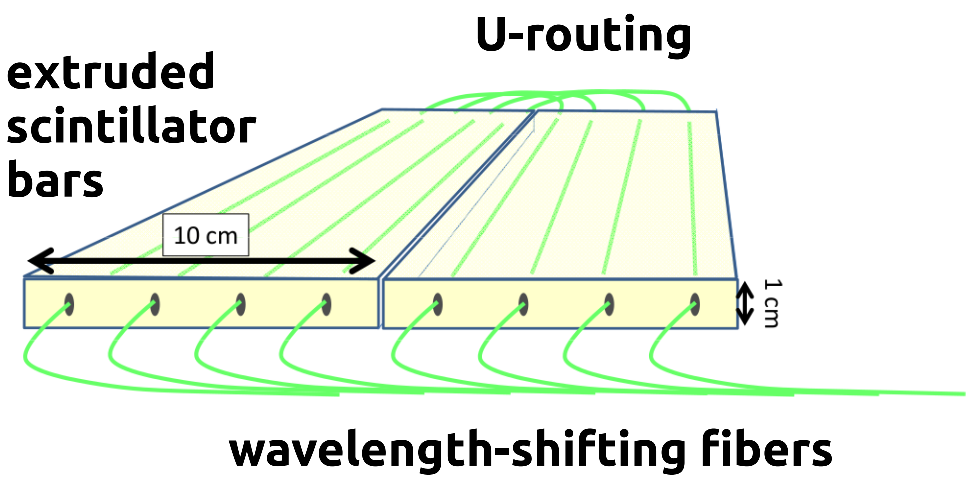
until 2025: data-taking

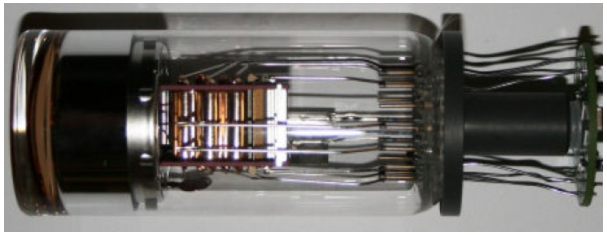


SSD Design

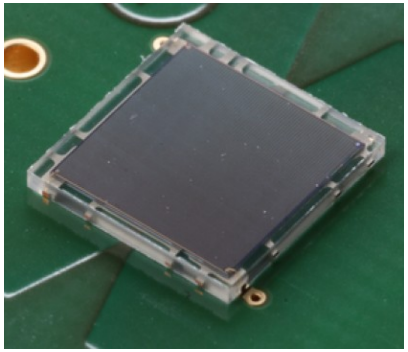


3.8 m²



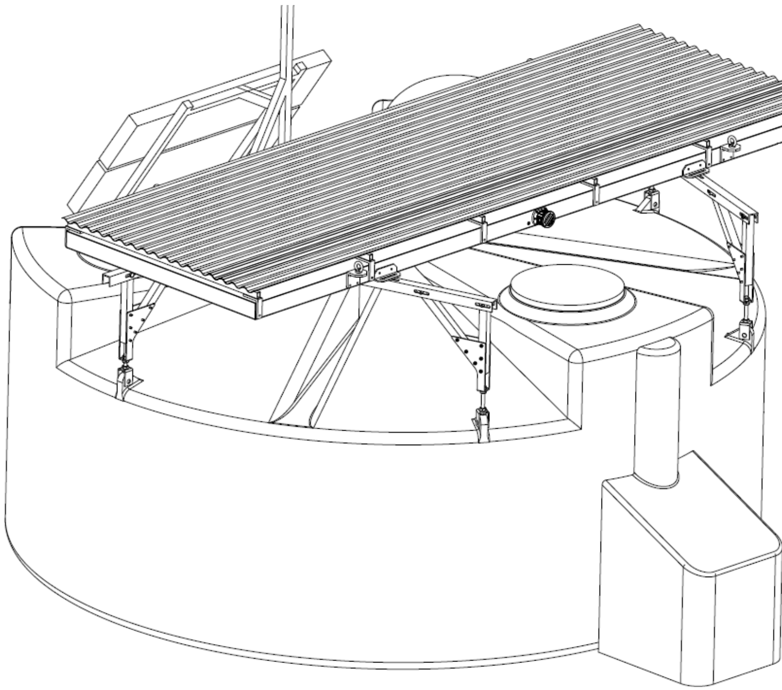


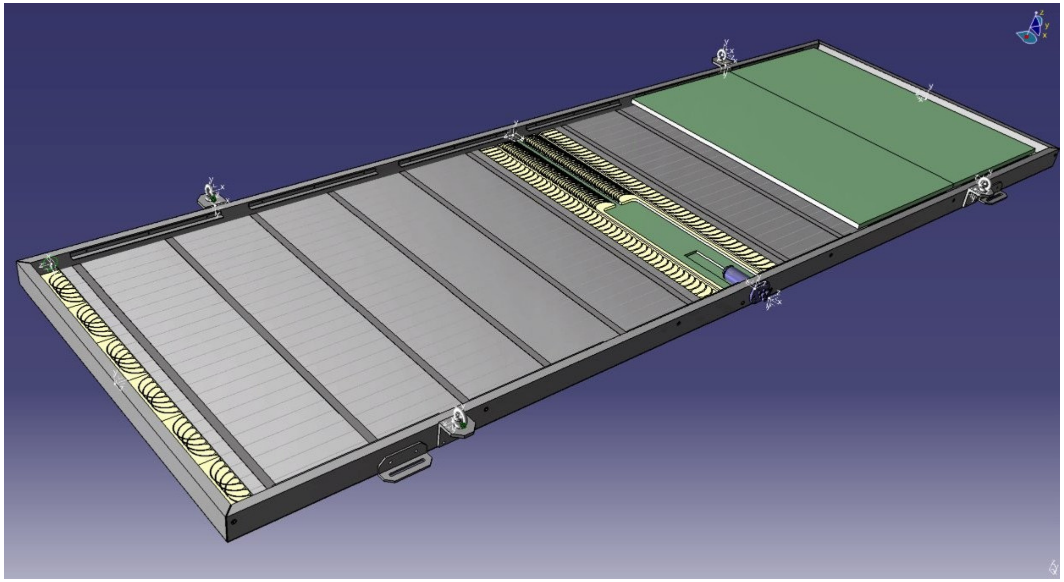
PMT



SiPM

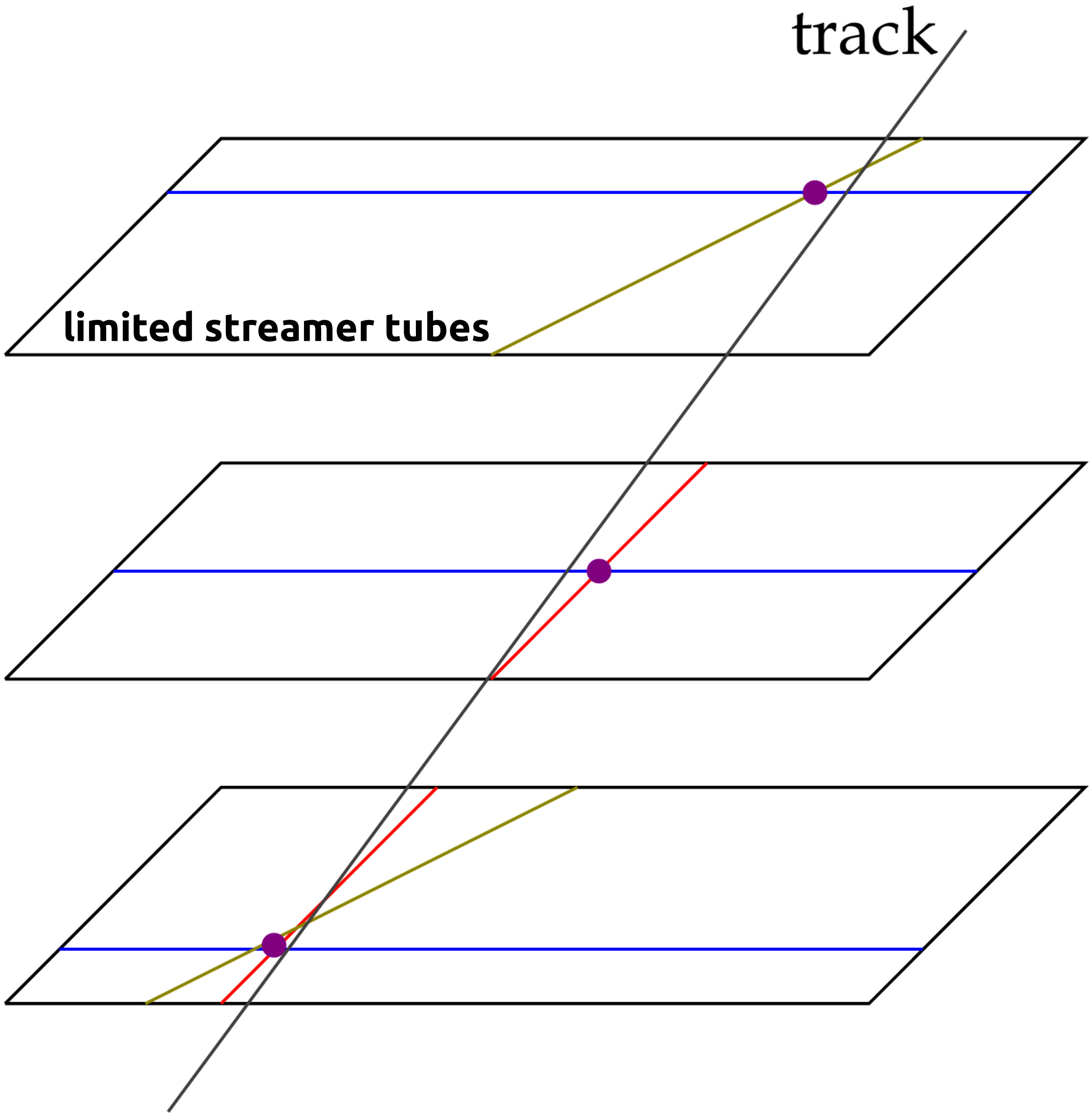
SSD Production





KASCADE Muon Tower

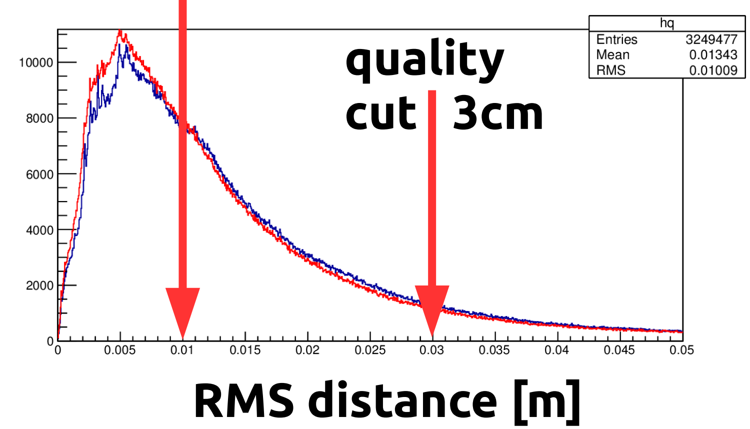
Muon Track Reconstruction



planes: single points

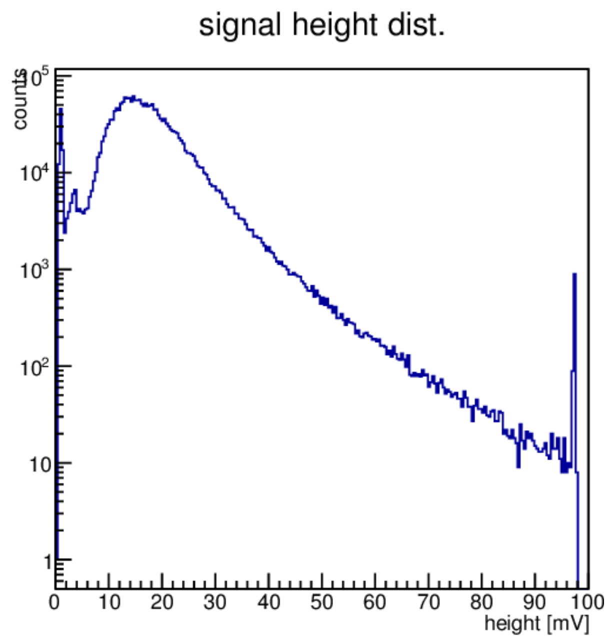
track: 3 points

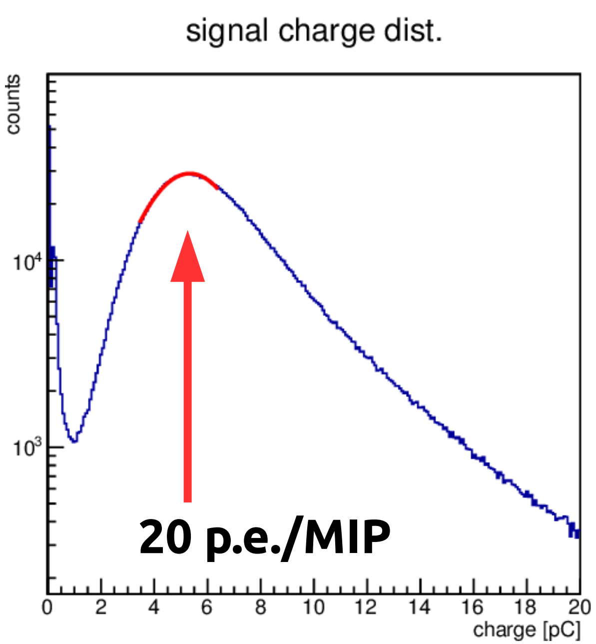
3-point track resolution ~ 1cm

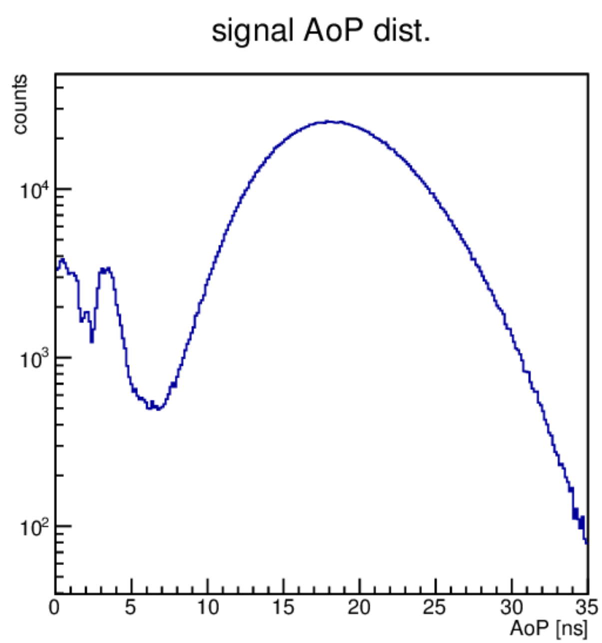


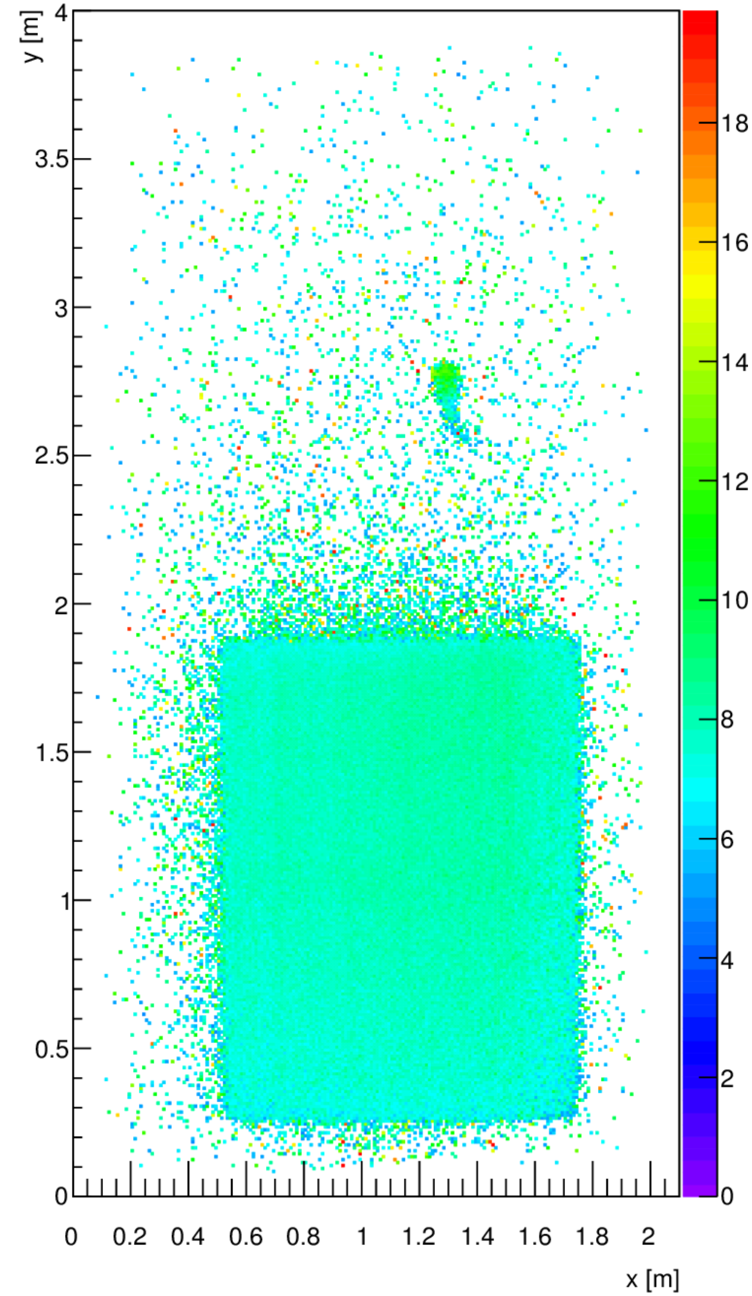
SSD Signal

Signal properties



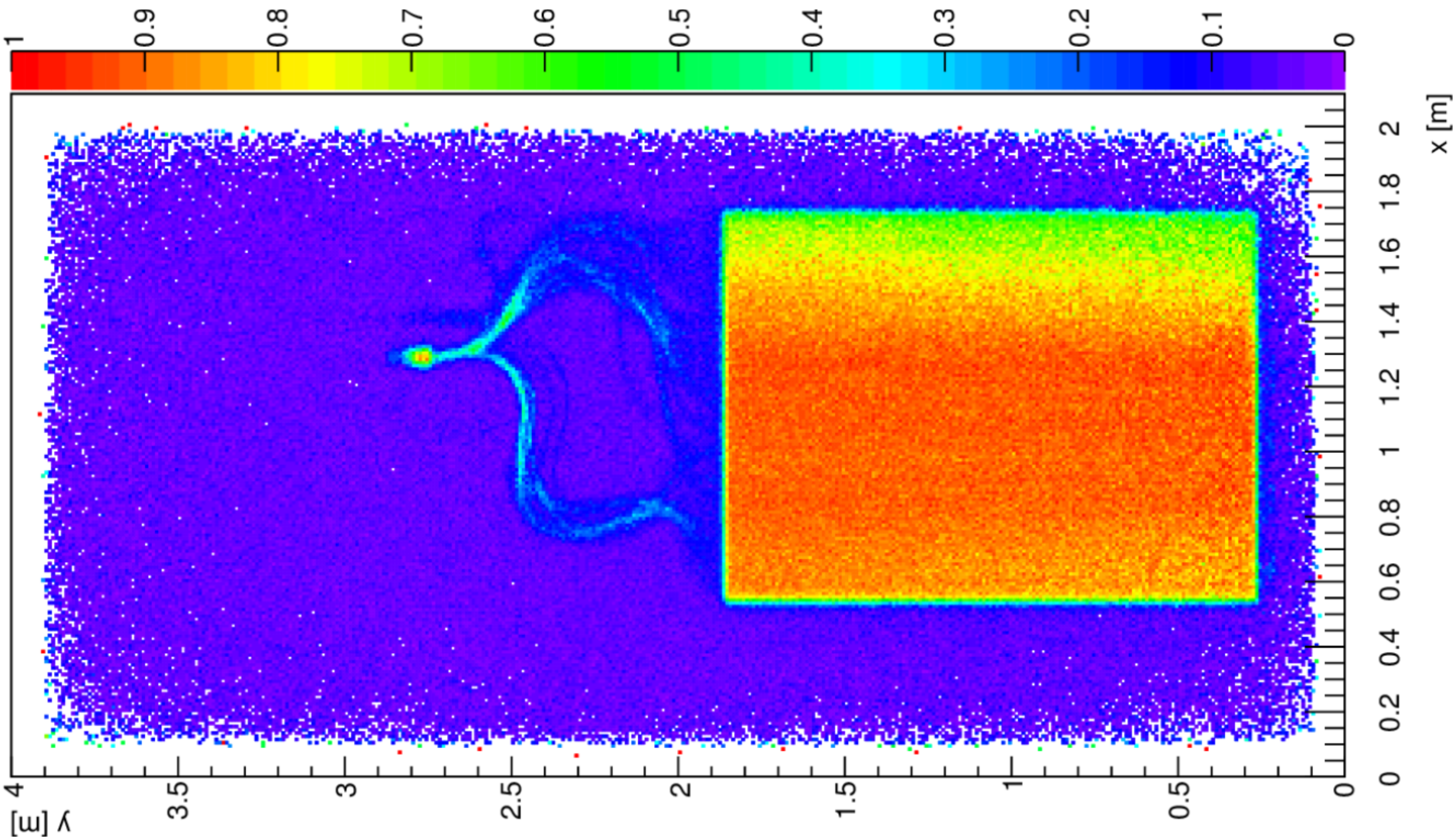






Muon Tomography

6h statistics, 1cm x 1cm binning



Summary

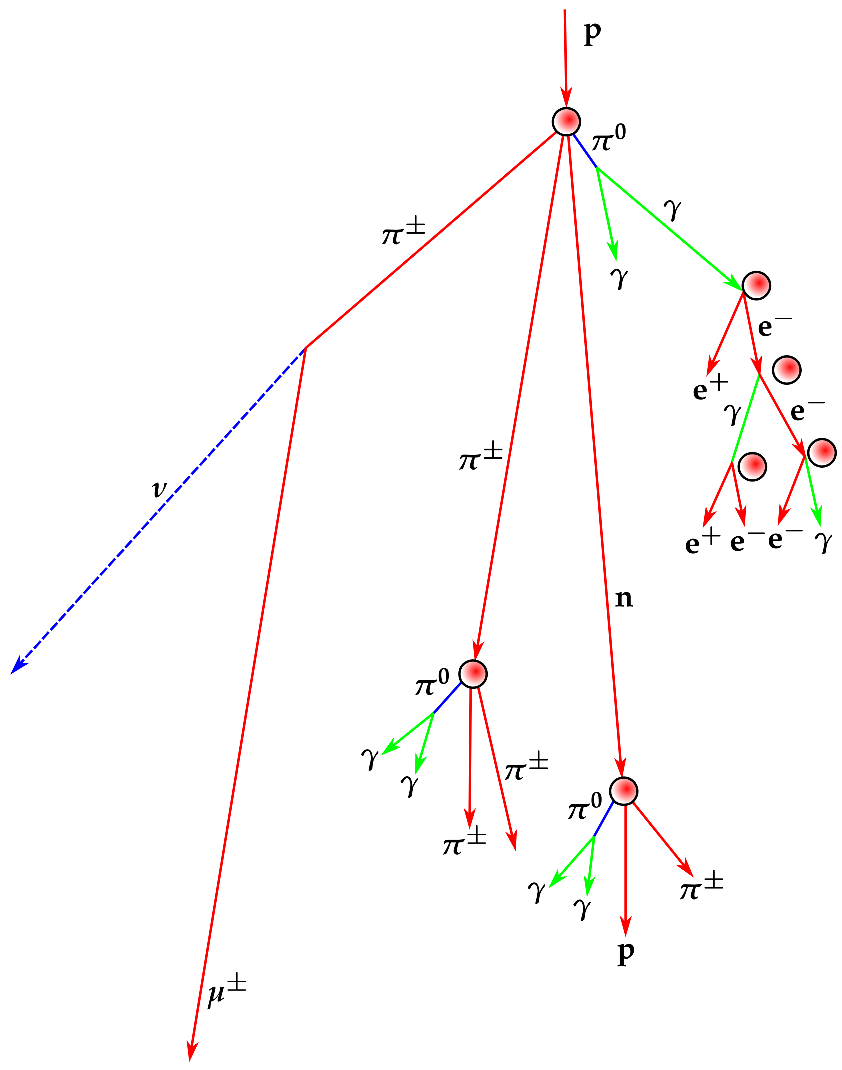
- extend Observatory operation 2018-2025
- equip 1600 stations with scintillators
- increase FD duty cycle
- doubling of event statistic
- but now with primary mass information

Steven Saffi 2014

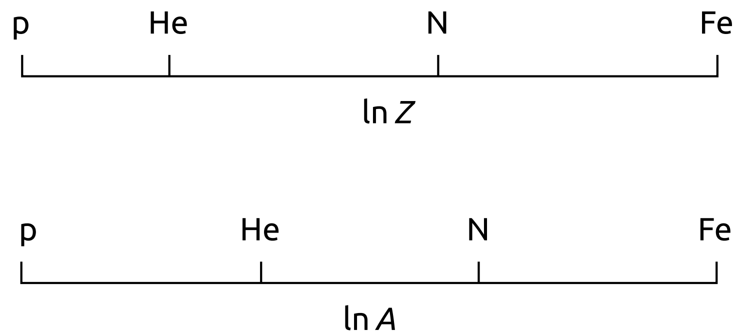
Thank you!

Empty

Backup

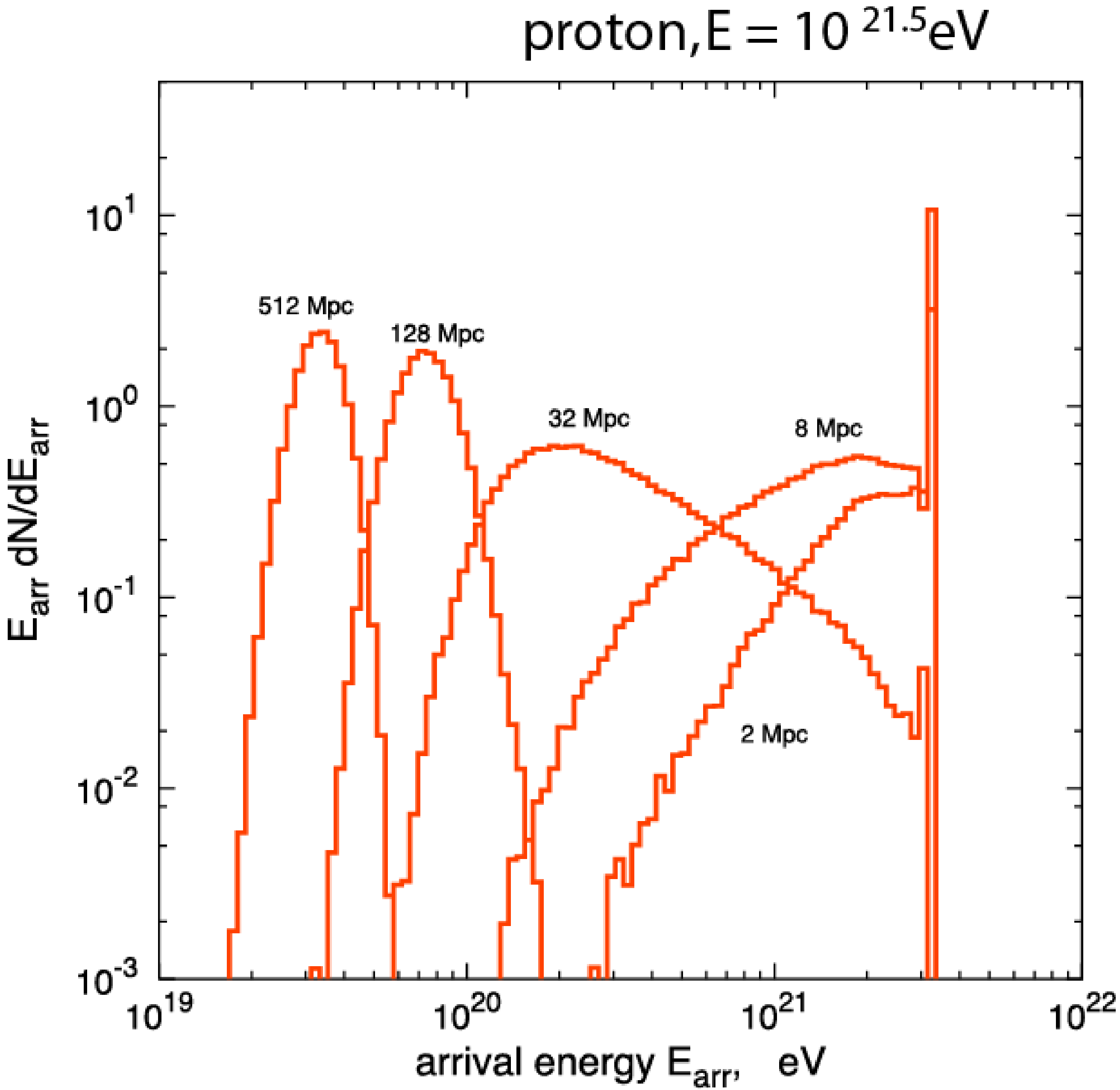


p
π^0
γ
$\pi^\pm$
γ
e^-
e^+
γ
e^-
ν
$\pi^\pm$
e^+ e^- e^- γ
n
π^0
γ
γ
$\pi^\pm$
$\pi^\pm$
π^0
γ
γ
$\pi^\pm$
p
$\mu^\pm$



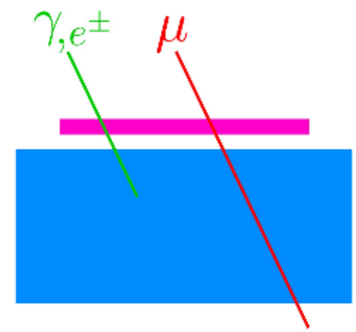
p He N Fe
ln Z
p He N Fe
ln A

GZK Energy Loss



Matrix formalism

$$\begin{pmatrix} S_{\mathrm{scin}} \\ S_{\mathrm{wcd}} \end{pmatrix} = \begin{pmatrix} a & b \\ 1-a & 1-b \end{pmatrix} \begin{pmatrix} S_{\gamma,\mathrm{e}^\pm} \\ S_{\mu^\pm} \end{pmatrix}$$



Signals are in MIP/VEM

Written plainly:

$$S_{\mathrm{scin}} = aS_{\gamma,e^\pm} + bS_{\mu^\pm}$$

$$S_{\mathrm{wcd}} = (1-a)S_{\gamma,e^\pm} + (1-b)S_{\mu^\pm}$$

Implied sums:

$$S_{\gamma,\mathrm{e}^\pm} = S^{\gamma,\mathrm{e}^\pm}_{\mathrm{scin}} + S^{\gamma,\mathrm{e}^\pm}_{\mathrm{wcd}}$$

$$S_{\mu^\pm} = S^{\mu^\pm}_{\mathrm{scin}} + S^{\mu^\pm}_{\mathrm{wcd}}$$

where:

$$a = \frac{S^{\gamma,\mathrm{e}^\pm}_{\mathrm{scin}}}{S^{\gamma,\mathrm{e}^\pm}_{\mathrm{scin}} + S^{\gamma,\mathrm{e}^\pm}_{\mathrm{wcd}}}$$

} Fraction of total electromagnetic signal measured by scintillator

$$b = \frac{S^{\mu^\pm}_{\mathrm{scin}}}{S^{\mu^\pm}_{\mathrm{scin}} + S^{\mu^\pm}_{\mathrm{wcd}}}$$

} Fraction of total muonic signal measured by scintillator

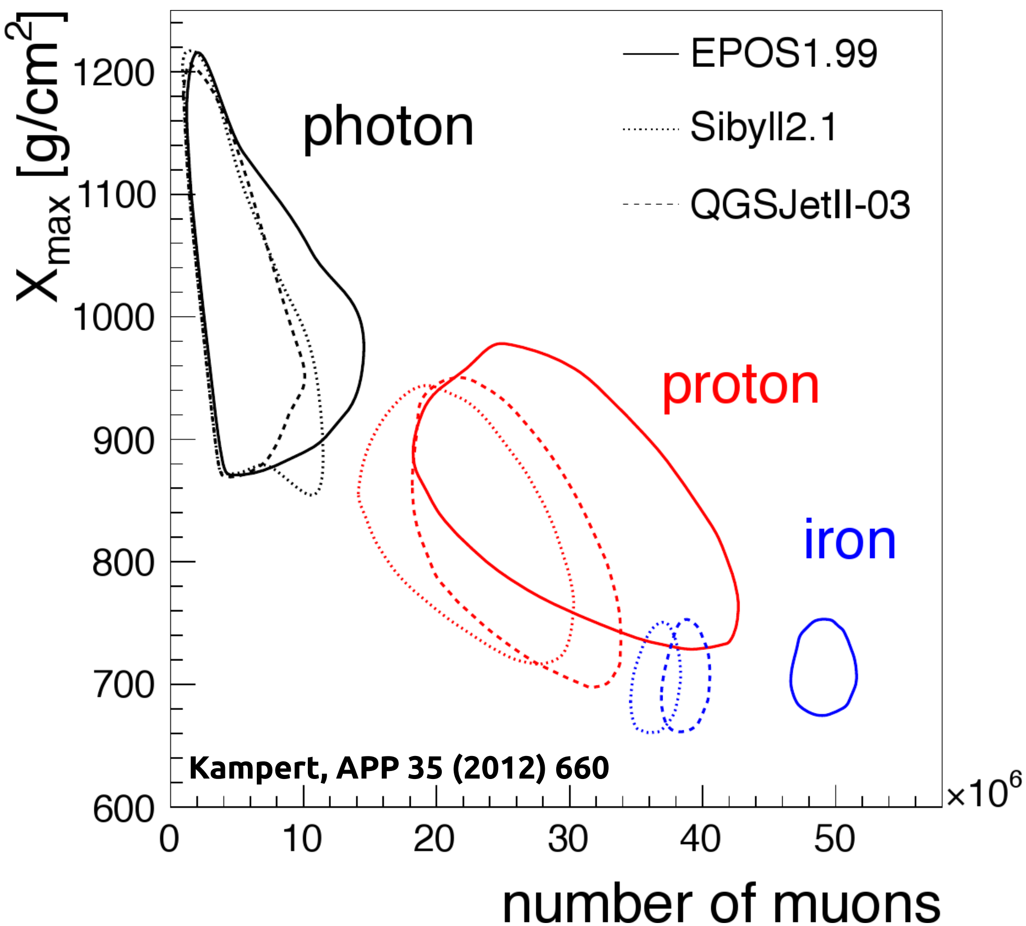
By means of inversion:

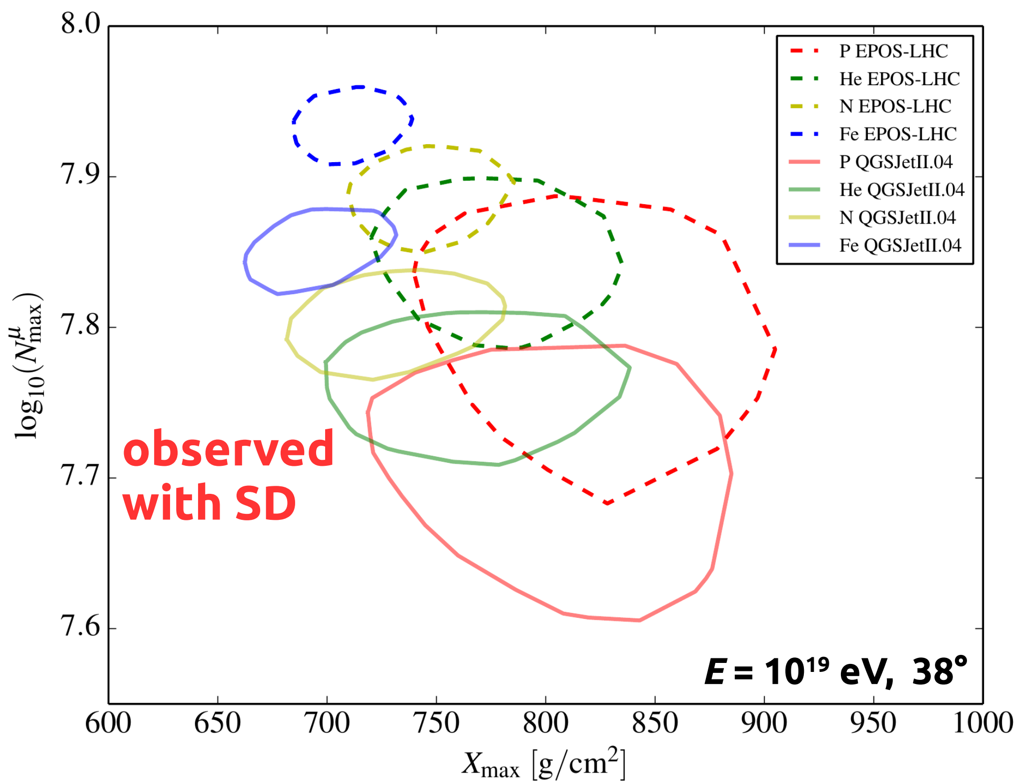
$$S_{\mu^\pm} = \frac{1}{a-b}\left((a-1)S_{\mathrm{scin}} + aS_{\mathrm{wcd}}\right)$$ and $$S^{\mu^\pm}_{\mathrm{wcd}} = (1-b)S_{\mu^\pm}$$

D. Schmidt, D. Veberic, M. Roth
Institute for Nuclear Physics (IKP)

Why Muons Matter!

- CR composition measurement → origin of flux suppression (sources), proton fraction (pair-production "dip", future of astronomy with CR, predict gamma & nu flux)

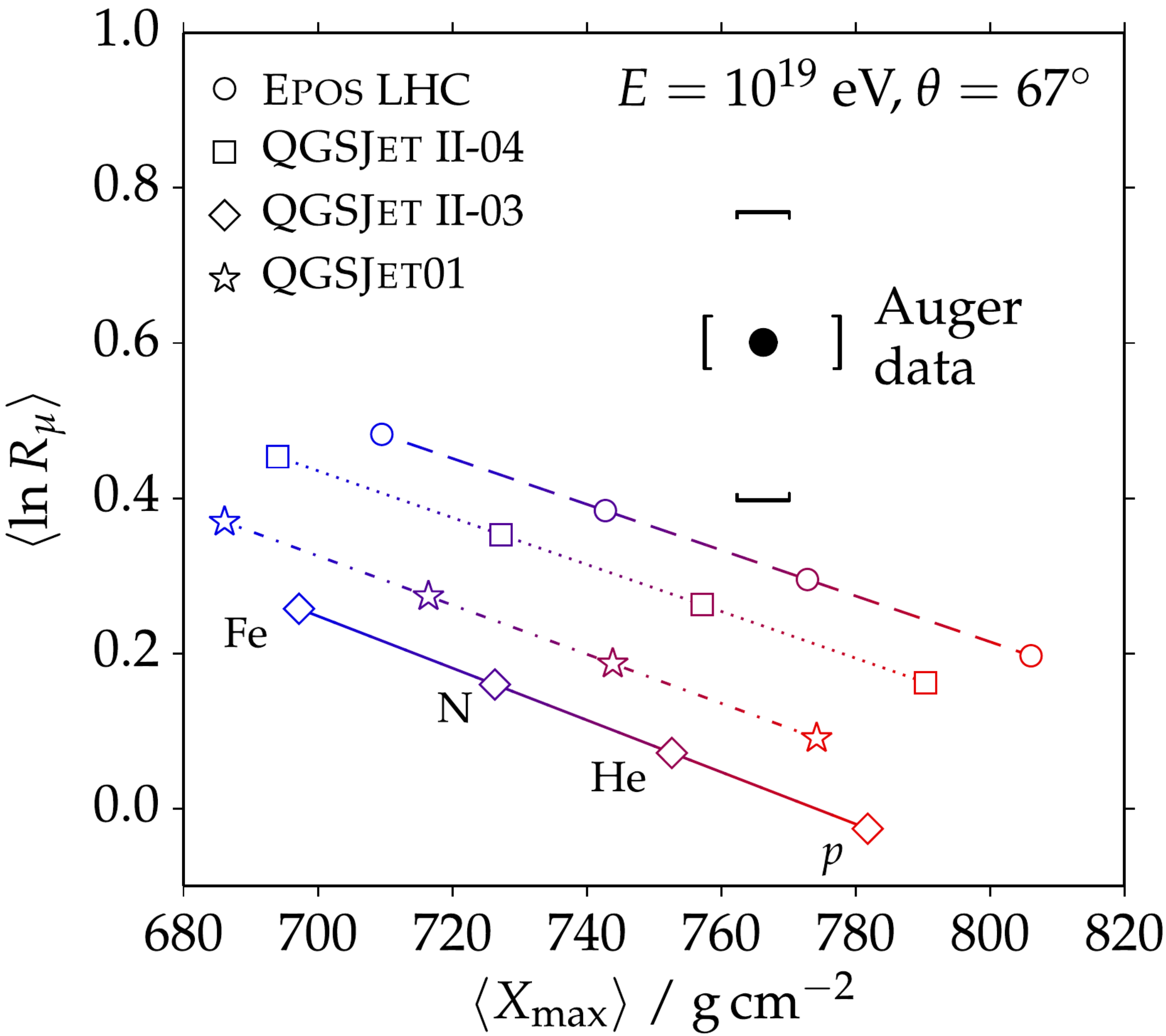




observed with FD (10% duty cycle)

- muons probe for models of hadronic interactions
- AugerPrime: upgrade → shower-to-shower determination of primary mass

R_μ vs. X_{max}



Auger, PRD 91 (2015) 032003

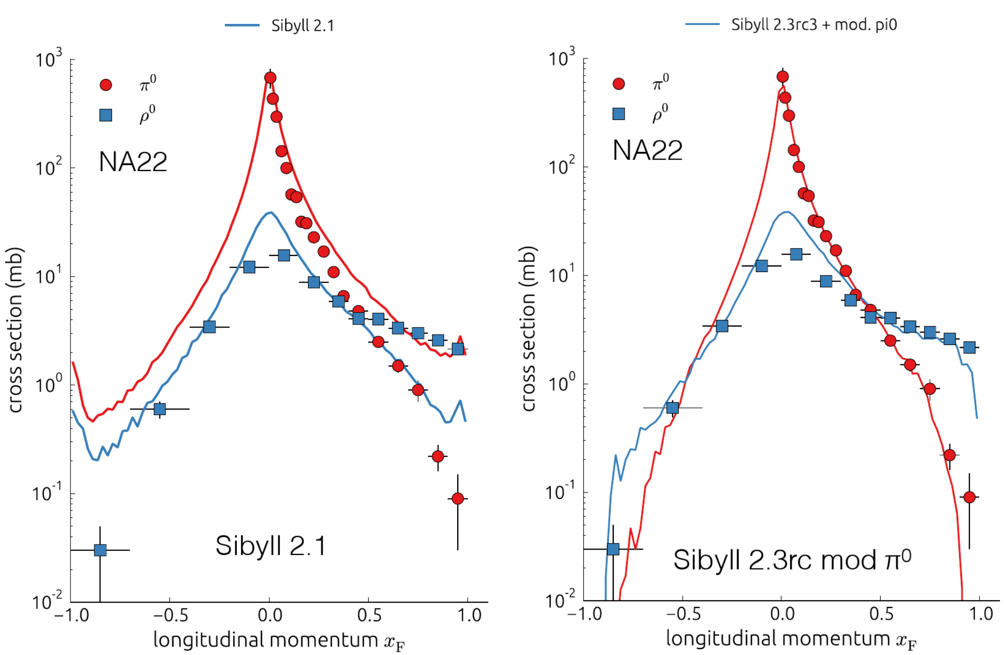
Change in EM Transfer

- **Baryon-antibaryon pair production:**
  Grieder, ICRC 1973; Pierog & Werner, PRL 101 (2008) 171101
- **Leading particle effect for pions:**
  Drescher 2007, Ostapchenko

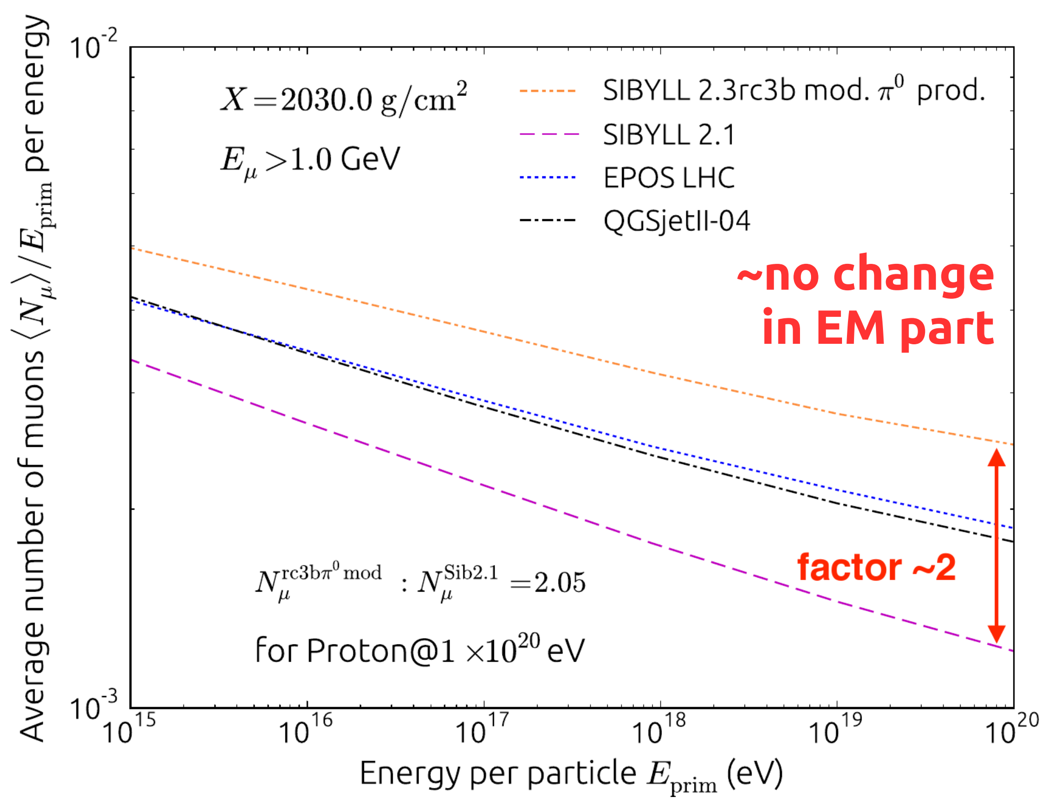
$$\pi^+ p \to \pi^0 \to 2\gamma$$ → **EM shower**

$$\pi^+ p \to \rho^0 \to \pi^+ \pi^-$$ → **muons**

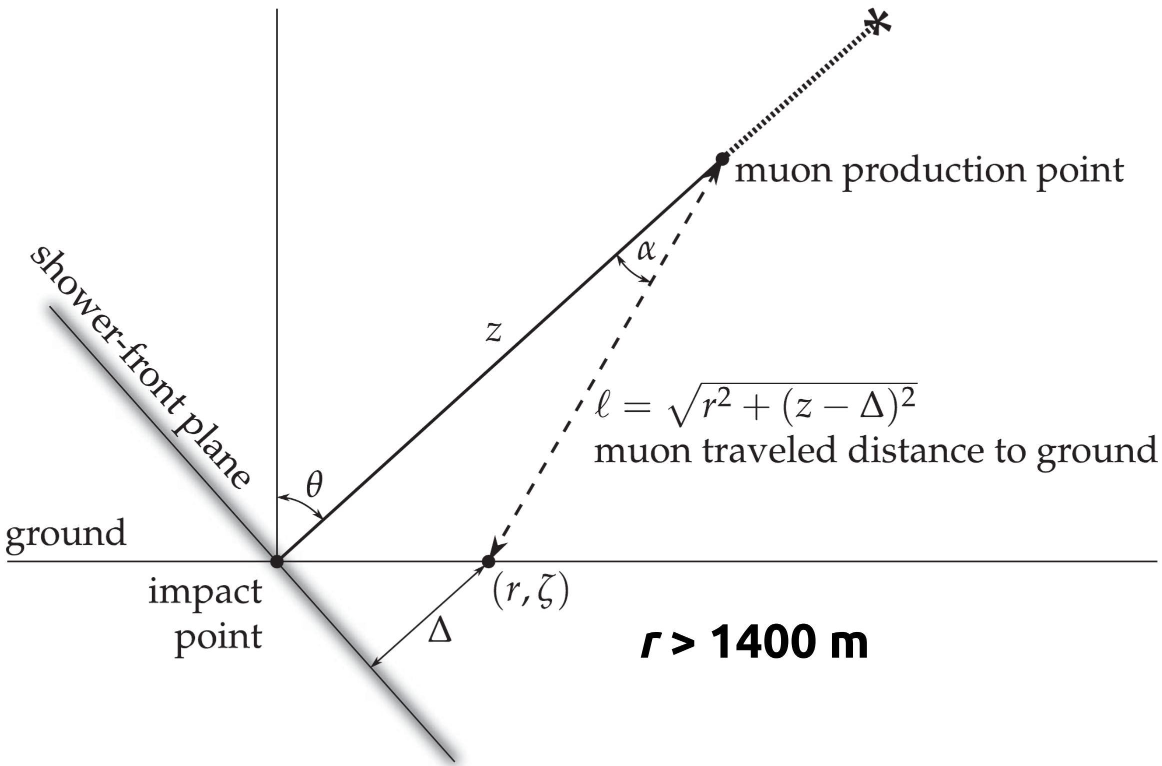
Engel, HAP Composition 2015



Riehn, HAP Composition 2015

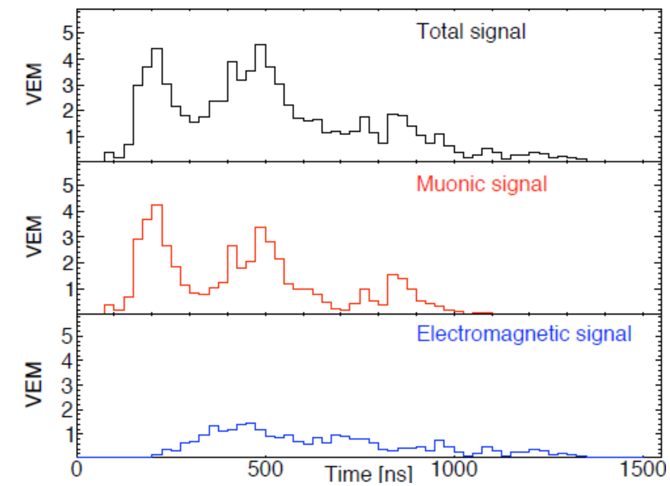


Muon Production Depth

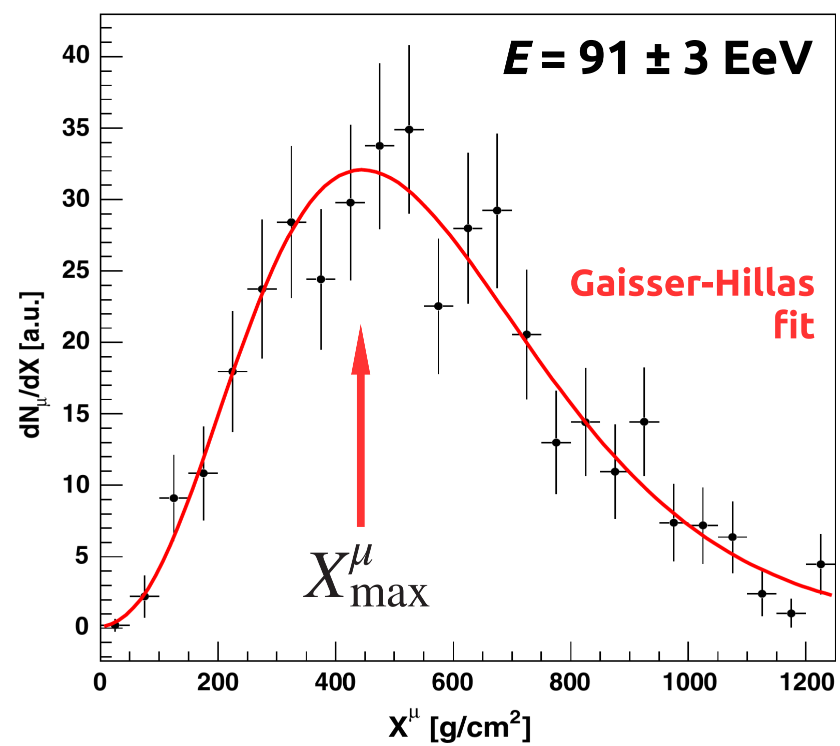


***r* > 1400 m**

$$z \simeq \frac{1}{2}\left(\frac{r^2}{c(t - \langle t_\varepsilon \rangle)} - c(t - \langle t_\varepsilon \rangle)\right) + \Delta - \langle z_\pi \rangle$$

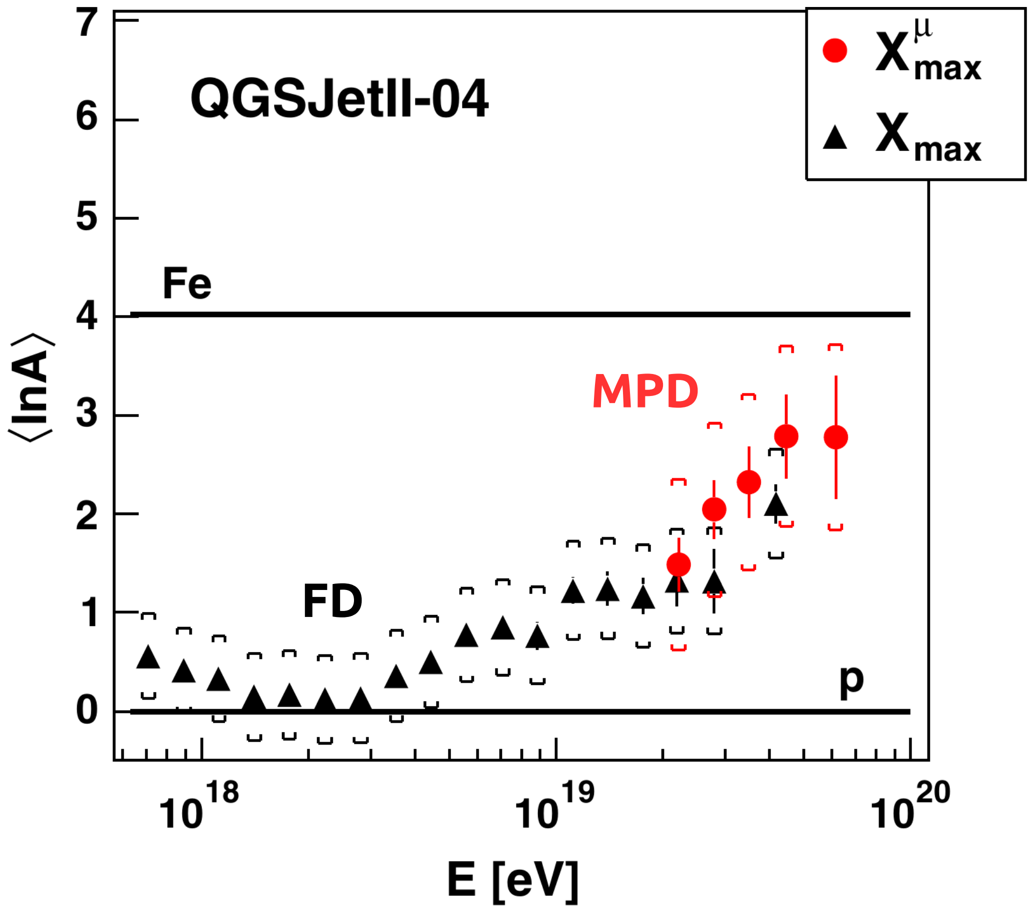


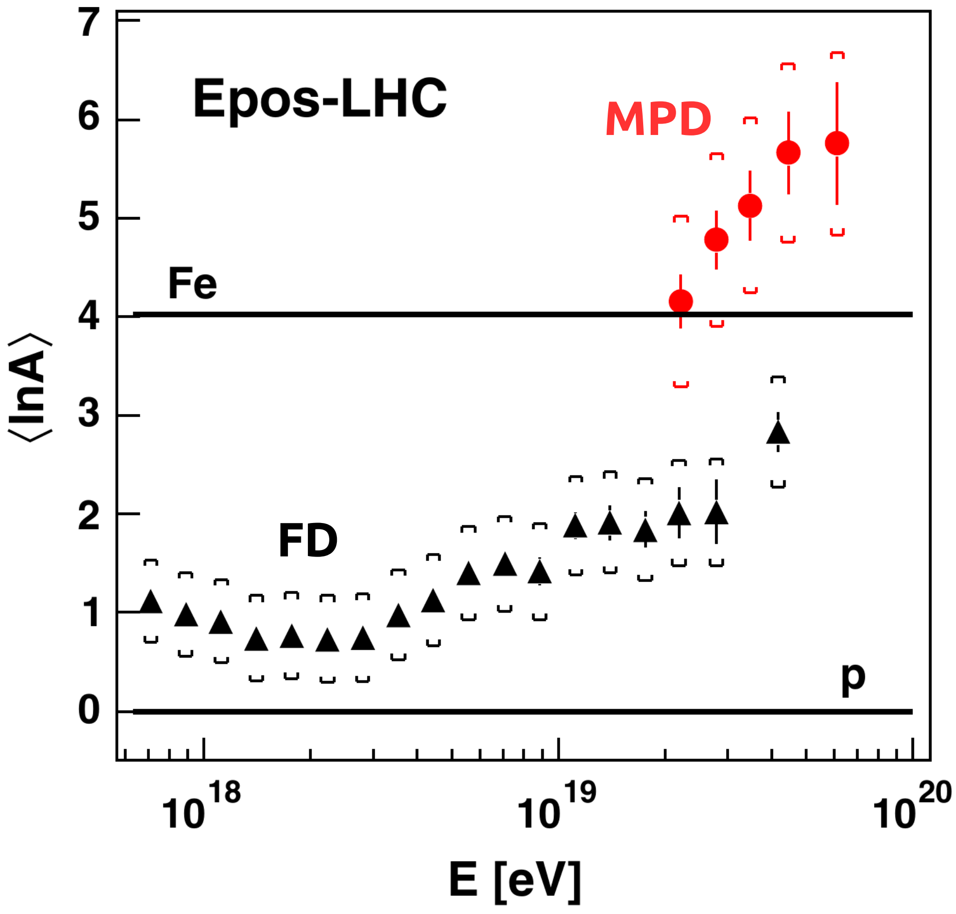
per event



Auger, PRD 90 (2014) 012012

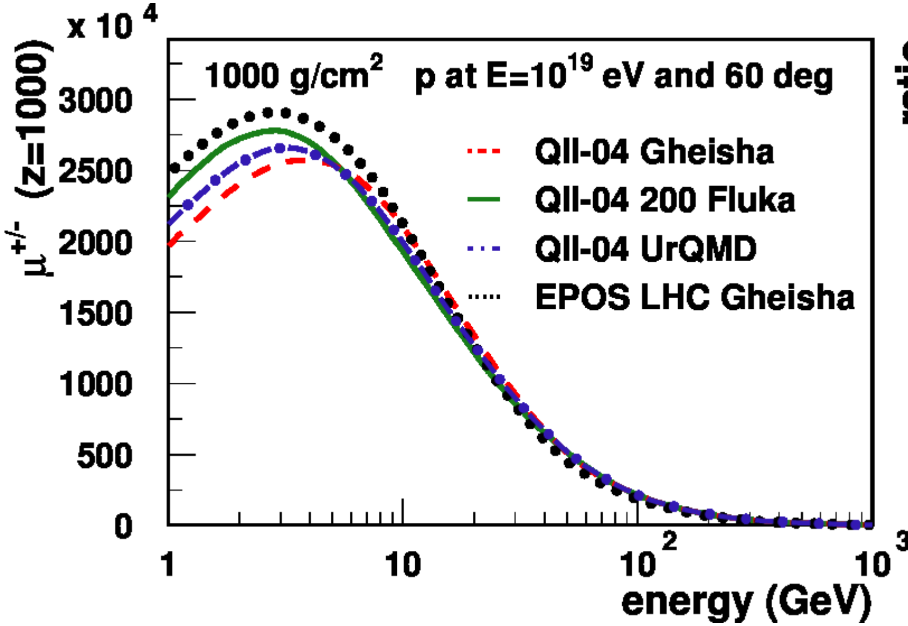
Muon Production Depth

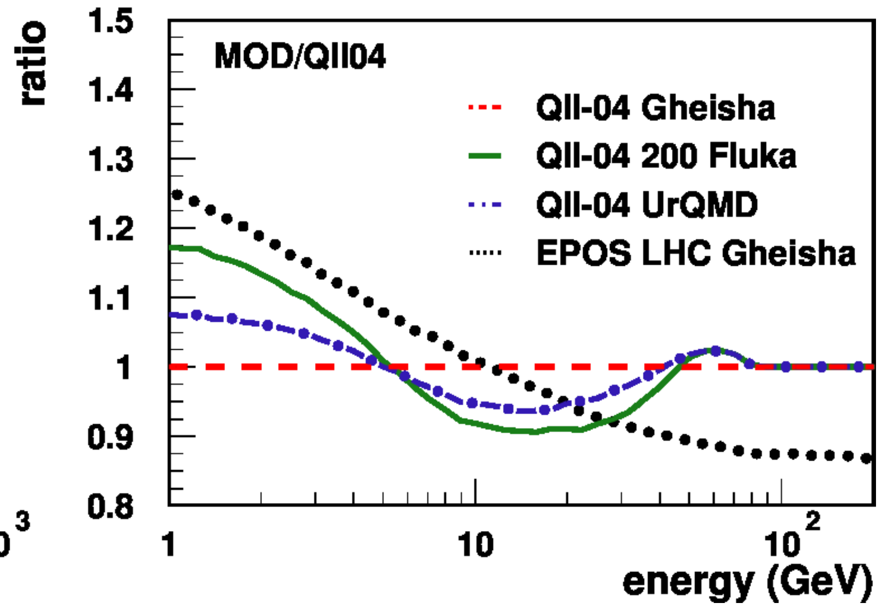


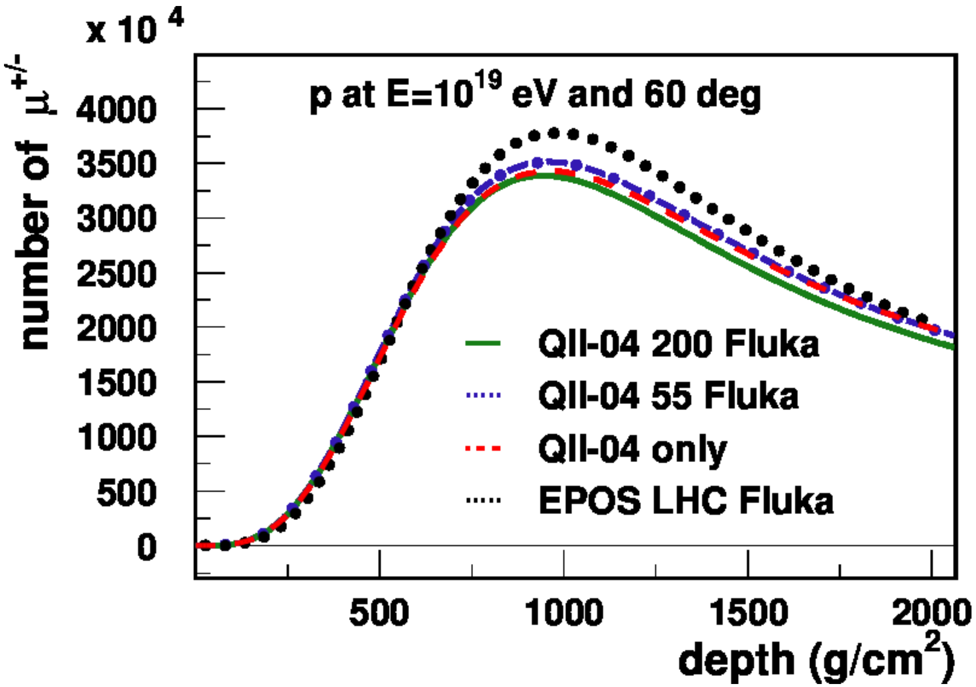


Auger, PRD 90 (2014) 012012

Current Level of Accuracy







diffs. in low-energy models start to matter

Pierog 2015