

RECENT RESULTS FROM THE PIERRE AUGER OBSERVATORY

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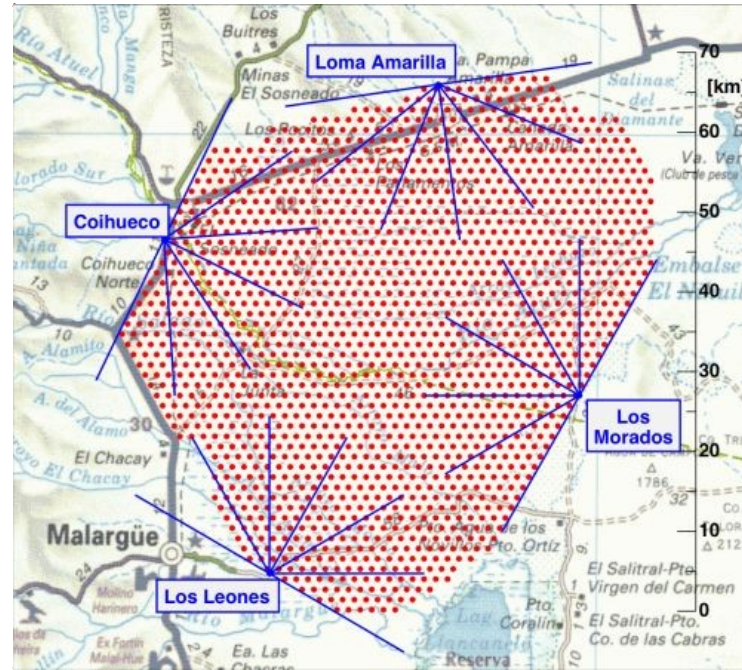
2) *Av. San Martín Norte 304, 5613 Malargüe, Argentina*



II Russian-Spanish Congress Particle and Nuclear Physics at all Scales and Cosmology
Saint-Petersburg, October 1-4, 2013

The Pierre Auger Observatory

- ➔ Malargüe, Argentina
- ➔ World's largest cosmic ray observatory.
- ➔ In operation since 2004.
Completed in 2008
- ➔ 3000 km²

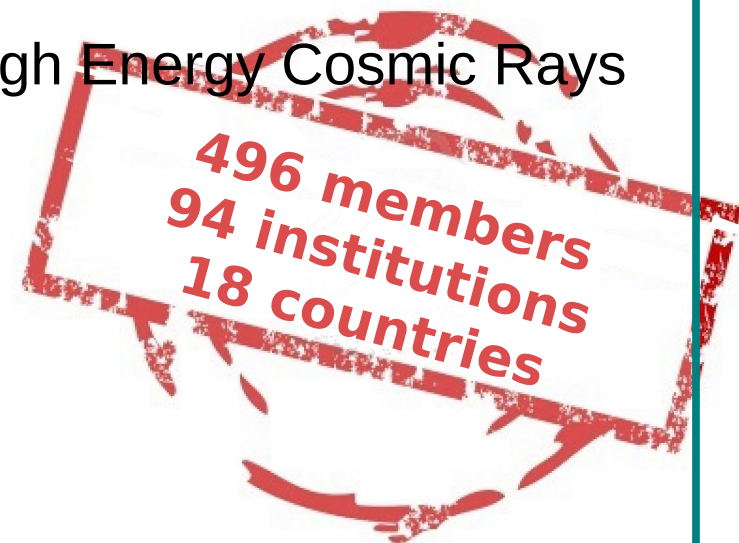


Main goal:

- Research the origin and the nature of Ultra High Energy Cosmic Rays

Physics:

- Energy Spectrum
- Composition
- Photon and neutrino searches
- Hadronic Physics
- Anisotropies and point sources



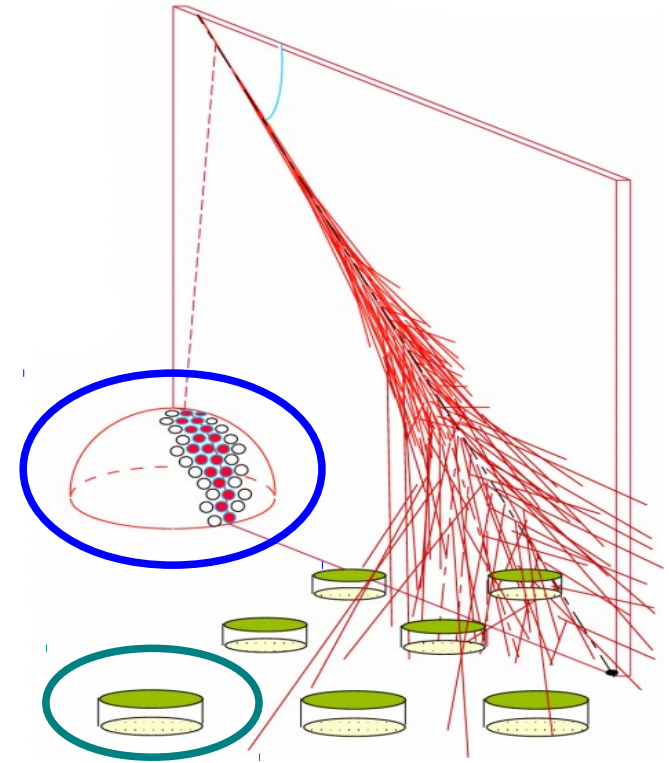
The Observatory: Hybrid detector

Hybrid detector:

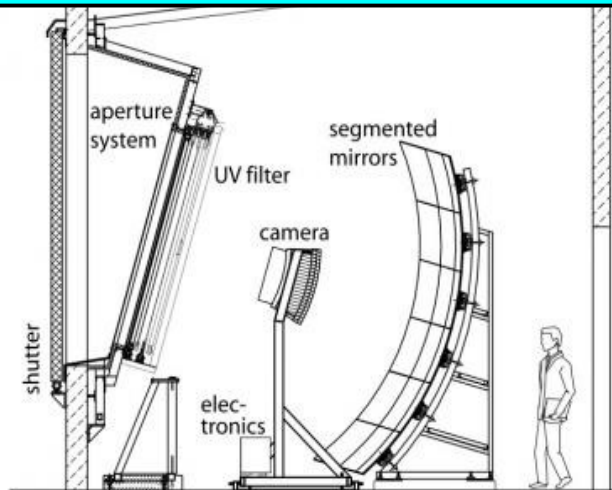
fluorescence + surface detectors

Independent and complementary:

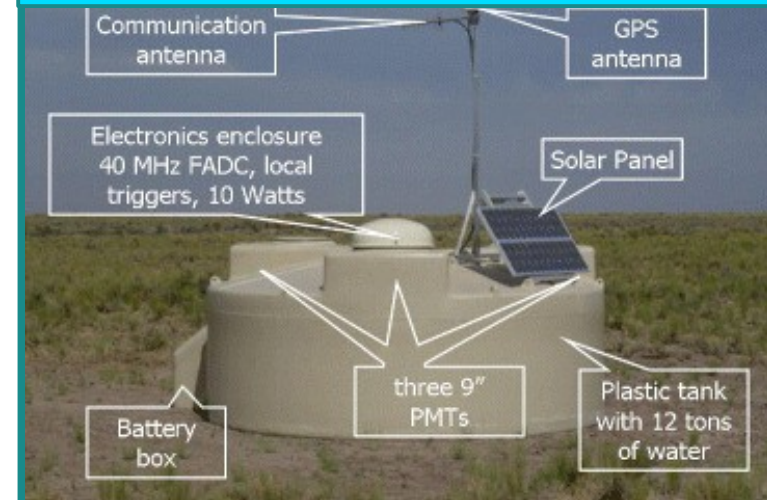
- ✓ Improved geometrical reconstruction with respect to individual components
- ✓ Cross-calibration between detectors
- ✓ Observation of different shower components



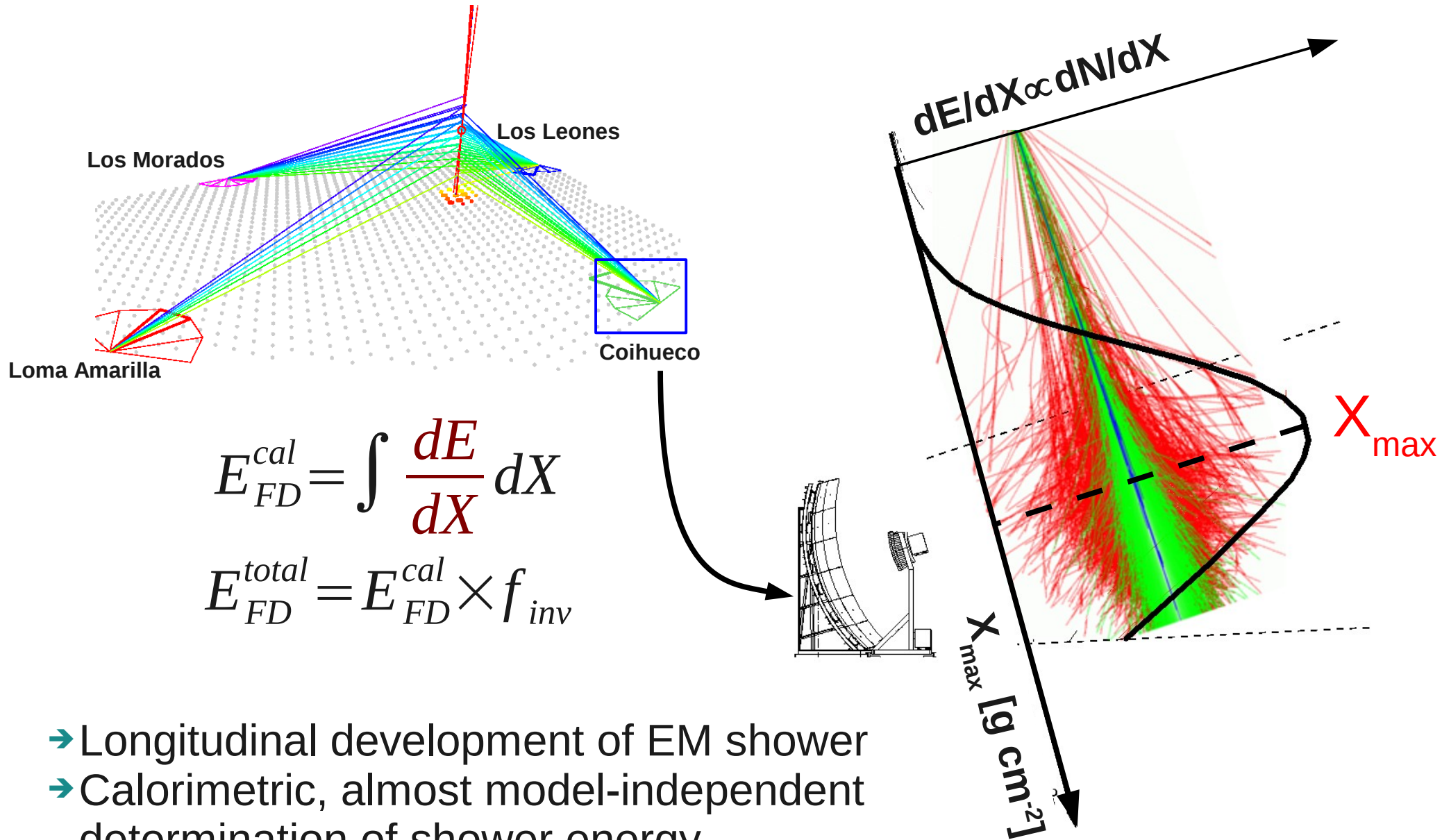
24 fluorescence telescopes at 4 sites



More than 1600 Water-Cherenkov tanks

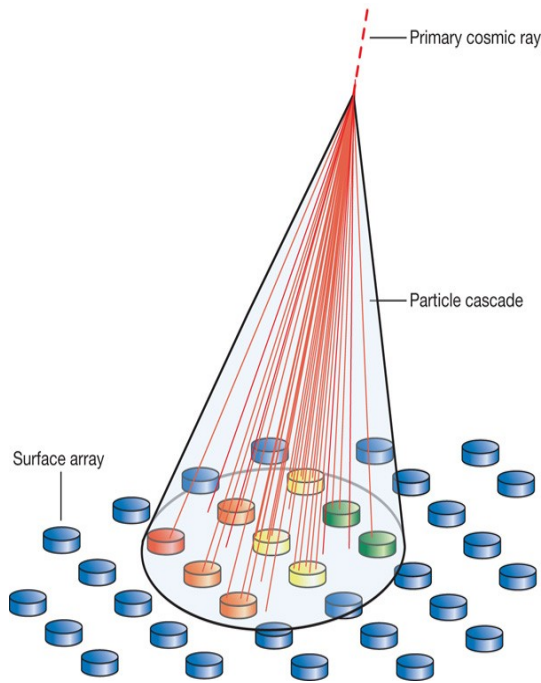


Air shower reconstruction: FD

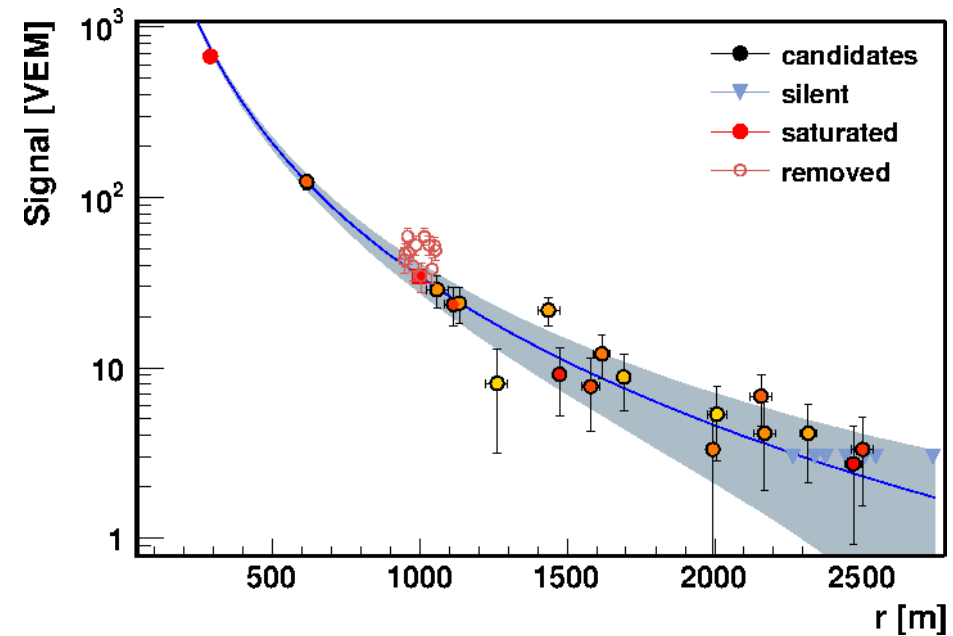


- Longitudinal development of EM shower
- Calorimetric, almost model-independent determination of shower energy
- “Invisible” energy (f_{inv}) carried by ν and HE μ (<10%)

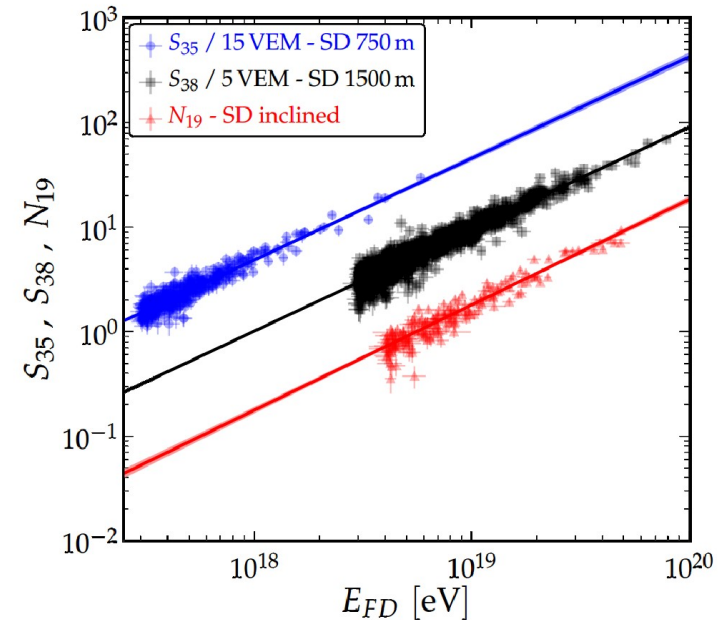
Air shower reconstruction: SD



tank signal vs
tank distance



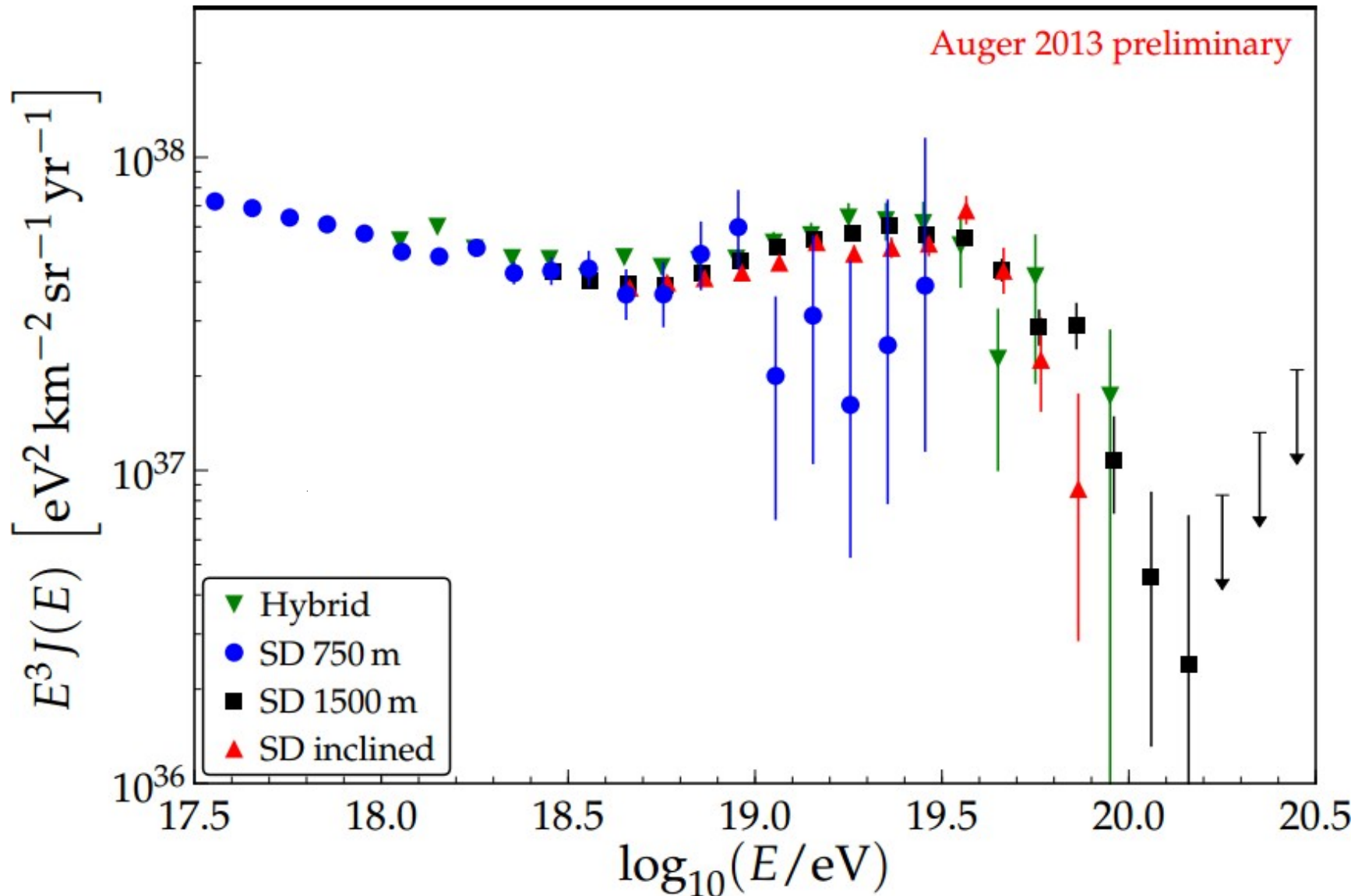
- SD energy obtained calibrating with the FD
- Different SD regimes → different calibrations
- All SD observables show a good correlation with the FD



The Spectrum of UHE

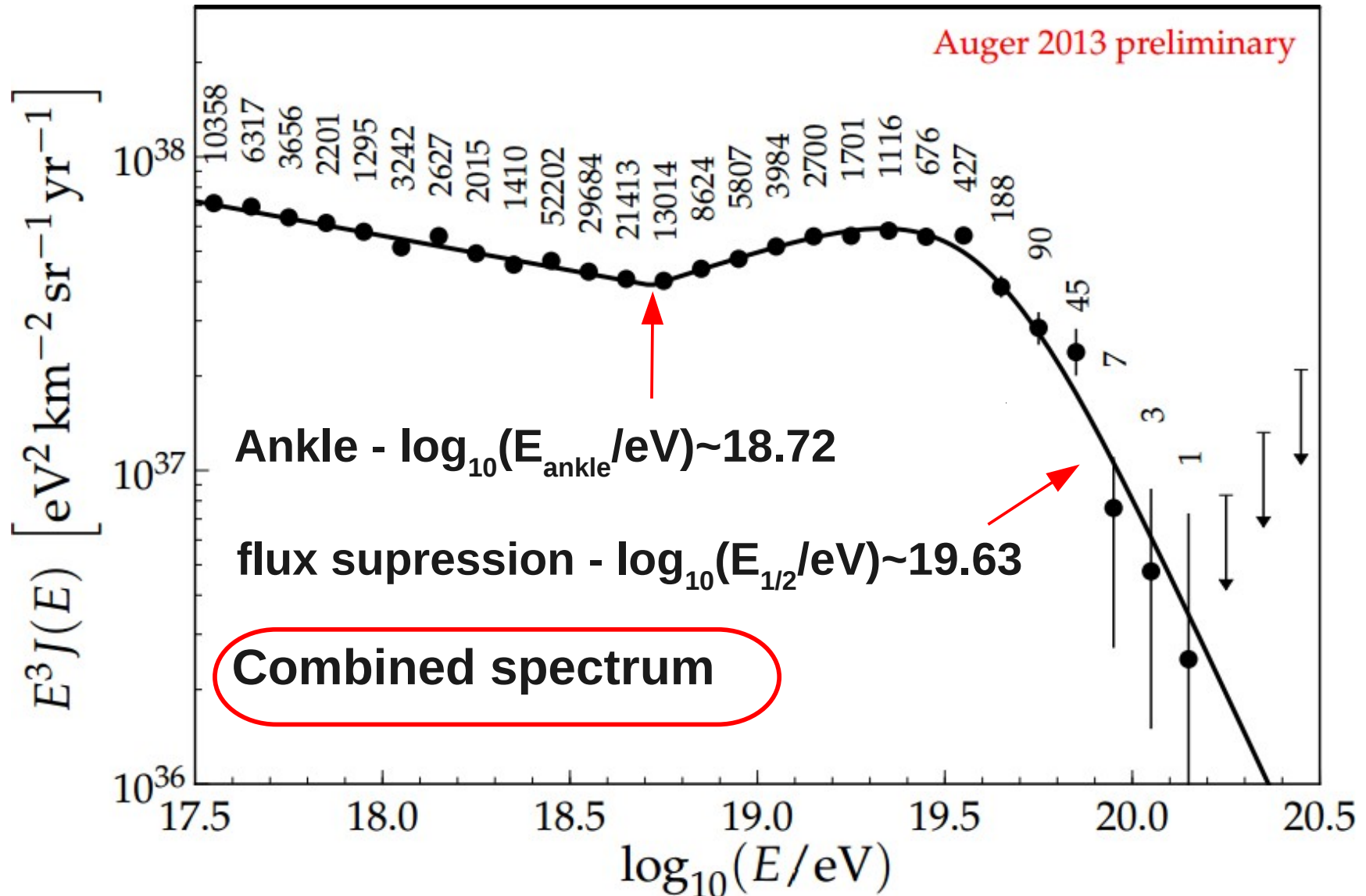
4 independent measurements using SD and FD:

- Standard SD array ($\theta < 60^\circ$) (■)
- Inclined events ($60^\circ < \theta < 80^\circ$) (▲)
- Infill array (750m) (●)
- Hybrid events (FD+ ≥ 1 SD) (▼)



The Spectrum of UHE

- **Ankle** and **flux suppression** visible in the combined spectrum.
- Interpretation relies on primary composition and sources distribution



Mass composition

Shower development → most direct information on composition

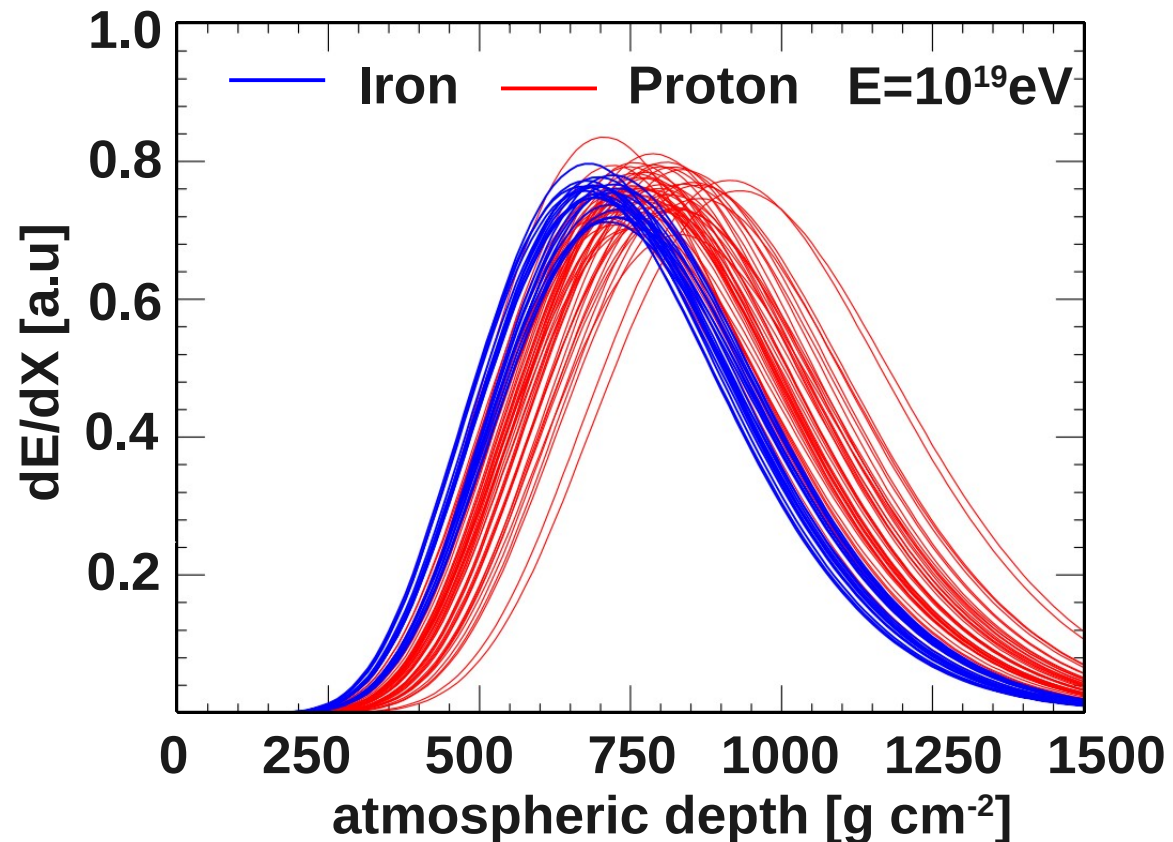
- **Proton showers** are more penetrating and fluctuate more
- **Iron shower** ~ Σ 56 proton showers with $E_p/56$ each:
 - Less penetrating (less energetic)
 - Less fluctuating (superposition)

FD

maximum of the EM profile

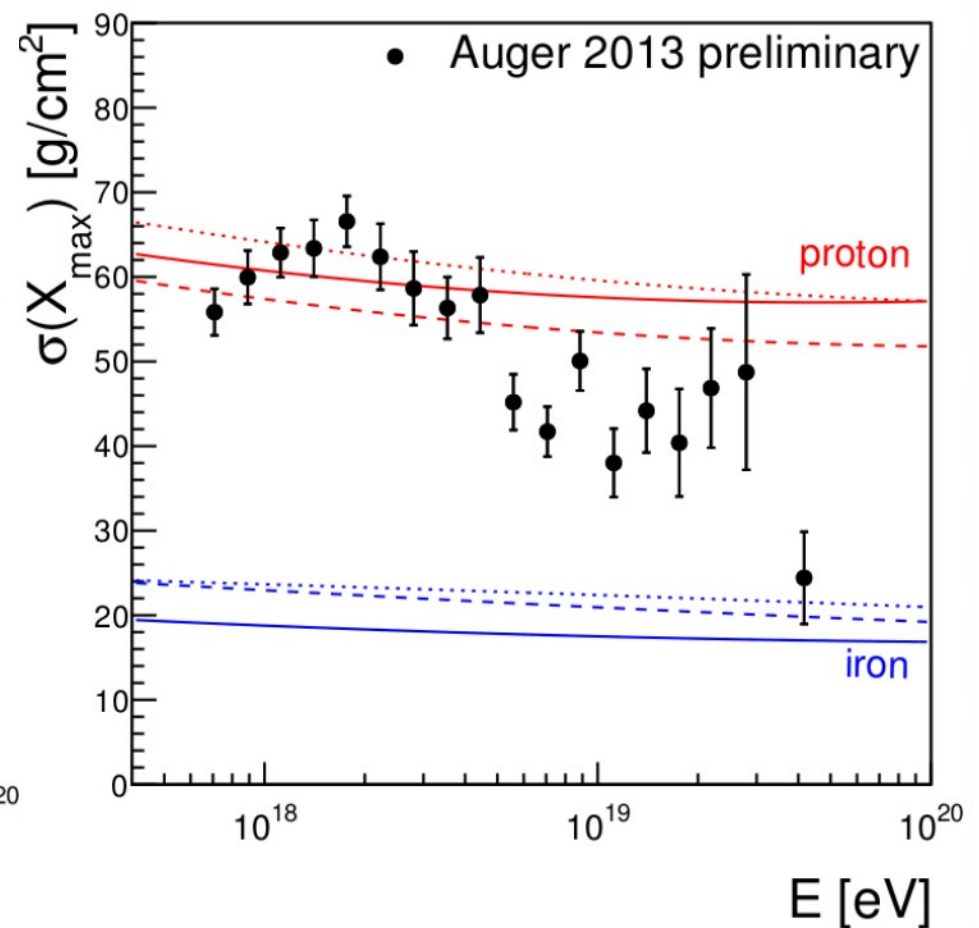
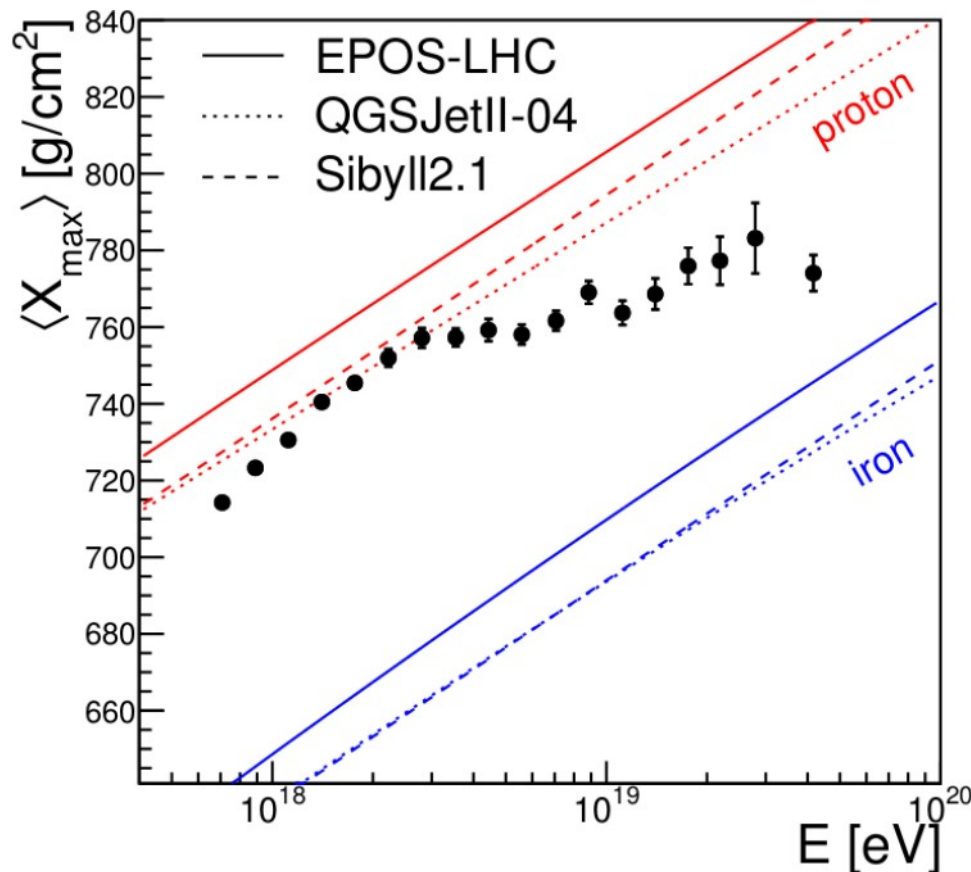
SD

maximum of the Muon
Production Depth (MPD)

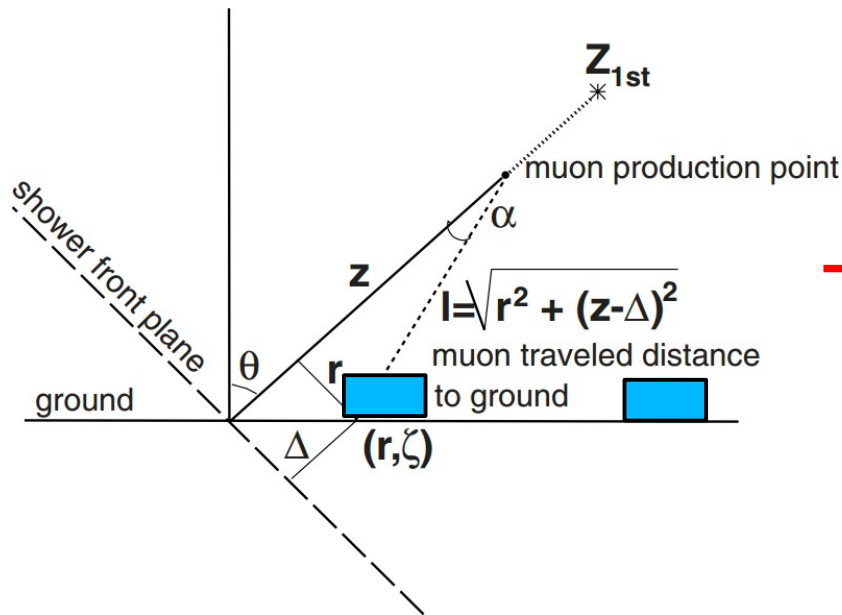


Mass composition: $\langle X_{\max} \rangle$ and $\text{RMS}(X_{\max})$ ⁹

- ✓ High-quality data set used to determine X_{\max} for each shower
- ✓ FD measurements are very precise: resolution $\sim 20 \text{ g cm}^{-2}$
- ✗ FD only operates on clear moonless nights: reduced statistics



Mass composition: MPD

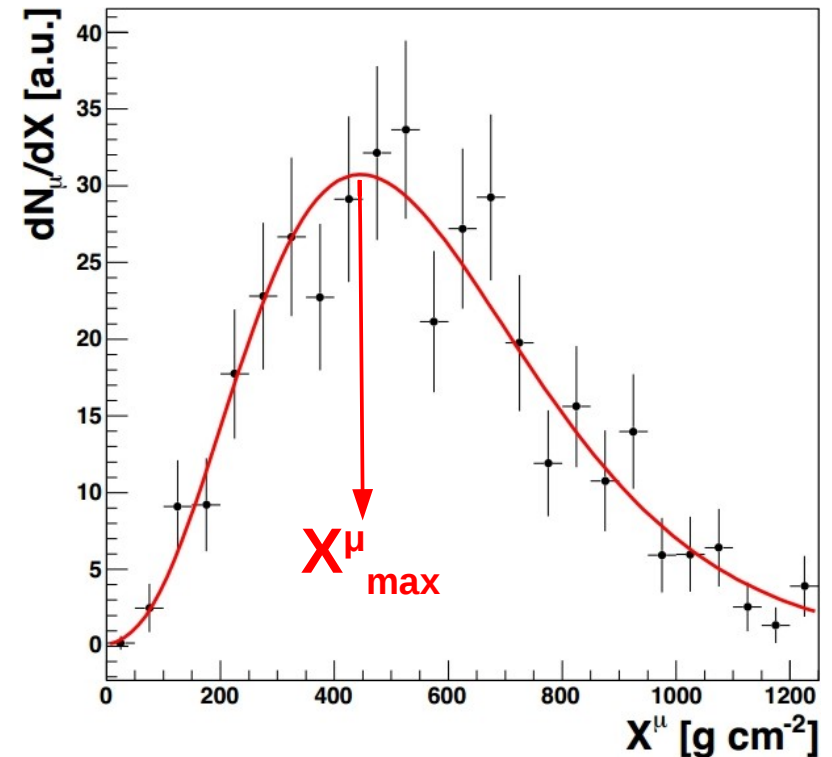


Arrival time \rightarrow production depth

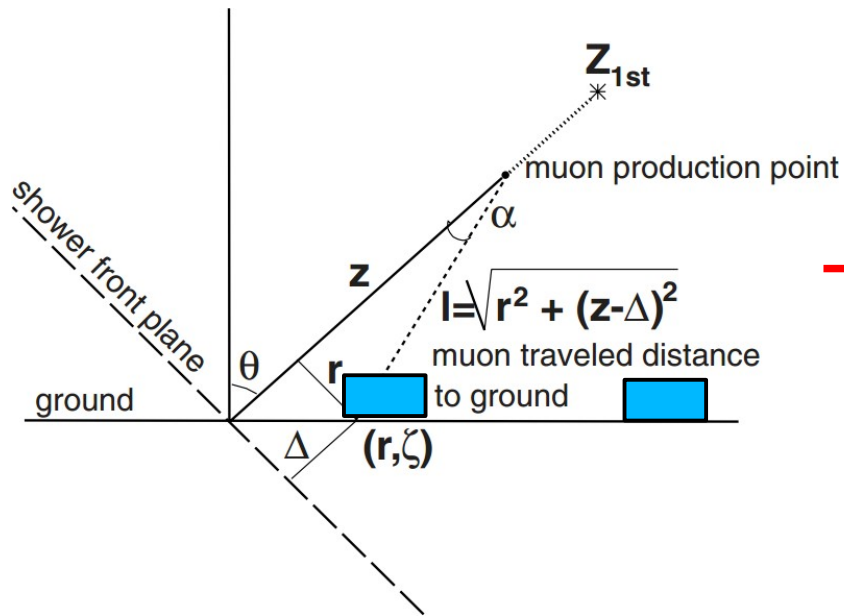
$$z = \frac{1}{2} \left(\frac{r^2}{c t_g} - c t_g \right) + \Delta$$

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

- \rightarrow Muons travel in straight lines from their production point to ground.
- \rightarrow MPD is the distribution of **number of muons vs production depth**
- \rightarrow Observable: maximum of the distribution X_μ^{max}



Mass composition: MPD

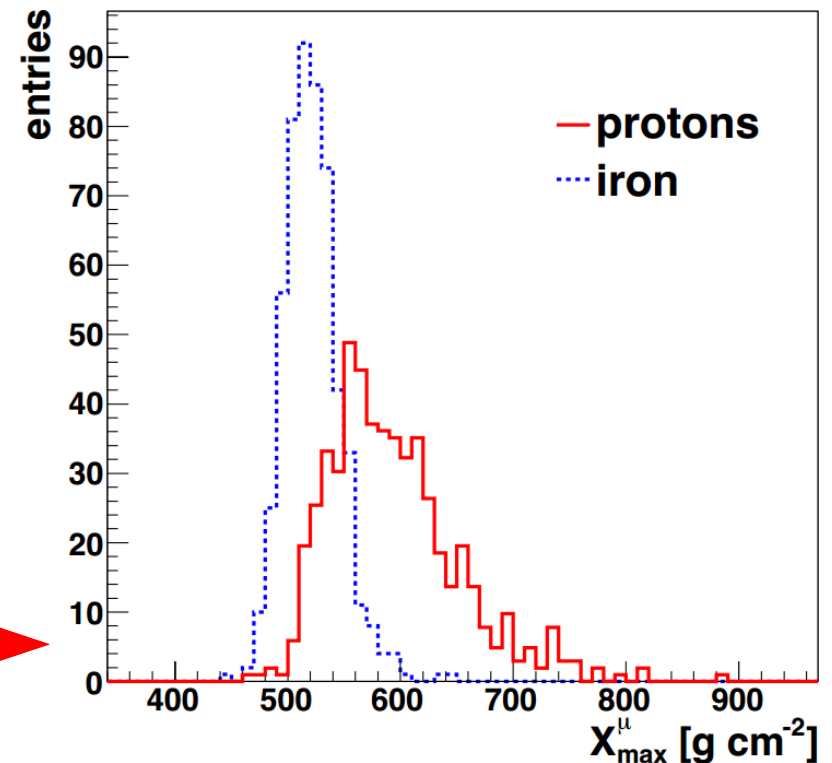


Arrival time \rightarrow production depth

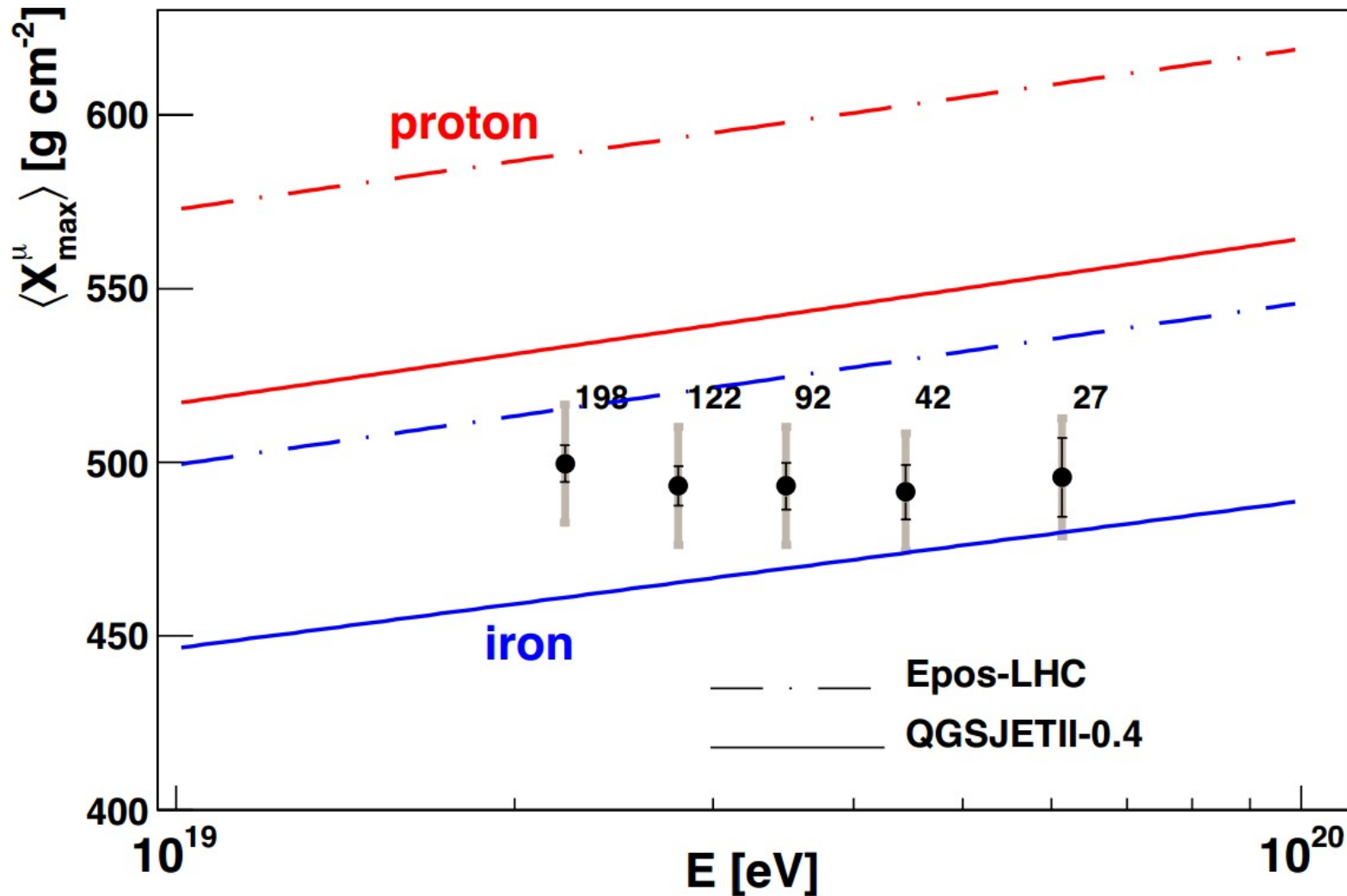
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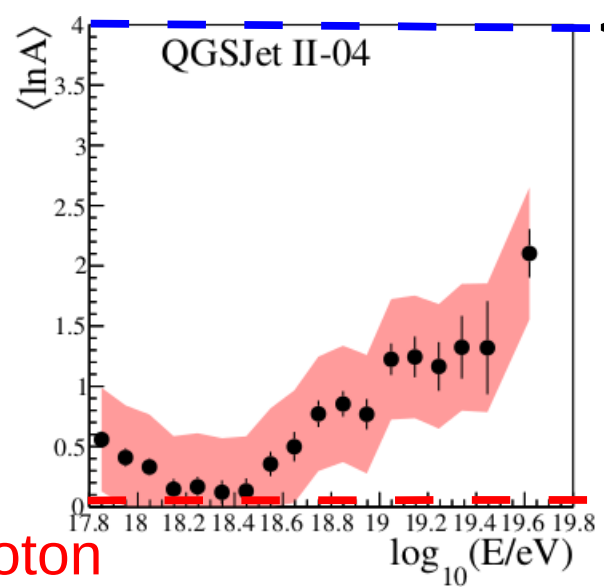
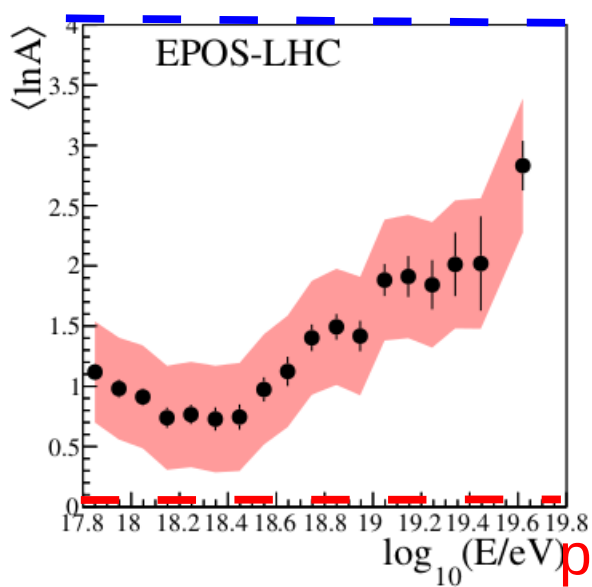
Mass composition: MPD



- ✓ SD observable independent of X_{\max} .
- ✓ Additional insight into hadronic models (muon production)
- ✗ Small zenith and energy window: $\theta \in [55^\circ, 65^\circ]$

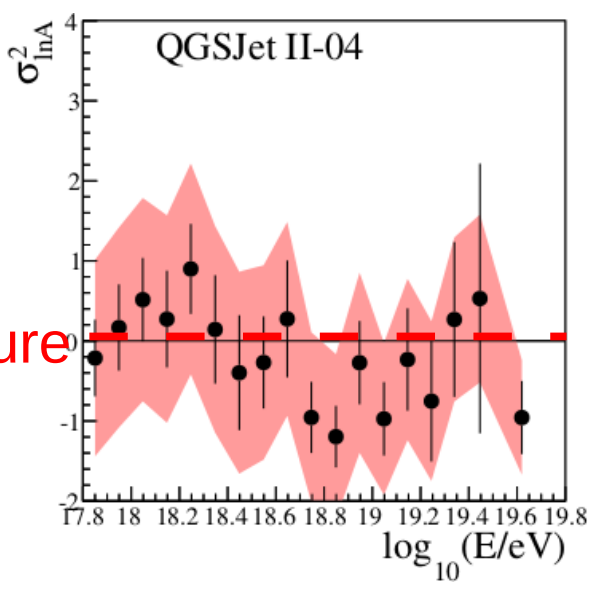
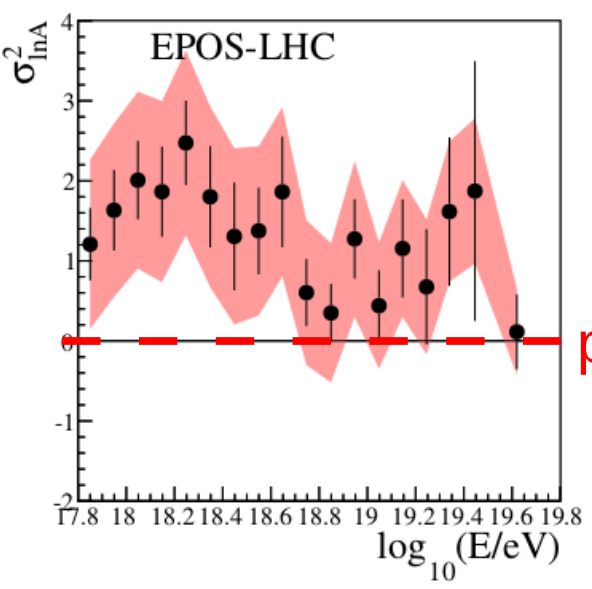
Evolution of $\langle X_{\max} \rangle$, $\sigma(X_{\max})$ and $\langle X_{\max}^{\mu} \rangle$ with E suggests composition becoming heavier up to UHE.

iron



$\langle X_{\max} \rangle, \sigma(X_{\max}) \Rightarrow \langle \ln A \rangle, \sigma^2_{\ln A}$

Uncertainties in hadronic interactions at UHE hinder the interpretation:
 → increase on mean mass?, or
 → inadequate interaction models?



Improve CR measurements

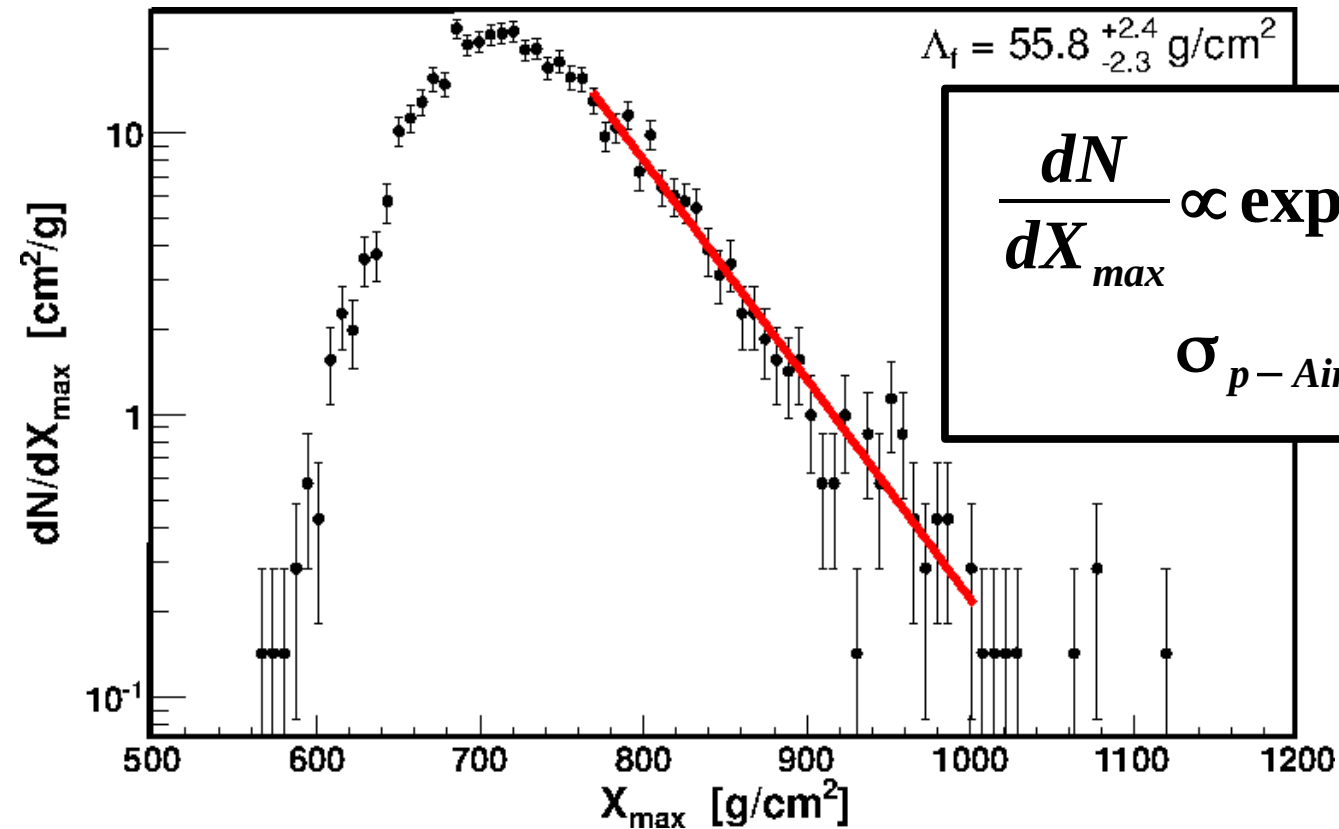


Constraint hadronic models



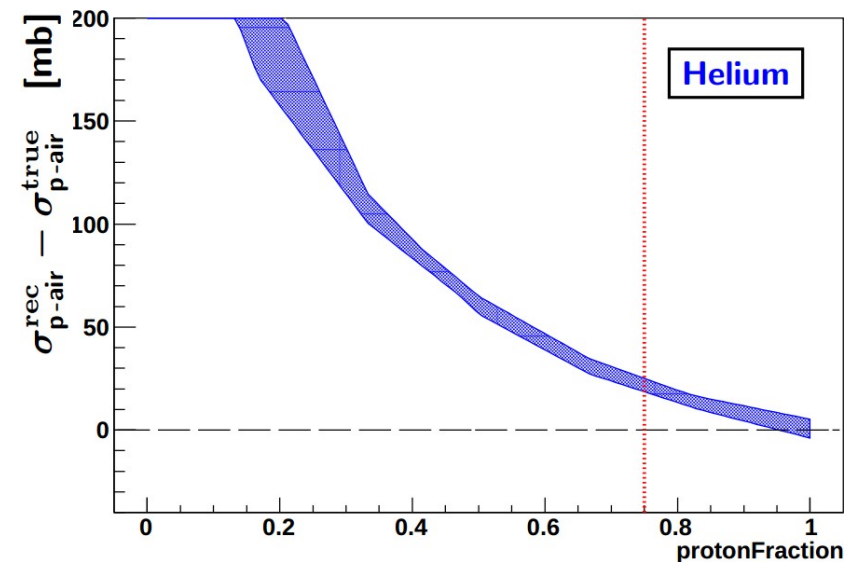
Improve CR interpretation

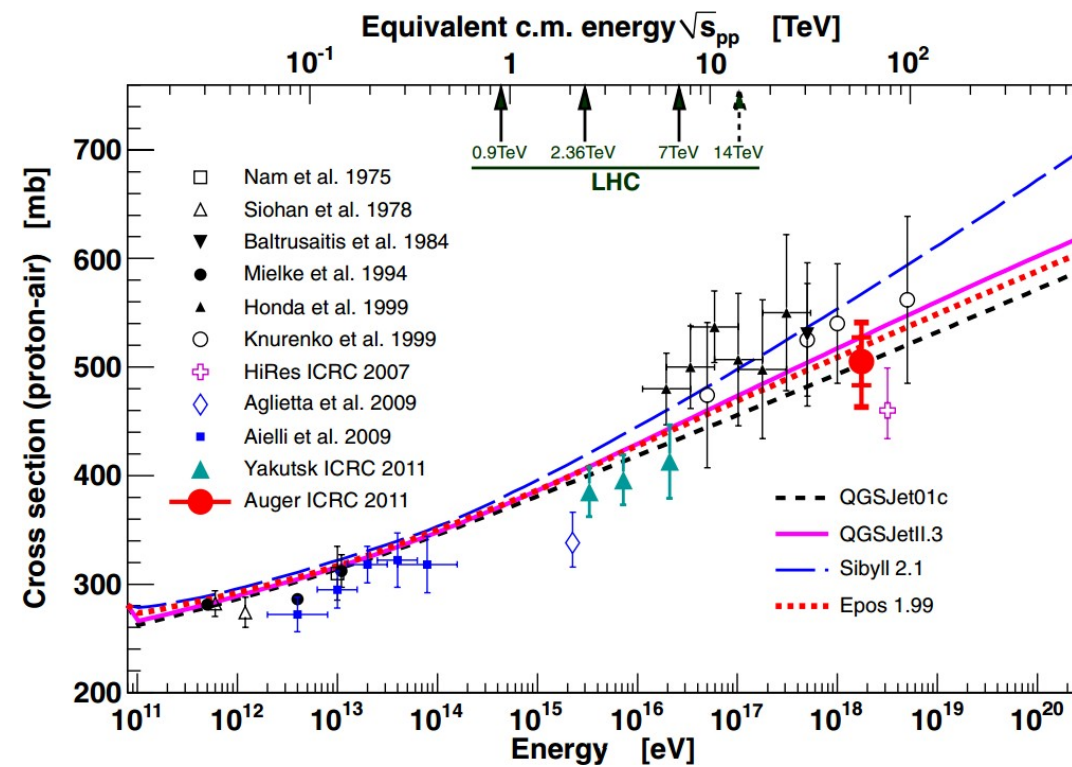
Hadronic interactions



f chosen so that biases from a $\text{He}_{\text{frac}} \leq 25\%$ are below statistical uncertainties

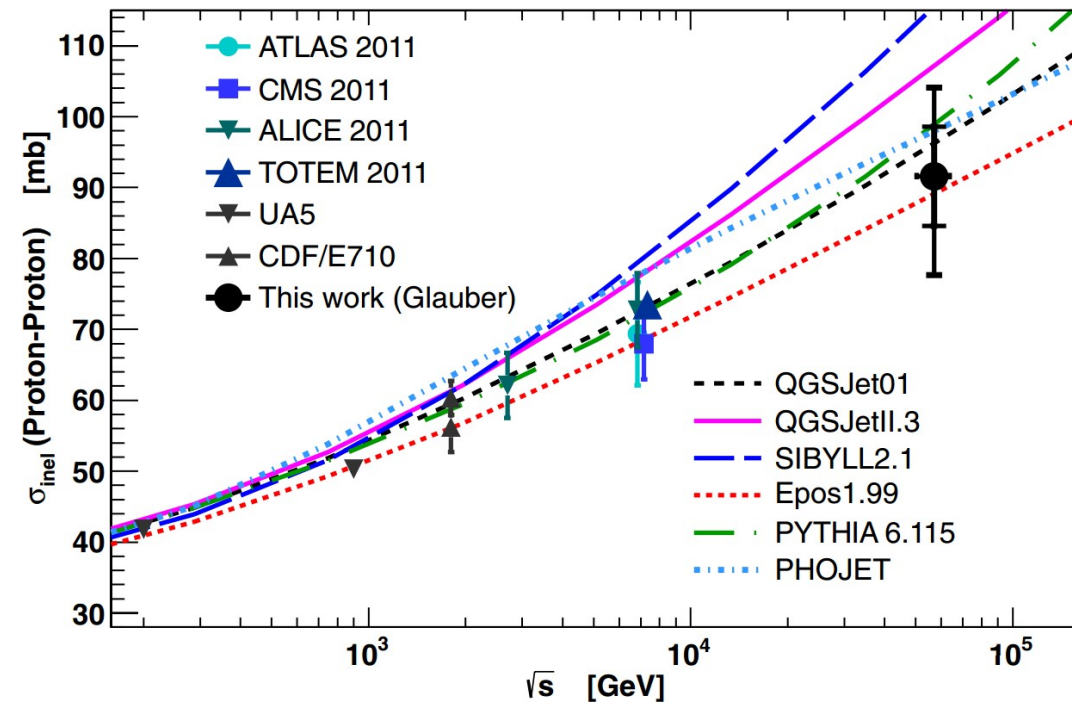
- Correlation between X_1 and X_{max}
- f : fraction of most deeply penetrating air showers used ($f = 0.2$)
- Large values of X_{max} correspond to proton rich samples (>80% for $f = 0.2$)





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

Extended Glauber model +
propagation of param.
uncertainties



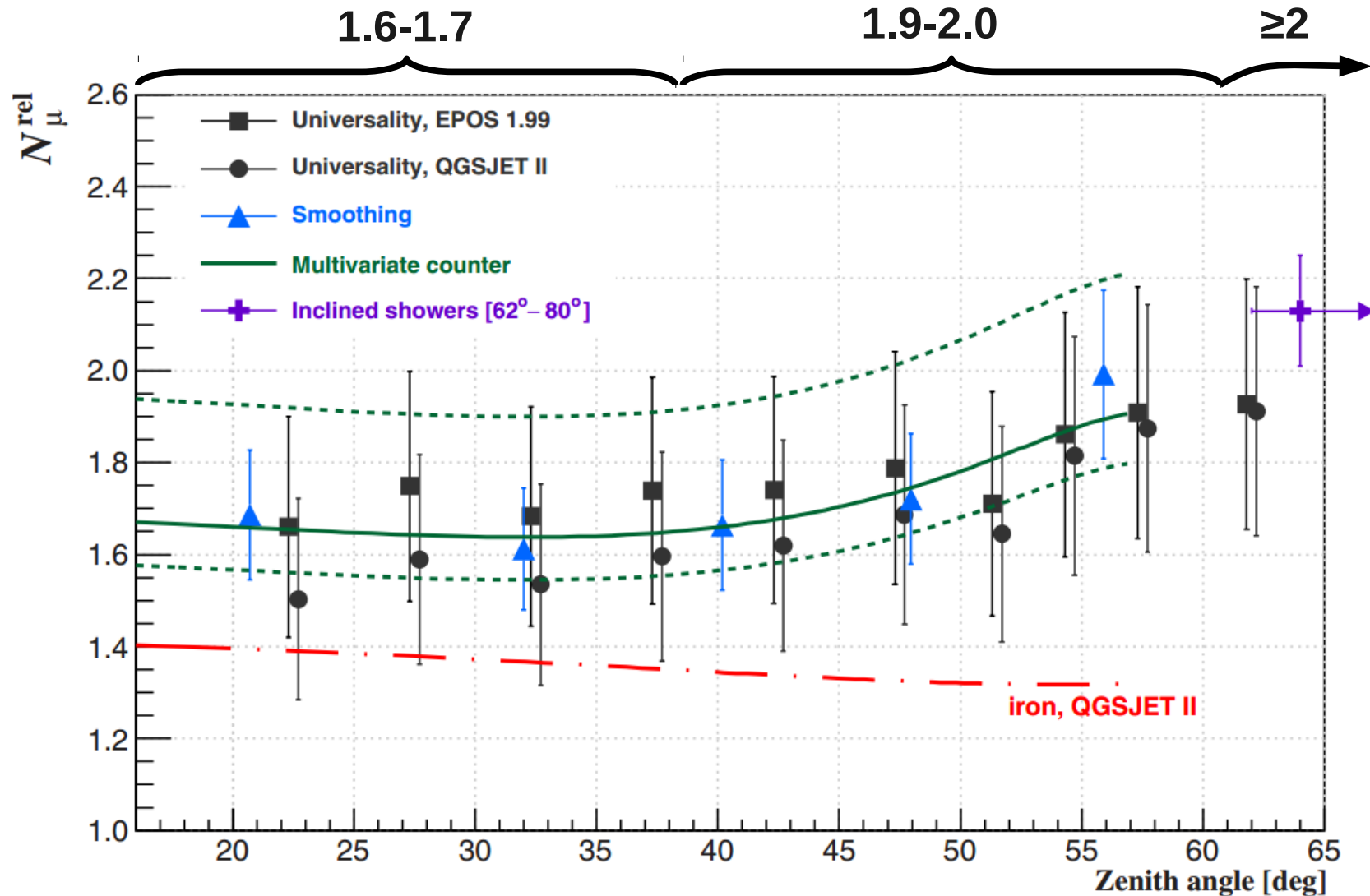
$$\sigma_{pp}^{\text{inel}} = 92 \pm 7 (\text{stat})_{-11}^{+9} (\text{sys})$$

$$\pm 7 (\text{Glauber}) \text{ mb}$$

- ✓ Measurement compatible with most model extrapolations
- ✓ Highest energy σ_{pp} value
- ✗ Model dependent

Muon deficit

- Several methods developed for estimating the muonic part of the signal observed in the Cherenkov detectors.
- All methods yield a muon content in data significantly larger than in simulations.



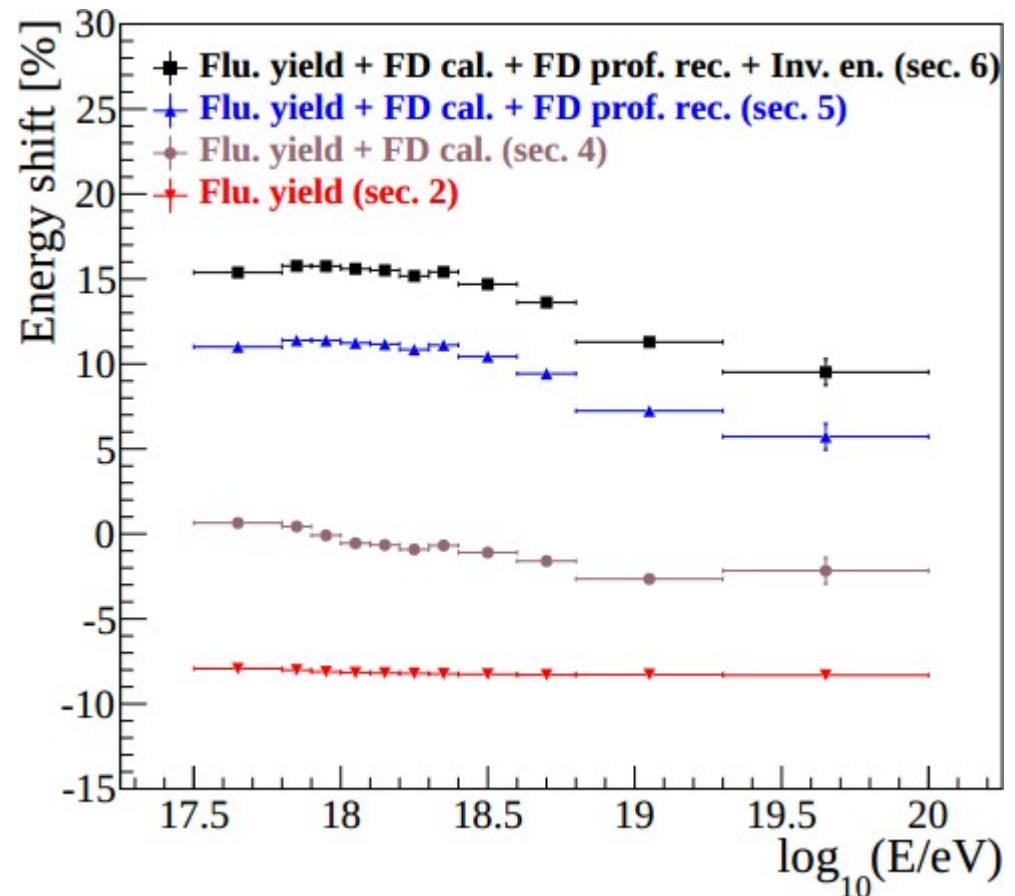
Summary

- Auger provides copious high quality data.
- Observables show a coherent behaviour.
- Trend to heavy, not pure composition.
- Flux suppression: clear observation, unclear interpretation (GZK? sources?)
- Highest energy data-derived σ_{pp} compatible with extrapolations from accelerator data.
- Cosmic Rays physics has potential to set constraints on hadronic models

- Energy Scale
- Fluorescence Detector Quality Cuts
- Spectrum comparison between experiments
- Mass composition comparison
- Correlation with Point Sources
- Photon and neutrino searches
- From Λ_f to $\sigma_{p\text{-Air}}$

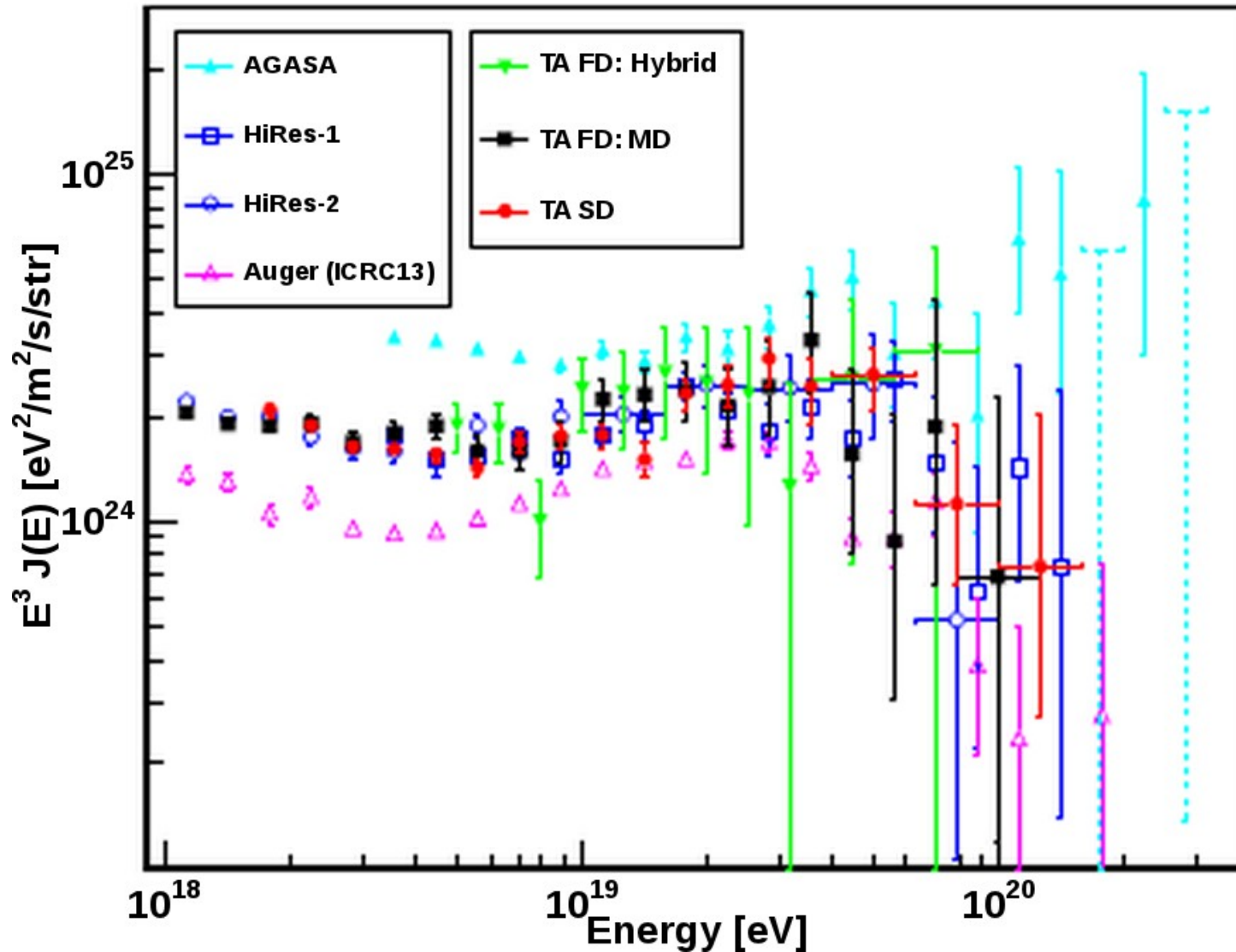
New energy scale

Systematic uncertainties on the energy scale	
Absolute fluorescence yield	3.4%
Fluor. spectrum and quenching param.	1.1%
Sub total (Fluorescence yield)	3.6%
Aerosol optical depth	3% ÷ 6%
Aerosol phase function	1%
Wavelength depend. of aerosol scatt.	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere)	3.4% ÷ 6.2%
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration)	9.9%
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec.)	6.5% ÷ 5.6%
Invisible energy	3% ÷ 1.5%
Stat. error of the SD calib. fit	0.7% ÷ 1.8%
Stability of the energy scale	5%
Total	14%



Down from **22%** (ICRC 2011) to **14 %** (ICRC 2013)

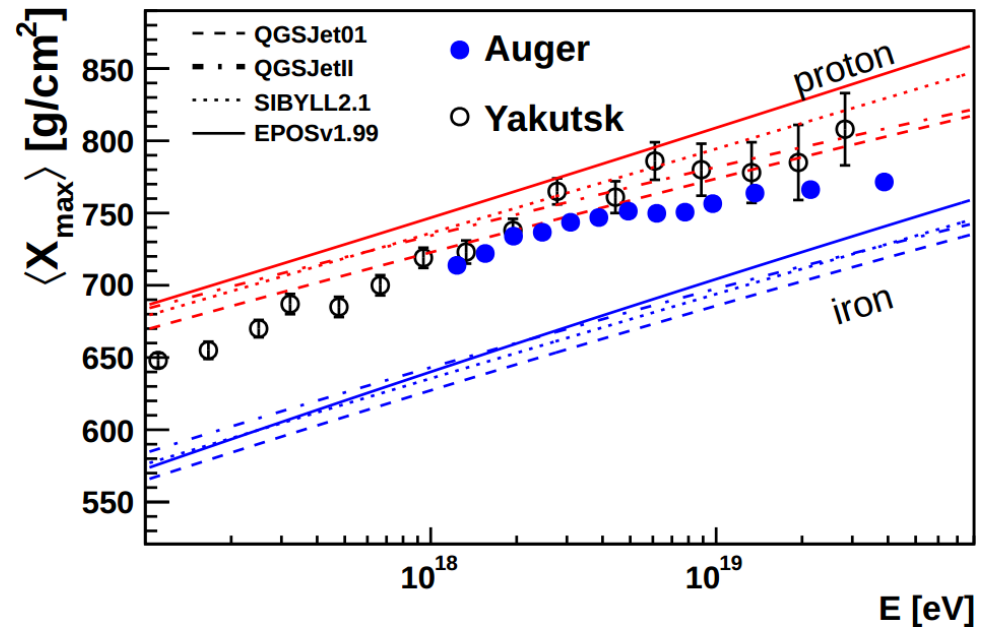
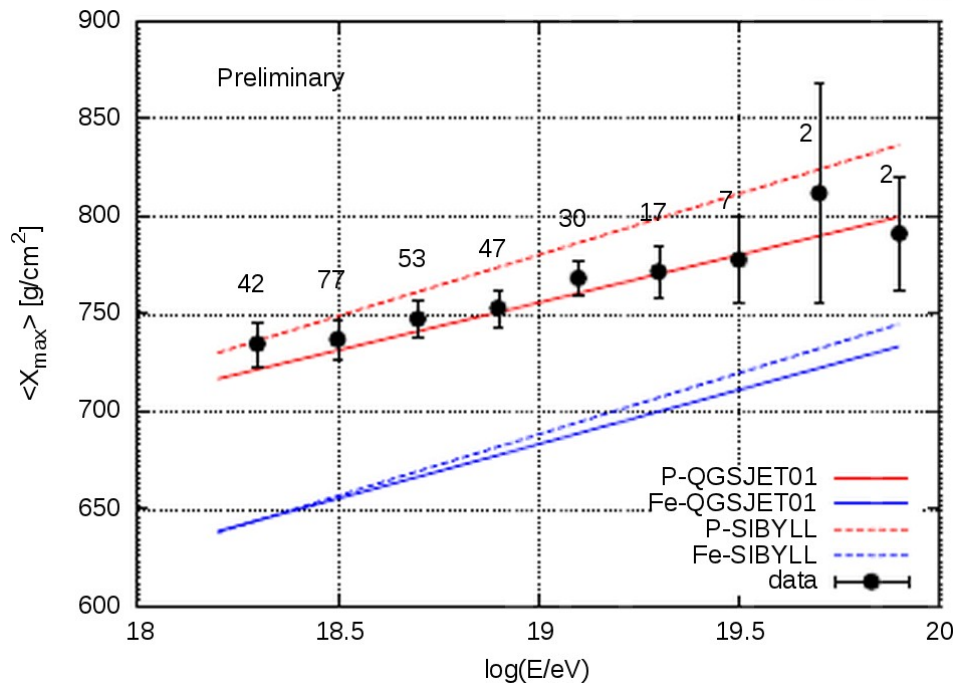
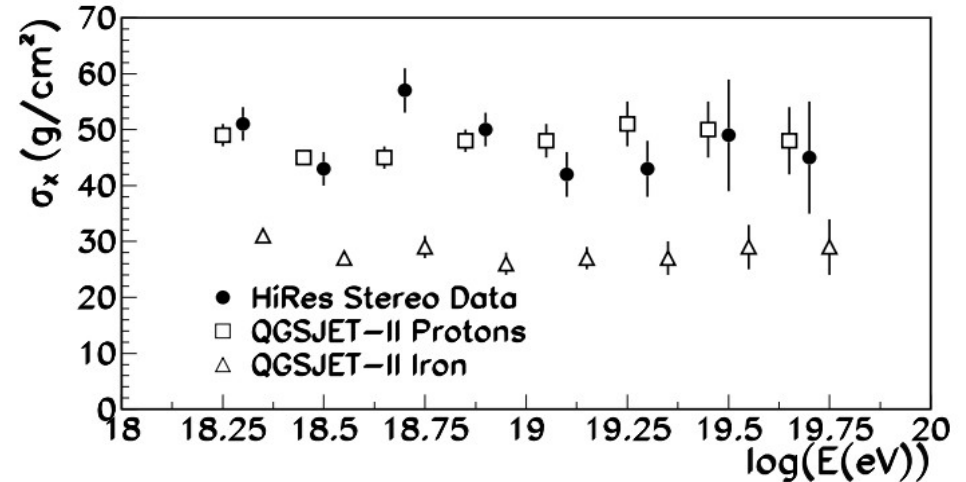
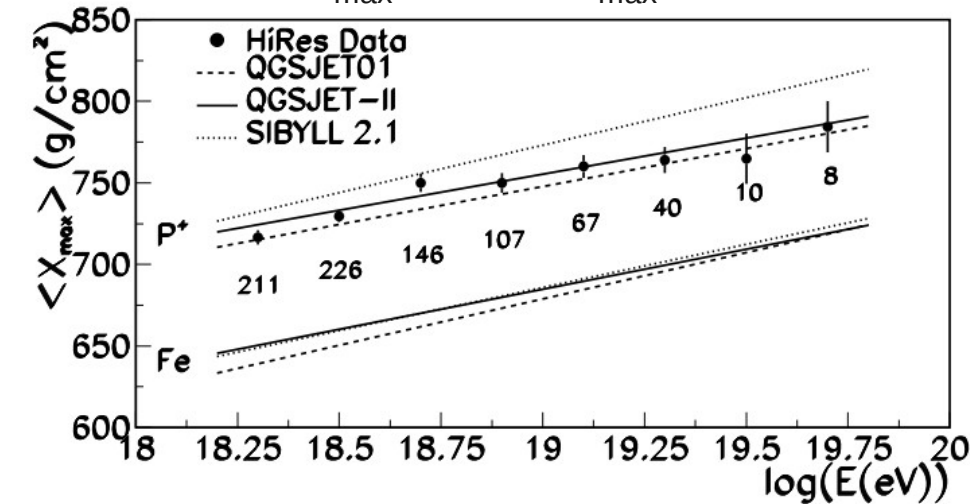
- 1) X_{\max} in the Field of view
- 2) $\Delta E/E < 20\%$
- 3) Cherenkov Fraction $< 50\%$
- 4) X^2 linear – X^2 GH > 4
- 5) Hole in the profile $< 20\%$
- 6) Vertical Aerosol Optical Distance @ 2.5 km < 0.1
- 7) Cloud Coverage $< 25\%$
- 8) Fiducial volume cuts (avoid systematics due to 1))
- 9) Reject bad/saturated pixels from FD reconstruction, and
- 10) Request at least 5 pixels for the axis reconstruction
- 11) $\Delta X_{\max} < 40 \text{ gr cm}^{-2}$
- 12) X^2 GH/ndf < 2.5
- 13) Hottest station distance to core $< 750\text{m}$



- Scale difference due to different energy assignment
- All experiments except AGASA show GZK-like cut-off at the highest energies
- Are the rest compatible?

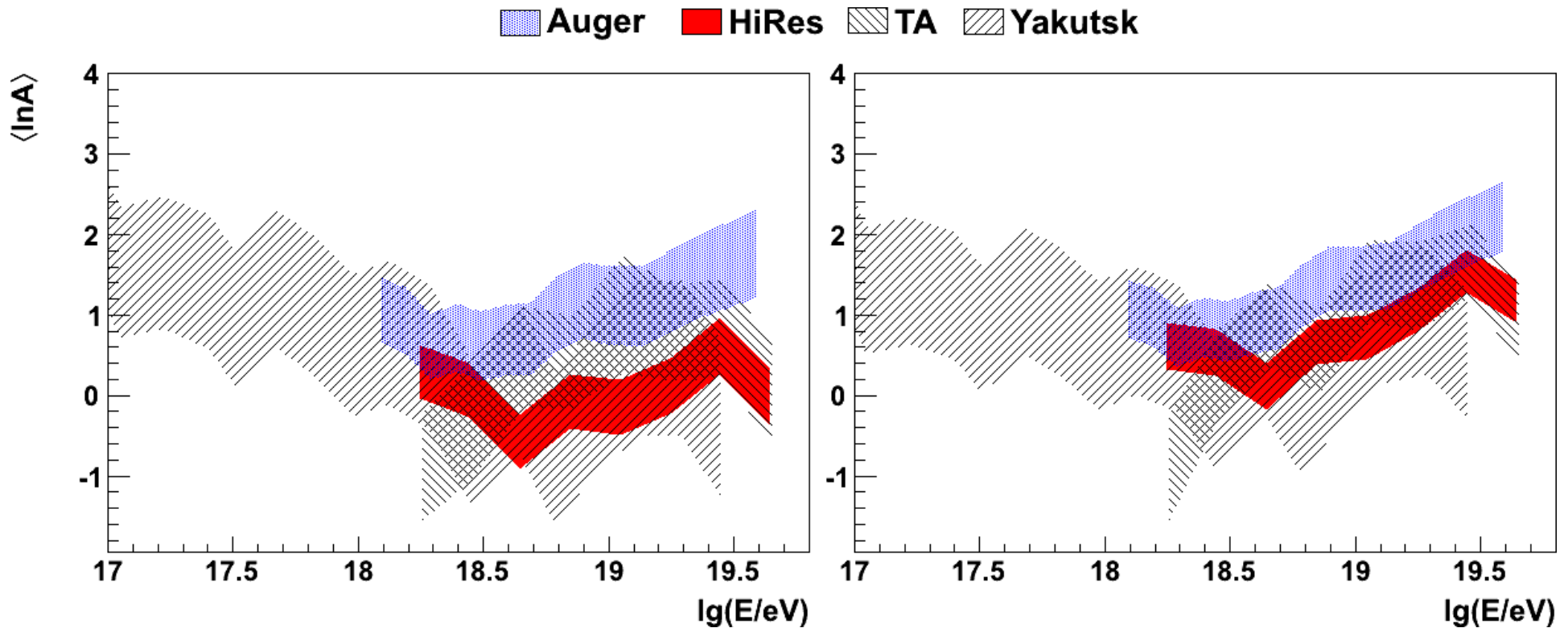
Mass composition

- HiRes X_{\max} and $\sigma(X_{\max})$ (1), Telescope array X_{\max} (2), Yakutsk X_{\max} (3)

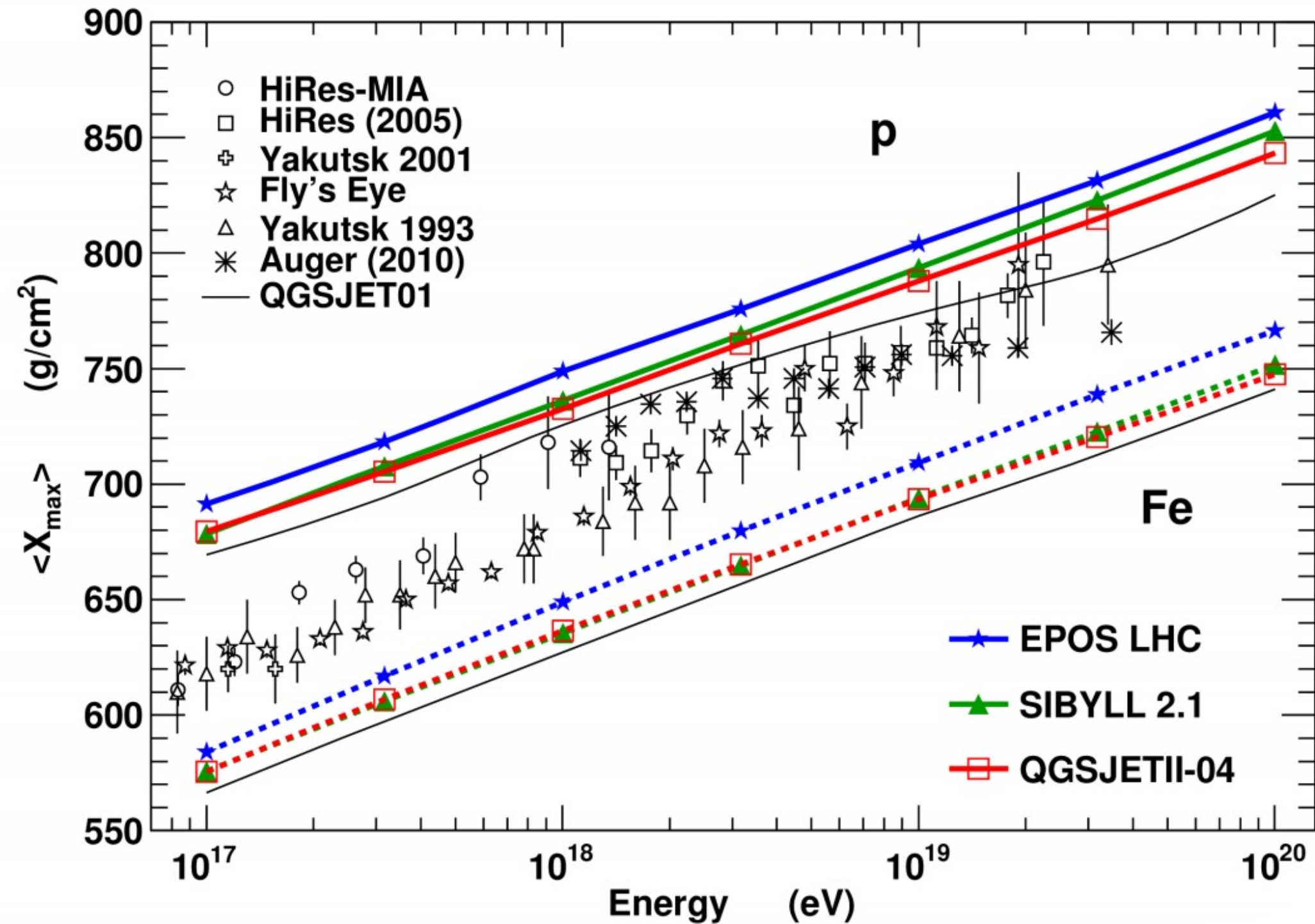


- (1) P. Sokolsky et al. Hires Collaboration. *Nucl. Phys. B- Proc. Supp.* 212,74 (2011)
- (2) H.Sagawa et al. Telescope Array Collaboration AIP Conf. Proc. 1367, 244 (2010)
- (3) M. Unger for the Pierre Auger and Yakutsk Collaborations *EPJ Web Conf.* 53 (2013) 01006

Results are converted to $\langle \ln A \rangle$ to be comparable, using QGSJETII (left) and Sibyll (right)

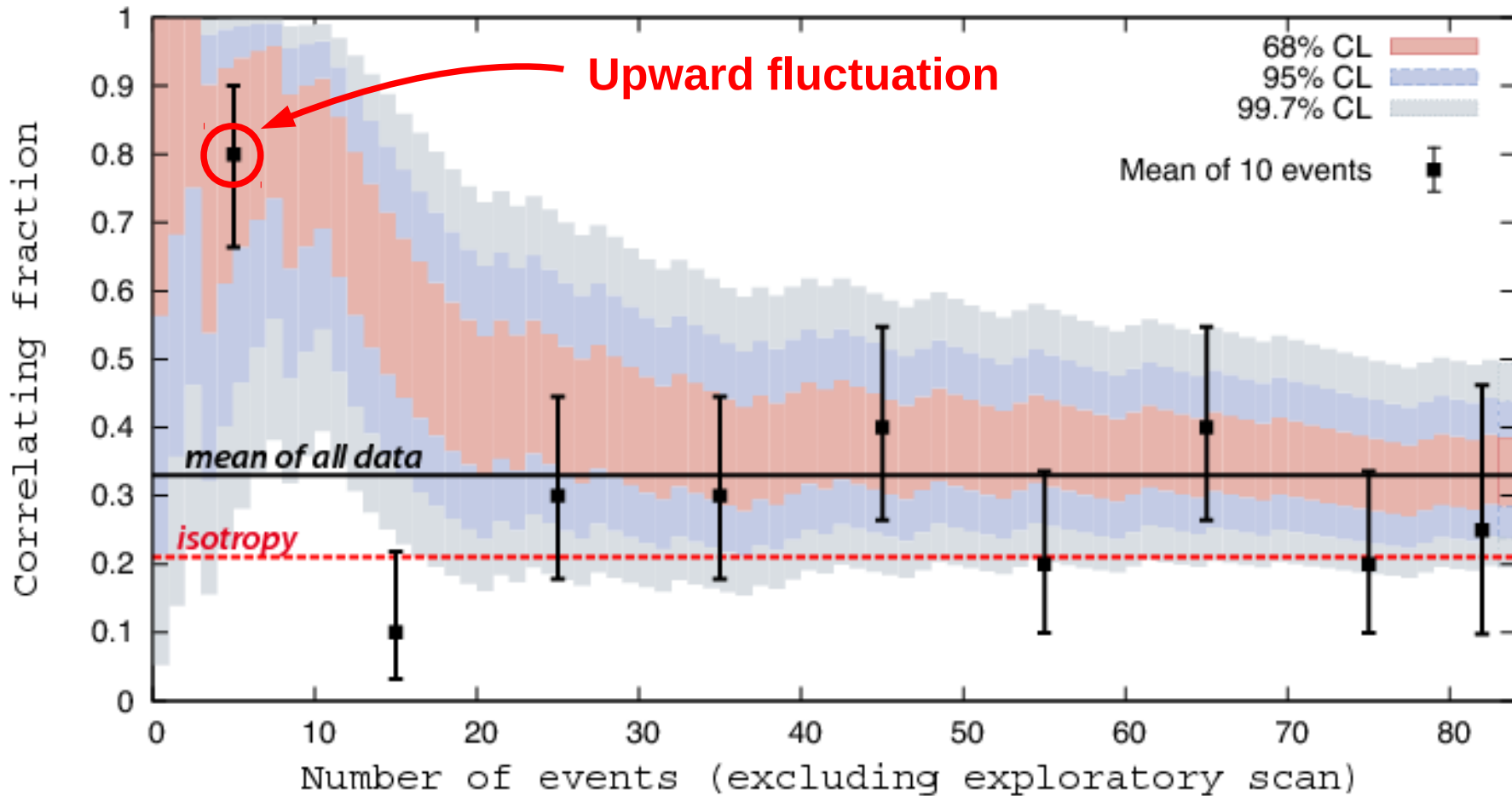


- Auger results are compatible to those of TA and Yakutsk within systematics uncertainties, but not with HiRes
- TA, Yakutsk and HiRes compatible within 5 g cm^{-2}
- Chemical evolution is an unsettled issue



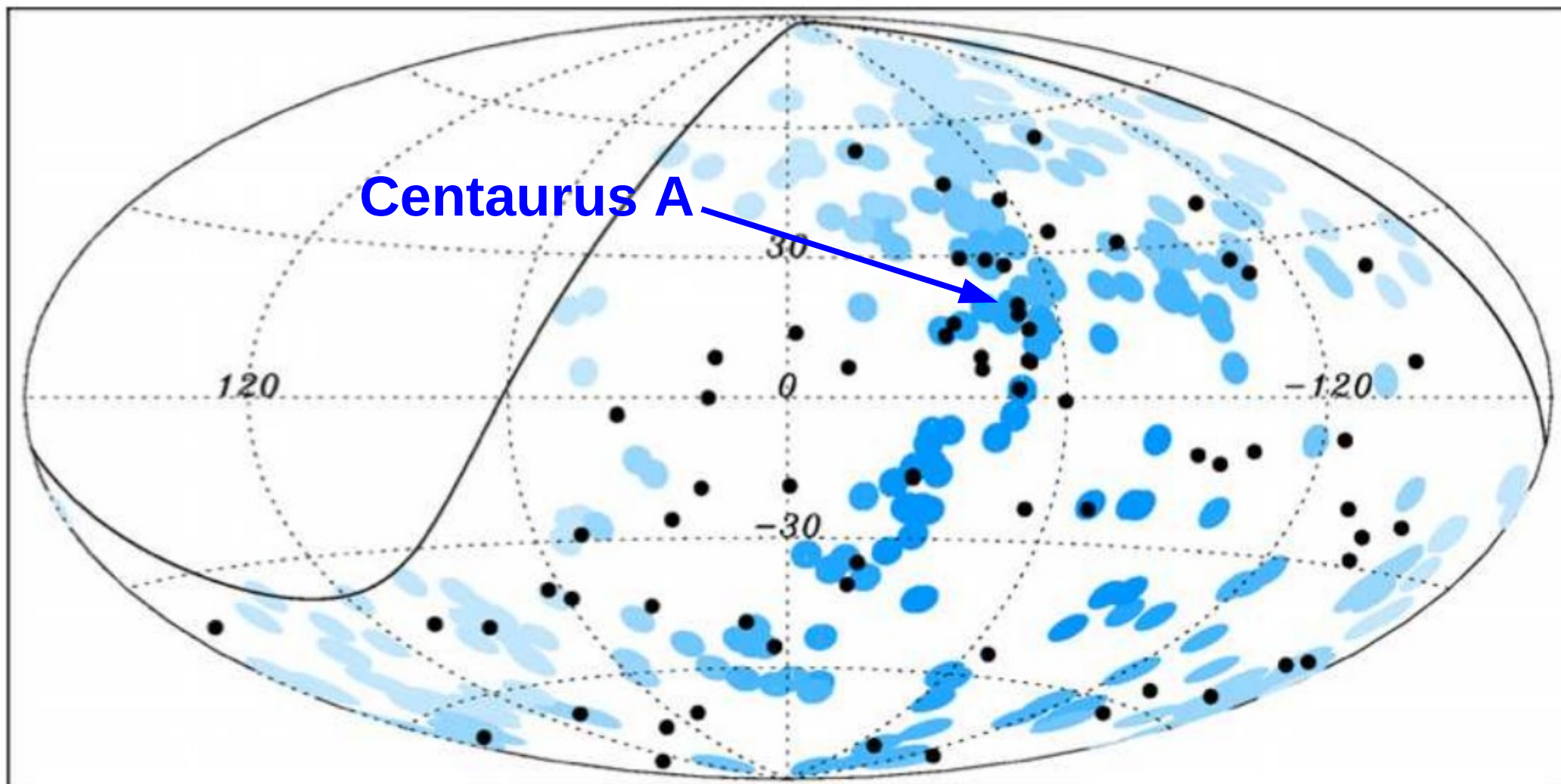
Correlation with point sources

Events above 55 EeV, AGNs within 75 Mpc, angular scale 3.1°.



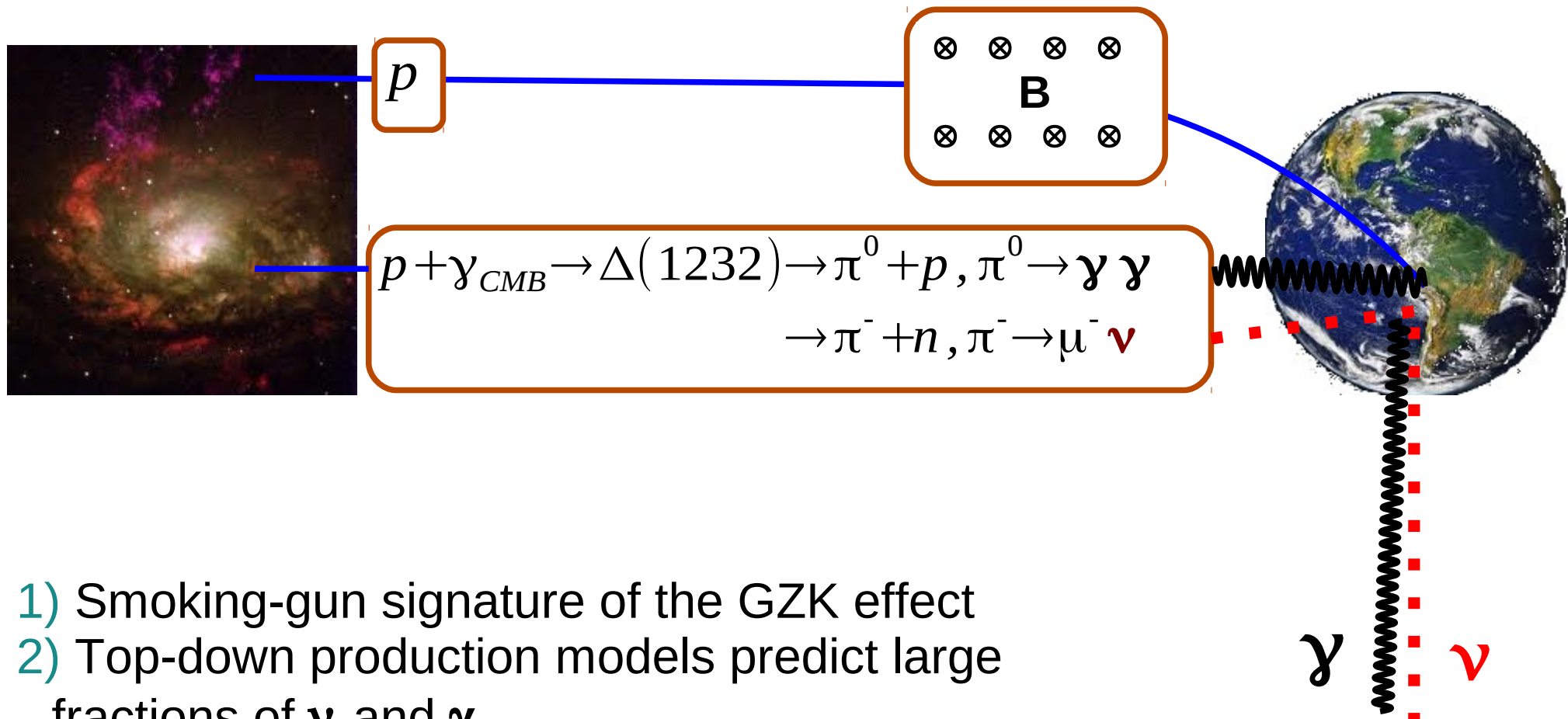
- Correlation $33 \pm 5\%$
- Chance probability from a random distribution $< 1\%$

No “fading” signal (10 events means are consistent)

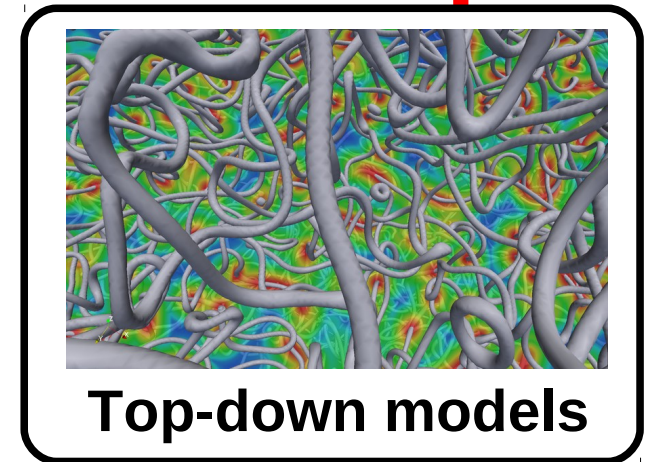


Distribution of the events with $E > 55$ EeV in angular windows of 3.1° around AGNs within 75 Mpc

Photon and neutrino detection

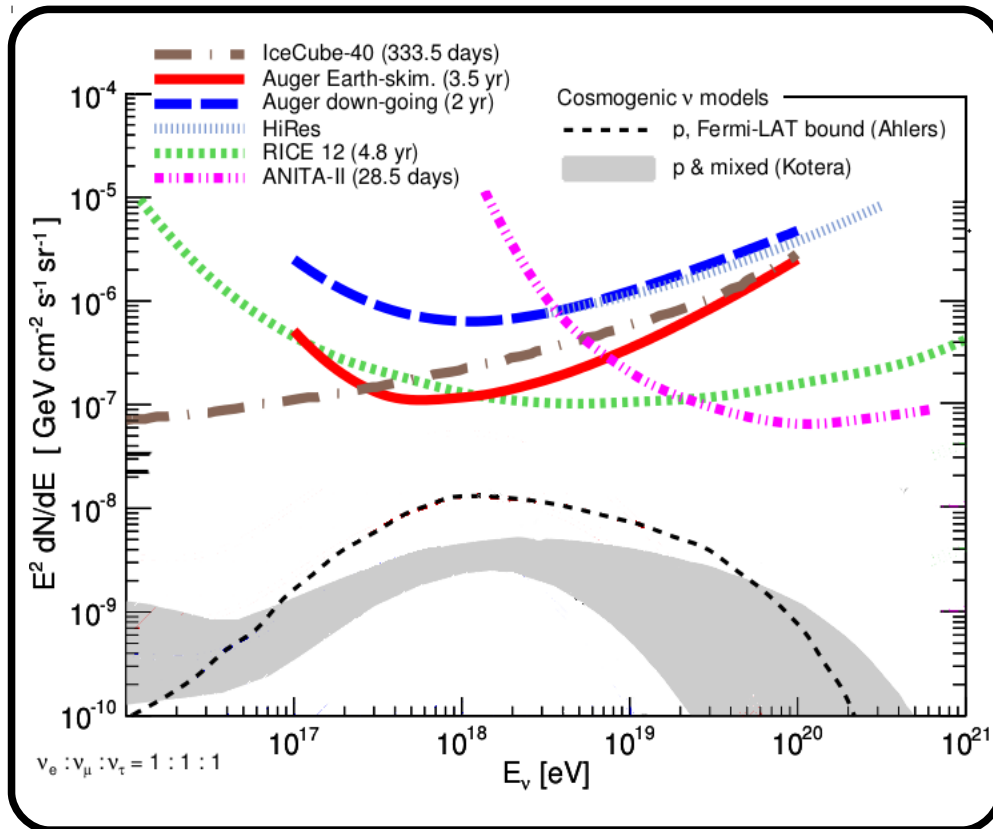


- 1) Smoking-gun signature of the GZK effect
- 2) Top-down production models predict large fractions of ν and γ
- 3) Astrophysics potential: ν and γ travel in straight lines and point to their production sites. Probes of source location and acceleration mechanisms.

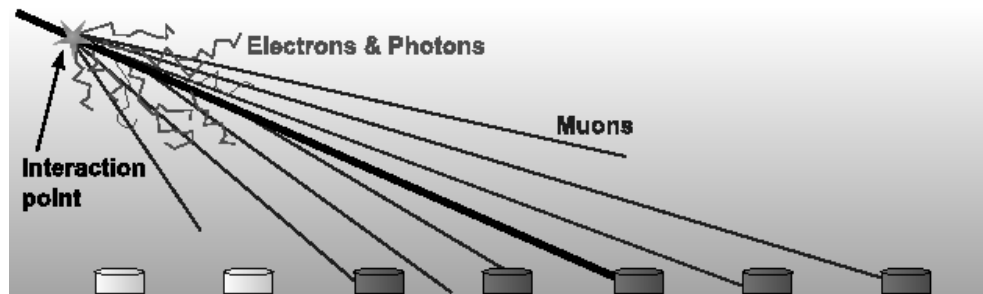


Neutrinos

- No candidates found in the search period
- Upper limit established

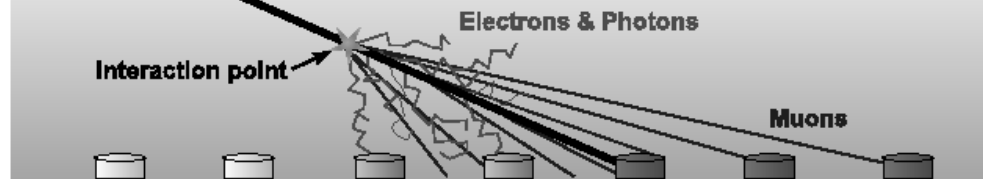


Inclined hadronic shower



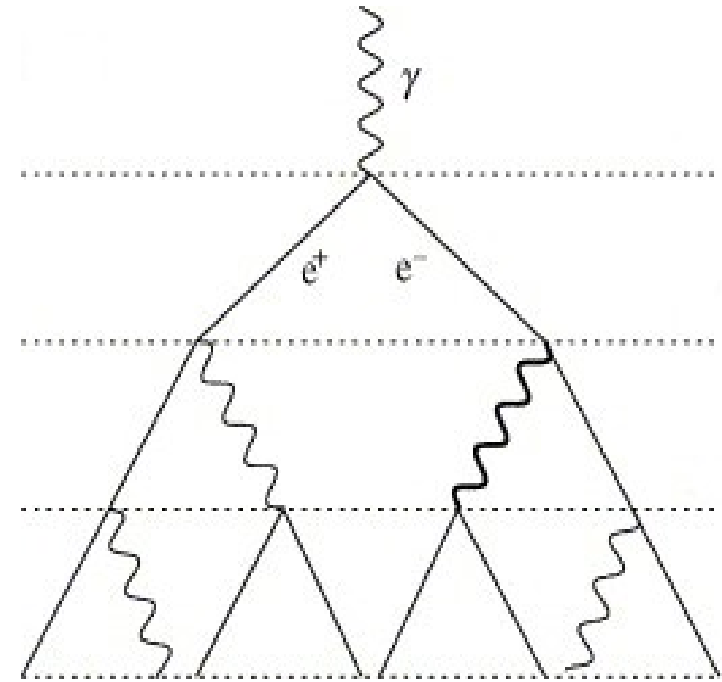
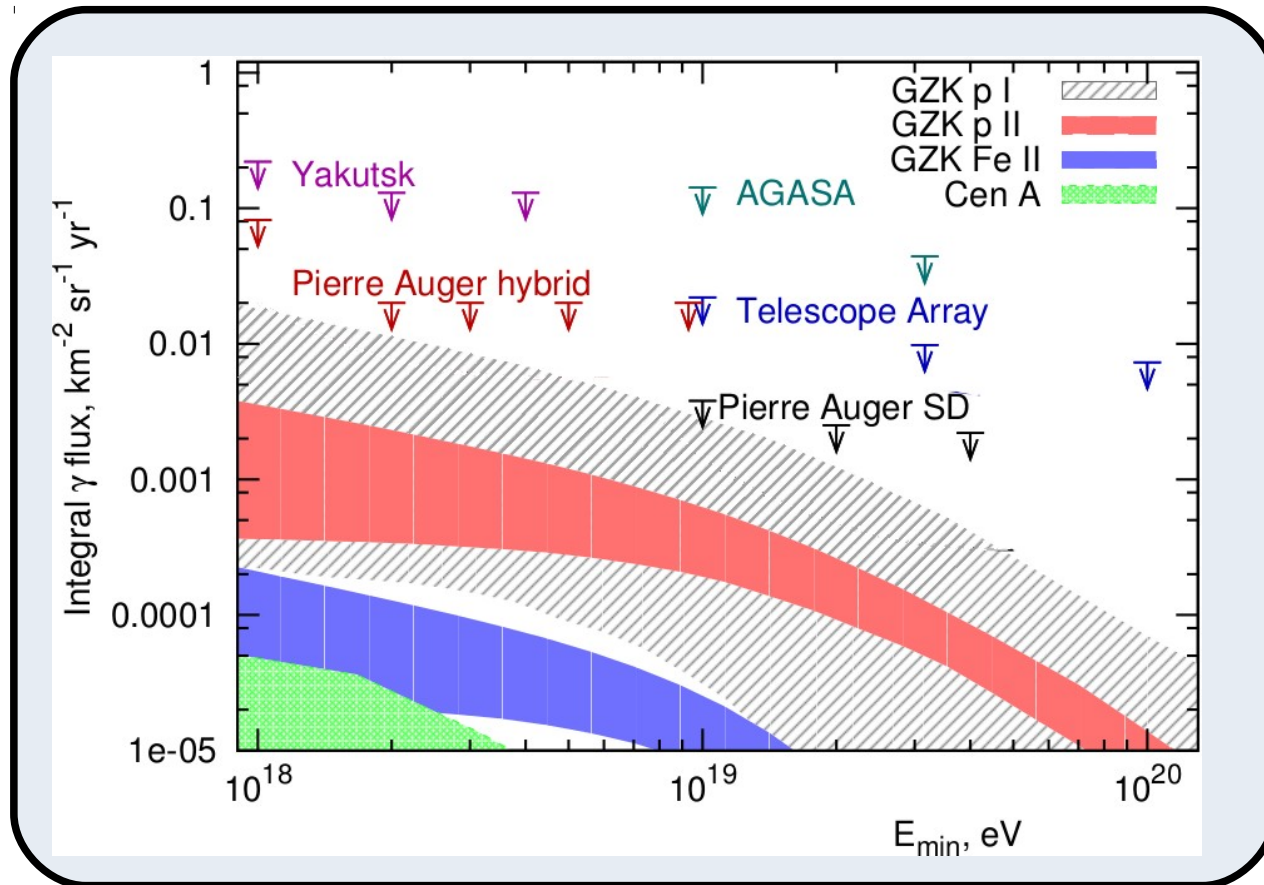
Essentially muons at ground level

Neutrino shower



Electromagnetic-rich inclined showers

Photons

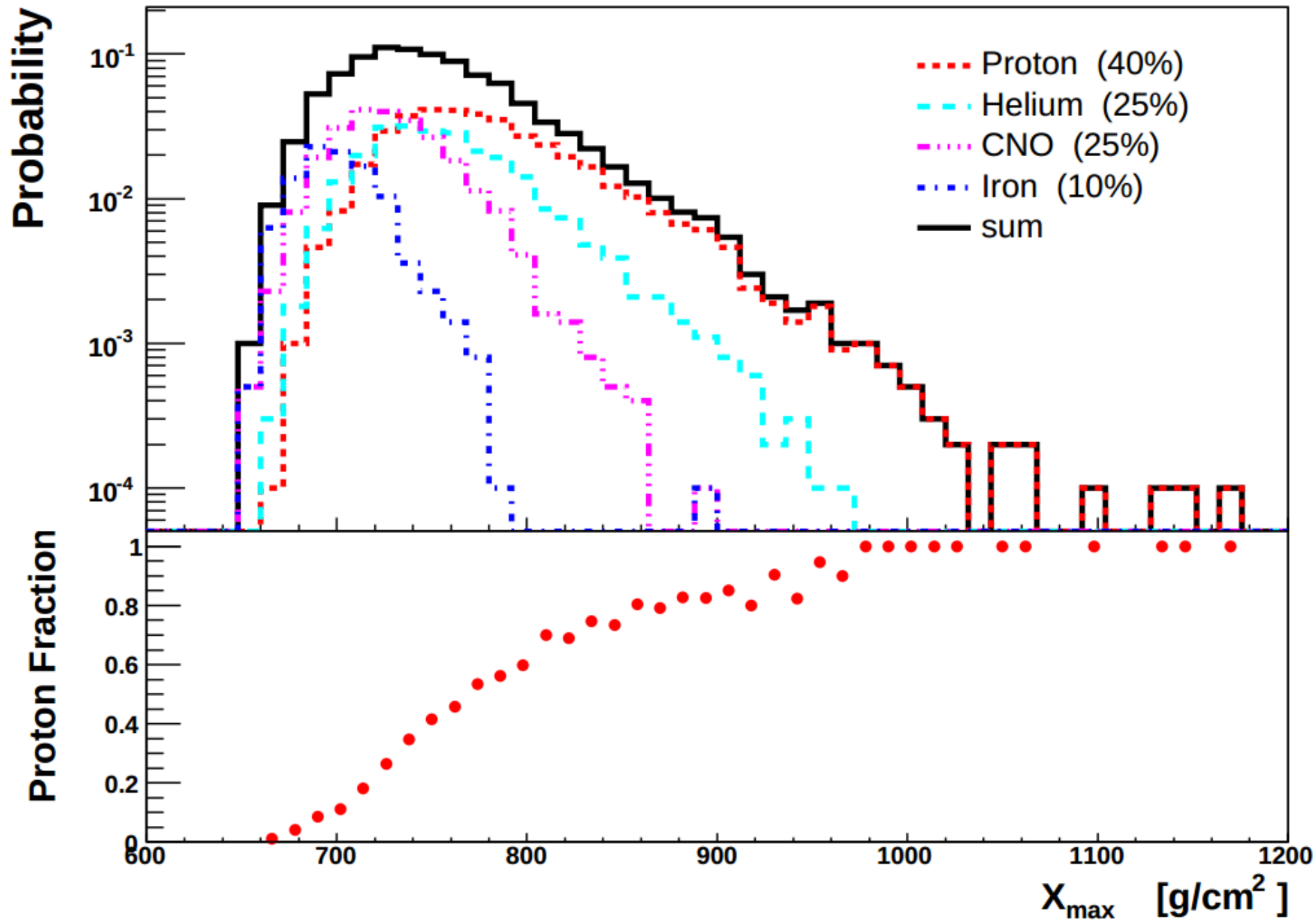


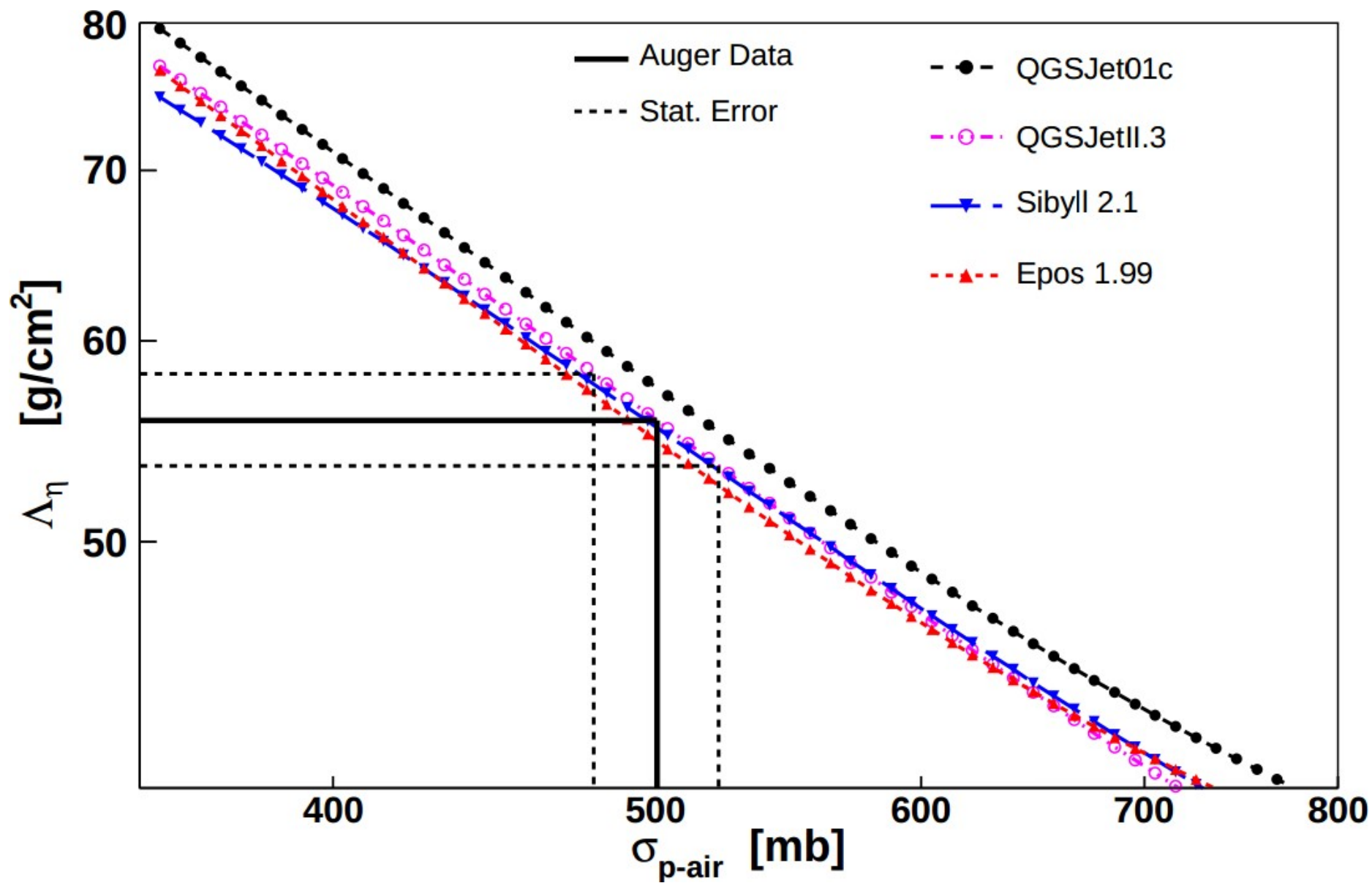
γ -induced showers

- Purely electromagnetic showers
- Deep X_{max}
- Slow shower development
- Large spread of ground signals

- No candidates found in the search period.
- Upper limit established.
- Top-down models very disfavored

From Λ_f to $\sigma_{p\text{-Air}}$: proton fraction-tail slope

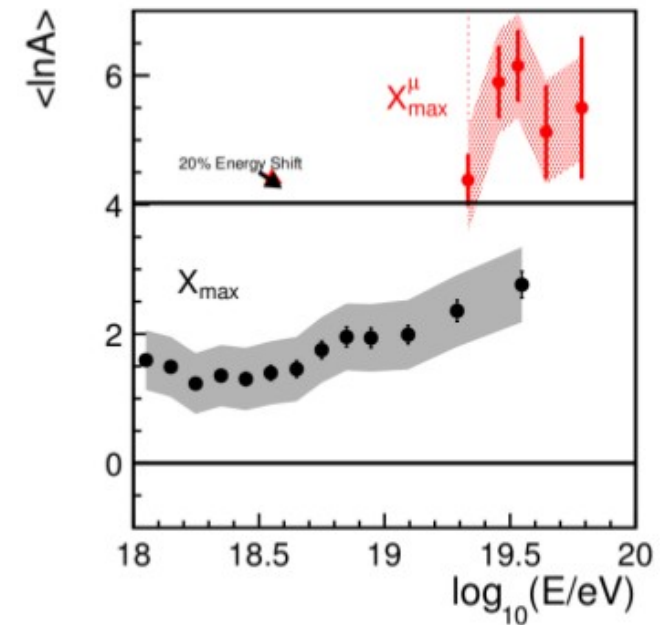


From Λ_f to $\sigma_{p\text{-Air}}$ 

New hadronic models

- Change in hadronic models changes the simulation of shower development and hence CR results.
- But consistency of CR results constrains hadronic models as well.

LHC EPOS



QGSJETII04

