RECENT RESULTS FROM THE PIERRE AUGER OBSERVATORY

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II Russian-Spanish Congress Particle and Nuclear Physics at all Scales and Cosmology
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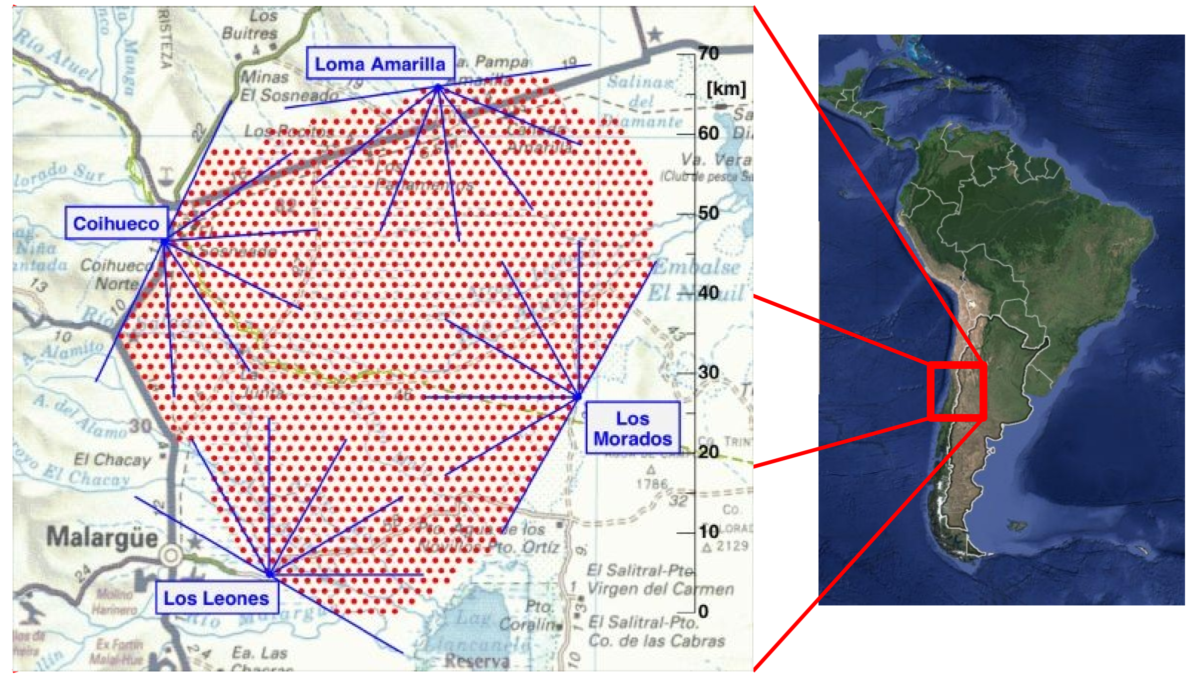
The Pierre Auger Observatory

- Malargüe, Argentina
- World's largest cosmic ray observatory.
- In operation since 2004. Completed in 2008
- 3000 km^2



Main goal:

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

Physics:

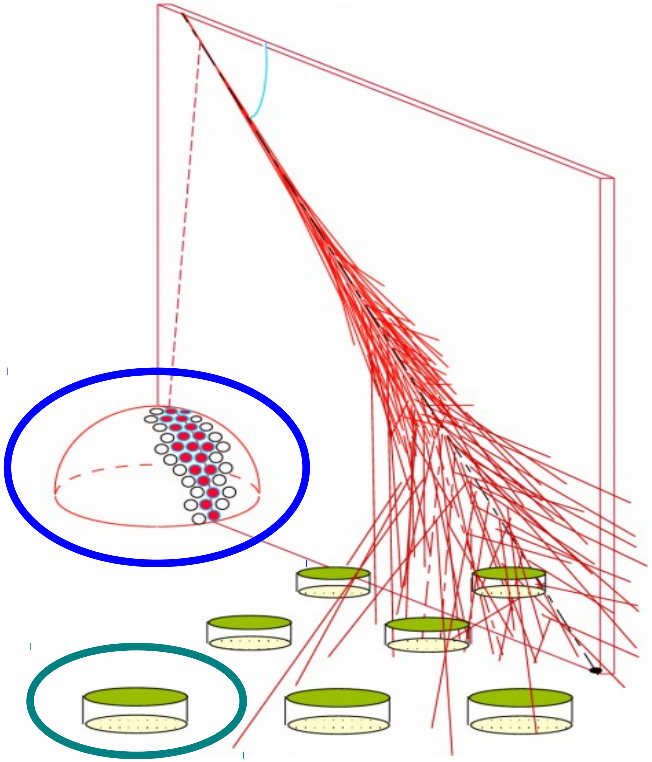
- Energy Spectrum
- Composition
- Photon and neutrino searches
- Hadronic Physics
- Anisotropies and point sources

496 members
94 institutions
18 countries

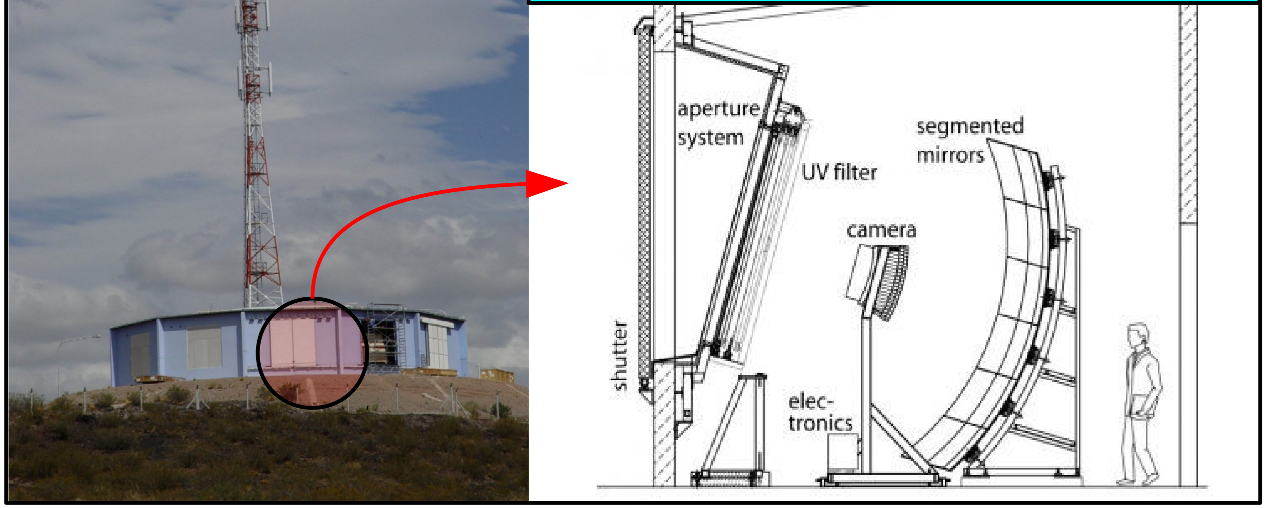
The Observatory: Hybrid detector

Hybrid detector:
fluorescence +surface detectors

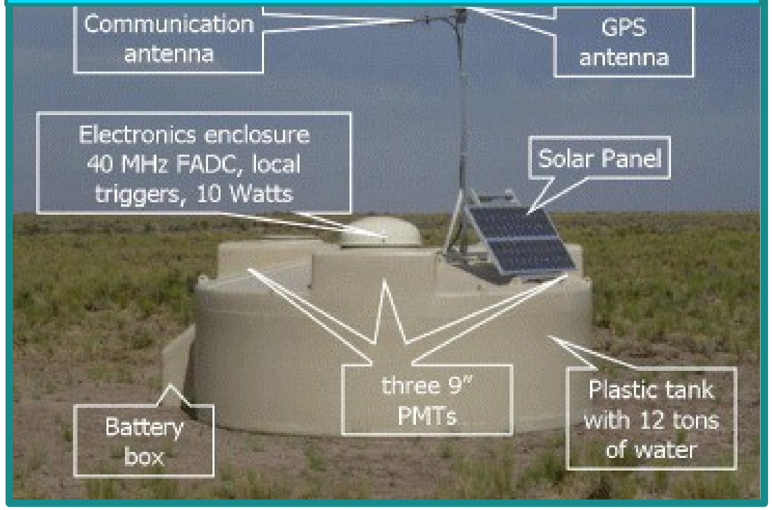
Independent and complementary:
- Improved geometrical reconstruction with respect to individual components
- Cross-calibration between detectors
- Observation of different shower components



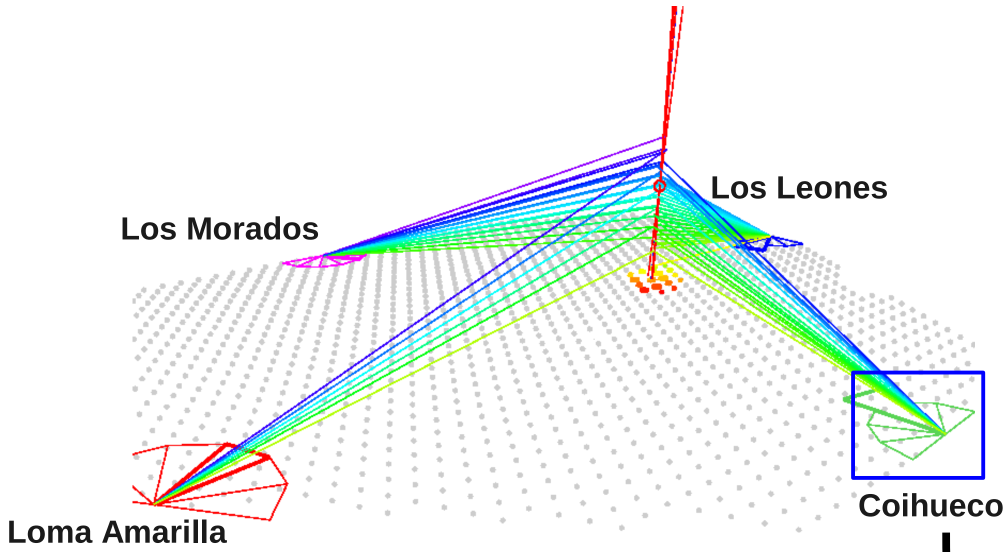
24 fluorescence telescopes at 4 sites



More than 1600 Water-Cherenkov tanks

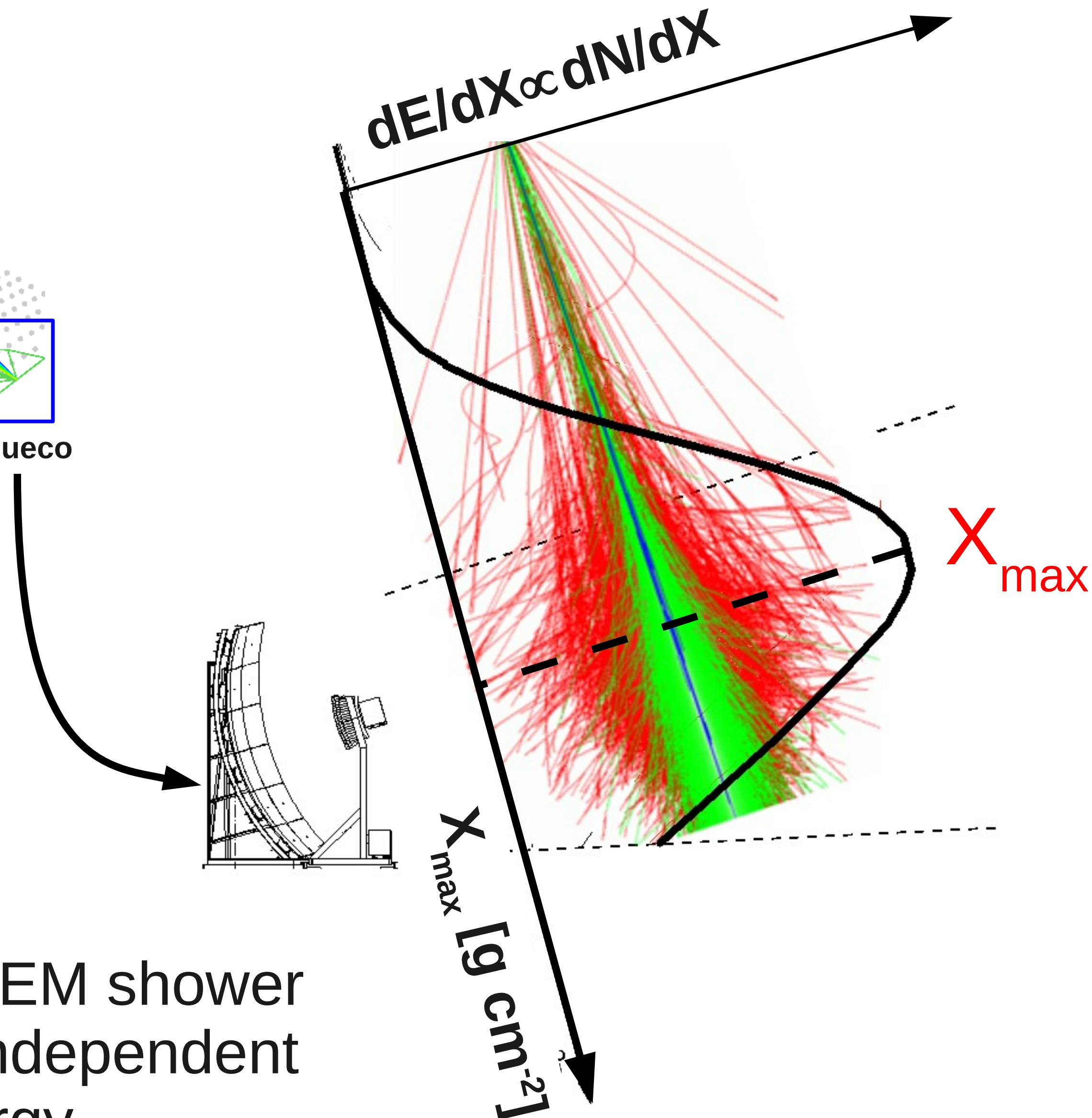


Air shower reconstruction: FD



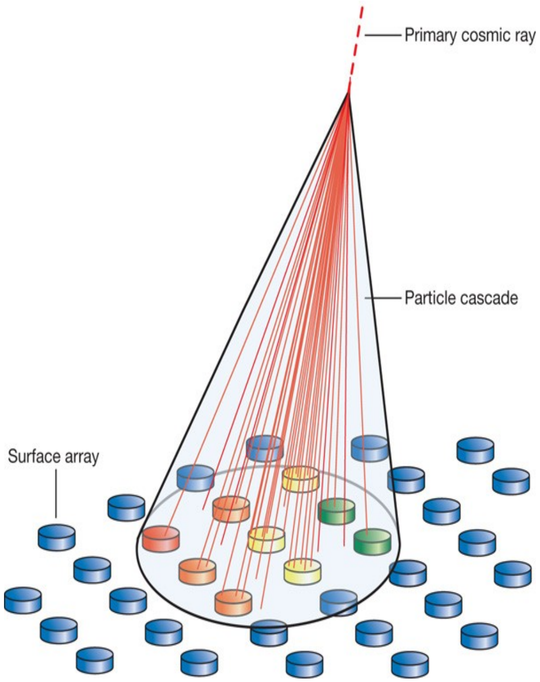
$$E_{FD}^{cal} = \int \frac{dE}{dX} dX$$

$$E_{FD}^{total} = E_{FD}^{cal} \times f_{inv}$$

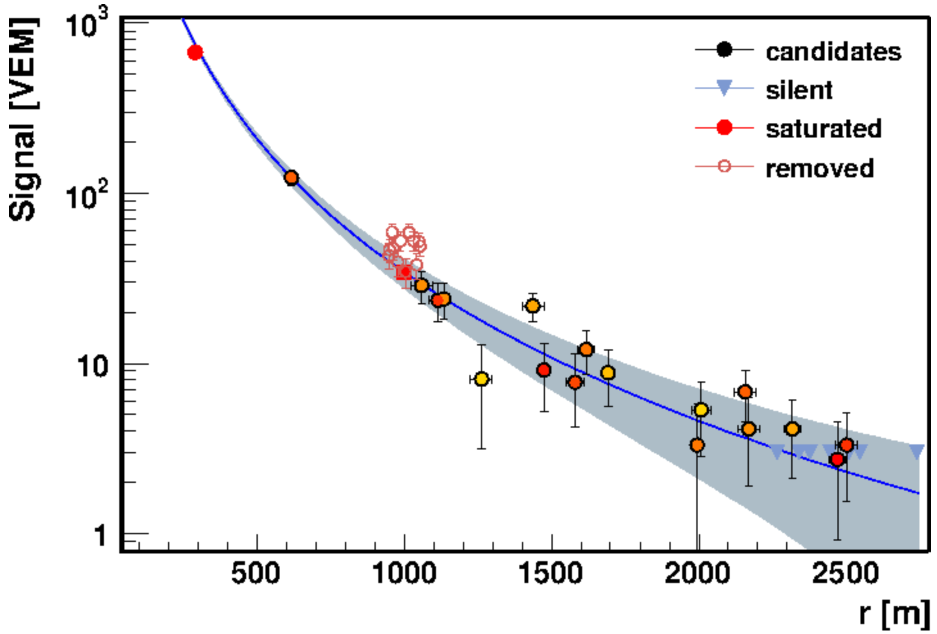


- Longitudinal development of EM shower
- Calorimetric, almost model-independent determination of shower energy
- "Invisible" energy (f_{inv}) carried by ν and HE μ (<10%)

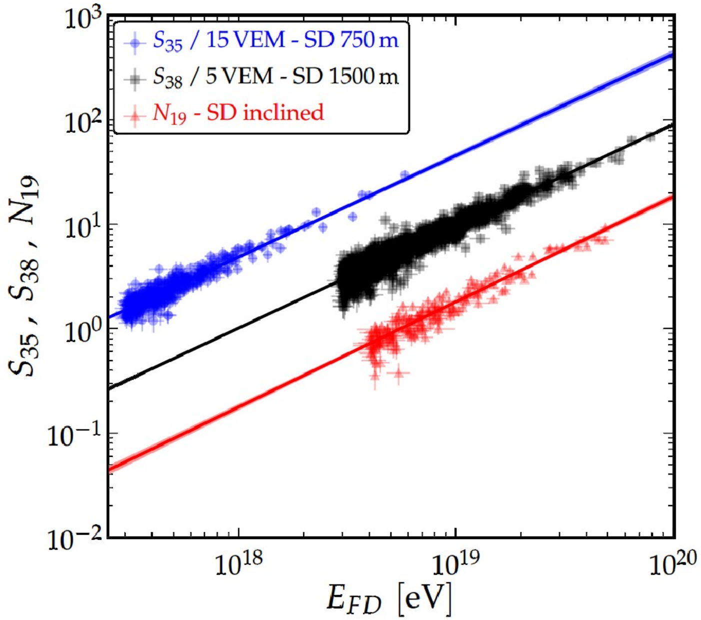
Air shower reconstruction: SD



tank signal vs tank distance



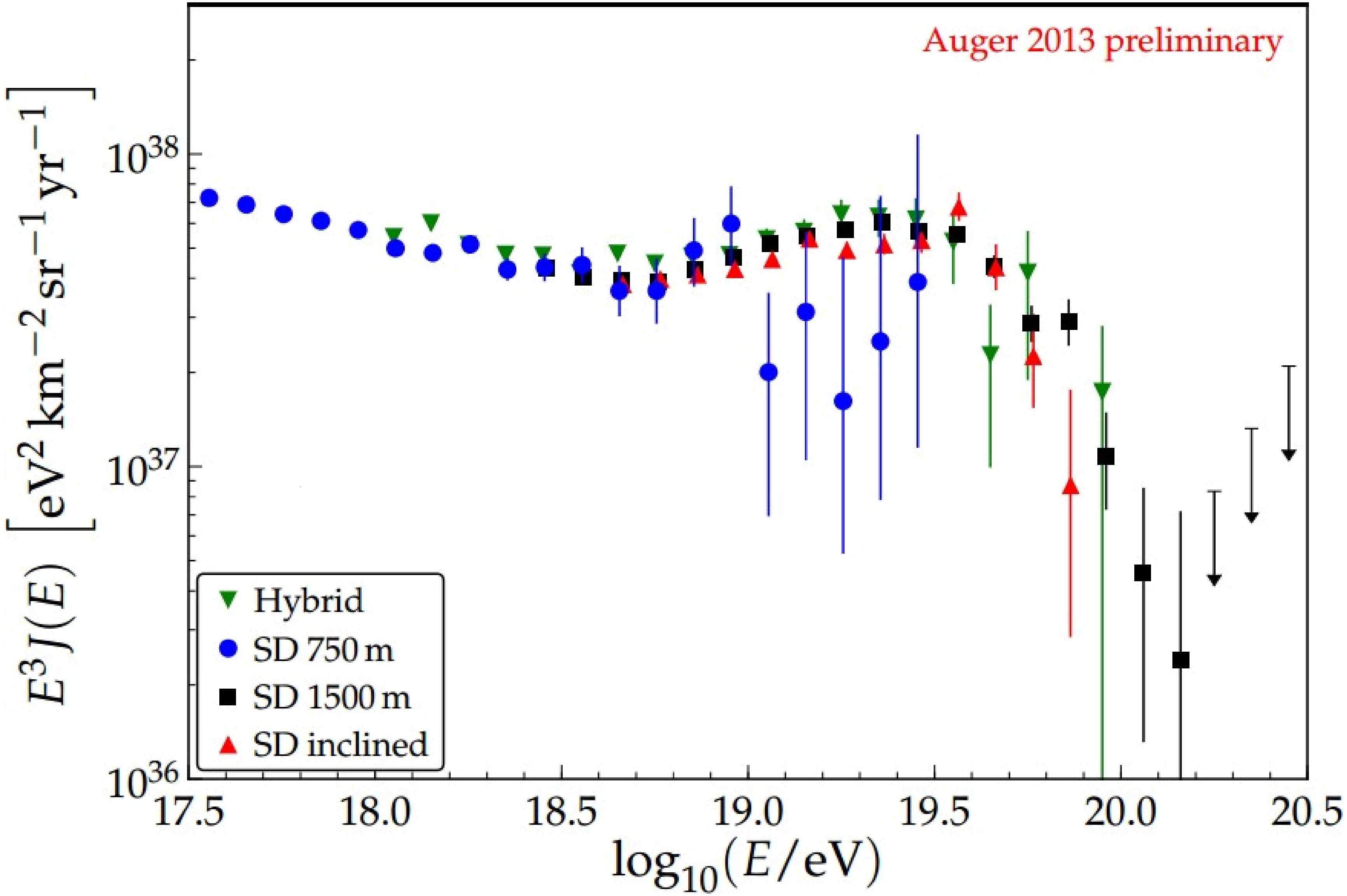
- SD energy obtained calibrating with the FD
- Different SD regimes → different calibrations
- All SD observables show a good correlation with the FD



The Spectrum of UHE

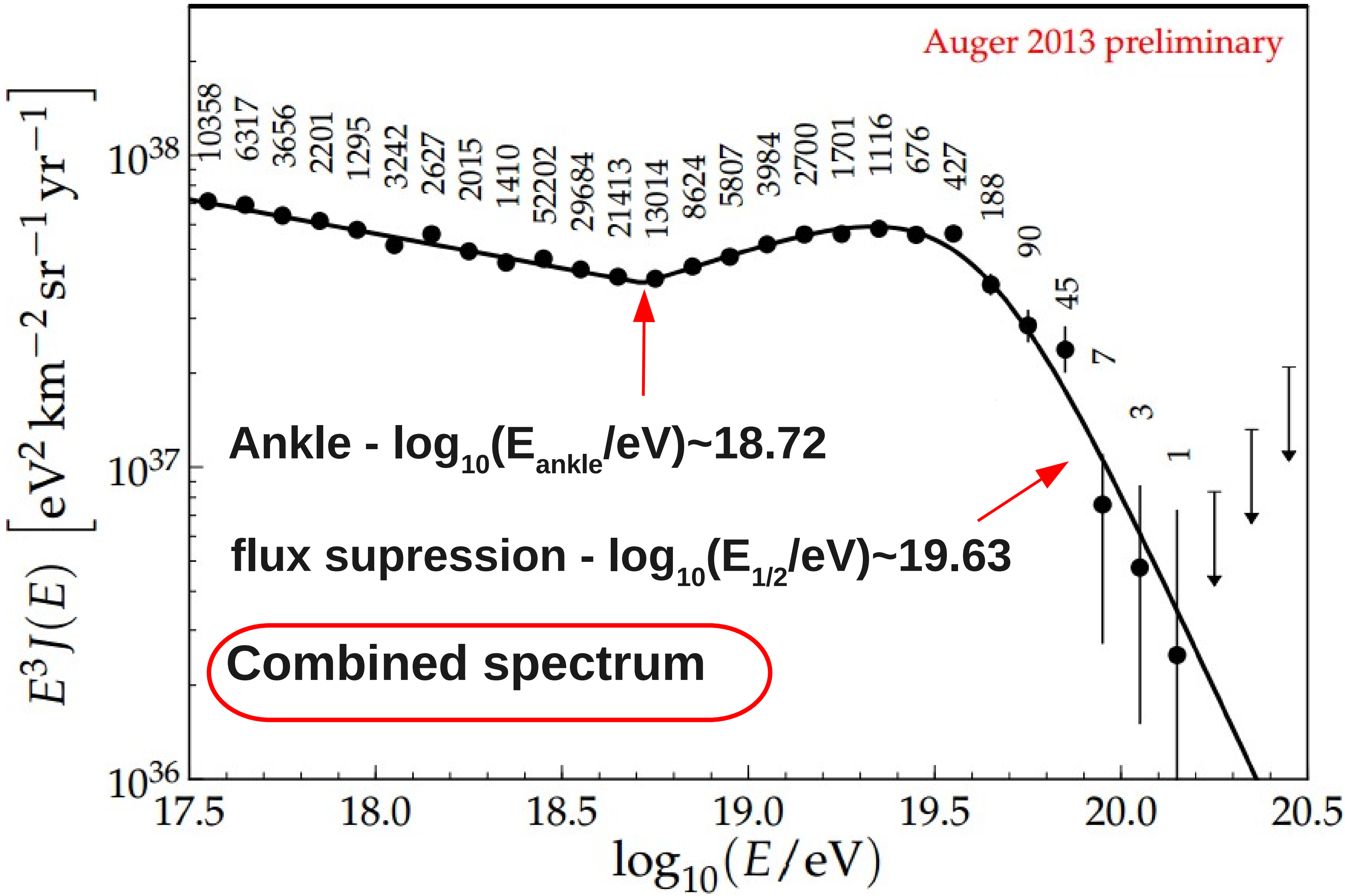
4 independent measurements using SD and FD:

- Standard SD array (θ<60º) (■)
- Infill array (750m) (●)
- Inclined events (60º<θ<80º) (▲)
- Hybrid events (FD+≥1SD) (▼)



The Spectrum of UHE

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



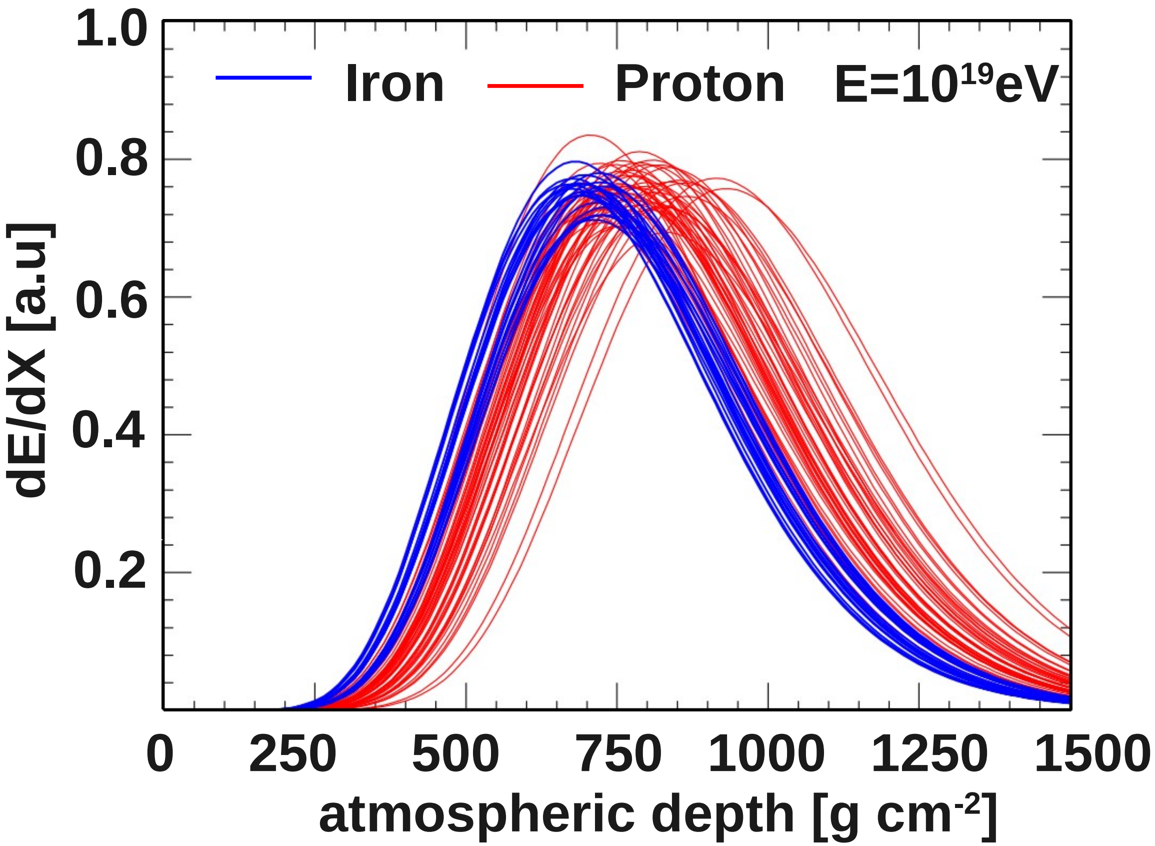
Mass composition

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)

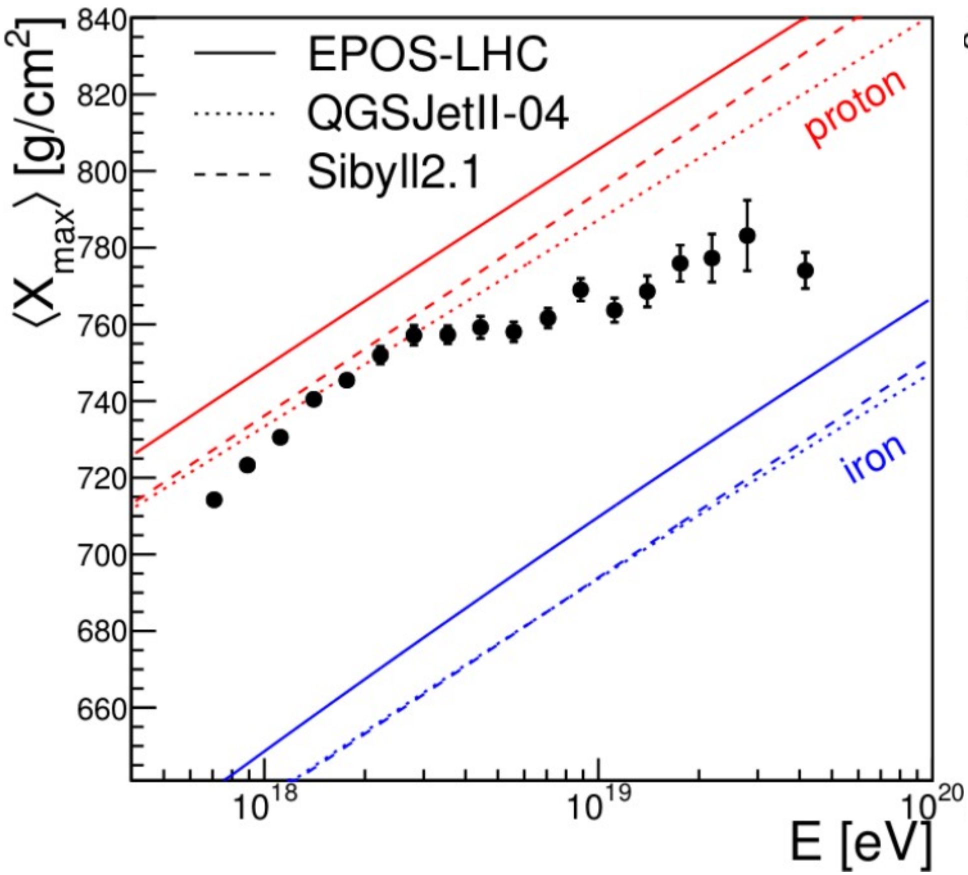
FD
maximum of the EM profile

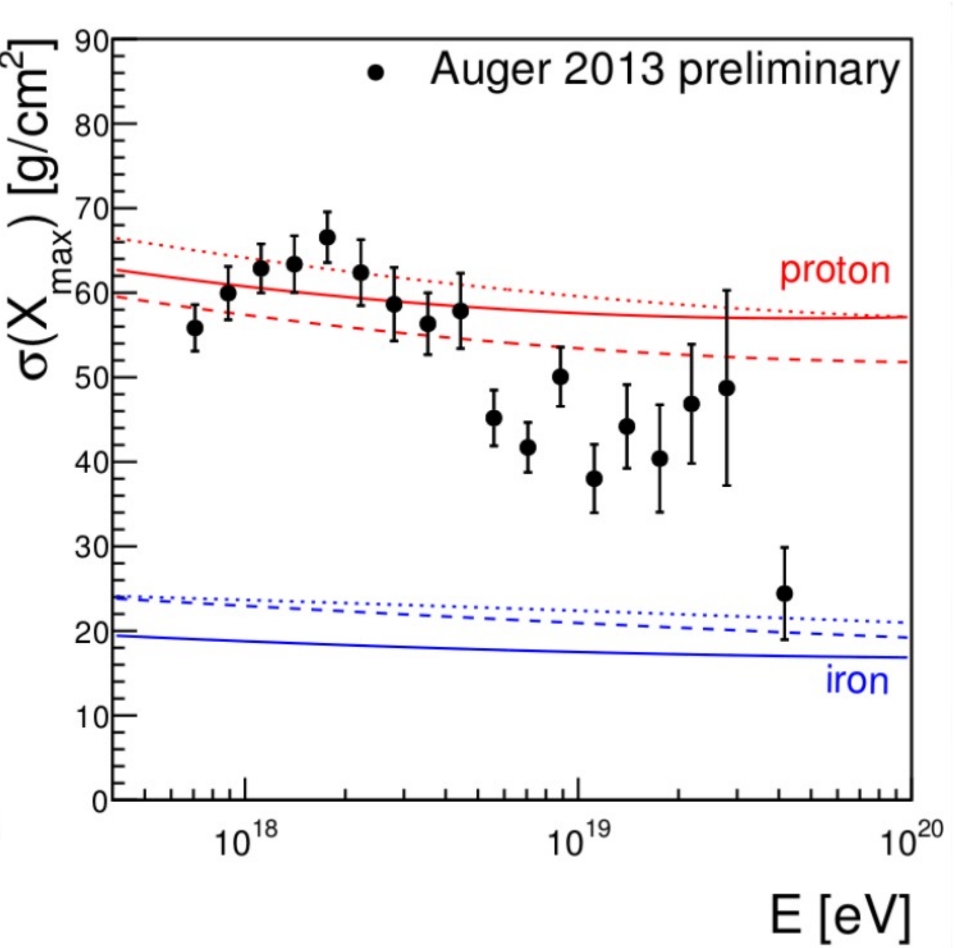
SD
maximum of the Muon Production Depth (MPD)



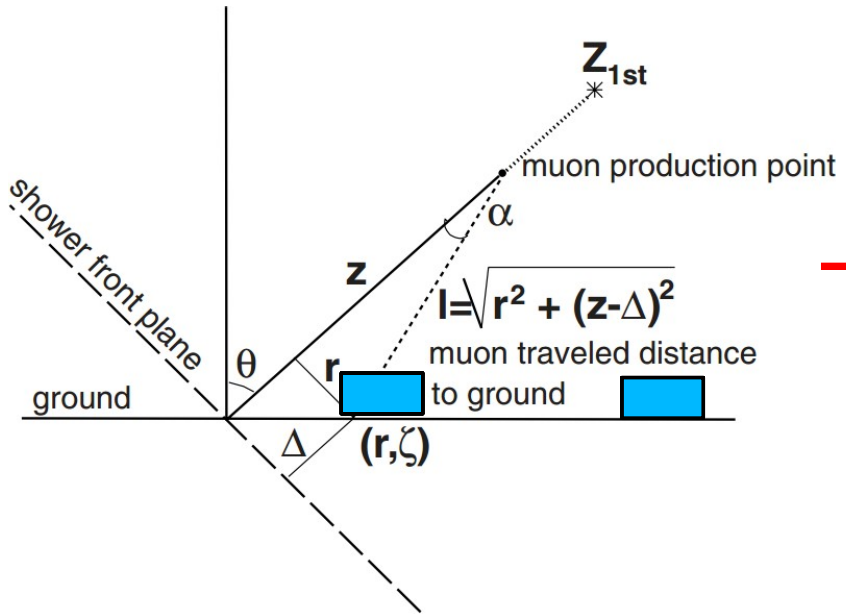
Mass composition: <X_{max}> and RMS(X_{max})

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





Mass composition: MPD

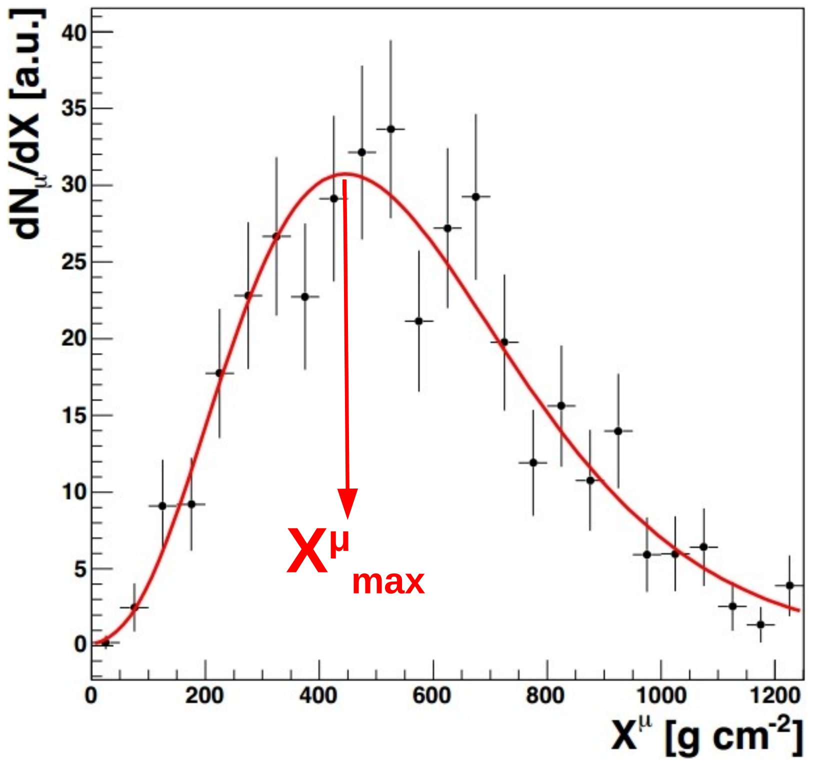


Arrival time → production depth

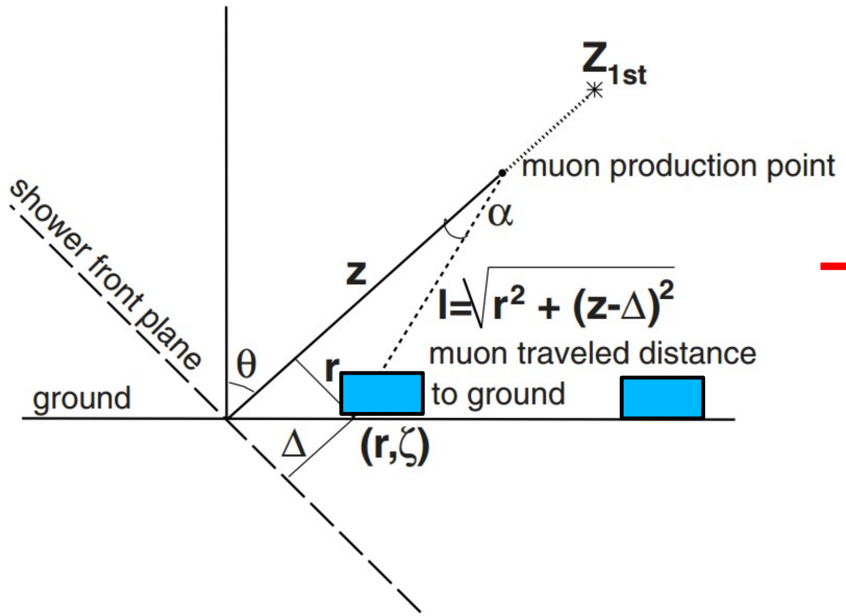
$$z = \frac{1}{2}\left(\frac{r^2}{c\,t_g} - c\,t_g\right) + \Delta$$

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

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



Mass composition: MPD



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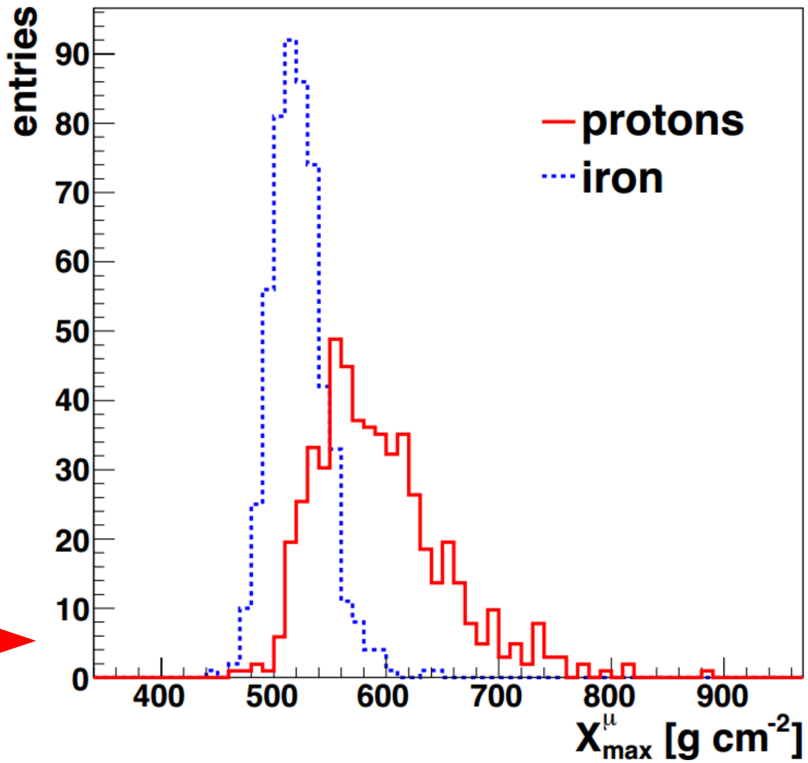
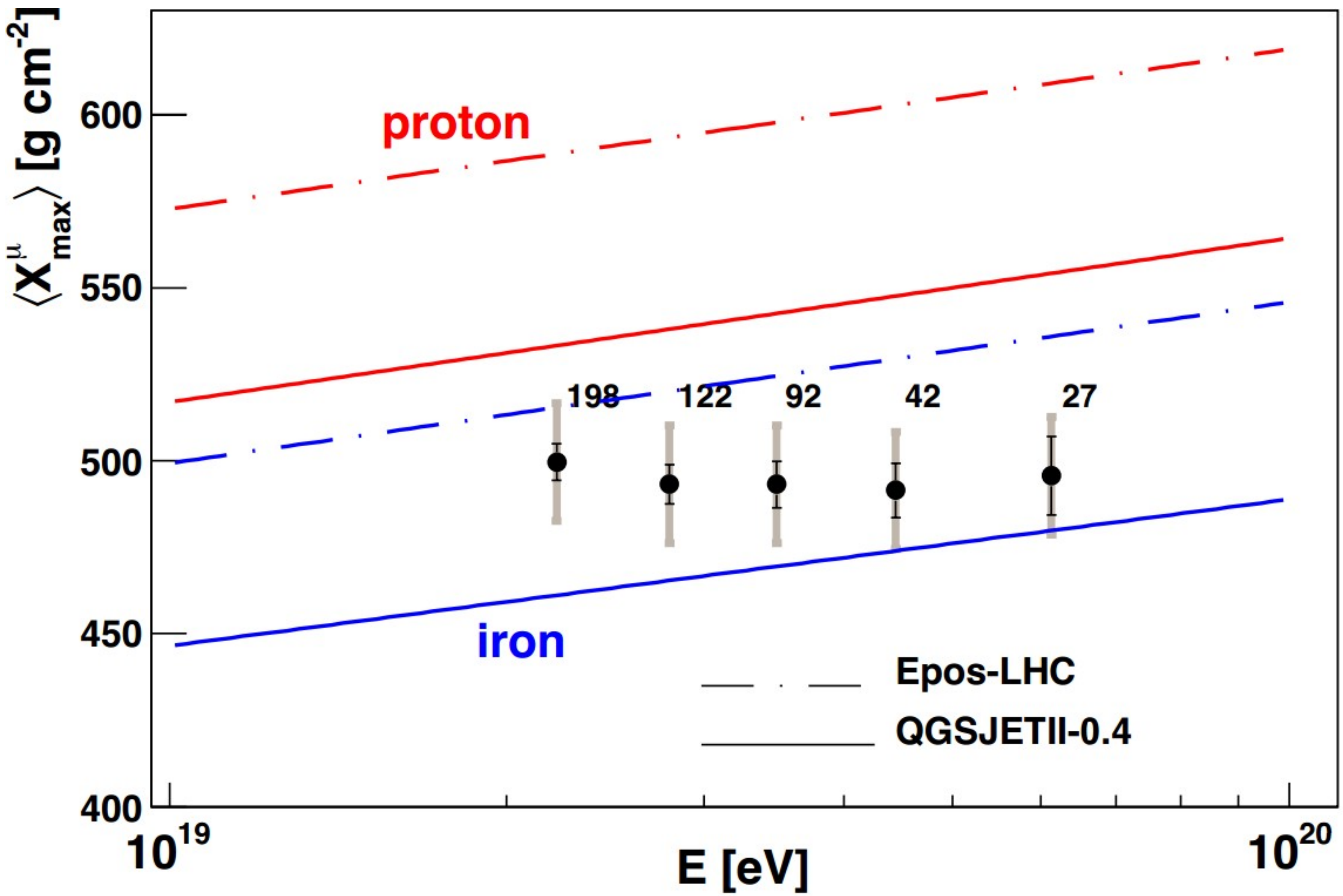
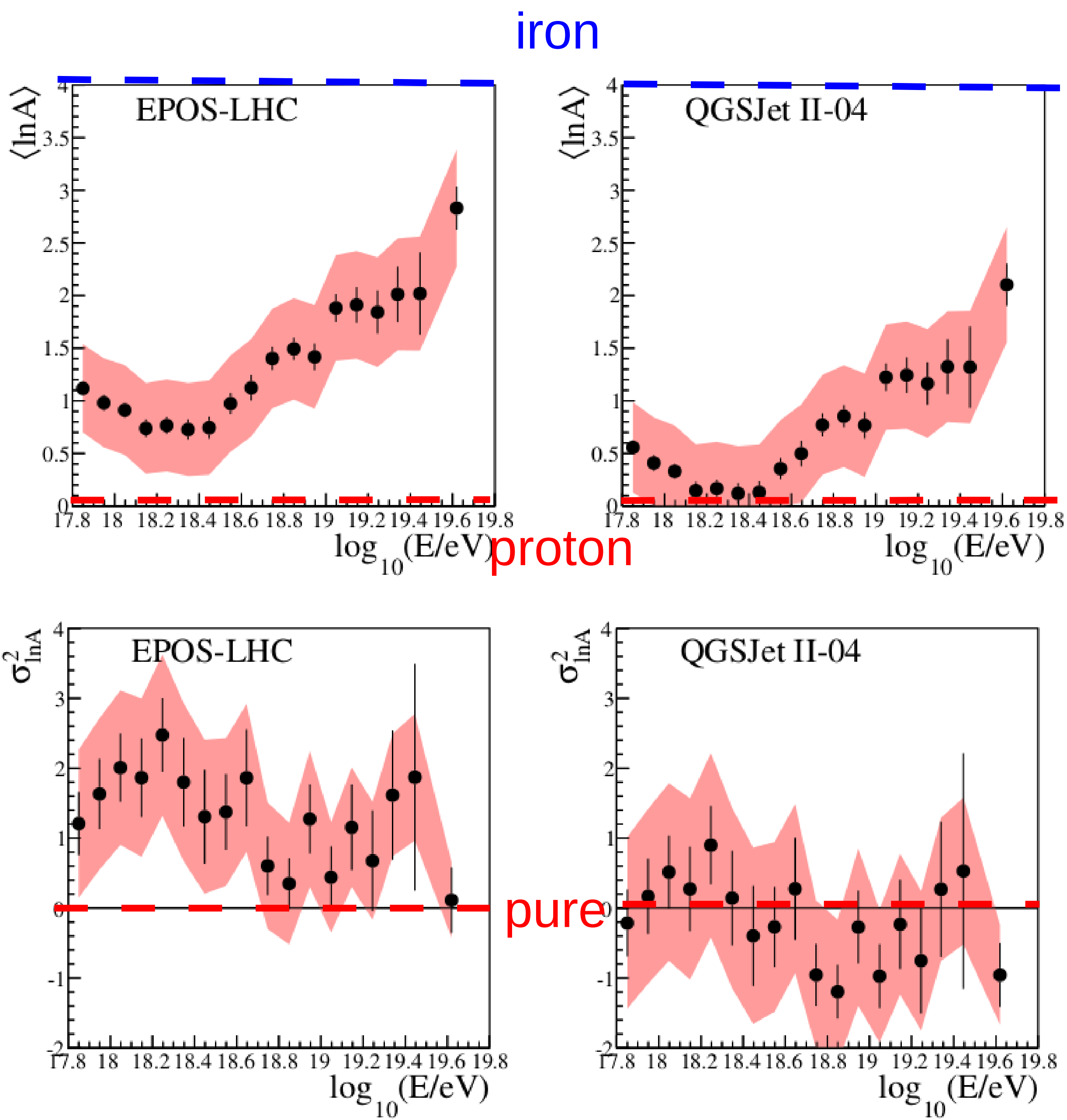


Mass composition: MPD



- ✔ SD observable independent of X_{max}.
- ✔ Additional insight into hadronic models (muon production)
- ✗ Small zenith and energy window: θ⊂[55º,65º]

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



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

Uncertainties in hadronic interactions at UHE hinder the interpretation:

- increase on mean mass?, or
- inedaquate interaction models?

Improve CR measurements

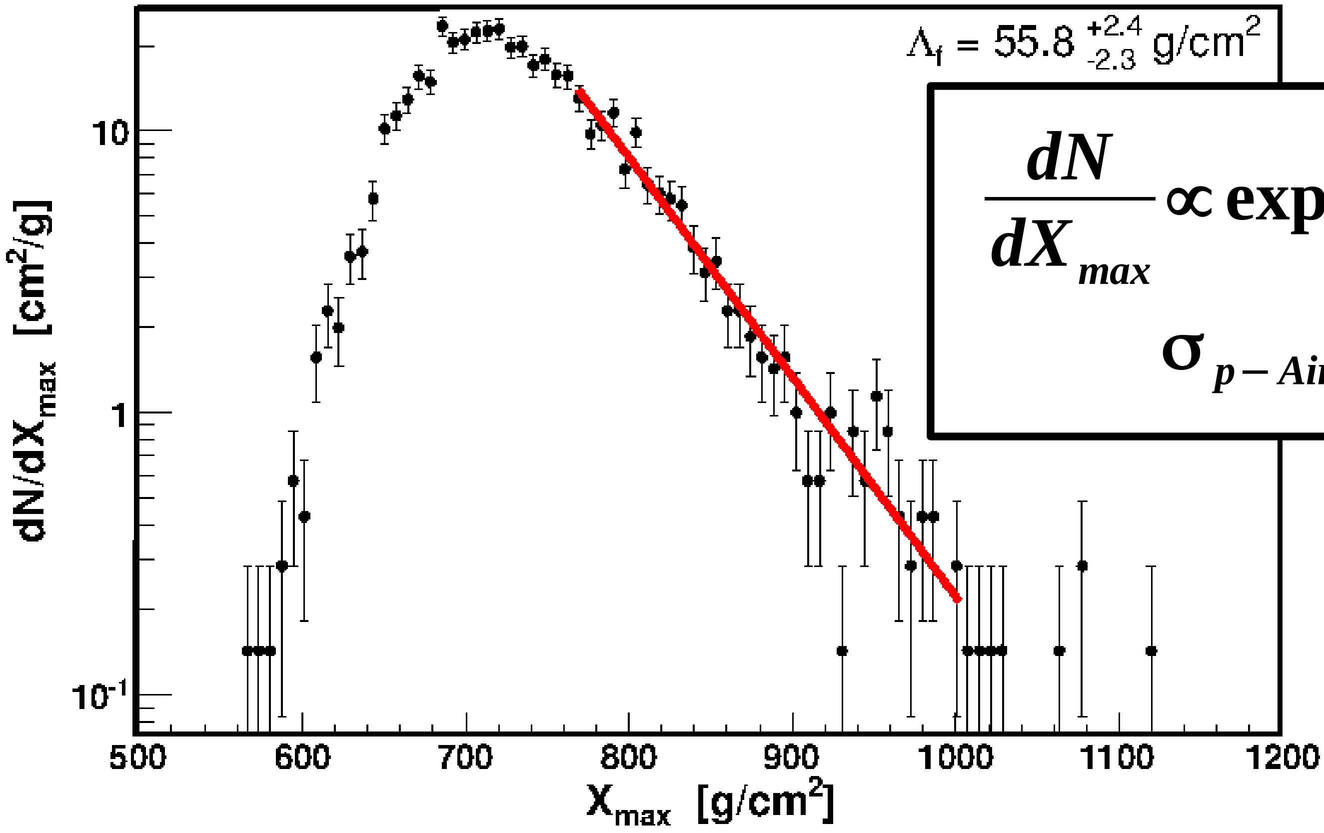
↓

Constraint hadronic models

↓

Improve CR interpretation

Hadronic interactions

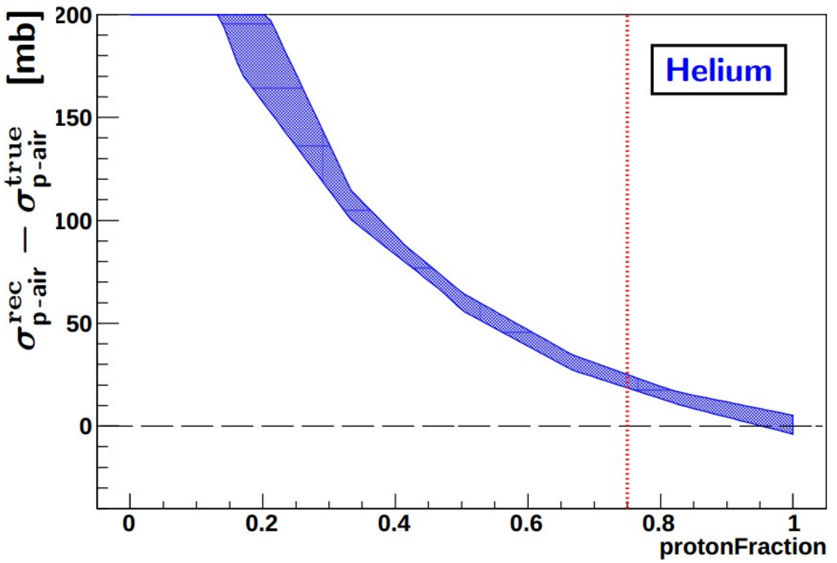


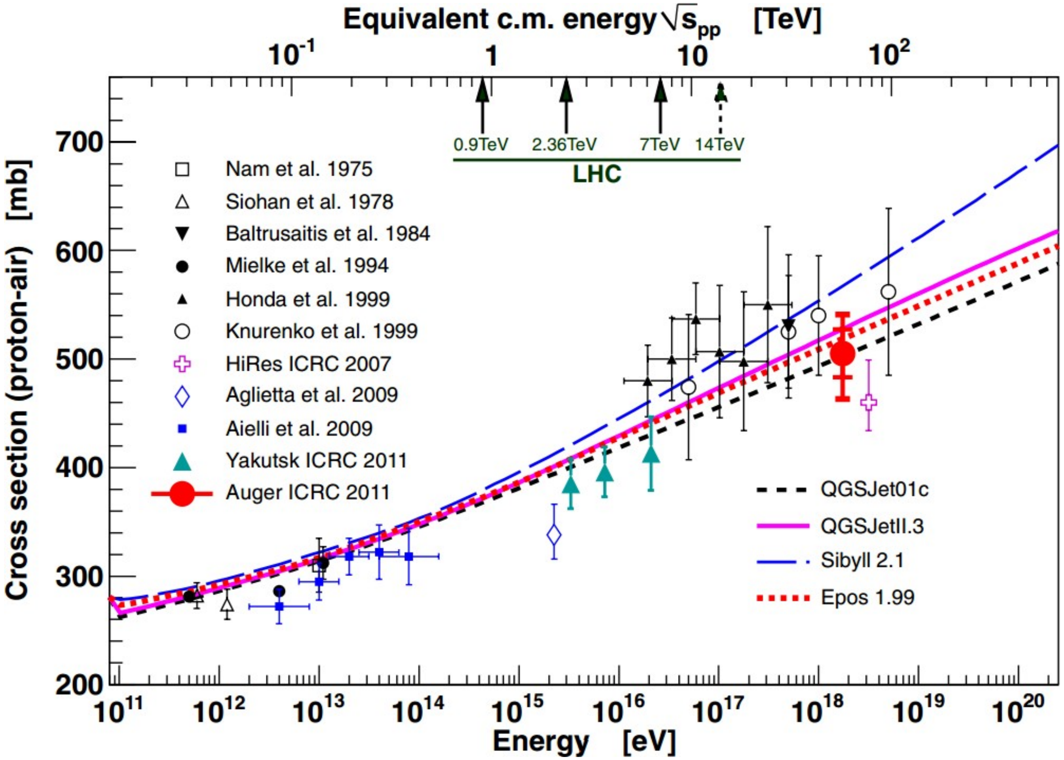
$$\frac{dN}{dX_{max}} \propto \exp(-X_{max}/\Lambda_f)$$

$$\sigma_{p-Air} \propto \Lambda_f^{-1}$$

f chosen so that biases from a $He_{frac} \leq 25\%$ 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)

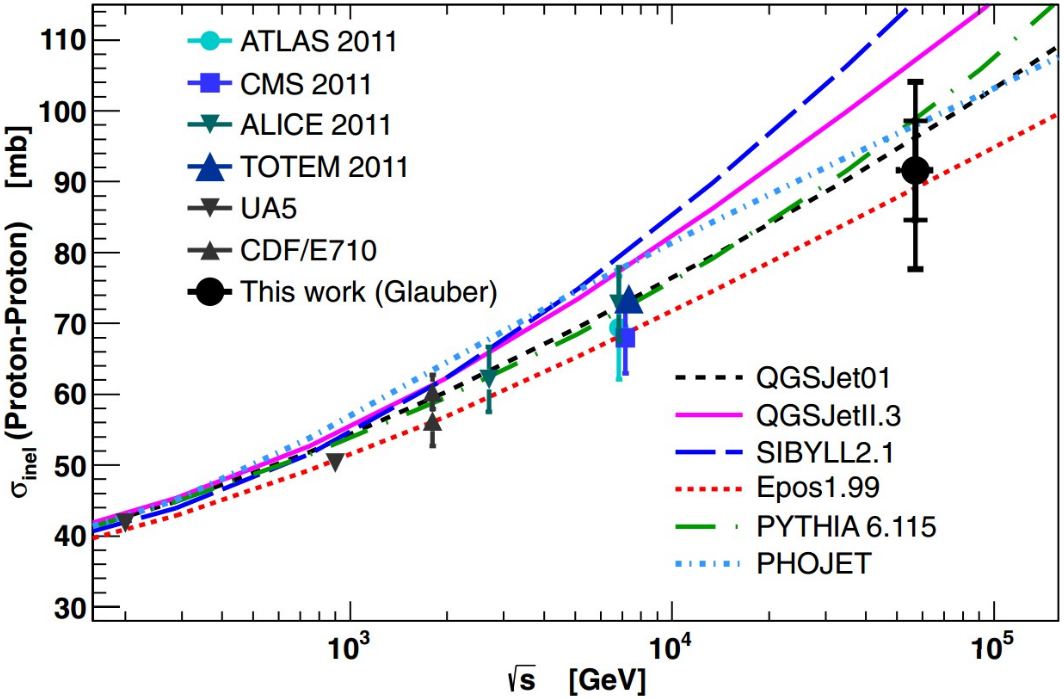




$$\sigma^{prod}_{p\text{-}Air} = [505 \pm 22(stat)^{+28}_{-36}(sys)]\,mb$$

Extended Glauber model + propagation of param. uncertainties

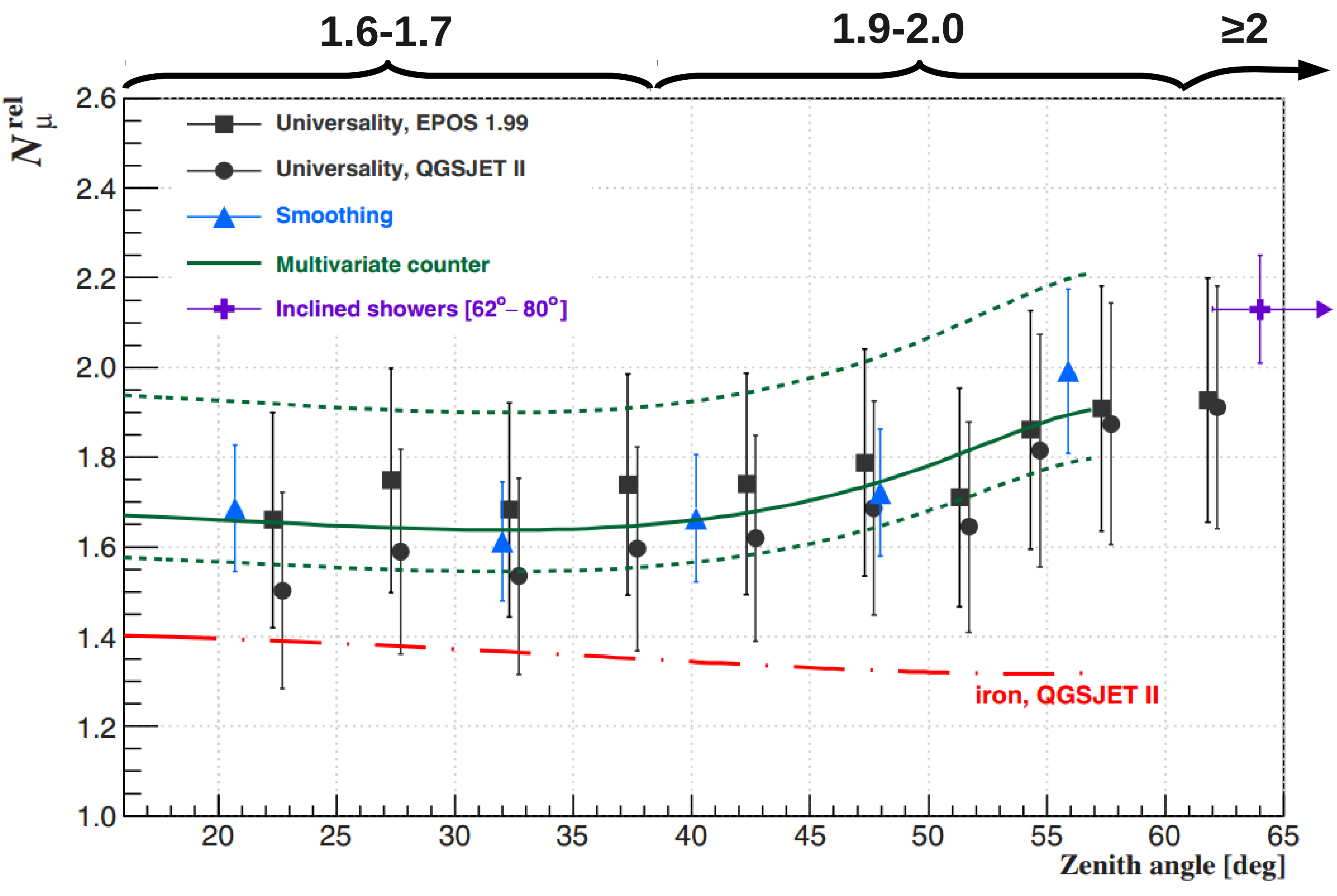
$$\sigma^{inel}_{pp} = 92 \pm 7(stat)^{+9}_{-11}(sys) \pm 7(Glauber)\,mb$$



- ✔ 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

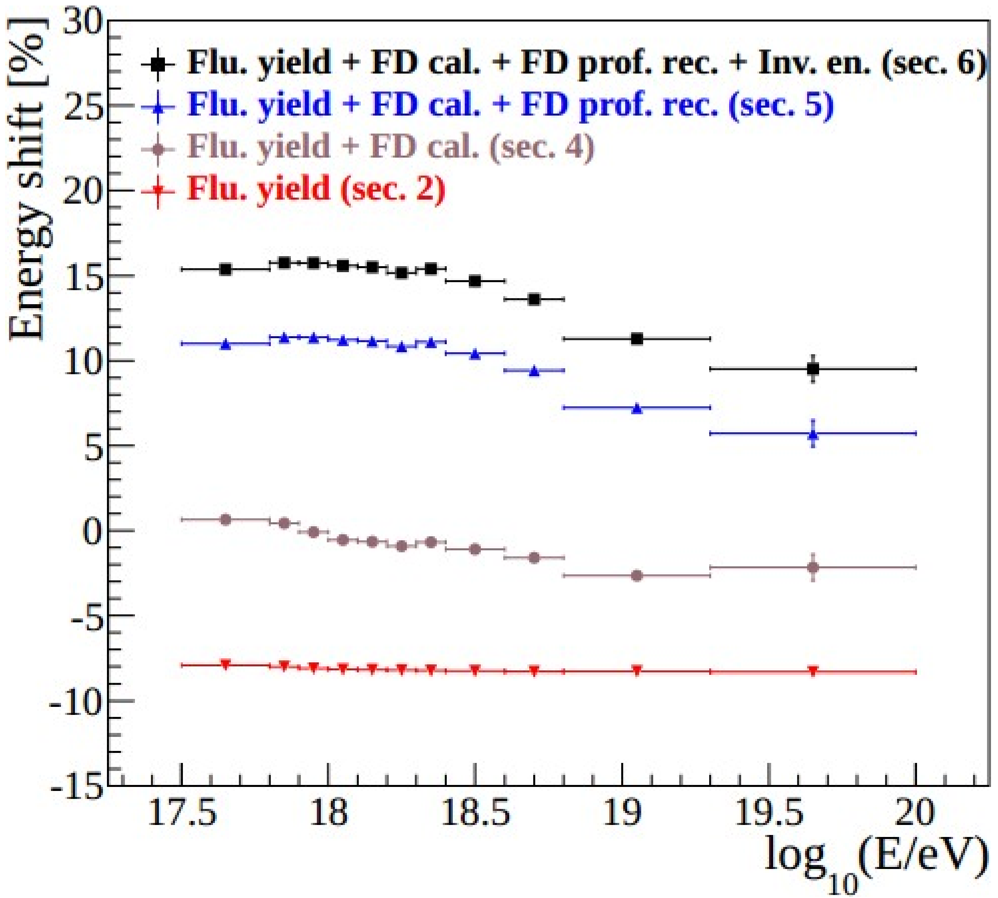
- Auger provides copious high quality data.
- Observables show a coherent behaviour.
- Trend to heavy, not pure composition.
- Flux suppression: clear observation, unclear interpretation (GZK? sources?)
- Highest energy data-derived σ_{pp} compatible with extrapolations from accelerator data.
- Cosmic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

BACKUP SLIDES

- 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%**

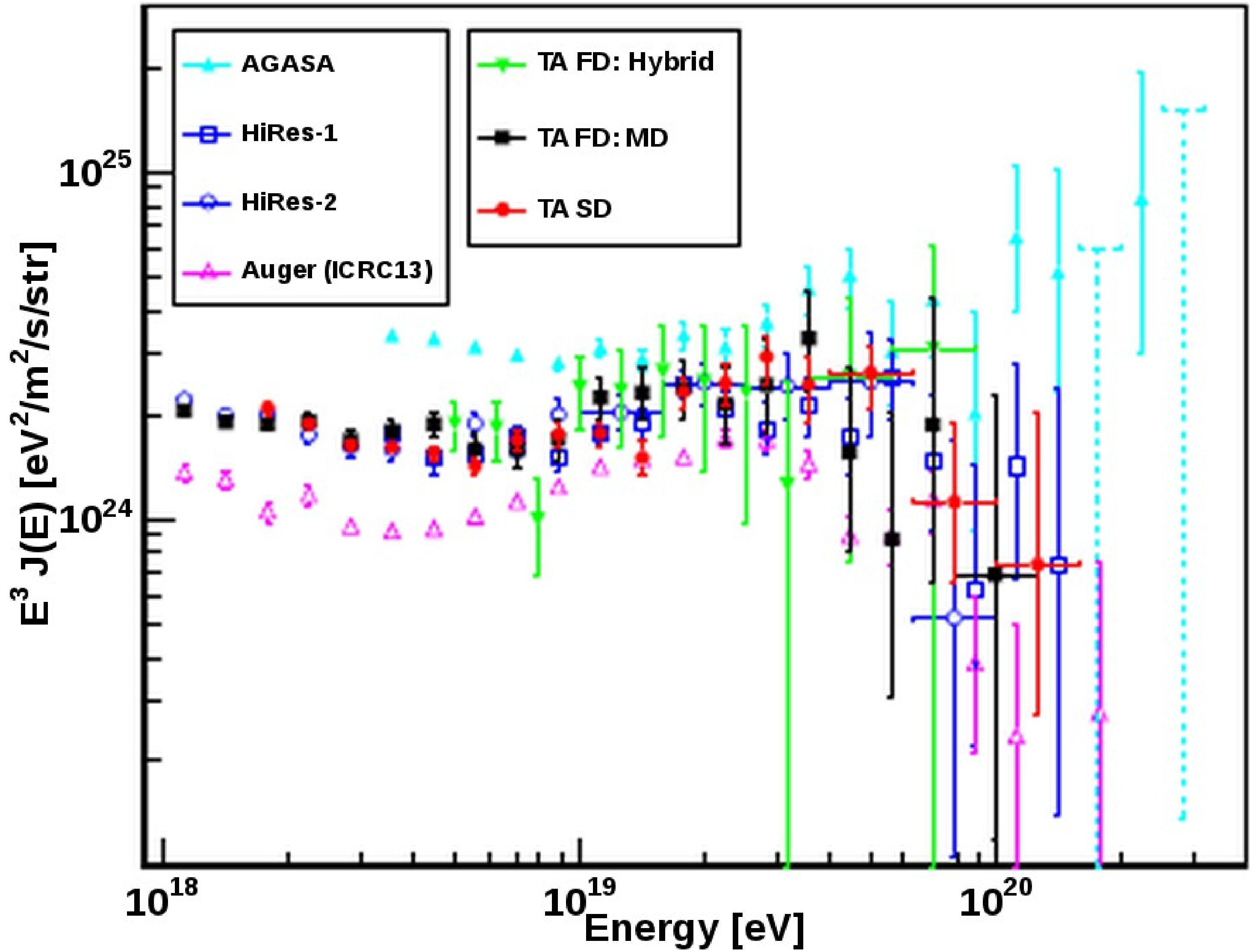


Down from 22% (ICRC 2011) to 14 % (ICRC 2013)

FD Quality Cuts

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) $\Delta X_{max} < 40$ gr cm^{-2}
12) X^2 GH/ndf < 2.5
13) Hottest station distance to core < 750m

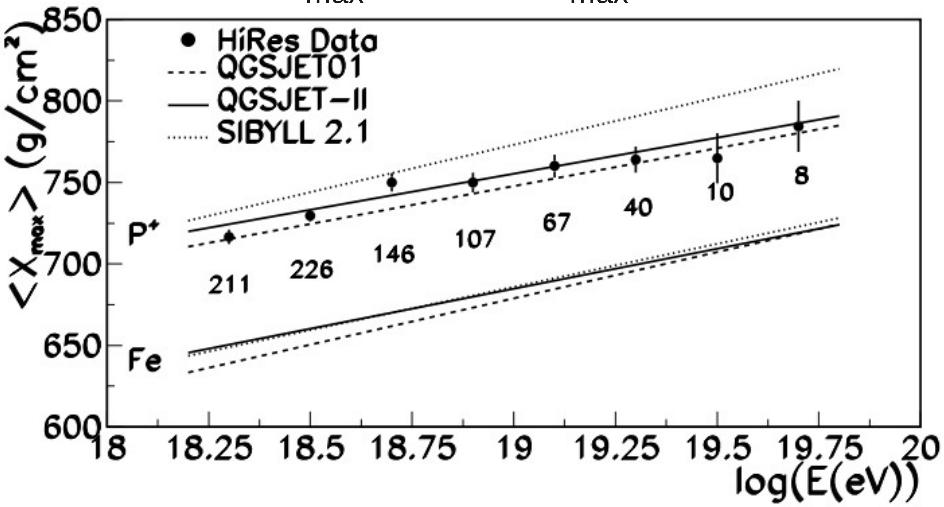
Spectrum

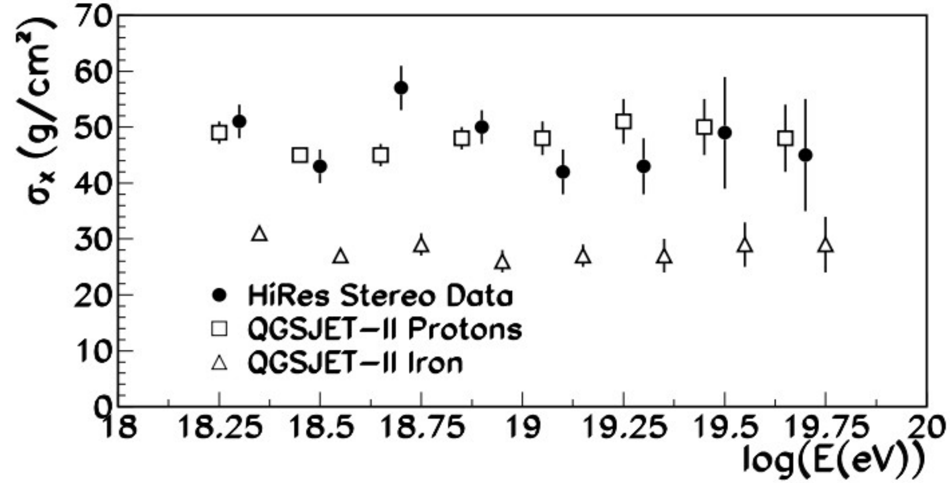


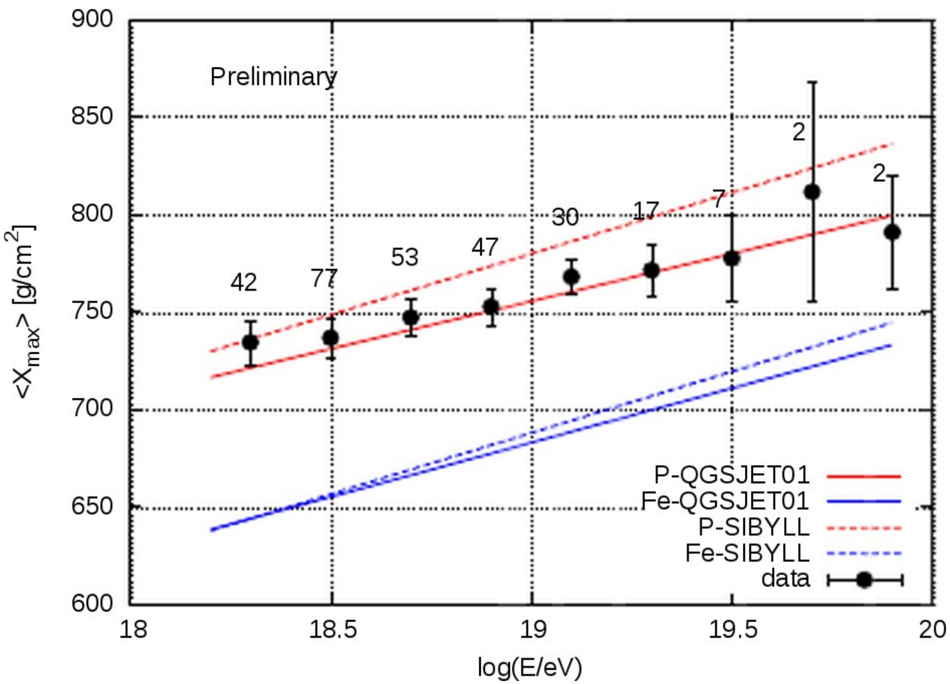
- Scale difference due to different energy assignment
- All experiments except AGASA show GZK-like cut-off at the highest energies
- Are the rest compatible?

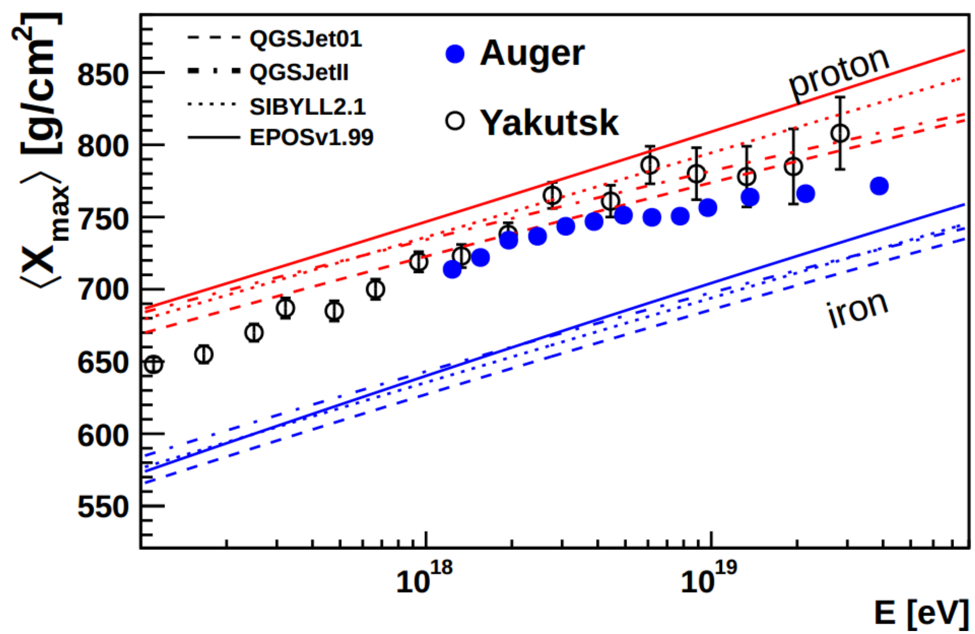
Mass composition

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



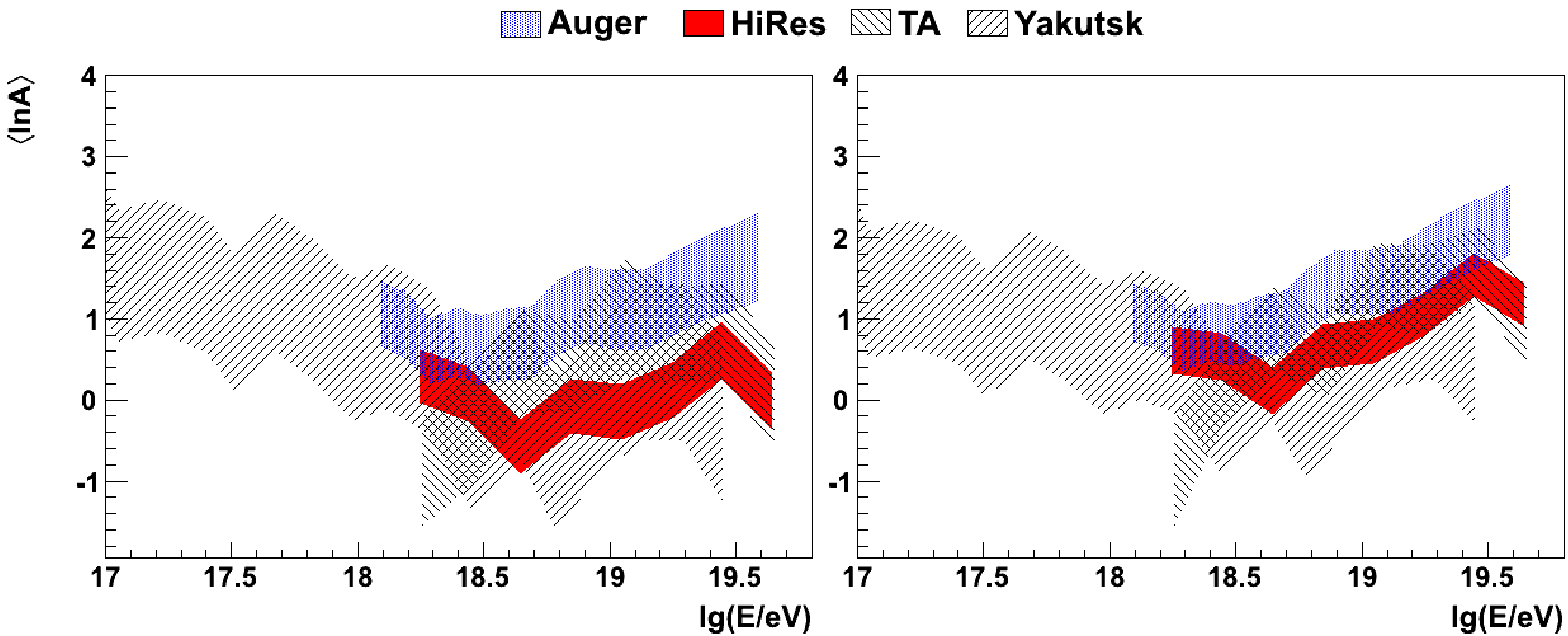






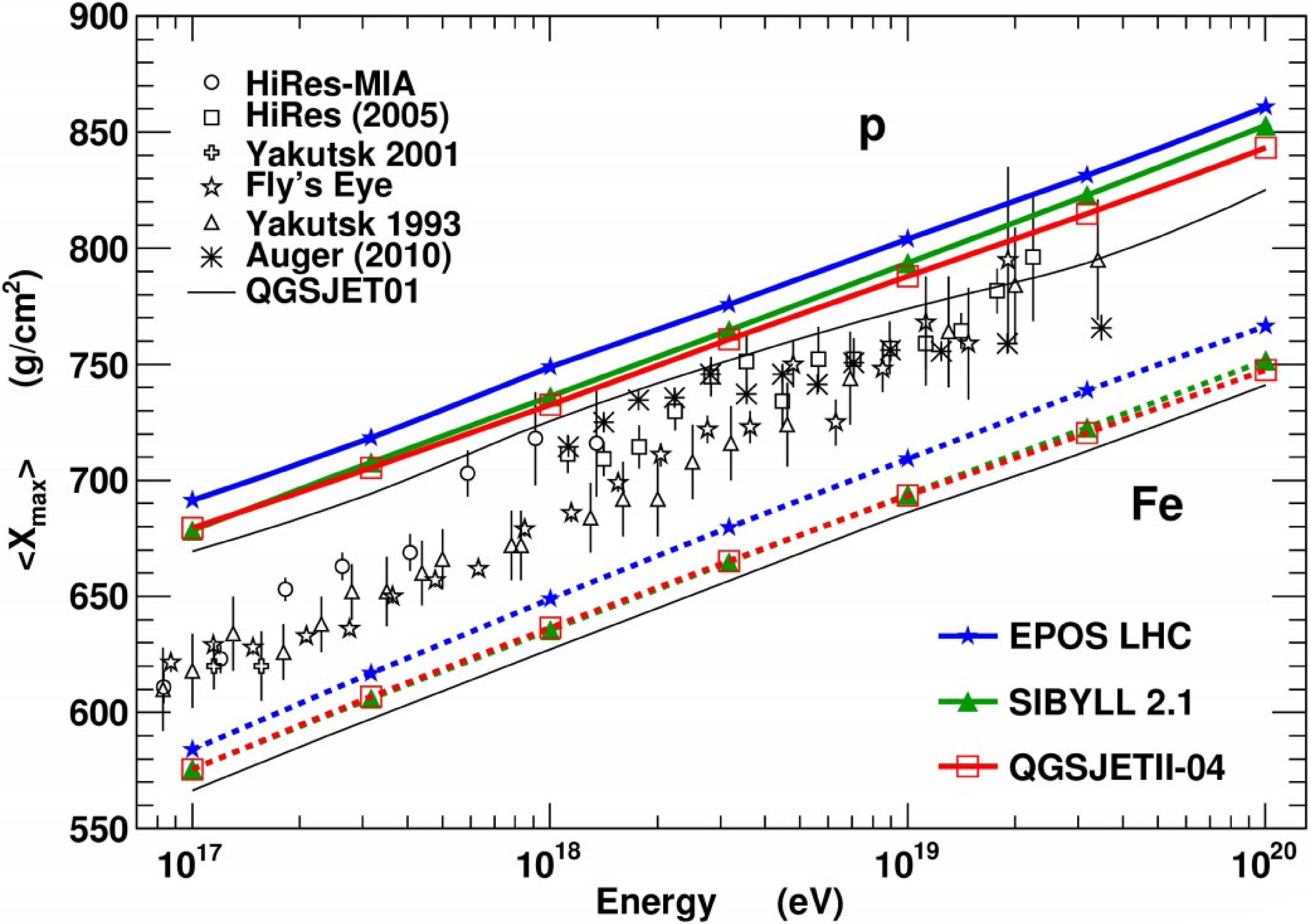
(1) P. Sokolsky et al. Hires Collaboration. *Nucl. Phys. B- Proc. Supp.* 212,74 (2011)
(2) H.Sagawa et al. Telescope Array Collaboration AIP Conf. Proc. 1367, 244 (2010)
(3) M. Unger for the Pierre Auger and Yakutks Collaborations *EPJ Web Conf.* 53 (2013) 01006

Results are converted to <ln A> 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

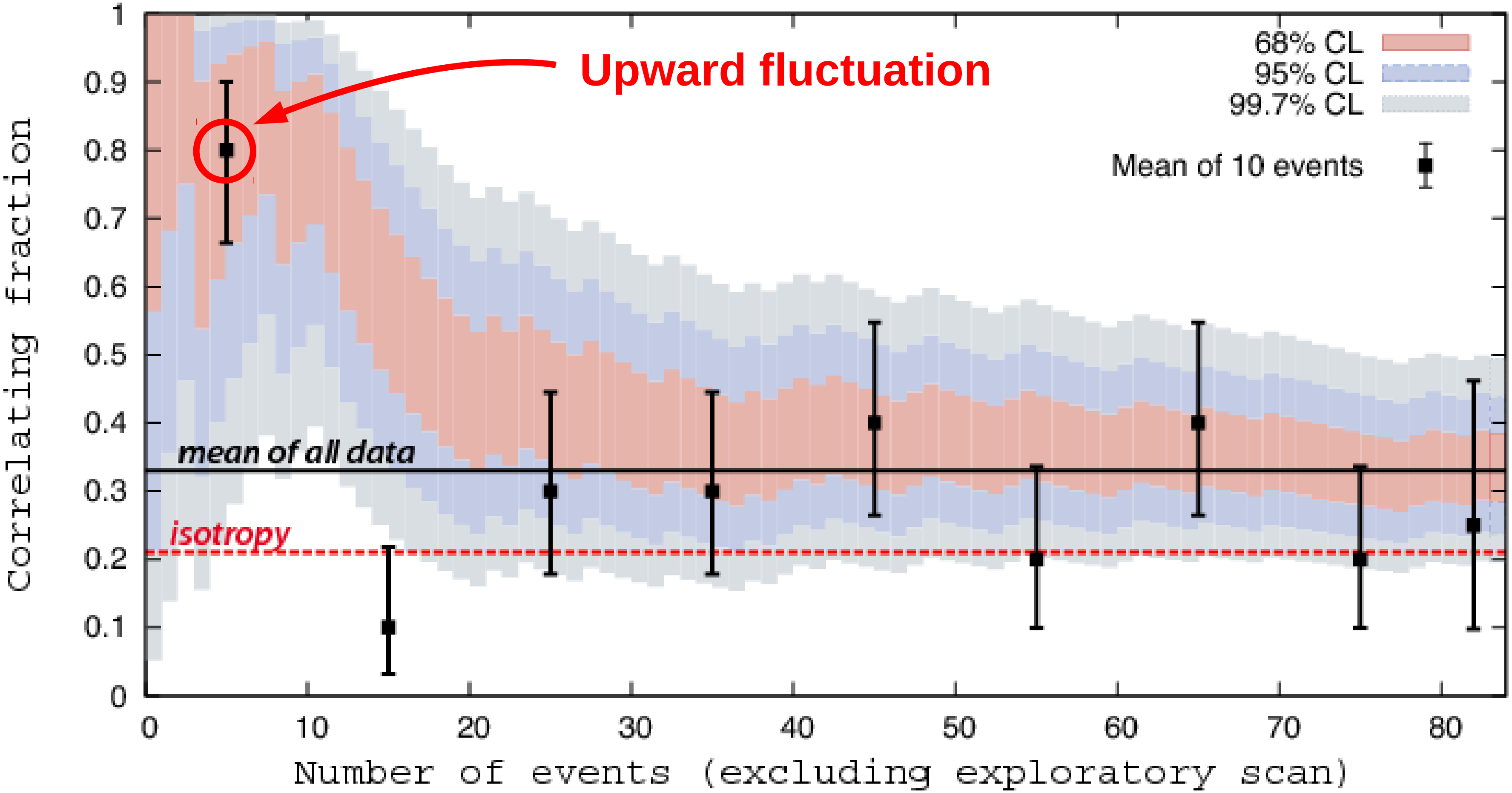
From M. Unger for the Pierre Auger and Yakutks Collaborations *EPJ Web Conf.* 53 (2013) 01006



HiRes-MIA
HiRes (2005)
Yakutsk 2001
Fly's Eye
Yakutsk 1993
Auger (2010)
QGSJET01
p
Fe
EPOS LHC
SIBYLL 2.1
QGSJETII-04
900
850
800
750
700
650
600
550
<X_max> (g/cm^2)
10^17
10^18
10^19
10^20
Energy (eV)

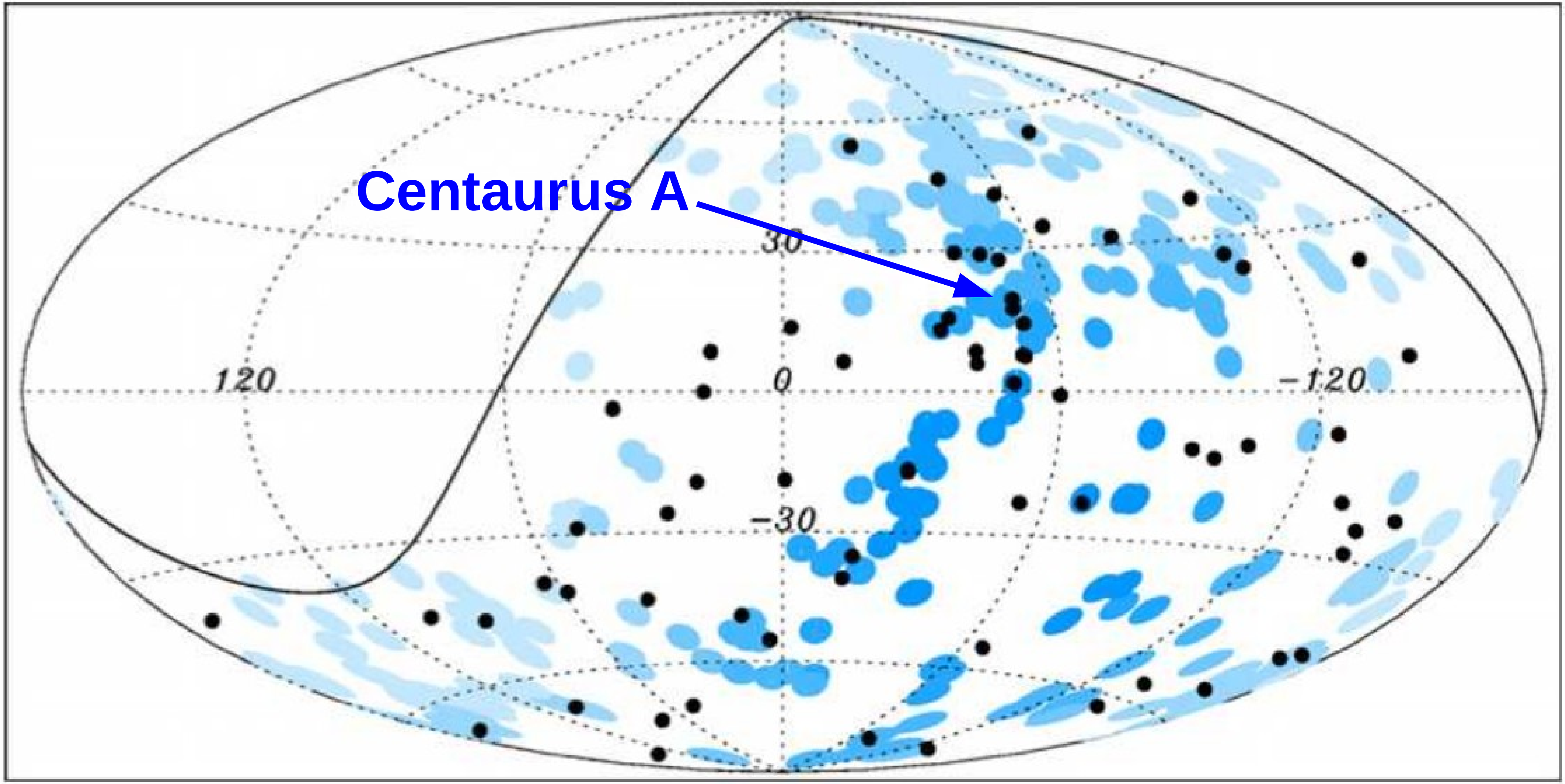
Correlation with point sources

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



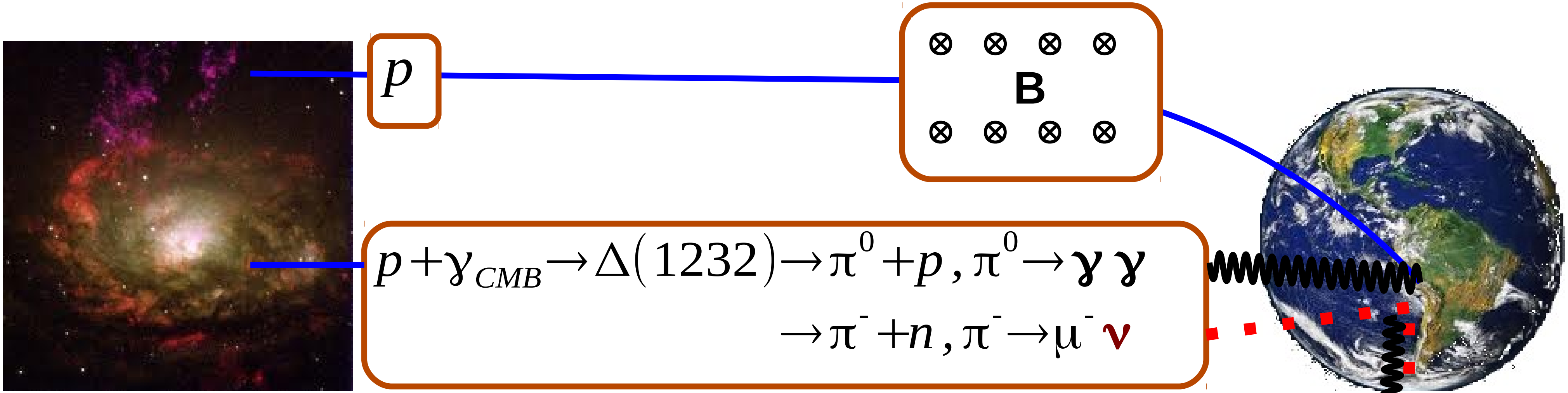
- Correlation 33±5%
- Chance probability from a random distribution < 1%

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

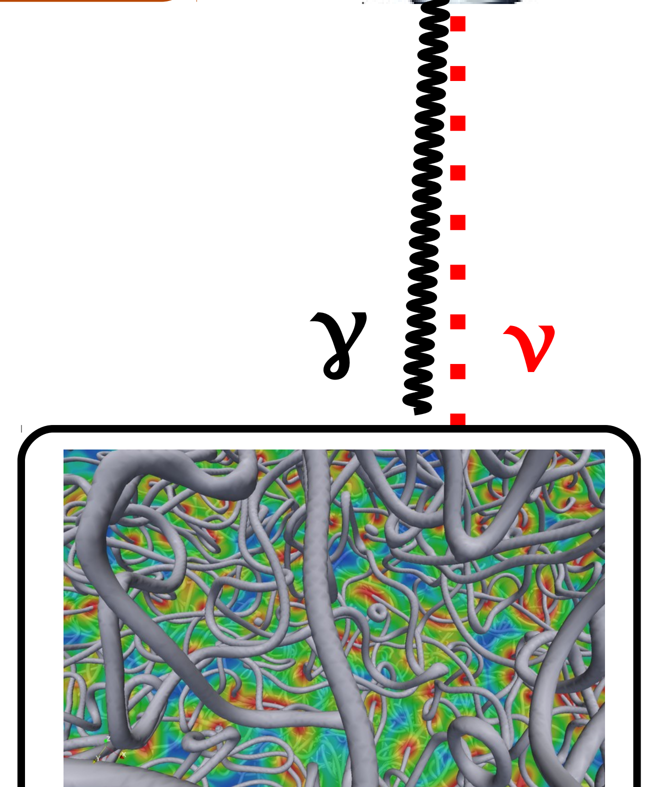


Distribution of the events with E > 55 EeV in angular windows of 3.1º around AGNs within 75 Mpc

Photon and neutrino detection



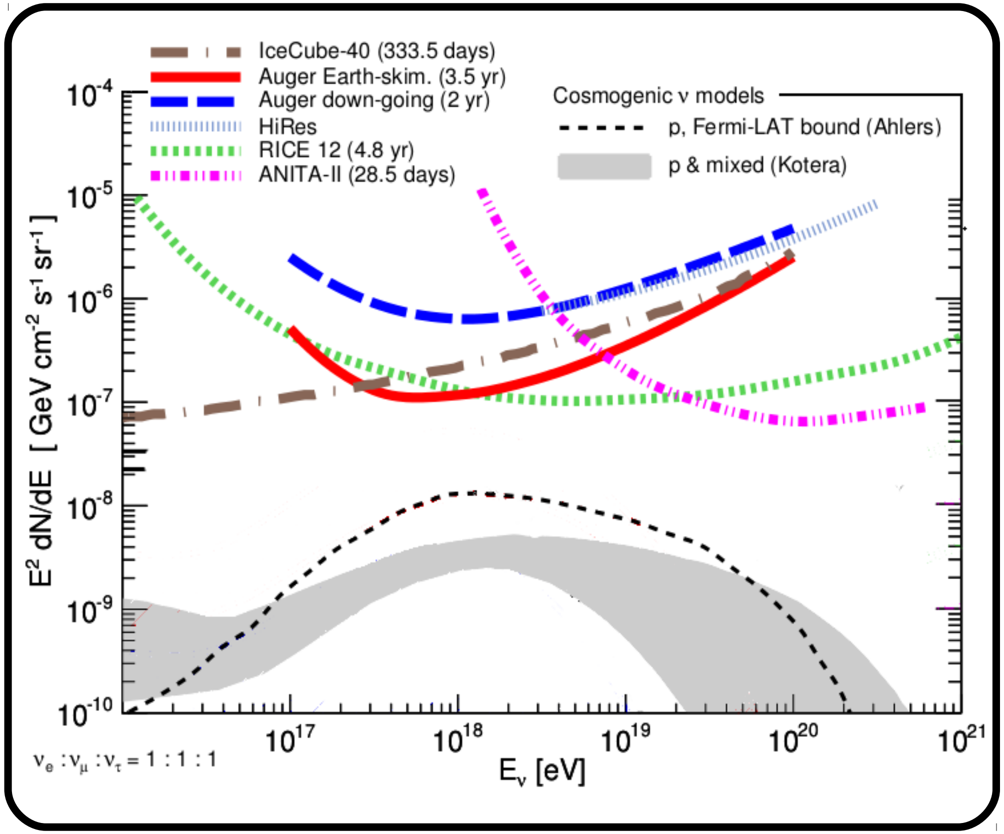
1) Smoking-gun signature of the GZK effect
2) Top-down production models predict large fractions of ν and γ
3) Astrophysics potential: ν and γ travel in straight lines and point to their production sites. Probes of source location and acceleration mechanisms.



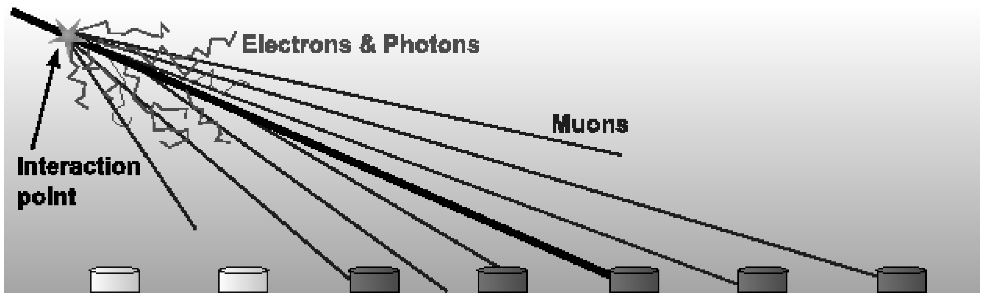
Top-down models

Neutrinos

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



Inclined hadronic shower

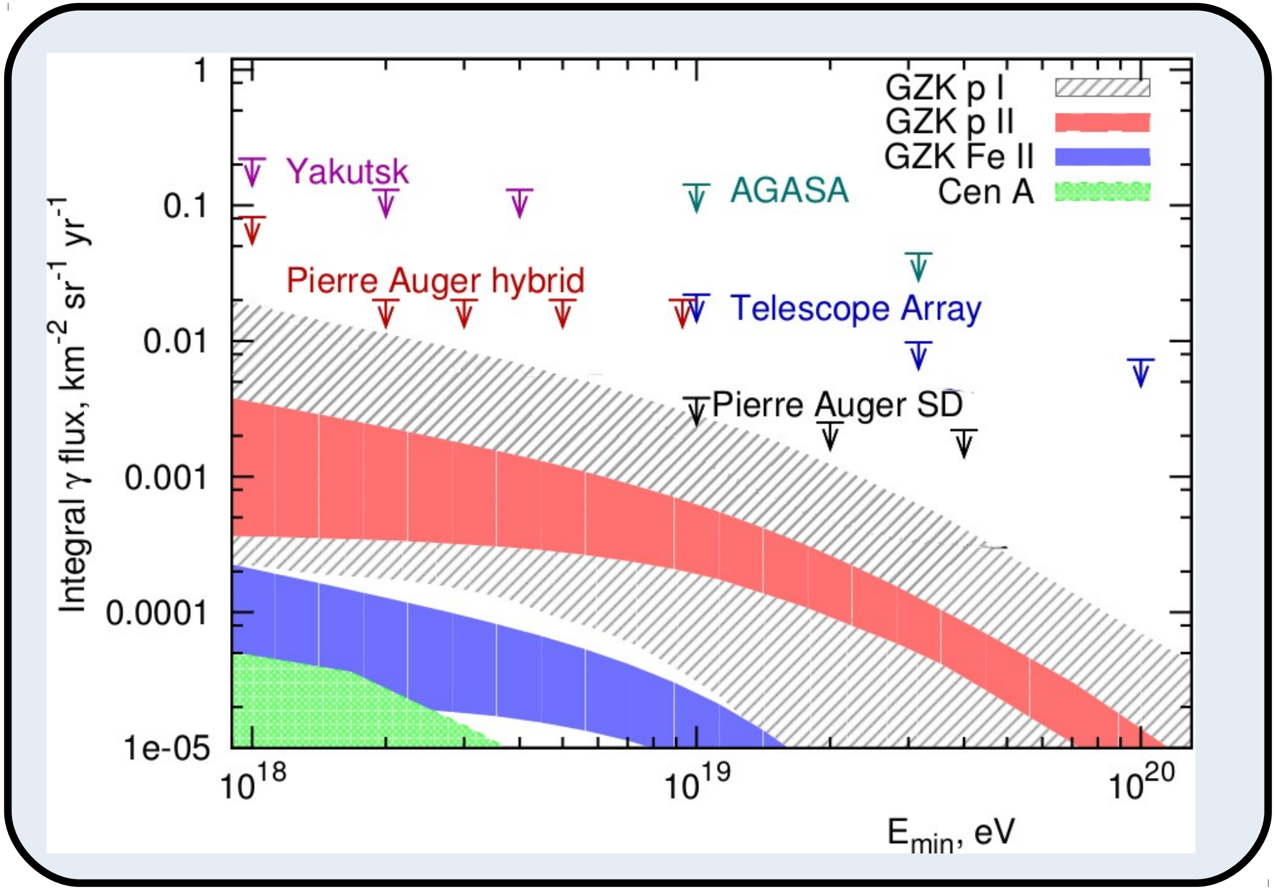


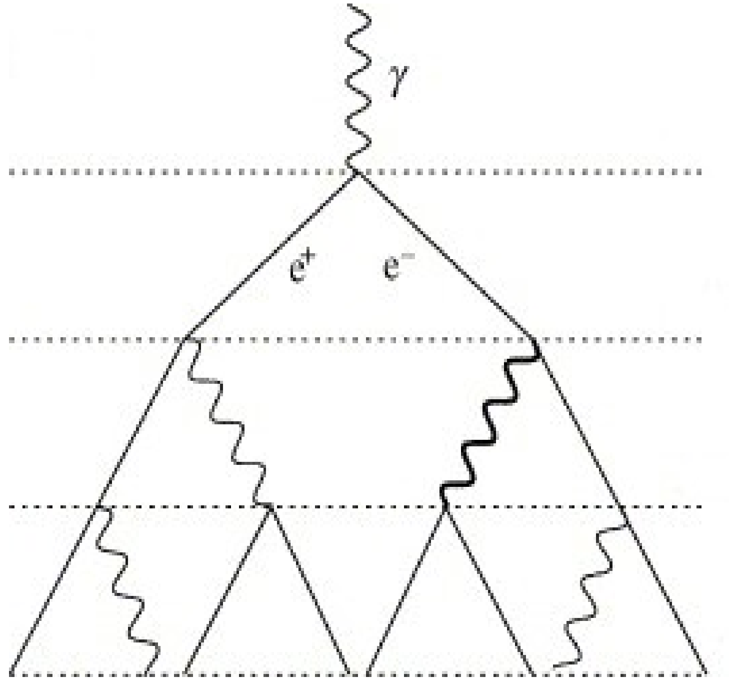
Essentially muons at ground level

Neutrino shower

Electromagnetic-rich inclined showers

Photons



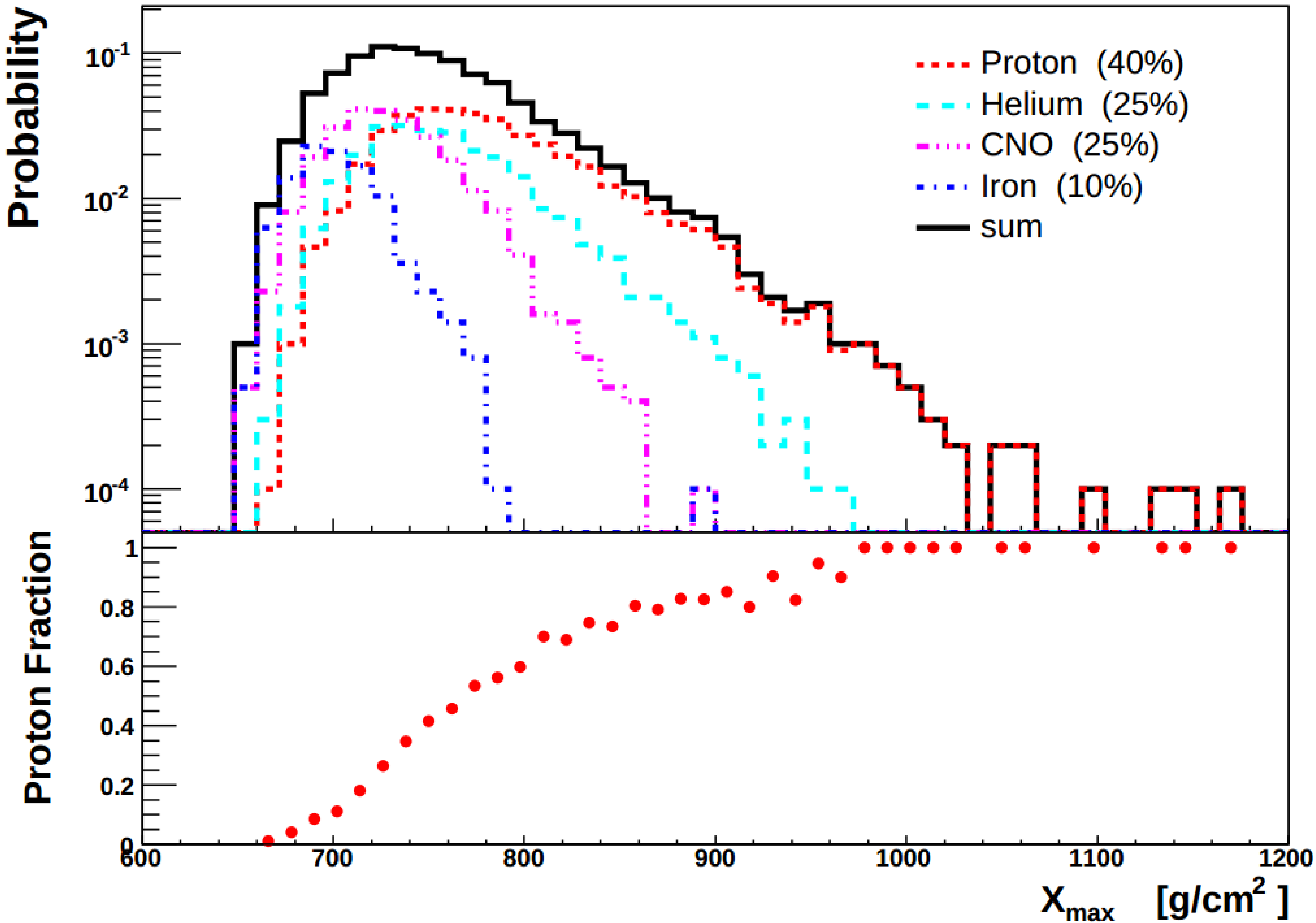


<u>γ-induced showers</u>

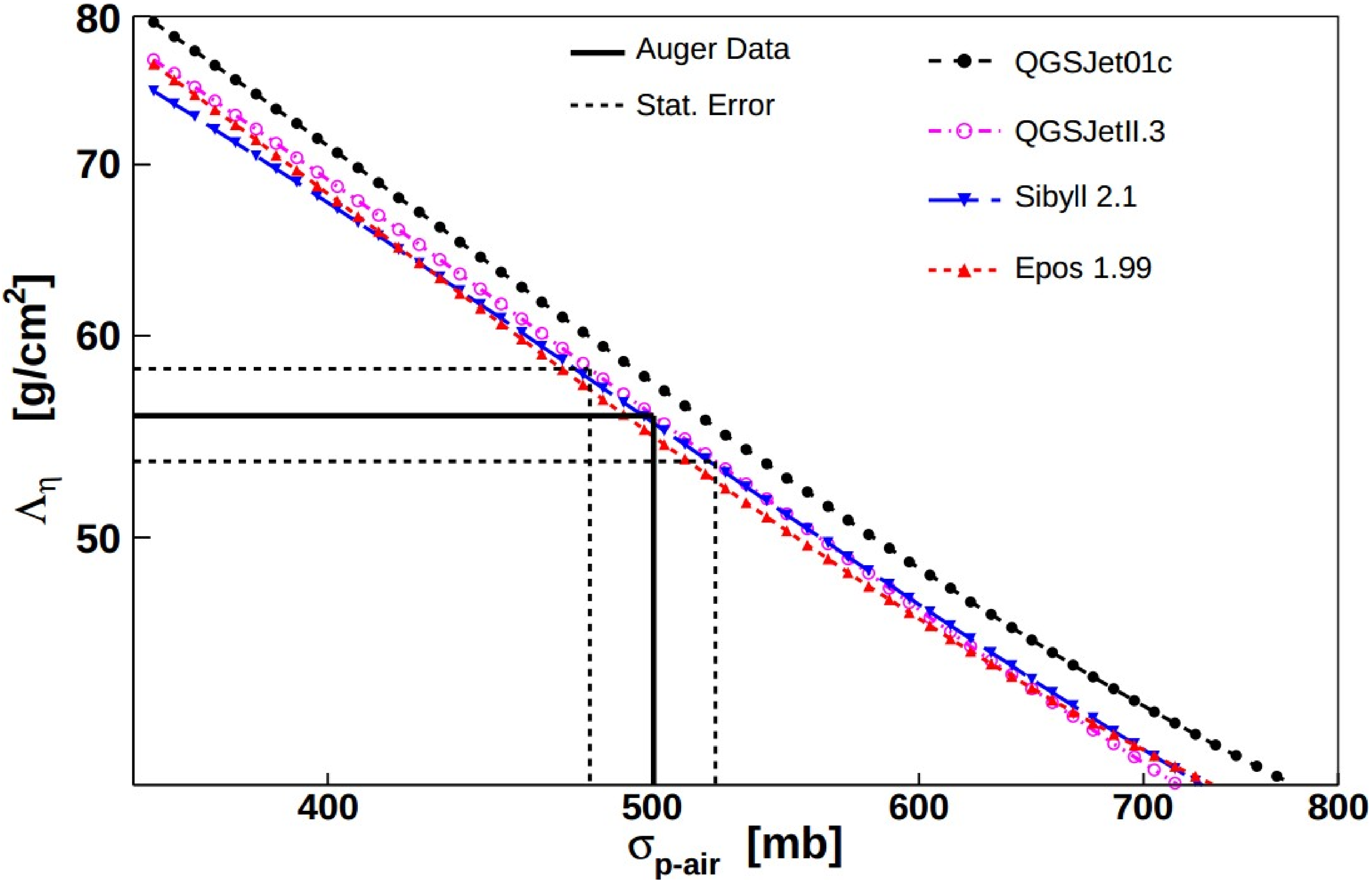
- Purely electromagnetic showers
- Deep X_{max}
- Slow shower development
- Large spread of ground signals

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

From Λ_f to σ_{p-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.