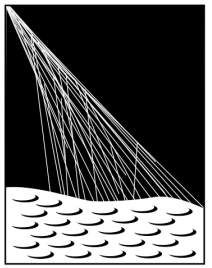
Up-to-date Physics results from the Pierre Auger Observatory

Bruno Zamorano for the Pierre Auger Collaboration

Matter to the Deepest – Ustron, Sept. 2013



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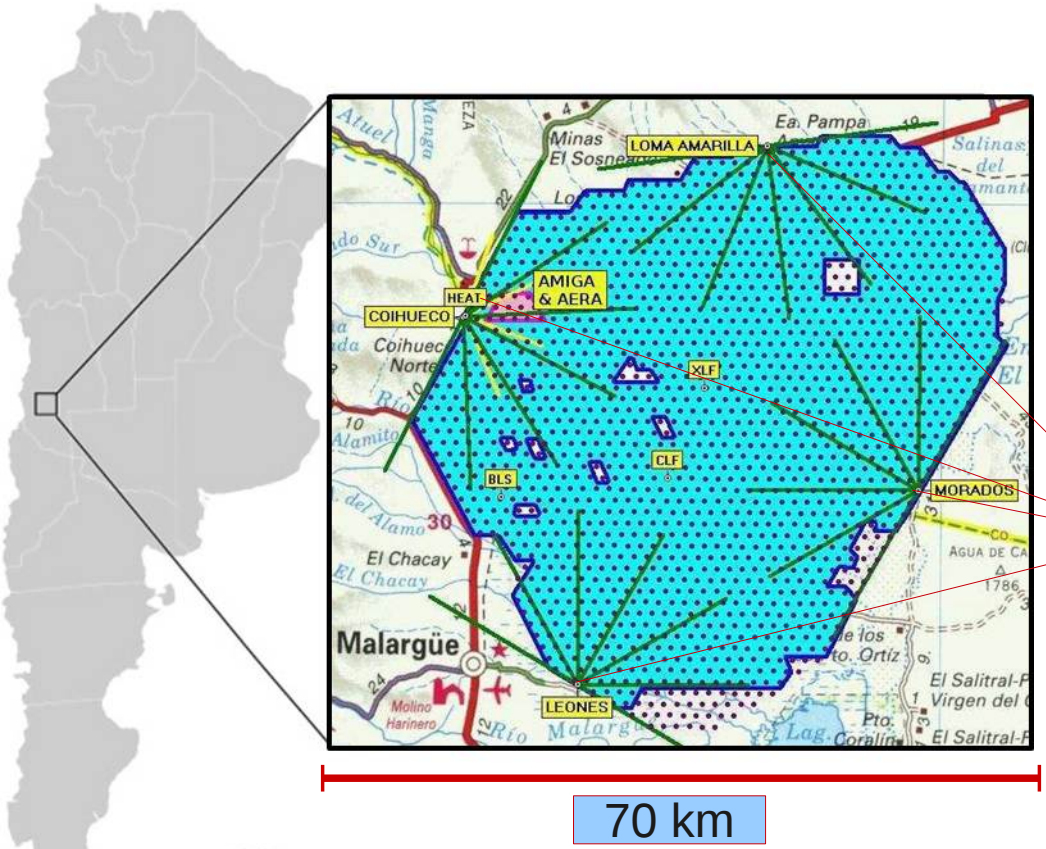
The Pierre Auger Observatory



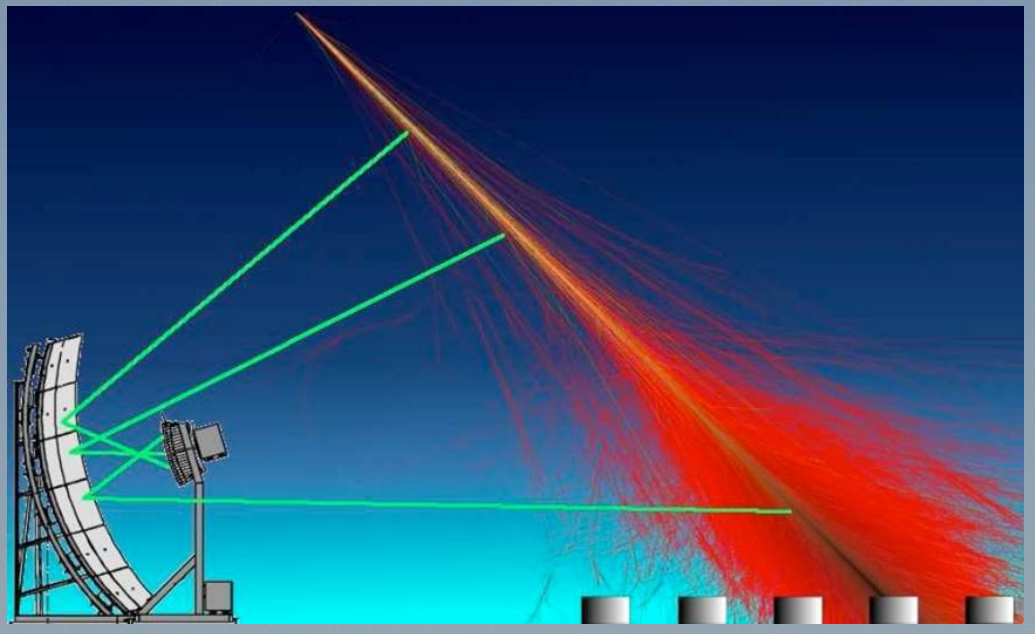
- Located near Malargüe (Argentina)
- More than **3000 km^2**
- **Hybrid detector**
  - **4** Fluorescence sites with 6 telescopes each (FD)
  - More than **1600** water Cherenkov detectors (SD)

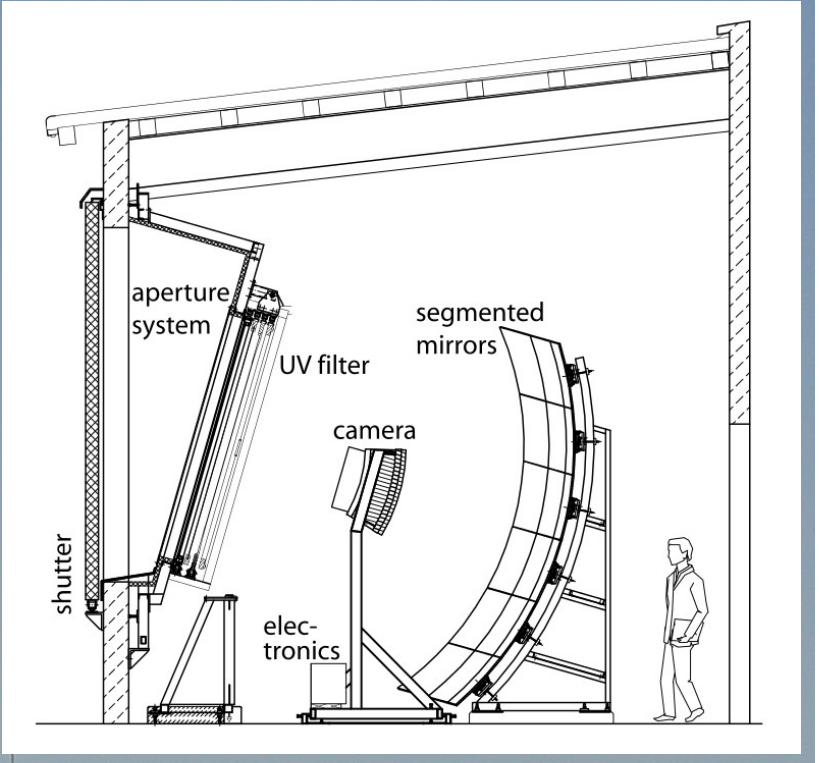
- FD → Longitudinal development of the E.M. Shower (14% duty cycle)
- SD → Transversal sampling of the shower front (~100% duty cycle)

Two independent and complementary detectors!

↓

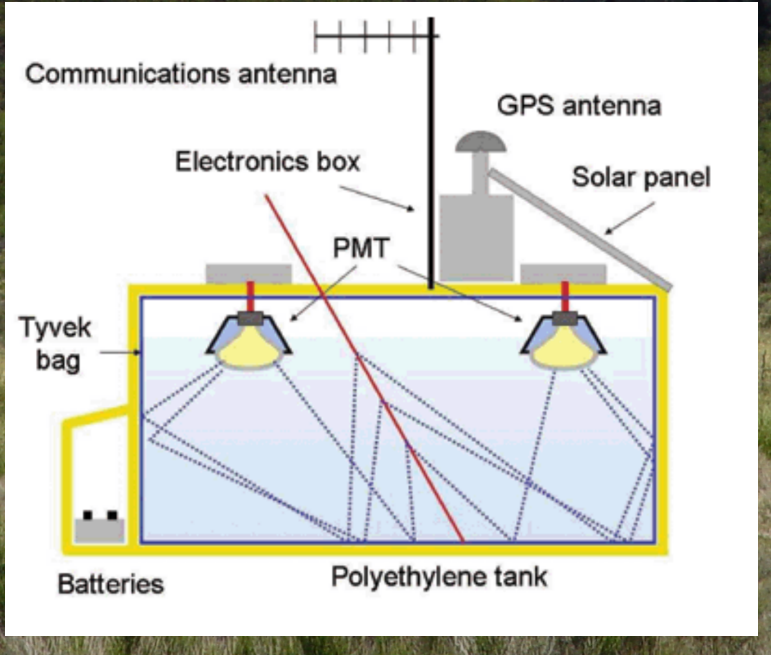
Data-driven calibration



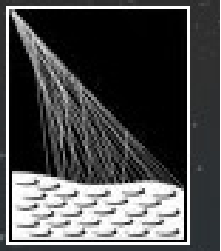


More than 500 scientists from 18 countries

~3 million SD events
~400 000 FD events



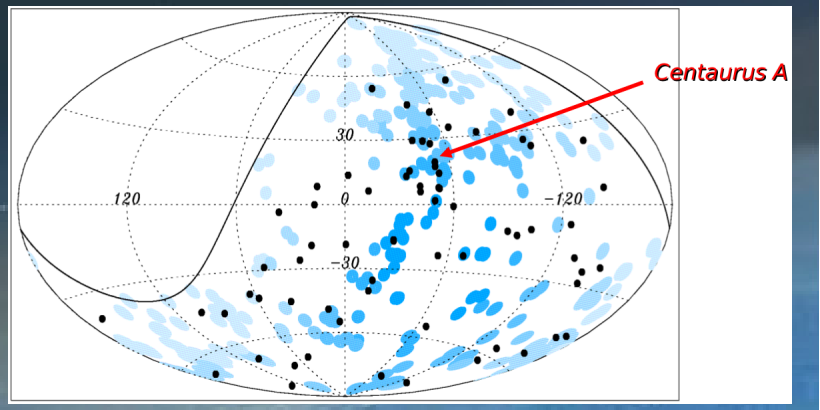
Physics @ Pierre Auger Observatory

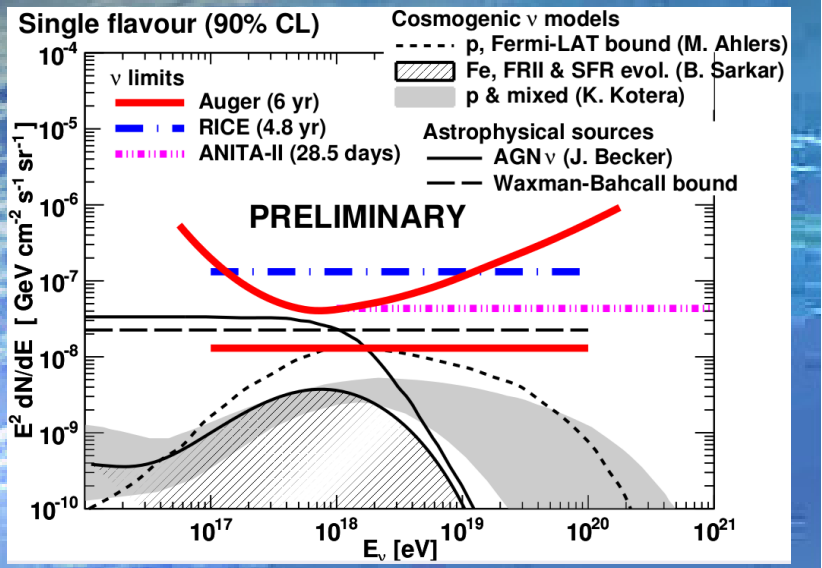


Pierre Auger Observatory

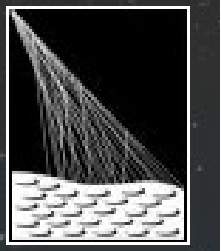
studying the universe's highest energy particles

- Energy spectrum
- Mass composition
- Large/small scale anisotropies
- Hadronic Physics
- Photon and neutrino searches
- Exotic searches





Physics @ Pierre Auger Observatory



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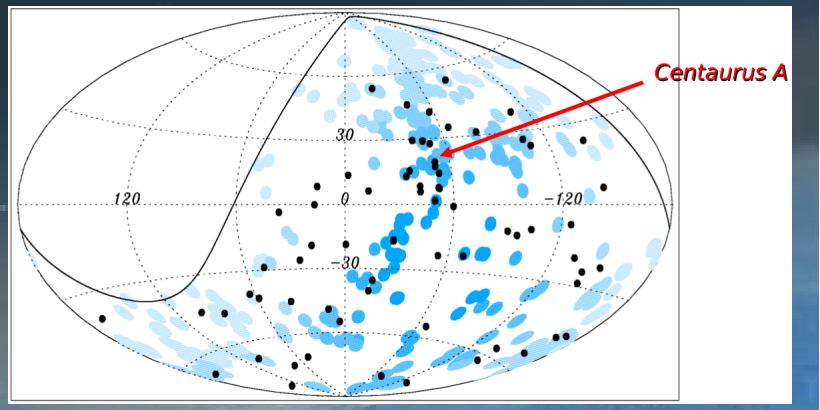
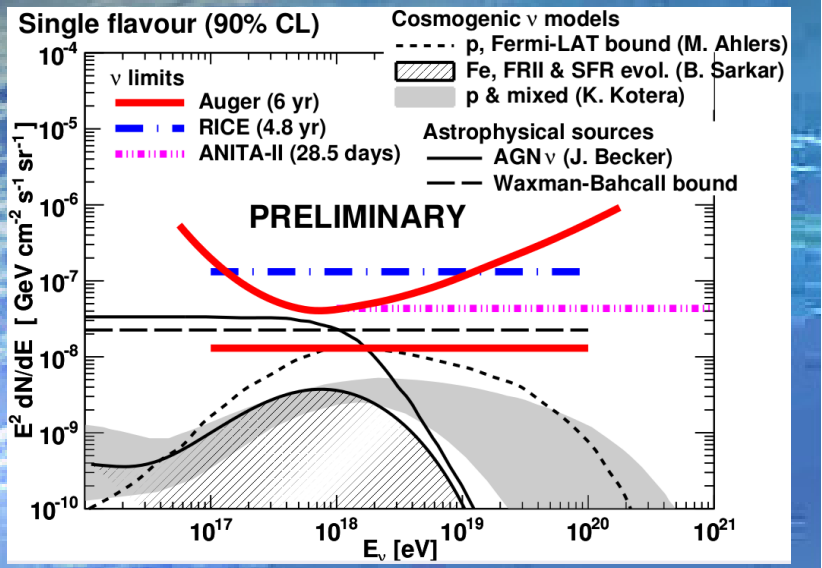
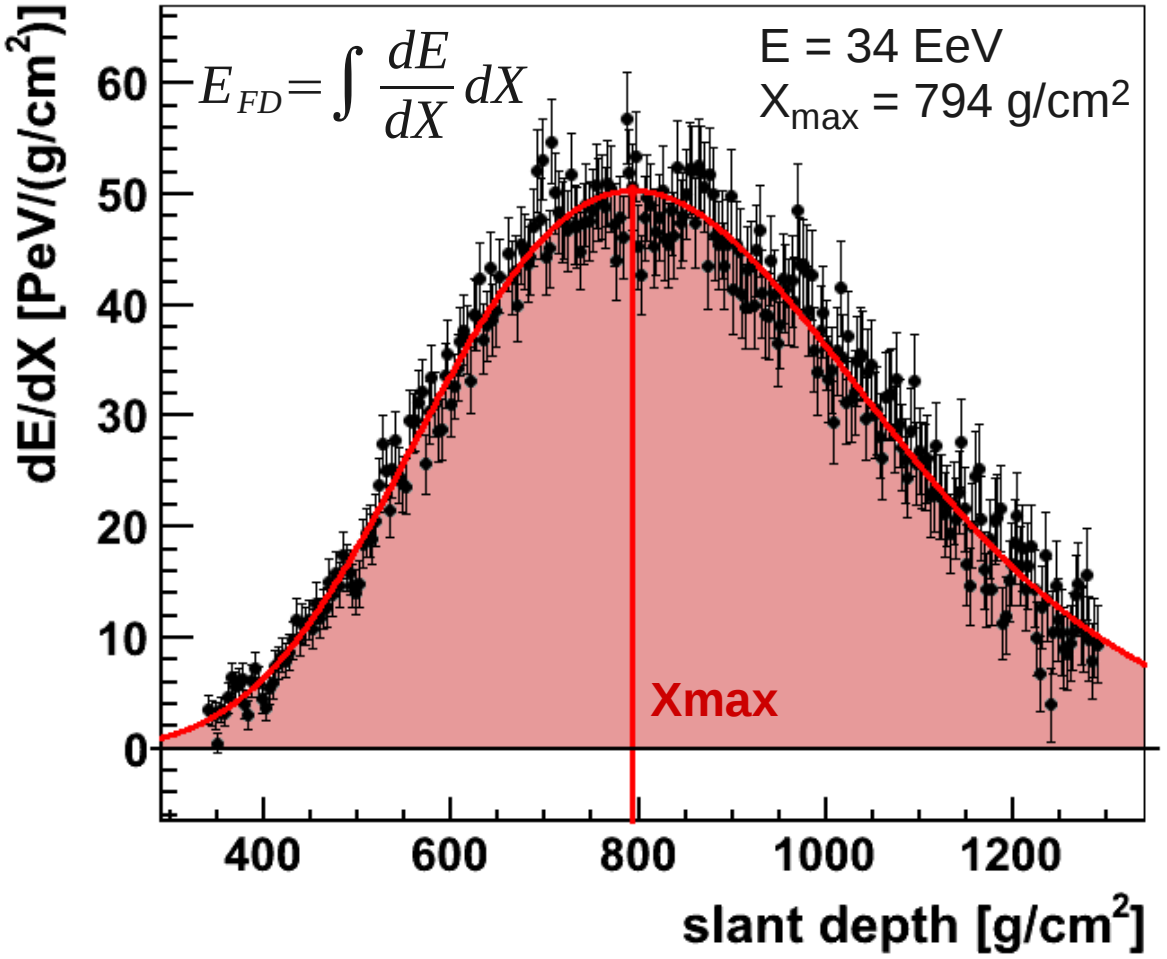




FD Energy determination



Systematic uncertainty on the energy scale:

ICRC 2011	**ICRC 2013**
22% →	**14%**

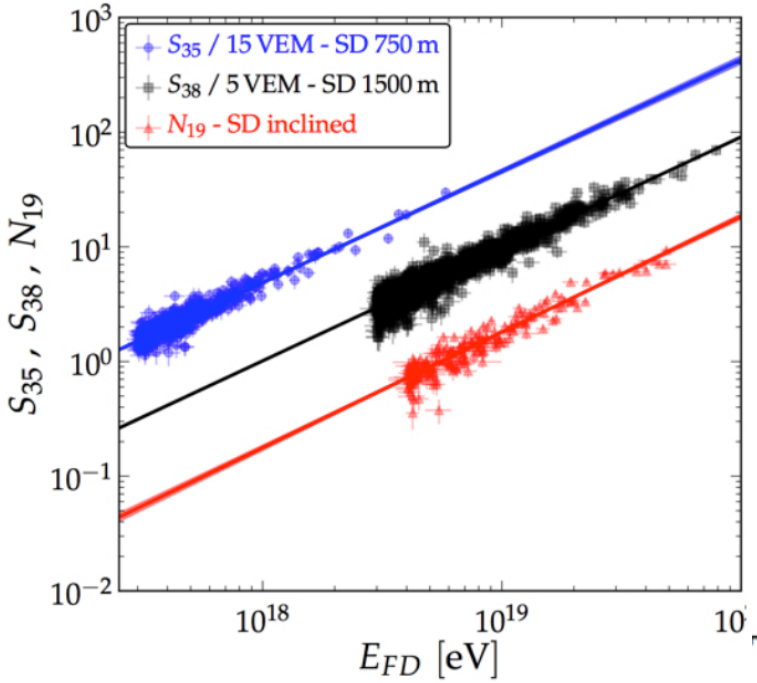
Several improvements: Absolute fluorescence yield, new calibration database ...

Calorimetric determination of E_{FD}
Almost model independent

→

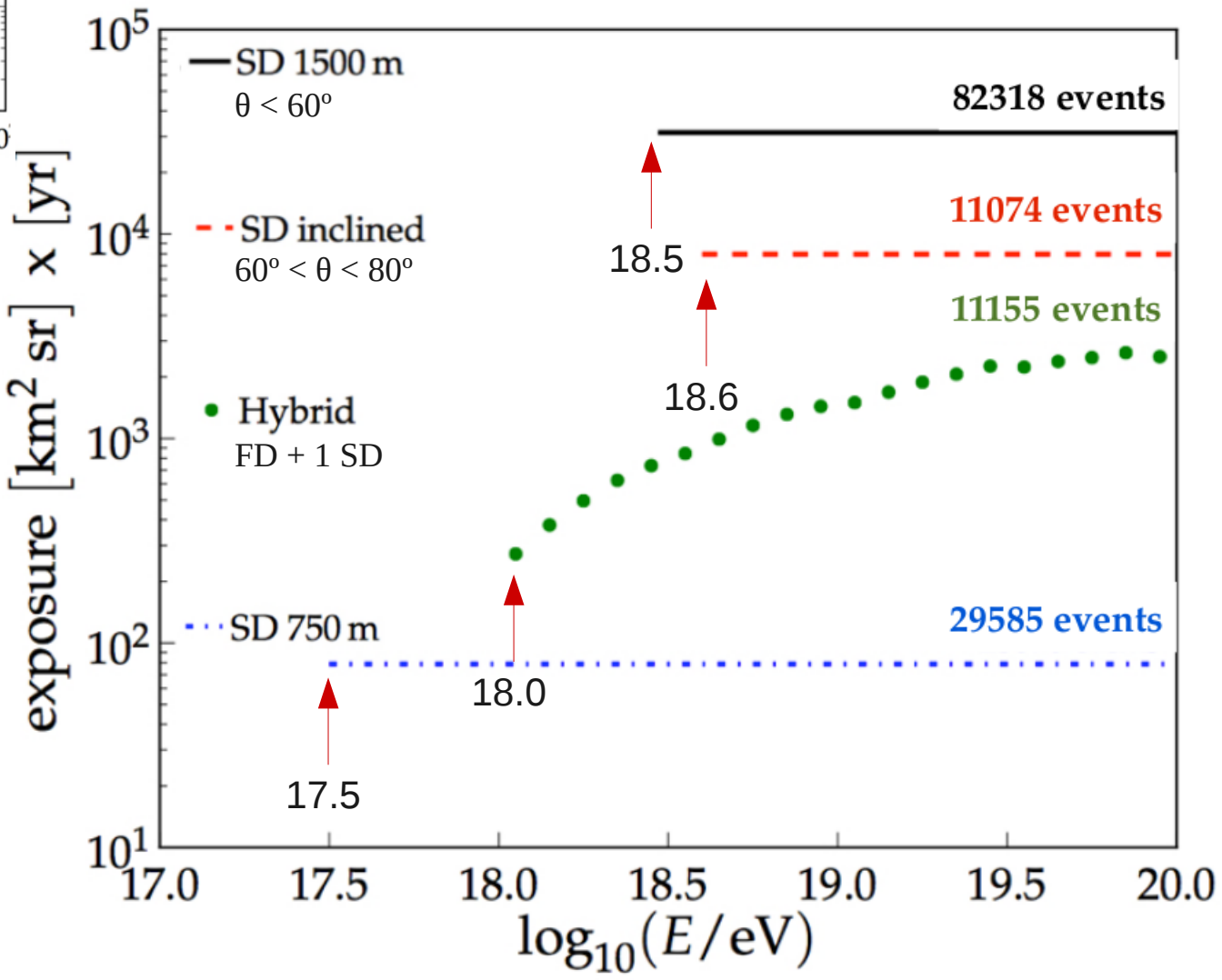
E_{SD} obtained through calibration with E_{FD}

SD Energy

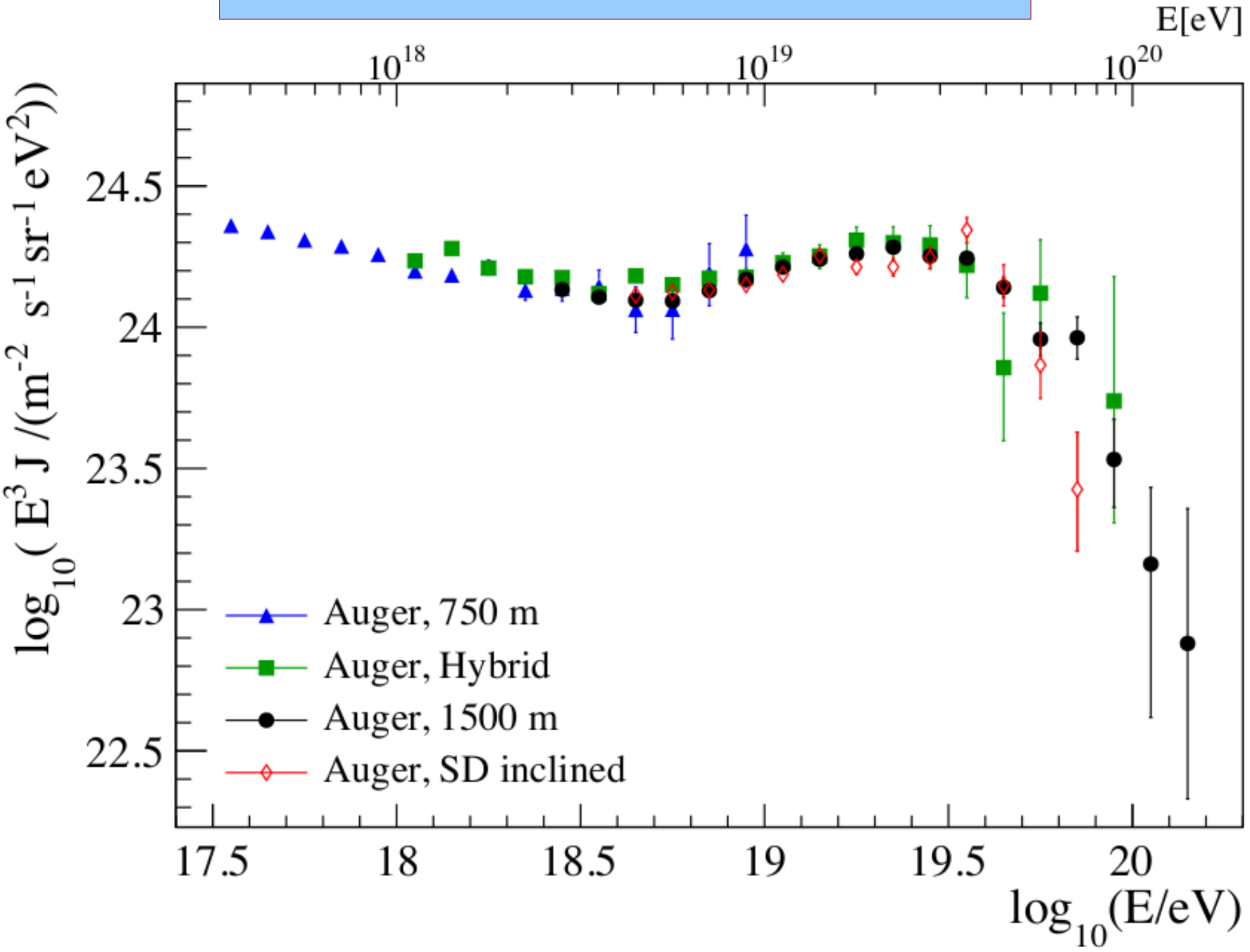


All SD energy observables correlate nicely with E_{FD}

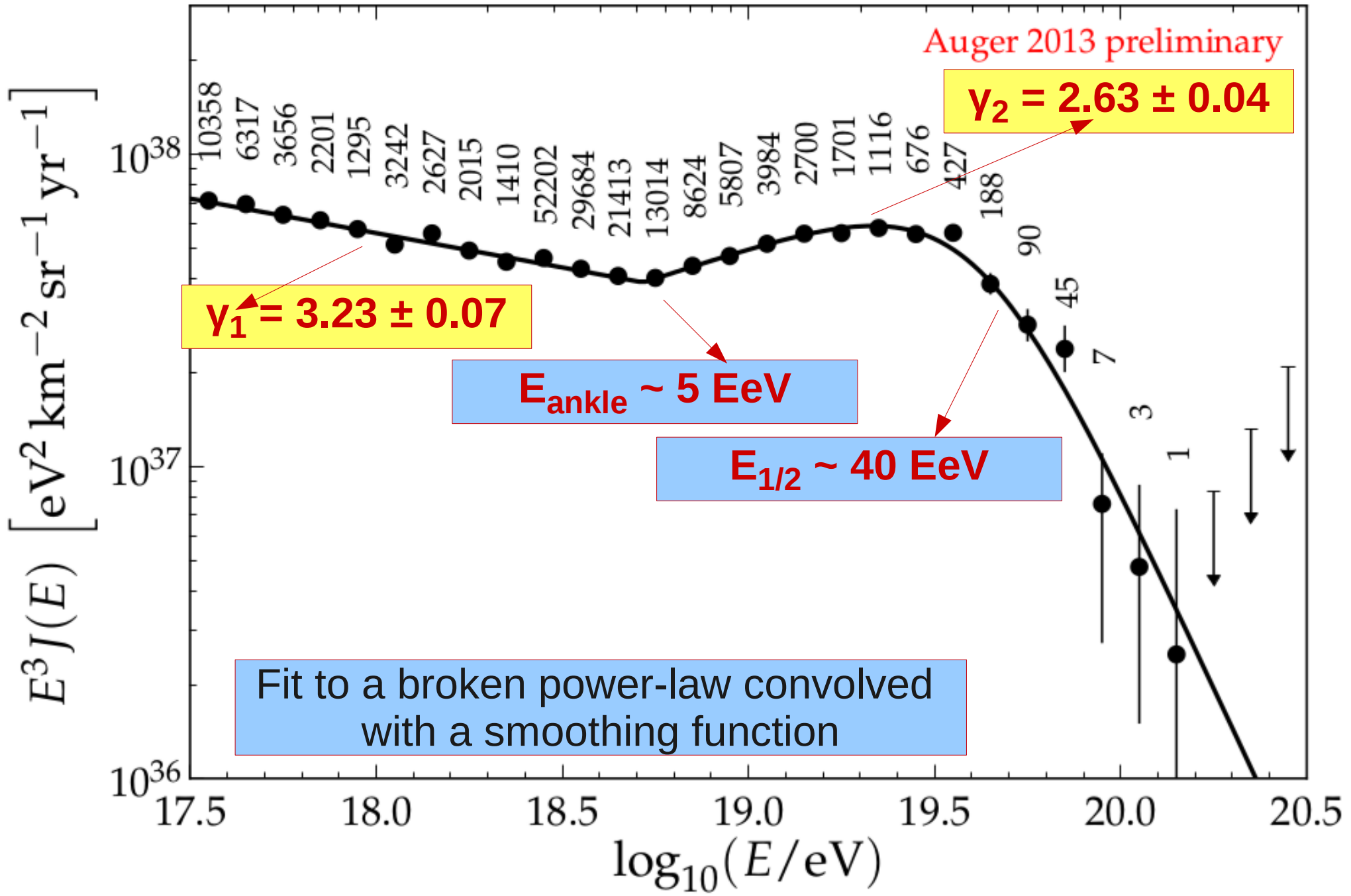
Four different contributions to the spectrum measurement



Good agreement among datasets

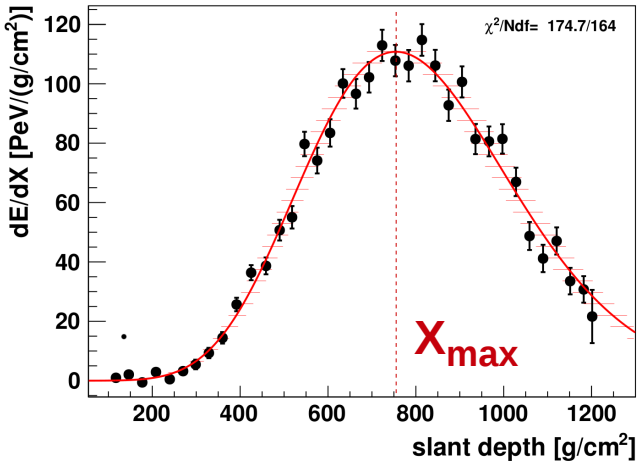


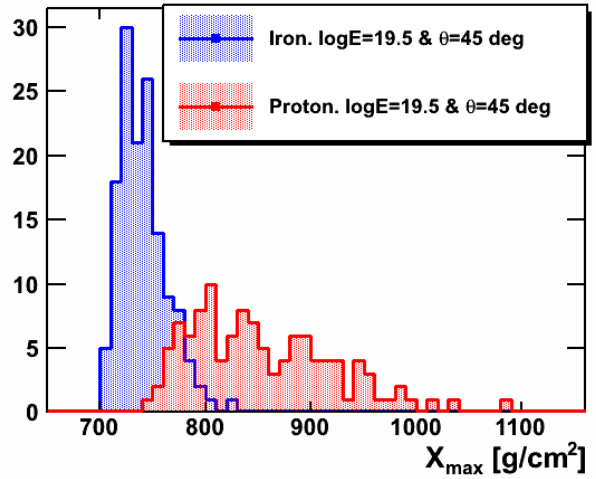
The Pierre Auger energy spectrum



Mass composition

FD: Maximum of the E.M. profile

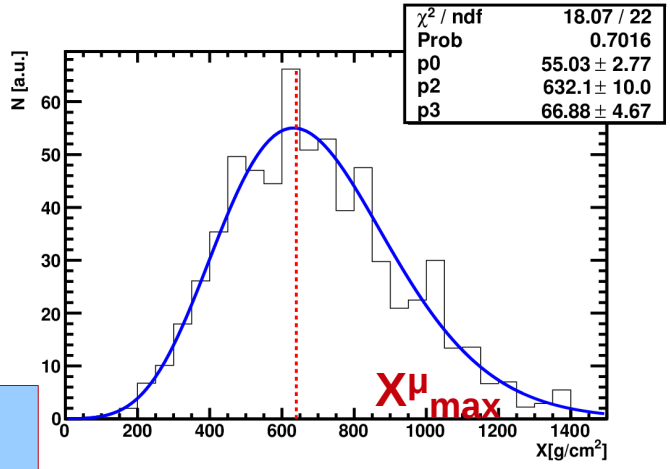


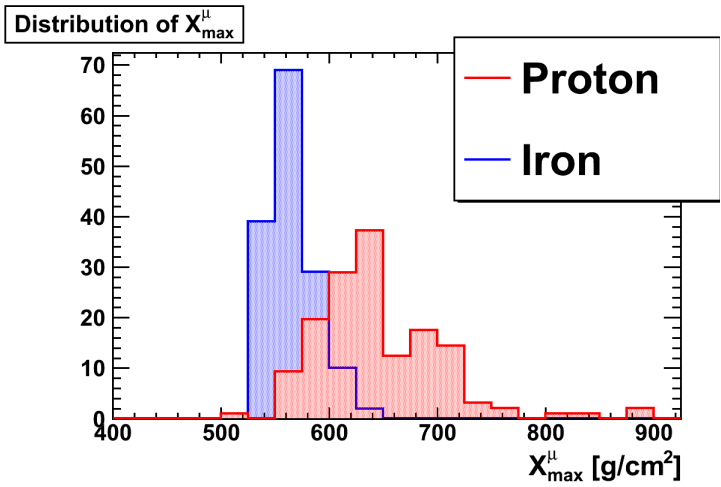


Analogous SD-FD observables, but they study different components of the shower

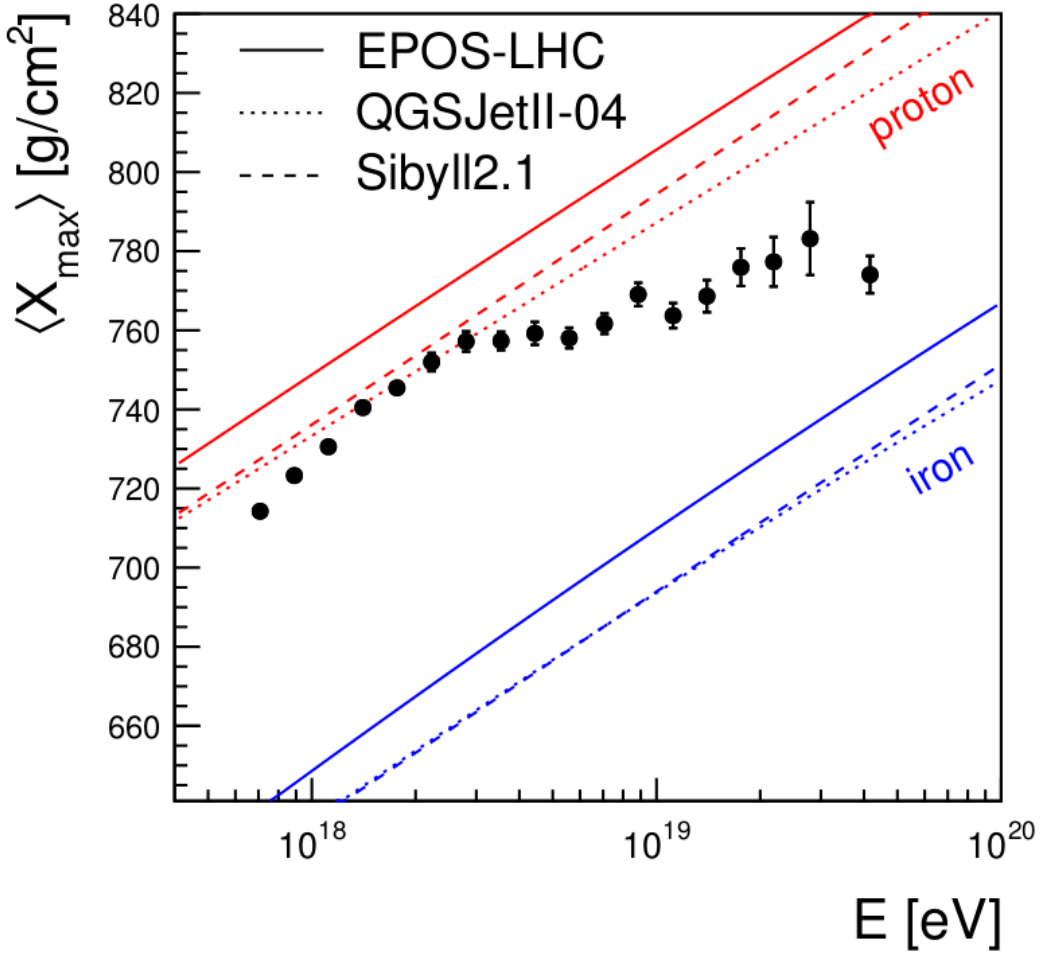
Both lay upon the same fact: protons are more penetrating and suffer higher fluctuations

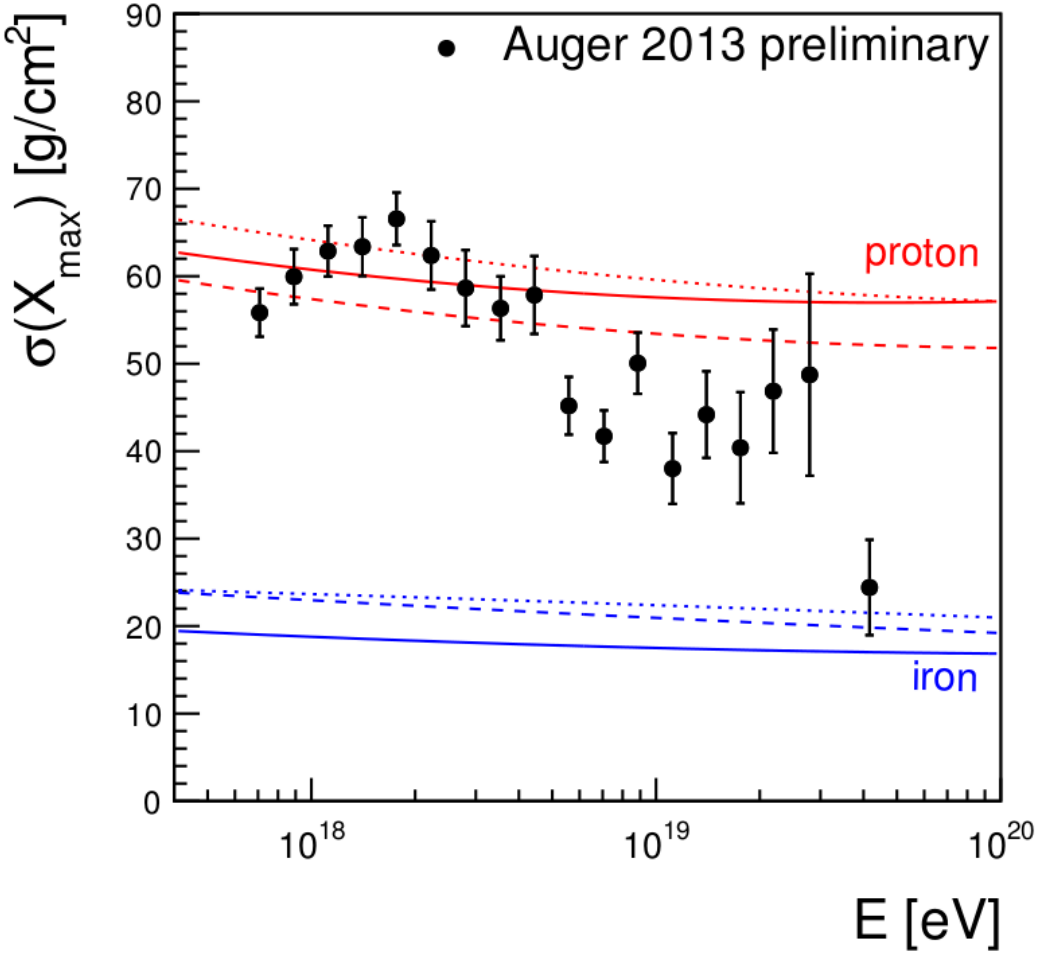
SD: Muon Production Depth (MPD) maximum





X_{max} results





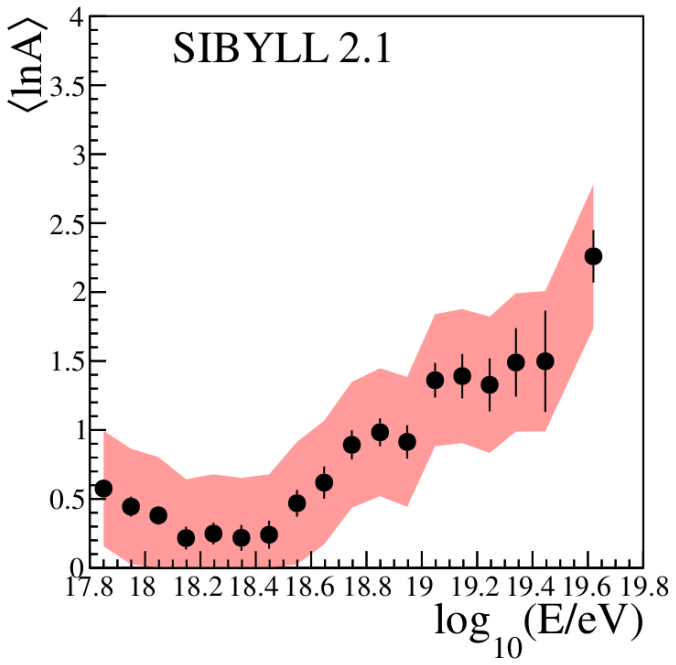
Cumulative bin starts at log(E/eV) = 19.3
Reduced statistics due to duty cycle, excellent resolution (20 g/cm^2)

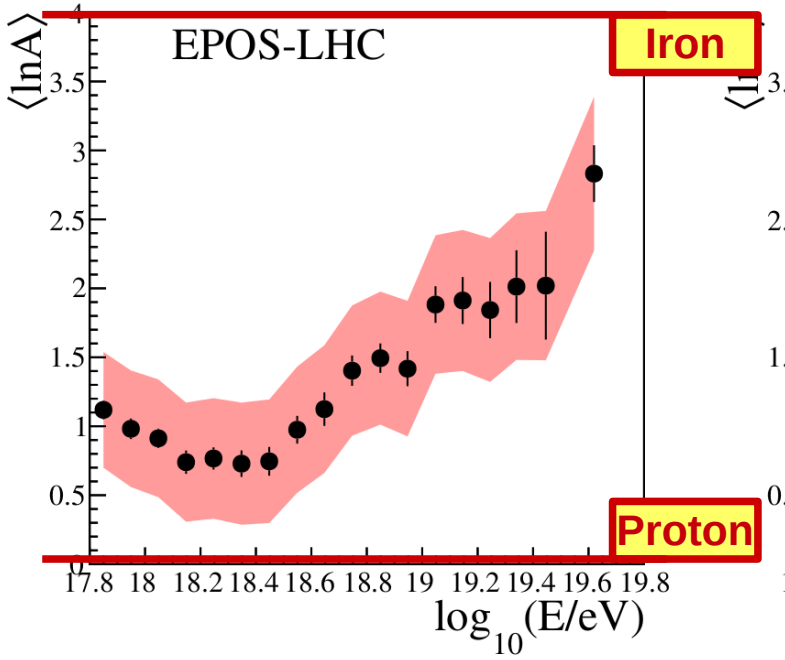
JCAP 1302 (2013) 026

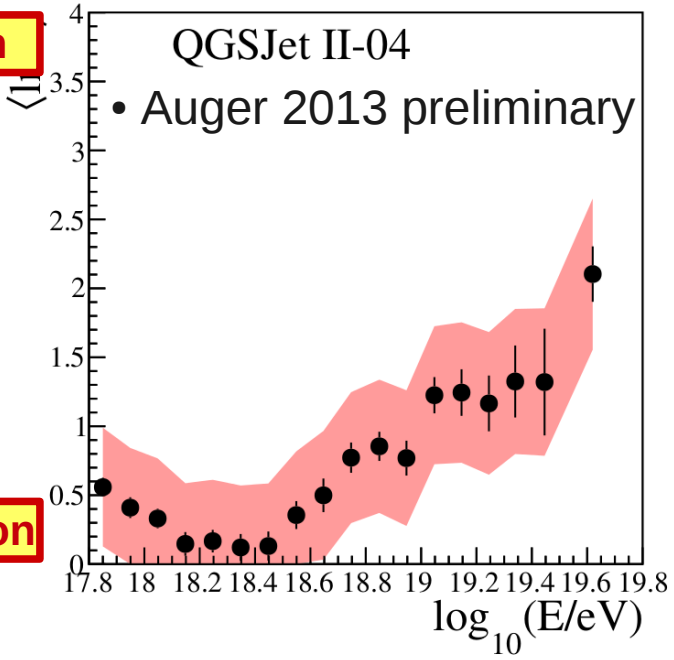
Superposition model

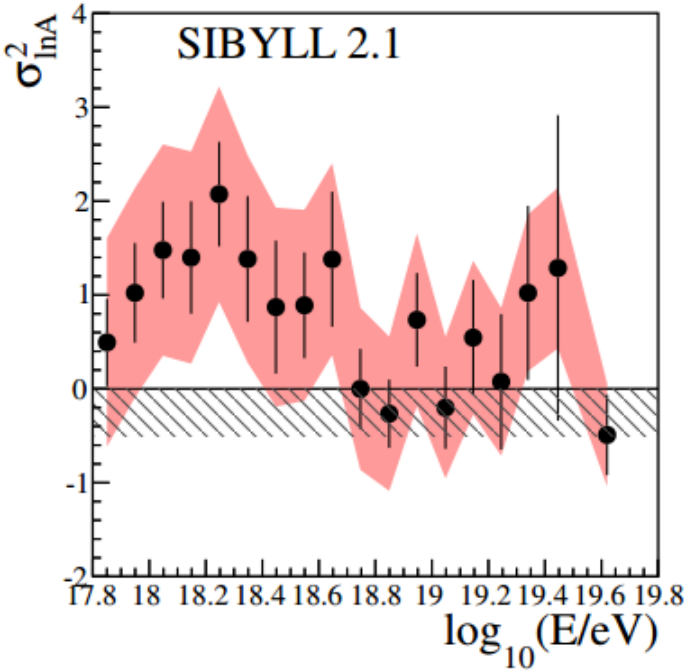
$$\langle X_{max} \rangle \approx \langle X^{p}_{max} \rangle - D_p \langle \ln(A) \rangle$$

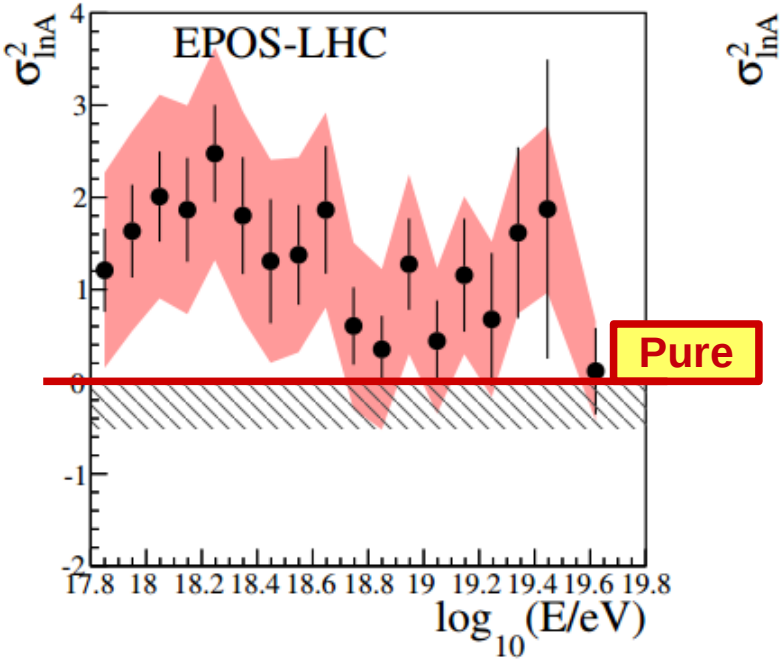
$$\sigma^2[X_{max}] \approx \langle \sigma^2_i \rangle + D^2_p \sigma^2[\ln(A)]$$

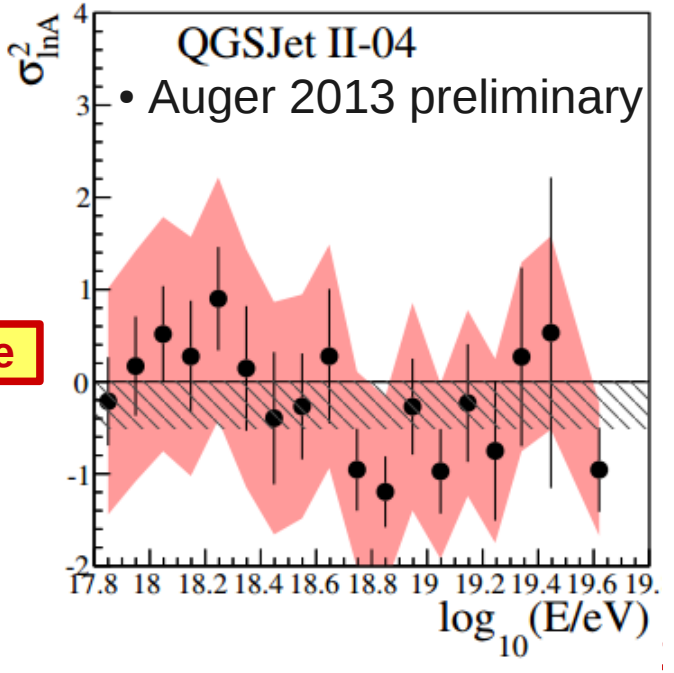












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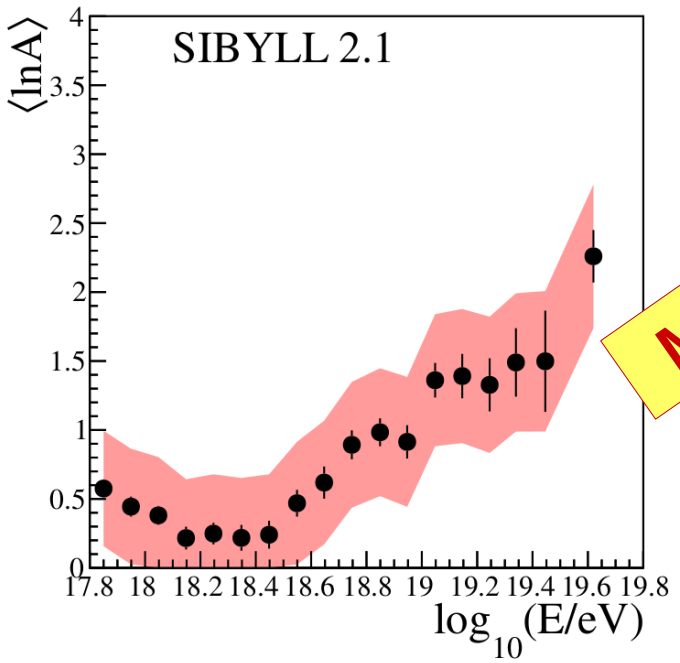
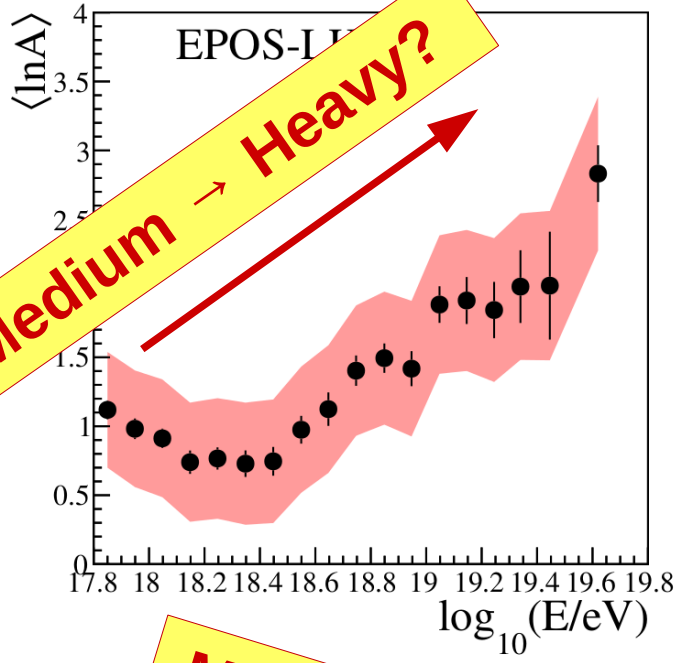
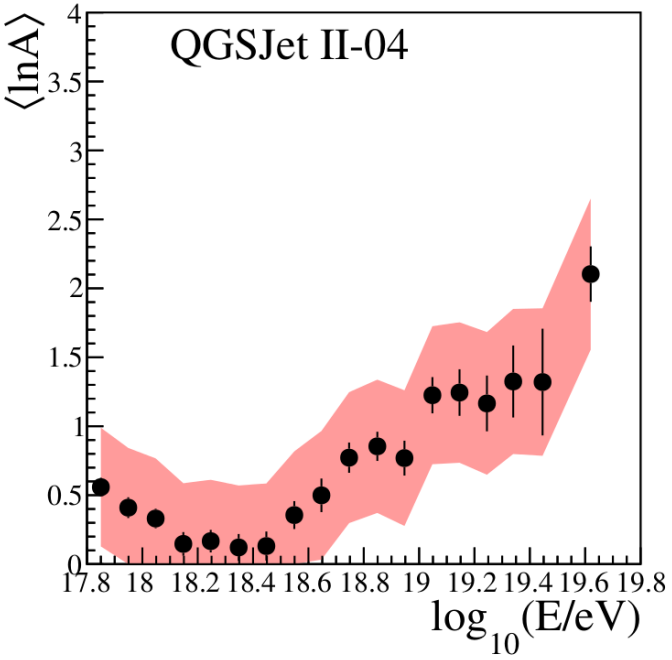
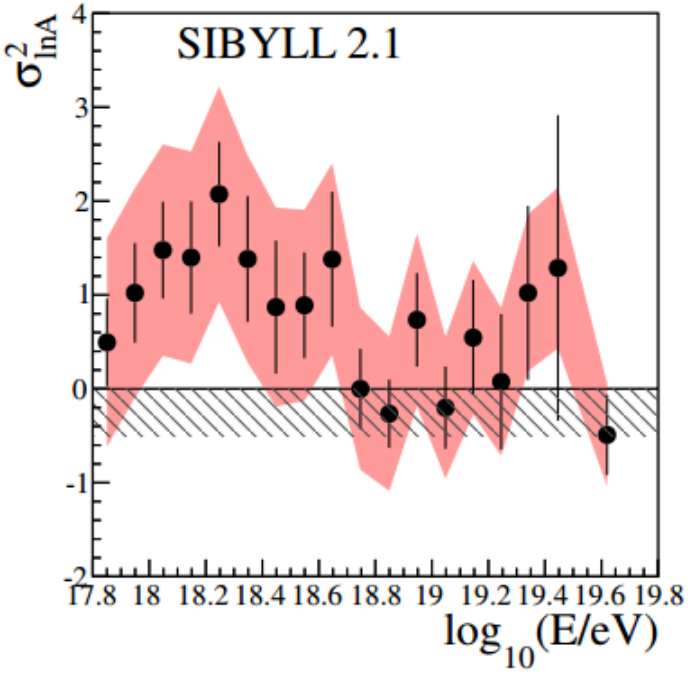


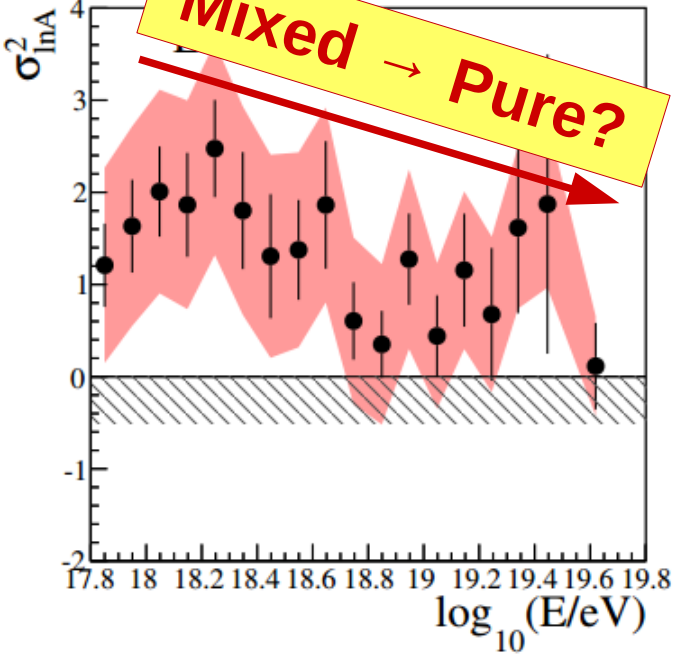


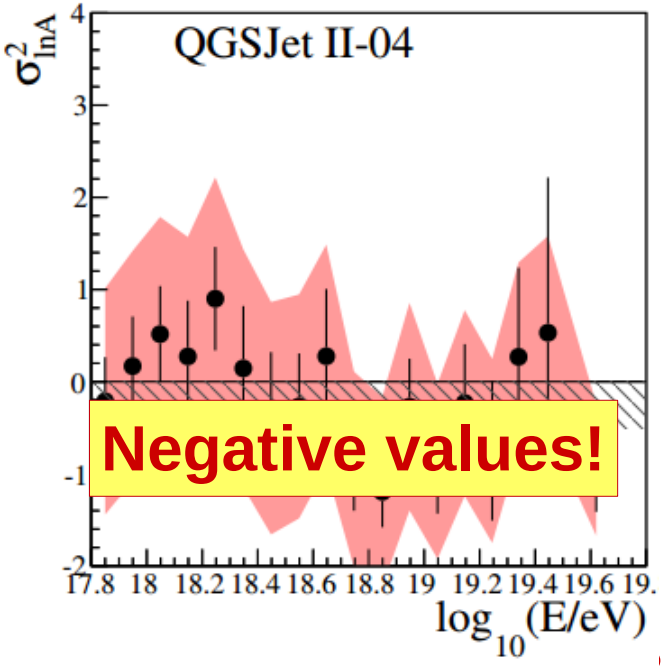
Medium → Heavy?





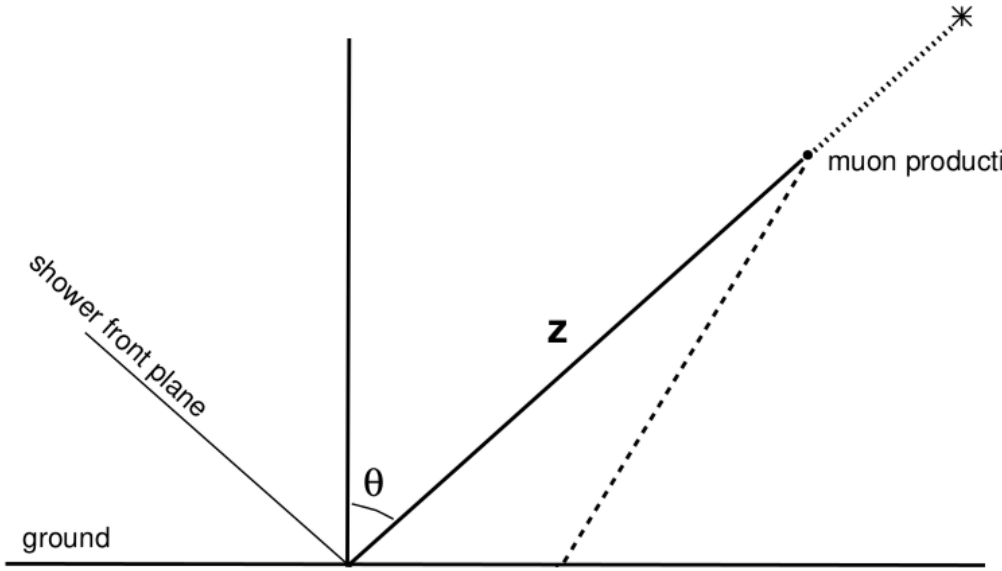
Mixed → Pure?

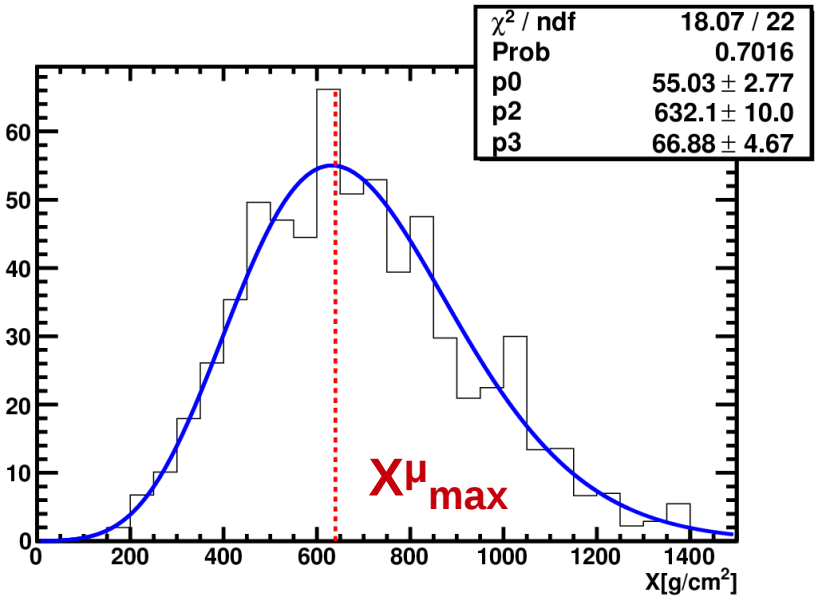




Negative values!

MPD in a nutshell





- Muons travel along straight lines close to the speed of light

Arrival time, *t* → **Production distance, *z*** → **Production depth, *X***

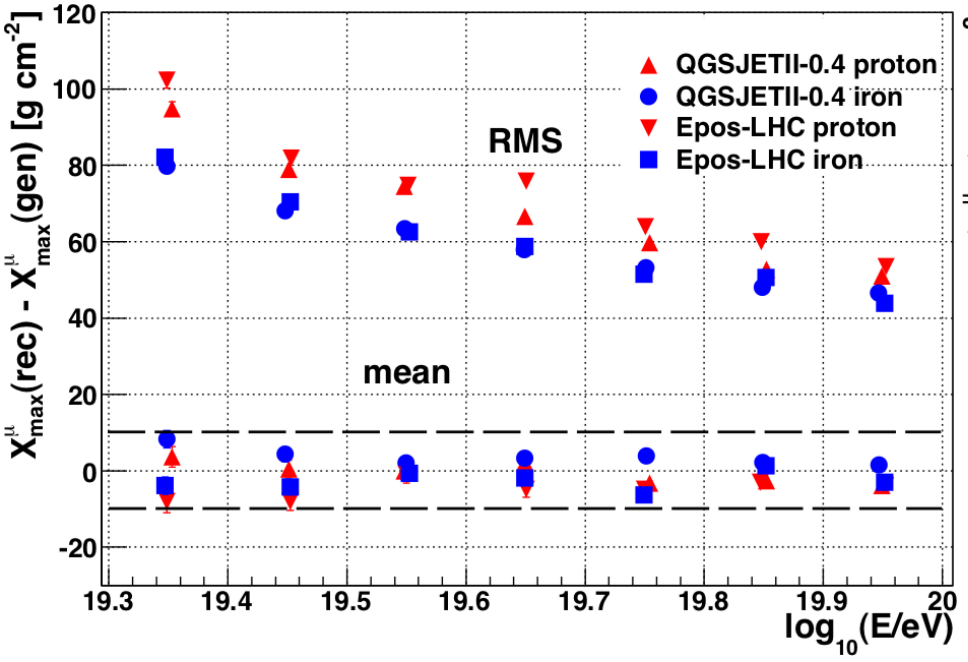
Kinematics *Atmosphere*

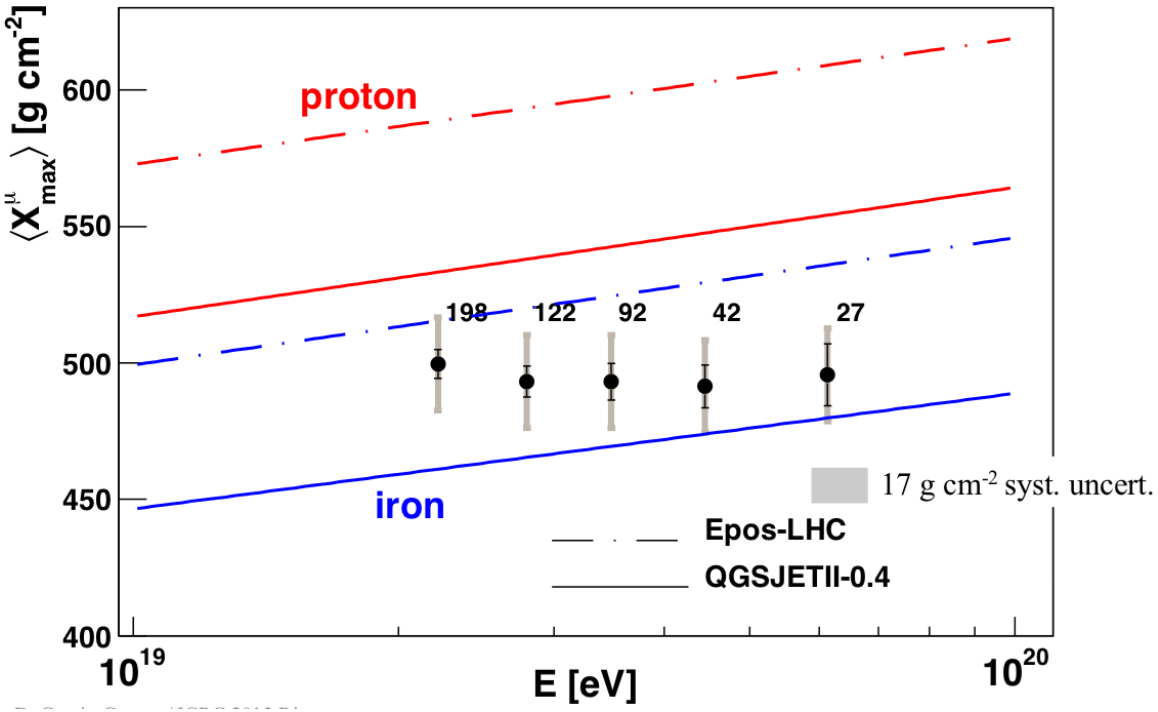
- The distribution of produced muons vs depth is the MPD

$$dN^{\mu}/dX^{\mu} \equiv MPD \xrightarrow{\text{Maximum}} X^{\mu}_{max}$$

[55º,65º] ~~EM~~

X^{μ}_{max} results



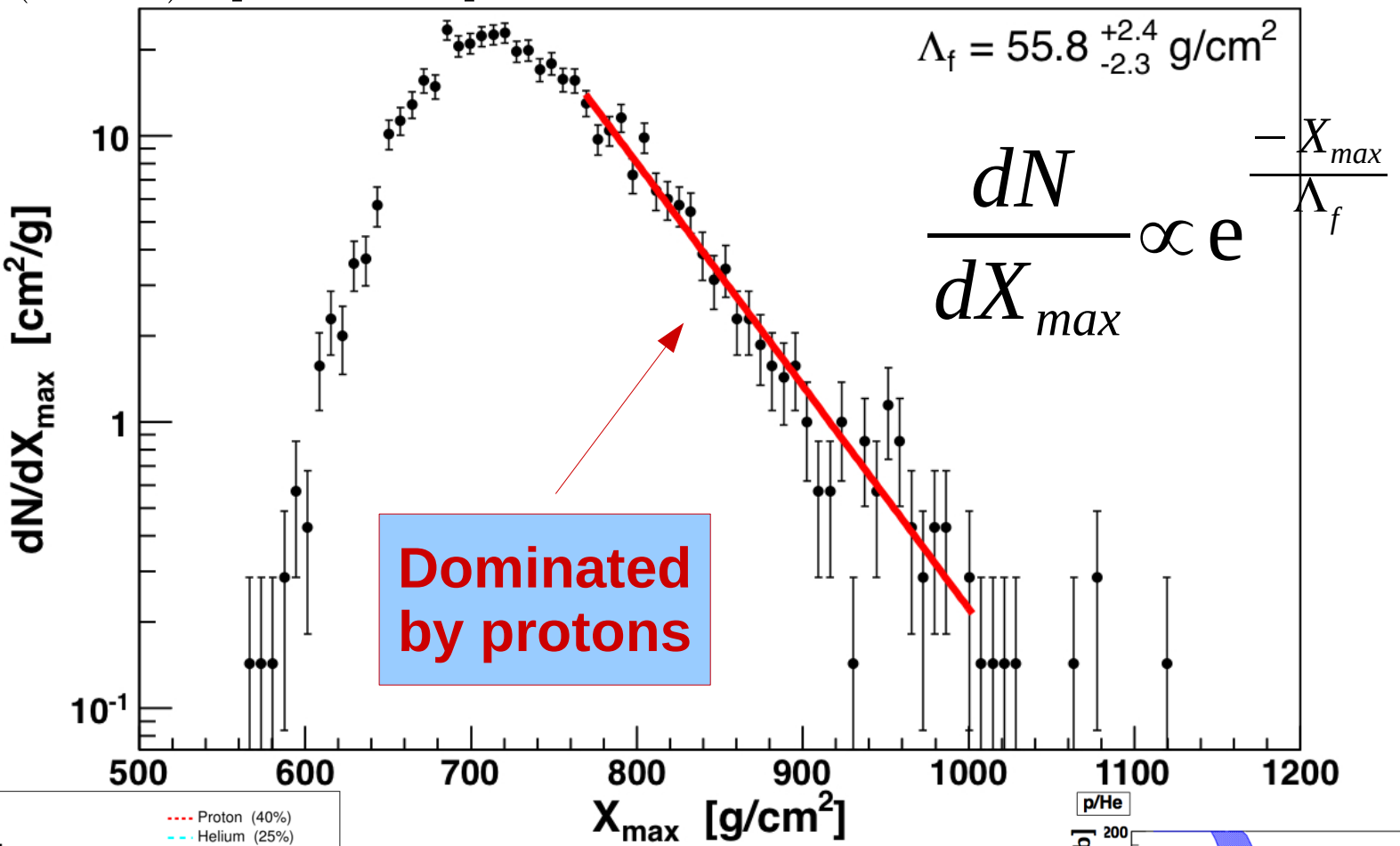


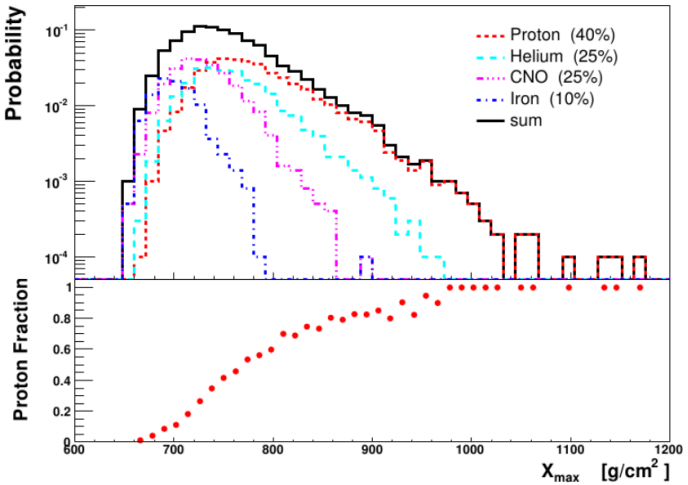
Only high energy events at 60º zenith.
Poor resolution at the lowest energies due to sparseness of the detector (low muon statistics)

Independent technique, allows additional constraints and further understanding of high energy hadronic models

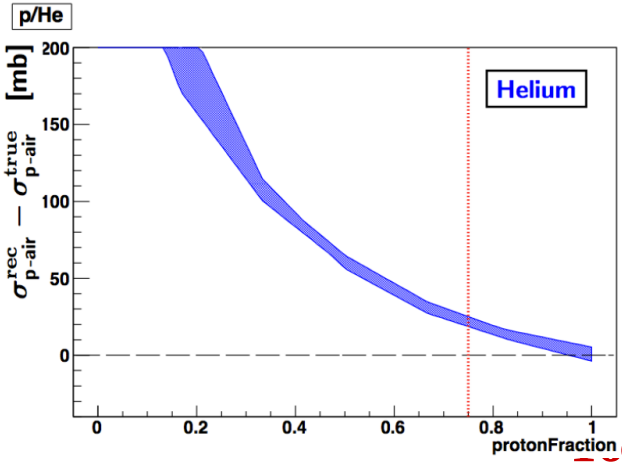
Hadronic interactions: cross section

$\log(E/eV) \in [18.0, 18.5]$

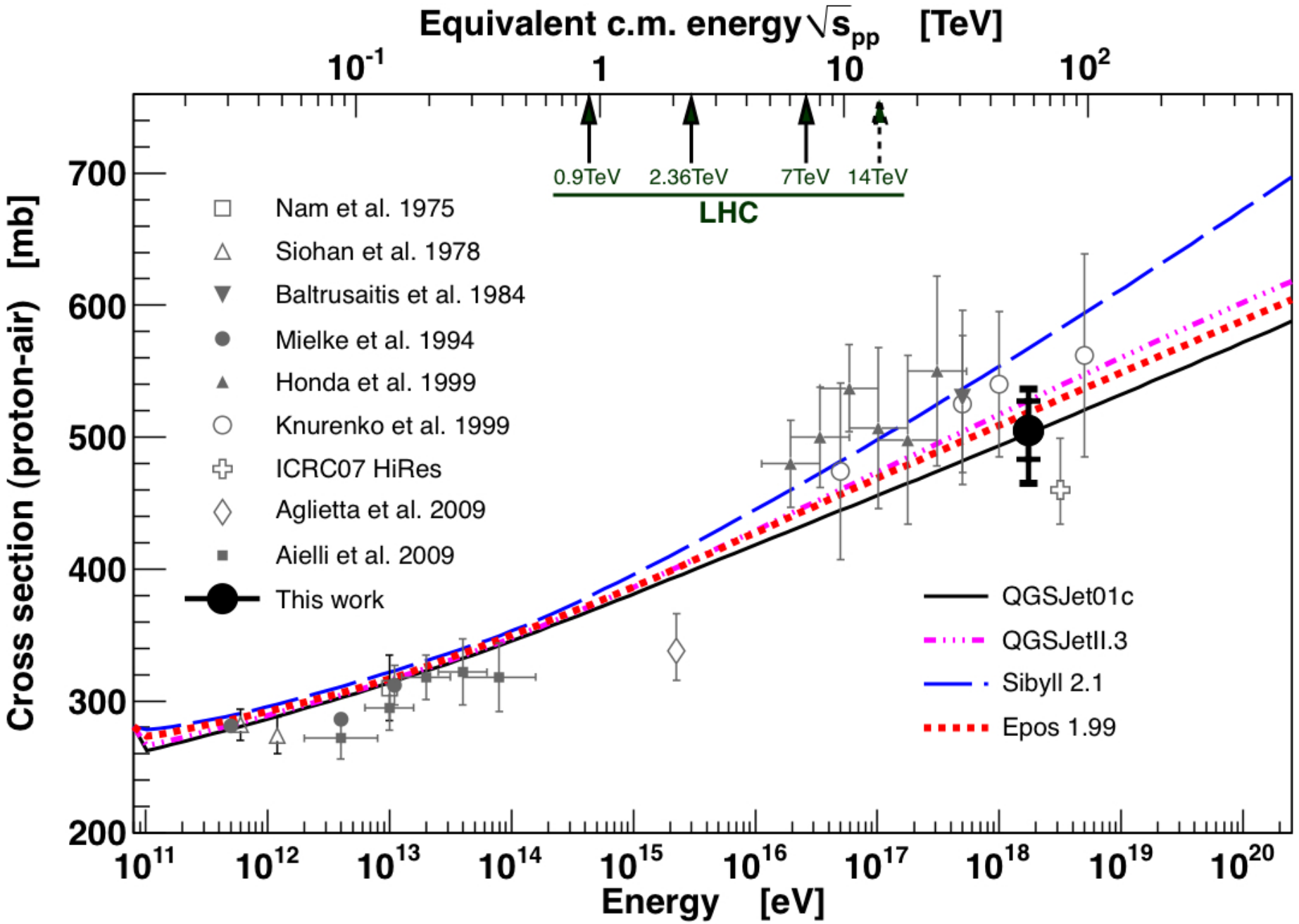




f is chosen so that a 25% He contamination gives a bias within uncertainties (*f*=0.8)

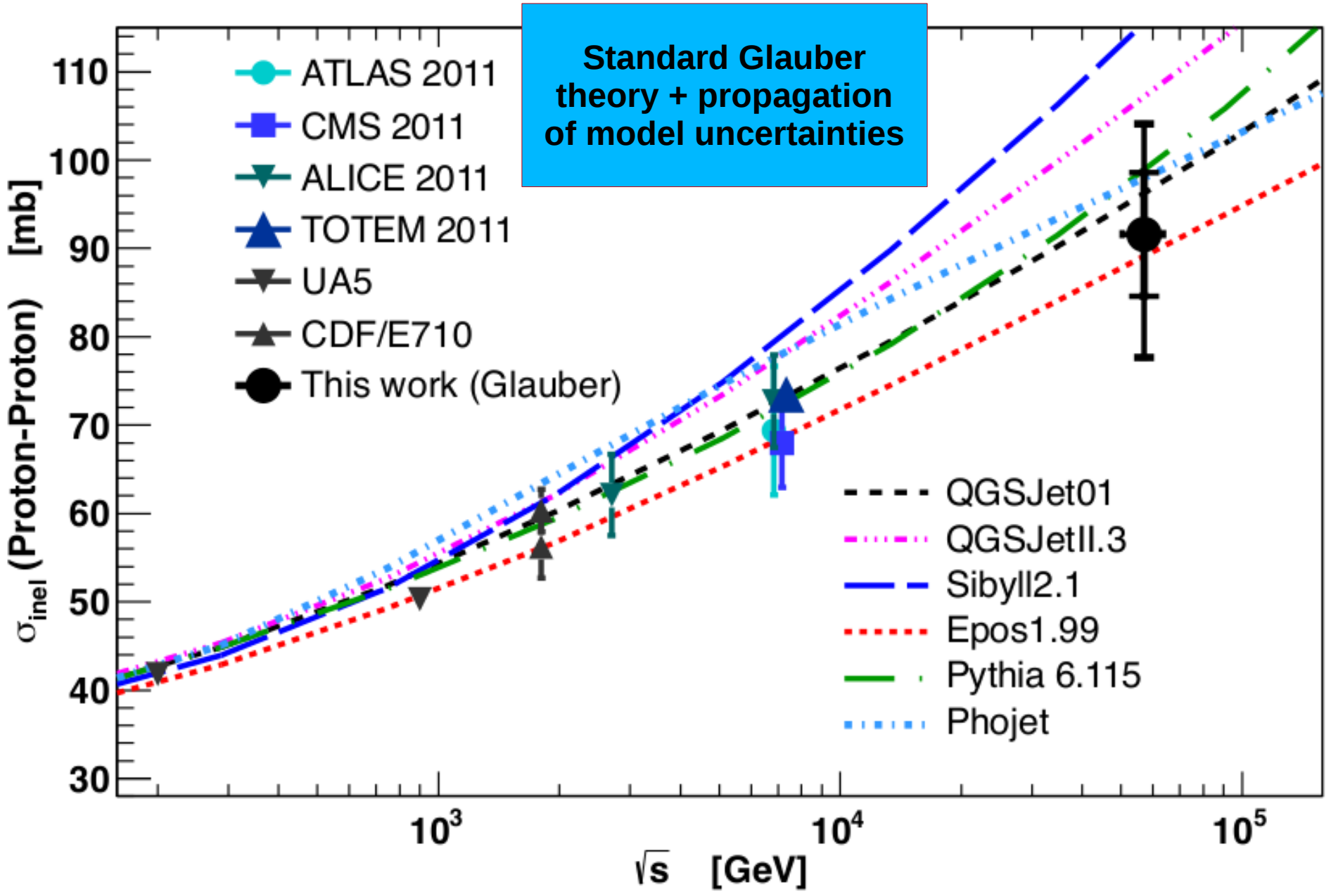


Phys. Rev. Lett. 109 (2012) 062002



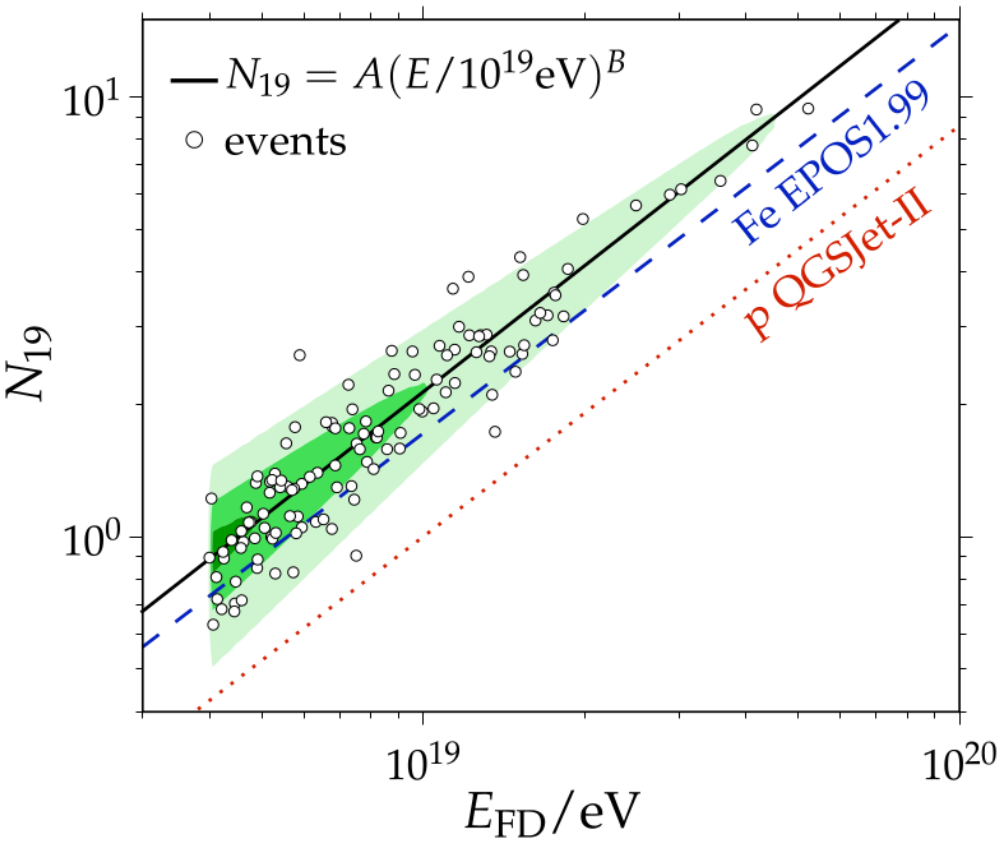
$$\sigma_{p\text{-}Air} = [505 \pm 22_{stat} (^{+28}_{-36})_{sys}]\ mb$$

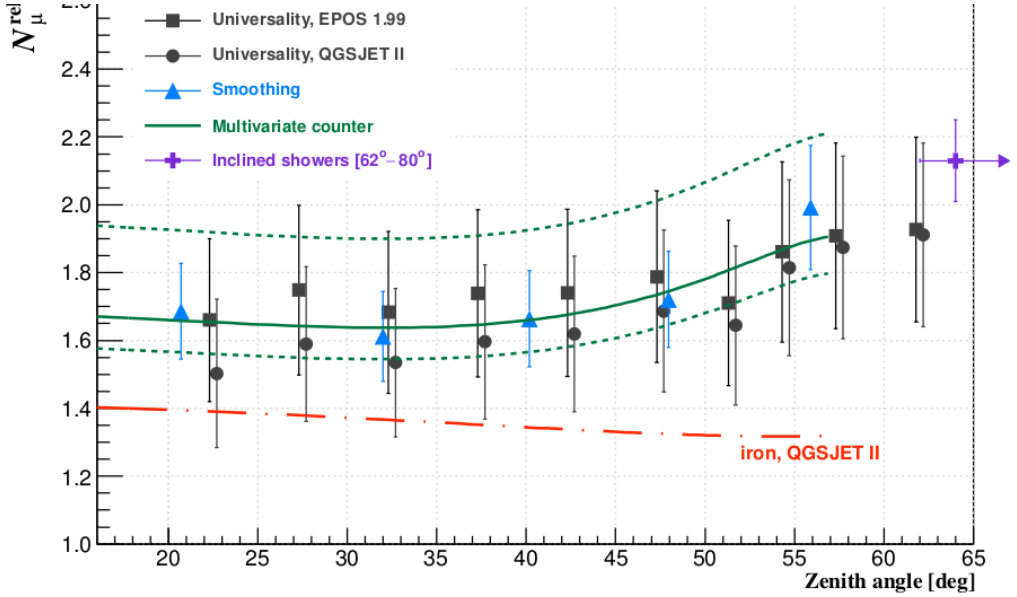
Inelastic p-p cross section at 57 TeV



$$\sigma^{inel}_{p\text{-}p} = [92 \pm 7_{stat} (^{+9}_{-11})_{sys} \pm 7_{Glauber}]\ mb$$

“Muon puzzle”





Horizontal Events (θ > 60º)

- Virtually null E.M. signal
- Shower size $N_{19} \sim N_\mu$
- The calibration of N_{19} with E_{FD} provides the muon deficit in simulations

$$\frac{N_\mu^{data}}{N_\mu^{MC}} = \frac{N_{19}^{data}}{N_{19}^{MC}} = \frac{A\left(E_{FD}/10\,EeV\right)^B}{A_{MC}\left(E_{FD}/10\,EeV\right)^{B_{MC}}}$$

Result confirmed by several different techniques

$$\frac{N_\mu^{data}}{N_\mu^{MC}} \approx 1.6-1.7\,;\,\theta<55^\circ$$

$$\frac{N_\mu^{data}}{N_\mu^{MC}} \approx 1.9-2.0\,;\,\theta>55^\circ$$

Results summary

- The observatory works like clockwork
- Our data exhibit a coherent behaviour of observables
- 20 σ flux suppression at log(E/eV) = 19.6 compatible with GZK but also with source exhaustion
- Pure composition of UHECRs is disfavoured by our data
- The highest energy constraint to p-p cross section so far (through Glauber model)
- New hints on the validity of high energy hadronic models

BACKUP

New energy scale

Absolute fluorescence yield	**-8.2%**
New opt. eff.	4.3%
Calibr. database update	3.5%
Sub total (FD cal.)	**7.8%**
Likelihood fit of dE/dX	2.2%
Folding with point. spr. func.	9.4%
Sub total (FD prof. rec.)	**11.6%**
Invisible energy	**4.4%**

E_{FD} change: 15.6%

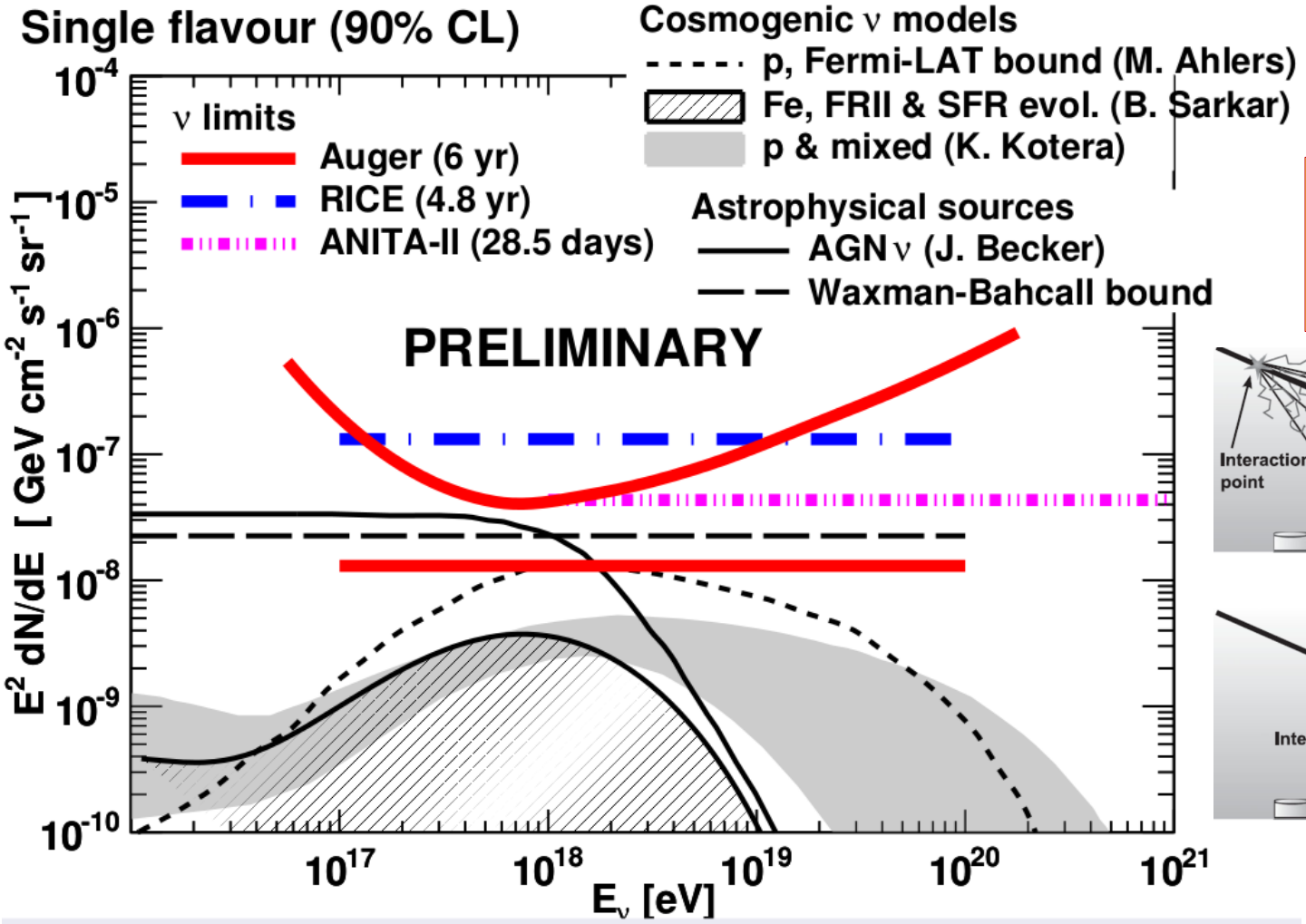
Aerosol optical depth	**3% ÷ 6%**
Horizontal uniformity of aerosols	**1%**
Atmosphere variability	**1%**
Nightly relative calibration	**3%**
Statistical error of the profile fit	**5% ÷ 3%**
Uncertainty in shower geometry	**1.5%**
Invis. Energy (shower-to-shower fluc.)	**1.5%**

E_{FD} resolution: 7% - 8%

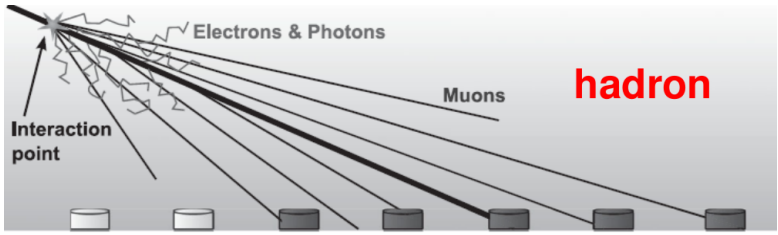
Absolute fluorescence yield	**3.4%**
Fluores. spectrum and quenching param.	**1.1%**
Sub total (Fluorescence Yield)	**3.6%**
Aerosol optical depth	**3% ÷ 6%**
Aerosol phase function	**1%**
Wavelength dependence of aerosol scattering	**0.5%**
Atmospheric density profile	**1%**
Sub total (Atmosphere)	**3.4% ÷ 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 reconstruction)	**6.5% ÷ 5.6%**
Invisible energy	**3% ÷ 1.5%**
Statistical error of the SD calib. fit	**0.7% ÷ 1.8%**
Stability of the energy scale	**5%**

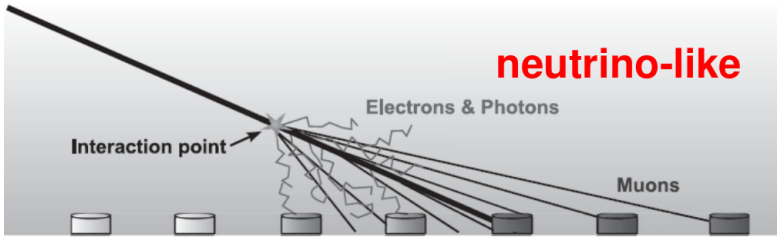
E_{SD} resolution: 14%

Neutrino searches



ν signature: young, wide showers

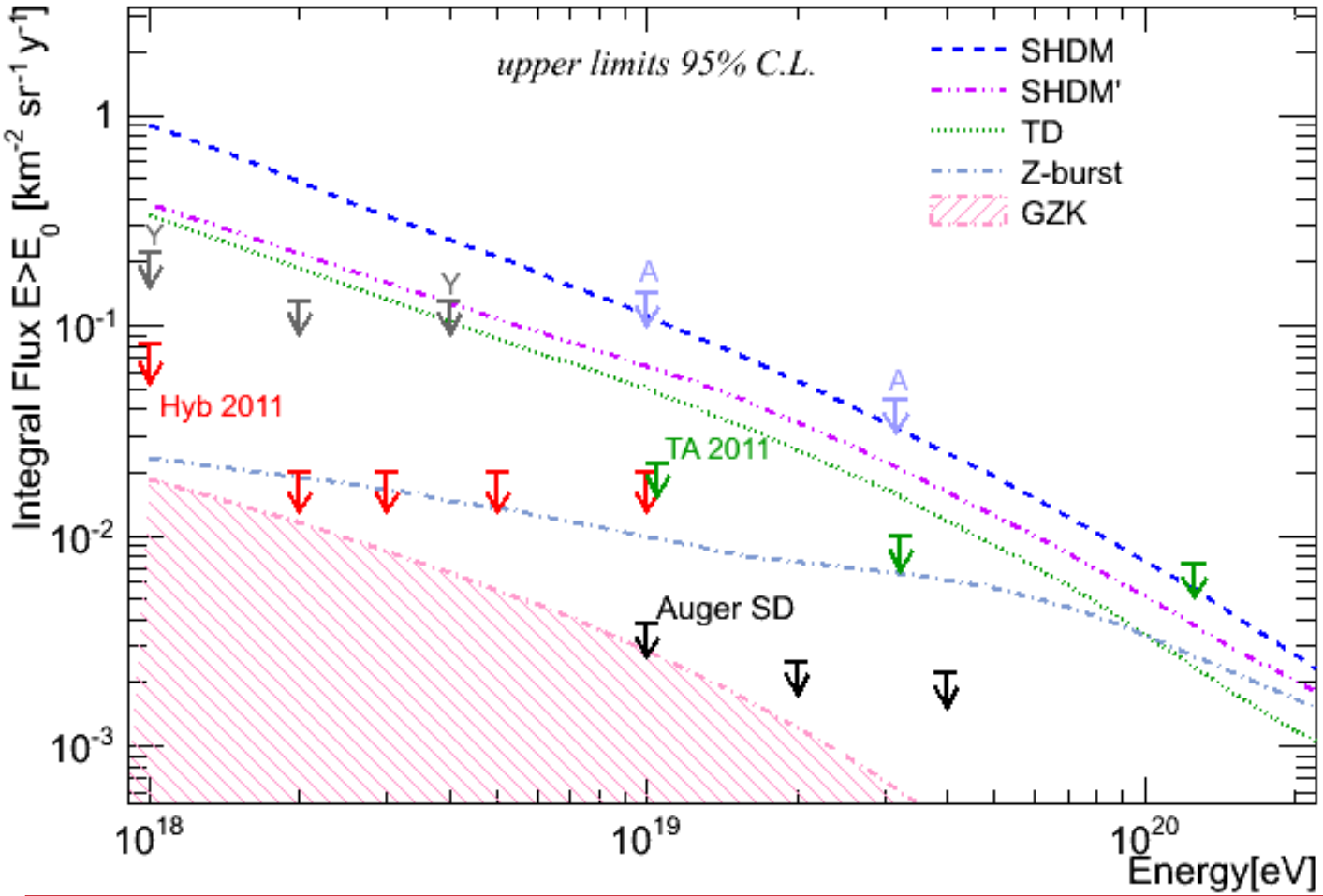


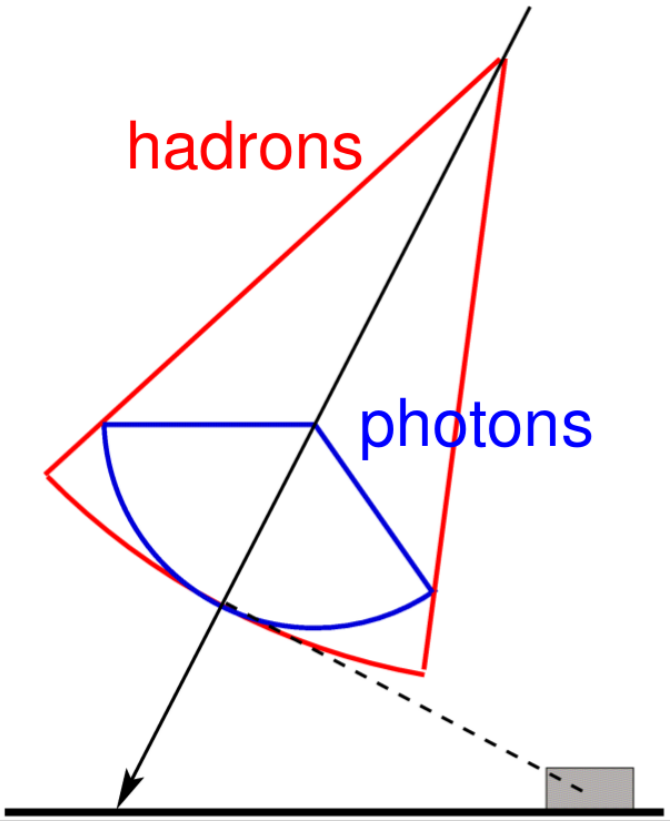


- Constrains on astrophysical source models
- Auger limit below Waxman-Bahcall upper bound
- IceCube E^{-2} flux at 0.1 - 1 PeV extrapolated to EeV excluded at ~ 90% C.L. (arXiv:1304.5356v1)

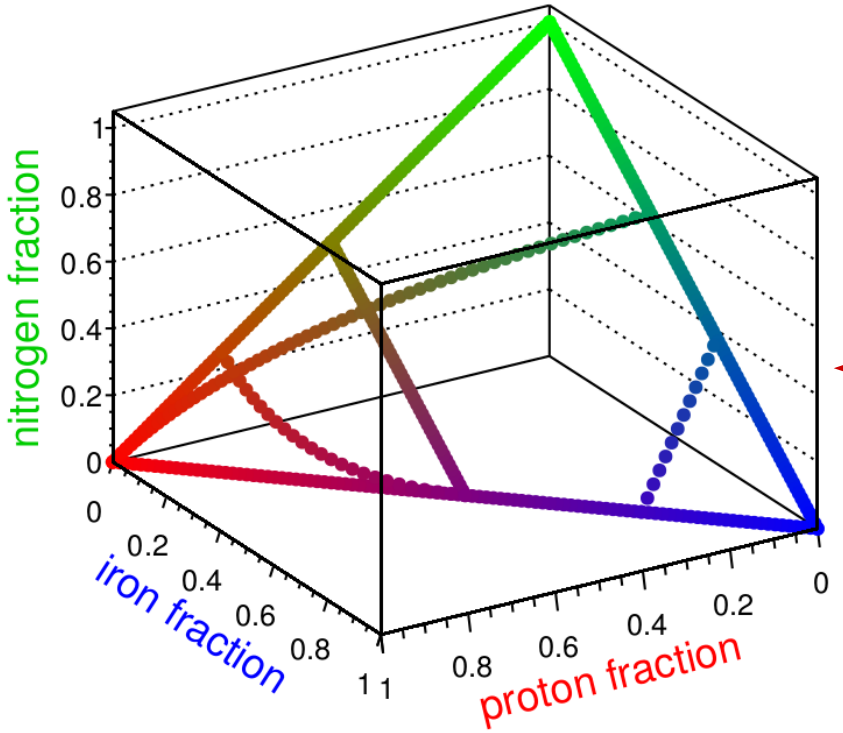
Photon searches

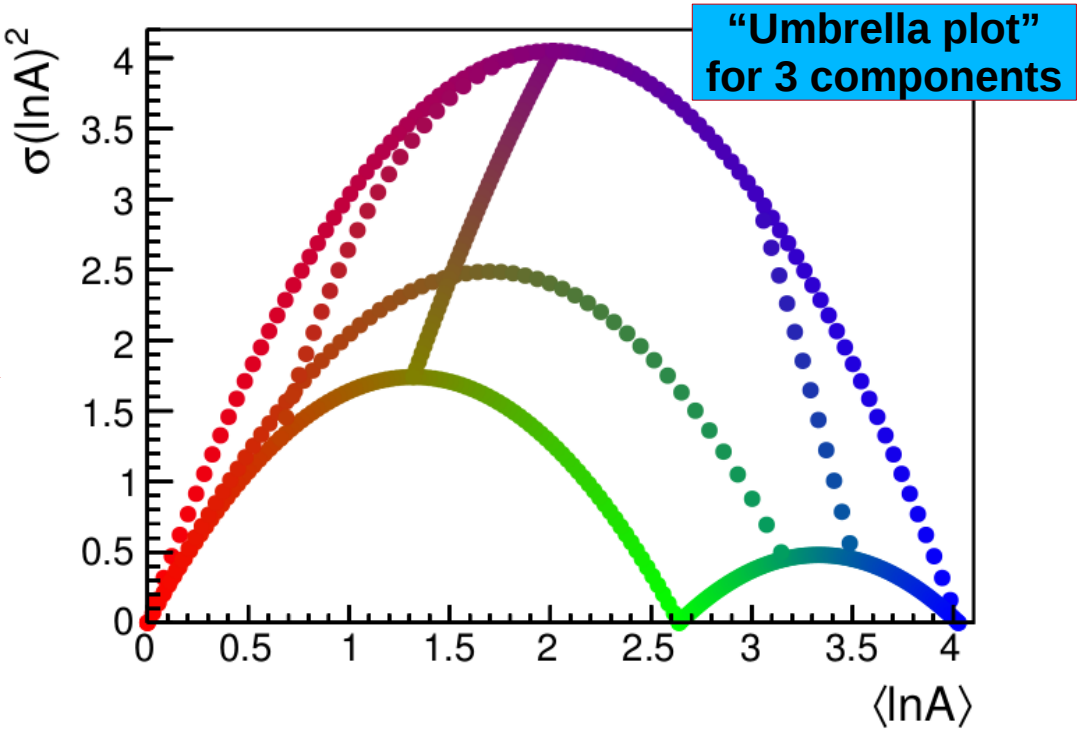
γ signature: deep, low-signal showers



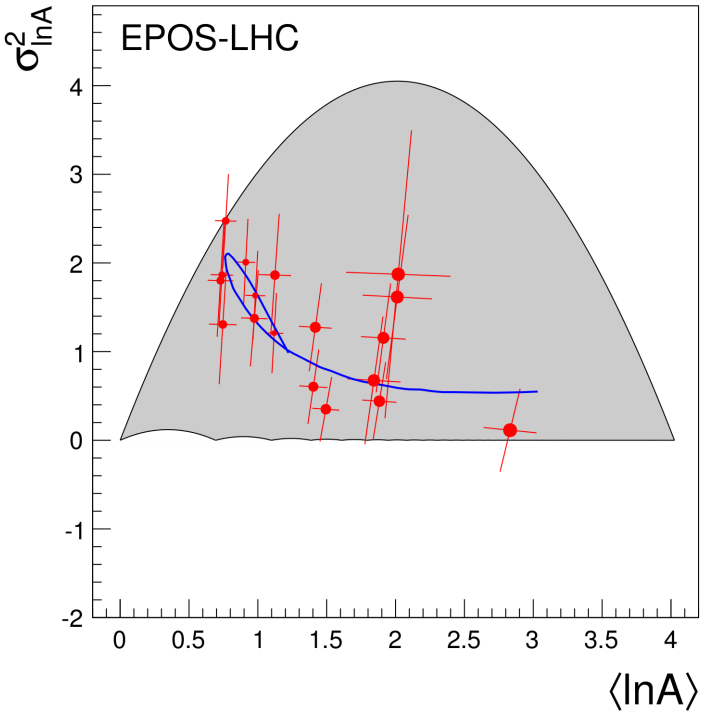


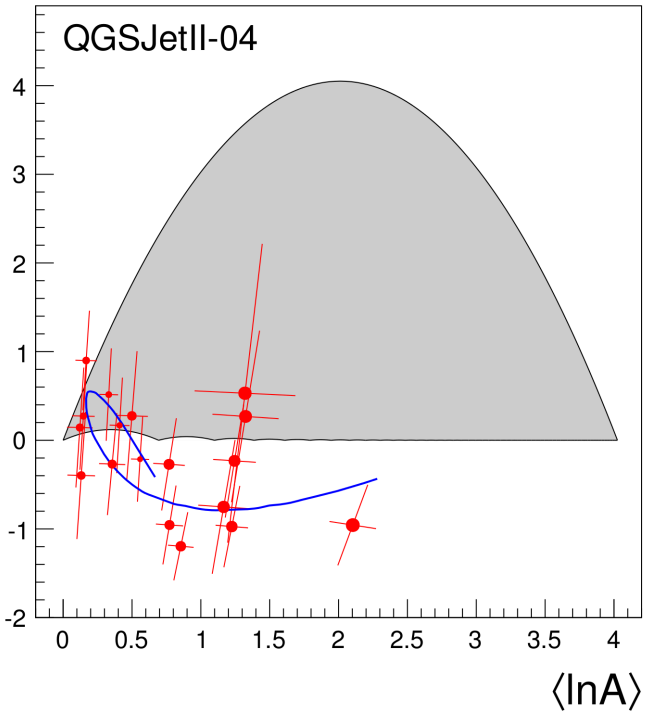
- Top-down model severely disfavoured
- Close to GZK prediction (would provide independent proof)

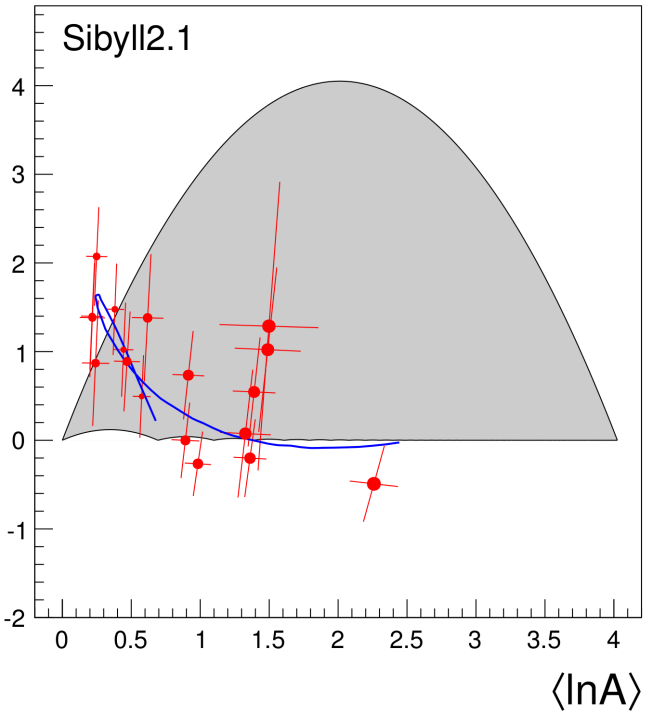




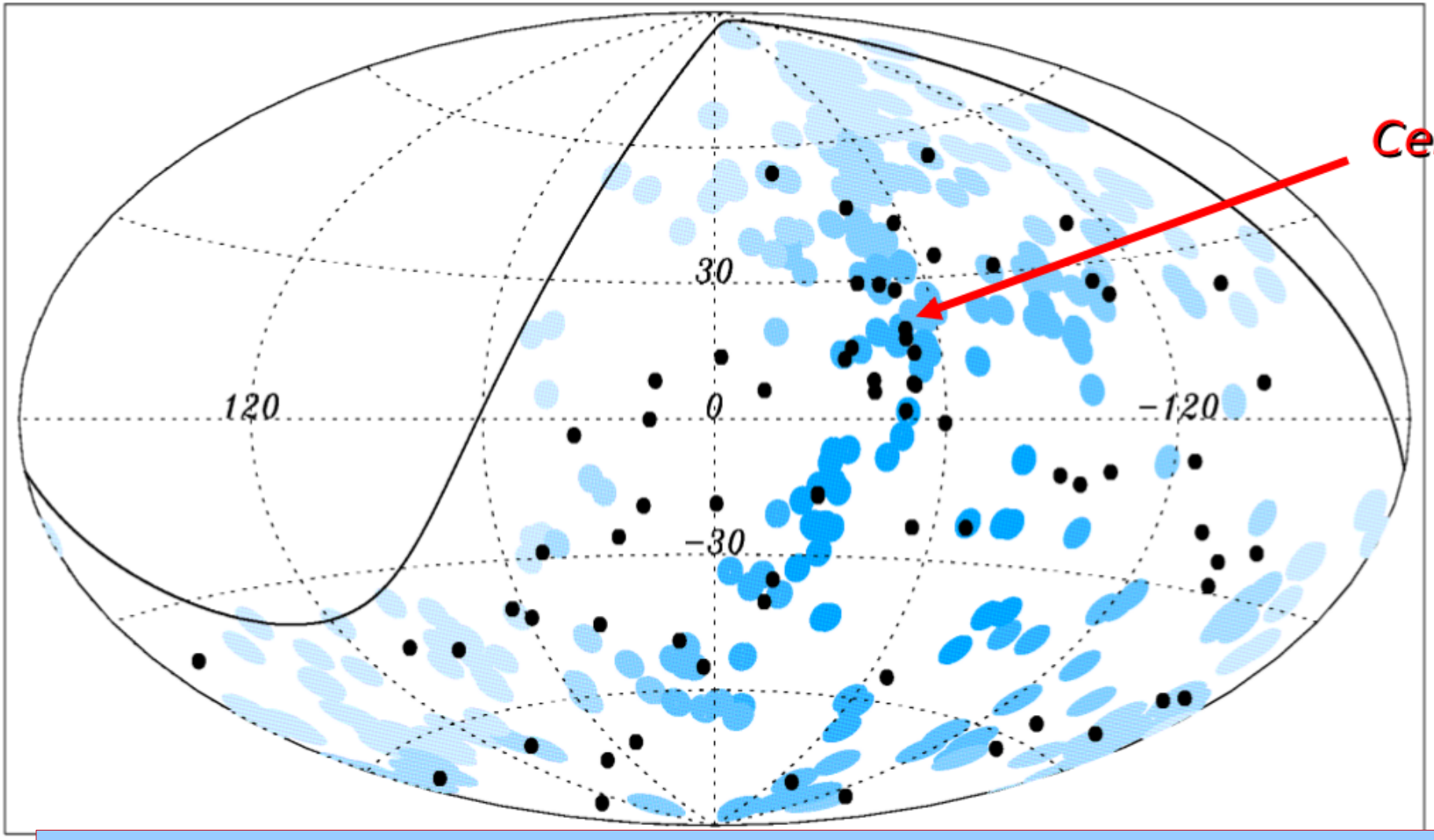
"Umbrella plot" for 3 components



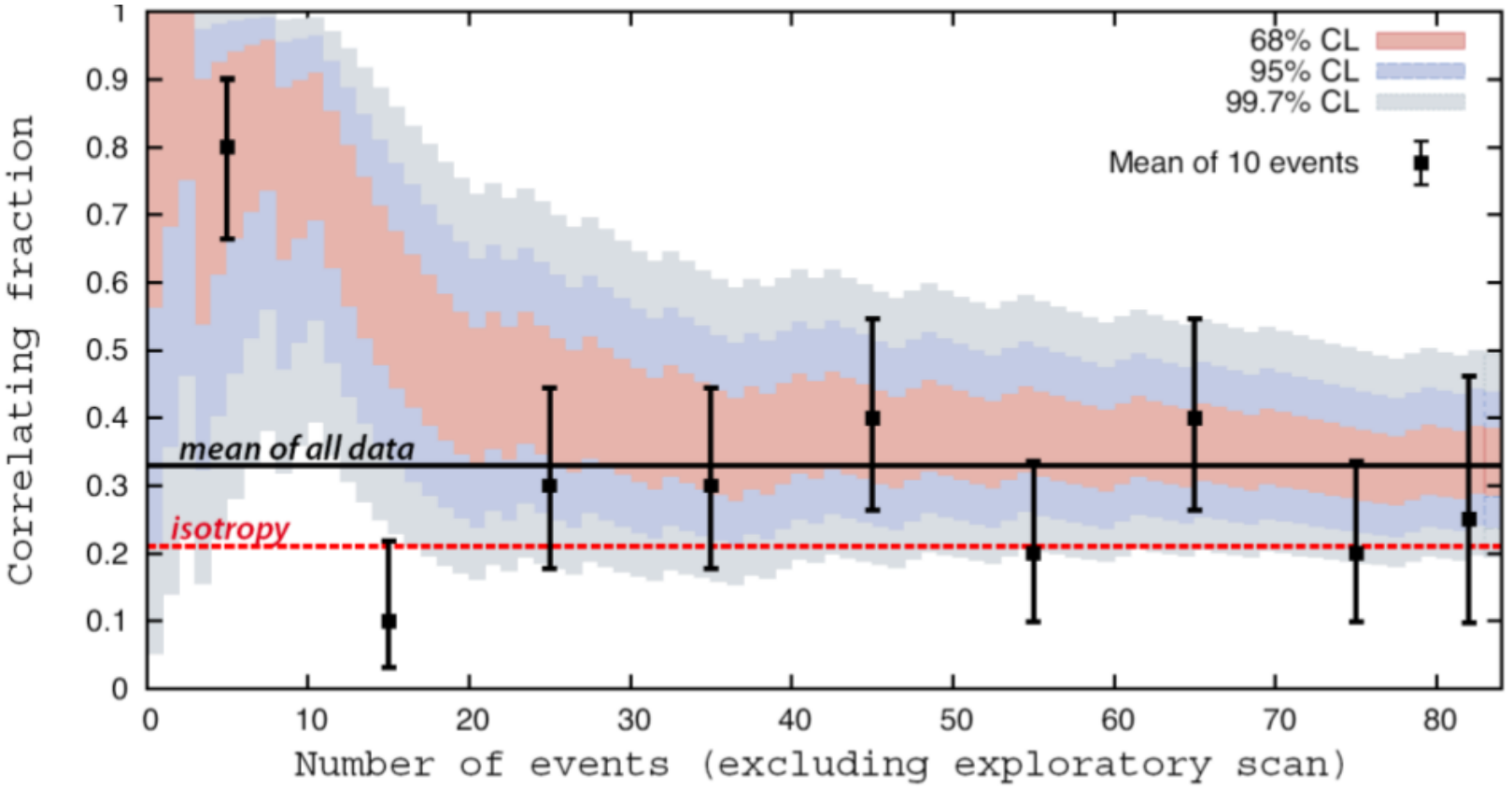


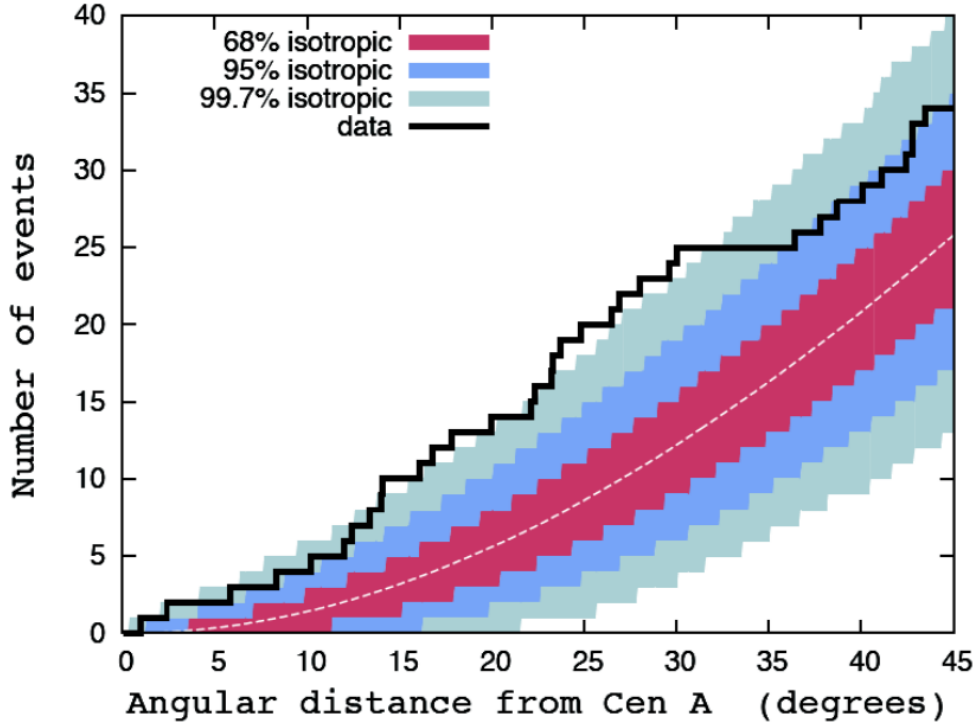


Anisotropy



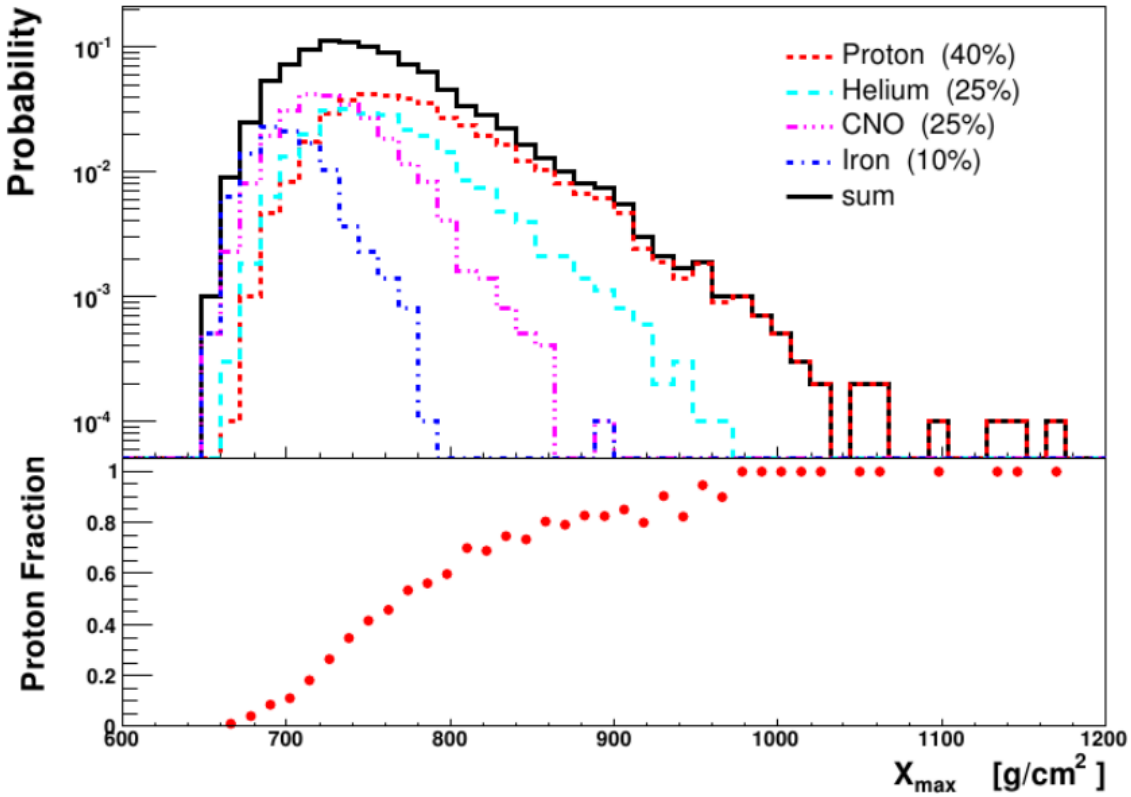
The 69 events with E > 55 EeV.
Blue circles of radius 3.1° centred at AGNs < 75 Mpc in the VCV cat.



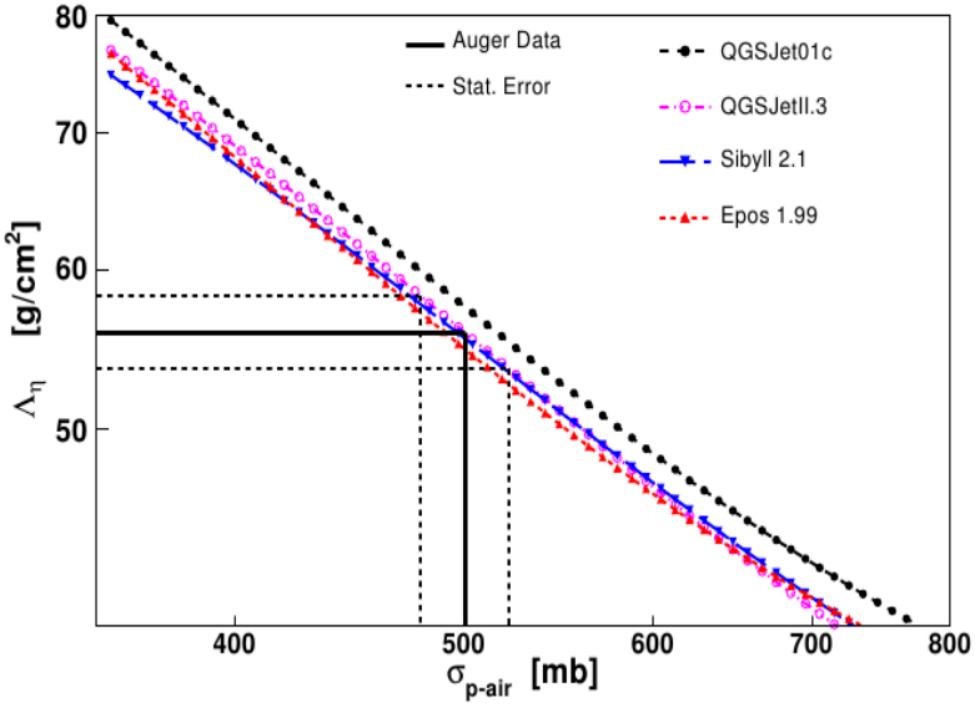


Anisotropy and excess around Cen A are of the order of 2-sigma

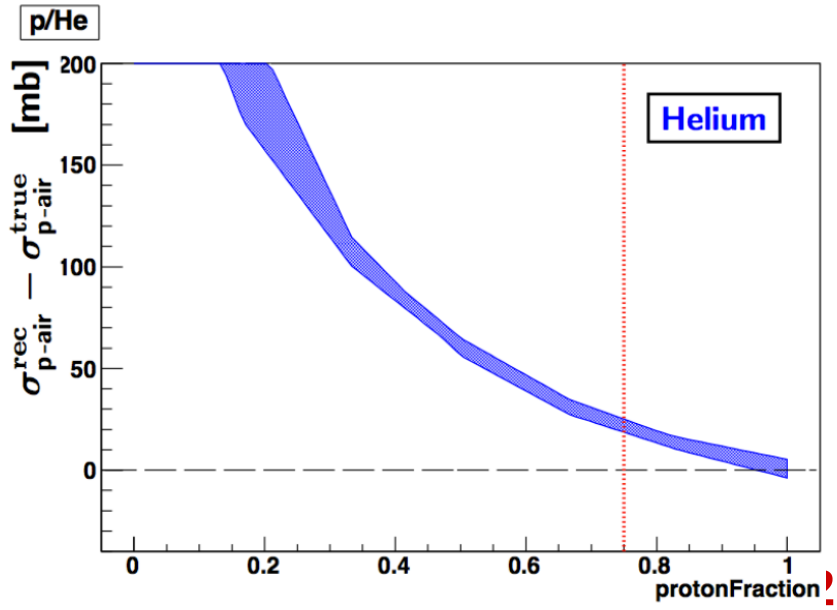
Select protons

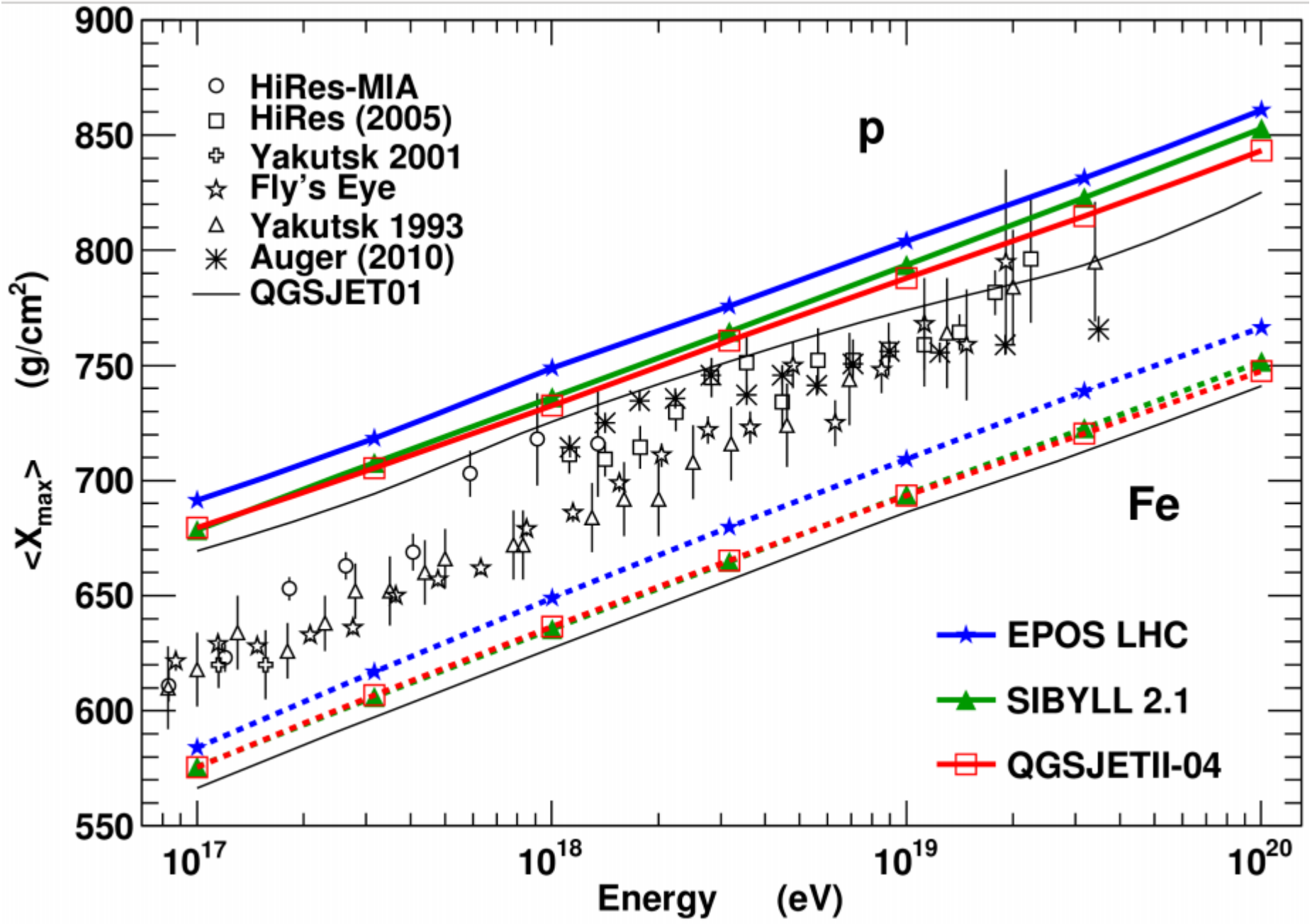


Conversion to cross section

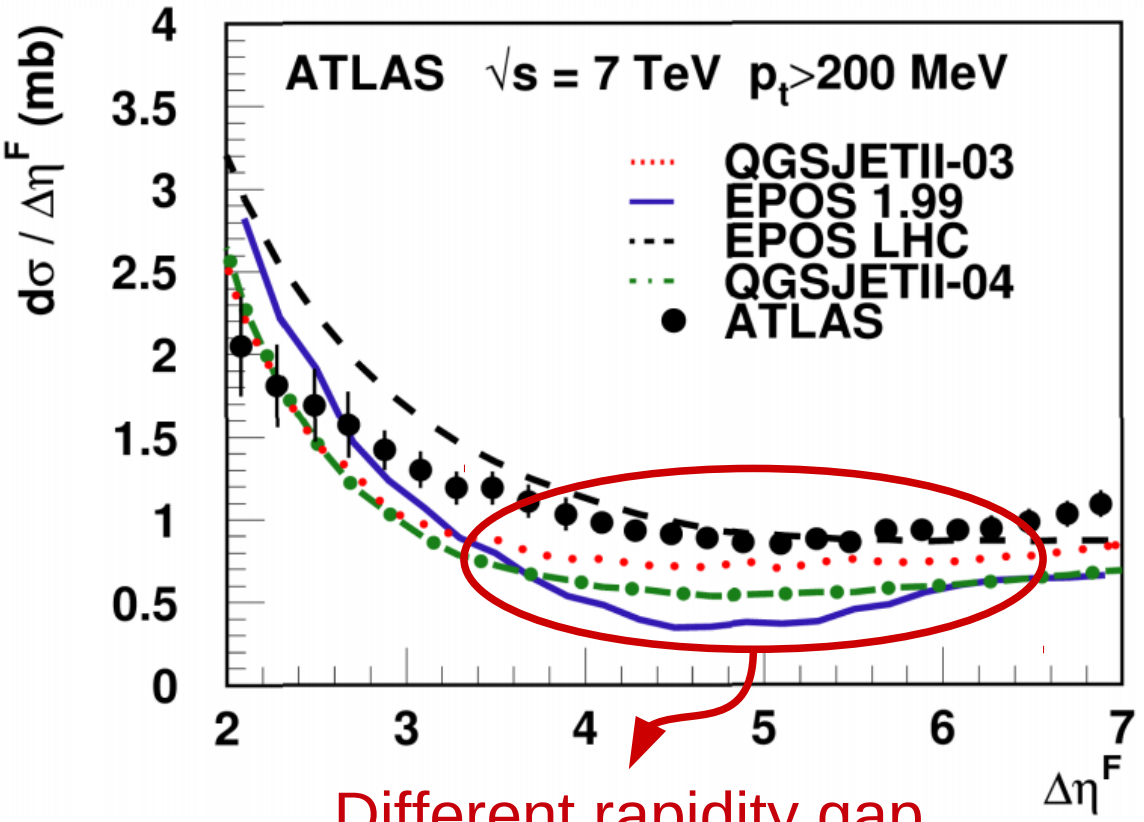


Reconstruction bias vs p fraction



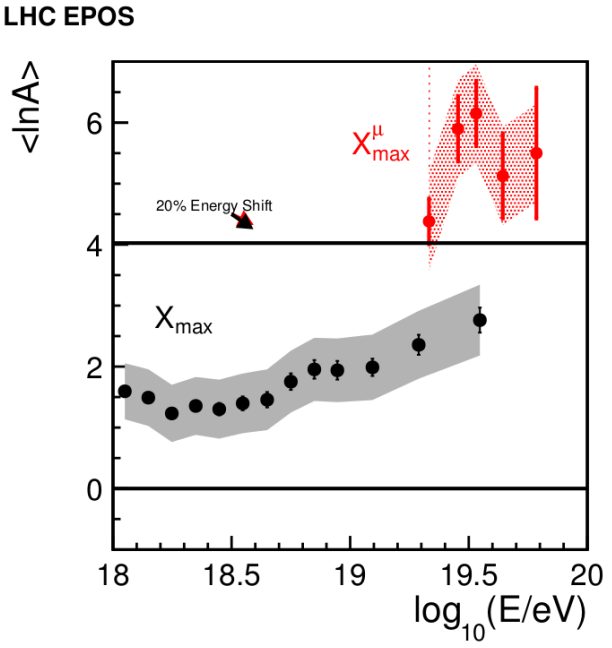


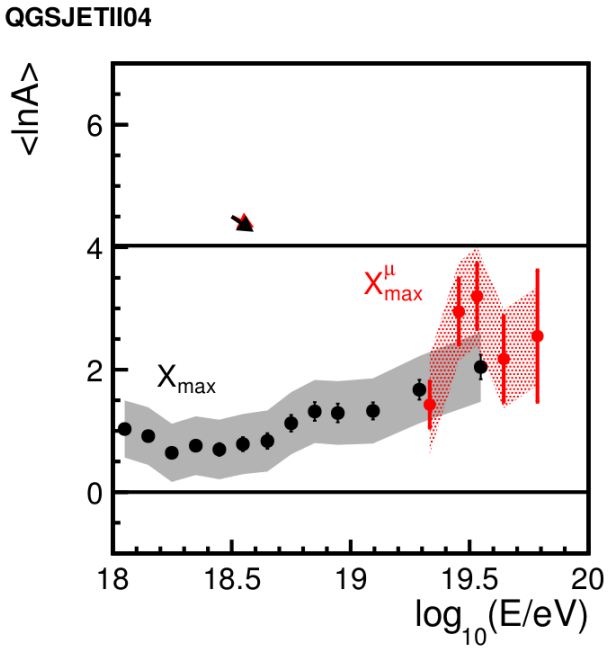
- Comparison among different experiments and new MCs (T. Pierog, Rencontres de Moriond, VHEPU, La Thuille, March 2013)



Different rapidity gap distributions

(T. Pierog, Rencontres de Moriond, VHEPU, La Thuille, March 2013)





L. Cazón