Ultra high energy cosmic rays: highlights of recent results

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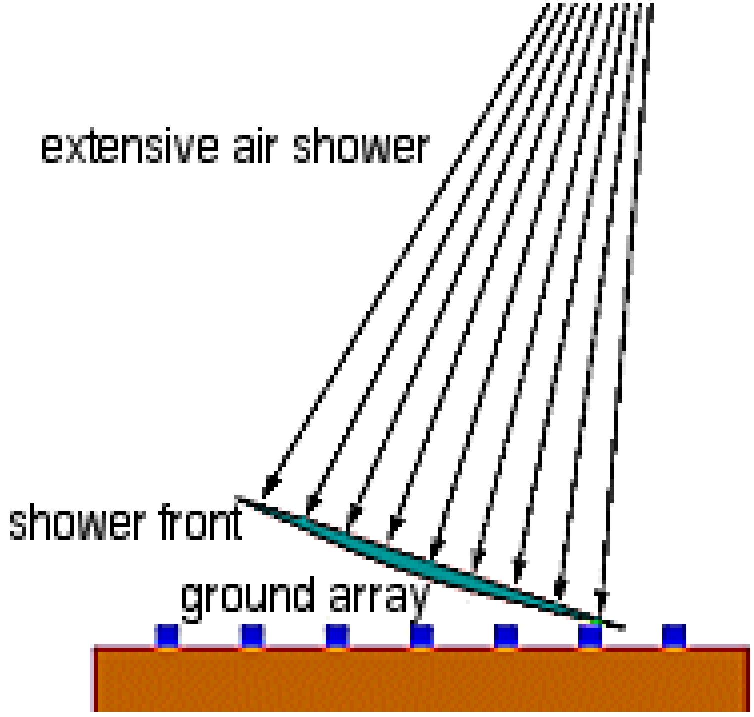
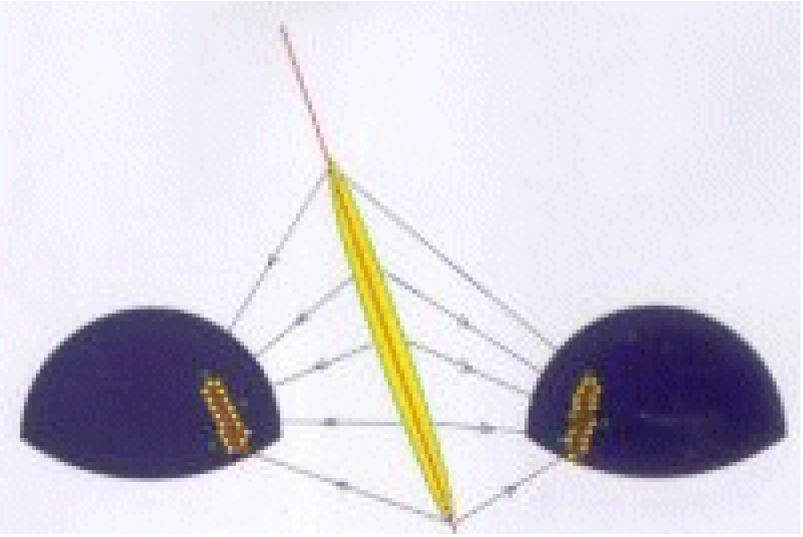
Pierre Auger Observatory
Louisiana State University
19 August 2014

International Symposium on Very High Energy Cosmic Ray Interactions, ISVHECRI 2014



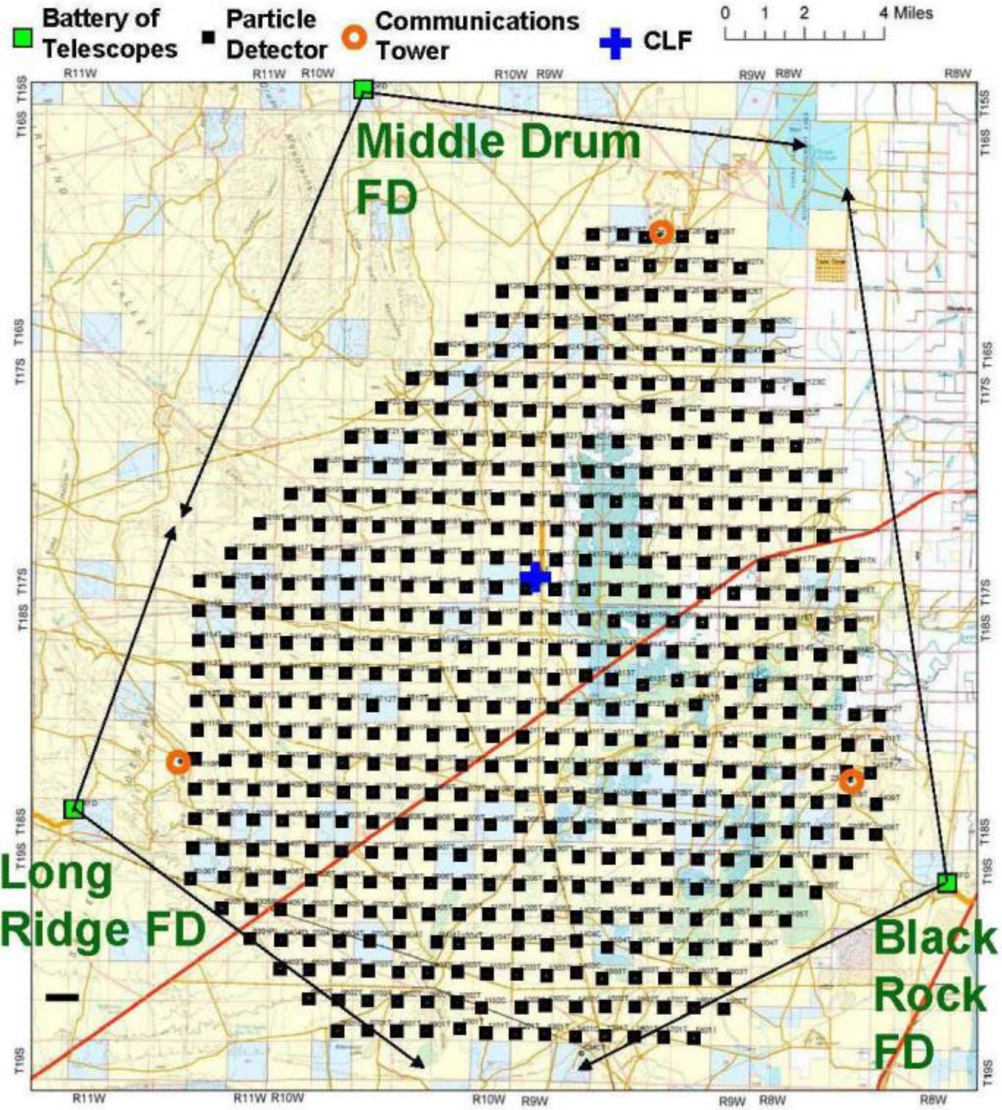


Surface Arrays and Fluorescence Detection

- *Arrays: 24/7 operation, large size (statistics)*

- *Fluorescence: 'calorimetry' = good energy resolution (spectrum)*

Telescope Array



Fluorescence: 3 telescopes

Surface Array: covers 700 km^2
507 scintillator stations (3 m^2, 1.2 km separation)

(See talk by P.Sokolsky, this meeting)

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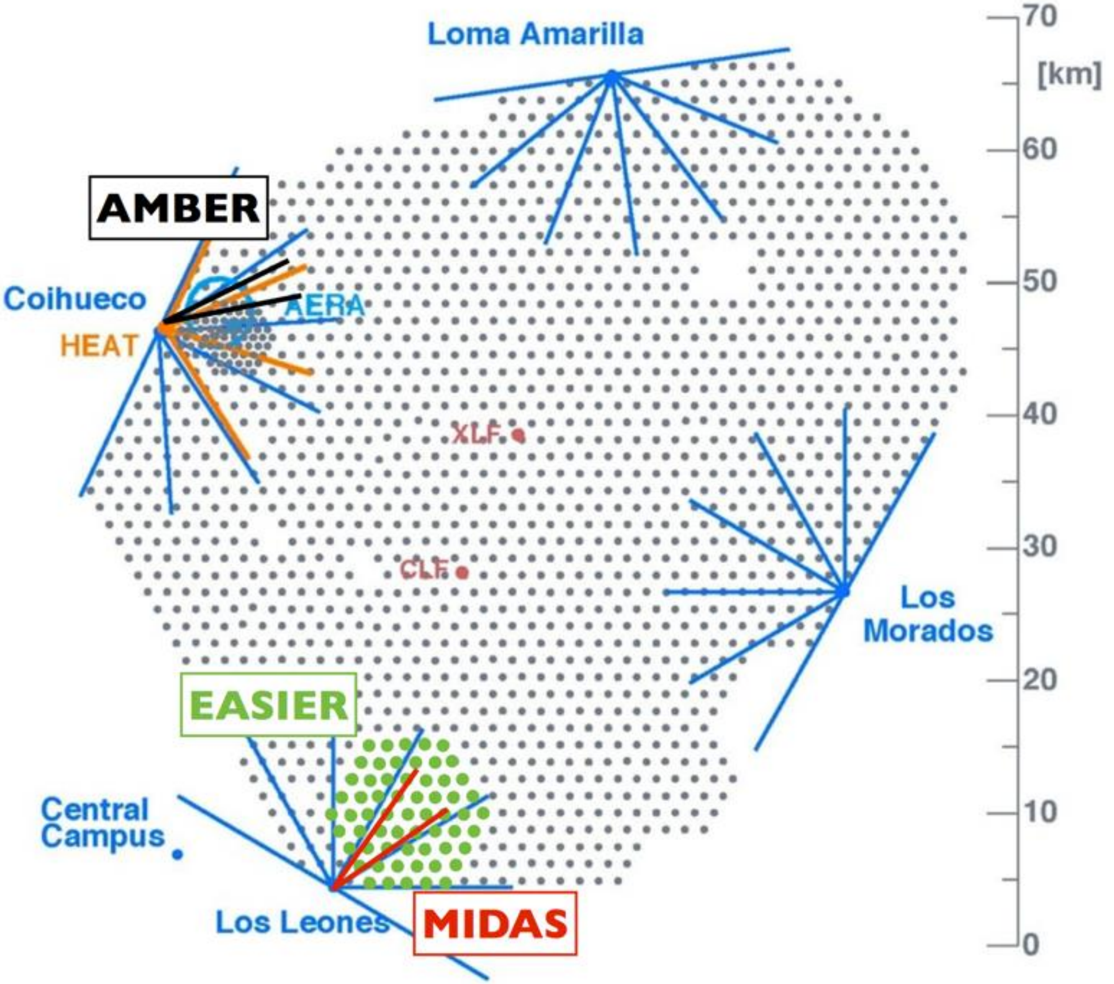
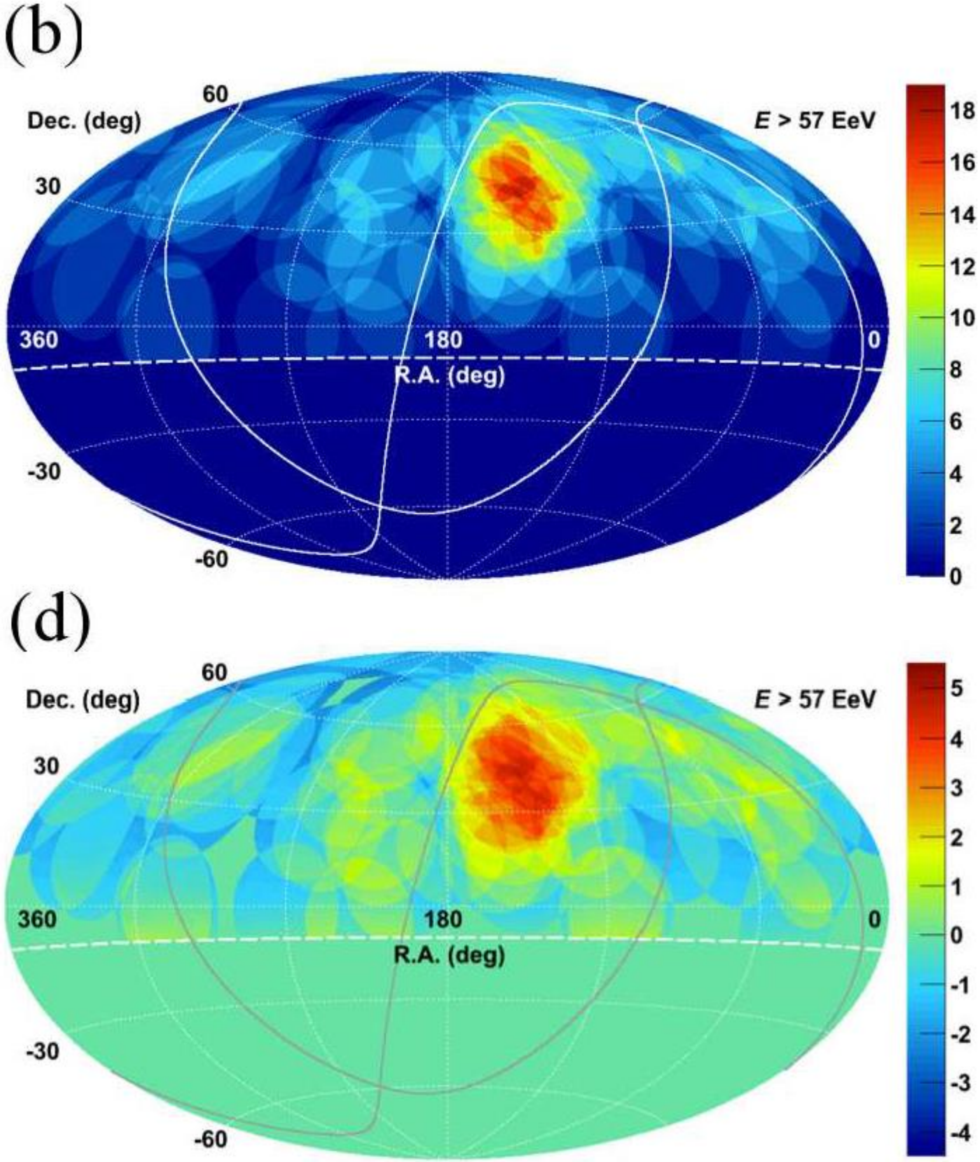
Fluorescence: 4 telescopes

Surface Array: covers 3000 km^2
1650 water-Cherenkov detectors
(10 m^2, 1.5 km separation)





Telescope Array

10^6 total events over 6 years

87 events > 57 EeV , < 60°

Shown: events within 20° of each point

Hot Spot at
RA= **148.4°** and dec**= +44.5°**
(*Mrk 421 is in the vicinity …)*

4.3 σ significance compared to isotropic fluctuation

R. Abbasi et al., Ap. J (Lett) ***790*** *(2014) L21; arXiv:1404.5890 [astro-ph.HE]*

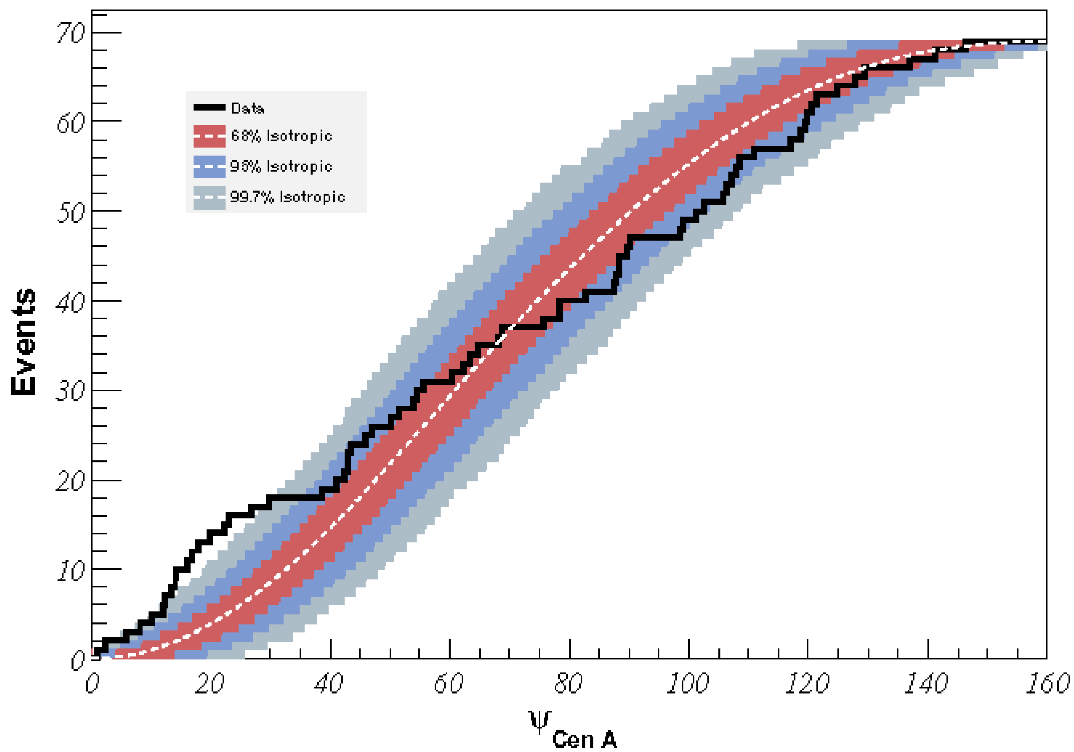


Fig. 9. Cumulative number of events with $E \geqslant 55$ EeV as a function of angular distance from the direction of Cen A. The bands correspond to the 68%, 95% and 99.7% dispersion expected for an isotropic flux.

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Events > 55 EeV

Excess from directions "near" (~20^{o}) **Cen-A**

P. Abreu et al. , Astropart. Phys. ***34*** *(2010) 314.*

The "GZK Cutoff"

The proton energy threshold for pion photoproduction on the CMBR is a **few x 10^{19} eV**. E.g.,

$$p + \gamma\,(2.7^{o}K) \rightarrow \Delta^{+} \rightarrow p + \pi^{o}\ ,\ n + \pi^{+}\ ,\ \ldots$$

1. Any observed CR proton **above this energy** must have originated "nearby" (within ~ 100 Mpc)

2. Similar thresholds, distances for nuclear photodisintegration.

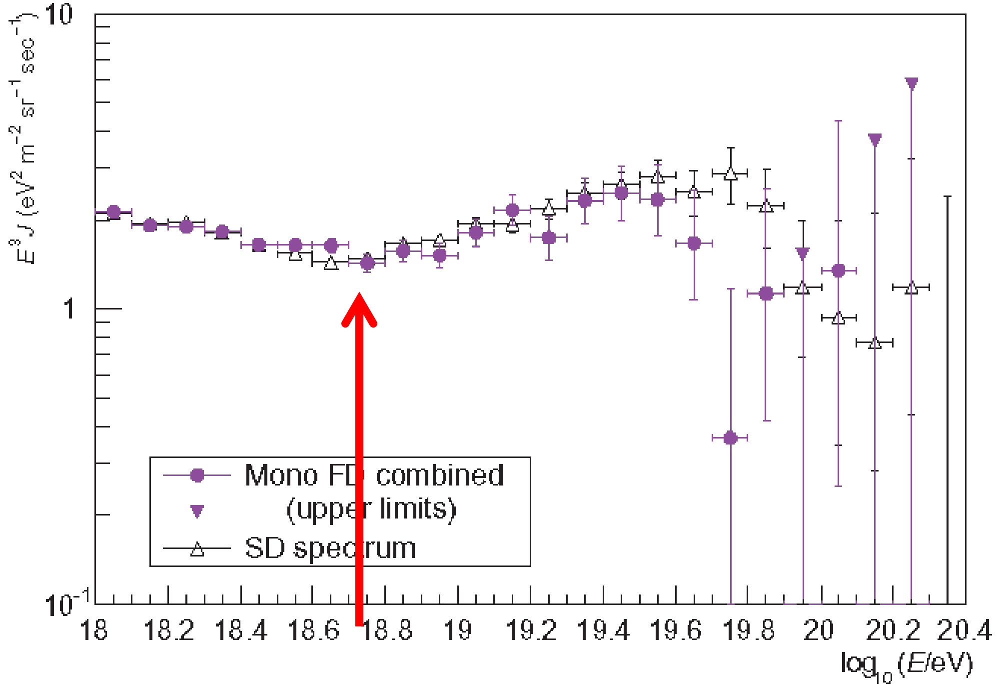
3. Spectrum **suppressed** if non-local sources

Energy Spectrum

Both experiments see spectral structure:

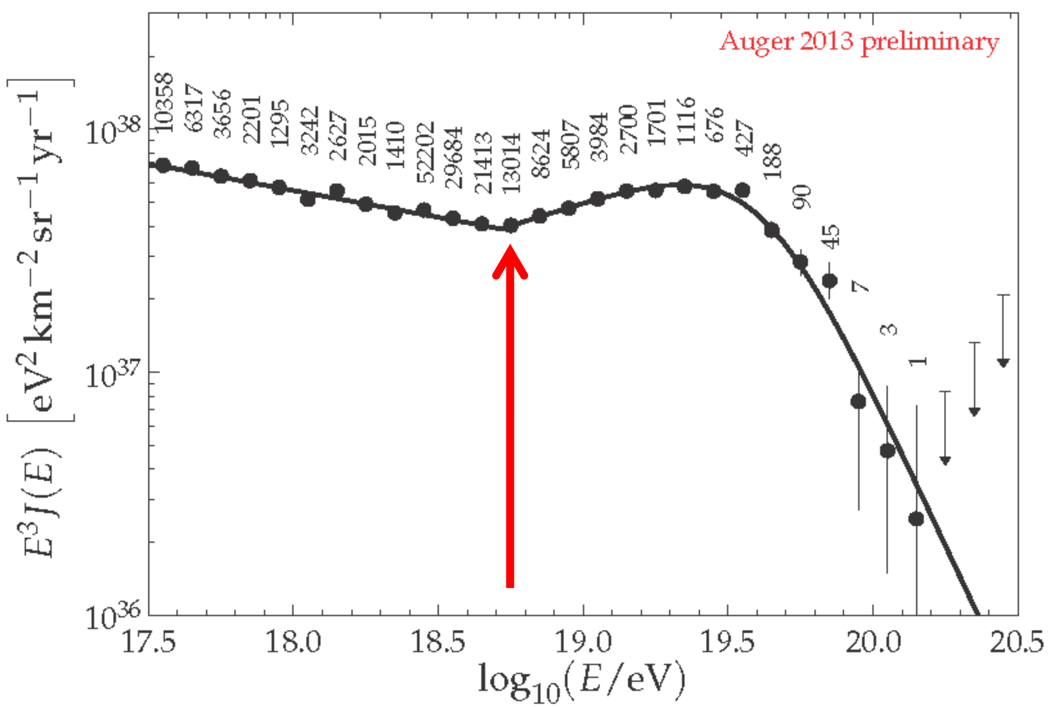
Flux **suppression** (GZK?)

The **"ankle"**



TA

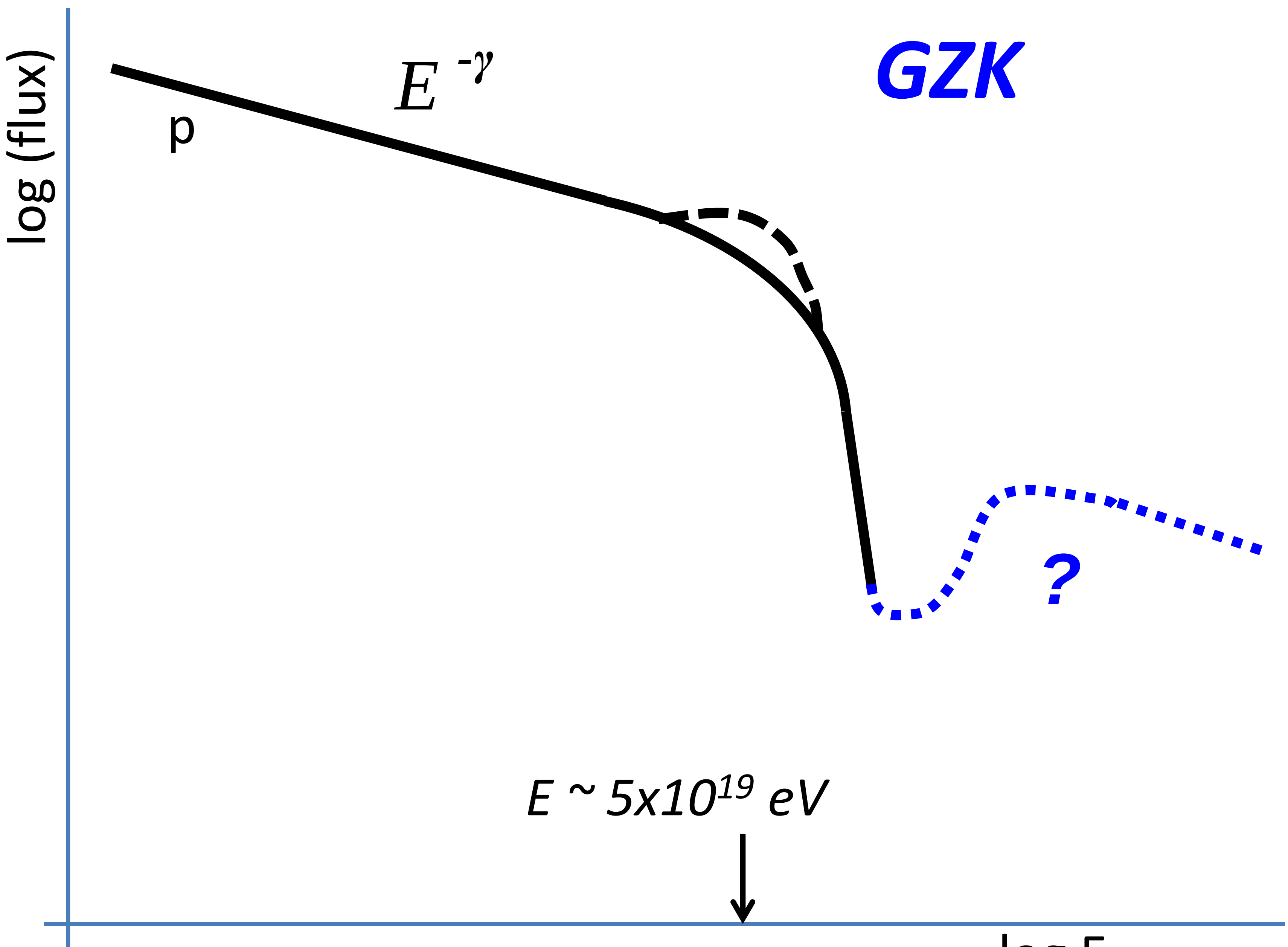
Astropart. Phys. ***48*** *(2013) 16*



(structures in the same place)

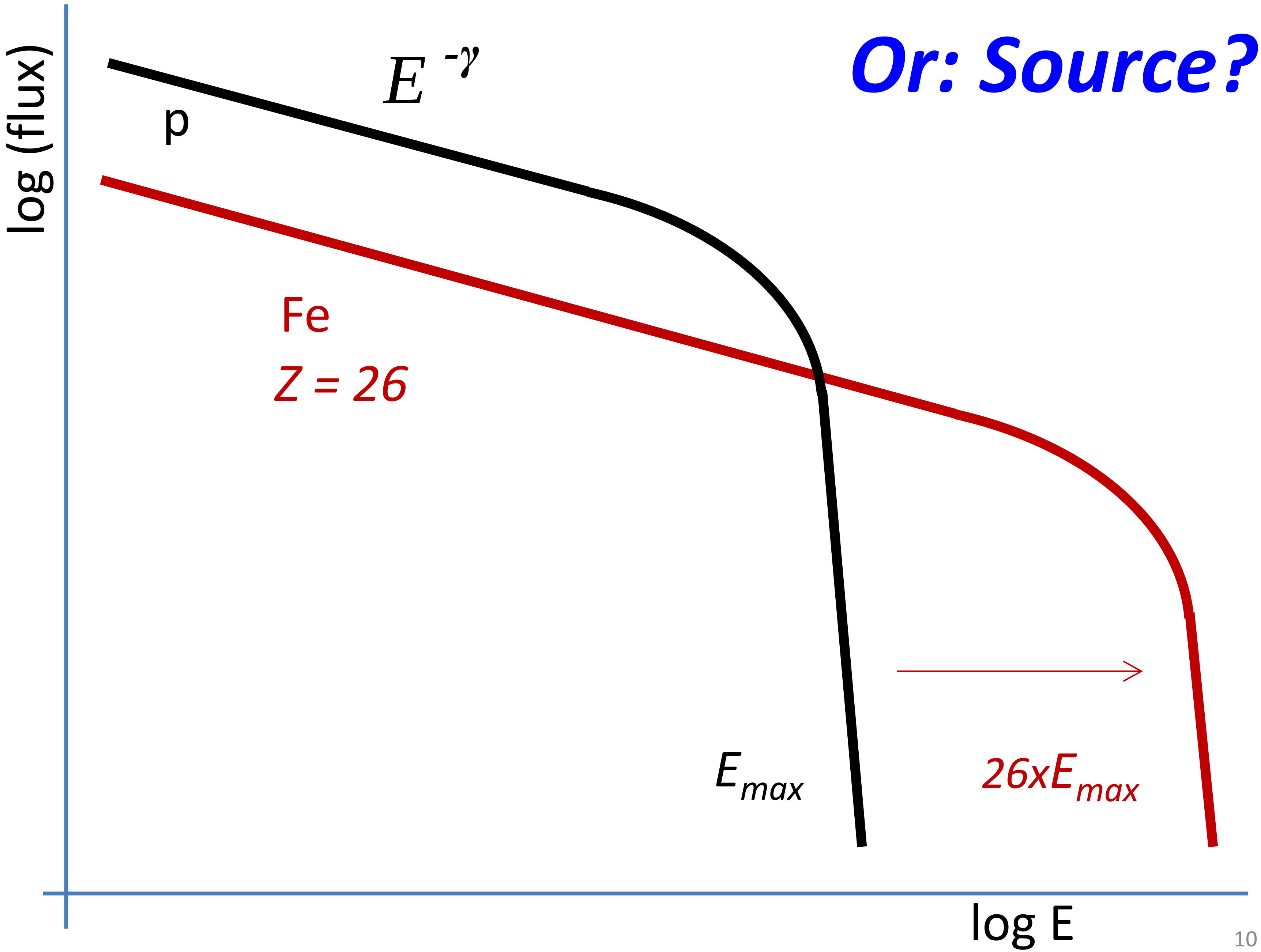
Auger

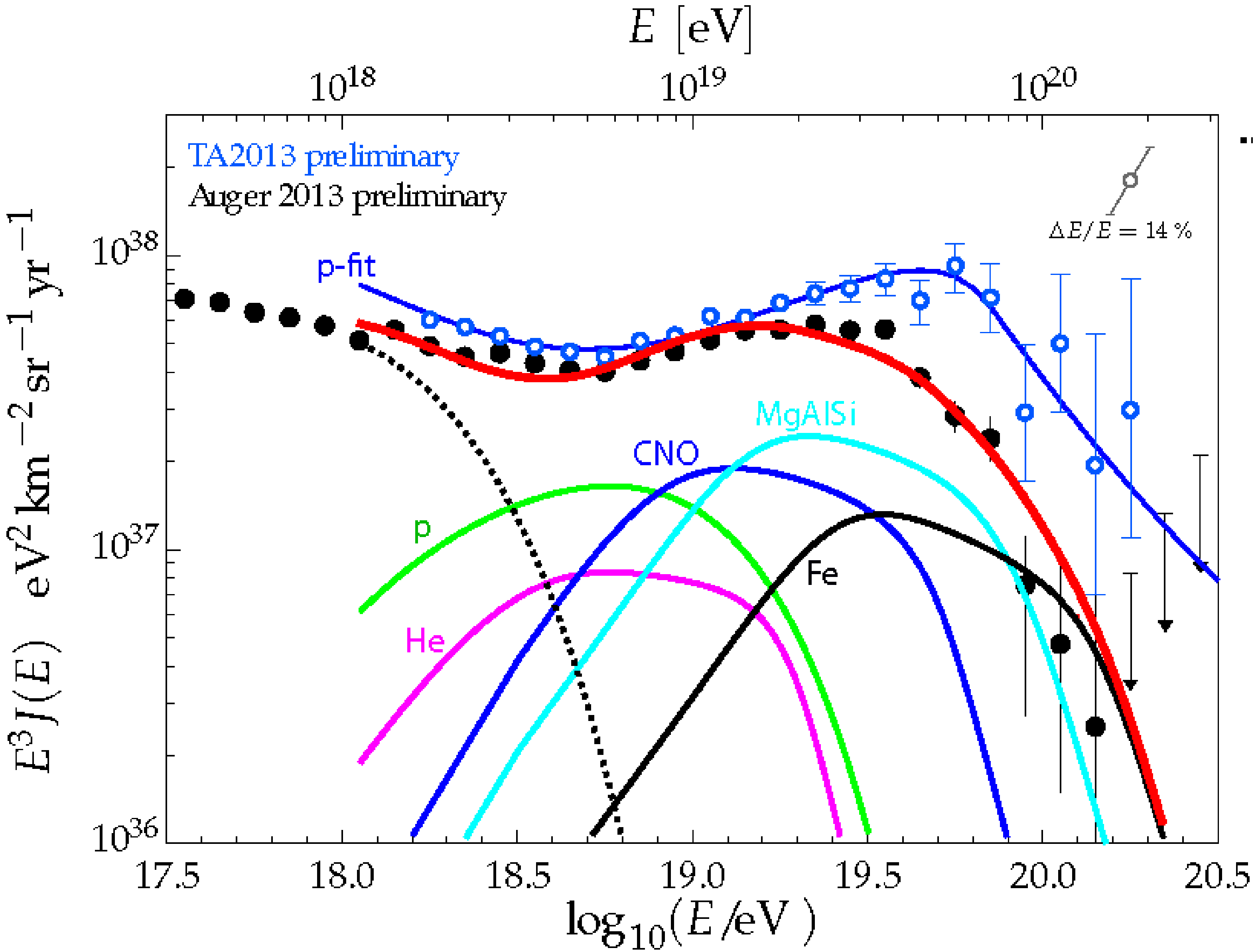
ICRC 2013



log (flux)
$E^{-\gamma}$
GZK
p
?
$E \sim 5x10^{19}$ eV
log E

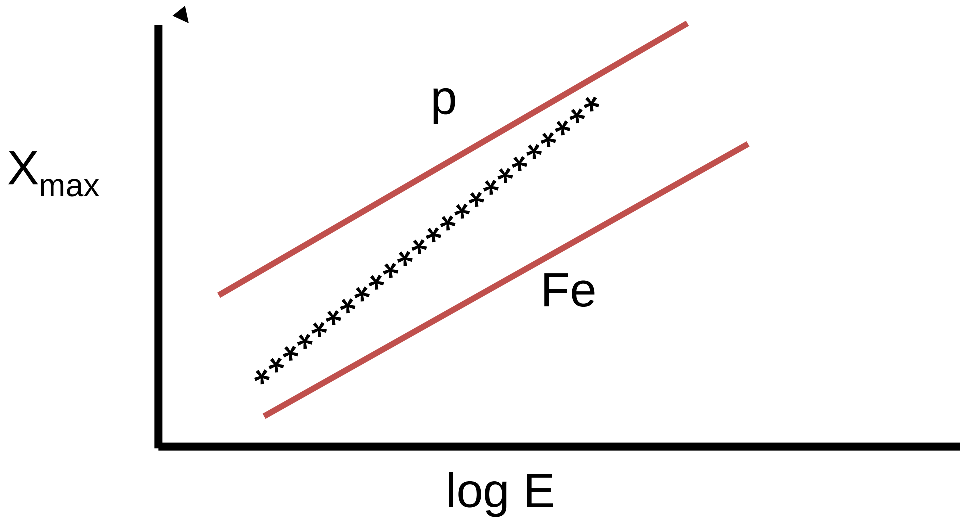
Or: Source?

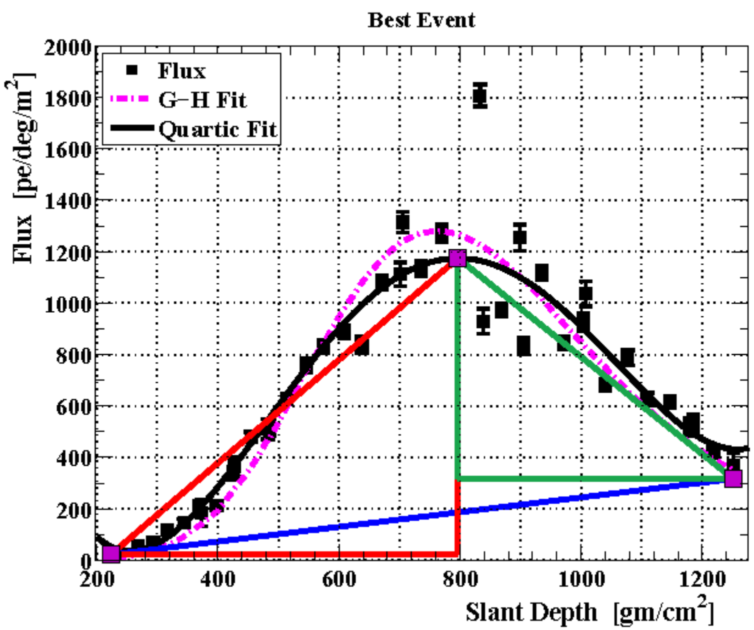




K.-H. Kampert and P. Tinyakov, Comptes Rendus Physique <u>15</u> , 318 (2014).

Composition: Variation of Depth of Maximum with Energy

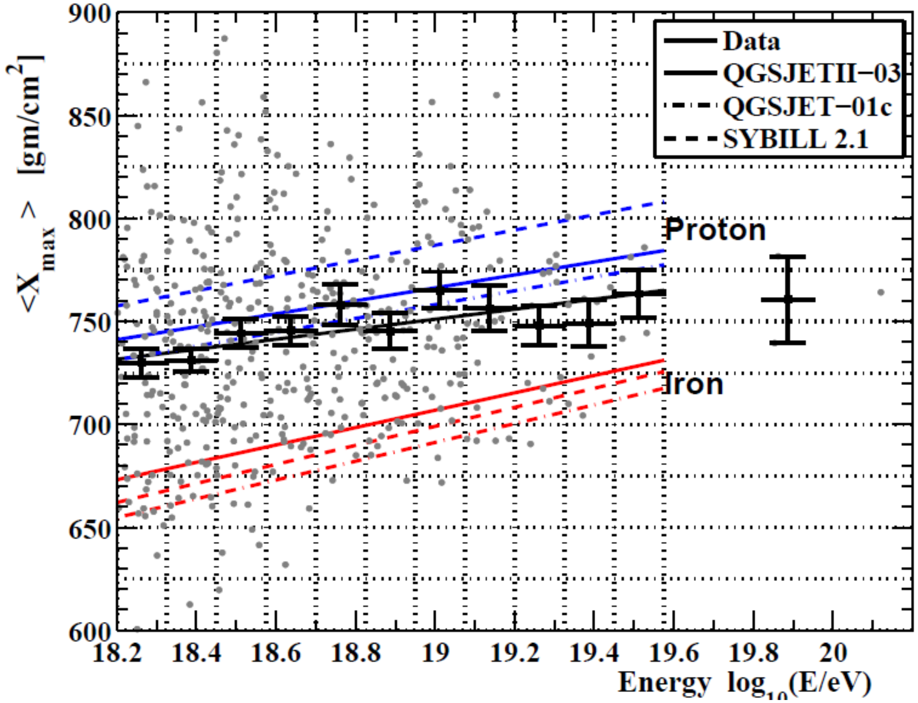


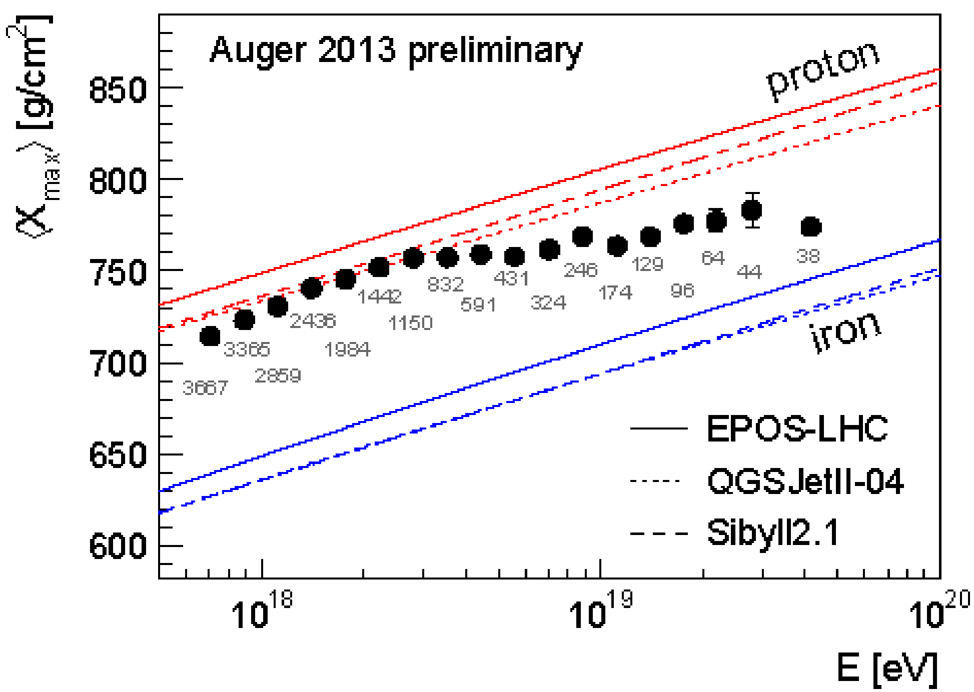


TA – New analysis

Geometric cuts plus (new) pattern recognition

Abbasi et al. arXiv:1408.1726v1





Composition

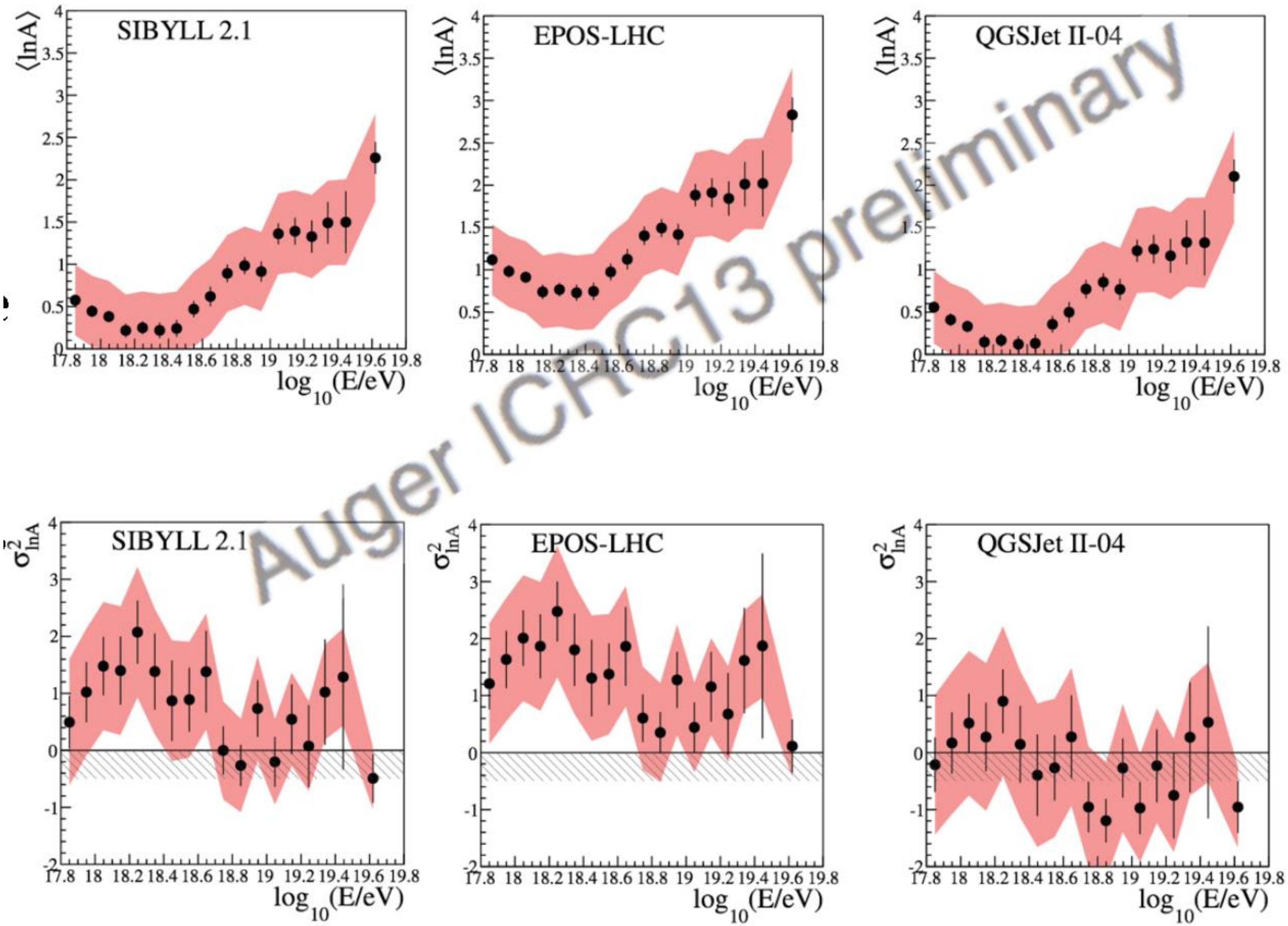
Measured using **depth of shower maximum** (*closely related to interaction length of primary*)

TA and Auger apparently differ

(Opinion: the data differ less than the interpretation based on models)

Abbasi et al. arXiv:1408.1726v1

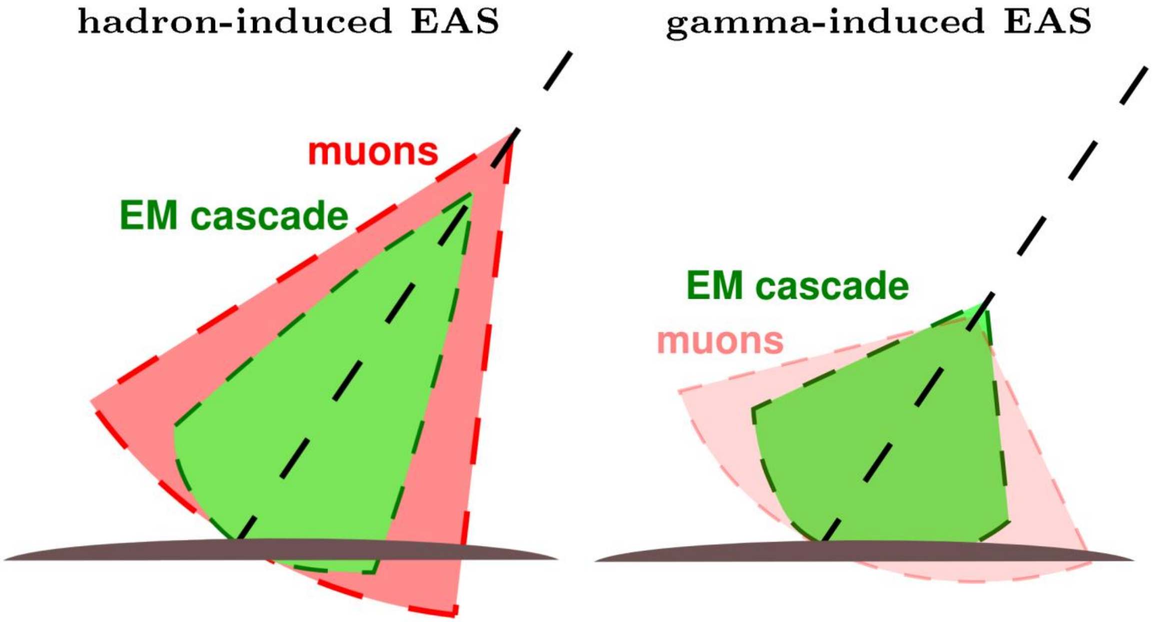
Letessier-Selvon et al. arXiv:1310.4620



(Letessier-Selvon et al. arXiv:1310.4620);

P.Auger Collab., JCAP 02 (2013) 026

Photon Searches



Photon-induced showers:

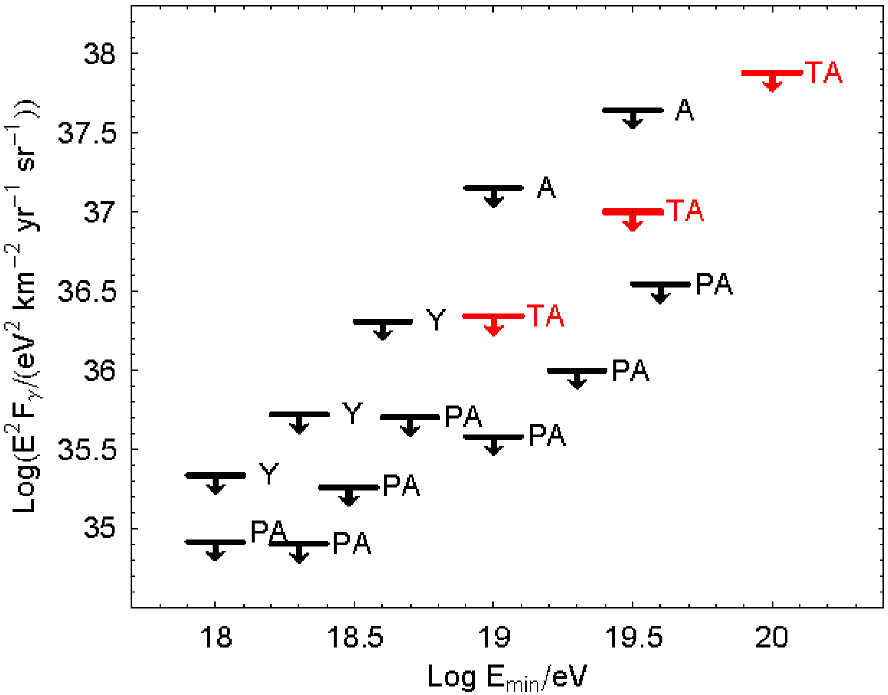
Deeper ($\mathbf{X_{max}}$)

More **curvature**

Fewer **muons**

Abu-Zayyad et al., arXiv:1304.5614 (2013)

TA: New Photon Limits



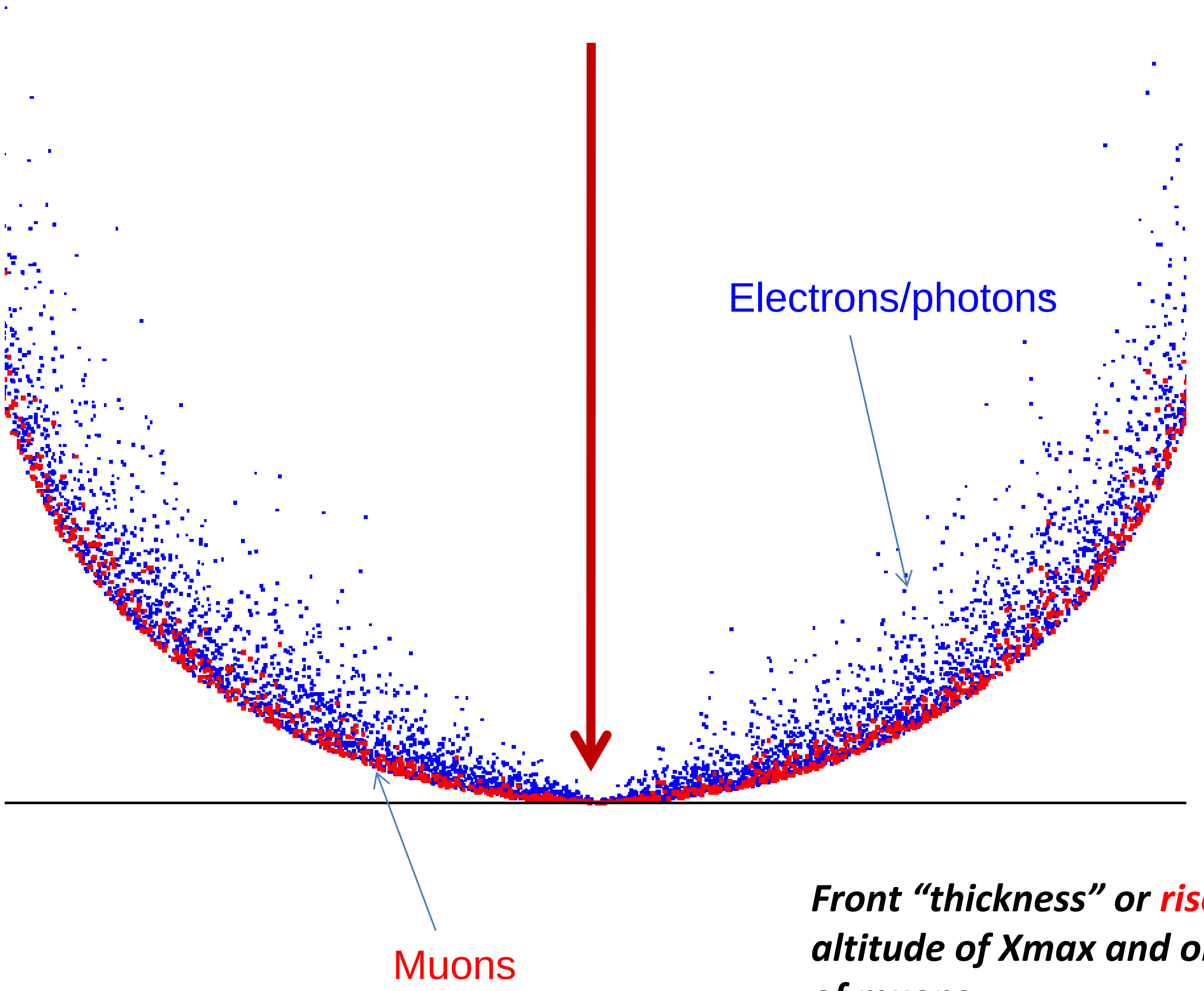
:G. 5: Photon flux limits of the present work (T
mpared to the previous limits by AGASA (A)
ıkutsk (Y) [7] and Pierre Auger Observatory (PA) [11, 1

Uses SD data

Shower front curvature

Compare to MC photons with same S800 (“E”)

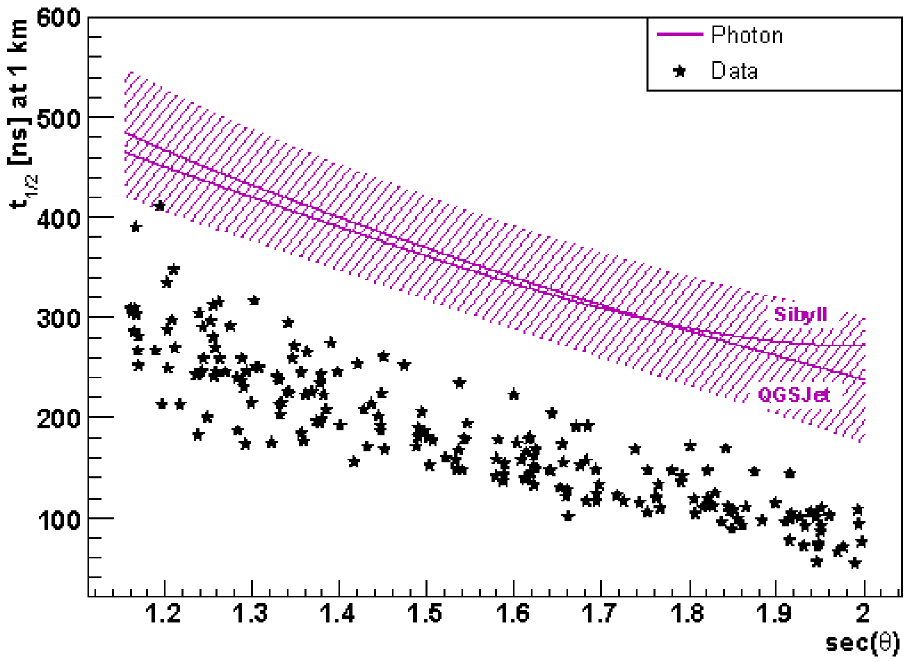
Abu-Zayyad et al., arXiv:1304.5614 (2013)

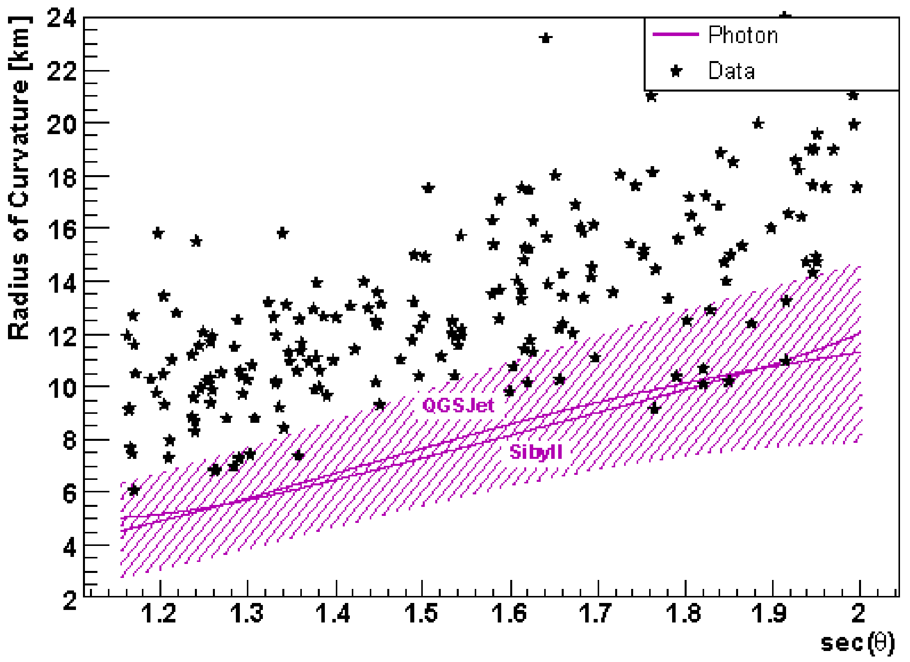


Front "thickness" or risetime depends on altitude of Xmax and on the relative number of muons

Auger: Photons above 10 EeV:

Shower curvature and risetime



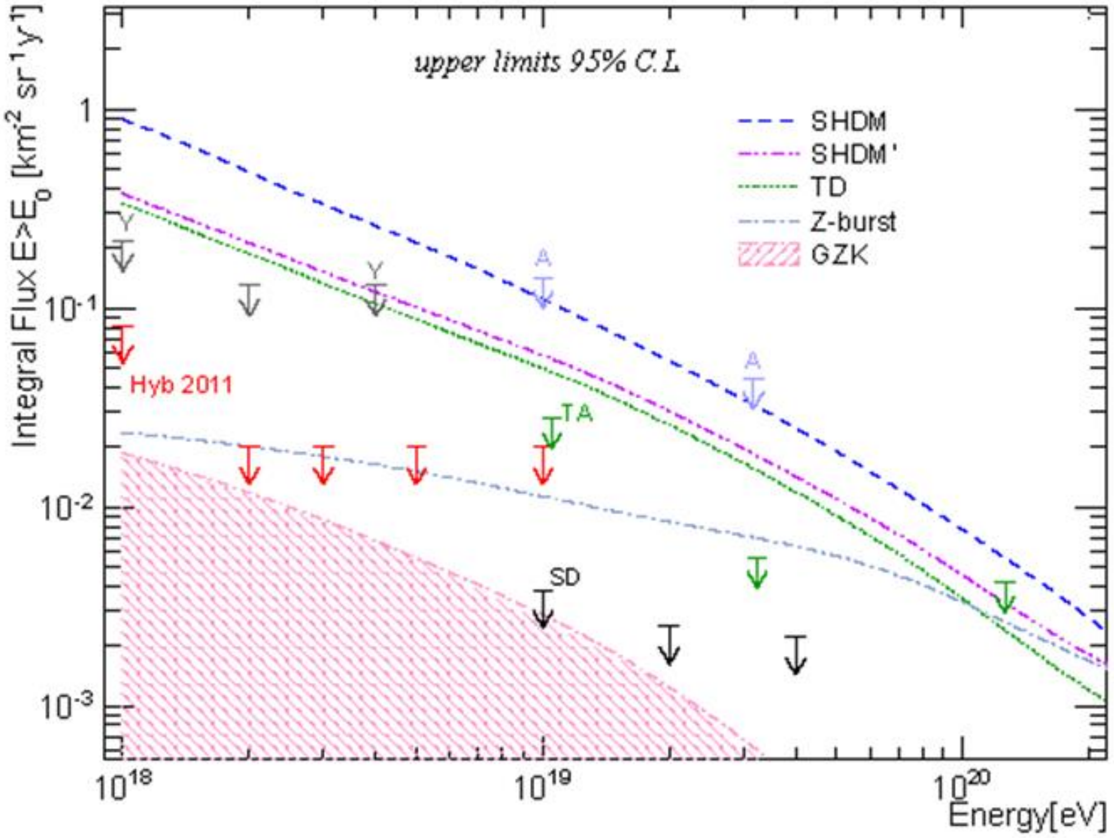


Settimo, Proceedings of *Photon 2013*

Auger: Photon Limits

Shower front curvature

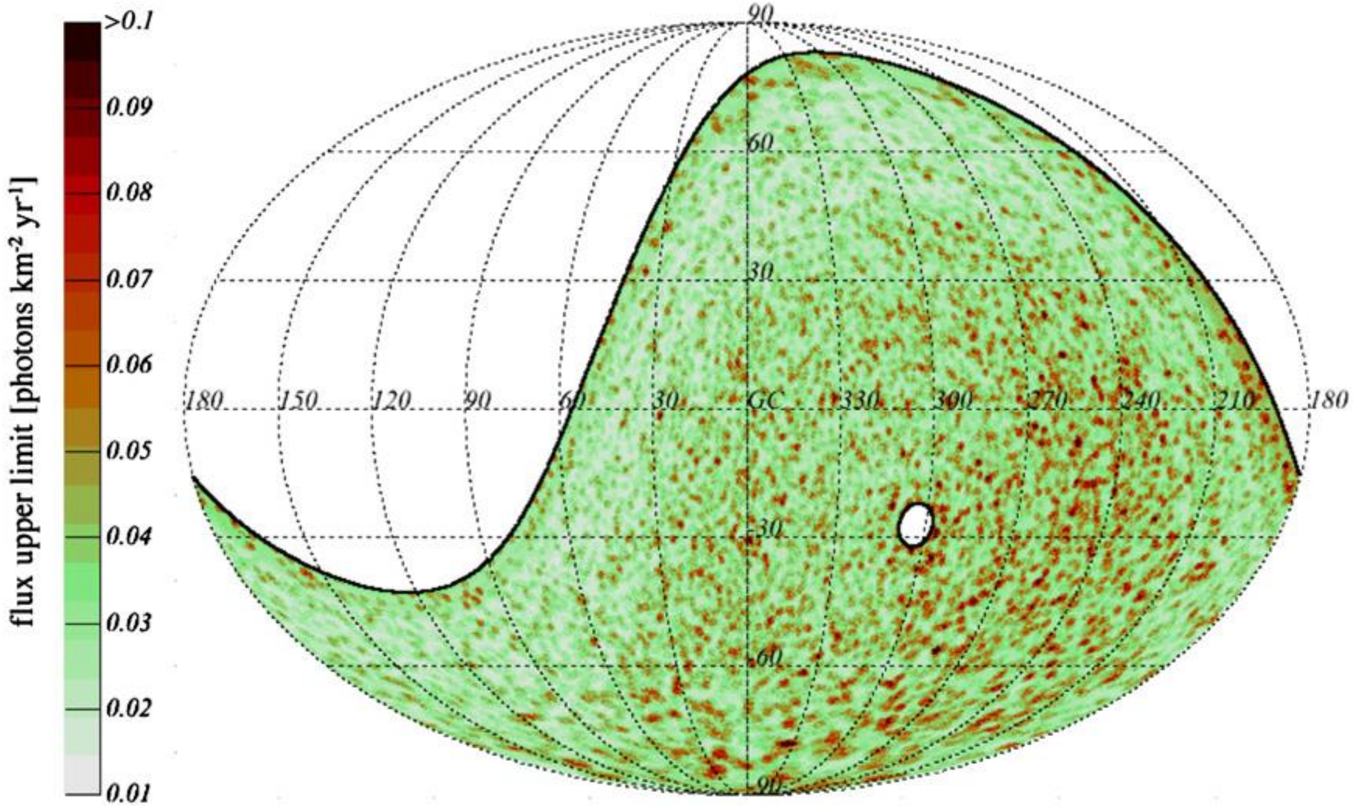
Early/late signal strength (i.e. muons)



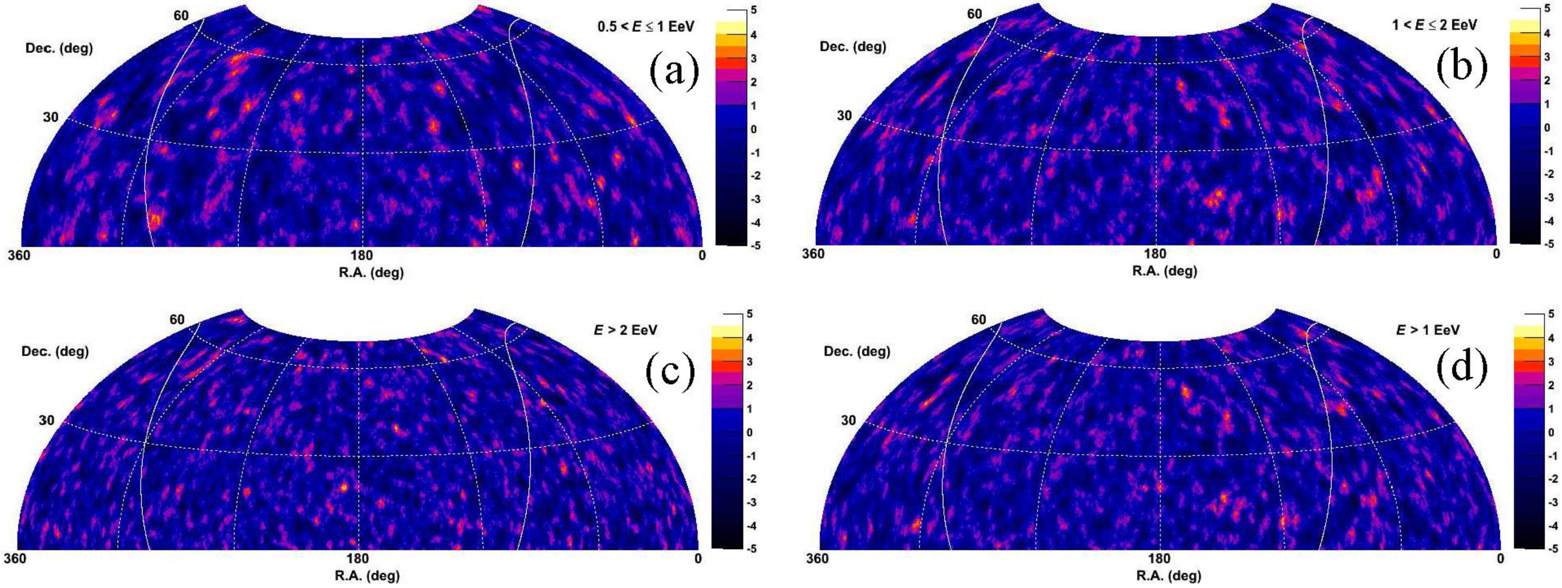
Settimo et al., Proceedings *Photon 2013*

Auger: new results on photon point sources

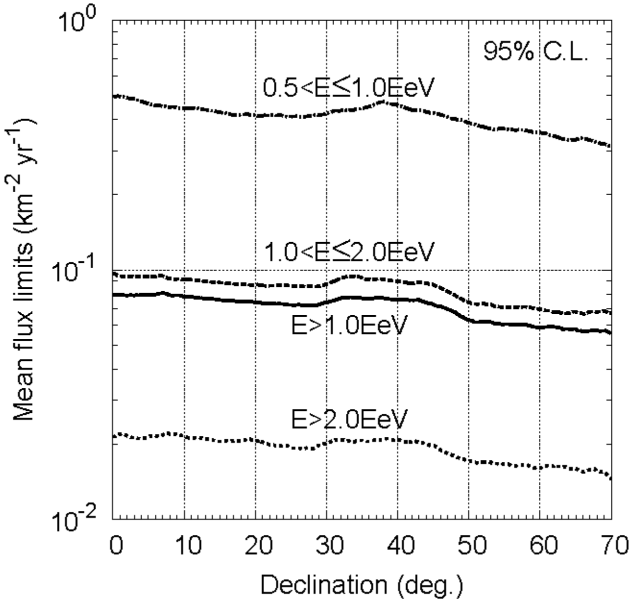
log(E) =17.3-18.5; hybrid events: **X_{max}**, **LDF**, **early/late**



P. Auger Collab. (Aab et al.), Ap. J. **789** (2014) 160



TA: Neutral particles



TA Collab. (Abbasi et al.), arXiv:1407.6145v1

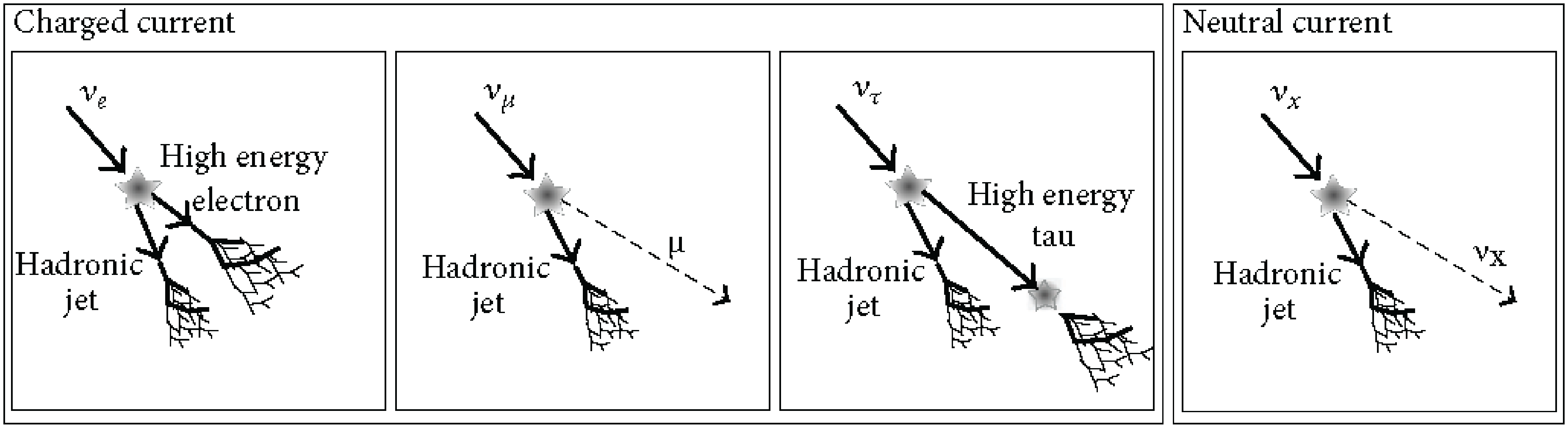
Auger: Neutrons

Results for the Most Significant Target from Each Target Set

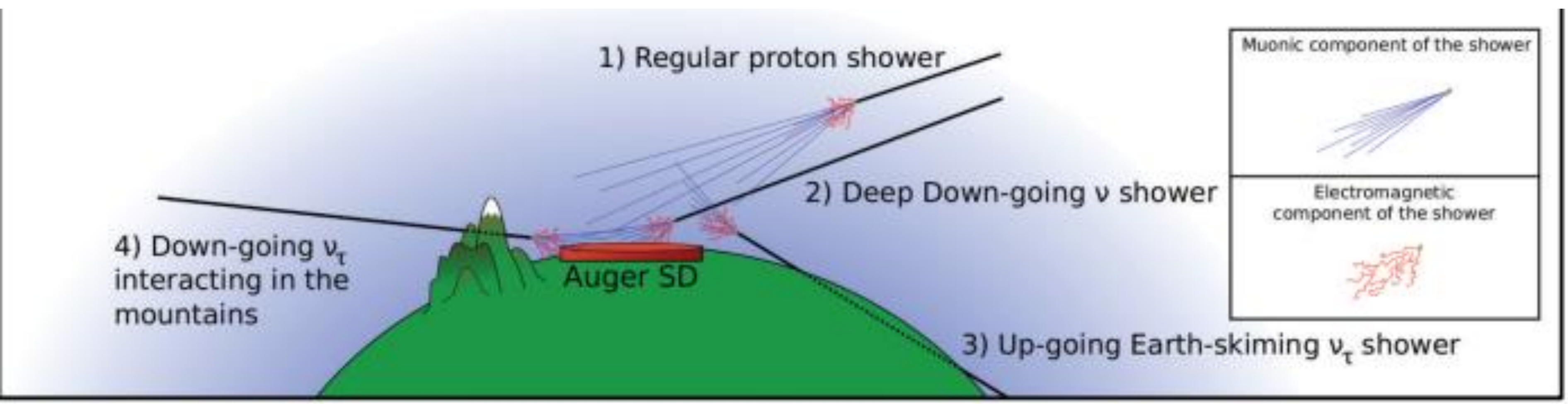
Class	R.A. [°]	Decl. [°]	Obs	Exp	Flux U.L. (km^{-2} yr^{-1})	E-Flux U.L. (eV cm^{-2} s^{-1})	p-value	p-value (penalized)
msec PSRs	260.27	–24.95	237	214	0.019	0.14	0.058	0.98
γ-ray PSRs	8.59	–5.58	176	149	0.024	0.18	0.016	0.70
LMXB	264.57	–26.99	265	219	0.028	0.20	0.0012	0.10
HMXB	152.45	–58.29	283	248	0.019	0.14	0.014	0.49
H.E.S.S. PWN	128.75	–45.60	275	248	0.018	0.13	0.043	0.53
H.E.S.S. other	269.72	–24.05	235	211	0.019	0.14	0.054	0.59
H.E.S.S. UNID	266.26	–30.37	251	227	0.018	0.13	0.055	0.57
Microquasars	262.75	–26.00	247	216	0.022	0.16	0.020	0.23
Magnetars	81.50	–66.08	268	241	0.016	0.11	0.040	0.48
Gal. center	266.42	–29.01	234	223	0.014	0.10	0.24	...
Gal. plane	$\lvert$Gal. lat.$\rvert$ < 1°.17		16965	17197	0.077	0.56	0.96	...

P. Auger Collab. (Aab et al.), Ap. J. (Lett) 789 (2014) L34

Neutrinos

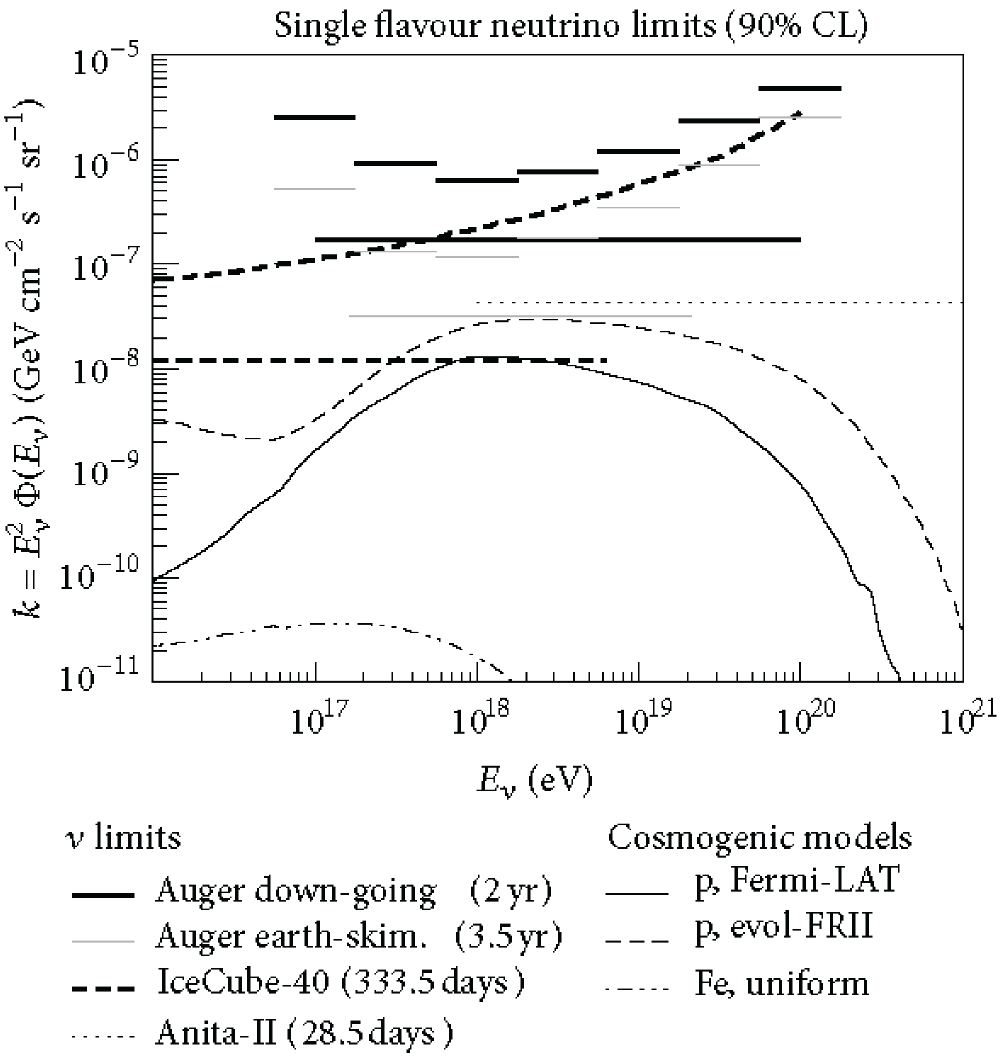


Charged current
ν_e
High energy electron
Hadronic jet
ν_μ
Hadronic jet
μ
ν_τ
High energy tau
Hadronic jet
Neutral current
ν_x
Hadronic jet
νx



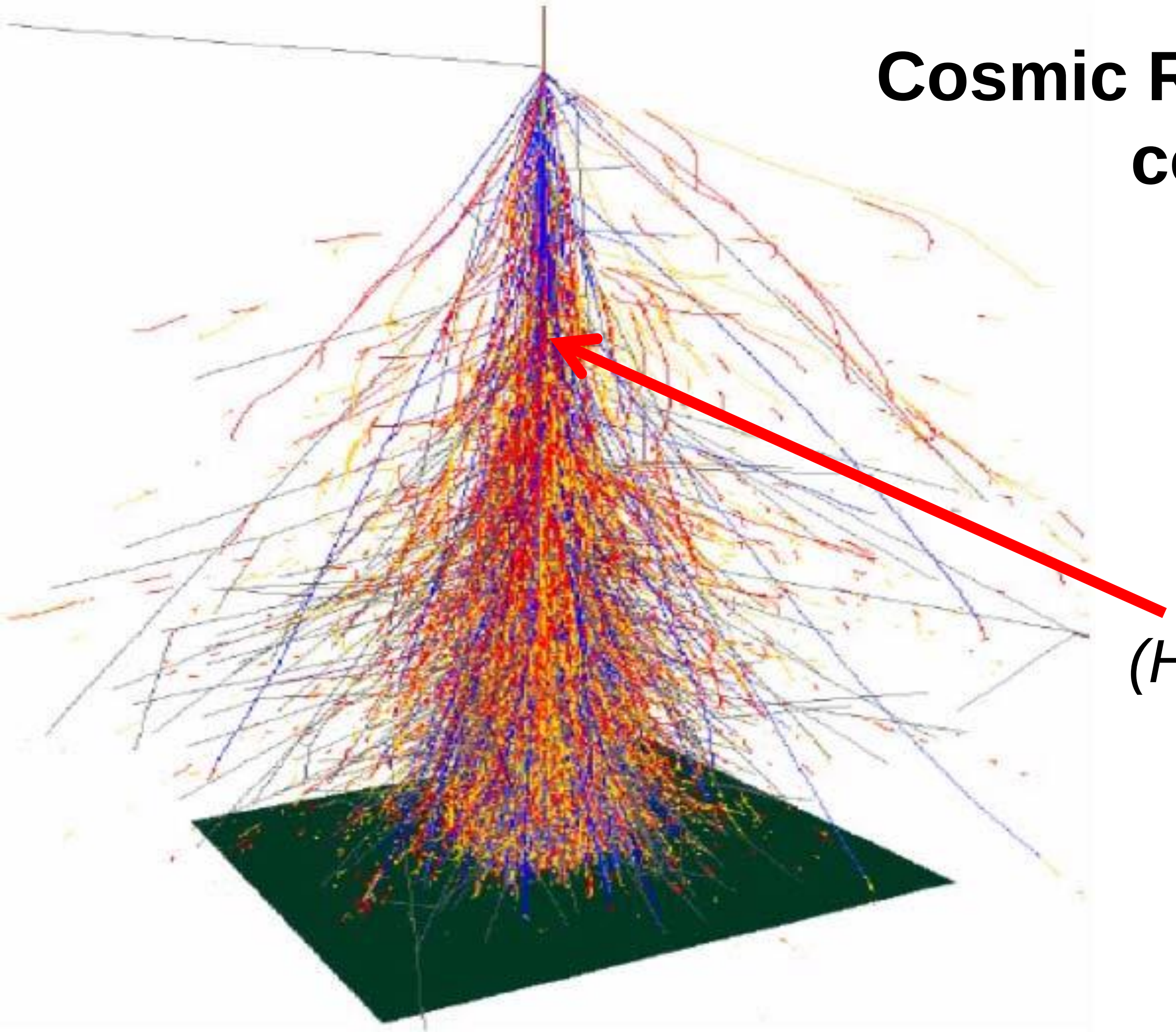
1) Regular proton shower
2) Deep Down-going ν shower
3) Up-going Earth-skiming ν_τ shower
4) Down-going ν_τ interacting in the mountains
Auger SD
Muonic component of the shower
Electromagnetic component of the shower

Auger Neutrino limits



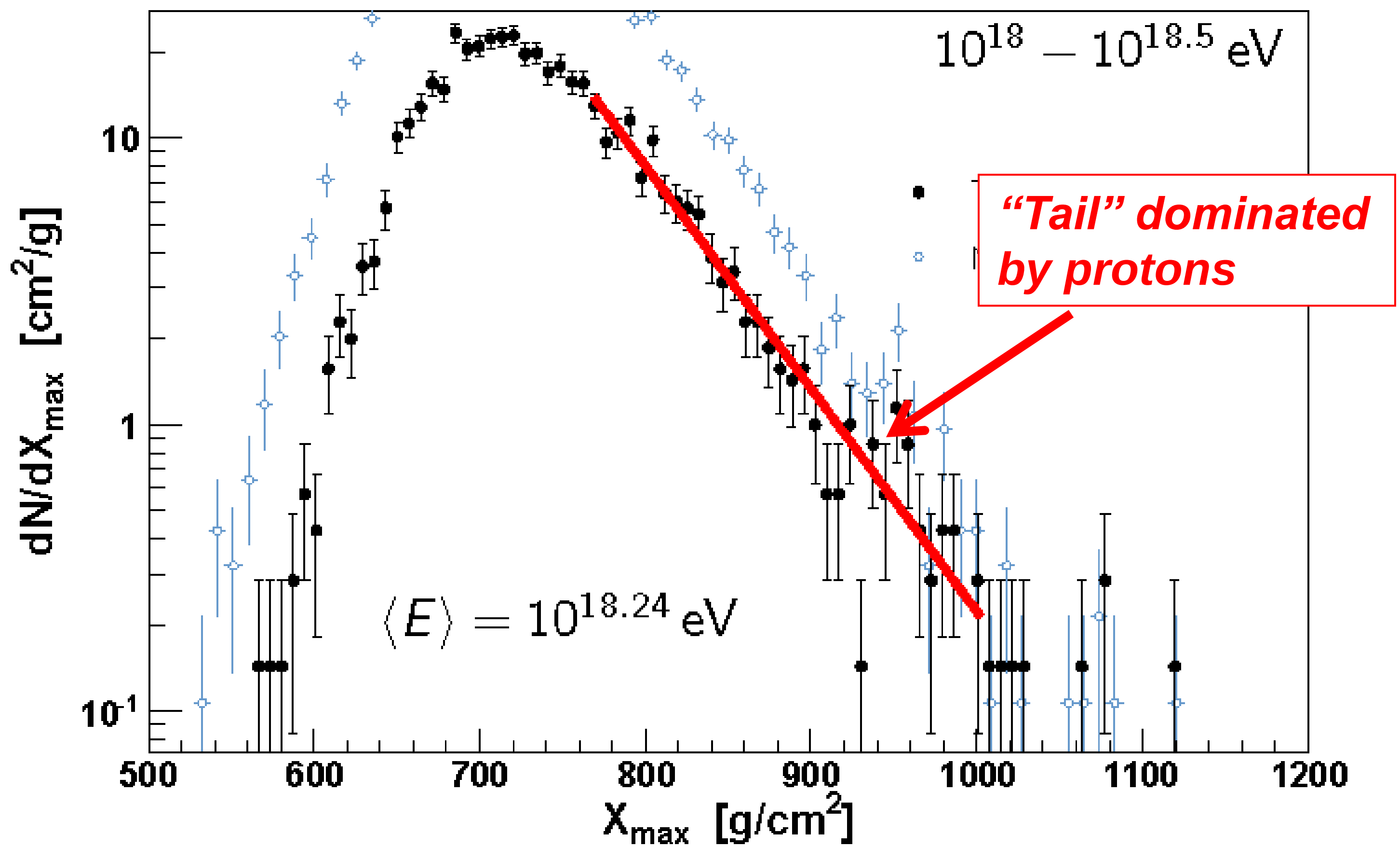
P. Auger Collab. (Abreu et al.), Advances in High Energy Physics **2013**, 708680

Cosmic Rays -- HEP connections



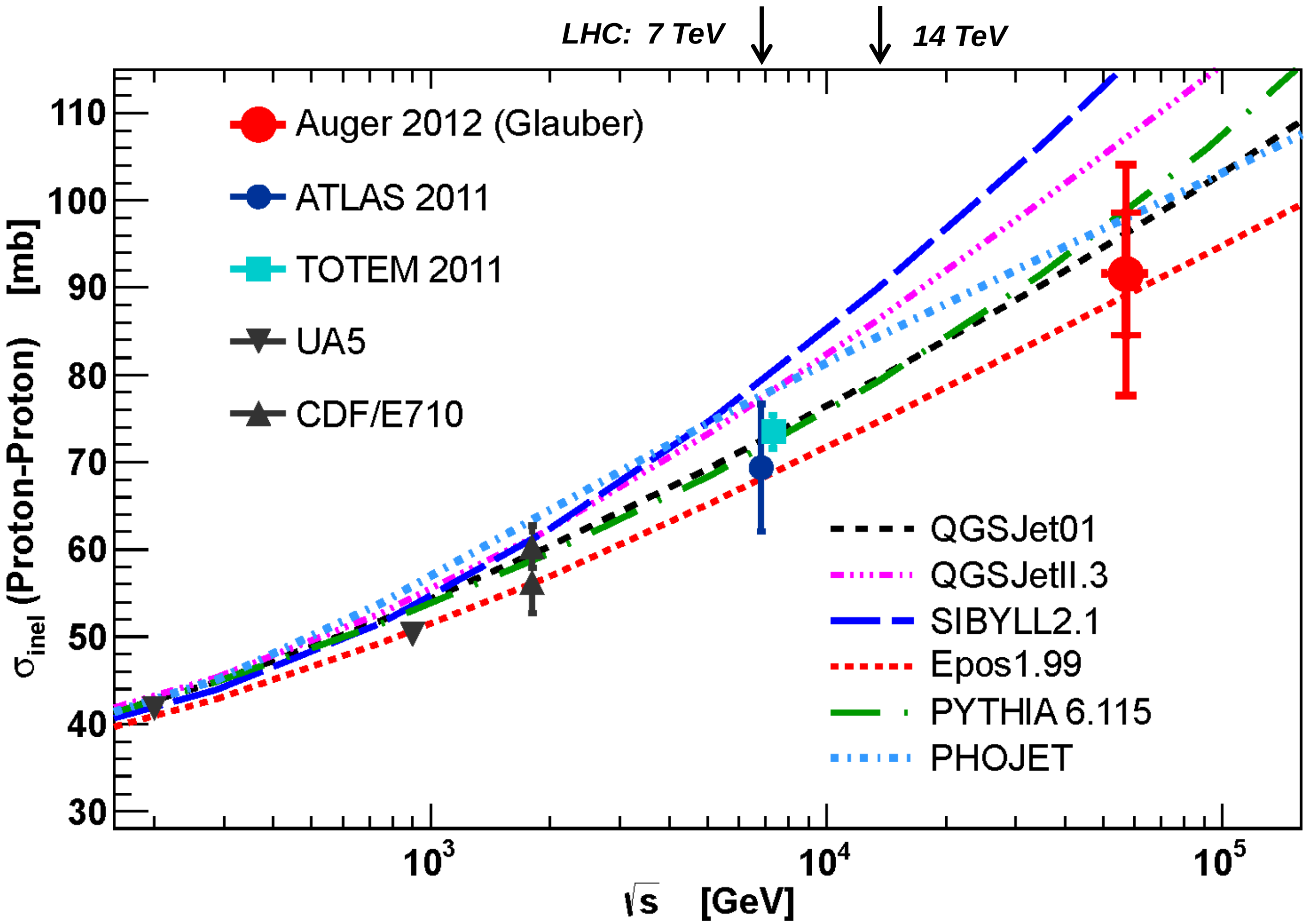
(Higgs Boson)

Proton-Air Cross Section from the Depth of Shower Maximum



$$\Lambda_\eta = [55.8 \pm 2.3_{\rm stat} \pm 1.6_{\rm sys}]\,{\rm g/cm^2}$$

P.Abreu et al., Phys. Rev. Lett. 109.062002 (2012)



$$\sigma_{pp}^{\mathrm{inel}} = [92 \pm 7(\mathrm{stat})^{+9}_{-11}(\mathrm{syst}) \pm 7(\mathrm{Glauber})]\ \mathrm{mb},$$

$$\sigma_{pp}^{\mathrm{tot}} = [133 \pm 13(\mathrm{stat})^{+17}_{-20}(\mathrm{syst}) \pm 16(\mathrm{Glauber})]\ \mathrm{mb}.$$

P.Abreu et al., Phys. Rev. Lett. 109.062002 (2012)

The proton is a black disk

(i) σ_{tot} and σ_{inel} behave as $\ln^2 s$ (saturates Froissart bound);
(ii) the ratio $\sigma_{inel}/\sigma_{tot} \rightarrow ½$;
(iii) proton interactions become flavor blind.

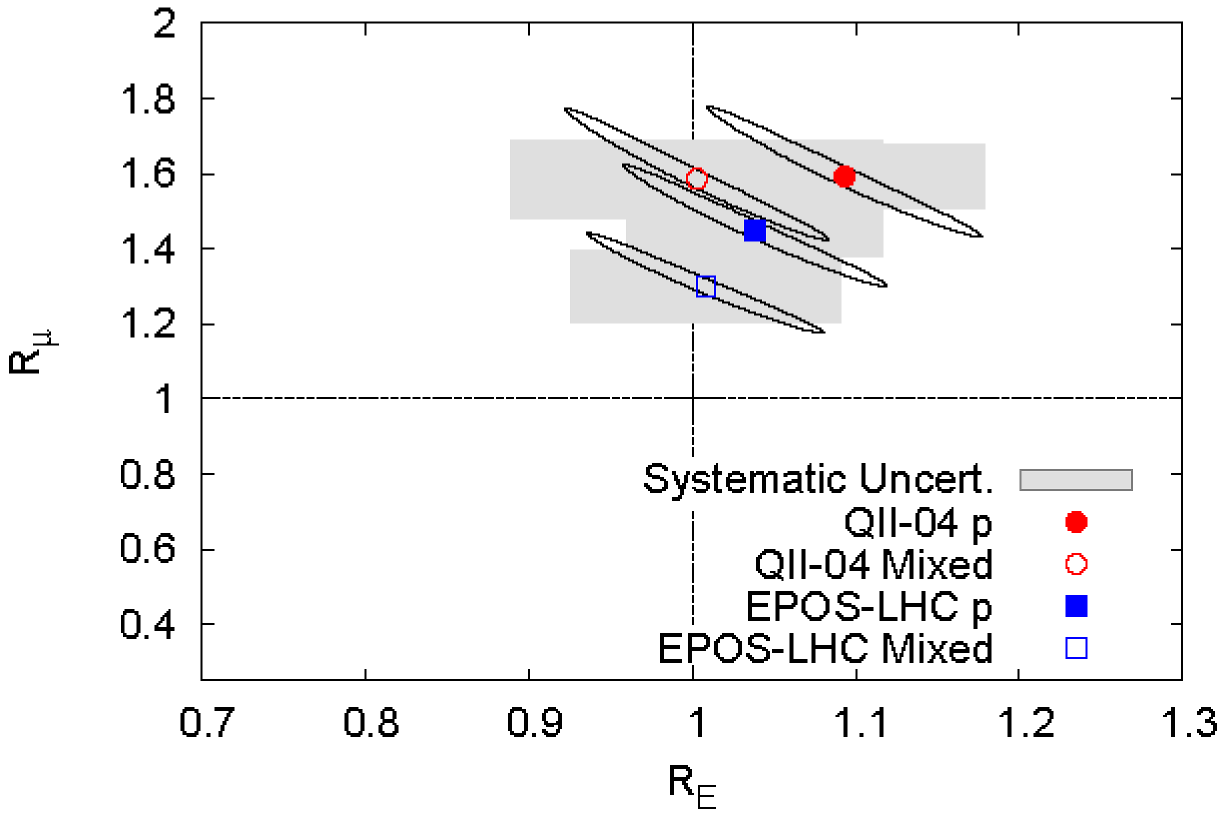
M.M. Block and F. Halzen, Phys. Rev. ***D86****.051504 (2012)*

Interaction Models

Air shower interpretation uses **EPOS**, **QGSJet**, **SIBYLL**, …

Model Development for Cosmic Rays and for LHC

Good results, but not perfect (e.g., ***too many muons*** observed?)



($10^{18.8}$ – $10^{19.2}$ eV)

Too many muons?

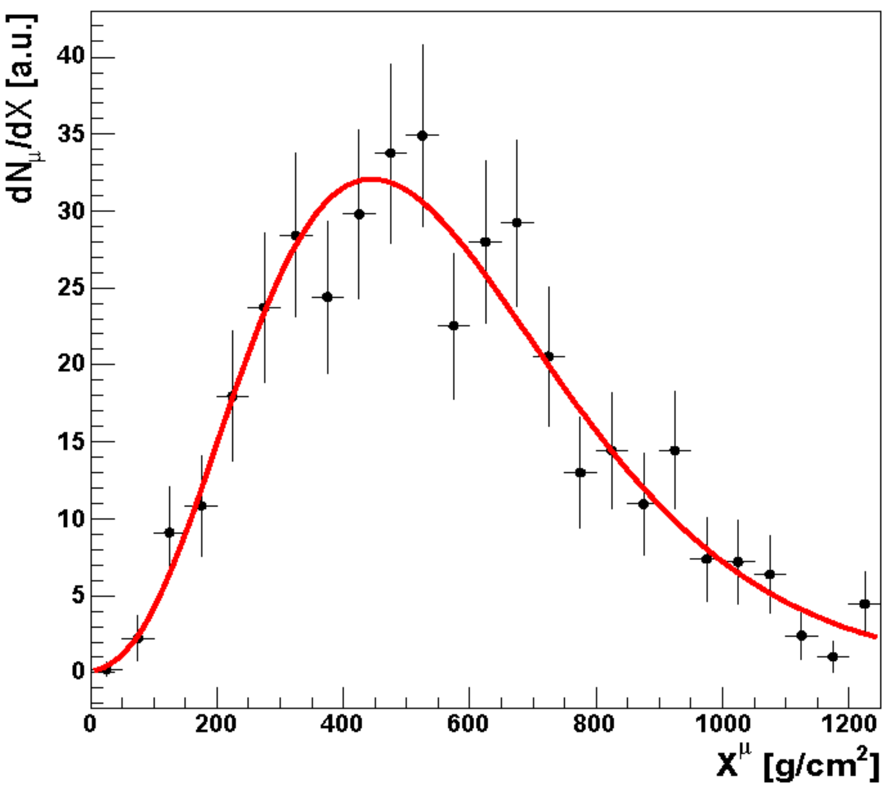
R = ratio of **observed/simulation** muons, S1000 ("E")

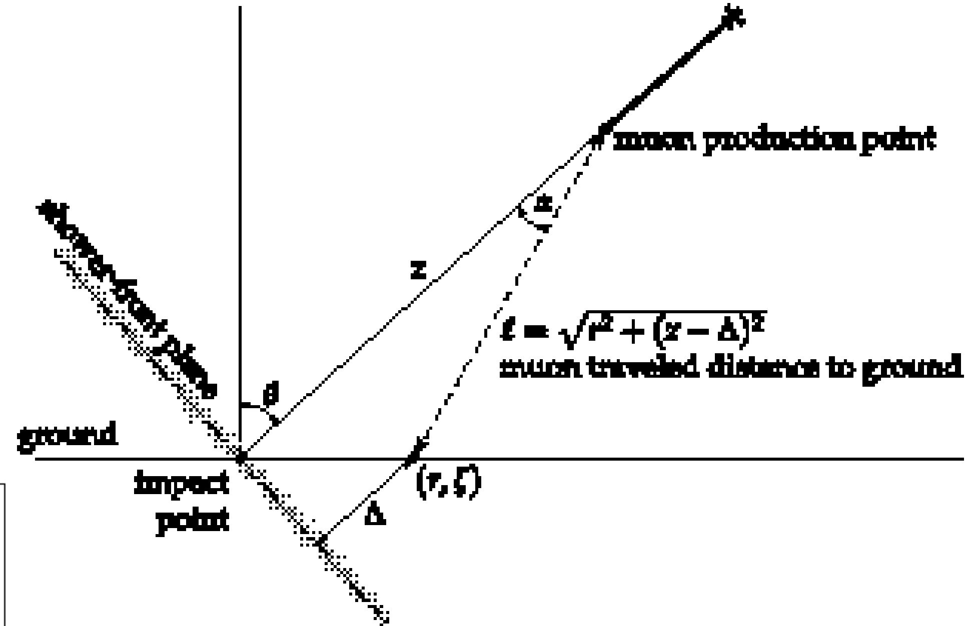
P. Auger Collab. (G. Farrar) Proc. 2013 ICRC (Rio).

Auger: **Muon** Shower Profiles

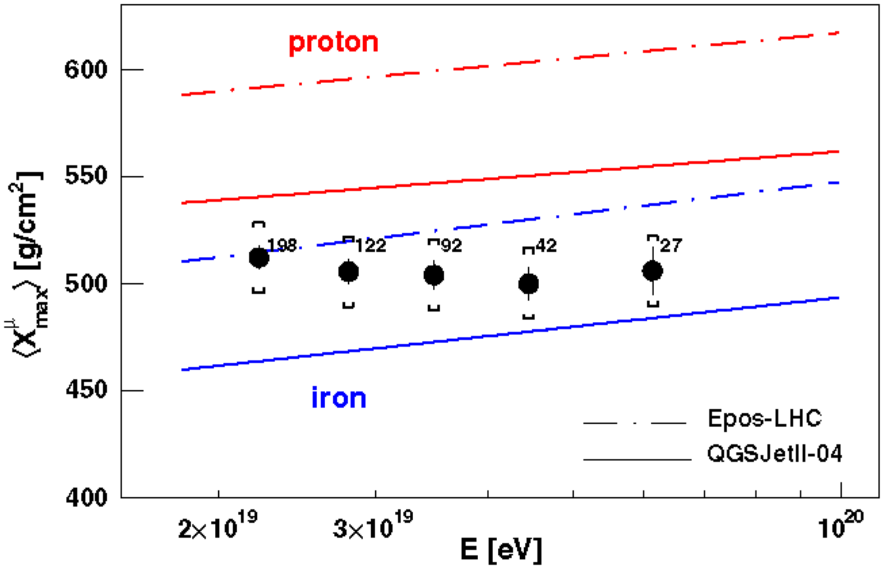
Muon Production Depth

(Events θ ~ 60°)





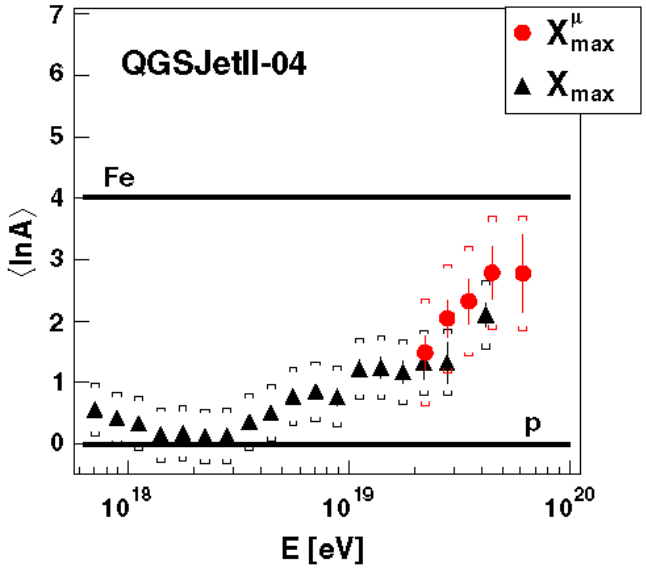
P. Auger. Collab.(Aab *et al*.),
Phys. Rev. **D90** (2014) 012012

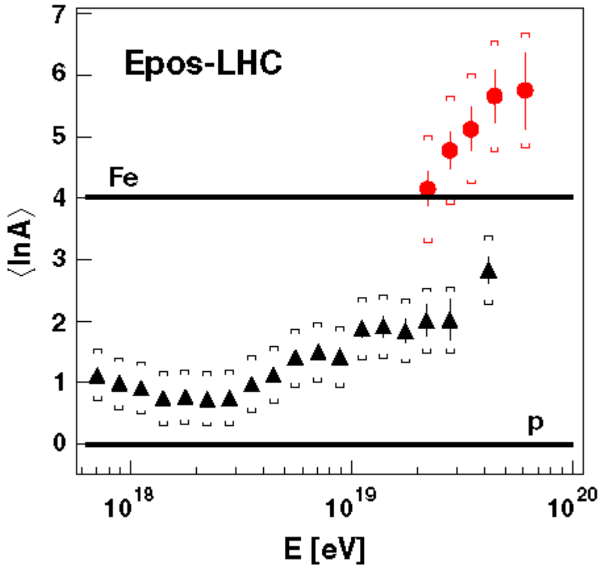


Muon depth of maximum

Same trend as shower max

… but model differences





P. Auger. Collab.(Aab et al.), Phys. Rev. **D90** (2014) 012012

What's next?

Sources; Nature of the spectral features; Hadron interactions

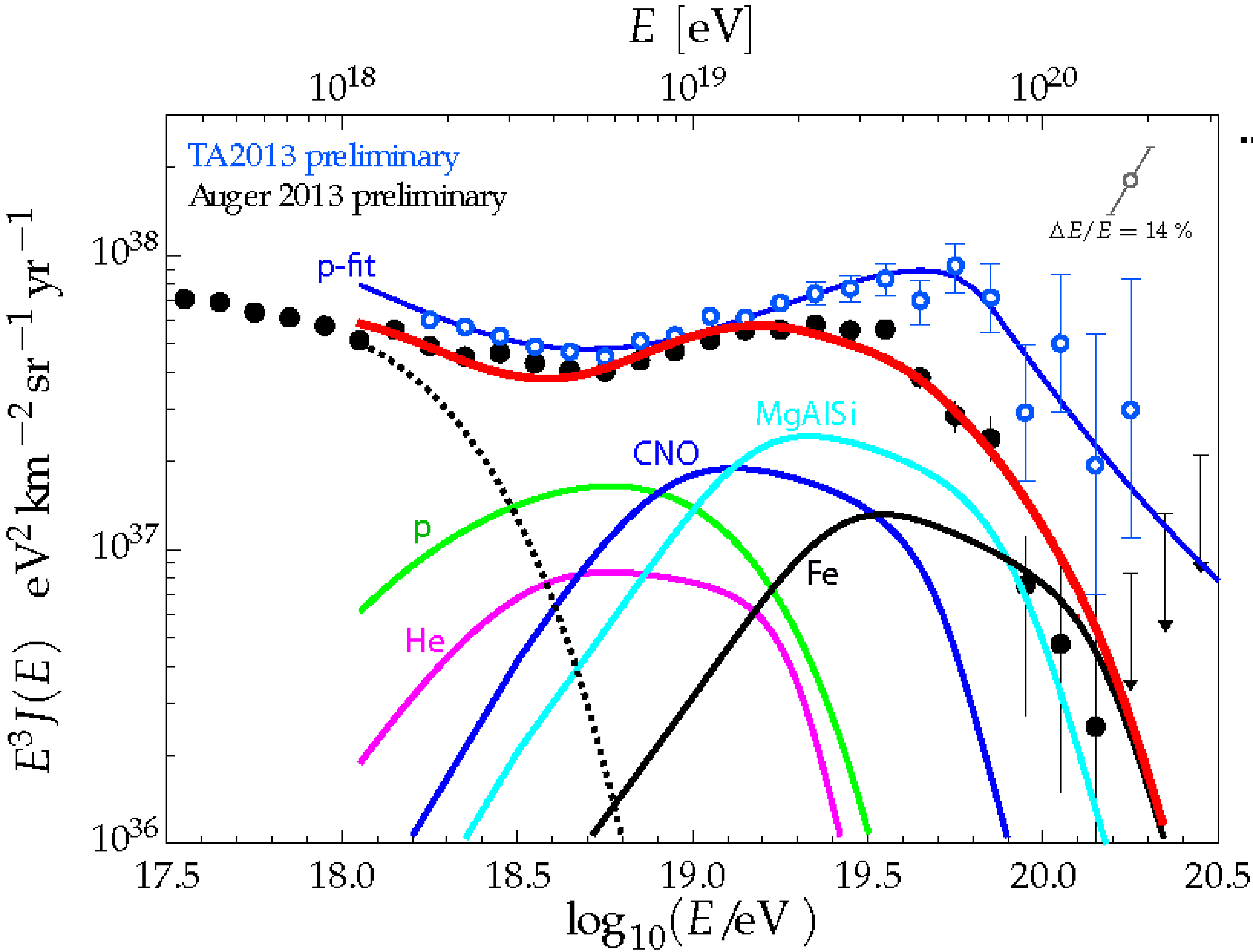
=> Composition and Statistics

TA and Auger each have enhancements underway:
Radar, Radio, "Infill" arrays, Lower thresholds, TALE

Future:

Expand TA to 3000 km^2

Expand Auger muon coverage: composition handle for all events



K.-H. Kampert and P. Tinyakov, Comptes Rendus Physique 15 , 318 (2014).

Meeting at CERN in early 2012 for the community was a success

Auger and TA have developed several joint working groups to assess the combined data sets and methods in detail

All are invited to the next one: **UHECR-2014** in October 2014

http://uhecr14.telescopearray.org