

The physics of Ultra-High Energy Cosmic Rays (I): long-lasting mysteries

- Where are they produced?
- What are they?
- How are they accelerated up to macroscopic energies? (remember: $1 \text{ J} = 6.24 \times 10^{18} \text{ eV}$)

BUT... THIS IS



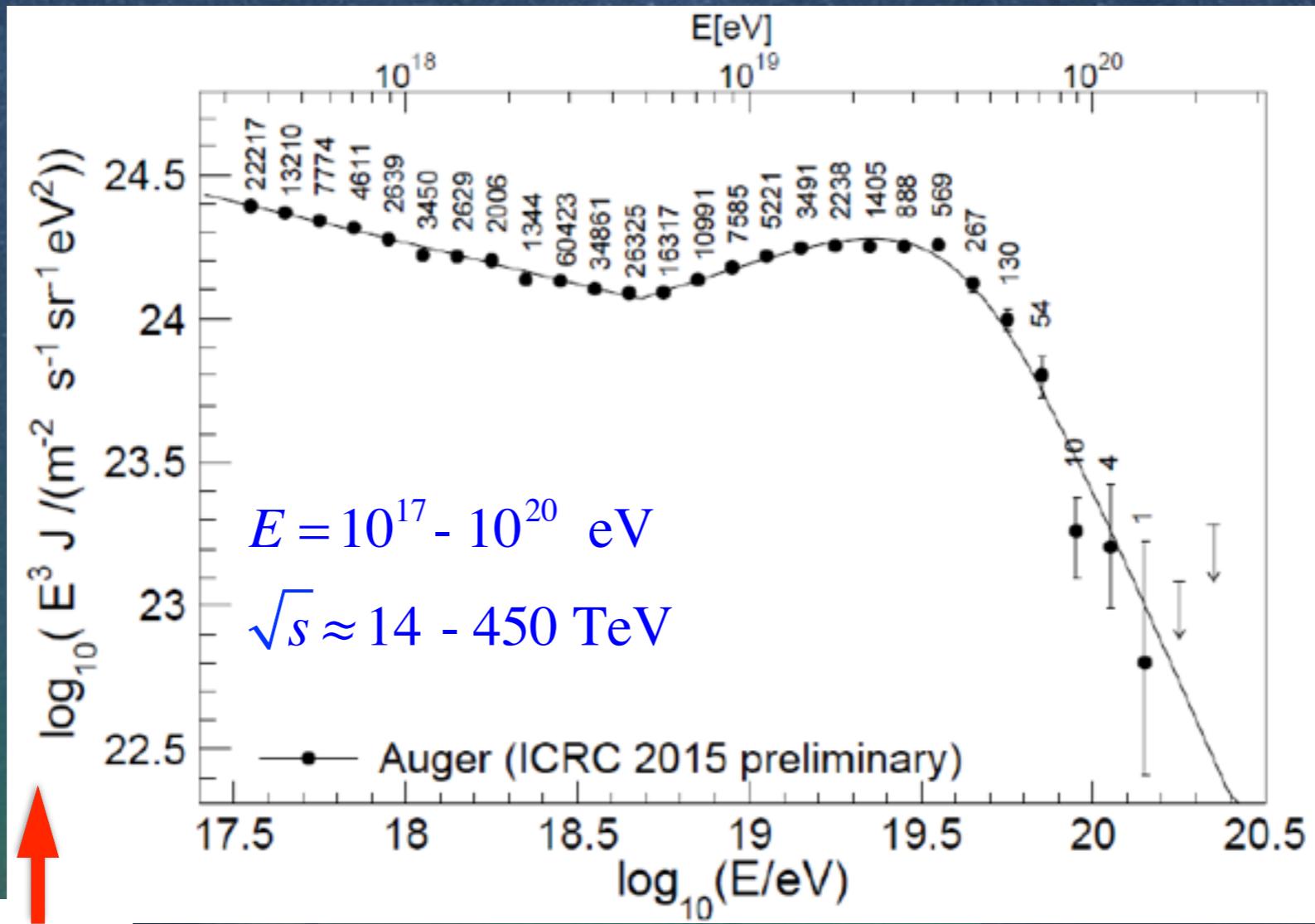
BUT... THIS IS
SOMEWHAT

A dark, atmospheric landscape at night. In the foreground, there's a dark, indistinct shape that looks like a car or a truck. To its left, a road sign stands on a pole. Further to the right, a tall, thin microphone stand is positioned next to a small, rectangular structure, possibly a sound booth or a small building. The background is very dark, suggesting a rural or industrial setting at night.

BUT... THIS IS SOMEWHAT

AN INCOMPLETE (OR POOR)
PICTURE OF THE PHYSICS WE CAN
DO WITH ULTRA-HIGH ENERGY
COSMIC RAYS (UHECR)

The physics of Ultra-High Energy Cosmic Rays (II)



- Explore kinematical regions not reachable by accelerators
- Perform tests of fundamental interactions at extreme energy regimes

UHECR meet Particle Physics

HADRONIC INTERACTIONS

- Cross section (p-air, p-p)
 - Auger: Phys. Rev. Lett. 109, 062002 (2012)
 - TA: Phys. Rev. D 92, 032007 (2015)
- Barion & meson production (tests of hadronic models)
 - Auger: Phys. Rev. D 91, 032003 (2015);
 - Phys. Rev. D 93, 072006 (2016); Phys. Rev. D 90, 012012 (2014); Phys. Rev. Lett. accepted for publication

EXOTICS

- Ultra-relativistic magnetic monopoles
 - ANITA-II: Phys. Rev. D 83, 023513 (2011); Auger: submitted for publication
- Violation of Lorentz invariance
- Searches for new particles: R-hadrons, glueballs, dark-photons, mirror particles, ...

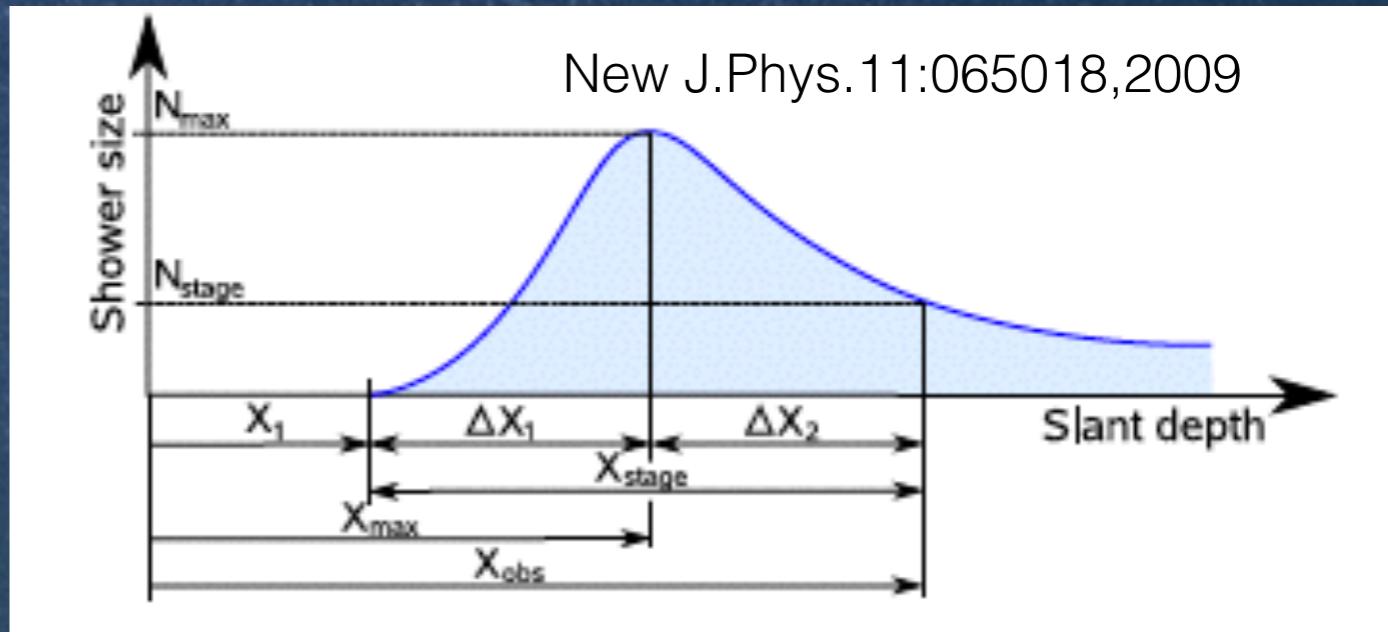
STANDARD-MODEL PARTICLE SEARCHES

- UHE photons
 - Auger: ApJ, 789 (2014) 160; Astropart. Phys. 31 (2009) 399; Astropart. Phys. 29 (2008) 243; Astropart. Phys. 27 (2007) 155
 - TA: Phys. Rev. D 88, 112005 (2013)
- UHE neutrinos
 - Auger: Phys. Rev. D 91, 092008 (2015); Advances in High Energy Physics, 2013 (2013) 708680; Astrophysical Journal Letters, 755 (2012) L4

Cross section measurement

$$\frac{dN}{dX_1} = \frac{1}{\lambda_{p-air}} \exp(-X_1 / \lambda_{p-air})$$

$$\sigma_{p-air} = \frac{\langle m_{air} \rangle}{\lambda_{p-air}}$$



- But we have no access to X_1 . We use instead X_{max}

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

Cross section measurement

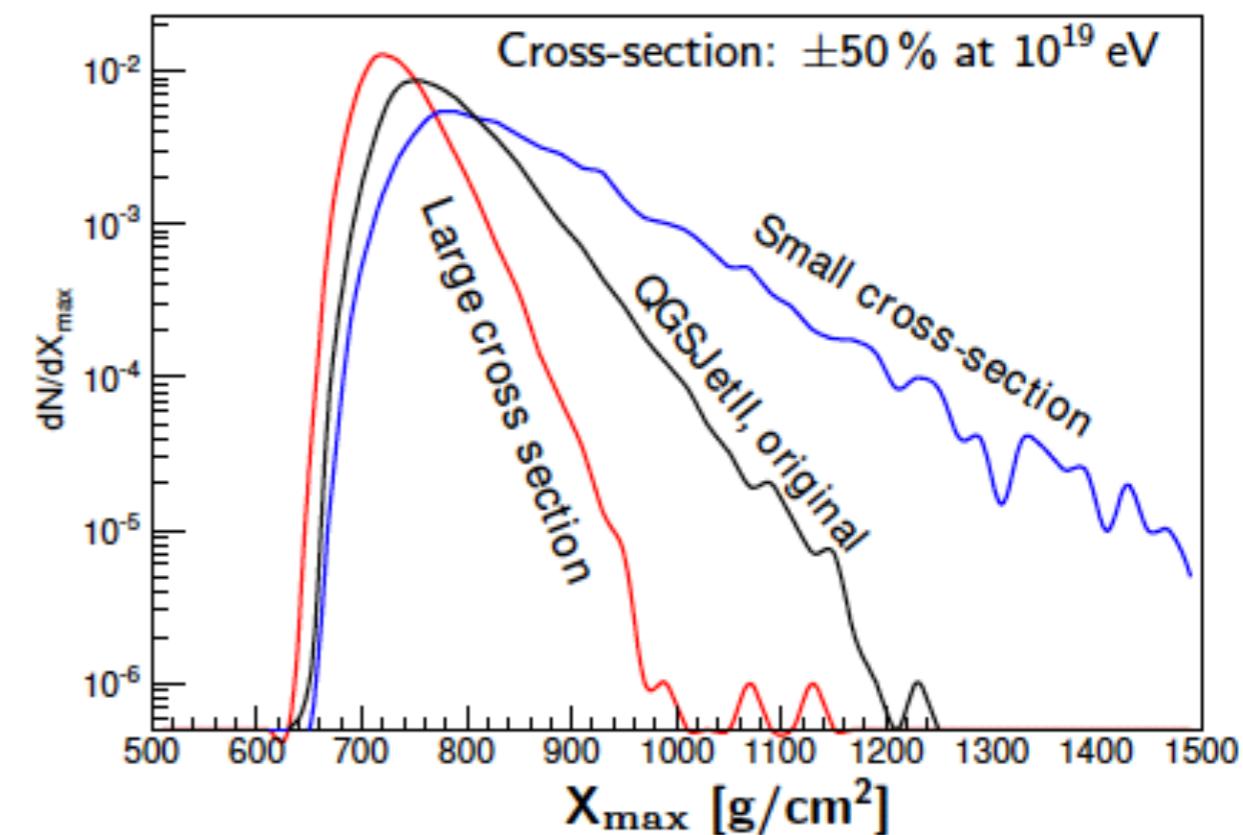
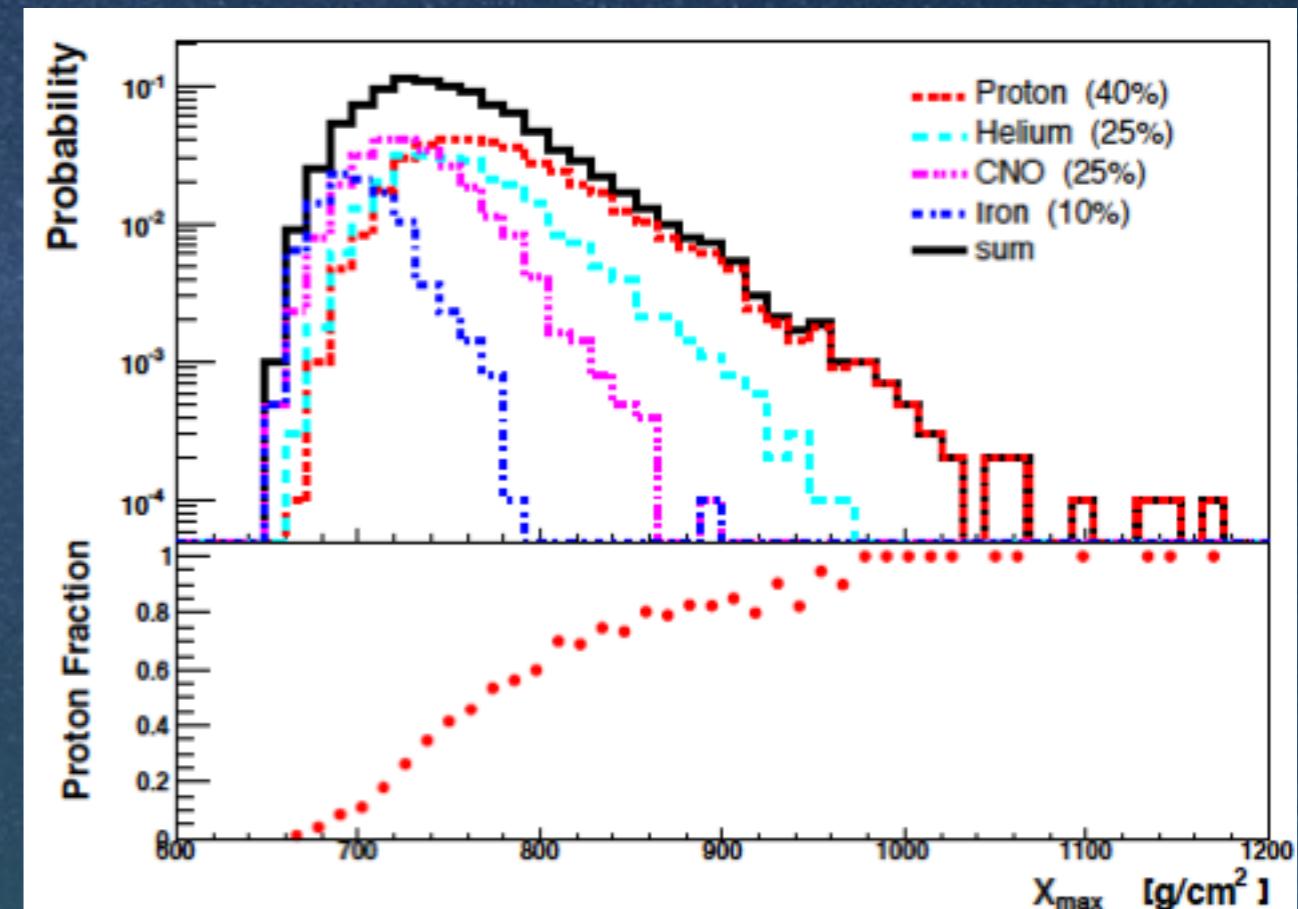
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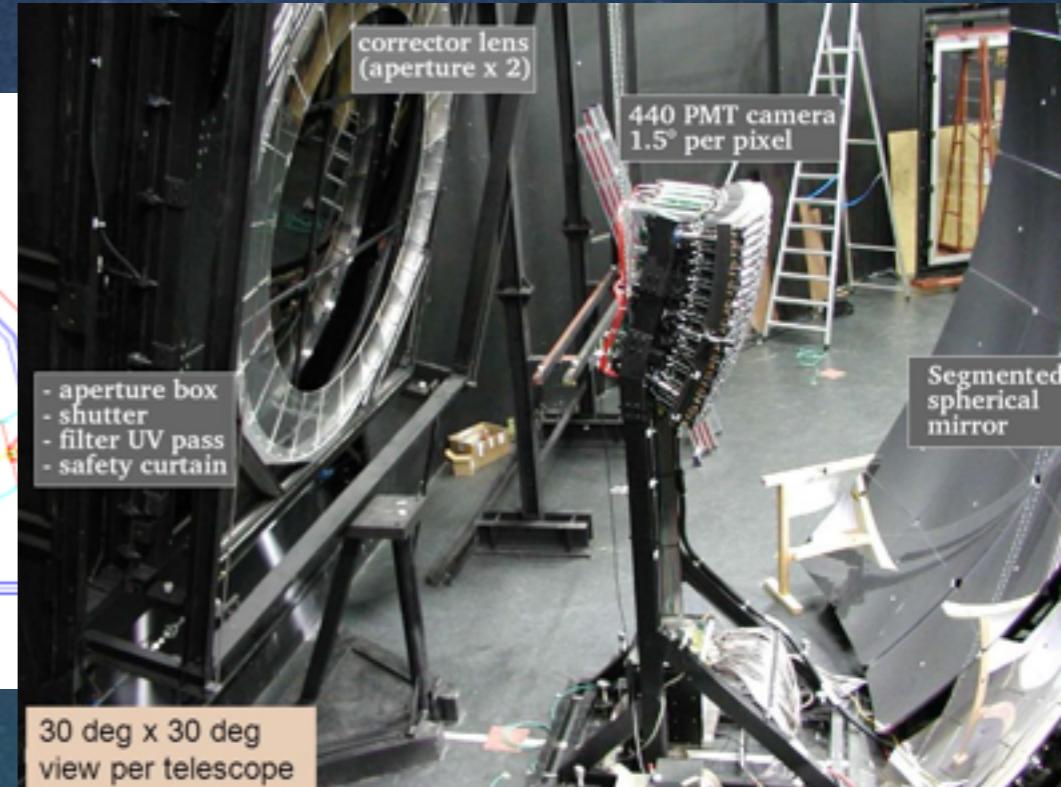
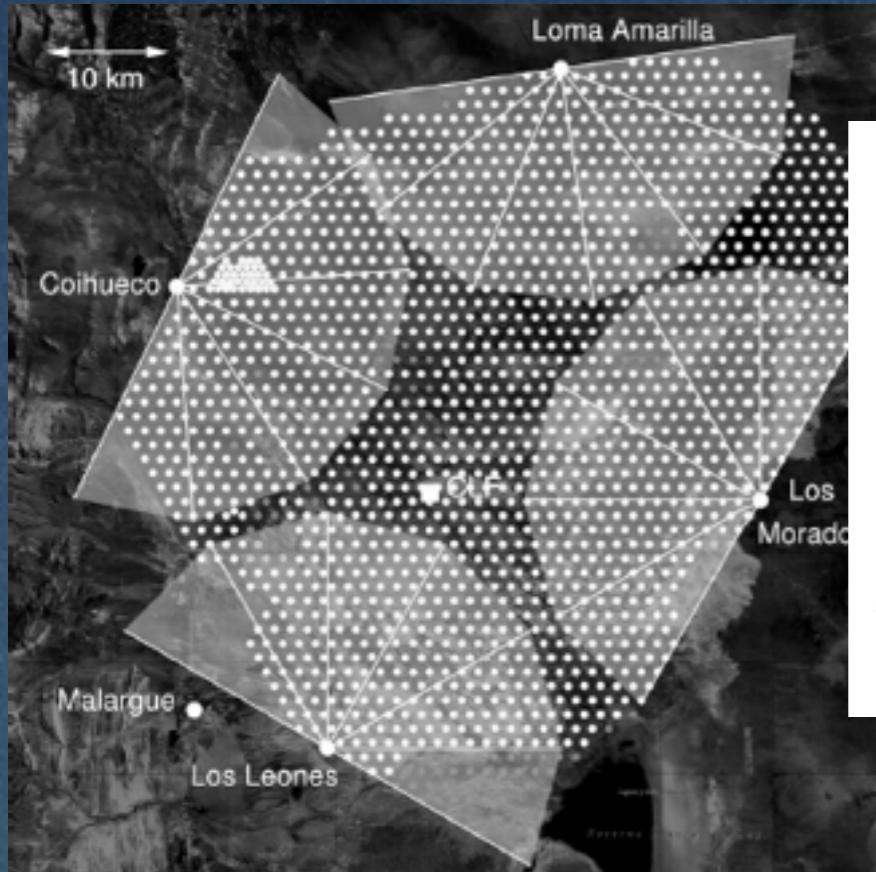
$$\frac{dN}{dX_{\max}} \propto \exp(-X_{\max} / \Lambda_{\eta})$$

- Select deeply penetrating showers to ensure proton dominance in the sample
 - η is the fraction of most deeply penetrating showers used



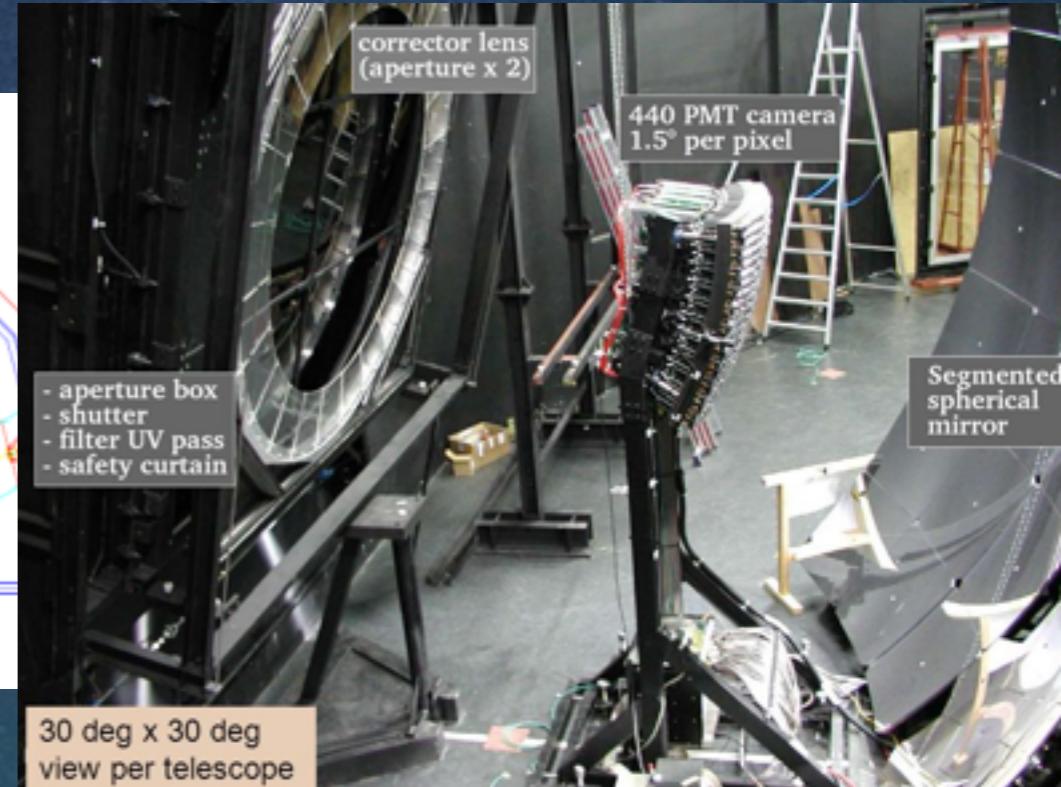
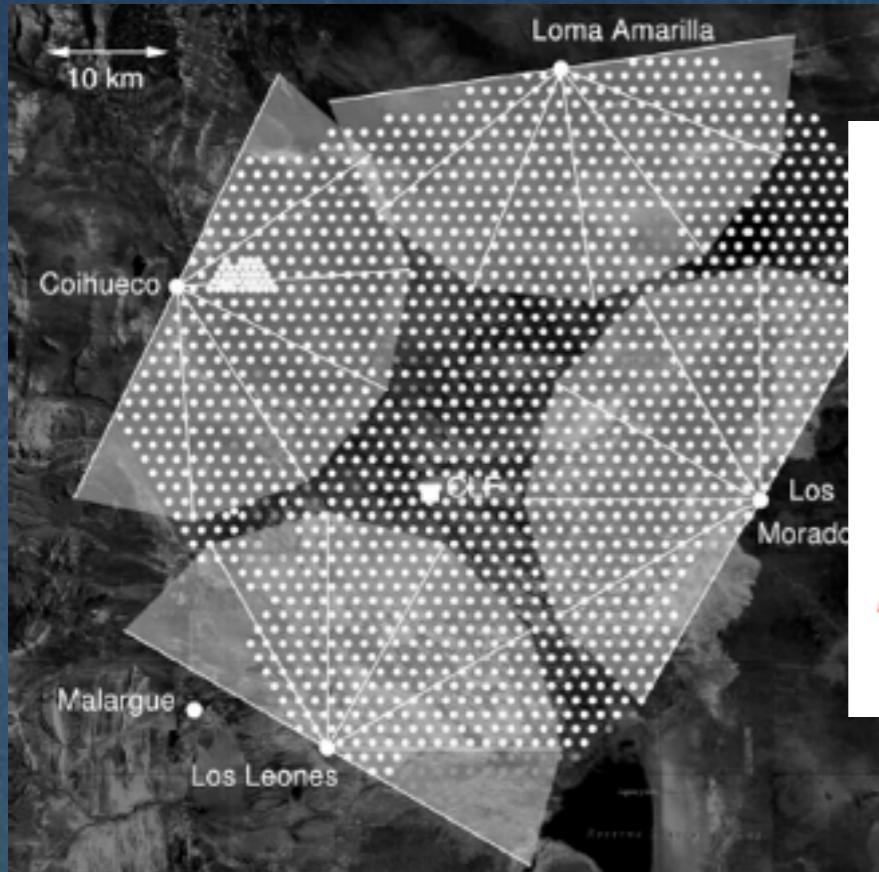
How do we measure X_{\max} ?

Pierre Auger Fluorescence Detector



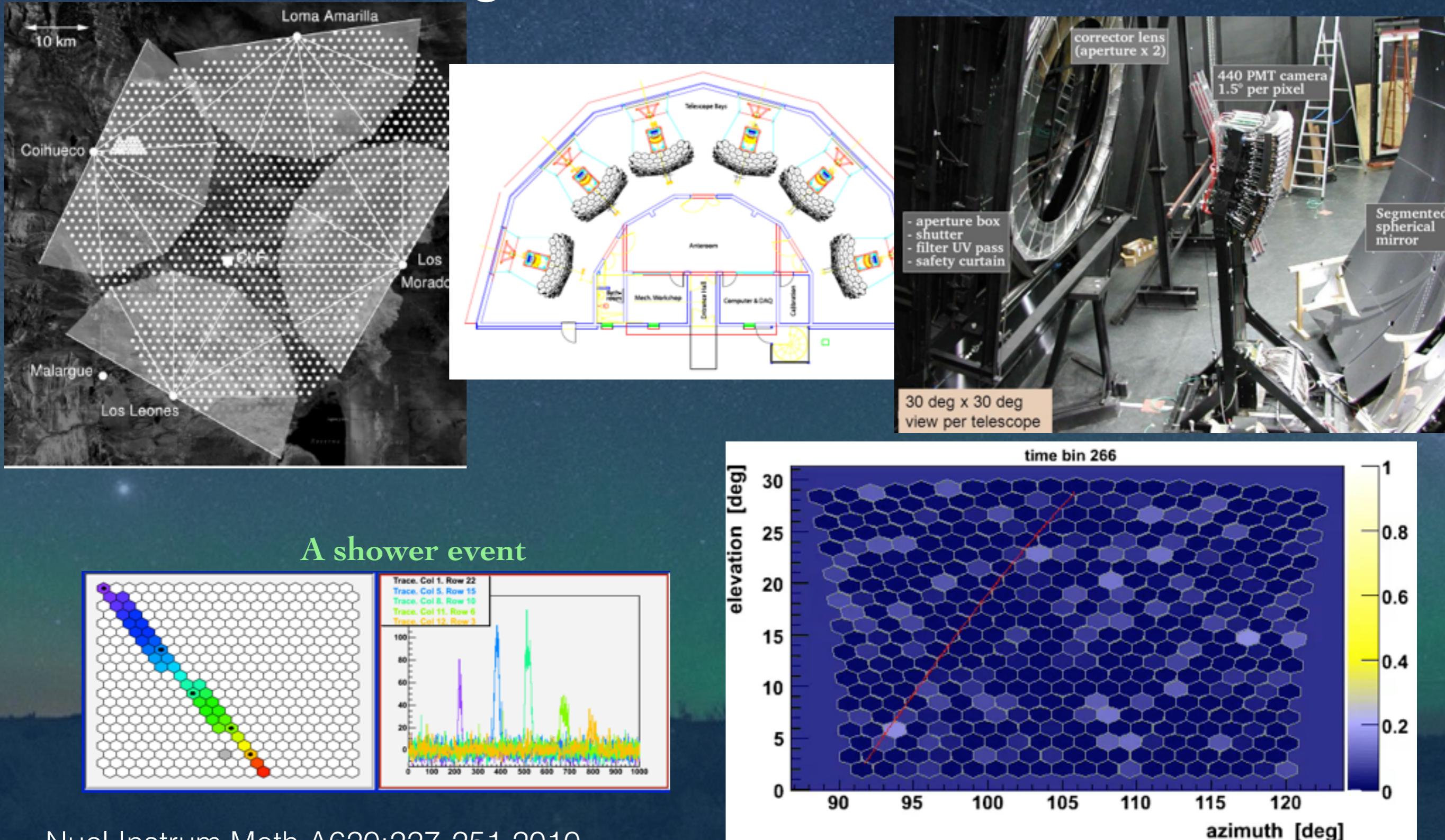
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Pierre Auger Fluorescence Detector



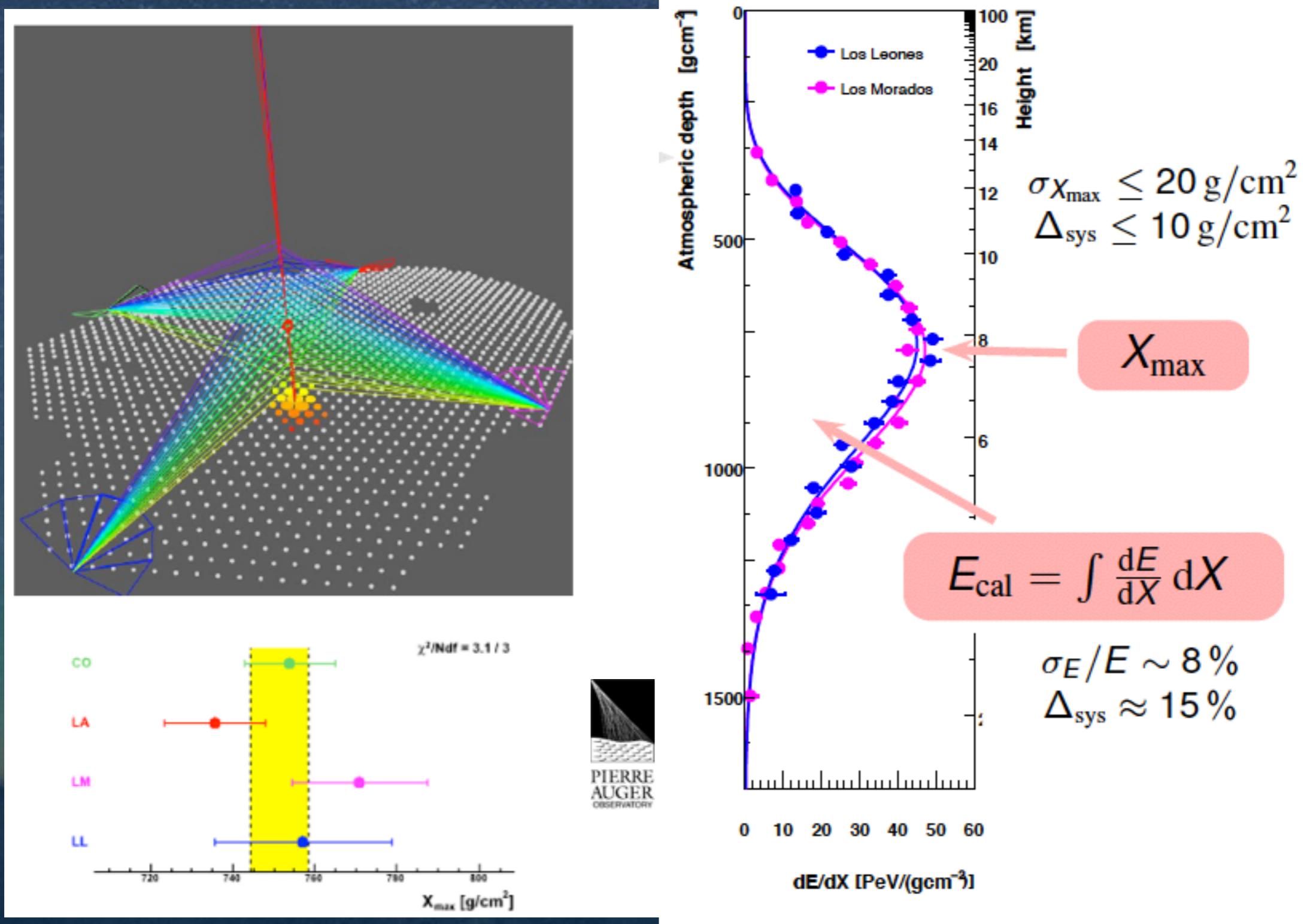
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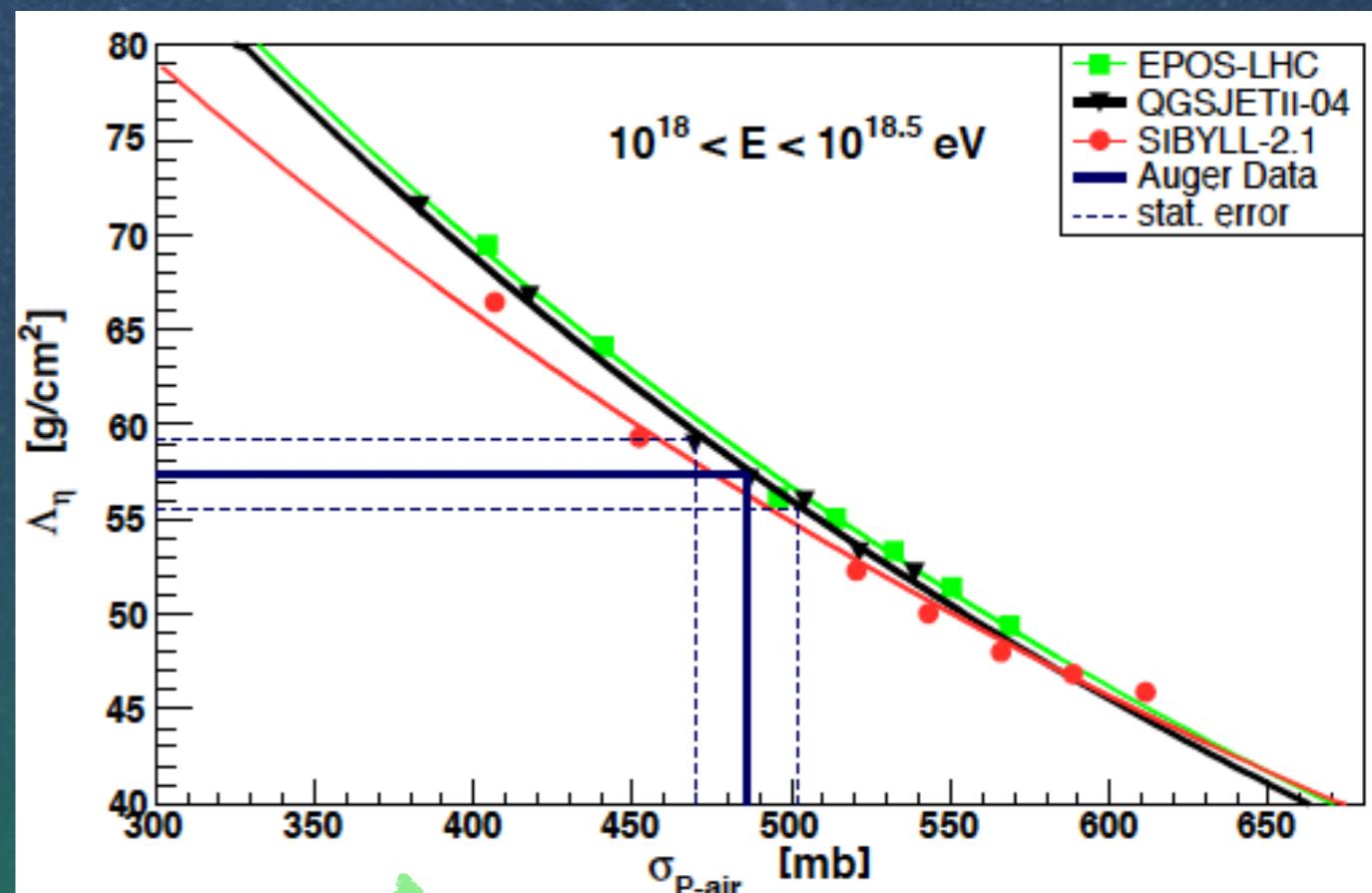
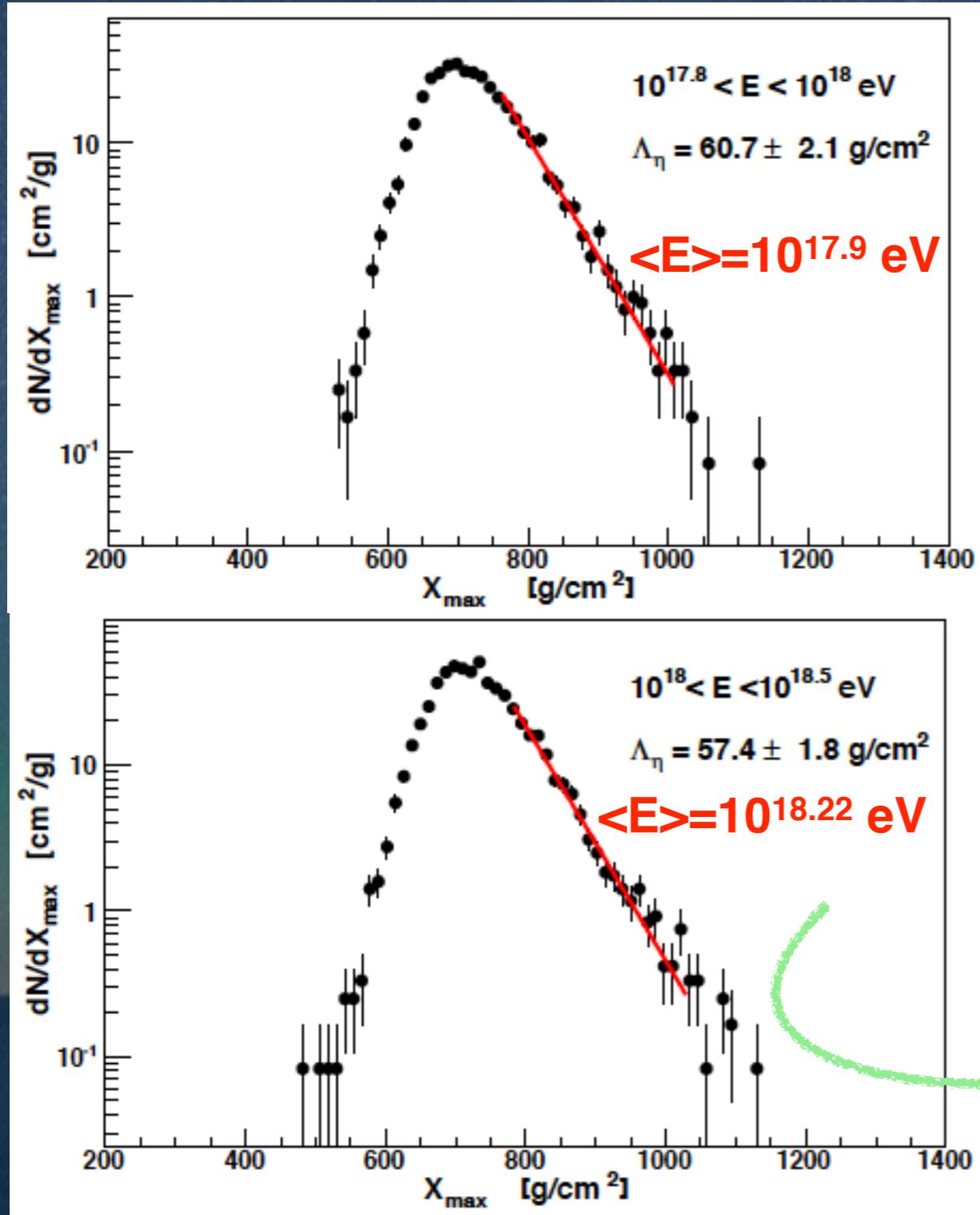
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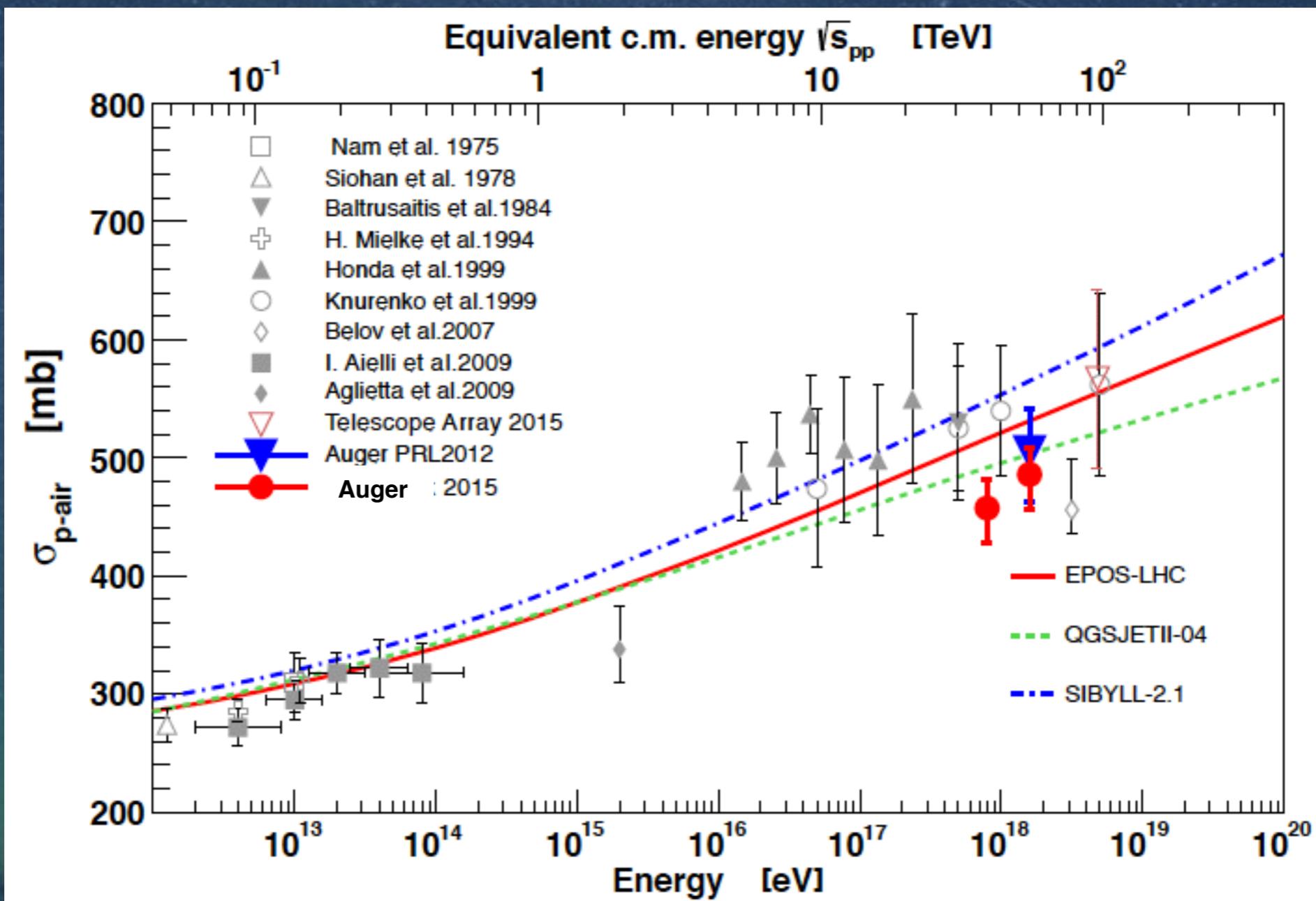
Measuring Λ_η

- $\eta = 0.2$ to guarantee $\sigma_{\text{stat}} \approx \sigma_{\text{sys}}$
- $\sigma_{\text{sys}} = 1.6 \text{ g/cm}^2$



Use air-shower simulations
to go from Λ_η to cross section

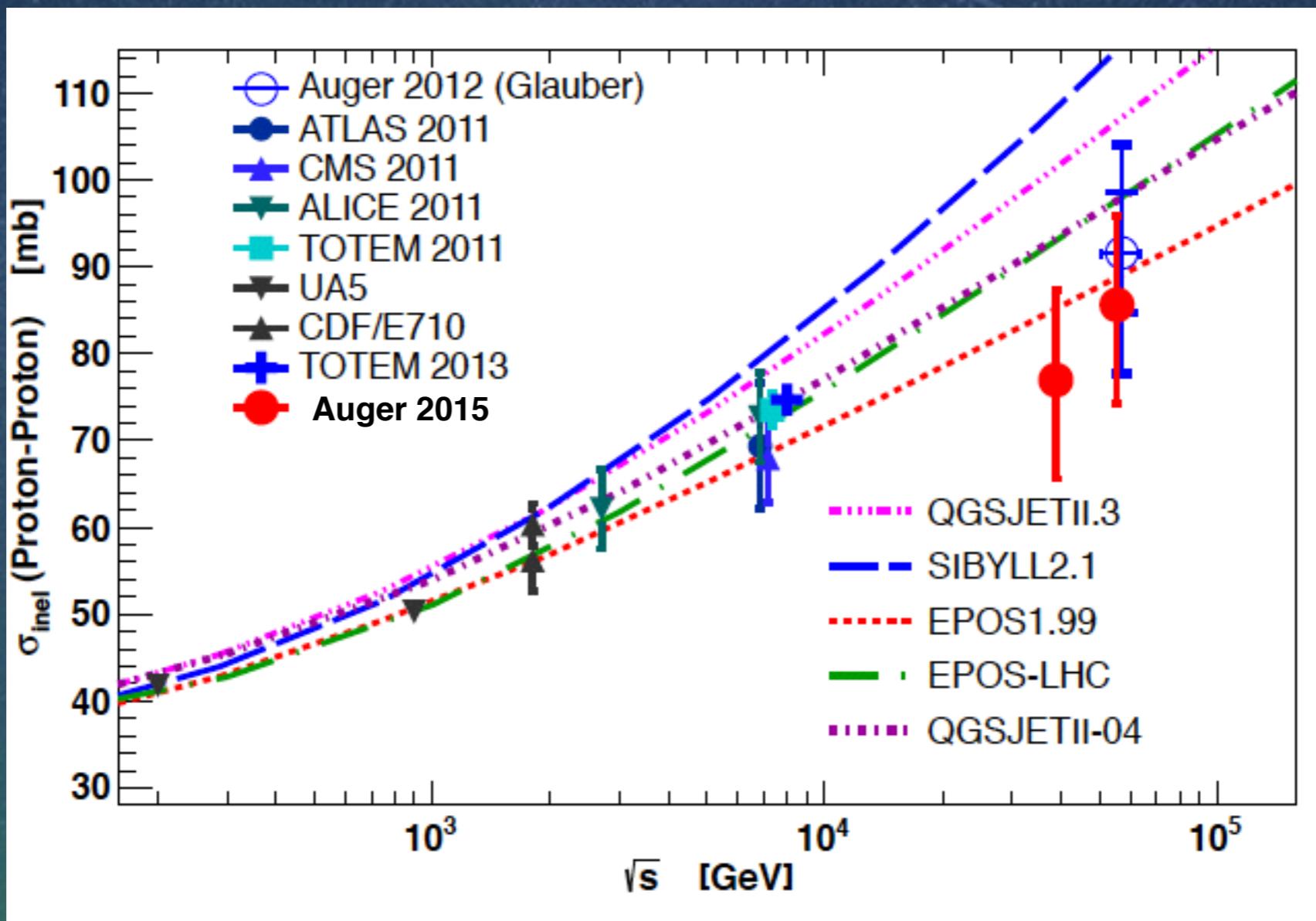
proton-air cross section



$$\sigma_{p\text{-air}} = 457.5 \pm 17.8(\text{stat}) + 19 - 25(\text{sys})\text{mb} \quad \text{at } \sqrt{s_{pp}} = 38.7 \pm 2.5 \text{ TeV}$$

$$\sigma_{p\text{-air}} = 485.8 \pm 15.8(\text{stat}) + 19 - 25(\text{sys})\text{mb} \quad \text{at } \sqrt{s_{pp}} = 55.5 \pm 3.6 \text{ TeV}$$

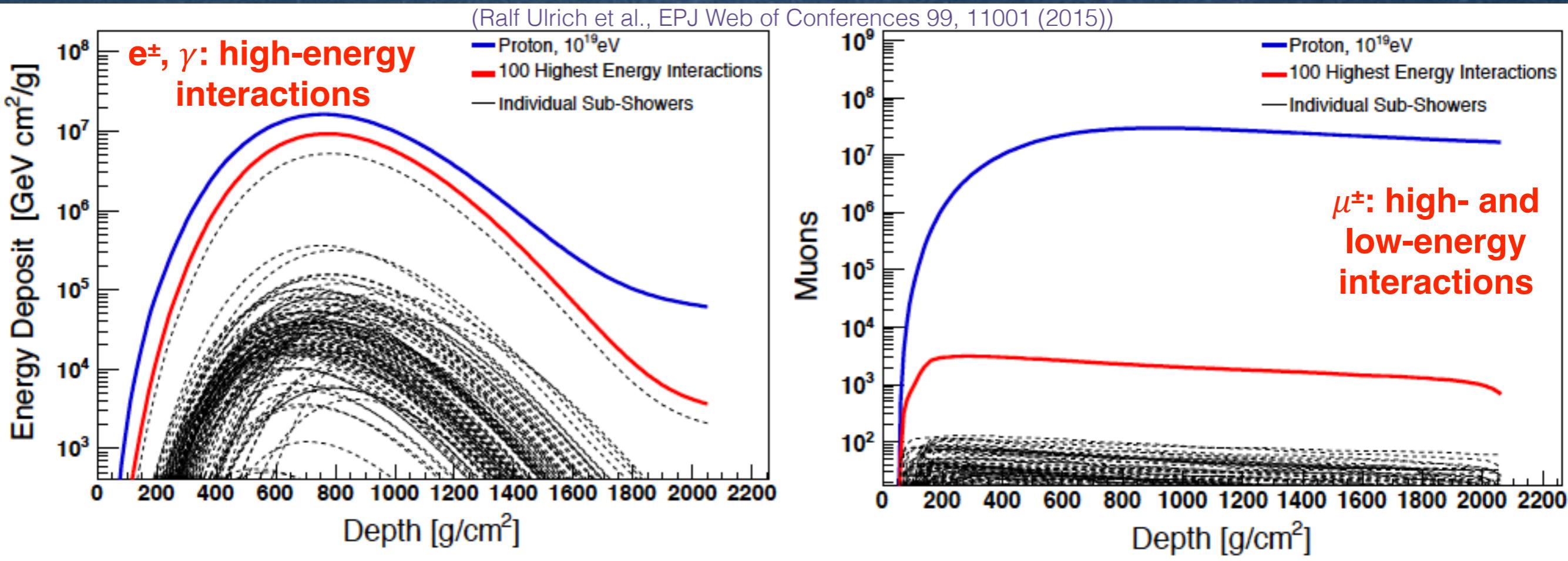
Inelastic proton-proton cross section



$$\sigma_{pp}^{inel} = 76.95 \pm 5.5(stat) + 5.2 - 7.2(sys) \pm 7.0(Glauber) \text{ mb} \quad \text{at } \sqrt{s} = 38.7 \pm 2.5 \text{ TeV}$$

$$\sigma_{pp}^{inel} = 85.62 \pm 5.0(stat) + 5.5 - 7.4(sys) \pm 7.1(Glauber) \text{ mb} \quad \text{at } \sqrt{s} = 55.5 \pm 3.6 \text{ TeV}$$

Shower development



Muons are a powerful tool to study strong interactions and hadron production at very high energies

PIERRE AUGER: SURFACE DETECTOR

NIM A 798 (2015) 172

Communication

antenna

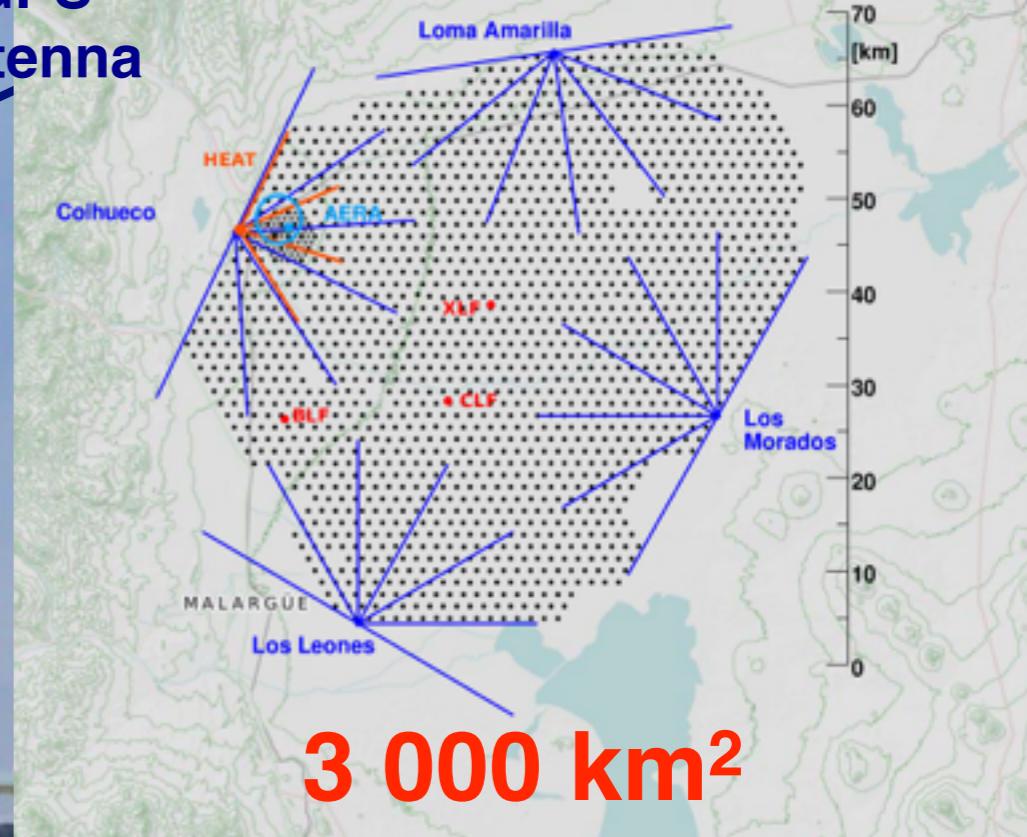
GPS

antenna

Electronics enclosure

40 MHz FADC, local triggers, 10 Wat

1 600 detectors



Battery

3 PMTs (9") for Cherenkov
light detection

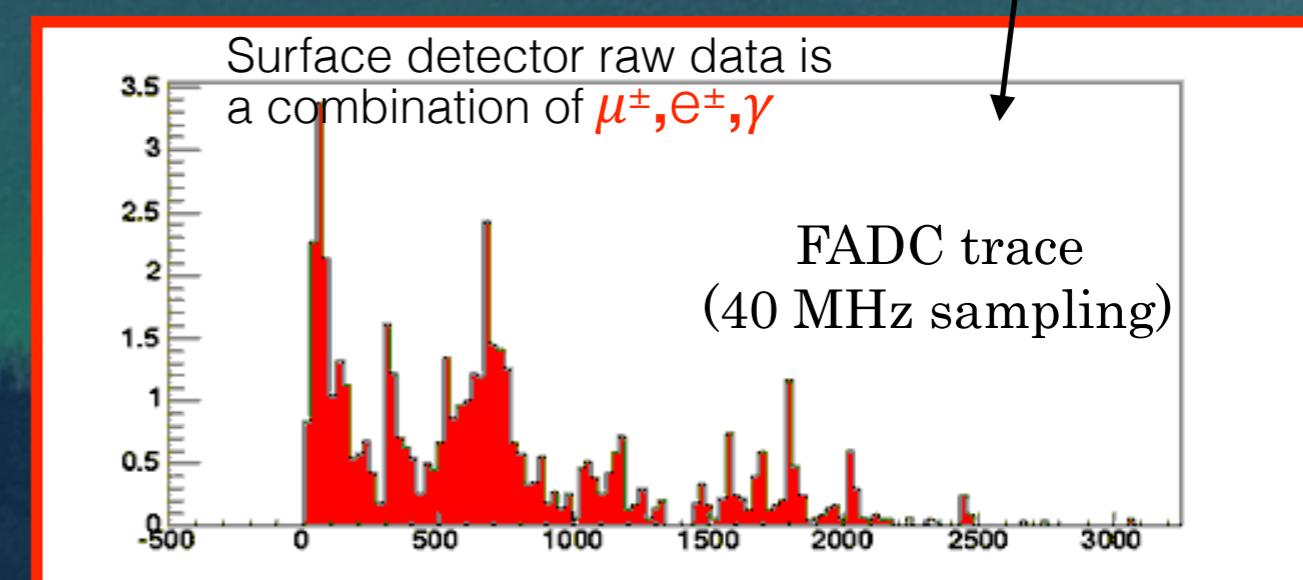
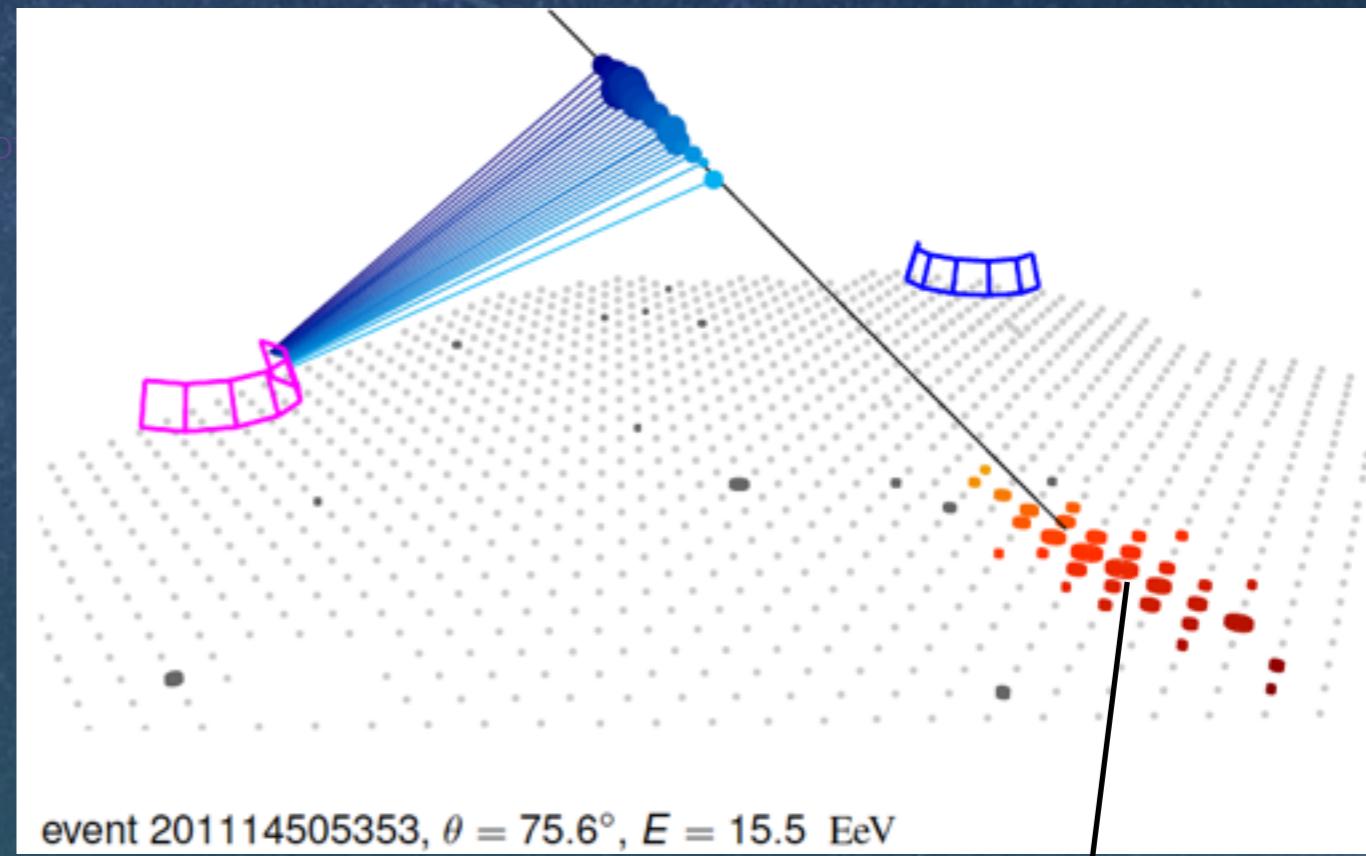
Angular resolution: 1-2°

Solar
Panel

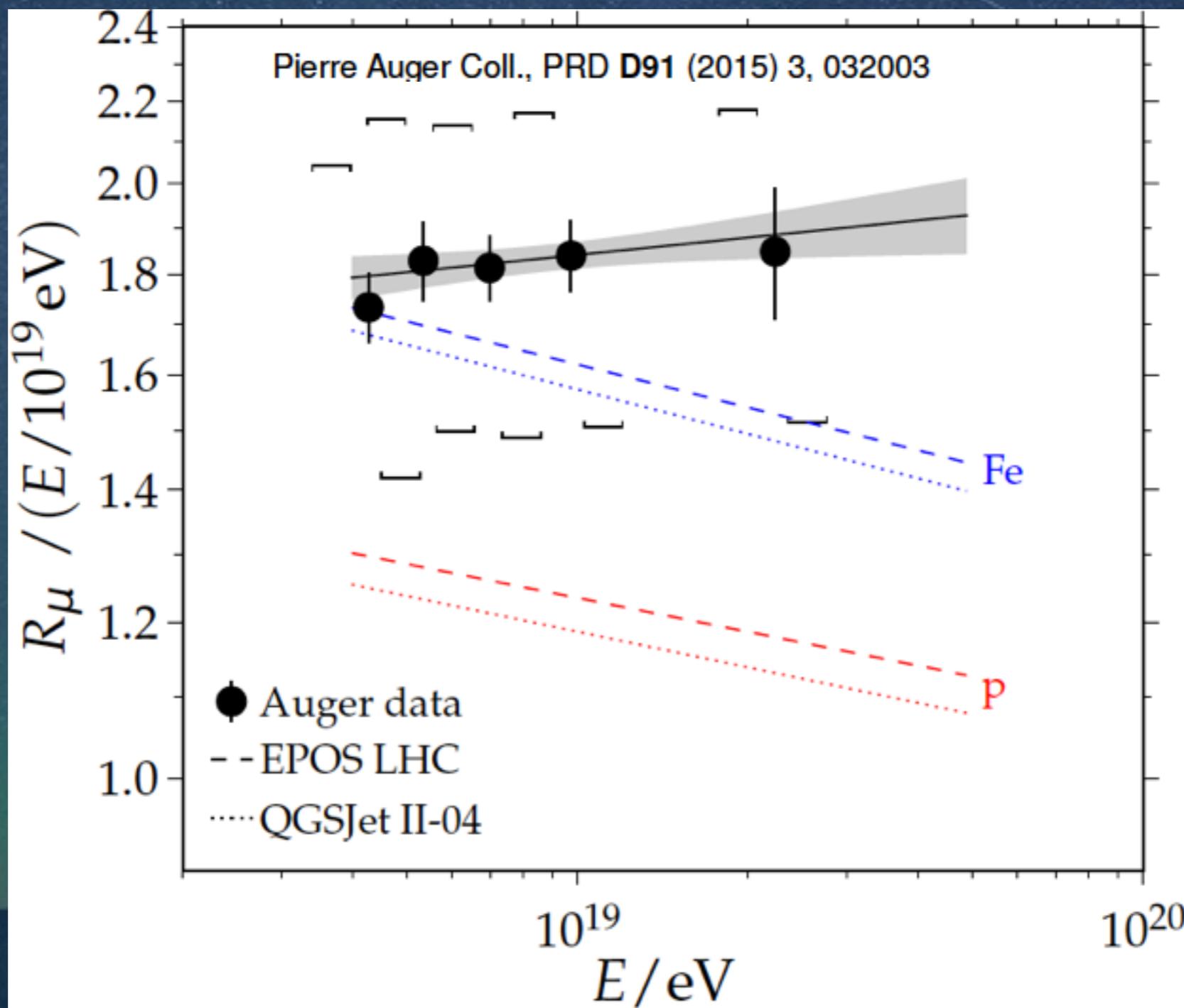
Plastic tank with
12 ton of water

Muons in atmospheric showers

- **Use hybrid events** (Ralf Ulrich et al., EPJ Web of Conferences, 2011, 32, 01002)
 - Simultaneous detection by fluorescence and surface detectors
- **Use inclined events (62-80 degrees in zenith)**
 - Electromagnetic component mostly absorbed
 - Analysis based on 174 events
- **Muon number for each event obtained by scaling a reference profile of the muon density at the ground (R_μ)**
 - $R_\mu = 1$ for protons, $E = 10^{19}$ eV, QGSJetII-03

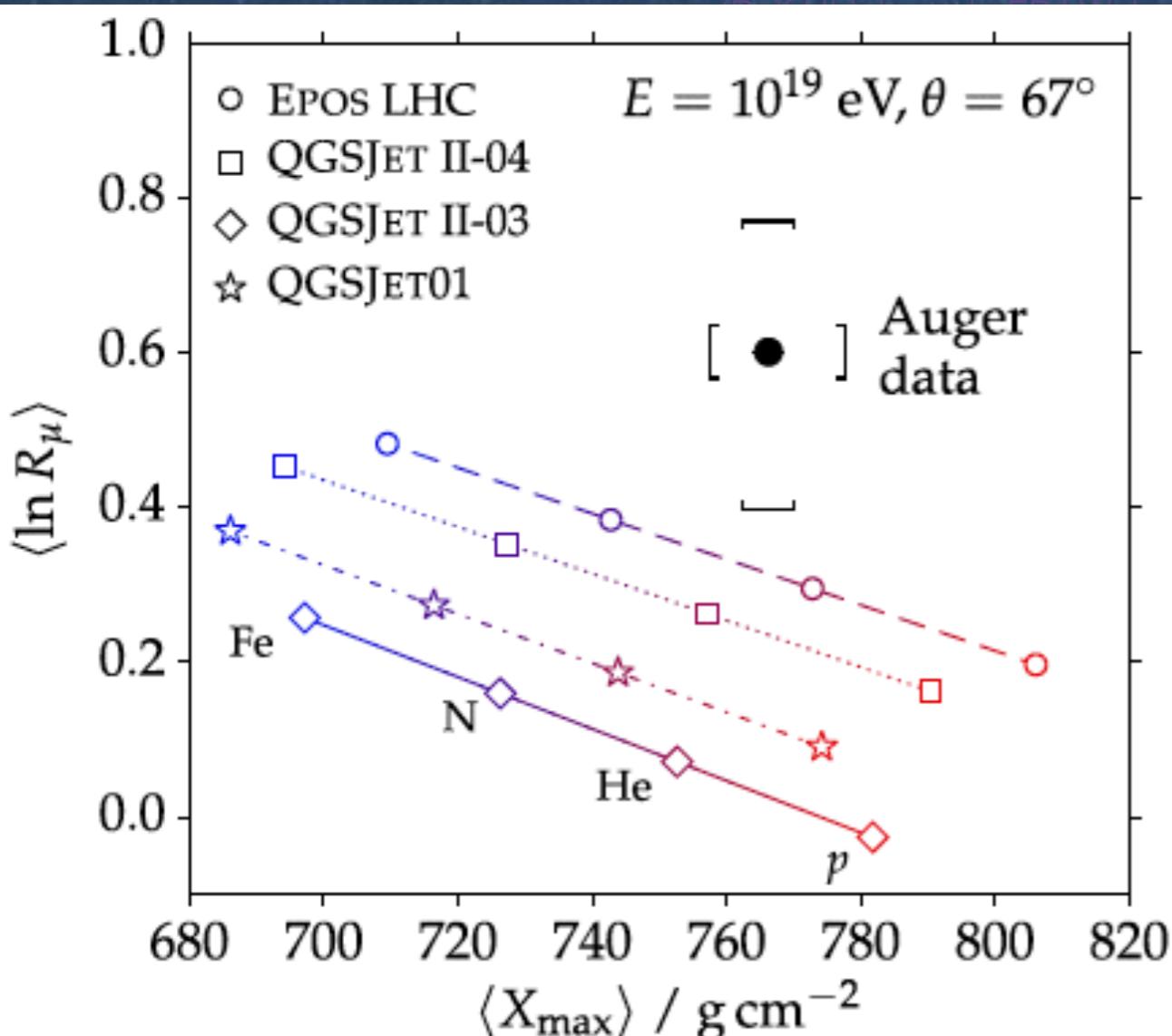


Muons excess in data

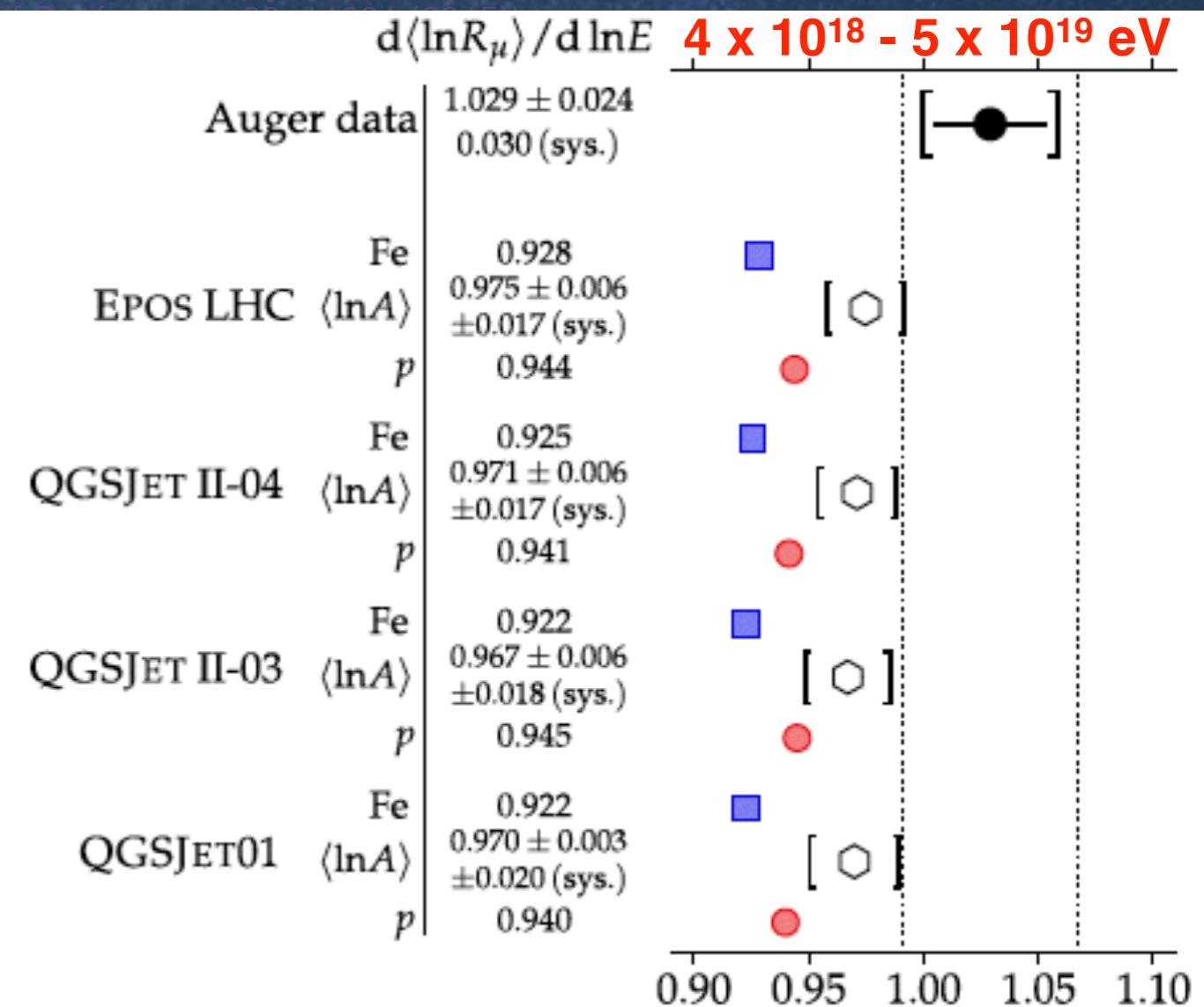


Muon excess in data

Muon scale vs. $\langle X_{\max} \rangle$



Logarithmic gain



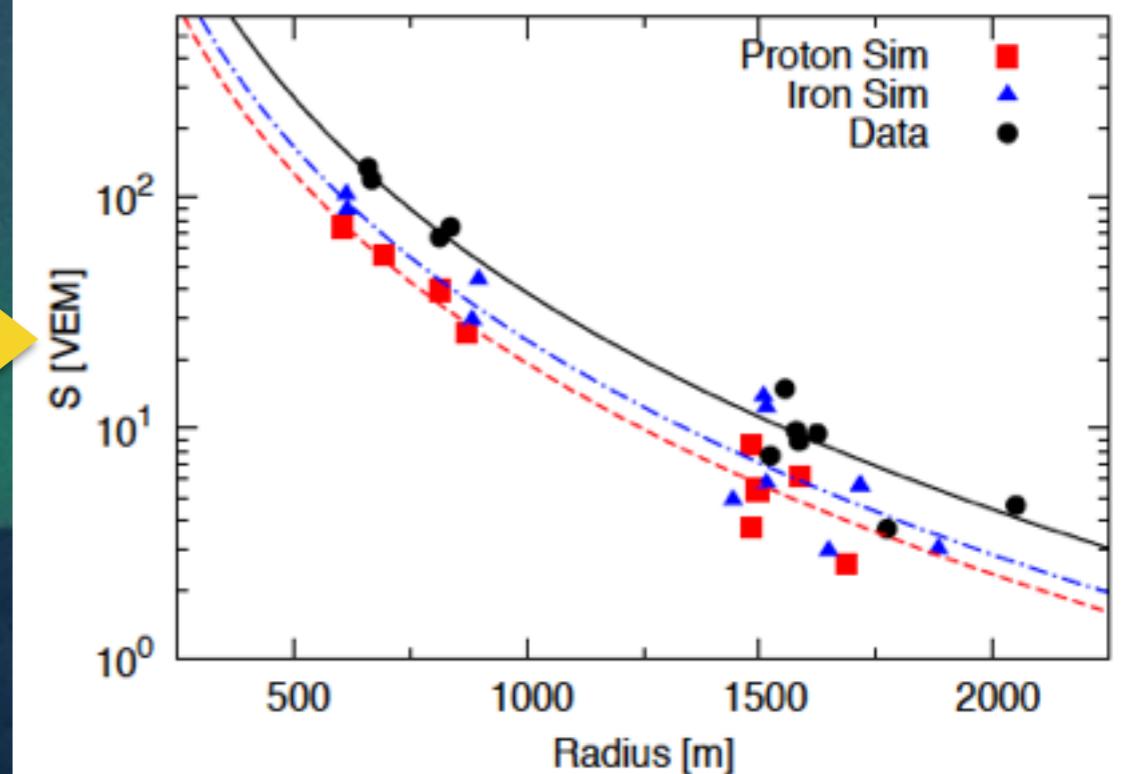
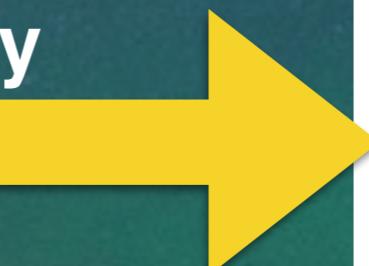
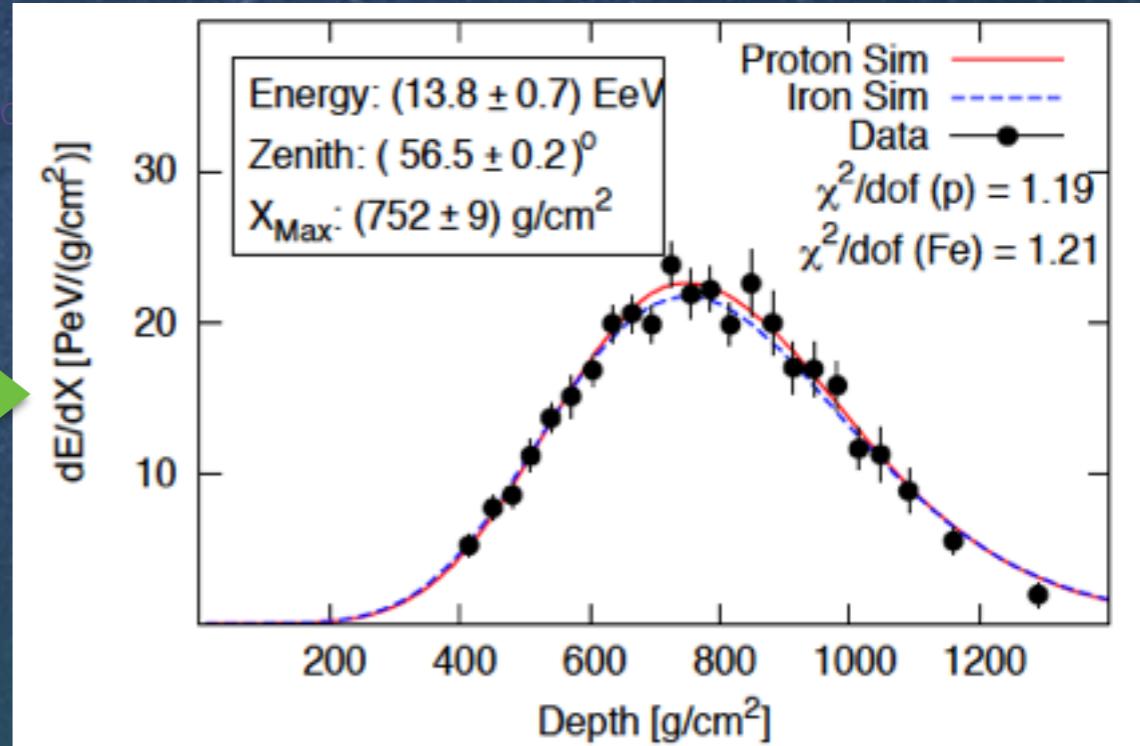
Pierre Auger Coll., PRD D91 (2015) 3, 032003

At 10^{19} eV , the muon deficit in simulations amounts to $30 - 80\%^{+17\%}_{-20\%}$ (sys) depending on the model

Testing hadronic interactions with hybrid events

(Ralf Ulrich et al., EPJ Web of Conference)

- Use “hybrid” data
- Select simulated events that reproduce longitudinal development of reconstructed data (Energy, Zenith angle and X_{max})
 - 411 events with $E_{\text{primary}} = 6-16$ EeV ($E_{\text{cm}} = 110-170$ TeV)
- Study ground signals and try to quantify discrepancies
 - Use rescaling parameters R_E (shift in energy calibration) and R_μ (hadronic contributions)

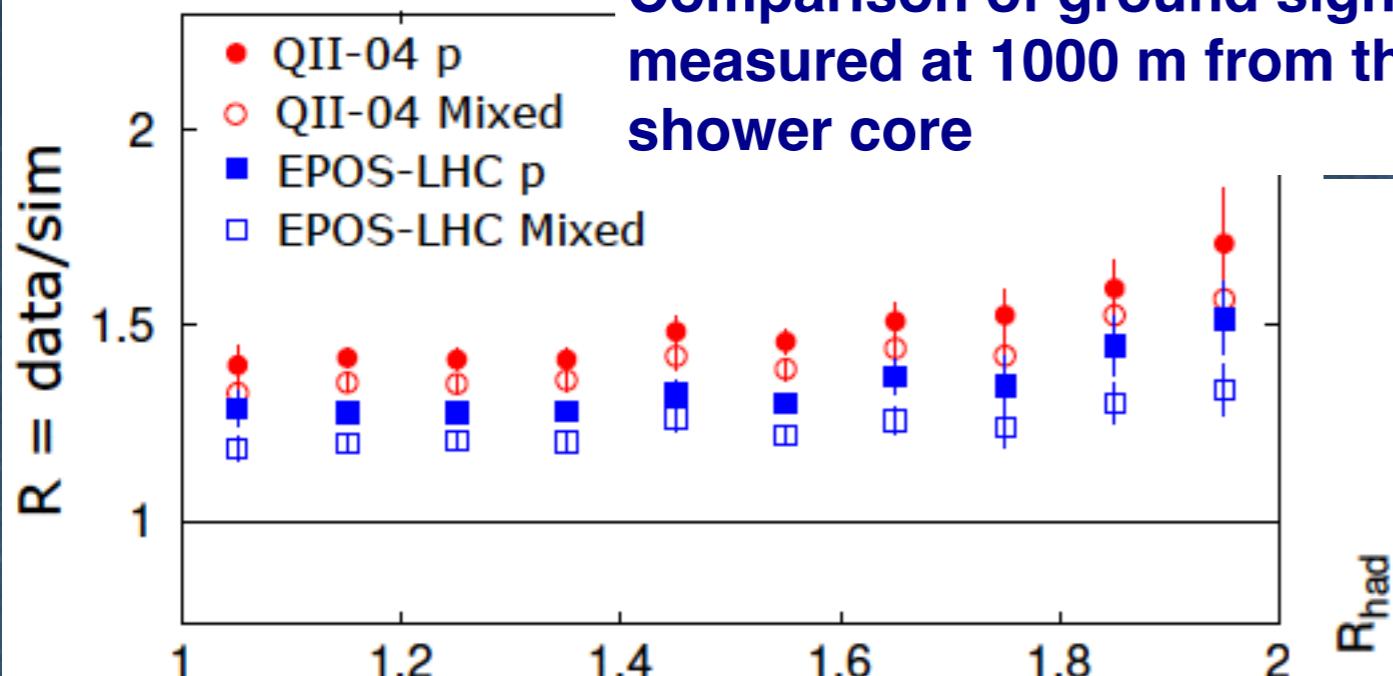


Testing hadronic interactions with hybrid events

**Comparison of ground signals
measured at 1000 m from the
shower core**

Apes 99, 11001 (2015)

Pierre Auger Collaboration, accepted for publication in PRL



**Rescaling parameters to
compensate discrepancies**

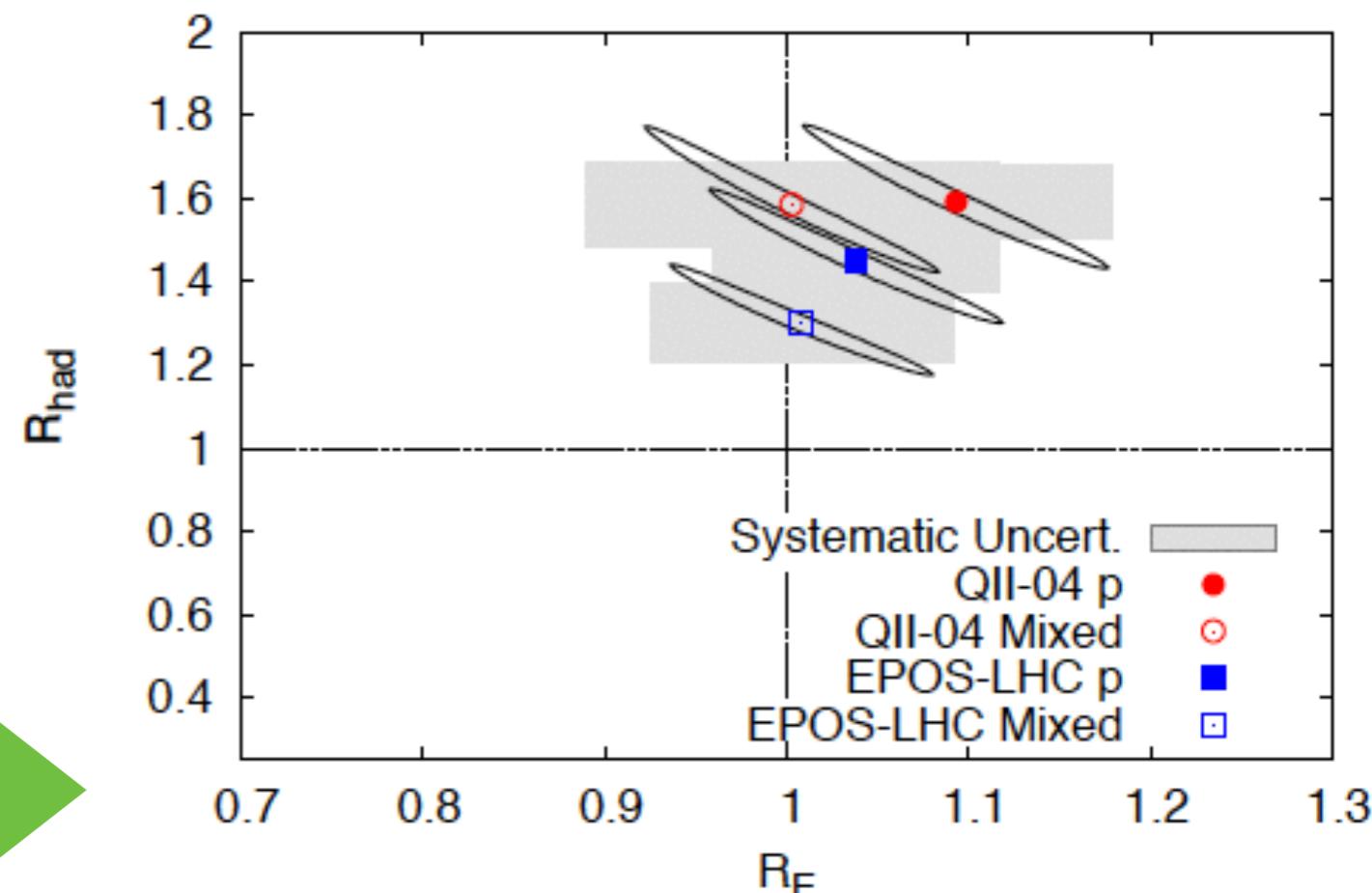


TABLE I. R_E and R_{had} with statistical and systematic uncertainties, for QGSJET-II-04 and EPOS-LHC.

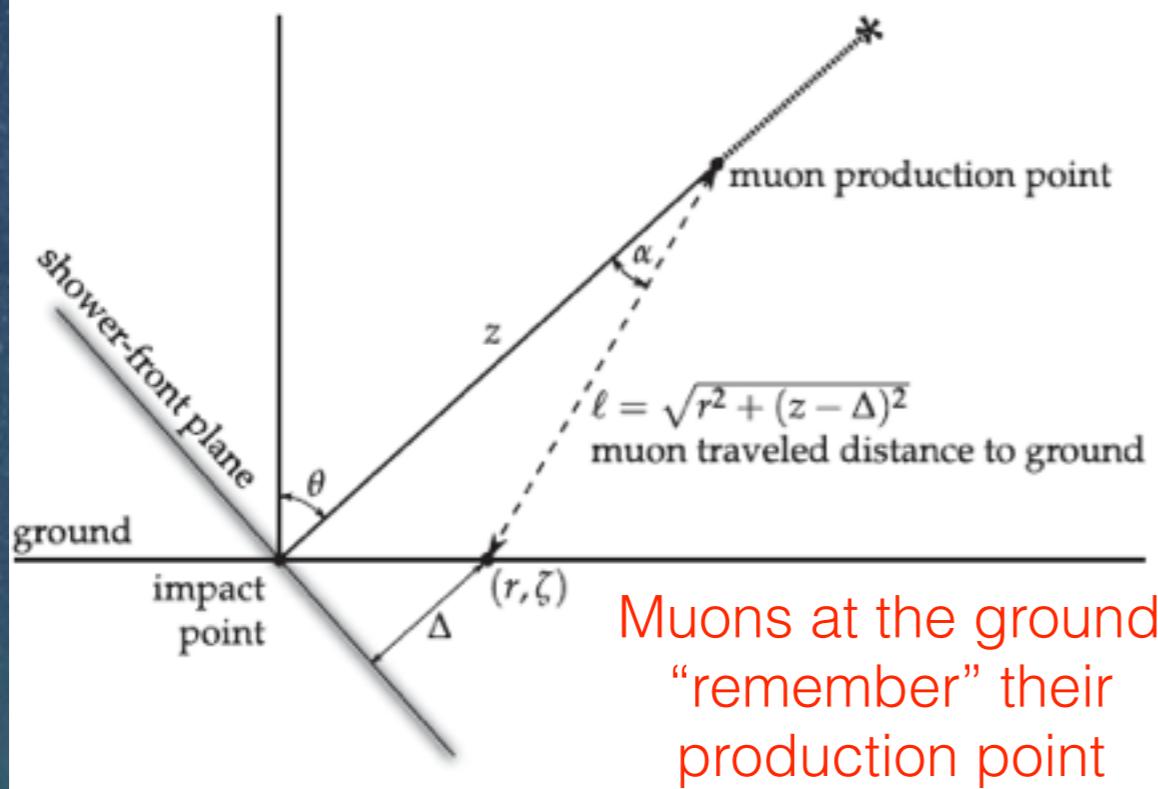
Model	R_E	R_{had}
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 Mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS Mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

Muon Production Depth (MPD)

Longitudinal development of the hadronic part of the shower using time measurements at the ground

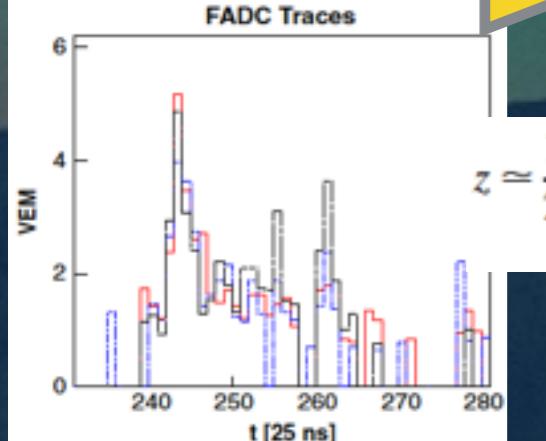
PHYSICAL REVIEW D 90, 012012 (2014)

Conferences 99, 11001 (2015))



Transform measured times into atmospheric depths

$t(\text{ns})$ \rightarrow $z(\text{m})$ \rightarrow $X(\text{g/cm}^2)$



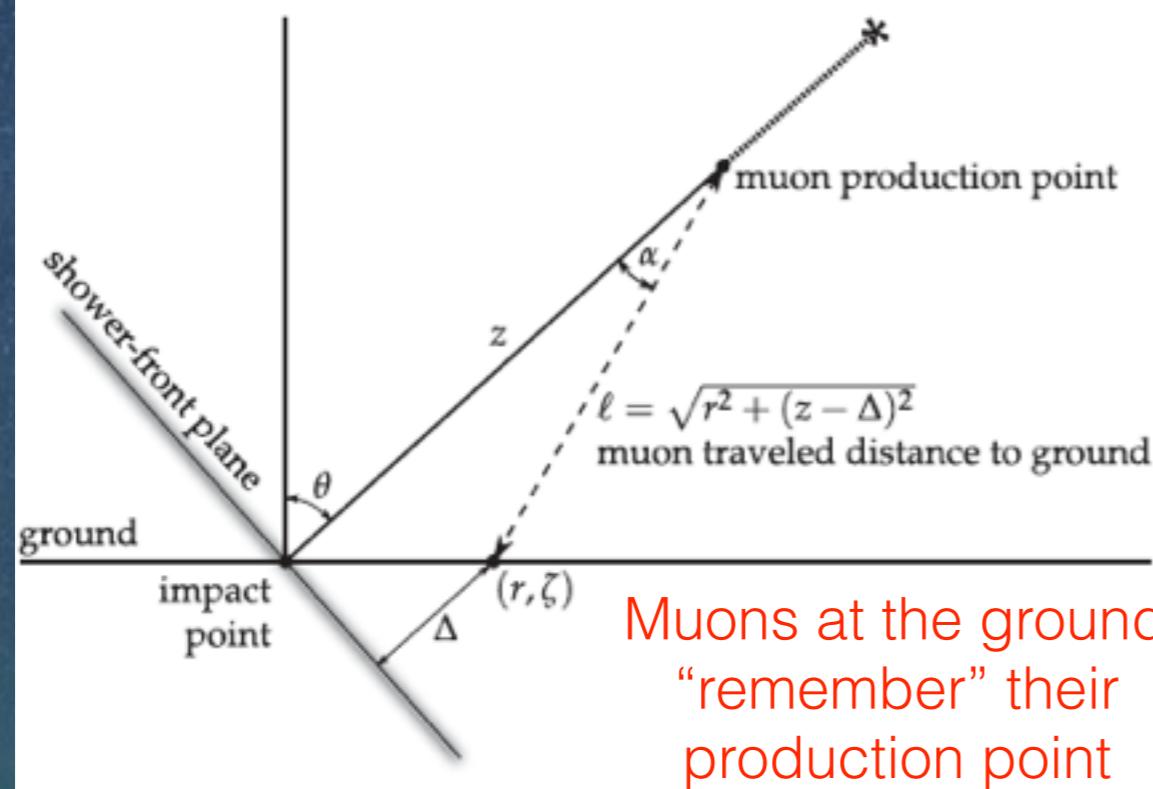
$$z \approx \frac{1}{2} \left(\frac{r^2}{c(t - \langle t_e \rangle)} - c(t - \langle t_e \rangle) \right) + \Delta - \langle z_\pi \rangle X^\mu = \int_z^\infty \rho(z') dz'$$

Muon Production Depth (MPD)

Longitudinal development of the hadronic part of the shower using time measurements at the ground

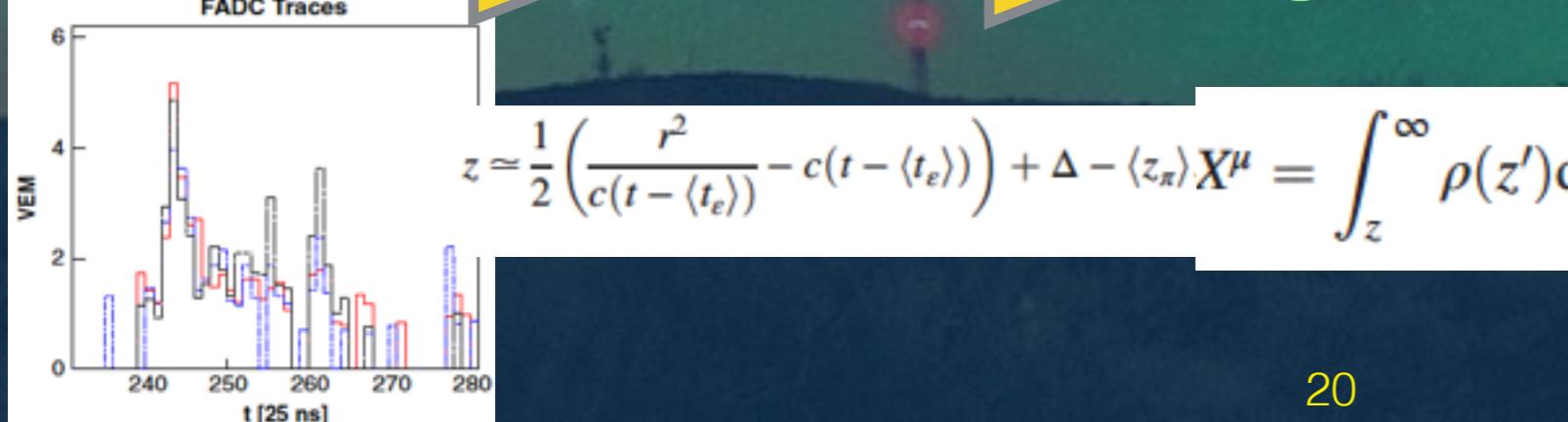
PHYSICAL REVIEW D 90, 012012 (2014)

Conferences 99, 11001 (2015)

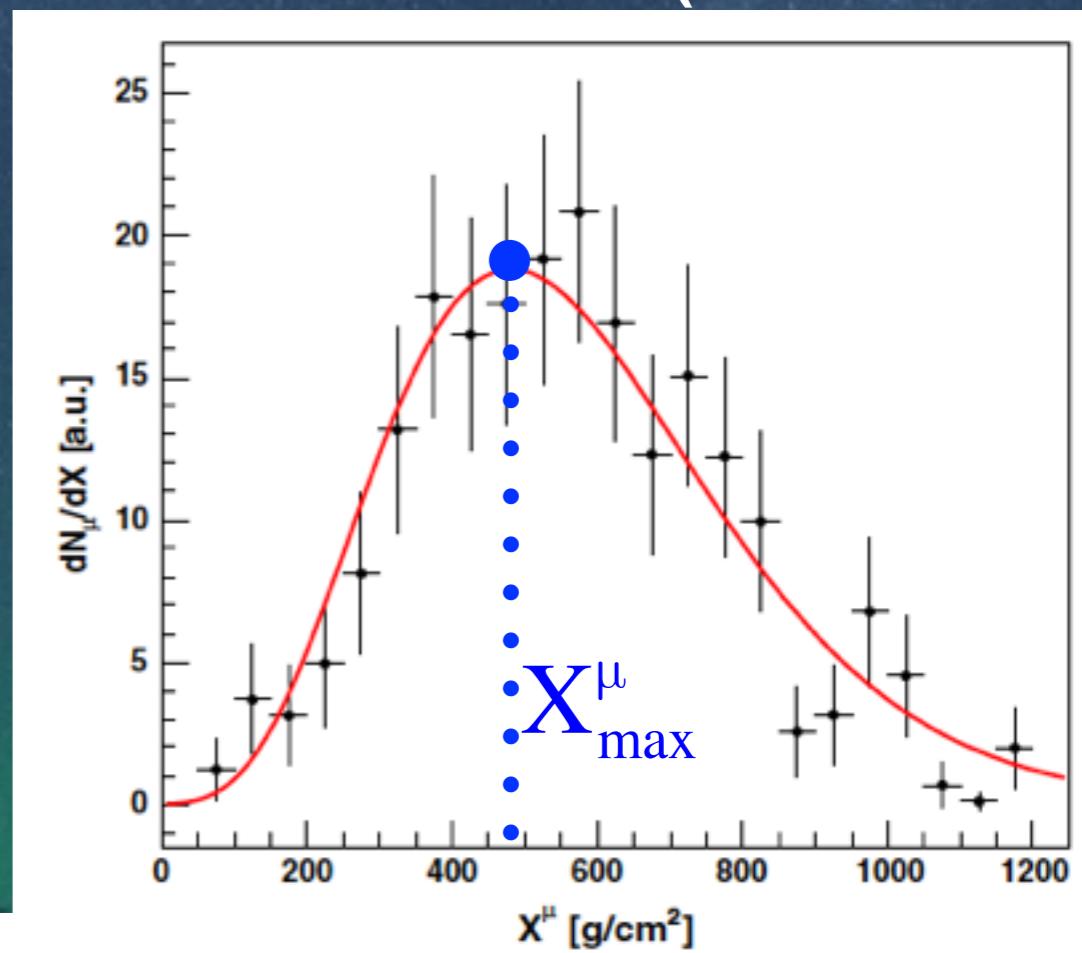


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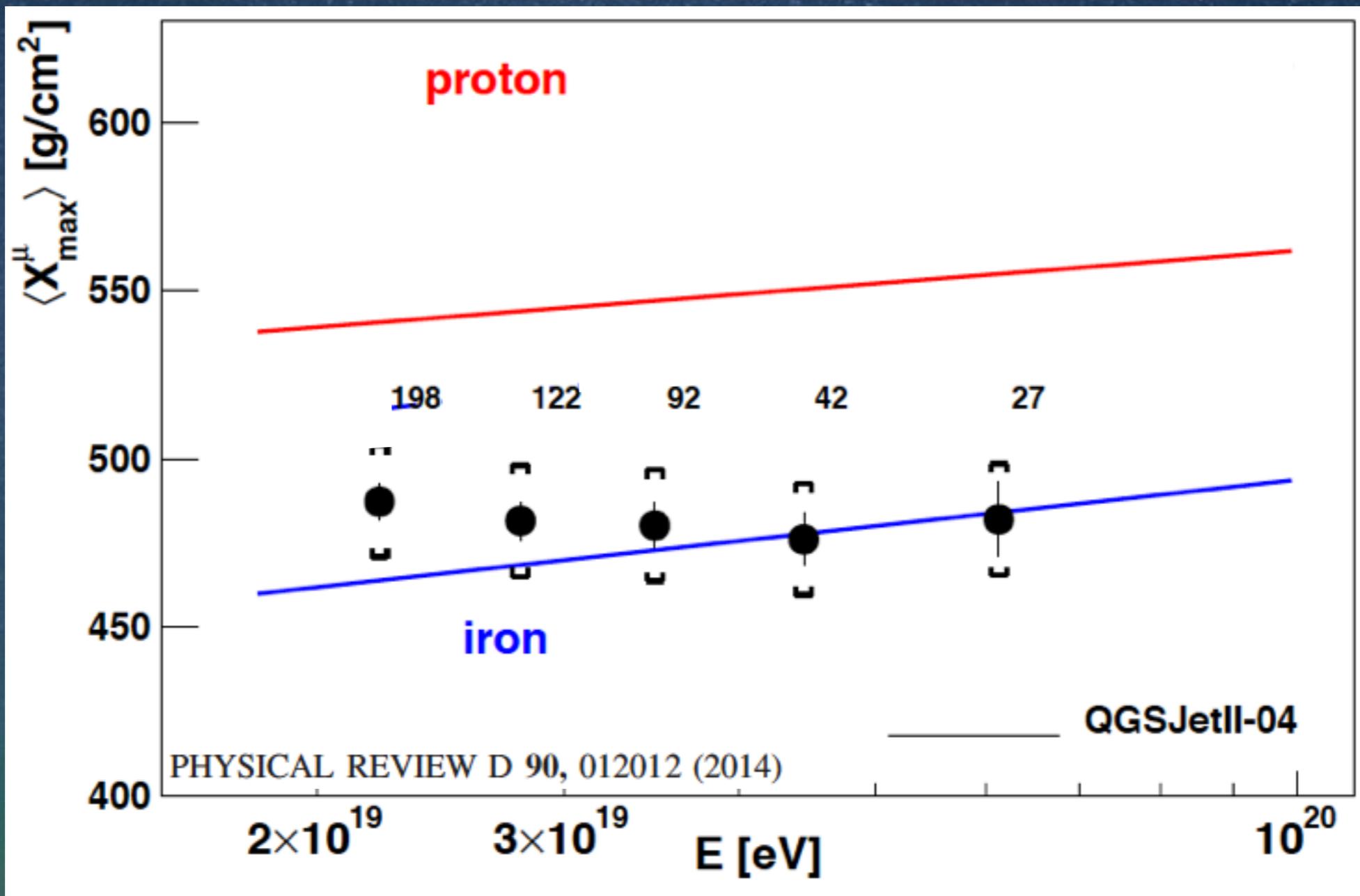
$t(\text{ns})$ \rightarrow $z(\text{m})$ \rightarrow $X(\text{g/cm}^2)$



Select muon-reach detectors
(>1700 from core)
for non-vertical events ($55^\circ < \theta < 65^\circ$)



Muon Production Depth (MPD)

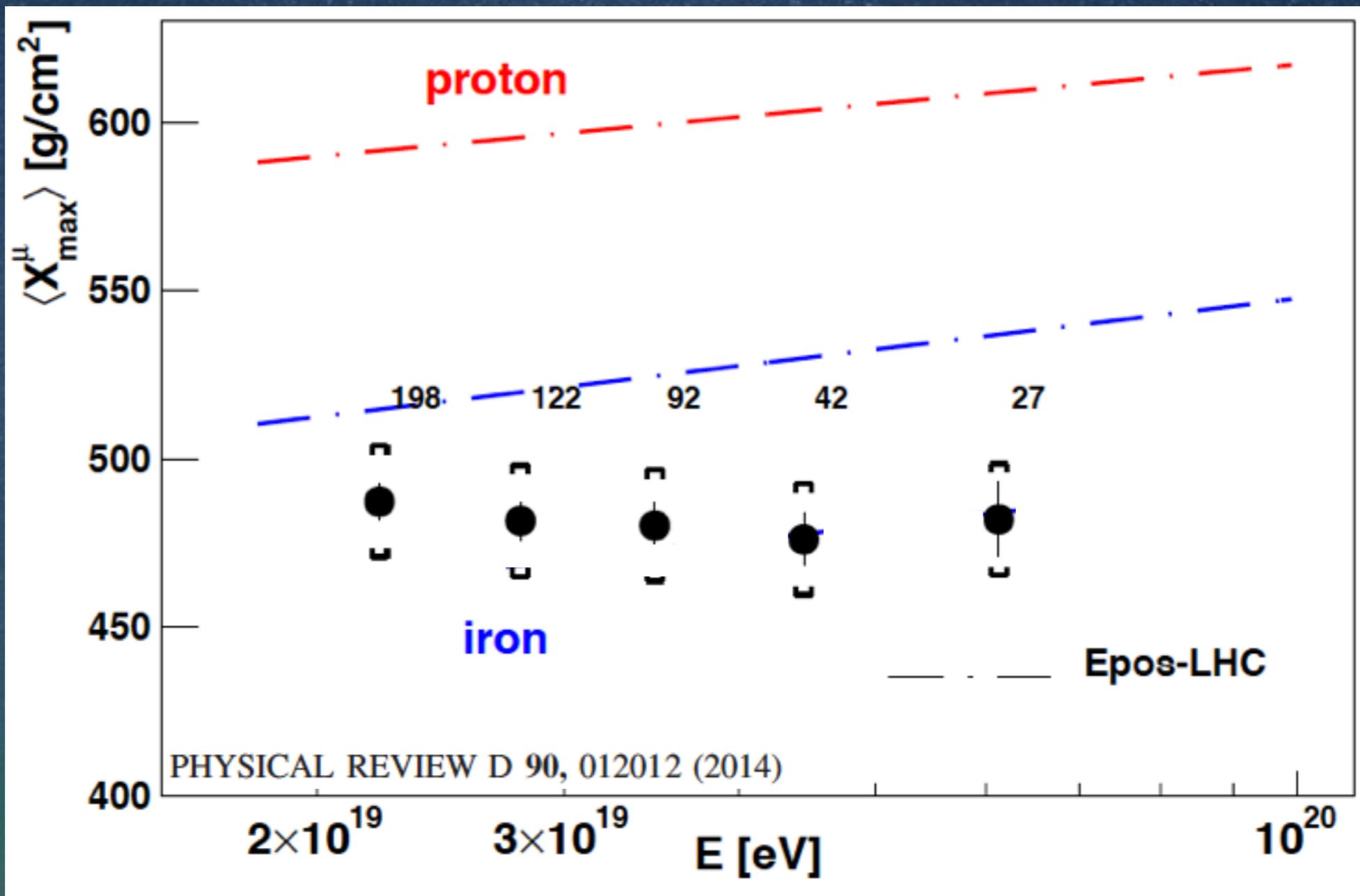


$d\langle X_{\max}^{\mu} \rangle / d\log_{10} E = -25 \pm 22(\text{stat}) \pm 21(\text{sys}) \text{ g} \cdot \text{cm}^{-2} / \text{decade}$ (data)

$d\langle X_{\max}^{\mu} \rangle / d\log_{10} E = 35.9 \pm 1.2 \text{ g} \cdot \text{cm}^{-2} / \text{decade}$ (proton)

$d\langle X_{\max}^{\mu} \rangle / d\log_{10} E = 48.0 \pm 1.2 \text{ g} \cdot \text{cm}^{-2} / \text{decade}$ (iron)

Muon Production Depth (MPD)



$d\langle X_{\max}^\mu \rangle / d\log_{10} E = -25 \pm 22(\text{stat}) \pm 21(\text{sys}) \text{ g} \cdot \text{cm}^{-2} / \text{decade}$ (data)

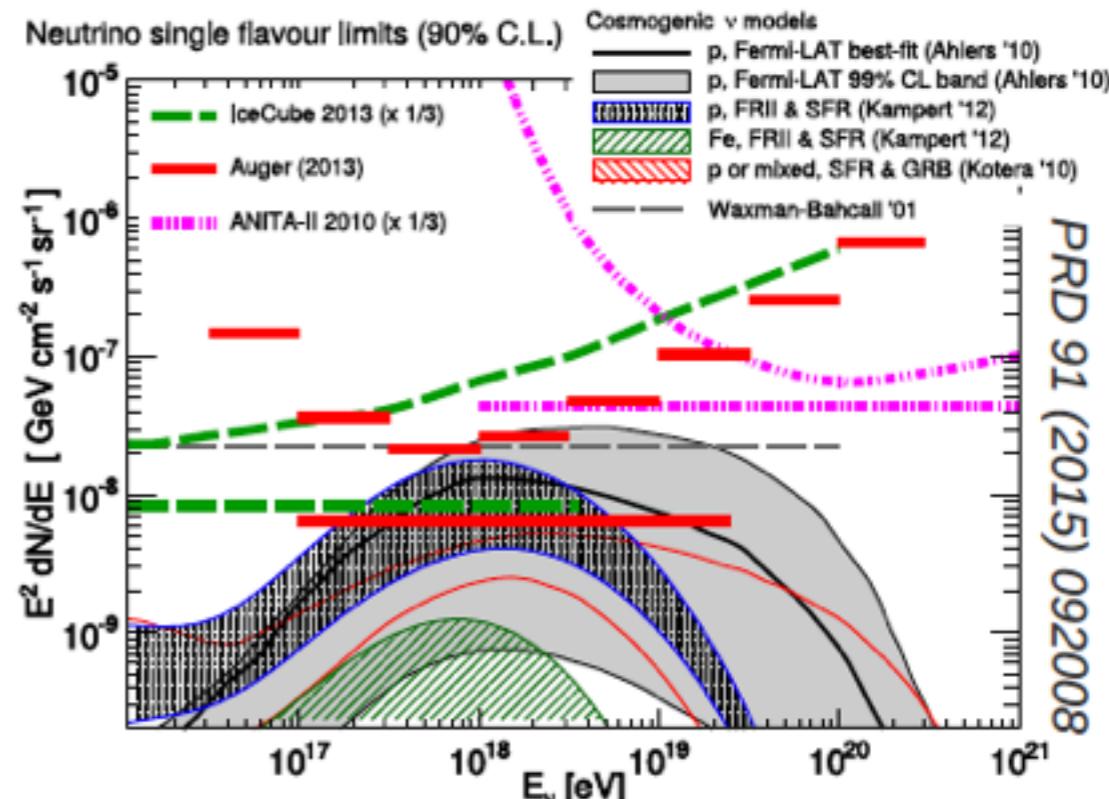
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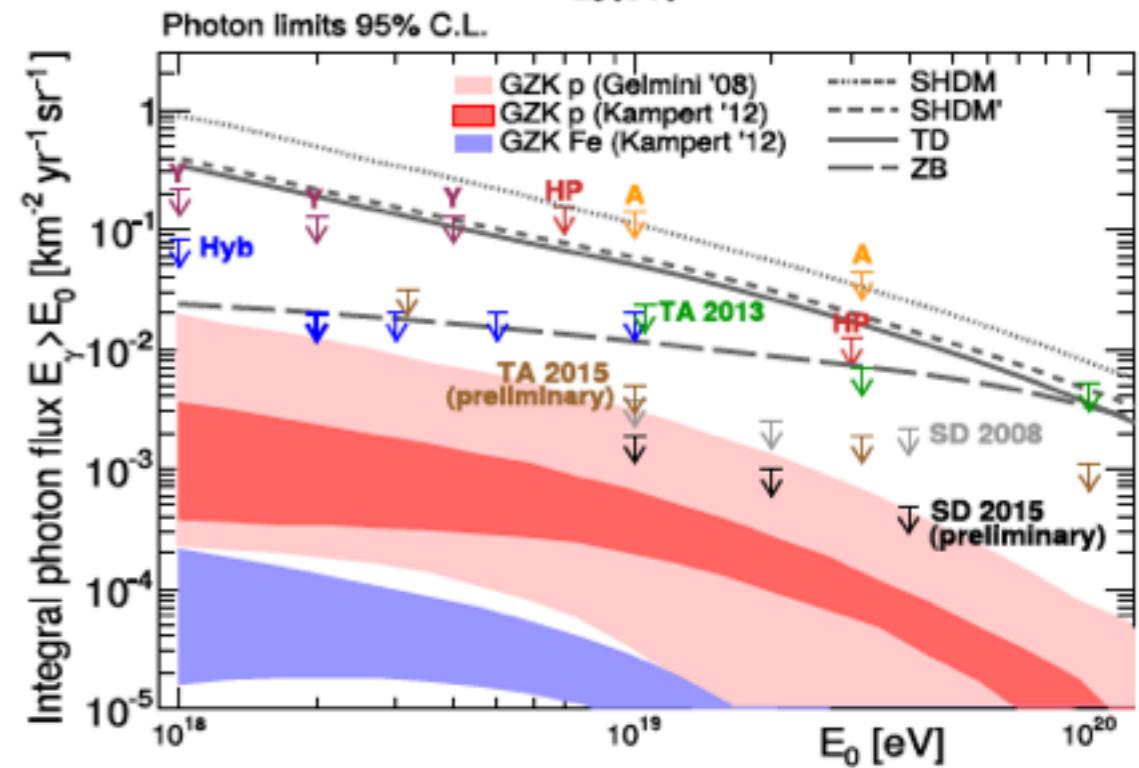
Search for Standard Model particles

C. Bleve for the Pierre Auger Collaboration,
Proc. 34th ICRC, arXiv:1509.3732

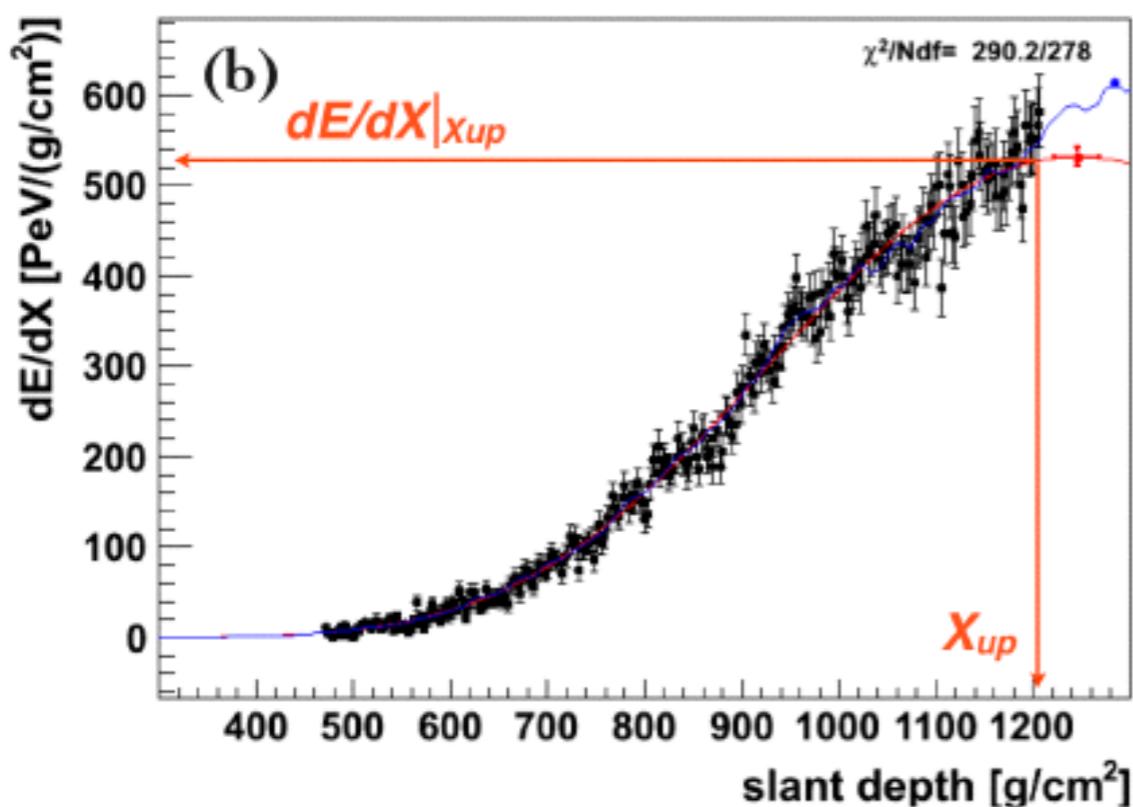
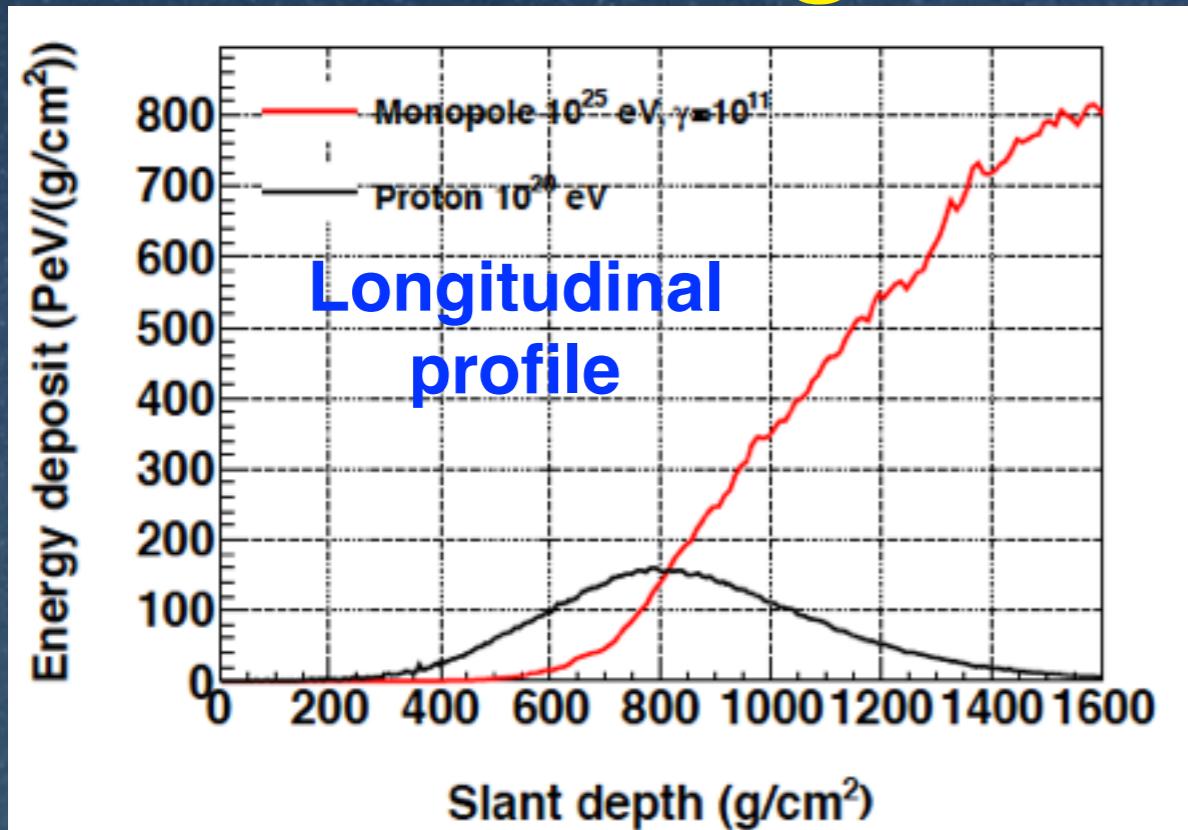
- 01/01/04–20/06/13 no ν candidate
- **search not limited by background**
- limit below the WB bound
- top-down (exotic) models strongly constrained
- **cosmogenic model with pure p composition at the source and strong FRII evolution disfavoured**



- 01/01/04–15/05/13
- 4 photon candidates above 10 EeV
- strictest limits in the range $E > 1$ EeV
- top-down model strongly disfavoured
- **preliminary U.L. above 10 EeV start constraining the most optimistic models of cosmogenic photons with p primaries injected at the source**



Search for Exotics: ultra-relativistic magnetic monopoles

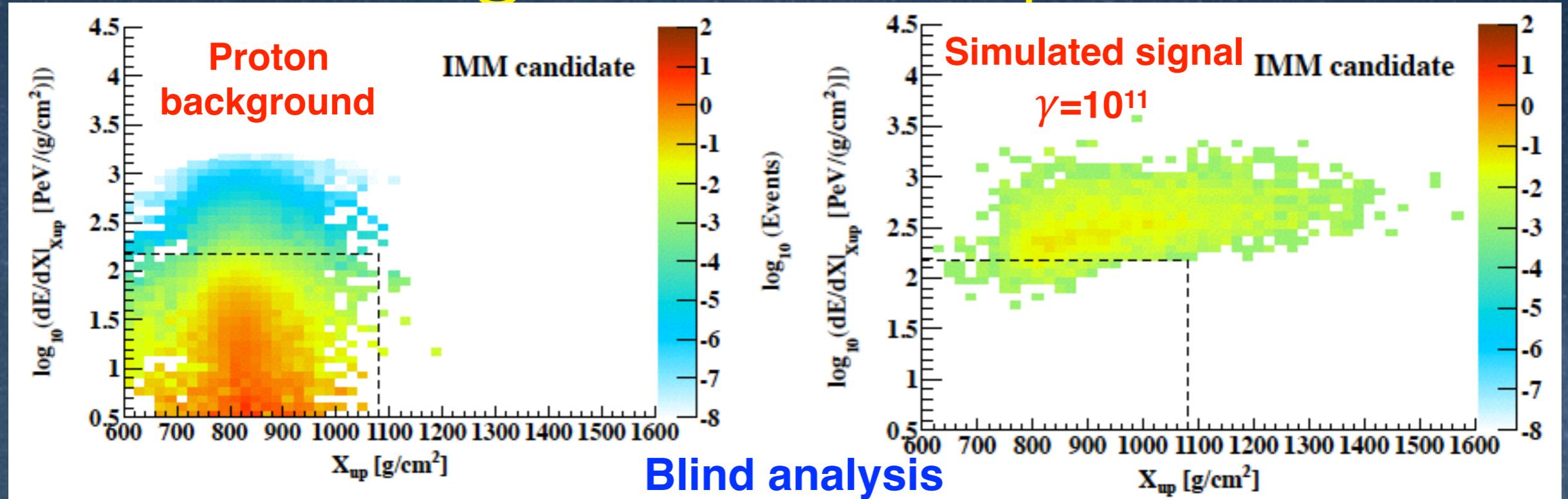


b of Conferences 99, 11001 (2015))

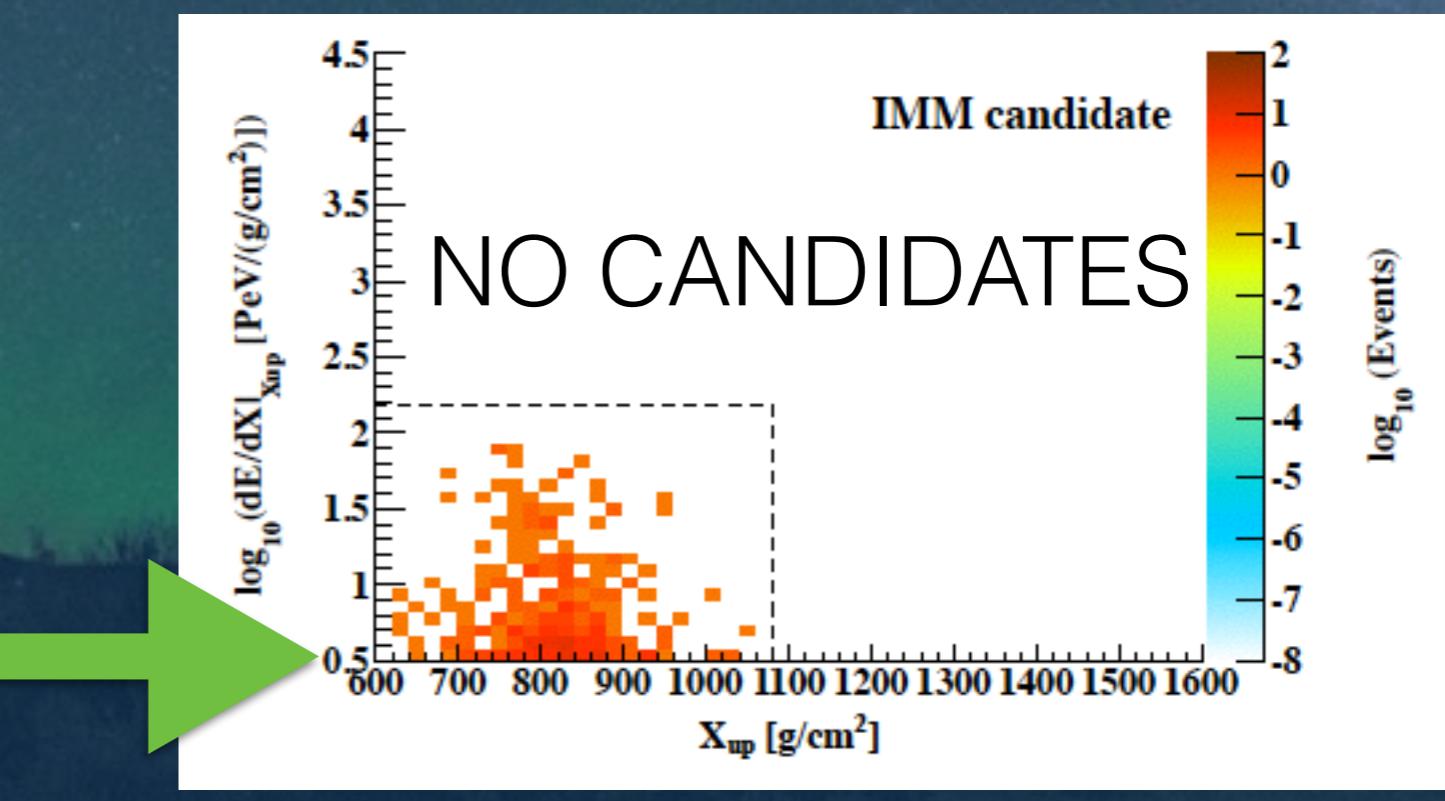
- **Intermediate Mass Monopoles (IMM): Larger energy deposit; deeper development**

- **Discriminating variables:**
 - X_{up} : slant depth at the upper field of view boundary
 - $dE/dX|_{X_{up}}$: energy deposited at X_{up}

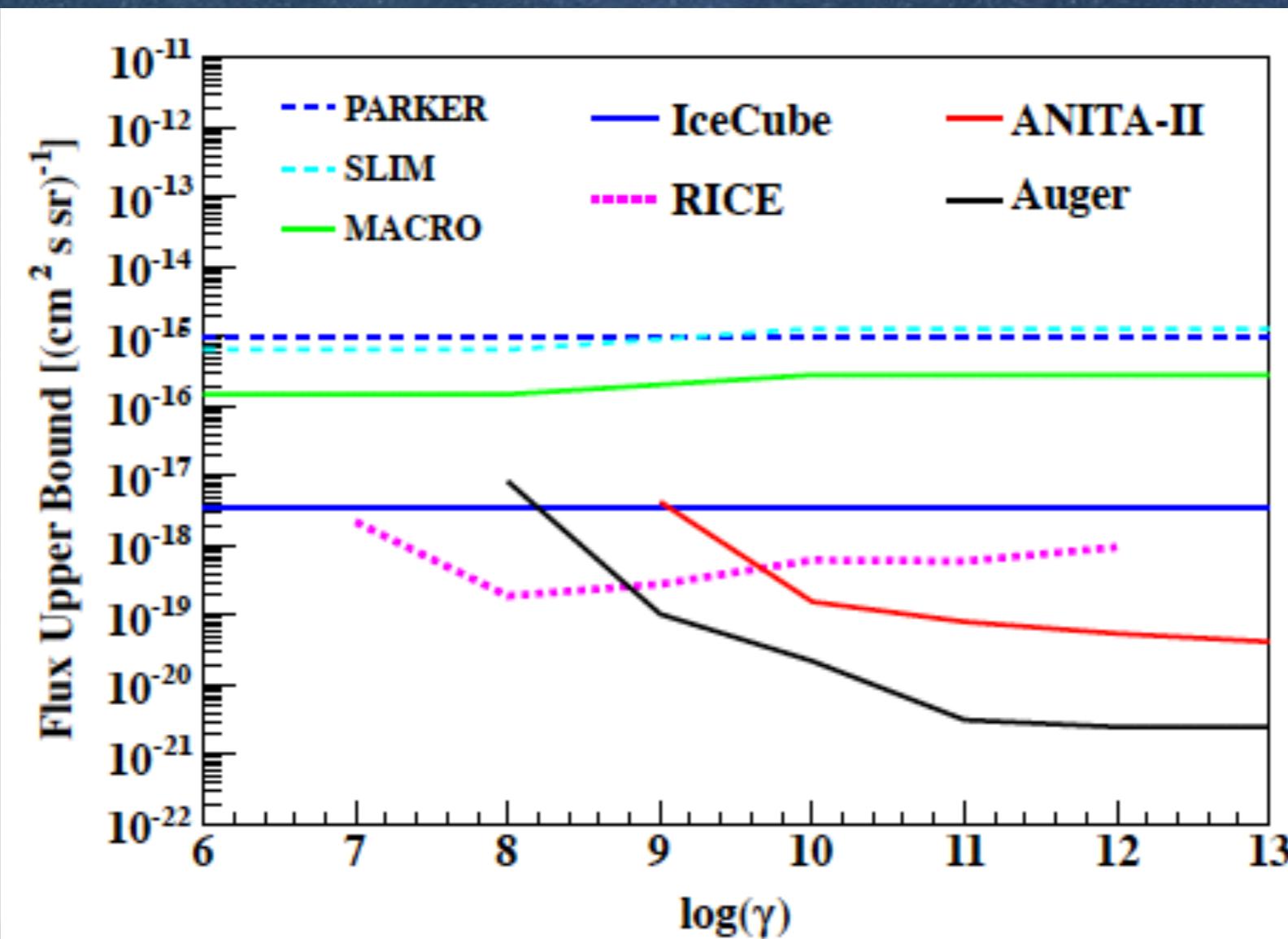
Search for Exotics: ultra-relativistic magnetic monopoles



Shower quality selection criteria	#events	f(%)
Reconstructed events	376084	—
Zenith angle < 60°	360159	95.8
Distance from nearest SD < 1500 m	359467	99.8
Number of FD pixels > 5	321293	89.4
Slant depth interval > 200 g/cm ²	205165	63.9
Gaps in profile < 20%	199625	97.3
profile fit $\chi^2/\text{ndf} < 2.5$	197293	98.8
$dE/dX _{X_{\text{up}}} > 3.0 \text{ PeV}/(\text{g/cm}^2)$	6812	3.5
<hr/>		
Magnetic Monopole selection criteria		
$X_{\text{max}} > X_{\text{up}}$	352	5.2
$X_{\text{up}} > 1080 \text{ g/cm}^2$ or	0	0.0
$dE/dX _{X_{\text{up}}} > 150 \text{ PeV}/(\text{g/cm}^2)$		



Search for Exotics: ultra-relativistic magnetic monopoles



T. Fujii for the Pierre Auger Collaboration,
Proc. 34th ICRC, arXiv:1509.3732

CODA

- For more than a century, UHECR have provided precious information about the most energetic processes of the non-thermal Universe
 - The pivotal questions still unanswered
- BUT SIMULTANEOUSLY with them we can also
 - Explore fundamental particle physics
 - Constrain or find hints of new phenomena beyond the Standard Model of Particle Physics