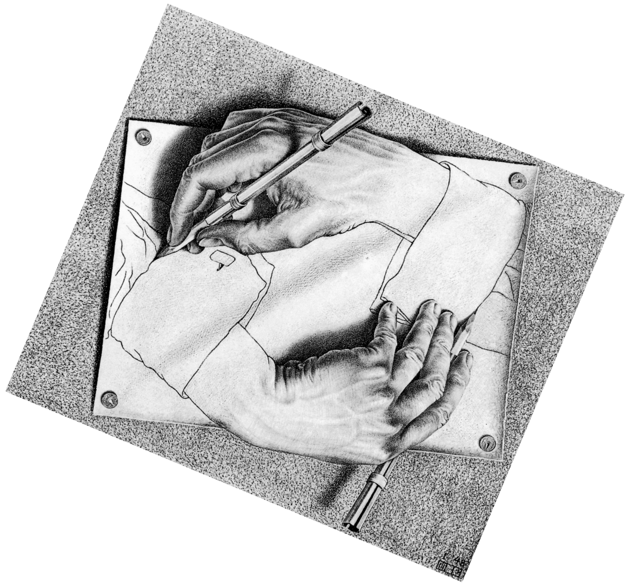
Tests of hadronic interactions at ultra-high energies with the Pierre Auger Observatory

L. Cazon for the Auger Collaboration
(Markus Roth as proxy)

Composition and hadronic interactions: a vicious circle

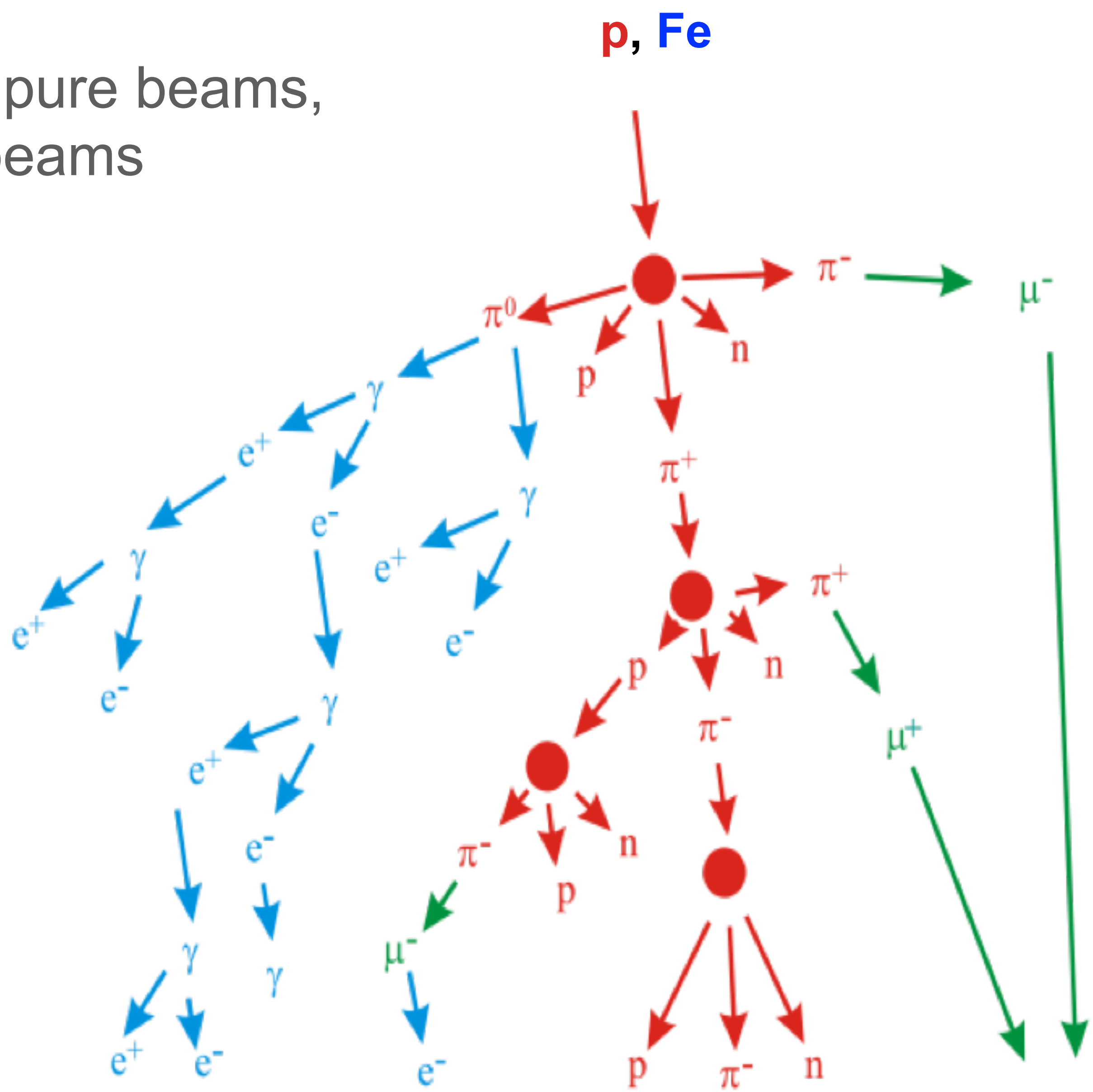


Deriving conclusions on hadronic interactions is inherently difficult.

Ideally you'd select pure beams, but selecting pure beams requires detailed understanding of hadronic interactions

Probe different shower components

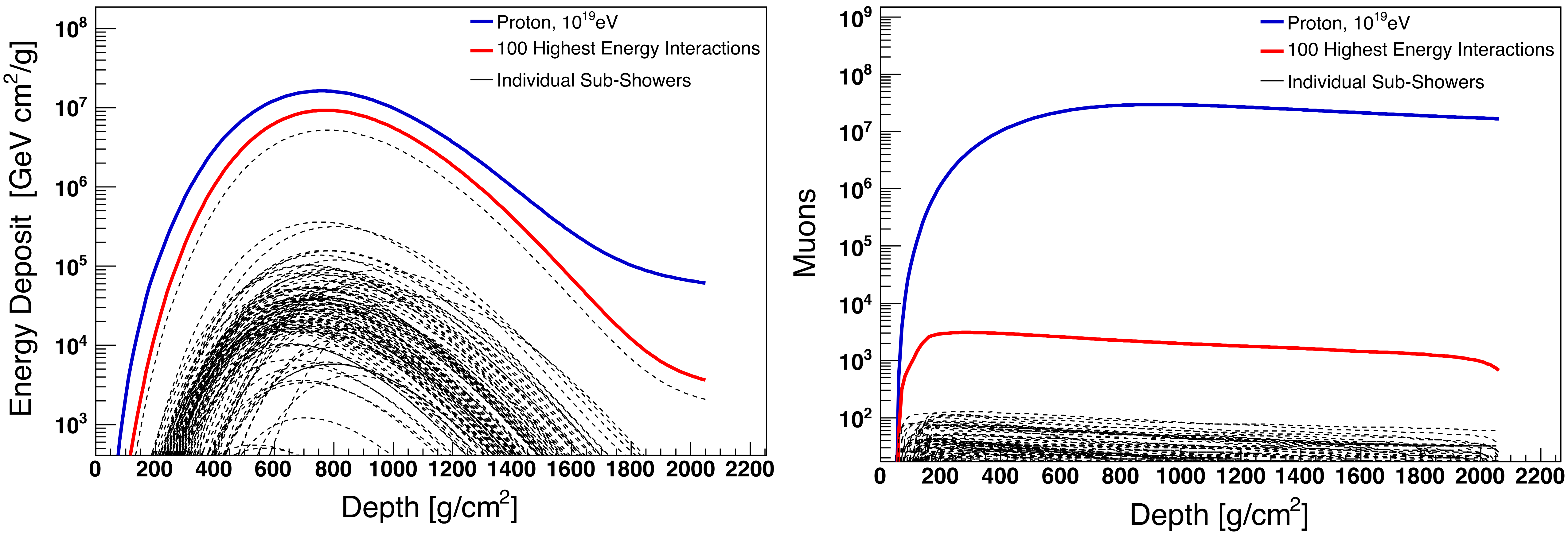
- EM component
  (Fluorescence detector)
- Muon component
  (Surface detector)



Muons trace the hadronic shower which is the backbone of the whole cascade

π^0 decays are the propellers of the EM cascade

Muons in air showers



R. Ulrich, APS 2010

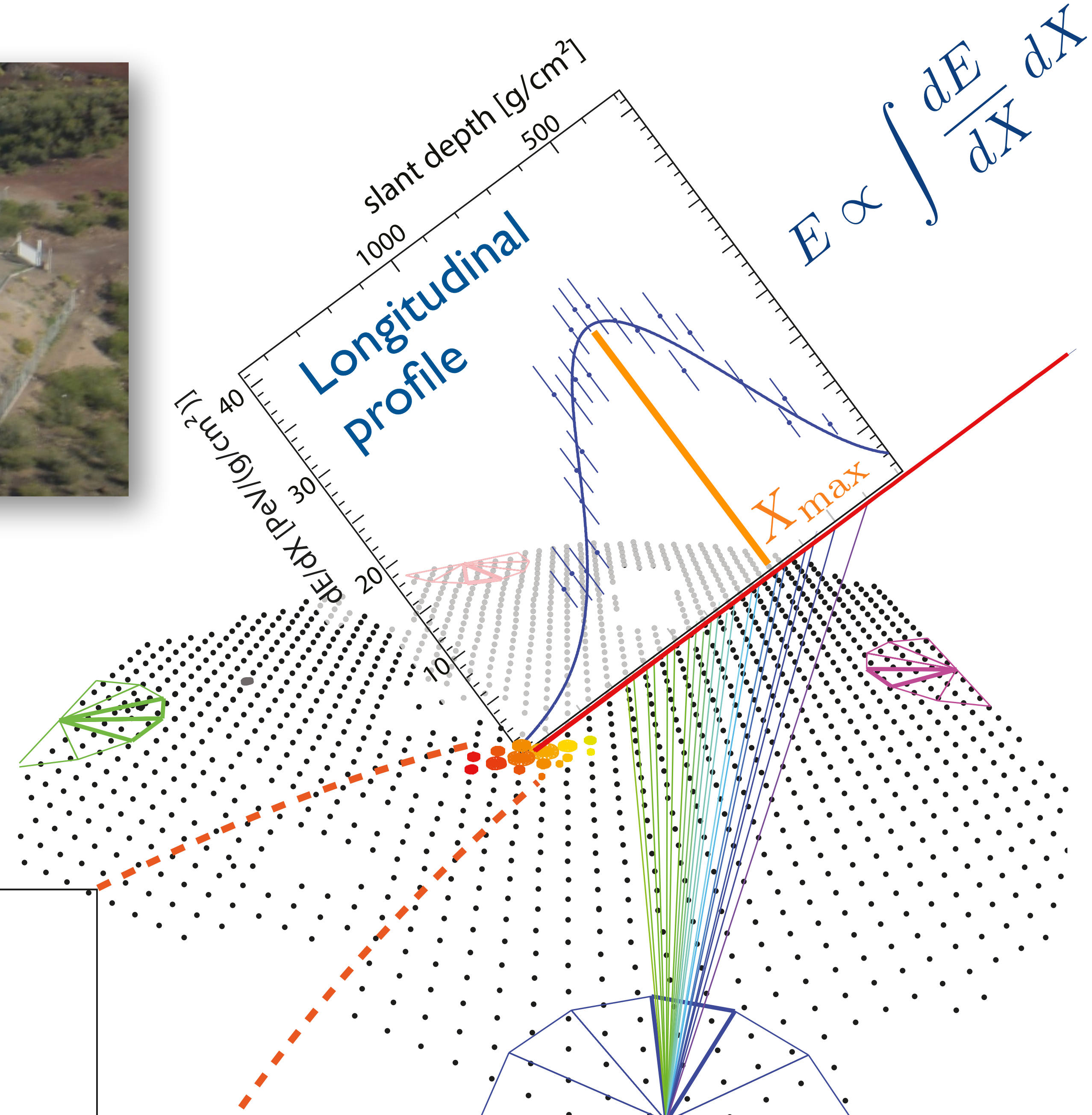
X_{max} is dominated by first interaction

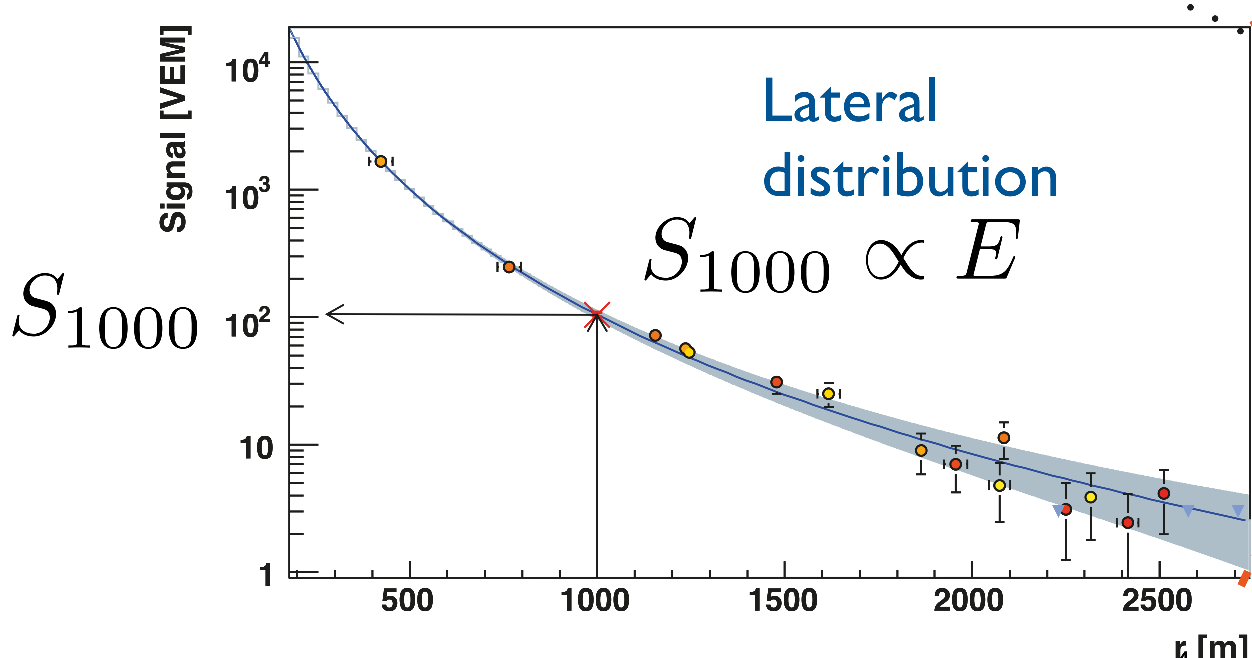
Muons are produced late in shower cascade

→ number of generations ~6 at 10^{19} eV

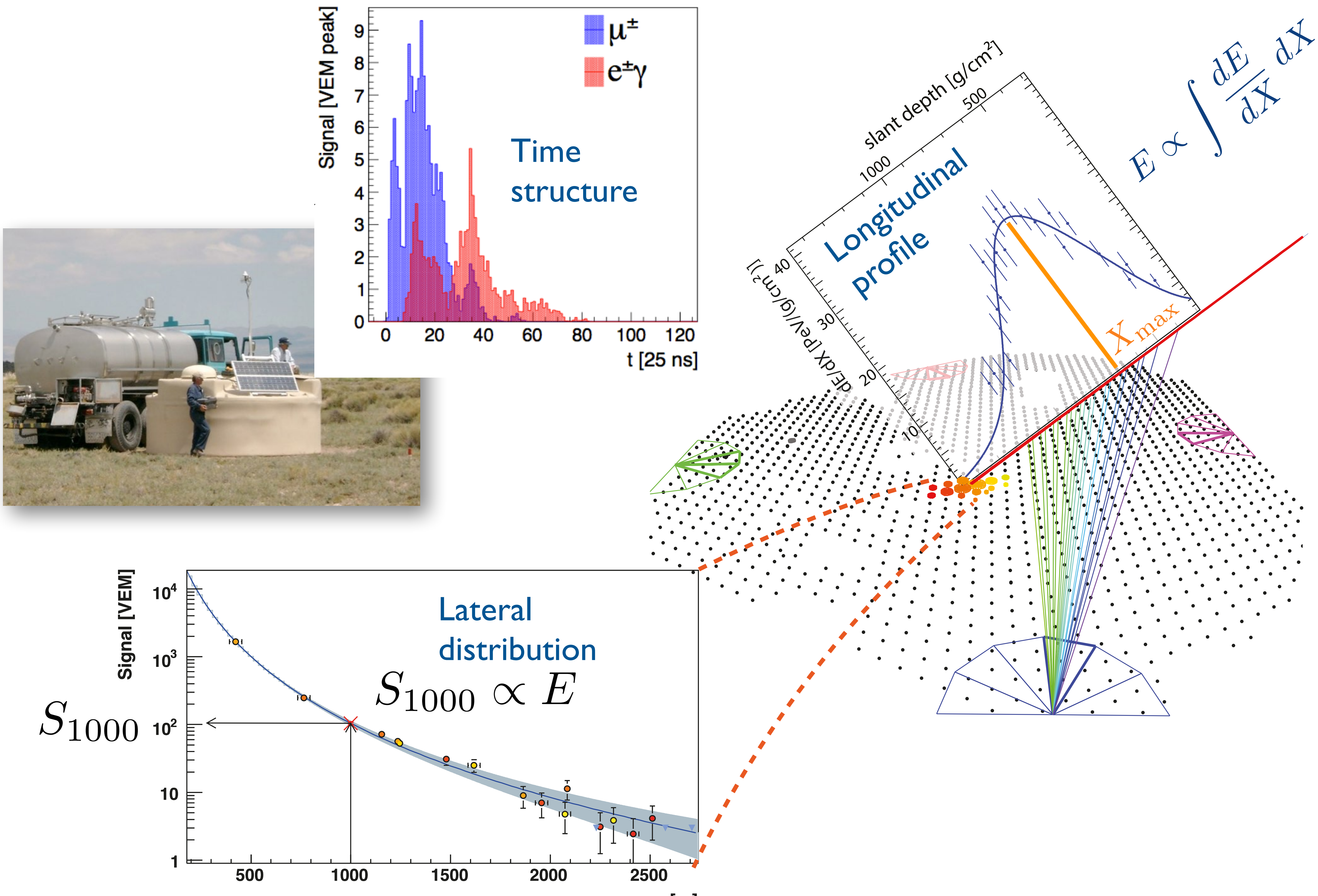
→ amplified sensitivity to hadronic interactions

Air showers recorded at Auger

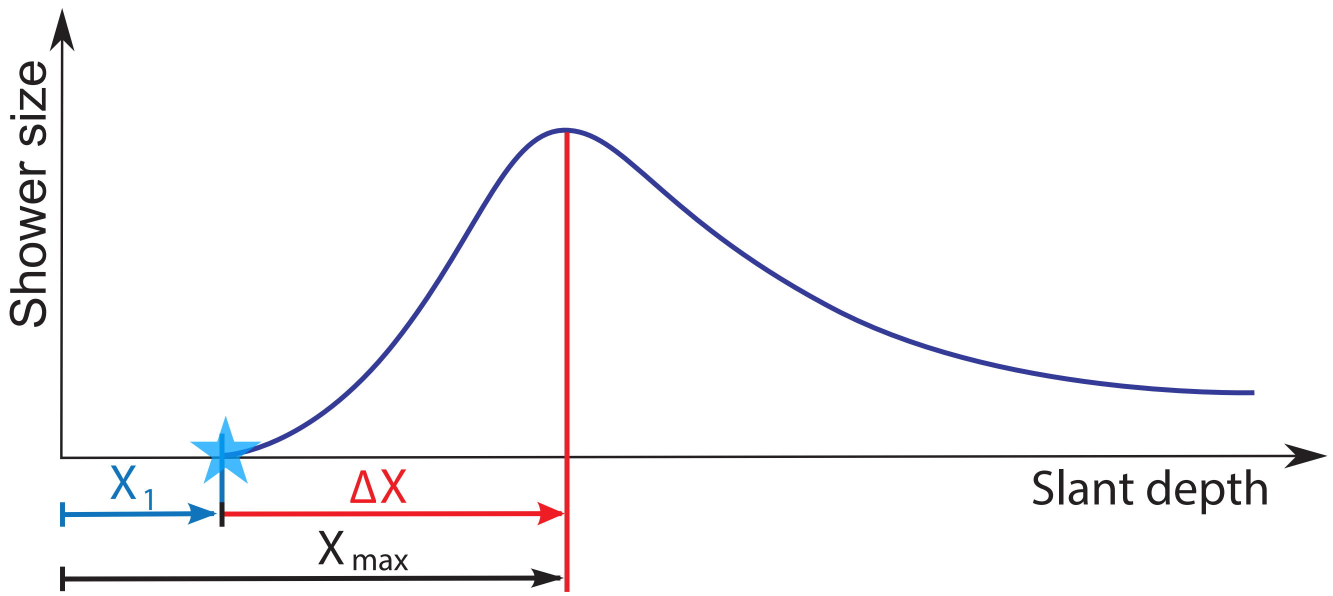




Air showers recorded at Auger



p-Air cross-section: method

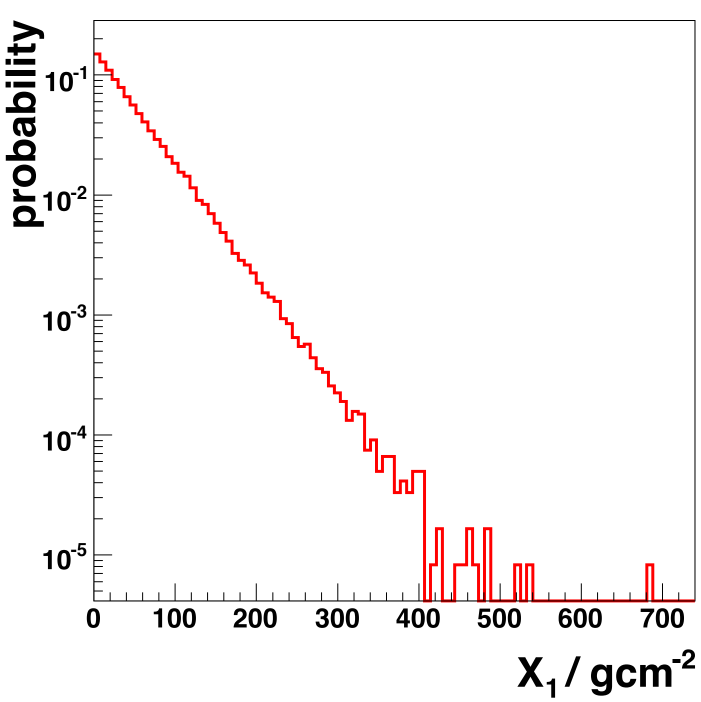


$$\sigma_{\mathrm{int}} = \frac{\langle m_{\mathrm{air}} \rangle}{\lambda_{\mathrm{int}}}$$

Tail of X_{max} distribution

$$\frac{\mathrm{d}\,p}{\mathrm{d}\,X_1} = \frac{1}{\lambda_{\mathrm{int}}} e^{-\frac{X_1}{\lambda_{\mathrm{int}}}}$$

$$\frac{\mathrm{d}\,N}{\mathrm{d}\,X_{\mathrm{max}}} \propto e^{-\frac{X_{\mathrm{max}}}{\Lambda_\eta}}$$



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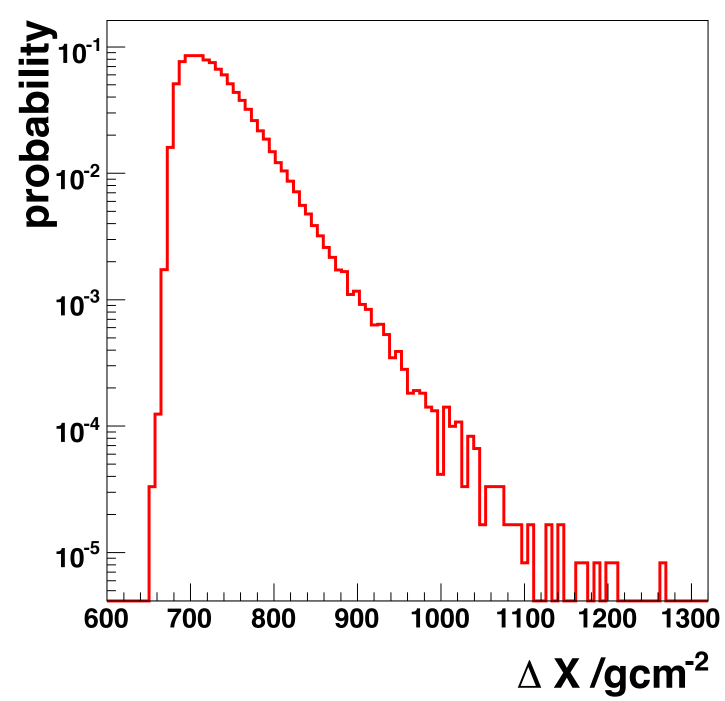

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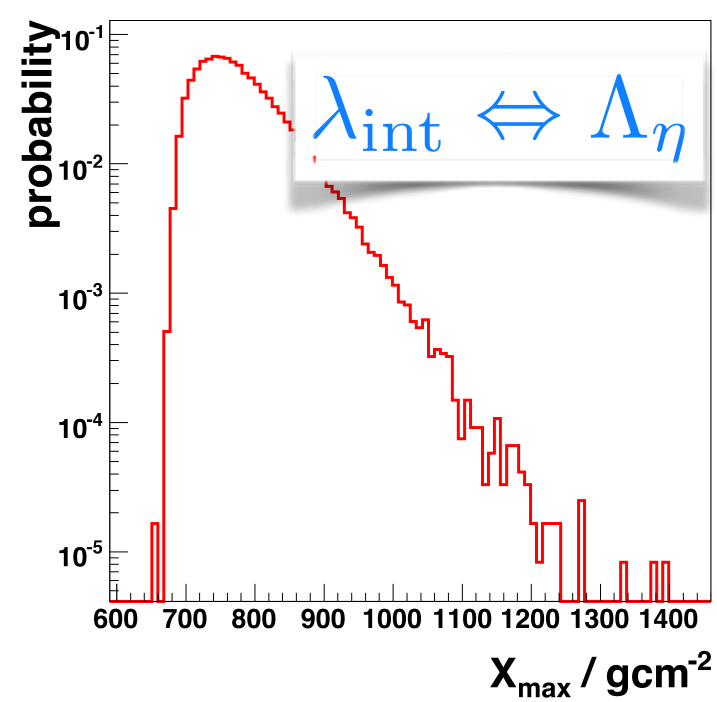
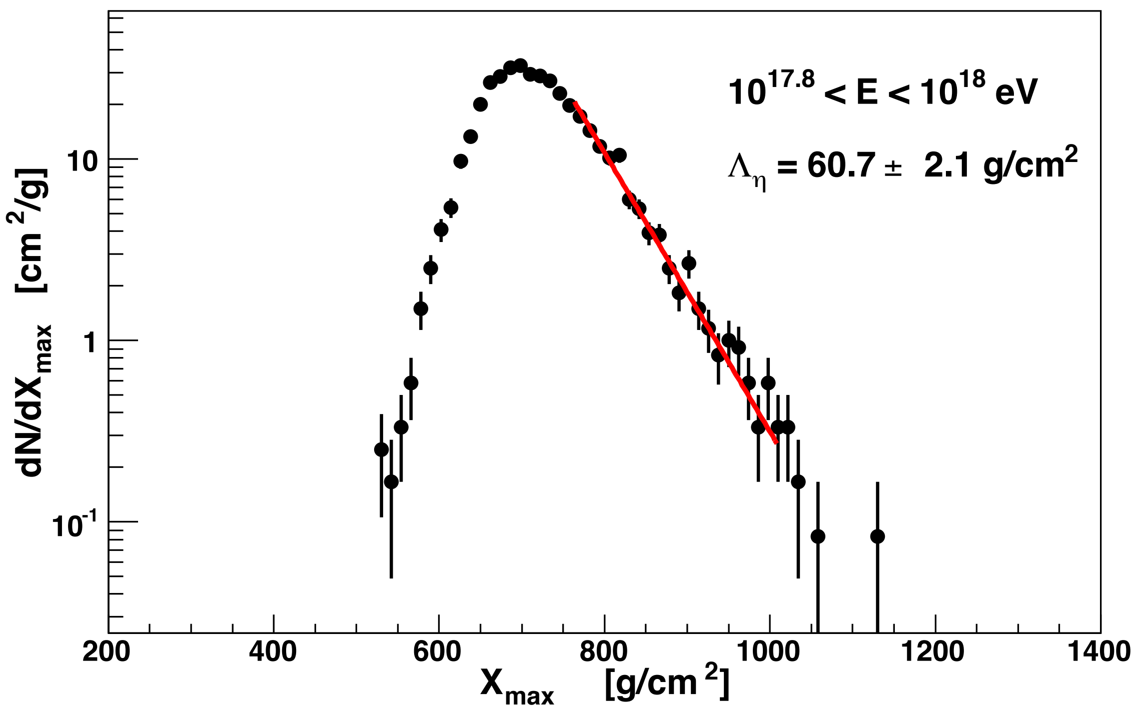
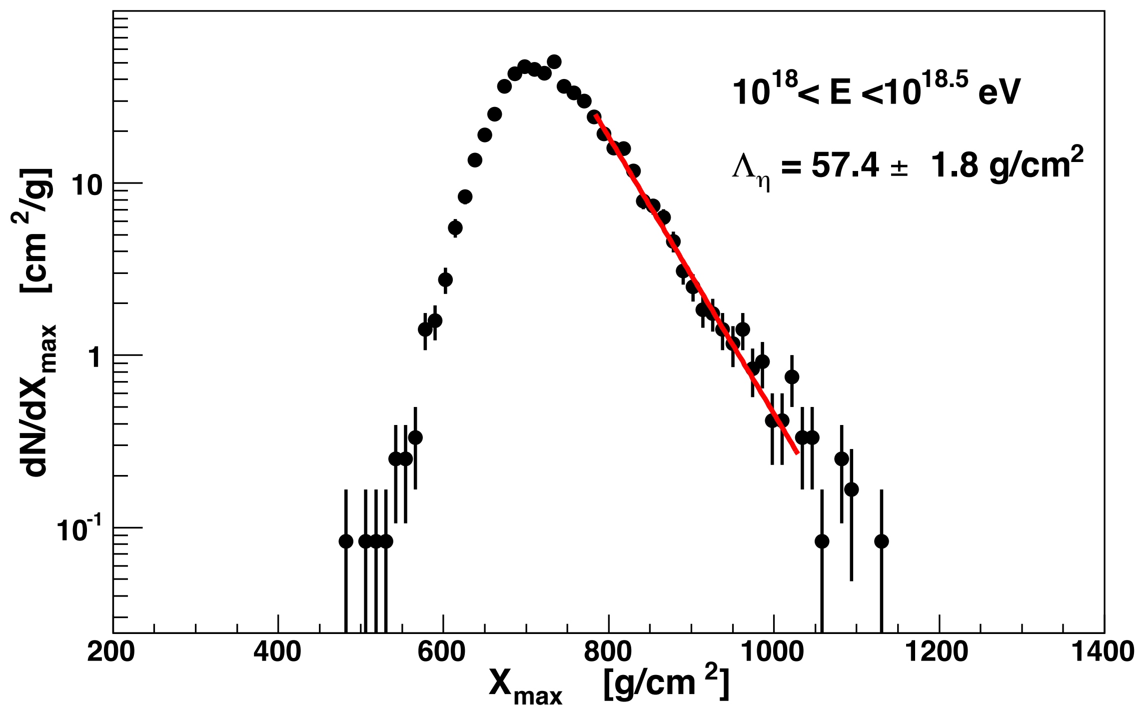
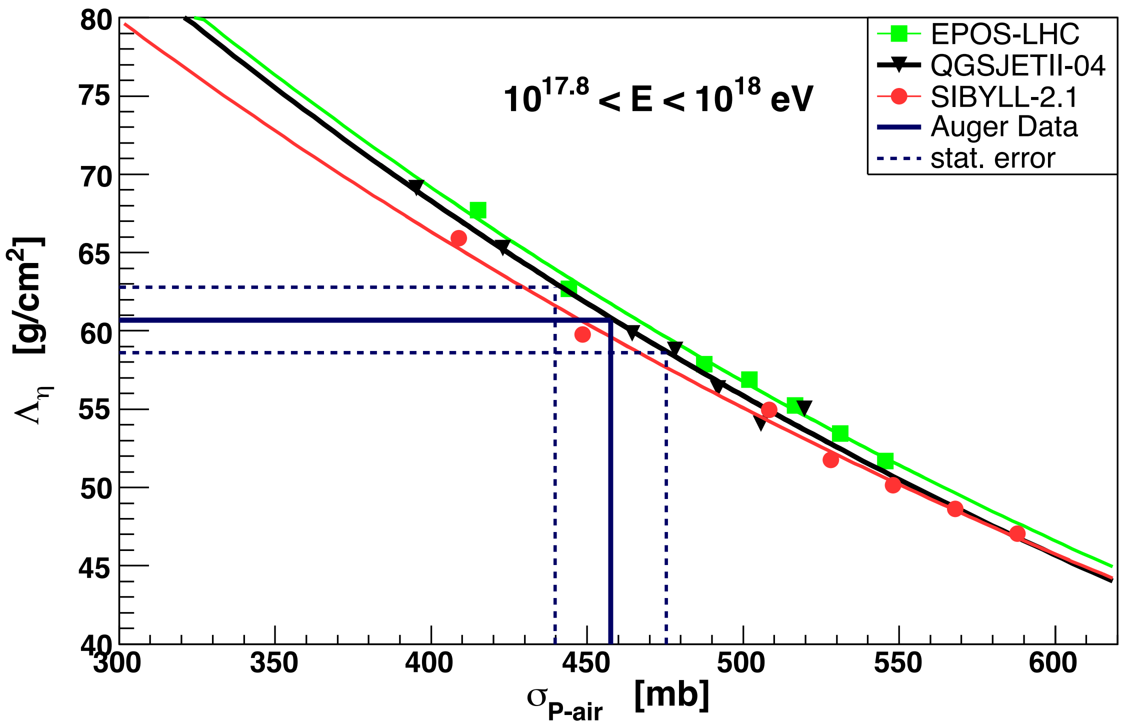


$$\lambda_{\mathrm{int}} \Leftrightarrow \Lambda_\eta$$

p-Air cross-section: result



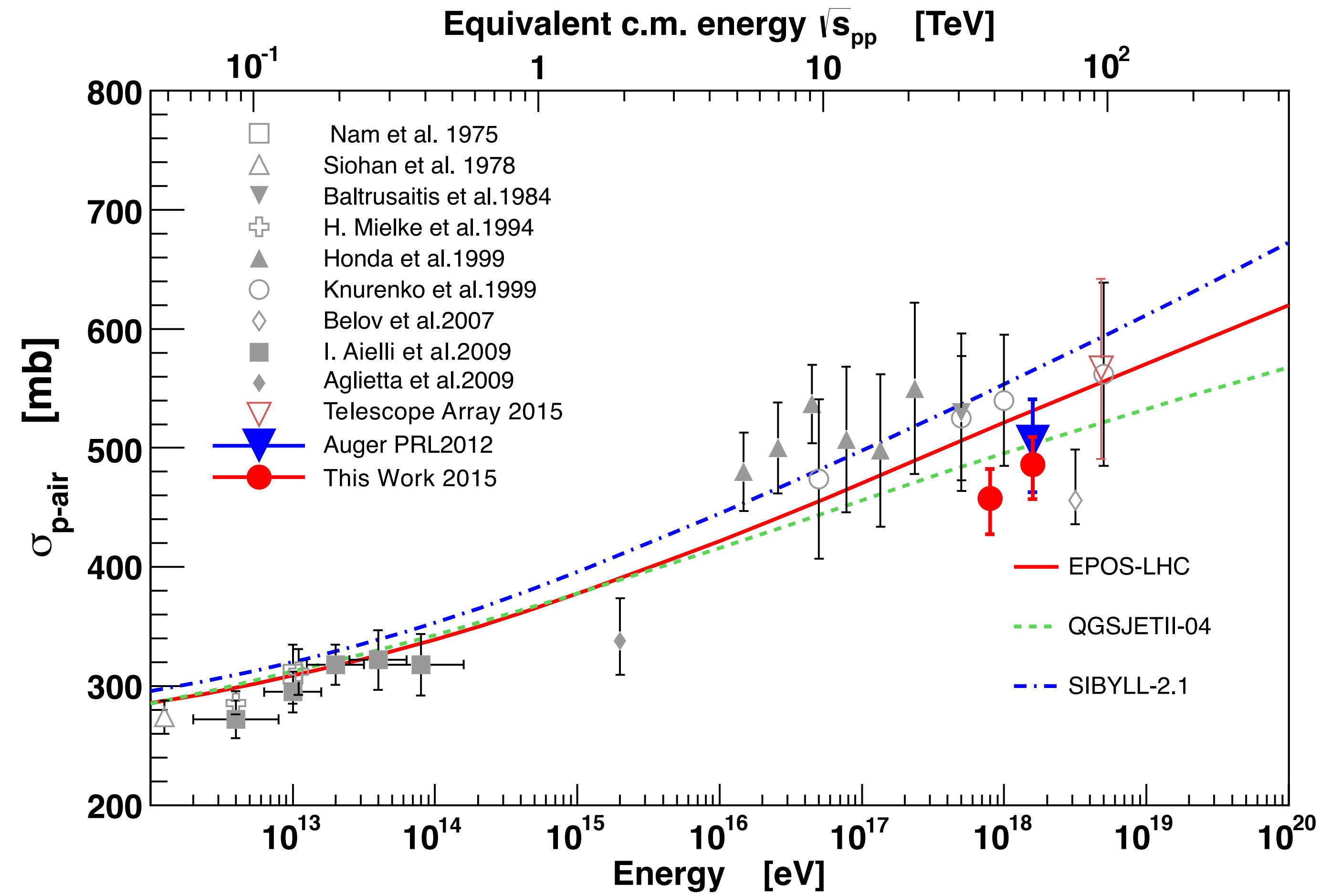


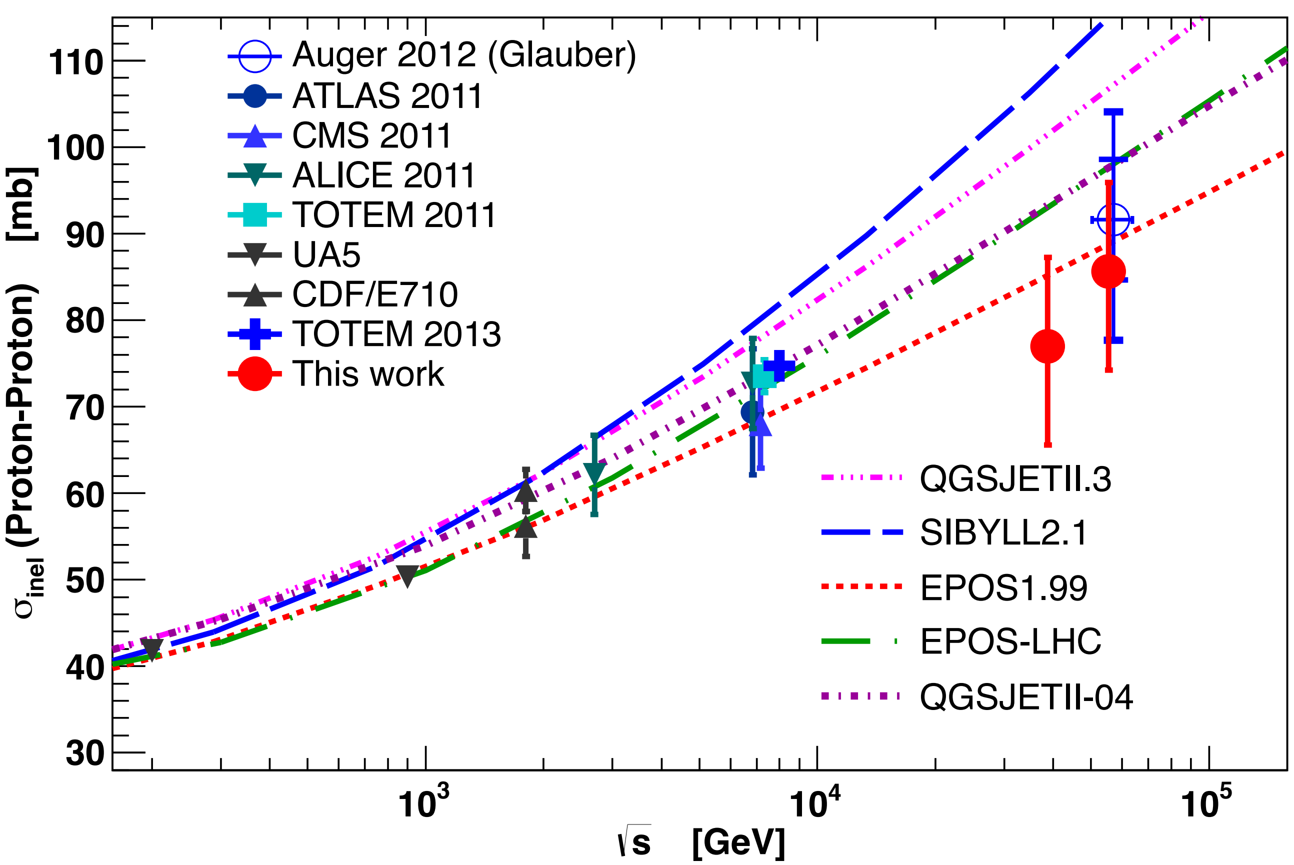


Possible He contamination main source of systematic uncertainty. 25% He maximum contamination assumed for sys. uncertainties

pp cross-section

Conversion from p-air to pp by Glauber theory to get inelastic pp x-section





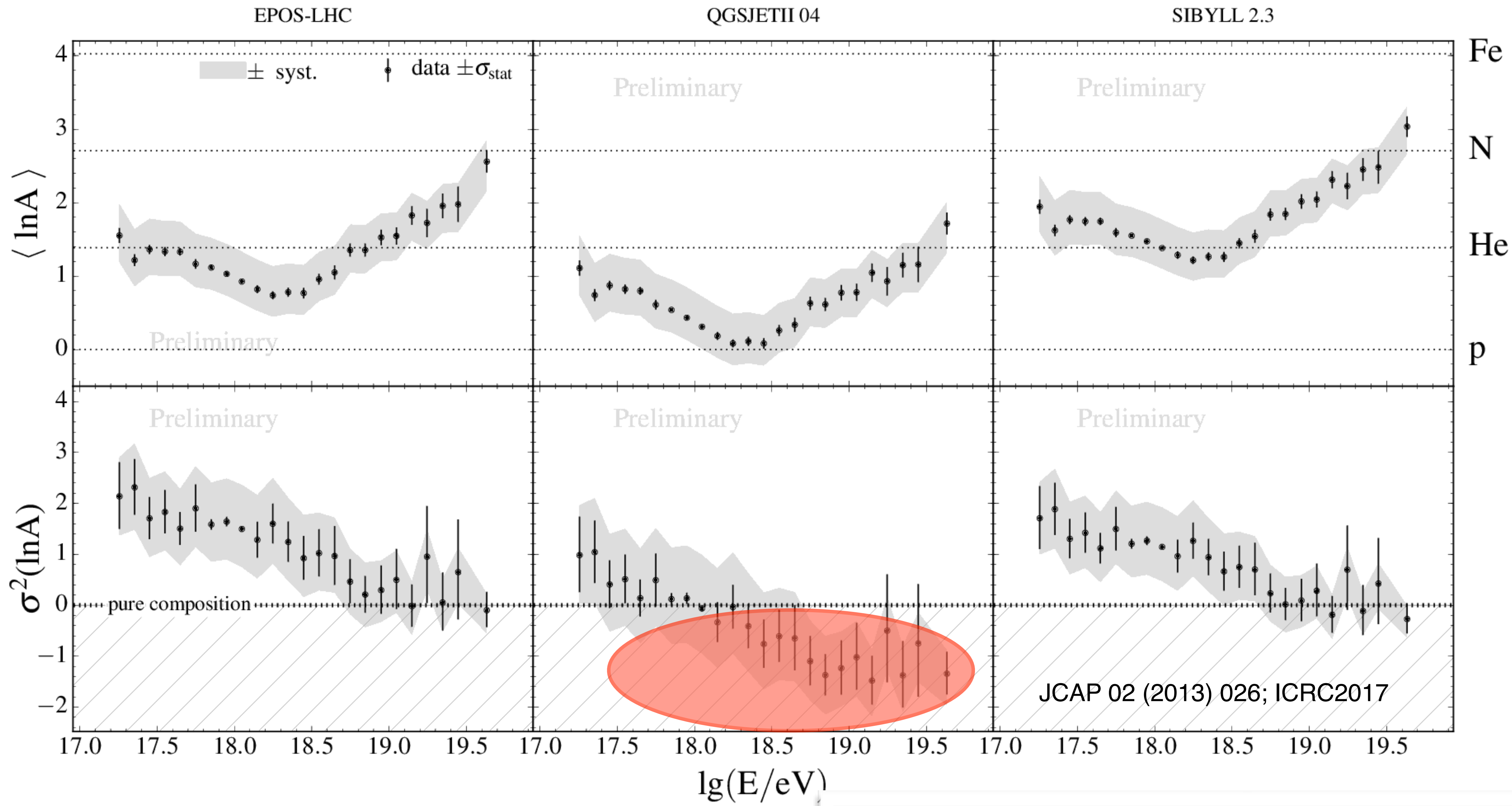
X-section in mb

$$76.95 \pm 5.4(\text{stat}) +^{-5.2}_{-7.2} (\text{syst}) \pm 7.1(\text{Glauber})$$
$$\text{at } \sqrt{s_{pp}} = 38.7 \pm 2.5\,\text{TeV}$$

$$85.62 \pm 5(\text{stat}) +^{-5.5}_{-7.4} (\text{syst}) \pm 7.1(\text{Glauber})$$
$$\text{at } \sqrt{s_{pp}} = 55.5 \pm 3.6\,\text{TeV}$$

Phys. Rev. Lett. 109, 062002 (2012); ICRC2015

Models show contradictions in the interpretation of X_{max}

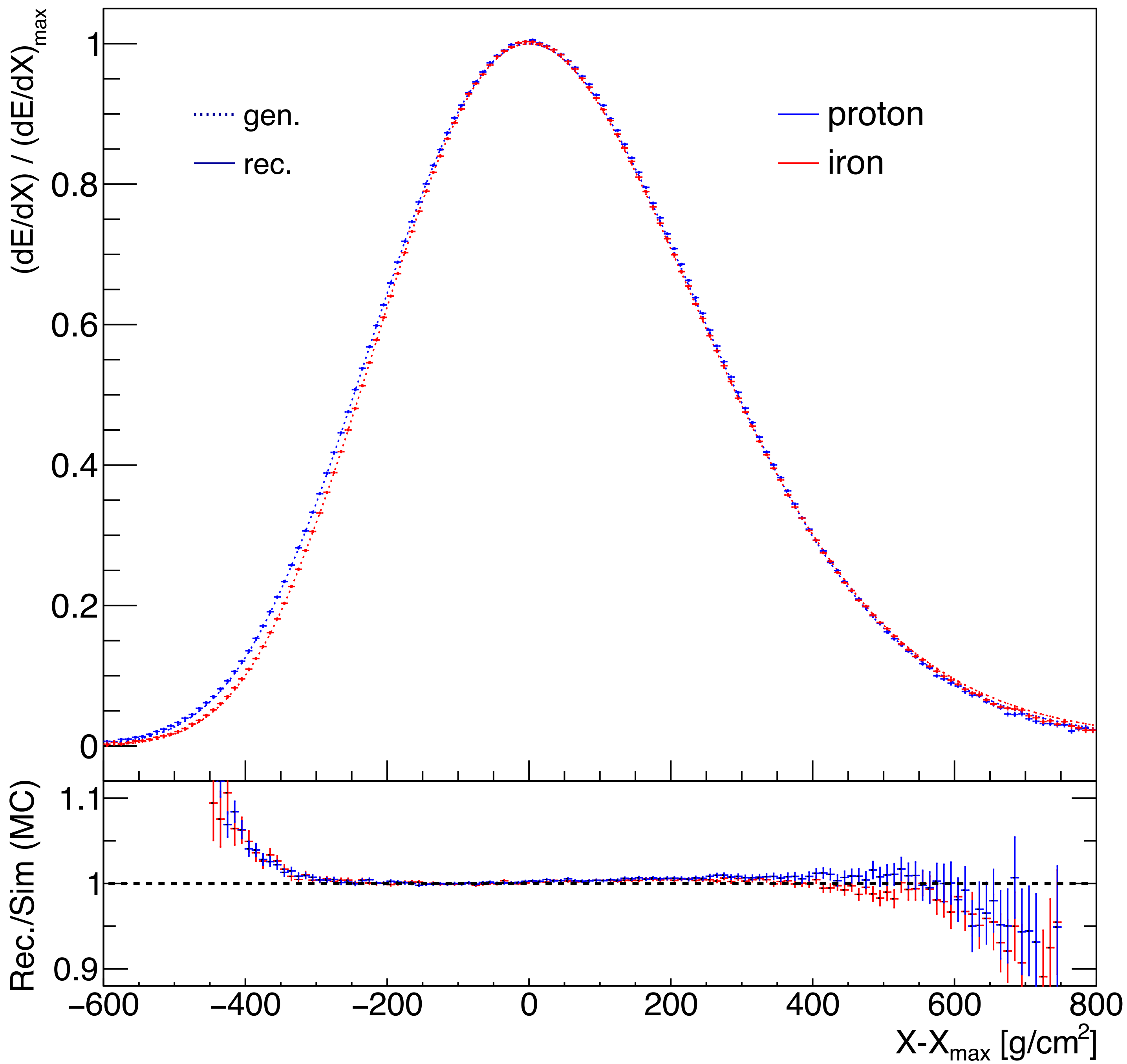


$$\langle X_{\max} \rangle = \langle X_{\max} \rangle_{\mathrm{p}} + f_E \langle \ln A \rangle$$

$$\sigma^2(X_{\max}) = \langle \sigma_{\mathrm{sh}}^2 \rangle + f_E^2\, \sigma^2(\ln A)$$

X_{max} distributions not well predicted by some models. Leading to unphysical results (QGSJetII-04).

EM longitudinal profile



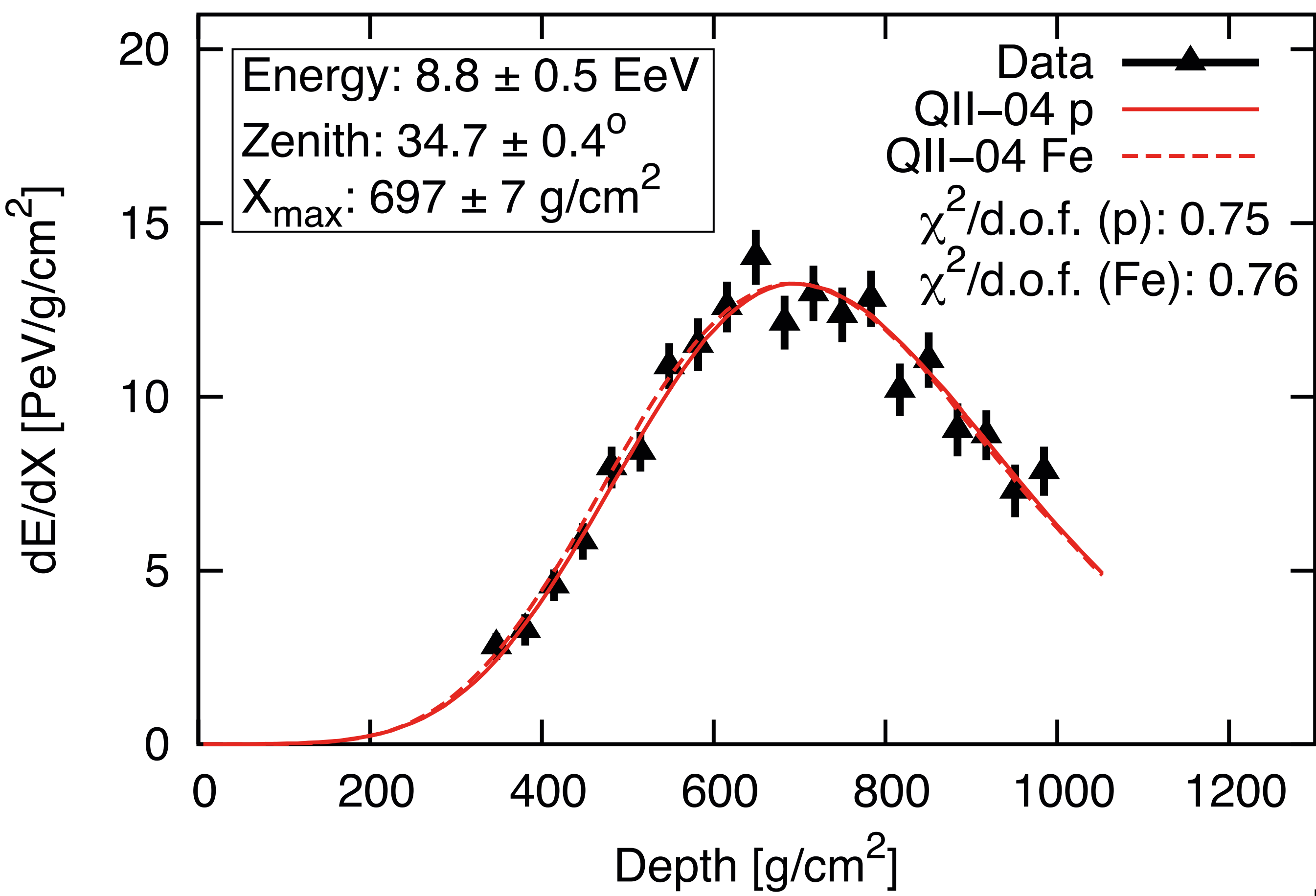
E: $10^{18.8}$ -$10^{19.2}$ eV

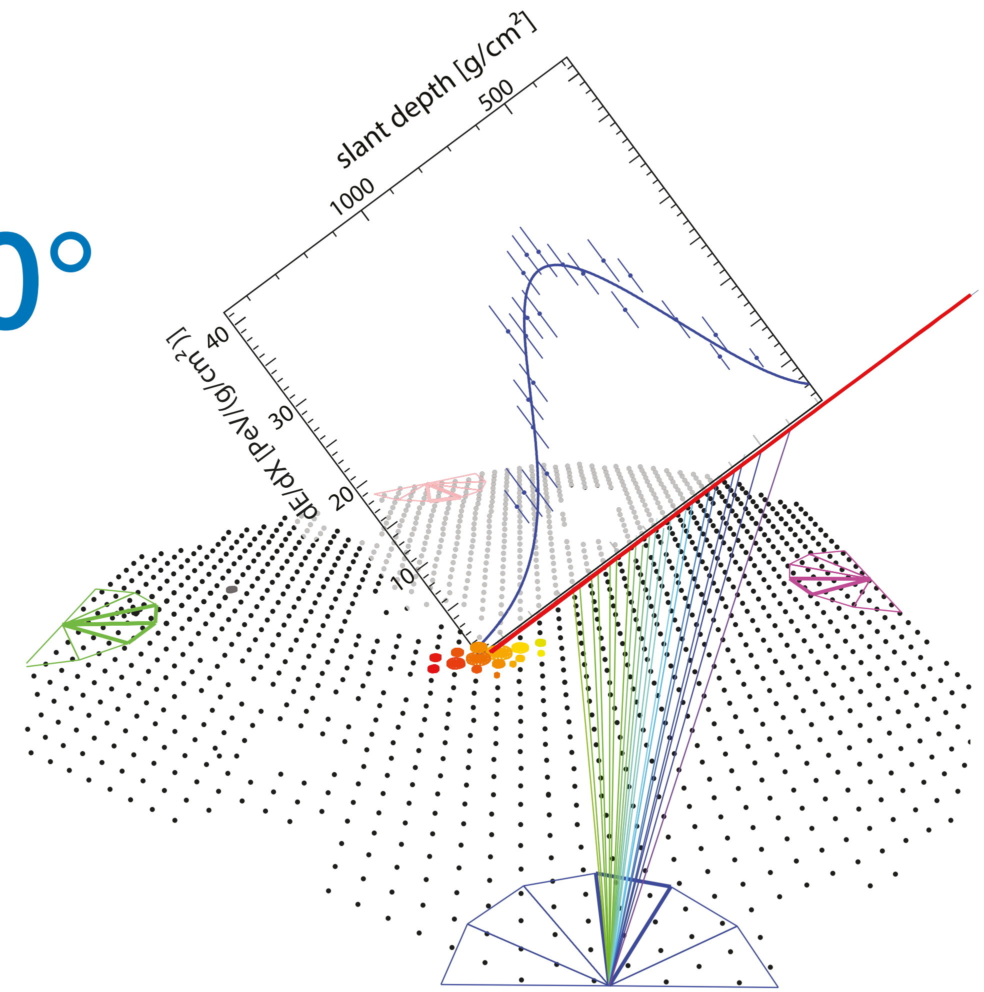
Average longitudinal shape well described by Gaisser Hillas function to the limits of our current precision.

Possible room for hadronic physics if we could reduce systematics

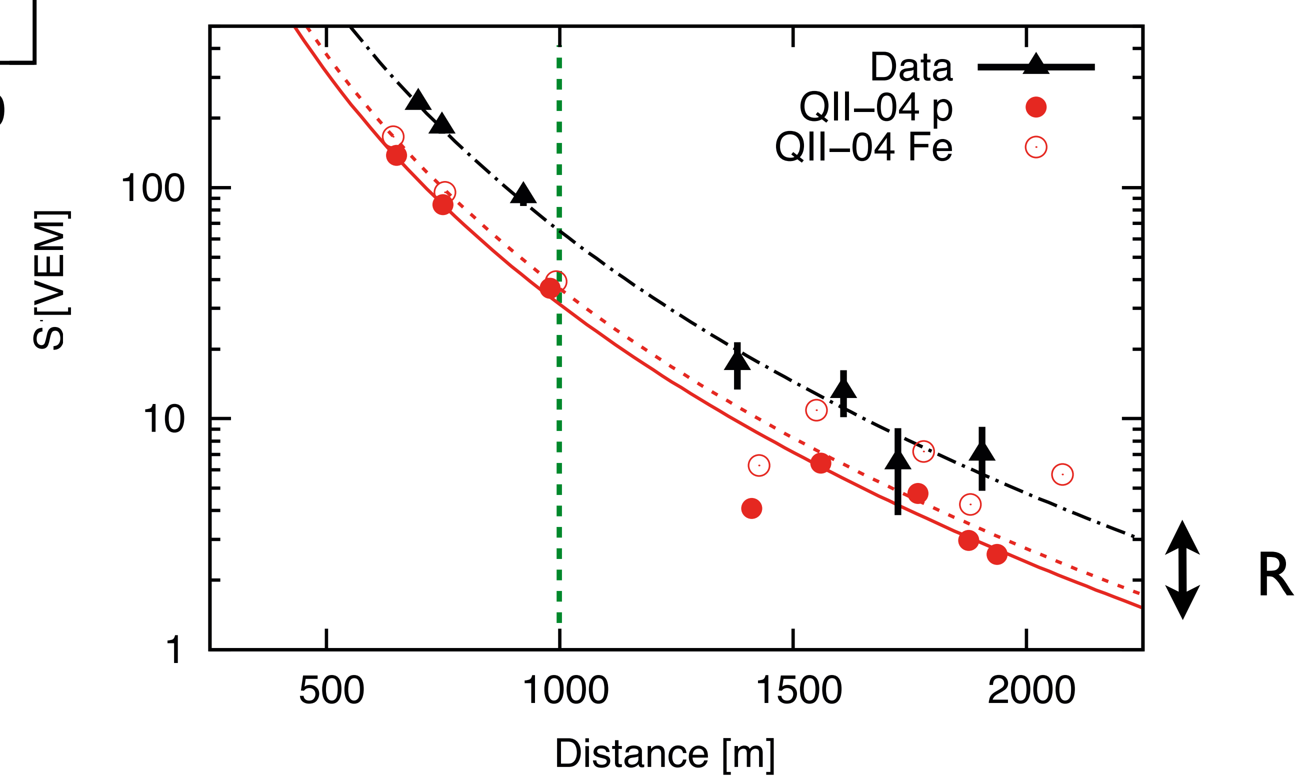
See poster by S. Andringa

Muon number in hybrid events with θ<60°

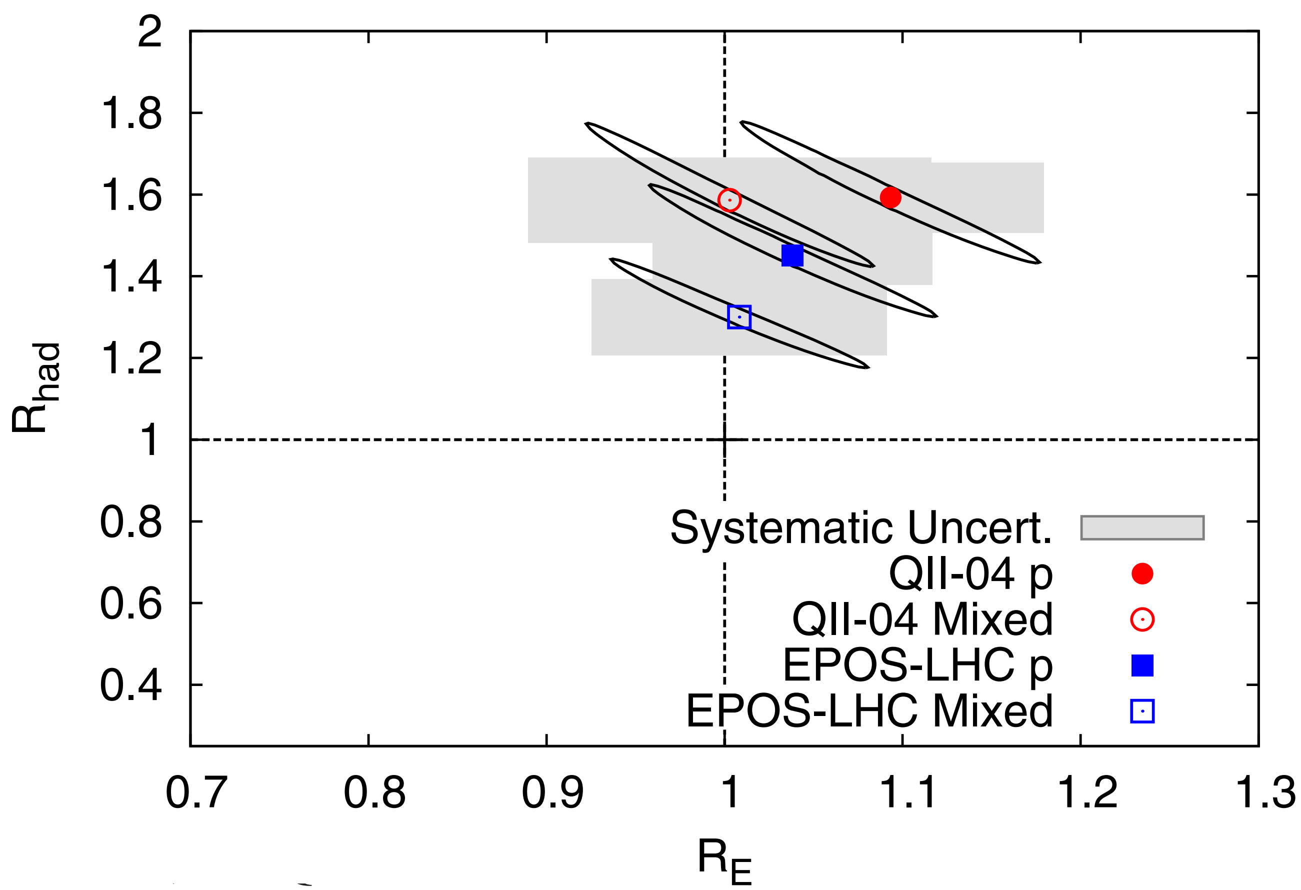




- $E = 10^{18.8}$ - $10^{19.2}$ eV
- Zenith angles [0°, 60°]
- 411 hybrid events after quality cuts



Muon number in hybrid events with θ<60°



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	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

Systematic uncertainties on R_E and R_{had} ~10 %

ML fit adjusting EM and muonic contribution to S1000

$$S_{\text{resc}} = R_E\, S_{\text{EM}} + R_{\text{had}}\, R_E^{\alpha}\, S_{\text{had}}$$

$$\alpha \simeq 0.9$$

$$R_\mu \approx 0.93\, R_E^{0.9}\, R_{\text{had}} + 0.07\, R_E$$

No energy rescaling is needed

The observed muon signal is a factor 1.3 to 1.6 larger than predicted by models

Smallest discrepancy for EPOS-LHC with mixed composition at the level of 1.9 σ

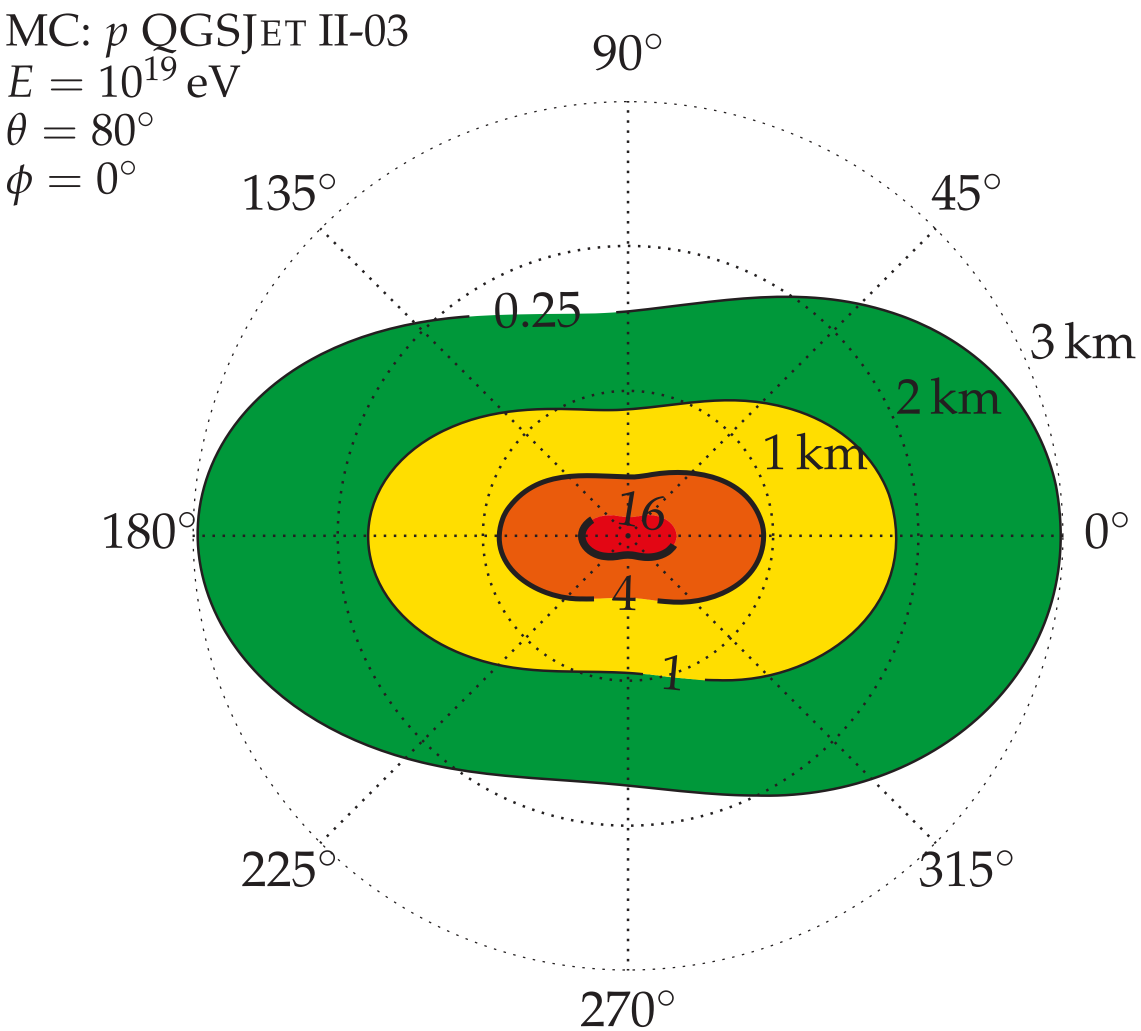
PRL 117, 192001 (2016)

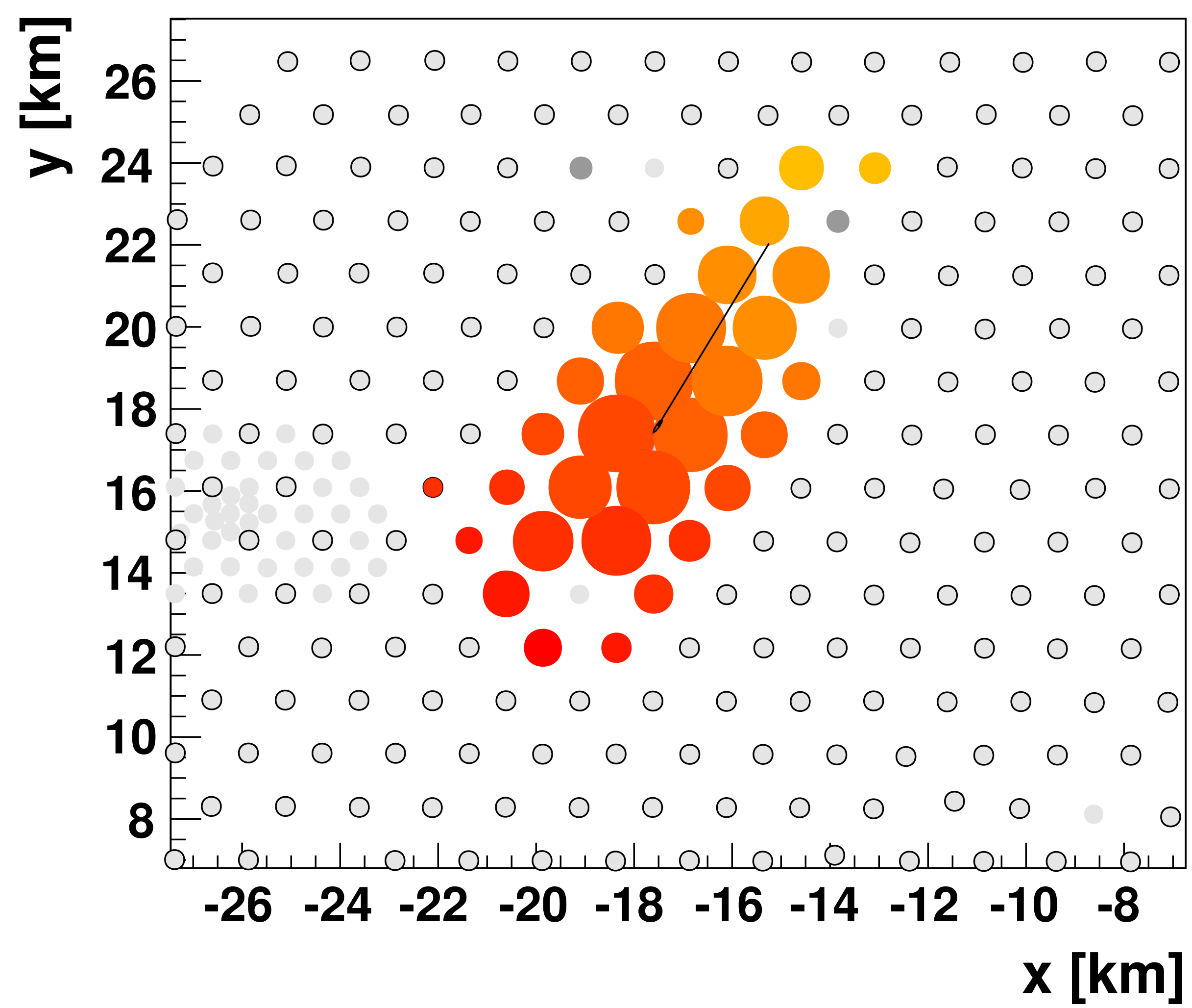
Muons in highly inclined events

$$\rho_\mu(\text{data}) = N_{19} \cdot \rho_\mu(\text{QGSJETII03},\ p, E = 10^{19}\ eV,\ \theta)$$

$$R_\mu = \frac{N_\mu^{data}}{N_{\mu,19}^{MC}}$$

- E > 4 x 10^{18} eV
- Zenith angles [62°, 80°]





R_μ in highly inclined events

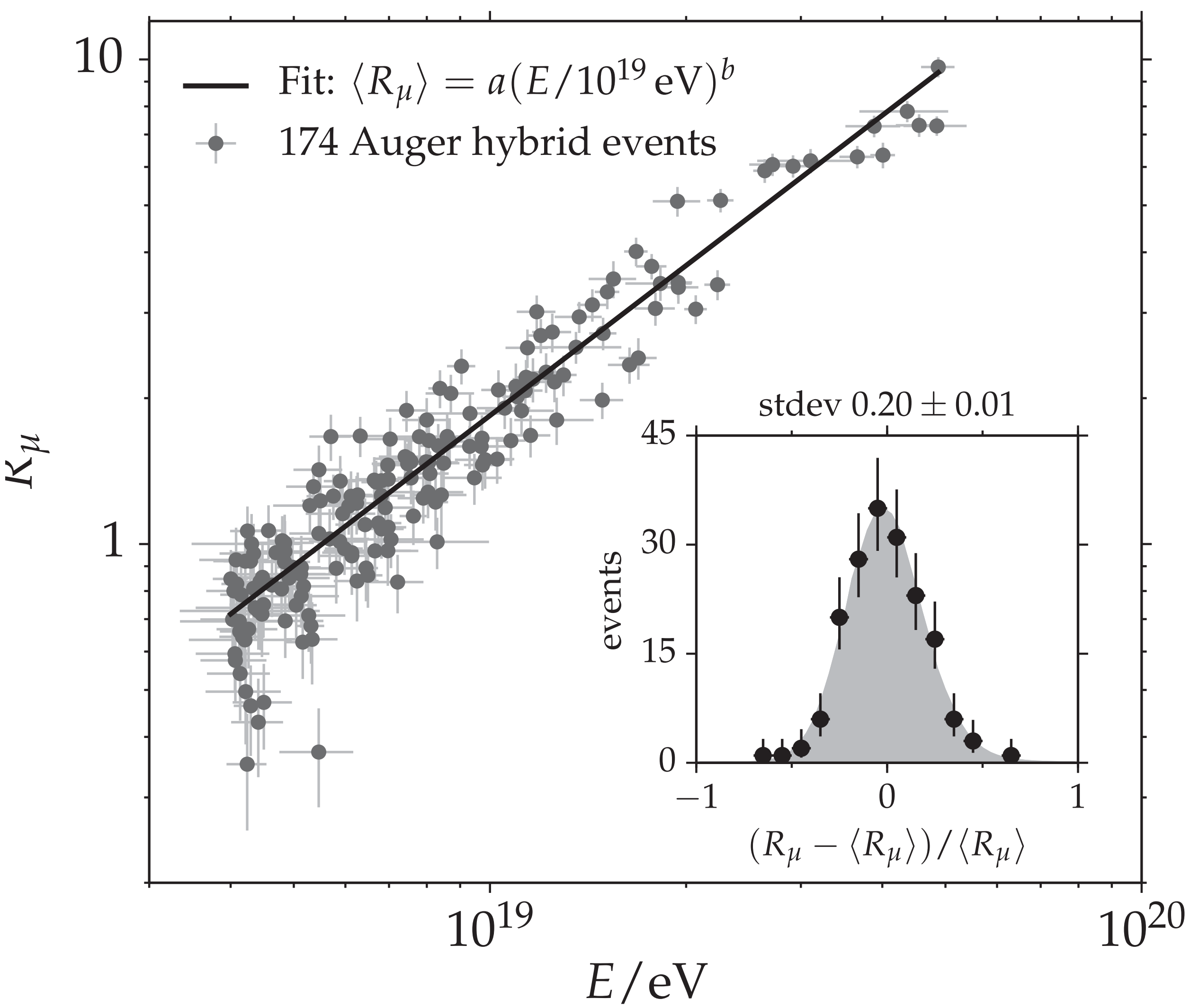
$$N_\mu = A\left(\frac{E/A}{\xi_c}\right)^\beta$$

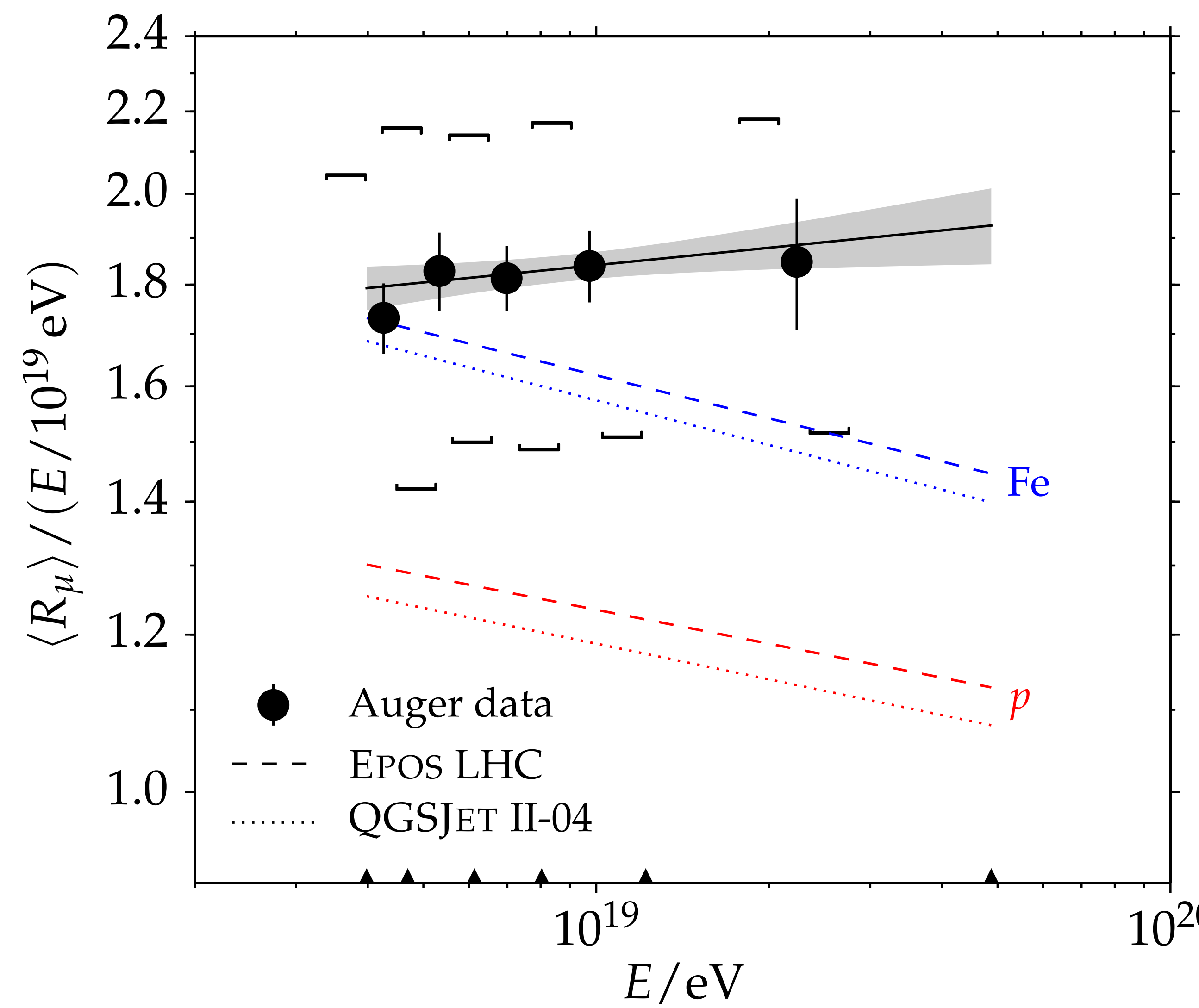
$$\langle R_\mu \rangle = a(E/10^{19}\ \text{eV})^b$$

$$a = \langle R_\mu \rangle(10^{19}\ \text{eV}) = (1.841 \pm 0.029 \pm 0.324(\text{sys})),$$

$$b = \mathrm{d}\langle \ln R_\mu \rangle / \mathrm{d} \ln E = (1.029 \pm 0.024 \pm 0.030(\text{sys})),$$

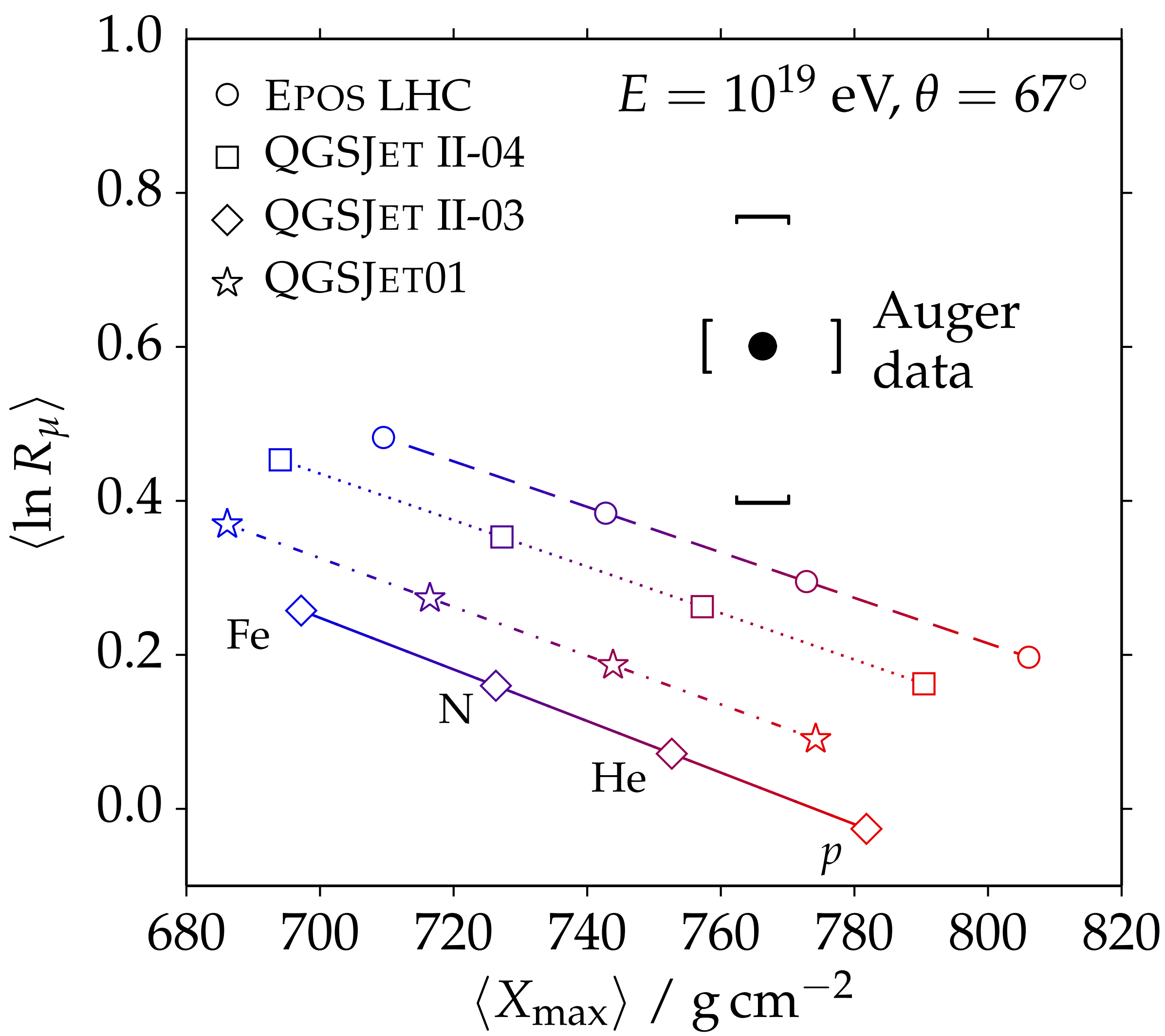
$$\sigma[R_\mu]/R_\mu = (0.136 \pm 0.015 \pm 0.033(\text{sys})).$$

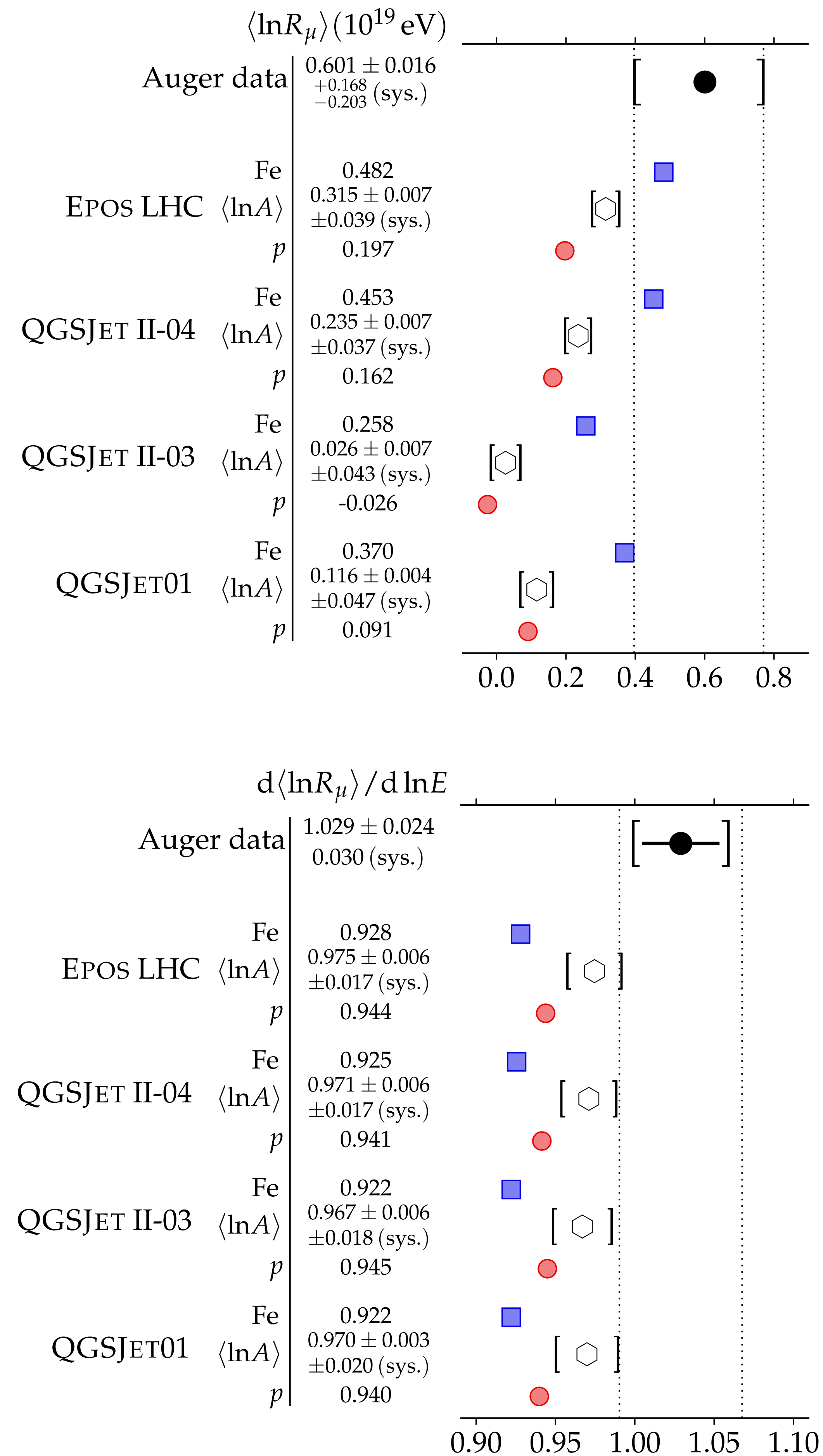




Phys. Rev. D 91, 032003 (2015)

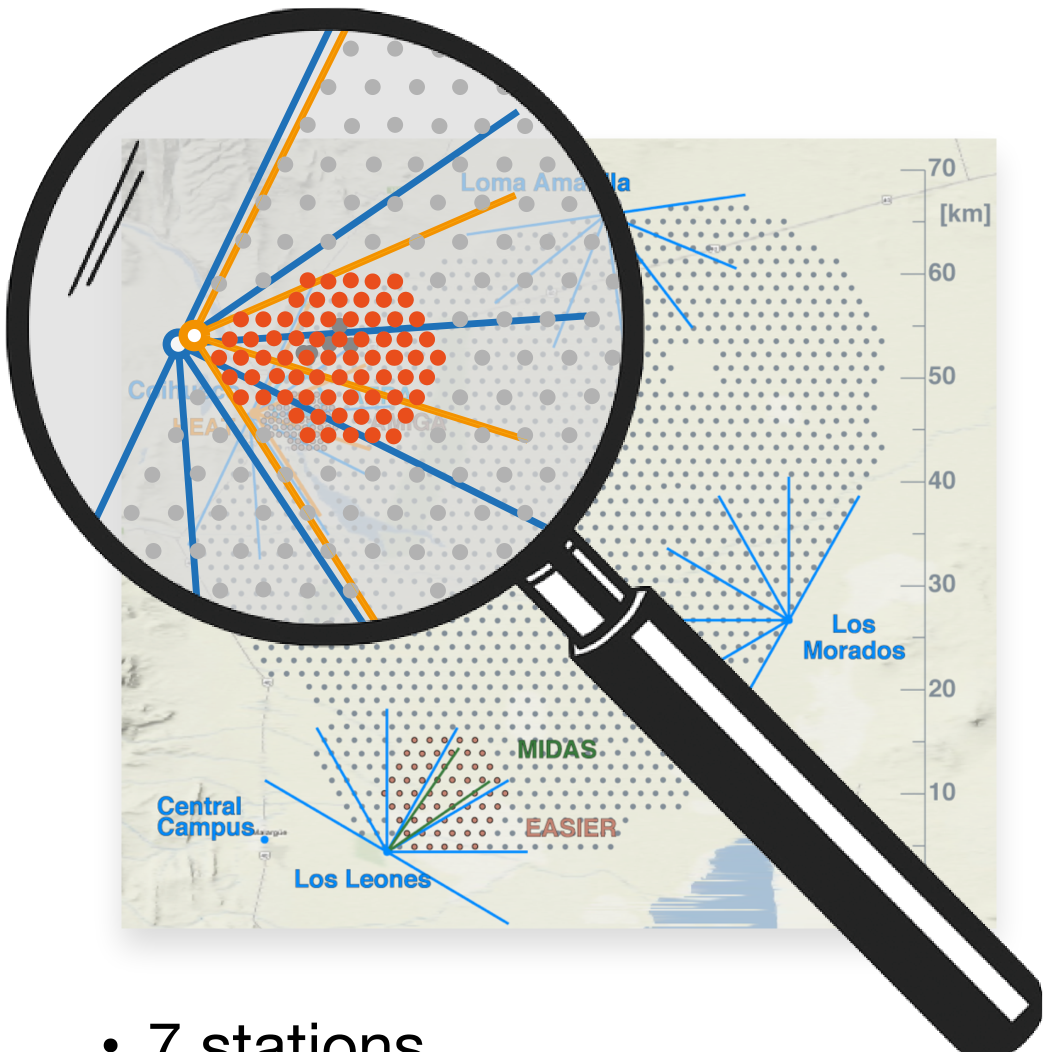
Results on ⟨ln R_μ⟩

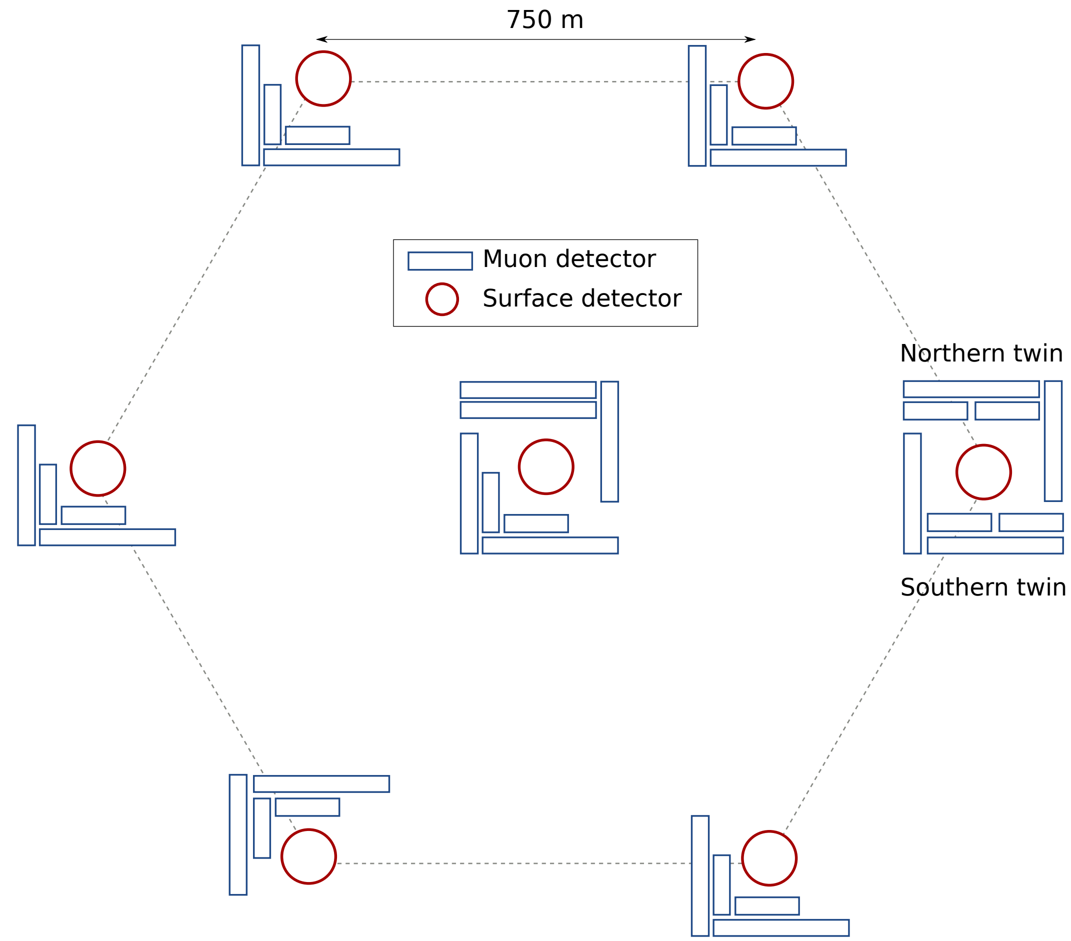




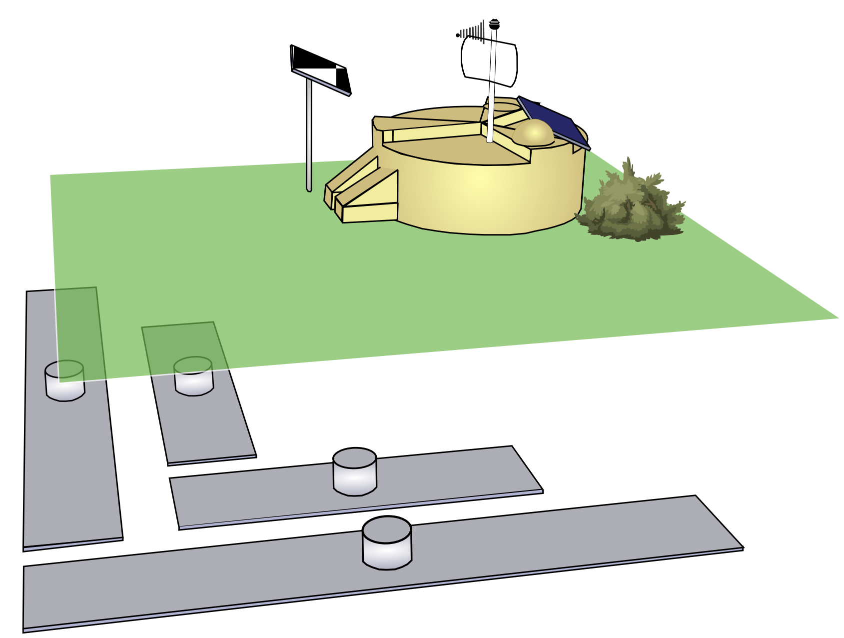
Muon deficit in sims,
and also deficit on
energy derivative (muon gain)

Direct muon measurement with AMIGA

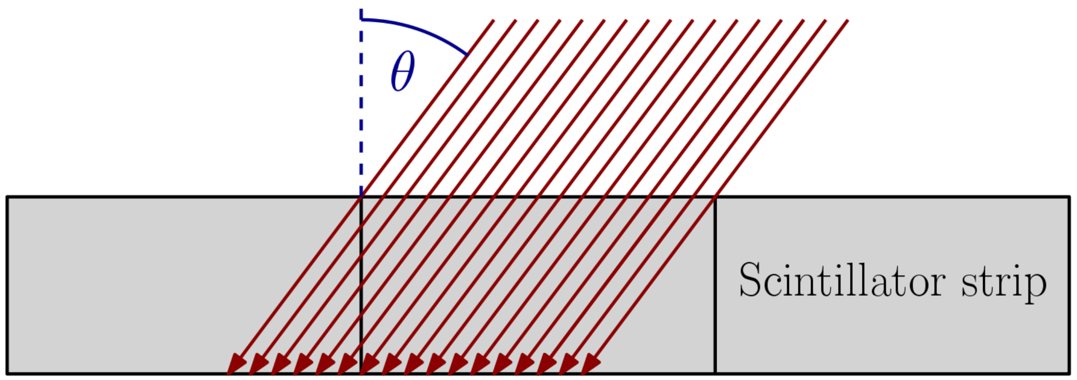


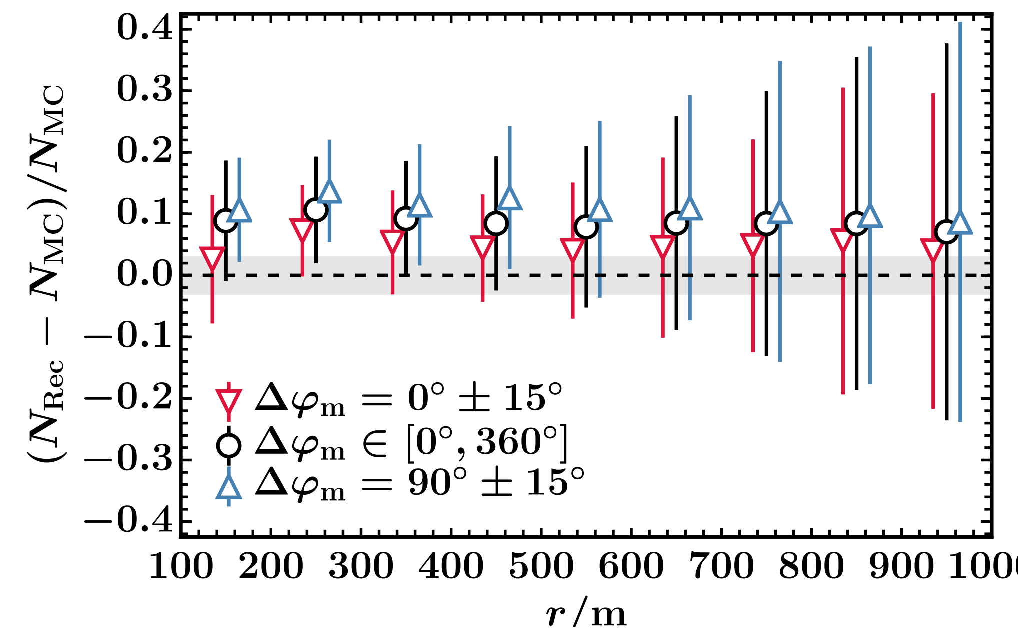


- 7 stations
- 30 (60) m² scintillator modules
- 2.3 m below ground
- 1 GeV/cosθ
- AMIGA in slave mode wrt SD station
- 1 full year of data with PMTs
- PMTs to be replaced by SiPMs

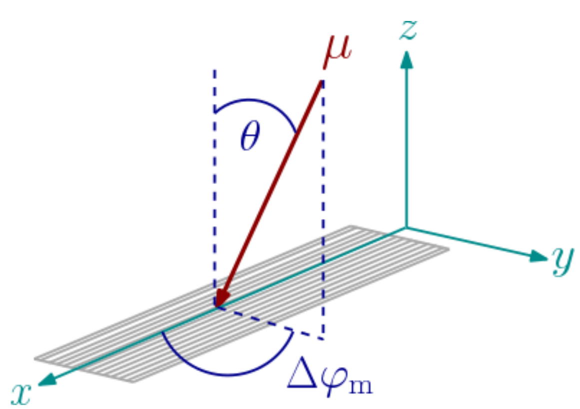


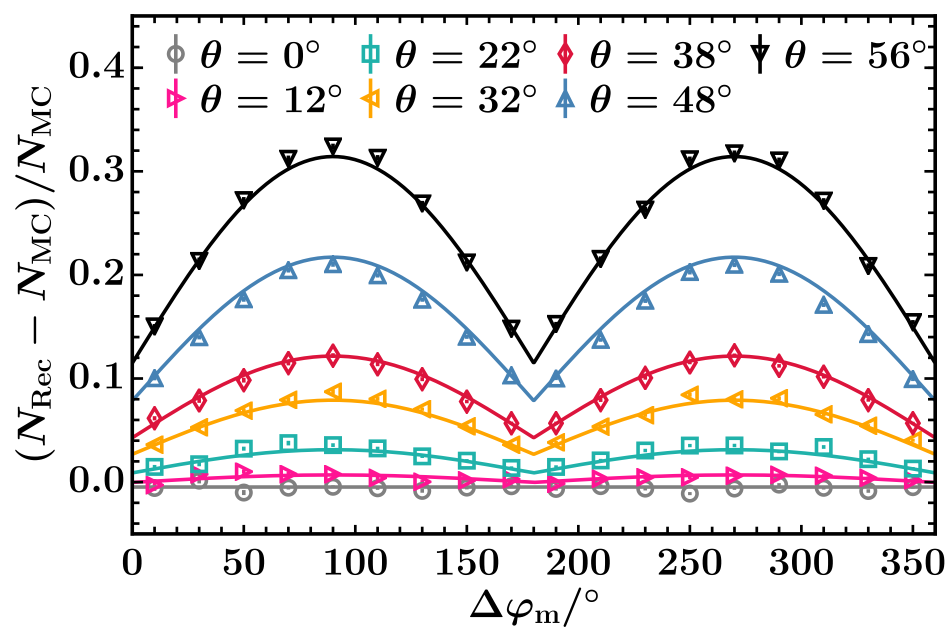
Systematic effects studied in detail, e.g. corner clipping muons

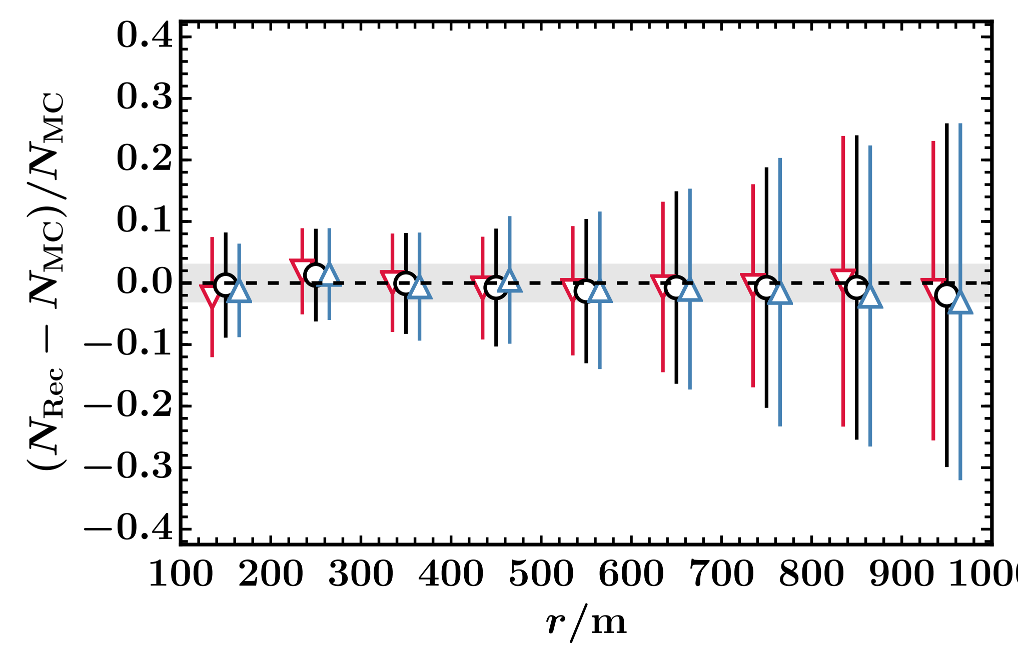




$$f_{\mathrm{clip}}\left(\theta, \Delta\varphi_{\mathrm{m}}\right) = a(\theta) + b(\theta) \cdot \left|\sin \Delta\varphi_{\mathrm{m}}\right|$$

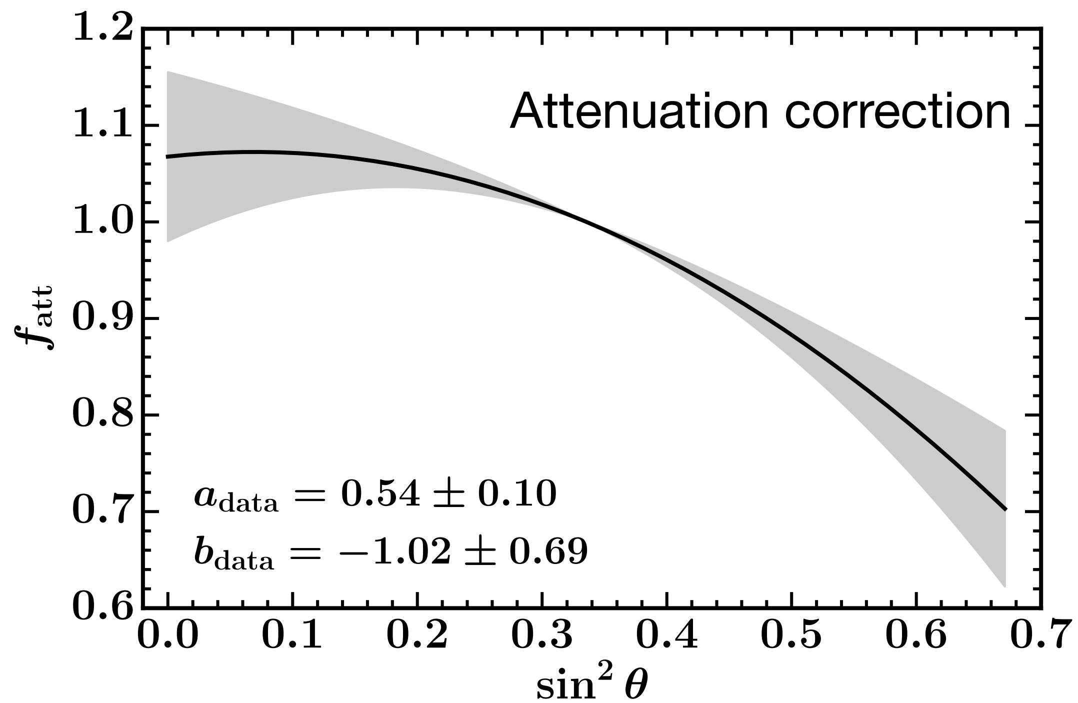


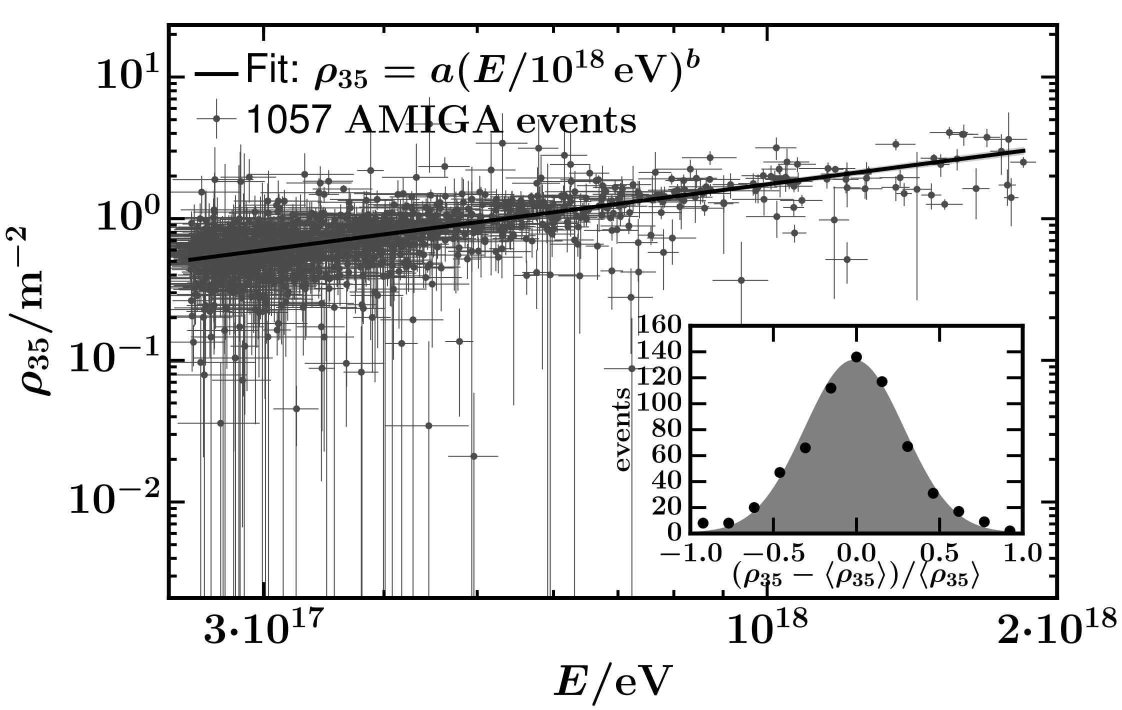


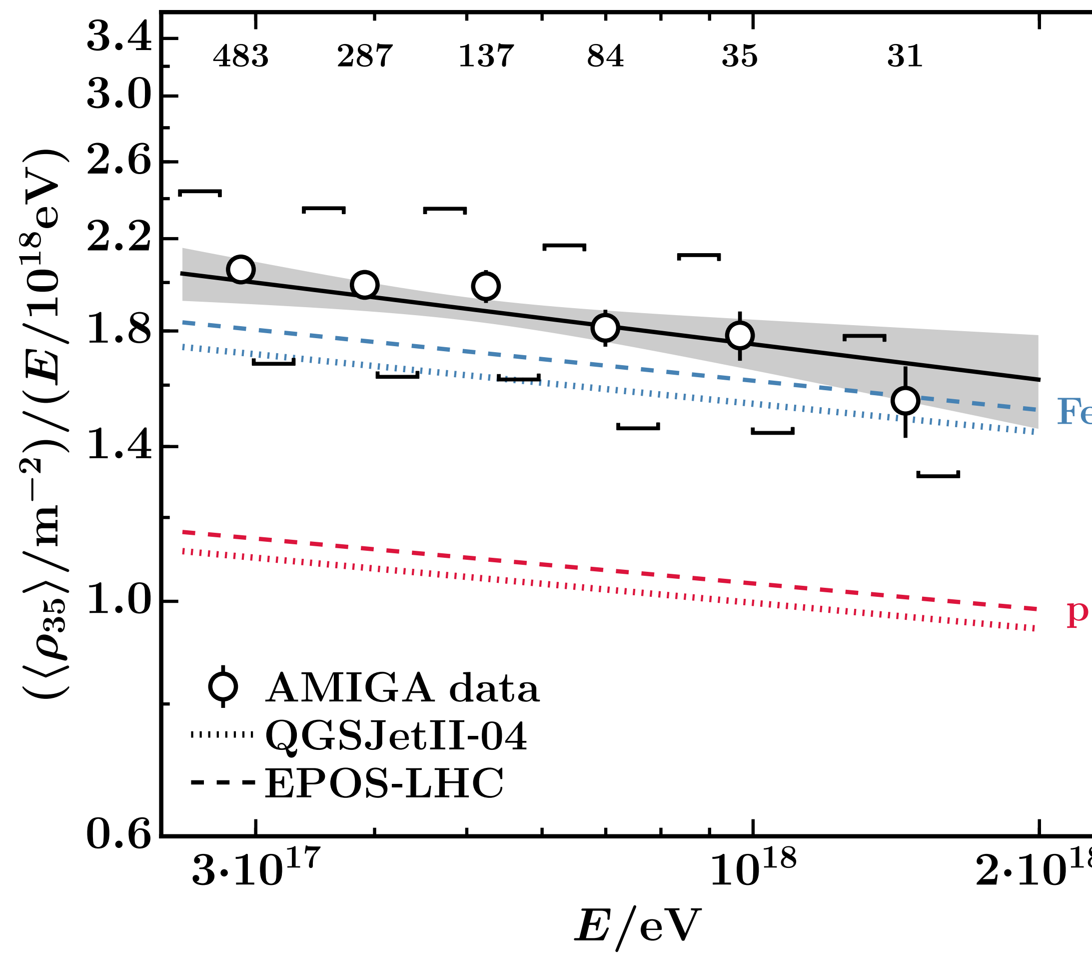


$$N_{\mathrm{Rec}}^{\mathrm{corr}}\left(\theta, \Delta\varphi_{\mathrm{m}}\right) = \frac{N_{\mathrm{Rec}}}{1 + f_{\mathrm{clip}}\left(\theta, \Delta\varphi_{\mathrm{m}}\right)}$$

Energy dependence of the muon density





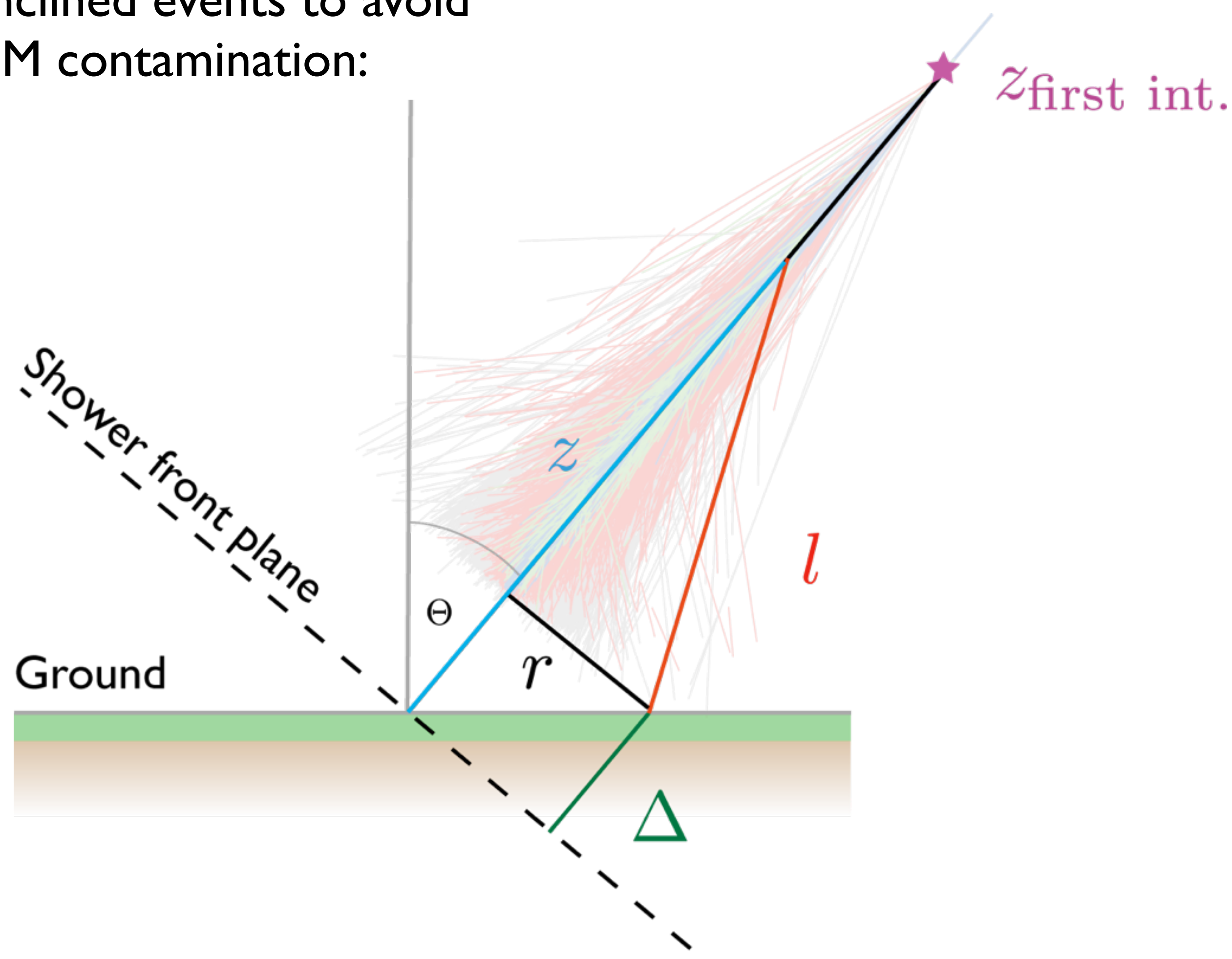


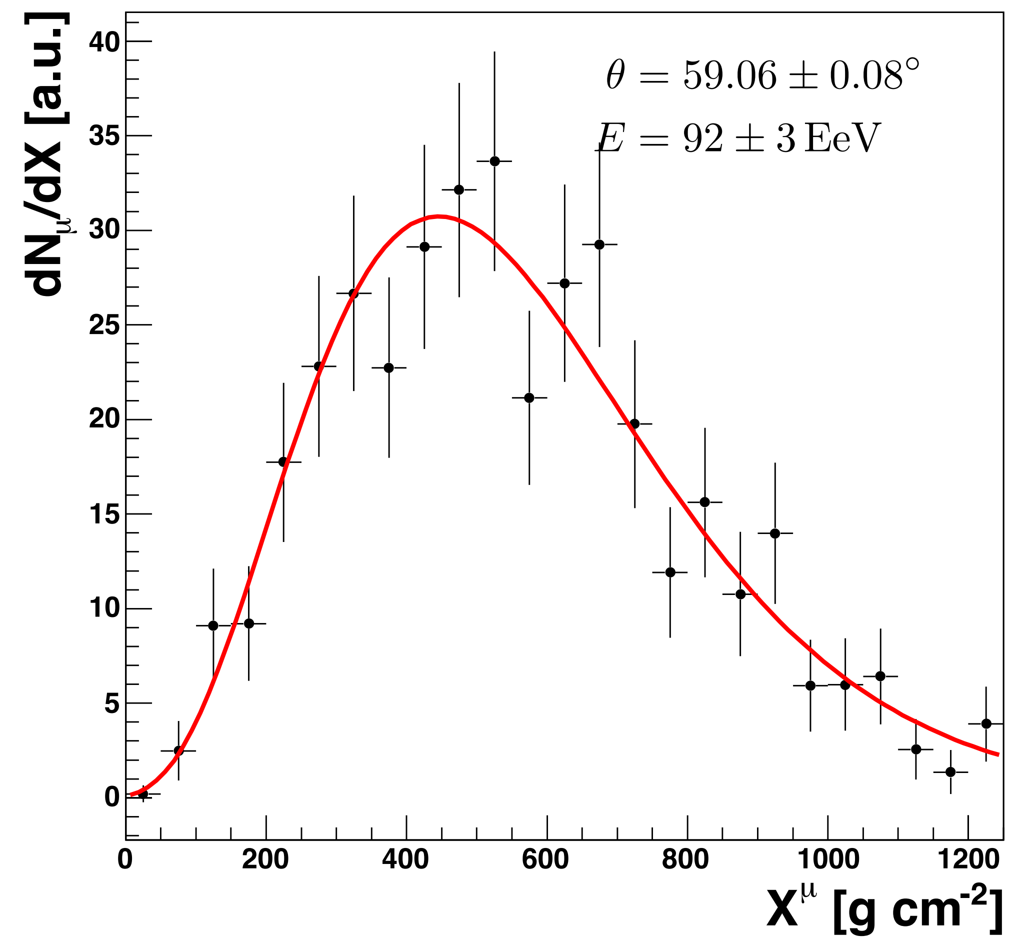
Further hint to muon deficit
in simulations at lower energies
(from X_{max}: dominated by light elements!)

For more details see poster by Sarah Müller

Muon Production Depth

Inclined events to avoid EM contamination:





Geometric time delay of arriving muons:

$$c \cdot t_g = l - (z - \Delta)$$
$$= \sqrt{r^2 + (z - \Delta)^2} - (z - \Delta)$$

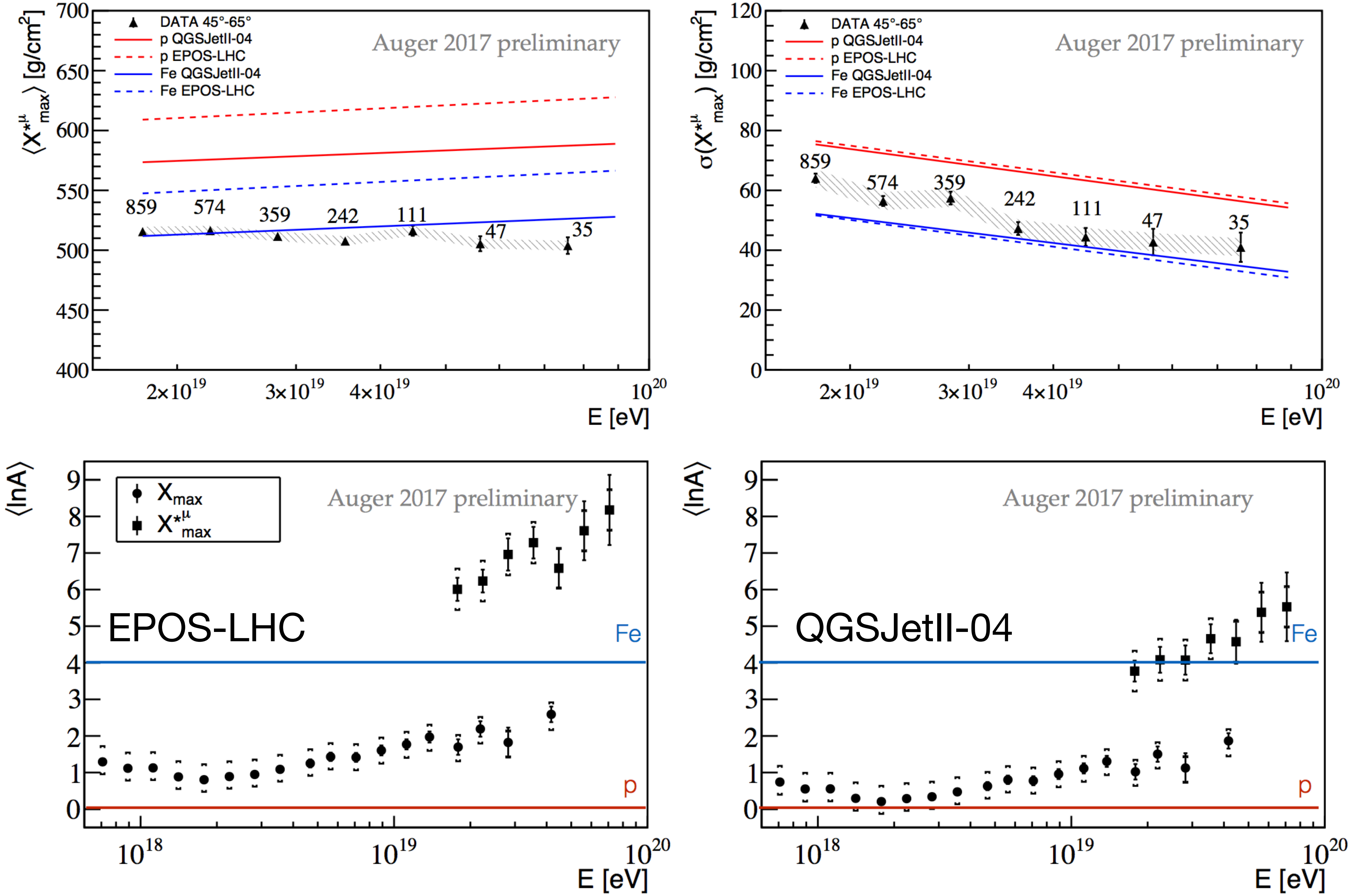
Mapped to muon production depth:

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

Two assumptions:

- Muons are produced in the shower axis
- Muons travel following straight lines

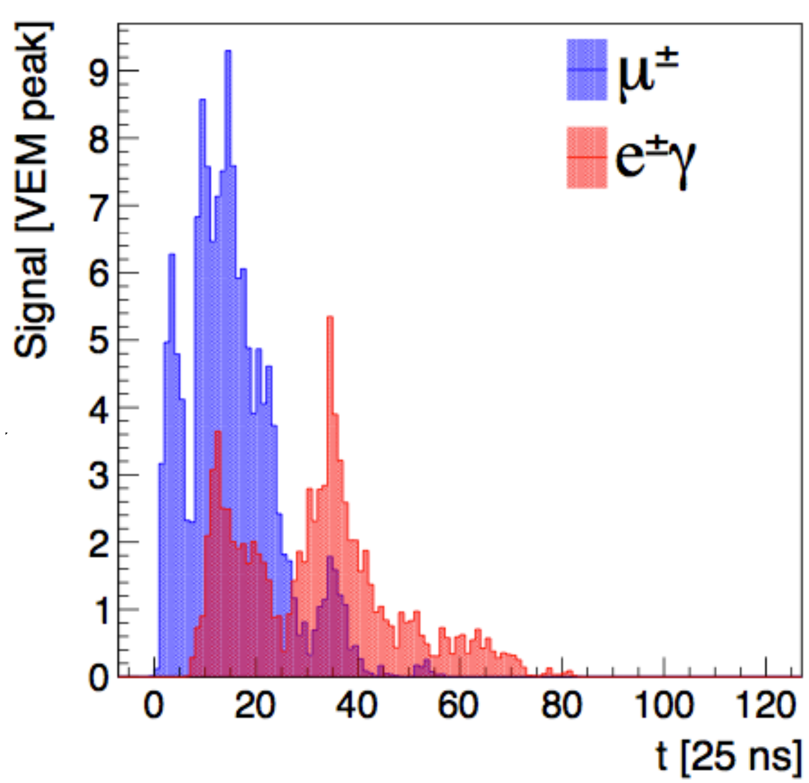
Muon Production Depth vs simulations

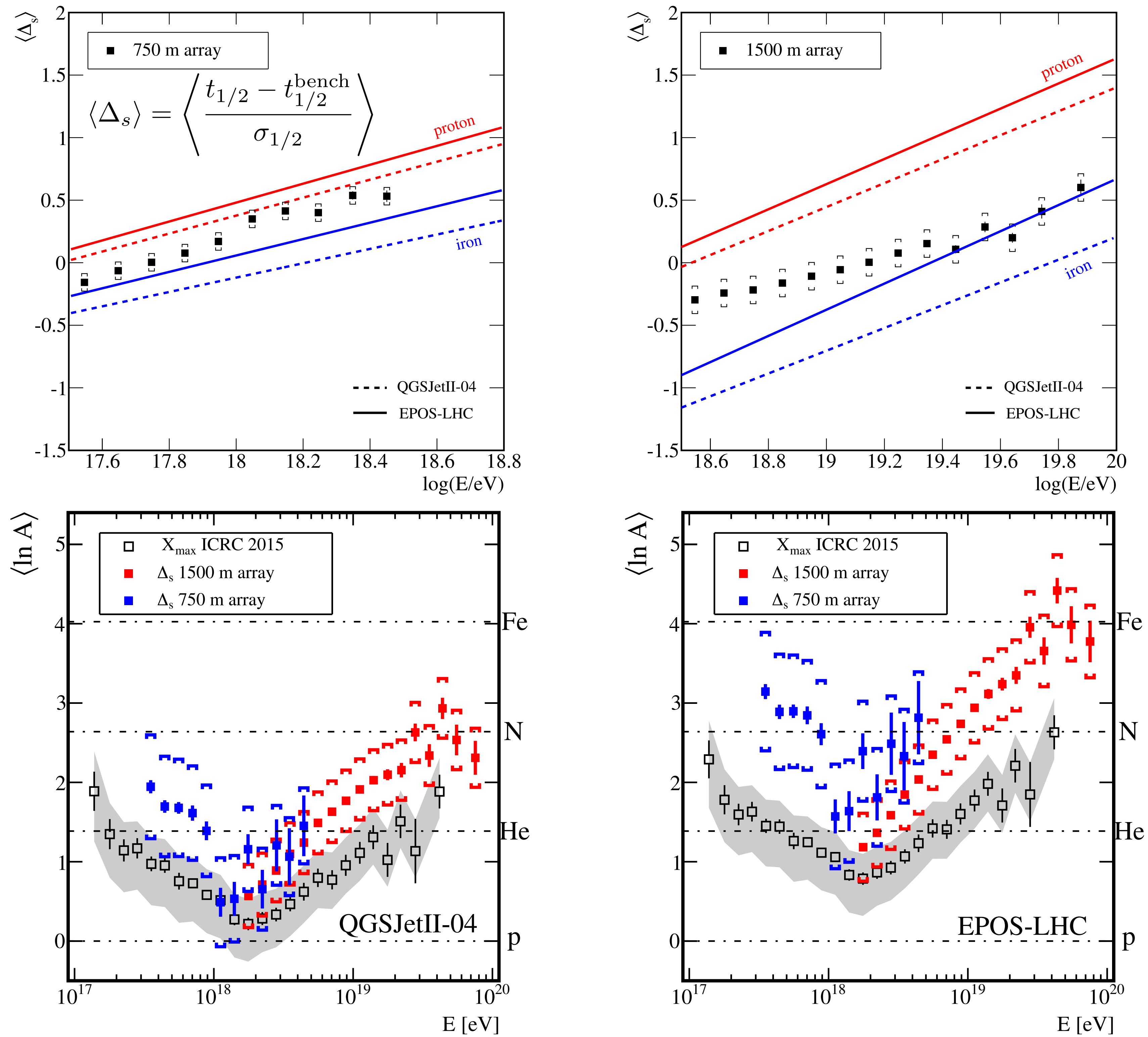


Phys. Rev. D 90, 012012 (2014)

Risetime measurement

- SD signal in vertical events
- Time elapsed between 10% and 50% of integrated signal
- Sensitive both to EM and muonic
-

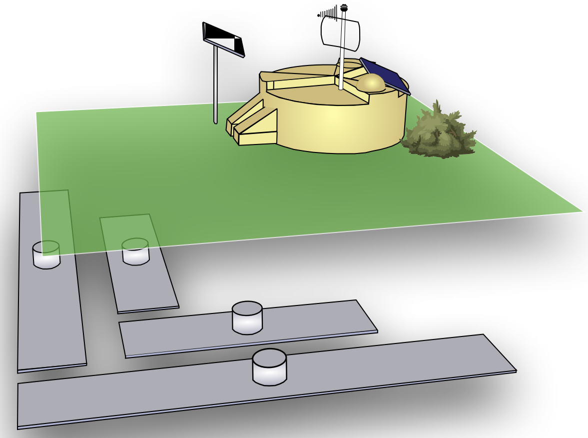




Phys. Rev. D 96, 122003 (2017)

Summary and conclusions

- FD: EM shower is fairly well described by models, our best mass estimator is X_{max}
- FD+SD: Measurements of muon content; X_{max} & S1000
  - No need for E rescaling, thus muon problem
    Muon rescaling factor 1.3-1.6
- SD: R_μ in inclined showers
  Increasing MC deficit with increasing energy
- SD: Muon Production Depth mismatch provides further constraints in hadronic models; timing of muons
- SD: risetime (EM+mu) reveal hadronic models inconsistency in a more convolved way
- AMIGA (new): extending down to 3×10^{17} eV; simulations at variance with data given X_{max} data



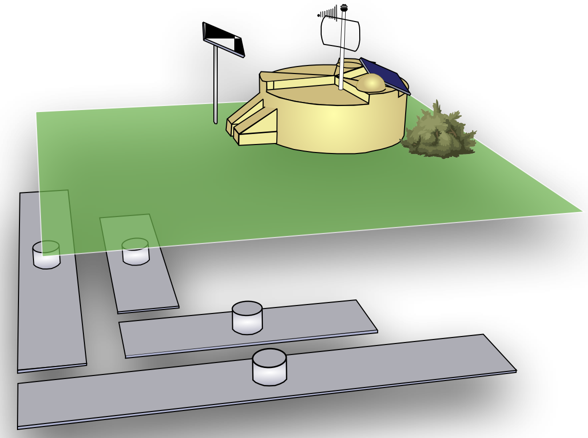
Summary and conclusions

- FD: EM shower is fairly well desc... , our best mass estimator i...
- FD+SD: Mea... 000
  - ...
- SD: ... Increa...
- SD: M... further ...
- SD: riset... inconsiste...
- AMIGA (ne... 3×10^{17} eV; simulations ... with data given X_{max} data

Muon predictions are at variance with Auger data

Synopsis shown by Hans Dembinski in this session

and check posters by Sophia Andringa and Sarah Müller




THANK YOU
JUSPAXAR
OBRIGADO
MATONDO
SALAMAT
KIITOS
KIA ORA
MULTUMESC
MAAKE
MOCHCHAKKERAM
TERMA KASIH
RAIBH MAITH AGAT
MERCI
CHOKRANE
SALAMAT
CAM ON BAN
GRAZIE
MULTUMESC
MERCI
RAIBH MAITH AGAT
MERCI
OBRIGADO
MOCHCHAKKERAM
GRAZIE
ASANTE
CHOKRANE
MATUR NUWUN
UA TSAUG RAU KOJ
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VINAKA
MAAKE
DANKON
OBRIGADO
MOCHCHAKKERAM
NIRRINGRAZZJAK
MULTUMESC
MOCHCHAKKERAM
OBRIGADO
SPASIBO

Backup

Systematic uncertainty of ρ$_{450}$

Systematic Uncertainty		**Percentage**
Eff. corr.	$\sigma_{\mathrm{sys,eff}}/\rho_{450}$	9.9%
Calibration	$\sigma_{\mathrm{sys,thr}}/\rho_{450}$	3.9%
Soil density	$\sigma_{\mathrm{sys,soil}}/\rho_{450}$	2.8%
LDF	$\sigma_{\mathrm{sys,LDF}}/\rho_{450}$	8.8%
Atten. corr.	$\sigma_{\mathrm{sys},f_{\mathrm{att}}}/f_{\mathrm{att}}$	2.3%
Total	$\sigma_{\mathrm{sys},\rho_{35}}/\rho_{35}$	**14.3**%

p-Air cross-section: uncertainties

	$10^{17.8} - 10^{18}$ eV	$10^{18} - 10^{18.5}$ eV
$\sigma_{\text{p-air}}$ uncertainties		
Λ_η, systematic uncertainties (mb)	13.5	14.1
Hadronic interaction models (mb)	10	10
Energy scale uncertainty, $\Delta E/E = 14\%$ (mb)	2.1	1.3
Conversion of Λ_η to $\sigma_{\text{p-air}}$ (mb)	7	7
Photons (mb)	4.7	4.2
Helium, 25% (mb)	-17.2	-15.8
Total systematic uncertainty on $\sigma_{\text{p-air}}$ (mb)	+19/-25	+19/-25