Karlsruhe Institute of Technology

Particle-physics aspects in air shower measurements with the Pierre Auger Observatory

ECRS 2016

PIERRE AUGER OBSERVATORY

Markus Roth for the Pierre Auger collaboration
KIT — Karlsruhe Institute of Technology

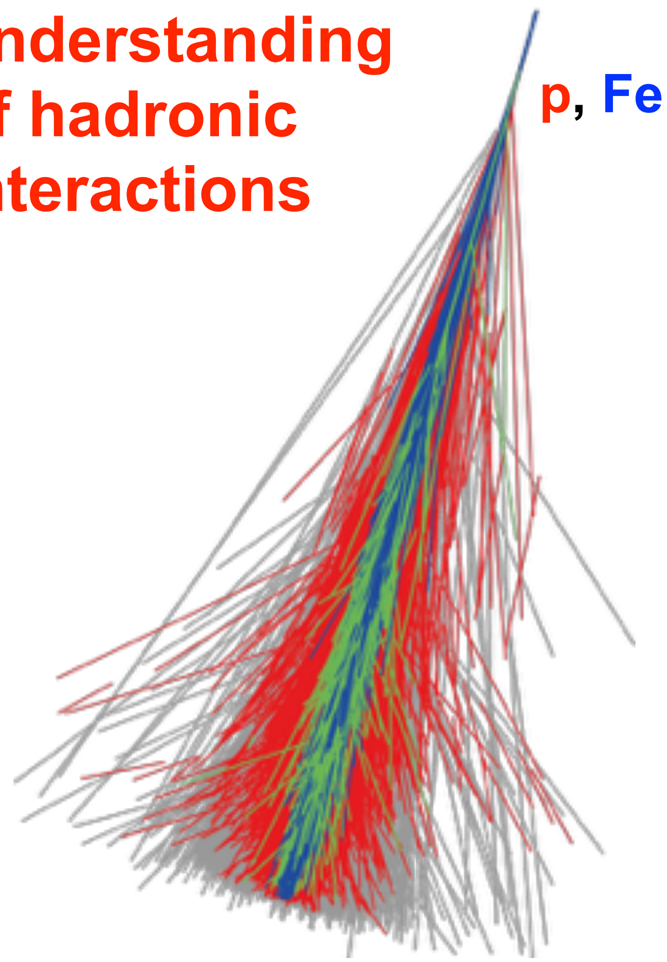
Karlsruher Institut für Technologie (KIT), Institut für Kernphysik, Karlsruhe, Germany

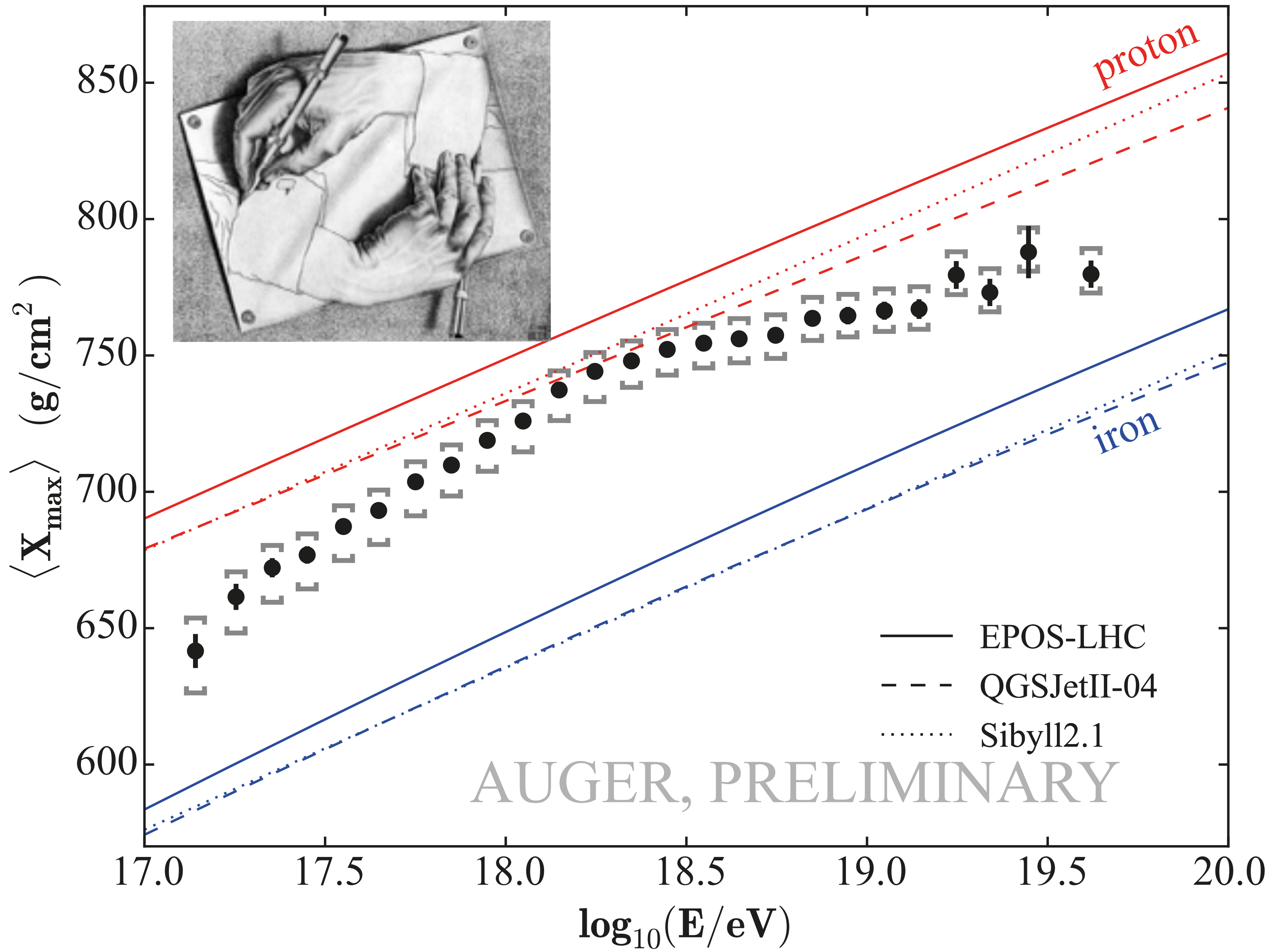
Photo by S.J. Saffi, University of Adelaide

Composition and hadronic interactions: a vicious circle

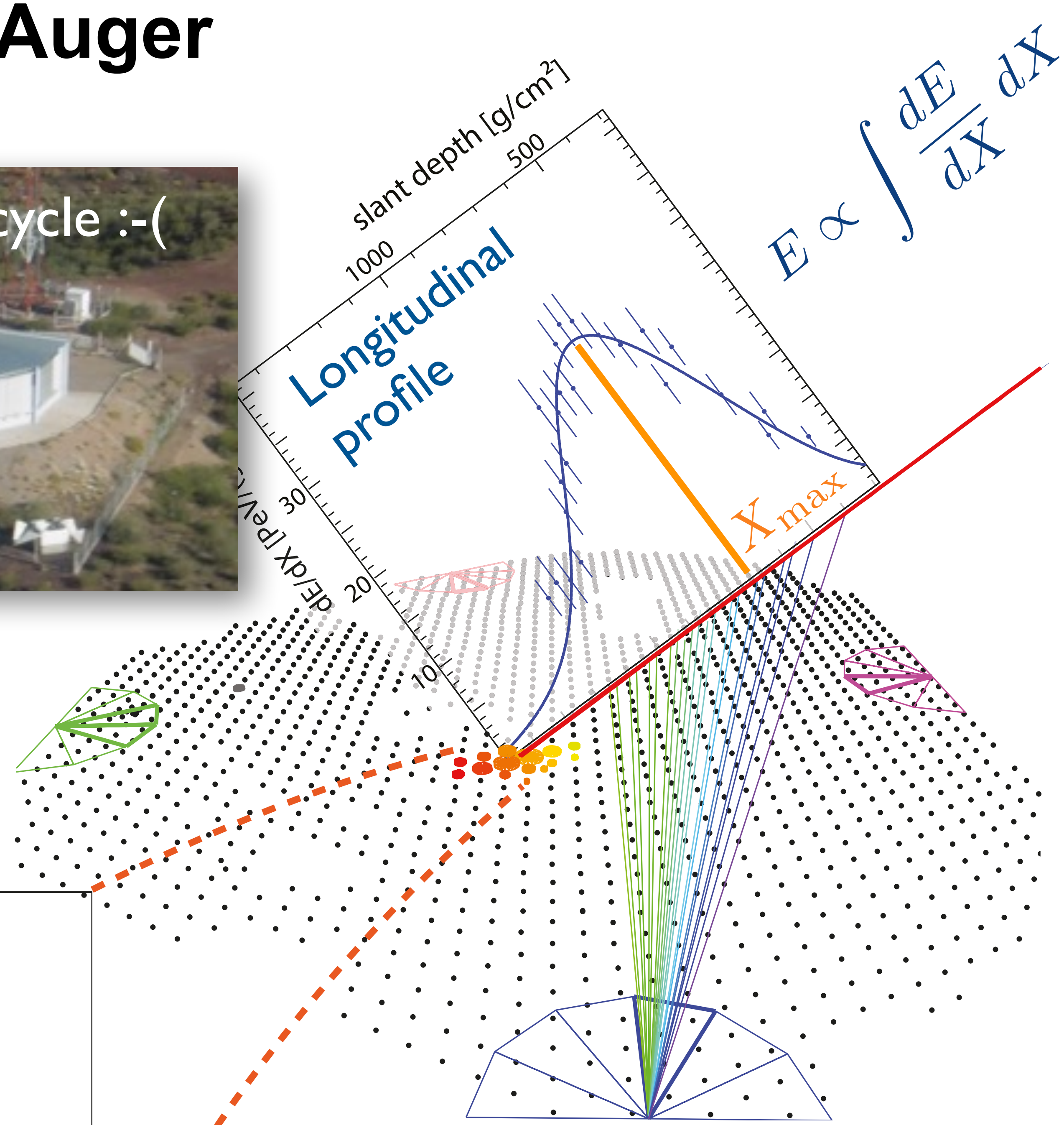
Pure beams are needed to study hadronic interactions

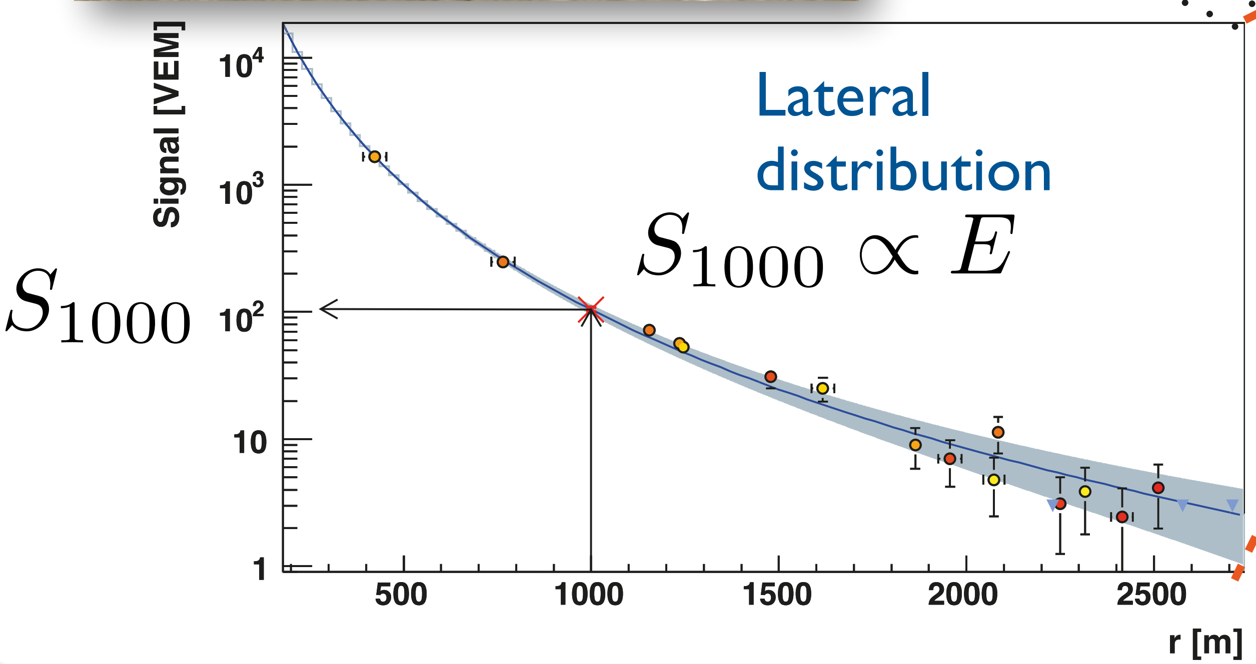
Selecting pure beams requires detailed understanding of hadronic interactions





Air showers recorded at Auger

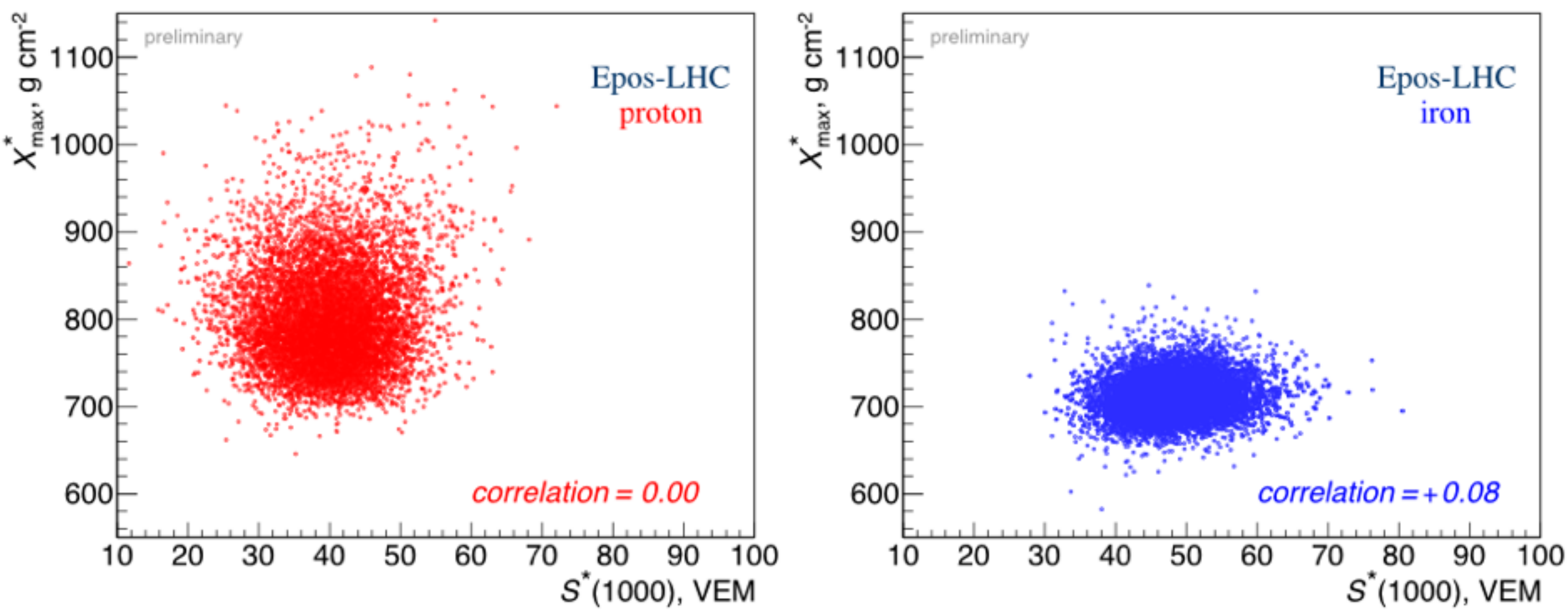




Karlsruher Institut für Technologie (KIT)
Institut für Kernphysik, Karlsruhe, Germany

Correlation between X_{max} and SD Signal

18.5 < lg(E/eV) < 19.0, X^*_{max}/S^*(1000): scaled to 10^{19} eV



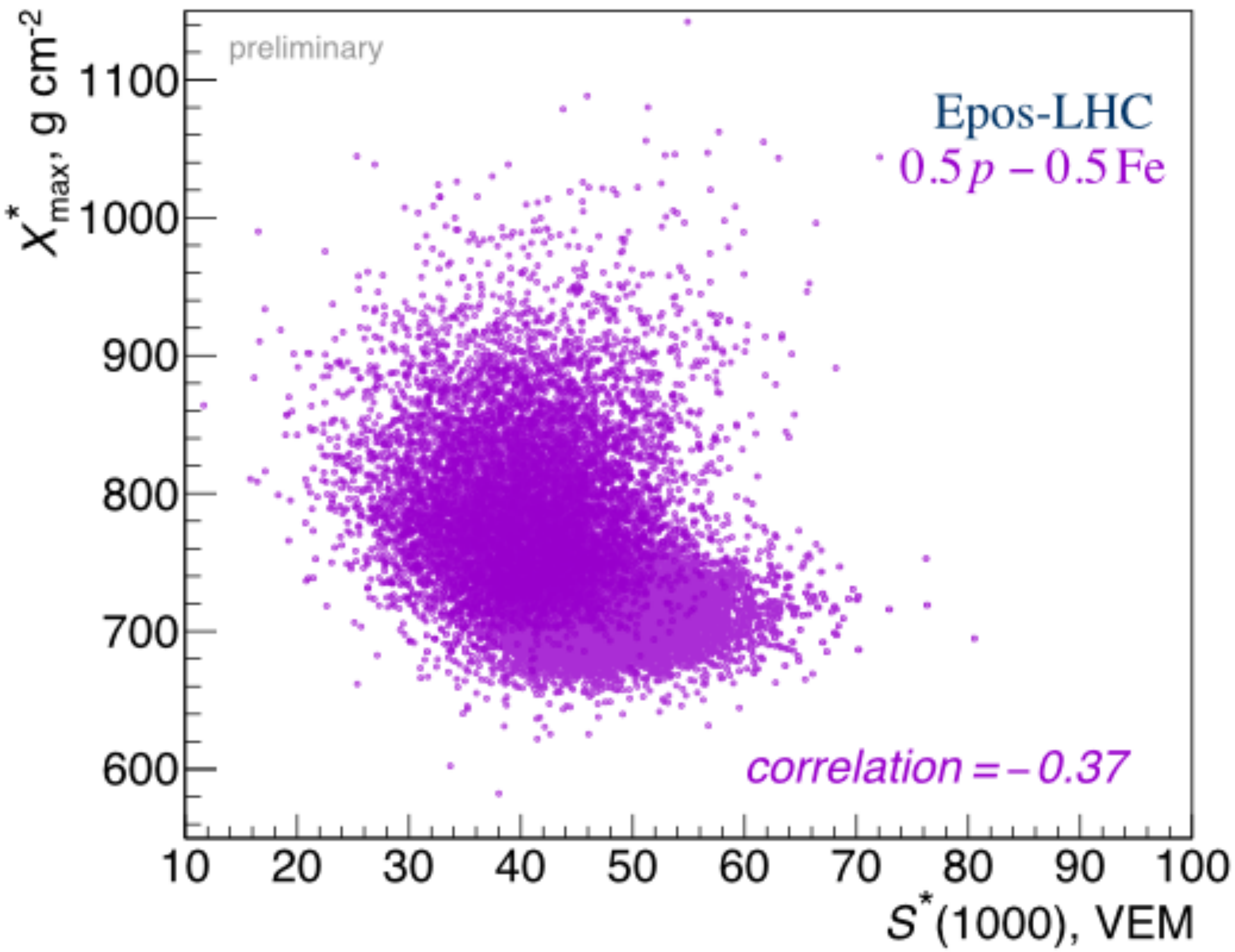
Pure compositions
⇒ correlation ≳ 0

Ranking coefficient r_G [R. Gideon, R. Hollister, JASA 82 (1987) 656]
A. Yushkov for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

The key idea

Heavier nuclei produce shallower showers with larger signal (more muons)

General characteristics of air showers / minor model dependence

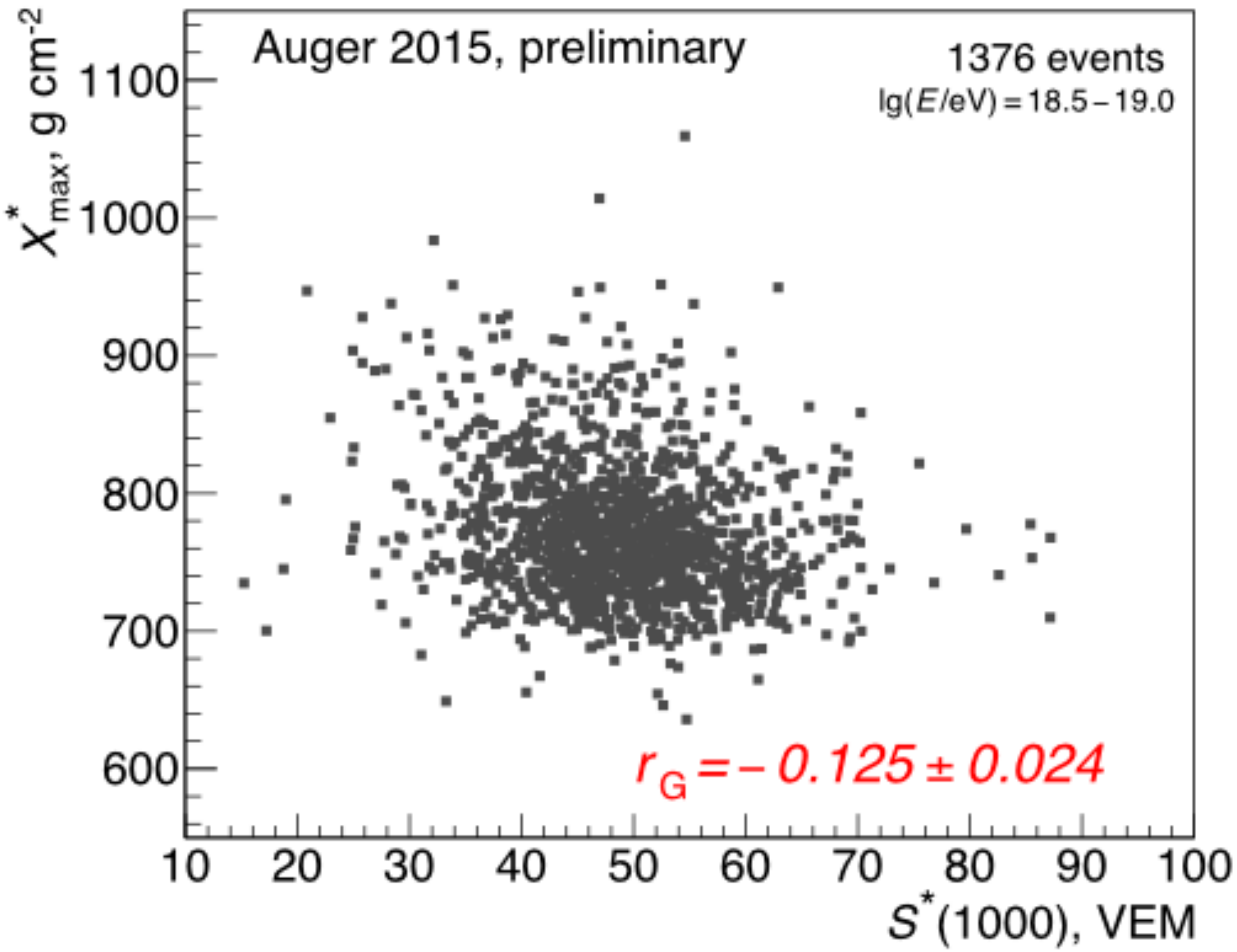


Correlation more negative ⇒ composition becomes more mixed

A. Yushkov for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Karlsruher Institut für Technologie (KIT)
Institut für Kernphysik, Karlsruhe, Germany

Correlation r_G in data



$r_G(X^*_{max}, S^*(1000))$ for protons

Epos-LHC	QGSJetII-04	Sibylle 2.1
0.00	+0.08	+0.07
≈5σ	≈8σ	≈7σ

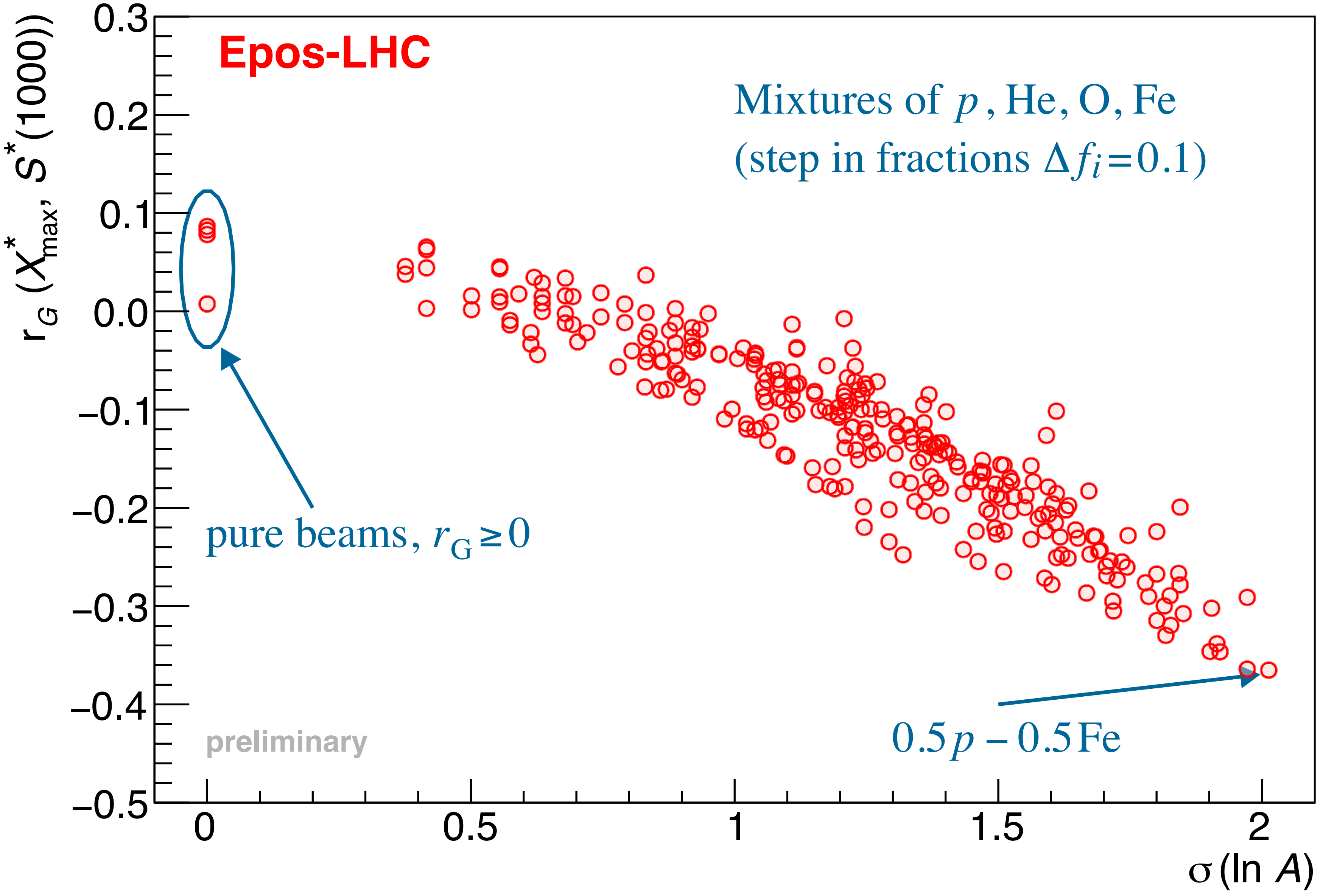
Difference is larger for other pure beams

Systematics plays only a minor role $\sigma_{syst}(r_G) \lesssim 0.01$

due to invariance of r_G to additive and multiplicative scale transformations

A. Yushkov for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

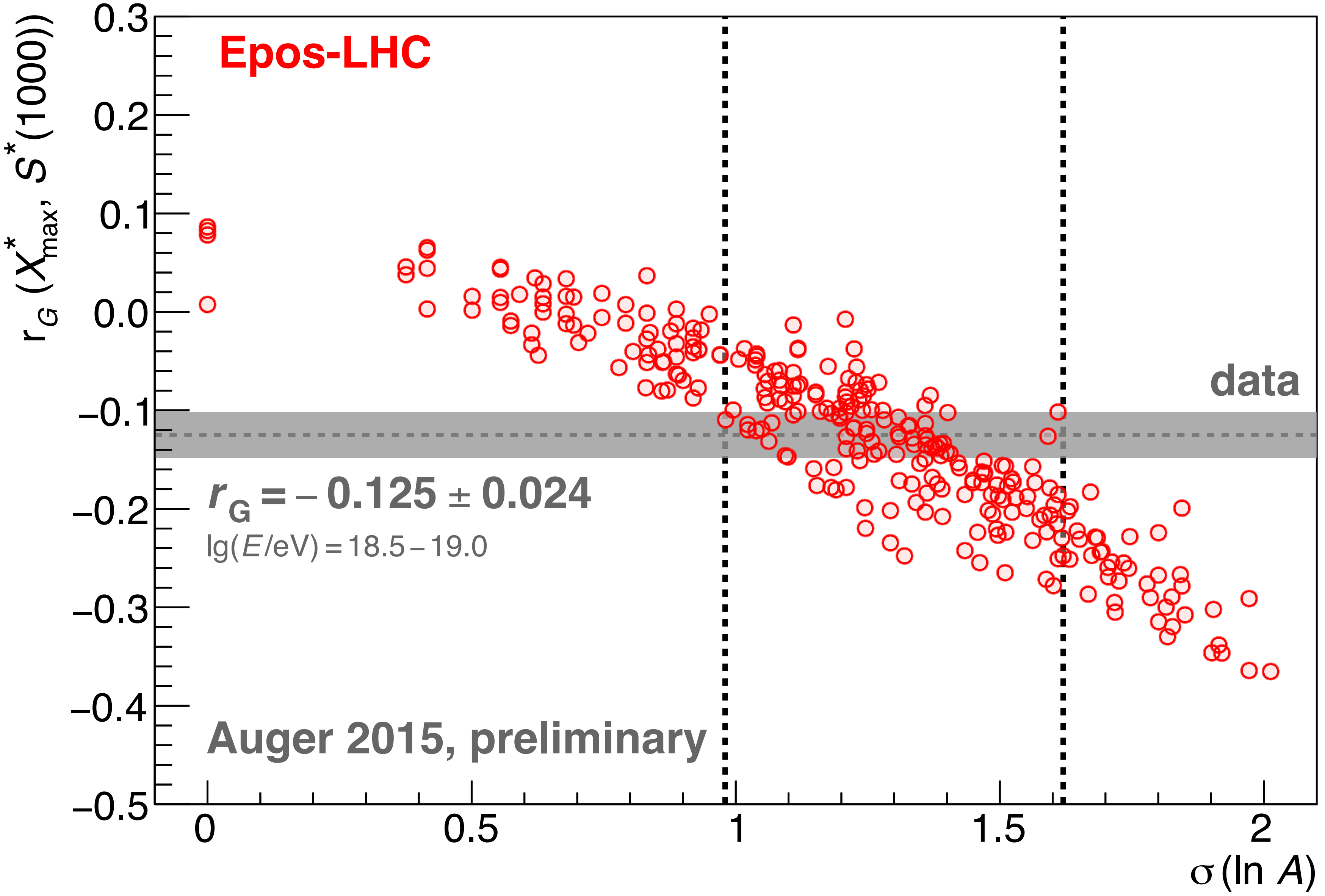
Relation of r_G to dispersion of masses $\sigma(\ln A)$



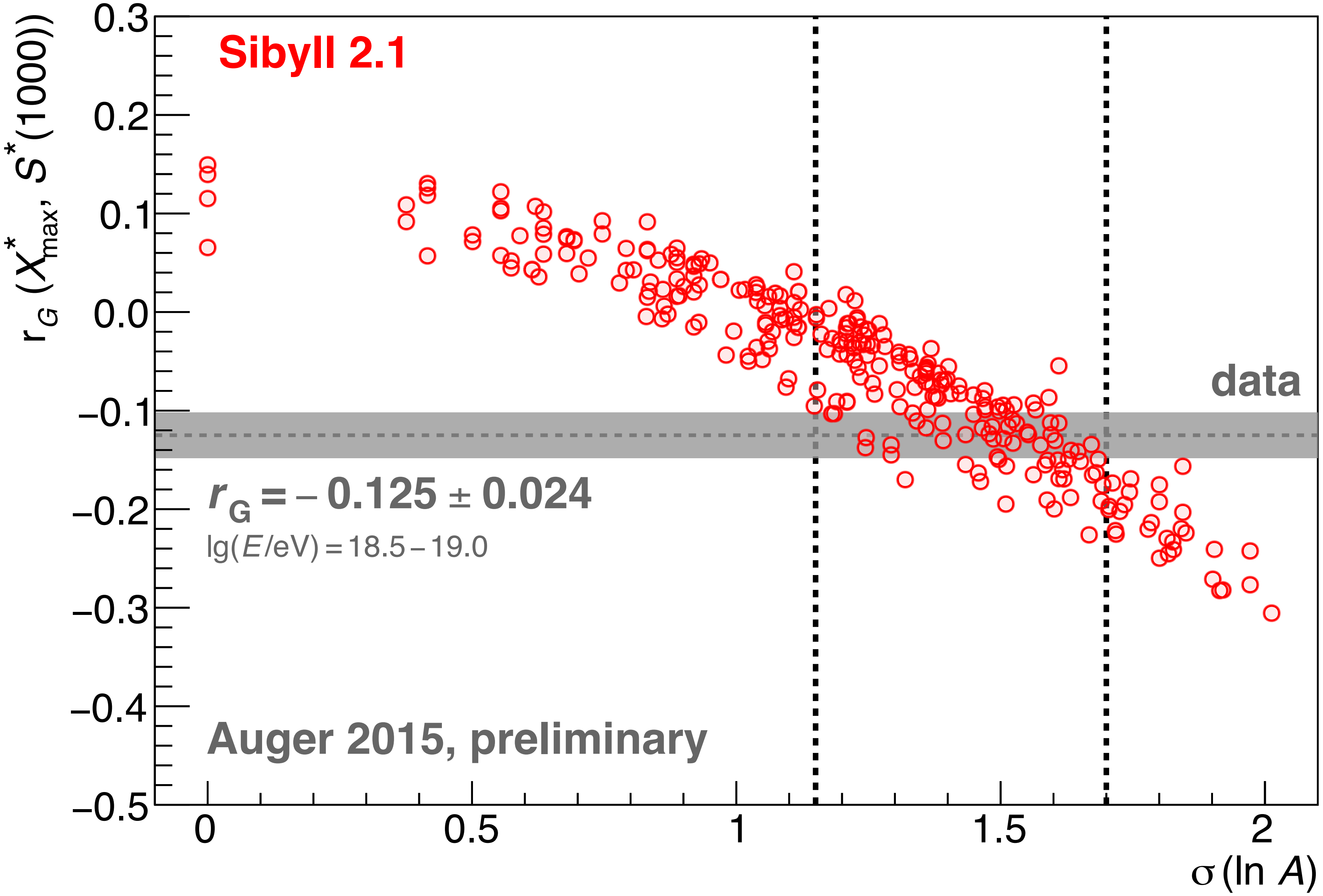
Karlsruher Institut für Technologie (KIT)
Institut für Kernphysik, Karlsruhe, Germany

Relation of r_G to dispersion of masses σ(ln A)

Karlsruhe Institute of Technology

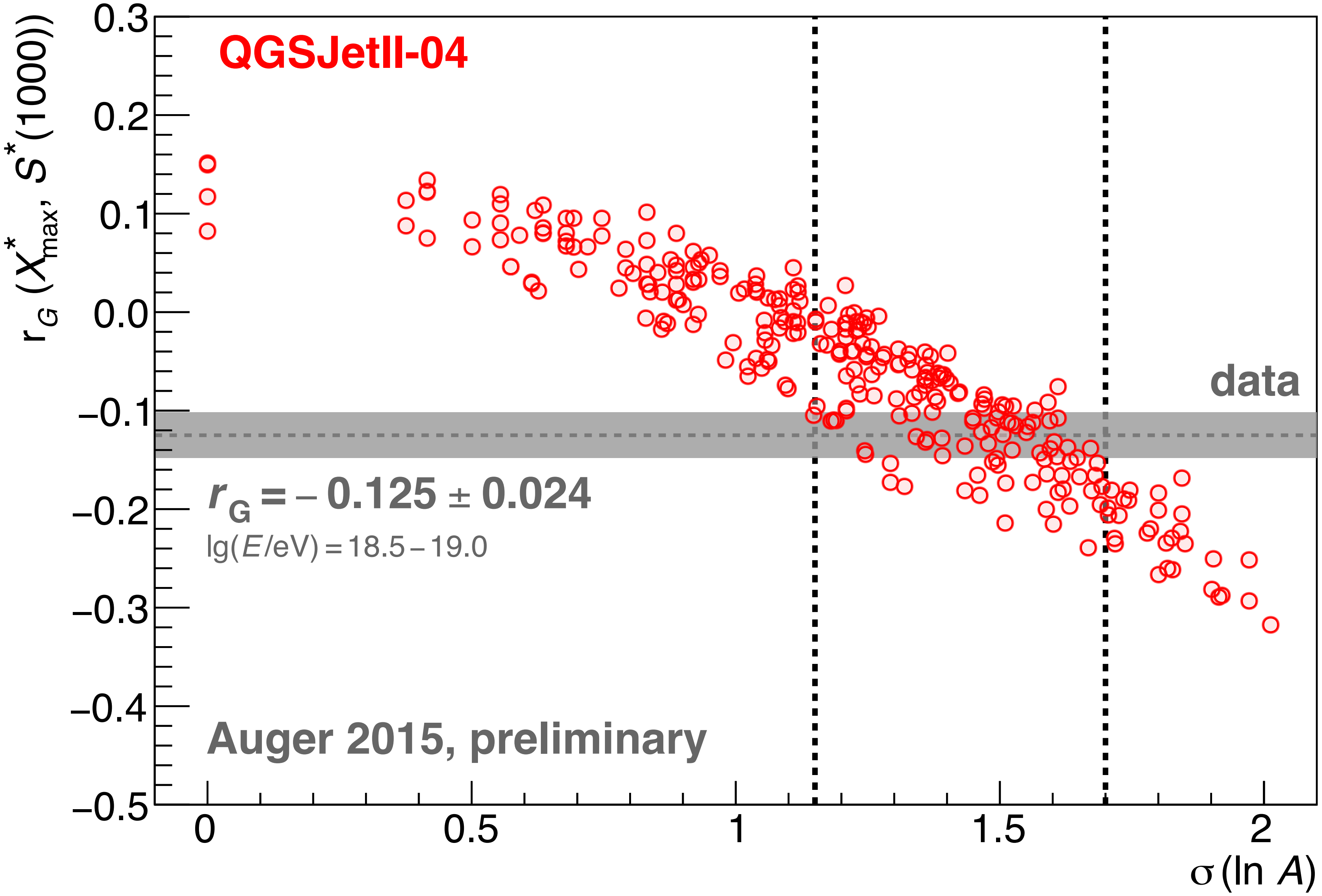


Relation of r_G to dispersion of masses $\sigma(\ln A)$



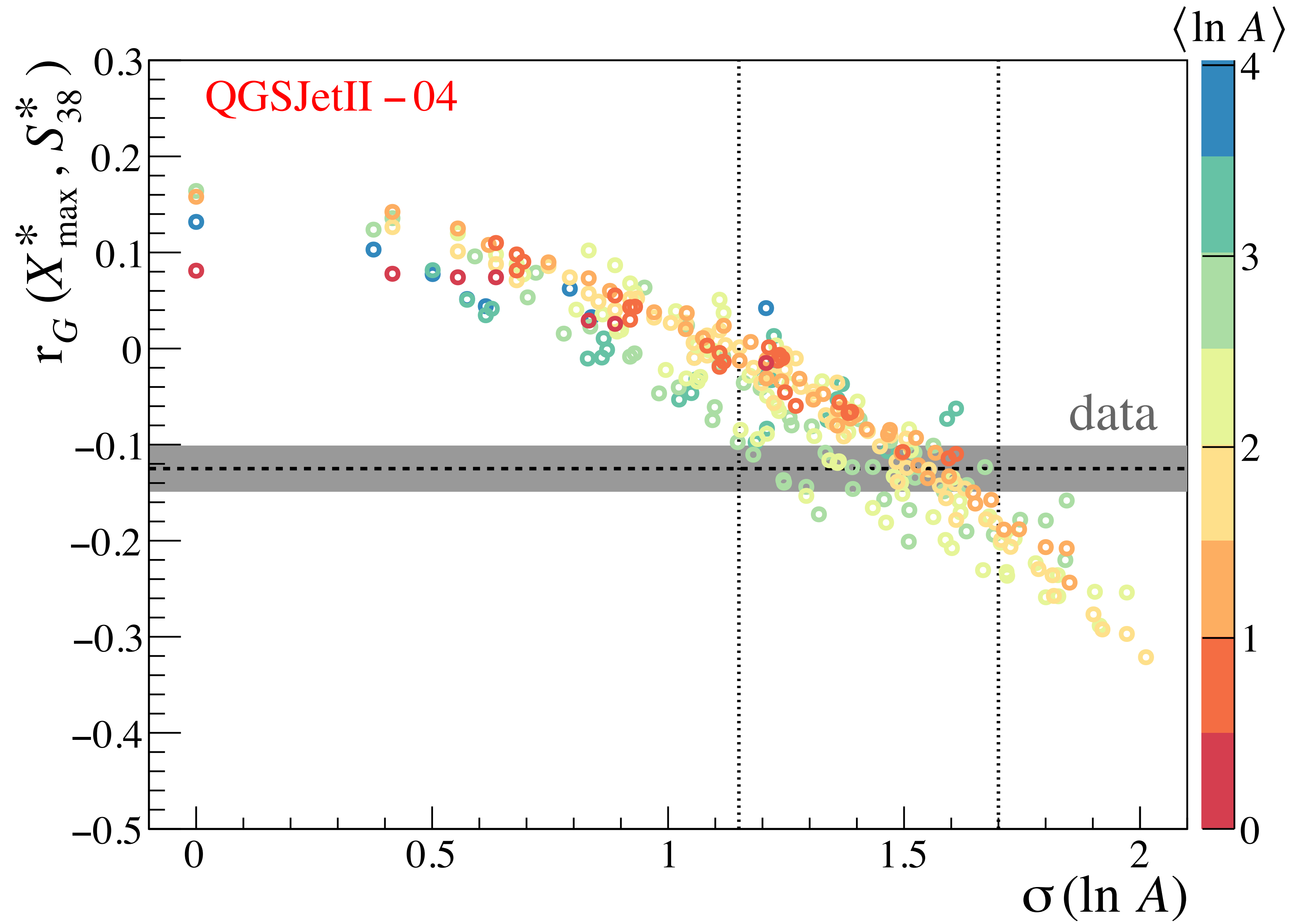
Karlsruher Institut für Technologie (KIT)
Institut für Kernphysik, Karlsruhe, Germany

Relation of r_G to dispersion of masses $\sigma(\ln A)$



Karlsruher Institut für Technologie (KIT)
Institut für Kernphysik, Karlsruhe, Germany

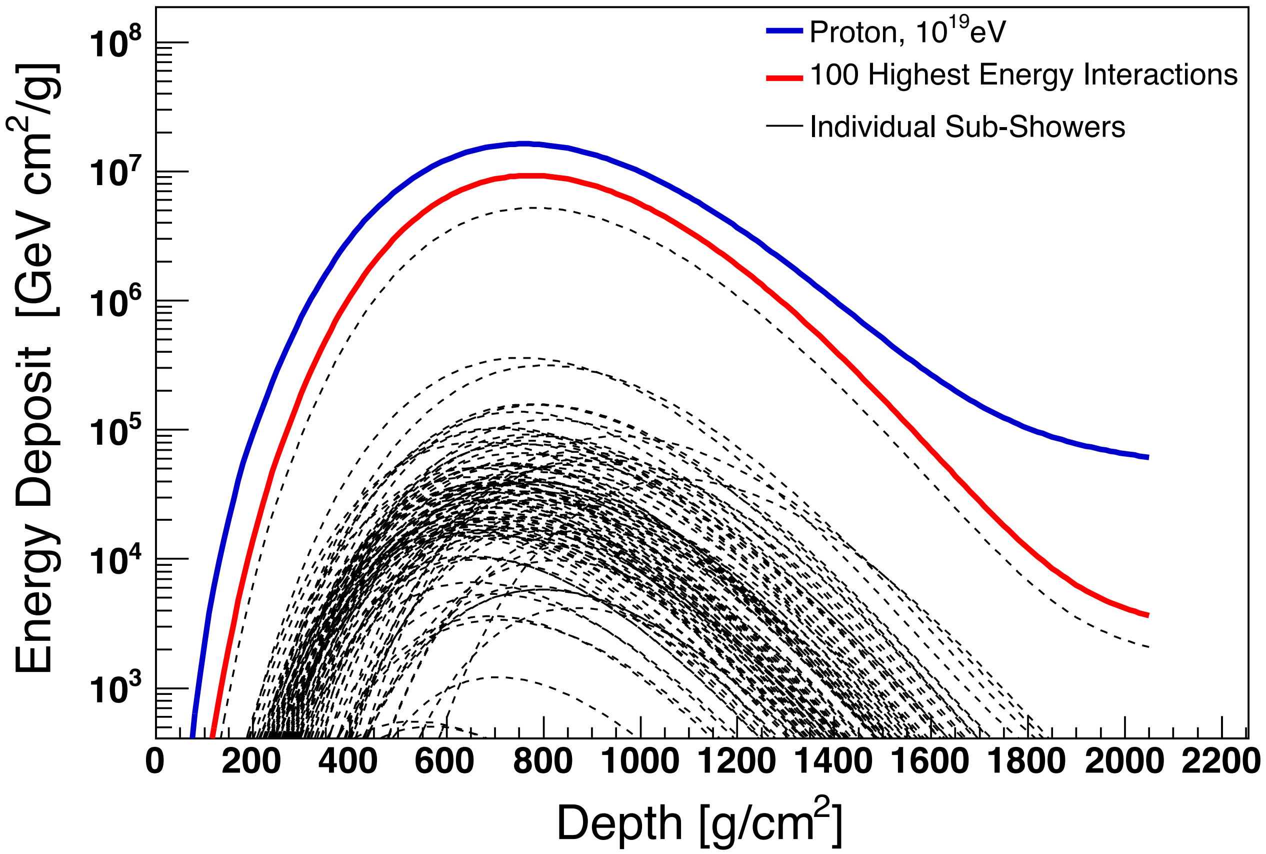
Relation of r_G to dispersion of masses σ(ln A)

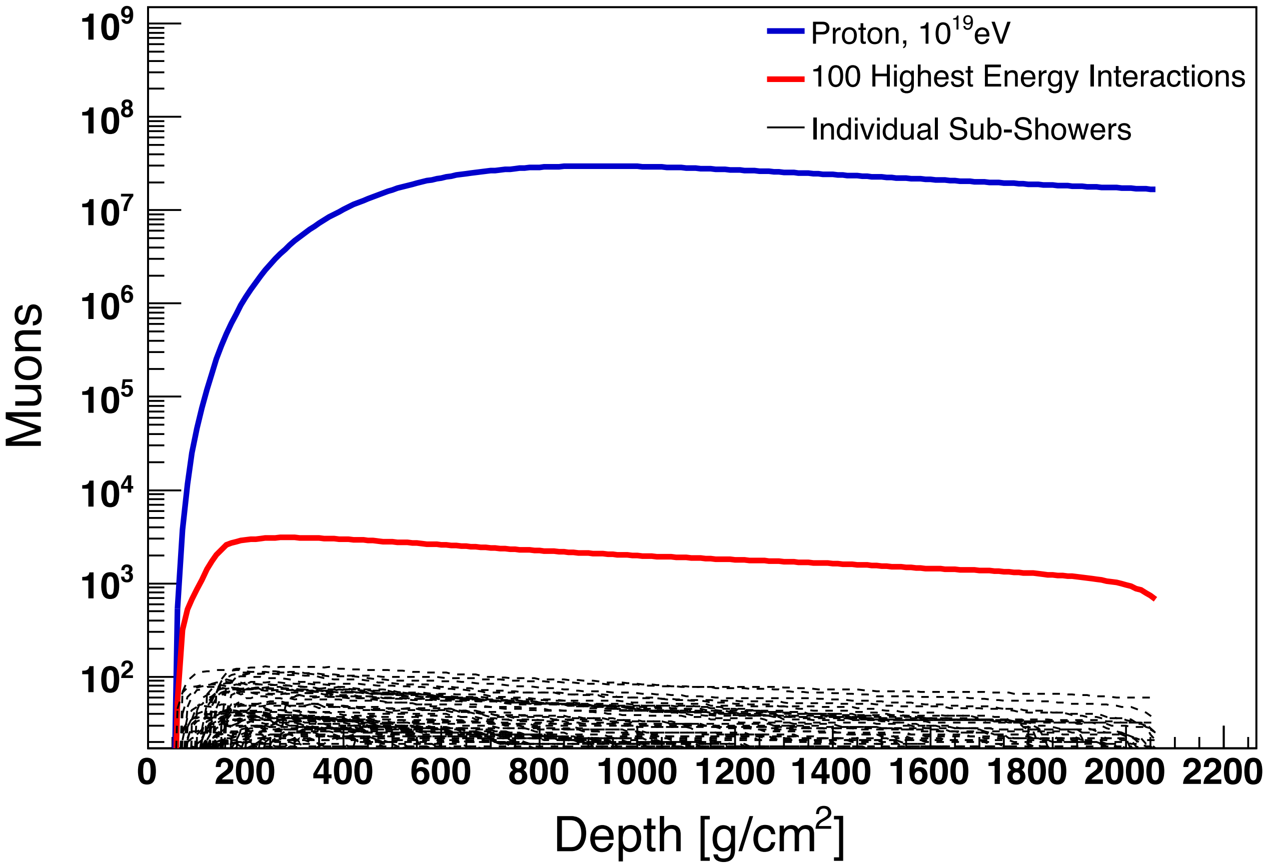


Data are compatible with dispersion of masses σ(ln A) ≳1

A. Yushkov for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Muons in air showers



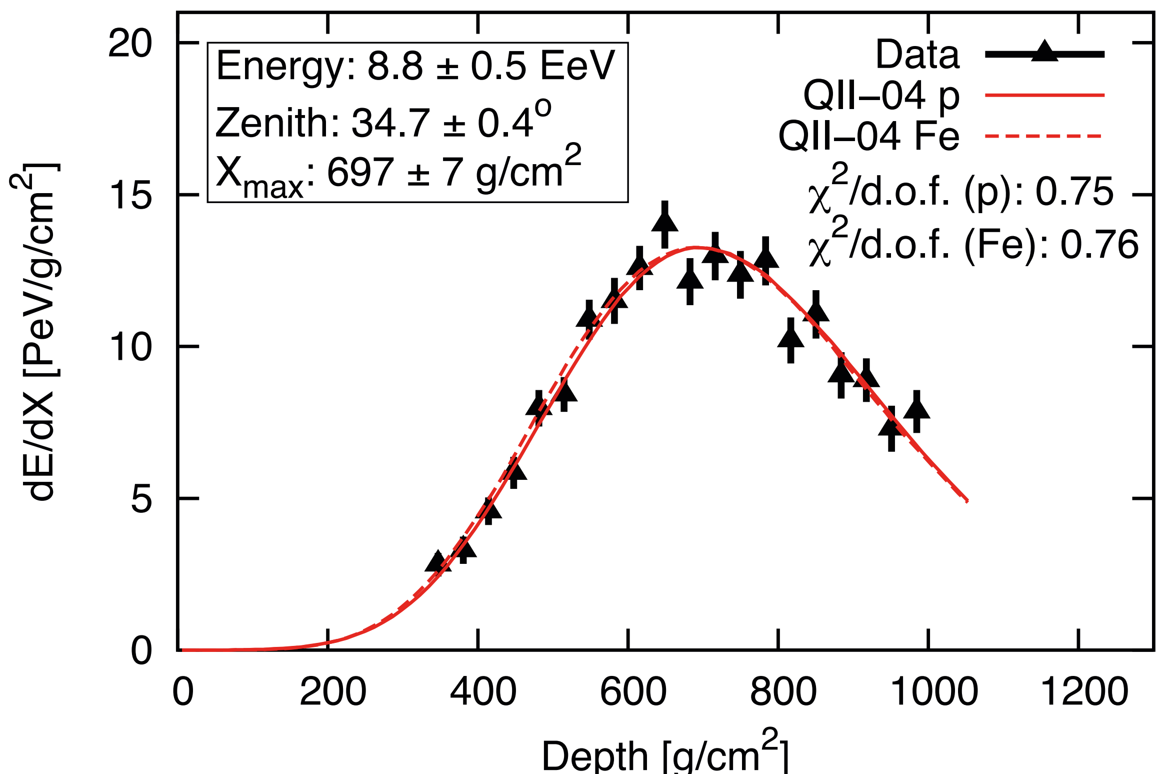


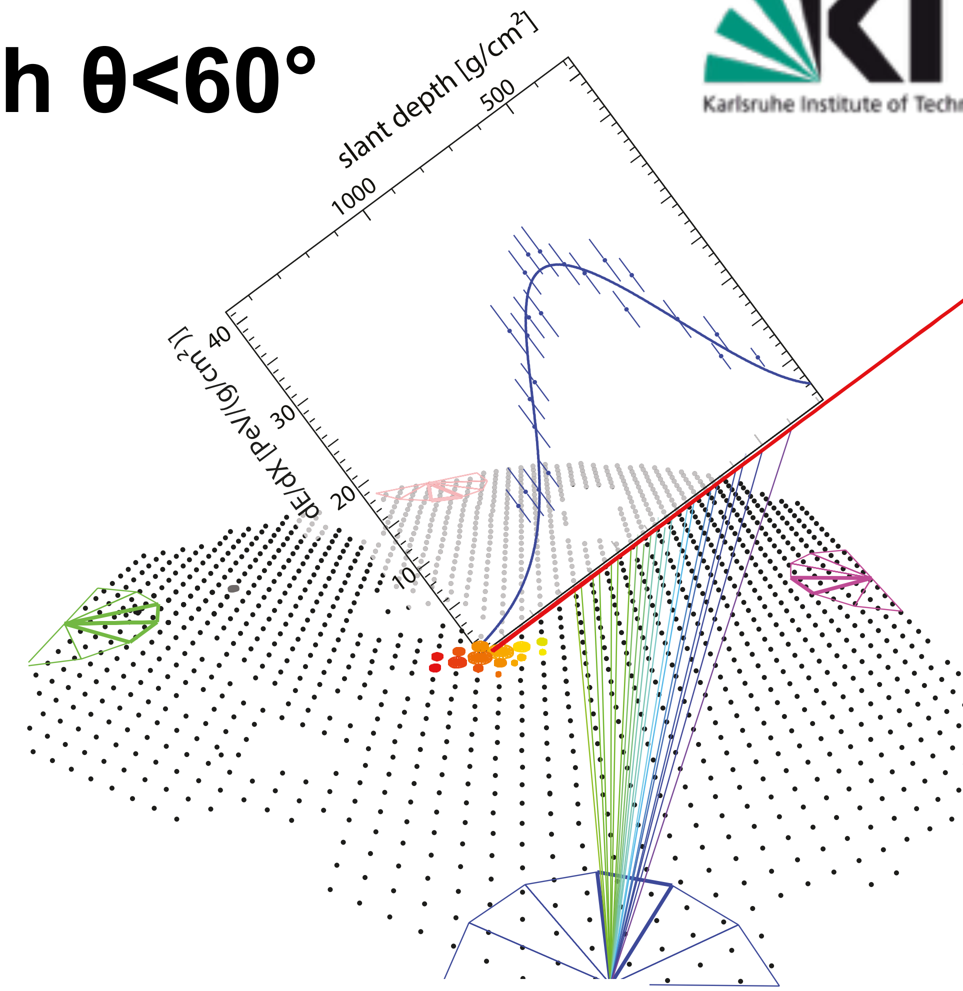
R. Ulrich, APS 2010

X_{max} is dominated by first interaction

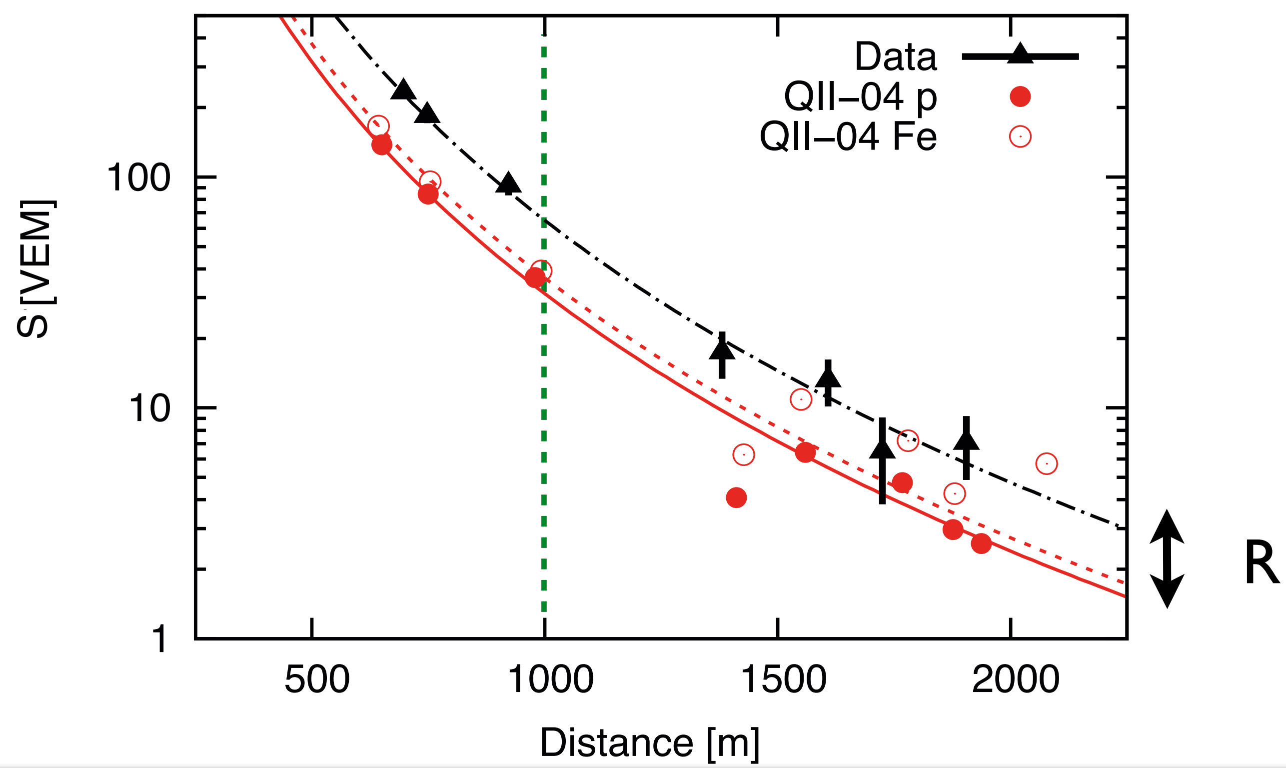
muons are produced late in the shower cascade
→ number of generations ~ 6 at 10^{19} eV
→ amplified sensitivity to hadronic interactions

Muon number in hybrid events with θ<60°

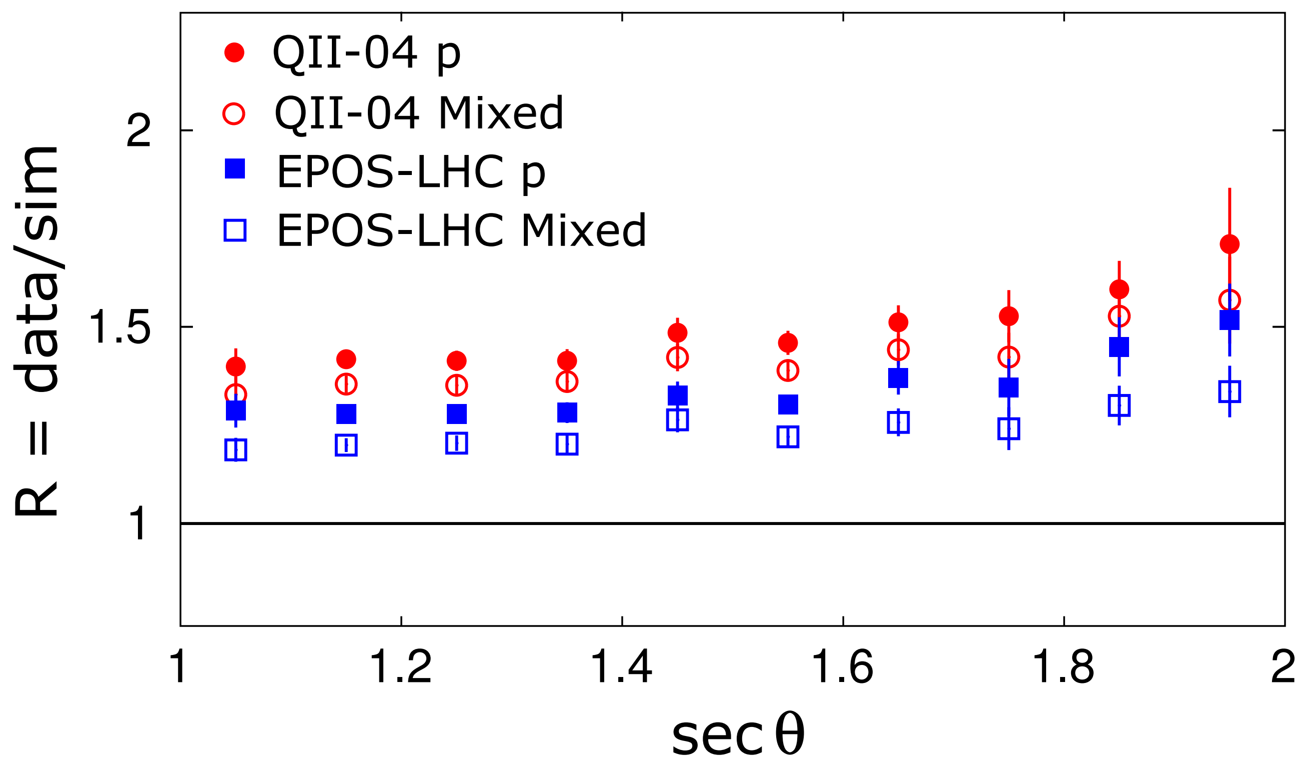


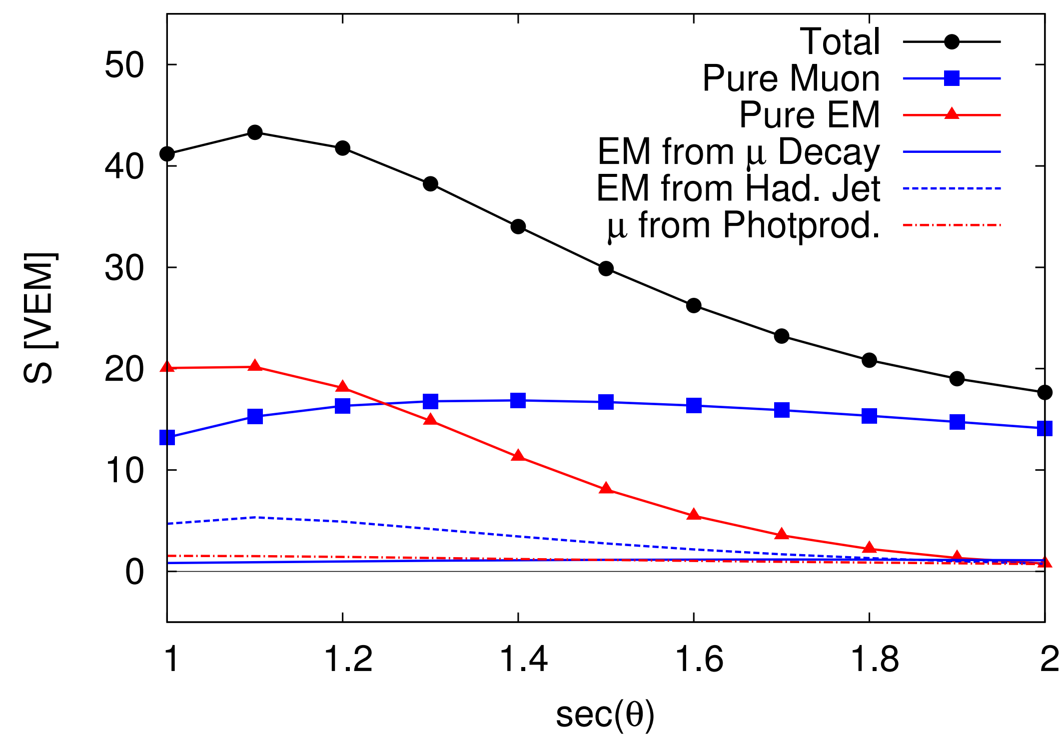


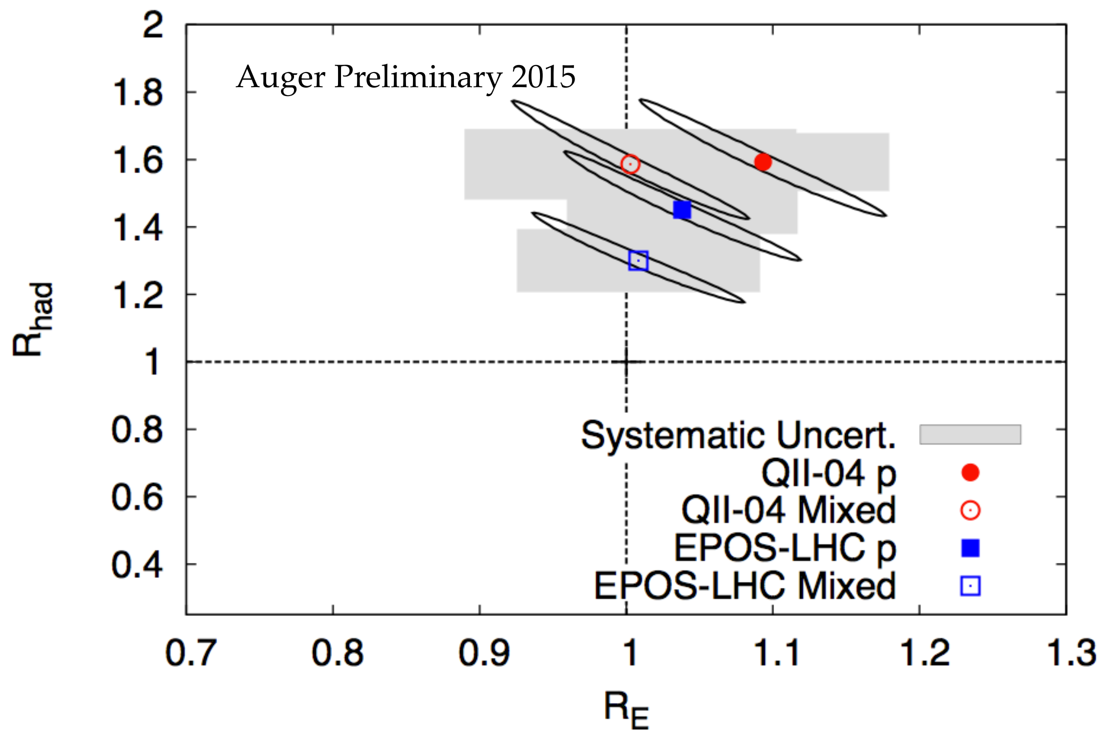
- E = $10^{18.8}$ - $10^{19.2}$ eV
- Zenith angles [0°, 60°]
- 411 hybrid events after quality cuts



Muon number in hybrid events with θ<60°







ML fit adjusting EM and muonic contribution to S1000

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

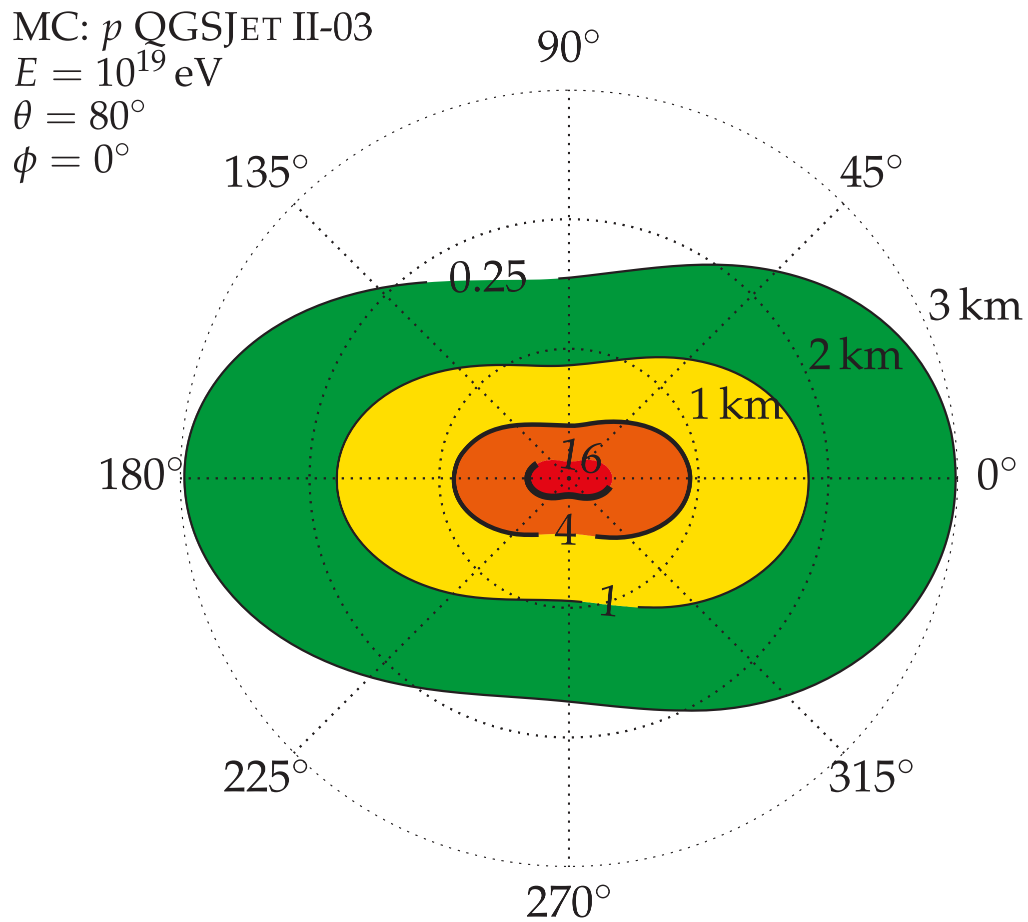
$$\alpha \simeq 0.9$$

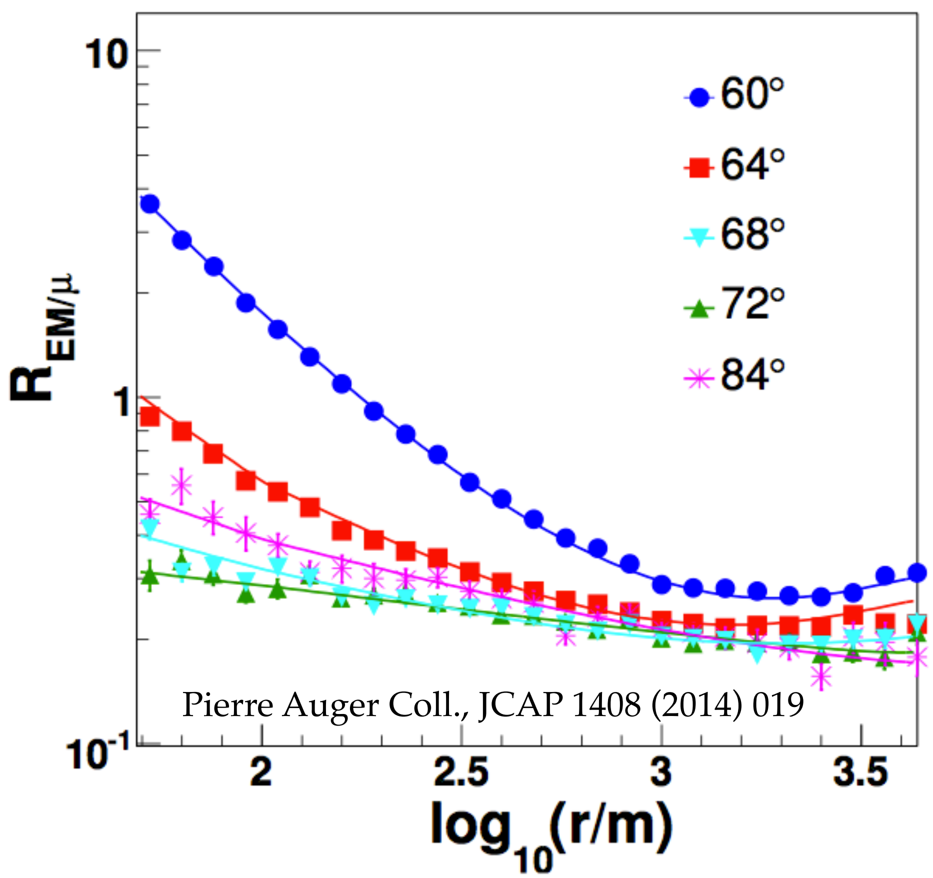
Systematic uncertainties on R_E and R_{had}: 10 %

Muons in highly inclined events

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

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

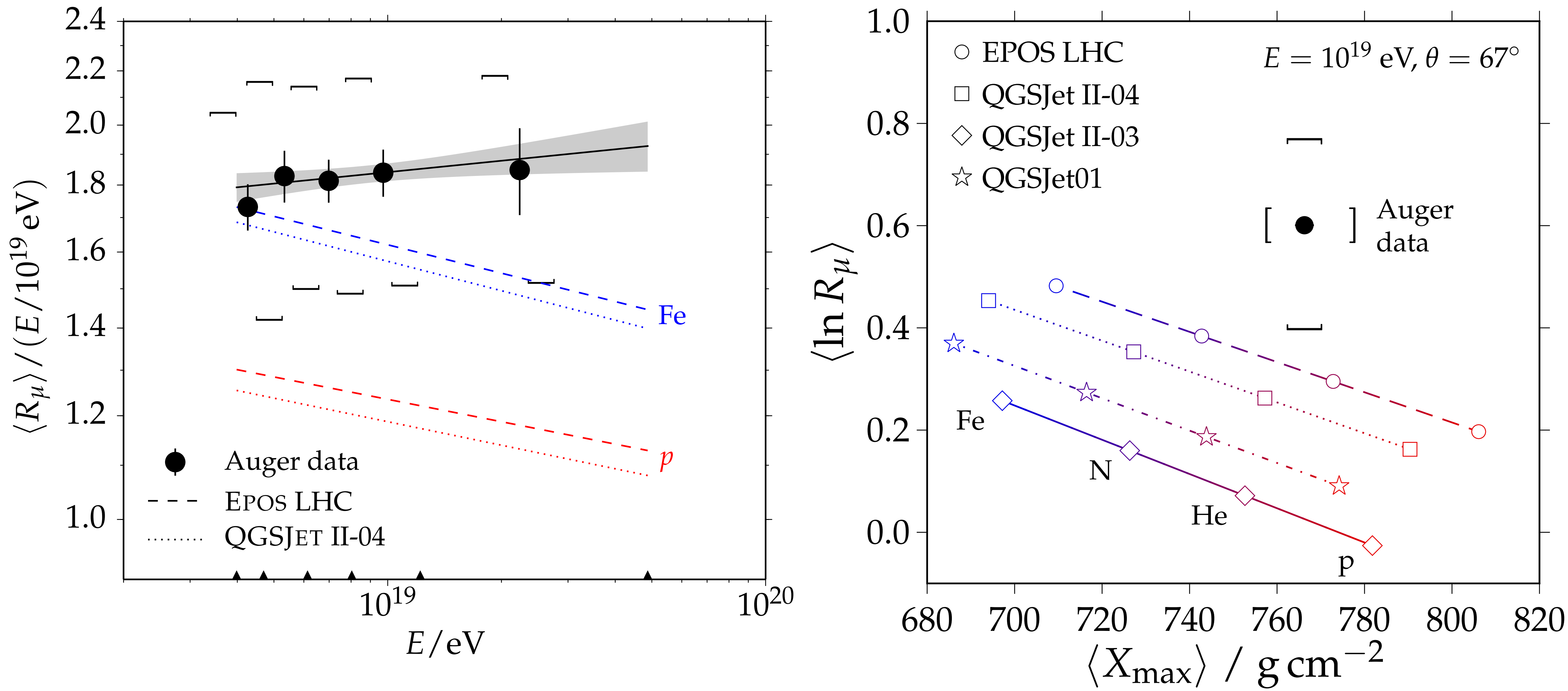




- E > 4 x 10^{18} eV
- Zenith angles [60°, 80°]
- 174 hybrid events after quality cuts
- Systematic uncertainty on R_μ: 11%

Karlsruher Institut für Technologie (KIT)
Institut für Kernphysik, Karlsruhe, Germany

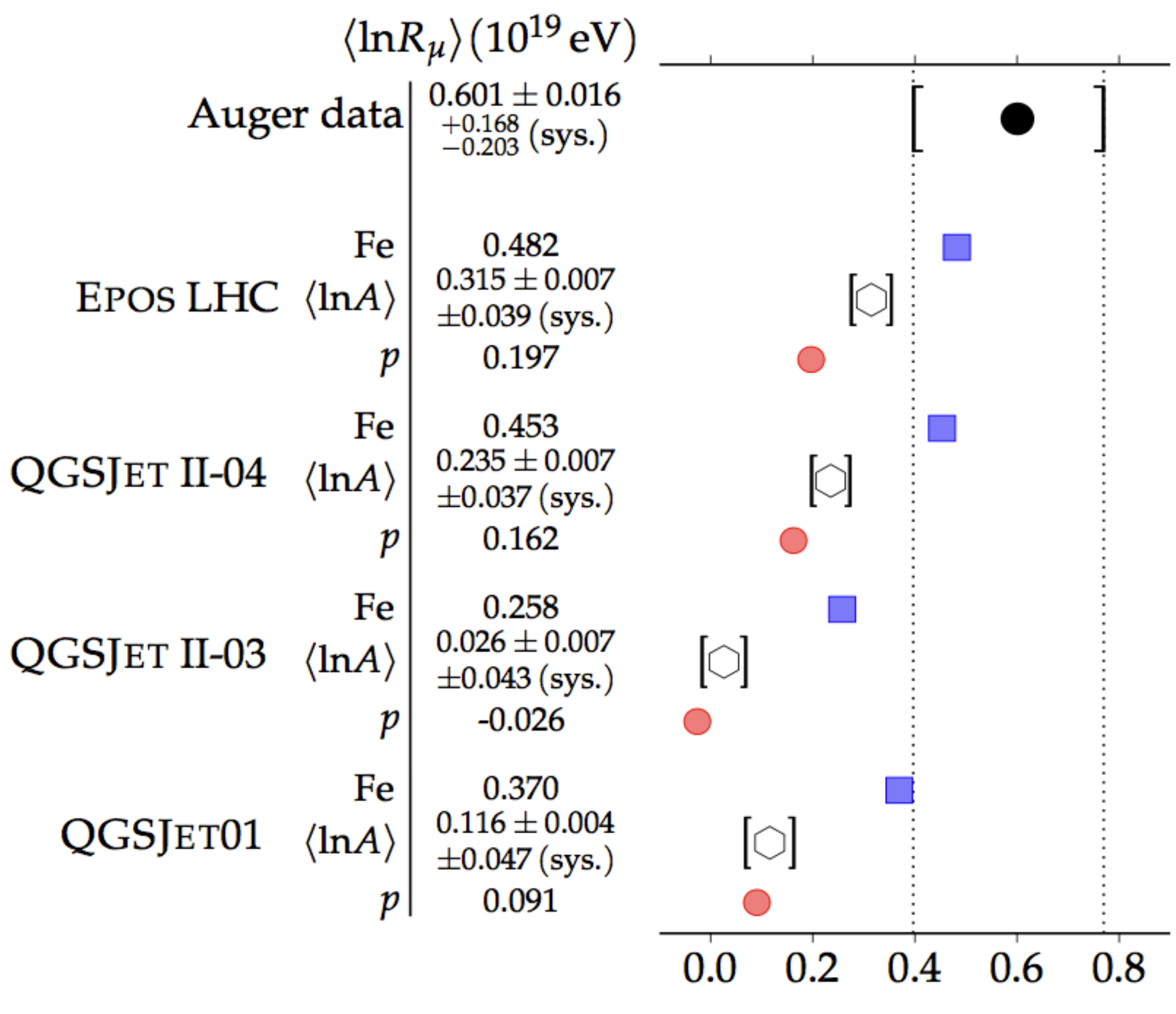
Data at variance with simulations

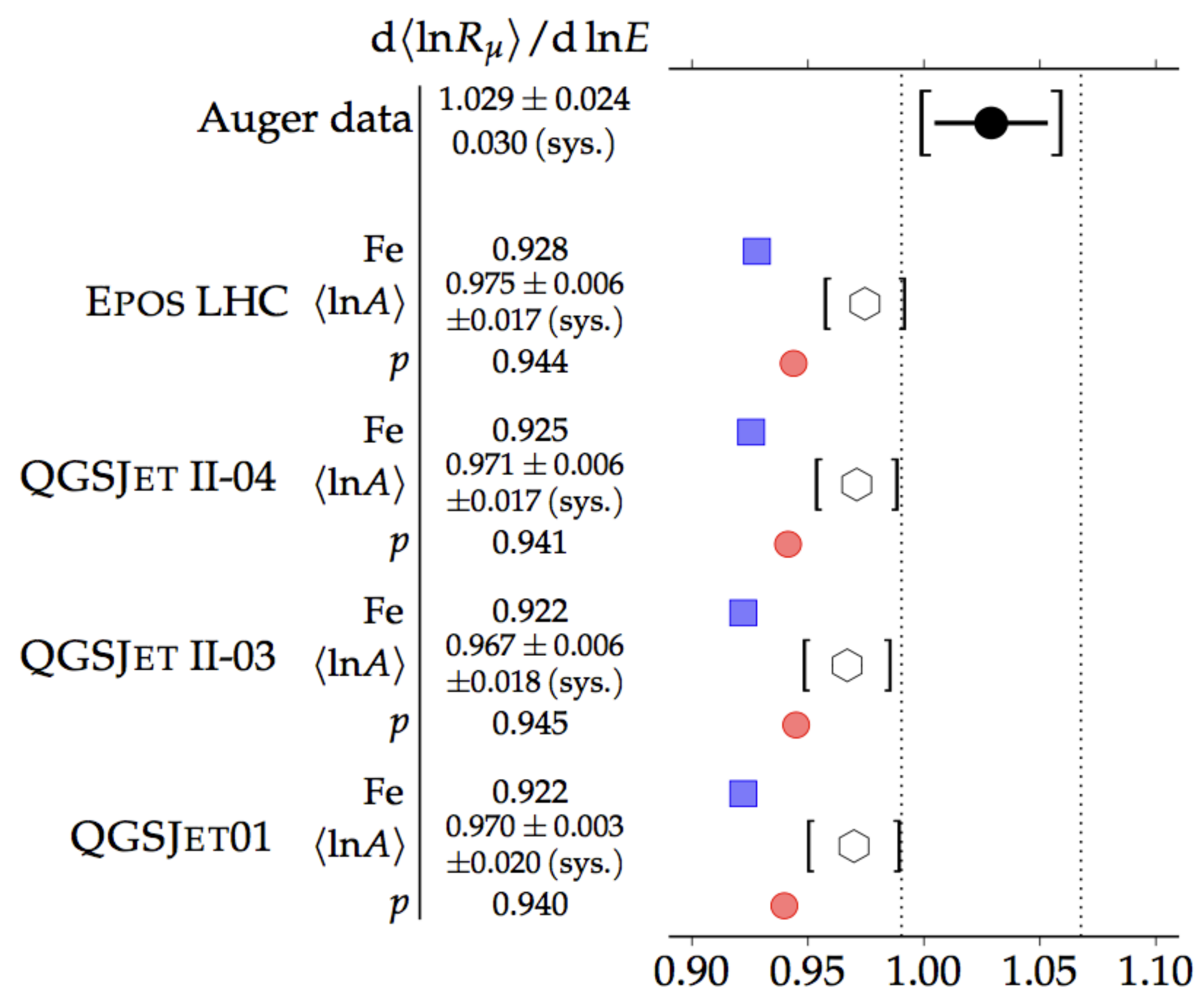


- $\langle R_\mu \rangle$ higher than MC iron predictions
- Tension between the X_{max} and muon measurements
- Older versions of QGSJet model are at odds with data taking into account the large systematic uncertainty

Pierre Auger Collaboration, PRD91 (2015) 3, 032003

The average muon content and the muon gain with energy

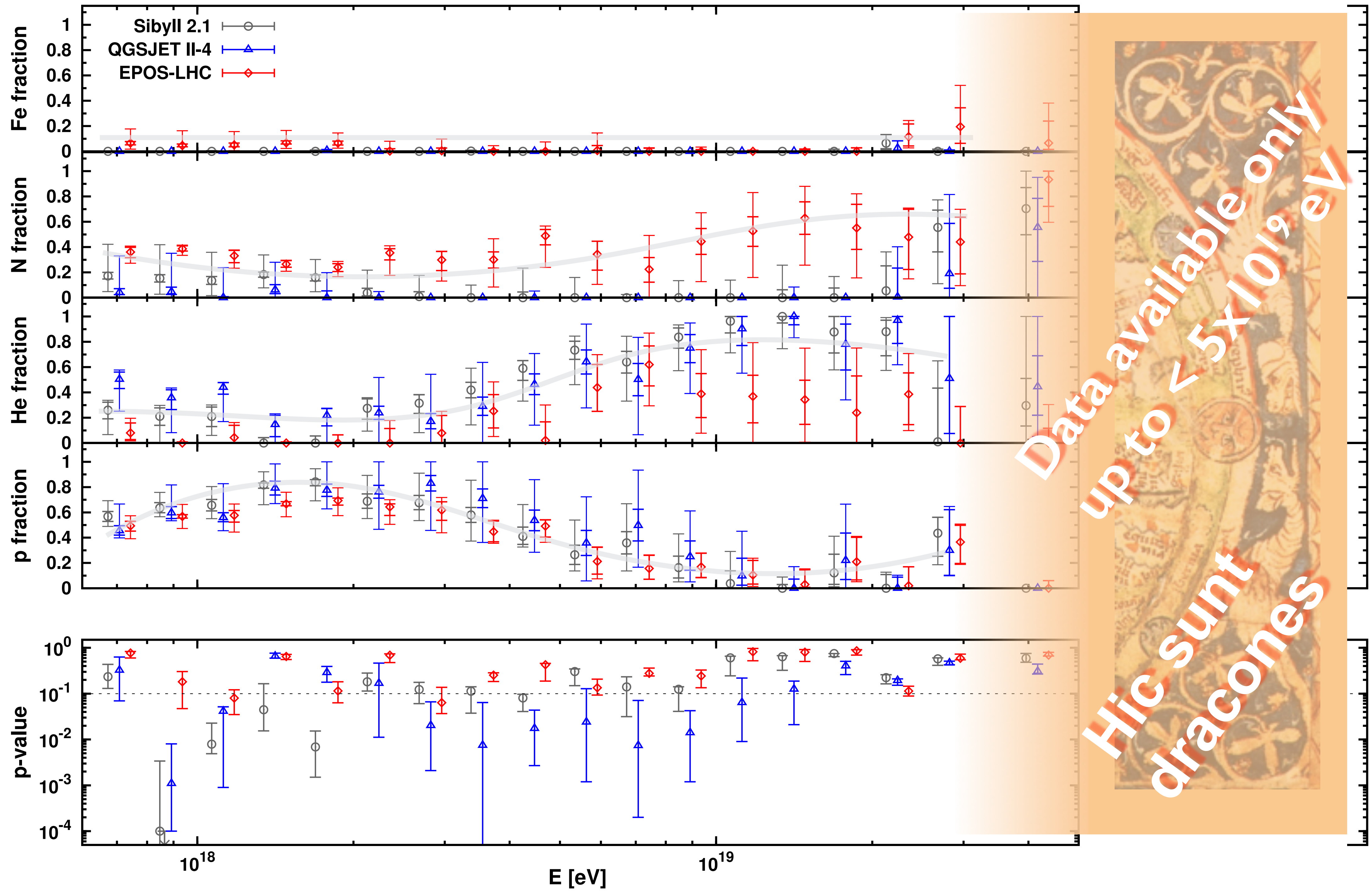




Muon deficit from 30% to 80% at 10^{19} eV depending on the model:
Best case for EPOS-LHC
(minimum deviation of 1.4 σ)

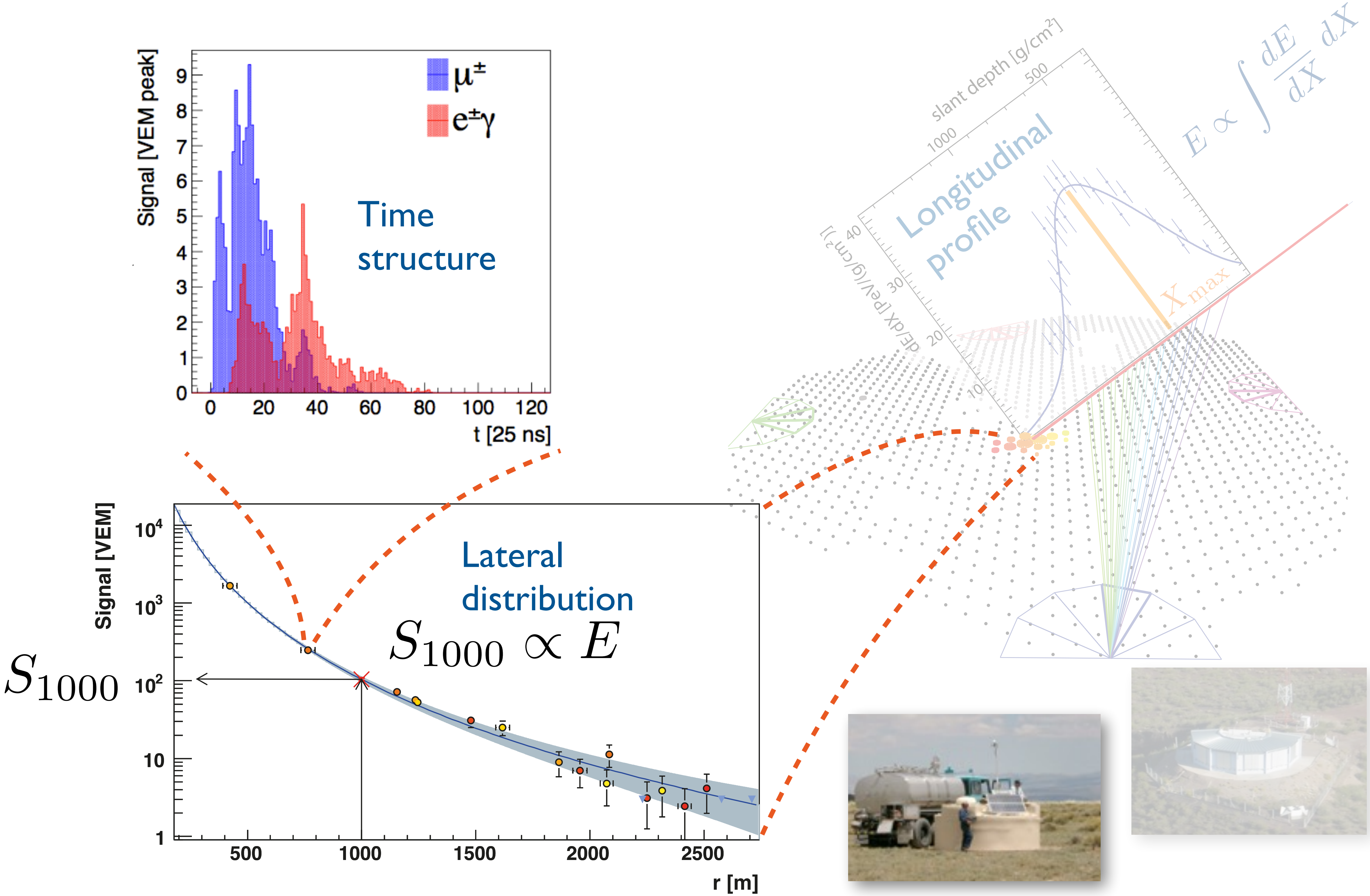
Deviations from a constant proton (iron) composition observed at the level of 2.2 (2.6) σ

Composition Fit (X_{max} distribution)



Pierre Auger Collaboration, PRD 90 (2014) 12, 122006

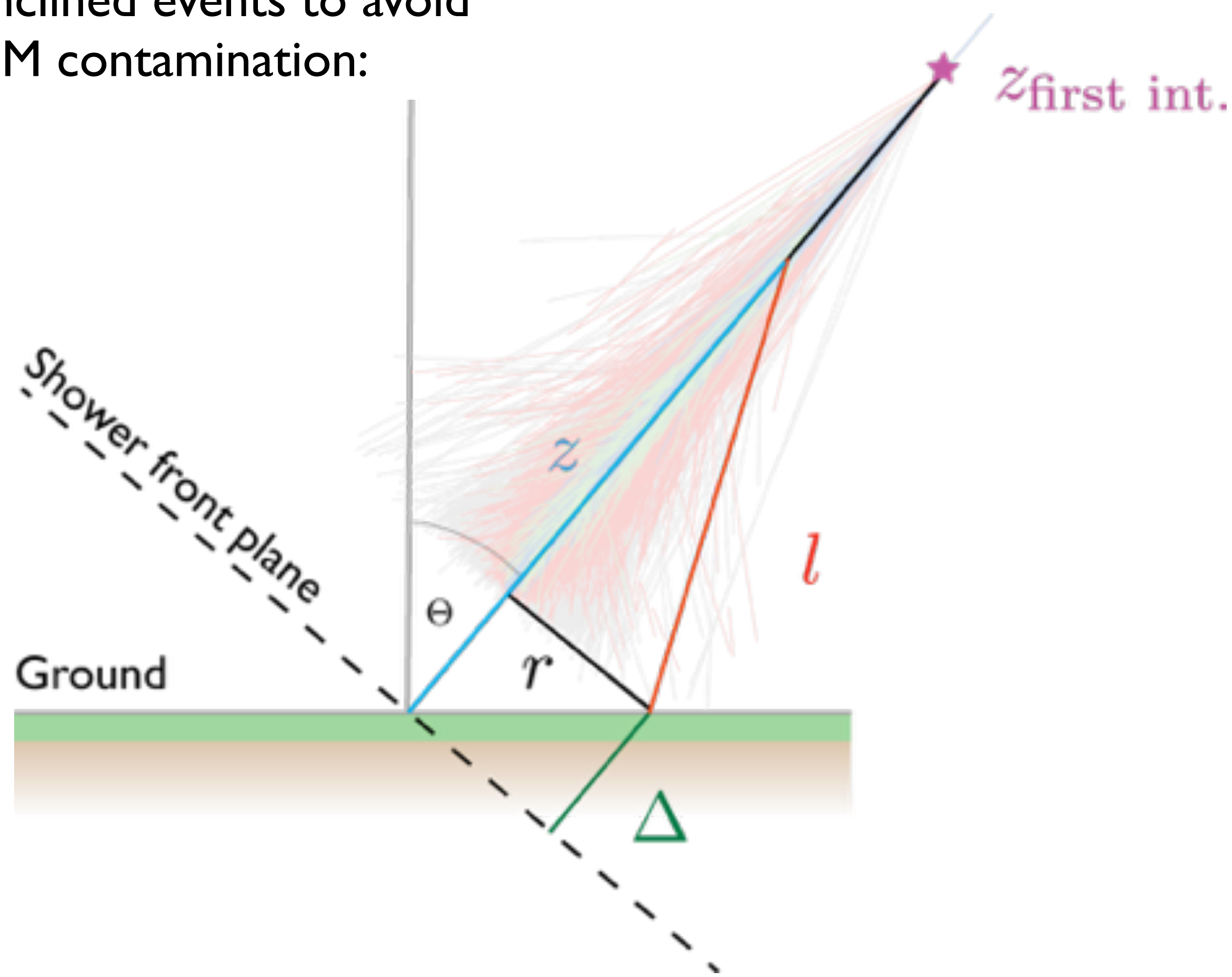
Surface detector data recorded with Auger

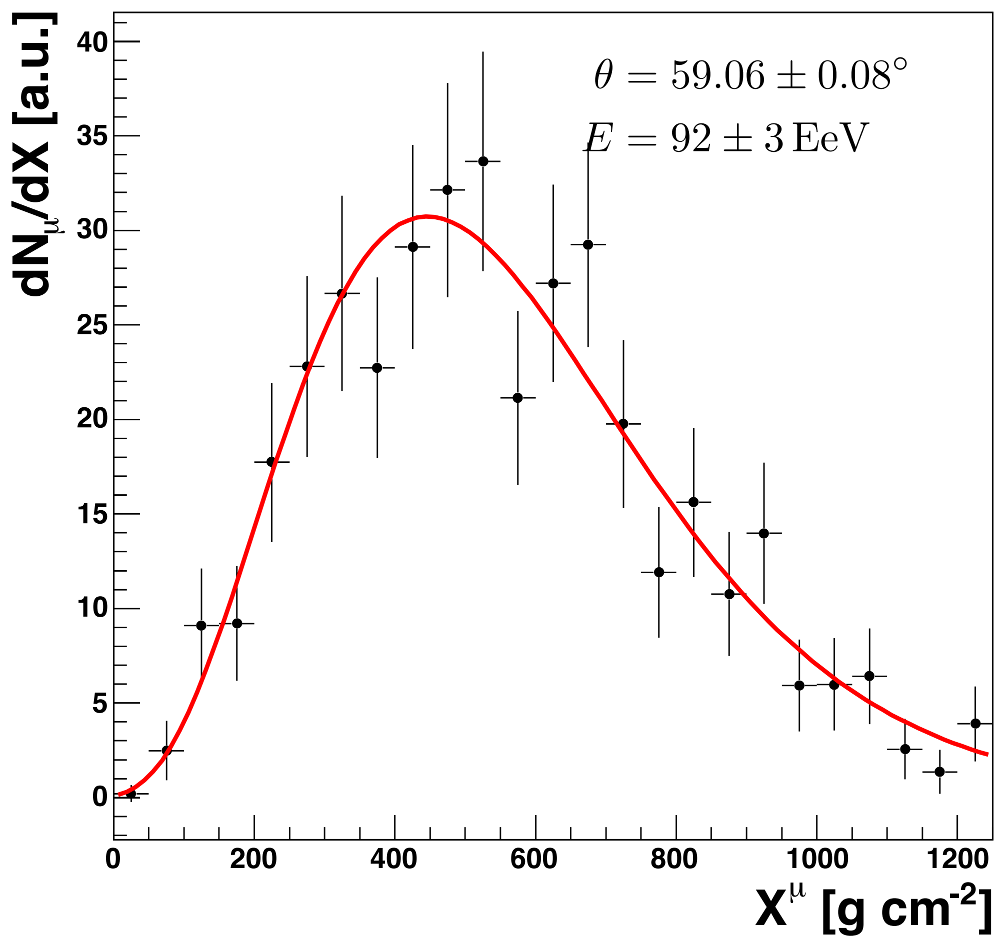


Karlsruher Institut für Technologie (KIT)
Institut für Kernphysik, Karlsruhe, Germany

Muon Production Depth distribution (MPD) in a nutshell

Inclined events to avoid EM contamination:





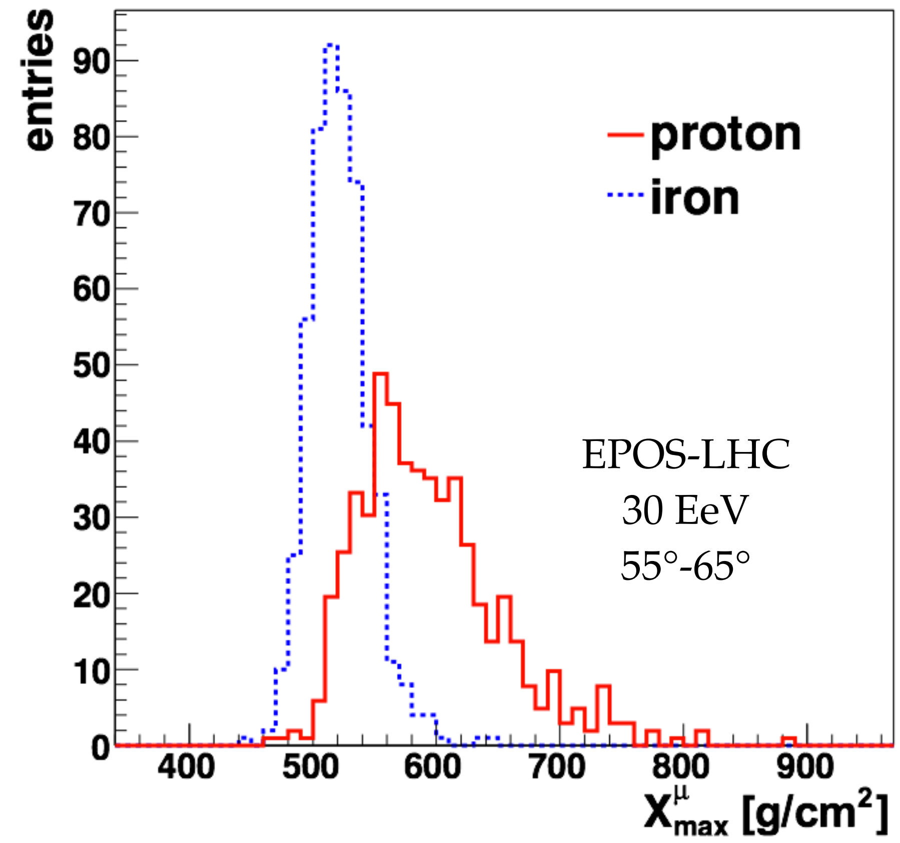
Geometric delay of arriving muons:

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

Mapped to muon production depth:

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

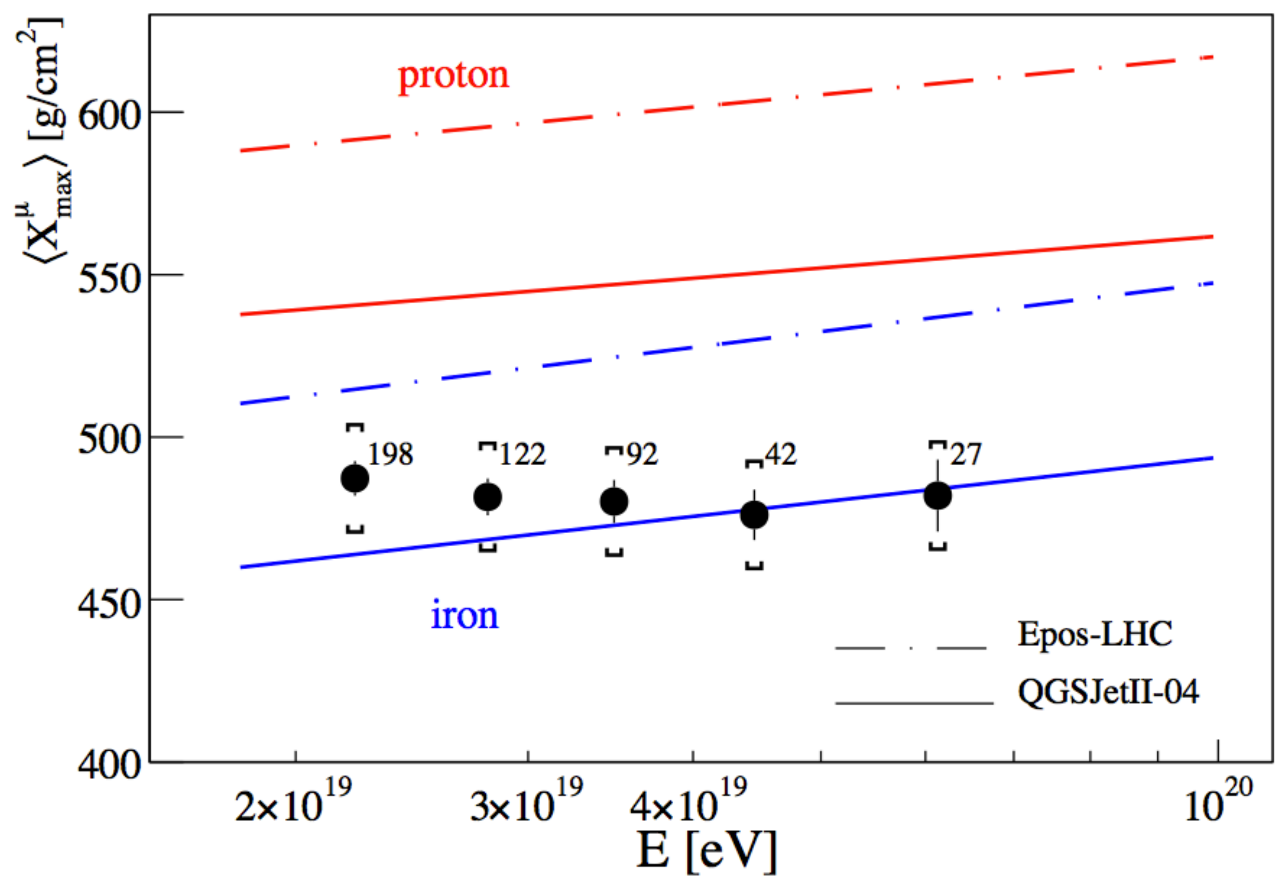
Muon Production Depth



- E > $10^{19.3}$ eV (enough muons/event)
- Zenith angles [55°,65°] (low EM contamination)
- Distances from the core [1700 m, 4000 m]
- 481 events after quality cuts
- Systematic uncertainties: 17 g/cm²

Resolution:

- 100 (80) g/cm² at $10^{19.3}$ eV for p (Fe)
- 50 g/cm² at 10^{20} eV

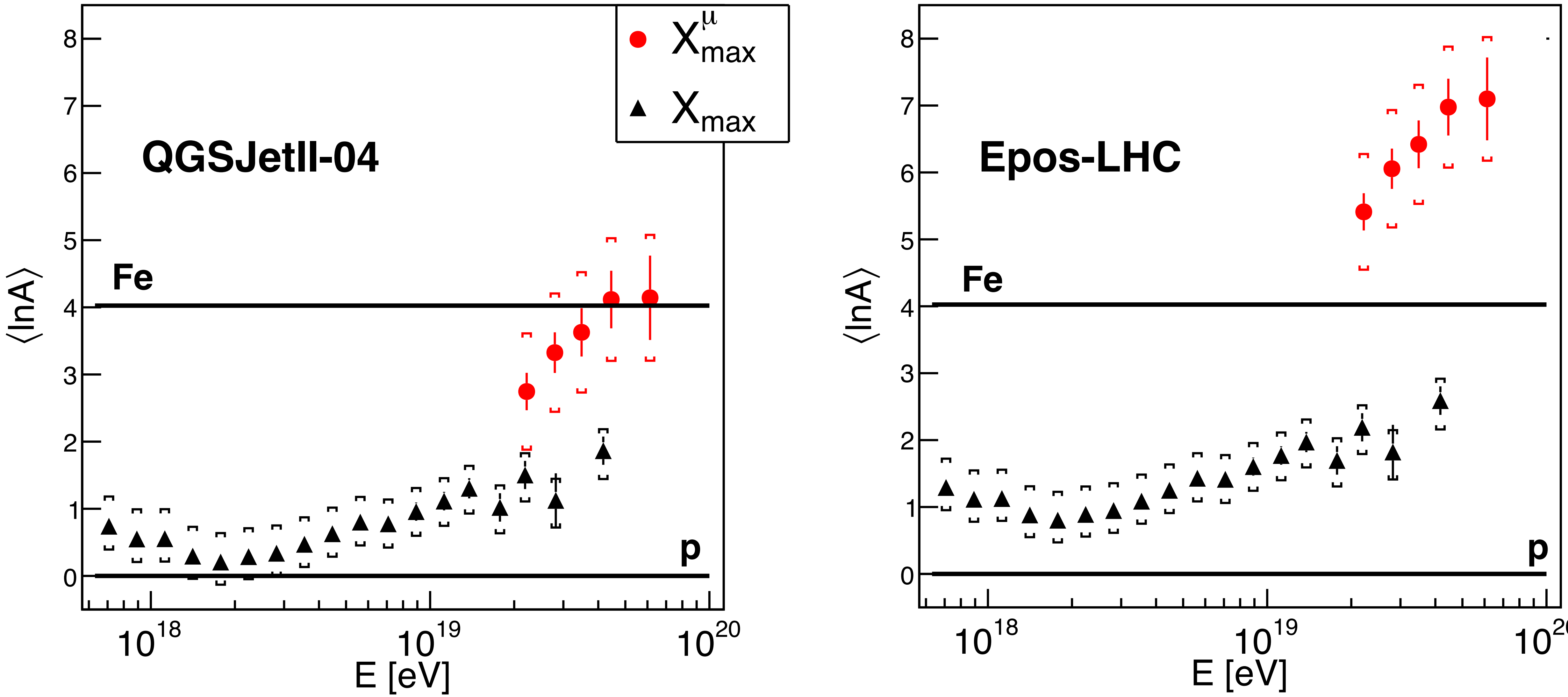


QGSJetII-04: data bracketed by predictions
EPOS-LHC: predictions above data

Karlsruher Institut für Technologie (KIT)
Institut für Kernphysik, Karlsruhe, Germany

Comparison of ⟨ln A⟩ from X_{max} and X^{μ}_{max}

lnA (FD) from *Phys. Rev.* D 90 (2014) 12



QGSJetII-04: Compatible values within 1.5 σ
EPOS-LHC: Incompatibility at a level of at least 6 σ

Karlsruher Institut für Technologie (KIT)
Institut für Kernphysik, Karlsruhe, Germany

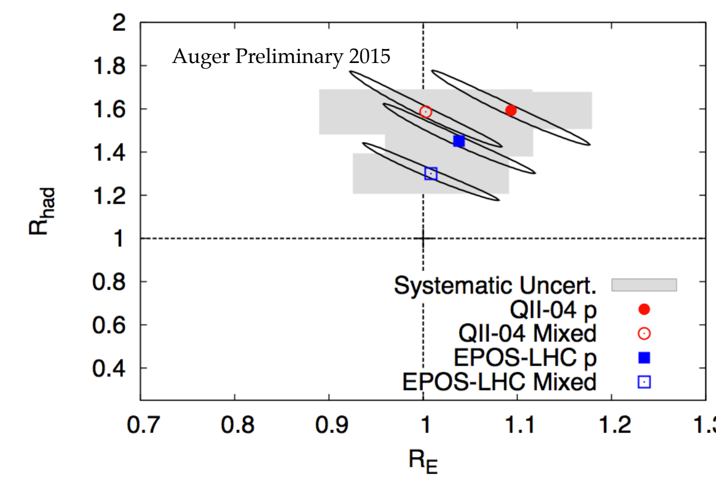
Summary

- ⟨X_{max}⟩, σ(X_{max}), r_G(X_{max}/S(1000))
  ➙ Mixed composition around and above the ankle
  (if LHC-inspired extrapolations are ok)

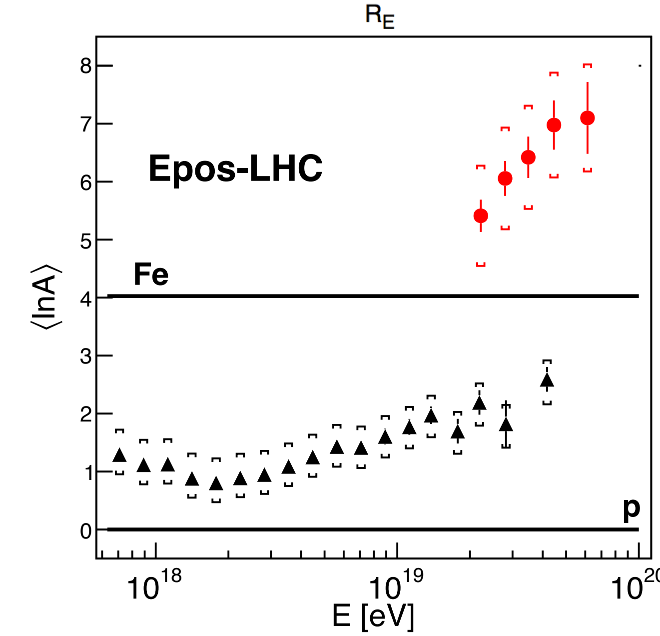
- Muon number
  ➙ At odds with predictions for mixed composition
  ➙ Muon deficit in simulations

- Muon production depth vs. X_{max}
  ➙ QGSjetII-04: marginally compatible
  ➙ EPOS-LHC: incompatible

Auger is going to extend the composition measurements up to highest energies
measuring e±/γ & muons with 2 arrays:
AugerPrime
(szintillators accompanying WCDs; see Tiina's talk)

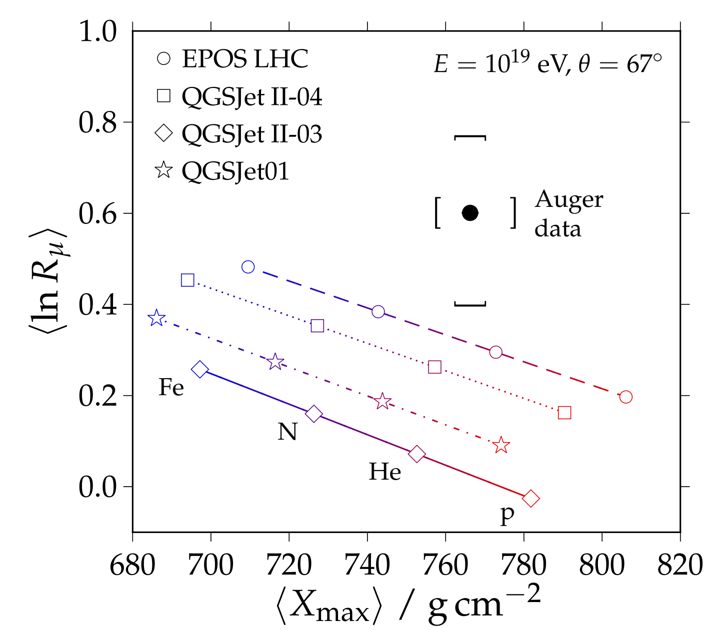


R_E, R_{had}



X^{μ}_{max}

X_{max}



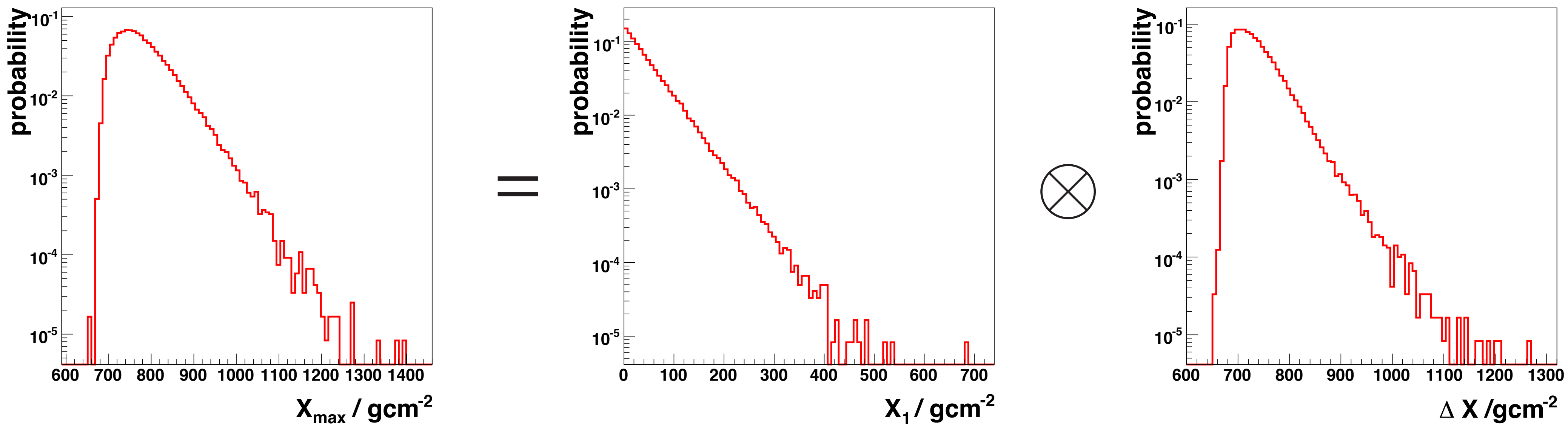
R_μ

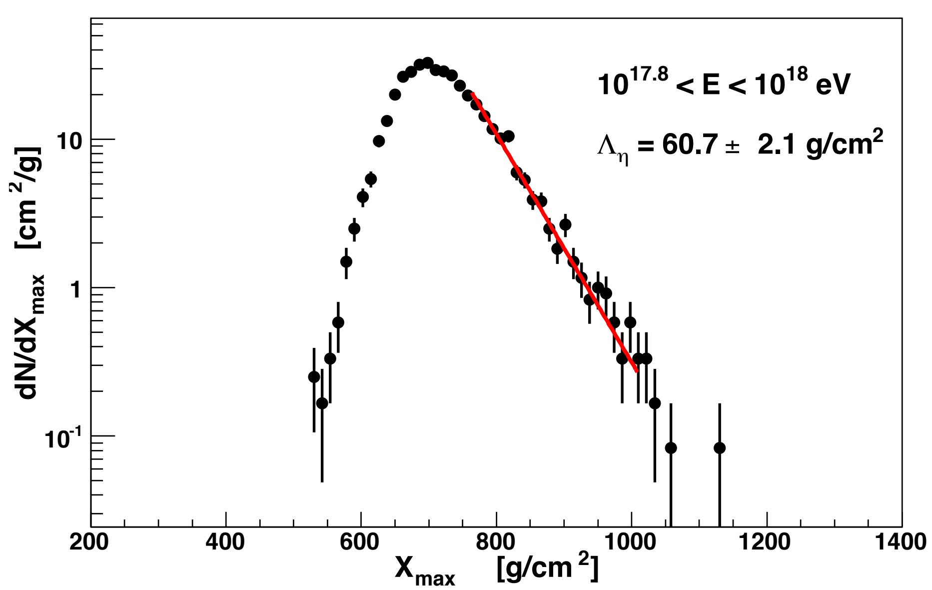
Karlsruher Institut für Technologie (KIT)
Institut für Kernphysik, Karlsruhe, Germany

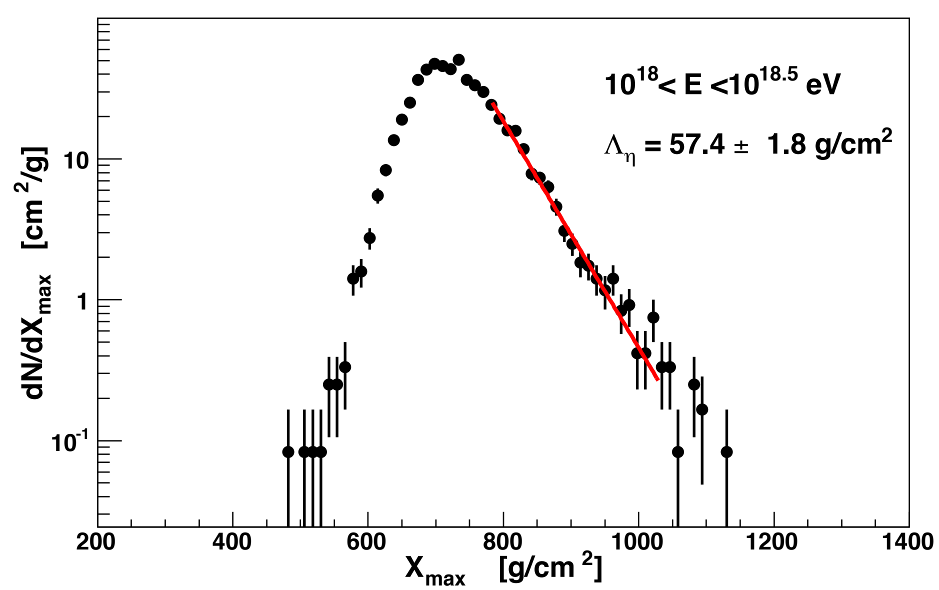
END

Measurement of the UHE Proton+Air Cross section

tail of X_{max} distribution:



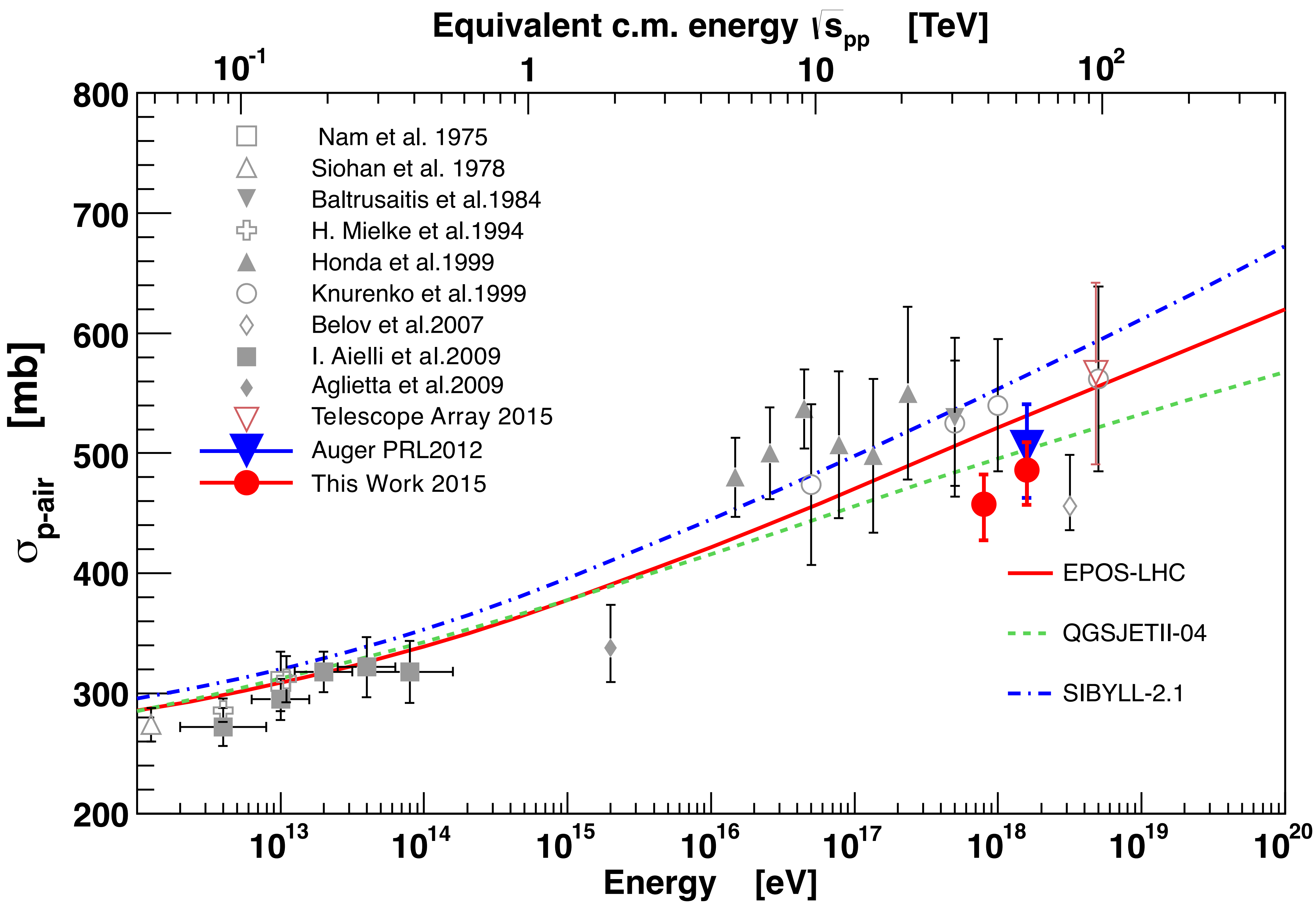




$\langle E \rangle = 10^{17.90}$ eV

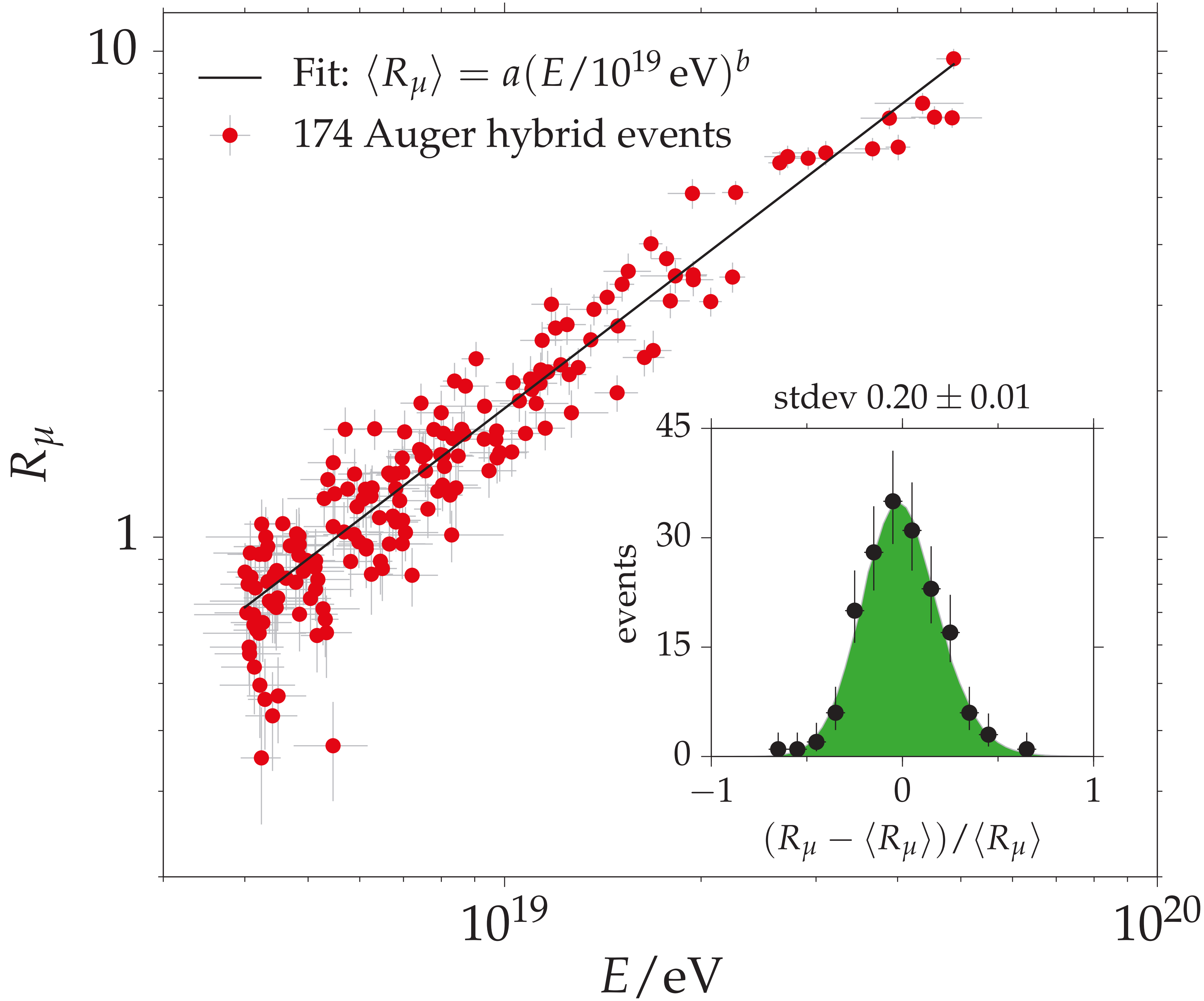
$\langle E \rangle = 10^{18.22}$ eV

Measurement of the UHE Proton+Air Cross section



R. Ulrich for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Karlsruher Institut für Technologie (KIT)
Institut für Kernphysik, Karlsruhe, Germany



Fit: $\langle R_\mu \rangle = a(E/10^{19}\,\mathrm{eV})^b$
174 Auger hybrid events
R_μ
10
1
10^{19}
10^{20}
E/eV
stdev 0.20 ± 0.01
events
45
30
15
0
−1
0
1
$(R_\mu - \langle R_\mu \rangle)/\langle R_\mu \rangle$