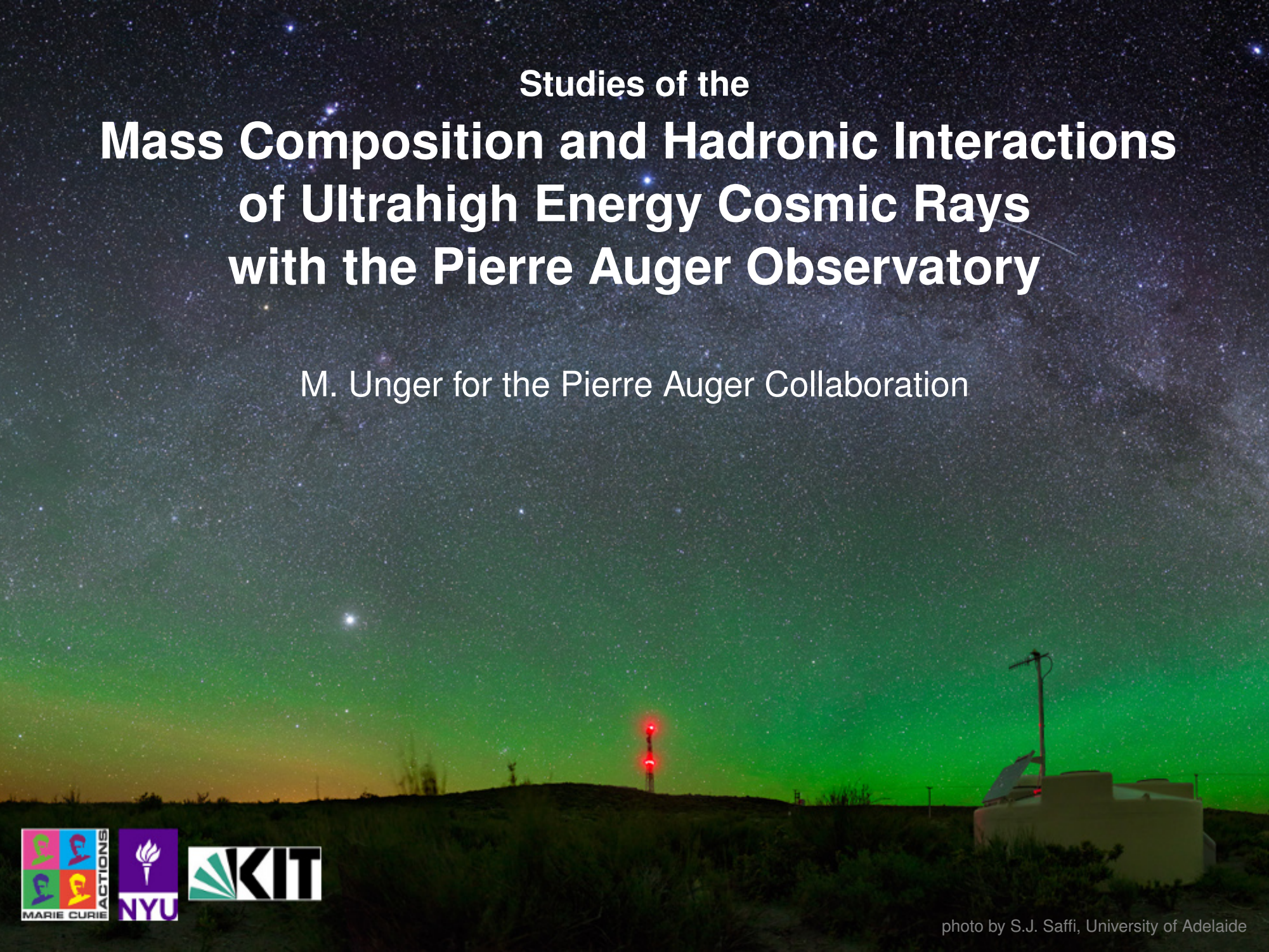


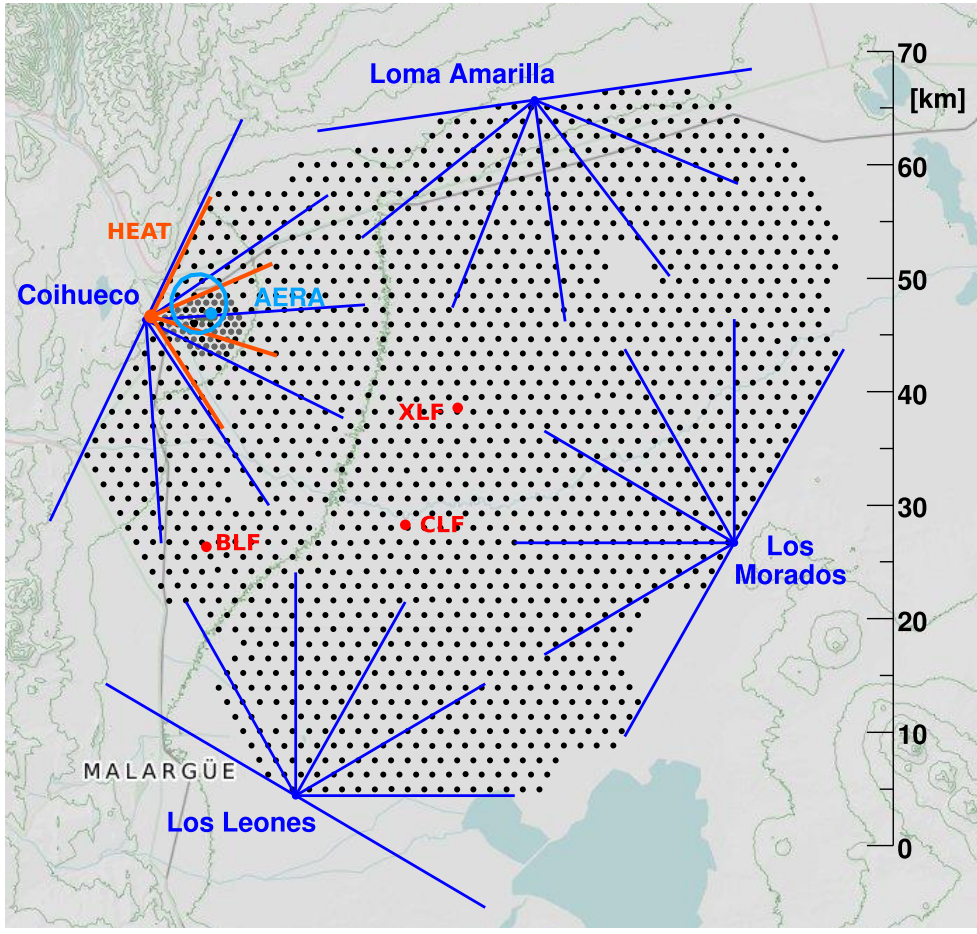
Studies of the

Mass Composition and Hadronic Interactions of Ultrahigh Energy Cosmic Rays with the Pierre Auger Observatory

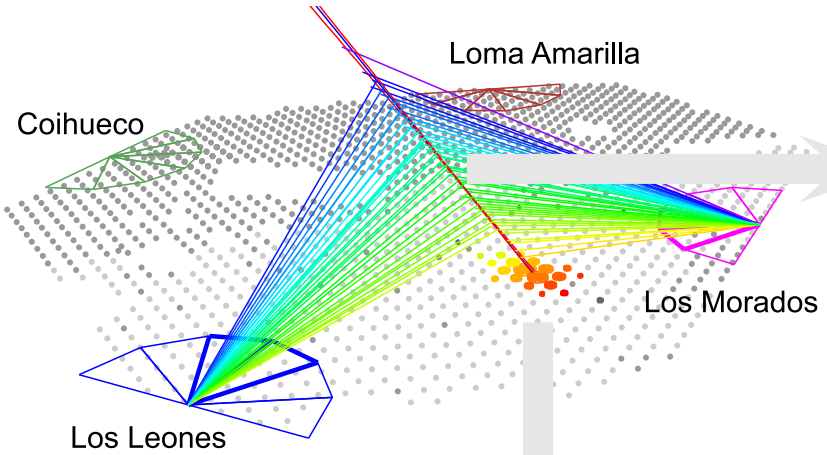
M. Unger for the Pierre Auger Collaboration

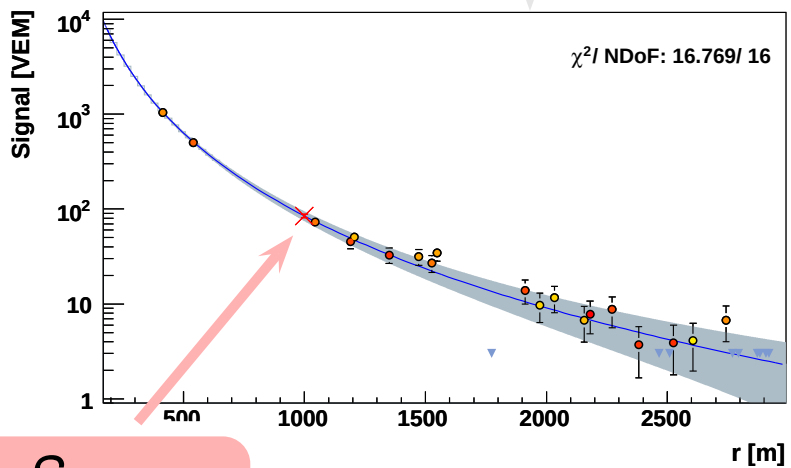
photo by S.J. Saffi, University of Adelaide

The Pierre Auger Observatory



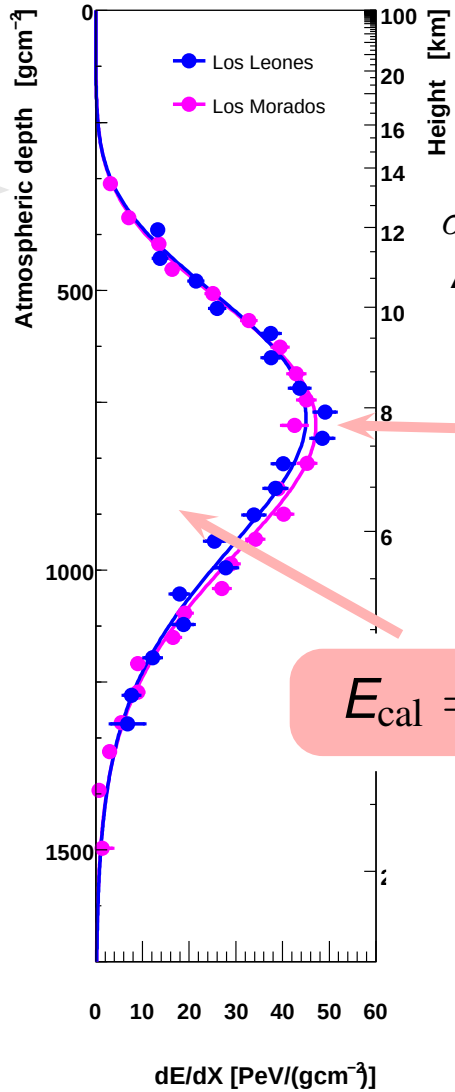
Hybrid Detection of Air Showers





S_{1000}

$E_{\text{surface}} = f(S_{1000}, \theta)$



$\sigma_{X_{\max}} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\text{sys}} \leq 10\,\mathrm{g/cm^2}$

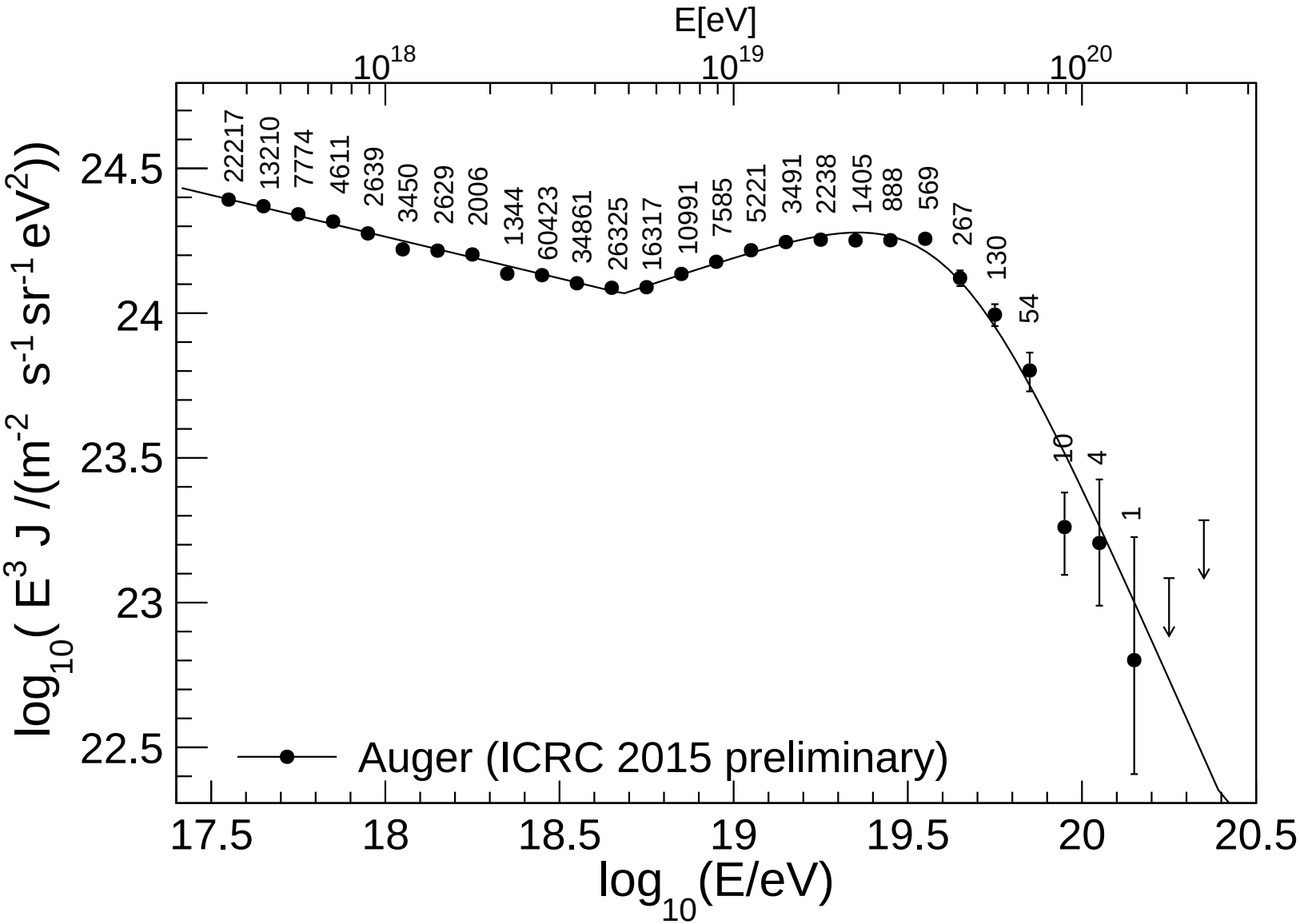
$X_{\max}$

$E_{\text{cal}} = \int \frac{dE}{dX}\, dX$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\text{sys}} \approx 15\,\%$

Auger Event Display, Event 3332245

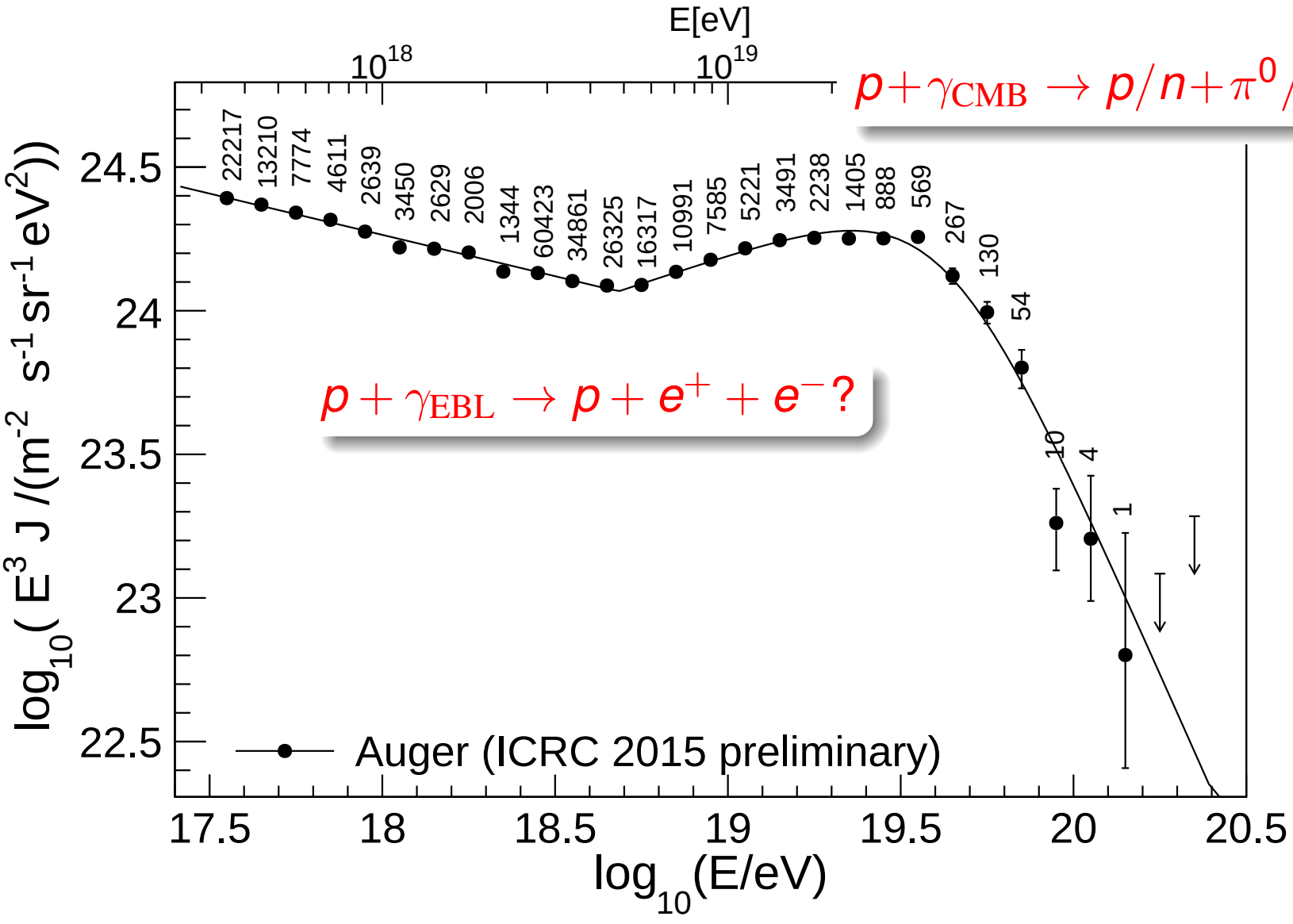
Energy Spectrum of UHECRs



exposure at UHE: $(5.34 \pm 0.13) \times 10^4$ km^2 sr yr

I. Valino for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Energy Spectrum of UHECRs



exposure at UHE: $(5.34 \pm 0.13) \times 10^4$ km^2 sr yr

(I. Valino for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732)

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  - Shower Maximum (X_{max})
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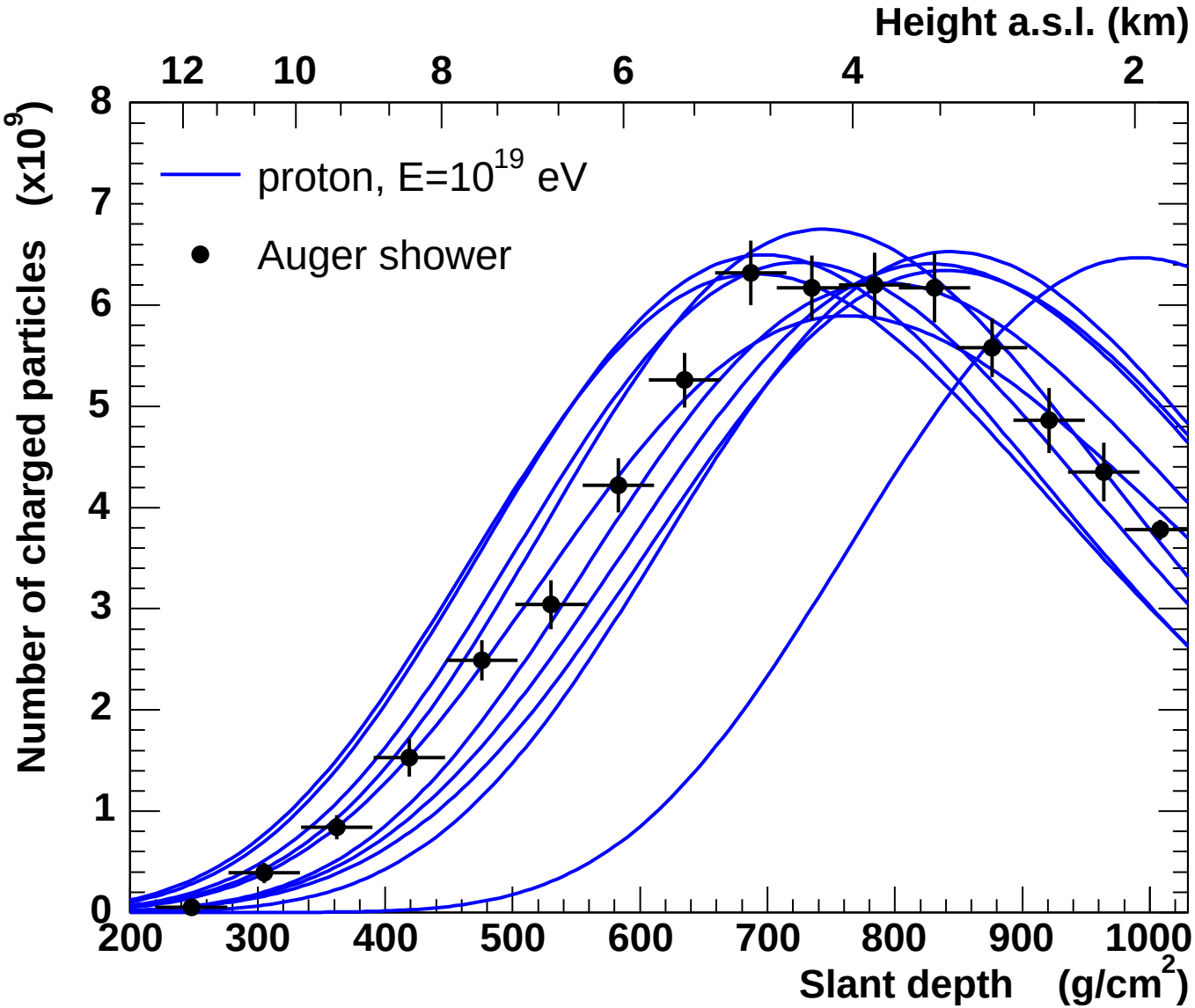
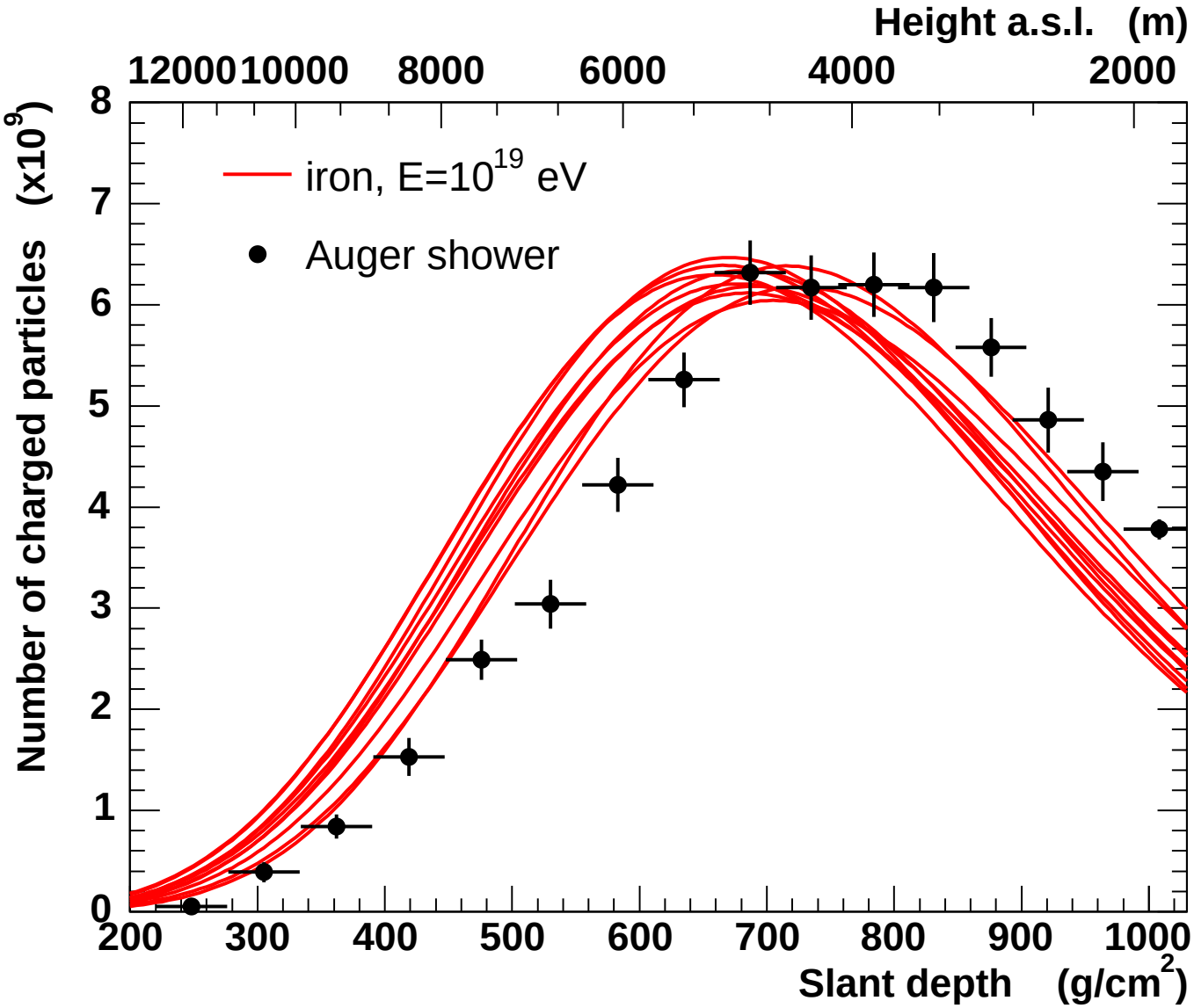
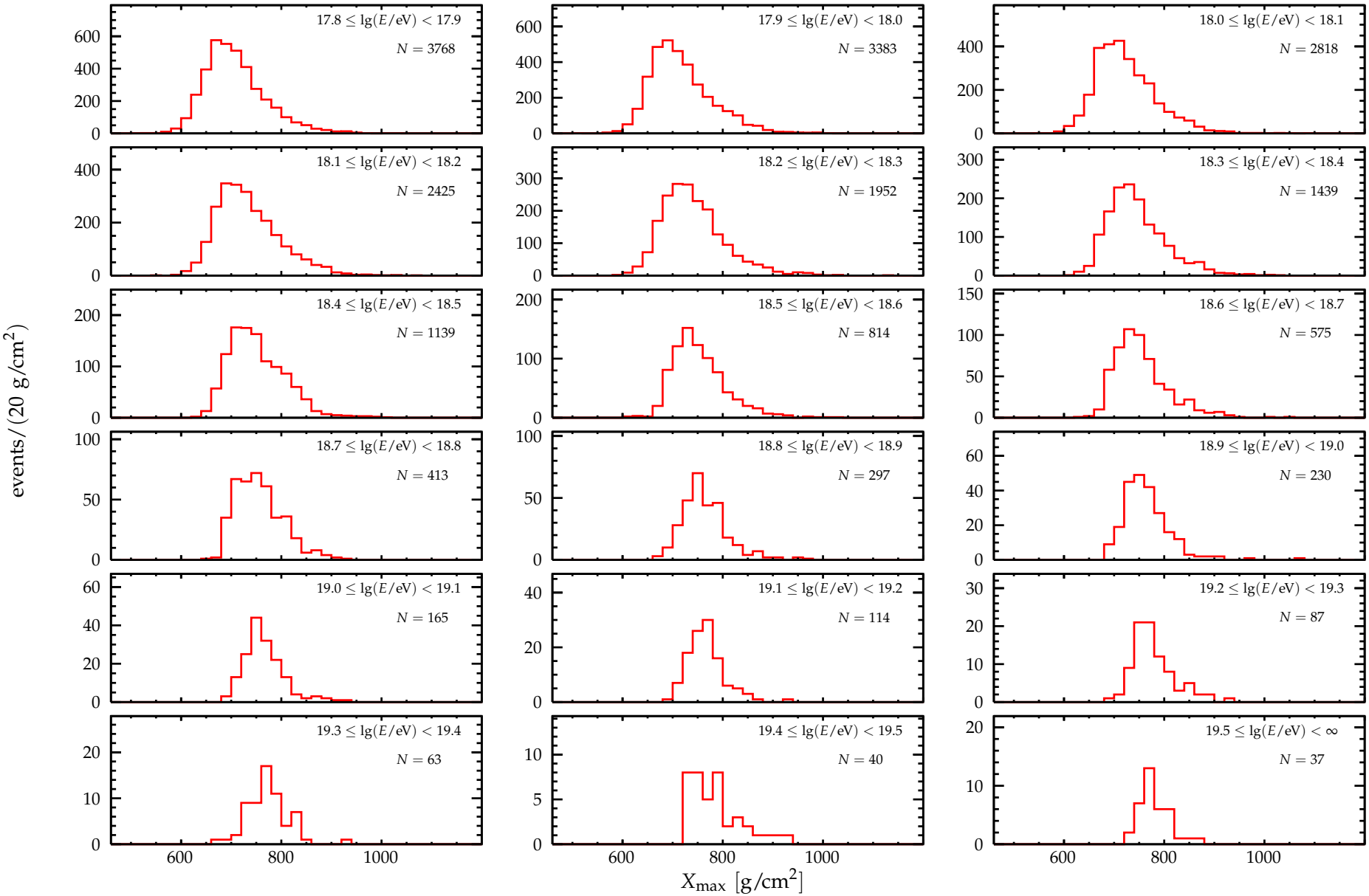
Primary Mass and Longitudinal Shower Profiles



Primary Mass and Longitudinal Shower Profiles

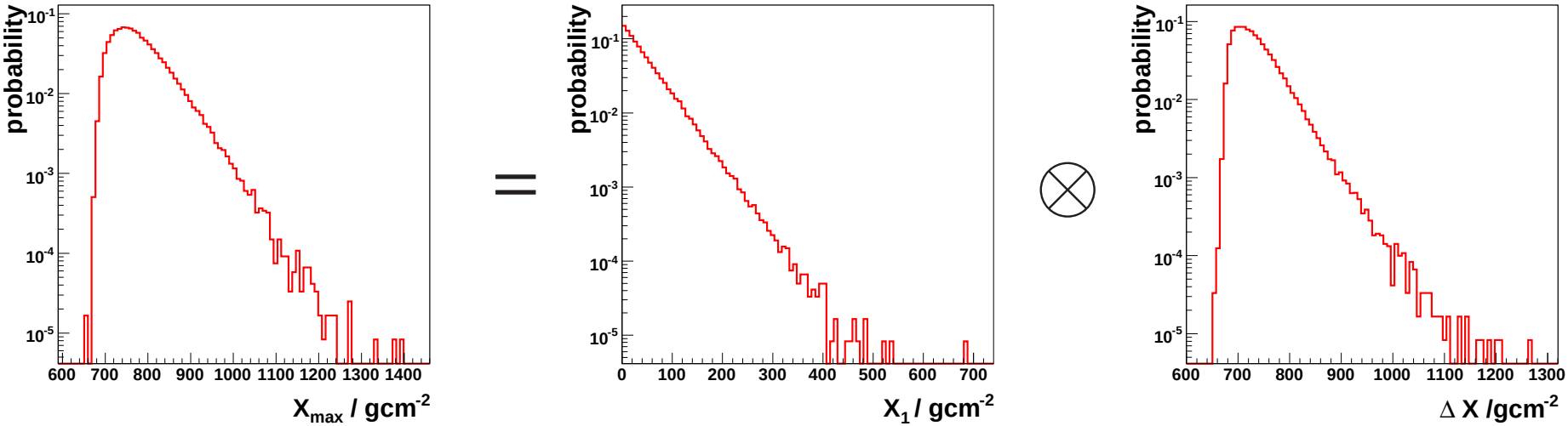


X_{max} Distributions



The Pierre Auger Collaboration, PRD **90** (2014) 12, 122005

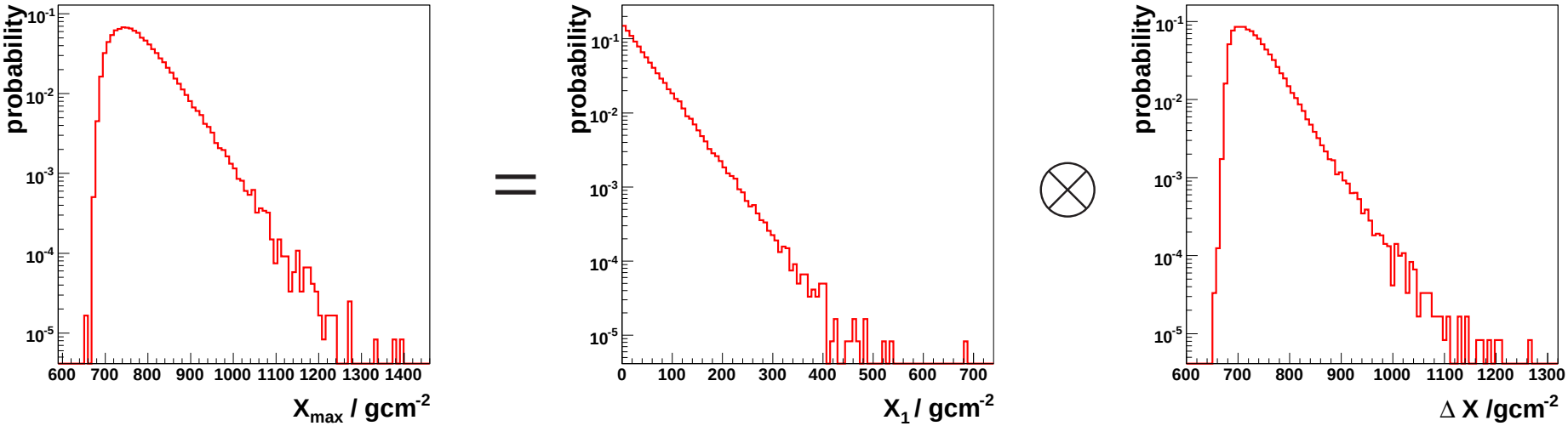
X_{max} Distribution: Mean



- first interaction $\langle X_1 \rangle$: λ_p
- shower development: $\langle \Delta X \rangle$: $\propto \ln E$
- $\langle X_{\mathrm{max}} \rangle_p \sim \lambda_p + D \ln E$

E: primary energy, λ_p: proton interaction length, D: elongation rate, A: mass number

X_{max} Distribution: Mean



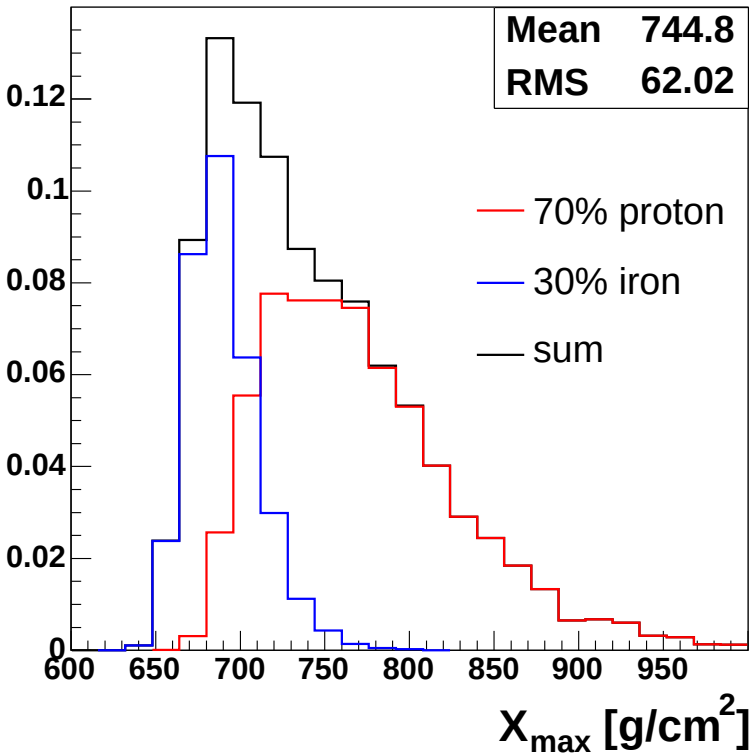
- first interaction $\langle X_1 \rangle$: λ_p
- shower development: $\langle \Delta X \rangle$: $\propto \ln E$
- $\langle X_{\max} \rangle_p \sim \lambda_p + D \ln E$

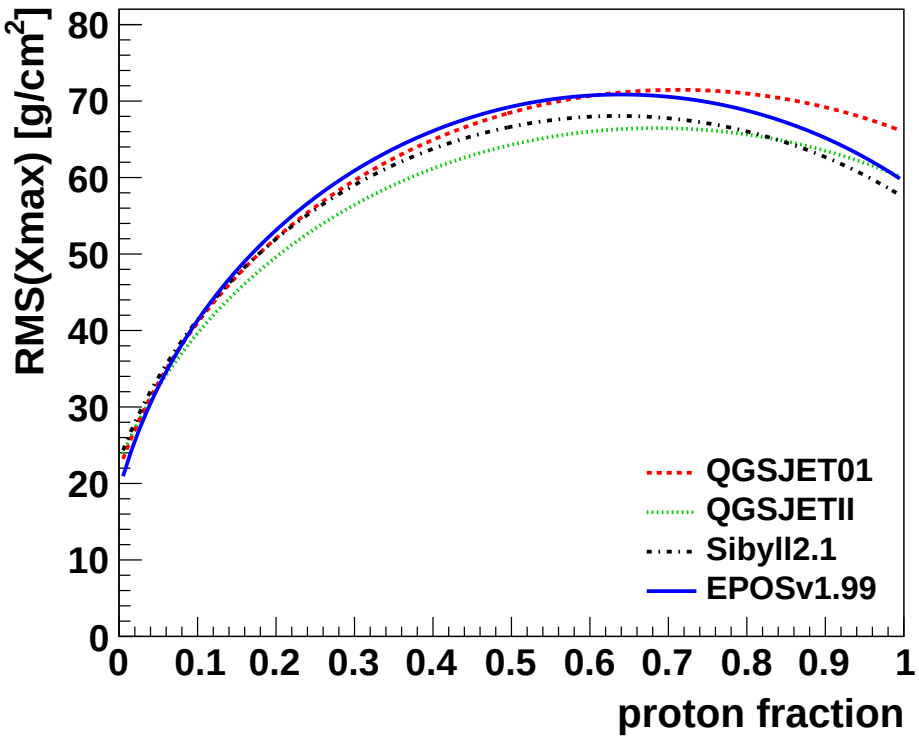
- superposition model: nucleus $(E,\ A) \equiv A$ nucleons $(E/A, 1)$
- $\langle X_{\max} \rangle_A \sim \lambda_p + D \ln(E/A)$

E: primary energy, λ_p: proton interaction length, D: elongation rate, A: mass number

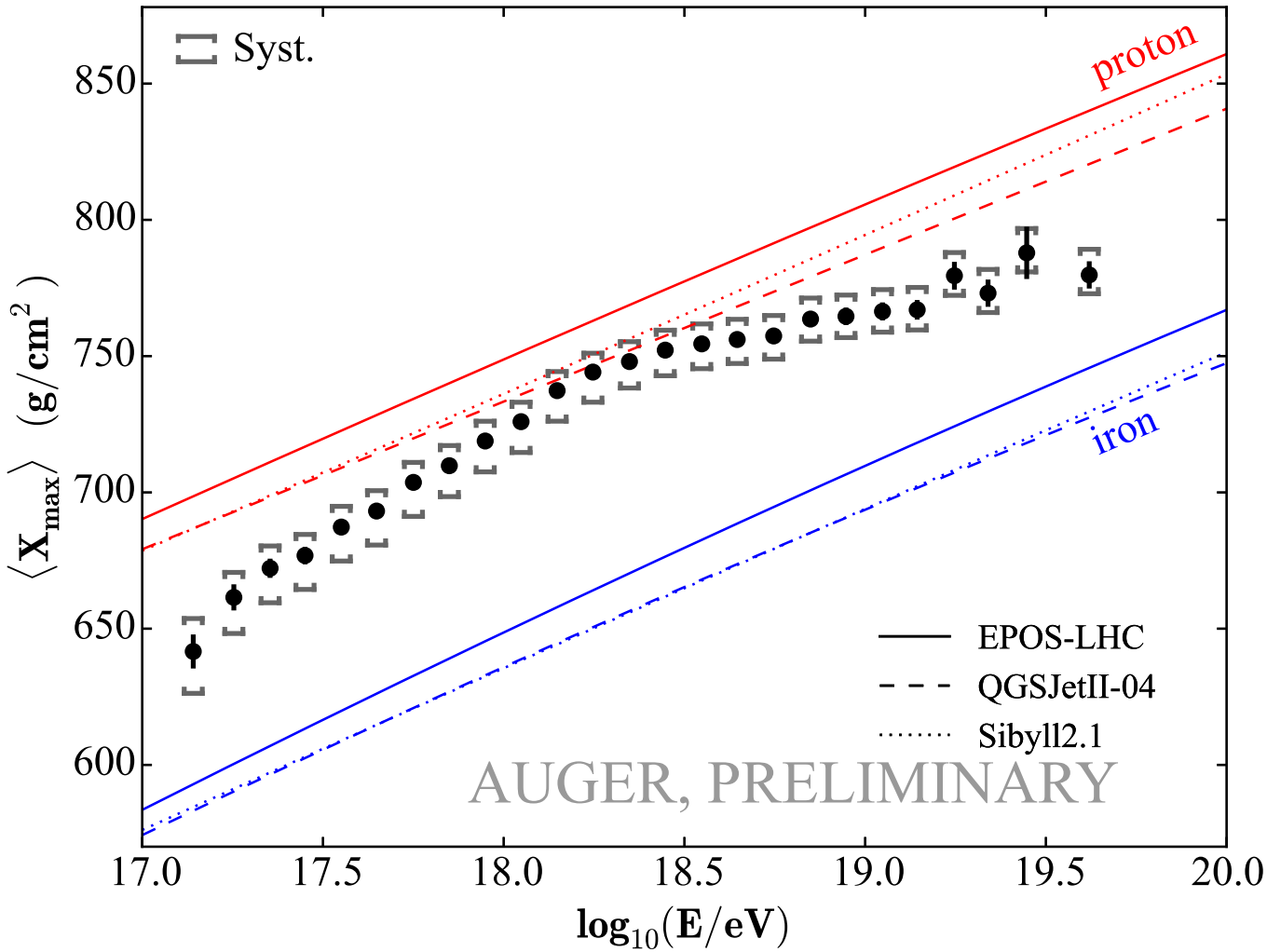
X_{max} Distribution: Standard Deviation

- $\sigma(X_{\max})_p > \sigma(X_{\max})_A > \sigma(X_{\max})_p/\sqrt{A}$
- mixed composition:



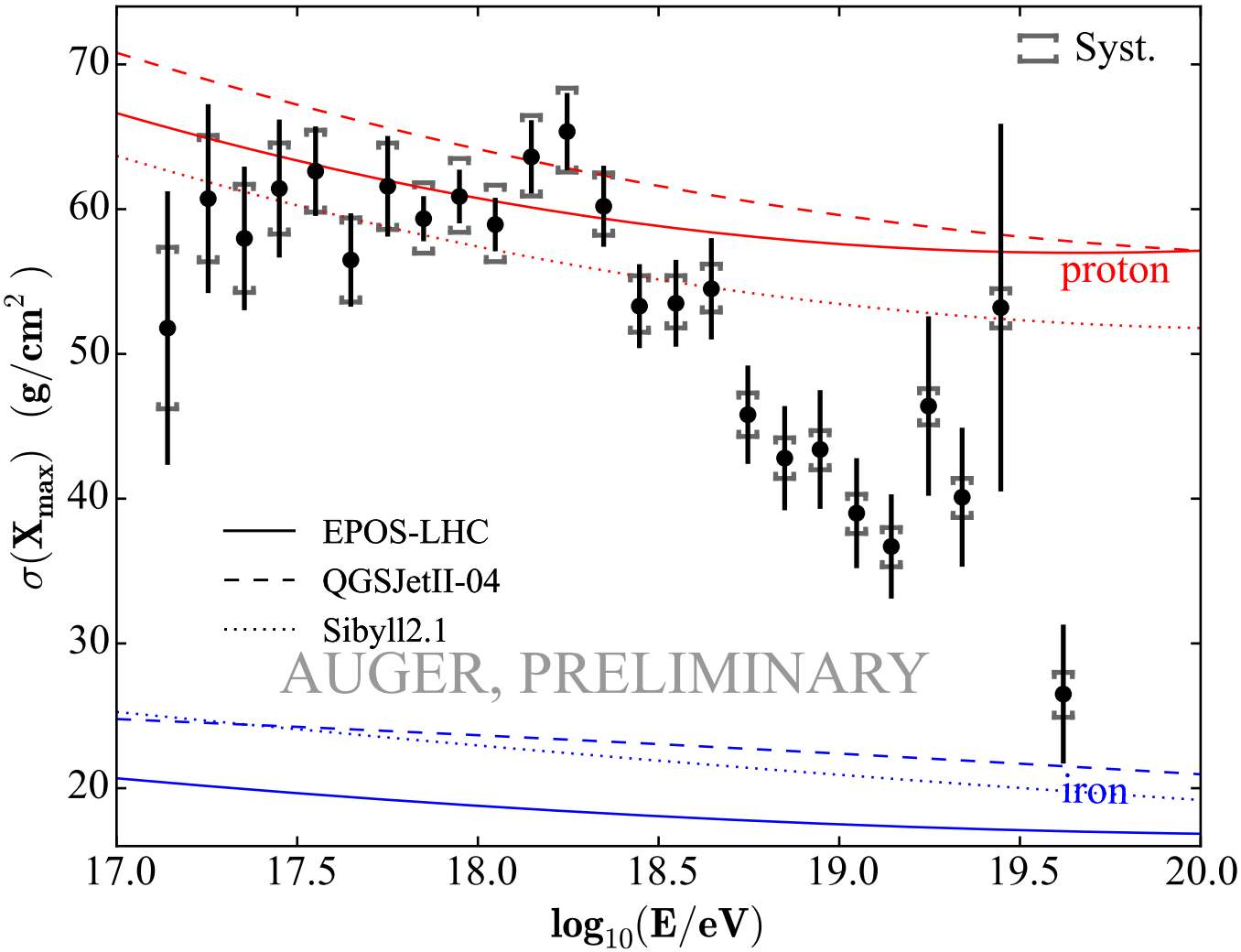


Measured $\langle X_{max} \rangle$



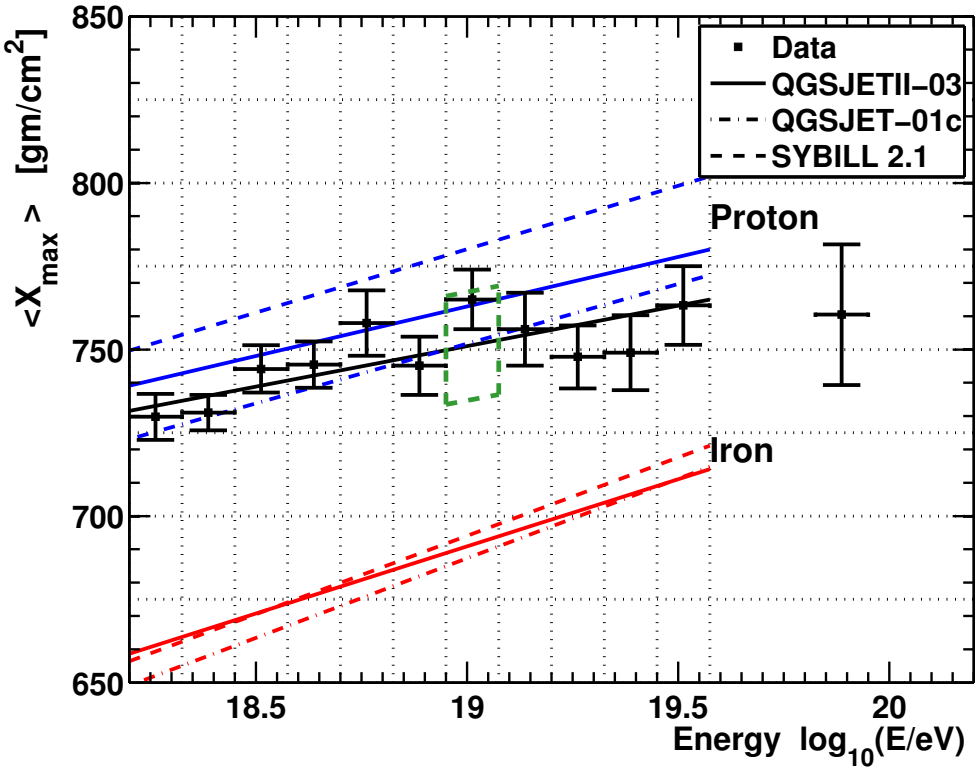
A. Porcelli for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Measured $\sigma(X_{max})$

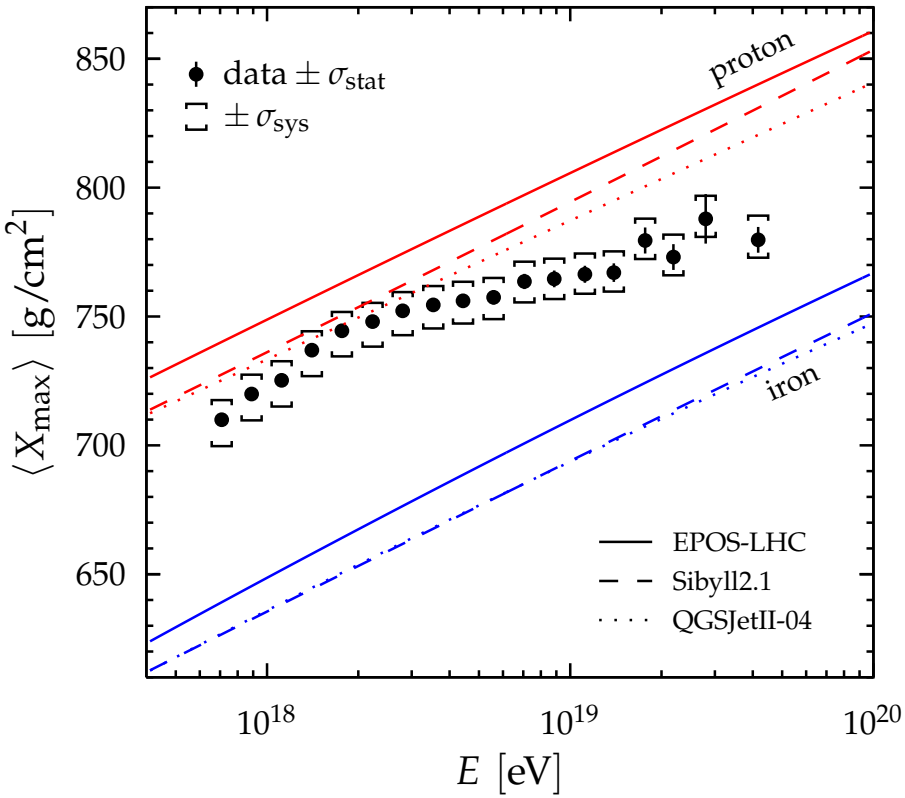


A. Porcelli for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Average Shower Maximum: Comparison to TA

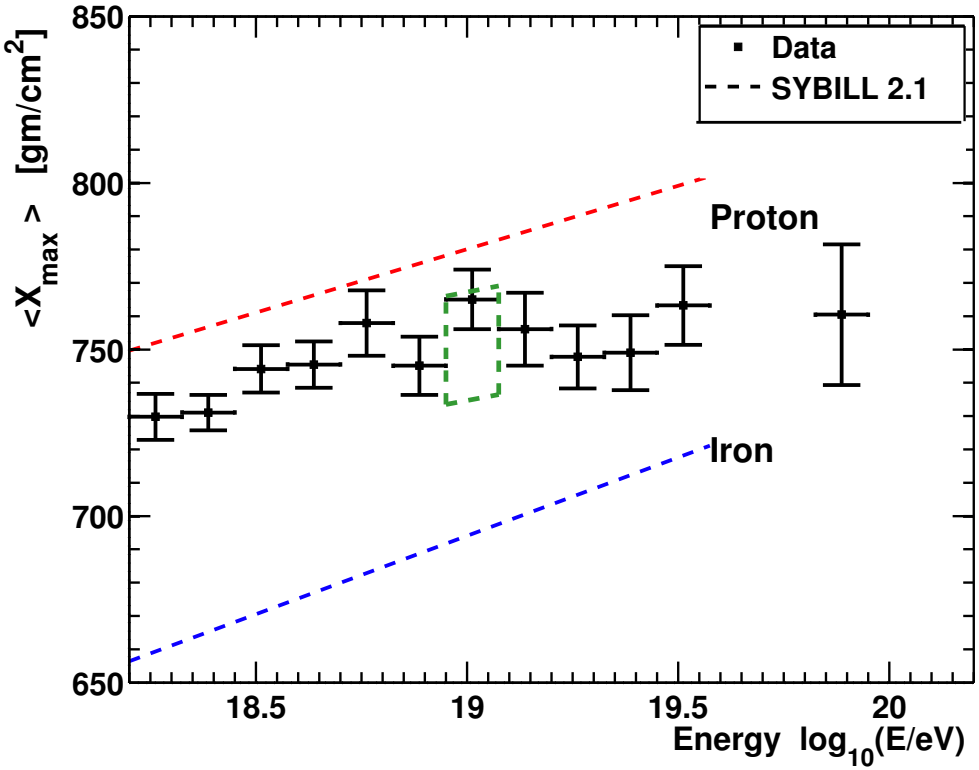


Telescope Array Coll., APP **64** (2014) 49

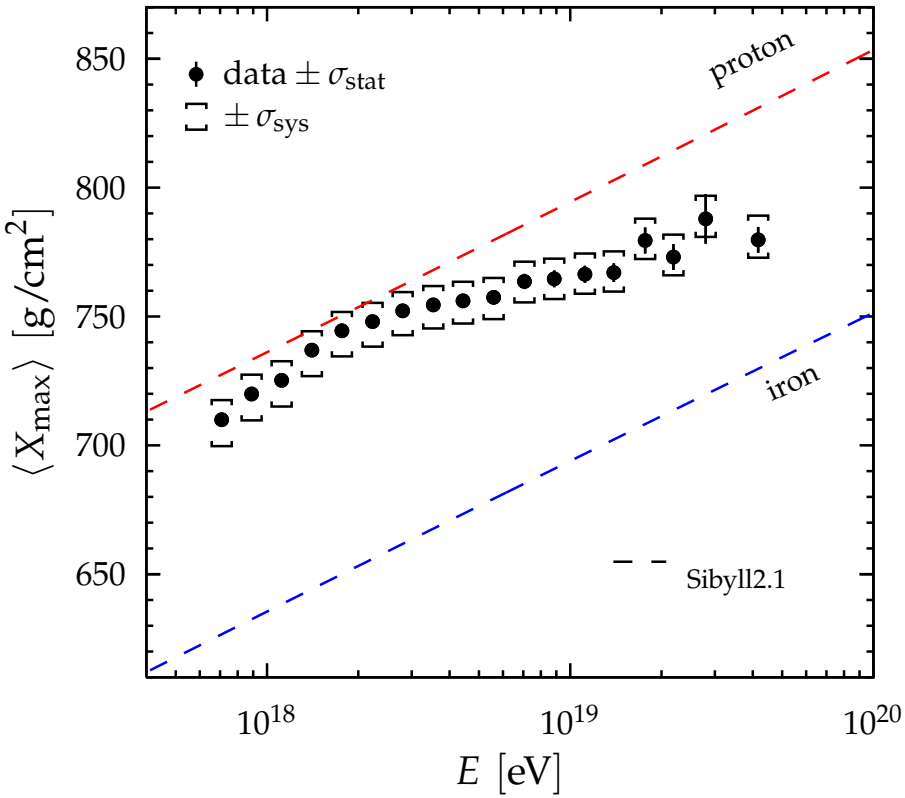


Pierre Auger Coll., PRD **90** (2014) 12, 122005

Average Shower Maximum: Comparison to TA

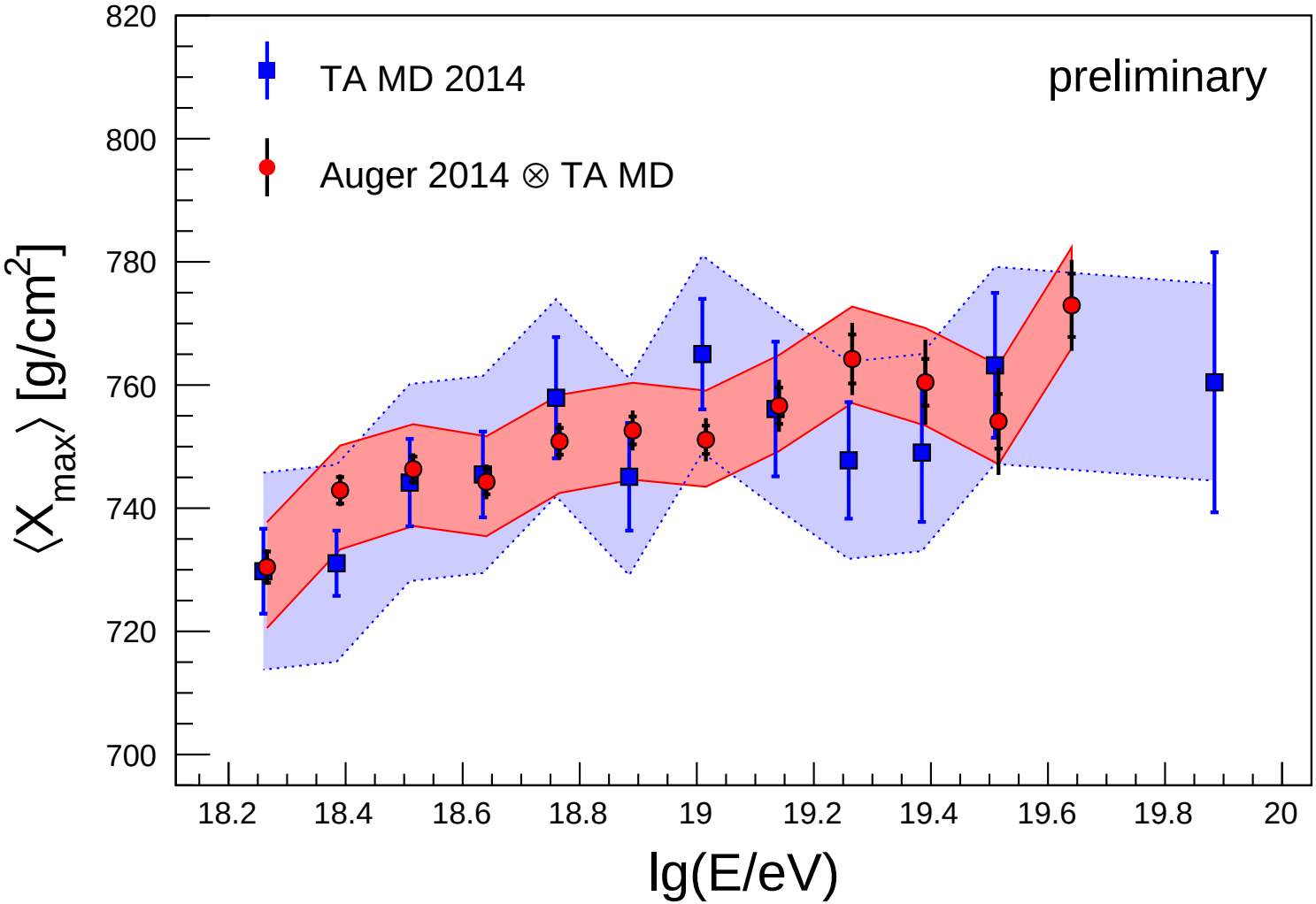


Telescope Array Coll., APP **64** (2014) 49



Pierre Auger Coll., PRD **90** (2014) 12, 122005

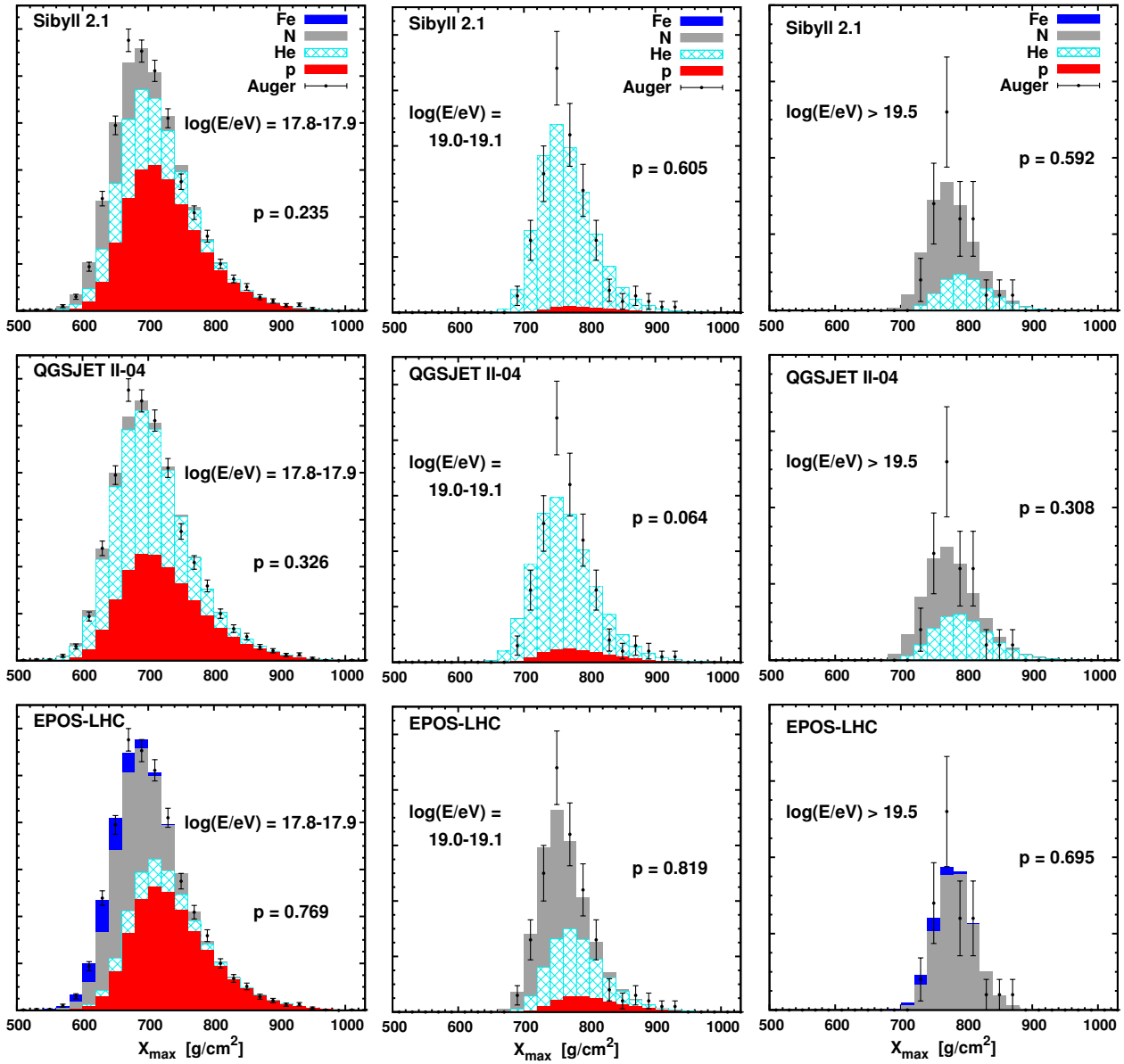
Average Shower Maximum: Comparison to TA



$$\langle \Delta \rangle = (2.9 \pm 2.7\ (\text{stat.}) \pm 18\ (\text{syst.}))\ \text{g/cm}^2$$

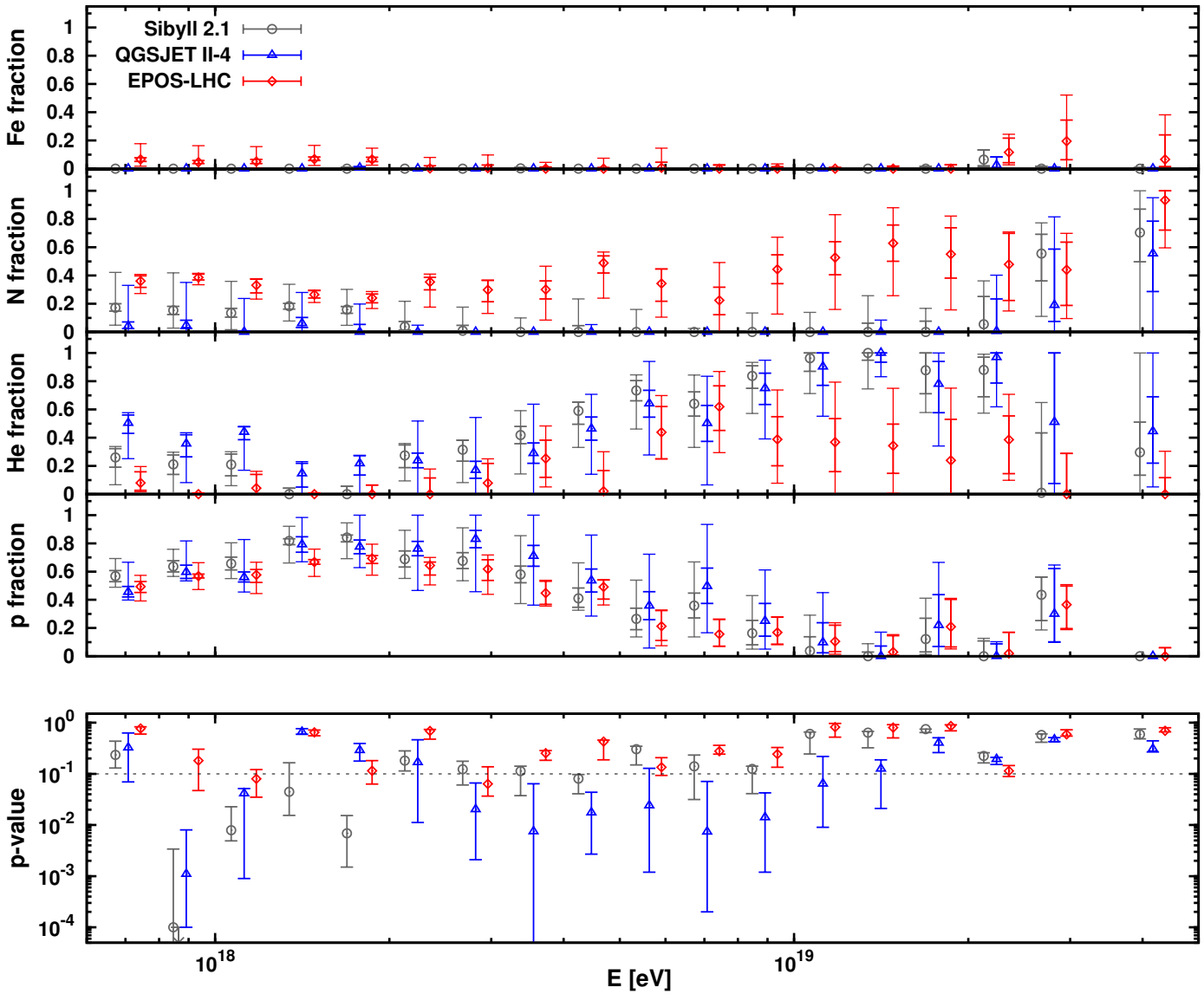
MU for the Pierre Auger and TA Collaborations, Proc. 34th ICRC, arXiv:1511.02103

Fit of X_{max} Distributions



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

Fit of X_{max} Distributions



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

Outline

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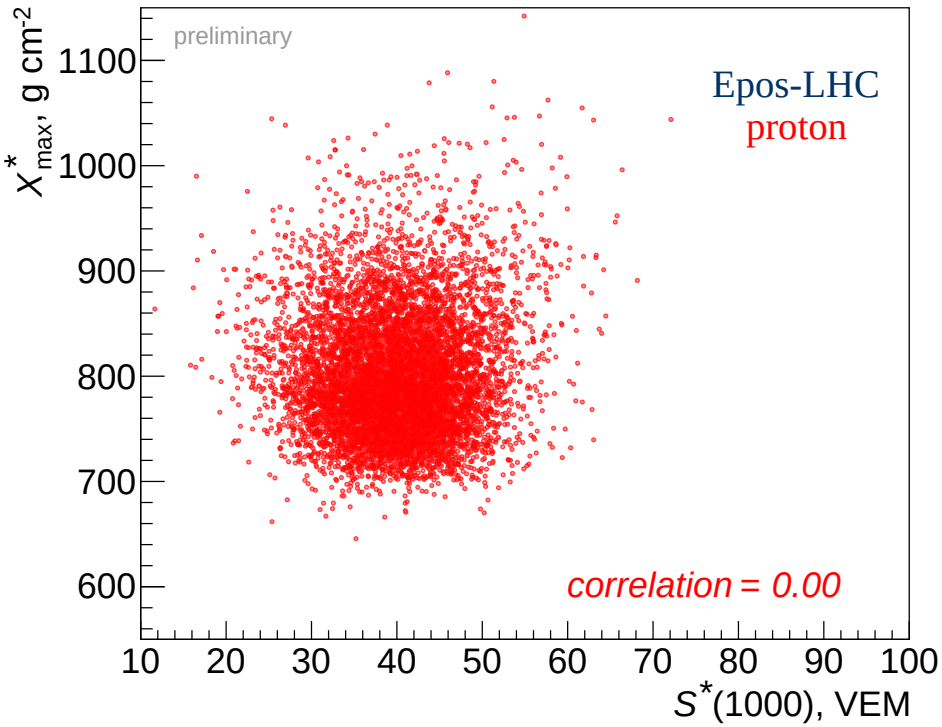
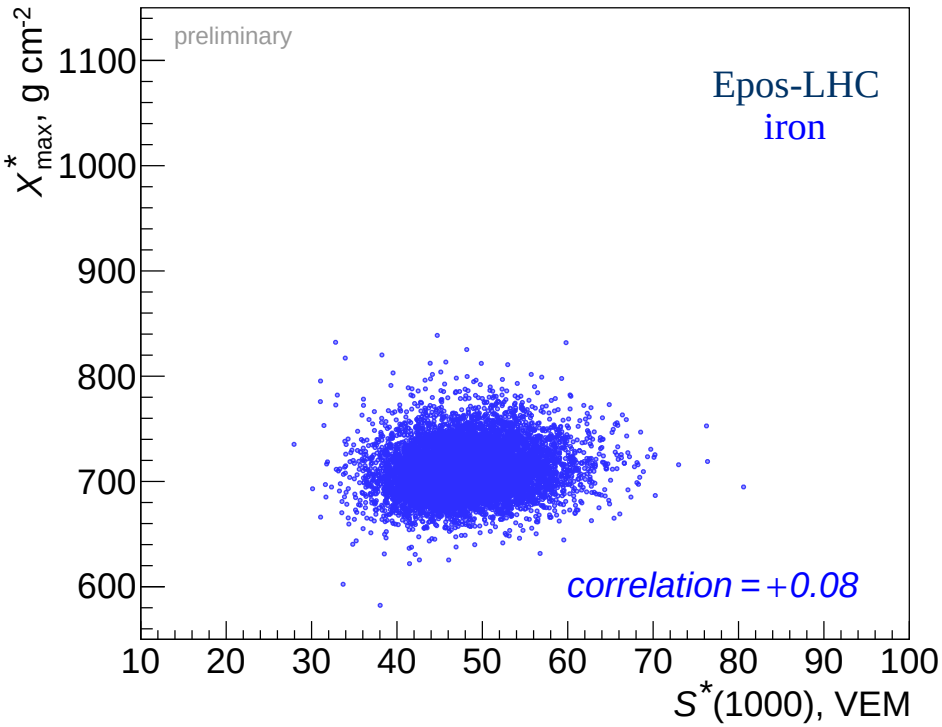
Correlation between X_{max} and SD Signal

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





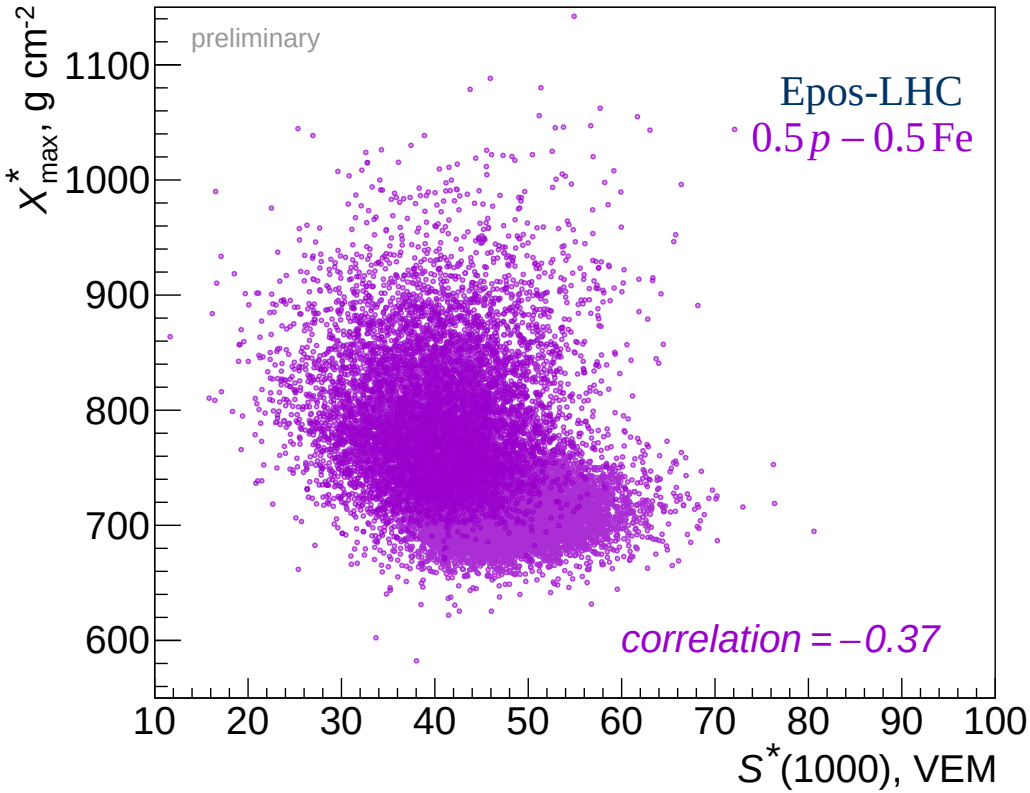
Pure compositions $\Rightarrow$ correlation $\gtrsim 0$

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

Correlation between X_{max} and SD Signal

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

general characteristics of air showers / minor model dependence

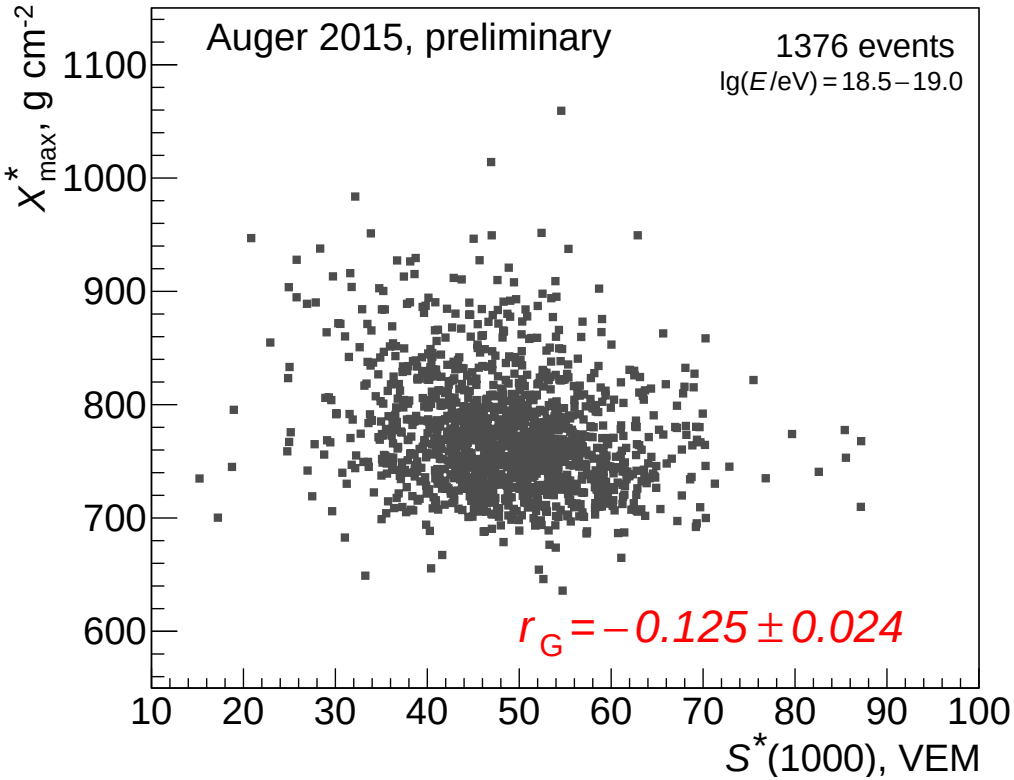


More negative correlation ⇒ more mixed composition

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

Correlation between X_{max} and SD Signal

Data:



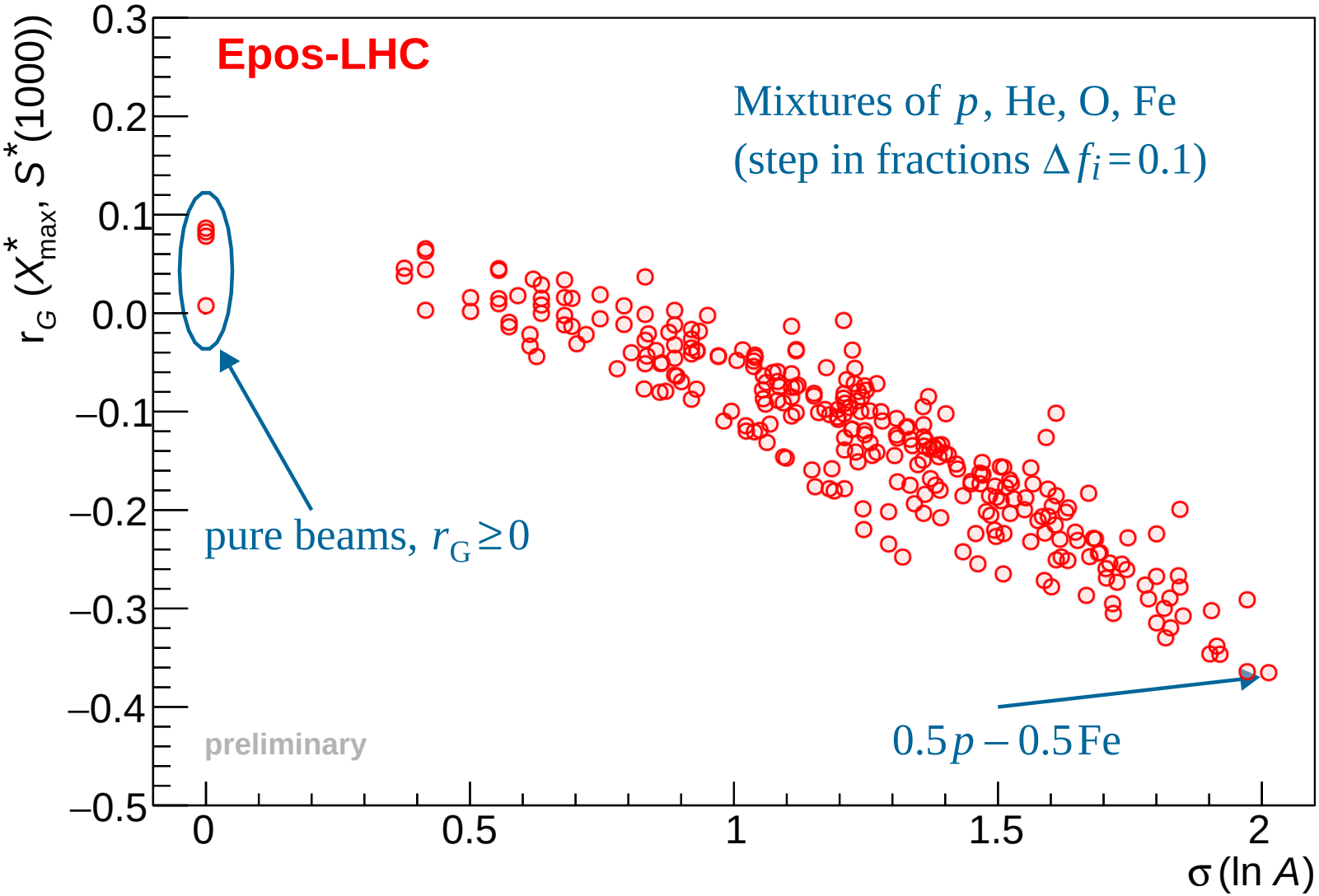
$r_{\mathrm{G}}(X^*_{\mathrm{max}},\, S^*(1000))$ for protons

Epos-LHC	QGSJetII-04	Sibyll 2.1
0.00	$+0.08$	$+0.07$
difference to data		
$\approx 5\sigma$	$\approx 8\sigma$	$\approx 7.5\sigma$

difference is larger for other pure beams

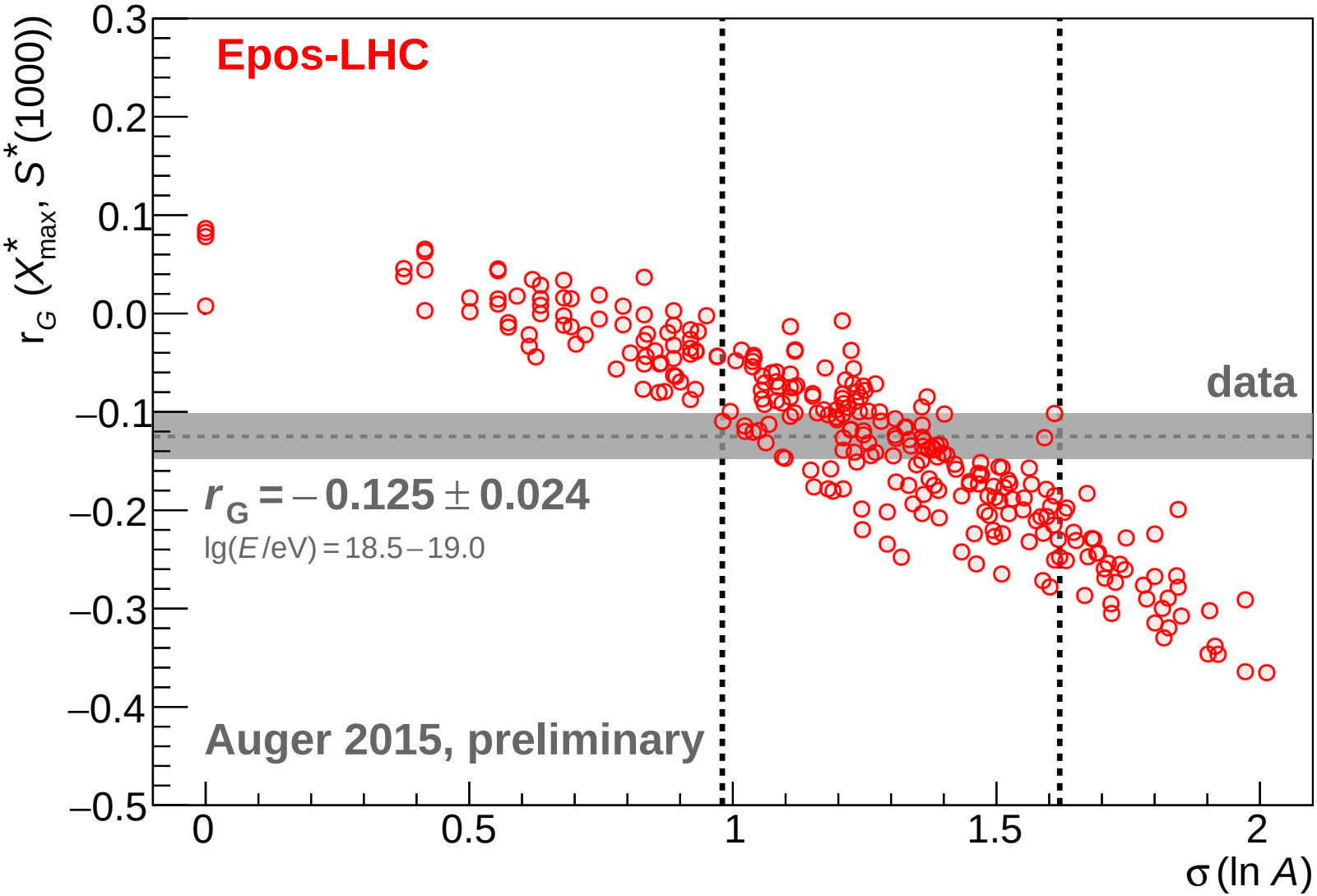
A. Yushkov for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Relation to Mass Dispersion



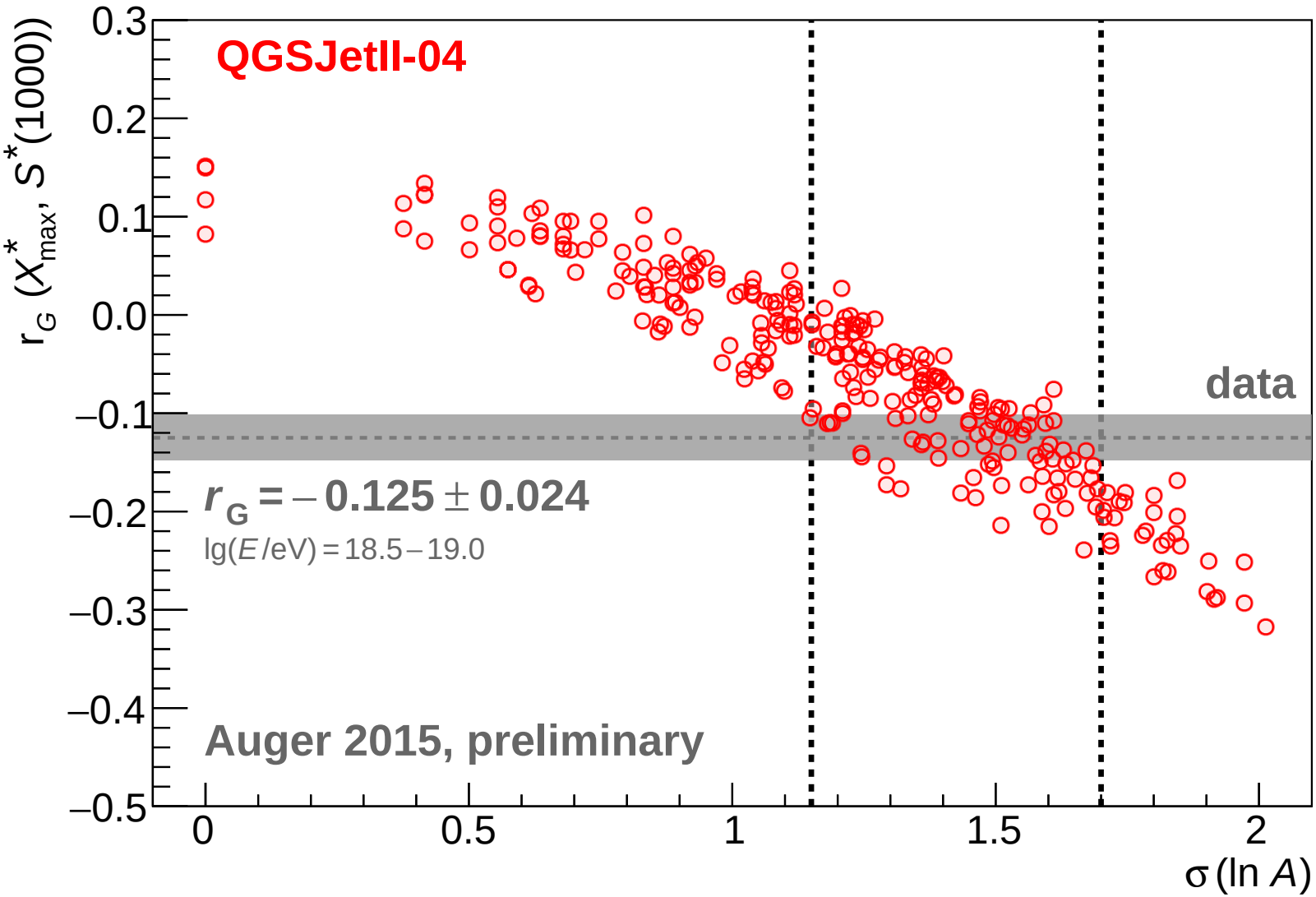
A. Yushkov for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Relation to Mass Dispersion



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

Relation to Mass Dispersion



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

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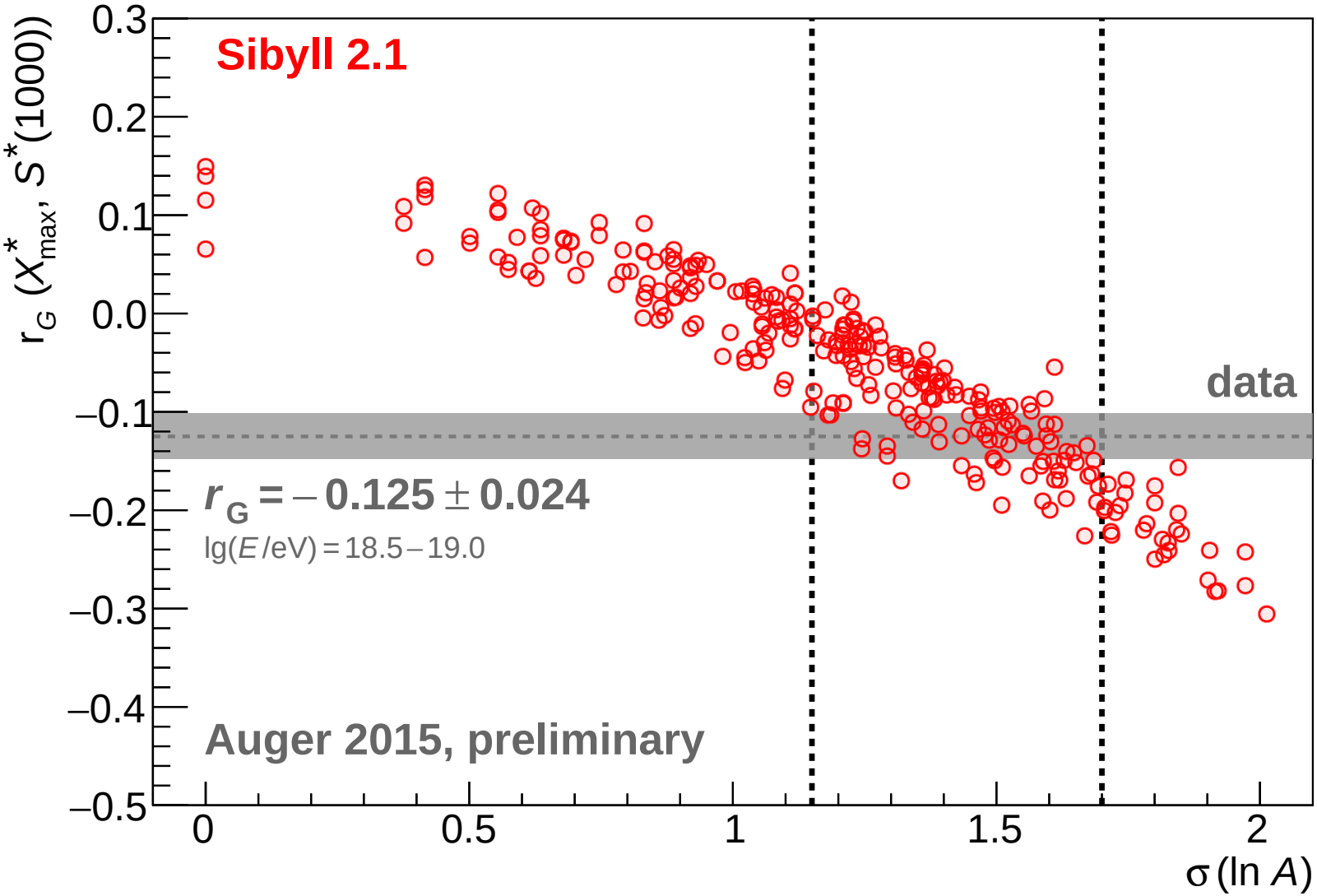

A. Yushkov for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

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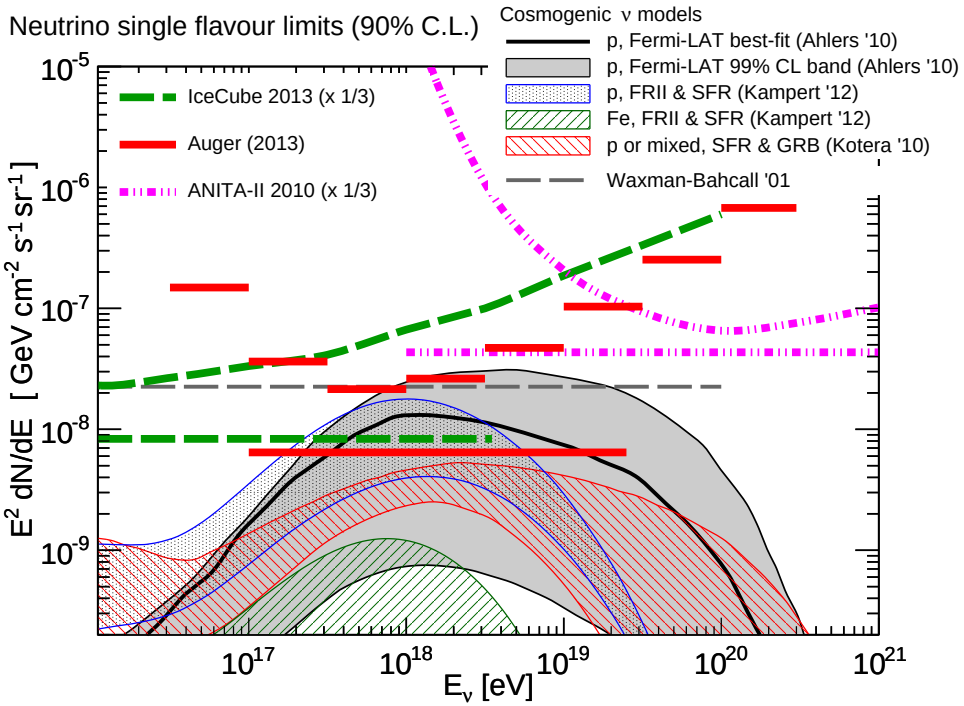
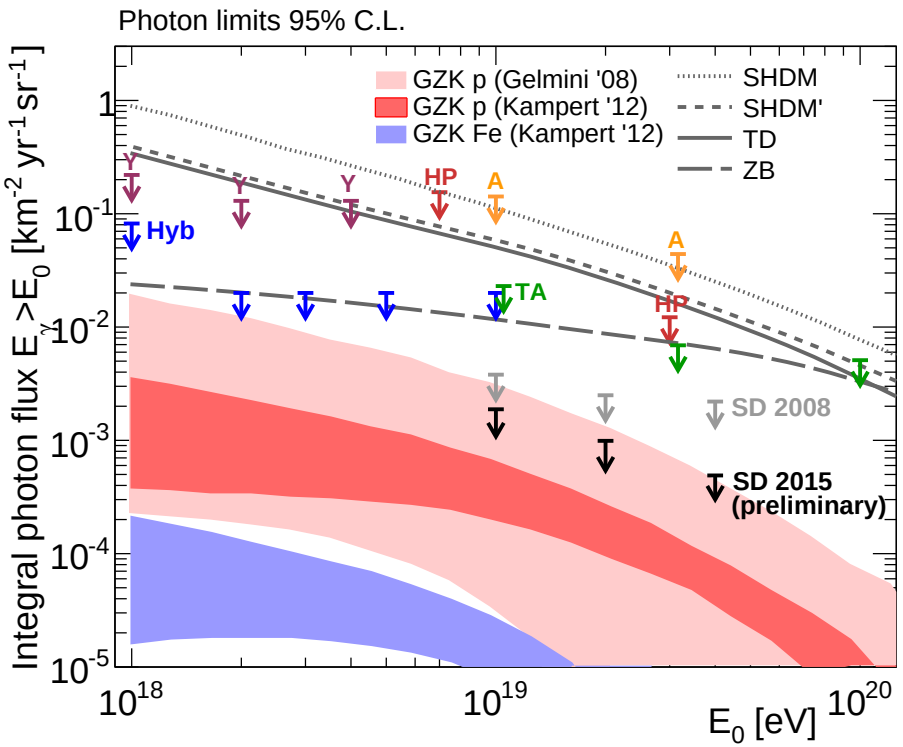
Neutrino- and Photon-Limits

"guaranteed" flux of cosmogenic photons and neutrinos if CRs are protons

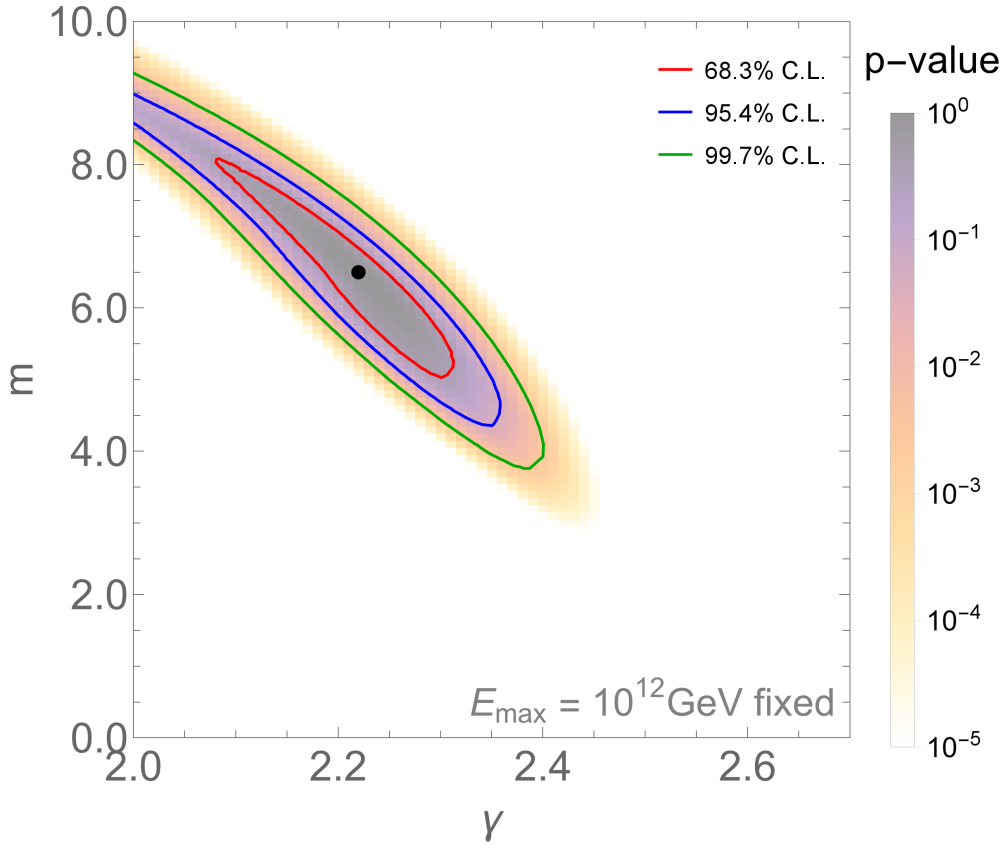


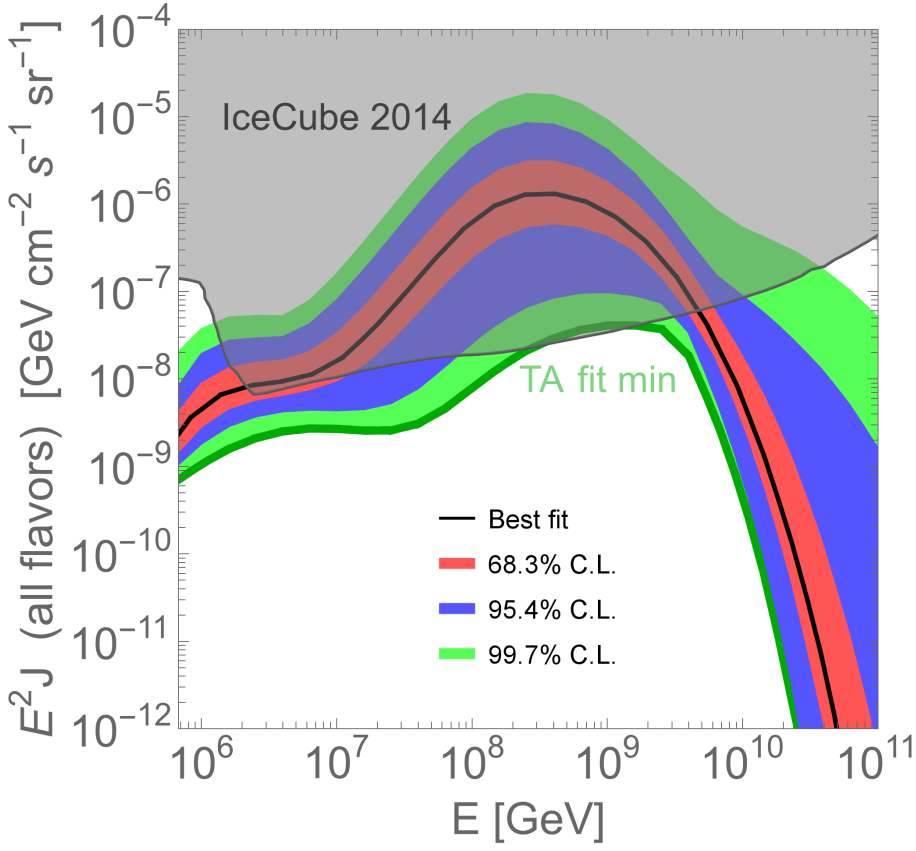


C. Bleve for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732

Self-Consistent CR+ν Analysis (TA Spectrum)

spectral index at source γ and source evolution $(1+z)^m$





... similar results for three-parameter fit ($m, \gamma, E_{\rm max}$)

J. Heinze, D. Boncioli, M. Bustamante, W. Winter, arXiv:1512.05988

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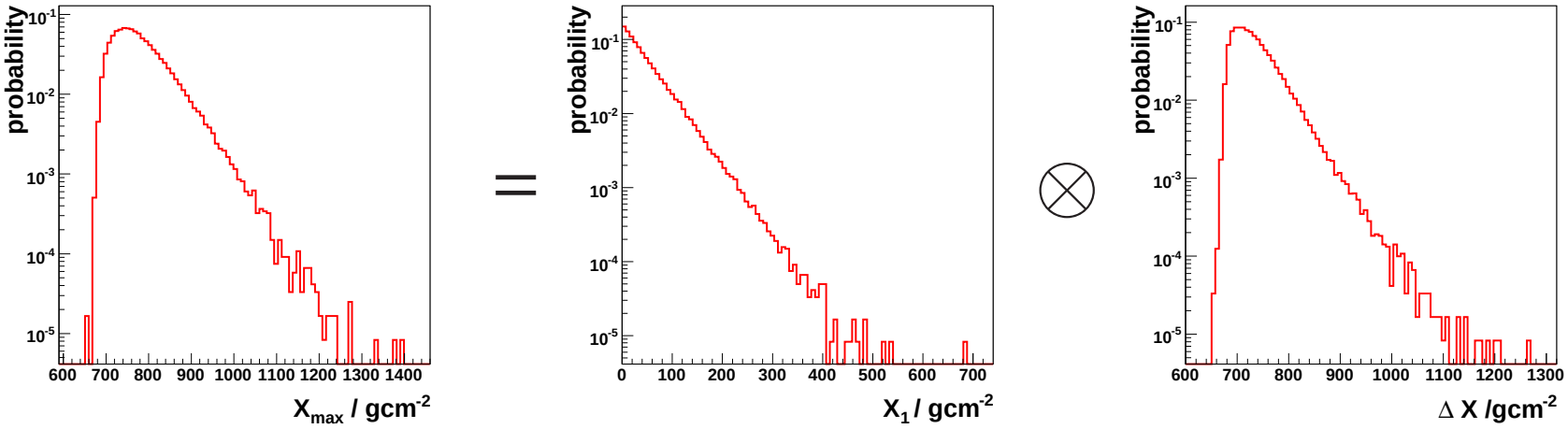
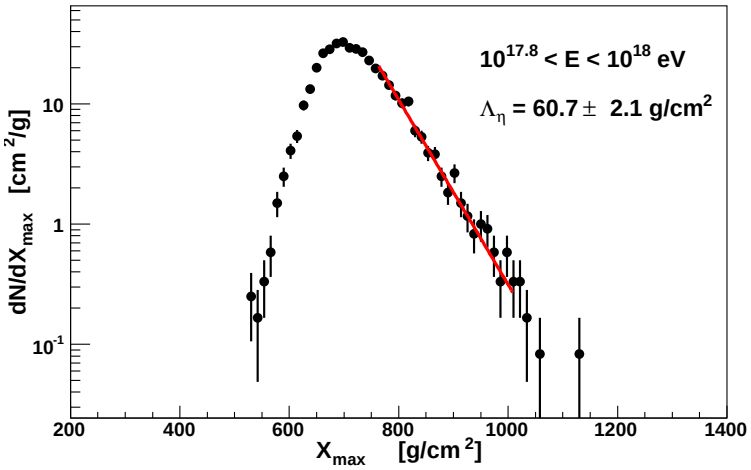
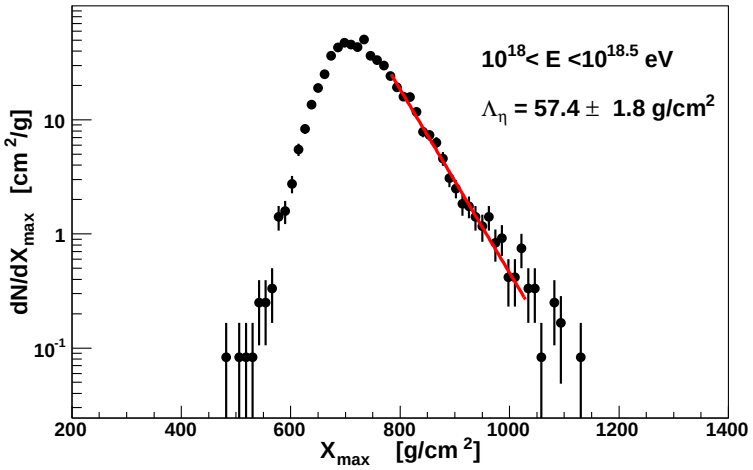
Measurement of the UHE Proton+Air Cross Section

tail of X_{max} distribution:



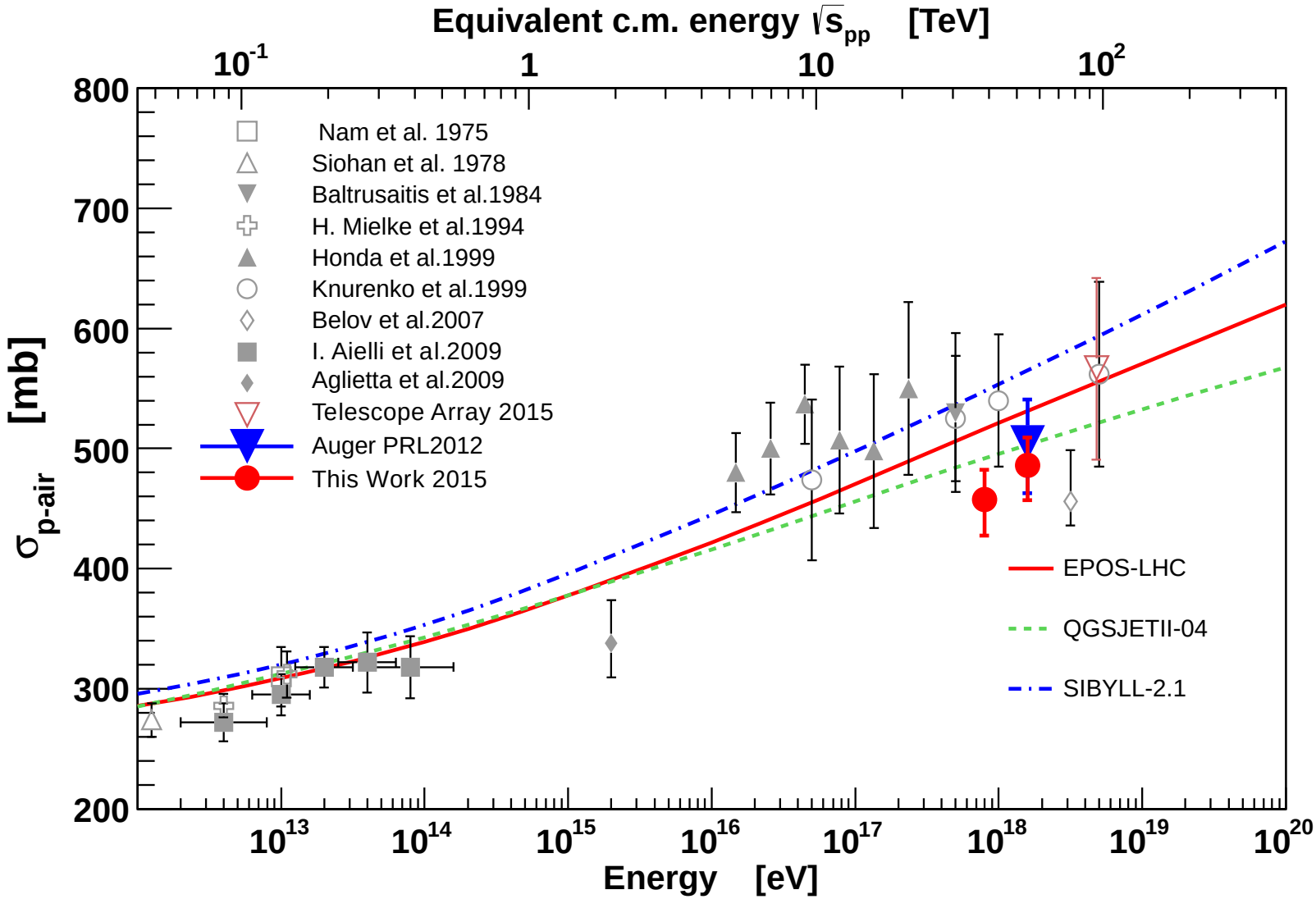




$\langle E \rangle = 10^{17.90}$ eV

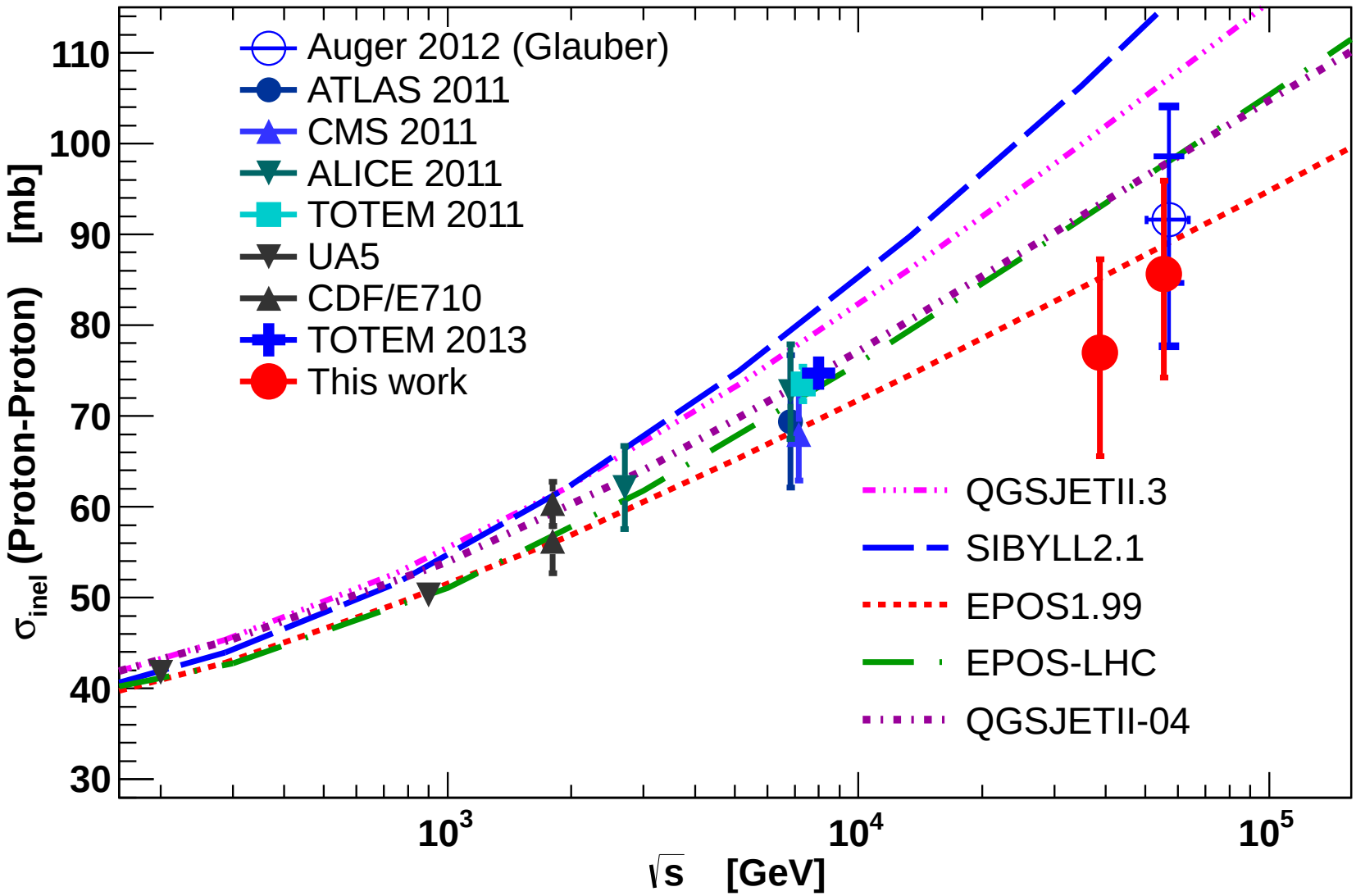
$\langle E \rangle = 10^{18.22}$ eV

Measurement of the UHE Proton+Air Cross Section



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

Derived UHE Proton+Proton Cross Section



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

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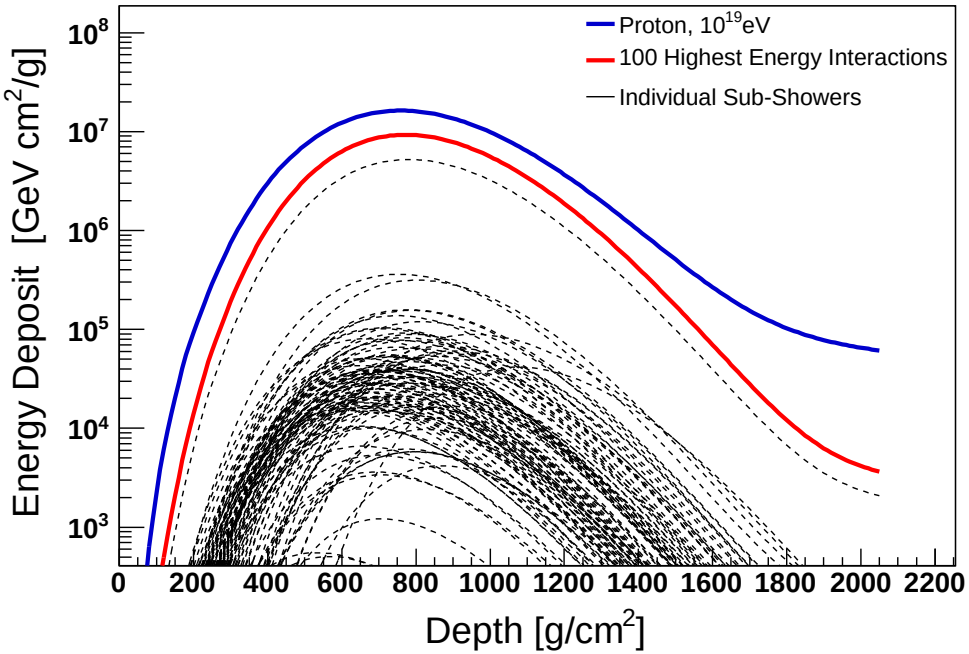
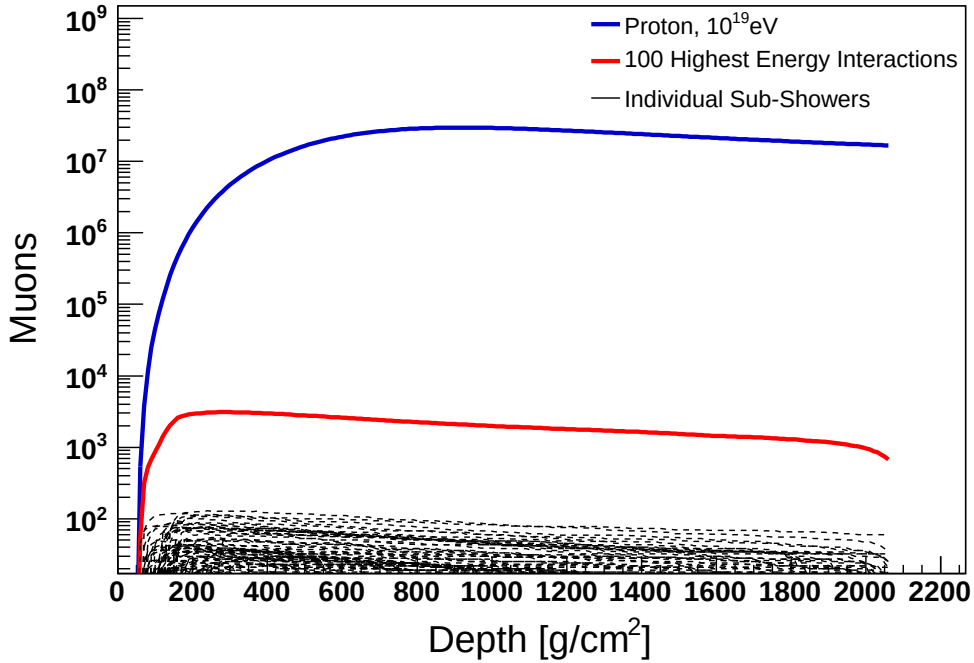
Muons in Air Showers



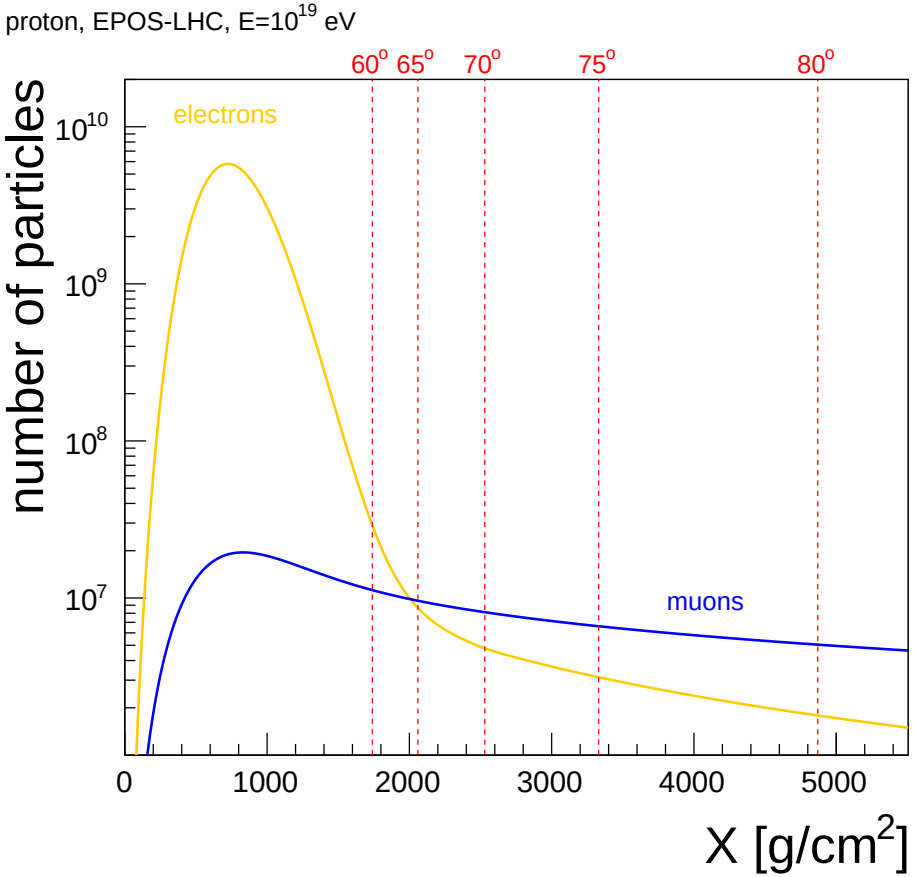


R. Ulrich, APS 2010

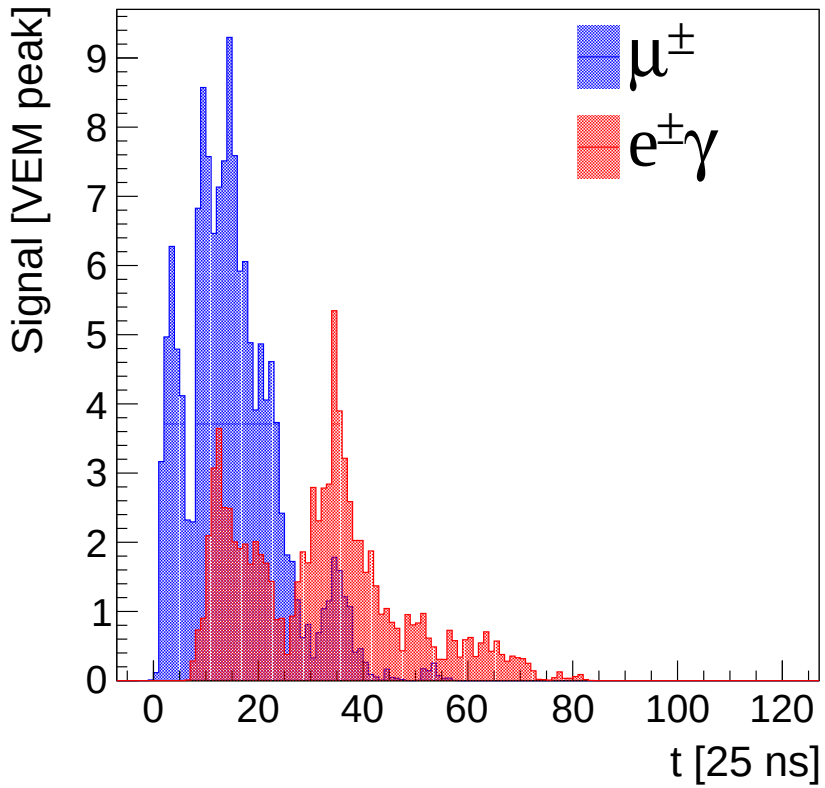
- muons are produced late in the shower cascade
  $\rightarrow$ number of generations $\sim$ 6 at 10^{19} eV
  $\rightarrow$ amplified sensitivity to hadronic interactions
- X_{max} is dominated by first interaction

Measurement of Muons with the Auger SD

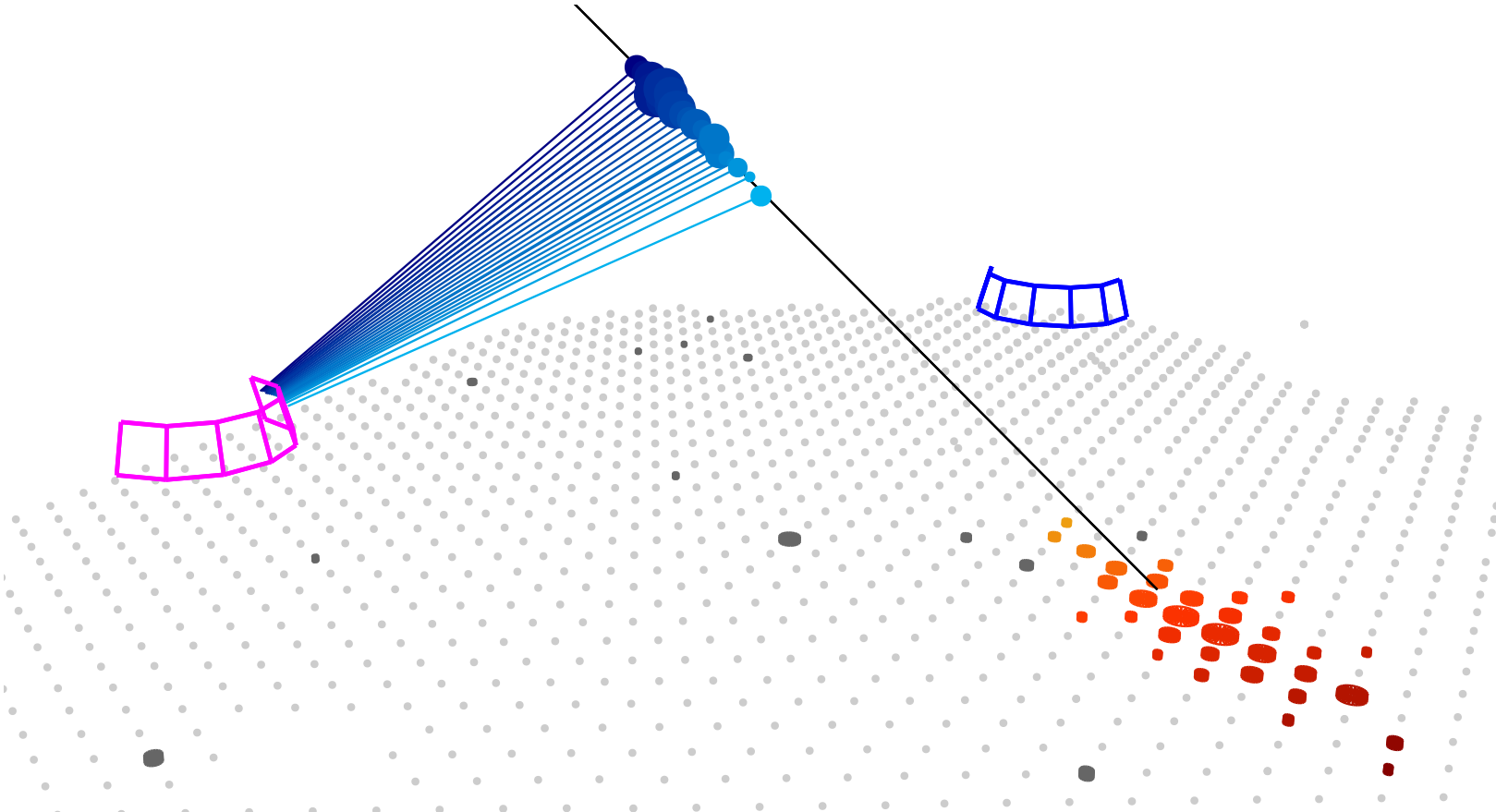
a) shielding of EM component:



b) time structure:



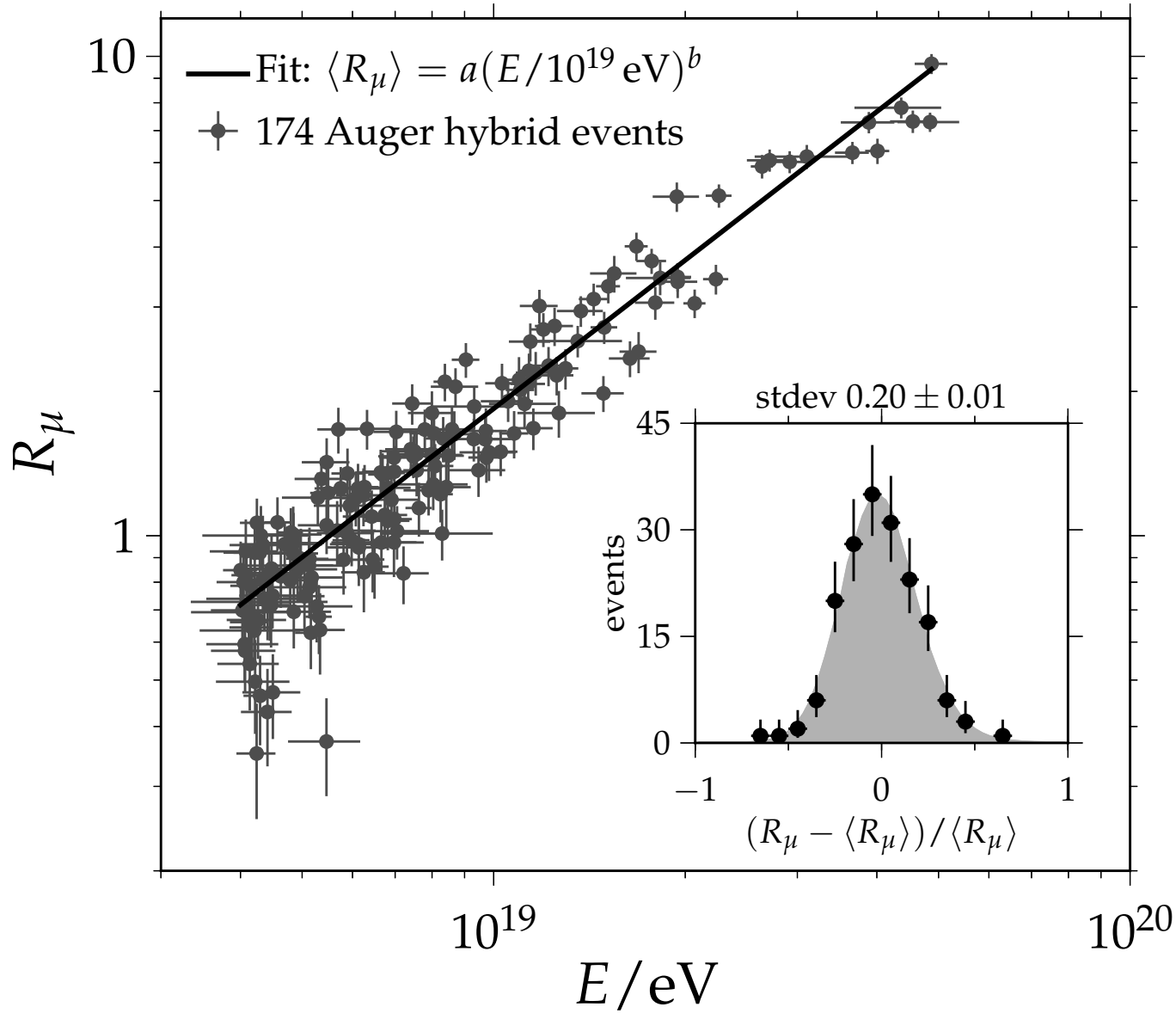
Muon Studies with Inclined Hybrid Events (62°-80°)



event 201114505353, $\theta = 75.6°$, $E = 15.5$ EeV

R_μ vs. E_{FD}

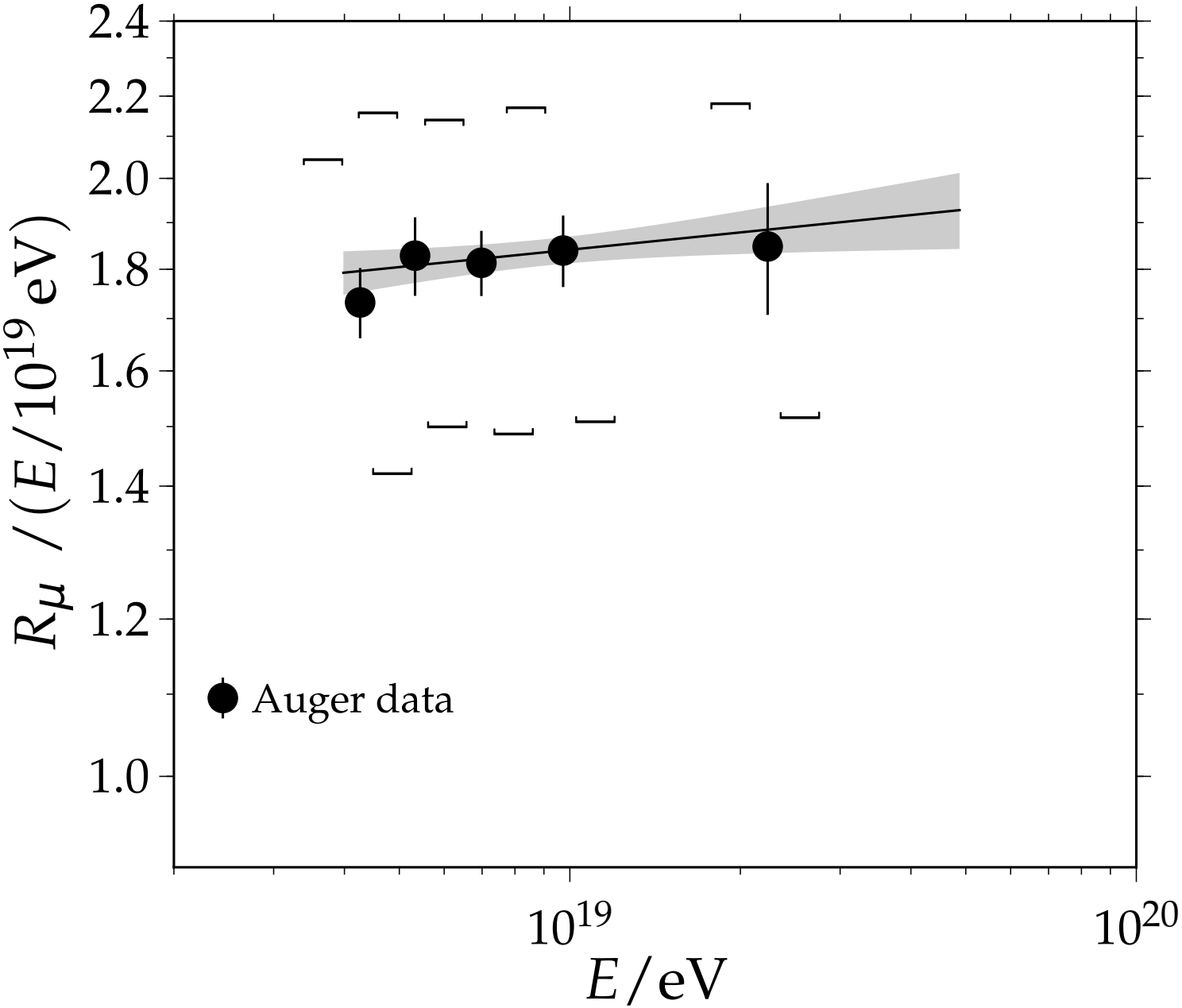
Pierre Auger Coll., PRD **D91** (2015) 3, 032003



QGSJETII-03, p, $E = 10^{19}$ eV $\rightarrow R_\mu = 1$

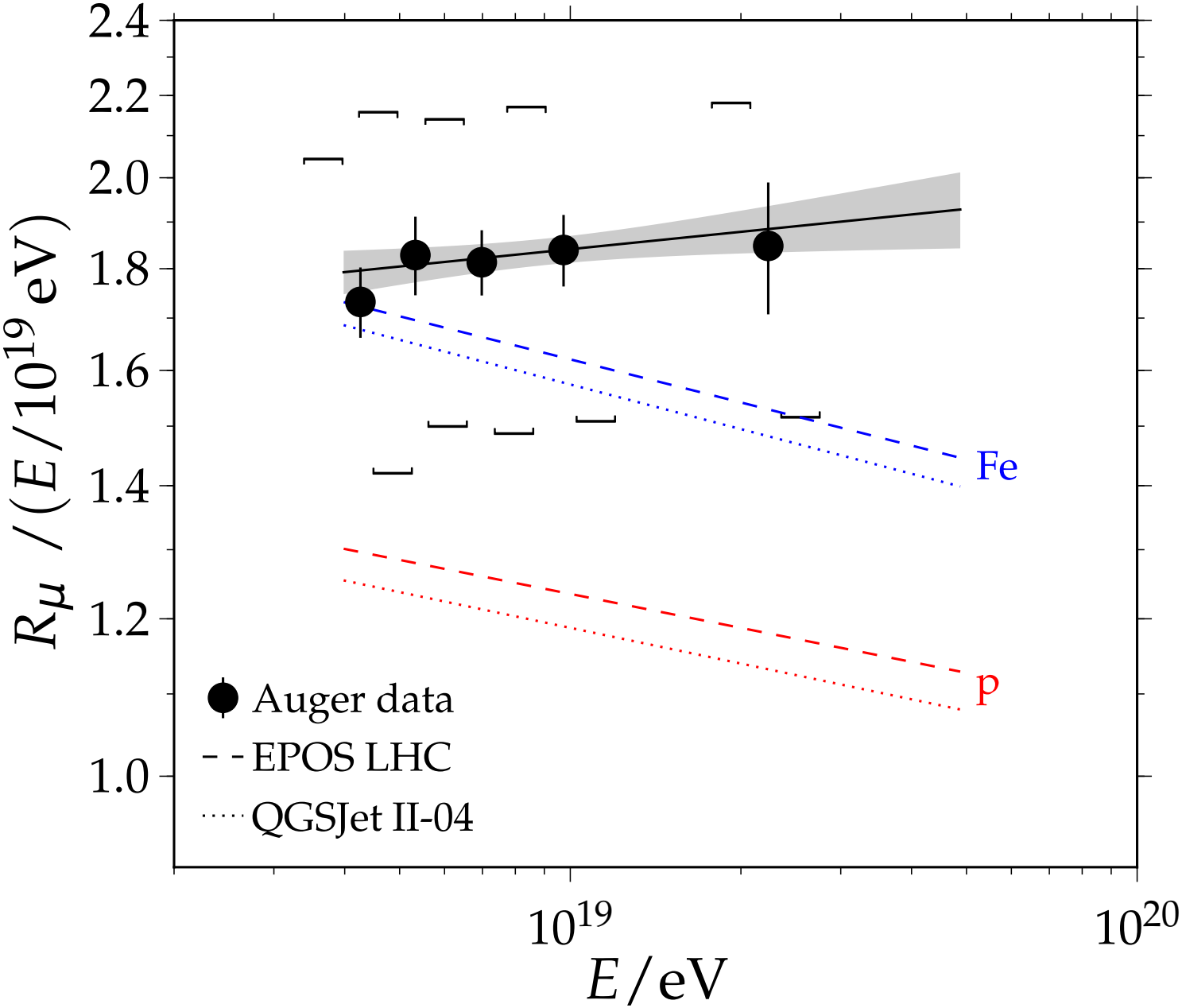
$\langle R_\mu \rangle / E_{FD}$ vs. E_{FD}

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

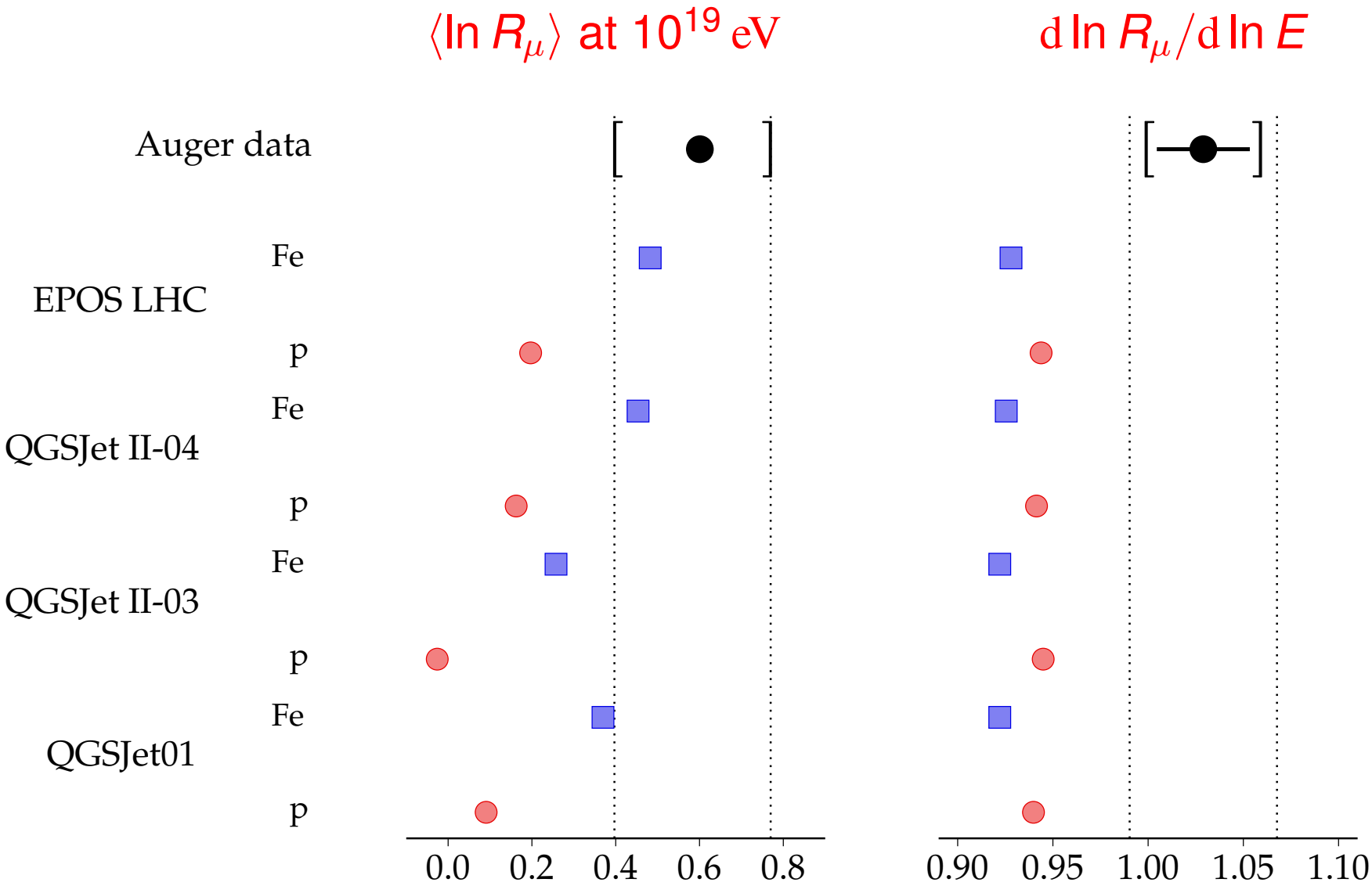


$\langle R_\mu \rangle / E_{FD}$ vs. E_{FD}

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



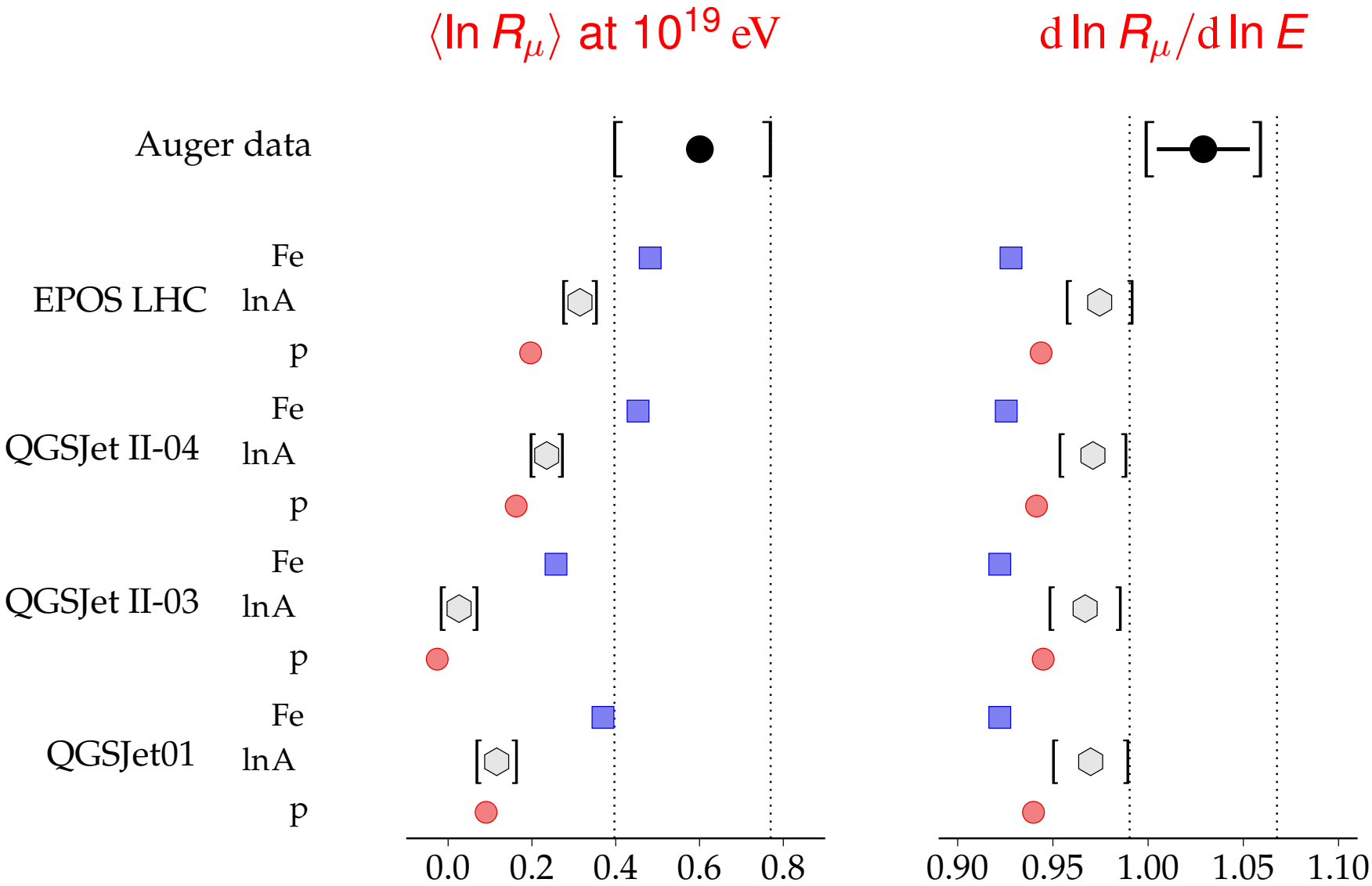
Muon "Elongation Rate" vs. p/Fe



N.B.: $R_\mu = 1 \leftrightarrow N_\mu = 1.455 \times 10^7$

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

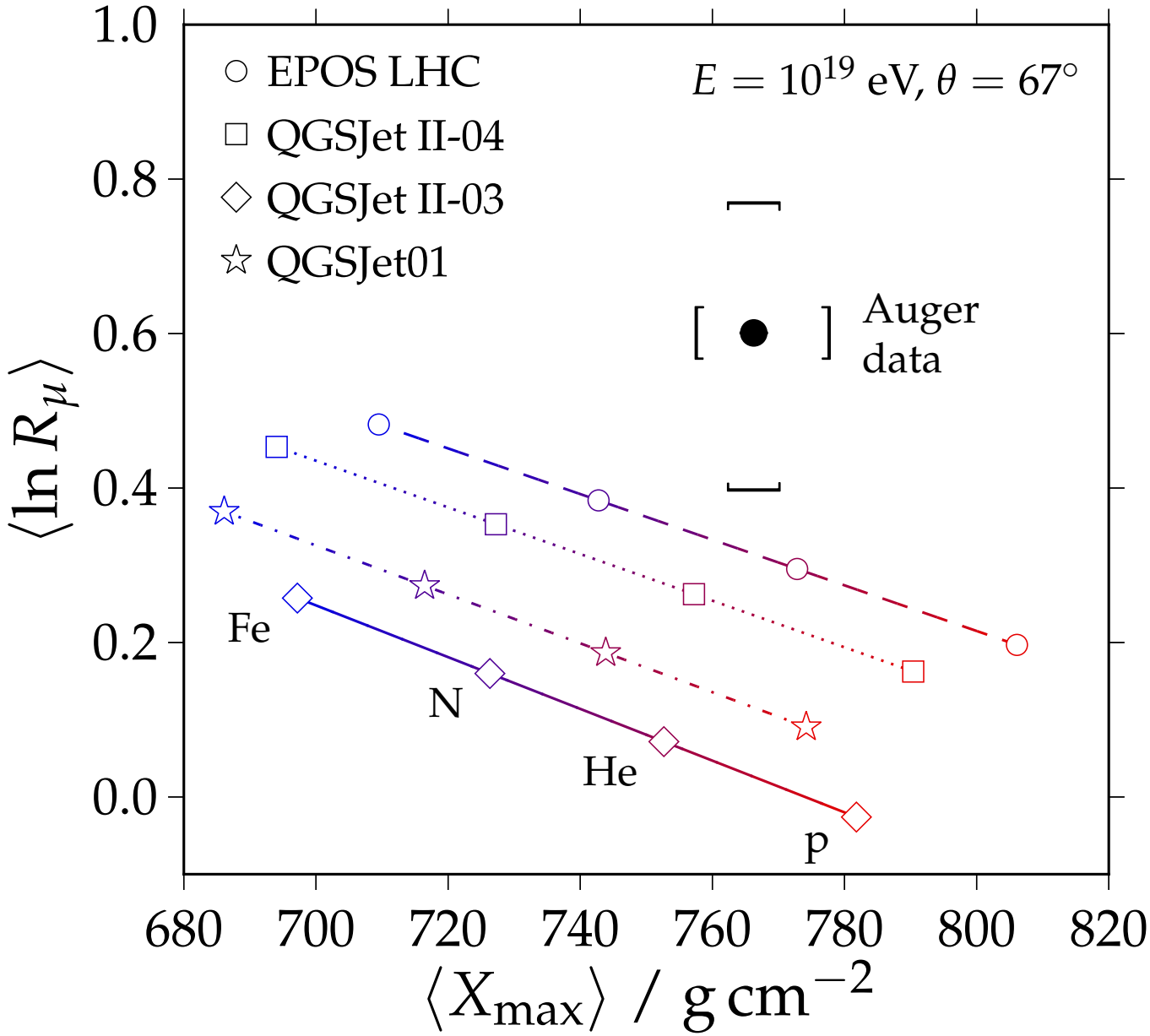
Muon "Elongation Rate" vs. p/Fe and lnA (FD)



N.B.: $R_\mu = 1 \leftrightarrow N_\mu = 1.455 \times 10^7$

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

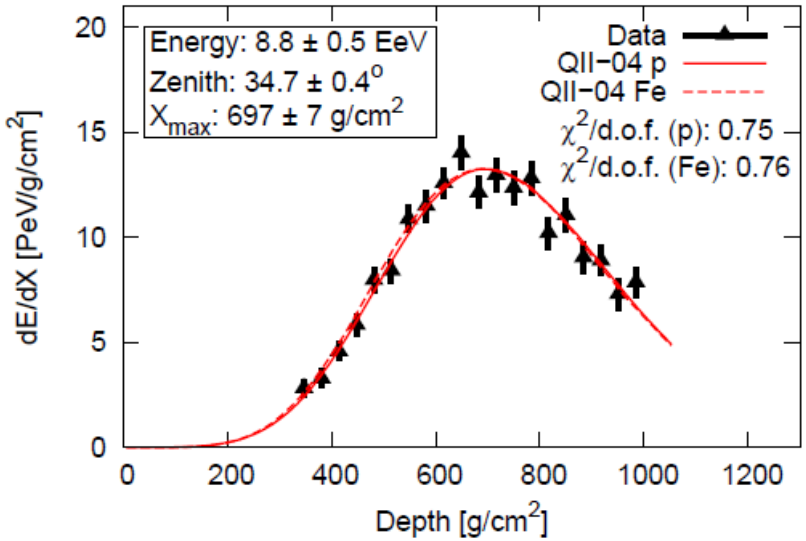
Muon Scale vs. X_{max} (FD)

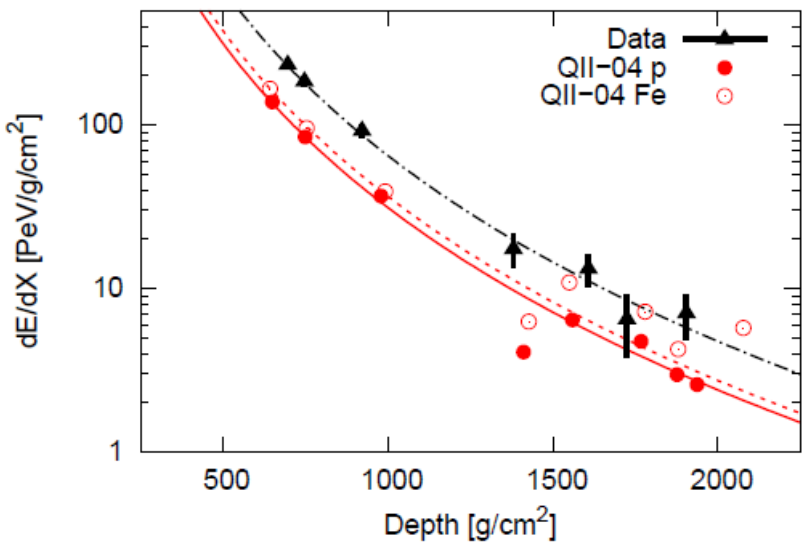


Pierre Auger Coll., PRD **D91** (2015) 3, 032003

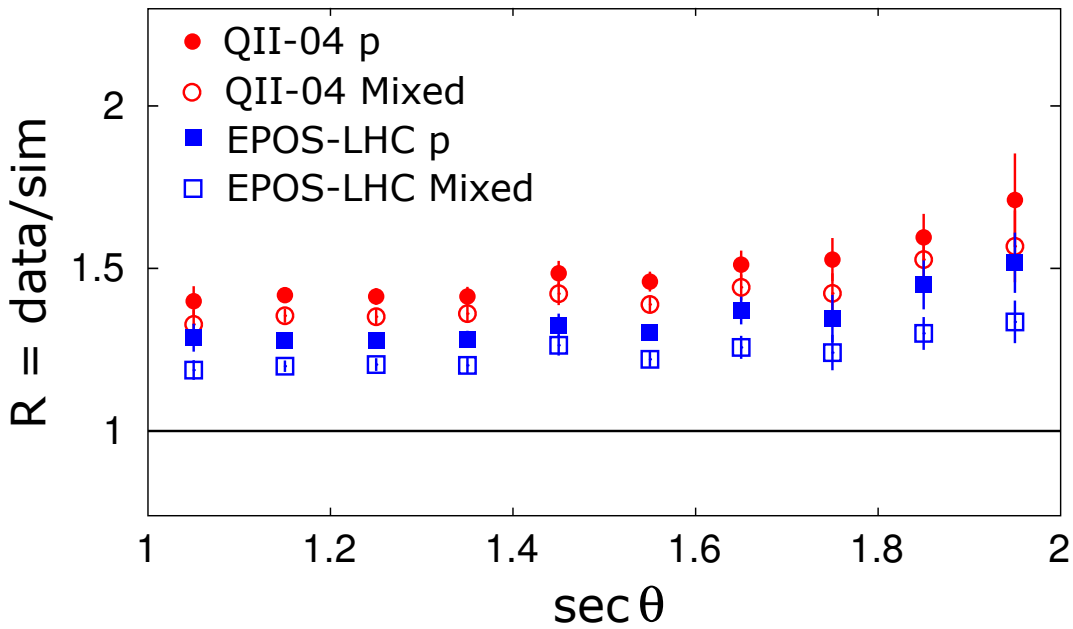
Hybrid Events, Data vs. Simulation

example:





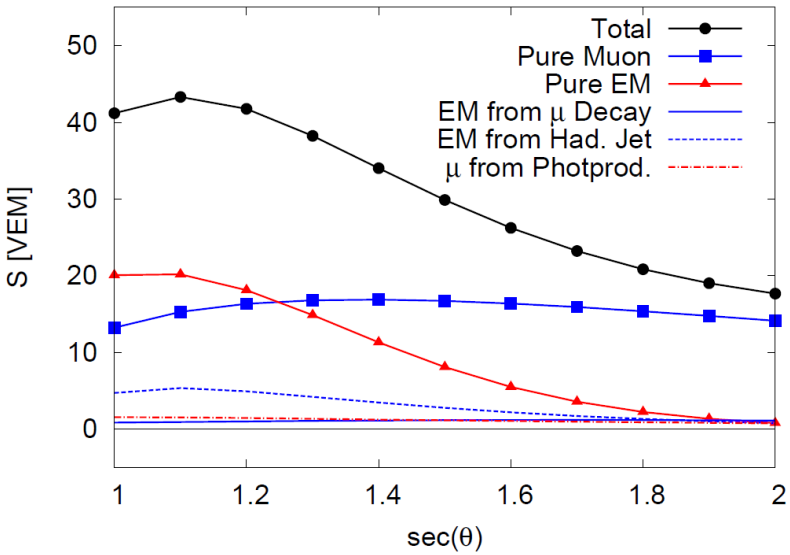
ratio of S(1000) data/MC:

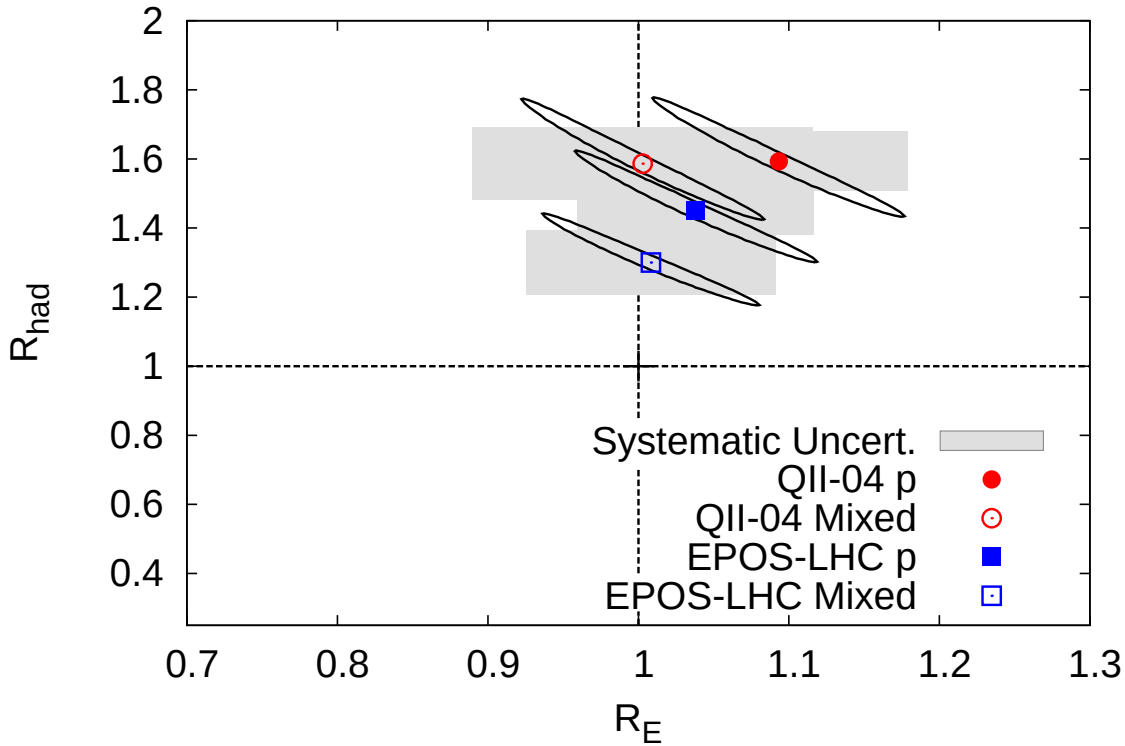


G. Farrar for the Pierre Auger Coll., Proc. 33th ICRC, arXiv:1307.5059

Hybrid Events, Data vs. Simulation

Combined fit of energy scale R_E and had. component rescaling $R_{\rm had}$





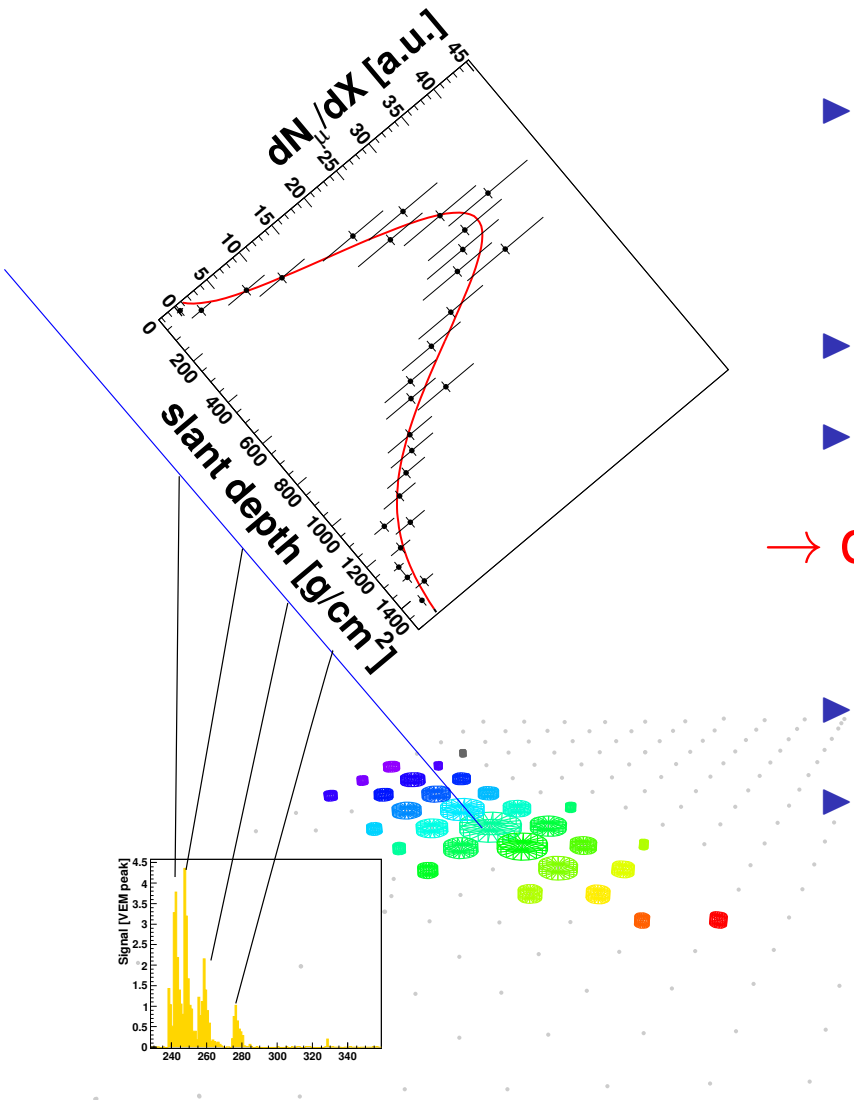
model	R_E	$R_{\rm had}$
QGSJETII-04, p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QGSJETII-04, mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS-LHC, p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS-LHC, mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

G. Farrar for the Pierre Auger Coll., Proc. 33th ICRC, arXiv:1307.5059

Outline

- Mass Composition
  - Shower Maximum (X_{max})
  - Correlation of Ground Signal and X_{max}
  - Secondaries (γ and ν)
- Hadronic Interactions
  - Proton+Air Cross Section
  - Number of Muons
  - Muon Production Depth

Muon Production Depth



- muon-rich stations:
  - events with zenith angle 55-65 deg.
  - stations with core distance $>$1.7 km
- projection of signal time traces to axis
- sum up stations

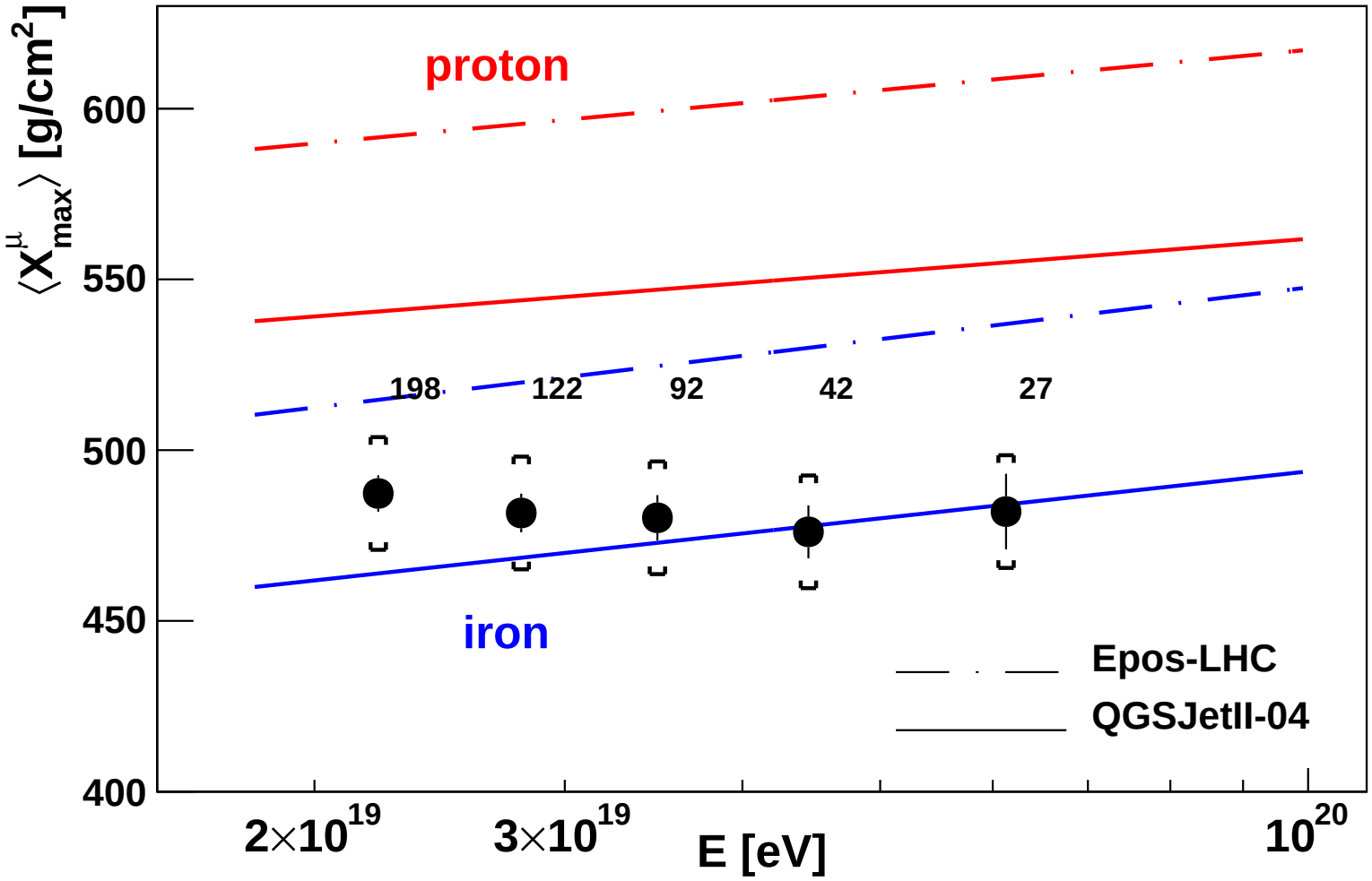
$\rightarrow$ distribution of muon production heights

- distance to slant depth conversion
- fit with Gaisser-Hillas

  $\rightarrow$ maximum at $X^{\mu}_{\max}$

L. Cazon et al., APP21 (2004), 71

X^{μ}_{max} vs. Energy

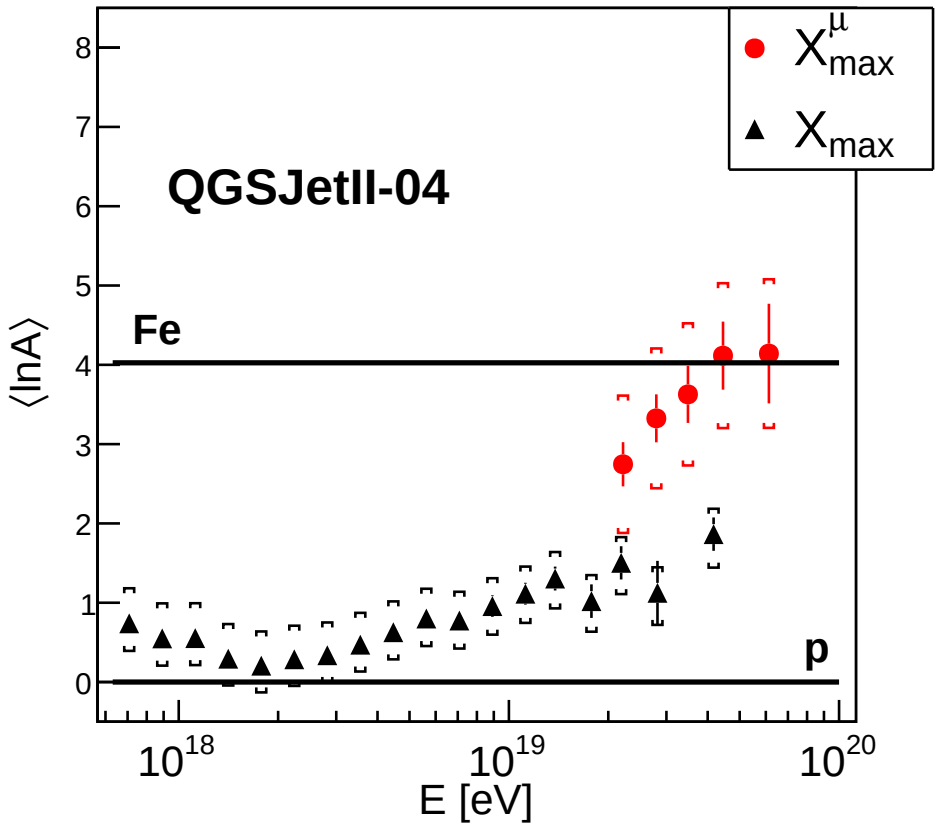


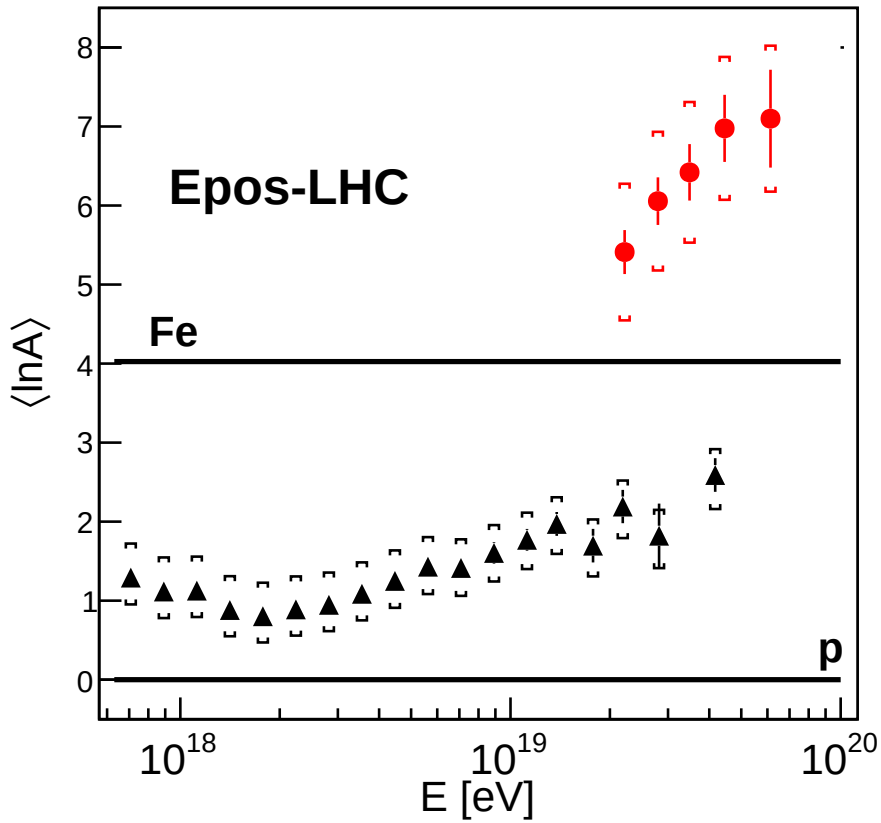
$$\mathrm{d}\langle X^{\mu}_{\mathrm{max}}\rangle/\mathrm{d}\lg E = -25 \pm 22\,(\mathrm{stat.}) \pm 21\,(\mathrm{syst.})\,\mathrm{g/cm^2/decade}$$

proton: 35.9 ± 1.2, iron: $48.0 \pm 1.2\,\mathrm{g/cm^2/decade}$

Pierre Auger Coll., PRD **D90** (2014) 1, 012012

Comparison of $\langle \ln A \rangle$ from X_{max}^{μ} and X_{max}(FD)





Pierre Auger Coll., PRD **D90** (2014) 1, 012012

Summary

- elongation rate, $\langle X_{\rm max} \rangle$, $\sigma(X_{\rm max})$, $r_G(X^*_{\rm max}/S^*(1000))$
  $\rightarrow$ mixed composition around and above the ankle
  (if LHC-inspired extrapolations are ok)
  $\rightarrow$ nature of flux suppression? See Jim's talk!
- neutrinos and photons
  $\rightarrow$ start probing cosmogenic fluxes from 100% *p*
- *p*+air cross section
  $\rightarrow$ compatible with model extrapolations
- muon number
  $\rightarrow$ at odds with predictions for mixed composition
- muon production depth vs. $X_{\rm max}$
  $\rightarrow$ QGSjetII-04: marginally compatible, EPOS-LHC: incompatible

Please check arXiv:1509.03732 for the complete list of recent Auger results!