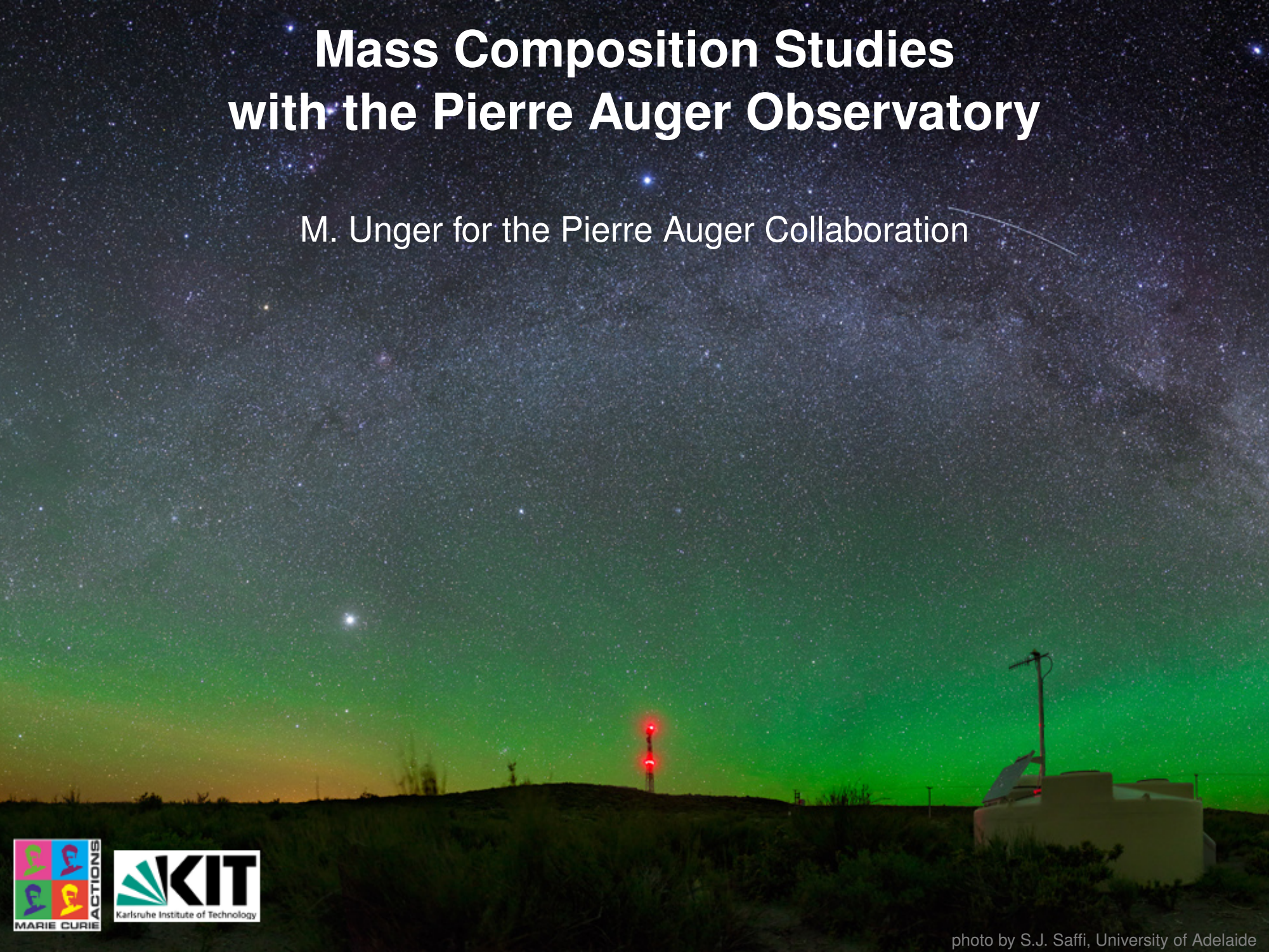
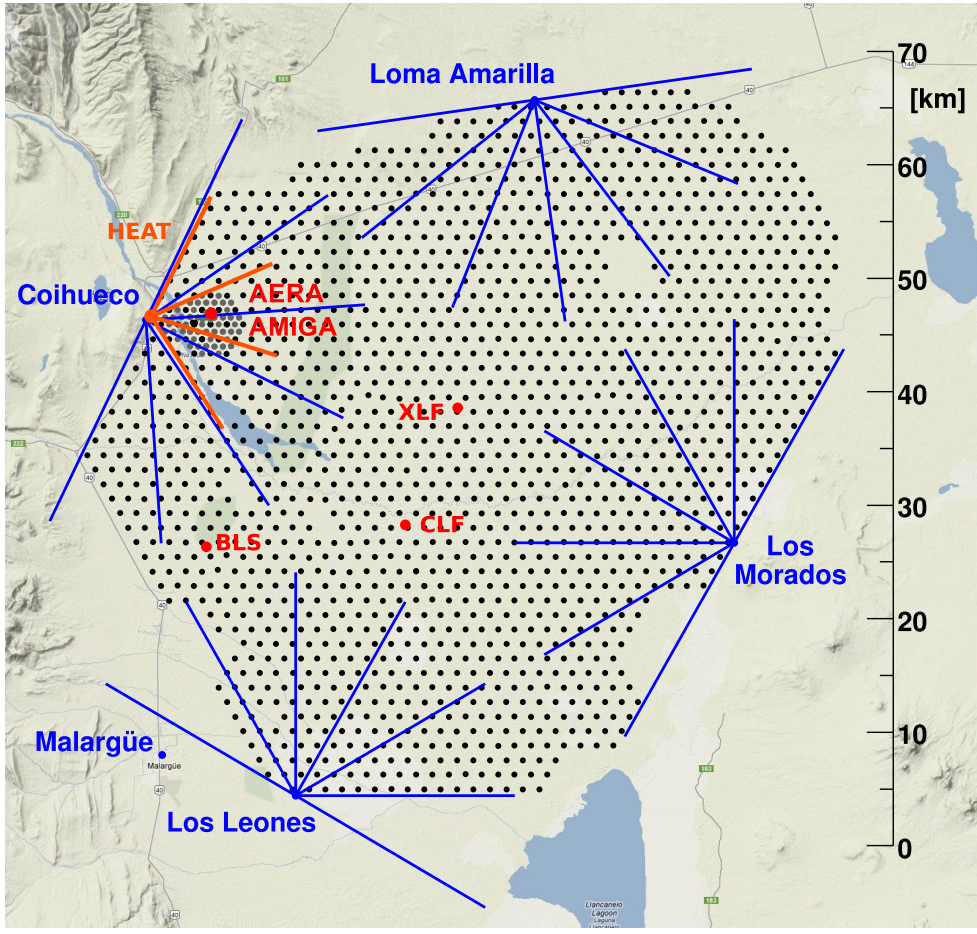
Mass Composition Studies with the Pierre Auger Observatory

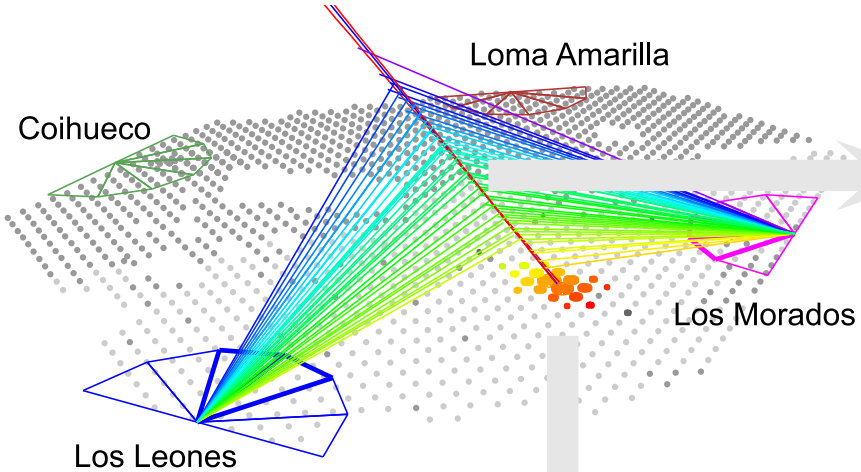
M. Unger for the Pierre Auger Collaboration

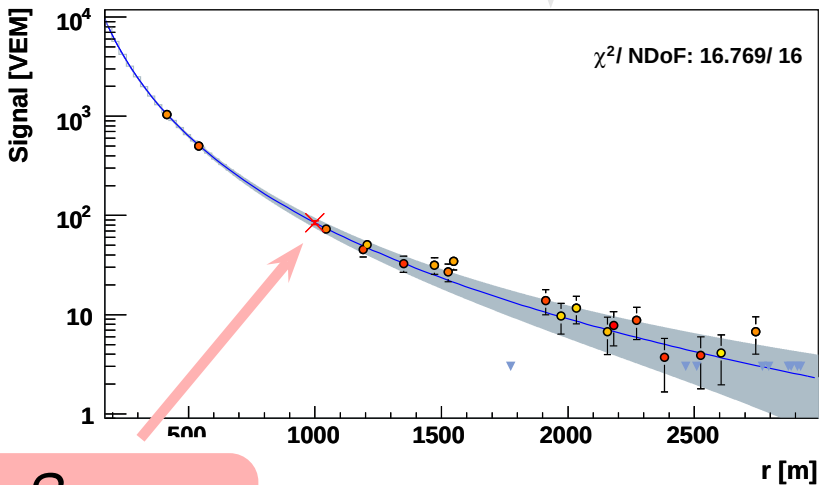


The Pierre Auger Observatory



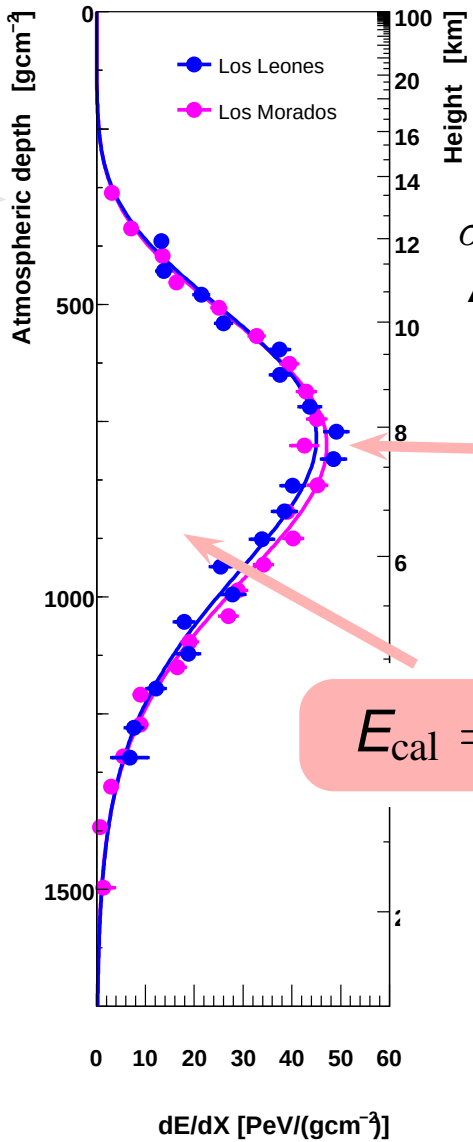
Air Shower Detection with the Pierre Auger Observatory





S_{1000}

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



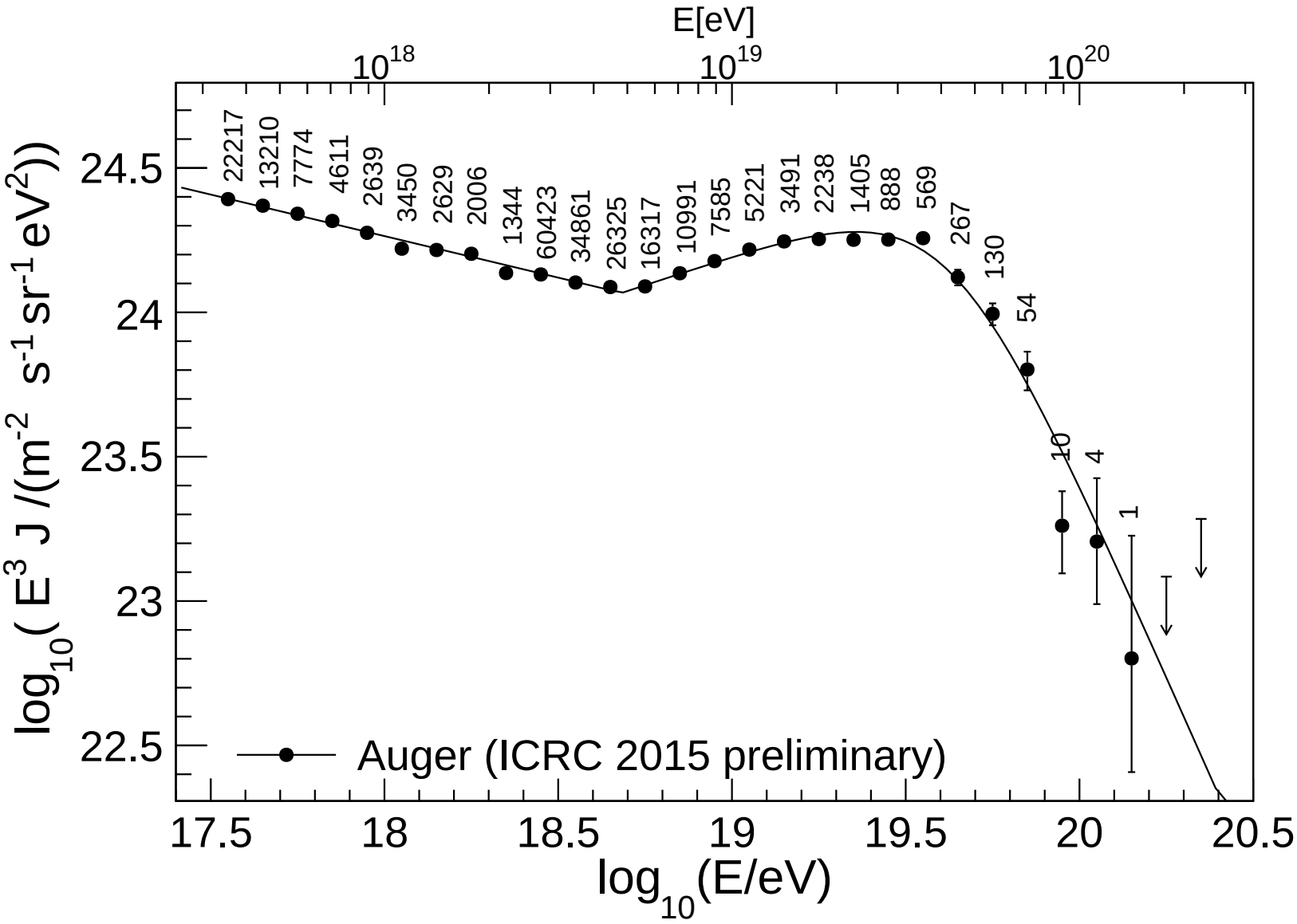
$\sigma_{X_{\max}} \leq 20\,\text{g/cm}^2$
$\Delta_{\text{sys}} \leq 10\,\text{g/cm}^2$

$X_{\max}$

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

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

Energy Spectrum of UHECRs



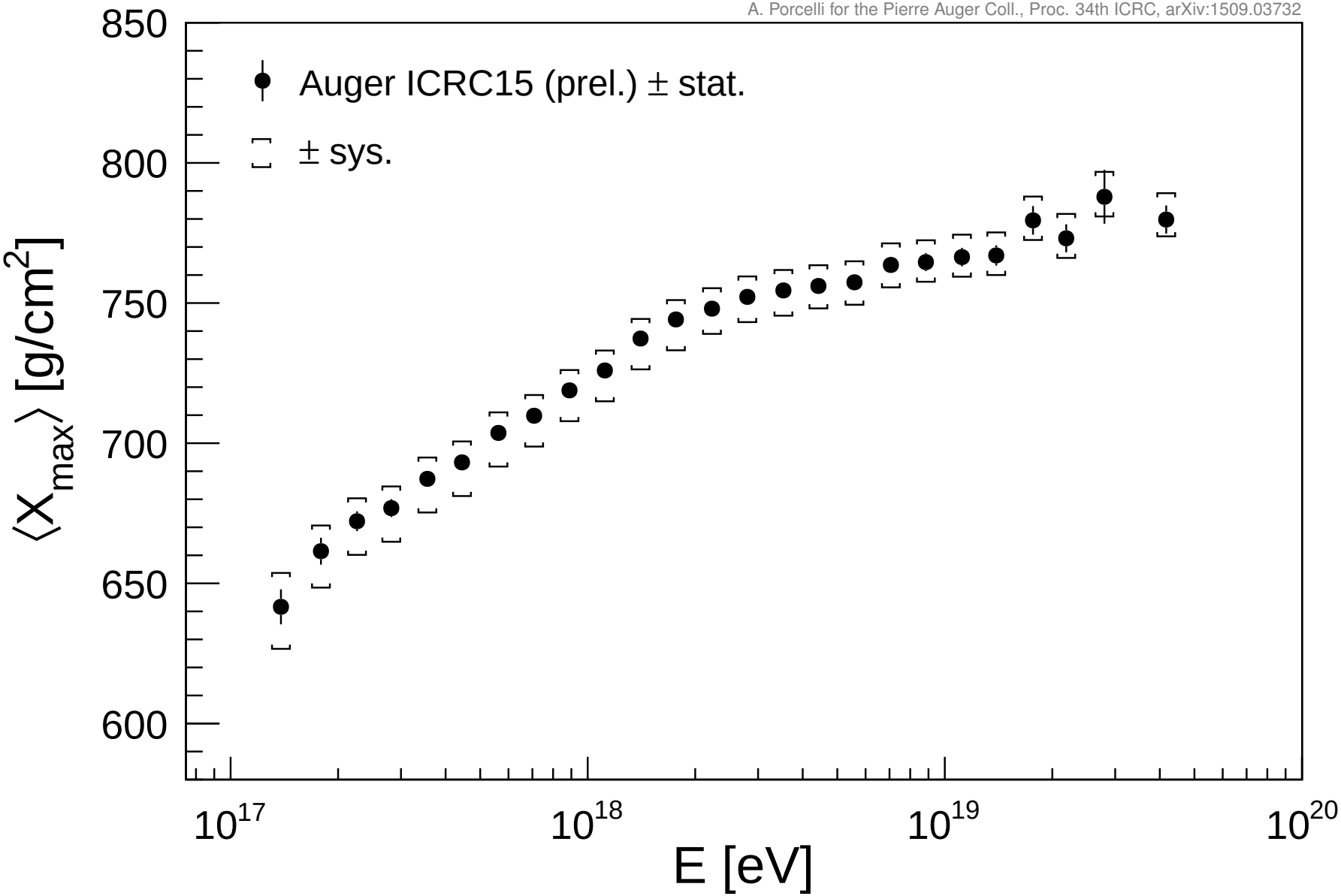
exposure at UHE: $(5.34 \pm 0.13) \times 10^4$ km^2 sr yr

Mass Composition Studies

(a) Longitudinal Development of Air Showers

Average Shower Maximum vs. Energy

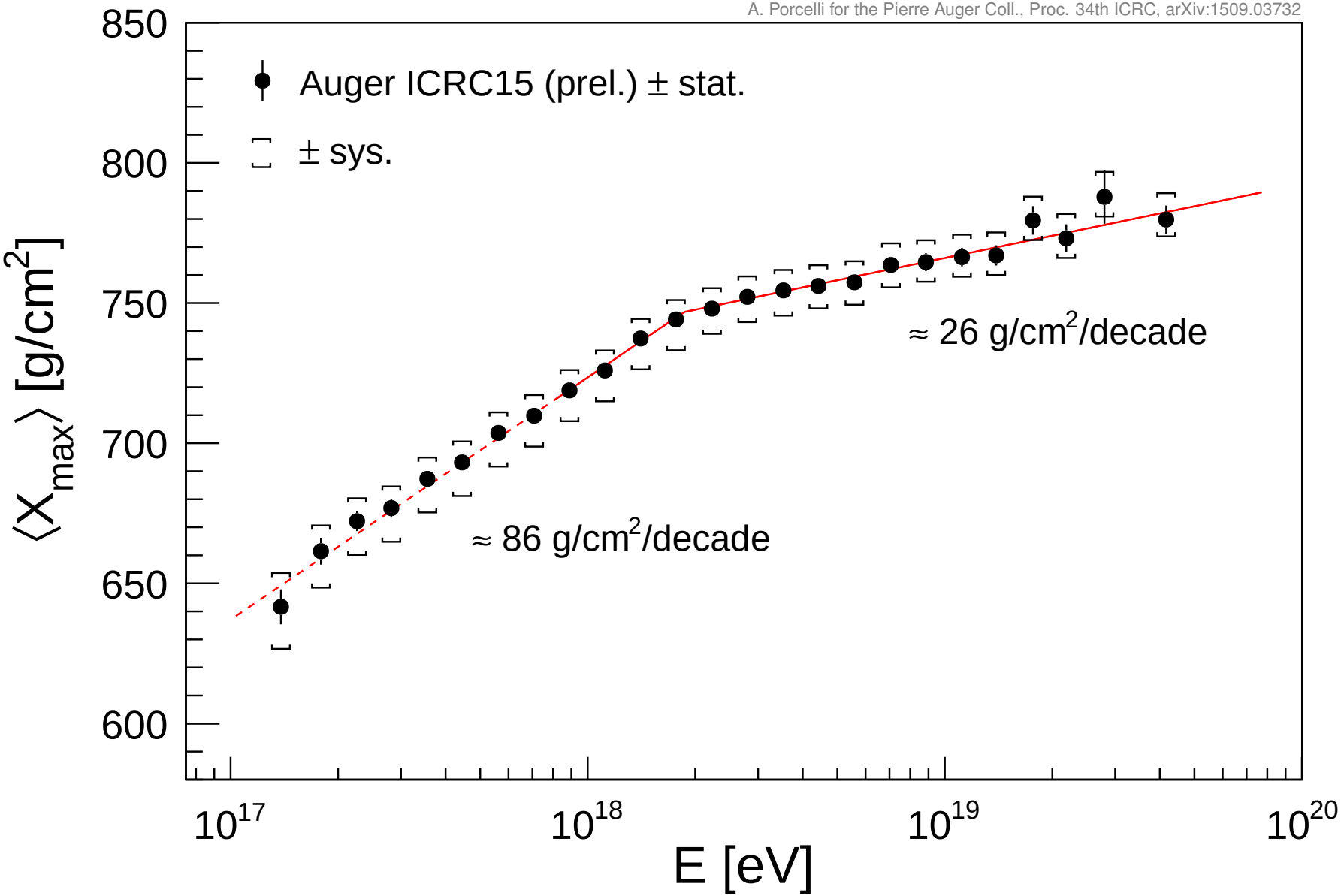
A. Porcelli for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732



$\langle X_{\max} \rangle \propto D_{10} \lg (E/A)$ (mass A, energy E, elongation rate $D_{10} \sim 54 - 64$ g/cm^2/decade)

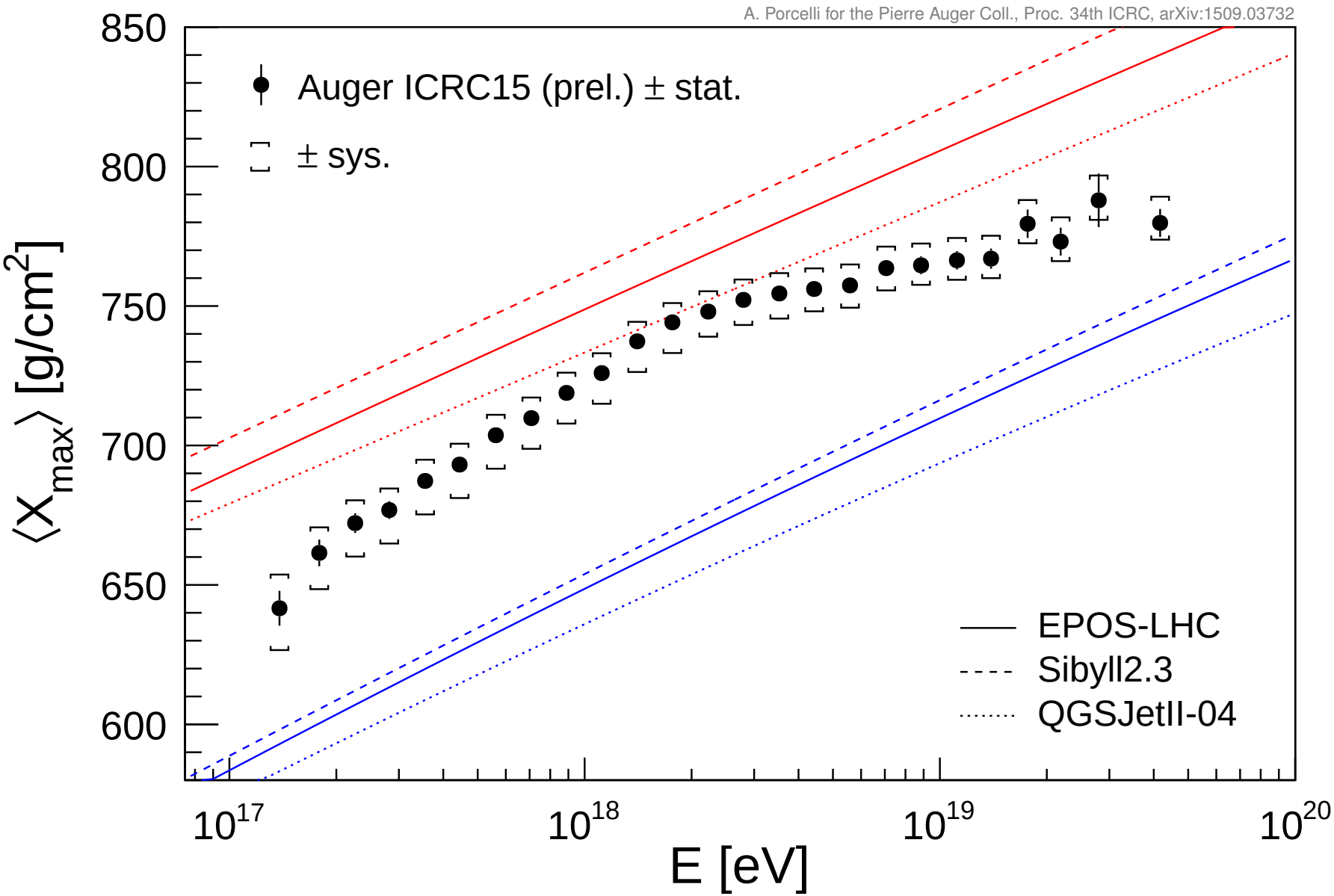
Average Shower Maximum vs. Energy

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



$\langle X_{\max} \rangle \propto D_{10} \lg(E/A)$ (mass A, energy E, elongation rate $D_{10} \sim 54 - 64$ g/cm^2/decade)

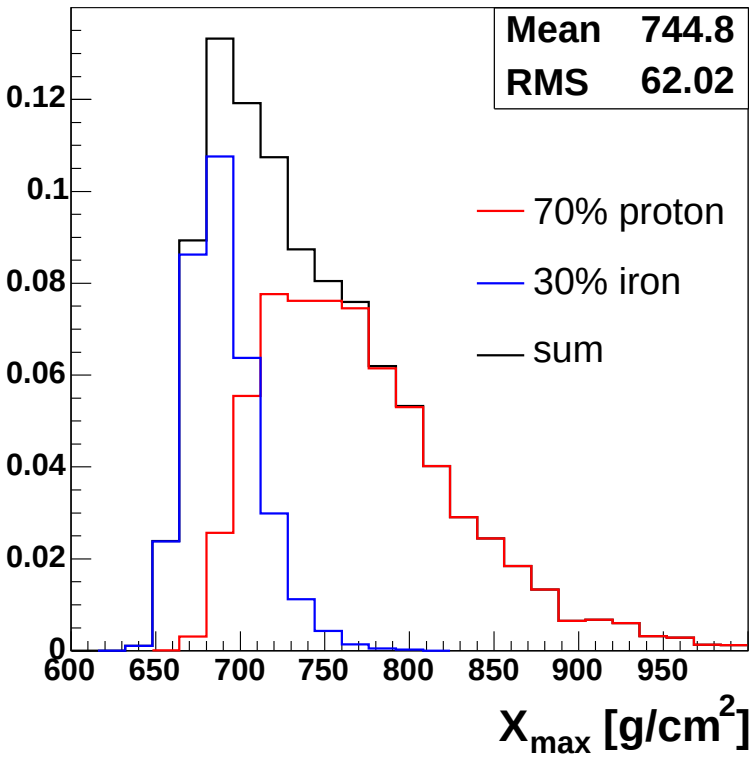
Average Shower Maximum vs. Energy

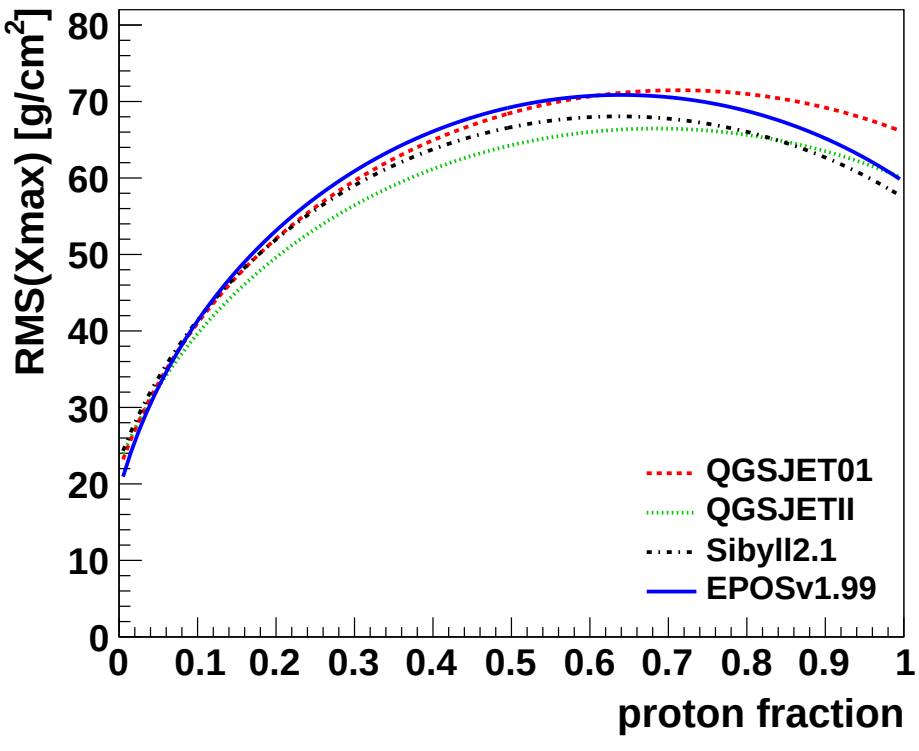


$\langle X_{\max} \rangle \propto D_{10} \lg(E/A)$ (mass A, energy E, elongation rate $D_{10} \sim 54 - 64$ g/cm^2/decade)

Standard Deviation of X_{max}

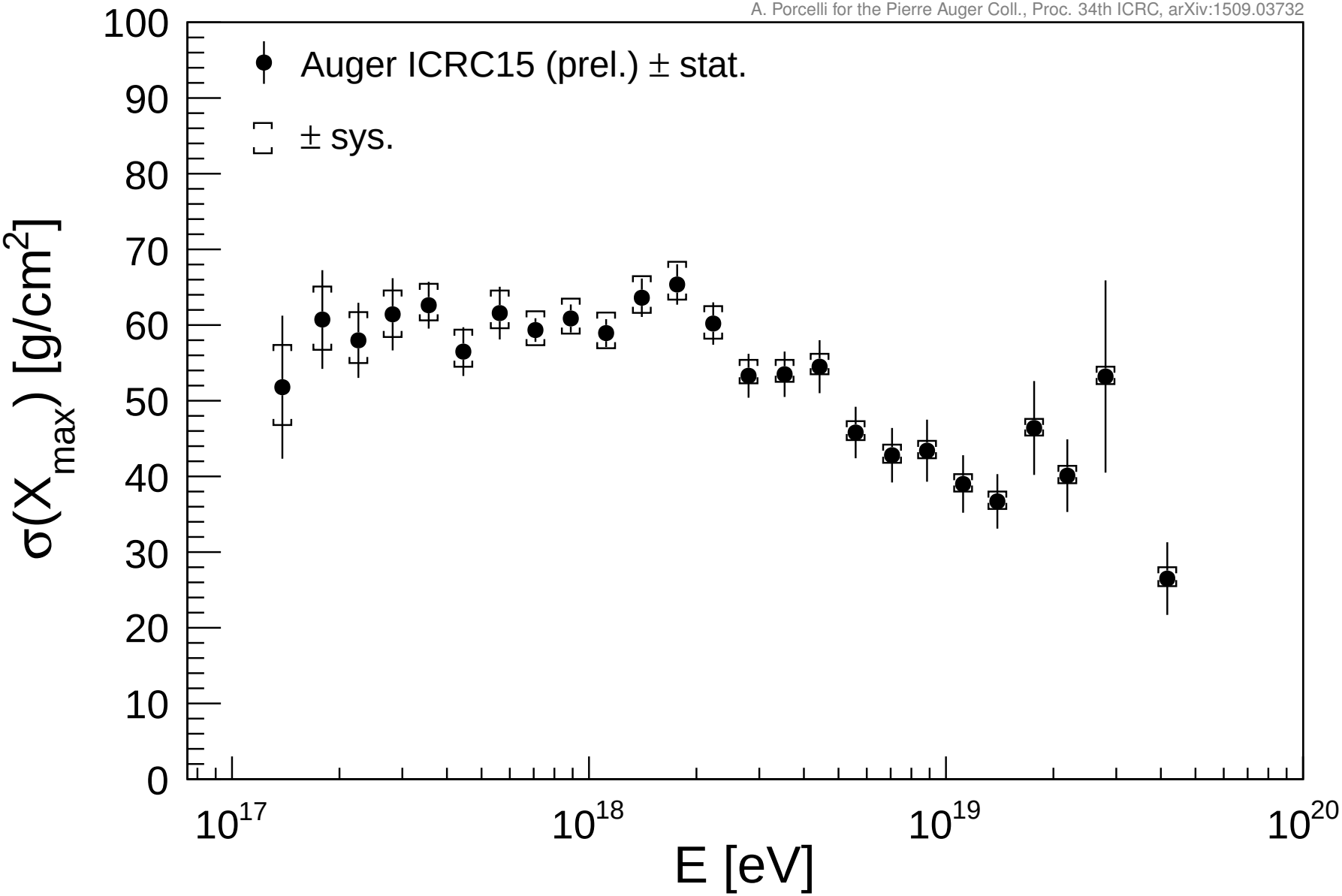
- $\sigma(X_{\max})_A^2 = \lambda_A^2 + \sigma(X_{\max} - X_{\text{first}})_A^2$
- $\sigma(X_{\max})_p > \sigma(X_{\max})_A > \sigma(X_{\max})_p/\sqrt{A}$
- mixed composition:
  $\sigma(X_{\max})^2 = \langle\sigma_i^2\rangle + \left(\left\langle\langle X_{\max}\rangle_i^2\right\rangle - \langle X_{\max}\rangle^2\right)$



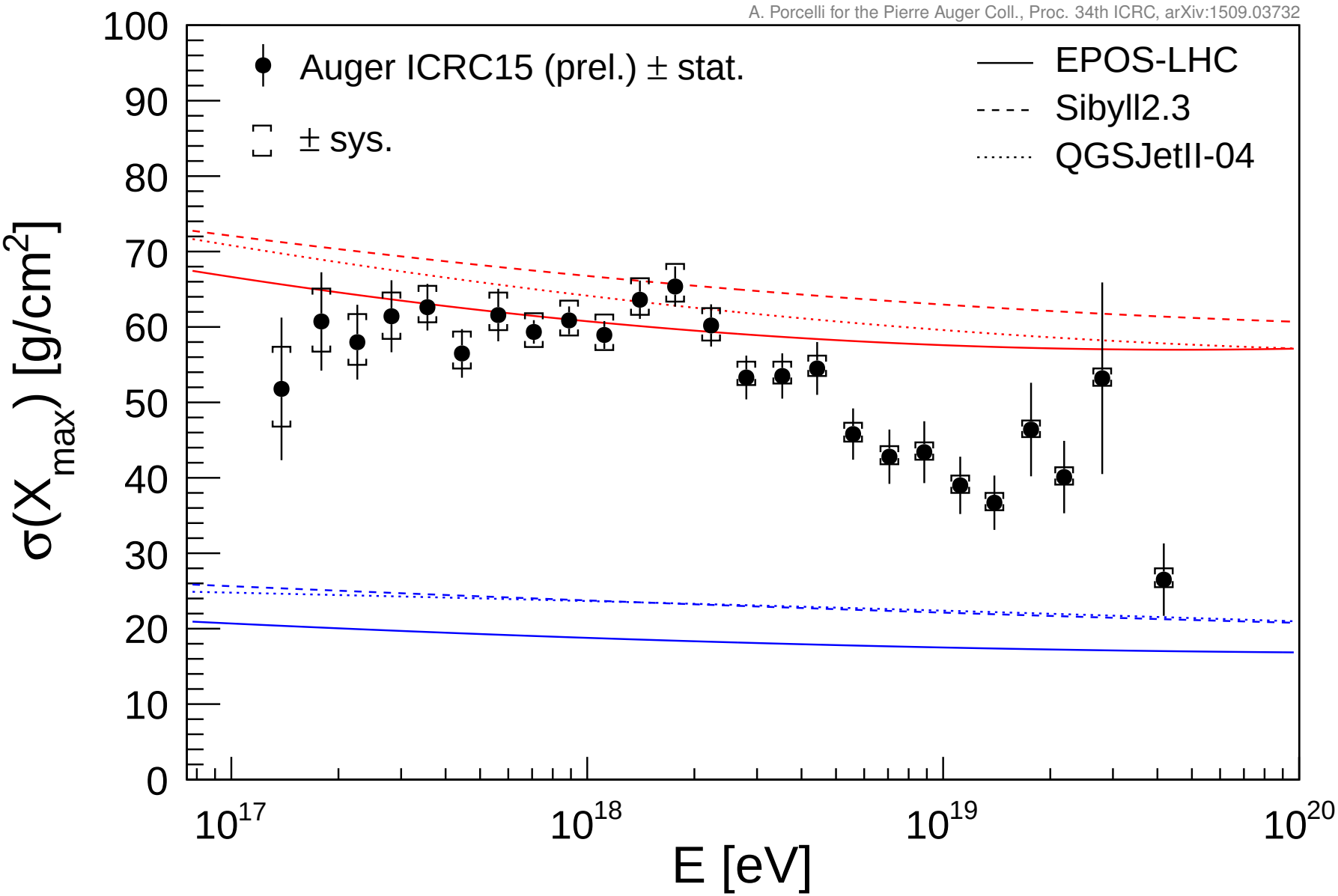


Standard Deviation of X_{max} vs. Energy

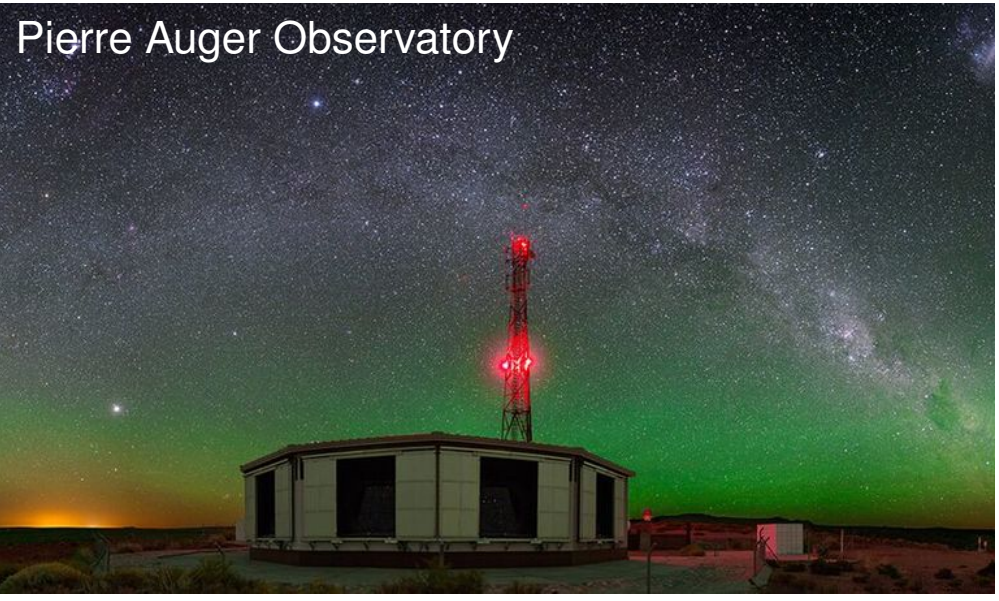
A. Porcelli for the Pierre Auger Coll., Proc. 34th ICRC, arXiv:1509.03732



Standard Deviation of X_{max} vs. Energy



Average Shower Maximum: Comparison to Telescope Array



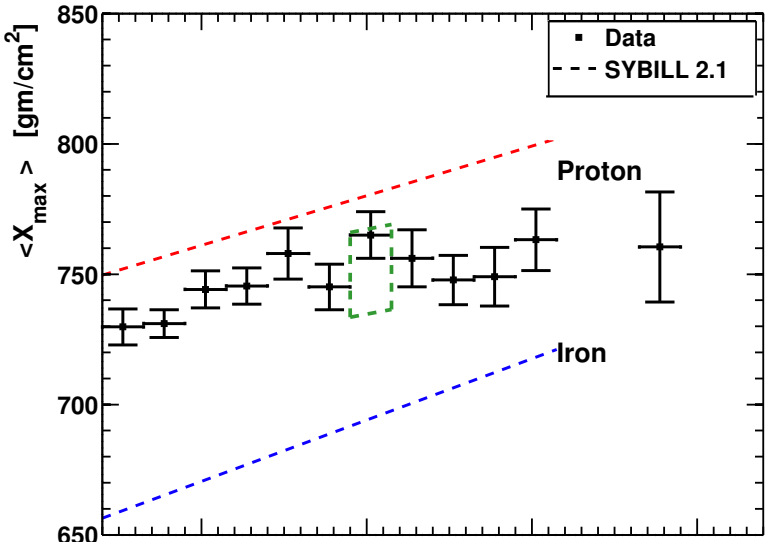
Auger-TA Working Group on Composition (UHECR conference series)

UHECR16, Kyoto

Comparison to Telescope Array

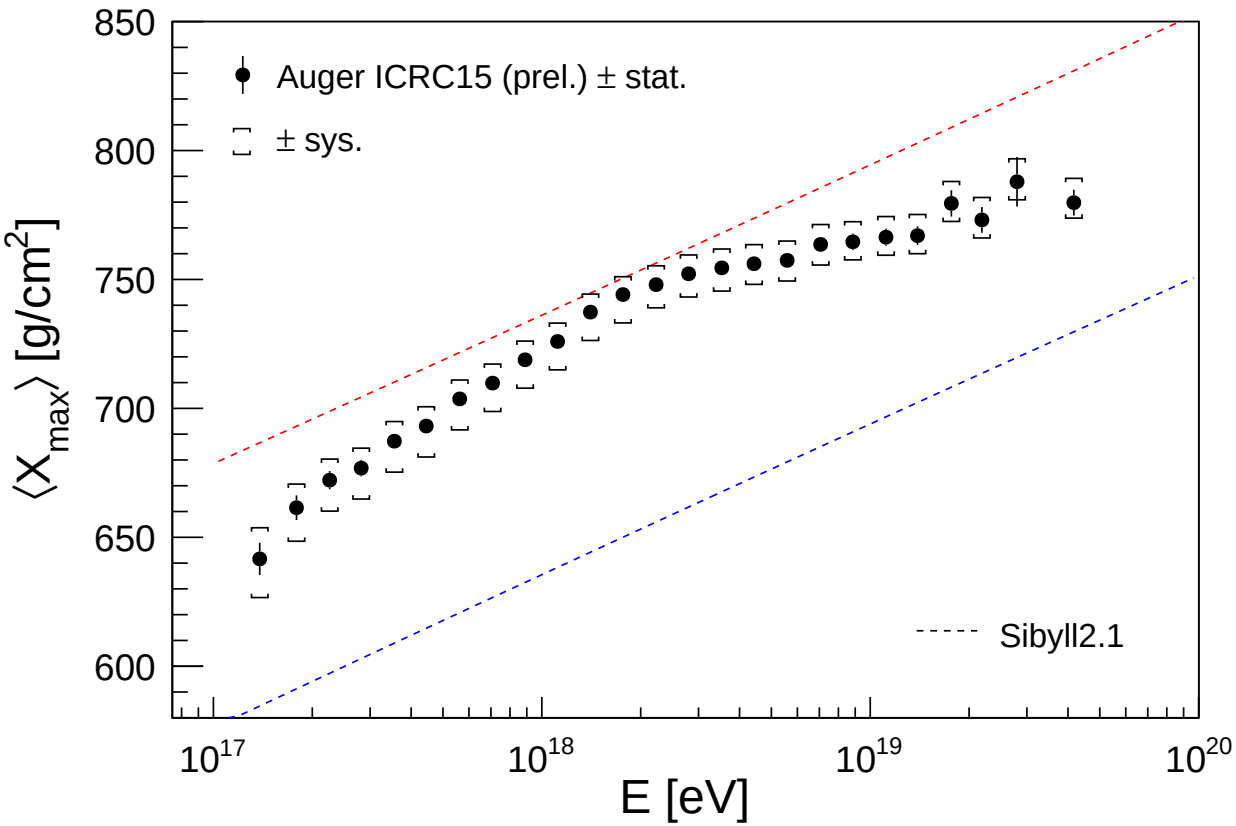
TA: $\langle X_{\max} \rangle$ biased by acceptance

TA Coll., APP **64** (2014) 49

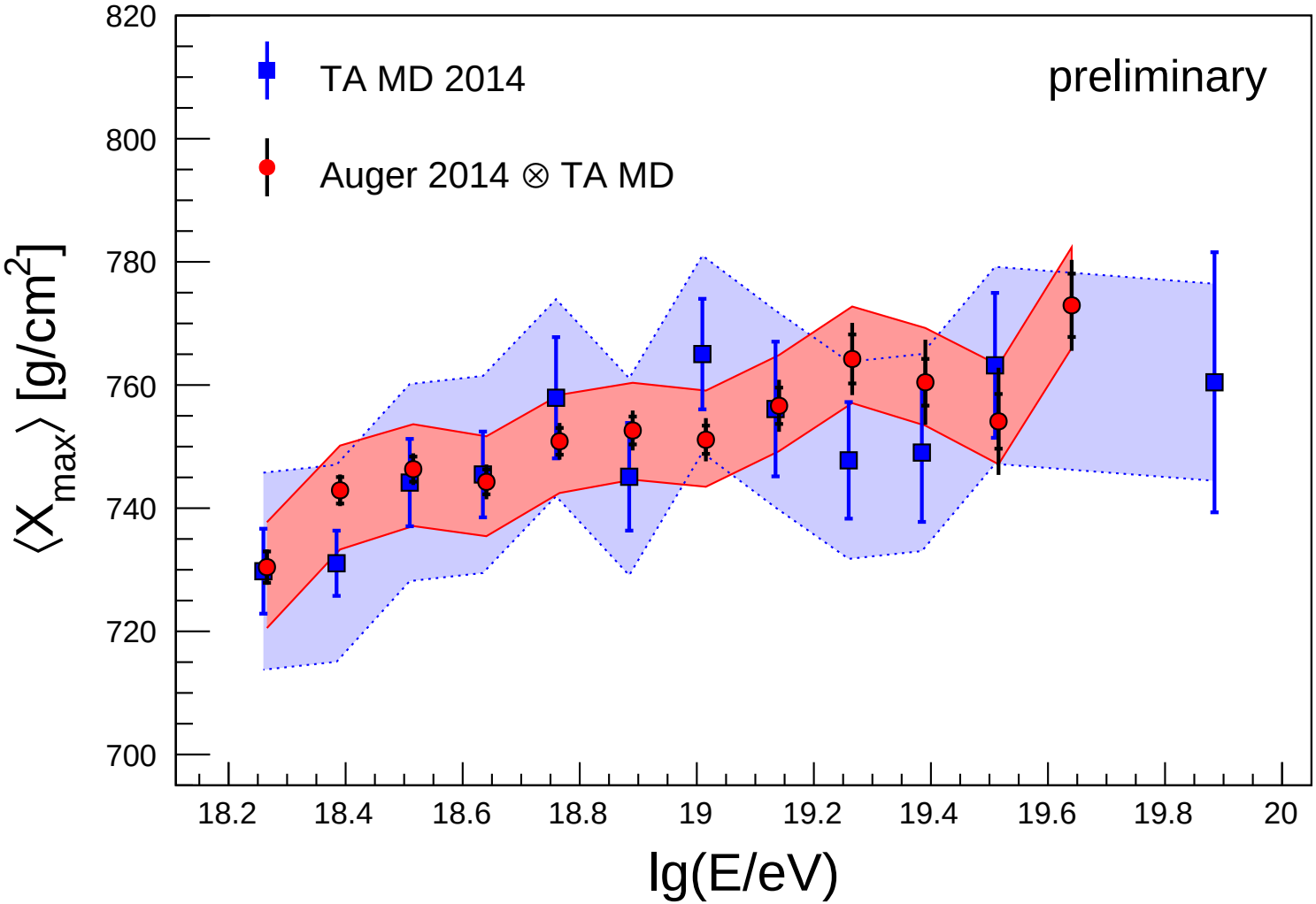


Auger: unbiased $\langle X_{\max} \rangle$

PRD **90** (2014) 122005 & ICRC15 prel.

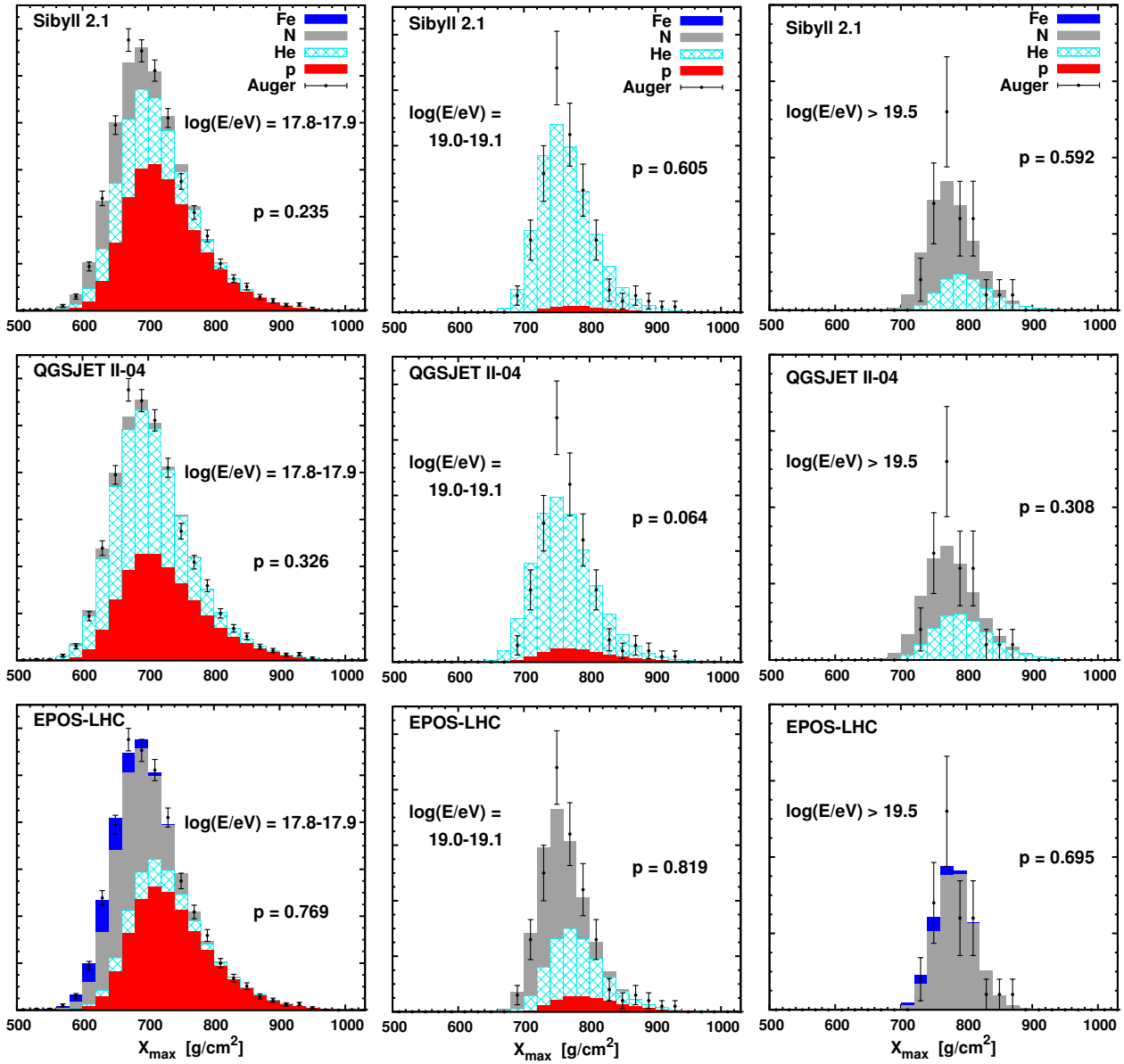


Comparison to Telescope Array



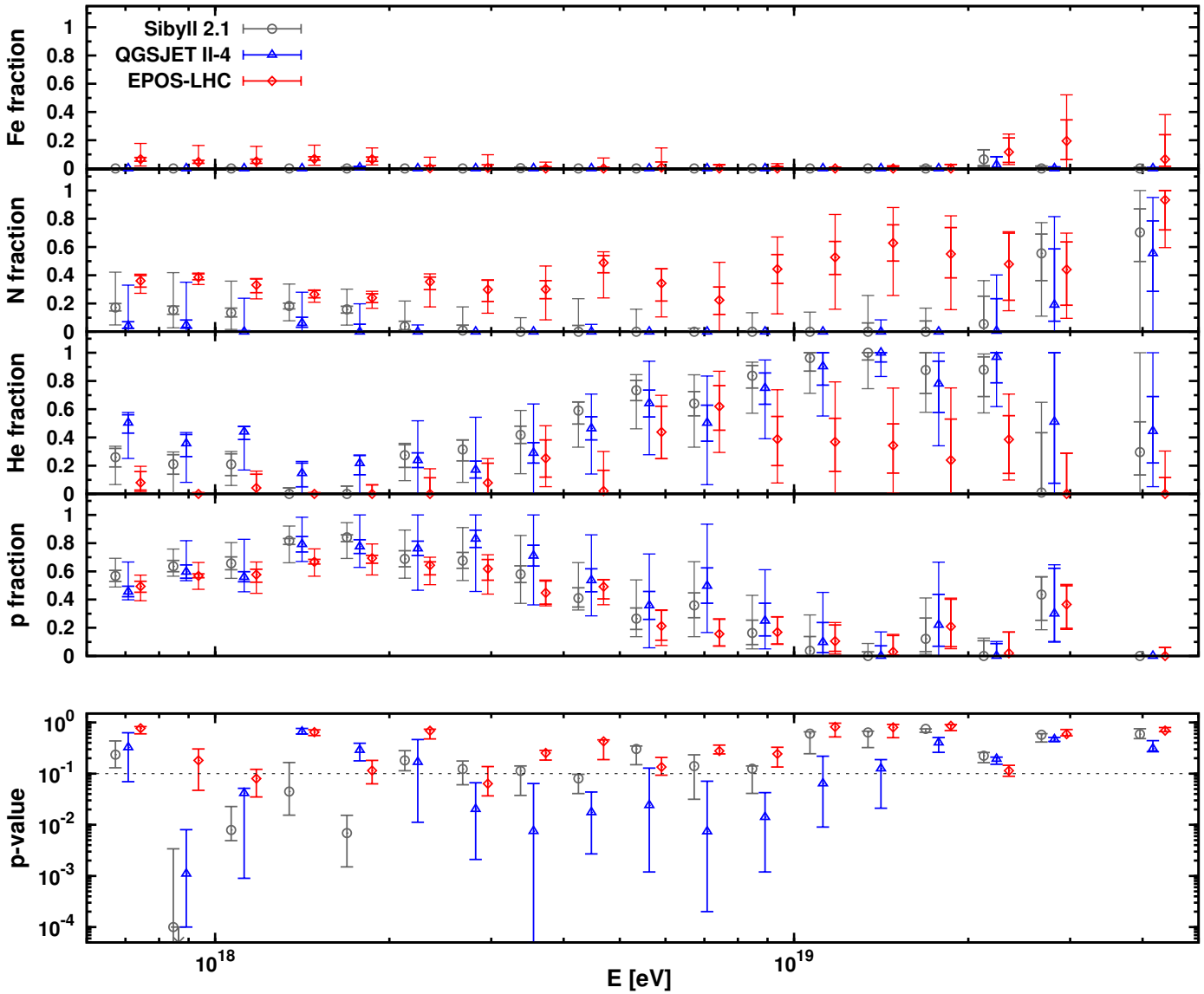
$$\langle \Delta \rangle = (2.9 \pm 2.7\ (\text{stat.}) \pm 18\ (\text{syst.}))\ \text{g/cm}^2$$

Fit of X_{max} Distributions



Pierre Auger Coll., PRD **90** (2014) 12, 122006

Fit of X_{max} Distributions

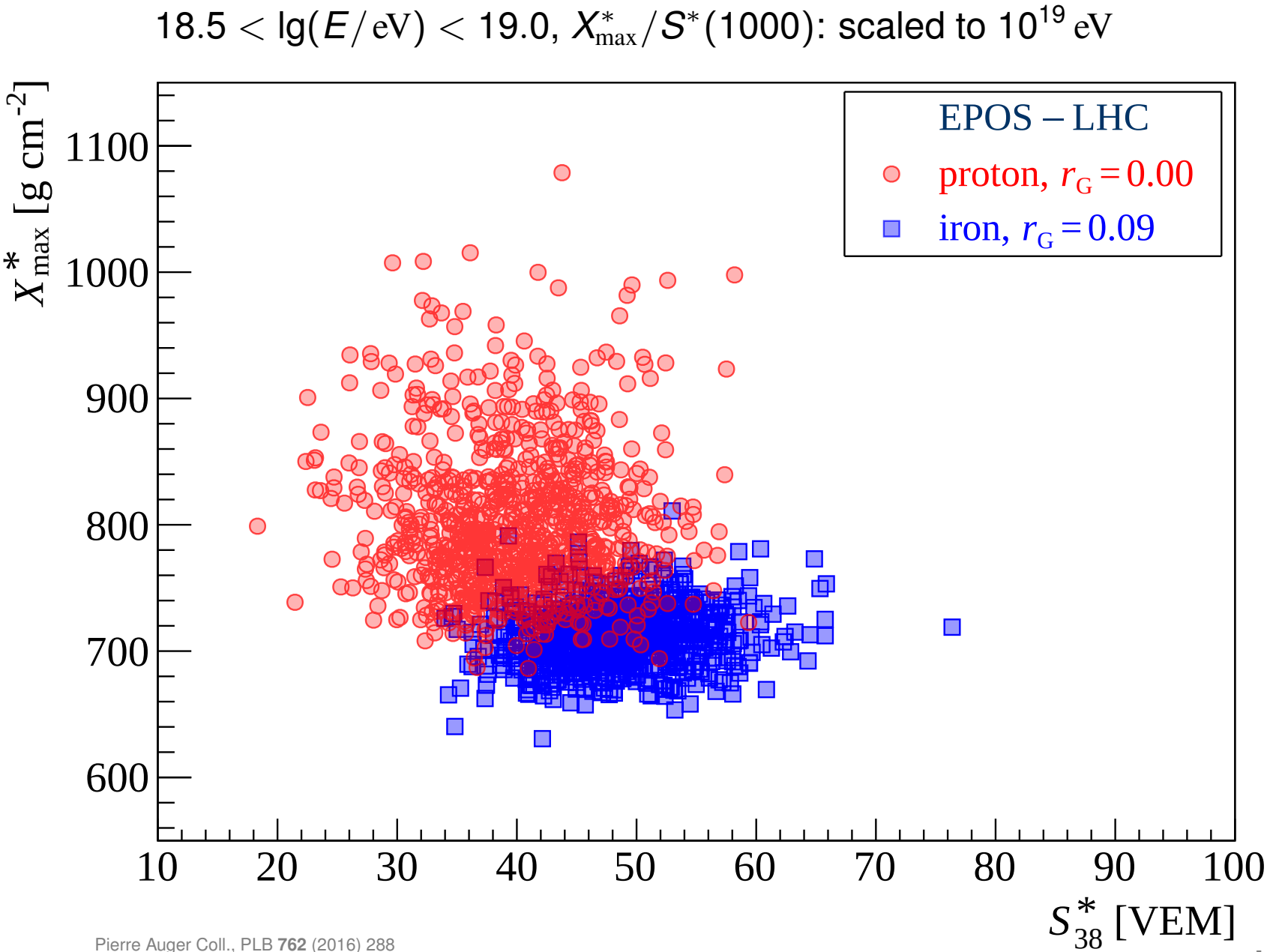


Pierre Auger Coll., PRD **90** (2014) 12, 122006

Mass Composition Studies

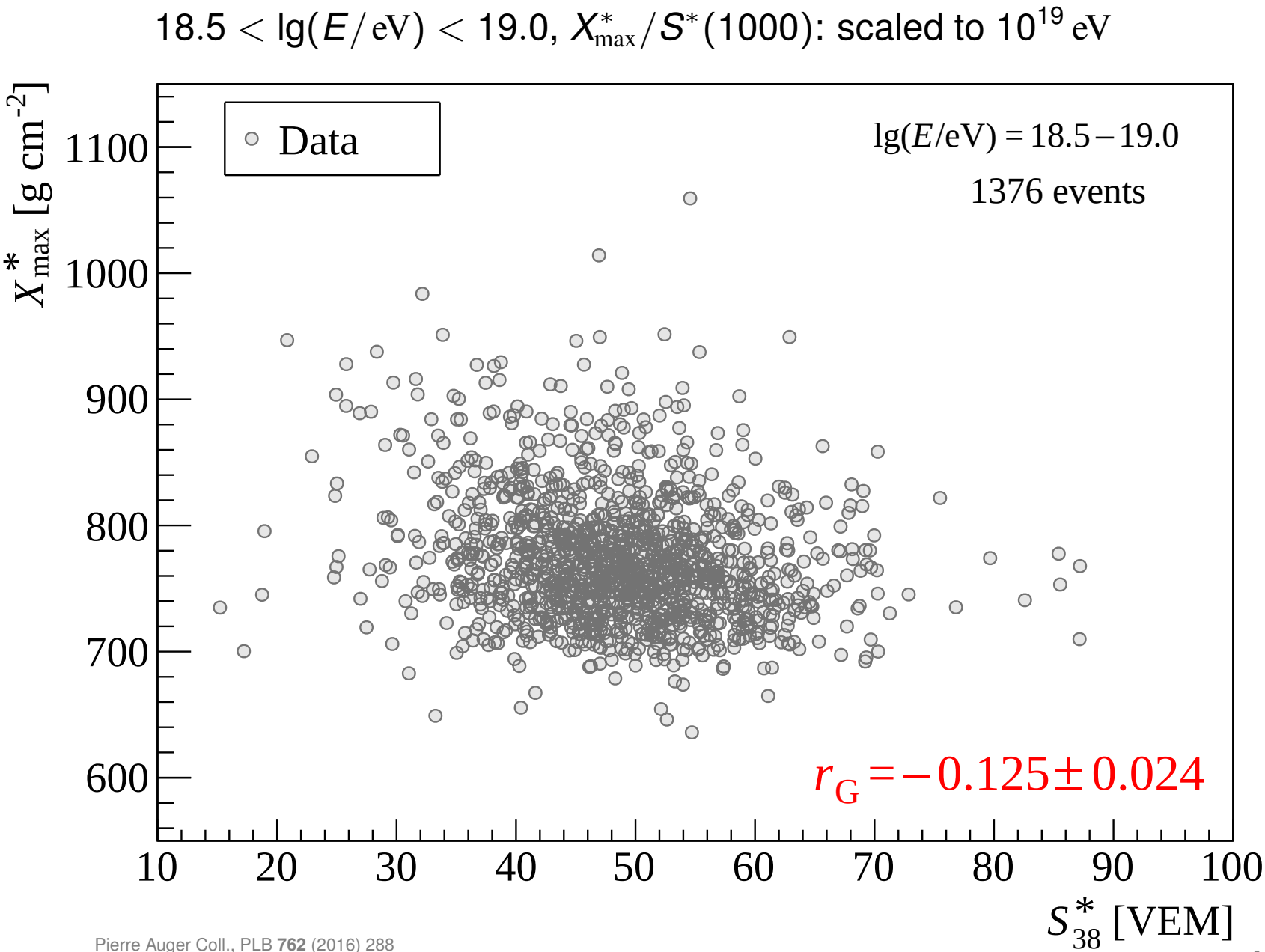
(b) Correlation of X_{max} and Ground Signal

Correlation of X_{max} and Ground Signal



Pierre Auger Coll., PLB **762** (2016) 288

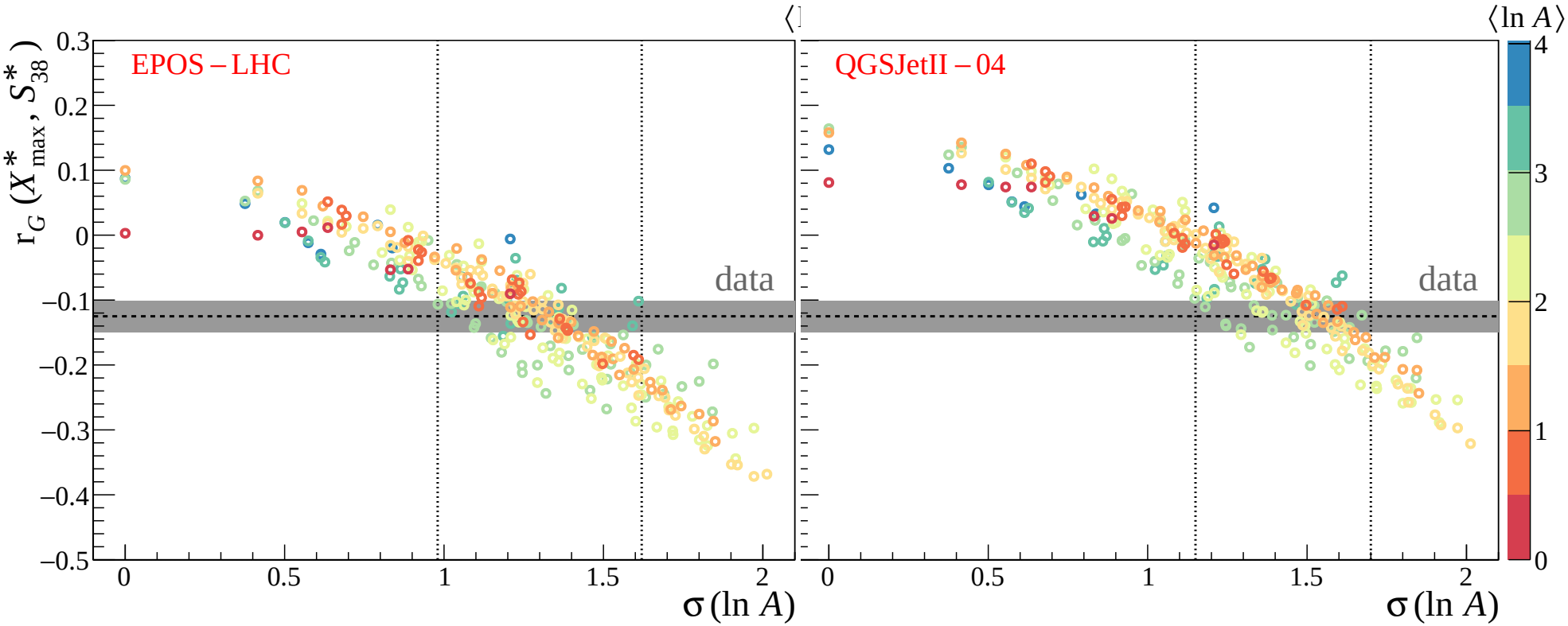
Correlation of X_{max} and Ground Signal



Pierre Auger Coll., PLB **762** (2016) 288

Correlation of X_{max} and Ground Signal

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



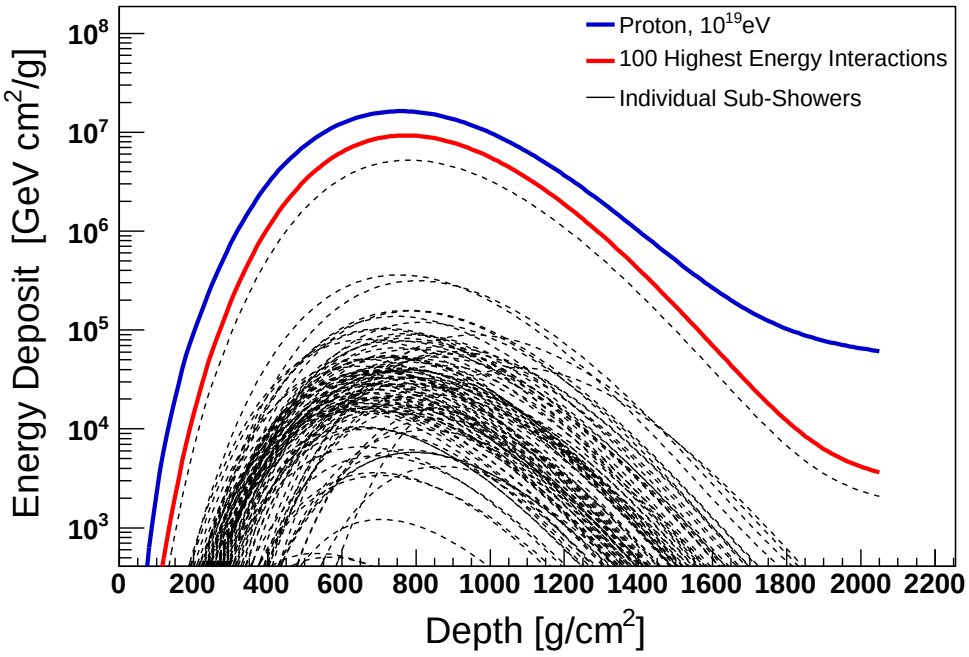
→mixed composition at the ankle, p-He mixtures excluded.

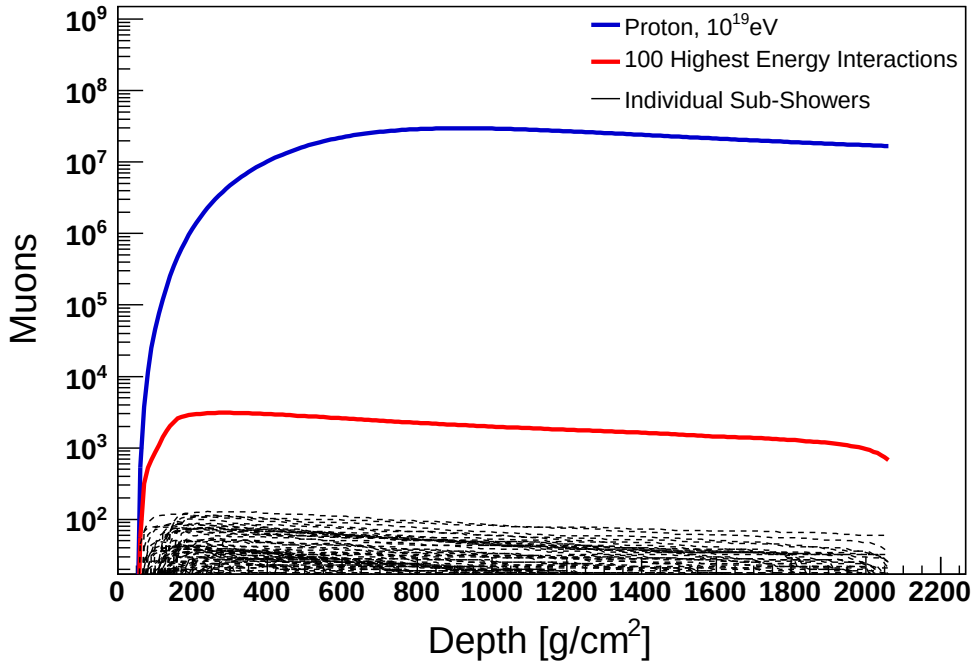
Pierre Auger Coll., PLB **762** (2016) 288

Mass Composition Studies

(c) Surface Detector Data

Muons in Air Showers

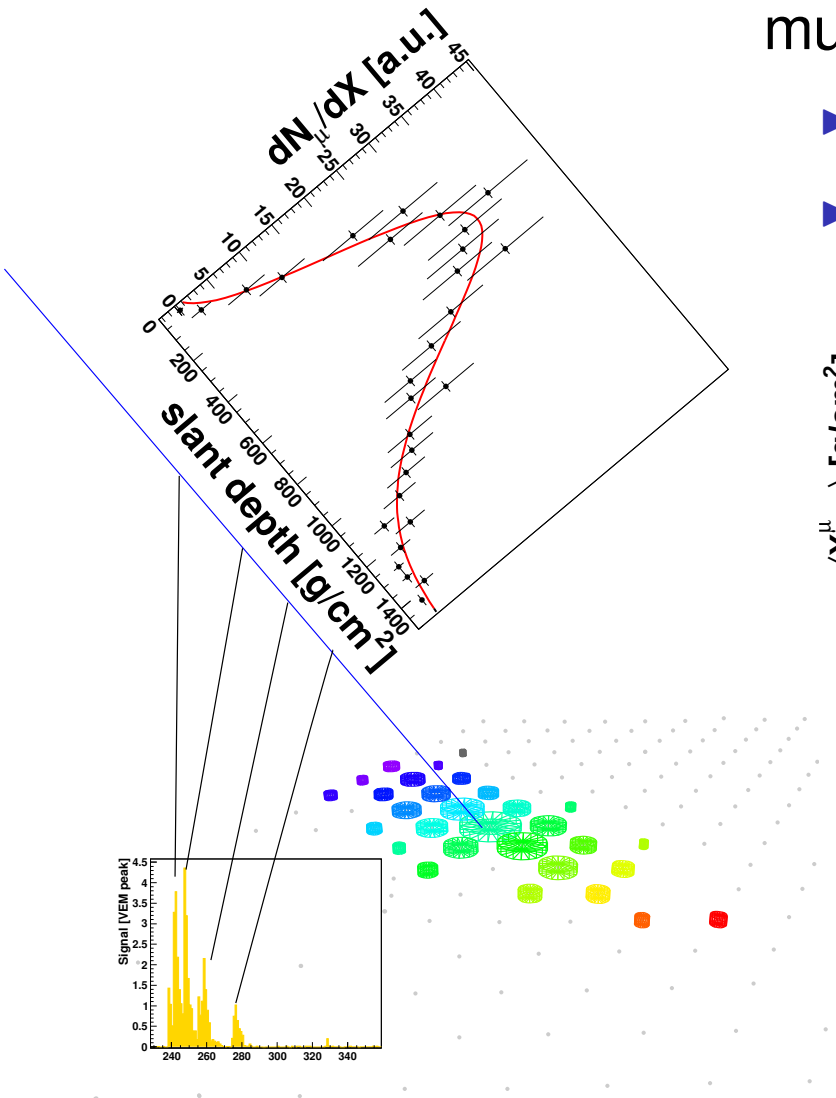




R. Ulrich, APS 2010

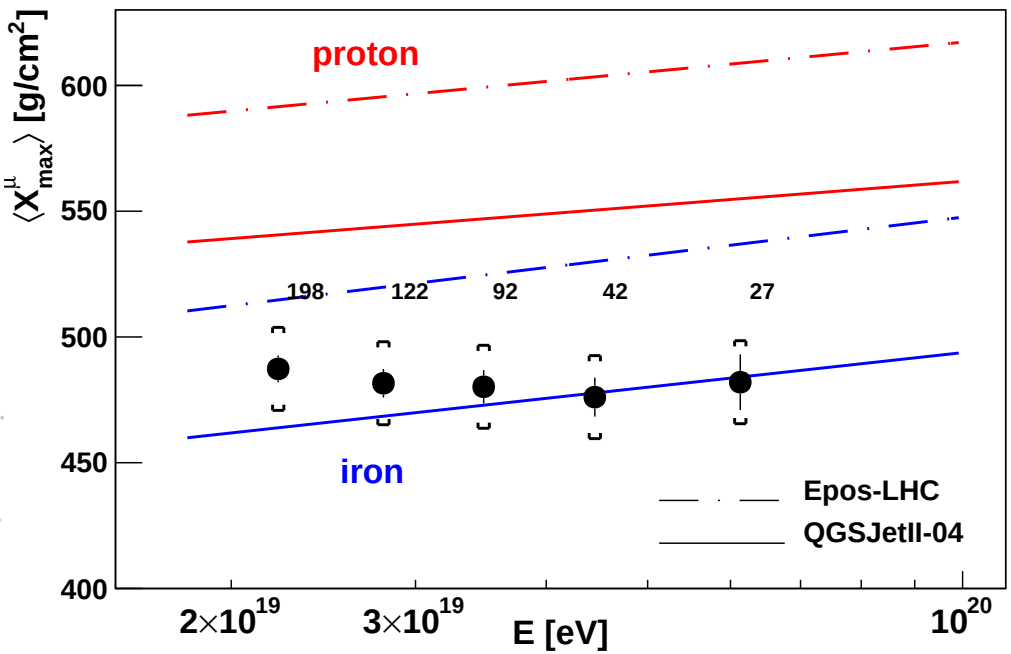
- muons from $\pi^{\pm}$ decay at late stage of cascade ($\lambda_{\rm dec} \sim \lambda_{\rm int}$)
  $\rightarrow$ number of generations ~ 6 at 10^{19} eV
  $\rightarrow$ amplified sensitivity to hadronic interactions
- $X_{\rm max}$ is dominated by first interaction

Muon Production Depth



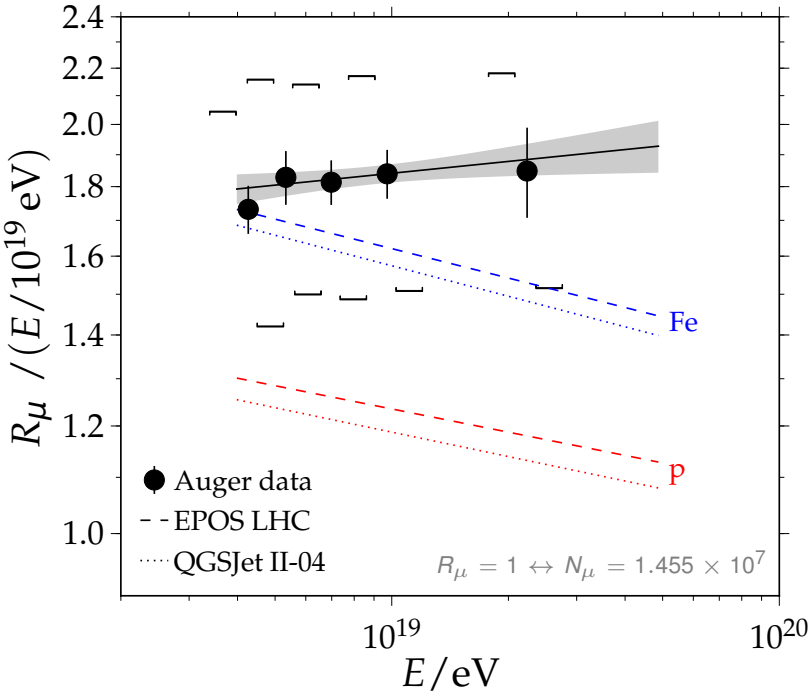
muon-rich stations:

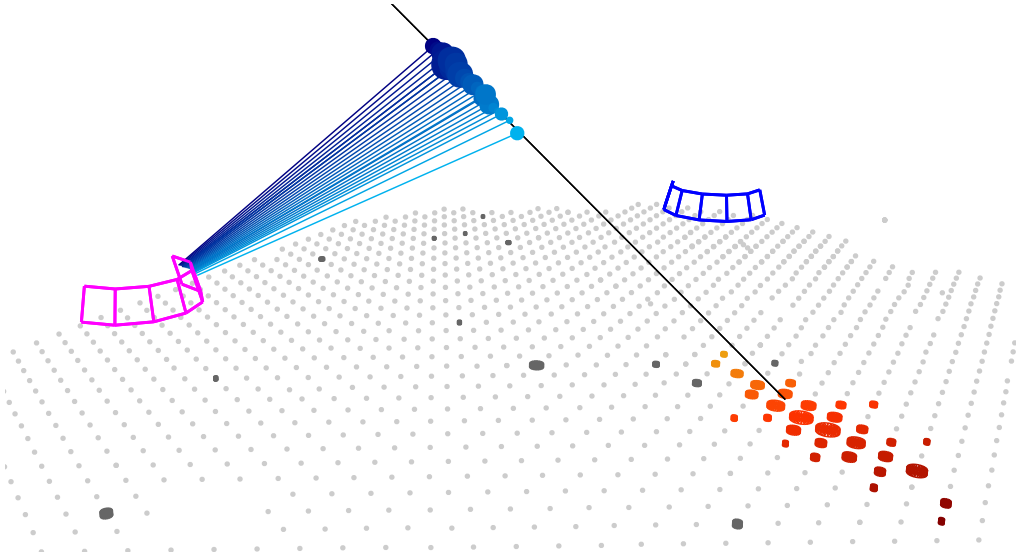
- events with zenith angle 55-65 deg.
- stations with core distance $>$1.7 km

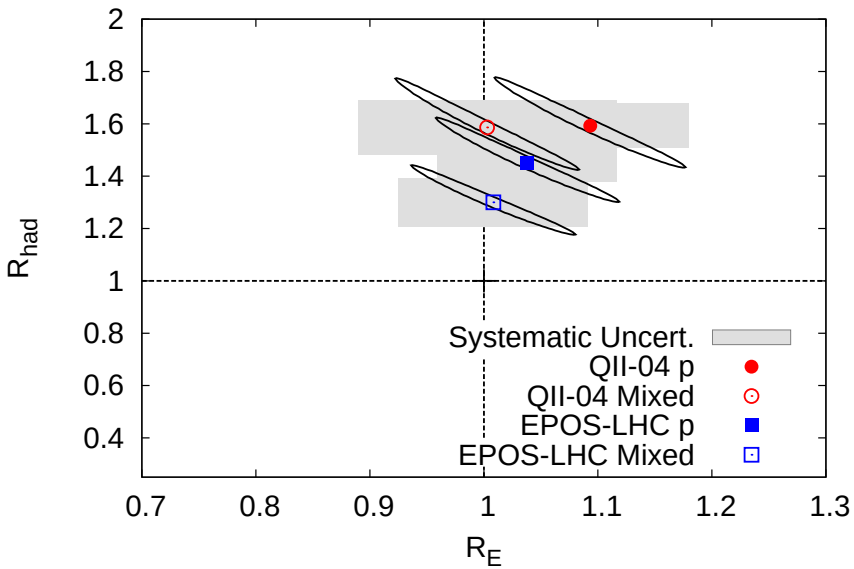


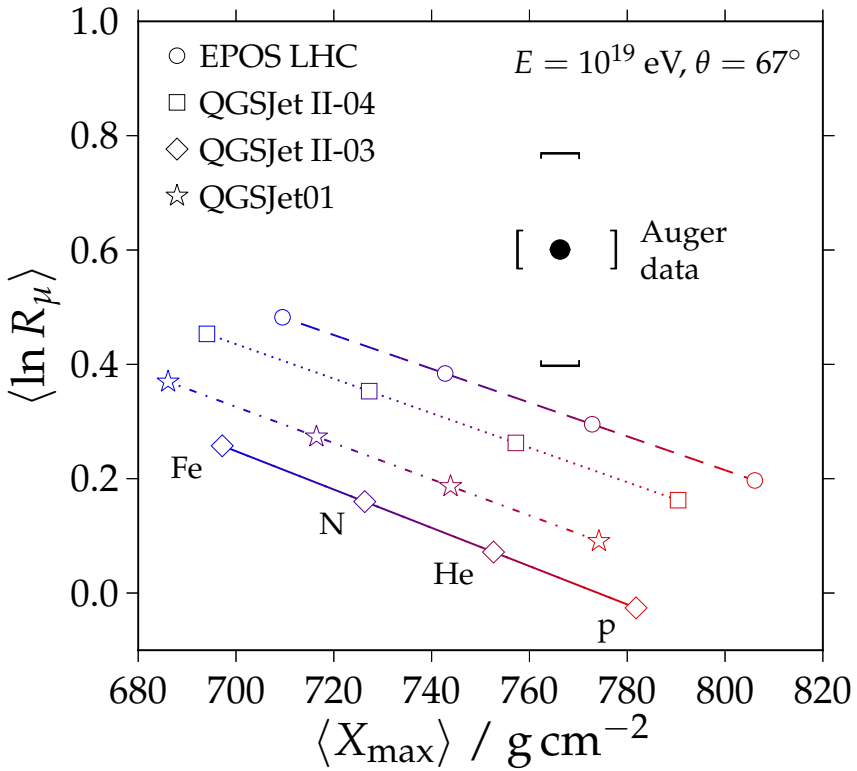
Pierre Auger Coll., PRD **D90** (2014) 1, 012012, erratum PRD92 (2015) no.1, 019903

Muon Deficit in Models?

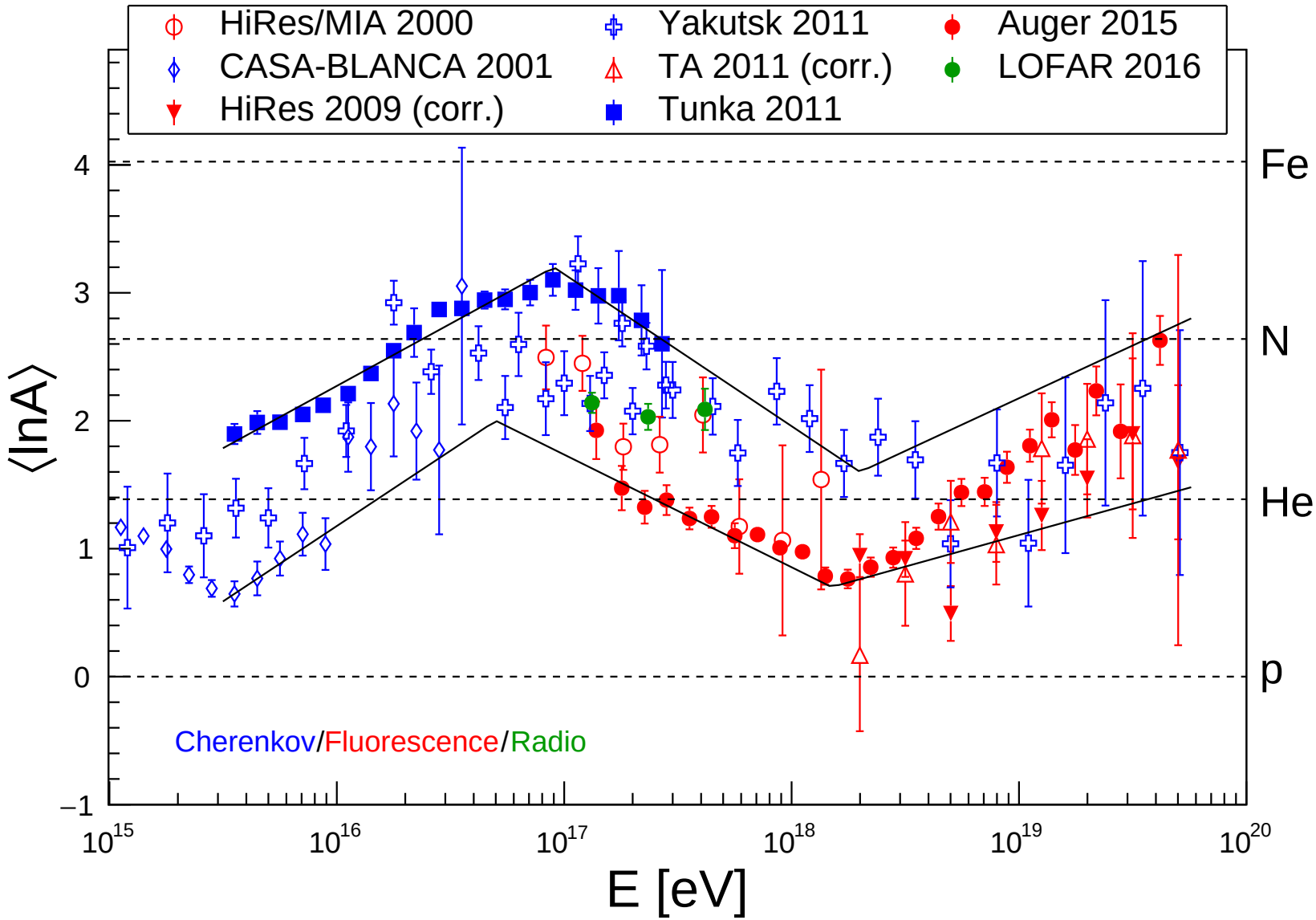








Summary: Mass Estimates with X_{max}



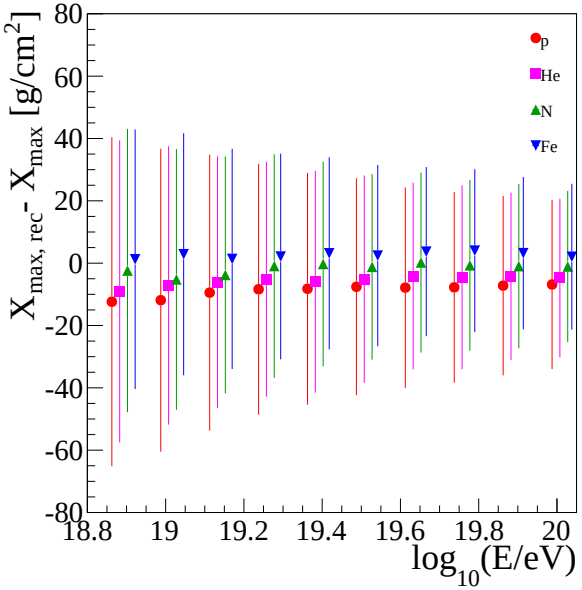
update of K.H. Kampert&MU APP **35** (2012) 660, (EPOS1.99)

Outlook: Upgrade of the Pierre Auger Observatory

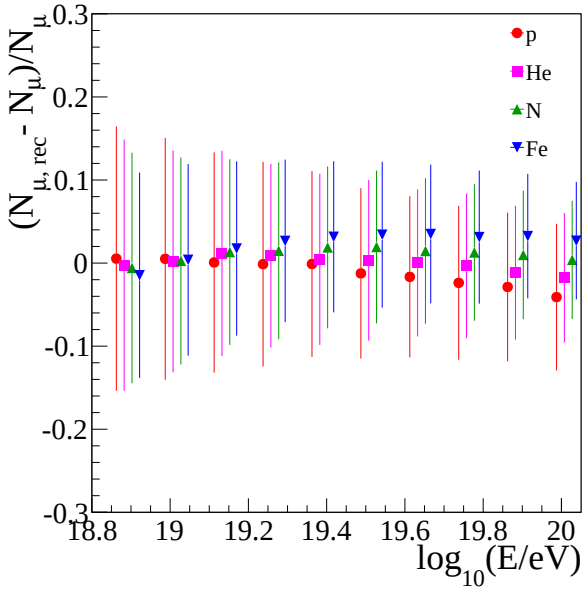
additional scintillators (4 m^2)

$\rightarrow$ event-by-event mass estimate,
100% duty cycle

X_{max} determination:



muon determination:



Pierre Auger Coll., arXiv:1604.03637