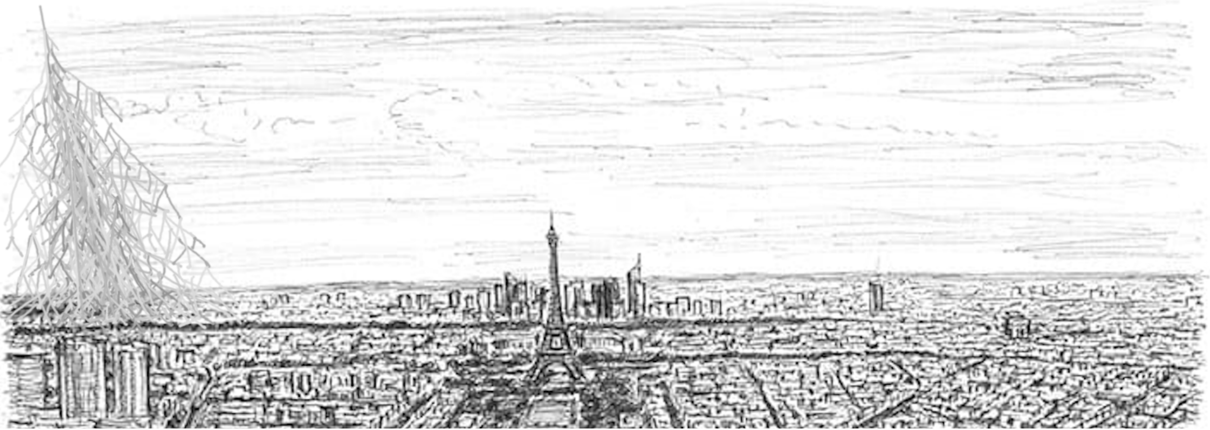
Composition and Interactions of Ultrahigh-Energy Cosmic Rays

Michael Unger, IAP, KIT

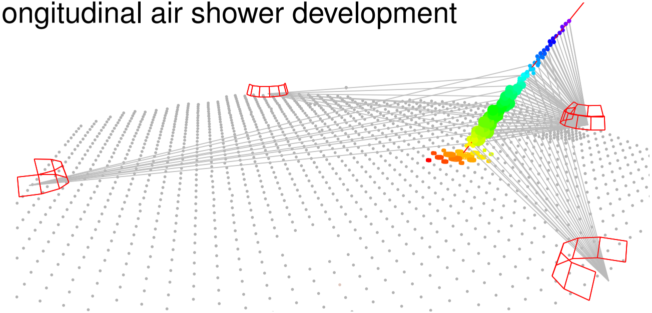


Cosmic Rays and Neutrinos in The Multi-Messenger Era, 7-11 December 2020

adapted from www.stephenwiltshire.co.uk

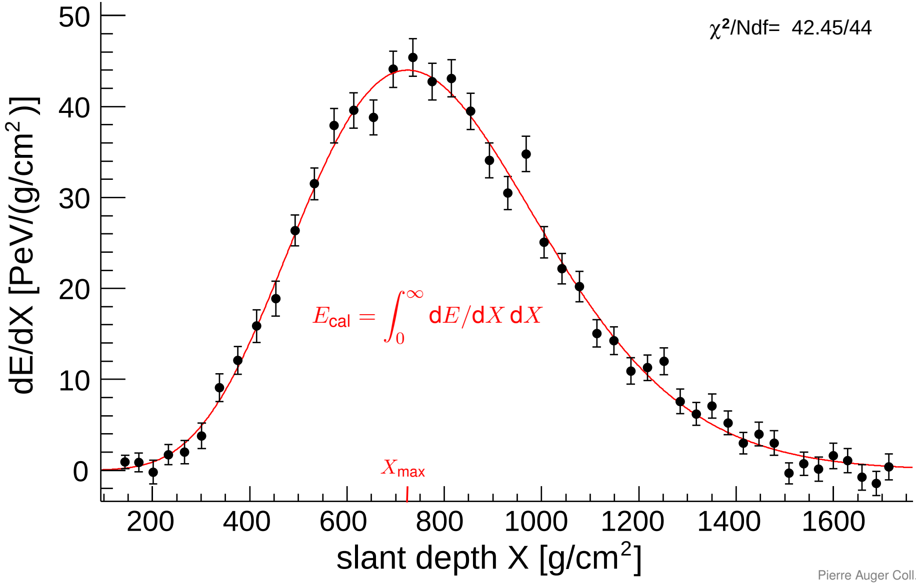
Air Shower Measurement with Fluorescence Telescopes

observation of longitudinal air shower development



Auger Event Display

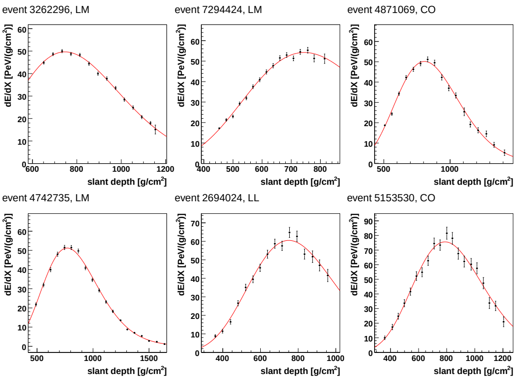
Air Shower Measurement with Fluorescence Telescopes



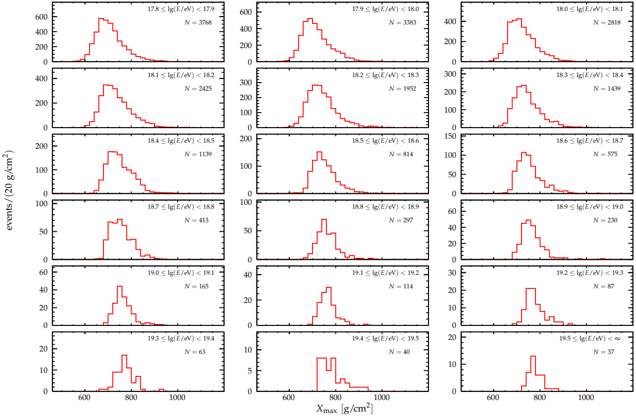
Pierre Auger Coll. NIM (2015)

X_{max} Distributions

individual air shower profiles (E, X_{max}) → X_{max} distributions in energy bins



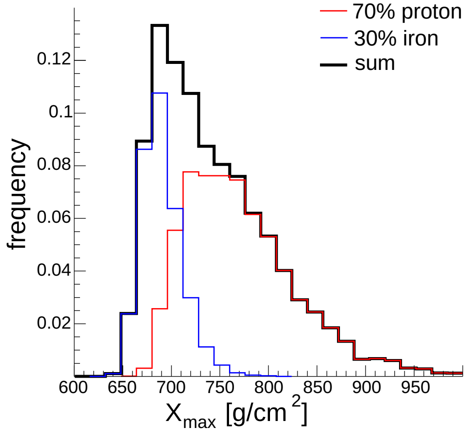
Pierre Auger Coll., SOCOR 2009



Pierre Auger Coll., PRD2014

X_{max} Distributions

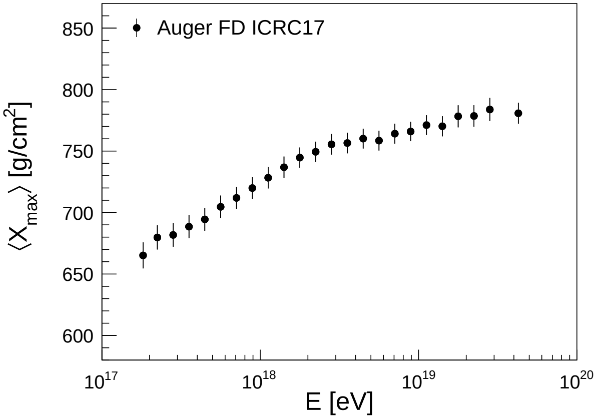
simulated example:

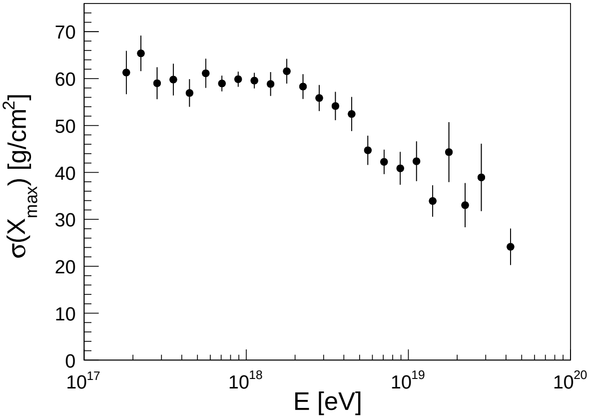


- mean:
  $\langle X_{max}\rangle \propto D\,(\lg E - \langle \ln A\rangle)$
- standard deviation:
  $\sigma(X_{max})^2 = \langle \sigma_i^2 \rangle + D^2\,\sigma(\ln A)^2$
- tail of distribution:
  approximately exponential with slope
  $\Lambda \propto \lambda_{prod}$

  - primary mass A
  - elongation rate $D \approx 60$ g/cm^2/decade
  - intrinsic fluctuations σ_i
    Fe: $\sigma_i \approx 20$ g/cm^2
    p: $\sigma_i \approx 60$ g/cm^2
  - λ_{prod}: hadronic interaction length
    Fe: $\lambda_{prod} \approx 11$ g/cm^2
    p: $\sigma_{prod} \approx 45$ g/cm^2

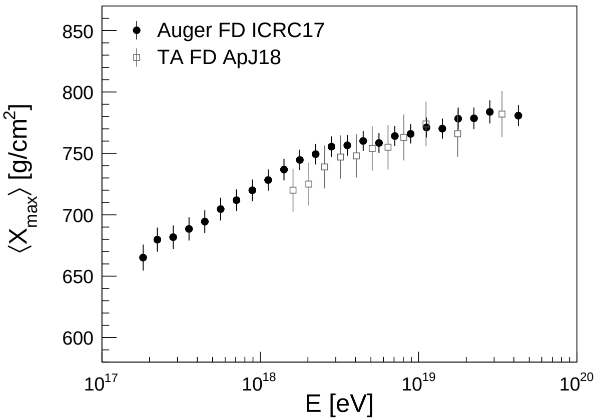
Mean and Standard Deviation of X_{max} Distributions

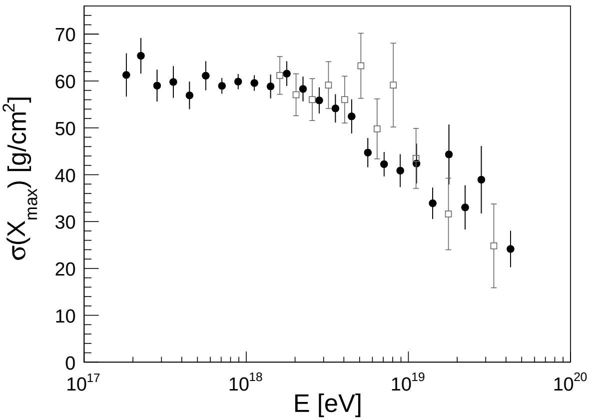




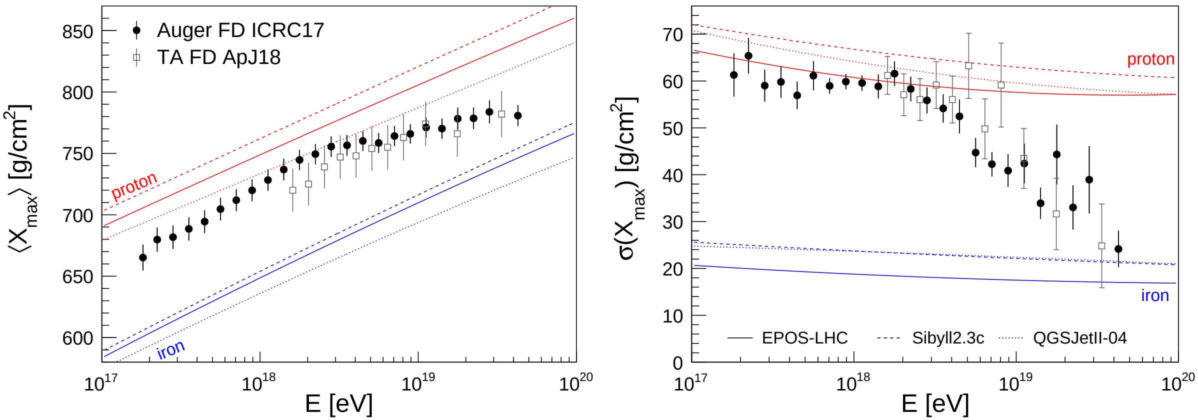
Pierre Auger Coll., ICRC17, see also update at ICRC19

Mean and Standard Deviation of X_{max} Distributions





Mean and Standard Deviation of X_{max} Distributions

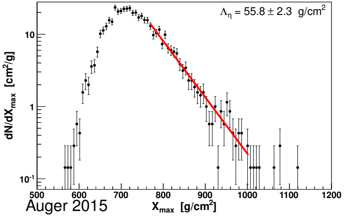


Reconcile X_{max} Measurements with UHE Protons?

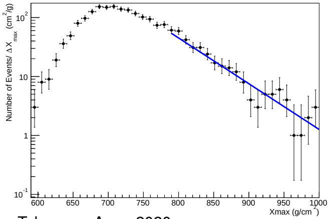
proton-air cross section at $E \sim 10^{18.2}$ eV:

good agreement with extrapolations of lab measurements

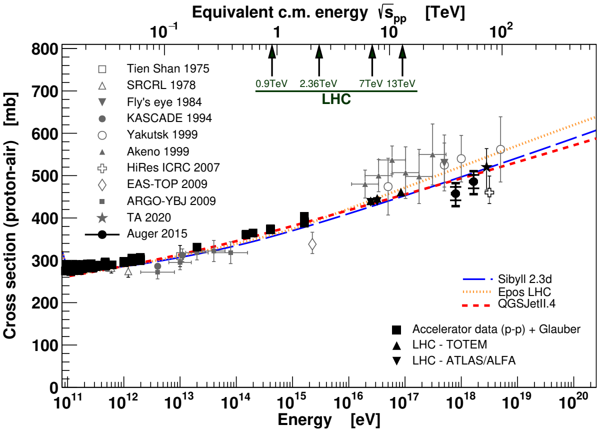
fit of tail of X_{max} distribution:



Auger 2015



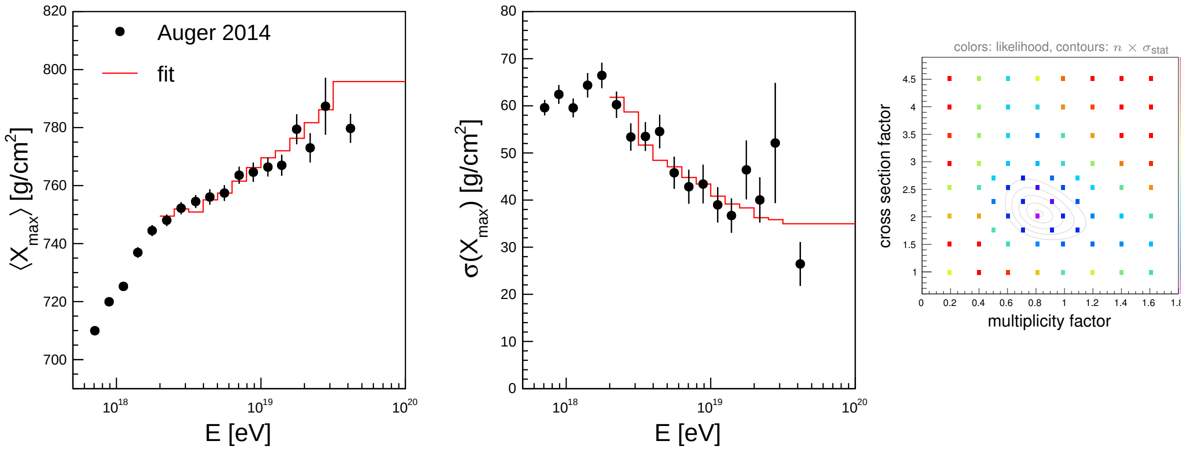
Telescope Array 2020



Pierre Auger Coll. PRL12, ICRC15; TA Coll. PRD20

Reconcile X_{max} Measurements with UHE Protons?

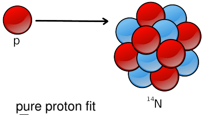
ad-hoc rescaling of proton-air cross section and multiplicity above $E \sim 10^{18.}$ eV
with factor $f(E, f_{19}) = 1 + (f_{19} - 1)(\lg E - 18.3)/0.7$ (see Ulrich+PRD11)

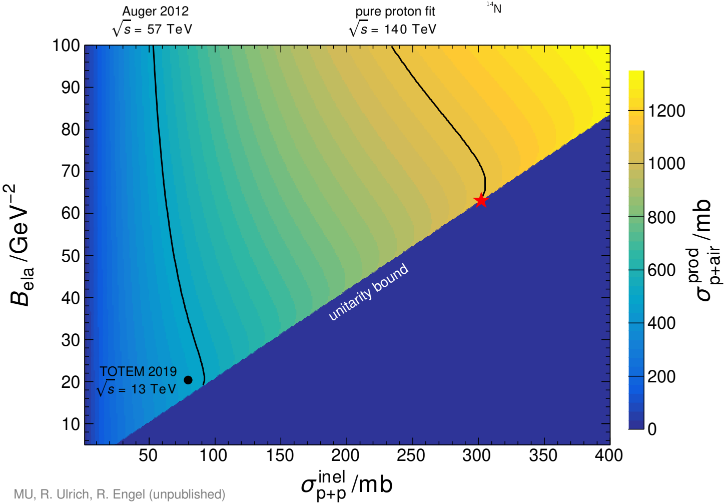


MU, R. Ulrich, R. Engel (unpublished); see also Allen&Farrar arXiv:1307.2322 and R. Ulrich PhD thesis 2008

... but how to double $\sigma_{\text{p+air}}$ at 10^{19} eV?

Glauber calculation





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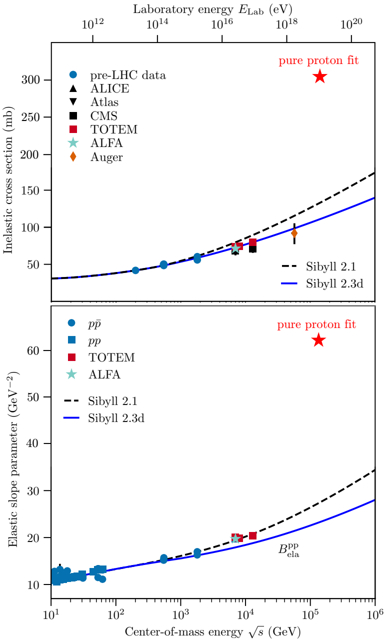
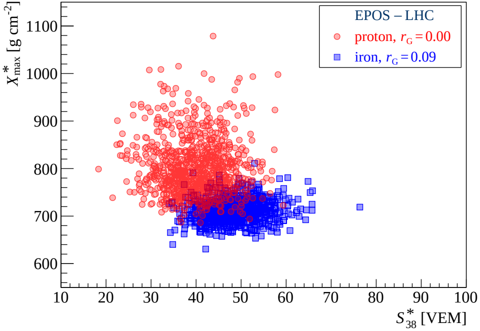
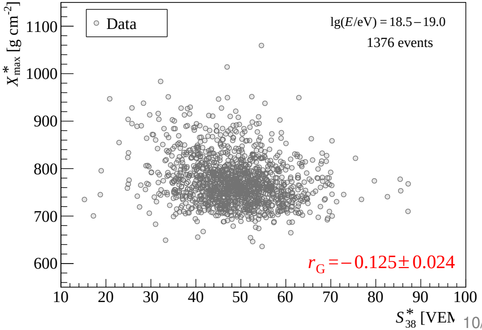


adapted from Riehn+PRD20

Constraints from Hybrid Data

correlation of X_{max} with ground level signal





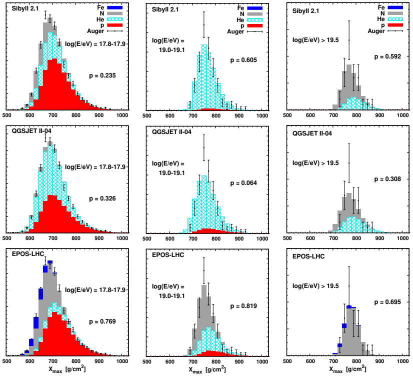
mixed composition!

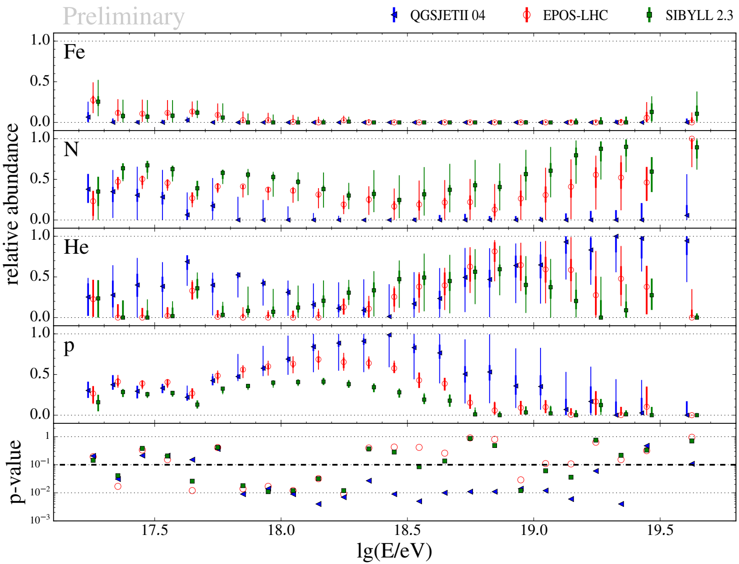
$18.5 < \lg(E/\mathrm{eV}) < 19.0$, $X^*_{\mathrm{max}}/S^*(1000)$: scaled to 10^{19} eV

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

Mixed-Composition-Fit of X_{max} Distributions (p, He, N, Fe)

examples:



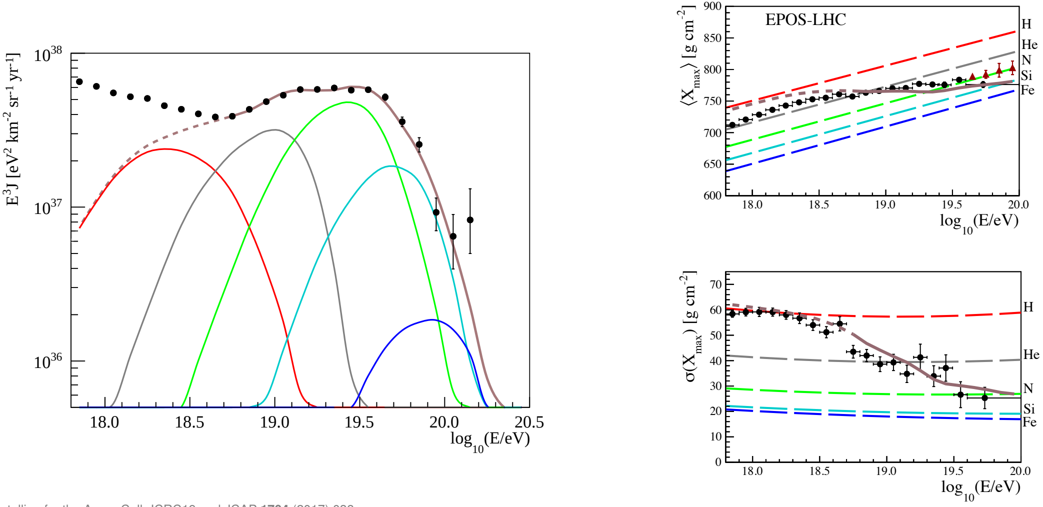


Pierre Auger Coll., PRD **90** (2014) 12, 122006; update at ICRC17

Maximum Rigidity Model, Peters Cycle?

B. Peters, Nuovo Cimento 22 (1961) 800

energy spectrum at source $\propto (E/Z)^{-\gamma}$



A. Castellina for the Auger Coll. ICRC19 and JCAP **1704** (2017) 038

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B. Peters, Nuovo Cimento 22 (1961) 800

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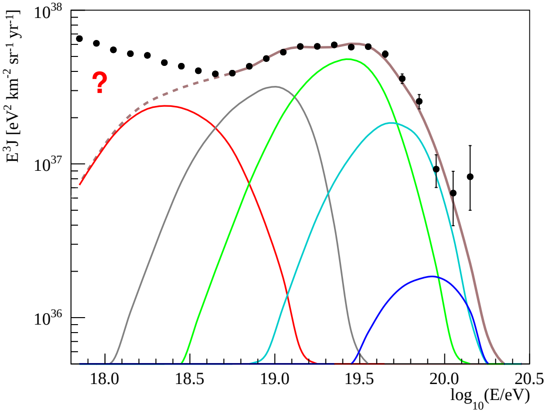
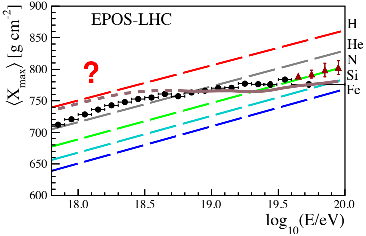
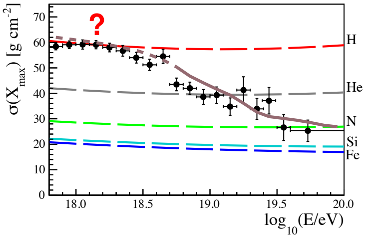
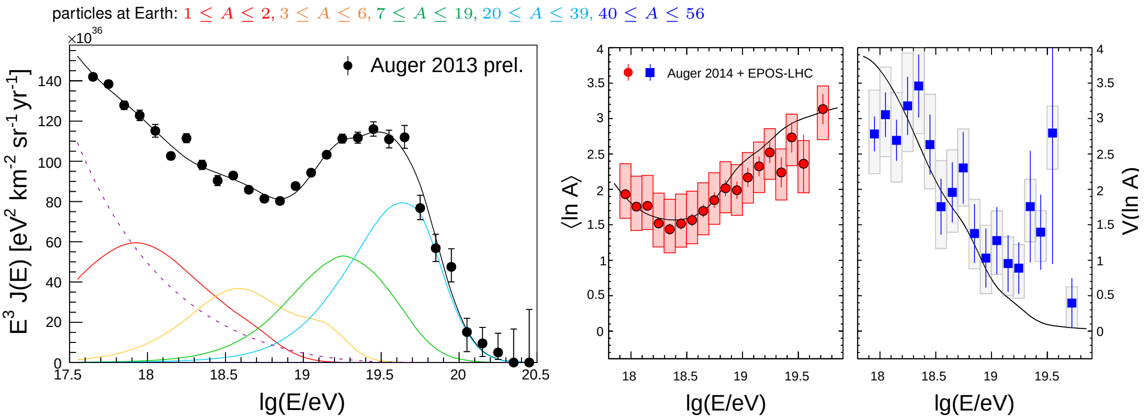






A. Castellina for the Auger Coll. ICRC19 and JCAP **1704** (2017) 038

Photonuclear Interactions in Source Environment?



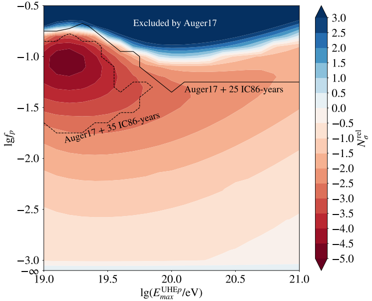
MU, G. Farrar, L. Anchordoqui, PRD **92** (2015) 123001

M. Muzio, MU, G. Farrar PRD100 (2019) 103008

see also Globus+15, Biel+17, Kachelriess+17, Supanitsky+18

see talk of Glennys this afternoon

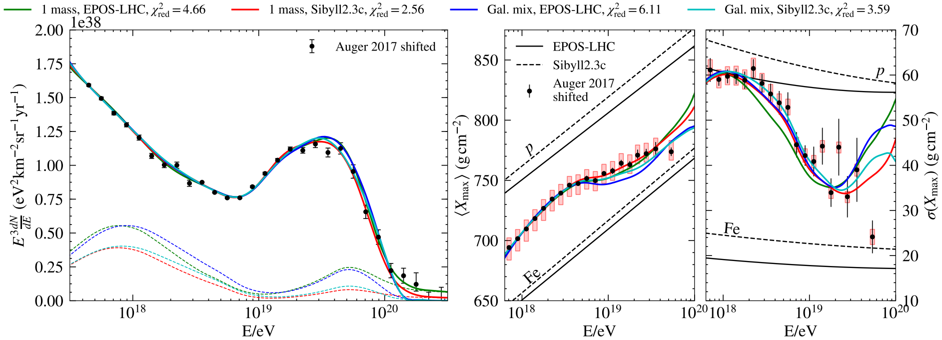
Proton Fraction at UHE?



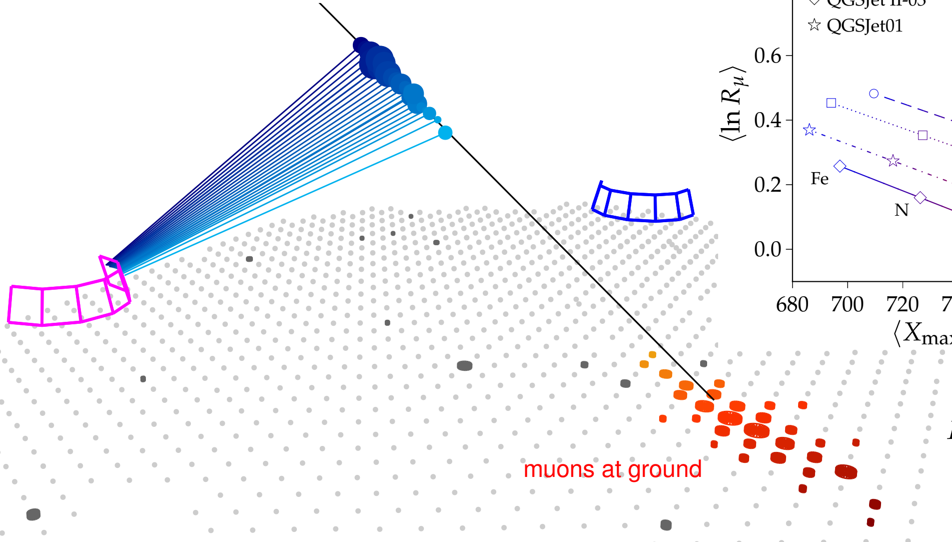
energy fraction escaping source:

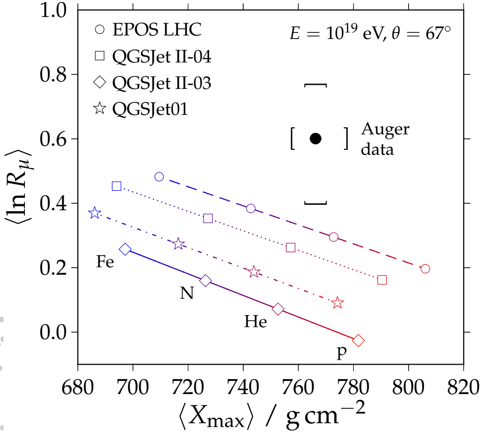
$$f_p = \frac{\int_{E_{\mathrm{ref}}}^{\infty} E\, Q_p \mathrm{d}E}{\int_{E_{\mathrm{ref}}}^{\infty} E\, (Q_p + Q_{\mathrm{mix}}) \mathrm{d}E}$$

($Q_p \sim E^{\gamma_p}\, e^{-E/E_{\max}^{\mathrm{UHE}p}}$, $\gamma_p = -1$ and $E_{\mathrm{ref}} = 10^{19}$ eV)



Reminder: Muon Excess in Horizontal Air Showers

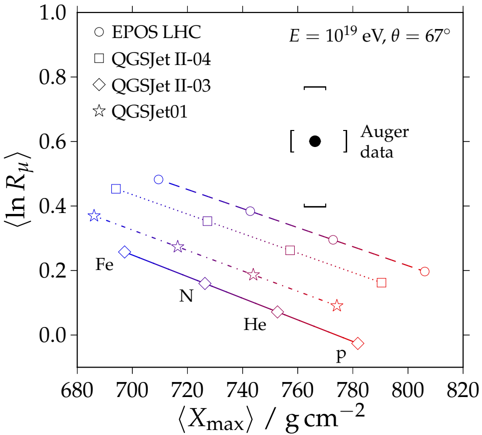


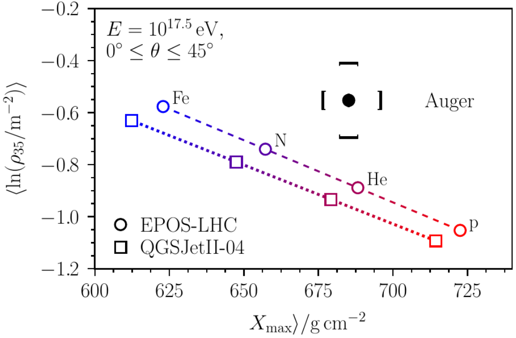


$$R_\mu \sim N_\mu / (1.5 \times 10^7)$$

Pierre Auger Coll., PRD **D91** (2015) 3, 032003, see also Phys.Rev.Lett. **117** (2016) 19, 192001

New Measurement with Underground Muon Detector



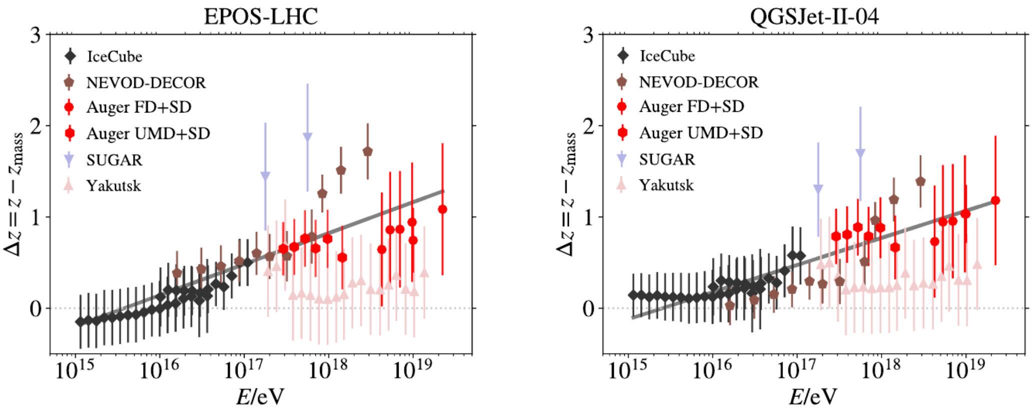


UMD engineering array, 7 stations, 30 m^2, 2.3 m deep (540 g/cm^2 shielding, 1 GeV muon threshold)

Pierre Auger Coll., PRD **D91** (2015) 3, 032003, EPJC (2020) **80** 751

Energy Dependence of Muon Excess

$$z = \frac{\ln(N_{\mu}^{\text{det}}) - \ln(N_{\mu_p}^{\text{det}})}{\ln(N_{\mu_{\text{Fe}}}^{\text{det}}) - \ln(N_{\mu_p}^{\text{det}})}, \qquad \Delta z = z - z_{\text{mass}} = z - z(A(E))$$

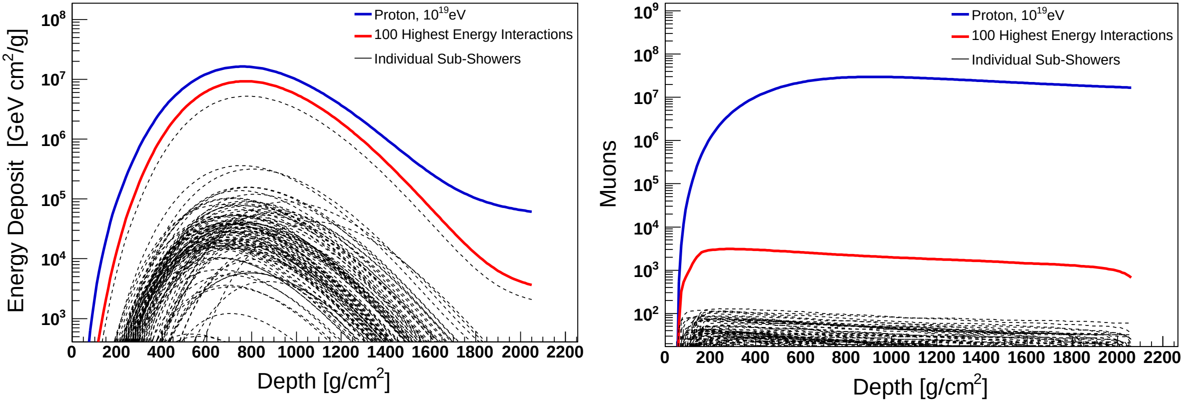


Working Group on Hadronic interactions (WHISP) EPJ Web Conf. 210 (2019) 02004, update for SNOWMASS21

Does the N_μ-Discrepancy Invalidate the Composition-Interpretation of X_{max}?

not necessarily:

$X_{\max}$ is dominated by first interactions, muons are generated all along shower

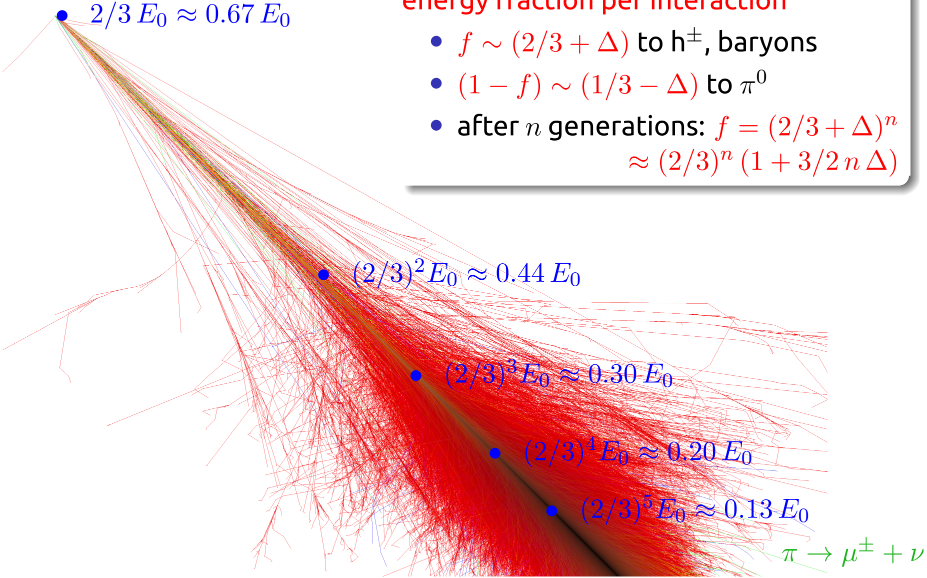


R. Ulrich, APS 2010

Muons in UHE Air Showers

energy fraction per interaction

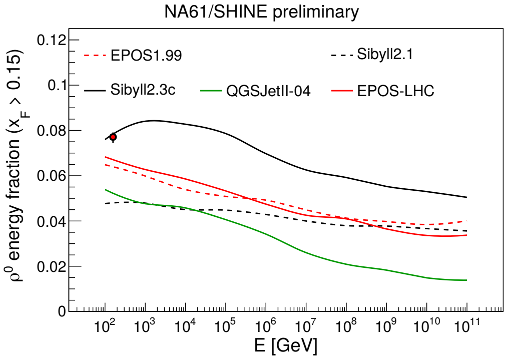
- $f \sim (2/3 + \Delta)$ to h$^{\pm}$, baryons
- $(1 - f) \sim (1/3 - \Delta)$ to π^0
- after n generations: $f = (2/3 + \Delta)^n \approx (2/3)^n \, (1 + 3/2 \, n \, \Delta)$

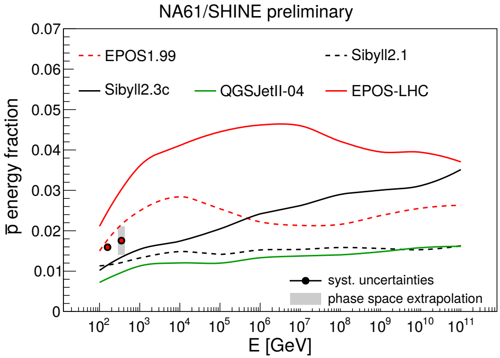


Muons in UHE Air Showers

examples of "Δ":

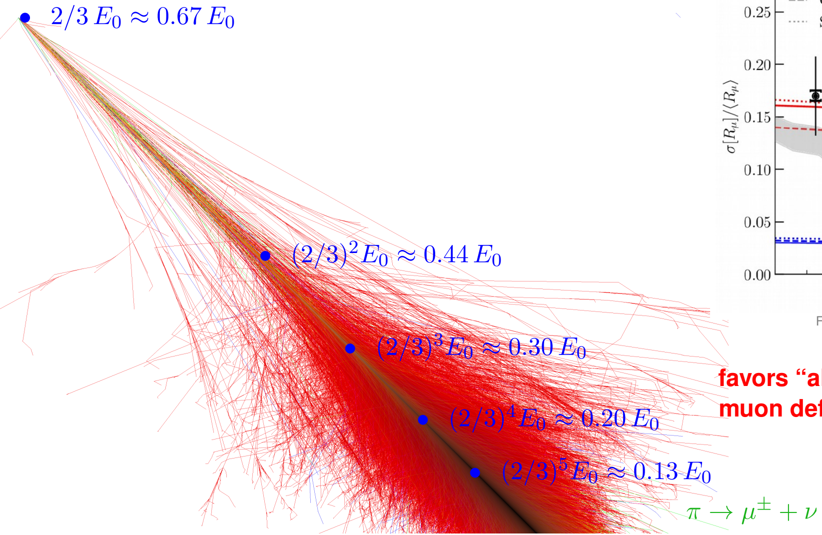
energy fraction of ρ^0 and $\bar{p}$:

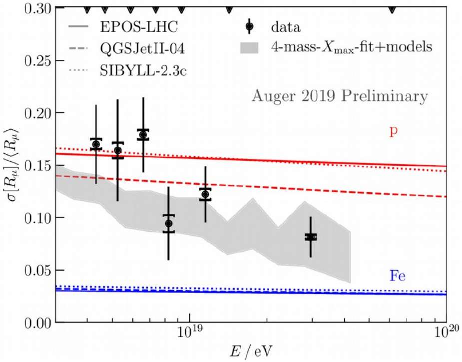




R. Prado for the NA61/SHINE Collaboration, ISVHECRI 2018, arXiv:1810.00642 and update in 1909.07136

Fluctuations of N_μ





F. Riehn for the Pierre Auger Coll. ICRC19 arXiv:1909.09073

favors "along-the-shower" origin of muon deficit rather than at first interaction

Summary

- $X_{\max}$ data suggests mixed composition at $\gtrsim 10^{18.5}$ eV
- robust with respect to (reasonable) extrapolation of hadronic interactions
- corroborated by correlation of $X_{\max}$ and shower size
- further constrains from cosmogenic secondaries (ν, γ):
  proton fraction given source evolution or vice versa (not covered in this talk)
- composition $\gtrsim 10^{19.5}$ eV uncertain due to low statistics $\rightarrow$ AugerPrime, TAx4, POEMMA, ...
- muon discrepancy increases with energy from IceTop to UHE
- new constraints on muon deficit from measurement of fluctuations