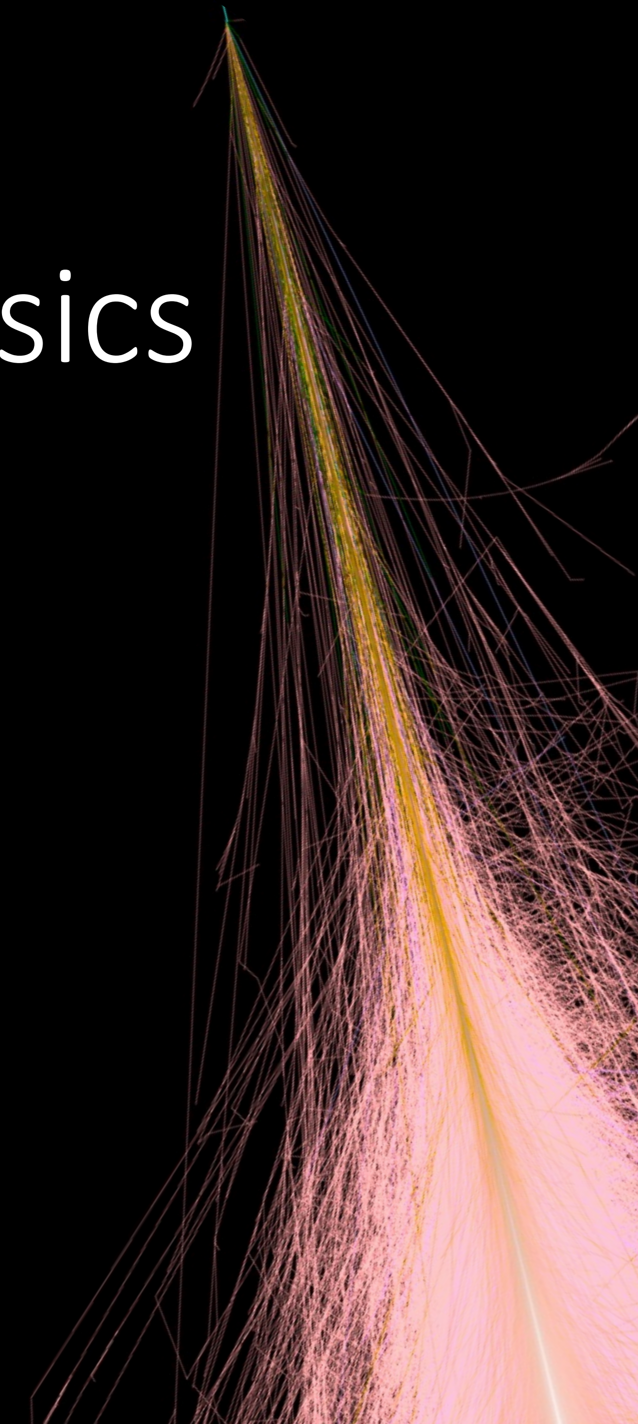
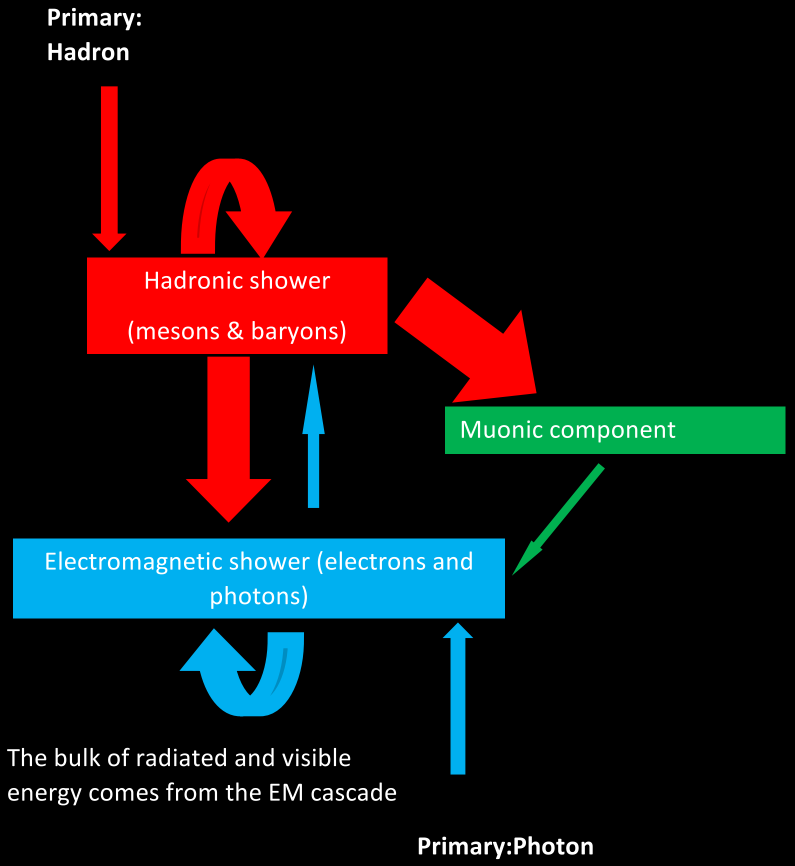
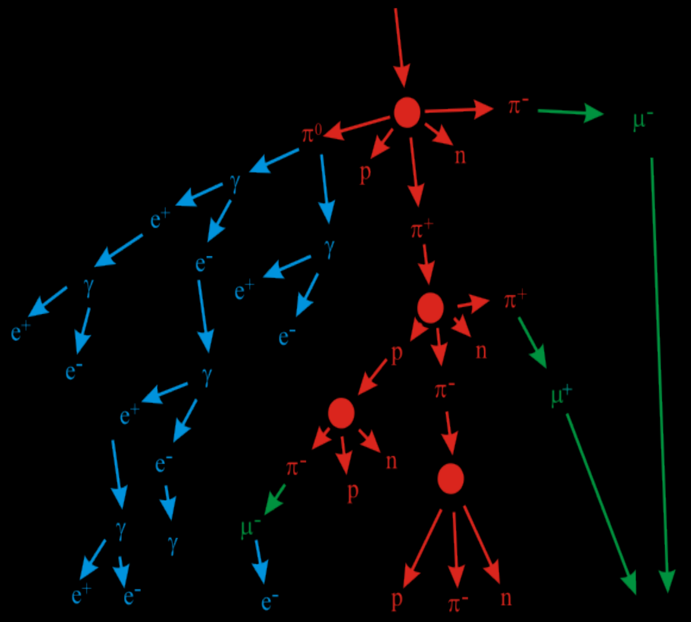
Hadronic and Shower Physics with the Pierre Auger Observatory

L. Cazon for the Pierre Auger Collaboration



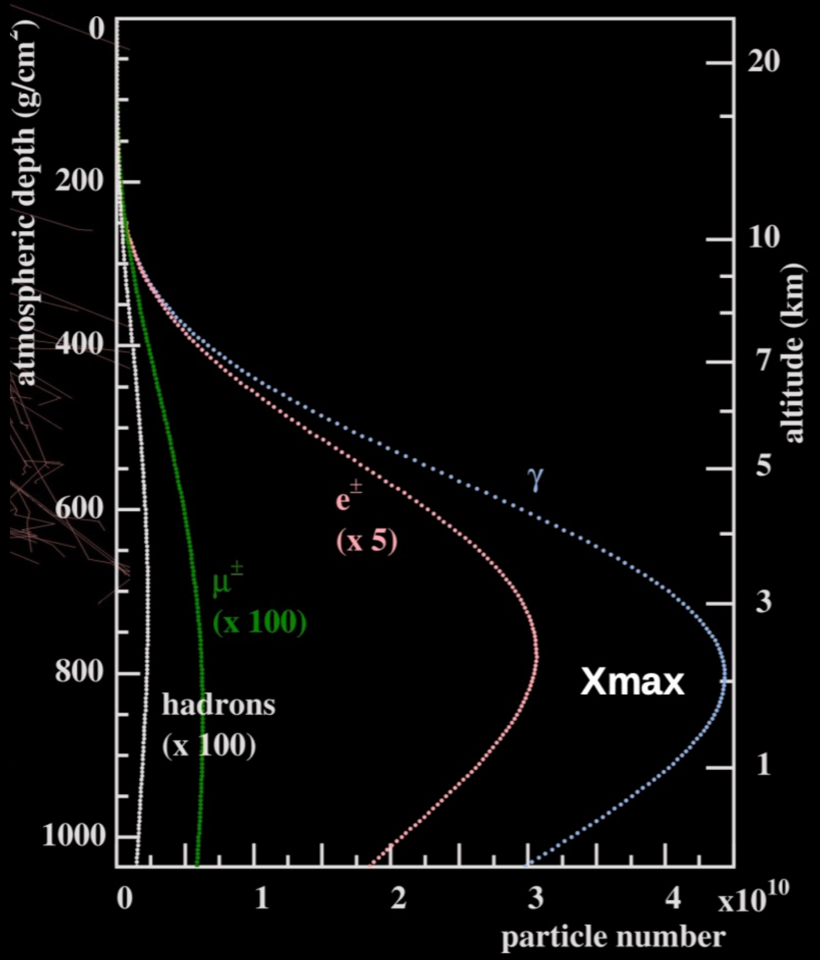
Air Shower:

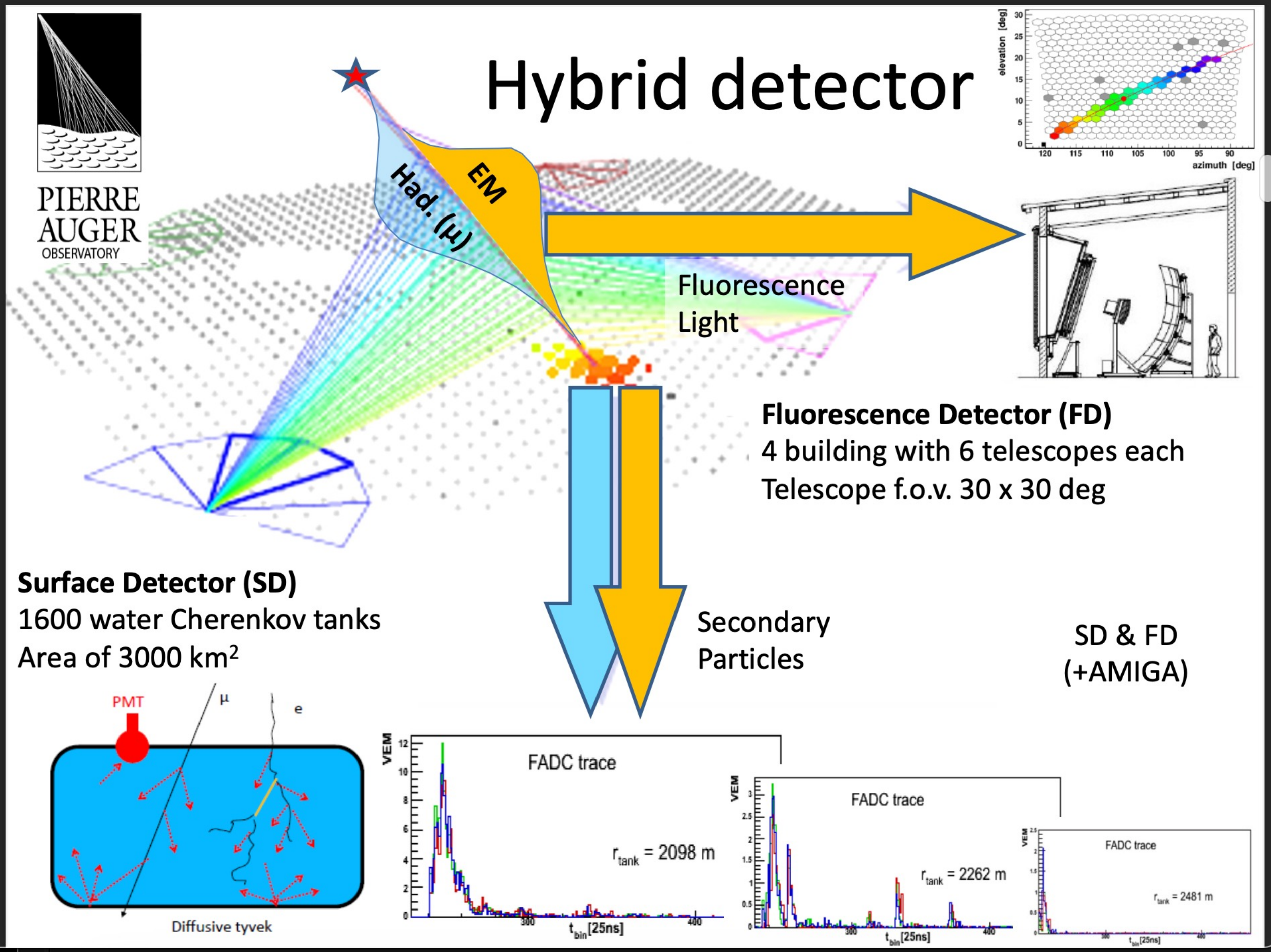




Muons trace the hadronic shower which is the backbone of the whole cascade

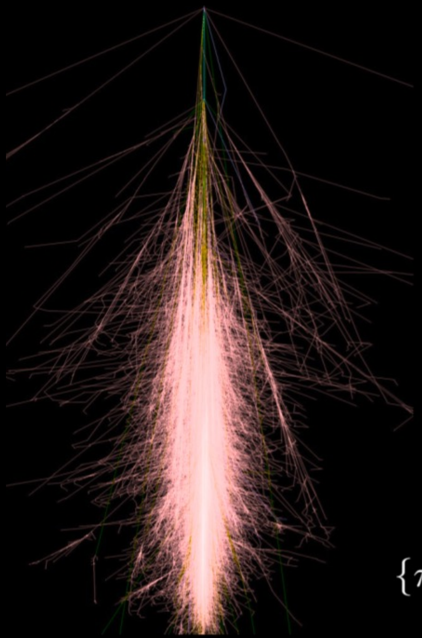
π^0 decays are the propellers of the EM cascade

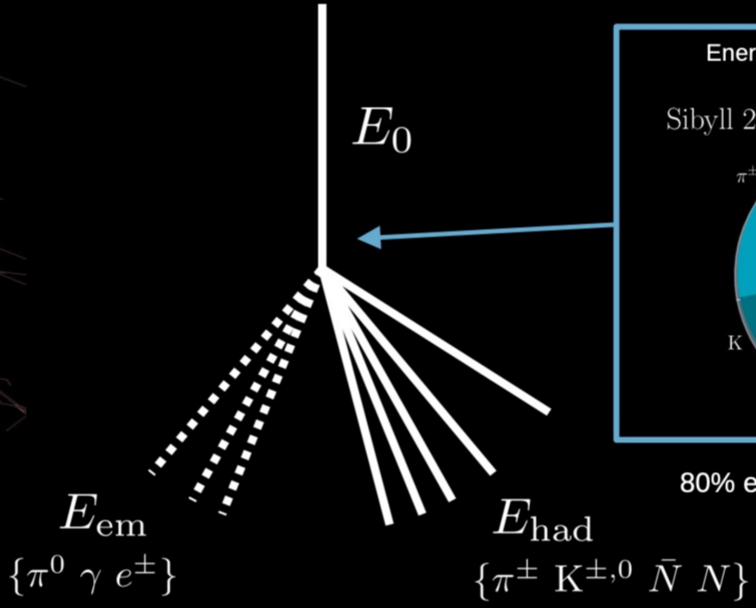


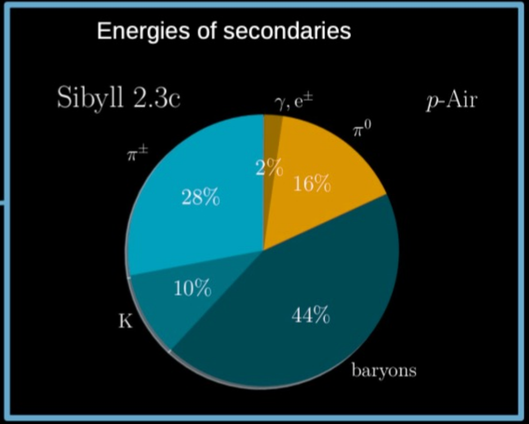


Hybrid detector
PIERRE AUGER OBSERVATORY
EM
Had. (μ)
Fluorescence Light
Fluorescence Detector (FD)
4 building with 6 telescopes each
Telescope f.o.v. 30 x 30 deg
elevation [deg]
azimuth [deg]
Surface Detector (SD)
1600 water Cherenkov tanks
Area of 3000 km²
Secondary Particles
SD & FD (+AMIGA)
PMT
μ
e
Diffusive tyvek
FADC trace
VEM
r_tank = 2098 m
r_tank = 2262 m
r_tank = 2481 m
t_bin [25ns]

Energy flow, averages and fluctuations







80% energy remains in hadrons ..

EM cascade

hadronic cascade

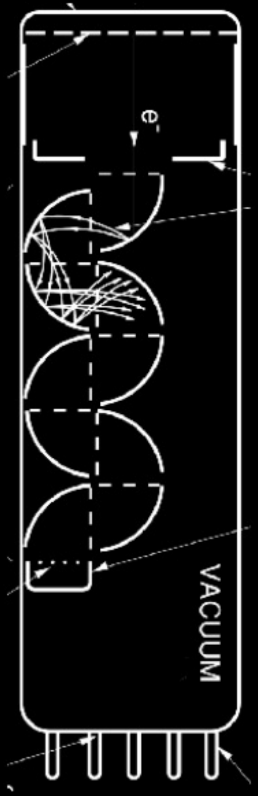
Energy flow

After n steps:

$$E_n^{\mathrm{had}} = 0.8^n\, E_0$$

$$E_n^{\mathrm{EM}} = (1 - 0.8^n)\, E_0$$

6



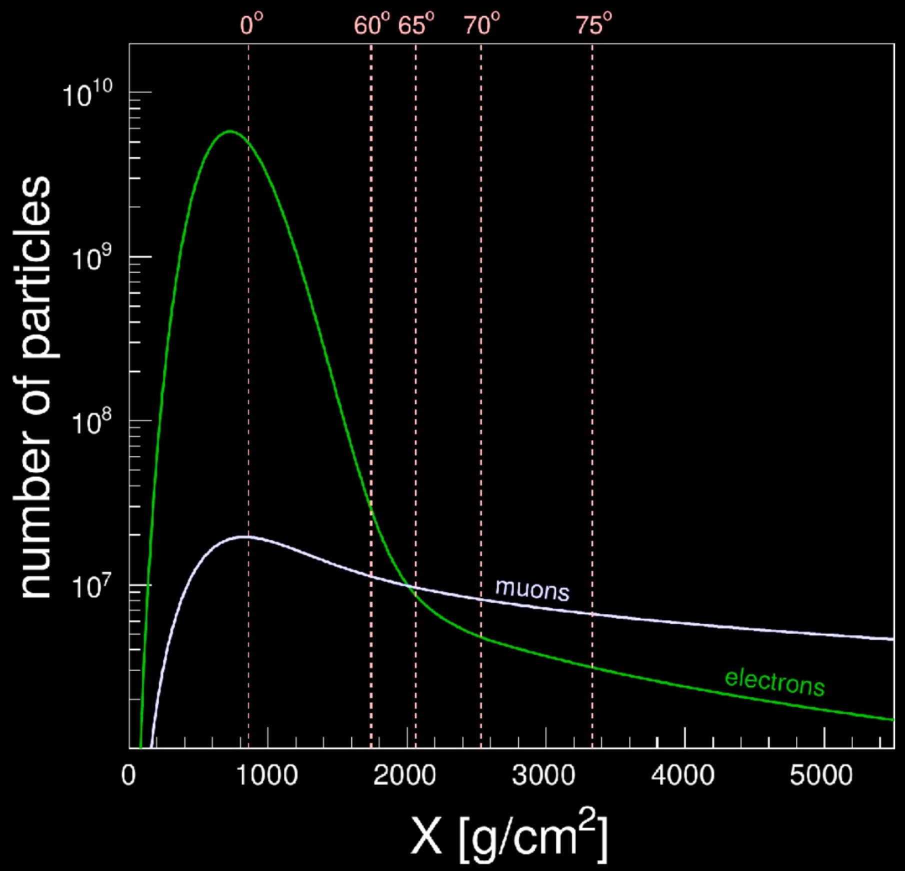
PMT analogy to shower

70% of fluctuations from first interaction

$$\left(\frac{\sigma(N_\mu)}{N_\mu}\right)^2 \simeq \left(\frac{\sigma(\alpha_1)}{\alpha_1}\right)^2 + \left(\frac{\sigma(\alpha_2)}{\alpha_2}\right)^2 + \ldots + \left(\frac{\sigma(\alpha_c)}{\alpha_c}\right)^2$$

Muon content

Muon content in inclined showers

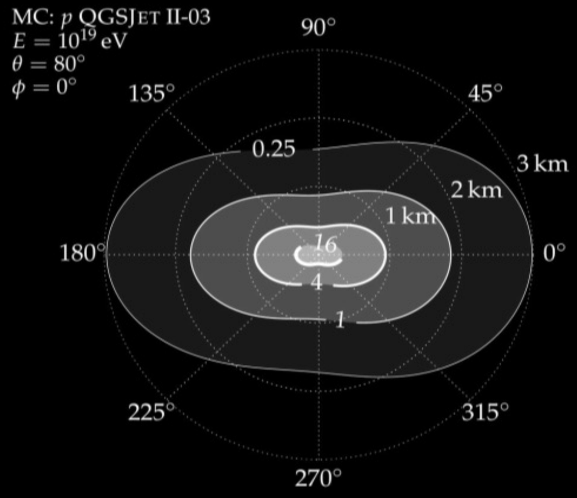


EM component attenuates
after 2000 gr/cm2

(PRD 91(2015) 032003, PRL 126 (2021) 152002)

Geomagnetic field
+ extended path

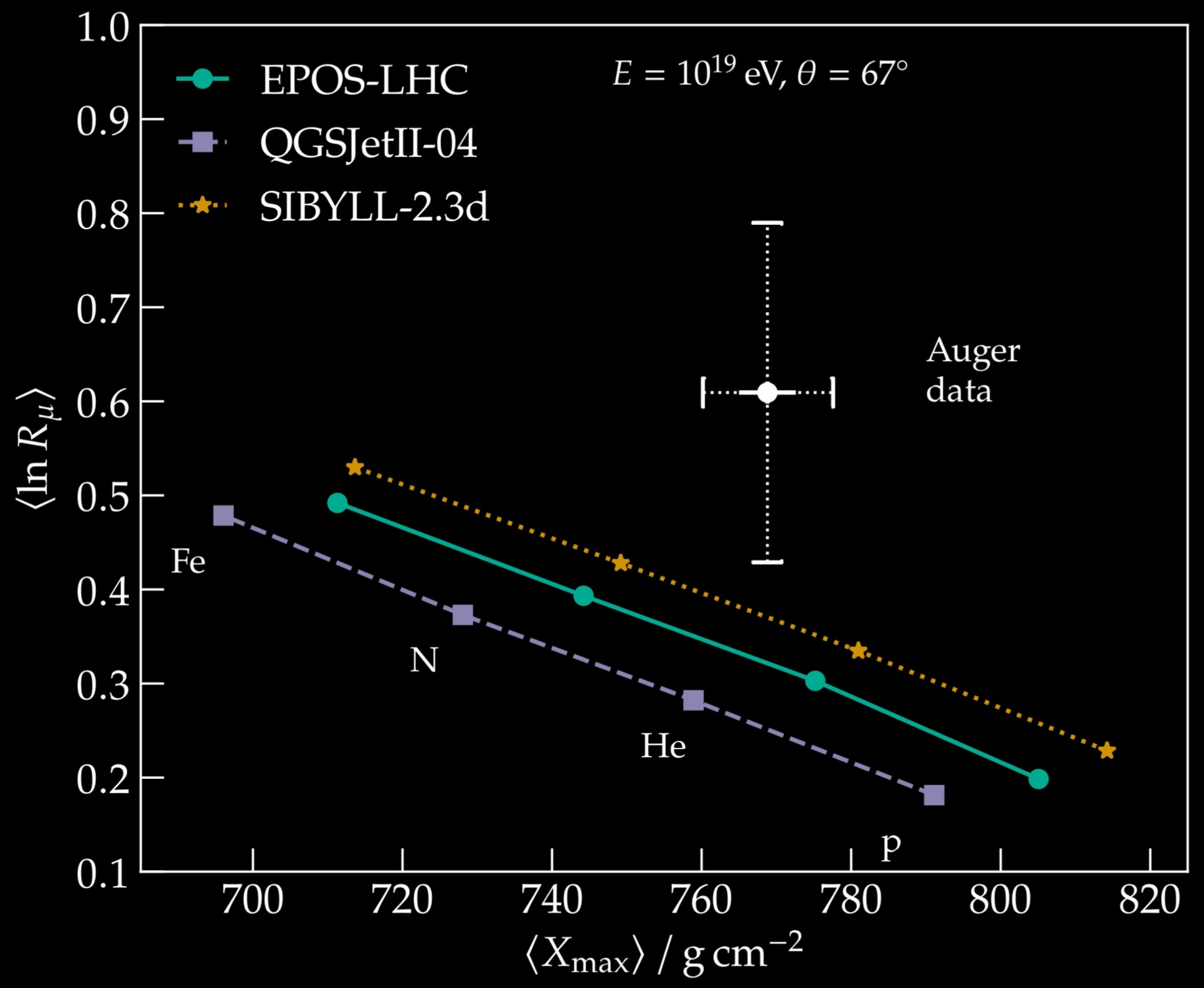
→ density at ground
not symmetric!



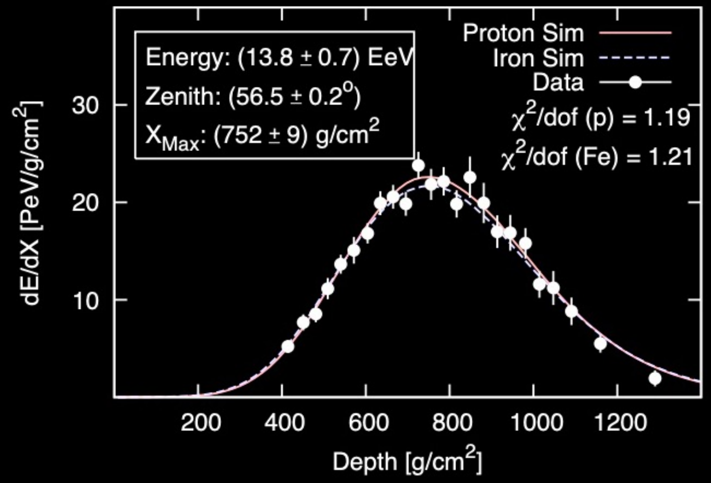
$$\rho_\mu(E,\theta,x,y) \;=\; R_\mu(E)\rho_\mu^{\mathrm{ref}}(\theta,x,y)$$

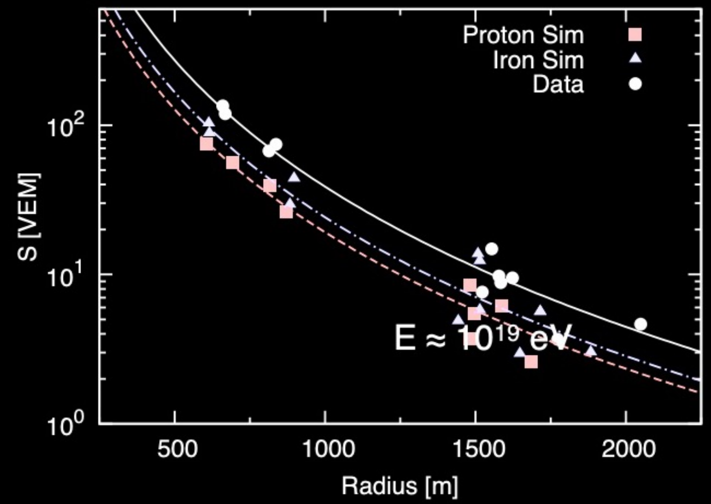
Measure scale relative to reference model

Muon content in inclined showers



Muon content in vertical showers



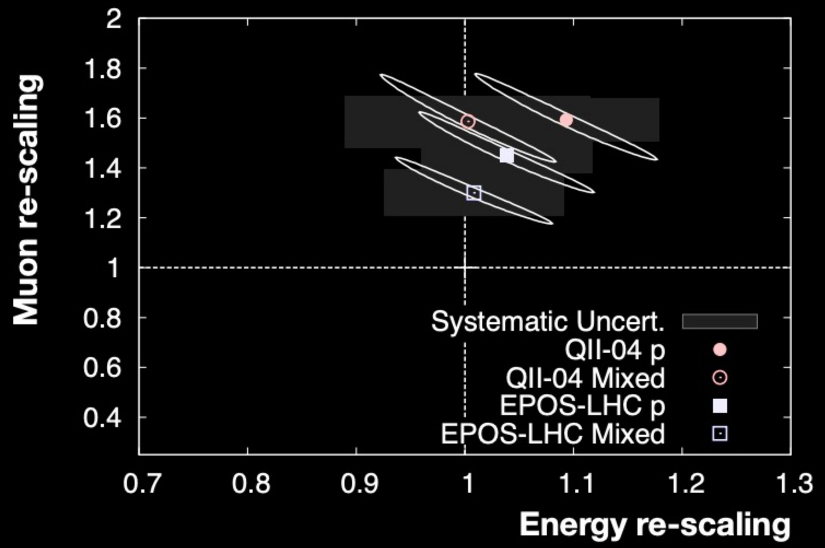


(Auger, PRL 117, 2016)

Energy scaling: em. particles and muons

Muon scaling: hadronically produced muons and muon interaction/decay products

Use showers of different zenith angles

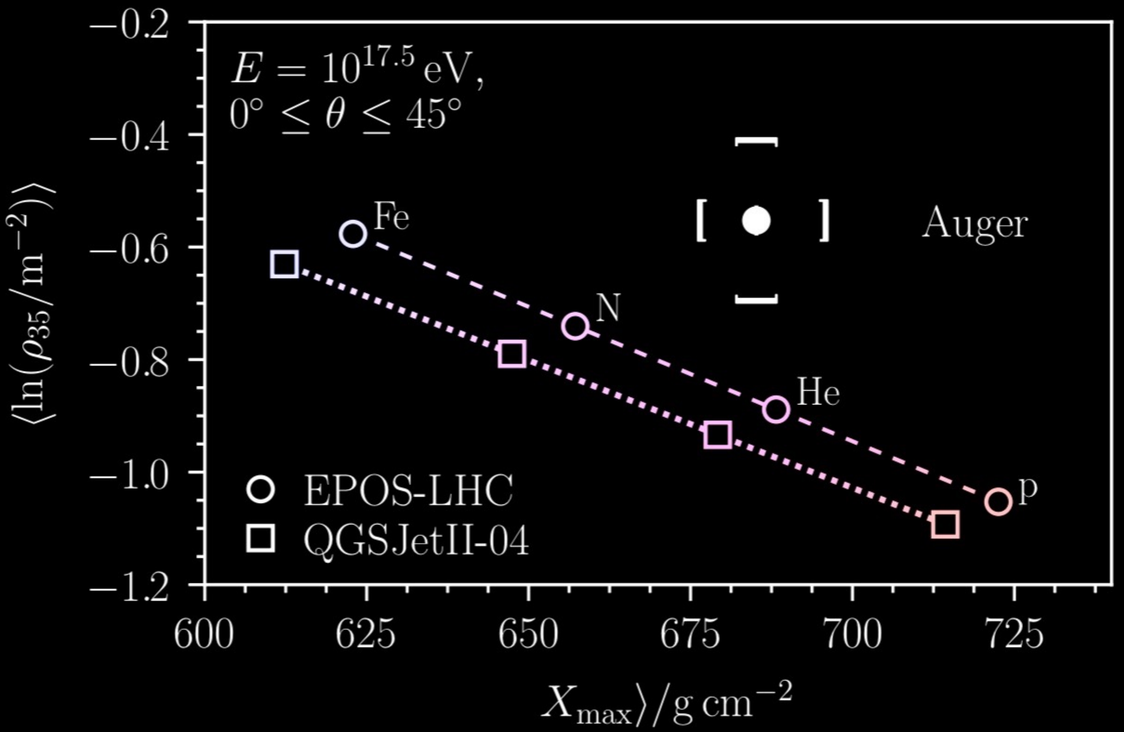


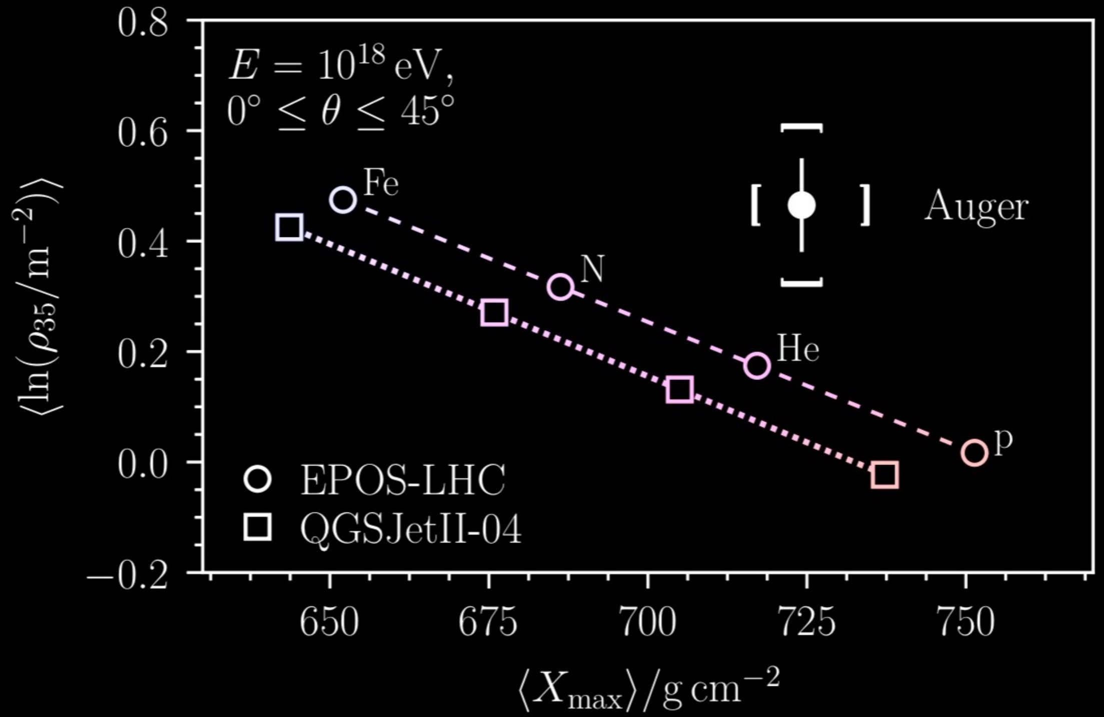
Consistently more muons in data than predicted

Direct muon content in vertical showers

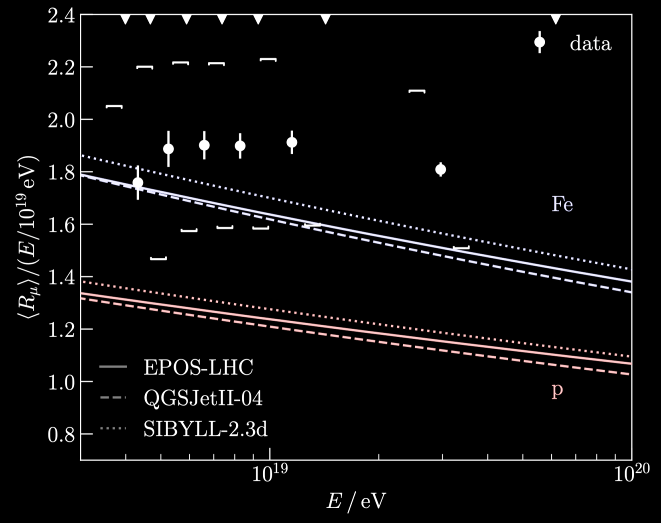
Underground Scintilators (UMD)

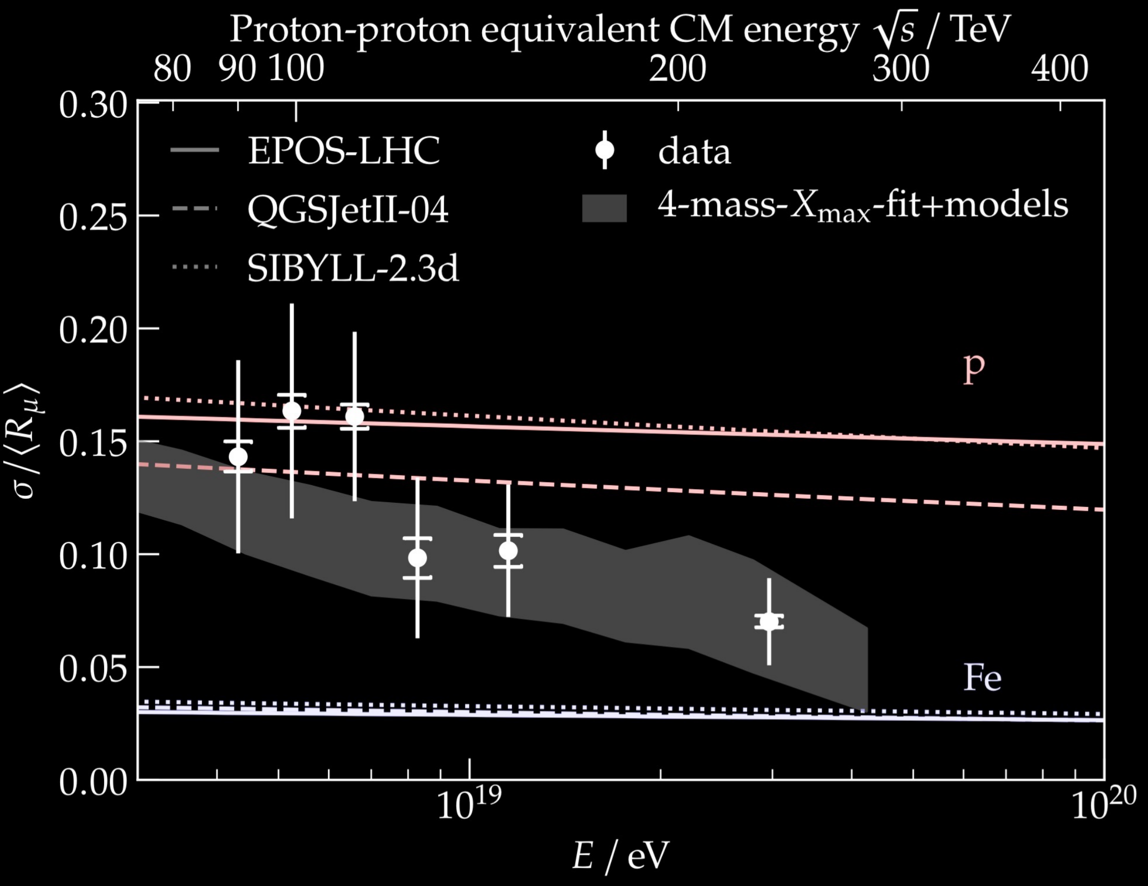
Eur. Phys. Journal C (2020)





Muon fluctuations



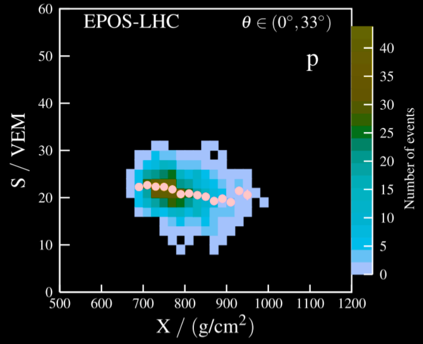


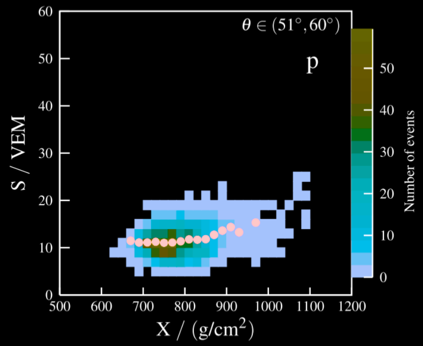
1st interaction of air shower is not exotic in terms of fluctuations

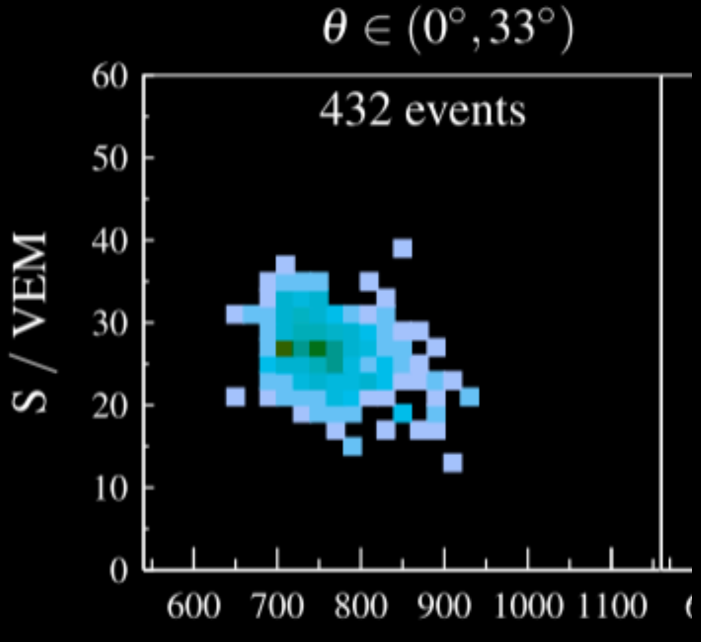
PRL (2021) 126

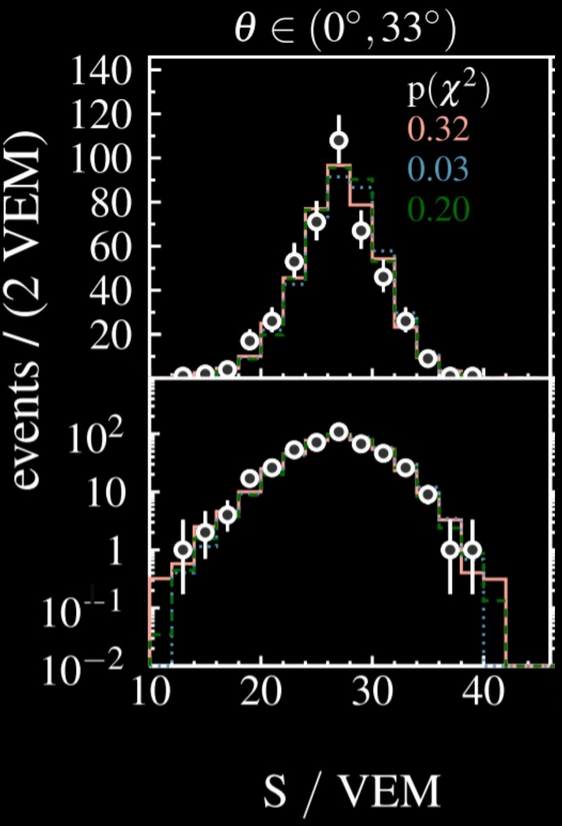
Longitudinal developement

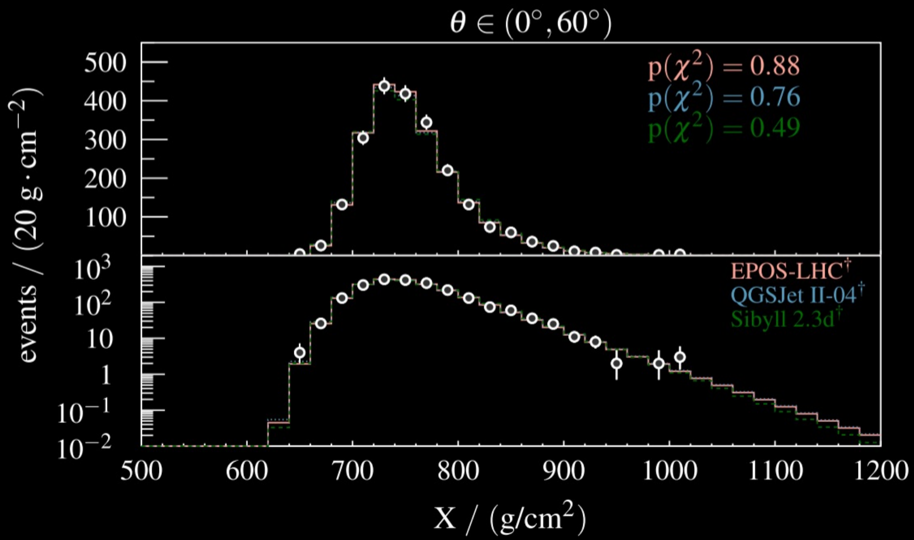
Fitting the Xmax - S1000 joint distribution











Phys. Rev. D 109 (2024)

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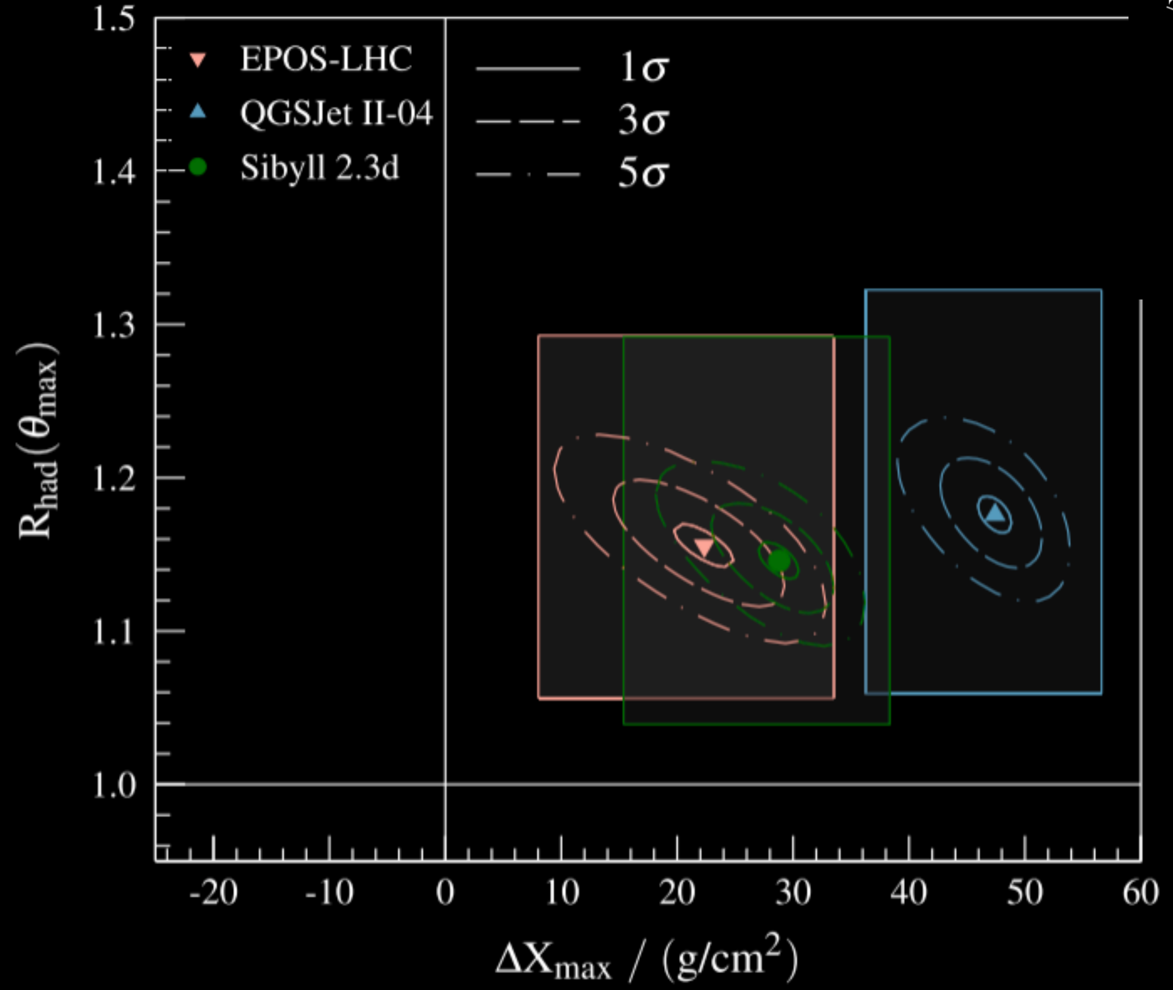
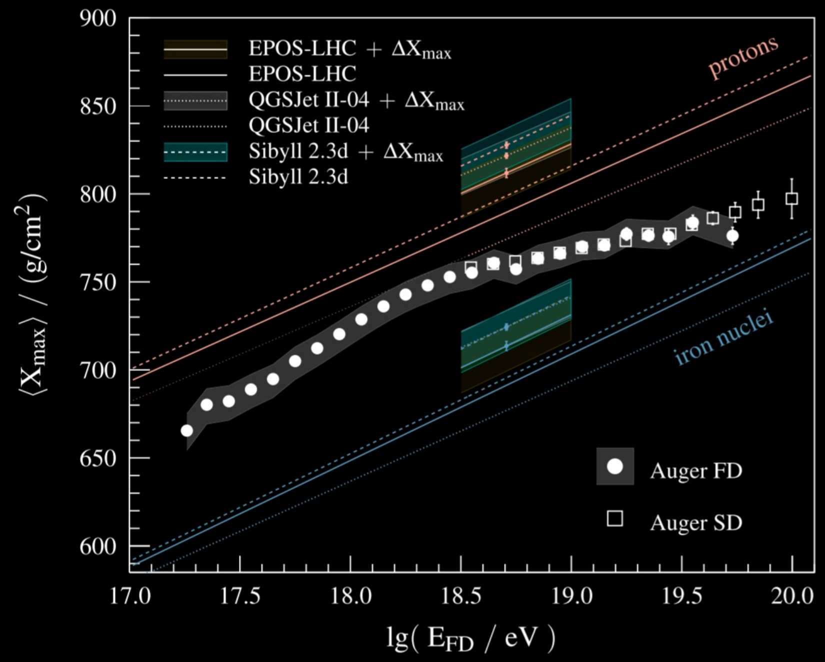
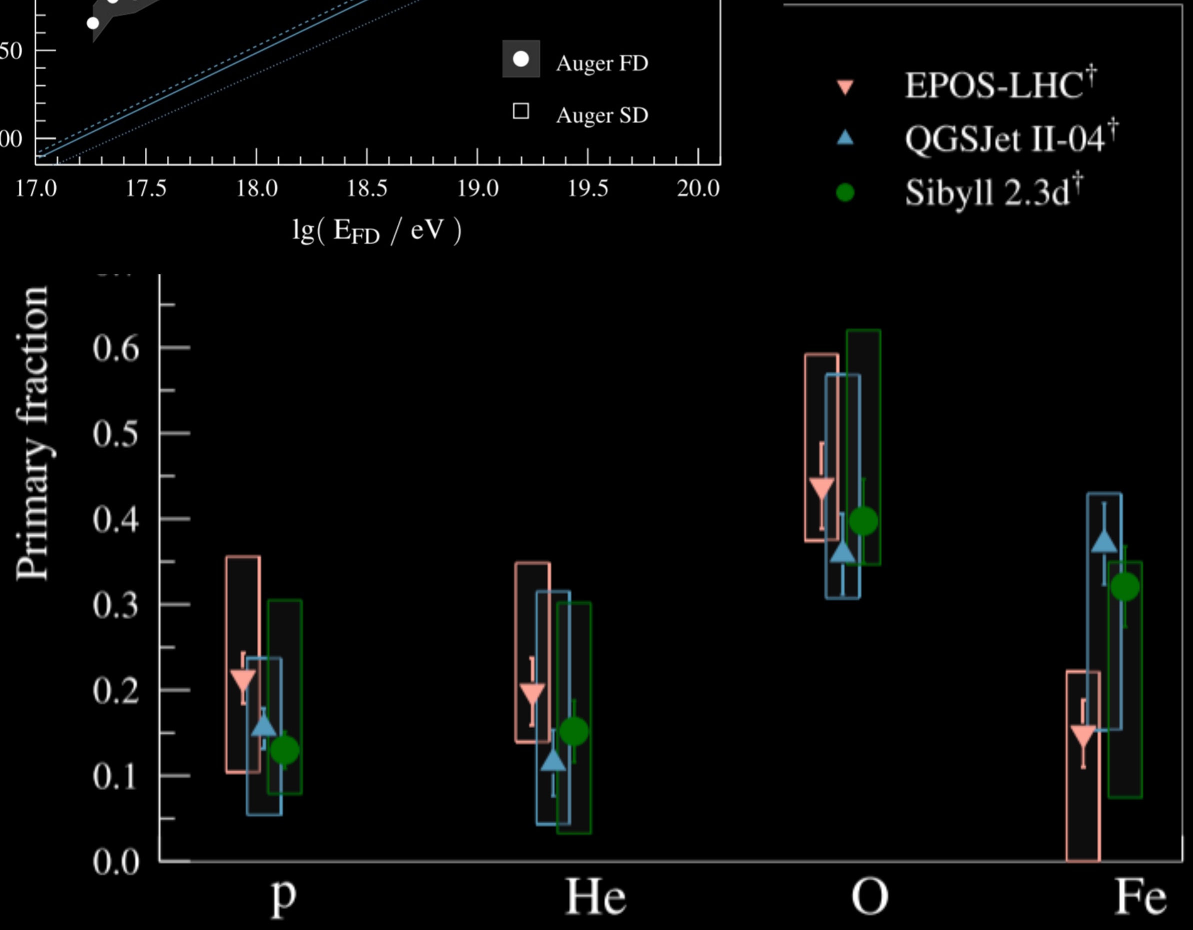
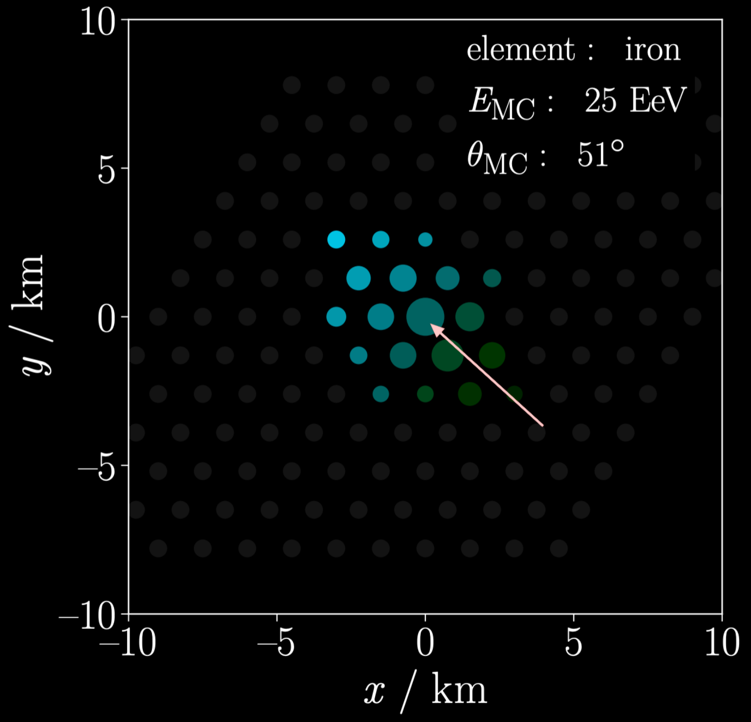
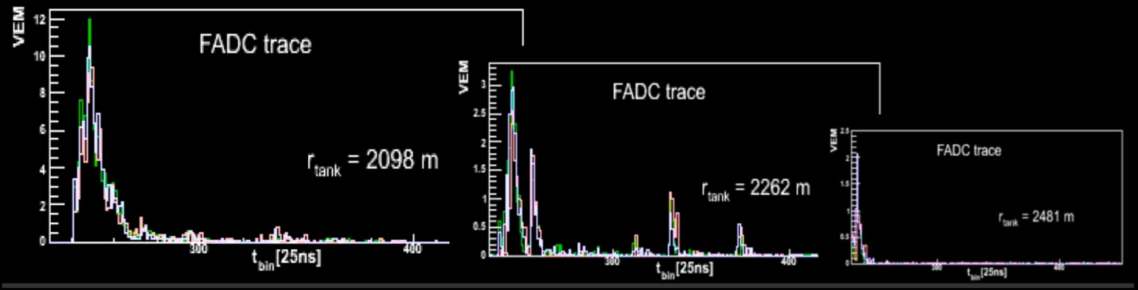


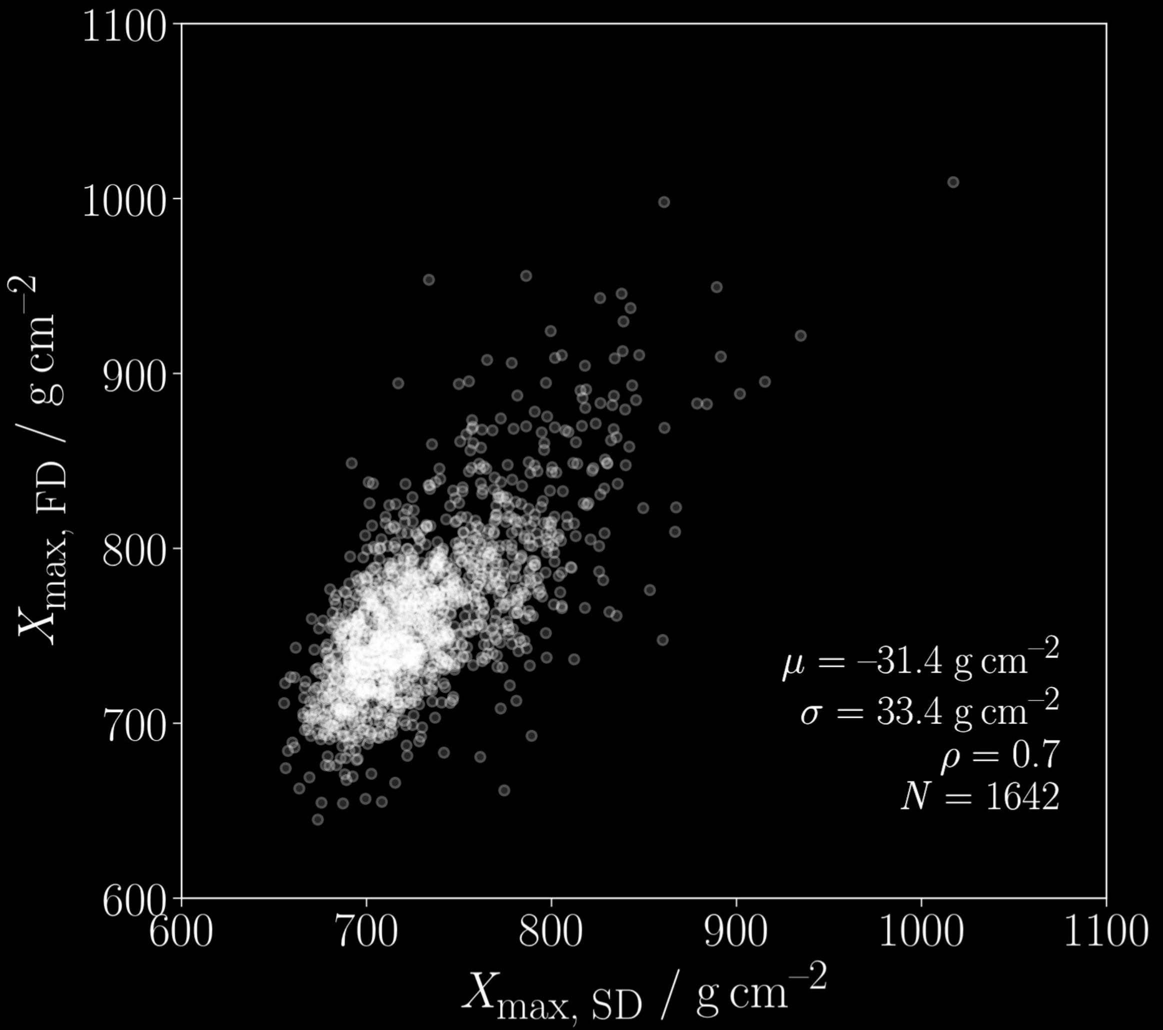




Xmax from DNN on SD traces

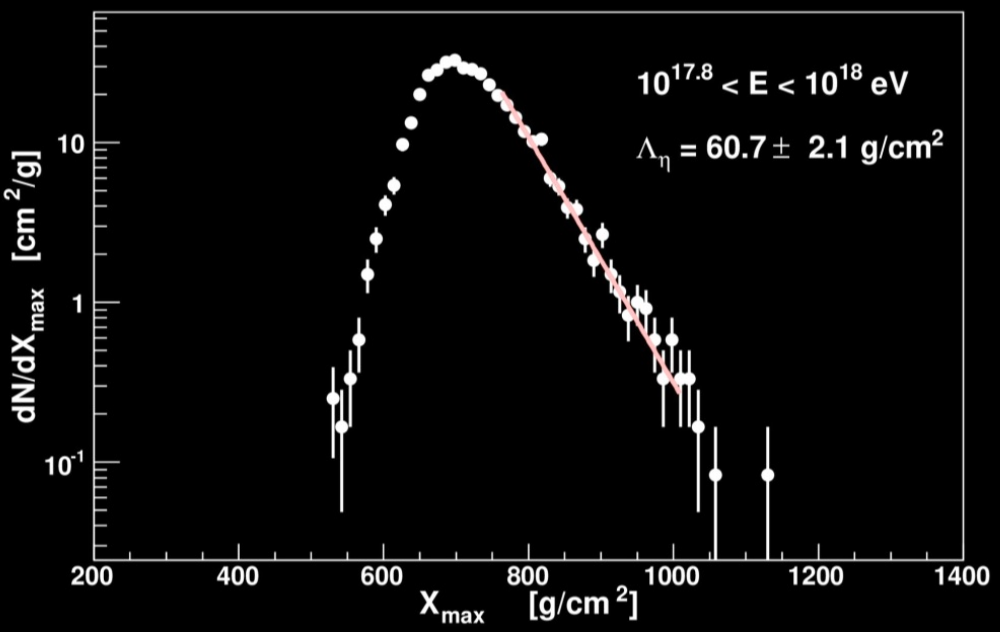






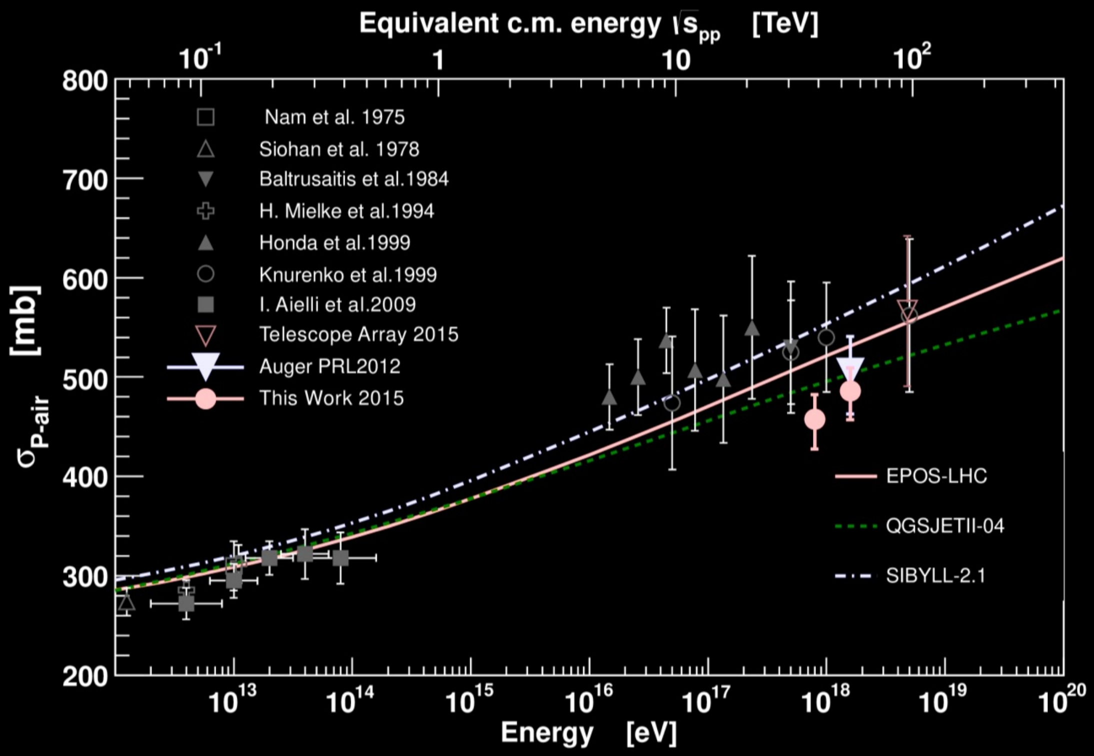
PRL and PRL 2024

p-Air cross section



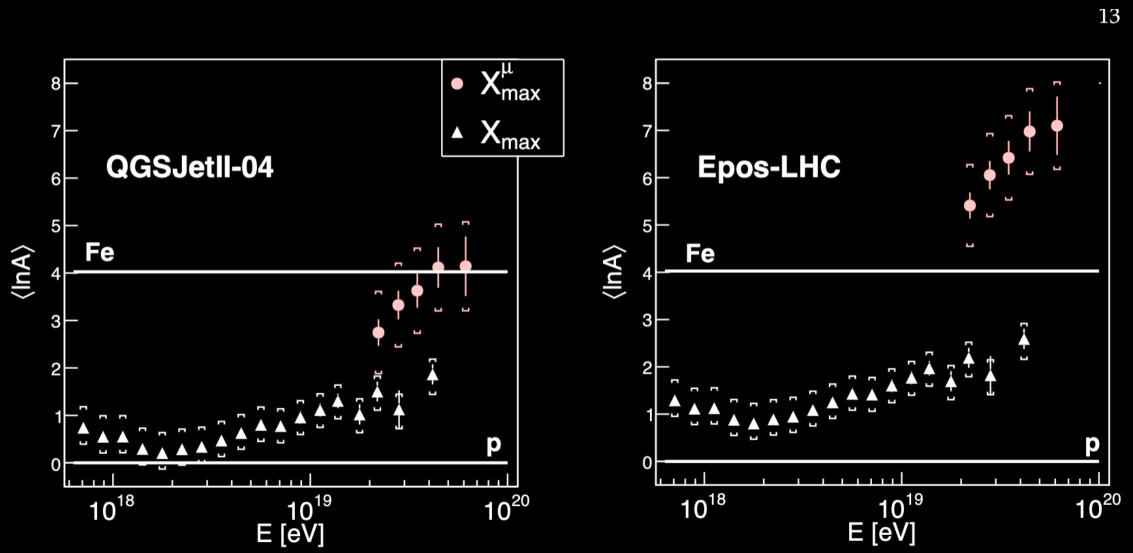
Deep showers → protons

8

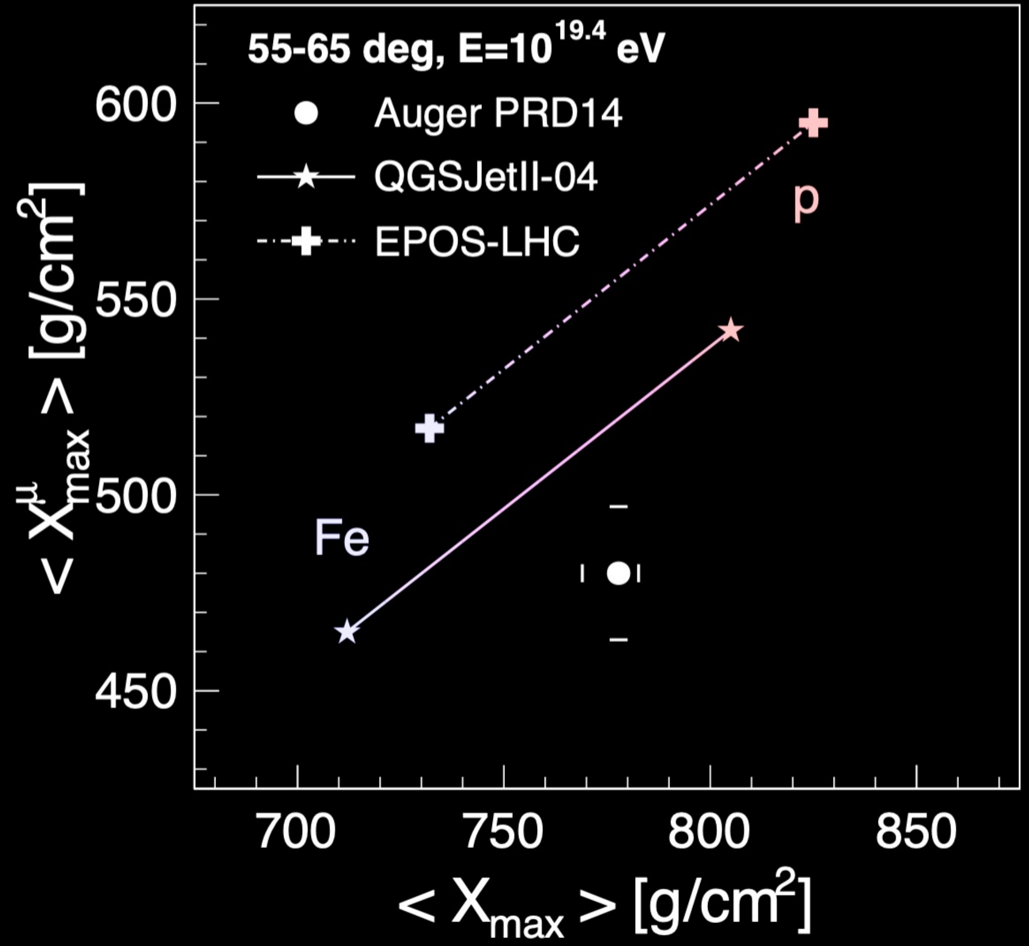


PRD 2012

Muon Production Depth



PRD 2015



Conclusions

- MUON PUZZLE
  - Auger finds a deficit of muons in sims. (All HI models) Results confirmed by independent measurements and different energies
    - Experimental confirmation that energy scale is not the problem
  - Muon fluctuations compatible with sims
      - A large deviation from expectations in the 1st interaction it is unfavoured
      - Most likely scenario is accumulation of small deviations along generations
- MUON PRODUCTION DEPTH
  - Off in models.
    - Related to pion-Air difraction cross section.
    - Fine tunning feedback with Xmax through Hadronic-EM flow in the cascade
- Xmax SCALE
  - not well explained by models by 20-50 gr/cm2

More to come

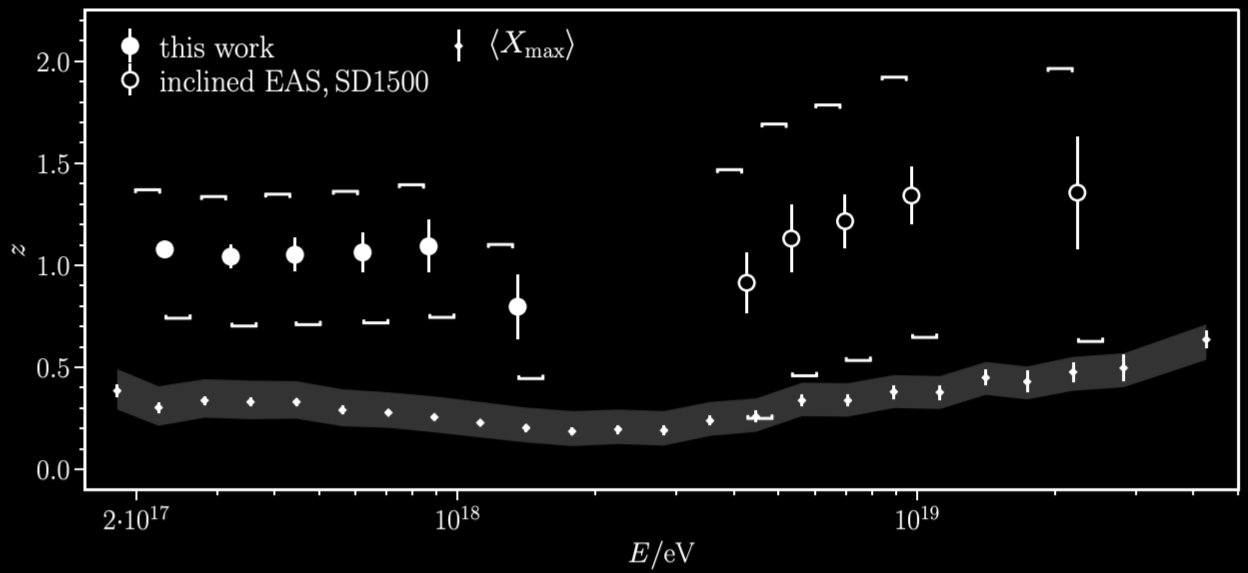
New publications coming soon

- LIV limits based on muon fluctuations (C. Trimarelli, ICRC2023)
- Muon measurements based on Shower Universality (M. Stadlemeier ICRC2023)
- Muon SD and Radio (AERA) (M. Gottowik ICRC2023)
- p-Air cross sections & composition fit (O. Tkatchenko ICRC23)

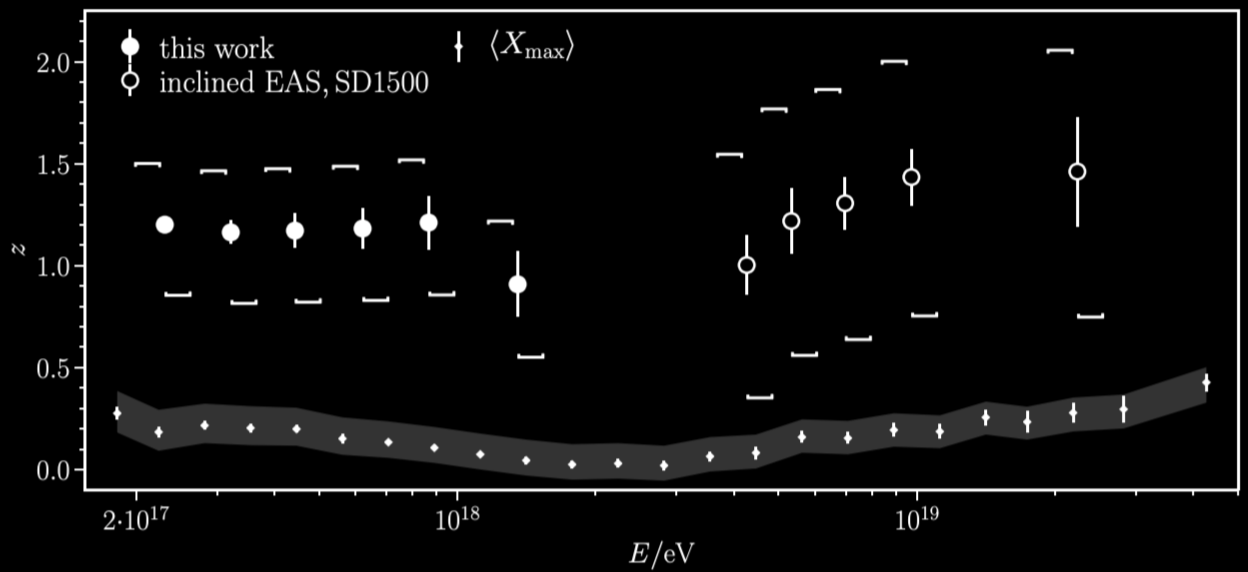
New detectors, new data: AugerPrime

- Radio
- Surface Scintillators
- Underground Scintillators
- Larger dynamic range for Water Cherenkovs
- New and faster electronics

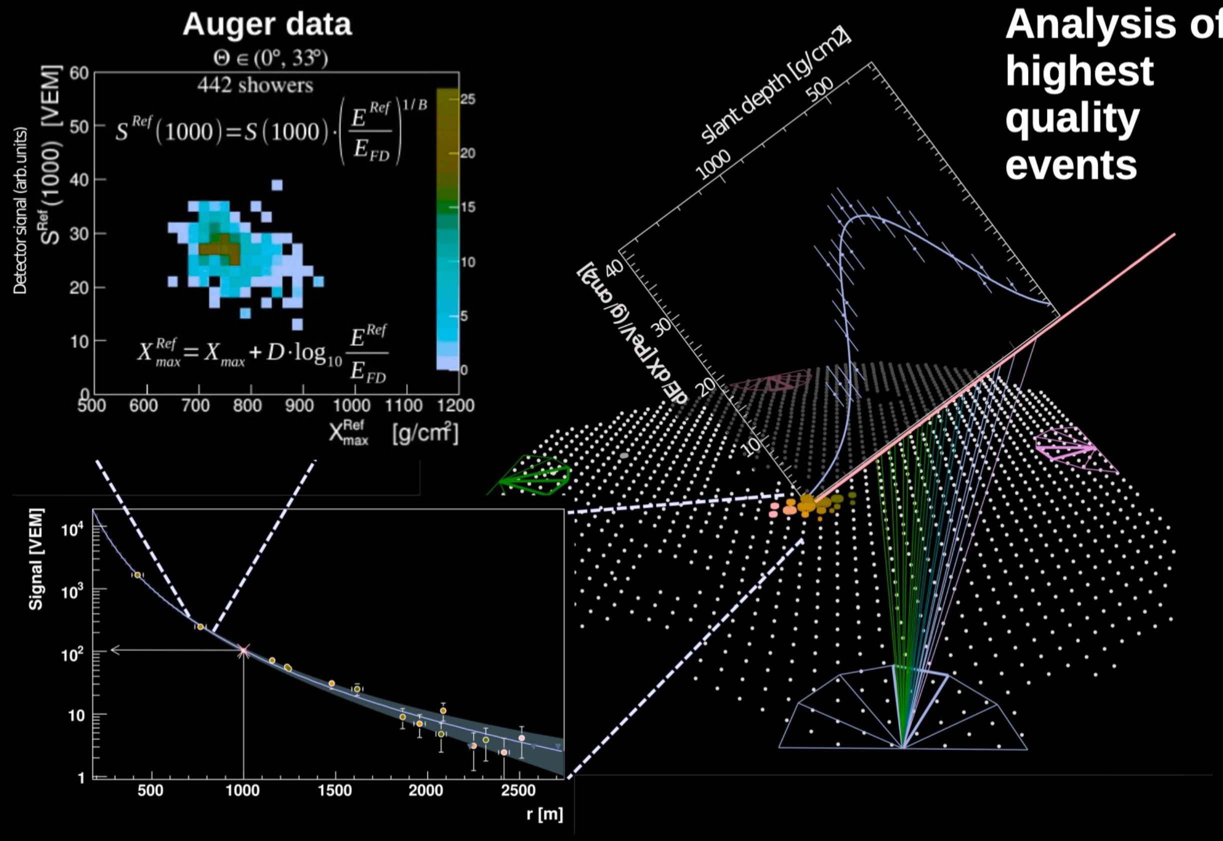
Back up

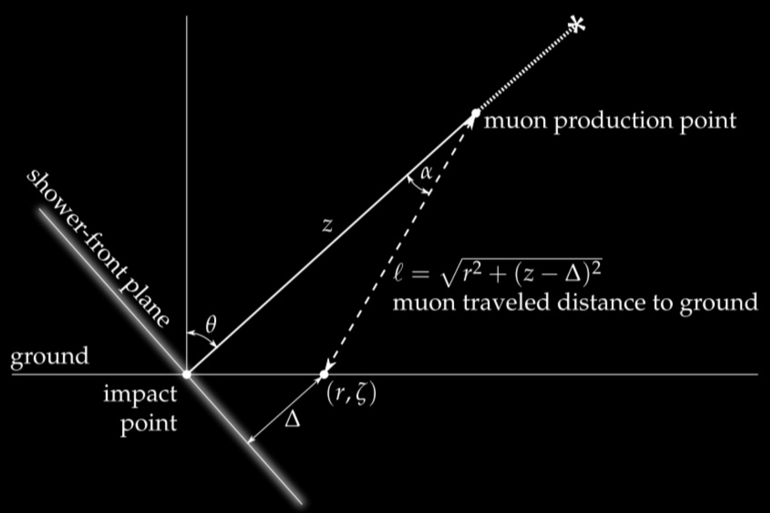

this work
inclined EAS, SD1500
⟨$X_{\max}$⟩
z
E/eV

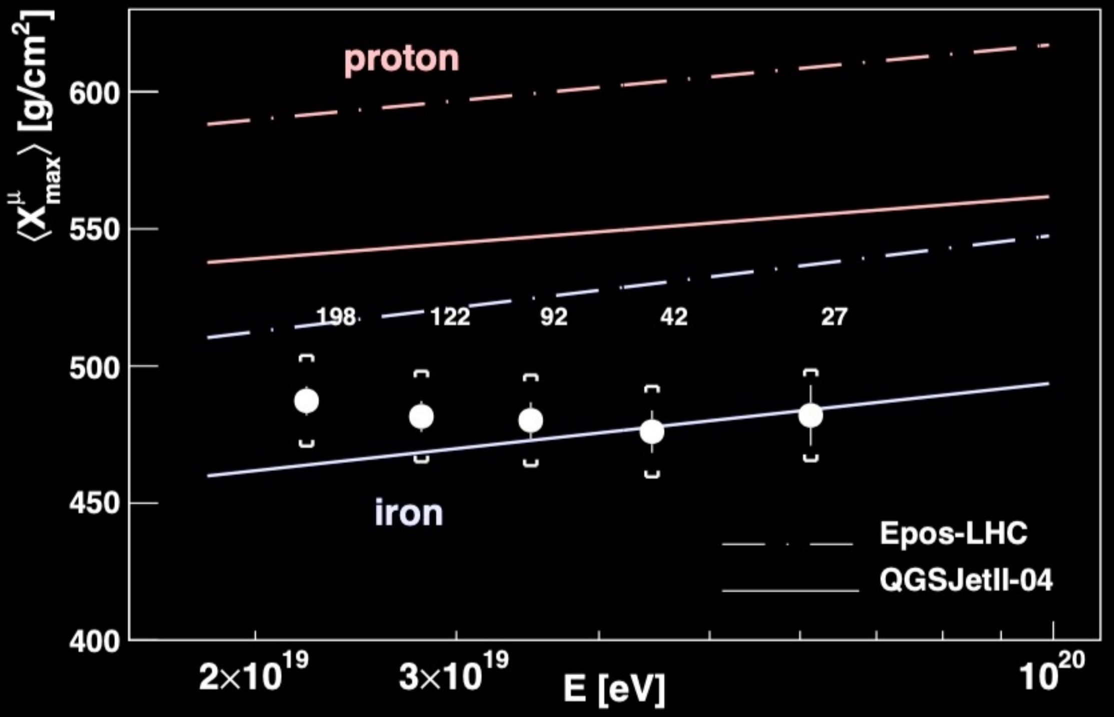
(a) EPOS-LHC


this work
inclined EAS, SD1500
⟨$X_{\max}$⟩
z
E/eV

Analysis of highest quality events




shower-front plane
muon production point
z
α
$\ell = \sqrt{r^2 + (z-\Delta)^2}$
muon traveled distance to ground
θ
ground
impact
point
Δ
(r, ζ)


$\langle X^{\mu}_{max} \rangle$ [g/cm^2]
proton
iron
198
122
92
42
27
600
550
500
450
400
2×10^{19}
3×10^{19}
10^{20}
E [eV]
Epos-LHC
QGSJetII-04