Instituto Galego de Física de Altas Enerxías

Results on Hadronic Physics with the Pierre Auger Observatory

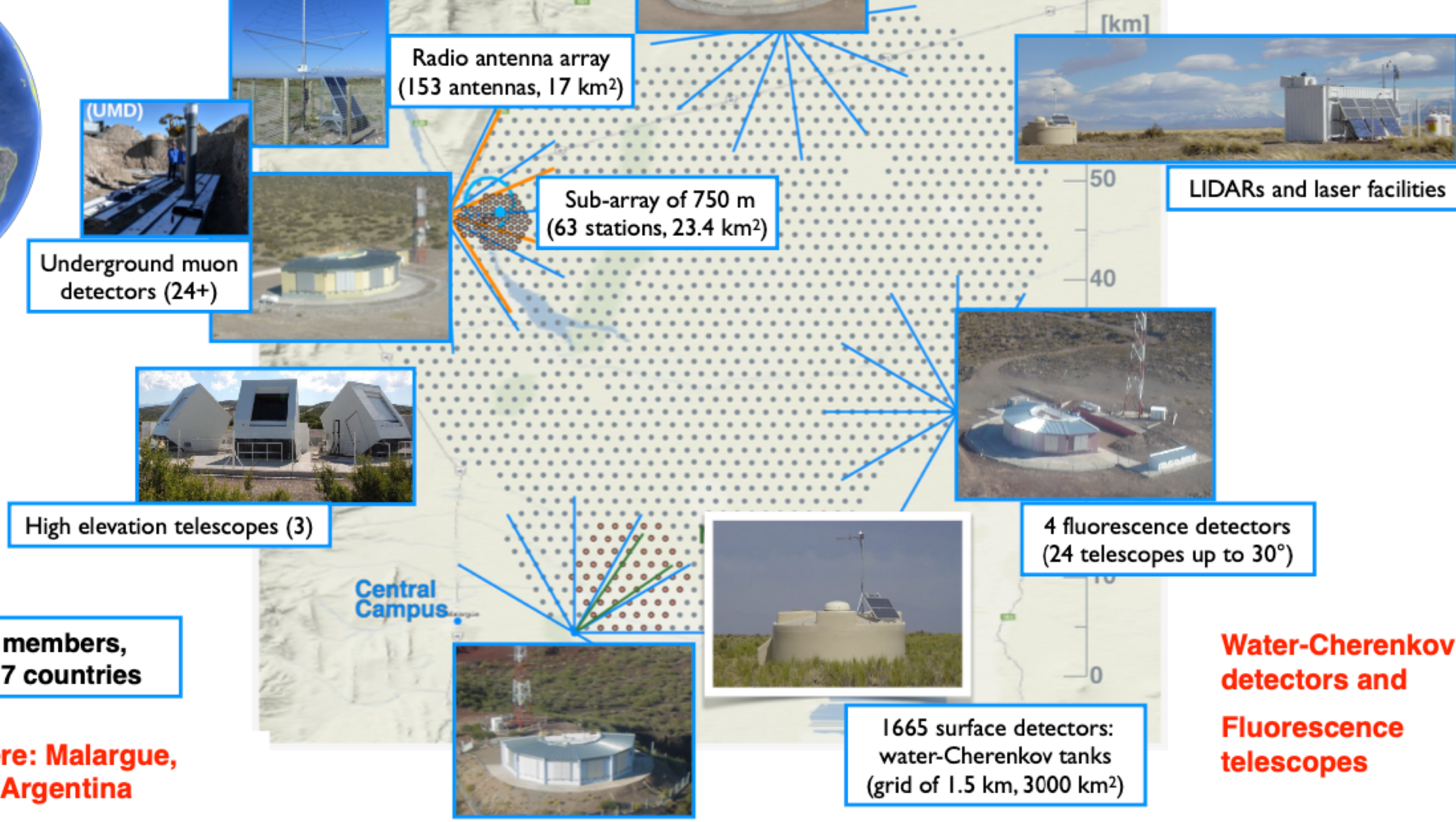
L. Cazon, for the Auger Collaboration

The Pierre Auger Observatory

Links to contributions at ICRC

(Christoph Schäfer)
(Andrew Puyleart)

Pierre Auger Observatory
Province Mendoza, Argentina

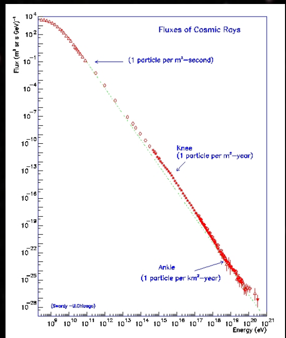


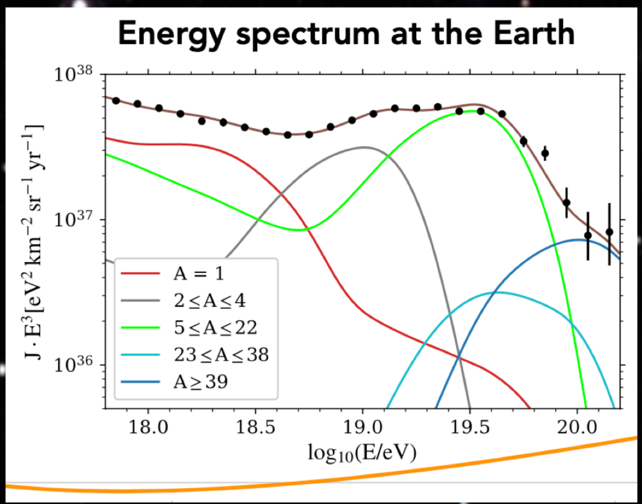
More than 400 members, 98 institutes, 17 countries

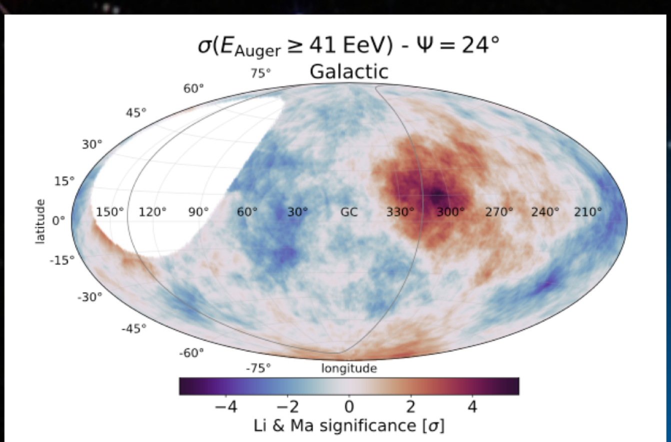
Southern hemisphere: Malargue, Province Mendoza, Argentina

Water-Cherenkov detectors and

Fluorescence telescopes



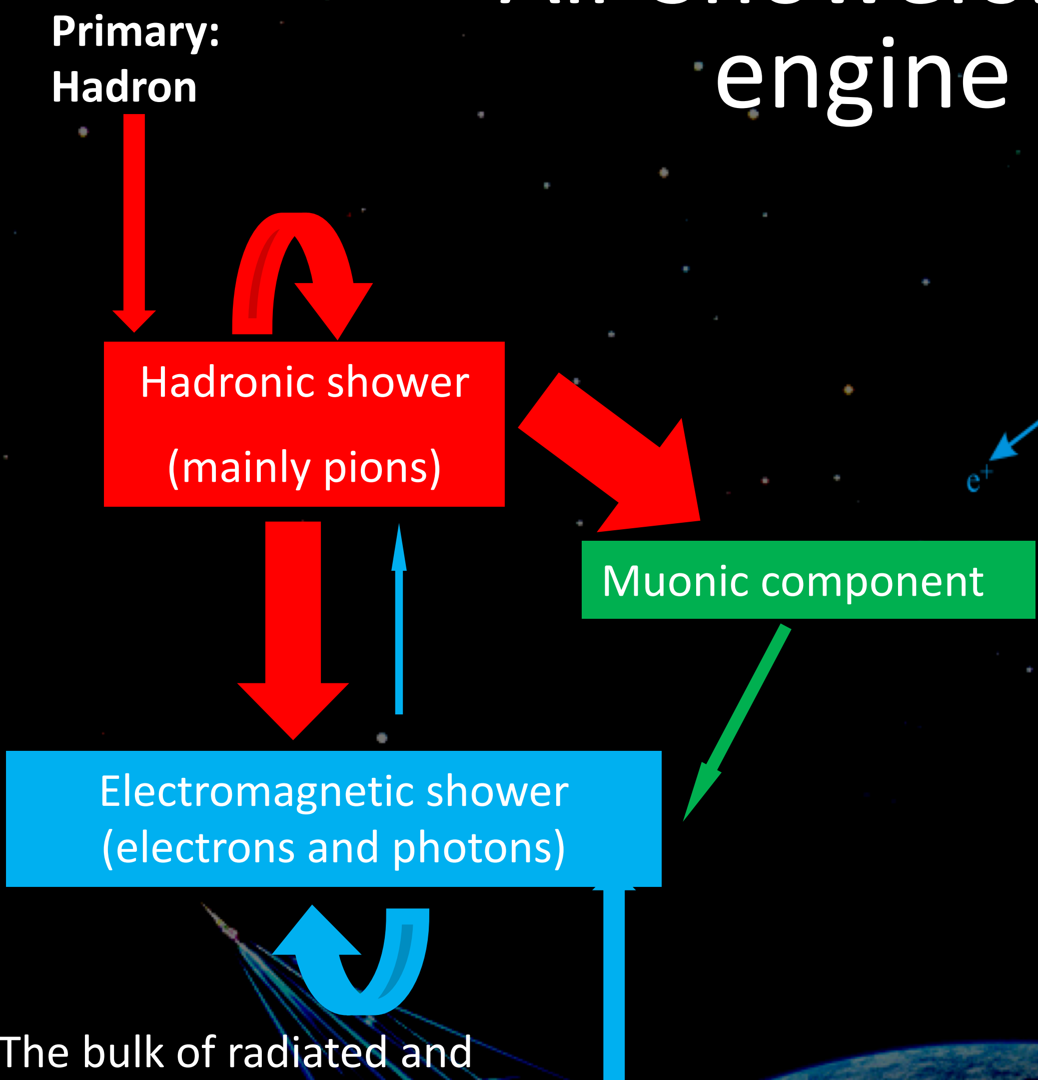




Main Results at a glance

- Top down scenarios (cosmological origin) disfavoured.
- UHECR extragalactin origin
- Sources are astrophysical
  - Starburst Galaxies, AGN...?
- Hard injection spectra
- Heavier composition
  - (compared to expectations)
- **Hadronic Physics beyond LHC energies**

Air Showers: the engine

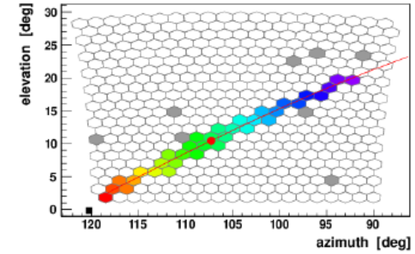


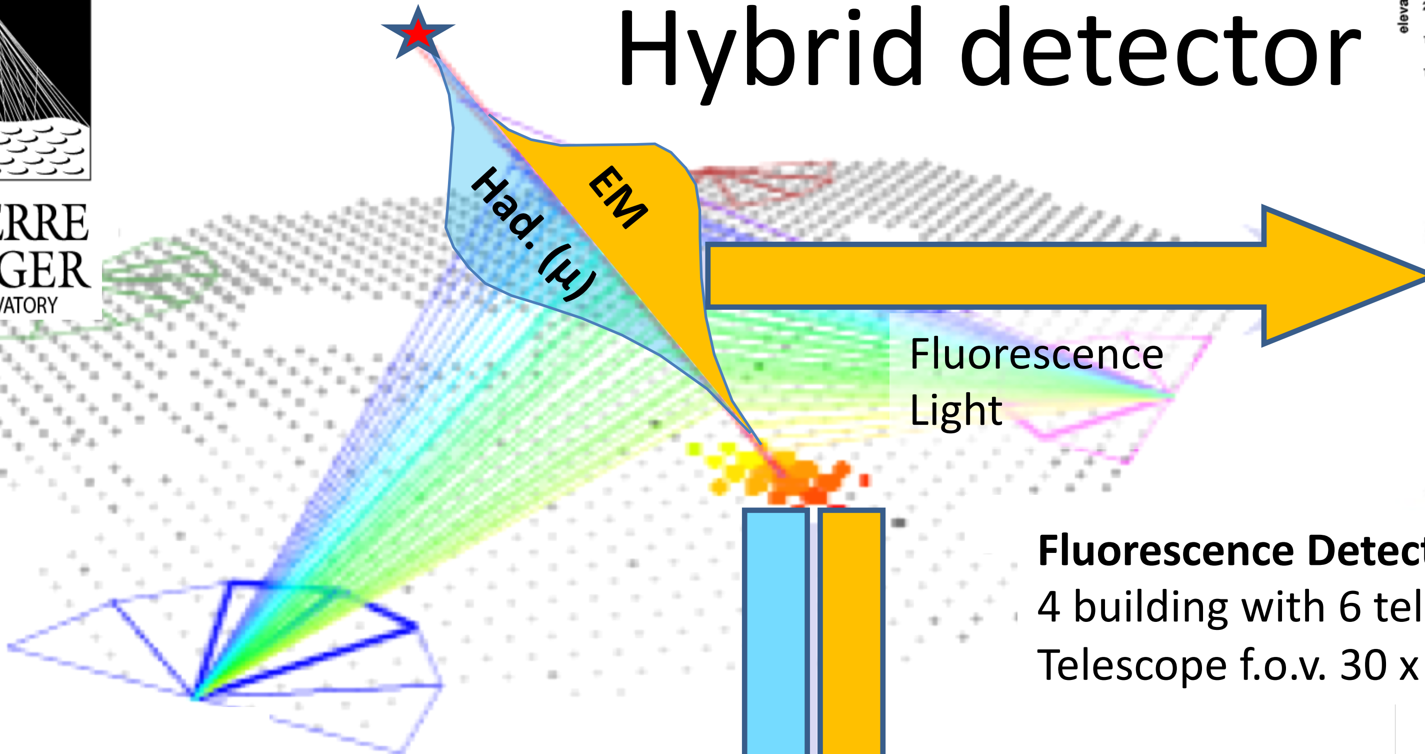
Muons trace the hadronic shower which is the backbone of the whole cascade

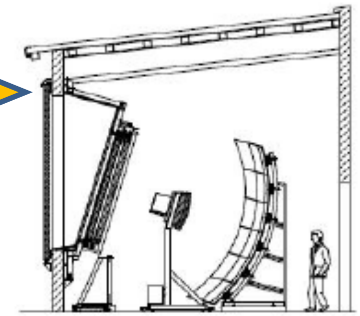
π^0 decays are the propellers of the EM cascade

The bulk of radiated and visible energy comes from the EM cascade

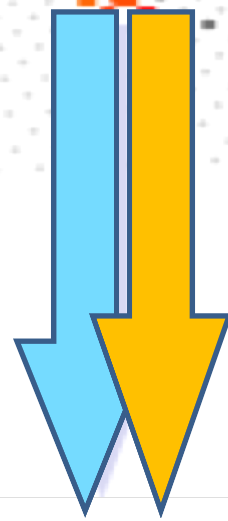
Hybrid detector





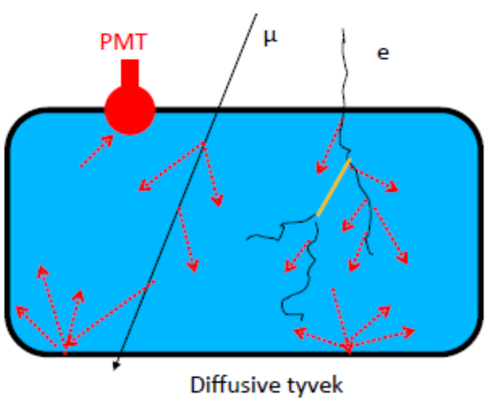


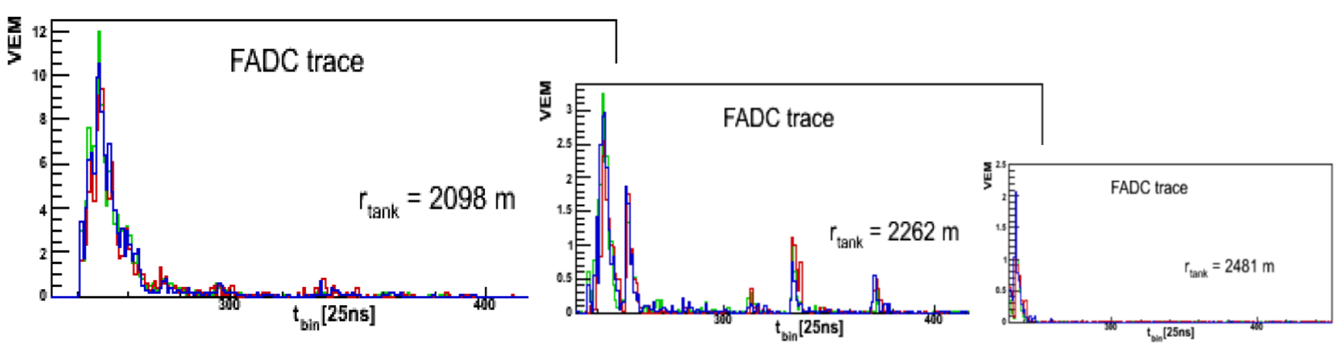
Fluorescence Detector (FD)
4 building with 6 telescopes each
Telescope f.o.v. 30 x 30 deg



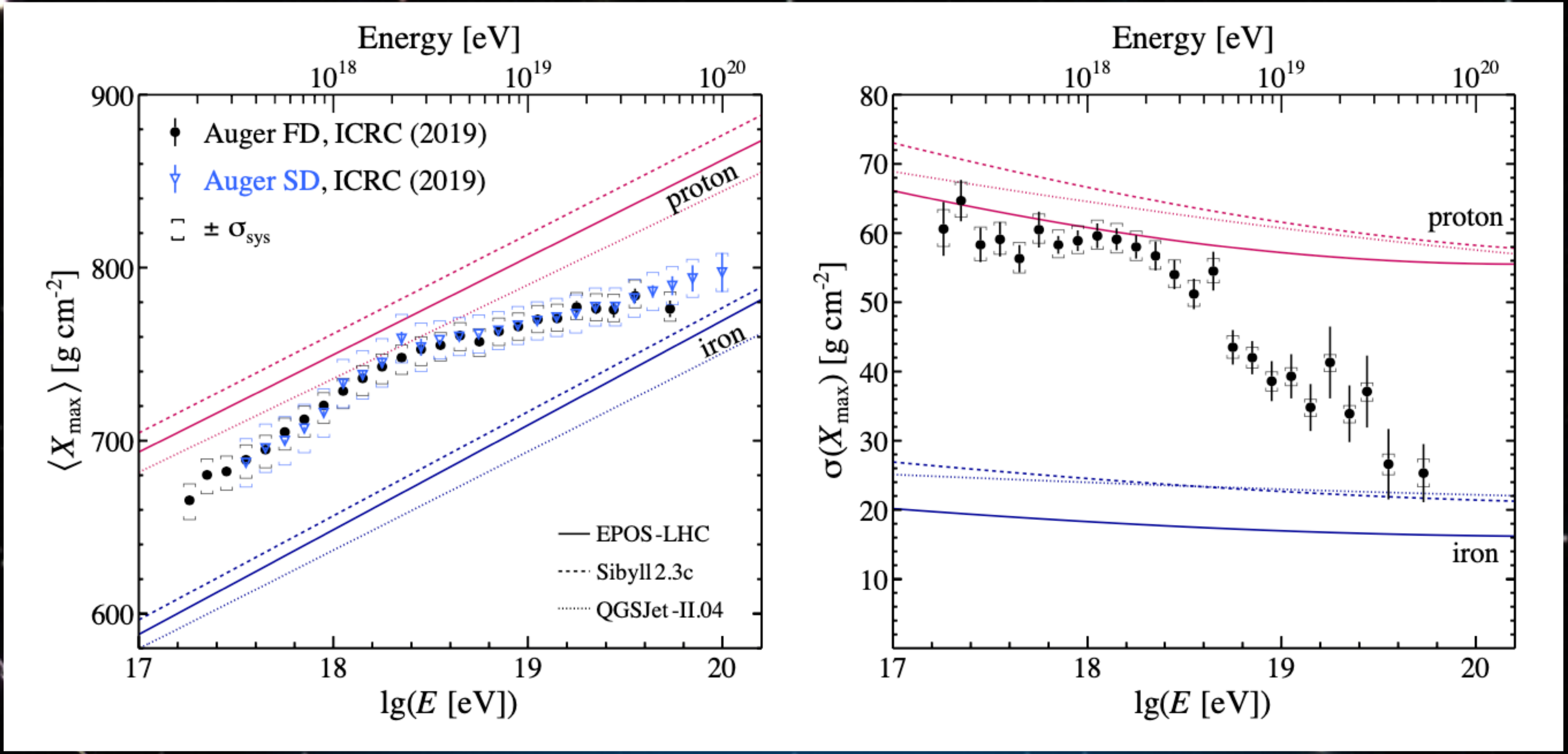
SD & FD
(+AMIGA)

Surface Detector (SD)
1600 water Cherenkov tanks
Area of 3000 km^2

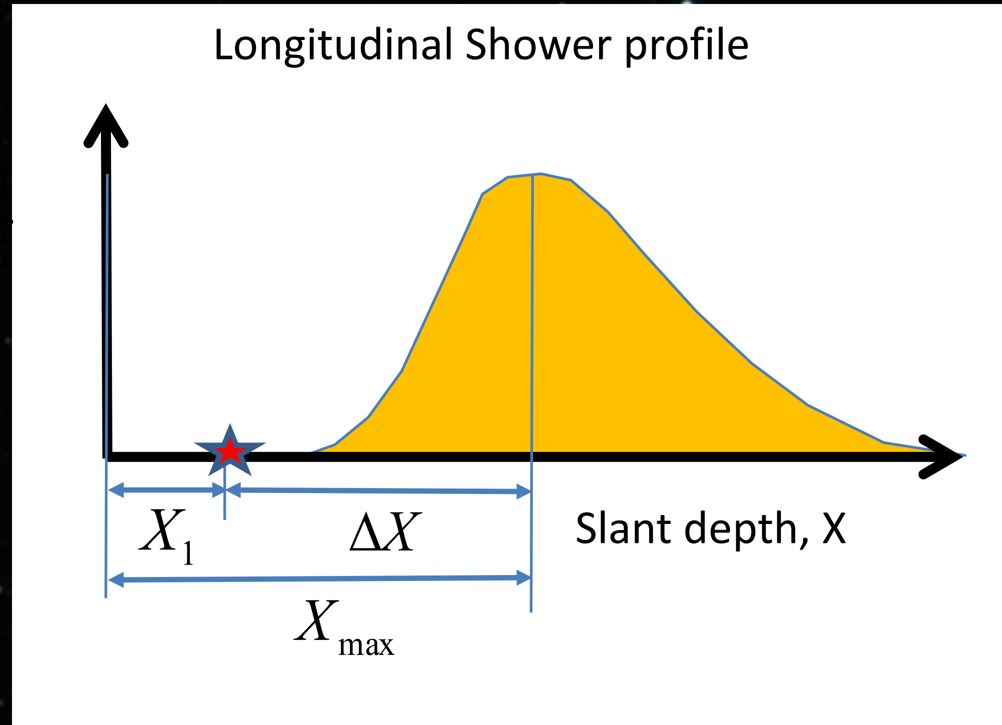




X_{max} : Mass interpretation



p-Air cross section

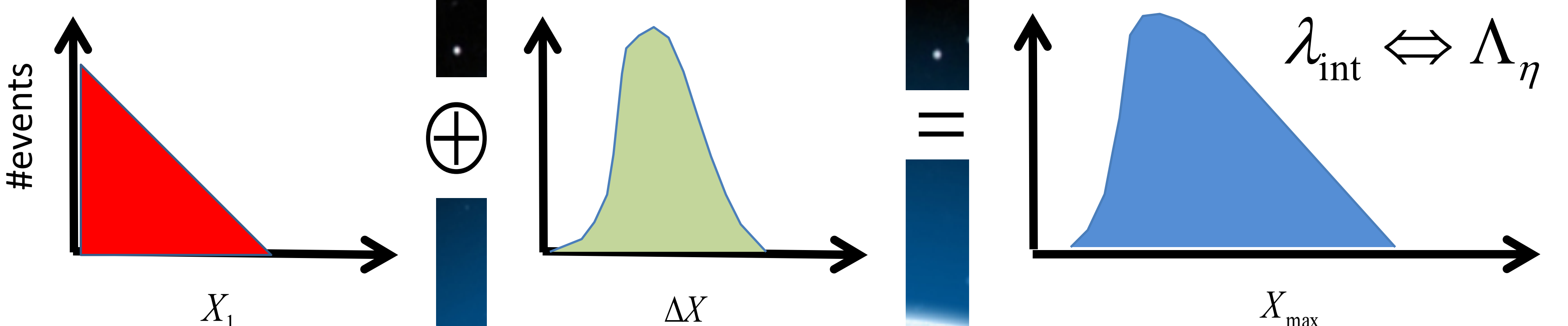


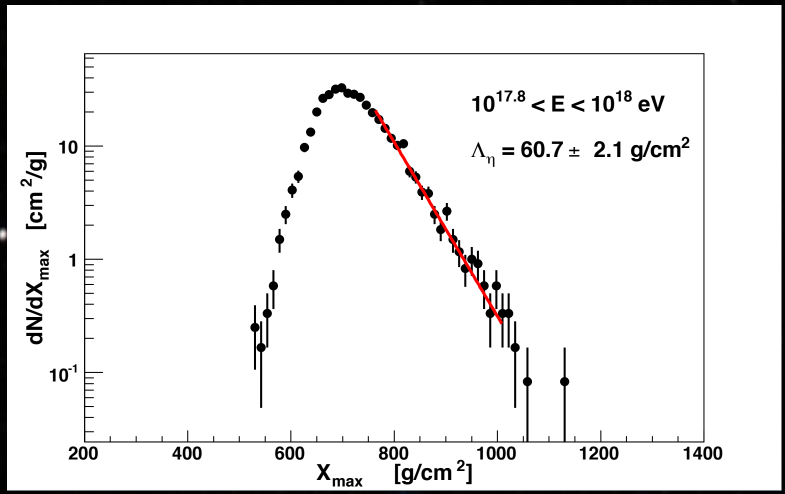
$$\sigma_{\text{int}} = \frac{< m_{air} >}{\lambda_{\text{int}}}$$

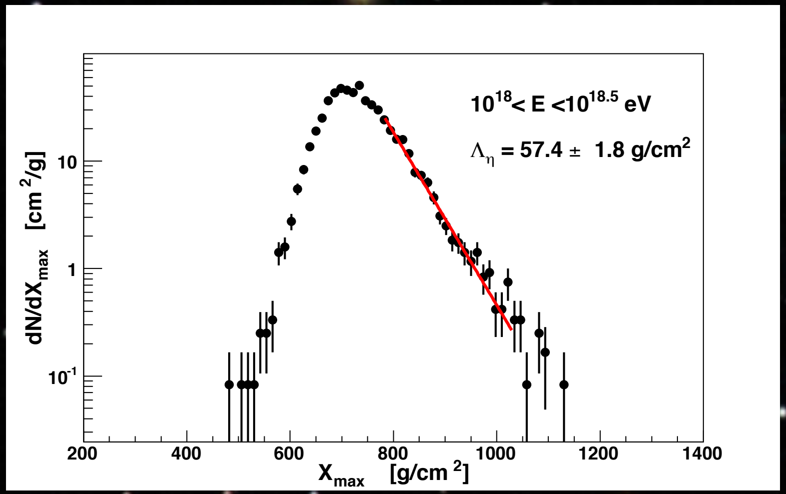
$$\frac{dp}{dX_1} = \frac{1}{\lambda_{\text{int}}} e^{-X_1 / \lambda_{\text{int}}}$$

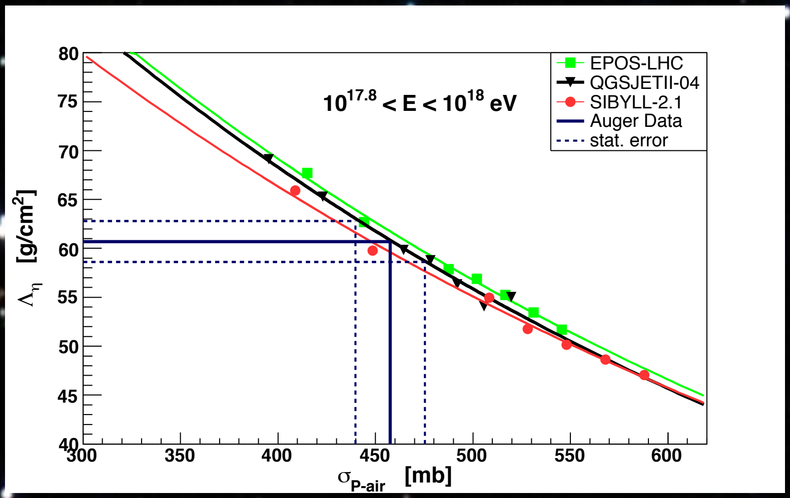
$\Rightarrow$ Tail of X_{max} – Distribution

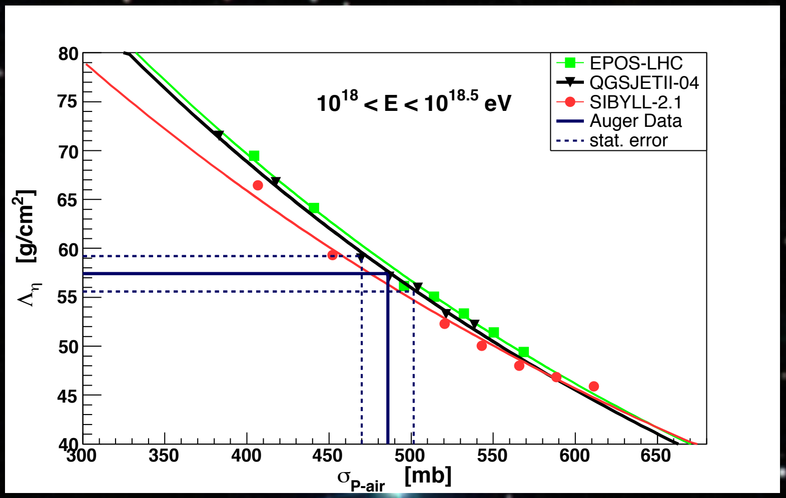
$dN/dX_{max} \propto \exp(-X_{max}/\Lambda_\eta)$





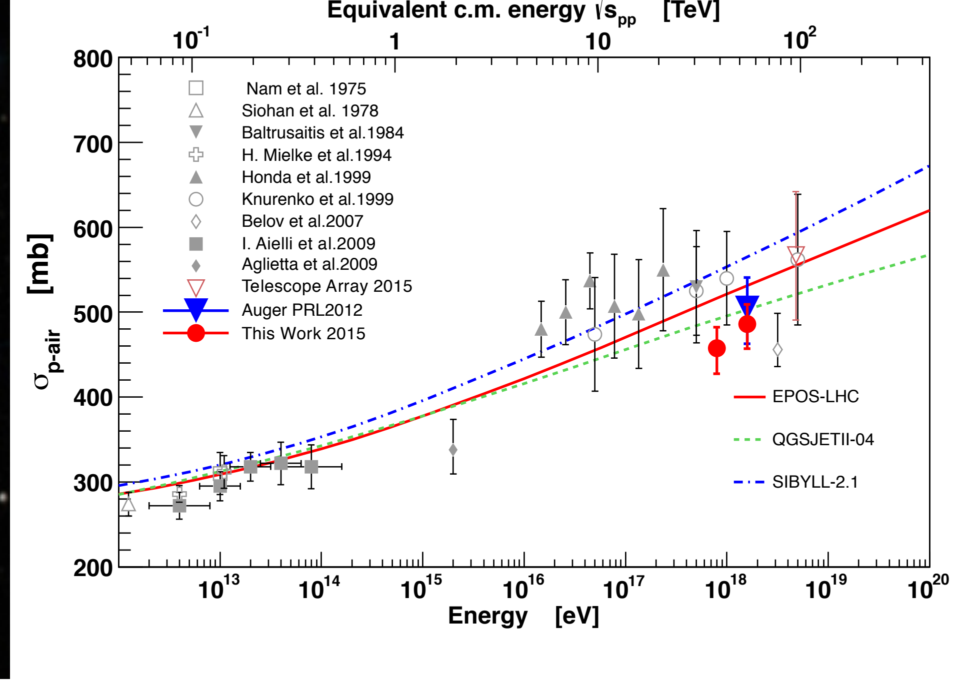


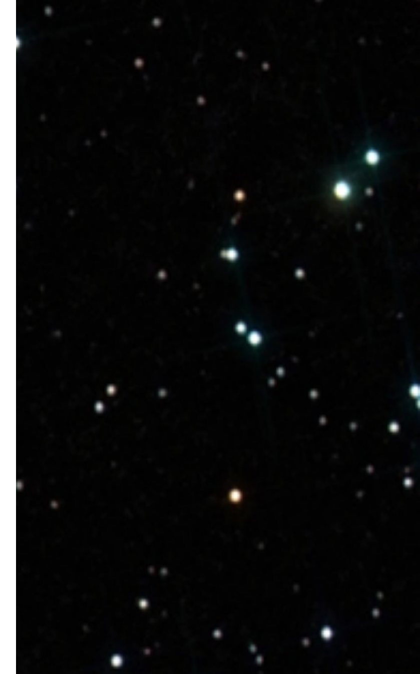


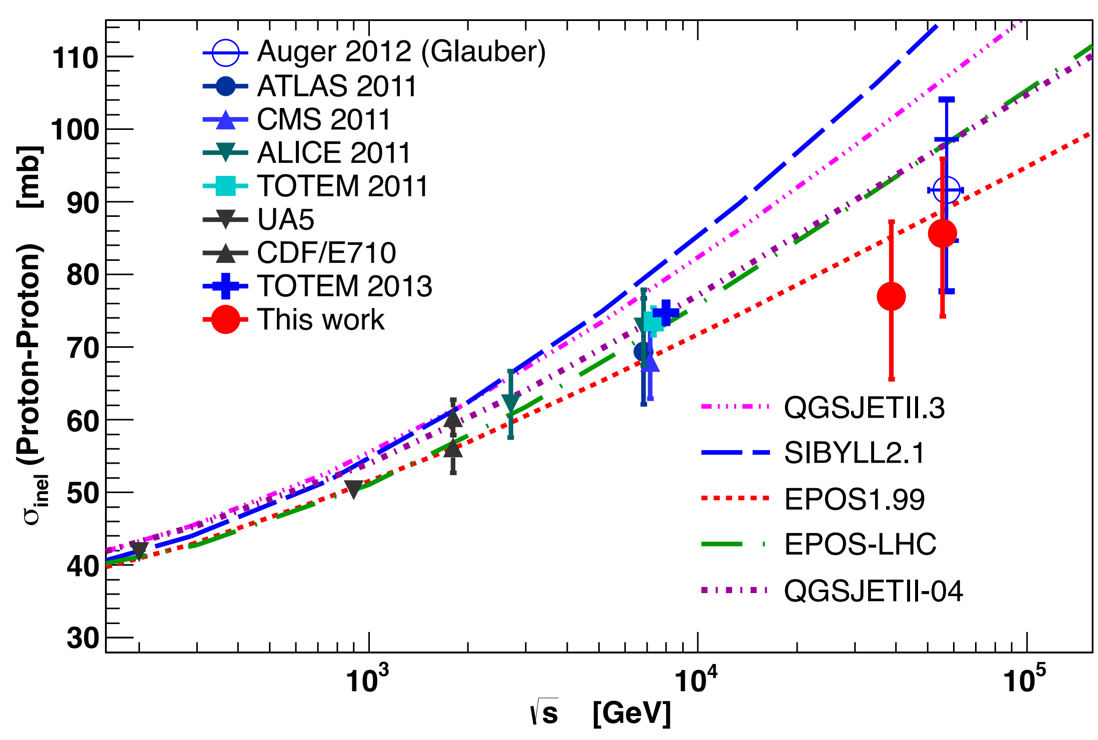


	$10^{17.8} - 10^{18}$ eV	$10^{18} - 10^{18.5}$ eV
$\sigma_{\text{p-air}}$ uncertainties		
Λ_η, systematic uncertainties (mb)	13.5	14.1
Hadronic interaction models (mb)	10	10
Energy scale uncertainty, $\Delta E/E = 14\%$ (mb)	2.1	1.3
Conversion of Λ_η to $\sigma_{\text{p-air}}$ (mb)	7	7
Photons (mb)	4.7	4.2
Helium, 25% (mb)	-17.2	-15.8
Total systematic uncertainty on $\sigma_{\text{p-air}}$ (mb)	+19/-25	+19/-25

Possible He contamination is the main source of systematic uncertainty. 25% He maximum contamination assumed for sys. uncertainties







Results, σ_{pp}^{inel} in mb

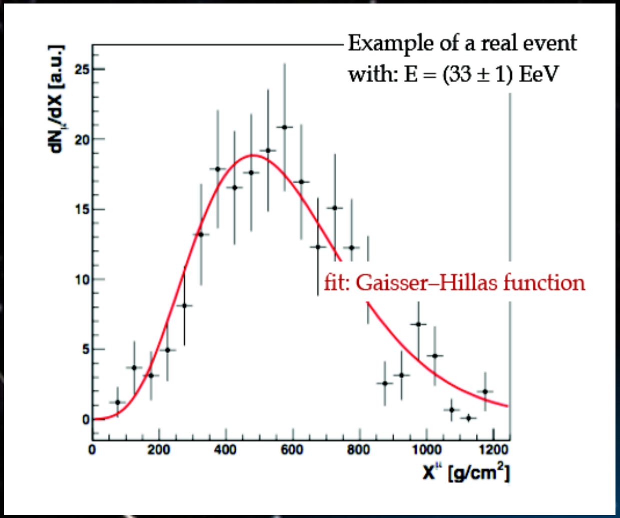
- Lower energy point
  76.95±5.4(stat)+5.2/-7.2(syst)±7(glauber)
  at $\sqrt{s_{pp}} = 38.7 \pm 2.5$ TeV

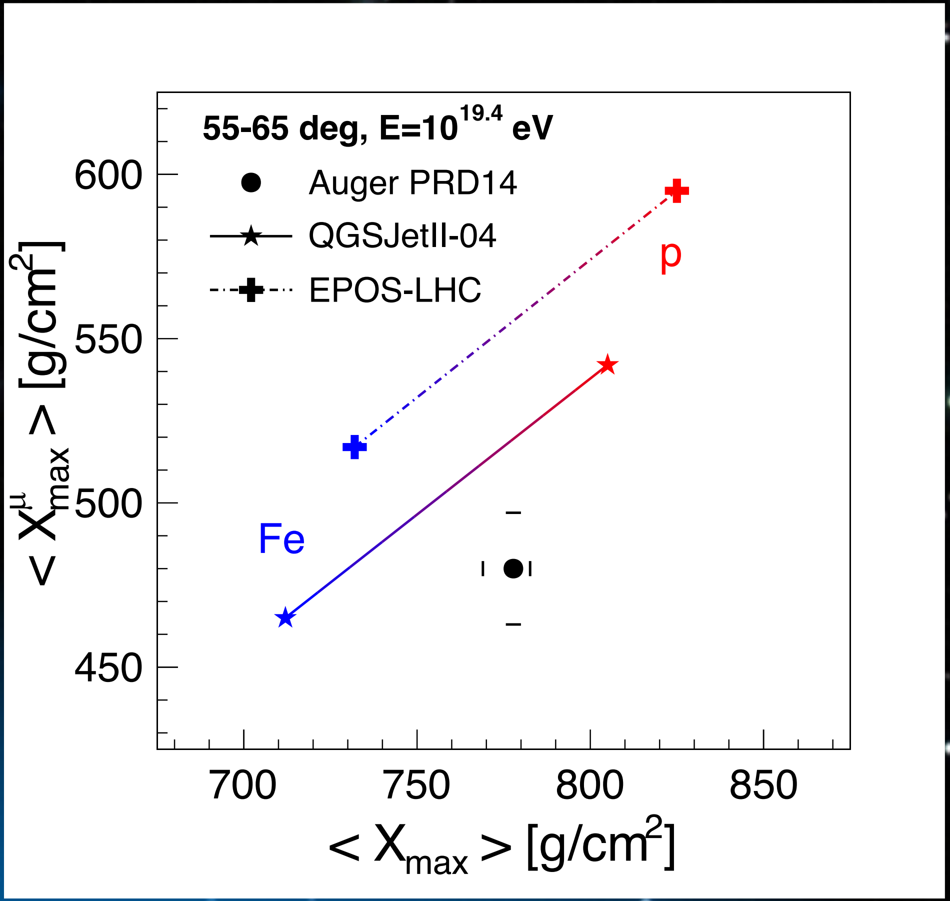
- Higher energy point
  85.62±5(stat)+5.5/-7.4(syst)±7.1(glauber)
  at $\sqrt{s_{pp}} = 55.5 \pm 3.6$ TeV

Muon Production Depth : $< X^{\mu}_{max} >$

Muon Production Depth profile can be estimated from the muon arrival times distributions

Muons are produced in the shower axis
Muons travel following straight lines





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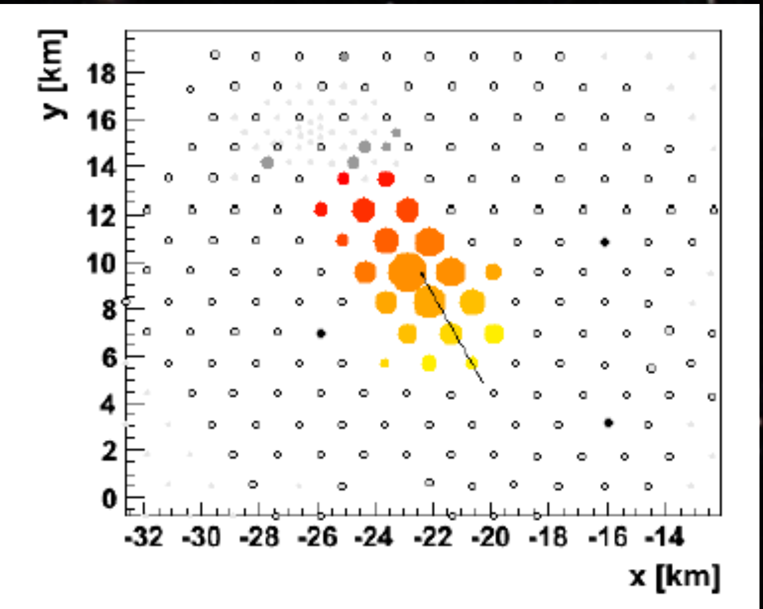
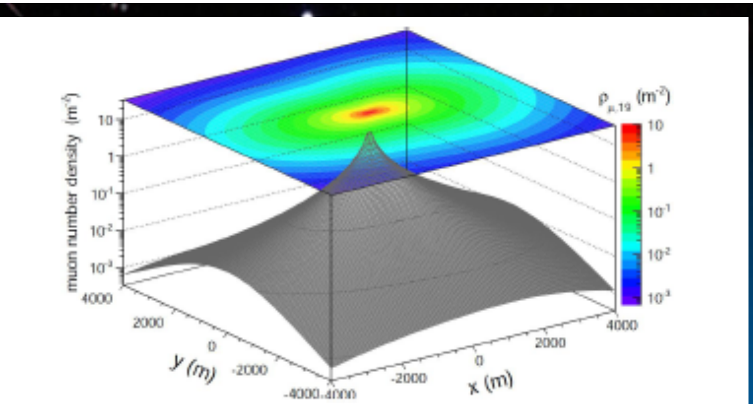
Number of muons in Inclined Showers

62<Θ<80 deg





Example of $\rho_{\mu,19}$ for proton showers at θ=80°, ϕ=0° and core at (x,y) = (0,0)

Fit the muon density in stations

$$\rho_\mu = N_{19}\rho_{\mu,19}(x,y)$$

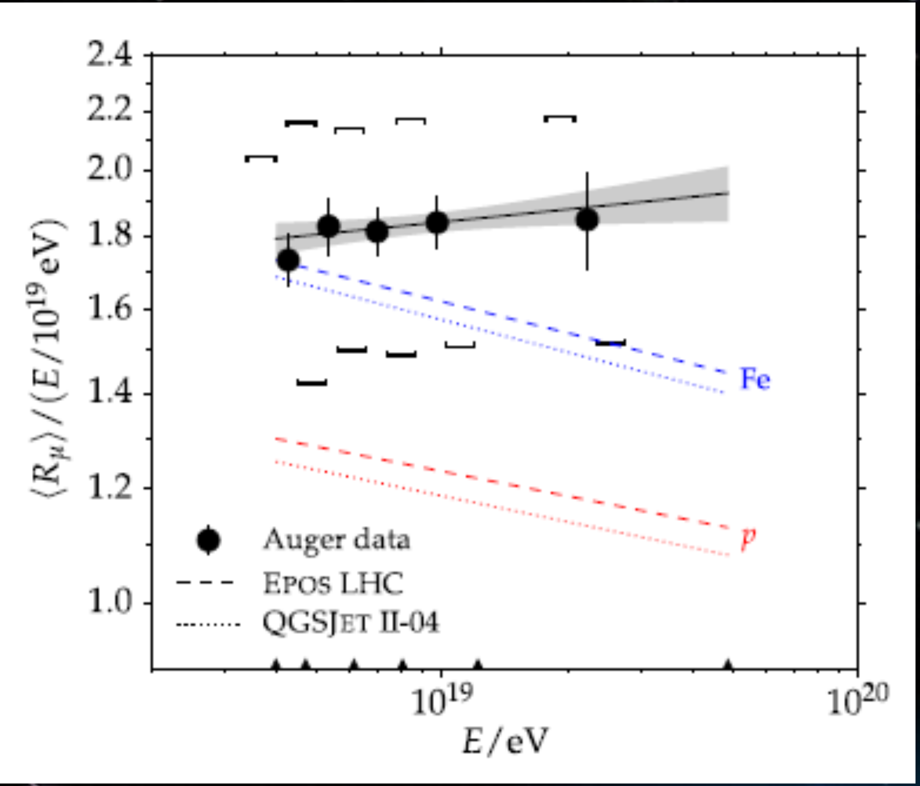
where N_{19} free parameter
And $\rho_{\mu,19}$ *(x,y)* is fixed, corresponding to proton QGSJetII-03 at 10^{19} eV

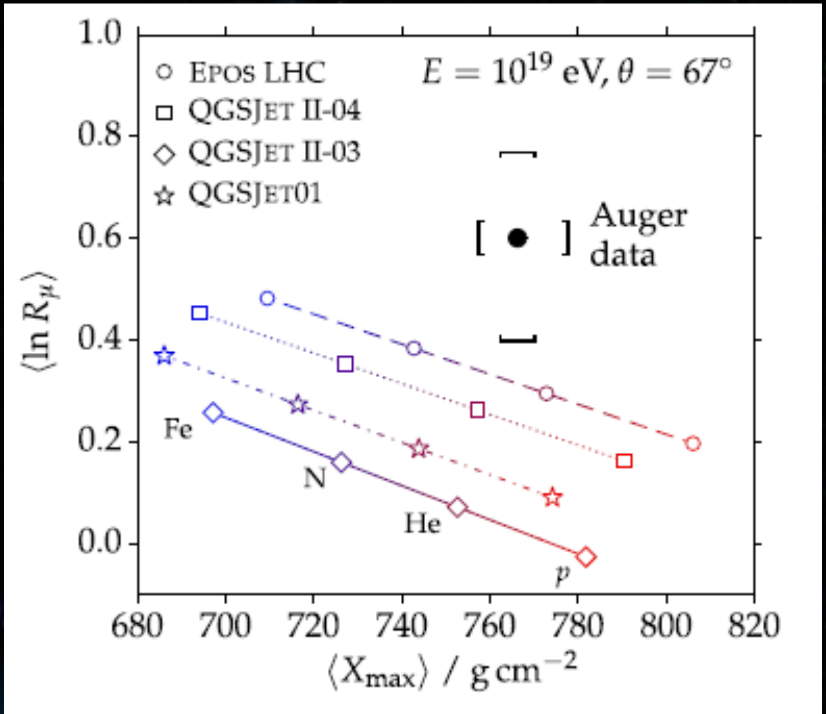
Ratio of the total number of muons N_μ to $N_{\mu,19}$ (proton QGSJetII-03 at 10^{19} eV)

$$R_\mu = N_\mu / N_{\mu,19}$$

Correspondence (<5% bias correction)

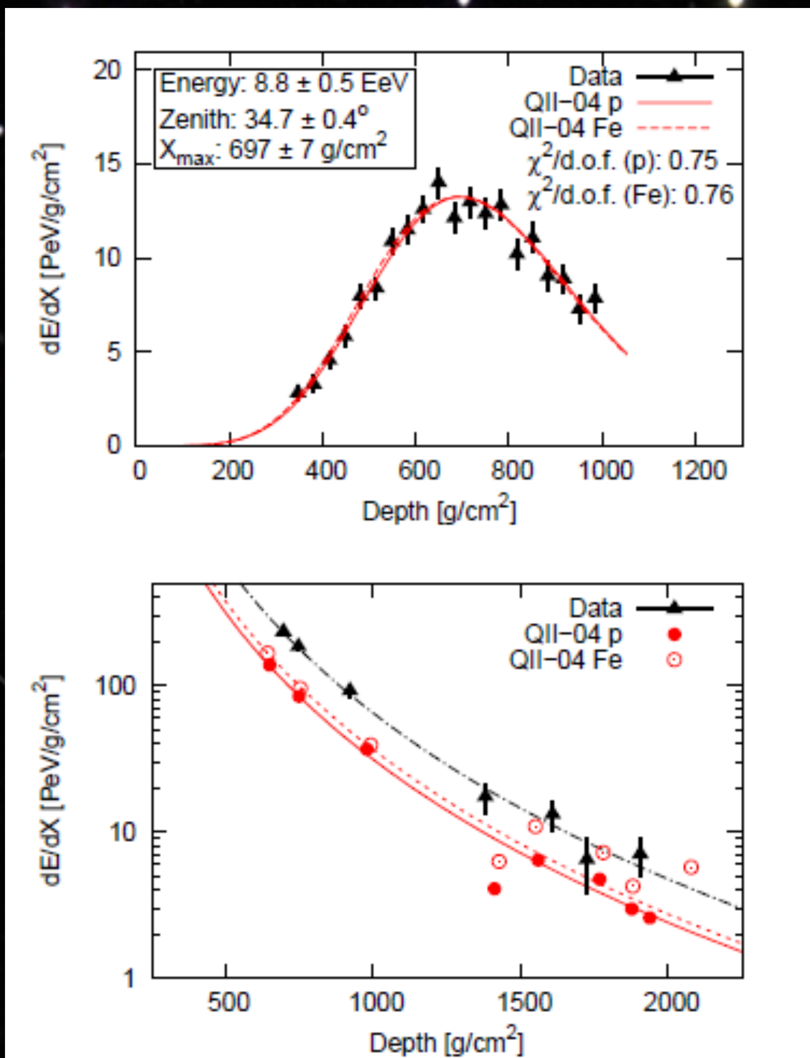
$$N_{19} \Leftrightarrow R_\mu$$





Muon deficit in sims, and also deficit on energy derivative (muon gain)

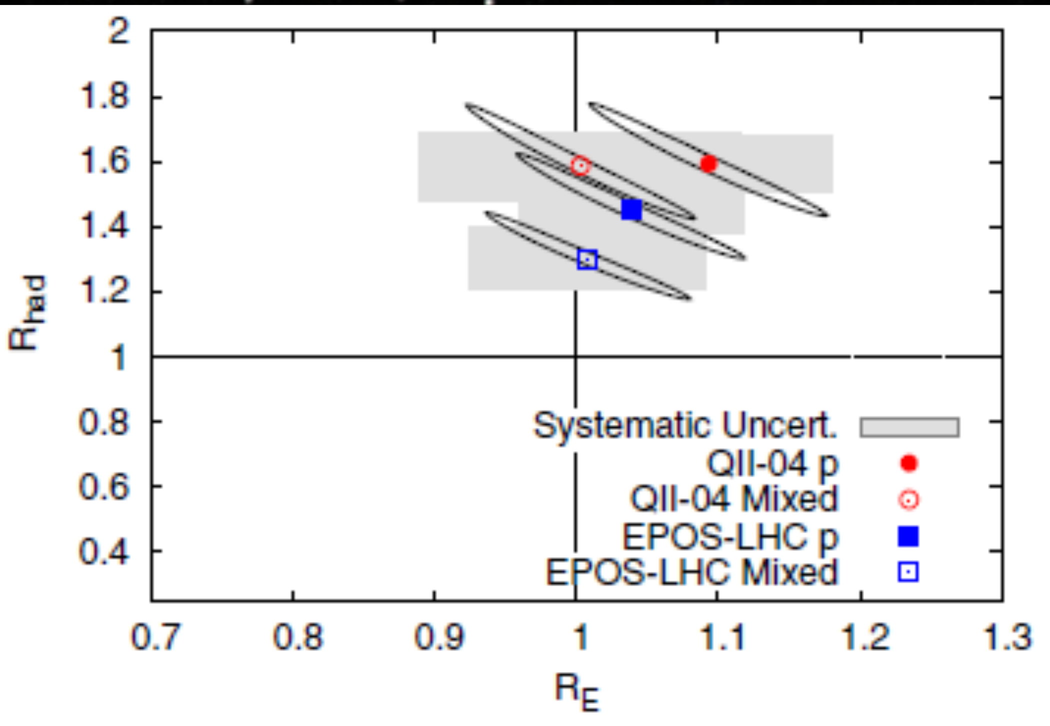
Number of Muons and Energy Scale from Vertical Showers



- Find simulations which match FD profile, **for each event**
- Compare SD signals for simulations and data
- Rescale muon content until simulated SD best match data

TABLE I: Approximated amount of signal for each one of the different components at 38 deg, 10^{19} eV.

component	scaling	signal
0) Total Signal		38.3 VEM
1) Pure EM	EM	15.8 VEM
2) Pure μ	hadronic	16.6 VEM
3) EM from low-E π_0'	hadronic	4.4 VEM
4) μ from Photoprod.	EM	1.3 VEM
5) EM from μ decay	$\sim$ hadronic	1.0 VEM

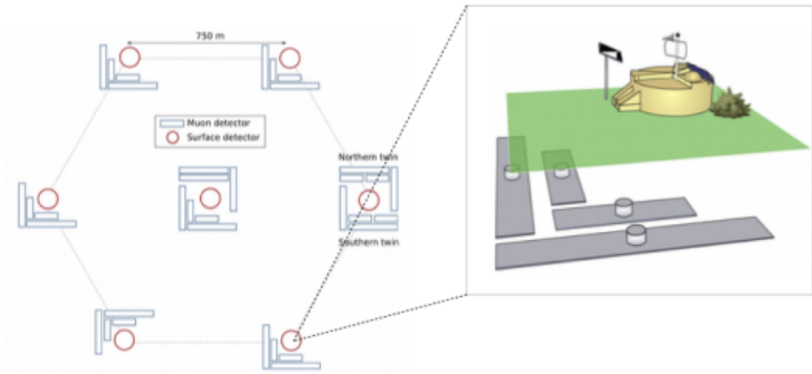


- **No energy rescaling is needed**

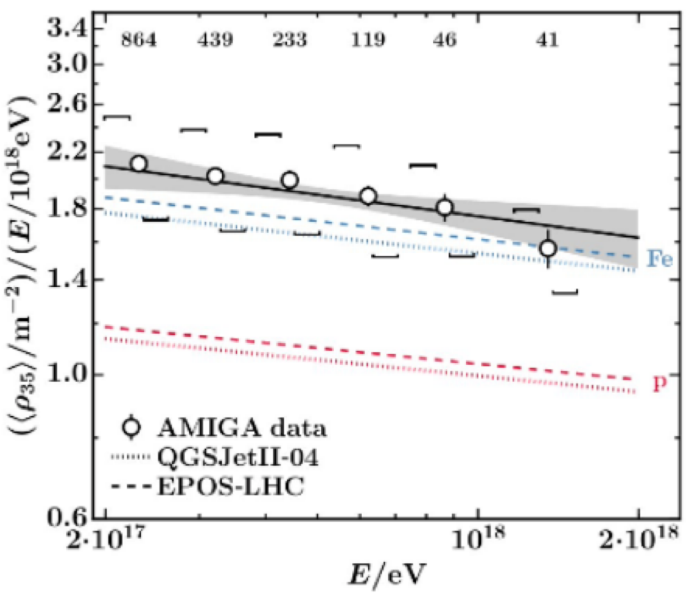
- The observed muon signal is a factor 1.3 to 1.6 larger than predicted by models

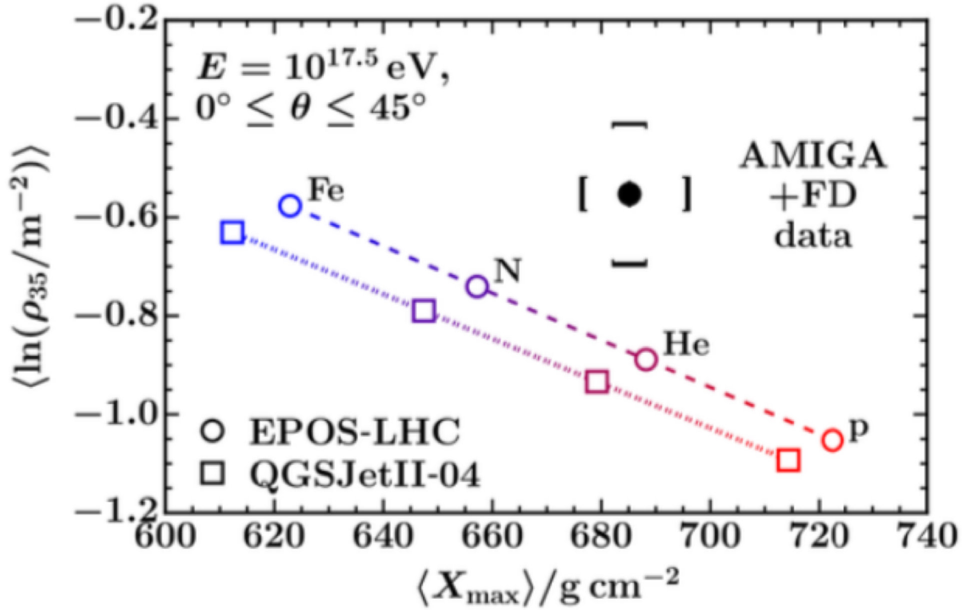
Model	R_E	R_{had}
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

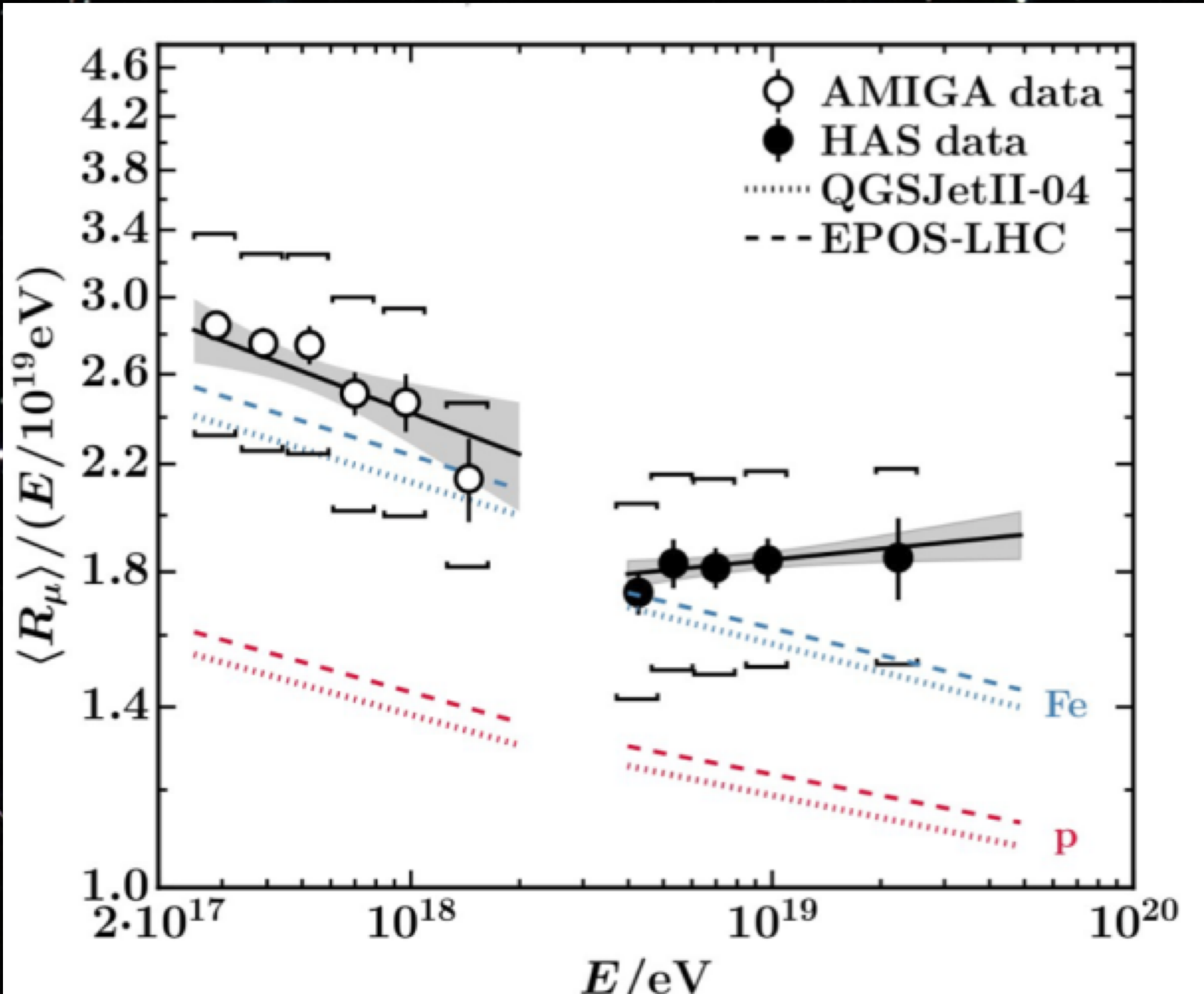
Underground Muon Detector



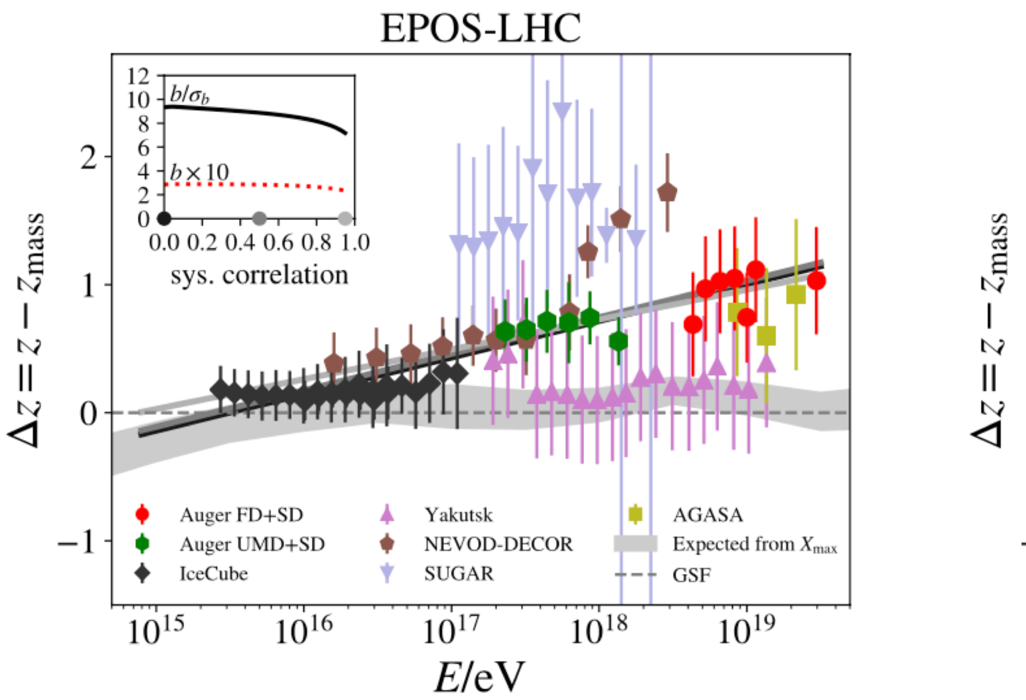
30 m^2 scintillators buried 2.3 m below surface at 7 WCD locations





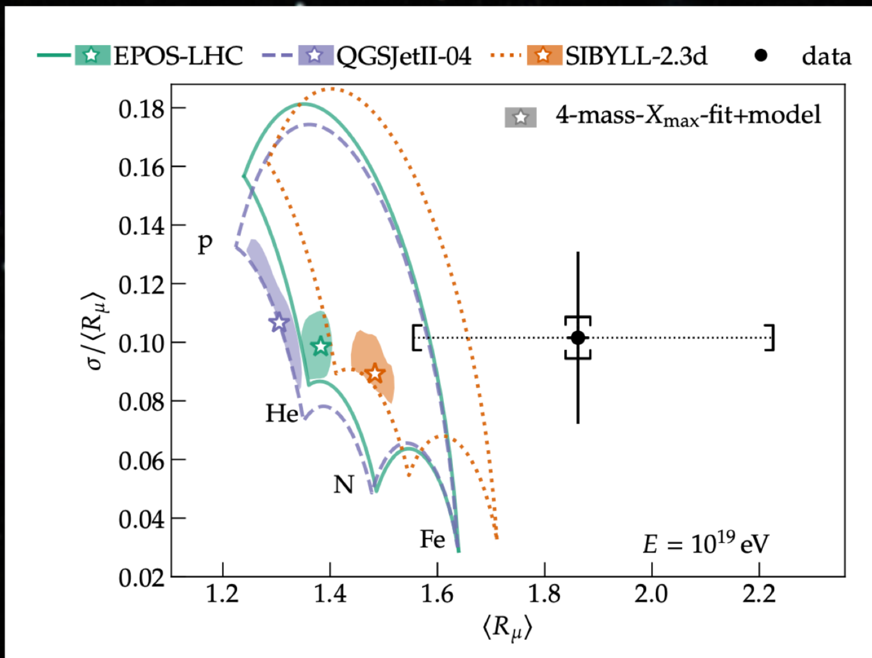

AMIGA data
HAS data
QGSJetII-04
EPOS-LHC
Fe
p
⟨R_μ⟩/(E/10^19 eV)
E/eV
4.6
4.2
3.8
3.4
3.0
2.6
2.2
1.8
1.4
1.0
2·10^17
10^18
10^19
10^20

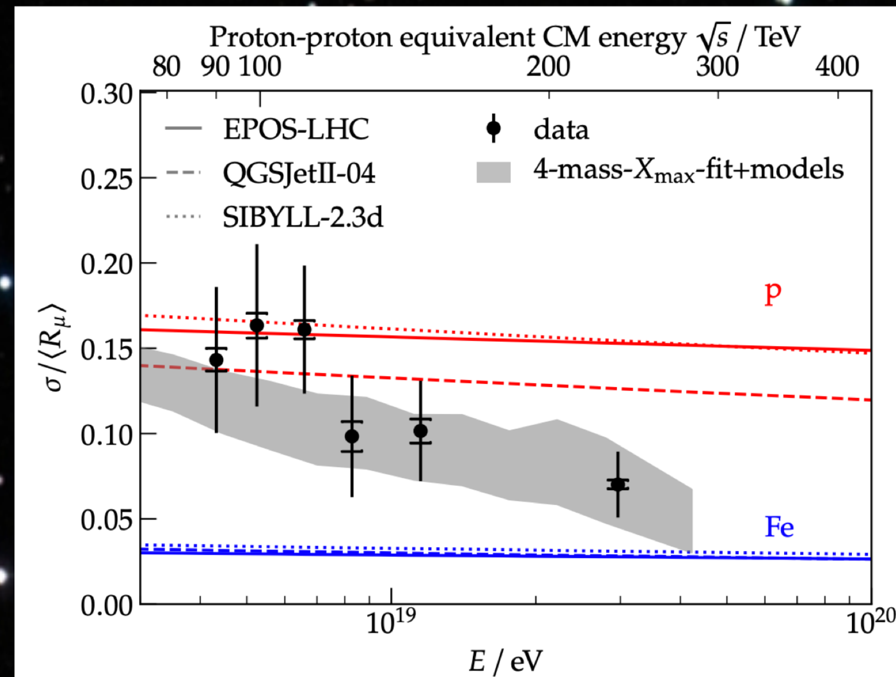
Working Group on Hadronic Interactions and Shower Physics



8 sigma significance

Muon Fluctuations





- Fluctuations are sensitive to the first interation.
  Muon average number missmatch cannot be explained solely due to a missmath in the 1st interaction.

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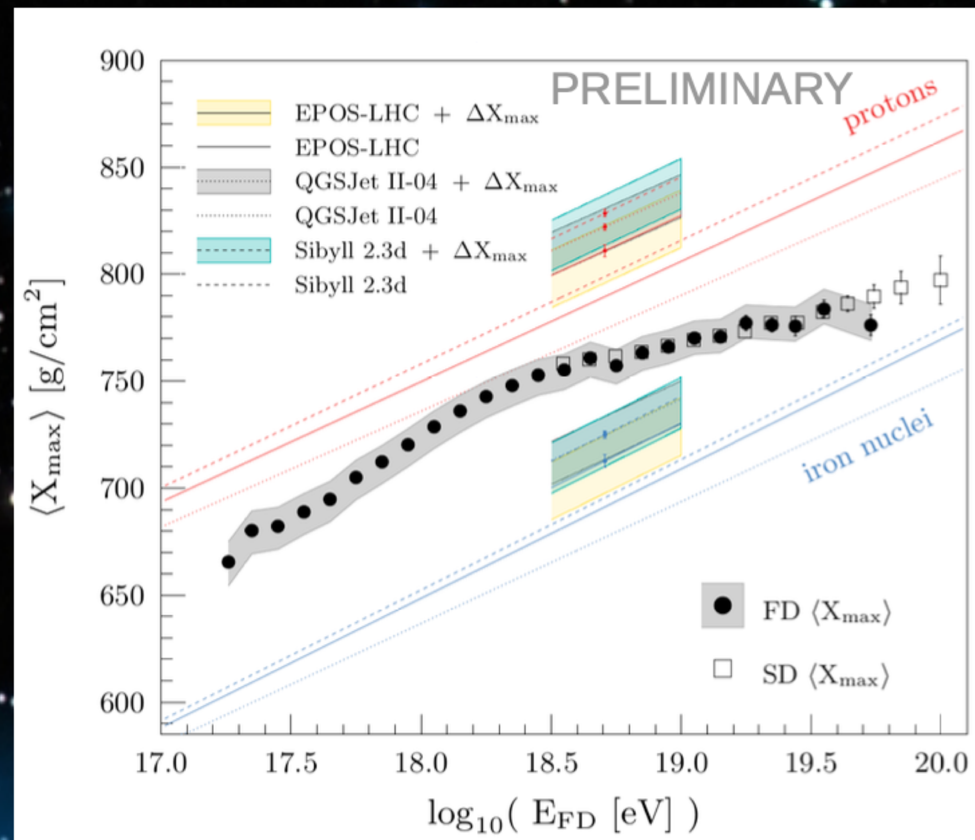
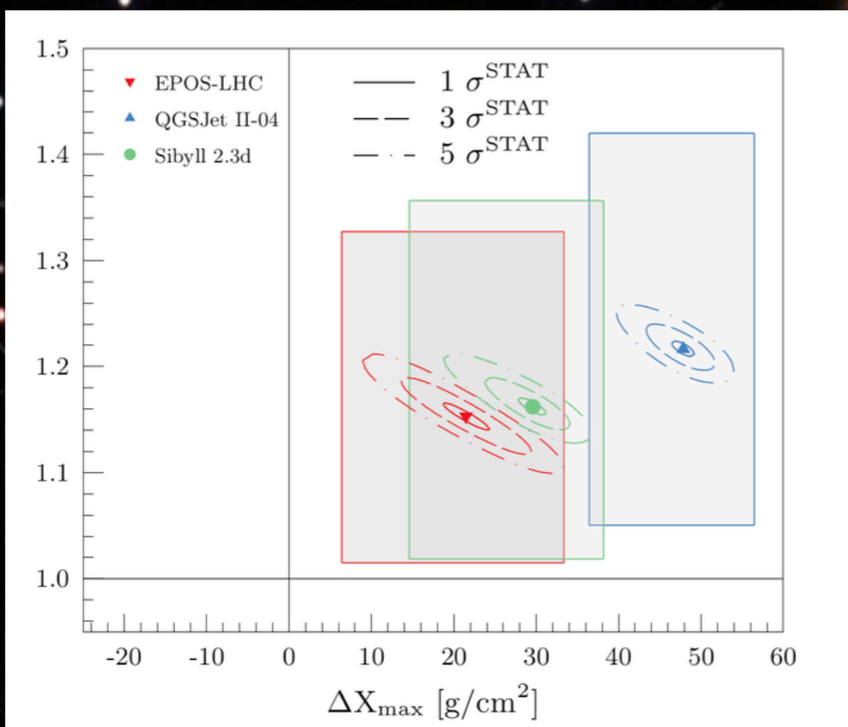
Preliminary: Models predict too deep < X_{max} >





Conclusions

- $\sigma_{p\text{-}Air}$ for particle production
- Muon Production Depth missmath provides further constraints in hadronic models
- Measurements of muon production
  - Muon rescaling factor 1.3-1.6
    - Also models present less muon number derivative wrt energy
    - WHISP confirms high significance. Missmath starts around 1E16 eV
- Intense Theoretical/phenomenological activity
  - Quark Gluon Plasma – Core Corona effect
  - Strange fireball
  - …

Many Tanks