UHE interactions using data from the surface and radio detectors at the Pierre Auger Observatory

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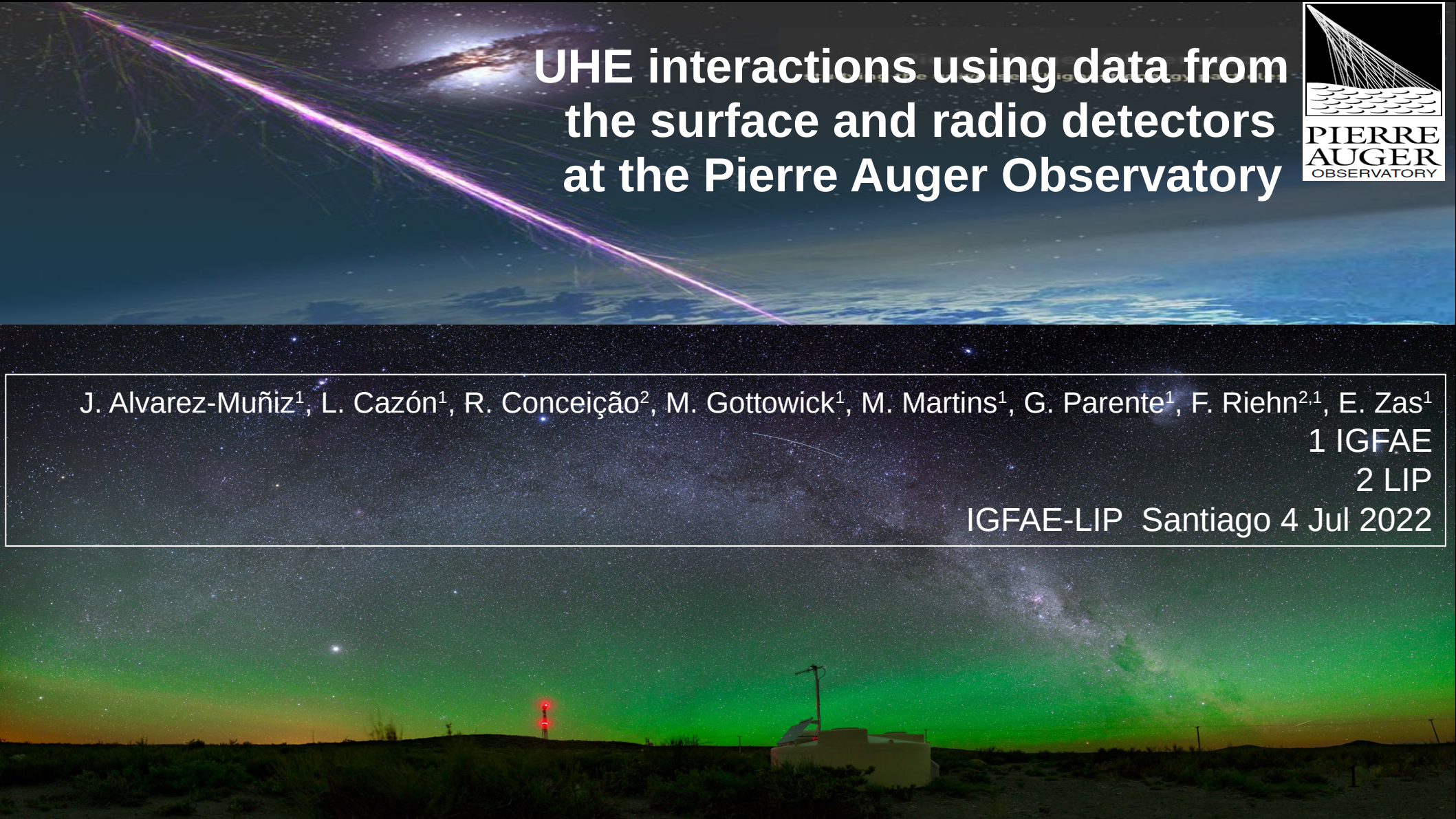
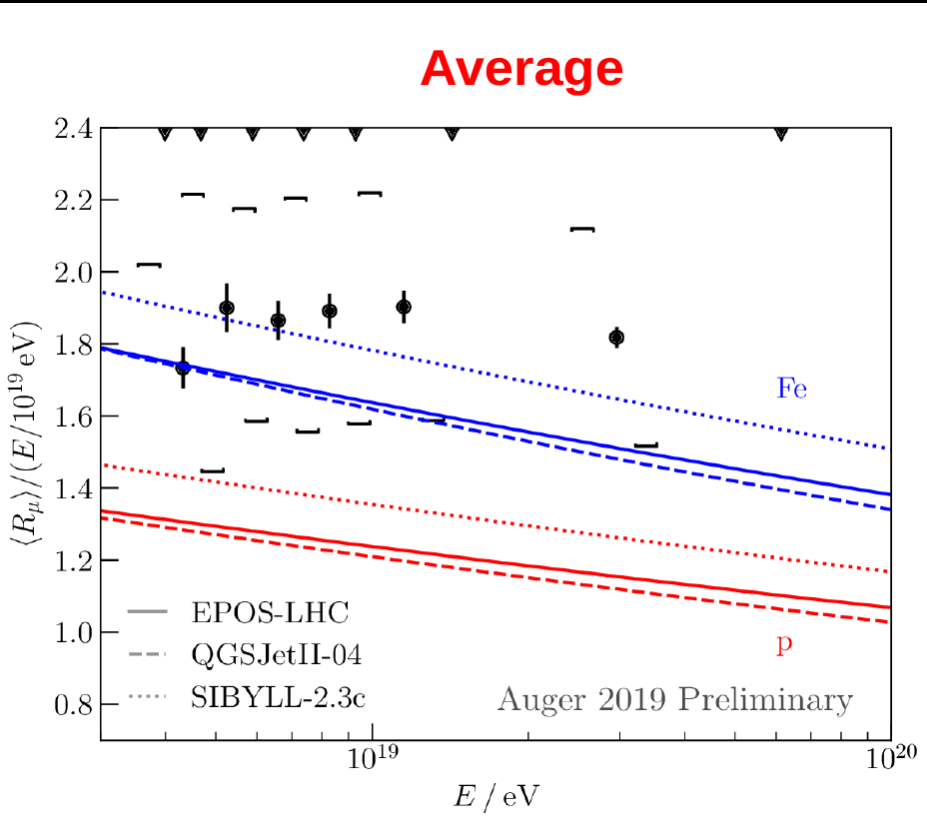
1 IGFAE
2 LIP
IGFAE-LIP Santiago 4 Jul 2022

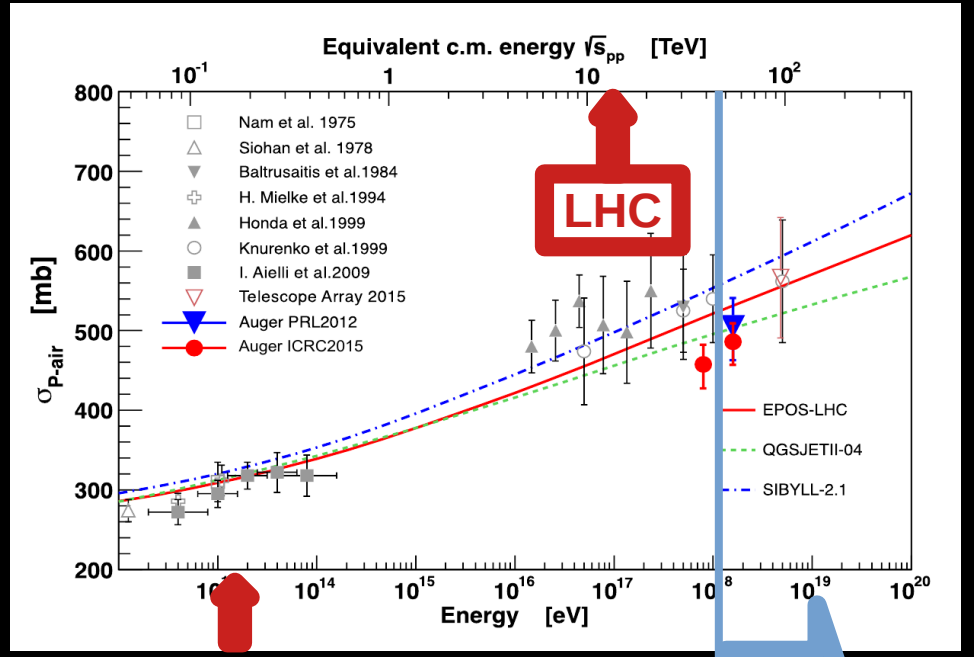


Auger: EeV scale

Depends on HE extrapolations

Can test particle physics beyond LHC





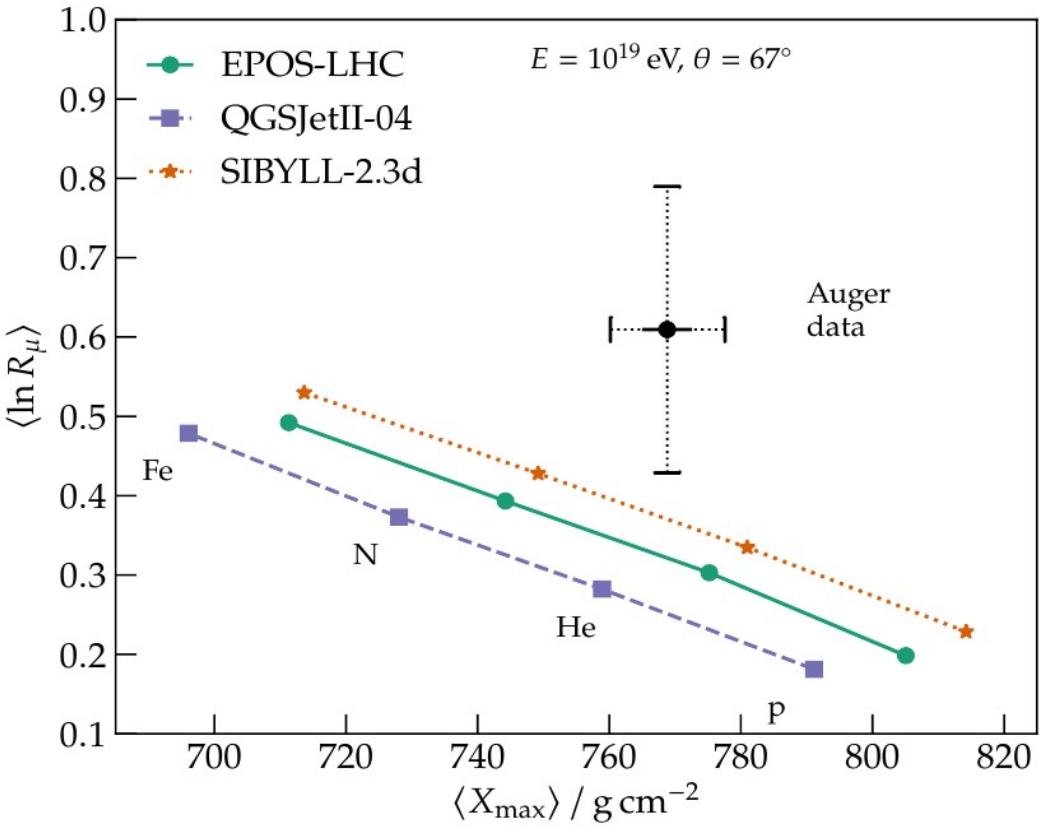
Auger

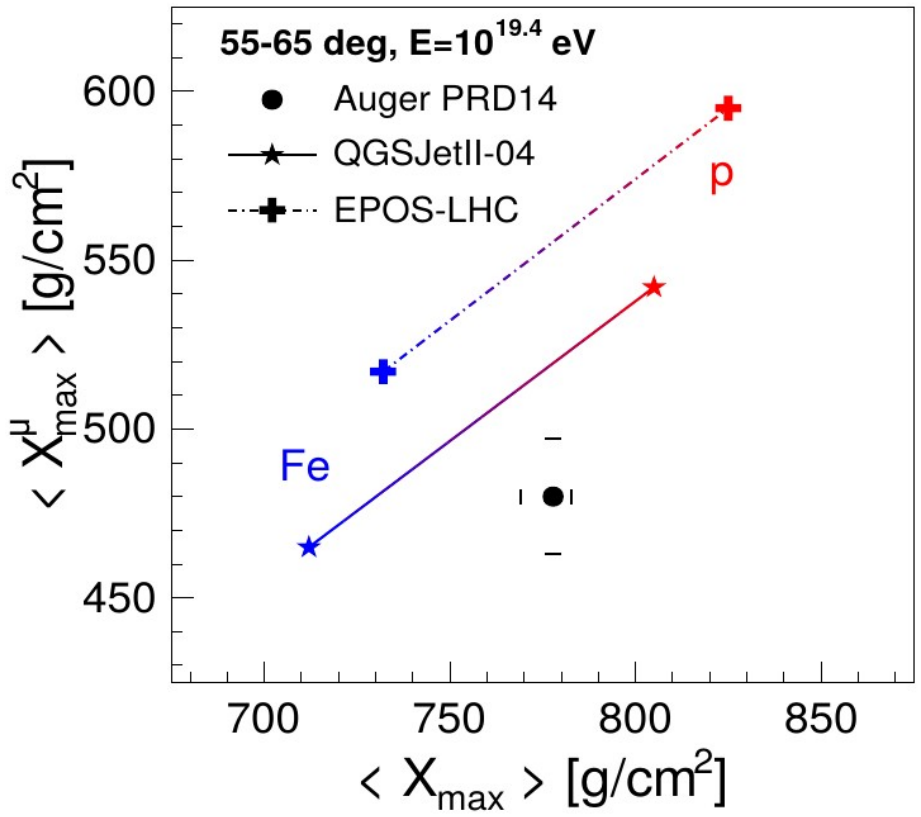
Redundant data allow test of extrapolations

Several results point to **model inconsistencies**

Shower maximum: First and second moments
Depth of muon production: X_μ^{max}
Average number of muons: N_μ => R_μ

Discrepancies more apparent when considering composition results from X_{max} measurements





Use variable "Z" to label composition as obtained using observable "α"
This is because observables typically related to composition through "lnA"

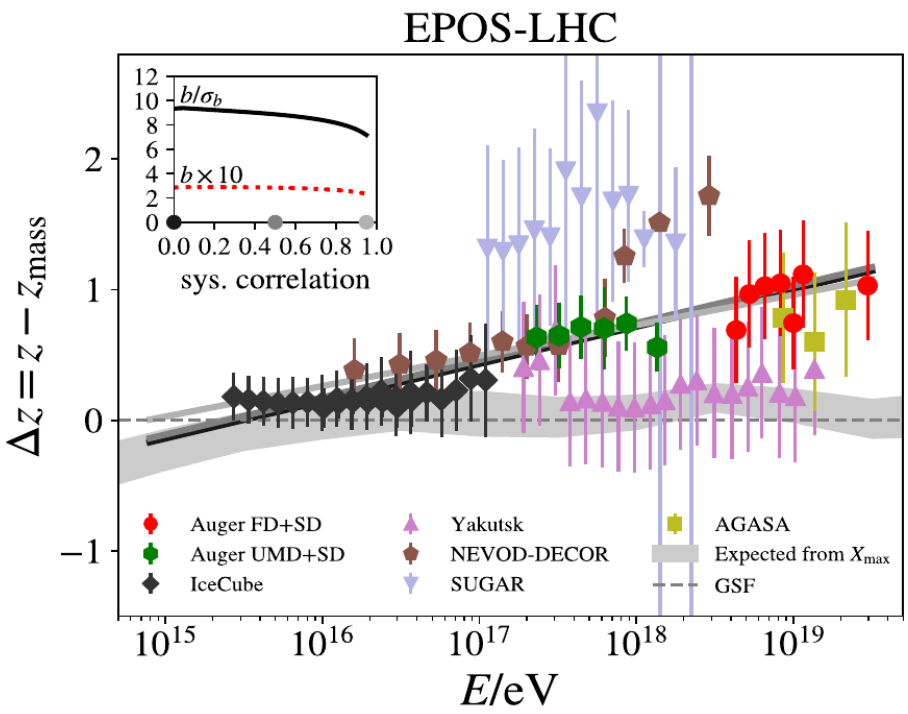
$$z_\alpha = \frac{\langle \ln(\alpha) \rangle - \langle \ln(\alpha) \rangle_p}{\langle \ln(\alpha) \rangle_{Fe} - \langle \ln(\alpha) \rangle_p}$$

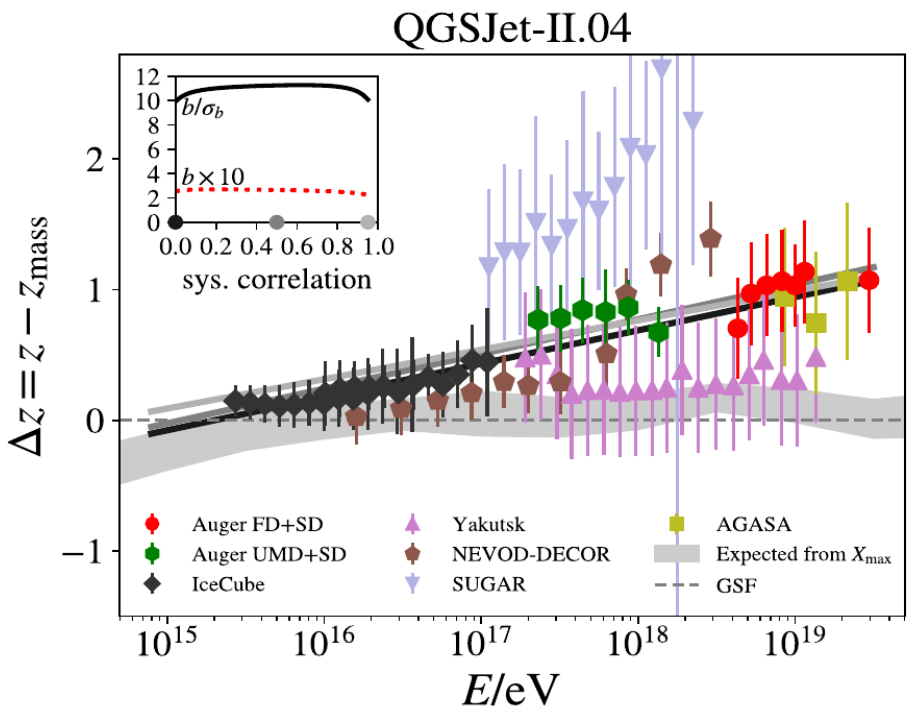
Z characterizes "lnA" assigning

0 for protons

1 for iron

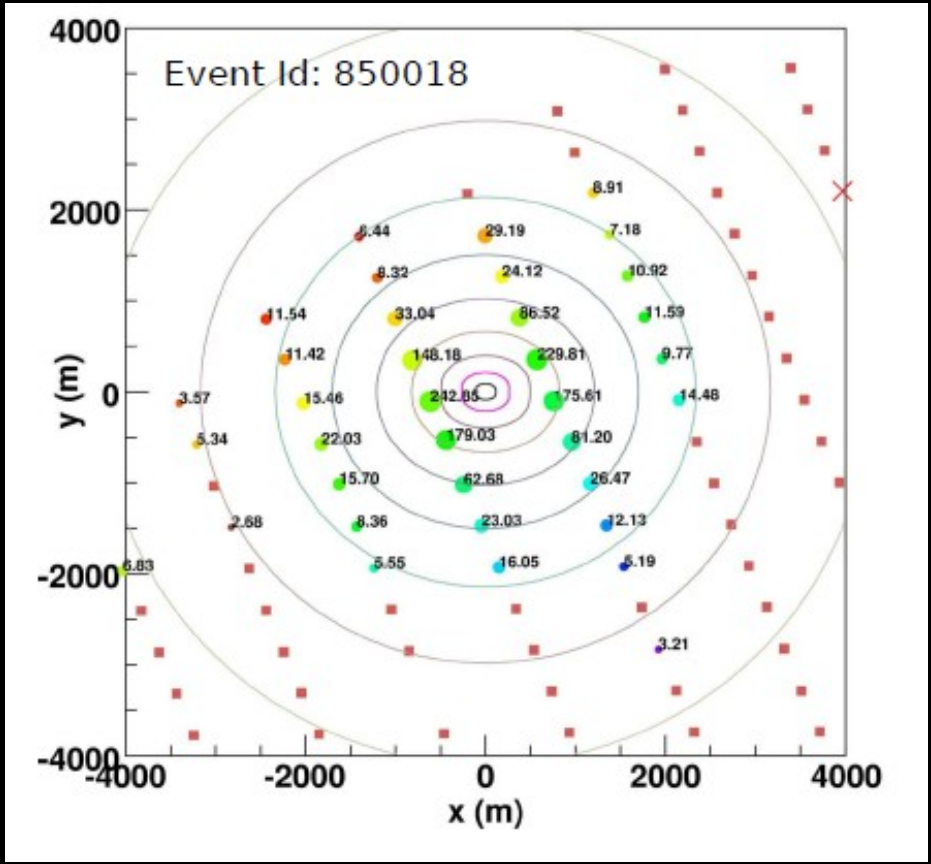
Muon deficit confirmed and measured in other energy ranges/experiments
WHISP (transcollaborative effort) Inconsistency: $\Delta z = z(N_\mu) - z(Xmax)$





J. Albrecht, L. Cazon, et al., Astrophys. and Space Science 367 (2022)

Muon Measurements: SD => Inclined showers + ...
Direct (AMIGA/AugerPrime)



Inclined reconstruction:

Fit 2D muon patterns for "muon size"

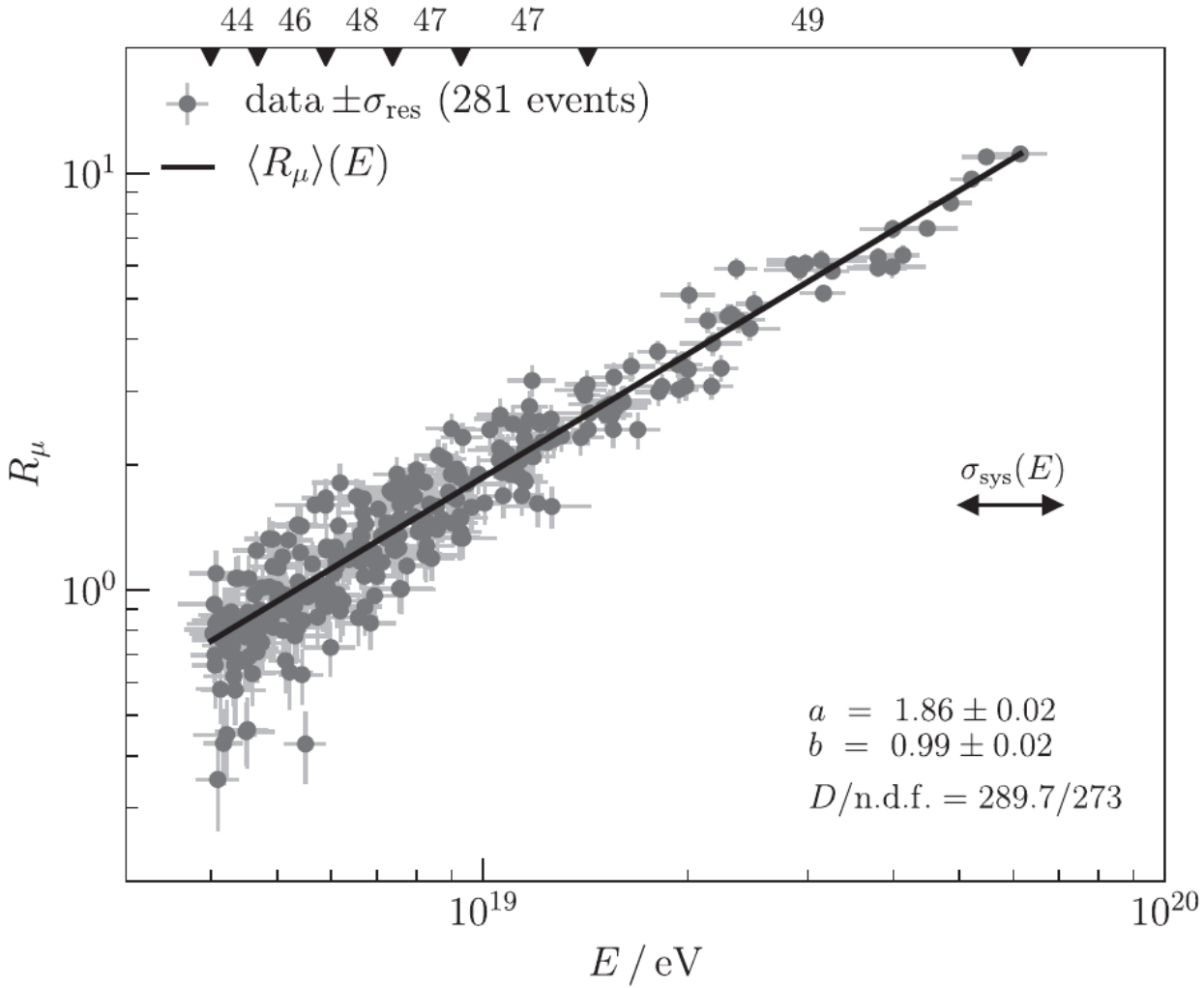
- *Universal pattern for given geometry*
- *Signal scales with energy*
  (Dependence on composition)
  (Dependence on hadronic model)

Standard SD reconstruction:

Muon size is SD energy estimator

Energy calibrated with FD

Energy Calibration: Muon size correlated with energy measurement from FD

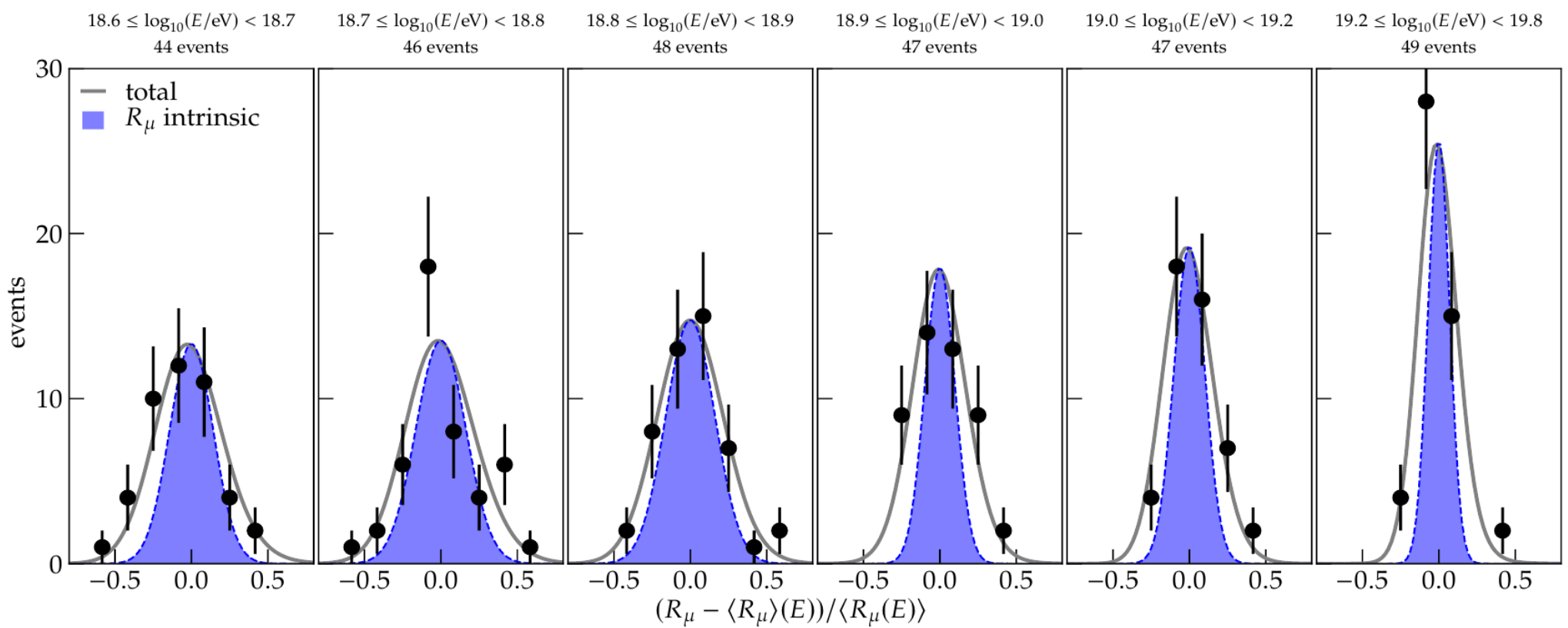


Muon measurement =>

- *Use hybrid data **only***
- *Independent energy (i.e. FD)*
- *Muon size => muon number*

A. Aab et al. Phys. Rev. D91 (2015) 032003
Err. Phys. Rev. D91 (2015) 059001
Phys. Rev. Lett. 126 (2021) 15, 152002

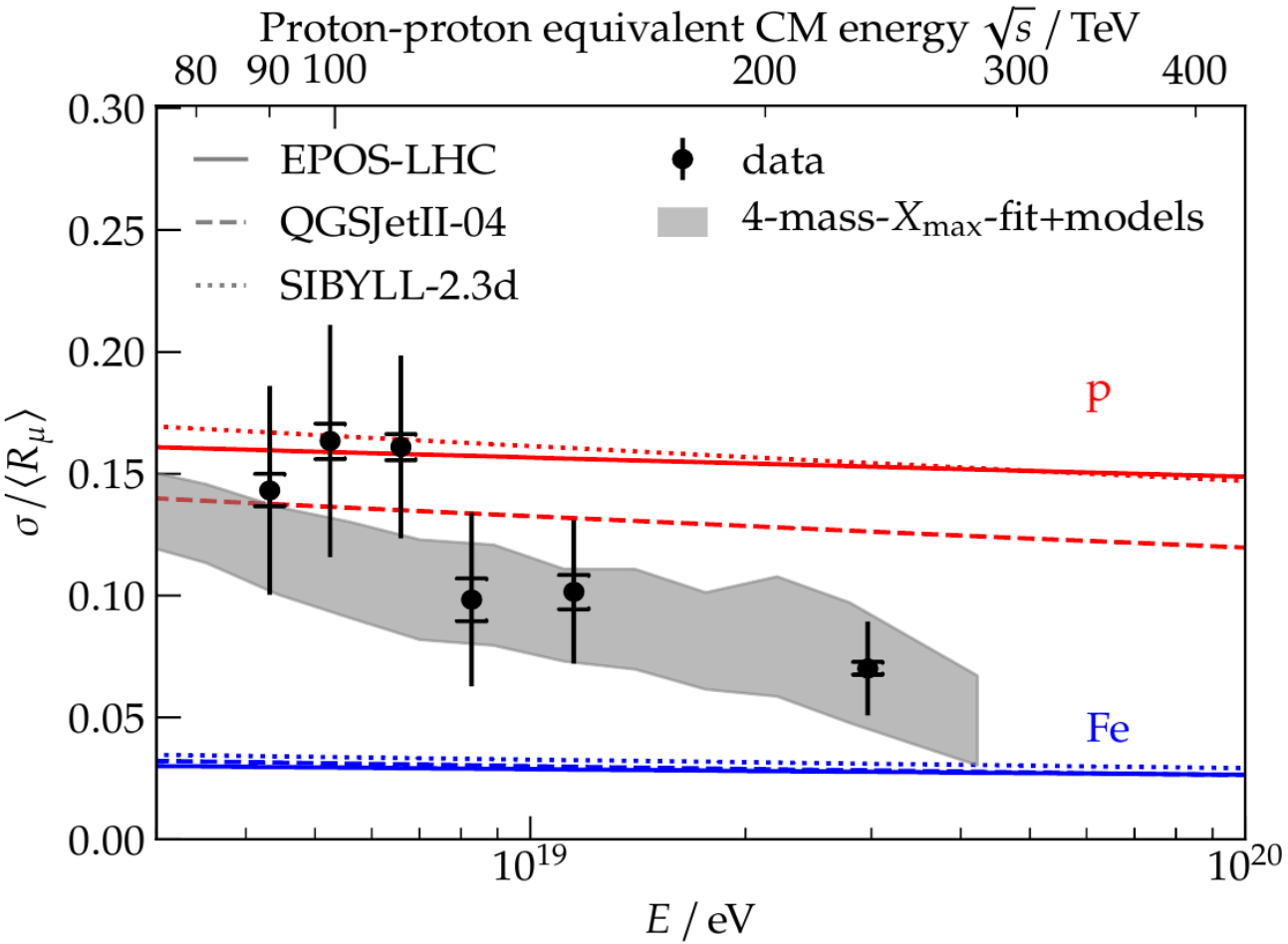
Fixing the Energy we can obtain distributions of muon number



A. Aab et al. Phys. Rev. Lett. 126 (2021) 15, 152002

MORE TO IT: Fluctuations (second moment) related to the first interaction!

L. Cazon, R. Conceição & F. Riehn, Phys. Lett. B 784 (2018) 68-76



(Normalized to size)

Consistent with X_{max}

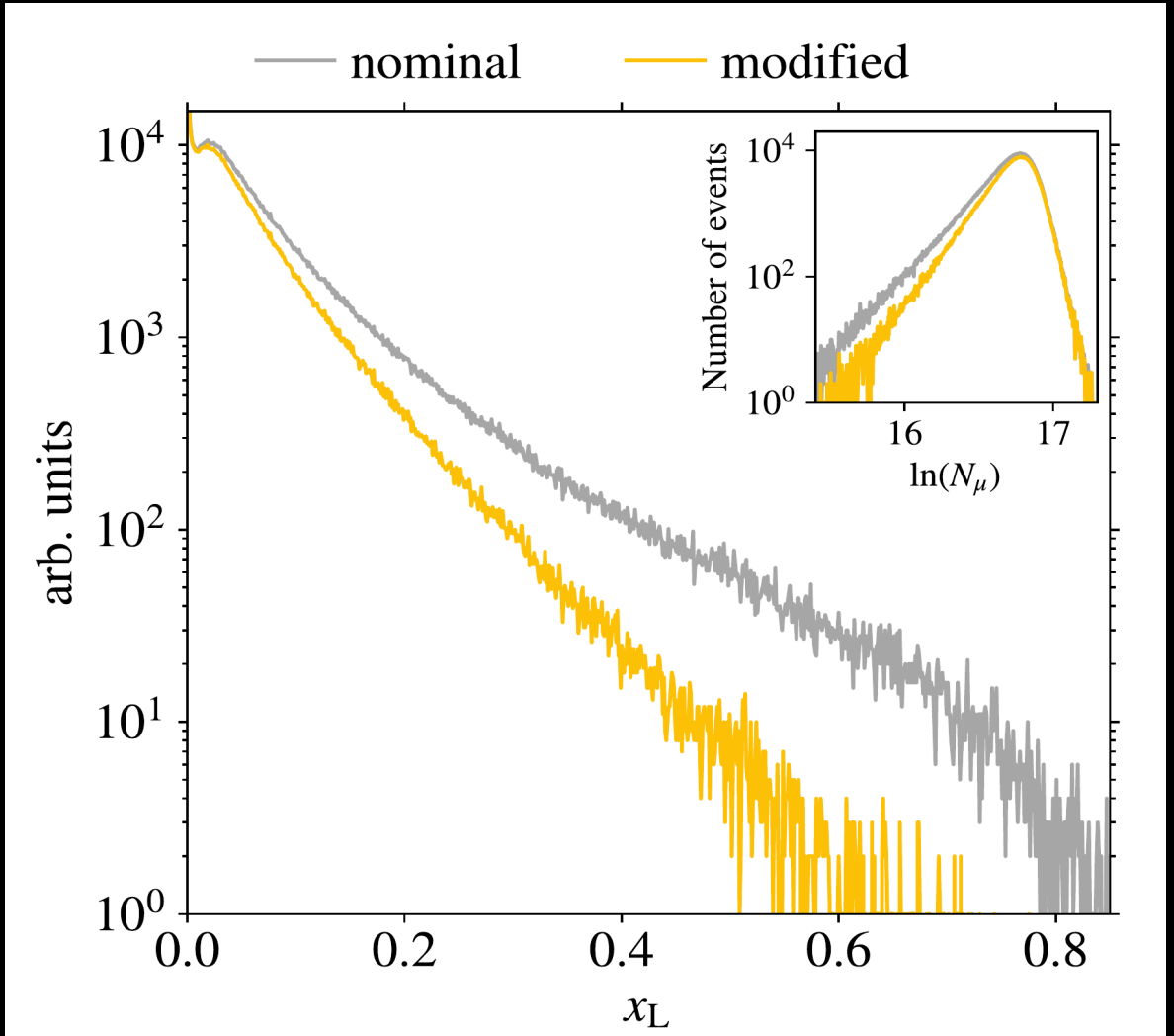
Muon deficit is not due to 1st interaction i.e. ***cummulative***

A. Aab et al. Phys. Rev. Lett. 126 (2021) 15, 152002

More links to 1st interaction:

Leading π^0 production
directed related to
shape of N_μ~R_μ distribution

It appears possible to obtain further properties of first interaction With machine learning techniques



Difficulties:

STATISTICS

Inclined data is scarce in hybrid mode

This becomes an issue for the 750-array

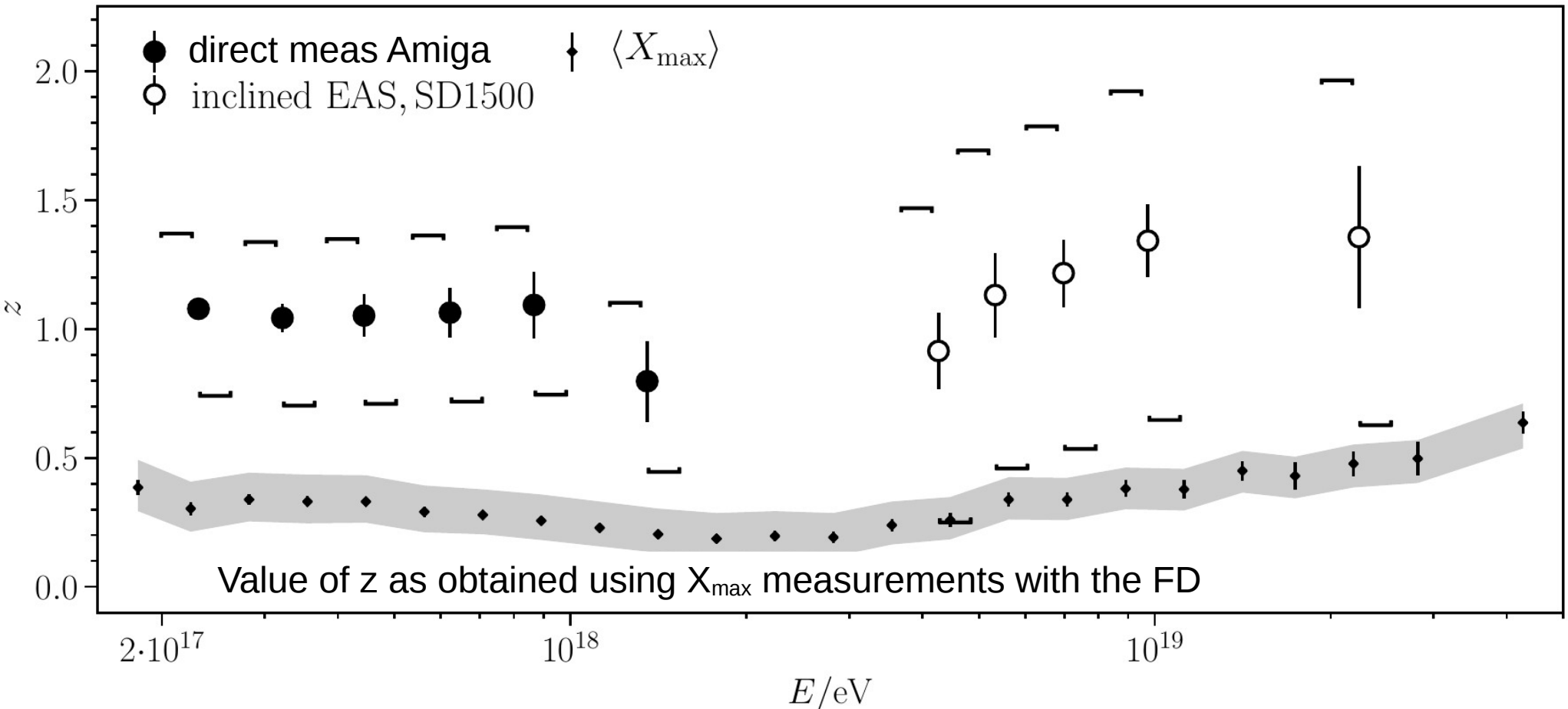
Systematics must be minimized

Alternatives

- *Calibrate with Radio*
- *Measure directly (AMIGA and AugerPrime developments)*

Muon measurements with Pierre Auger Observatory

$$z_\alpha = \frac{\langle \ln(\alpha) \rangle - \langle \ln(\alpha) \rangle_p}{\langle \ln(\alpha) \rangle_{Fe} - \langle \ln(\alpha) \rangle_p}$$



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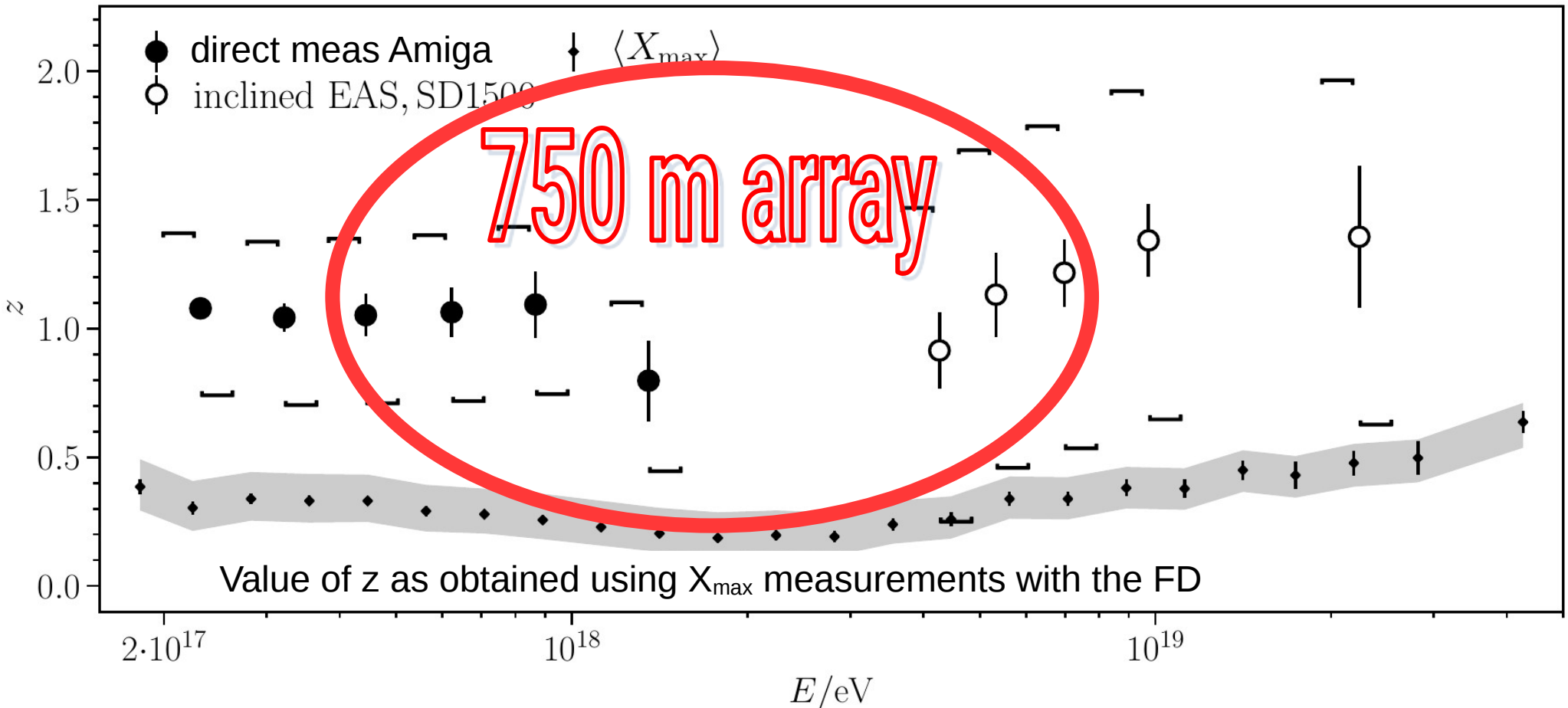

Plan for muon analysis:

Adjust inclined reconstruction for 750 m array

Optimize reconstruction and migrate to Offline

Prepare alternative calibration with AERA (radio data)

Objectives

- *Infill data production for spectrum, muon content …*
- *Obtain muon distributions and measure moments*
- *Extract parameters of leading p0 in first interaction*
- *Apply ML techniques for further properties of first interaction*

Thank you