Energy spectrum estimation and mass composition inferences from X_{max} measurements of cosmic rays detected at the Pierre Auger Observatory and at the Telescope Array: an inter-collaborative look at the differences at the highest energies

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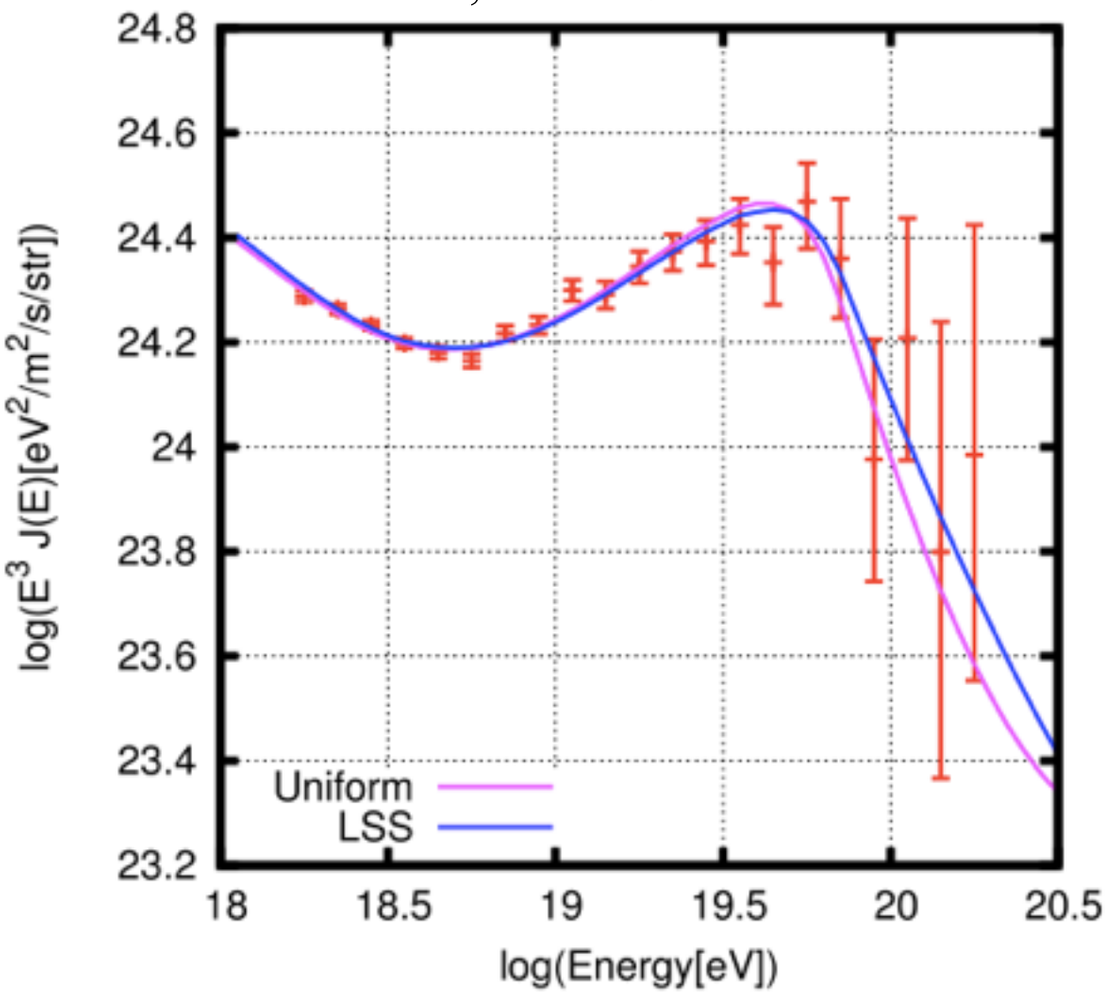
Based on common reports UHECR2016, ICRC2017

i) Implications of the energy spectrum and mass composition of UHECRs

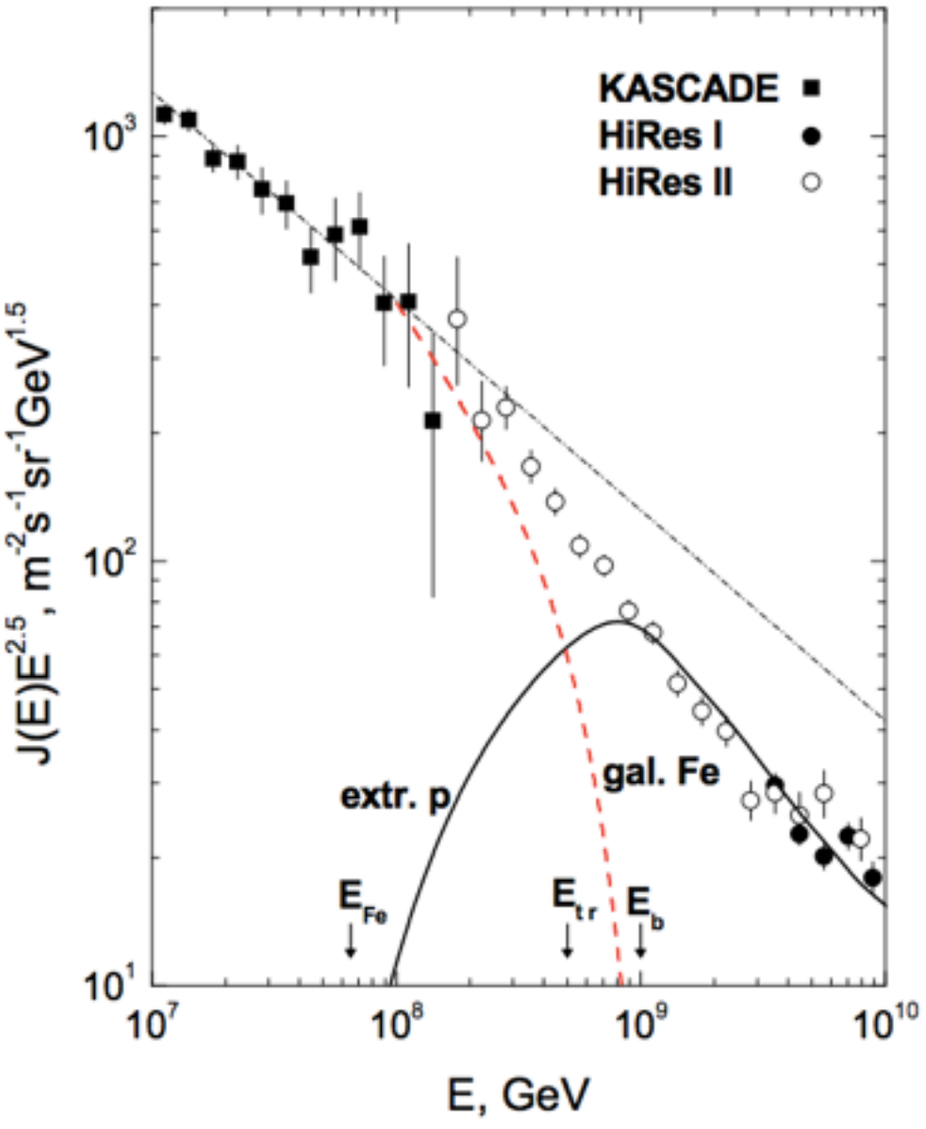
UHECR spectrum as a signature of pure protons?

➡ Unique explanation for both the ankle feature and the GZK suppression (the 'dip model')

TA, ICRC2015

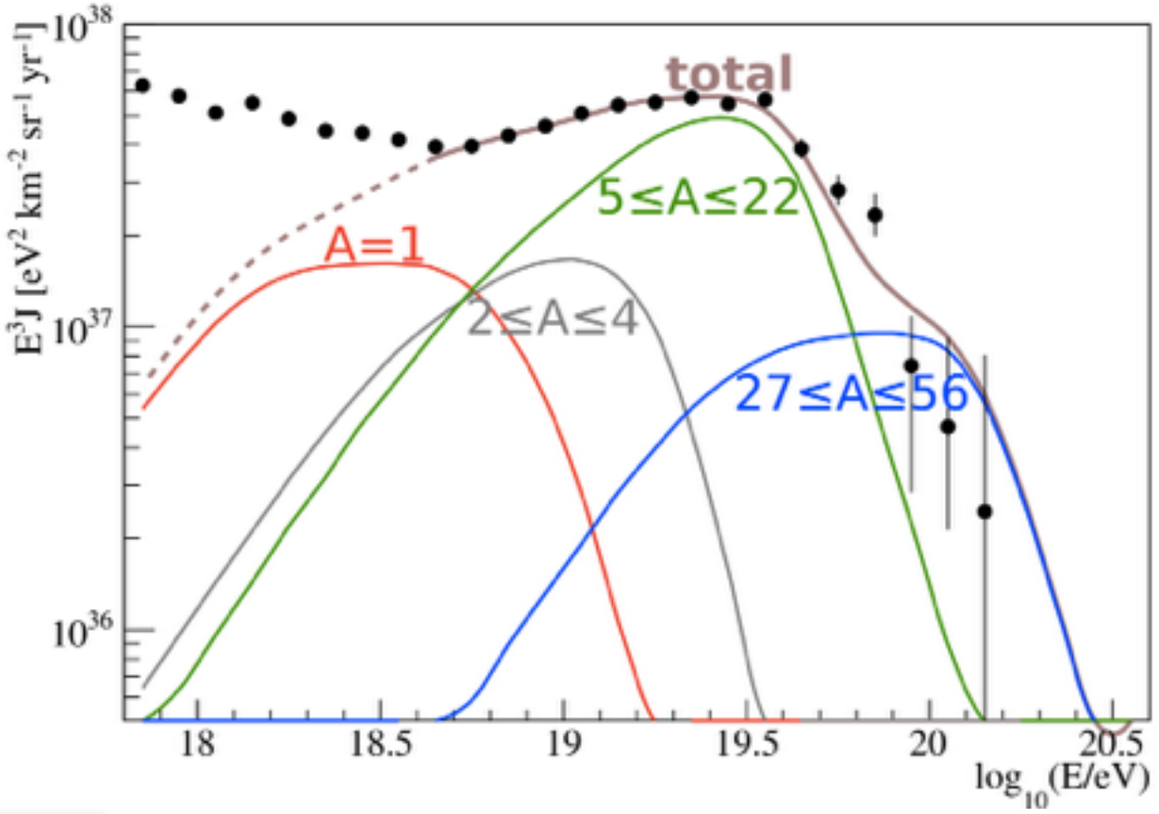


Aloisio et al., PRD D77 025007



➡ Spectral feature marking the transition: second knee

Origin of the suppression at UHE?

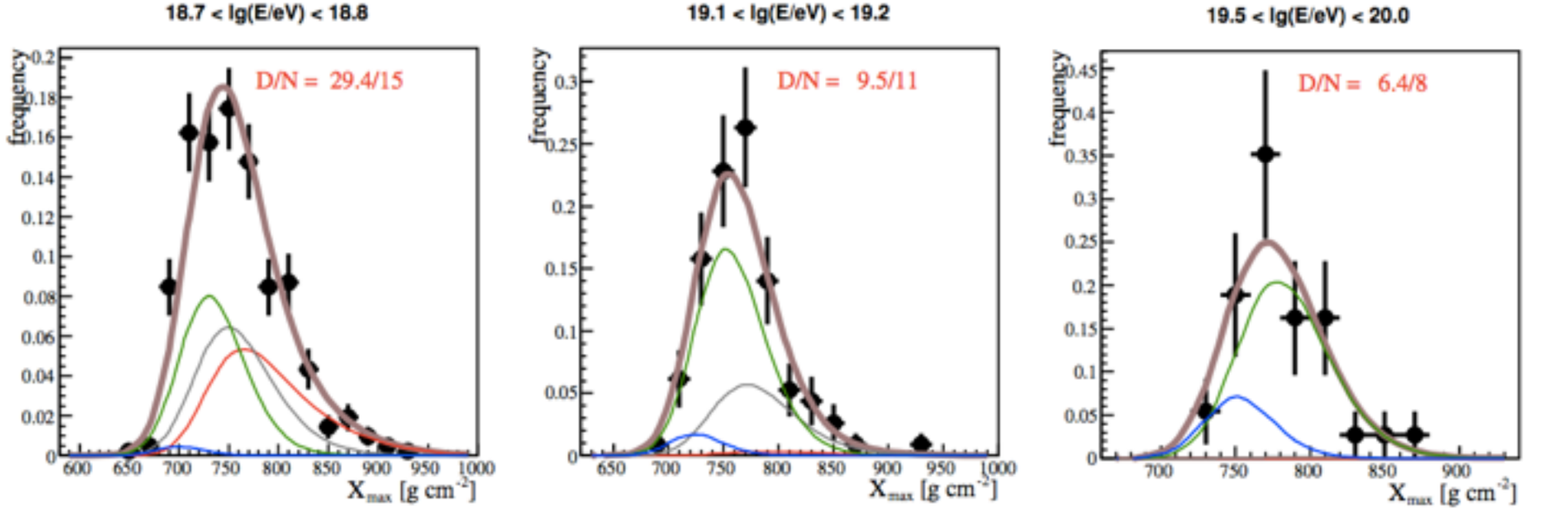


➡ Hard spectral index, meal-rich injection, low cutoff ($R_{cut} \sim 10^{18.7}$ V)

- Mainly due to narrow X_{max} distributions (little mixing of different masses at the same energy)

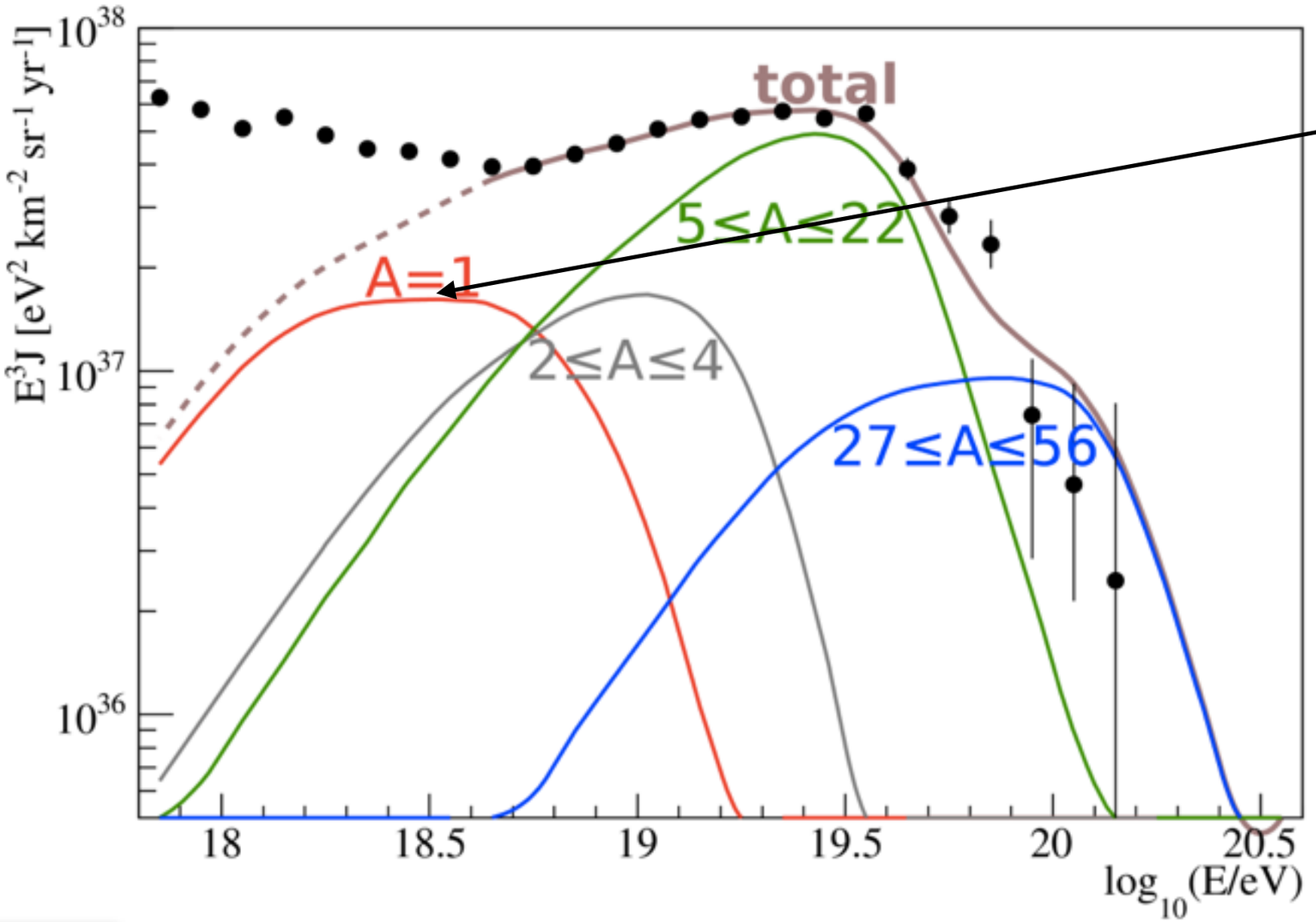
- **NB: Relies on extrapolations of the mass at UHE**

[Auger coll., JCAP 04(2017)038]



- red: $A = 1$
- gray: $2 \leq A \leq 4$
- green: $5 \leq A \leq 22$
- blue: $A \geq 23$
- thick brown: total
- **black dots**: Auger data

Ankle feature?



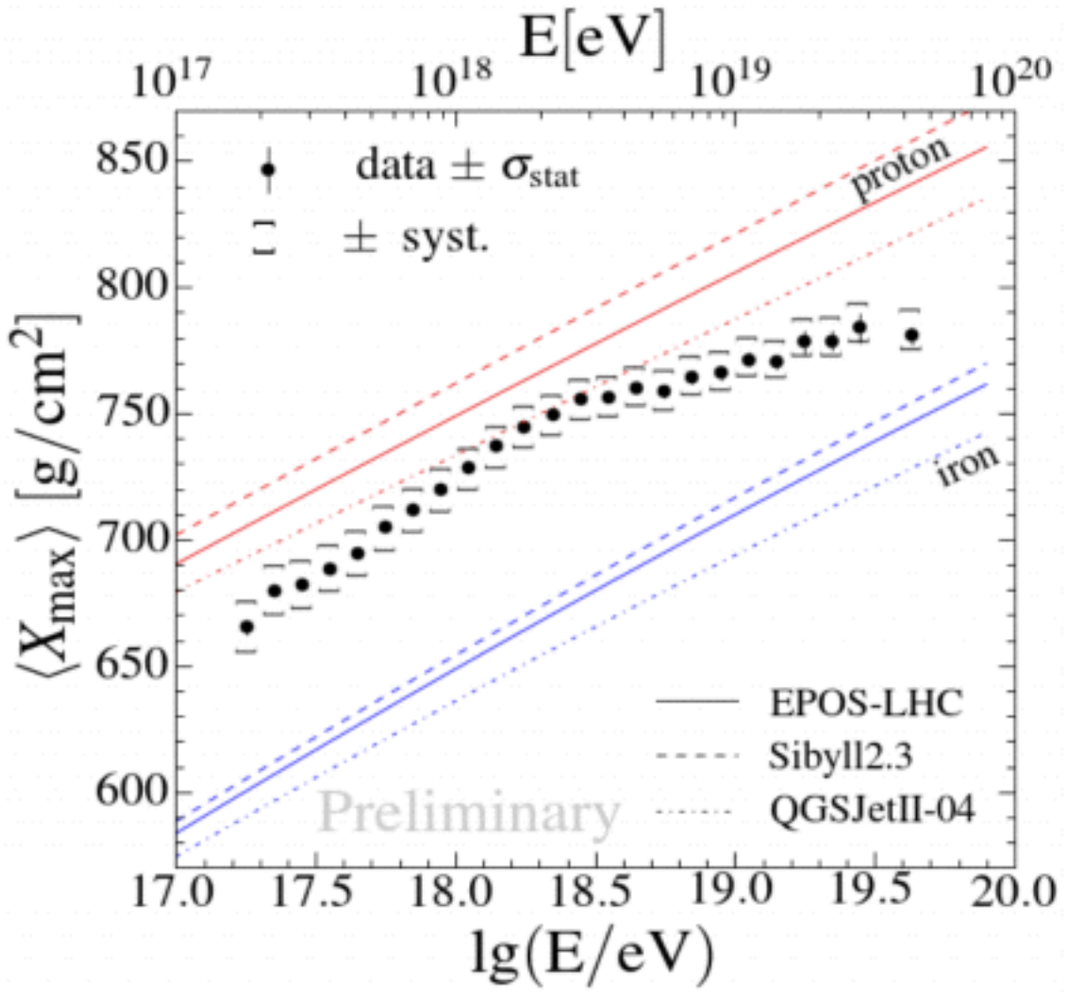
Sub-EeV extragalactic protons as secondaries from interactions of HE intermediate/heavy nuclei

➡ Ankle as the spectral feature marking the end of one component of different origin from the extragalactic one

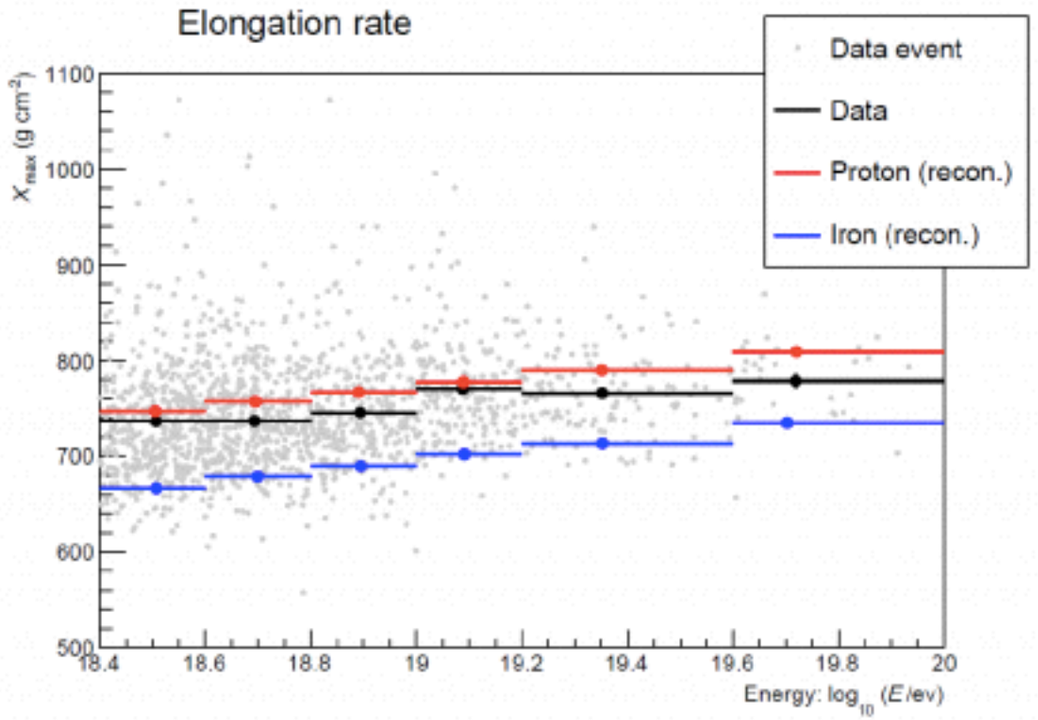
ii) Mass composition inferences from X_{max} measurements at the Pierre Auger Observatory and at the Telescope Array

William Hanlon, UHECR2016
Vitor de Souza, ICRC2017

Pure protons vs mixed composition: a controversy?



Auger Collaboration, ICRC2017

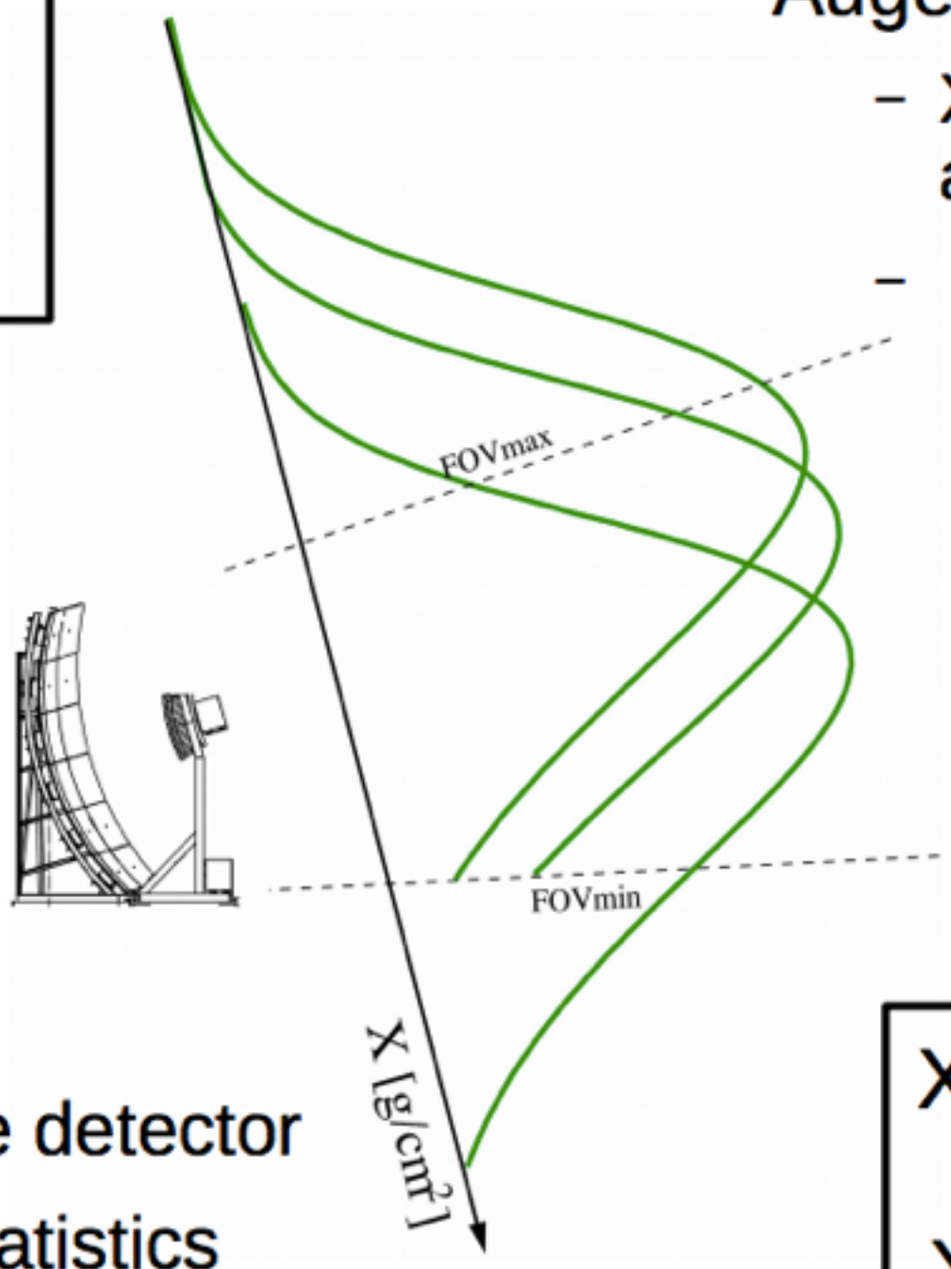


TA Collaboration, ICRC2017

➡ **Straightforward comparison? Controversy?**

Comparing apples and oranges

Auger bias
≠
TA bias



Auger

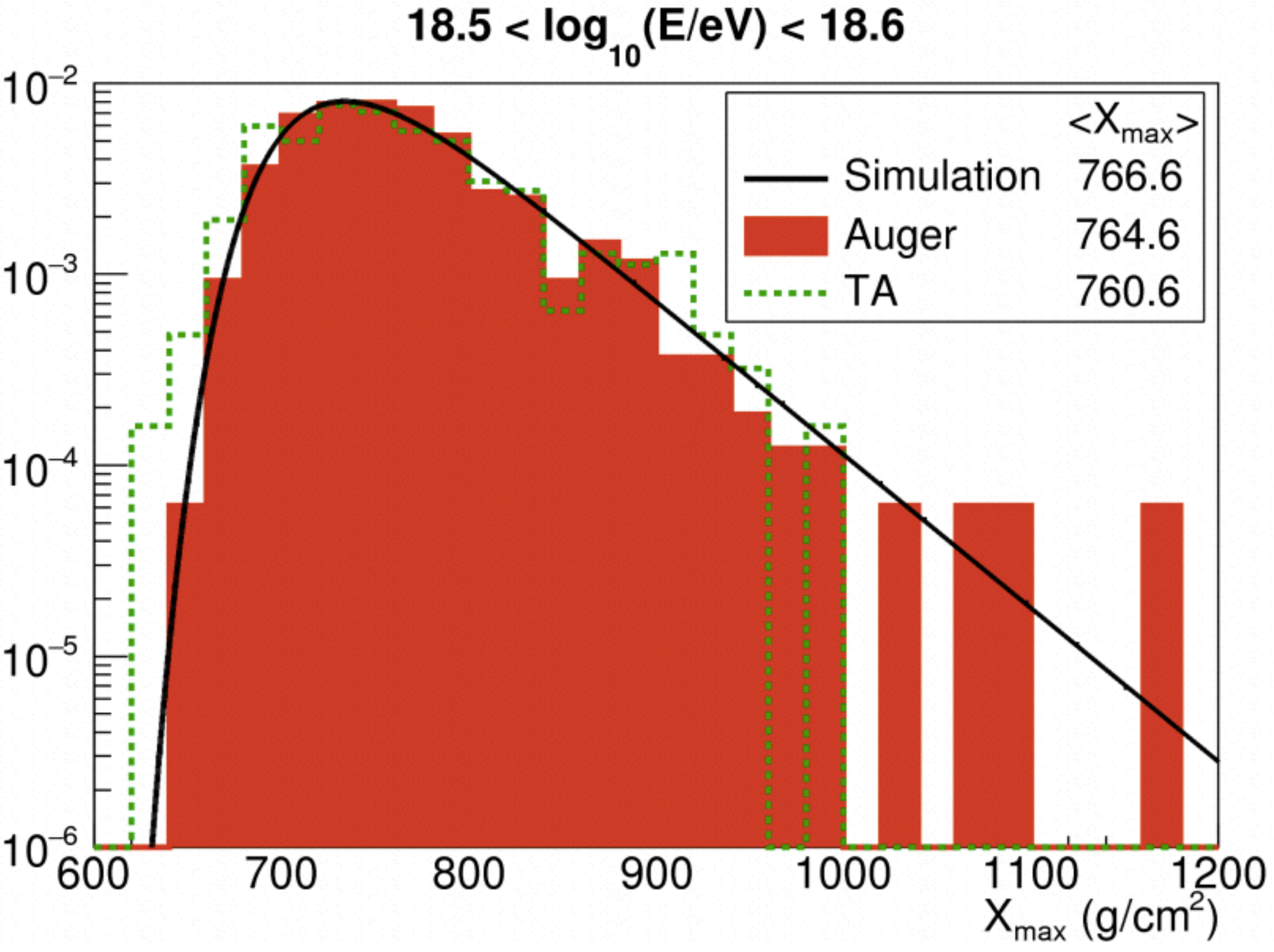
- Xmax at the atmosphere
- Approx. unbiased

TA

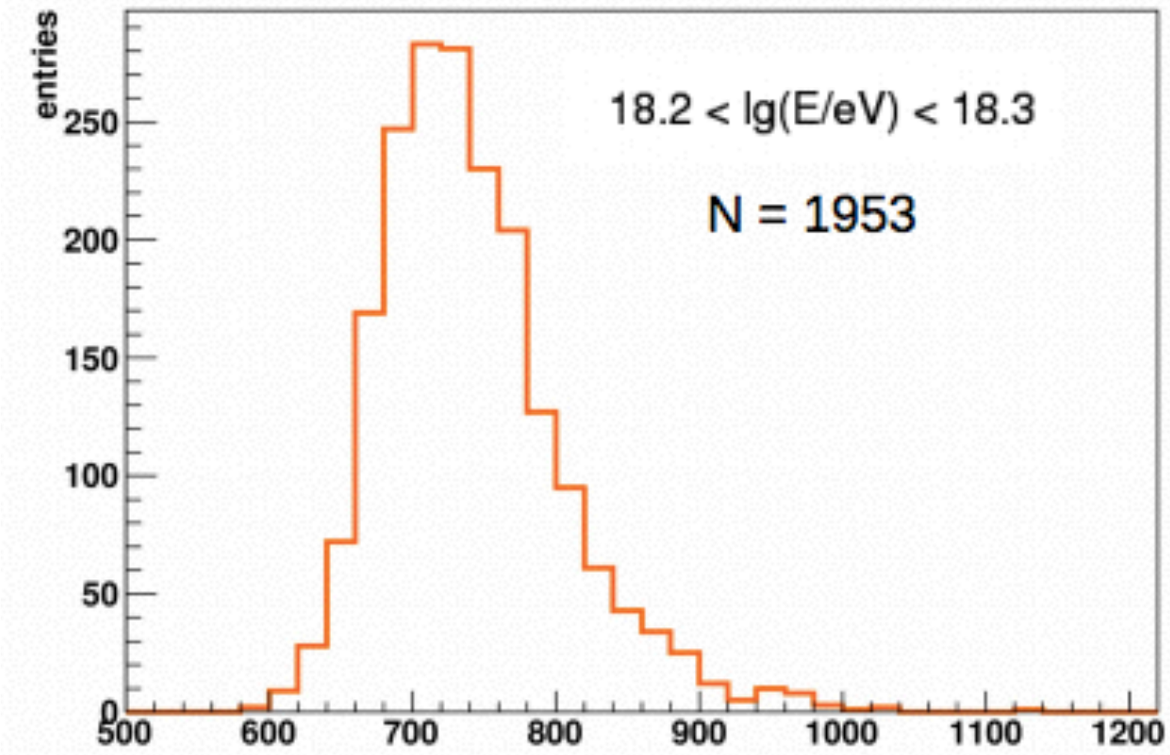
- Xmax in the detector
- Enhance statistics

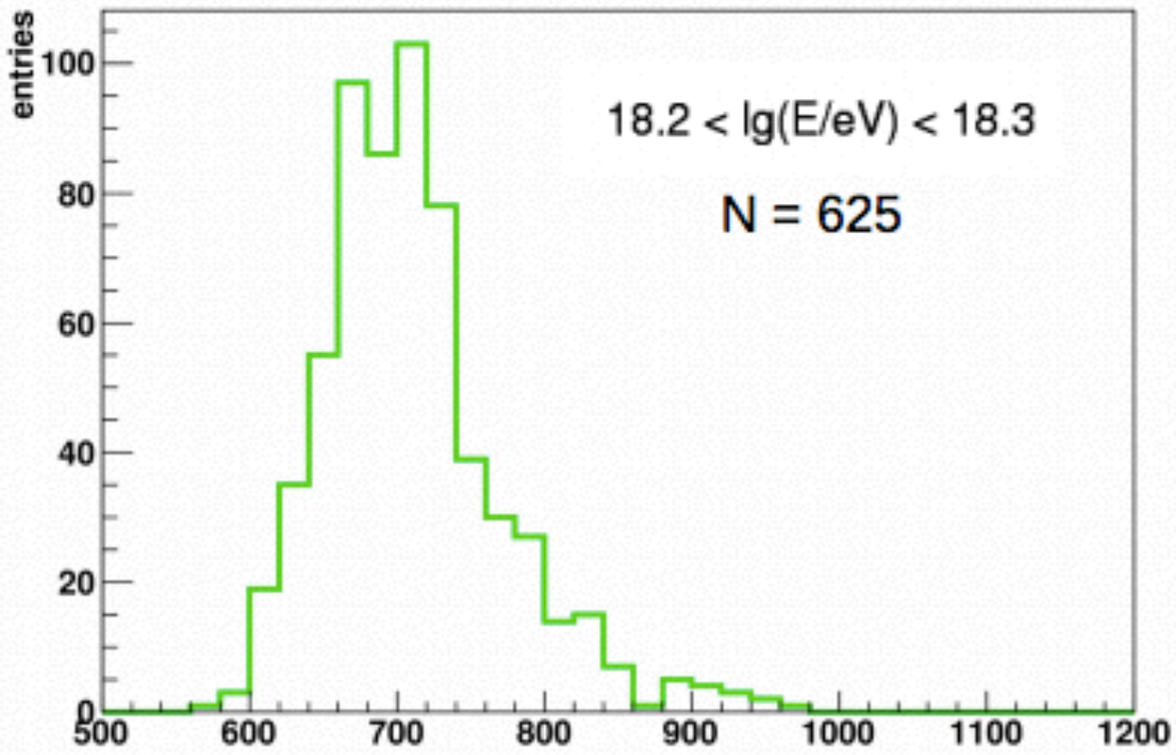
Xmax ATM
≠
Xmax DET

Responses to a pure proton scenario



Comparing X_{max} from Auger and TA?



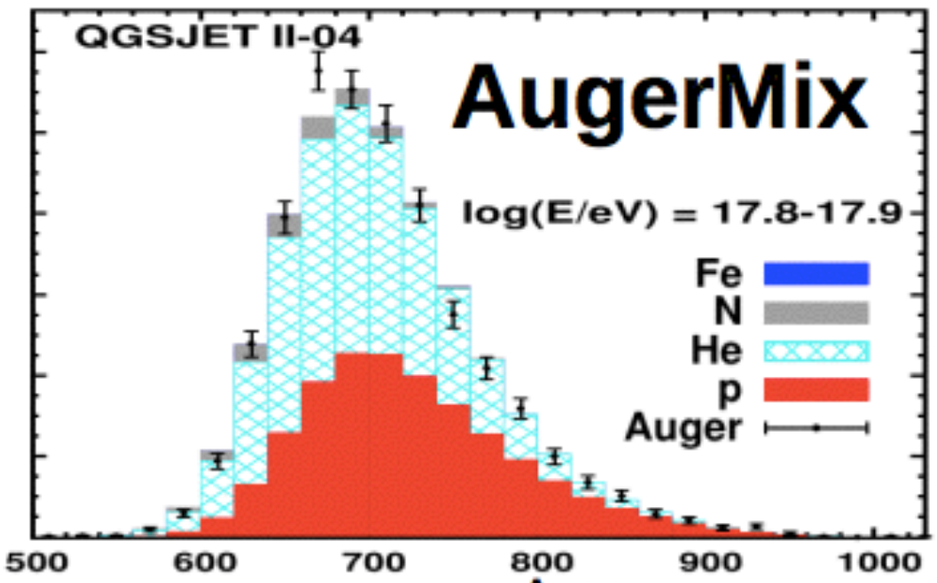


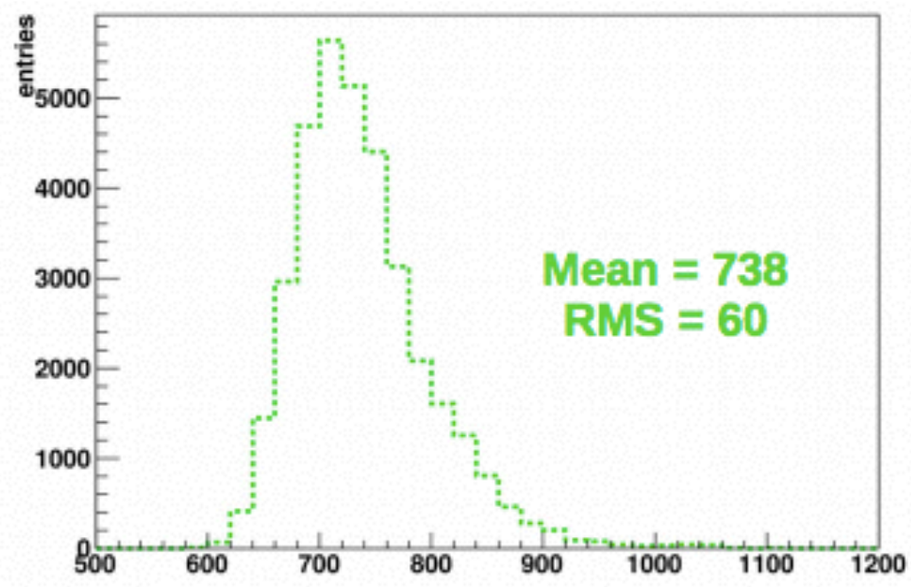
Xmax^{Auger}

Xmax^{TA}

X_{max} in g/cm^2

Comparing X_{max} from Auger and TA—AugerMix



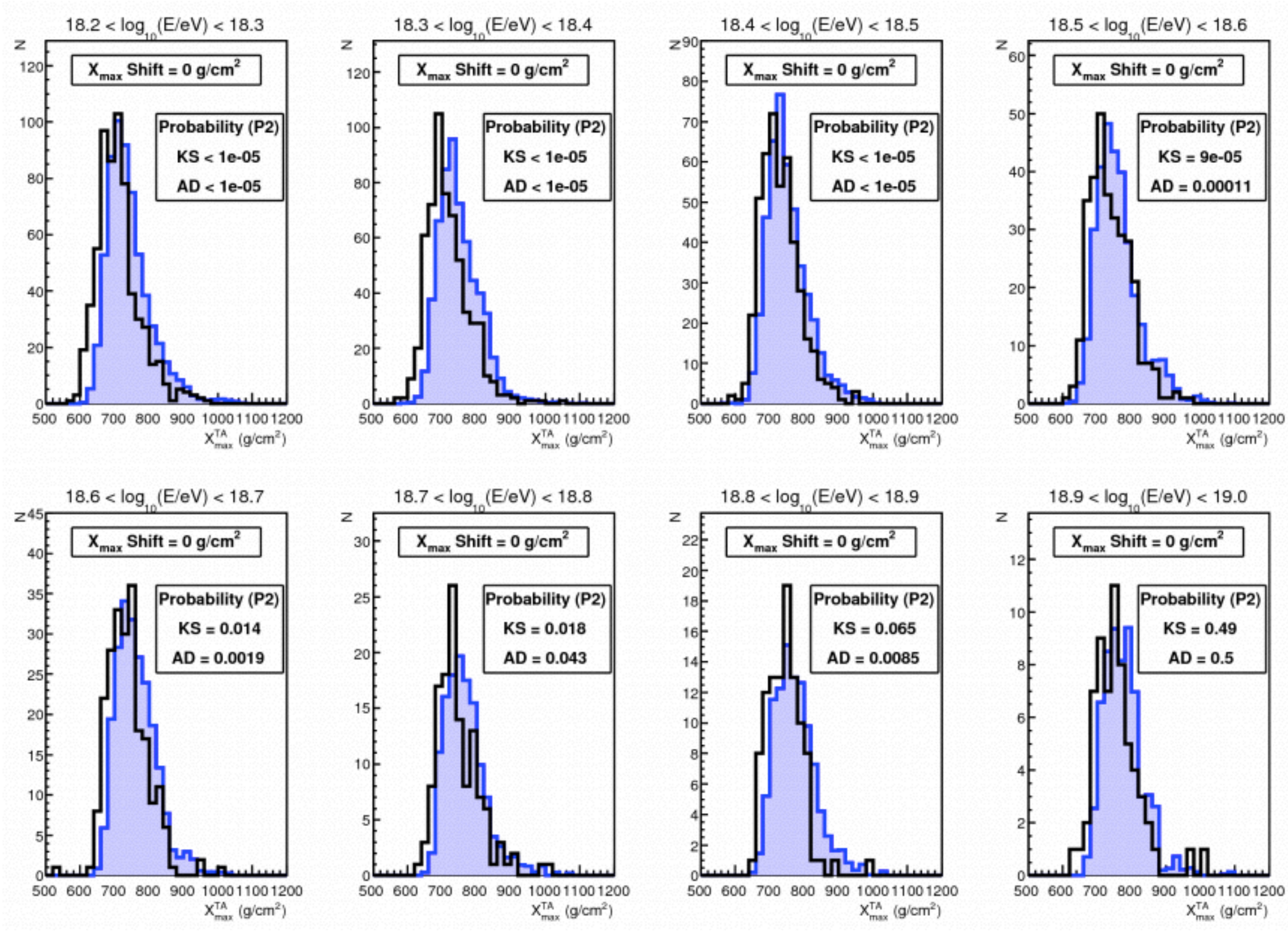


SAME RESULTS WITH EPOS-LHC

TA Detector Simulation

TA Analysis

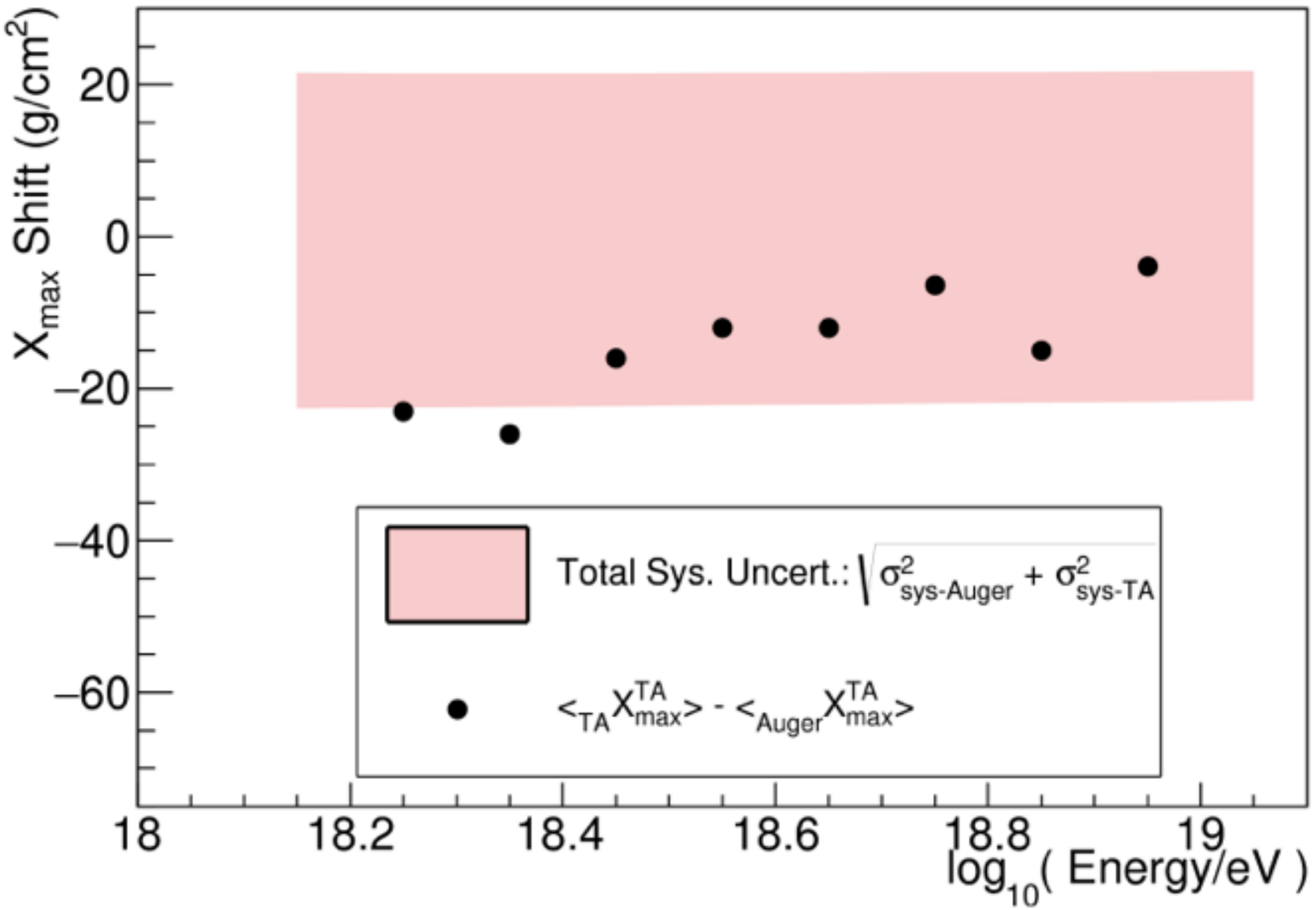
Results between 18.2<$\log_{10}(E/\mathrm{eV})$<19.0



Systematic uncertainties

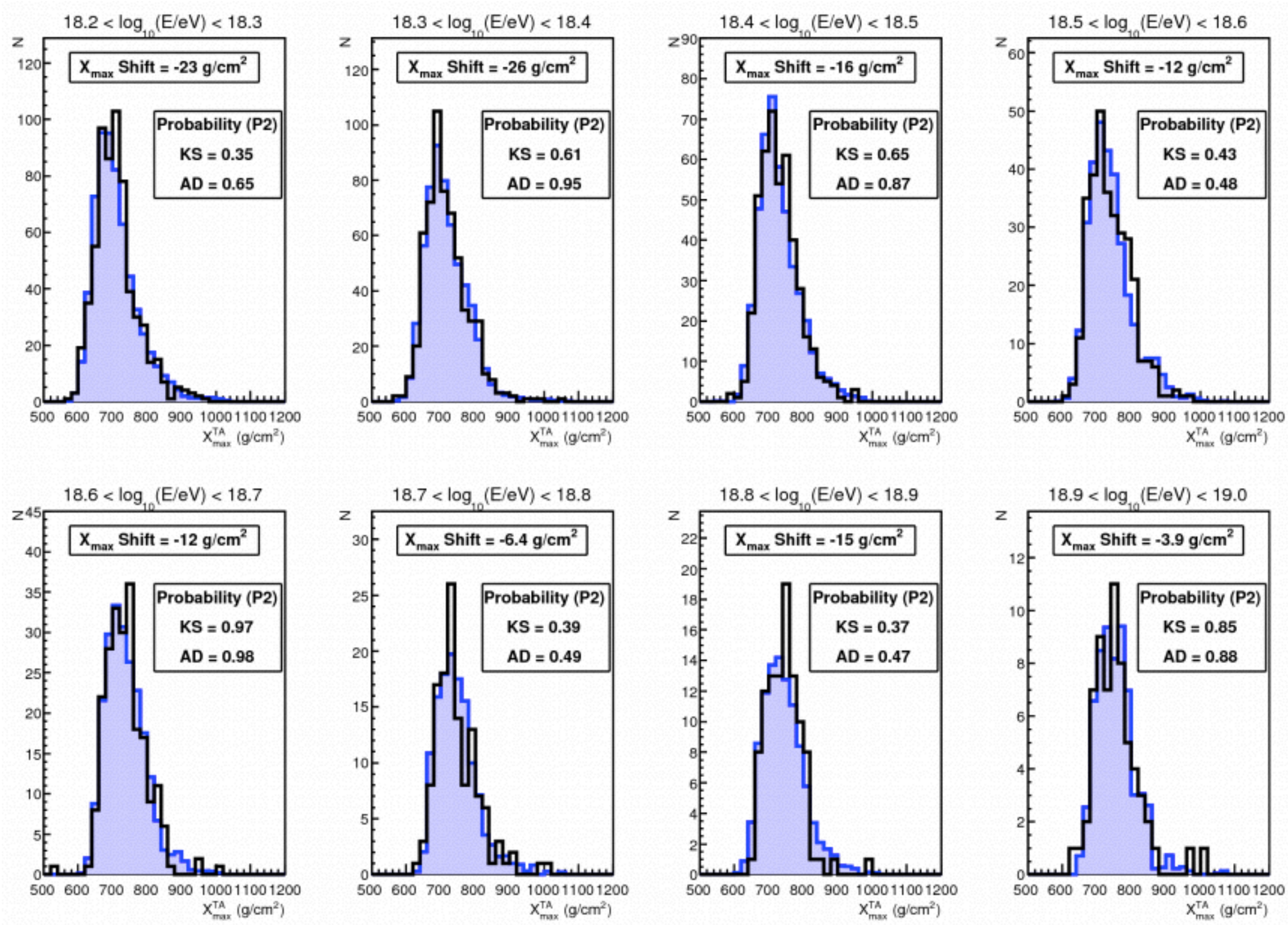
TA: 20.3 g/cm^2

Auger: -10/+8 g/cm^2

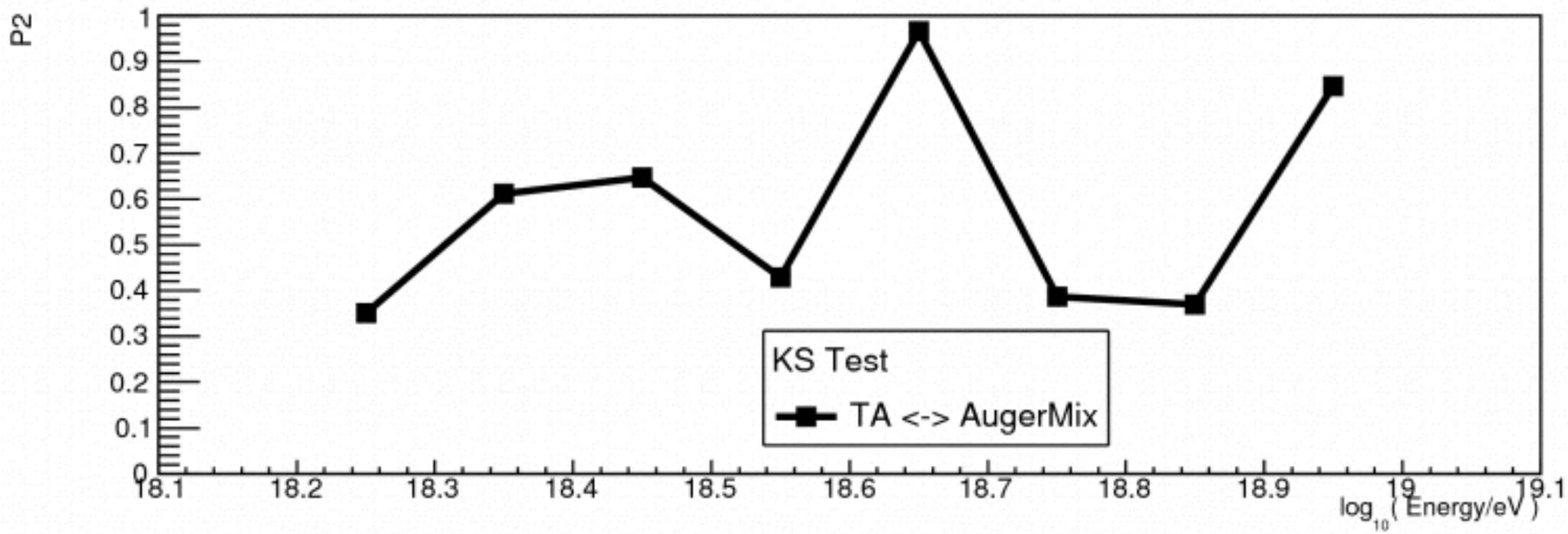


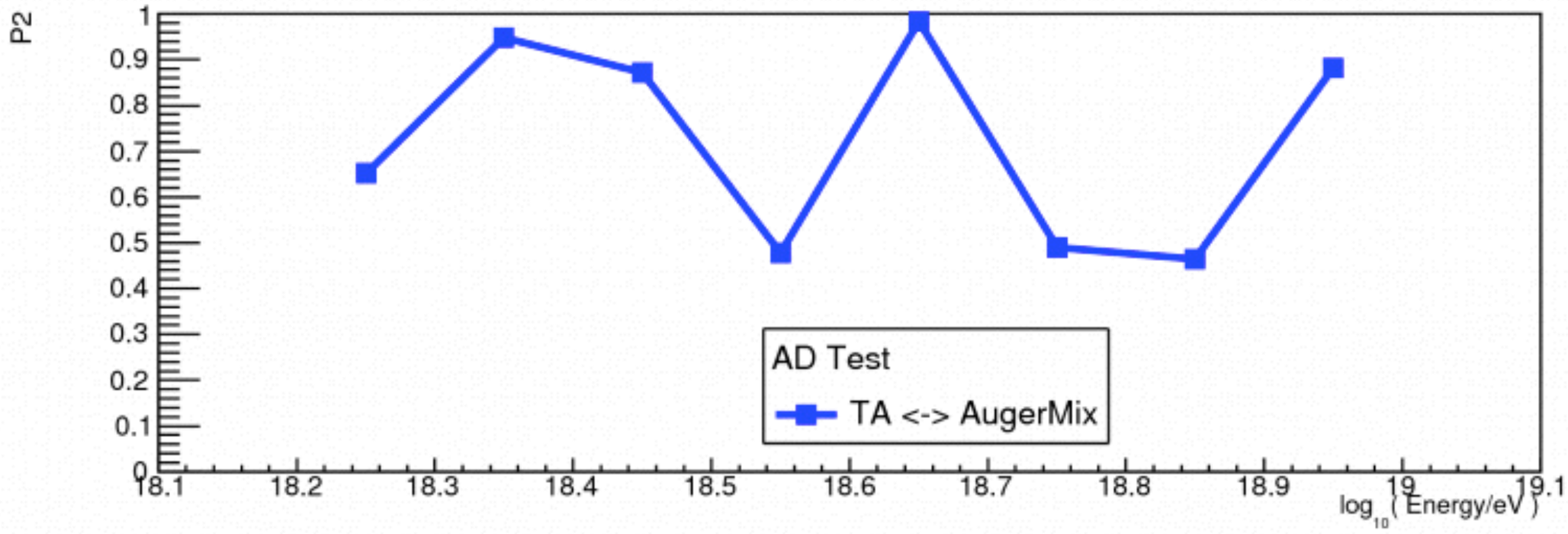
➡ Shift needed so that the means of the distributions match

Results between 18.2<$\log_{10}(E/\mathrm{eV})$<19.0

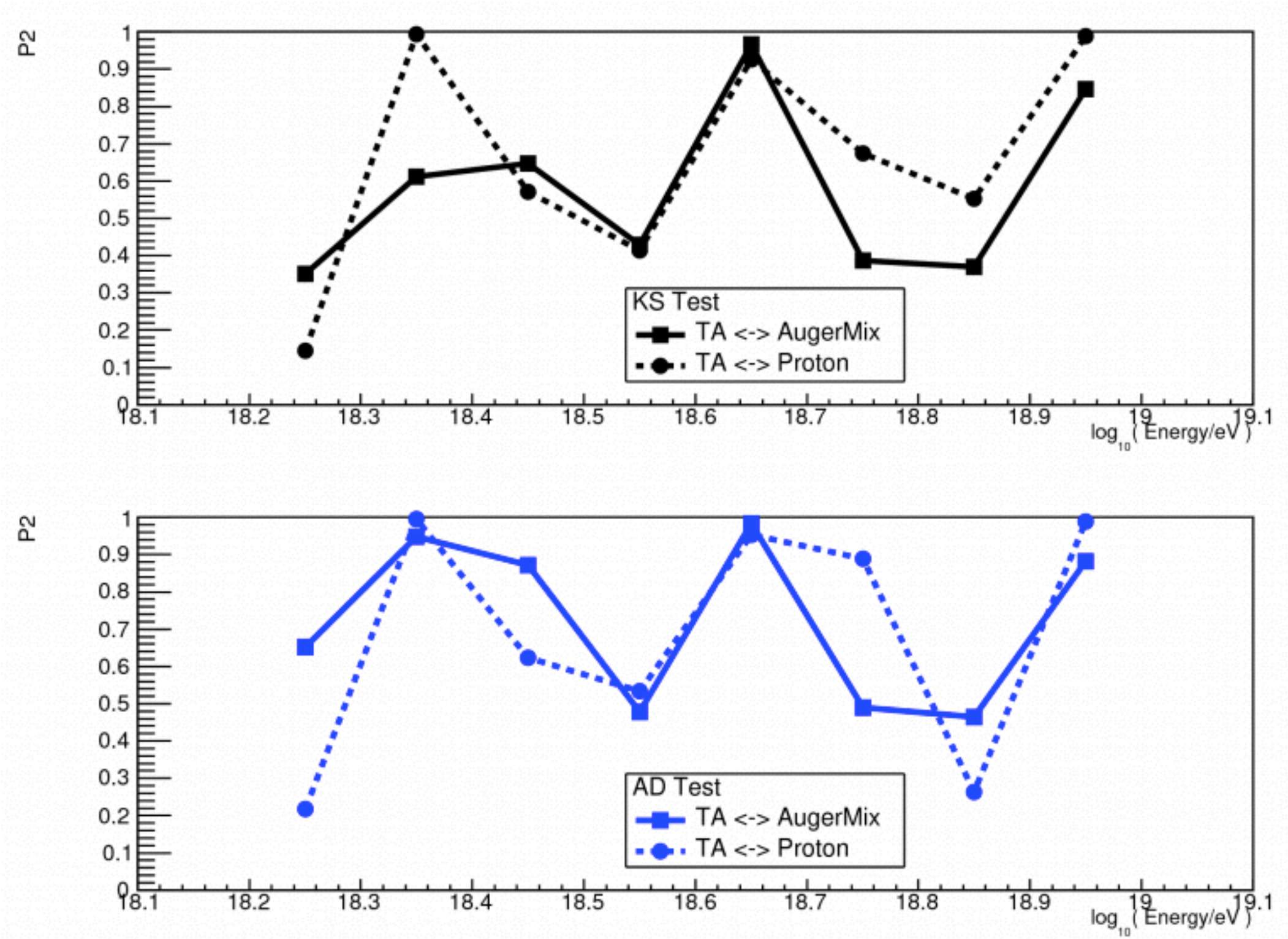


Results between $18.2 < \log_{10}(E/\mathrm{eV}) < 19.0$



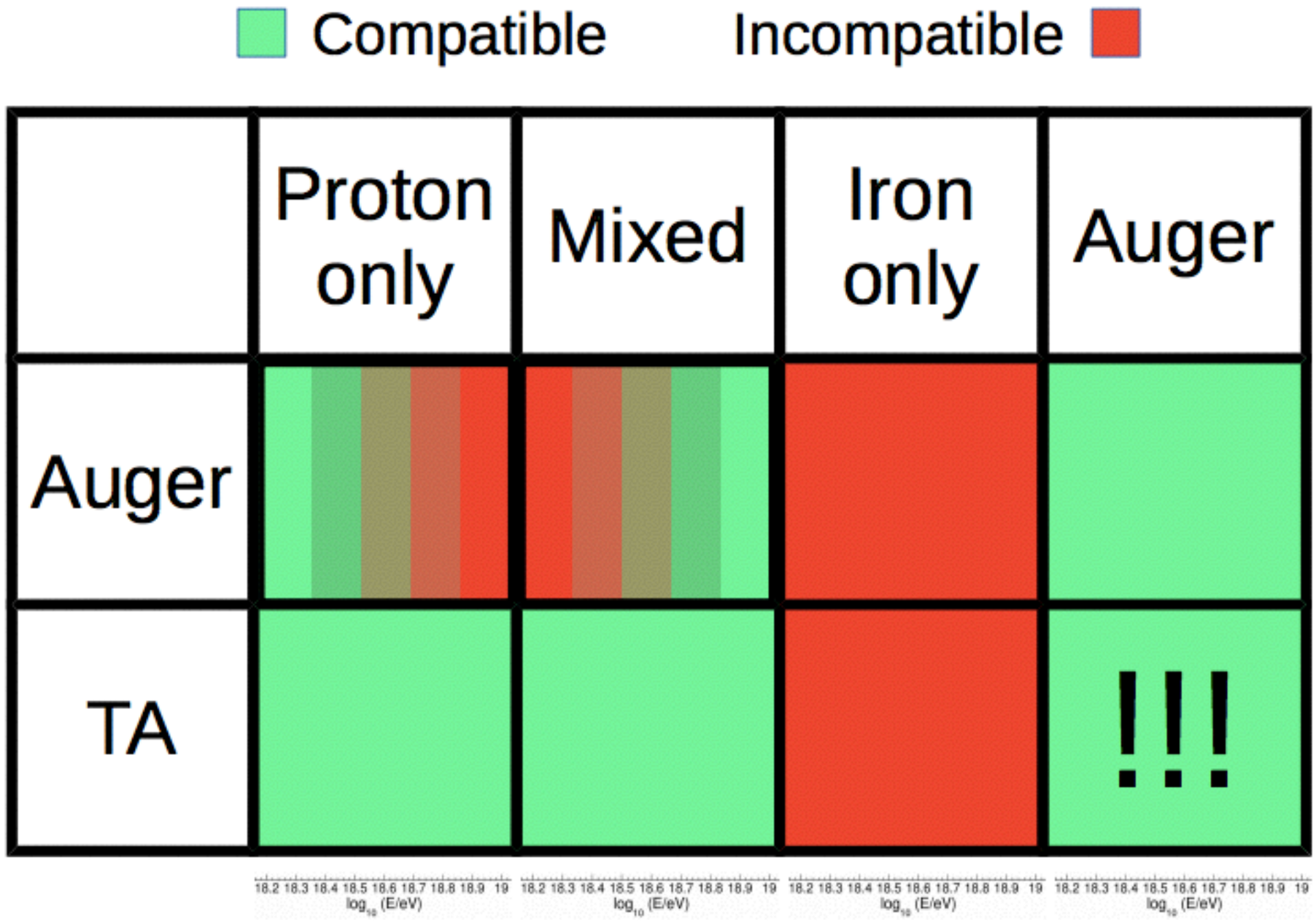


Comparison of TA data with AUGERMIX and protons



X_{max} compatibility table— $18.2<\log_{10}(E/\mathrm{eV})<19.0$

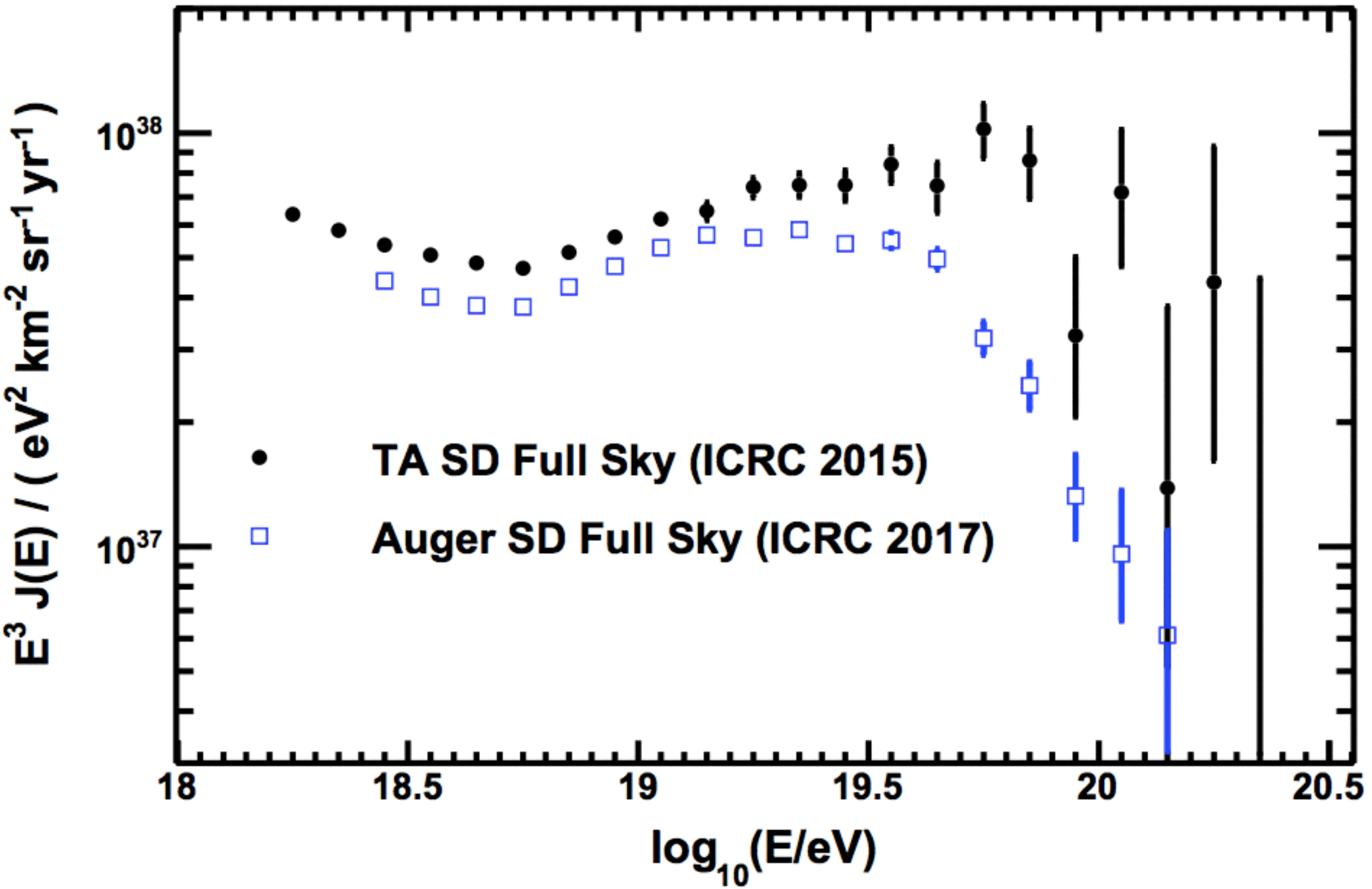
➡ **Within systematic uncertainties**



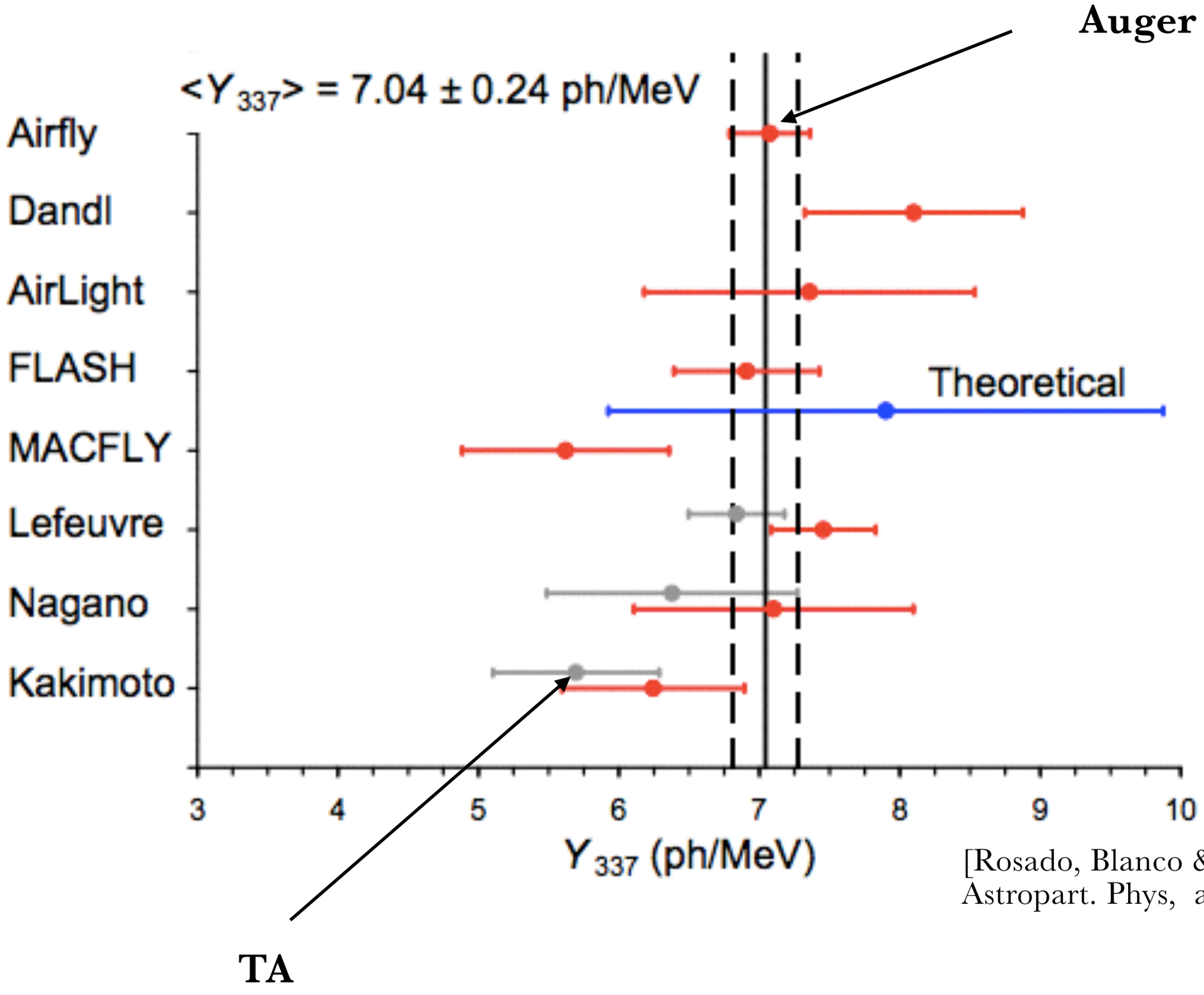
iii) Energy spectrum

Valerio Verzi, UHECR2016
Dimitri Ivanov, ICRC2017

Energy spectrum

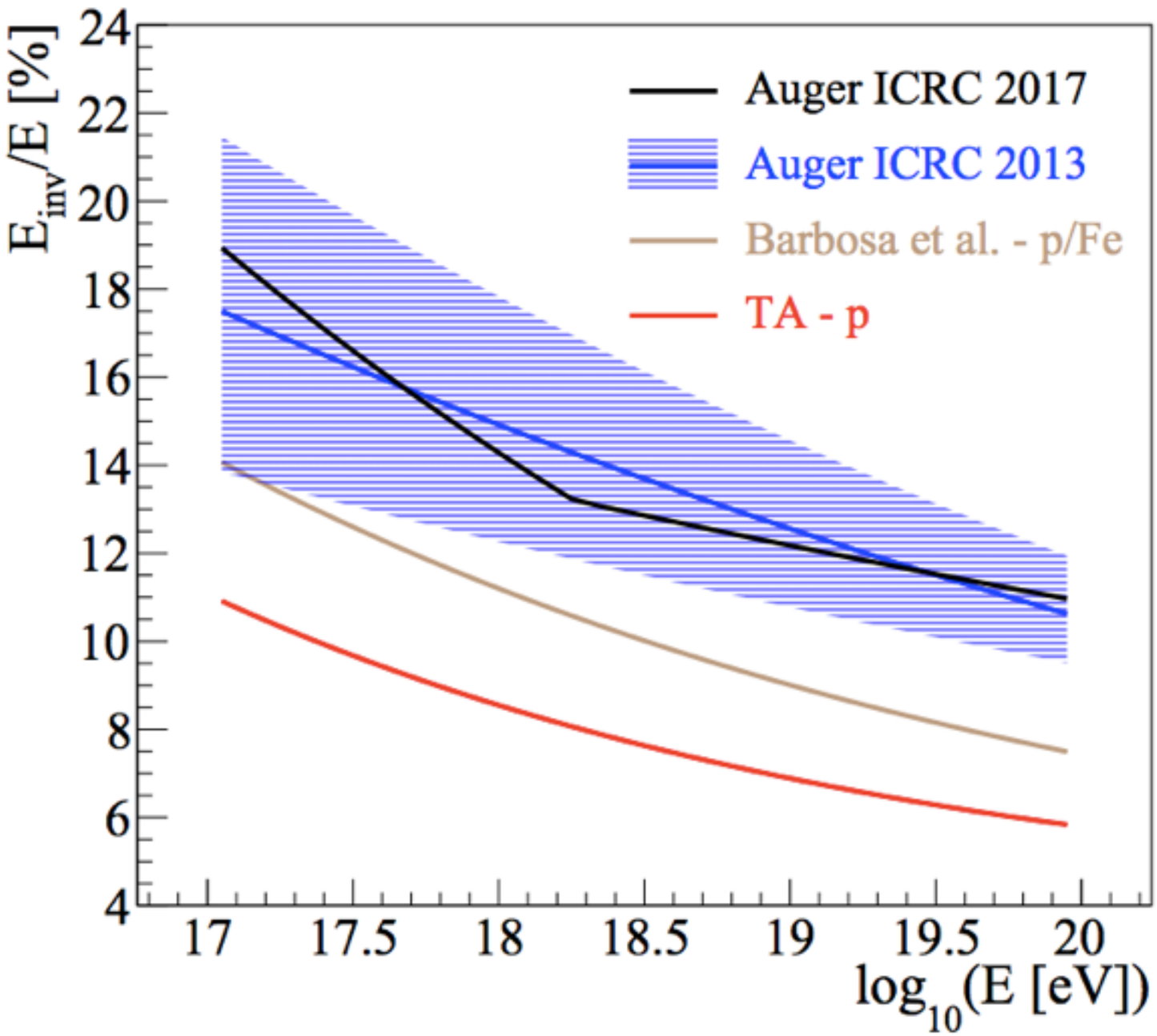


Fluorescence yield



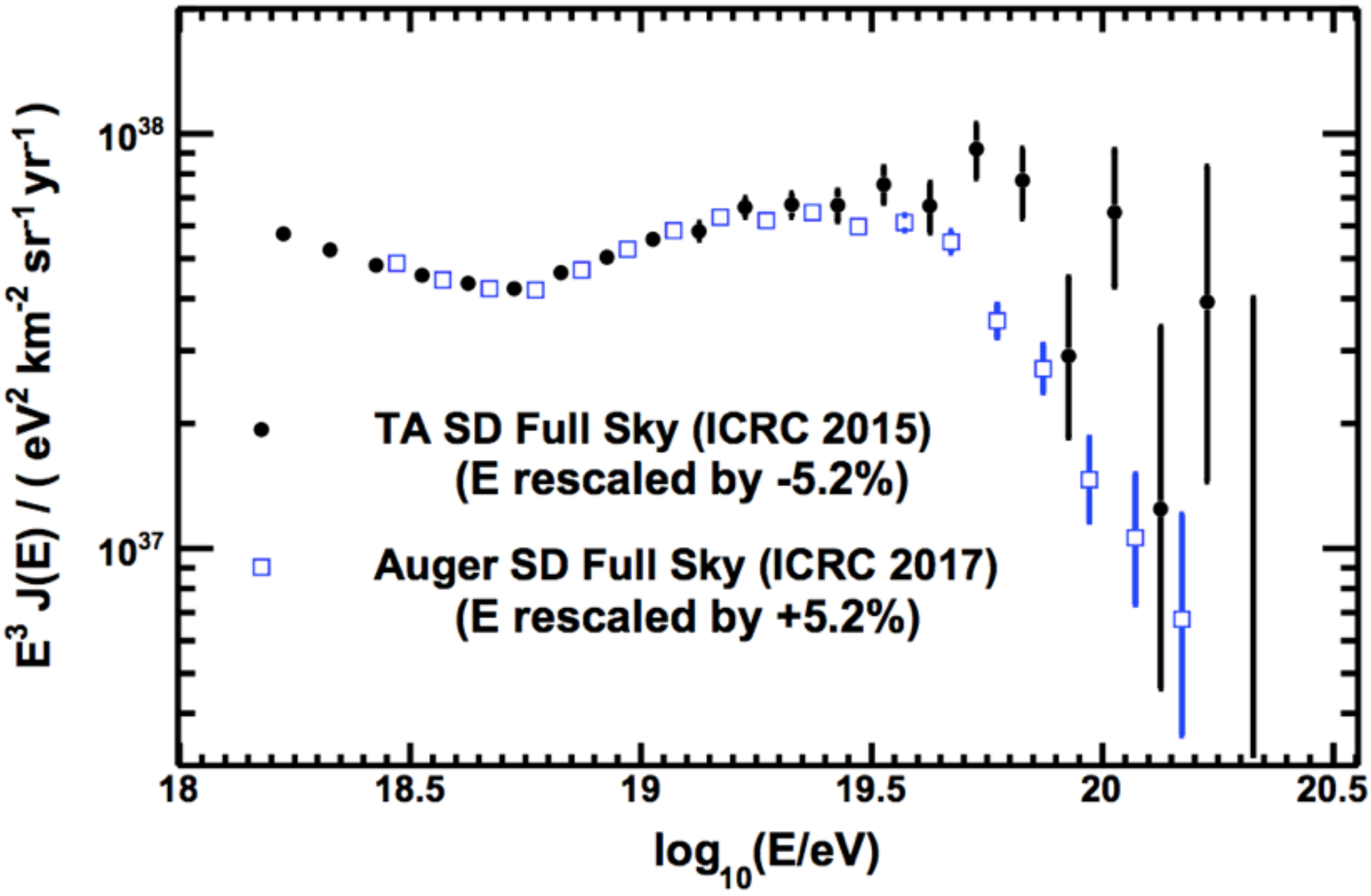
[Rosado, Blanco & Arqueros, Astropart. Phys, arXiv:1401.4310]

Invisible energy



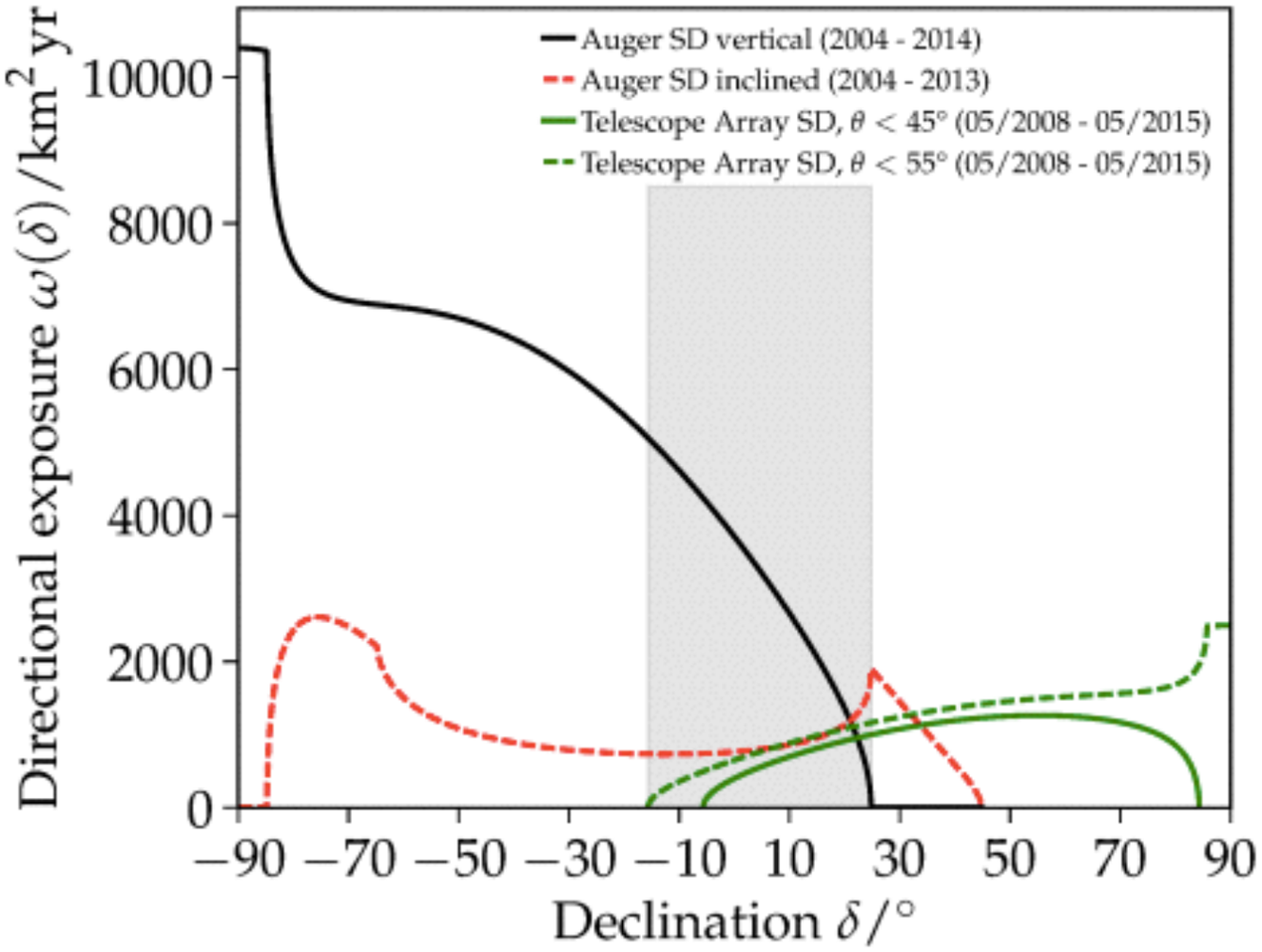
➡ **Good rationale to understand the global difference and so to apply a global rescaling**

Rescaled energy spectrum



➡ **Astrophysical effect or systematic uncertainties?**

Focus on the common field of view

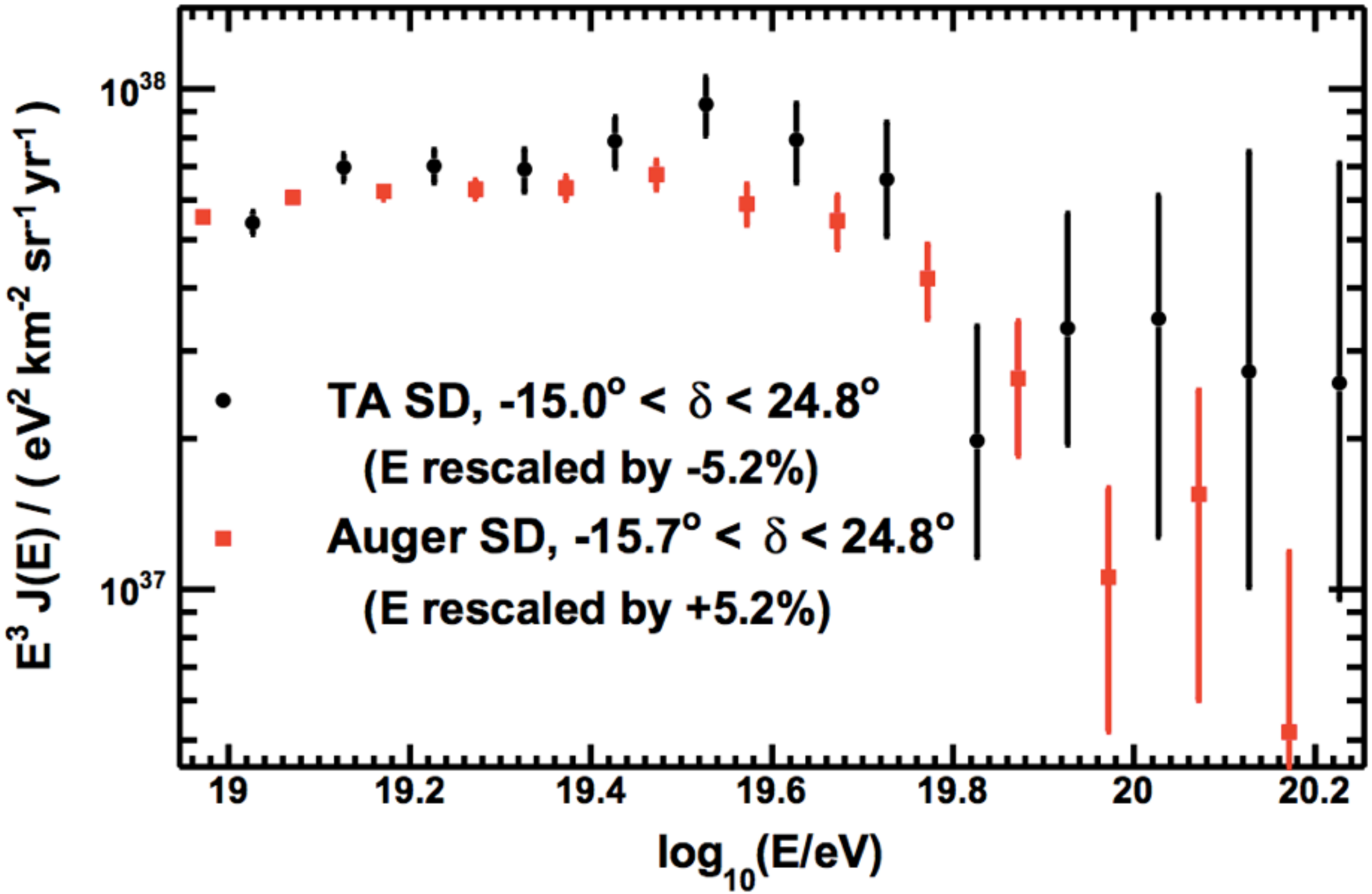


- Possibly, different intensities in different regions of the sky >10 EeV
- *But* same intensity in the common field of view
- If anisotropies, possible distortions by the directional exposure functions

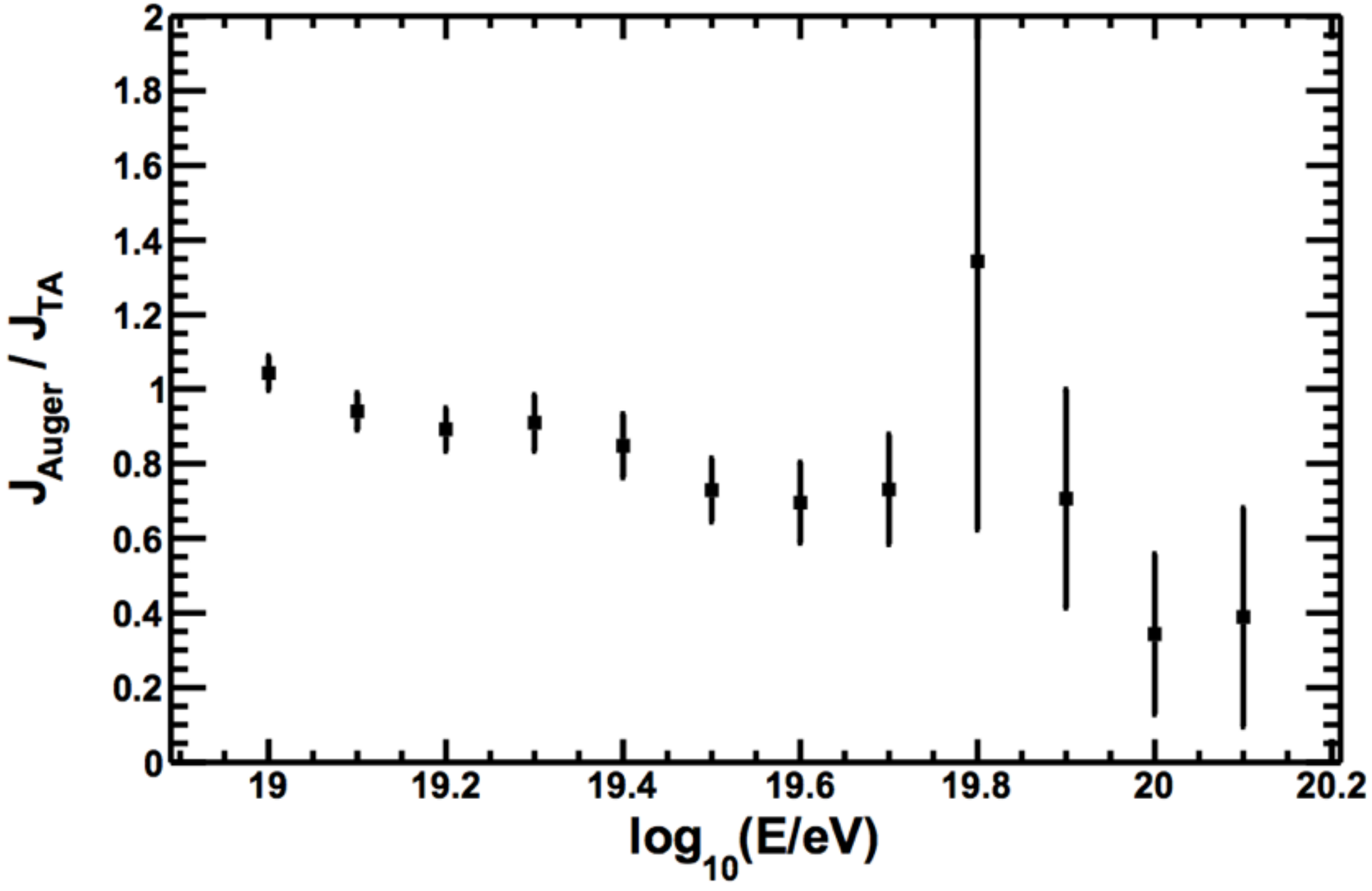
➡ Remove distortions induced from different directional exposures in case of anisotropies:

$$J_{1/\omega}(E) = \frac{1}{\Delta\Omega\Delta E}\sum_{i=1}^{N}\frac{1}{\omega(\delta_i)}$$

Results in the common sky—shifted energies



Results in the common sky—shifted energies



➡ **Persisting energy-dependent systematic uncertainties**

iv) Perspectives

➡ **UHECR2018, Paris, 8/12 Oct.**

Summary and perspectives

- Within systematic uncertainties, no real controversy in $X_{\max}$

  - $18.2<\log_{10}(E/\mathrm{eV})<19.0$

    ➡ Ongoing journal paper

  ➡ Extend the comparisons >19.0 (MoU under discussion)

- Persisting energy-dependent differences of experimental origin in the energy spectrum to be further investigated

  - Crucial to establish the directional dependence of the UHECR intensity

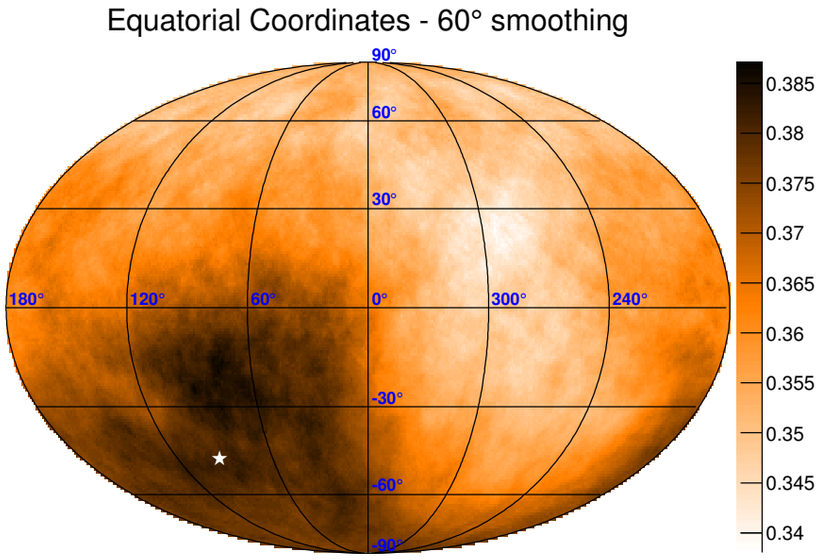
    ➡ To be followed up, UHECR2018

Summary and perspectives

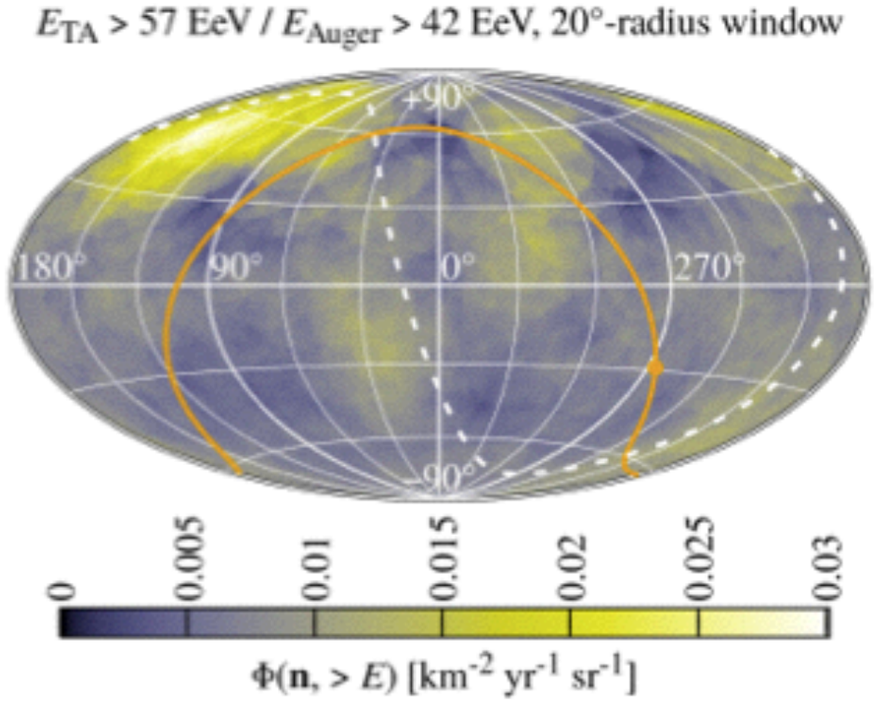
- Ultimate goal: **full-sky** survey of UHECR patterns in the sky
  - Large scale studies >~10 EeV (beyond the dipole)
  - Over-densities/correlations with xGal matter at UHE

➡ Expected progress for UHECR2018

E_{TA}>10 EeV / E_{Auger}>8.5 EeV



➡



➡ UHECR2018

ApJ 794 (2014) 172

A. Di Matteo, UHECR2016