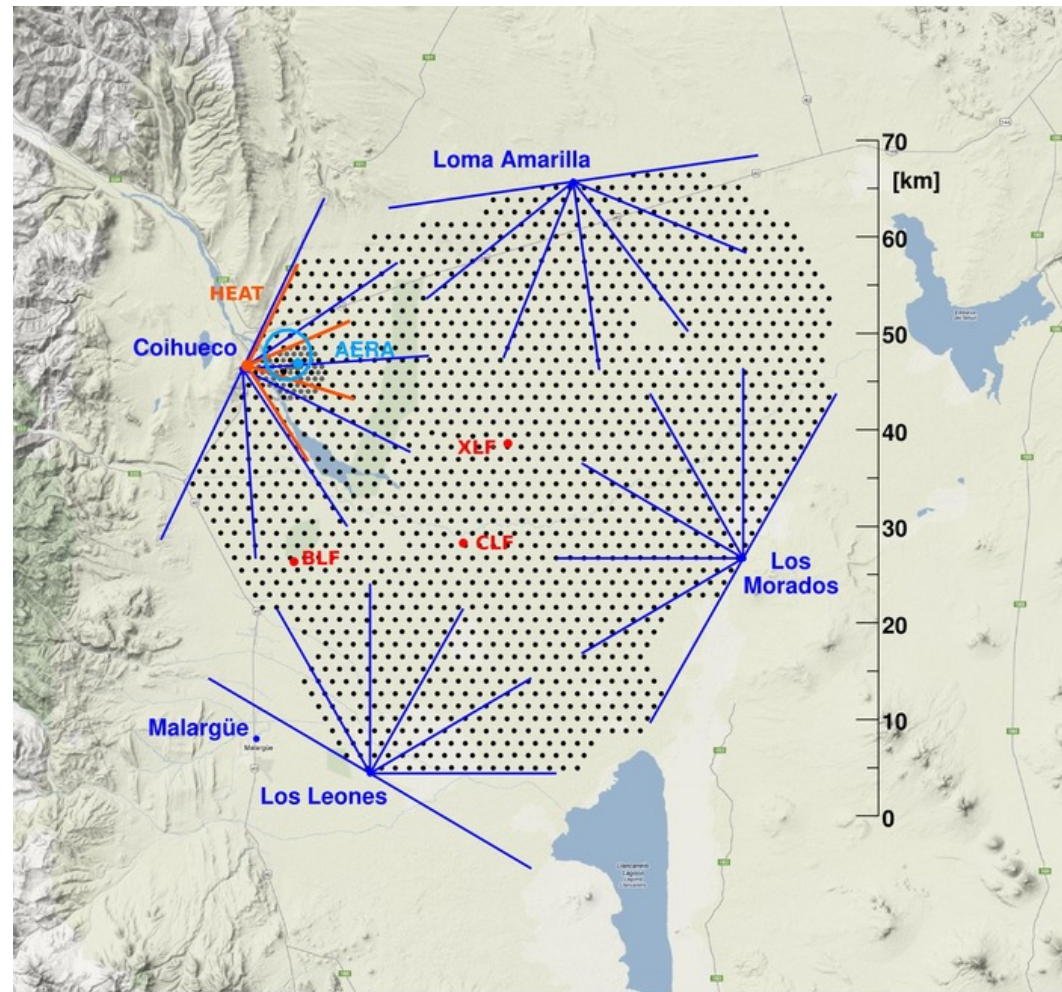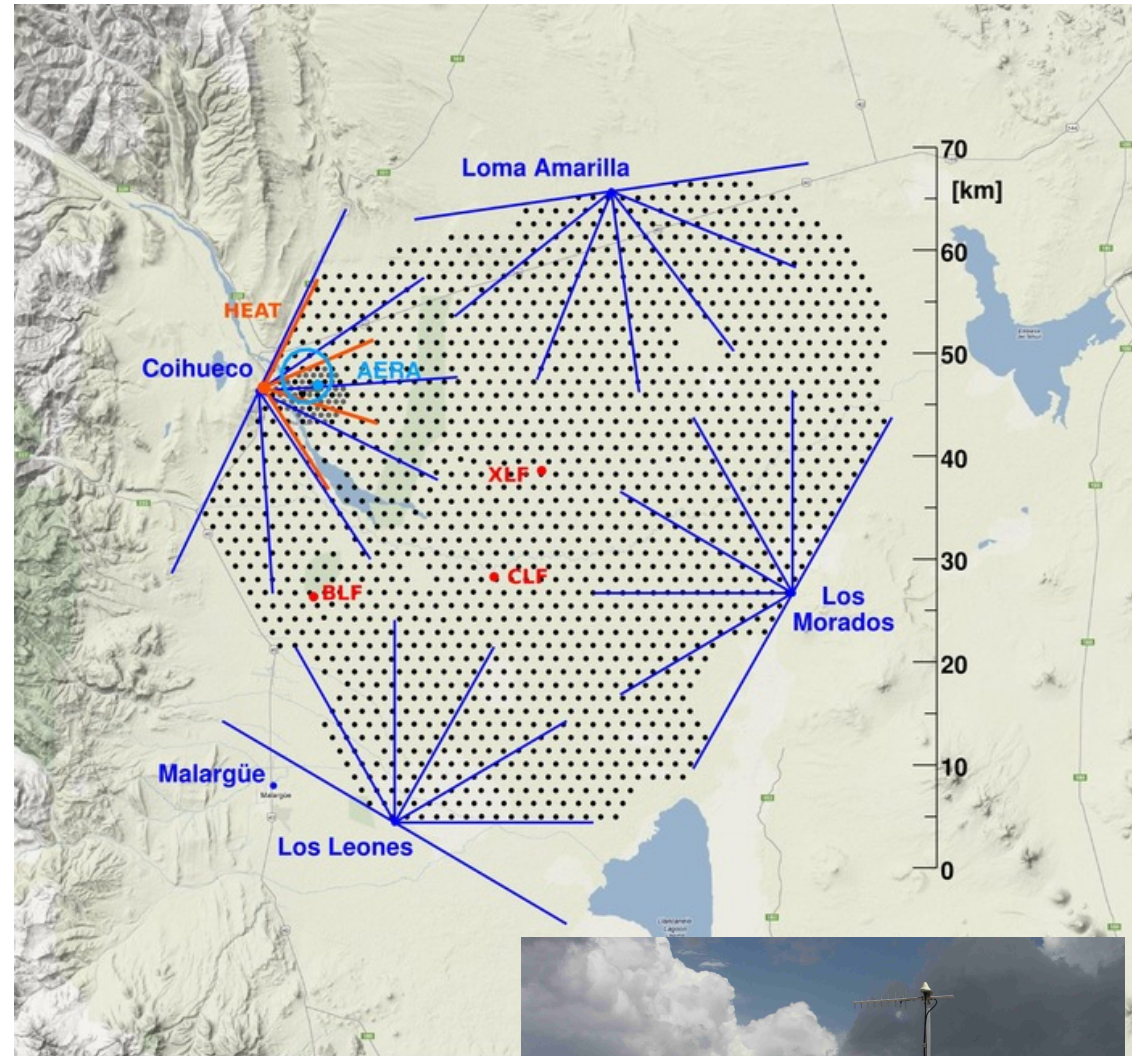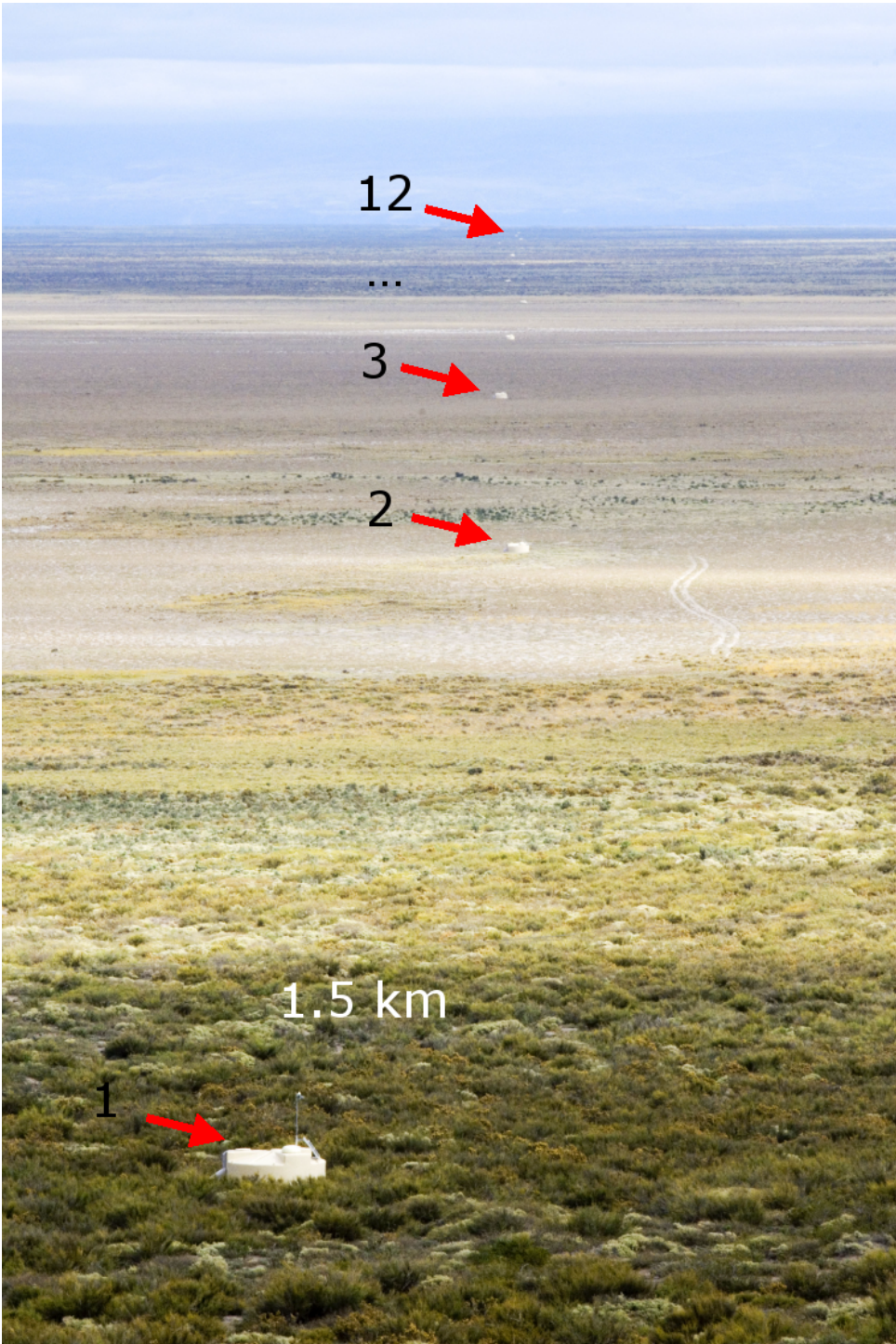# Highlights from the Pierre Auger Observatory
Composition and Hadronic Interactions at Ultra-High Energies

Darko Veberič
University of Nova Gorica, Slovenia
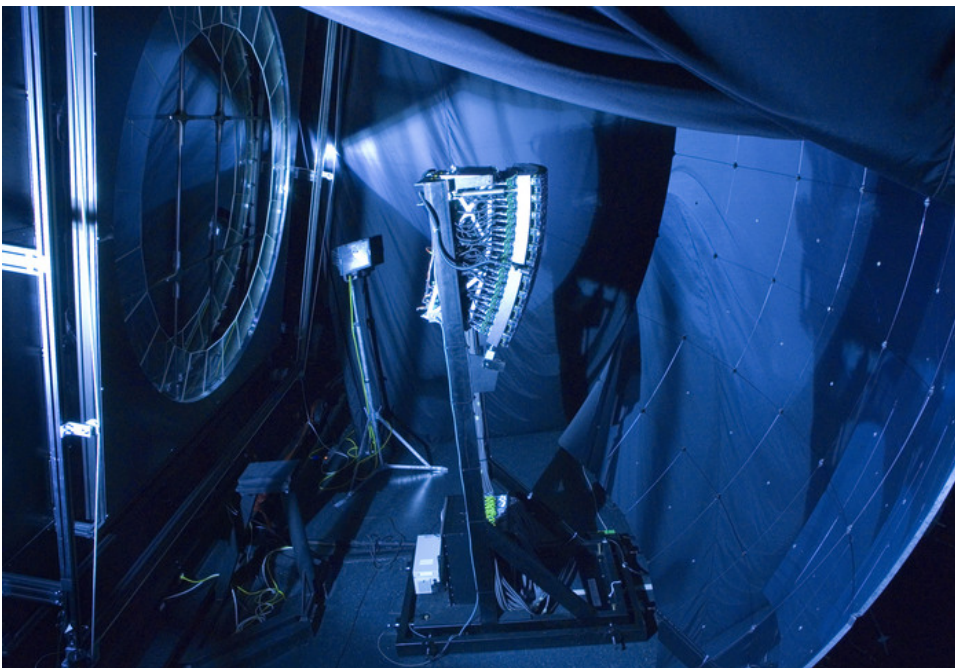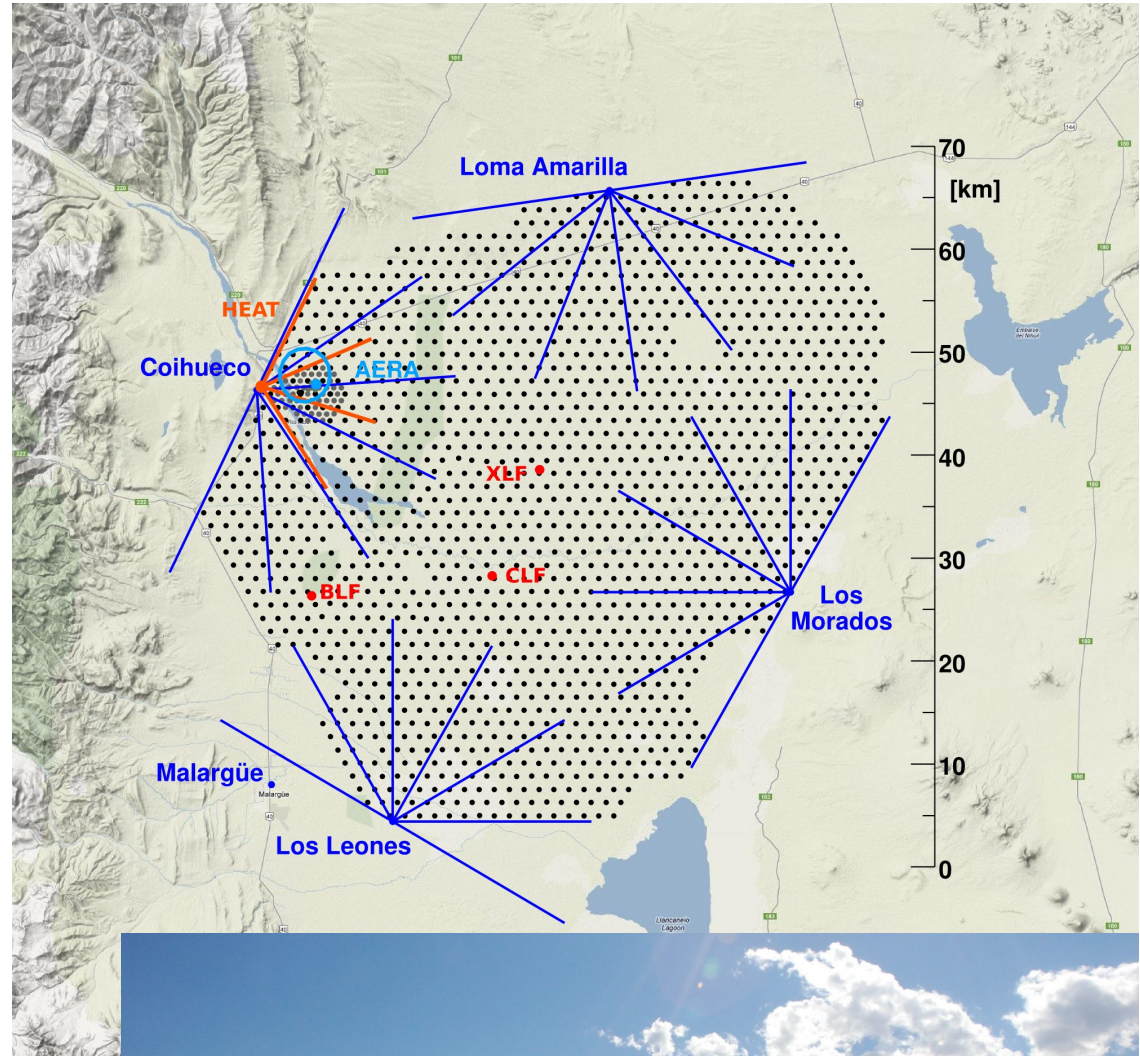**on behalf of the Pierre Auger Collaboration**

Surface Detector

12 →

...

3 →

2 →

1.5 km

1 →

3000 km²
1600 x, 1500m
80 x, 750m
12 t water-Cherenkov
Detectors
constr. 2004-2008

Loma Amarilla

HEAT

Coihueco   AERA

XLF

BLF   CLF

Los
Morados

Malargüe

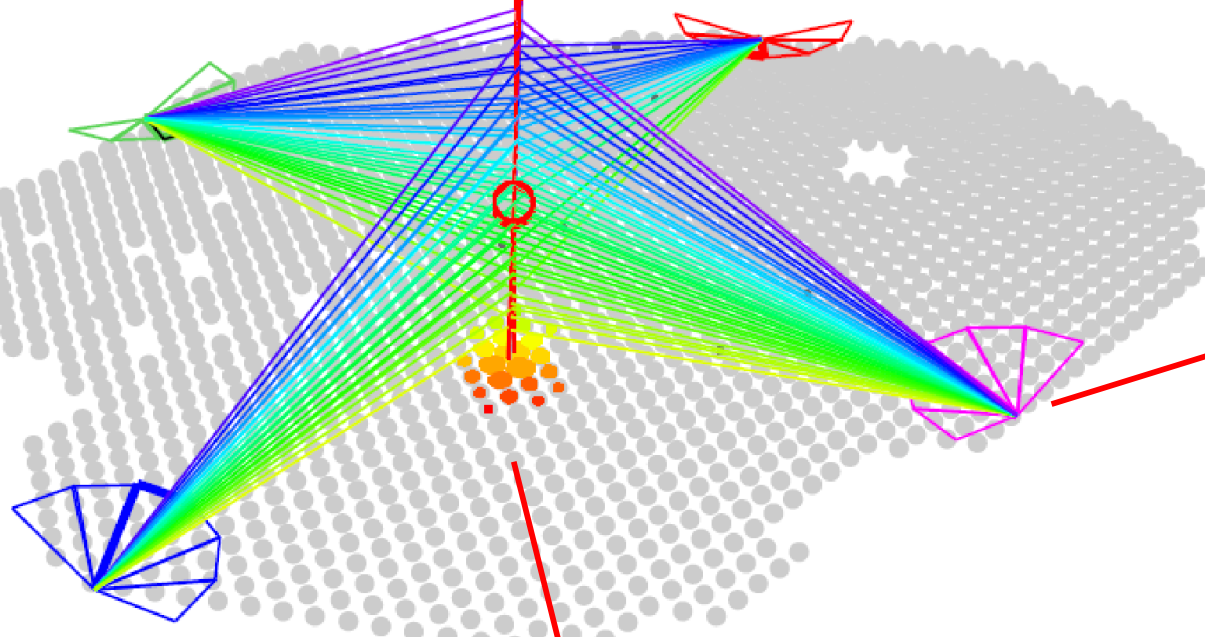Los Leones

70 [km]

60

50

40

30

20

10

0

Fluorescence Detector

4 sites

27 telescopes, 440 PMT camera

Loma Amarilla

HEAT

Coihueco

AERA

XLF

BLF

CLF

Los Morados

Malargüe

Los Leones

70
[km]
60
50
40
30
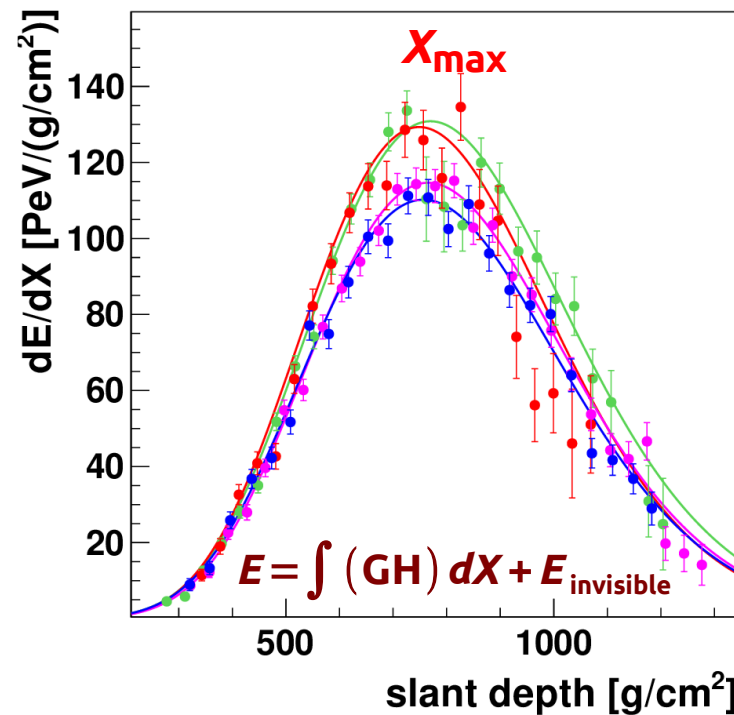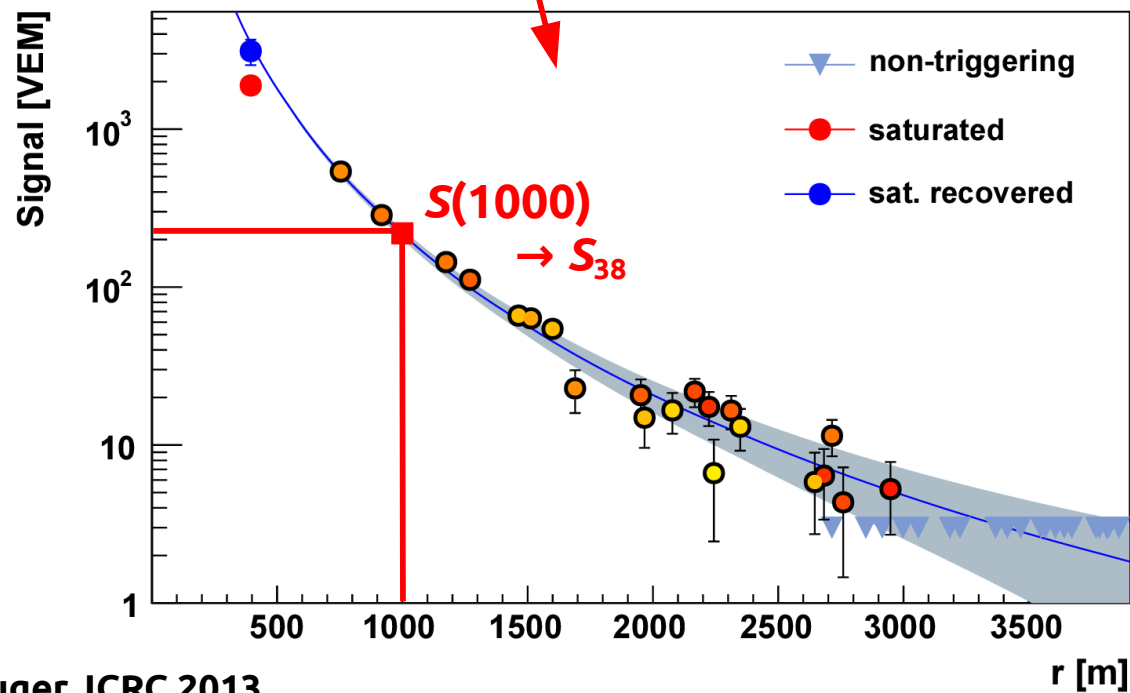20
10
0

Event reconstruction

Fluorescence Detector, 13%

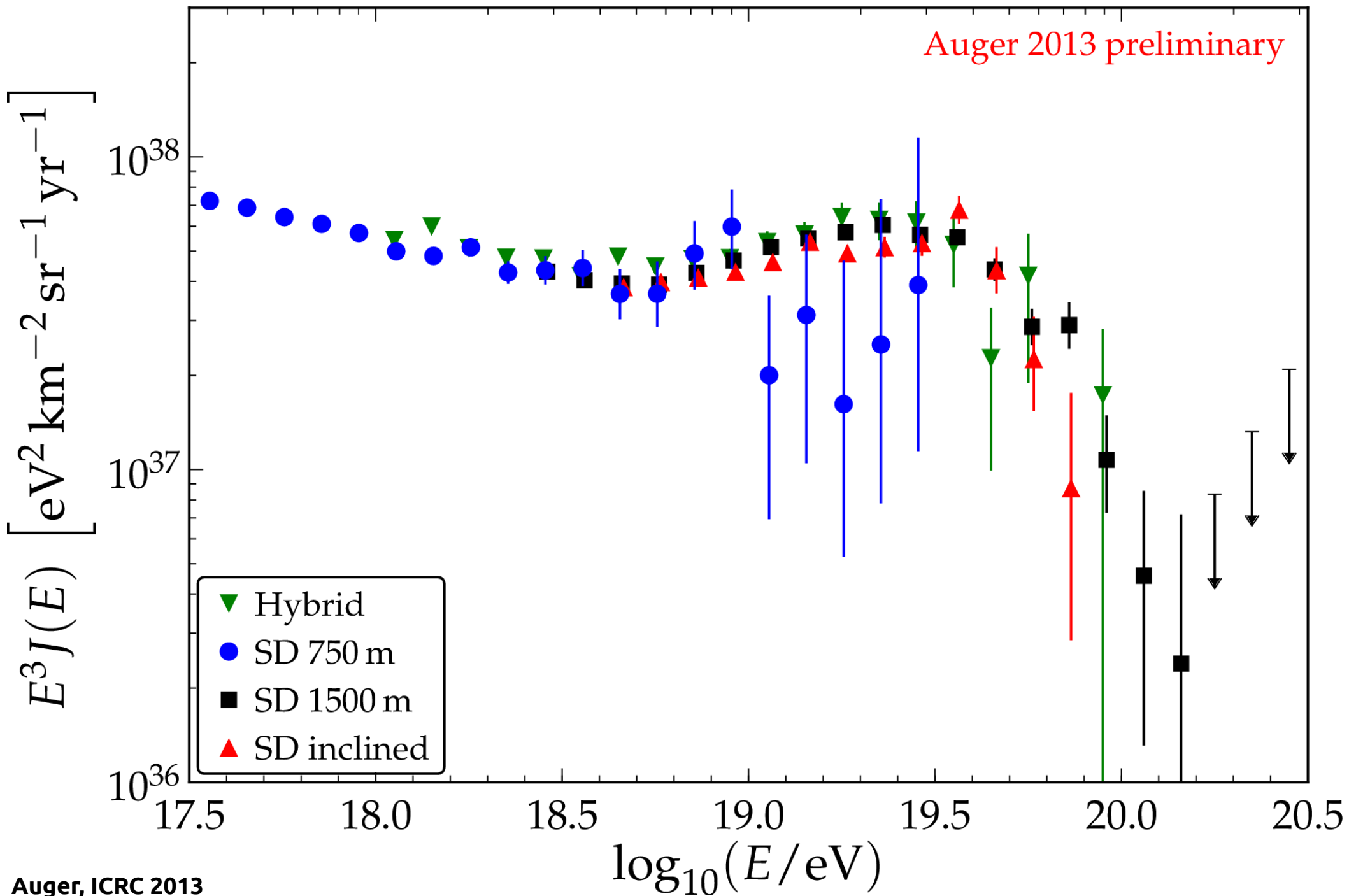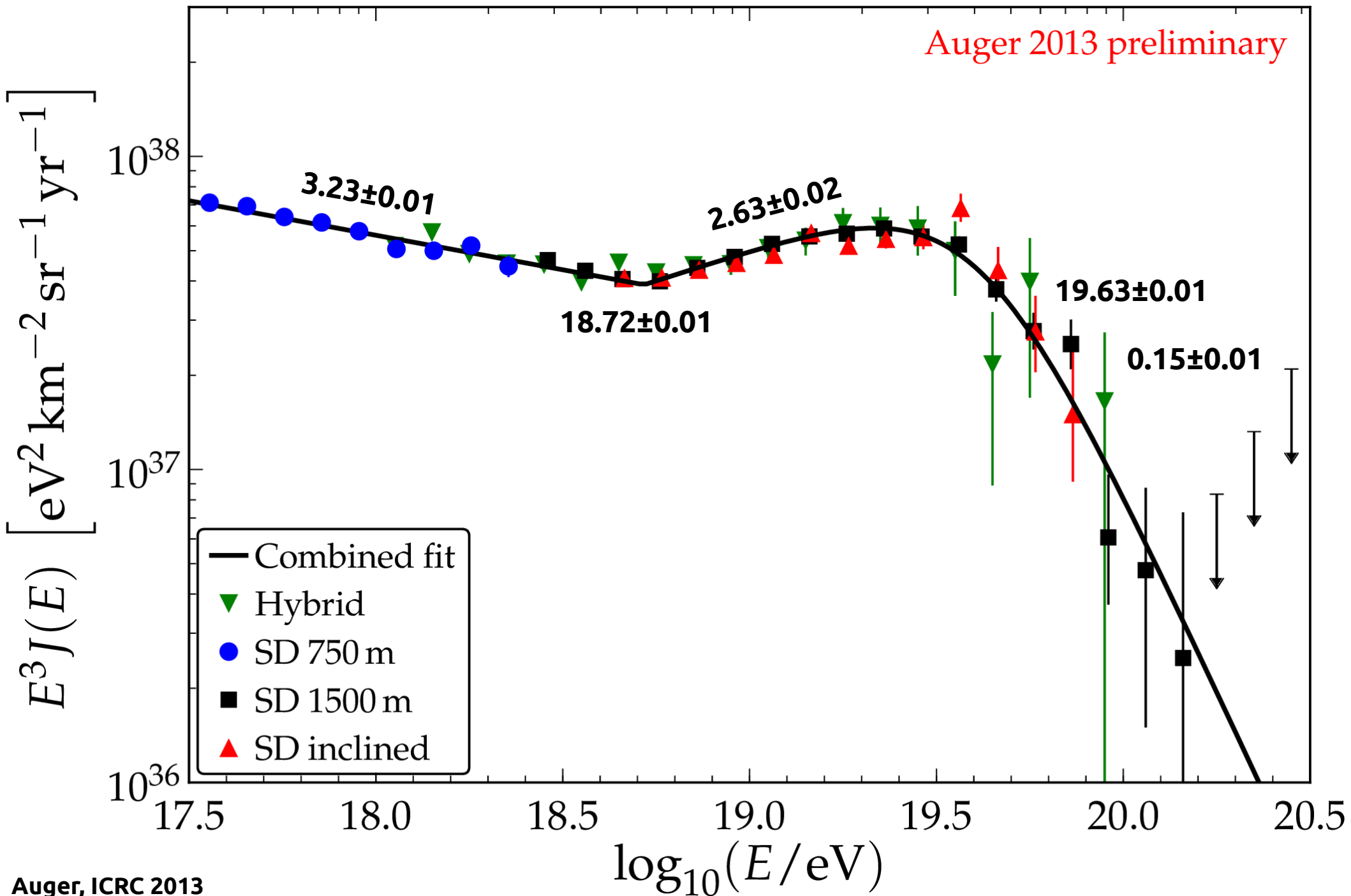Surface Detector, 100%

$S(1000)$

$\rightarrow S_{38}$

non-triggering

saturated

sat. recovered

Auger, ICRC 2013

X_{max}

$E = \int (\text{GH}) \, dX + E_{\text{invisible}}$

Energy calibration

Spectrum

Auger 2013 preliminary

Legend:
- ▽ Hybrid
- ● SD 750 m
- ■ SD 1500 m
- ▲ SD inclined

Axes: $\log_{10}(E/\mathrm{eV})$ versus $E^3 J(E)\ [\mathrm{eV}^2\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}]$

Auger, ICRC 2013

Spectrum features

Auger 2013 preliminary

3.23 ± 0.01

18.72 ± 0.01

2.63 ± 0.02

19.63 ± 0.01

0.15 ± 0.01

— Combined fit
▽ Hybrid
● SD 750 m
■ SD 1500 m
▲ SD inclined

$E^3 J(E) \left[\mathrm{eV}^2\, \mathrm{km}^{-2}\, \mathrm{sr}^{-1}\, \mathrm{yr}^{-1} \right]$
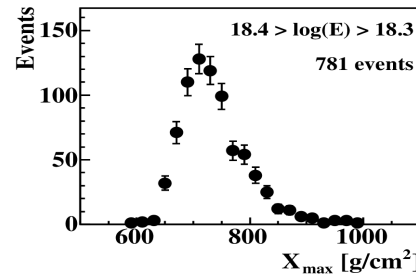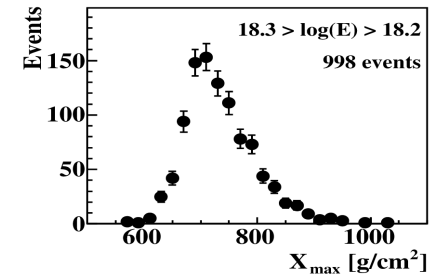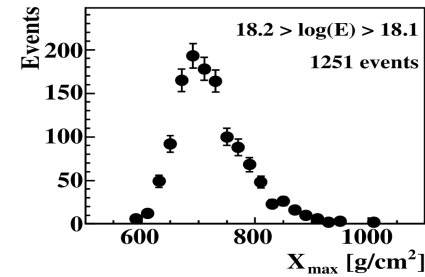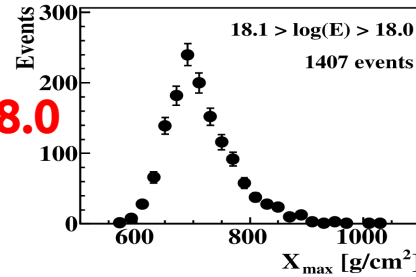
$\log_{10}(E/\mathrm{eV})$

Auger, ICRC 2013

X_{max} distributions

Fluorescence Detector

Los Leones
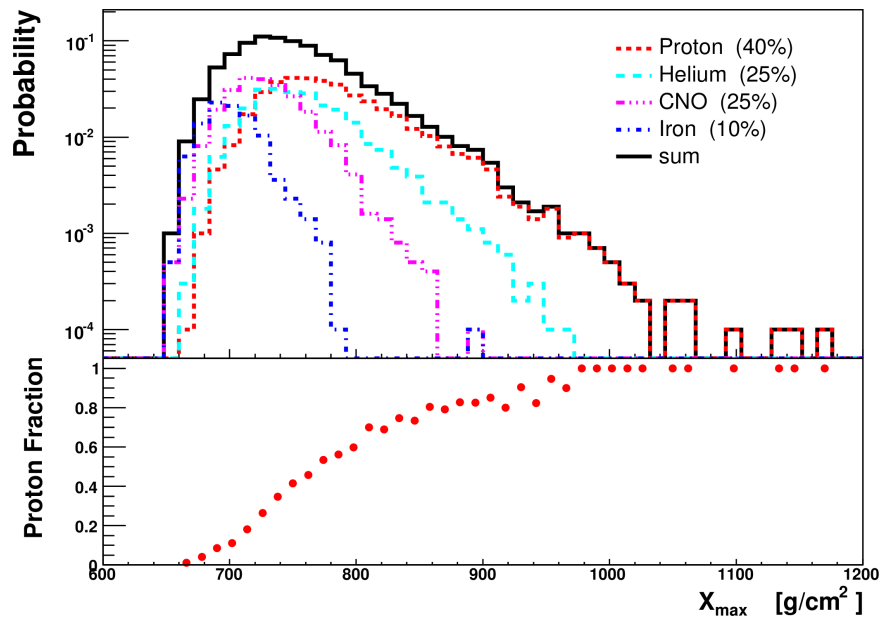Los Morados

$\sigma_{X_{max}} < 20\,g/cm^2$
$\Delta_{sys} \approx 15\,g/cm^2$

X_{max}

$\sigma_E / E \sim 8\%$
$\Delta_{sys} \approx 22\%$

18.0

$18.1 > \log(E) > 18.0$
1407 events

$18.2 > \log(E) > 18.1$
1251 events

$18.3 > \log(E) > 18.2$
998 events

$18.4 > \log(E) > 18.3$
781 events

$18.5 > \log(E) > 18.4$
619 events

$18.6 > \log(E) > 18.5$
457 events

$18.7 > \log(E) > 18.6$
331 events

$18.8 > \log(E) > 18.7$
230 events

$18.9 > \log(E) > 18.8$
188 events

$19.0 > \log(E) > 18.9$
143 events

$19.2 > \log(E) > 19.0$
186 events

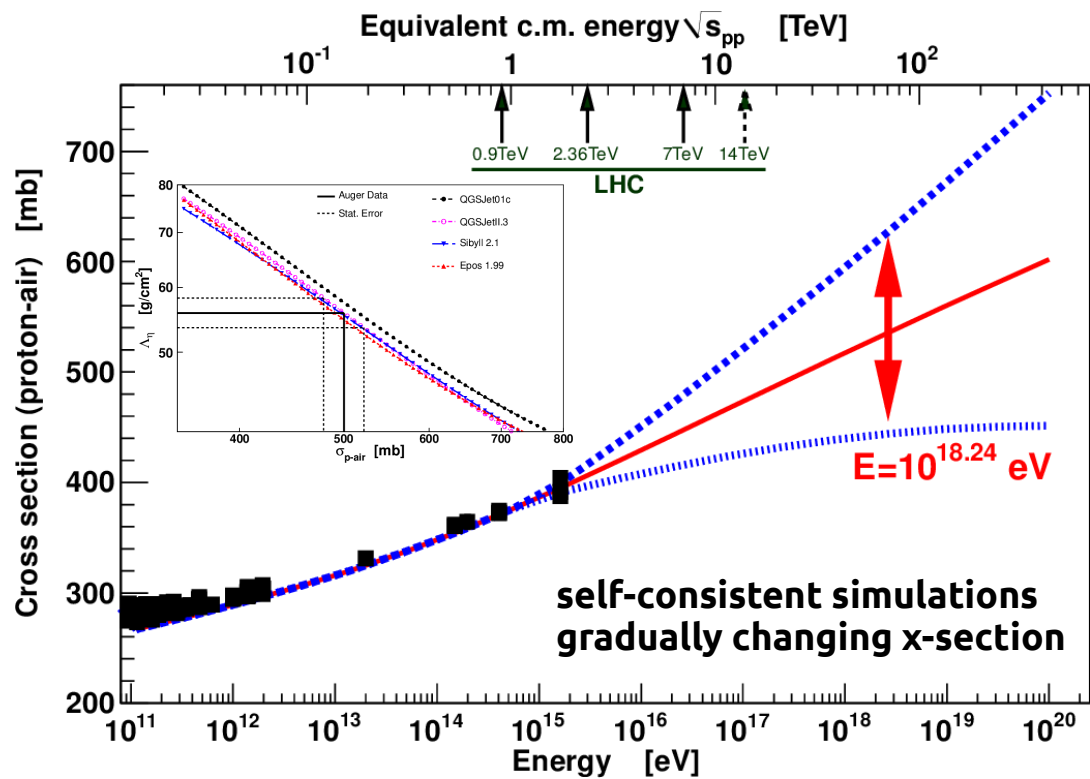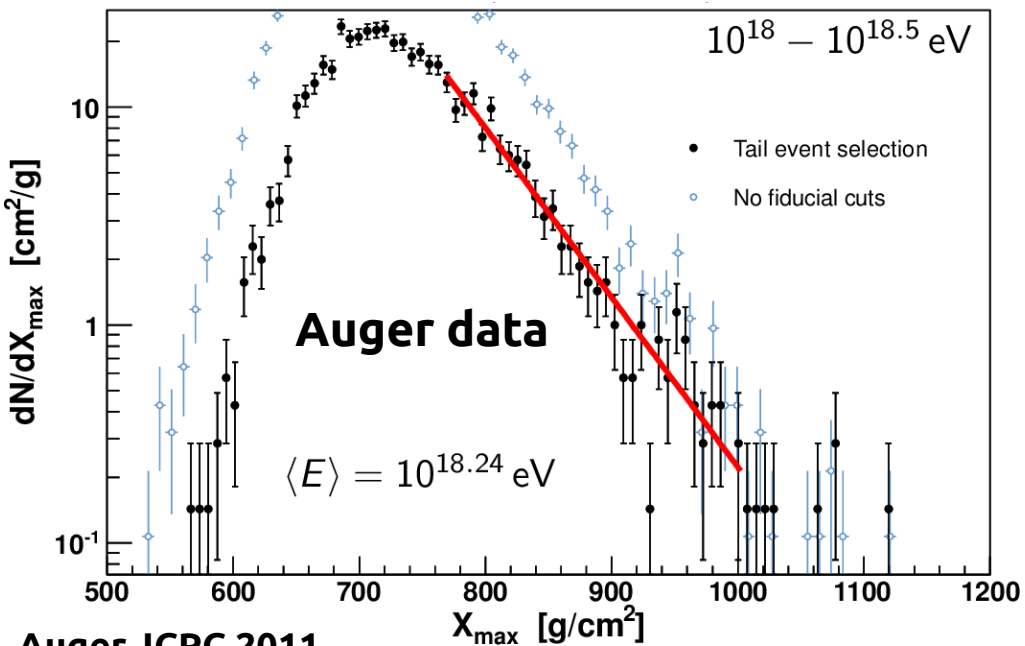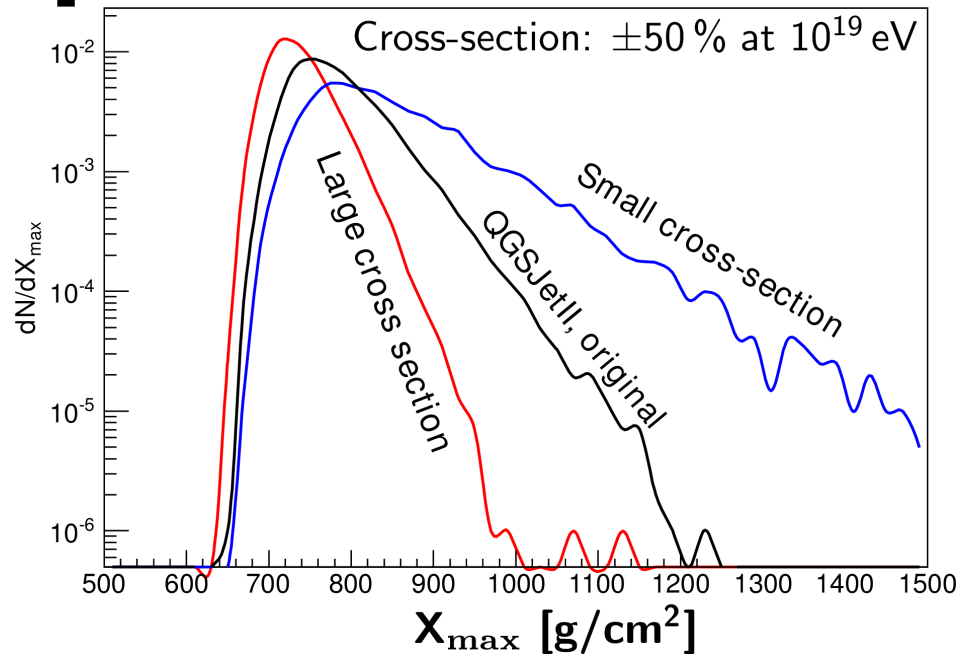$19.4 > \log(E) > 19.2$
106 events

$\log(E) > 19.4$
47 events

19.4

Auger, ICRC 2011

Cross section proton-air

mixed composition: tail p dominated

Proton (40%)
Helium (25%)
CNO (25%)
Iron (10%)
sum

Cross-section: $\pm 50\,\%$ at 10^{19} eV

Large cross section

QGSJetII, original

Small cross-section

Auger data

$\langle E \rangle = 10^{18.24}$ eV

$10^{18} - 10^{18.5}$ eV

Tail event selection
No fiducial cuts

Auger, ICRC 2011

Equivalent c.m. energy $\sqrt{s_{pp}}$ [TeV]

0.9TeV 2.36TeV 7TeV 14TeV

LHC

Auger Data
Stat. Error
QGSJet01c
QGSJetII.3
Sibyll 2.1
Epos 1.99

$E = 10^{18.24}$ eV

self-consistent simulations gradually changing x-section

X_{max} distributions

18.0 → 18.5

3082 events

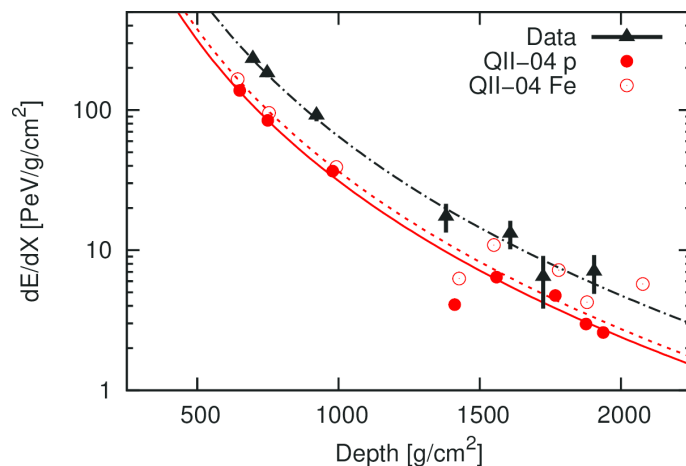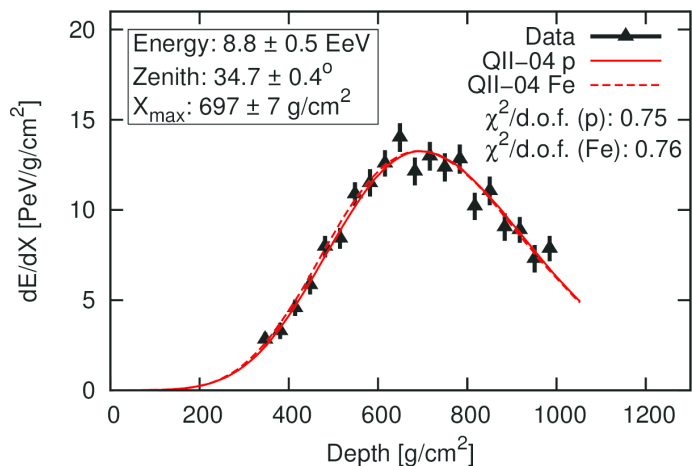Auger, ICRC 2011

Cross section proton-air
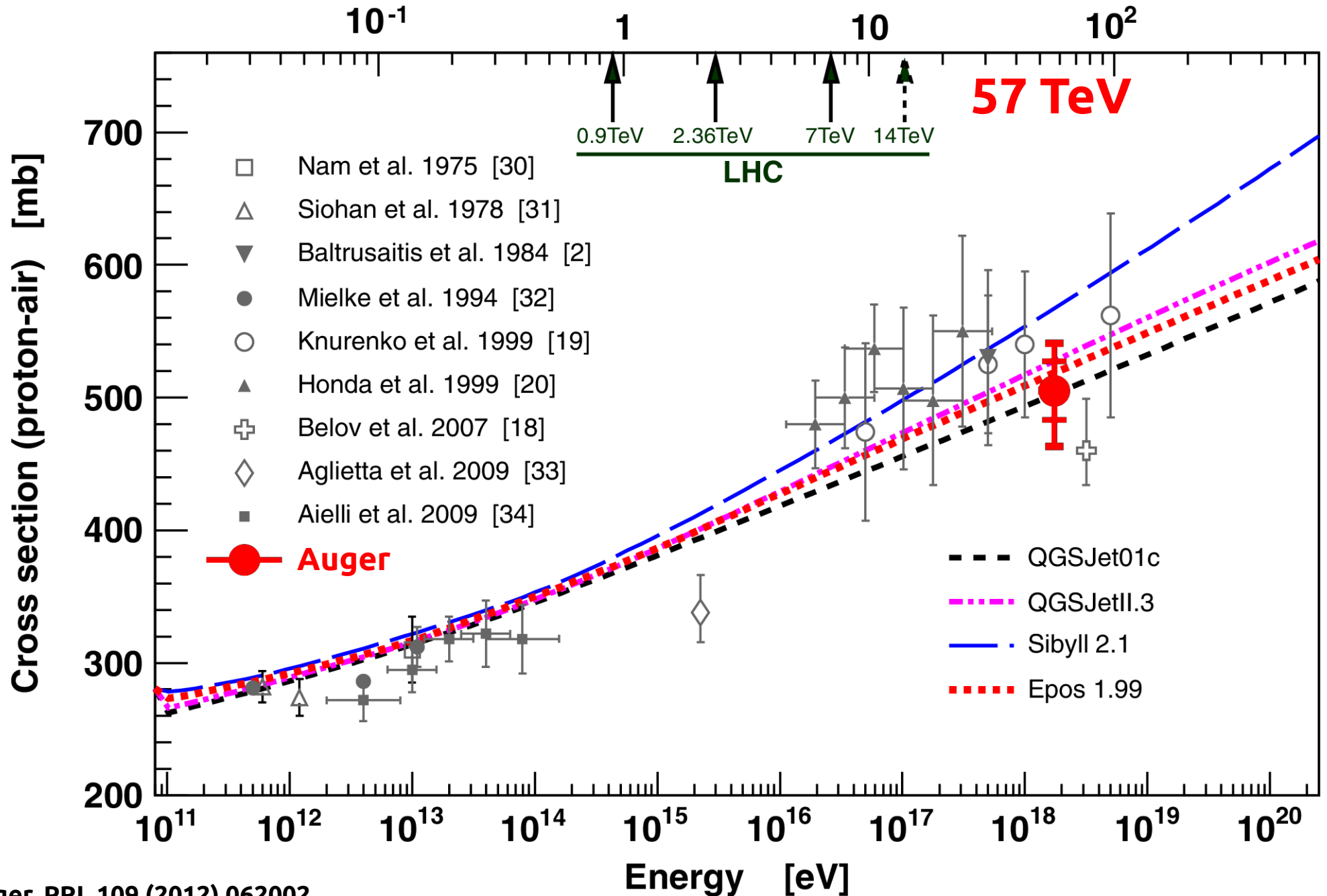
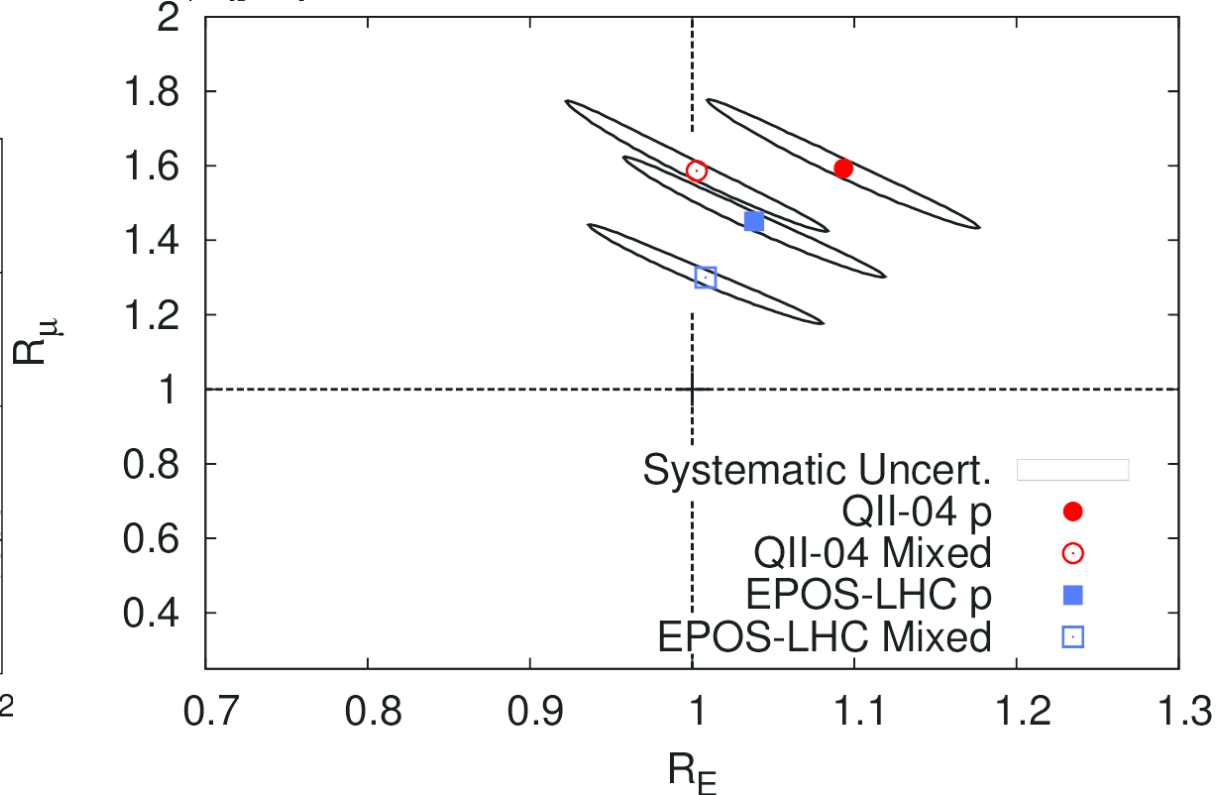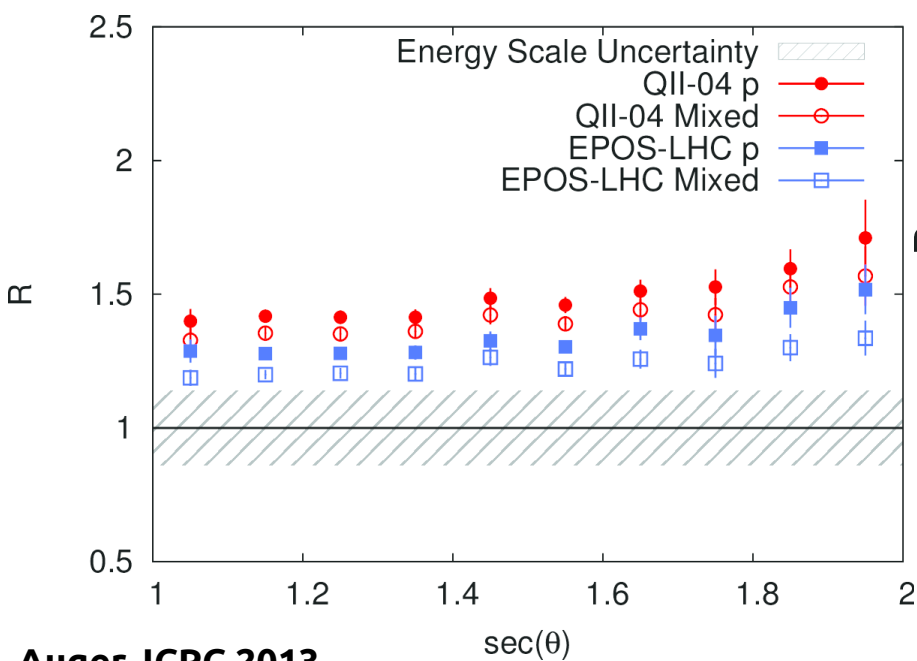# Cross section proton-proton
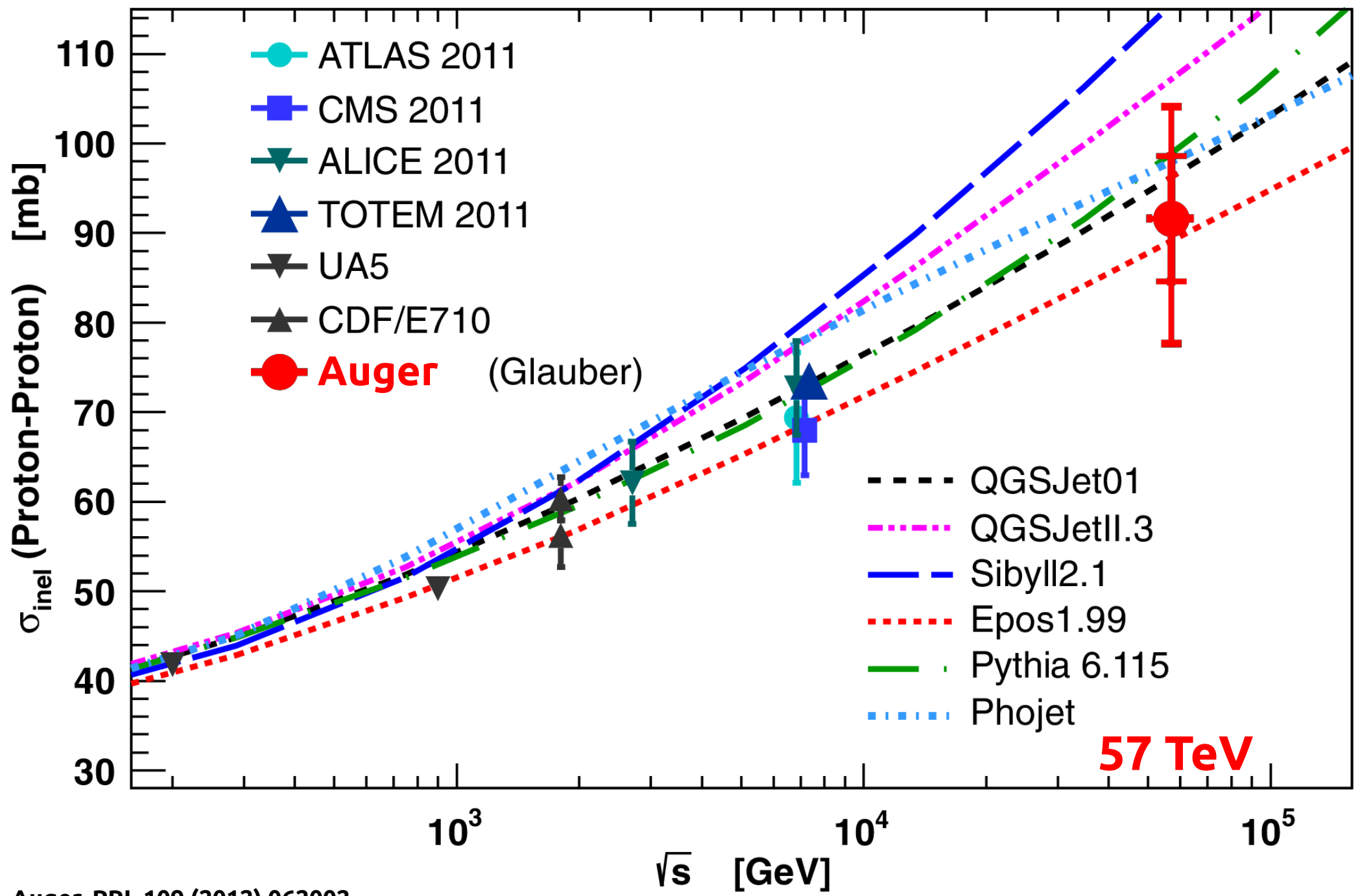
Depth of maximum X_{max}
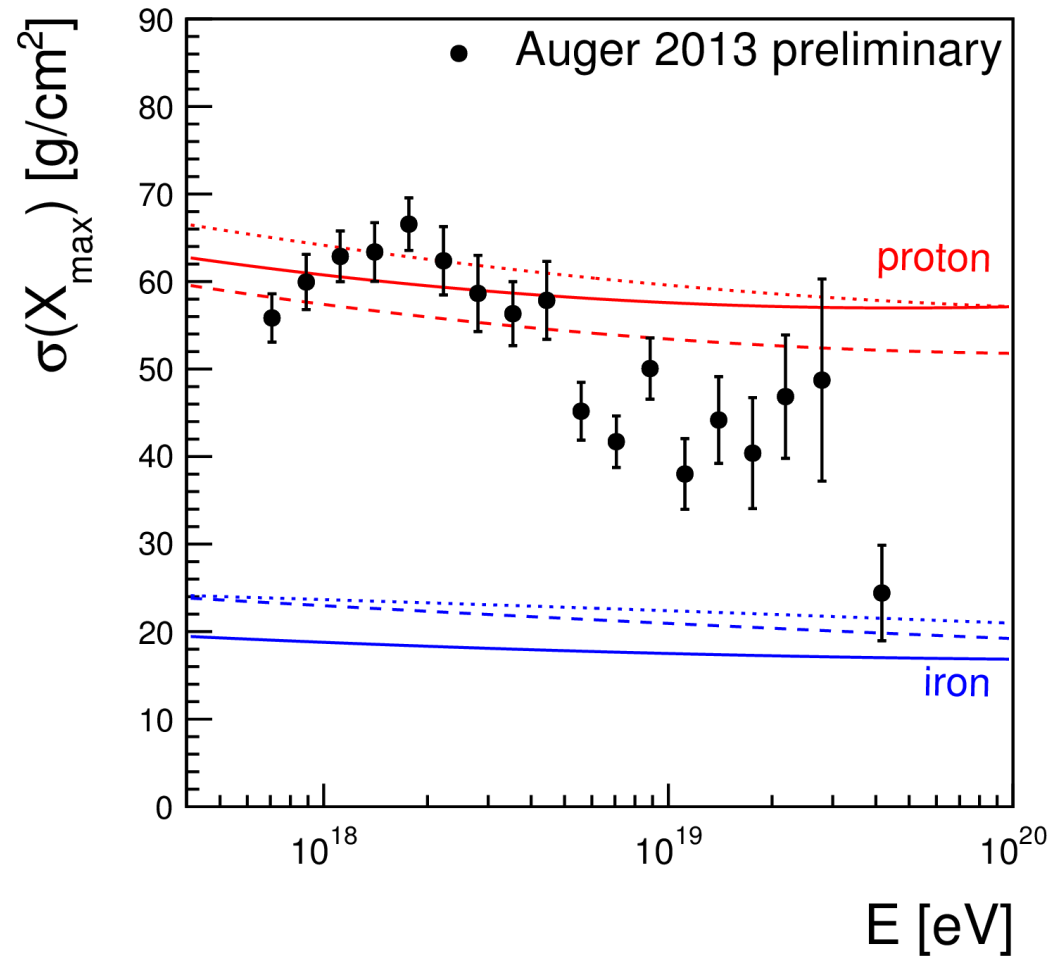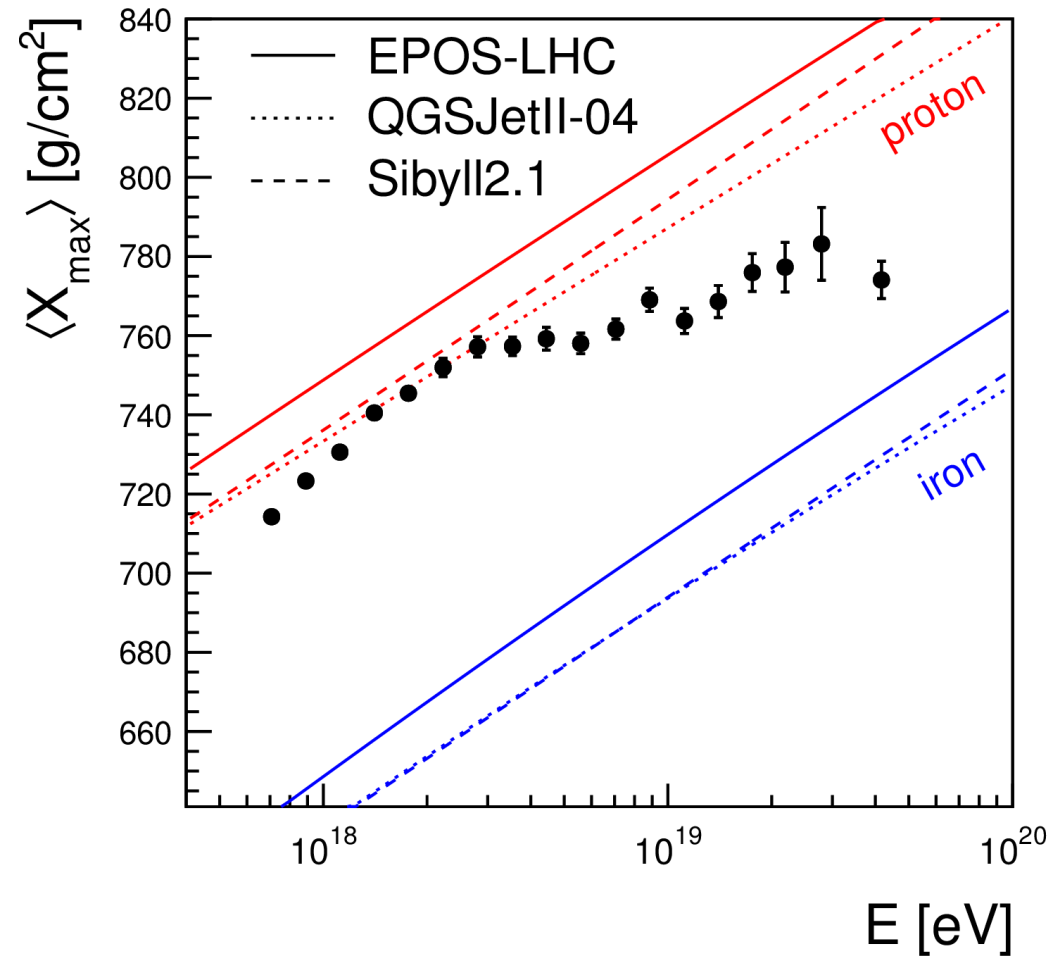
transition to heavy
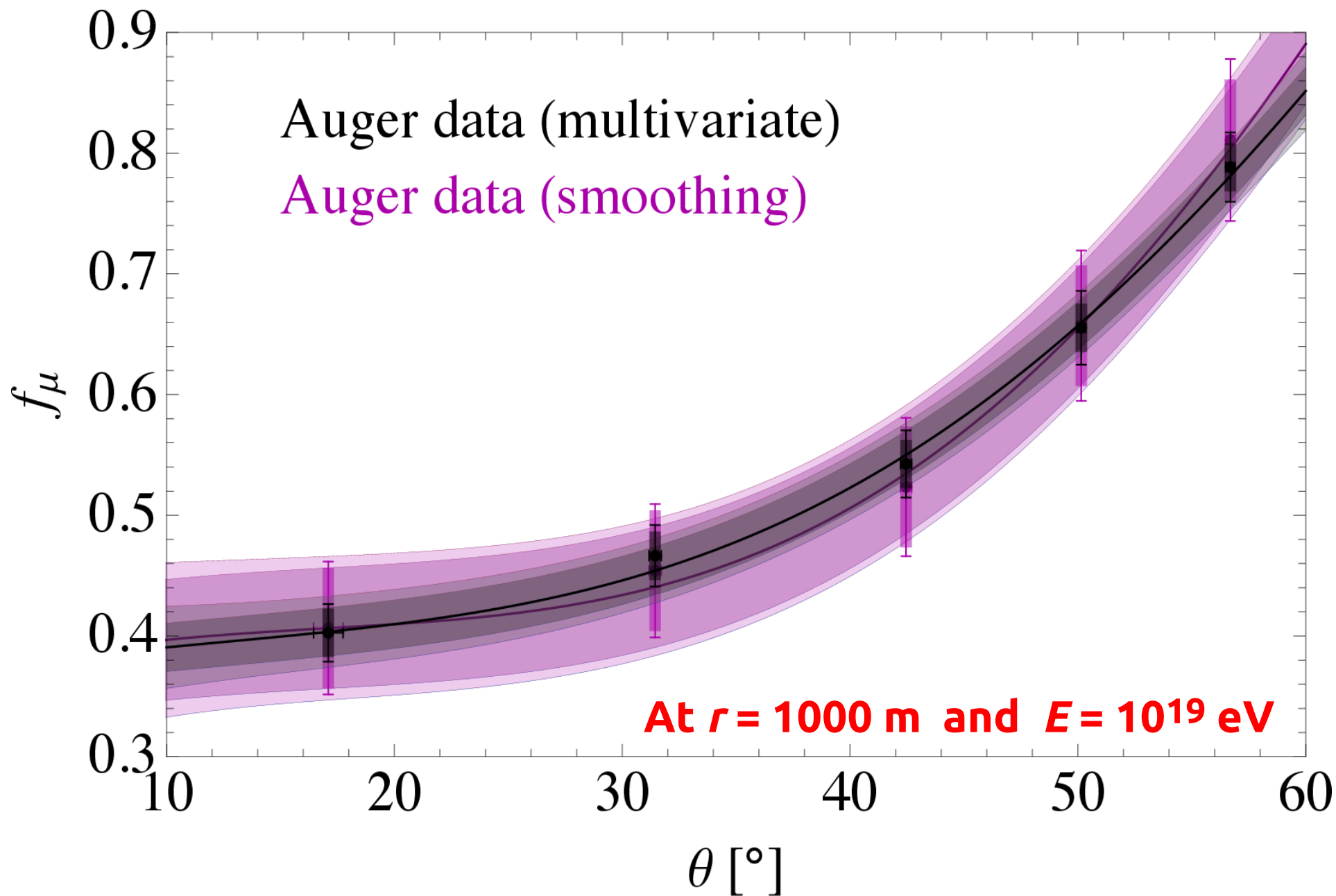and/or change in hadronic interactions?

Auger, ICRC 2013

Top-down analysis

- For each event: find simulation matching FD profile
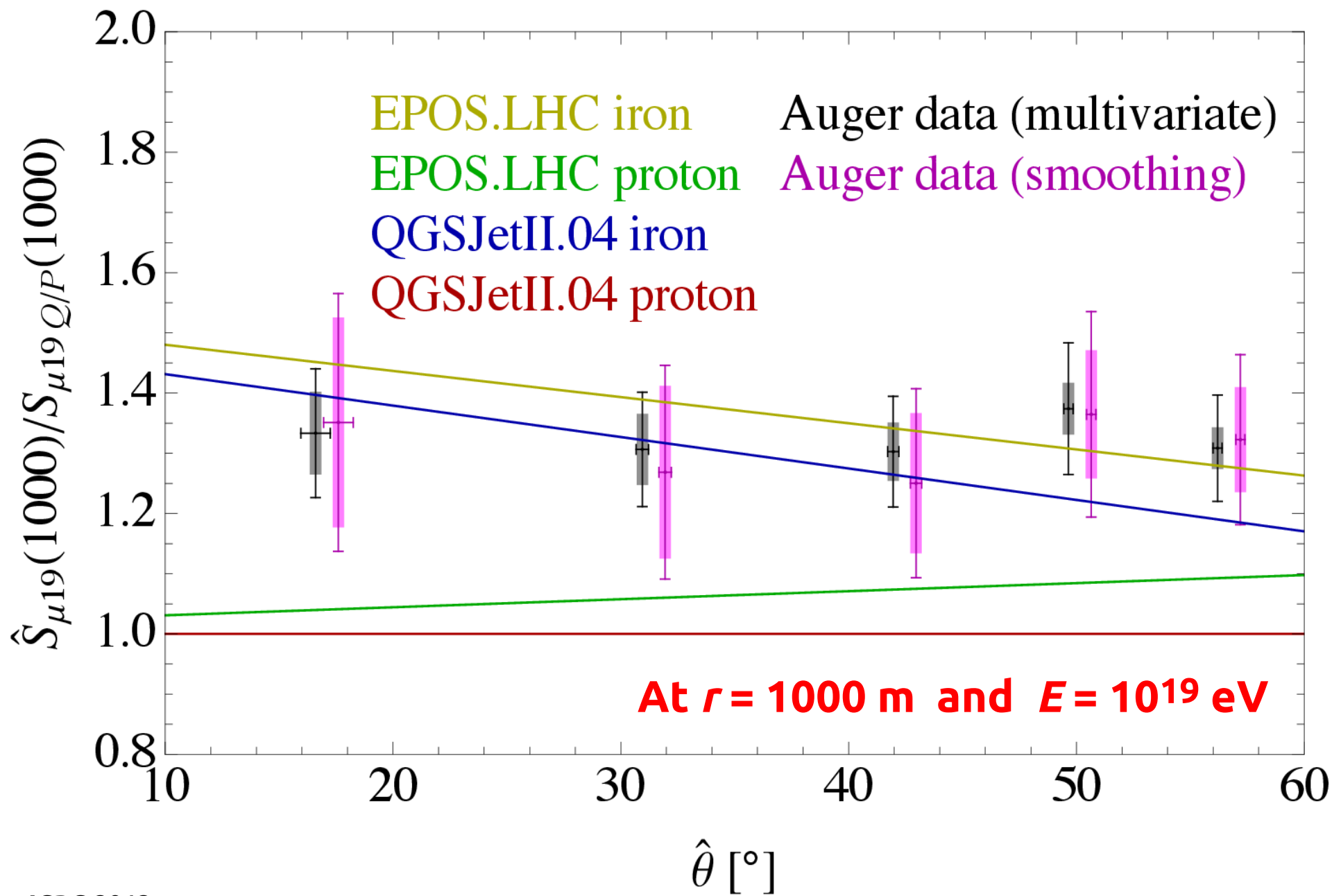- Rescale energy and muon content of simulated showers to match SD signal

$$S_{\mathrm{resc}}(R_E, R_\mu)_{i,j} \equiv$$
$$R_E\, S_{\mathrm{EM},i,j} + R_E^\alpha\, R_\mu\, S_{\mu,i,j}$$

Auger, ICRC 2013

Muons from signal structure

Auger data (multivariate)
Auger data (smoothing)

At $r = 1000$ m and $E = 10^{19}$ eV

Muons from signal structure

Inclined showers

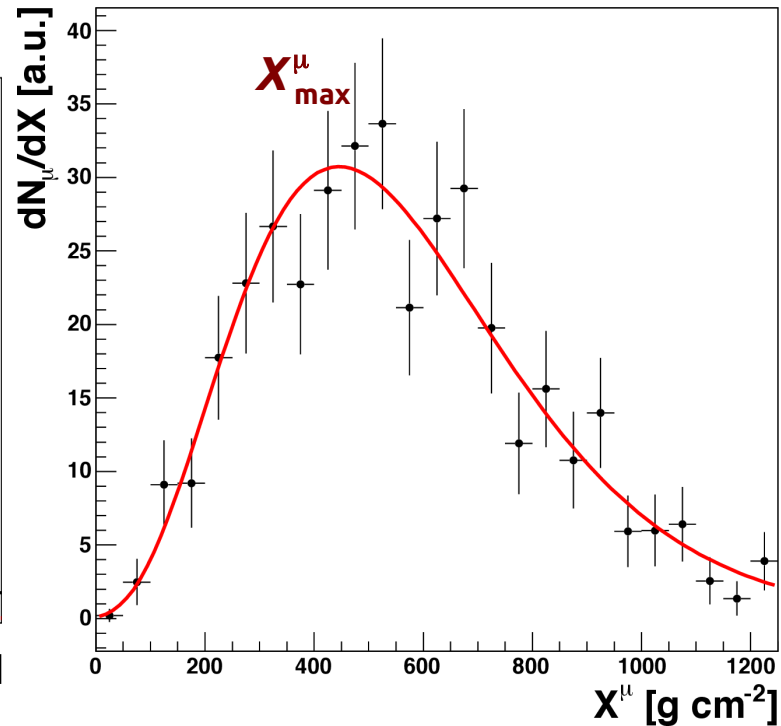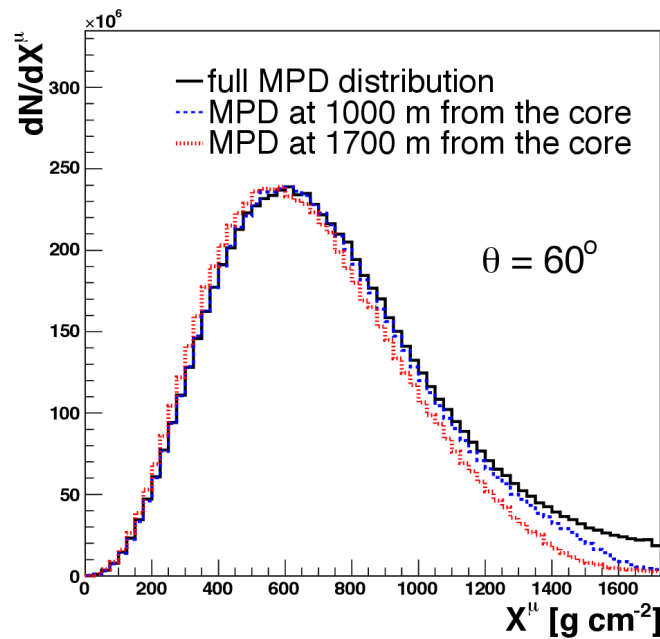θ = (63.5±0.1)°
φ = (294.8±0.1)°
E = (3.1±0.2) x 10^19 eV

QGSJetII-03

Data: $R_\mu = (1.84 \pm 0.03) (E/10^{19}eV)^{(1.03 \pm 0.02)}$

• 174 events

MC predictions

— p QGSJetII-03
— p QGSJetII-04
···· p EPOS LHC
— Fe QGSJetII-03
— Fe QGSJetII-04
···· Fe EPOS LHC
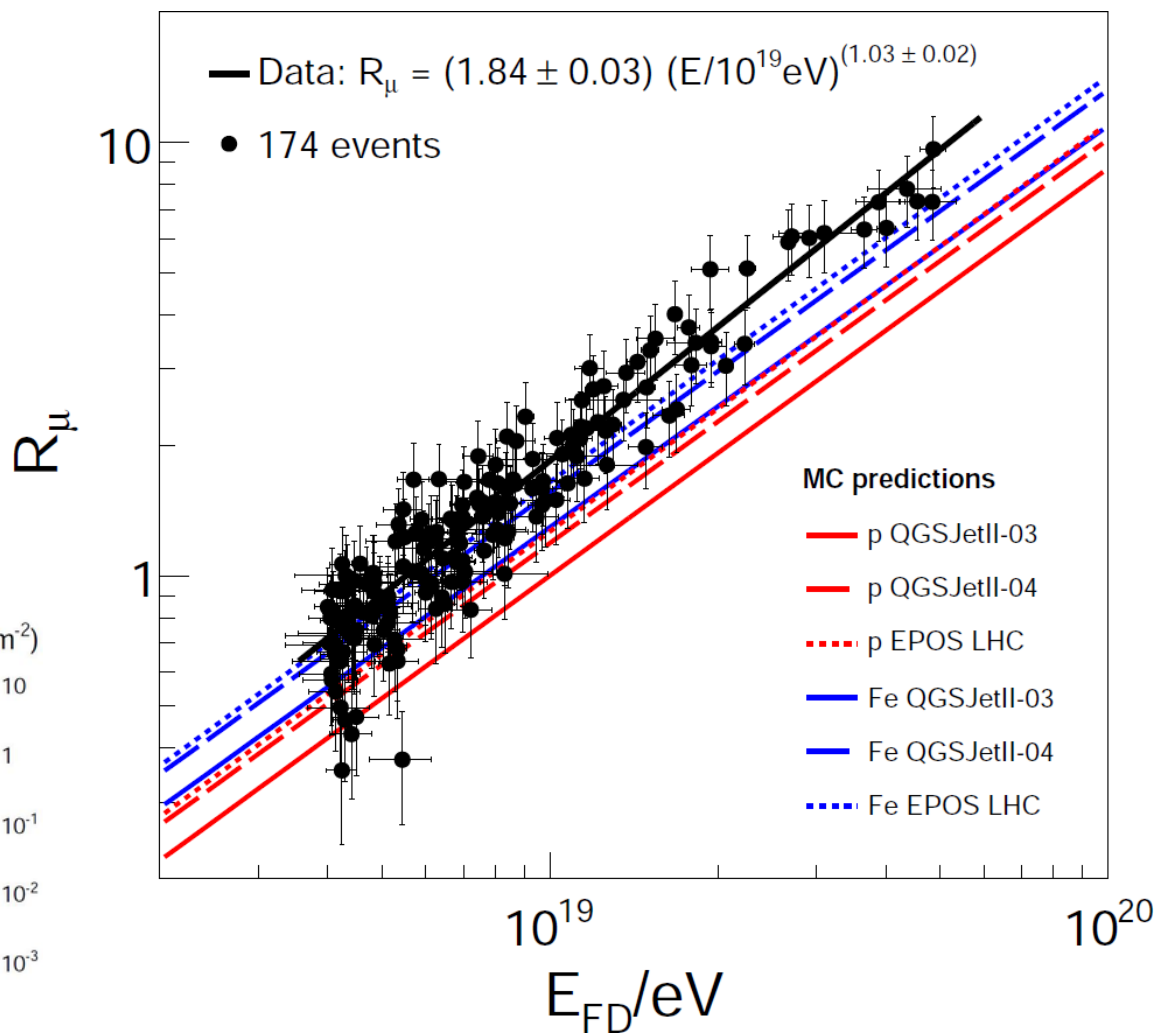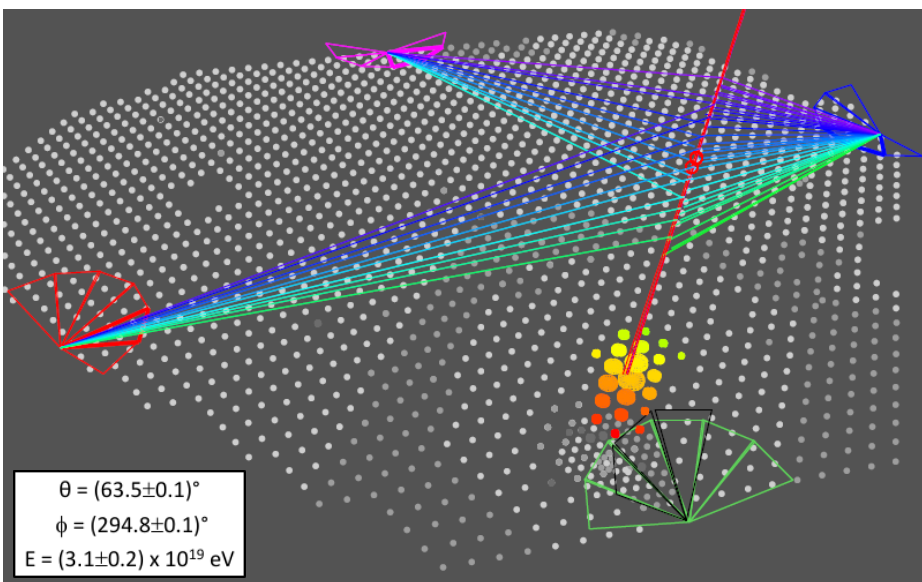
Auger, ICRC 2013
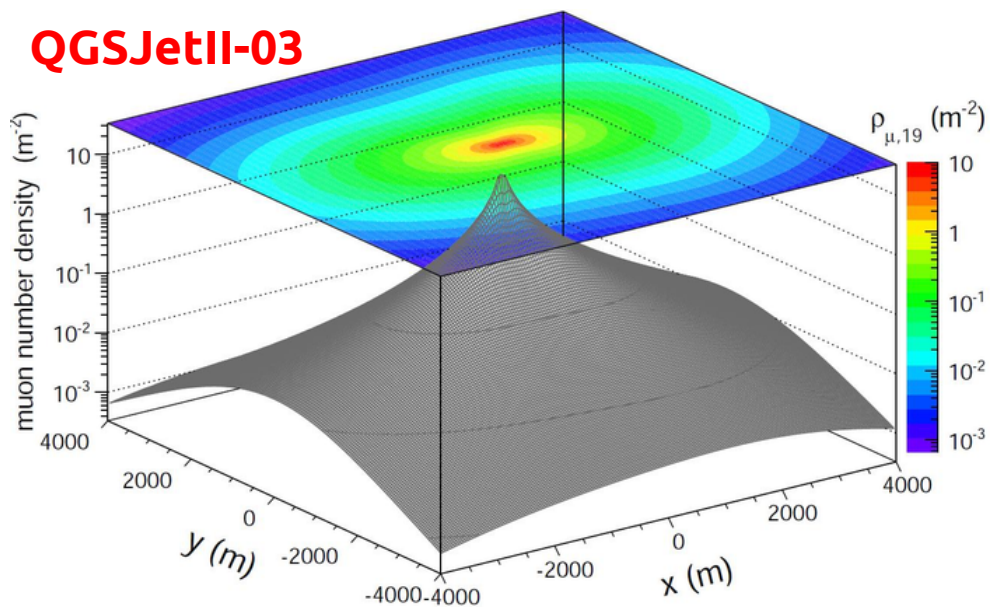
Inclined showers: muon ratio

Auger, ICRC 2013
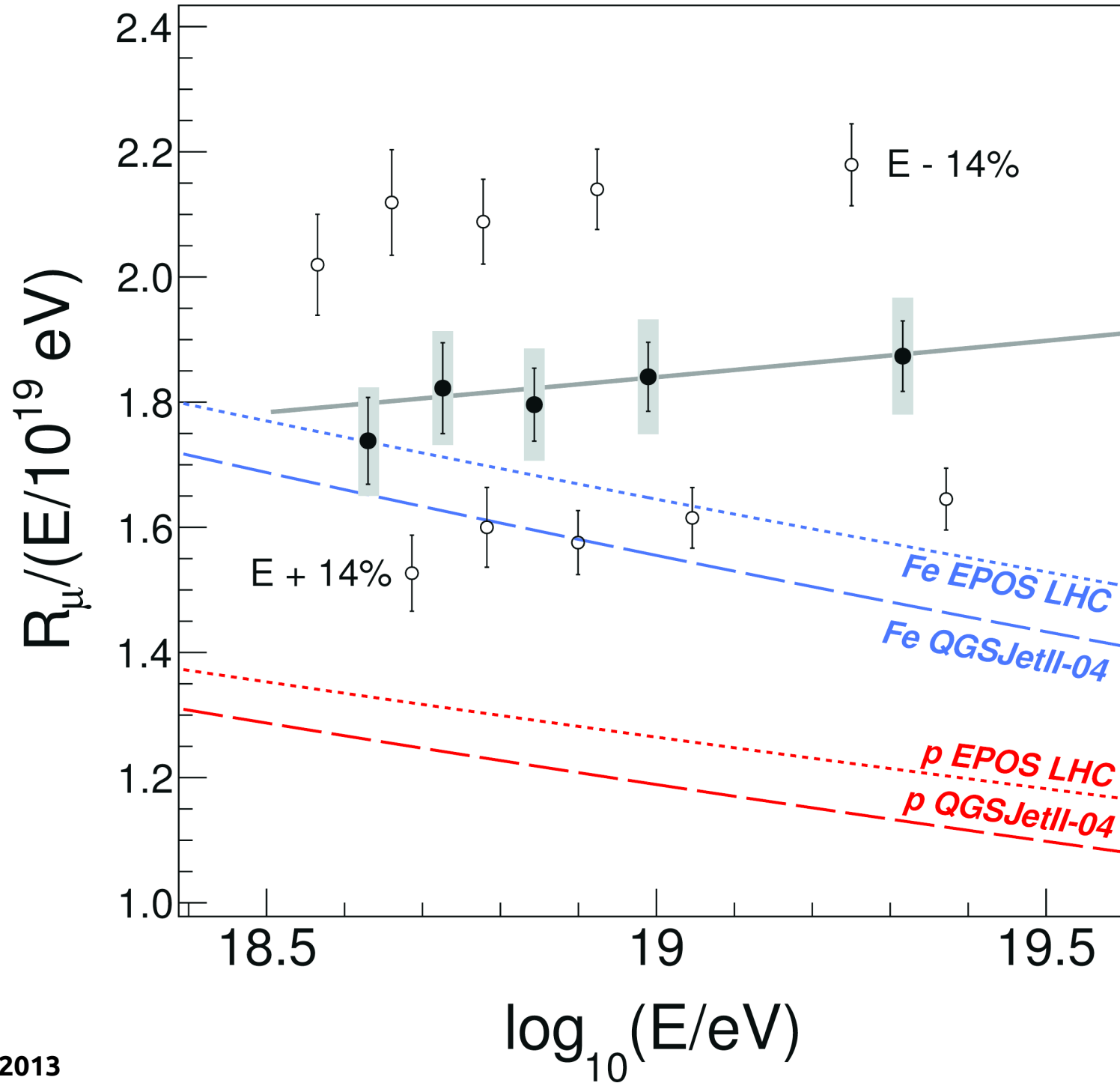
Muon production depth

Auger, ICRC 2013
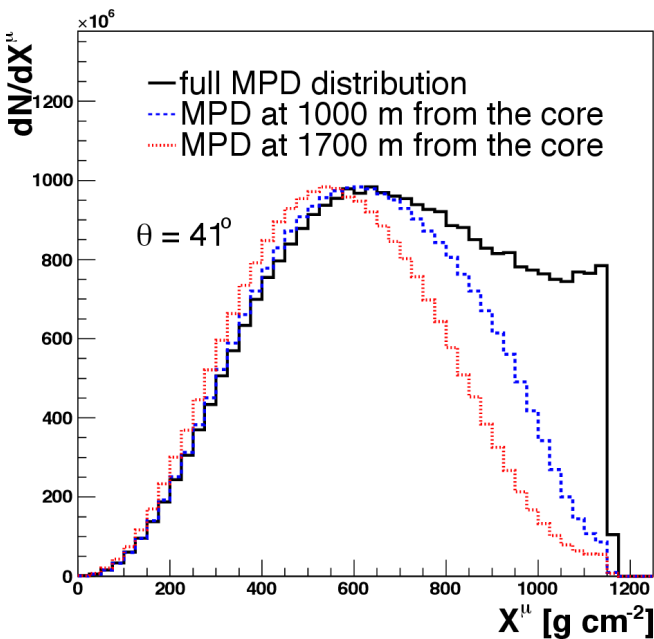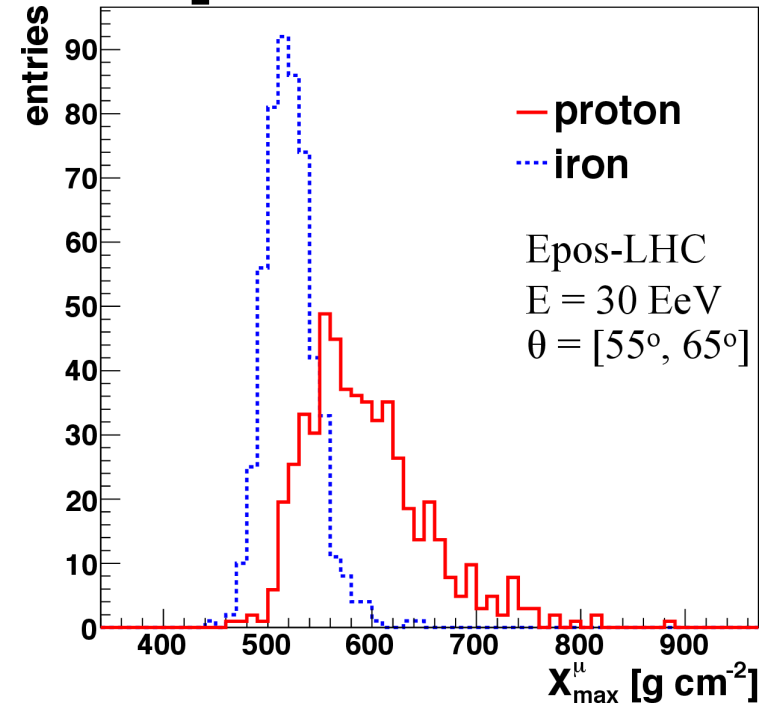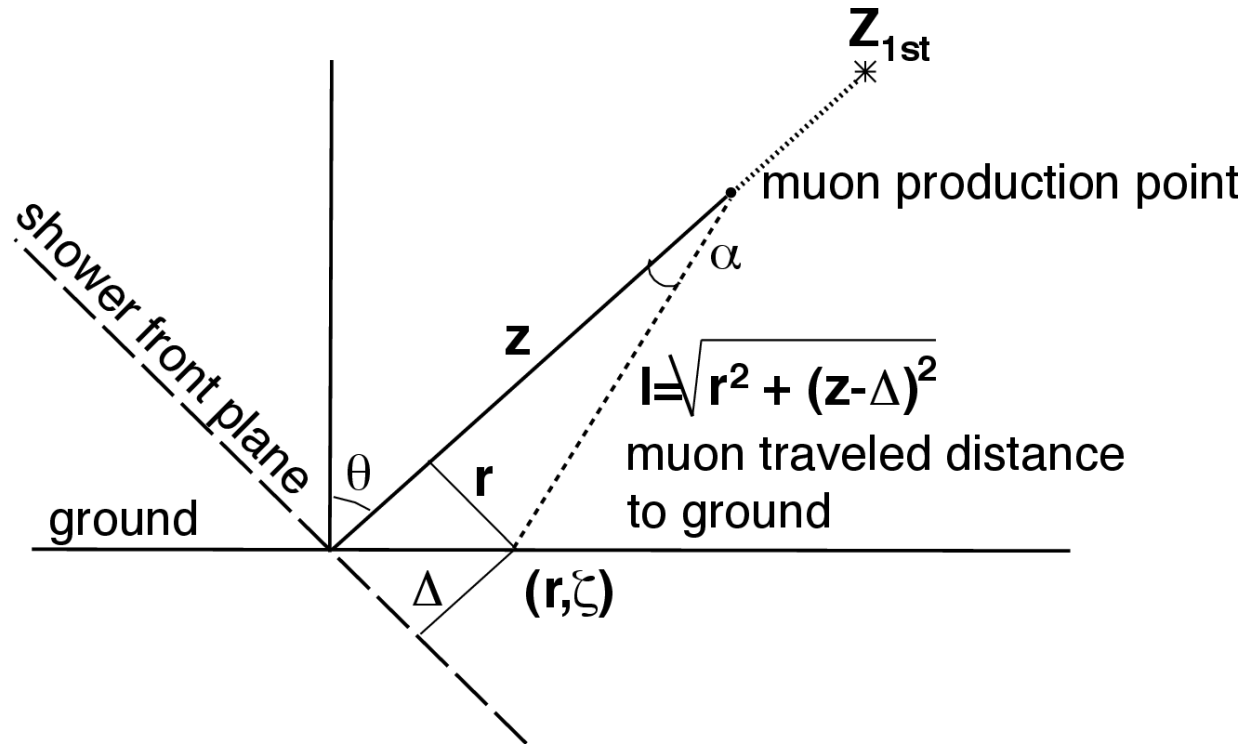
Muon production maximum

Auger, ICRC 2013
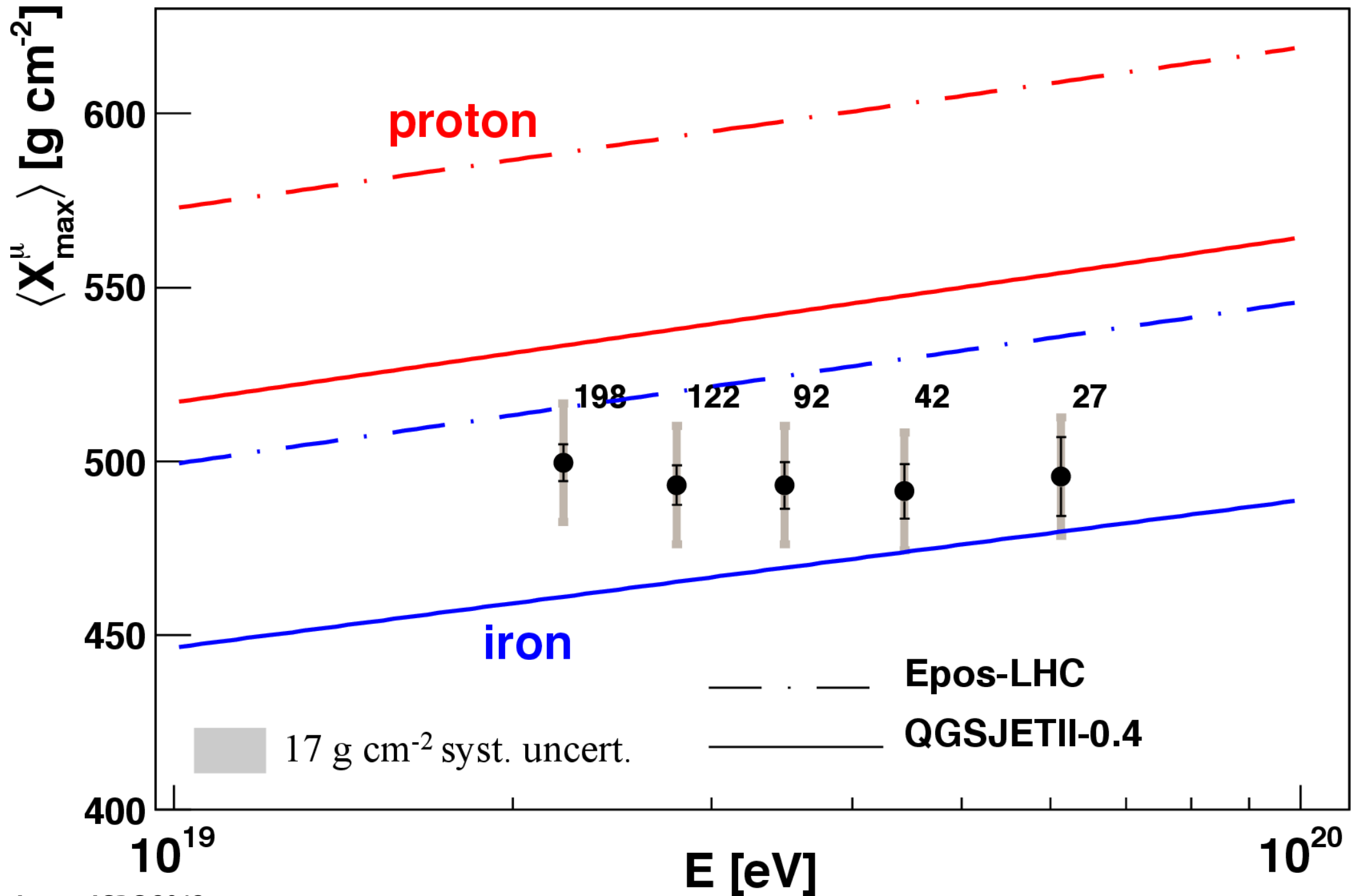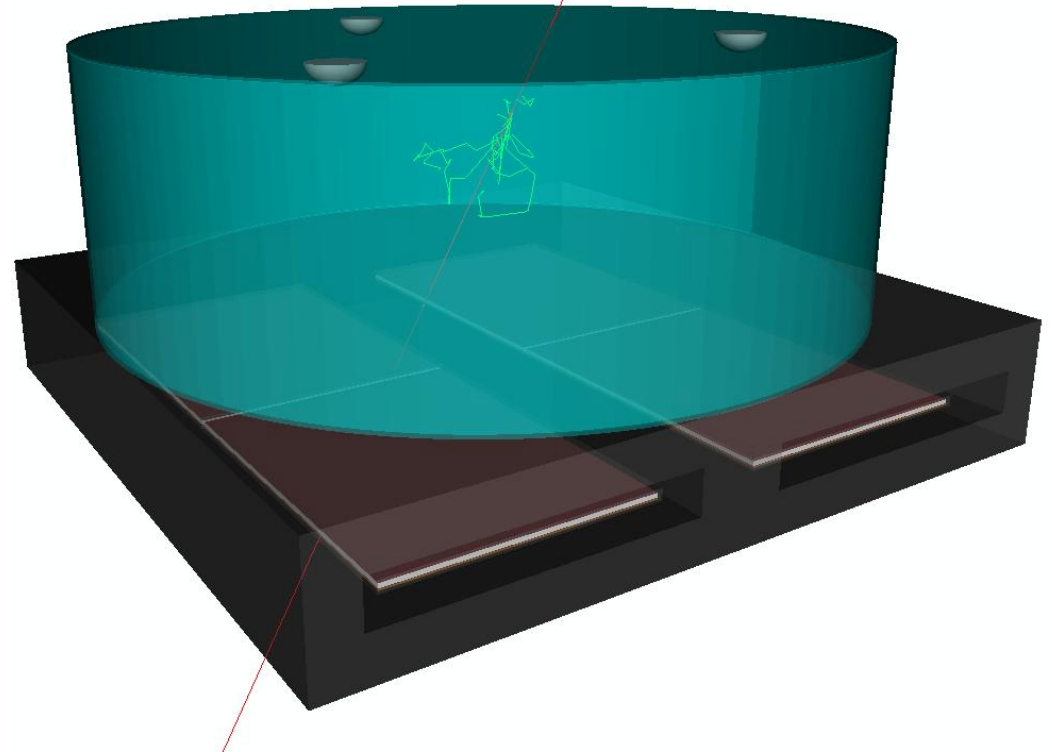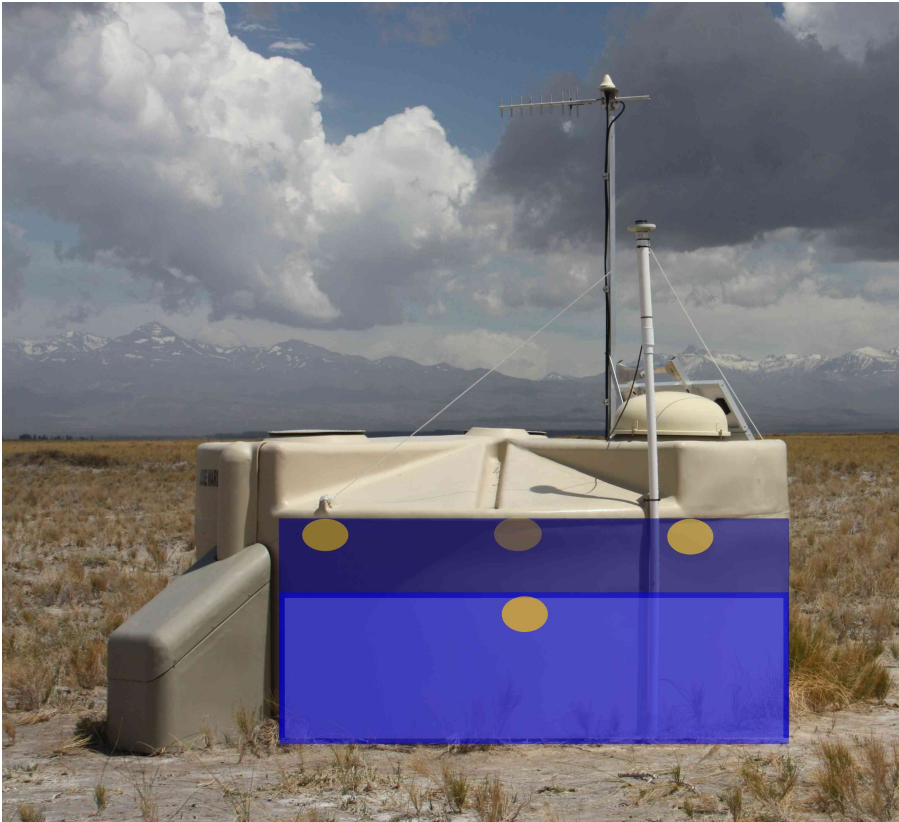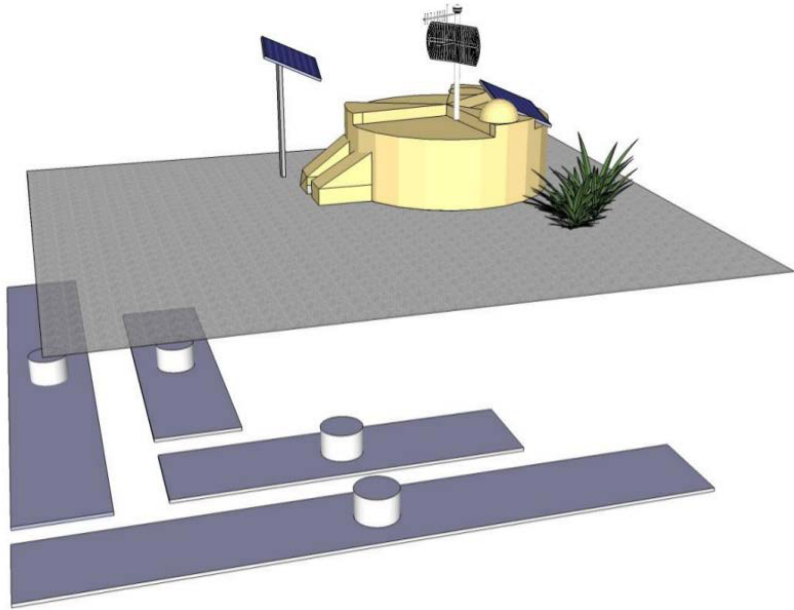
Future

LHC → models

R&D on upgrades:
ev.-to-event composition determination
resolve spectrum, origin
charged-particle astronomy
composition-enhanced corr. Studies
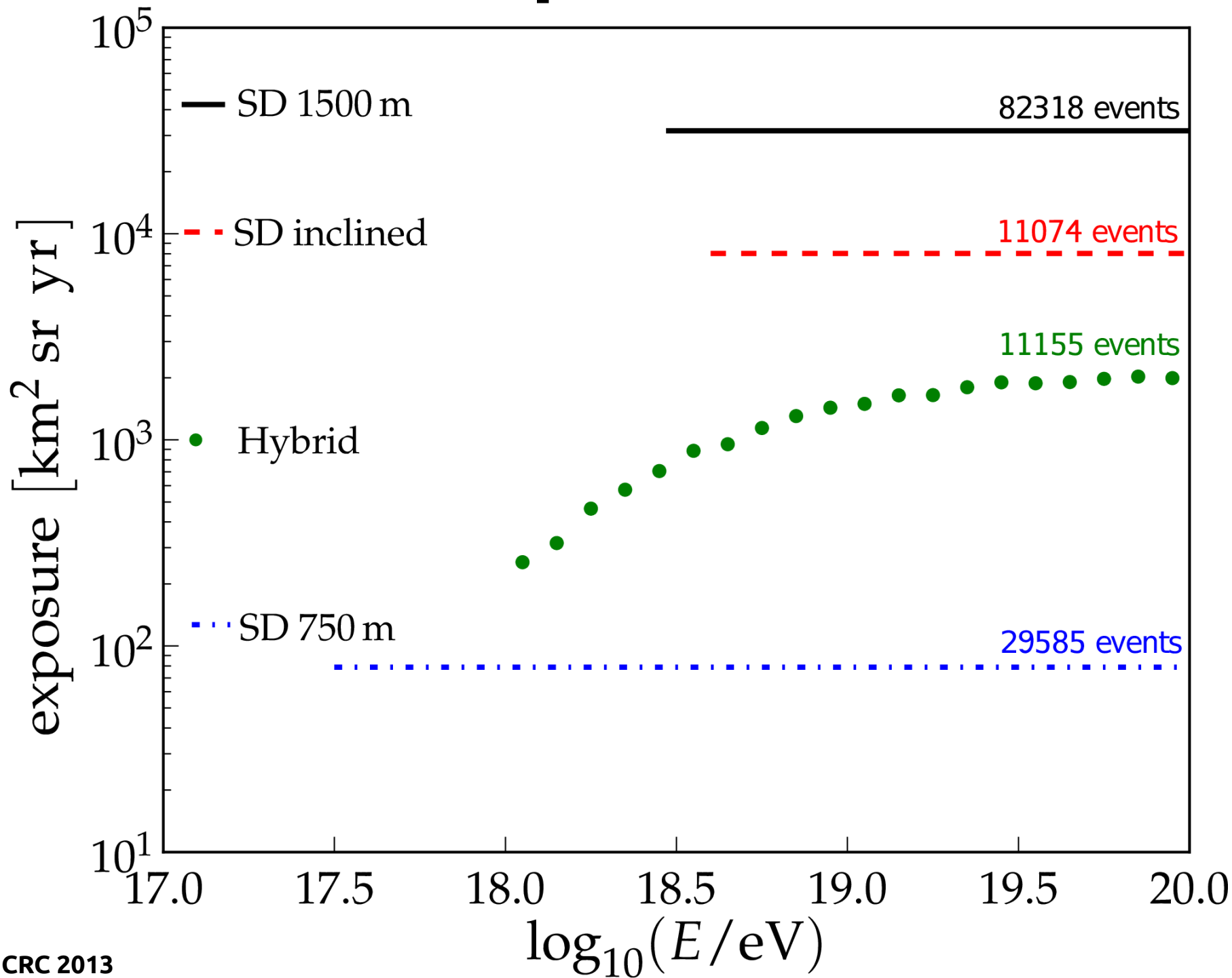extend operation to 2024

Thank you!

Pierre Auger Collaboration
550 scientists, technicians, students
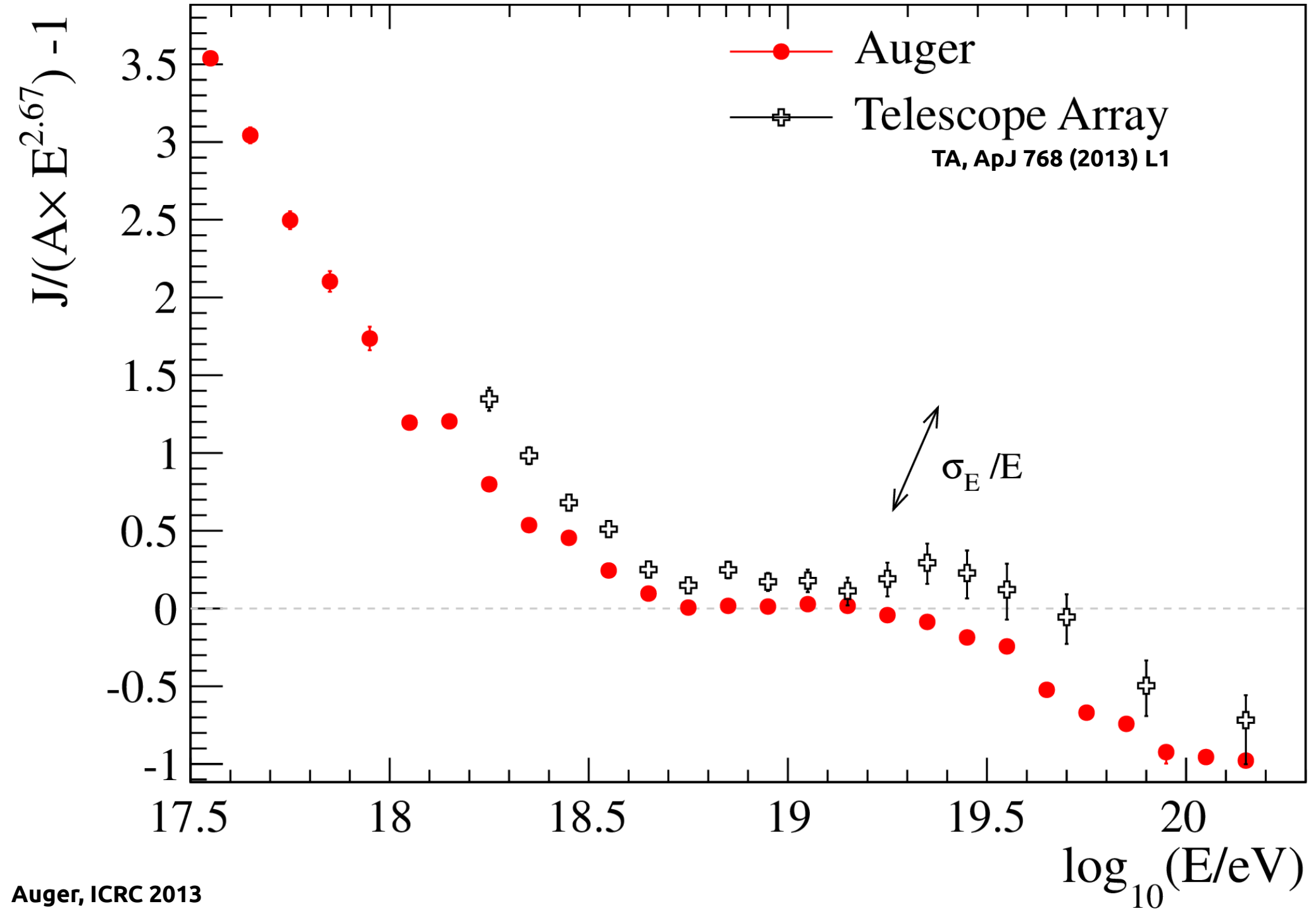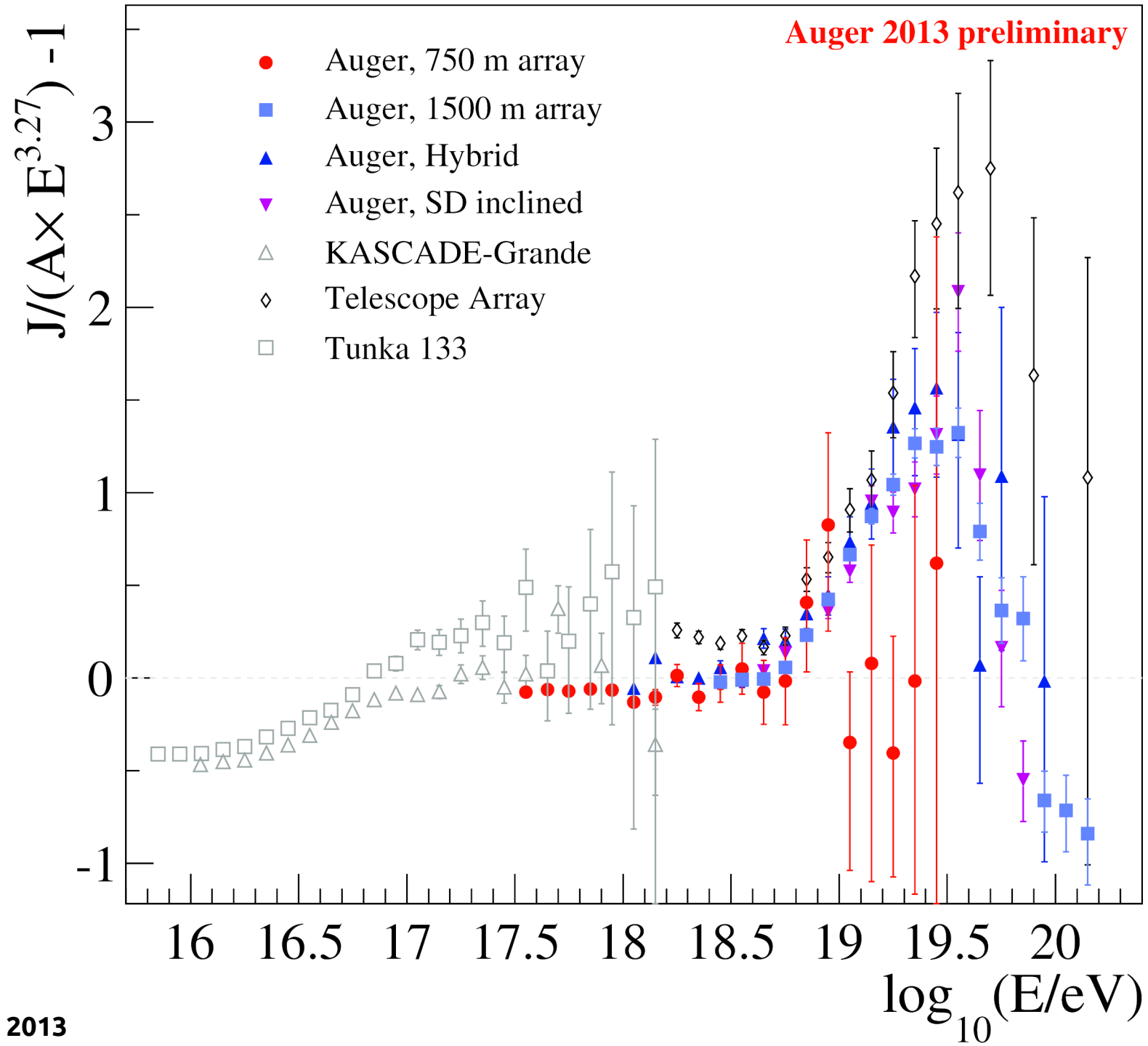**94 institutions**
19 countries

backup slides

Exposure

Auger, ICRC 2013

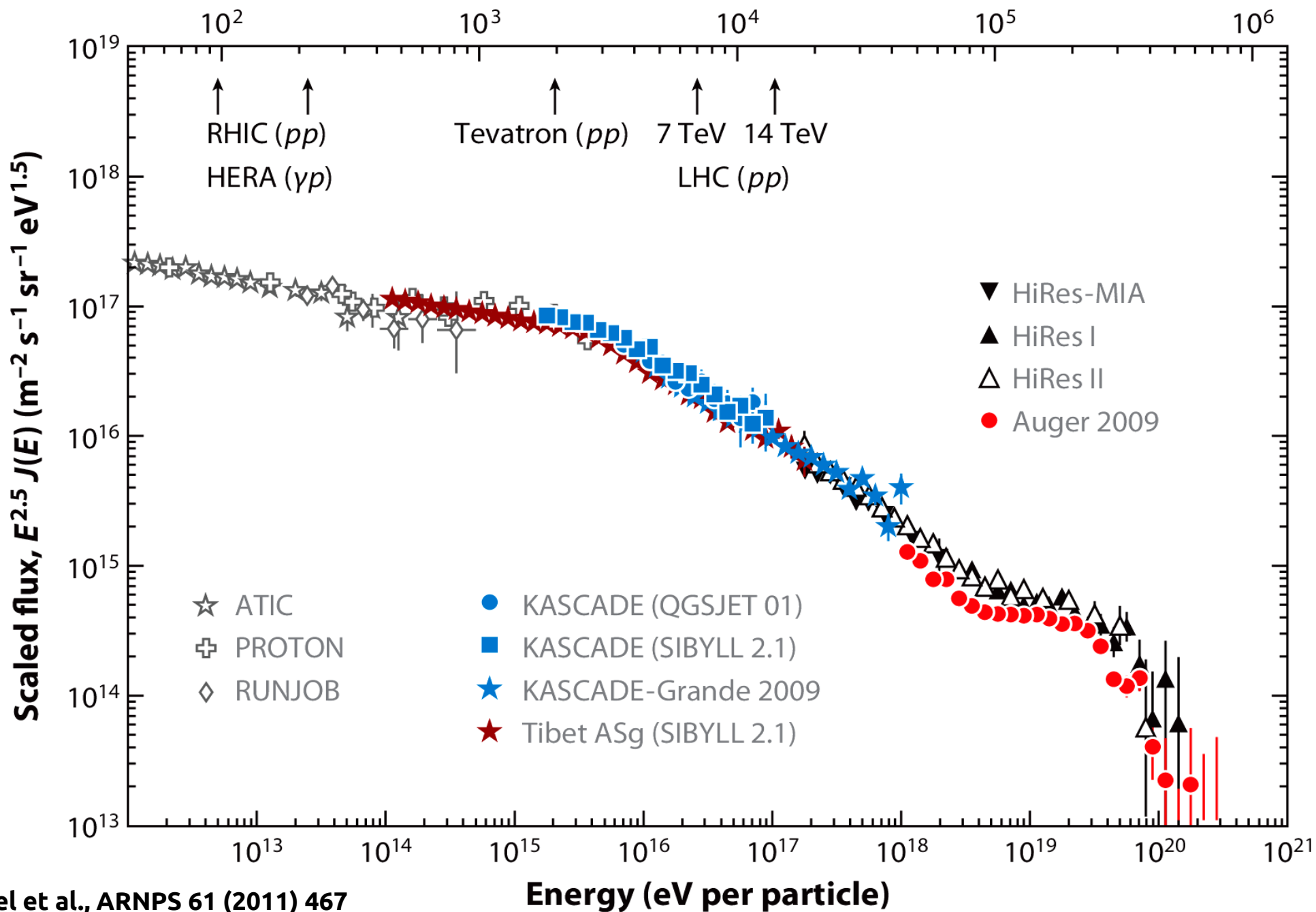# Auger + Telescope Array

Auger + more

Auger, ICRC 2013

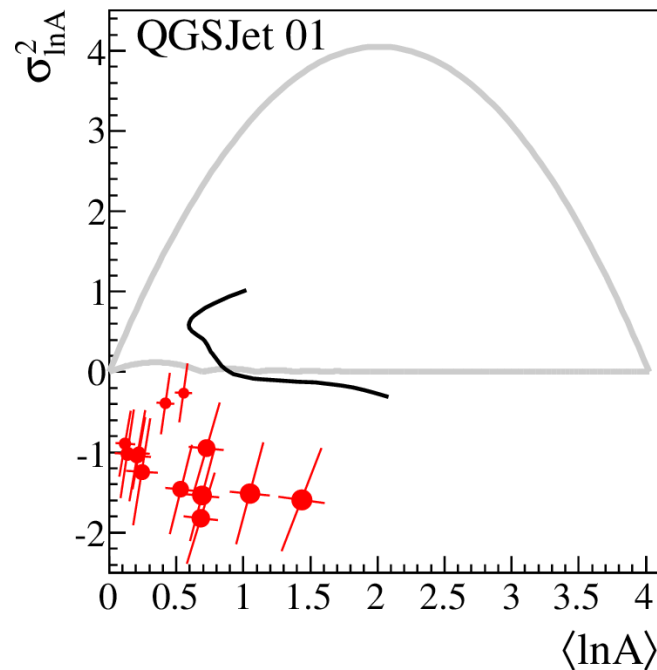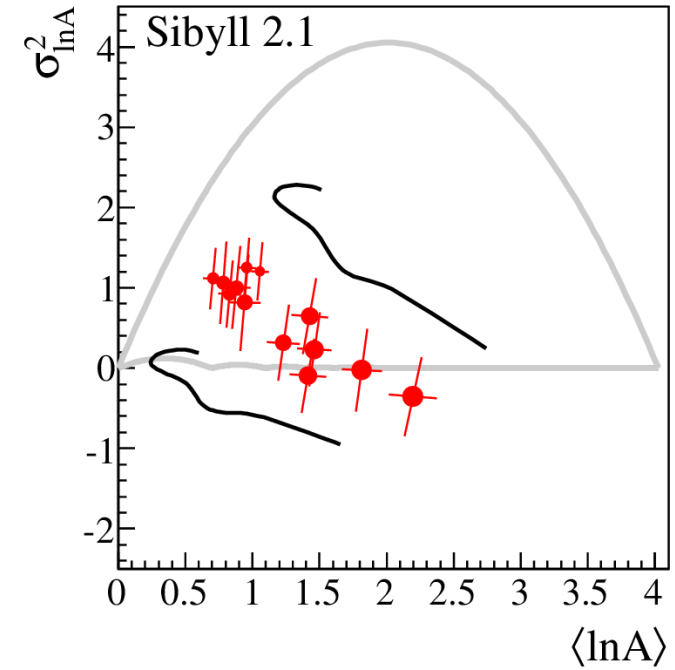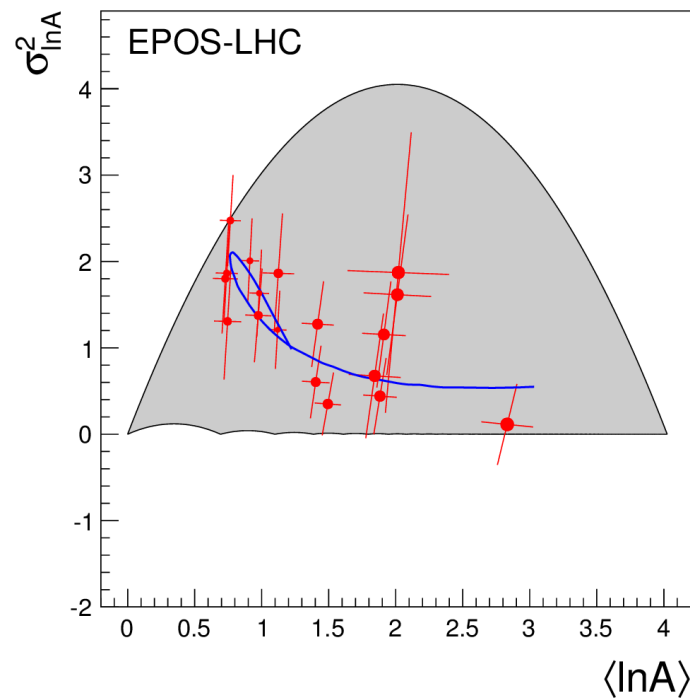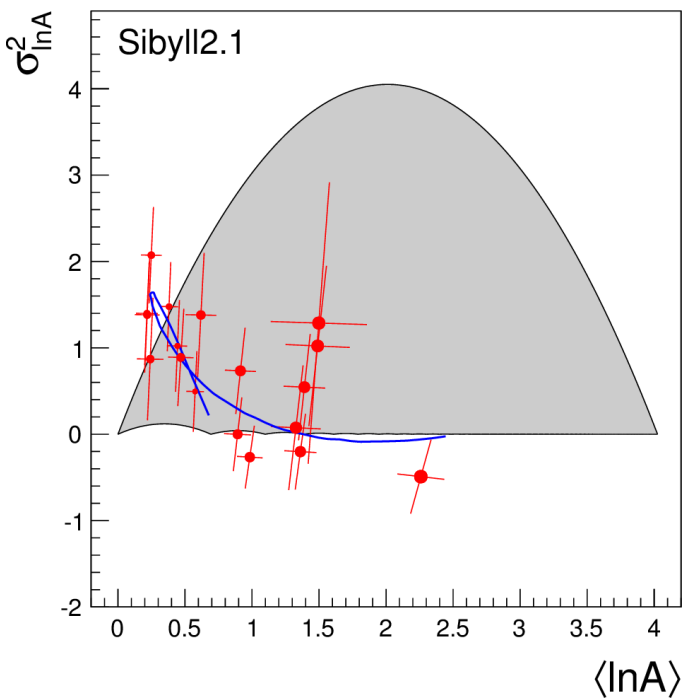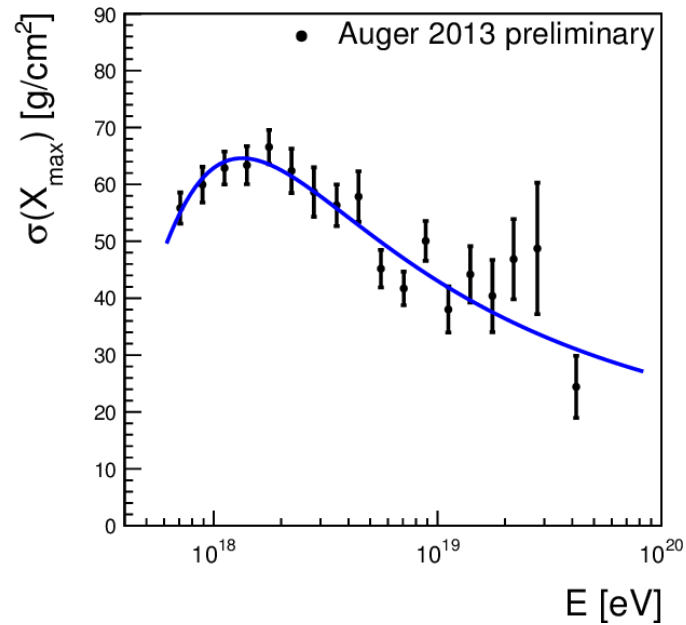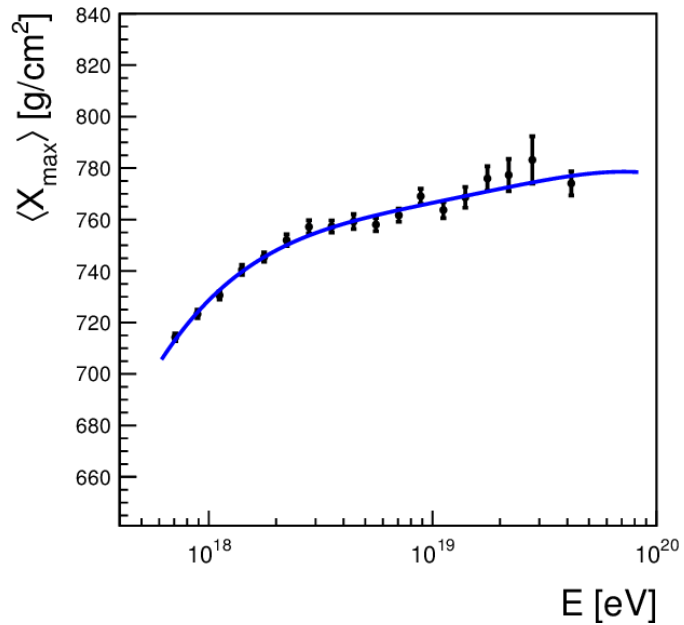# Auger + more

Mass interpretation

$$\langle \ln A \rangle = \frac{\langle X_{\max} \rangle - \langle X_{\max} \rangle_p}{f_E}$$

$$\sigma^2_{\ln A} = \frac{\sigma^2(X_{\max}) - \sigma^2_{\mathrm{sh}}(\langle \ln A \rangle)}{b\, \sigma^2_p + f^2_E}$$
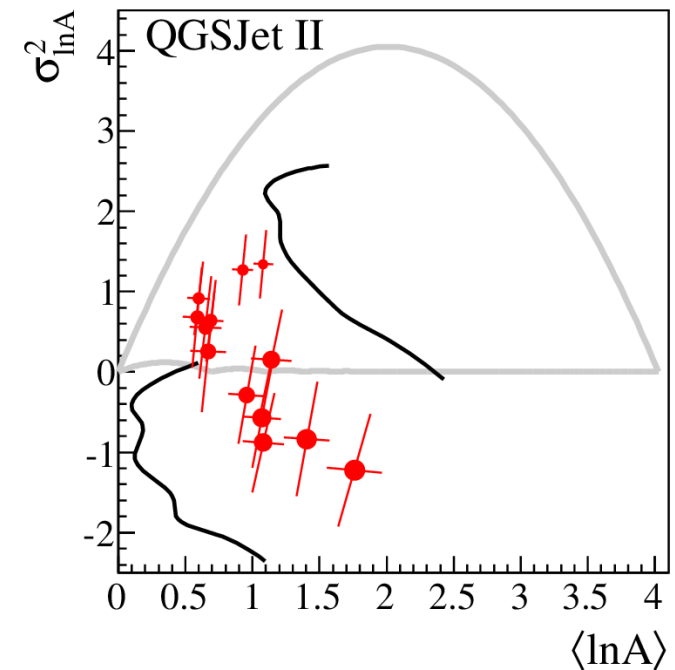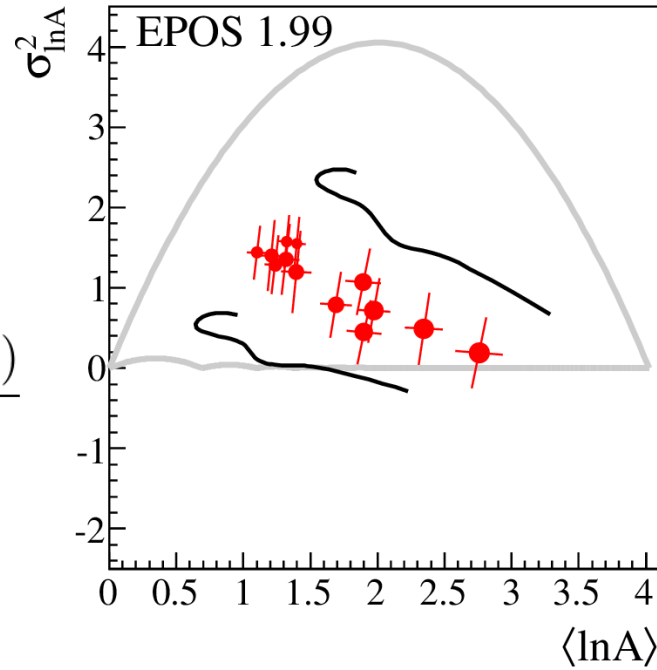
Mass interpretation, 2013

Mass interpretation

Engel *et al.*, ARNPS 61 (2011) 467