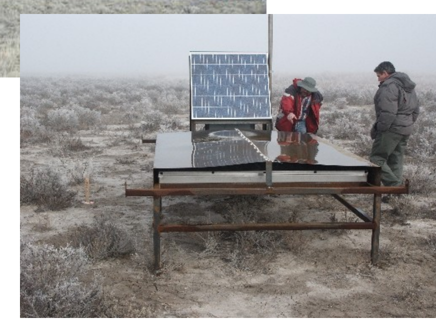
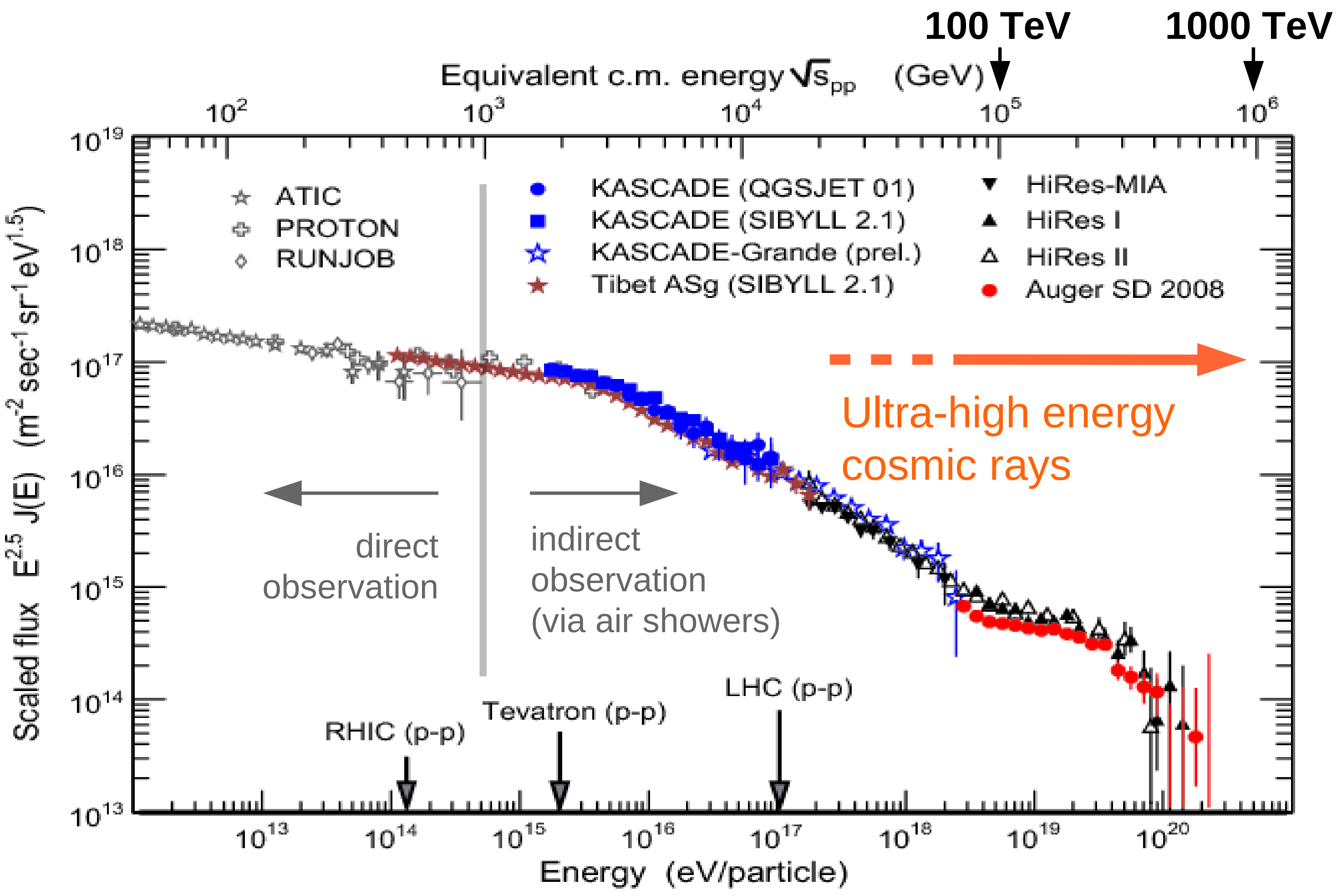
Karlsruhe Institute of Technology

Recent measurements of ultra-high energy cosmic rays and their impact on hadronic interaction modeling

Hans Dembinski
KIT Karlsruhe



Outline



100 TeV
1000 TeV
Equivalent c.m. energy $\sqrt{s}_{pp}$ (GeV)
10^2
10^3
10^4
10^5
10^6
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande (prel.)
Tibet ASg (SIBYLL 2.1)
HiRes-MIA
HiRes I
HiRes II
Auger SD 2008
Ultra-high energy cosmic rays
direct observation
indirect observation (via air showers)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)
Scaled flux $E^{2.5}$ J(E) ($m^{-2}sec^{-1}sr^{-1}eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV/particle)

Outline

Introduction and experiments

Energy spectrum

X_{max} and other mass-sensitive observables

Limits on photons/neutrinos

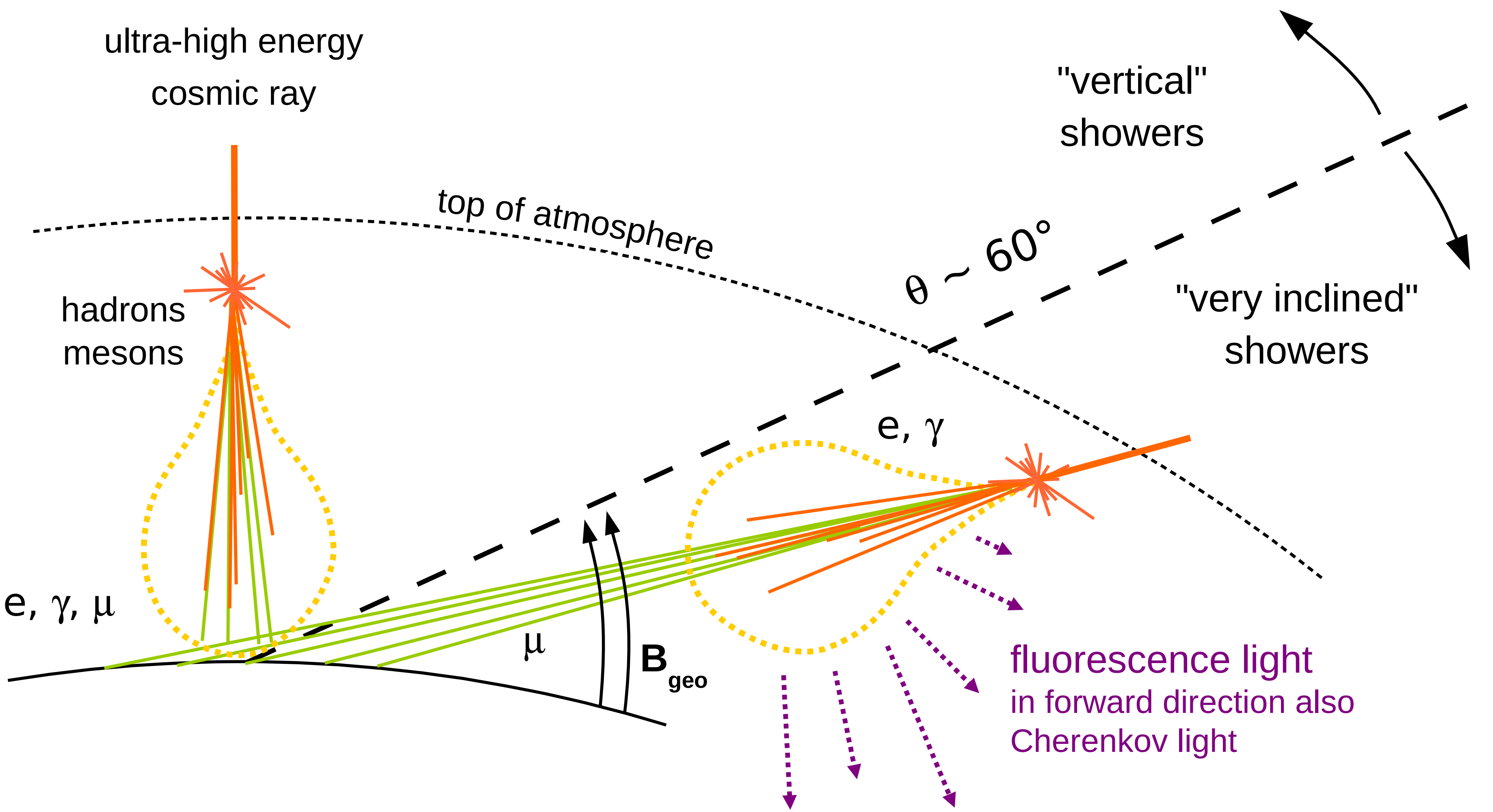
p-air cross-section

Muon number

Hadronic interaction properties $\leftrightarrow$ air shower observables

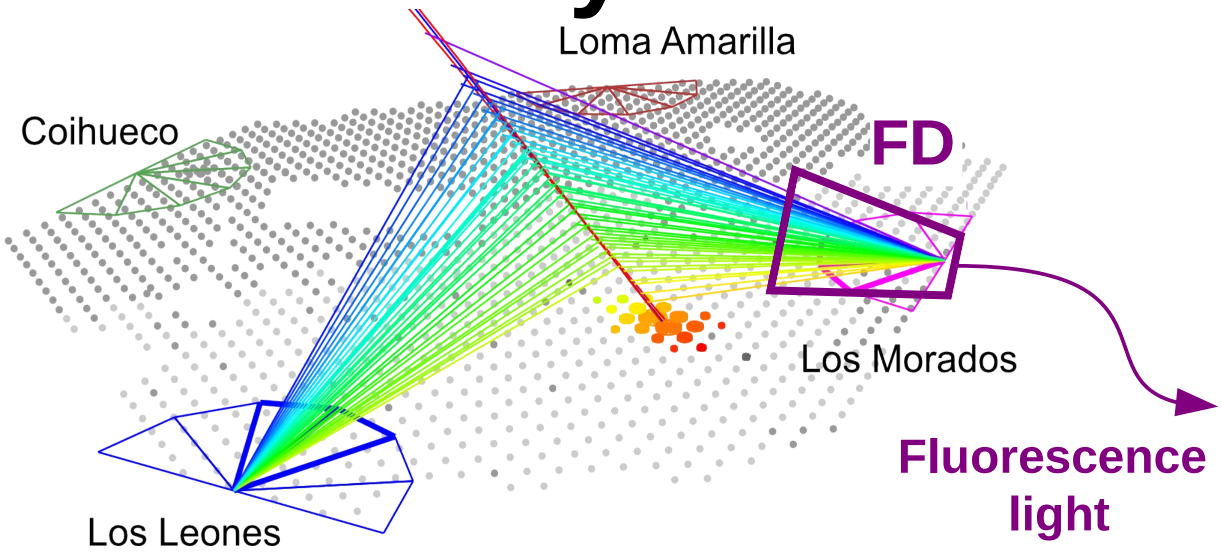
Bottom line:
Air shower experiments **can** be used to **indirectly** measure
p-air cross-section, elasticity, multiplicity at E > 50 TeV –
but in a highly model dependent way.

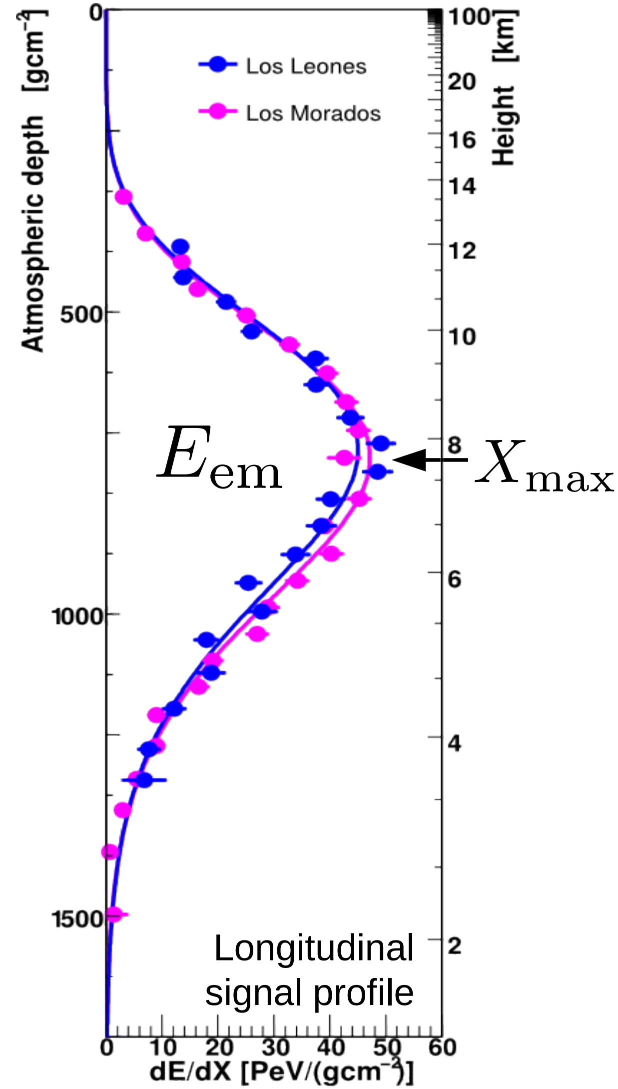
Air showers



ultra-high energy
cosmic ray
top of atmosphere
"vertical"
showers
θ ~ 60°
"very inclined"
showers
hadrons
mesons
e, γ
e, γ, μ
μ
B geo
fluorescence light
in forward direction also
Cherenkov light

Cosmic ray measurement





$$\frac{dN_{\gamma,fl}}{dx} \propto \frac{dE_{\rm em}}{dx}$$ Fluorescence yield measured in lab

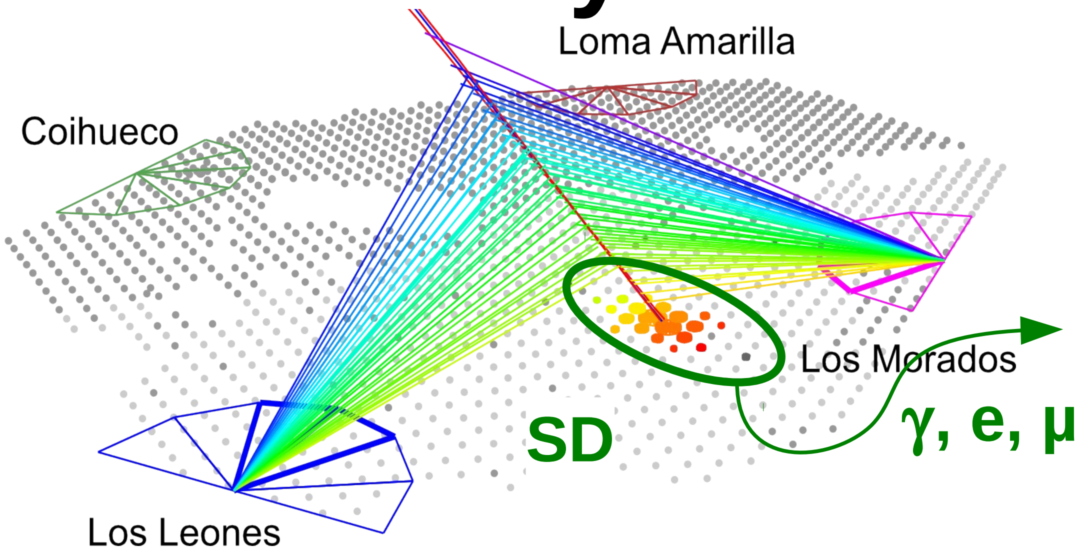
Integrate $dE_{\rm em}/dx$ to get energy E_{em}

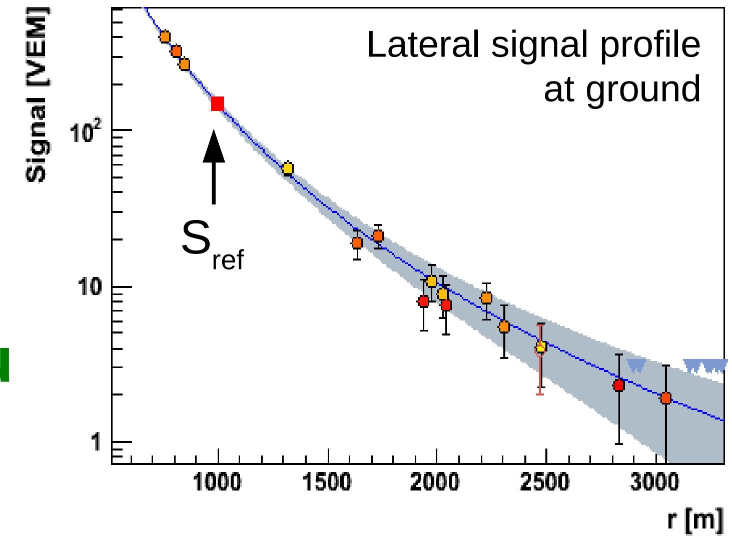
μ and ν are invisible

$$\mathrm{E}_{\rm em} = E - E_{\rm inv} \approx 0.9E$$

weakly model dependent above 10^{18} eV

Cosmic ray measurement





SD observes only slice of shower development

SD samples lateral density profile
of e, μ, and possibly γ, depending on detector type

Very inclined showers can be observed
if detectors have "depth": measure muon component

SD cross-calibrated to FD

S_{ref} μ E
(θ < 60°)

Auger: θ > 60°
N_{19} μ N_{μ} μ E

Experiments

Experiments above 10^{18} eV

Northern Hemisphere

HiRes (aka Fly's Eye) 1981 - 1992
Telescope Array 2008 - ...
(Successor of **HiRes** and **AGASA**)

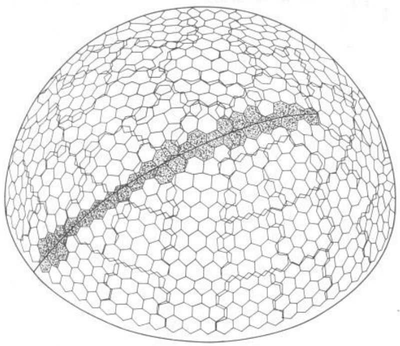
Southern Hemisphere

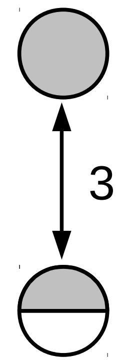
Pierre Auger Observatory 2004 - ...

Other experiments: Volcano Ranch, SUGAR, Haverah Park, Yakutsk, AGASA

HiRes (High Resolution Fly's Eye)

“Fly's Eye” formed by overlapping field of views of fluorescence telescopes





Fly's eye I
– 67 telescopes
– 360° field of view

3.4 km

Fly's eye II
– 180° field of view

Western desert of Utah, U.S.A.
1500 m asl

Monocular operation (HiRes-I)

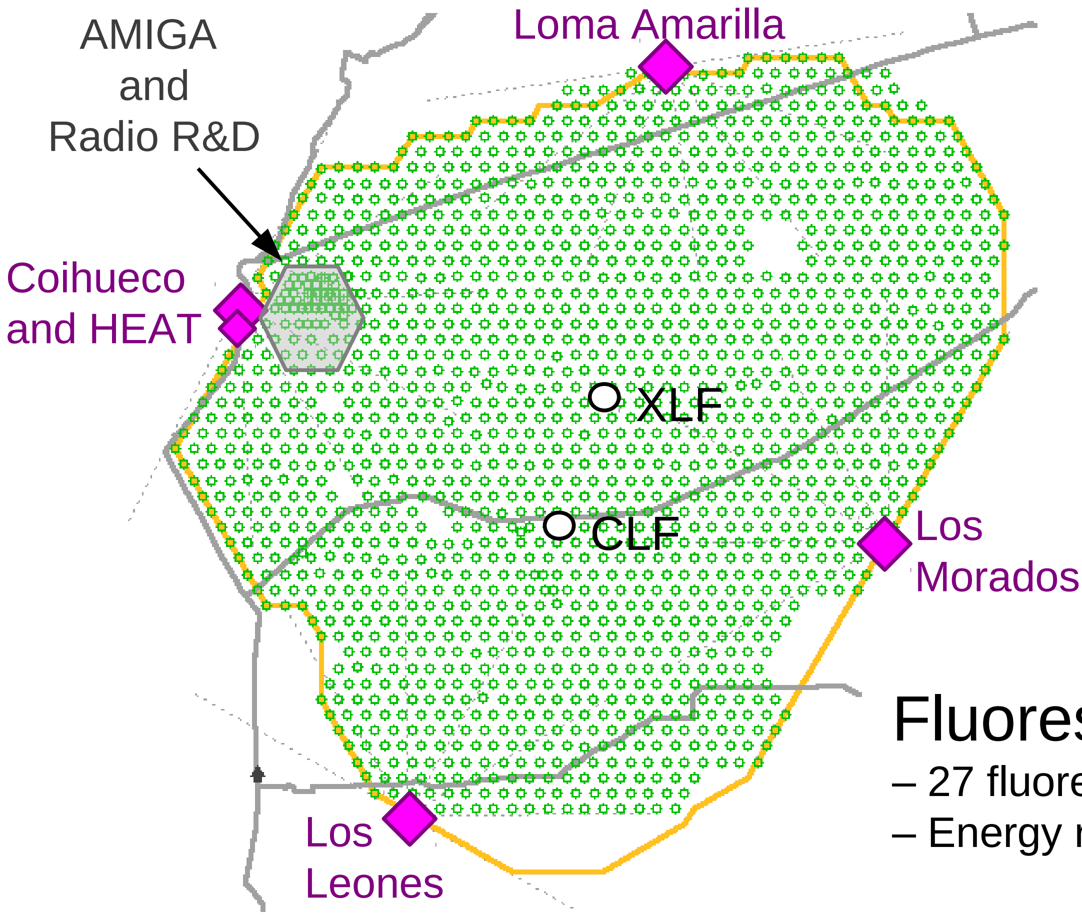
– Energy resolution ~27 %

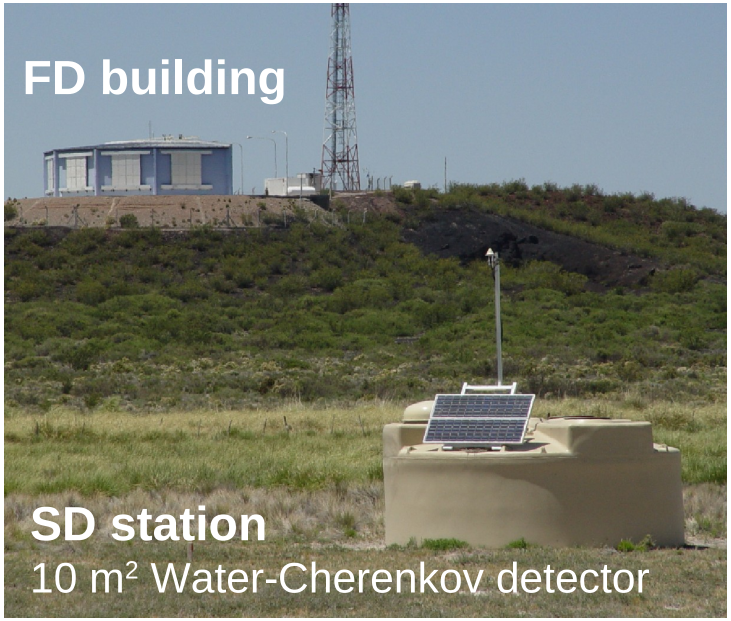
Stereo operation (HiRes-II)

– Energy resolution ~20 %
– ~1/7 exposure of monocular

D. Bird et al., Astrophys. J., 1994

Pierre Auger Observatory





Fluorescence detector (**FD**)

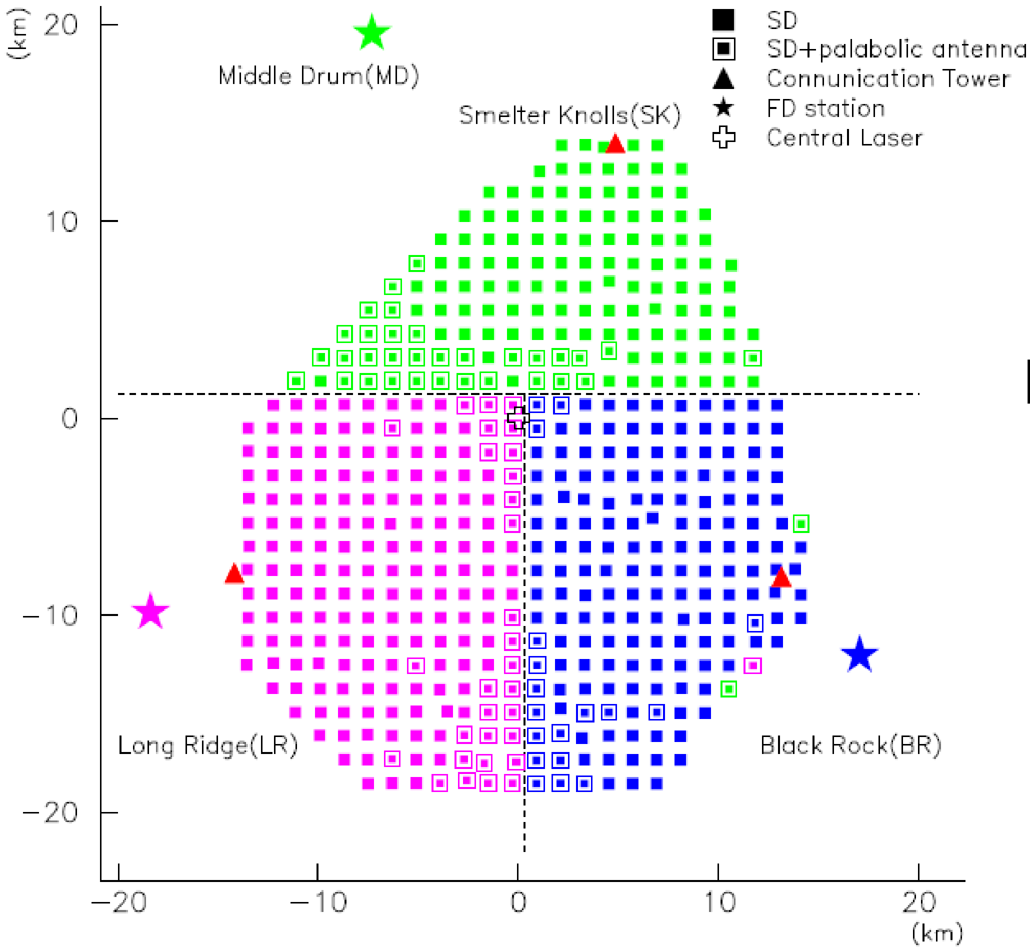
– 27 fluorescence telescopes
– Energy resolution ~10 %

Surface detector (**SD**)

– 1660 stations
– Energy resolution ~(15 – 20) %

Malargüe, Argentina
1400 m asl

Telescope array



Western desert of Utah, U.S.A.
1500 m asl

Fluorescence detector (**FD**)

Middle Drum

– 14 refurbished HiRes telescopes
– Energy resolution ~16 %

Long Ridge and Black Rock

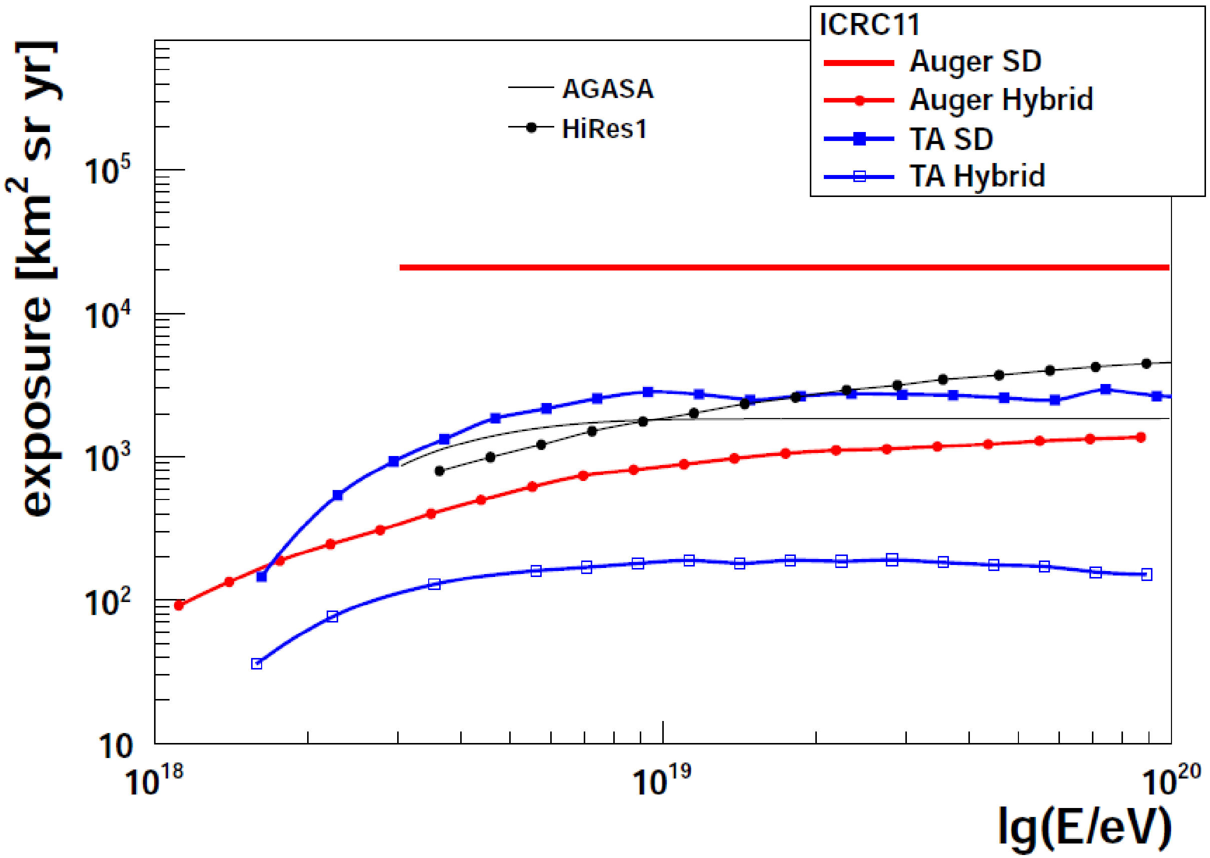
– 24 fluorescence telescopes
– Energy resolution ~8 %

Surface detector (**SD**)

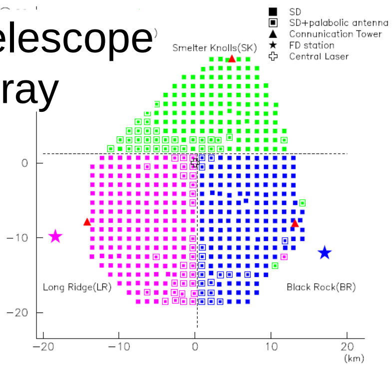
– 507 stations
– Energy resolution ?

S. Ogio [TA Collab.]; T. Nonaka [TA Collab.]; D. Ikeda [TA Collab.], ICRC Beijing, 2011

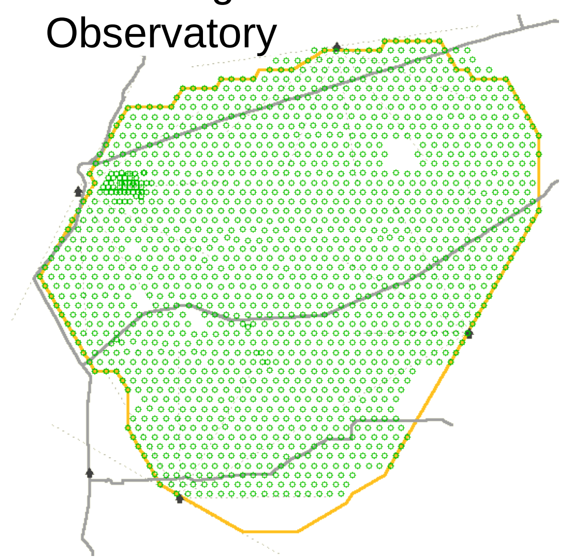
Exposure



Telescope Array



PierreAuger Observatory

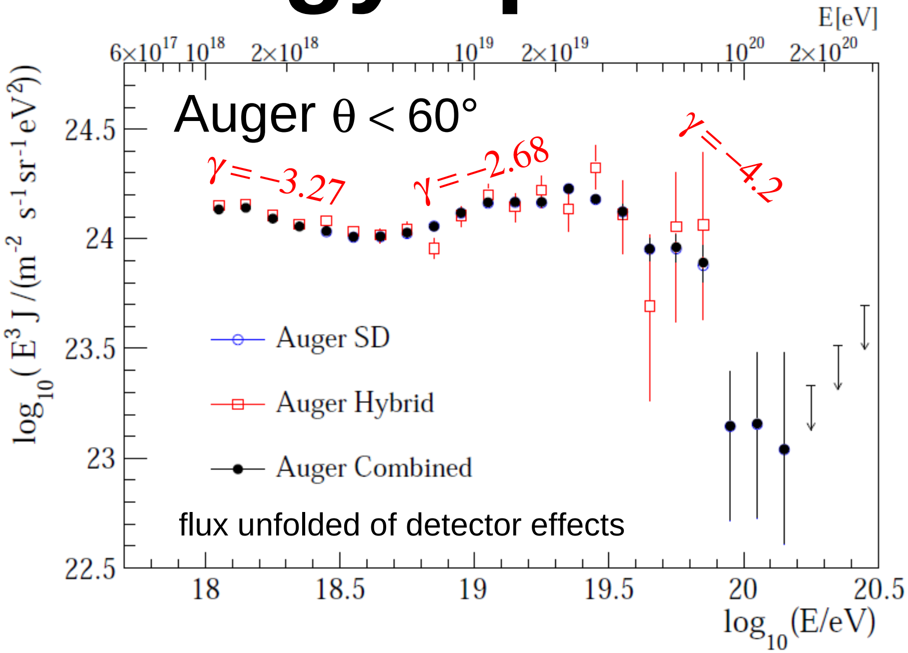


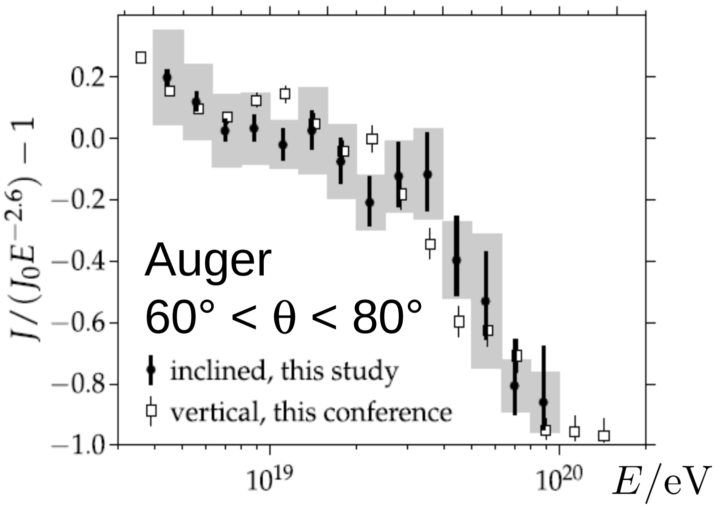
D.C. Rodriguez [TA Collab.]; F. Salamida [Auger Collab.], ICRC Beijing, 2011

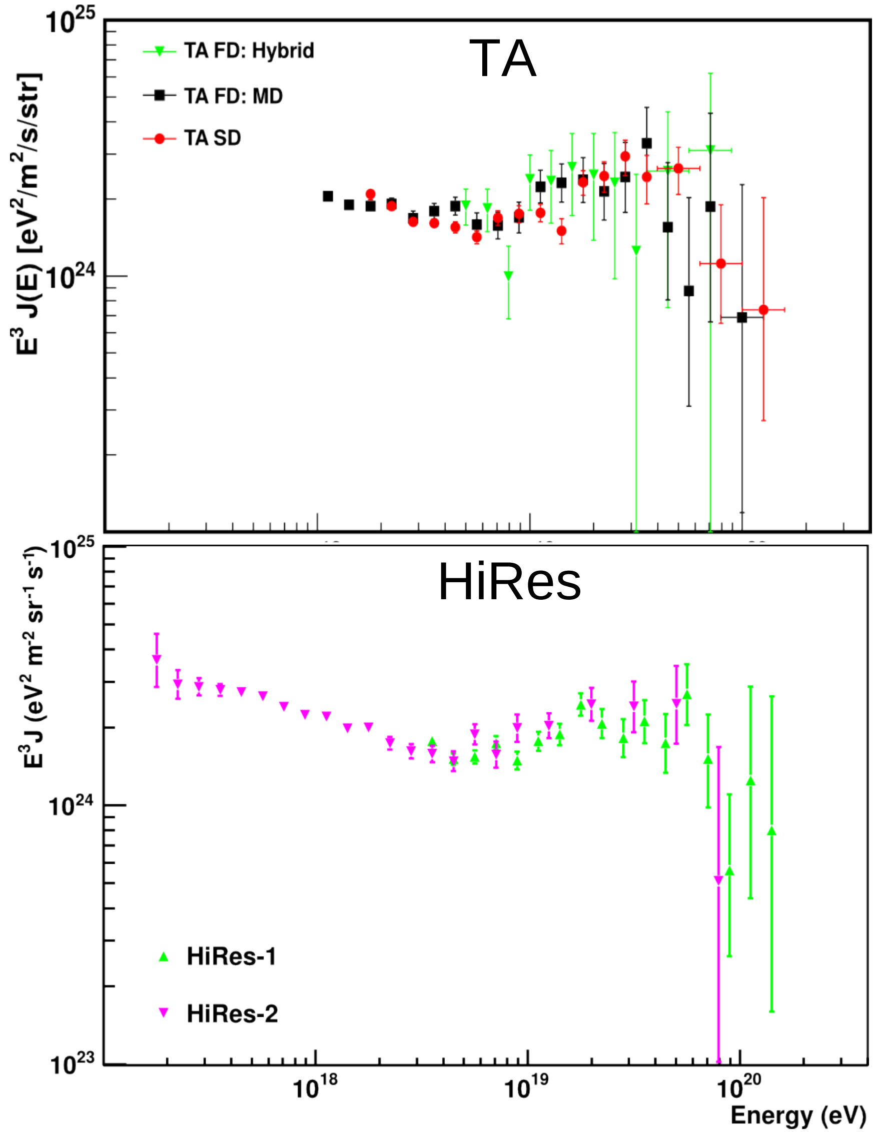
Energy spectrum

Energy spectrum

F. Salamida [Auger Collab.]; H. Dembinski [Auger Collab.];
D. Ikeda [TA Collab.]; ICRC Beijing, 2011
R.U. Abasi et al., Astropart. Phys., 2005

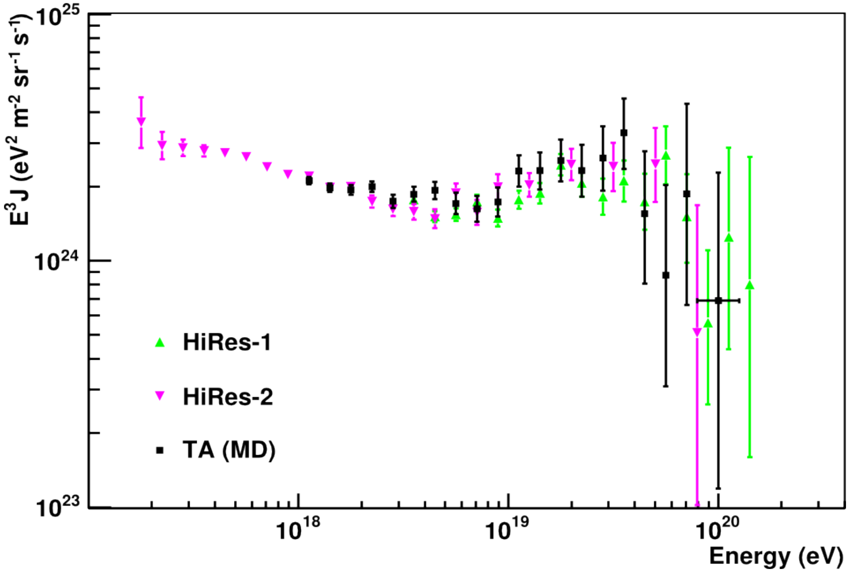




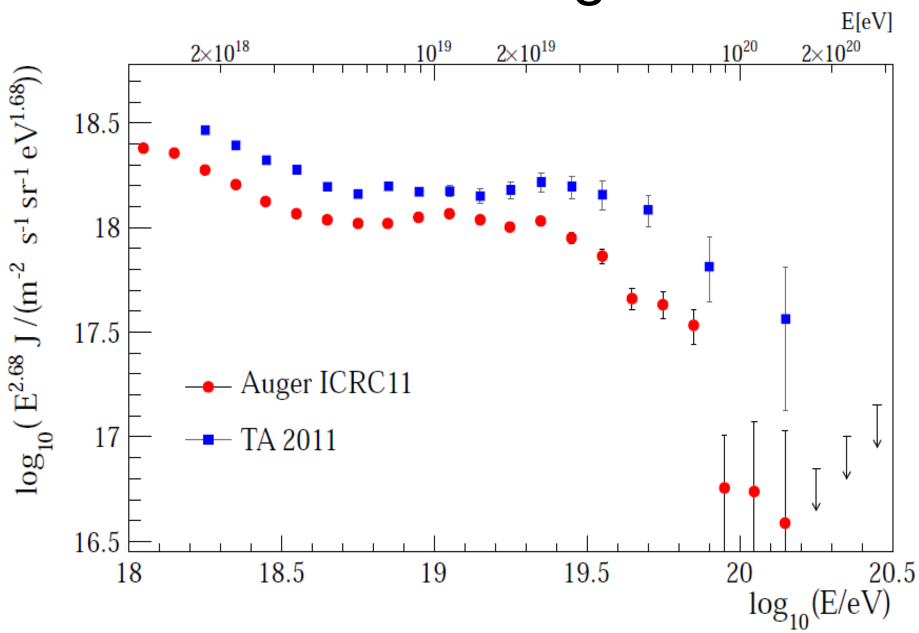


Energy spectrum

TA vs. HiRes



TA vs. Auger



Agreement, but not so surprising...

Middle drum = refurbished HiRes telescopes
Data analyis largely the same
Same fluorescence yield

Fluorescence yields and absolute FD calibration differ

Agreement between Auger and TA if energy is rescaled by 16 %

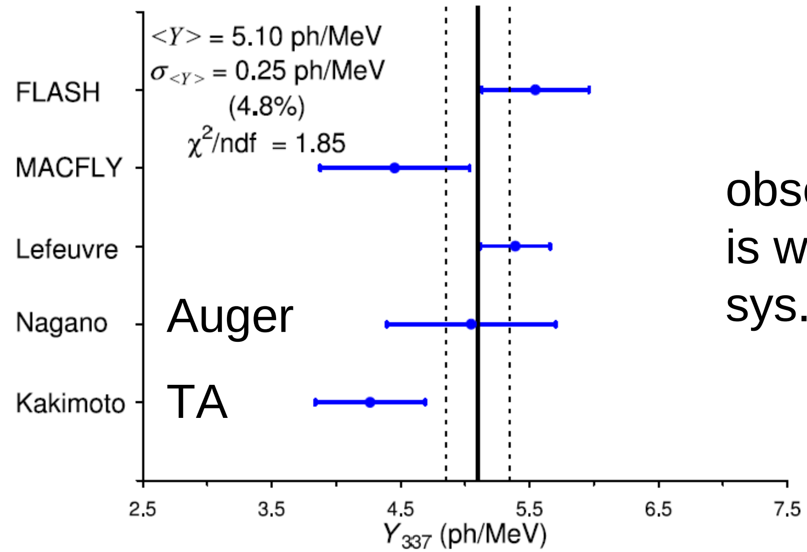
R. Pesce [Auger Collab.], ICRC Beijing, 2011
T. Abu-Zayyad [TA Collab.], ICRC Beijing, 2011

FD energy scale

Auger	
calibration	9.5%
reconstruction	10%
atmospheric	8%
fluorescence yield*	14%
invisible energy†	4%
tot. quad. sum	**22%**

Telescope Array	
calibration	10%
reconstruction	10%
atmospheric	11%
fluorescence yield** invisible energy††	11%
tot. quad. sum	**21%**

Lab measurements of fluorescence yield



observed difference is well within estimated sys. uncertainty of *E*-scale

*yield: Nagano, spectrum: AIRFLY **yield: Kakimoto, spectrum: Bunner †QGSJet mixed ††QGSJet proton

Observables related to mass composition

Depth of shower maximum X_{max}

Shower maximum X_{max} of **proton** showers compared to **iron** showers

... develops deeper on average

... fluctuates more

$$\langle X_{\max} \rangle = \alpha(\ln E - \langle \ln A \rangle) + \beta$$

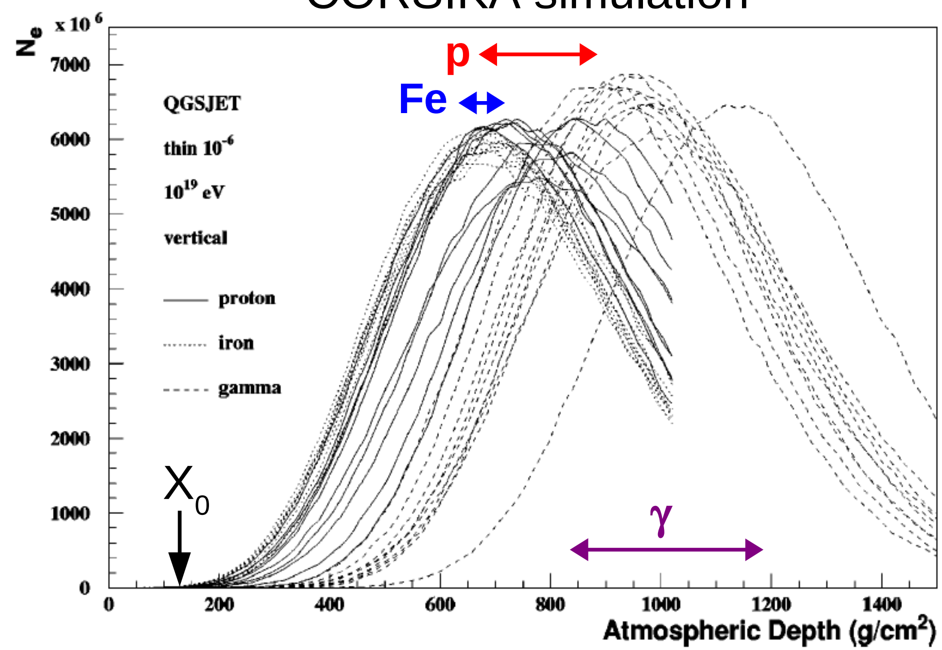
depend on hadronic interaction model

$$\mathrm{RMS}^2[X_{\max}]$$

$$= \mathrm{RMS}^2[X_0] + \mathrm{RMS}^2[\Delta X]$$

$$\lambda_{\mathrm{int}}^2 \qquad \sigma_{\mathrm{int}} = \frac{\langle m_{\mathrm{air}} \rangle}{\lambda_{\mathrm{int}}}$$

CORSIKA simulation

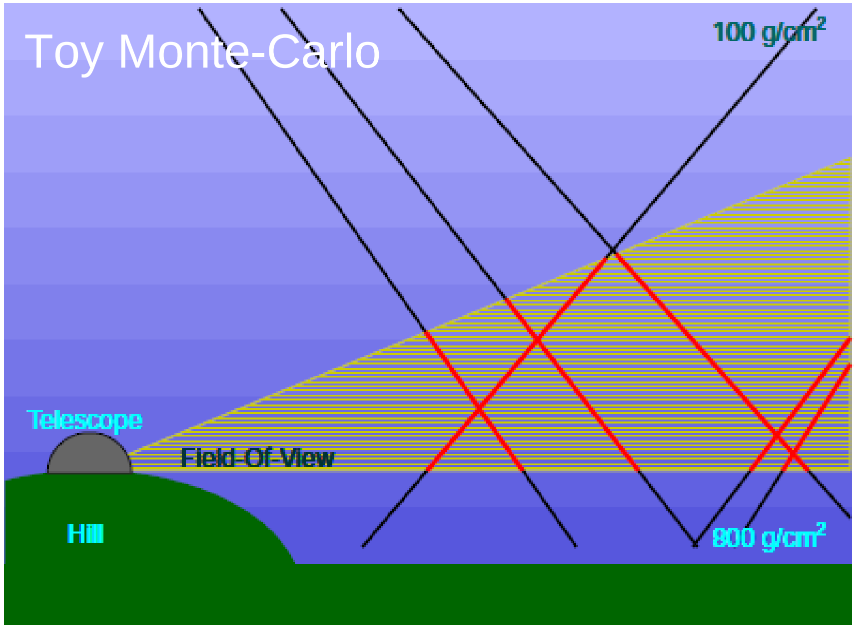


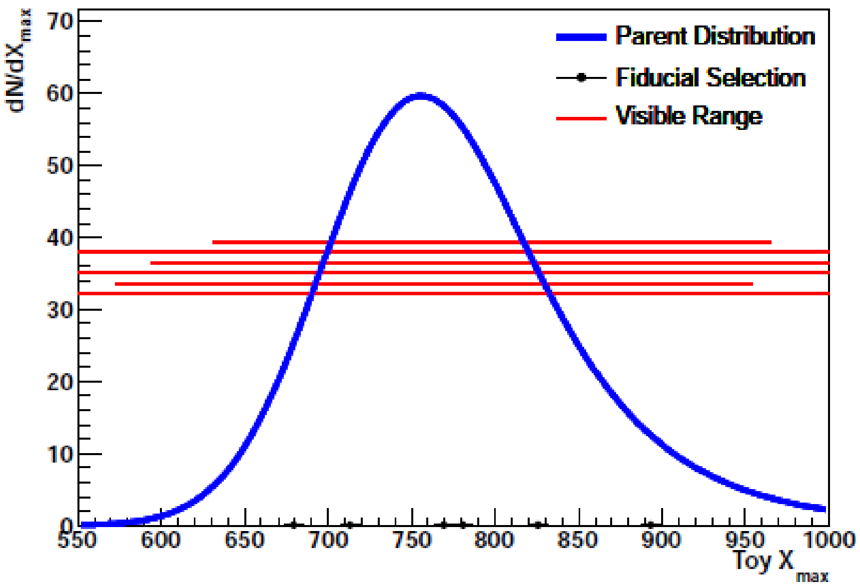
Heck et al., FZKA6019, 1998

Photons behave like super-light hadrons: very deep showers, muon poor

R. Ulrich [Auger Collab.], ICRC Beijing, 2011

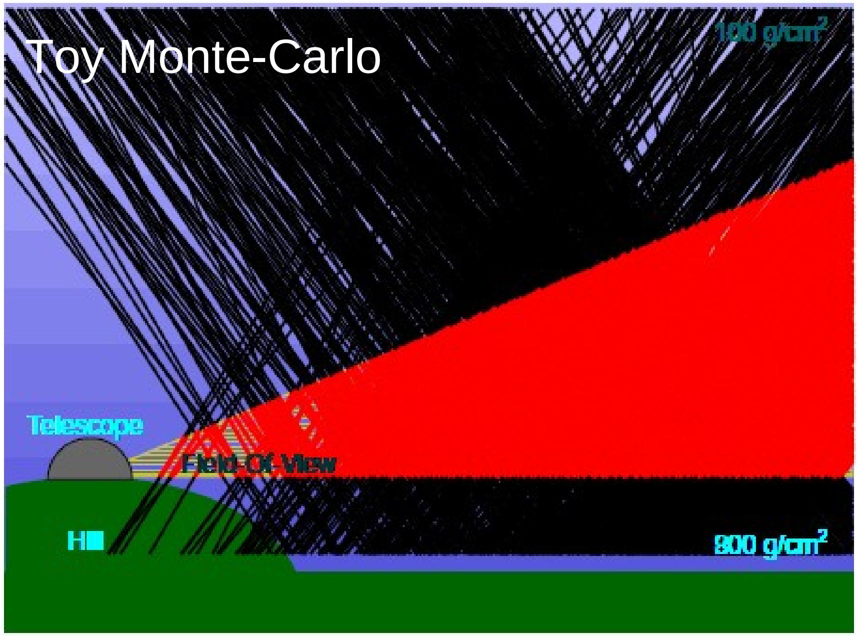
Field of view bias

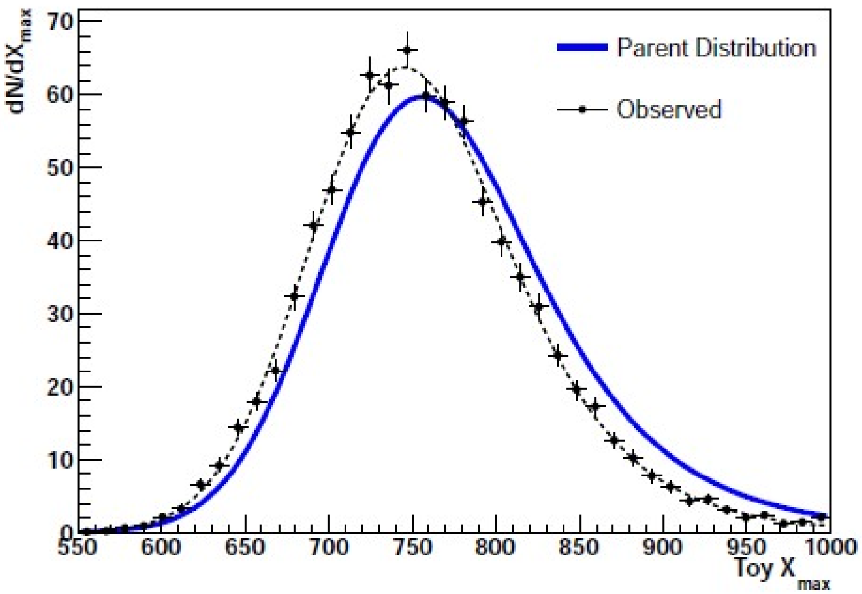




Field of view of FD telescopes does not cover full X_{max} range for all shower geometries

Field of view bias





Not all shower geometries allow to observe the full X_{max} range

HiRes and TA approach

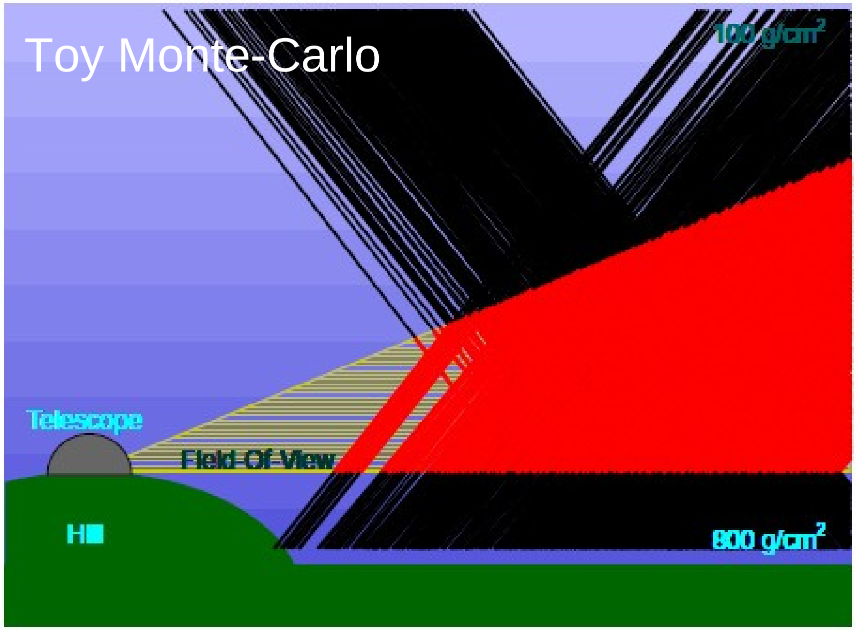
– Do not correct bias

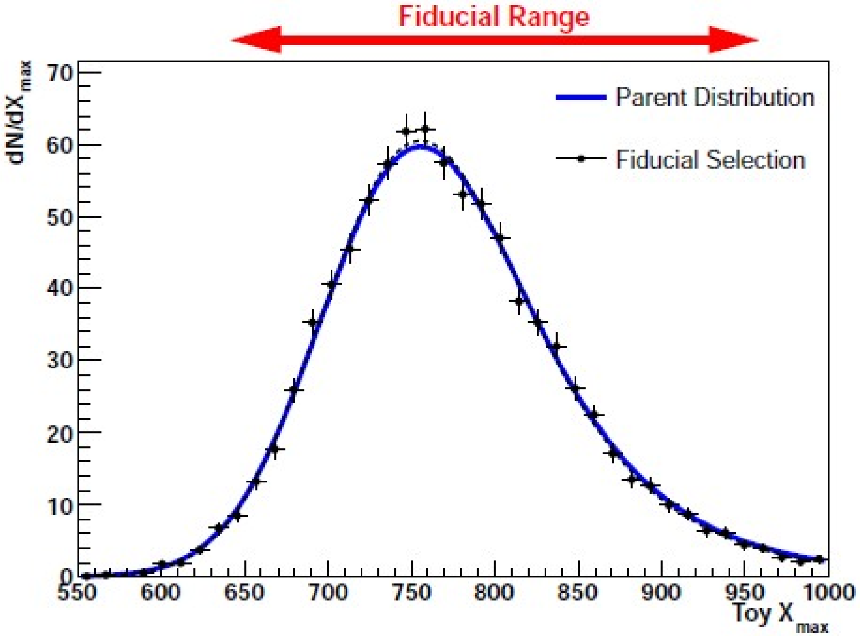
– Apply detector simulation to generator-level prediction to be consistent

Results are detector dependent

R. Ulrich [Auger Collab.], ICRC Beijing, 2011

Field of view bias





Auger approach

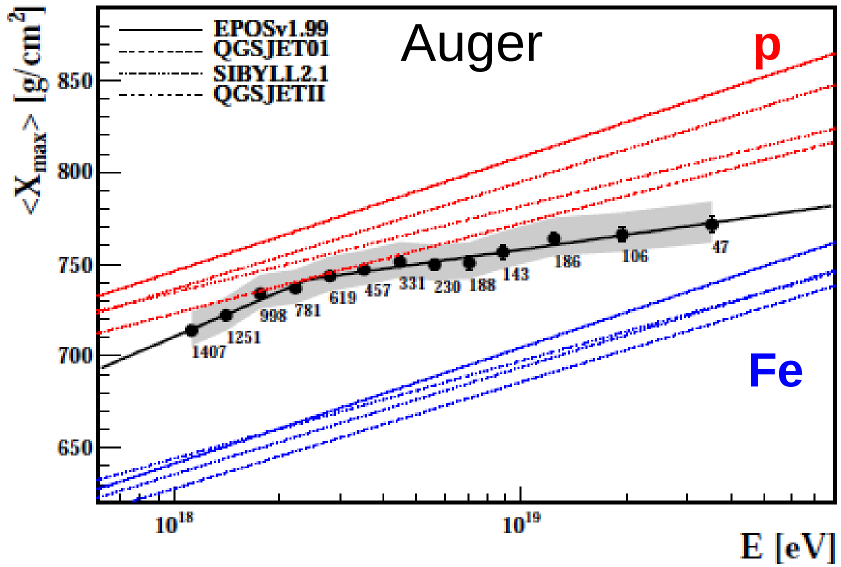
– Select only shower geometries that cover full X_{max} range

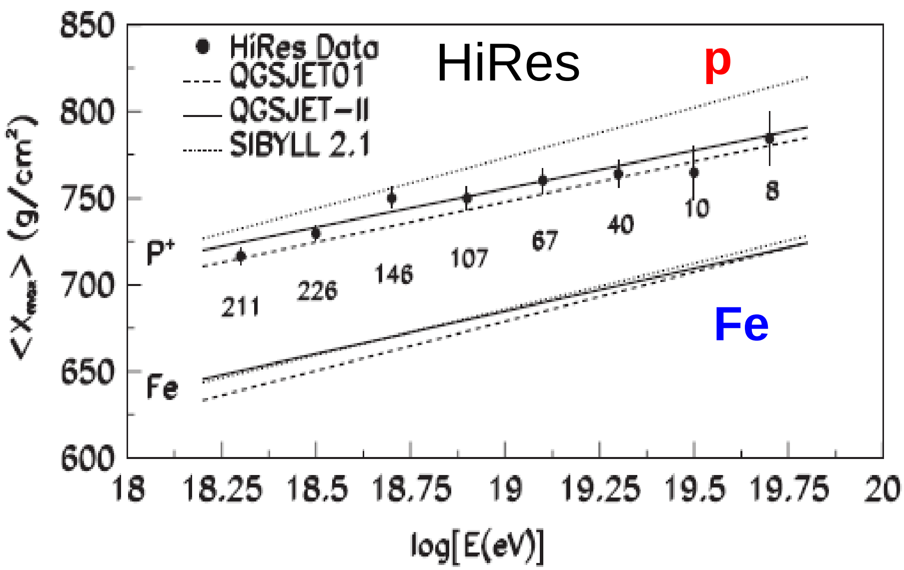
– Compare measurement directly with generator-level prediction

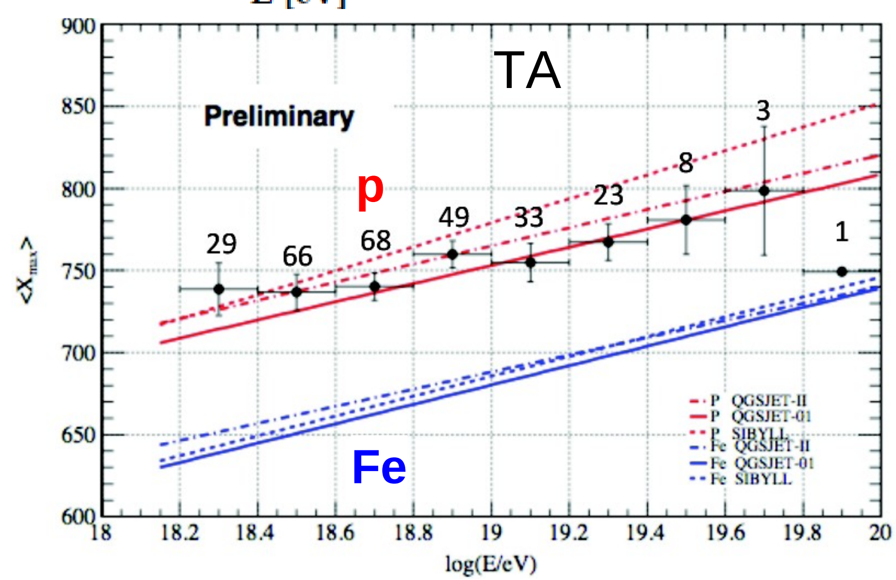
Results are detector independent

Mean X_{max}

P. Facal San Luis [Auger Collab.]; Y. Tameda [TA Collab.], ICRC Beijing, 2011
R.U. Abbasi et al., Astrophys. J., 2005



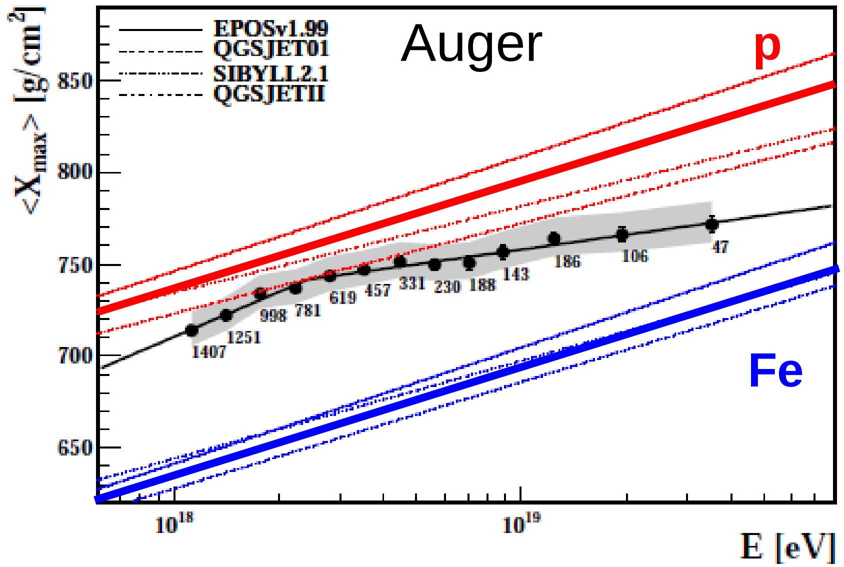


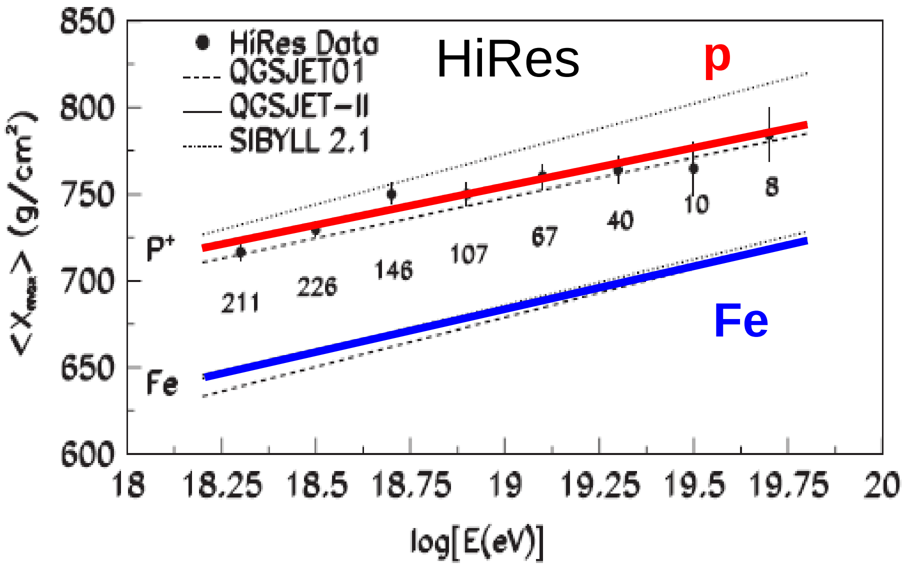


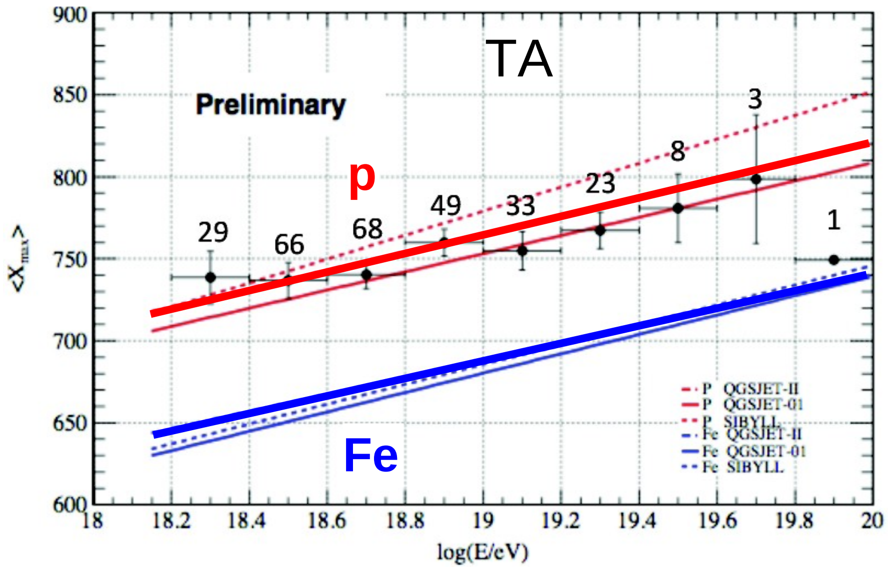
Mean X_{max}

P. Facal San Luis [Auger Collab.]; Y. Tameda [TA Collab.], ICRC Beijing, 2011
R.U. Abbasi et al., Astrophys. J., 2005

QGSJet-II

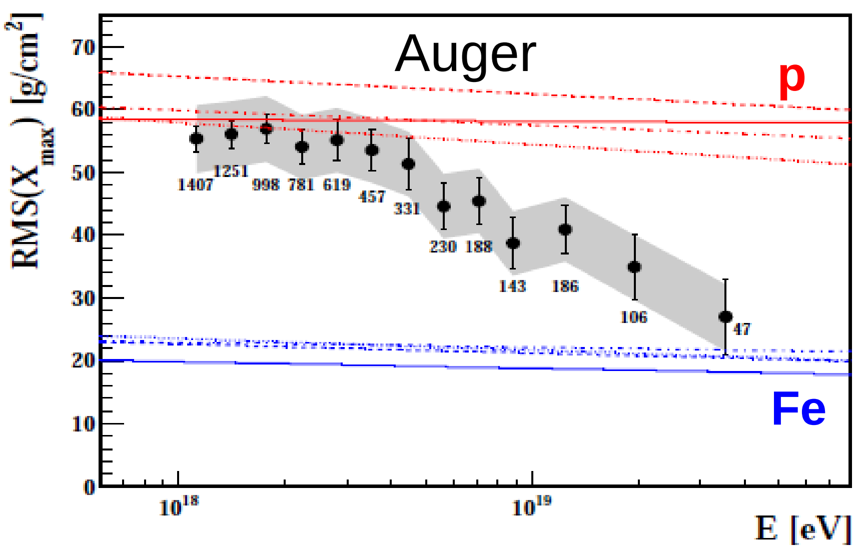


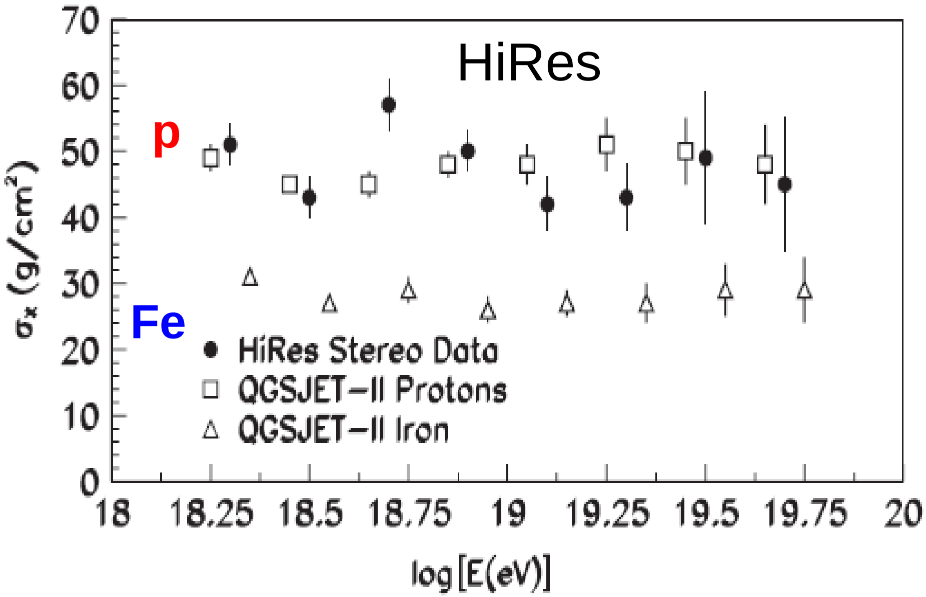




X_{max} fluctuations

P. Facal San Luis [Auger Collab.], ICRC Beijing, 2011
R.U. Abbasi et al., Astrophys. J., 2005





Detector resolution subtracted from data

Detector resolution folded into prediction

σ_{res} 27 g cm^{-2} σ_{res} 18 g cm^{-2}

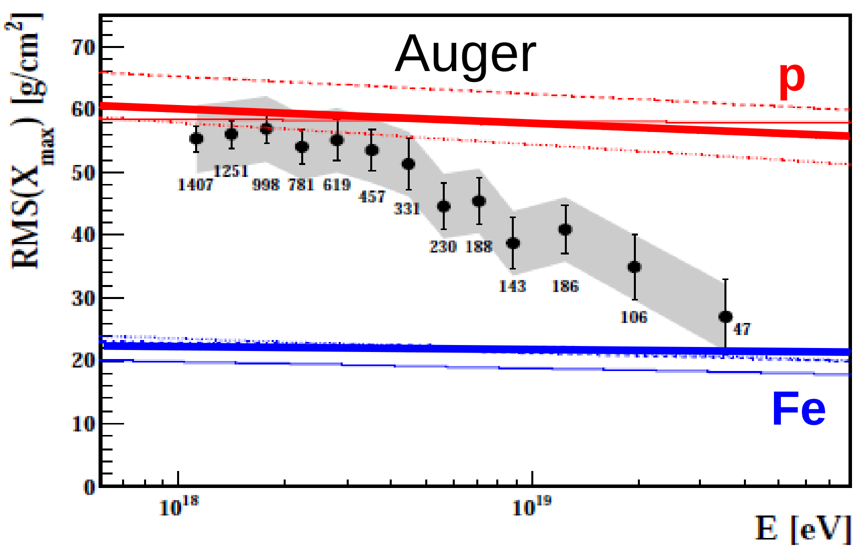
Variance of distribution in each bin

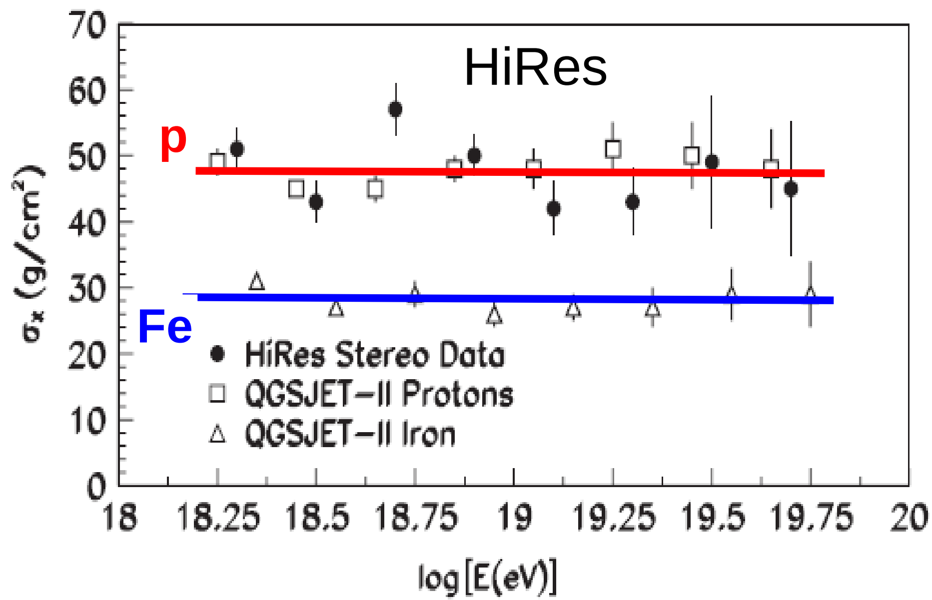
Fit of truncated Gaussian
to suppress long tails

X_{max} fluctuations

P. Facal San Luis [Auger Collab.], ICRC Beijing, 2011
R.U. Abbasi et al., Astrophys. J., 2005

QGSJet-II





Detector resolution subtracted from data

Detector resolution folded into prediction

σ_{res} 27 g cm^{-2} σ_{res} 18 g cm^{-2}

Variance of distribution in each bin

Fit of truncated Gaussian
to suppress long tails

D. Garcia-Gamez [Auger Collab.], ICRC Beijing, 2011

Auger: X^{μ}_{max}

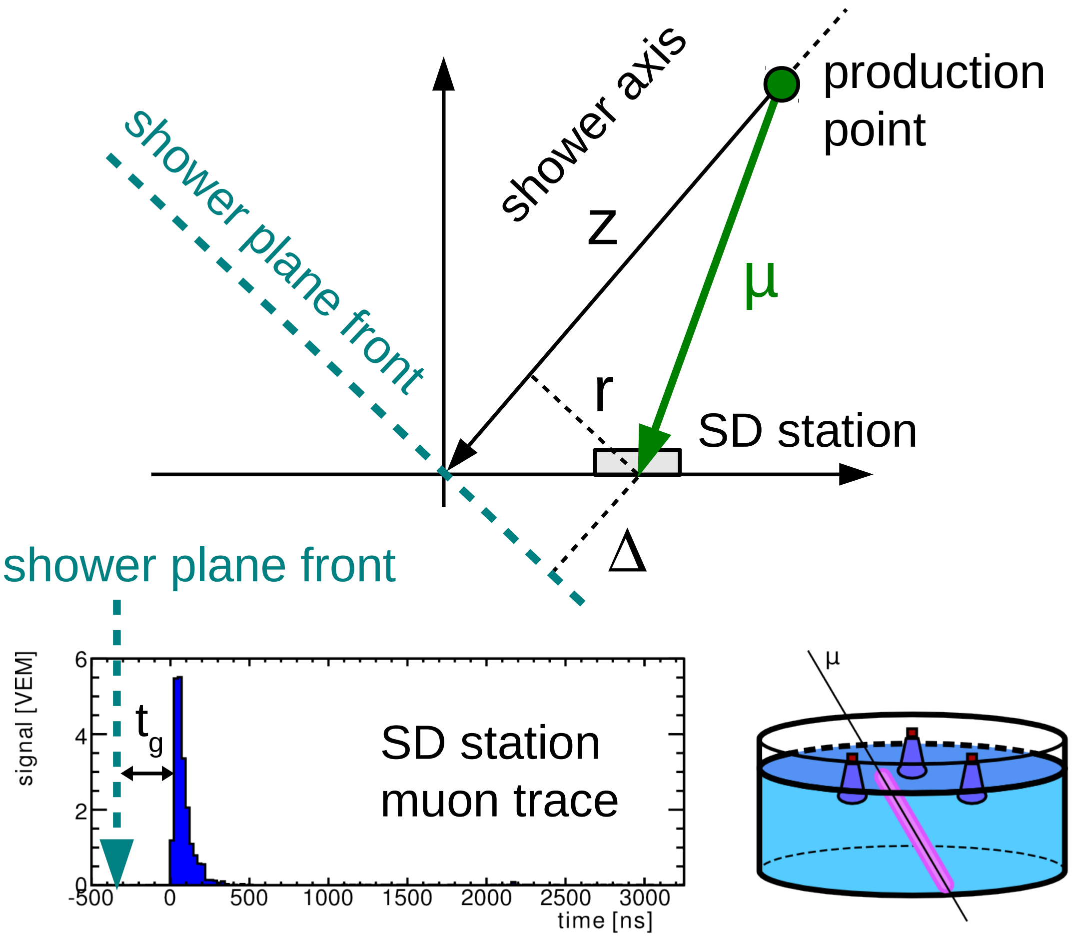
Geometrical (optical) model of muon propagation

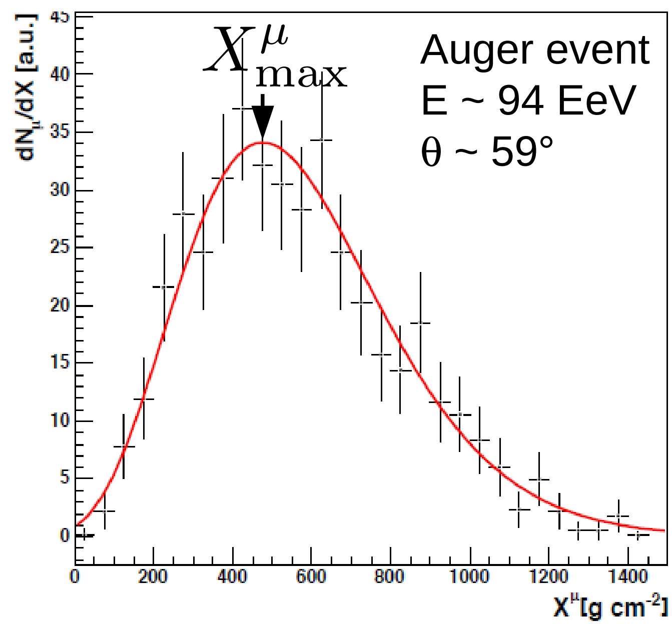
Good approximation for $55^\circ \lesssim \theta \lesssim 65^\circ$

$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$

$$X^{\mu} = \int_z^{\infty} \rho(z') \mathrm{d}z'$$

Muon production depth





D. Garcia-Pinto [Auger Collab.], ICRC Beijing, 2011

Auger: Mass observables

SD observables

$$X^{\mu}_{\max}$$

muon production depth

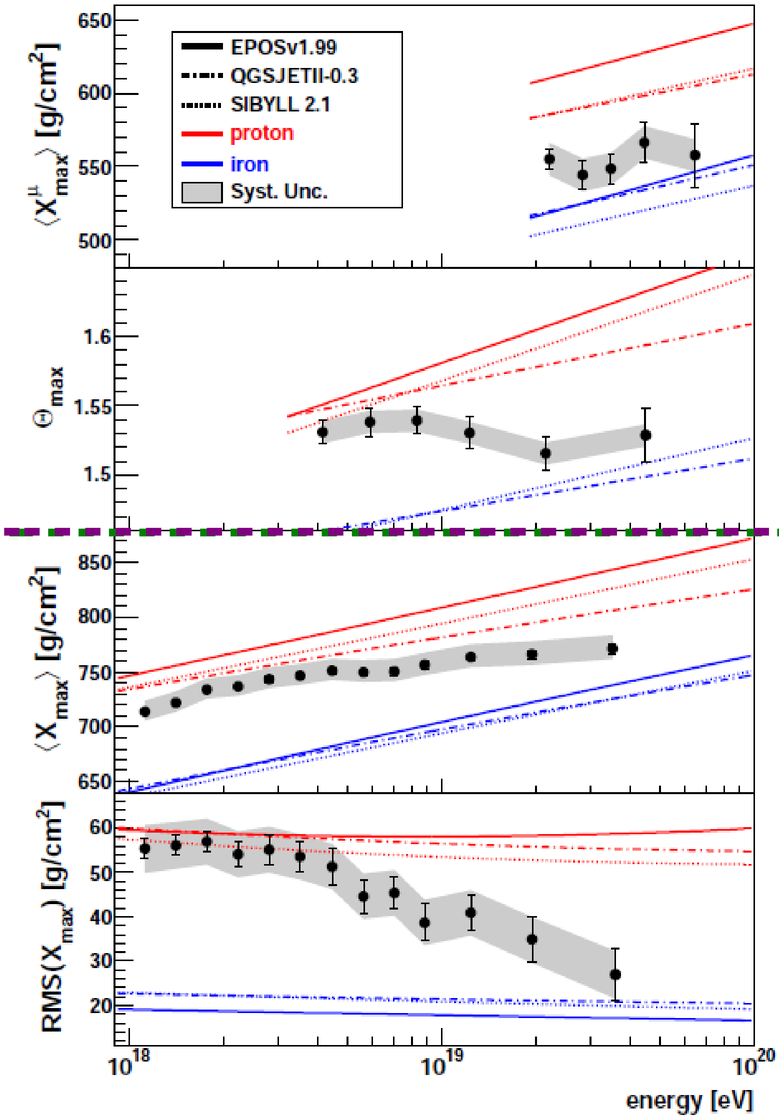
$$\Theta_{\max} = \sec \theta_{\text{asym,max}}$$

inclination angle with largest rise time asymmetry

FD observables

$$\langle X_{\max} \rangle$$

$$\text{RMS}(X_{\max})$$



Searches for photons and neutrinos (very briefly)

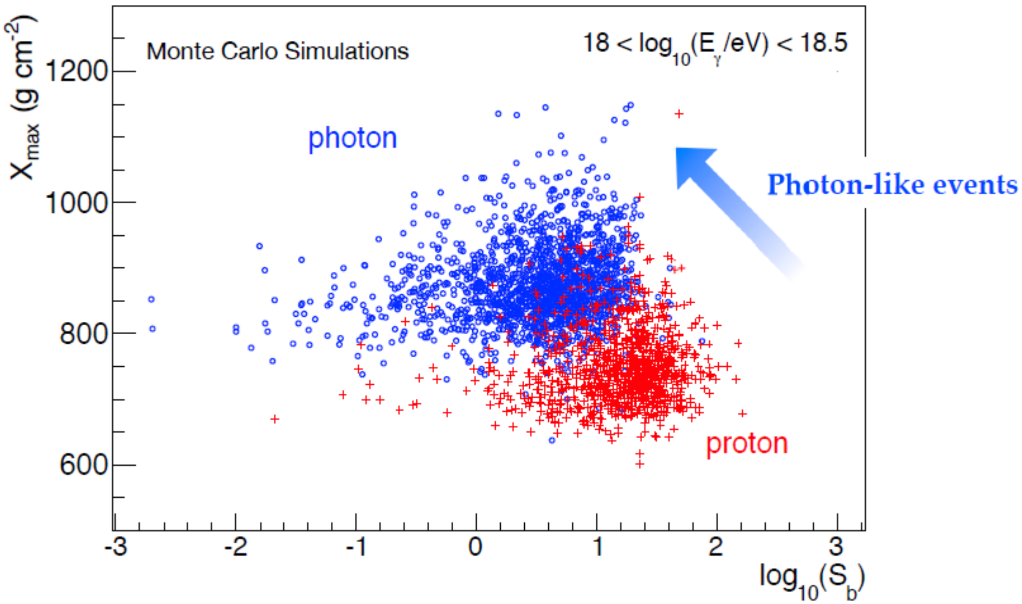
M. Settimo [Auger Collab.]; G.I. Rubtsov [TA Collab.], ICRC Beijing, 2011

Photon limits

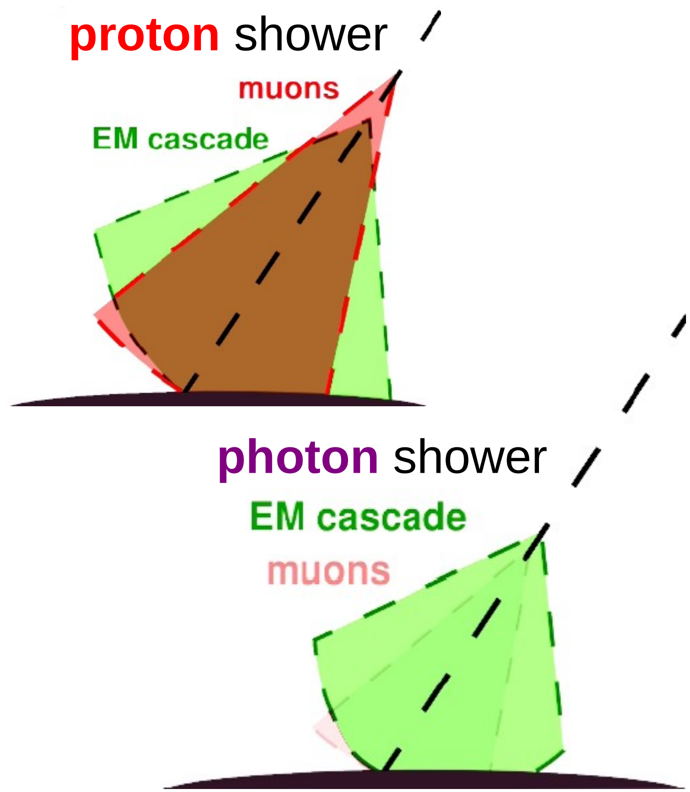
Photons develop deeper → larger X_{max} and front curvature

Photons muon poor → smaller signal deposited in SD, larger signal rise time

Auger below 10^{19} eV: Hybrid analysis, combining X_{max} and $S_b = \sum_i S_i \left(\frac{r}{1000\,\mathrm{m}}\right)^4$



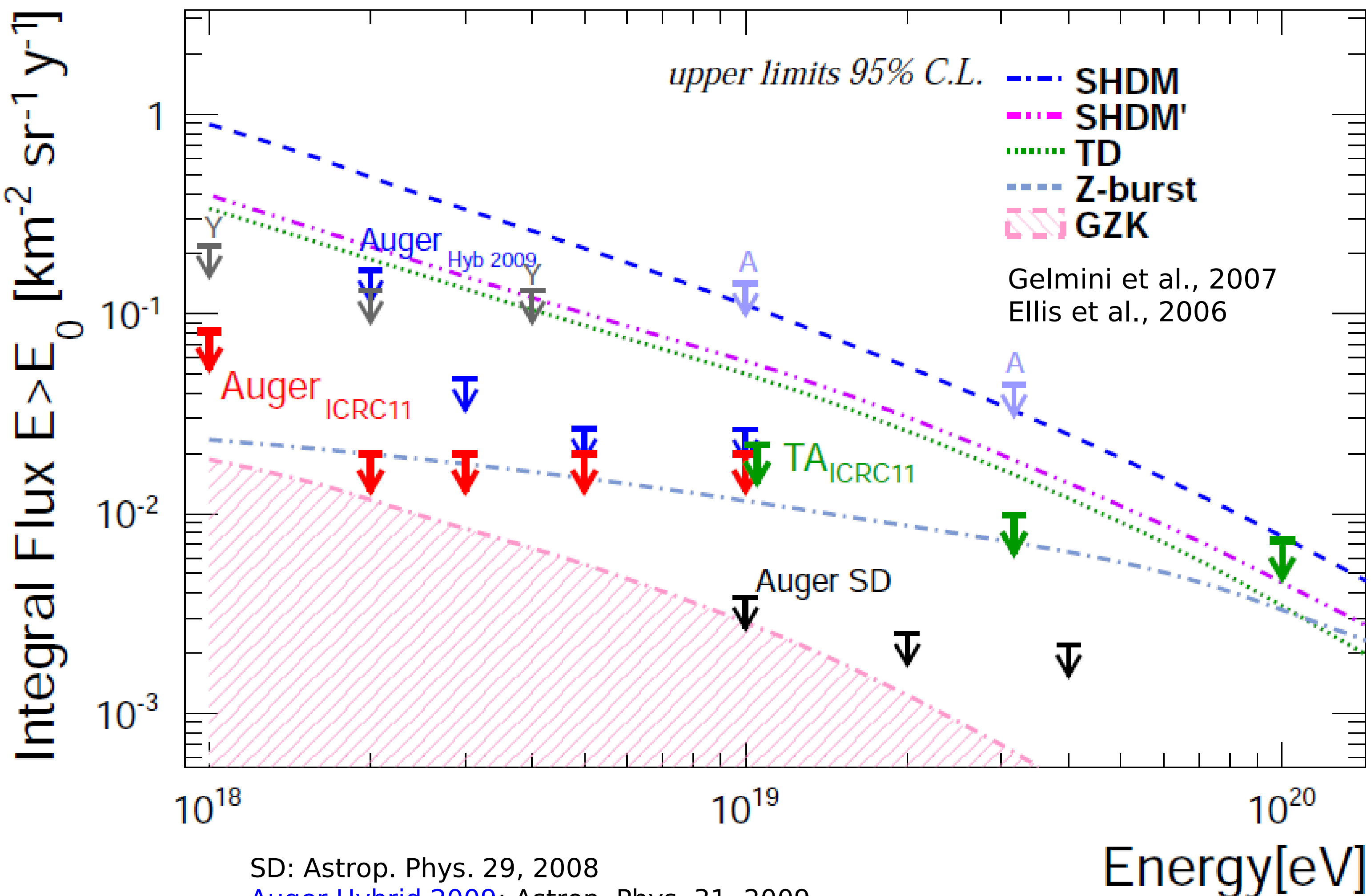
TA: SD analysis, using front curvature



Auger above 10^{19} eV: SD analysis, combining rise time and front curvature

M. Settimo [Auger Collab.]; G.I. Rubtsov [TA Collab.], ICRC Beijing, 2011

Photon limits

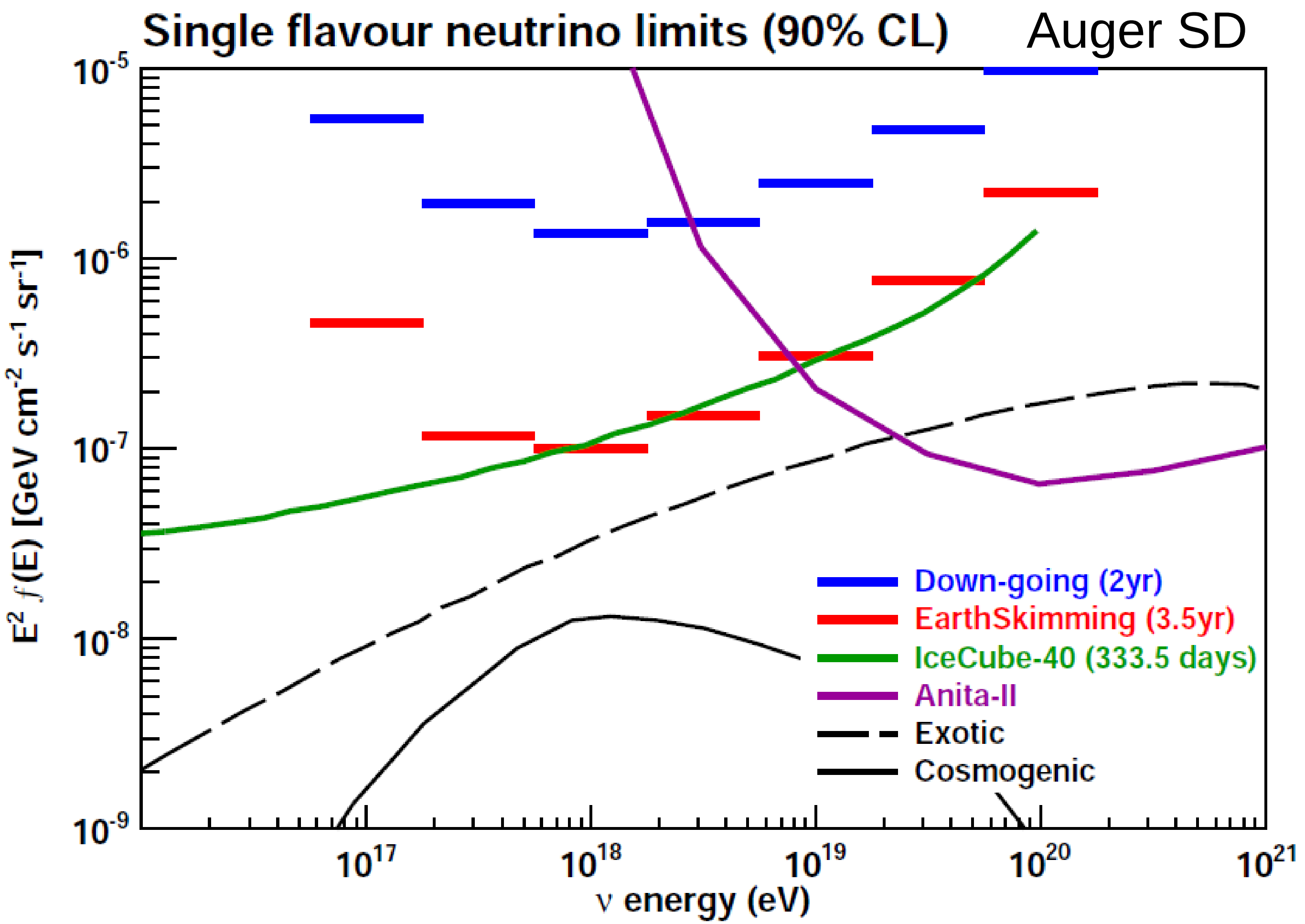


SD: Astrop. Phys. 29, 2008
Auger Hybrid 2009: Astrop. Phys. 31, 2009
A (AGASA), Shinozaki et al., 2002
Y (Yakutsk), Glushkov et al., 2002

Y.Guardincerri [Auger Collab.], ICRC Beijing, 2011

Neutrino limits

Similar techniques as for photon search, but look for **horizontal** deep showers



assumptions:
ν-flux µ E^{-2}
$\nu_e:\nu_\mu:\nu_\tau = 1:1:1$

ν-exposure computed from simulations

p-air cross section

Auger method: X_{max} tail

R. Ulrich [Auger Collab.],
ICRC Beijing, 2011

$$\mathrm{RMS}^2[X_{\mathrm{max}}] = \mathrm{RMS}^2[X_0] + \mathrm{RMS}^2[\Delta X]$$

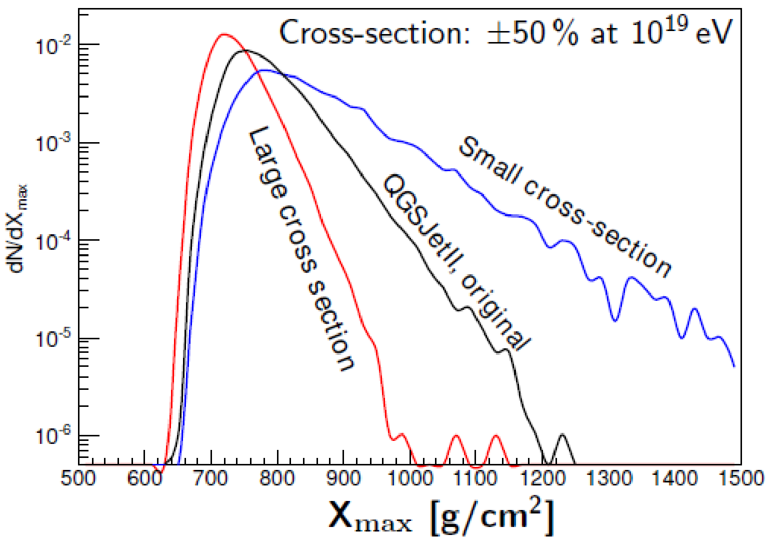
$$\mathrm{RMS}^2[X_0] = \lambda_{\mathrm{int}}^2 \qquad \sigma_{\mathrm{int}} = \frac{\langle m_{\mathrm{air}} \rangle}{\lambda_{\mathrm{int}}}$$

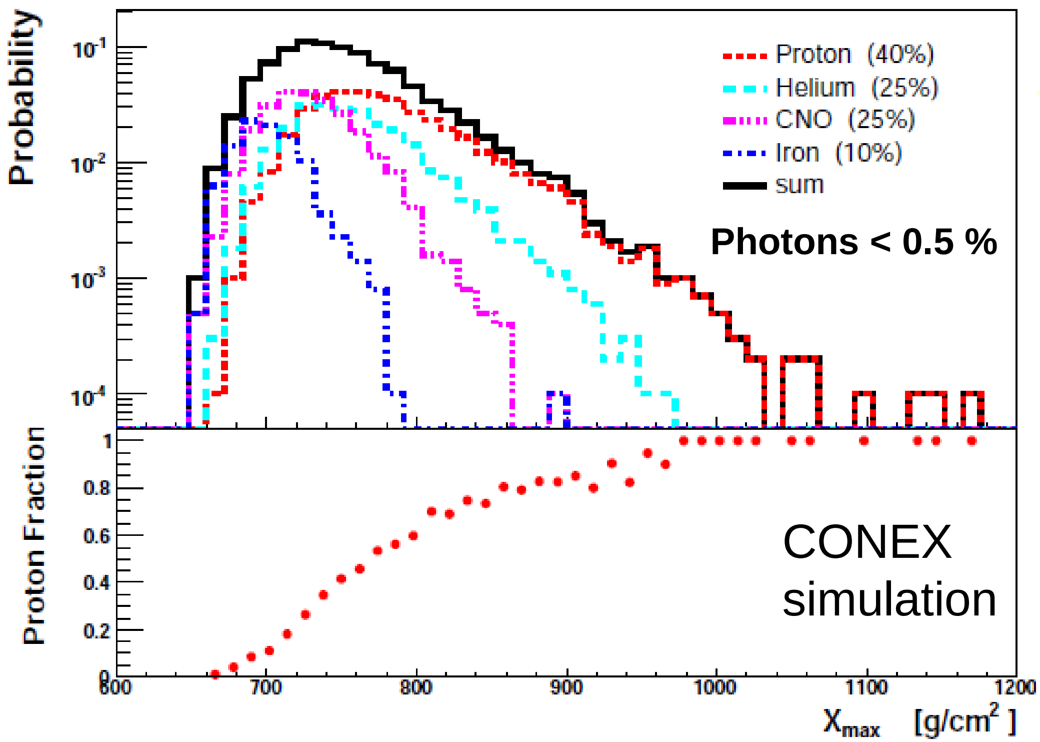
But: Can only observe X_{max} with possibly mixed composition

Ellsworth et al. PRD 1982
Baltrusaitis et al. PRL 1984

Idea
Use tail of X_{max} distribution

CONEX simulation





Auger method: X_{max} tail

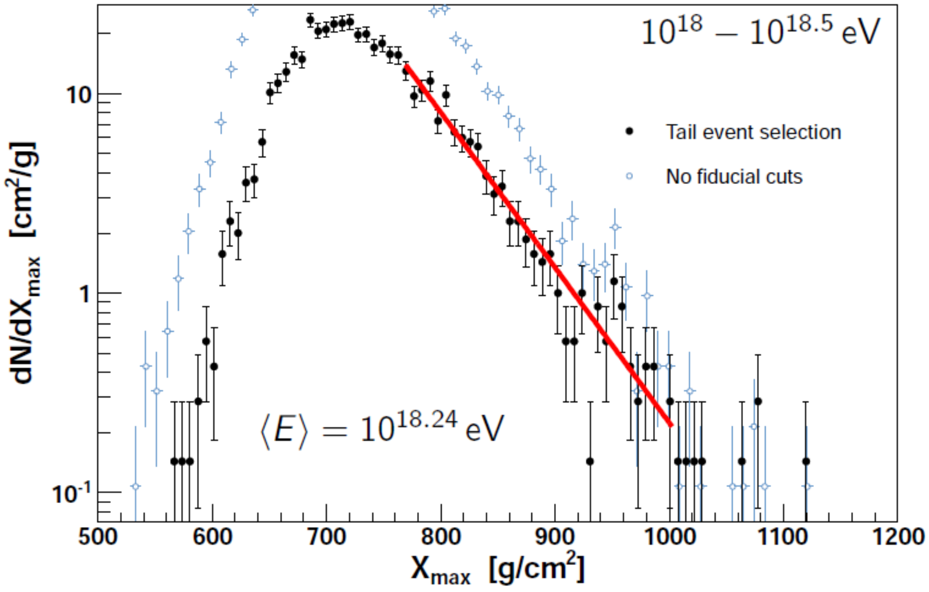
R. Ulrich [Auger Collab.],
ICRC Beijing, 2011

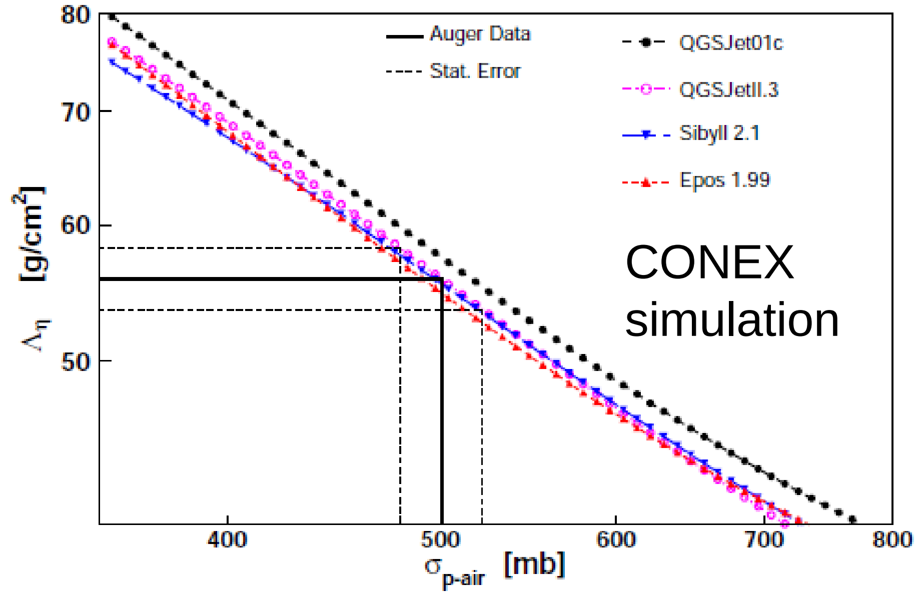
Fit X_{max} tail with exponential distribution in energy range 10^{18} - $10^{18.5}$ eV to obtain slope Λ_η

Shift $\sigma_{\text{p-air}}$ in simulations up and down to get mapping

$$\sigma_{\text{p-air}} \to \Lambda_\eta$$

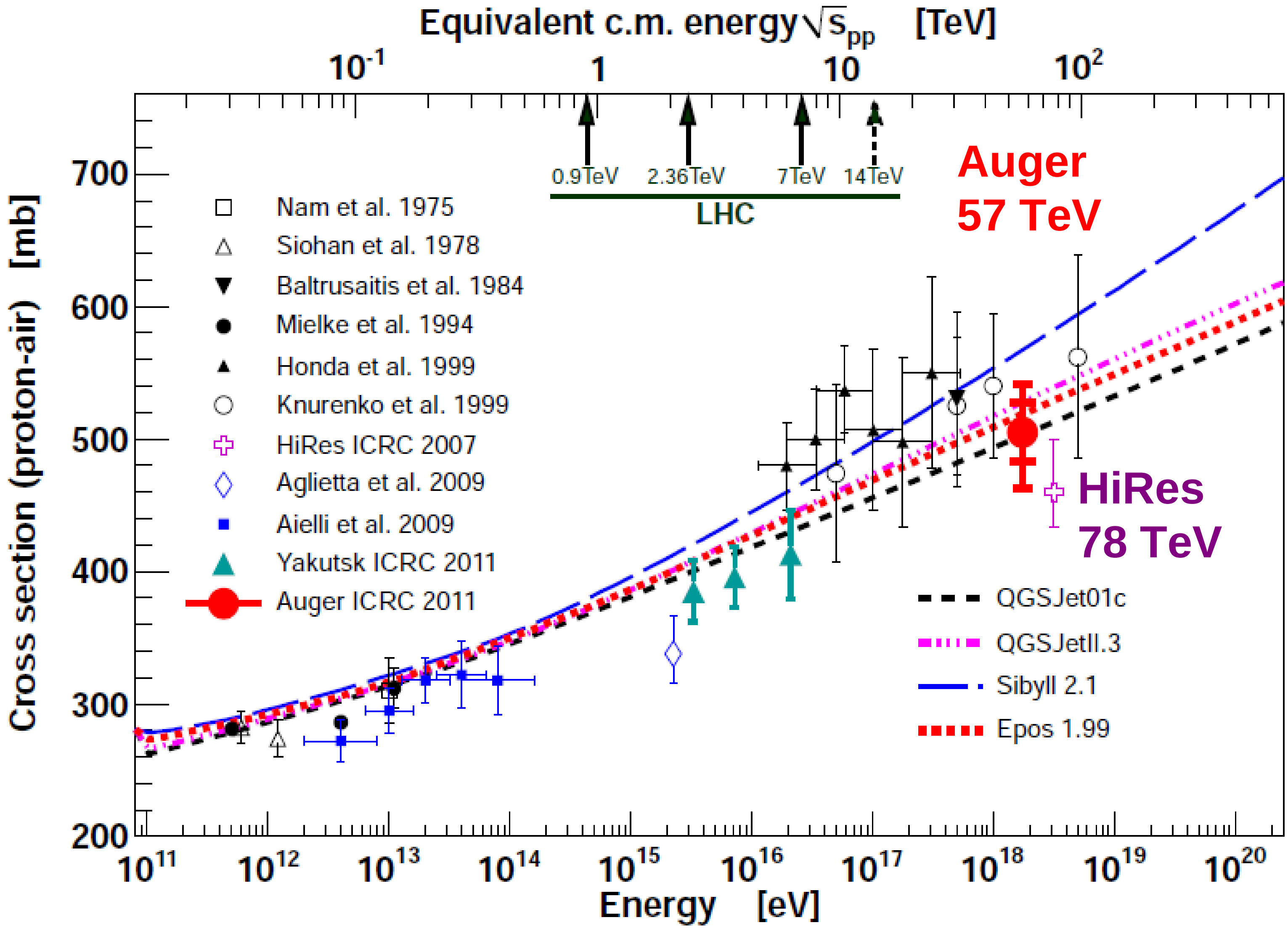
Then invert this mapping to get $\sigma_{\text{p-air}}$ from measured Λ_η





p-air cross-section

R. Ulrich [Auger Collab.], ICRC Beijing, 2011
K. Belov [HiRes Collab.], ICRC Mexico, 2007

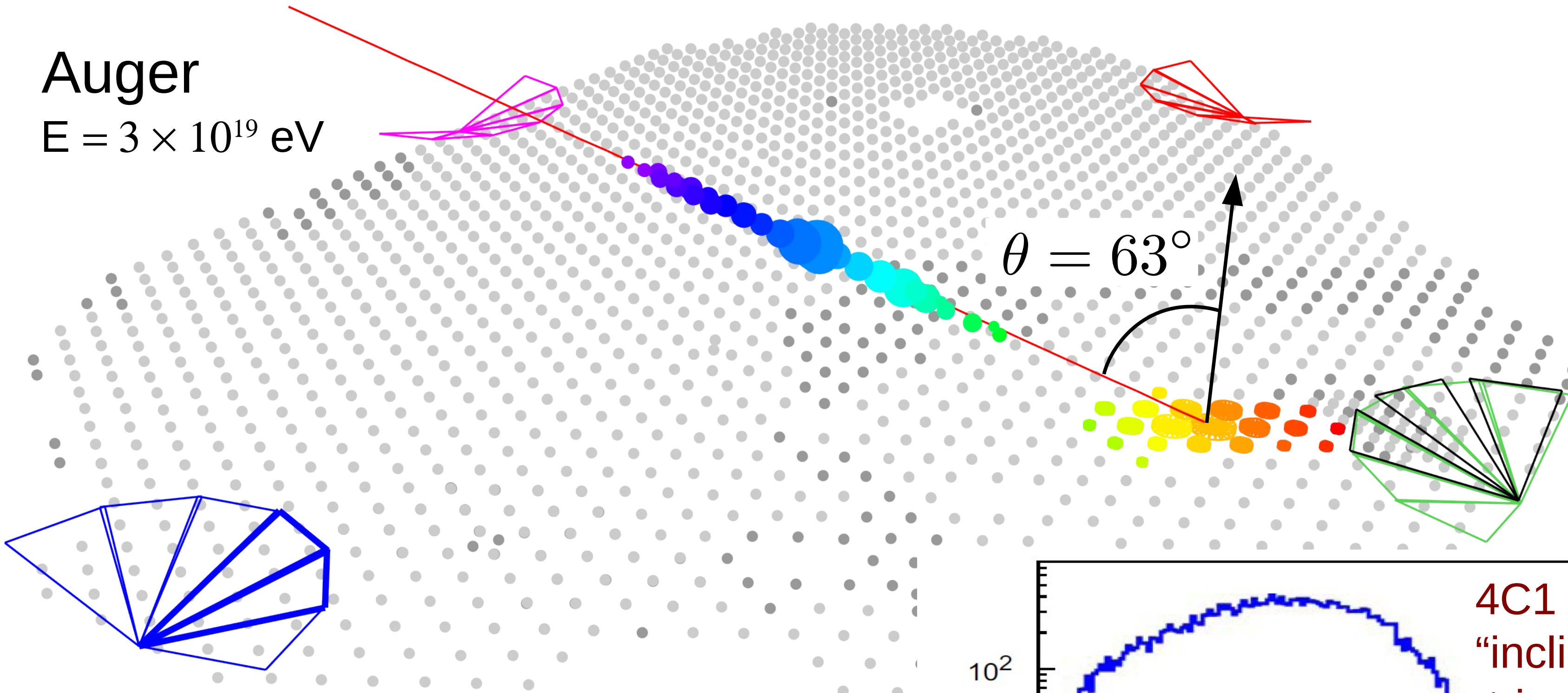


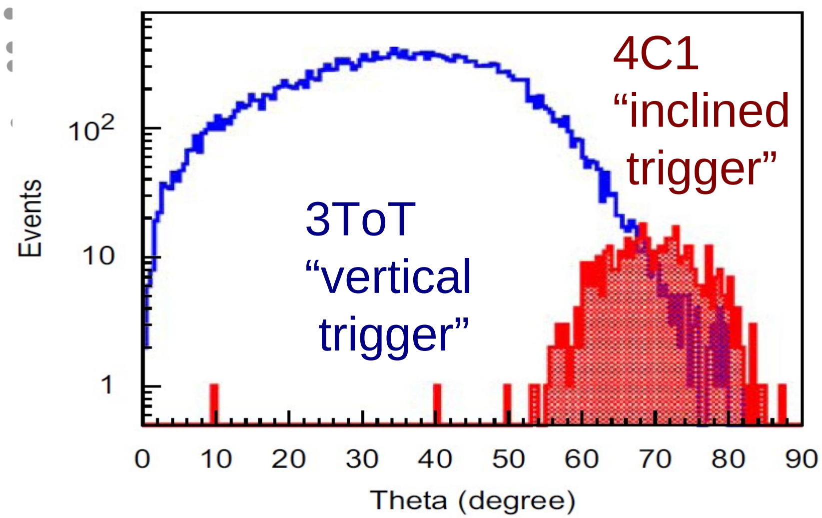
Muon content

Very inclined events $60^\circ \lesssim \theta \lesssim 80^\circ$

Auger

$E = 3 \times 10^{19}$ eV





1/4 of all events are very inclined

Auger remains efficient up to $\theta \approx 80^\circ$

G. Rodríguez [Auger Collab.],
ICRC Beijing, 2011

Muon scale N_{19}

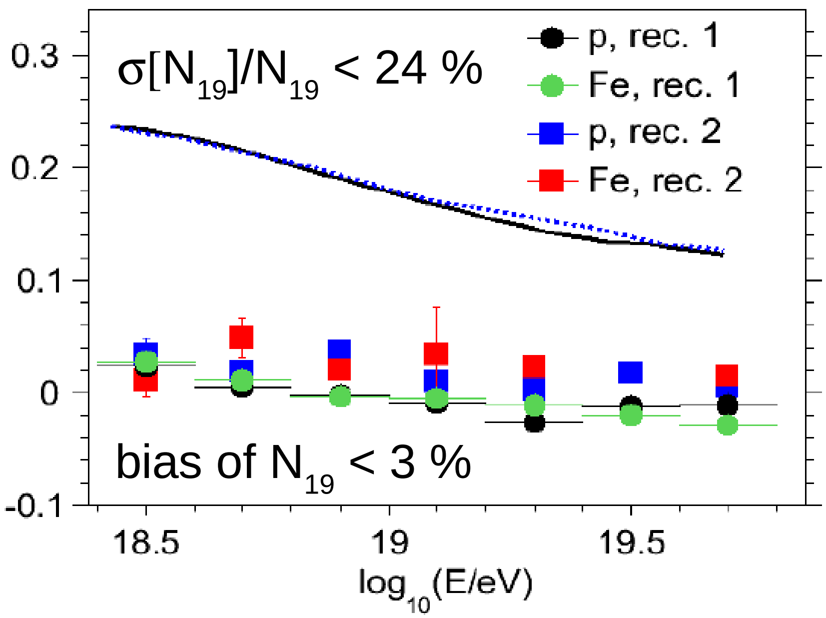
Auger $60^\circ < \theta < 80^\circ$

Reconstruction of muon scale N_{19}

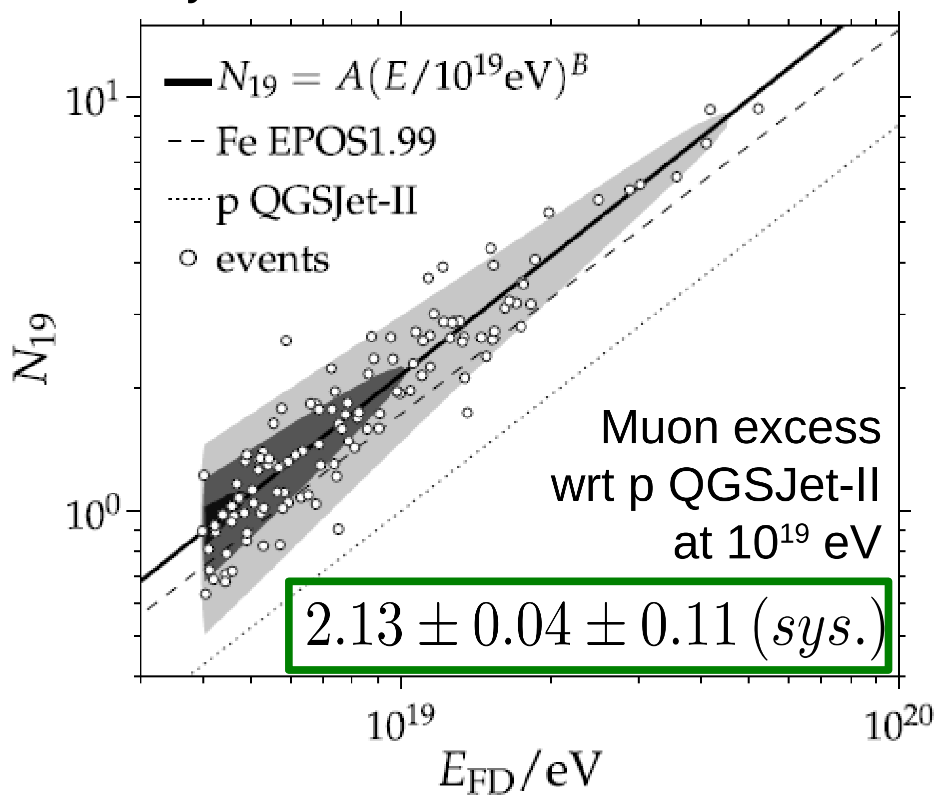
$$N_{19}(E, A) = \frac{N_\mu(E, A, \theta)}{N_\mu^{\text{sim}}(10^{19}\,\text{eV}, 1, \theta)}$$

$$n_\mu = N_{19}(E, A) \times n_{\mu,19}(x, y | \theta, \phi)$$

scale factor — universal lateral profile



Hybrid events



J. Allen [Auger Collab.], ICRC Beijing, 2011

Auger: Muon excess

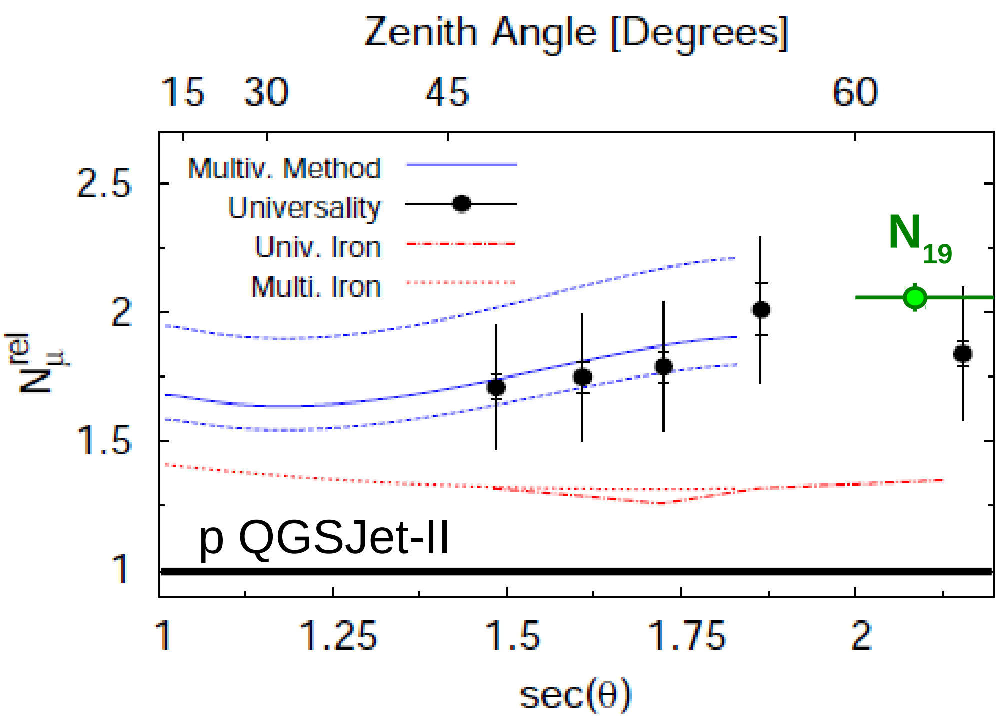
Auger

Multivariate muon jump method $0^\circ < \theta < 55^\circ$

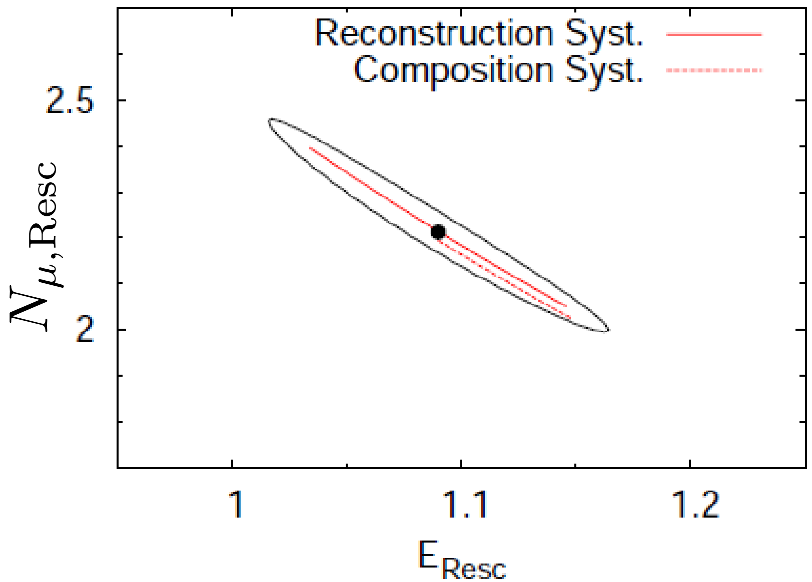
Shower universality method $45^\circ < \theta < 65^\circ$

Simulation matching method $0^\circ < \theta < 60^\circ$

N_{19} method $60^\circ < \theta < 80^\circ$



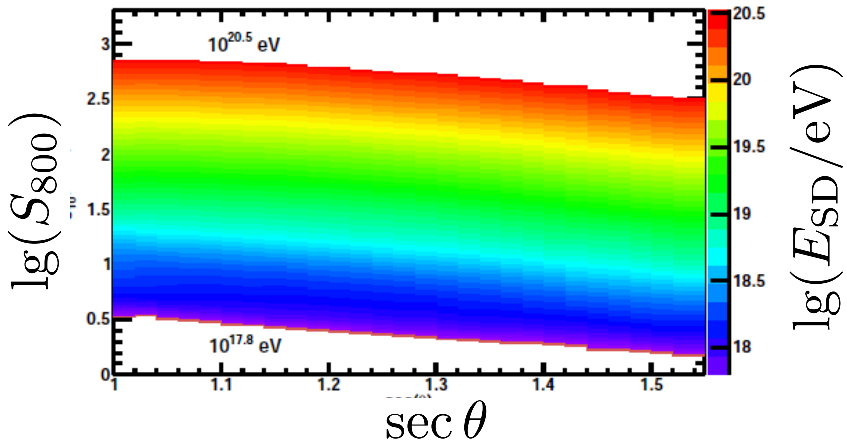
Simulation matching method using SENECA



T. Abu-Zayyad [TA Collab.],
ICRC Beijing, 2011

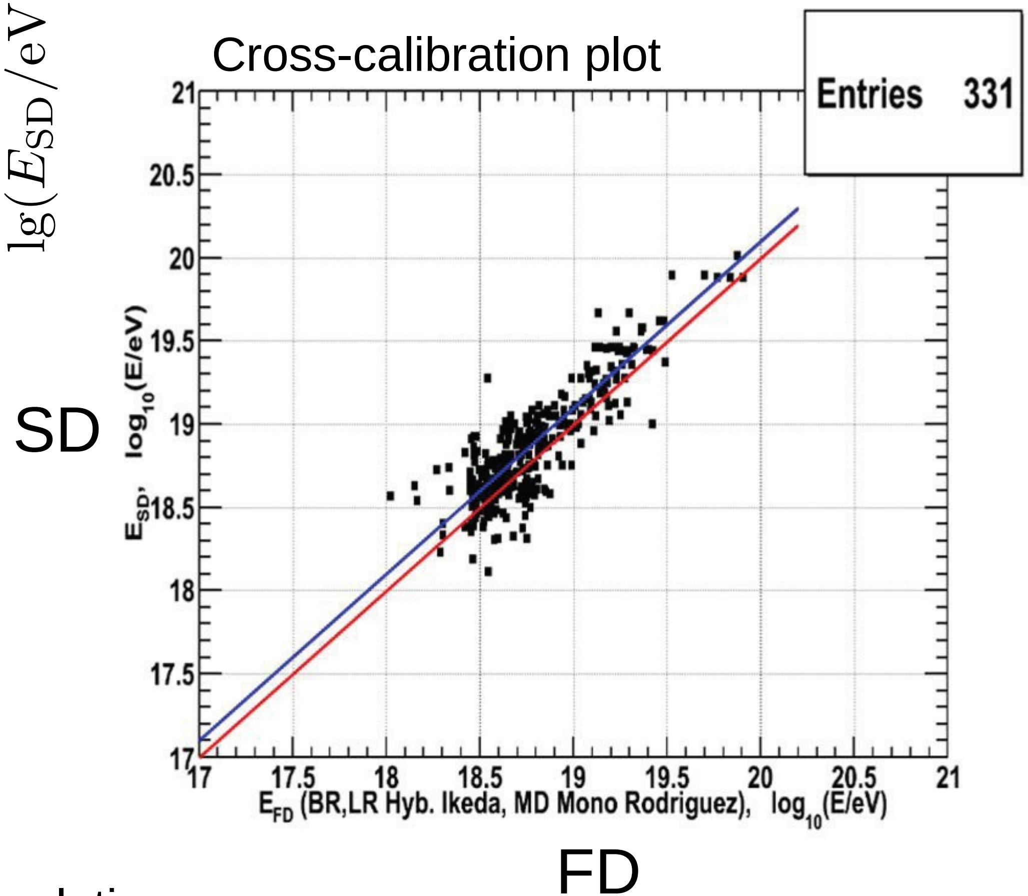
Muon excess in TA?

E_{SD} from COSMOS simulation



From cross-calibration
of TA hybrids

$$E_{\mathrm{SD}} = 1.27 \times E_{\mathrm{FD}}$$



Ground signal S_{800} larger than
expected from COSMOS proton simulations

Air shower observables and Hadronic interactions

R. Ulrich, R. Engel, M. Unger,
Phys. Rev. D, 2011

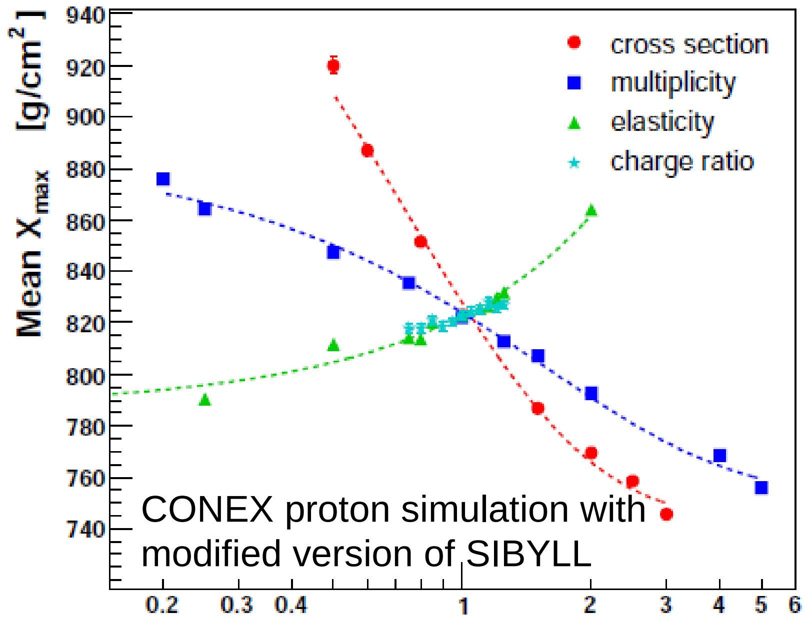
Hadronic interactions

Investigate connection

X_{max}, N_e, N_μ (Mean, Fluctuation) ↔ cross-section, multiplicity, elasticity, A

N_μ can be observed with SD at θ > 60° and dedicated muon detectors (e.g. AMIGA)

$\langle X_{max} \rangle$	X-section, multiplicity, elasticity
RMS(X_{max})	**X-section**
$\langle N_e \rangle$	X-section, multiplicity, elasticity
RMS(N_e)	X-section, multiplicity
$\langle N_\mu \rangle$	$\pi^{+/-}$ to π^0 ratio, **multiplicity**
RMS(N_μ)	**elasticity**



f_{19} energy dependent scale factor

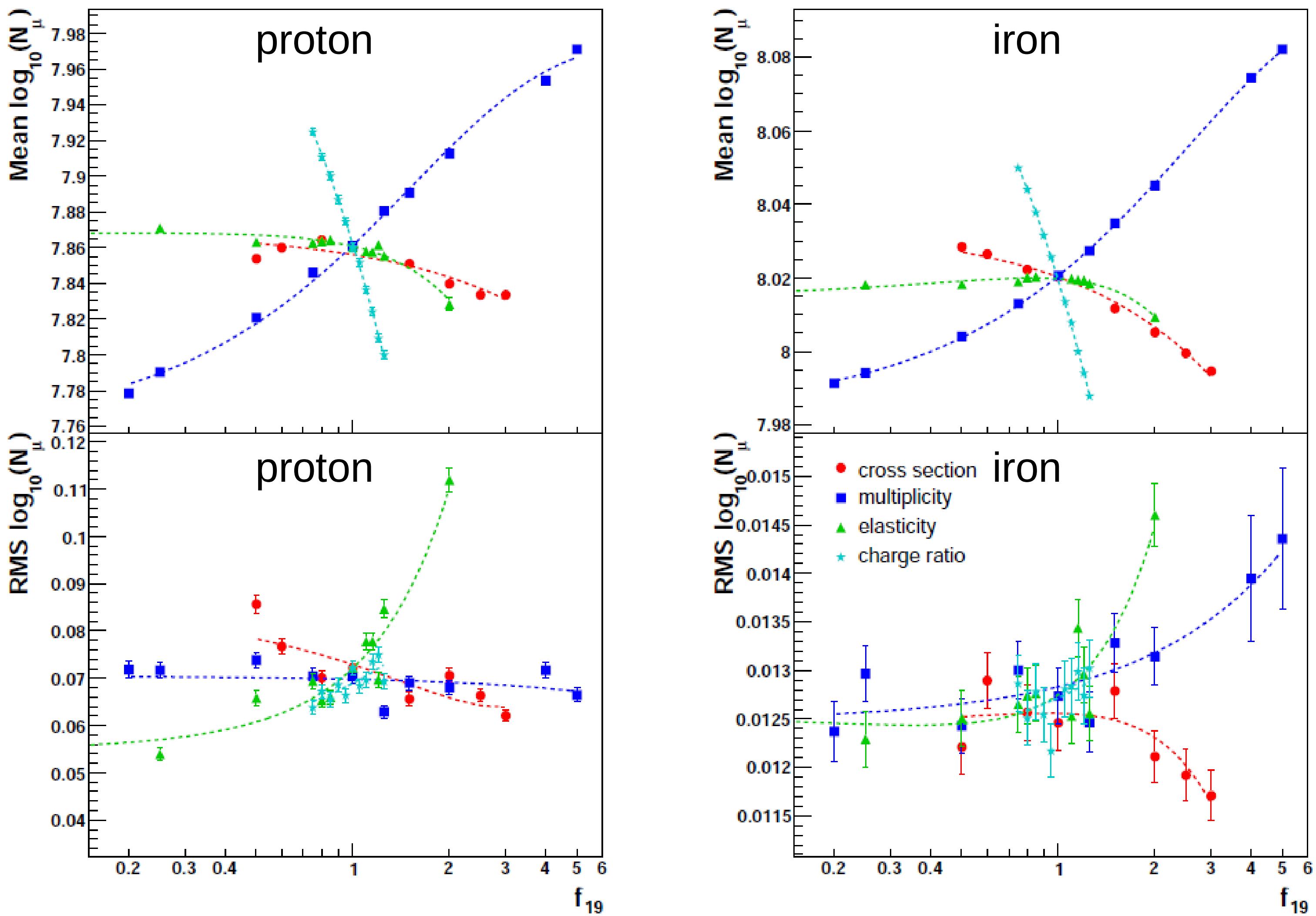
Challenge: $\langle \ln A \rangle \neq 0$ and changing with *E*
effect needs to be modeled, too

Summary

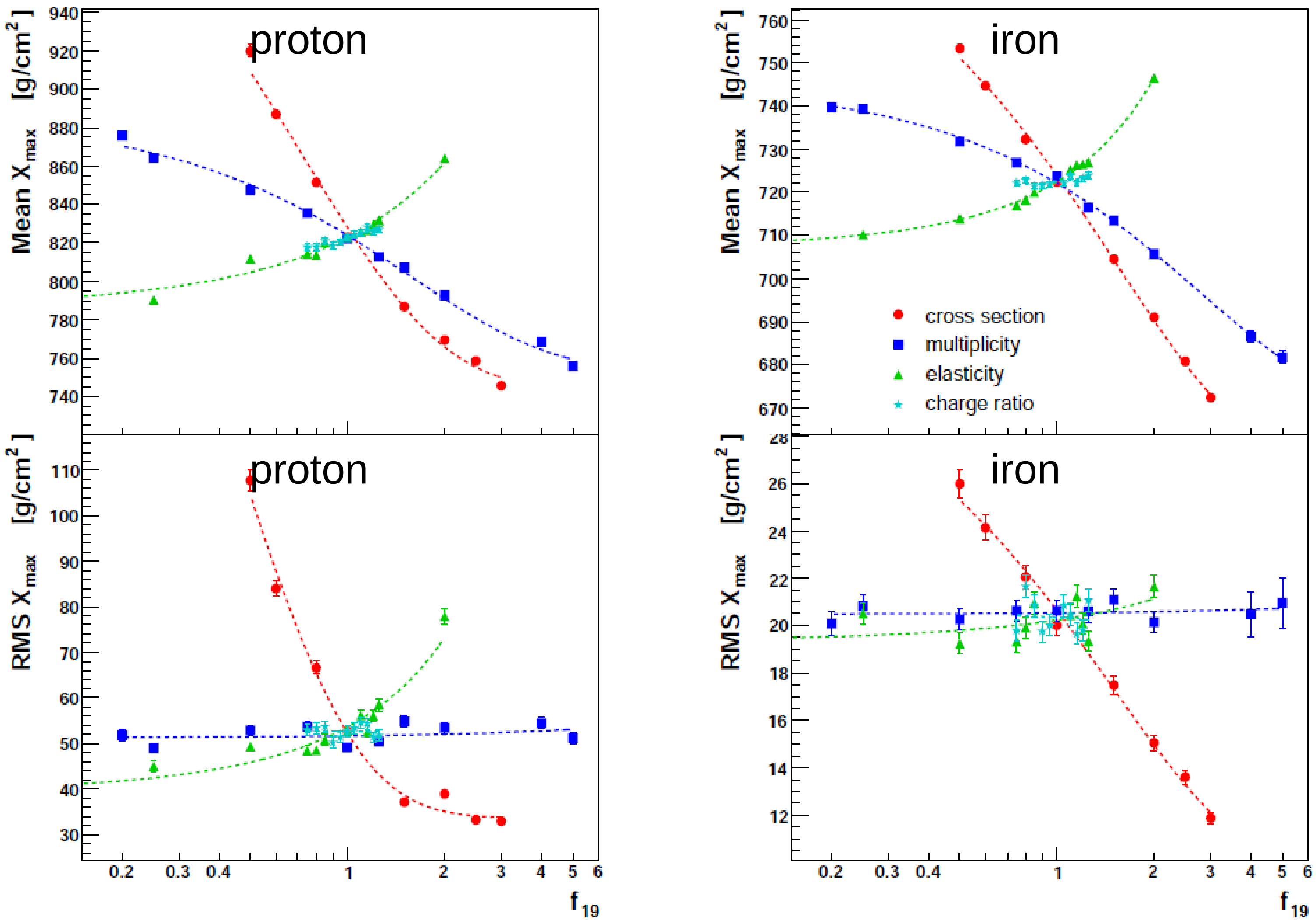
- Energy spectrum (HiRes, Auger, TA) **+++**
  - Agreement within systematic uncertainty of energy scale
  - Cross-calibration desirable, need world-average of fluorescence yield
- Mass composition (HiRes, Auger, TA) **++**/**––**
  - Consistency between Auger FD and Auger SD
  - **Discrepancy** between HiRes (possibly TA) and Auger! Analysis/Interpretation issue?
- Limits on photons/neutrinos (HiRes, Auger, TA) **+++**
- p-air cross-section (HiRes, Auger) **++**
- Muon number (Auger) **++**
  - Large muon excess in data for any mass assumption/model, TA also sees hints
- Hadronic interaction properties: cross-section, elasticity, multiplicity
  - Only indirect measurement with significant model dependency
  - Best observables $\langle X_{\mathrm{max}} \rangle$, $\mathrm{RMS}(X_{\mathrm{max}})$, $\langle N_\mu \rangle$, $\mathrm{RMS}(N_\mu)$

Backup

Hadronic model influence



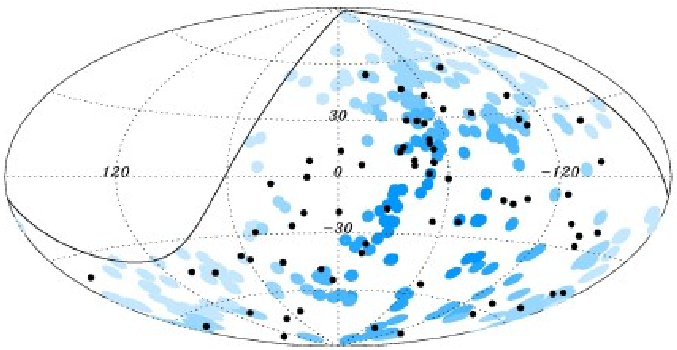
Hadronic model influence



Anisotropy

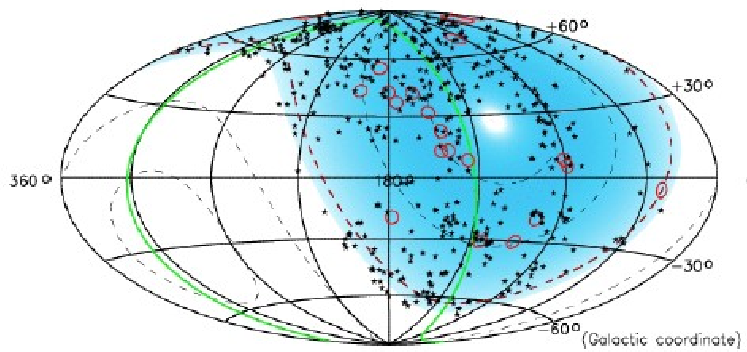
VCV catalogue, E> 57 EeV, z<0.018, distance < 3.1 deg.

Auger



28 out of 84 correlate

TA

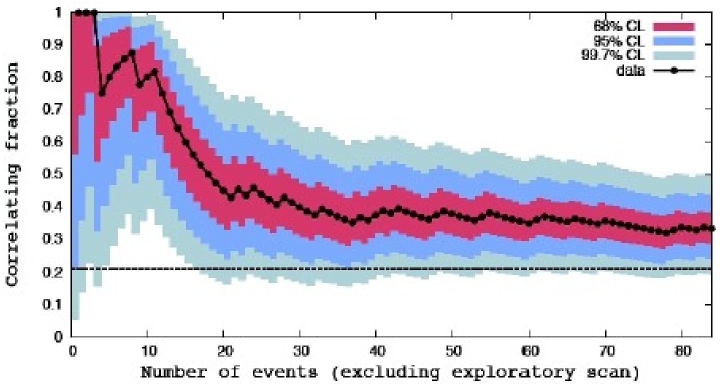


8 out of 20 correlate

Anisotropy

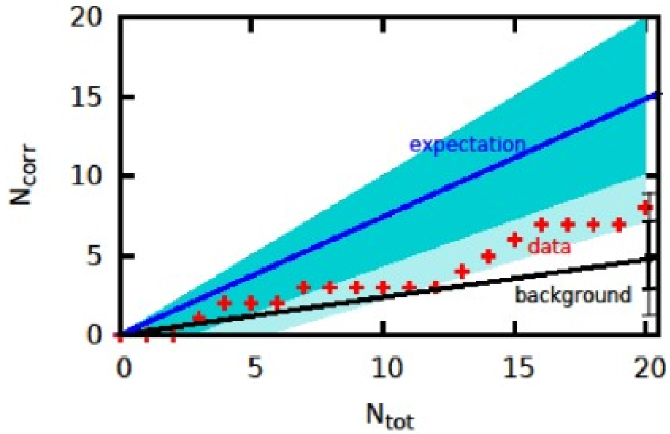
VCV catalogue, E> 57 EeV, z<0.018, distance < 3.1 deg.

Auger



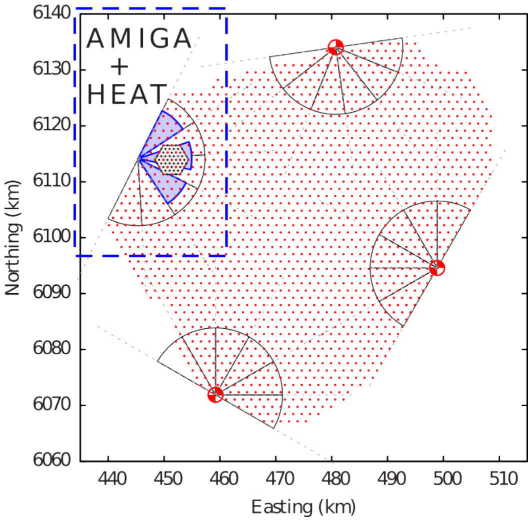
$P = 0.006,\ f = 33 \pm 5\%$

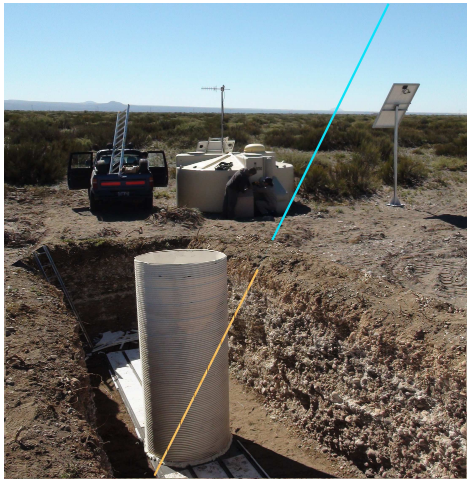
TA



compatible with isotropy and updated (!) Auger

Pierre Auger Observatory (10^{17} – 10^{18}) eV

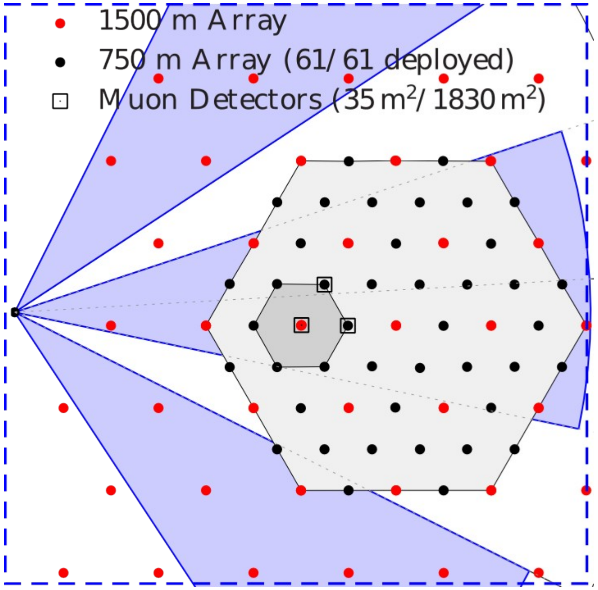


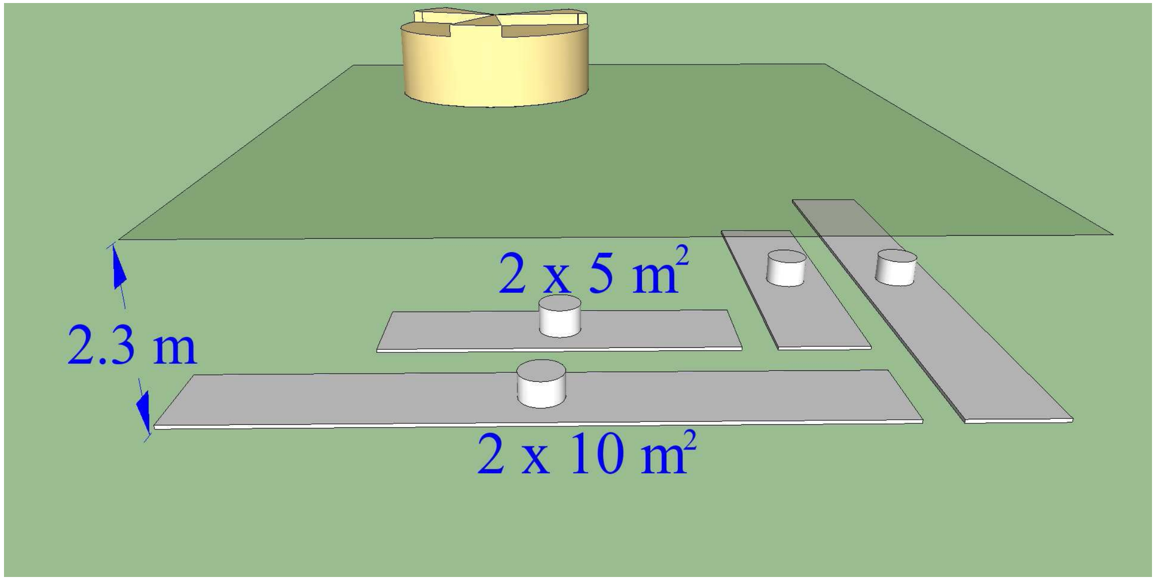


AMIGA

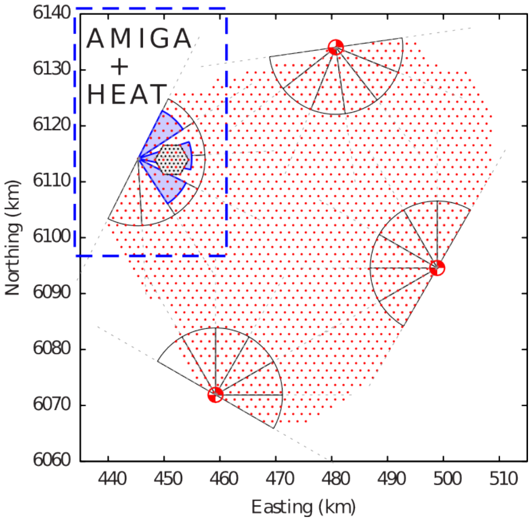
– Auger stations with 750 m spacing
– Buried 30 m² scintillation detectors (muon counters)

$$E^{\mu}_{\mathrm{thr}} \approx 1\mathrm{GeV}$$



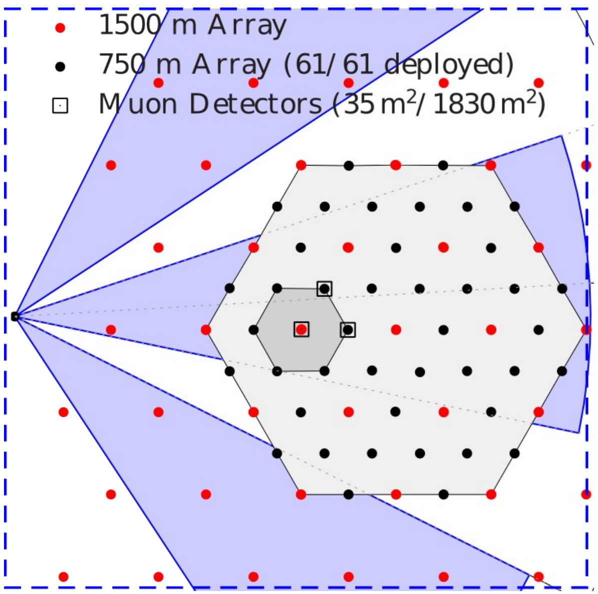


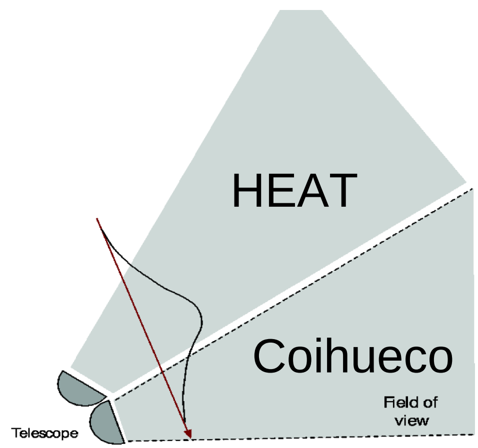
Pierre Auger Observatory (10^{17} – 10^{18}) eV

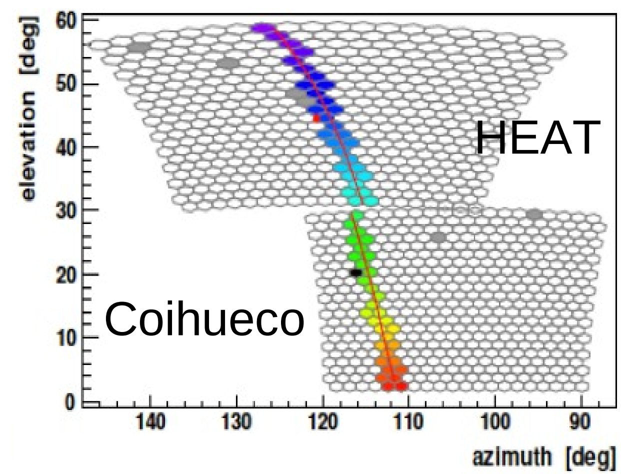


HEAT

– Tiltable Auger FD telescopes
– Elevated field of view from 30° to 60°
– Double time resolution

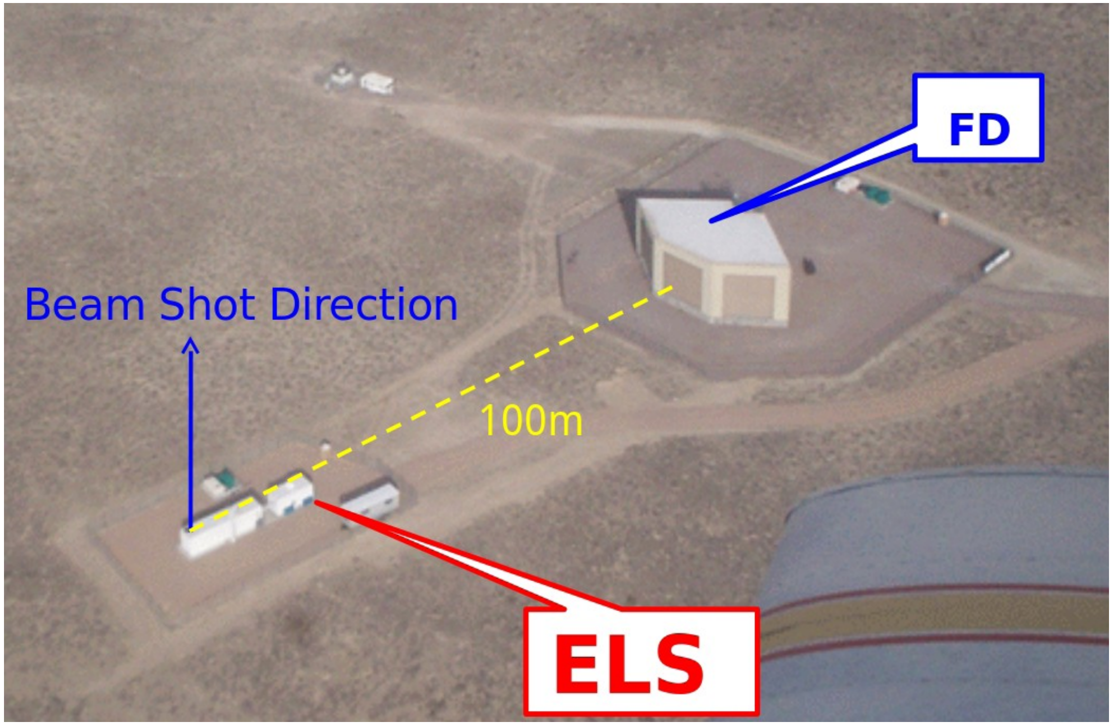


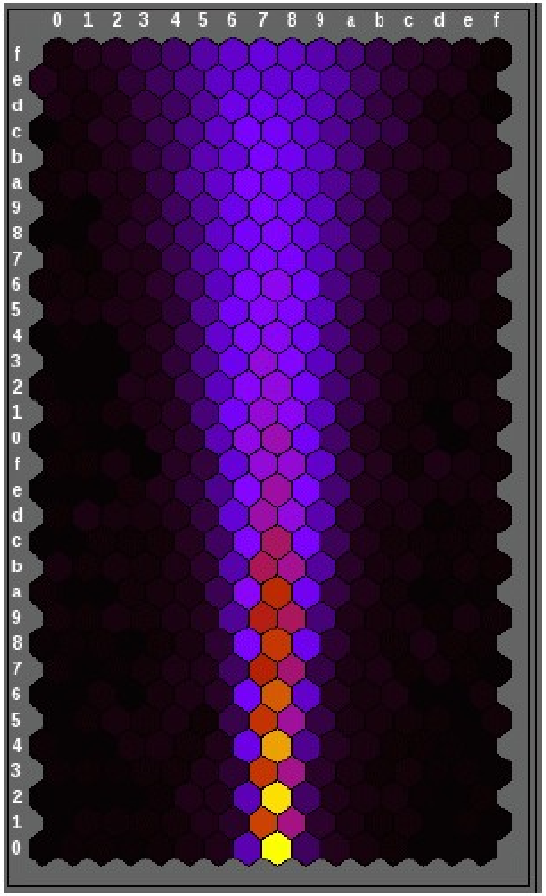




Improved calibration techiques

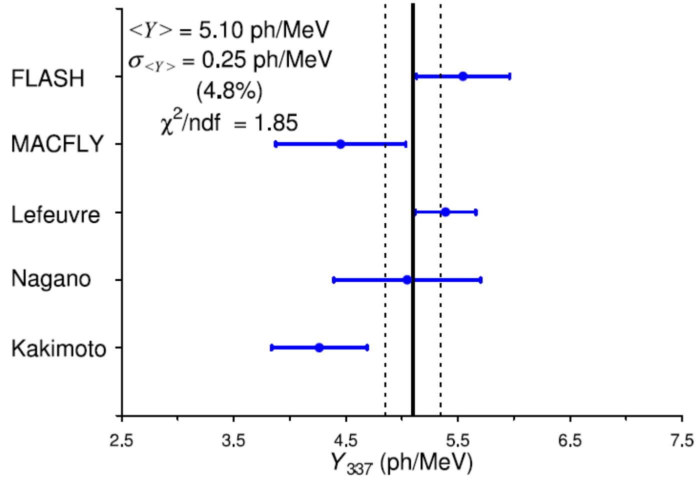
Electron light source at Telescope array site





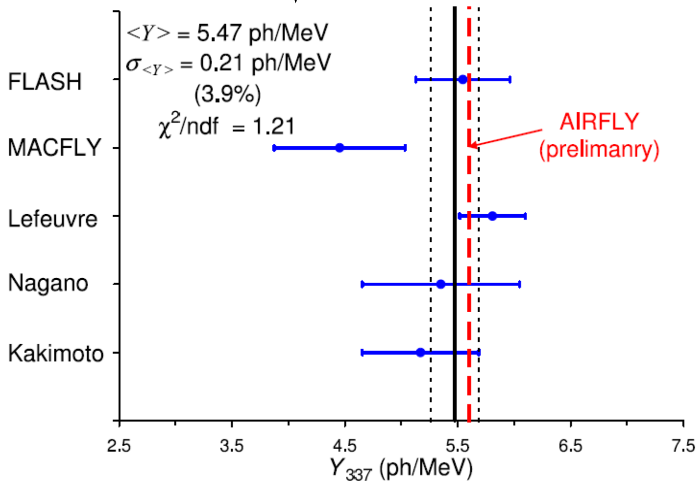
40 MeV electron beam pulse as seen by TA telescope

FD energy scale



MC corrections

F. Arqueros et al.
ICRC 2011, Beijing



Fluorescence yield
– New AIRFLY measurements σ_{sys} ~ 4 %
– Experiments should decide on world average

Experiments should cross-calibrate using common light source