Some Comments on the Energy Scale of the Pierre Auger Observatory

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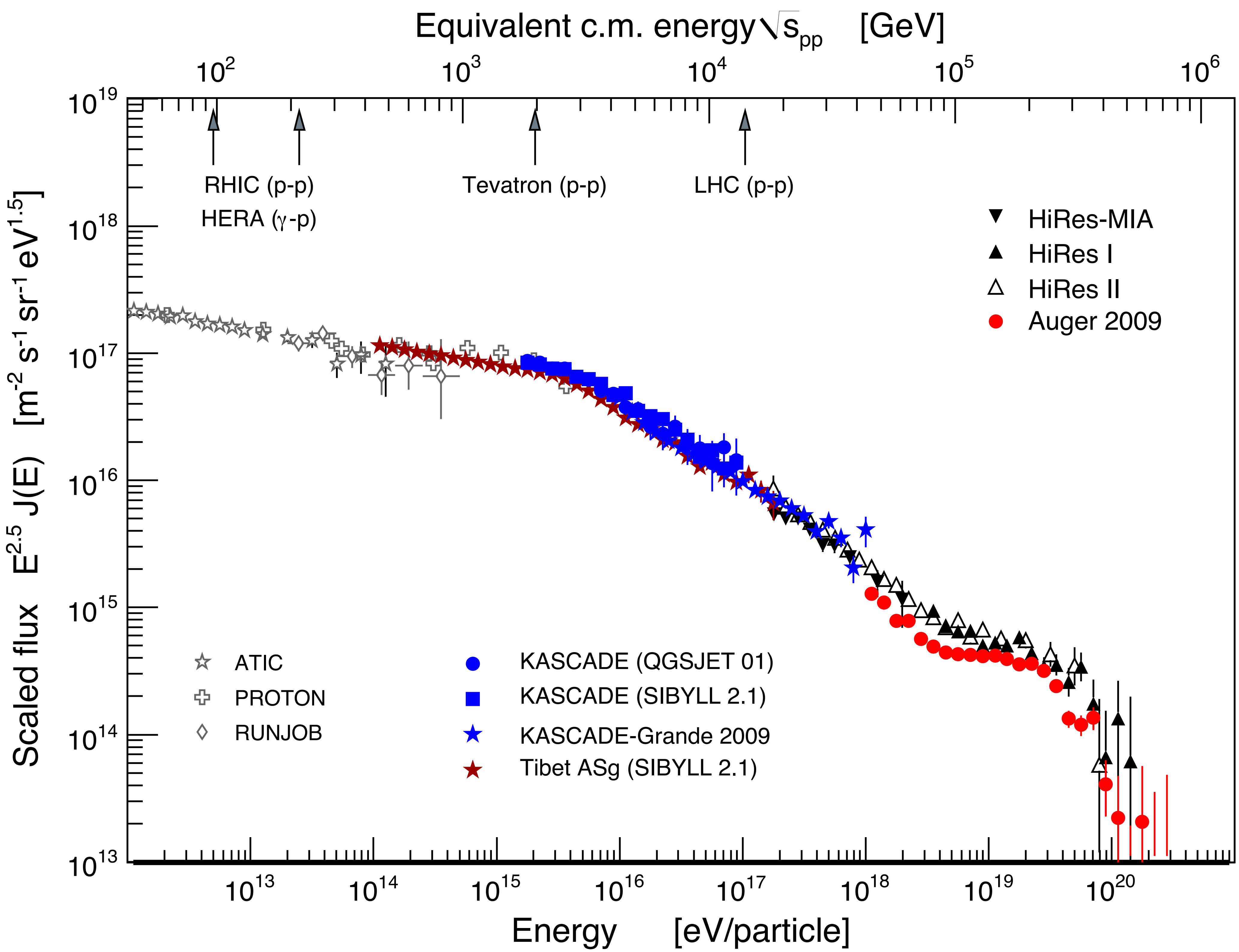
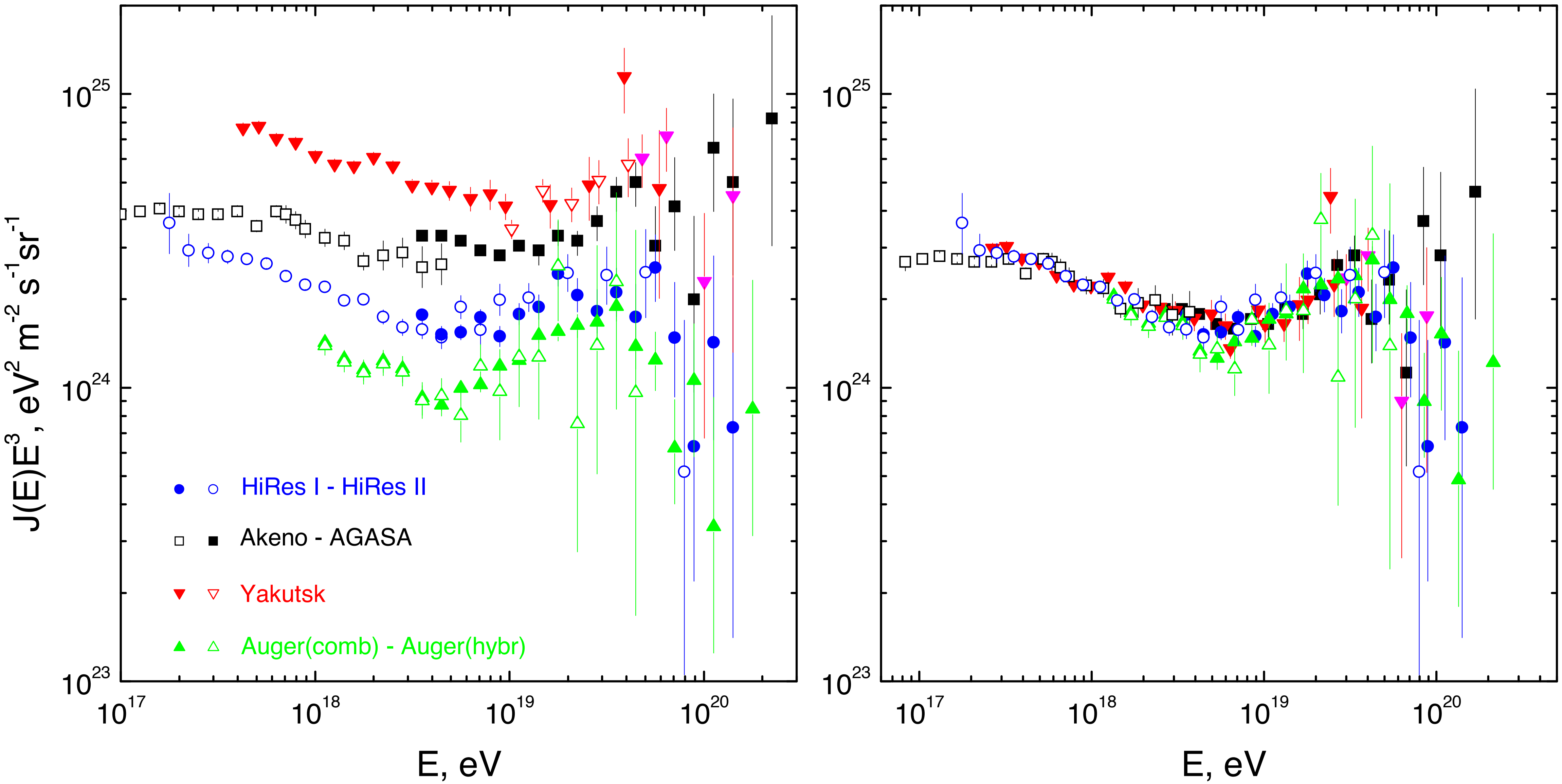
Current status of all-particle flux



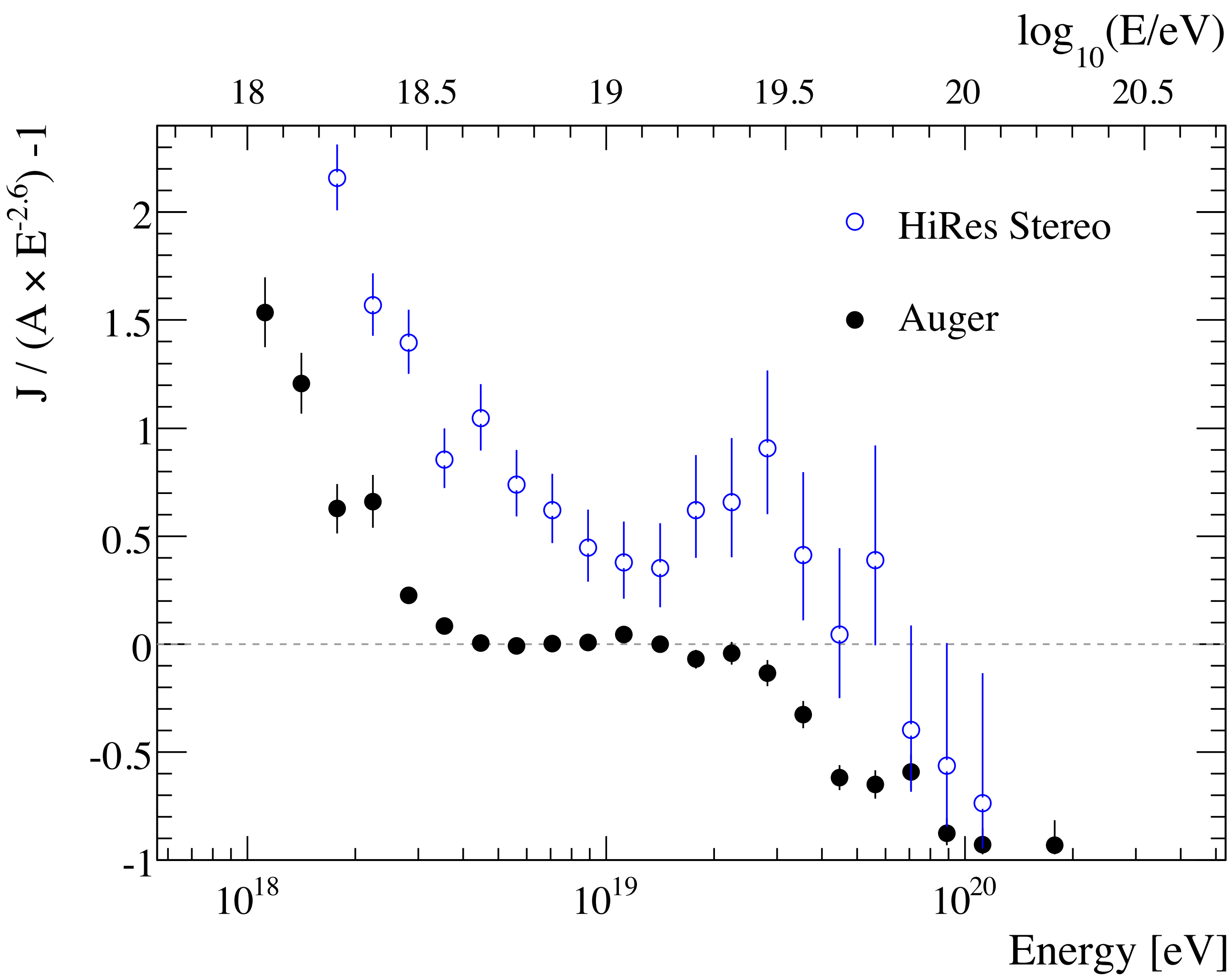
Energy scale uncertainty vs. all-particle flux (iv)

Good agreement between different experiments if energy is shifted

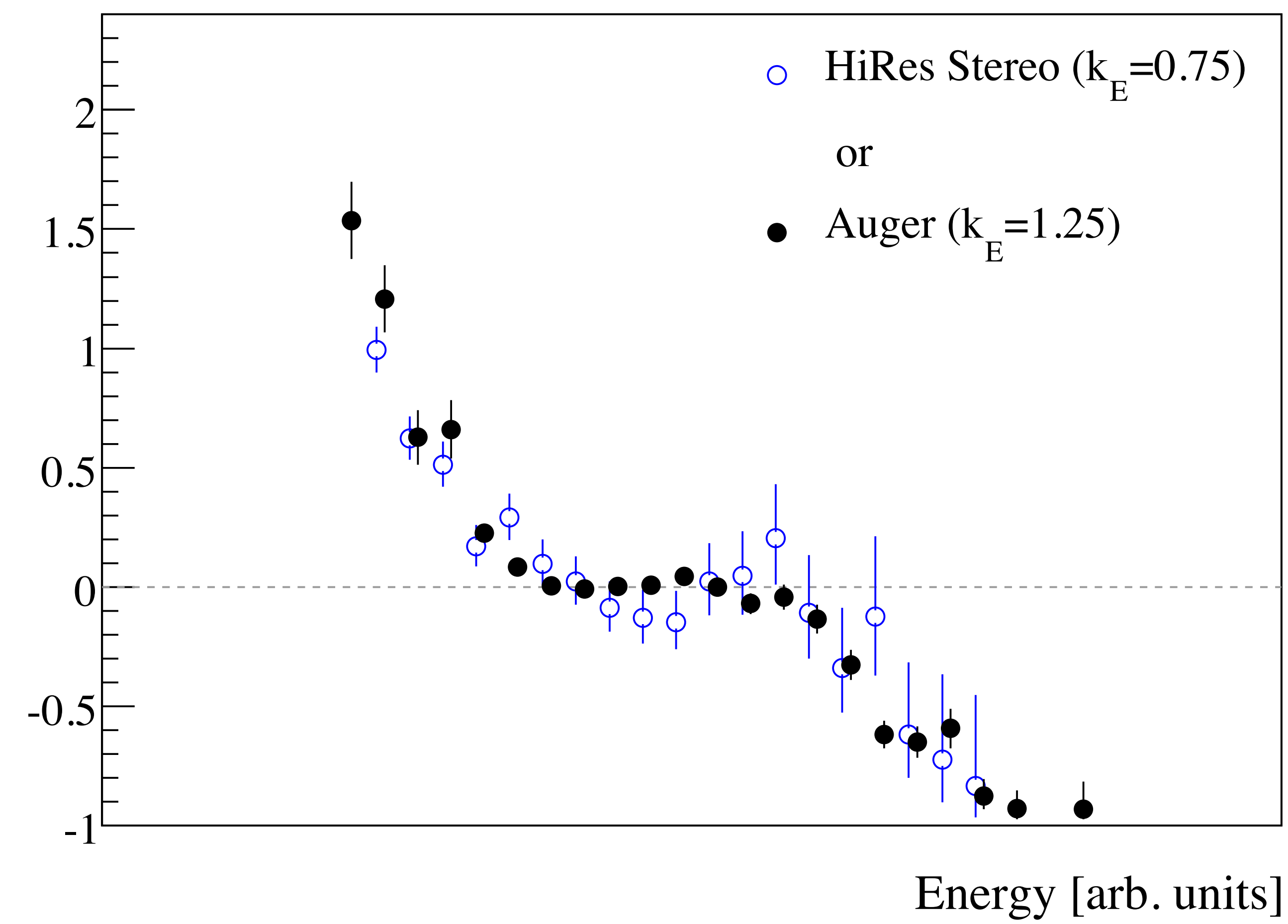


(Berezinsky, J. Phys. Conf. Ser., 2008)

Energy scale uncertainty vs. all-particle flux (ii)



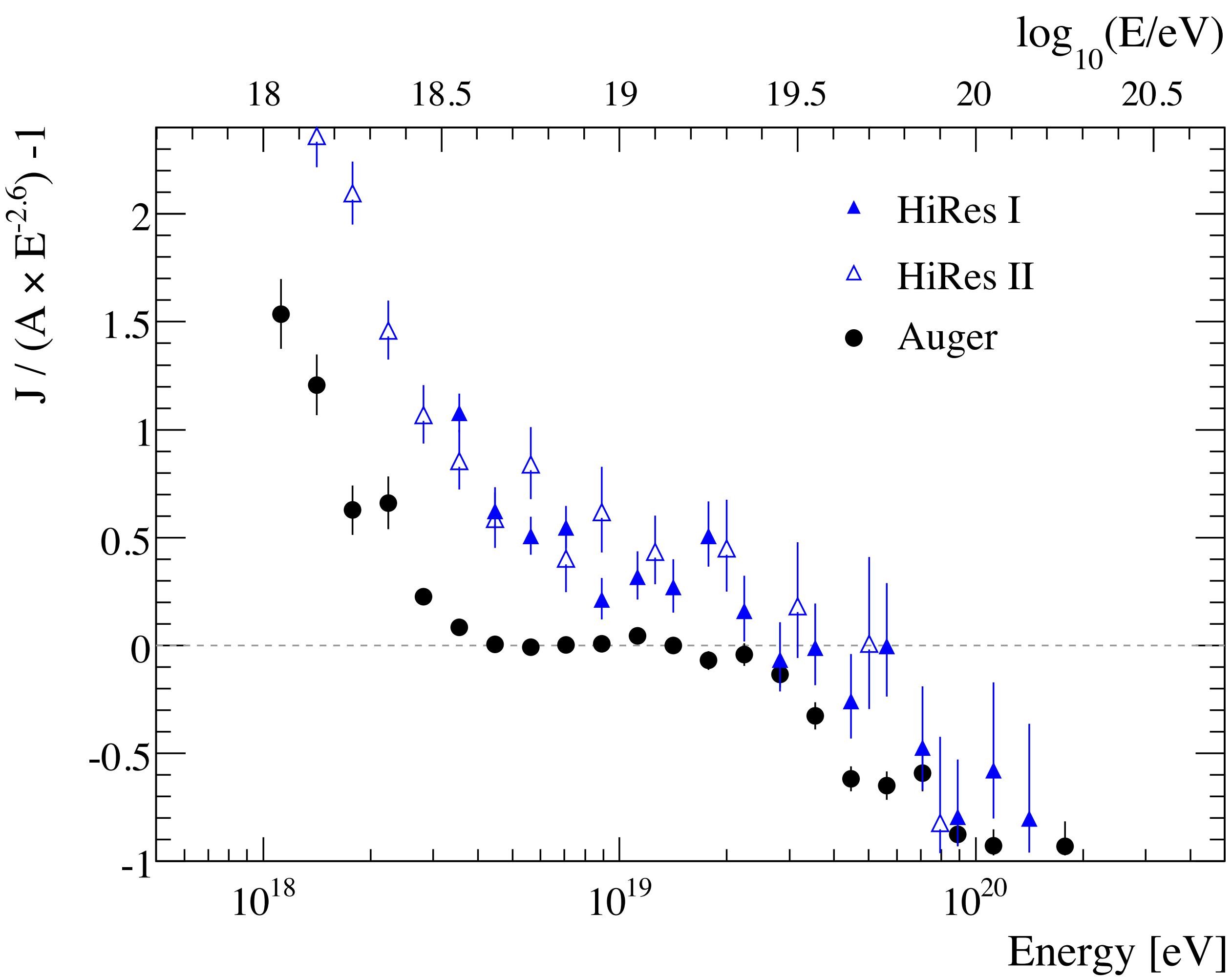
Auger combined spectrum:
22% sys. uncertainty



HiRes stereo spectrum:
17% sys. uncertainty

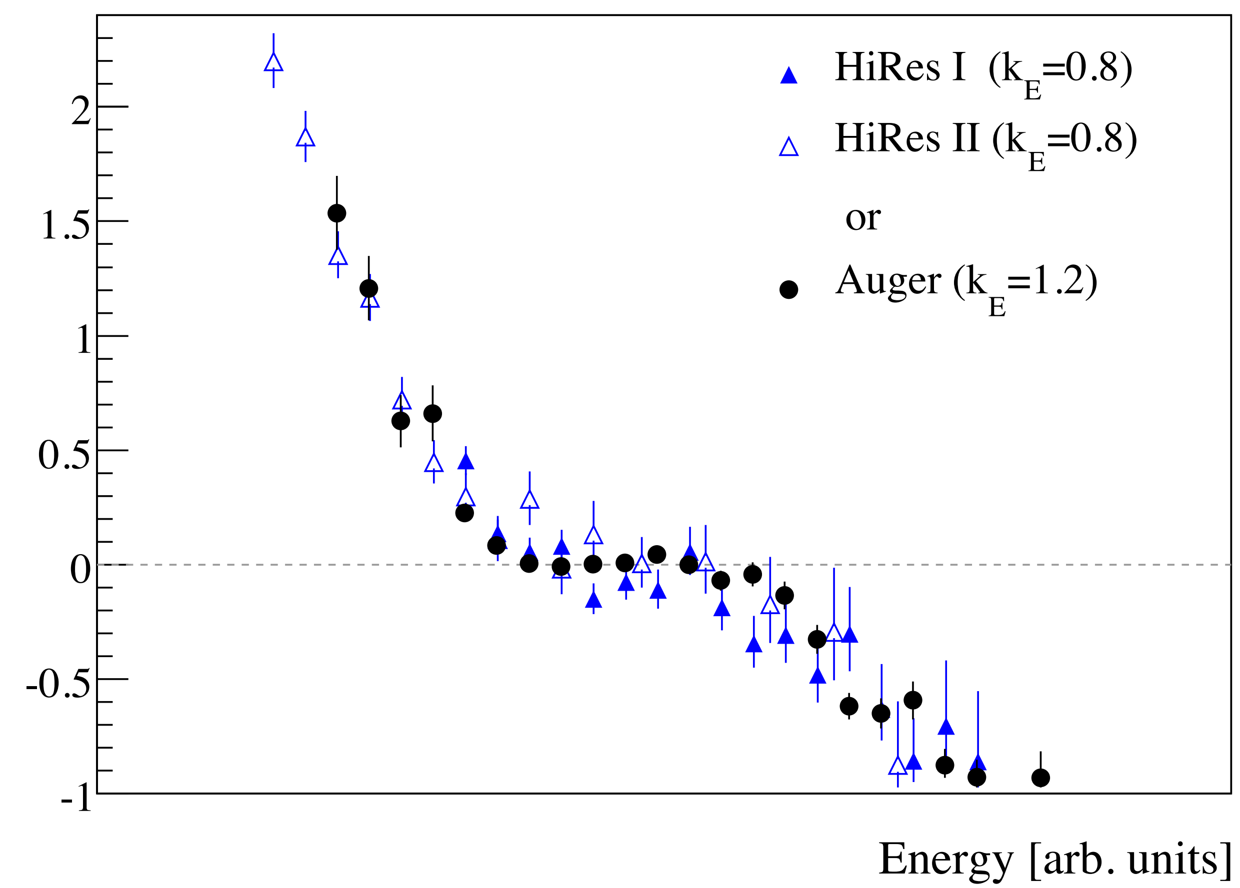
Total energy shift ~25%

Energy scale uncertainty vs. all-particle flux (iii)



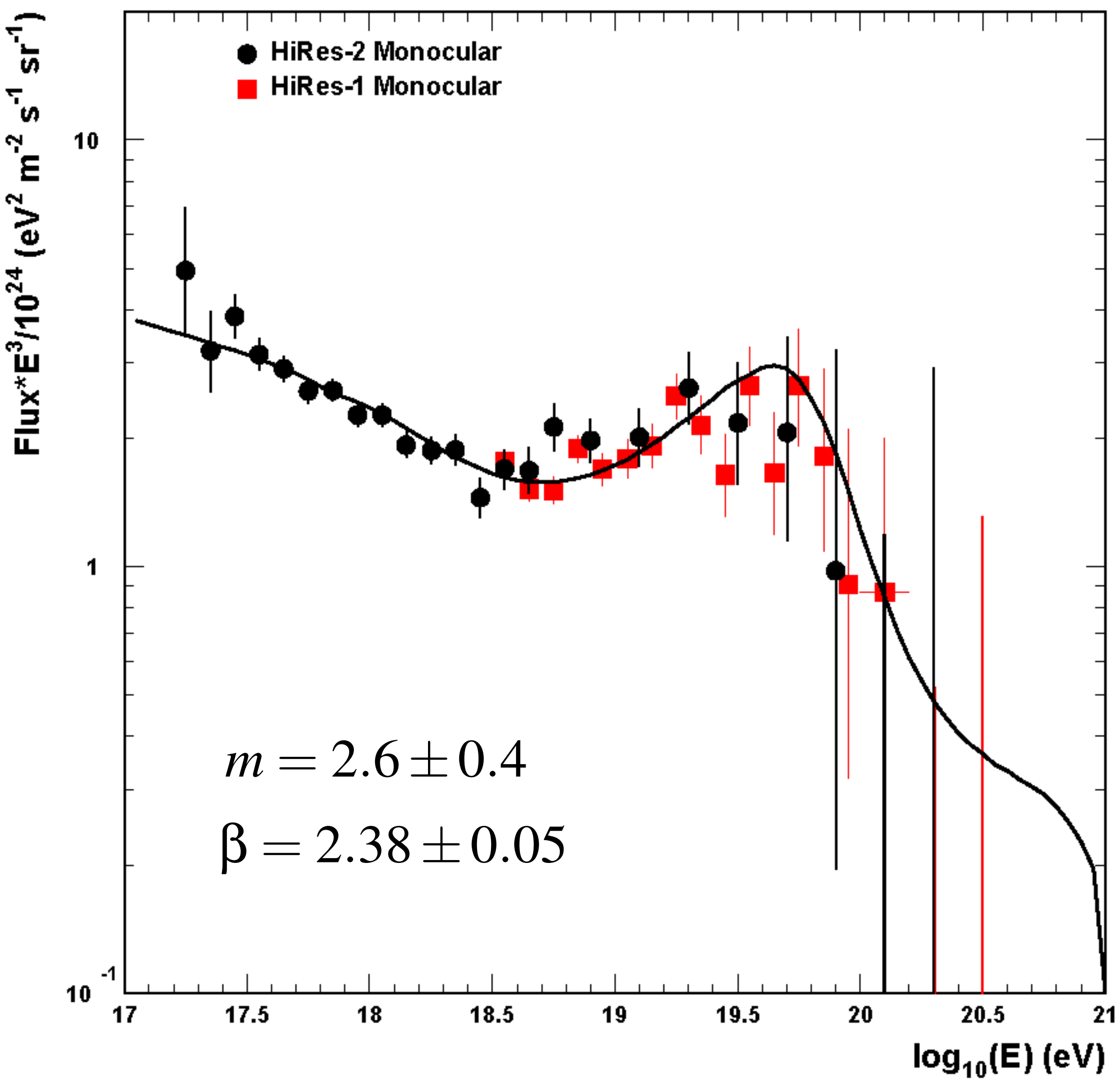
HiRes I & II mono spectra:
17% sys. uncertainty

Auger combined spectrum:
22% sys. uncertainty



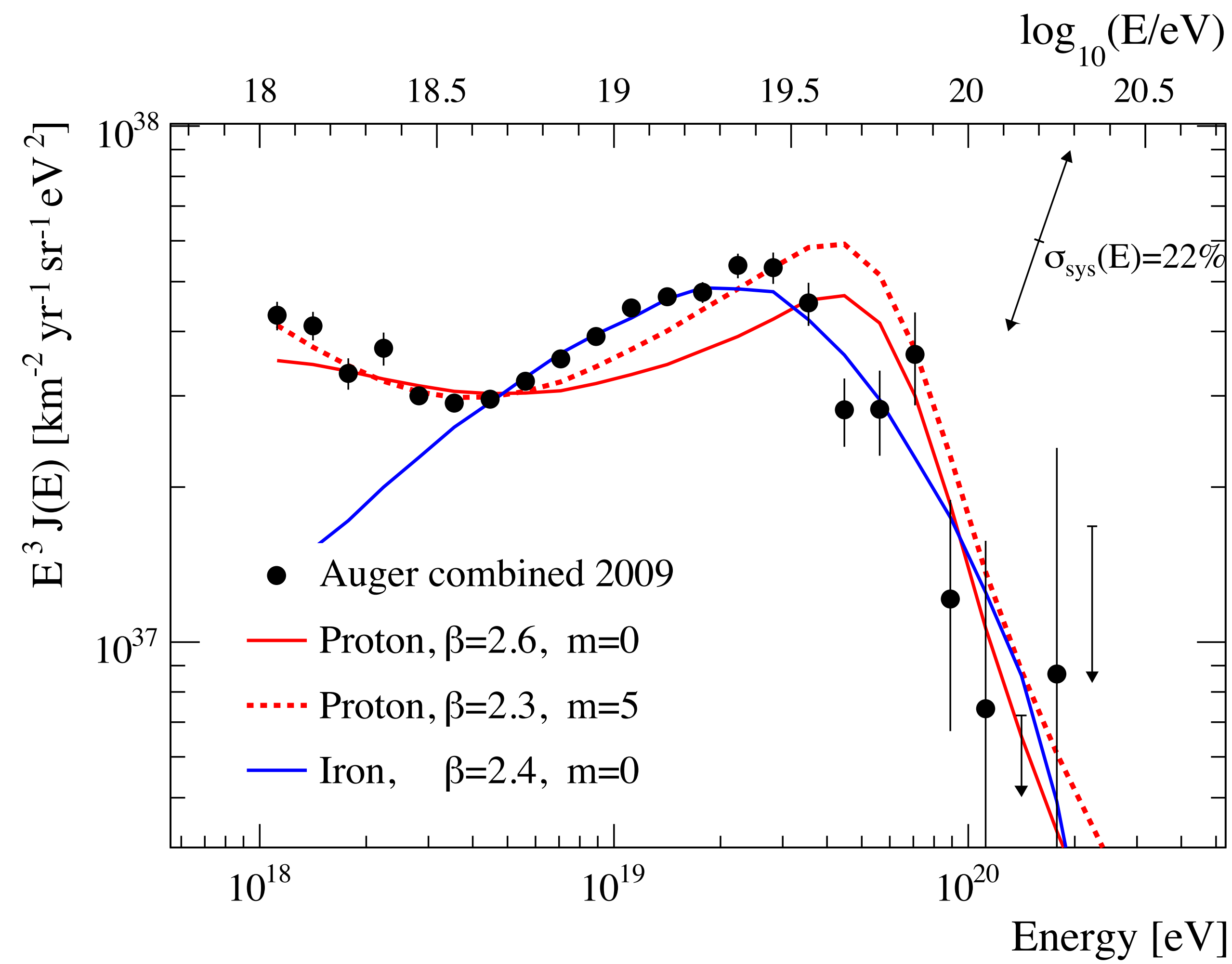
Total energy shift ~20%

Energy scale uncertainty vs. all-particle flux



(HiRes, Phys. Lett. B, 2005)

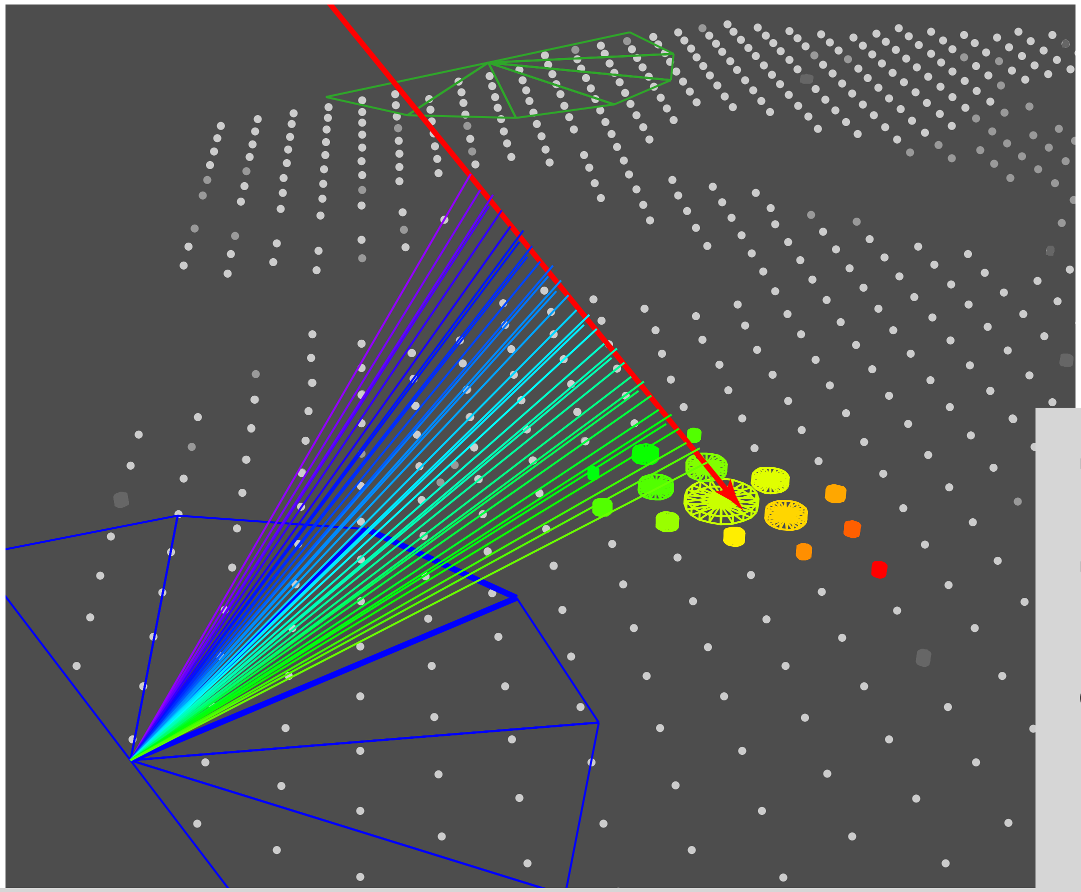
$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim (1+z)^m \, E^{-\beta}$$



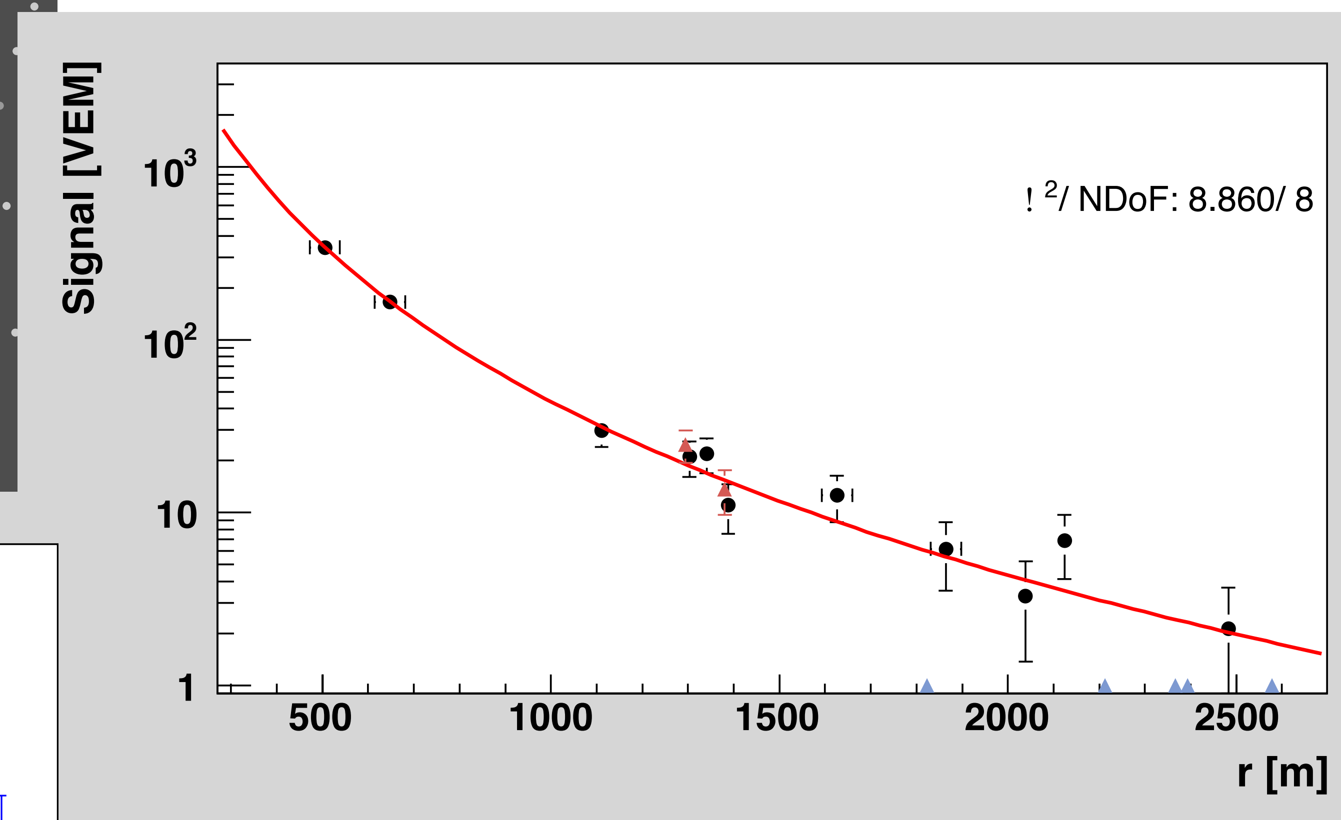
(Auger, ICRC 2009)

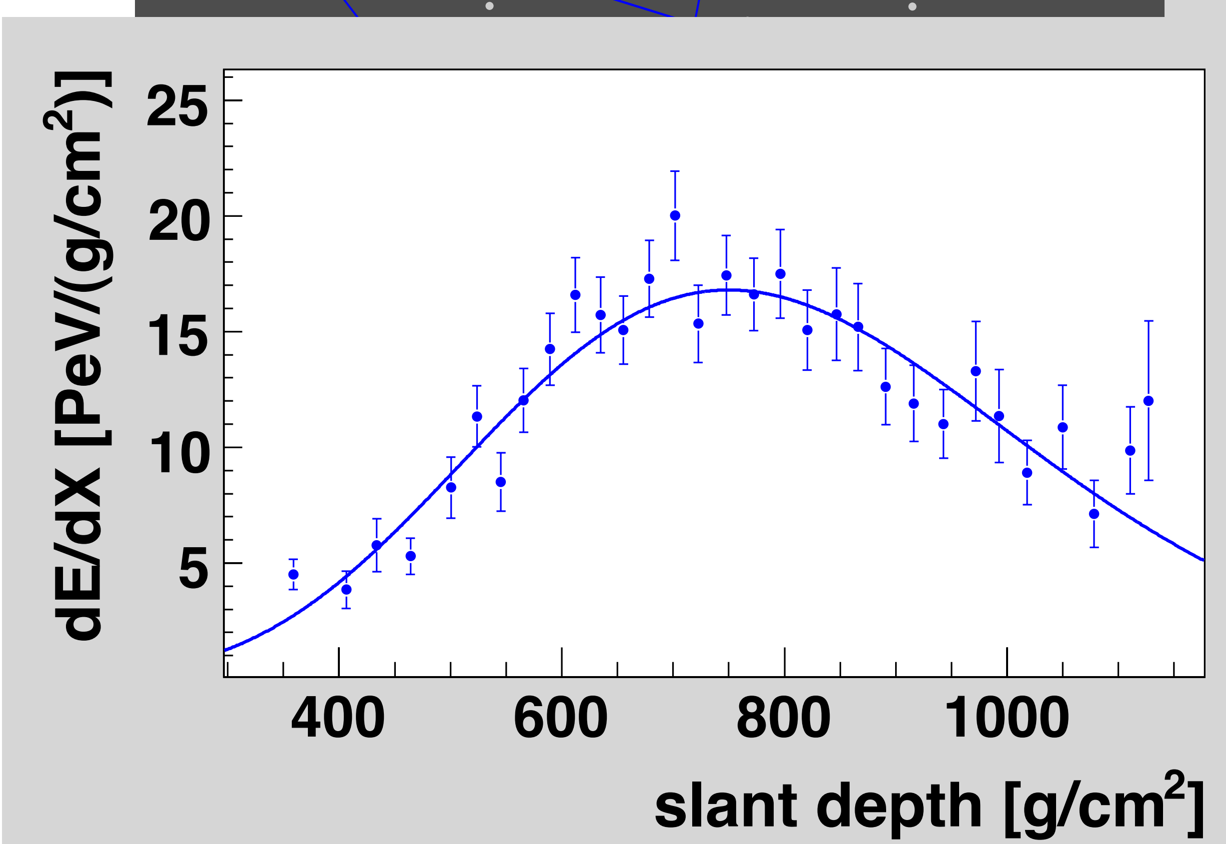
Physics interpretation only possible if sys. uncertainty of flux will be reduced

Recap of energy assignment to showers



- S1000 as energy estimator
- Transformation to 38°
- Calibration with hybrid events





Calorimetric energy $$E_{\rm cal} = \int \frac{{\rm d}E_{\rm ion}}{{\rm d}X}\,{\rm d}X$$

Missing energy correction $$E_{\rm tot} = f \cdot E_{\rm cal}$$

Method of constant intensity cuts

Model independent method for isotropic arrival direction distribution

In general energy-dependent function, within current statistics same shape

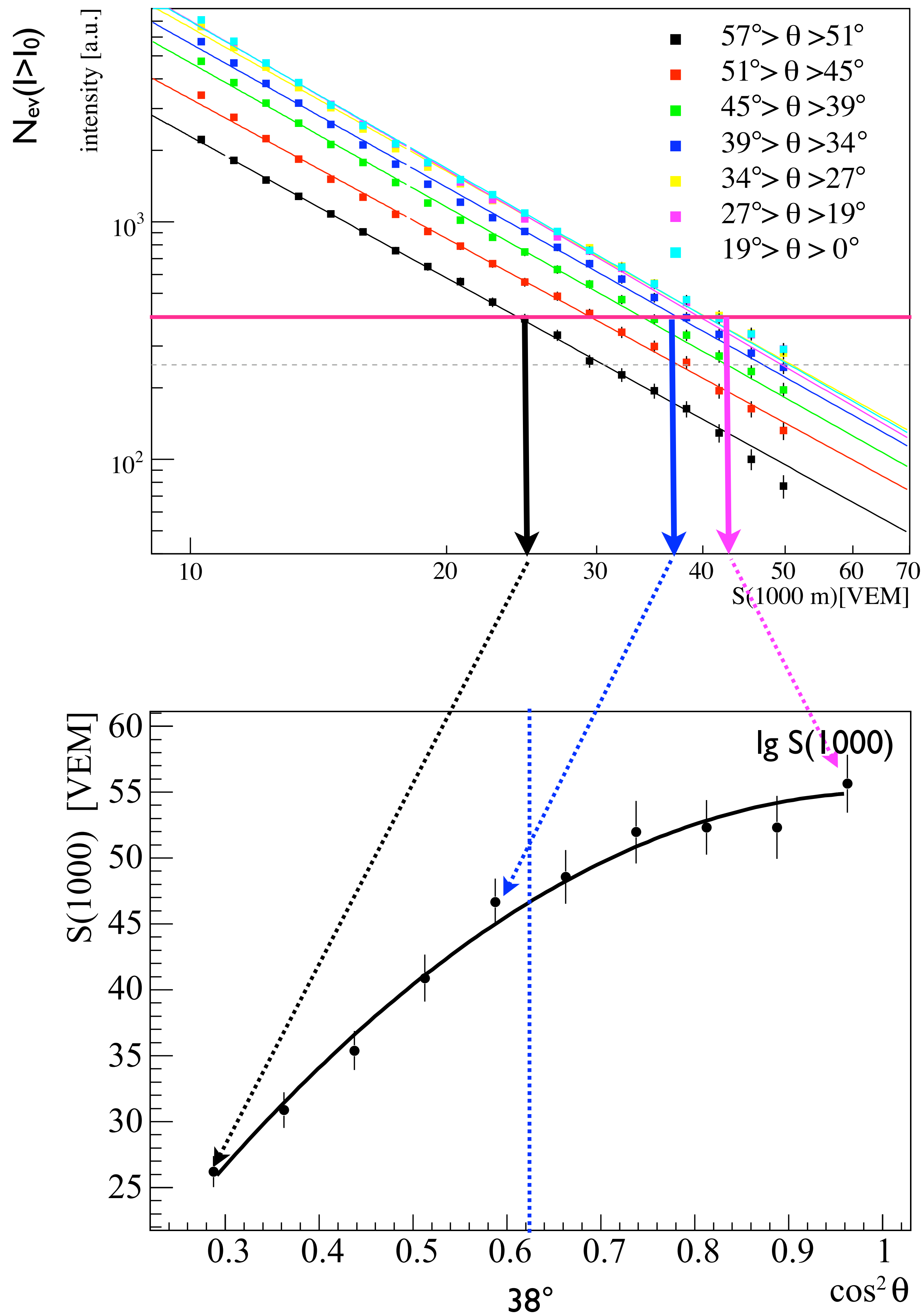
$$S_{38^\circ} = S(1000)/CIC(\theta)$$

$$CIC(\theta) = 1 + ax + bx^2$$

$$x = \cos^2\theta - \cos^2 38^\circ$$

$$a = 0.90 \pm 0.05$$

$$b = -1.26 \pm 0.21$$



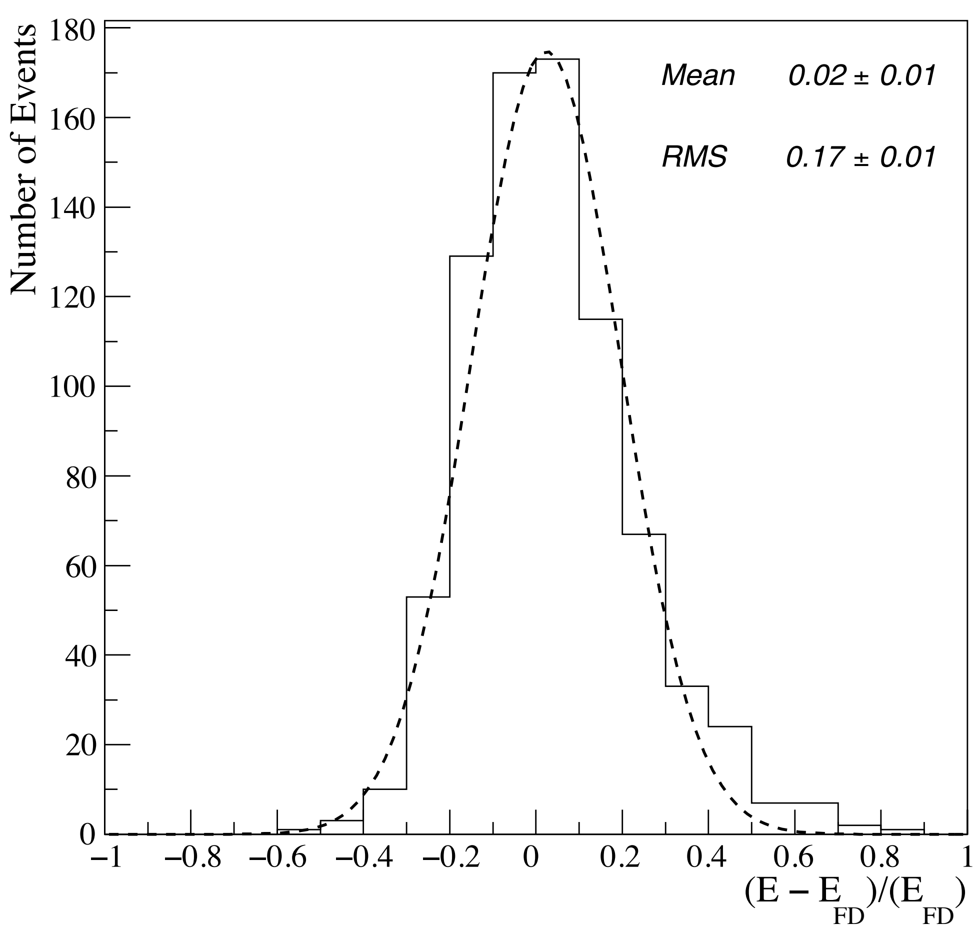
(Auger, ICRC 2009)

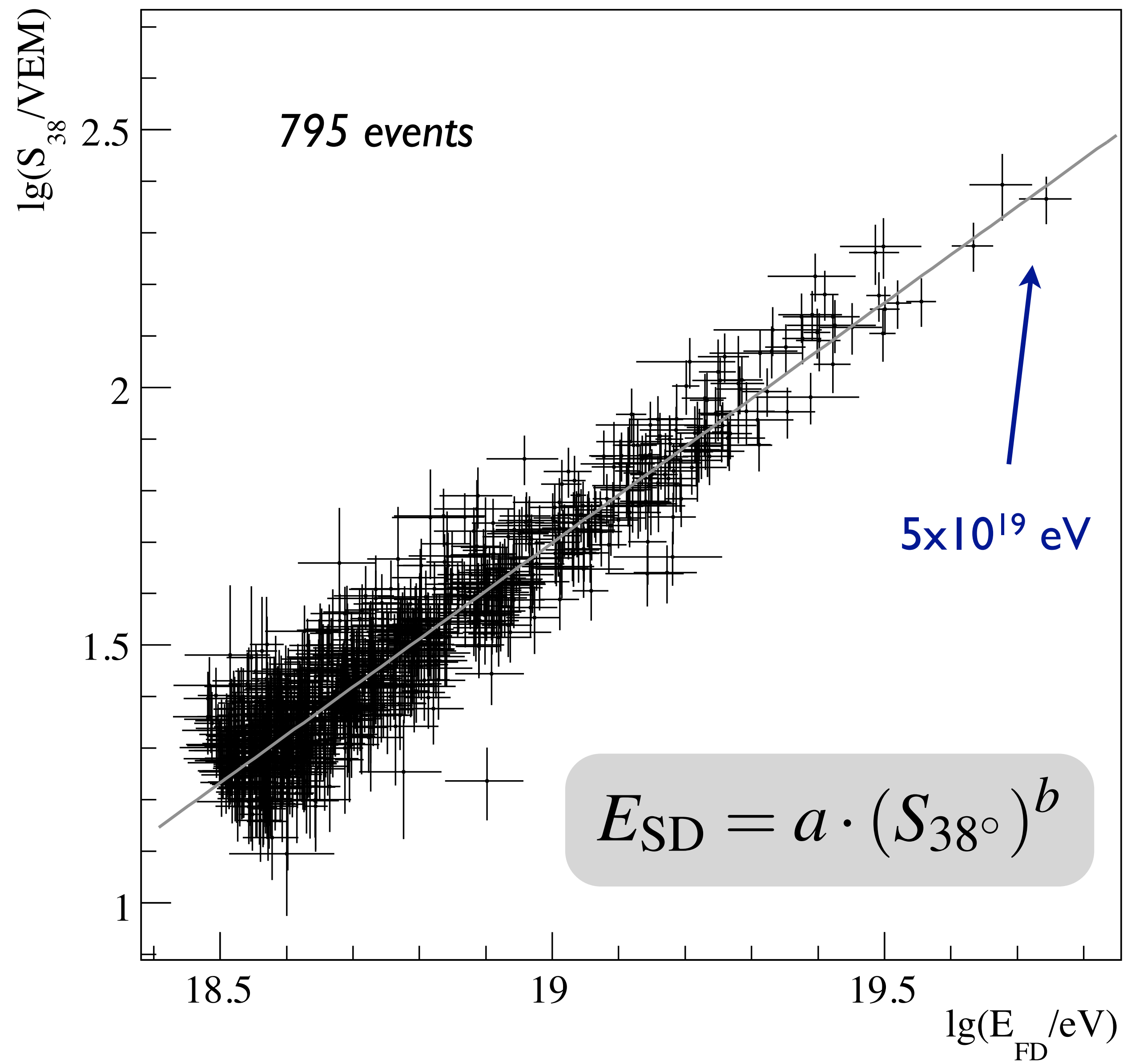
Fluorescence-to-surface detector cross-calibration

Energy uncertainty from cross-calibration procedure:

- 7% at 10^{19} eV
- 15% at 10^{20} eV

Will improve with increased hybrid statistics





With current statistics: no curvature required

$$a = (1.51 \pm 0.06(stat) \pm 0.12(syst)) \times\ 10^{17}\,\text{eV}$$
$$b = 1.07 \pm 0.01(stat) \pm 0.04(syst),$$

(Auger, ICRC 2009)

Summary of sources of uncertainty: fluorescence energy

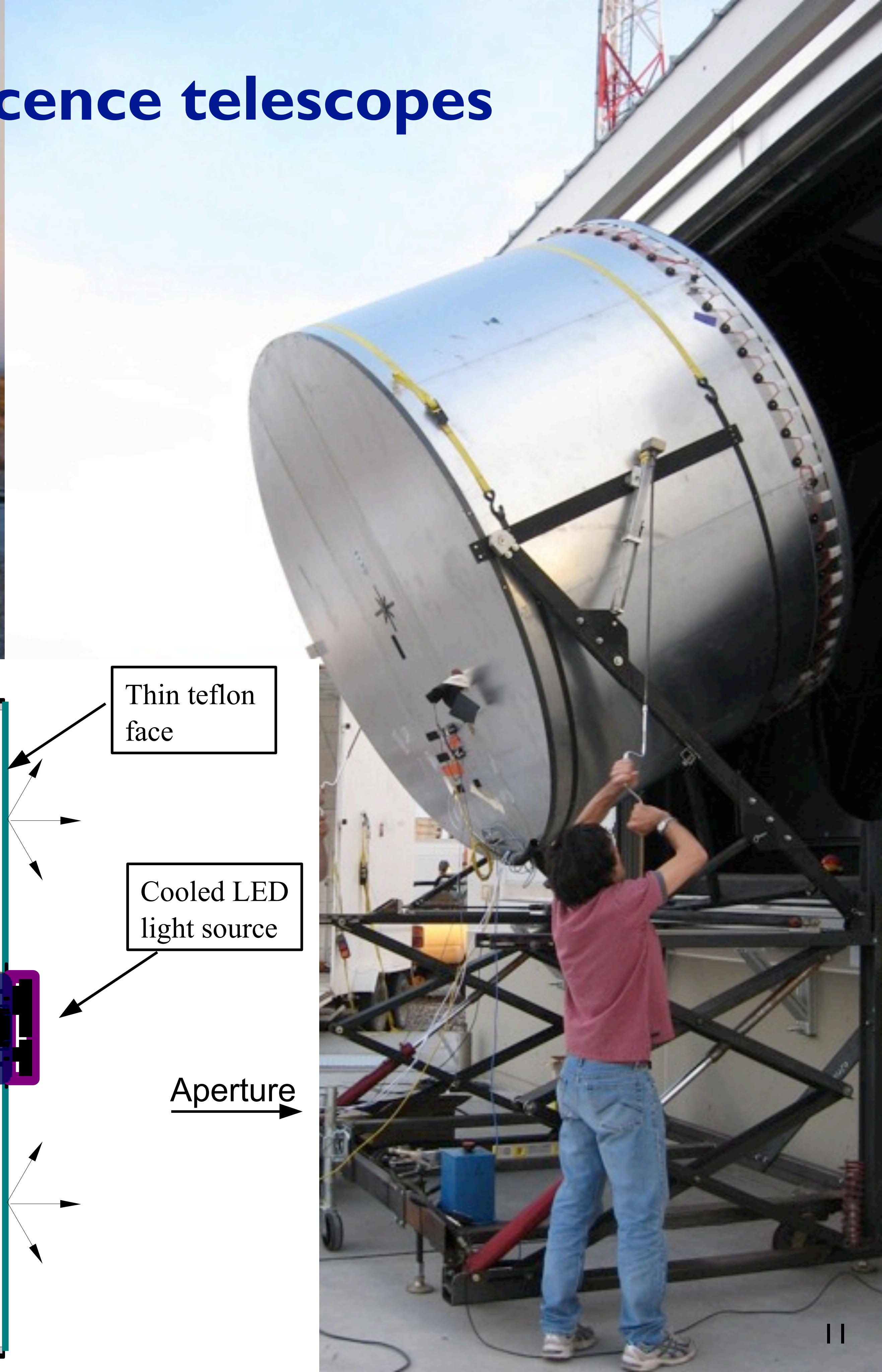
Auger Observatory 2009/2010

Uncertainty (%)	Source
14	Absolute fluorescence yield
10	Reconstruction of the longitudinal shower profile
9	Absolute calibration of the fluorescence telescopes
7	Aerosol optical depth
5	Water vapour quenching
4	Invisible energy
3	Wavelength dependent response
1	Molecular optical depth
1	Multiple scattering models
22	Total

HiRes mono spectra 2008

Photon calibration	10 %
Fluorescence yield	6 %
Missing energy correction	5 %
Aerosol concentration	5 %
Mean energy loss estimate	10 %
Total	**17 %**

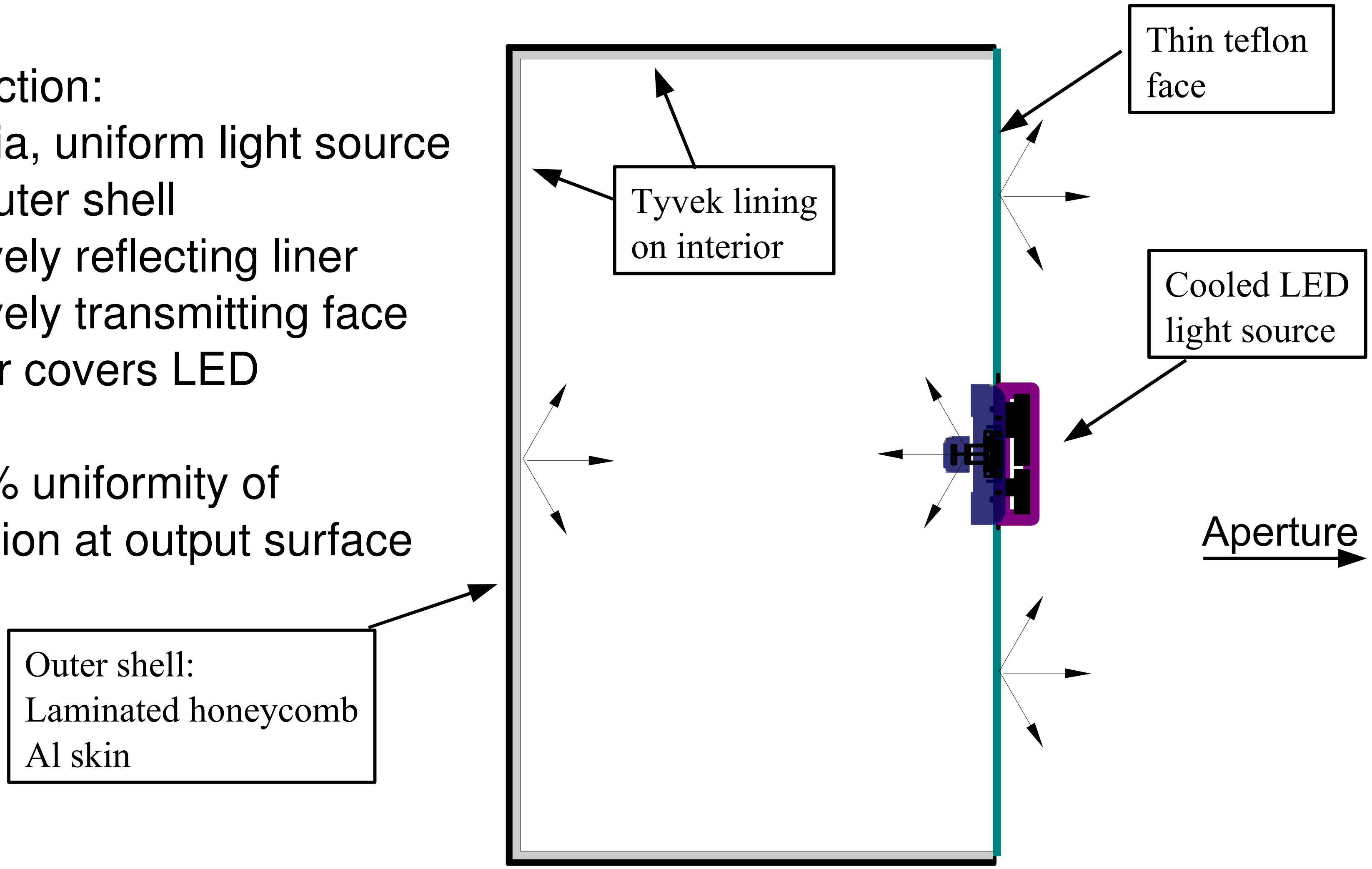
Optical calibration of fluorescence telescopes



Construction:

- 2.5m dia, uniform light source
- Hard outer shell
- Diffusively reflecting liner
- Diffusively transmitting face
- Diffuser covers LED

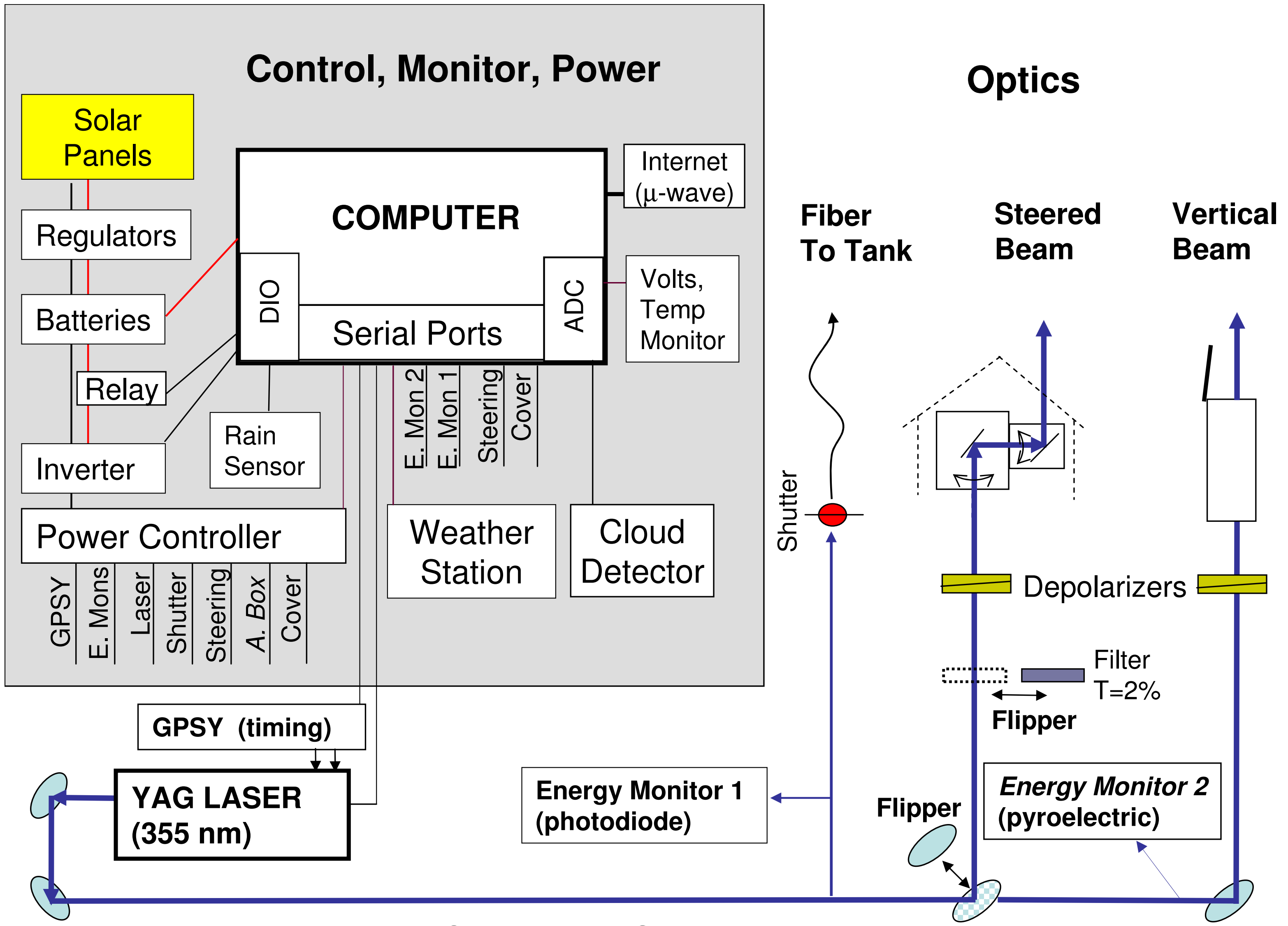
==> ~2% uniformity of illumination at output surface



Optical calibration of fluorescence telescopes

Drum intensity transfer to calibrated Si photodiode	6.0%
NIST calibration[2]	1.5%
Temperature effects	3.5%
Geometrical (alignments, areas, etc.)	1.8%
Reflections (at FD and in lab)	1.3%
Wavelength distribution effects	2.5%
Drum non-uniformities	2.5%
Signal readouts (currents, FADC traces, etc.)	2.3%
Camera Response Variations	4.0%
Total	**9.5%**

Light transmission and attenuation (i)



Pierre Auger Observatory Central Laser Facility

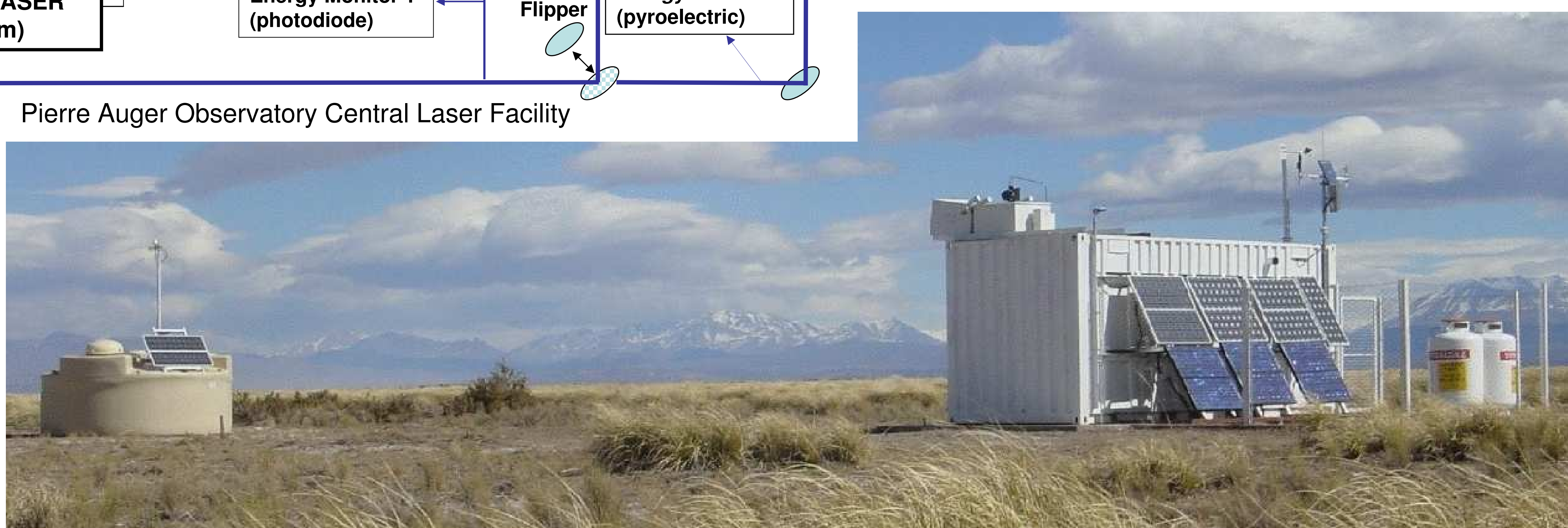
Vertical beam

absolute: 10%
relative: 2%
direction: 0.04°

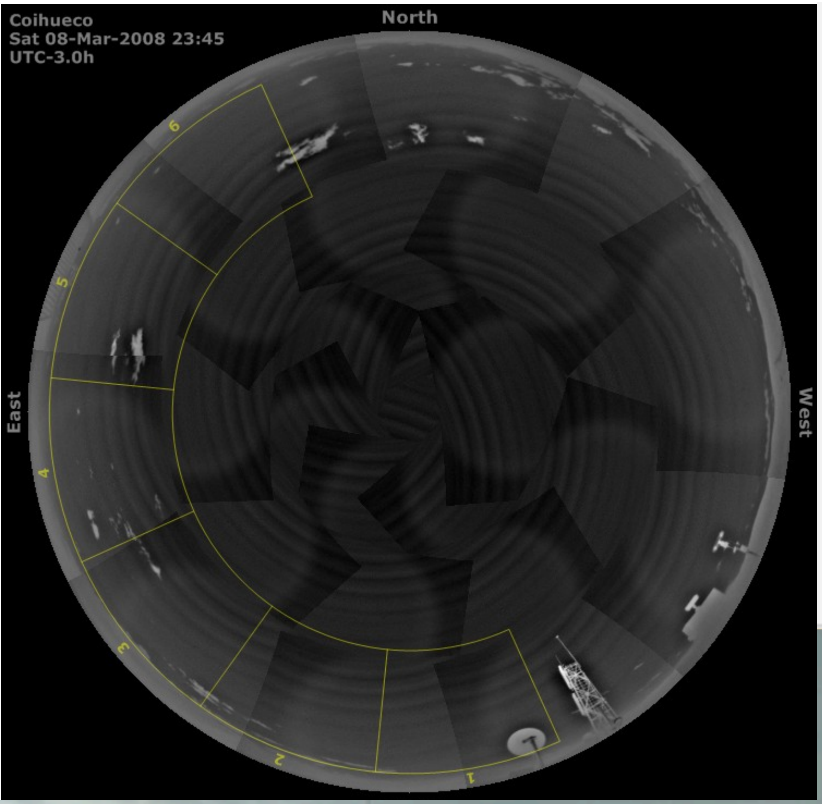
Steered beam

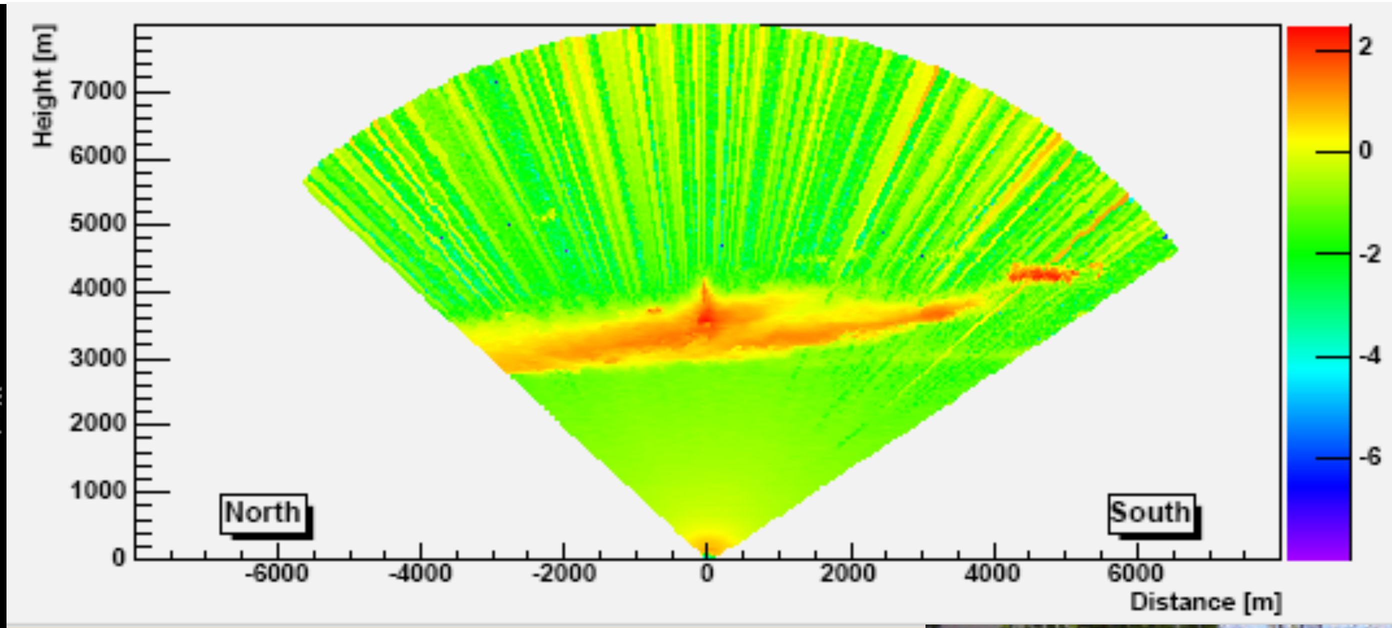
absolute: 12%
relative: 3%
direction: 0.2°

(Fick et al. JINST 1 (2006) P11003)

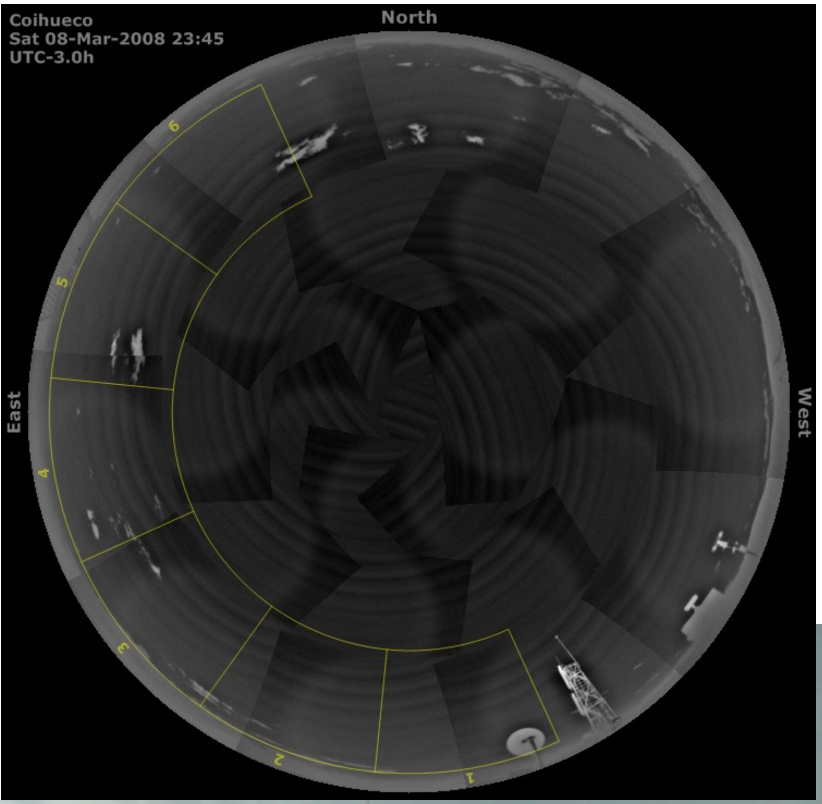


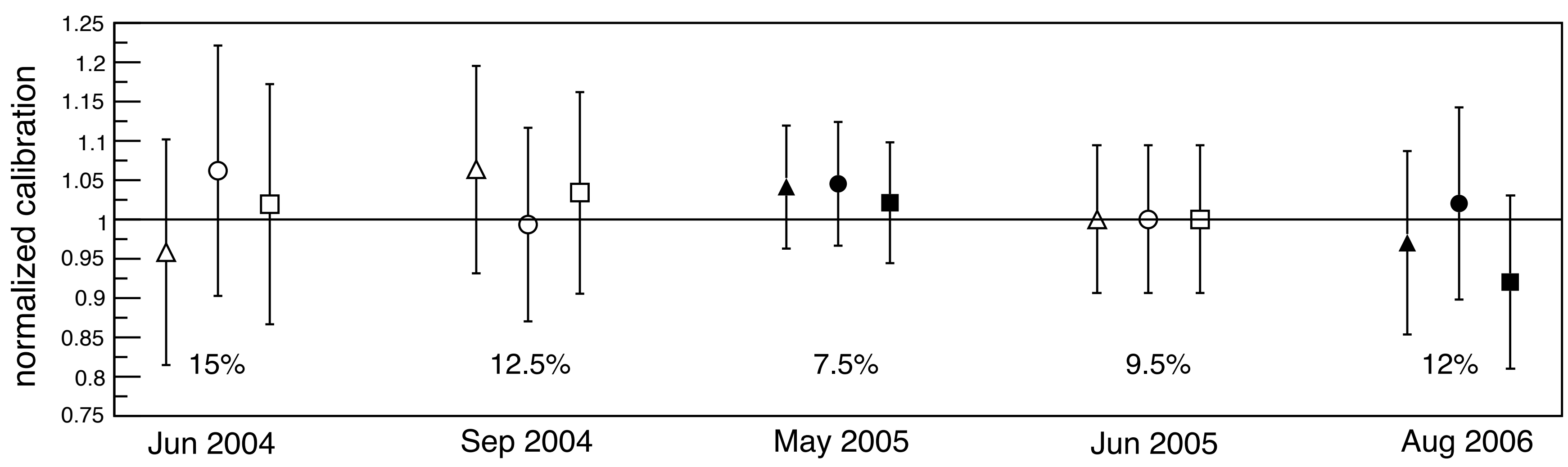
Light transmission and attenuation (ii)





Light transmission and attenuation (iii)

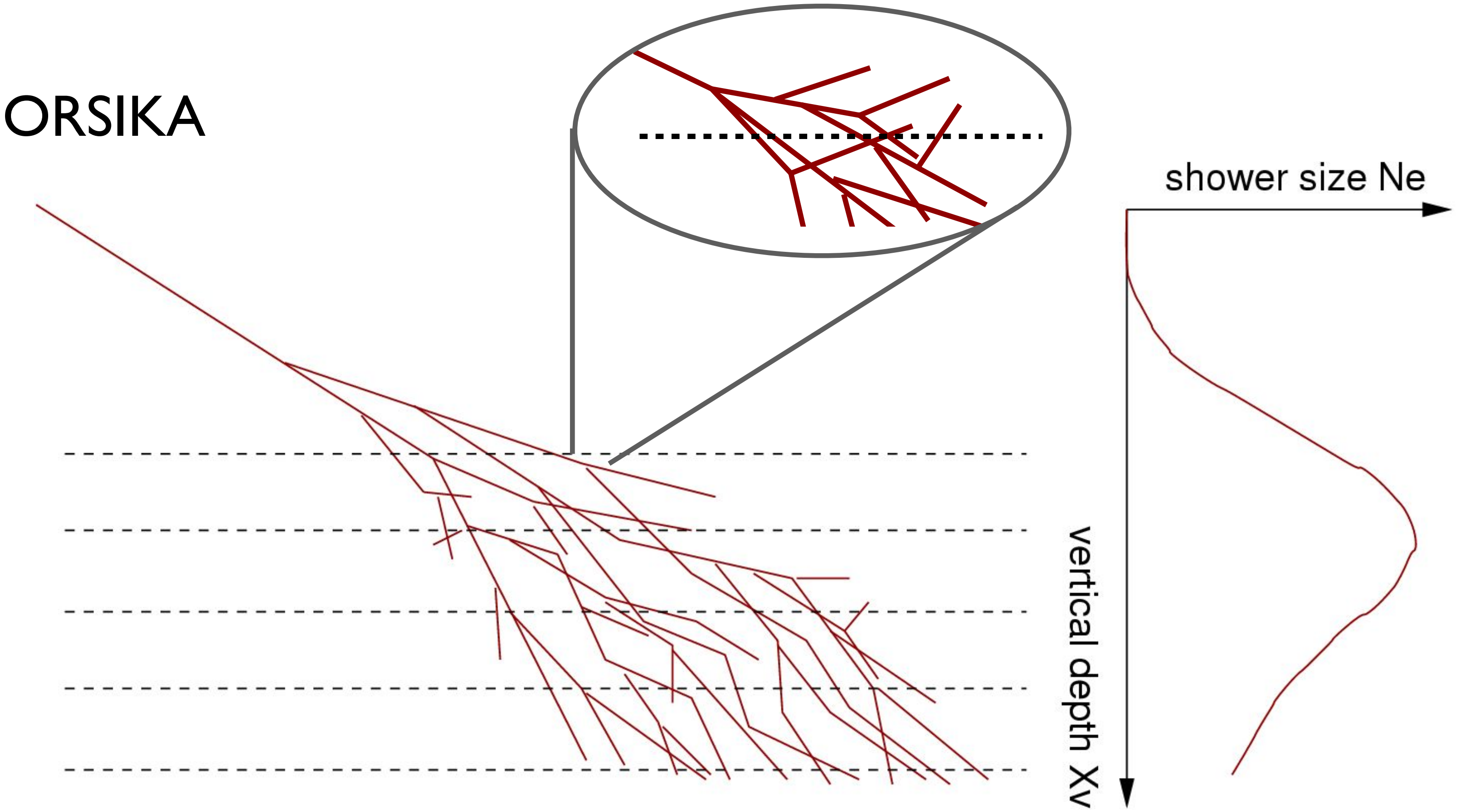




Energy deposit vs. shower size (i)

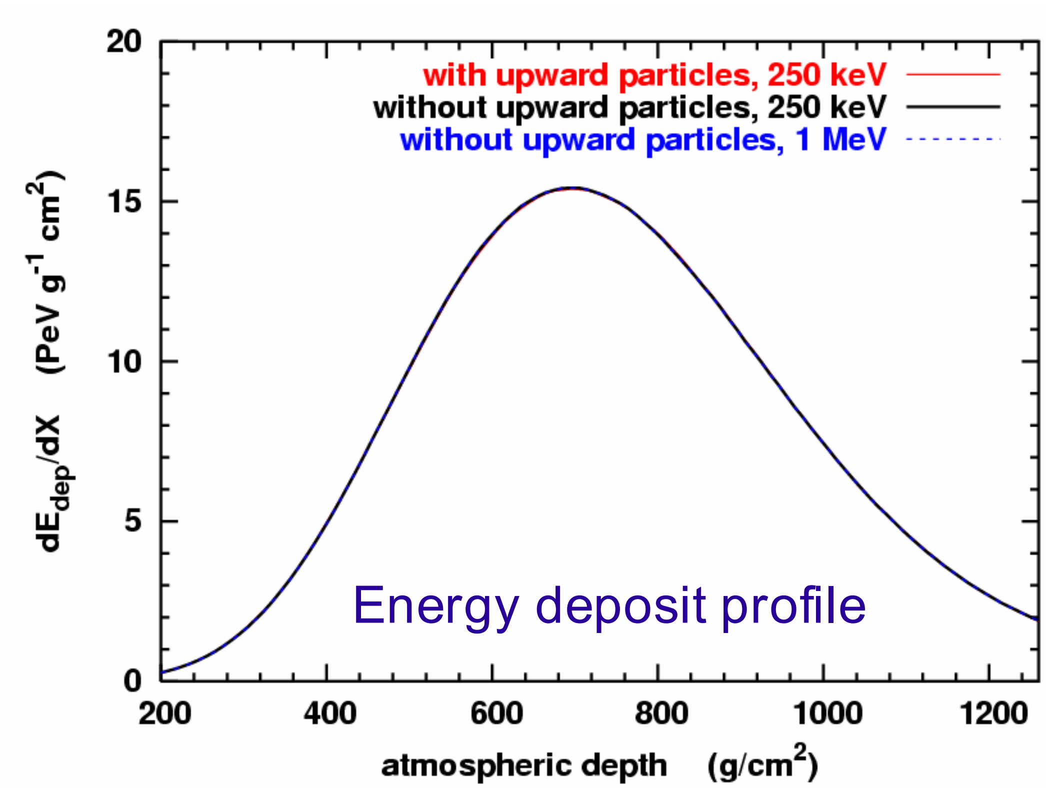
Shower size is not well defined quantity

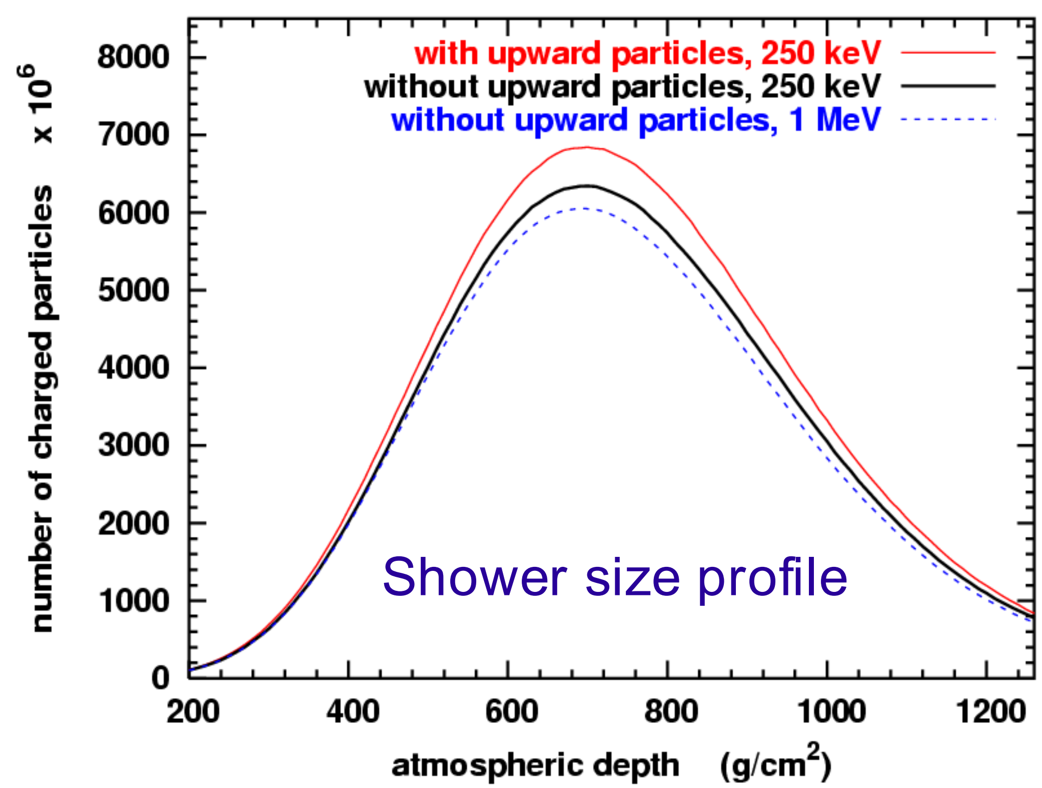
CORSIKA



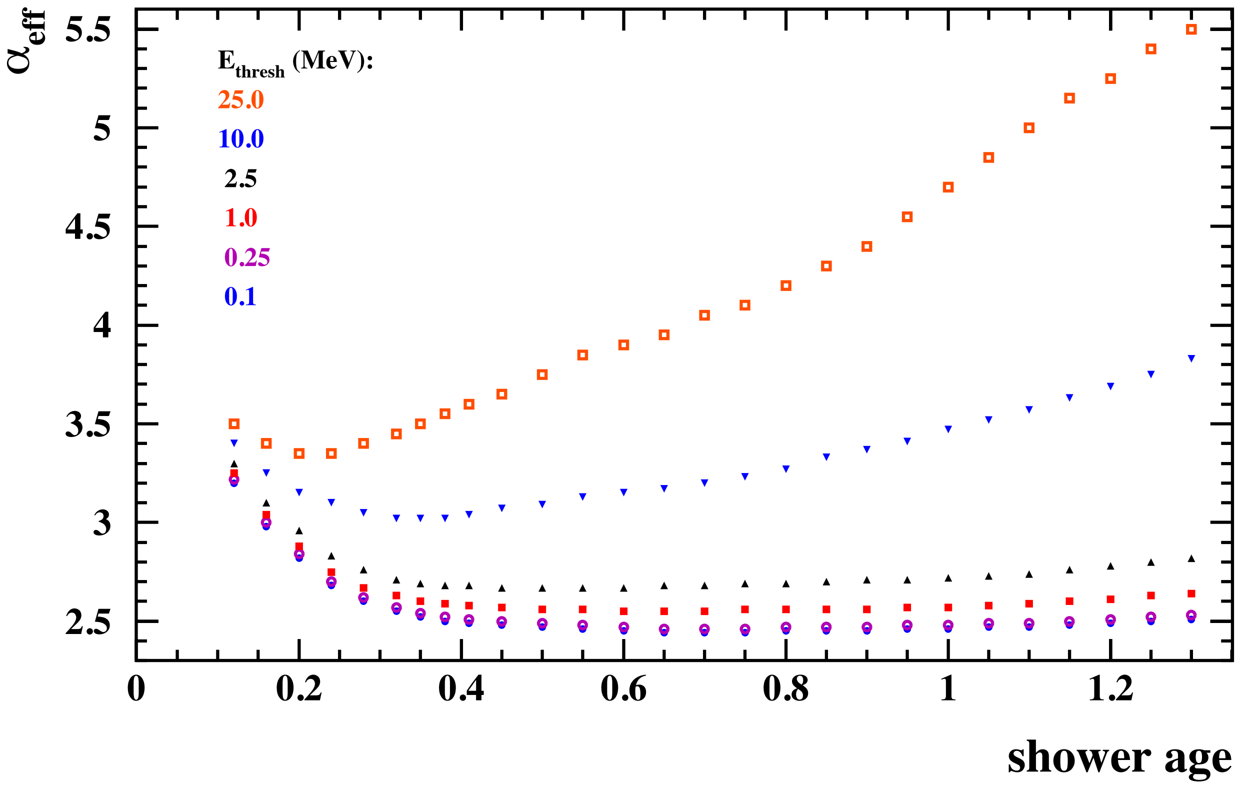
$$E_{\rm cal} = \alpha_{\rm eff} \int N_{\rm ch}(X)\, {\rm d}X$$

(Risse & Heck, APP 20 (2004) 661)



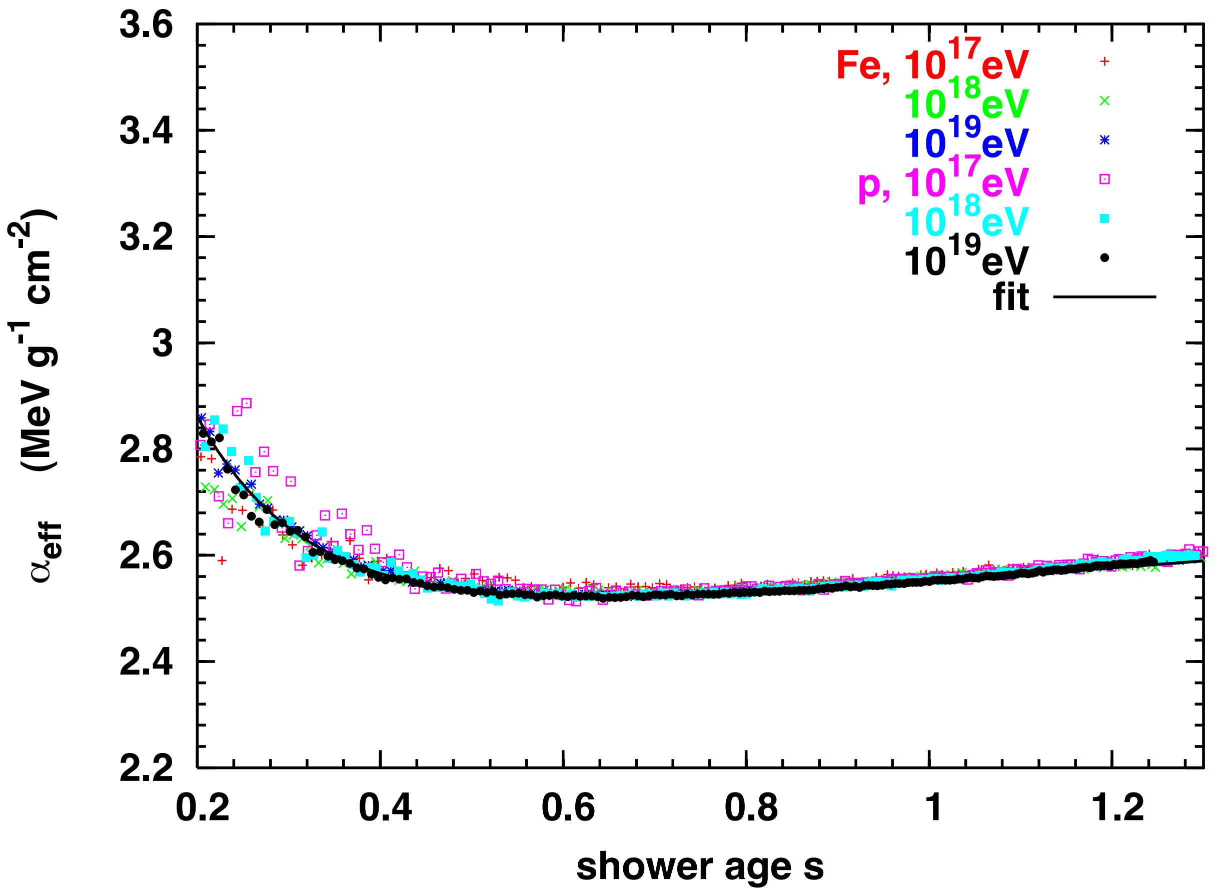


Energy deposit vs. shower size (ii)



Conversion from energy deposit to particle number for fixed low-energy threshold

(Nerling et al. APP 24 (2006) 421)



$$N_{\mathrm{ch}}(X) = \frac{1}{\alpha_{\mathrm{eff}}(s, E_{\mathrm{cut}})} \frac{\mathrm{d}E_{\mathrm{ion}}}{\mathrm{d}X}$$

Shower universality:

energy and particle independent function

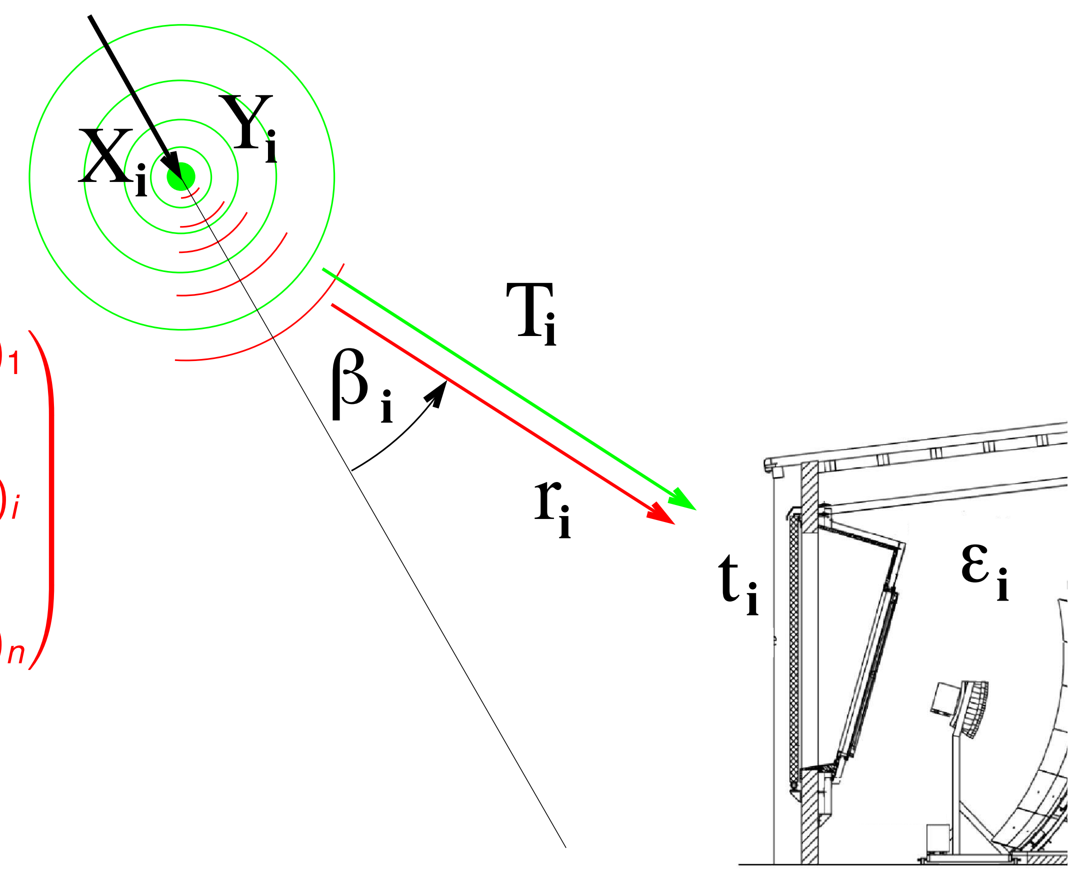
Reconstruction based on energy deposit

$$n_i^d = \underbrace{\frac{T_i\,\varepsilon_i}{4\pi\, r_i^2}}_{\text{attenuation to detector}} \cdot \underbrace{\left[Y_i^f + Y_i^C(\beta_i)/\alpha_i\right]}_{\text{light yields}} (\mathrm{d}E/\mathrm{d}X)_i$$

(Unger et al. NIMA 588 (2008) 433)

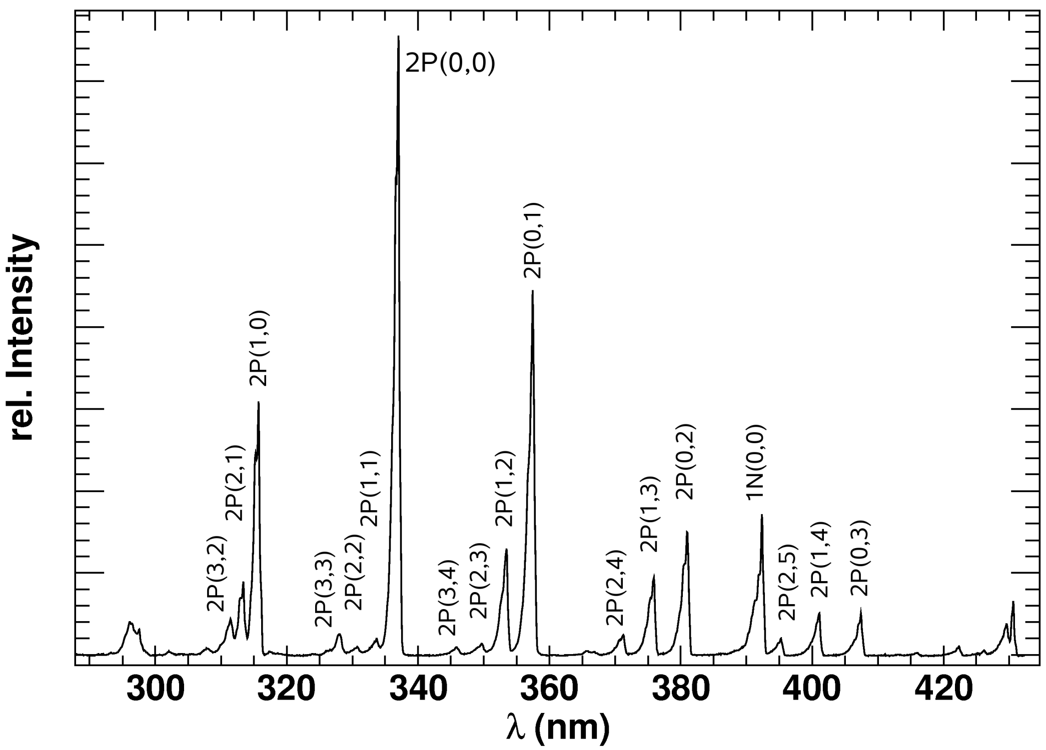
$$n_i^s = \underbrace{\frac{T_i\,\varepsilon_i}{4\pi\, r_i^2}}_{\text{attenuation to detector}} \cdot \overbrace{f(\gamma_i)}^{\text{scattering to detector}} \cdot \underbrace{\sum_k Y_k^C/\alpha_k\, \mathcal{T}_{ki}\, (\mathrm{d}E/\mathrm{d}X)_k}_{\text{Cherenkov beam}}$$

$$\begin{pmatrix} n_1 \\ \vdots \\ n_i \\ \vdots \\ n_n \end{pmatrix}_{\text{tot}} = \begin{pmatrix} s_{11}+d_1 & 0 & \dots & 0 & 0 \\ s_{12} & \ddots & & & 0 \\ \vdots & & s_{ii}+d_i & & \vdots \\ s_{1(n-1)} & & & \ddots & 0 \\ s_{1n} & s_{2n} & \dots & s_{(n-1)n} & s_{nn}+d_n \end{pmatrix} \begin{pmatrix} (\mathrm{d}E/\mathrm{d}X)_1 \\ \vdots \\ (\mathrm{d}E/\mathrm{d}X)_i \\ \vdots \\ (\mathrm{d}E/\mathrm{d}X)_n \end{pmatrix}$$



Fluorescence yield calculation

Spectrum measured by AIRFLY (34 bands)



Kakimoto et al. 1996 & Bunner 1967

$$\varepsilon = \frac{(dE_{\rm dep}^{\rm tot}/dX)}{(dE_{\rm dep}^{\rm tot}/dX)_{1.4\ {\rm MeV}}} \cdot \rho \left\{ \frac{A_1}{1+\rho B_1\sqrt{T}} + \frac{A_2}{1+\rho B_2\sqrt{T}} \right\}$$

Nagano et al. 2004 (17 wavelength bands)

$$\varepsilon = \frac{(dE_{\rm dep}^{\rm tot}/dX)}{(dE_{\rm dep}^{\rm tot}/dX)_{0.85\ {\rm MeV}}} \cdot \left\{ \frac{\rho A_\lambda}{1+\rho B_\lambda\sqrt{T}} \right\}$$

AIRFLY et al. 2007

34 wavelength bands,
normalized to 337.1nm of Nagano

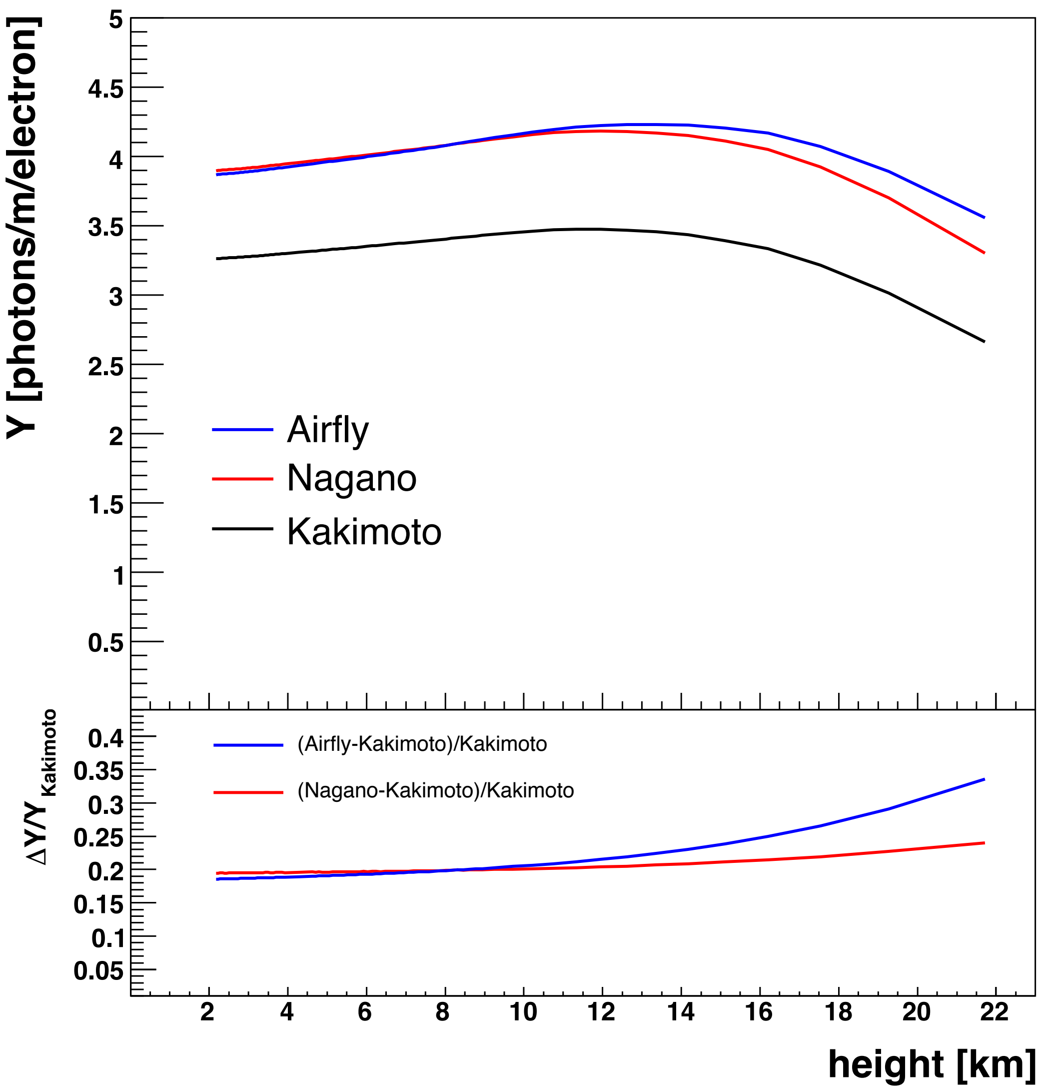
$$Y_\lambda(P,T) = Y_{337}(P_0,T_0)\cdot I_\lambda(P_0,T_0) \times \frac{1+\frac{P_0}{P'(\lambda,T_0)}}{1+\frac{P_0}{P'(\lambda,T_0)\sqrt{T/T_0}}}$$

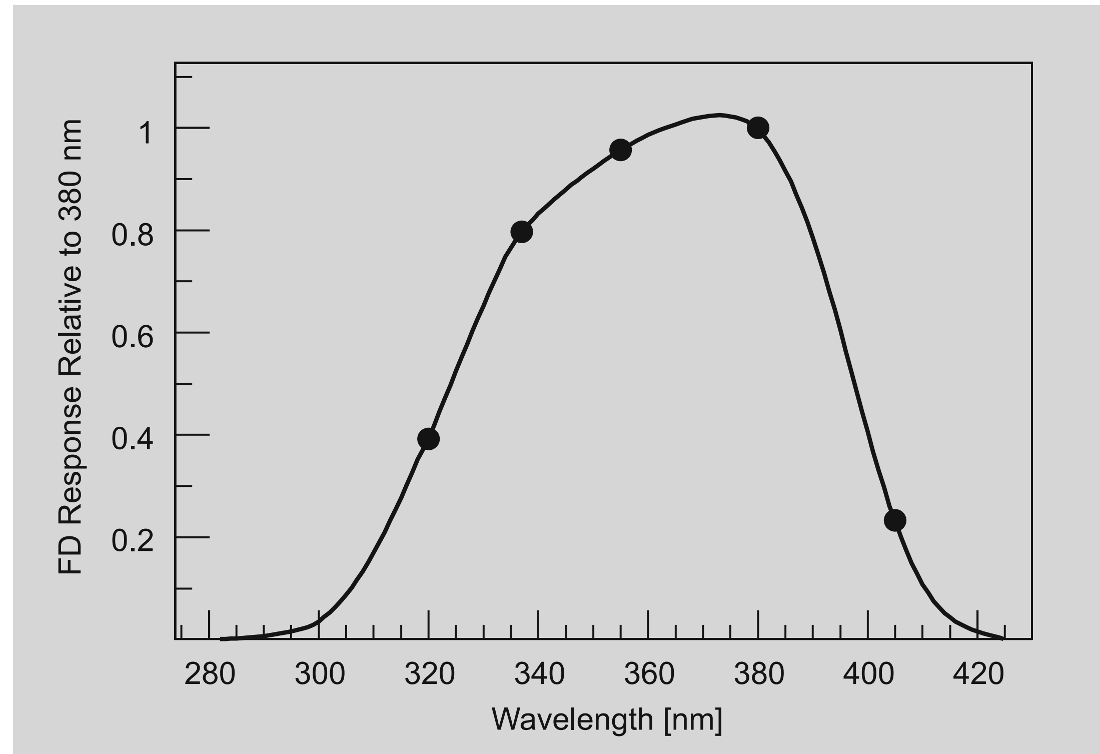
Plans: extension of FY calculation to include water vapor quenching and temperature effects

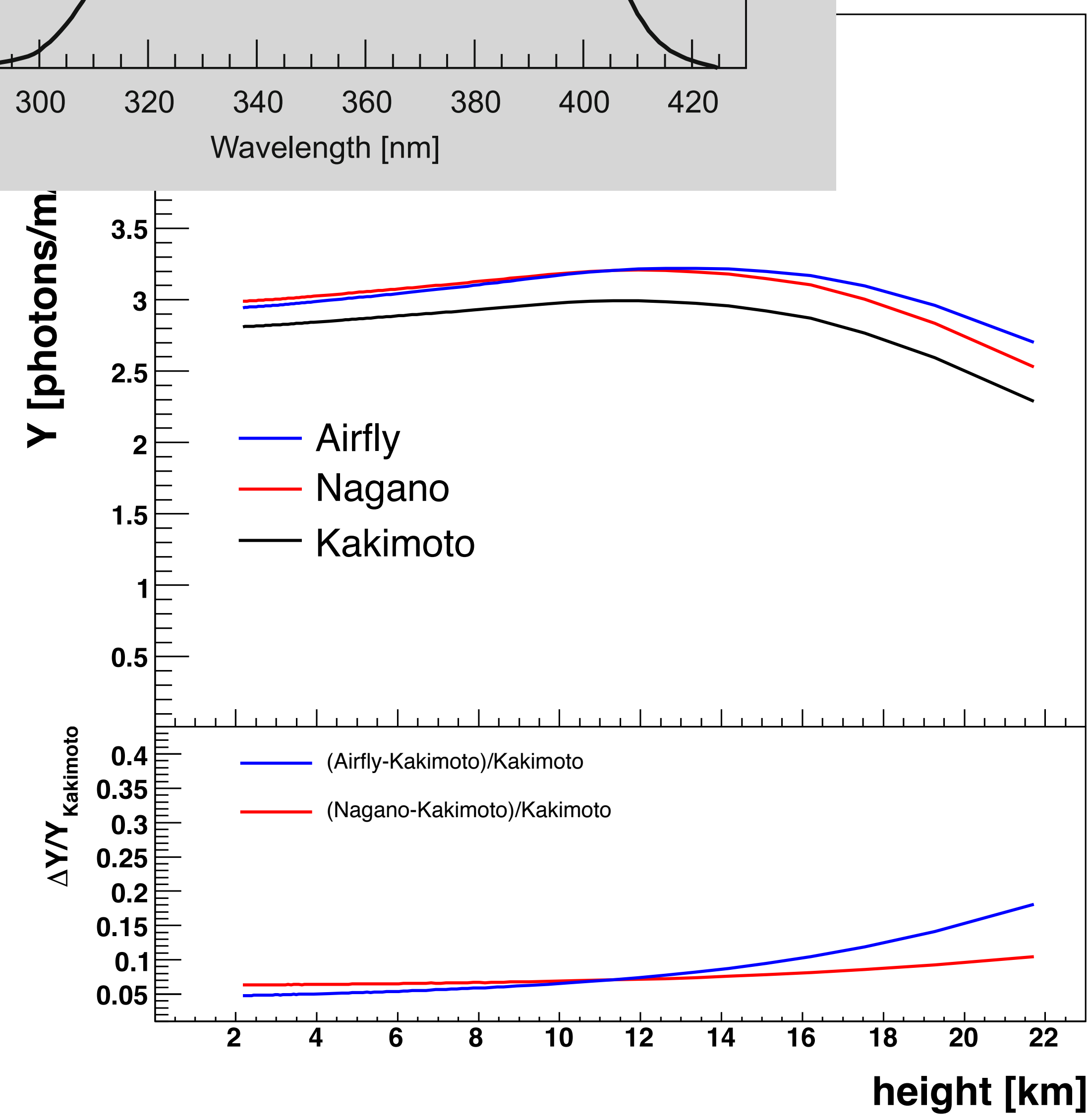
Impact of wavelength dependence of efficiency

HiRes FY model:

- yield of Kakimoto et al. 1996
- spectrum of Bunner 1967
- track length calculation



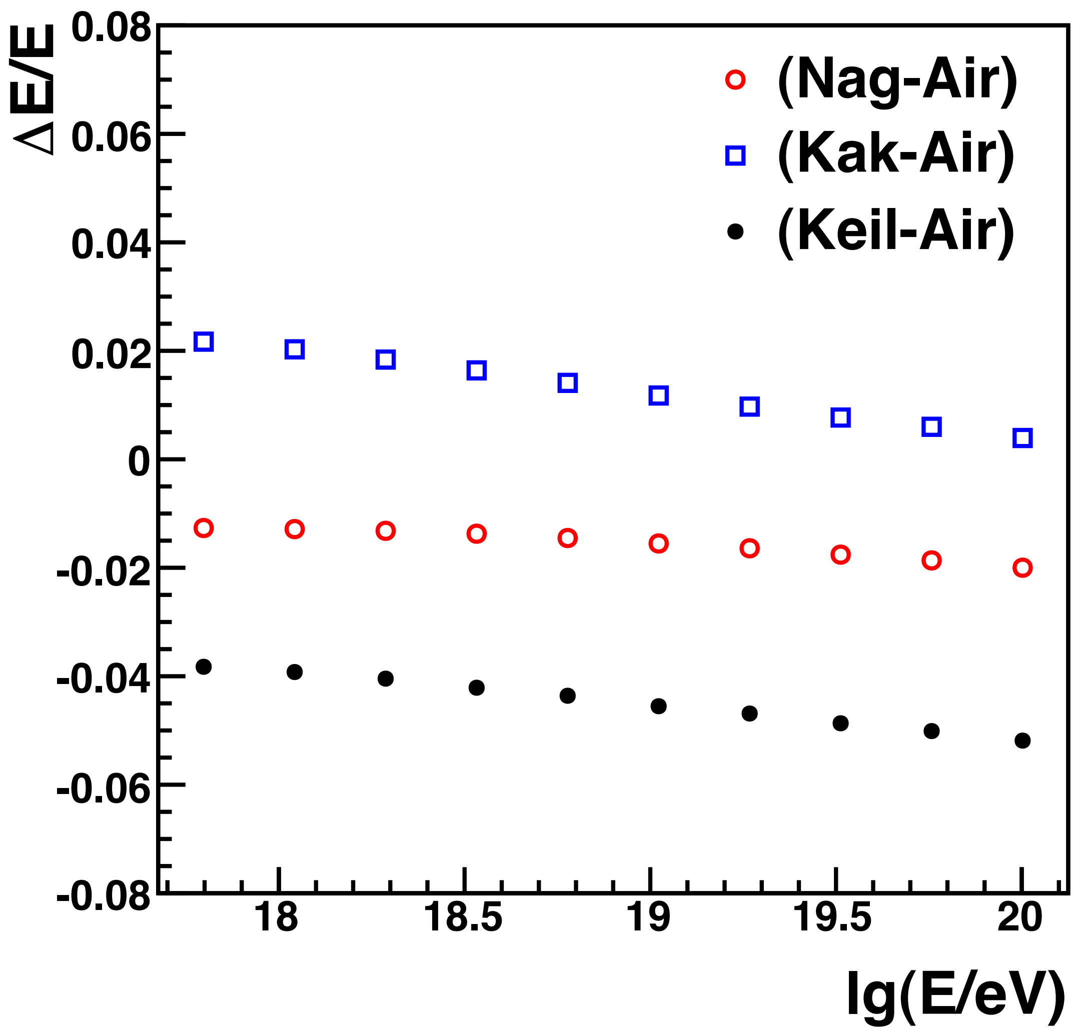


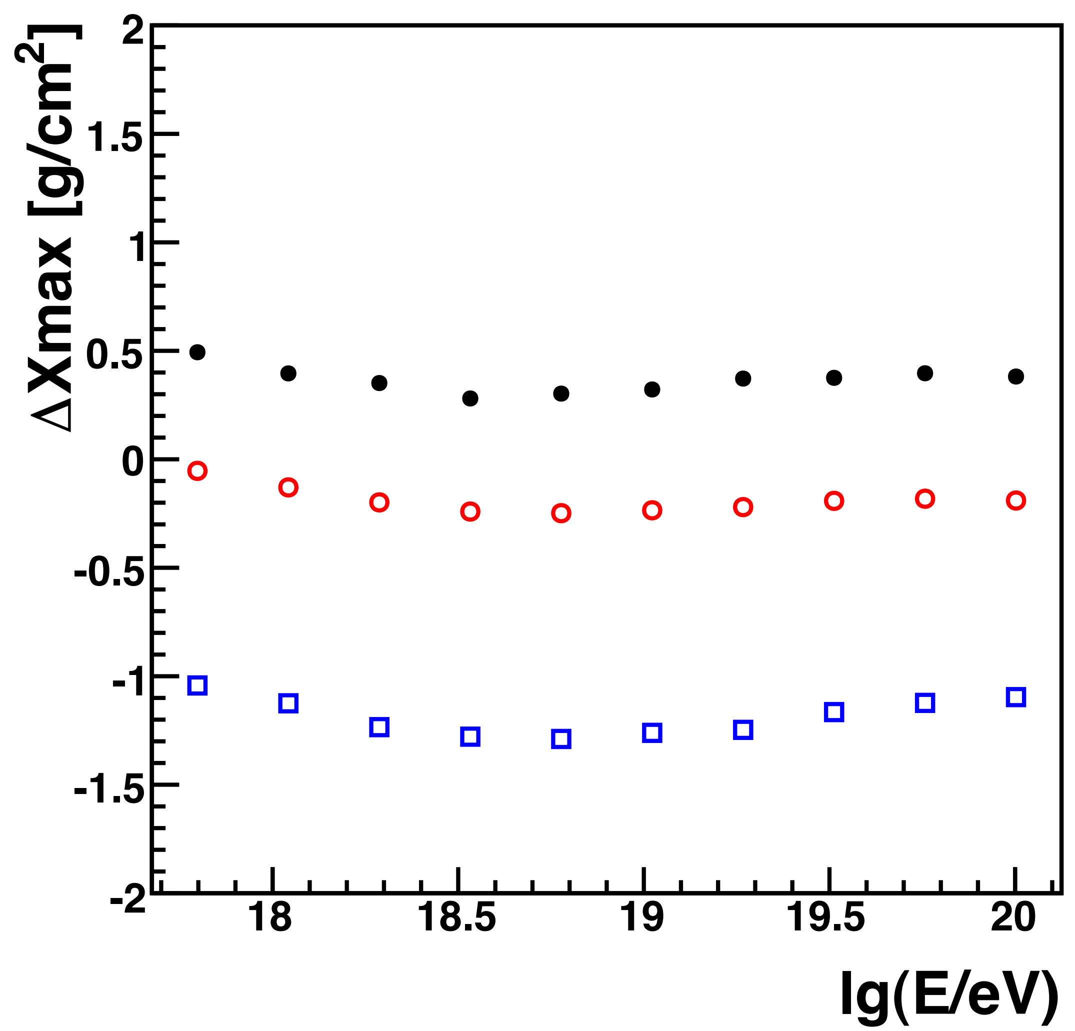


(Unger & Keilhauer, 6th Fluorescence yield workshop 2008 & ICRC 2009)

Impact of fluorescence yield model

Attention: direct comparison of Auger and HiRes fluorescence yields not possible





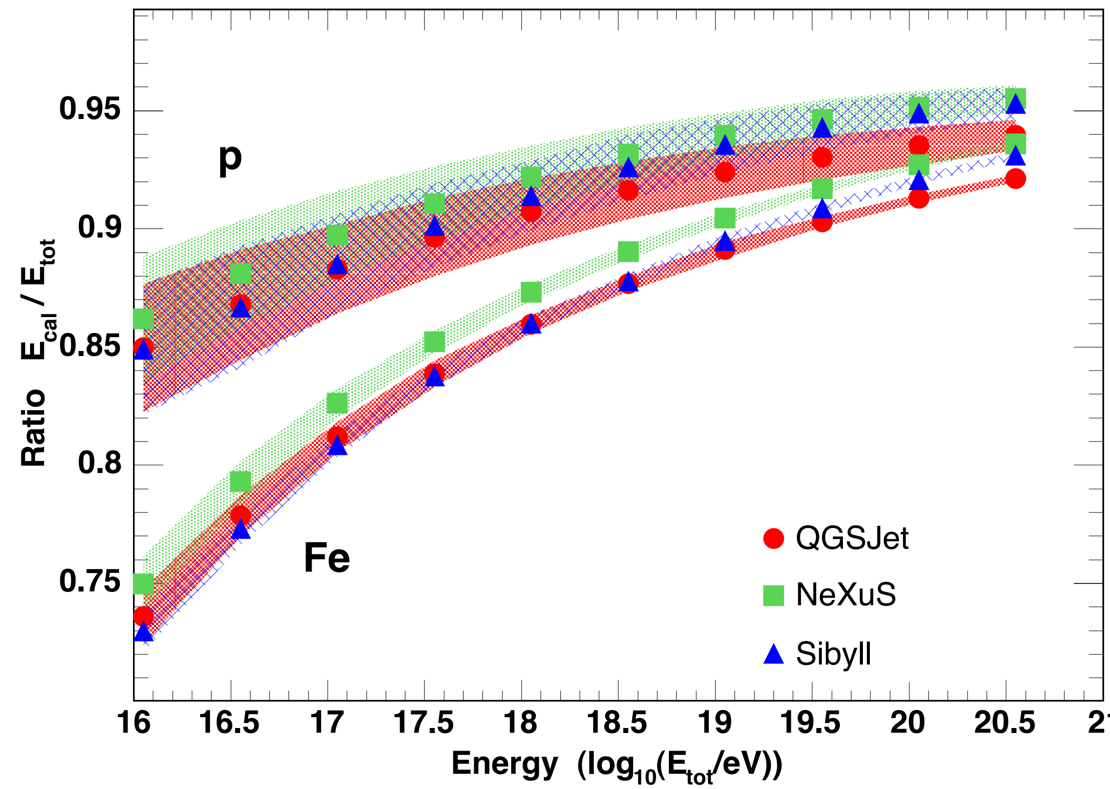
Differences small if energy deposit is used in calculation

(Unger & Keilhauer, 6th Fluorescence yield workshop 2008 & ICRC 2009)

Calorimetric vs. total shower energy

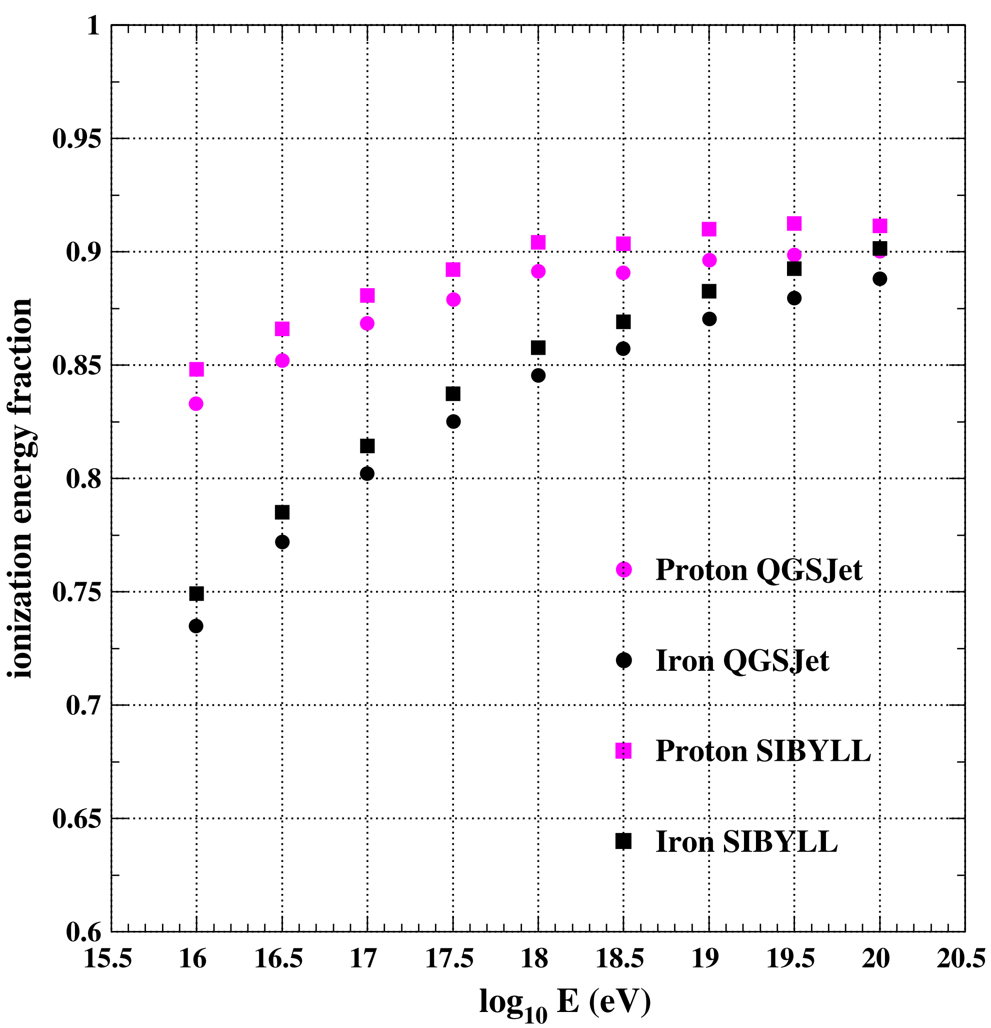
Auger reconstruction:

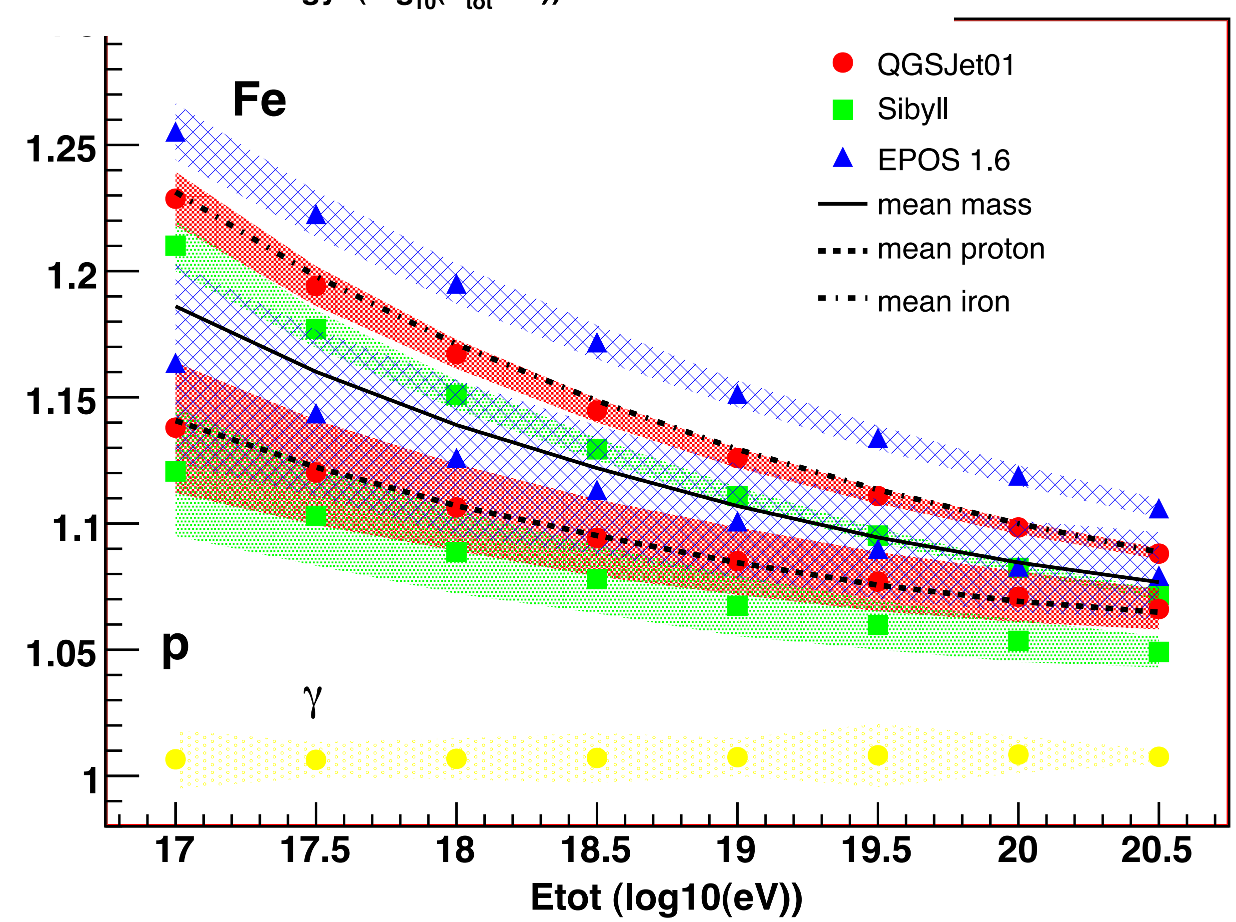
- energy correction for QGSJET 01
- mean of p and Fe
- *Barbosa et al. APP 22 (2004) 159*



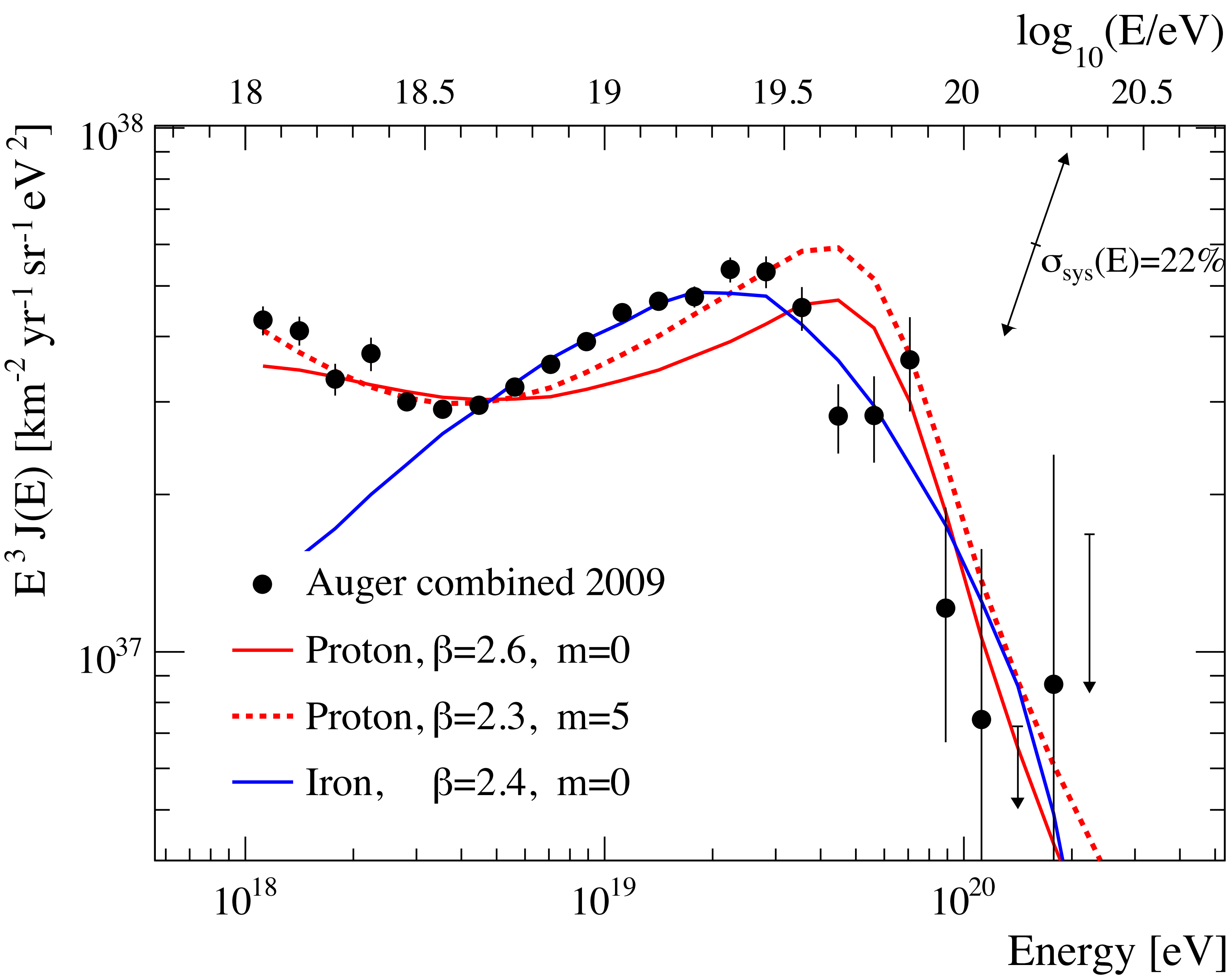
T. Pierog et al., ICRC 2007)

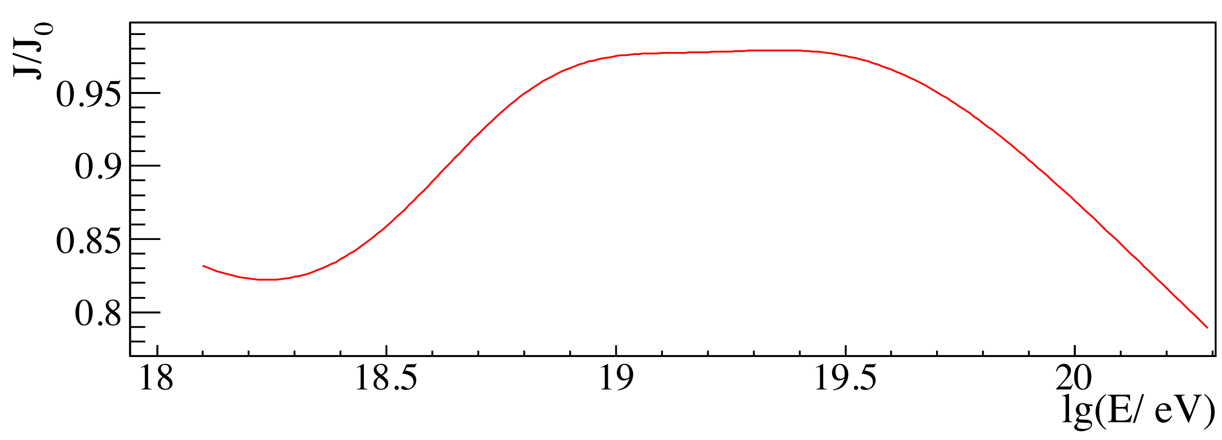
(HiRes, APP 27 (2007) 370)





Correction of spectrum for energy resolution



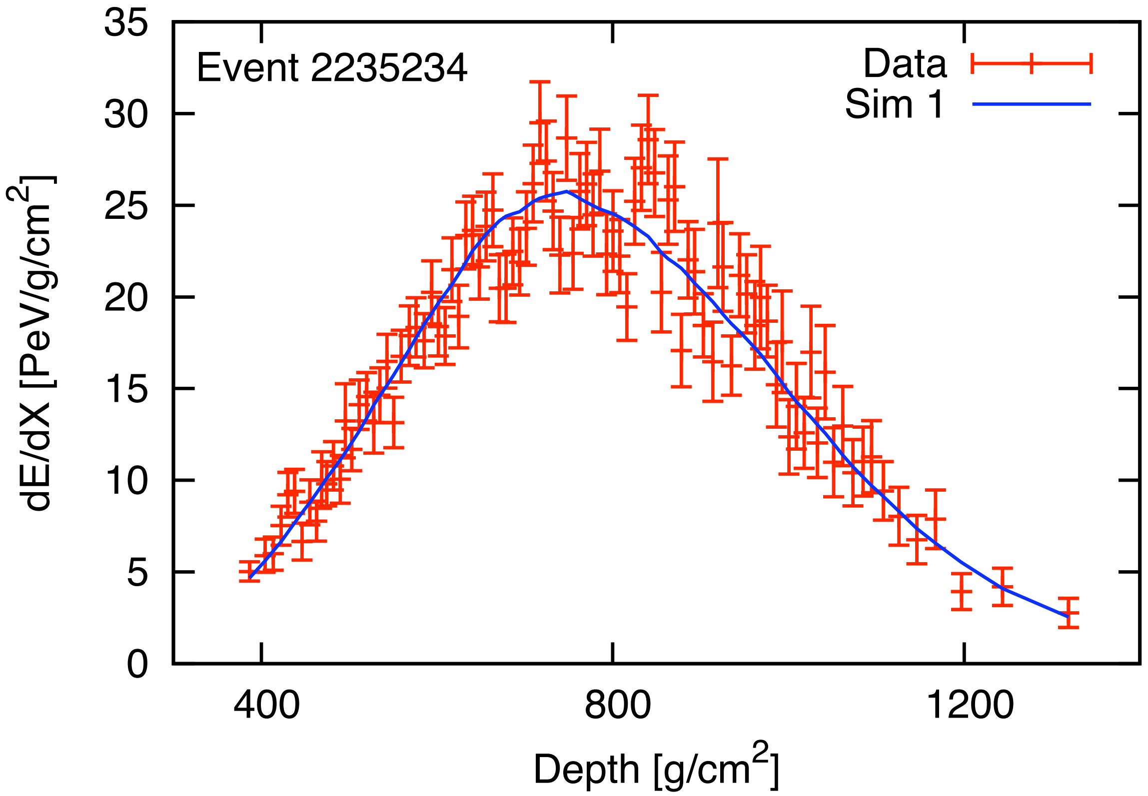


Forward-folding:
steep parts have have to be corrected more than flat parts

Auger: energy scales of FD and SD different

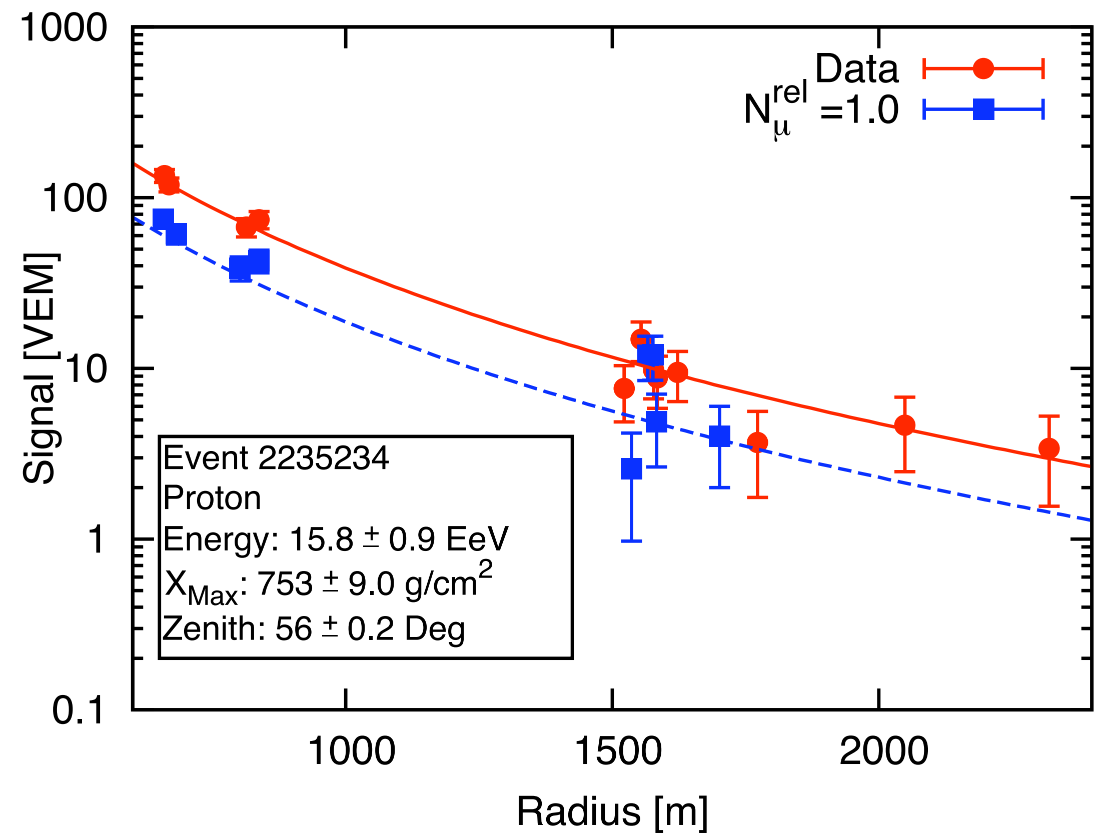
Procedure

- Simulation of 400 showers with reconstructed geometry
- Proton or iron primaries
- SD simulation for best long. profile
- Reconstruction of hybrid event

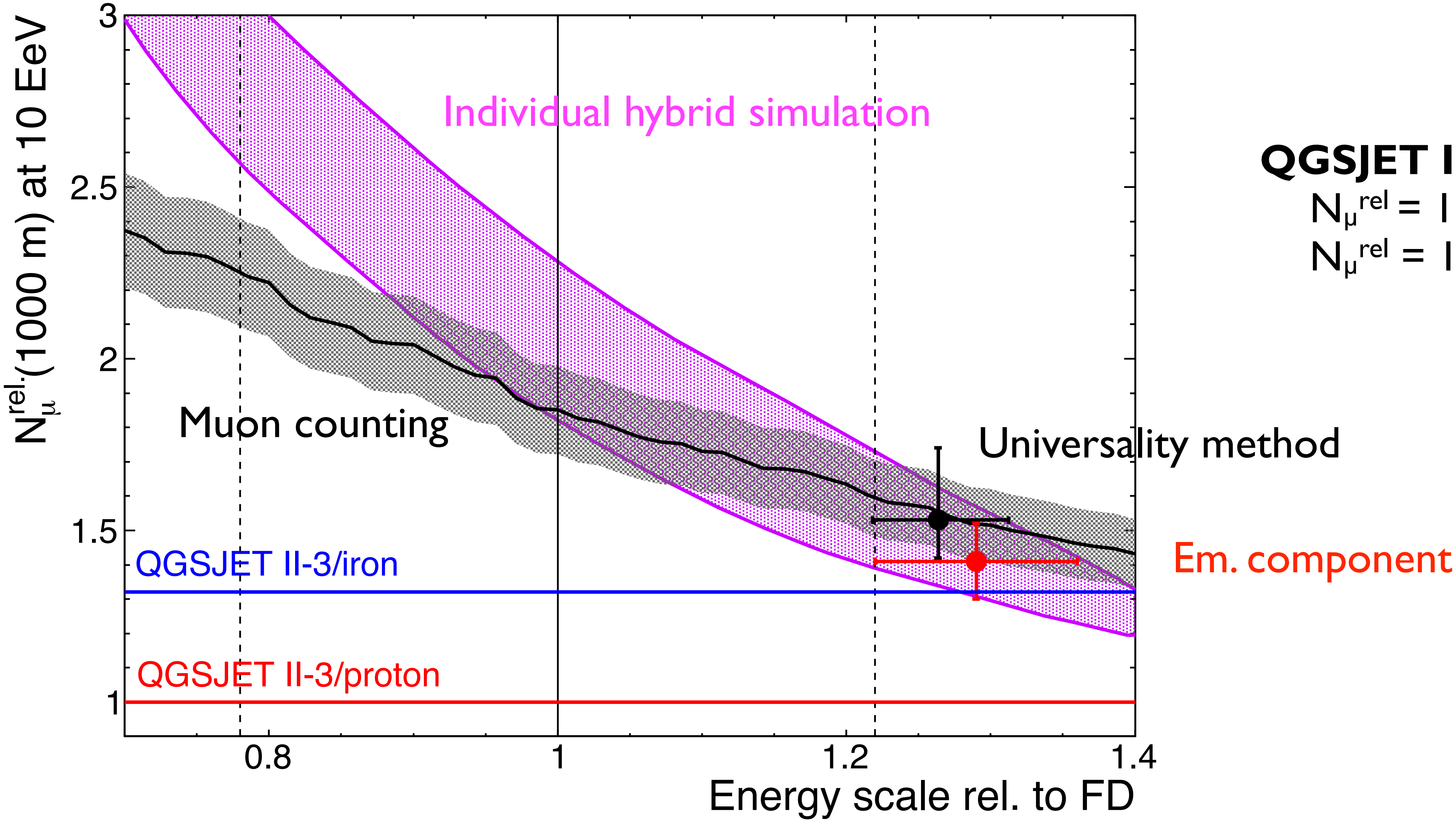


Results

- Muon deficit found in both proton and iron like showers
- Showers with same X_{max} show 10-15% variation of S(1000)



Auger: comparison of results



QGSJET II:

N_μ^{rel} = 1.0 (protons)

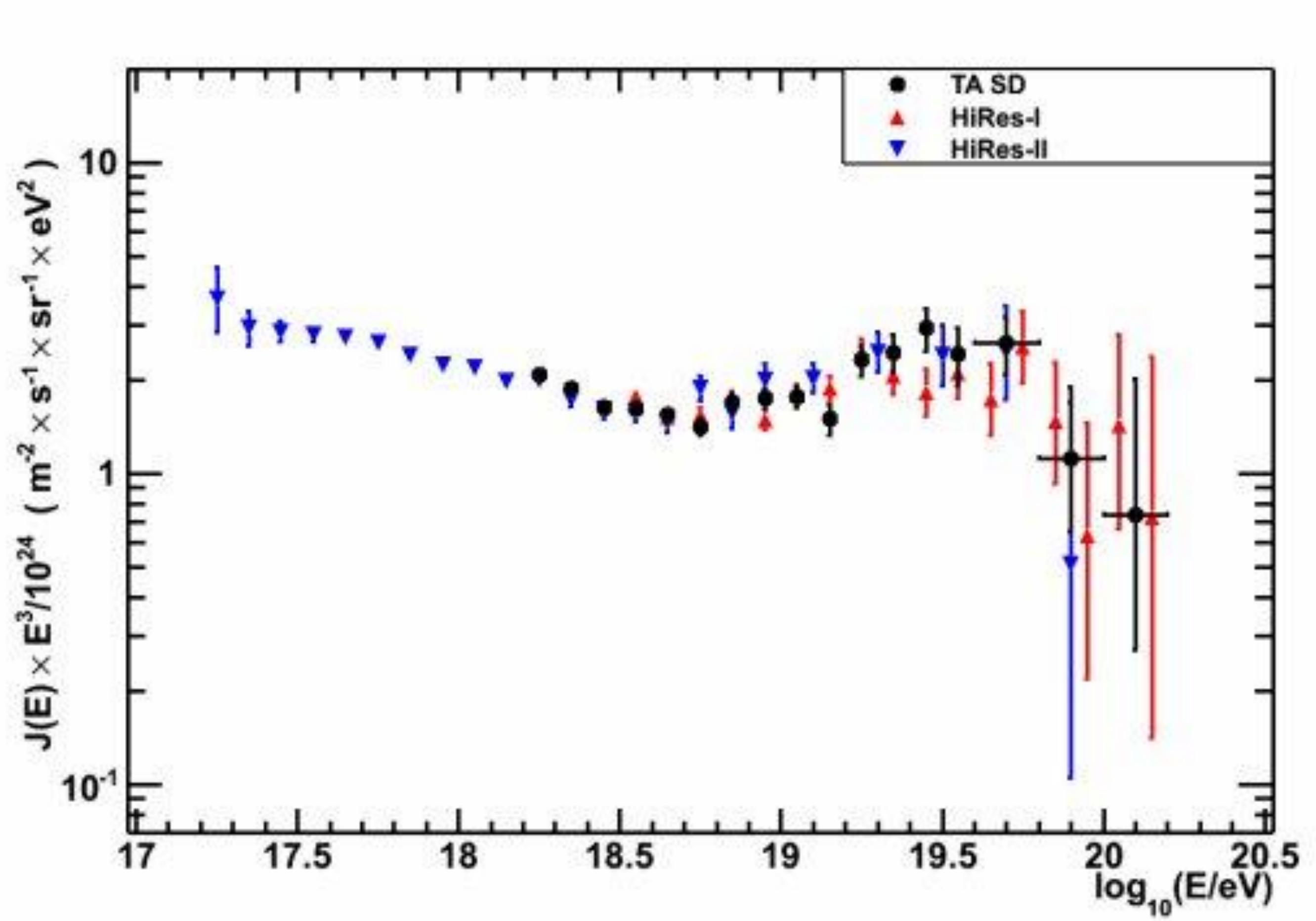
N_μ^{rel} = 1.32 (iron)

Results of different methods consistent

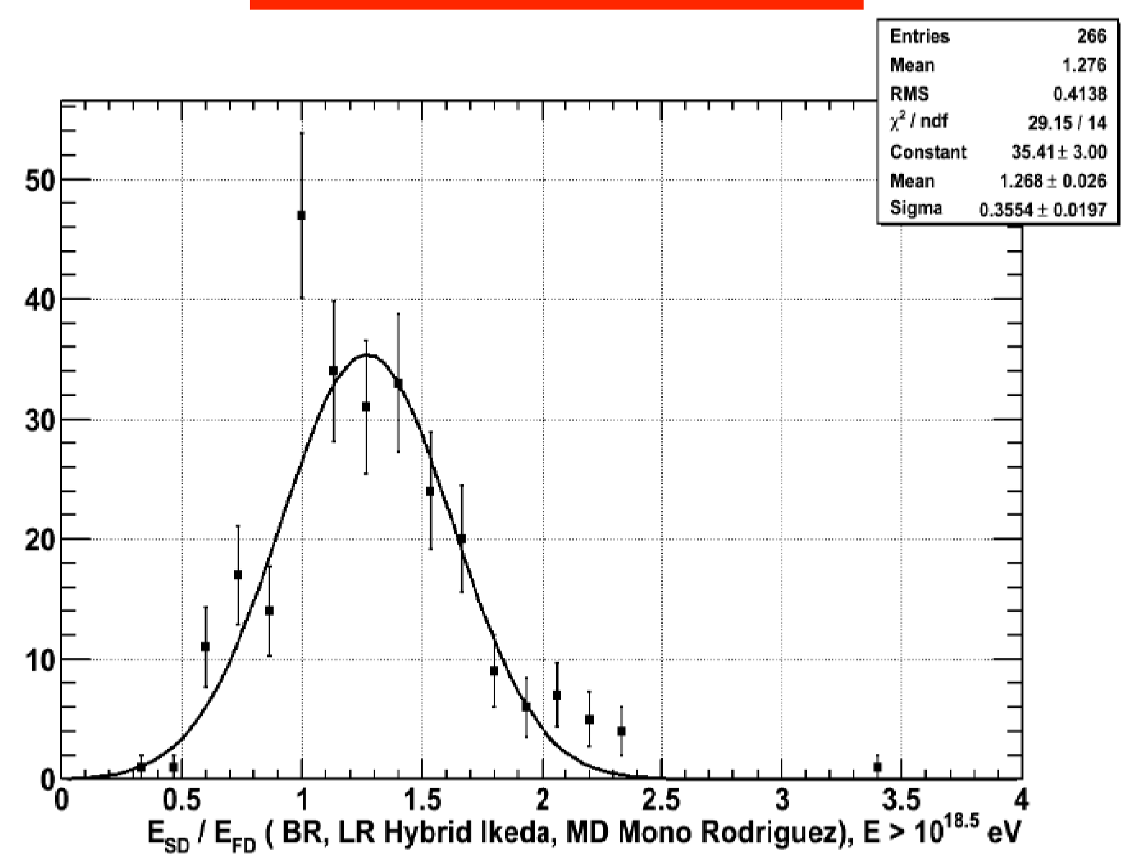
- shift of energy scale expected
- muon deficit in simulation even with shifted energy scale

But: All results depend directly or indirectly on simulation of em. component

Telescope Array: similar energy scale difference



- Energy scale is determined more accurately by FD than by CORSIKA QGSJET-II
- Set SD energy scale to FD energy scale using well-reconstructed events seen by both detectors:
- 27% renormalization.



Suppression of flux at ultra-high energy confirmed with scintillator array

(TA Collab., Thomson, ICHEP 2010)

Status of energy scale uncertainty

- Typical uncertainty scale 20%, but sources different (consistency?)
- Experiments agree within systematic uncertainties
- Many small differences, but no obvious source for a 20% energy shift

- **What about the different energy scales of SD and FD ?**
- **Are we happy with this status ?**
- **How to make progress ?**

Proposal: cross-calibration of Auger and TA

(Diploma theses Maria Radosz, Julia Parrisius, Felix Werner)

Electronically stabilised

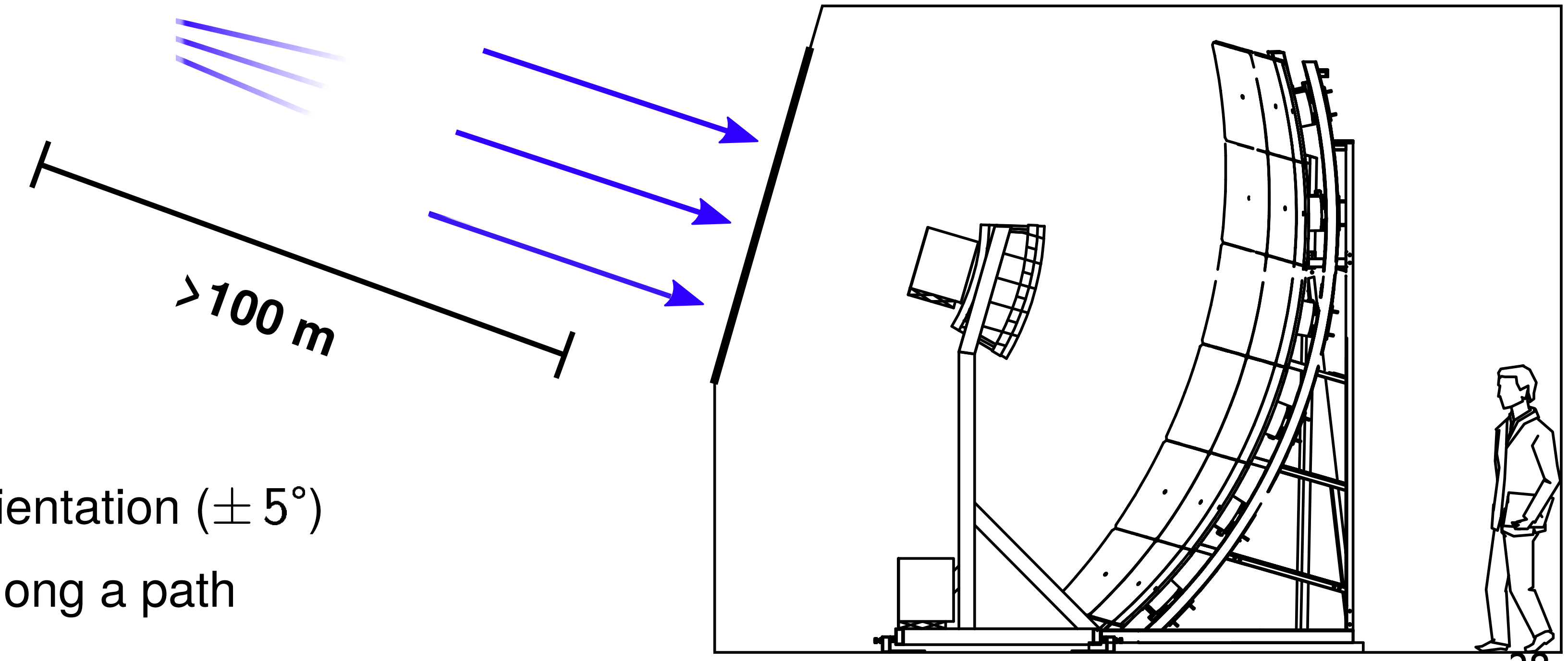
2.5 kg without payload

Payloads up to ~1 kg

Powered by LiPo battery (4S)

20 min flight time

40 km/h rising speed

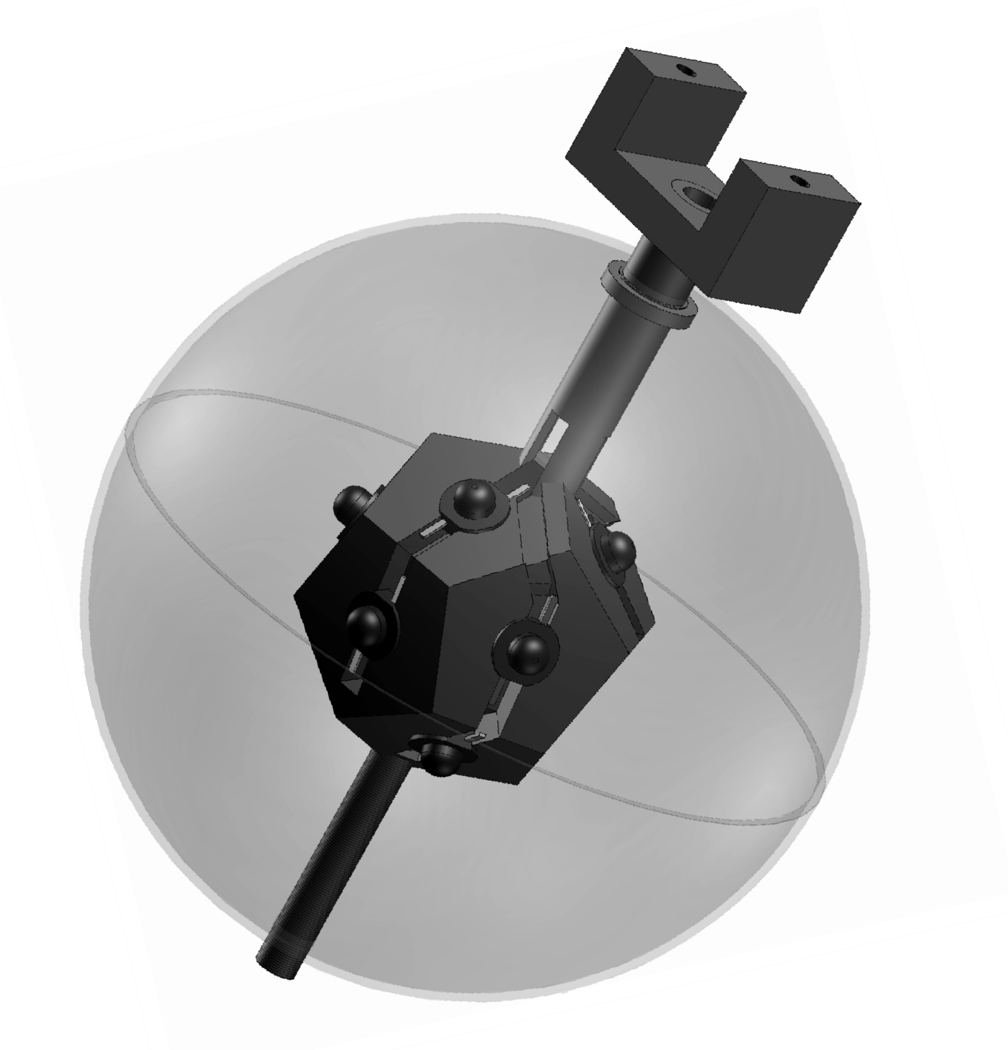


GPS receiver and 3d compass:

Stabilisation of position ($\pm$ 2 m) and orientation ($\pm$ 5°)

2d waypoint flight → program to fly along a path

Calibrated and stabilized light source



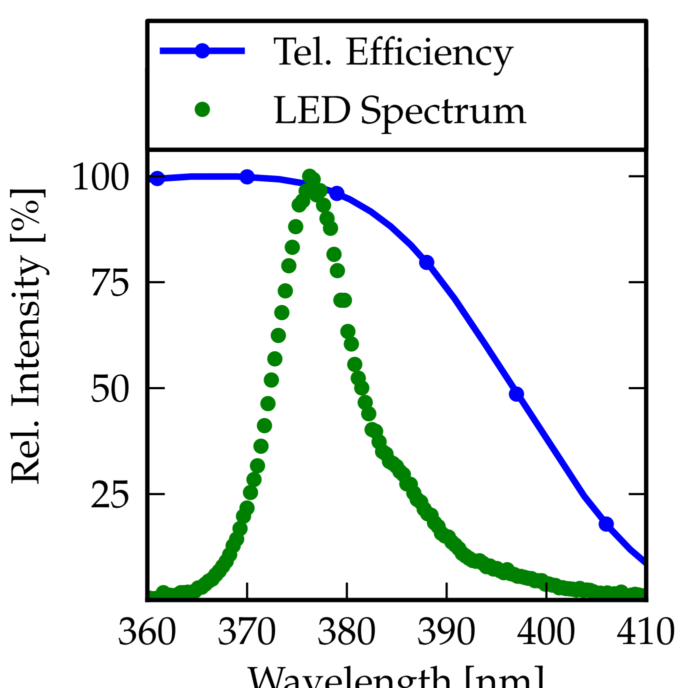
12 UV-LEDs with silicone lenses

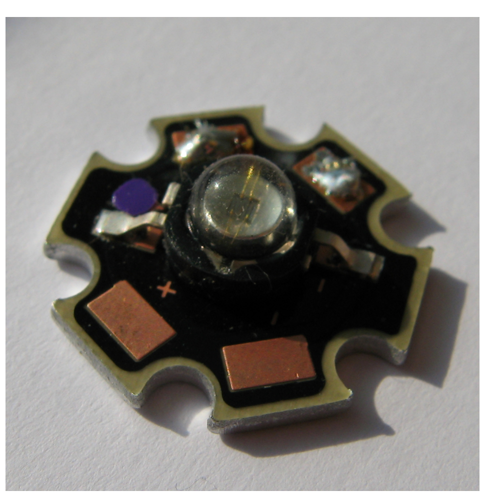
Dodecahedron (ABS) as body

Tyvek coating of body

∅ 10 cm diffuser (polystyrene)

Uncertainty (%)	Source
2.0	Reflections and geometry
2.0	Inaccuracy of electrometer
1.5	Responsivity and active area of photodiode (from NIST)
1.0	Intensity stability of the light source
3.4	Total





Roithner-Laser H2A1-H375