THE ENERGY SPECTRUM OF THE PIERRE AUGER OBSERVATORY

Valerio Verzi
for the Pierre Auger Observatory

INFN, Sezione di Roma "Tor Vergata"

PIERRE AUGER
OBSERVATORY

UHECR 2014
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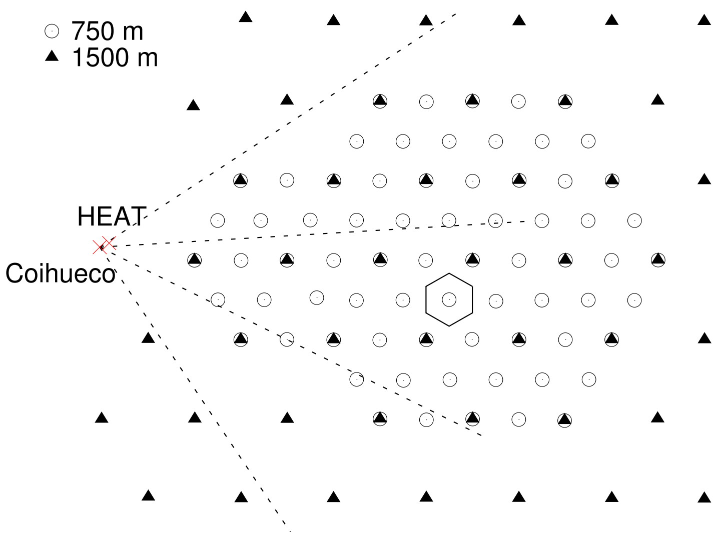
THE PIERRE AUGER OBSERVATORY

Surface detector (SD):

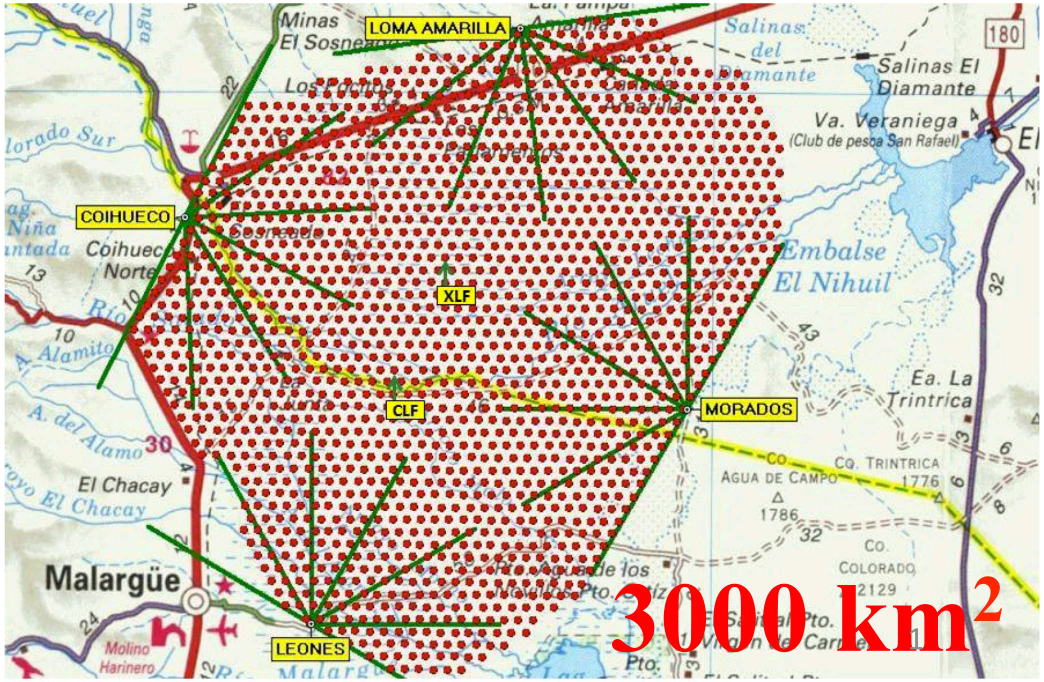
- hexagonal grid of 1600 water Cherenkov detectors with 1500 m spacing
- 49 additional detectors with reduced spacing of 750 m

Fluorescence detector (FD)

- 24 fluorescence telescopes in 4 buildings
- three additional telescopes with higher elevation angles



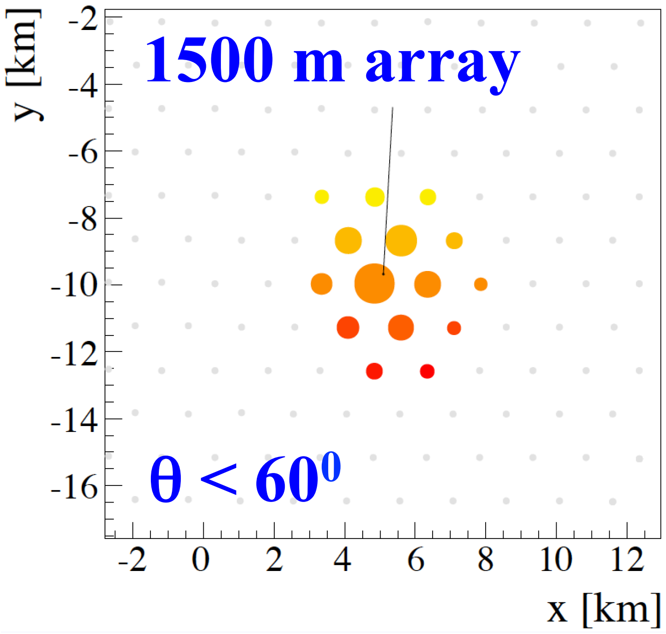
Infill - 27 km^2



ENERGY SPECTRUM OVER 3 DECADES IN ENERGY

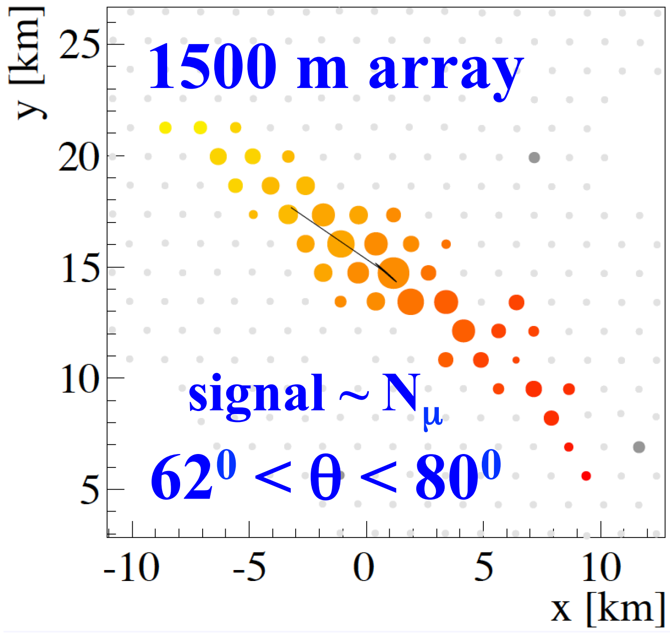
SD vertical

energy thr.
3 EeV



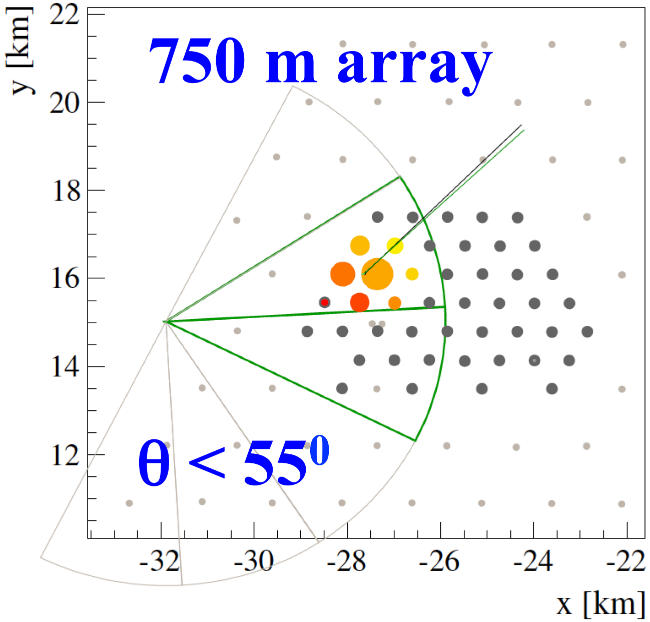
SD Inclined

energy thr.
4 EeV



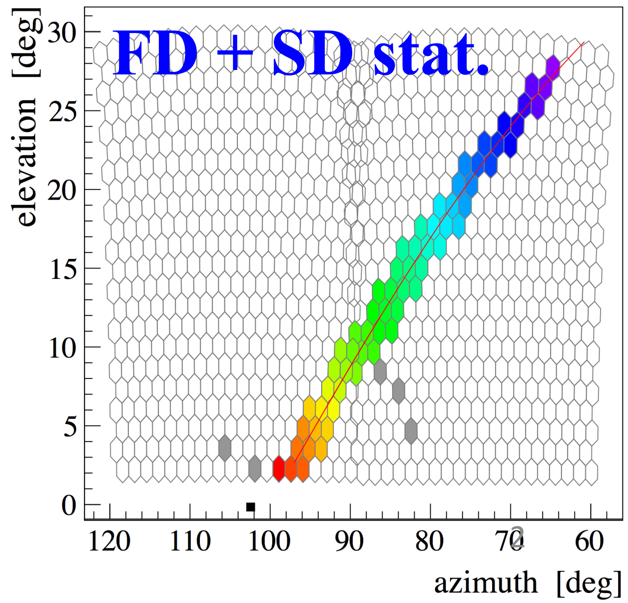
SD infill

energy thr.
0.3 EeV

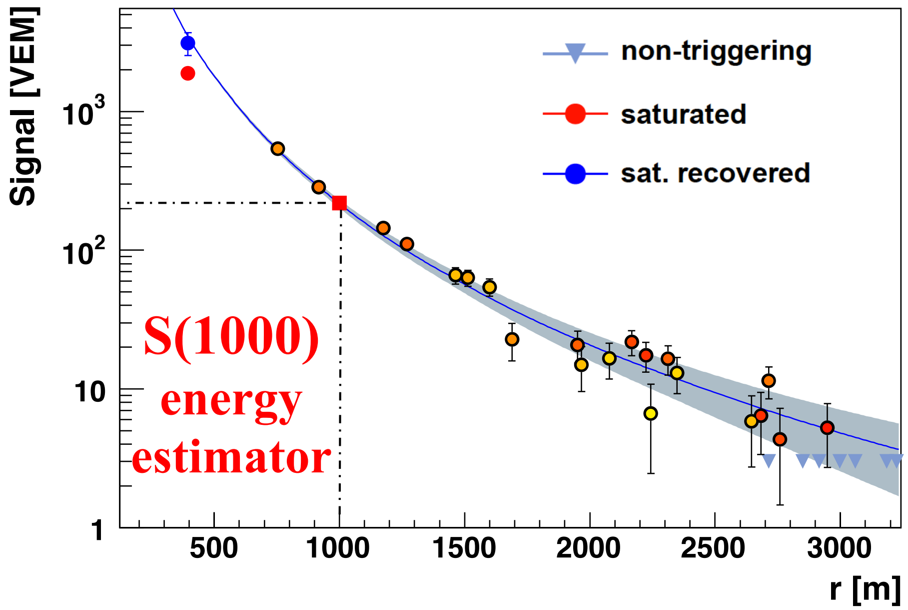


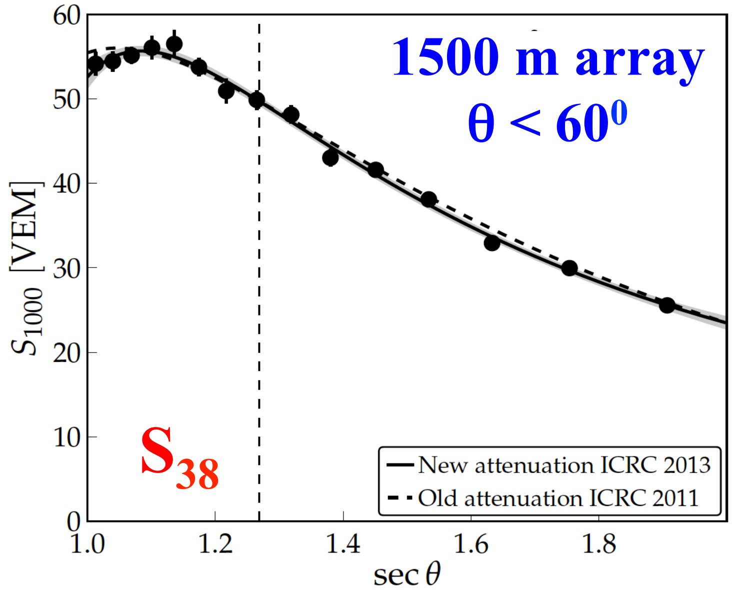
hybrid
13% duty cycle

energy thr.
1 EeV

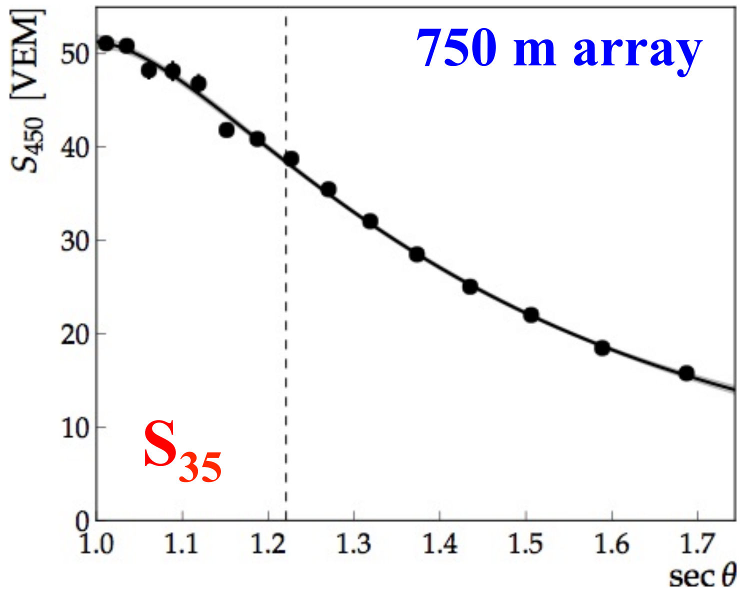


SD VERTICAL: ENERGY ESTIMATOR





S(1000): 1500 m array θ < 60⁰
S(450): 750 m array



use the CIC method to remove the zenith angle dependence of S(1000) / S(450)

➡ S_{38} / S_{35}

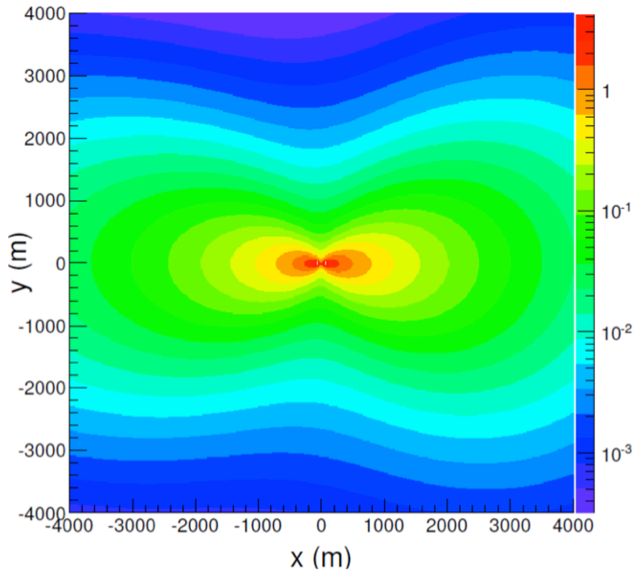
correction determined from data (no use of simulations)

SD EVENTS: ENERGY ESTIMATORS

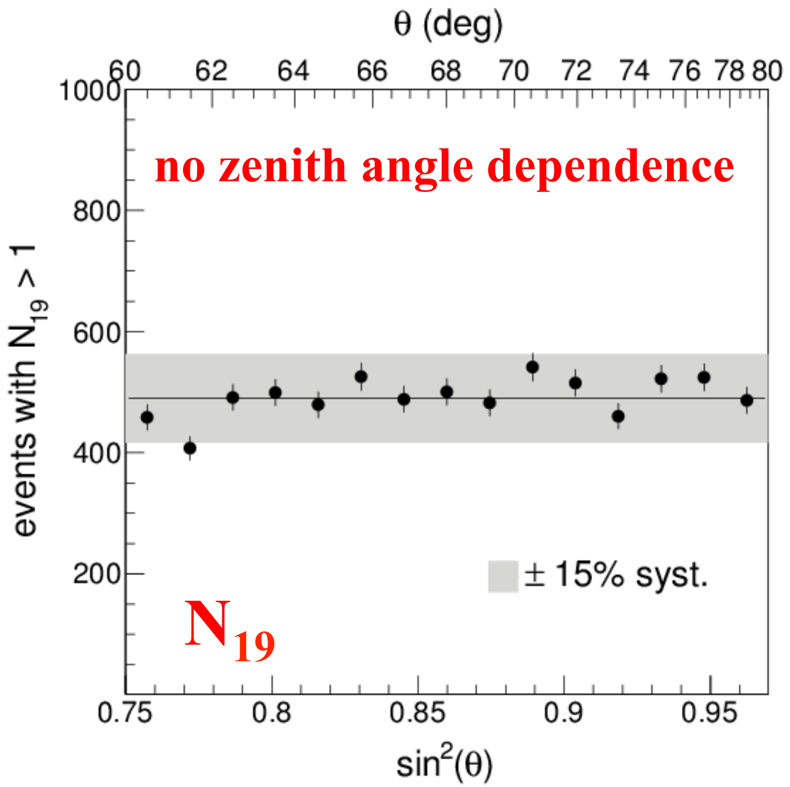
1500 m array **$62^0 < \theta < 80^0$**

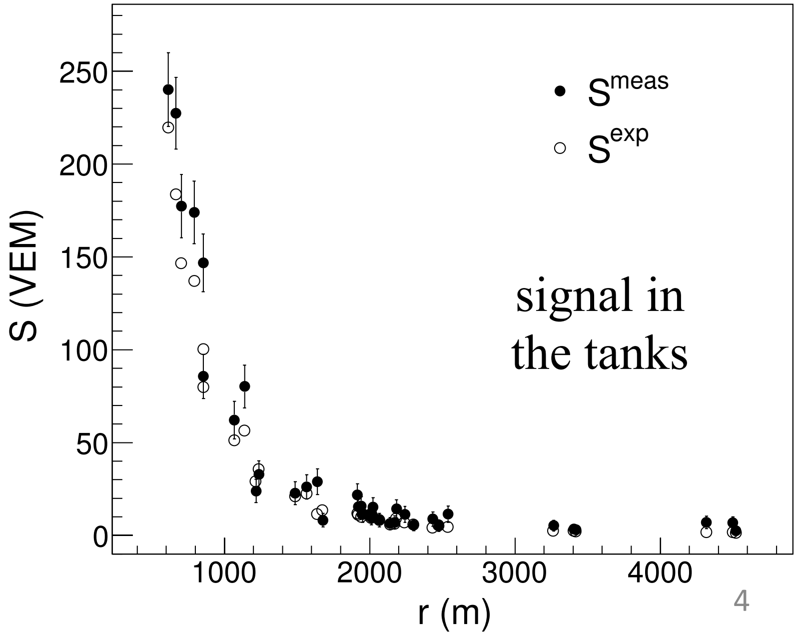
size at ground from muons density maps

$$\rho_\mu = N_{19}\ \rho_{\mu,19}(r,\theta,\phi)$$



The Pierre Auger Collaboration JCAP 08 (2014) 019
see also M.Unger talk

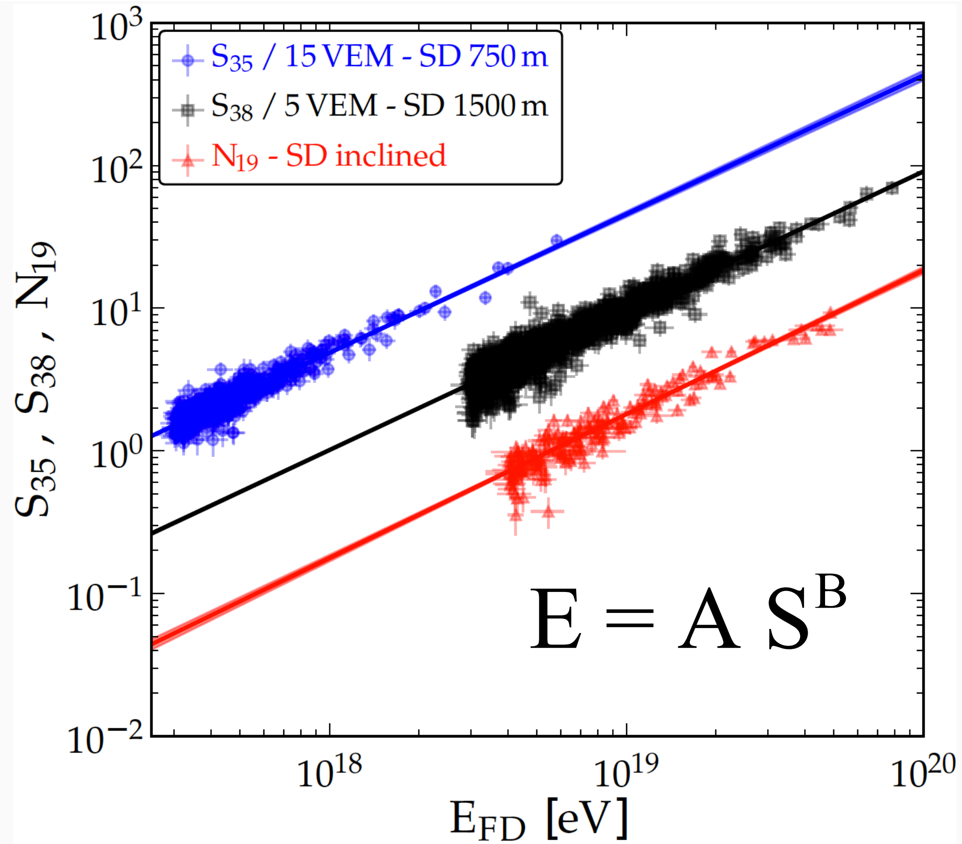




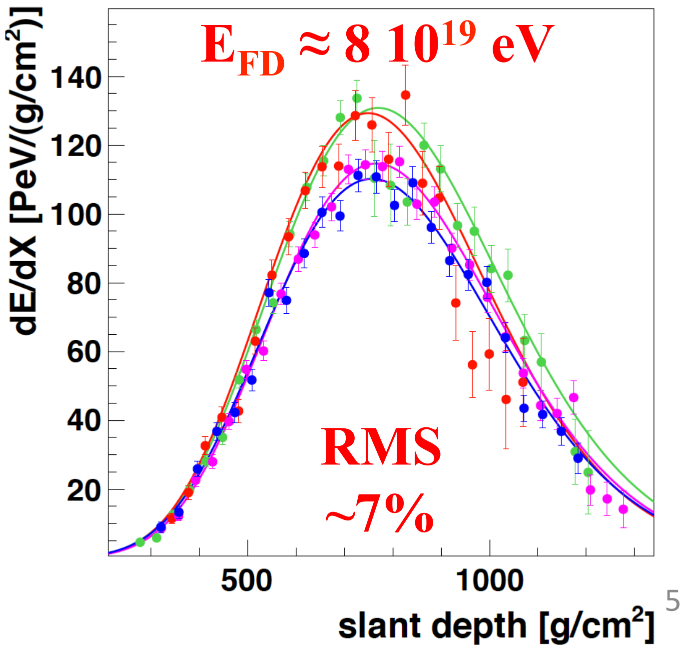
SD EVENTS: ENERGY CALIBRATION

hybrid showers: calibrate SD signal against FD calorimetric energies

avoid uncertainties on air showers simulations

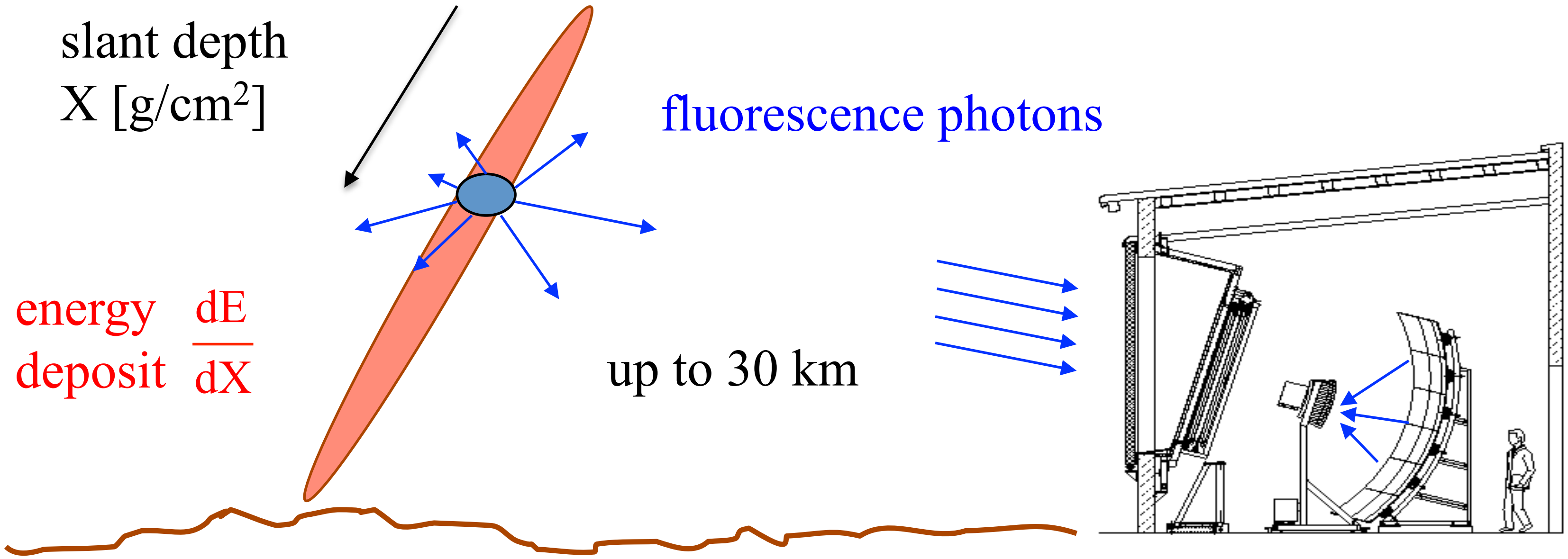


FD longitudinal profiles



SD 1500 m	$A = (0.190 \pm 0.005)$ EeV $B = 1.025 \pm 0.007$
SD inclined	$A = (5.61 \pm 0.1)$ EeV $B = 0.985 \pm 0.02$
SD 750 m	$A = (1.21 \pm 0.07) \times 10^{-2}$ EeV $B = 1.03 \pm 0.02$

FD ENERGY SCALE



Fluorescence yield **dE/dX reconstruction** $\Rightarrow E_{cal} = \int \frac{dE}{dX} dX$

Atmosphere **Invisible energy (ν, μ, ..)** $\Rightarrow E_{inv}$

FD calibration

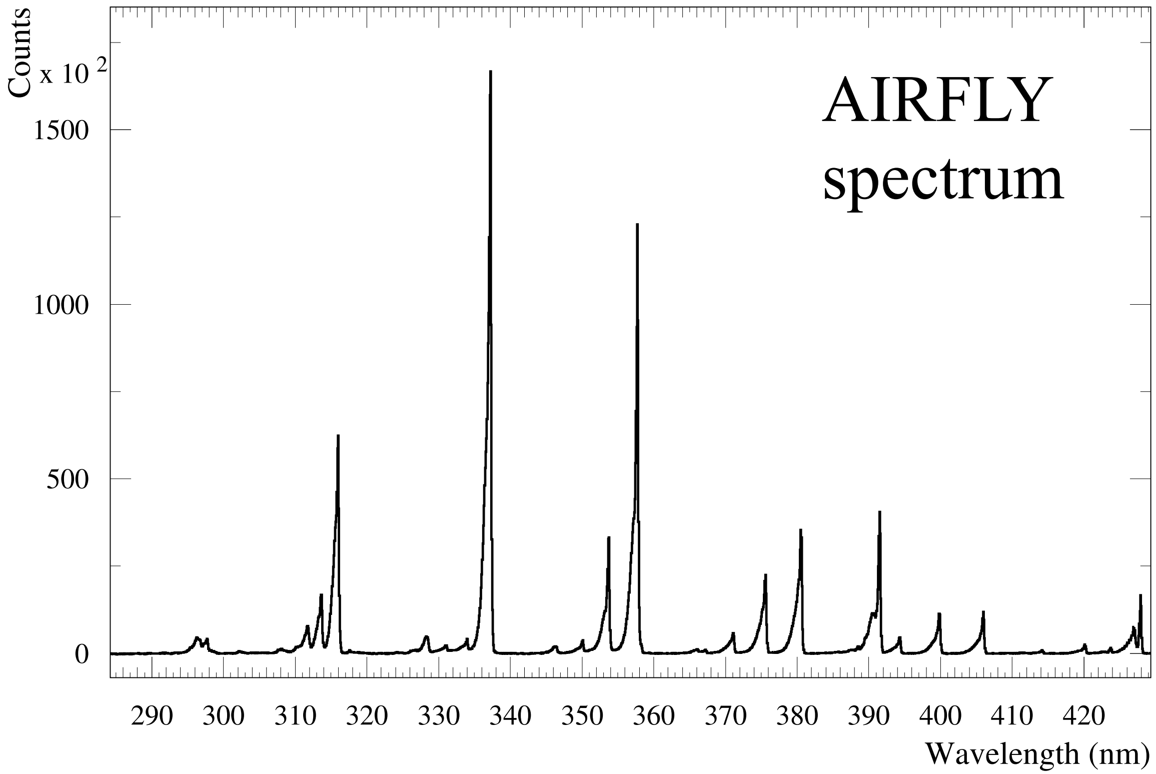
$$E = E_{cal} + E_{inv}$$

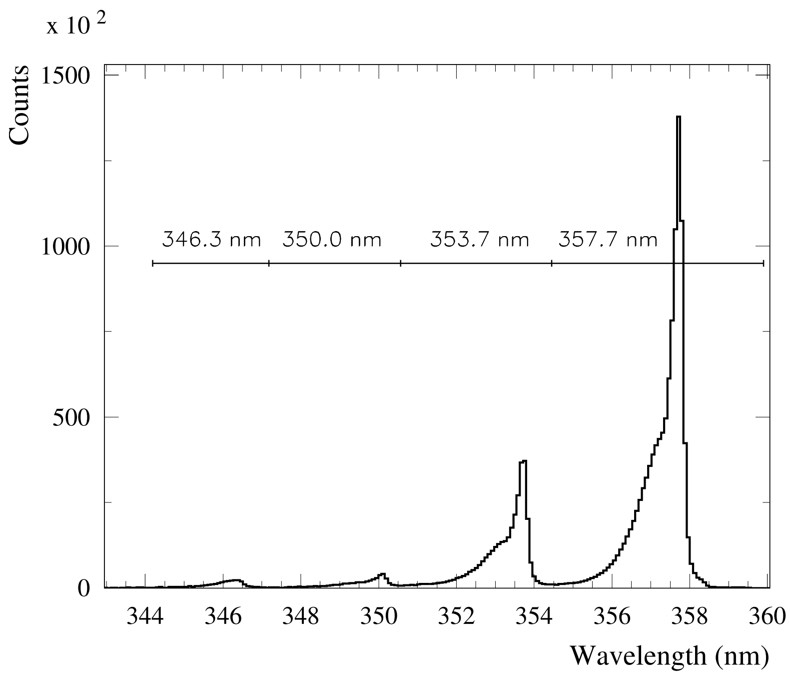
systematic uncertainties correlated and uncorrelated among different showers (crucial to correctly propagate the FD uncertainties to SD energies)

AIRFLY - FLUORESCENCE YIELD

The Airfly Collaboration: Astropart. Phys. **42** (2013) 90. Astropart. Phys. **28** (2007) 41. Nucl. Inst.. Meth. A 597 (2008) 50. M. Bohacova talk at 6th Air Fluor. Workshop

- **relative spectrum and its pressure dependence**
- **humidity and temperature dependence of collisional cross sections**
- **absolute intensity of the 337 nm line**





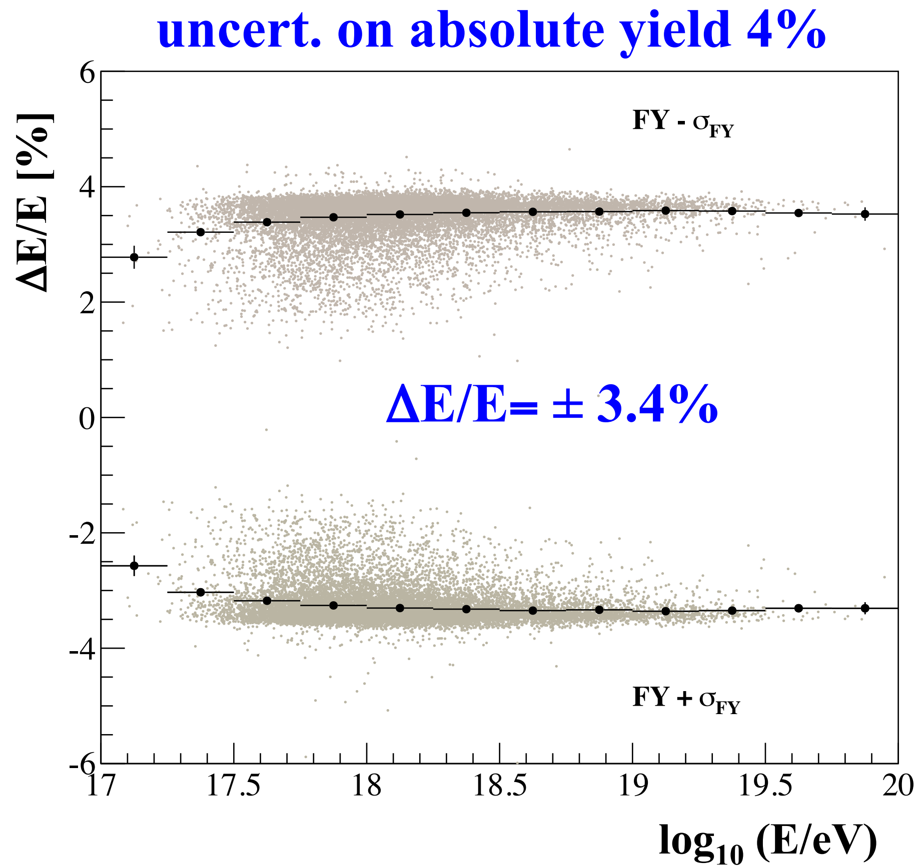
"effective" definition of the wavelength bands

- ➢ **don't care of possible contaminations between nearby bands**
- ➢ **straightforward and correct propagation of Airfly measurement uncertainties**

FLUORESCENCE YIELD

Propagation of the Airfly measurement uncertainties into the energy scale

(take into account the degree of correlation of the measurements)

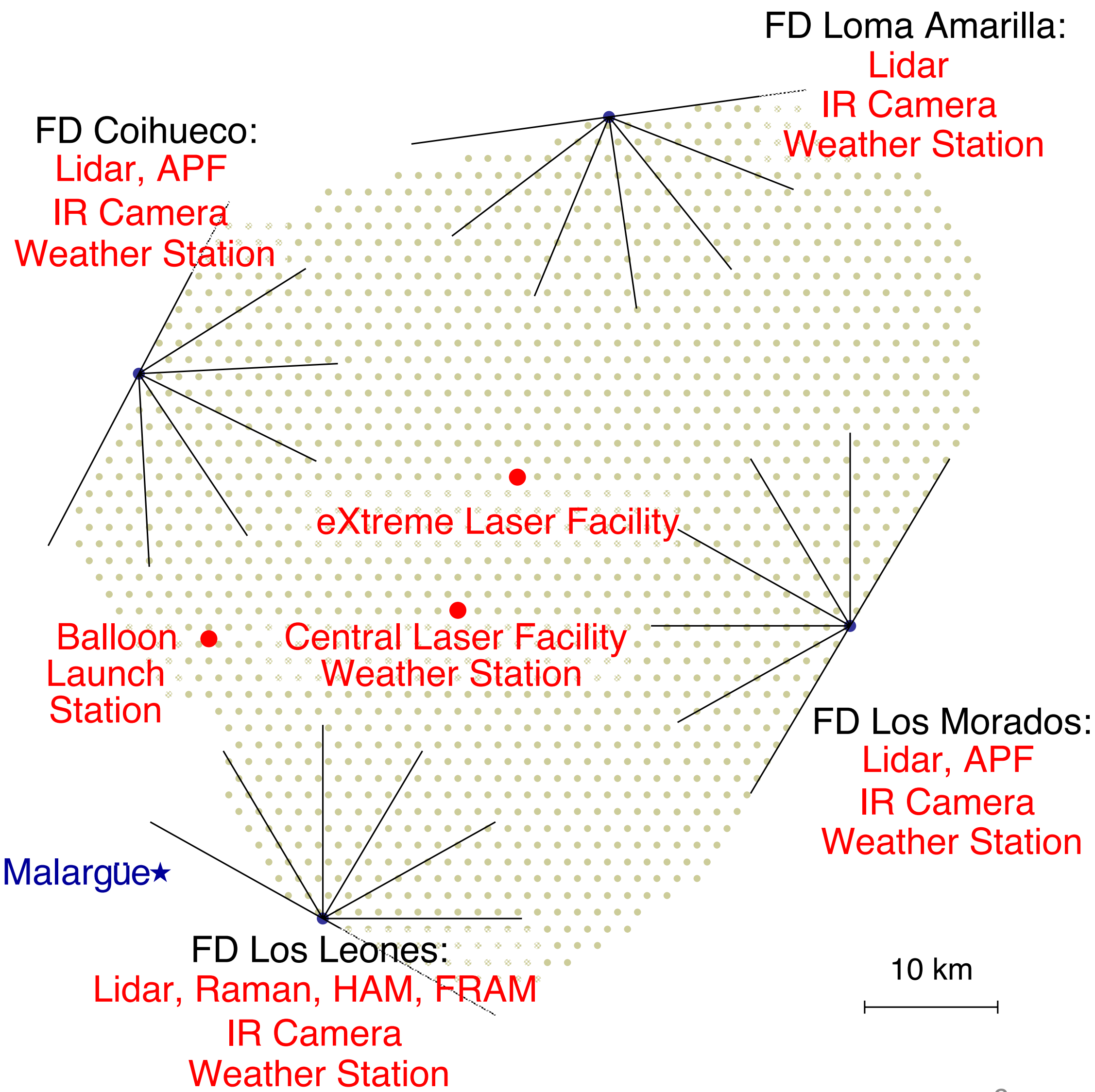


Absolute fluorescence yield	3.4%	
Relative band intensities	1%	
Pressure dependence	0.1%	
Temperature dependence	0.3%	ΔE/E
Humidity dependence	0.1%	
Dependence of humidity cross section on temperature	0.05%	
TOTAL (Fluorescence Yield)	3.6%	

ATMOSPHERE

production and transmission of the light (aerosols and molecular scattering)

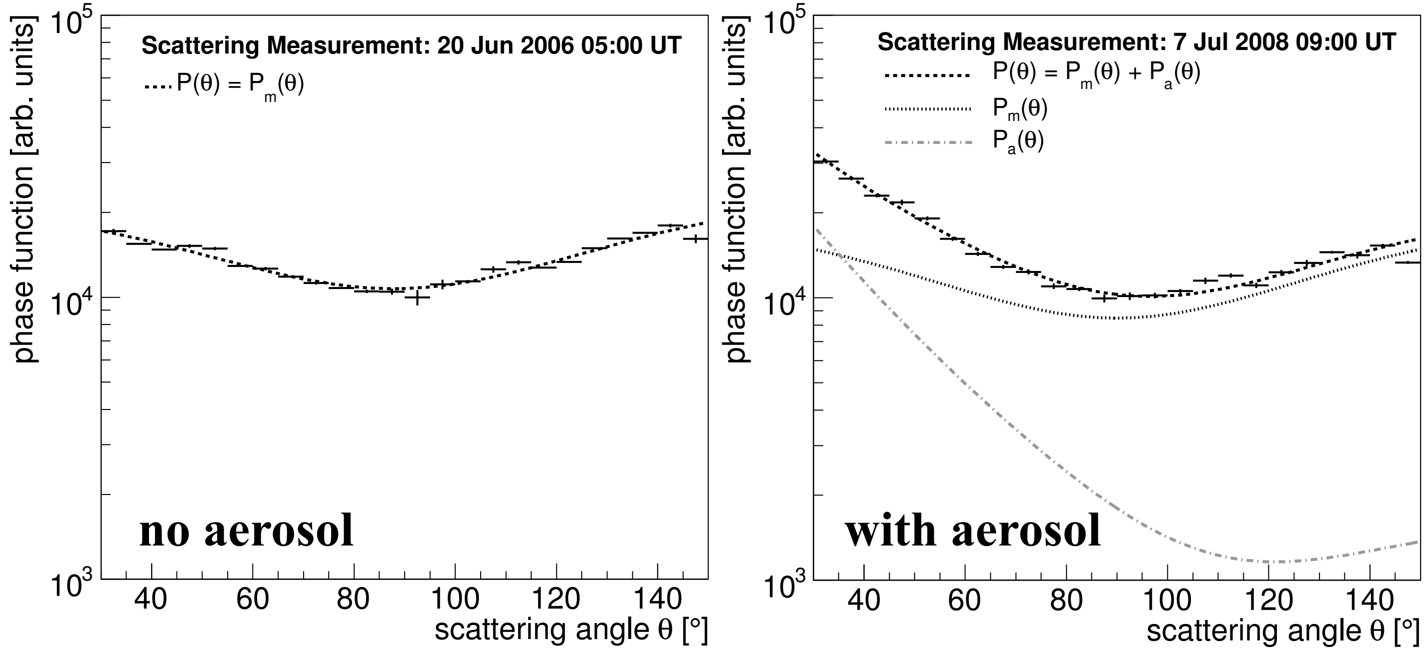
- **atmospheric profiles from Global Data Assimilation System (GDAS)**
- **hourly aerosol optical depth profiles**
- **aerosol phase function**
- **λ dependence of aerosol scattering cross sec.**
- **cloud coverage**



The Pierre Auger Collaboration
Astropart. Phys. **33** (2010) 108
Astropart. Phys. **35** (2012) 591
JINST **8** (2013) P04009
L. Valore ICRC 2013 #0920

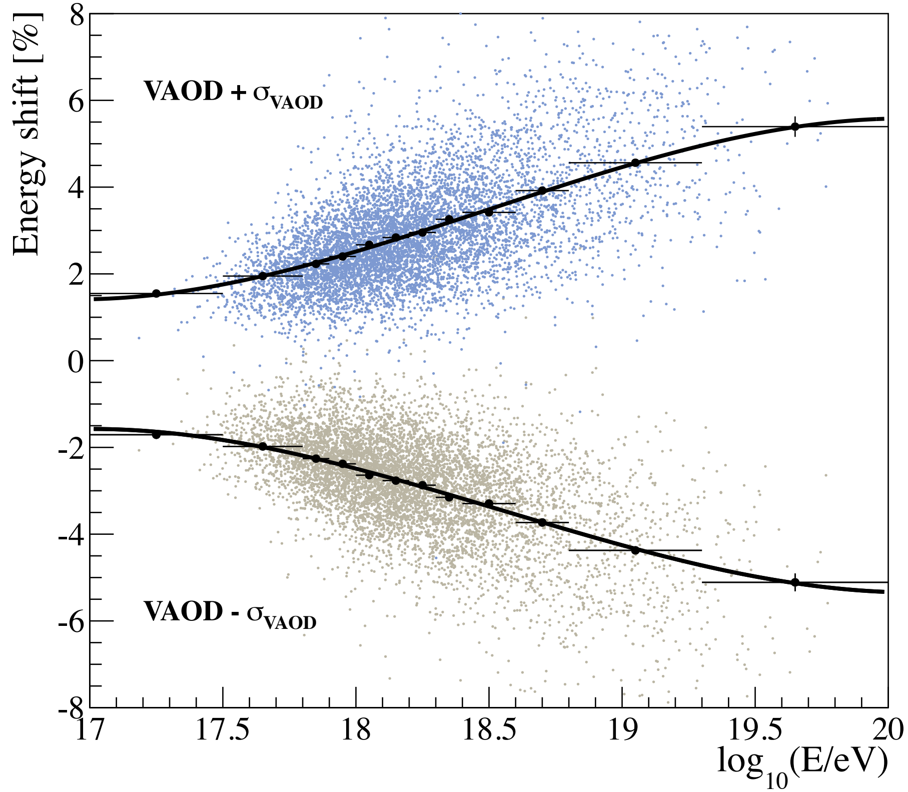
example of measurements of the aerosol phase function

ΔE/E ~ 1%



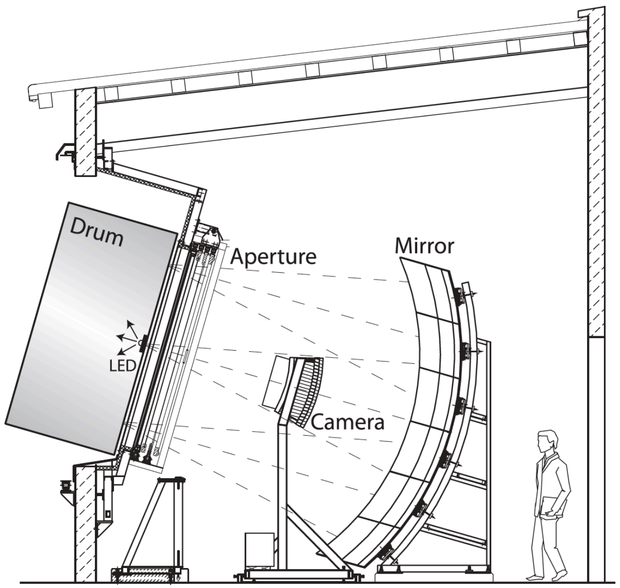
largest uncertainty from the aerosol optical depth

ΔE/E ranges from 3% to 6% for both types of uncertainty



ATMOSPHERE

FD CALIBRATION



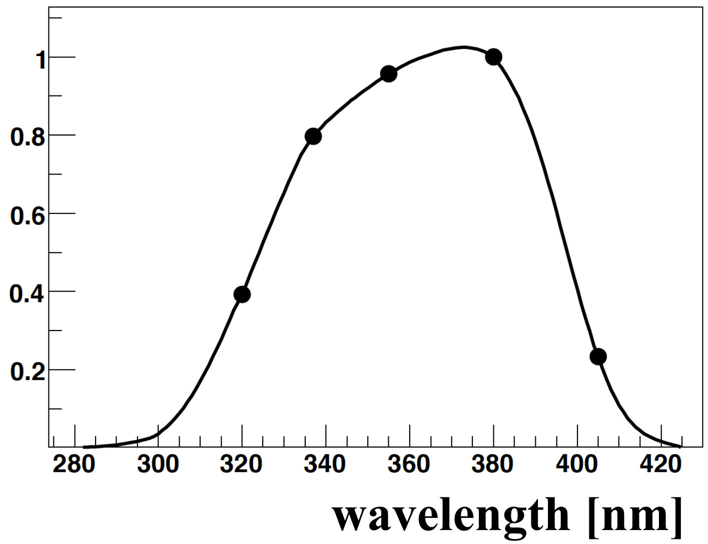
Drum

end-to-end absolute calibration at 375 nm

Relative calibrations at the beginning/end of each night

➡ **track the absolute calibration between drum campaigns**

Response relative to 380 nm



Relative optical efficiency

drum multi-wavelength measurements

total ΔE/E 9.9%

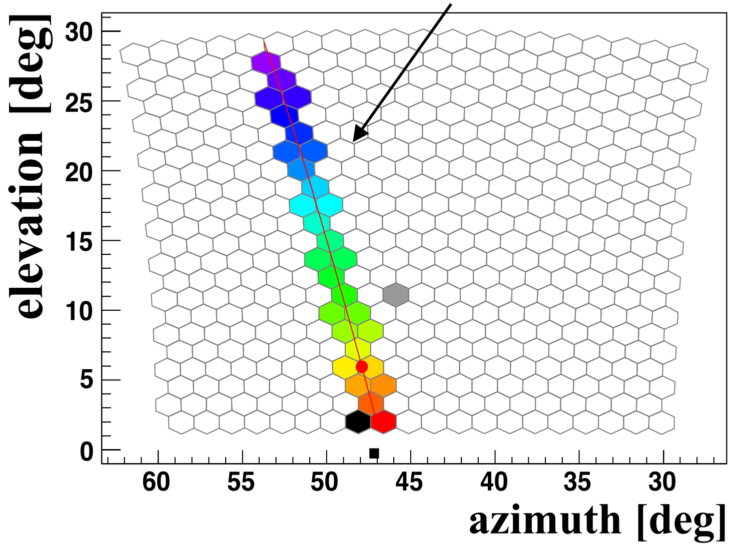
dominated by the absolute calibration

working to reduce at 5% level

J. T. Brack et al., JINST **8** (2013) 5014

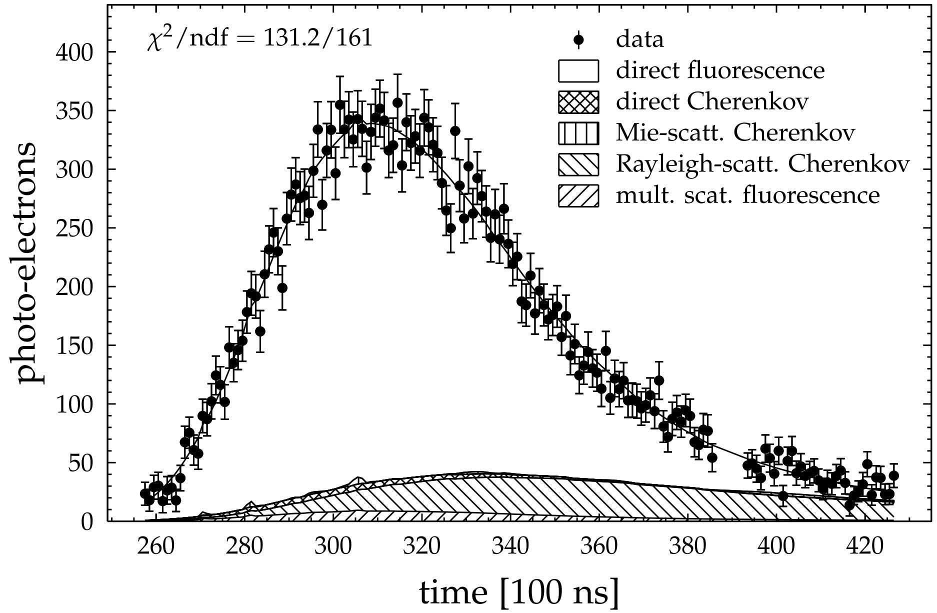
LONGITUDINAL PROFILE RECONSTRUCTION

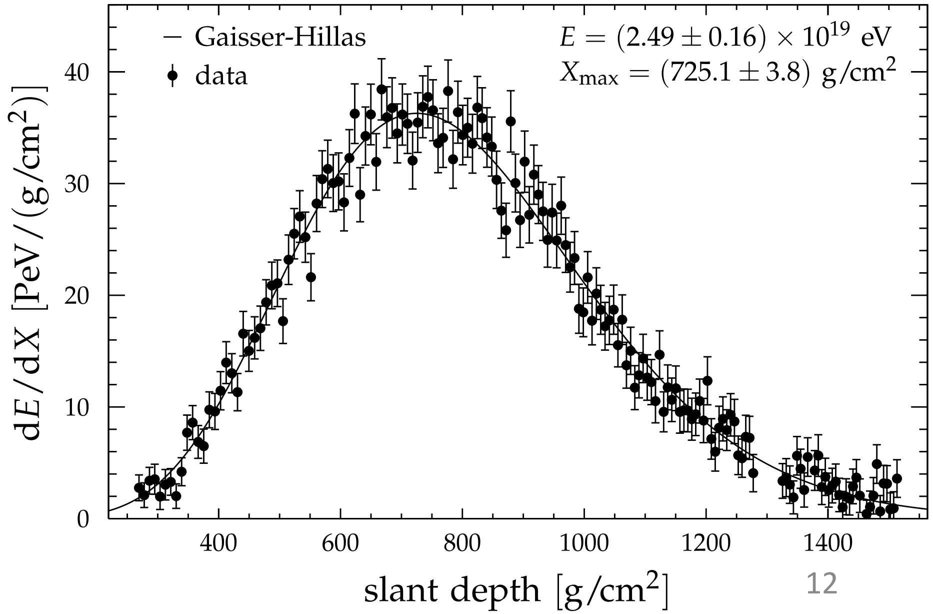
Light collection: select pixels close to the image of the shower axis to maximize the signal to noise ratio
pmt - shower tack < 1.5^0 (pixel size)



reconstruct the dE/dX and fit a Gaisser-Hillas profile

uncorrelated ΔE/E = 7% ÷ 8%
correlated ΔE/E = 6.5% ÷ 5.6%

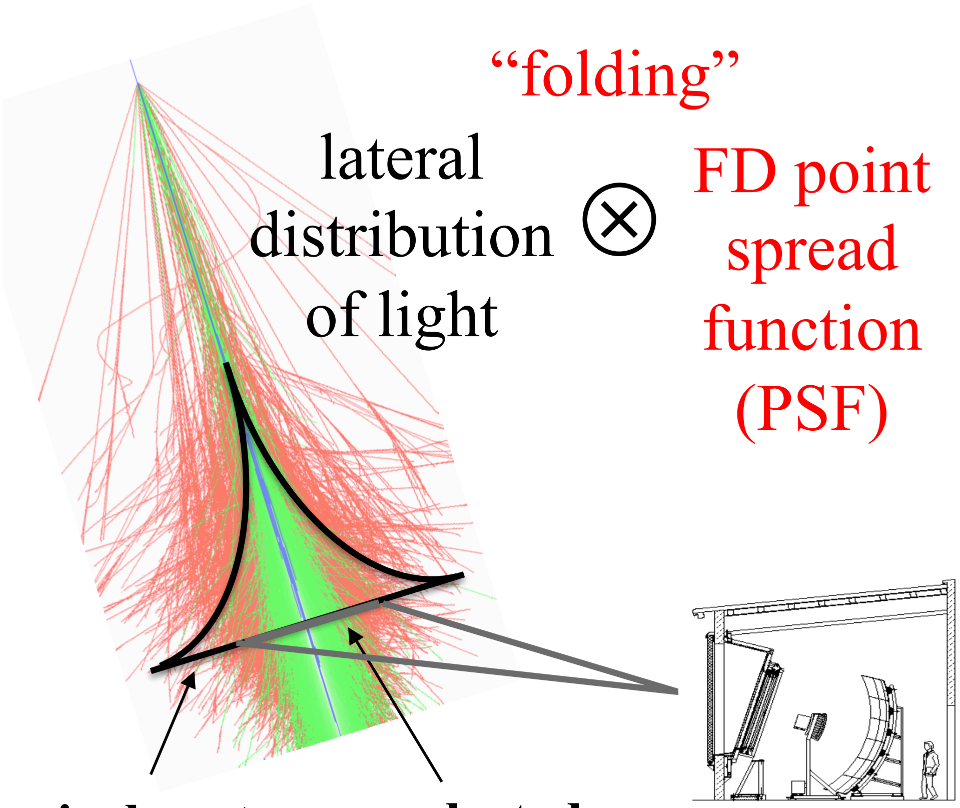




LONGITUDINAL PROFILE RECONSTRUCTION

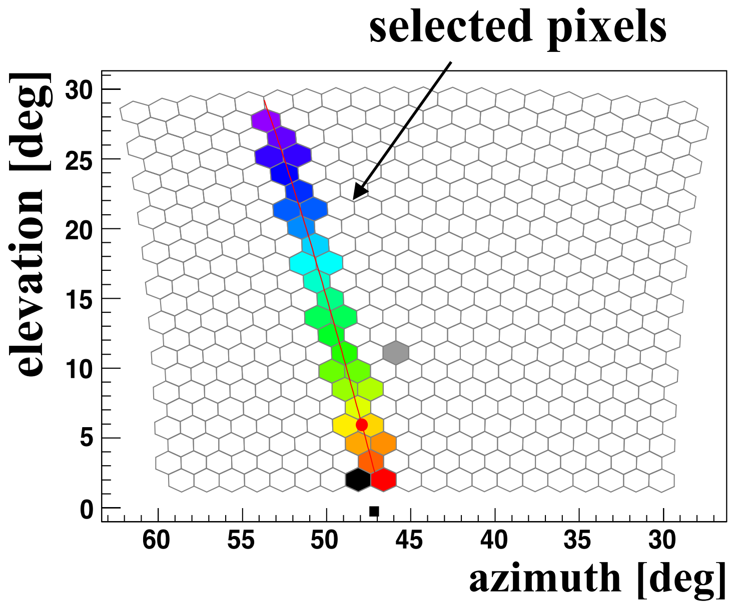
“folding”

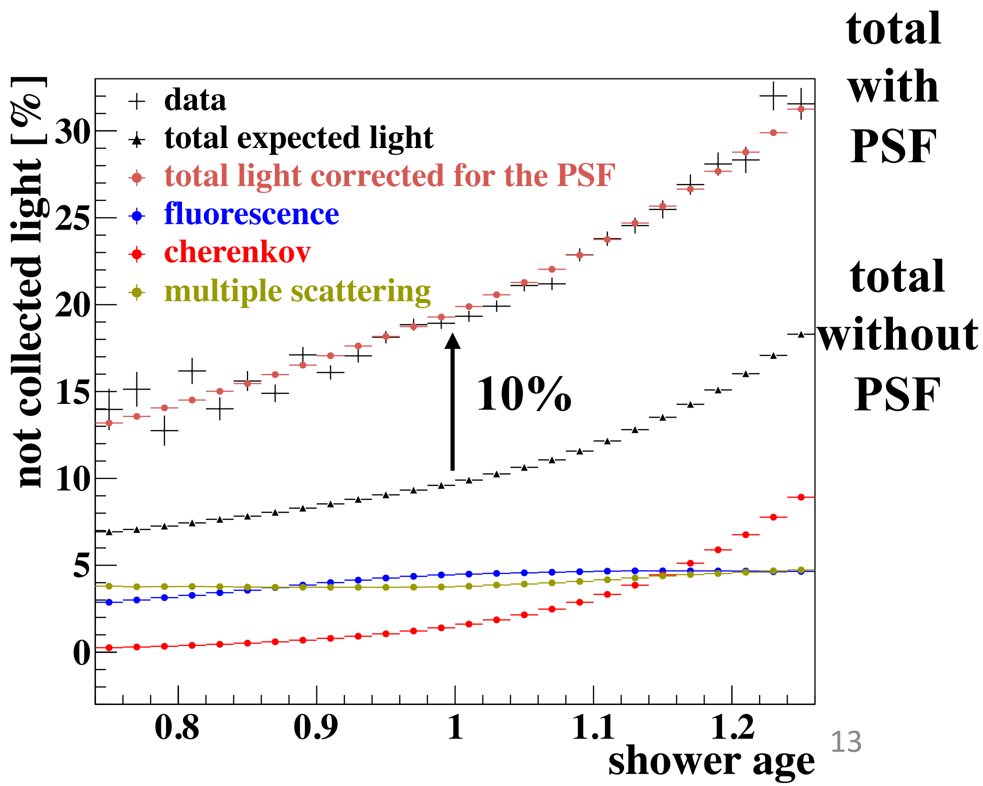
lateral distribution of light ⊗ FD point spread function (PSF)



pixels not selected

selected pixels





empirical parameterization of the folding with PSF increase the energy by 10%

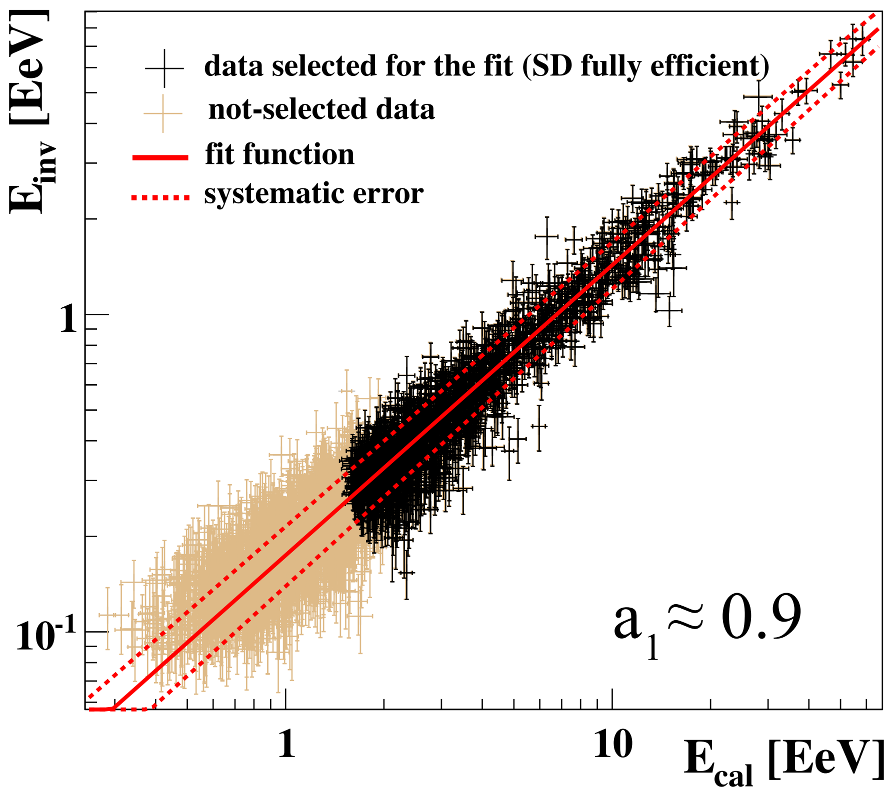
INVISIBLE ENERGY

estimated from Auger data $\log_{10}E_{inv} = A(X_g - X_{max}) + B\log_{10}S_{1000}$

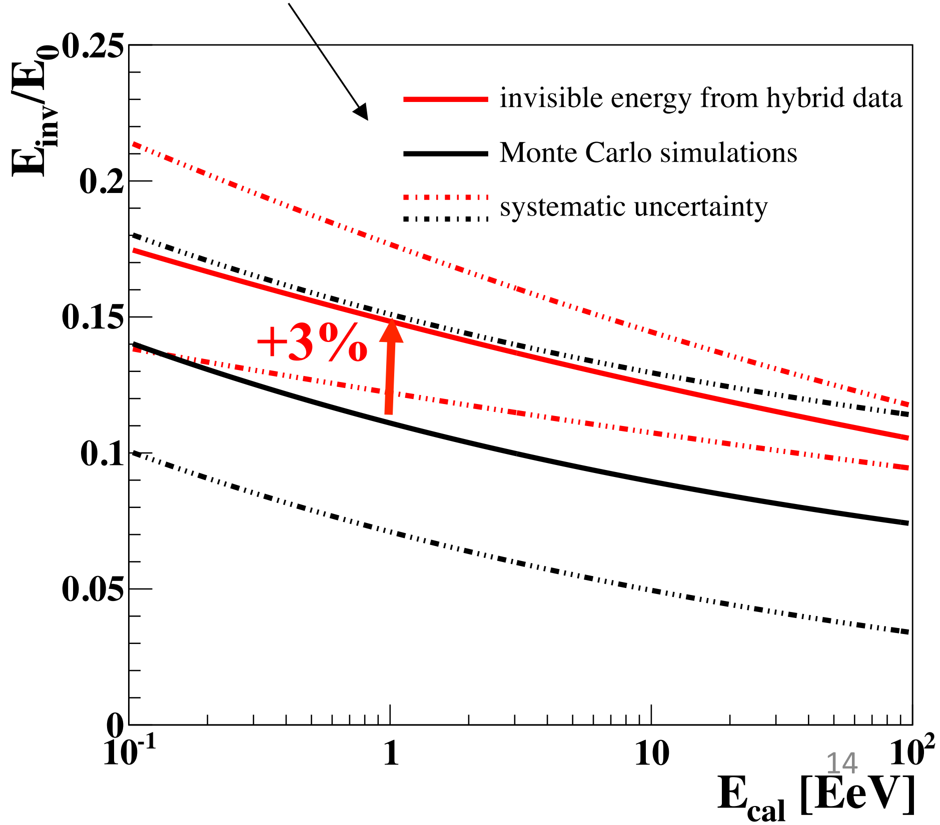
➡ **reduction of uncertainties on air shower simulations and mass composition**

Fit a parametrization $E_{inv} = a_0(E_{cal})^{a_1}$

M. Tueros ICRC 2013 #0705
arXiv:1307.5059 [astro-ph]

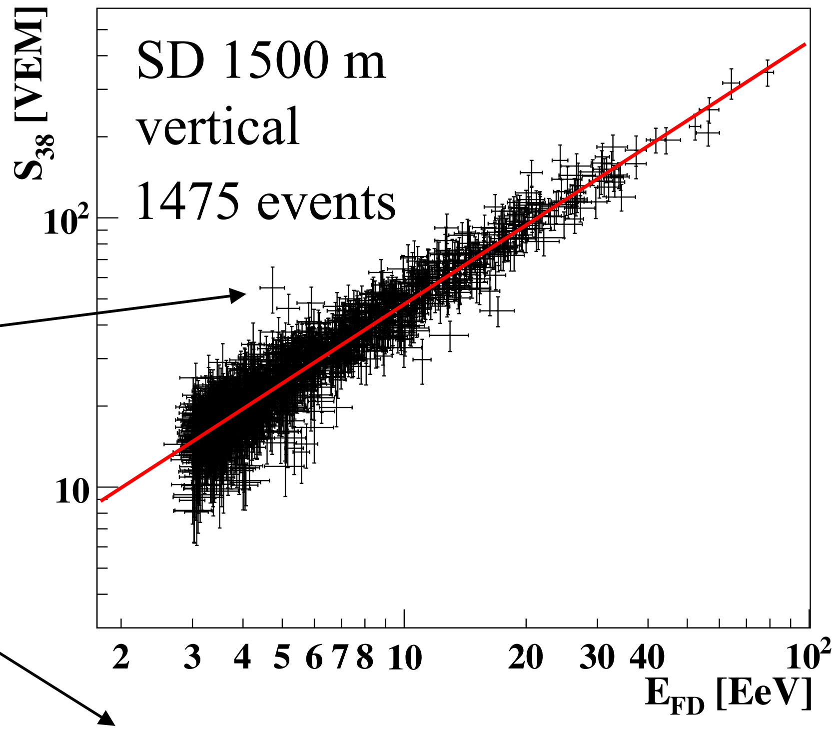


previously from simulation (50% p – 50% Fe)
H. M. J. Barbosa et al., Astropart. Phys. **22** (2004) 159

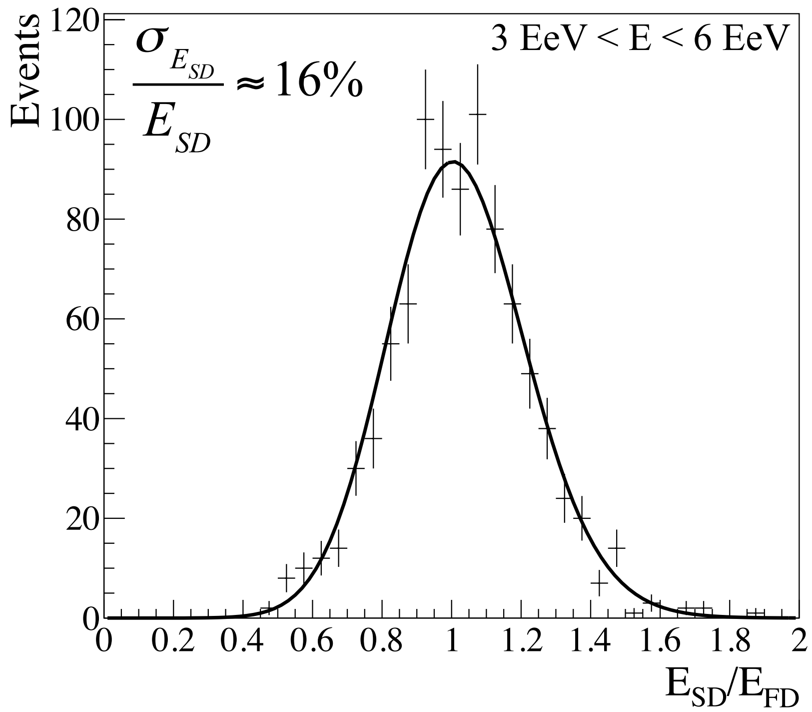


FD UNCORRELATED UNCERTAINTIES

- **used in the likelihood of the SD calibration fit**
- **used to estimate the SD energy resolution from distribution of E_{SD}/E_{FD}**



Aerosol optical depth	**3% ÷ 6%**
Horizontal uniformity of aerosols	**1%**
Atmosphere variability	**1%**
Nightly relative calibration	**3%**
Statistical error of the profile fit	**5% ÷ 3%**
Uncertainty in shower geometry	**1.5%**
Invis. Energy (shower-to-shower fluctuations)	**1.5%**
Total FD energy resolution	**7% ÷ 8%**



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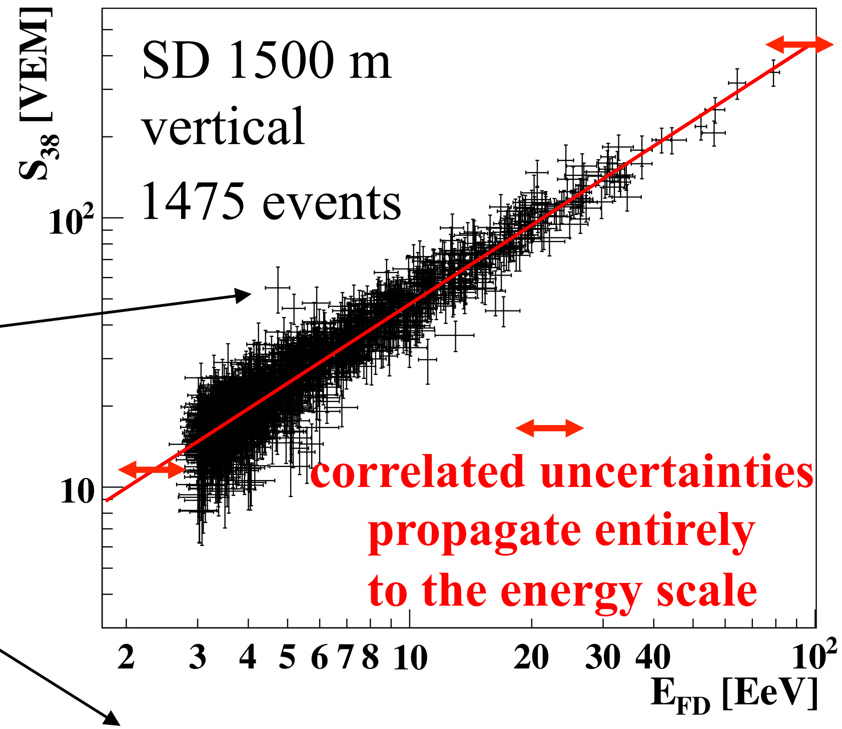

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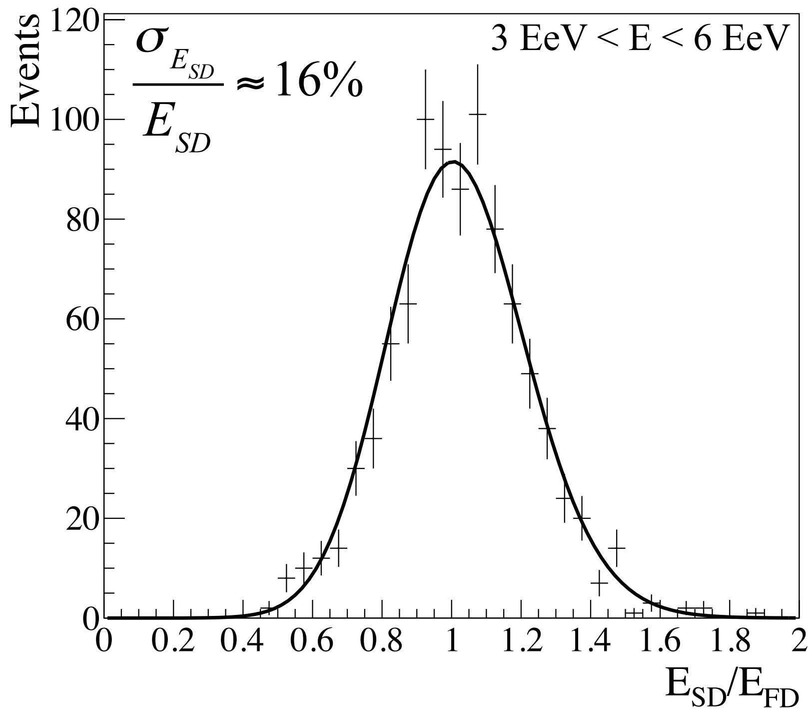


FD CORRELATED UNCERTAINTIES

Absolute fluorescence yield	3.4%
Fluores. spectrum and quenching param.	1.1%
Sub total (Fluorescence Yield)	**3.6%**
Aerosol optical depth	3% ÷ 6%
Aerosol phase function	1%
Wavelength dependence of aerosol scattering	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere)	**3.4% ÷ 6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration)	**9.9%**
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec.)	**6.5% ÷ 5.6%**
Invisible energy	**3% ÷ 1.5%**
Statistical error of the SD calib. fit	**0.7% ÷ 1.8%**
Stability of the energy scale	**5%**
TOTAL	**14%**

largest contribution from FD calibration

TOTAL UNCERTAINTY 14%
≈ energy independent

1500 m array $\theta < 60^0$

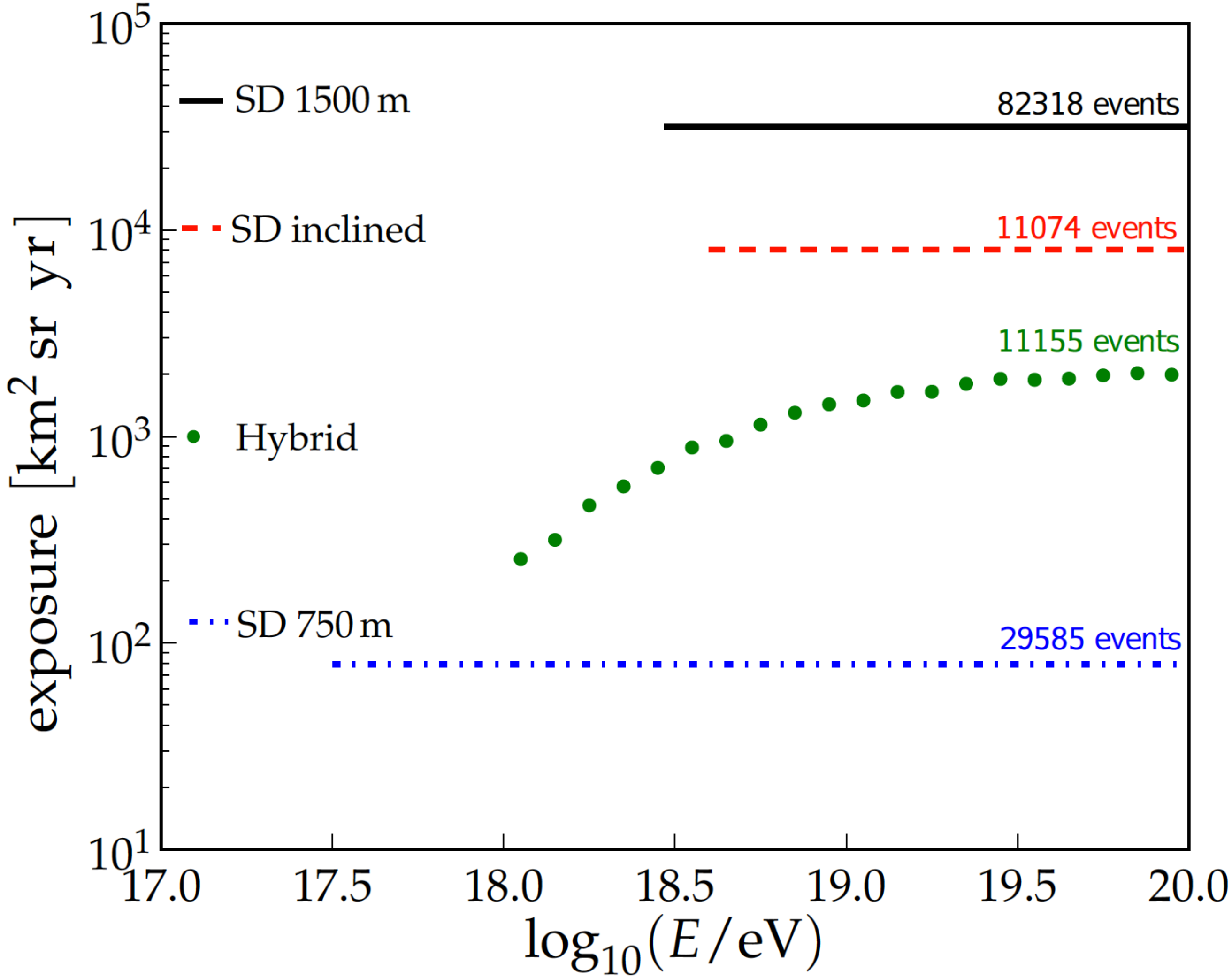
UPDATE OF THE ENERGY SCALE AT ICRC 2013

Change to reconstruction	maximum energy shift – 10^{18} eV	previous uncertainty	current uncertainty
Fluorescence yield (use the absolute value of Airfly)	**-8.2%**	**14%**	**3.6%**
Atmosphere (improved analysis of aerosols optical depth)	**≈ 0%**	**5% ÷ 8%**	**3.4% ÷ 6.2%**
New opt. eff. Calibr. database update **Sub total (FD calibration)**	4.3% 3.5% **7.8%**	**9.5%**	**9.9%**
Likelihood fit of dE/dX Folding with point spread function **Sub total (FD profile rec.)**	2.2% 9.4% **11.6%**	**10%**	**6.5% ÷ 5.6%**
Invisible energy	**4.4%**	**4%**	**3% ÷ 1.5%**
TOTAL	**15.6%**	**22%**	**14%**

ALL CHANGES COMPATIBLE WITH PREVIOUS SYSTEMATICS

EXPOSURE

SD: geometrical calculation
FD: calculation using real MC simulation



exposures at 10^{19} eV [km^2 sr yr]

SD vertical
31645 ± 950

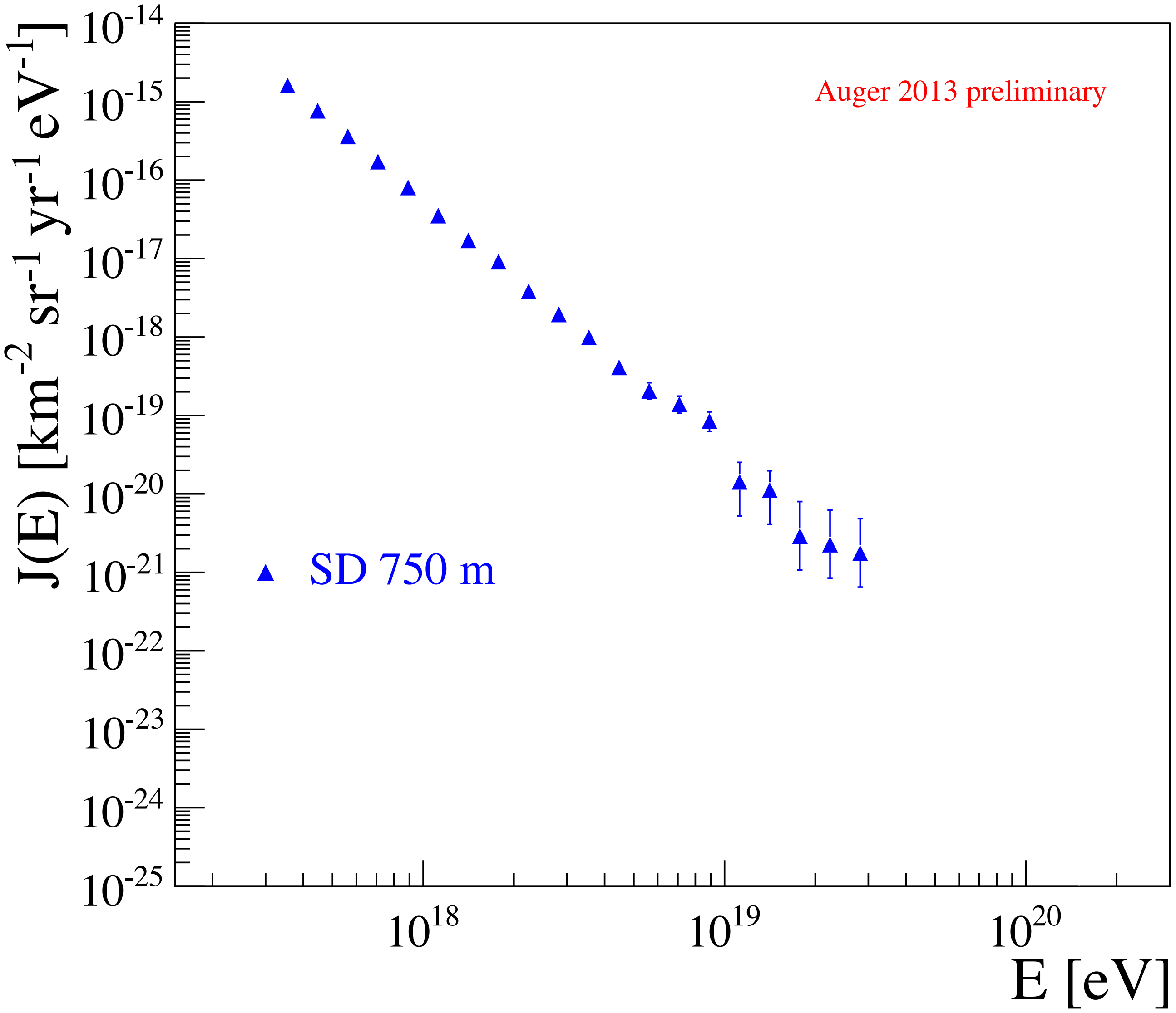
SD inclined
8027± 240

Hybrid
1496 ± 25

SD 750 m
79 ± 4

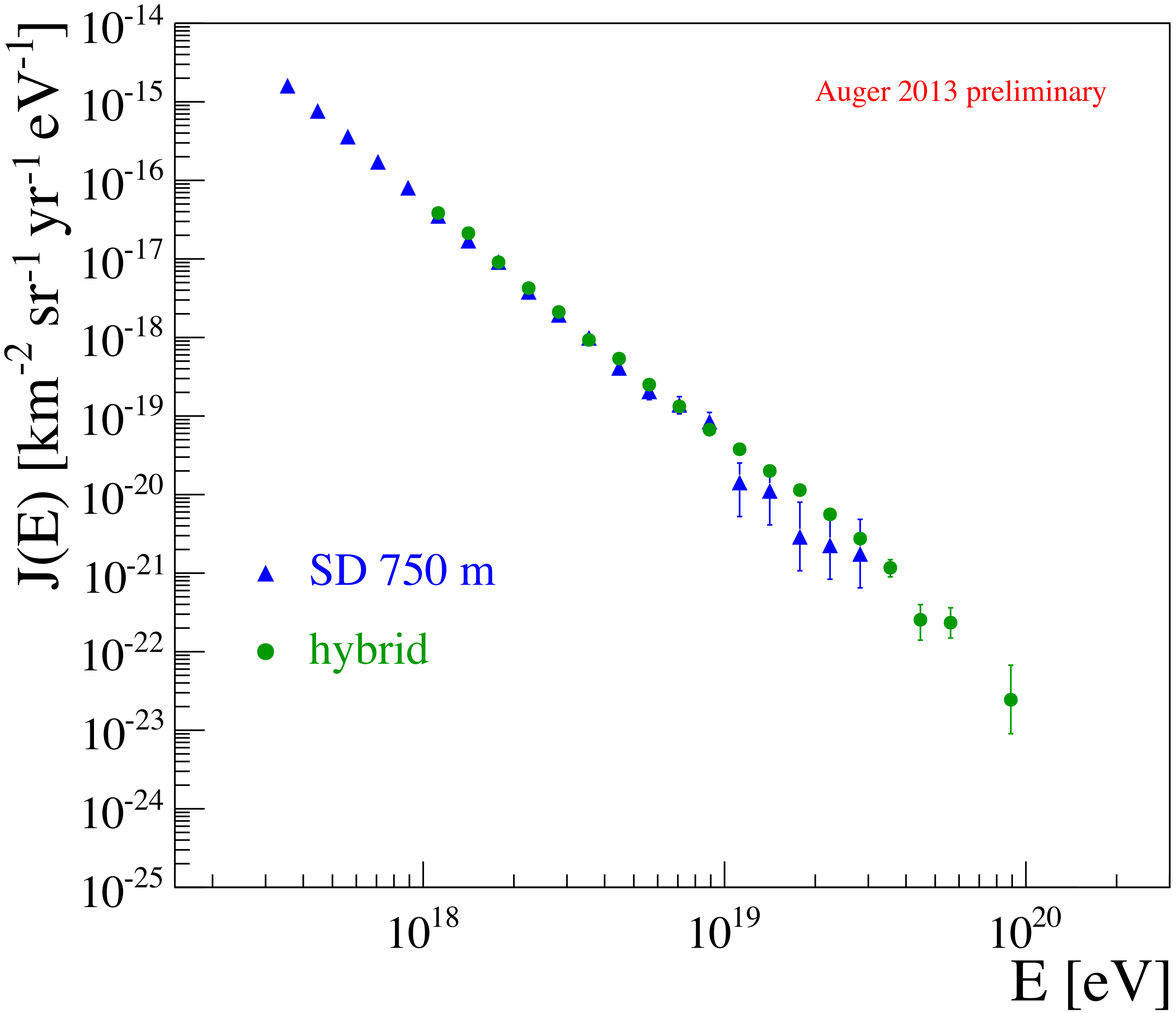
ENERGY SPECTRA

- SD 750 m spectrum: 29585 events above 3×10^{17} eV (08/2008 – 12/2012)
- correction for bin-to-bin migrations due to the detector resolution and steepness of spectrum (< 15%)



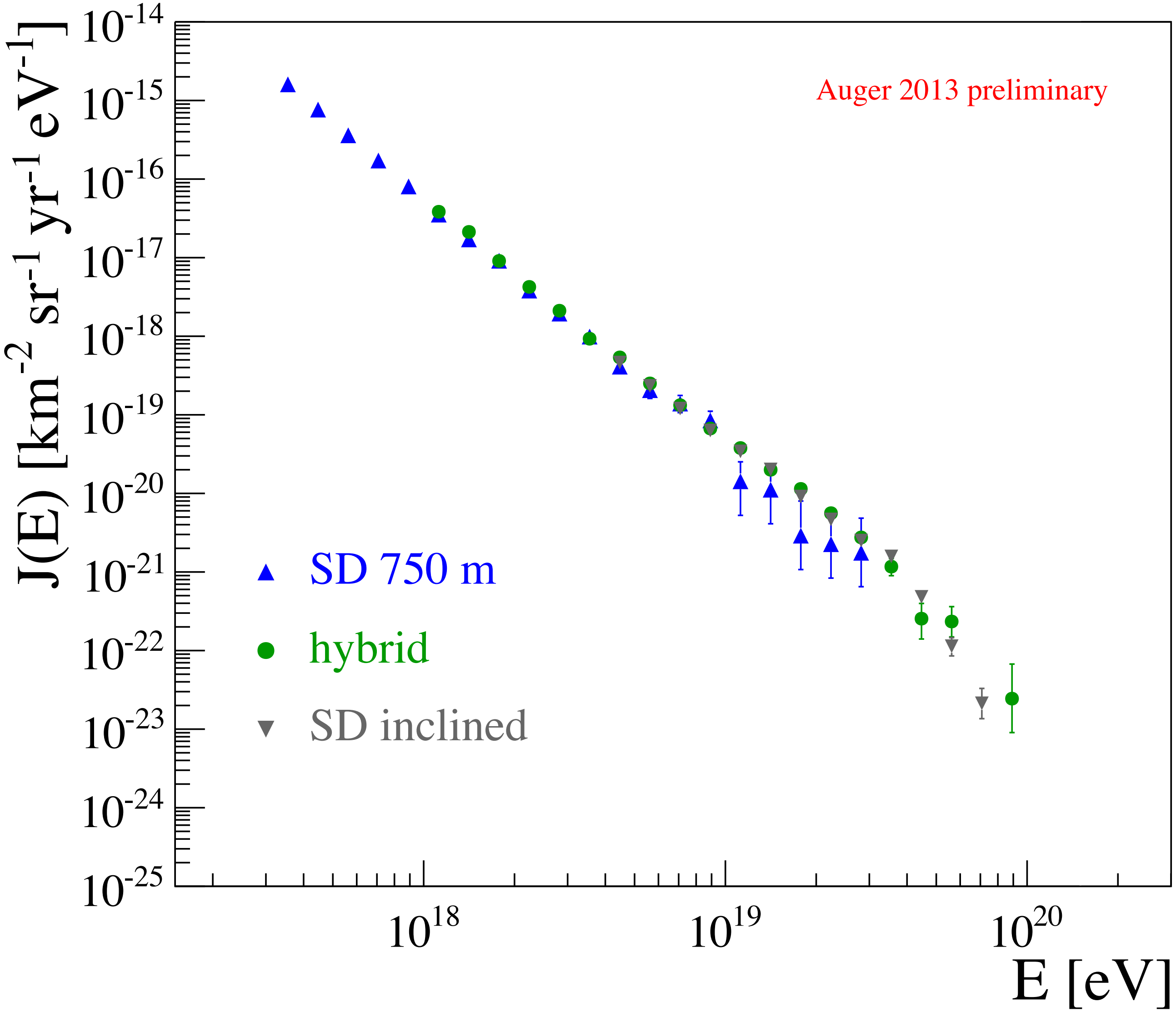
ENERGY SPECTRA

- hybrid spectrum: 11155 events above 10^{18} eV (11/2005 – 12/2012)
- correction for bin-to-bin migrations due to the detector resolution and steepness of spectrum (< 3%)



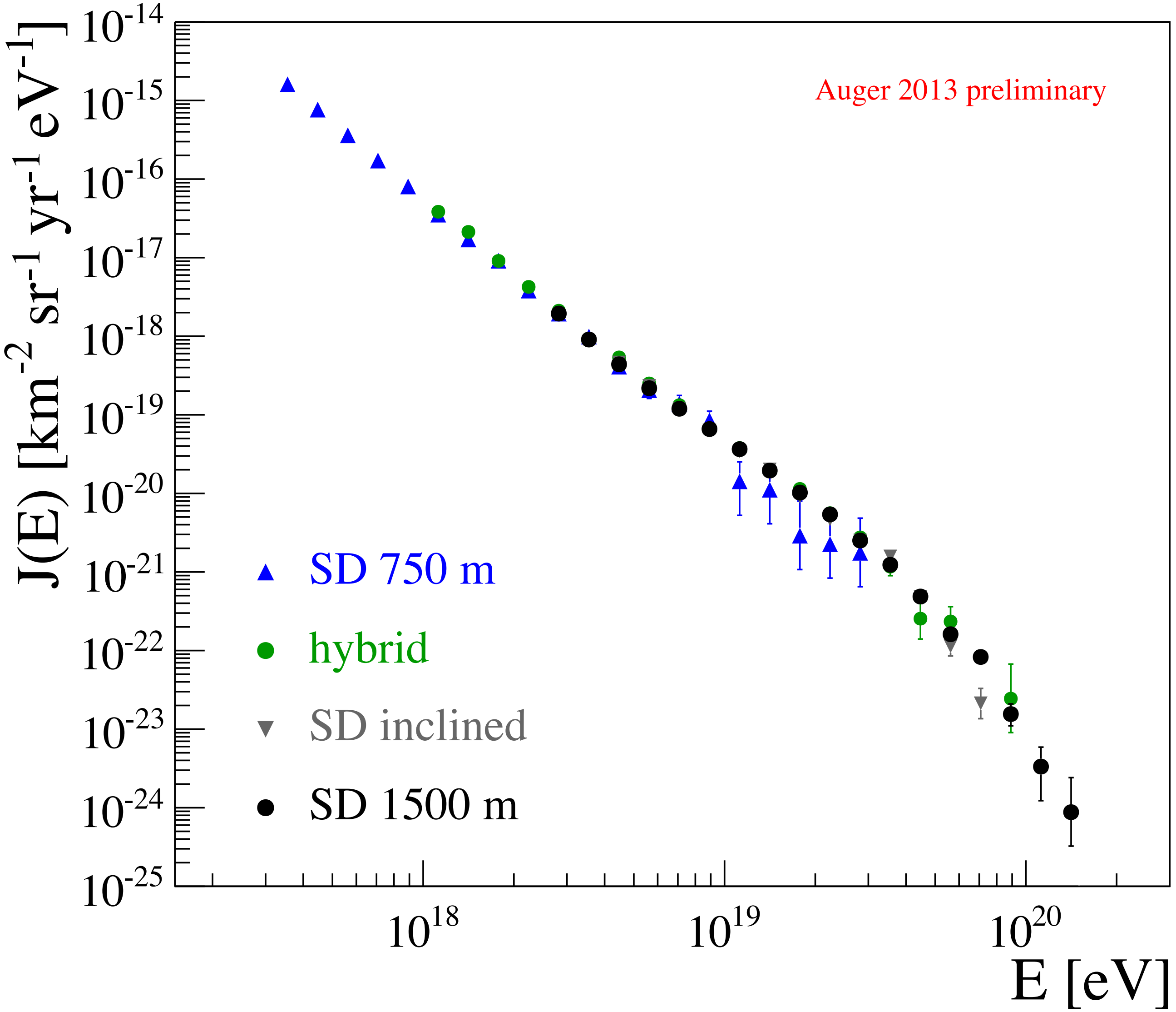
ENERGY SPECTRA

- SD inclined: 11074 events above 4×10^{18} eV (01/2004 – 12/2012)
- correction for bin-to-bin migrations due to the detector resolution and steepness of spectrum (< 12%)



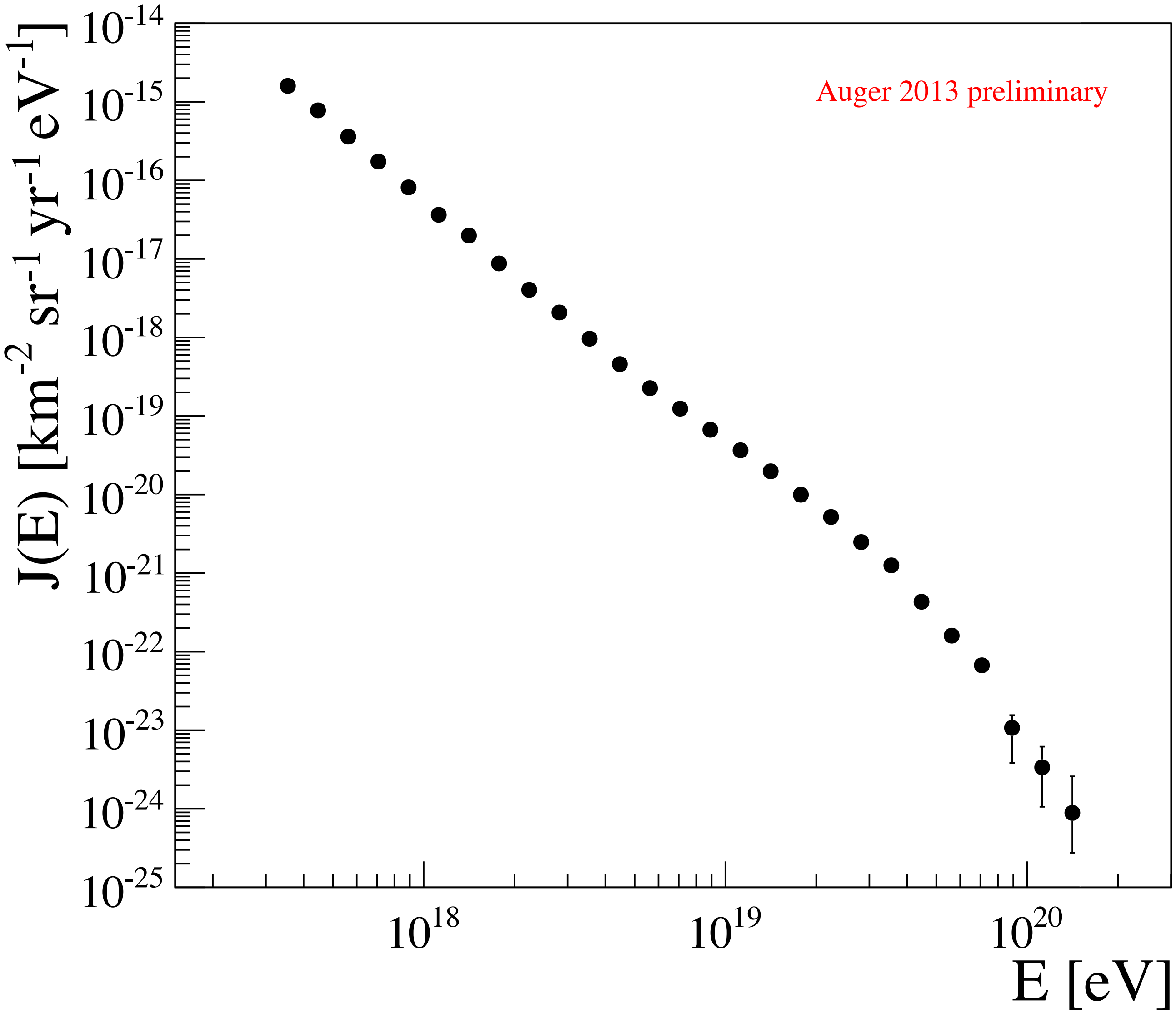
ENERGY SPECTRA

- SD inclined: 82318 events above 3×10^{18} eV (01/2004 – 12/2012)
- correction for bin-to-bin migrations due to the detector resolution and steepness of spectrum (< 17%)



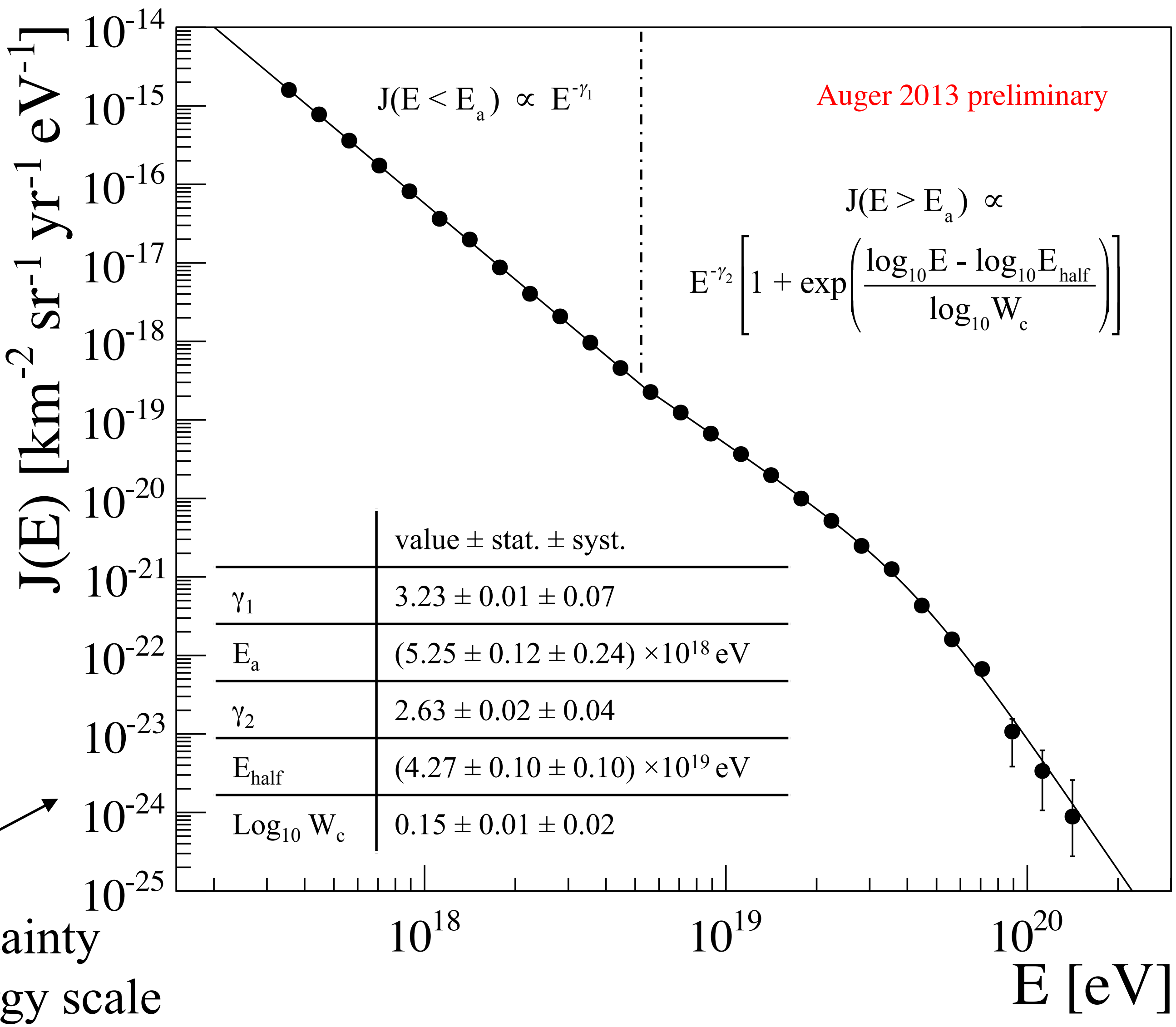
COMBINED ENERGY SPECTRA

- combination after few % correction to the normalizations



COMBINED ENERGY SPECTRA

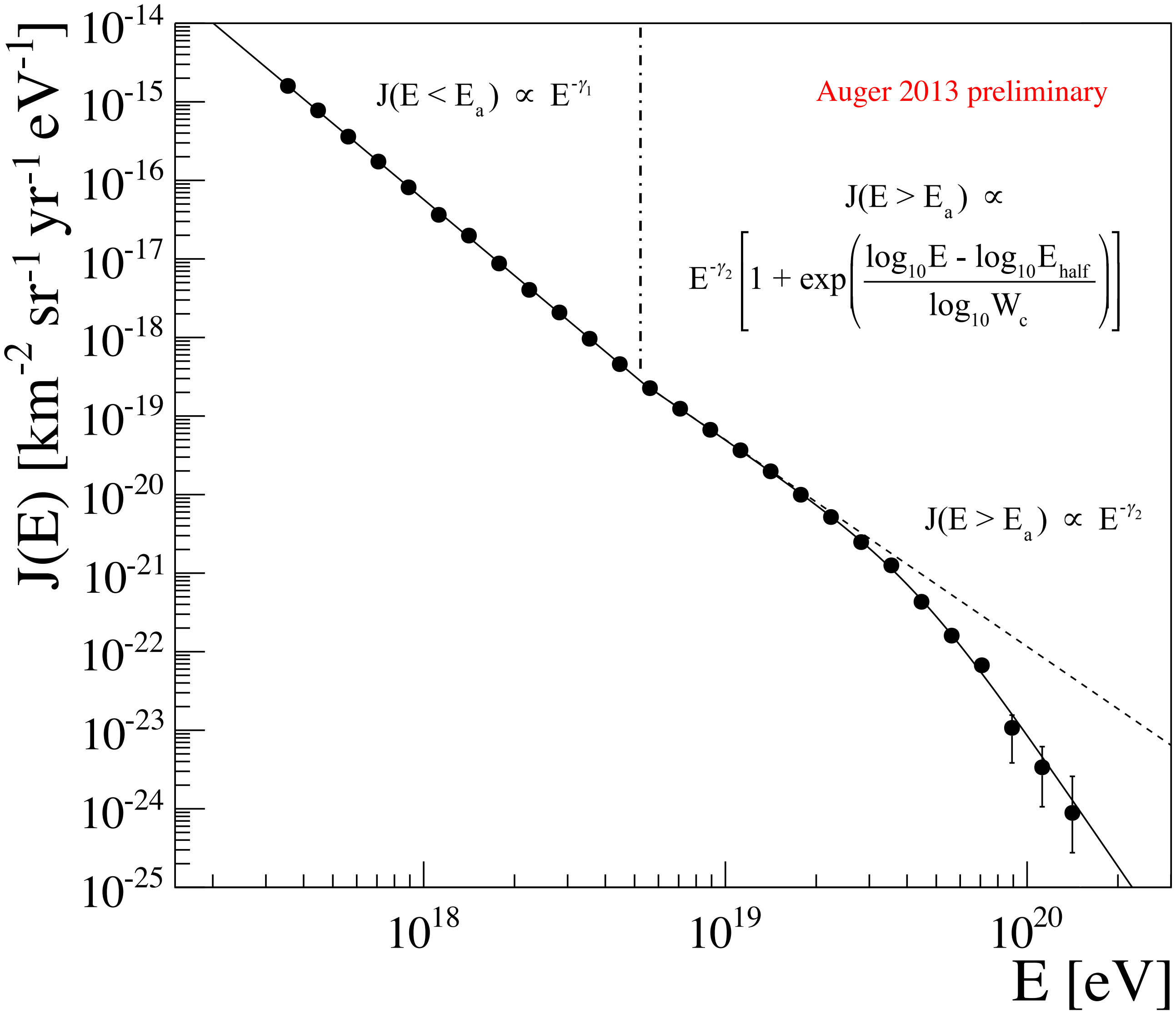
- power low + smooth suppression above ankle (E_a)



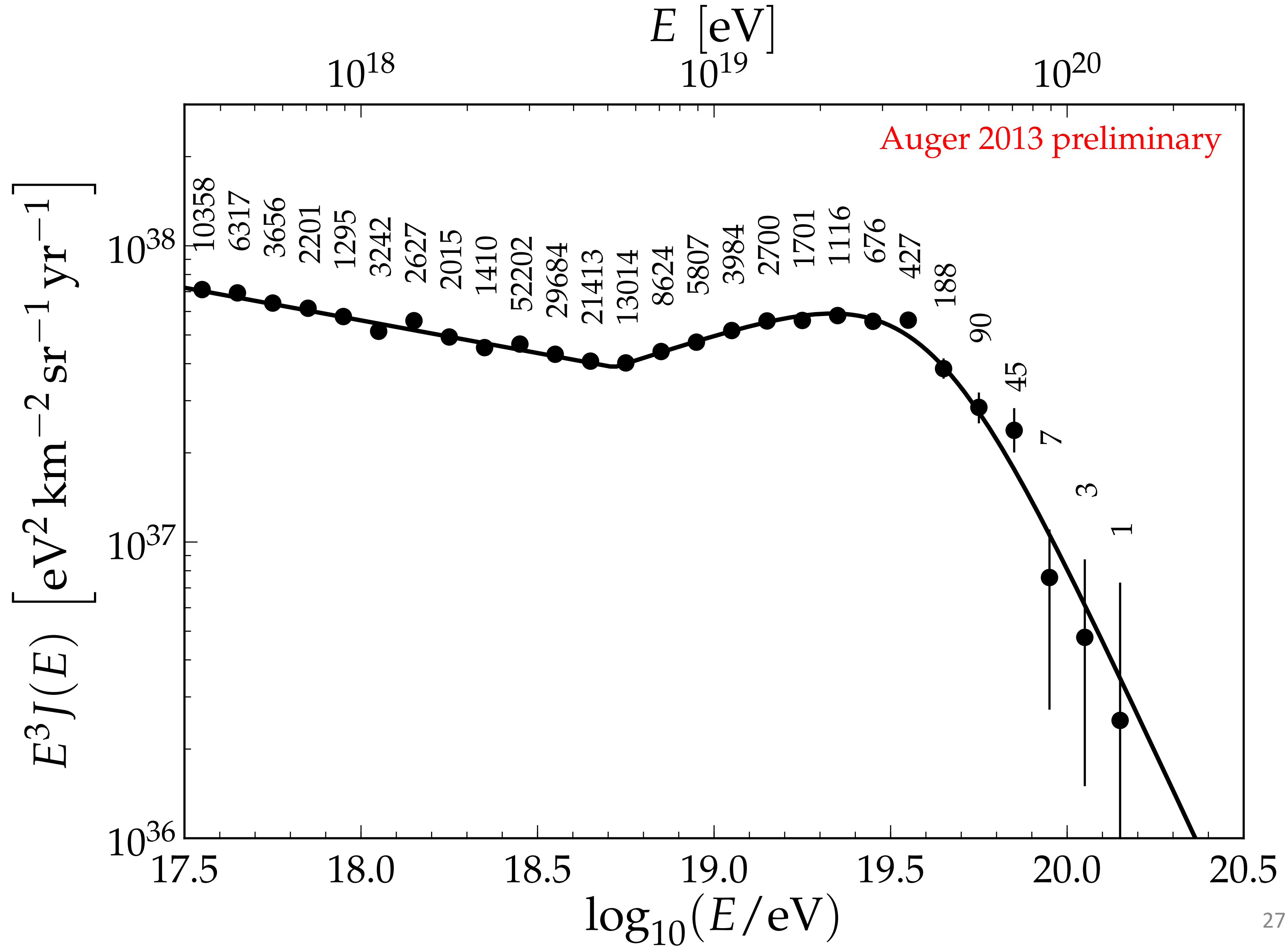
+ 14% uncertainty
from the energy scale

COMBINED ENERGY SPECTRA

- power low + smooth suppression above ankle (E_a)

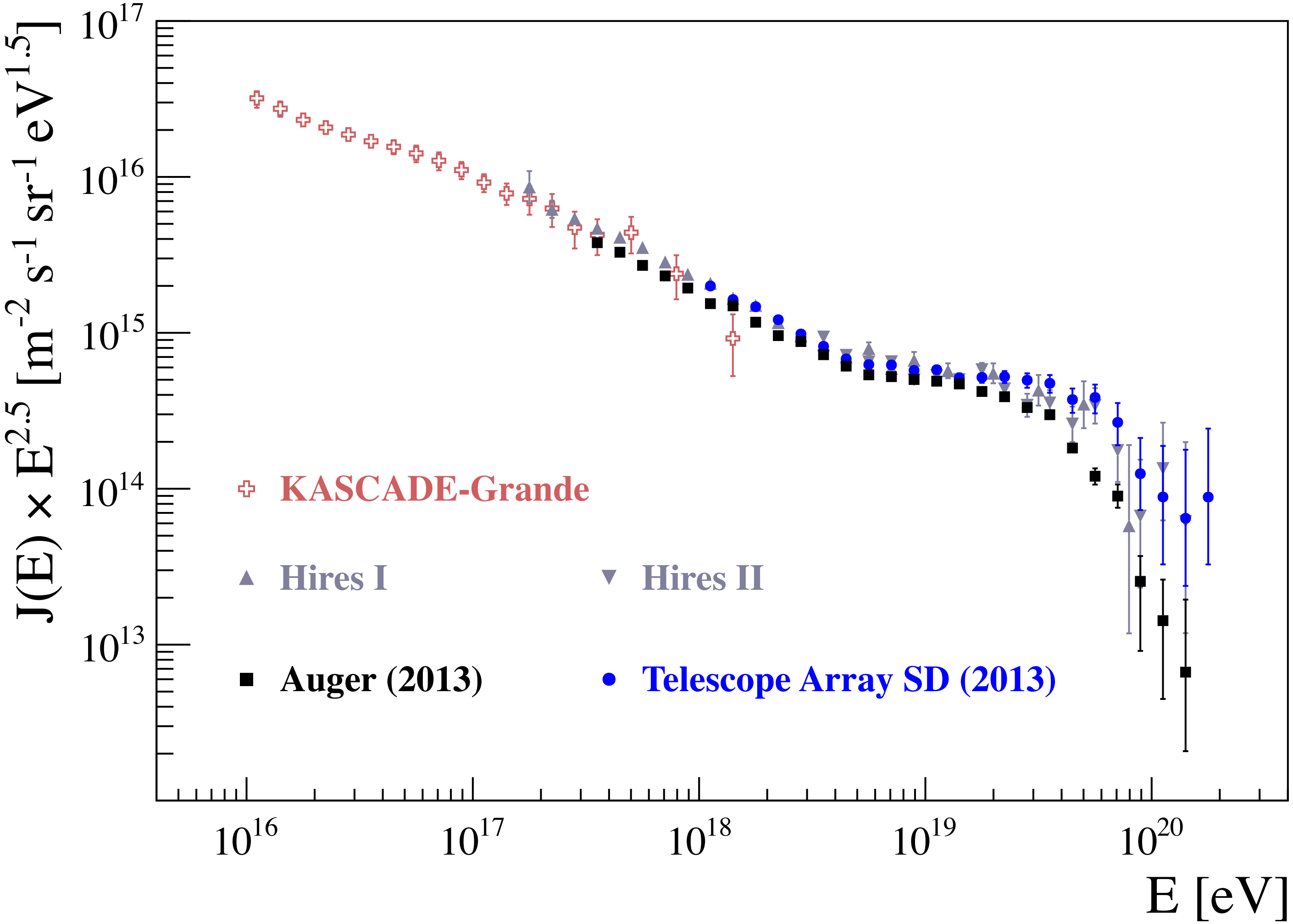


COMBINED ENERGY SPECTRA



OUTLOOK

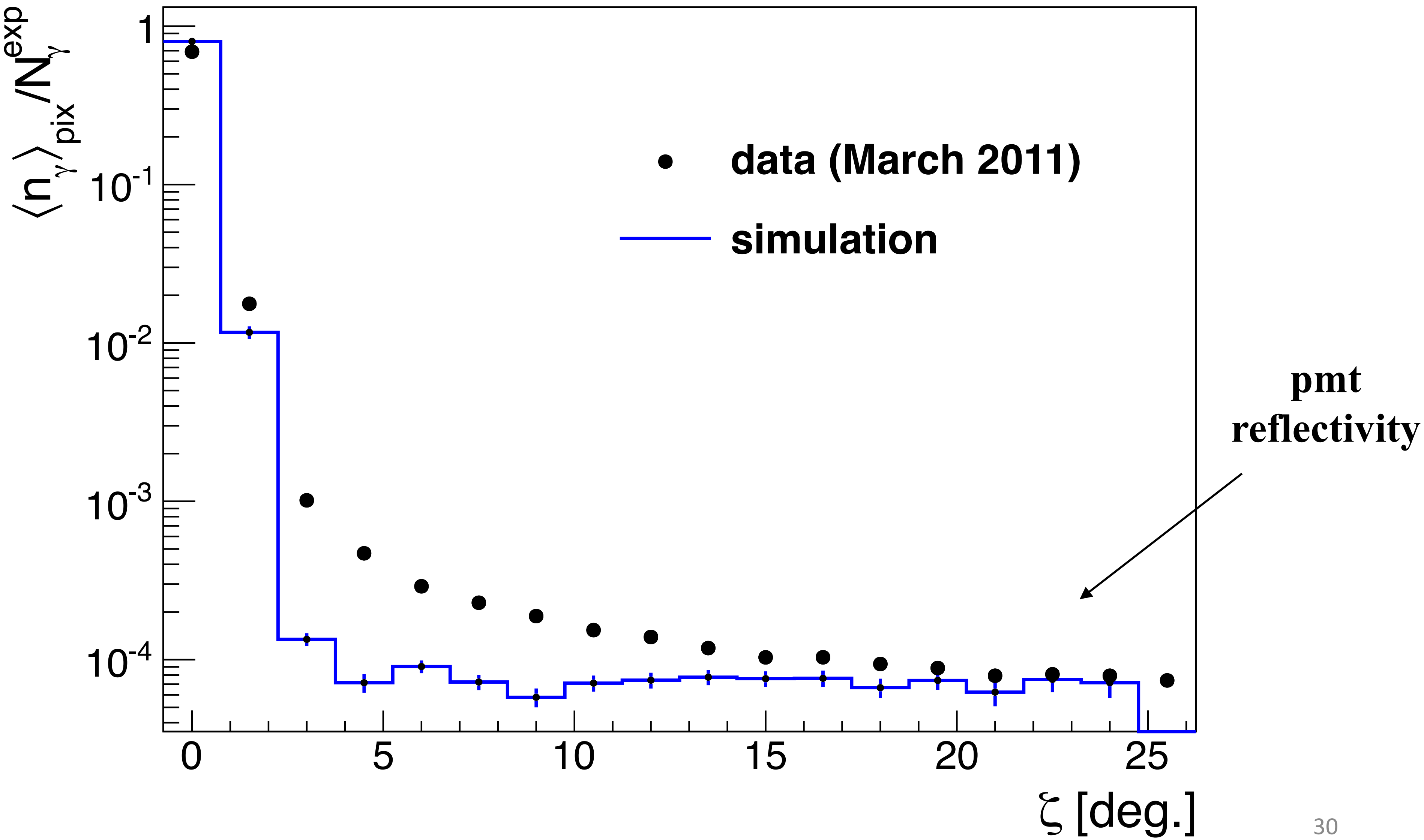
- **Four independent measurements using both the SD and FD**
- **Combined energy spectrum**
- **Energy scale with an uncertainty of 14%**



see spectrum WG talk

BACKUP SLIDES

J. Bäuml ICRC 2013 #0705
arXiv:1307.5059 [astro-ph]



Heitler Matthews model

$$E_0 = \xi_c^e \, N_e + \xi_c^\pi \, N_\mu \qquad N_\mu = \beta_0 \left(\frac{E_0}{\xi_c^\pi}\right)^\beta$$

$$E_0 = \gamma_0(\Delta X)\,[S(1000)]^\gamma$$

$$\Delta X = X_g - X_{max}$$

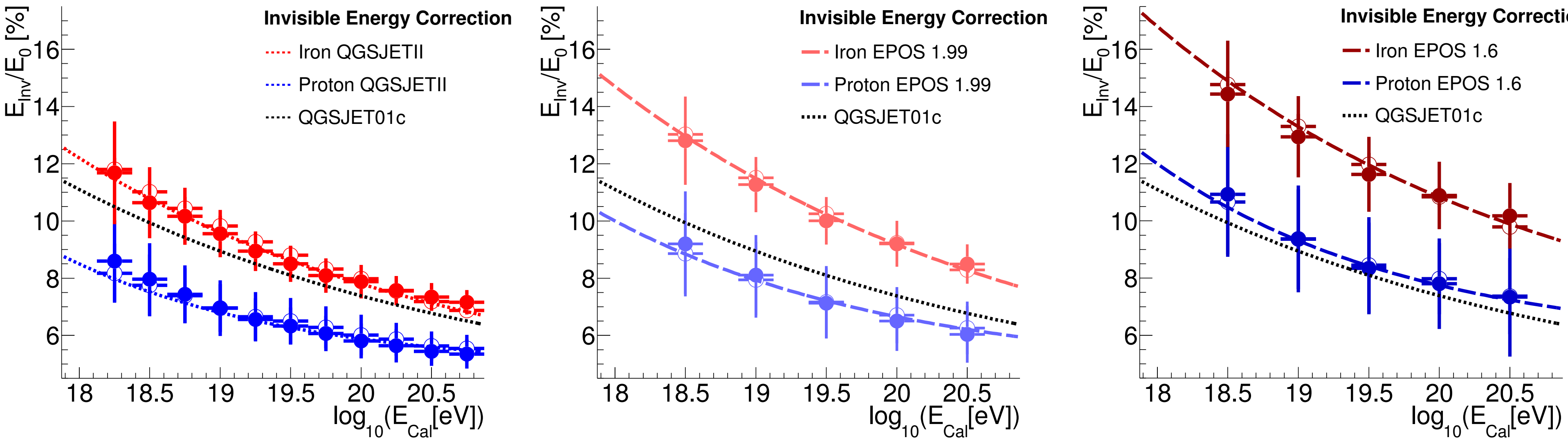
$$E_{inv} = \xi_c^\pi \, N_\mu \propto \left[\gamma_0(\Delta X)\,[S(1000)]^\gamma\right]^\beta$$

$$\log_{10} E_{inv} = A(X_g - X_{max}) + B \log_{10} S_{1000}$$

$$A = (1-\beta)\log_{10}\xi_c^\pi + \log_{10}\beta_0 + \beta \log_{10}\gamma_0(\Delta X)$$

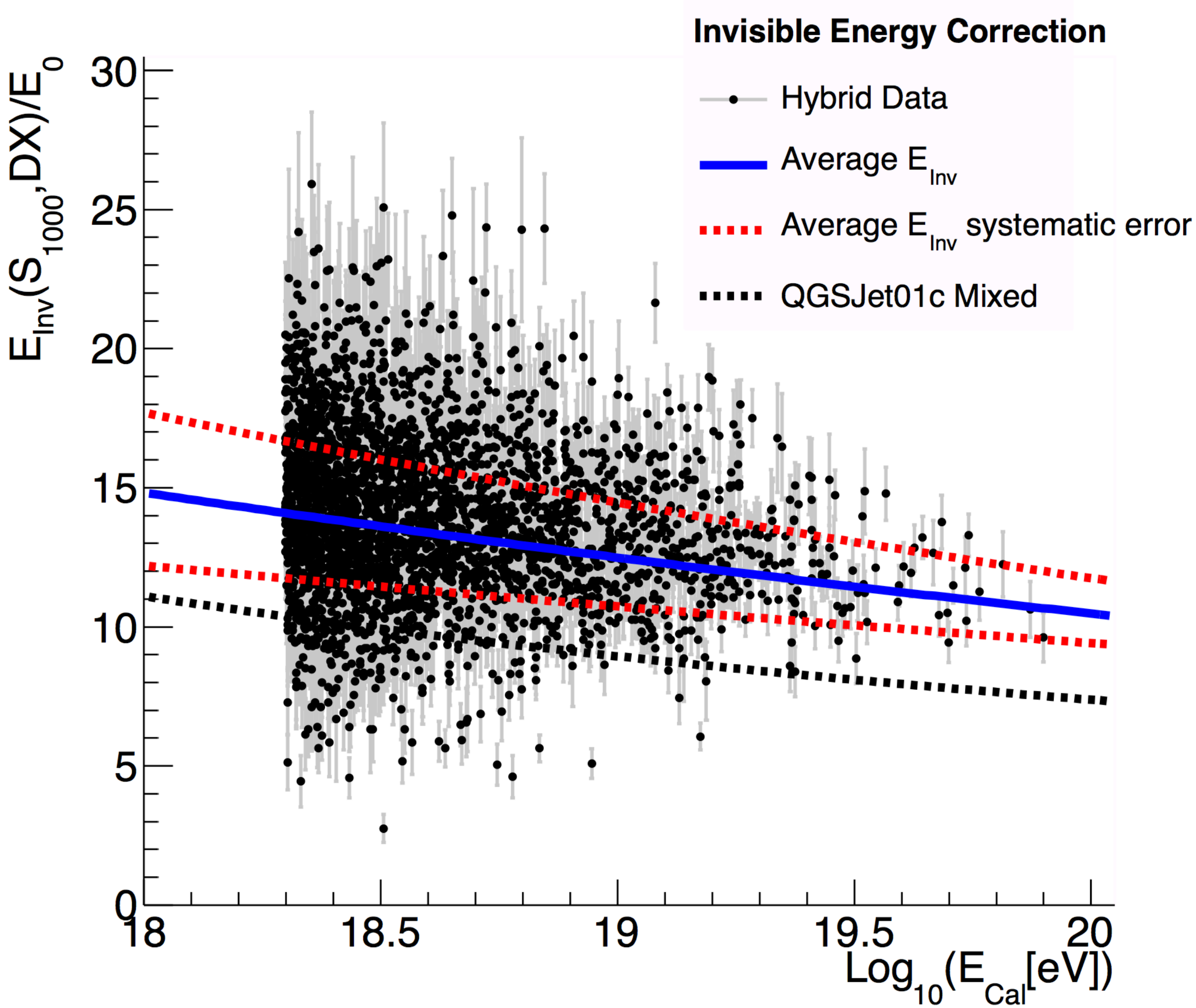
$$B = \beta\,\gamma$$

- **Use QGSJet-II 50%p-50%Fe to estimate A and B**
- **<u>Test on a different simulation</u>: recover an unbiased estimator of E_{inv} after a correction to A for attenuation (γ_0) and muons (β_0)**

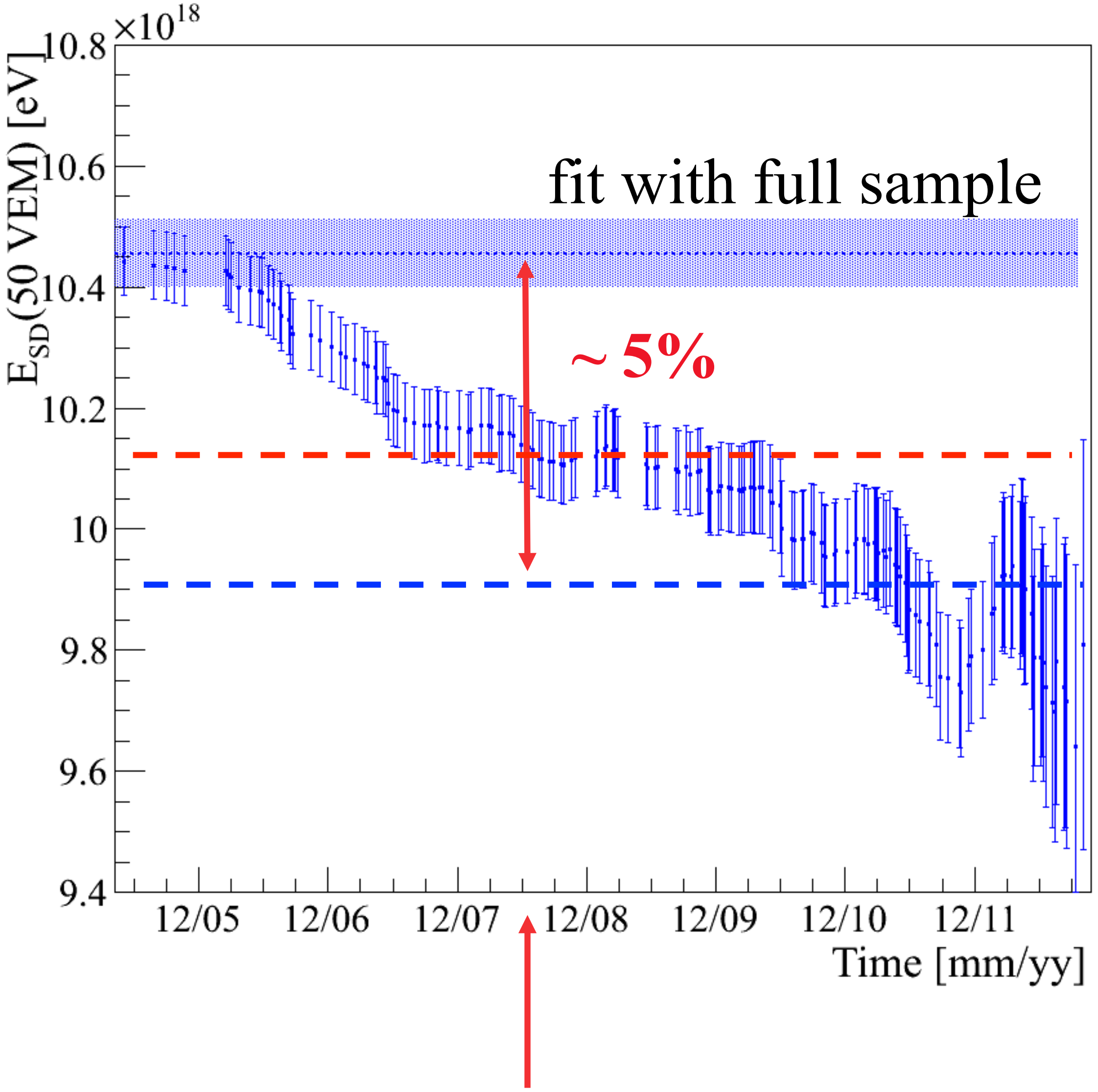


E_{inv} almost model and mass independent

- **Use QGSJet-II 50%p-50%Fe to estimate A and B**
- **<u>Application to the data</u>: estimate of E_{inv} after a correction to A for attenuation (γ_0) and muons (β_0 using N_{19})**

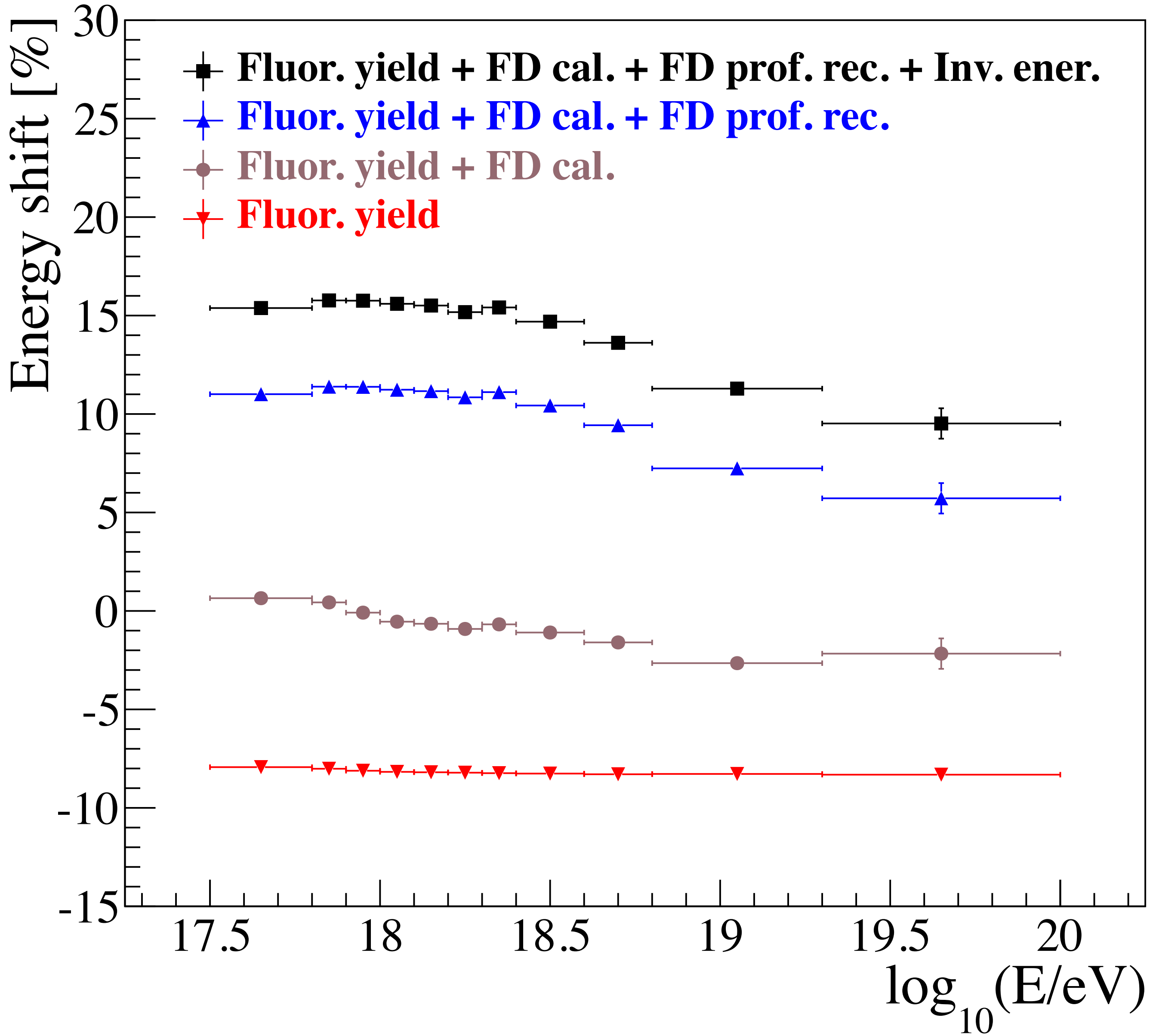


eight years of operation of the Observatory



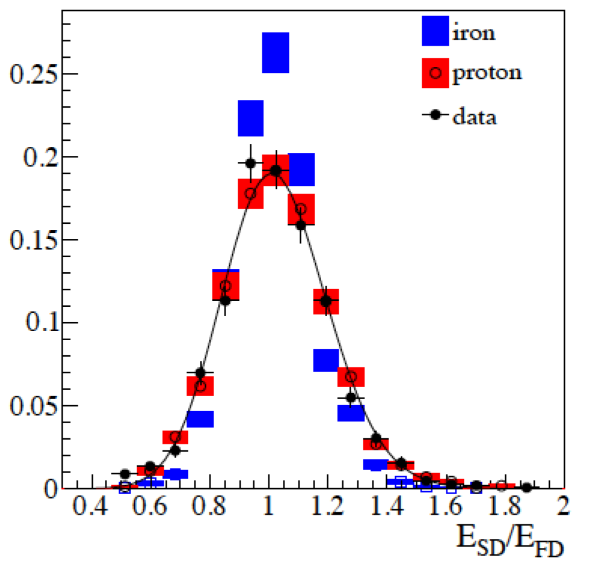
Observatory completed

CHANGE IN FD ENERGIES



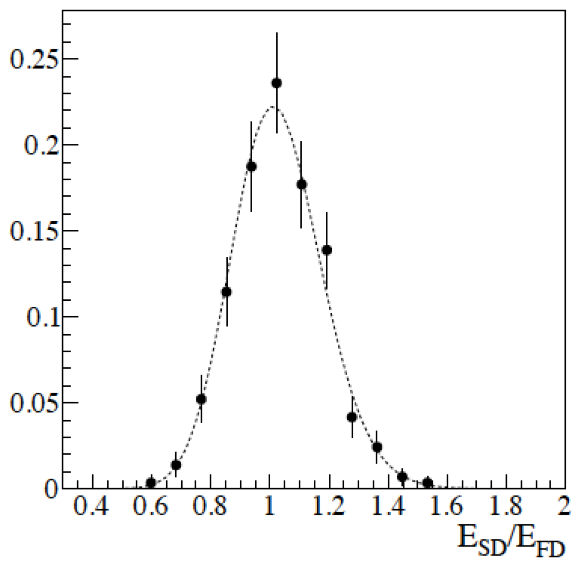
Total change between 16% ÷ 10%

$E > 3\,\mathrm{EeV}$



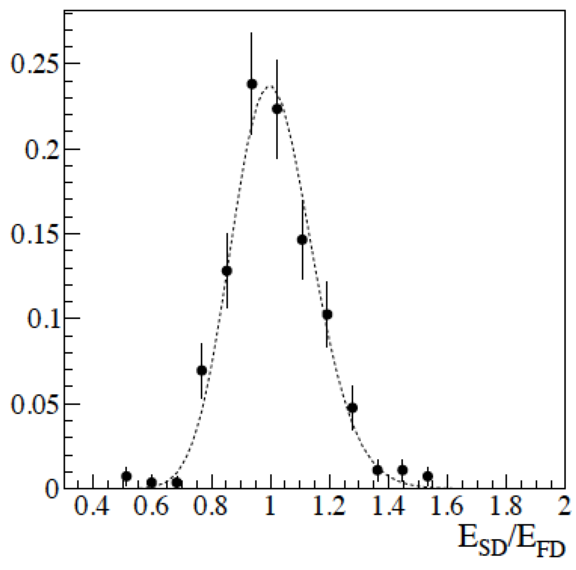
$\sigma_{SD}/E_{SD} = (16 \pm 1)\%$

$6\,\mathrm{EeV} < E < 10\,\mathrm{EeV}$



$\sigma_{SD}/E_{SD} = (13 \pm 1)\%$

$10\,\mathrm{EeV} < E$



$\sigma_{SD}/E_{SD} = (11 \pm 1)\%$

Statistical error of the $S(1000)$ fit [3]	$12\% \div 3\%$
Uncert. in lateral distrib. function [3]	5%
shower-to-shower fluctuations [3]	10%
Sub total SD energy resolution	**$16.5\% \div 11.6\%$**

- Astrophysical scenarios for different models (β-injection index, m-source evolution)
- Models calculated with CRPropa and validated with SimProp