SciNeGHE 2012

Lecce, Italy, 20-22 June 2012

Latest results of the Pierre Auger Observatory

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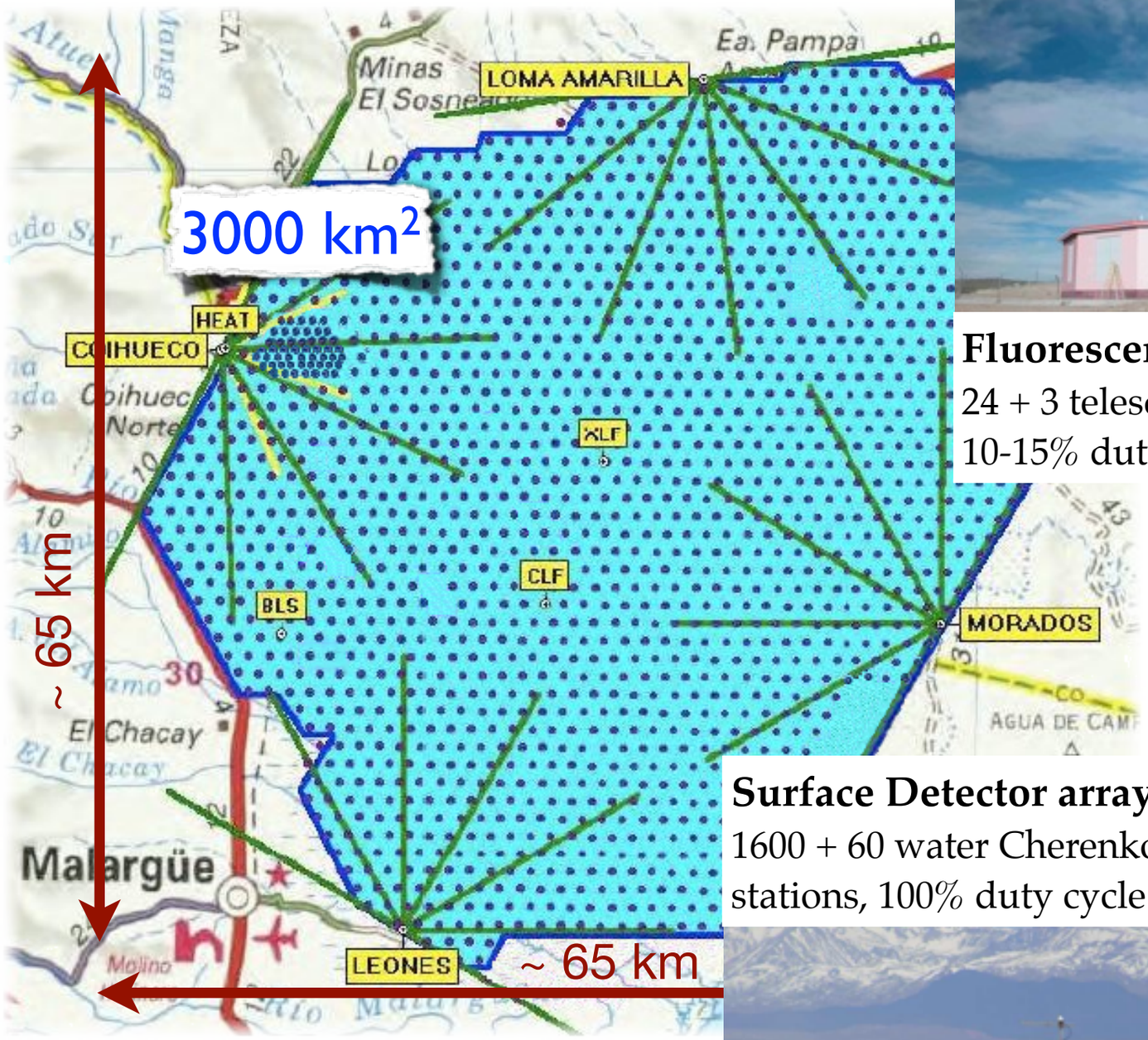
GEFÖRDERT VOM

Outline

- The **Pierre Auger Observatory**:
  the physics case and the hybrid detector

- **Recent results**:
  - Energy spectrum
  - Arrival directions
  - Mass composition
    - Search for UHE photons

The Pierre Auger Observatory



Malargüe (Mendoza, Argentina)
1400 m s.l.

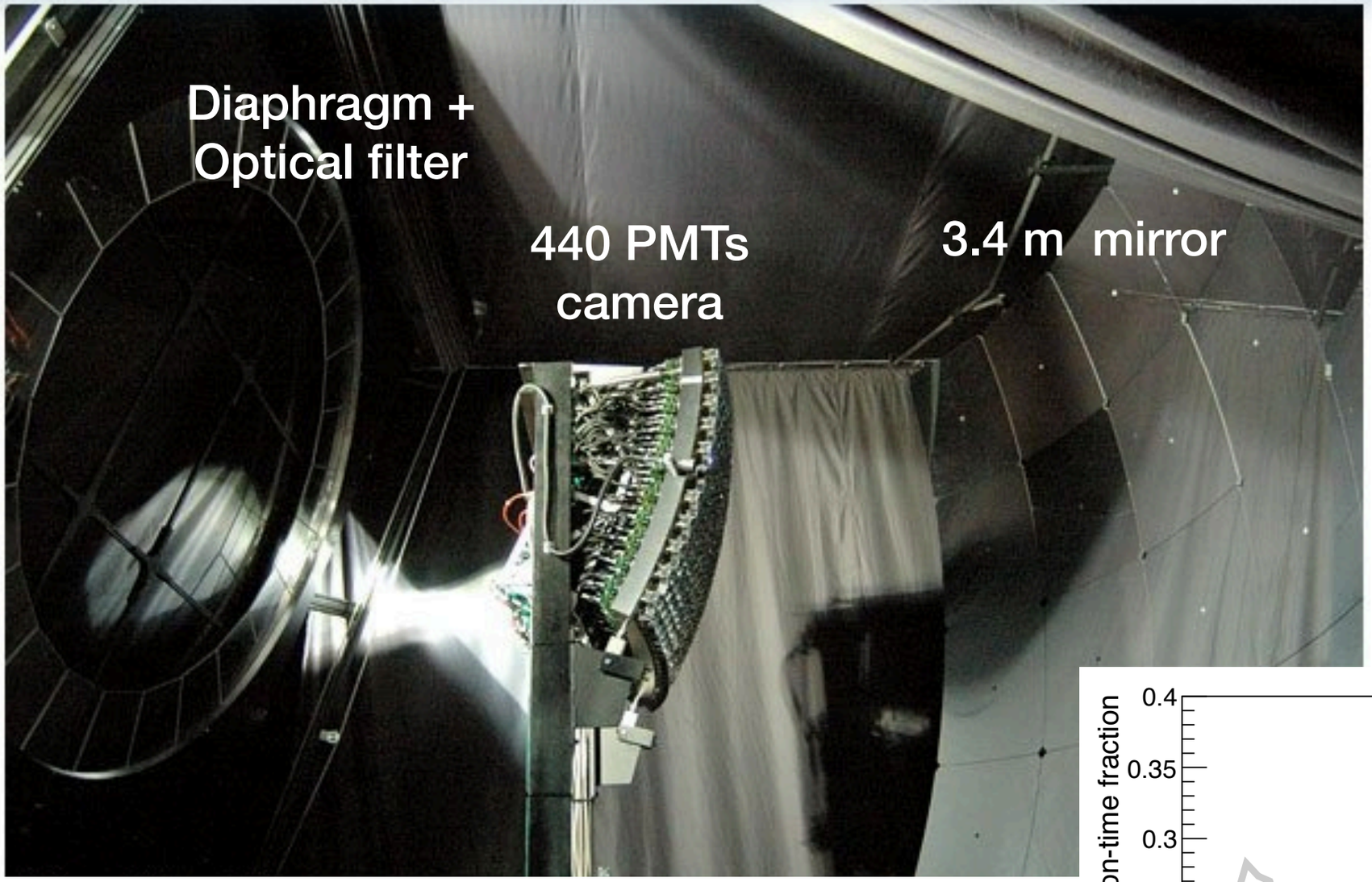
Fluorescence Detector (FD)
24 + 3 telescopes,
10-15% duty cycle

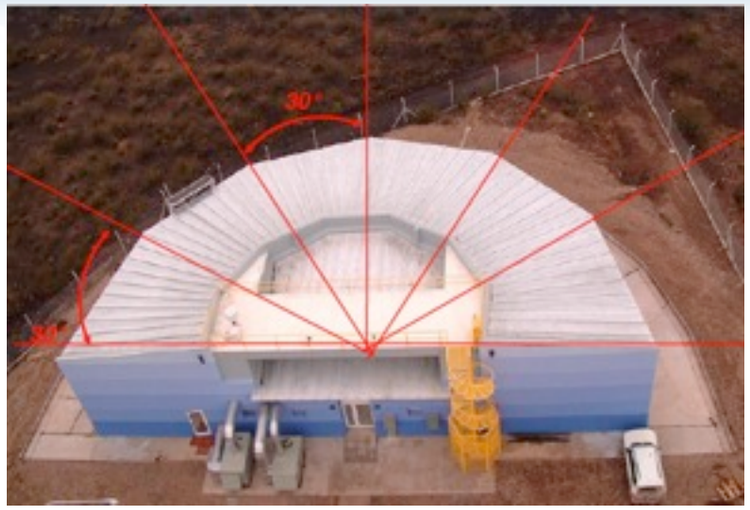
Surface Detector array (SD)
1600 + 60 water Cherenkov stations, 100% duty cycle

Investigate cosmic rays with $E \gtrsim 10^{17}$ eV

- Energy spectrum
- Mass composition
- Arrival direction

The Fluorescence Detector (FD)



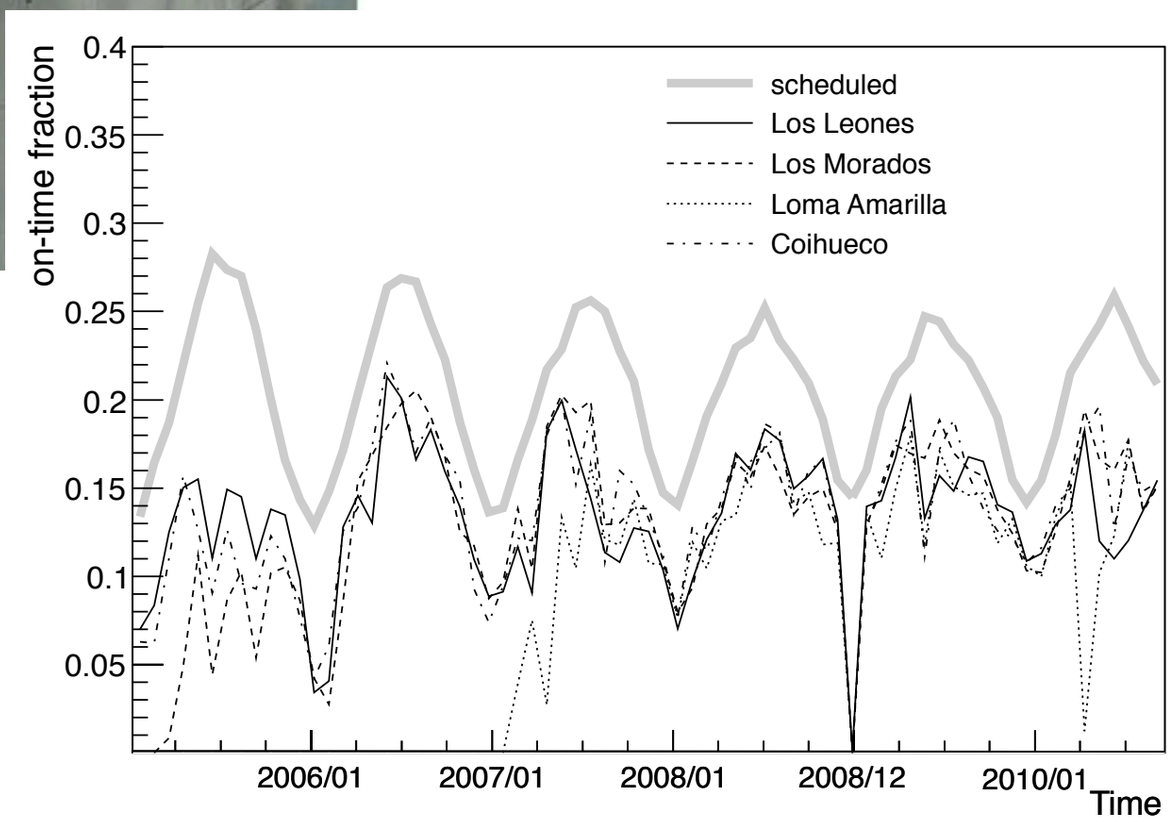


- **24 telescopes in 4 sites**
- **Field of view:**
  0-30° in elevation
  0-180° in azimuth

duty cycle ~ 10 - 15%

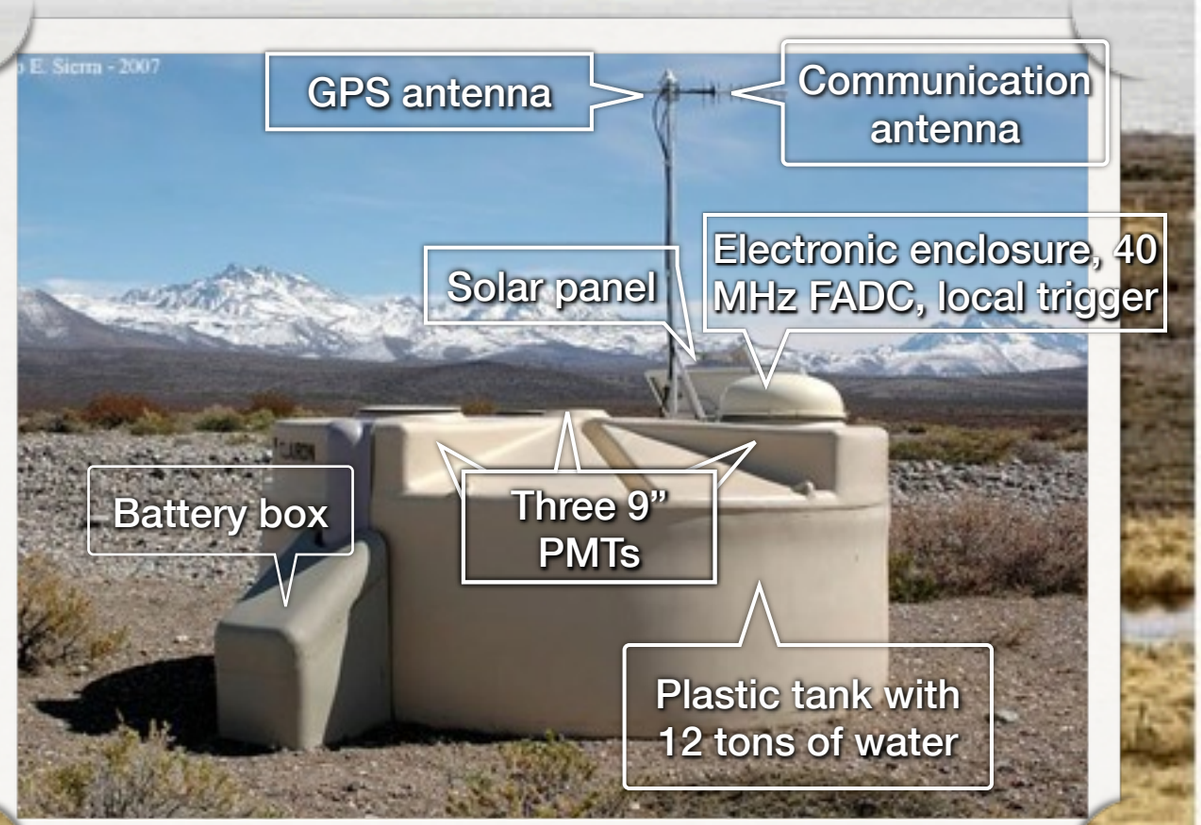
- DAQ ***scheduled:*** clear and moonless nights

- ***on-time fraction:*** weather conditions + DAQ, detector and communication system efficiencies

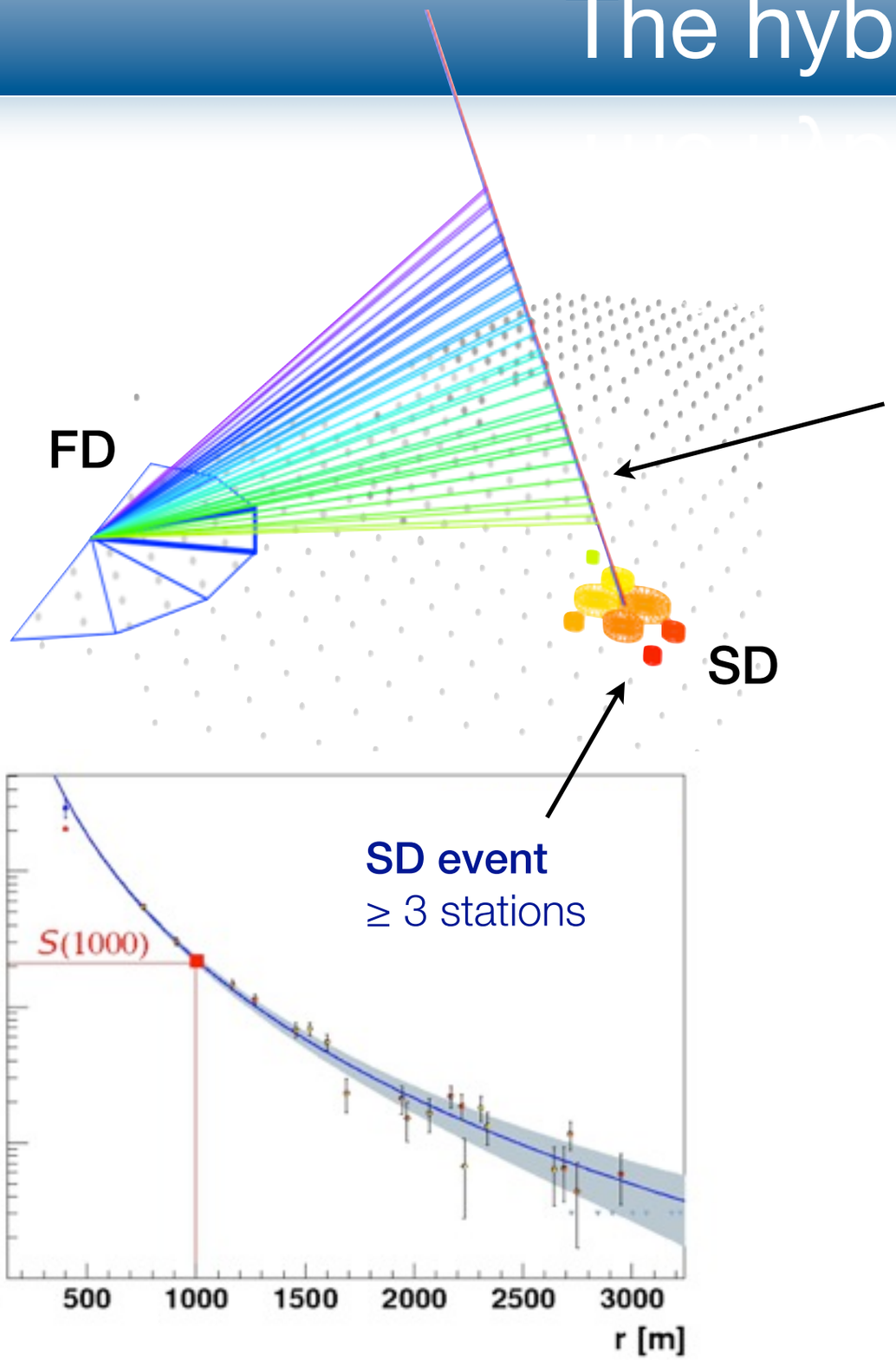


The Surface Detector (SD)

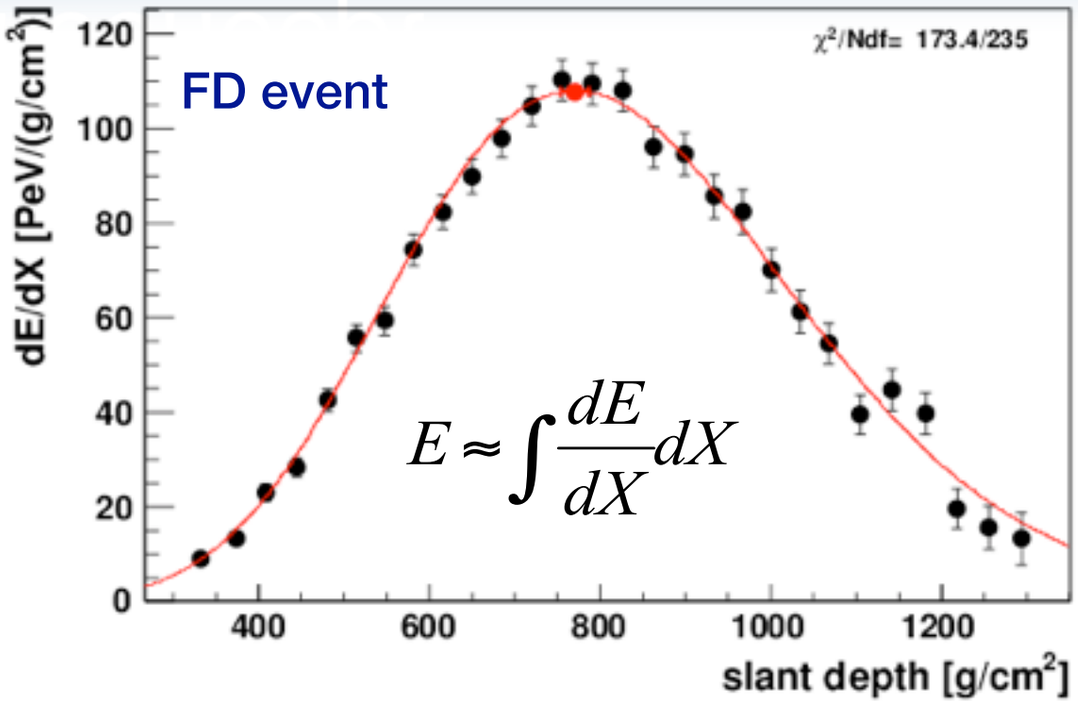
1.5 km
1.5 km
1.5 km
1.5 km



The hybrid concept

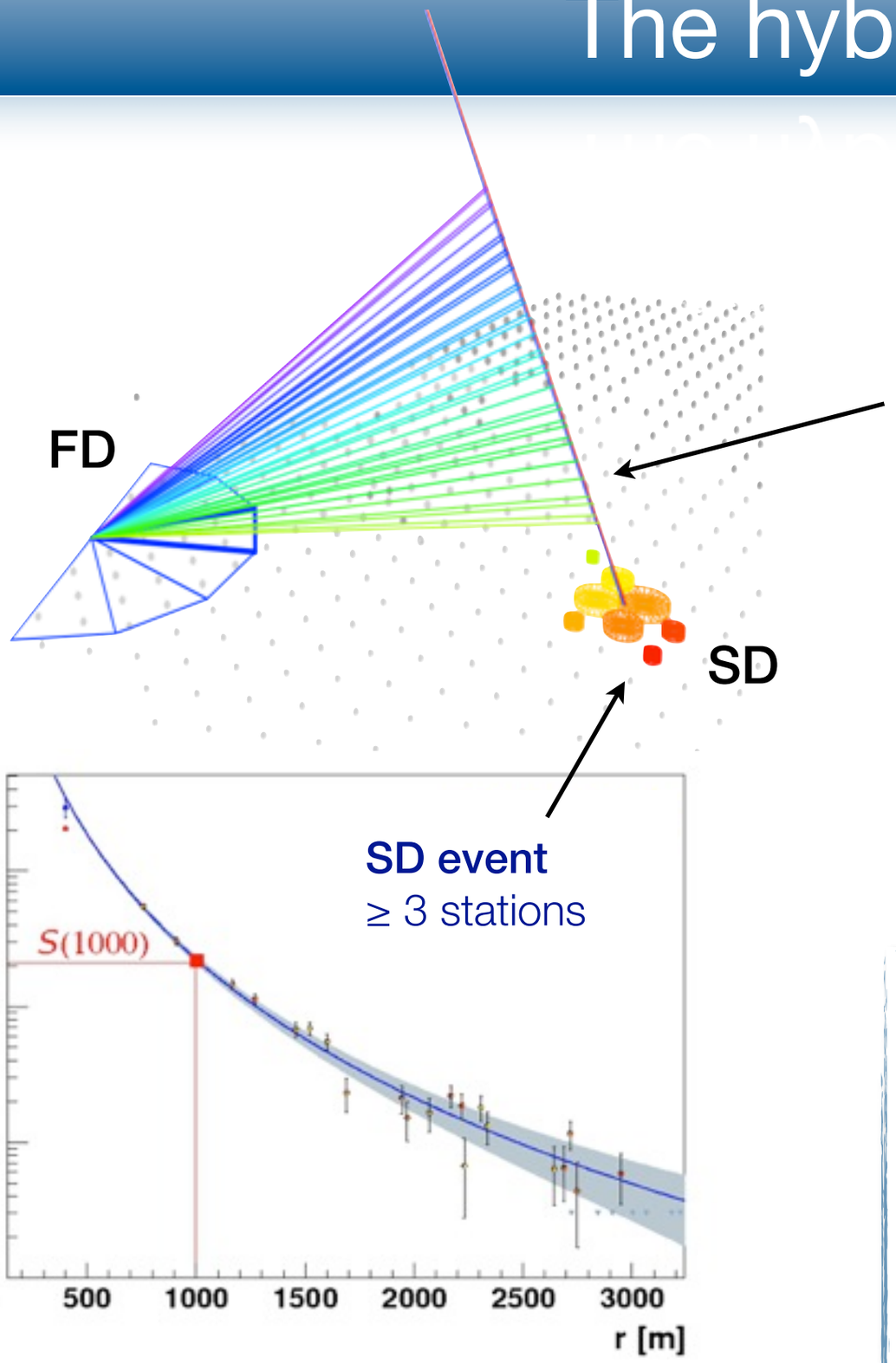


- *lateral distribution* of secondary particles
- energy proportional to the signal **S(1000)** at 1000 m



- observation of *longitudinal profile*
- calorimetric energy (almost independent of hadronic interaction models)

The hybrid concept



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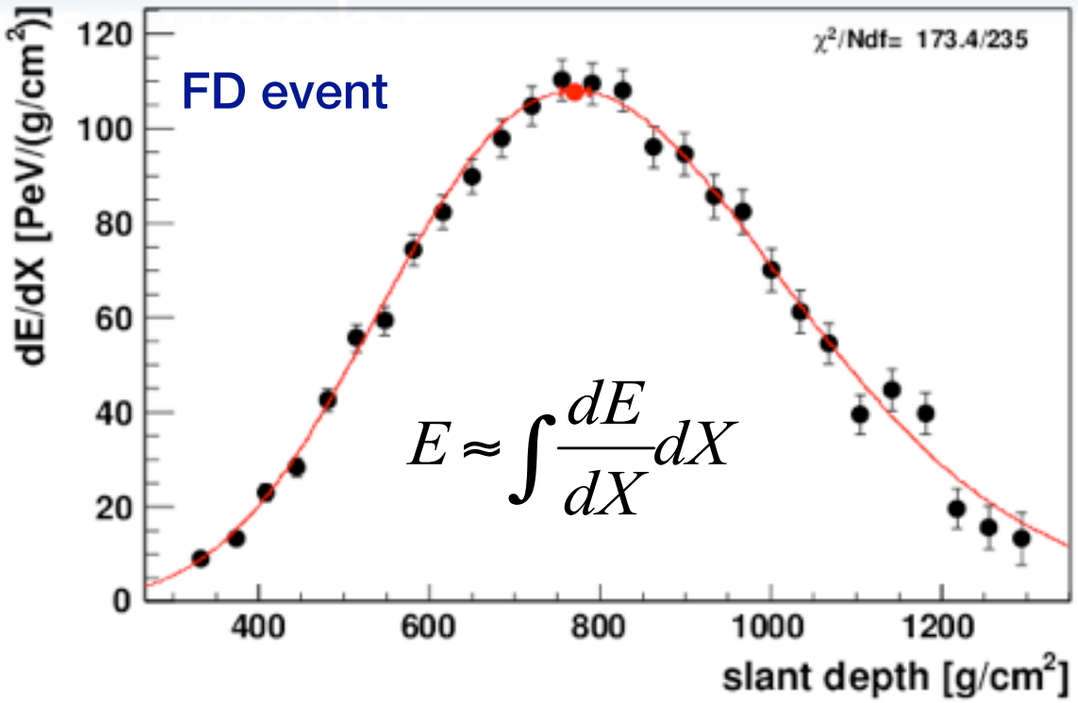


- observation of *longitudinal profile*
- calorimetric energy (almost independent of hadronic interaction models)

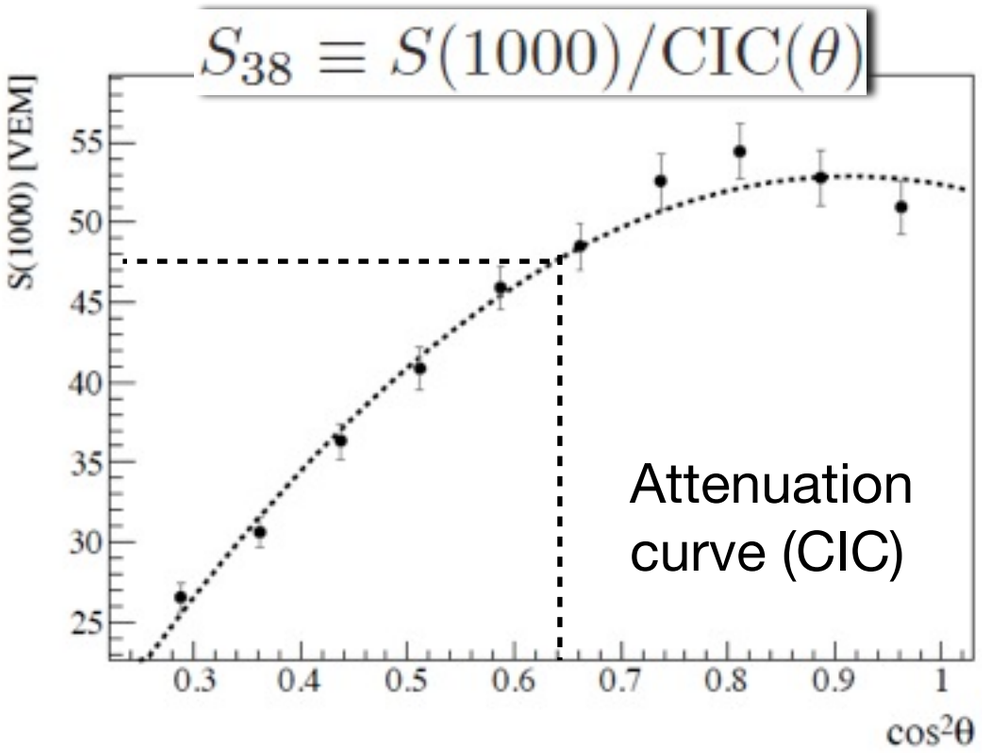
SD and FD combined in the ***hybrid mode***
(i.e. FD + at least 1 SD)

- accurate energy and direction measurements
- complementary mass sensitive parameters
- calibration of the energy scale for SD events using ***golden hybrid*** data (FD + ≥ 3 SD stations)

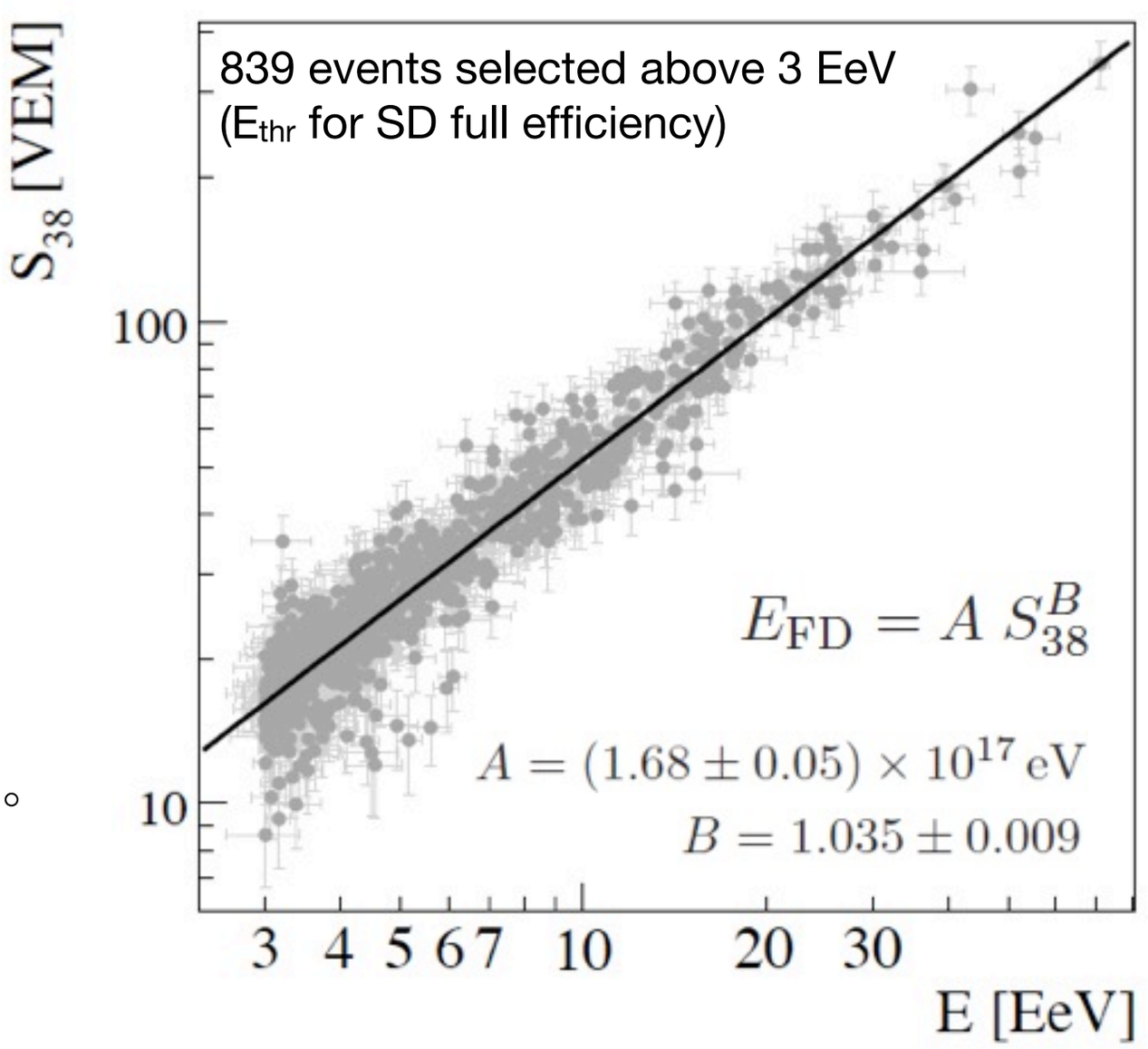
Calibration of the SD energy scale

SD energy calibrated with the calorimetric one measured by FD (almost independent of the hadronic interaction models) using the sub-sample of **golden hybrid** data

R. Pesce for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4809



convert to S_{38}: *S1000 that a shower would have produced if it had arrived with a zenith angle of 38°*

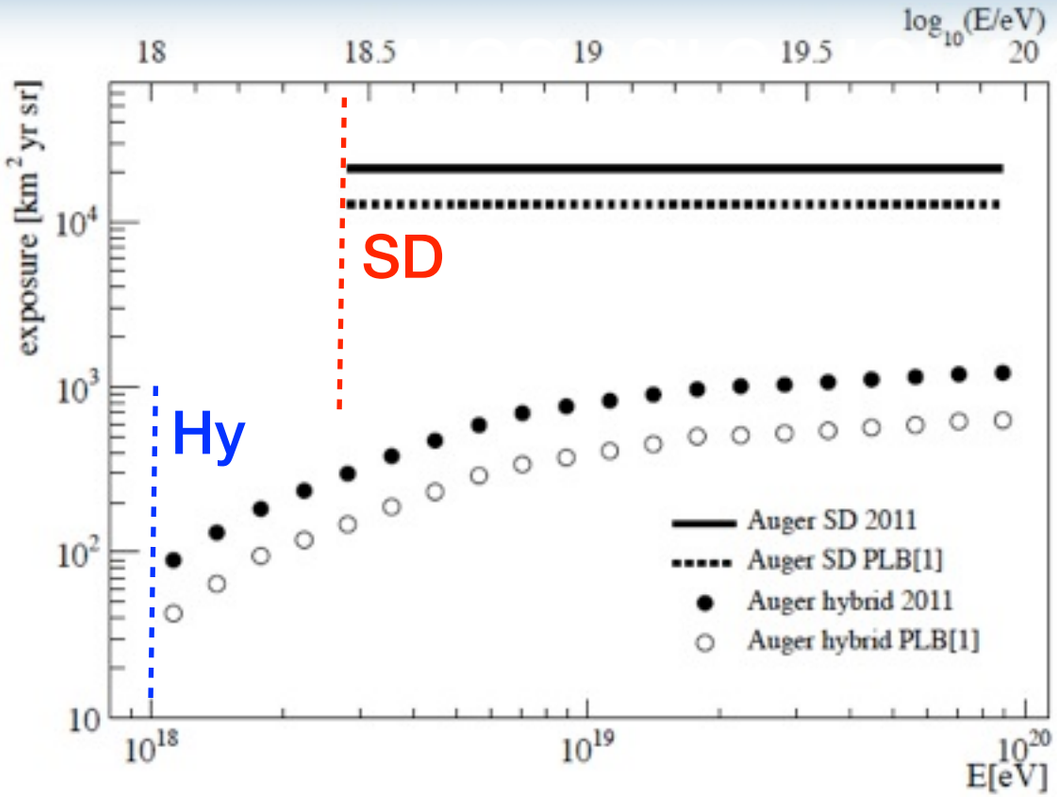


SD ENERGY RESOLUTION: E_{SD}/E_{FD} ~ 15%

SYSTEMATIC UNCERTAINTIES:

- SD calibration: 7% at 10 EeV; 15% at 100 EeV
- FD energy scale: 22% (dominated by Fluorescence Yield)

Measurement of the energy spectrum

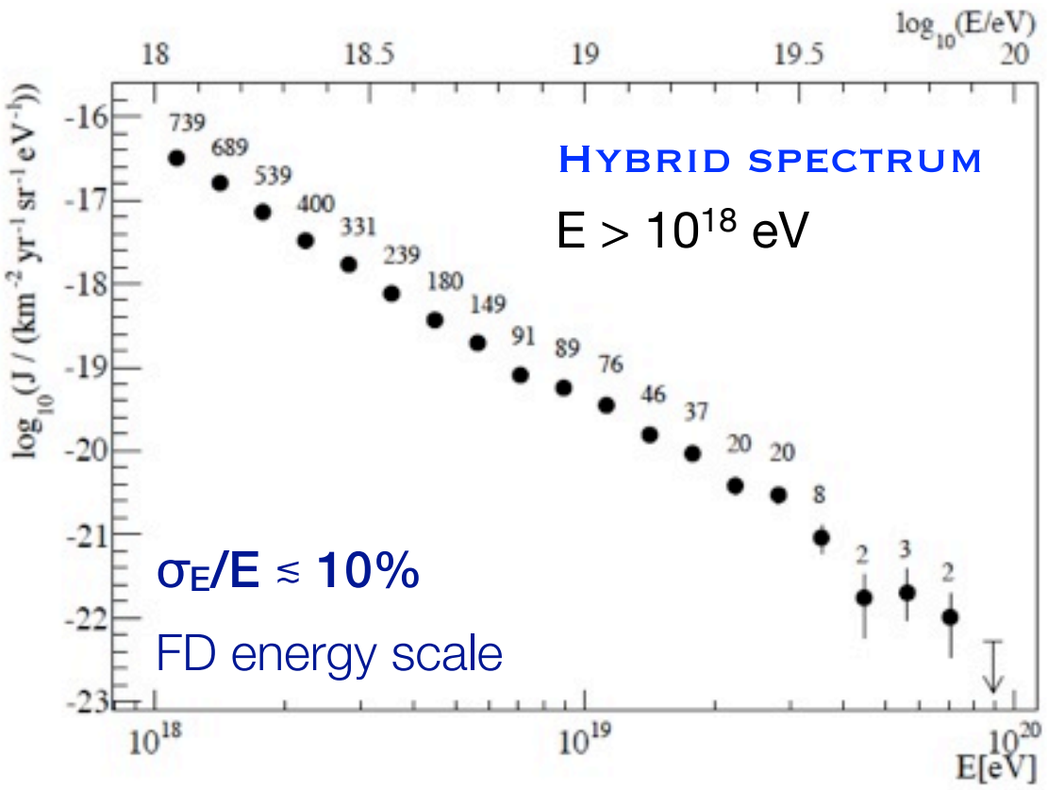


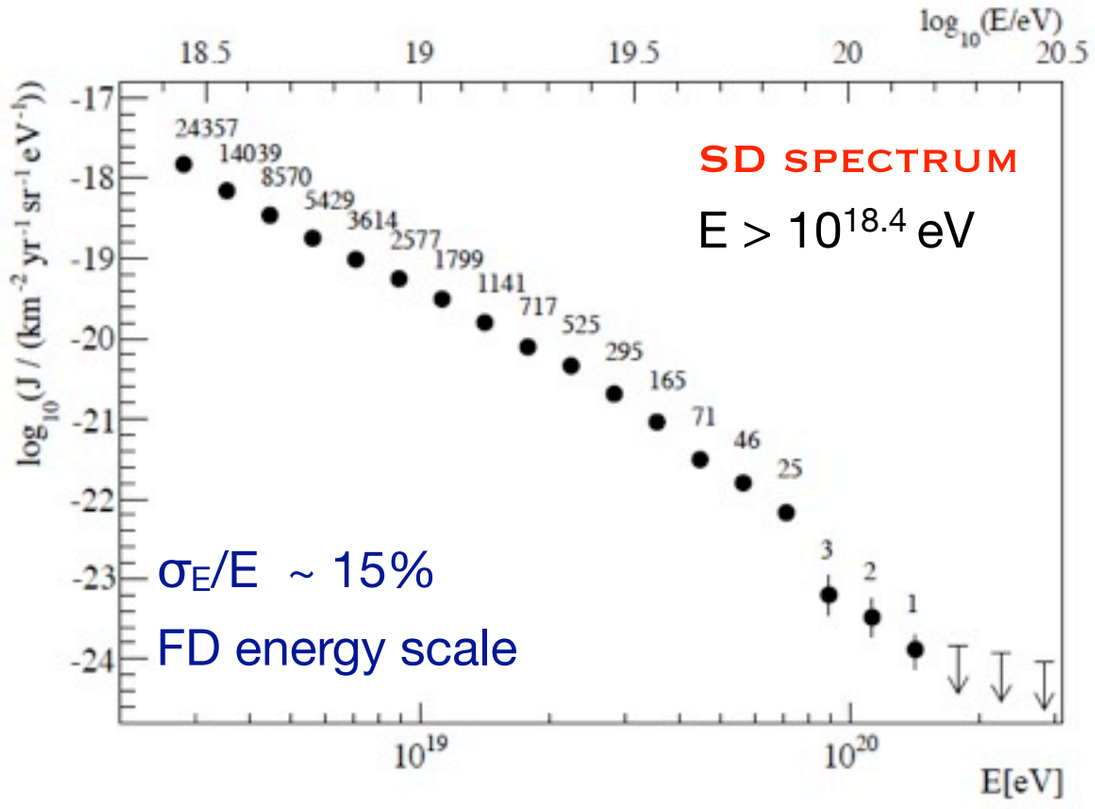
SD Exposure (01/2004-12/2010)

- geometrical calculation (~ 21000 km^2 yr sr)
- syst. uncertainties: ~ 3%

Hybrid Exposure (11/2005-09/2010)

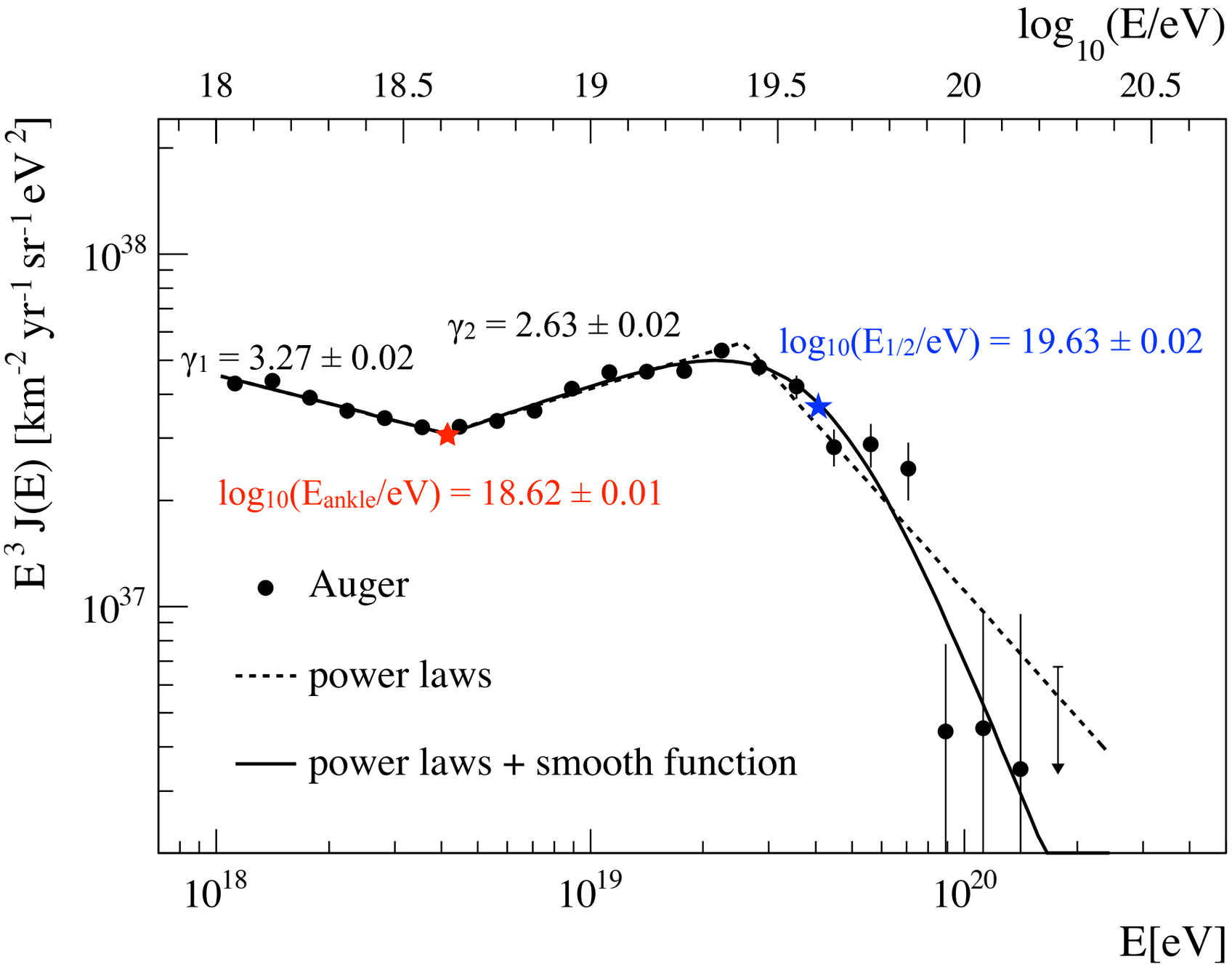
- time-dependent Monte Carlo simulations
- syst. uncertainties ~10% (6%) at 10^{18} eV (10^{19} eV)





Measurement of the energy spectrum

F. Salamida for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4809
M.S. for the Pierre Auger Collaboration, to be published on EPJ Plus



Combined Spectrum

- **Hybrid**: accurate energy measurement down to 10^{18} eV

- **SD** huge statistics (E > $10^{18.5}$ eV)

syst. FD energy scale 22%

- fluorescence yield 14%
- FD absolute calibration 9.5%
- invisible energy 4%
- reconstruction 10%
- atmospheric effects 8%

- Ankle: may indicate a change in the origin of UHECR (galactic to extragal. composition)
- Flux suppression above $10^{19.5}$ eV found with 20 σ significance

Arrival direction and anisotropy

Search for anisotropy using nearby AGN (Veron-Cetty Veron Catalog)

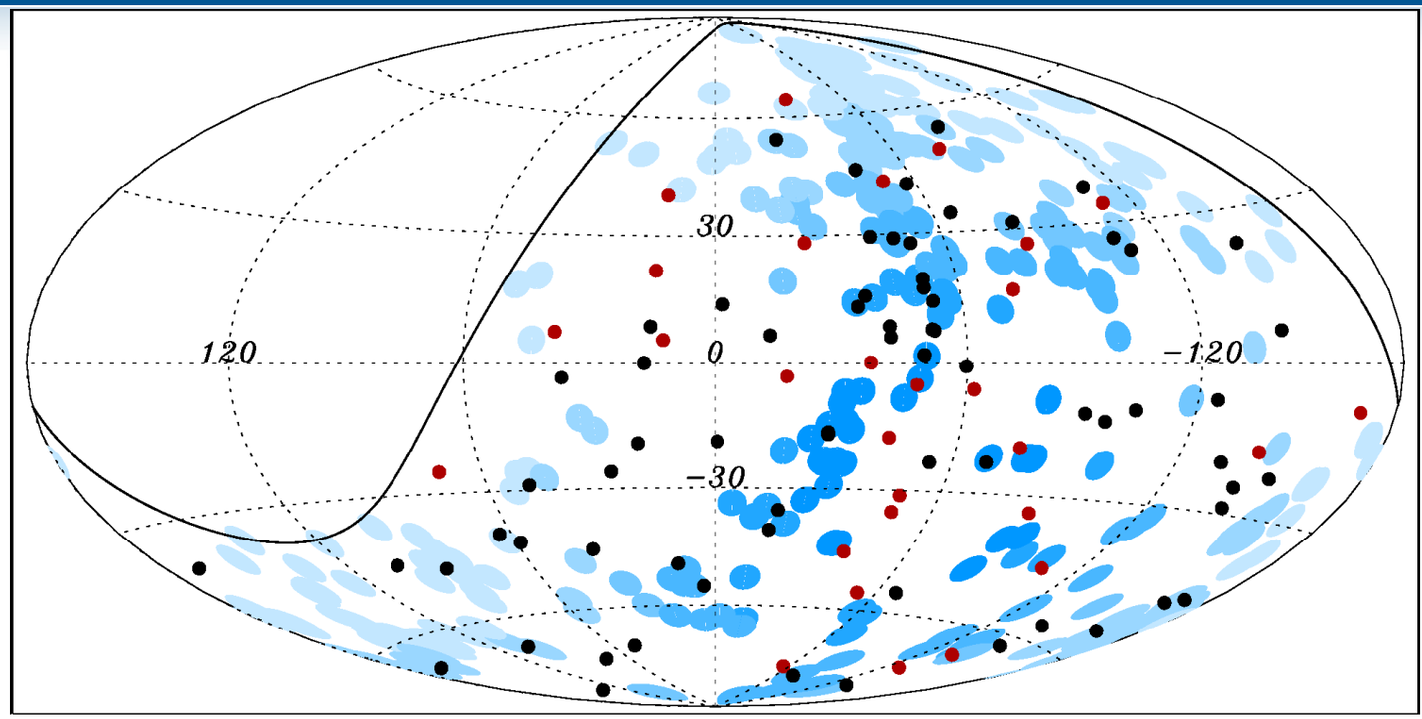
28/84 events (up to Jun 2011)

$E >$ 55 EeV

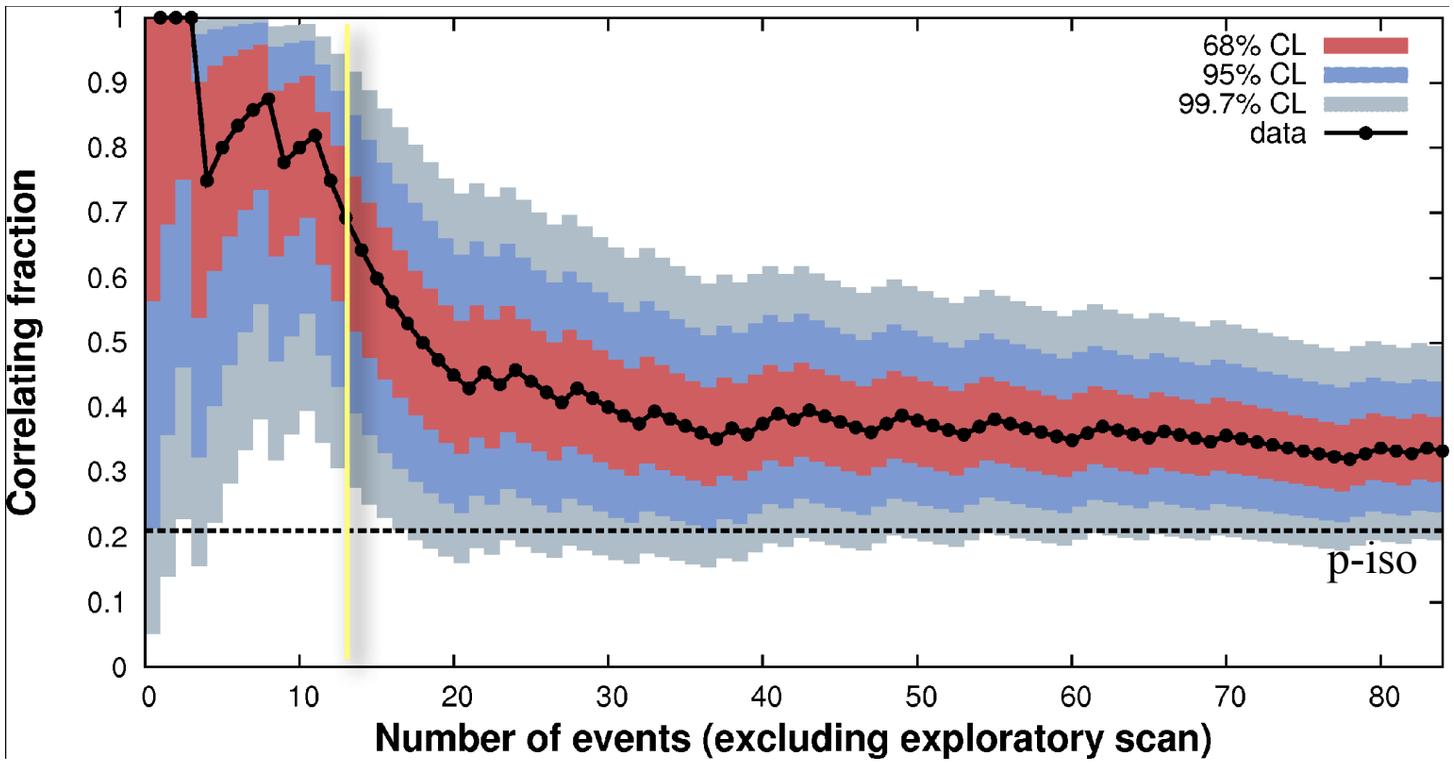
$\psi = 3.1°$

$d_{max} = 75$ Mpc

12 events inside a window of 13° close to CenA



The Pierre Auger Collaboration, Astroparticle Physics 34 (2010) 314–326
K. H. Kampert for the Pierre Auger Collab., Highlight at ICRC 2011



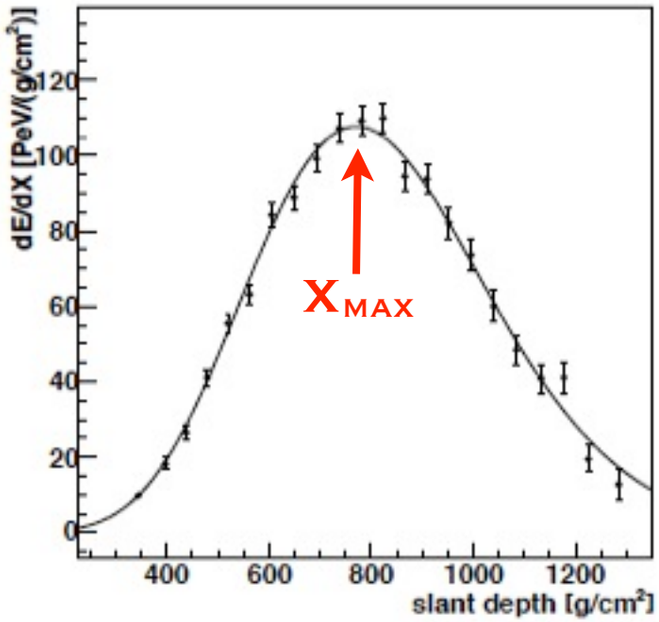
fraction of correlating events

$P_{data} = 0.33$

- *VCV not a complete catalog*
- *AGN traces the matter distribution*

Mass composition

X_{MAX} AND RMS(X_{MAX}) MEASURED FROM THE LONGITUDINAL PROFILE OBSERVED BY FD

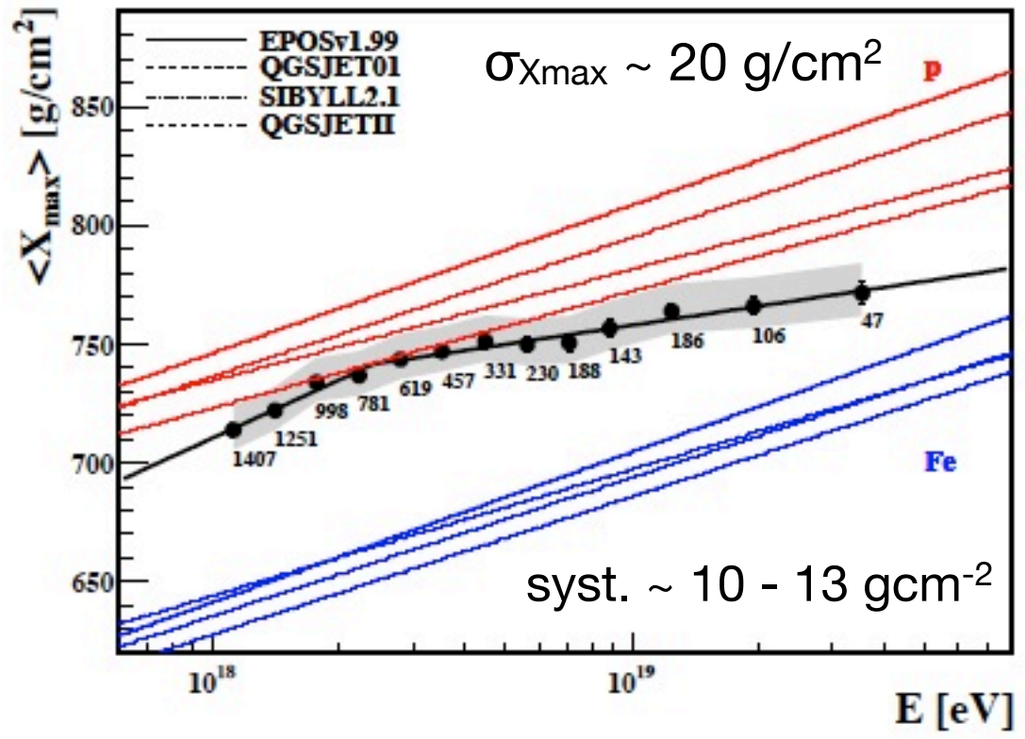


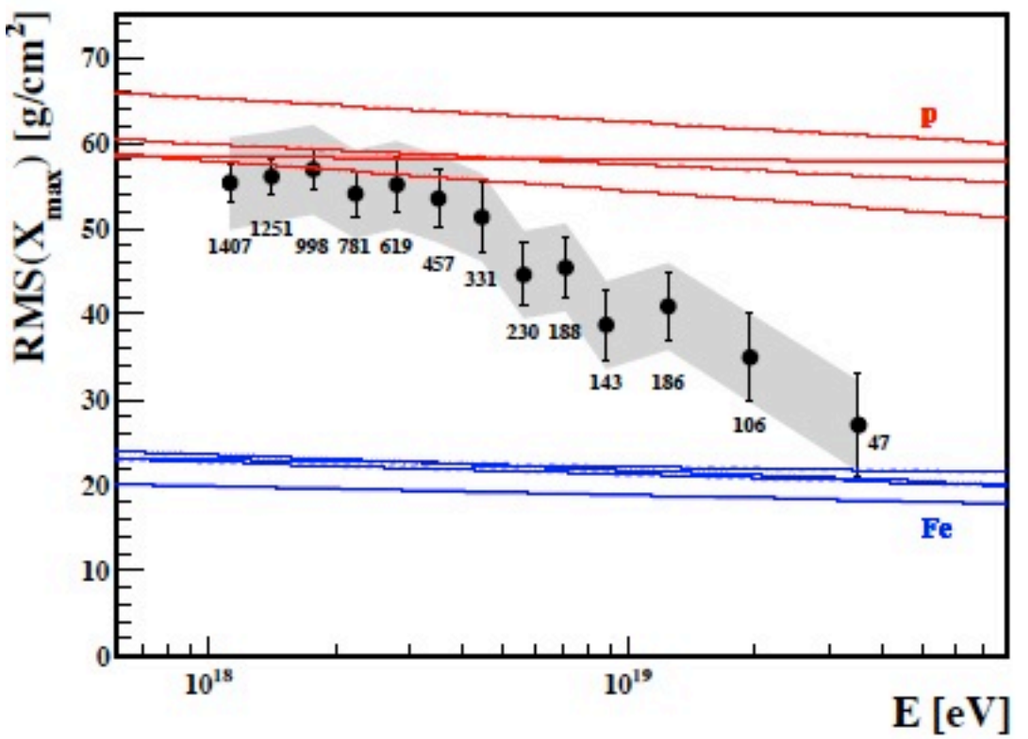
Dec 2004 - Sep 2010:
6744 hybrid $E>10^{18}$ eV

- Break of the elongation rate at ~ 2.4 x 10^{18} eV
- from **light** to **heavier** composition at high energy
- similar indication from RMS(X_{max}) and measurement using SD data

significant departure from the predictions of the hadronic models would modify this interpretation

P. Facal for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4804





Search for UHE photons

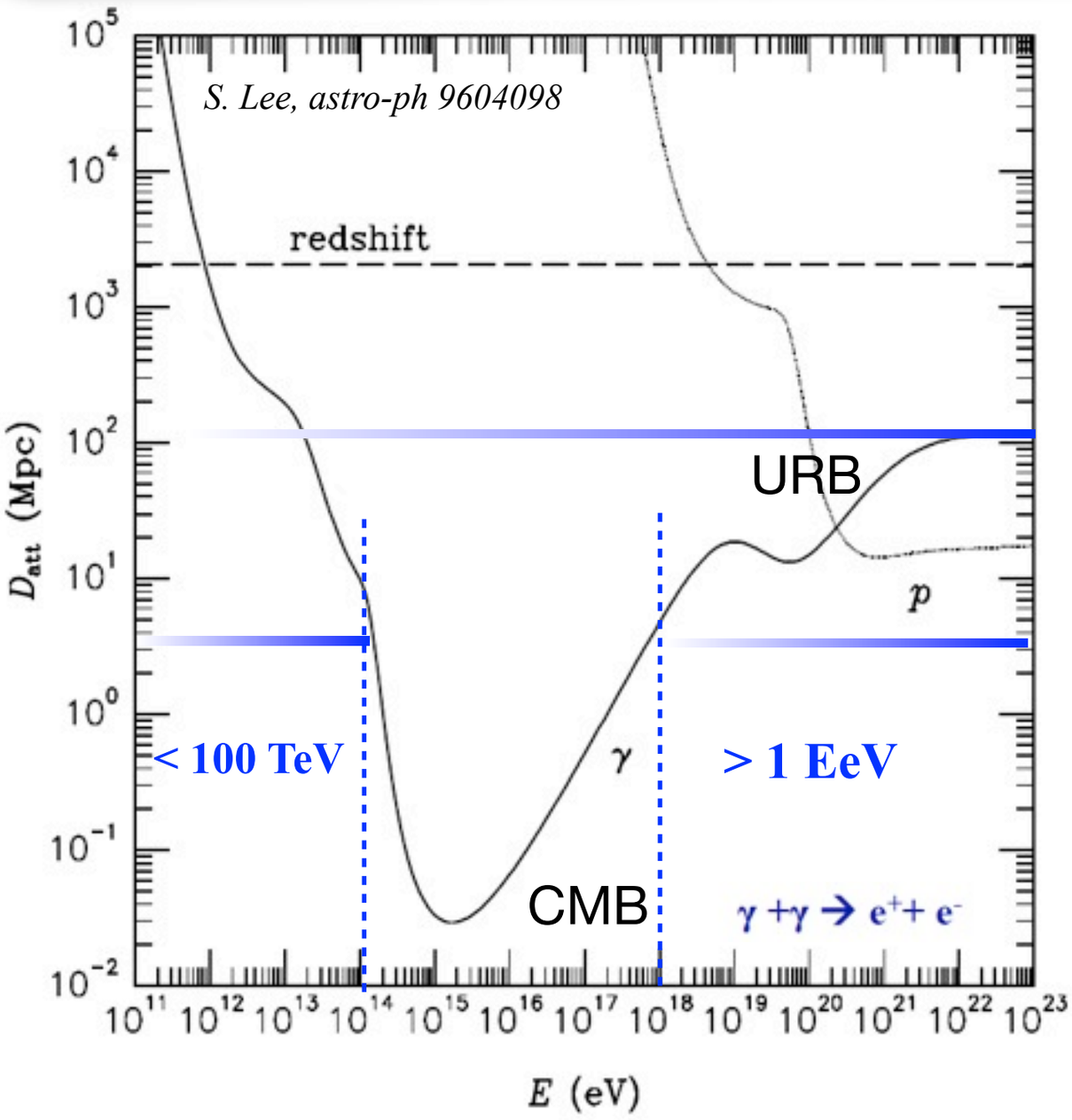
UHE photons mainly produced as:

- secondaries of the photo-pion production (**GZK effect**) of nuclei

photon fraction at Earth~ 0.1 - 1%

- product in t**op-down models** for UHECR acceleration

photon fraction at Earth ≳ 10%



Photons interact with background radiation via e^+e^- production

← CLOSEST BLAZARS

← CLOSEST AGN

← GALACTIC CENTER
≳ 10^{14} eV photons absorbed on CMB

Search for photons with SD

Different air shower development for photon primaries:

- *deeper showers*
- *electromagnetic component*

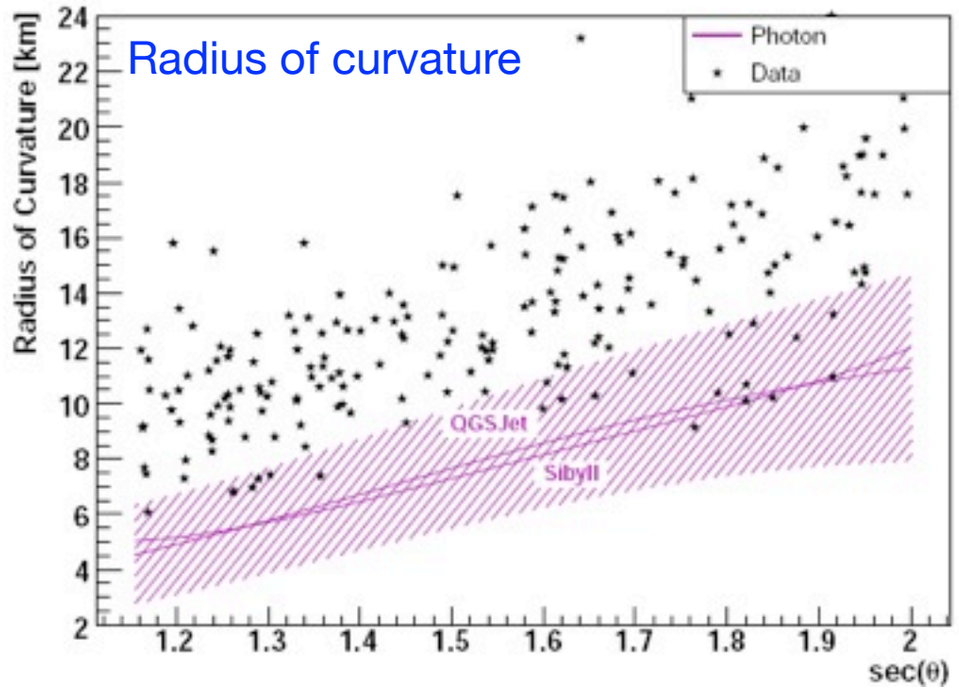
- Events observed by SD-alone

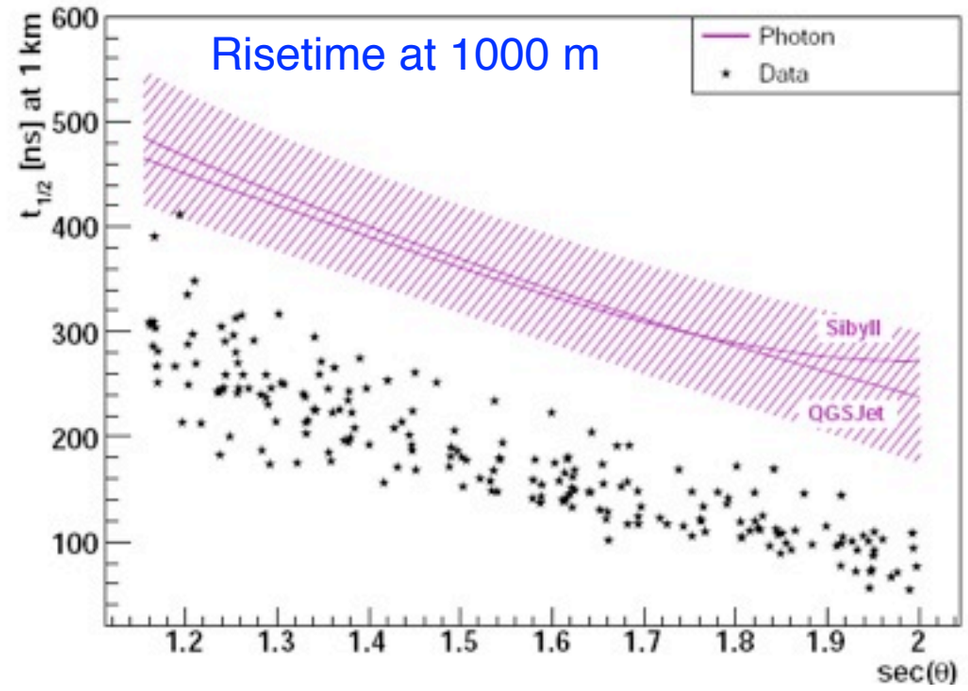
- **radius of curvature** and **risetime** $t_{1/2}$ at 1000 m used for photons identification

Deviations of data from the mean value of R and $t_{1/2}$ expected for photon showers combined with a **Principal Component Analysis**

Data sample:
Jan 2004 - Dec 2006

No photon candidates found

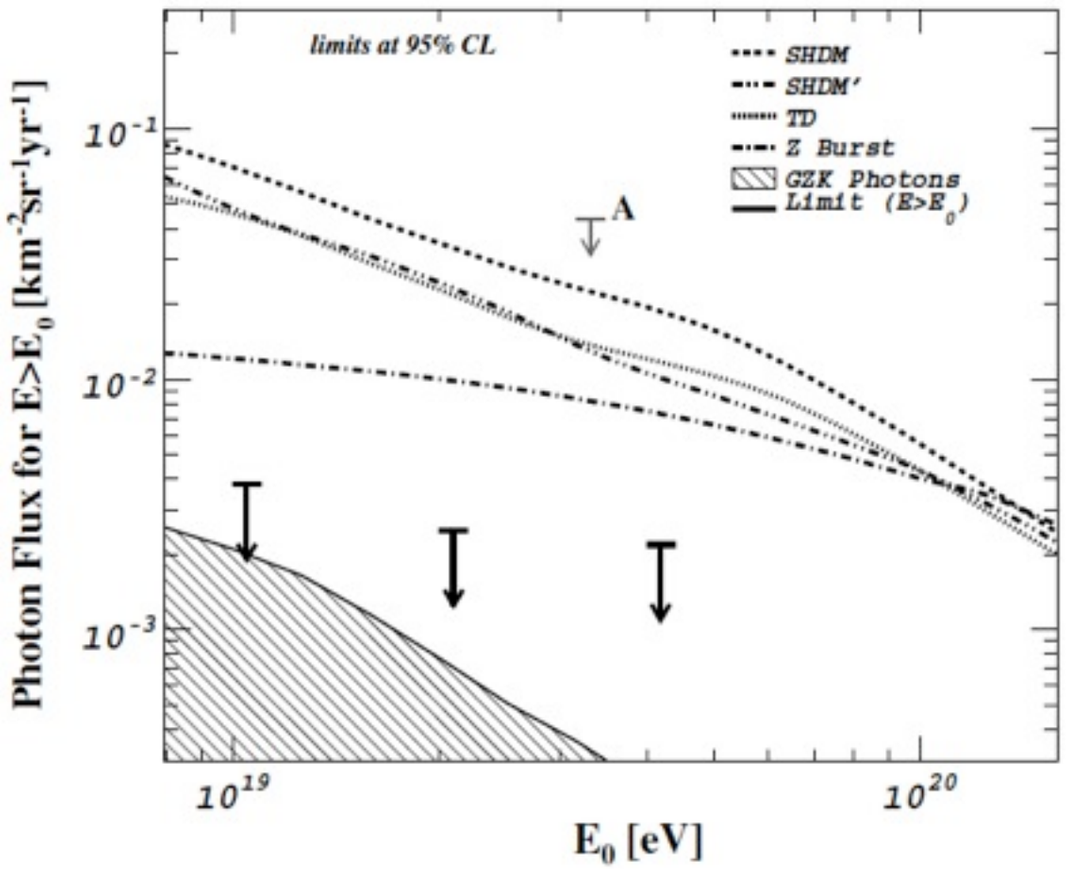


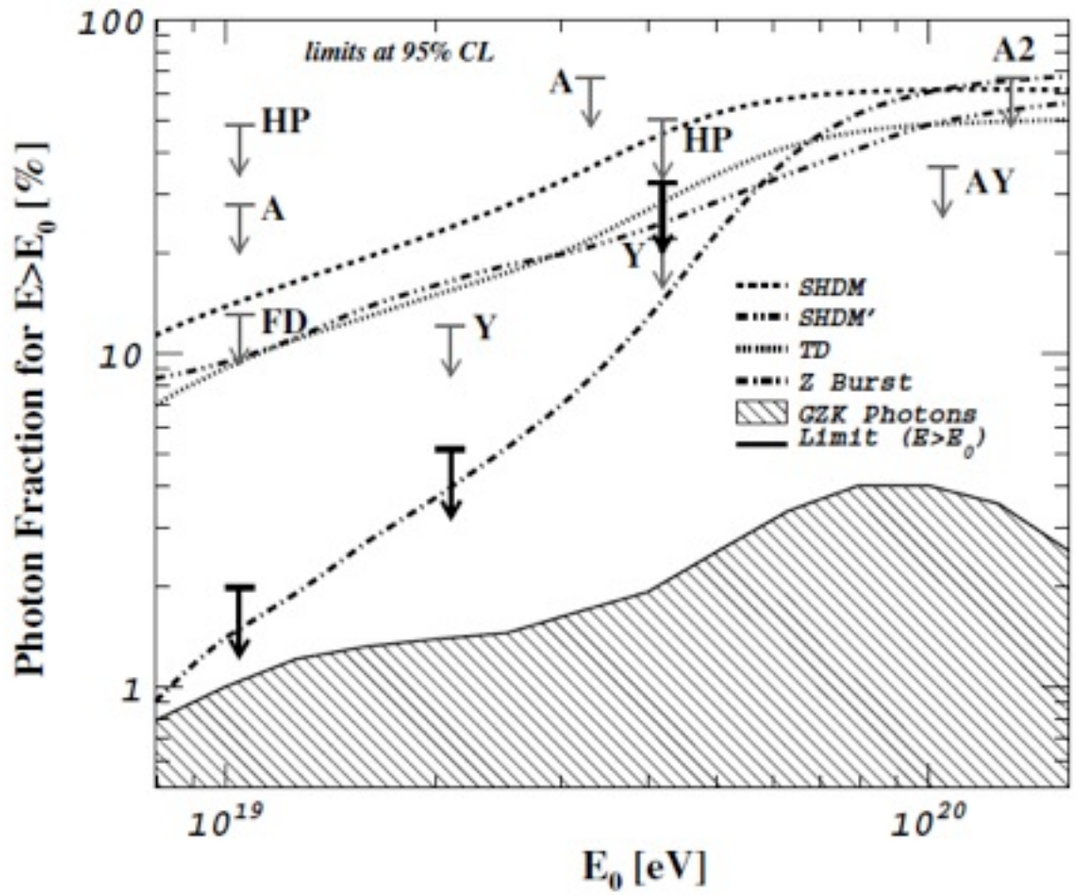


Upper Limits with SD

Upper Limits to the photon flux and the photon fraction placed:

First limits disfavoring top-down models





$E_{\rm min}$	$N(E_\gamma > E_{\rm min})$	N_γ	$\mathcal{N}_\gamma^{0.95}$	$N_{\rm non\text{-}\gamma}$	ε	$\Phi_{0.95}$	$\mathcal{F}_{0.95}$ (%)
10	2761	0	3.0	570	0.53	3.8×10^{-3}	2.0
20	1329	0	3.0	145	0.81	2.5×10^{-3}	5.1
40	372	0	3.0	21	0.92	2.2×10^{-3}	31

Pierre Auger Collaboration, Astrop. Phys. 29 (2008) 243

Search for photons with hybrid events

M.S. for the Pierre Auger Collaboration, ICRC 2011, arXiv: 1107.4805

- **FD:**

  - **Deeper development of the air showers**

  → **Larger X_{max}**

- **SD:**

  - **Smaller detected signal at a given distance**

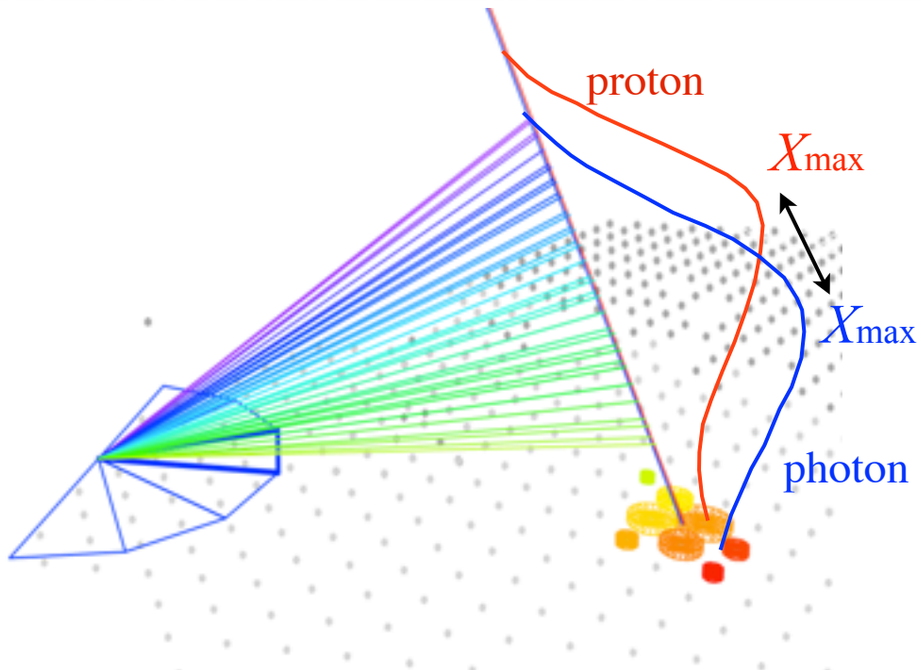
  - **Fewer triggered stations**

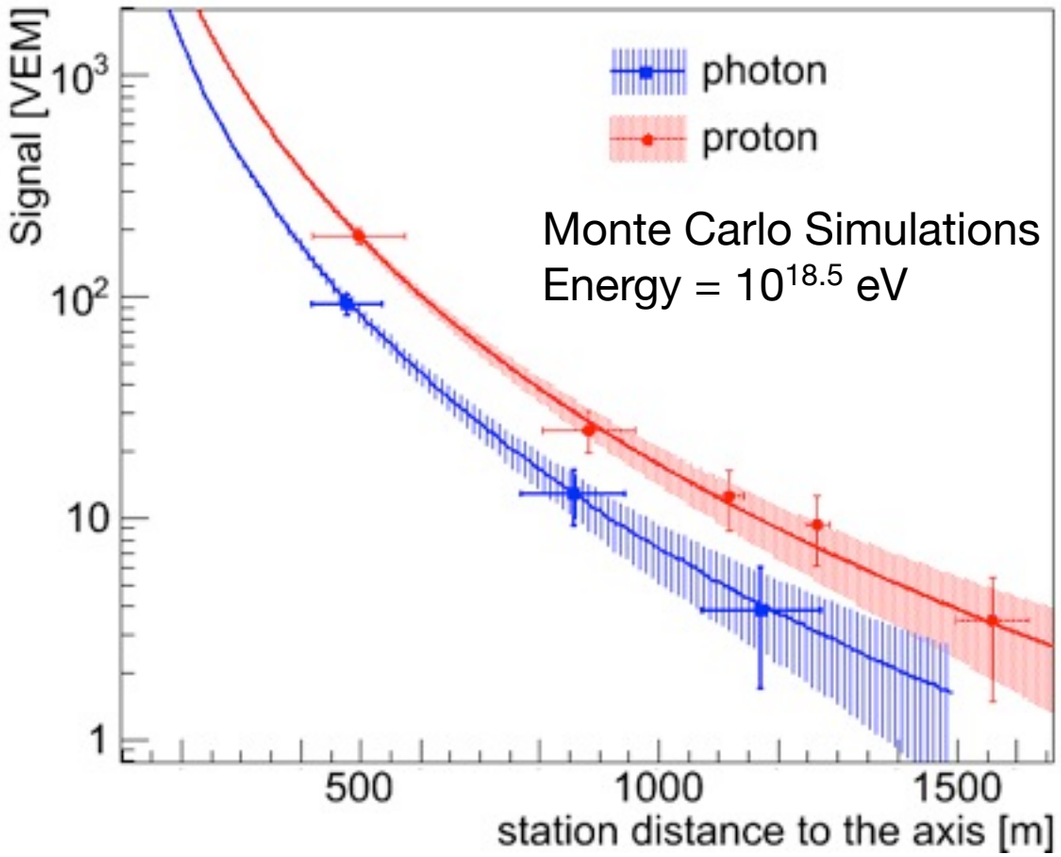
$$S_b = \sum_i S_i \left(\frac{R_i}{1000}\right)^4$$

S_i : station signal [VEM]
R_i : station distance to the shower axis [m]

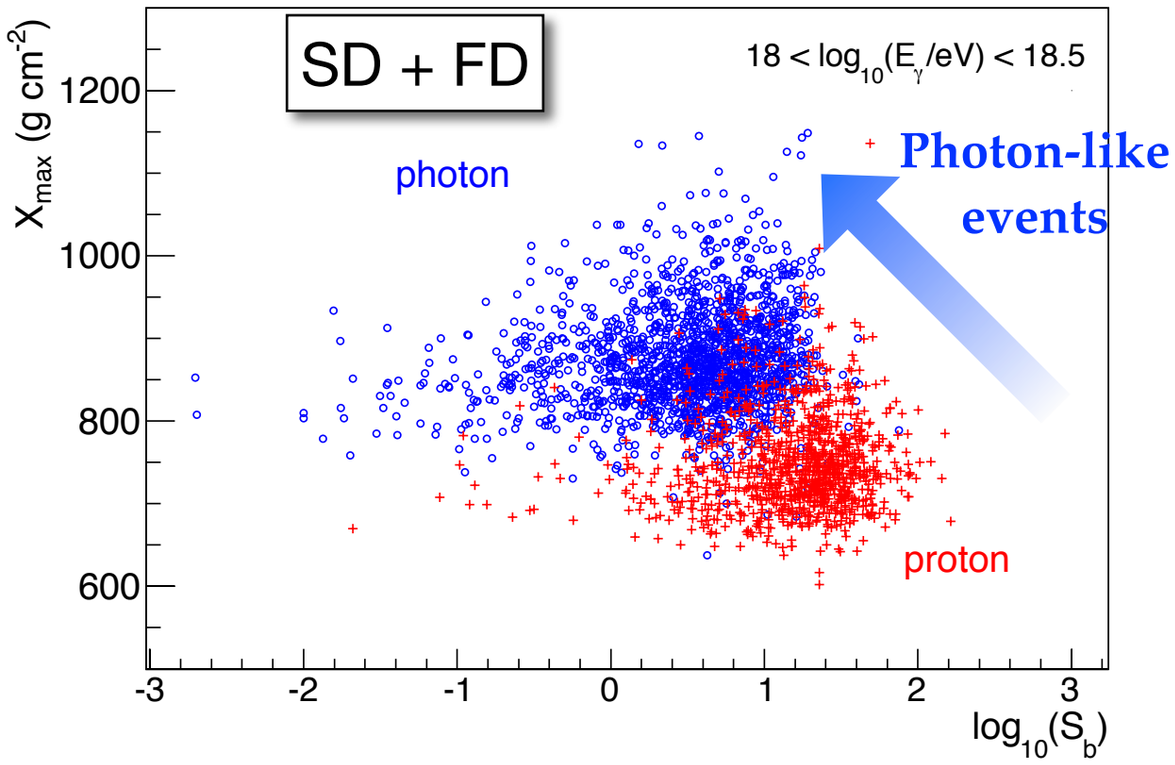
details on S_b: G. Ros et al., arXiv 1104.3399

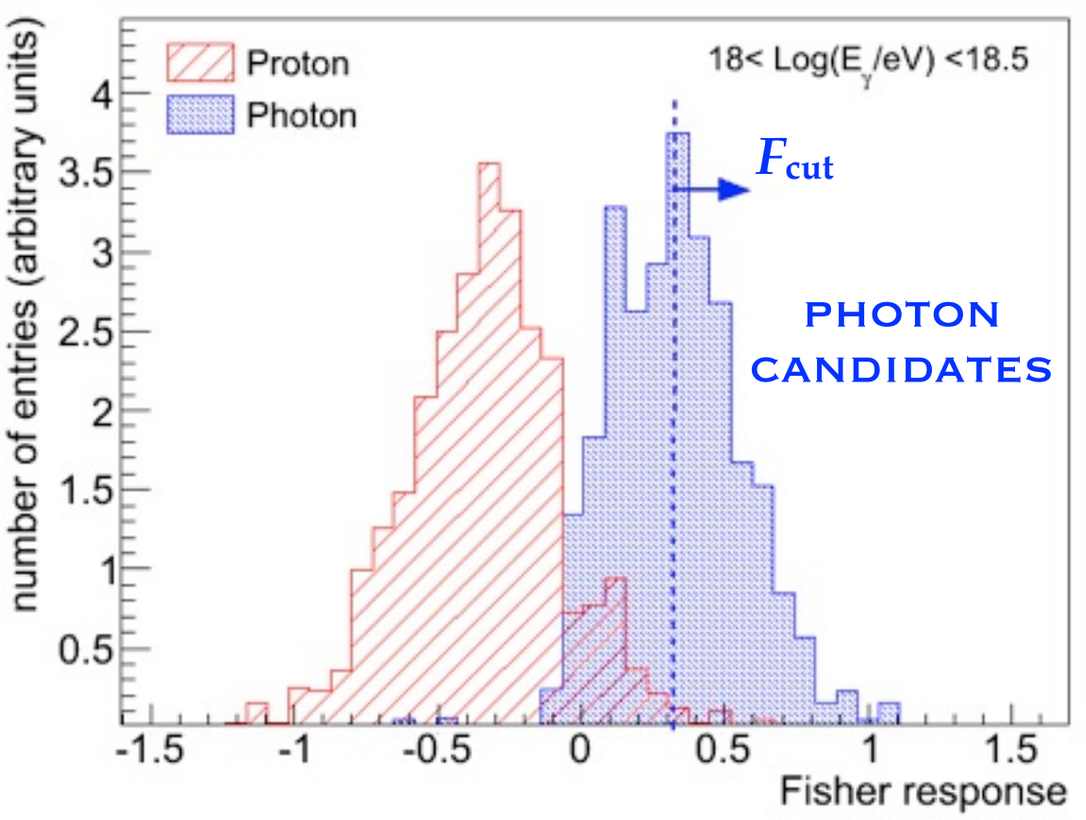
→ **Smaller S_b**





Search for photons with hybrid events





Fisher Analysis combining X_{max} and S_b

"a priori" cut @ photon selection efficiency = 50%
Events are marked as photon candidates for $F > F_{cut}$

- Proton Background on average ≲ 1%

HYBRID DATA JAN 2005 - SEP 2010

6, 0, 0, 0 and 0 candidates above
1, 2, 3, 5 and 10 EeV

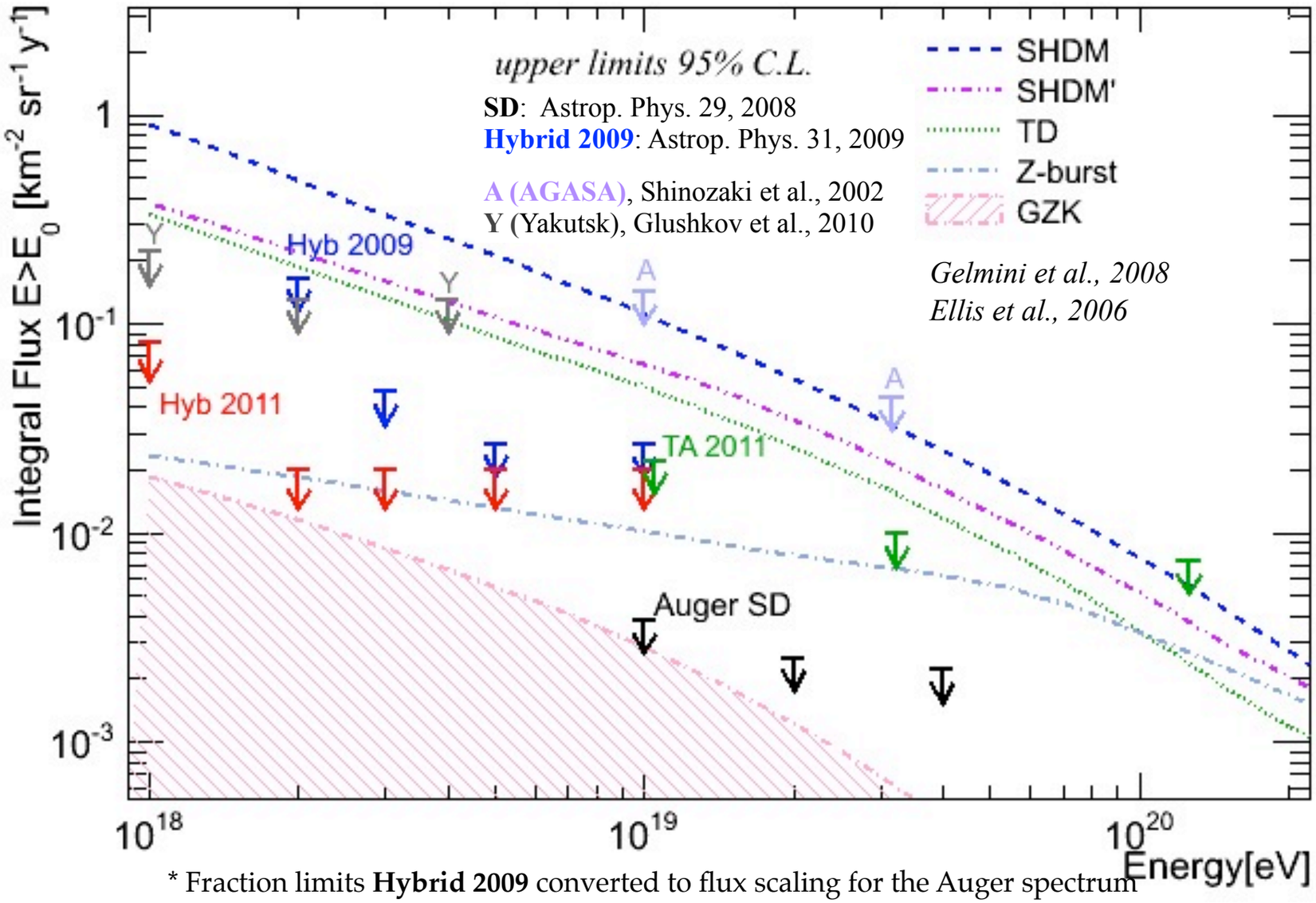
Number of candidate compatible with the expected nuclear background and additionally checked with dedicated simulations for each candidate

Upper Limits to the Integral Photon Flux:

$$\phi_\gamma^{95CL}(E_\gamma > E_0) = \frac{N_\gamma^{95CL}(E_\gamma > E_0)}{\mathcal{E}_{\gamma,min}}$$

M.S. for the Pierre Auger Collaboration, ICRC 2011, arXiv: 1107.4805

Upper limits to photon flux



* Fraction limits **Hybrid 2009** converted to flux scaling for the Auger spectrum

E_0 [EeV]	N_γ	$\phi_\gamma^{95CL}(E_\gamma > E_0)$ [km^{-2} sr^{-1} y^{-1}]
1	6	8.2×10^{-2}
2	0	2.0×10^{-2}
3	0	2.0×10^{-2}
5	0	2.0×10^{-2}
10	0	2.0×10^{-2}

Upper limits to the integral photon fraction assuming the **Auger Spectrum**

0.4%, 0.5%, 1.0%, 2.6% and 8.9% @ E>1, 2, 3, 5 and 10 EeV

Impact of systematic uncertainties

(Exposure, ΔX_{max}, ΔS_b, Energy scale, hadronic interaction model and mass composition assumptions)

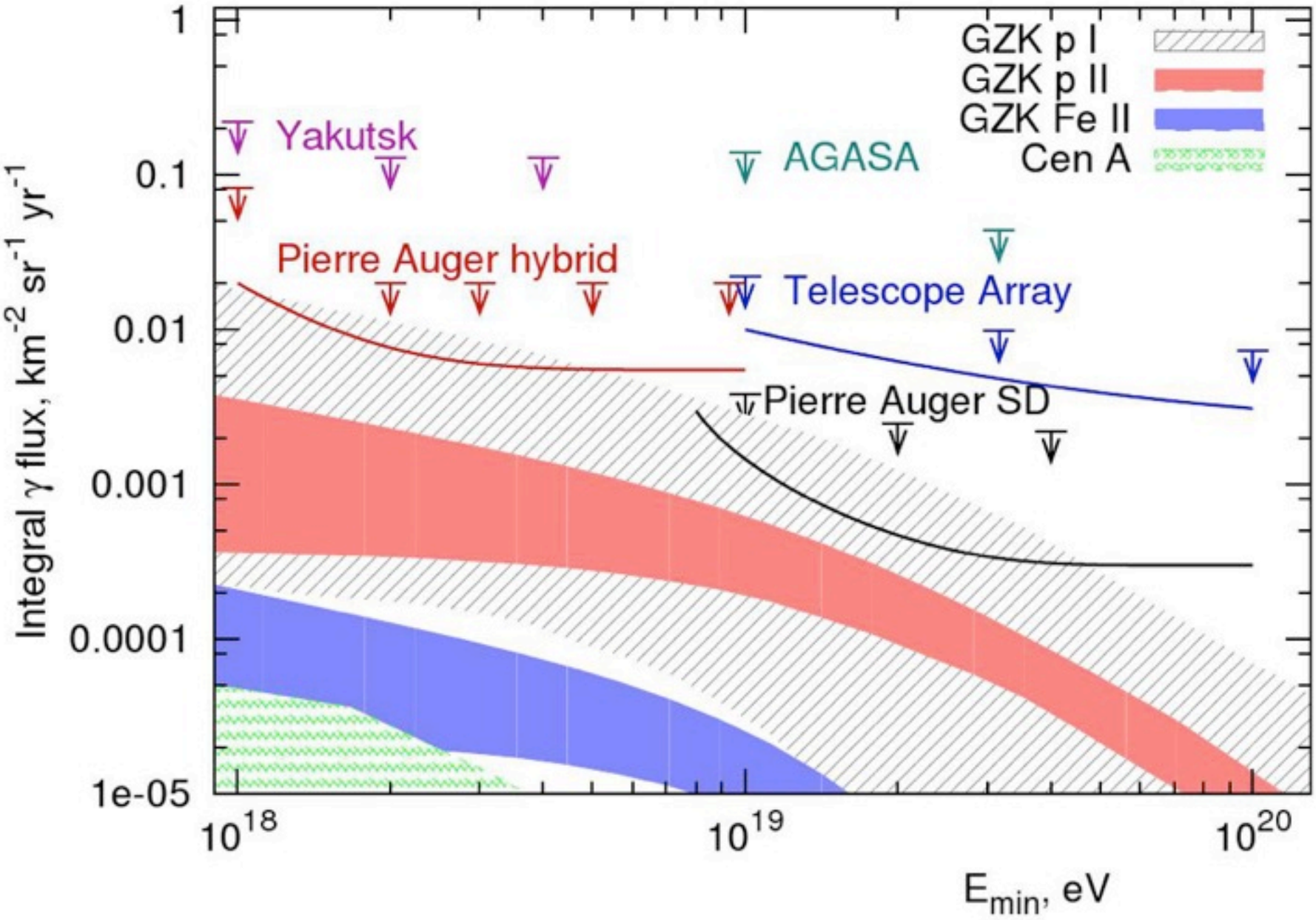
$$^{+20\%}_{-64\%} \ (E_0 = 1 \text{ EeV})$$

$$^{+15\%}_{-36\%} \ (E_0 > 1 \text{ EeV})$$

M.S. for the Pierre Auger Collaboration, ICRC 2011, arXiv: 1107.4805

Sensitivity to UHE photons

Expected sensitivity in 2015 with Telescope Array and Pierre Auger Observatory



Gelmini et al. 2008

B. Sarkar et al. 2011

Kachelriess et al. 2010

Photon observation possible (in optimistic models)

M. Risse et al., Symposium UHECR 2012, CERN

Summary

Energy Spectrum Measurement

- **Ankle** position ($10^{18.62}$ eV) and **flux suppression** ($10^{19.4}$ eV) measured with high accuracy using SD and hybrid data

Arrival Direction

- **anisotropy** of the arrival direction of CR with E > 55 EeV measured with a p-value of 33%. Directional search and large scale anisotropy studied.

Mass Composition

- The $\langle X_{max} \rangle$ and the RMS(X_{max}) vs E indicates a change from **light to heavier** composition for increasing E. Interpretation of results relies on hadronic models.

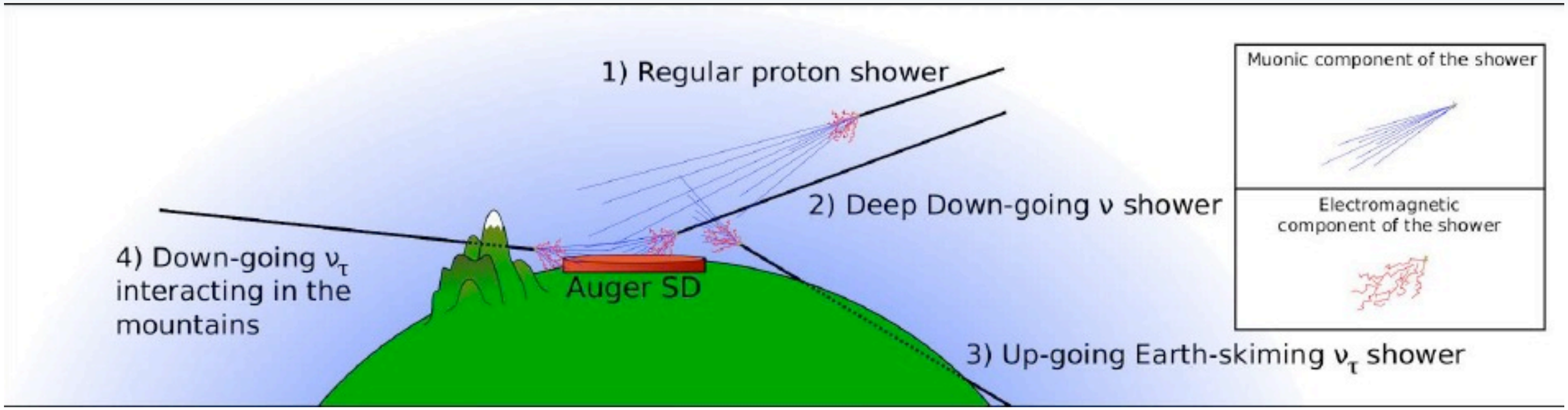
- **Upper limits on photon fraction**: 0.5% at 10^{18} eV (Hybrid) and ~ 2% above 10^{19} eV (SD).
  - *photon limits are reaching the region of the most optimistic GZK predictions*
  - provide **tighter constraints for models** and allow **reducing systematic uncertainties** on mass composition, energy spectrum and cross section measurements

Other results (p-Air cross section, test of hadronic interaction models, neutrino search) not shown here!

Extension of the Auger analyses below 10^{18} eV with the HEAT and INFILL enhancements
Test of new detection techniques (radio, microwave) are in progress

BACKUP

Search for neutrinos



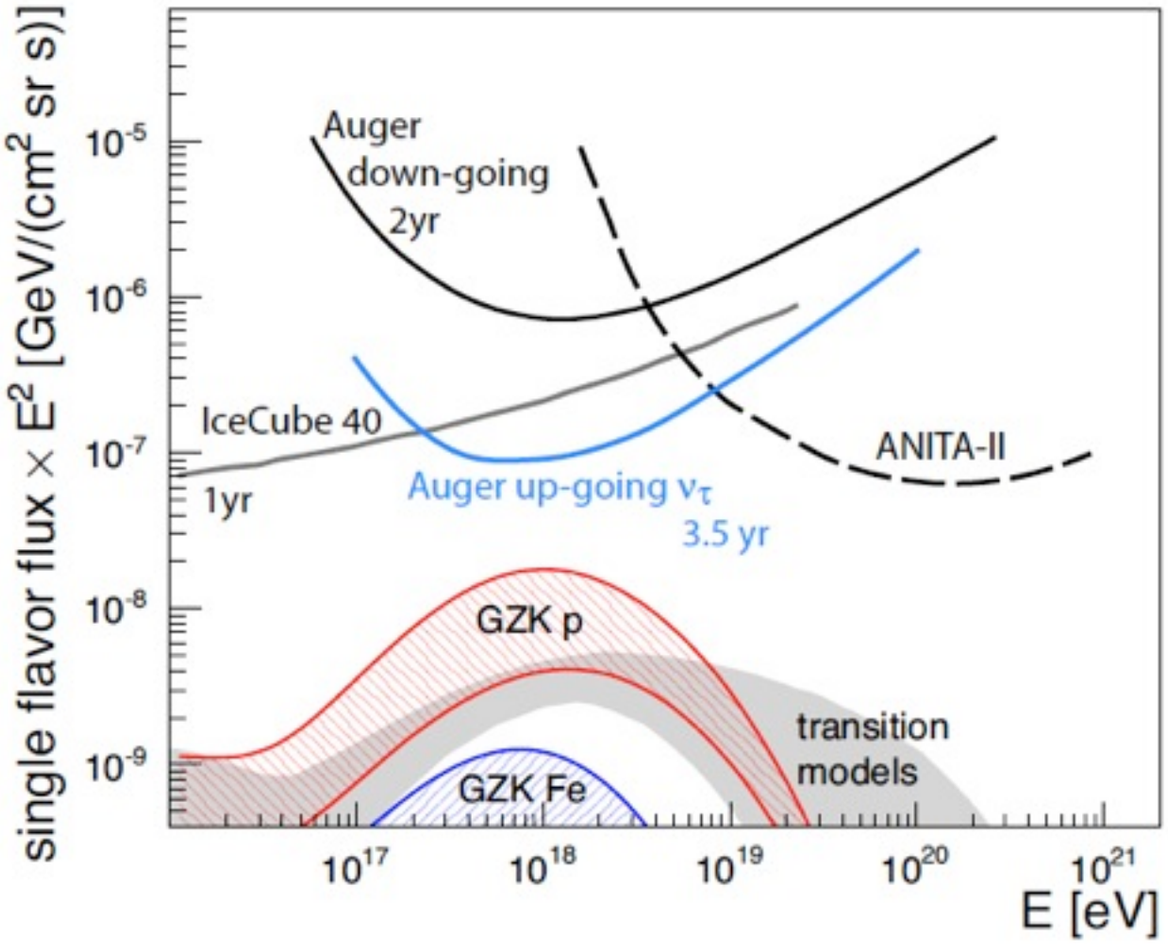
Neutrinos/hadron discrimination:

- **inclined events** (elongated footprint at ground) with SD signals typical of **young showers** (large contribution of em component)

Jan 2004 - May 2010 (down-going)

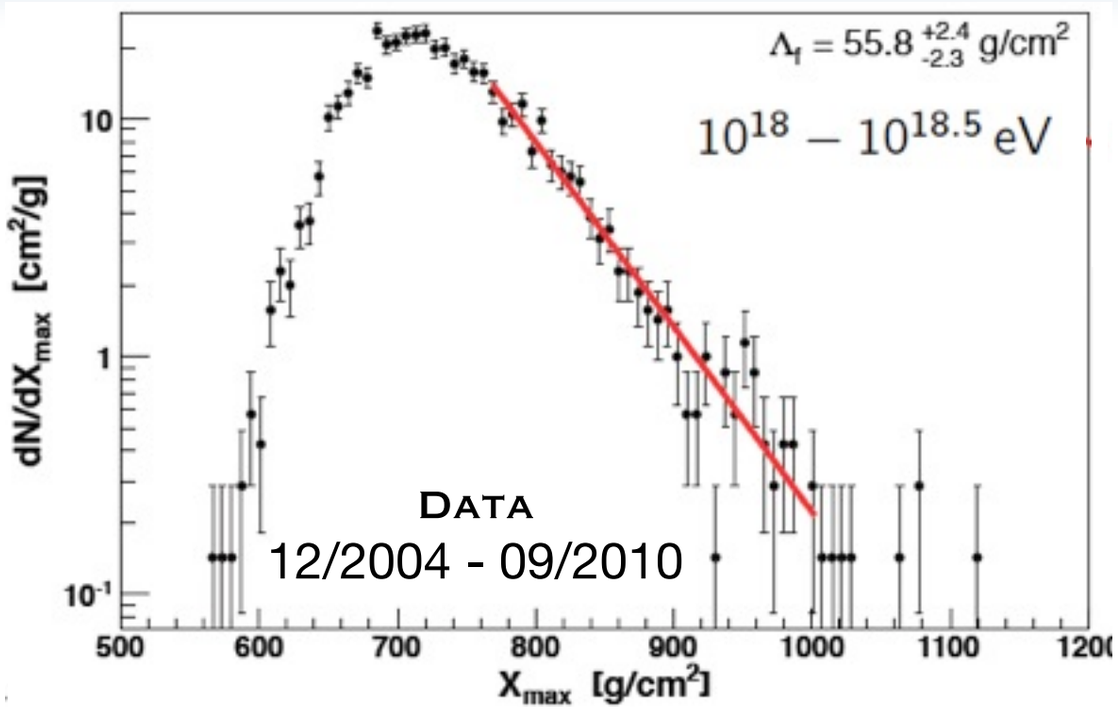
Nov 2007 - May 2010
(up-going Earth -Skimming)

No candidate found so far



The Pierre Auger Collaboration, Astrophysical Journal Letters, in press, 2012

Estimate of the p-Air cross section



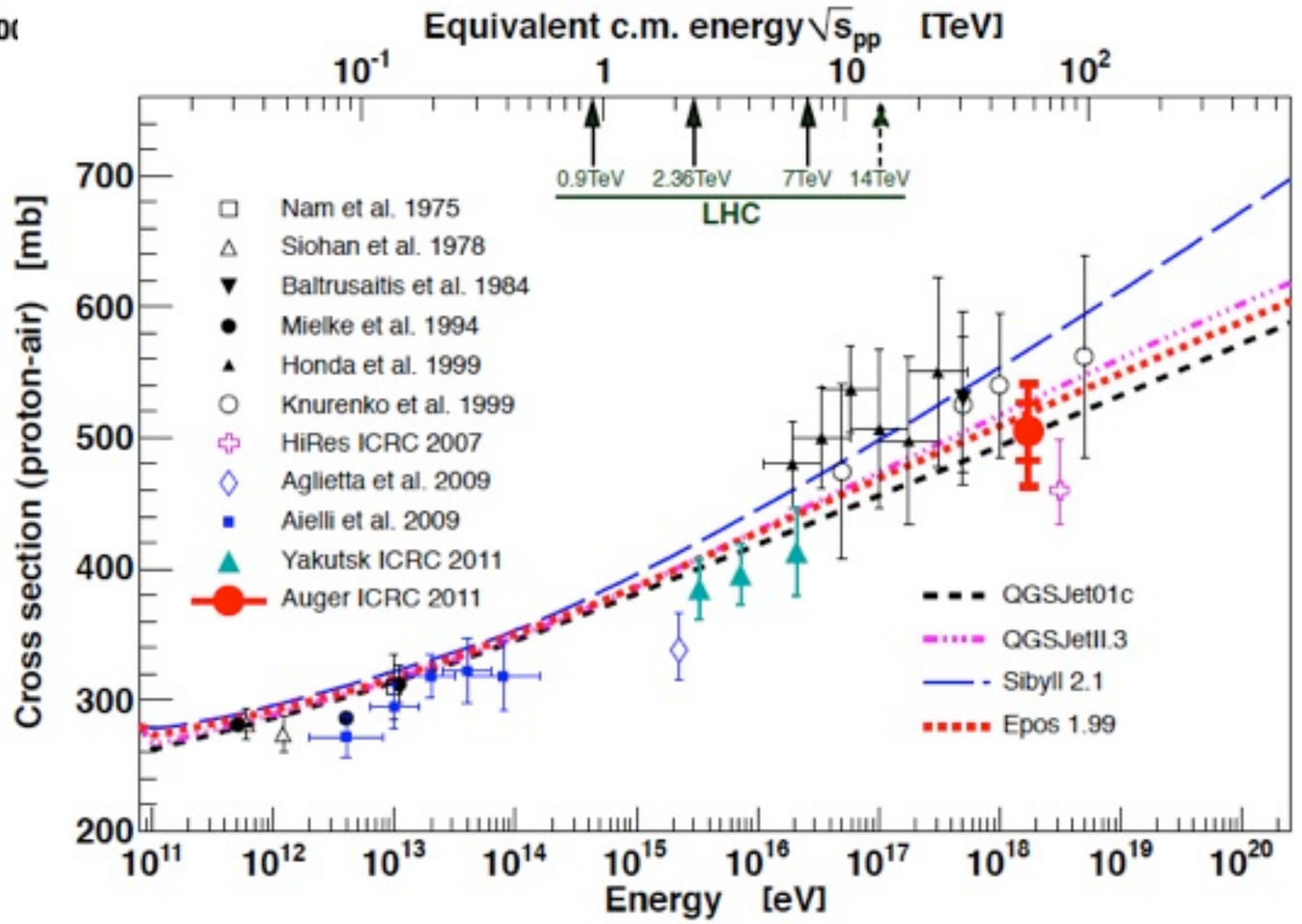
The exponential tail of the X_{max} distribution is sensitive to proton-air cross section.

$$dN/dX_{max} \propto \exp\left(-X_{max}/\Lambda_\eta\right)$$

η denotes the fraction of deep showers used to enhance the proton fraction (η = 20%)

$$\Lambda_f = (55.8 \pm 2.3_{\rm stat} \pm 0.6_{\rm syst})\ {\rm g/cm^2}$$

$$\sigma_{\rm p-air} = \left(505\ \pm 22_{\rm stat}\ \ (^{+20}_{-15})_{\rm syst}\right)\ {\rm mb}$$

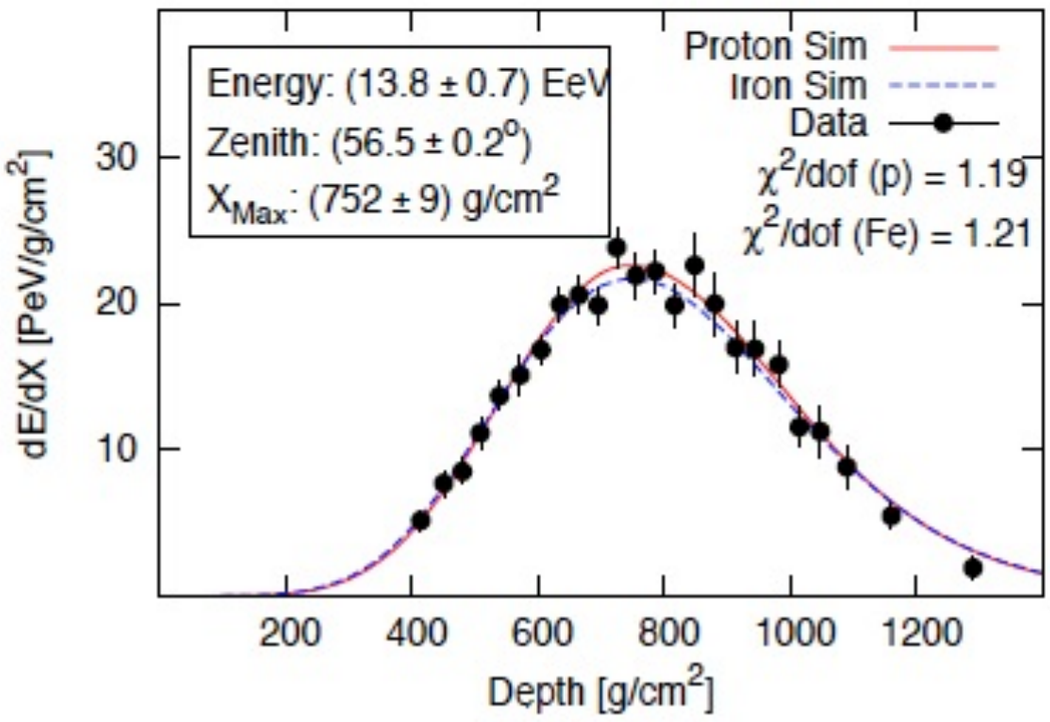


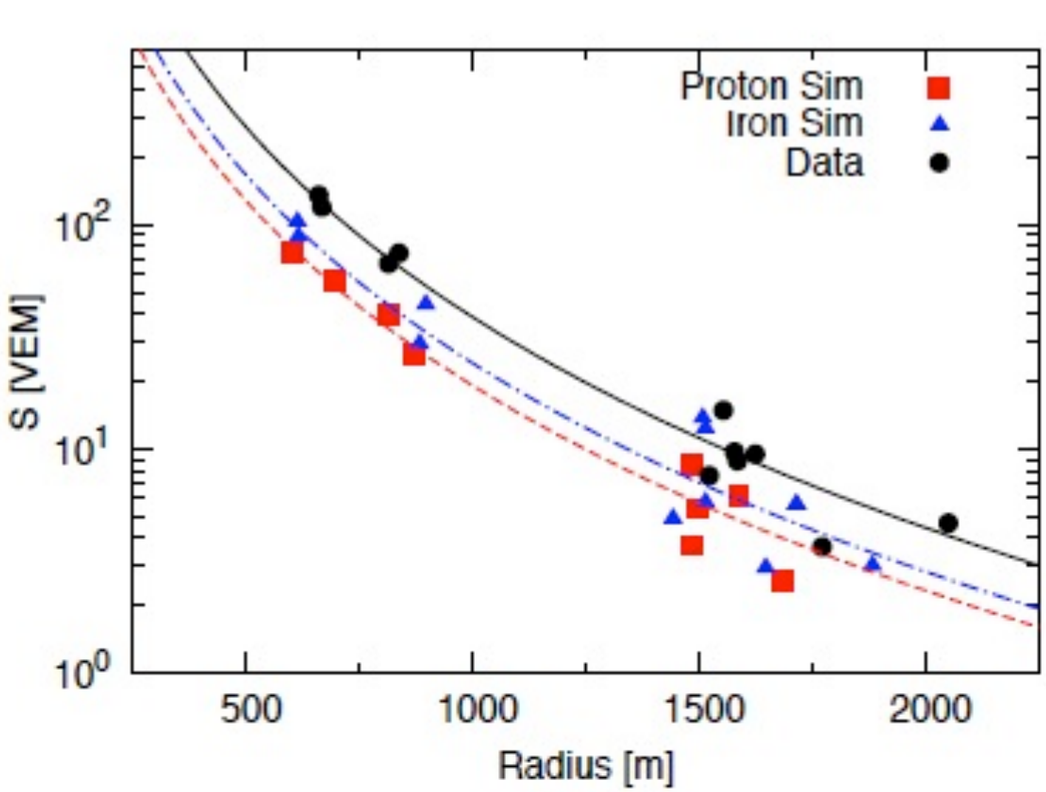
Systematic uncertainties

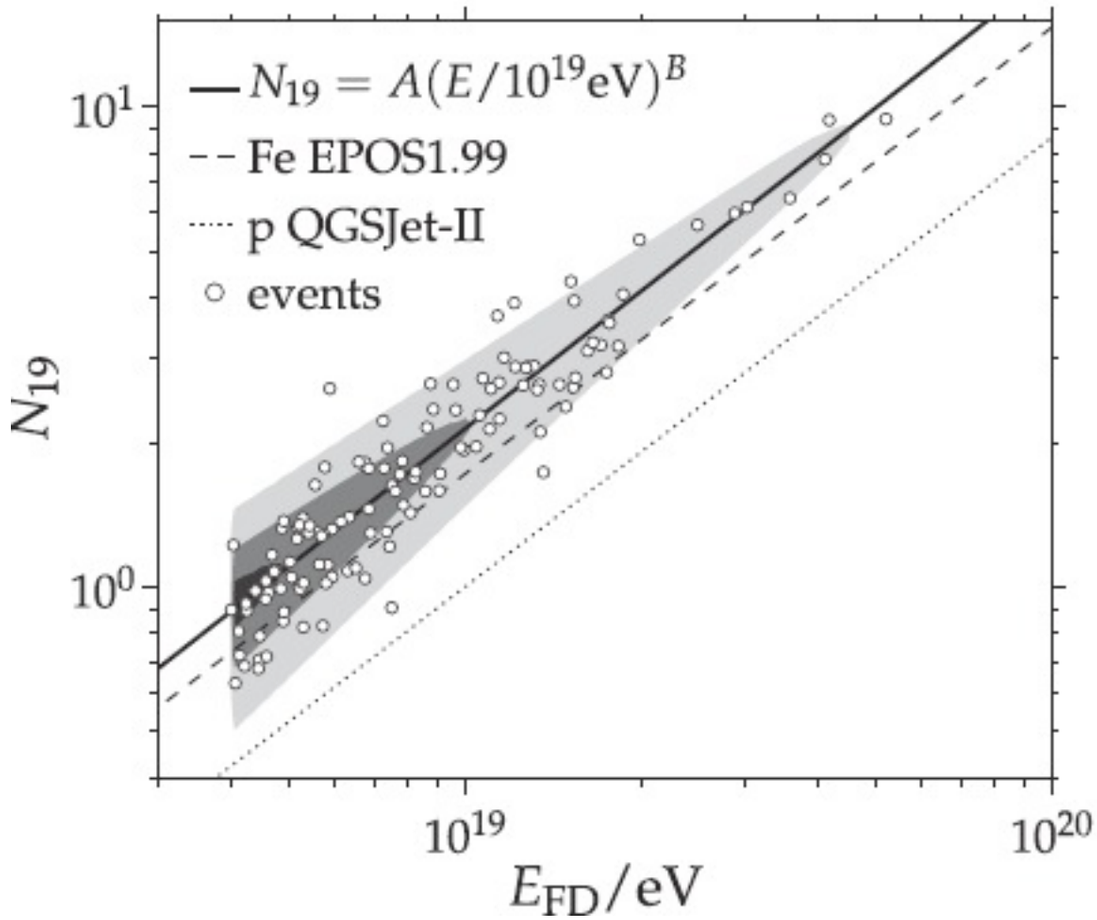
- Λ_η systematics
- Energy scale
- Hadronic models + simulations
- Composition:
  - < +10 mb for < 0.5% of photons
  - -12mb (-80 mb) for 10% (50%) of He

R. Ulrich for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4804

Test of hadronic interaction models







A deficit of muons observed comparing data and Monte Carlo:

- from **golden hybrid** events
- from **inclined** events
- independent of the primary particle (i.e. not due to mass composition assumption)

J. Allen for the Pierre Auger Collaboration, ICRC 2011, arXiv:1107.4804