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The search for UHE photons with the hybrid detector of the Pierre Auger Observatory

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PIERRE AUGER OBSERVATORY

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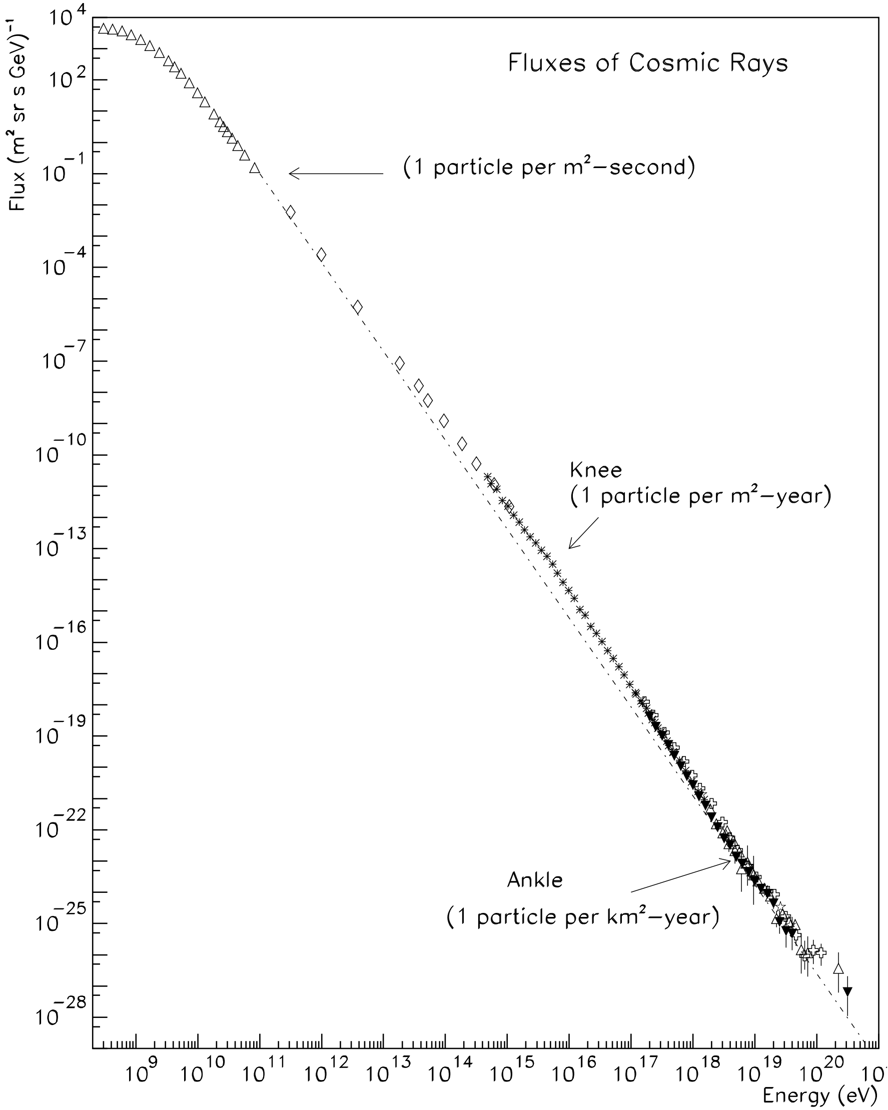
Introduction: cosmic rays



- **All-particle spectrum** of primary cosmic rays
- Differential **flux**:

$$\frac{\mathrm{d}\phi}{\mathrm{d}E} \propto E^{-\gamma}$$

  with γ piecewise constant
- **Basic questions** here:
  - Where do ultra-high-energy cosmic rays (UHECR, $E > 10^{18}$ eV) come from?
  - How can they be measured?

Introduction: theoretical models

- **Bottom-up models:**
  - **Accelerate** lower-energy particles step-by-step to high energies
  - **Examples:** active galactic nuclei, gamma-ray bursts, supernovae...
  - **But:** very difficult to accelerate up to 10^{20} eV...
- **Top-down models:**
  - Hypothetical massive objects **decay** into UHE particles
  - **Examples:** super-heavy dark matter, topological defects, WIMPZILLAS...
  - **But:** exotic...
- How to **differentiate** between these two classes of models?

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Introduction: theoretical models

- **Bottom-up models:**
  - **Accelerate** lower-energy particles step-by-step to high energies
  - **Examples:** active galactic nuclei, gamma-ray bursts, supernovae...
  - **But:** very difficult to accelerate up to 10^{20} eV...

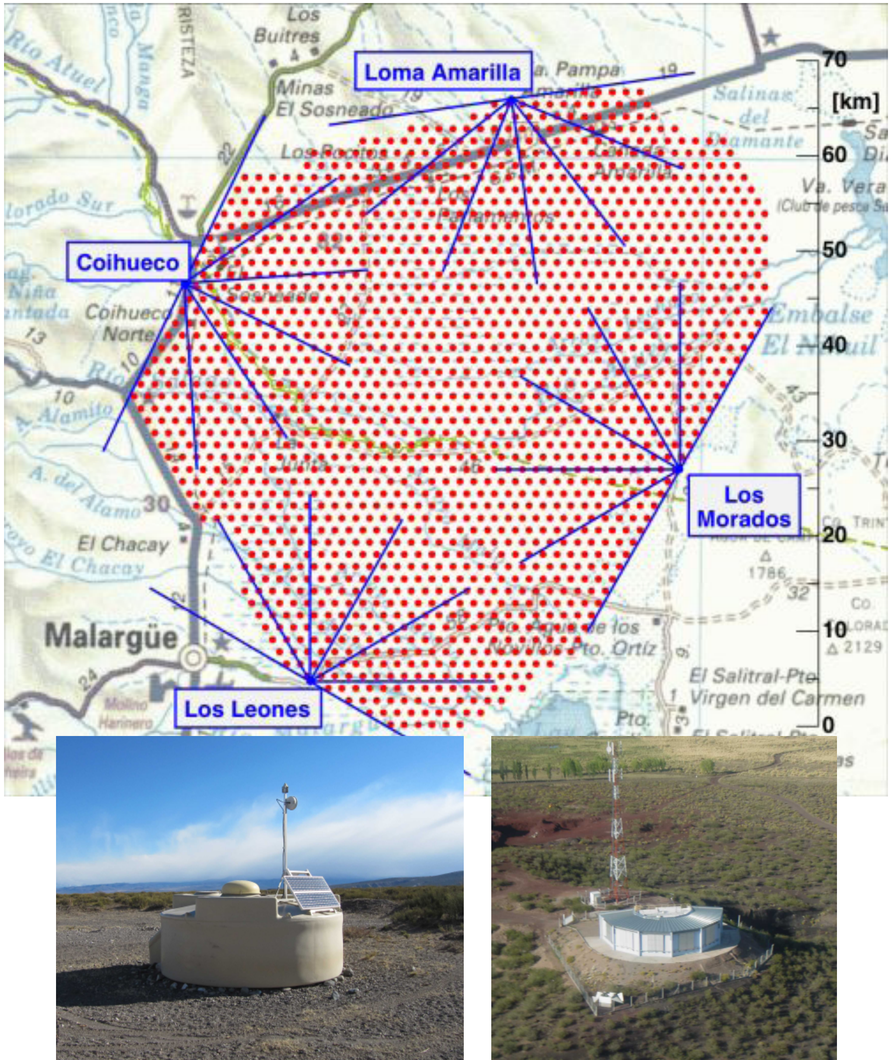
Expected UHE photon fraction < 1 % (from GZK-type process)

- **Top-down models:**
  - Hypothetical massive objects **decay** into UHE particles
  - **Examples:** super-heavy dark matter, topological defects, WIMPZILLAS...
  - **But:** exotic...

Expected UHE photon fraction > 10 %

- How to **differentiate** between these two classes of models? **Photon fraction**

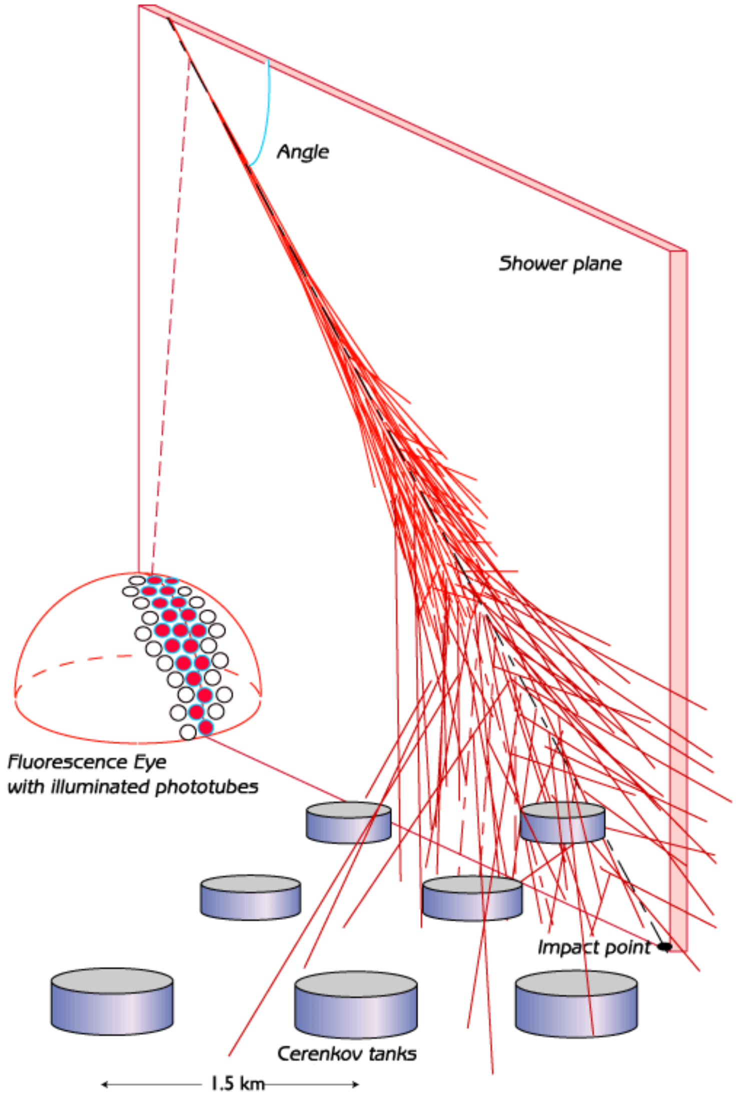
The Pierre Auger Observatory



- International **air shower experiment** optimized for UHECR
- **Two sites** for full sky coverage:
  - Southern hemisphere (**Malargüe**, Argentina): completed
  - Northern hemisphere: planning stage
- Two **independent** detector systems (hybrid concept):
  - **SD:** 1660 surface detector stations (water-Cherenkov detectors), covering 3000 km^2
  - **FD:** 24 fluorescence telescopes, overlooking the SD array

Hybrid Reconstruction (I)

- General idea of the **hybrid concept:**
  - Use **simultaneous** measurements from both the **SD** (lateral shower profile on ground level) and the **FD** (longitudinal shower profile above the array)
  - **“Ideal” case:** full SD and FD information available from reconstructions **(“golden hybrid”)**
  - **Lower energies:** Only one or two SD stations with a signal, not enough for full SD reconstruction
  - Standard hybrid reconstruction: use **only timing information from the SD** to constrain event geometry



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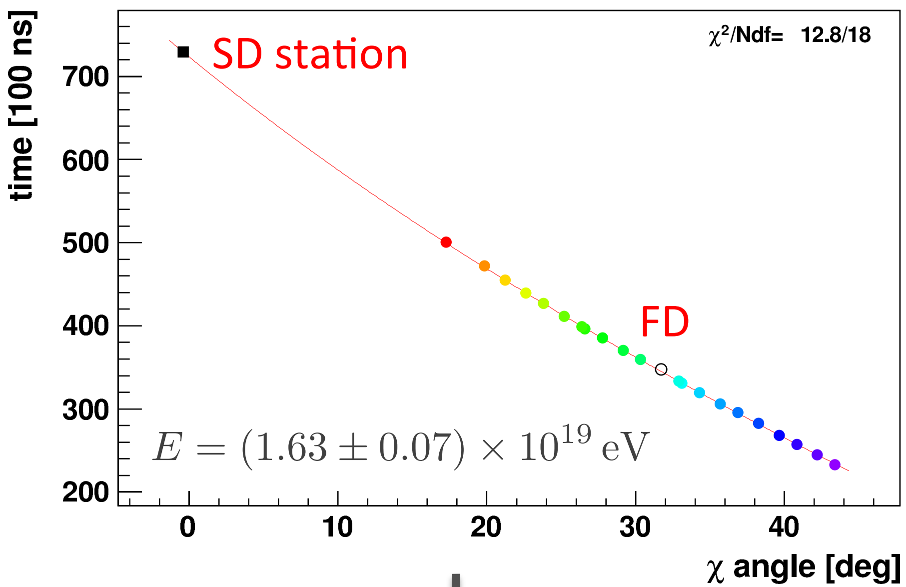
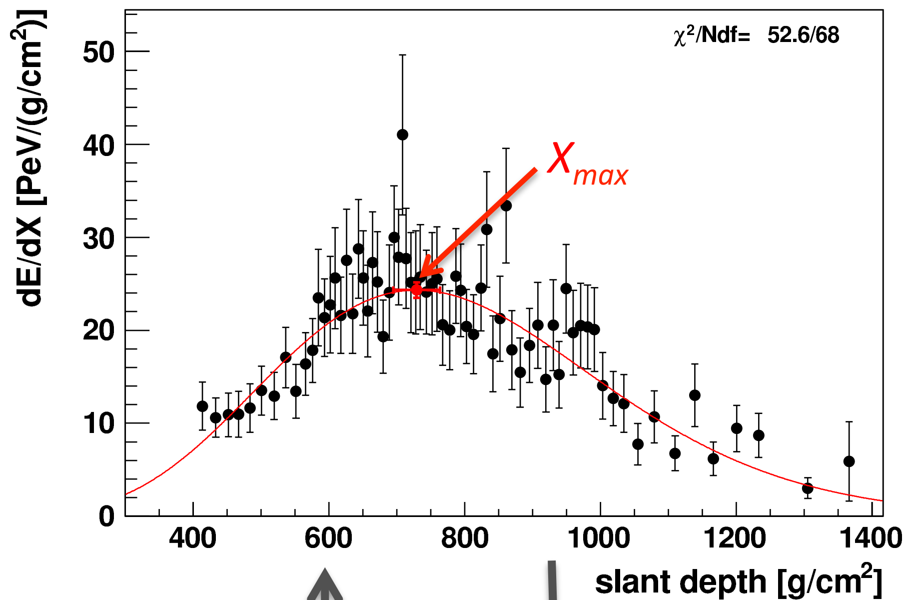
Hybrid Reconstruction (II)





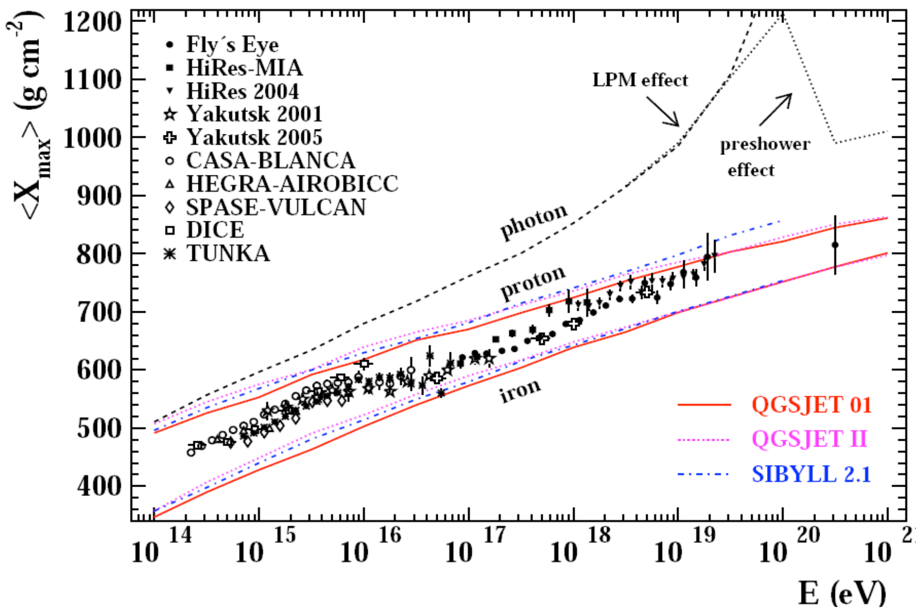
Atmospheric monitoring

- **Event geometry**
  - Shower core position
  - Zenith /Azimuth angle

- X_{max}
- E_{Hybrid}

The search for UHE photons: status (I)

- So far: photons **up to 100 TeV** observed (γ-ray astronomy)
  - No UHE photons identified yet
  - **Upper limits** on UHE photon flux and fraction
- **Identifying photons**:
  - Deeper shower development compared to hadrons (**larger X_{max}**)
  - **LPM** and **preshower effects** have to be taken into account
  - Complement X_{max} (FD parameter) with an SD-related parameter to **improve discrimination power** for hybrid events

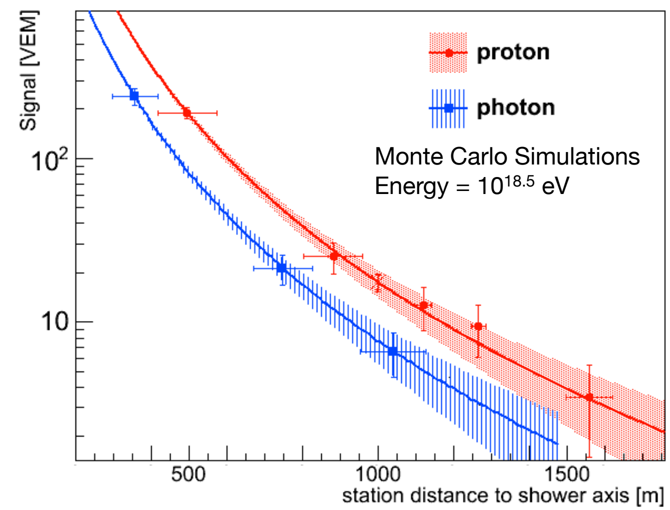


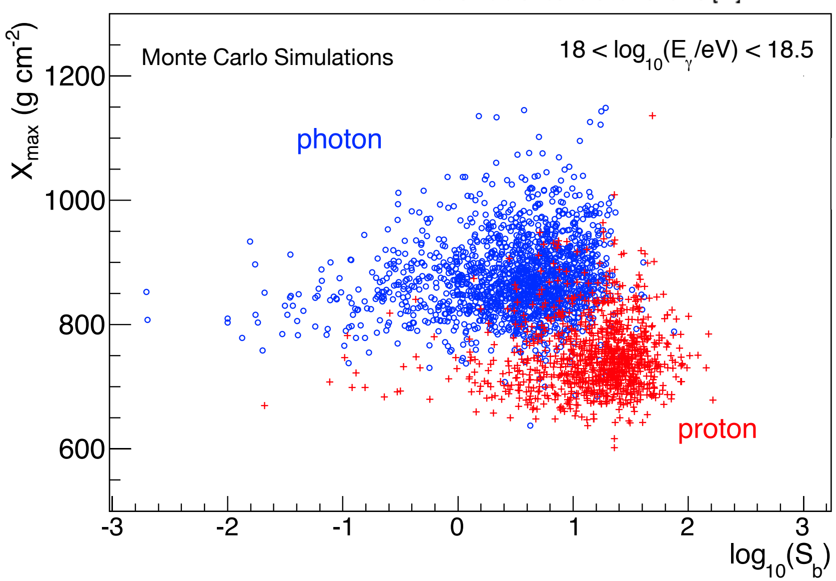
The search for UHE photons: status (II)

- **Idea:** use time integrated SD signals as additional parameter for **photon/hadron separation**
  - Photons show steeper lateral distribution function (LDF): **smaller signal *S*** at a given distance *R* from the shower core and **fewer triggered stations** as compared to hadrons
  - Current hybrid photon analysis: **S_4 parameter**

$$S_4 = \sum_i S_i \left(\frac{R_i}{1000\,\mathrm{m}} \right)^4$$

  - Combining X_{max} and S_4: **linear discriminant**





The search for UHE photons: status (III)

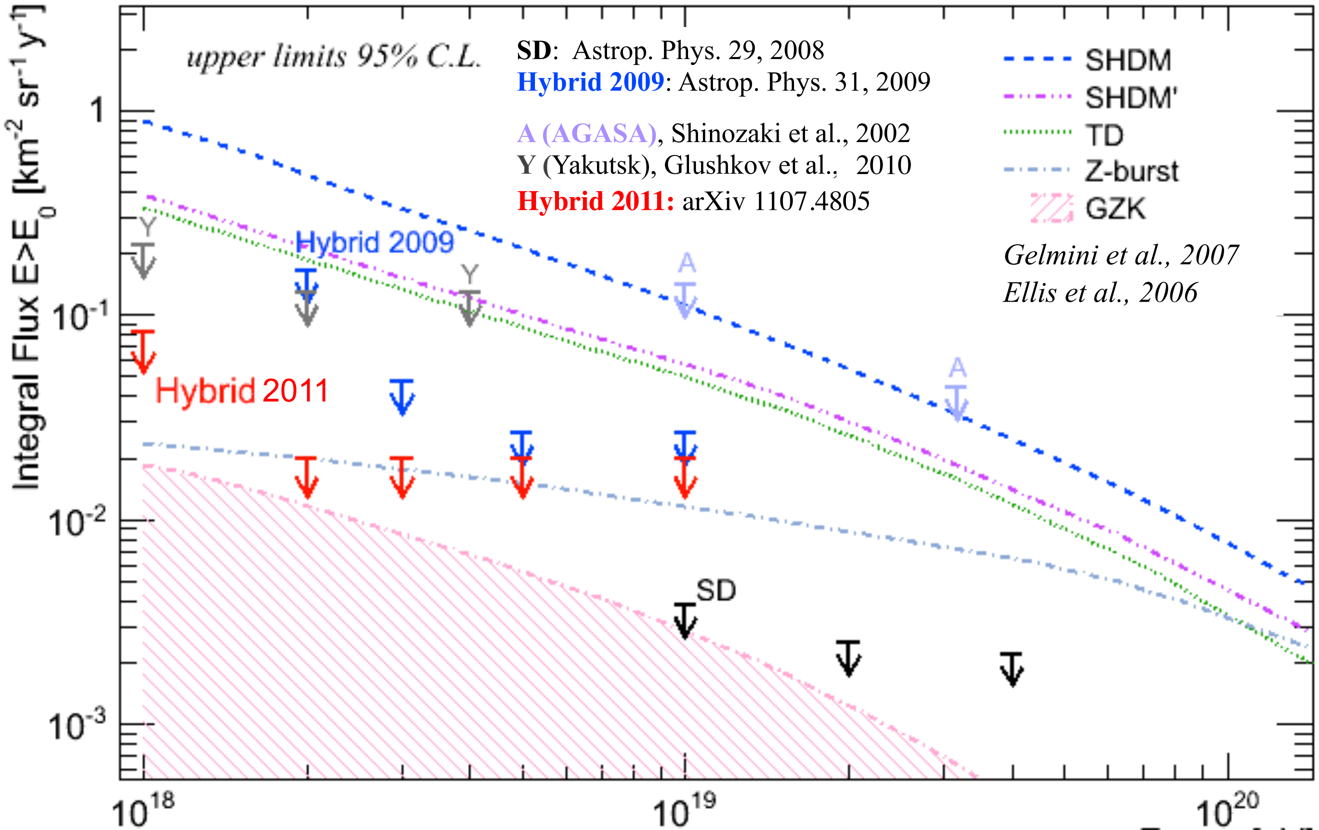
- Use data from **Jan 2005 – Sep 2010:**
  - Only events selected with at least 4 active SD stations, good geometry and longitudinal profile, zenith angle < 60°, without clouds...
  - **6, 0, 0, 0 and 0** photon candidate events above **1, 2, 3, 5 and 10 EeV**
  - Numbers compatible with the **expected hadron background**
  - Calculate upper limits on **integral photon flux** using the **exposure** of the observatory for photons:

$$\phi_{\gamma,\mathrm{max}}(E_\gamma > E_0) = \frac{N_\gamma(E_\gamma > E_0)}{\mathcal{E}_{\gamma,\mathrm{min}}}$$

  - Exposure: **time-integrated aperture** of the detector, derived from simulations:

$$\mathcal{E}(E) = \int_T \mathcal{A}(E,t)\mathrm{d}t = \int_T \int_\Omega \int_S \varepsilon(E,t,\theta,\phi,x,y)\cos\theta \mathrm{d}S\mathrm{d}\Omega\mathrm{d}t$$

The search for UHE photons: status (IV)



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

- Current photon limits already **rule out top-down models**
- Predictions for **GZK photons** are within reach

Outlook: improving the analysis (I)

- **Weakness** of the current analysis: requires ≥ 4 active SD stations around the shower core (no holes in the array)
- **Alternative parameter** (also based on SD signals): F_γ
  - Use a **photon-optimized likelihood LDF fit** (including stations with no signal) to obtain $S_{1000|\gamma}$
  - **NKG type** LDF:

$$S = S_{1000} \left(\frac{R}{1000\,\mathrm{m}} \right)^{\beta} \left(\frac{R + 700\,\mathrm{m}}{1700\,\mathrm{m}} \right)^{\beta}$$

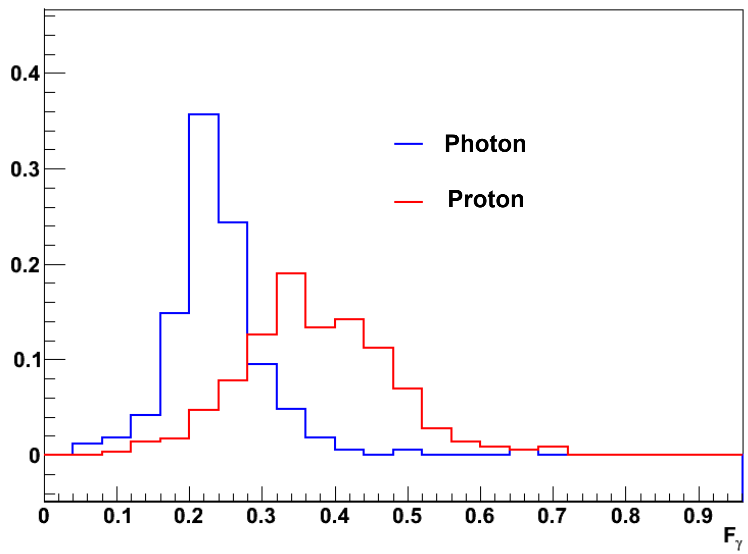
  - Value of β is **not free**, but **parameterized** as a function of S_{1000} and the zenith angle ϑ; **here:** multiply parameterization of β with a **factor of 1.4** to account for steeper photon LDF
  - Convert E_{Hybrid} to an **average SD signal** at a distance of 1000 m ($S_{1000|Hybrid}$) using the known energy calibration equations for the hybrid detector

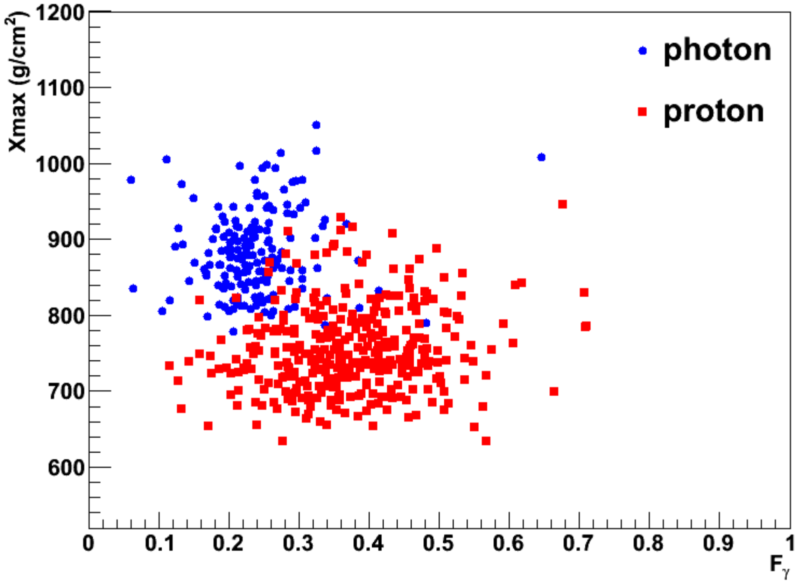
Outlook: improving the analysis (II)

- Take F_γ as the **ratio** of both S_{1000} quantities to eliminate the energy dependence:

$$F_\gamma = \frac{S_{1000|\gamma}}{S_{1000|Hybrid}}$$

- **Performance** of F_γ comparable to S_4 and X_{max} (at 1 - 3 EeV)





- Still some room to improve this parameter...

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Summary

- **UHE photons** can provide a handle on the **differentiation of theoretical models** for the origin of UHECR
- **Current results** from the **Pierre Auger Observatory** already rule out top-down models
- Experimental challenge: **photon identification**
- **Shown here:** combination of FD (X_{max}) and SD (S_4) information in **hybrid mode**
- **Possible improvement** of the analysis: new parameter (F_γ), based on a photon-optimized LDF fit

Backup Slides

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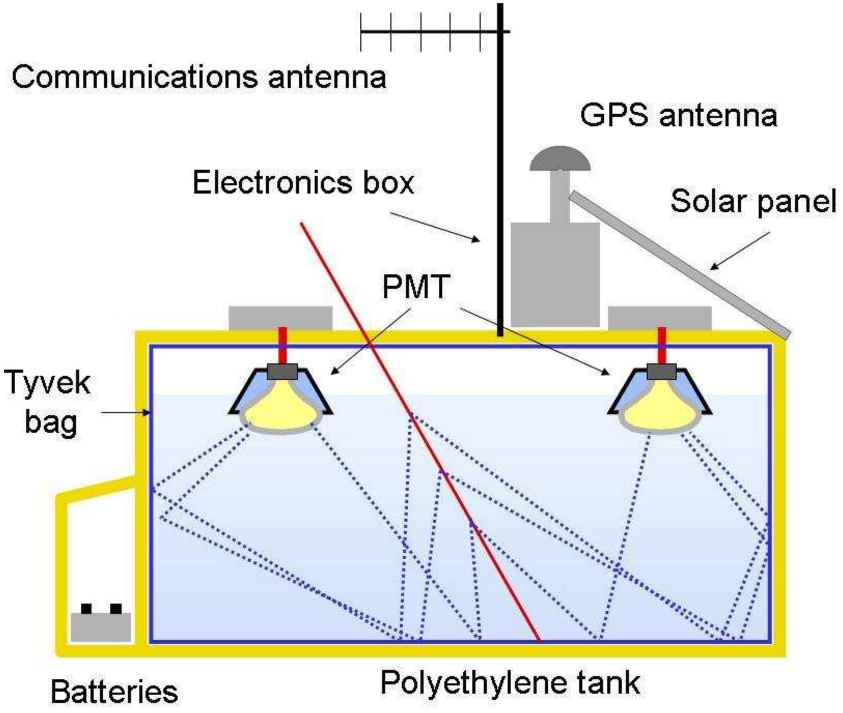
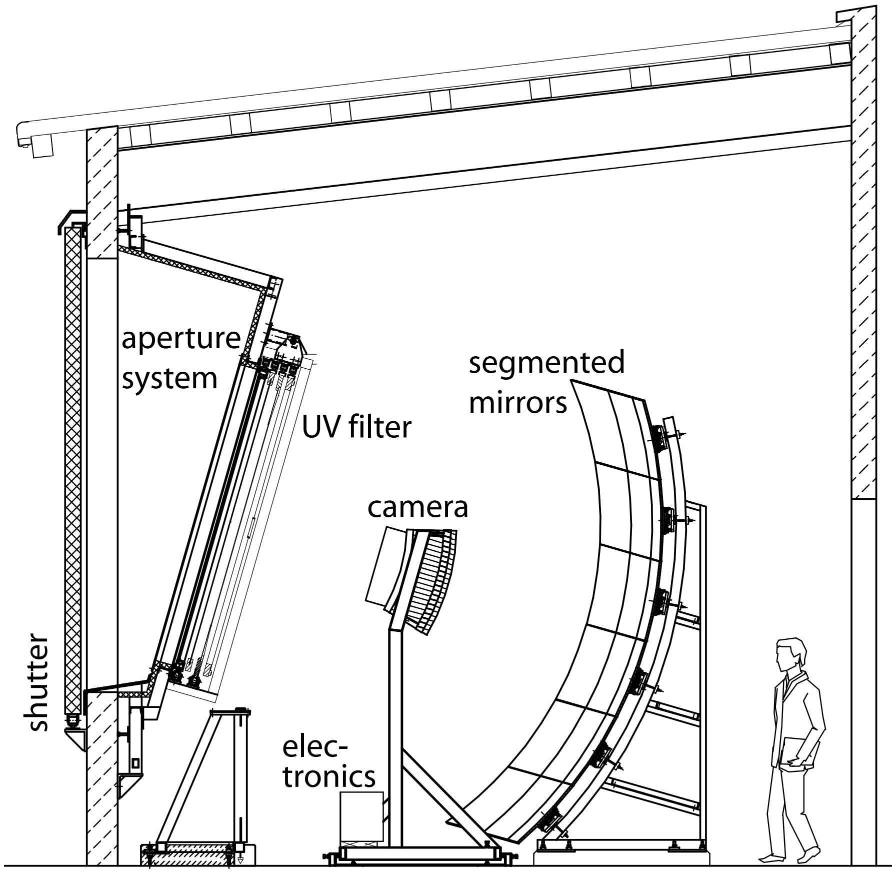
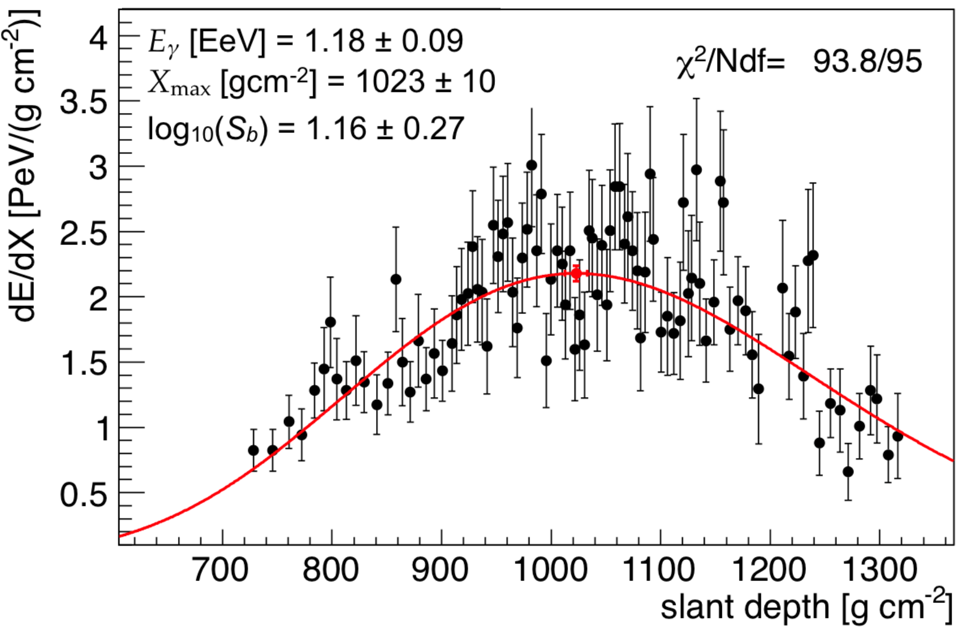
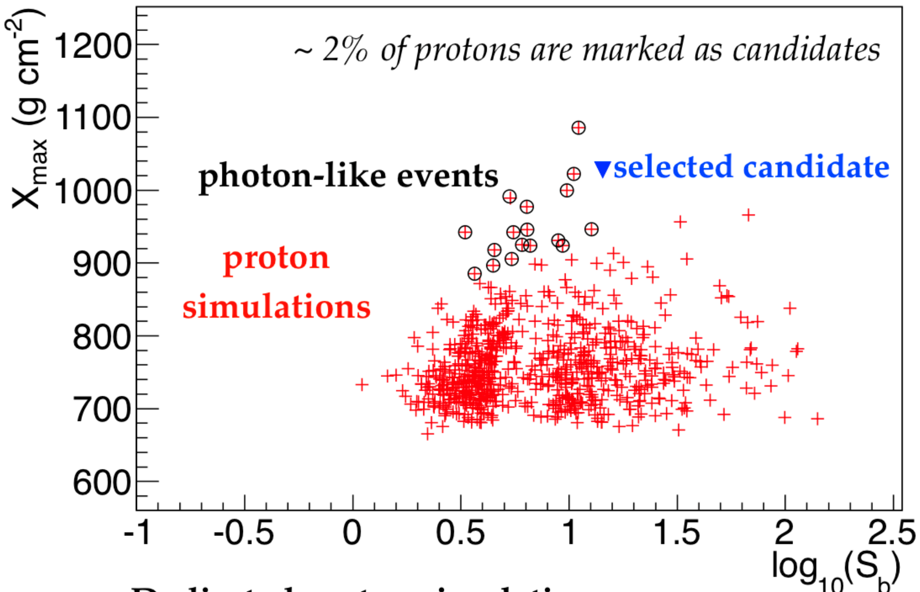
SD and FD





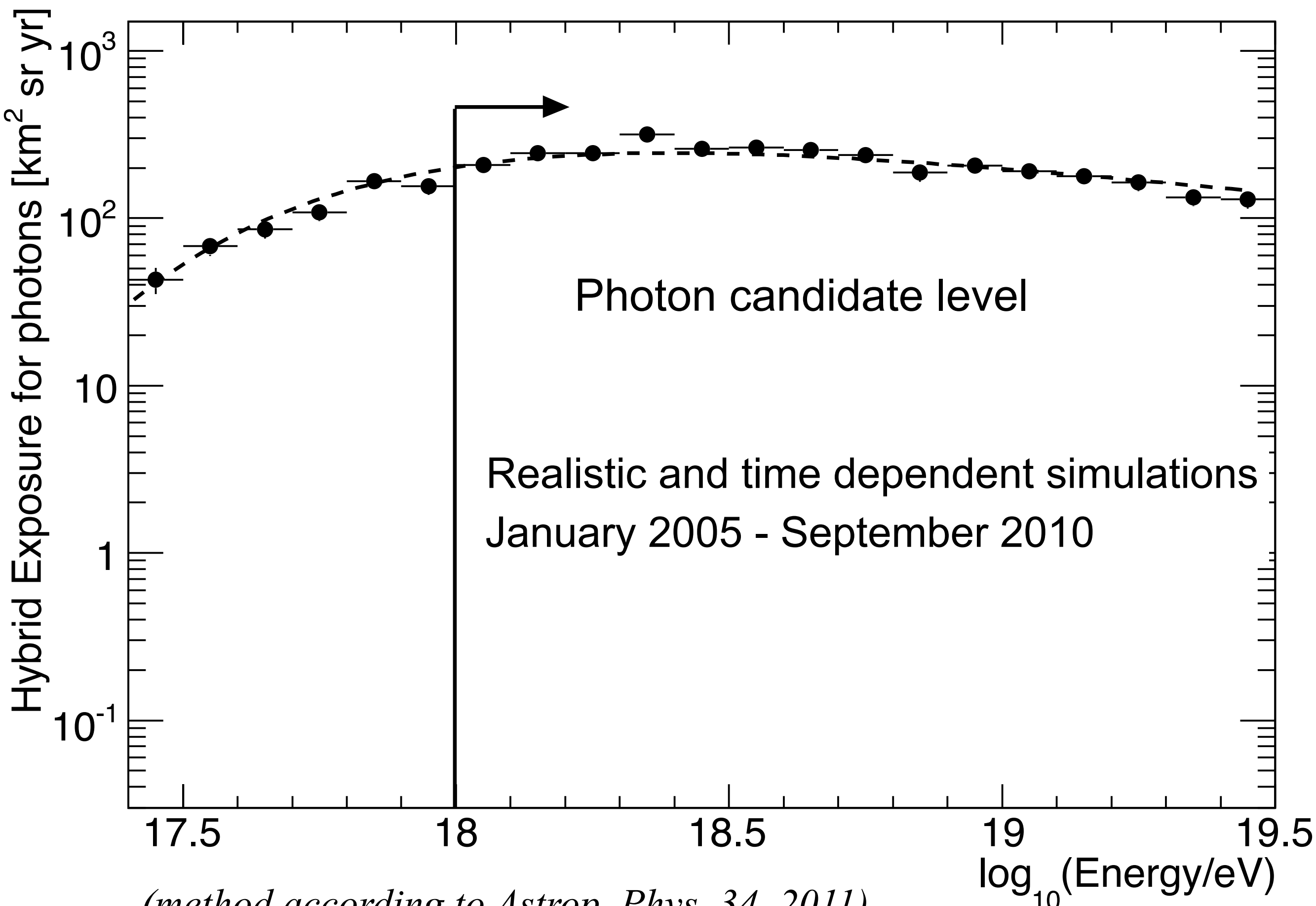
Example of a photon candidate event





Dedicated proton simulations:
same energy, arrival direction, core position and detector configuration of the selected candidate

Hybrid exposure for photons



(method according to Astrop. Phys. 34, 2011)

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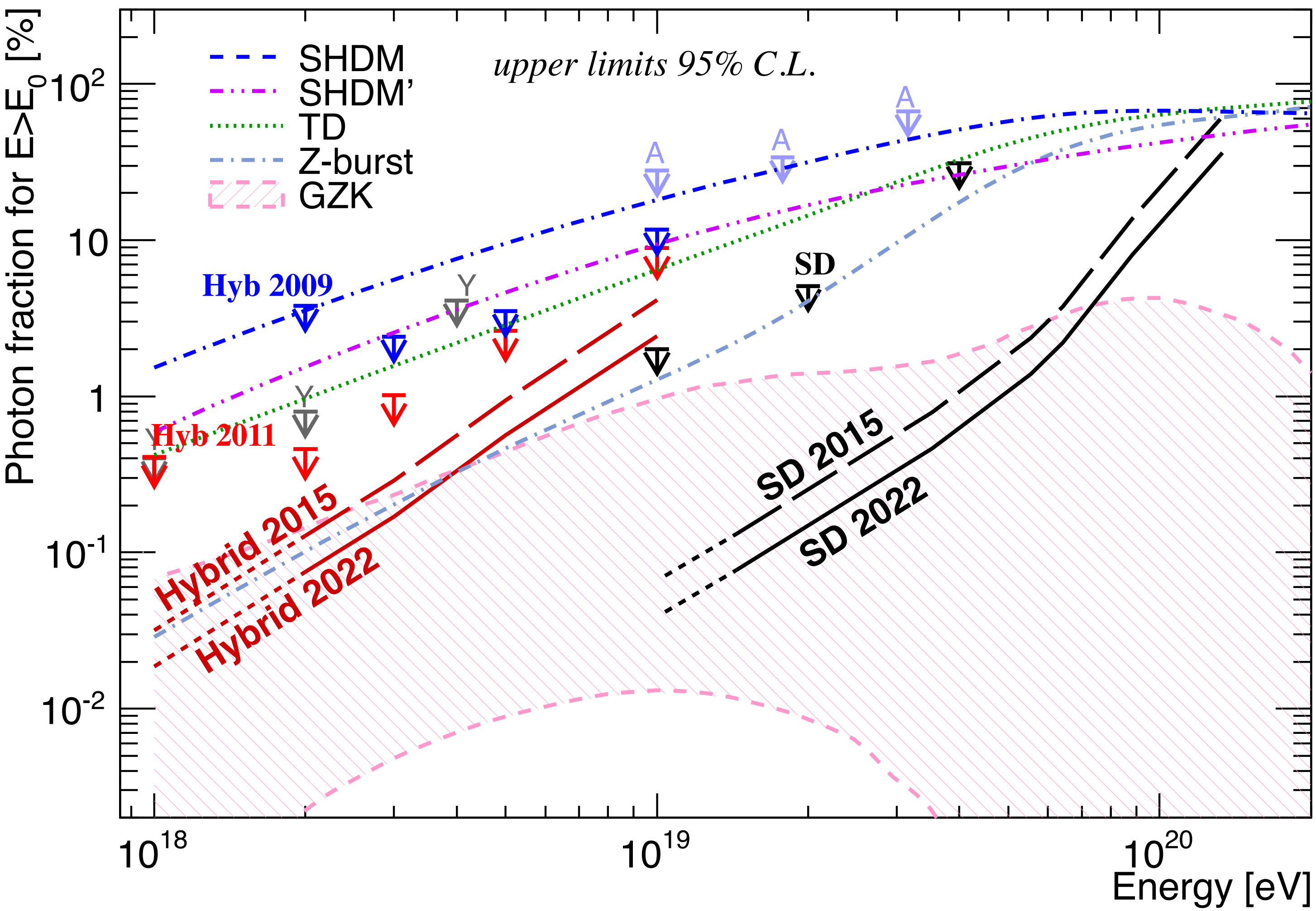
Auger sensitivity to photons



Parameterization of β

- **Use modified low energy LDF parametrization (originally for 750 m infill array):**

Factor to account for steeper photon LDF

$$\beta = \underbrace{1.4}\,\underbrace{\left(C_0 + C_1 x + C_2 \sec\vartheta + C_3 x \sec\vartheta + C_4 \sec^2\vartheta + C_5 x \sec^2\vartheta\right)}$$

$$x = \log(S_{1000}\,[\mathrm{VEM}]) - \log 20$$

$$C_0 = a_0 + a_1 \log 20$$

$$C_2 = b_0 + b_1 \log 20$$

$$C_4 = c_0 + c_1 \log 20$$

$$C_1 = -0.817 \pm 0.159$$

$$C_3 = 0.724 \pm 0.234$$

$$C_5 = -0.296 \pm 0.0845$$

GAP-2009-047 [P. Younk]

$$a_0 = -3.35 \pm 0.23$$

$$a_1 = -0.125 \pm 0.151$$

$$b_0 = 1.33 \pm 0.31$$

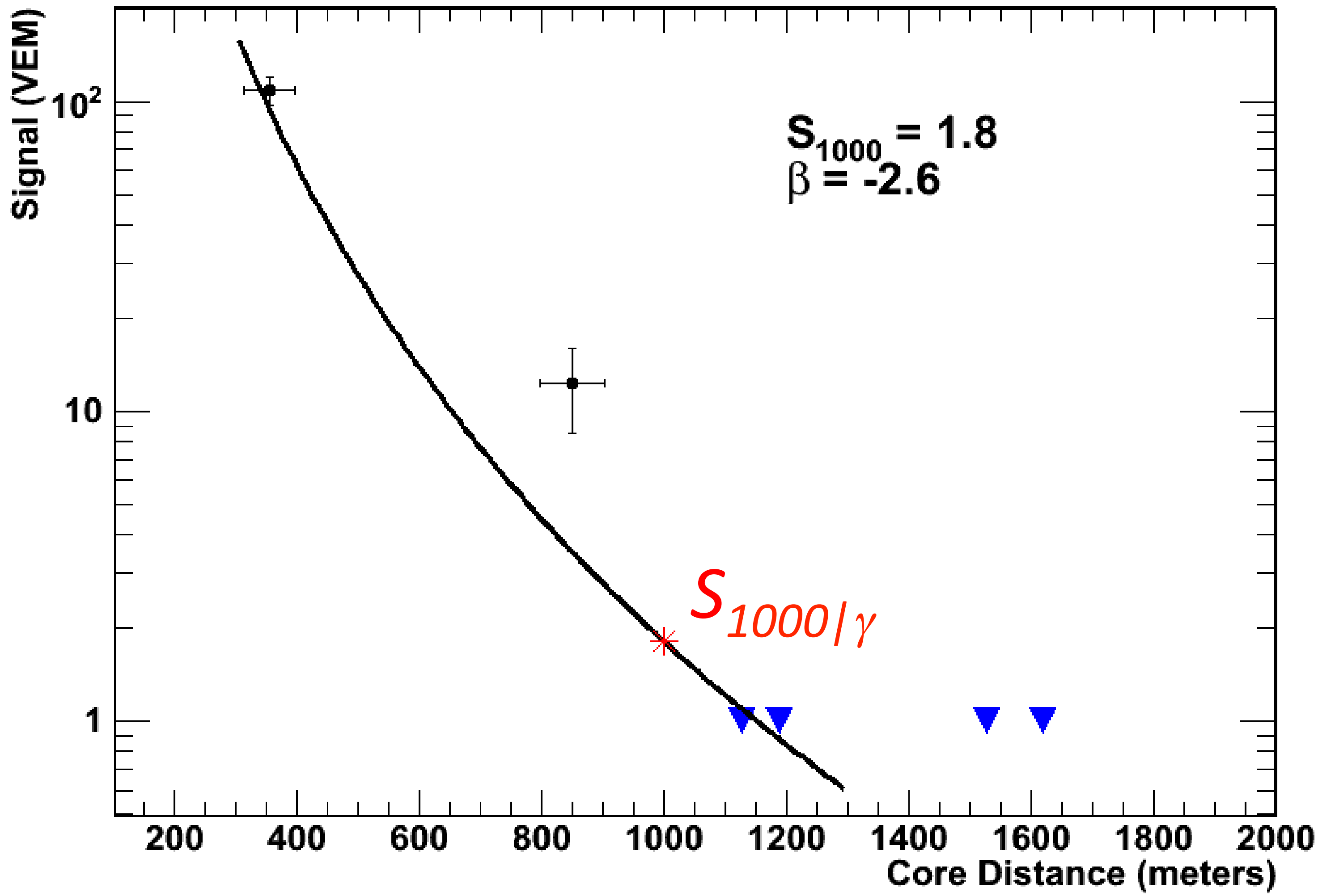
$$b_1 = -0.0324 \pm 0.2114$$

$$c_0 = -0.191 \pm 0.105$$

$$c_1 = -0.00573 \pm 0.07210$$

GAP-2007-106 [T. Schmidt et. al.]

Example of a photon-optimized LDF fit



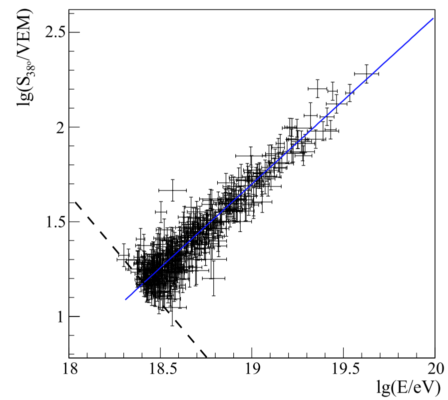
Energy calibration and CIC function

- **Energy calibration based on PRL 101, 061101 (2008) [Pierre Auger Collaboration]**

$$S_{38^\circ}\,[\mathrm{VEM}] = \sqrt[b]{\frac{E_{Hybrid}\,[\mathrm{eV}]}{a}}$$

$$a = [1.49 \pm 0.06 \pm 0.12] \times 10^{17}\,\mathrm{eV}$$

$$b = 1.08 \pm 0.01 \pm 0.04$$



- **CIC function based on astro-ph/0706.2096v1 [M. Roth, 2007 ICRC contribution]**

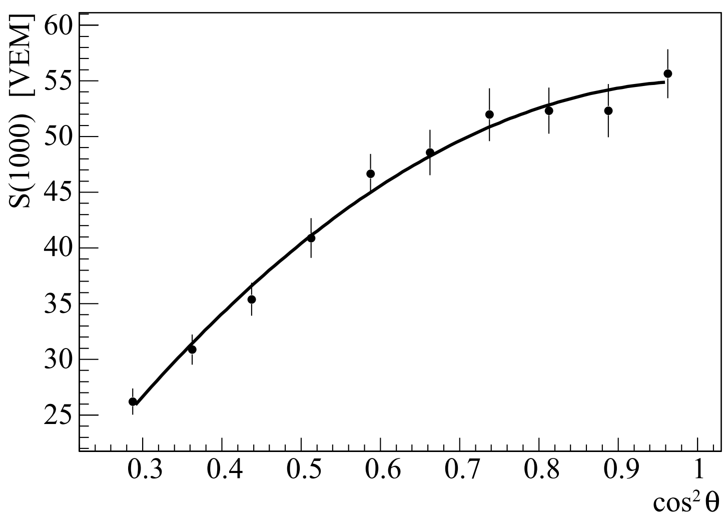
$$S_{1000} = S_{38^\circ} \cdot CIC(\theta)$$

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

$$x = \cos^2(\vartheta) - \cos^2(38^\circ)$$

$$a = 0.94 \pm 0.06$$

$$b = -1.21 \pm 0.27$$



Quality cuts and event selection

- **Geometry level:**
  - NTankOn > 0
  - Zenith angle < 60°
  - Station distance to axis < 1500 m
  - SD/FD offset < 200 ns
  - SDP fit $\chi^2/Ndf < 7$
  - Time fit $\chi^2/Ndf < 8$
- **Profile level:**
  - Gaisser-Hillas fit $\chi^2/Ndf < 2.5$
  - X_{max} in FOV
  - Cherenkov fraction < 50 %
  - Relative energy error < 20 %
- **Common quality cut:**
  - Time periods with clouds rejected

- **Quality cut for S_4:**
  - ≥ 4 active SD stations
- **Quality cut for F_γ:**
  - Relative $S_{1000|\gamma}$ error < 30 %

Number of Events, data period Jan 2005 – Sep 2010:
- Triggered: ≈ 1,000,000
- Reconstructed: ≈ 380,000
- After profile level cut: ≈ 145,000
- After quality cuts for S_4: ≈ 1700

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Introduction: extensive air showers

- **Flux** of cosmic rays at **10^{20} eV**: 1 particle per century and km^2
  - **Direct** measurements (balloons, satellites) are not feasible
  - Measure properties of the (primary) cosmic rays **indirectly** using the **extensive air showers** induced by the primary particles in the atmosphere