Photon 2013

LPNHE, Paris, 20 - 24 May 2013

Search for Ultra High Energy Photons with the Pierre Auger Observatory

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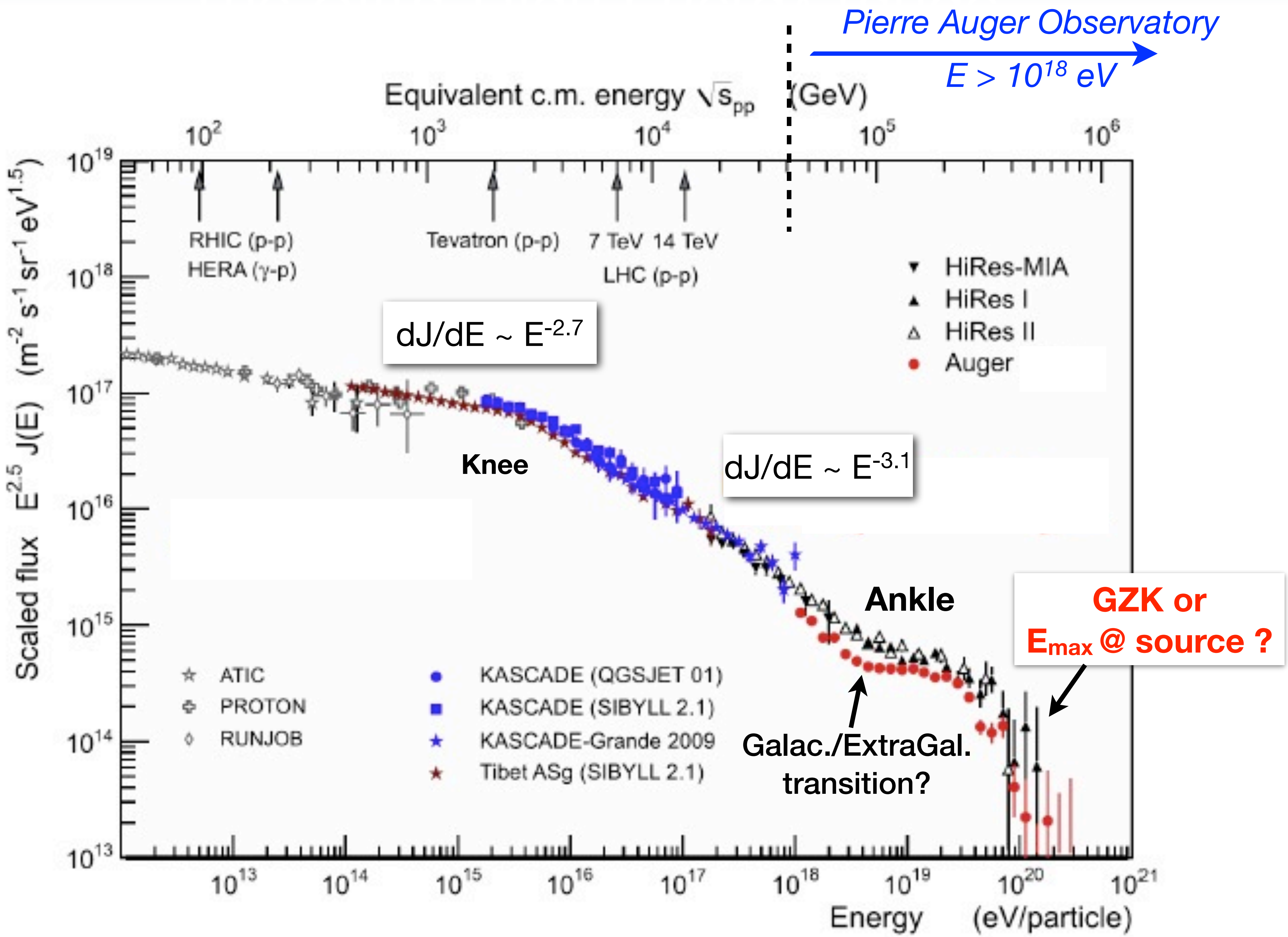
for the Pierre Auger Collaboration

LPNHE, Universitaire Paris 6 and Paris 7

The Ultra-High Energy range



UHE photon production and propagation

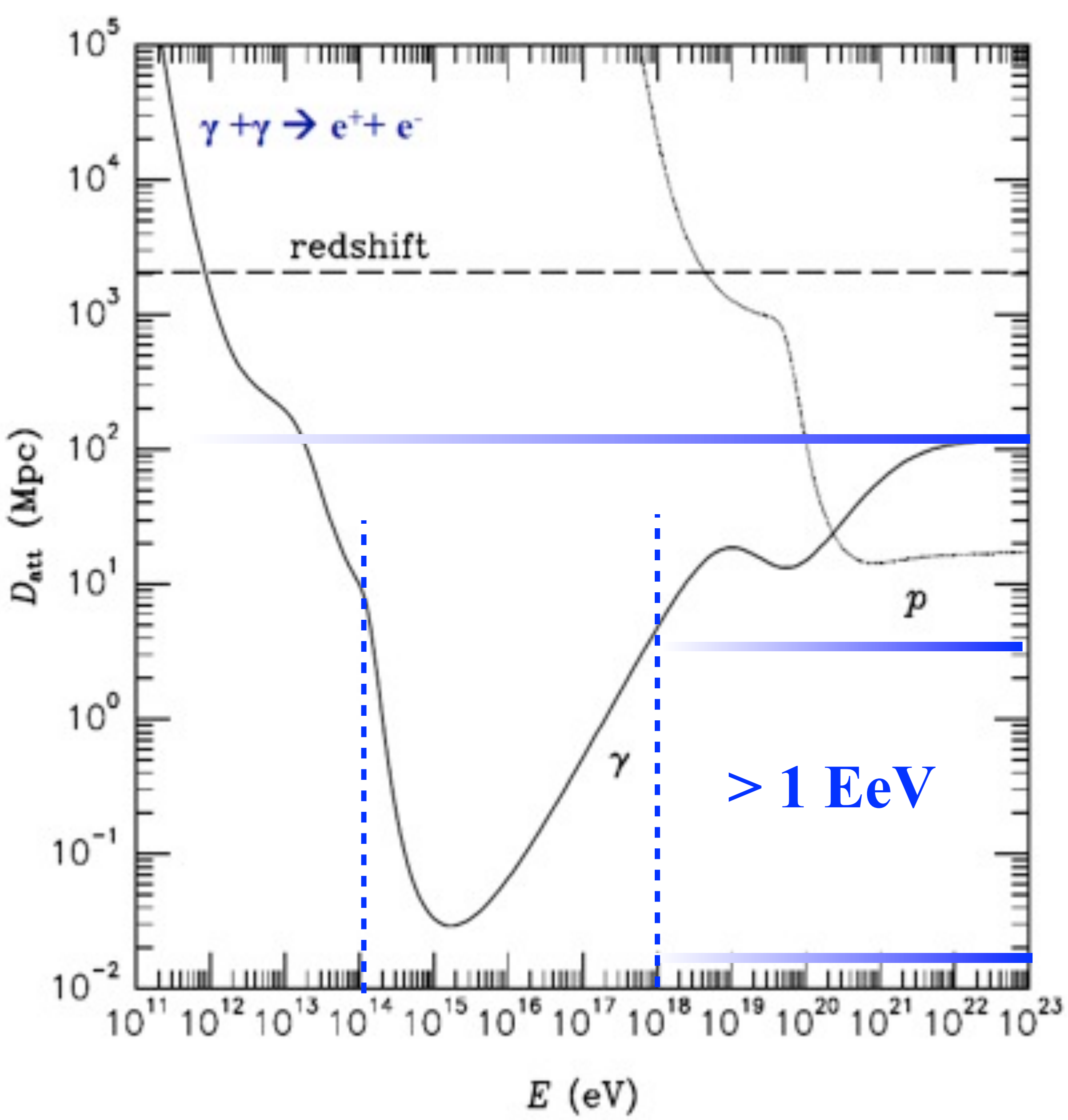
A detectable flux of UHE photons ($E > 10^{18}$ eV) is predicted in different scenarios:

- *photo-pion production (**GZK effect**)*

$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^\pm$$
$$\rightarrow p + \pi^0$$
$$\searrow \gamma + \gamma$$

E_{GZK} ~ 5 x 10^{19} eV
Inelasticity: ~ 20%

- ***top-down models** for the origin of UHE cosmic rays (SHDM, Z-burst,...)*



- Photons interact with EBR via e^+e^- production
- Electrons cool down via ICS

Electromagnetic cascades

← CLOSEST BLAZARS

← CLOSEST AGN

← GALACTIC CENTER

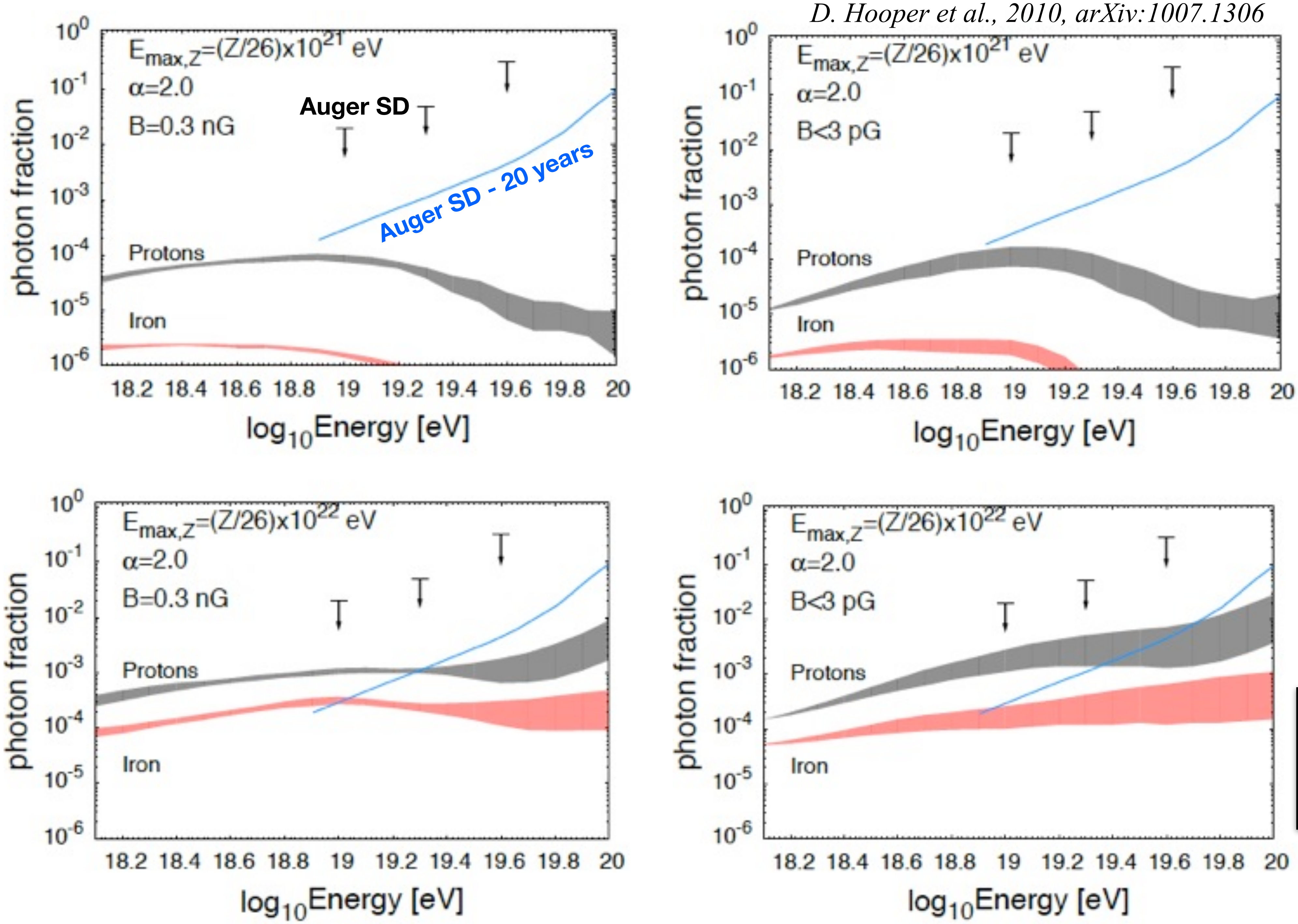
≳ 10^{14} eV photons absorbed on CMB

Expected GZK photon fluxes at Earth

Photon flux predictions sensitive to:

- **source features** (distribution and evolution, injection spectrum, maximum energy, primary types)
- **propagation** (EBL, magnetic fields)

D. Hooper et al., 2010, arXiv:1007.1306



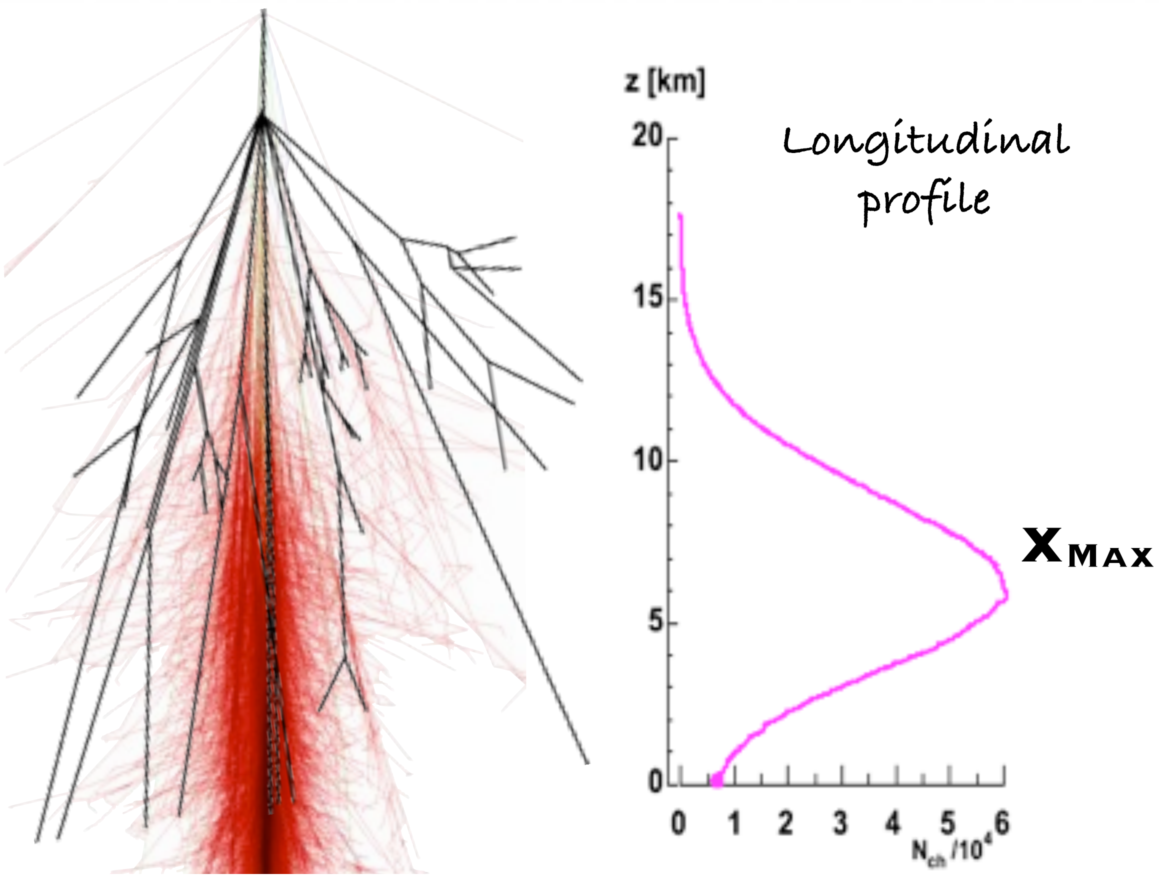
UHE photon flux can constrain the phase space of parameters

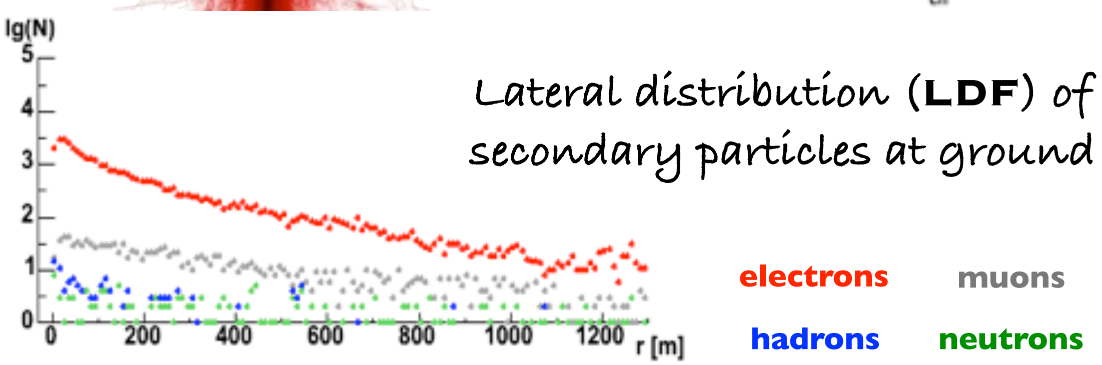
UHE photon search: motivations

Observation/Non-observation of photons:

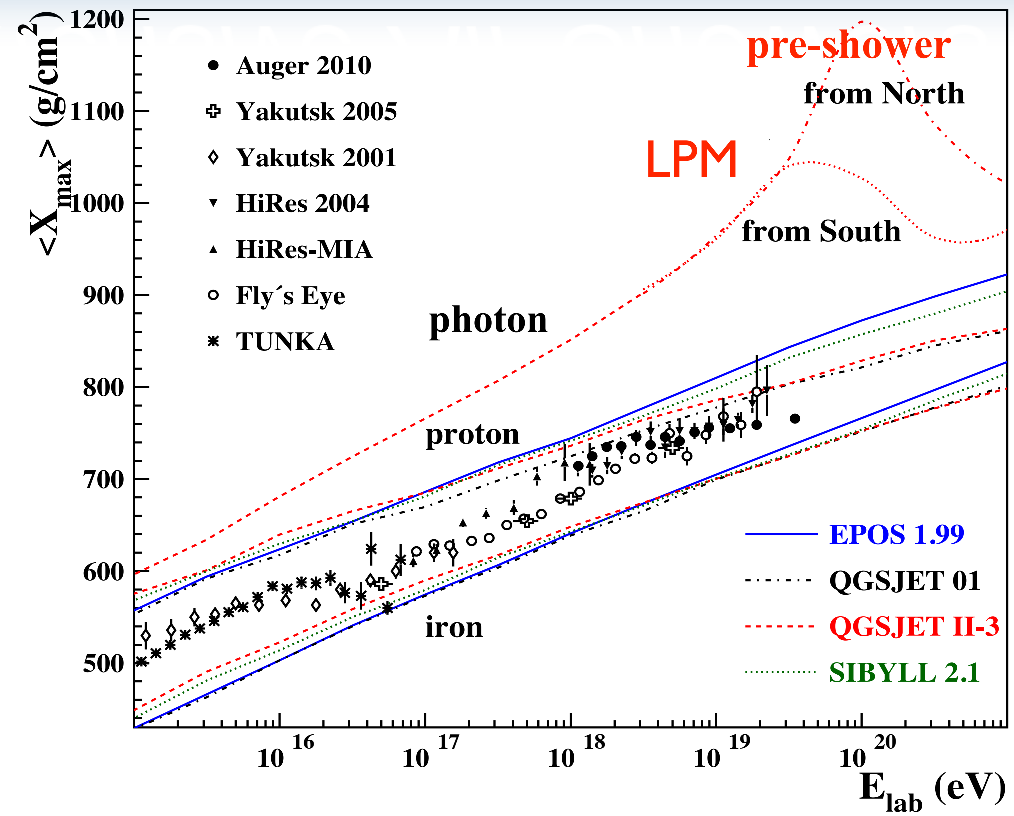
- Independent prove of the **GZK effect** (nature of the observed flux suppression)
- hints/constraints on **astrophysical scenarios**
- Disfavor/constrains **top-down models**
- Open the most extreme window for **astronomy**
- Impact on the measurements of **energy spectrum**, **cross sections**, **mass composition** and possible consequences for **fundamental physics** (LIV).

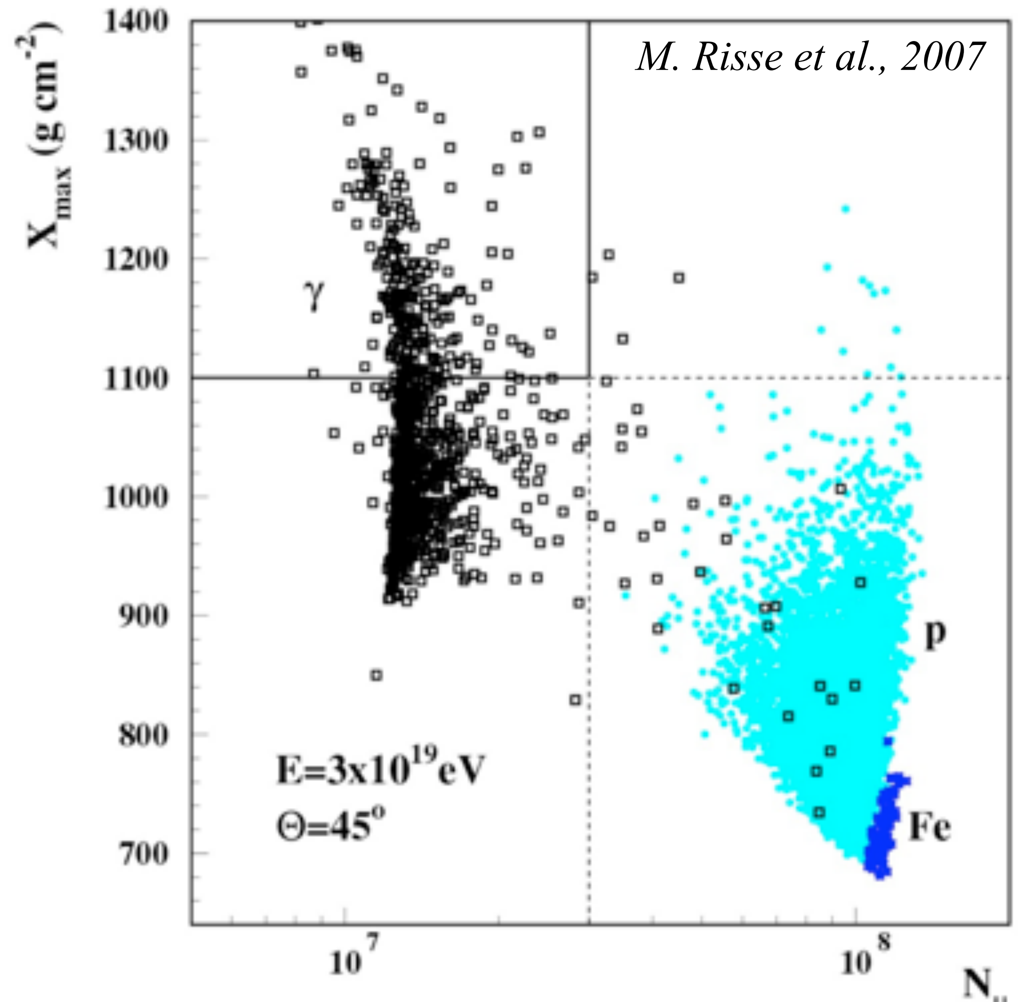
Observation of UHECR: *Extensive Air Showers*





http://www-ik.fzk.de/corsika/





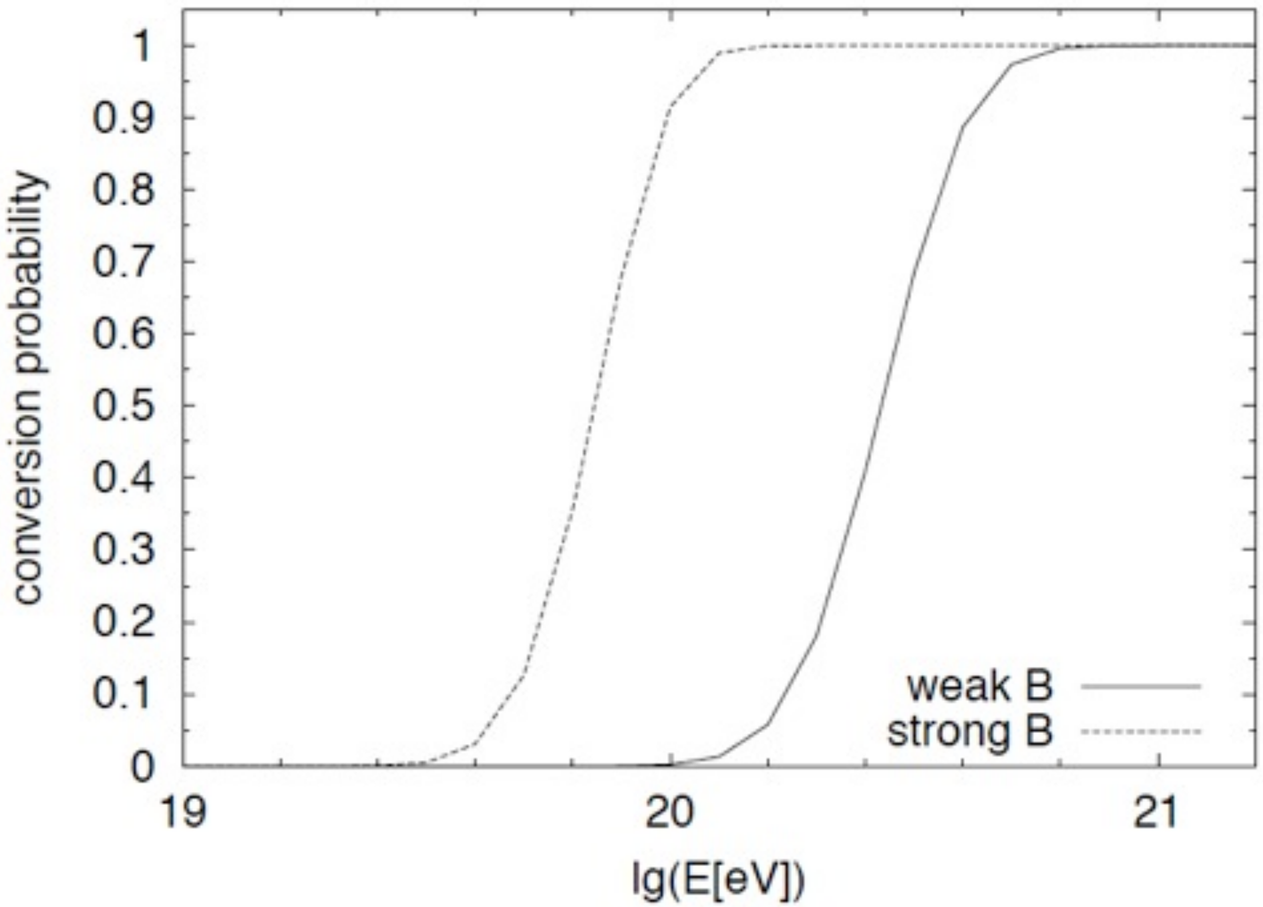
Electromagnetic showers:
- Deeper development (i.e.large X_{max})
- Smaller muon content

Conversion in the geomagnetic field (pre-showering)

Photons above 50 EeV have a large probability to convert into a e^+e^- pair in the magnetic field of the Earth. Instead of a single UHE photon a bunch of particles (**pre-shower**) enters the atmosphere.

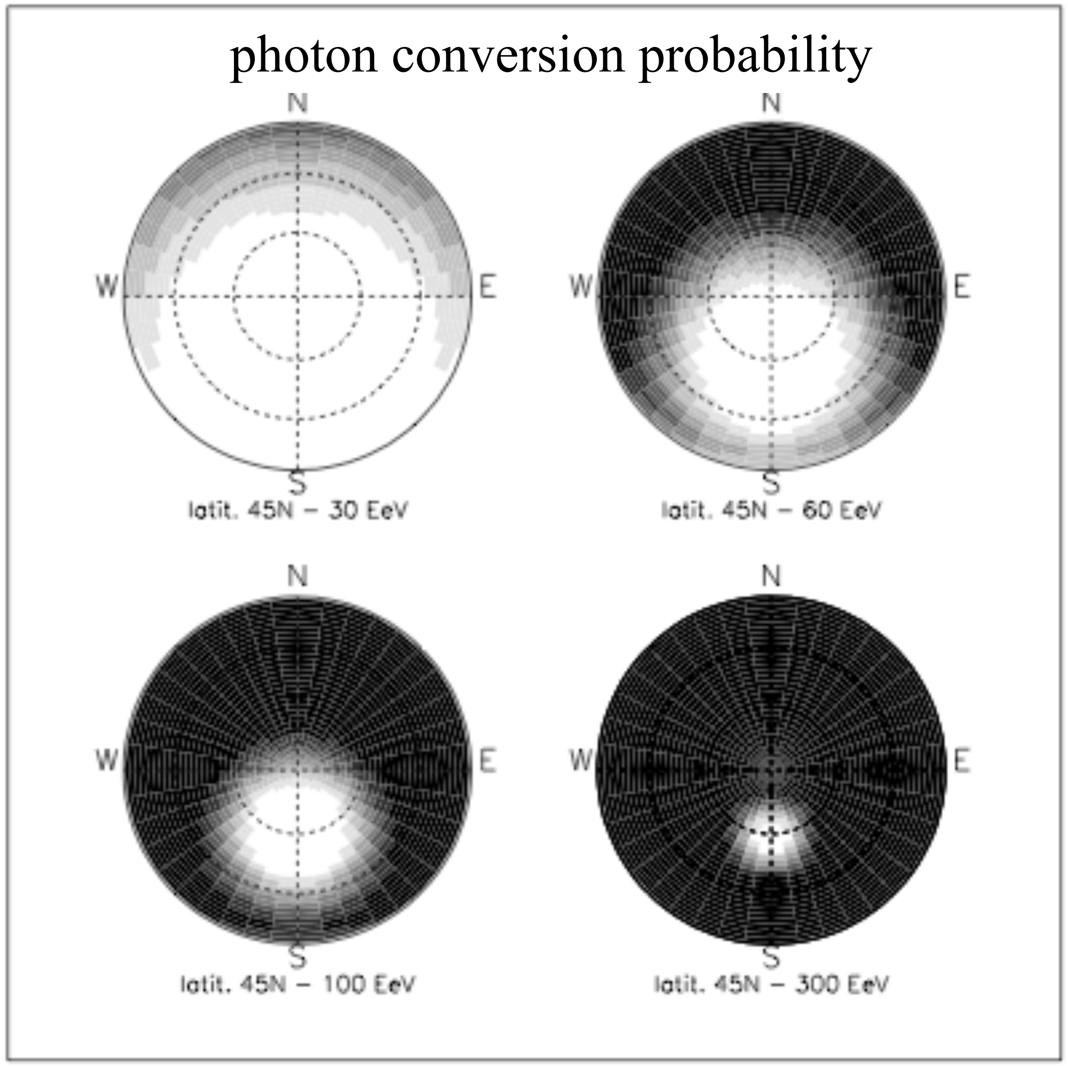
Conversion probability depends on the photon energy and on the transverse component of geomagnetic field

P. Homola et al., astro-ph/0311442 (2003)



At 10^{20} eV: negligible vs ~100% conversion probability, depending on the strength of magnetic fields

X. Bertou et al., Astrop.Part.Phys. 14 (2000)

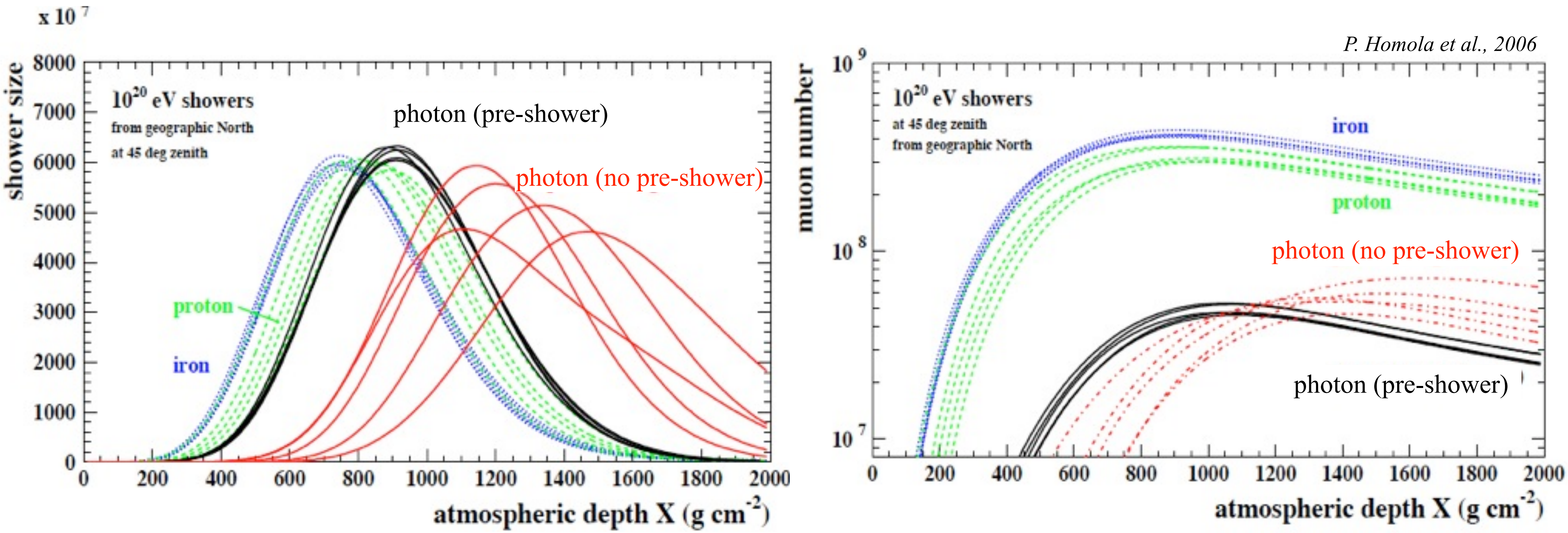


Photon conversion probability as a function of direction for increasing energy

Pre-shower: impact on EAS development

The spread of the pre-shower particles in transverse distance and arrival time at the top of the atmosphere is negligible compared to the EAS and below the resolution of current experiments.

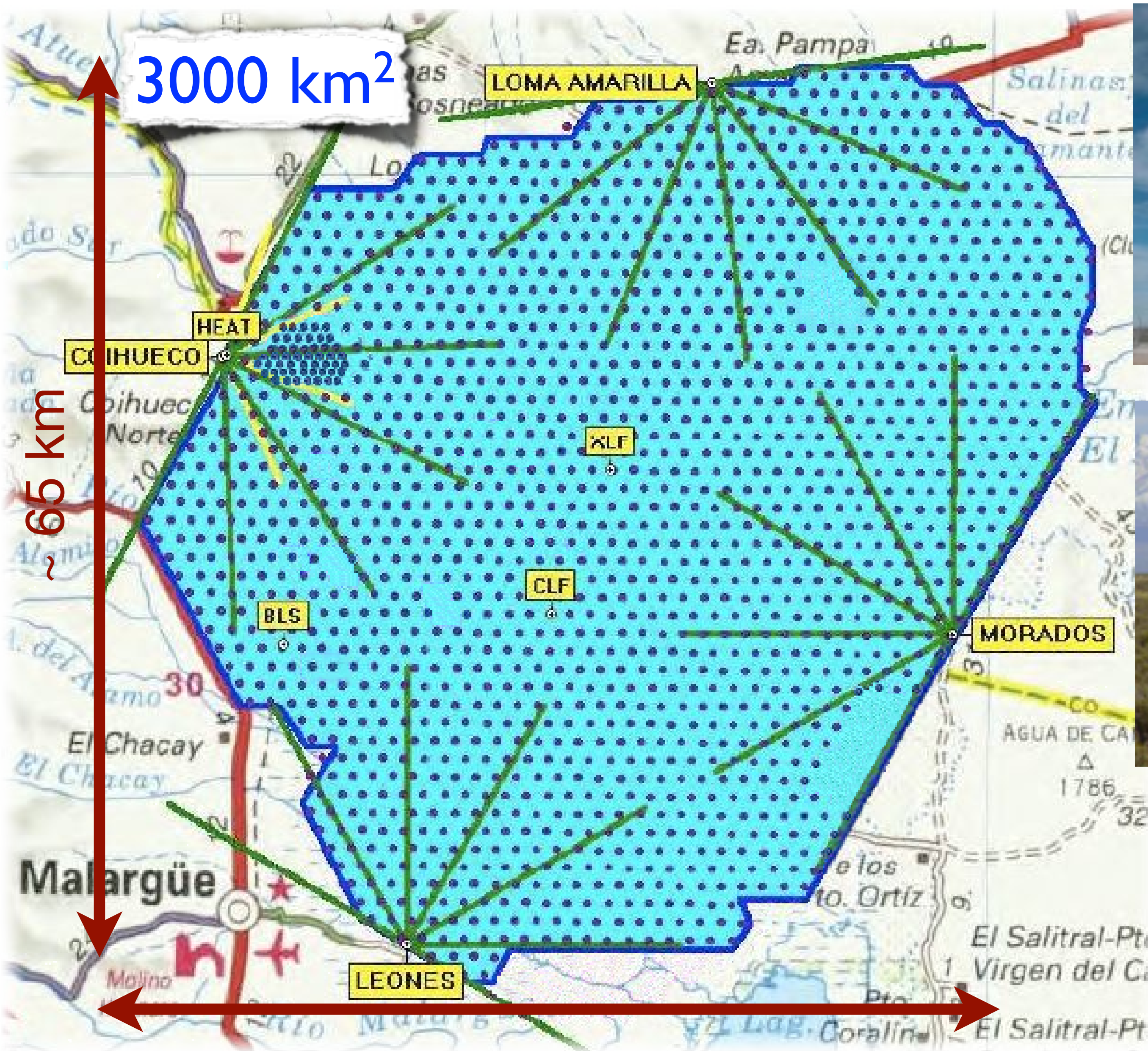
➡ Pre-shower observed as a one single event.



- Smaller X_{max} and fluctuations
- Fewer muons and smaller fluctuations

converted showers more similar to proton

The Pierre Auger Observatory

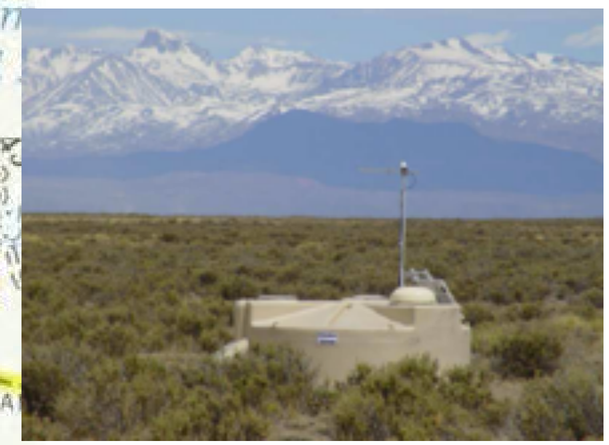


~ 65 km

Malargüe (Argentina), 1400 m a.s.l.

FD completed in May 2007
SD completed in June 2008

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



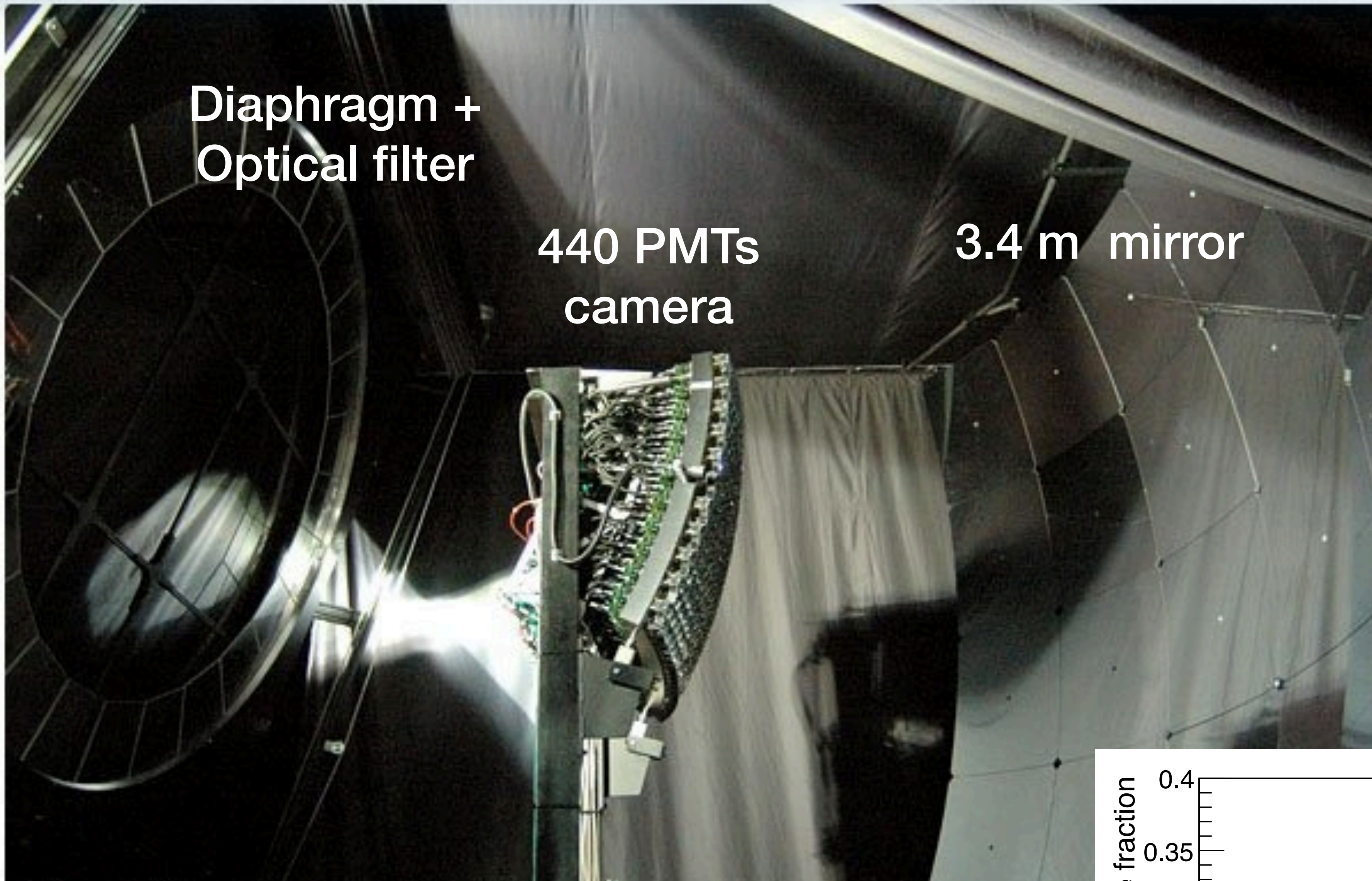
Surface Detector array (SD)
1600 + 60 water Cherenkov stations, 100% duty cycle

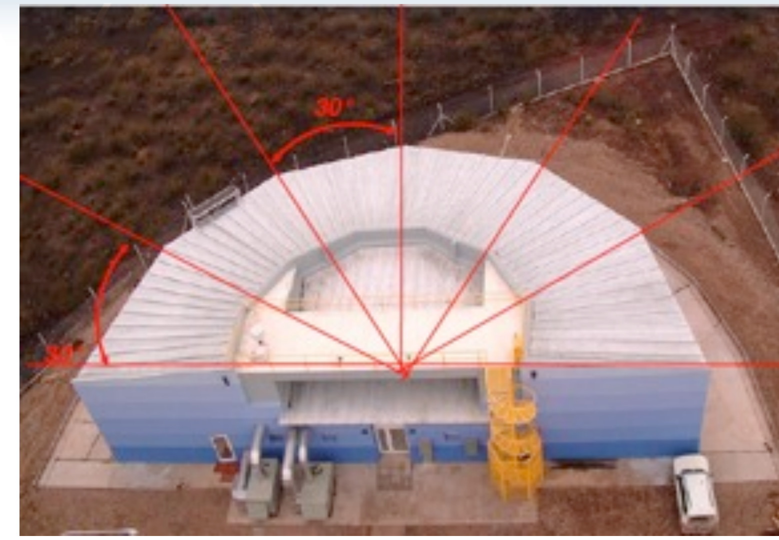
FD and SD combined in *Hybrid design*

INVESTIGATE COSMIC RAYS WITH E $\gtrsim 10^{17}$ EV

- Energy spectrum
- Mass composition/photons
- Arrival direction

The fluorescence detector (FD)

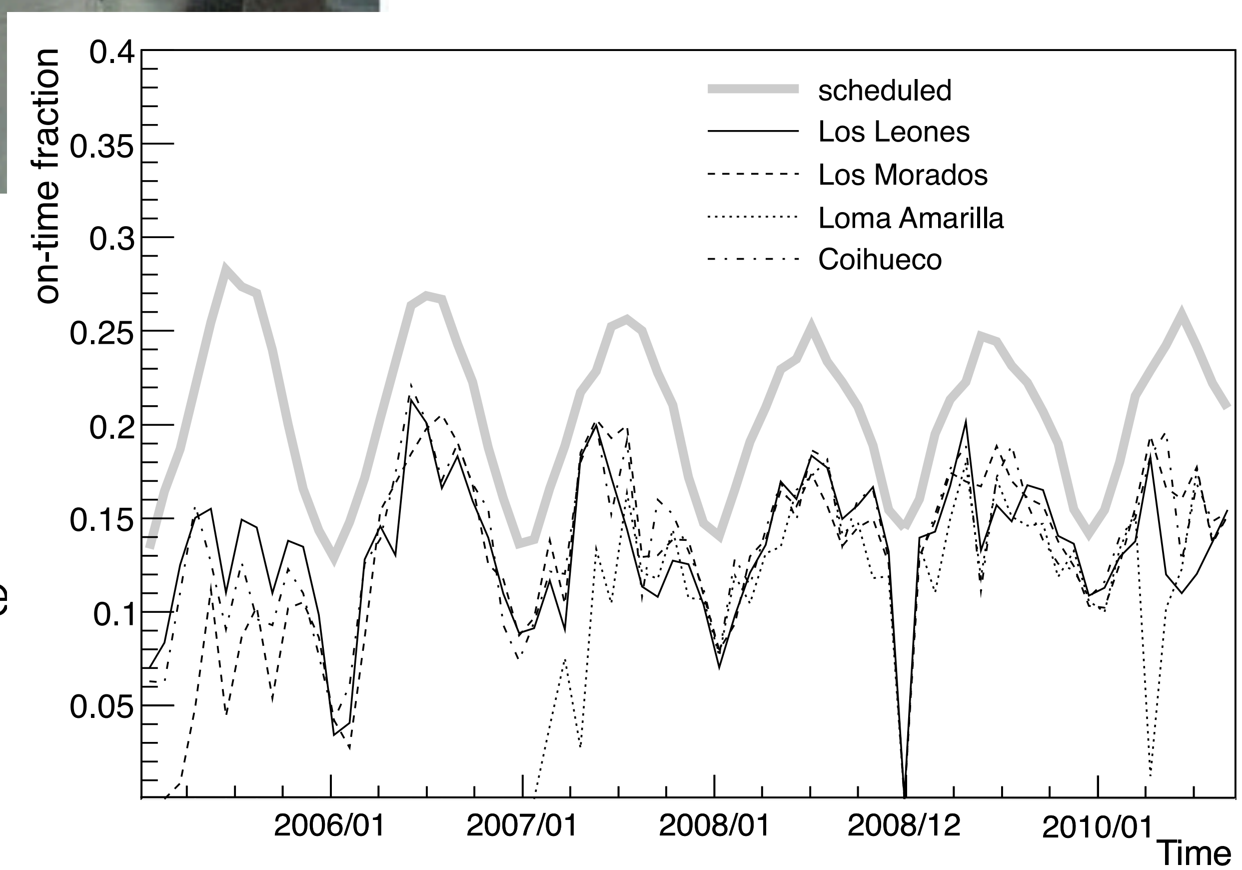




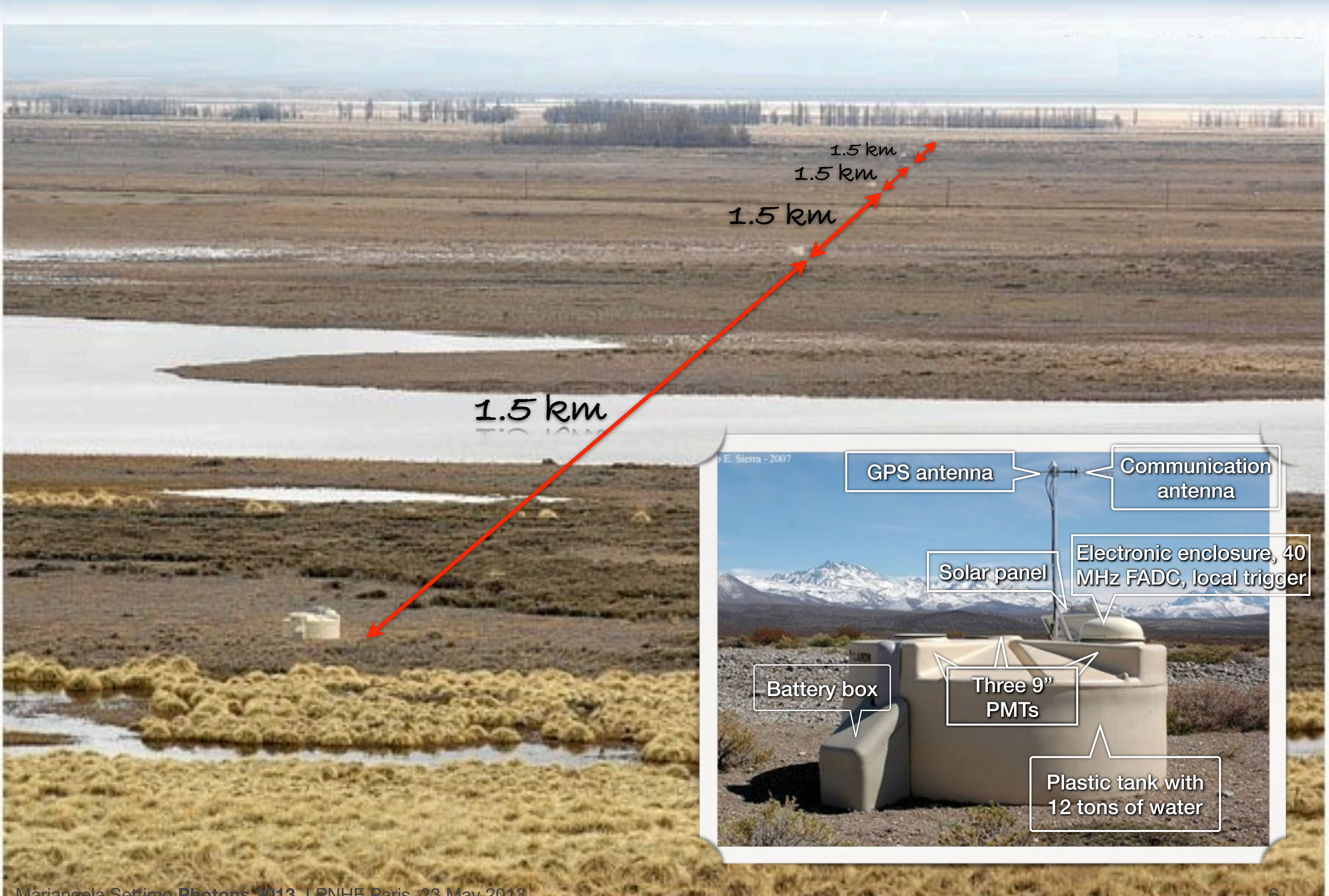
- **24 telescopes in 4 sites**
- **Field of view:**
  0-30º in elevation
  0-180º in azimuth

duty cycle ~ 10 - 15%

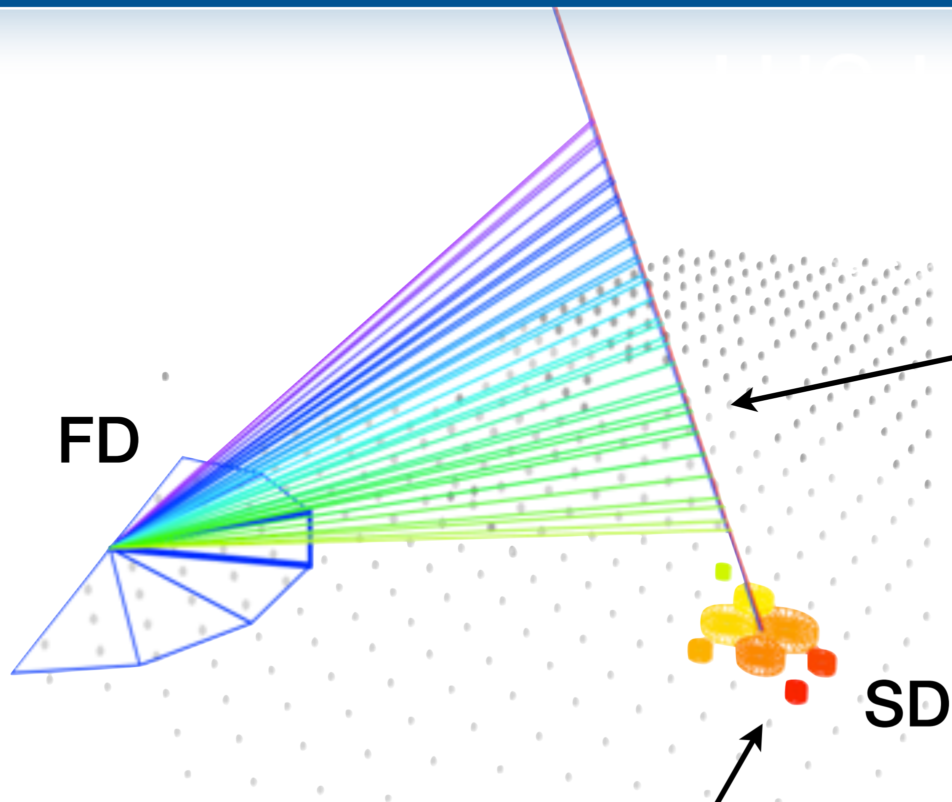
- DAQ ***scheduled:*** clear and moonless nights
- ***on-time fraction:*** weather conditions + DAQ, de and communication system efficiencies

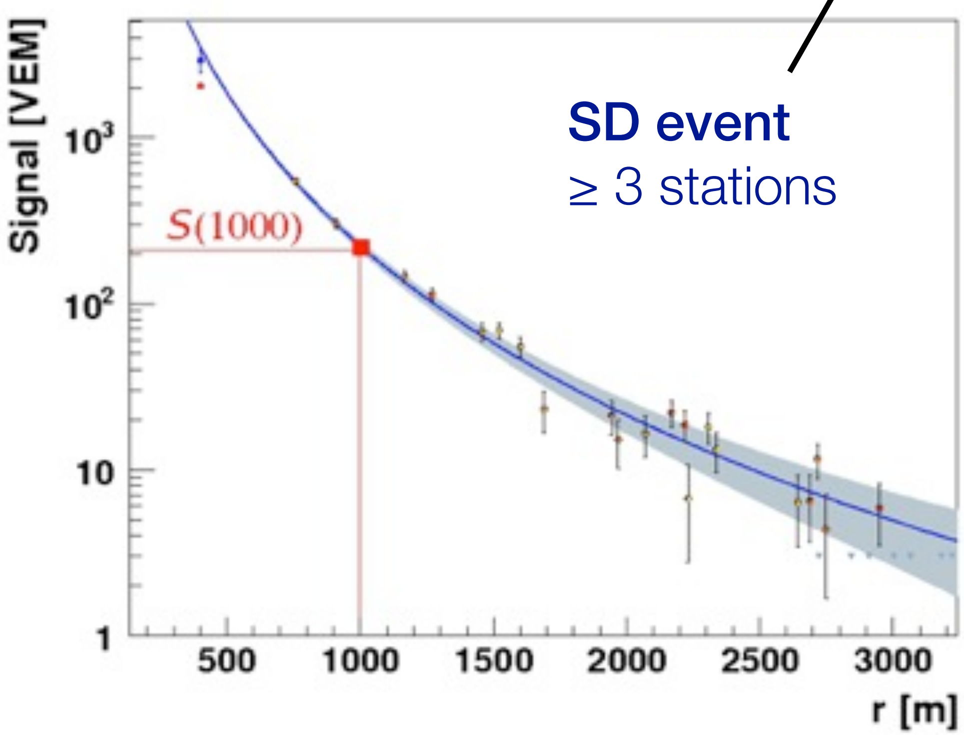


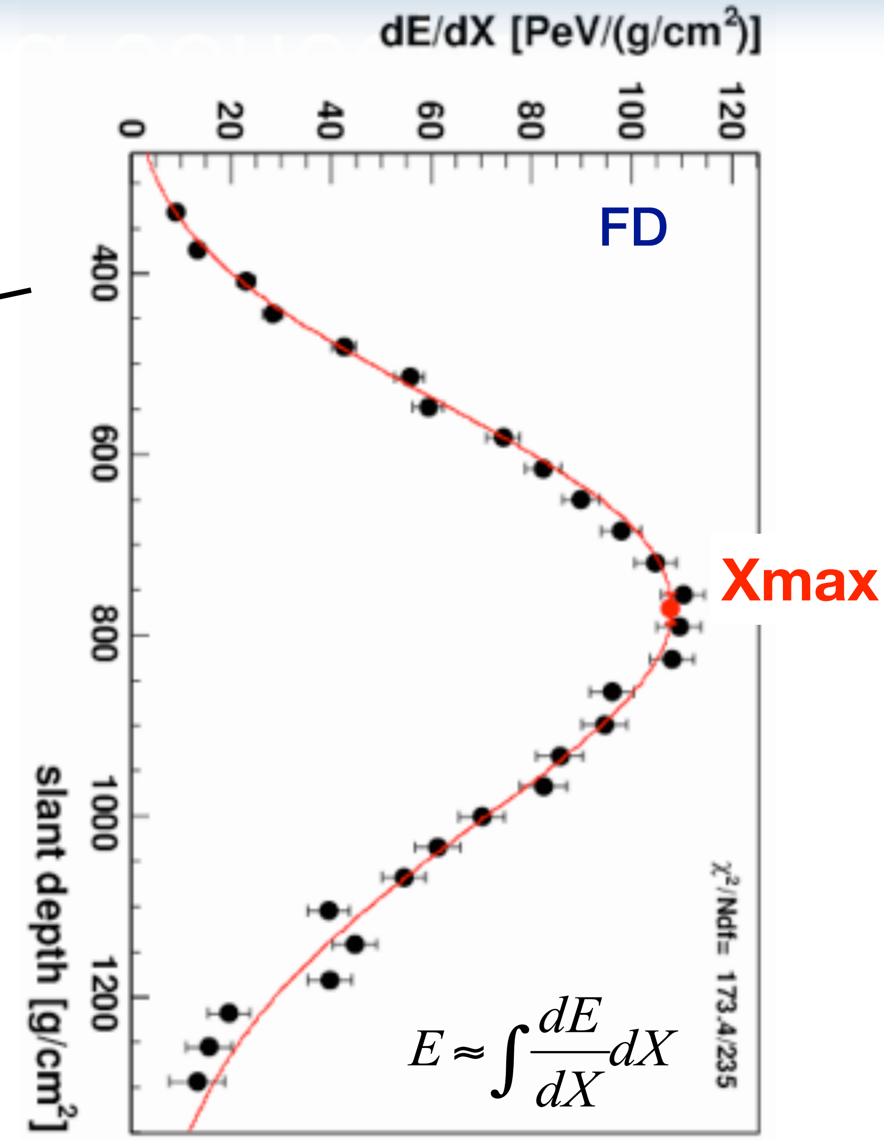
The surface detector (SD)



The hybrid concept







- observation of the *longitudinal profile*
- calorimetric energy measurement

- *lateral distribution* of secondary particles
- signal at 1000 m **S(1000) ➔ energy**

Hybrid event (1FD + at least 1 SD)

- *accurate energy and direction measurements*
- *complementary mass sensitive parameters*
- *calibration of the energy scale for SD events*

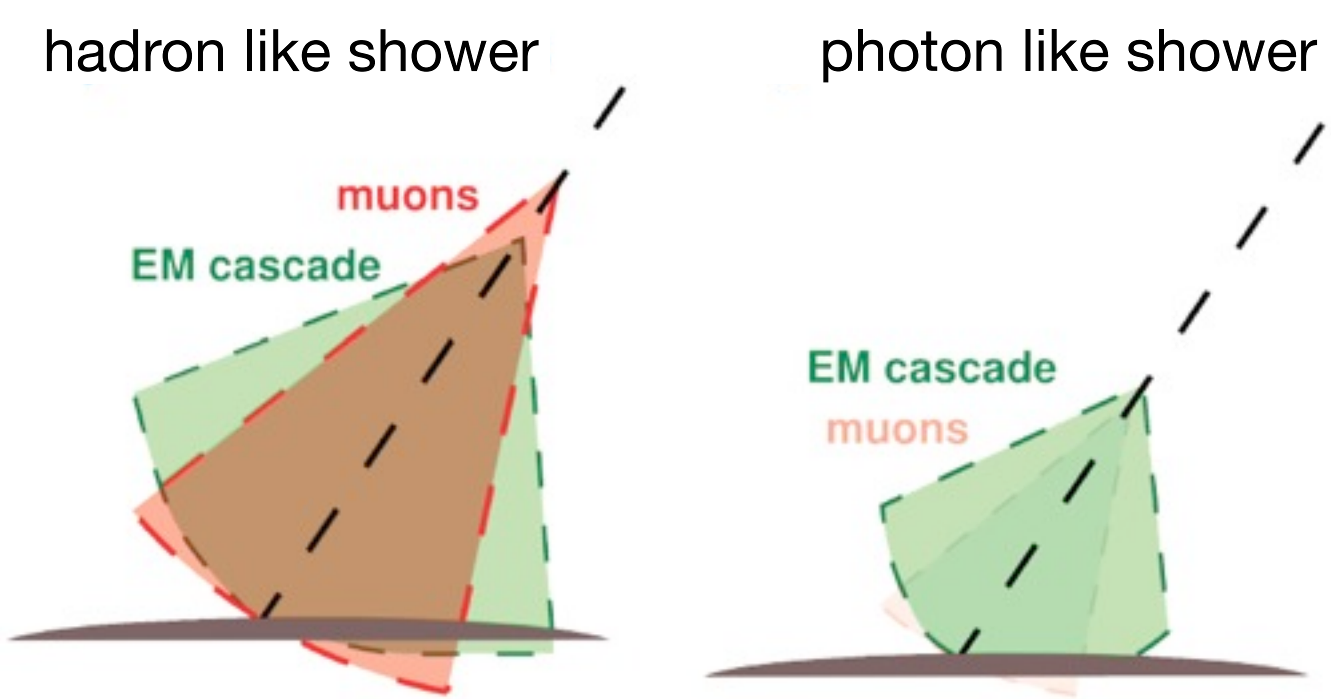
Search for photons with SD

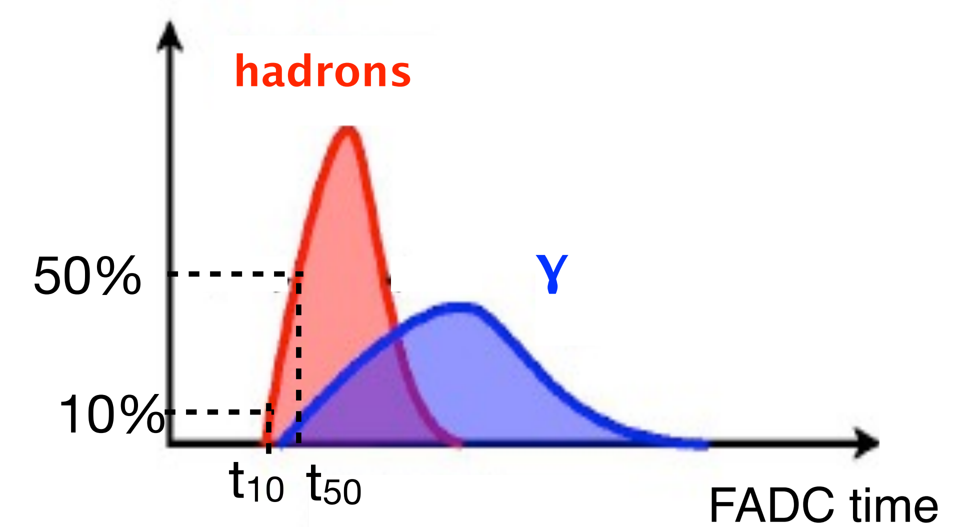
Identification of photon induced showers using SD events based on:

- **em/muon competition**
  larger spread of the arrival time for em secondary particles
- **shower age**
  deeper shower have larger curvature

SMALLER RADIUS OF CURVATURE

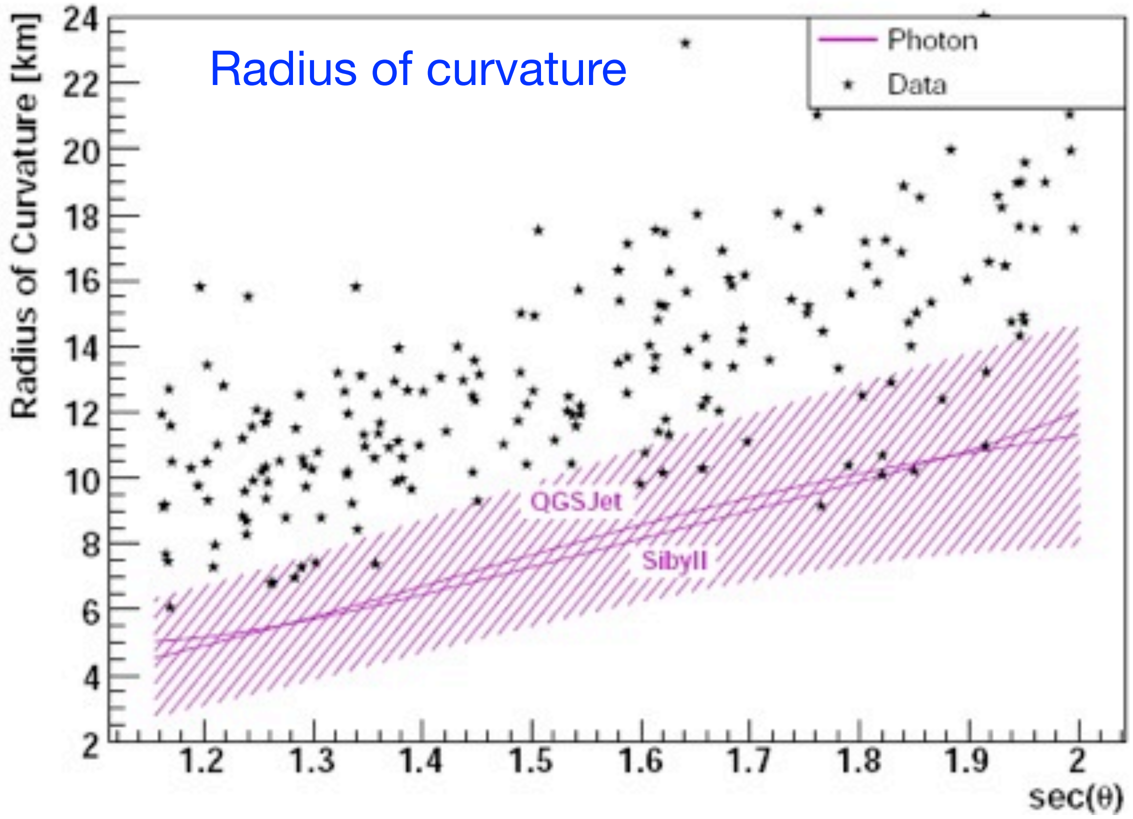
LARGER RISETIME





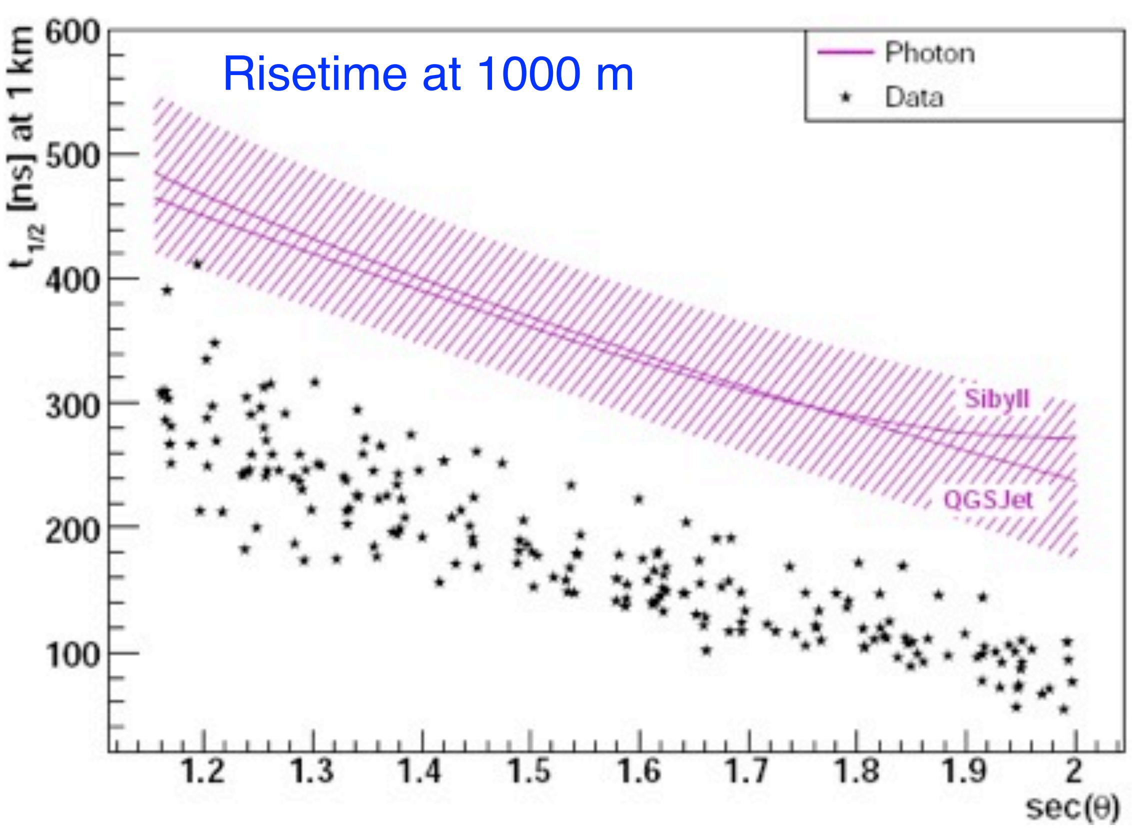
Risetime: $t_{1/2} = t_{50\%} - t_{10\%}$

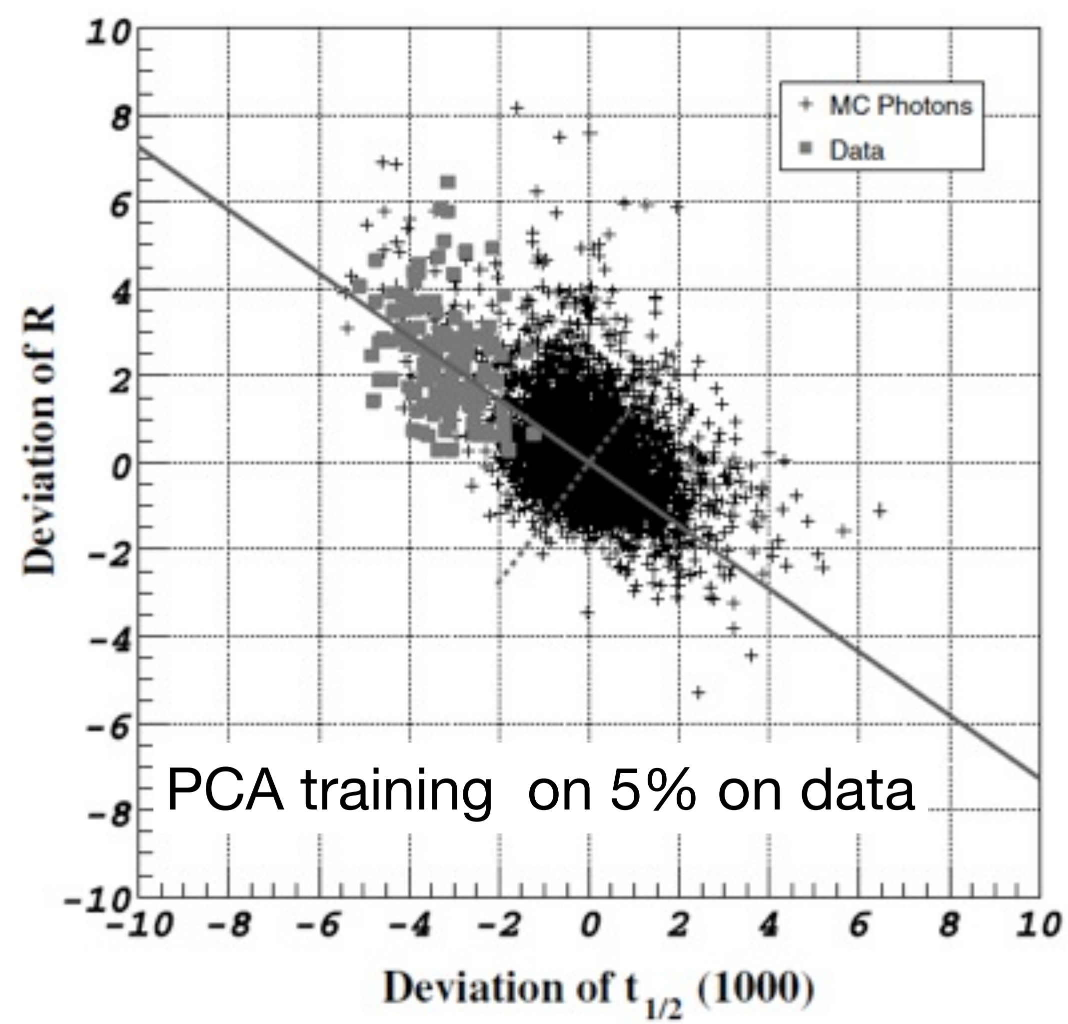
Search for photons with SD: observables



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

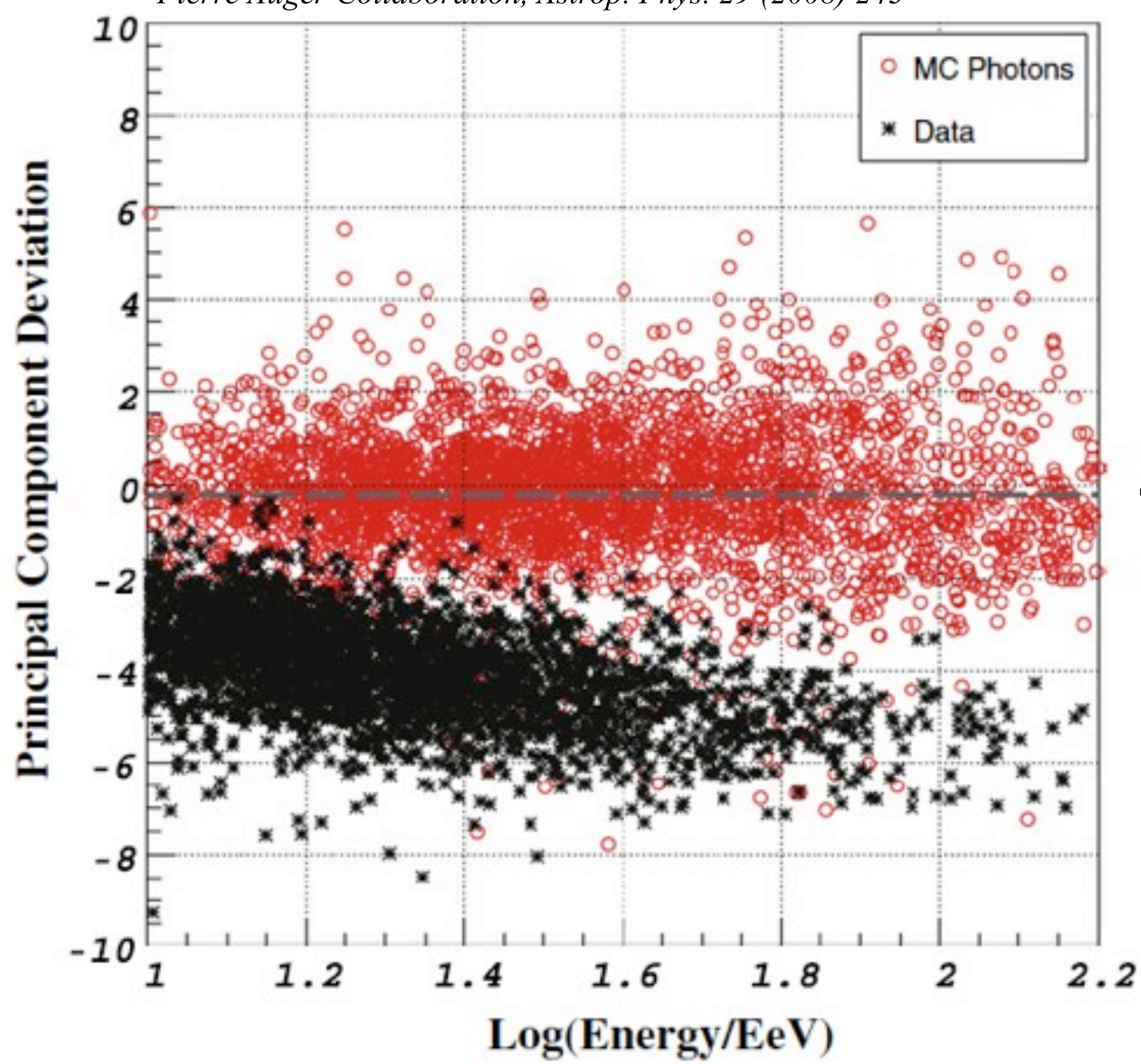
Deviations of data from the mean value of R and $t_{1/2}$ expected for photon showers combined with a **Principal Component Analysis**





Search for photons with SD: PCA

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



Data sample: Jan 2004 - Dec 2006

- \> 4 triggered detectors with 10 VEM signal
- impact point within the array
- 30° < zenith < 60°

A priori cut at photon median:
candidate if above!

No photon candidates found

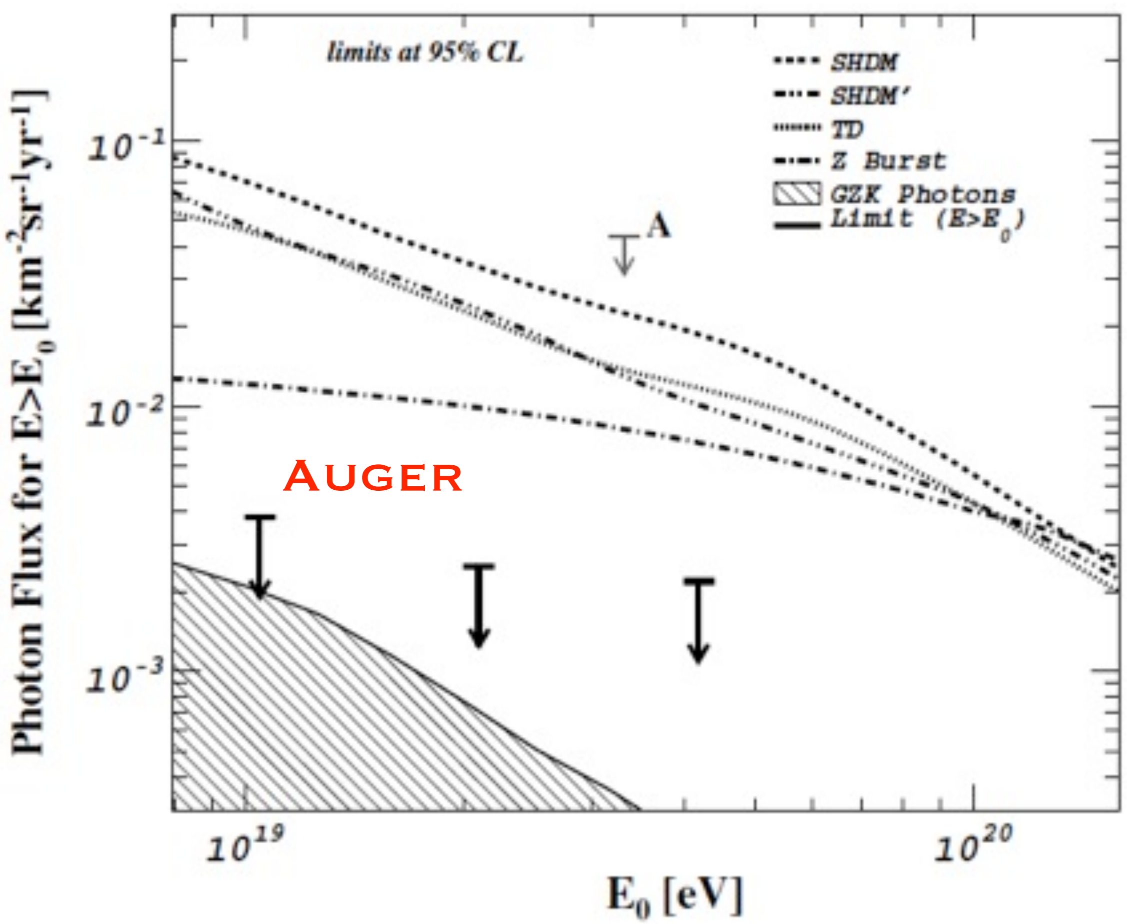
$$\Phi_{\mathrm{CL}}(E > E_{\mathrm{min}}) = \frac{\mathcal{N}_{\gamma}^{\mathrm{CL}}(E_{\gamma} > E_{\mathrm{min}}) \times \frac{1}{f} \times \frac{1}{\varepsilon}}{0.95A}$$

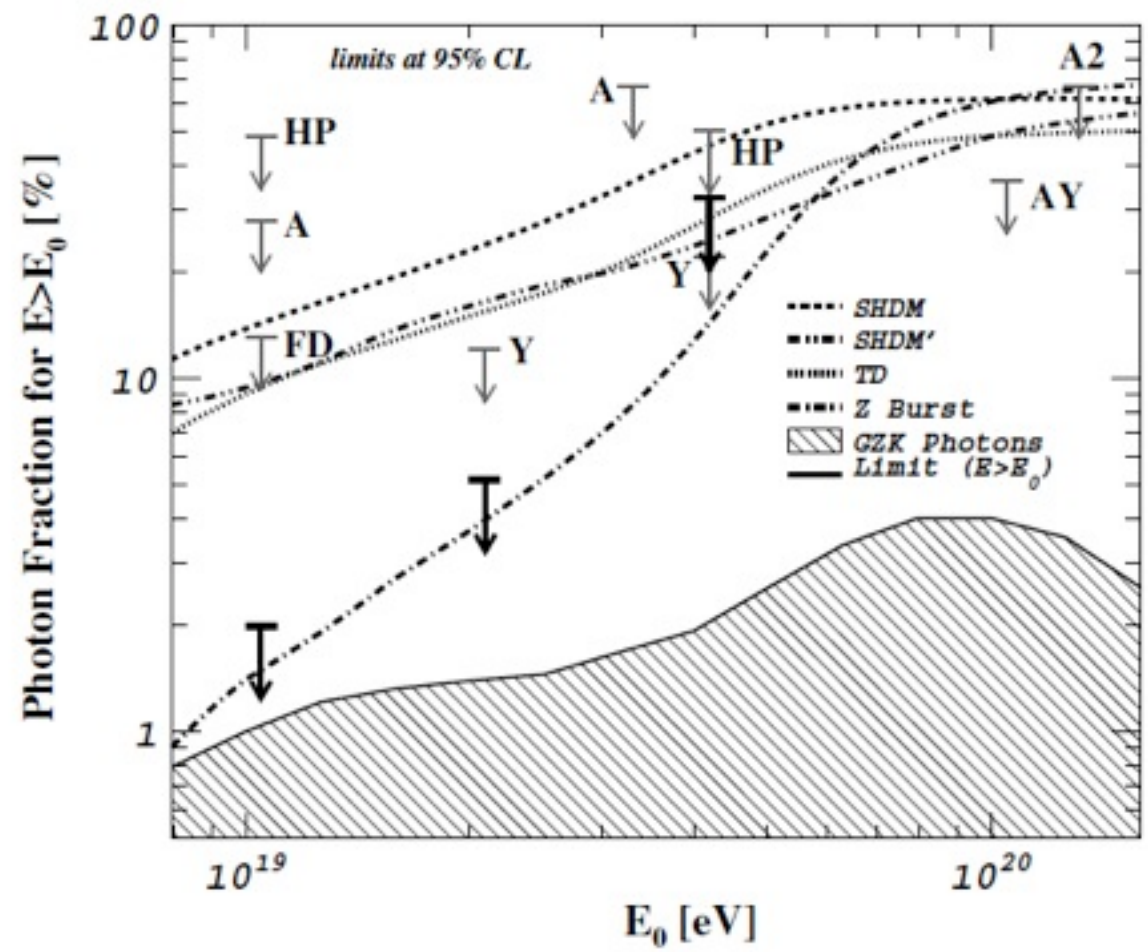
$$\mathscr{F}_{\mathrm{CL}}(E > E_{\mathrm{min}}) = \frac{\mathcal{N}_{\gamma}^{\mathrm{CL}}(E_{\gamma} > E_{\mathrm{min}}) \times \frac{1}{f} \times \frac{1}{\varepsilon}}{N_{\gamma}(E_{\gamma} > E_{\mathrm{min}}) + N_{\text{non-}\gamma}(E_{\text{non-}\gamma} > E_{\mathrm{min}})}$$

Upper limits on photon flux/fraction

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

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





E_{min}	$N(E_\gamma > E_{min})$	N_γ	$\mathcal{N}_\gamma^{0.95}$	$N_{non\text{-}\gamma}$	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

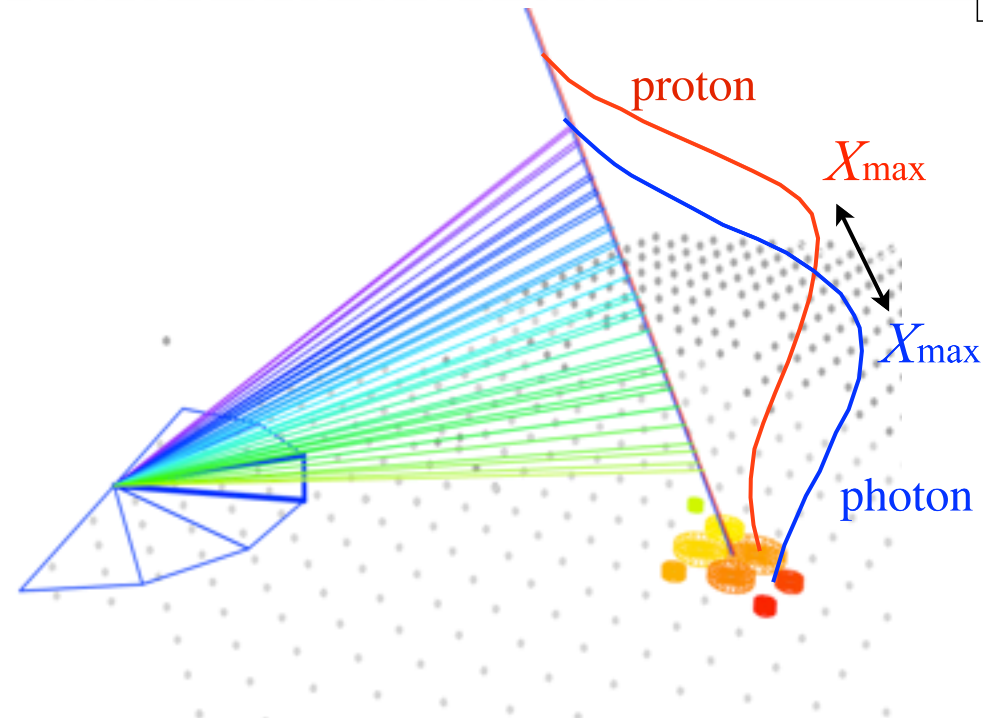
TOP-DOWN MODELS DISFAVORED

Photon search: the hybrid approach

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

- **FD:**
  - **Deeper development of the air showers**

→ **Larger X_{max}**



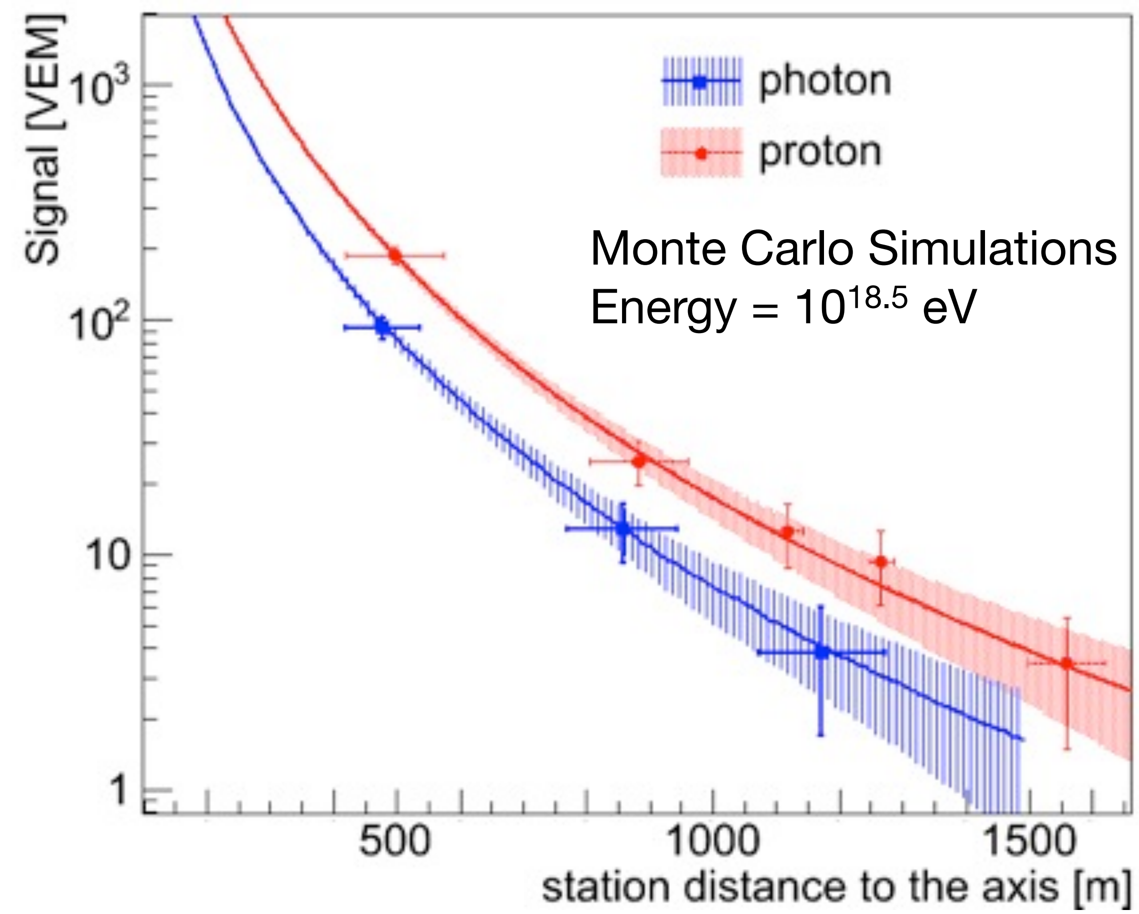
- **SD:**
  - **Smaller detected signal at a given distance**
  - **Fewer triggered stations**

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

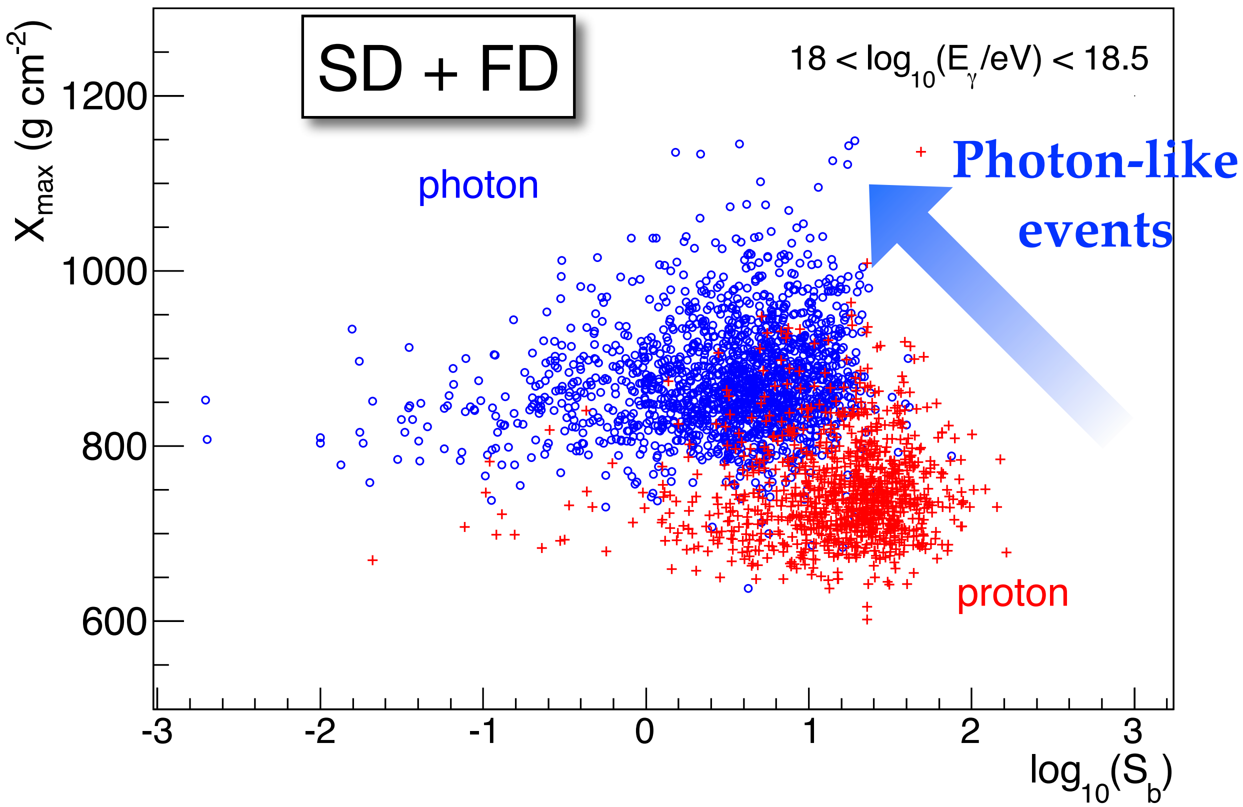
S_i : station signal [VEM]
R_i : station distance to the shower axis [m]

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

→ **Smaller S_b**



Search for photons with SD

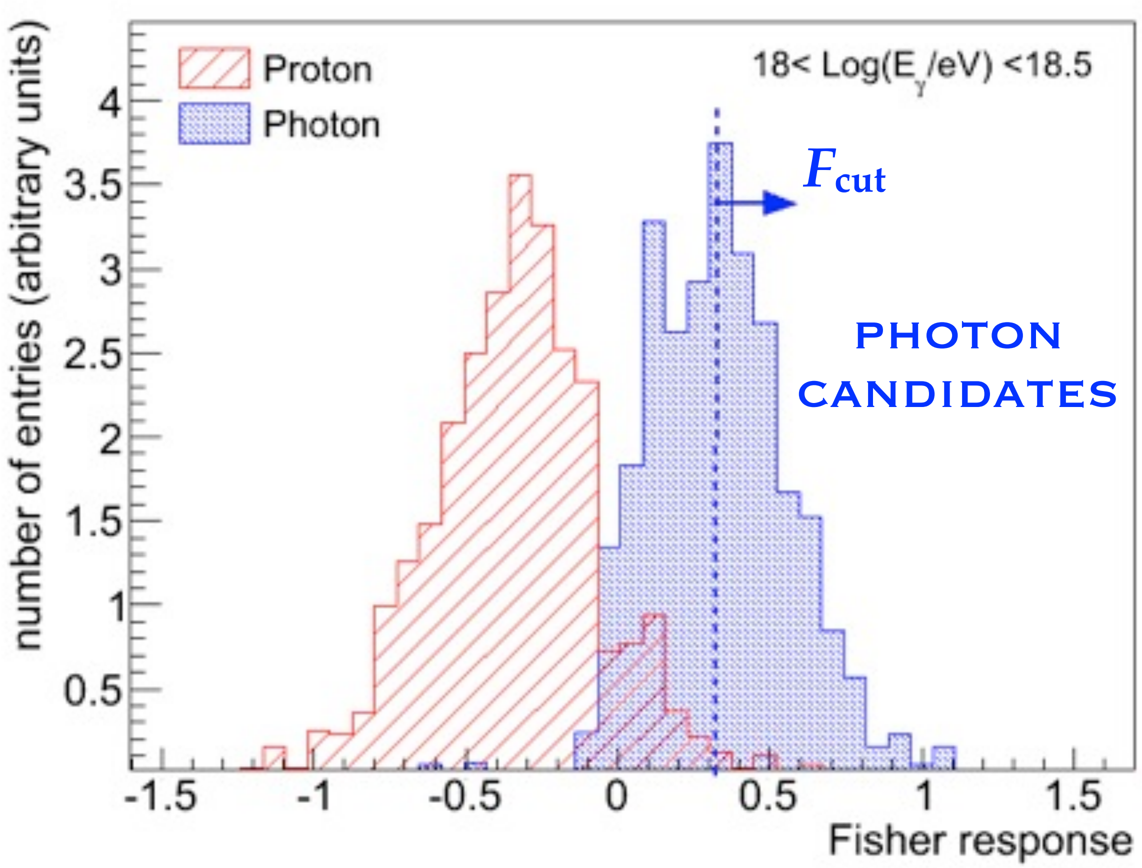


Reconstruction Level

- Good **geometry** and **longitudinal profile**
- Zenith angle < 60°
- **X_{max} observed** in the FD field of view

Reliability of X_{max} and S_b

- Time periods with **clouds** rejected
- At least 4 **active stations** within 2 km from the shower axis



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%

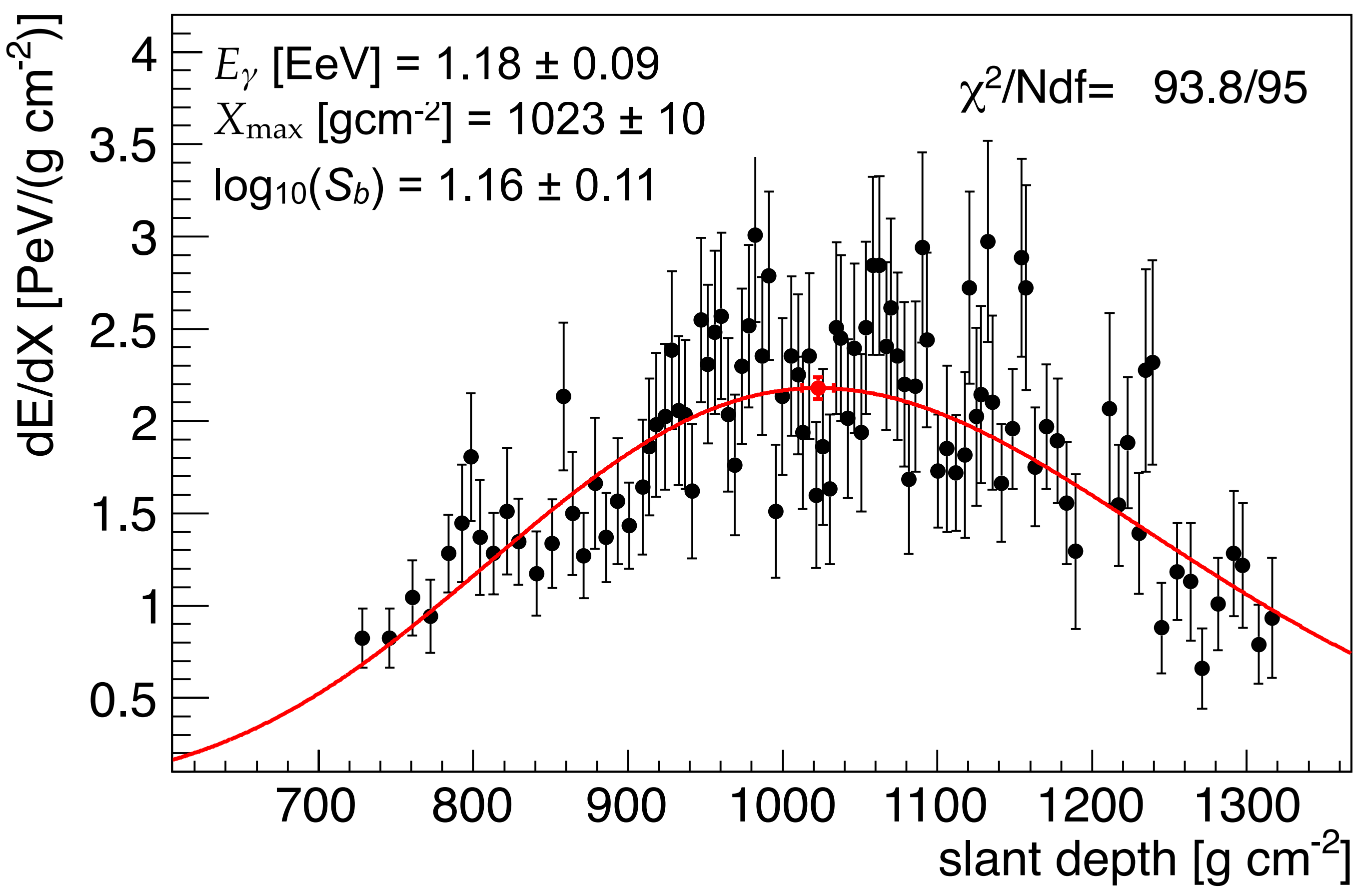
M.S. for the Pierre Auger Collaboration, ICRC 2011, arXiv: 1107.4805

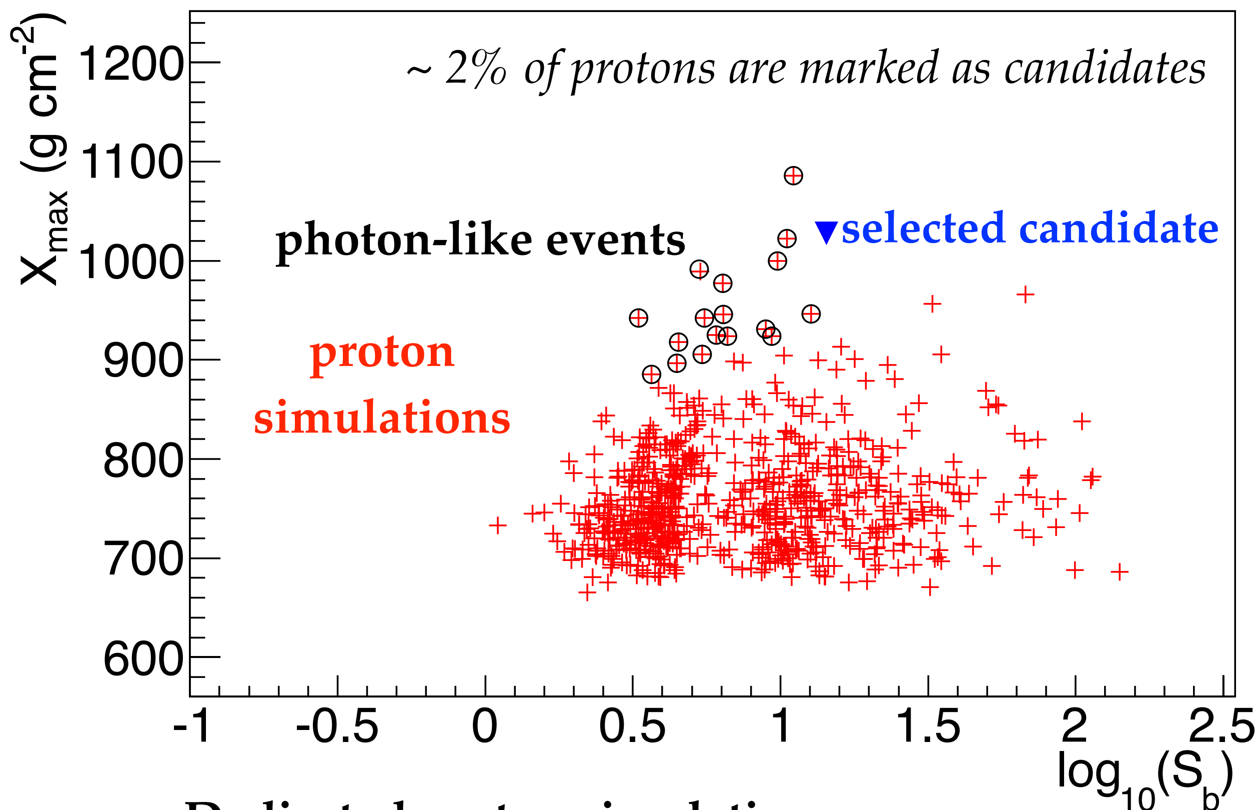
Photon identification using hybrids

Hybrid data
JAN 2005 - SEP 2010

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

EXAMPLE OF A SELECTED CANDIDATE





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

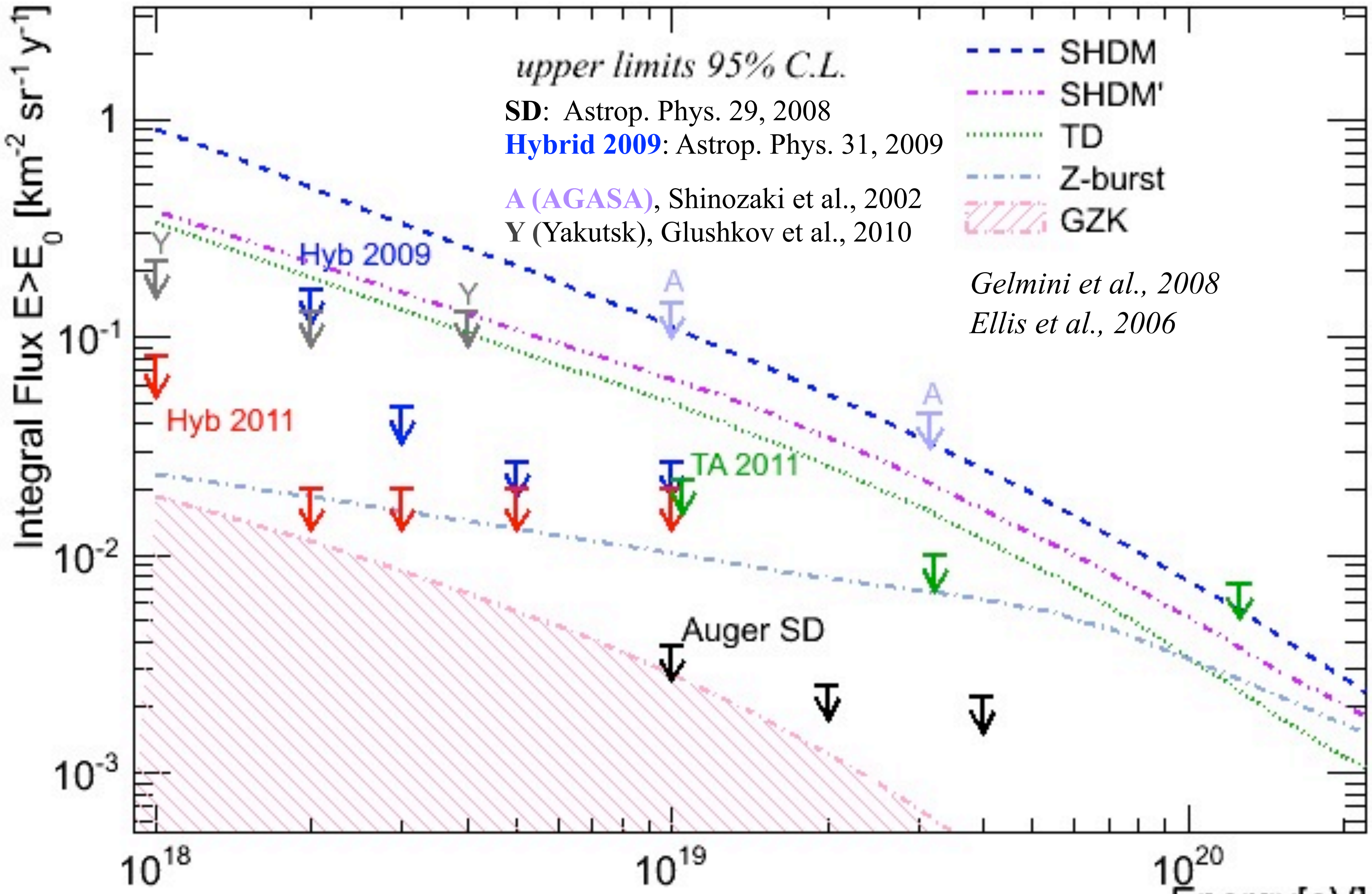
Number of candidates compatible with the expected nuclear background and additionally checked with dedicated simulations for each candidate

Upper Limits to the Integral Photon Flux:

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

exposure: time dependent MC simulations

Upper limits on 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}

Impact of systematic uncertainties

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

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

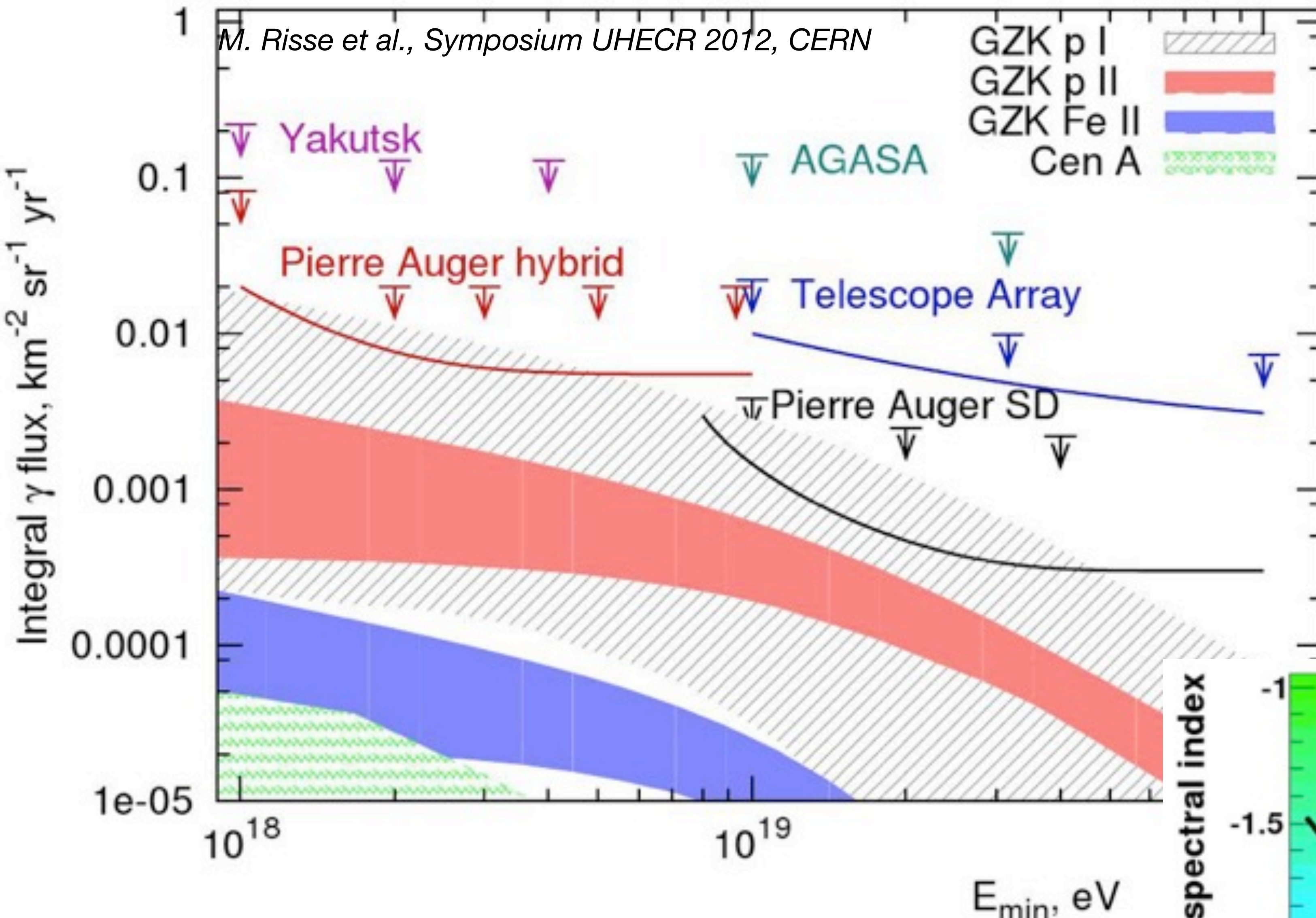
$$^{+15\%}_{-36\%}\ (E_0 > 1\ \mathrm{EeV})$$

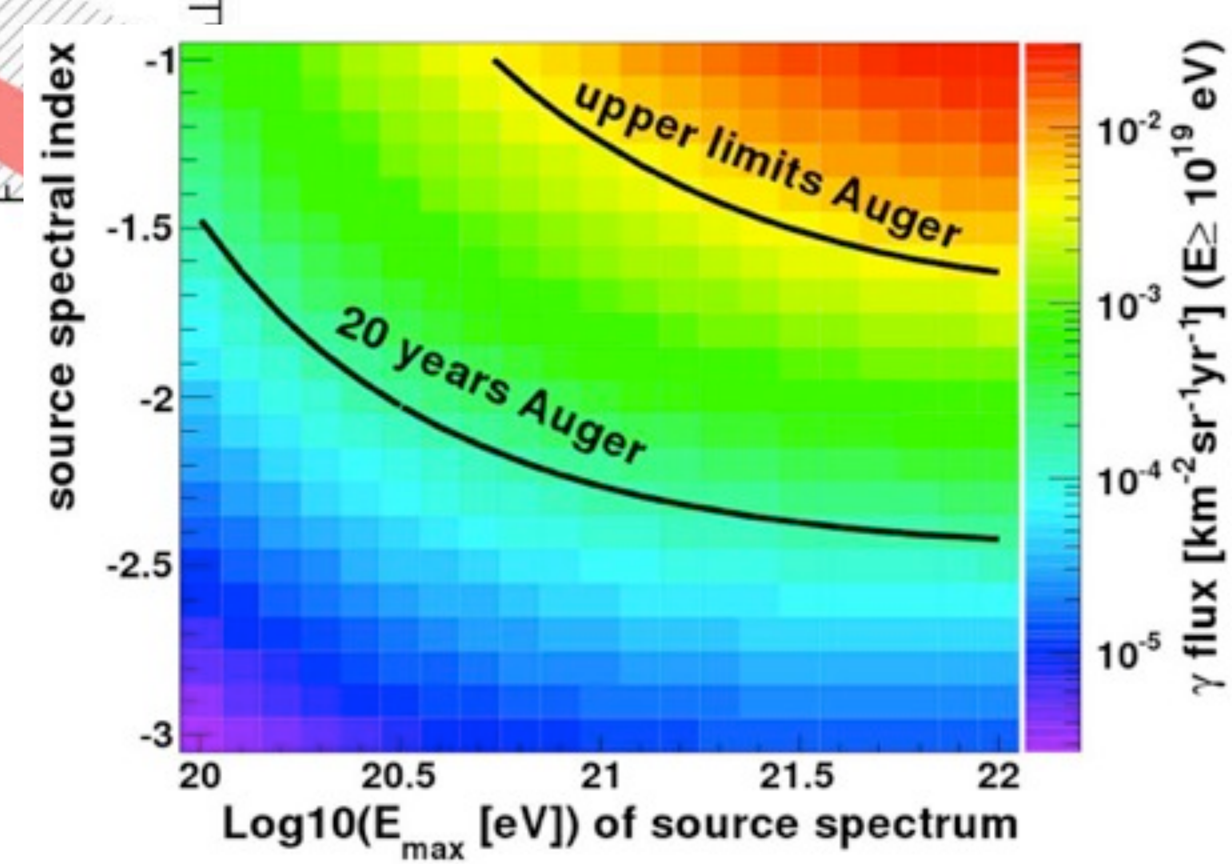
Upper limits to the integral photon fraction assuming the **Auger Spectrum**

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

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

Expected sensitivity





for the current analyses and
assuming no photon candidates

Photon observation possible
(in optimistic models)

Summary and outlook

The search for primary photons above ~1 EeV is relevant in the framework of cosmic ray and particle physics at the highest energies

- UHE photons as decay products (GZK-effect, top-down models)
  confirm on **GZK-effect** with hints on the nature of **flux suppression**, constrains **astrophysical scenarios**, confirm **geomagnetic conversion**

- photons signatures:
  deeper XMax & **fewer muons** (hence: **larger curvature, larger risetime, steeper LDF**, ...)

Search for photons with independent techniques:

NO PHOTONS IDENTIFIED SO FAR

- *Upper bounds on the integral photon fraction: 0.5% above 1 EeV and a ~ 2 % at 10 EeV*

- *top-down models disfavored*
  - **GZK region** within reach in the next few years (in the optimistic prediction)
  - Provide tighter constraints for models and allow reducing systematic uncertainties on **mass composition**, **energy spectrum** and **cross section** measurements

Backup slides

The Landau, Pomerachuk, Migdal (LPM) effect

- **electromagnetic interactions reduced** at high energy (≳10^{19} eV)
- **asymmetric energy** distribution favored
- increases with **air density and particle energy** (secondary interactions correspondingly reduced)

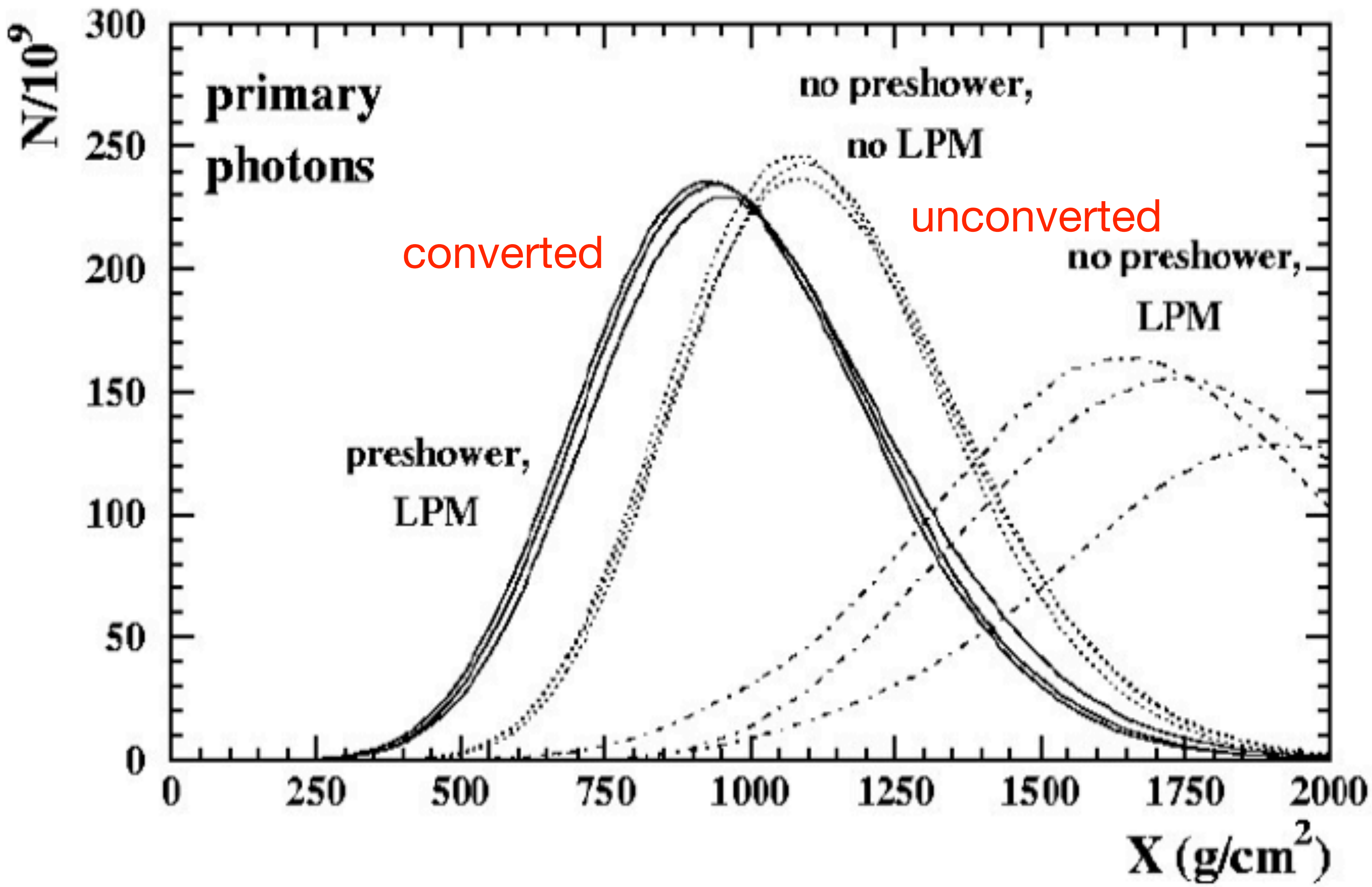
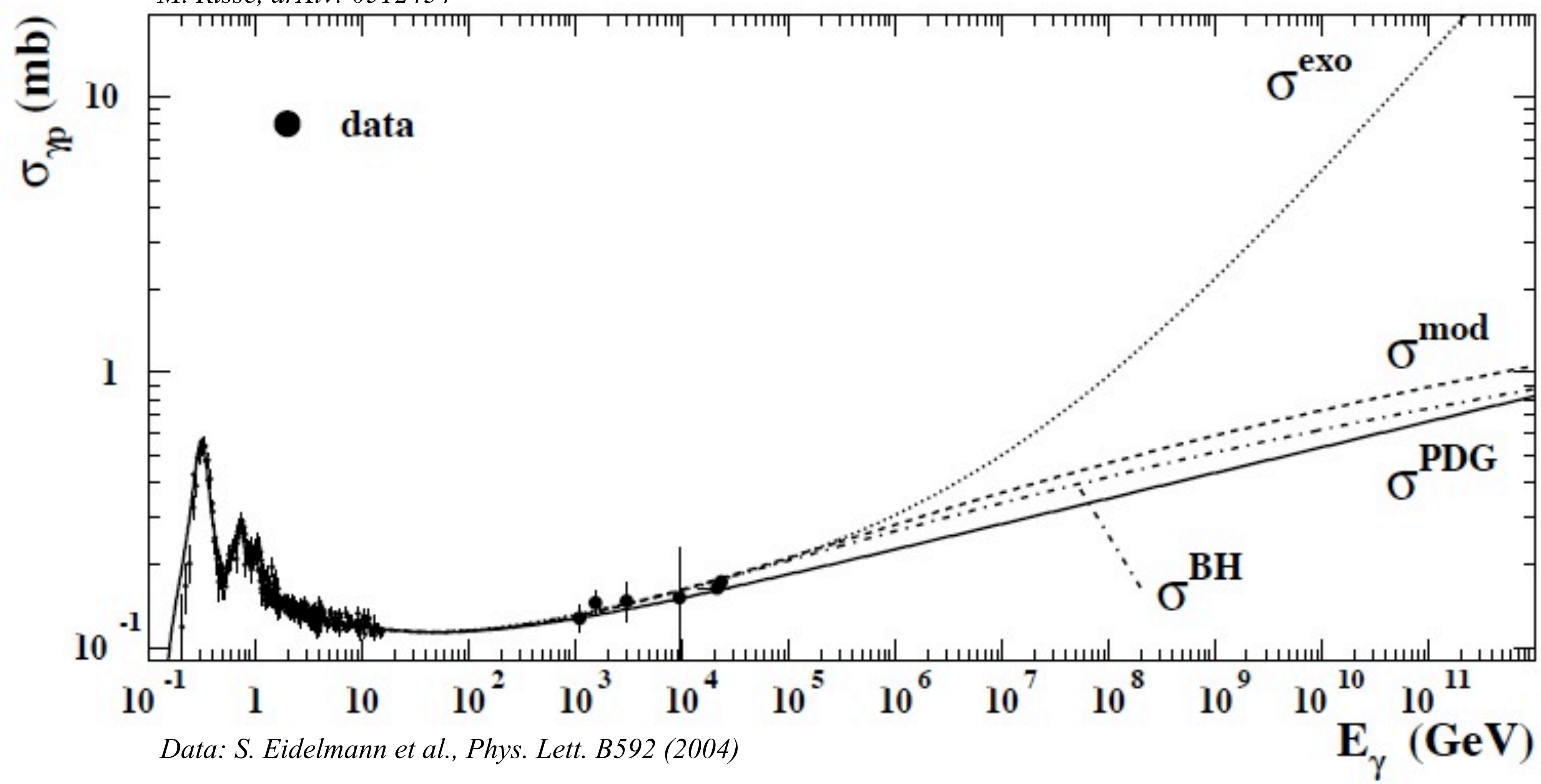


Photo-nuclear cross section

M. Risse, arXiv: 0512434



Data: S. Eidelmann et al., Phys. Lett. B592 (2004)

σ^{exo} + 70-80% muons (~ 70-80%)
- X_{max} reduced by ~(100) 30 gcm^{-2} for (un)converted

A. Donnachie et al., Phys. Lett. B518 (2001)

σ^{mod} + 10% muons
- 7 gcm^{-2} X_{max}

L/ Bezrukovet al., Sov. J. Nucl. Phys. 33 (1981)

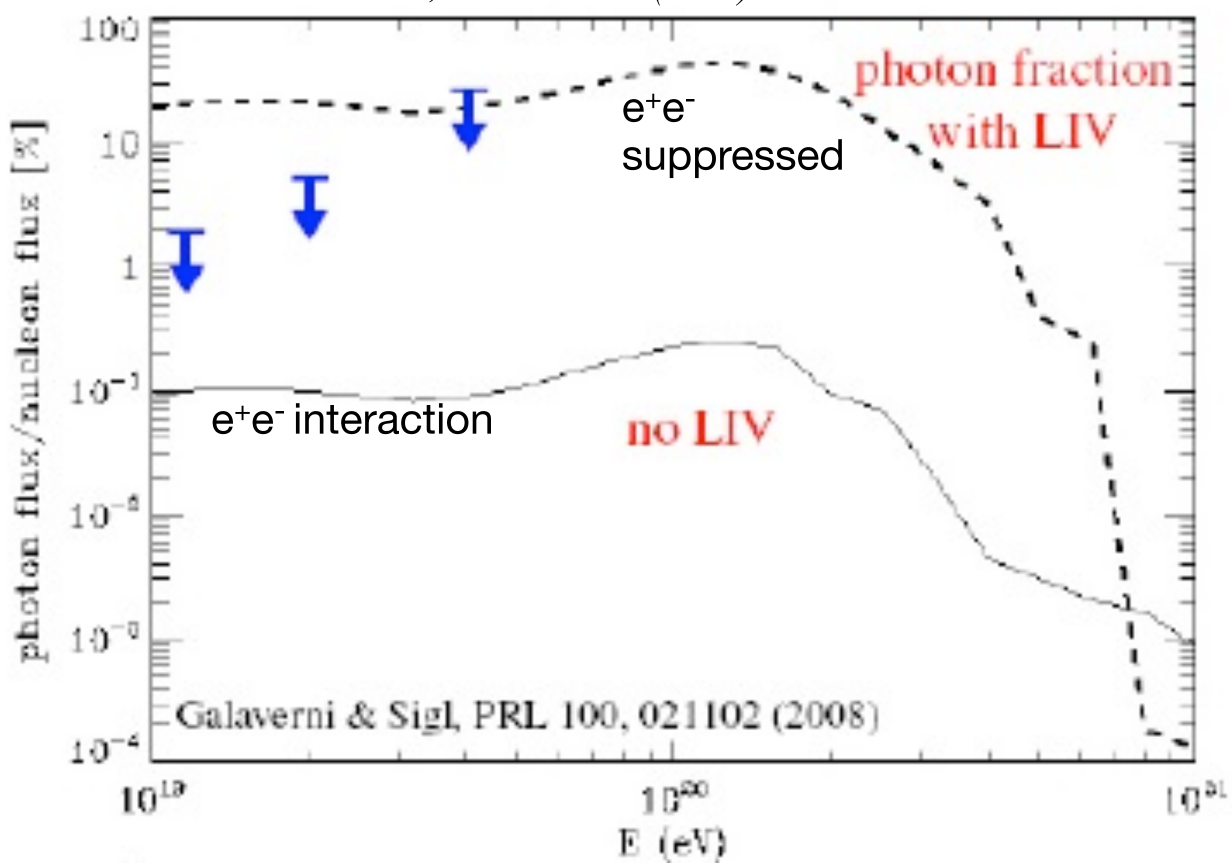
UHE photons and Lorentz Invariance Violation

- In **Lorentz Invariance Violation, LIV,** (electromagnetic sector):

➡ "*Vacuum Cherenkov radiation*" allowed

➡ e^+e^- pair production suppressed (*Universe transparent to UHE photons*)

M. Galaverni et al., Rev. Lett 100 (2008)

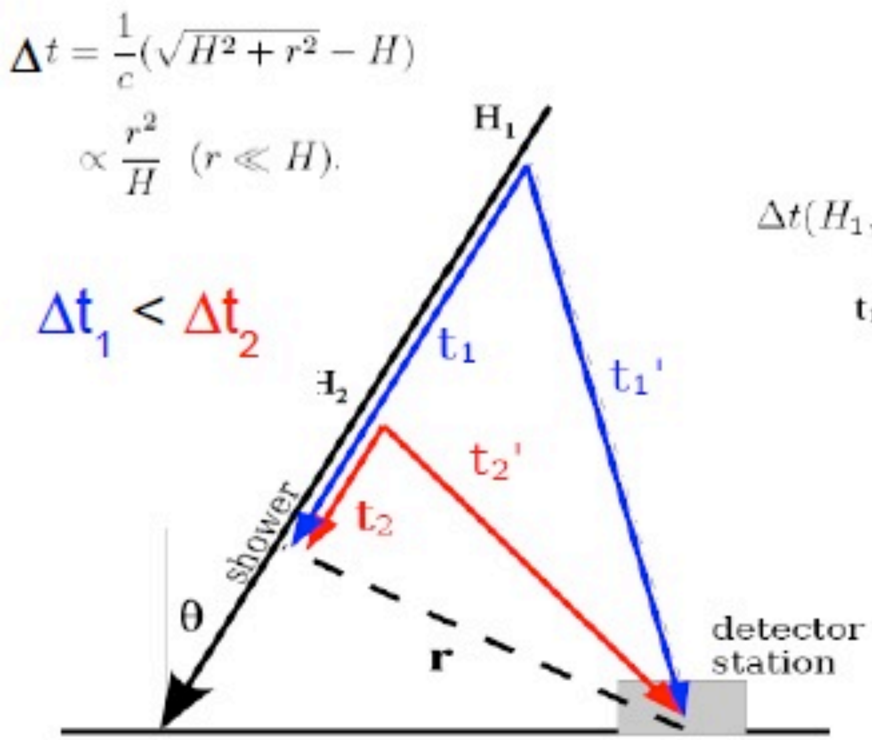


- Some constraints placed by the observation of multi-TeV photons and by timing of transient events (GRB, AGN flares)

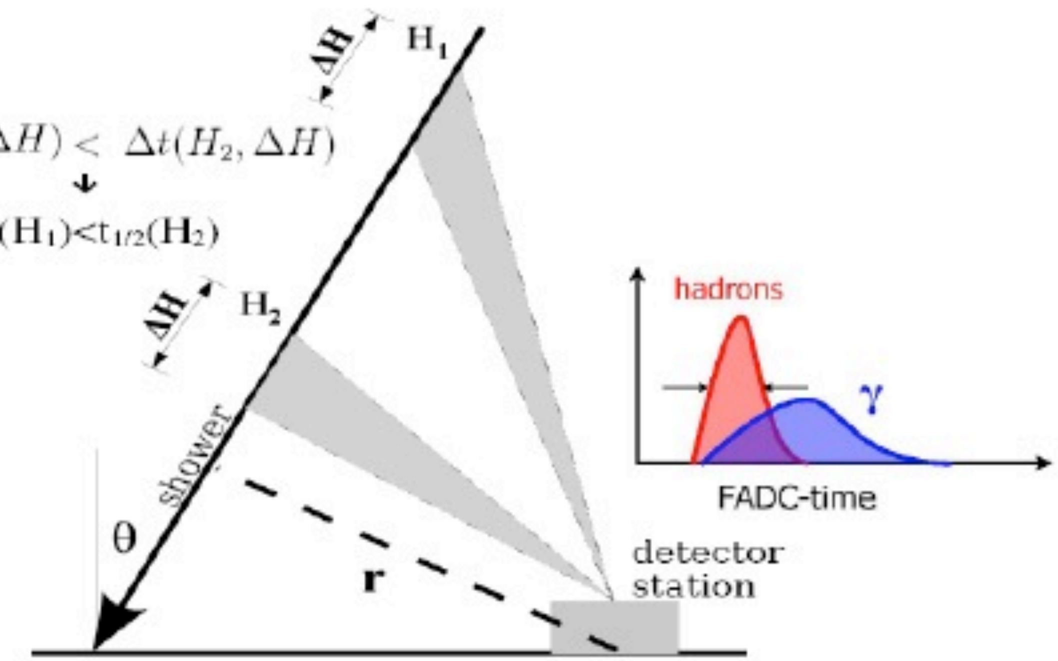
- Detection of UHE photons would further constrains LIV parameters in some models

Search for photons with SD

Radius of curvature of the shower front
Risetime of the signal in the surface detectors



Smaller radius of curvature for deeper showers (i.e. photons): *geometric reason and muon content*



Larger risetime of the signal for deeper showers *(less muon; larger geometric spread of the particle arriving time to the station)*