PIERRE AUGER OBSERVATORY

ICRC
The Astroparticle Physics Conference
34th International Cosmic Ray Conference
July 30 - August 6, 2015
The Hague, The Netherlands

Update of the neutrino and photon limits from the Pierre Auger Observatory

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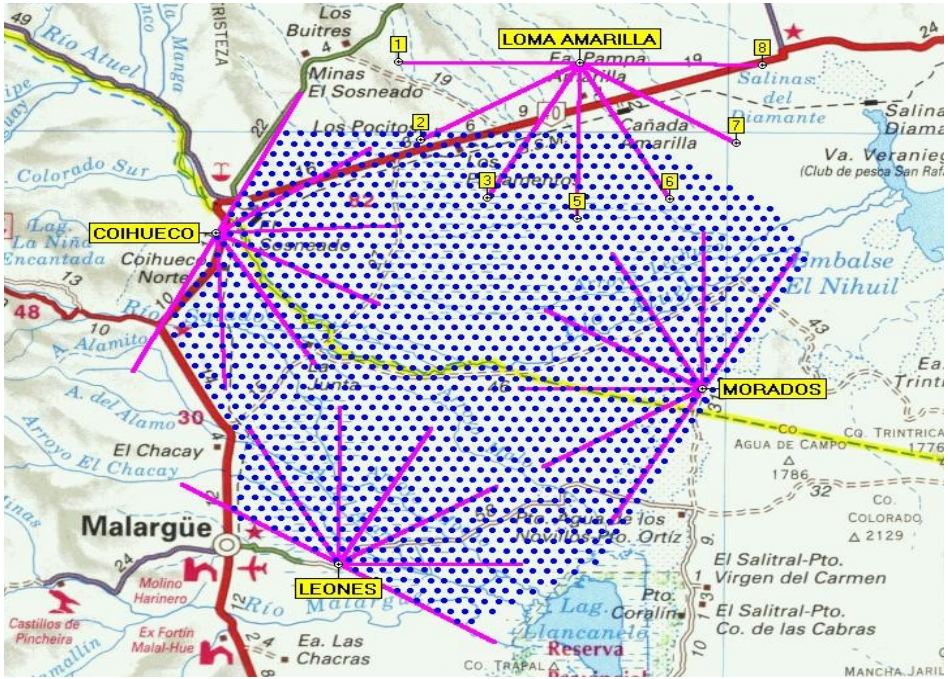
A detector of UHE neutrinos and photons

The Surface Detector (SD) array of the Pierre Auger Observatory:

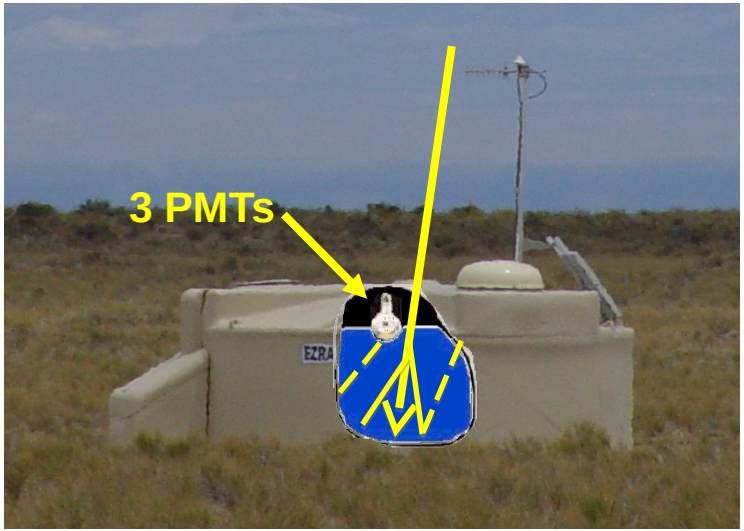
~ 3000 km^2 large exposure for neutrino and photon searches

~ 1600 water-Cherenkov stations on a triangular grid (spacing 1.5 km)



35.5º S, 69.3º W

1400 m a.s.l.
(880 g cm^{-2})



→ sensitive to electromagnetic and muonic component (not separately)

→ can measure the time structure of the signal induced by electrons and muons

Search for UHE neutrinos
$E > 10^{18}$ eV

Inclined showers and UHE neutrinos

→ Protons & nuclei initiate inclined showers high in the atmosphere.

Shower front at ground:

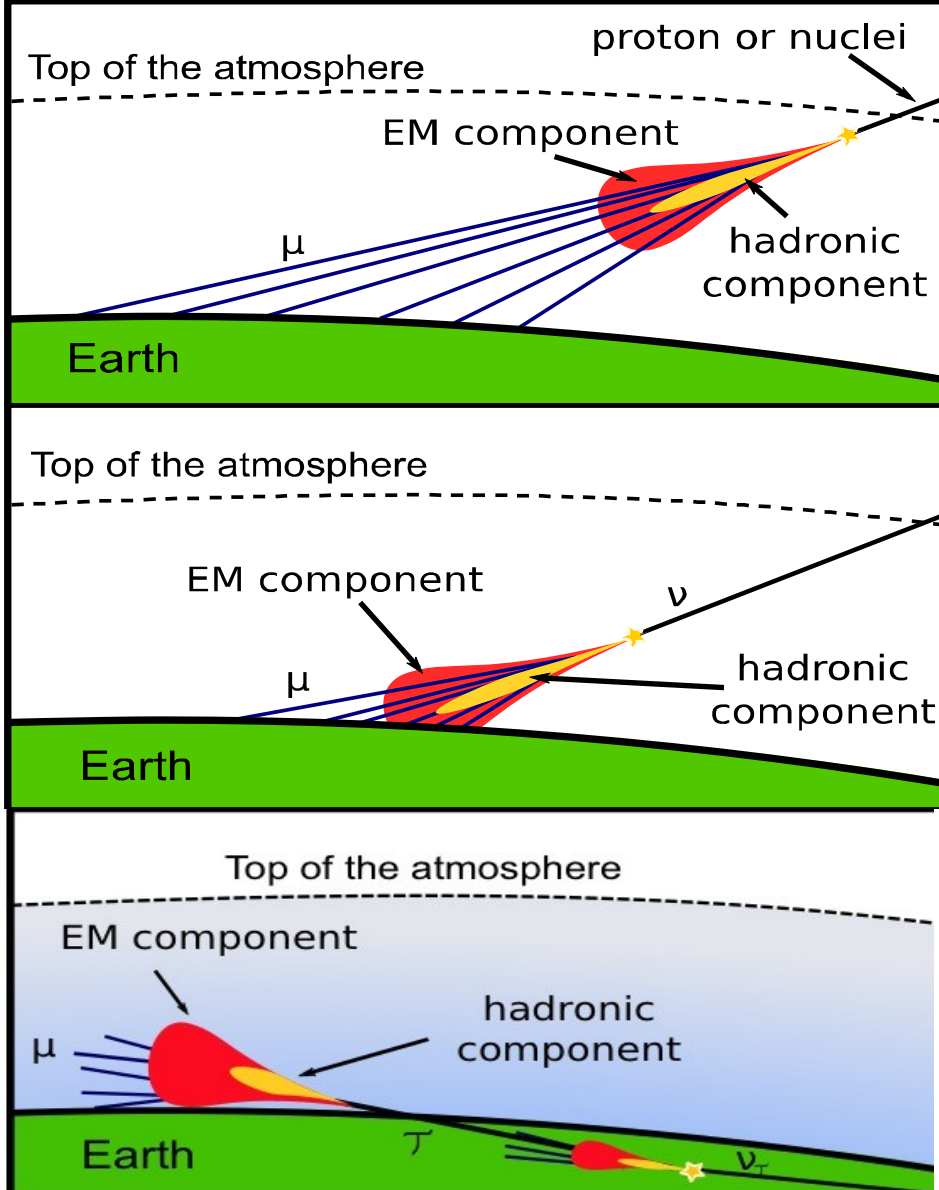
- electromagnetic component absorbed in atmosphere.
- mainly muons remaining

→ Neutrinos can initiate deep showers close to ground.

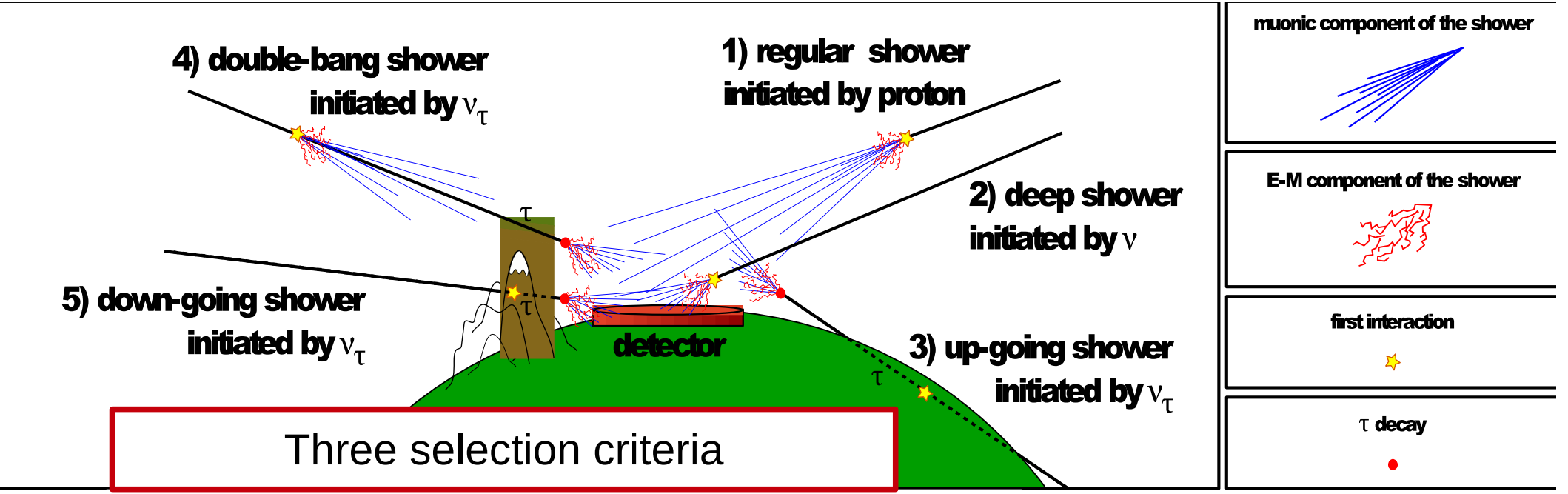
Shower front at ground:

<u>electromagnetic + muonic components</u>

Searching for neutrinos
⇒ inclined showers
with electromagnetic component



Sensitivity to all flavours and channels



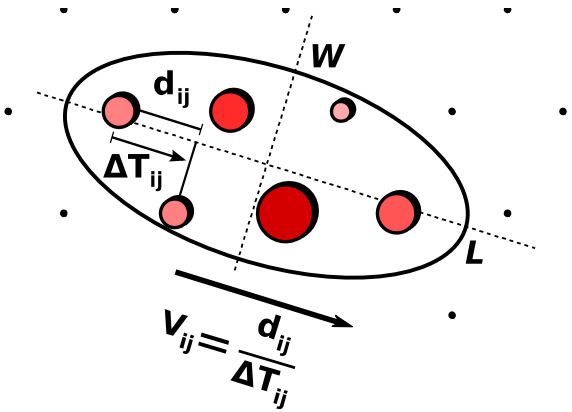
Three selection criteria

Down-going low angle (2 and 4) DGL 60º-75º
Down-going high angle (2, 4 and 5) DGH 75º-90º
} all flavours

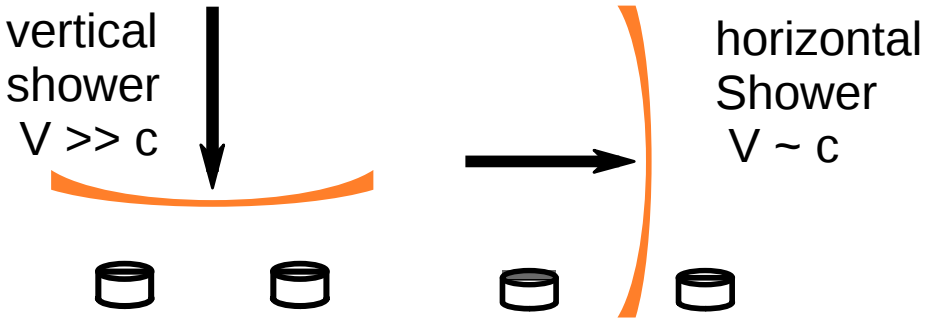
Earth-skimming (3) ES 90º-95º ν_τ

Selection of inclined events

(1) Elongated footprint



(2) Apparent velocity V of propagation of the shower front along major axis L

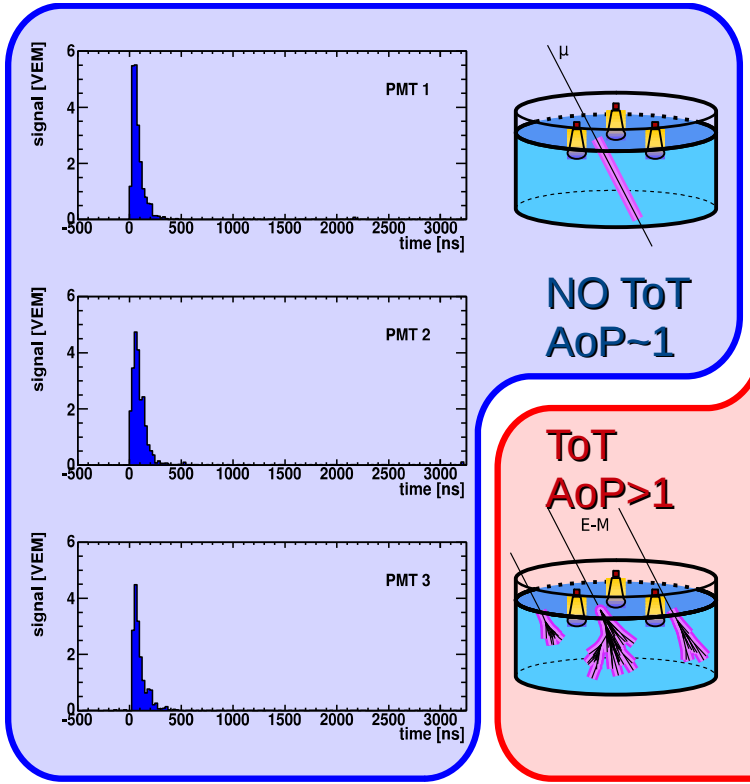


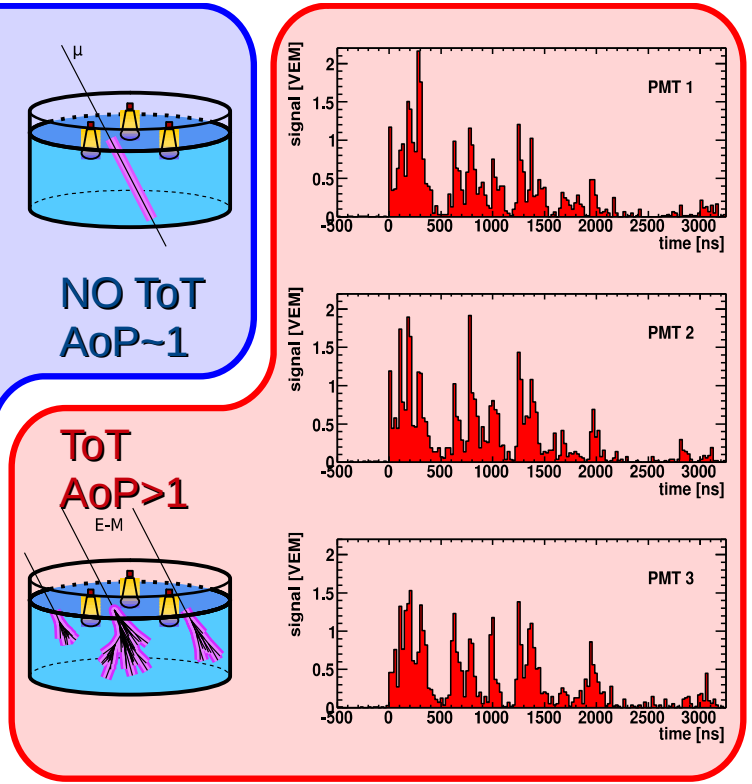
(3) Reconstructed zenith angle

	Earth-Skimming $(90°, 95°)$	Down-going High $(75°, 90°)$	Down-going Low $(65°, 75°)$
(1)	$L/W > 5$	$L/W > 3$	–
(2)	$\langle V \rangle \in (0.29,\ 0.31)$ m ns^{-1}	$\langle V \rangle < 0.313$ m ns^{-1}	–
(2)	RMS$(V) < 0.08$ m ns^{-1}	RMS$(V)/\langle V \rangle < 0.08$	–
(3)	–	$\theta_{\rm rec} > 75°$	$\theta_{\rm rec} \in (58.5°,\ 76.5°)$

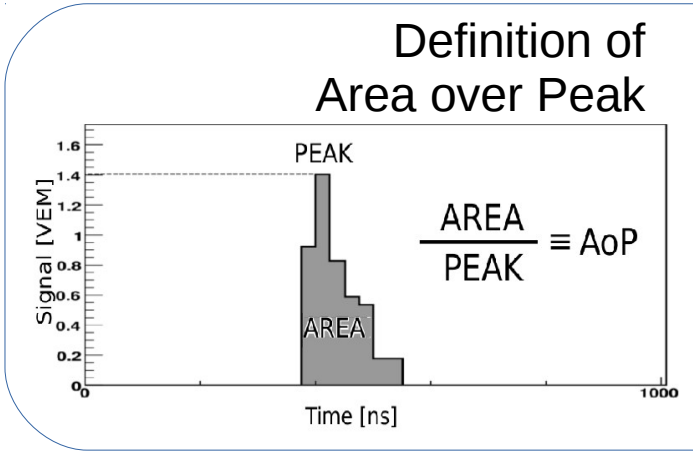
Identifying electromagnetic shower fronts

Muonic shower front: narrow signals





EM shower front: broad signals



Select stations with:

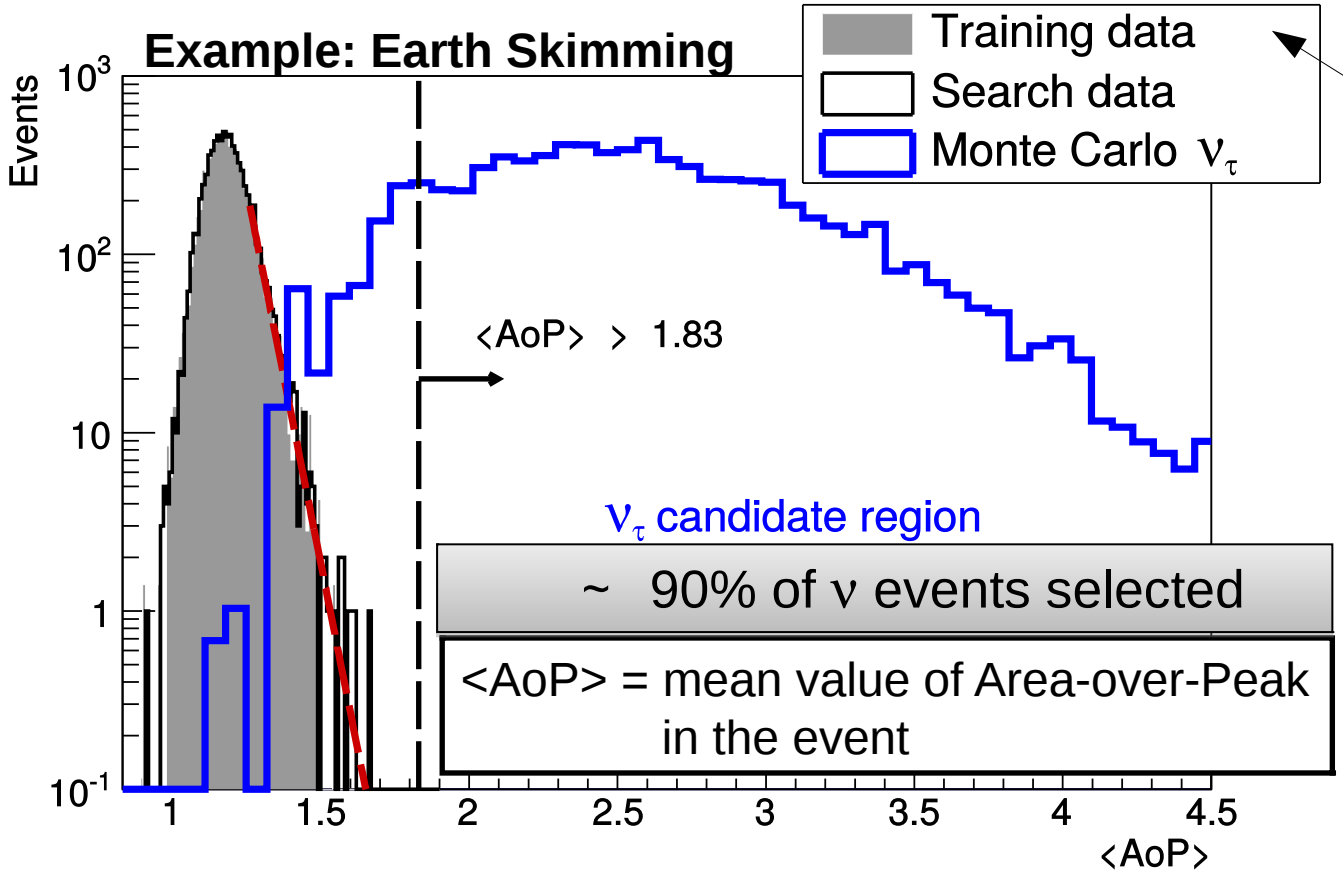
- Time-over-Threshold (ToT) trigger

AND/OR

- Large Area-over-Peak (AoP)

Using the time structure of signals in WCDs, search for signals extended in time.

Identification of UHE neutrinos in Auger data



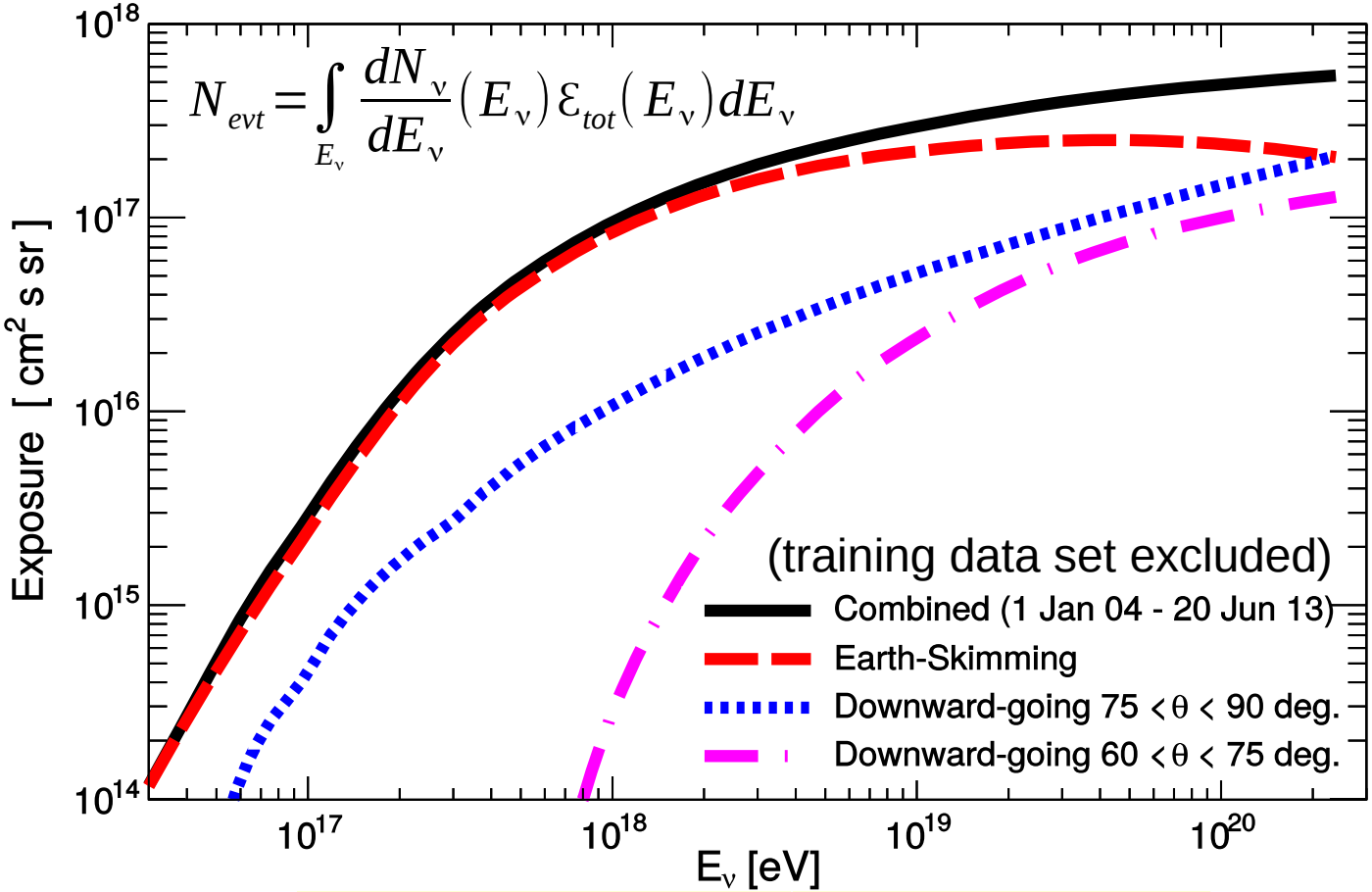
~20% of the data are used to estimate the expected background

Data taking:
01/01/04 – 20/06/13

Identification criteria applied "blindly" to the search data set
=> No candidates found in Earth Skimming or Downward-going

Neutrino exposure calculation

Upper limit to the number of neutrinos: Feldman-Cousins + Conrad (includes uncertainties in the exposure calculation)



Upper limits for a k E^{-2} spectrum:

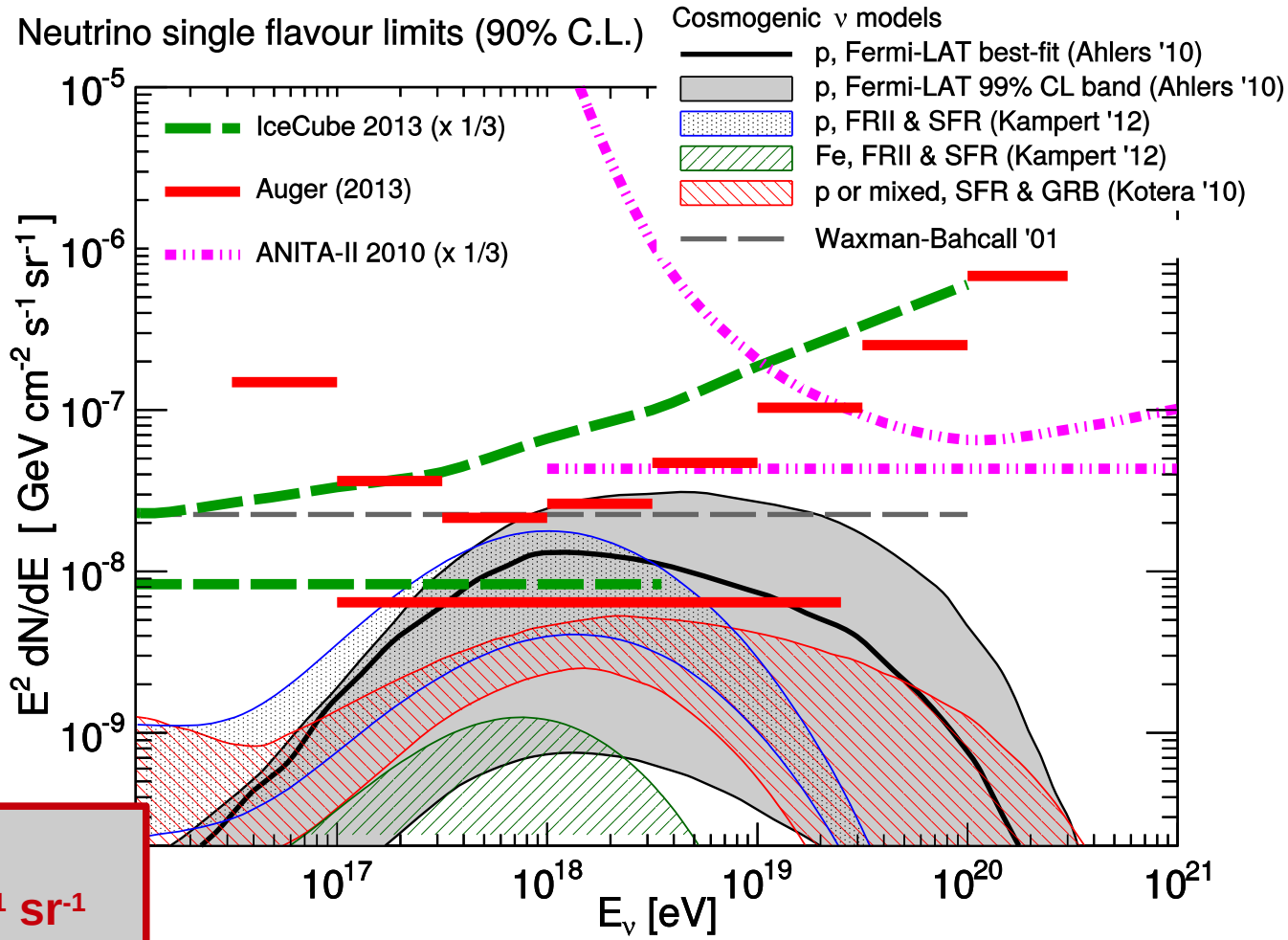
$$k^{90\%} = \frac{N^{90\%}}{\int E_\nu^{-2}\,\varepsilon_{tot}(E_\nu)\,dE_\nu}$$

Systematic Uncertainties

Simulations	~ +4%, -3%
ν cross-section & τ E-loss	~ +34%, -28%
Topography	~ +15%, 0%
Total	~ +37%, -28%

Upper limits to the diffuse flux of neutrinos

Phys. Rev. D 91 (2015) 092008



$dN/dE = k\,E^{-2}$

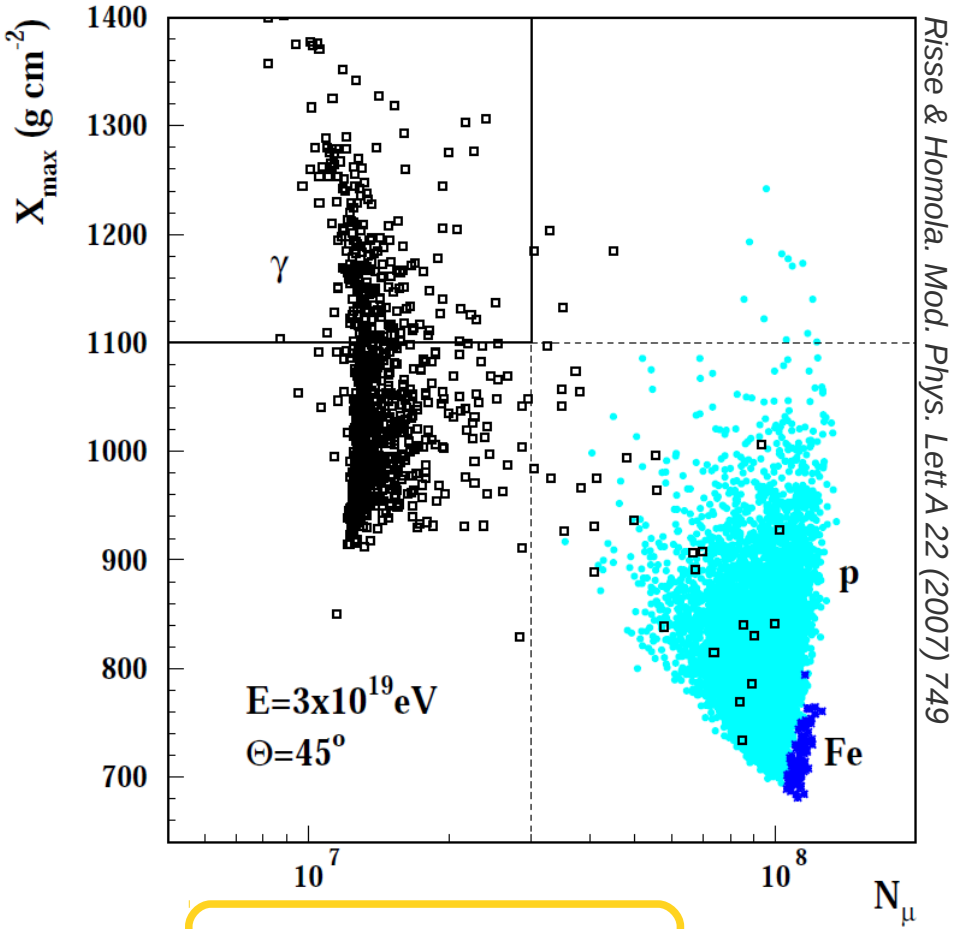
→ **$k \sim 6.4 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}**

90% C.L. in the energy range 0.1 – 25 EeV

Auger limit constrains models with proton primaries & strong evolution with redshift

Search for photons
$E > 10^{19}$ eV

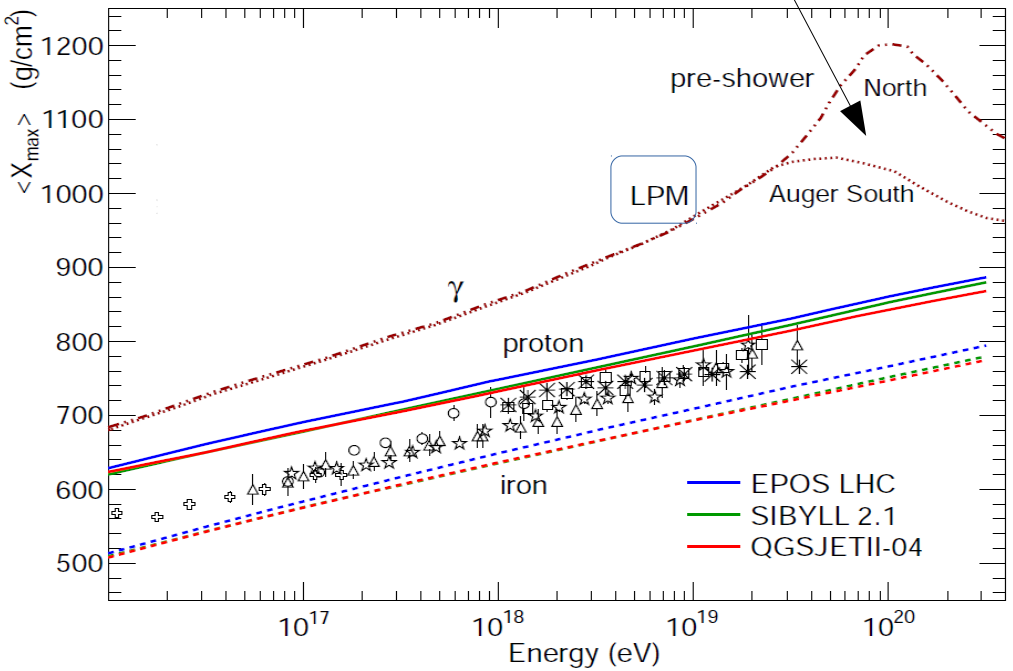
How to recognize a photon shower



Risse & Homola. Mod. Phys. Lett A 22 (2007) 749

→ Mostly **EM** showers
→ Minor photo-nuclear or muon pair production

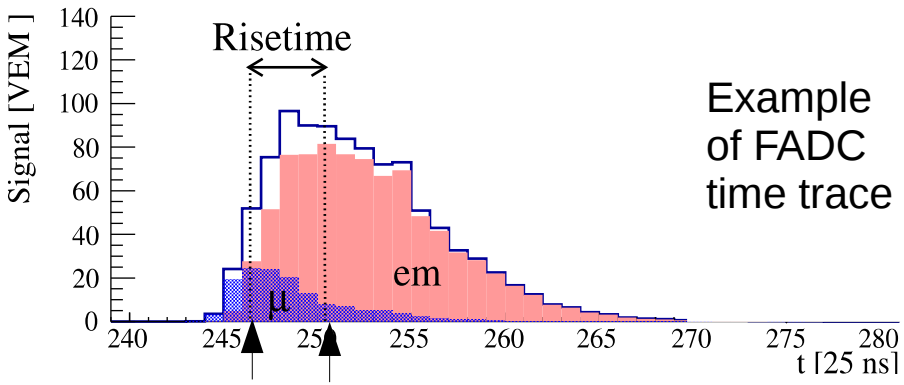
Pre-shower in the geomagnetic field



→ **Xmax**
→ **Muon content**

Experimental observables

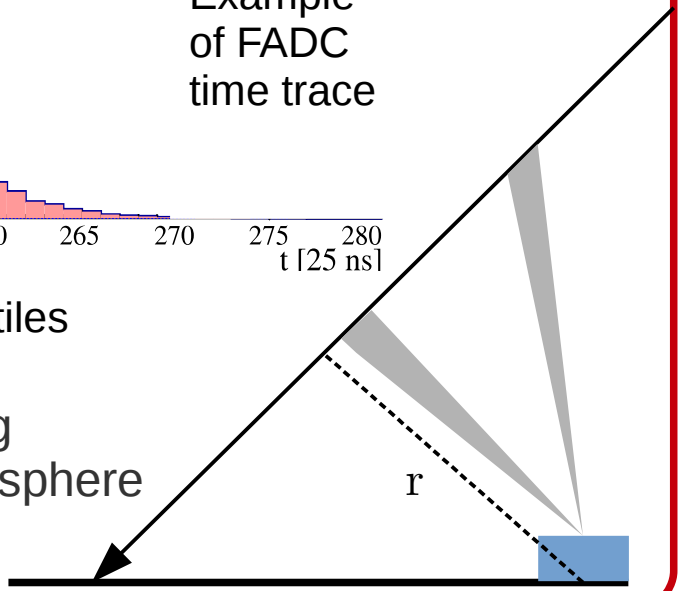
Risetime of the signal in a SD station:
time difference between the 50% and 10% trace quantiles. Larger for:
(a) signals dominated by the em component



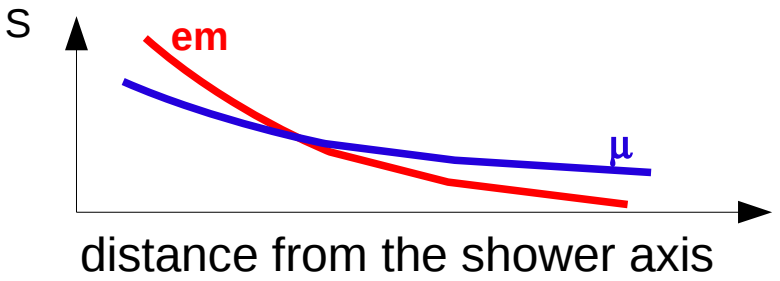
Example of FADC time trace

10% 50% quantiles

(b) showers developing deeper in the atmosphere

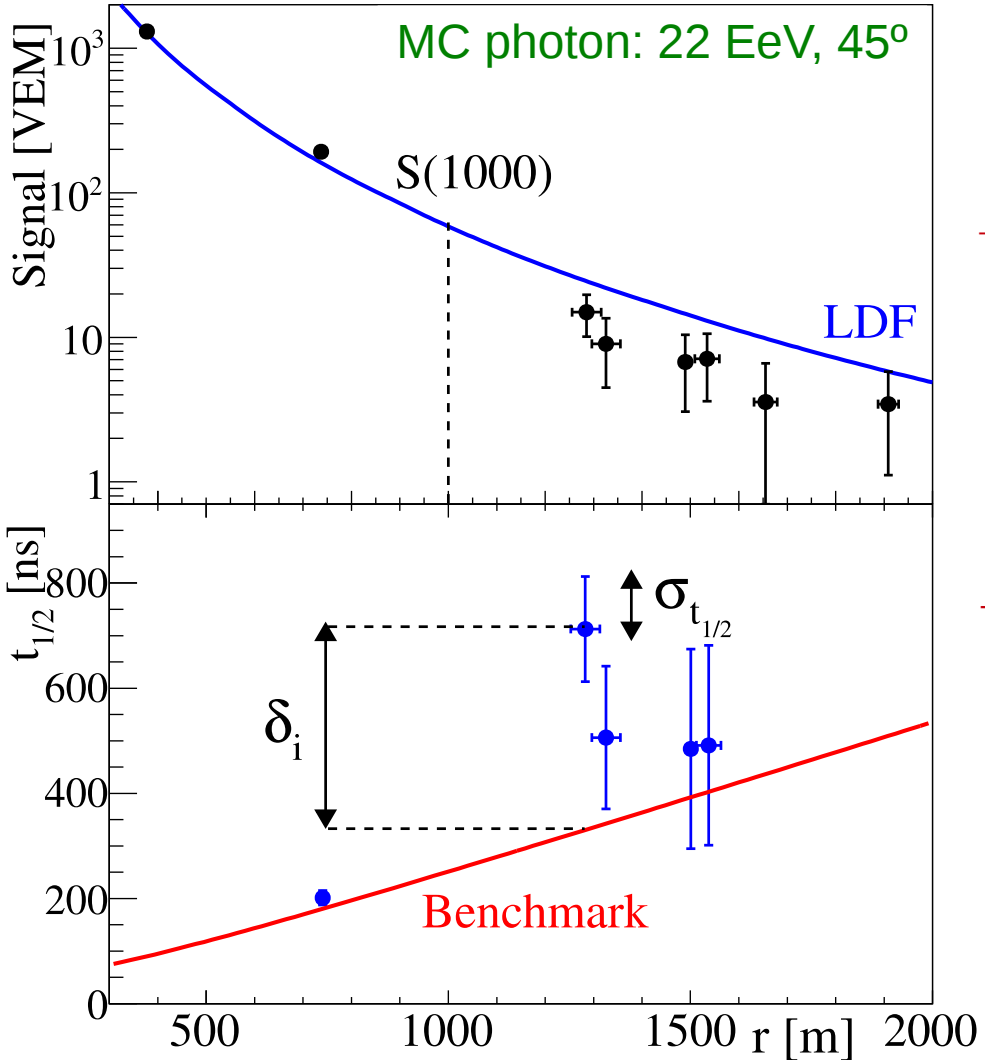


Lateral distribution of total signal
steeper than the average LDF of data for showers rich in electromagnetic component



Search for photons:
select showers with steep LDF and large risetimes

Event variables for the photon search



Photon-initiated EAS are characterised, with respect to the background, by:

→ **steeper LDF**

$$L_{LDF} = \log_{10}\left(\sum S_i / LDF(r_i)\right)$$

measurement of deviation from the data LDF

Expected ~1 for background

<u>station selection:</u> r_i > 1000 m

→ **broader shower front (larger risetime)**

$$\Delta = \left(\sum \delta_i\right) / N$$

average deviation from the data benchmark

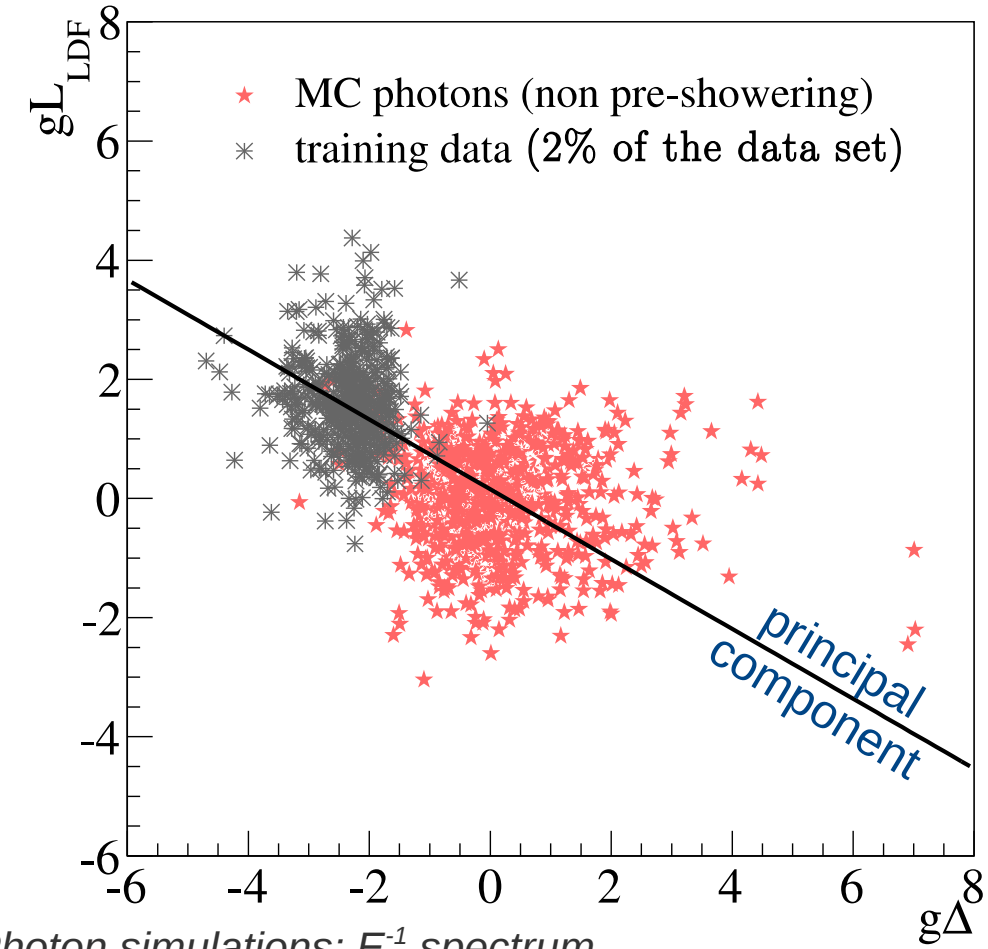
Expected ~0 for background

$$\delta_i = \frac{t_{1/2} - t^{Bench}}{\sigma_{t_{1/2}}}$$

<u>station selection:</u>

S_i > 6 VEM, $r_i \in$ [600,2000] m

Principal Component Analysis



Photon simulations: E^{-1} spectrum
CORSIKA + QGSjetII.03

Photon energy reconstruction:
(S1000, ϑ) → E_γ
calibrated with photon simulations

→ Redefine separation observables:
taking x = L_{LDF} or x=Δ

$$gx = (x - \overline{x_\gamma}(E_\gamma, \theta)) / \sigma_\gamma(E_\gamma, \theta)$$

→ Find the linear combination that maximizes the signal/background separation

→ Use the principal component to identify photons

Identification of photons

data 01/01/04 – 15/06/13 zenith 30º-60º

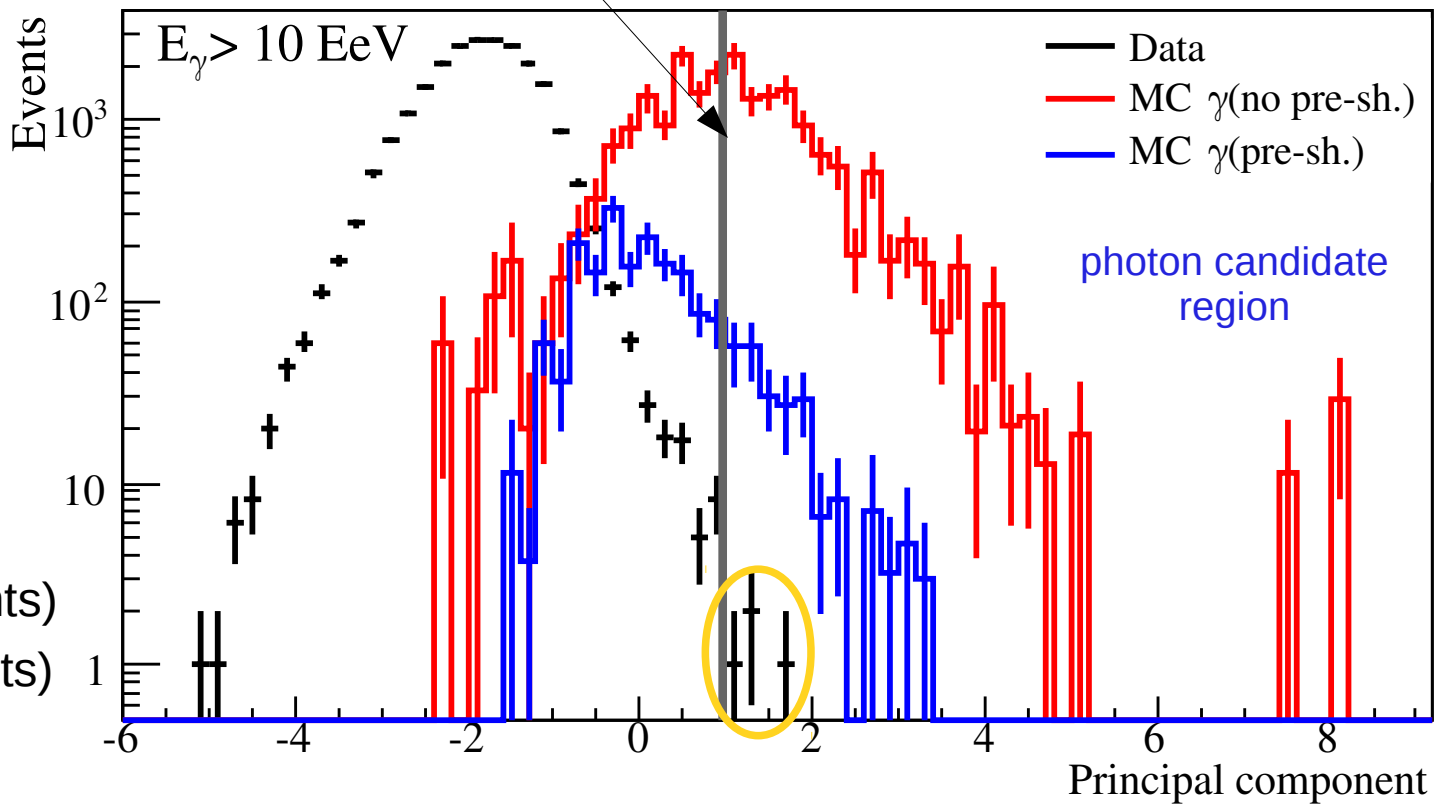
Candidate cut: median of non pre-showering photon distribution (spectrum E^{-2})

Search data sample (98% of the total): 22853 events

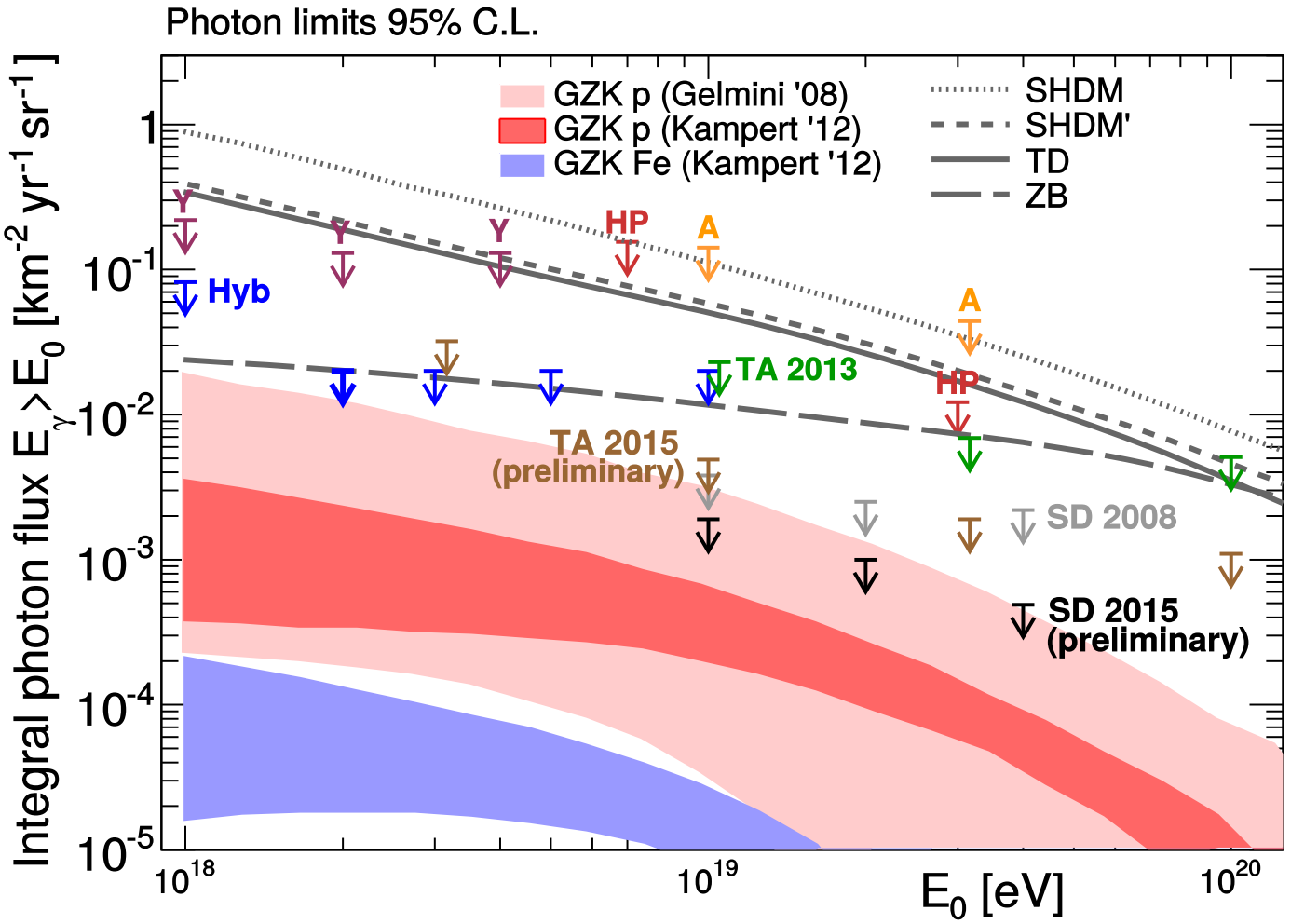
4 photon candidates

2 for E >20 EeV (8225 events)

0 for E>40 EeV (1941 events)



Upper limits to the integrated photon flux



Feldman-Cousins limit to the number of photons

$$F_\gamma(E_\gamma > E_0) = \frac{N_\gamma}{\langle \mathcal{E} \rangle}$$

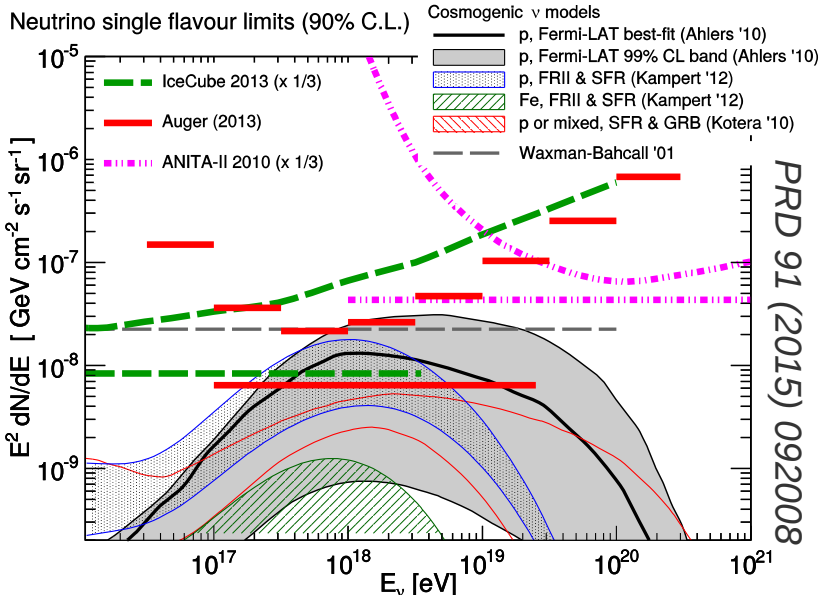
E^{-2} spectrum-weighted average exposure for $E_\gamma > E_0$

E_0 [EeV]	$\langle \mathcal{E} \rangle$ [km^2 sr yr]	F_γ (95% CL) [$km^{-2}\,yr^{-1}\,sr^{-1}$]
10	5200	1.9×10^{-3}
20	6800	1.0×10^{-3}
40	6300	4.9×10^{-4}

Conclusions

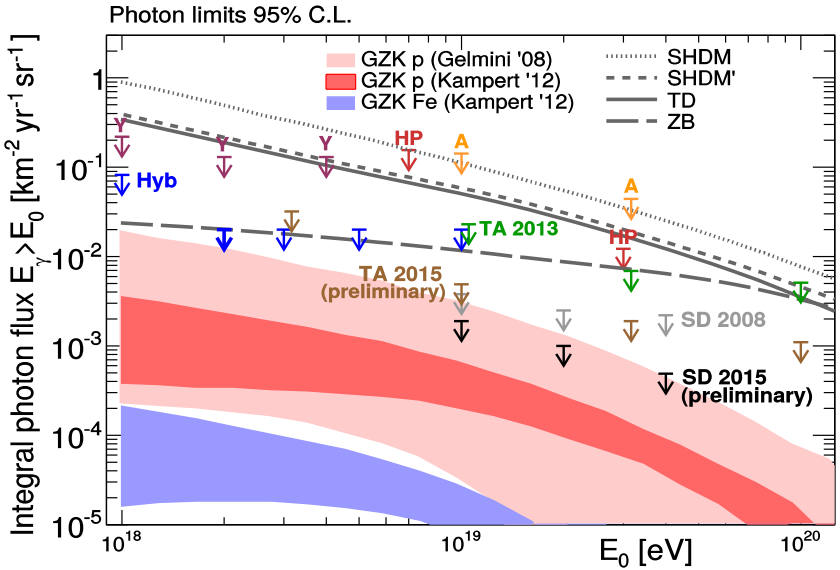
ν

→ 01/01/04–20/06/13 no ν candidate
→ search not limited by background
→ limit below the WB bound
→ top-down (exotic) models strongly constrained
→ cosmogenic model with pure p composition
at the source and strong FRII evolution disfavoured



γ

→ 01/01/04–15/05/13
4 photon candidates above 10 EeV
→ strictest limits in the range E > 1 EeV
→ top-down model strongly disfavoured
→ <u>preliminary</u> U.L. above 10 EeV start constraining
the most optimistic models of cosmogenic photons
with p primaries injected at the source



More on neutrino and photon searches with the Pierre Auger Observatory

→ Search for point-like sources of UHE neutrinos

The Pierre Auger Collaboration, Astrophysical Journal Letters, 755 (2012) L4

→ Search for a diffuse flux of photons with hybrid data (>1 EeV)

The Pierre Auger Collaboration, Astropart. Phys. 27 (2007) 155
The Pierre Auger Collaboration, Astropart. Phys. 31 (2009) 399
M. Settimo, for the Pierre Auger Collaboration, 32nd ICRC, Beijing, China, 2 (2011) 55

→ Search for point sources of EeV photons with hybrid data

(1) blind: *The Pierre Auger Collaboration, ApJ, 789 (2014) 160*
(2) targeted: ongoing