Measurements of the muon content of air showers and search for ultra-high energy neutrinos and photons at the Pierre Auger Observatory

INÉS VALIÑO[1], for the Pierre Auger Collaboration[2]

[1] Dept. de Física de Partículas e IGFAE, Universidade de Santiago de Compostela, Spain
[2] Full author list: http://www.auger.org/archive/authors_2013_05.html

Science goals of the Pierre Auger Observatory

COSMIC RAY PHYSICS

Energy spectrum *(see M. Roth talk)*

Anisotropy studies *(see M. Mostafa talk)*

Mass composition :

- Nuclear mass from X_{max} and muon production depth distributions *(see A. Porcelli talk)*
- **Neutrinos**
- **Photons**

PARTICLE PHYSICS

High-energy hadronic interactions of cosmic rays in the atmosphere :

- **Muon number**

UHE neutrinos and photons search: motivations

All scenarios of UHECRs production predict secondary neutrinos and photons:

- "bottom-up": by interaction of CR with matter or radiation within sources ("astrophysical").
- "top-down": by decay of ultra massive objects.

Neutrinos and photons are also produced during CR propagation:

- By interaction of CR with the cosmic microwave background ("cosmogenic").

$$p,\ldots Fe + \gamma_{CMB/source} \longrightarrow \pi^{\pm} \longrightarrow \mu^{\pm} + \nu_{\mu}$$

$$\mu^{\pm} \longrightarrow e^{\pm} + \nu_{\mu} + \nu_{e}$$

$$p,\ldots Fe + \gamma_{CMB/source} \longrightarrow \pi^{\circ} \longrightarrow \gamma\gamma$$

ν´s travel in straight line, low interaction probability

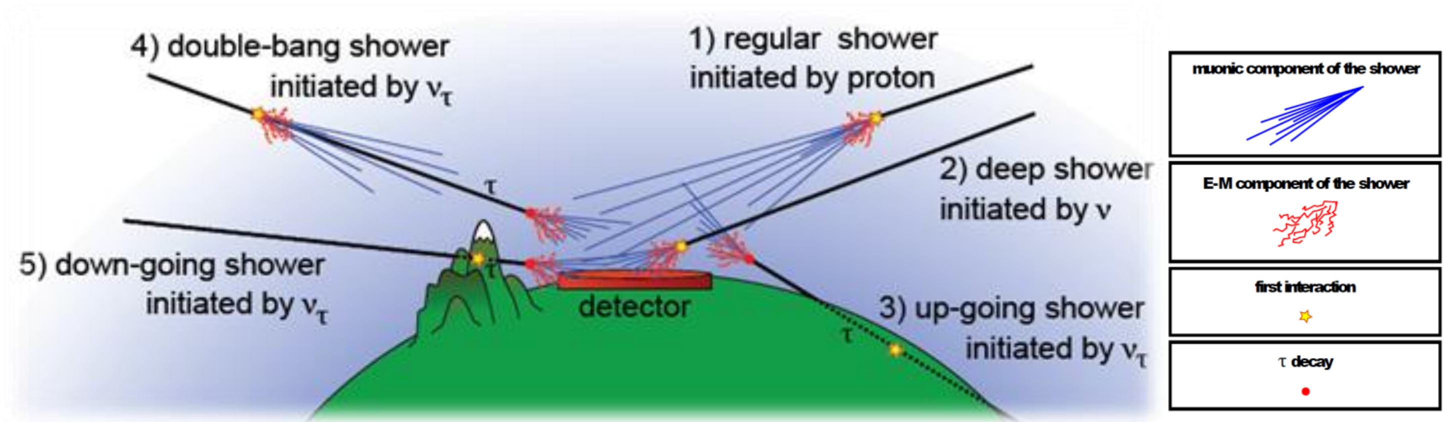
γ´s travel in straight line, but can´t travel far at high energies

Neutrinos and photons are excellent messengers:

- Open the most extreme window to astronomy: point back to the sites of production
- Hints/constrains on astrophysical origin scenarios
- Disfavour/constrains top-down models
- Tracers of the UHECR propagation effects (GZK, photodisintegration)
- Photons test the more local Universe, while neutrinos can probe cosmological distances.

UHE neutrino search with extensive air showers

ICRC 2013 (0697)



Identification of ν-showers in a background of nucleonic showers enhanced by looking at inclined showers recorded at the Surface Detector (SD) array:

(1) **Inclined hadronic showers** initiated high in the atmosphere : mainly composed of muons at ground .

(2-5) **Neutrino induced showers** can be initiated close to the ground: shower with large electromagnetic component.

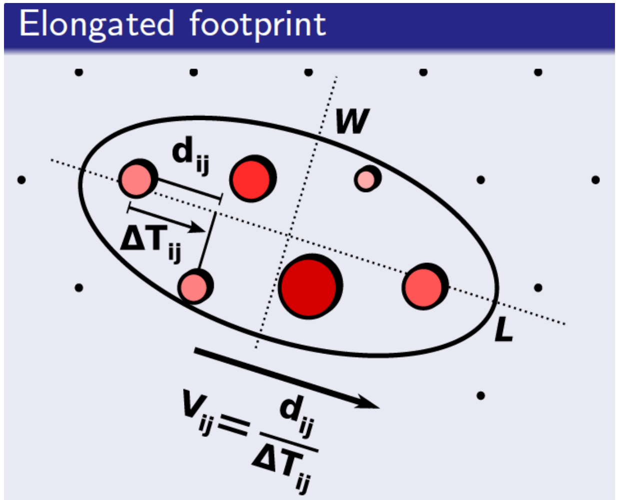
Basis of identification criteria: inclined deep (young) showers

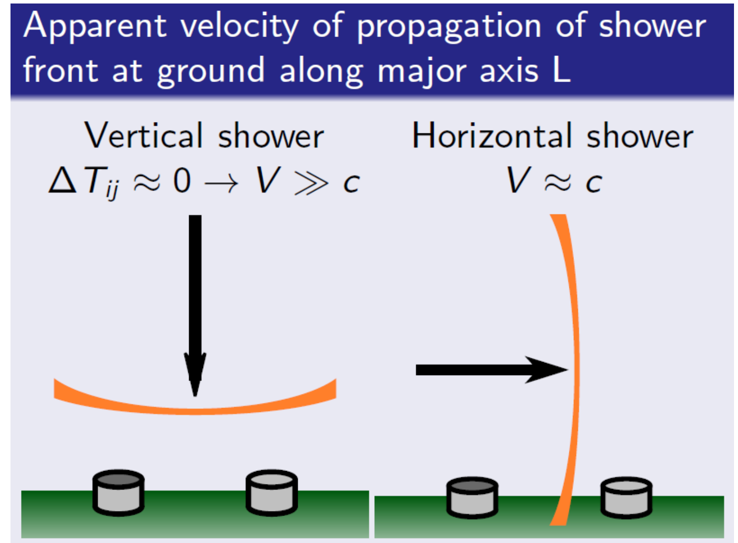
Identification criteria developed using : training data sample + MC neutrino simulations

UHE ν-detection channels at Auger

- Earth-skimming (ES): $\nu\tau$ CC , θ = [90°-95°]
- Down-going high angle (DGH): all flavours CC & NC, θ = [75°,90°]
- Down-going low angle (DGL): all flavours CC & NC, θ = [60°,75°]

ν-showers identification : inclined showers selection





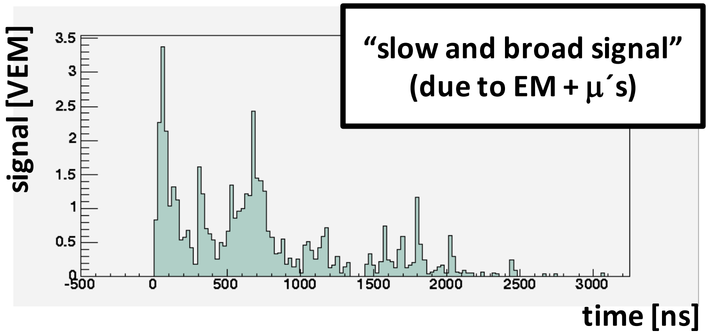
Quality cuts for inclined shower selection:

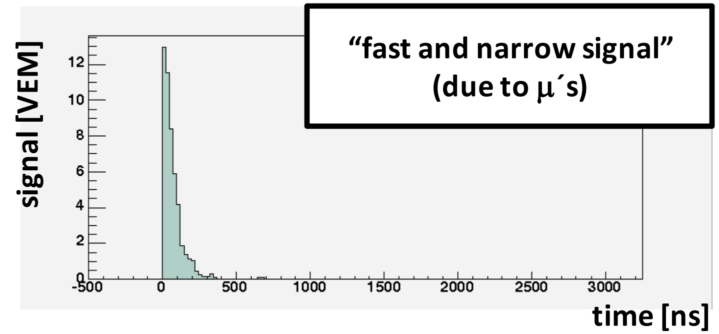
- shape (elongated footprint) : large L/W
- apparent speed of signal propagation (V) close to speed of light and small RMS(V)
- for DG showers, zenith angle is reconstructed (θ_{rec})

ES	DGH (75°,90°)	DGL (60°,75°)
L/W > 5	L/W > 3	-
$<V> \in$ (0.29, 0.31) m ns^{-1}	$<V>$ < 0.313 m ns^{-1}	-
RMS(V) < 0.08 m ns^{-1}	RMS(V)/V < 0.08	-
-	$\theta_{rec} > 75°$	$\theta_{rec} \in$ (58.5°,76.5°)

ν-showers identification : deep showers selection

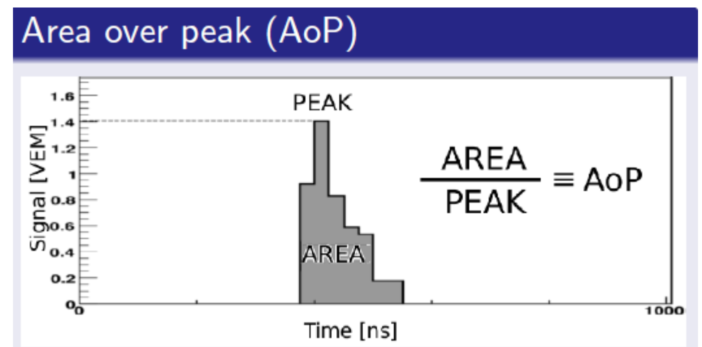
With the SD, we can distinguish muonic from electromagnetic (EM) shower fronts using the time structure of the signals in the water Cherenkov detectors:





Quality cuts based on deep showers induce signals extended in time:

- Broad signals in time induce ToT trigger.
- Narrow signals in time induce AoP ~ 1



ES	DGH (75°,90°)	DGL (60°,75°)
Data 1 Jan 2004 - 31 May 2010: ≥ 60% stations with ToT & AoP_{min} > 1.4	Fisher discriminant based on AoP of early stations	≥75% of stations close to shower core with ToT & Fisher discriminant based on AoP of early stations close to shower core
Data 1 Jun 2010 - 31 Dec 2012: <AoP> > 1.83 or AoP_{min} > 1.4 if 3 stations		

ν-search in Auger data

Blind analysis : search for ν-candidates in data excluding training samples

0 candidates found

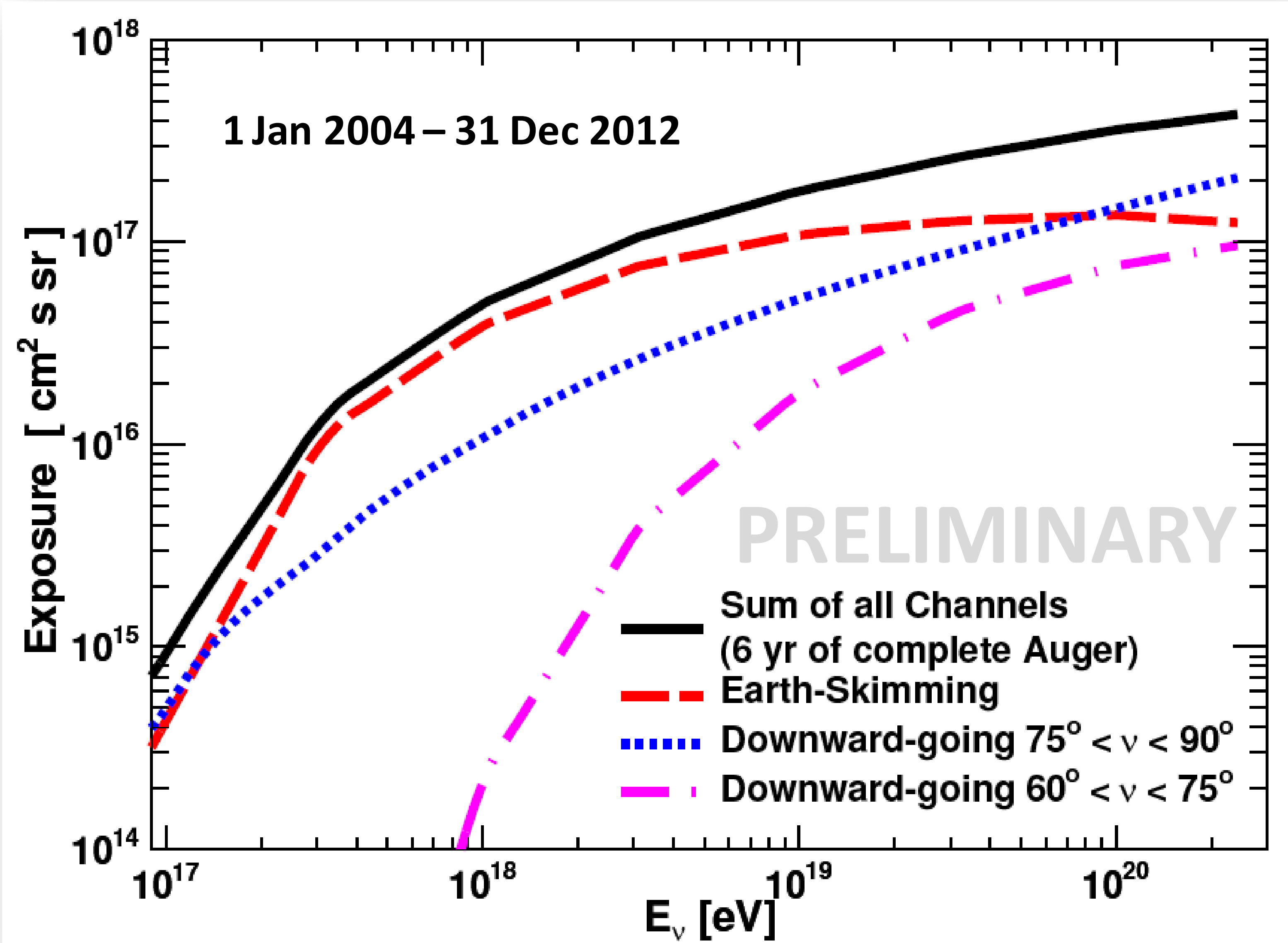
in ALL analyses

from 1 Jan 2004 to 31 Dec 2012 (~ 6 yr of full Auger data)

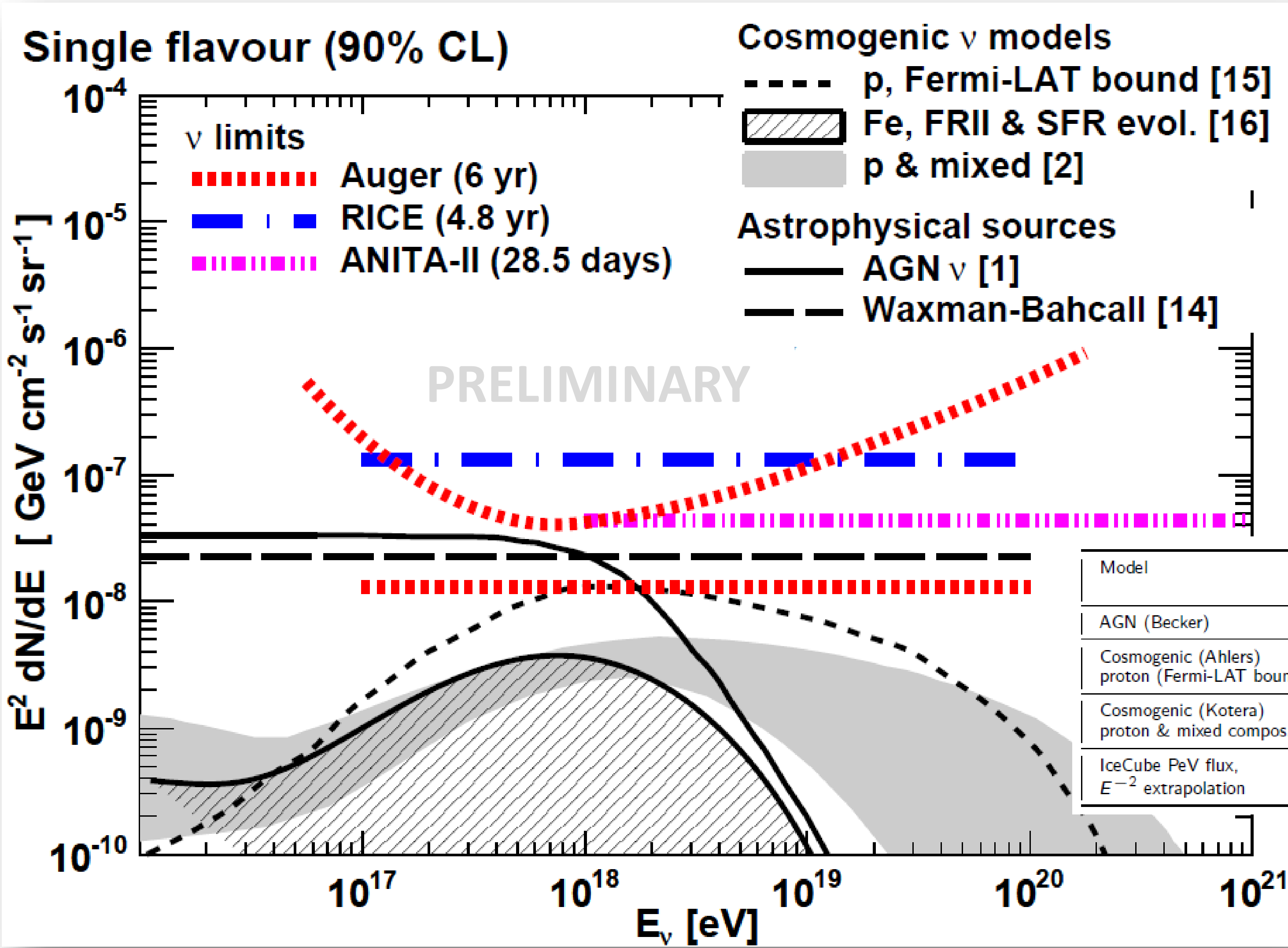
An upper limit to UHE ν diffuse flux can be placed

Combined exposure

Each simulated ν-event regardless of its θ if passes either ES or DGH or DGL selection criteria contributes to the exposure corresponding to its θ. Example: simulated DGH shower passing ES criterio contributes to ε_{DGH}



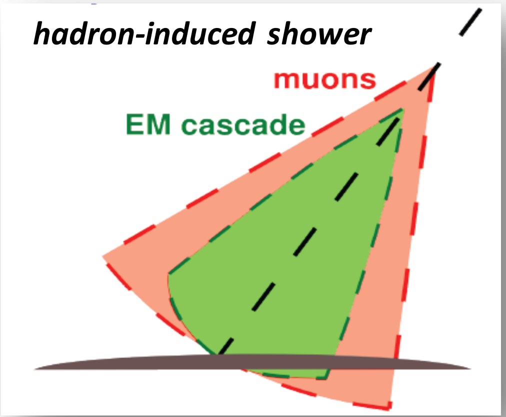
Update on integral and differencial limits to diffuse fluxes

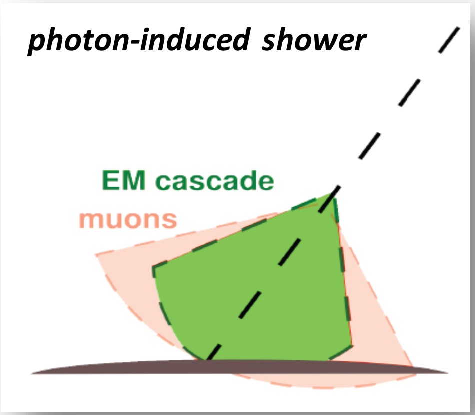


Model	Expected number of events
AGN (Becker)	~ 3.1
Cosmogenic (Ahlers) proton (Fermi-LAT bound)	~ 1.4
Cosmogenic (Kotera) proton & mixed compos.	~ 0.2 - 0.6
IceCube PeV flux, E^{-2} extrapolation	~ 2.2

$k_{up} = 1.3 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} at 90% C.L. in 10^{17} eV < E < 10^{20} eV

UHE photon search with extensive air showers





Photon induced showers:

- develop deeper in the atmosphere
- have smaller muon content

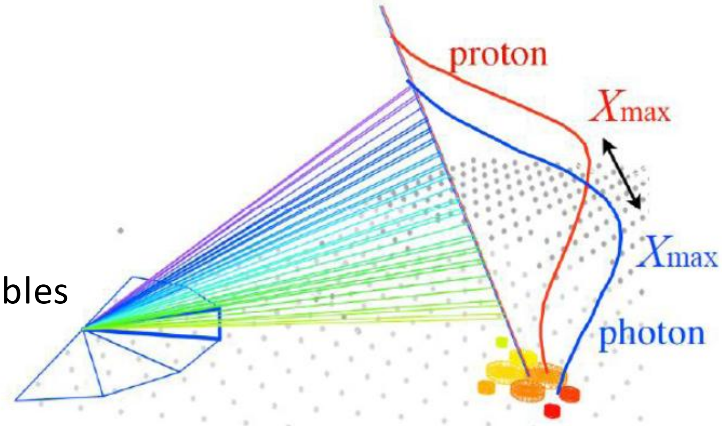
than hadronic showers.

Basis of identification criteria

larger X_{max}, smaller detected signal at the same distance and fewer stations triggered at SD

Search strategy

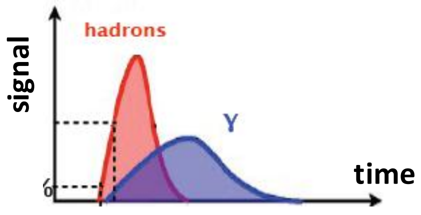
- Diffuse photon searches :
  - search with SD observables
  - search combining SD and Fluorescence Detector (FD) observables
- Directional photon search :
  - multivariate analysis using SD and FD observables

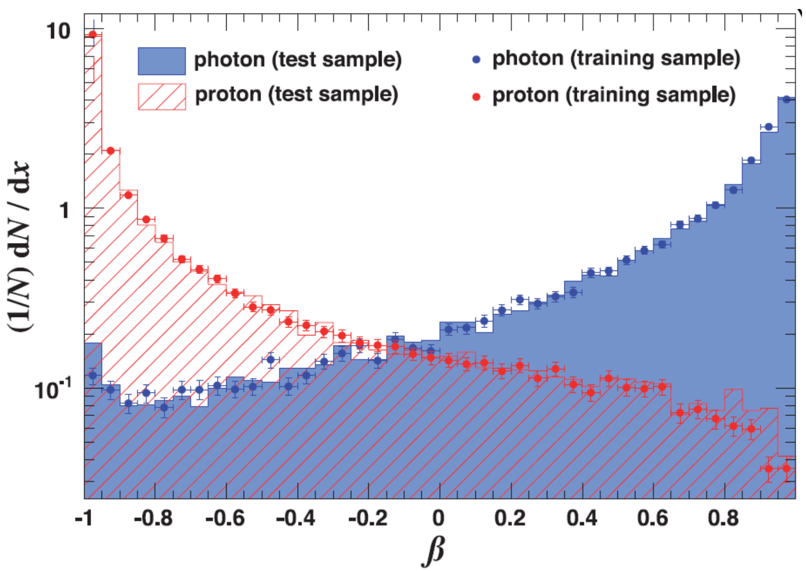


γ-shower identification : Multivariate analysis (MVA)

ICRC 2013 (0669)

- FD observables:
  - X_{max} : larger values than those of hadronic induced showers
  - Fit of Greisen function to the longitudinal profile (χ^2/ndof): better fit for photon induced showers
  - Greisen energy (E_{gr}) / energy from fit to a Gaisser-Hillas function (E_{FD})
- SD observables:
  - S_3 parameter, $S_3 = \sum_{i=1}^{N} \left[S_i \cdot \left(\frac{r_i}{1000\text{ m}} \right)^3 \right]$: sensitive to the shape of the lateral distribution functions at ground.
  - Shape parameter: ratio of the early arriving to the late arriving integrated time trace measured in the station with largest signal, $\text{ShapeP}(r,\theta) = \frac{S_{\text{early}}(r,\theta)}{S_{\text{late}}(r,\theta)}$





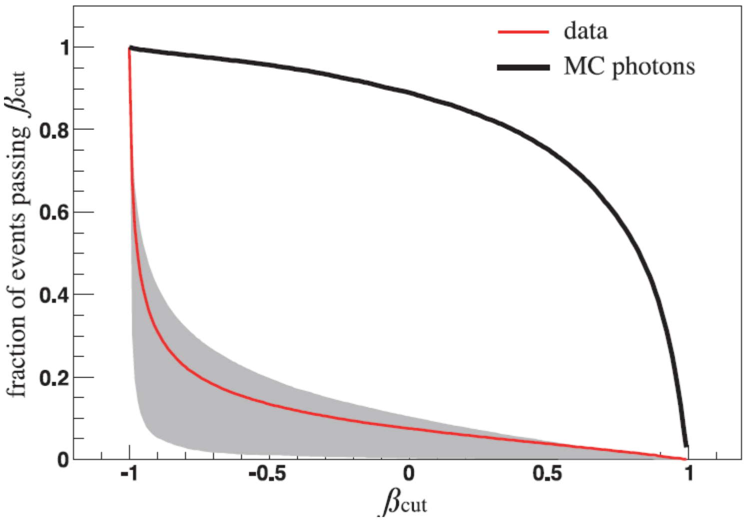
MVA response value β for proton and photon primaries using BDT.

Observables combined using boosted decision trees (BDT) as classifier

BDT trained and tested using MC simulations.

Energy and zenith angle added as input observables

γ-search method



Dataset :

- Hybrid events (detected by both SD and FD) collected between 1 Jan 2005 and 30 Sep 2011
- Energy: $10^{17.5}$ eV - $10^{18.5}$ eV
- Zenith angle < 60°
- High-quality reconstruction
- 241466 events

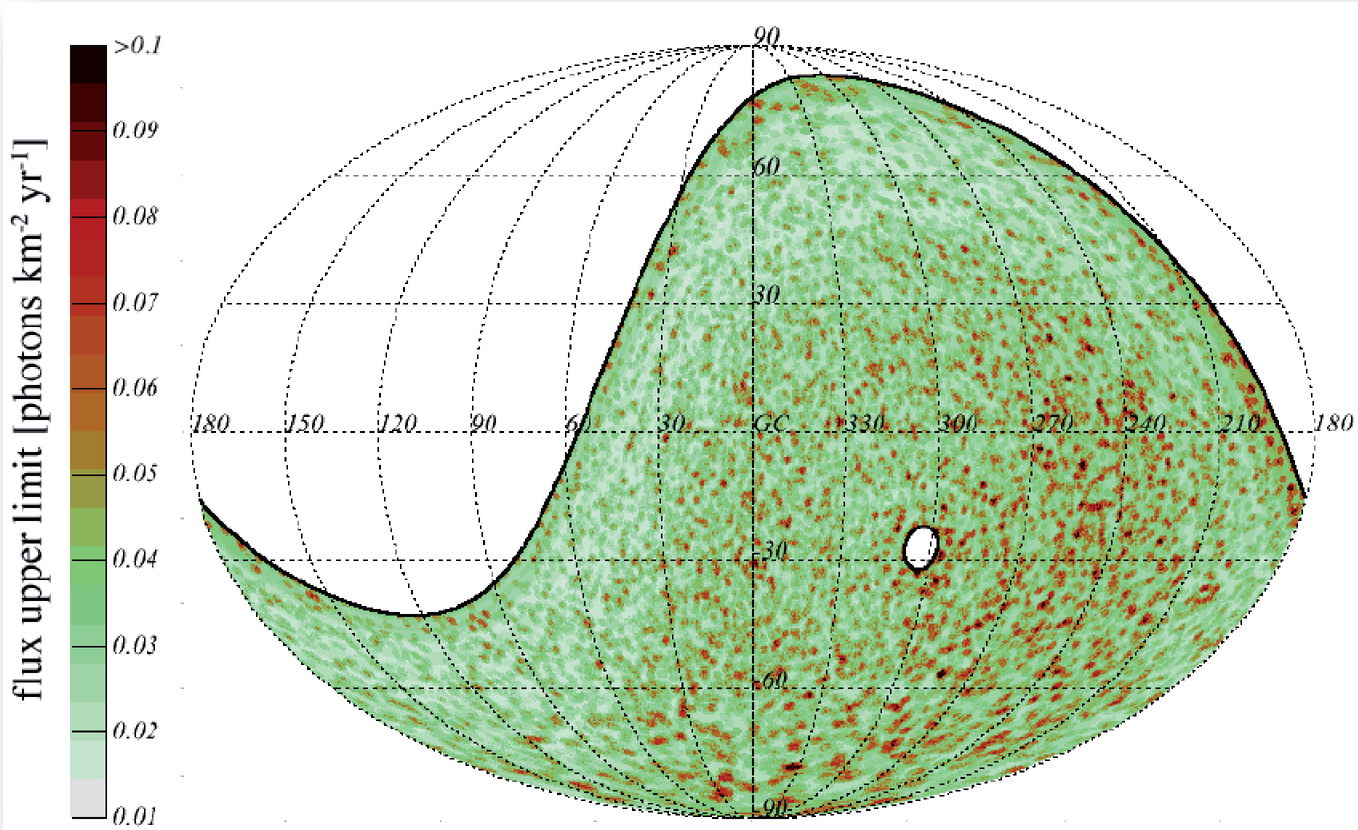
Expected background contribution from a given targed direction:

- Target centers taken as central points of a HEALPPix grid of the sky map
- Declination: -85°< δ < 20° (~ 0.3° separation)
- Expected signal from a point source contained in a top-hat counting with radius 1°
- 0.7° angular resolution

Photon exposure

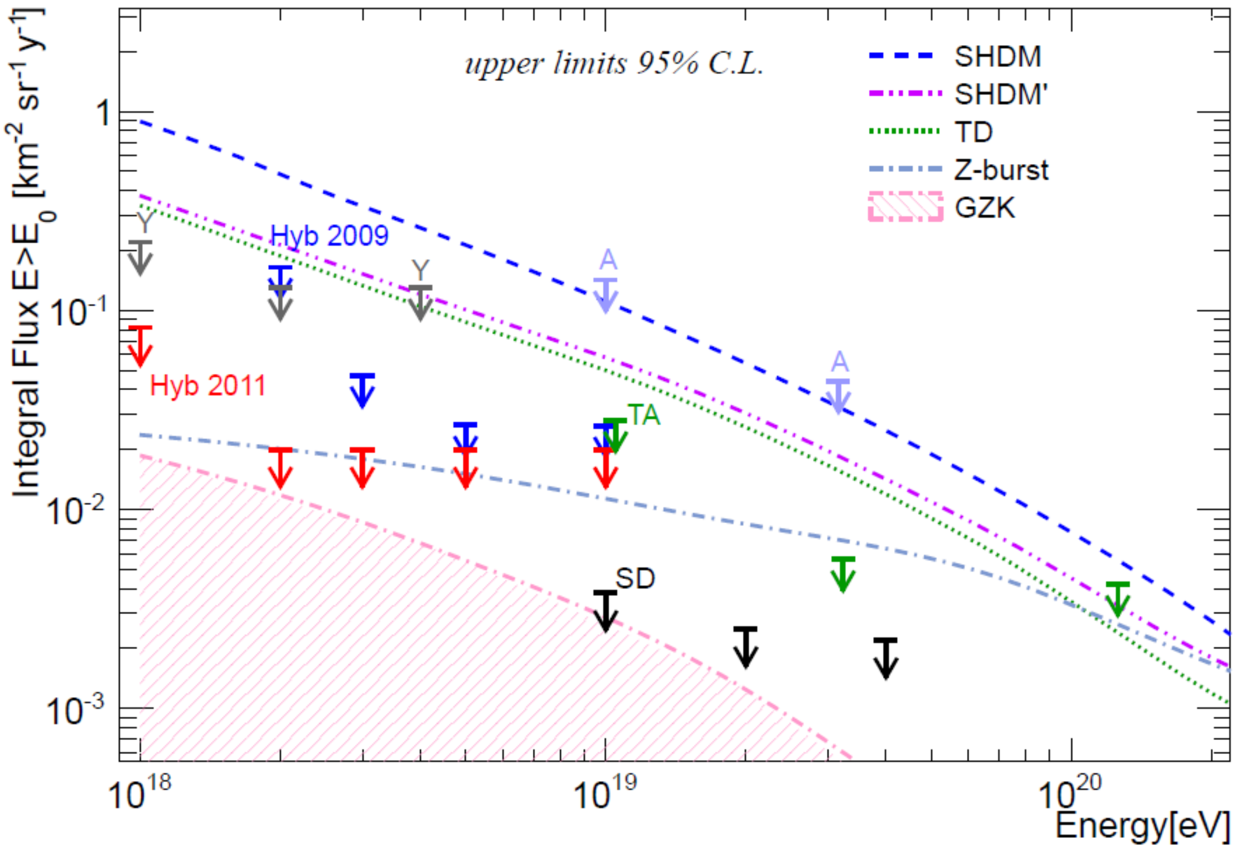
- Calculated using time-dependent simulations

Upper limits to directional photon fluxes



- No significan photon point source excess observed
- Minimum p-value: 4.5 10^{-6} (chance probability = 36%)
- Photon flux upper limits < 0.14 γ km^{-2} yr^{-1} (mean = 0.035 γ km^{-2} yr^{-1}) $\longrightarrow$ Energy flux <0.25 eV cm^{-2} s^{-1}
- Expected energy flux from E^{-2} source of 0.25 eV cm^{-2} s^{-1} in EeV decade: limits on regularly emitting non-beamed photon sources constrain models for accelaration in the Galaxy of EeV protons.

Upper limits to the integral photon flux



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}

- Exotic models disfavoured
- GZK region within reach in the next few years

Auger ICRC 2011(0393)
TA ICRC 2013 (0149)

Methods to measure the muon content in shower

One of the most mass sensitive observables is the muon content of extensive air showers at ground.

Muon content also provides information about the properties of hadronic interactions at high energies.

DIRECT METHODS **:**

- Using temporal distribution of the signals measured with the SD array :
  - A multivariate method — ICRC 2013 (0860)
  - A smoothing method
- Using inclined showers — ICRC 2013 (0635)

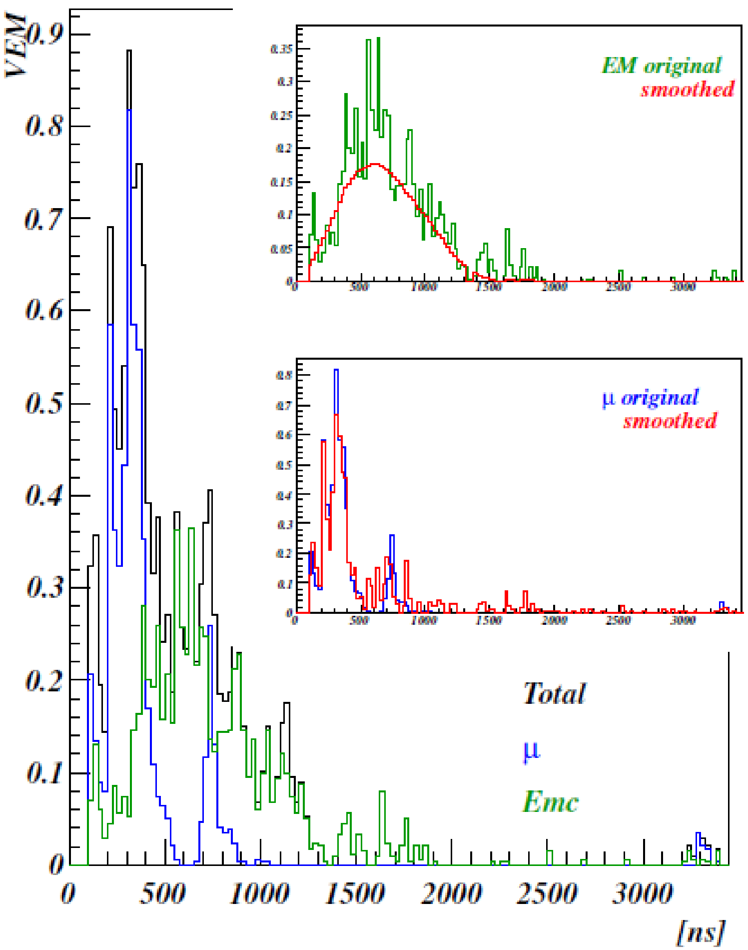
INDIRECT METHODS **:**

- Fitting of individual hybrid events — ICRC 2013 (1108)

Smoothing method

Differences between signals induced by muonic and electromagnetic (EM) components at the SD detectors:

- amplitude distribution of the particle responses: muon signal is peaky, EM signal is smooth
- arrival time distributions: muonic signal is short and high, EM signal is low and elongated



Basic idea of the method

To smooth the signal with a low-pass rectangular filter to gradually separate the low-frequency smooth EM component from the high-frequency component which is assigned to muons.

Convolute range optimized to account for the functional dependence of the average muon pulse per bin on θ

Muon signal derived from method used to estimate the muon fraction:

$$f_\mu = S_\mu / S$$

Systematic uncertainty of 5% due to hadronic models and primaries

Average resolution of 0.08

Multivariate method

Basic idea of the method

Muon fraction measured by combining muon-content characteristics of the FADC signal :

$$\hat{f}_\mu = a + b\,\hat{\theta} + c\,f_{0.5}^2 + d\,\hat{\theta}\,P_0 + e\,\hat{r}$$

Signal portion in FADC bins larger than 0.5 VEM

Normalize zero-frequency component of the power spectrum

$f_{0.5}$ and P_0 sensitive to large relative fluctuations and short signals as those when muons are signal dominant

Fit parameters (a, b, c, d, e) estimated using MC simulations

Systematic uncertainty of 2% due to hadronic models and primaries and an average resolution of 0.08

Multivariate and smoothing methods derive the muon fraction from explointing the information on the temporal estructure of the FADC signal at 1000 m from the shower core for 10 EeV showers with $\theta < 60°$

Background of high-energy γ´s < 10% (15%) for proton (iron) showers.

Muon content from inclined showers (θ>60°) (I)

- Muons dominate at ground as the EM component is absorbed in the atmosphere
- Inclined showers generate asymmetric and elongated patterns patterns in the SD array

Basic idea of the method

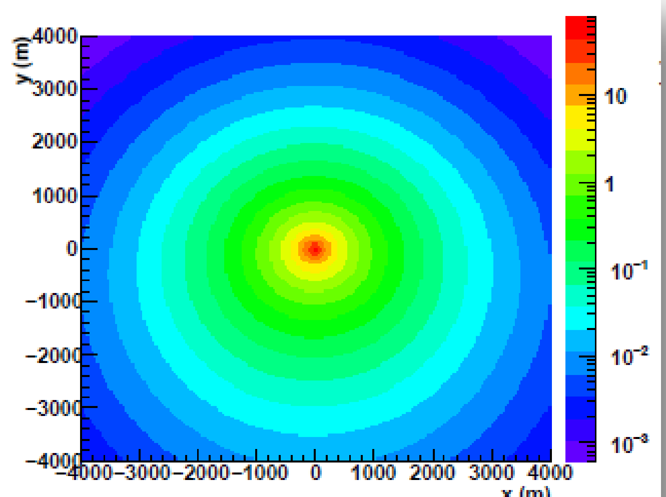
Muon content for each shower is estimated via a scale factor (the shower size parameter, N_{19}) so that a simulated reference distribution of the lateral muon density fits the data

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

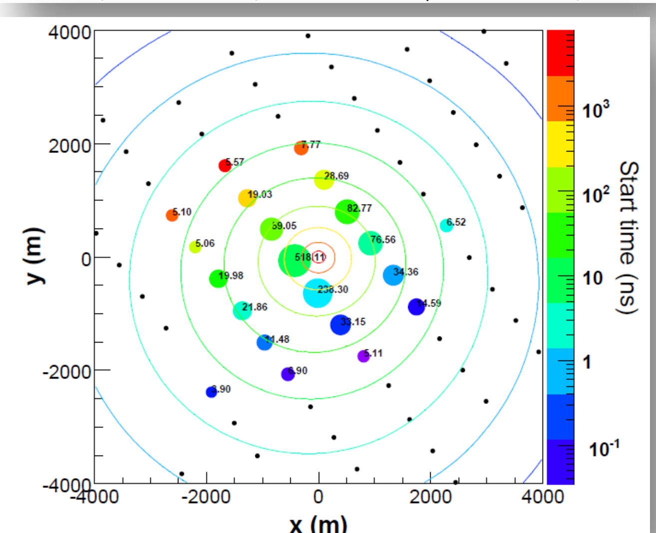
Model prediction for muon density at ground used to fit the signals recorded at the detectors

Reference profile from parameterisation of muon density at ground of 10 EeV proton showers simulated with QGSJetII-03

N_{19}: the relative number of muons at ground wrt the density muons of the refence distribution $N_{19} = N_\mu / N_{\mu,19}$



Example of reference profile for θ = 60°, ϕ=0° and core (x,y)=(0,0)



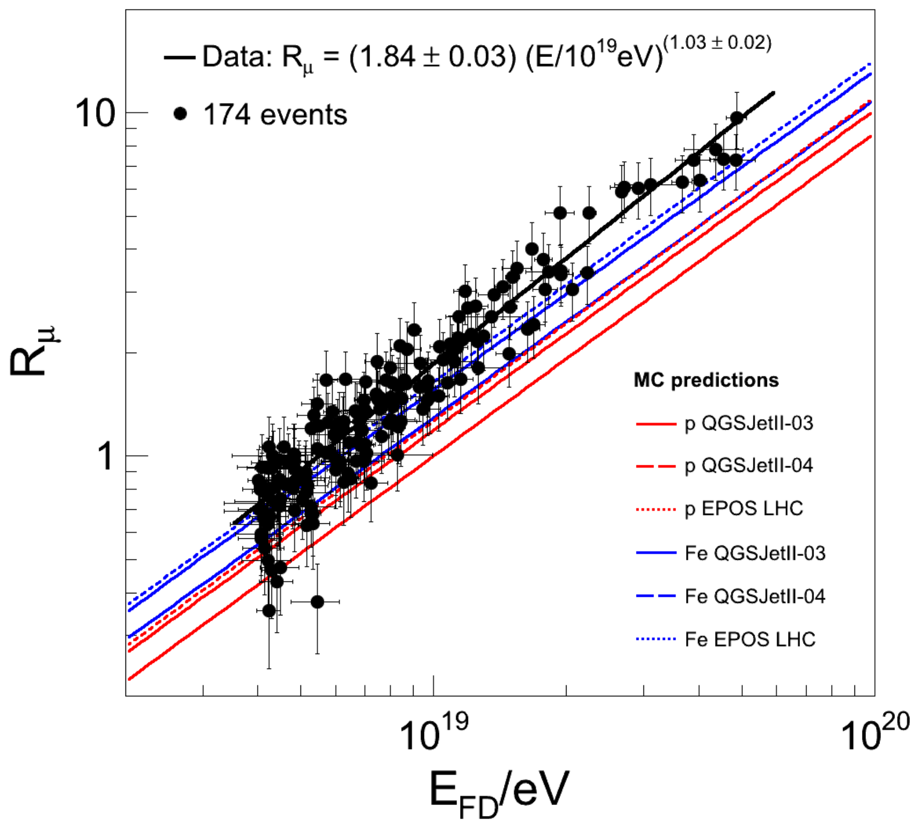
Example of event projected onto the shower plane with the contour plot of the fitted distribution superimposed.

Muon content from inclined showers (θ>60°) (II)

N_{19} provides a direct measurement of the relative muon number with bias < 5% (tested with MC):

- $\boldsymbol{R_\mu}$ defined as the measured N_{19} after correction for the average bias.

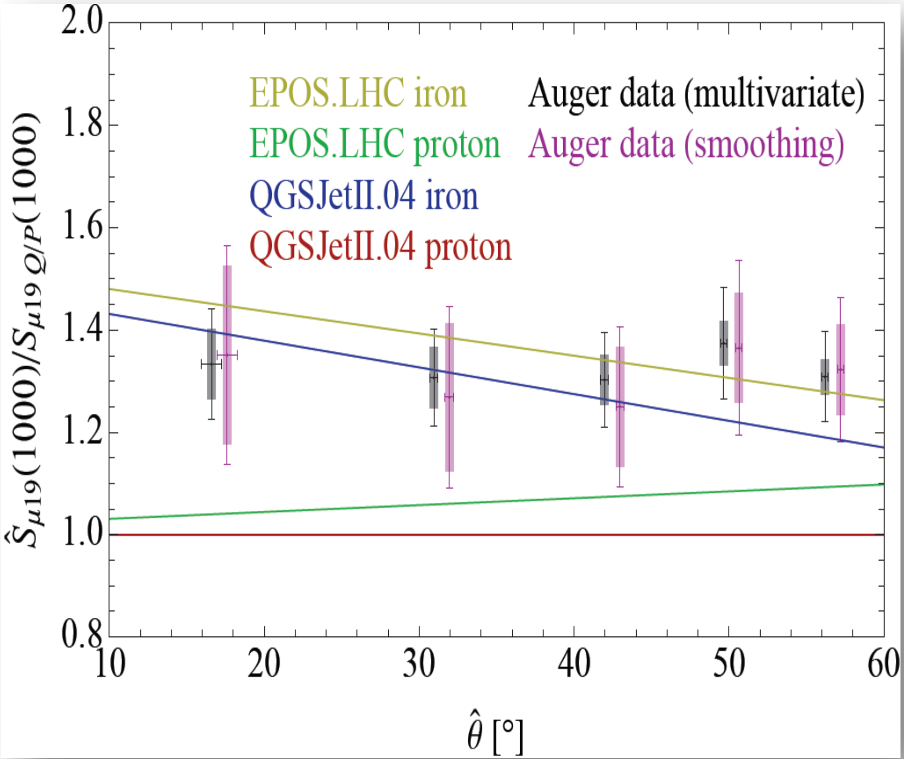
The average muon content $\boldsymbol{R_\mu}$ is obtained as a function of the calorimetric energy from high-quality events measured simultaneously with the SD array and the FD.

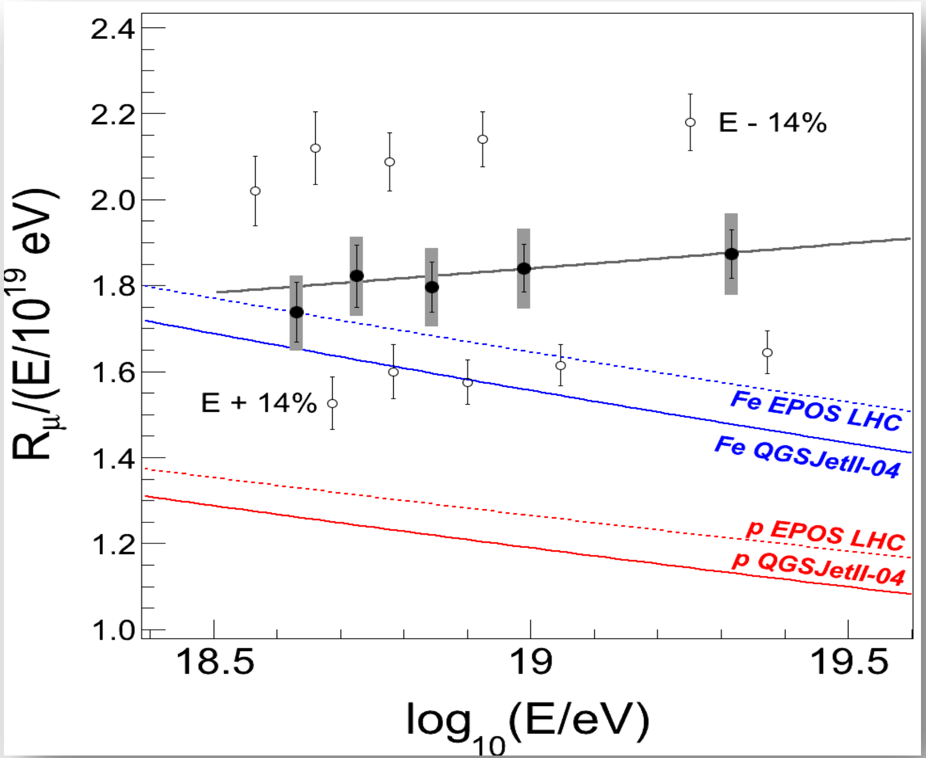


Direct measurements of the muon content

Multivariate: 1.33 ± 0.02 (stat) ± 0.05 (sys)
Smoothing: 1.31 ± 0.02 (stat) ± 0.09 (sys)

Inclined ev. (at 10 EeV): 1.84 ± 0.03 (stat) ± 0.08 (sys)

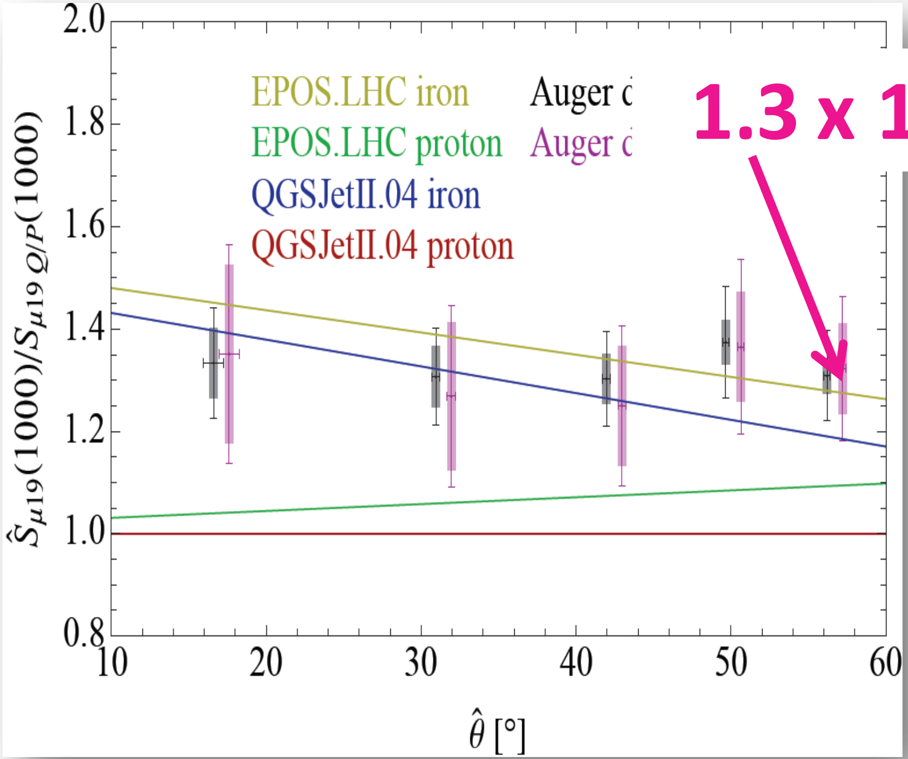


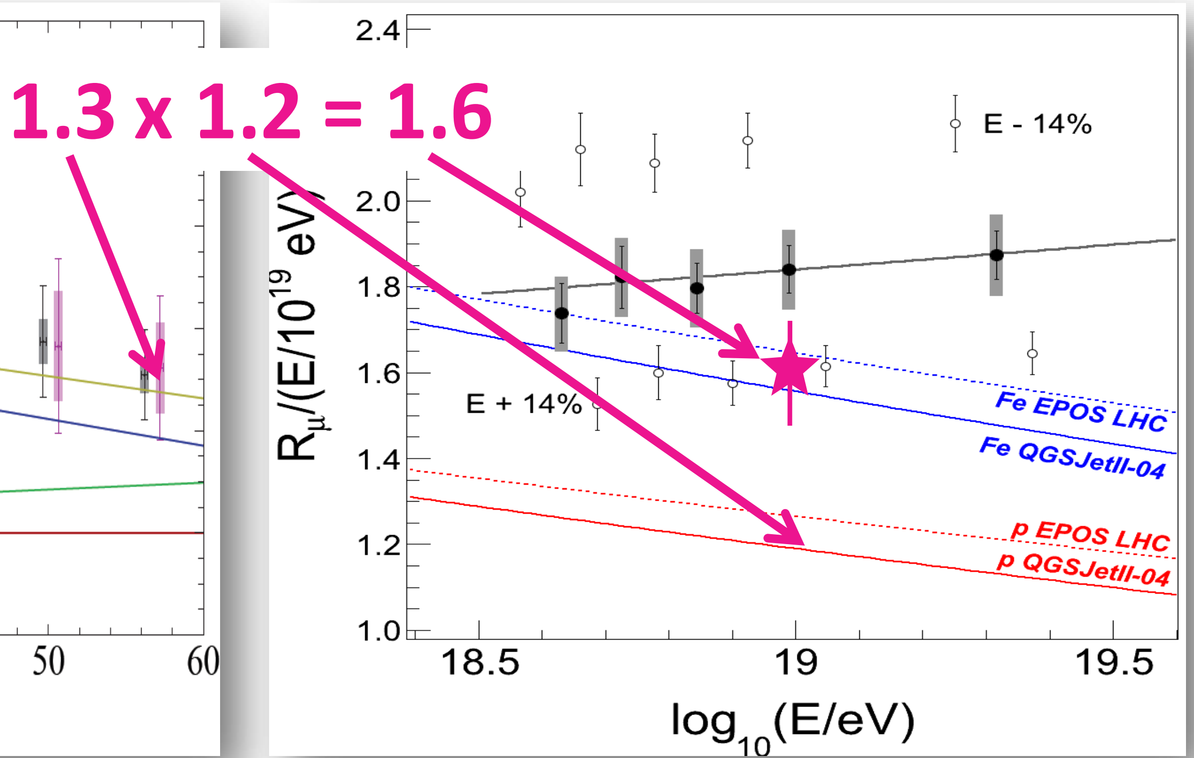


- From FADC traces at 1000 m from shower core
- SD events with $\theta < 60°$
- Reconstructed energy: $10^{18.98} - 10^{19.02}$ eV
- Normalized to QGSJetII-04 and EPOS LHC

- From inclined showers
- Hybrid events with $62° < \theta < 80°$
- Calorimetric energy measured with FD
- Normalized to QGSJetII-03

Direct measurements of the muon content





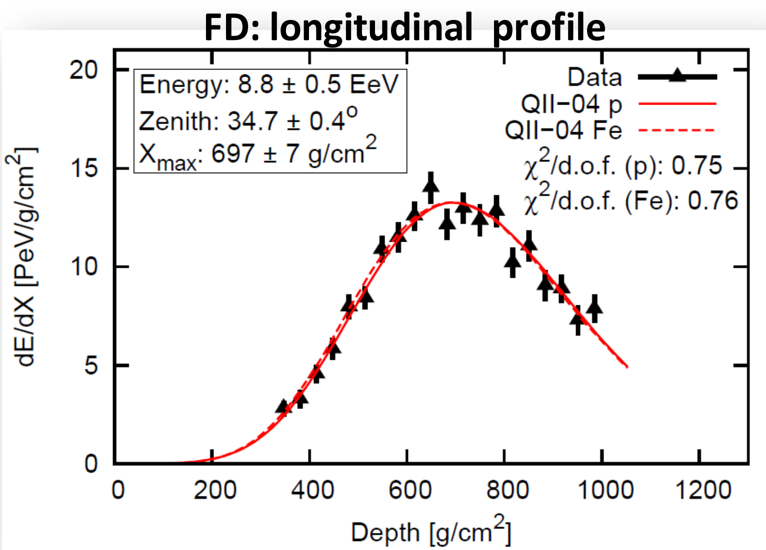
- From FADC traces at 1000 m from shower core
- SD events with $\theta < 60°$
- Reconstructed energy: $10^{18.98} - 10^{19.02}$ eV
- Normalized to QGSJetII-04 and EPOS LHC

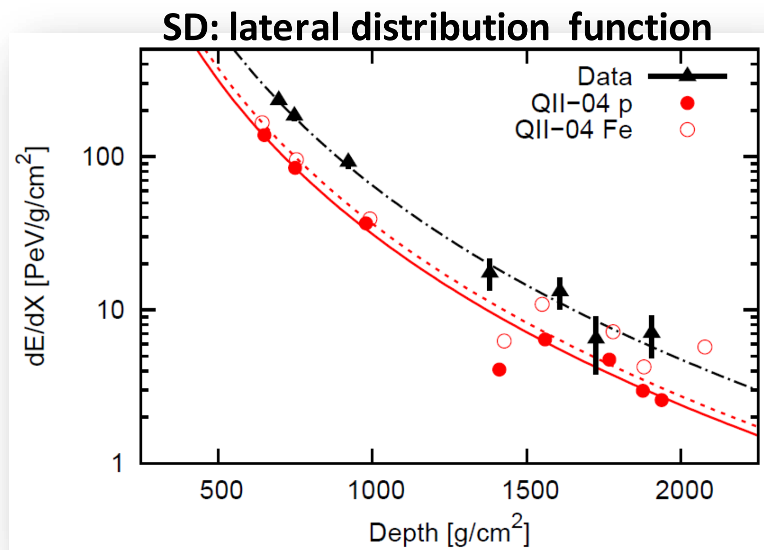
- From inclined showers
- Hybrid events with $62° < \theta < 80°$
- Calorimetric energy measured with FD
- Normalized to QGSJetII-03

Muon content from hybrid events

Basic idea of the method

- For each event, find simulations which match measured FD profile
- Compare the ground signals between the simulations and data
- Rescale muon content so that simulated ground showers best-match observed ones.

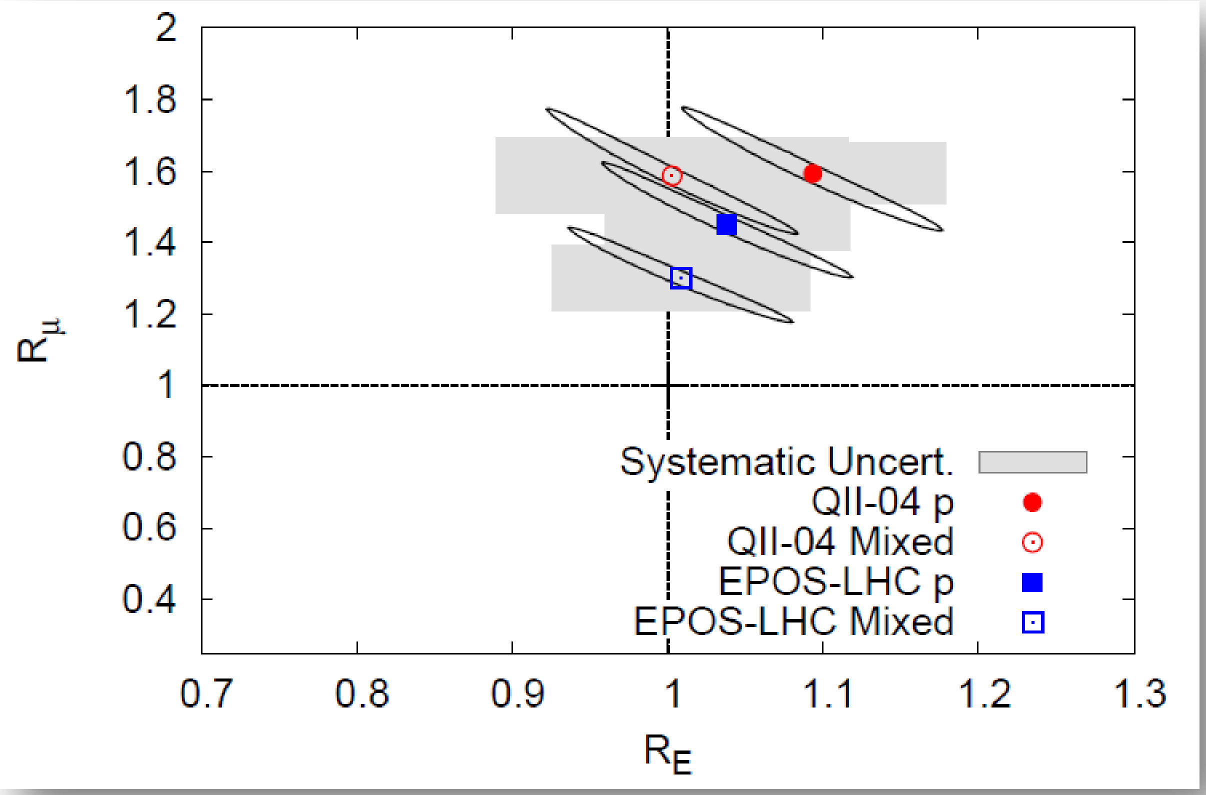




$$S_{\mathrm{resc}}(R_E, R_\mu)_{i,j} \equiv R_E\, S_{EM,i,j} + R_E^\alpha\, R_\mu\, S_{\mu,i,j}$$

R_E: energy rescaling factor, that rescales both EM and muonic components
R_μ: muon rescaling factor, that rescales only the muonic component
α : energy scaling of the muonic signal = 0.89 for both hadronic models

Indirect measurement of the muon content



Model	R_E	R_μ
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 Mixed	$1.00 \pm 0.08 \pm 0.11$	$1.59 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS Mixed	$1.01 \pm 0.07 \pm 0.08$	$1.30 \pm 0.13 \pm 0.09$

- No energy rescaling needed
- Hadronic showers too small

Summary

No neutrinos or photon candidates found yet :

- ✓ constrain exotic production and galactic models
- ✓ getting closer to cosmogenic production models

Measurements of the muon content in showers:

- ✓ Direct (indirect) results comparable with Fe-like (mixed-like) predictions from post-LHC models.
- ✓ Observed X_{max} distribution (EM component) not compatible with Fe-dominated composition: discrepance between data and hadronic interaction models.