Search for upward-going extensive air-showers at the Pierre Auger Observatory

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The Pierre Auger Observatory

about 400 members, 17 countries

Surface detector (SD)

an array of 1660 Cherenkov stations on a 1.5 km hexagonal grid (~ 3000 km²)

Fluorescence detector (FD)

4+1 buildings overlooking the array (24+3 telescopes)

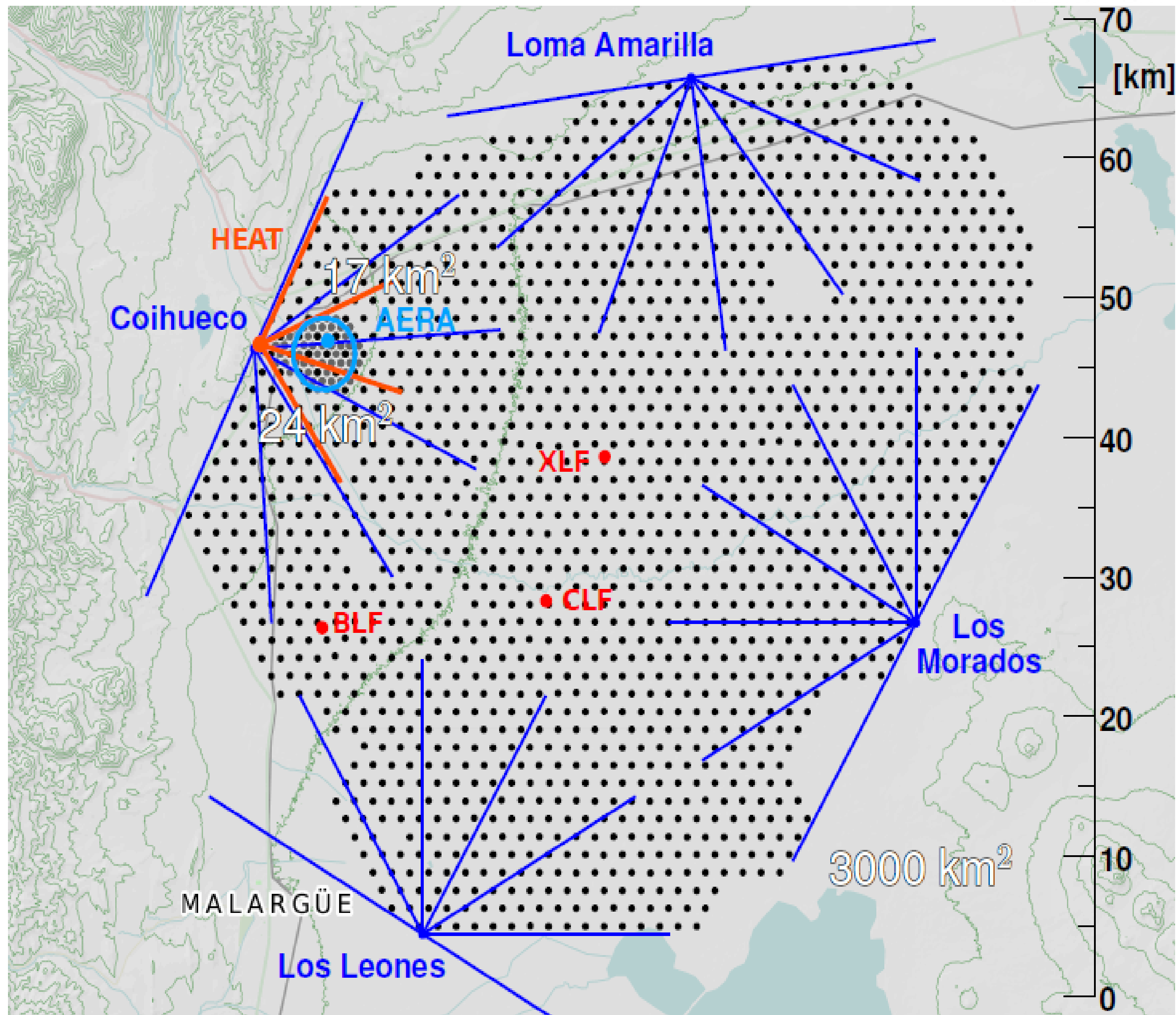
Radio detector (RD)

153 Radio Antenna → AERA

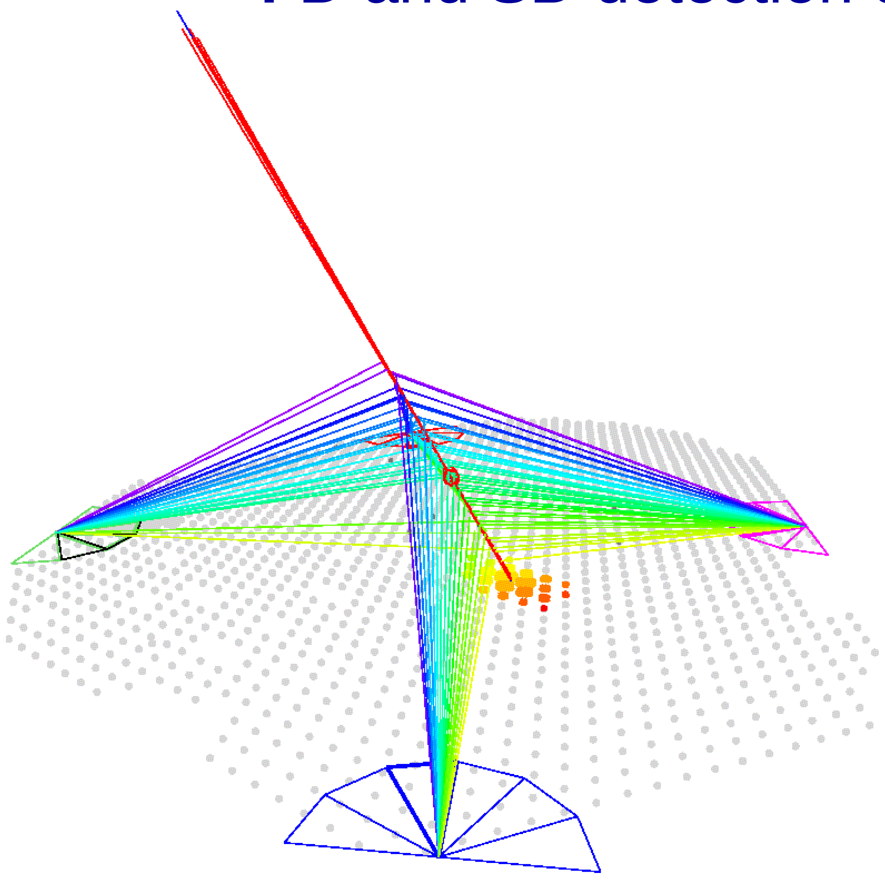
Low energy extensions

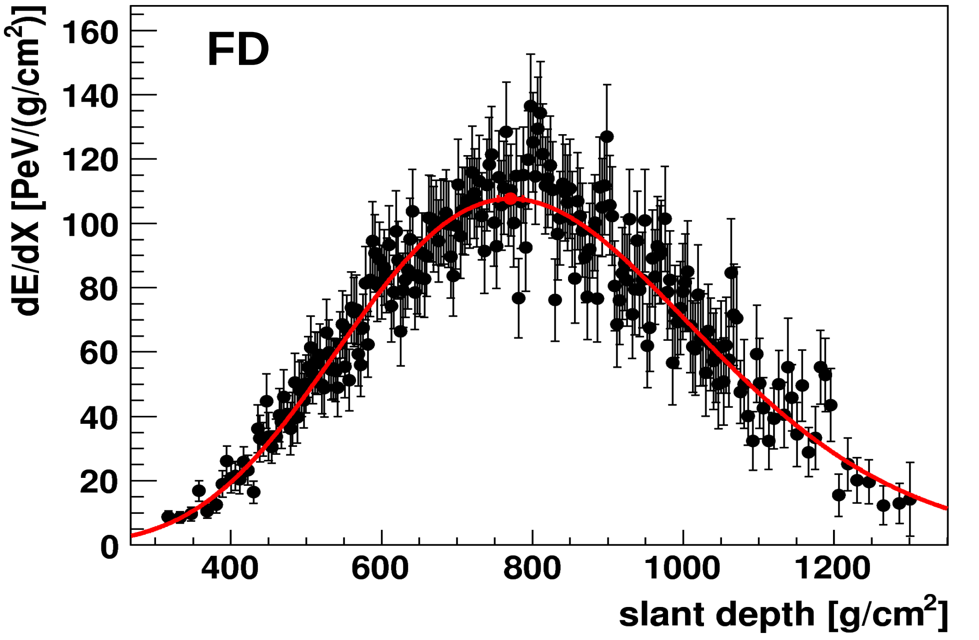
- Dense array (24km²) plus muon detectors → UMD
- 3 further high elevation FD telescopes → HEAT

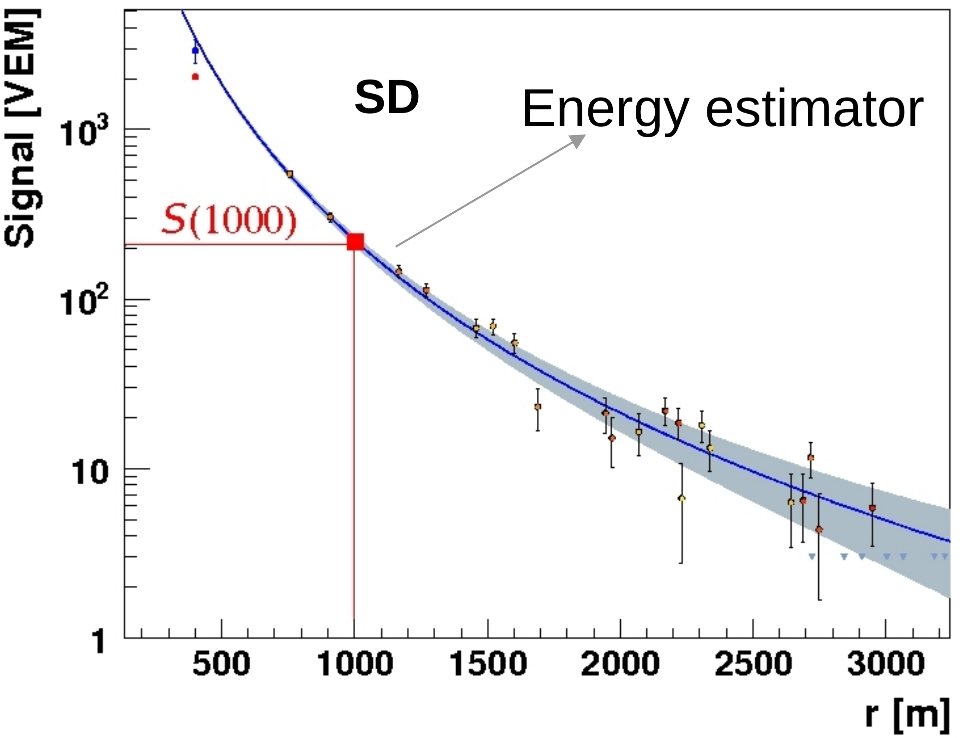
3000 km²



FD and **SD** detection concept







Longitudinal profile

FD - calorimetric measurement

- duty cycle 15%

Density of particles at the ground

SD - duty cycle ~ 100%

Use the energy scale provided by FD to calibrate the entire SD data sample

The Pierre Auger Observatory as a detector of upward-going extensive air-showers

Standard search with the SD

“earth-skimming” channel
90°< zenith < 95°

UHE neutrinos interacting in the Earth crust → taus→ upward-going air-showers

Pierre Auger Coll., JCAP 10 (2019) 022

Multimessenger (TXS0506)

Pierre Auger Coll., Ap. J., 902:105 (2020)

neutrino physics and astronomy

“New” search with the FD

Motivated by the “anomalous” ANITA events, zenith >110°

Generic search for upward-going extensive air-showers

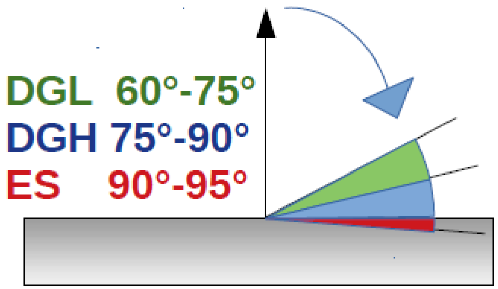
M. Mastrodicasa for the Pierre Auger Coll. PoS, ICRC2021:1140, 2021.

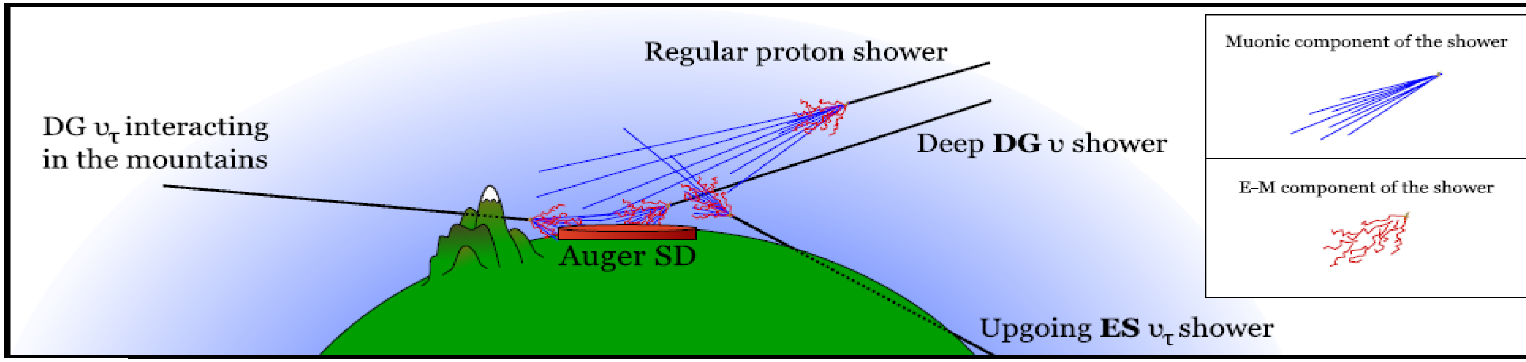
Specific tau “scenario”

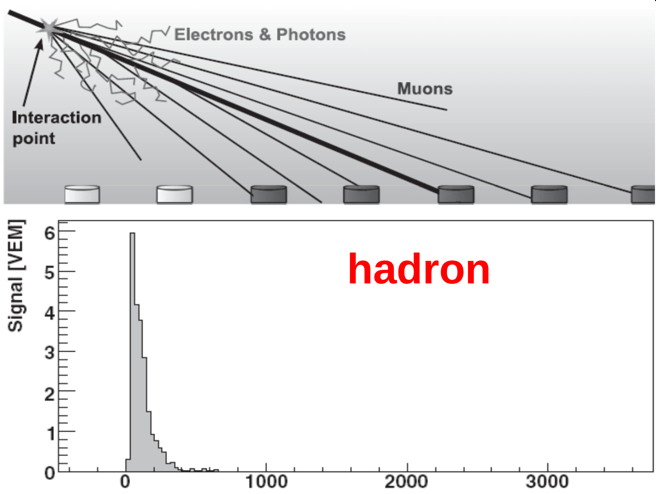
I.A. Caracas for the Pierre Auger Coll. PoS, ICRC2021:1145, 2021.

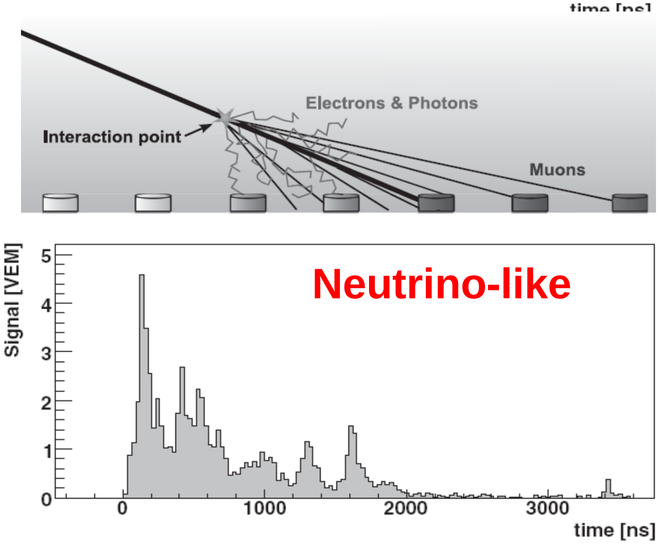
benchmark for BSM physics

UHE neutrinos with SD: detection channels and sensitivity

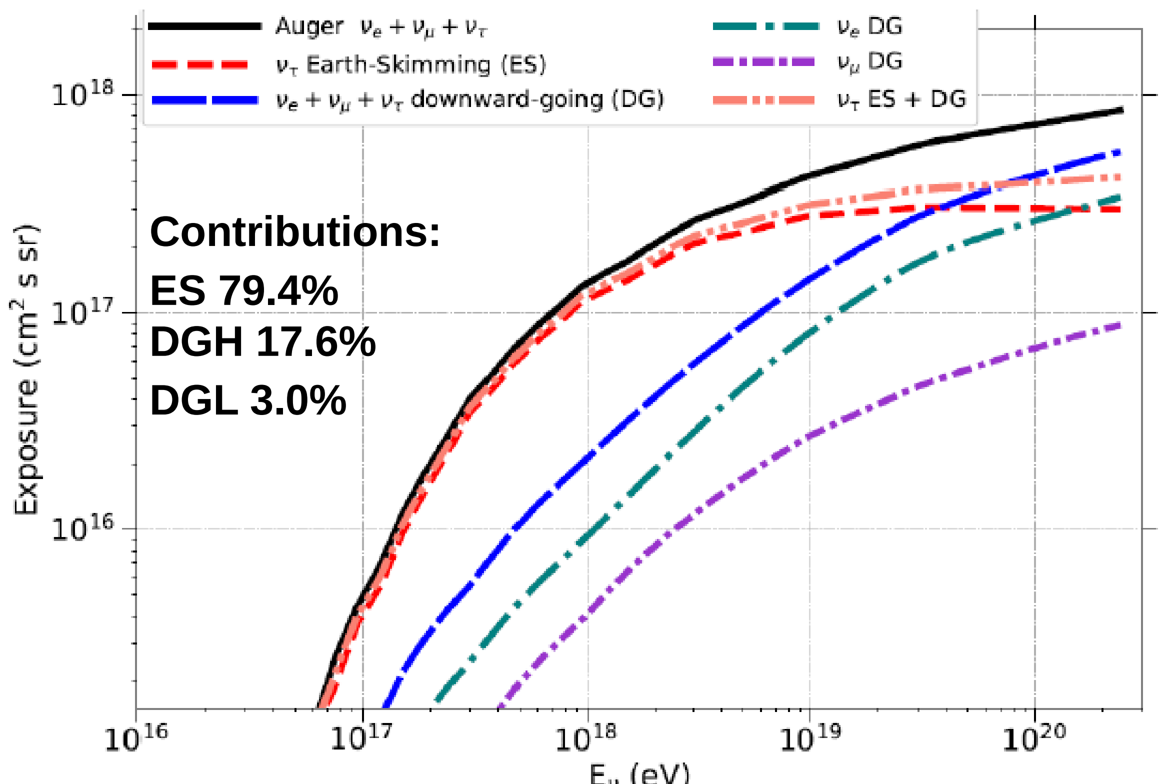








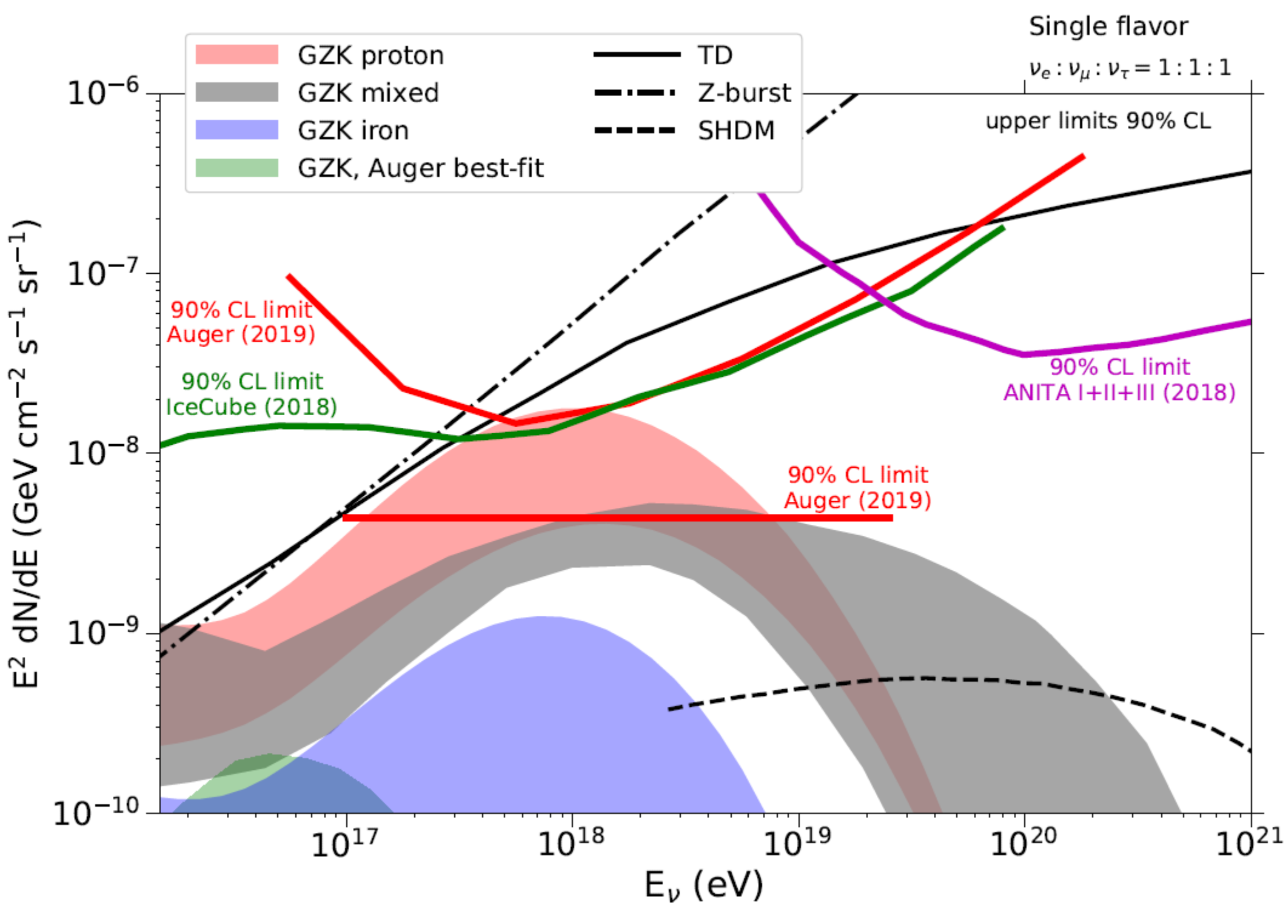
Sensitivity to different channels



ν_τ ES sensitivity dominant

Upper limits on the diffuse neutrino flux

Pierre Auger Coll., JCAP 10 (2019) 022



Identification criteria applied "blindly" to the search data set

Point-like sources

also in coincidence with observations by other experiments

For example the recent TXS 0506+056

Coincidence with GW

For example GW170817

NO Candidates found

NO Candidates found

Maximum sensitivity **~ 1 EeV**

Upper limits set assuming dN/dE = k E^{-2}

→ k ∼ 4.4 x 10^{-9} GeV cm^{-2} s^{-1} sr^{-1} [0.1 – 25] EeV

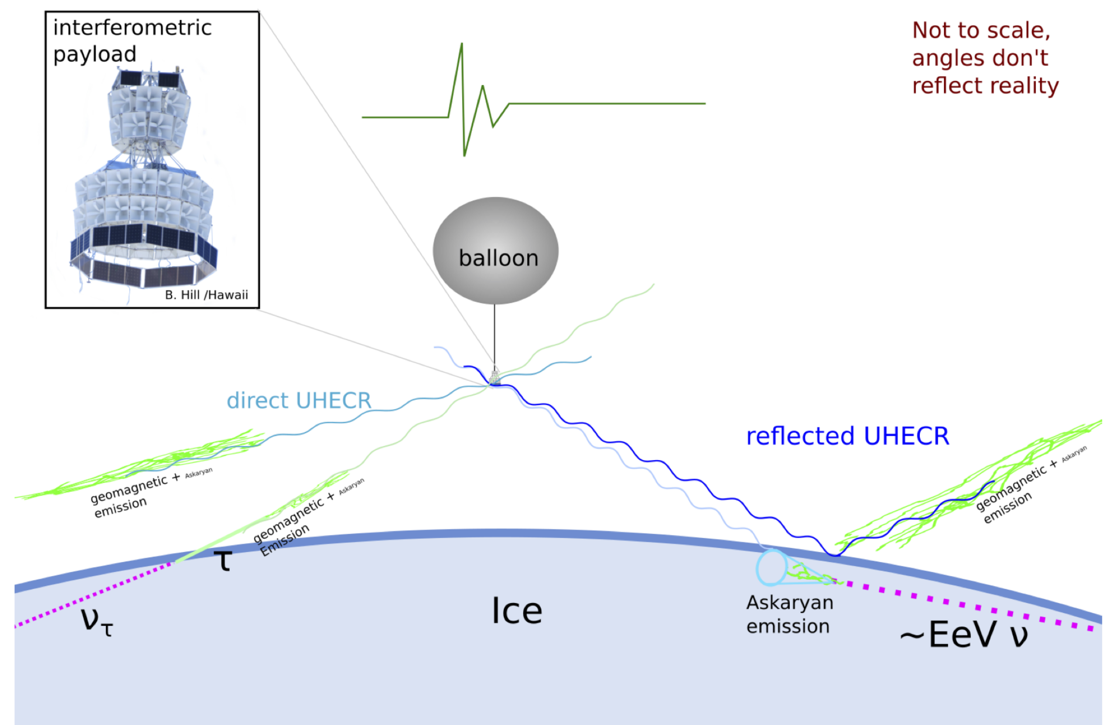
Heavy constraints on models assuming sources of CR accelerating only protons with strong evolution in z

Search for upward-going showers with FD

The ANITA experiment detected two anomalous events with non-inverted polarity, consistent with upward-going showers
PRL 117 071101 (2016)
PRL 121 161102 (2018)

$E_{1,2} \gtrsim 0.2$ EeV
exit angle $\approx 27° \approx 35°$

More recently, observation of 4 events very close to horizon
PRL 126 071103 (2021)



Fervent debate about the interpretation of these observations

- Quantify the sensitivity of the FD to upward-going showers

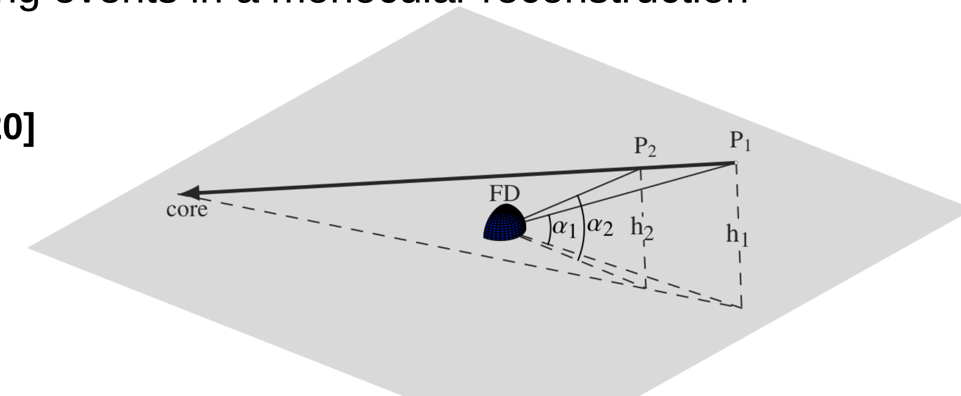
- Use 14 years of FD data (2005-2018) for a dedicated search

M. Mastrodicasa for the Pierre Auger Collaboration, PoS (ICRC2021) 1140

BACKGROUND SIMULATION

Downward-going events with specific geometries can mimic upward-going events in a monocular reconstruction

Zenith [0°- 90°]
log10 (E/eV) [17-20]



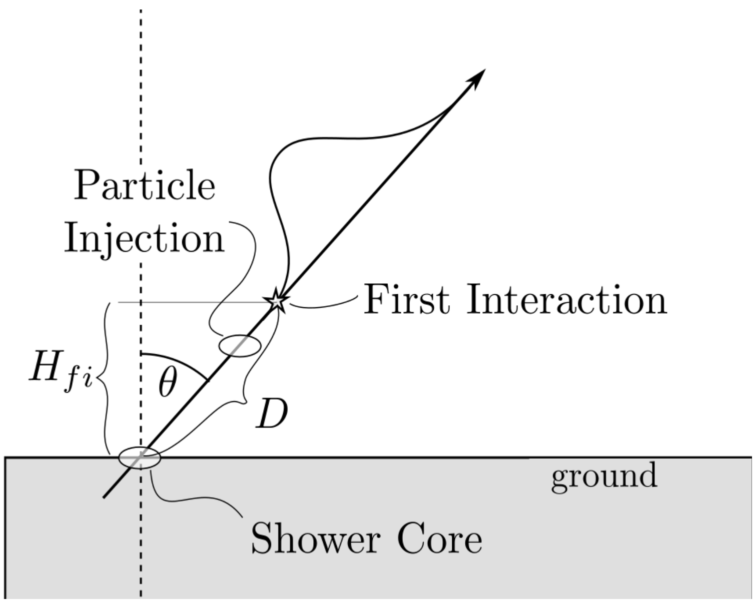
$\alpha_1 < \alpha_2$
$h_1 > h_2$

Signal from P_1 reaches the FD before the signal from P_2 → downward-going event reconstructed as upward-going

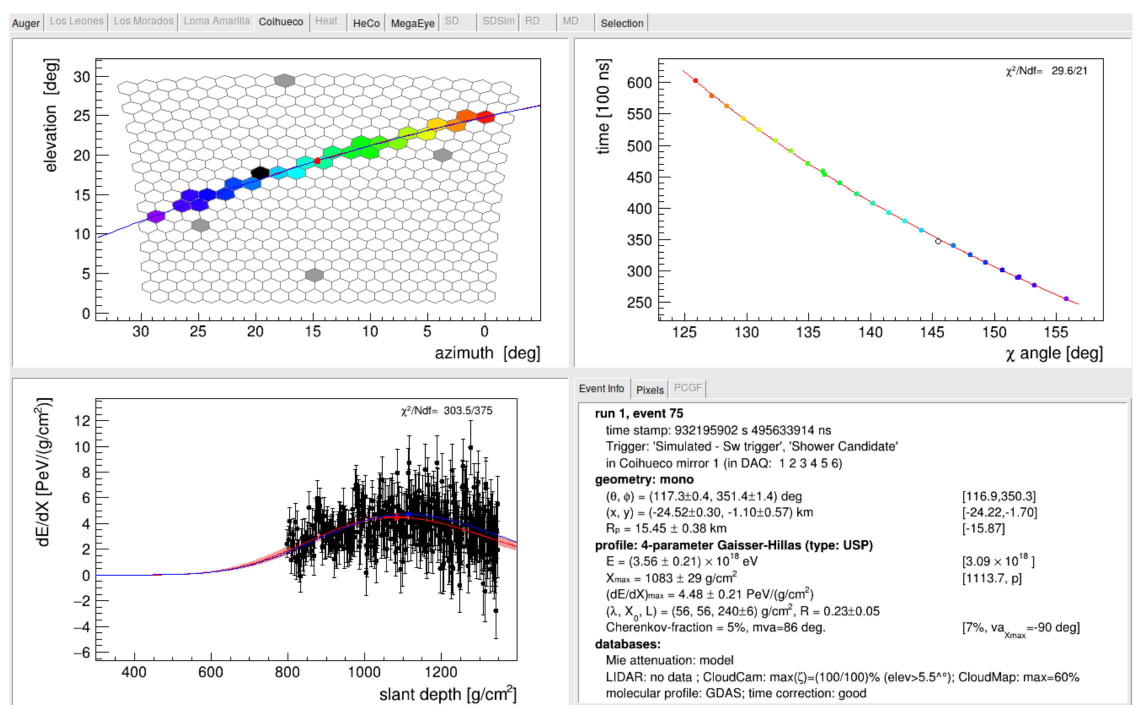
Also events with a core far away from the array can produce background and need to be simulated

Detector and atmospheric effects included in simulation: Real Monte Carlo approach

SIGNAL SIMULATION

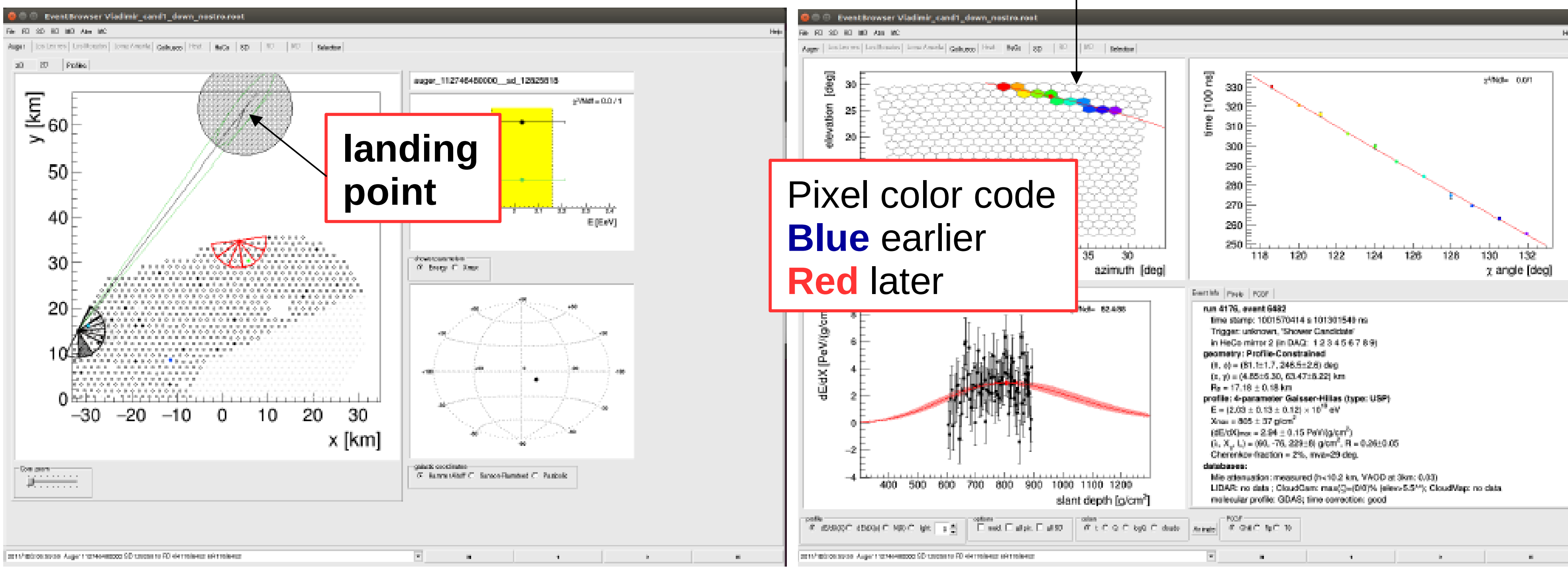


Zenith [110°- 180°]
log10 (E/eV) [16.5-18.5]



Exemplary background event
AugerId=11274648000

Time sequence in the camera just “apparently” upward-going



Inclined event (~80°) passing over Coihueco and landing behind Loma Amarilla

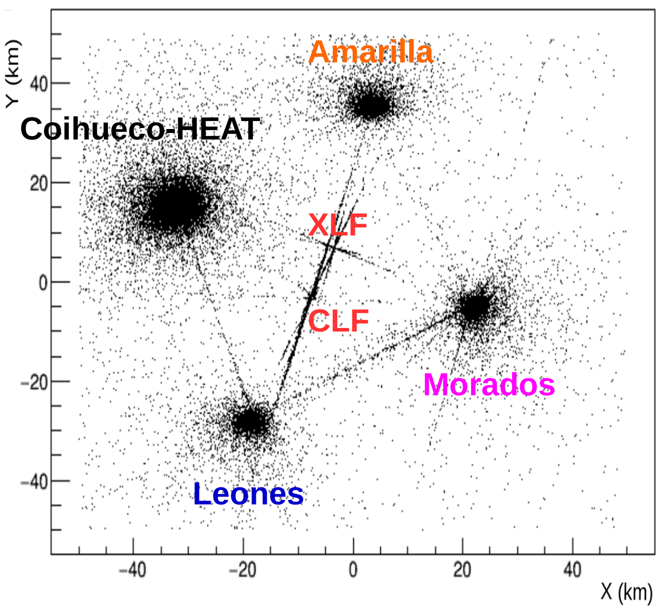
Data cleaning using a burnt data sample

Blind analysis performed using 10% of the FD data from 14 years of FD operation

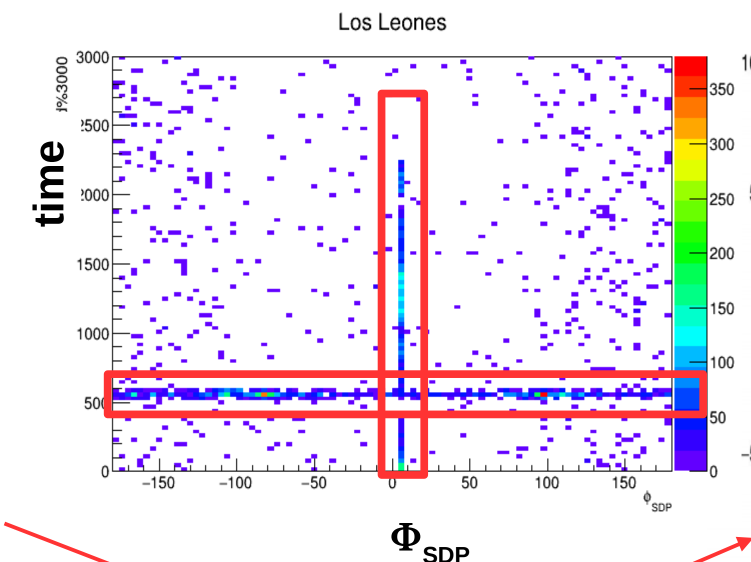
FIRST STEP: remove untagged laser events used to monitor the atmosphere

Lidar shots have a specific frequency of 333 Hz → they pile up in a GPSMicroSecond%3000 histogram

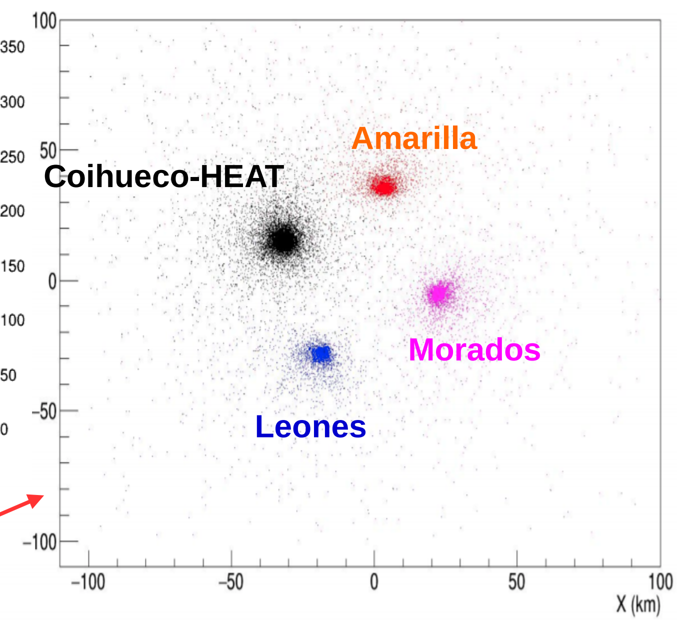
CLF and **XLF** have a known position → the angle Φ_{SDP} that define the intersection of the shower detector plane (SDP) with the ground can be used to identify the associated event



Exit points before cleaning



Data driven filtering algorithm



Exit points after cleaning

Reconstruction and candidate selection

FD reconstruction with a recursive approach to optimize geometry and profile reconstruction → **P**rofile **C**onstrained **G**eometry **F**it (**PCGF**)

Scan of parameters to allow for an upward-going geometry reconstruction, then scan over parameters leading to a downward-going solution (if any).

compare the likelihoods for both configurations

Variable used: $l=\mathrm{atan}(-2\log(\mathbf{L}_{down}/\mathbf{L}_{all})/50)/(\pi/2)$

$\mathbf{L}_{down/up}$ = maximum likelihood for the downward/upward mode

$\mathbf{L}_{all}$ = maximum bewteen $\mathbf{L}_{down}$ and $\mathbf{L}_{up}$

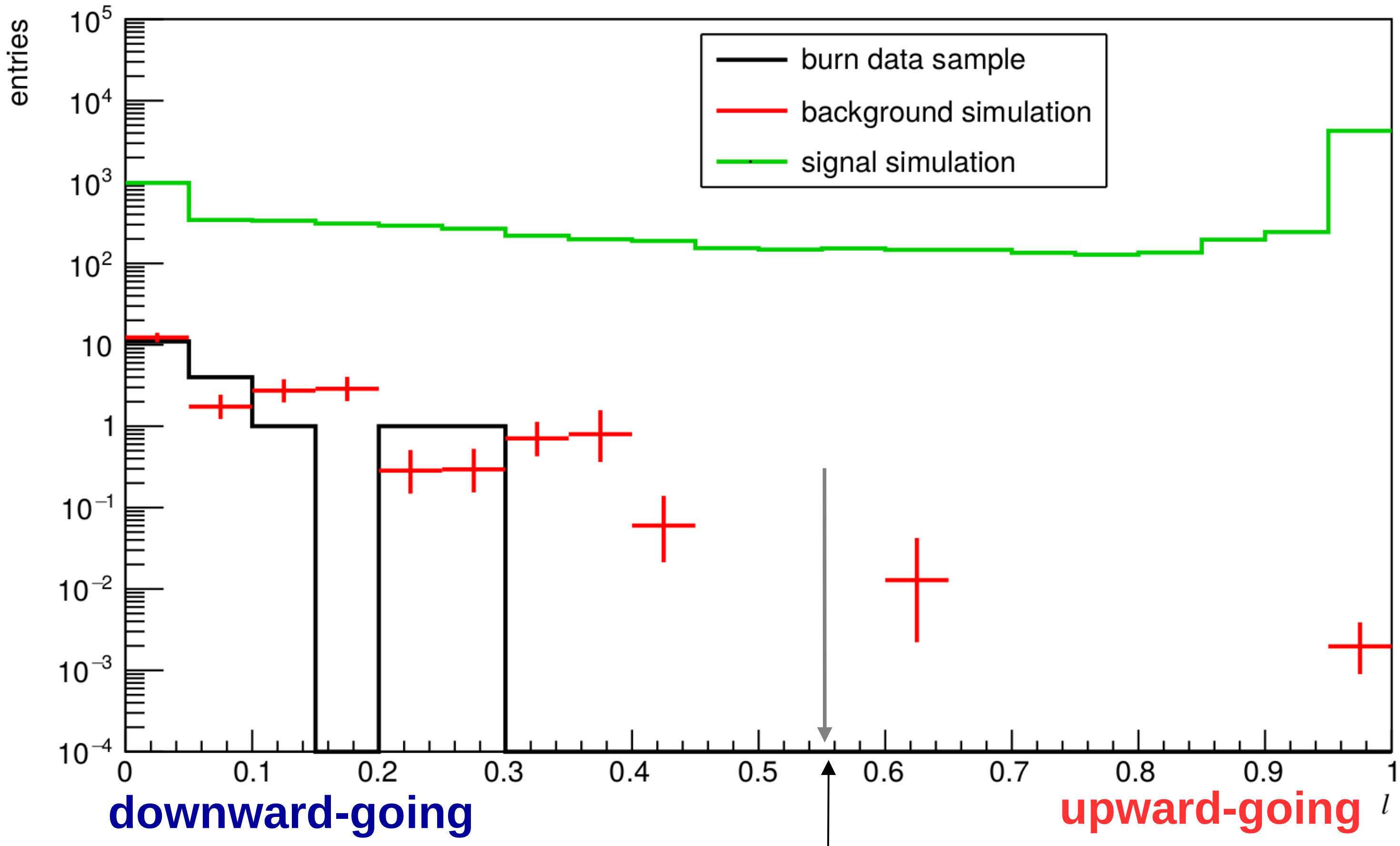
↓ $l \to \mathbf{0}$ (downward mode is favored)

↑ $l \to \mathbf{1}$ (upward mode is favored)

Signal discrimination

Set of selection cuts to preserve the quality applied to burnt sample and to simulations (signal and background). Discrimination between signal and background done through the variable l

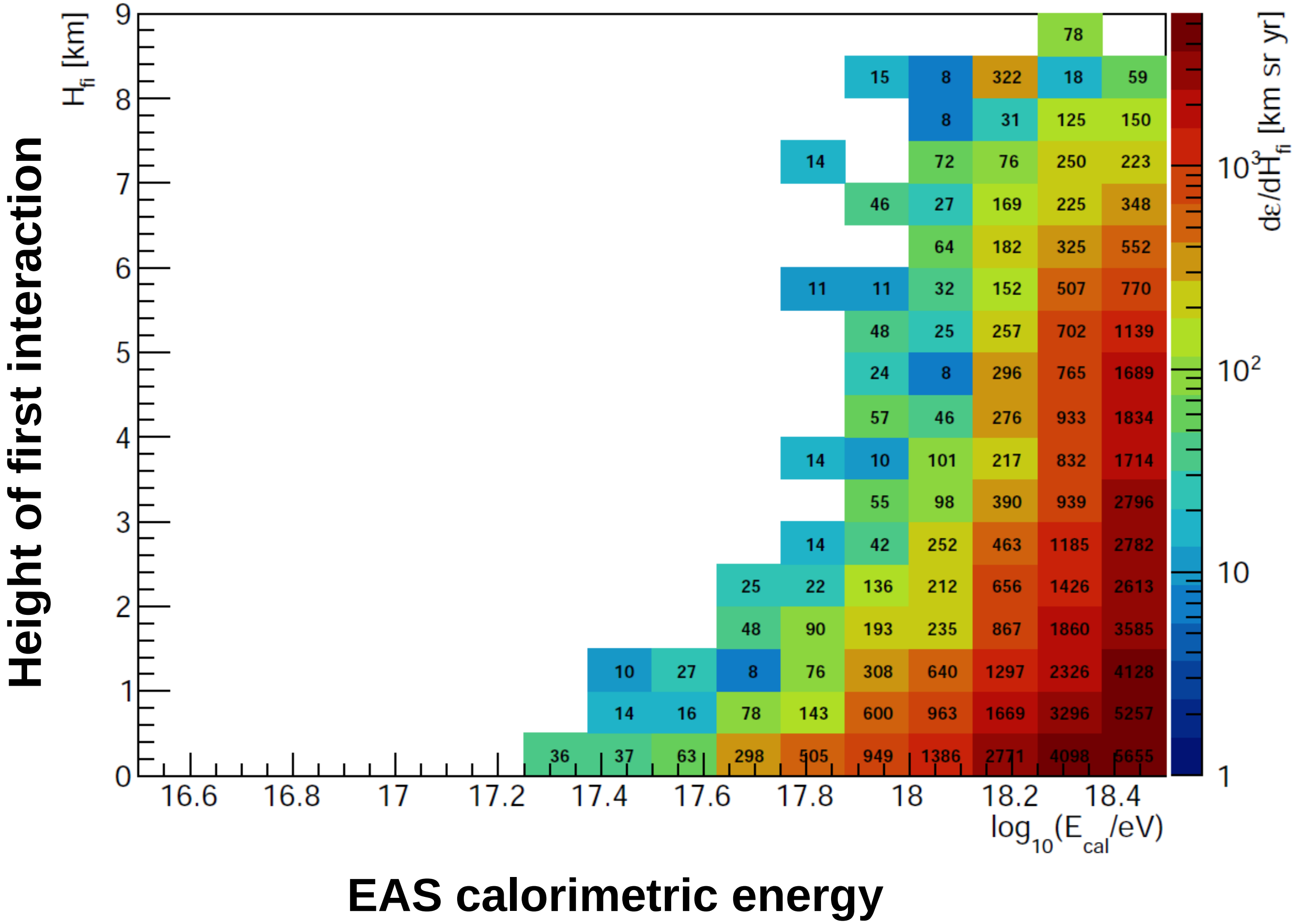
background simulation weighted to burn sample → good agreement between burn sample and background simulation



cut value on l optimized to reach the maximum sensitivity

Cut to select more likely upward-going events: $l > 0.55$

Differential Exposure in height vs energy

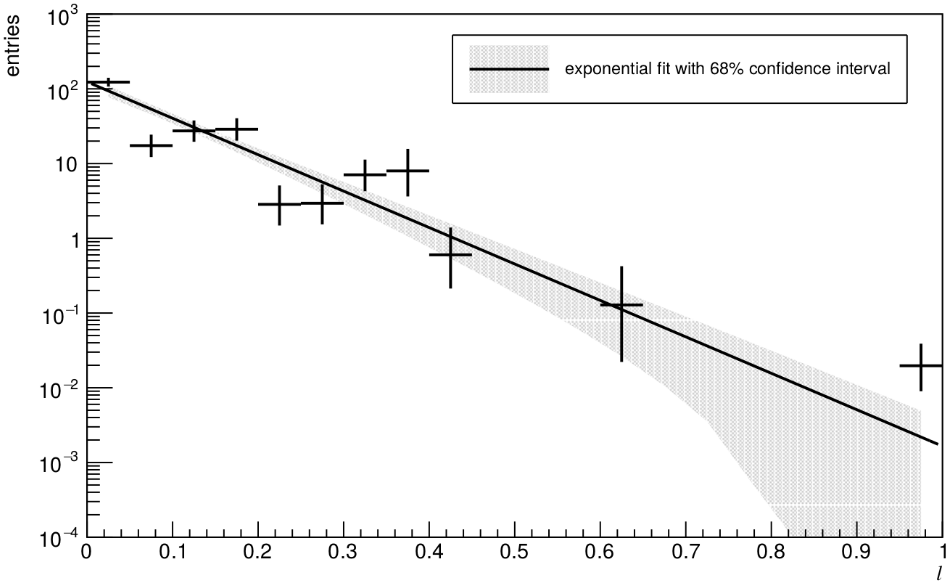


Detector sensitivity over a wide range of energies and height of first interaction

Useful to test various physics scenarios

Integral upper limits

Exponential fit to simulated background, weighted to CR flux



$\mathbf{n_{bkg} = 0.45 \pm 0.18}$

for $l > 0.55$

After the unblinding of the data **1 event** observed to pass all selection criteria. This number is consistent with the expected number of background events

FD data 2005-2018

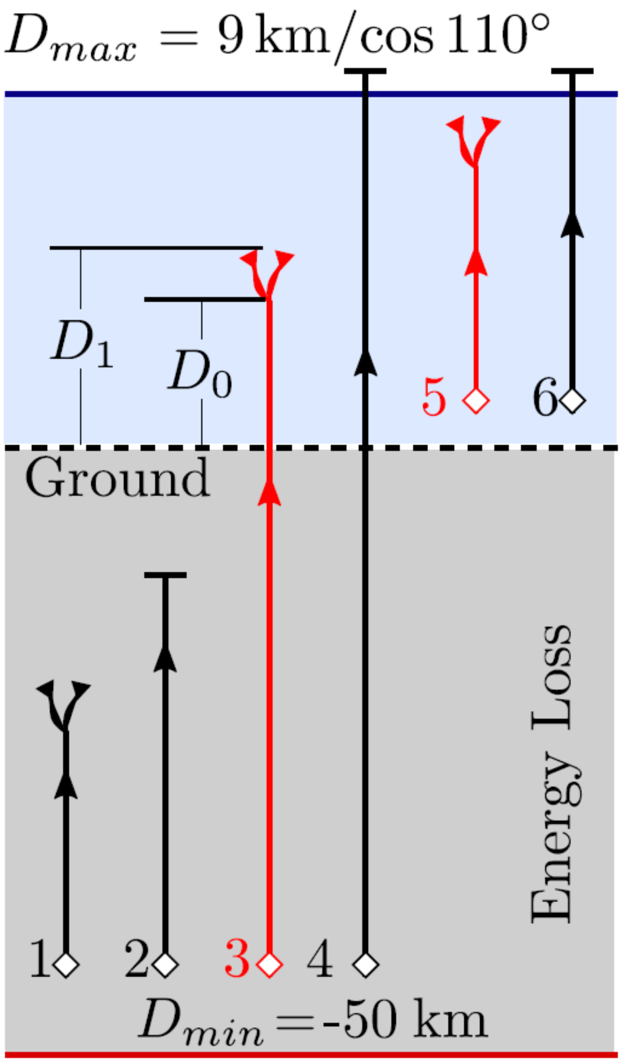
Using Rolke the **integral upper limits** for $\log_{10}(E_{cal}/eV)>17.5$ with $n_{bkg} = 0.45 \pm 0.18$ and $n_{obs} = 1$ is:

→ **3.6×10^{-20} cm^{-2} sr^{-1} s^{-1}** if exposure is weighted with **E^{-1}**

→ **8.5×10^{-20} cm^{-2} sr^{-1} s^{-1}** if exposure is weighted with **E^{-2}**

A specific case: the tau scenario

I. Caracas for the Pierre Auger Collaboration, PoS (ICRC2021) 1145



Tau propagation --> NuTauSim
J. Alvarez-Muñiz et al., Phys. Rev. D 97 (2018) 023021

Tau decay → Tauola
M. Chrzaszcz, et al. Comput. Phys. Commun. 232 (2018) 220

main decay branches considered
$e^{+/-}$, $\pi^{+/-}$, π^0, $K^{+/-}$, K^0, contributing to the formation of air showers.

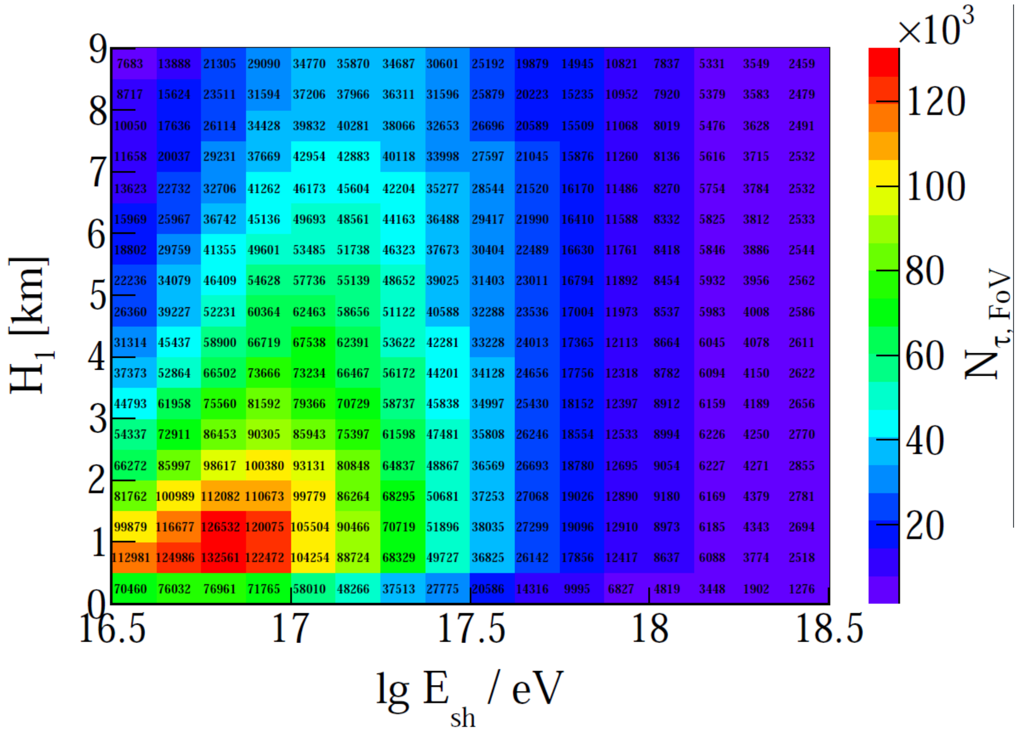
Dmin set by the tau range in standard rock

Dmax set by the FoV of the FD

Channel **3** and **5** are producing air showers within the field of view of FD

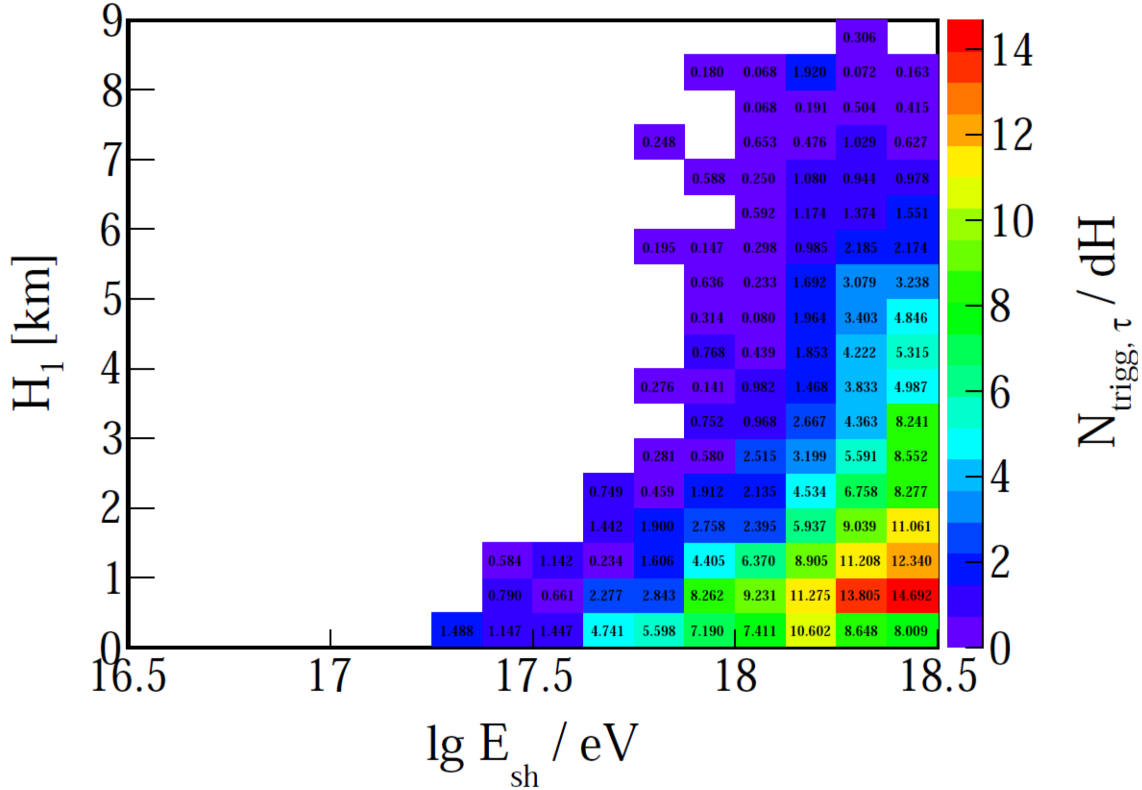
Height of first interaction H1 derived from average of the first interaction depth of each secondary, zenith and atmospheric profile

Folding the FD response with taus in FOV



⊗ FD detector acceptance for generic upwards-going EAS

Observable events

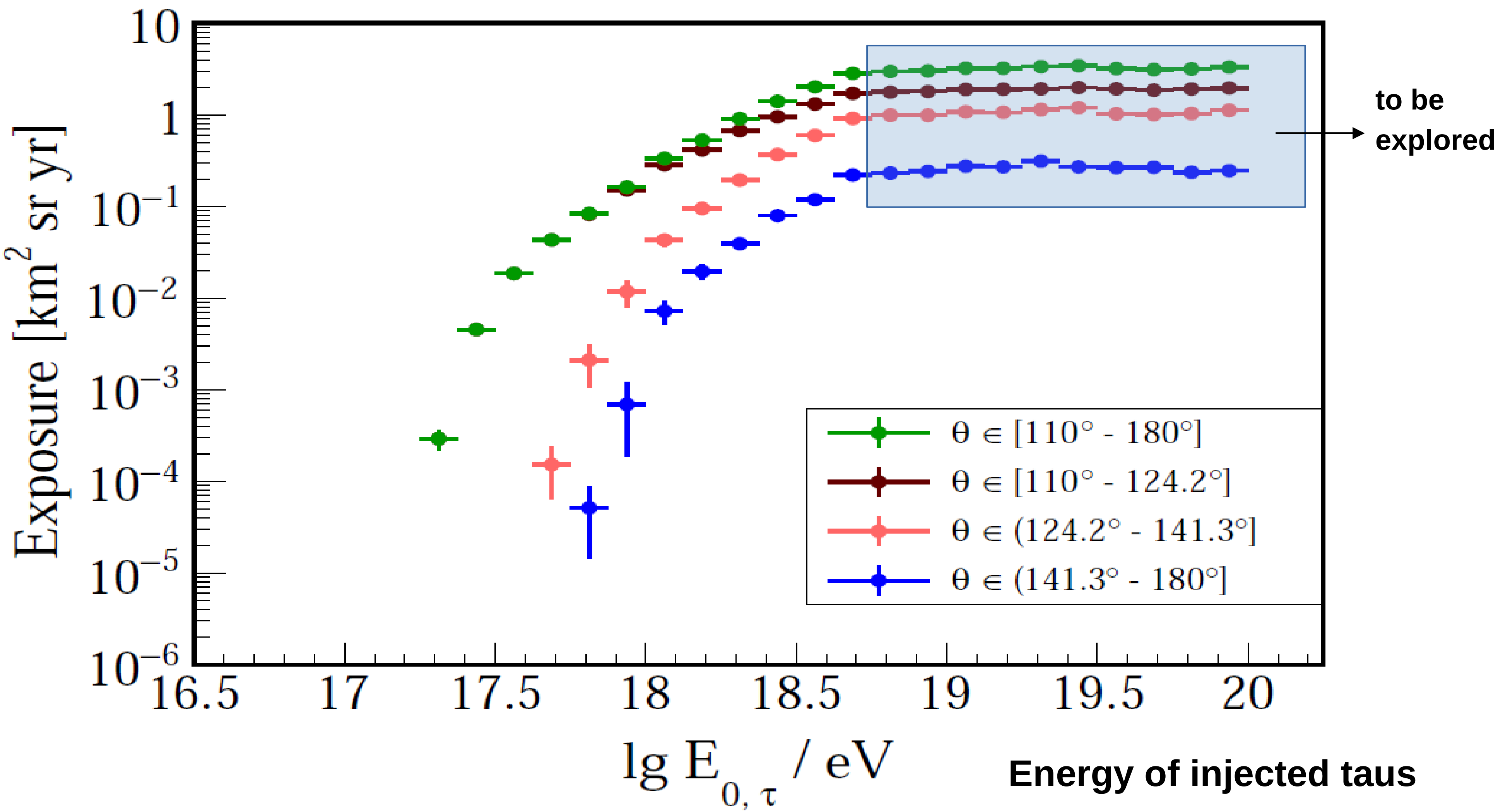


H_1 → height of first interaction

E_{sh} → energy of the induced shower

Selection criteria and energy range inherited from the generic search

Exposure for different zenith bands



lgE < 18.5 increasing detector efficiency with energy mitigated by the lengthening of tau decay length

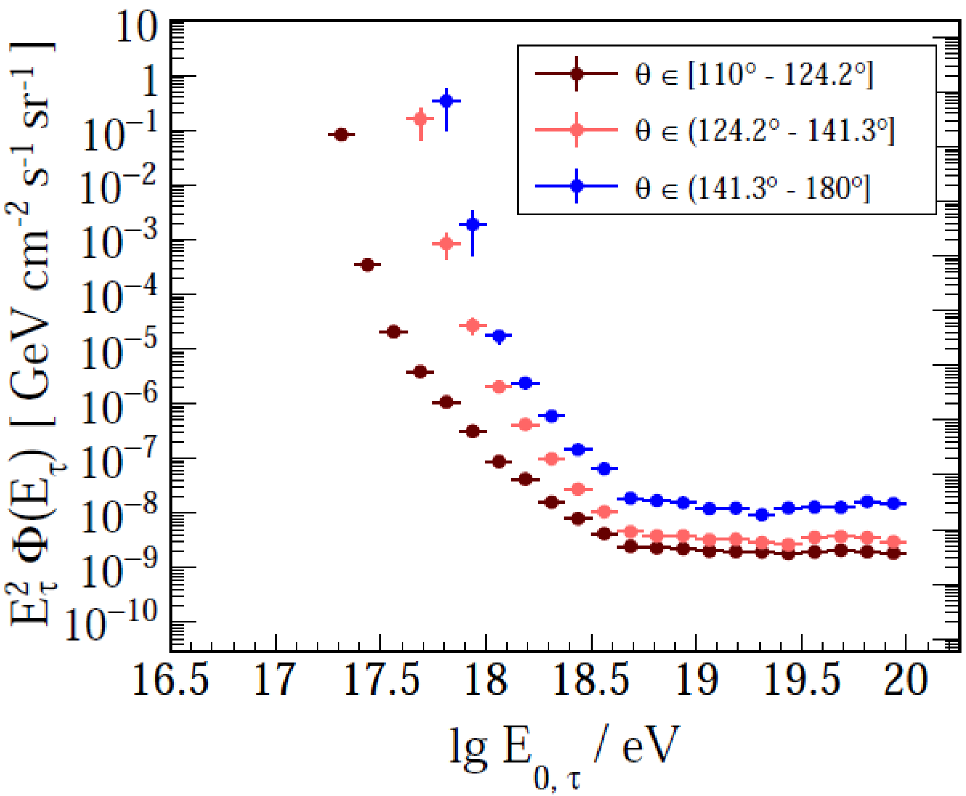
lgE > **18.5** FD response not explored yet (flattening is a reasonable assumption)

Differential upper limits

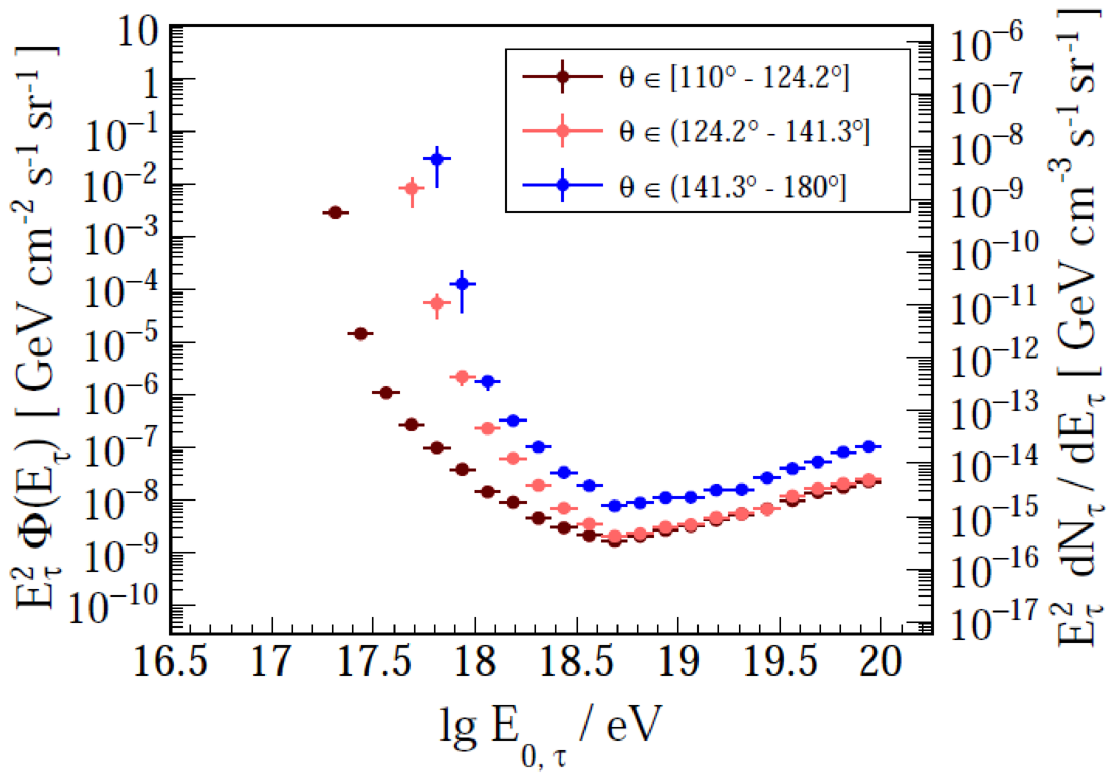
1 event observed, 0.5 expected

$$\Phi_\tau^{95\%}(E_0) = \frac{N_{\mathrm{FC}}(E_0)}{\mathcal{E}_\tau(E_0)}$$

Two injection spectra



(a) $\Phi_\tau \propto E_0^{-1}$



(b) $\Phi_\tau \propto E_0^{-2}$

Better limits for inclined events

Conclusions and perspective

The potential of the Pierre Auger Observatory as a detector for upward-going EAS discussed

SD → wide multi-messenger physics program using the earth skimming (90°-95°) channel

Competitive acceptance in the EeV energy range, though narrow FOV

UL for diffuse and point like sources of neutrinos

FD → sensitivity over a wide zenith angle range

Integral UL to upward-going EAS for $17.5 < \log10(E/eV) < 18.5$ and zenith> 110°

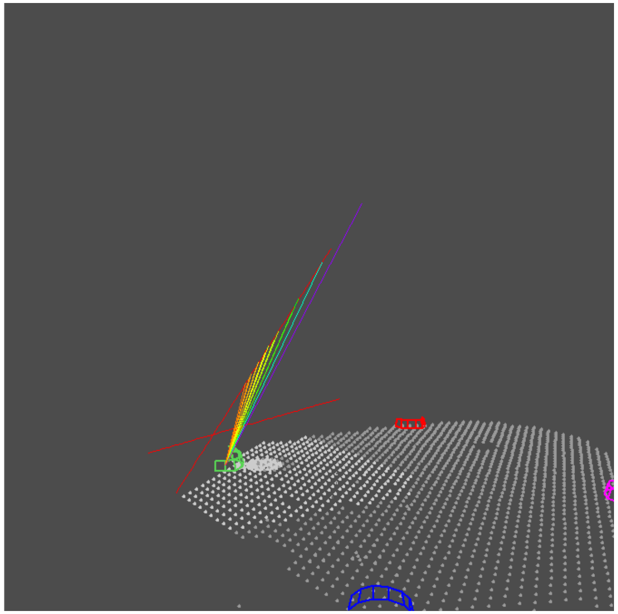
Tau scenario discussed and differential UL of primary flux of taus presented

- **Integral UL to be compared with ANITA findings**
- **Investigate the implications in the context of beyond standard model physics**

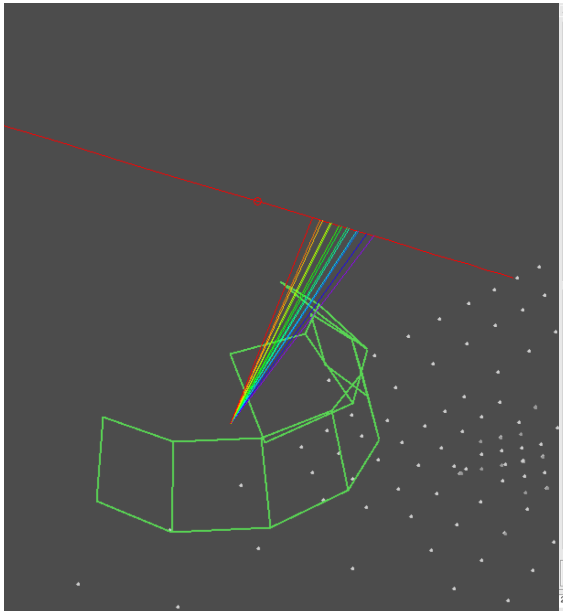
PRELIMINARY

Event AugerId=140346001900

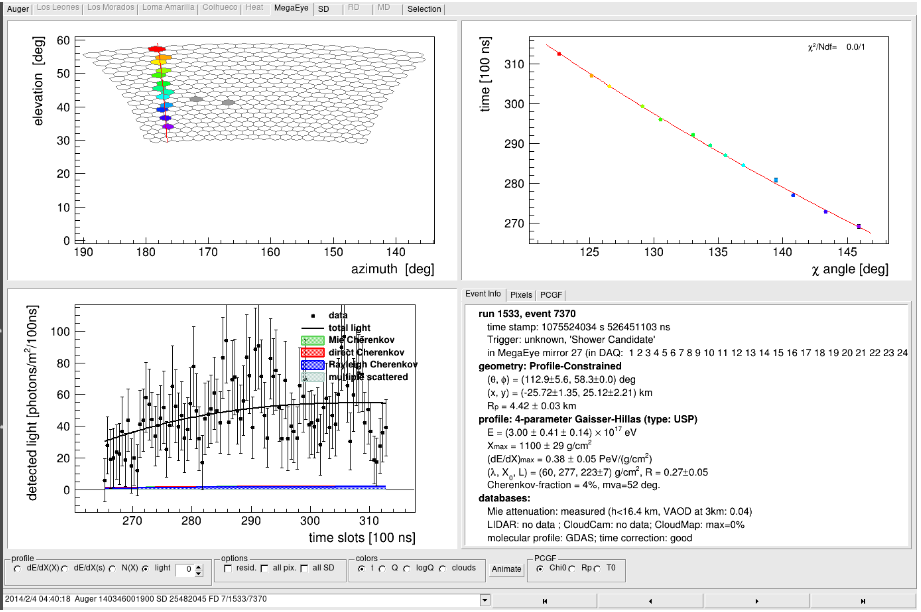
3D view of the downward mode reconstruction



3D view of the upward mode reconstruction



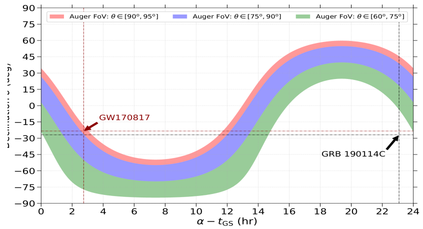
Light profile view of the upward mode reconstruction

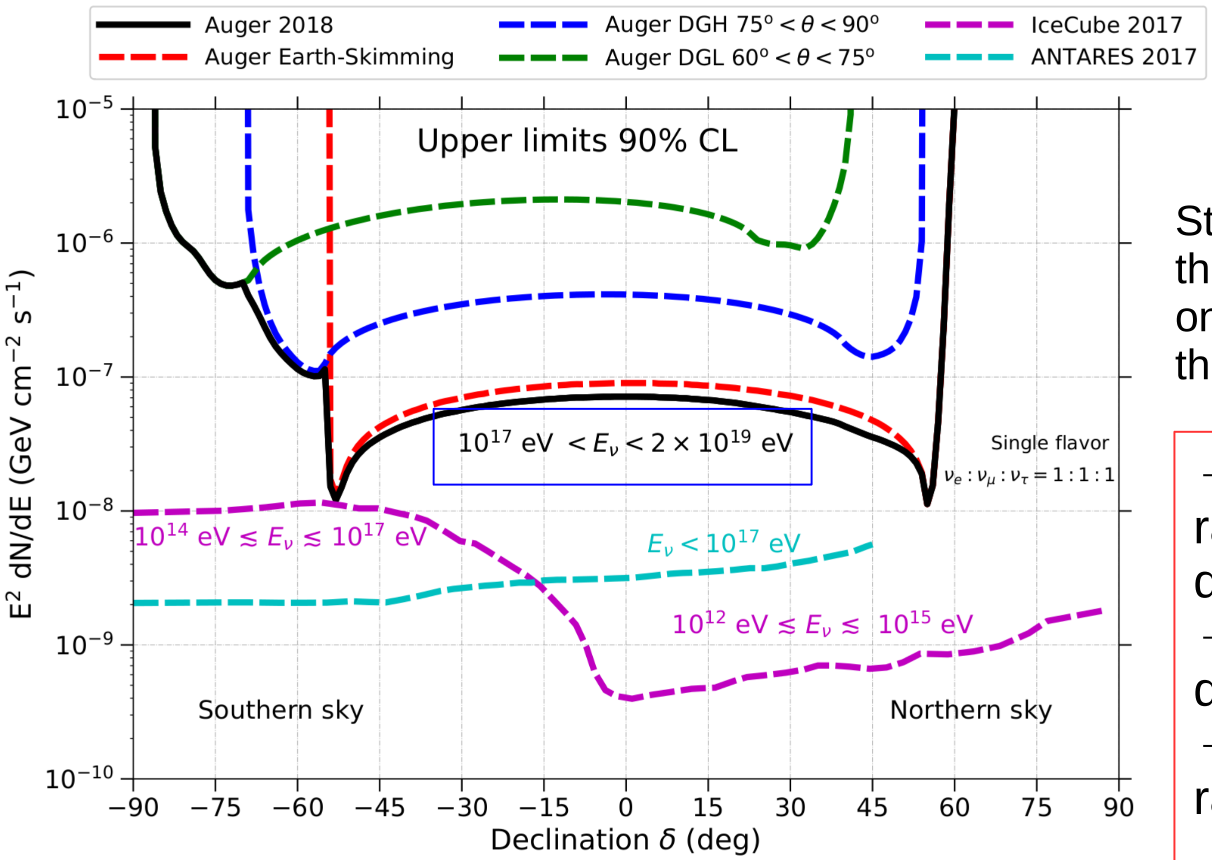


➔ The event is not a laser. The trigger occurs in the Heat camera. Even if the geometry from the downward mode reconstruction might be similar to the ones expected for background events, this is a genuine candidate

UHE neutrinos: point like sources limits

Pierre Auger Coll., JCAP 11 (2019) 004





Strong dependence on zenith angle: the observation capability depends on where the source is in the FoV of the SD detection channels

→ good sensitivity in the EeV range in a broad range of declinations

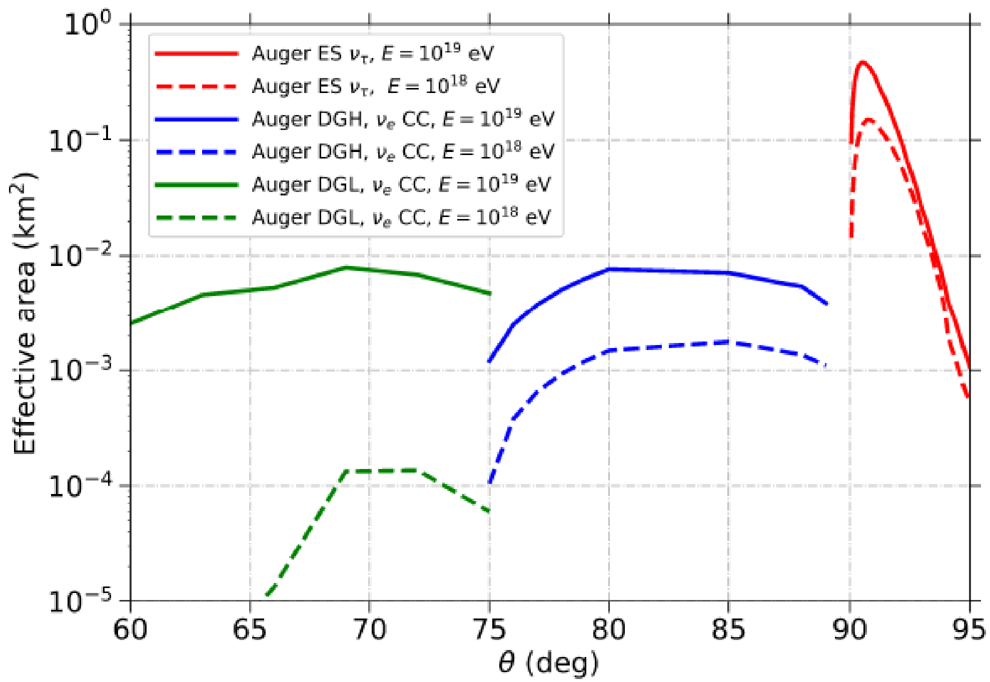
→ Maximum sensitivity at declinations -53° and 55°

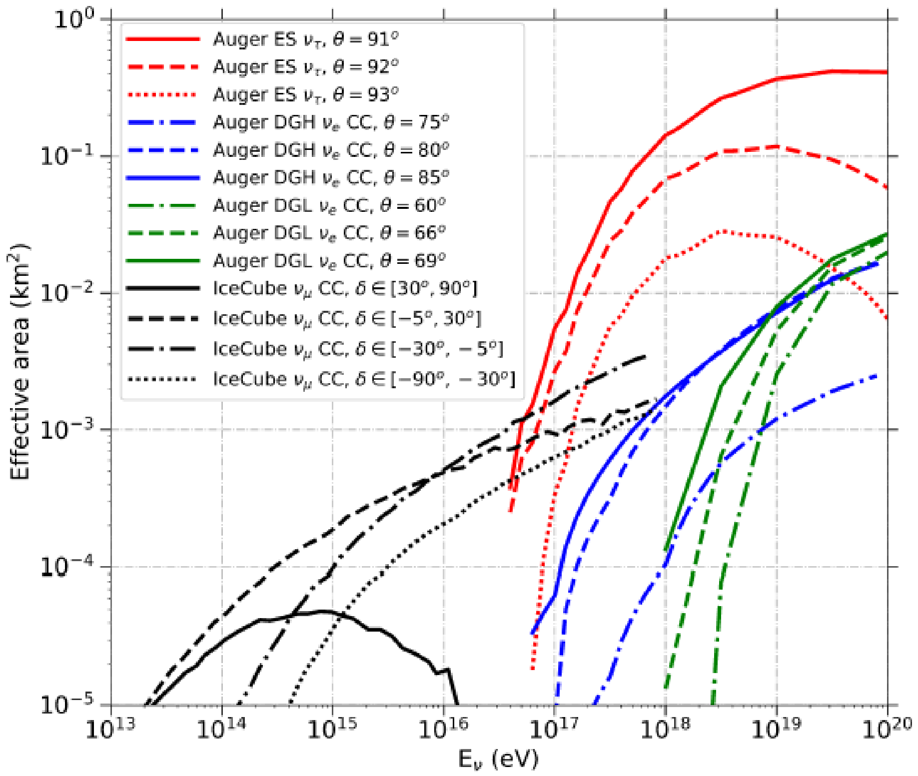
→ complementary energy range: $10^{17} \div 2 \cdot 10^{19}$ eV

UHE neutrinos: point source effective area

Pierre Auger Coll., JCAP 11 (2019) 004

strong dependence on zenith angle





Unrivalled sensitivity in the EeV range
if source is in ES field of view

UHE neutrinos with SD: detection channels

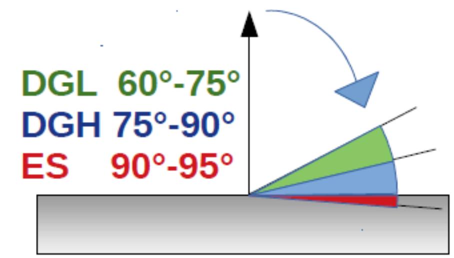
Earth-skimming (ES):
upward going τ neutrinos CC
zenith angle 90° ÷ 95°

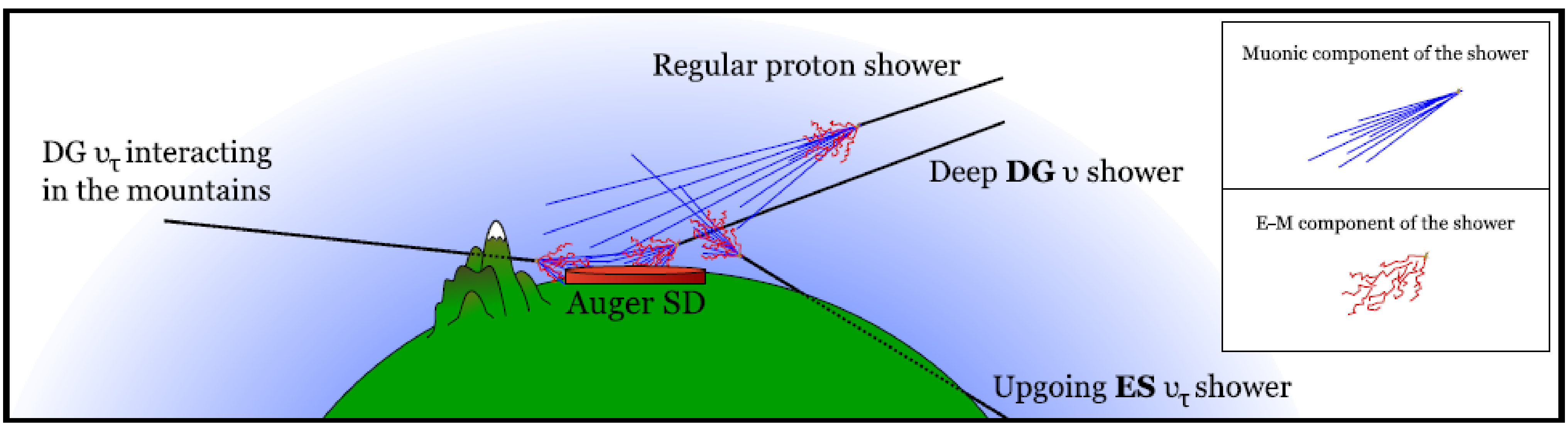
τ can emerge from the Earth crust and decay close to the detector

D. Fargion, Astrophys. J. 570, 909 (2002)
A. Letessier-Selvon, AIP Conf. Proc. 566, 157 (2001)

Downward Going (DG):
deeply interacting ν all flav. CC & NC
zenith DGL 60°÷75° DGH 75°÷90°

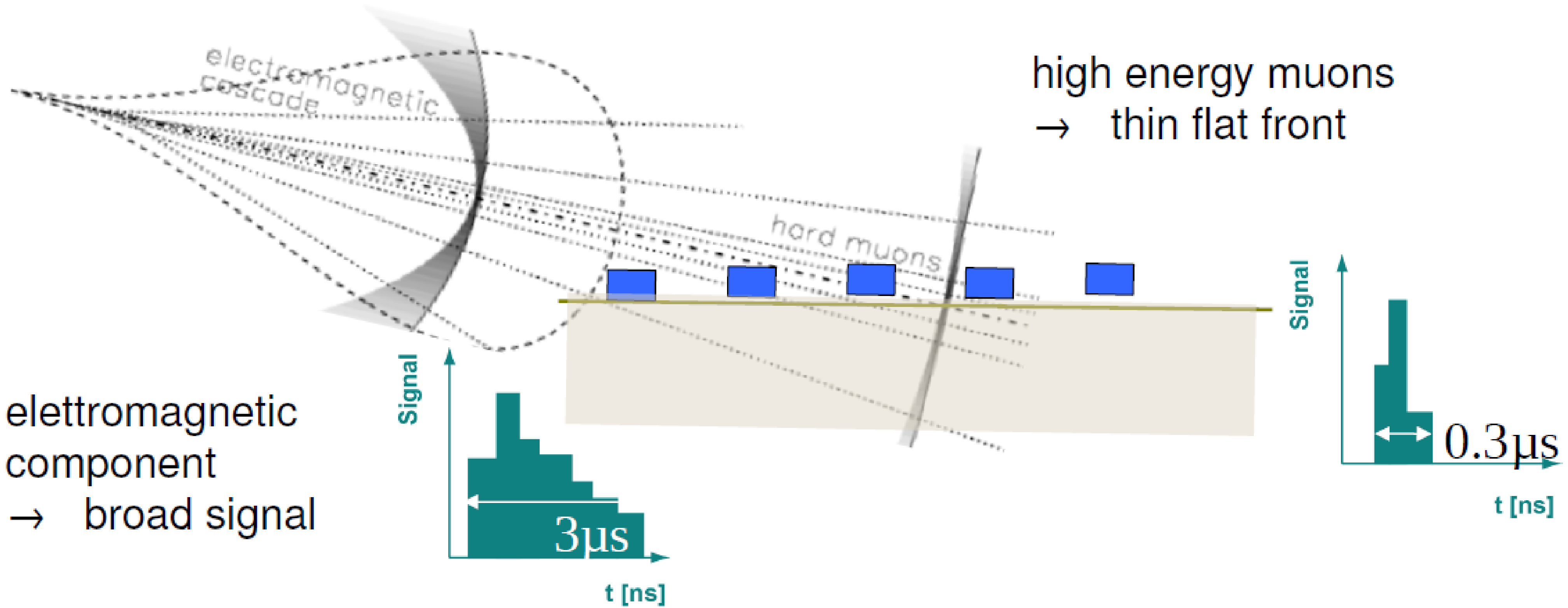
Sensitivity to ALL ν flavours and ALL interaction channels





UHE neutrinos: signature

neutrino signature:
young shower i.e. with large electromagnetic component
→ inclined event with slow rising and broad signal

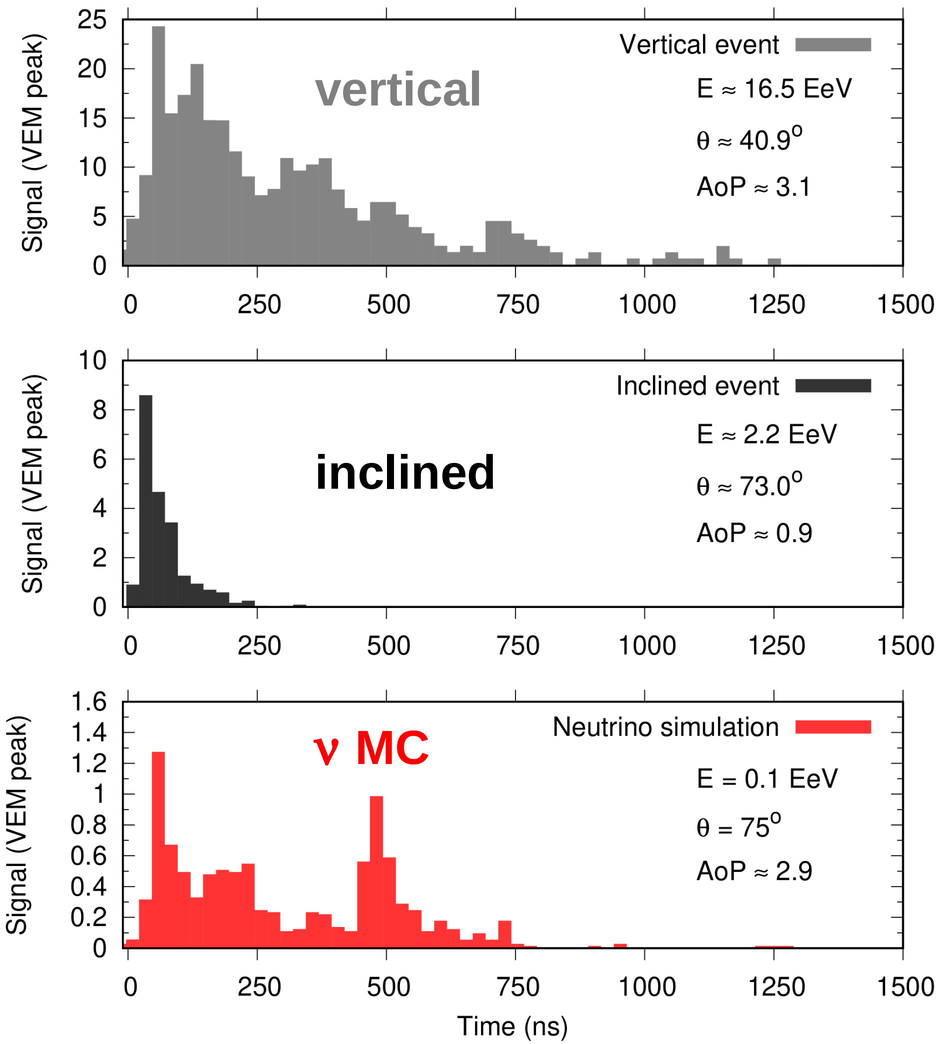


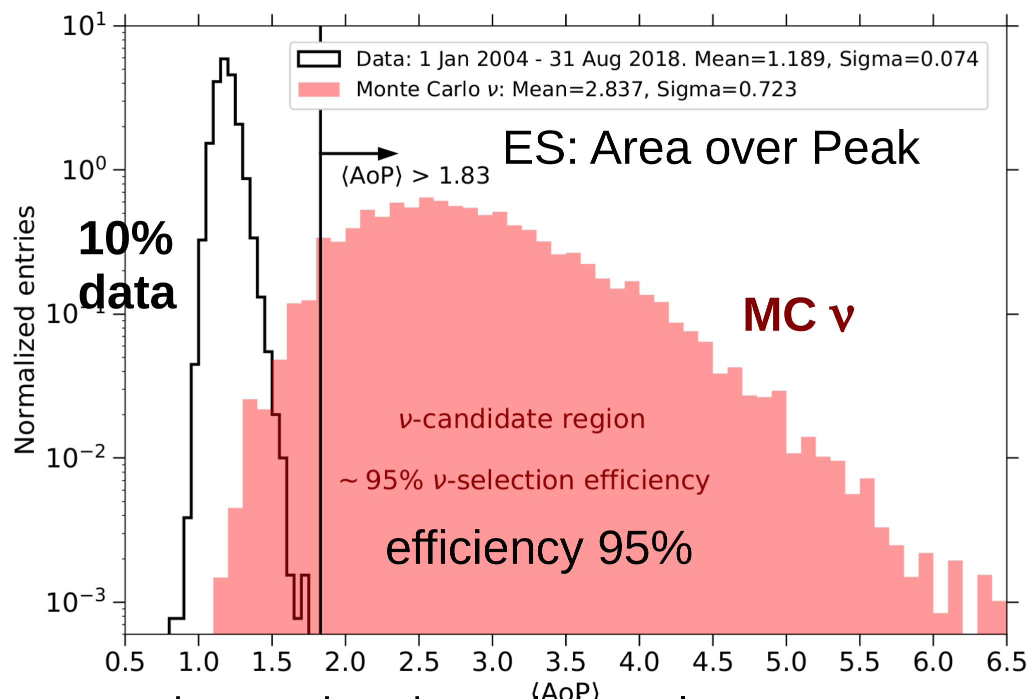
UHE neutrinos detectable as almost horizontal young showers

UHE neutrinos: data selection

Pierre Auger Coll., JCAP 10 (2019) 022

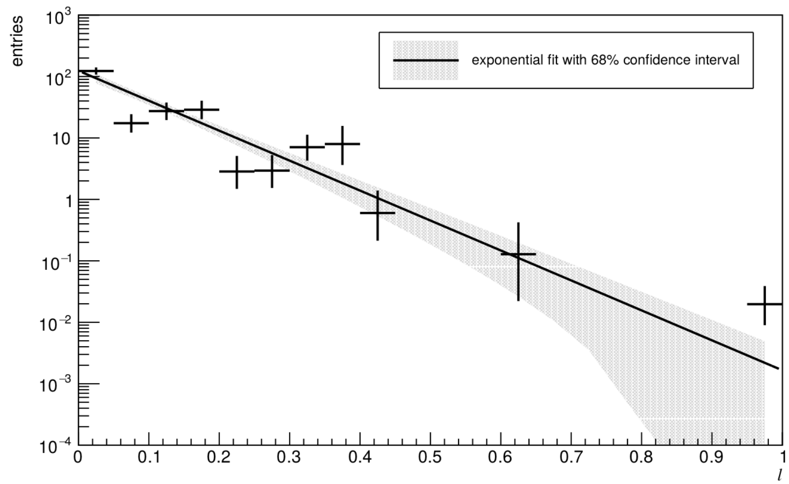
- Data 2004 – 2018 14.7 yr of stable operation
  ~10% of the data for background estimation
  → **bkg expected: <1 event in 50 years**
- Selection tuned on the different det. channels





down-going channels have lower
ν-selection efficiency (85% and 72%)

Background discrimination with likelihood ratio based cut



weighted likelihood fit

Cut to select more likely upward-going events:
l > 0.55

cut value can be tuned with the UL minimization

$$F^{95\%} = \frac{N^{95\%}}{< \varepsilon >}$$

Method of Rolke with $n_{obs} = n_{bkg}$

mean exposure

$$< \varepsilon > = \frac{\int_{E_{min}}^{E_{max}} \varepsilon(E_{cal}) E_{cal}^{-\gamma} dE}{\int_{E_{min}}^{E_{max}} E_{cal}^{-\gamma} dE}$$

$\log_{10}(E_{cal}/eV) > 17.5$