CRIS-MAC 2024

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and Multi-messenger Astroparticle Conference

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INFN
Istituto Nazionale di Fisica Nucleare

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Hunting for new physics with upward-going air shower at the Pierre Auger Observatory

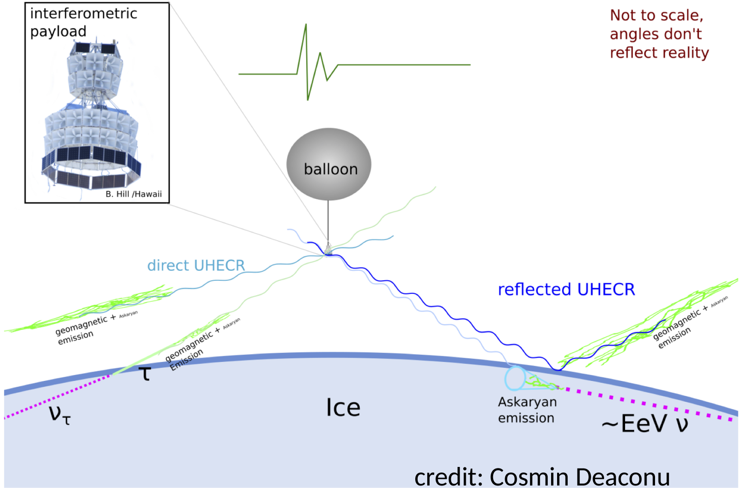
E. De Vito for the Pierre Auger Collaboration

Outline

- Motivation: the ANITA anomalous events
- Search for upward-going showers with FD
- Comparison of Auger upper limits with ANITA observations
- Tau-induced air showers scenario
- Two simple BSM models

ANITA anomalous events

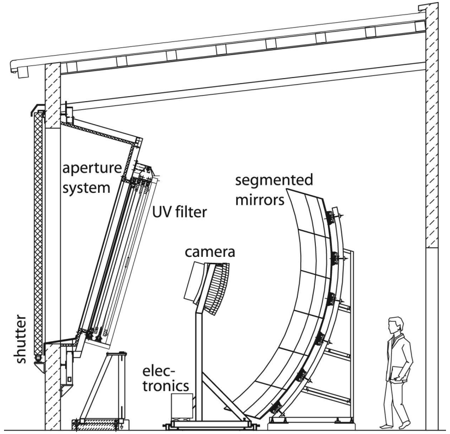
- Observation of two steeply upward-going air showers with non-inverted polarity, consistent with the direct detection of upward-going showers by ANITA[1]
- $E_{1,2} > 0.2$ EeV
- zenith $\theta_1 \simeq 117^\circ$ and $\theta_2 \simeq 125^\circ$ (elevations 27° and 35°)
- Challenging to reconcile with Standard Model predictions



credit: Cosmin Deaconu

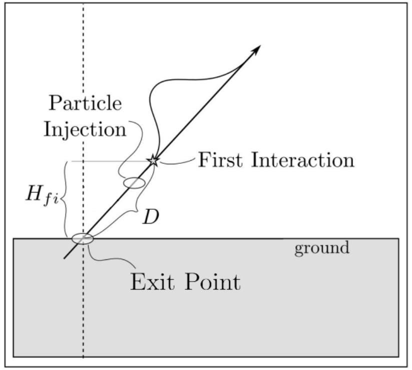
The Fluorescence Detector of the Pierre Auger Observatory is sensitive to upward-going air showers

- ➢ Simulate and reconstruct upward-going air-showers within the Offline framework to calculate the FD exposure to upward-going air showers

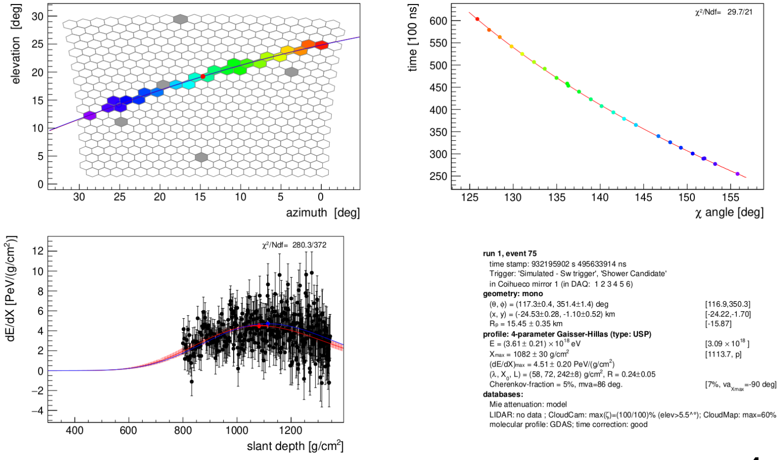


[1] P.W. Gorham et al. (ANITA Collaboration), *Phys. Rev. Lett.*, **121**, 161102, 2018.

Signal simulations



- Actual status of all components of the FD detector and realistic atmospheric conditions taken into account in the simulation
- Primary protons, easily adaptable to other scenarios
- Energy → log(E/eV) ∈ [16.5, 19] , 2 x 10^7 showers simulated with E^{-1} spectrum
- Very important to calculate the FD detection efficiency with high precision below $10^{17.5}$ eV for the comparison with ANITA
  - 4.5 x 10^7 additional showers below $10^{17.5}$ eV
  - more accurate exposure calculation at the lowest energies
- Zenith → θ ∈ [110°, 180°] (elevation [20°, 90°])
- Generation area → 100 x 100 km^2
- Height of first interaction → [0, 9] km above ground

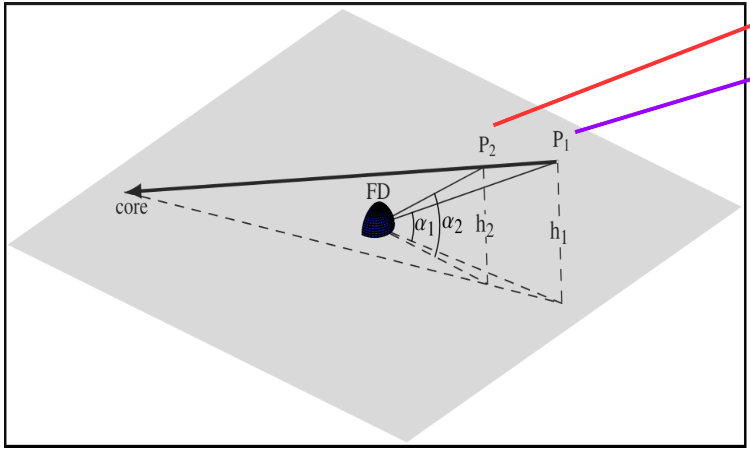


```
run 1, event 75
  time stamp: 932195902 s 495633914 ns
  Trigger: 'Simulated - Sw trigger', 'Shower Candidate'
  in Coihueco mirror 1 (in DAQ:  1 2 3 4 5 6)
geometry: mono
  (θ, φ) = (117.3±0.4, 351.4±1.4) deg                    [116.9,350.3]
  (x, y) = (-24.53±0.28, -1.10±0.52) km                  [-24.22,-1.70]
  Rp = 15.45 ± 0.35 km                                   [-15.87]
profile: 4-parameter Gaisser-Hillas (type: USP)
  E = (3.61 ± 0.21) × 10^18 eV                           [3.09 × 10^18 ]
  Xmax = 1082 ± 30 g/cm^2                                [1113.7, p]
  (dE/dX)max = 4.51 ± 0.20 PeV/(g/cm^2)
  (λ, X0, L) = (58, 72, 242±8) g/cm^2, R = 0.24±0.05
  Cherenkov-fraction = 5%, mva=86 deg.                   [7%, va_Xmax=-90 deg]
databases:
  Mie attenuation: model
  LIDAR: no data ; CloudCam: max(ζ)=(100/100)% (elev>5.5^°); CloudMap: max=60%
  molecular profile: GDAS; time correction: good
```

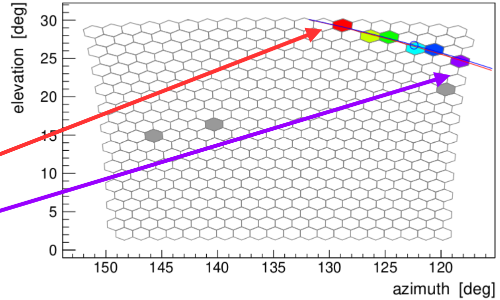
Background simulations

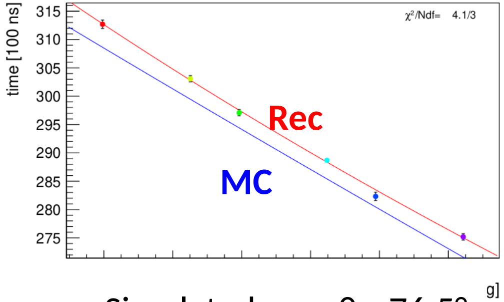
- Downward-going Cosmic Rays can mimic upward-going track in the FD camera
- Primaries → protons + helium, nitrogen and iron nuclei, re-scaled to the CR spectrum
- Energy → log(E/eV) ∈ [17, 20], 2.5 x 10^8 showers simulated
- Zenith → θ ∈ [0°, 90°]

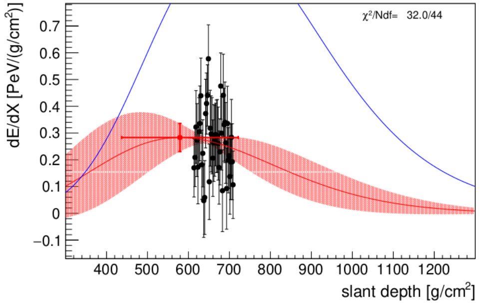
Example of a downgoing shower looking upgoing



Simulated downgoing shower reconstructed as upgoing

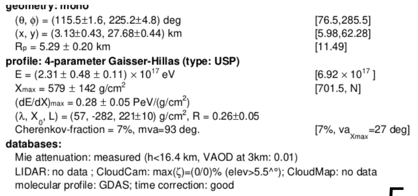






Simulated θ≃76.5°

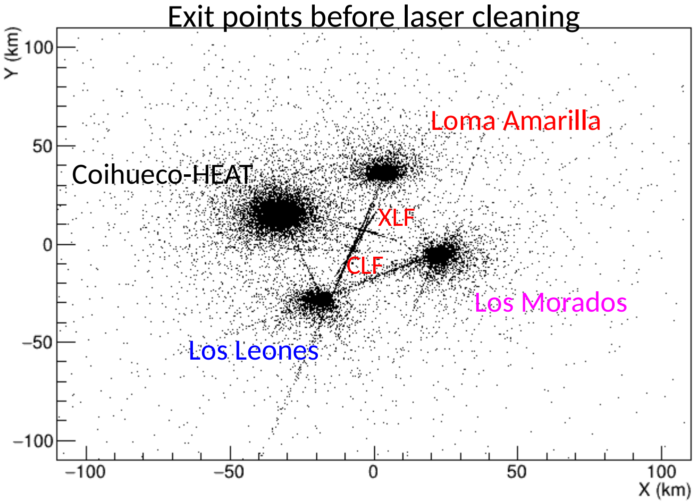
reconstructed 115.5°

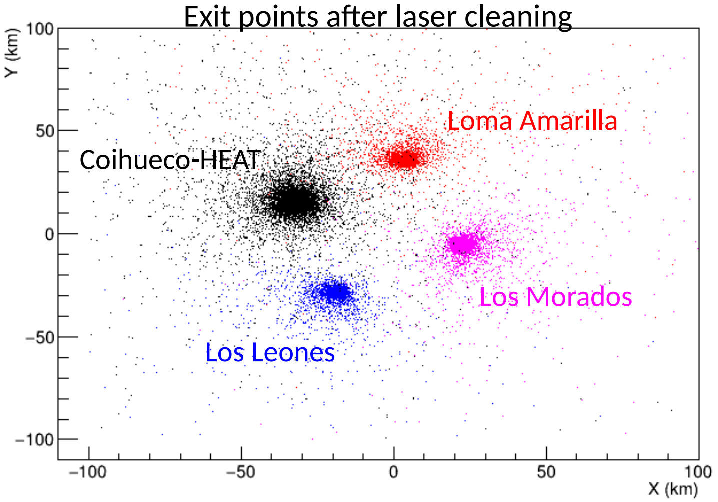


```
geometry: mono
  (θ, φ) = (115.5±1.6, 225.2±4.8) deg                        [76.5,285.5]
  (x, y) = (3.13±0.43, 27.68±0.44) km                        [5.98,62.28]
  Rp = 5.29 ± 0.20 km                                        [11.49]
profile: 4-parameter Gaisser-Hillas (type: USP)
  E = (2.31 ± 0.48 ± 0.11) × 10^17 eV                        [6.92 × 10^17 ]
  Xmax = 579 ± 142 g/cm^2                                    [701.5, N]
  (dE/dX)max = 0.28 ± 0.05 PeV/(g/cm^2)
  (λ, X_0, L) = (57, -282, 221±10) g/cm^2, R = 0.26±0.05
  Cherenkov-fraction = 7%, mva=93 deg.                       [7%, va_Xmax=27 deg]
databases:
  Mie attenuation: measured (h<16.4 km, VAOD at 3km: 0.01)
  LIDAR: no data ; CloudCam: max(ζ)=(0/0)% (elev>5.5^°); CloudMap: no data
  molecular profile: GDAS; time correction: good
```

Data cleaning

- Blind analysis on 10% of FD data from 14 years of operations (2004-2018, 0.8 x 10^6 events) to identify and remove untagged laser events used for atmospheric monitoring
- Pre-selection cuts applied on data and simulations requiring
  - successful reconstruction and good atmospheric conditions
- Laser removed based on their specific GPS time tag and position inside the SD array


Exit points before laser cleaning

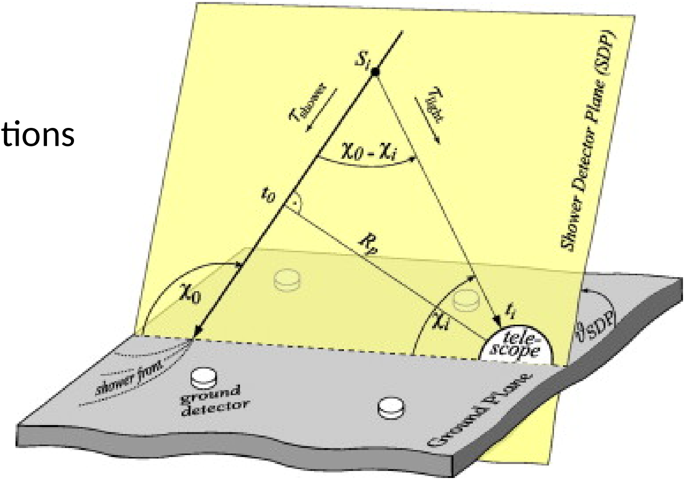

Exit points after laser cleaning

Reconstruction and event selection

- Data and simulations reconstructed with an iterative procedure combining the profile reconstruction with the geometry, testing upward (negative χ_0) and downward (positive χ_0) solutions
- Selection criteria requiring compact pattern of pixels in the FD camera, θ > 110° and observed fraction of longitudinal profile > 80 g cm^{-2}
- The likelihood of the combined fit, L_{down} and L_{up}, can be used to compare the two reconstructions
- Definition of a new variable for the comparison of the two reconstructions

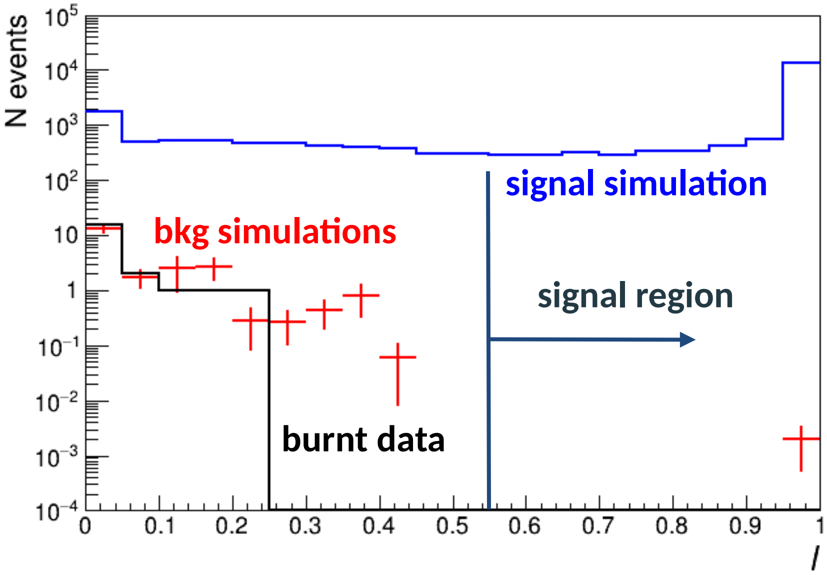
$$l = \frac{\arctan\left(-2\log\left(\mathrm{L_{down}}/\max\left\{\mathrm{L_{down}},\mathrm{L_{up}}\right\}\right)/50\right)}{\pi/2}$$

$0 \le l \le 1$, if $l = 0$ downward favoured, if $l \to 1$ upward favoured



Expected background and signal identification

- Distribution of variable *l* for data (black, 10% of the total) signal simulations (blue) background simulations (red)
- Background weighted to CR spectrum and scaled to the burn sample fraction → good agreement with data
- Cut is at ***l* > 0.55** with expected background for the full sample of $n_{bkg} = 0.27 \pm 0.12$



From [2]

$$l = \frac{\arctan\left(-2\log\left(\mathrm{L_{down}}/\max\left\{\mathrm{L_{down}},\mathrm{L_{up}}\right\}\right)/50\right)}{\pi/2}$$

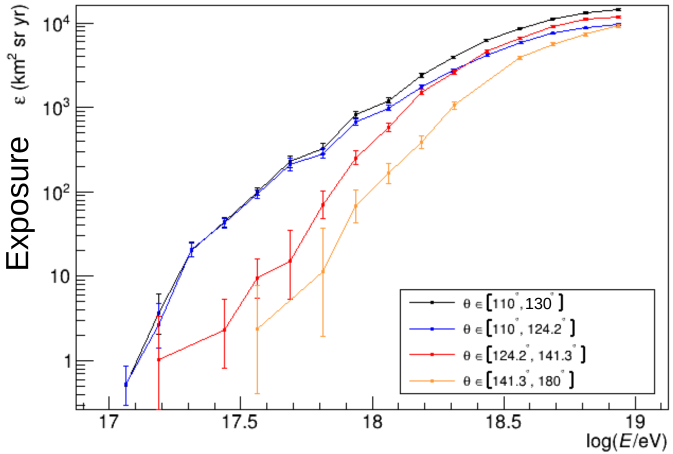
l = 0 downward favoured

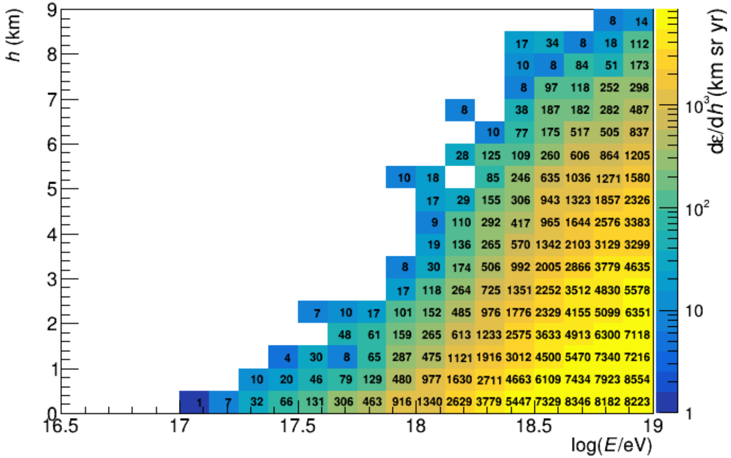
l → 1 upward favoured

[2] E. De Vito for the Pierre Auger Collaboration, *PoS(ICRC2023)*1099

Exposure and upper limits

From [2]





- One event found after the unblinding, consistent with expected background
- FD exposure as a function of the shower energy (top), calculated for different zenith sub-ranges
- Exposure as a function of the shower energy and the height of first interaction (bottom)
- Using Rolke[3], the integral upper limit to the flux of upgoing showers above 10^{17} eV:

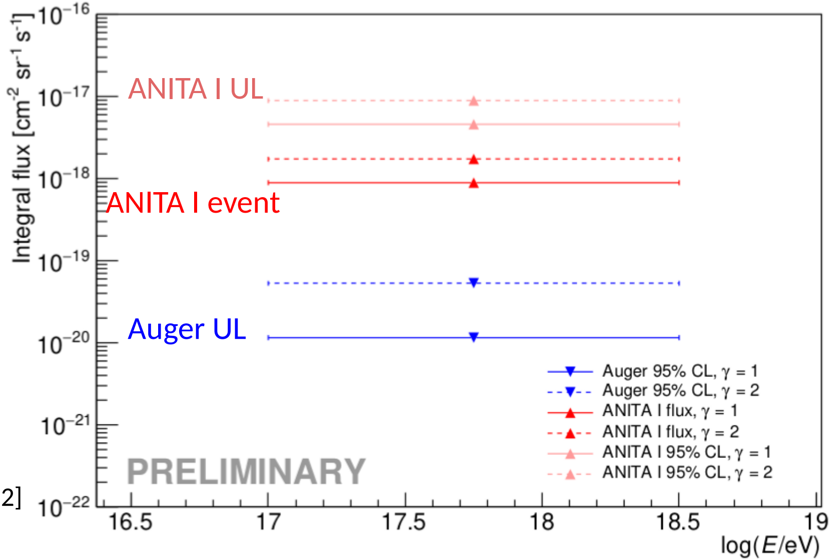
  → **$(7.2 \pm 0.2)\times10^{-21}$ cm^{-2} s^{-1} sr^{-1}** assuming a E^{-1} spectrum

  → **$(3.6 \pm 0.2)\times10^{-20}$ cm^{-2} s^{-1} sr^{-1}** assuming a E^{-2} spectrum

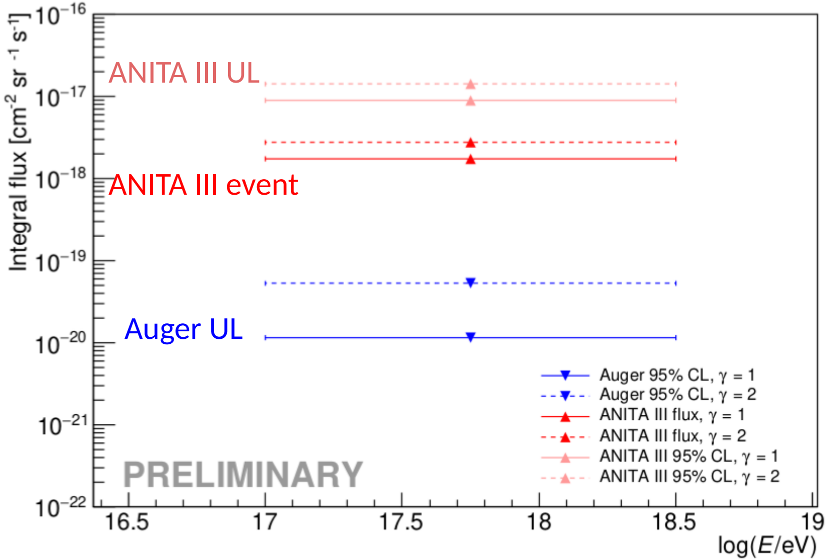
[3] Limits in presence of nuisance parameters. W. Rolke, A.M. Lopez, J. Conrad, *Nucl. Instrum. Meth. A*, **551** (2005).

Comparison with ANITA observations

- Joint effort with members of the ANITA Collaboration to make an analytic calculation of ANITA exposure for the two anomalous events between 10^{17} eV and $10^{18.5}$ eV and $\theta \in [110°, 130°]$
- Comparison of Auger integral UL (blue) with ANITA flux (red) and ANITA UL (light red) for two spectral indices $\gamma = 1, 2$
- For both events, Auger limits are 100 and 30 times lower than ANITA for E^{-1} and E^{-2} spectra respectively

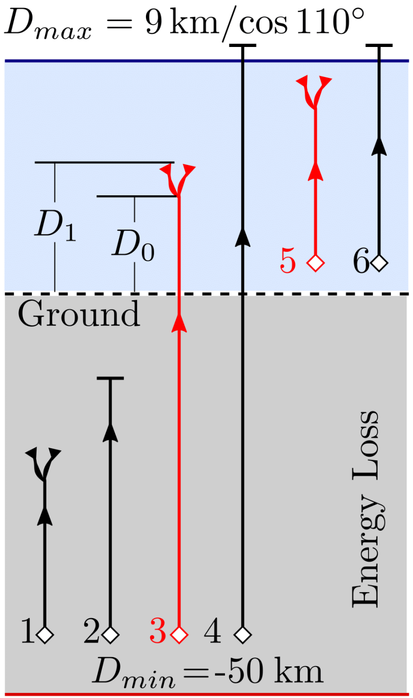


From [2]



Tau-induced air showers

- Auger exposure obtained using protons, easily scalable to other particles (e.g. taus) by folding it with the corresponding FD detection efficiency
- Dedicated simulations of tau leptons generated within ~50 km below the Earth crust
- NuTauSim[4] used for the propagation and TAUOLA[5] used for decays
- Taus can propagate through the Earth crust and generate an air shower
- 3 and 5 are the most relevant cases where the shower develops in the atmosphere and can be observed with FD



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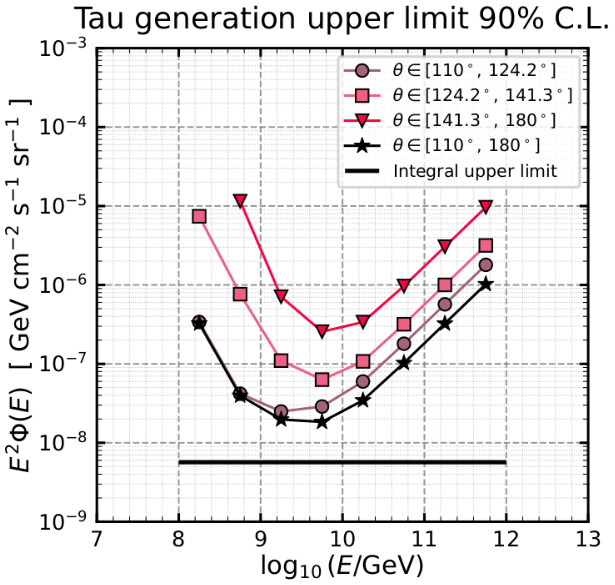
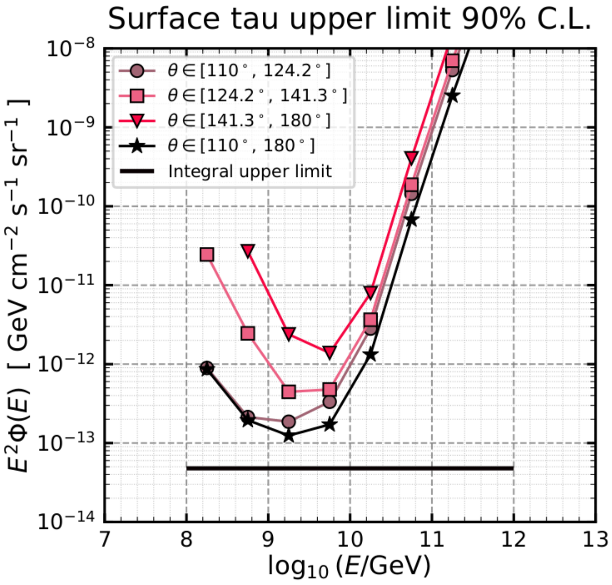
[4] J. Alvarez-Muniz, W.R. Carvalho Jr, K. Payet, A. Romero-Wolf, H. Schoorlemmer, E. Zas, *Phys. Rev. D*, **97** (2018) 023021.
[5] N. Davidson *et al.*, *Computer Physics Communications*, **183**, 3 (2012) pp.821-843

Tau-induced air showers

- Tau simulations used to calculate the FD detection efficiency and then folded with Auger exposure
- Tau upper limits considering all generated taus (left) or only those exiting the Earth (right)



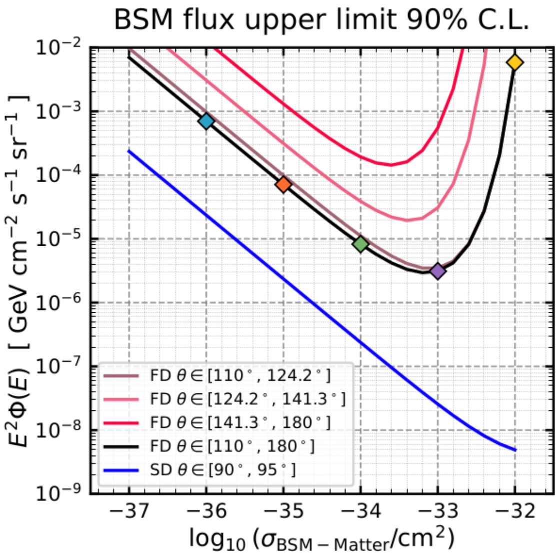


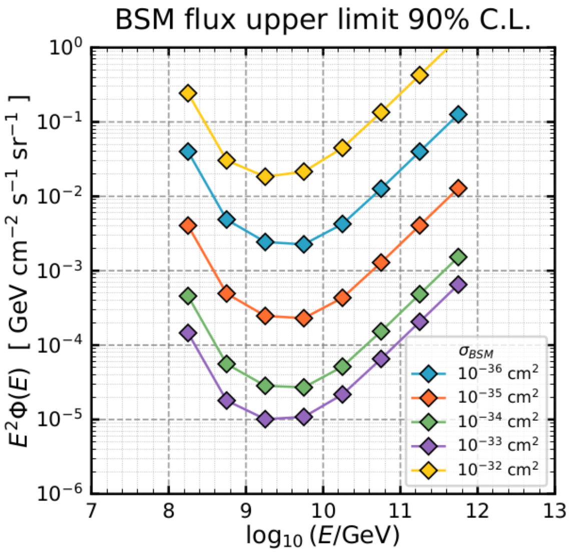
From [6]

[6] B. Yue for the Pierre Auger Collaboration, *PoS(ICRC2023)*1095

The reduced cross section BSM model: first scenario

- At these energies, the Earth is opaque to neutrinos. On the other hand BSM particles could in principle produce tau leptons if their interaction cross section with matter is sufficiently low
- We study a model in which a BSM particle produces a tau-leptons which then generate an upward-going air shower as a function of the unknown particle cross section
- First scenario with a constant cross section at all energies





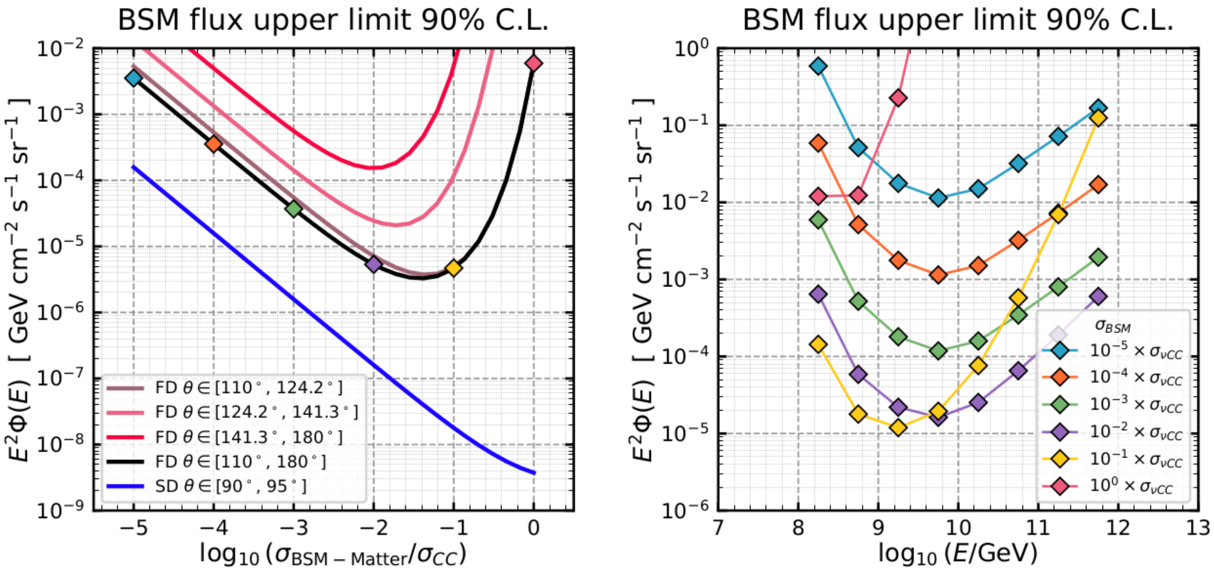
From [6]

Strongest limits at $\sigma \sim 10^{-33}$ cm^2

Auger SD Earth-skimming upper limit shown in blue

The reduced cross section BSM model: second scenario

- Second scenario, the cross section mimics a charged current neutrino cross section scaled by a fixed factor (between 10^{-5} and 1)



Strongest limits if σ_{BSM} is 3% of neutrino charged current σ_{CC}

Auger SD Earth-skimming upper limit shown in blue

From [6]

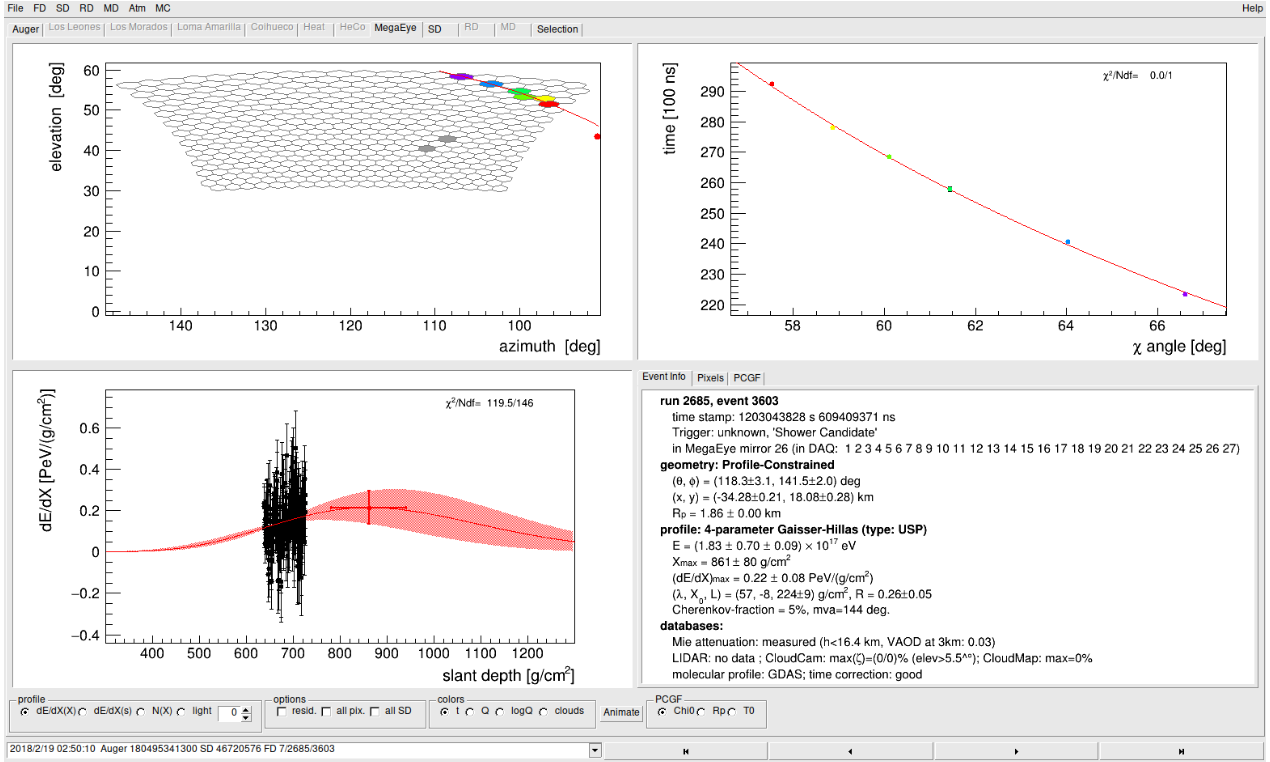
Summary

- Blind analysis searching for upward-going air showers with the Fluorescence Detector of the Pierre Auger Observatory
- One candidate found, consistent with the expected background
- Auger integral upper limit on the flux of upward-going air showers are found to be 100 and 30 times lower than the inferred ANITA fluxes in the case of a E^{-1} and E^{-2} spectrum for both ANITA I and ANITA III observations
- Upper limits converted to the case of a tau-induced air shower
- We have tested two possible scenarios of BSM particles of unknown cross section producing a tau-lepton

Thank you for your attention!

Backup slides

The “candidate”



run 2685, event 3603

time stamp: 1203043828 s 609409371 ns

Trigger: unknown, 'Shower Candidate'

in MegaEye mirror 26 (in DAQ: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27)

geometry: Profile-Constrained

$(\theta, \phi) = (118.3\pm3.1, 141.5\pm2.0)$ deg

$(x, y) = (-34.28\pm0.21, 18.08\pm0.28)$ km

$R_p = 1.86 \pm 0.00$ km

profile: 4-parameter Gaisser-Hillas (type: USP)

$E = (1.83 \pm 0.70 \pm 0.09) \times 10^{17}$ eV

$X_{max} = 861 \pm 80$ g/cm^2

$(dE/dX)_{max} = 0.22 \pm 0.08$ PeV/(g/cm^2)

$(\lambda, X_0, L) = (57, -8, 224\pm9)$ g/cm^2, $R = 0.26\pm0.05$

Cherenkov-fraction = 5%, mva=144 deg.

databases:

Mie attenuation: measured (h<16.4 km, VAOD at 3km: 0.03)

LIDAR: no data ; CloudCam: max(ζ)=(0/0)% (elev>5.5^°); CloudMap: max=0%

molecular profile: GDAS; time correction: good

2018/2/19 02:50:10 Auger 180495341300 SD 46720576 FD 7/2685/3603

Few pixels at the border of the FD camera

$\theta \simeq 118°$

Short profile

Core is behind the FD telescope