UHE Astrophysics: the Pierre Auger Observatory & the future of radio

Enrique Zas

IGFAE
INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS
25 1999 2024

RENATA meeting – Zaragoza - Sept 22nd 2025

PIERRE AUGER OBSERVATORY

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

AGENCIA ESTATAL DE INVESTIGACIÓN

XUNTA DE GALICIA

CENTROS gusR

EXCELENCIA MARÍA DE MAEZTU 2024-2030

Cofinanciado pola Unión Europea

Fondos Europeos

The UHE domain: CR

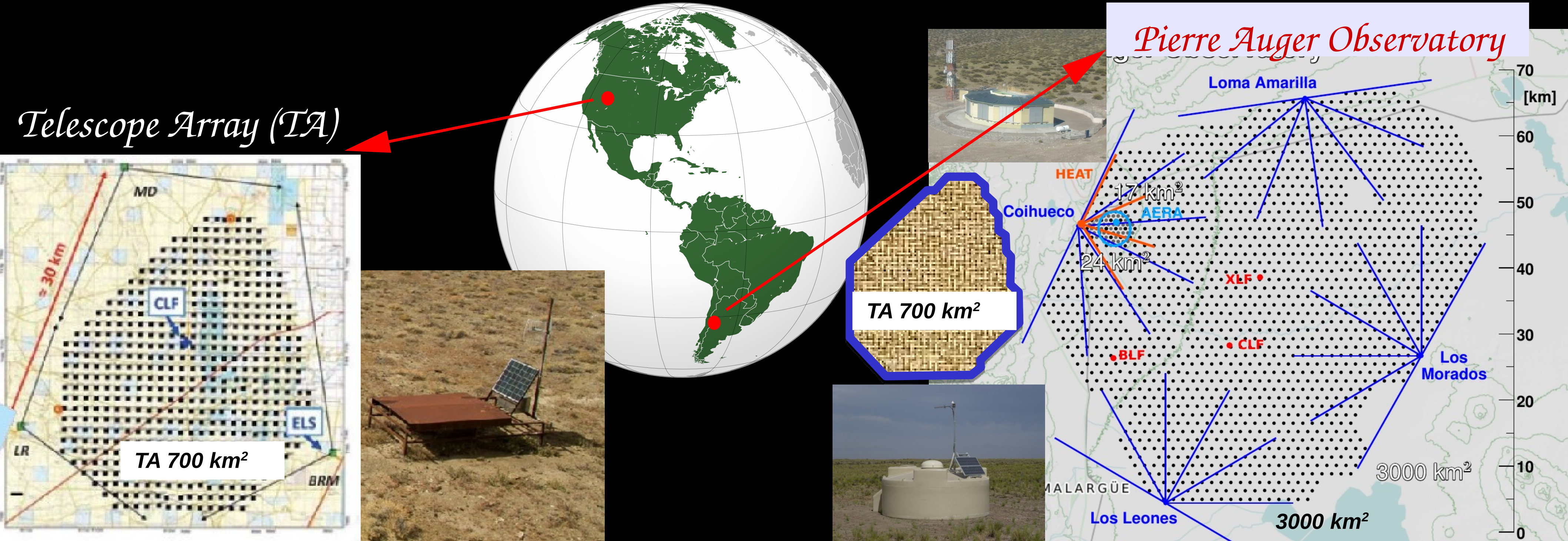
E > 1 EeV = 10^{18} eV

Extragalactic (dipole), violent, but unknown sources

Access: cosmic rays (nuclei) up to ~200 EeV → Auger & TA (Hybrid success)

secondary ν typically ~E_{CR}/20 km3NET > 0.1 EeV astrophysical

(γ degraded with CMB to ~ MeV – GeV) cosmological

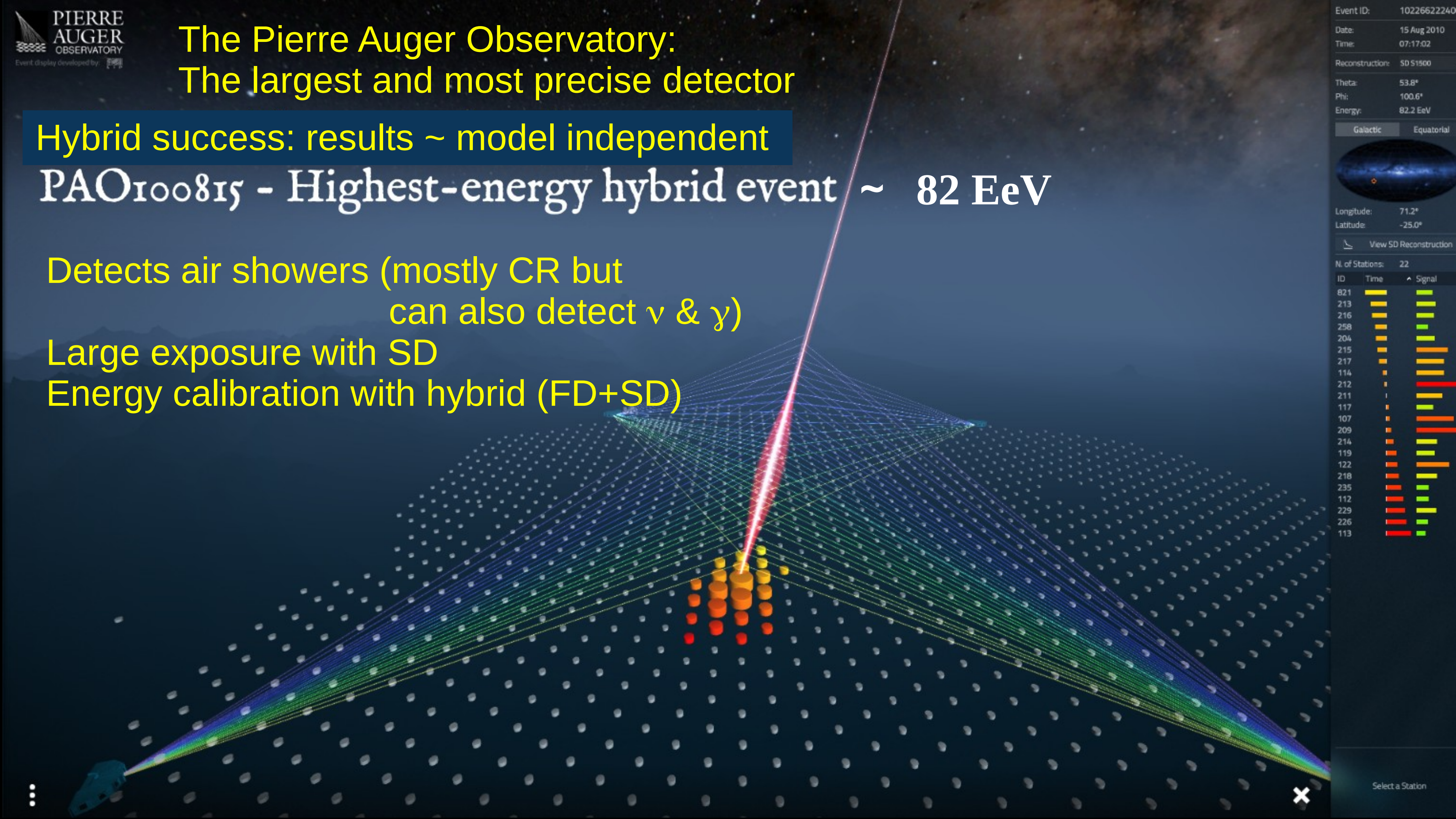


The Pierre Auger Observatory:
The largest and most precise detector

Hybrid success: results ~ model independent

PAO100815 - Highest-energy hybrid event ~ 82 EeV

- Detects air showers (mostly CR but can also detect ν & γ)
- Large exposure with SD
- Energy calibration with hybrid (FD+SD)

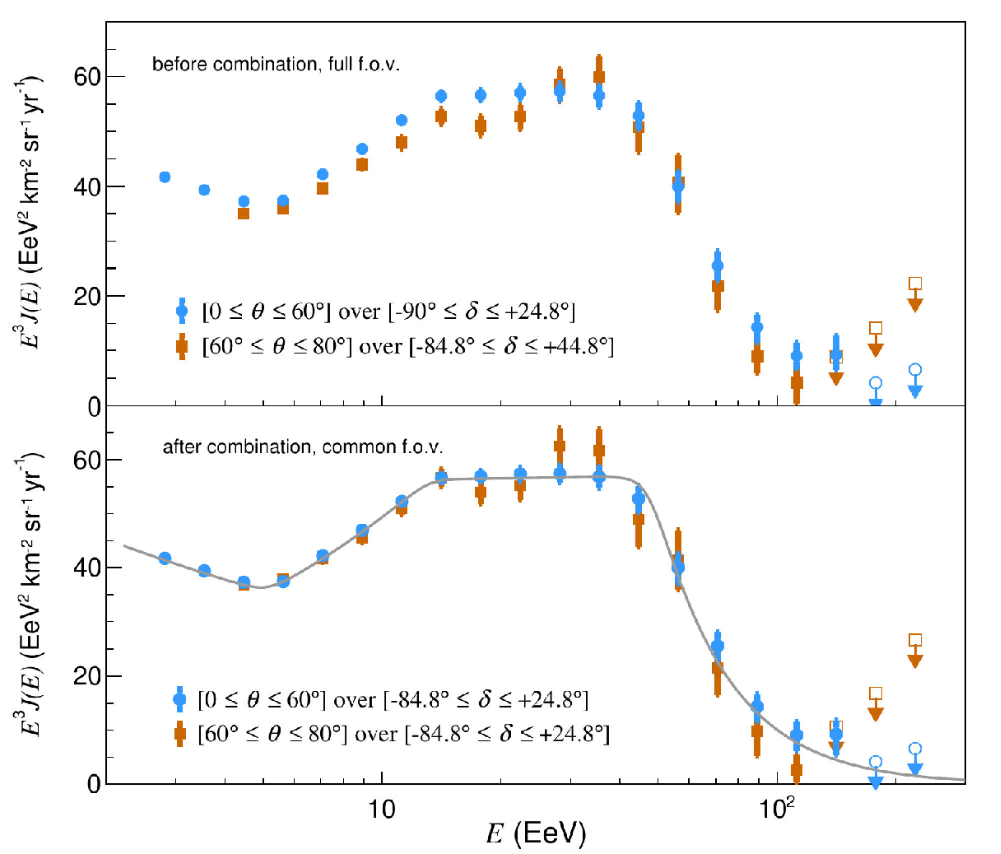


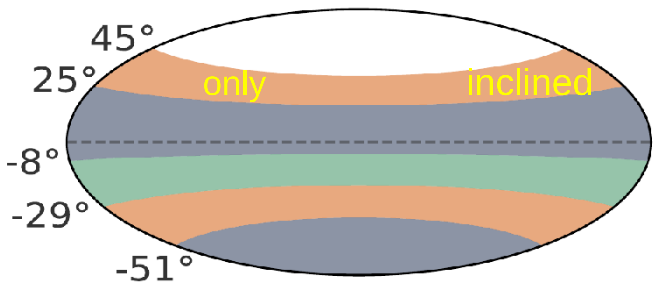
AUGER SPECTRUM HIGHLIGHTS E > 4 EeV PRL submitted

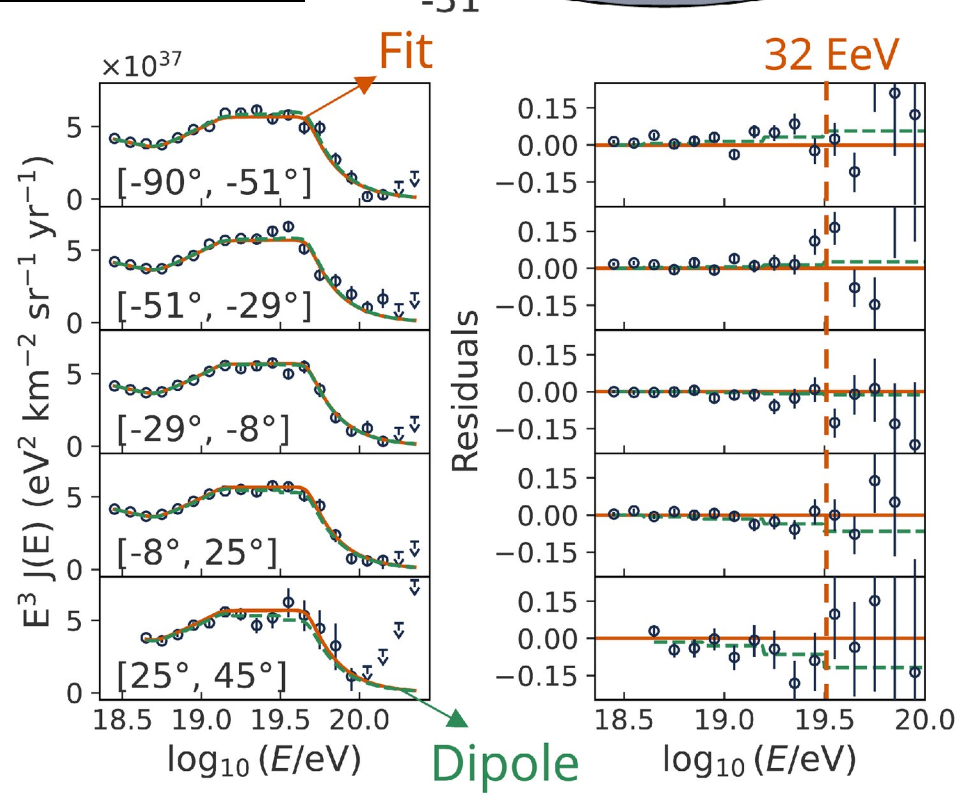
Vertical (0^0-60^0) - Horizontal (60^0-80^0) combination

Instep feature (PRL 125 (2020) 121106) now 5σ

5 declination bands → No dependence



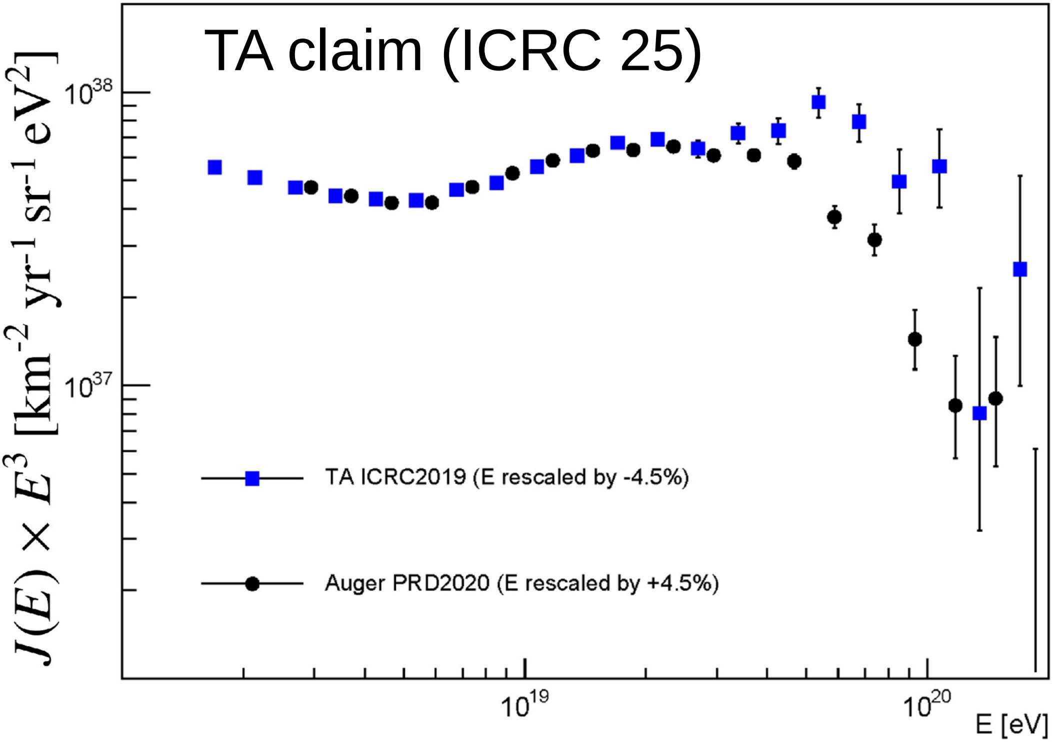




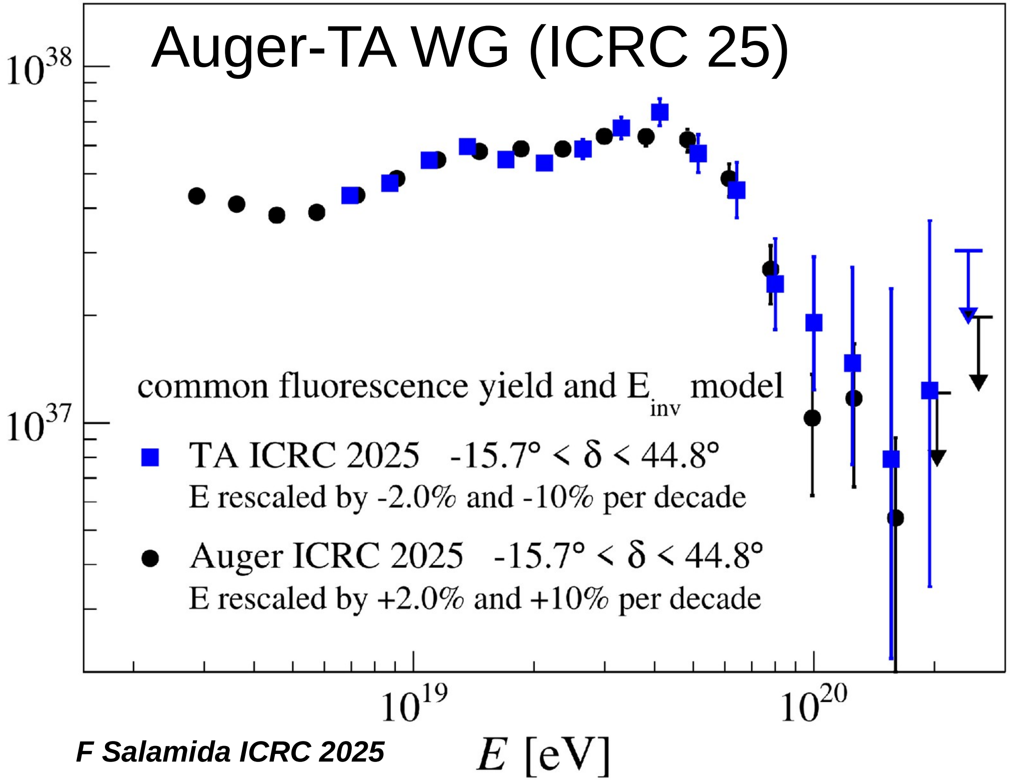
Why is this relevant?

Highlights the relevance of the absolute energy scale

- Instep not due to a small number of foreground sources
- 20 EeV steepening → rather similar sources (interplay between He & CNO fluxes)
- Disproves TA claim (declination dependence accounts for discrepancies with Auger)



J Kim ICRC 2025

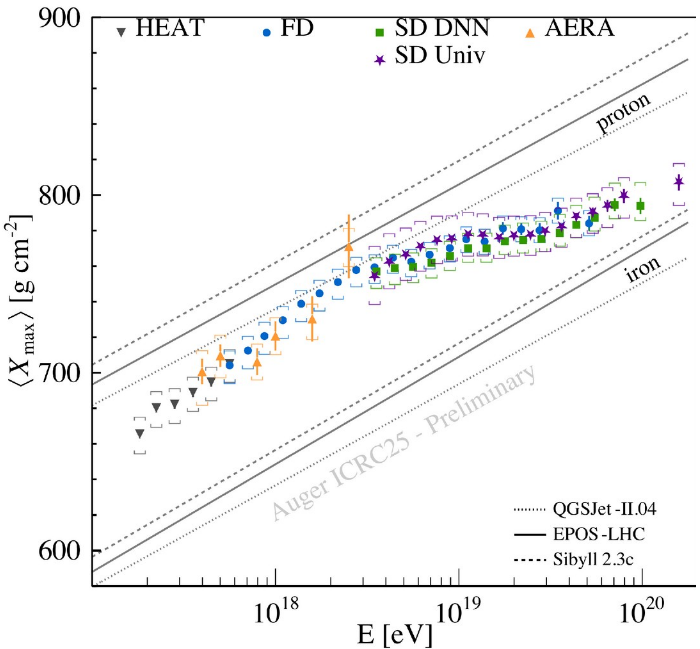


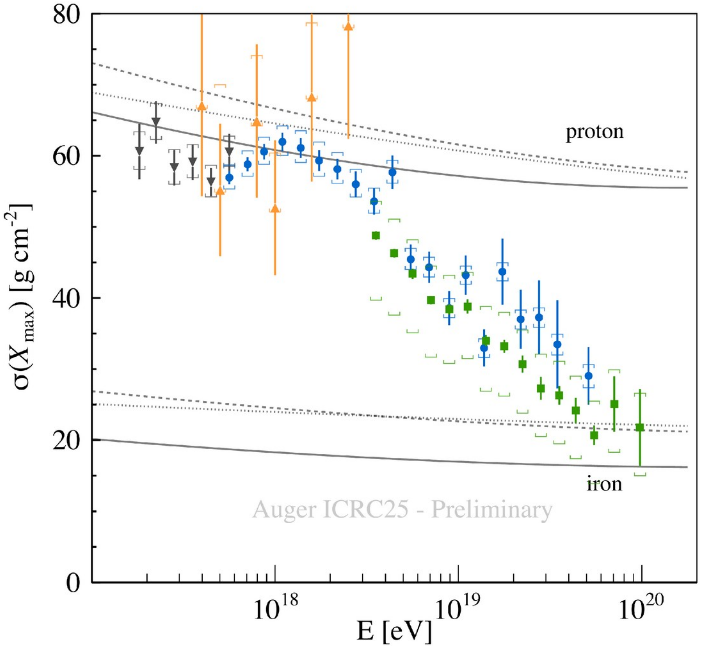
F Salamida ICRC 2025

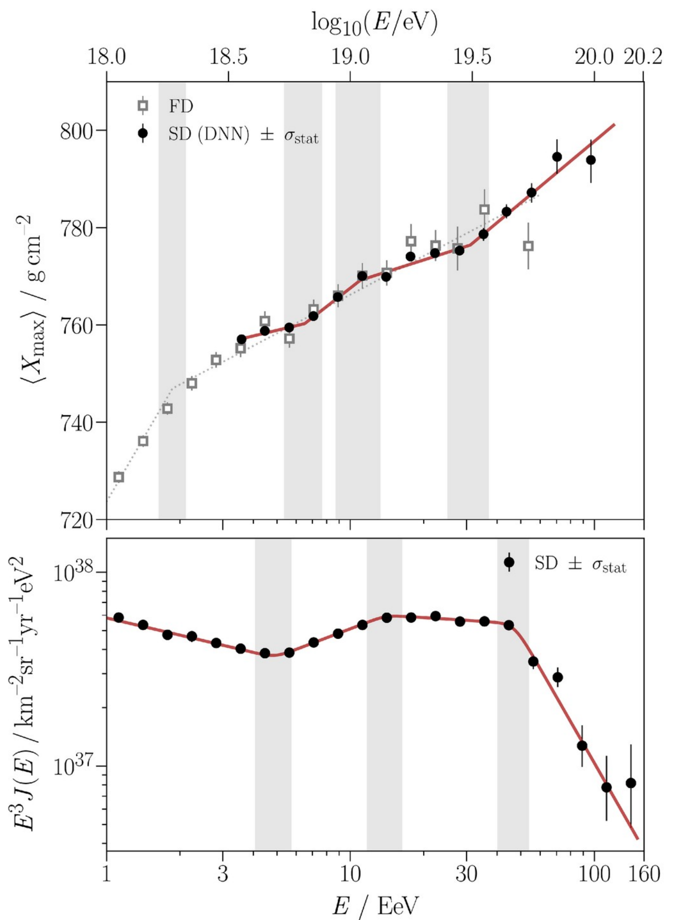
COMPOSITION HIGHLIGHTS

PRL 134 (2025) 021001
PRL 111 (2025) 022003

- Becomes heavier and purer, reinforced
  FD update + SD (x10 stat) Risetime Universality DNN
- Elongation rate has breaks
  Appear related to spectrum breaks
- Radio comes into play (AERA)







HADRONIC MODEL HIGHLIGHTS

Models extrapolate accelerator data (particle phisics interplay)

Composition is model dependent (general behavior is solid but details not)

- X_{max} (used for composition) → changes ~ 100 gcm^{-2} between p and Fe for a given model
- Model differences → X_{max} changes ~ 25 gcm^{-2} (lower limit)

All models have inconsistencies

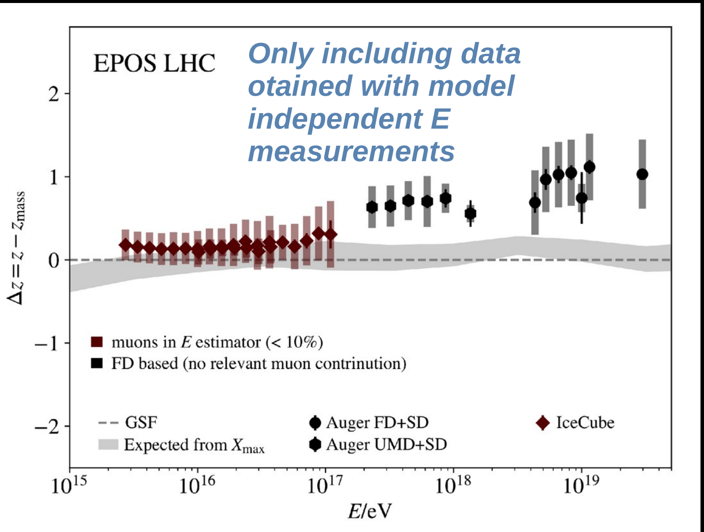
- Test: Multiple observables / Hybrid approach
- Muon deficit updates (first from inclined showers)

PRD 109 (2024) 102001

TABLE I. Indicative summary of the results of tests of models using Auger data (✓—no tension, ✗—tension). In the case of SIBYLL 2.3d, we also show estimations based on the previous version of the model Sibyll when available in the literature.

Test	Energy/EeV	$\theta/°$	Epos-LHC	QGSJet-II-04	SIBYLL 2.3d
X_{max} moments [8–11]	~3 to 50	0 to 80	✓	✗	✓ (2.3c)
X_{max}: $S(1000)$ correlation [11,12]	3 to 10	0 to 60	✓	✗	✓ (2.3c)
Mean muon number [13,15]	~10	~67	✗	✗	✗
Mean muon number [14]	0.2 to 2	0 to 45	✗	✗	...
Fluctuation of muon number [15]	4 to 40	~67	✓	✓	✓
Muon production depth [16]	20 to 70	~60	✗	✓	...
$S(1000)$ [17]	~10	0 to 60	✗	✗	...

J. Albrecht et al. (WHISP), "Roadmap for tuning models"
Nature Rev Phys accepted, arXiv2508.21796



New variables found related to fluctuations in first interaction

L Cazon, R. Conceicao, M Martins, F. Riehn; PRD 112 (2025) 4, 043016

Absolute energy scale is again crucial here!

Allow for model modifications: PRD 109 (2024) 102001

X_{max} shift & R(θ)-factor on μ-signal

3 parameters: ΔX_{max} $R_{had}(\theta_{max})$ $R_{had}(\theta_{min})$

Fit them to distributions of X_{max} and signal at 1000 m

data: E ~ 3-10 EeV in 5 zenith angle bins

All models "prefer" deeper X_{max} (besides increase of μ signal)

→ Reduced muon deficit

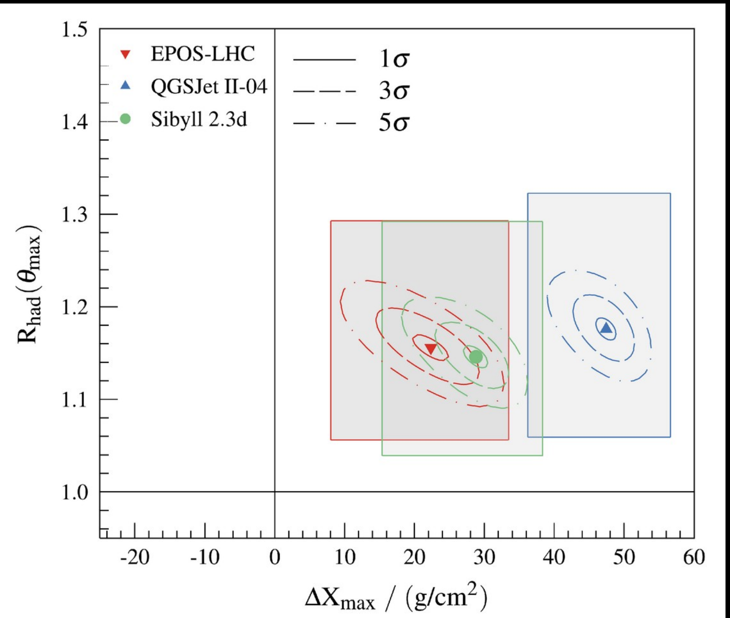
→ Reduced model dispersion

→ Heavier & purer composition

Trans Fe component?

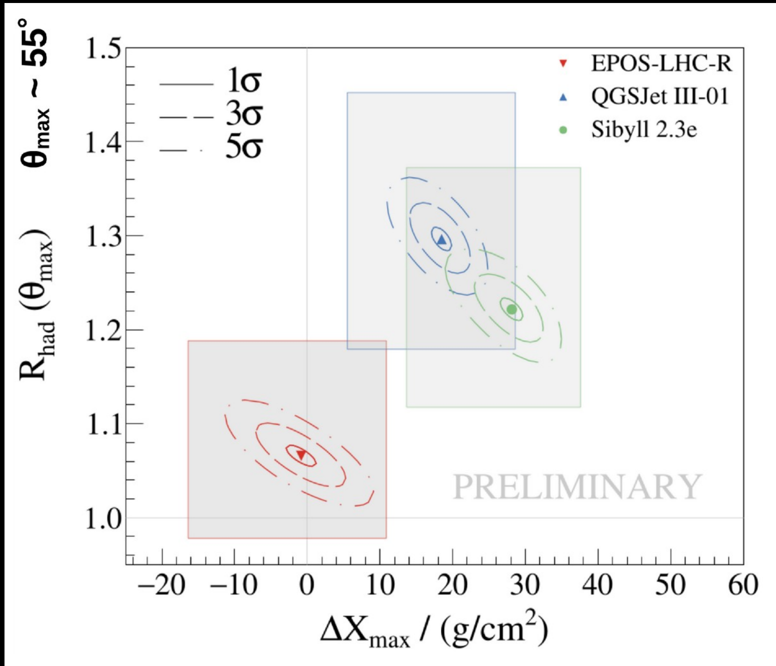
BNS merger origin?

GR Farrar, PRL 134 (2025) 081003



Update models

J. Vicha 528 ICRC 2025

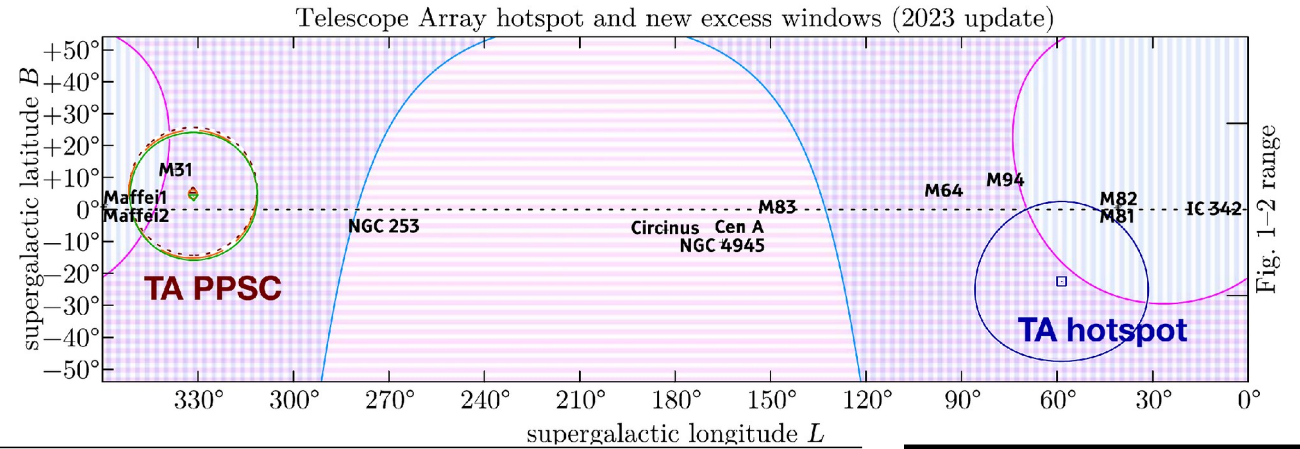


AUGER ANISOTROPY HIGHLIGHTS

- Dipole 6.5% E>8 EeV at 6.8σ, 16% E>32 EeV (Science 357 (2017) , APJ 976 (2024))
  113^0 away from Galactic Center → extragalactic origin
- Correlations with CEN A and SBG at ~ 4σ, to reach 5σ in ~ 2027
  (APJ 935 (2022) 170)

- TA excess claims (~3σ)
  hotspot & PPSC
  (Pisces Perseus Super Cluster)
  Comparable exposure
  No excess found

APJ 984 (2025) 123



	TA (Telescope Array Collaboration 2023)									Pierre Auger Observatory (This Work)							
	E_{min}	N_{tot}	$\frac{\mathcal{E}_{in}}{\mathcal{E}_{tot}}$	N_{bg}	N_{in}	$\frac{\Phi_{in}}{\Phi_{out}}$	Z_{LM}	99% L.L.	post-trial	E_{min}	N_{tot}	$\frac{\mathcal{E}_{in}}{\mathcal{E}_{tot}}$	N_{bg}	N_{in}	$\frac{\Phi_{in}}{\Phi_{out}}$	Z_{LM}	99% U.L.
(a)	57 EeV	216	9.47%	18.0	44	$2.44^{+0.44}_{-0.39}$	$+4.8\sigma$	1.60	2.8σ	44.6 EeV	1074	1.00%	10.7	9	$0.84^{+0.31}_{-0.25}$	-0.5σ	1.76
(b1)	$10^{19.4}$ eV	1125	5.88%	64.0	101	$1.58^{+0.17}_{-0.16}$	$+4.1\sigma$	1.22	3.3σ	20.5 EeV	8374	0.84%	70.1	65	$0.93^{+0.12}_{-0.11}$	-0.6σ	1.23
(b2)	$10^{19.5}$ eV	728	5.87%	41.1	70	$1.70^{+0.22}_{-0.20}$	$+4.0\sigma$	1.25	3.2σ	25.5 EeV	5156	0.84%	43.5	39	$0.90^{+0.15}_{-0.14}$	-0.7σ	1.29
(b3)	$10^{19.6}$ eV	441	5.84%	24.6	45	$1.83^{+0.31}_{-0.27}$	$+3.6\sigma$	1.23	3.0σ	31.7 EeV	2990	0.87%	26.0	27	$1.04^{+0.21}_{-0.19}$	$+0.2\sigma$	1.61

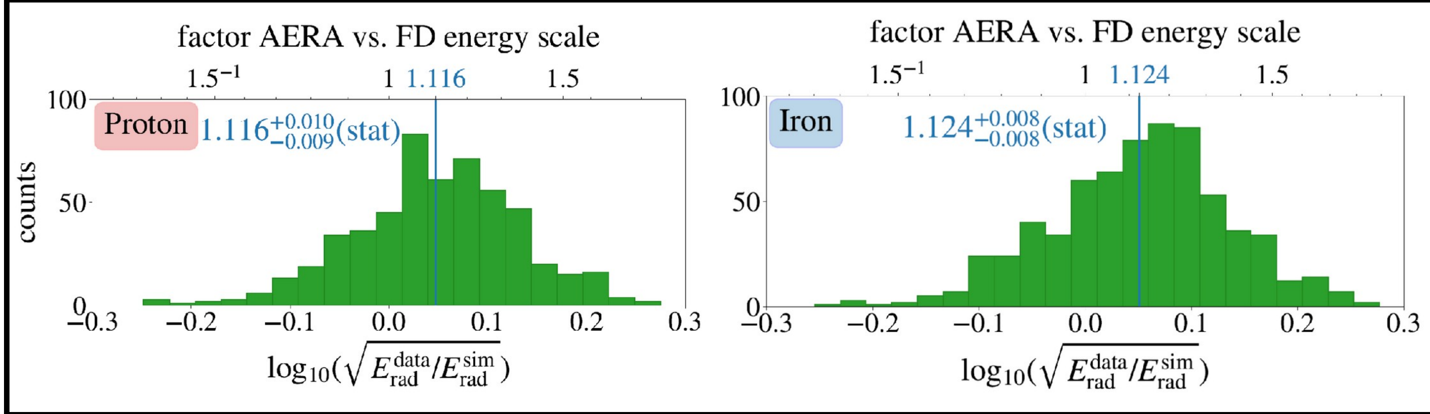
RADIO HIGHLIGHTS

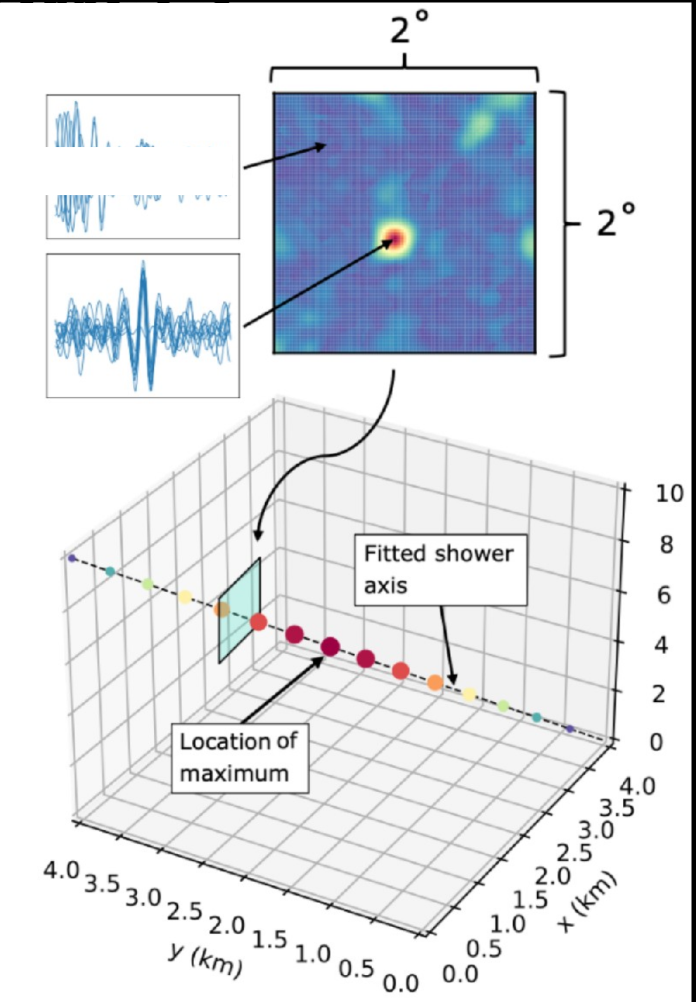
Two breakthroughs with AERA that promise a future

- Independent energy scale with radio

1.12 factor, consistent with FD

T. Huege 616 ICRC 2025





- “Interferometric tomography” proved (AERA)

needs ns timing (beacons)

Improved gemetrical reconstruction

→ angular resolution

energy scale

reduction of systematics

H. Schoorlemmer 297 ICRC 2025

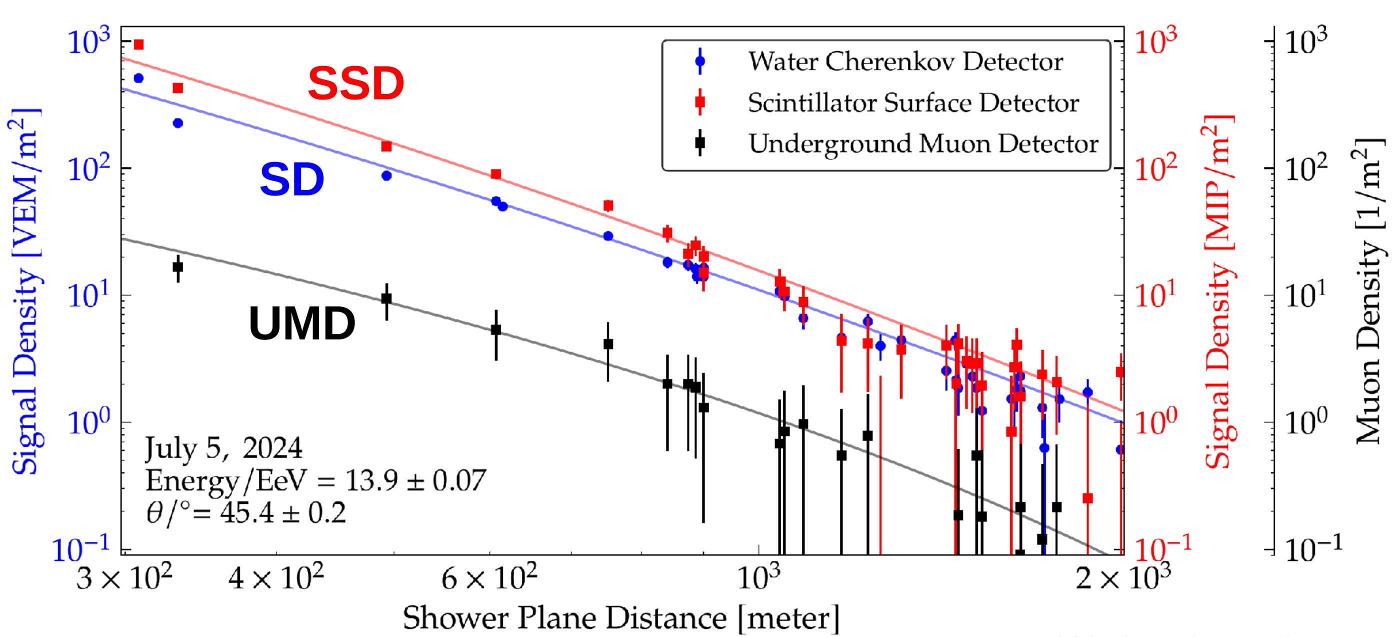
H. S. & W.R. de Carvalho

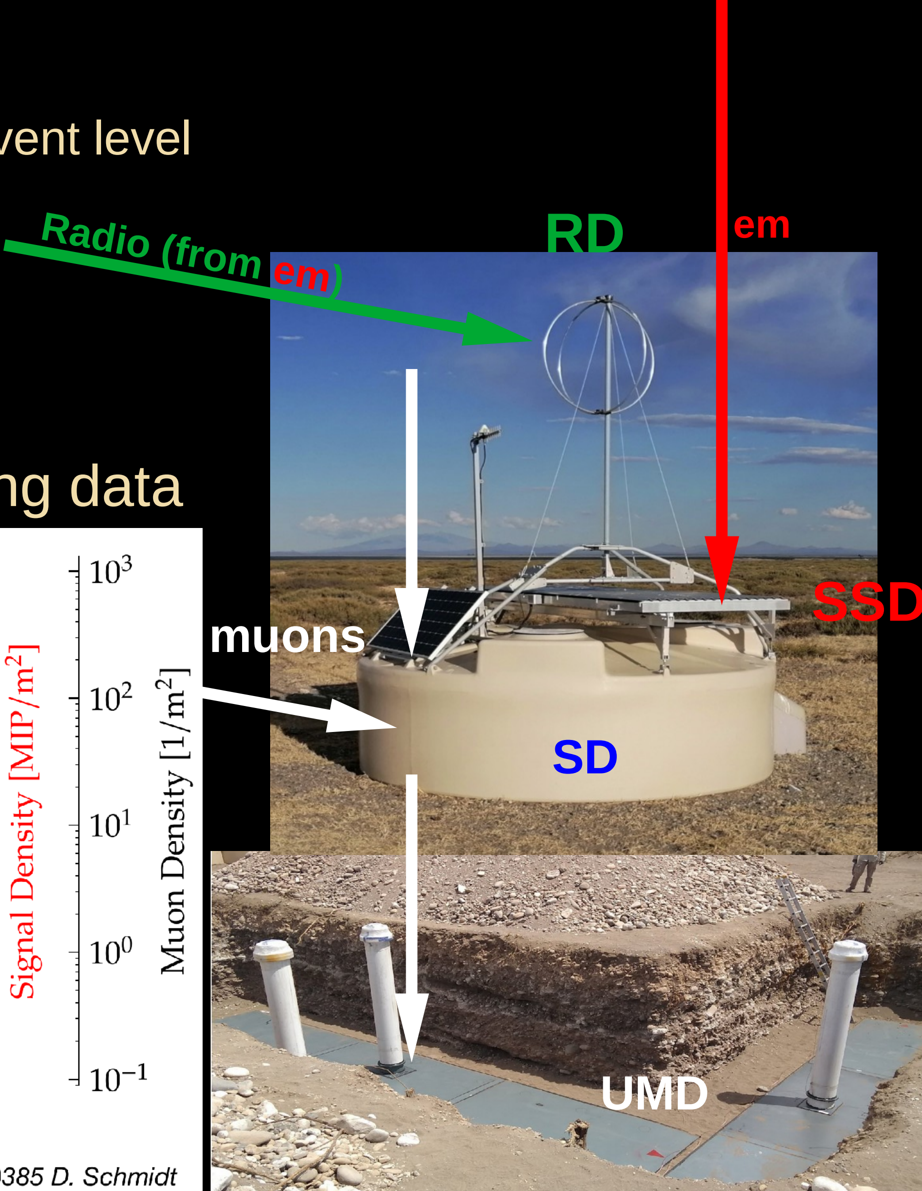
Eur.Phys.J.C 81 (2021) 12, 1120

AUGERPRIME

Enhance hybrid approach: Composition sentivity at event level
Separate muons and electrons (em) adding:
Scintillator slabs: on top SSD
Underground UMD
Antennas: RD

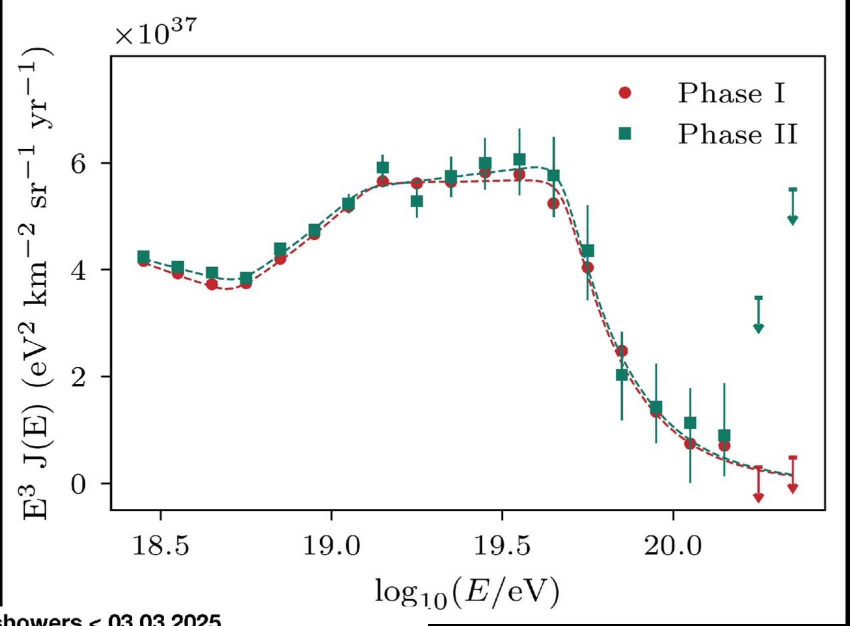
now taking data

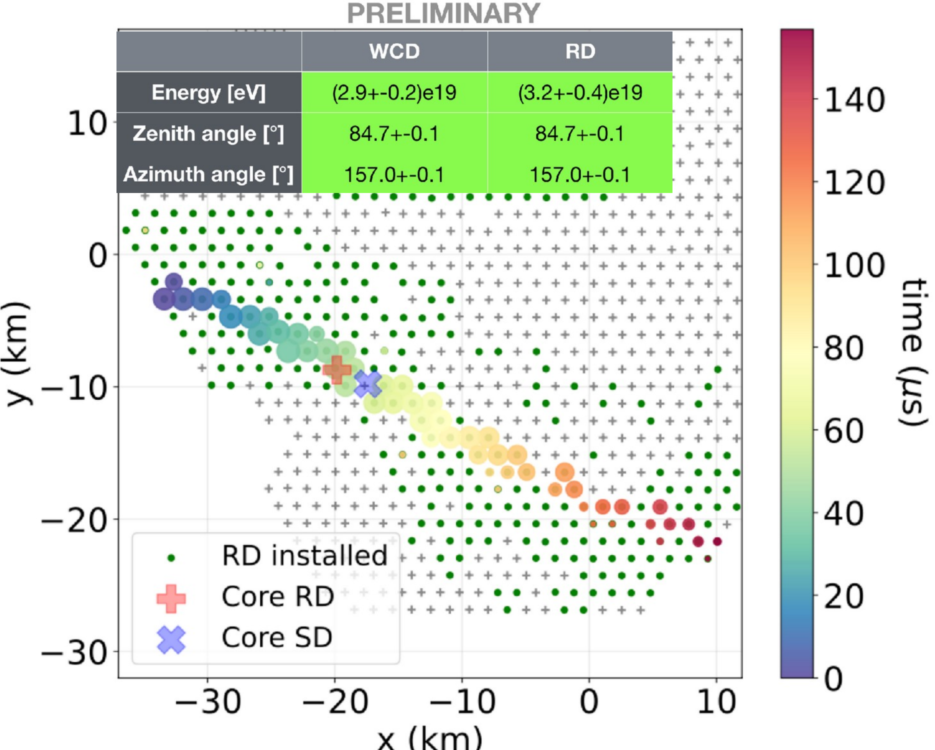




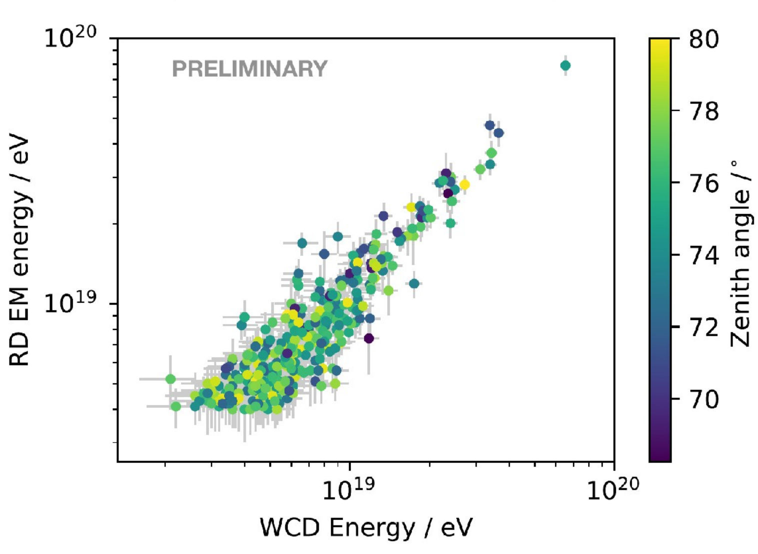
PoS(ICRC2025)385 D. Schmidt

Exposure: 9200±300 km^2 sr yr ~10% Phase I
Consistent spectra of Phase I and II
High confidence in incoming data





Measured air showers < 03.03.2025



The UHE domain: ν E > ~0.1 EeV = 10^{17} eV

New window to explore

Muon/Tau tracks & showers:

Optical (fluorescence/Cherenkov):
- Dense media
  - Ice IceCube
  - Water ANTARES

Only showers:

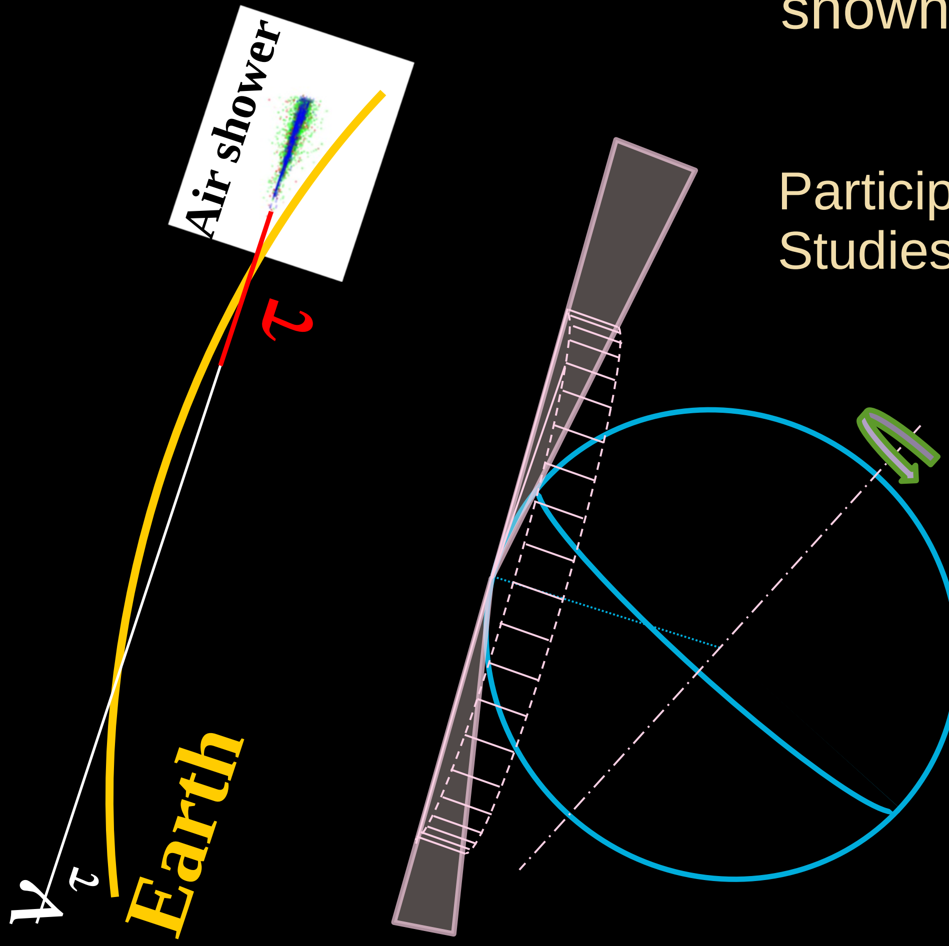
Particles:
- Air
  - Pierre Auger Observatory

Radio:
- Dense ICE
  - From surface RNO-G
  - From above ANITA → PUEO
- Air
  - From balloon ANITA → PUEO

Auger Observatory: huge effective area for earth skimming neutrinos

also for UHE photons: Earth skimming showers

shown for GW170817 [A. Aab et al. Ap.J.Letts. **850:L35** (2017)]

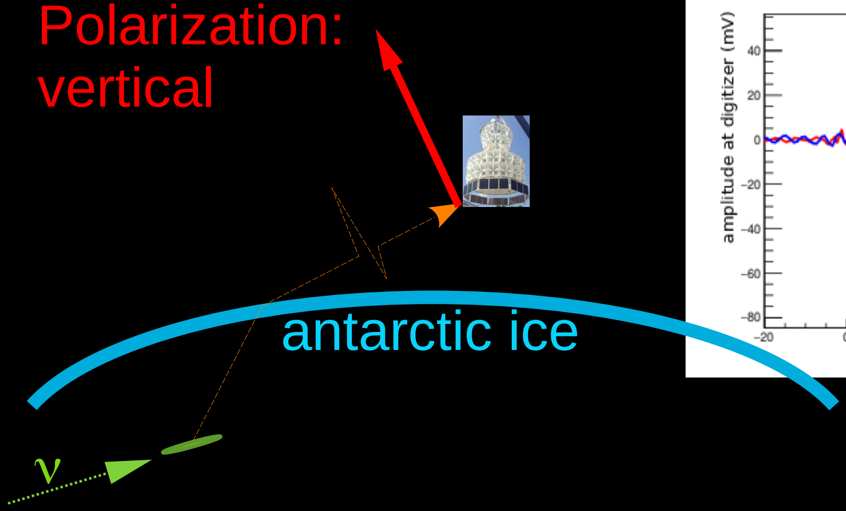


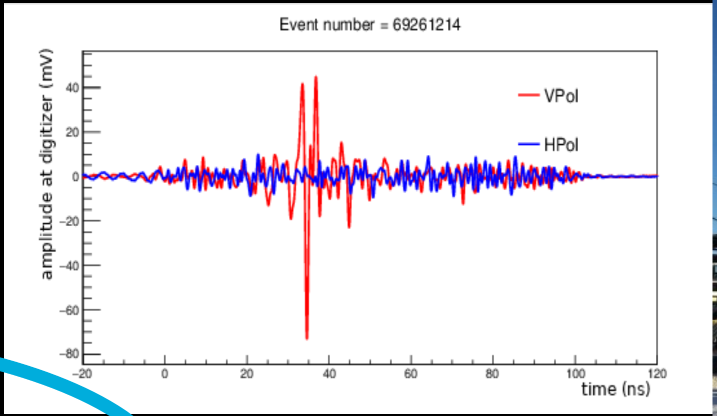
Participation in Astrophysical Center Multimessenger Studies in Europe (ACME)

SEARCH FOR UPGOING SHOWERS (Auger FD)

Motivated by ANOMALOUS **ANITA** EVENTS

PRL134 (2025)121003





ANITA

To detect GHz pulses from showers

- -Set ν limits for E_ν > 30 EeV
- -Observed CR pulses
- -Found unexplained Anomalous events

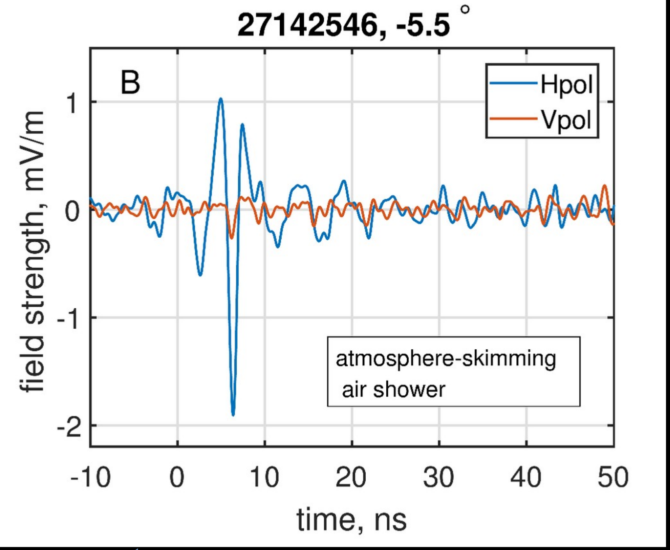
ANITA: ANtarctic Impulsive Transient Antenna

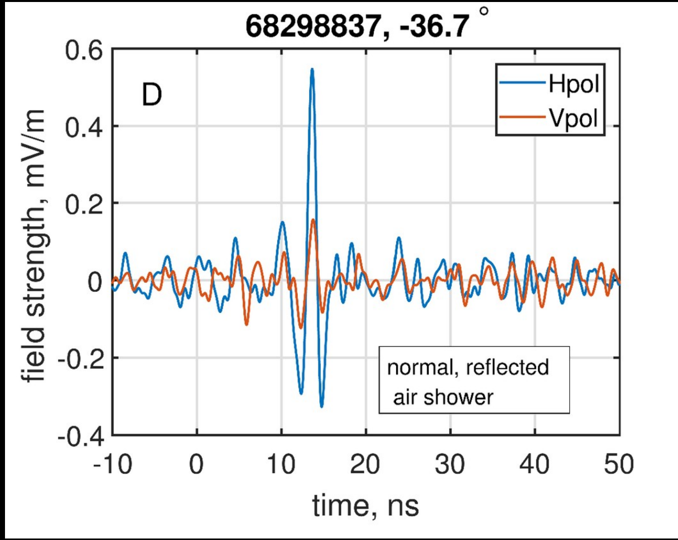
Horizontal polarization → air shower (vxB)

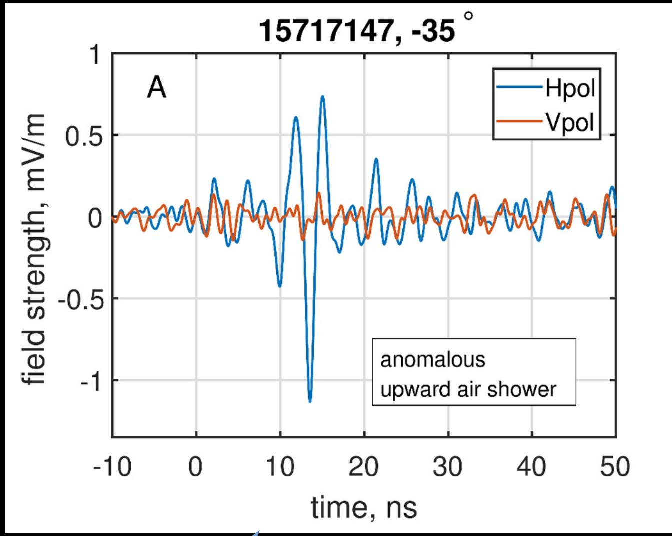
CR event DIRECT

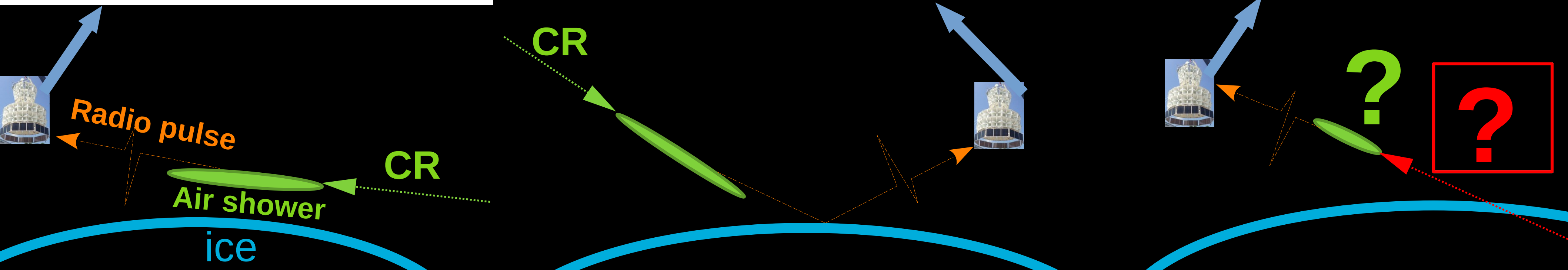
CR event REFLECTED
Opposite POLARITY

ANOMALOUS events
polarity → direct









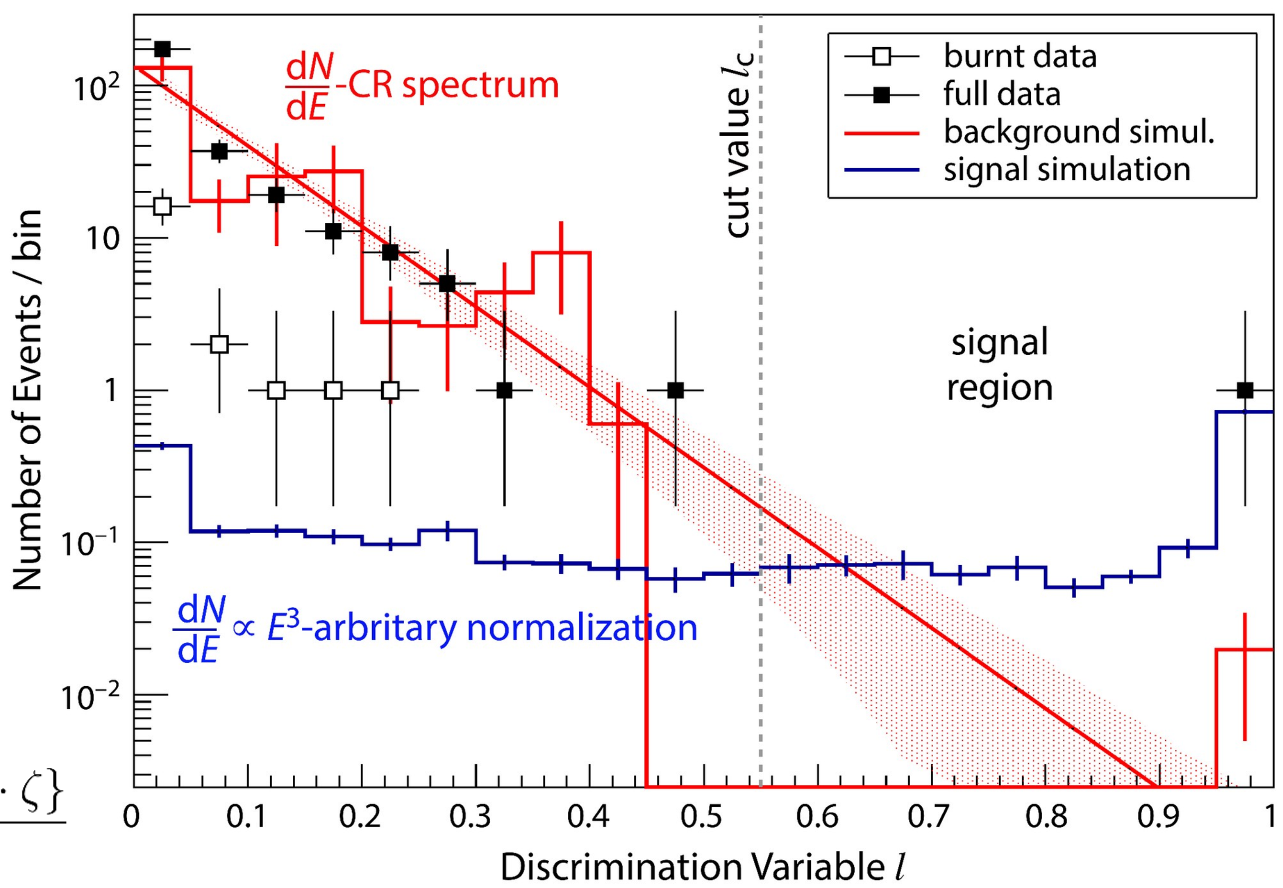
Search procedure (Preselection without lasers: 6.4 Million events)

Eliminate untagged lasers (burn 10% of FD data) 4.7M events

Simulate CR background & Signal

Design cut sequence

- Laser cuts	$7.6\ 10^6$ events
- Quality	$4.7\ 10^6$
clean atmosphere, low cloud coverage, 6 or more pixels	
- Regular fit upward going	$6\ 10^5$
- Global Fit upward	$1.65\ 10^5$
- Reconstrcution quality	2774
X_{max} above ground slant depth < 80 g cm^{-2})	
- Horizontal events	986
$\theta>110^0$	
- Ambiguous events:	**255**
$\chi^2_{up} < 1.2\ \chi^2_{down}$	
- Discrimination variable	**1 event left**
Optimized cut l>0.55	



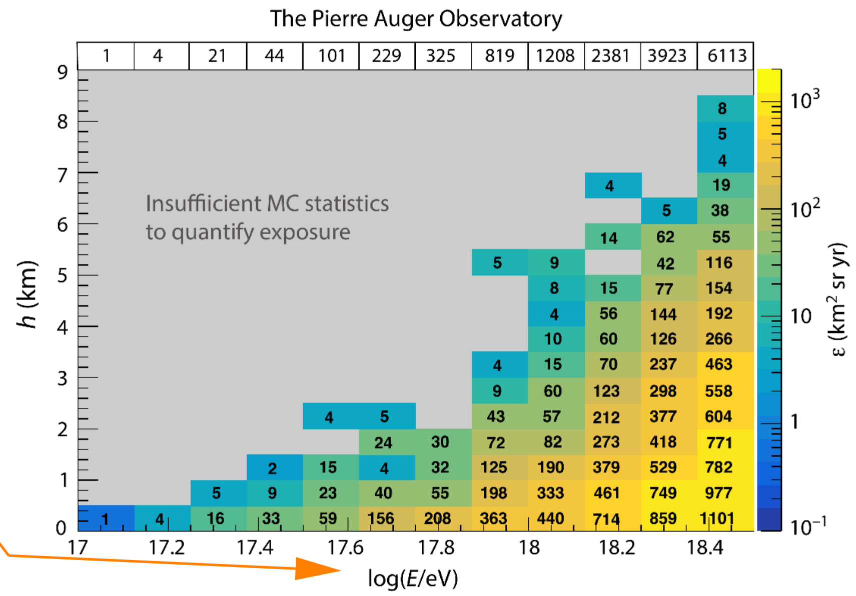
$$l = \frac{\arctan\{\ln[\max(L_{up}, L_{down})/L_{down}] \cdot \zeta\}}{\pi/2}$$

Compare exposures & implications

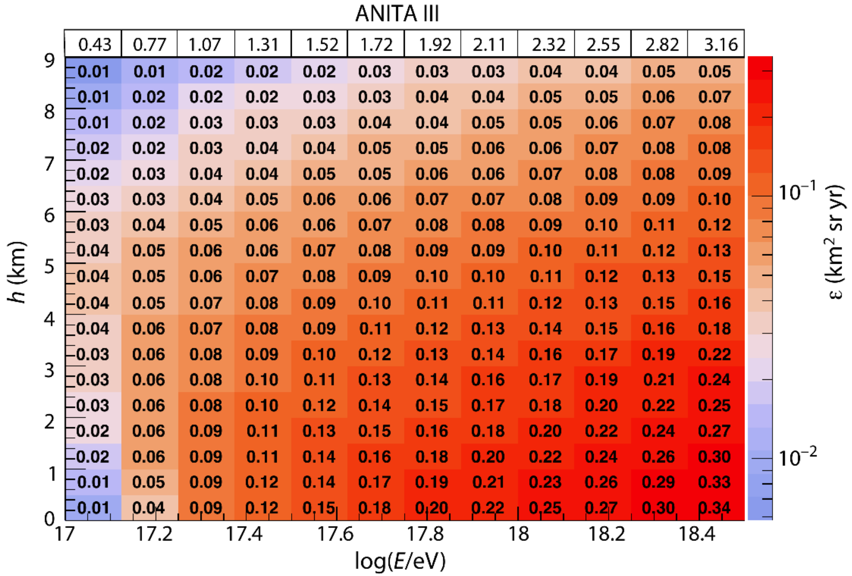
Exposures depend on shower altitude (h) & energy (E)

	Normalize to ANITA I event	Normalize to ANITA III event
Flux E^{-3} Uniform in h	59	69
Flux E^{-3} h-distrib: τ-decay	37	34
Flux E^{-5} Uniform in h	12	8.1
Flux E^{-5} h-distrib: τ-decay	18	11

ANITA



Auger



Expected number of events at Auger vs. one observed (compatible with background)

DISMISS upgoing shower interpretation

PRL134 (2025)121003

The Future of UHEν

Optical (fluorescence/Cherenkov):

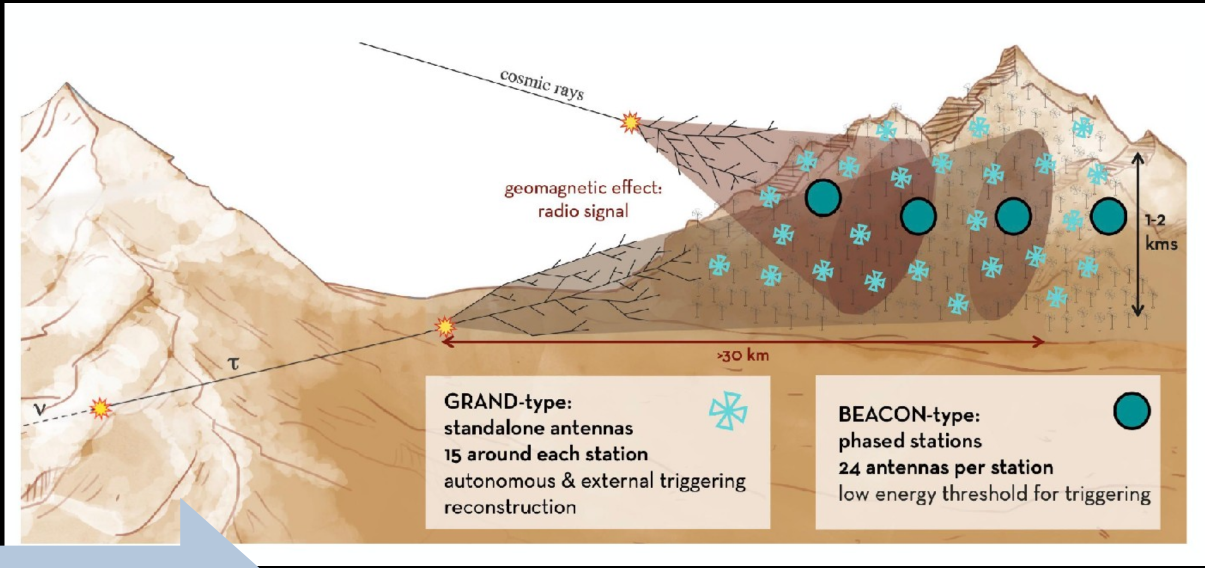
- Dense
  - Ice: IceCube Gen2
- Air (showers)
  - From satellite POEMMA
  - From balloon EUSO-SPB
  - From mountain TRINITY

Radio:

- Dense ICE
  - From within ICECube Gen2 Radio
  - From surface RNO-G
- Air
  - From mountain BEACON
  - From ground GRAND

Particles:

- Air
  - V-Valley TAMBO



HERON (last phase of Synergy grant)

Astroparticle Physics group at IGFAE-USC

Permanent staff

Jaime Alvarez-Muñiz
Professor

Lorenzo Cazón
Ramón y Cajal
Sept. 2021

Gonzalo Parente
Professor

Enrique Zas
Professor

PhD Students

Sergio Cabana-Freire
Xunta de Galicia
Oct. 2022

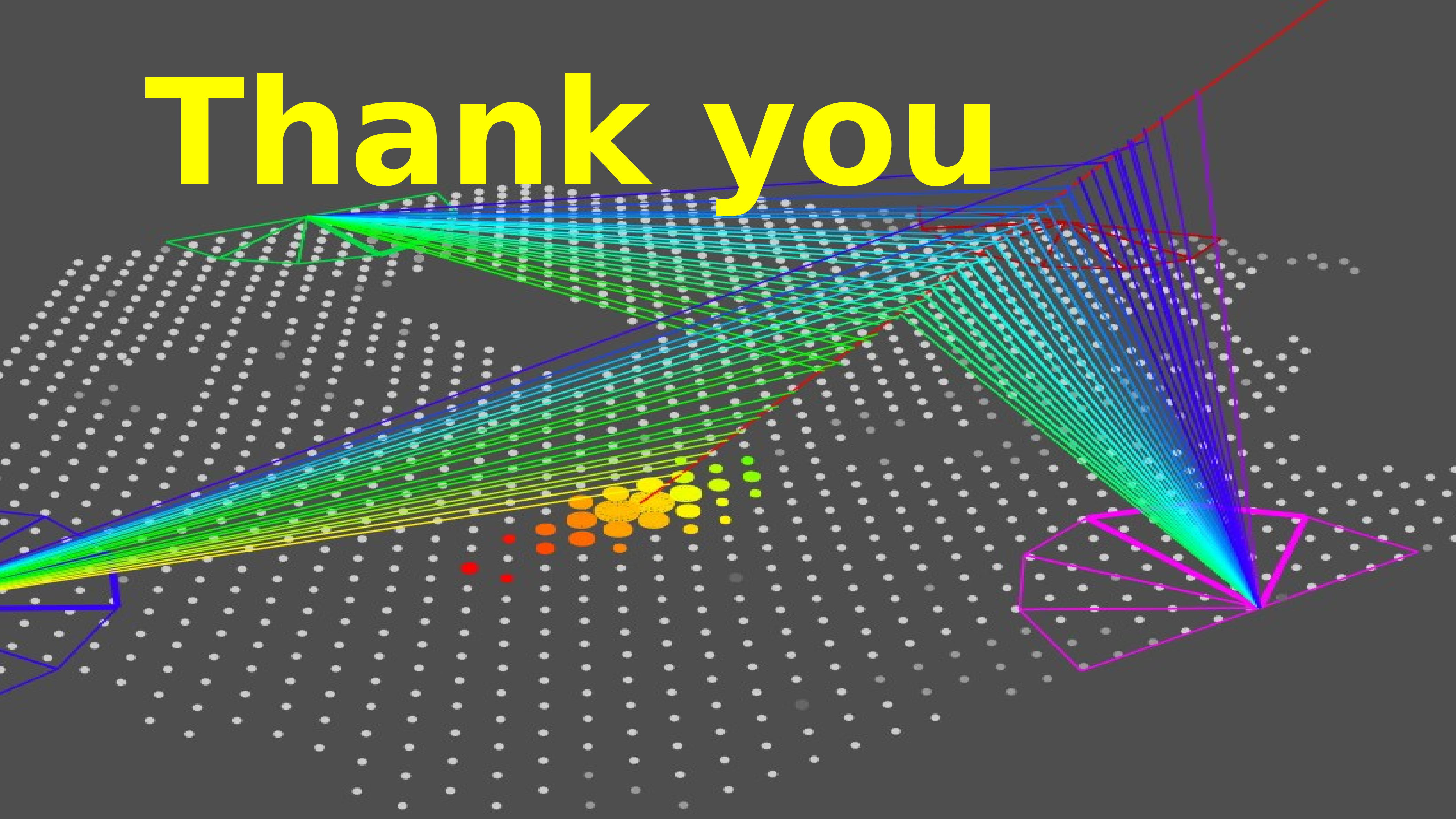
Yago Lema-Capeáns
Xunta de Galicia
Oct. 2022

Miguel A. Martins
INPHiNIT La Caixa
Jan. 2022

Carmen Pavon
Xunta de Galicia
Oct. 2024

Francisco Sánchez
IGFAE (Auger) FPI
March 2024

Thank you

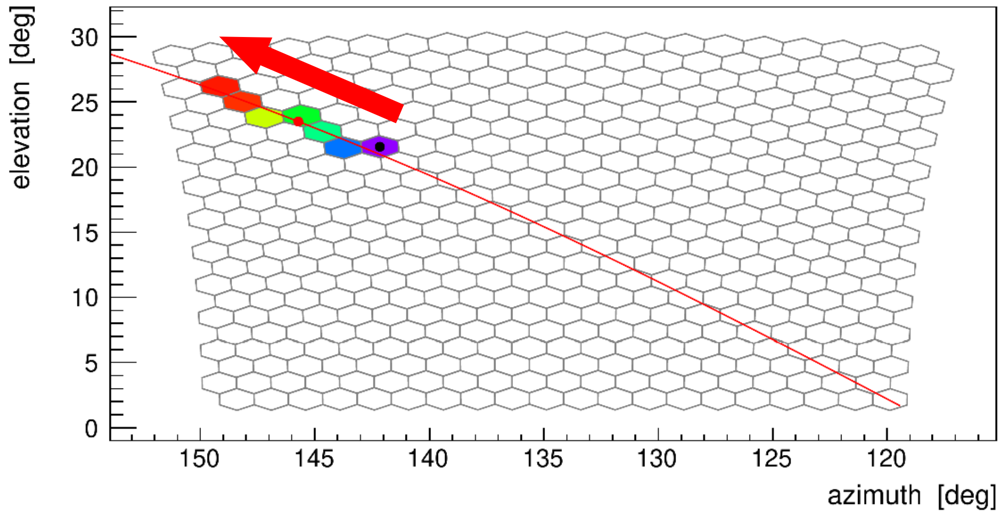


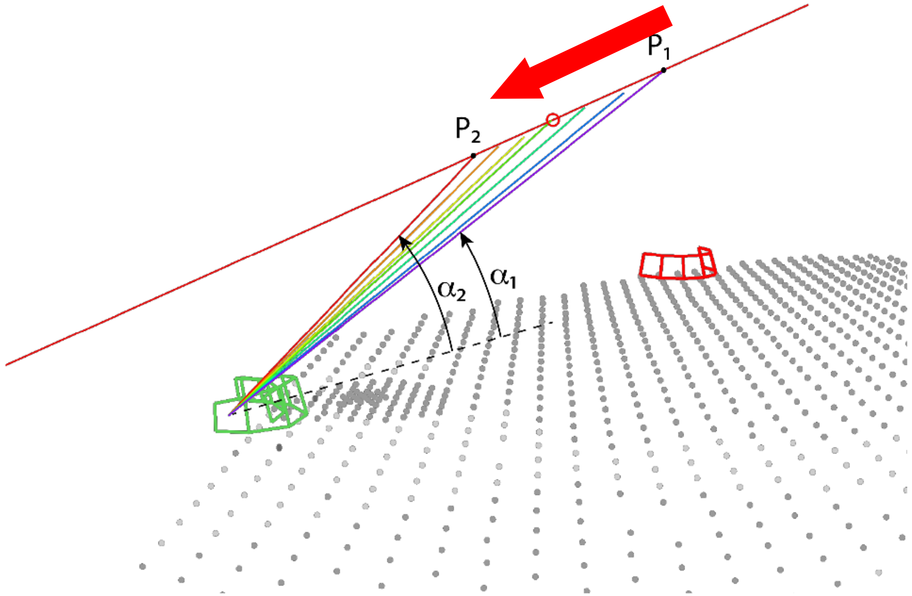
Procedure:

Simulate signal & background
Develop a selection procedure
Apply to data

Calculate exposures
(ANITA + Pierre Auger Obs)

Obtain expected number of upgoing events in Auger



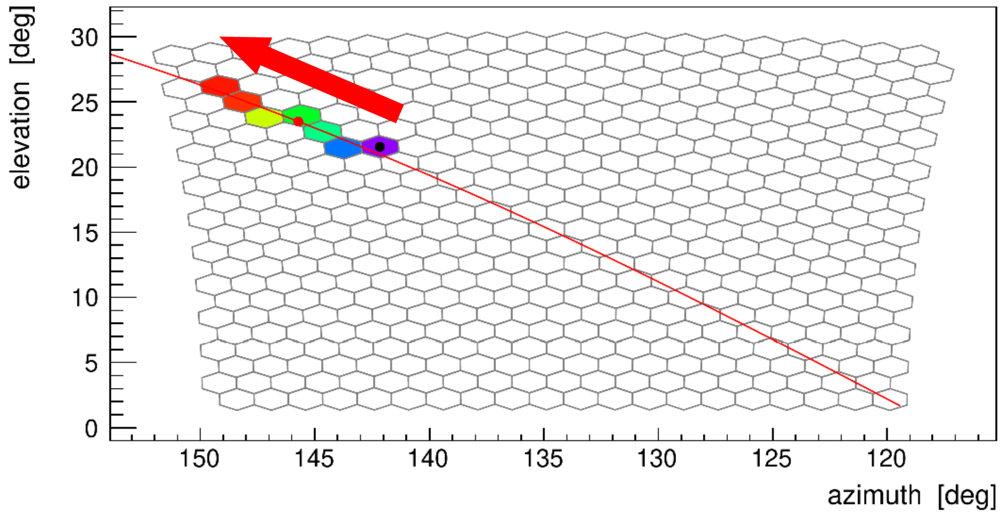


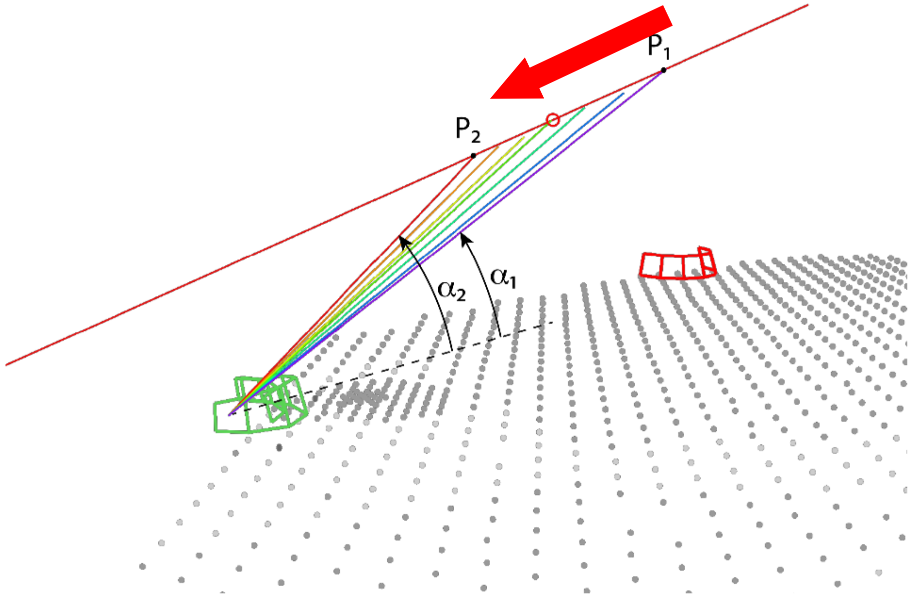
Procedure:

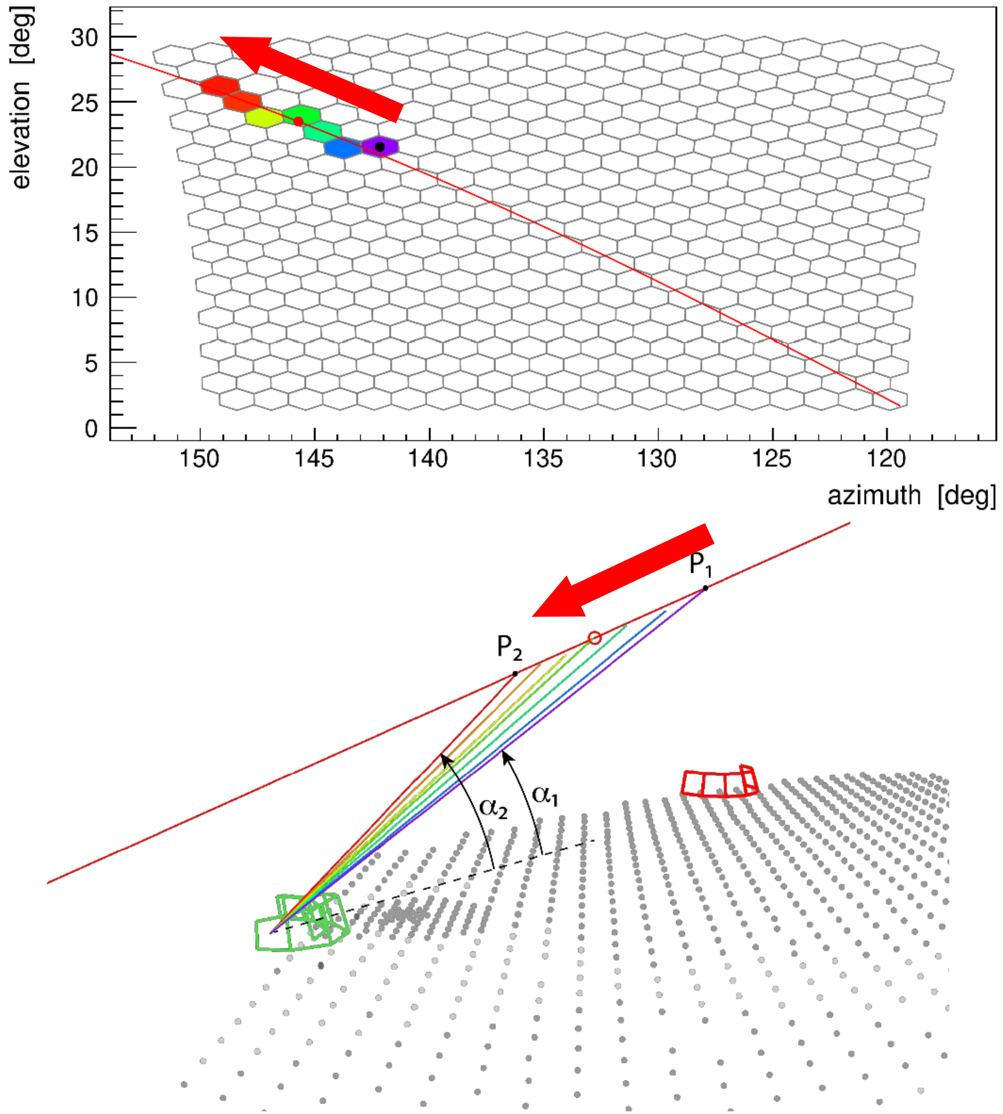
Simulate signal & background
Develop a selection procedure
Apply to data

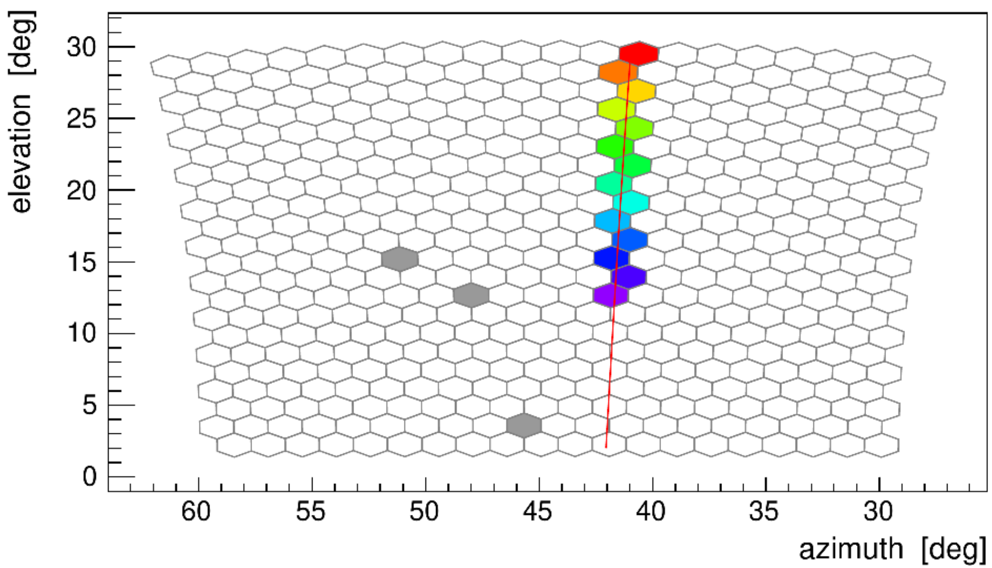
Calculate exposures
(ANITA + Pierre Auger Obs)

Obtain expected number of upgoing events in Auger

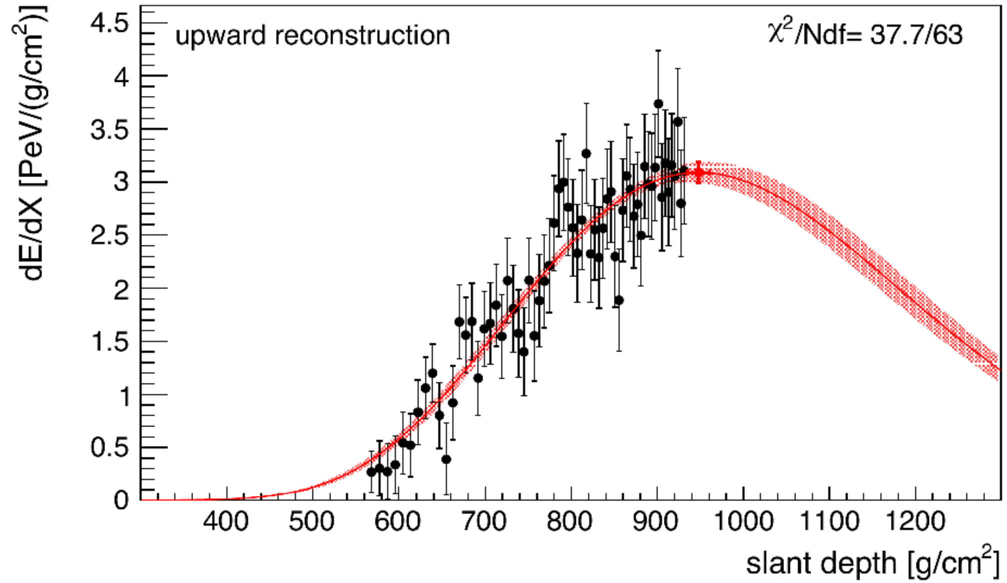




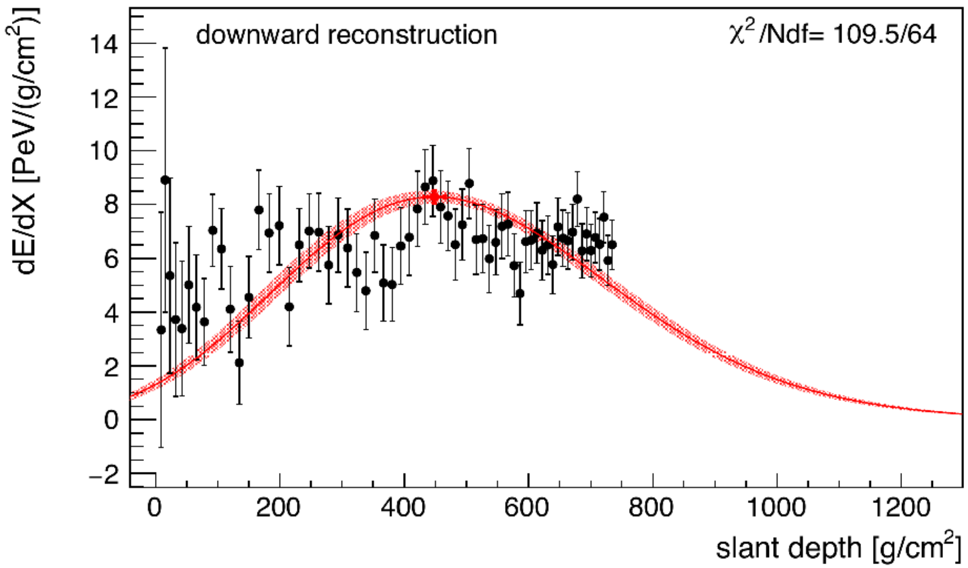

elevation [deg]
azimuth [deg]
30
25
20
15
10
5
0
150
145
140
135
130
125
120
P1
P2
α2
α1



elevation [deg]
30
25
20
15
10
5
0
60
55
50
45
40
35
30
azimuth [deg]



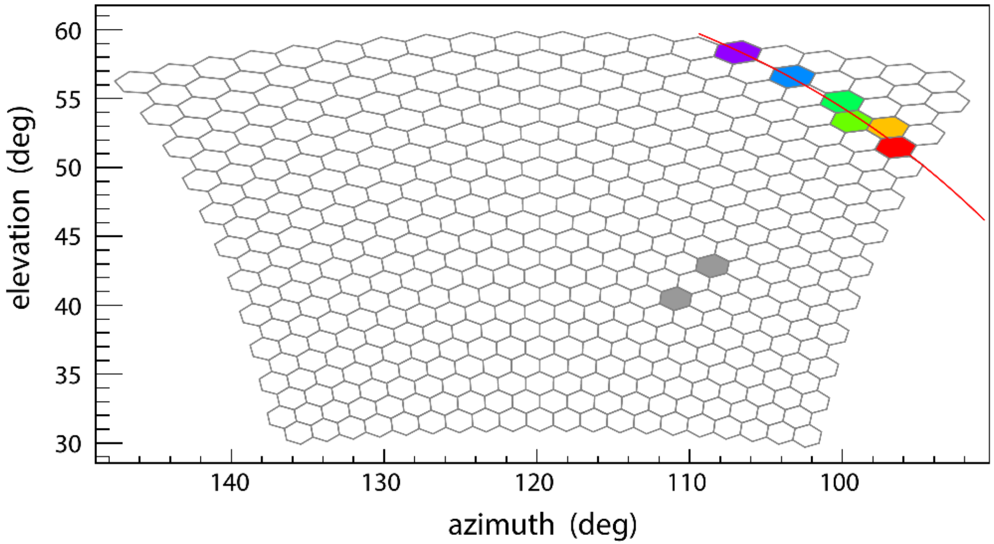
upward reconstruction
χ^2/Ndf= 37.7/63
dE/dX [PeV/(g/cm^2)]
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
400
500
600
700
800
900
1000
1100
1200
slant depth [g/cm^2]

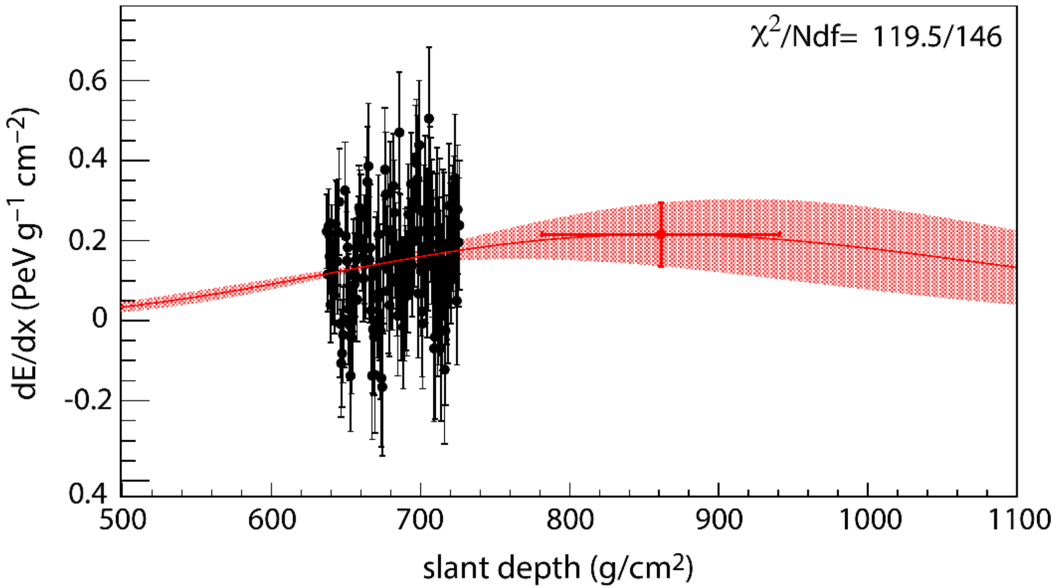


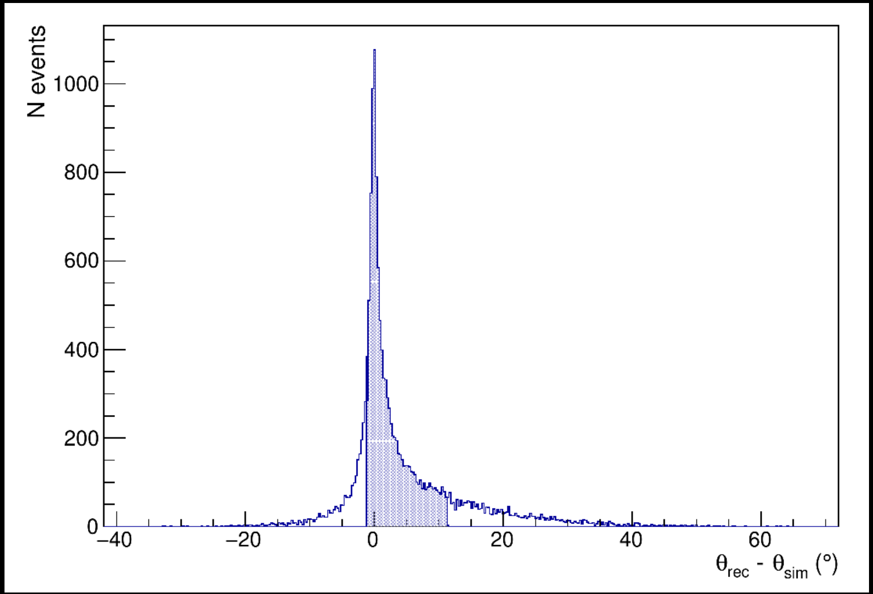
downward reconstruction
χ^2/Ndf= 109.5/64
dE/dX [PeV/(g/cm^2)]
14
12
10
8
6
4
2
0
−2
0
200
400
600
800
1000
1200
slant depth [g/cm^2]

Result consistent with expectations

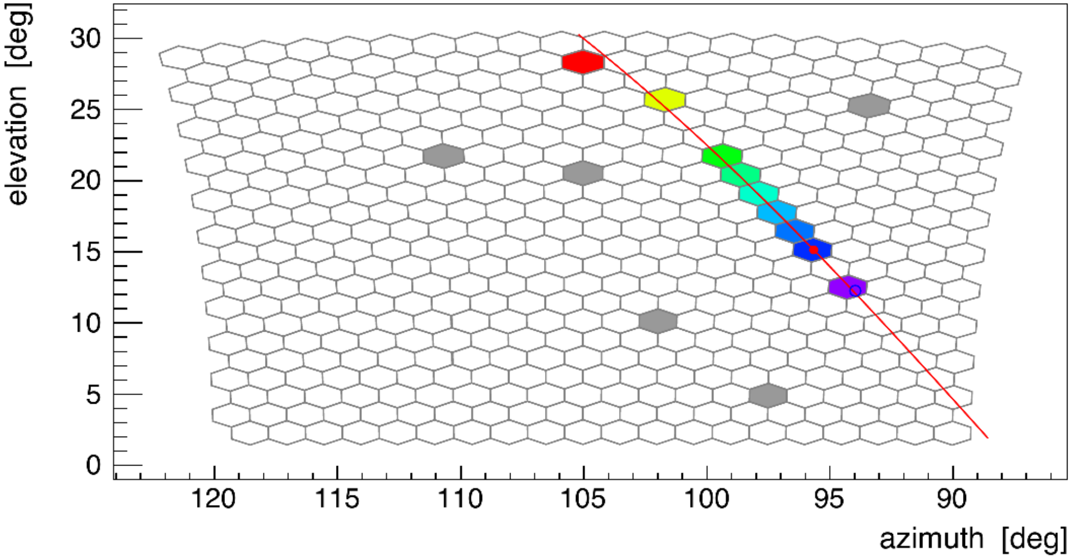
Note:
Low quality event
Has few pixels (only 6)
Crosses corner of camera

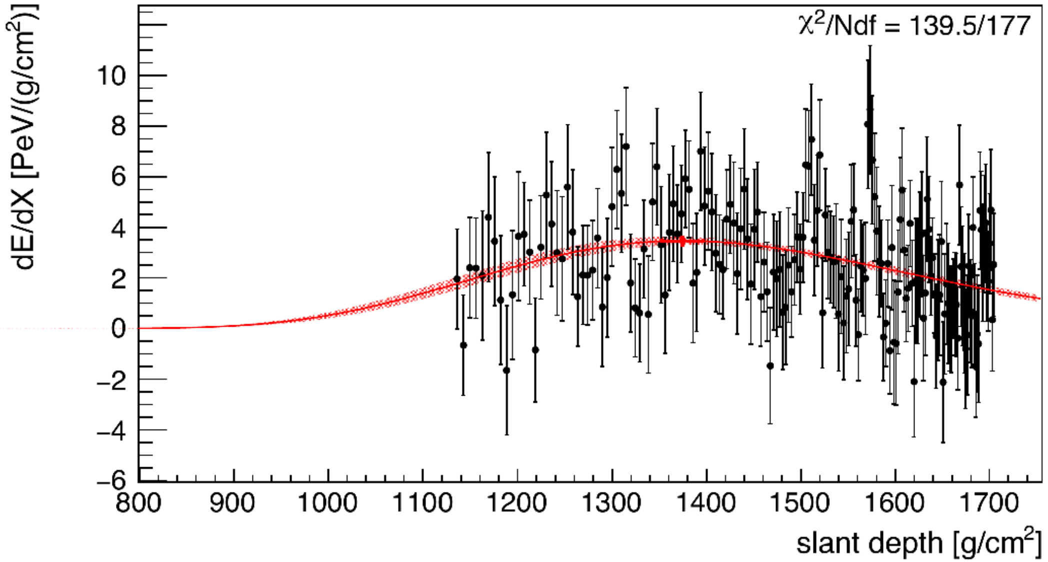






$$\theta_{\rm sim} = 89.6^\circ \; ; \; \theta_{\rm rec} = 116.6^\circ$$
$$\theta_{\rm sim} = 90.7^\circ \; ; \; \theta_{\rm rec} = 142.1^\circ$$
$$\theta_{\rm sim} = 90.8^\circ \; ; \; \theta_{\rm rec} = 115.6^\circ$$
$$\theta_{\rm sim} = 91.9^\circ \; ; \; \theta_{\rm rec} = 112.7^\circ$$
$$\theta_{\rm sim} = 93.0^\circ \; ; \; \theta_{\rm rec} = 136.1^\circ.$$





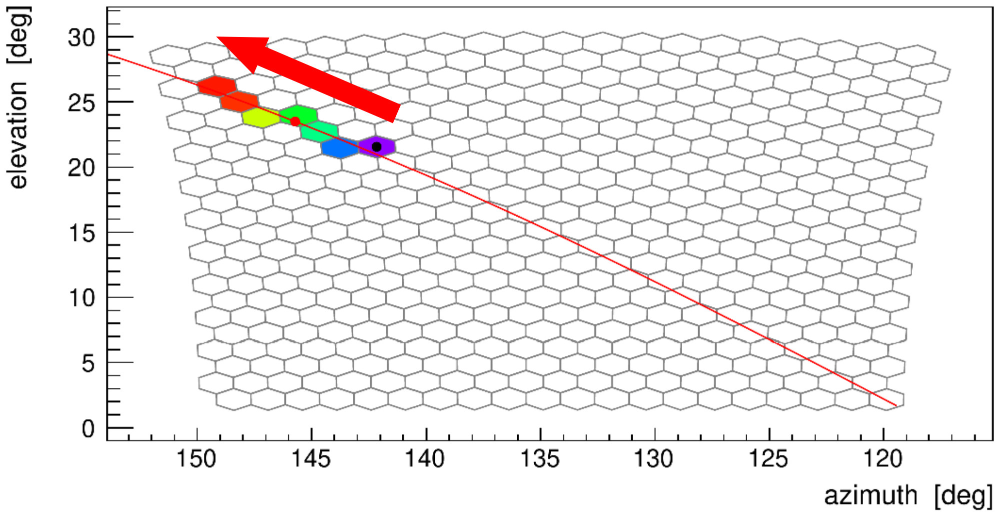
Background:

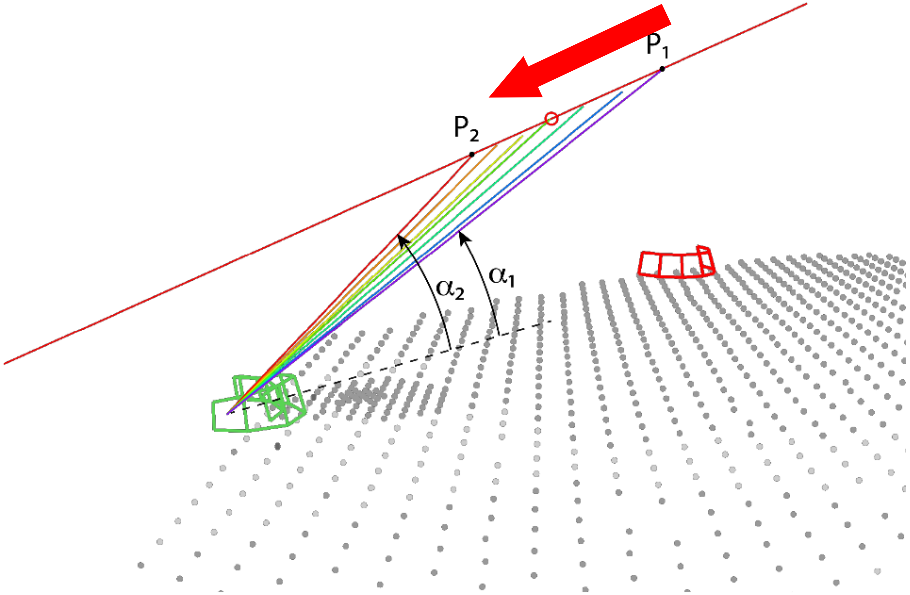
Large Background:
- Laser shots (fired upwards)
- CR “Up” vs “Down” → not straight-forward

FD RECONSTRUCTION:

Standard:
1- Fit direction to pixel data (time)
2- Extract the shower profile

We need
“Global Fit”: (PCGF) (more restrictive)
Fit - arrival times &
- shower profile (Gaisser-Hillas)

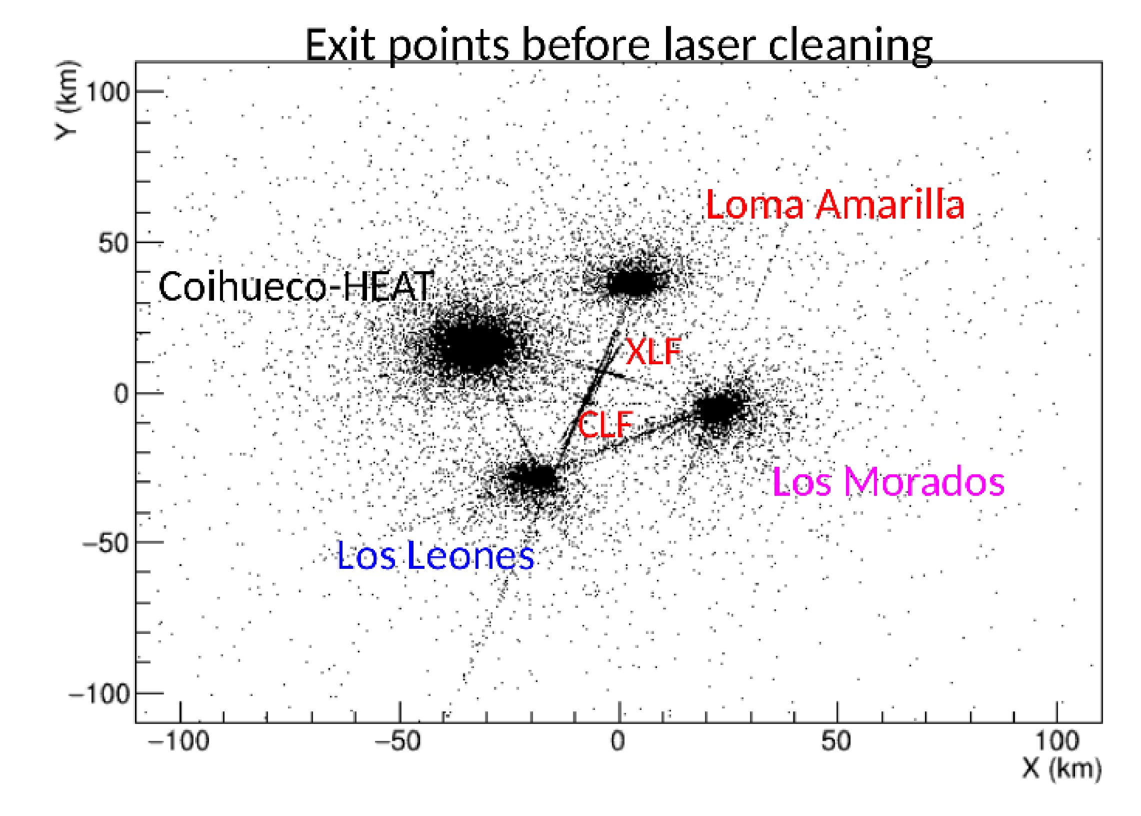




Laser shots:

Several devices used for
- Atmospheric monitoring
- Testing reconstruction

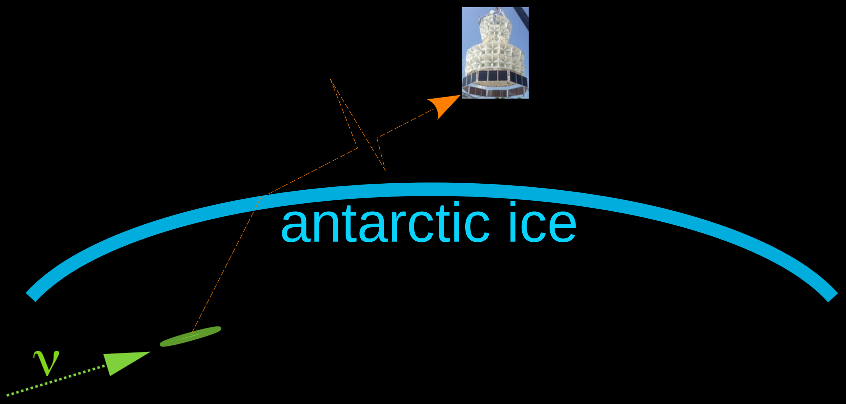
Important issue
Many (average rate ~150 Hz)
About 0.01% not properly tagged

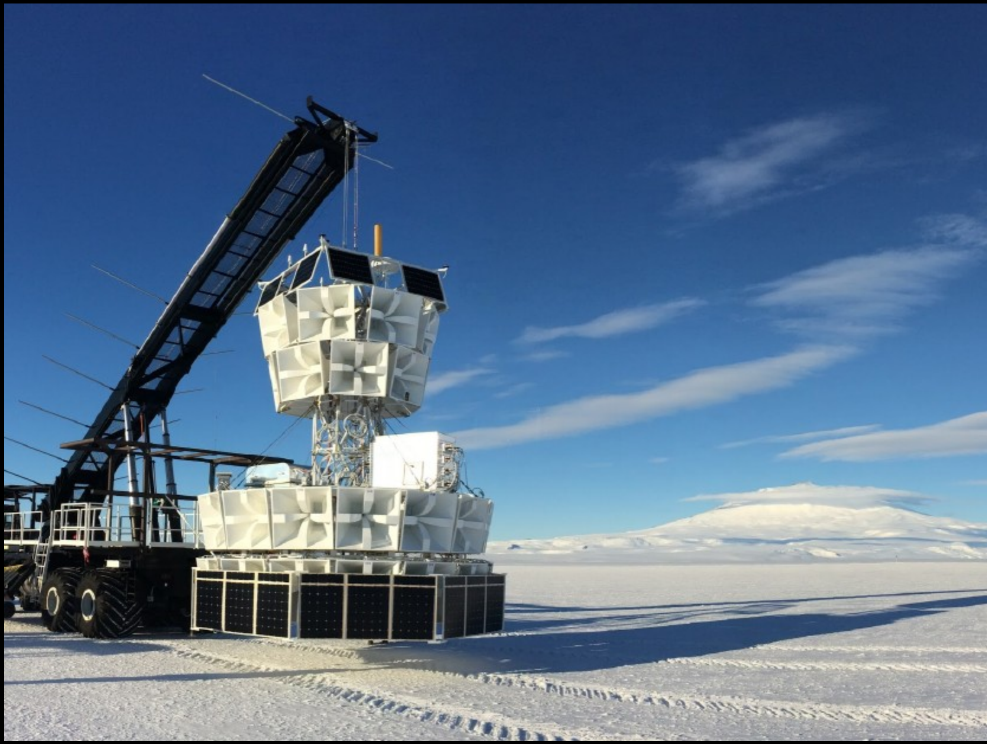


STRATEGY
- Search in burn sample: 10% of data to 31-12-18
- Identify selection cuts to clean it
- Use frequency and location of impact point

Motivation:

ANITA *Antartic Impulsive Transient Antenna*

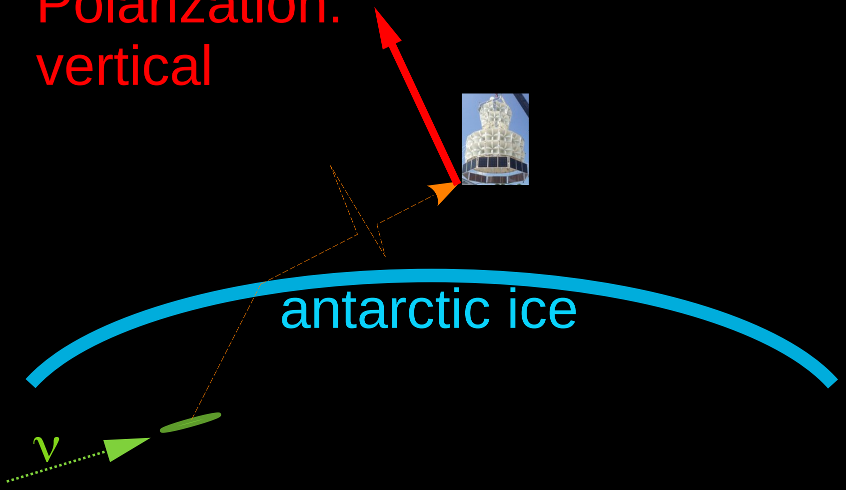




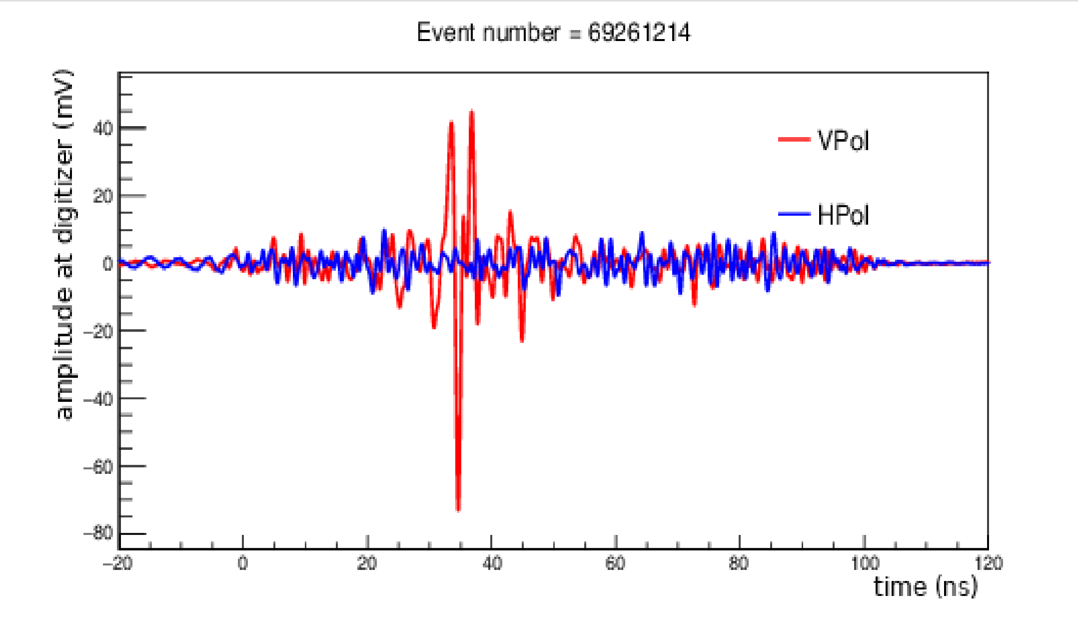
Designed for pulses from ν showers

- -Set ν limits for E_ν > 30 EeV
- -Observed CR pulses from AIR showers
- -Found unexplained Anomalous events

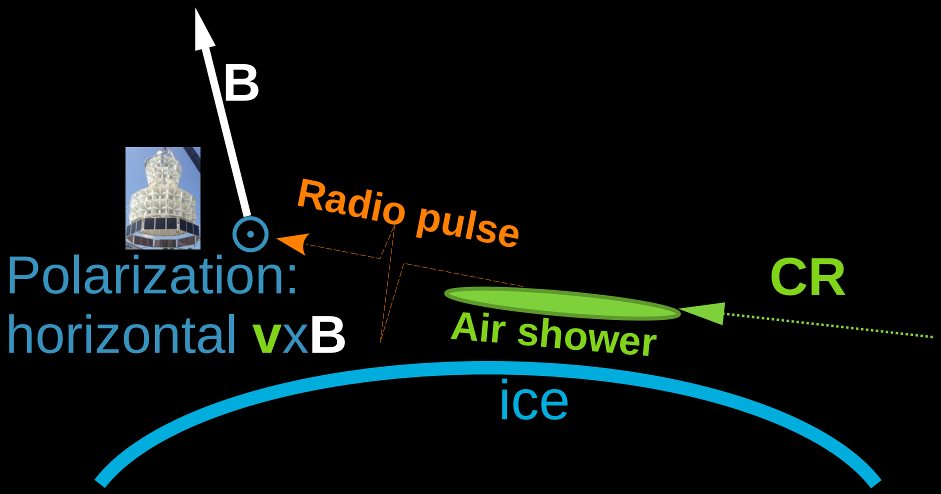
ANITA



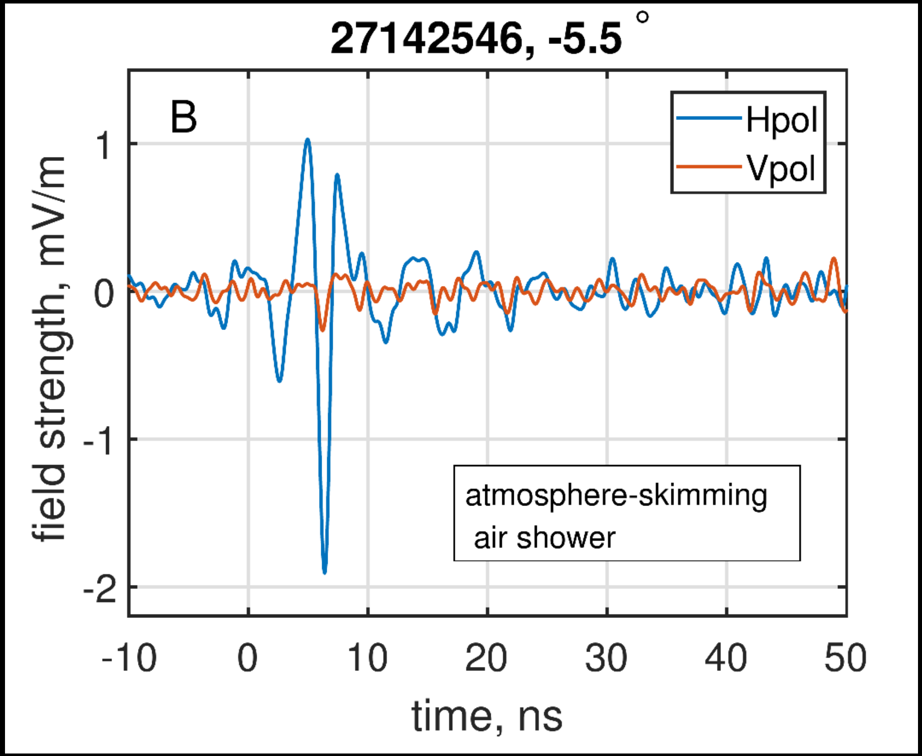
Expected signal from a neutrino



Designed for pulses from ν showers

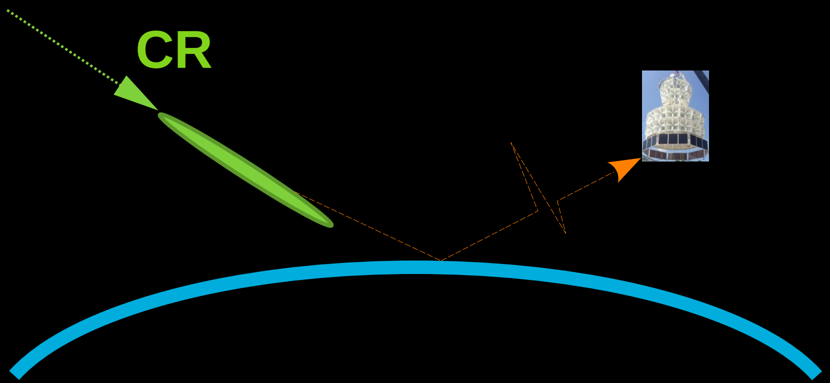


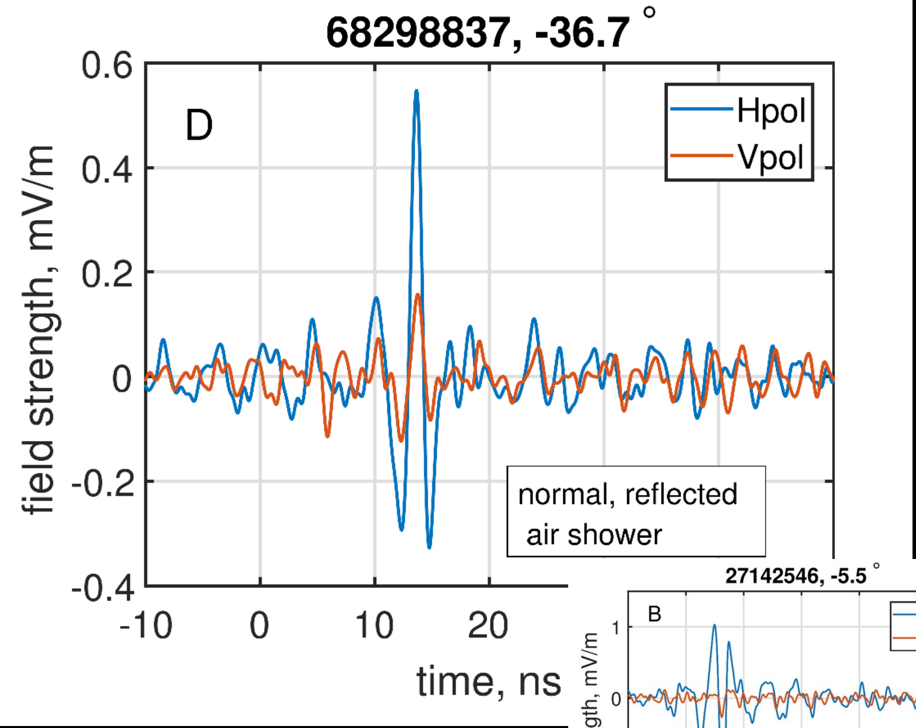
Direct Signal from a CR

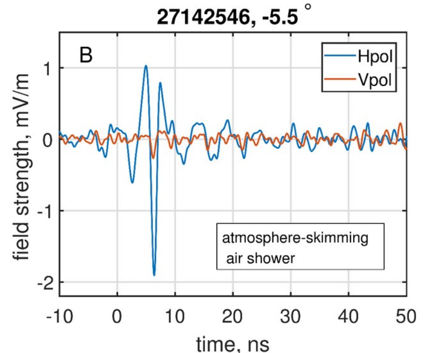


- -Observed CR pulses from AIR showers
- -Horizontal Polarization
- -Two types: Direct and reflected

Reflected Signal from a CR



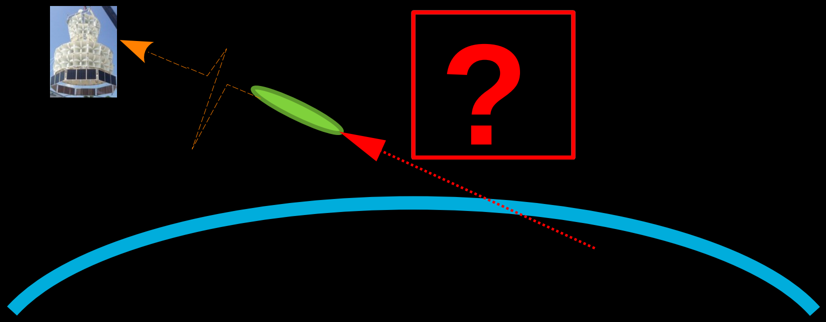


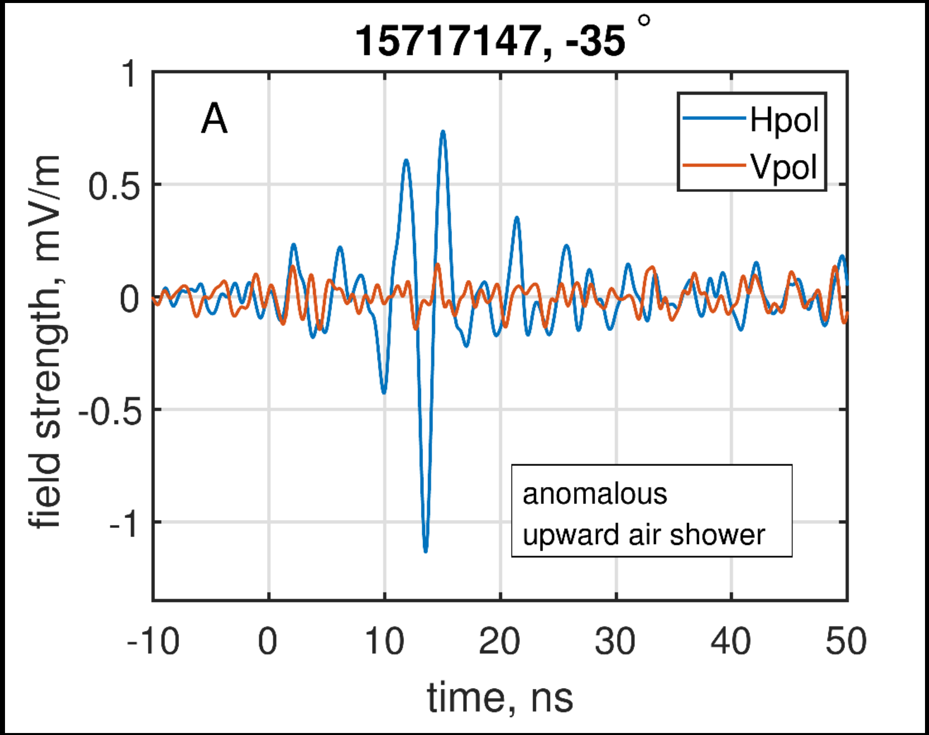


-Reflected pulses from AIR showers

→ inverted polarity

Anomalous Event





Unexplained Anomalous events:

appear direct (not inverted) BUT below horizon

Cosmic Ray background:

- Nearly horizontal showers with large zenith angle uncertainty
- Ambiguous events (admit both upward and down-going fits)
- Earth missing showers (Zenith angle defined at array center!)

STRATEGY

- Simulate CR showers to find selection cuts for background reduction
- Optimize cuts using simulation of upward going showers (signal)
- Test with burn data sample
- Apply blindly to remaining data set

Simulations:

Simulate signal & background (CONEX)

- CR:
  - Simulate on surface of sphere (radius 90 km) centered on the array
    - $1.66\ 10^8$ showers p, He, N & Fe 0.1-100 EeV θ (0^0-100^0)
    - + $9.3\ 10^7$ showers p 0.1-0.3 EeV θ (60^0-100^0)

- Signal:
  - Showers in 100 km x 100 km square centered on the array
  - Vary the altitude of the shower injection from 0 to 9 km
    - $6\ 10^7$ showers p 0.1-10 EeV θ (110^0-180^0)

Selection sequence:

- Laser cuts 7.6 10^6 events
- Quality (clean atmosphere, low cloud coverage, at least 6 pixels) 4.7 10^6
- upward going fit (monocular reconstruction) 6 10^5
- Global Fit allowed 1.65 10^5
- Reconstrcution quality (X_{max} above ground slant depth < 80 g cm^{-2}) 2774
- Restrict to $\theta > 110^0$ 986
- Remove ambiguous events with $\chi^2_{up} < 1.2\ \chi^2_{down}$ **255 events left**

255 events left

Define variable "l" based on likelihood (L) to remove ambiguous events

$$l = \frac{\arctan\left\{\ln\left[\max(L_{\mathrm{up}}, L_{\mathrm{down}})/L_{\mathrm{down}}\right] \cdot \zeta\right\}}{\pi/2}$$

ζ tuned to distribute uniformly in interval [0,1]

$l \rightarrow 1$ means more likely upward

Find optimal l value to cut

- Fit l-distribution for simulations
- Find cut that maximizes flux limit (E^{-1} & E^{-2}) for the expected background

$\Rightarrow$ l_c=0.55

Expected background 0.27 ± 0.12 events

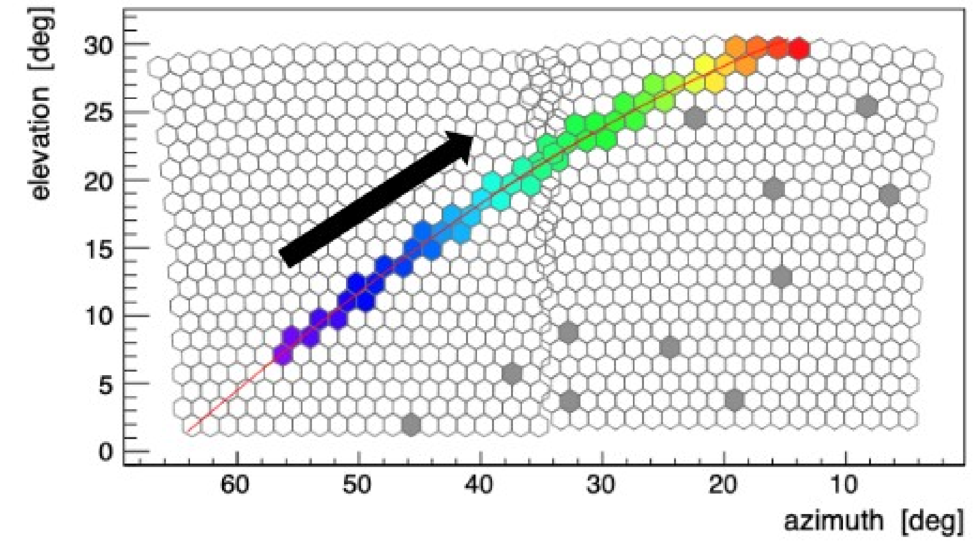
Test data reduction:

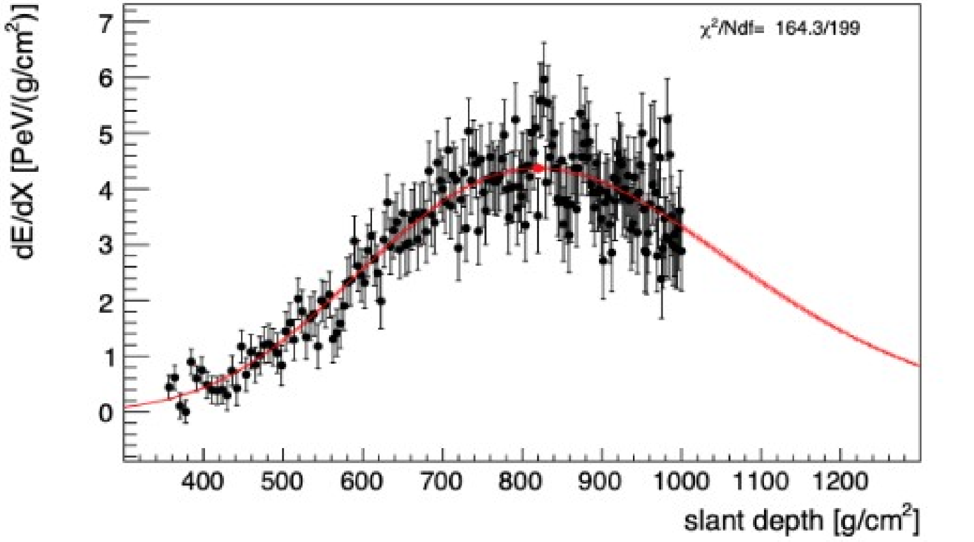
Successive selection cuts	Fluorescence data	background simulation
mono pre-selection	165k	279k
GF up-ward mode	2774	2905
quality cuts	986	1157
$\theta > 110^\circ$	928	1064
$\chi^2_{\mathrm{up}} < 1.2\ \chi^2_{\mathrm{down}}$	255	292
$l > 0.55$	1	0.27

Simulated upward shower reconstructed with FD

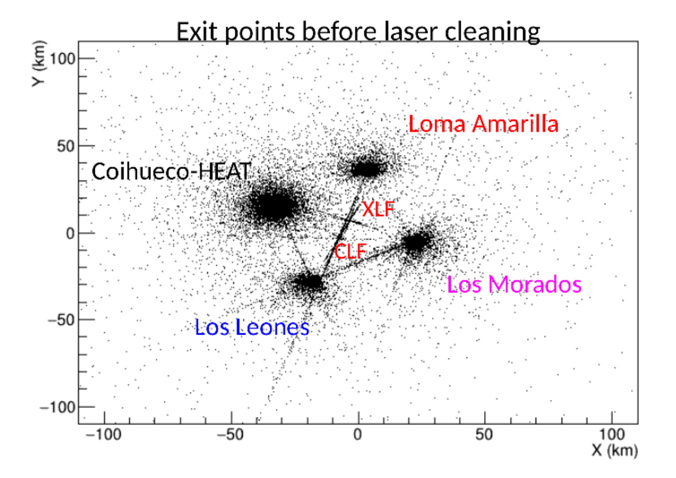
Standard:
1- Fit direction to pixel data (time)
2- Extract the shower profile

Global Fit: (Profile constrained)
Fit - arrival times
- shower profile (Gaisser-Hillas)





Search procedure (Preselection without lasers: 6.4 Million events)



Simulate -CR background to optimize search
-Signal to calculate the exposure

Eliminate untagged lasers (burn 10% of FD data) 4.7M
Quality: clean air, low cloud coverage, >=6 pixels: 600k
Time fit upward: 165k → device more cuts

Use Global Fit (GF): time & signal to match GH profile
(upward & downward modes)

Get upward events; most also
have a downward fit (ambiguous)