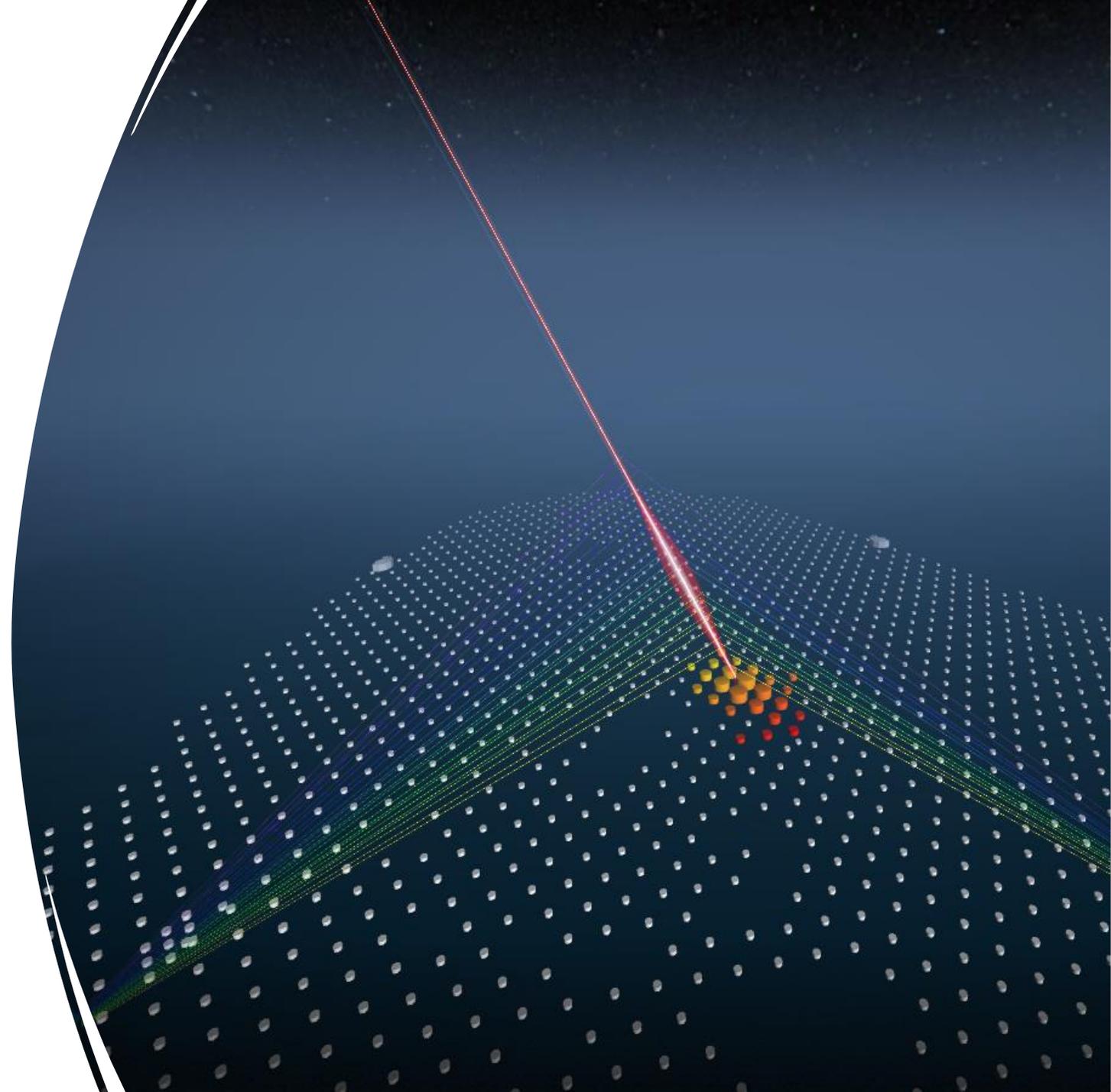




A detailed presentation of the highest-energy cosmic rays recorded at the Pierre Auger Observatory

Mario Buscemi
for the Pierre Auger Collaboration

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Università degli Studi di Palermo
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Why a Catalog?

(ICRC 2005)

A discussion is given of the highest energy events so far recorded by the Pierre Auger Observatory. We present these to illustrate the quality of the information that they contain.

After the conclusion of Phase I of operation, with an integrated exposure of 122,000 km² sr yr, the Pierre Auger Collaboration is releasing a catalog to demonstrate the quality of the data that lie behind measurements of the energy spectrum, the distribution of arrival directions, and the mass of the highest-energy cosmic rays

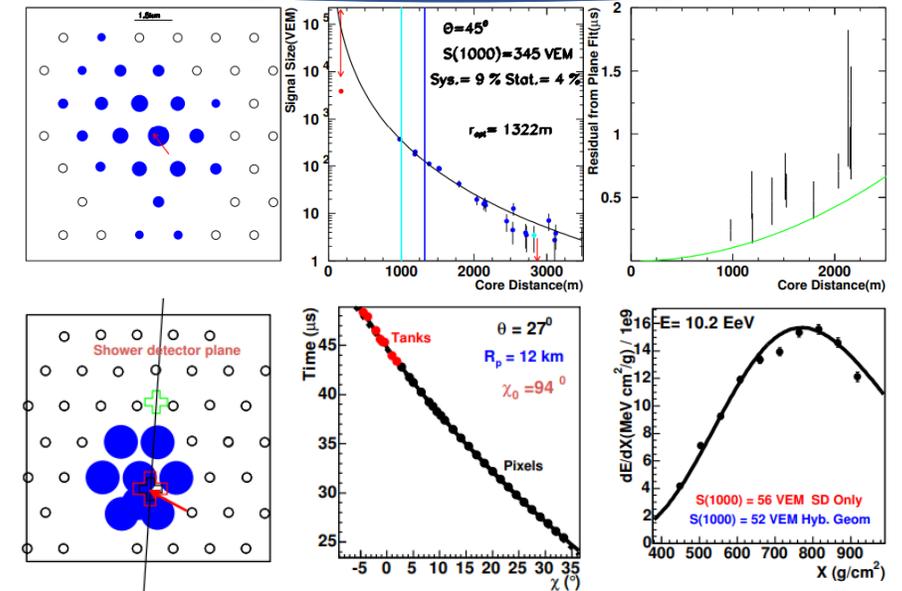
A description of some ultra high energy cosmic rays observed with the Pierre Auger Observatory

M. Ave Pernas for the Pierre Auger Collaboration

Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA

Presenter: James Matthews (matthews@phys.lsu.edu) usa-ave-pernas-M-abs1-he14-oral

A discussion is given of the highest energy events so far recorded by the Pierre Auger Observatory. We present these to illustrate the quality of the information that they contain. The surface detectors are used to measure a rich set of parameters that will eventually help characterise the mass of the incoming primary particle.



Event Id	θ	S(1000)	Multiplicity	r_{opt}	β	E(EeV)
1096757	45.1 ± 0.2	344 ± 15 ± 33	21	1322	—	86 ± 9
1225537	34.4 ± 0.2	364 ± 10 ± 13	14	909	2.48 ± 0.06	79 ± 4
787469	59.7 ± 0.2	204 ± 8 ± 11	31	1173	2.03 ± 0.06	76 ± 5
762238	47.3 ± 0.2	248 ± 11 ± 12	18	1135	2.22 ± 0.07	64 ± 4
1102721	23.8 ± 0.2	318 ± 22 ± 52	12	1467	—	63 ± 11
1233429	54.3 ± 0.2	201 ± 9 ± 16	21	1261	—	63 ± 6
1018639	26.9 ± 0.2	294 ± 19 ± 26	10	1196	2.93 ± 0.13	59 ± 6
1264145	16.3 ± 0.2	289 ± 12 ± 11	11	910	2.65 ± 0.11	56 ± 3
1263529	20.7 ± 0.2	264 ± 20 ± 34	7	1470	—	51 ± 8
634746	51.6 ± 0.2	174 ± 9 ± 12	14	1203	—	48 ± 4

Table 1. The 10 highest energy events recorded by the Surface Detector.

The Catalog

- Details of **100 highest-energy cosmic rays**, in the range 78 EeV to 166 EeV included in the data set used in a discussion of the arrival directions of events above 32 EeV, without any interpretation.
- Further **9 very energetic events** that have been used in the calibration procedure adopted to determine the energy of each primary. Some hybrid events with energies close to 100 EeV, used in a recent study of mass composition are not included as different selection criteria were adopted.
- The events are identified with a catalog number (#N) and by a name, **PAOddmmyy**, that indicates the day, month and year of detection.

DATASET

JOURNAL, 935:170 (24pp), 2022 August 20
<https://doi.org/10.3847/1538-4357/ac7d4c>
 Published by the American Astronomical Society.
 CrossMark

Arrival Directions of Cosmic Rays above 32 EeV from Phase One of the Pierre Auger Observatory

Table 3
 Excerpt of the Full Data Set of 2635 Events Above 32 EeV Collected at the Pierre Auger Observatory Between 2004 January 1 and 2020 December 31

Year	JD	UTC	Zenith Angle, θ	Azimuth Angle, ϕ	R.A., α	Decl., δ	E EeV	Cumulative Exposure km ² sr yr
2019	314	1573399408	58.6	-135.6	128.9	-52.0	166	111,900
2007	13	1168768186	14.2	85.6	192.9	-21.2	165	9,800
2020	163	1591895321	18.9	-47.7	107.2	-47.6	155	116,800
2014	293	1413885674	6.8	-155.4	102.9	-37.8	155	70,600
2018	224	1534096475	47.9	141.7	125.0	-0.6	147	101,400
2008	268	1222307719	49.8	140.5	287.8	1.5	140	21,300
2019	117	1556436334	14.8	-32.7	275.0	-42.1	133	107,400
2017	361	1514425553	41.7	-30.5	107.8	-44.7	132	96,100
2014	65	1394114269	58.5	47.3	340.6	12.0	131	65,300
2005	186	1120579594	57.3	155.7	45.8	-1.7	127	3,100
2015	236	1440460829	20.1	-46.1	284.8	-48.0	125	77,700
2008	18	1200700649	50.3	178.9	352.5	-20.8	124	16,100
2016	26	1453874568	22.6	-14.7	175.6	-37.7	122	81,200
2016	21	1453381745	13.7	-179.8	231.4	-34.0	122	81,100
2011	26	1296108817	24.9	90.9	150.0	-10.4	116	39,300
2016	68	1457496302	23.7	108.7	151.5	-12.6	115	82,100
2015	268	1443266386	77.2	-172.0	21.7	-13.8	113	78,400
2016	297	1477276760	49.5	104.5	352.1	13.2	111	86,800
2020	66	1583535647	41.4	-20.6	133.6	-38.3	110	114,600
2018	174	1529810463	42.7	4.3	300.0	-22.6	110	100,200

Note. See the main text for a description of the columns. Events are sorted here by decreasing energy, E , and only the 20 highest-energy events are displayed. The full data set is available in the same format at <https://doi.org/10.5281/zenodo.6504276> and in machine-readable format in the online article. (This table is available in machine-readable form.)

See Ugo's talk tomorrow!

Ready for submission to APJs

A Catalog of the Highest-Energy Cosmic Rays recorded during Phase I of Operation of the Pierre Auger Observatory

THE PIERRE AUGER COLLABORATION

Online event browser

Catalog of the Highest-Energy Cosmic Rays recorded during Phase I of Operation of the Pierre Auger

This page provides a simple Event Display, that can be used to display any event. Once an event is selected its components can be browsed in different tabs.

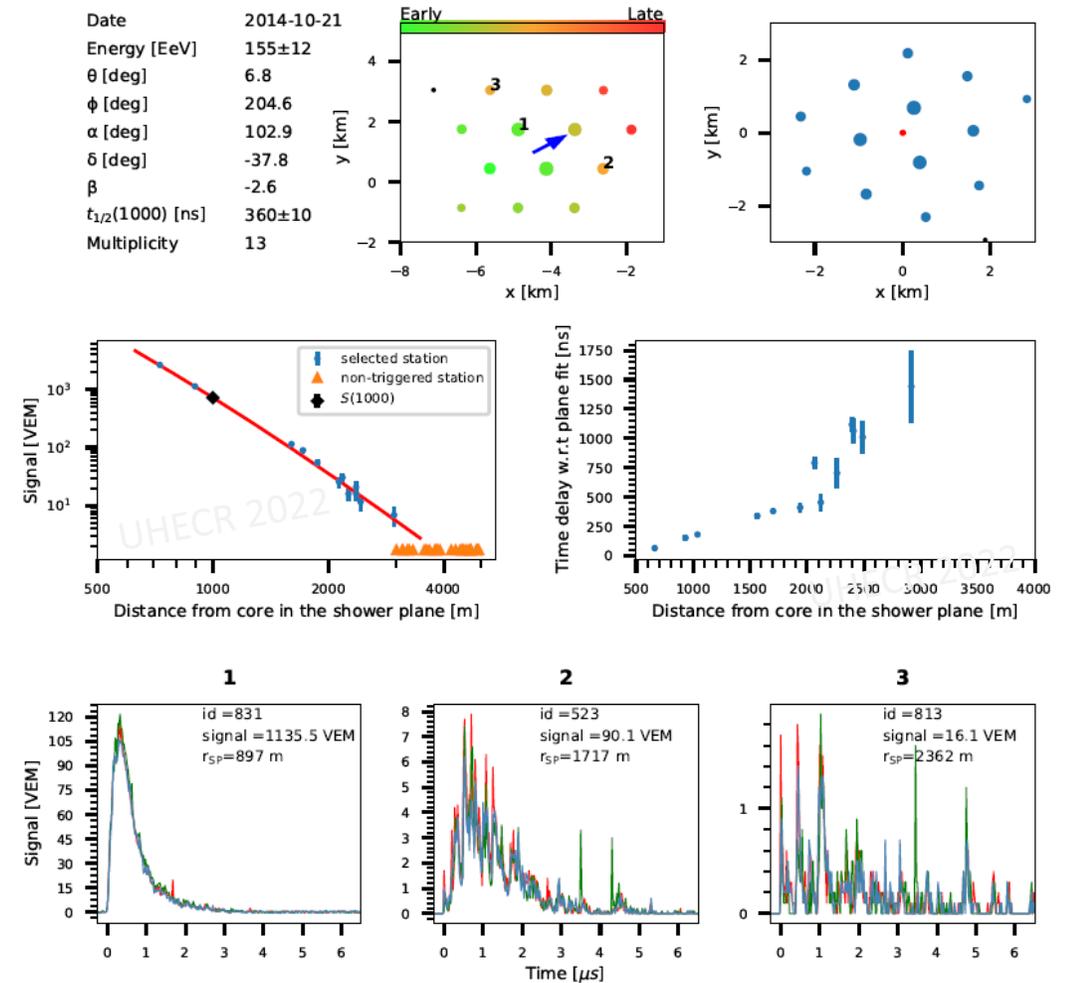
Catalog

01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20
 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60
 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80
 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100
 101 102 103 104 105 106 107 108 109

PAO

- Section 1:
INTRODUCTION
- Section 2:
THE DETECTION OF HIGH-ENERGY COSMIC RAYS
AND THE PIERRE AUGER OBSERVATORY
- Section 3:
RECONSTRUCTION OF SHOWER PARAMETERS
- Section 4:
THE EVENTS OF THE CATALOG
 - 4 *Vertical* events
 - 2 *Inclined* events
 - 2 Hybrid events
- Section 4:
A SKY MAP OF THE 100 HIGHEST-ENERGY EVENTS

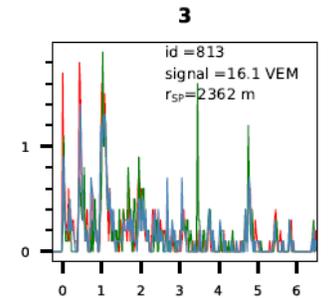
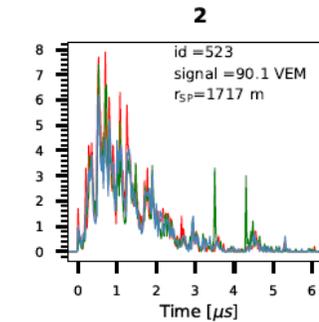
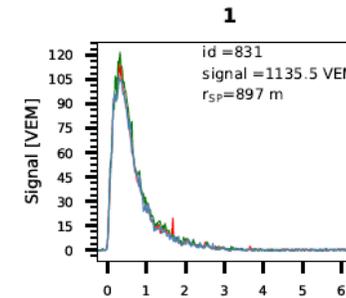
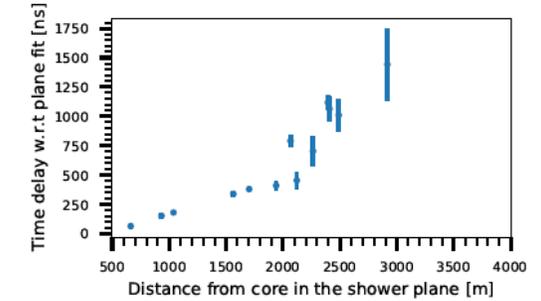
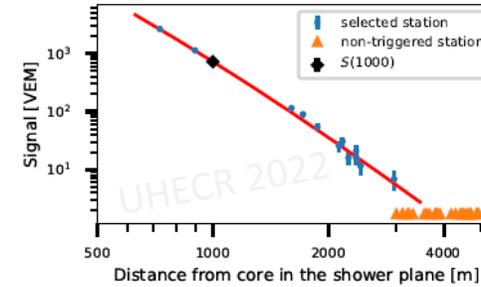
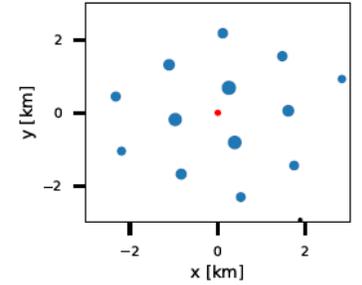
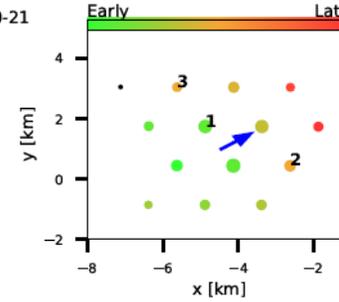
#4 -PAO141021



- Footprint on the ground and in a plane perpendicular to the arrival direction;
- Lateral distribution of the recorded signals as a function of the distance to the shower core;
- Time delays with respect to a fit that assumes a plane shower;
- Arrival time distributions of the signals recorded at each water-Cherenkov detector;

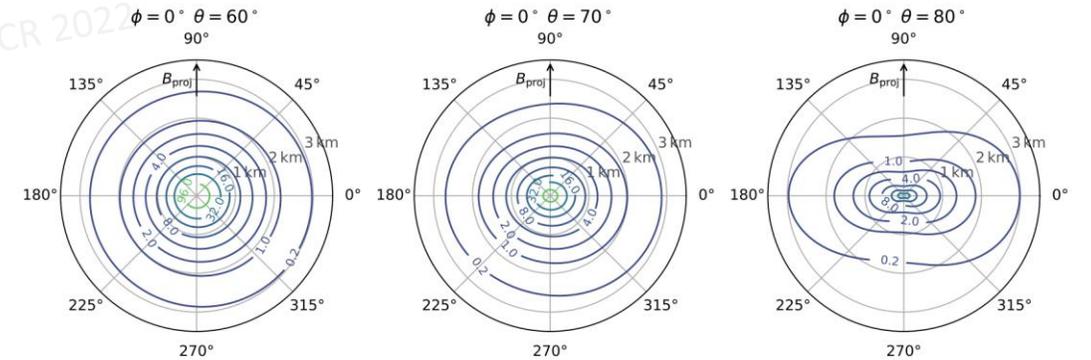
#4 -PAO141021

Date	2014-10-21
Energy [EeV]	155±12
θ [deg]	6.8
ϕ [deg]	204.6
α [deg]	102.9
δ [deg]	-37.8
β	-2.6
$t_{1/2}(1000)$ [ns]	360±10
Multiplicity	13



Events recorded by the Surface-Detector

- Footprint on the ground and in a plane perpendicular to the arrival direction;
- Lateral distribution of the recorded signals as a function of the distance to the shower core;
- Time delays with respect to a fit that assumes a plane shower;
- Arrival time distributions of the signals recorded at each water-Cherenkov detector;



Different procedures are used to reconstruct the energy of *vertical* ($\theta < 60^\circ$) and *inclined* ($\theta > 60^\circ$) showers. Asymmetry of the radial distribution of the muons in the shower increases with zenith angle, becoming particularly apparent above 70° .

The most energetic event



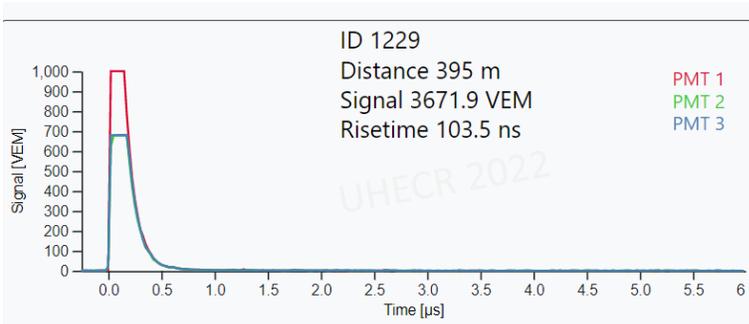
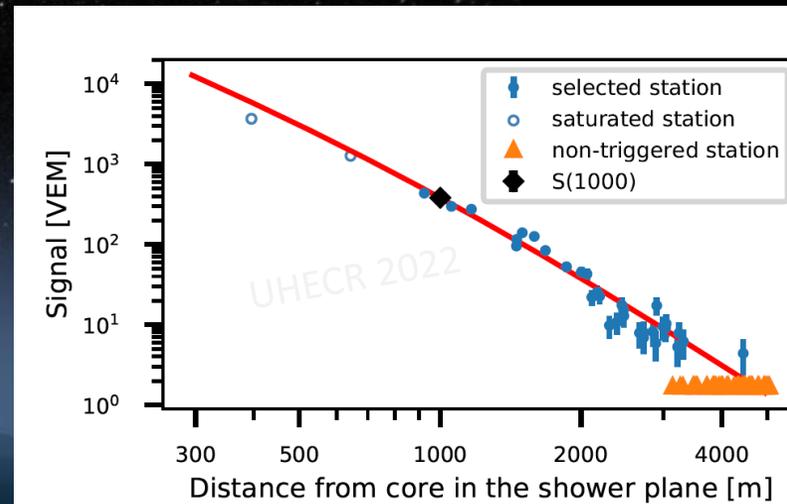
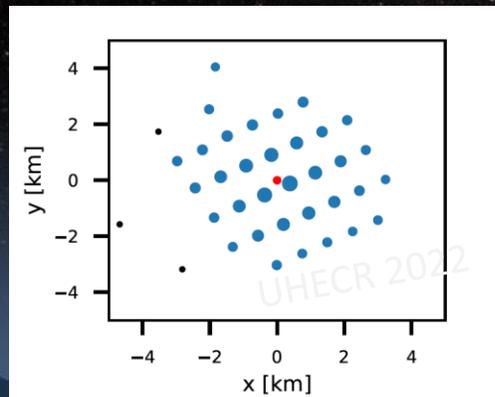
The most energetic event

#1 - PAO191110

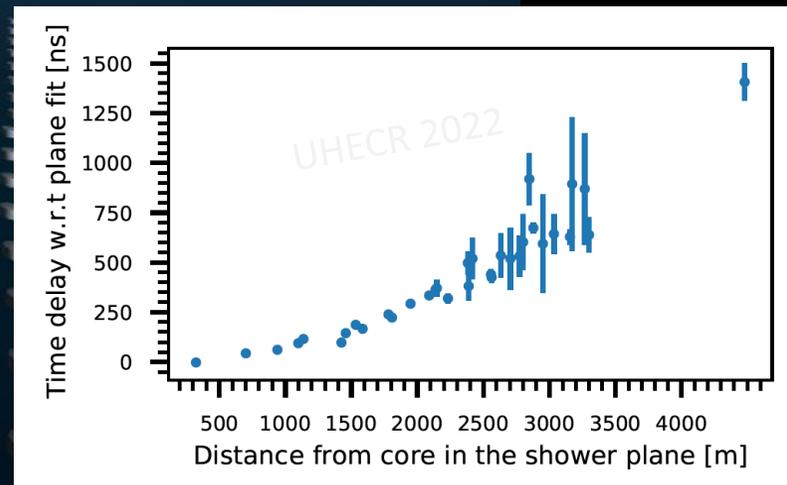
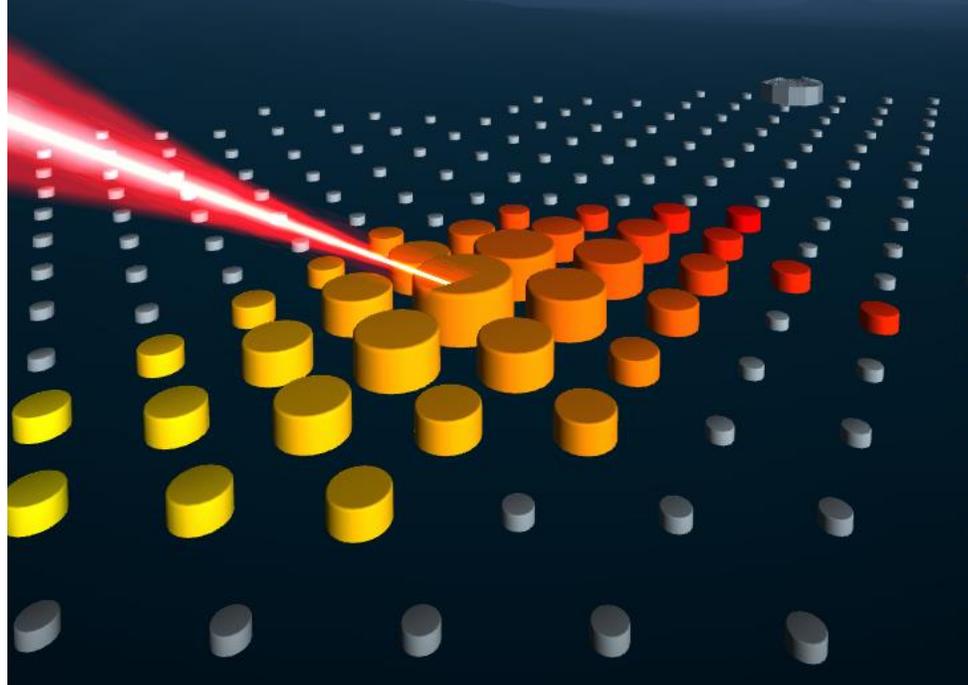
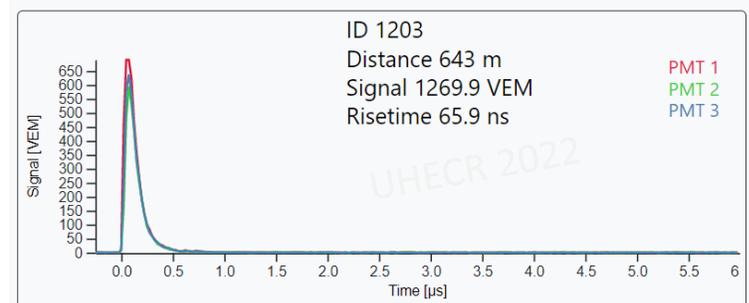
Event display developed by



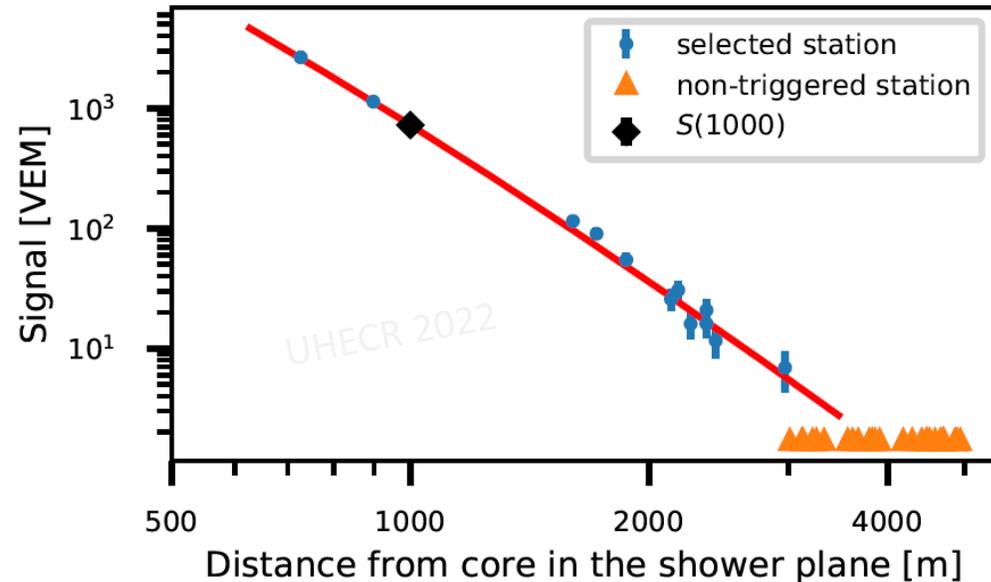
Energy [EeV]	166±13
θ [deg]	58.6
φ [deg]	224.4
α [deg]	128.9
δ [deg]	-52.0
β	-2.0
t _{1/2} (1000) [ns]	98±3
Multiplicity	34
Area	~(13 x 6) km ²



2 saturated stations



Vertical events ($\theta < 60^\circ$)



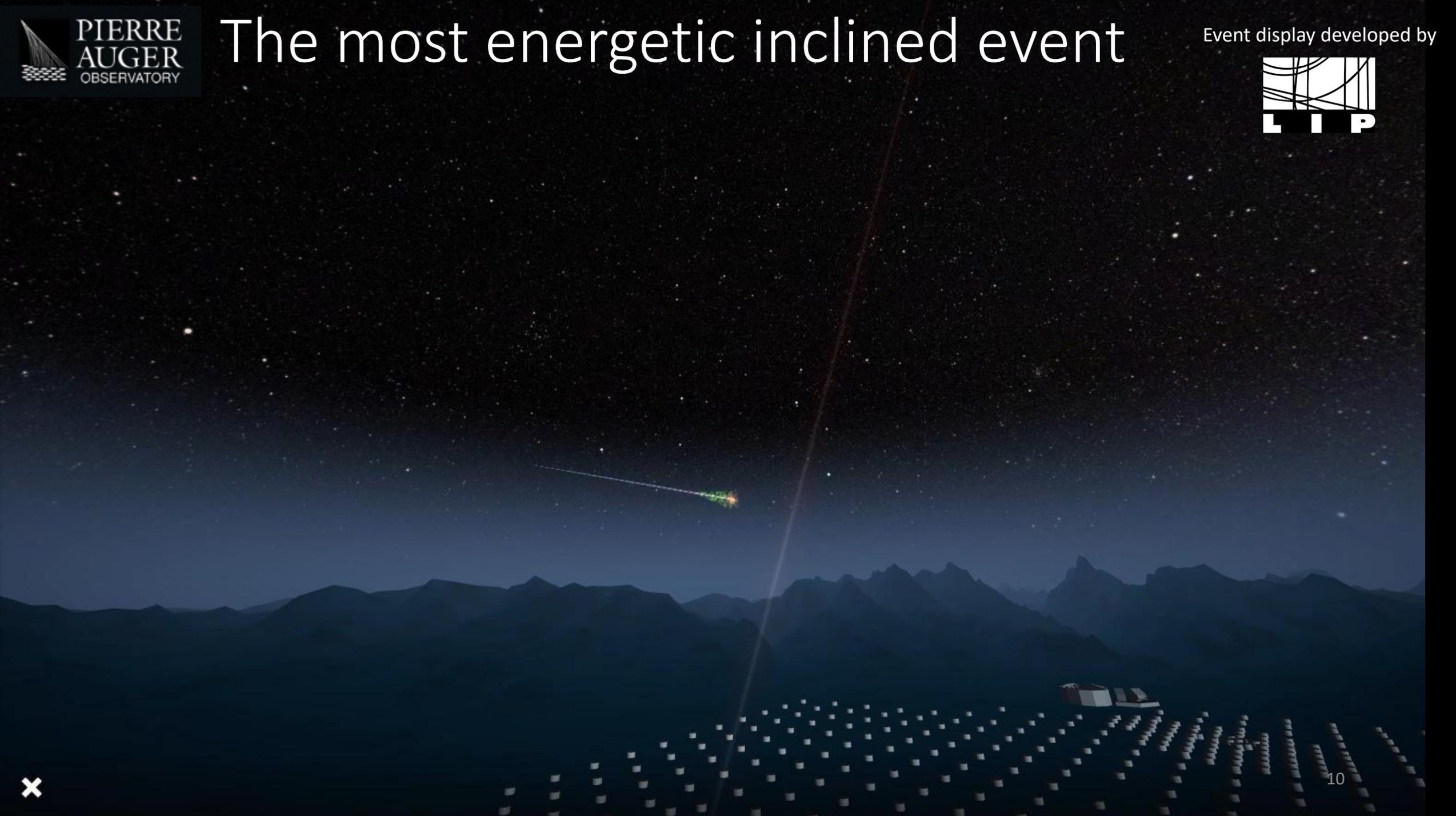
The lateral spread of the signals is described by the modified Nishimura-Kamata-Greisen (NKG) lateral distribution function (LDF)

$$S_{LDF}(r) = S(1000) \left[\left(\frac{r}{r_{opt}} \right) \left(\frac{r + r_s}{r_{opt} + r_s} \right) \right]^\beta$$

The energy resolution, obtained from the spread of E_{SD} values at a given E_{FD} in the calibration events, is $\sim 8\%$ at the highest energies. Directional uncertainties are $< 1^\circ$.

The most energetic inclined event

Event display developed by

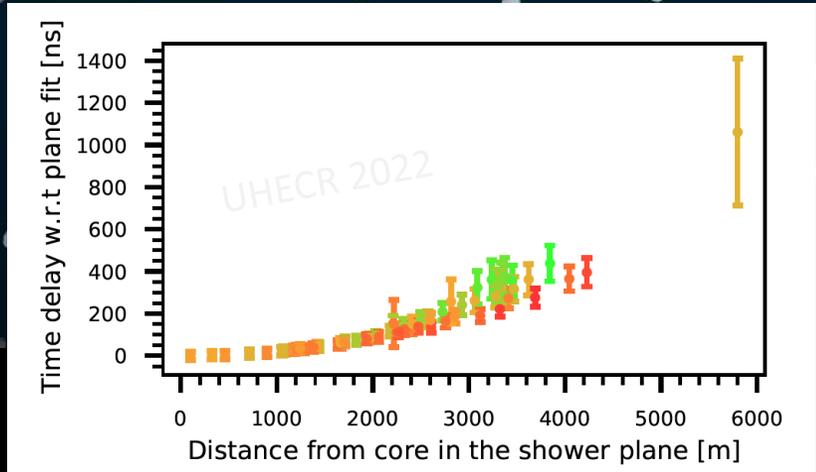
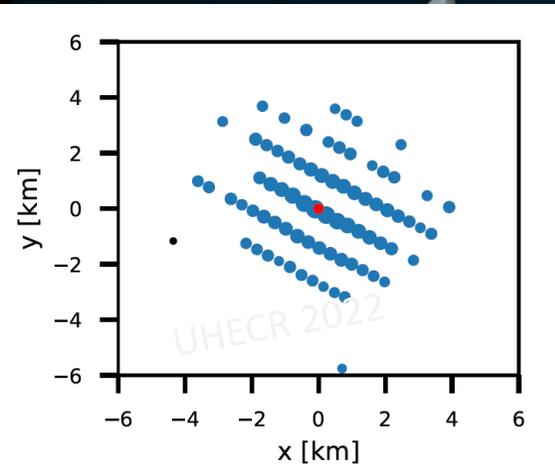
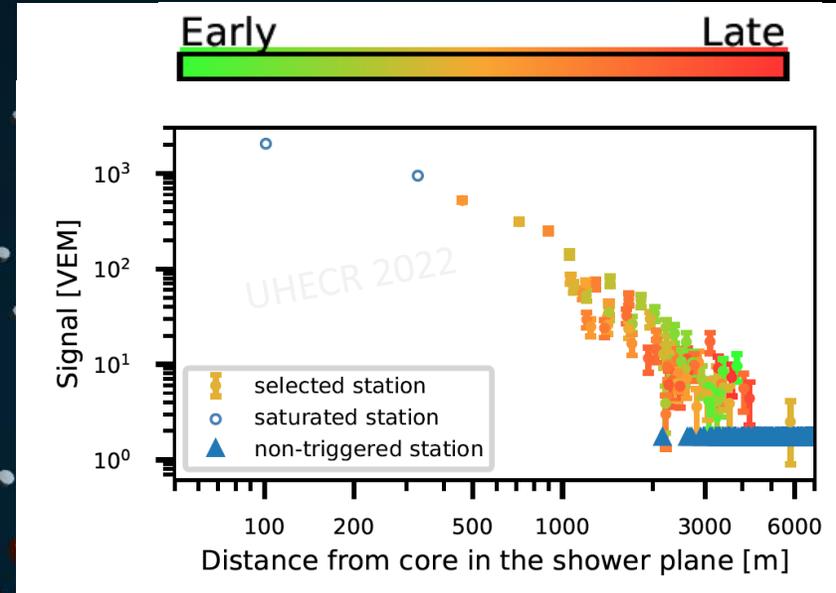
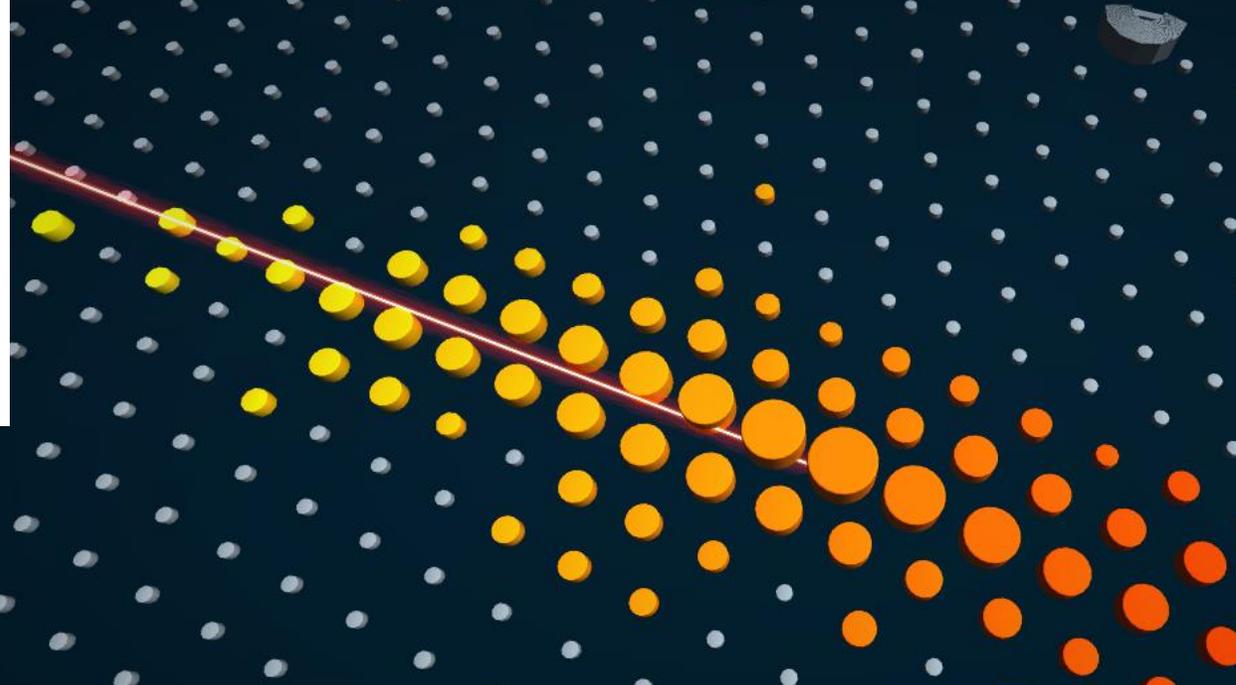


The most energetic inclined event



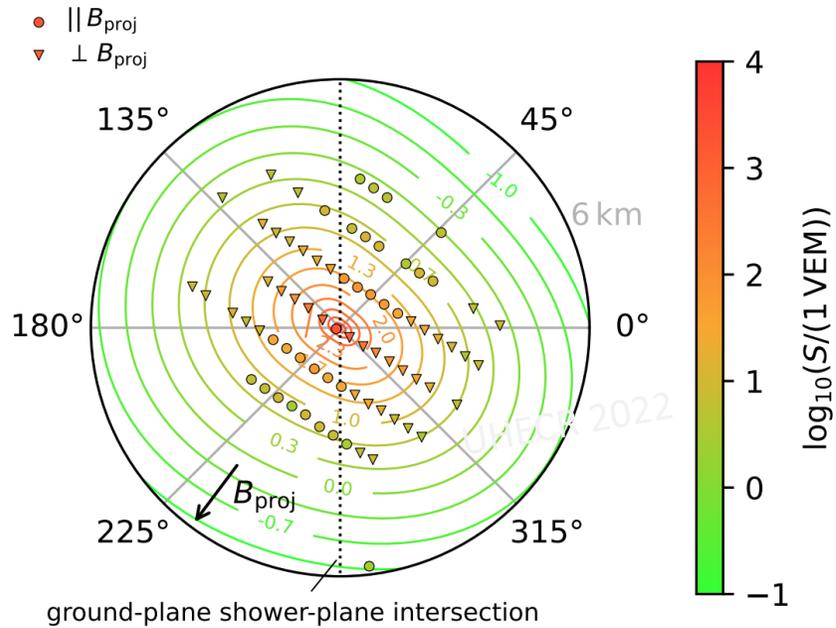
#17 - PA0150926

Energy [EeV]	113±14
θ [deg]	77.2
ϕ [deg]	188.0
α [deg]	21.7
δ [deg]	-13.8
Multiplicity	75
Area	~(35 x 6) km ²



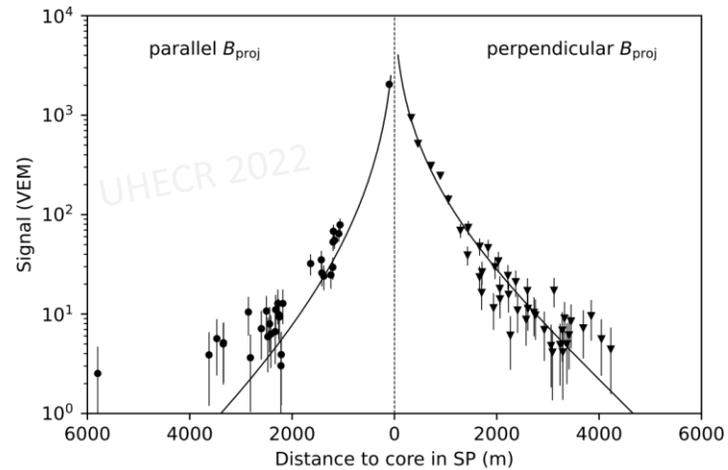
Inclined events ($\theta > 60^\circ$)

- Exposure of the Observatory enhanced by 30%.
- Sky coverage extended to regions that would otherwise be inaccessible.



Triangular markers are stations which, seen from the position of the core, lie within 45° of a direction perpendicular to the direction of the magnetic field in the shower plane, B_{proj} .

The muon signal scales with energy as $\rho_\mu(r) \propto E^\alpha$ with α in the range 0.90 to 0.95. The expected density of muons at the ground is given by $\rho_\mu(r) = N_{19} \rho_{\mu,19}(r, \theta, \phi)$, where N_{19} , is chosen by convention, as a measure of shower size using a reference shower model and comparing the signals to those expected from simulated showers of 10 EeV with the same arrival direction. The energy resolution is estimated as 12%, at the highest energies, from a comparison of N_{19} with E_{FD} .



More particles reach those stations, lie within 45° of a direction perpendicular to B_{proj} (enhancing the signal) compared to stations that are at the same distance to the core but that lie along the direction of the magnetic field

The most energetic hybrid event

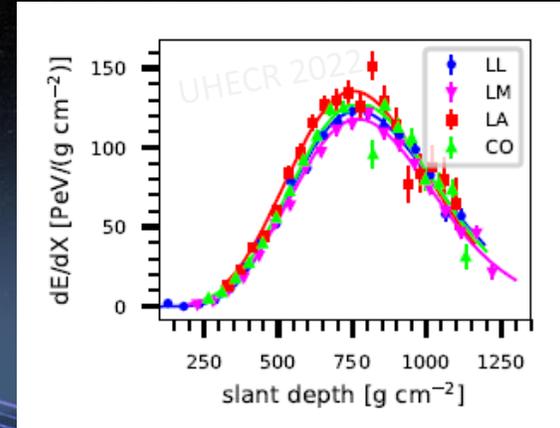
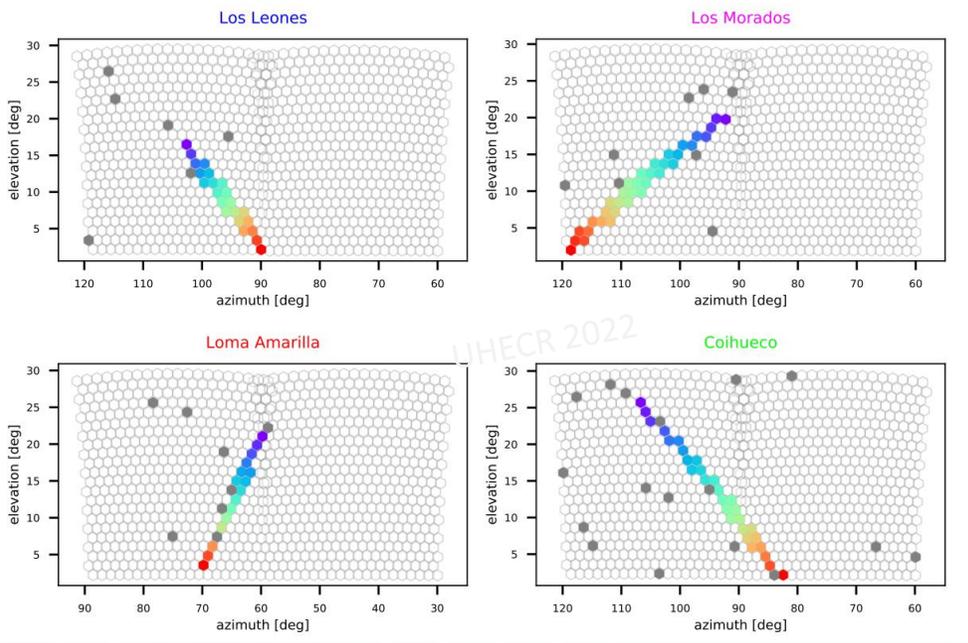
Event display developed by



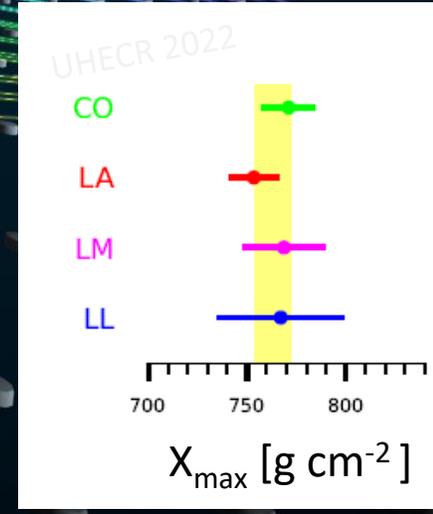
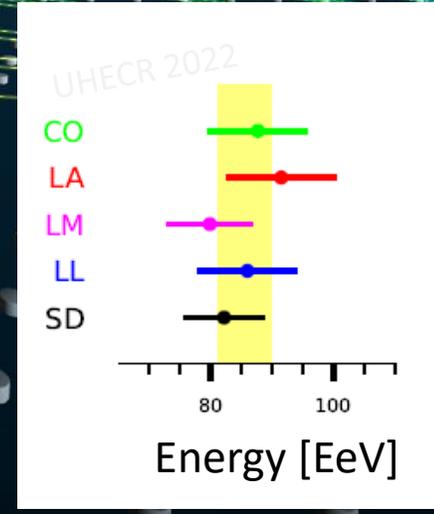
The most energetic hybrid event



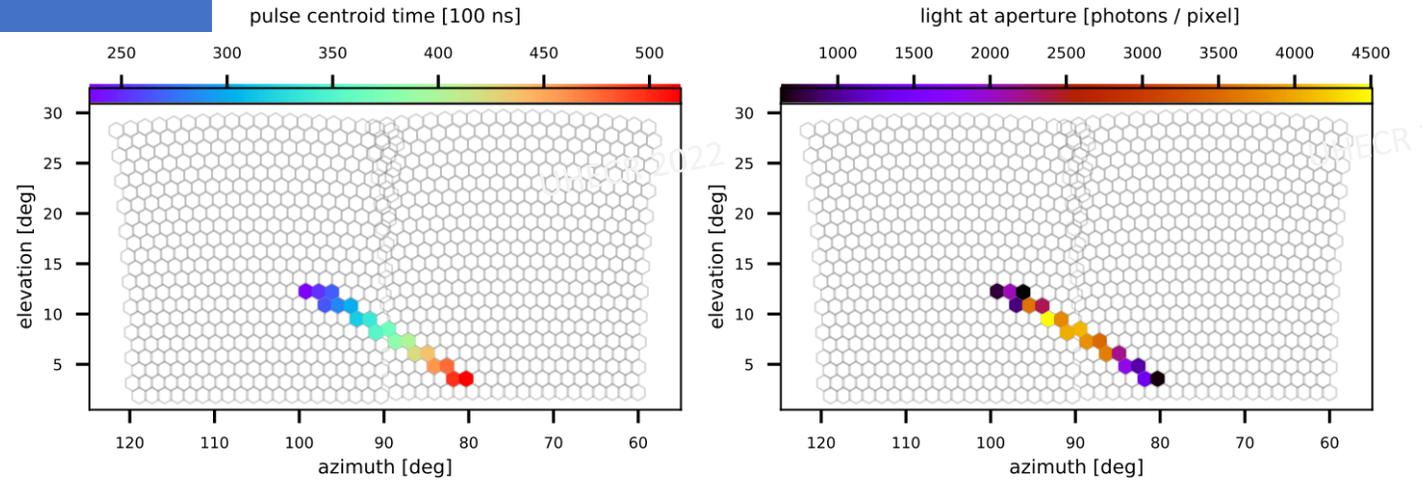
#84 - PAO100815



Energy [EeV]	82 ± 7
θ [deg]	53.8
φ [deg]	100.6
α [deg]	324.5
δ [deg]	17.8
β	-2.1
t _{1/2} (1000) [ns]	127 ± 5
Multiplicity	22

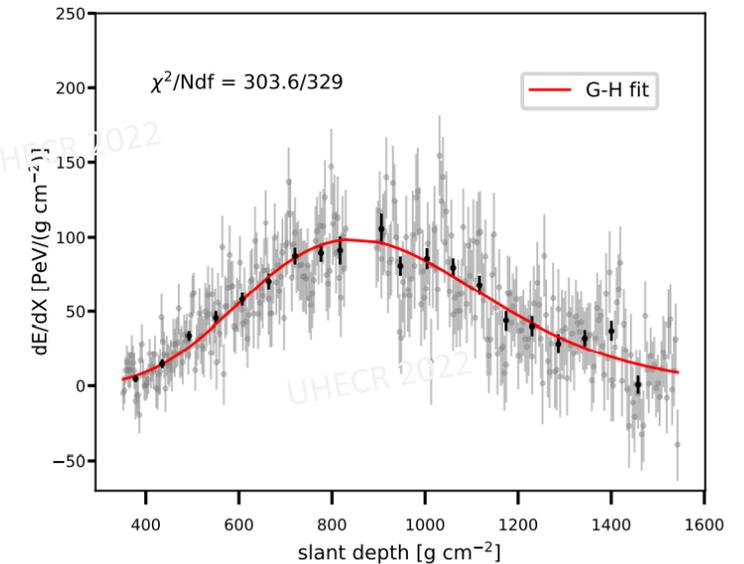
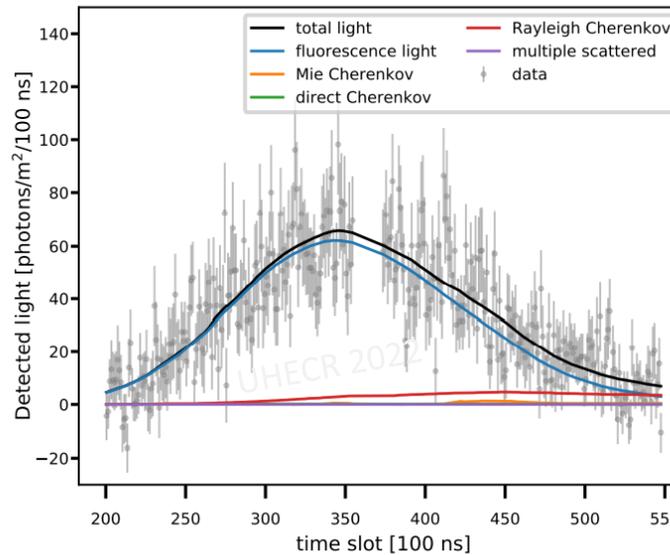


- Camera views from telescopes
- Reconstructed profiles of the energy deposition in the atmosphere



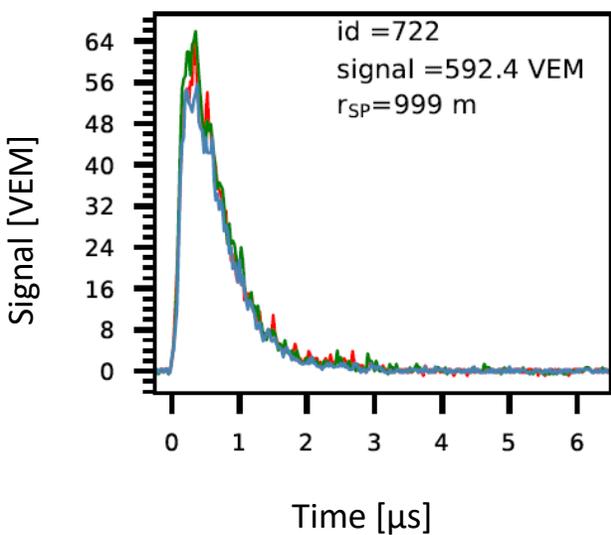
The Fluorescence Detectors:

- Provide a calorimetric measurements of the showers energy to set the energy scale of the SD sample
- Measure the longitudinal development of air showers in the atmosphere and the shower maximum -> Key measurement for mass estimation

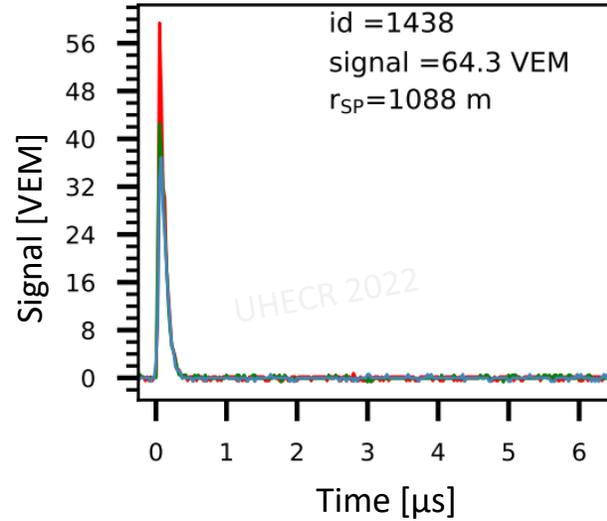


$$f(X) = \left(\frac{dE}{dX}\right)_{\max} + \left(1 + \frac{R}{L}(X - X_{\max})\right)^{1/R^2} \exp\left(-\frac{X - X_{\max}}{RL}\right)$$

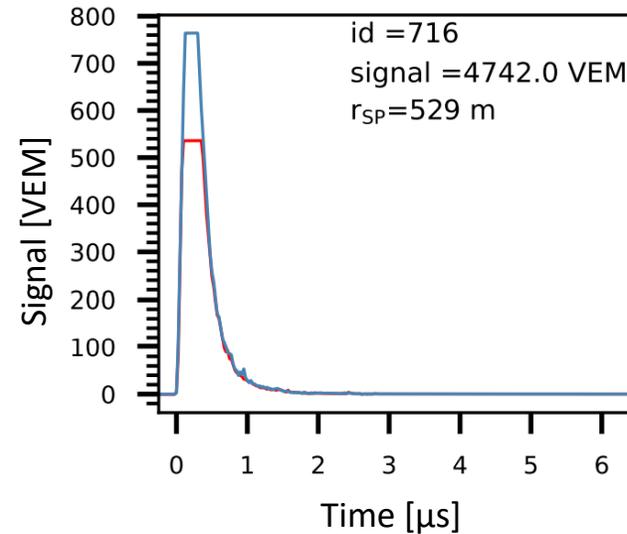
Some WCDs signals



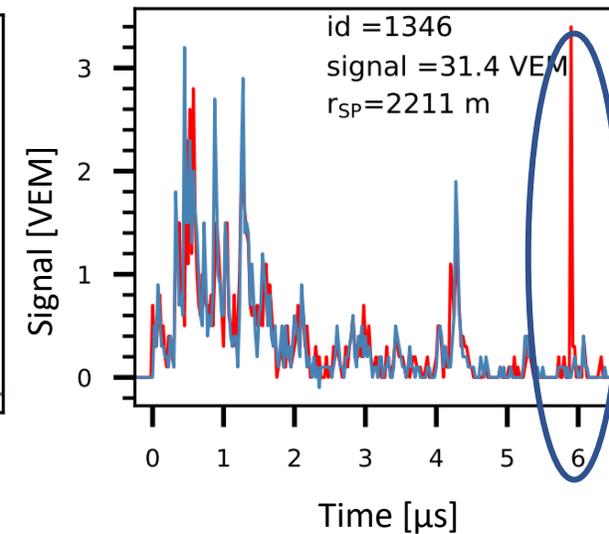
Typical signal produced in a vertical event



Signal produced by muons in an inclined event



Saturated signal due to the overflow of the finite dynamic range of the read-out electronics/PMT



Direct light reaching one photomultiplier at about 6 μ s

👁 Catalog of the Highest-Energy Cosmic Rays recorded during Phase I of Operation of the Pierre Auger Observatory

This page provides a simple Event Display, that can be used to display any event. Once an event is selected its components can be browsed in different tabs.

Catalog

01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60
61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100
101 102 103 104 105 106 107 108 109

PAO

👁 Catalog of the Highest-Energy Cosmic Rays recorded during Phase I of Operation of the Pierre Auger Observatory

This page provides a simple Event Display, that can be used to display any event. Once an event is selected its components can be browsed in different tabs.

Catalog

01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20
21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60
61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80
81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100
101 102 103 [104](#) 105 106 107 108 109

PAO

Different views of the event are available by selecting the corresponding tabs.

[Event summary](#)

[Ground array view](#)

[Shower plane view](#)

[SD traces](#)

[SD reconstruction](#)

[SD time residuals](#)

[FD sky-view](#)

[FD reconstruction](#)

The Catalog: online event browser

Different views of the event are available by selecting the corresponding tabs.

[Event summary](#)

[Ground array view](#)

[Shower plane view](#)

[SD traces](#)

[SD reconstruction](#)

[SD time residuals](#)

[FD sky-view](#)

[FD reconstruction](#)

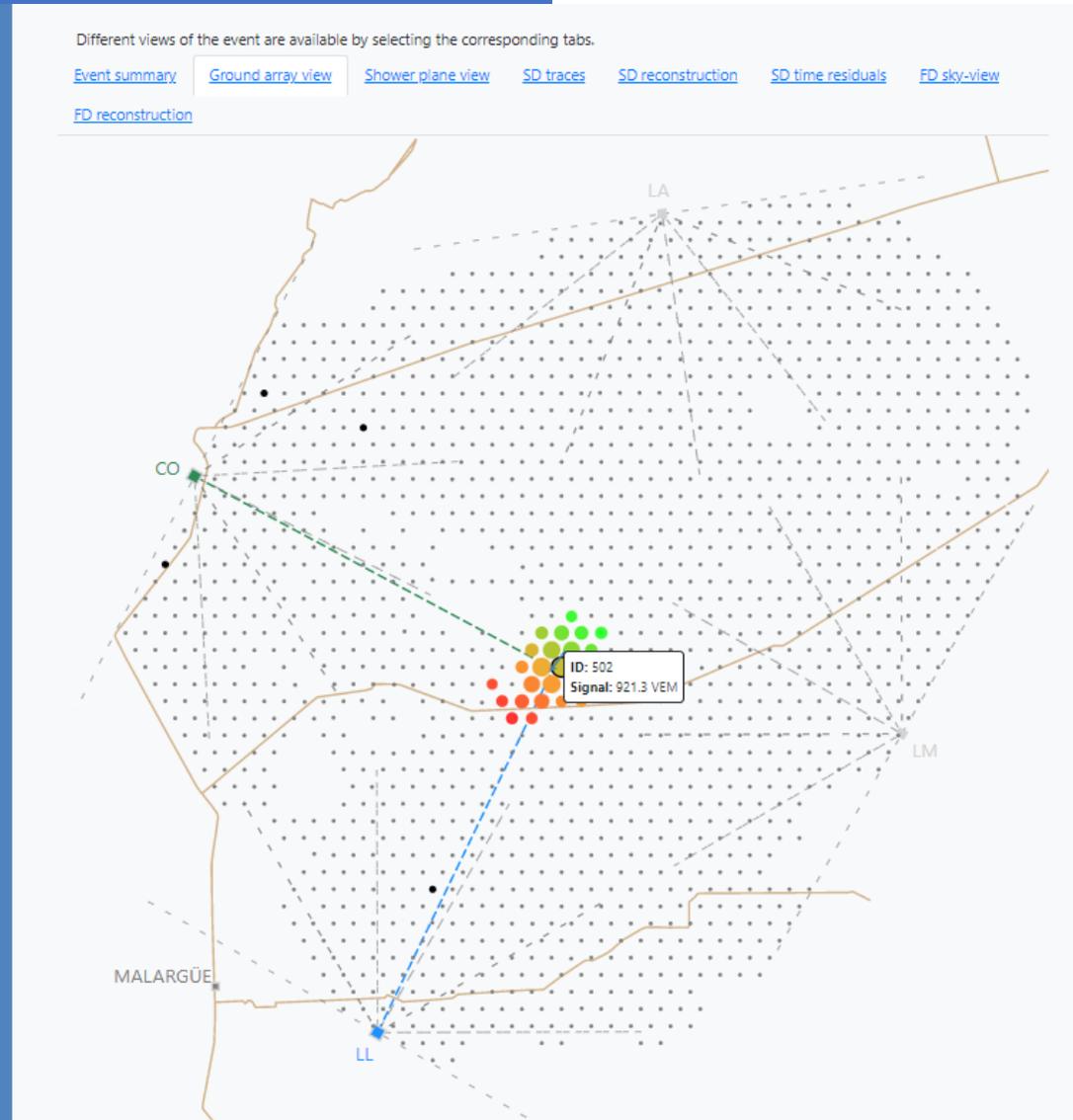
SD reconstruction

PAO080703a	
Date	2008-07-03
Energy	57 ± 5 EeV
θ	53.8°
φ	53.9°
β	-2.1
$t_{1/2}(1000)$	131 ± 4 ns
δ	11.0°
α	33.0°
Multiplicity	24

Hybrid reconstruction

FD site	Energy [EeV]	X_{\max} [g cm^{-2}]	θ [deg]	φ [deg]
1	55.7 ± 4.8	772.3 ± 13.3	54.0 ± 0.3	55.0 ± 0.8
4	60.6 ± 5.2	799.7 ± 24.2	53.9 ± 0.6	53.6 ± 0.4

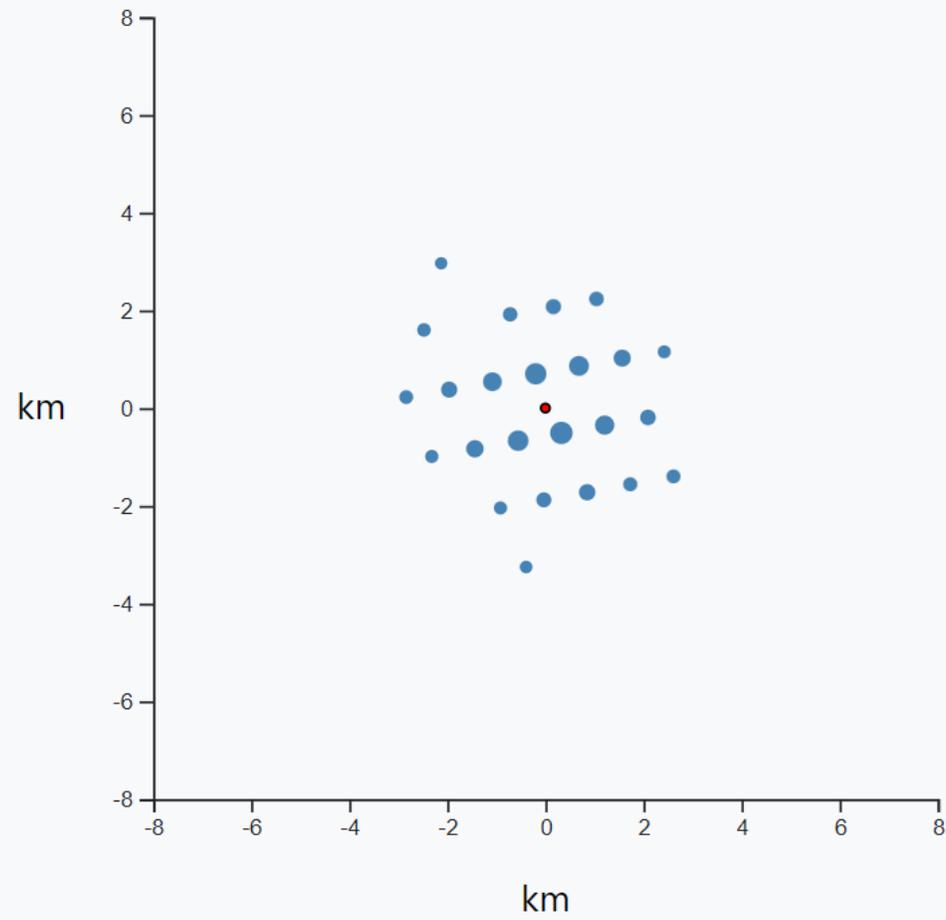
The Catalog: online event browser



The Catalog: online event browser

Different views of the event are available by selecting the corresponding tabs.

[Event summary](#) [Ground array view](#) [Shower plane view](#) [SD traces](#) [SD reconstruction](#) [SD time residuals](#) [FD sky-view](#)
[FD reconstruction](#)



The Catalog: online event browser

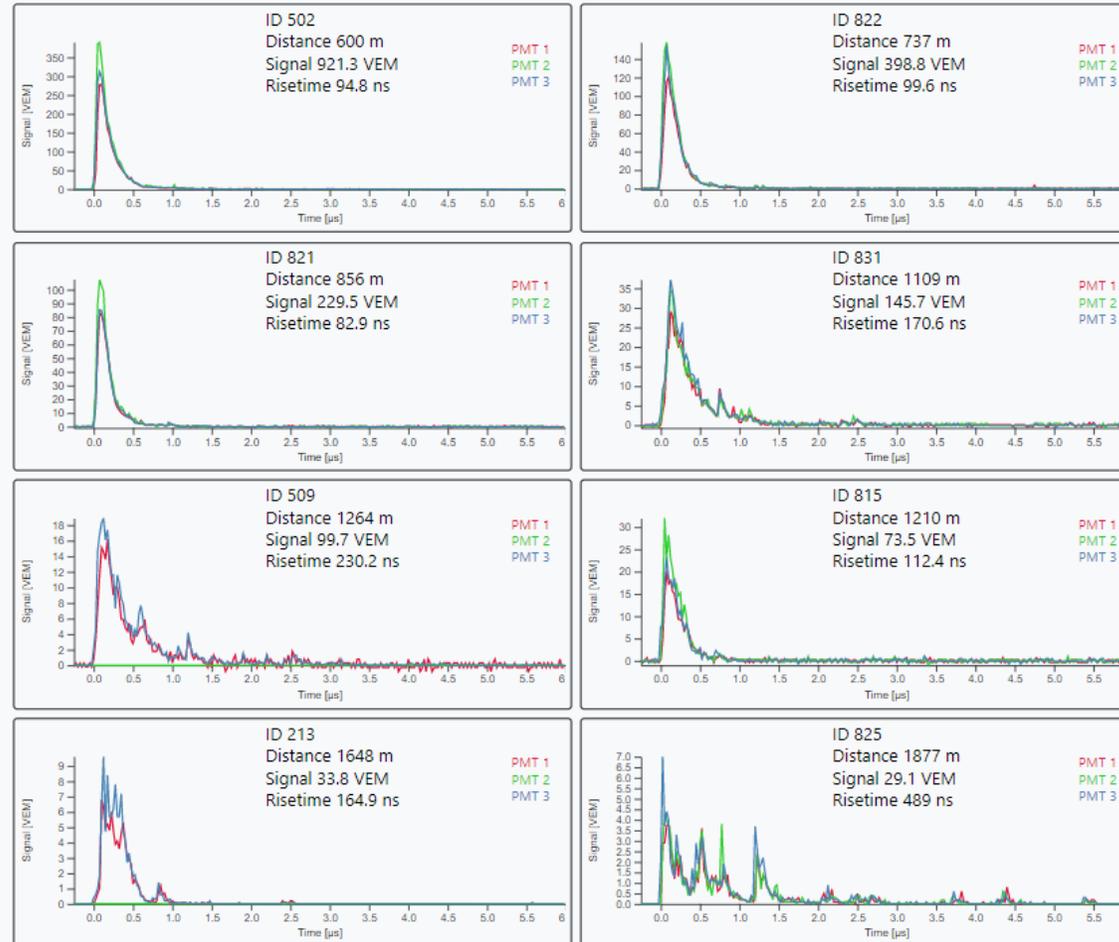
Different views of the event are available by selecting the corresponding tabs.

[Event summary](#) [Ground array view](#) [Shower plane view](#) [SD traces](#) [SD reconstruction](#) [SD time residuals](#) [FD sky-view](#)

[FD reconstruction](#)

In this tab the FADC traces of the 3 PMTs of all triggered stations are displayed. Inactive PMTs are displayed with a signal of 0. Stations determined to be random coincidences and not being part of the event are dimmed and listed at the end.

Stations used for reconstruction



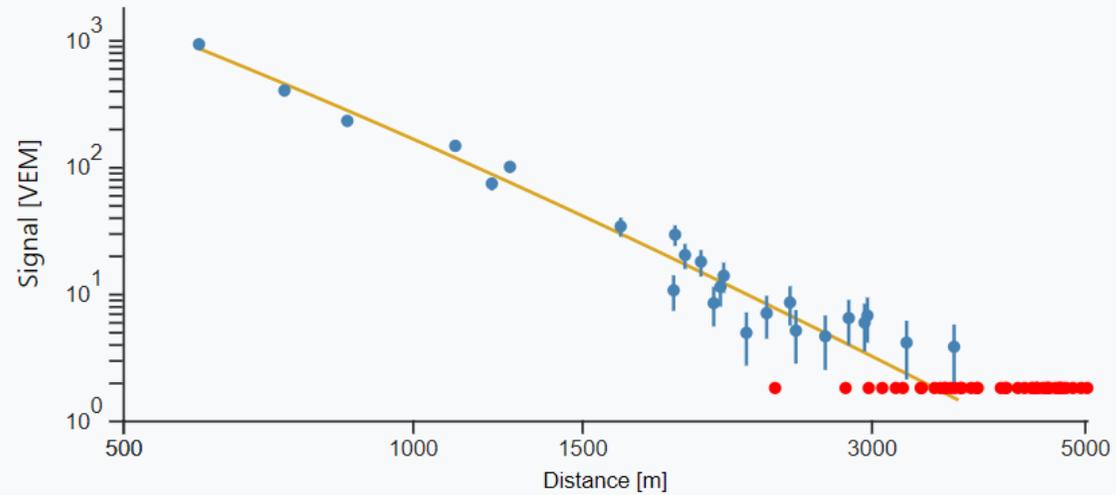
The Catalog: online event browser

Different views of the event are available by selecting the corresponding tabs.

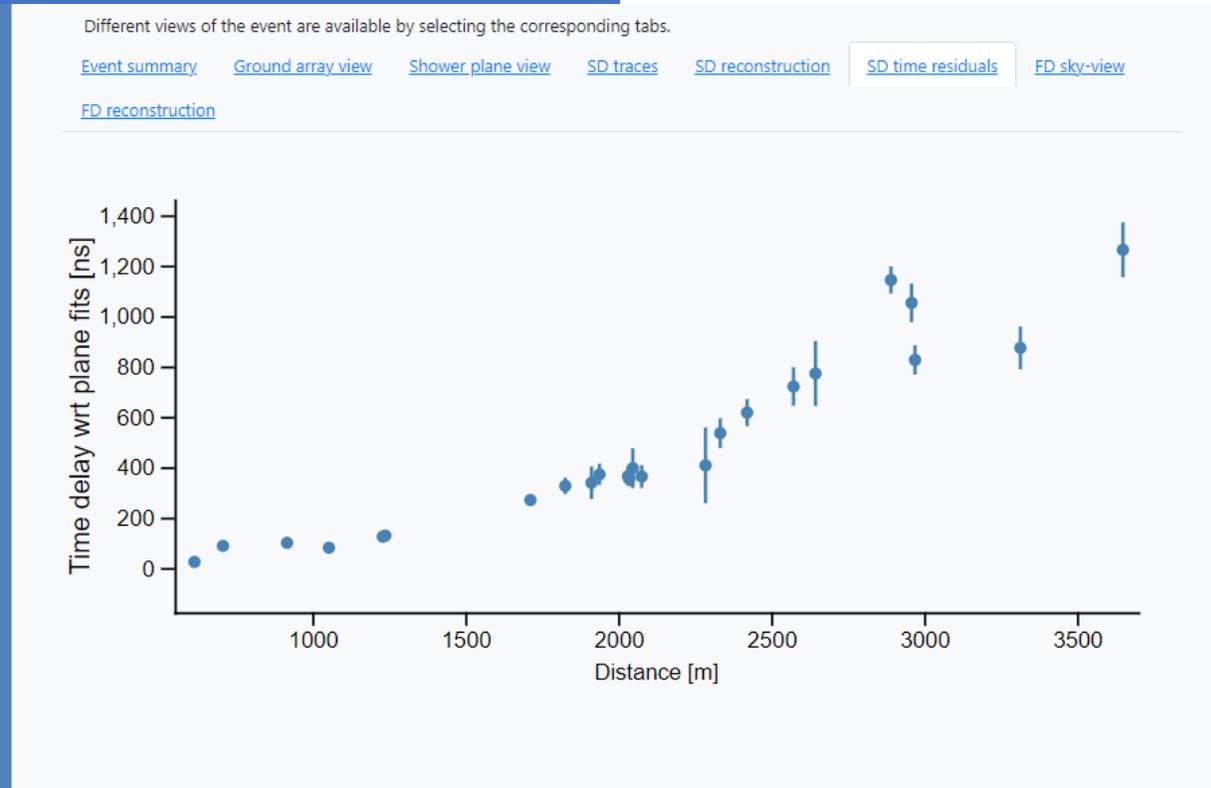
[Event summary](#) [Ground array view](#) [Shower plane view](#) [SD traces](#) [SD reconstruction](#) [SD time residuals](#) [FD sky-view](#)

[FD reconstruction](#)

This tab shows the SD LDF reconstruction: the total signal in the different stations versus the distance of the station to the event core. The signal at 1000m from the core is used as an energy estimate.



The Catalog: online event browser



The Catalog: online event browser

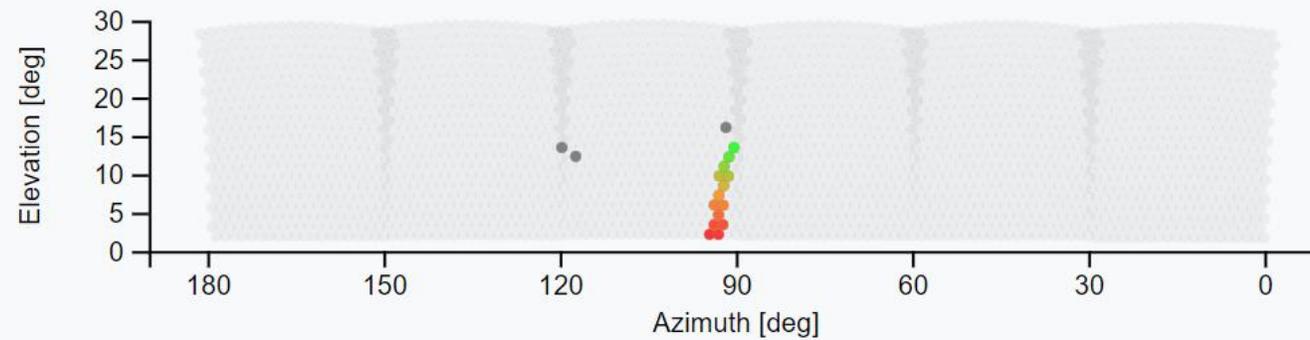
Different views of the event are available by selecting the corresponding tabs.

[Event summary](#) [Ground array view](#) [Shower plane view](#) [SD traces](#) [SD reconstruction](#) [SD time residuals](#) [FD sky-view](#)

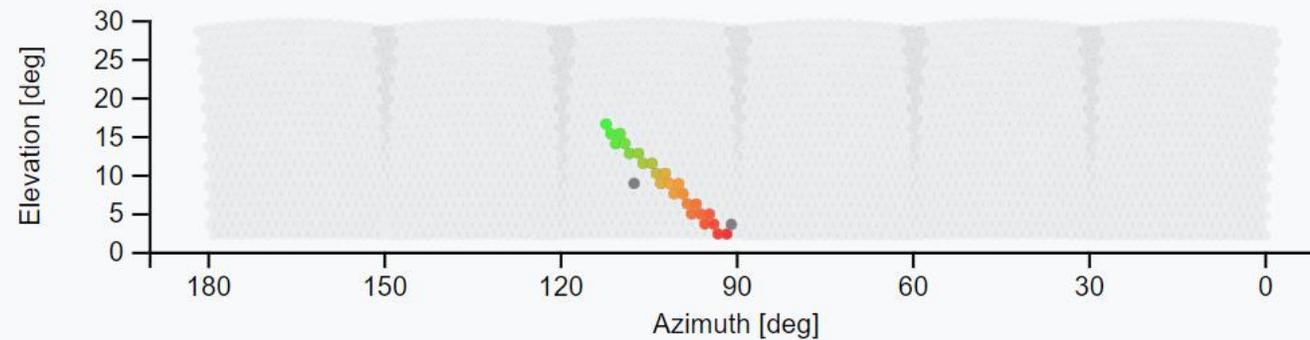
[FD reconstruction](#)

The FD camera view of the event is displayed below. The color code corresponds to the time at which the light reaches each pixel. Dark pixels are random coincidences and not used in the reconstruction.

Camera view for Los Leones



Camera view for Coihueco



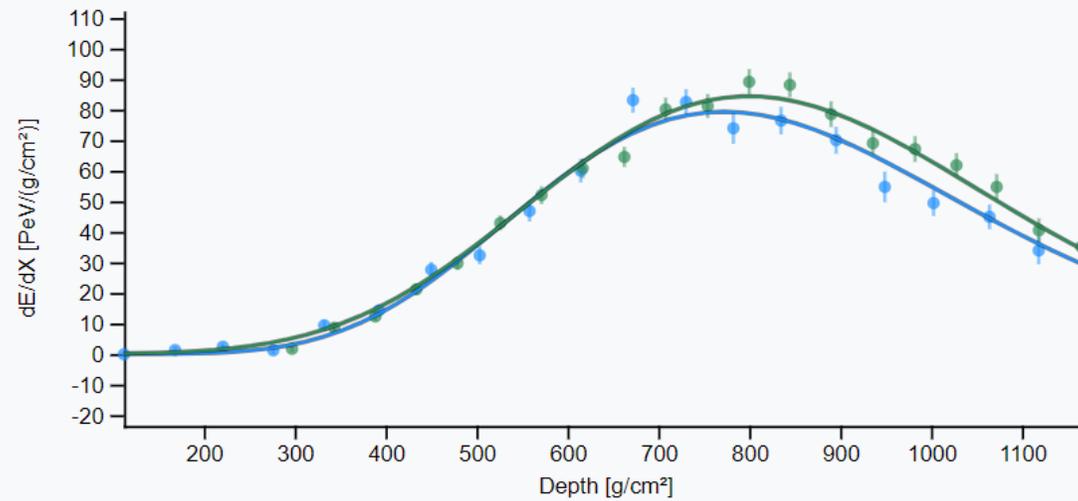
The Catalog: online event browser

Different views of the event are available by selecting the corresponding tabs.

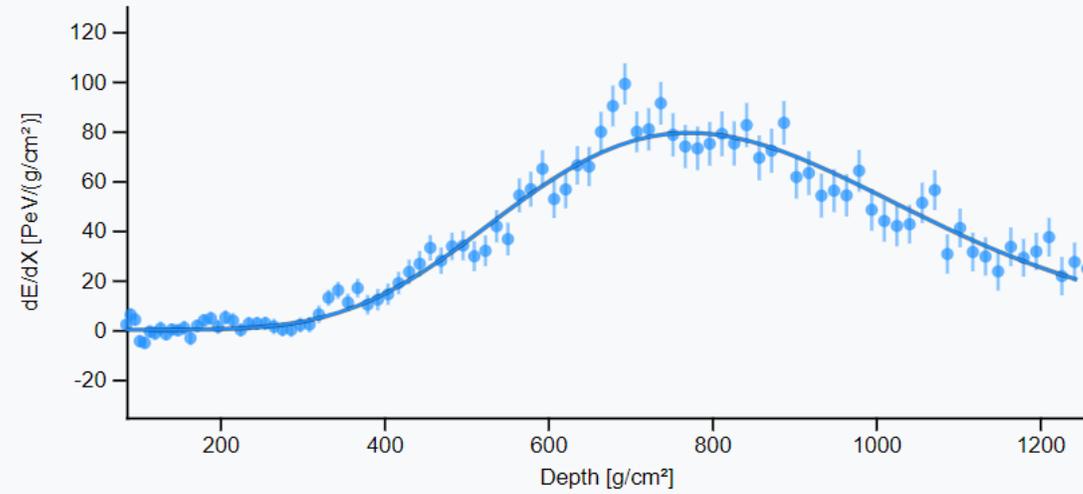
[Event summary](#) [Ground array view](#) [Shower plane view](#) [SD traces](#) [SD reconstruction](#) [SD time residuals](#) [FD sky-view](#)

[FD reconstruction](#)

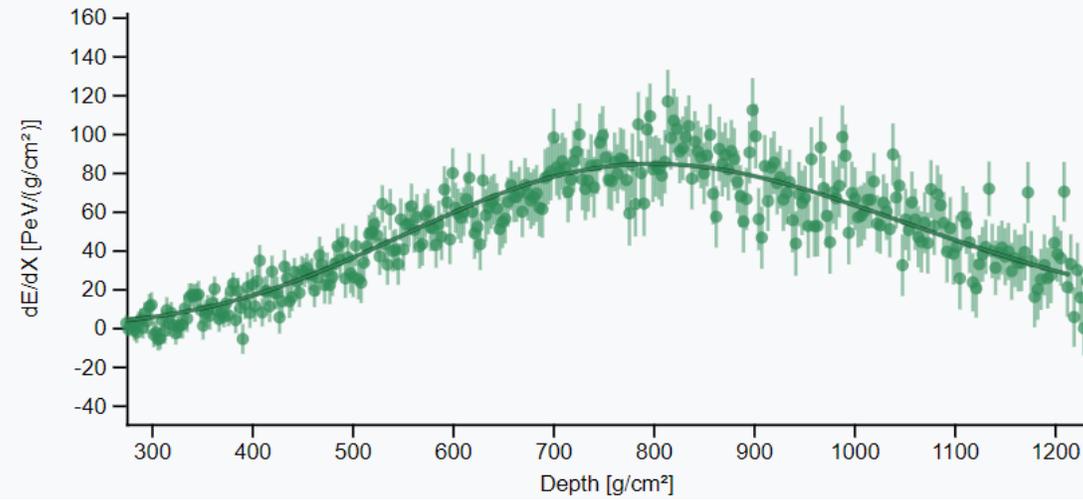
This tab shows the FD reconstructed profile, the energy deposited in the atmosphere as a function of the slant depth crossed by the cosmic ray. The integral of this curve gives a direct measurement of the calorimetric energy, while the depth at which the maximum of the energy deposition occurs is used to infer the primary particle properties.



The Catalog: online event browser

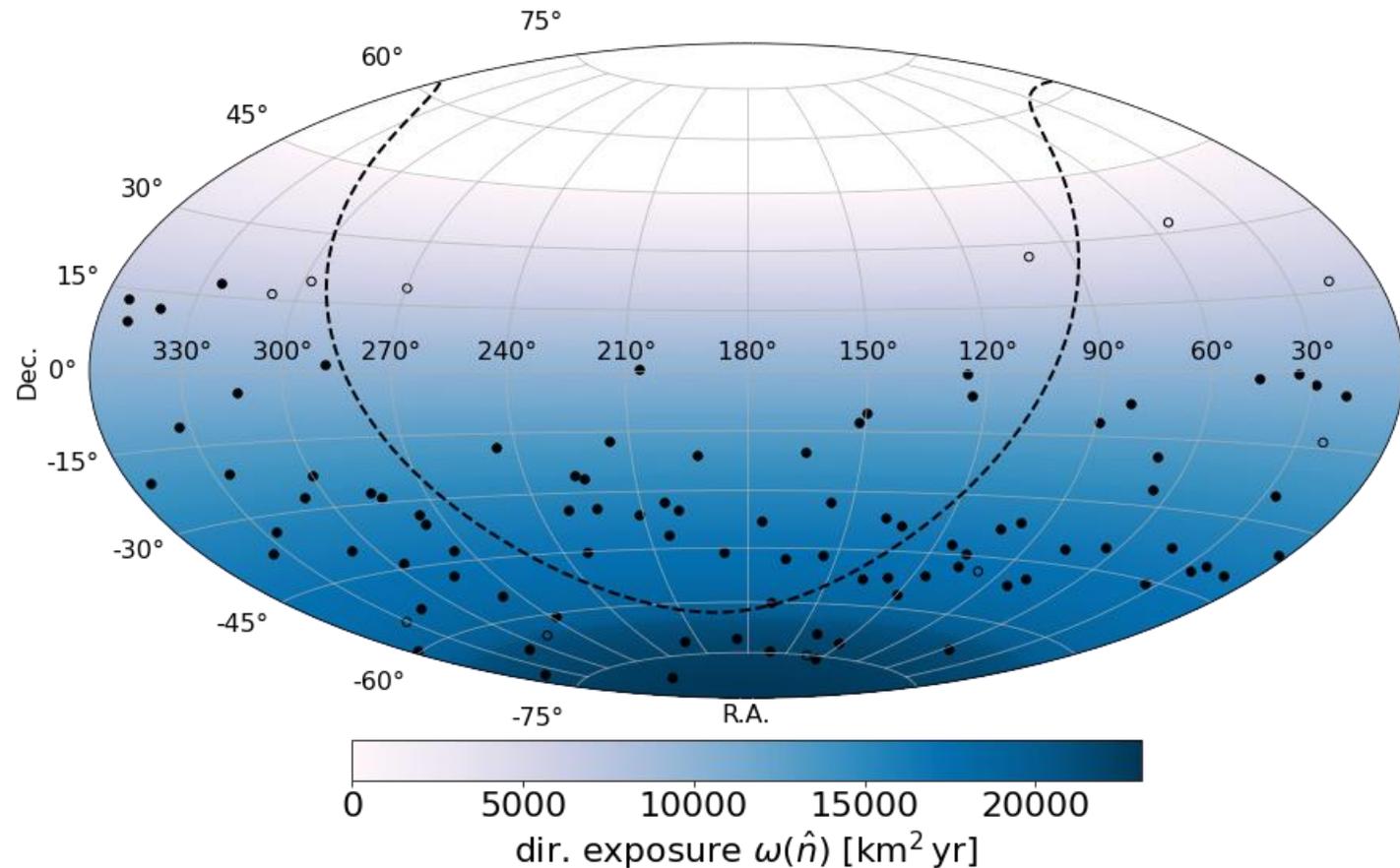


Coihueco



Conclusions

- **100 highest-energy cosmic rays**, in the range 78 EeV to 166 EeV
- Further **9 very energetic hybrid events**
- Detection and reconstruction of shower parameters
- Footprint on the ground and in the shower plane, LDF, time delays w.r.t to a plane fit, WCDs signals, FD camera traces, FD energy deposited profiles



The positions of the arrival directions of the 100 highest-energy cosmic rays detected at the Pierre Auger Observatory shown in equatorial coordinates



A detailed presentation of the highest-energy cosmic rays recorded at the Pierre Auger Observatory

Mario Buscemi
for the Pierre Auger Collaboration

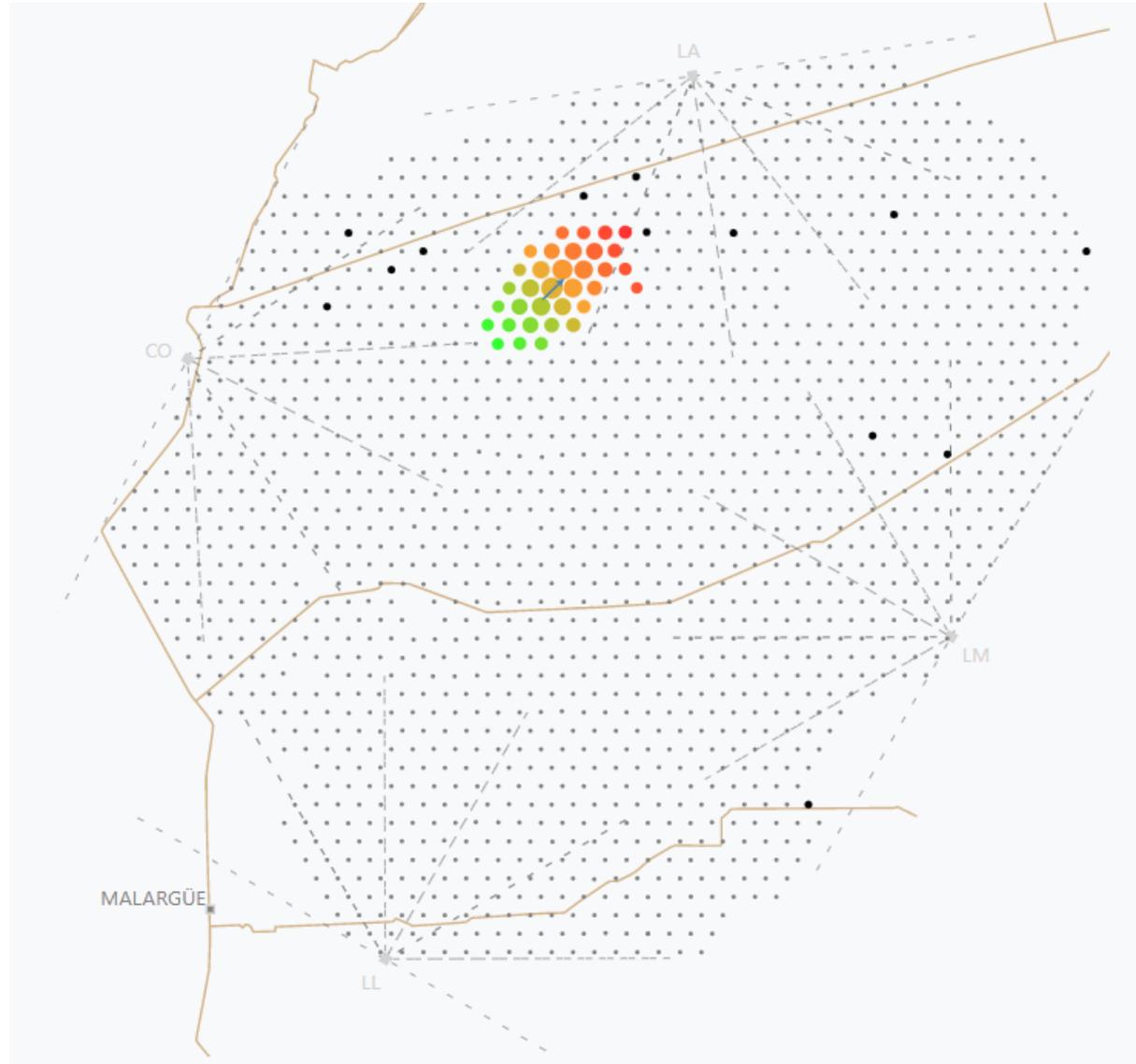
Dipartimento di Fisica e Chimica “E. Segrè”
Università degli Studi di Palermo
& INFN Sezione di Catania
mario.buscemi@ct.infn.it

Thank you

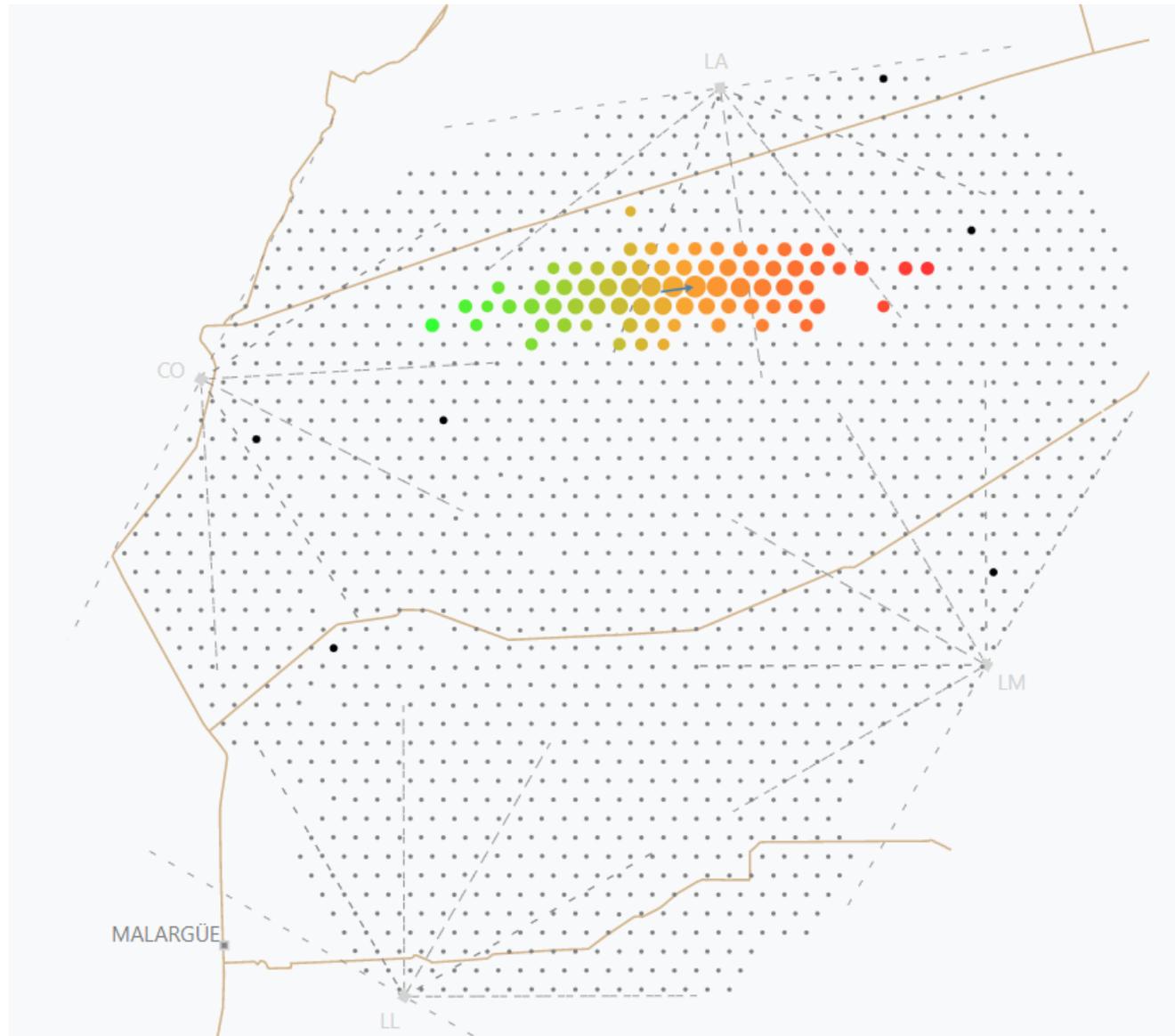


Backup

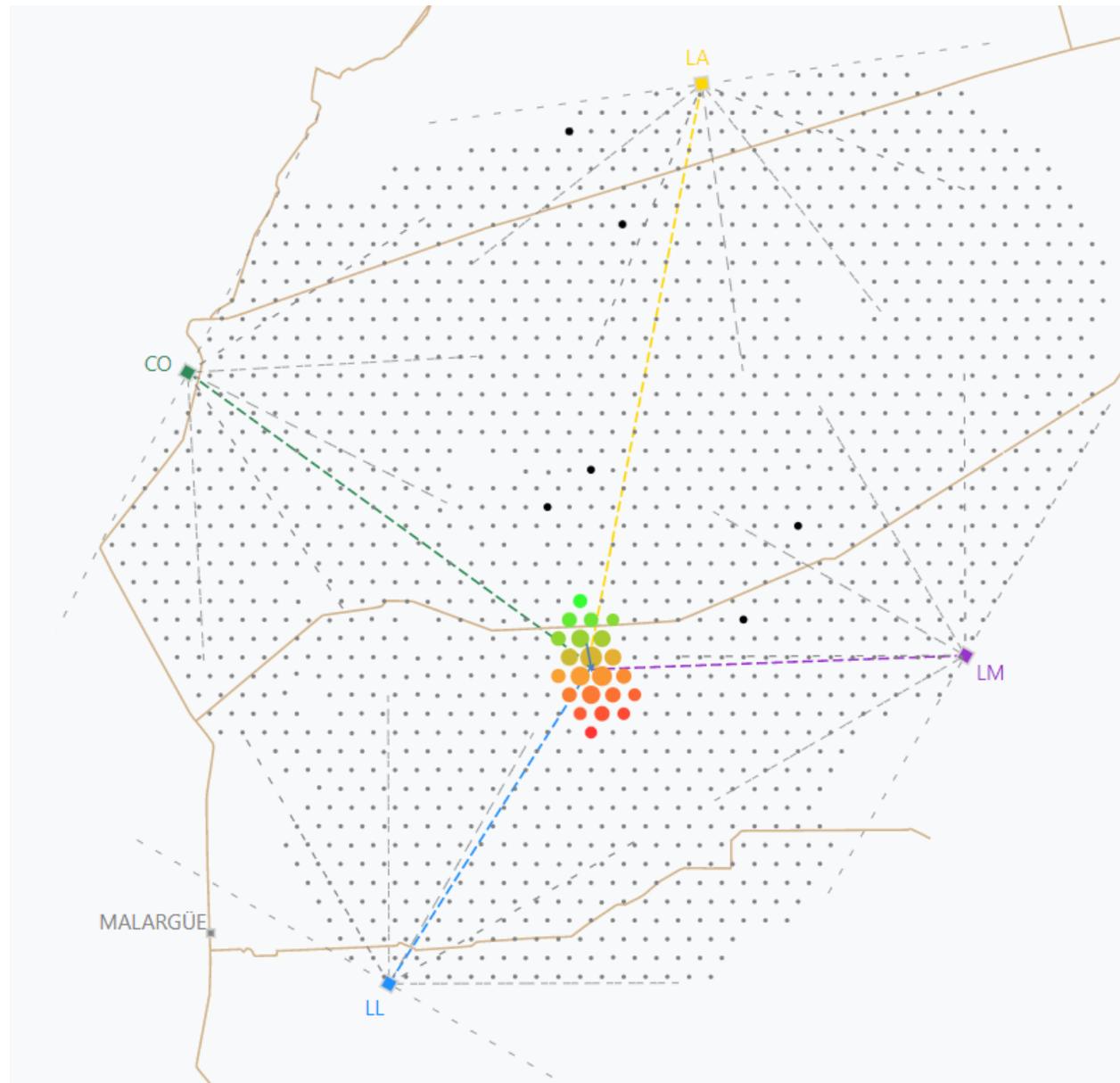
#1 - PAO191110



#17 - PAO150926

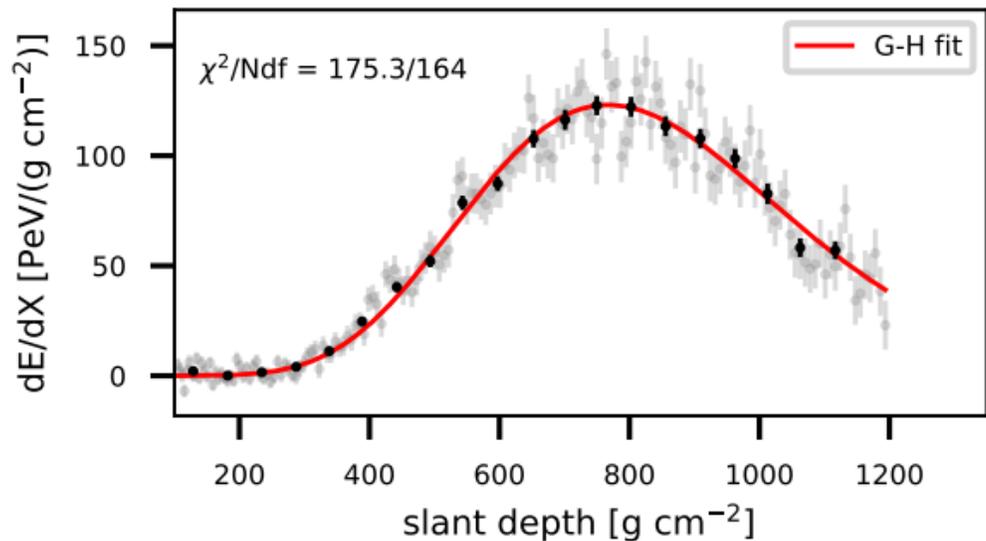


#84 - PAO100815

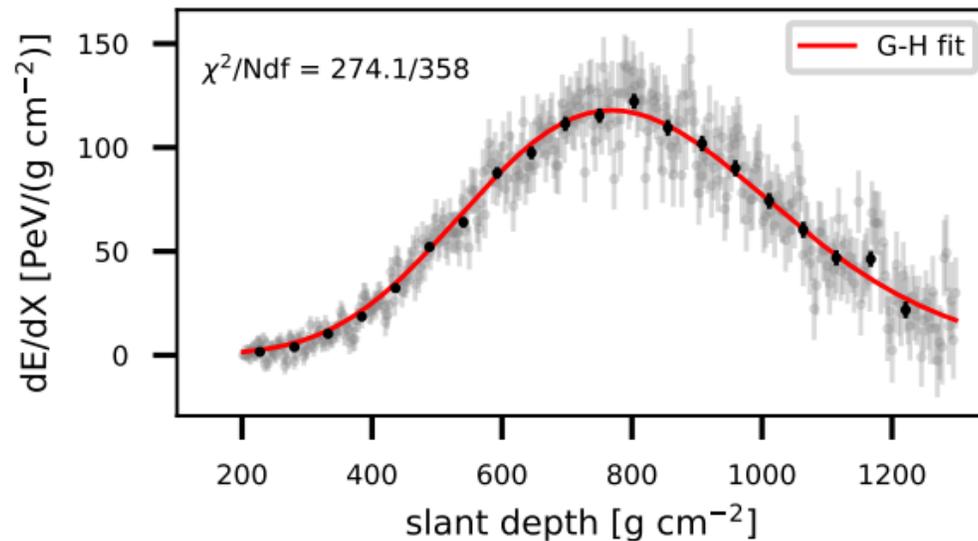


#84 - PAO100815

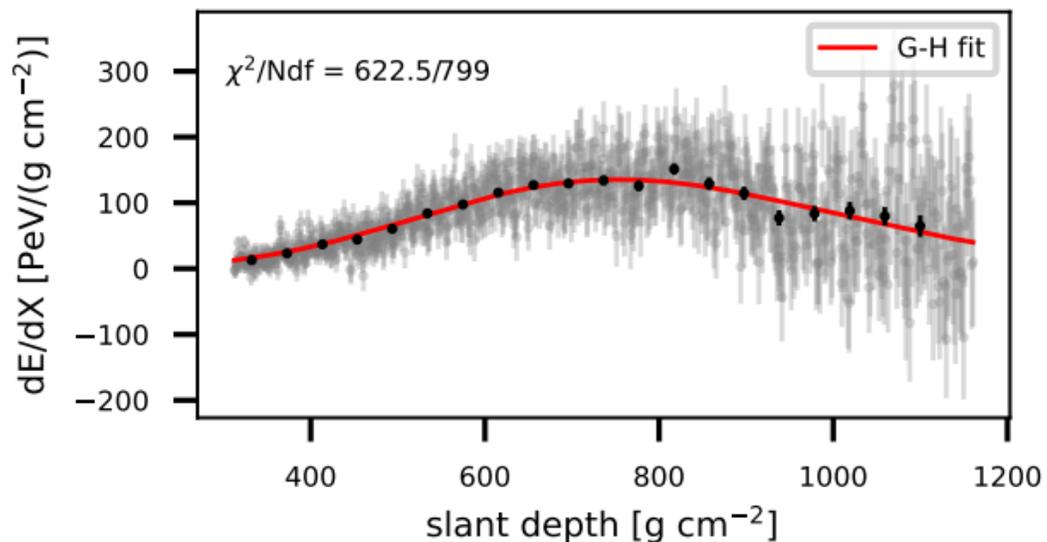
Los Leones



Los Morados



Loma Amarilla



Coihueco

