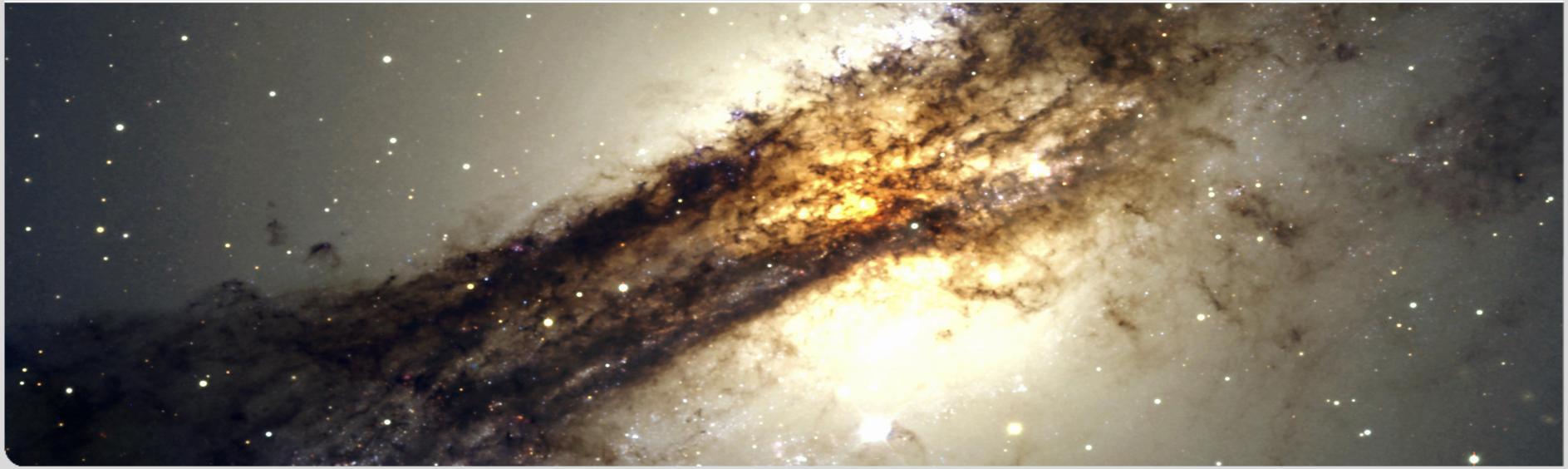
The Pierre Auger Observatory: upgrade and prospects in the EeV region.

A. M. Botti[1,2]

Research Technique Seminar 09/10/2019

[1] Instituto de Tecnologías en Detección y Astropartículas, CNEA-CONICET-UNSAM
[2] Institute of Nuclear Physics (IKP), Karlsruhe Institute of Technology (KIT)



Ana Martina Botti – ana.botti@iteda.cnea.gov.ar

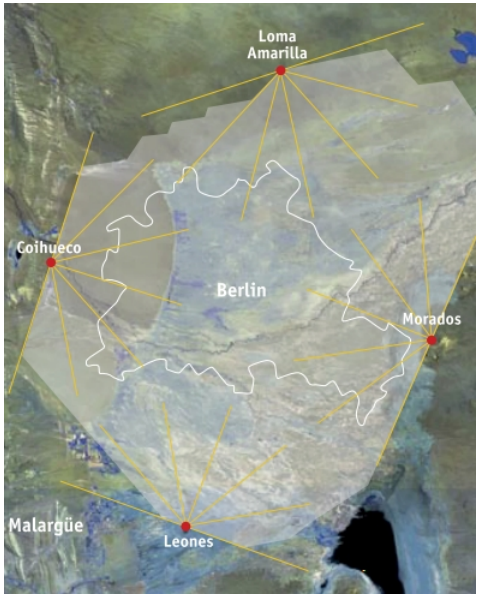
Outline

- **Introduction**:
  - Ultra High Energy Cosmic Rays.
  - Extensive Air Showers.

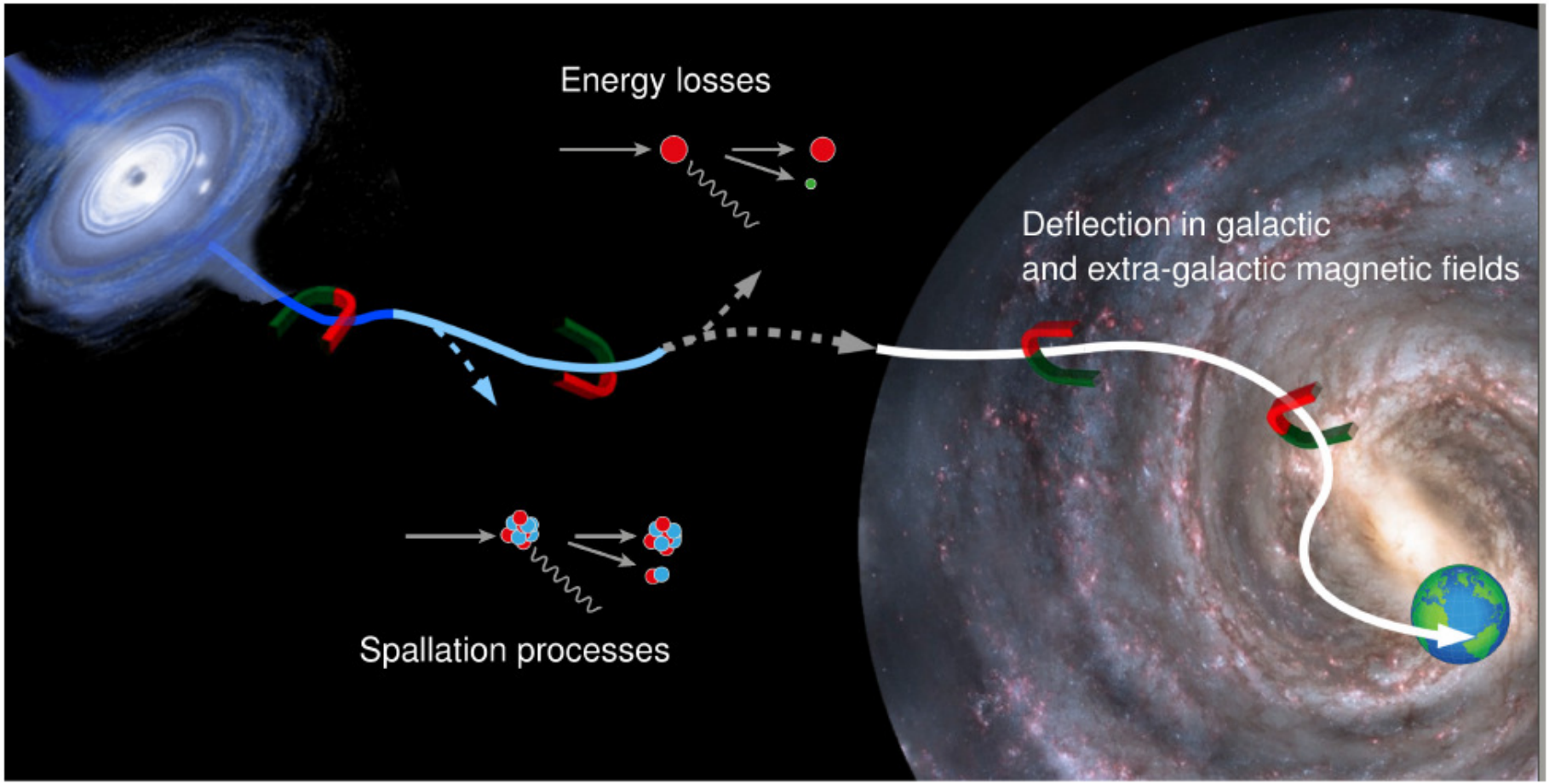
- **The Pierre Auger Observatory**:
  - Detectors.
  - Summary of physical results.

- **AugerPrime.**

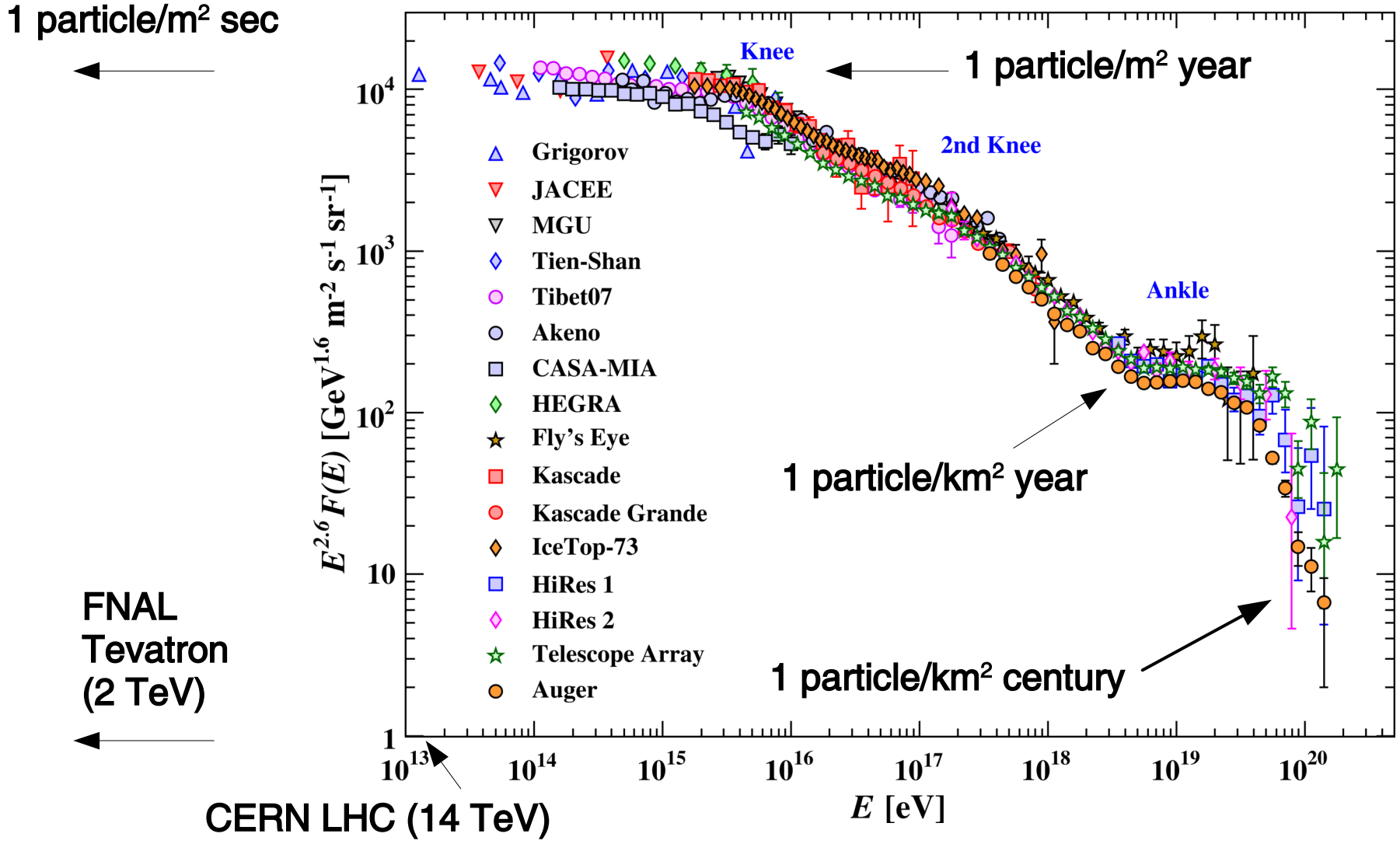
- **Underground Muon Detector:**
  - Silicon photomultipliers.
  - Noise sources.
  - Calibration and performance.



Ultra High Energy Cosmic Rays

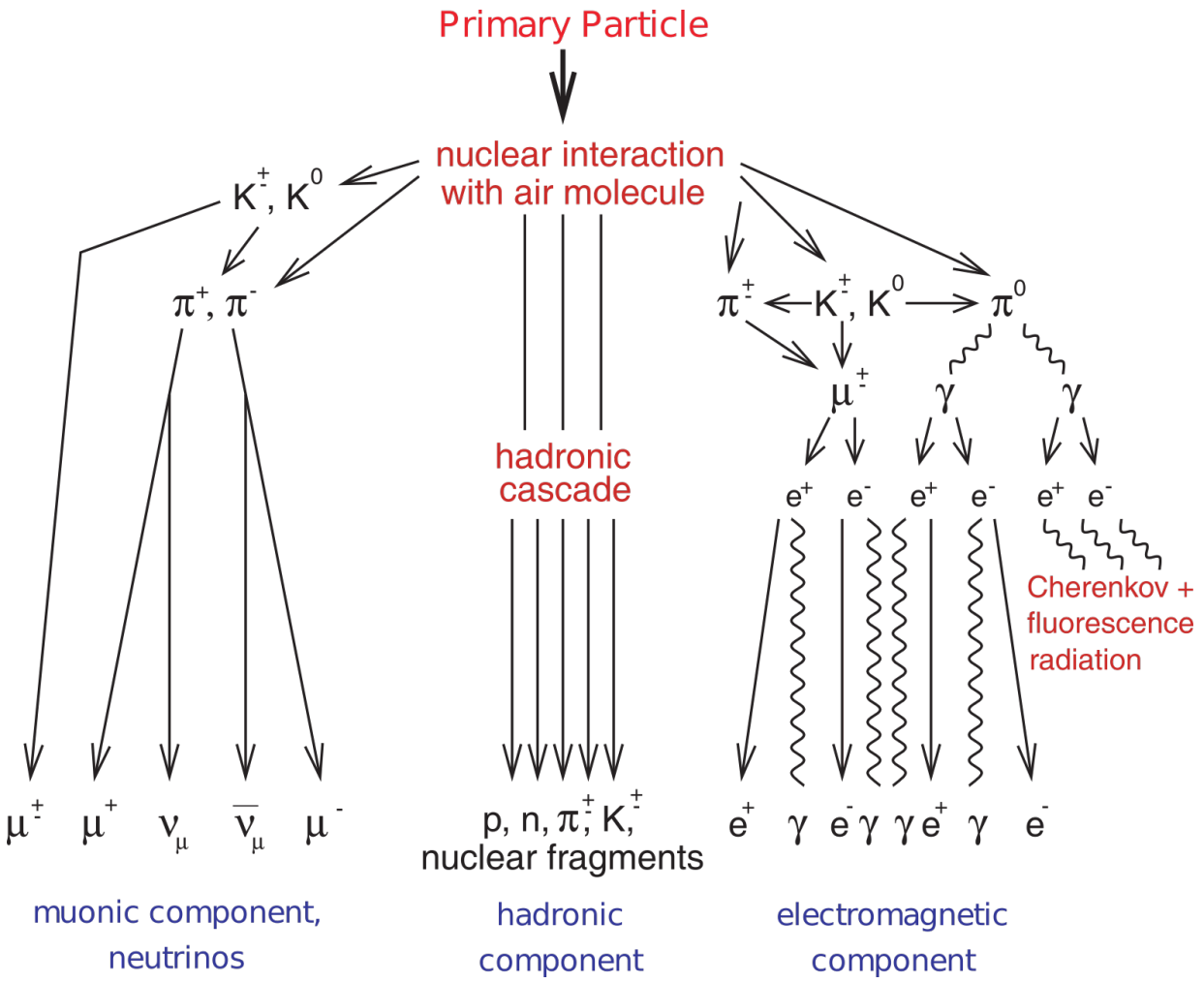


(Ultra High Energy) Cosmic Rays



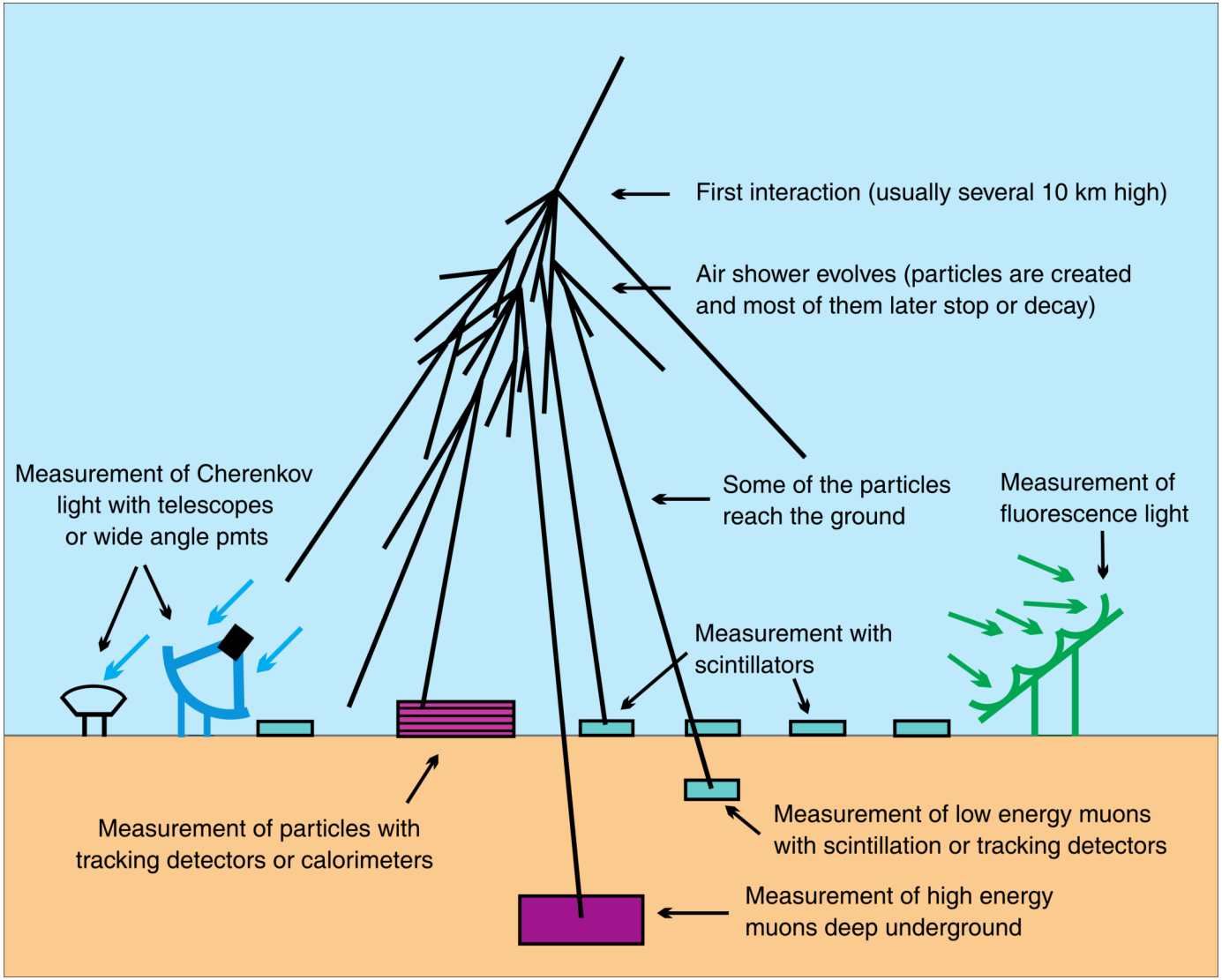
Adapted from PDG

Extensive air showers



2003 Rep. Prog. Phys. 66 1145

Extensive air showers



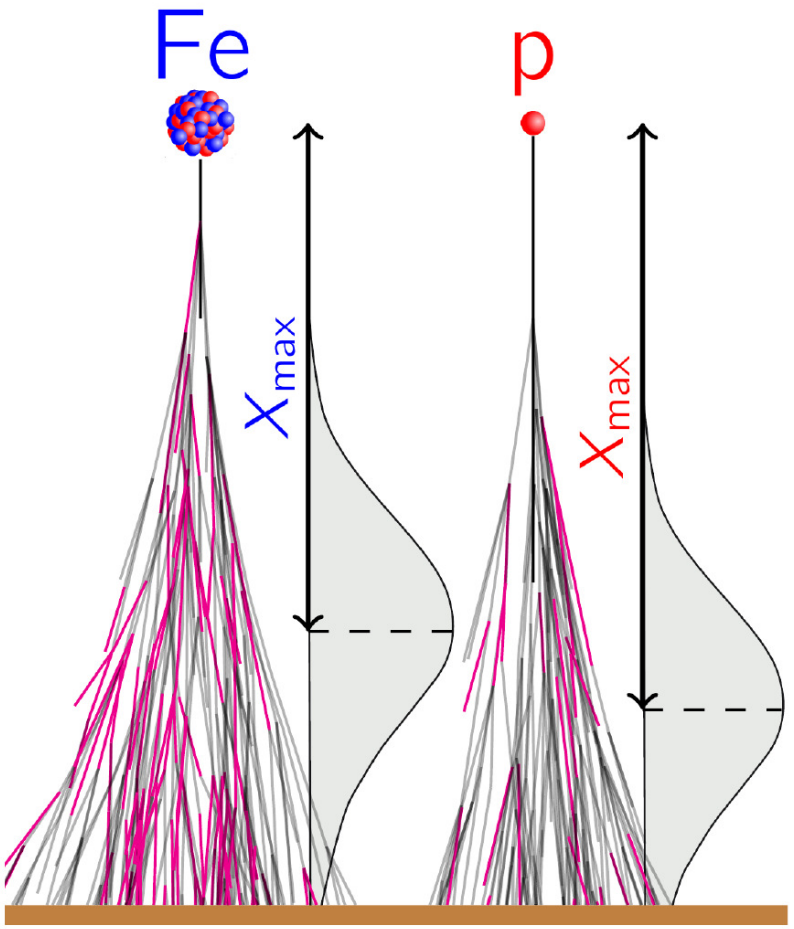
2003 Rep. Prog. Phys. 66 1145

Extensive air showers

Depth of **EAS** Maximum development ($\mathbf{X_{max}}$) ⟶ **Mass composition** and **energy**

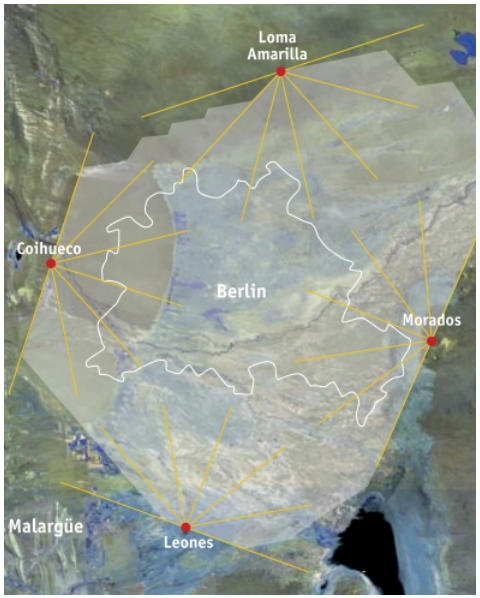
Muon content ⟶ **Mass composition** and **energy**

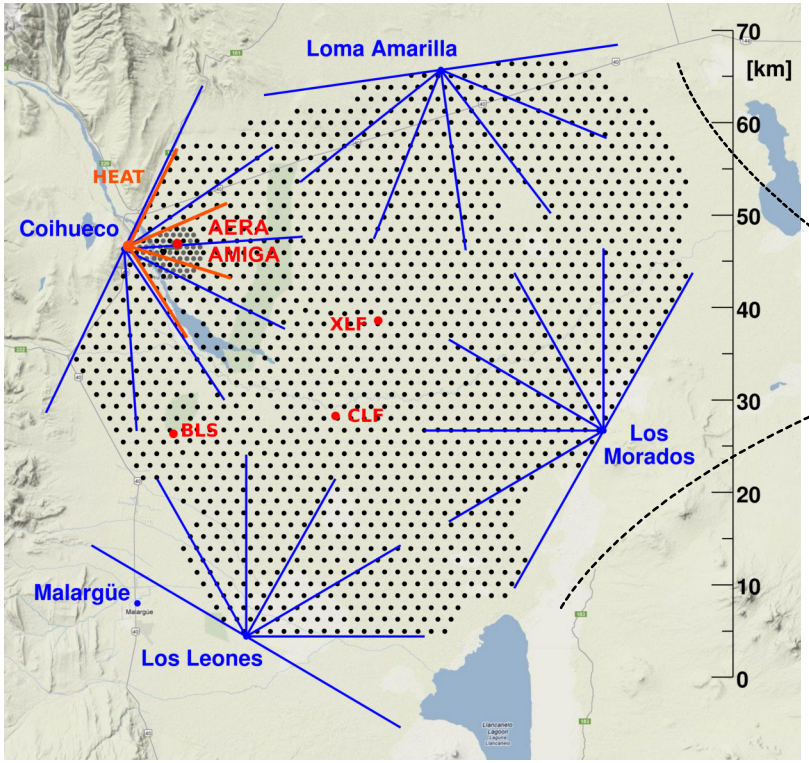
Electromagnetic content ⟶ **Energy**



2003 Rep. Prog. Phys. 66 1145

The Pierre Auger Observatory





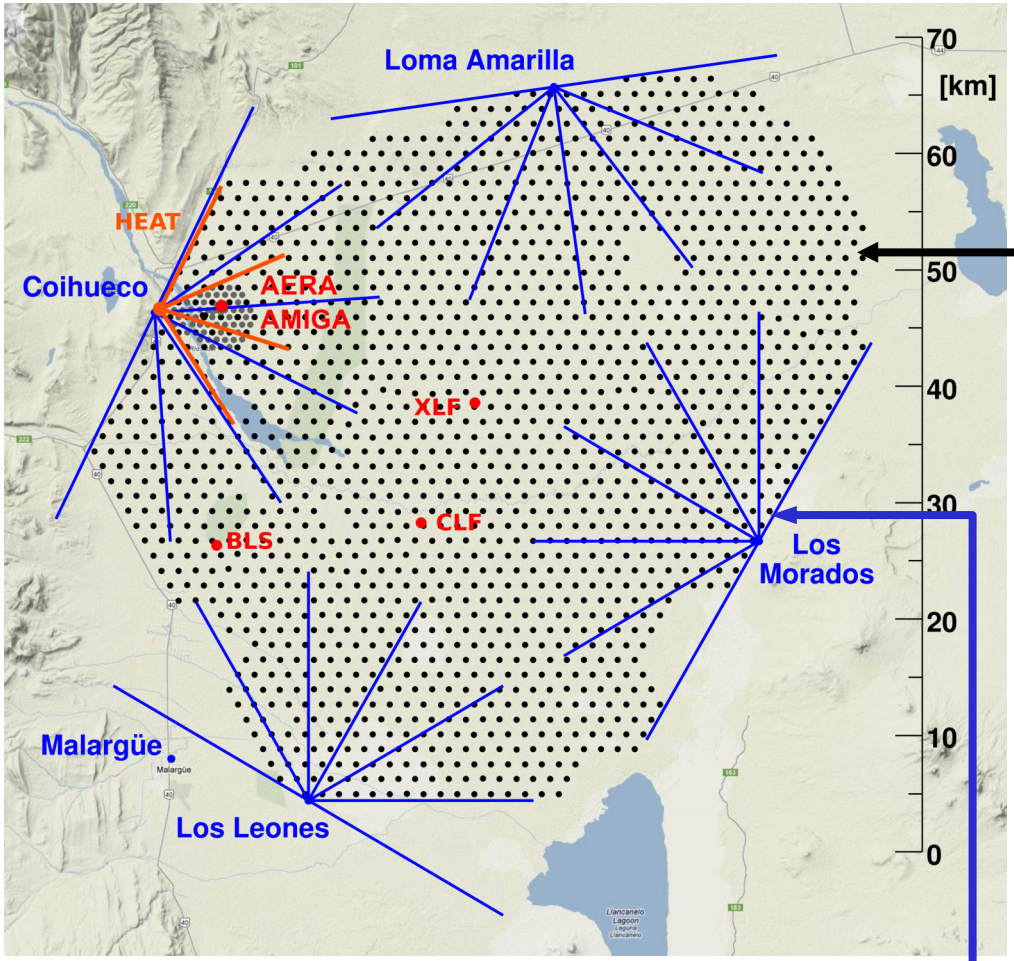
Berlin ~ 890 km^2

Surface Detector ~ 3000 km^2

Buenos Aires City ~ 203 km^2

Chicago ~ 606 km^2

The Pierre Auger Observatory



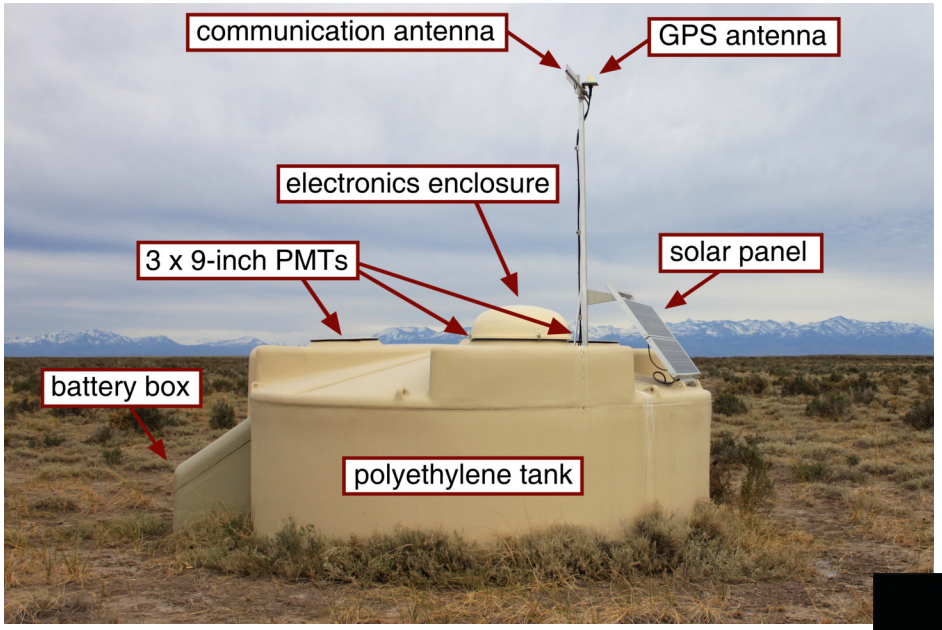
SD

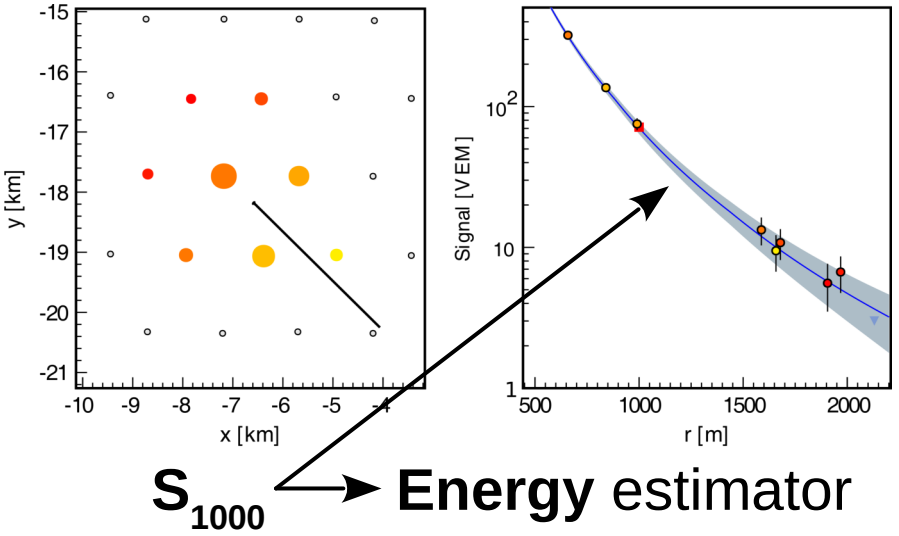
- **3000 km²** array
- **1660 WCD**
- **3.6 m x 1.2 m**
- **1.5 km** between **WCD**

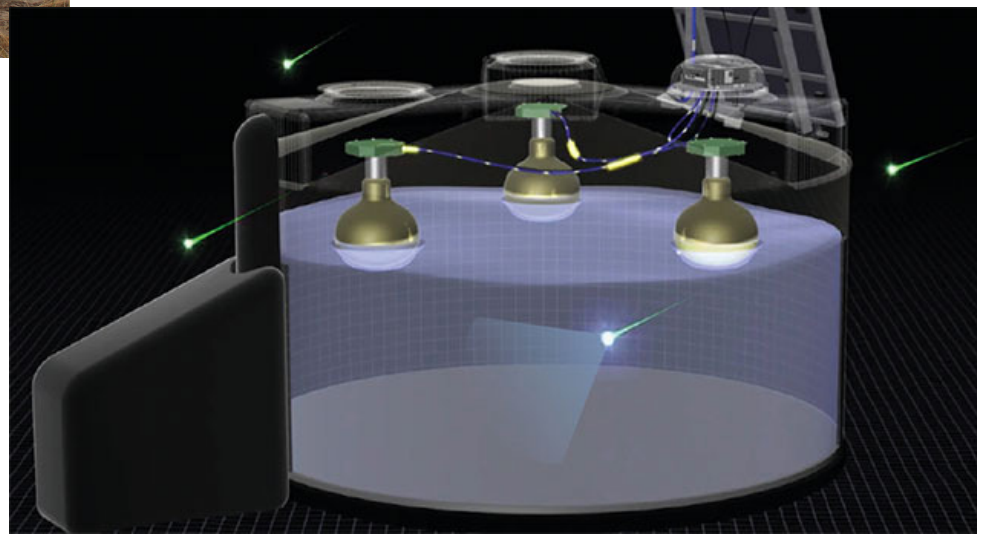
FD

- **27** fluorescence telescopes
- **4** buildings

Surface Detector (1660 WCD)







3.6 m diamater
1.2 m height
12000 l water
3x **9-in** diameter **PMT**s
530 kg

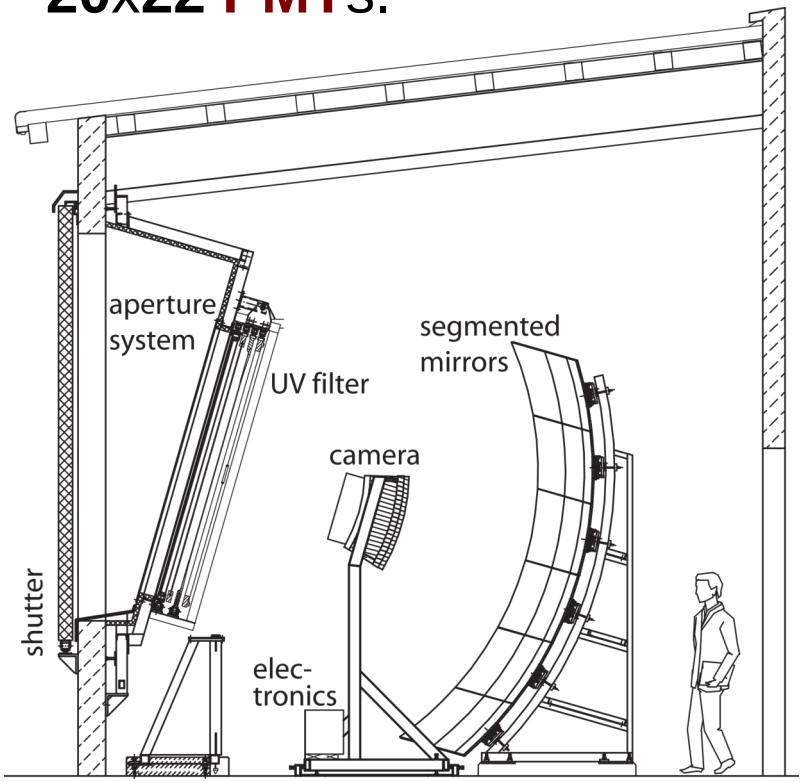
* NIM A, 798 (2015) 172-213 & CERNCOURIER

Fluorescence Detector

30º x **30º** field of view.

Each building **180º.**

20x**22 PMT**s.

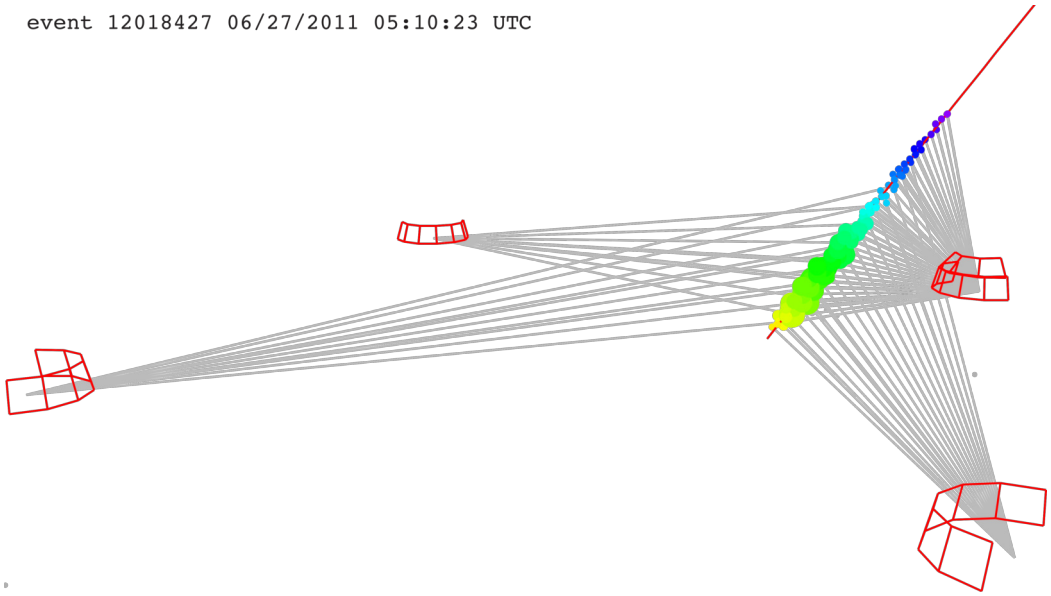


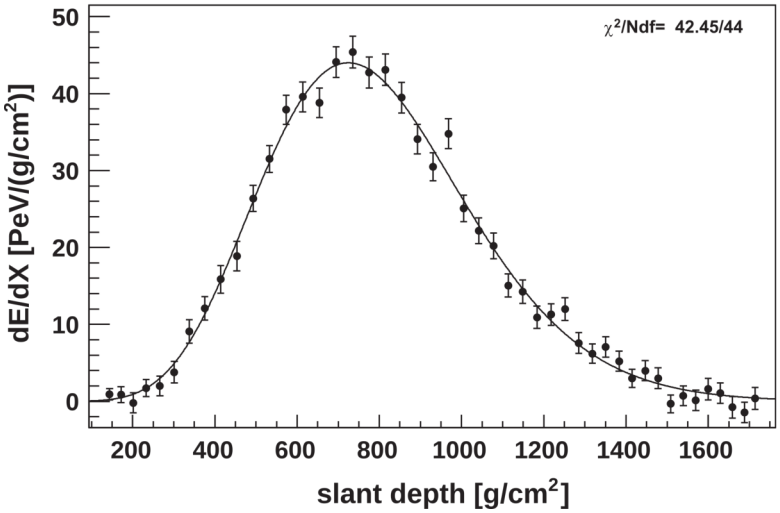
* NIM A, 798 (2015) 172-213 & CERNCOURIER

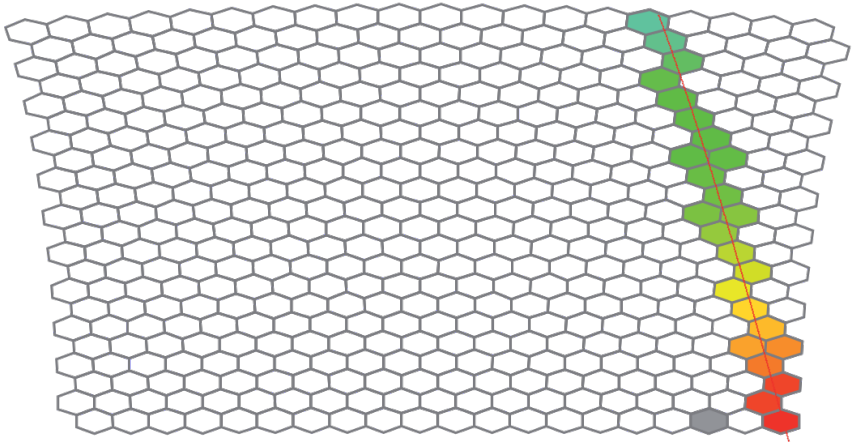
Fluorescence Detector

Calorimetric **energy.**

Xmax ⟶ **Energy** and **composition**.





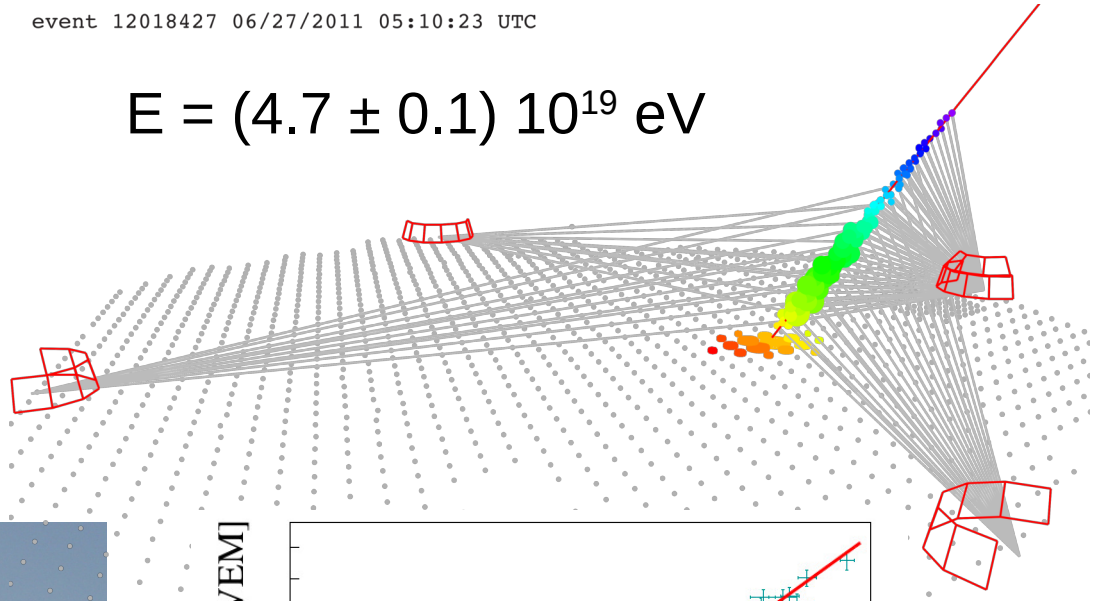


* NIM A, 798 (2015) 172-213 & EPJ Web of Conferences 53 04009(2013)

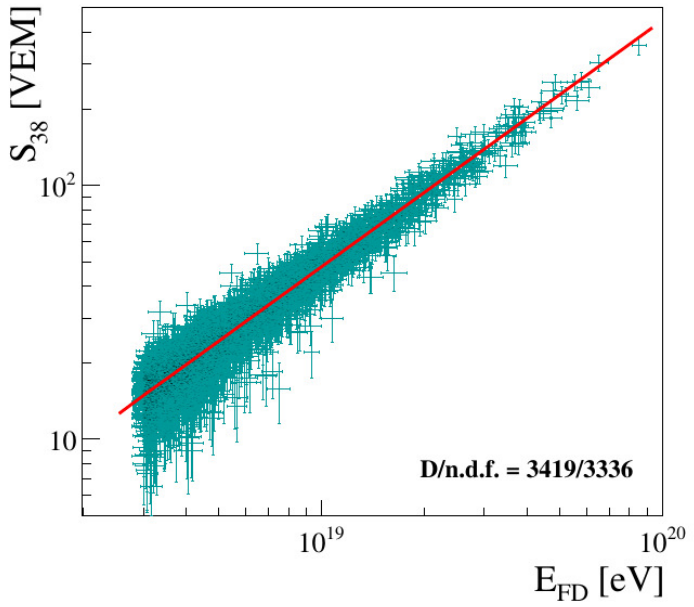
Hybrid detection

Combine detectors to reduce **systematics**.

Cross calibrate.

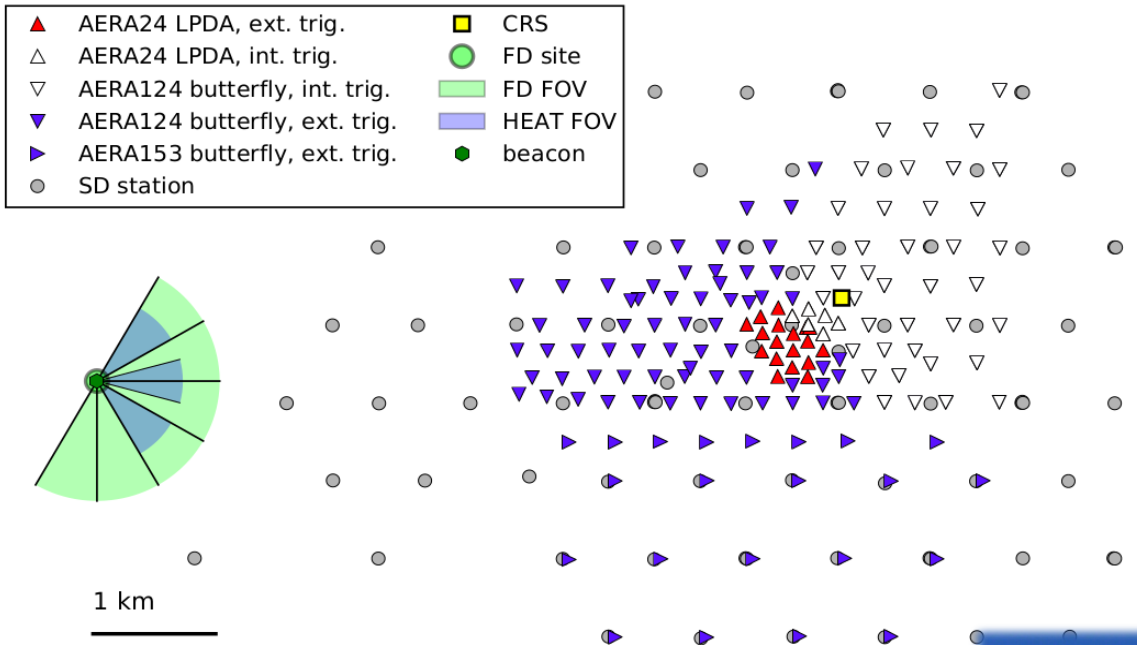


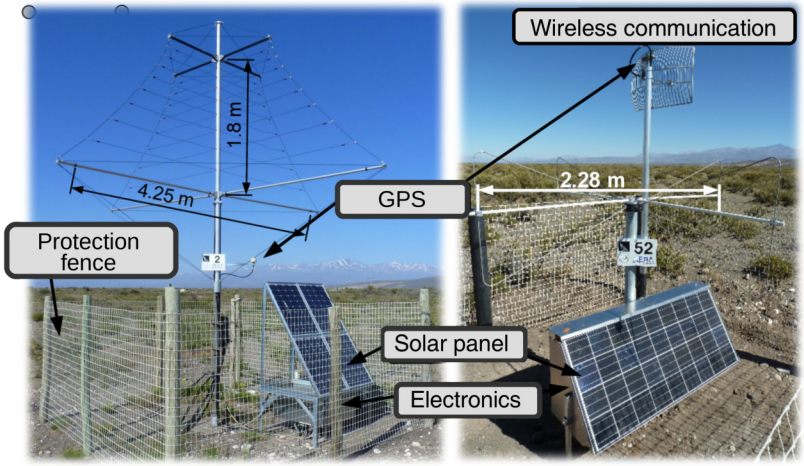
$E = (4.7 \pm 0.1)\ 10^{19}$ eV



* NIM A, 798 (2015) 172-213 & EPJ Web of Conferences 53 04009(2013)

Low energy enhancements





* PoS(ICRC2017)492 & 10 7529/ICRC2011/V03/0761

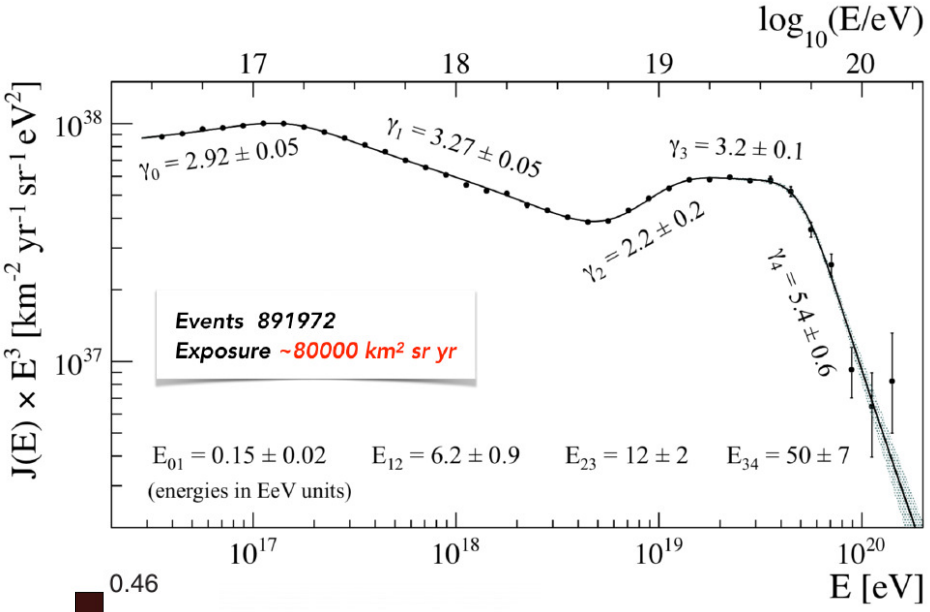
Results

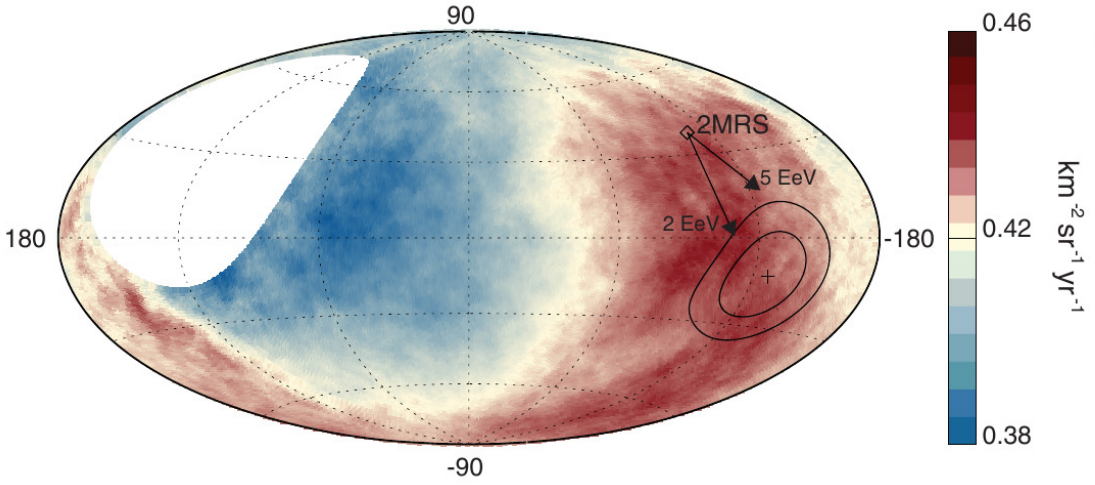
Spectrum:

Flux suppresion confirmed.

2nd knee was observed.

Highest statistics at **UHE**.





Anisotropy:

Dipole away from **galactic center** ⟶
Strong evidence of **extragalactic** origin @ E > 8 10^{18} ev.

* PoS(ICRC2019)450 & Science paper

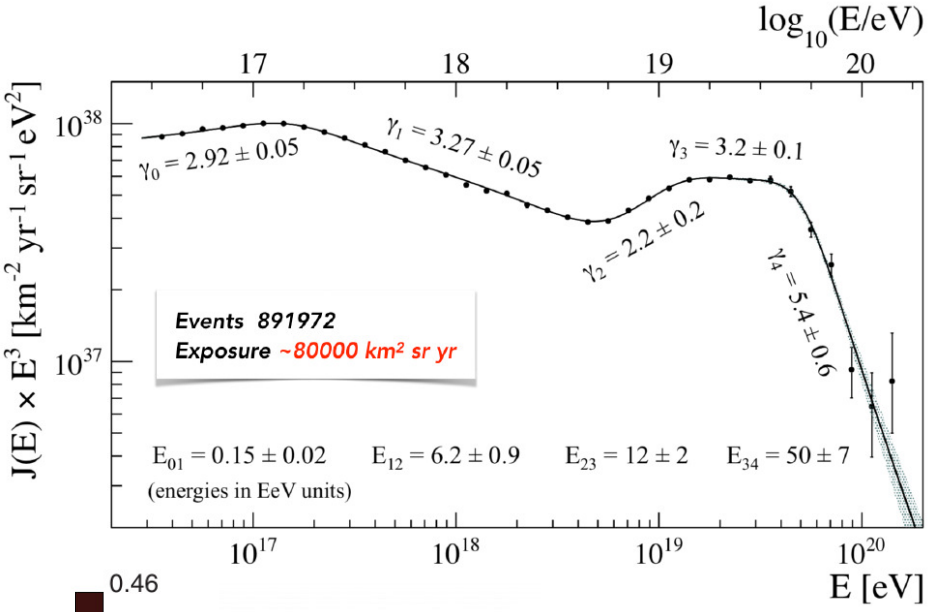
Results

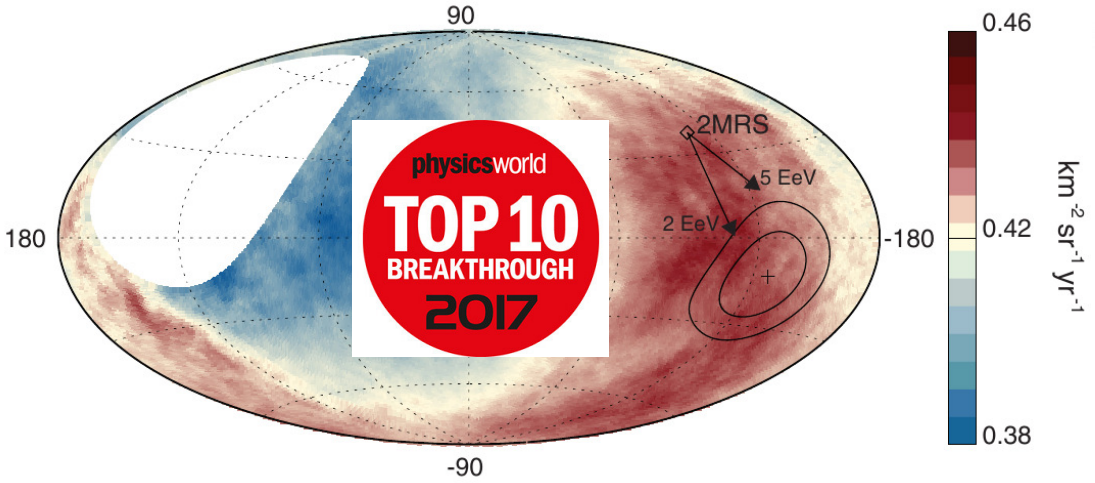
Spectrum:

Flux suppresion confirmed.

2nd knee was observed.

Highest statistics at **UHE**.





Anisotropy:

The Pierre Auger Collaboration, **Science** 357, 1266–1270 (2017)

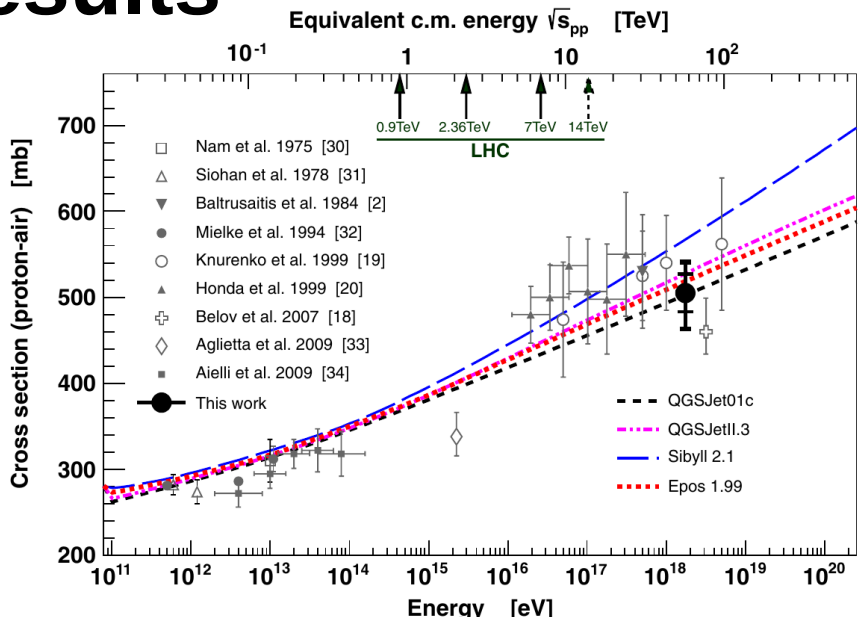
"To the Pierre Auger Observatory collaboration for showing that ultra-high-energy cosmic rays come from **outside the Milky Way**."

* PoS(ICRC2019)450 && Science paper

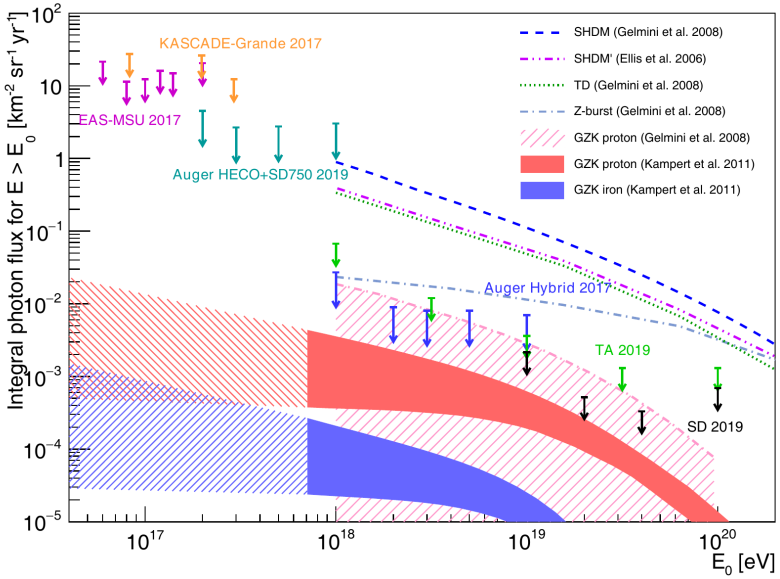
Results

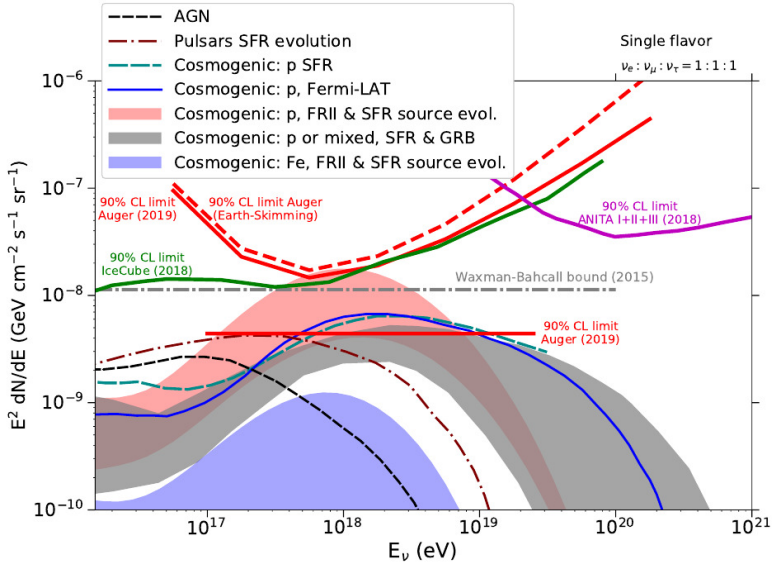
Cross section proton-air (and proton-proton):

Study **hadronic models** at energies above **LHC** (57 ± 0.3 ± 6) TeV



Photon and neutrino flux:





* Phys.Rev.Lett. 109 (2012) 062002 & PoS(ICRC2019)979 & PoS(ICRC2019)398

Results

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

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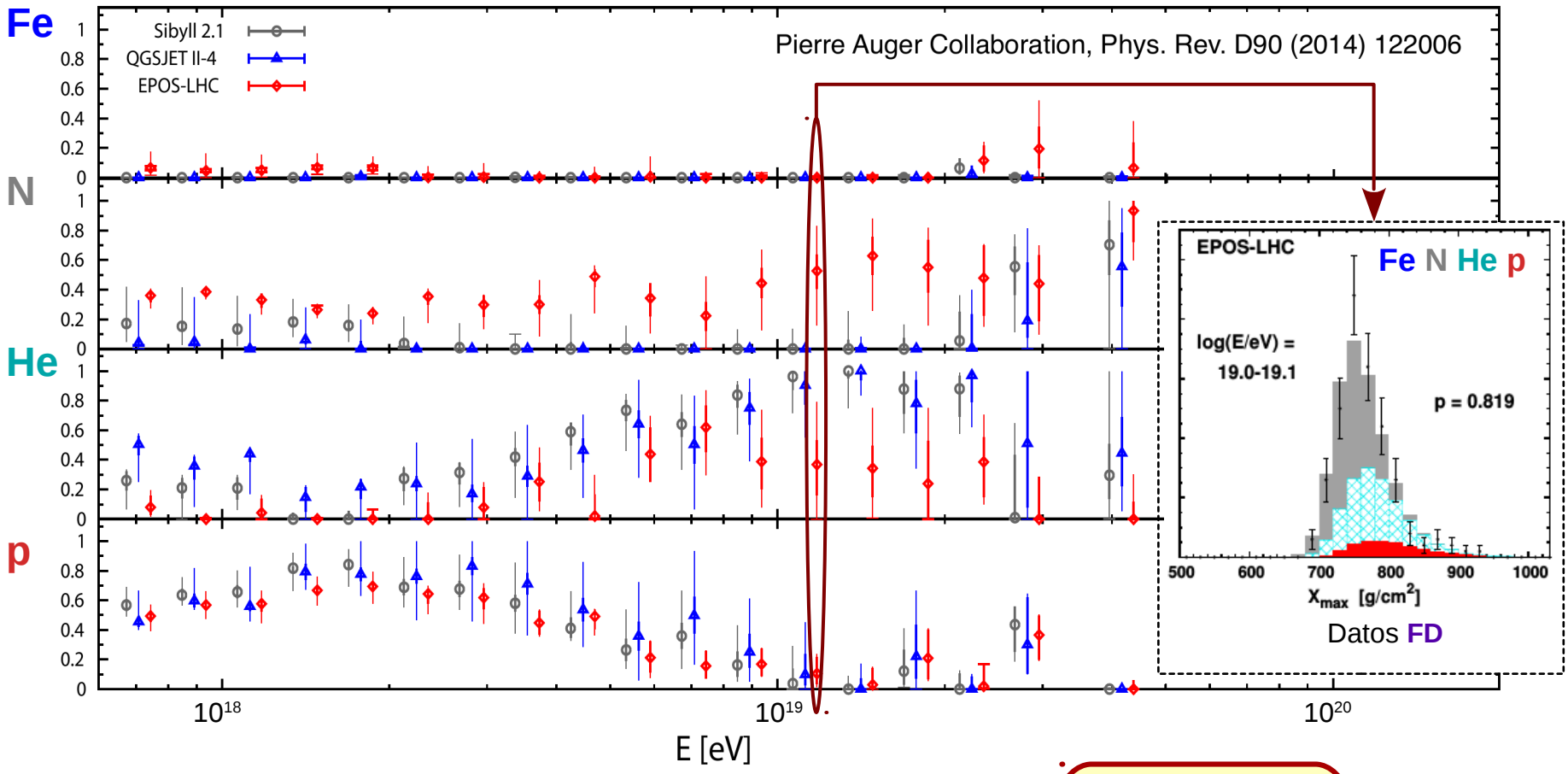
The Pierre Auger Observatory carried out a search for ultra-high-energy (UHE) neutrinos above $\sim 10^{17}$ eV using its Surface Detector (Aab et al. 2015a). UHE neutrino-induced extensive air showers produced either by interactions of downward-going neutrinos in the atmosphere or by decays of tau leptons originating from tau neutrino interactions in the Earth's crust can be efficiently identified above the background of the more numerous ultra-high-energy cosmic rays (Aab et al. 2015b). Remarkably, the position of the transient in NGC 4993 was just between $0.^{\circ}3$ and $3.^{\circ}2$ below the horizon during $t_c \pm 500$ s. This region corresponds to the most efficient geometry for Earth-skimming tau neutrino detection at 10^{18} eV energies. No neutrino candidates were found in $t_c \pm 500$ s (Alvarez-Muniz et al. 2017) nor in the 14 day period after it (A. Albert et al. 2017, in preparation).

Pierre Auger can also contribute to Multi-messenger astronomy

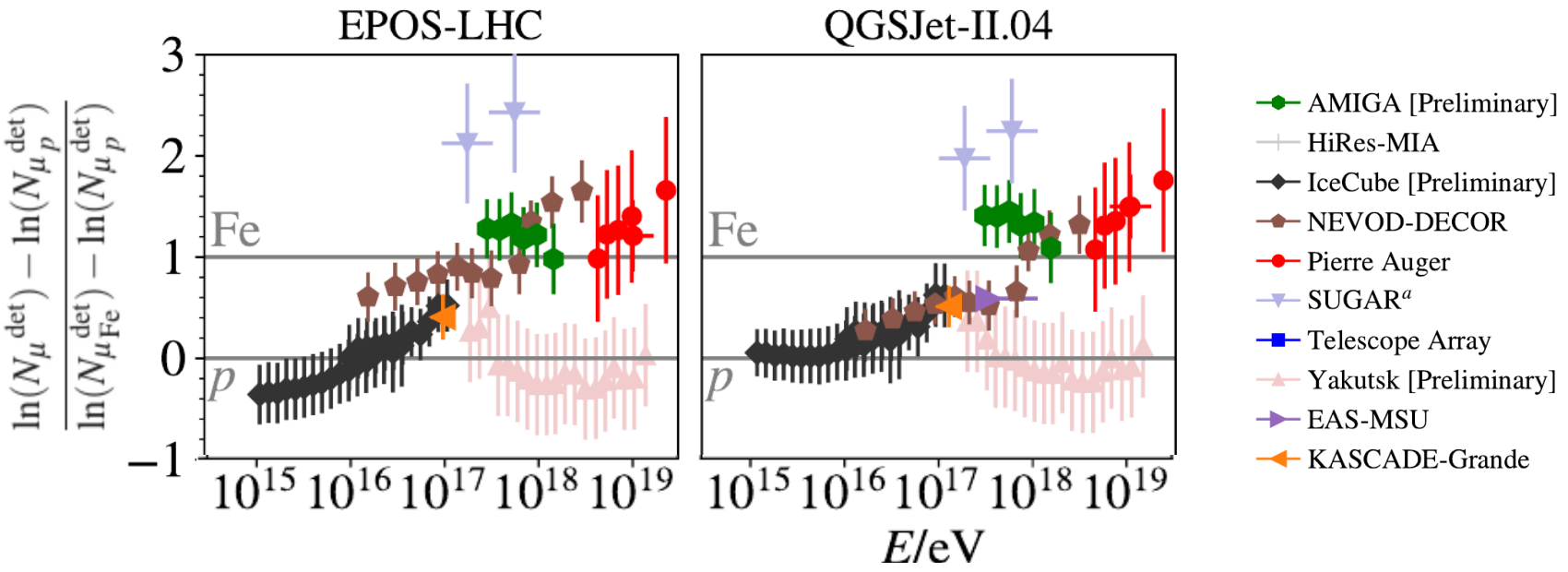
AugerPrime motivation arXiv:1604.03637

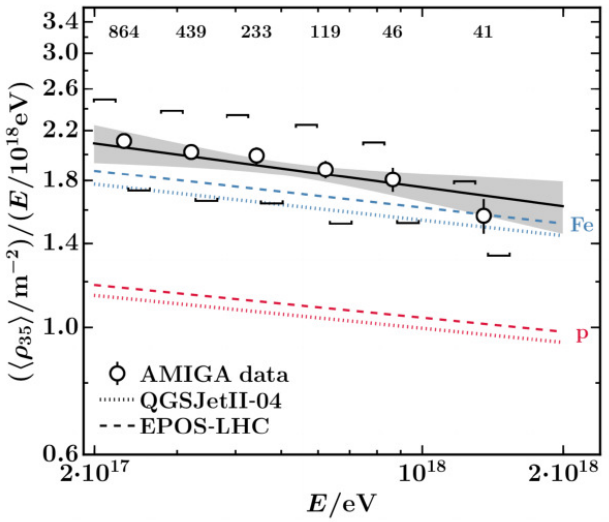


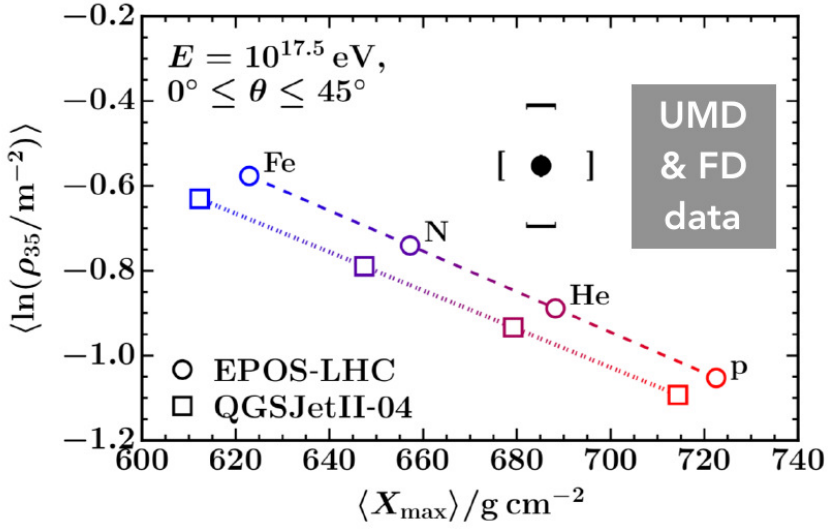
- **Mass composition** cosmic rays with **E > 10^{19} eV.**
- **Protons** with **E > 10^{19} eV.**
- **Hadronic models.**

Improve statistics and **mass discrimination**

Motivation: muon content in EAS

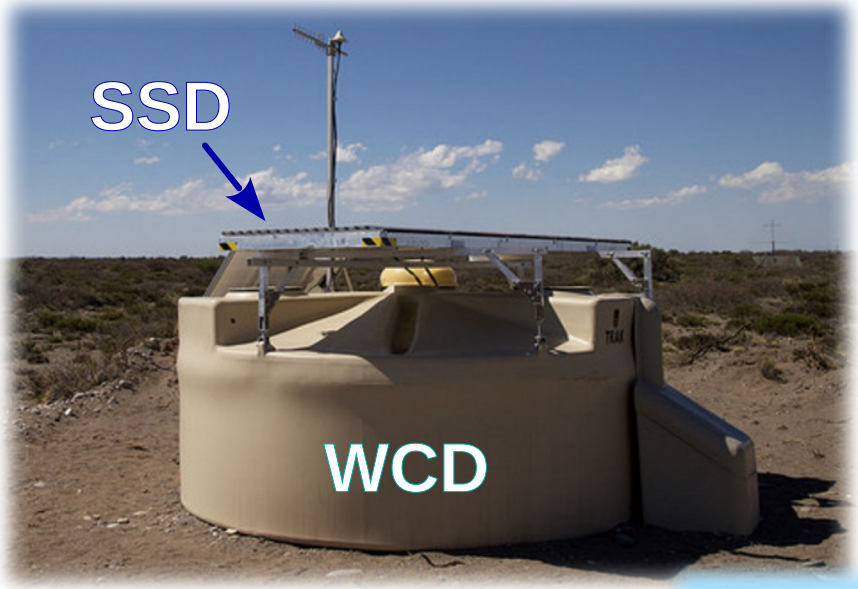




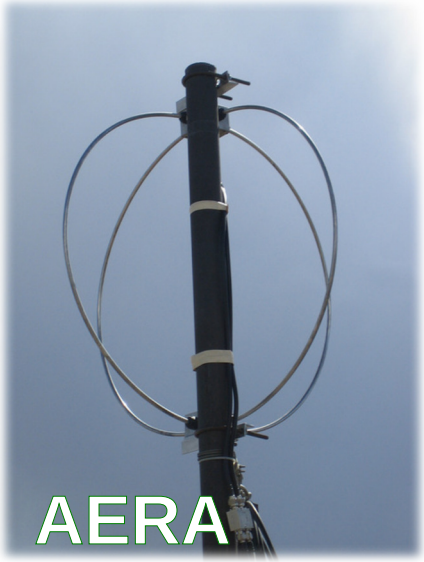


PoSICRC2019)214 + PoS(ICRC2019)411

Upgrade components

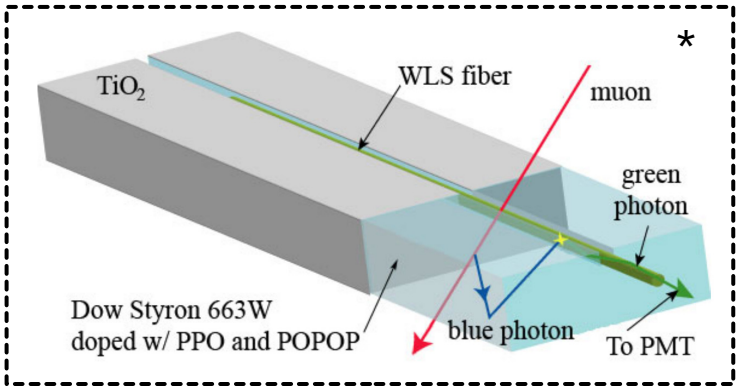


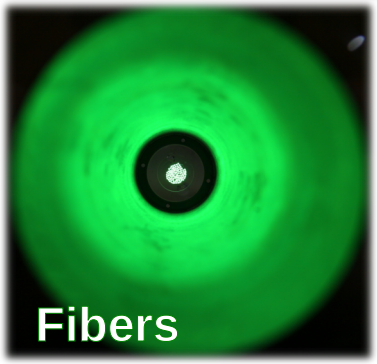
- **New electronics for the WCD:**
  + resolution, **sample time** and **dynamic range.**
- **+ *duty cycle*** del **FD** (de **15 %** hasta **30 %**)**.**
- Scintillator Surface Detector (**SSD**) over each **WCD** (**1500 m**).
- Underground Muon Detector (**UMD-AMIGA**) close to each **WCD** (**750** and **433 m**).
- Auger Engineering Radio Array **(AERA) over *each* WCD** (**1500 m**).



Scintillator Surface Detector (SSD)

- **3.8 m²** scintillator
- **48** scintillator strips **+** WLS optical fiber
- PMT
- **Aluminium** casing

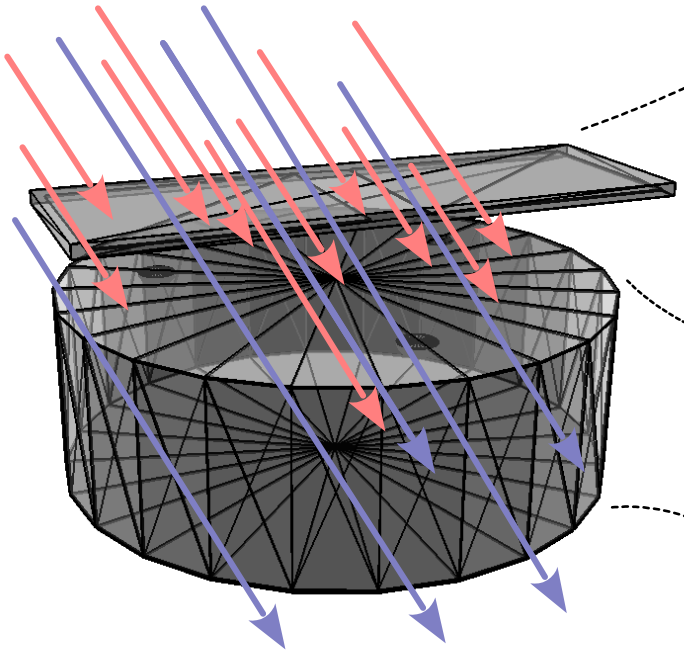


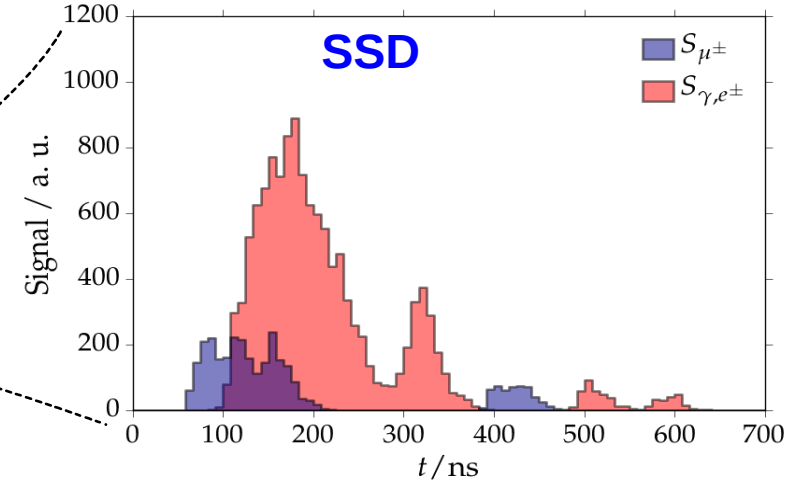


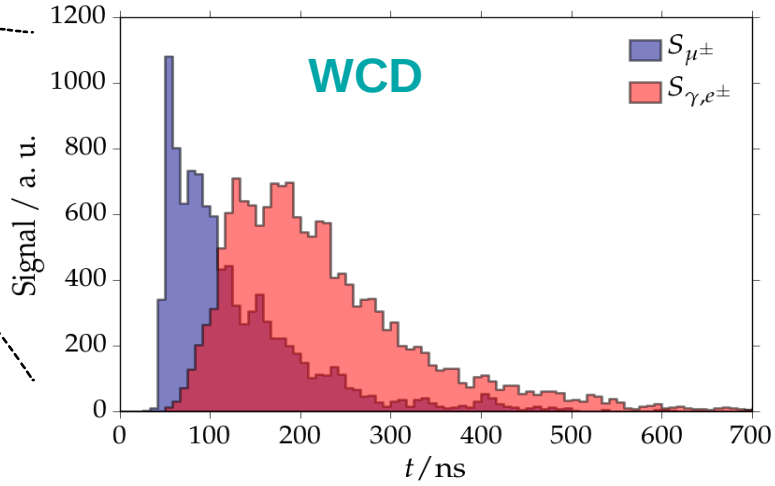
* JINST 6 (2011) P06006

Scintillator Surface Detector (SSD)

- **Complementary response** between **SSD** and **WCD.**
- **Electromagnetic** and **muon separation.**



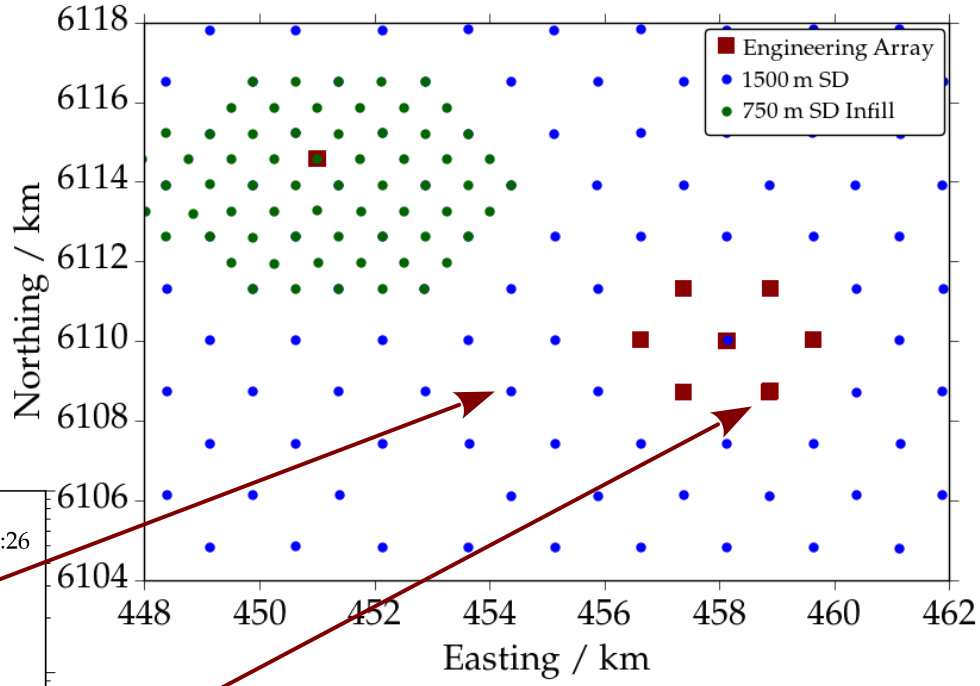


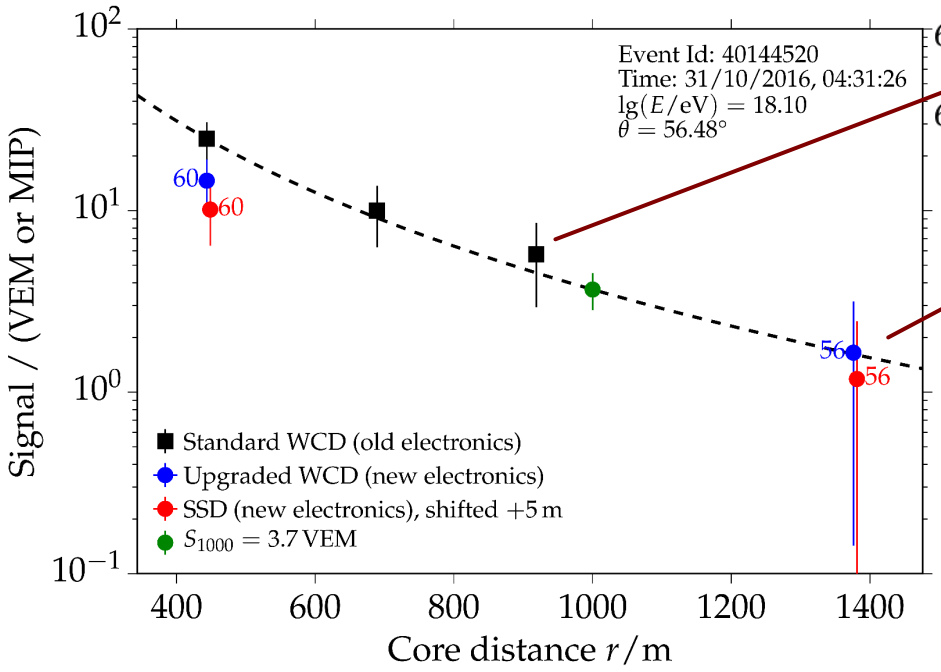


$$S_{\mu,\mathrm{WCD}} = \mathrm{a}S_{\mathrm{WCD}} + \mathrm{b}S_{\mathrm{SSD}}$$
$$S_{\mathrm{em},\mathrm{WCD}} = \mathrm{c}S_{\mathrm{WCD}} + \mathrm{d}S_{\mathrm{SSD}}$$

First engineering array data (SSD)

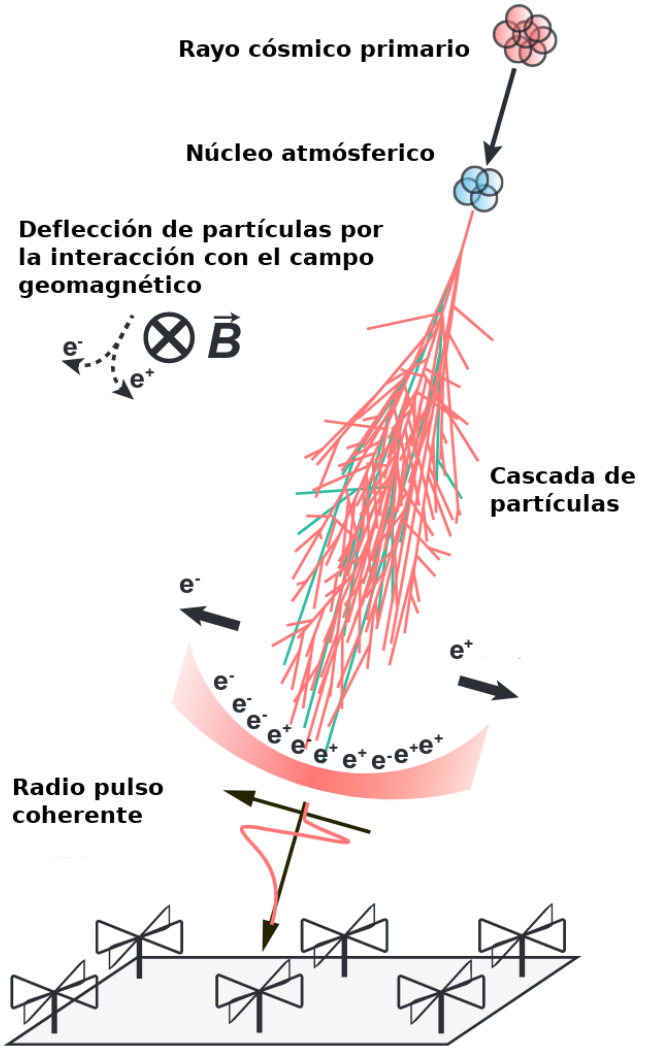
12 SSDs in engineering array.
Adquisition since **October 2016.**

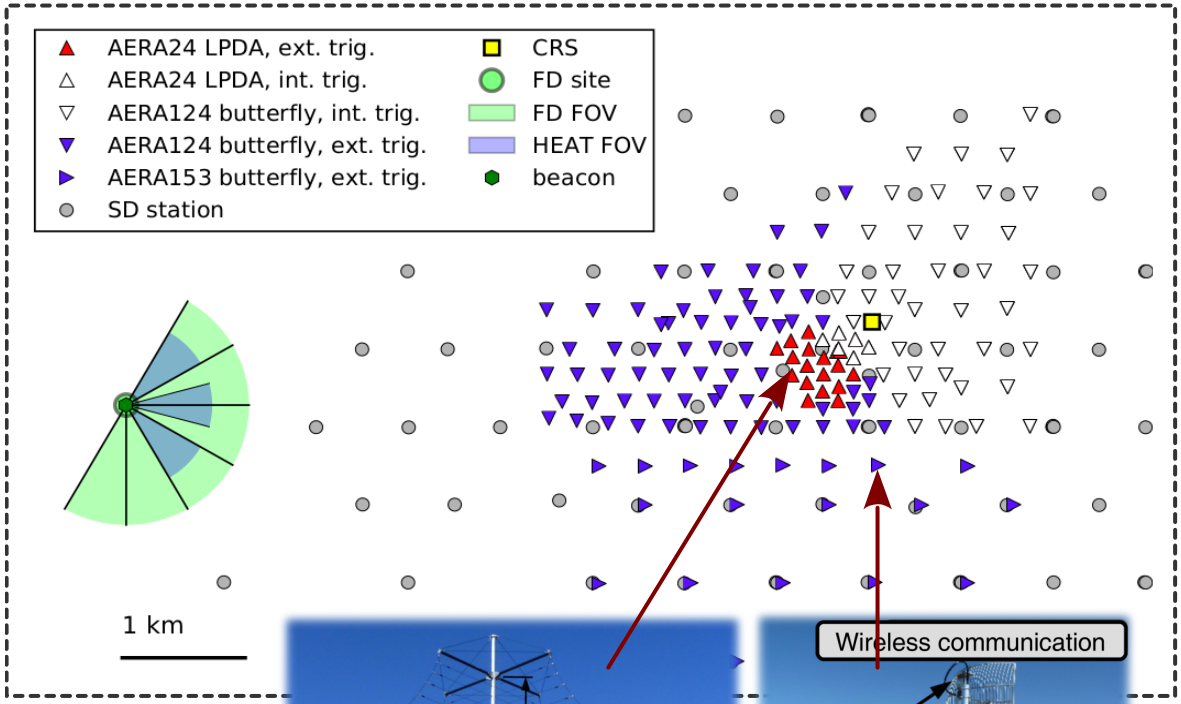


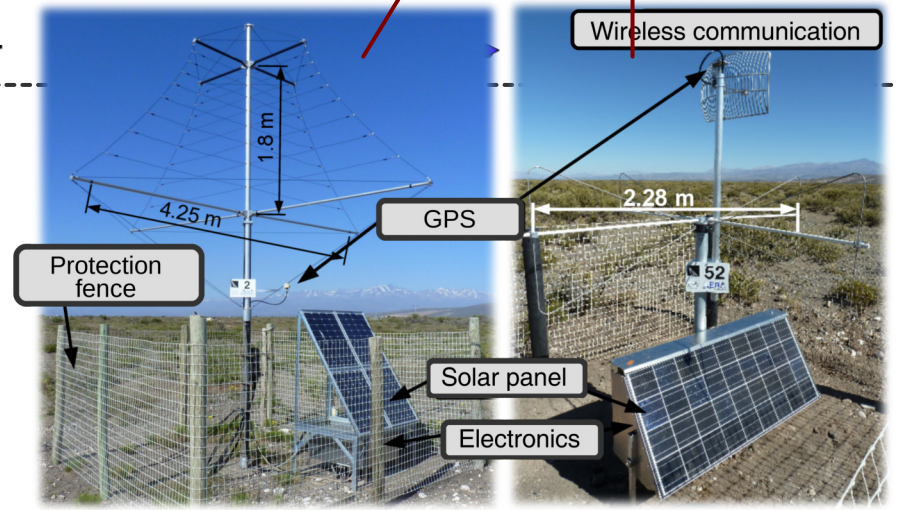


Reconstruction of Lateral Distribution Functions (**LDFs**) with **SSDs** y **WCDs.**

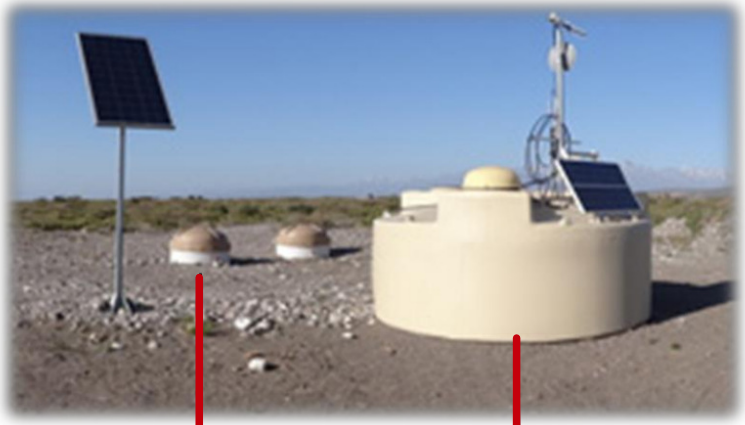
Auger Engiennering Radio Array (AERA)

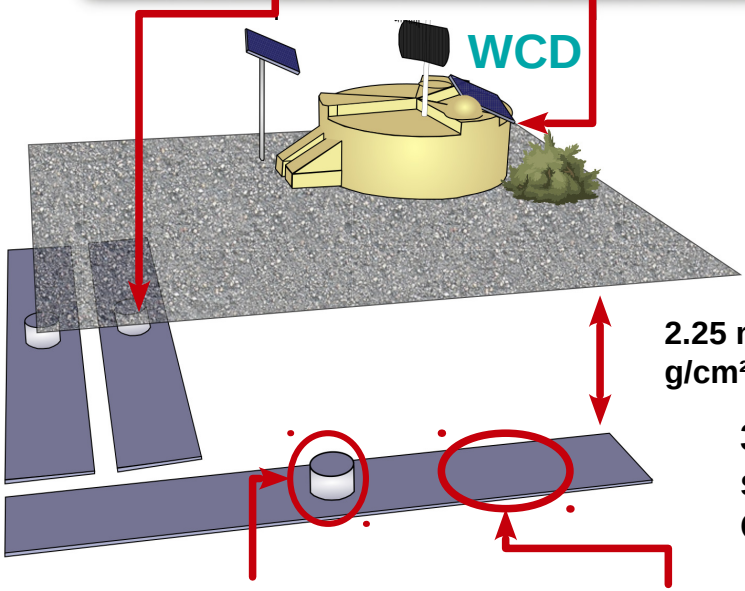






Underground Muon detector (UMD-AMIGA)





Infill

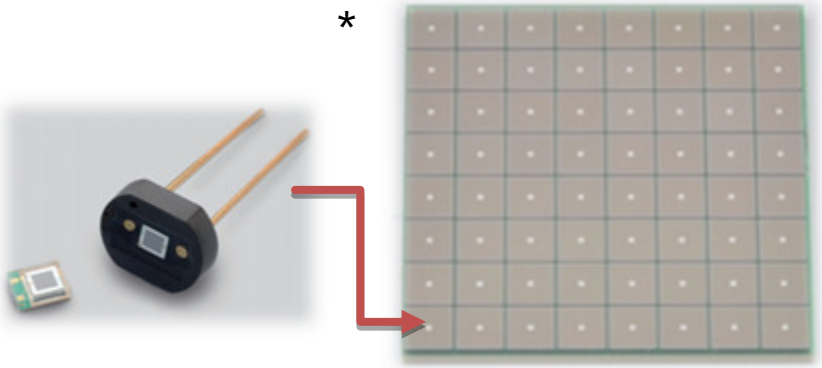
- 61 WCD
- SD 750 m

- SD 433 m

Underground Muon Detector (UMD-AMIGA)

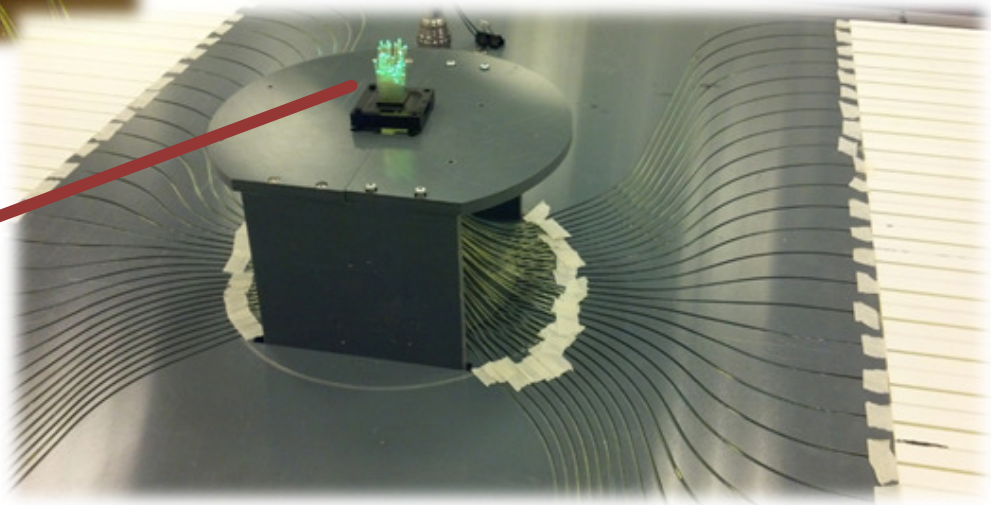
64 scintillator strips

*



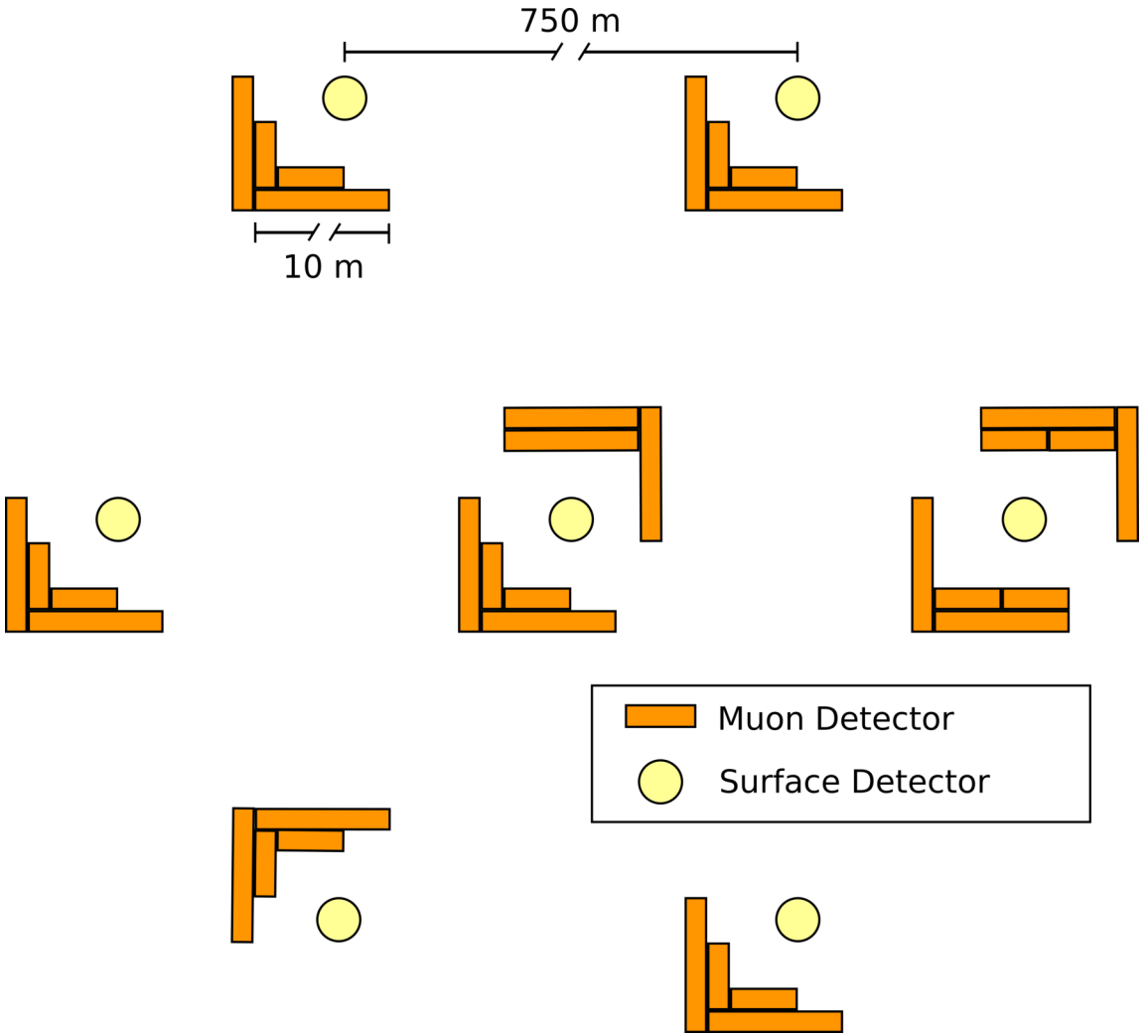
8x8 array of silicon photomultipliers (SiPM).

WLS optical fiber

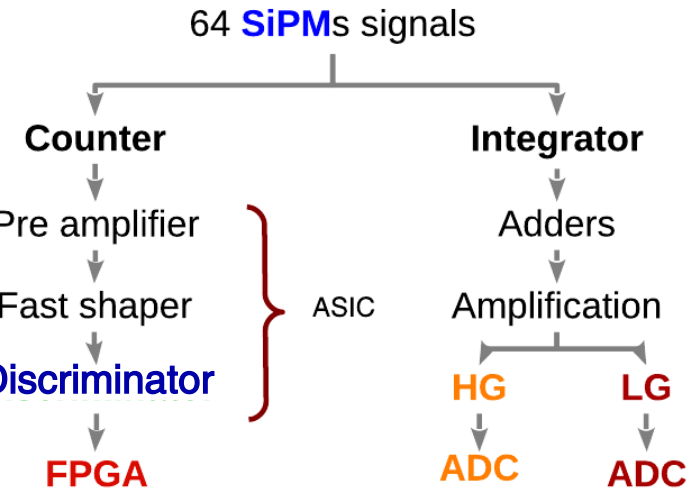


* Picture from Hamamatsu MPPC array S13361-3050NE-08

AMIGA Engineering array



UMD-AMIGA Electronics

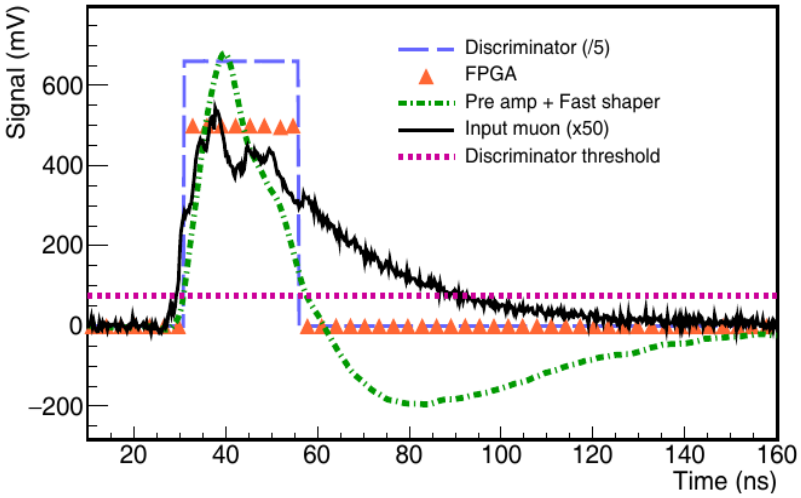


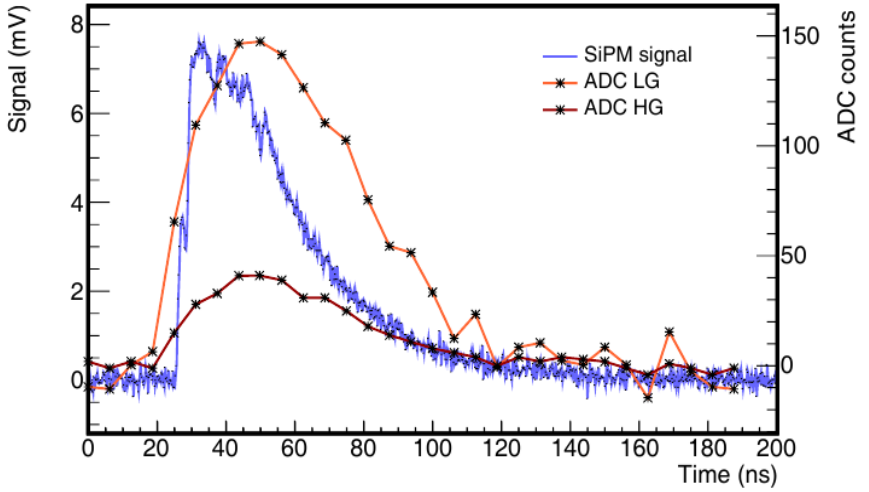
Low muon densities

High muon densities

64x 2048 bit @ 3.125ns

2x 1024 samples @ 6.25ns



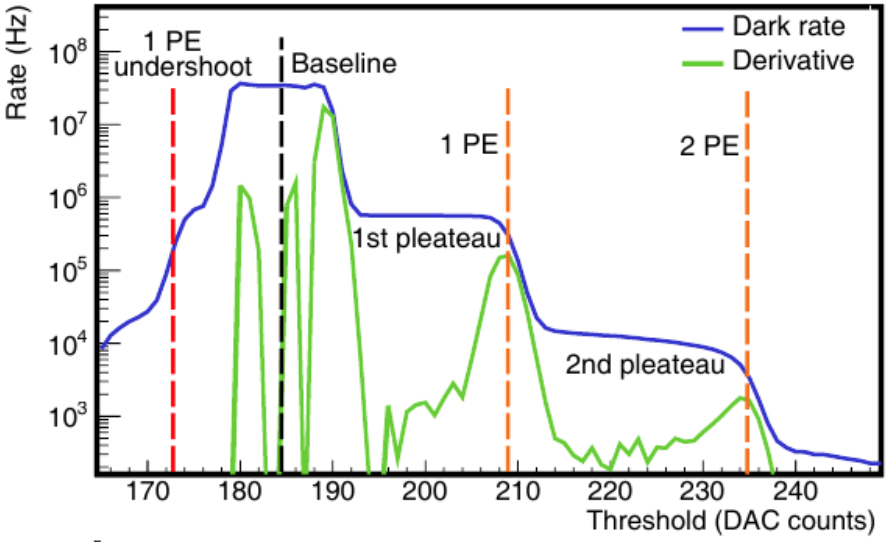


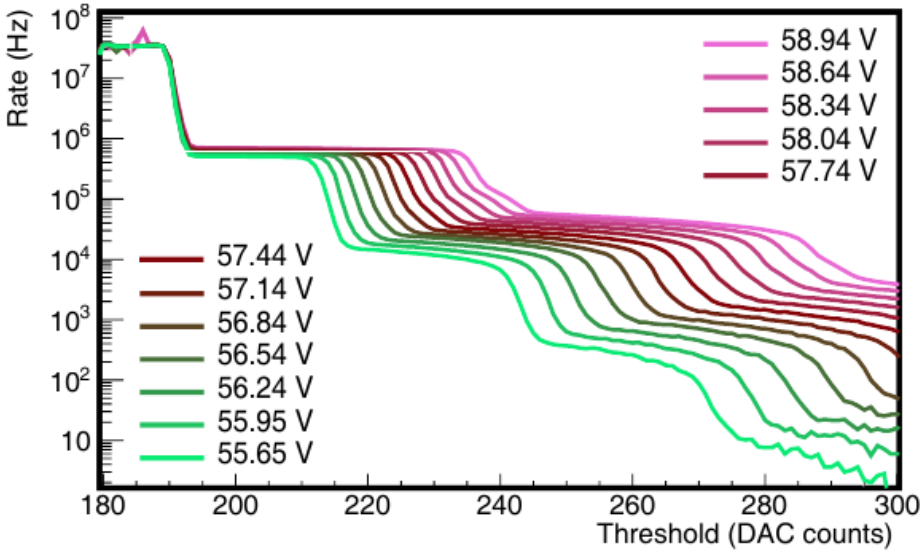
PoS(icrc2019)202

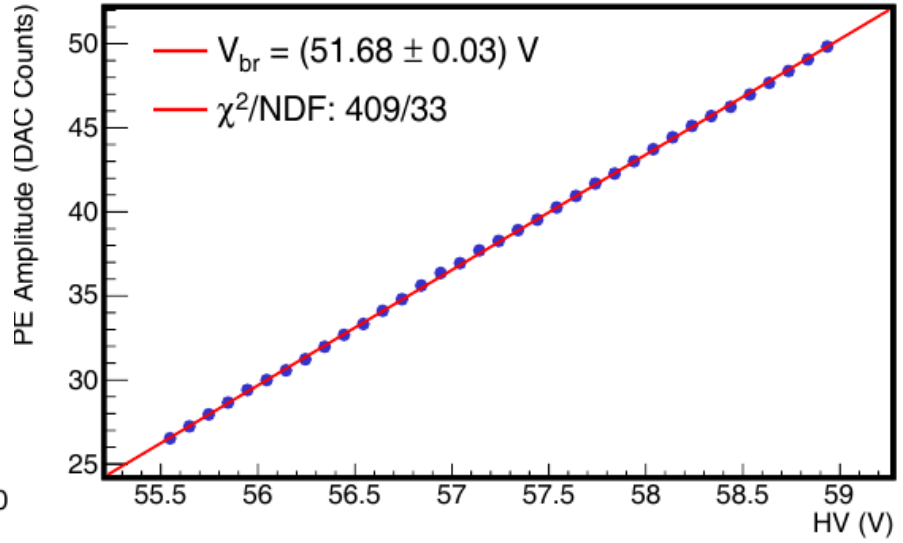
SiPM Calibration

Goal: obtain **breakdown voltage, V_{br},** (minimum voltage to operate in Geiger mode).

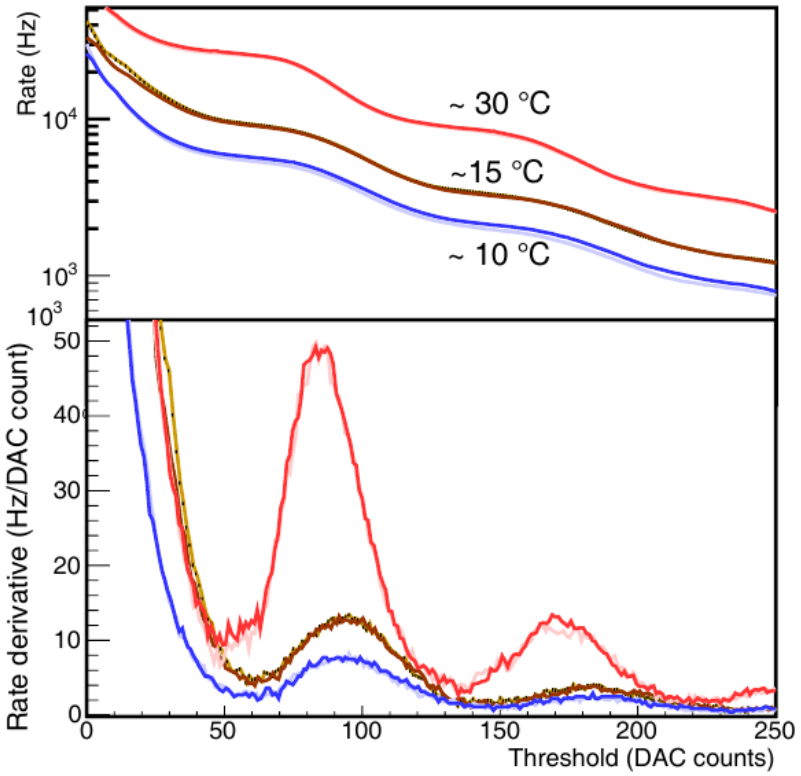
SiPM gain ~ **HV - V_{br}**

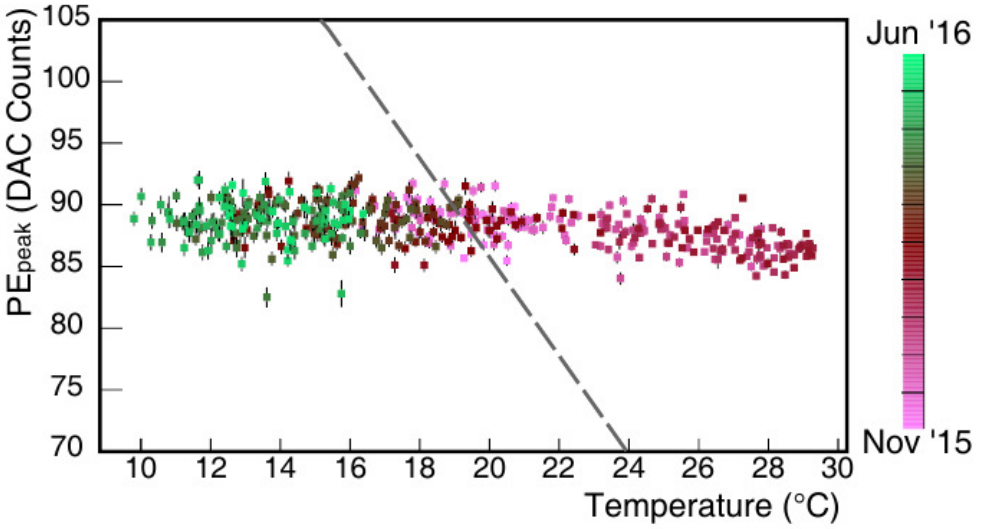


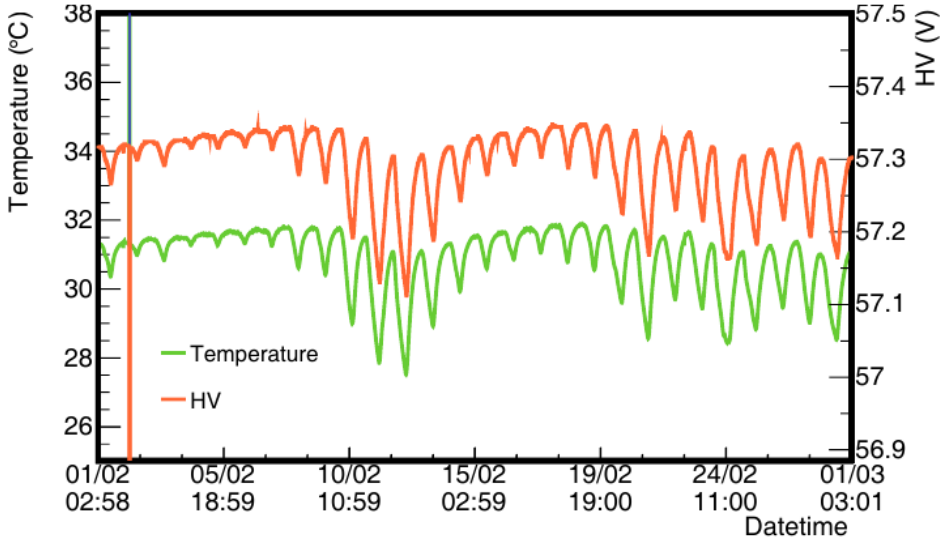




SiPM Temperature dependance







Breakdown voltage depends on Temperature.

HV compensation.

Noise sources (per channel)

...111111111000000000000000011000...

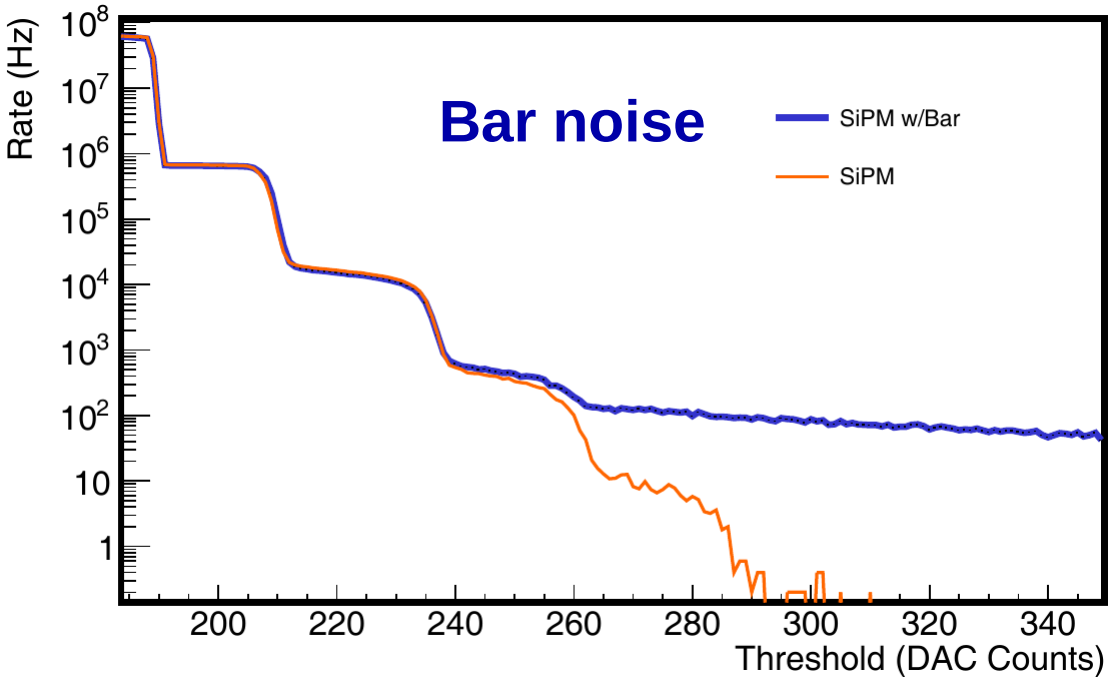
Muon signal **Noise**

Dark rate:
(460 - 630) kHz

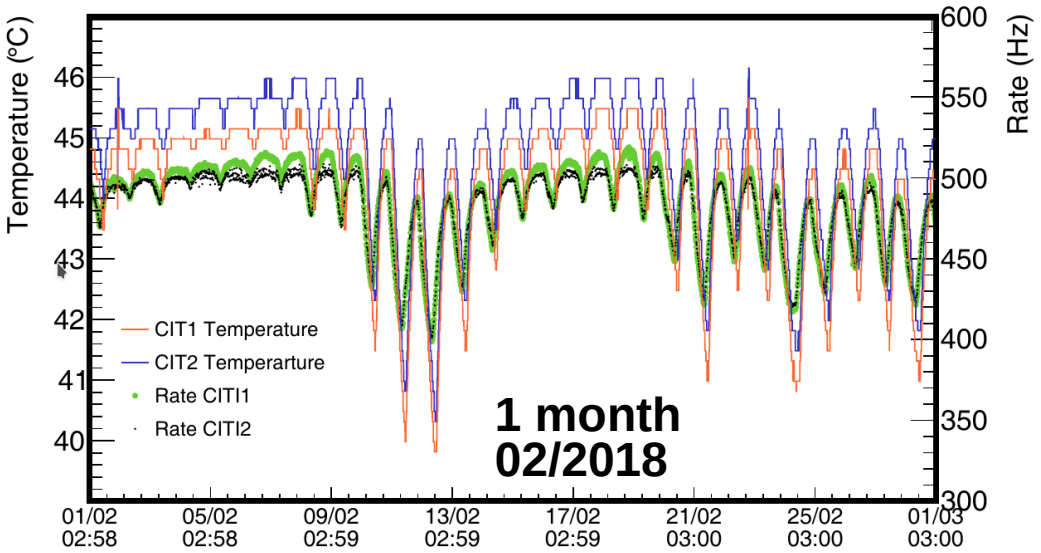
Cross-talk:
(1.5 – 2.2) %

SiPM noise > 3 PE:
(103 - 305) Hz

SiPM noise > 4 PE:
(2 – 8) Hz



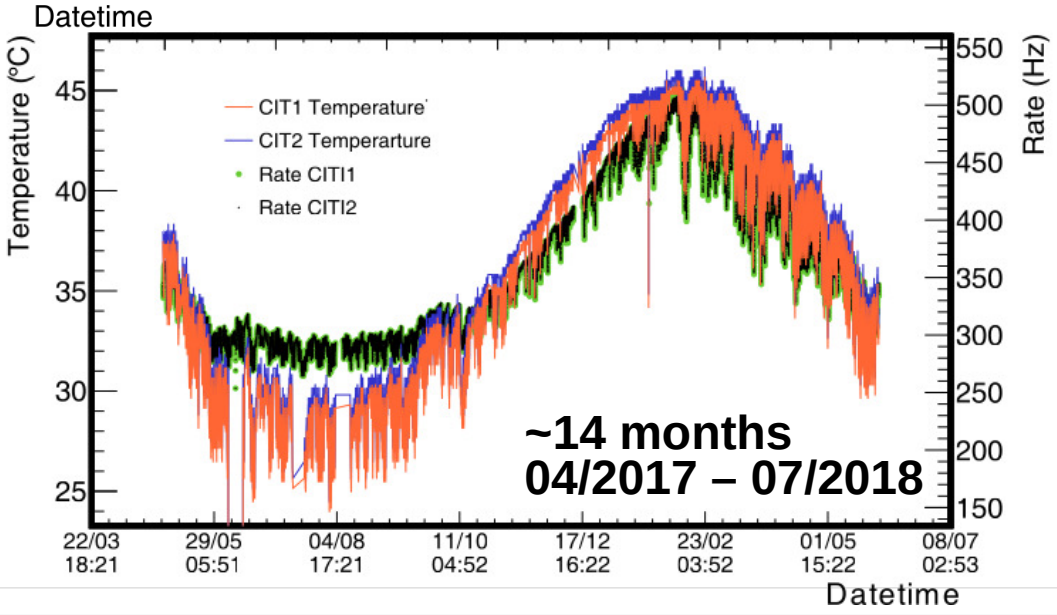
Noise in the field



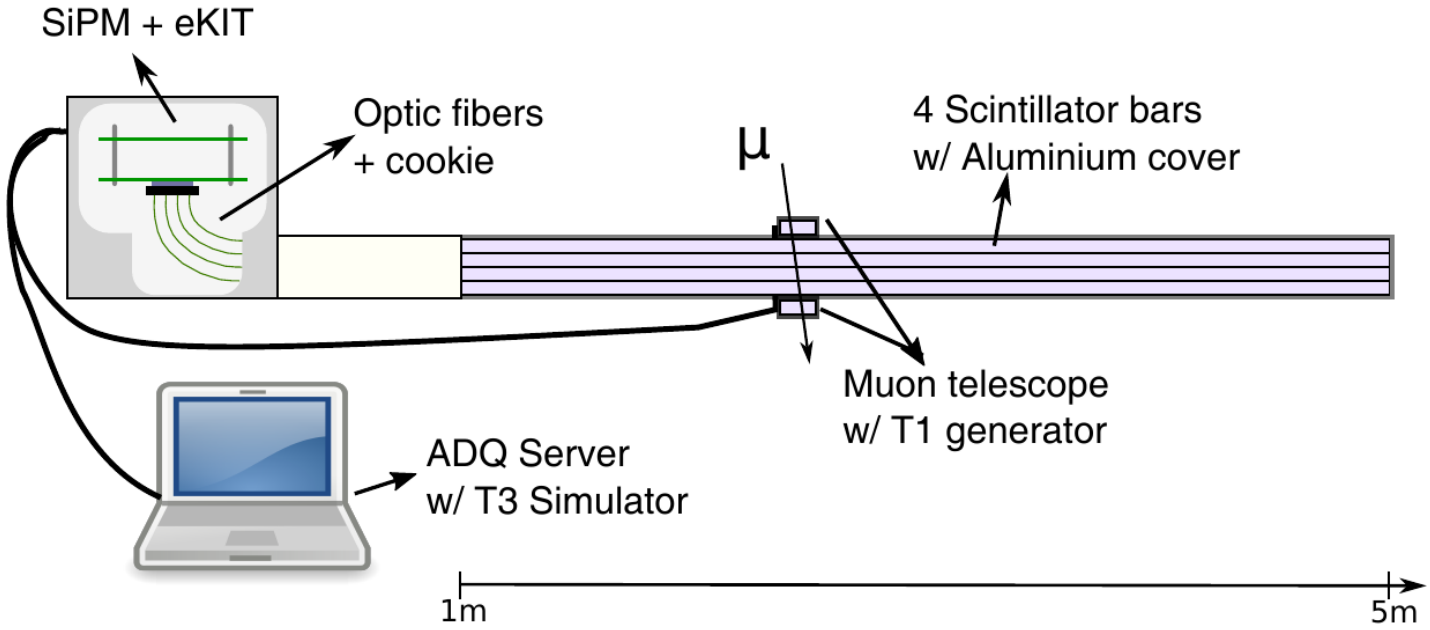
Monitoring data:

- Threshold @ **2.5 PE**
- Pattern **1x**
- **6.4 µs** trace

(10-20) % probability of over-counting 1 muon in 1 event per module (In the lab: **14.6%**). It can be reduced to **5.5 %** with **1111x** pattern.



Binary traces in lab setup

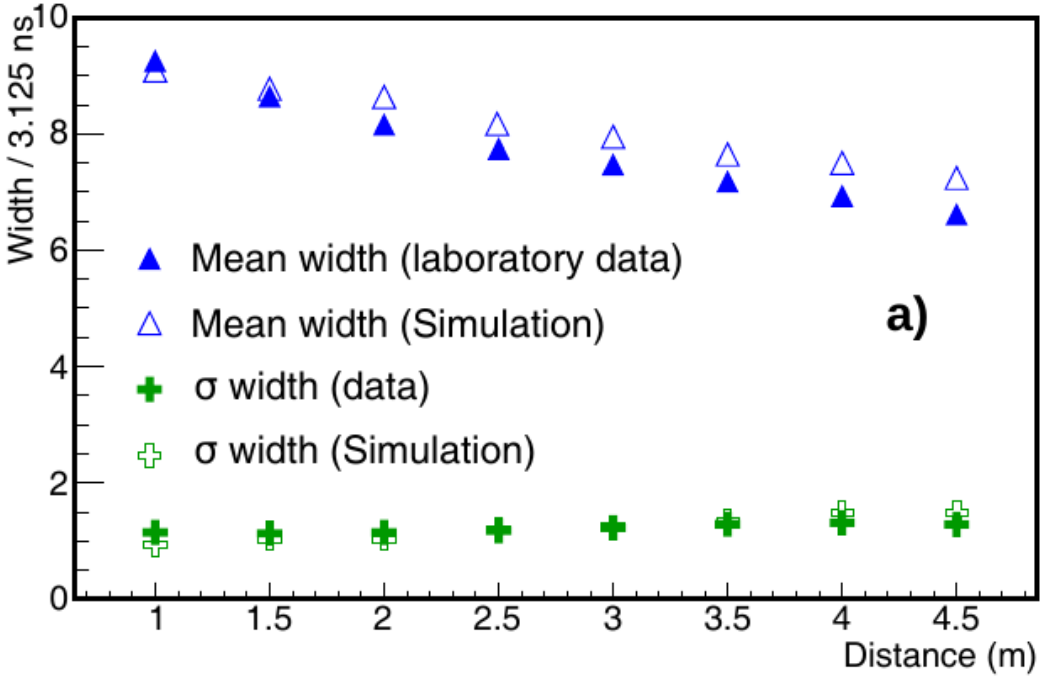


Time

Samples

63	58	23	18	Channels
1438	0	1	1	==> (3) 63 23 18
1439	1	1	1	==> (4) 63 58 23 18
1440	1	1	1	==> (4) 63 58 23 18
1441	1	1	1	==> (4) 63 58 23 18
1442	1	1	1	==> (4) 63 58 23 18
1443	1	1	1	==> (4) 63 58 23 18
1444	1	1	1	==> (4) 63 58 23 18
1445	1	1	1	==> (4) 63 58 23 18
1446	0	1	1	==> (3) 63 58 18
1447	0	0	1	==> (2) 63 18

Muon counting and noise rejection



000**1111111**00000 ✔

1 Muon

b)

11111111111100 ✔

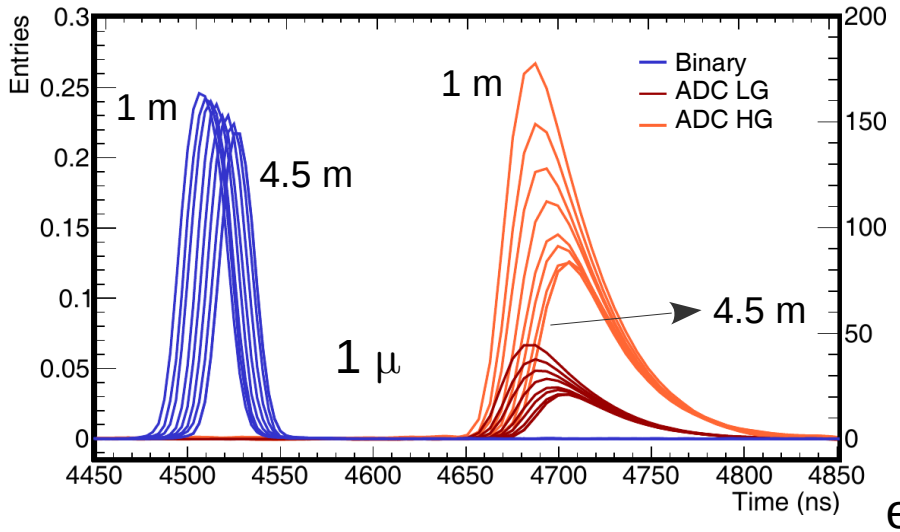
1 Muon

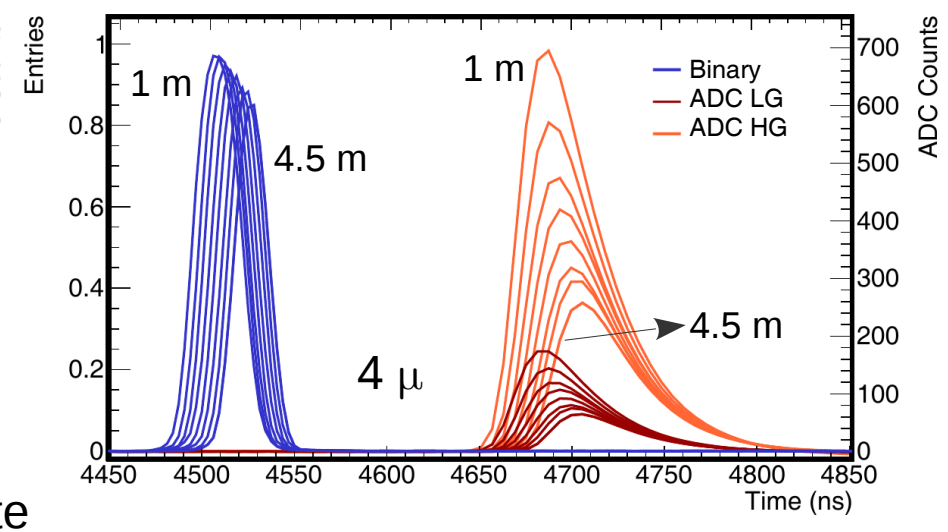
0000**11**0000000000 ✗

noise

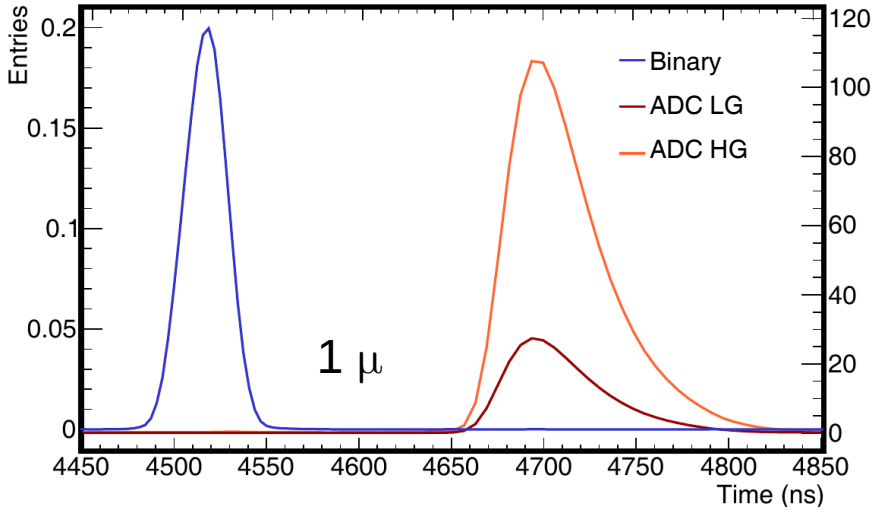
Muon signal width: μ = **24.4 ns** and σ = **4.3 ns.**
3 photon-equivalent (PE) dark rate: < **12.5 ns.**
Strategy: a **muon** has between **4** and **12** positive samples.
Counting strategy → reduces background by a factor of **~2.7**.

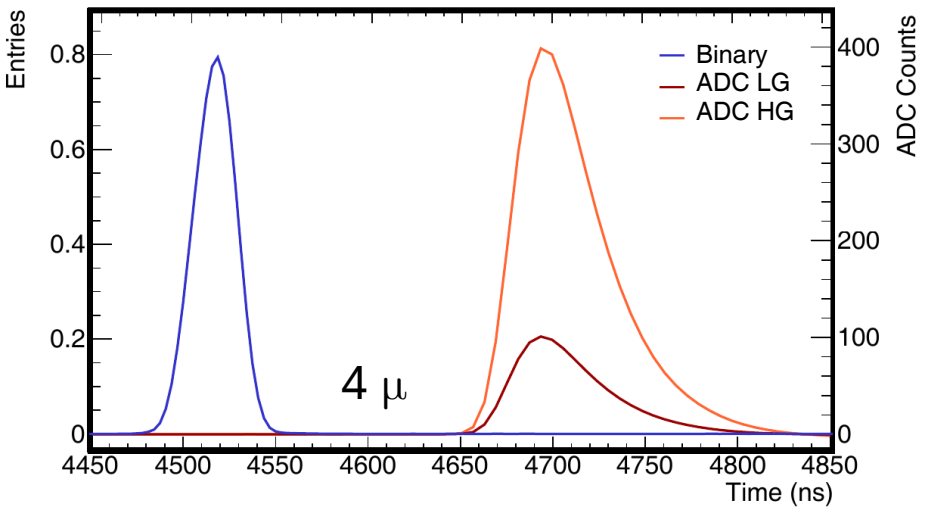
Binary/ADC traces



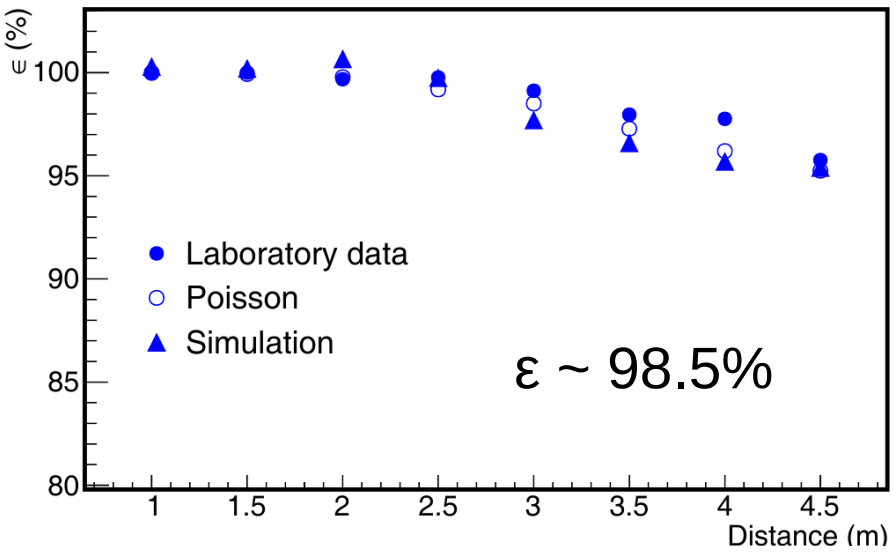


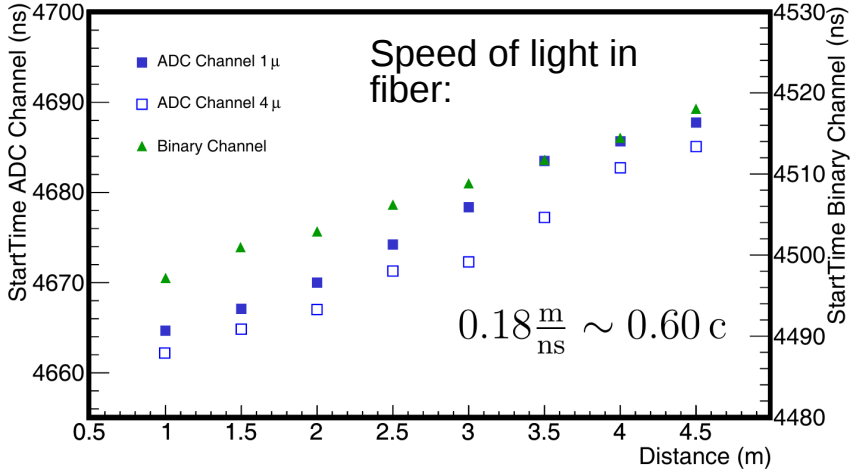
ete

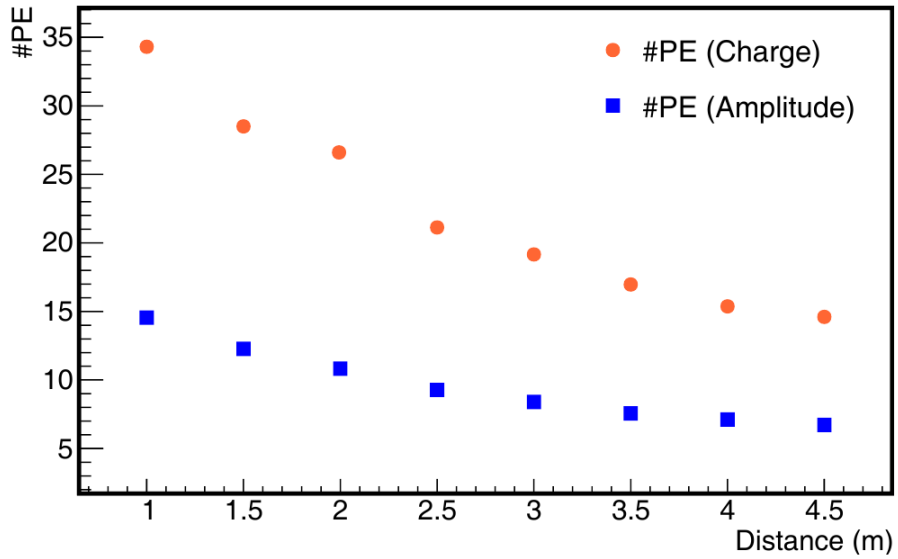


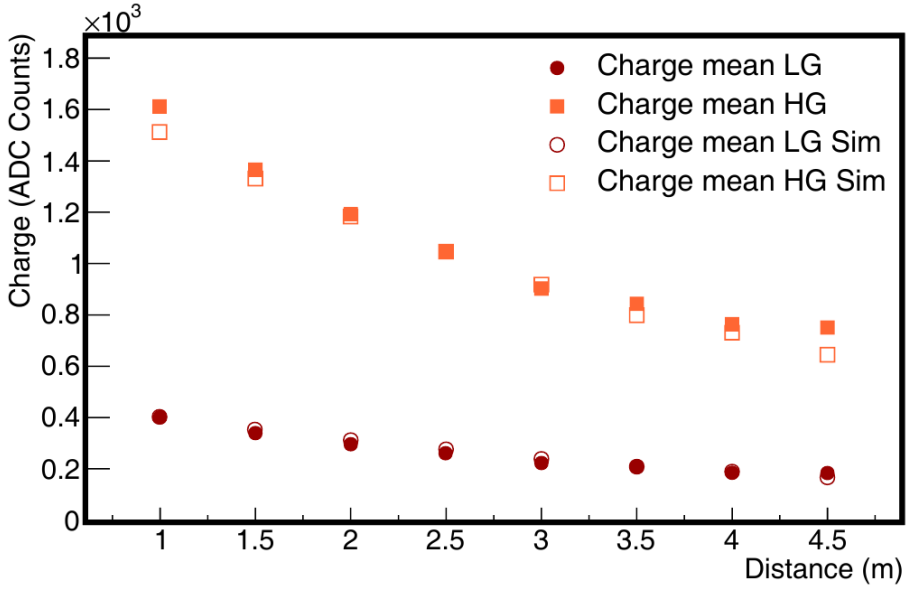


Efficency and attenuation



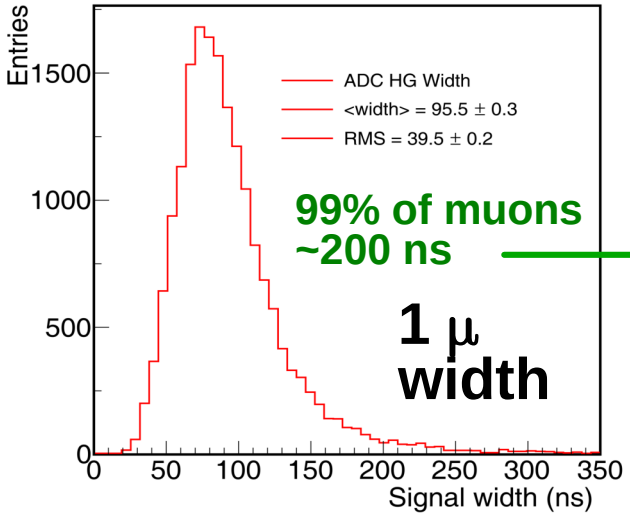






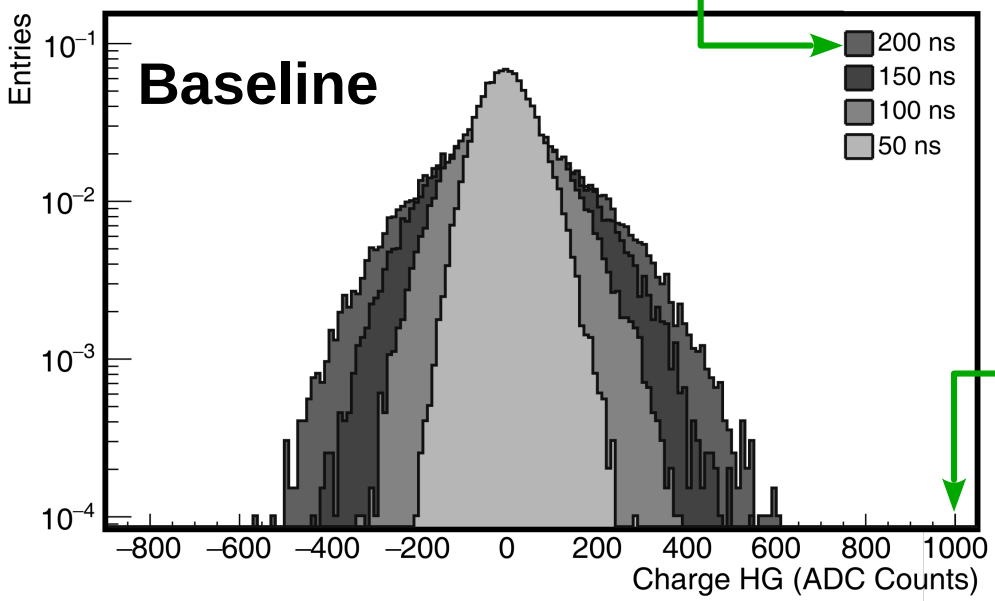
PoS(icrc2019)202

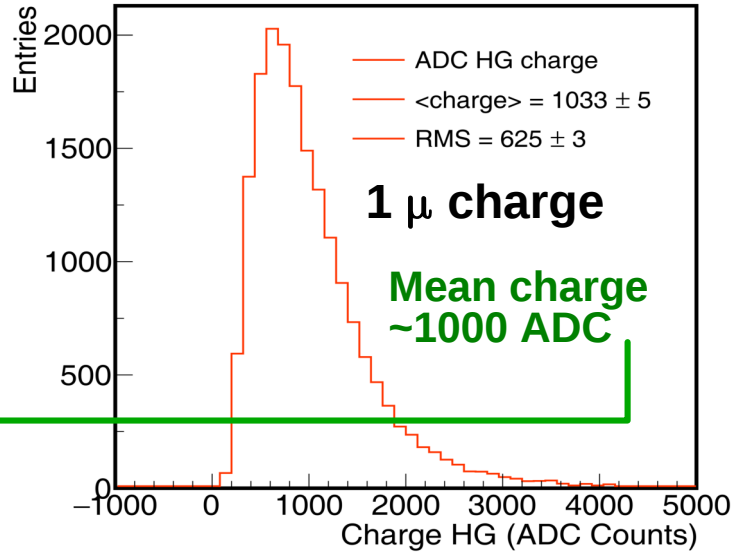
Muon ADC signal in LAB*



MIP separated from baseline.

In **LAB**, events triggered with background muons.





*GAP2019_016

ADC calibration in the field

Online calibration using background data?

- Muon detector triggered with **WCD T1** (**mostly** background muons).
- **T1** events in muon detector **mostly** baseline.
- **T1**s are not stored (data sent on **T3** request).

➔ Station **93** (Corrientes), module **101**. Out of acquisition since **24-08-2018**.

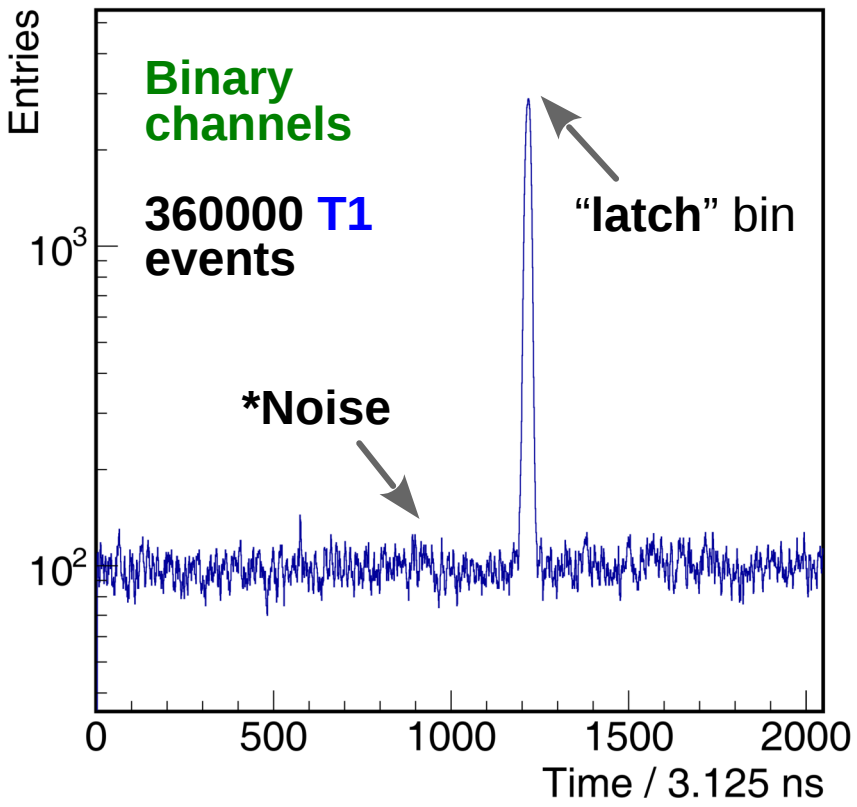
➔ Stores one **T1** event per second (**1 Hz**).

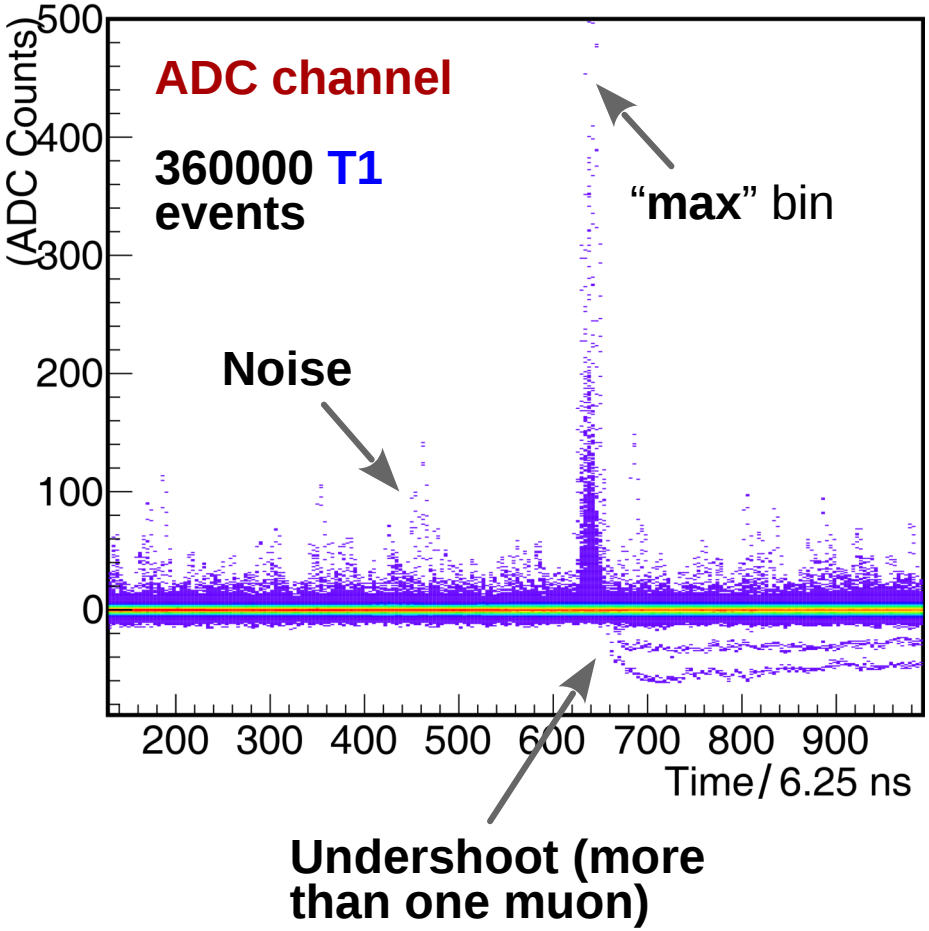
➔ Data set: **360000** events ≡ 1 hour of all **T1**s (**100 Hz**).

➔ Use **binary channel** to separate signal from noise in **ADC**.

* AMIGA with SiPMs: calibration and efficiency. Auger Collaboration Meeting Nov, 2017.

T1 Binary/ADC traces



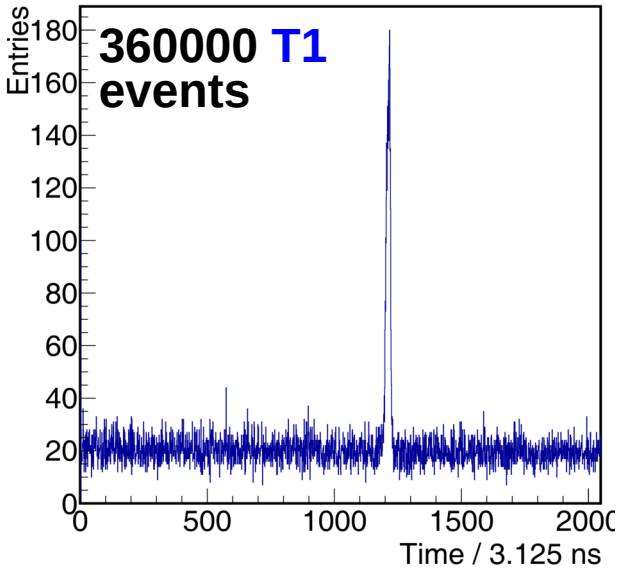


Note time shift between **binary** and **ADC** signal.

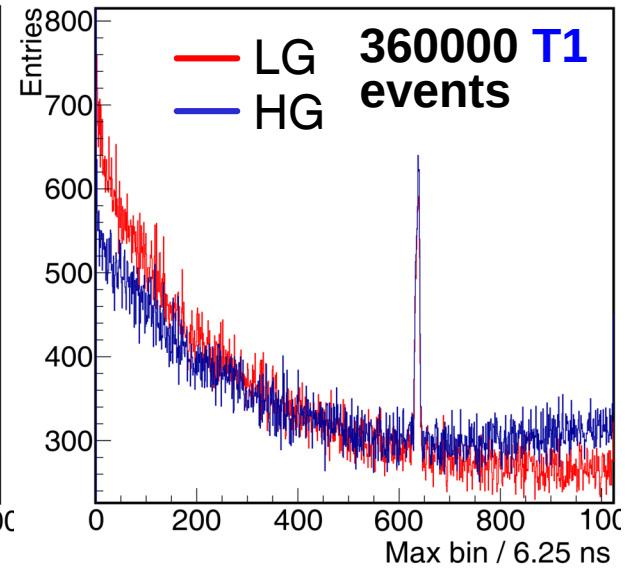
*GAP2018_049

T1 Binary/ADC time shift

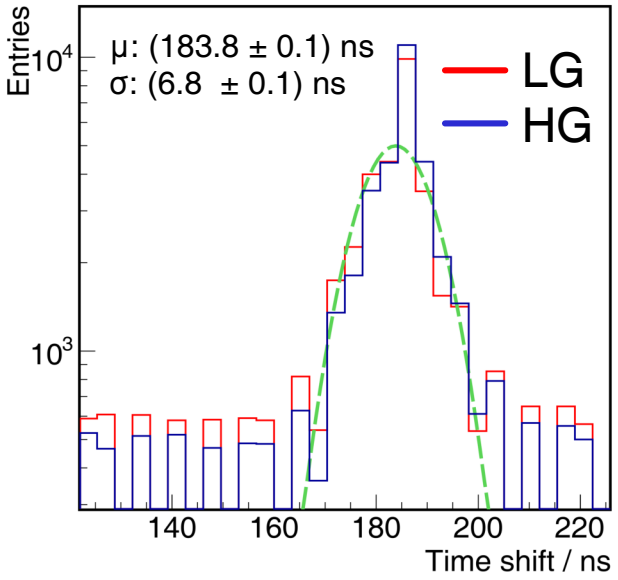
Binary channels
star time (1st one in trace):



ADC channel
maximum signal bin:



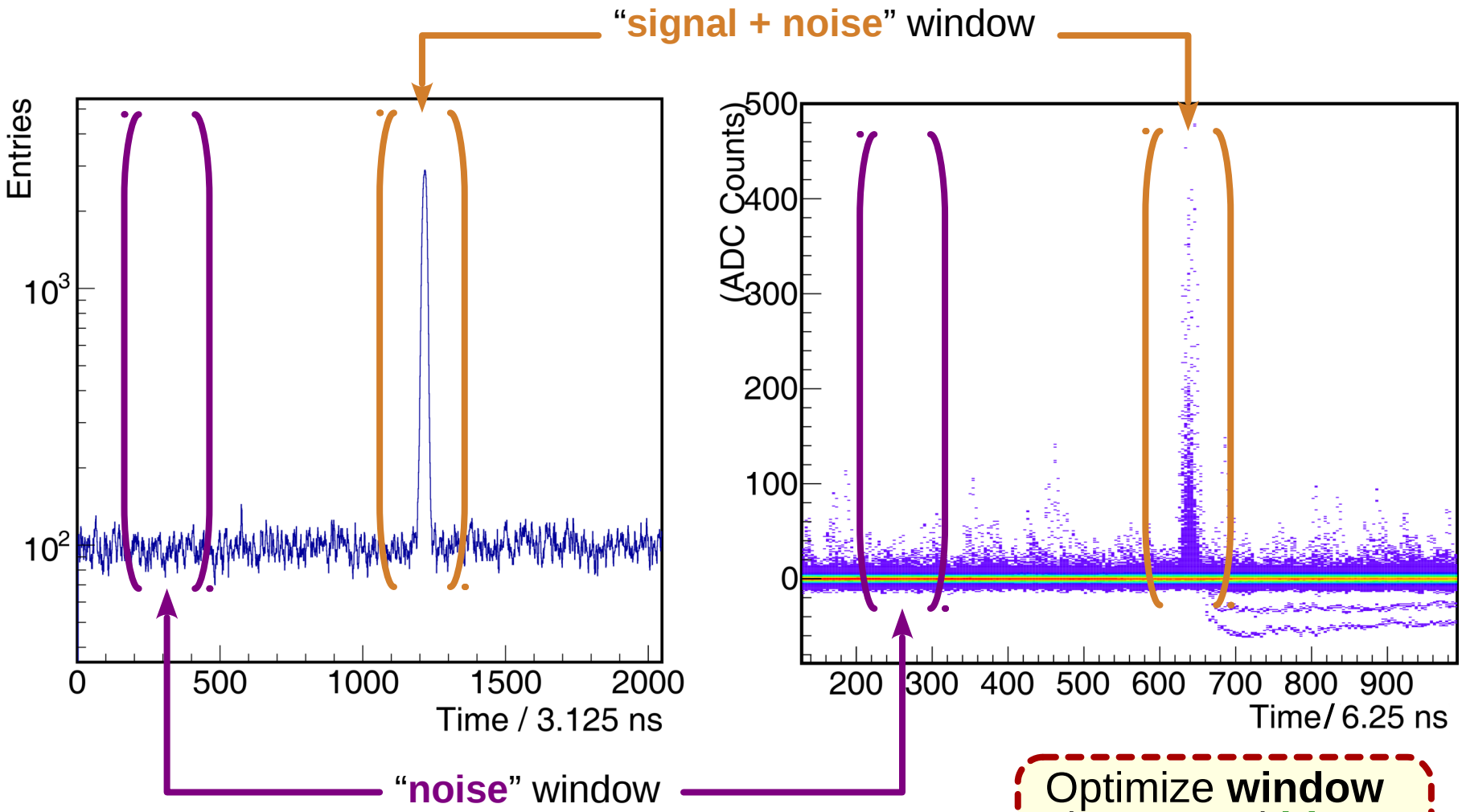
Time shift:



Signal **cuts** (1 muon→lab data) :

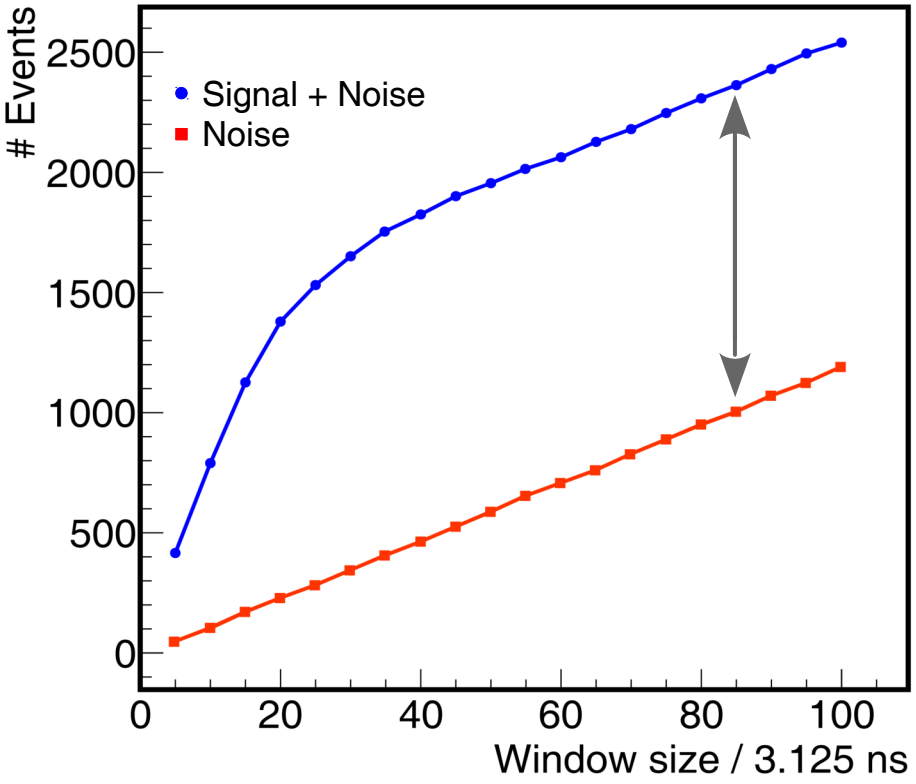
- **1111x** pattern.
- **< 12** positive samples.
- **1 channel on**.

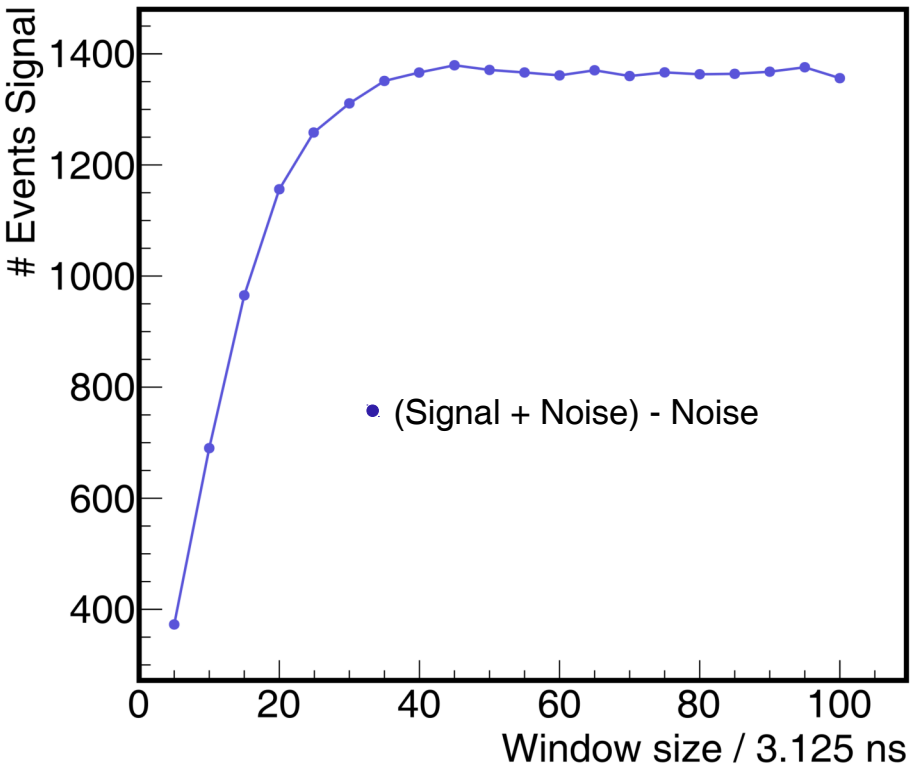
T1 Binary/ADC traces



Optimize **window** size around **binary** latch.

T1 number of events

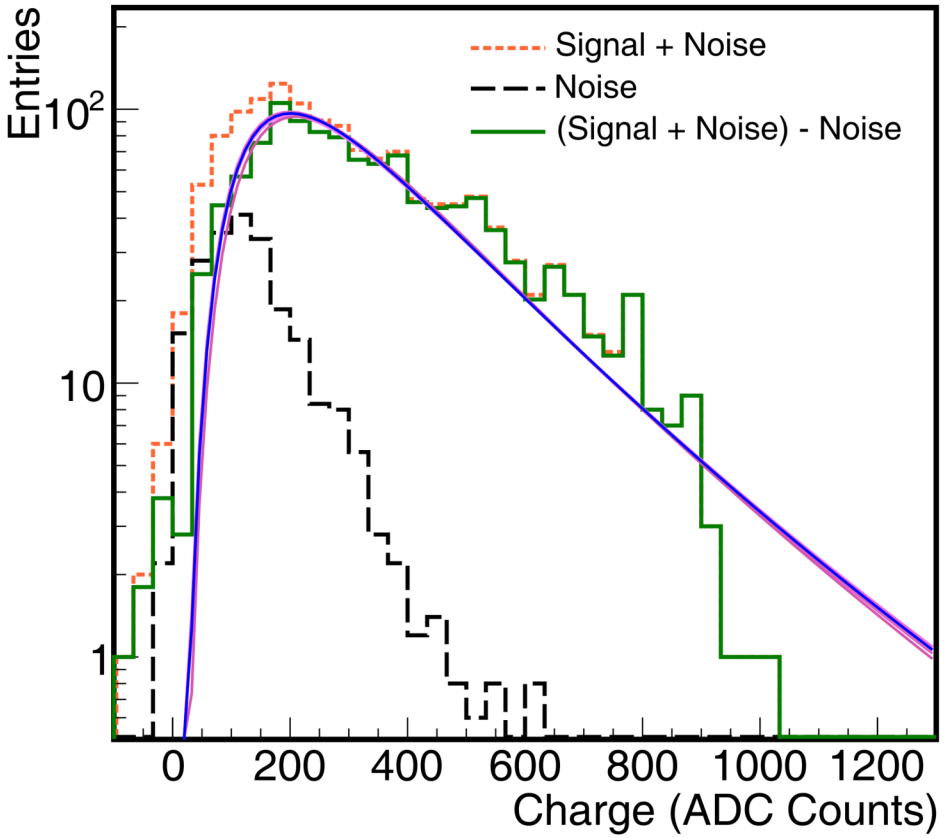




~40 bin window contains all signal events

T1 calibration histograms

20-bin window



Calibration histogram **built** from **T1** data.

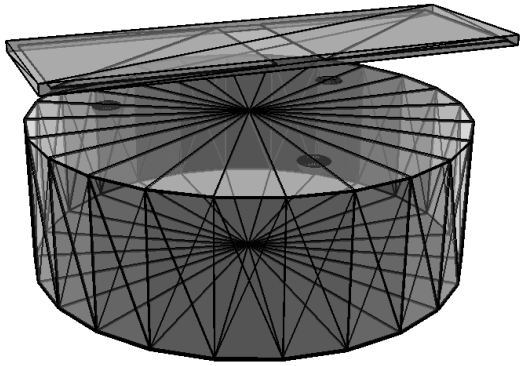
Lognormal fit.

Mean: (358 ± 7) ADC Counts

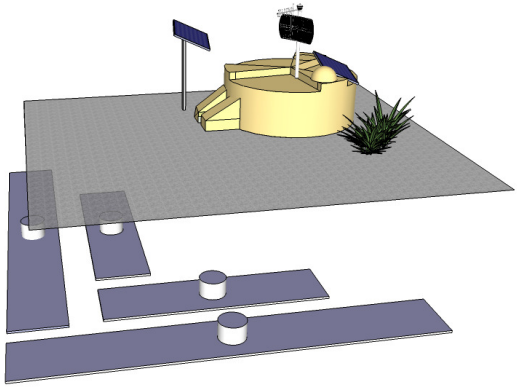
Conclusion

New detectors ⟶ improve **mass discrimination**

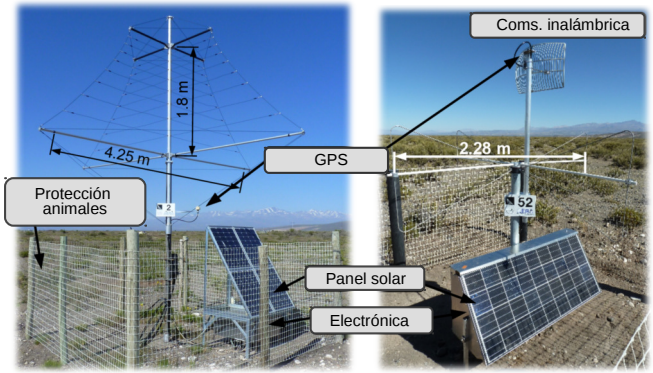
SSD (μ, em)



UMD-AMIGA (μ)



AERA (em)



Increse **FD duty cycle** ⟶ + X_{max} **statistics**

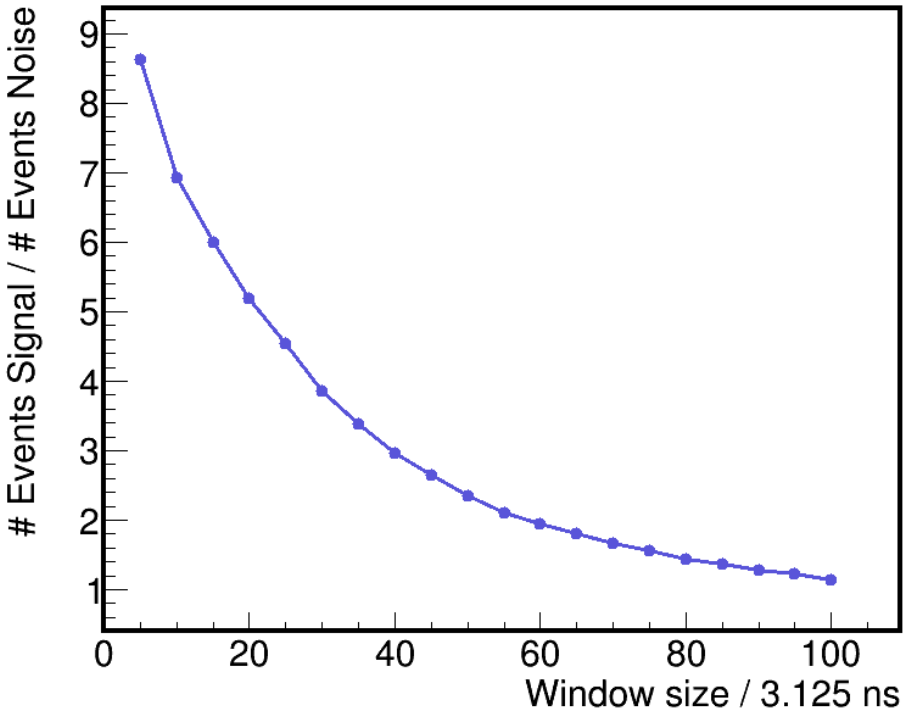
New **electronics WCD** ⟶ + sampling speed**, resolution and dynamic range.**

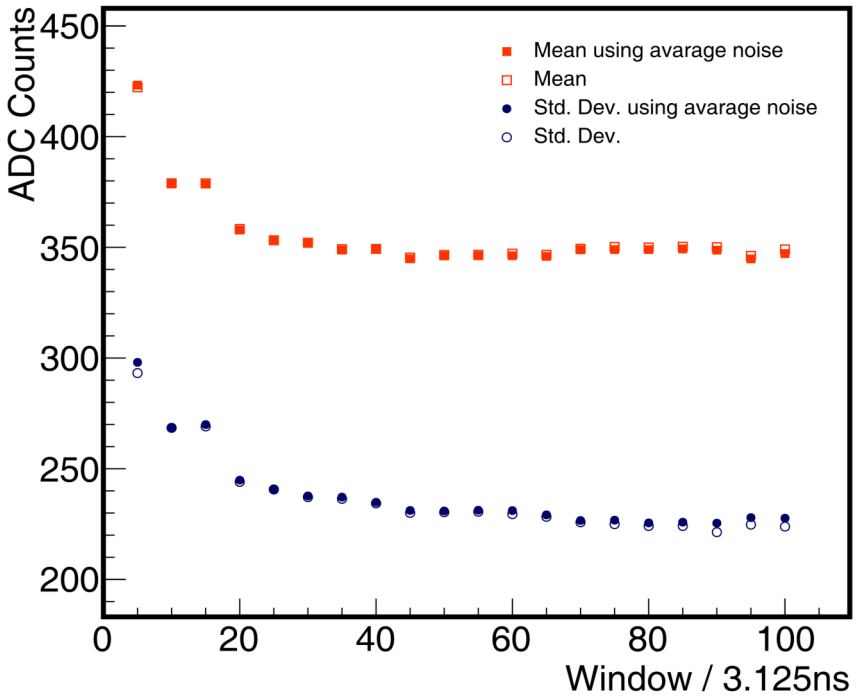
Conclusions

- Fully characterized **binary** and **ADC** traces.
- **SiPM** caibration achieved.
- Temperature compensation working.
- Muon counting strategy to reduce background.
- **ADC** calibration with **T1** possible (already implemented in electronics!).
- **Online** calibration every **hour** could be achieved.
- Compatible with **offline** calibration with **T3**.
- **Consistent** for different matching **patterns**.
- **Stable** in current range (**24-08-2018** to **02-03-2019**).

BKP

T1 Signal / Noise



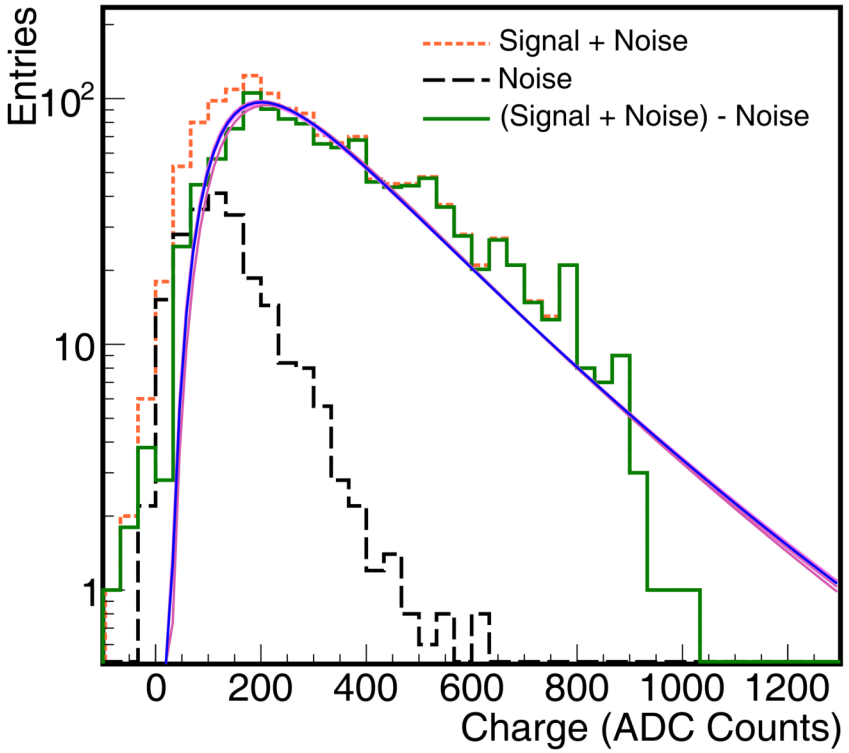


Mean stable @
~ **20 bins**

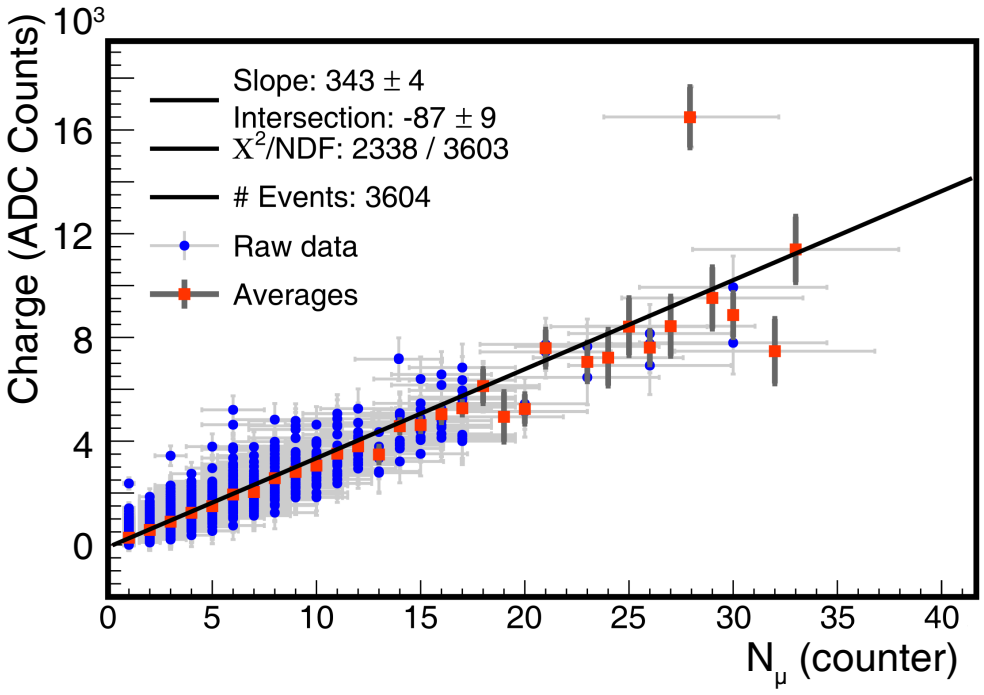
T1 vs T3 calibration

T1/T3 calibrations **consistent**

20-bin window



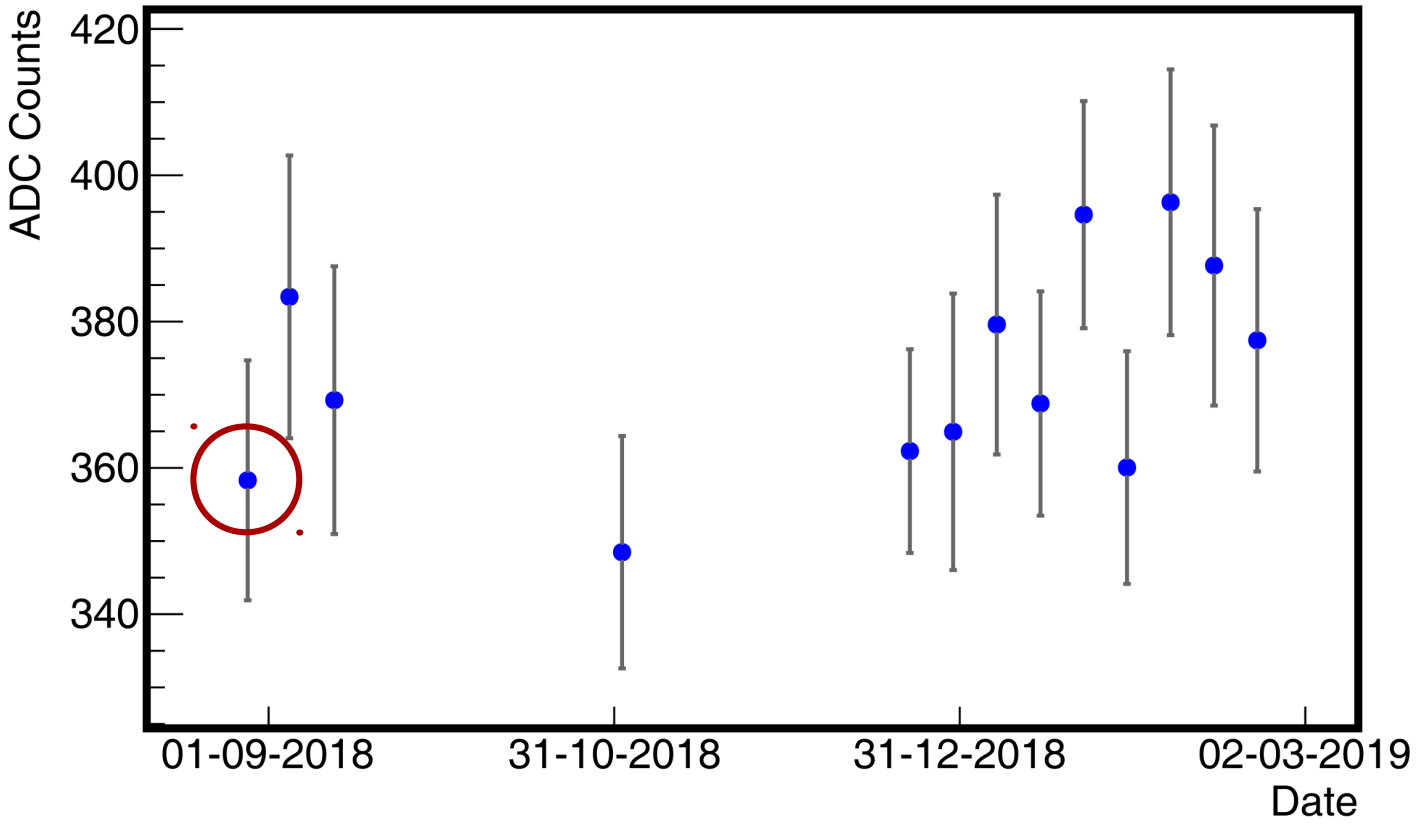
Offline calibration with **T3** events



T1 muon mean: (358 ± 7) ADC Counts

T3 muon mean: (343 ± 4) ADC Counts

Long term monitoring and stability



Mean: 373
RMS: 14

< 4% fluctuation in this range.

BKP

Ana Martina Botti – ana.botti@iteda.cnea.gov.ar

$$E^{\gamma,e^\pm} = E^{\gamma,e^\pm}_{\text{ssd}} + E^{\gamma,e^\pm}_{\text{wcd}}$$

$$m = \frac{E^{\gamma,e^\pm}_{\text{ssd}}}{E^{\gamma,e^\pm}_{\text{ssd}} + E^{\gamma,e^\pm}_{\text{wcd}}}$$

$$E^{\mu^\pm} = E^{\mu^\pm}_{\text{ssd}} + E^{\mu^\pm}_{\text{wcd}}$$

$$n = \frac{E^{\mu^\pm}_{\text{ssd}}}{E^{\mu^\pm}_{\text{ssd}} + E^{\mu^\pm}_{\text{wcd}}}$$

$$\begin{pmatrix} E_{\text{ssd}} \\ E_{\text{wcd}} \end{pmatrix} = \begin{pmatrix} m & n \\ 1-m & 1-n \end{pmatrix} \begin{pmatrix} E^{\gamma,e^\pm} \\ E^{\mu^\pm} \end{pmatrix}$$

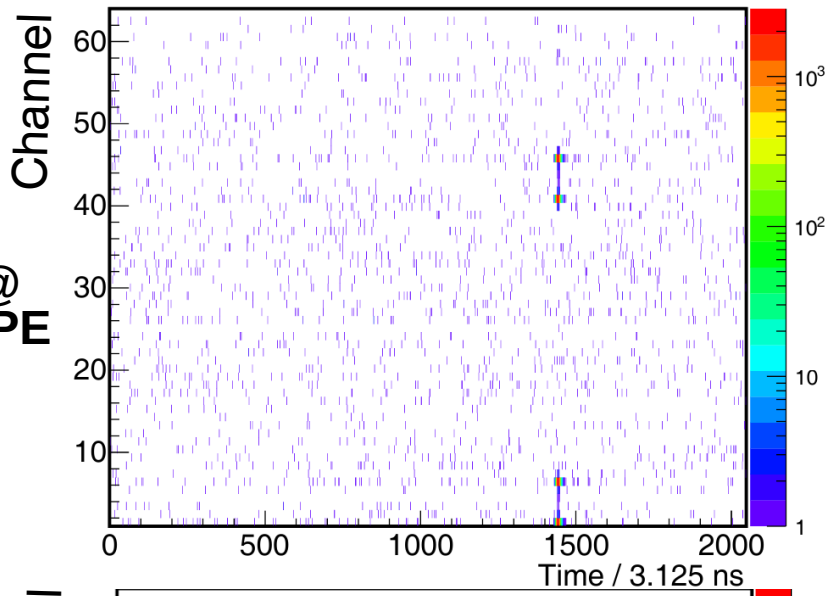
$$E^{\gamma,e^\pm}_{\text{wcd}} = \frac{1-m}{m-n}\left[(1-n)E_{\text{ssd}} - nE_{\text{wcd}}\right]$$

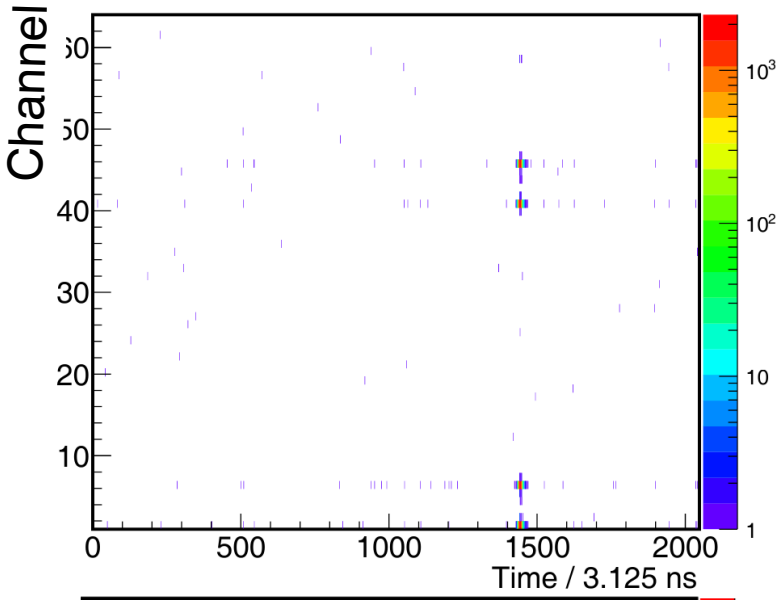
$$E^{\mu^\pm}_{\text{wcd}} = \frac{1-n}{m-n}\left[(m-1)E_{\text{ssd}} + mE_{\text{wcd}}\right]$$

D. Schmidt, Ph.D. Thesis

Counting strategy: patterns (1x, 111x, 1111x)

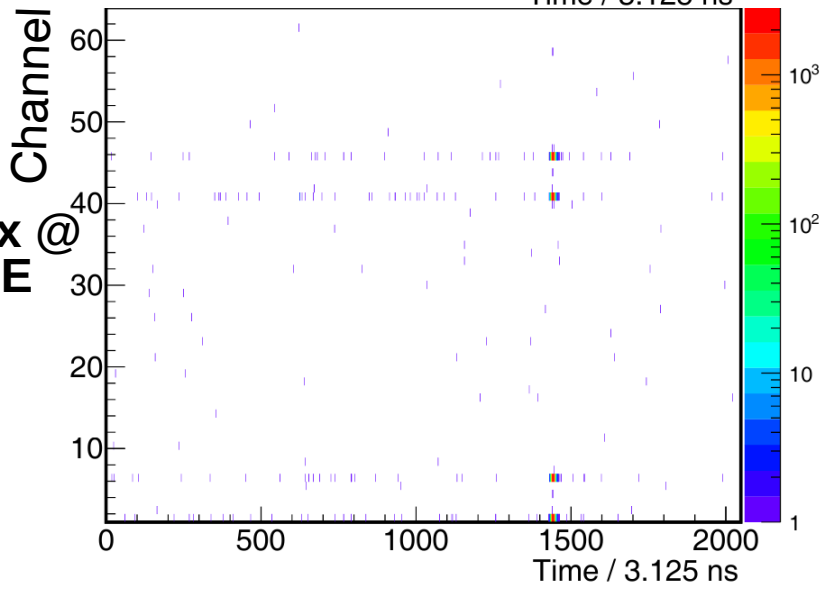
1x @ 2.5 PE

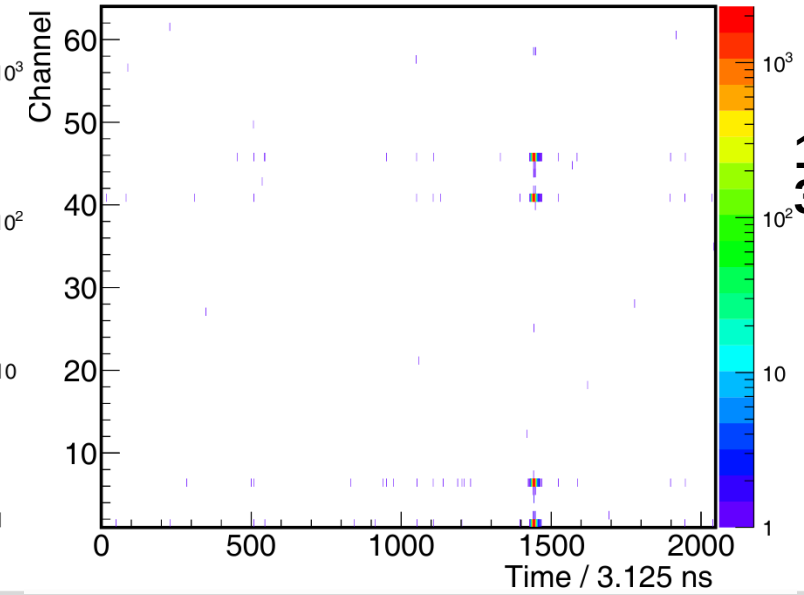




1x @ 3.5 PE

1111x @ 2.5 PE





111x @ 3.5 PE

$$N^{A}{}_{EM,max}(E_0) = AN^{p}{}_{EM,max}(E_0/A) \approx N^{p}{}_{EM,max}(E_0)$$

$$X^{A}{}_{max}(E_0) = X^{p}{}_{max}(E_0/A), \quad \text{and}$$

$$N^{A}{}_{\mu} = A\left(\frac{E_0/A}{E_{dec}}\right)^{\alpha} = A^{1-\alpha}N^{p}{}_{\mu}(E_0)$$