AugerPrime

The Pierre Auger Observatory Upgrade

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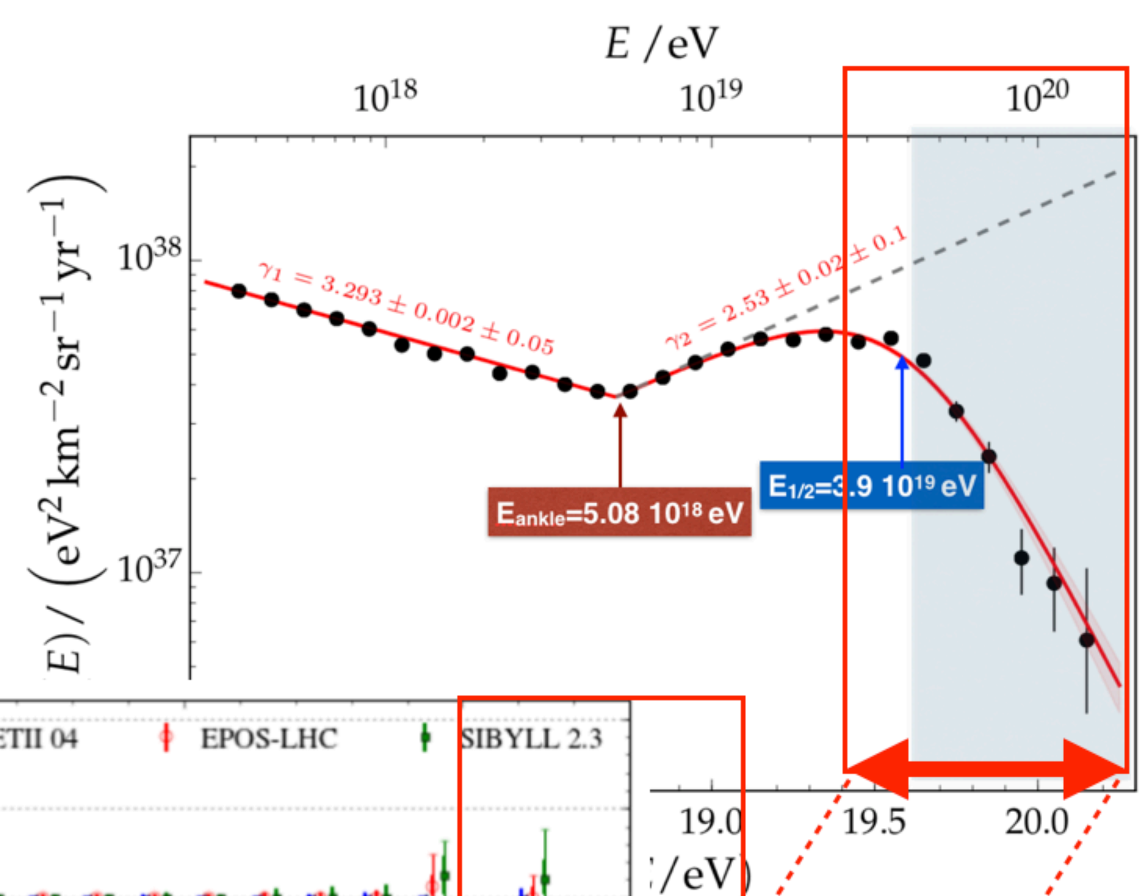
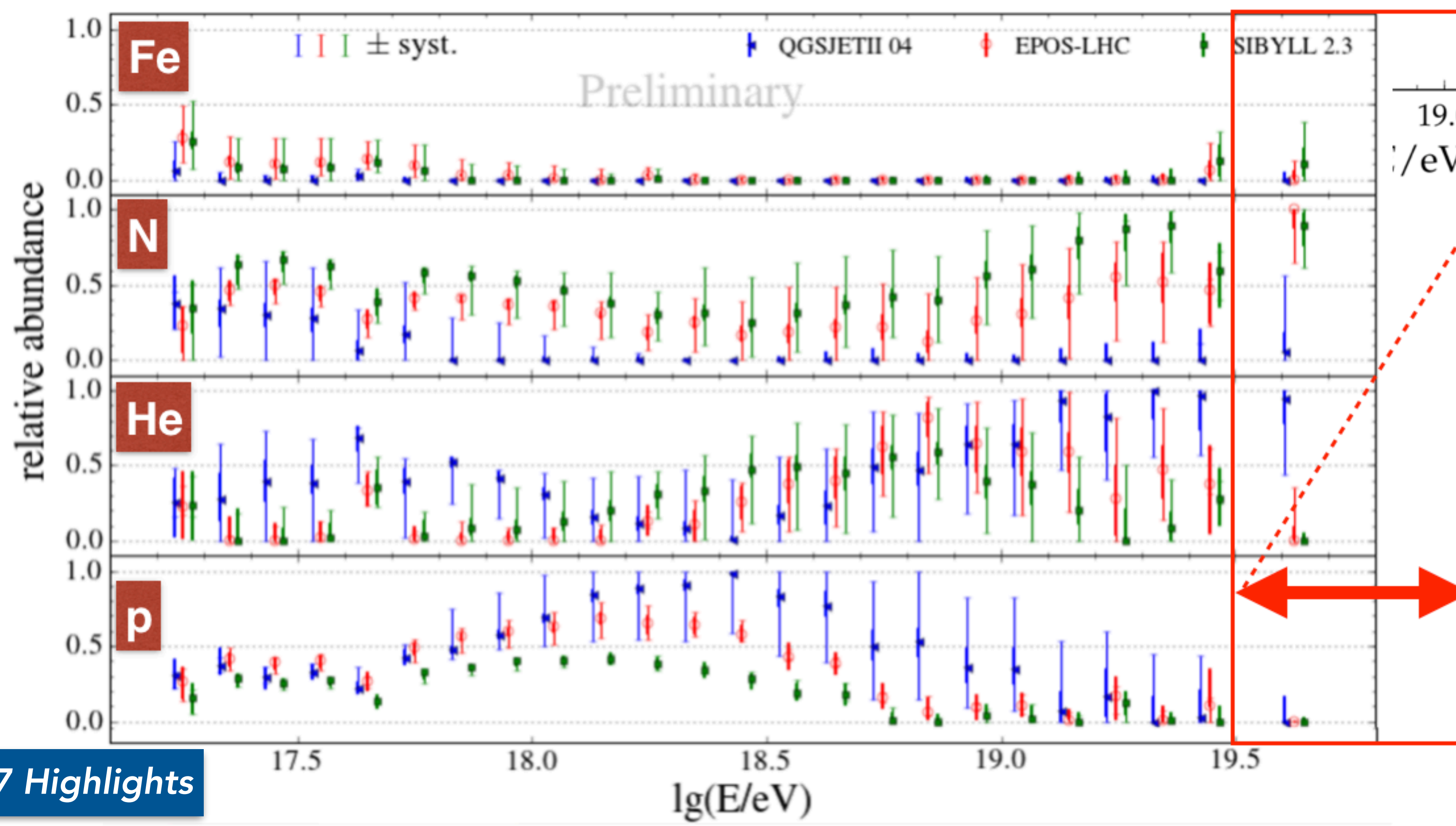
UHECR2018, Paris, 8-12 October 2018

Prologue

- a wealth of information collected at the Pierre Auger Observatory: a complex astrophysical scenario
- need for key additional measurements

→ ***AugerPrime***





M.Unger, Auger, ICRC2017 Highlights

The AugerPrime science case

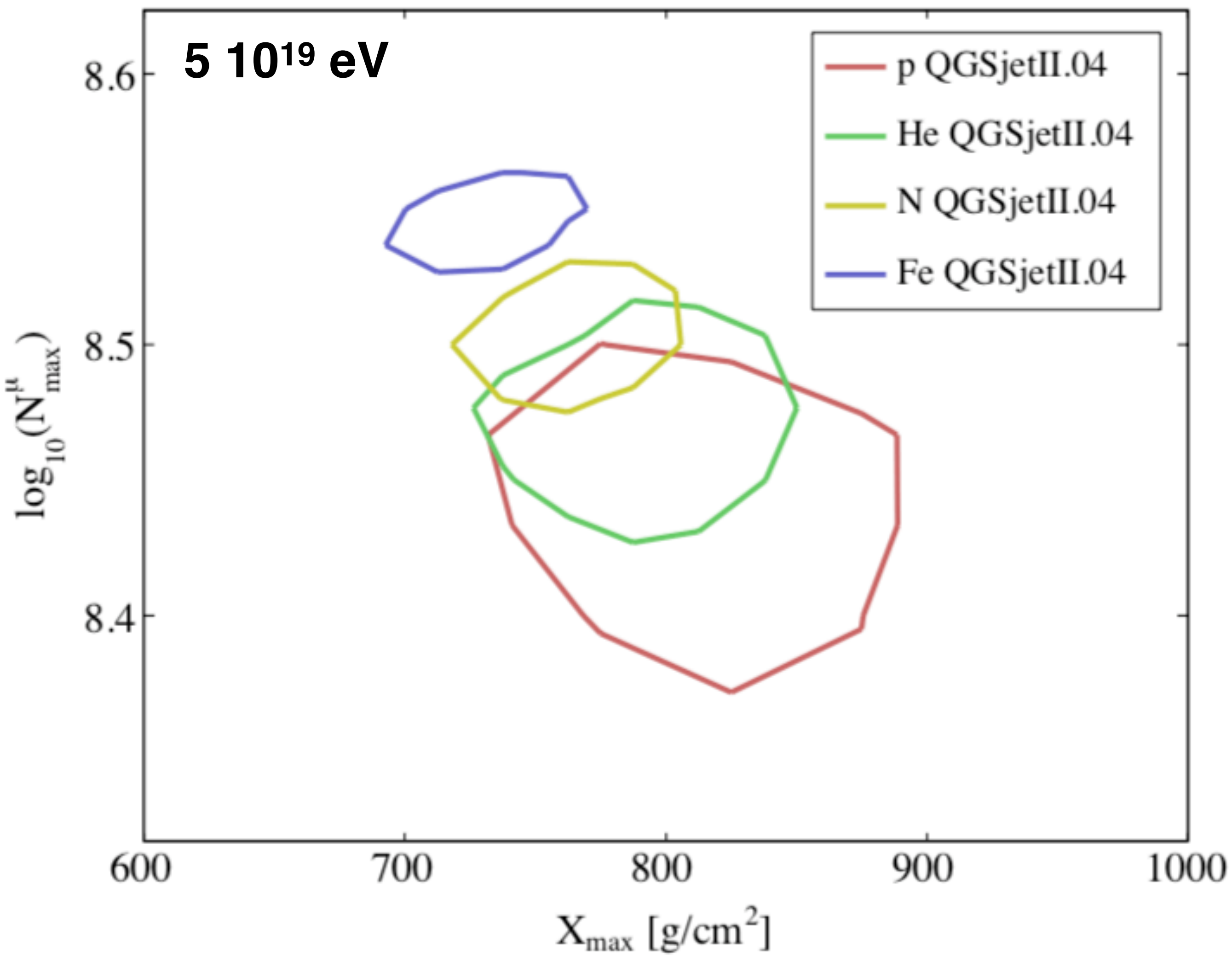
- study the origin of the suppression
- select light primaries for charged particle astronomy
- provide better estimates of the neutrino and γ flux, as such establishing the potential of future CR experiments
- better measure the shower components and so study the hadronic interactions at UHE and look for non standard physics

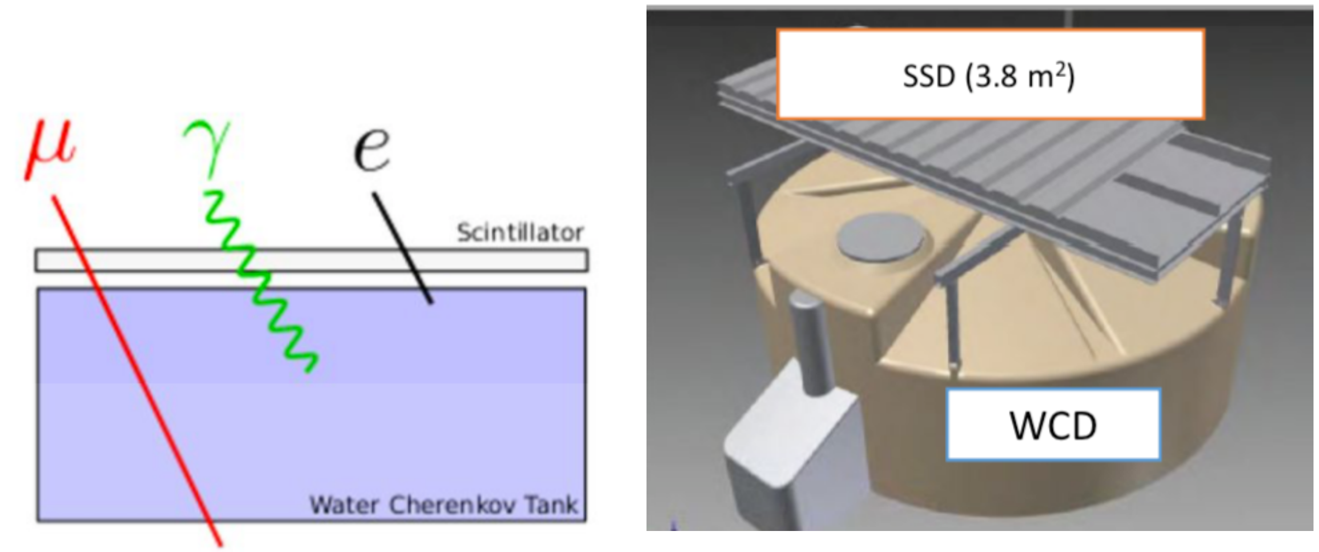
Extend operations to 2025, increasing the statistics

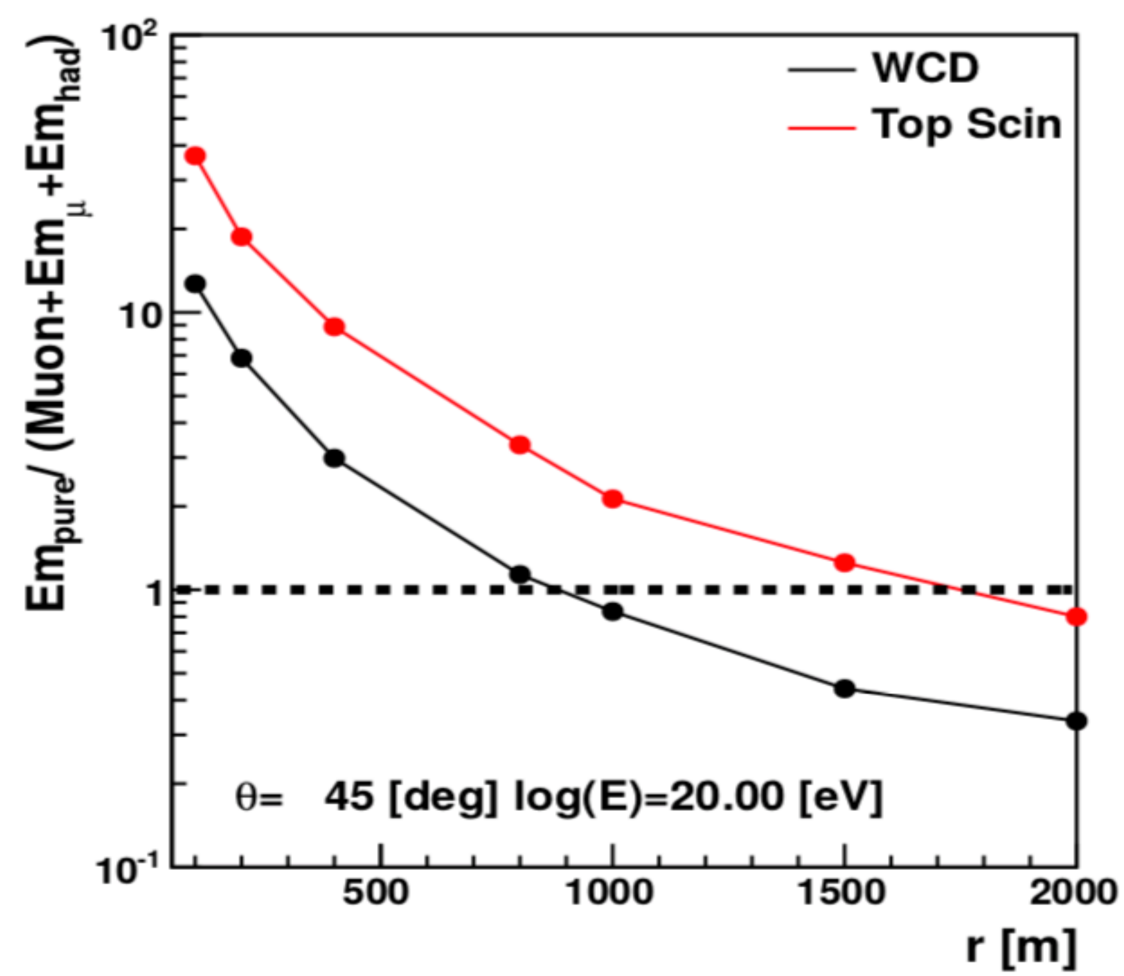
Improve the sensitivity to the composition at UHE : disentagle the electromagnetic and muonic components

AugerPrime Design Report, arXiv:1604.03637

Composition sensitivity







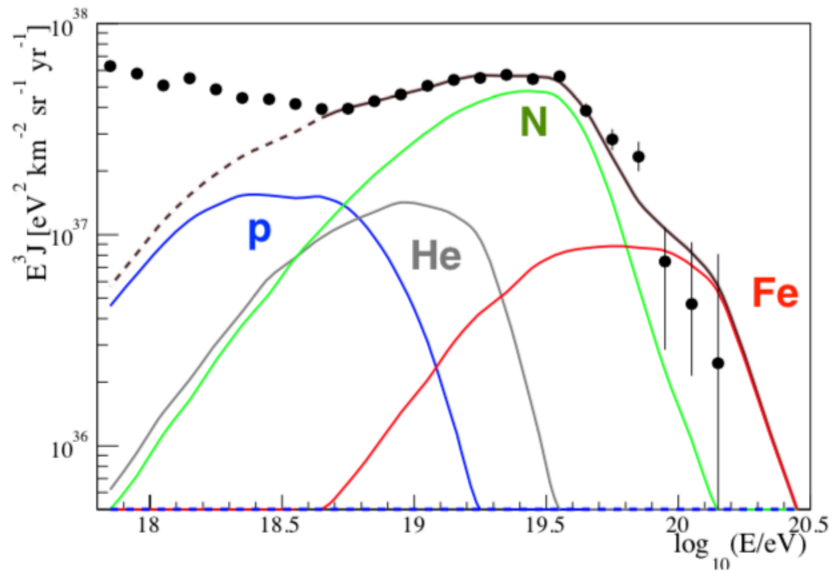
100% duty cycle of the SD
15% duty cycle of the FD

exploit the complementarity of response to particles to discriminate the muonic and electromagnetic components of extensive air showers

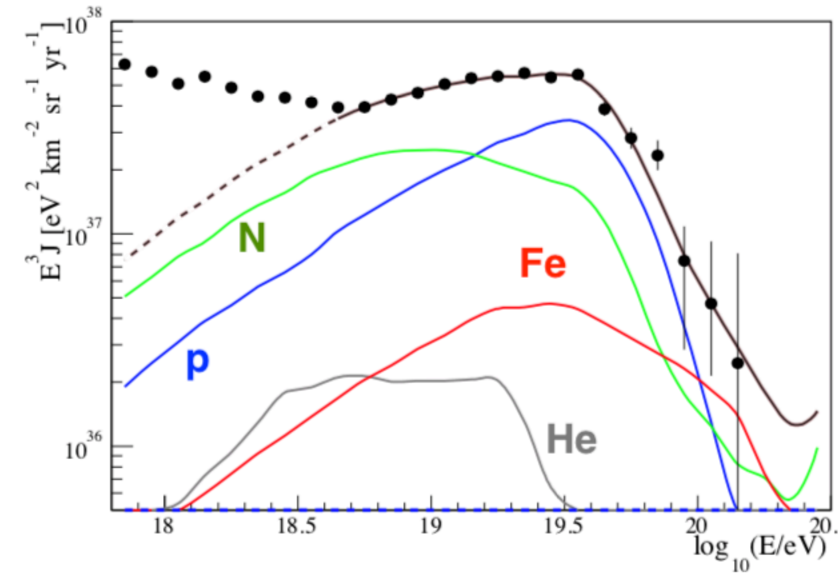
Discrimination of astrophysical scenarios

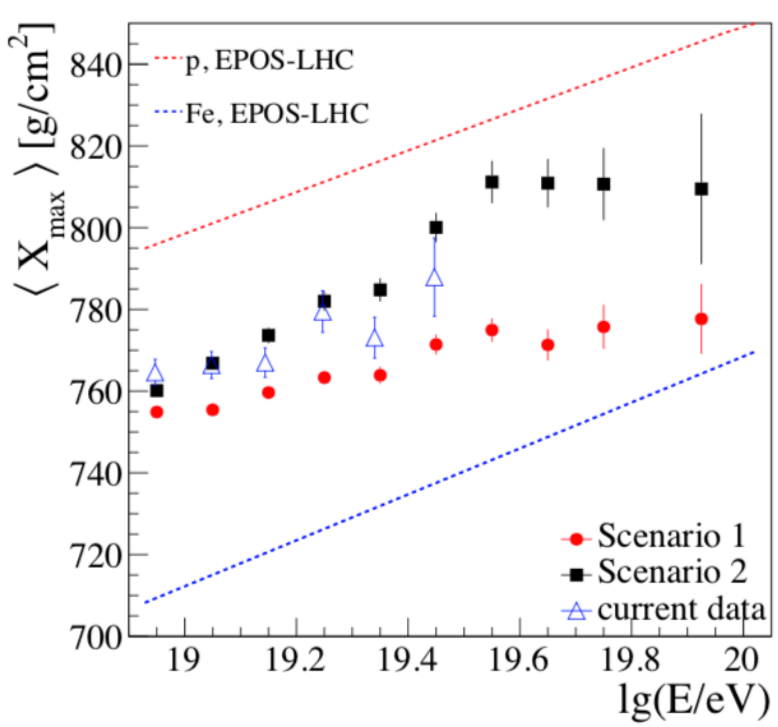
Simplified benchmark scenarios :

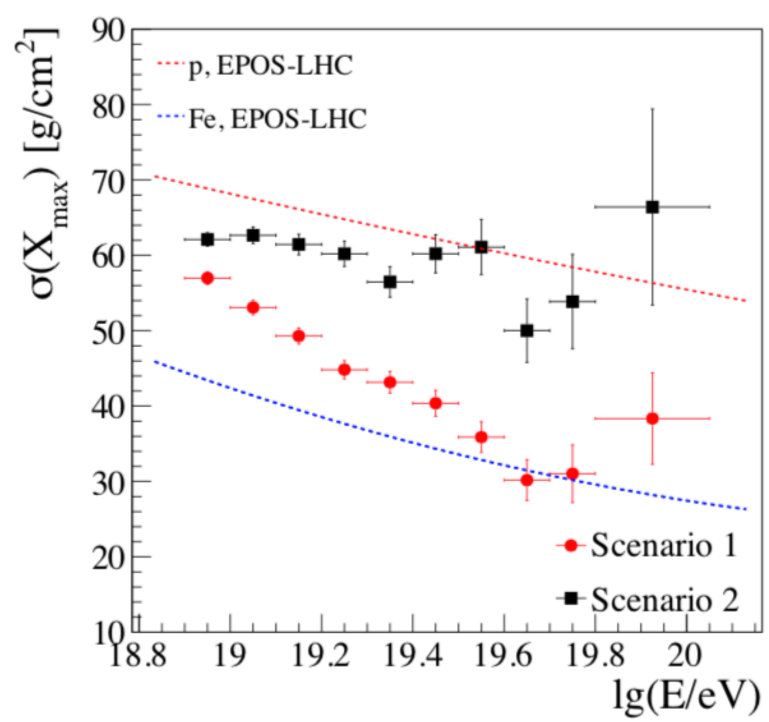
Scenario 1: maximum rigidity model

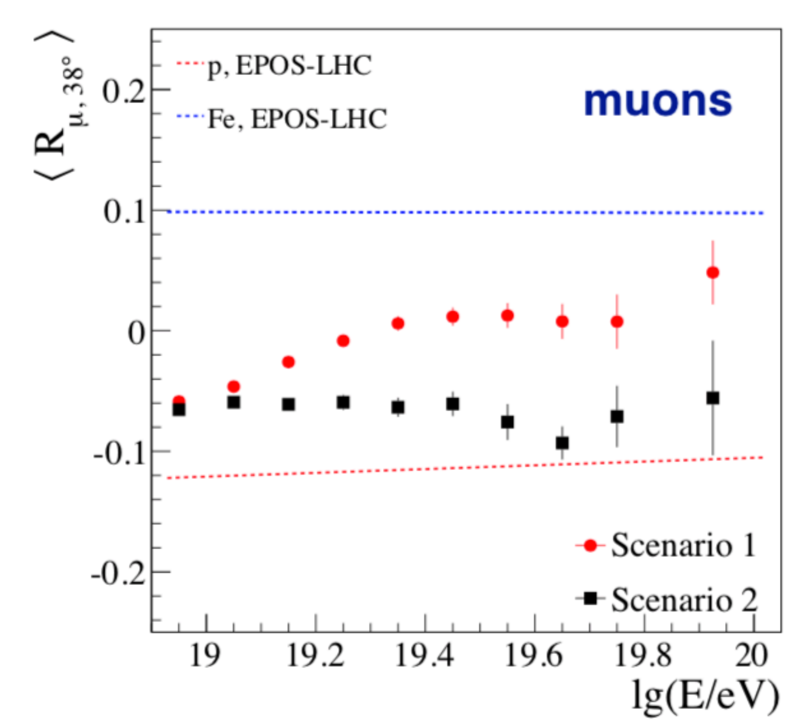


Scenario 2: photo-disintegration model

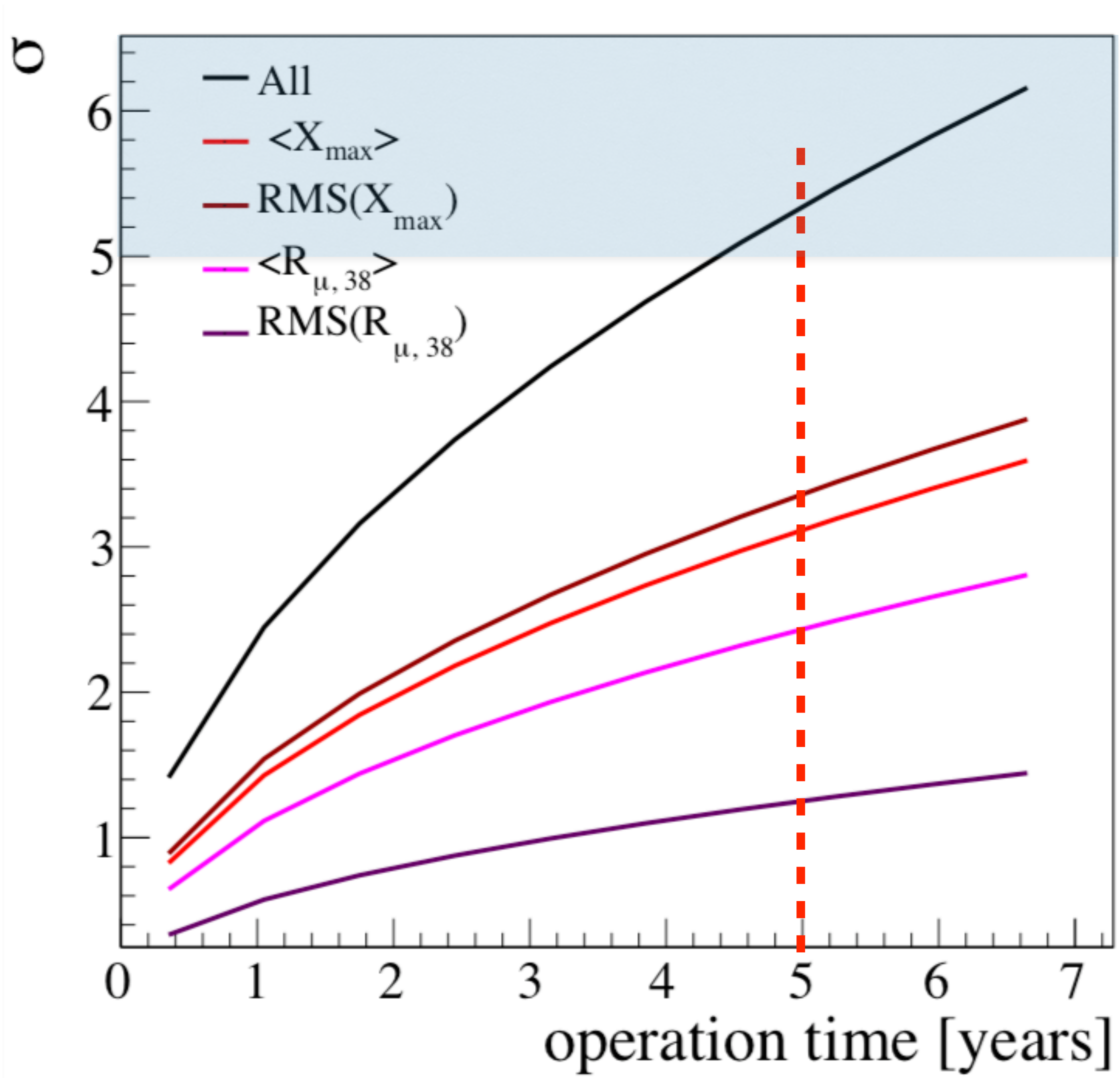








Sensitivity to proton fraction



Significance of distinguishing two different realisations of Scenario 1 (maximum rigidity model) :

- as it predicts, i.e. no protons at UHE
- adding 10% protons

For the combined significance

$$\sigma^2 = \sigma^2(\langle X_{\max}\rangle) + \sigma^2(RMS(X_{\max})) + \sigma^2(\langle R_{\mu,38}\rangle) + \sigma^2(RMS(R_{\mu,38}))$$

>5σ in 5 years of operations

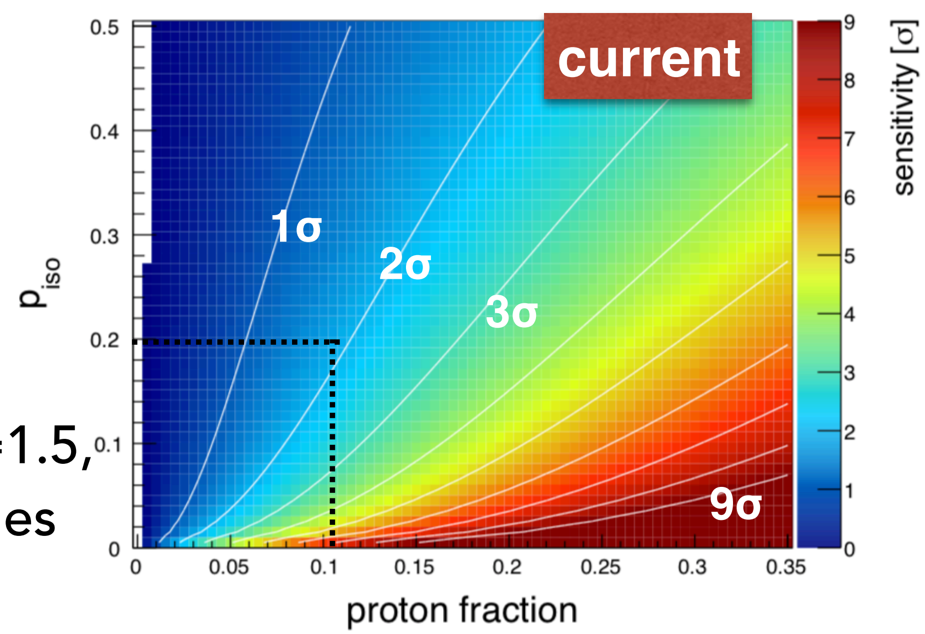
Composition-driven anisotropy search

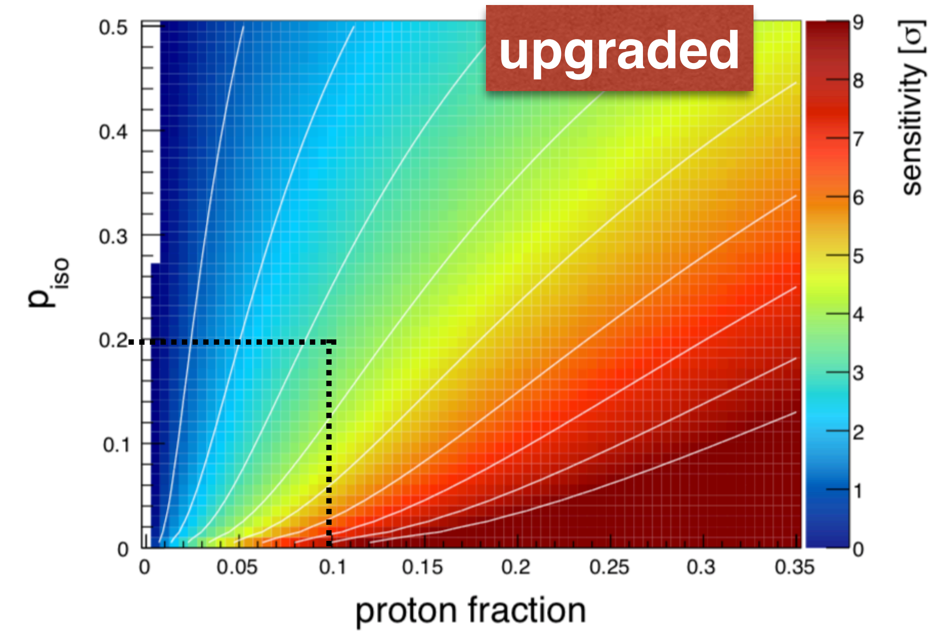
Source correlation study (no specific assumptions)

155 events above 5.5 10^{19} eV correlated by chance

isotropic heavy elements
75% protons correlating

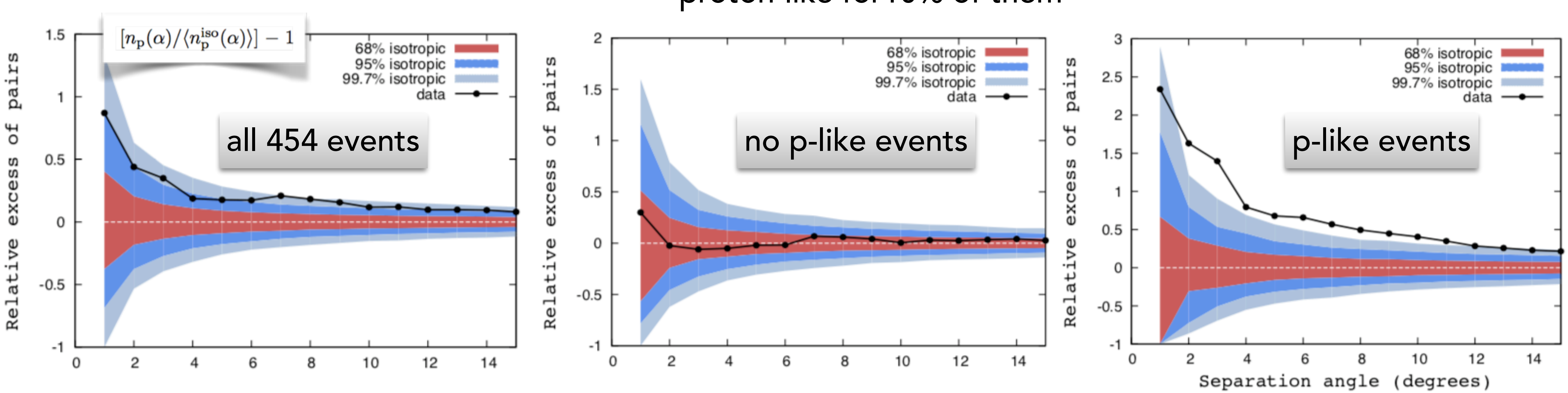
If p can be selected with MF=1.5, deviation from isotropy doubles



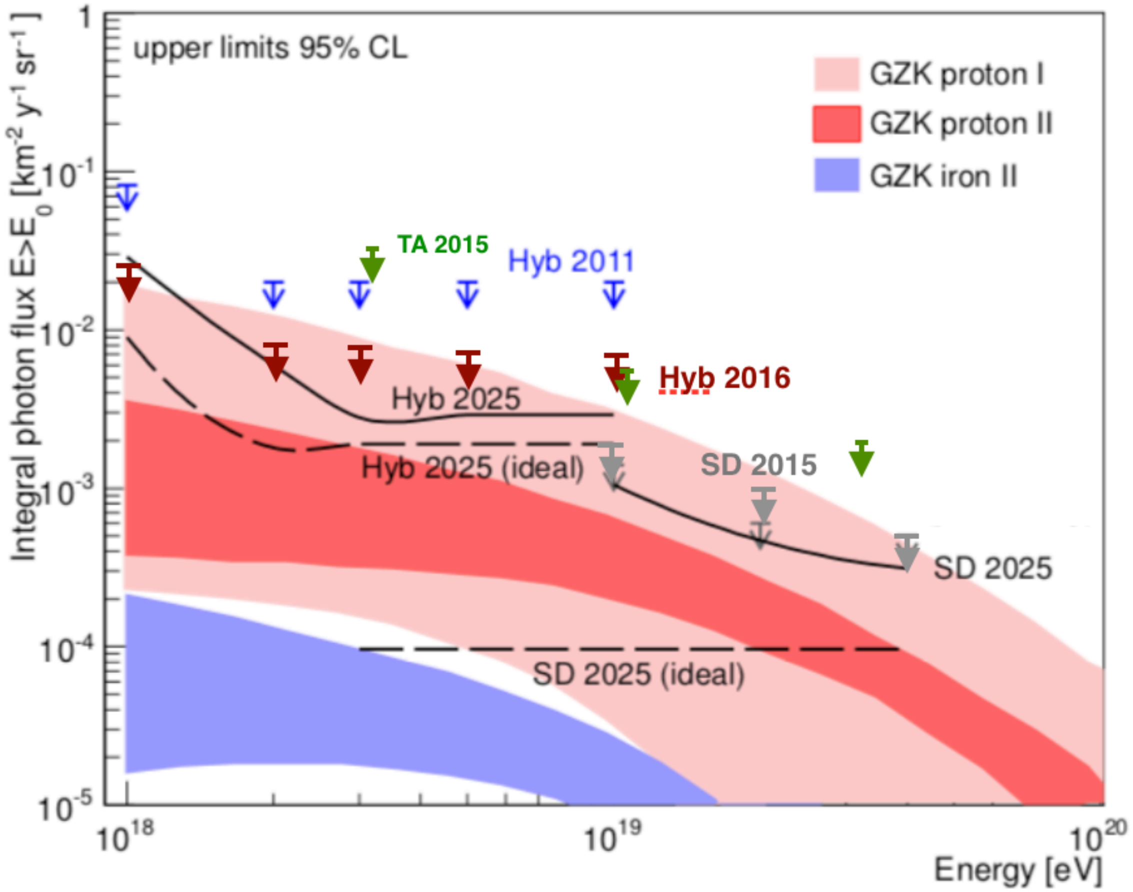


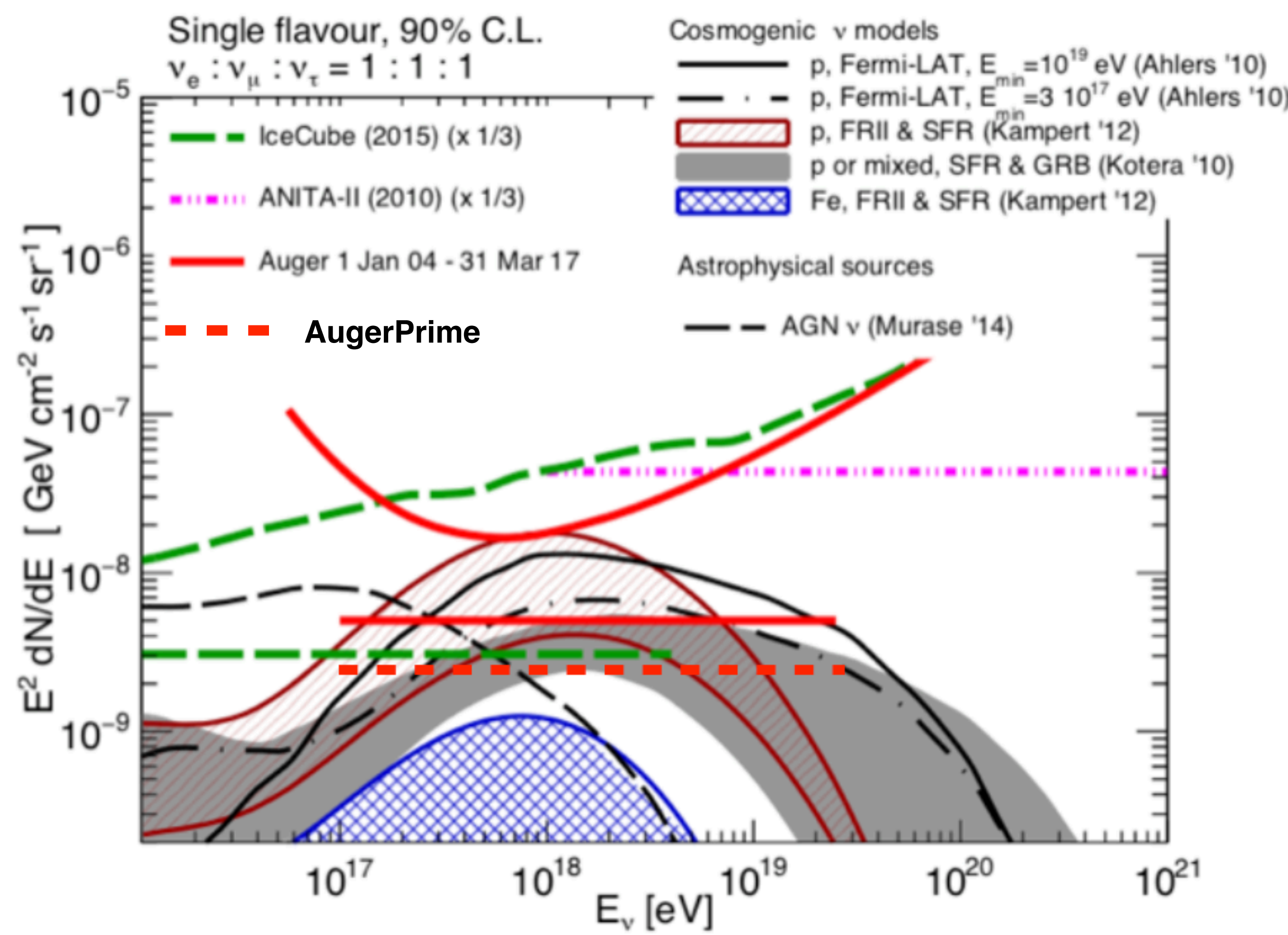
Specific source (AGN from Swift-BAT <100 Mpc) correlation study

454 events with E>4 10^{19} eV, $\vartheta<60^0$ ⟶ for each, keep ϑ, assign X_{max} according to scenario 1, proton-like for10% of them



Information on neutrinos and photons





M.Unger, Auger, ICRC2017 Highlights

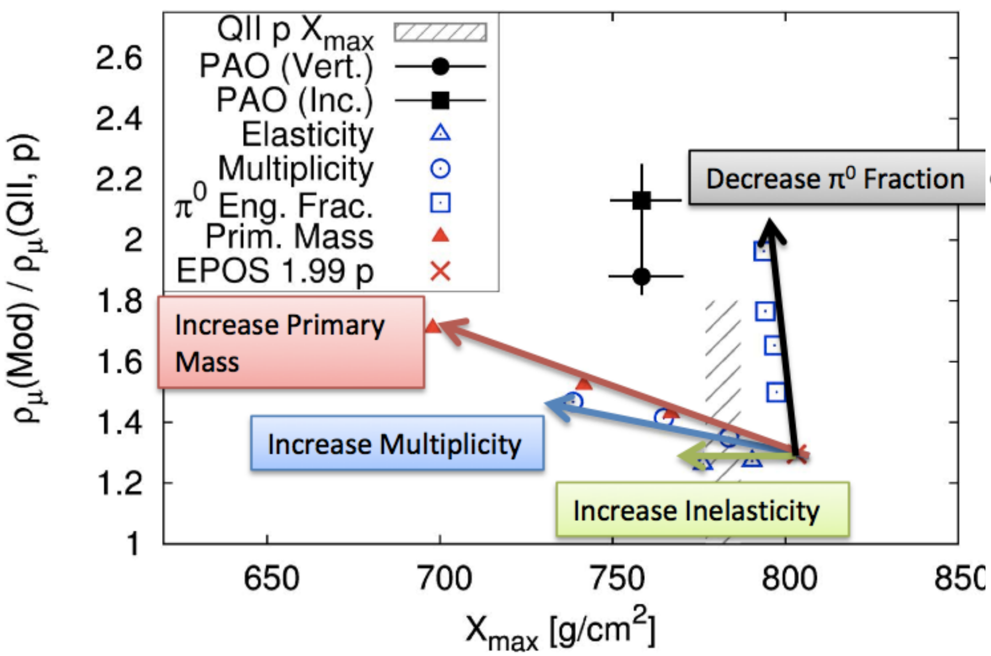
Expected improvements

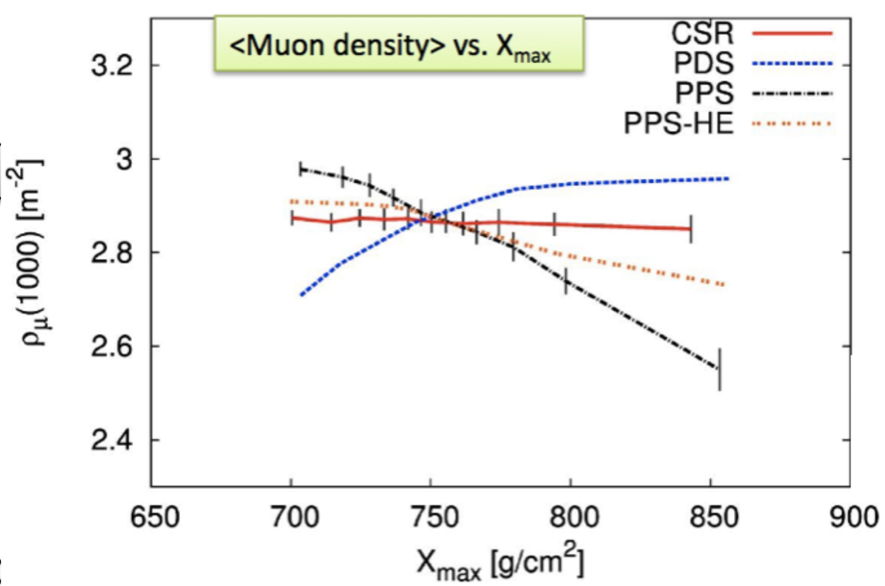
- increase in exposure
- largely improved discrimination power:
  - new triggers lowering the trigger thresholds
  - new electronics
  - better muon component evaluation, as such better photon/hadron and neutrino/hadron discrimination

Particle physics

- Kinematic regions not reachable by accelerators
- Tests of fundamental interactions in extreme energy regimes
- Tests of hadronic interaction models

$$E = 10^{17} - 10^{20}\ \mathrm{eV}$$
$$\sqrt{s} \approx 14 - 450\ \mathrm{TeV}$$

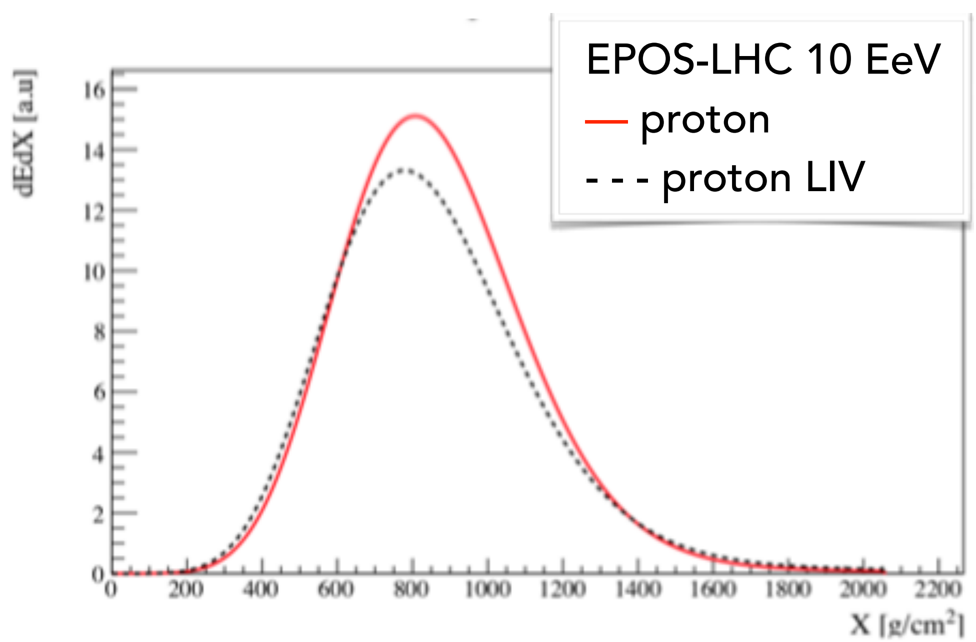


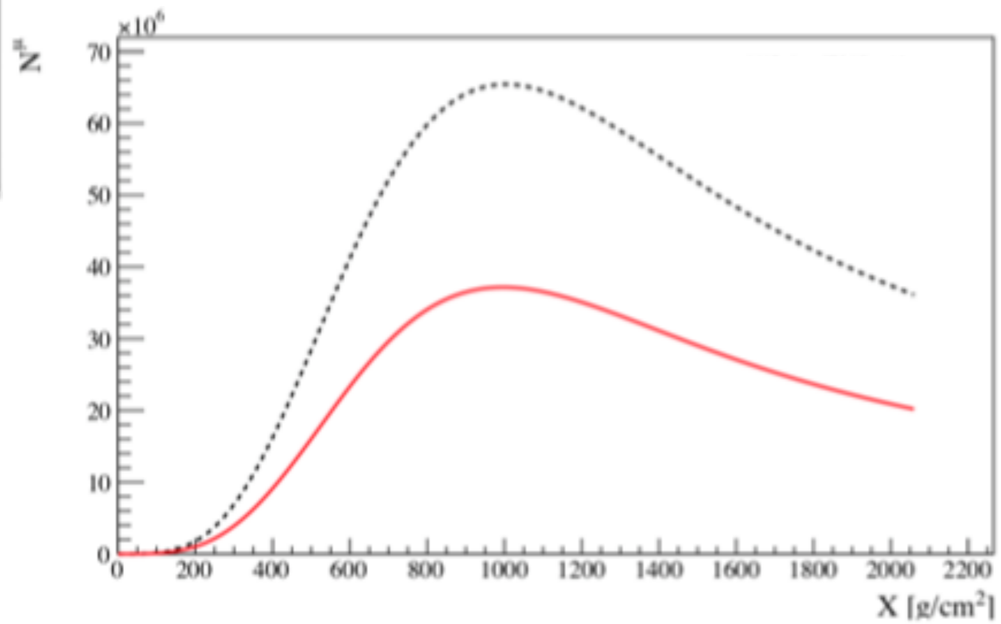


More muons :

- pion production suppression
- pion decay suppression
- leading particle effect : π^0 replaced with $\boldsymbol{\rho}^0$
- baryon-antibaryon production
- ….others

- + constrain or find hints of new phenomena (e.g.violation of Lorentz invariance,…)





AugerPrime

a large exposure detector with composition sensitivity above ~4 10^{19} eV

EM+μ

Surface Scintillator Detectors (SSD)

- to improve the separation power for the different components of the shower
- 3.8 m^2 above each WCD, 1 cm thick, read-out by WLS fibers

Water Cherenkov Station (WCD) → ***New Upgraded Electronics (UUB)***

- to acquire WCD+SSD+SPMT
- 120 MHz, better GPS timing

↓

Small PMT (SPMT)

- to increase the dynamic range of the measurement in the WCD
- one small PMT in each WCD

μ

Direct Muon Detector (AMIGA)

- to directly measure the muon component
- scintillators+WLS fibers, 2.3 m underground aside the Infill WCD (23.4 km^2)

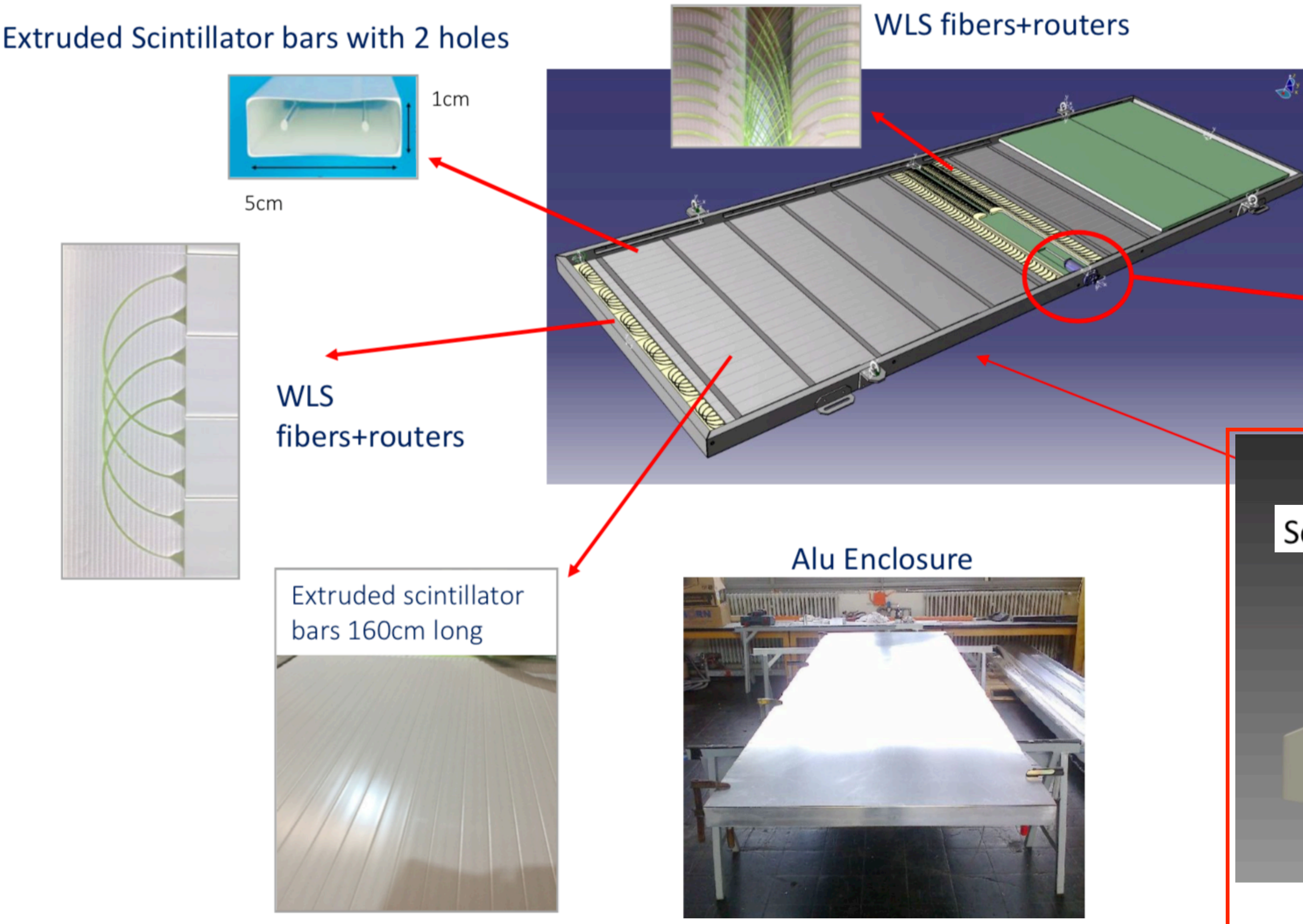
EM

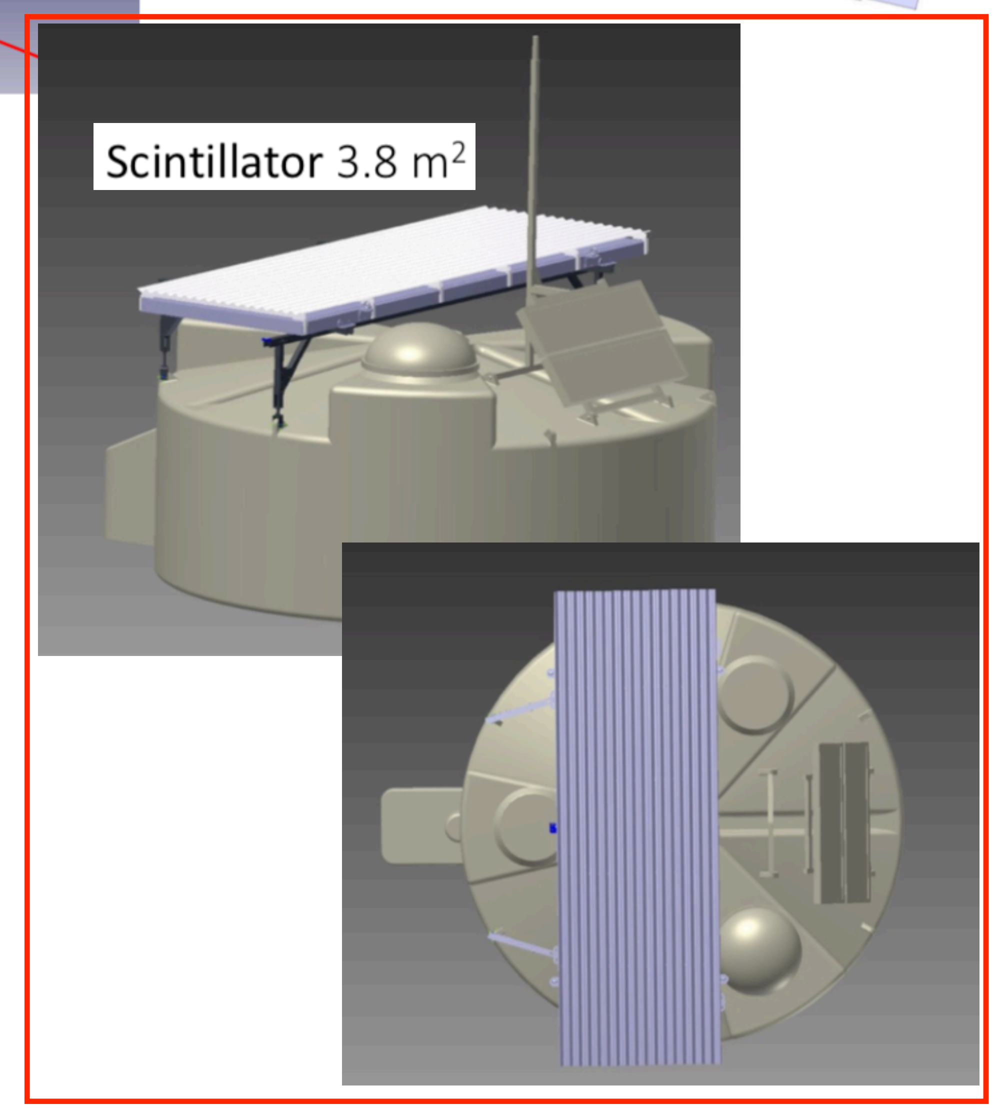
Extension of the Fluorescence Detector duty cycle

- 50% increase by lowering the PMT HV

Radio antennas (next talk)

The Surface Scintillator Detector





A scintillator plane on top each WCD station

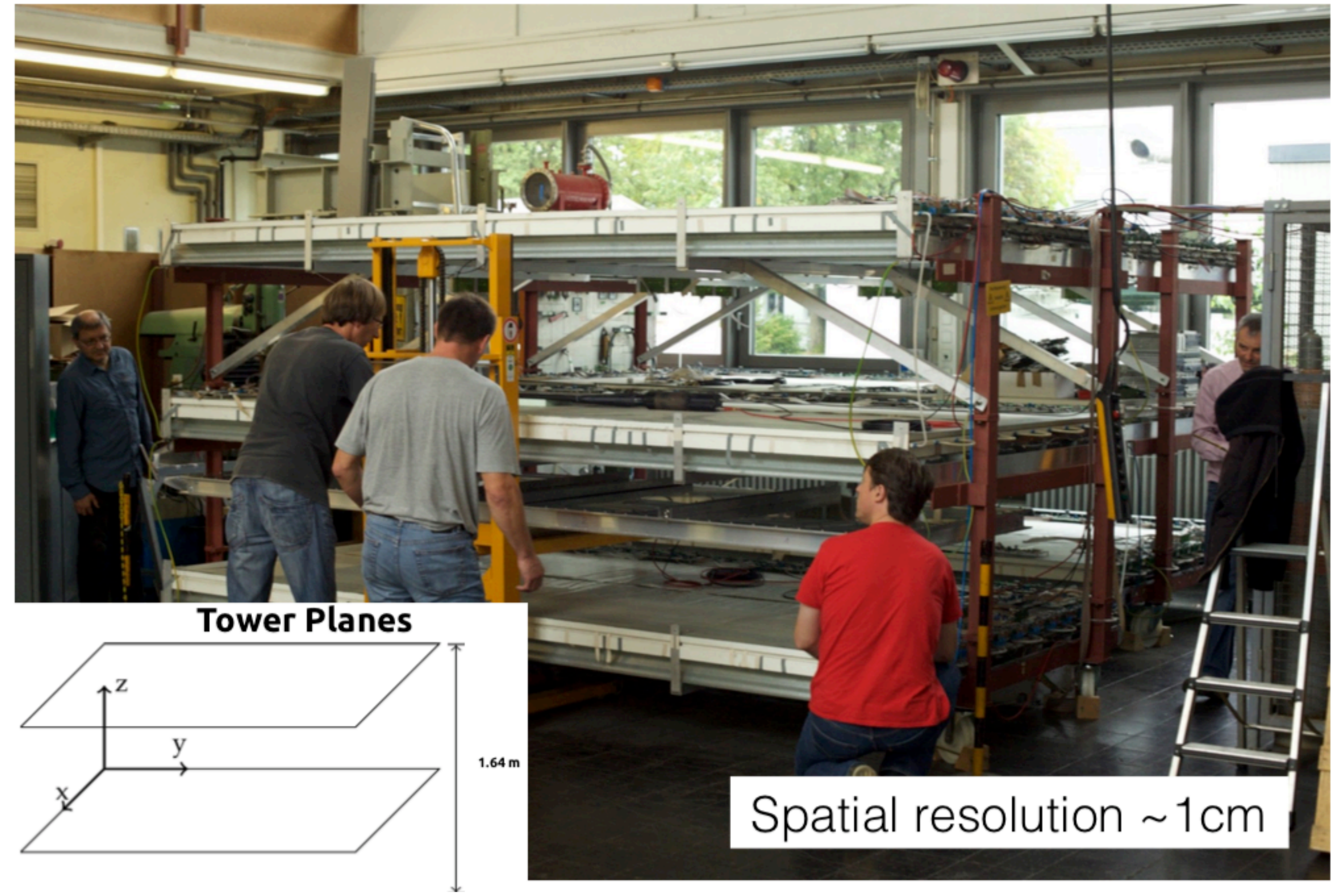
- robust and well understood
- complementary to the WCD in the measurement of the shower components

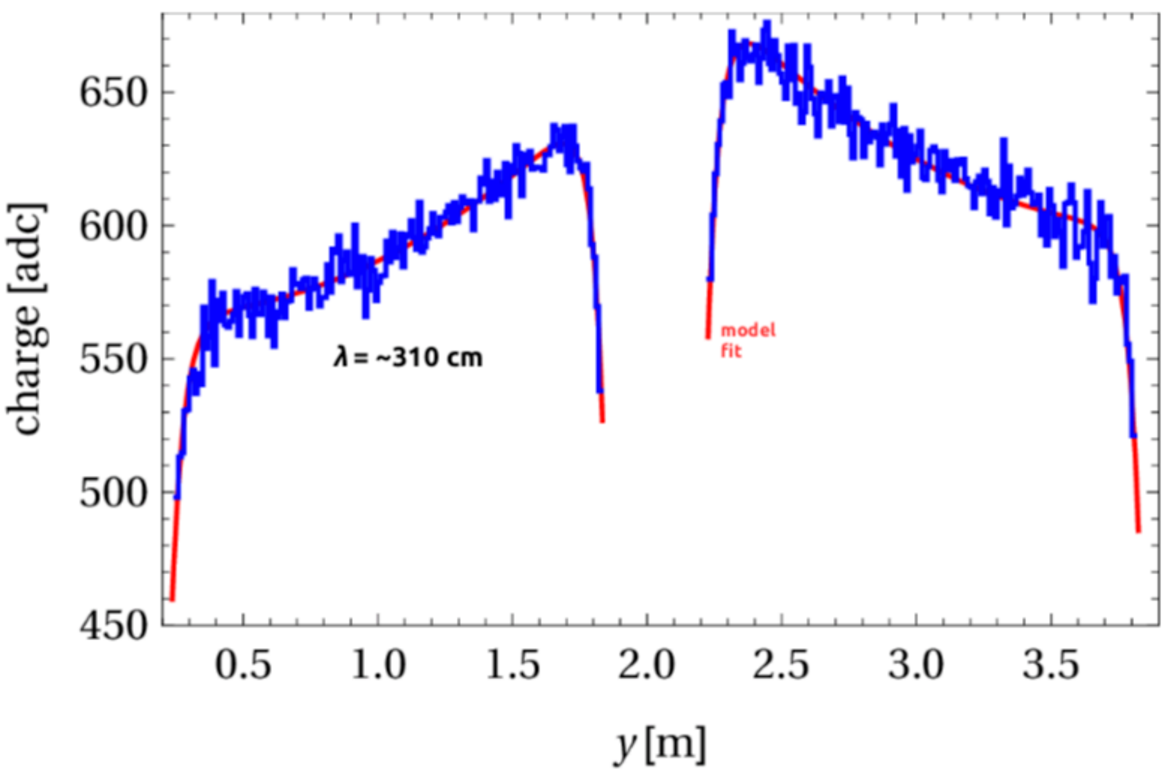
SSD Performances

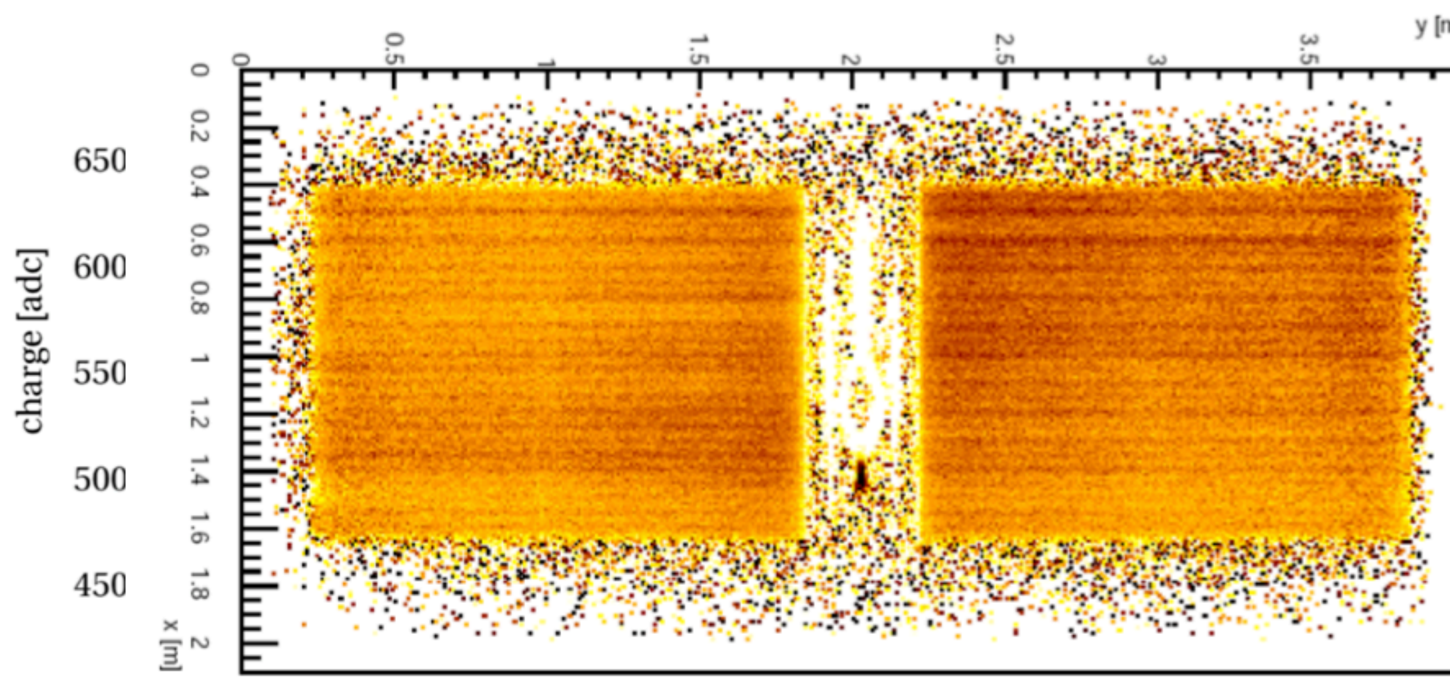
Muon telescope (from Kascade experiment)

- attenuation lenght of the light in fibers
  λ=310±3 cm
- uniformity **better than ±5%**

- **30±2 p.e./vMIP [<37 p.e./MIP>]**







The SD Upgraded Electronics

Increase in data quality

- 6 ⟶ 10 ADC channels to process signals from WCD and SSD
  - 2x3 WCD-LPMTs, 2x1 SSD-PMT, 1 WCD-SPMT
- faster sampling : 40 ⟶ 120 MHz
- better timing accuracy
- increased dynamic range

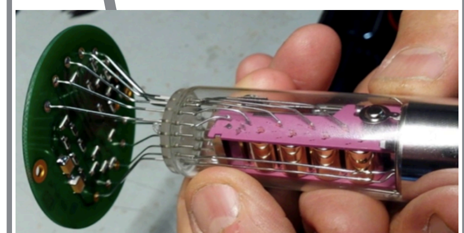
Faster data processing and enhanced local triggers

- more powerful processor and FPGA

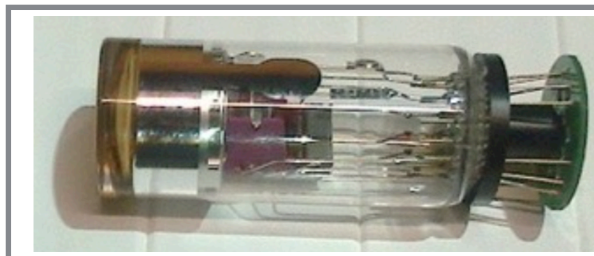
Improved calibration and monitoring capabilities

- >90 monitoring variables managed by slow-control
- low gain to high gain calibration purely electronic (both for WCD and SSD)

XP1805 Photonis, 9″ ∅



Hamamatsu R8619, 1″ ∅

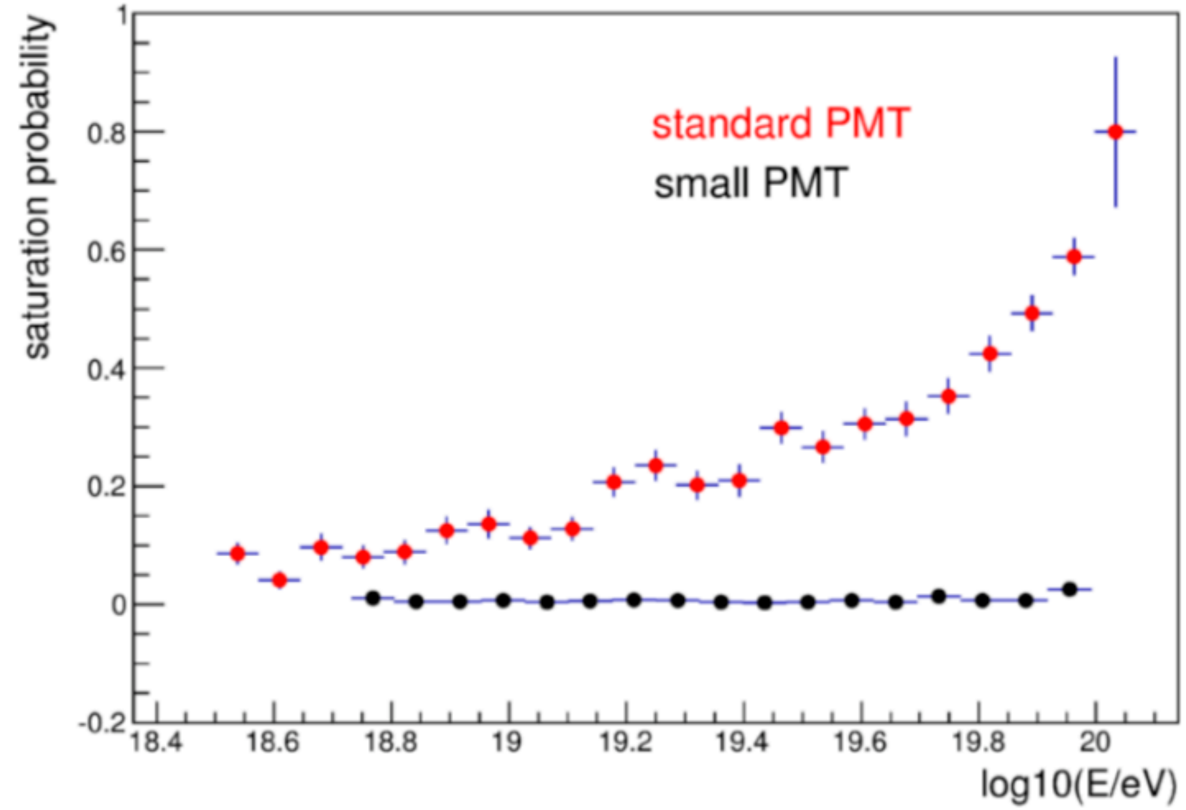


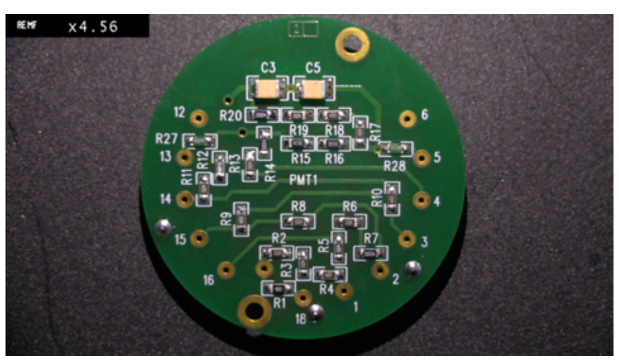
Hamamatsu R9420, 1.5″ ∅

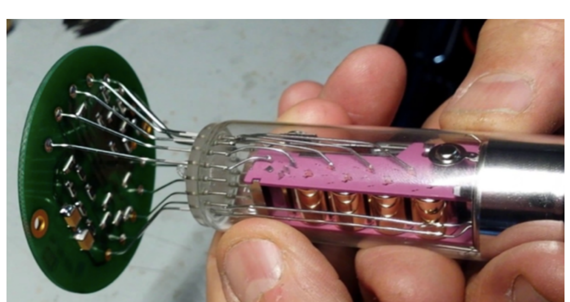
Extending the dynamic range

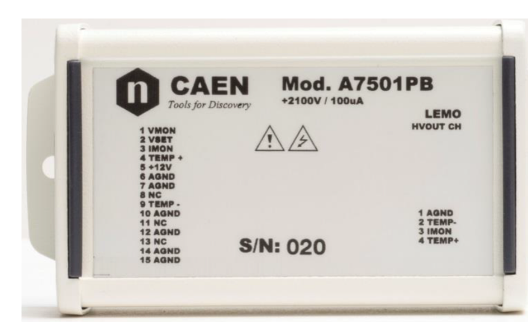
Extra small PMT in the WCD (1″ ∅)

- x32 dynamic range : **~20000 VEM**
- **P(≥1 saturated SD) ~0** at all energies
- signals measured **as close as 250 m** from the core
- easy installation (no mechanical modification of SD tanks)
- dedicated input in the UUB
- comparable dynamic range in WCD and in SSD

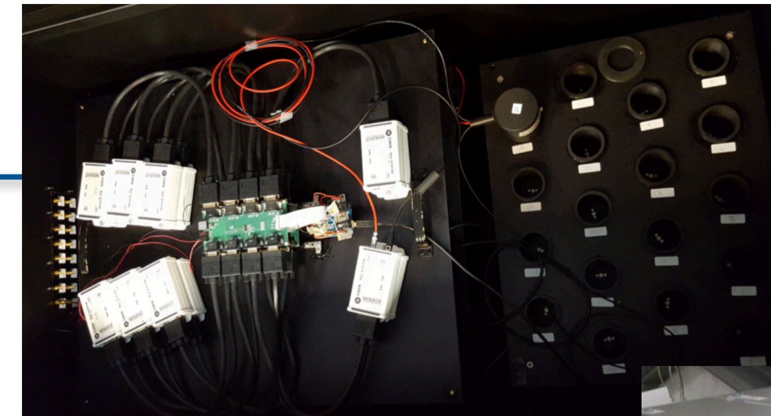




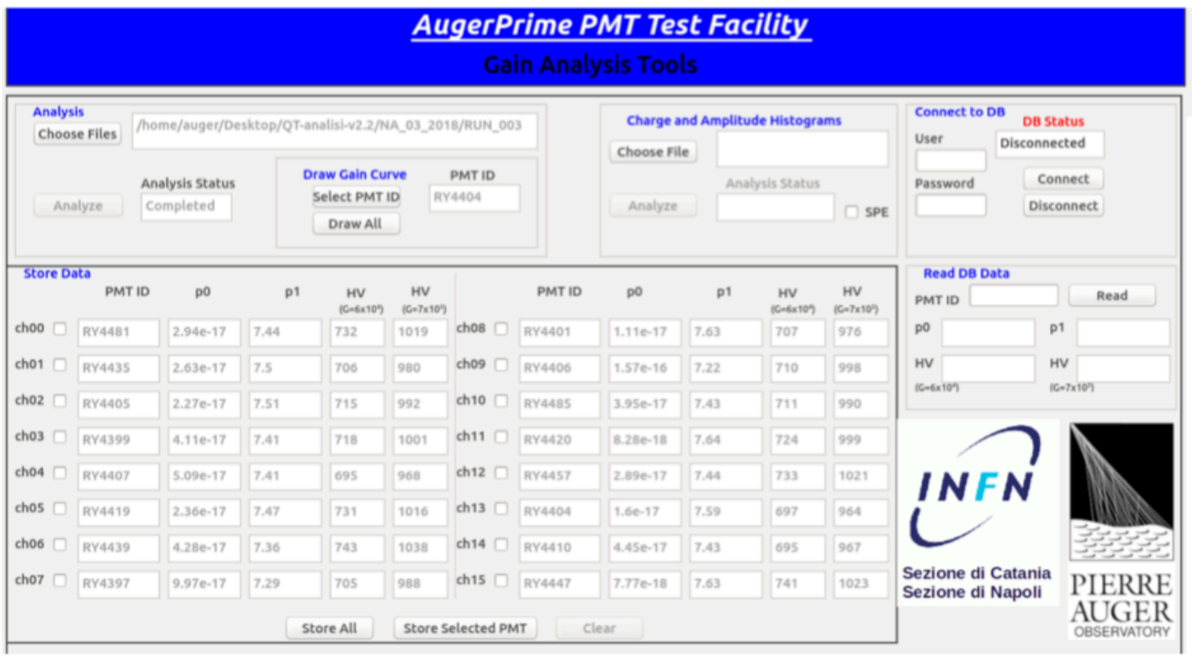


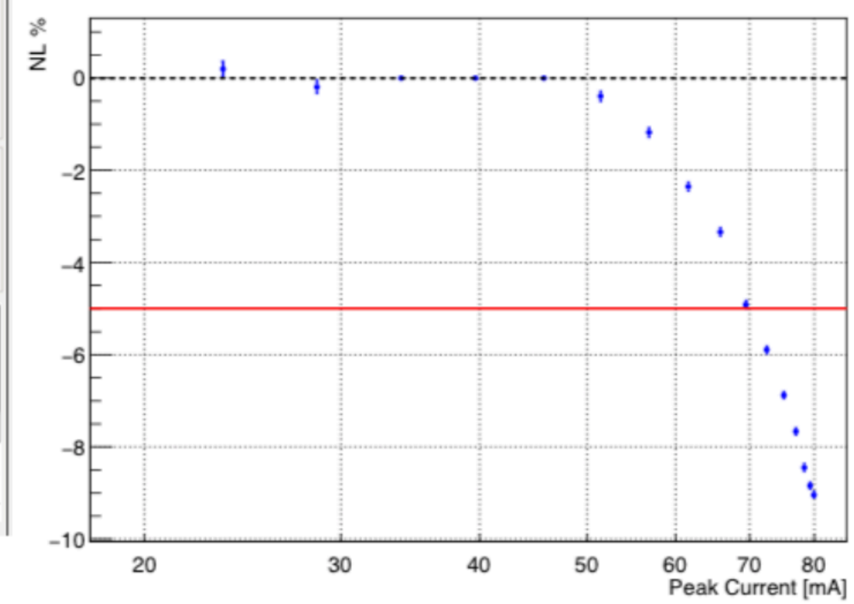


SPMT Performances



Test facility (Napoli, Catania, Torino)

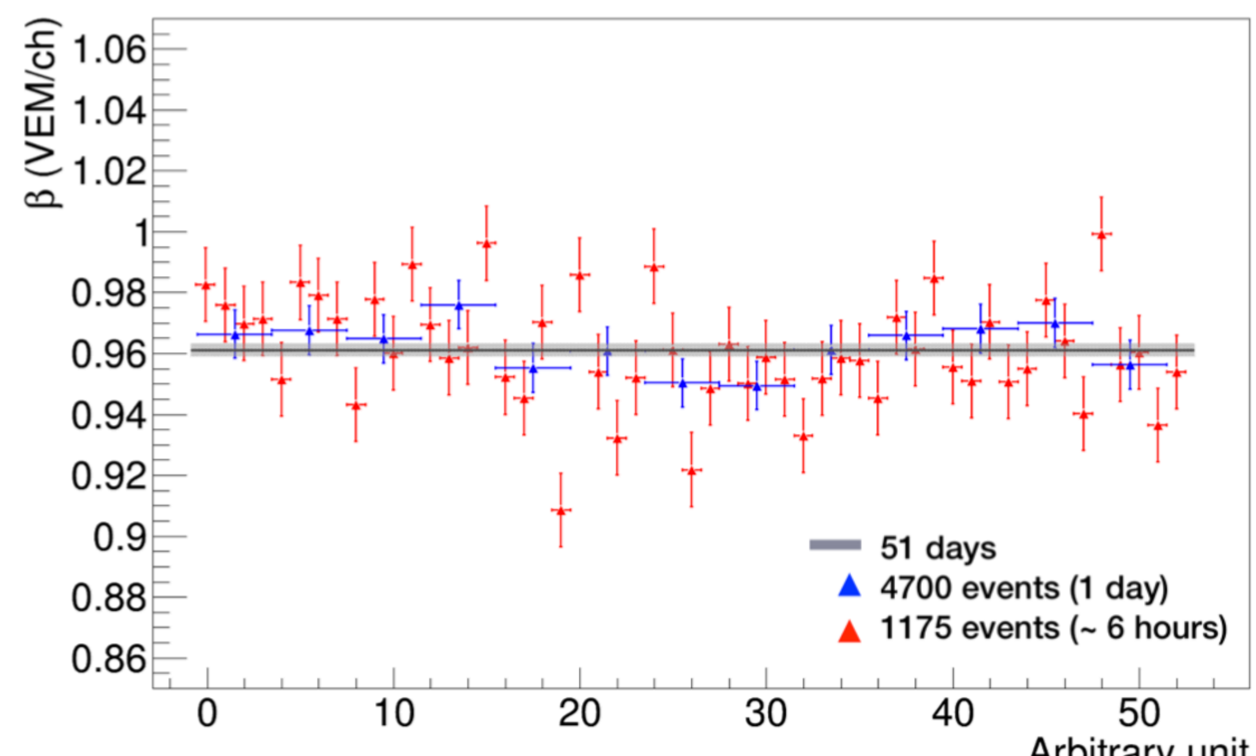




Intercalibration (in local stations)

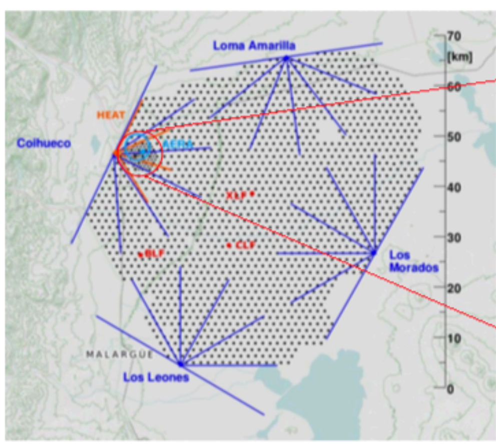
$$S_{LPMT} = \beta S_{SPMT} + Q_0$$

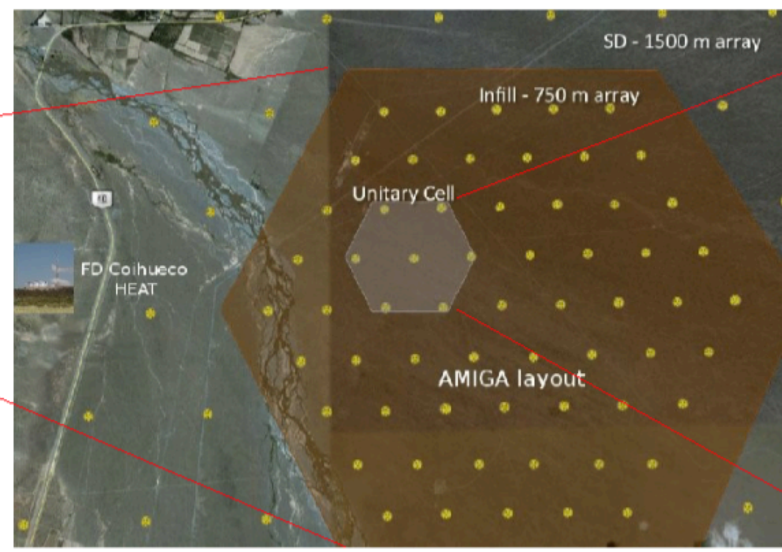
- accuracy of intercalibration technique within 2.2%
- calibration accuracy within 10% above superposition region
- procedure feasible every 6 hours

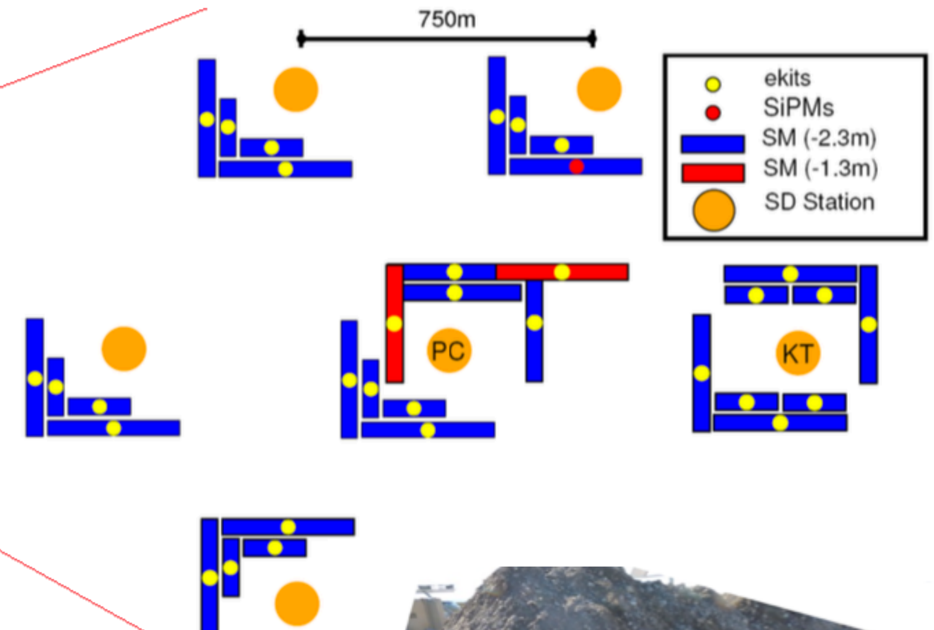


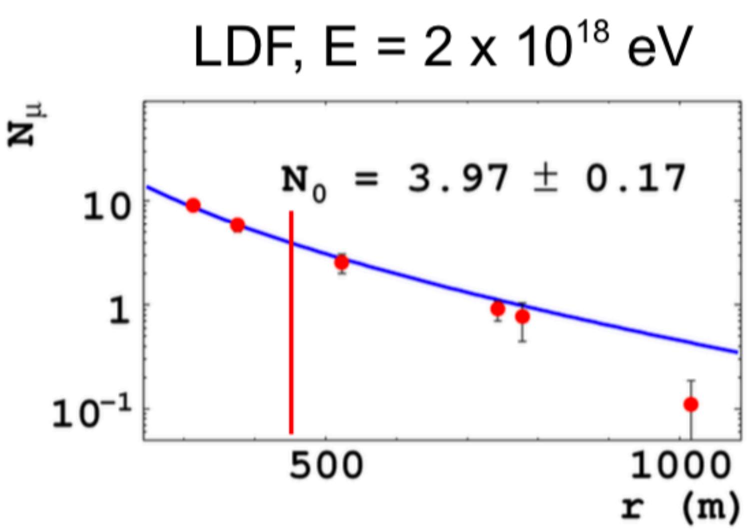
Underground Muon Detector

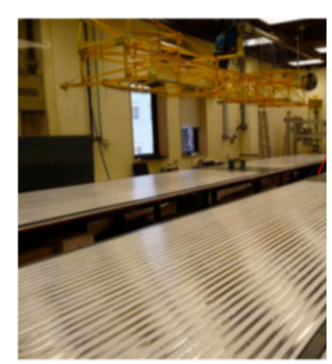
- 61 detectors in the Infill area (23.5 km² in a 750 m grid)
- 4 modules/WCD (~30 m²), 2.25 m underground, triggered by the surface detectors
- **direct measurement of the muon content and its time structure in showers with E≳$10^{17.5}$ eV**
- muon energy threshold ~600 MeV/cosϑ_μ
- cross-check of the SSD-WCD combined analysis











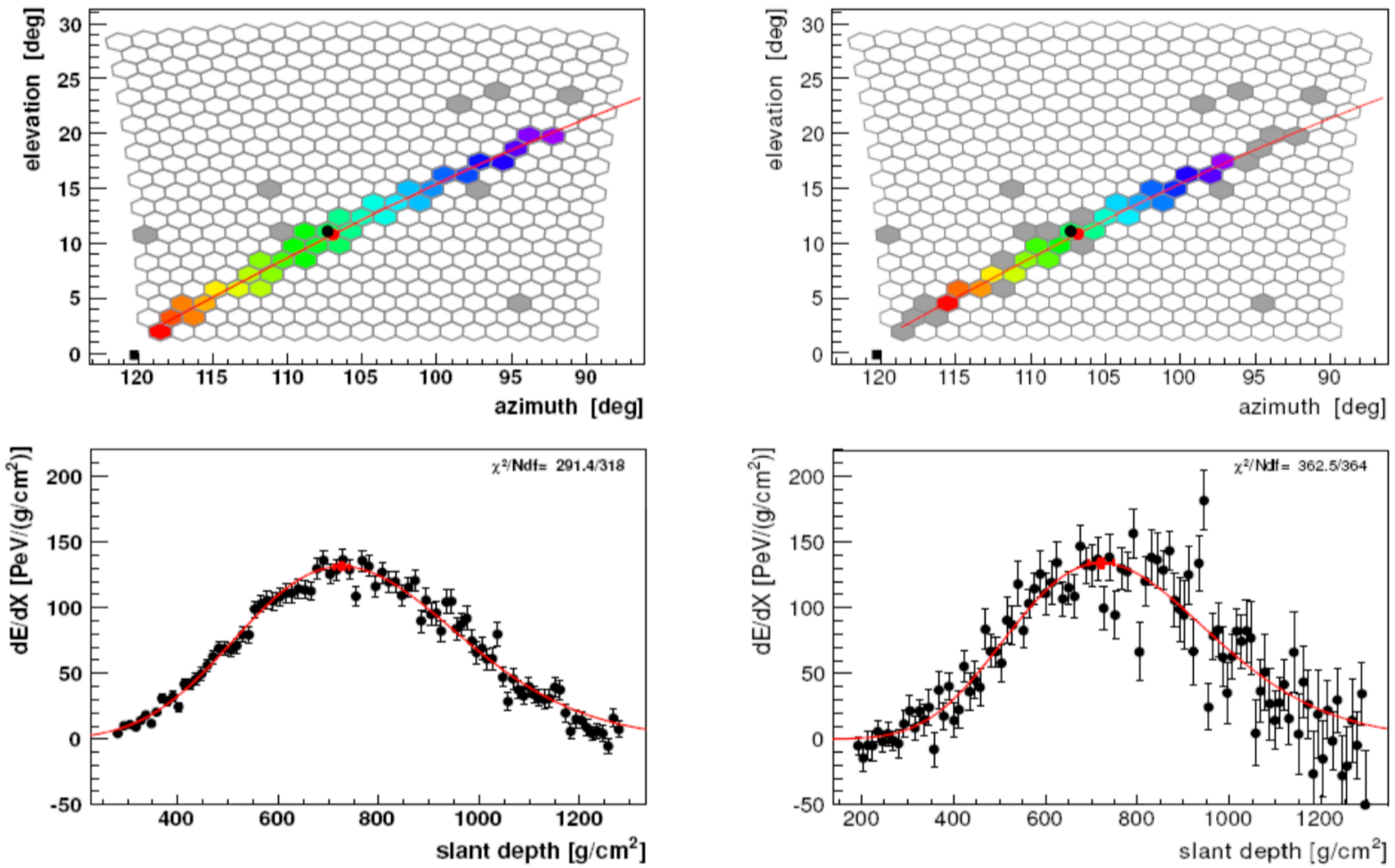
2.3 m of soil (550 g/cm², E_μ > 1 GeV)

Auger, JINST 11(2016) P02012

Extend the FD duty cycle

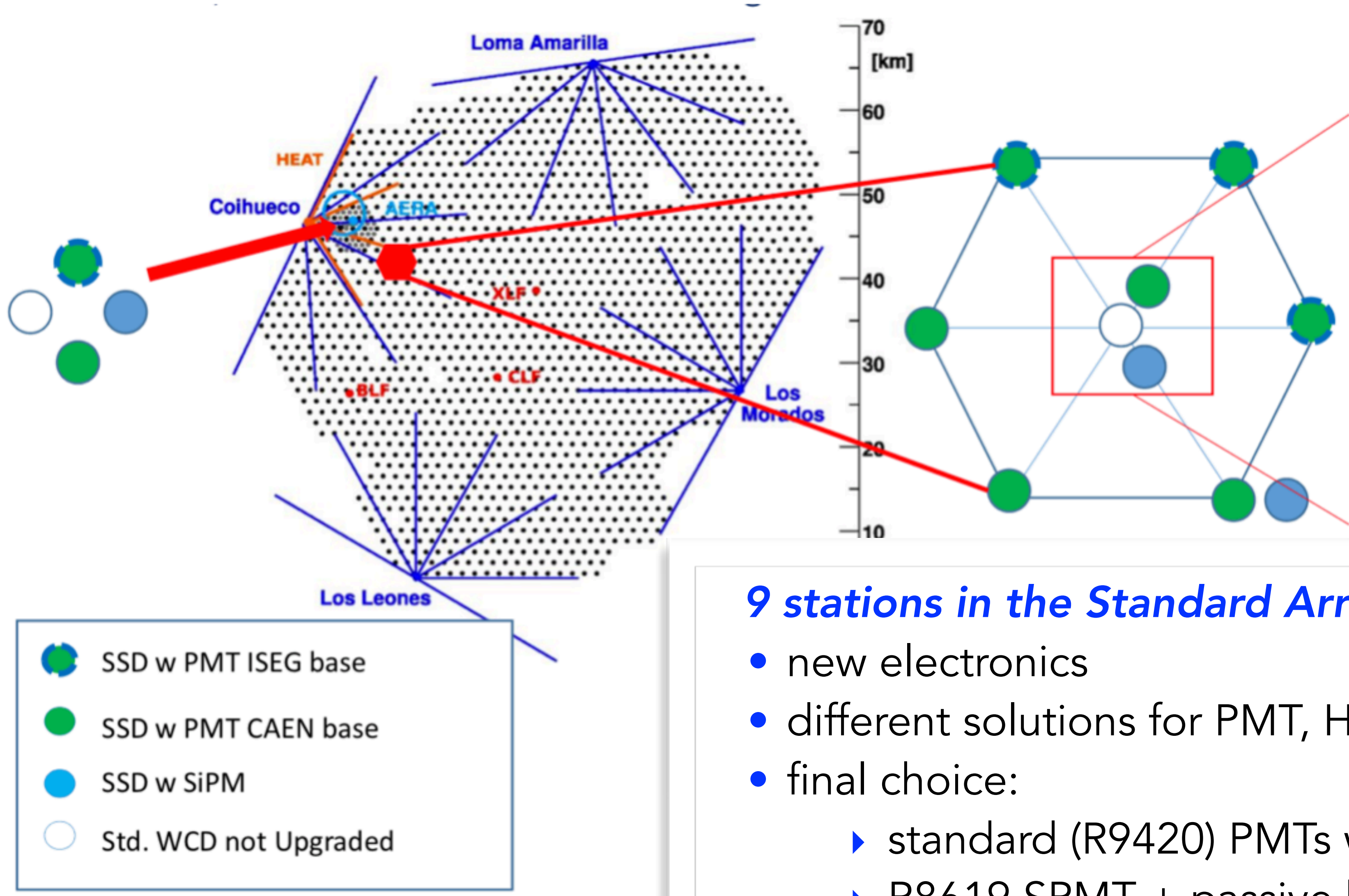
- current criteria for FD measurements
  1. Sun >18^0 below horizon
  2. Moon below horizon for > 3 hours
  3. illuminated fraction of Moon <70%
- extension by relaxing 2 and 3
  - x10 reduction of PMT gain by reducing the supplied HV
  - **uptime increased by 50%**

Clear sky, no moonlight *40 times higher NSB (90% moon)*



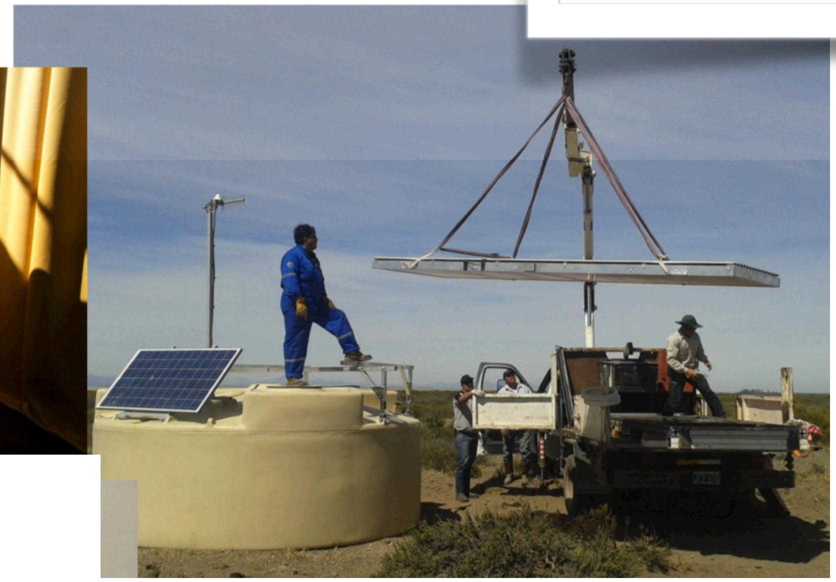
- procedure successfully tested
- existing measured showers reanalysed with standard reconstruction when random noise is added to the FADC traces

The Engineering Array

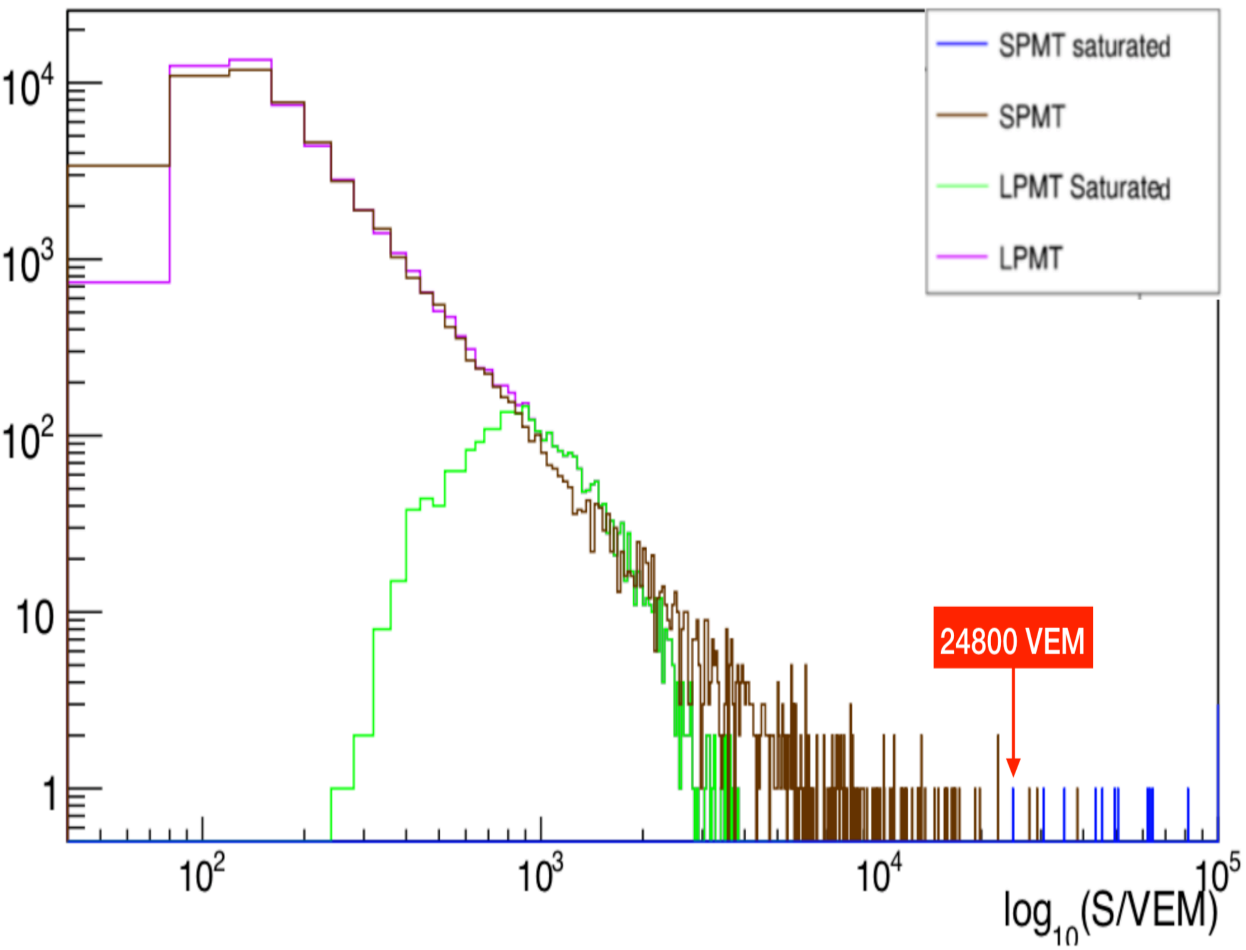


9 stations in the Standard Array + 3 in the Infill area

- new electronics
- different solutions for PMT, HV and bases were tested
- final choice:
    - standard (R9420) PMTs with active bases for SSD,
    - R8619 SPMT + passive base for WCD

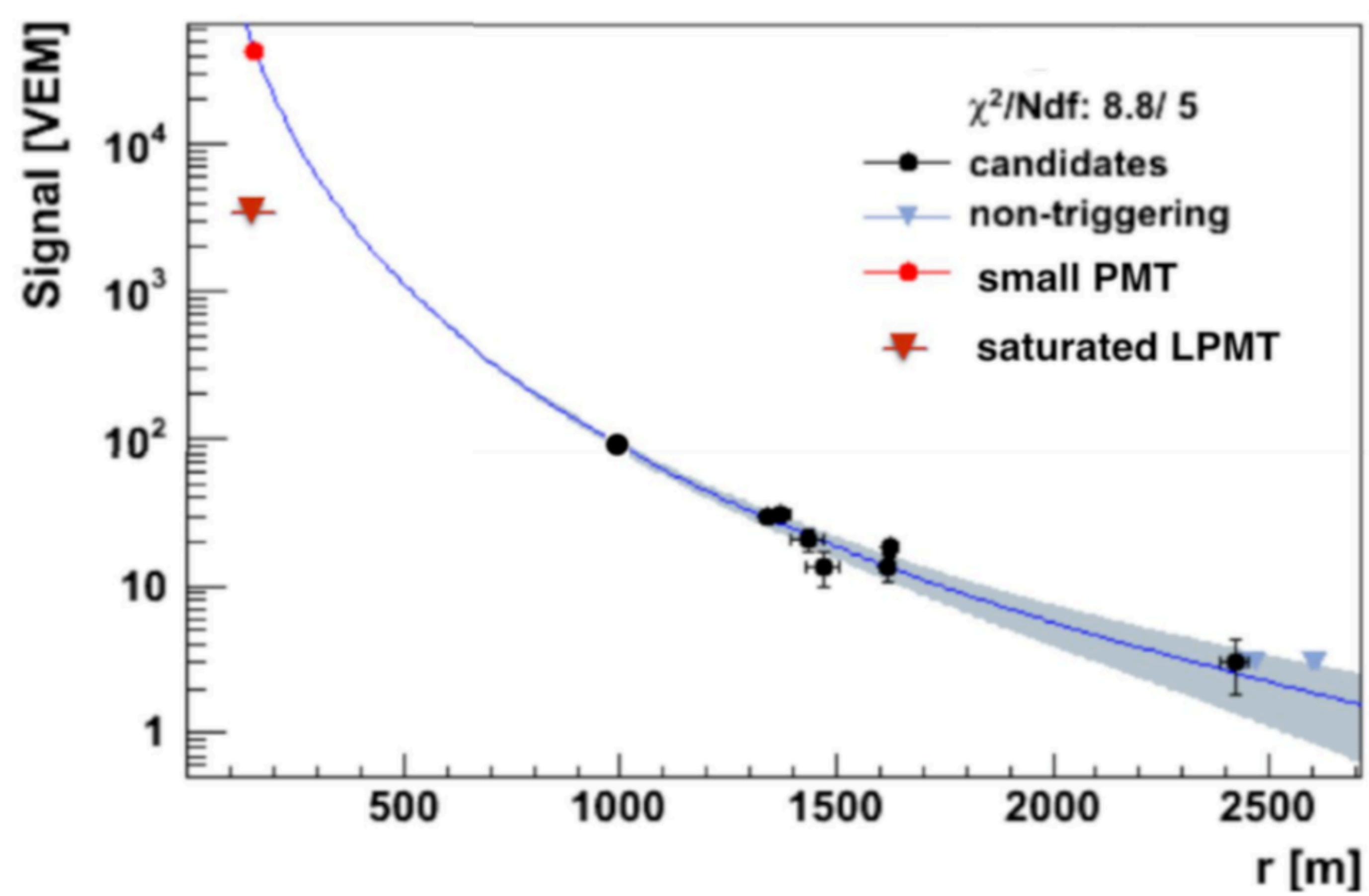


Data from the Engineering Array

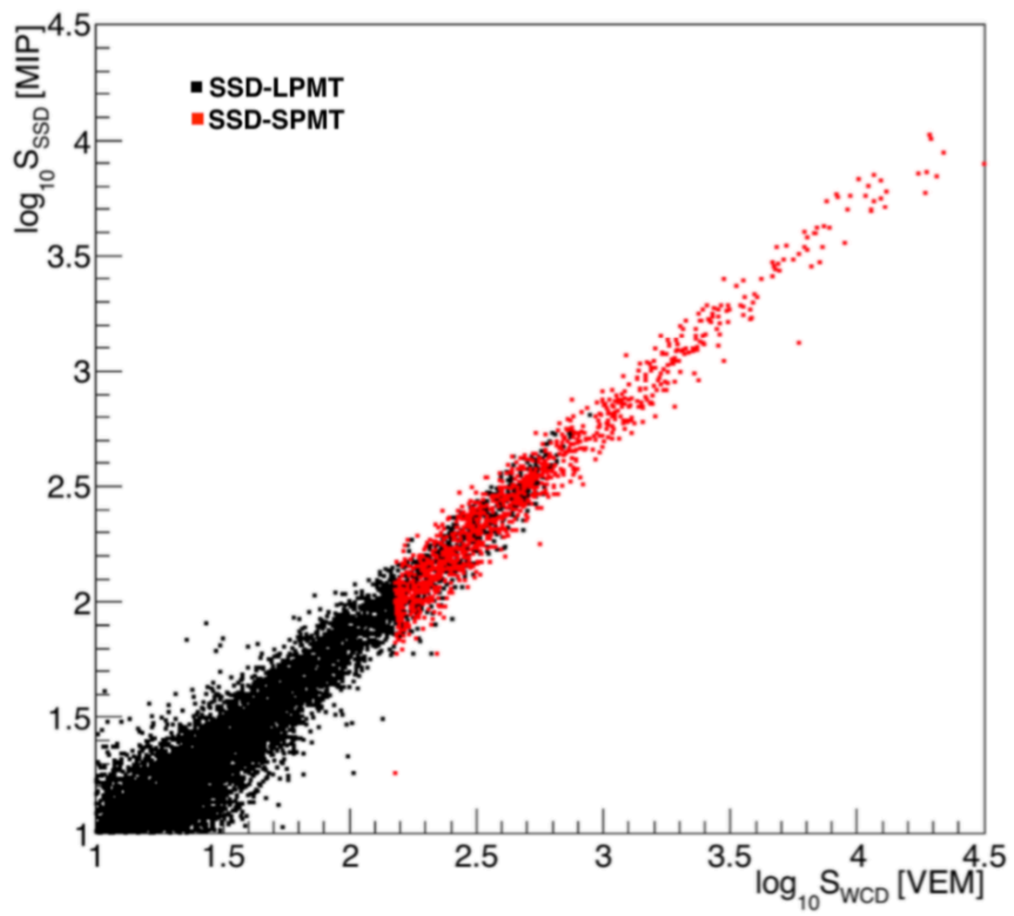


Extended charge spectrum in WCD

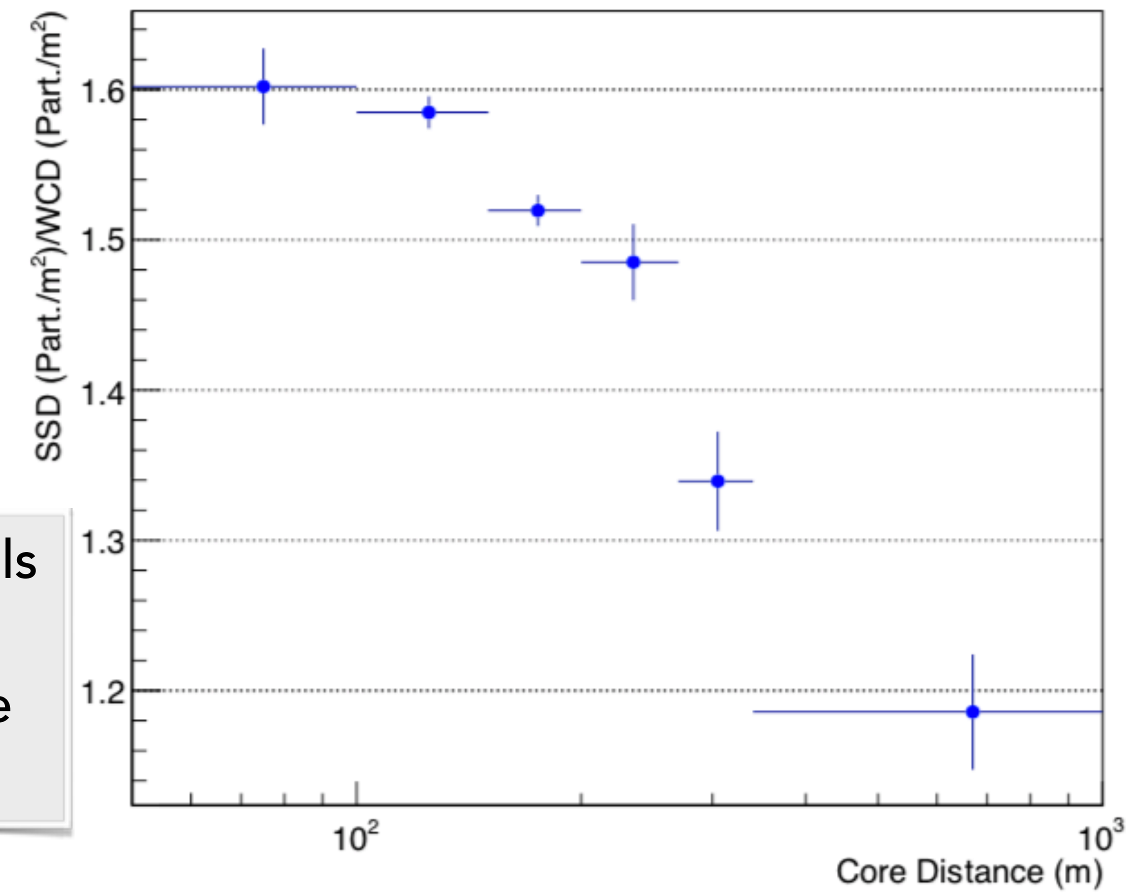
LDF for one event in the Engineering Array



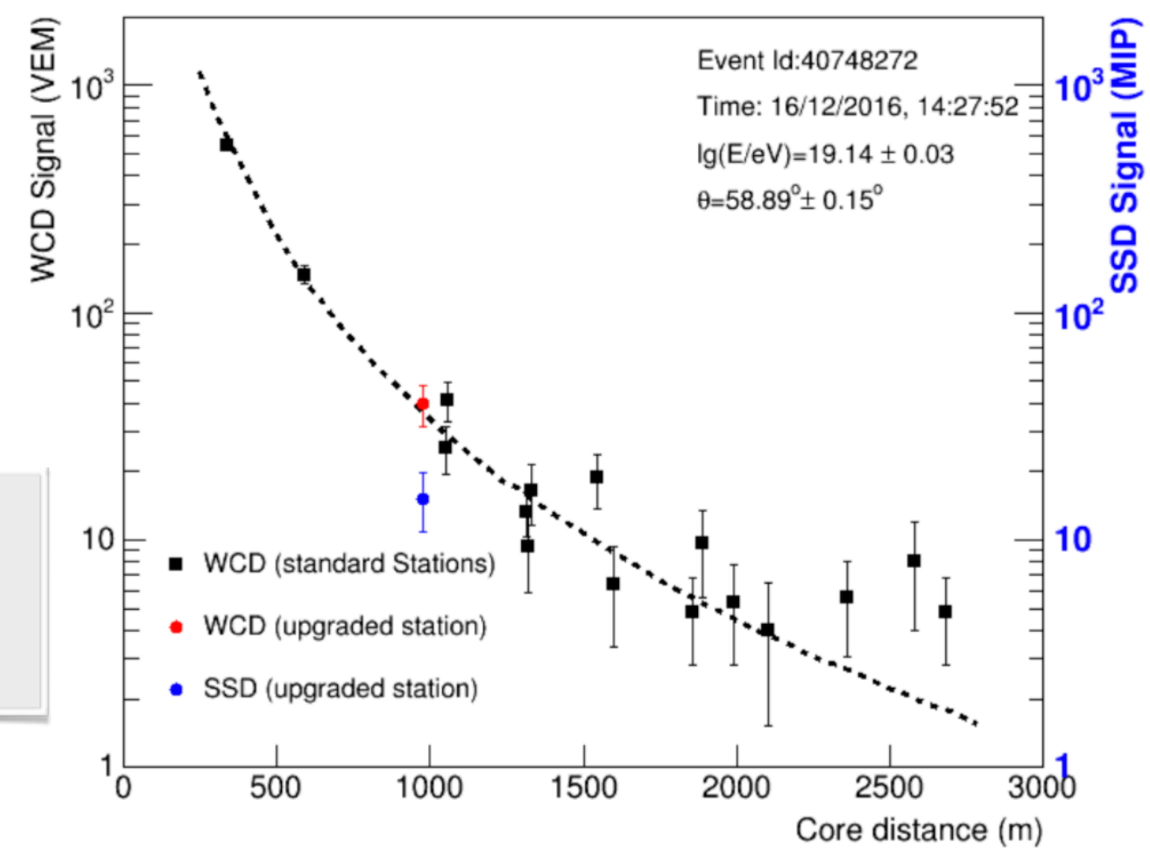
Data from the Engineering Array



Correlation of calibrated signals in SSD and in WCD



Ratio of signals in SSD and WCD vs core distance



LDF for a single event in standard stations (black) wrt upgraded ones (red)

Conclusion

Main aims of the upgrade

Origin of flux suppression and composition in the extreme energy region.

Evaluation of the proton contribution above ~6 10^{19} eV for charged particle astronomy

Test of hadronic interactions and search for non standard particle physics at EHE

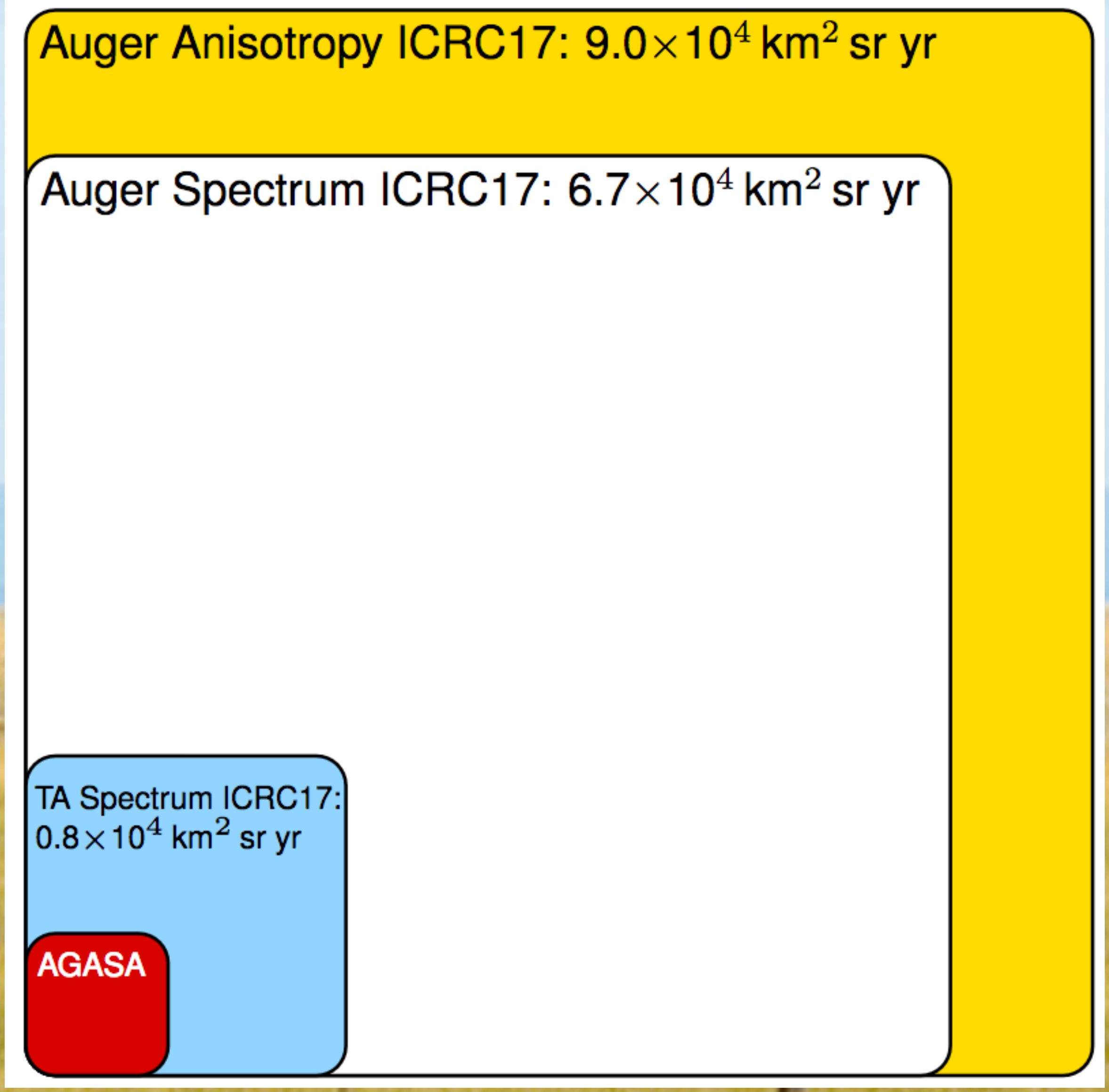
AugerPrime can address these open questions

- November 2015: MoU signed for the extension of the Observatory data taking to 2025
- April 2016: upgrade approved by funding Agencies
- Autumn 2016: Engineering Array taking data
- Autumn 2017: definition of final detectors and start of construction
- currently:
  - >150 SSD detections ready in Malargüe: deployment starting
  - pre-production UUB on test in the field
  - >200 SPMTs ready
- full deployment foreseen end of 2019
- ***2020-2025 : Data taking (up to 40000 km² sr yr)***

Backup slides

Full efficiency
SD1500 : >3 10^{18} eV
SD750 >3 10^{17} eV

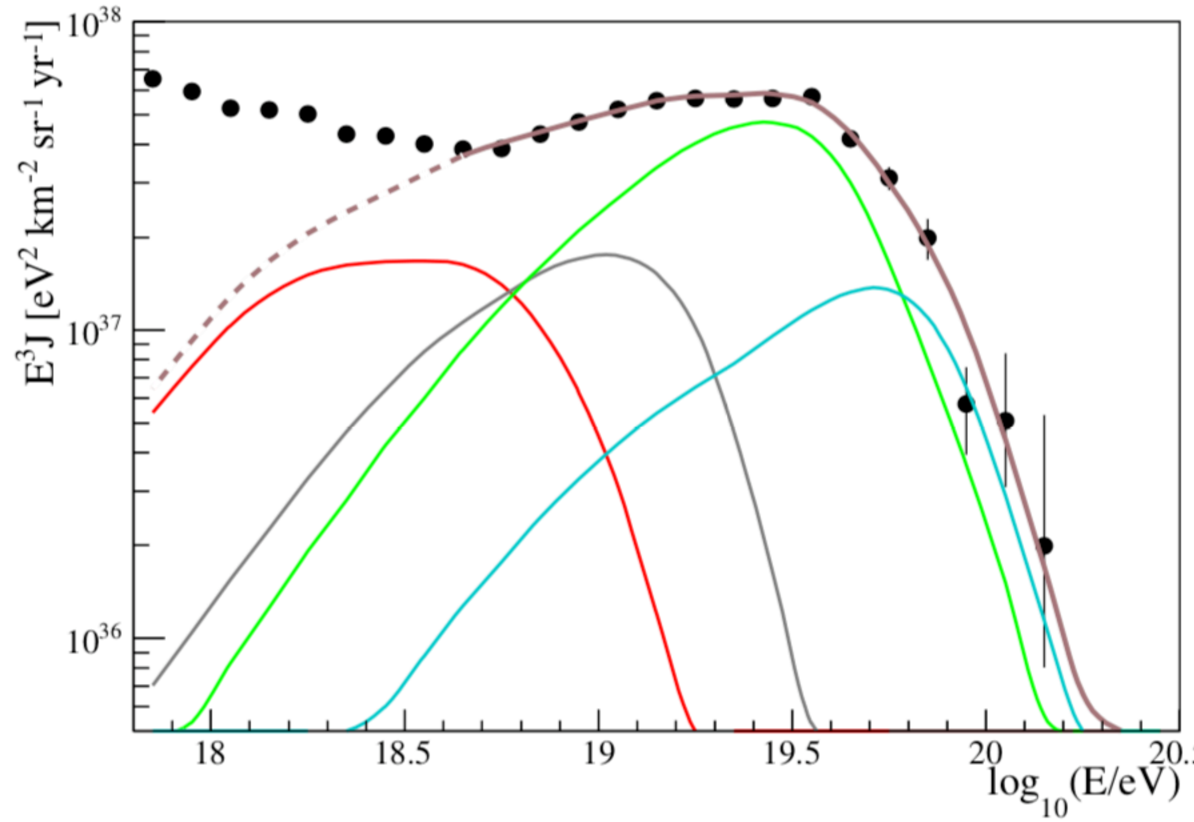
85% coverage of the celestial sphere

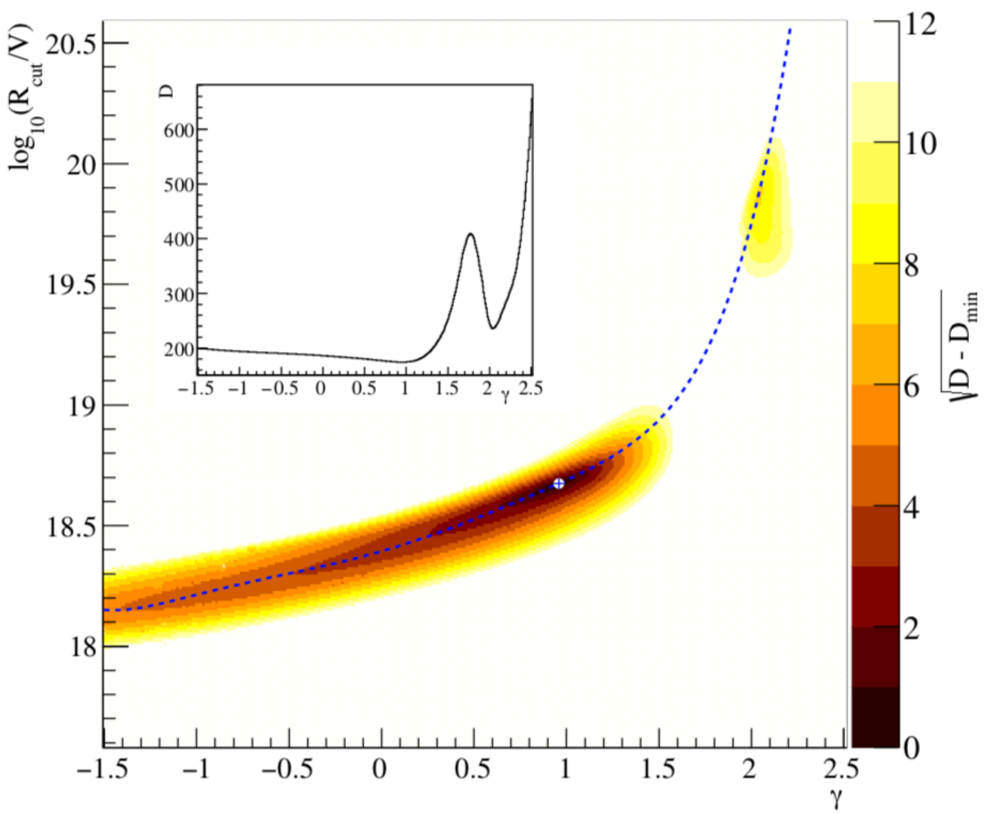


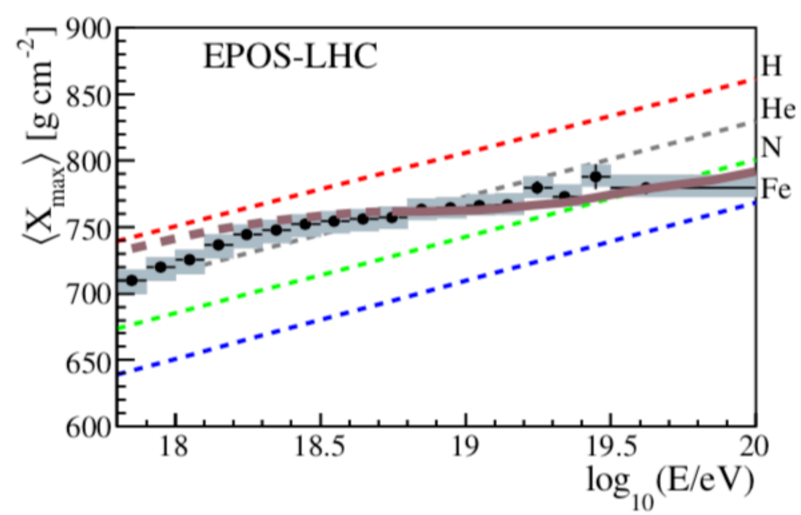
SD	
SD annual exposure, $\theta < 60°$	$\sim$5500 km^2 sr yr
T3 rate	0.1 Hz
T5 events/yr, $E > 3$ EeV	$\sim$14,500
T5 events/yr, $E > 10$ EeV	$\sim$1500
Reconstruction accuracy (S_{1000})	22% (low E) to 12% (high E)
Angular resolution	1.6° (3 stations)
	0.9° (> 5 stations)
Energy resolution	16% (low E) to 12% (high E)
FD	
On-time	$\sim$15%
Rate per building	0.012 Hz
Rate per HEAT	0.026 Hz
Hybrid	
Core resolution	50 m
Angular resolution	0.6°
Energy resolution (FD)	8%
X_{max} resolution	< 20 g/cm^2

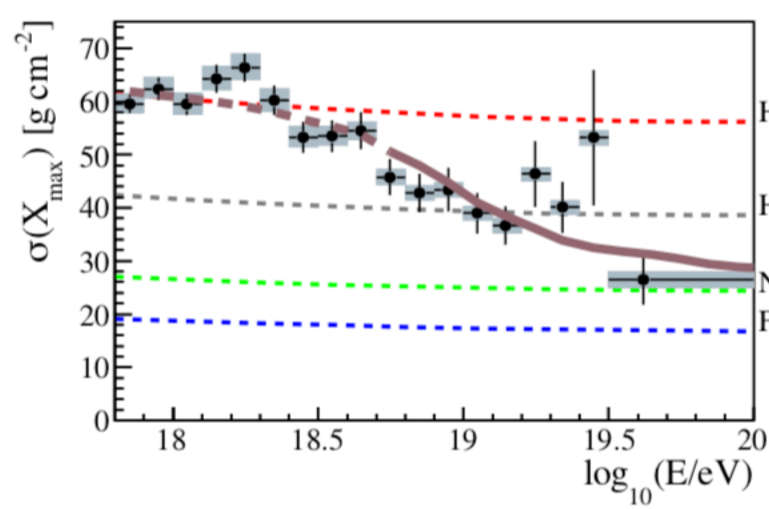
Combined fit

- combined fit of spectrum and X_{max} distributions above the ankle
  low maximum injection energy
  hard spectra
  heavier composition for increasing E





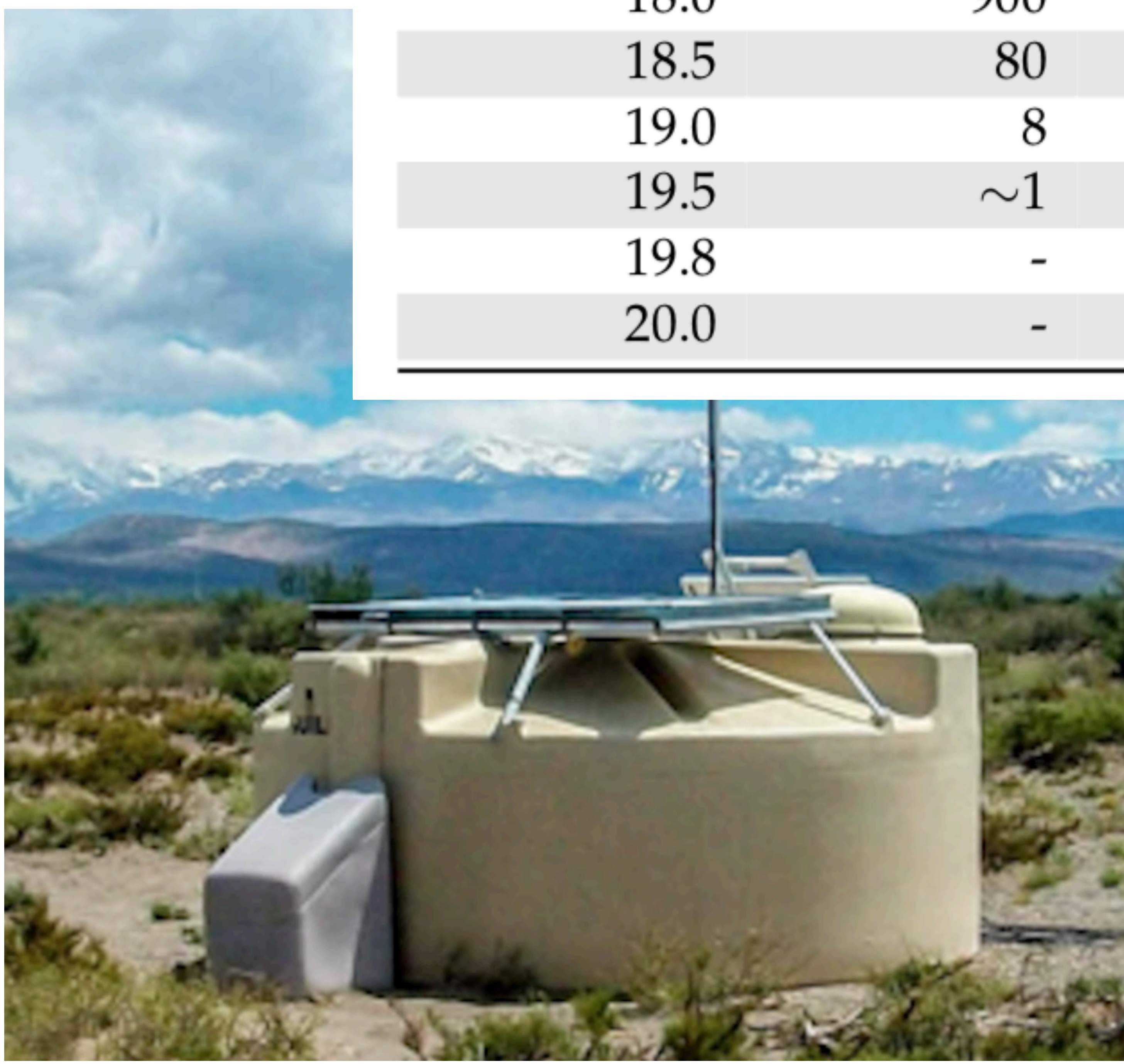




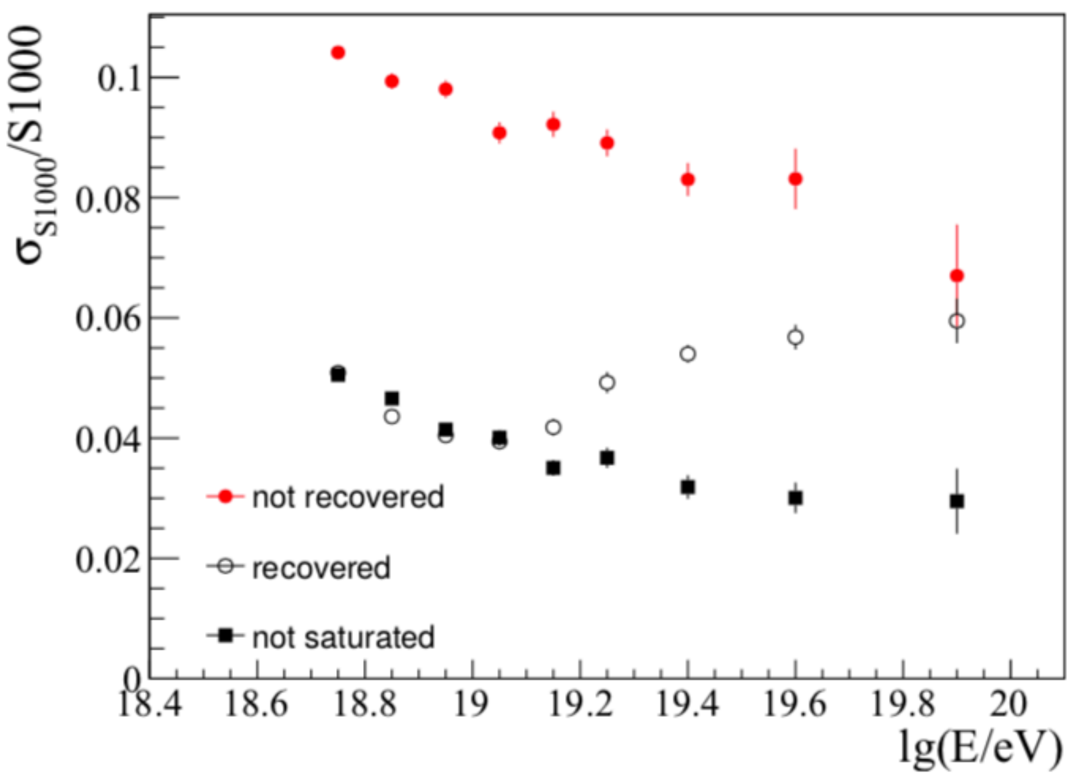
Pierre Auger Coll., JCAP04 (2017) 038

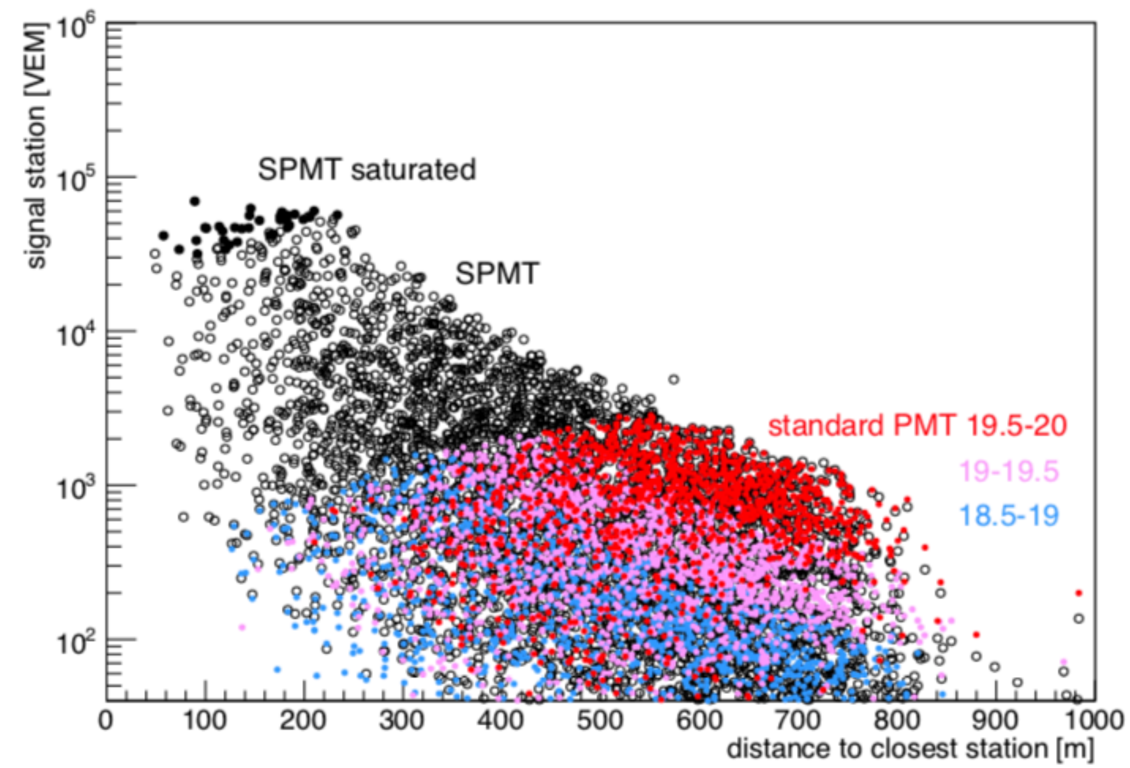
AugerPrime

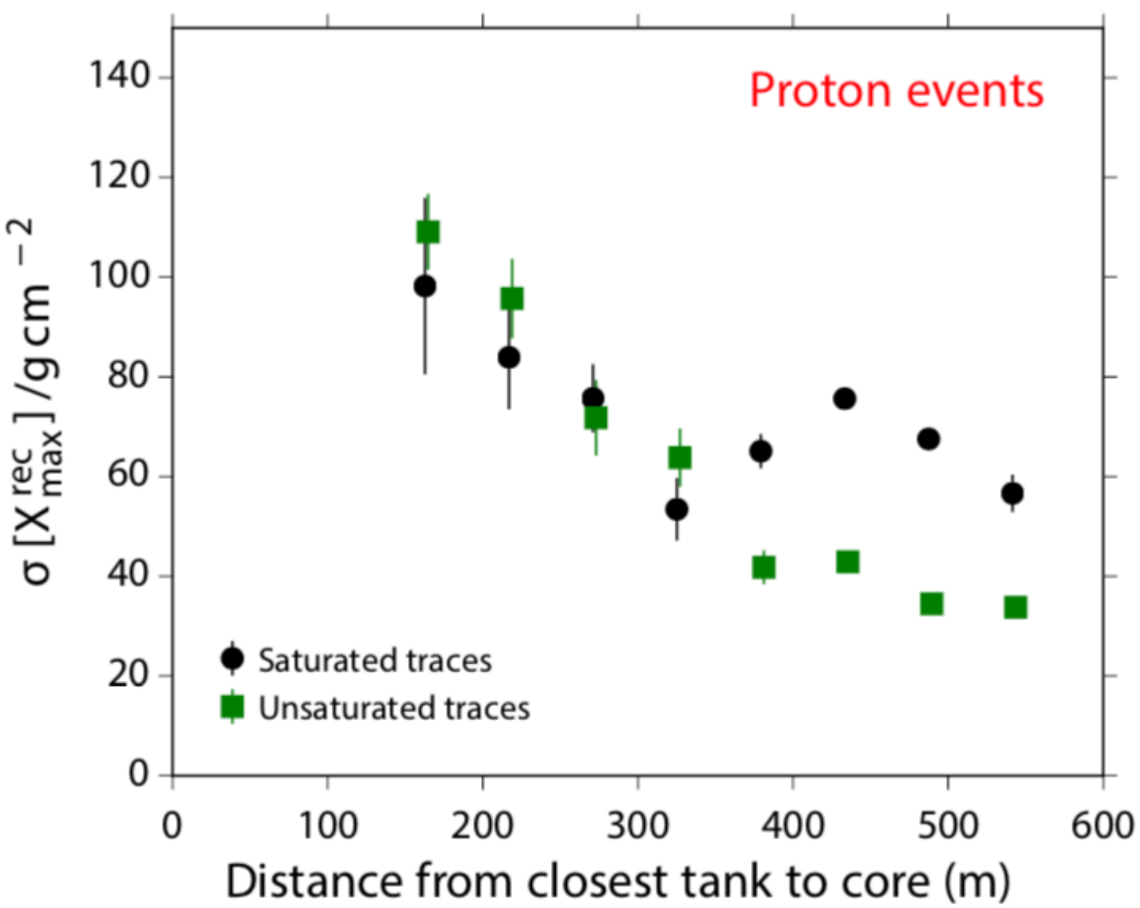
$\log_{10}(E/\mathrm{eV})$	$\mathrm{d}N/\mathrm{d}t\vert_{\mathbf{infill}}$ $[\mathrm{yr}^{-1}]$	$\mathrm{d}N/\mathrm{d}t\vert_{\mathbf{SD}}$ $[\mathrm{yr}^{-1}]$	$N\vert_{\mathbf{infill}}$ [2018-2024]	$N\vert_{\mathbf{SD}}$ [2018-2024]
17.5	11500	-	80700	-
18.0	900	-	6400	-
18.5	80	12000	530	83200
19.0	8	1500	50	10200
19.5	$\sim$1	100	7	700
19.8	-	9	-	60
20.0	-	$\sim$1	-	$\sim$9

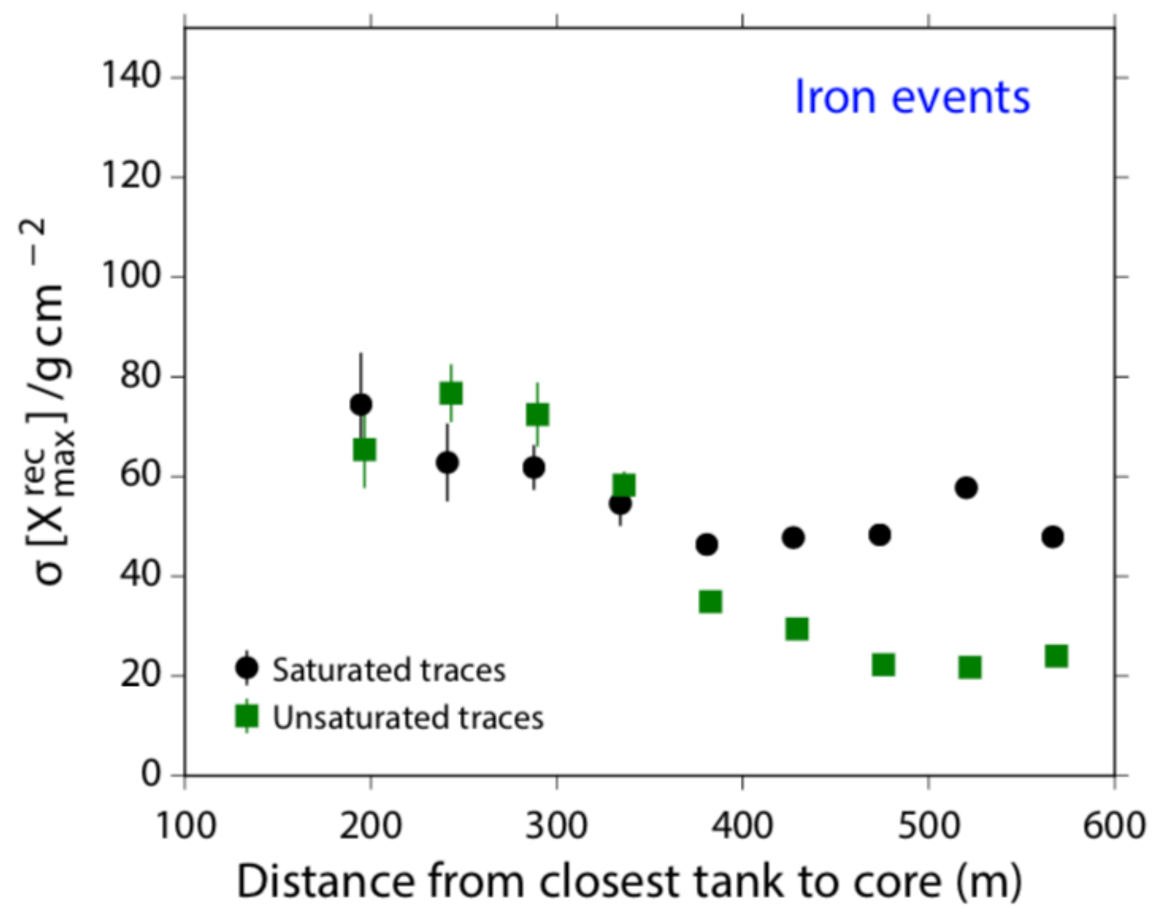


Unsaturated stations

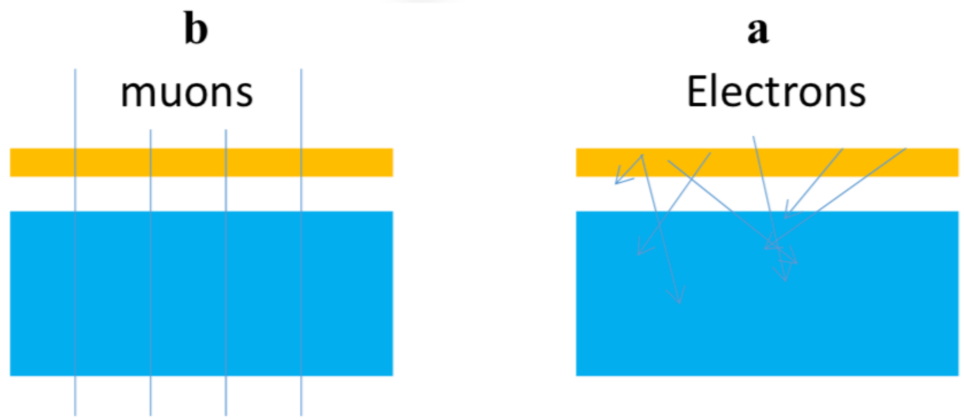








Measuring the muon content - 1



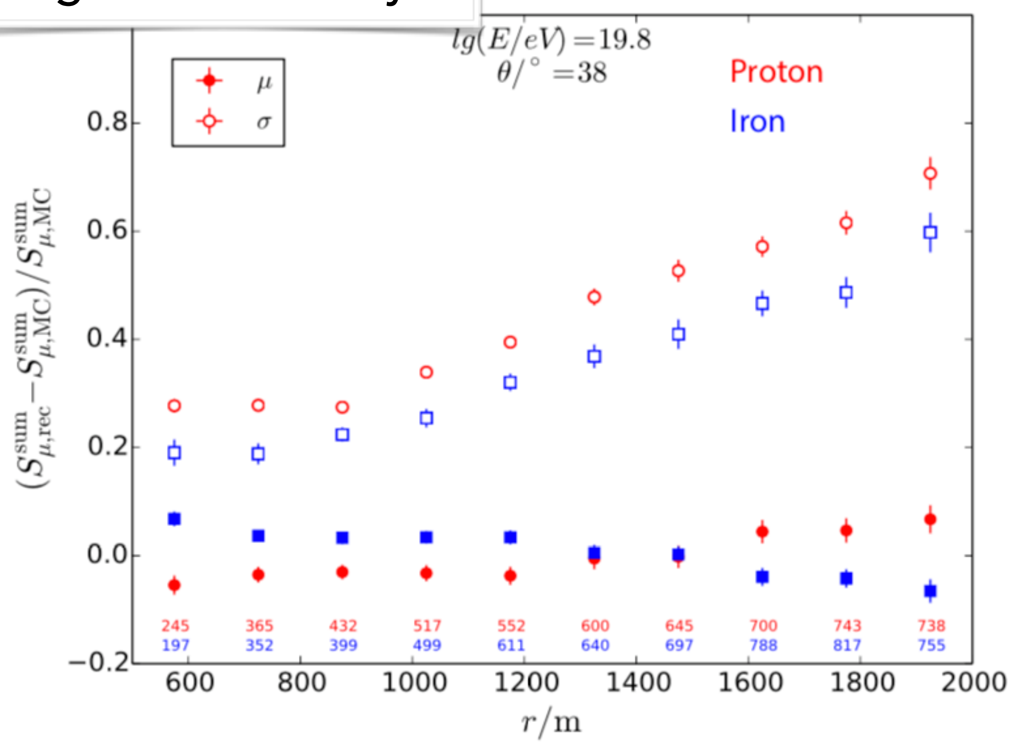
$$\begin{pmatrix} S_{\mathrm{SSD}} \\ S_{\mathrm{WCD}} \end{pmatrix} = \begin{pmatrix} \lambda\, \mathcal{A}_{\mathrm{SSD}} & \mathcal{A}_{\mathrm{SSD}} \\ \beta\, \mathcal{A}_{\mathrm{WCD}} & \mathcal{A}_{\mathrm{WCD}} \end{pmatrix} \begin{pmatrix} \mathcal{F}_{\mathrm{em}} \\ \mathcal{F}_{\mu} \end{pmatrix}$$

Matrix Inversion Method

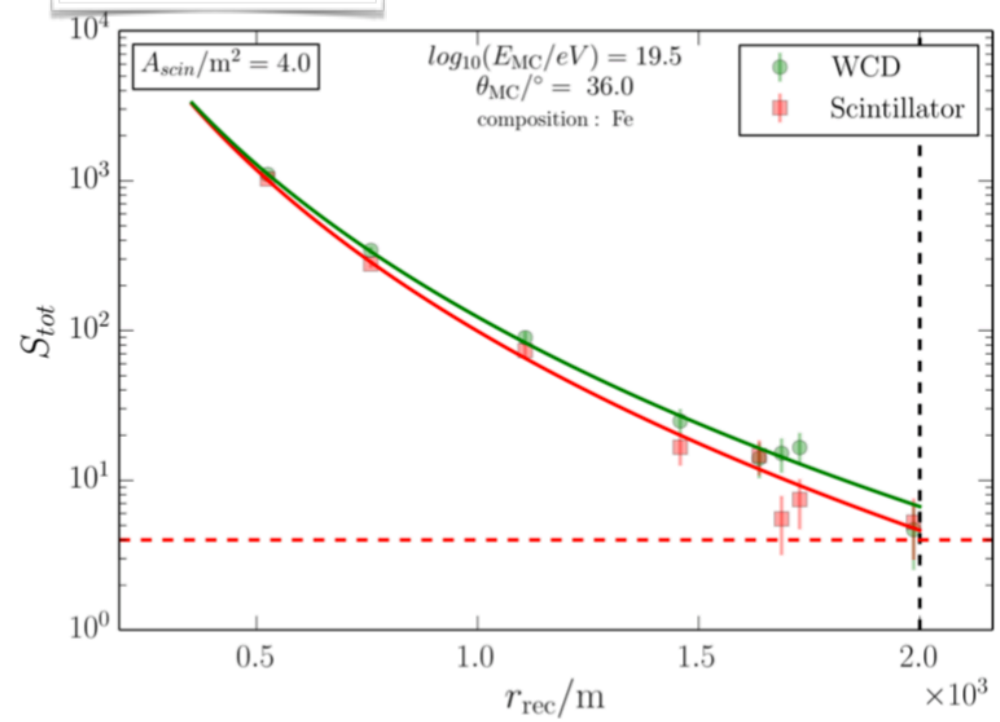
Figure of merit

$$f_{\mathrm{p,Fe}} = \frac{|\langle S_{\mathrm{Fe}}\rangle - \langle S_{\mathrm{p}}\rangle|}{\sqrt{\sigma(S_{\mathrm{Fe}})^2 + \sigma(S_{\mathrm{p}})^2}}$$

Single station analysis



LDF analysis



Resolution at $10^{19.8}$ eV

$$\left.\frac{\sigma[S_\mu(800)]}{\langle S_\mu(800)\rangle}\right|_{\mathrm{proton}} \approx 22\%$$

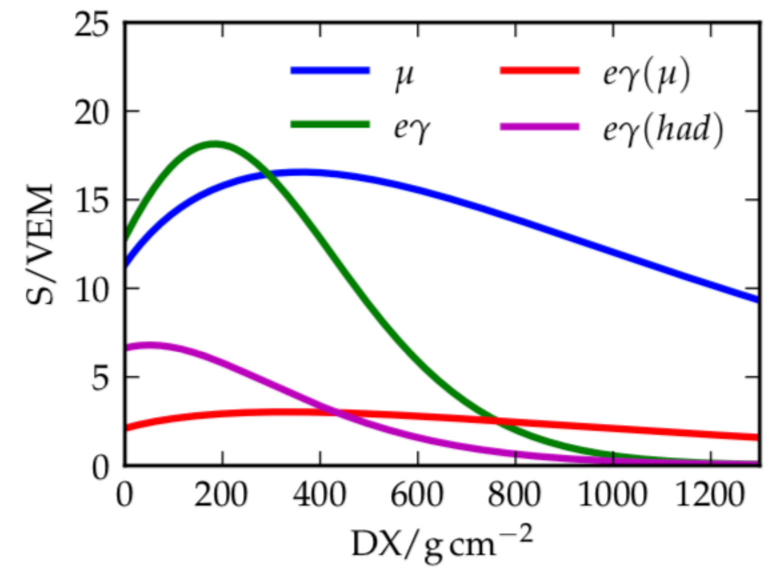
$$\left.\frac{\sigma[S_\mu(800)]}{\langle S_\mu(800)\rangle}\right|_{\mathrm{iron}} \approx 14\%$$

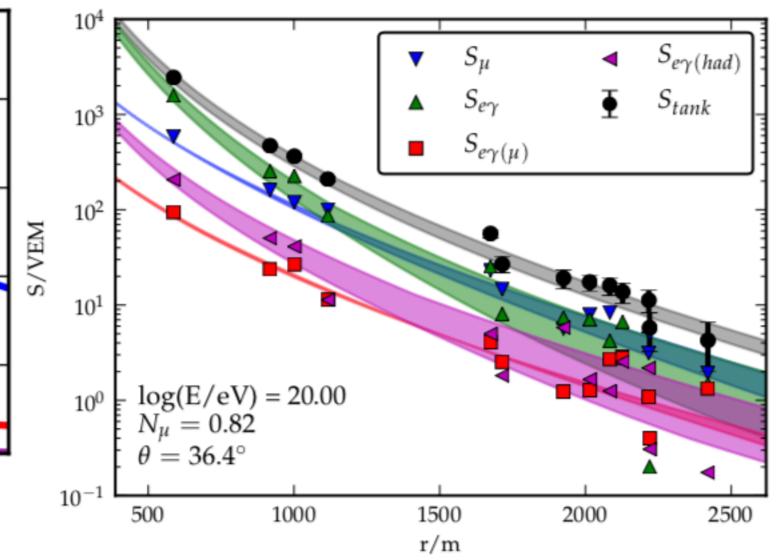
$$f_{\mathrm{p,Fe}} \sim 1.5$$

Measuring the muon content - 2

Universality Method

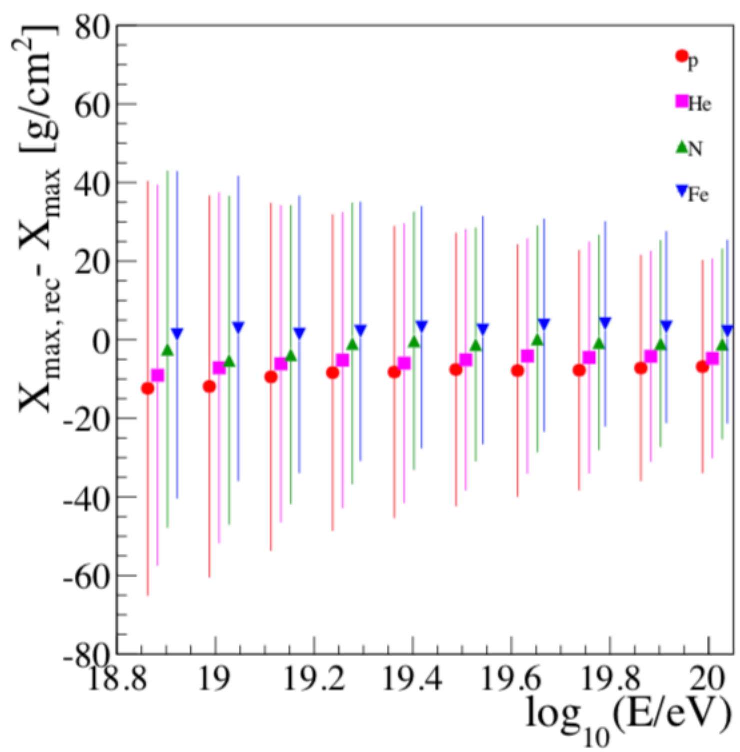
$$
\begin{aligned}
S_{\mathrm{tot}} = \; & S_{\mathrm{em}}(r, DX, E) \\
& + N_{\mu}^{\mathrm{rel}} \left[S_{\mu}^{\mathrm{ref}}(r, DX, E) + S_{\mathrm{em}}^{\mu}(r, DX, E) \right] \\
& + (N_{\mu}^{\mathrm{rel}})^{\alpha} S_{\mathrm{em}}^{\text{low-energy}}(r, DX, E)
\end{aligned}
$$

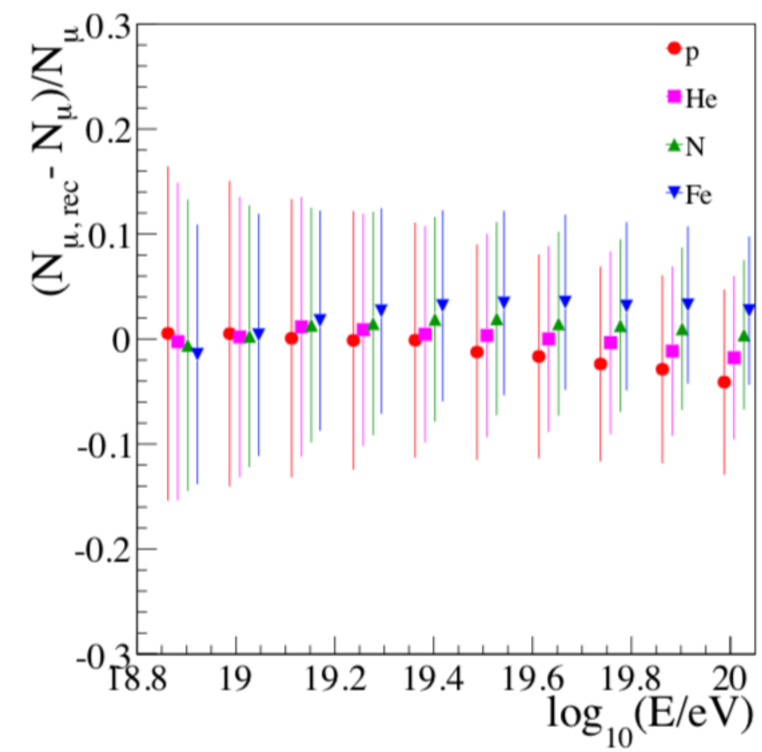




Event-by event reconstruction of X_{max} and N_{μ} using SD-only data:

- the temporal structure of signals
- the integrated signal





Model	Energy	Composition	Zenith angle	$f_{\mathrm{MF}}^{\mathrm{F}}$	$f_{\mathrm{MF}}^{\mathrm{Rec}}$
QGSJetII-04	63 EeV	Proton-Iron	21°	2.08	1.56
QGSJetII-04	63 EeV	Proton-Iron	38°	1.97	1.67
QGSJetII-04	63 EeV	Proton-Iron	56°	2.14	2.1

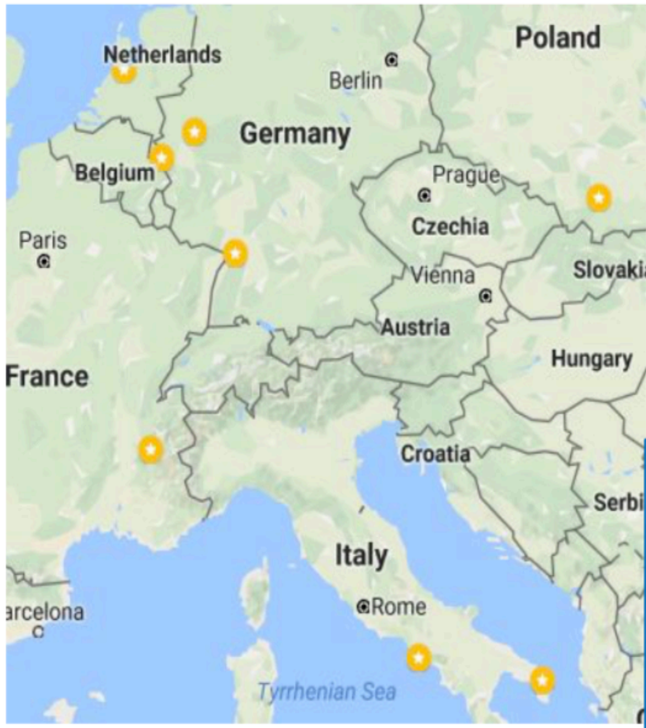
SSD Production

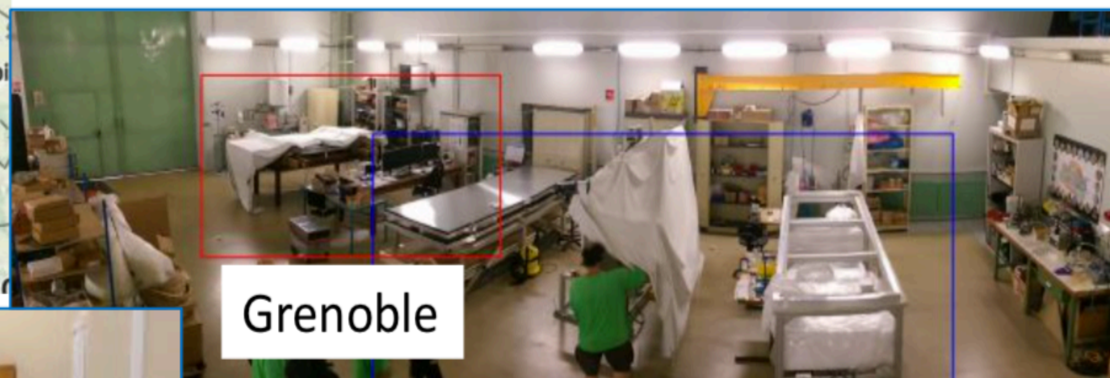
6 institutions are assembling the SSD modules: **Aachen, Grenoble, KIT, Krakow, Lecce, Nikhef**

2 institutions are preparing and validating the PMTs: **Napoli** and **Wuppertal**

Many institutions are involved in the design and testing of the new electronics

Started Oct. 2017





SPMT Production

NeOhm (Torino)

Base production

Hamamatsu

PMT+base assembly and tests

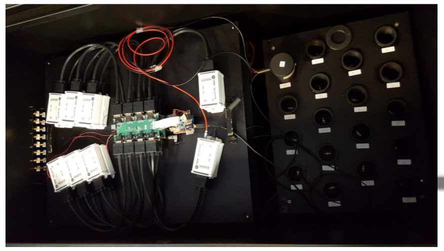
CMT (Torino)

Mechanics

Zener (Napoli)

assembly

INFN Naples



sPMT tests

CAEN

HVPS production

INFN Torino and Catania

HVPS tests

Final test & installation Malargue

Started June 2017