The AugerPrime science case

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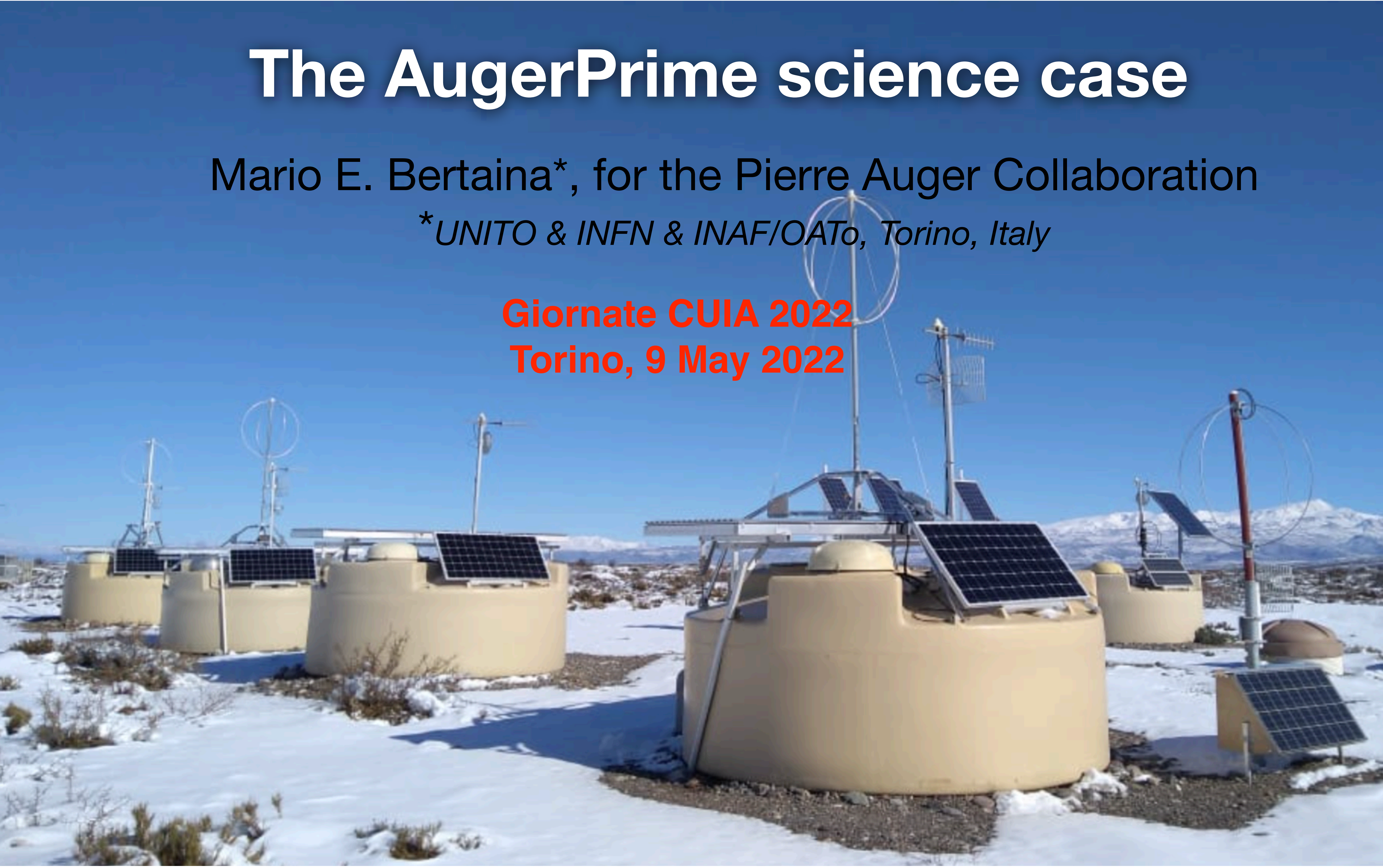


UNIVERSITÀ DEGLI STUDI DI TORINO
Universidad Nacional de San Martín
CONICET Consejo Nacional de Investigaciones Científicas y Técnicas
CUIA
INFN Istituto Nazionale di Fisica Nucleare
INAF Istituto Nazionale di Astrofisica

The AugerPrime science case

the quest for the sources

- photon limits exclude non astrophysical sources
- neutrino limits exclude many models of source evolution and injected composition
- large scale dipolar anisotropy shows that UHECRs above 8 EeV are extragalactic
- intermediate scale searches give hints for possible correlation to SBGs

the origin of the flux suppression

- combined information from spectrum+Xmax points to a source effect (Emax)
- propagation effects (GZK) may be present too

hadronic interaction properties /new physics

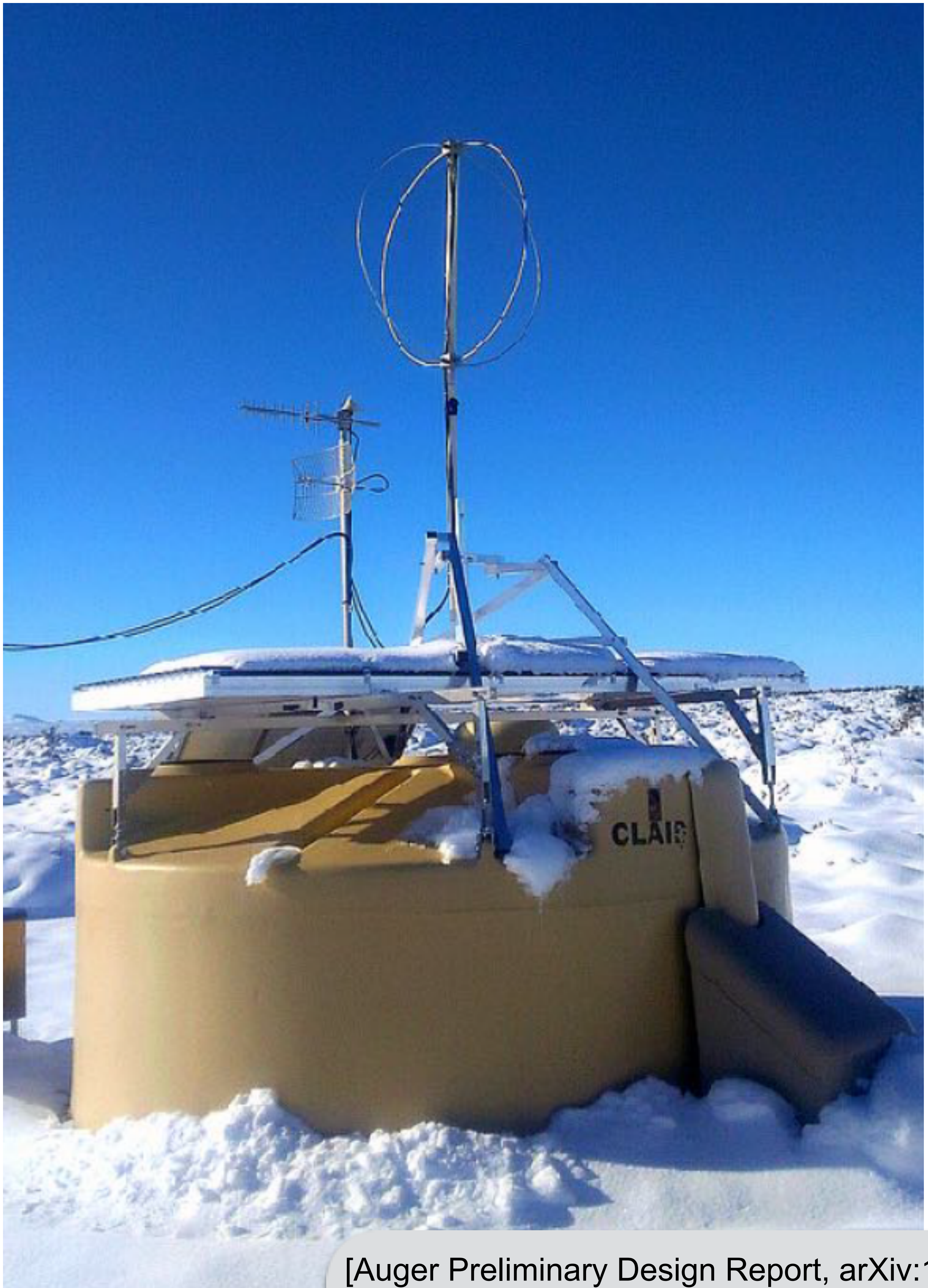
- extrapolations from lower energy do not allow for a coherent description of the shower components
- standard $\sigma_{p\text{-}Air}$
- limits on relativistic monopoles, LIV, etc.

Primary mass composition information at UHE

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

AugerPrime Design Report, arXiv:1604.03637

Elements of AugerPrime



[Auger Preliminary Design Report, arXiv:1604.03637]
[EPJ Web of Conf.210 (2019) 06002]

- **Surface Scintillator Detector (SSD)** to measure the mass composition in combination with the Water Cherenkov Detectors (WCD).

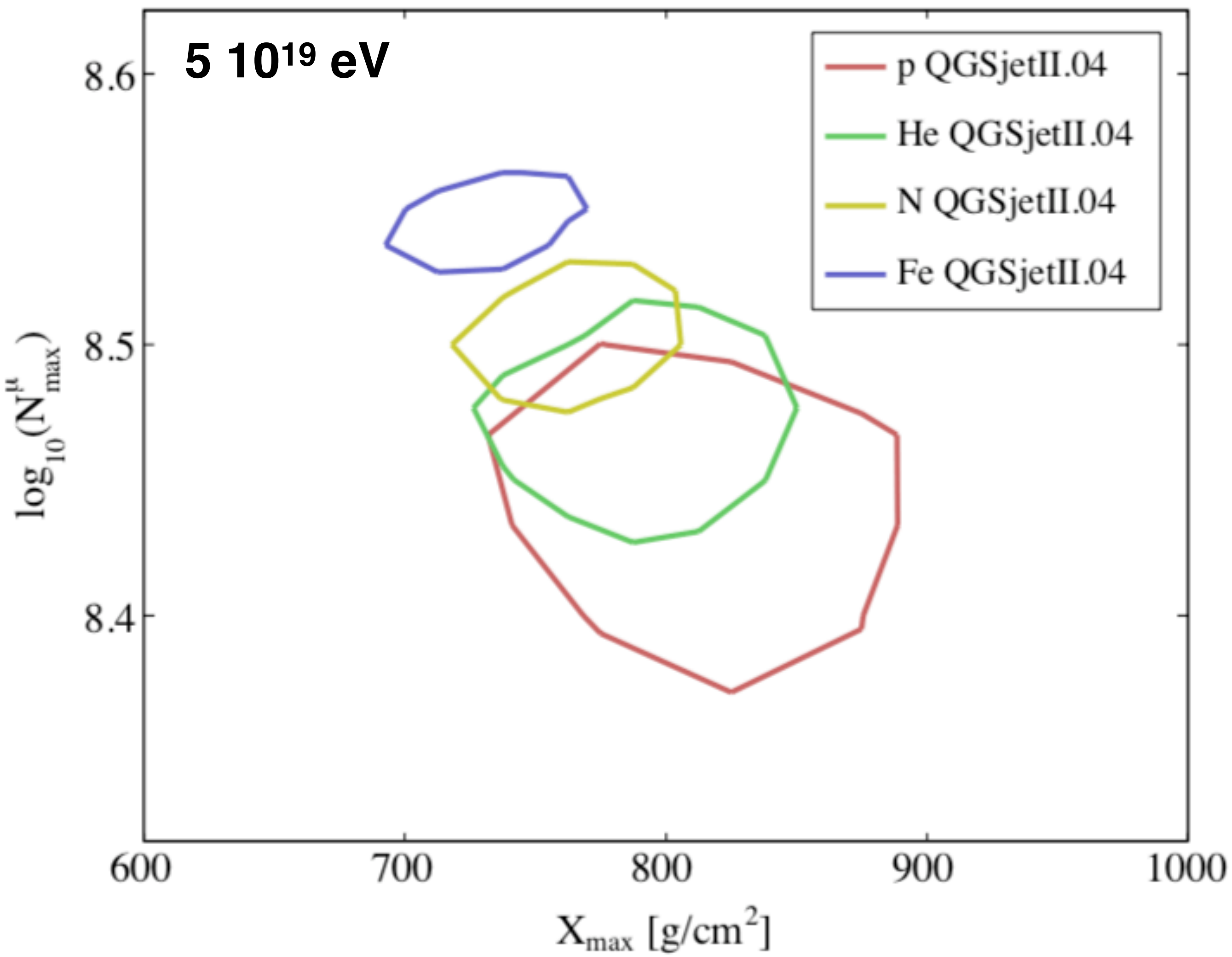
- **Upgraded Surface Detector Electronics** to improve the performance of the WCD

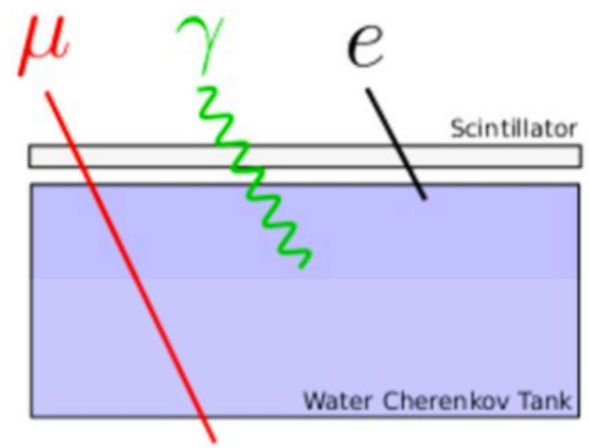
- **small PMT** to increase the dynamic range of the WCD.

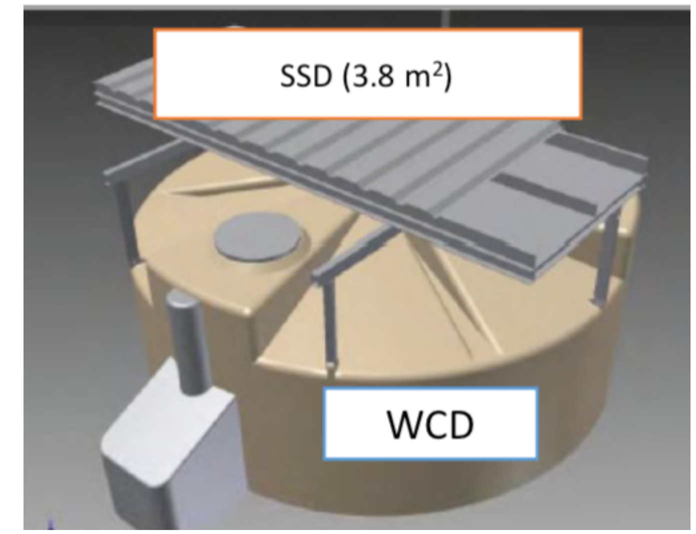
- **radio antenna** to measure the radio emission of showers in atmosphere (30-80 MHz)

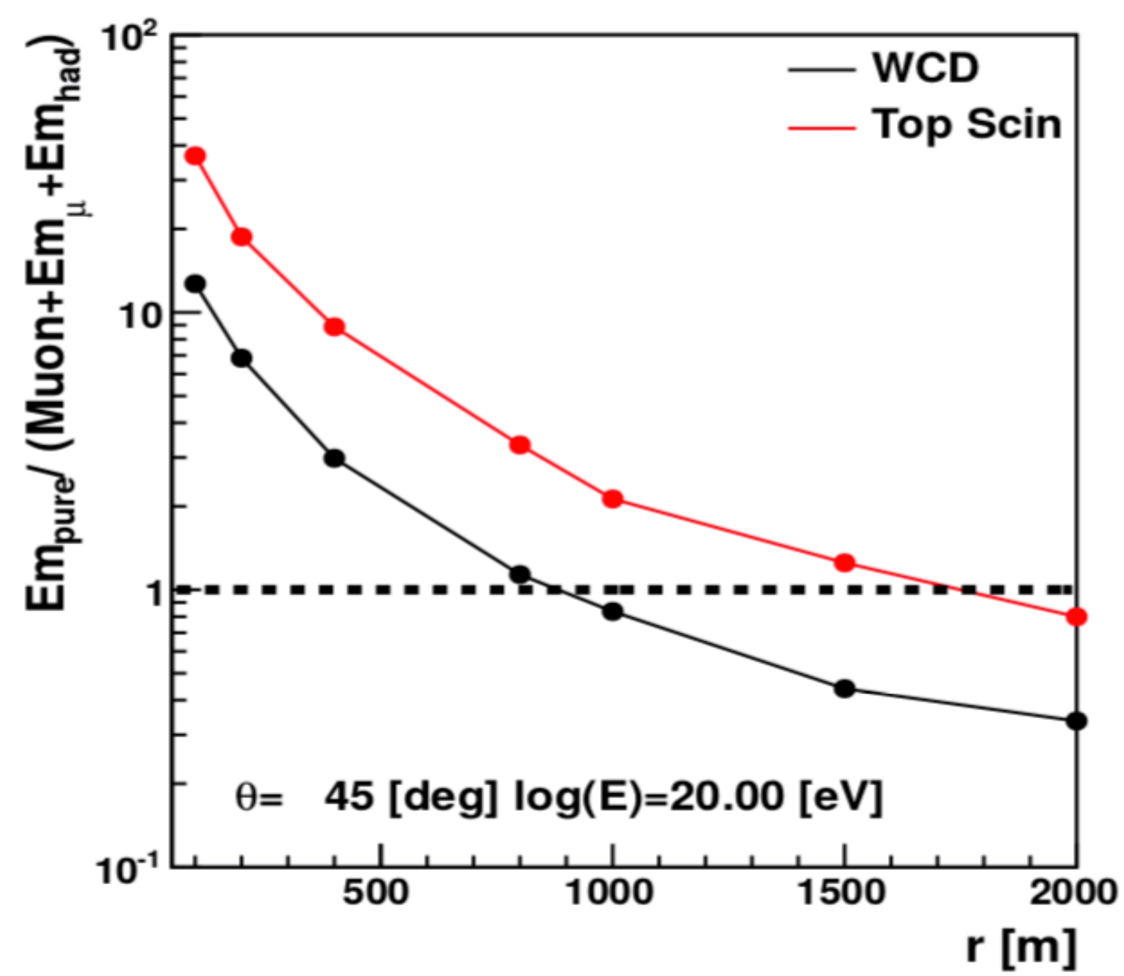
- **Underground Muon Detector (AMIGA)** to have a direct muon measurement and cross-check the SSD-WCD combined analysis (infill area, 61positions)

Composition sensitivity





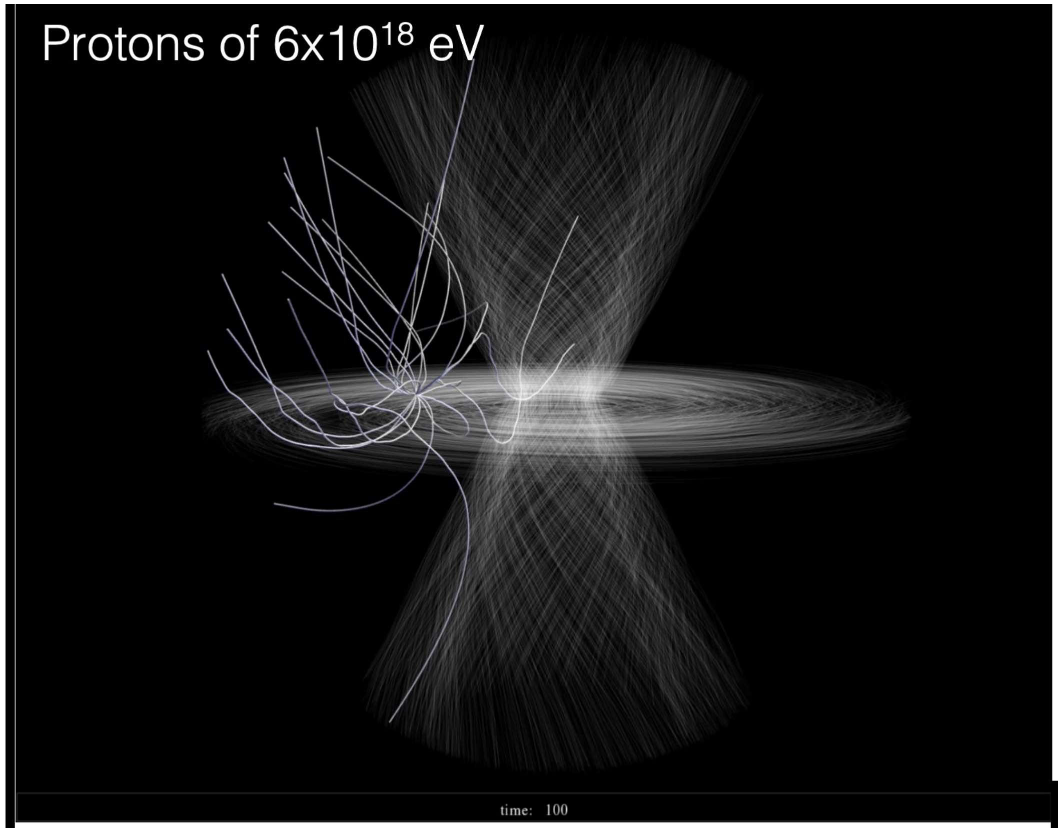




100% duty cycle of the SD
15% duty cycle of the FD

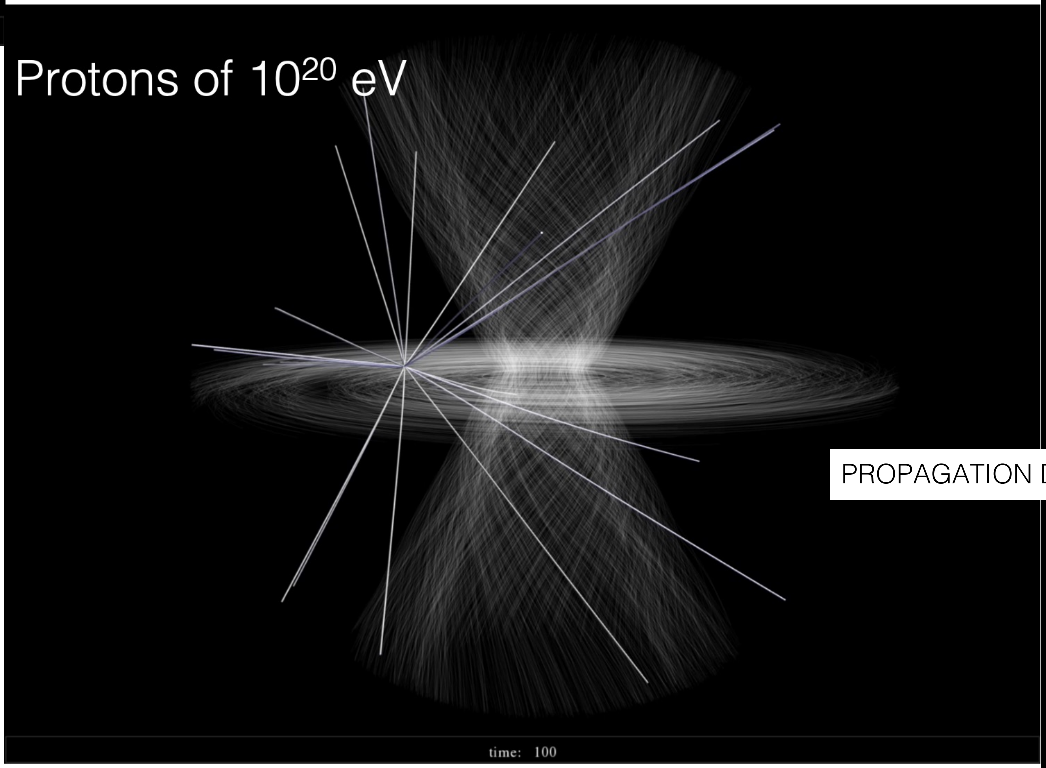
exploit the complementarity of response to particles to discriminate the muonic and electromagnetic components of extensive air showers

Iron of ~10^{20} eV



(G. Farrar & J. Sandstrom, NASA)

NOT POSSIBLE TO TRACK BACK THE SOURCES



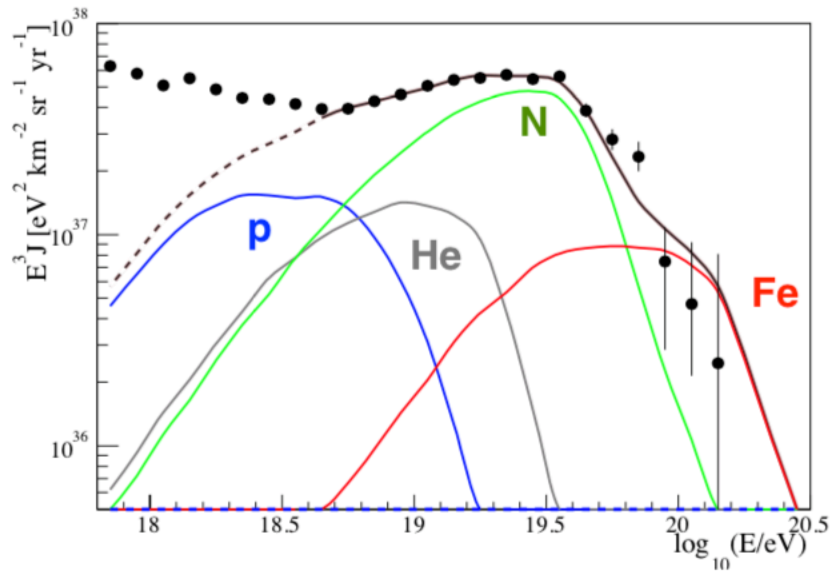
POSSIBLE TO TRACK BACK THE SOURCES

PROPAGATION DISTANCE (Mpc)

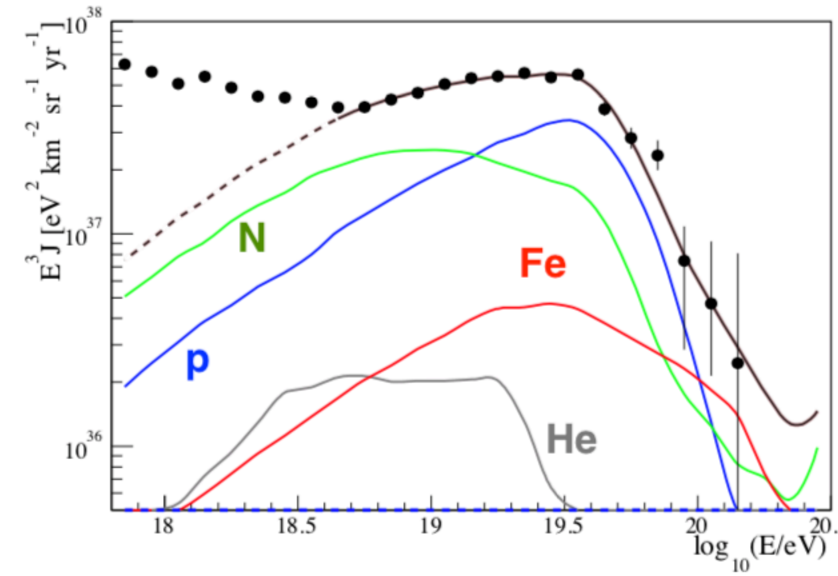
Discrimination of astrophysical scenarios

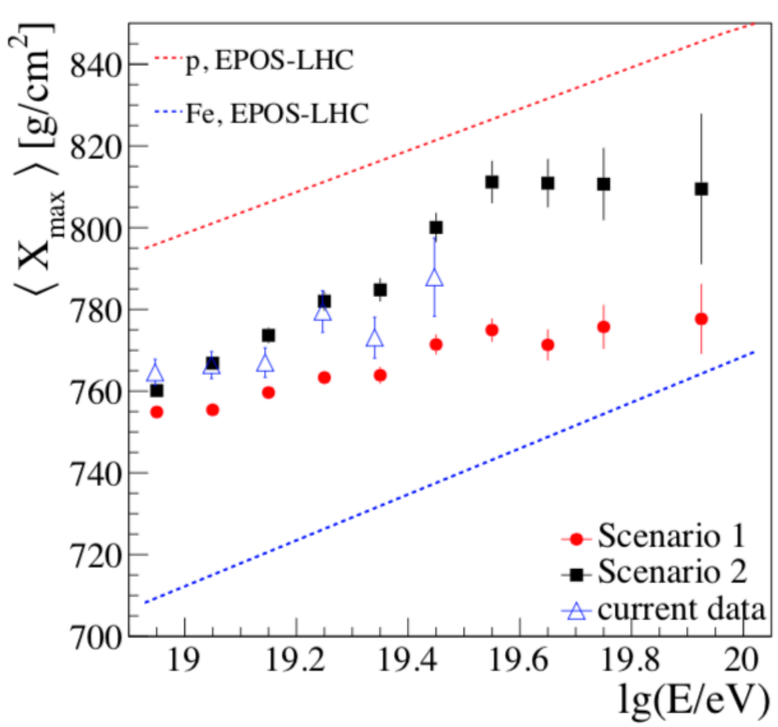
Simplified benchmark scenarios :

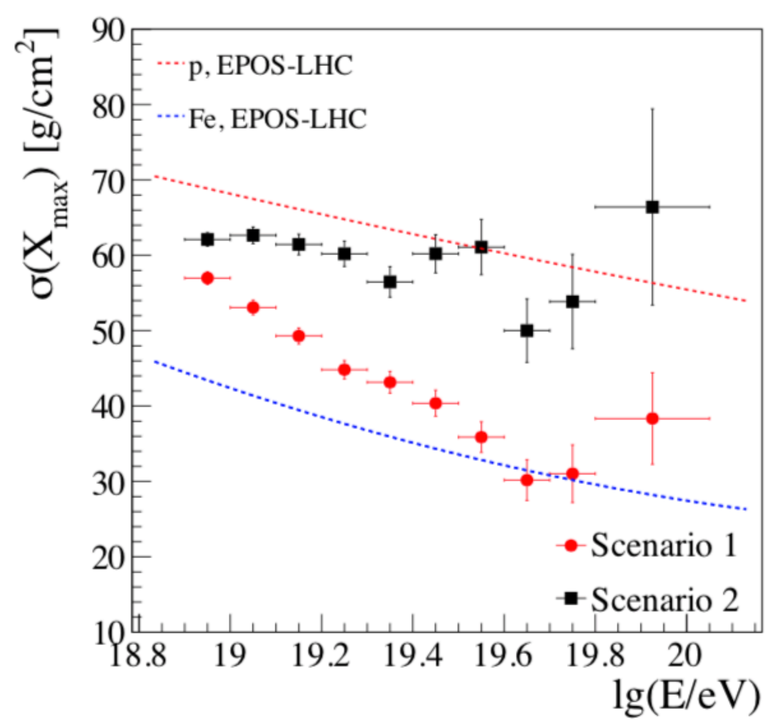
Scenario 1: maximum rigidity model

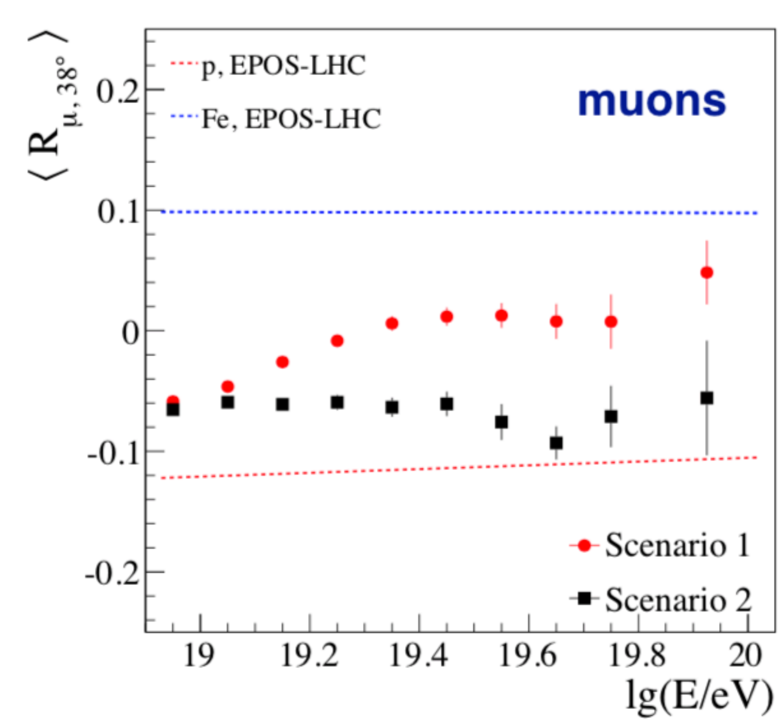


Scenario 2: photo-disintegration model

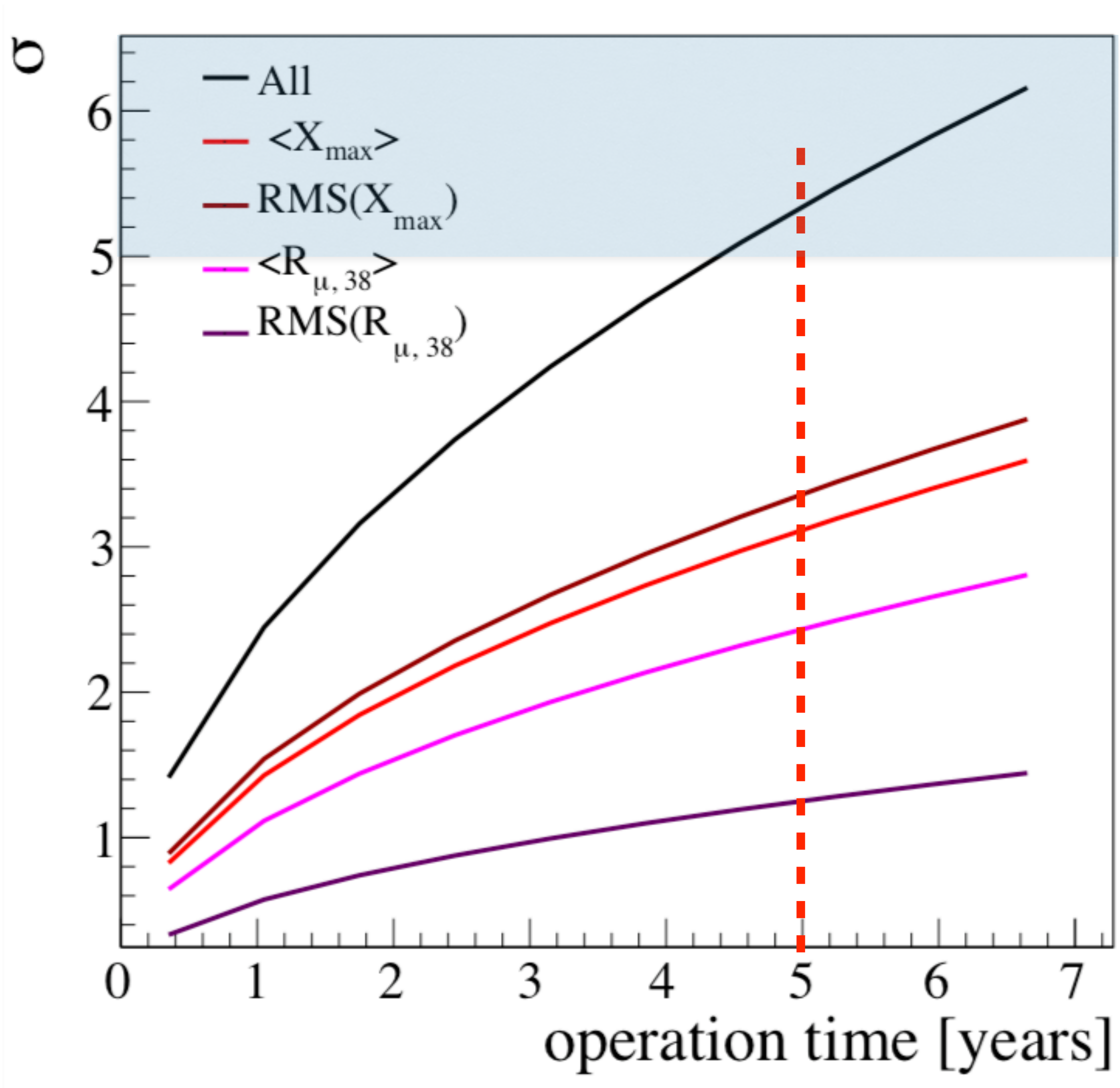








Sensitivity to proton fraction



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

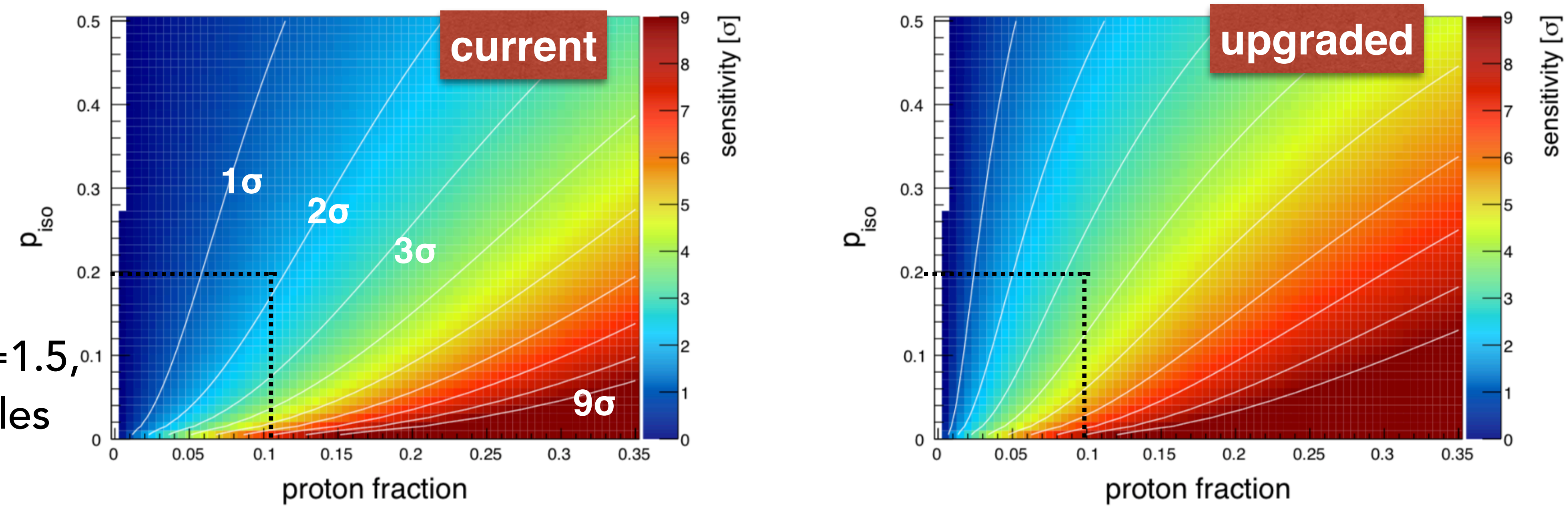
Composition-driven anisotropy search

Source correlation study (no specific assumptions)

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

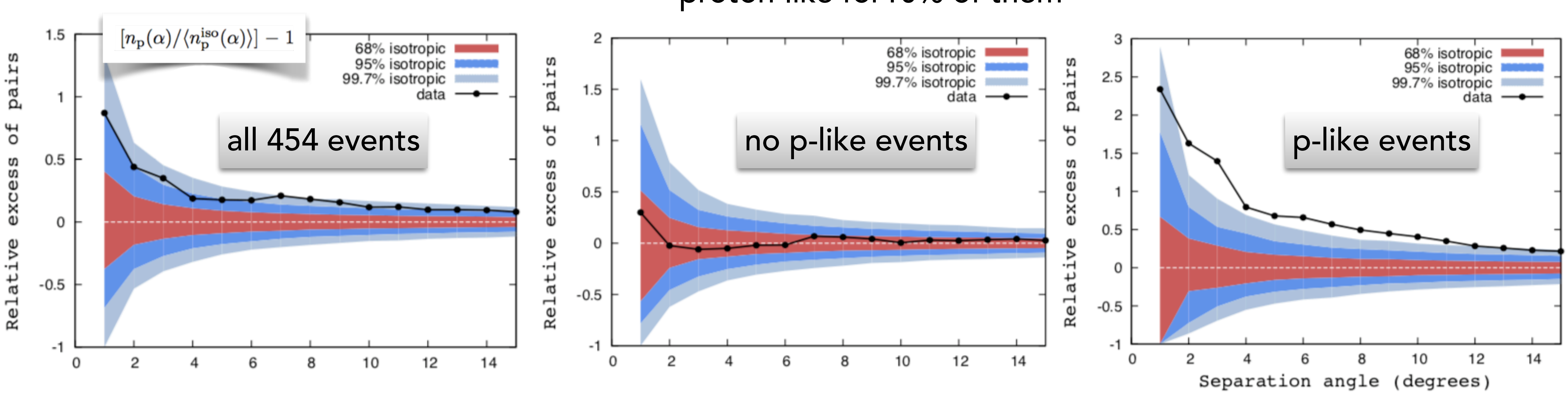
isotropic heavy elements
75% protons correlating

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

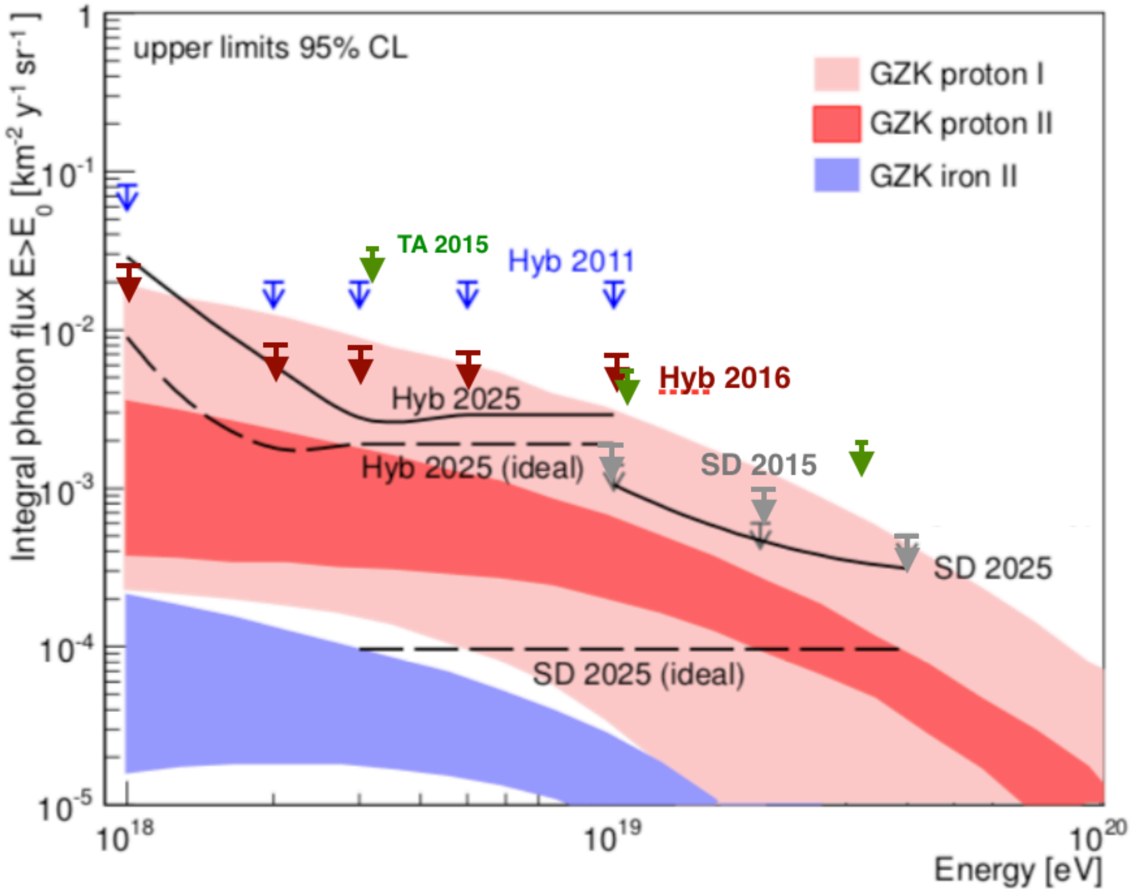


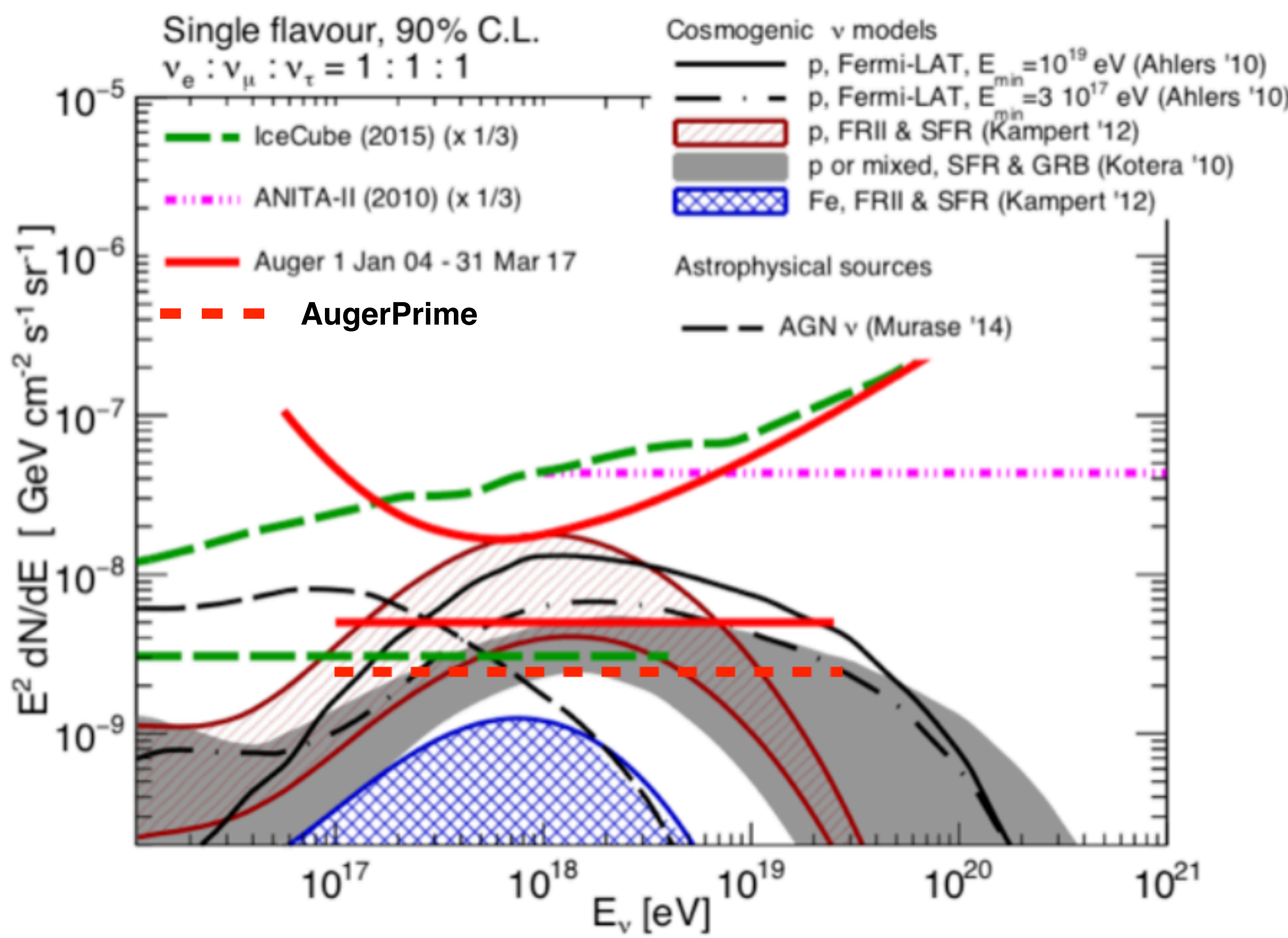
Specific source (AGN from Swift-BAT <100 Mpc) correlation study

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

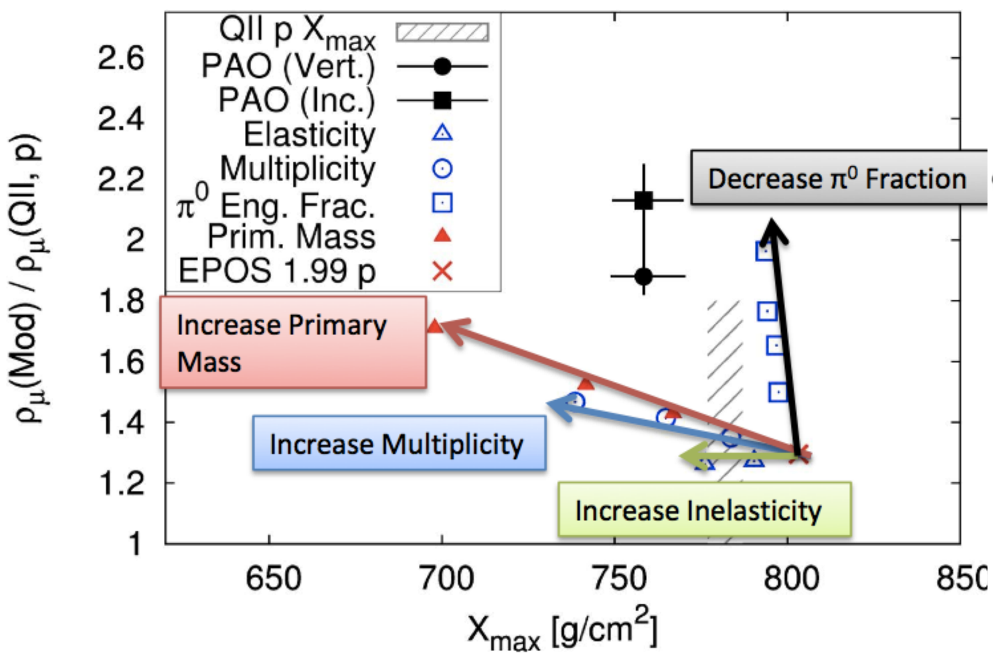
Expected improvements

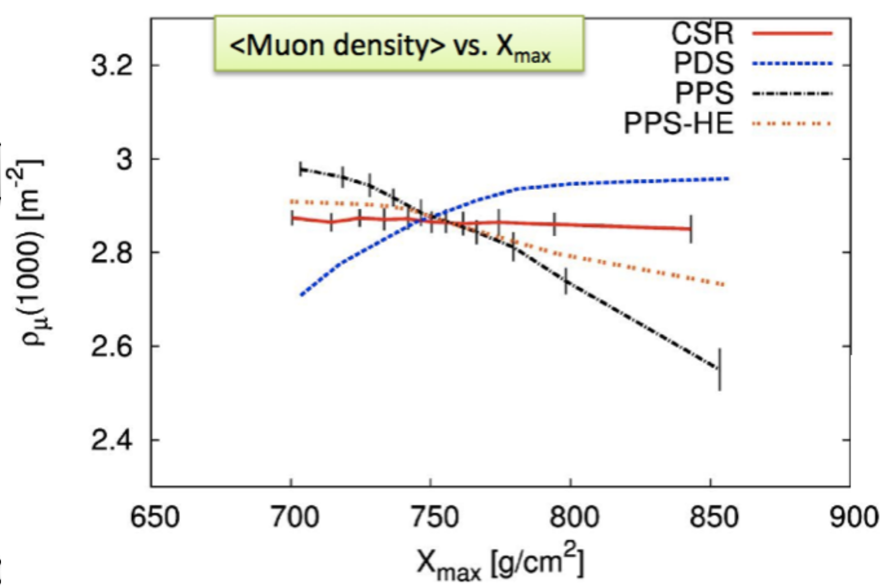
- increase in exposure
- largely improved discrimination power:
  - new triggers lowering the trigger thresholds
  - new electronics
  - better muon component evaluation, as such better photon/hadron and neutrino/hadron discrimination

Particle physics

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

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

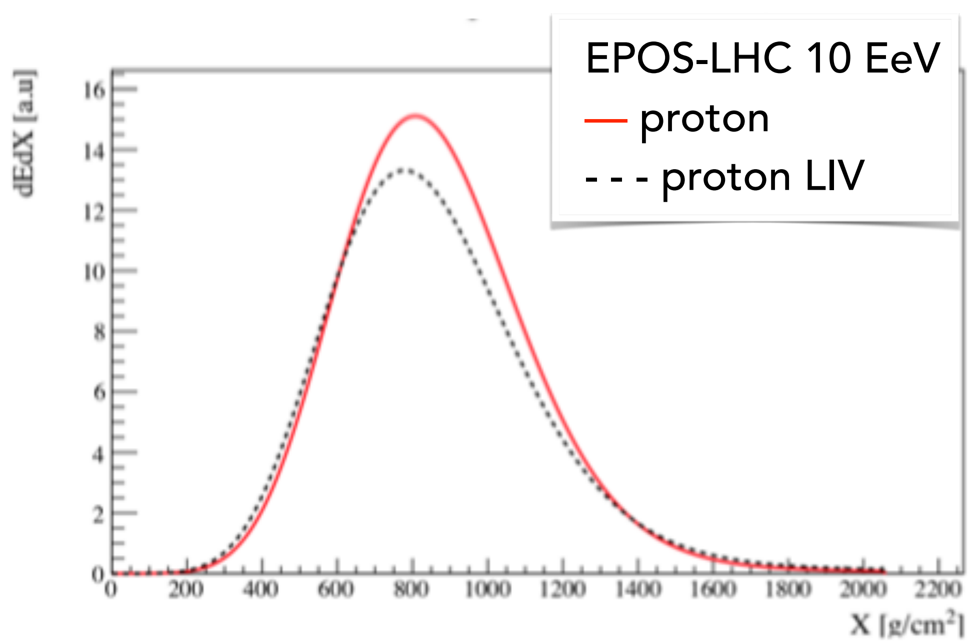


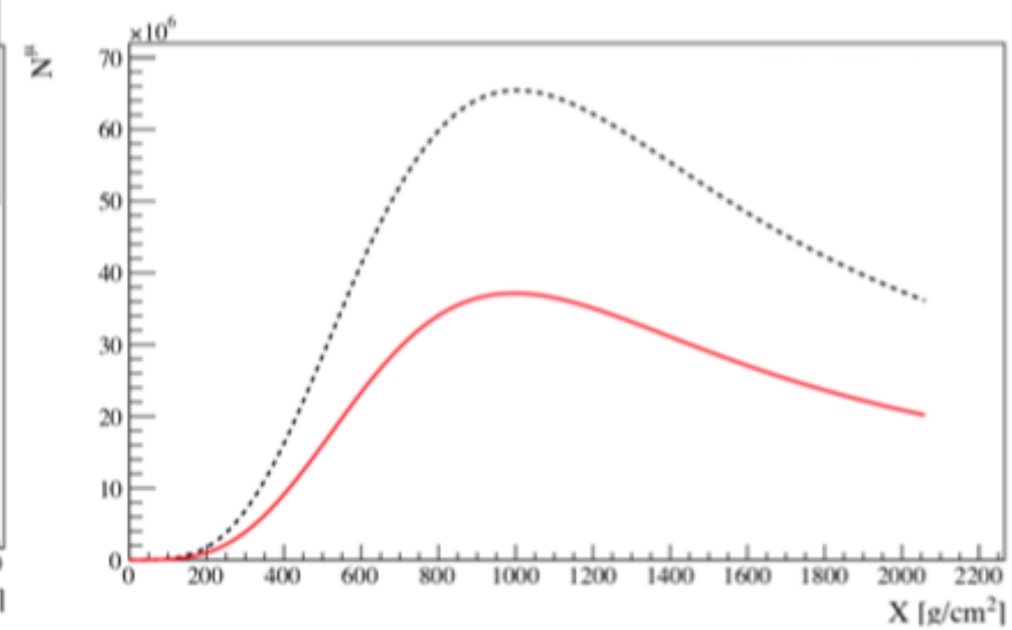


More muons :

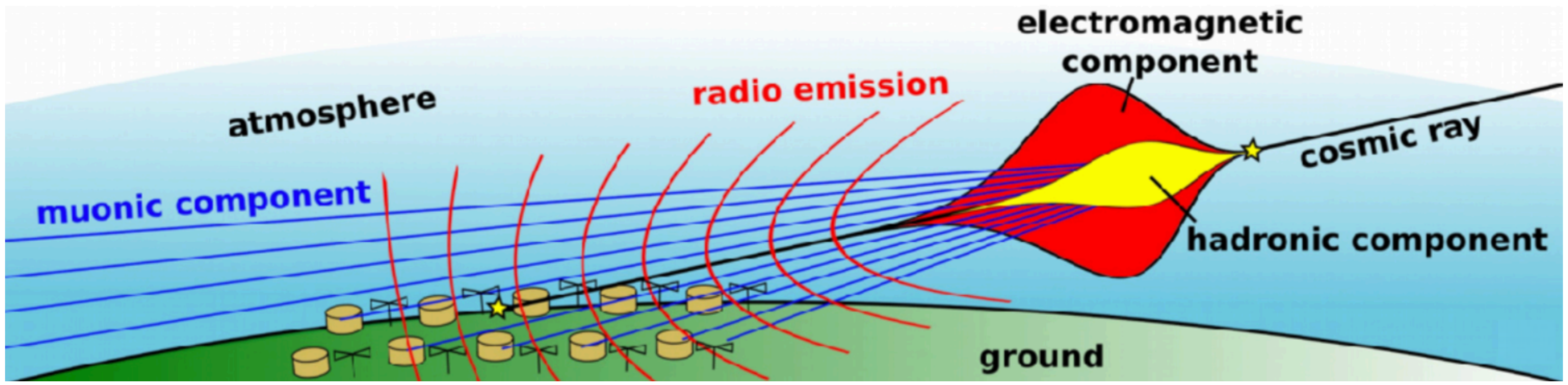
- pion production suppression
- pion decay suppression
- leading particle effect : π^0 replaced with ρ^0
- baryon-antibaryon production
- ....others

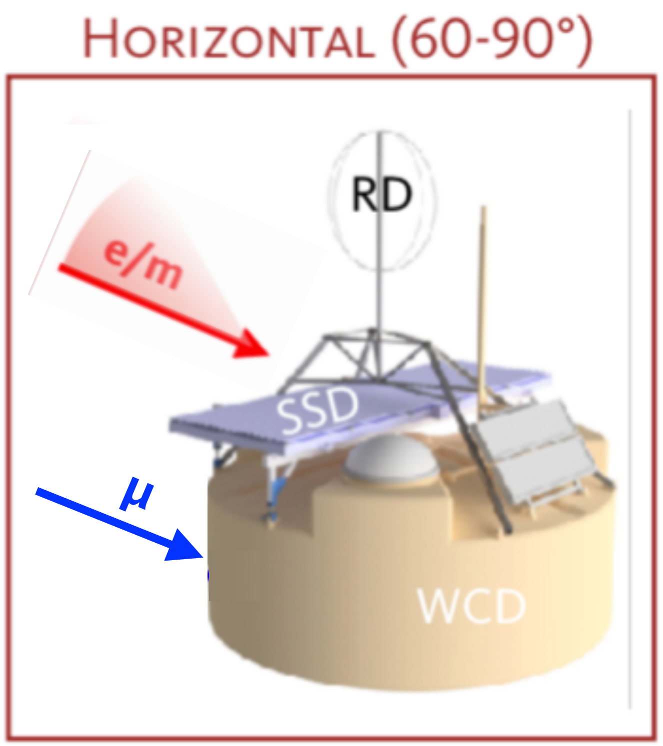
- + constrain or find hints of new phenomena (e.g.violation of Lorentz invariance,...)





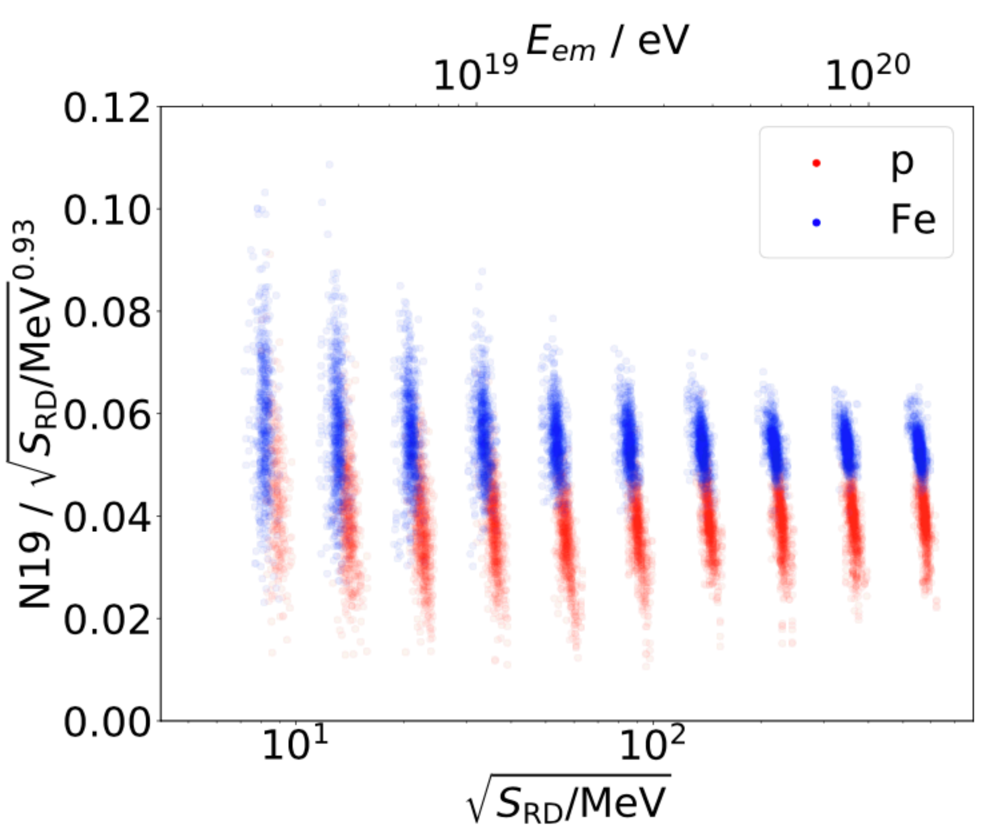
More hybrid data for horizontal showers: radio detection

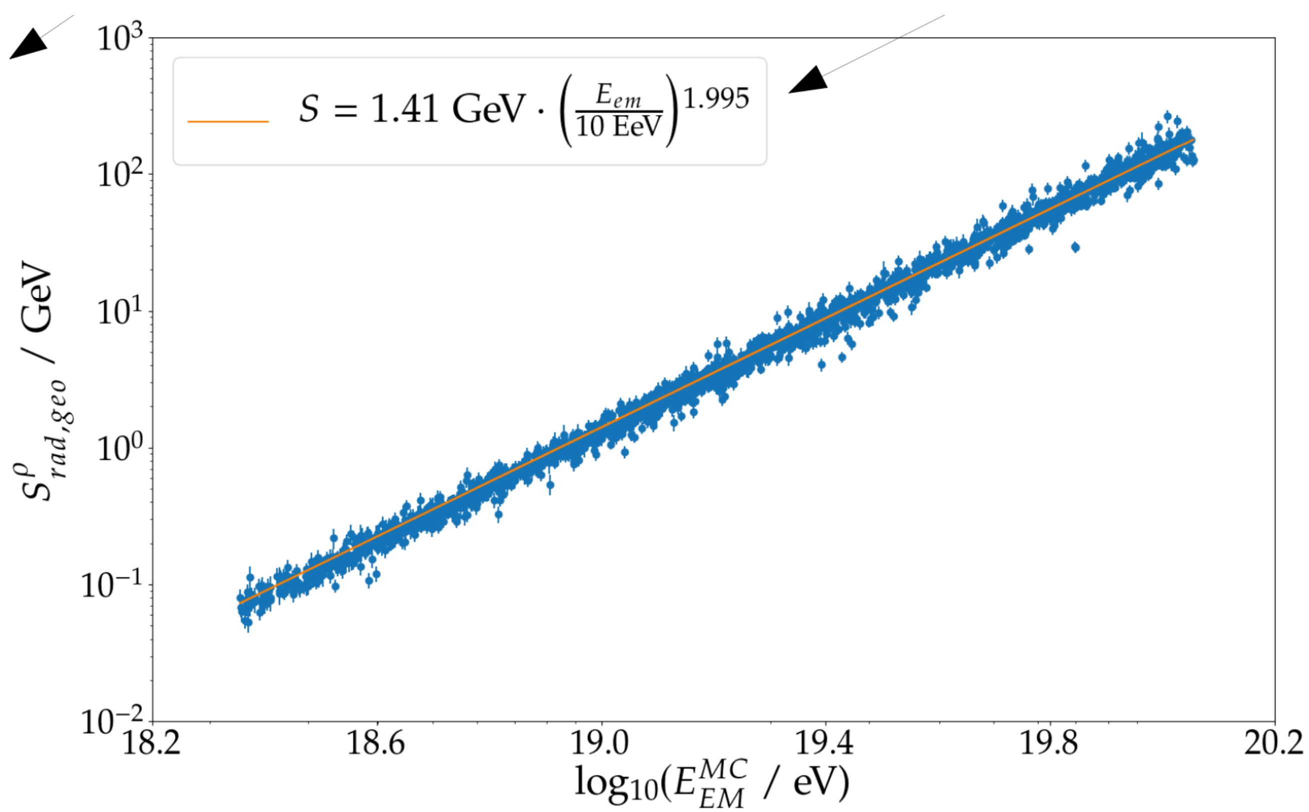




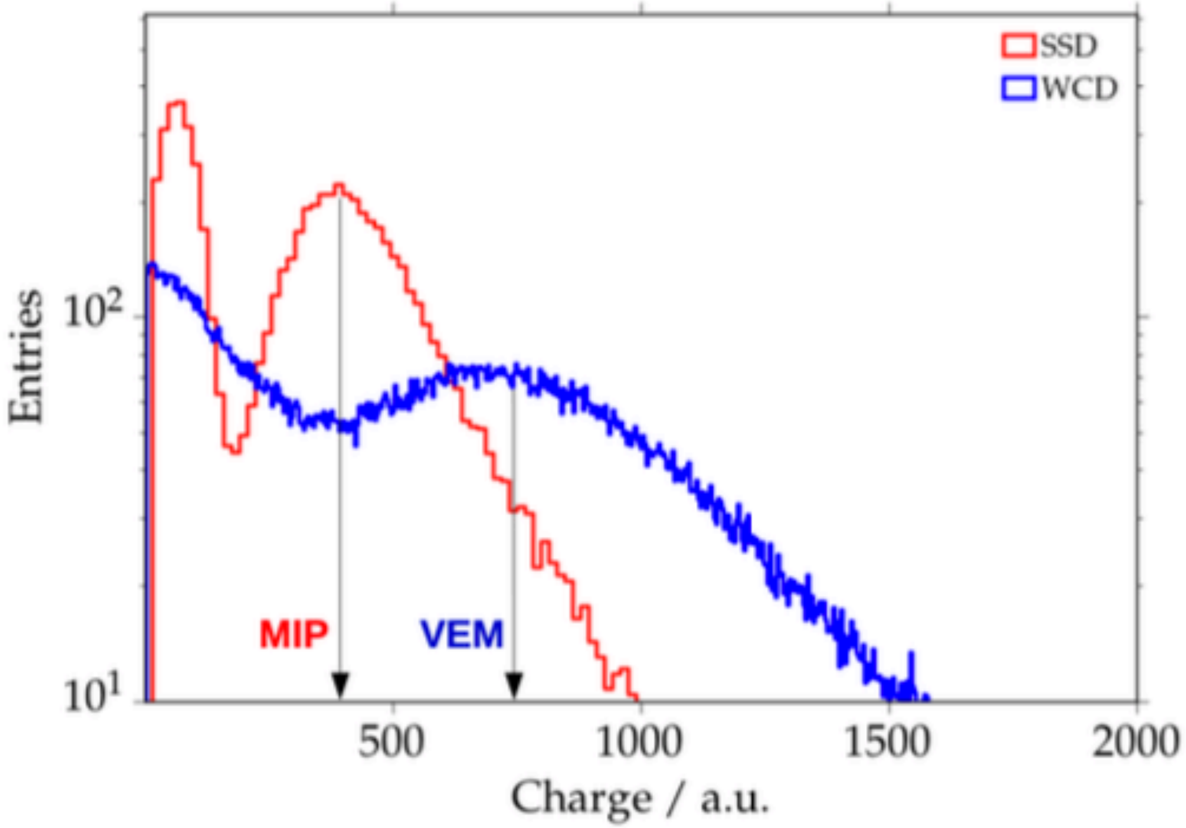
- Radio detection established as standard tool for cosmic ray physics
- Direction, energy and particle type resolutions as for other techniques

E_{rad} from radio, muons from WCD



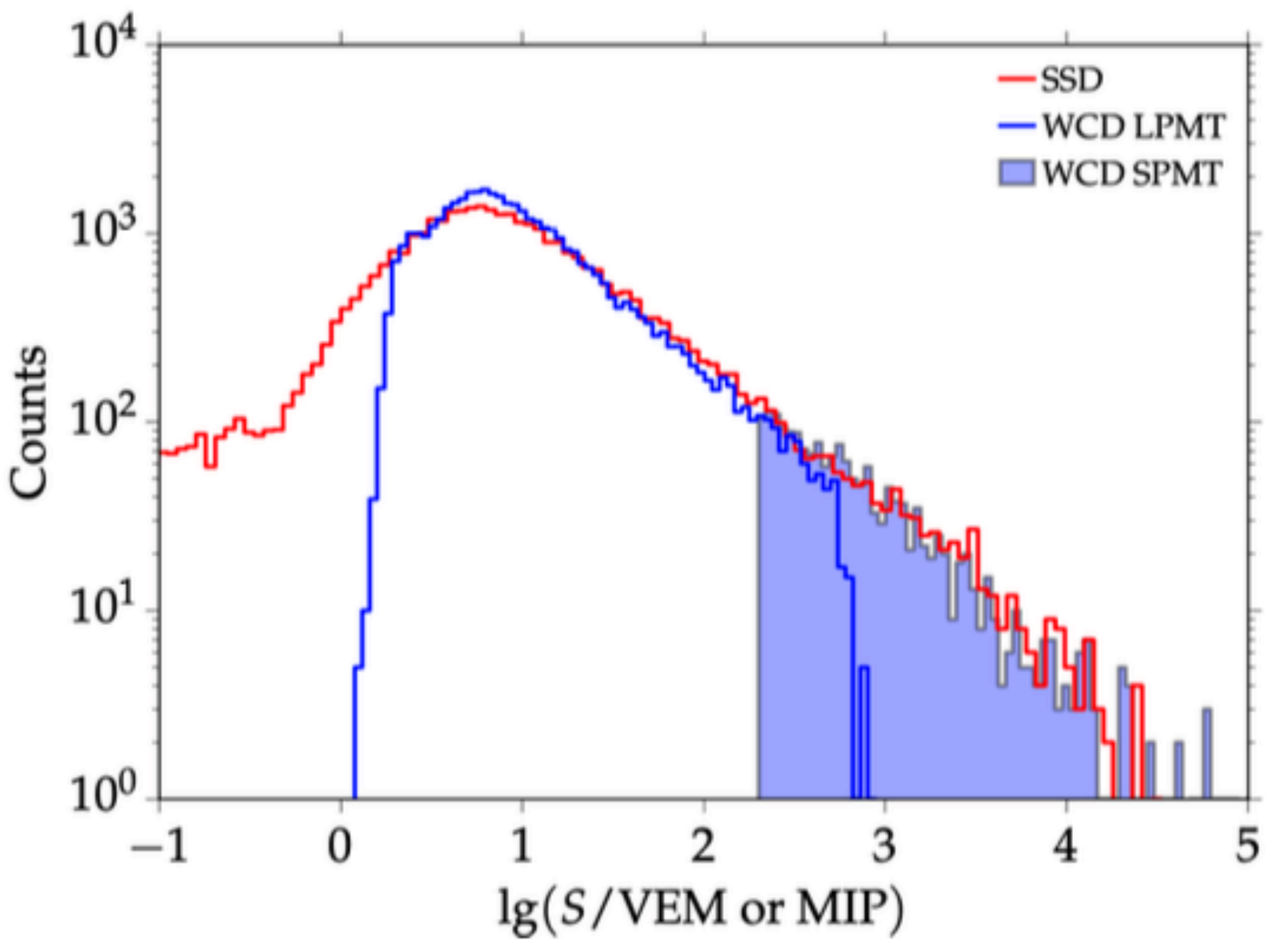


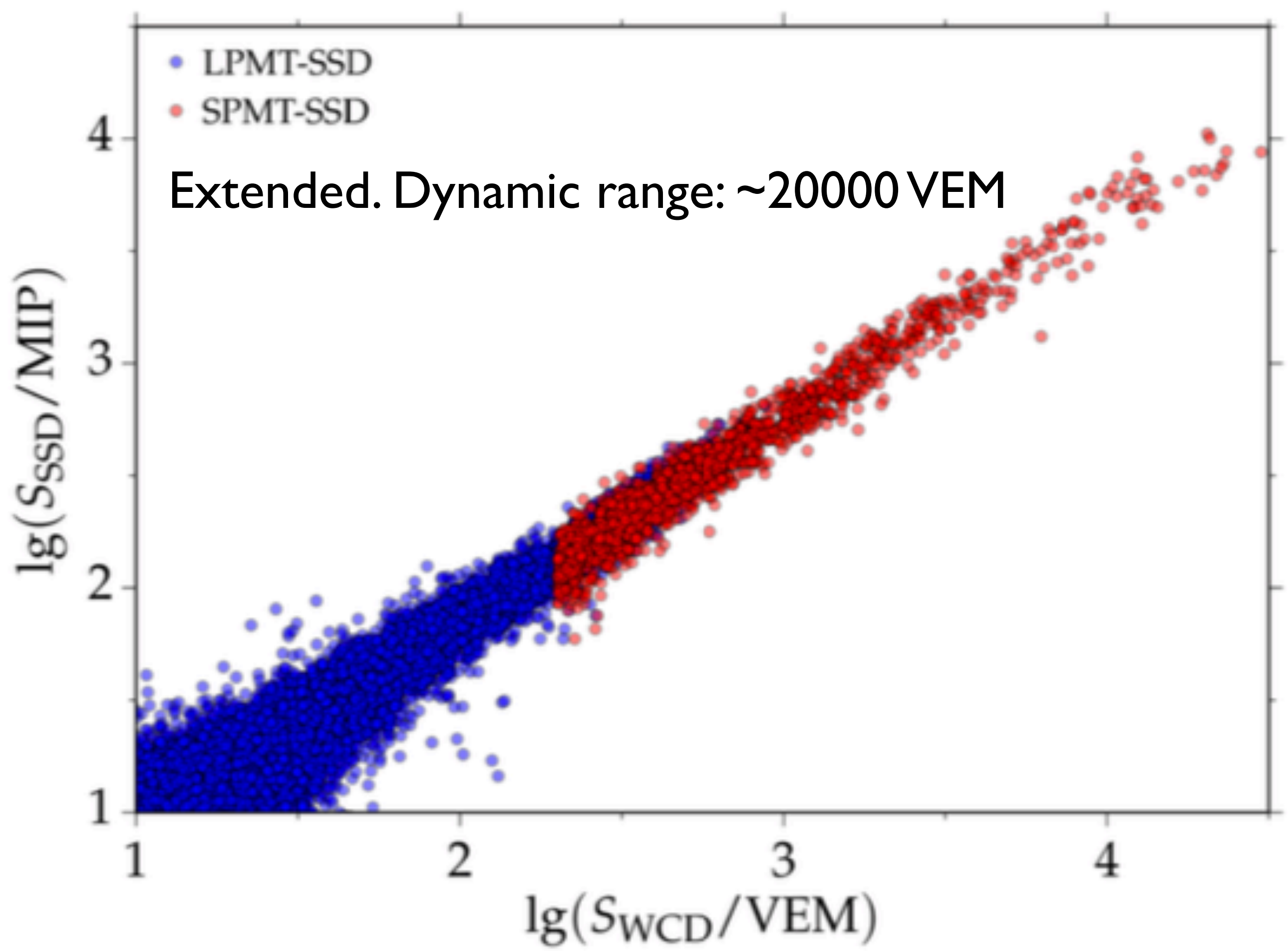
Pre-production array data



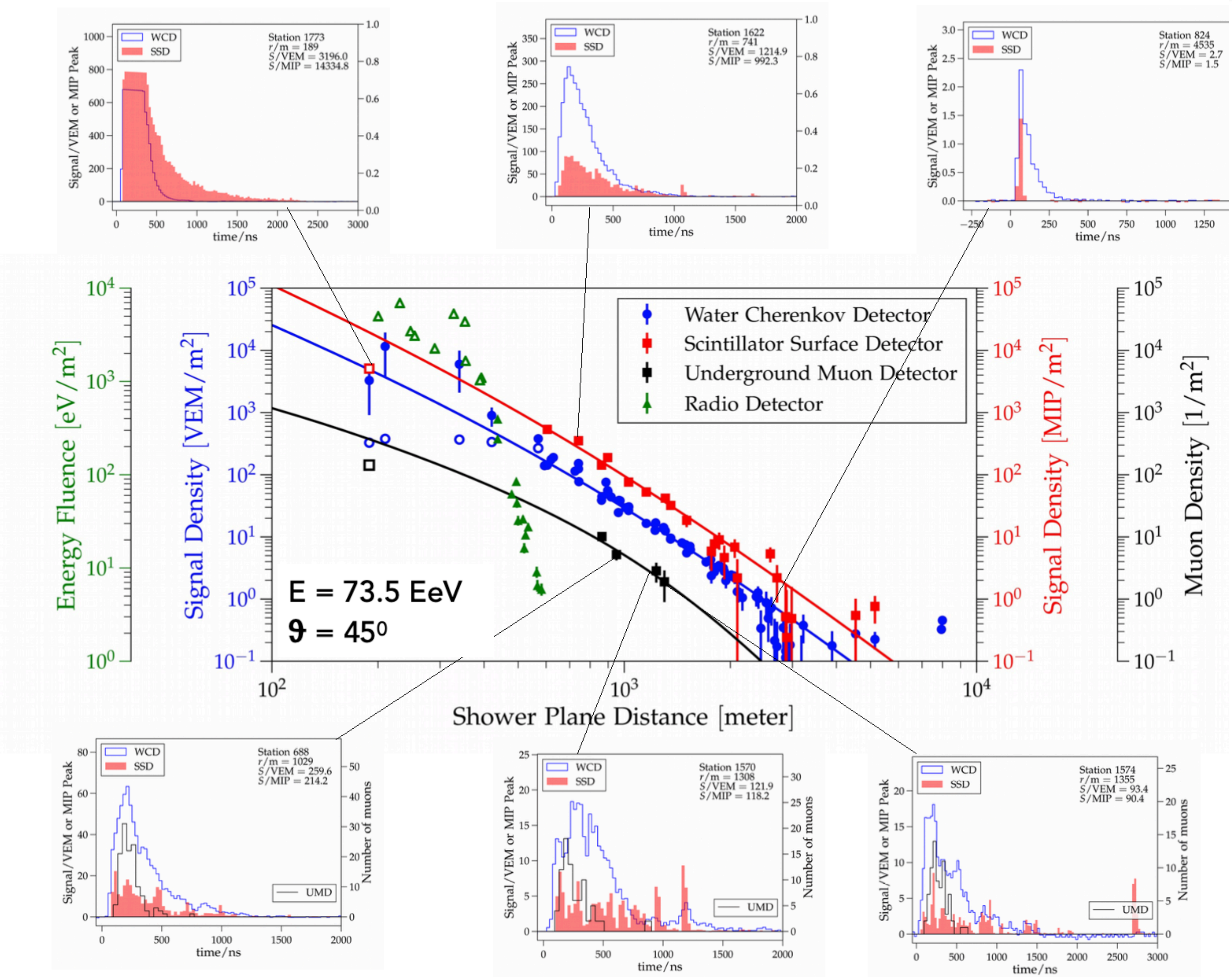
Calibration

- VEM$_{WCD}$: from calibration with atm.muons, ~95 PE/VEM
- VEM$_{SPMT}$: selectionof small showers to cross-calibrate with calibrated LPMT signal
- MIP: single of MIP crossing the detector. ~40% of calib trigger of the WCD produce a MIP in the SSD





Example: UHE event in AugerPrime



Conclusion

Main aims of the upgrade

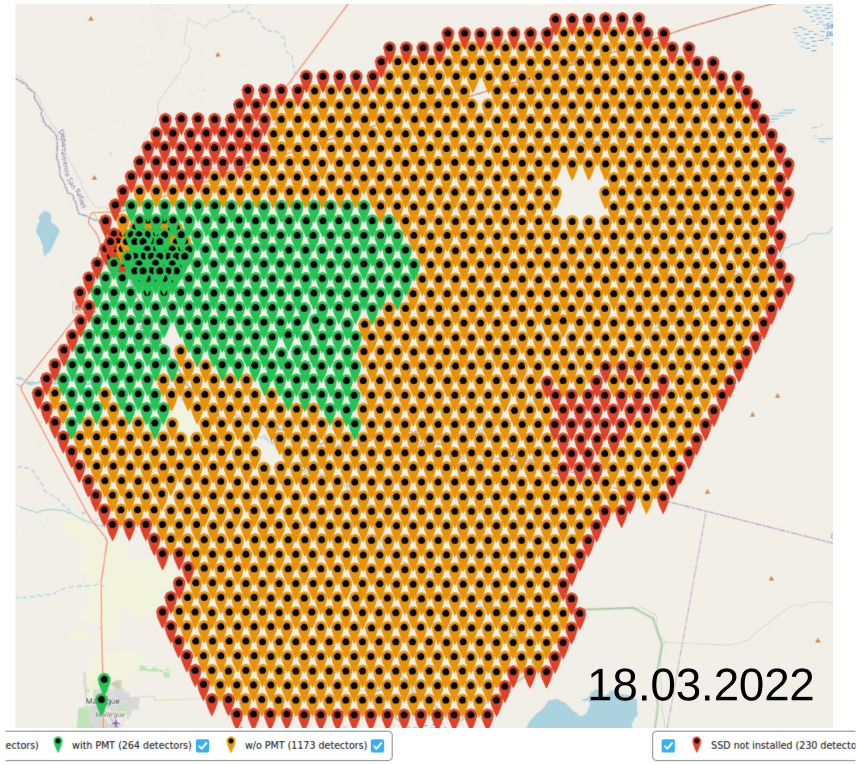
Origin of flux suppression and composition in the extreme energy region.

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: see right picture and next talk (progressing well!)
- full deployment to be completed by the end of 2022
- ***2023-2030 : Data taking (Phase 2 - upgraded Observatory)***

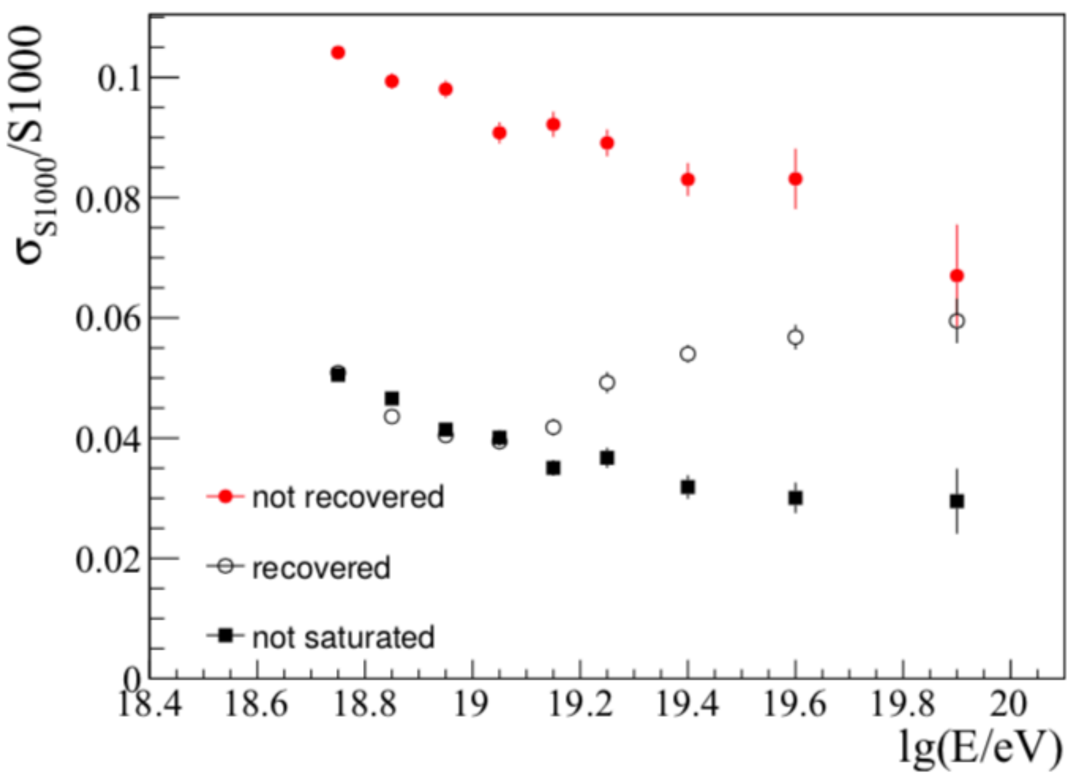


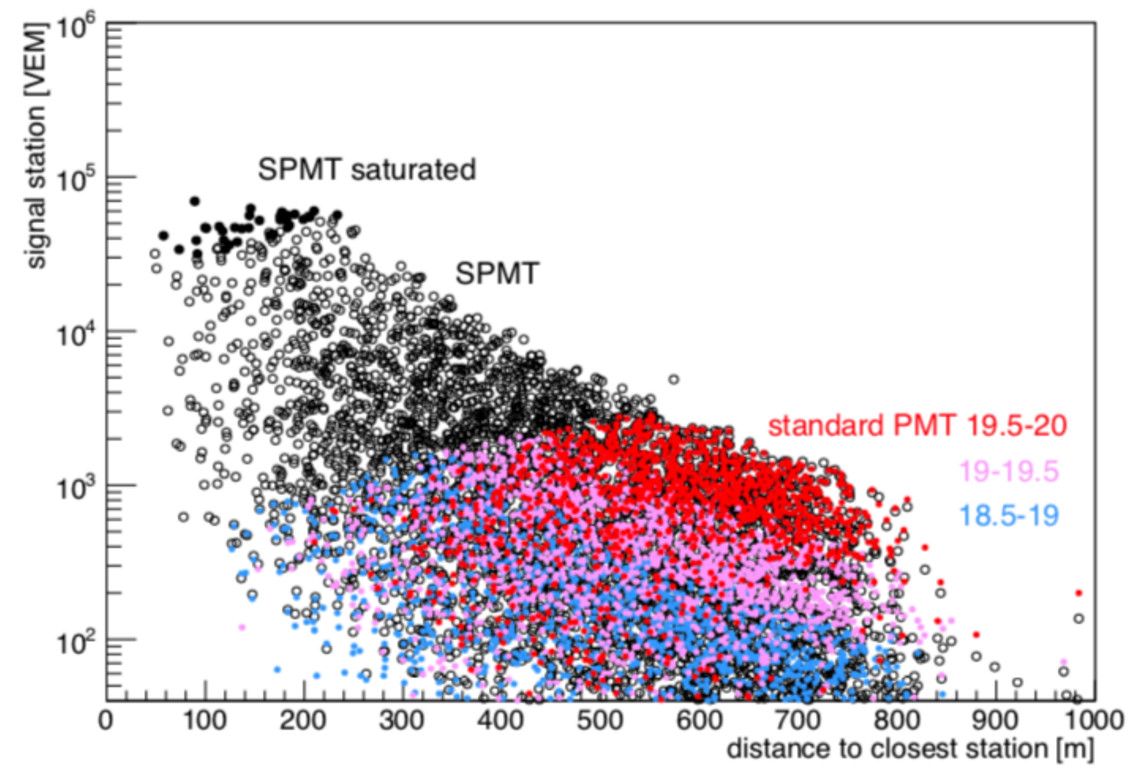
Thank you very much for your attention!

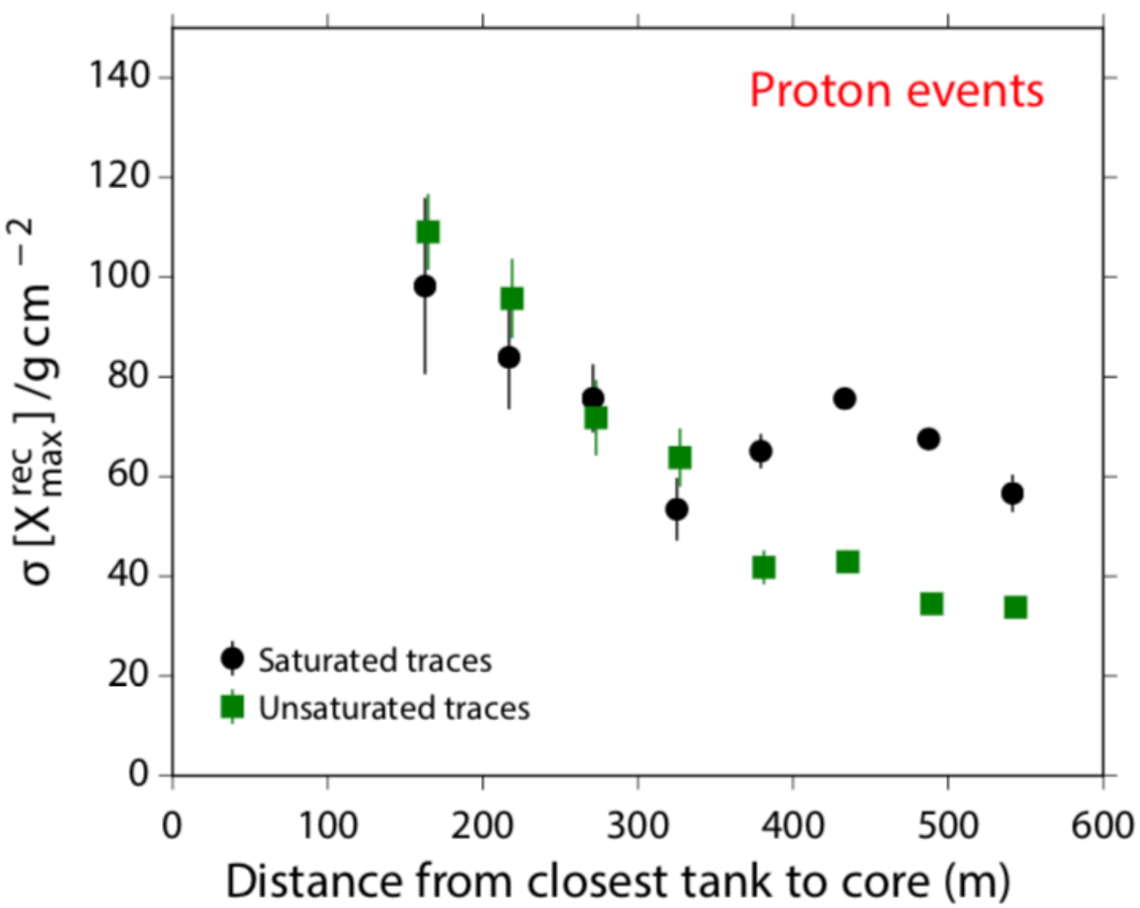
AugerPrime

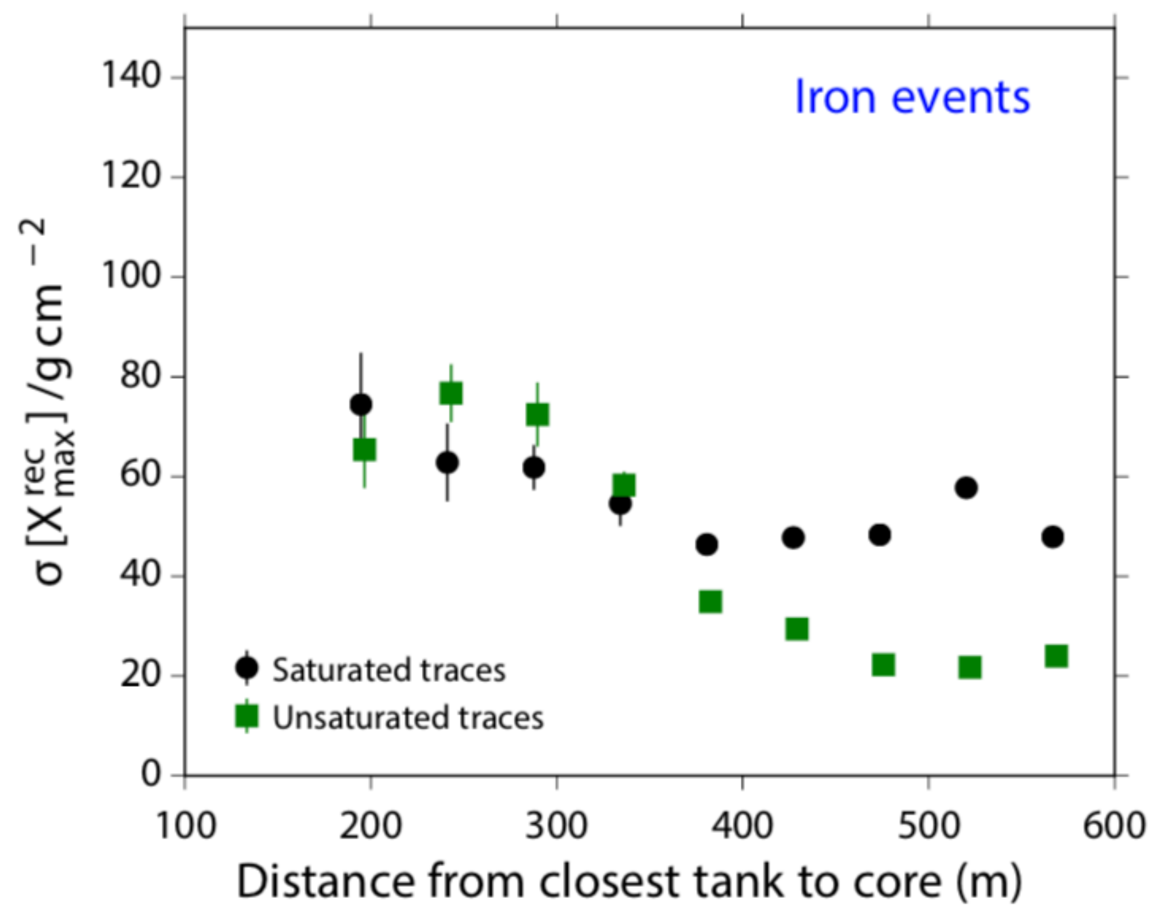
$\log_{10}(E/\mathrm{eV})$	$\mathrm{d}N/\mathrm{d}t\|_{\mathbf{infill}}$ [yr^{-1}]	$\mathrm{d}N/\mathrm{d}t\|_{\mathbf{SD}}$ [yr^{-1}]	$N\|_{\mathbf{infill}}$ [2018-2024]	$N\|_{\mathbf{SD}}$ [2018-2024]
17.5	11500	-	80700	-
18.0	900	-	6400	-
18.5	80	12000	530	83200
19.0	8	1500	50	10200
19.5	$\sim$1	100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

Unsaturated stations

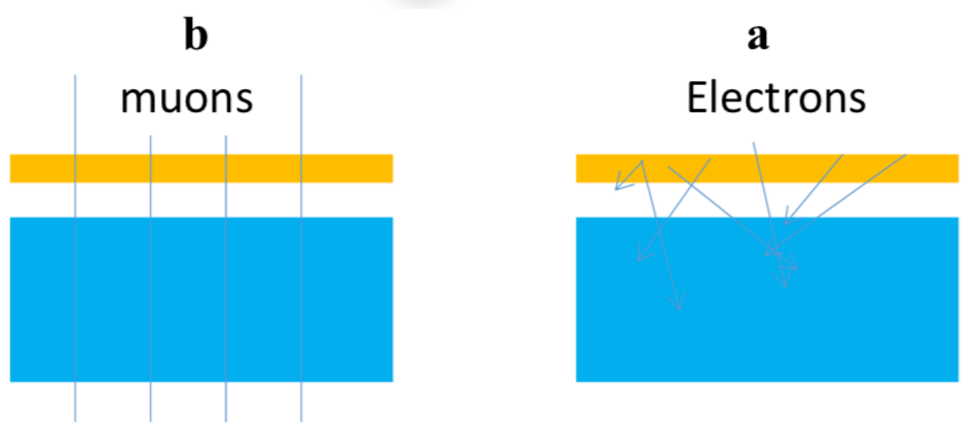








Measuring the muon content - 1



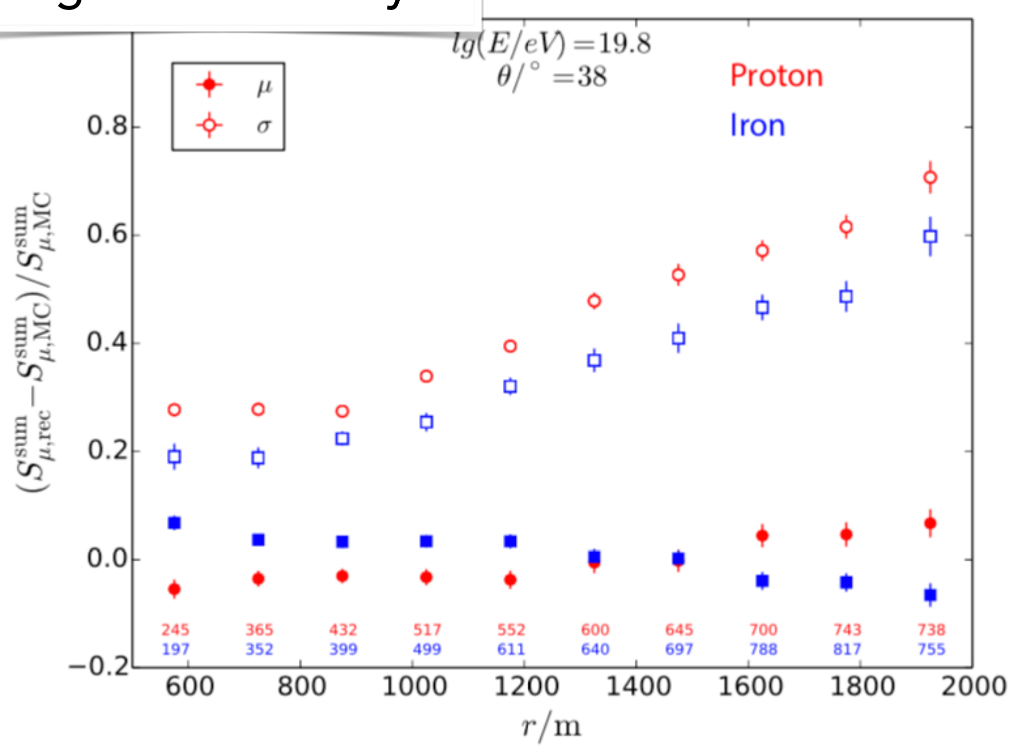
$$\begin{pmatrix} S_{\mathrm{SSD}} \\ S_{\mathrm{WCD}} \end{pmatrix} = \begin{pmatrix} \lambda\, \mathcal{A}_{\mathrm{SSD}} & \mathcal{A}_{\mathrm{SSD}} \\ \beta\, \mathcal{A}_{\mathrm{WCD}} & \mathcal{A}_{\mathrm{WCD}} \end{pmatrix} \begin{pmatrix} \mathcal{F}_{\mathrm{em}} \\ \mathcal{F}_{\mu} \end{pmatrix}$$

Matrix Inversion Method

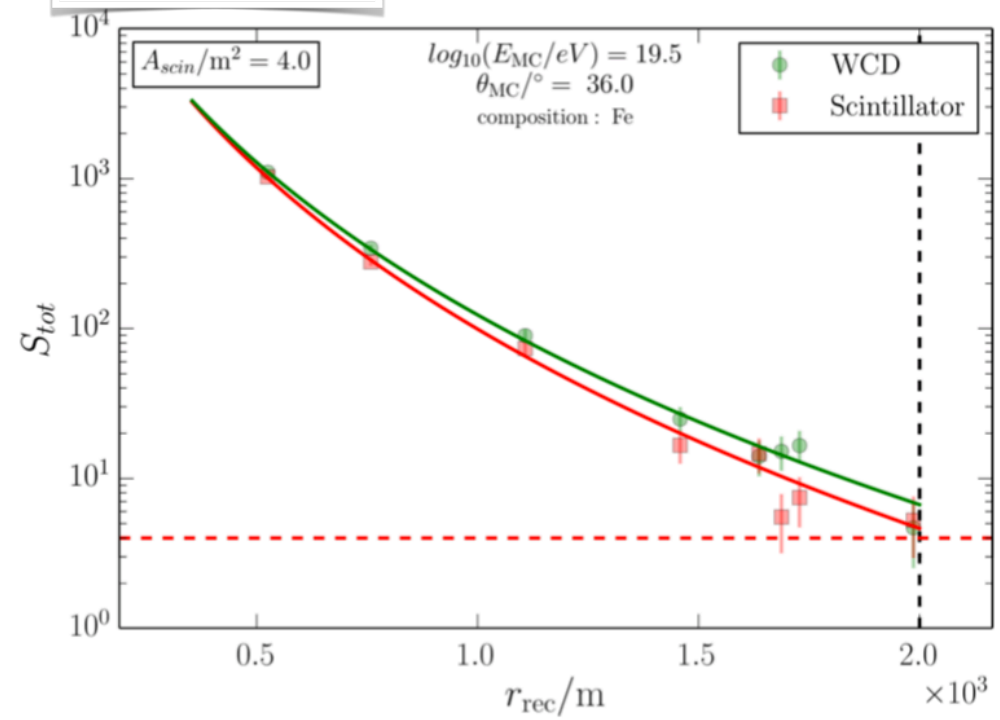
Figure of merit

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

Single station analysis



LDF analysis



Resolution at $10^{19.8}$ eV

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

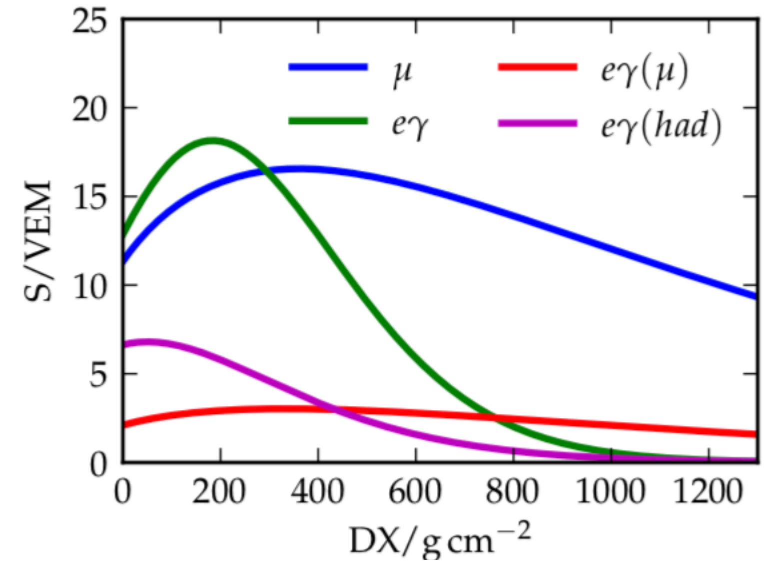
$$\left.\frac{\sigma[S_\mu(800)]}{\langle S_\mu(800)\rangle}\right|_{\mathrm{iron}} \approx 14\%$$

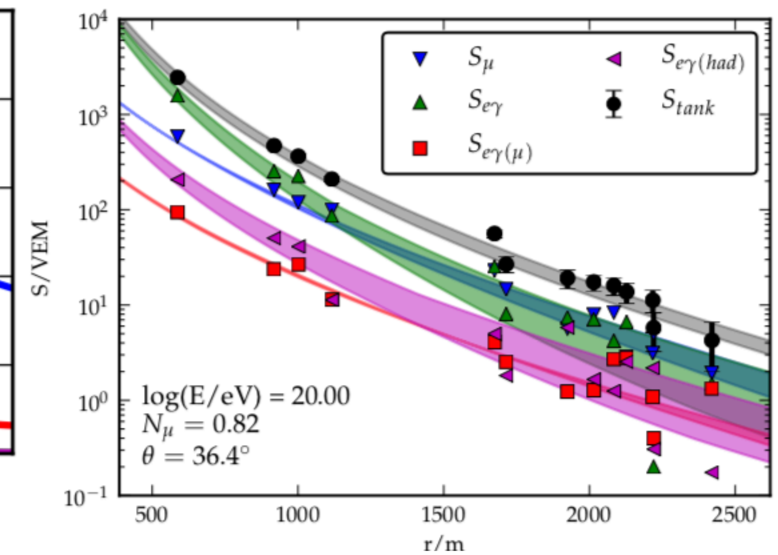
$$f_{\mathrm{p,Fe}} \sim 1.5$$

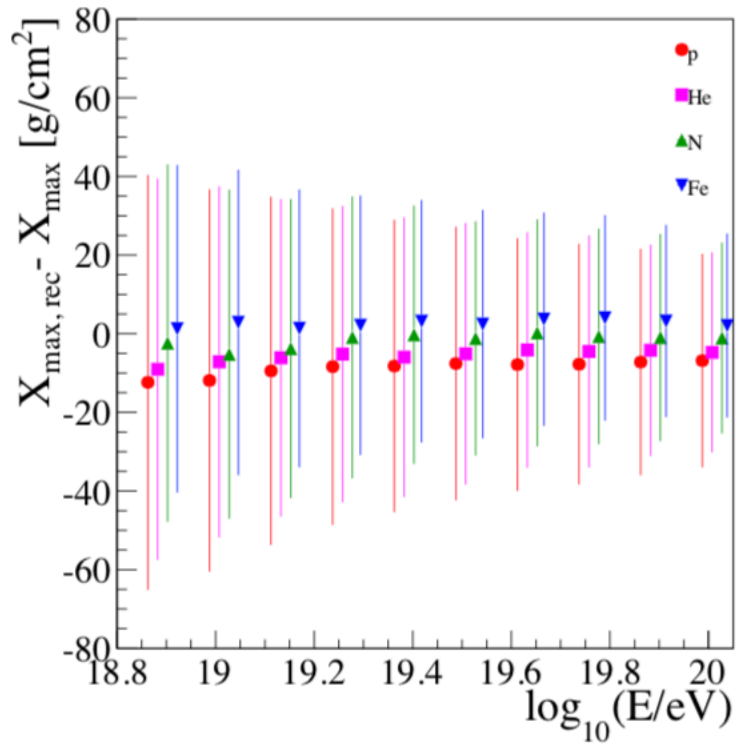
Measuring the muon content - 2

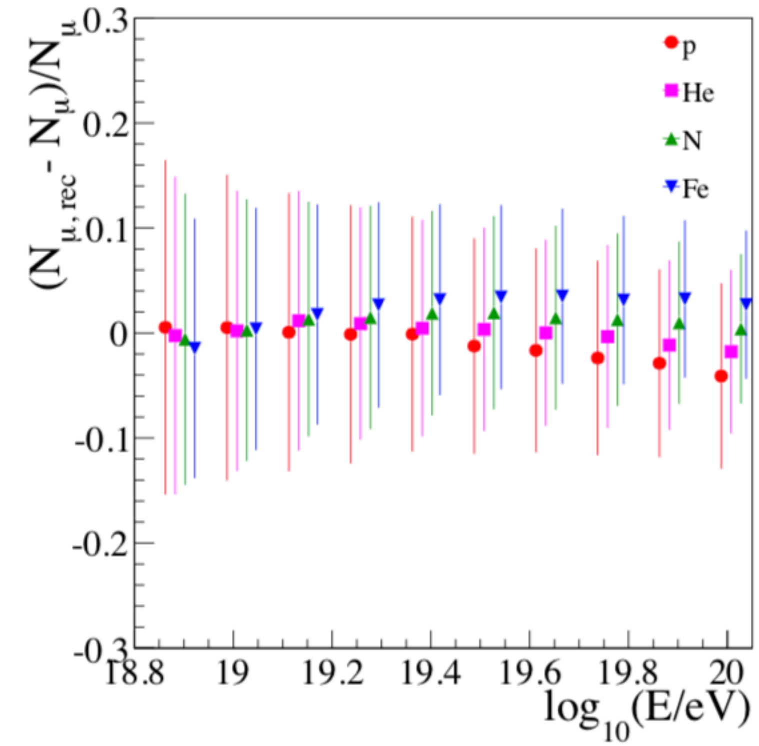
Universality Method

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









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

- the temporal structure of signals
- the integrated signal

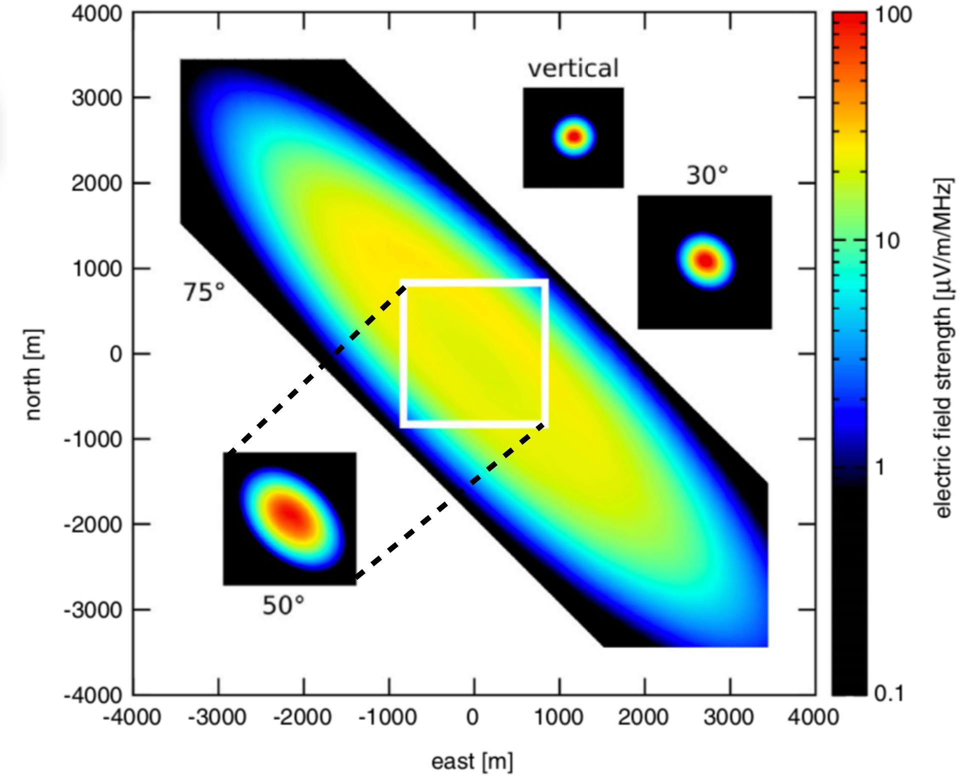
Model	Energy	Composition	Zenith angle	f_{MF}^{F}	f_{MF}^{Rec}
QGSJetII-04	63 EeV	Proton-Iron	21°	2.08	1.56
QGSJetII-04	63 EeV	Proton-Iron	38°	1.97	1.67
QGSJetII-04	63 EeV	Proton-Iron	56°	2.14	2.1

The Radio Detector in AugerPrime

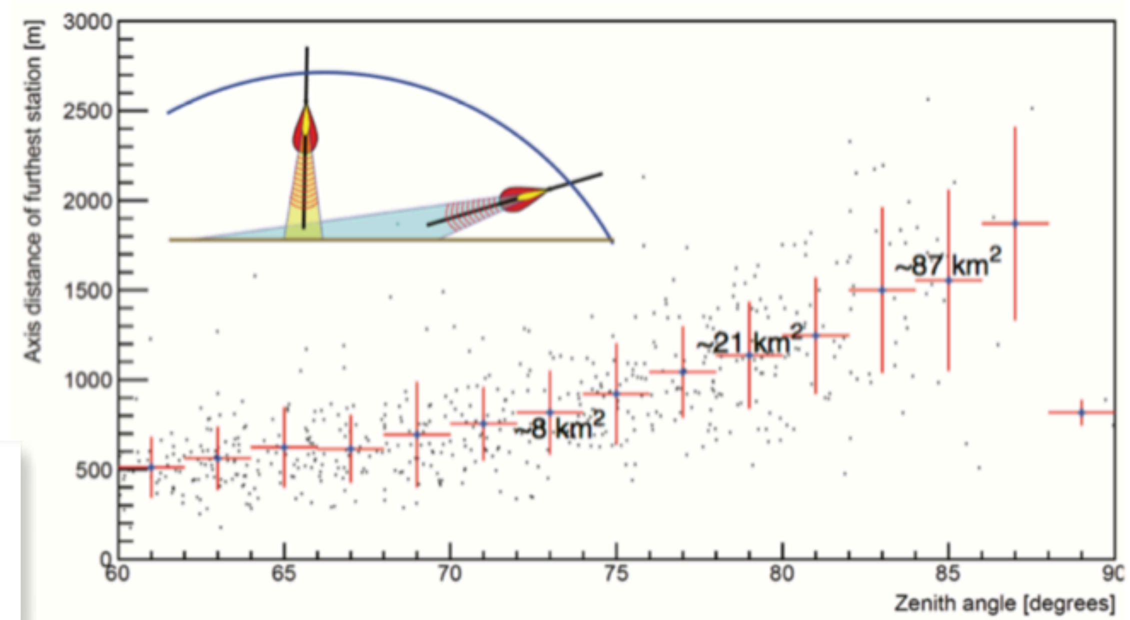
As it is not absorbed in atmosphere, the radio emission depends on the source distance and not on the amount of traversed matter

inclined air showers can be detected by a sparse antenna grid (> 1 km mutual distance)
- lower E amplitude
- larger footprint
- less steep LDF

≥5 stations with signals above bkg



$$E_{30-80\,\mathrm{MHz}} = (15.8 \pm 0.7\,(\mathrm{stat}) \pm 6.7\,(\mathrm{sys}))\ \mathrm{MeV} \times \left(\sin\alpha\,\frac{E_{\mathrm{CR}}}{10^{18}\,\mathrm{eV}}\,\frac{B_{\mathrm{Earth}}}{0.24\,\mathrm{G}}\right)^2$$



- ✓ precision measurement of EM component
- ✓ duty cycle ≳95% (in fair weather conditions)
- ✓ complementarity with the SSD+WCD (optimized for <60⁰ showers)
- ✓ increase in statistics for the study of the lower energy region (complementarity with AMIGA)
- ✓ yearly exposure of FD reachable equipping ~300 km² area