Upgrading the water Cherenkov tanks for atmospheric shower identification

Pierre Billoir (LPNHE Paris)

- UHE cosmic rays (> 10^{16} eV) are observed through atmospheric showers (longitudinal profile + ground particles):

  spectrum is well established, but sources are still unknown
- a key point to understand the origin:

  identifying the primary (light/heavy nucleus, photon, neutrino ?)
- main criteria to discriminate the primaries:

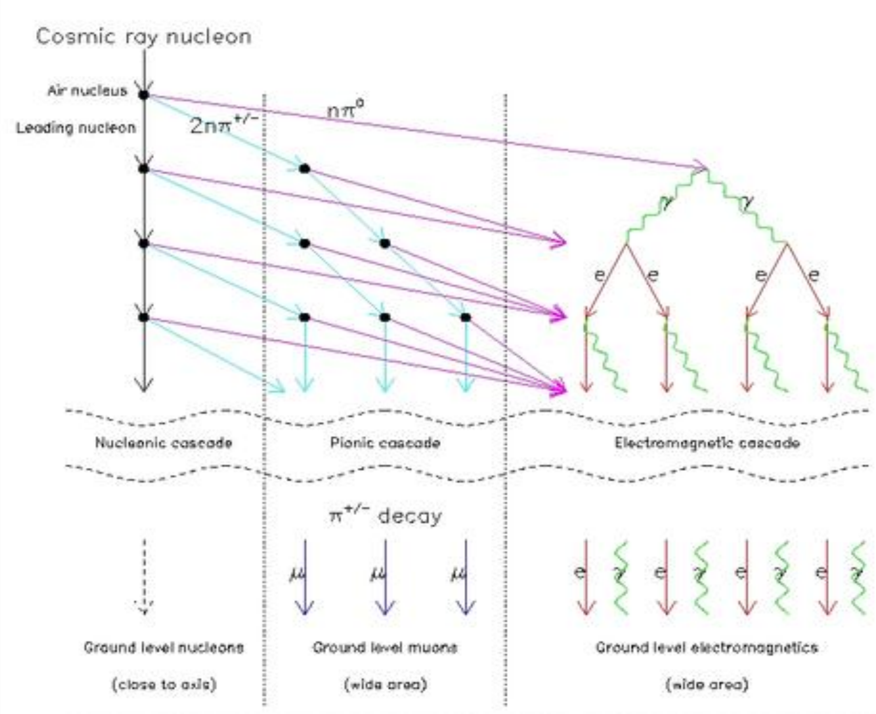
  depth of maximum + ***muonic vs electromagnetic component***
- Cherenkov water tanks to sample the ground particles:

  sensitive to both; indirect and model dependent separation
- how to improve the separation ?

  essentially: use a 2-fold detector with different sensitivities

  internal modification of the tank or addition of another detector

atmospheric cascade



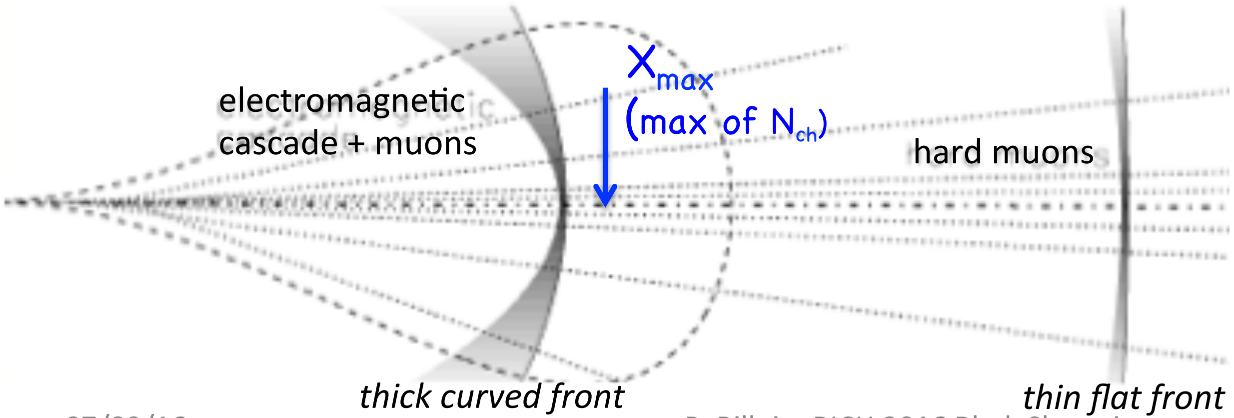
hadronic interactions:

large multiplicity at high E
in average ~1/3 of E → neutral mesons (mainly $\pi^0 \to \gamma\gamma$)
at the end: few GeV mesons decay → muons
(some of them propagate down to ground)

electromagnetic cascade:

$\gamma \to e^+e^-$ (pair production)
$e^\pm \to e^\pm \gamma$ (bremsstrahlung)

- in air (index n) charged particles produce Cherenkov light if $\beta n > 1$ (tightly collimated)
- excitation of nitrogen molecules: isotropic **fluorescence** light (isotropic)
- emission of radio waves

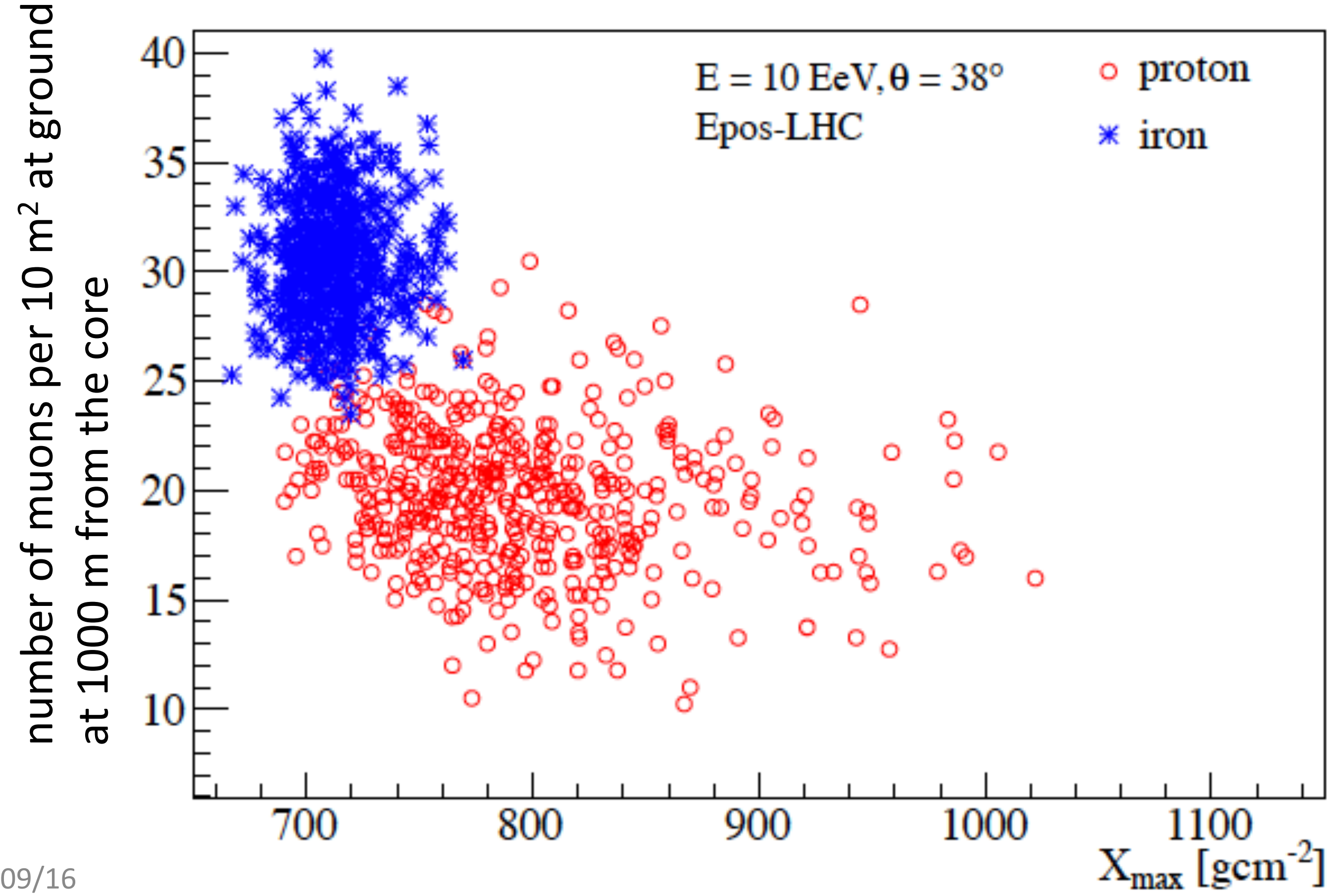


1 atmosphere
(~ 30 rad. lengths)

X_{max} and muons to discriminate primaries

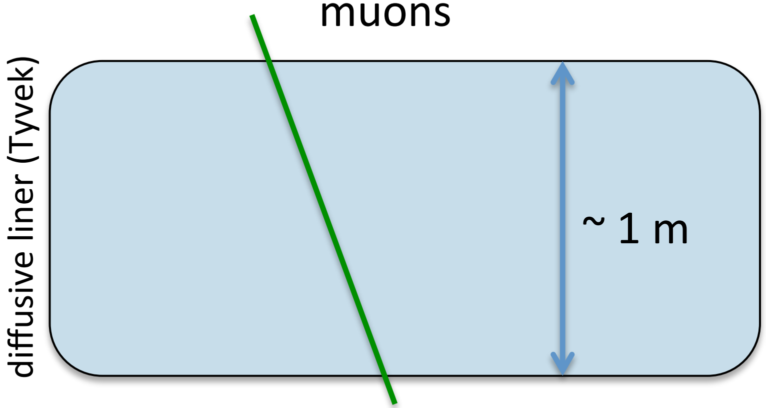
for a given primary energy: heavier nucleus ➔ less steps in the hadronic cascade ➔

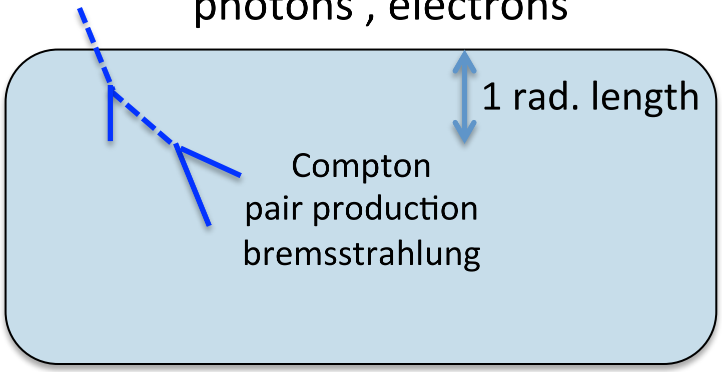
- faster longitudinal development: lower X_{max}
- less energy going to e.m. cascade: more muons



response of a water tank

good approximation:
integrated signal: proportional to Cherenkov light amount
~ total length of charged trajectories





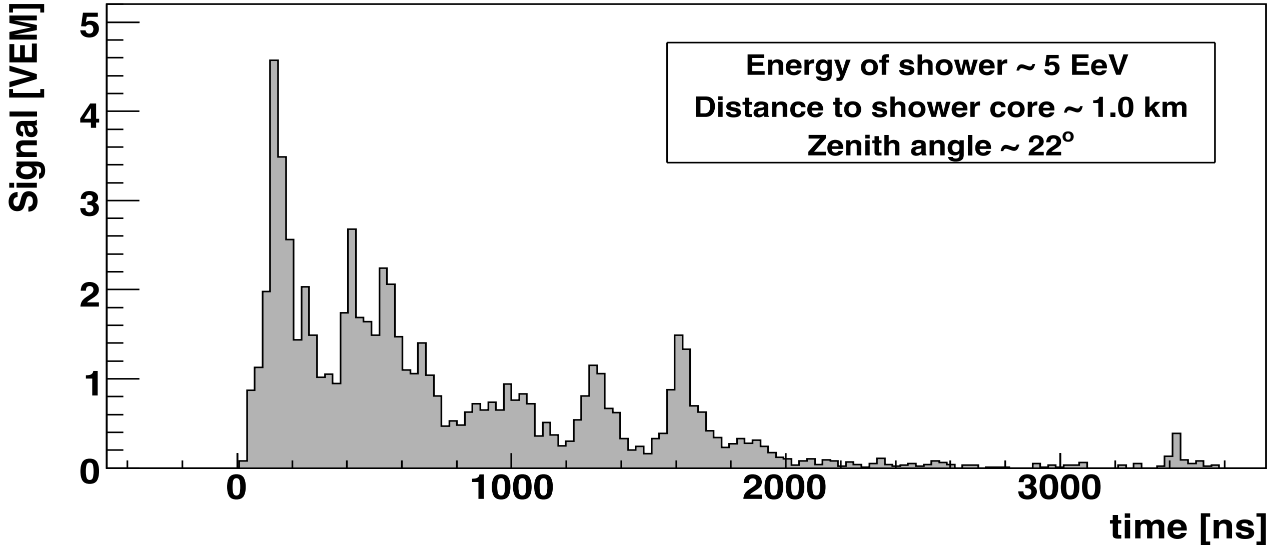
Energy scale: GeV
mostly *through-going* trajectory
typical length 1 to 2 m
response driven by ***geometry***

1 muon ➔ 1 short light flash
peaks in FADC trace may be distinguished if enough spread out (far from the shower core)

Energy scale: soft spectrum, typically ~ 10 MeV
mostly *contained* cascade
quasi ***calorimetric*** *response*

more or less continuous light production
in average: γ e^+ e^- arrive later than muons
global time structure is an indicator

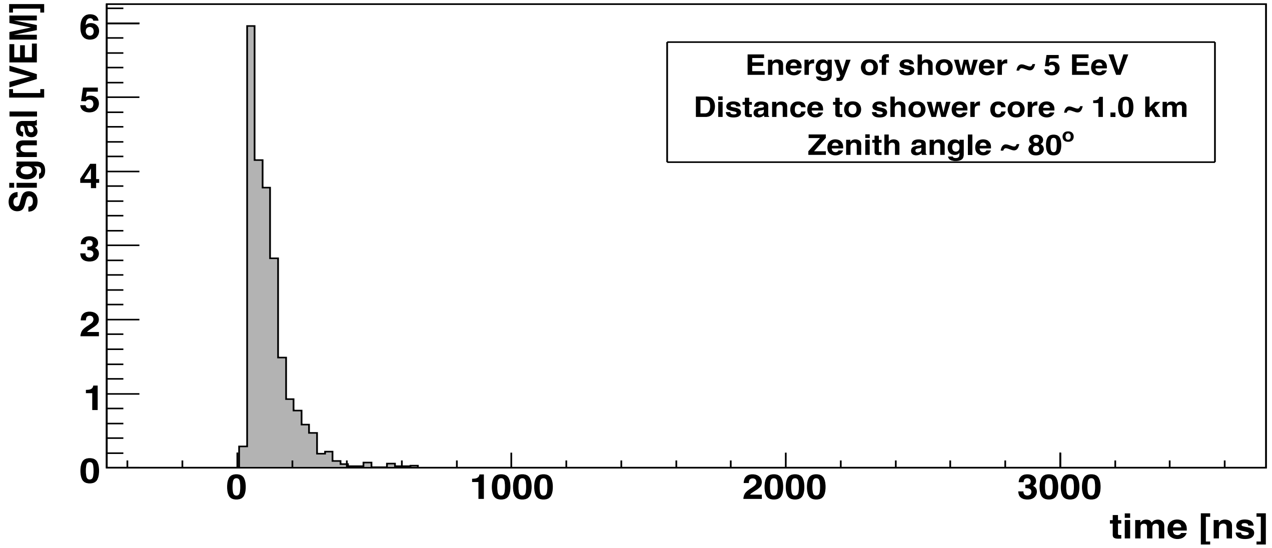
FADC traces from a shower (AUGER tank)



quasi-vertical («young») shower: large spread

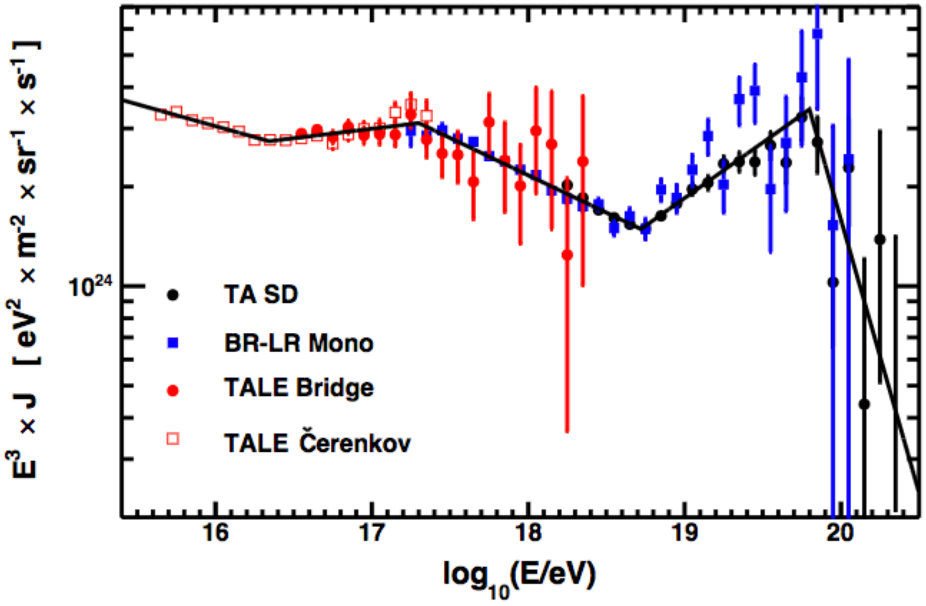
smooth e.m. signal
+ peaks (mainly muons, or energetic g or e^+e^-)
→ sensitivity to muonic content

global shape, front curvature are related to the «age» of the shower
→ sensitivity to X_{max}

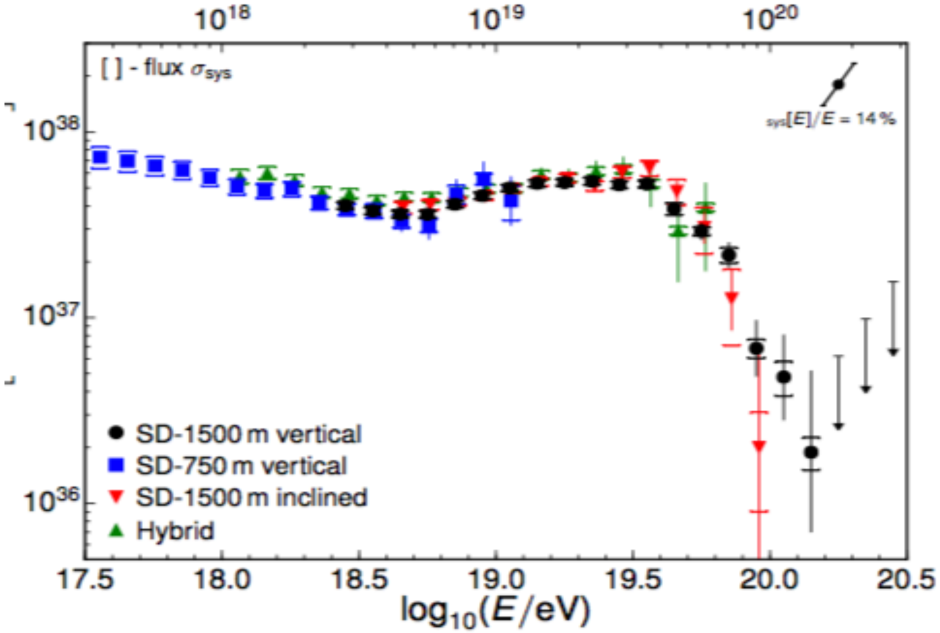


horizontal («old») shower:
superposition of muon peaks within a short time
no visible structure
good time precision

the spectrum of UHECR (ICRC 2015)



Telescope Array



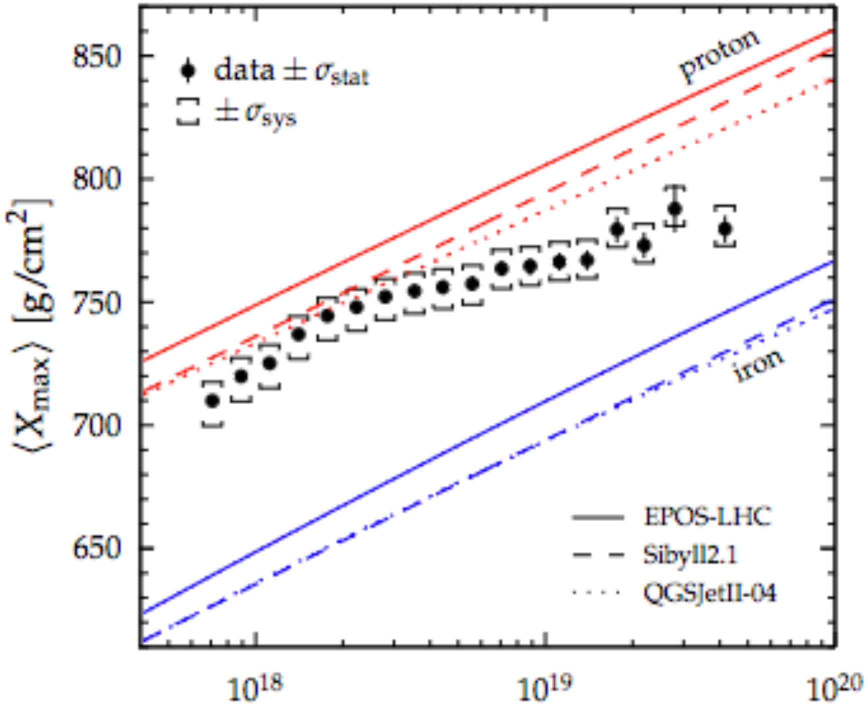
AUGER

clear « broken line » structure:

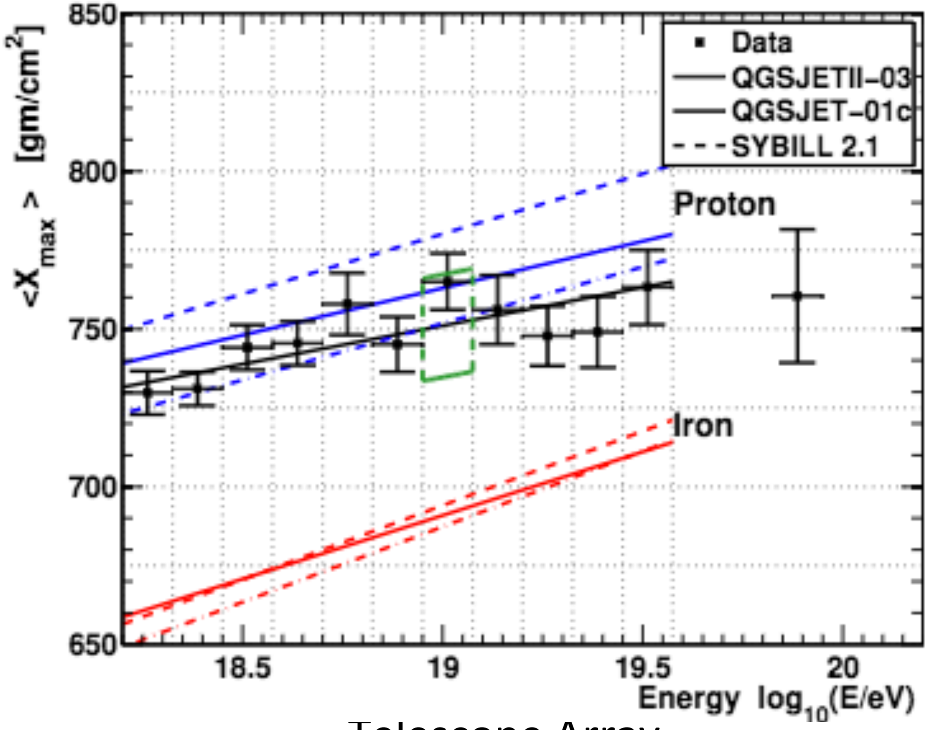
- ankle at ~ 18.5
- cutoff at ~ 19.6

ambiguous interpretation: the energy of cutoff matches the GZK effect (interaction of protons with CMB) but it could be the upper limit of sources (heavy nuclei favoured)

X_{max} results (ICRC 2015)



AUGER

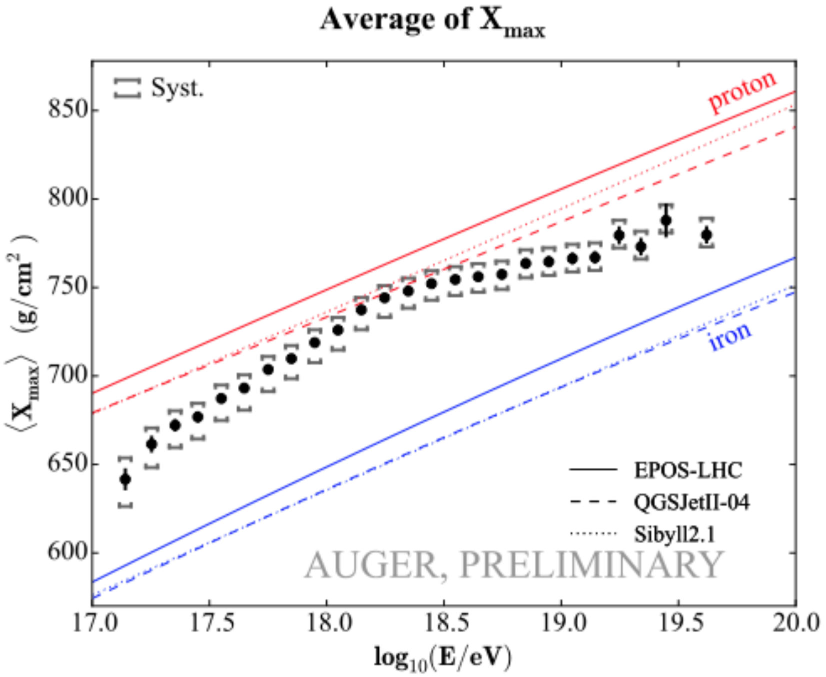


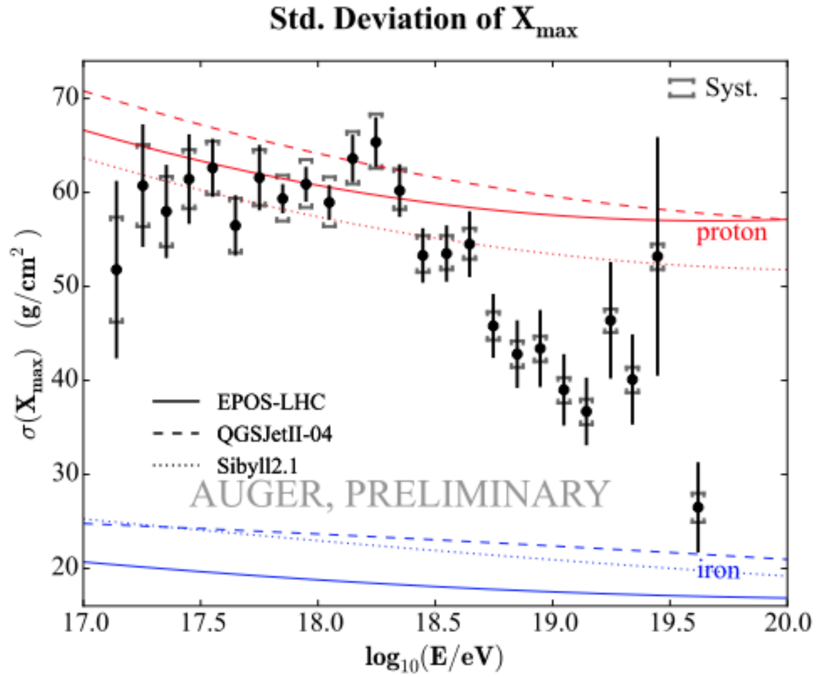
Telescope Array

rough agreement (but TA uncertainties still large) :

- change of slope at the « ankle » where light nuclei dominate
- trend to heavy nuclei at highest energies
- different models do not give strongly different predictions
- not enough data above the cutoff

X_{max} vs $\sigma(X_{max})$ (Auger)


Average of X_{max}

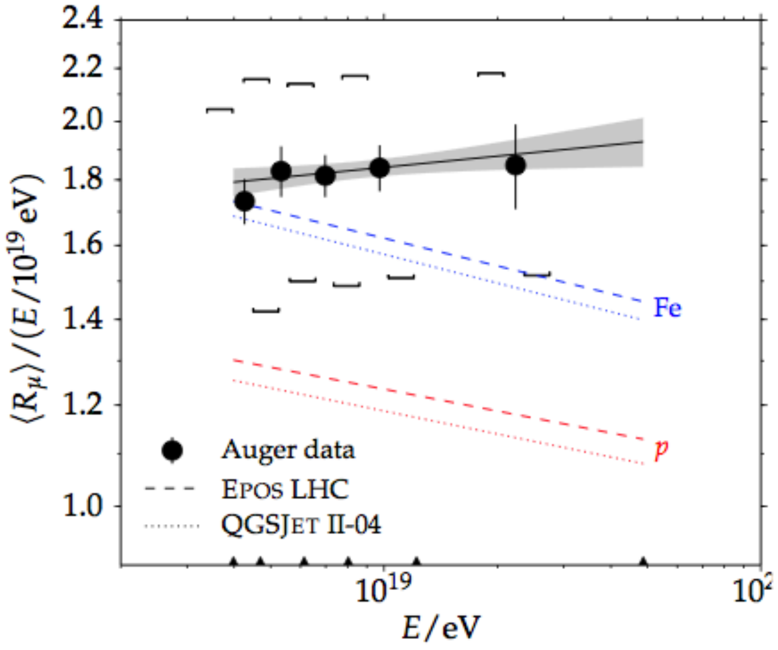

Std. Deviation of X_{max}

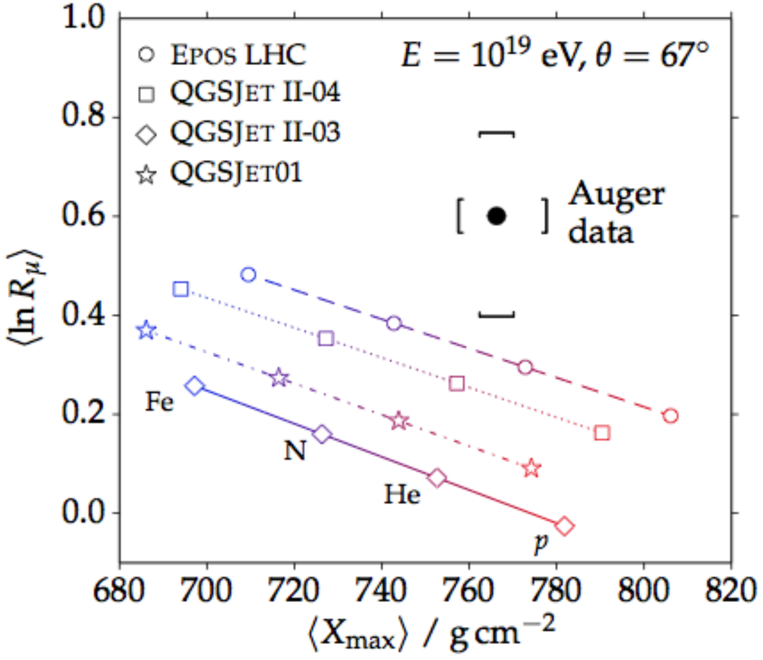
- consistent with « pure proton » around the ankle
- higher energy is more difficult to interpret: decreasing $\sigma(X_{max})$ is expected with increasing A, but not well compatible with a mixture of different nuclei

muonic component (Auger, ICRC2015)

using « inclined » events (above 60 deg) to select a pure muonic shower, compare the muon density to the expectation from fluorescence energy.

reference : E = 10^{19} eV, hadronic model QGSJET II-03





none of the models is compatible with the data (the *muon deficit* problem)

similar problems found using other muon signatures (e.g. the *muon production depth* deduced from the time of arrival, or the structure of FADC traces in tanks)

“muonic component“ is ambiguous

muon counting methods explore a limited part of the phase space

- lower cut on momentum (especially for underground detector)
- lower cut on distance to core (FADC trace structure, production depth from arrival time)

dependence on muonic component model

e.g.: an error on angular distribution (very steep) results in a large error in lateral density (Cherenkov tanks do not see the direction of incidence)

➔ need for additional information on the muons

especially at short distance from the core: big signals, but difficult to disentangle the e.m. and muonic components

how to improve the discrimination ?

1- « black top » option: faster absorption of light ➔ less photo-electrons in PMTs, but tighter muon peaks in the FADC traces (easier to count)

2- coupling the tank to a charged particle detector (in practice: scintillator)
  - just above (counting electrons+muons)
  - just below (counting muons+ few through going electrons)
  - underground (counting hard muons)

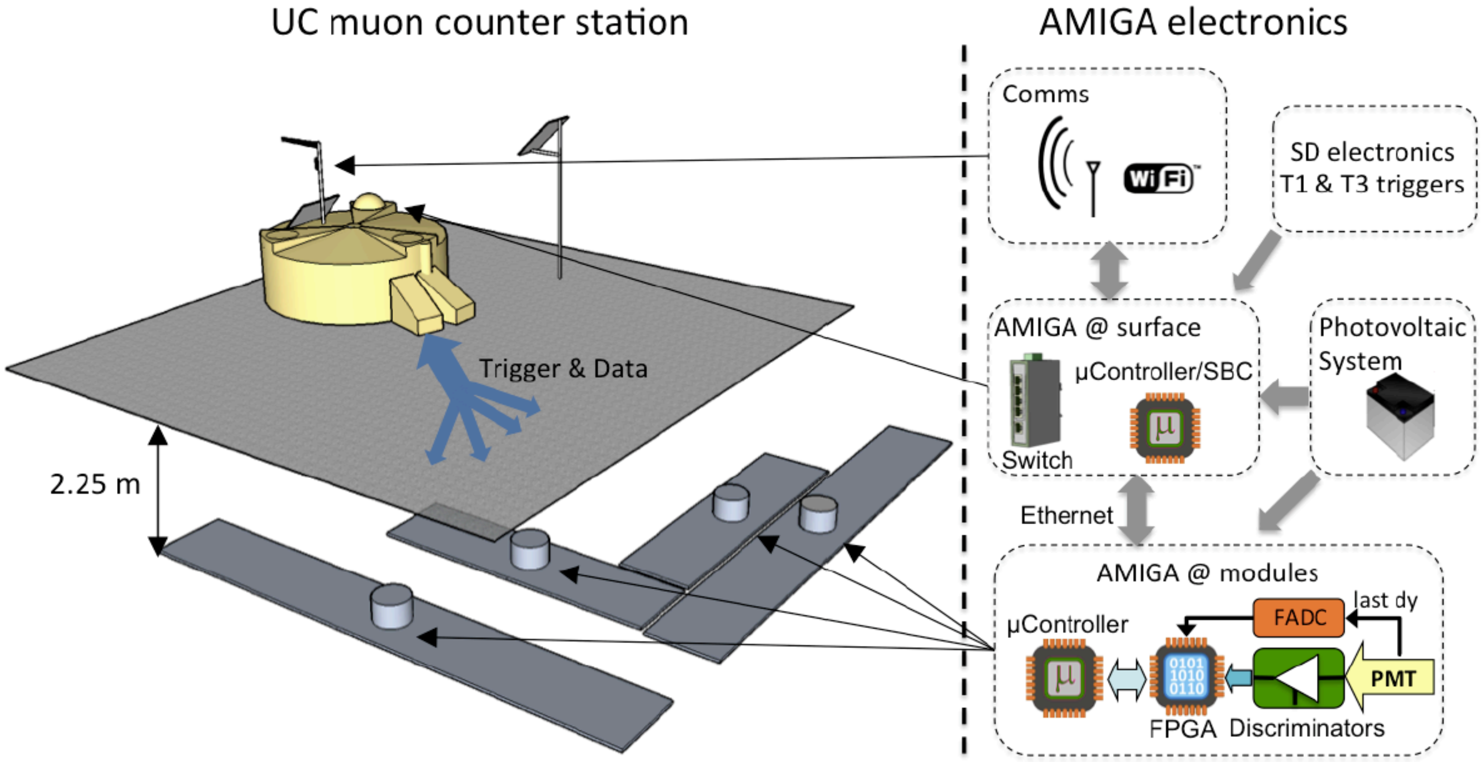
3- splitting the tank in two parts (the « Layered Surface Detector »)

for 2 and 3: observed signals $S_1 = A_1\Phi_\mu + B_1\Phi_{em}$, $S_2 = A_2\Phi_\mu + B_2\Phi_{em}$
➔ Φ_μ and Φ_{em} through a linear system (good if A_1/A_2 significantly > B_1/B_2)

4- using an external source of information (e.g. geomagnetic distortion of the muonic component)

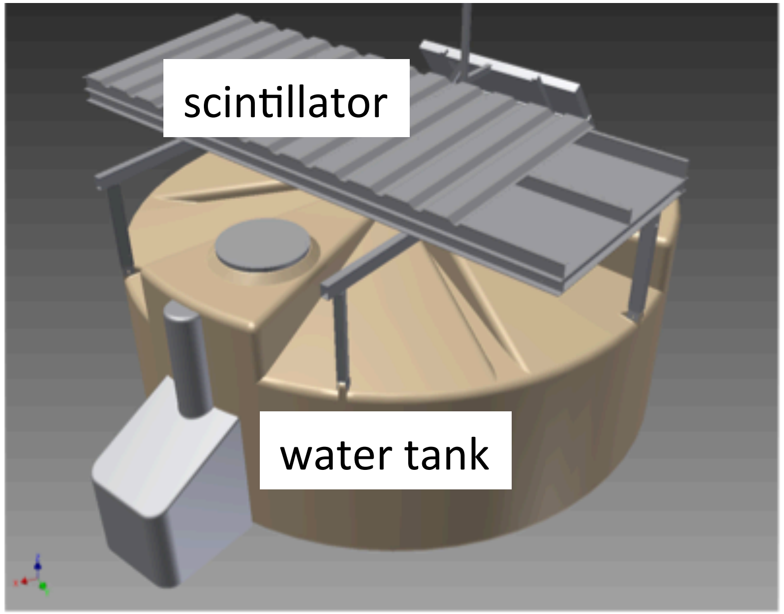
more or less details in the following

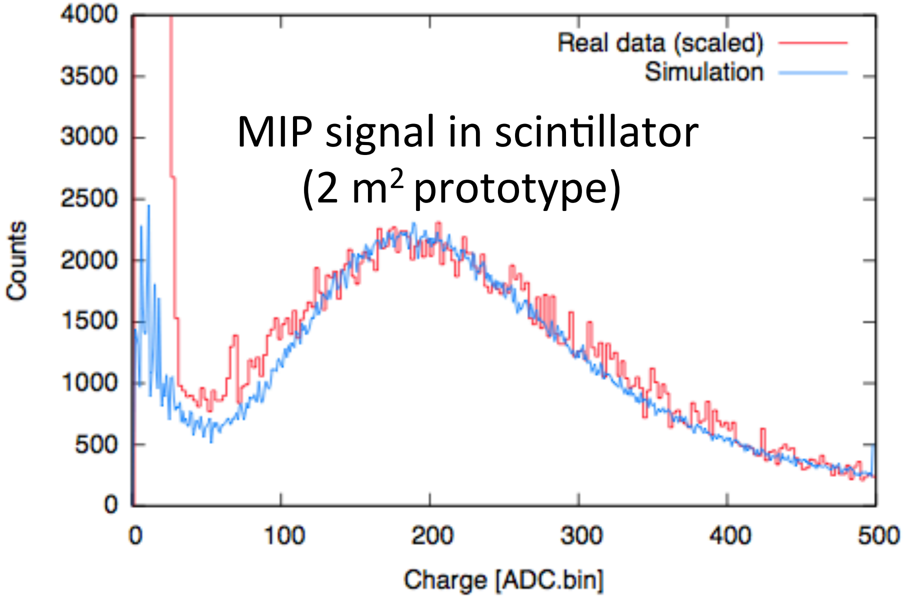
AMIGA in Auger (JINST 11 P02012)



- 2.25 m under ground surface ➔ lower cut for muons at 1 GeV or more (depending on incidence angle) ; e.m. component strongly suppressed
- muon samples in tank and scintillator are decorrelated (quadratic addition of fluctuations from Poisson statistics)

AugerPrime (ICRC 2015)





if scintillator (SSD) ≈ *counter of charged particles*

- 5 muons in SSD (no cut on momentum) ≈ 4 vertical muons in tank
- 1 GeV of e.m. energy (eq. to 4 vertical muons in tank) contains 6 to 8 e^+/e^-

➔ the scintillator is relatively more sensitive to the e.m. component than the tank

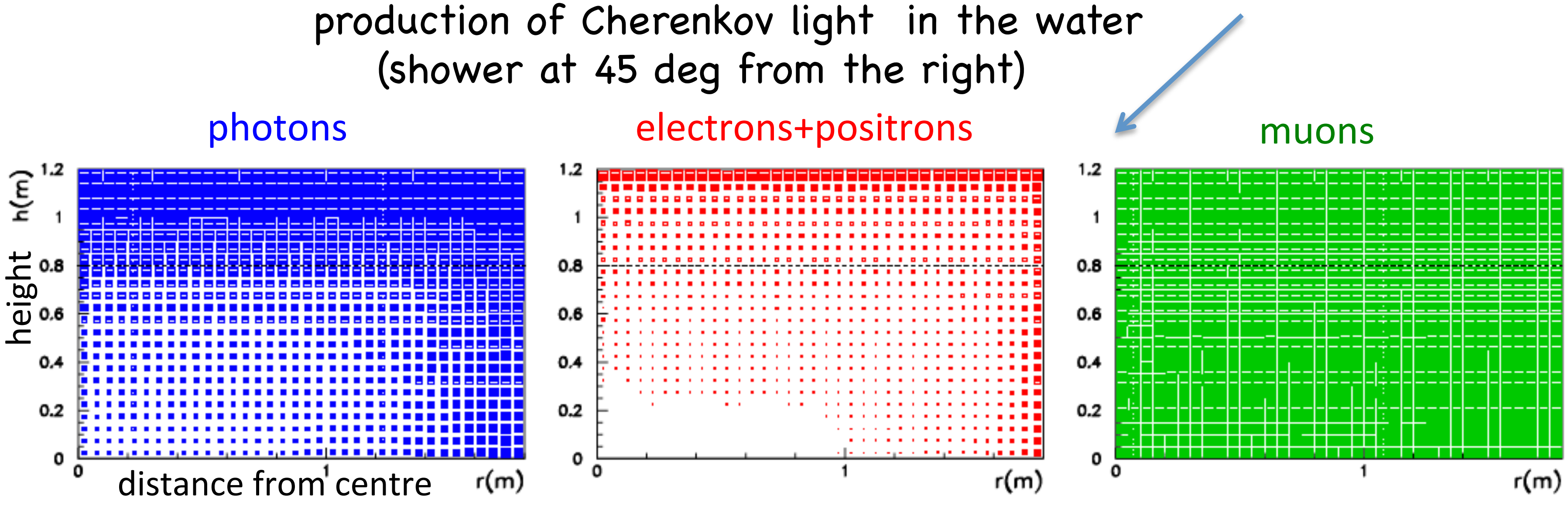
muon samples in scintillator (4 m^2) and tank (10 m^2) are partly correlated

➔ partial compensation of Poisson errors

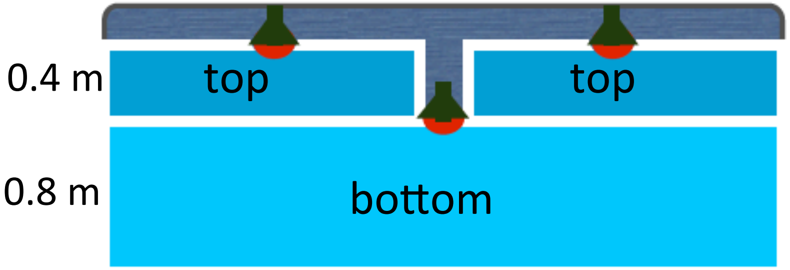
Layered Surface Detector

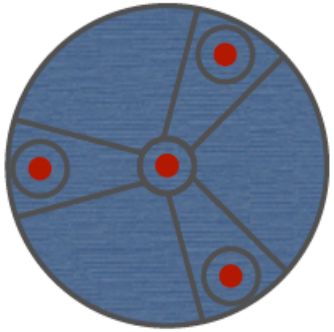
(A. Letessier-Selvon, P.B., M. Blanco, I. Maris, M. Settimo, NIM A 767 (2014) 41)

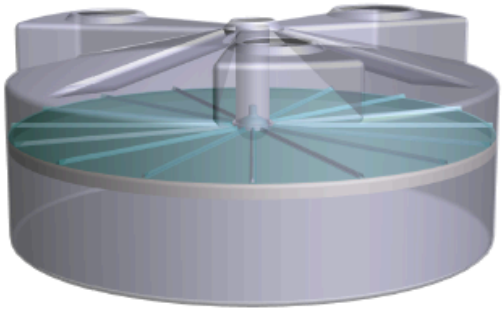
production of Cherenkov light in the water
(shower at 45 deg from the right)



proposed design (internal modification of Auger tank)



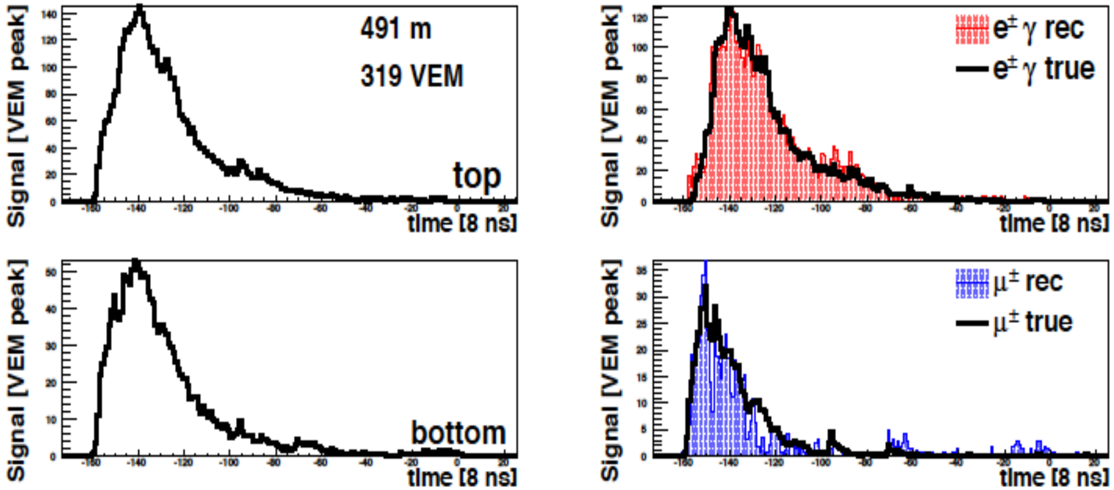




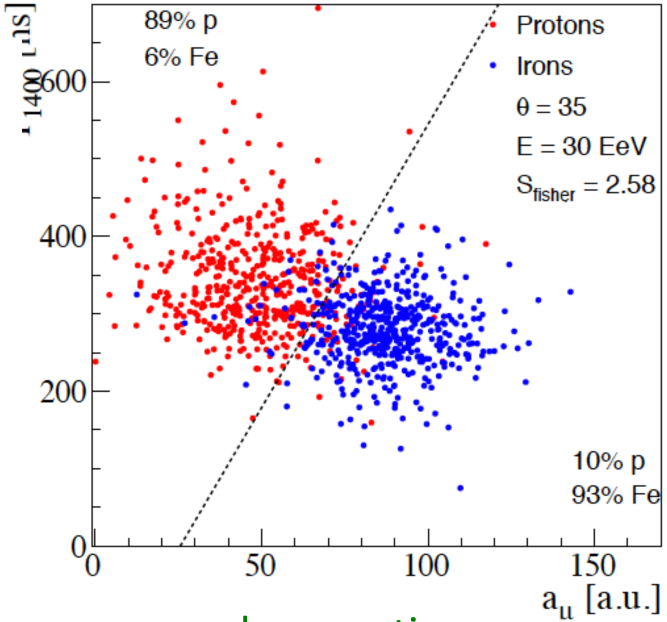
- electromagnetic signal : ≈ 60 % in top, 40 % in bottom (almost independent of incidence)
- muonic signal: 40 % in top, 60 % in bottom

results from the prototype

simulation

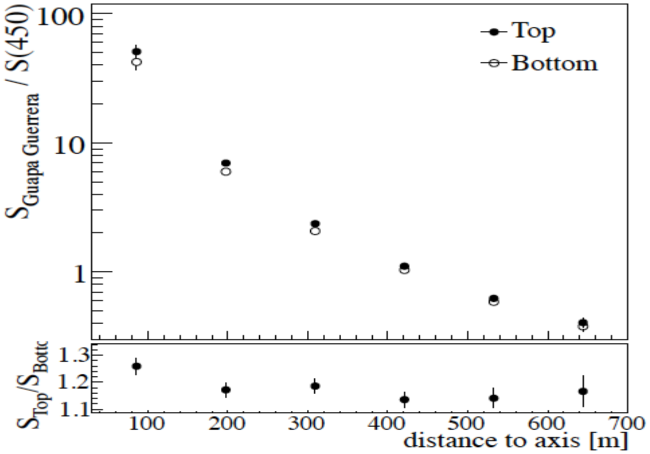


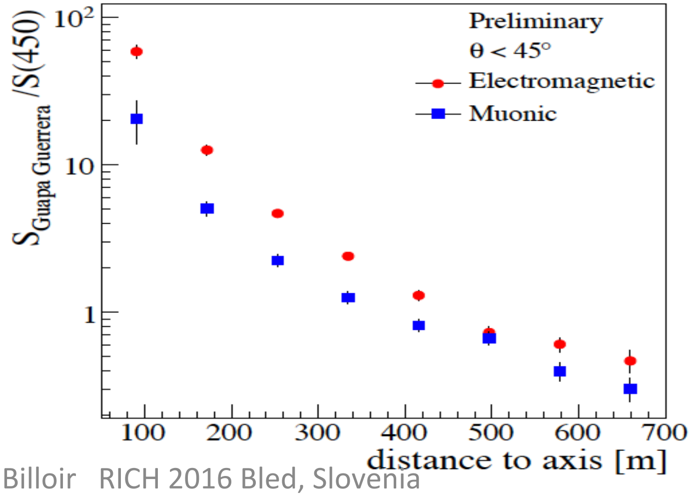
good restoration of separate contributions to FADC trace



good separation power

real data





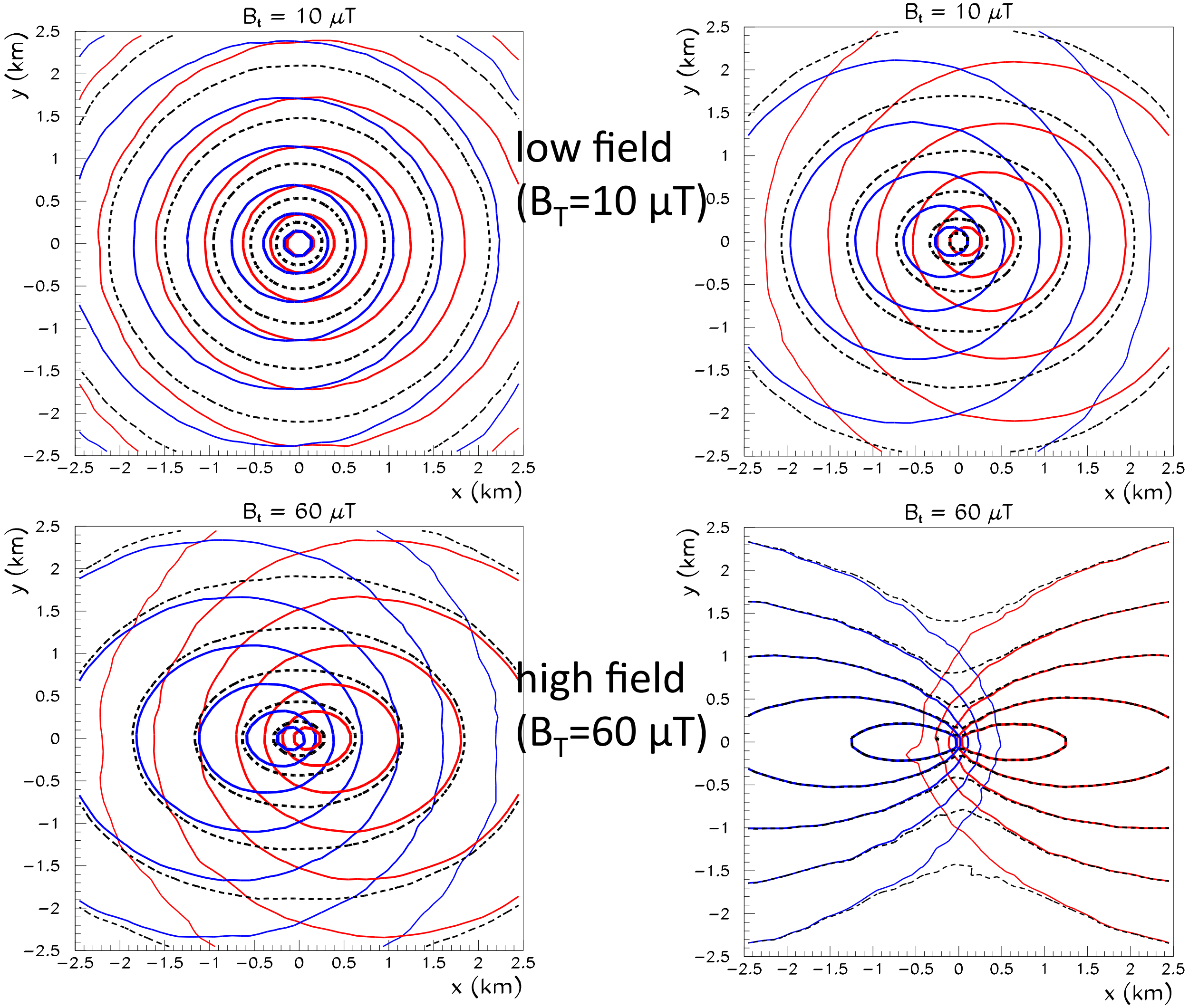
separate lateral distributions:
as expected
(e.m. steeper than muonic)

geomagnetic distortion

(P.B., M. Settimo, M.Blanco, Astropart. Phys. 74 (2016) 14)

zenith angle 64 deg

80 deg



low field (B_T=10 μT)

high field (B_T=60 μT)

very inclined showers (purely muonic):
density in transverse plane is more or less distorted

empirical parametrization:
radial(ρ) × angular(ϕ)

$$\rho = (r/r_{ref})^{1/2} - 1$$

$$f(\rho,\phi) = \exp(\lambda\rho + \alpha.\cos(2\phi))$$

$$\lambda = \lambda_0+\lambda_1\rho+\lambda_2\rho^2$$

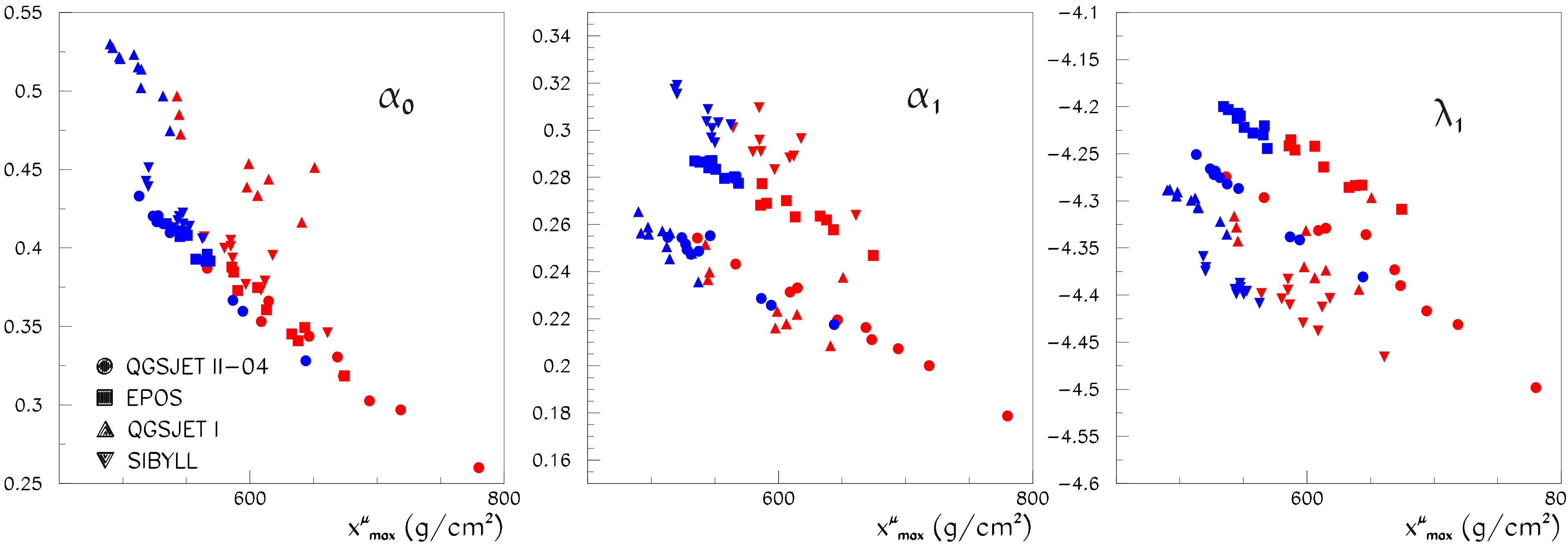
$$\alpha = \alpha_0+\alpha_1\rho+\alpha_2\rho^2$$

the α_i and λ_i carry information about the longitudinal muon profile e.g. defining X^{μ}_{max}, tightly correlated to X_{max}

exploiting the distortion

α,λ parameters as functions of X^{μ}_{max} with *different models*

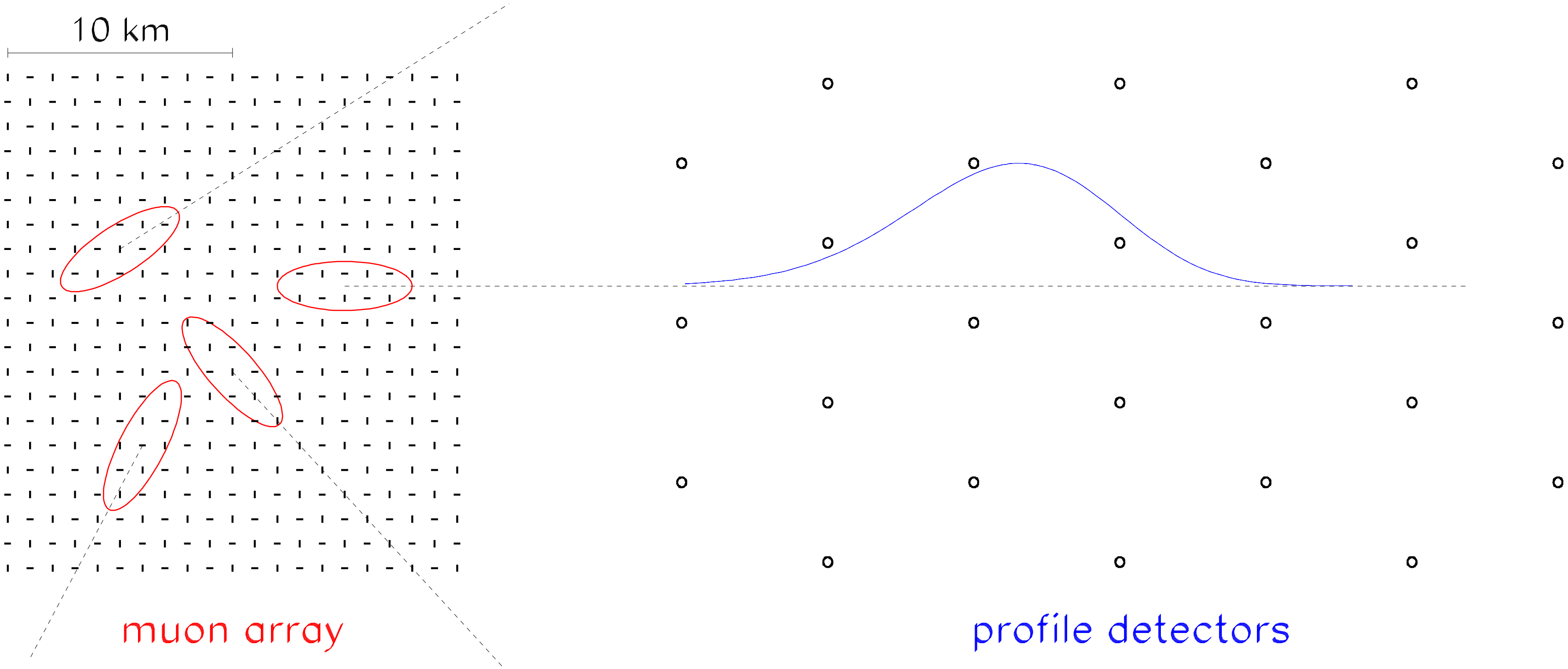
(here: zenith angle 72 deg, B_T = 30 µT, proton and iron showers)



- for a given model, different nuclei are on the same line: α,λ provide ***an identification of primary*** with a consistency check between parameters
- if X_{max} is measured independently (e.g. through fluorescence): ***better model discrimination***

ideally: dedicated hybrid detector of inclined showers (muons at ground + profile) to measure (α,λ) and (X_{max} , N_{max}) on the same events

a possible detector layout



spacing ~ 500 m or less to ensure a large multiplicity at 1 EeV (good precision on α, λ needed)

may be single fluorescence eyes with a large field of view, as proposed in arXiv:1504.00692

hybrid events are used to calibrate the relation between α, λ and X_{max} and provide a discrimination between the models of hadronic interactions

summary

Cherenkov tanks are proven to be good and robust detectors of ground particles produced by extensive atmospheric showers. especially when associated to a longitudinal profile detector (fluorescence, MHz radio)
but there are still open issues about the nature and the origin of the ultra energetic cosmic rays.

To go further, a better identification of primaries is needed, mainly through a better separation of muonic/electromagnetic components

generic idea: make two measurements with different *relative* mu/em sensitivity (additional detector or layered tank)

Unavoidable problem: systematic errors due to the modelling of the hadronic interactions at ultra high energies
possible constraints from complementary observations (e.g. geomagnetic distortion) ?