Pierre Auger Observatory
studying the universe's highest energy particles

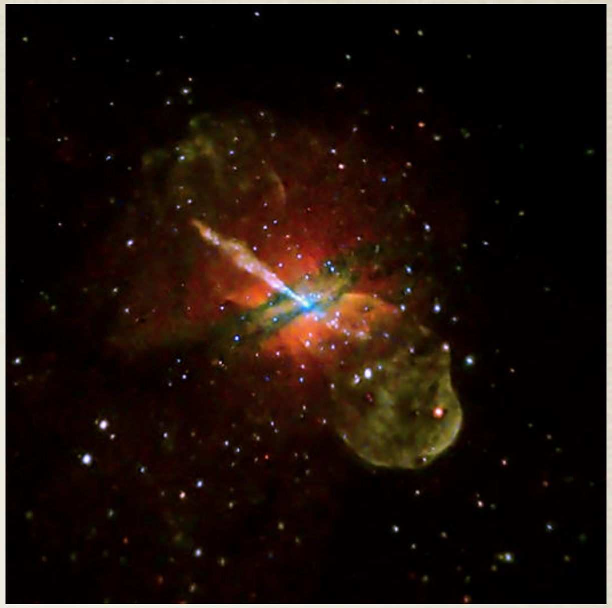
MASS COMPOSITION STUDY AT THE PIERRE AUGER OBSERVATORY

Laura Collica
University of Milano

INFN
Istituto Nazionale
di Fisica Nucleare

Mini-workshop 2012

Outline

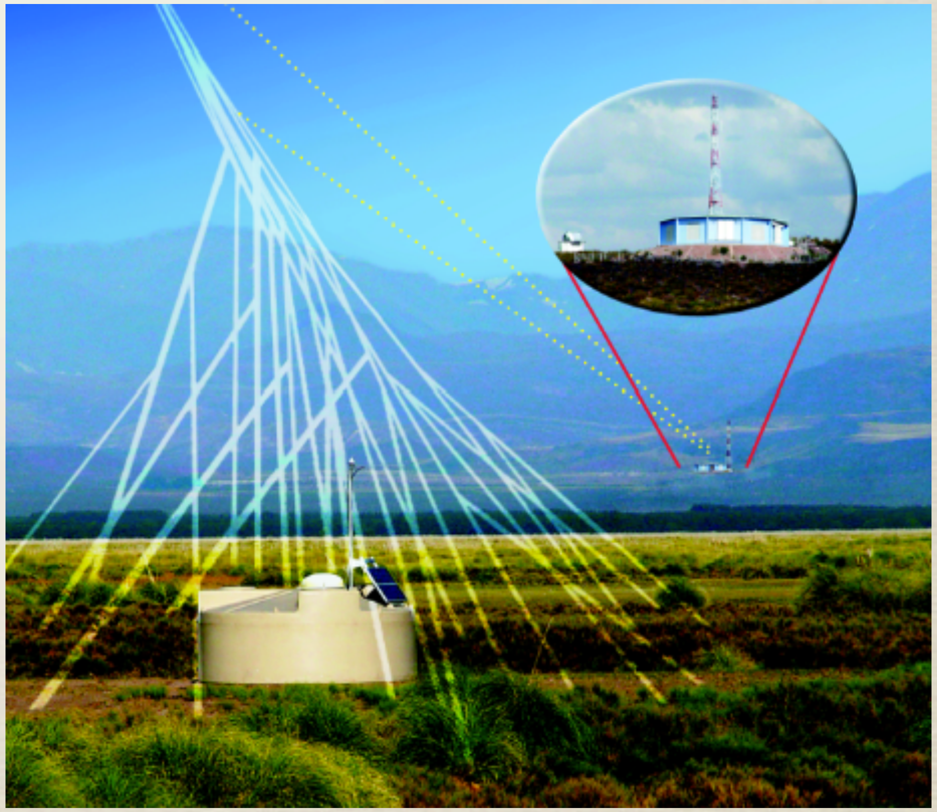


The physics:

- The UHECR spectrum
- Extensive Air Showers

The Pierre Auger Observatory:

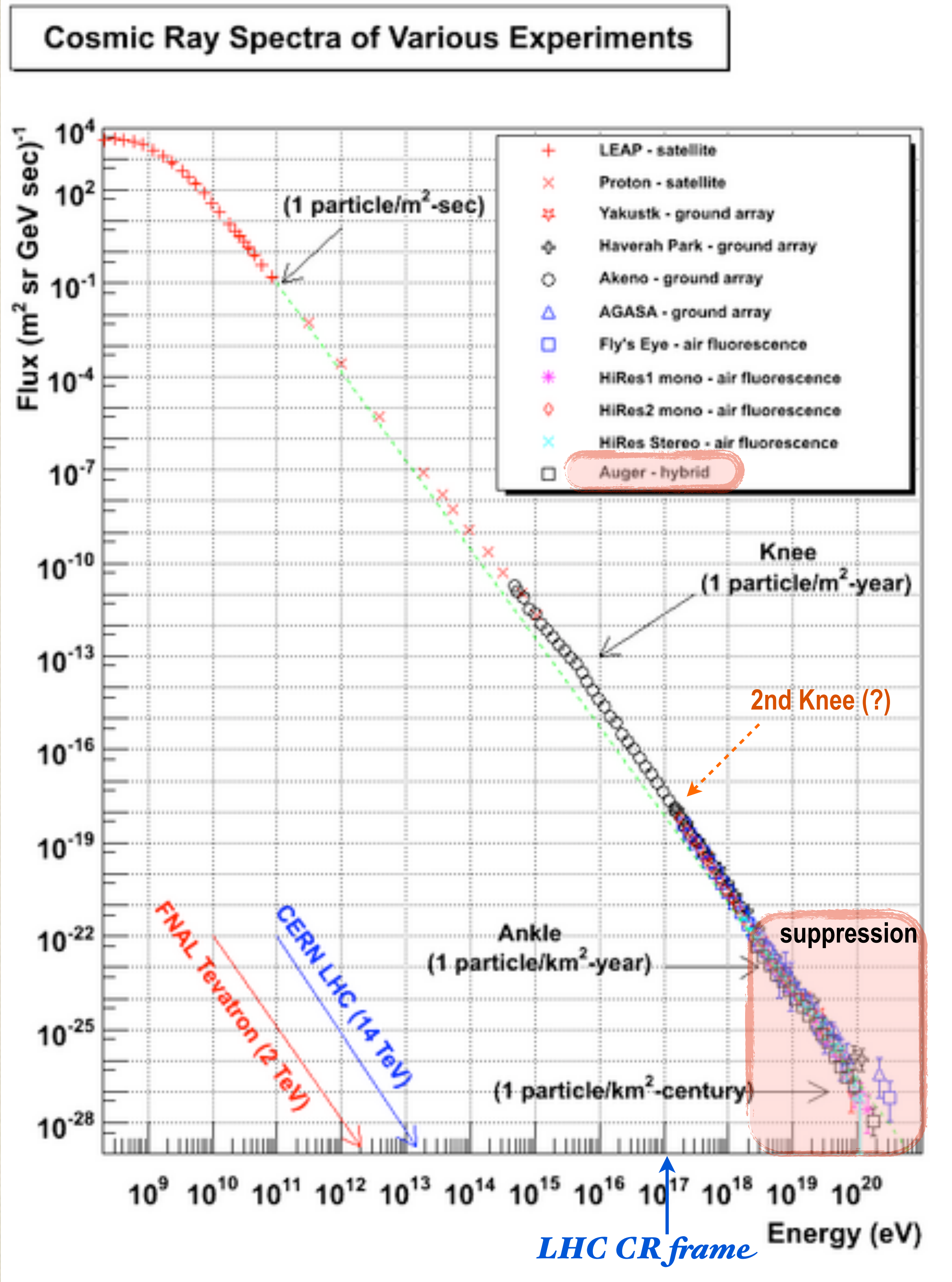
- Fluorescence Detector
- Surface Detector



UHECRs Mass Composition:

- Observables
- Experimental Results

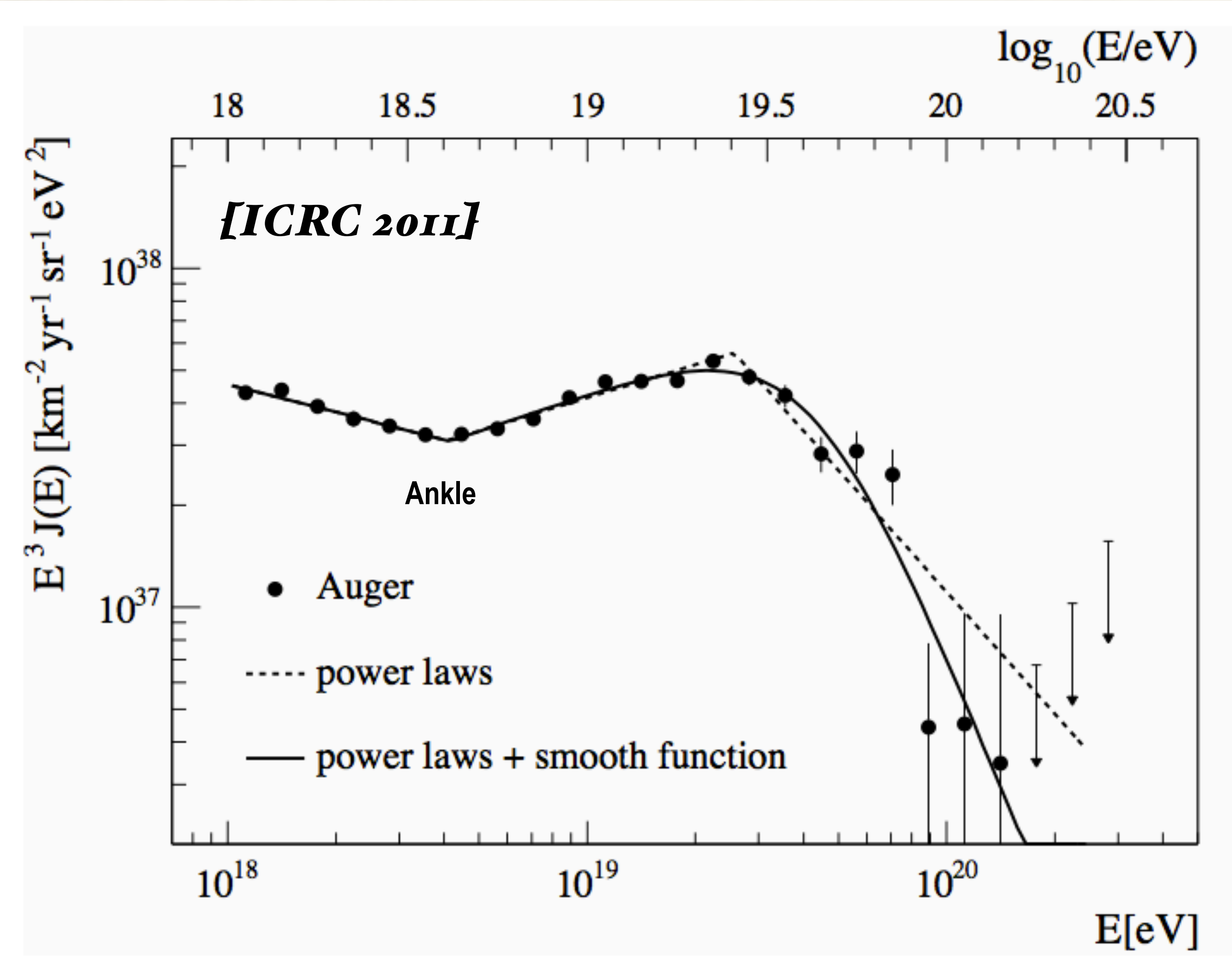
Ultra-High Energy Cosmic Rays



- UHECR are energetic particles which originate from outer space. E>10^19 eV
- Nature and origin not yet known 100 years after their discovery.
- Power-law flux over many orders of magnitudes.
- <u>3 features</u>: knee, ankle and flux suppression.
- Direct measurements only below 10^15 eV. UHECRs are characterized by a very low flux:

⇨ Earth detectors with huge collection area!

End of the CR spectrum:
GZK effect or exhaustion of the sources?



Propagation Scenario

Greisen-Zatsepin-Kuz'min effect (1966): Interaction with the cosmic microwave background (CMB)

Proton:

$$\left.\begin{array}{l}\gamma_{CMB} + p \rightarrow \Delta^+ \rightarrow n + \pi^+ \\ \gamma_{CMB} + p \rightarrow \Delta^+ \rightarrow p + \pi^0\end{array}\right\} E \geq 7 \cdot 10^{19} eV$$

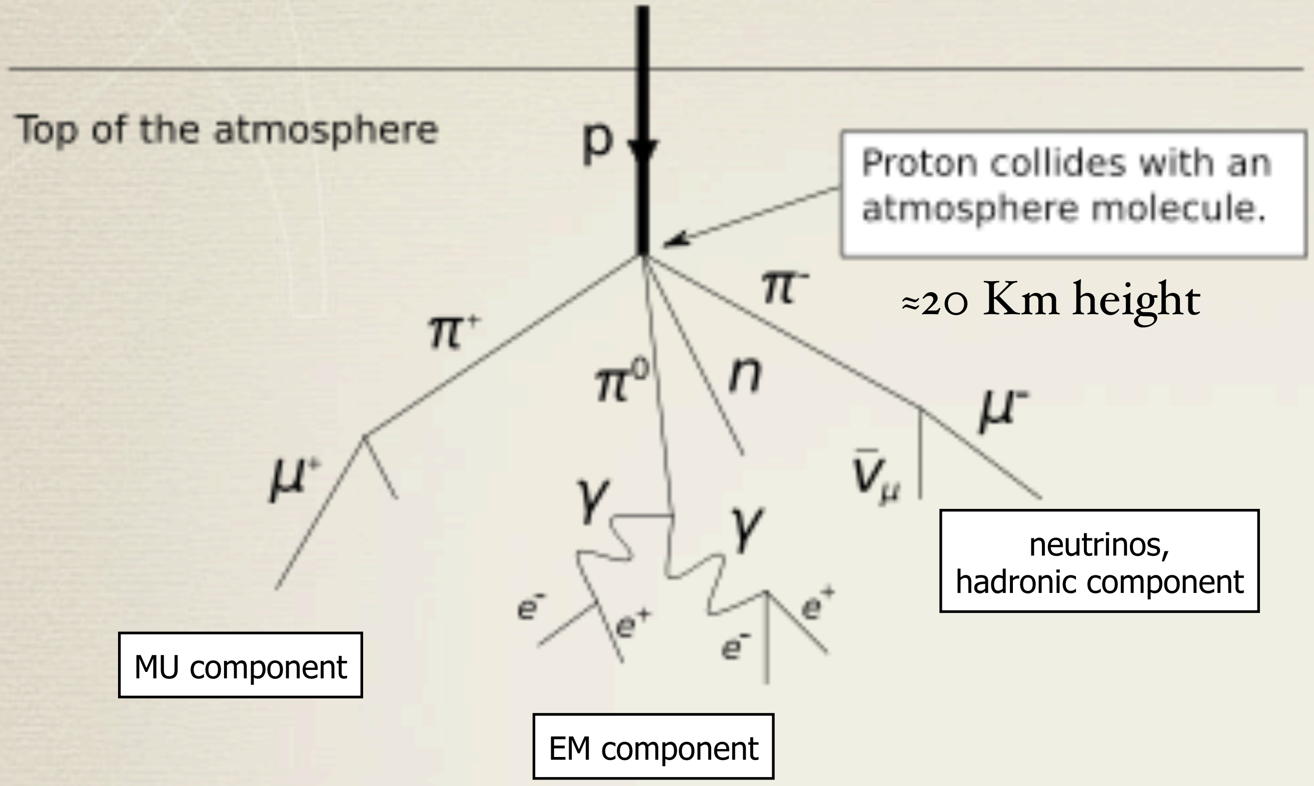
Nuclei: Photo-disintegration on CMB

“horizon” ~ 100 Mpc (~10^20 eV)

Source Scenario Maximum Energy of the source: $E_{max} \propto ZBR$

⇨ **The knowledge of composition at the highest energies and the detection of cosmogenic neutrino and/or photons is the main challenge for near future!**

UHECR Detection via Extensive Air Showers



Proton collides with an atmosphere molecule.

≈20 Km height

neutrinos, hadronic component

MU component

EM component

Atmosphere acts like an homogeneous calorimeter!

- EAS=only way to study UHECRs due to their low flux (< 1 particle/km^2/year)
- Detection techniques are developed for measuring both the energy deposit in the atmosphere and the particle density at ground
- Data MC comparison is based on EAS simulations (CORSIKA, AIRES) which include extrapolations for hadronic interactions up to UHE based on different models (QGSJET, EPOS, SYBILL)

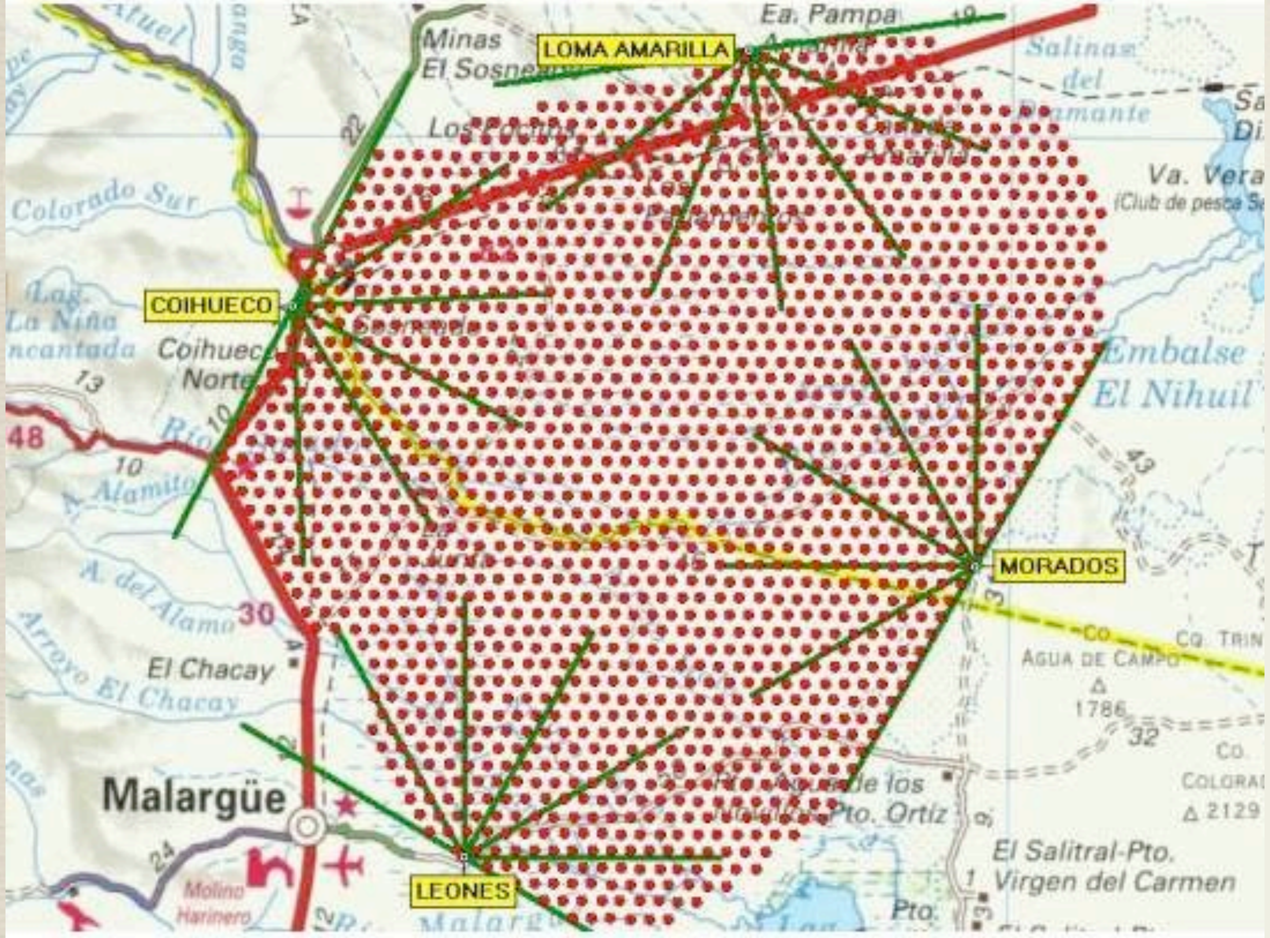
<u>The uncertainties in the models are the main source of systematics</u>

➜ need for many independent observables to study primary mass composition

The Pierre Auger Observatory

69° W, 35° S, 1420 m a.s.l.

Province of Mendoza, Argentina



Surface Detector

1600 Water Cherenkov stations on a 1.5 km triangular grid (~ 3000 km^2)

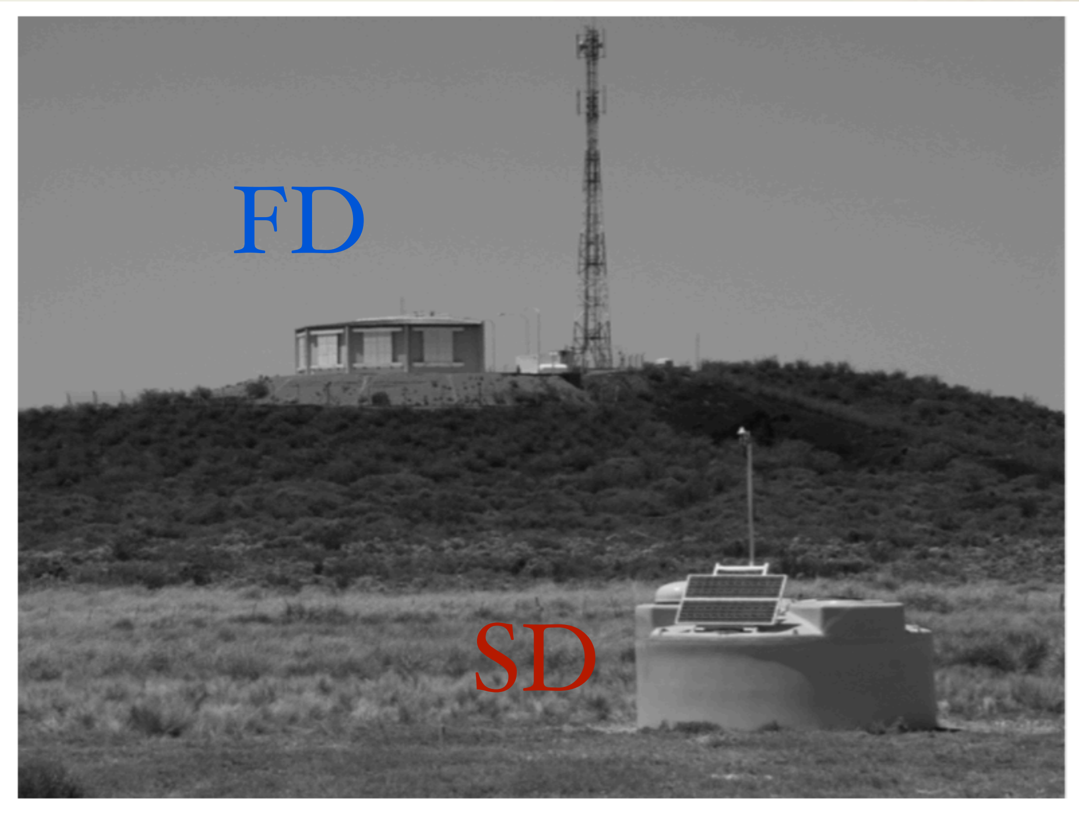
Fluorescence Detector

24 UV telescopes grouped in 4 buildings overlooking SD array

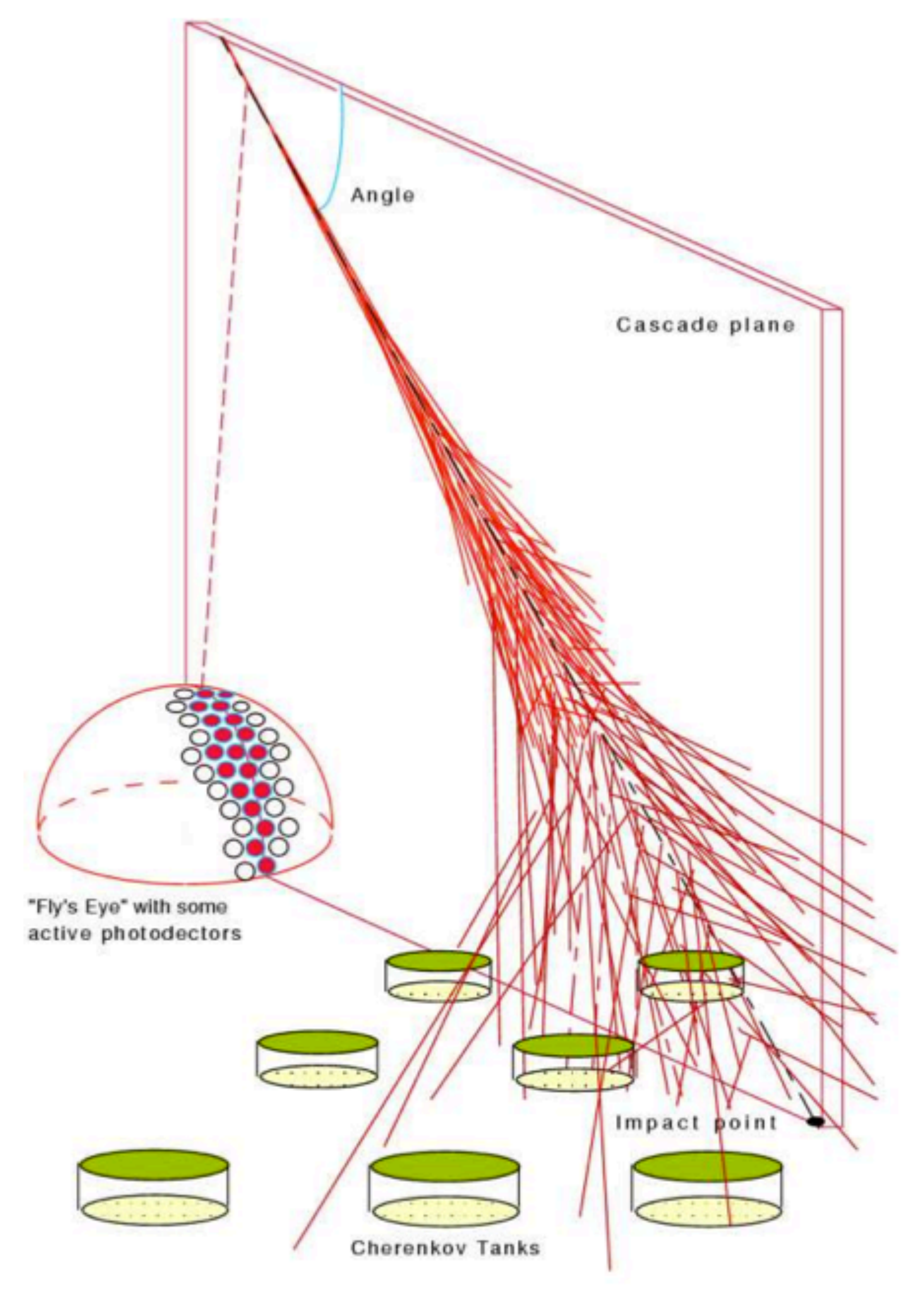
Low energy enhancement

AMIGA: dense array plus muon detectors

HEAT: three further high elevation FD telescopes



Hybrid detection technique



SD observables:
signals and shower temporal profile
~**100% duty cycle**

➜ lateral distribution of particles

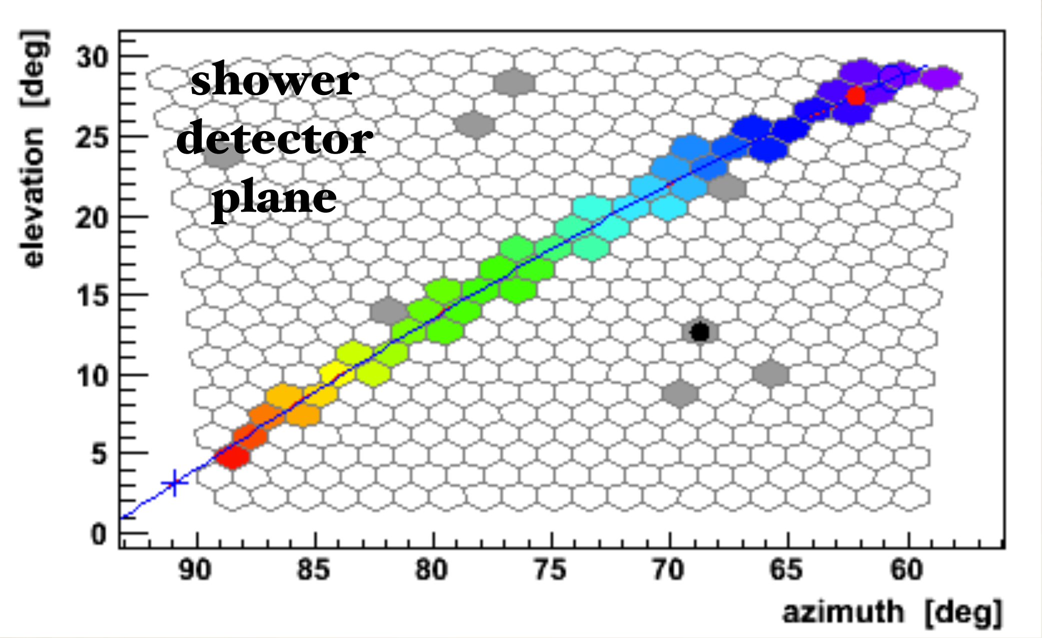
FD observables:
nitrogen fluorescence emission and time sequence on PMTs
~**13% duty cycle** (operative during moonless night)

➜ longitudinal profile, calorimetric energy measurement, SD energy calibration

accurate energy and arrival direction measurement

mass composition studies in a complementary way

Observation of longitudinal profile with FD

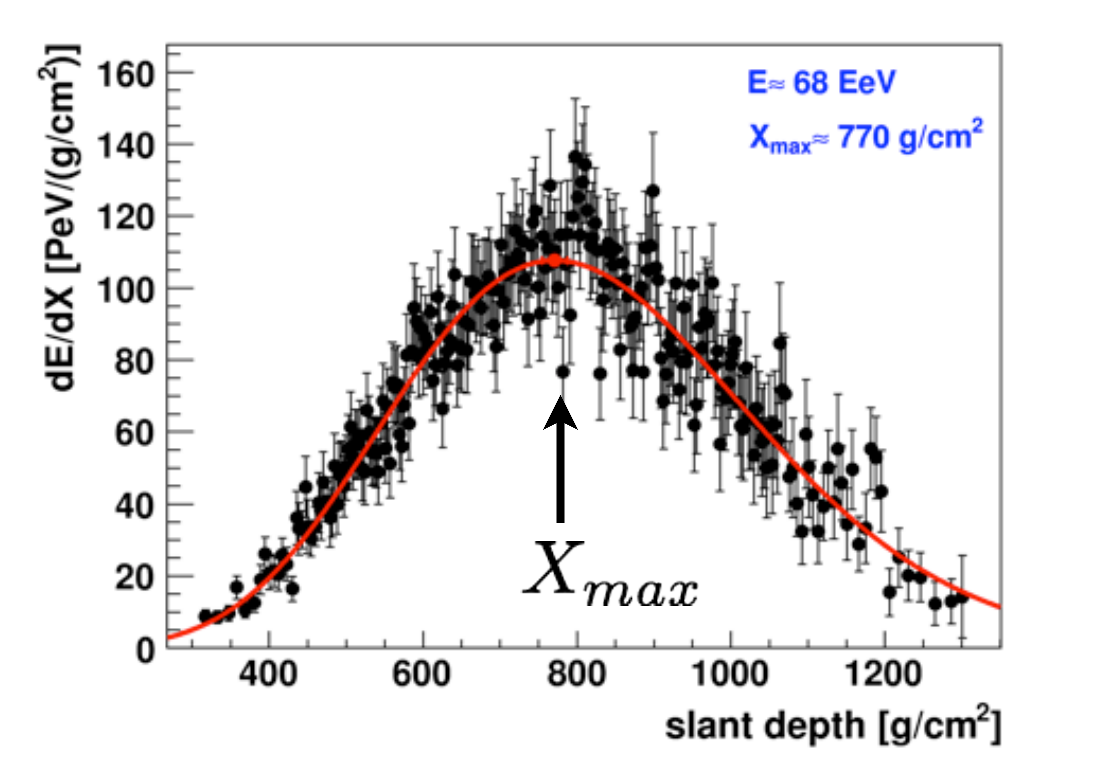


1 event seen by Coihueco telescope

Hybrid reconstruction of geometry

⇨

Atmosphere attenuation correction



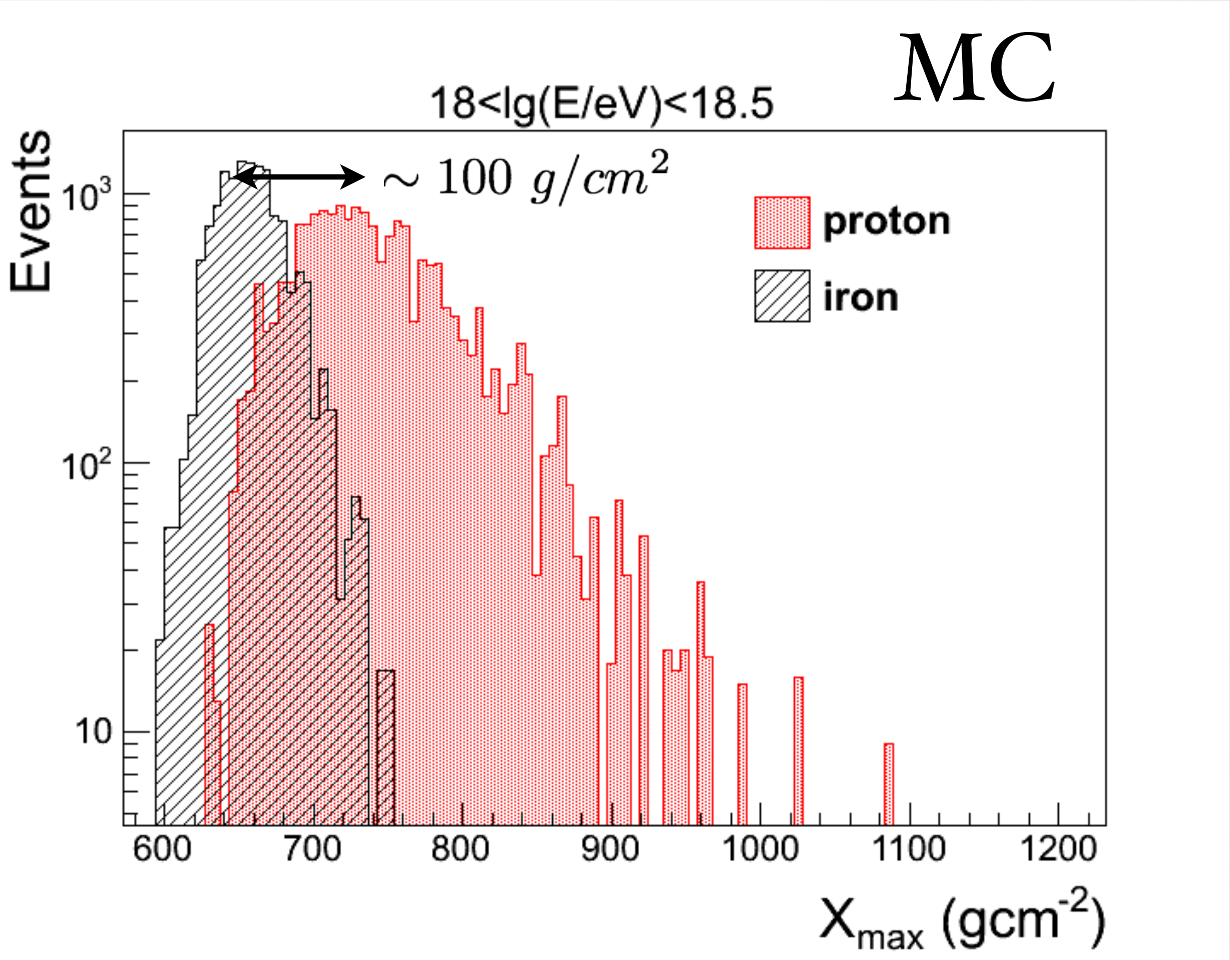
X_{max} determined by
the depth of the first interaction
the depth that it takes the cascade to develop

$$< X_{max} >= \alpha(lnE - < lnA >) + \beta$$

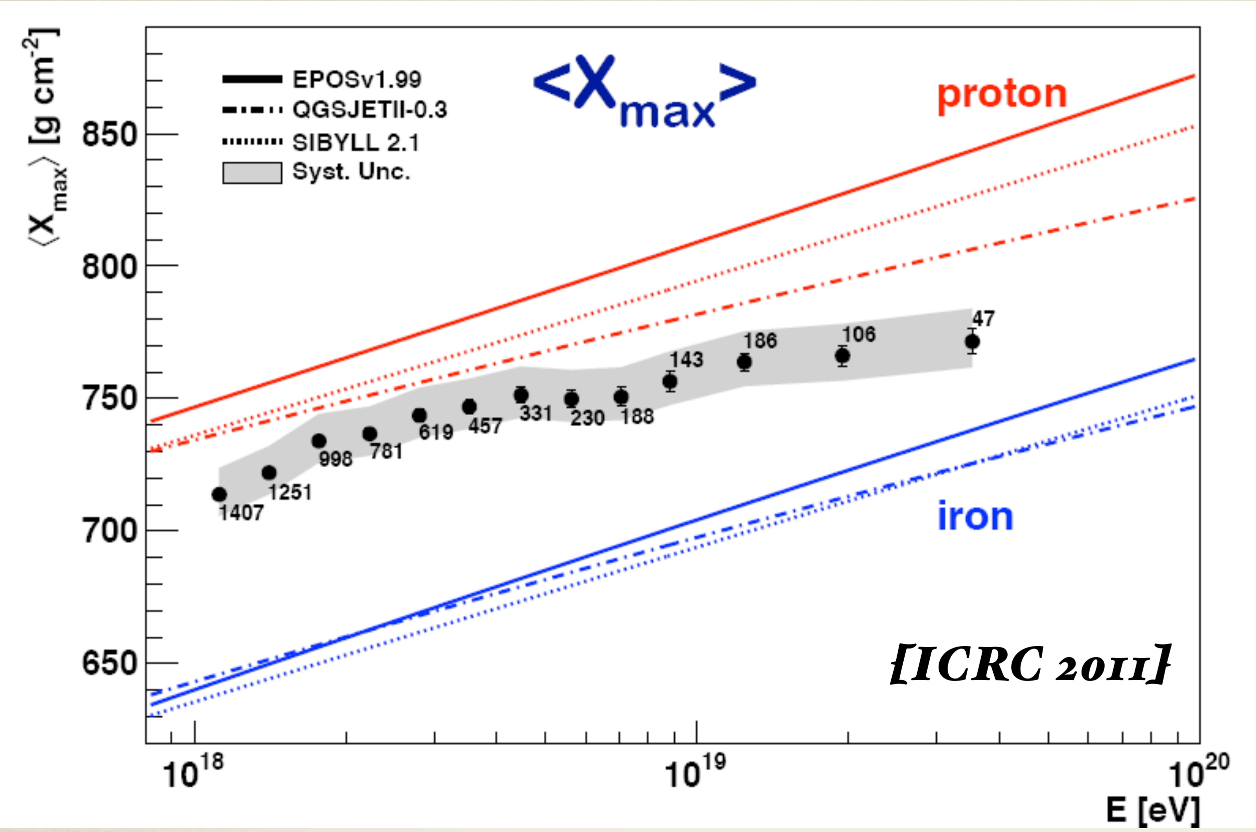
$$\Delta X_{max} \propto A^{-1}$$

$X_{max}, \Delta X_{max}$

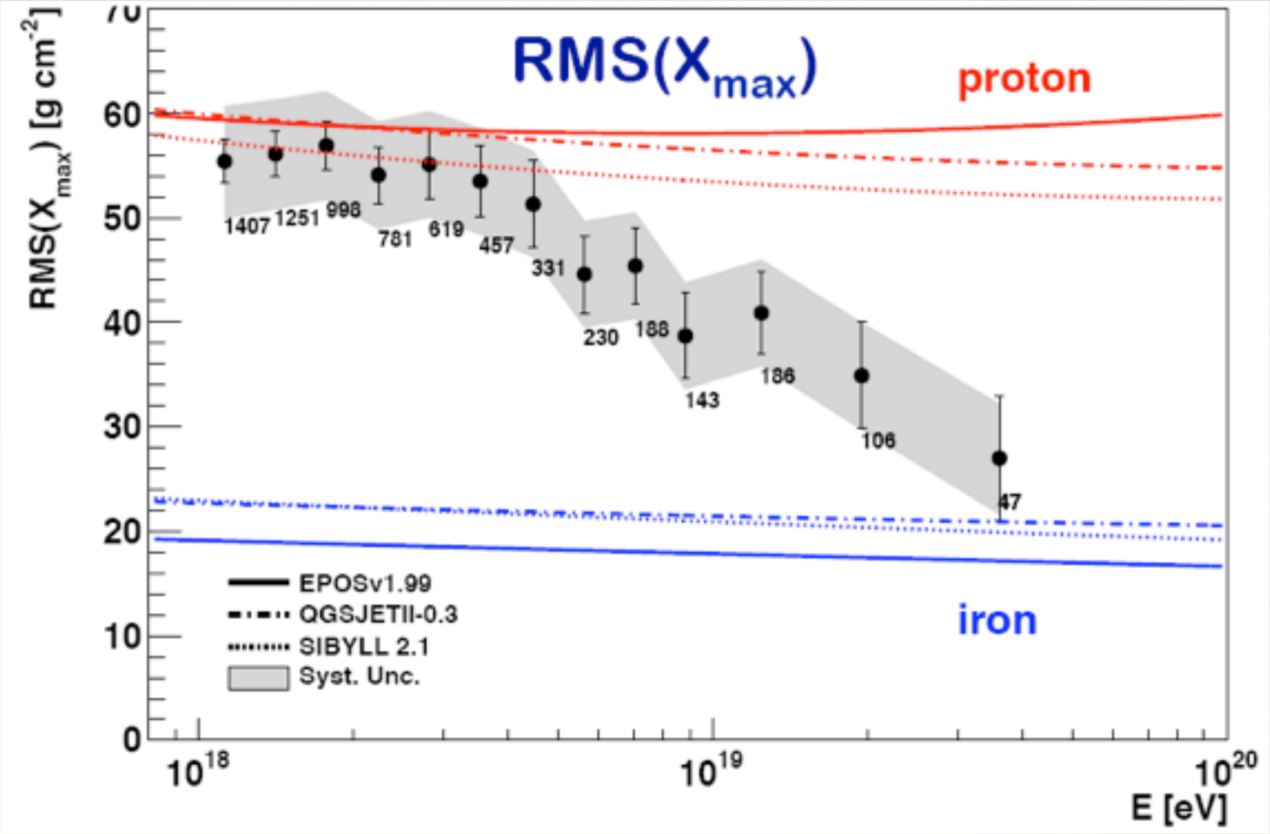
SENSITIVE TO MASS COMPOSITION



Composition with FD



Syst uncertainty < 13 g cm^{-2}



Xmax resolution ~ 20 g cm^{-2}

➜results suggest that composition gets heavier as E increases

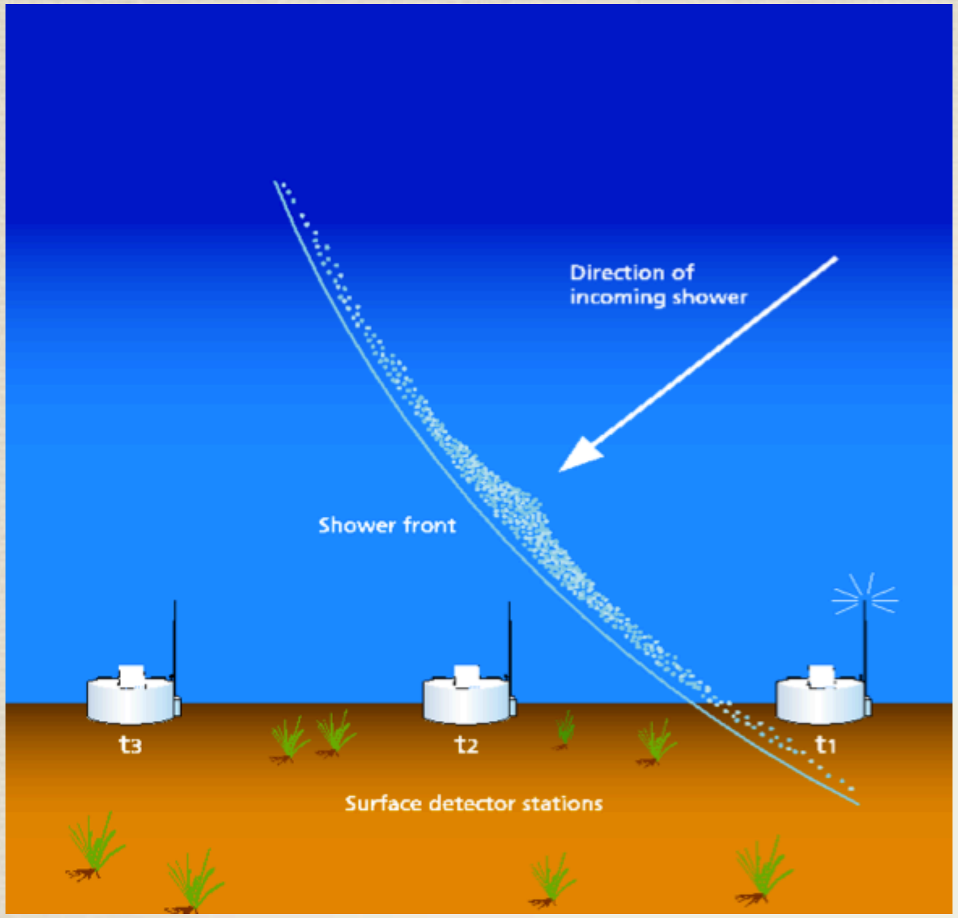
➜ interpretation depends on hadronic interaction models

LIMIT: low statistics at UHE (FD duty cycle ~13%)

→ collect more statistics

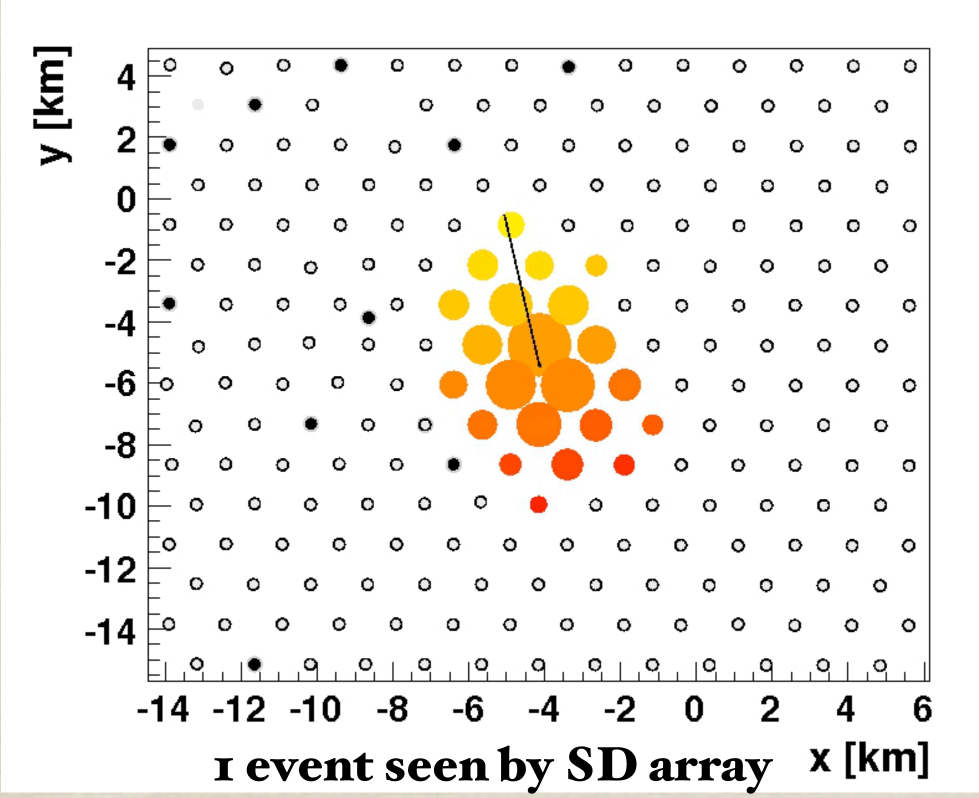
→ SD mass sensitive observables

UHECRs Observation with SD

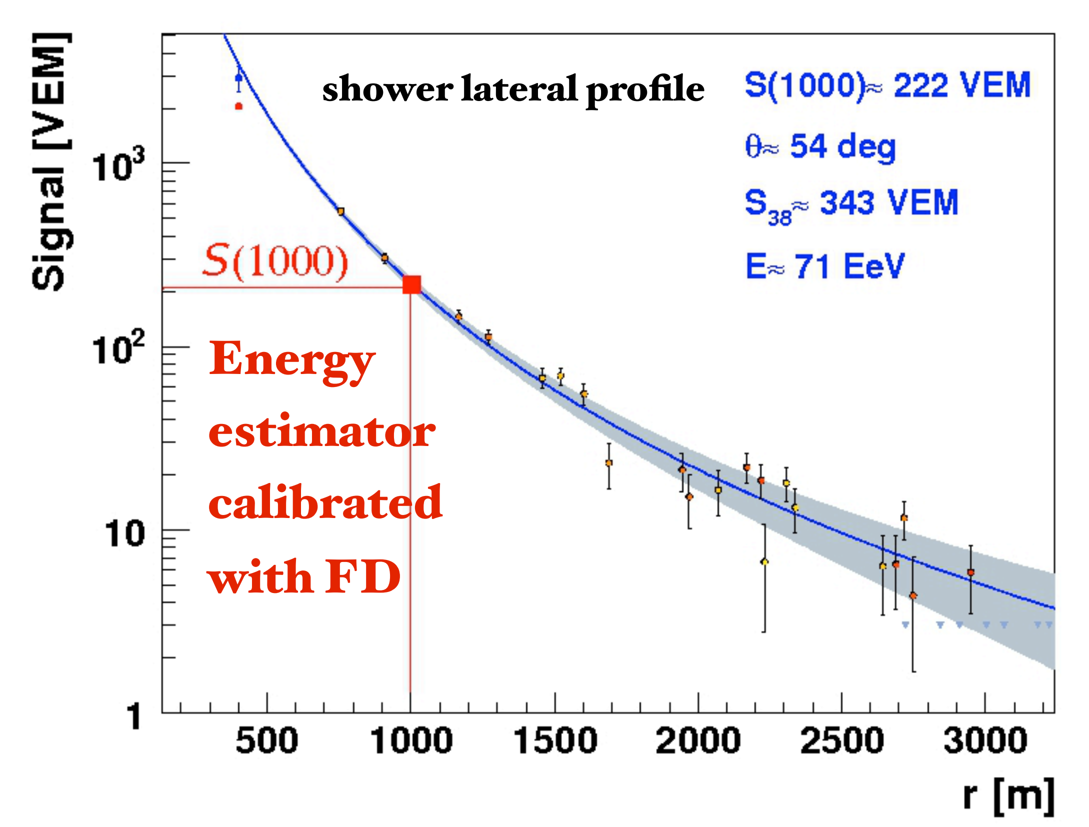


- Particles are sampled on the ground, at a single atmospheric depth
- UHECR direction: fit to arrival times sequence of particles in shower front

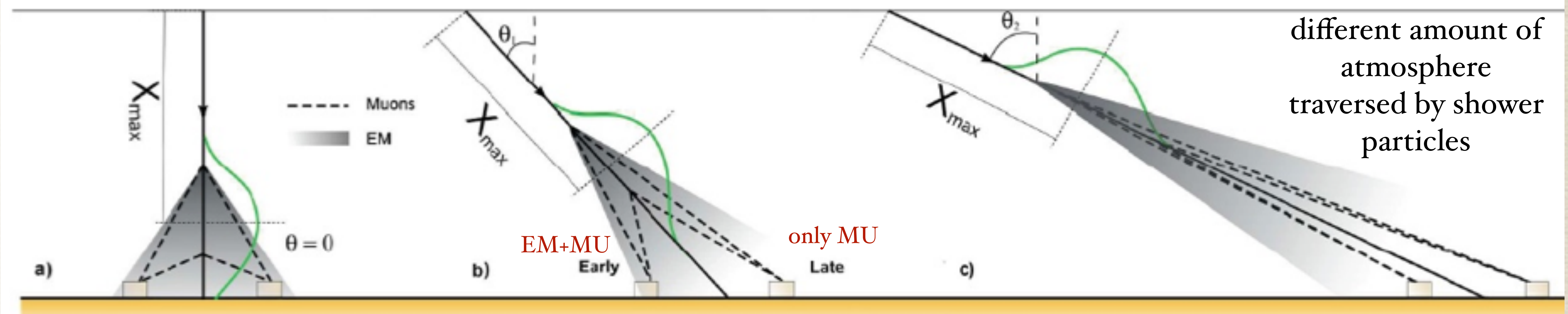
Good angular resolution
$E > 10^{18}$ eV, ~ 3 stations, < 2°
$E > 10^{19}$ eV, ~ 6 stations, < 1°



1 event seen by SD array



Composition with SD



different amount of atmosphere traversed by shower particles

<u>Rise Time of the tank signals (10% to 50%) related to the muon content of the shower</u>

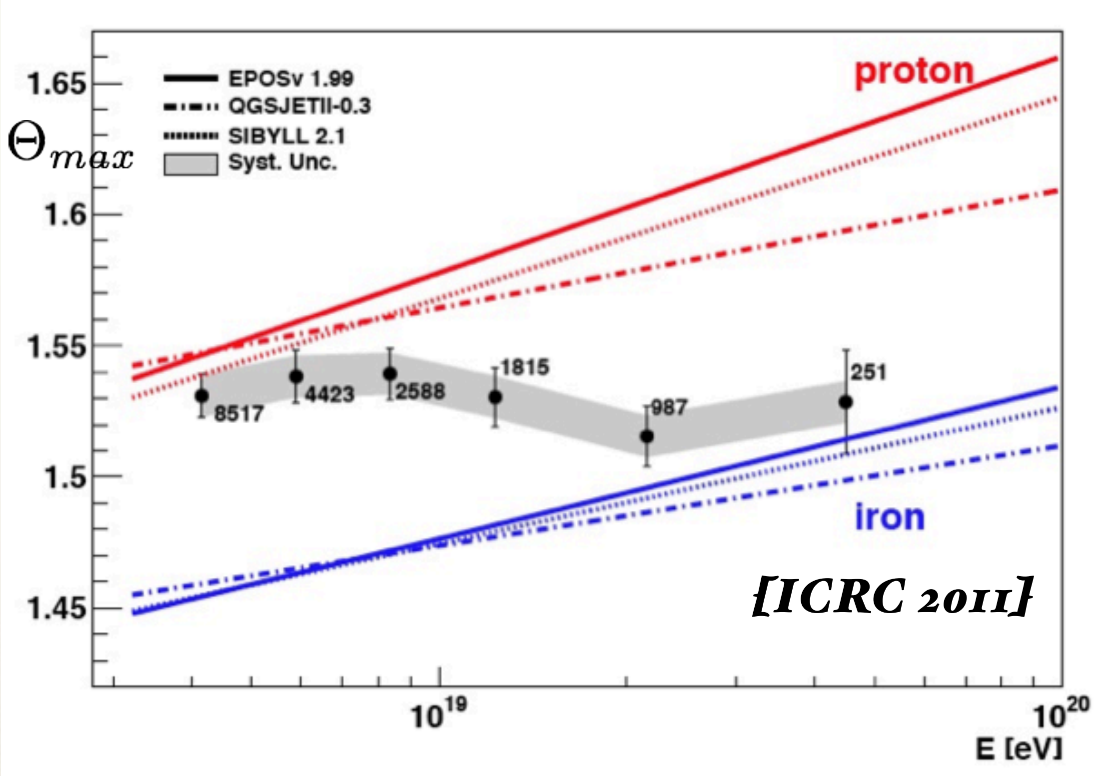
The fast part of the signal is dominated by the muons
EM is more spread out in time (due to multiple scattering)

- <u>Rise time asymmetry</u>: the zenith angle at which the asymmetry becomes maximum is related to the shower development

LIMIT:

Only for non-vertical shower (30°-60°)

Not on an event-by-event basis:
events grouped in bins of E and sec θ



[ICRC 2011]

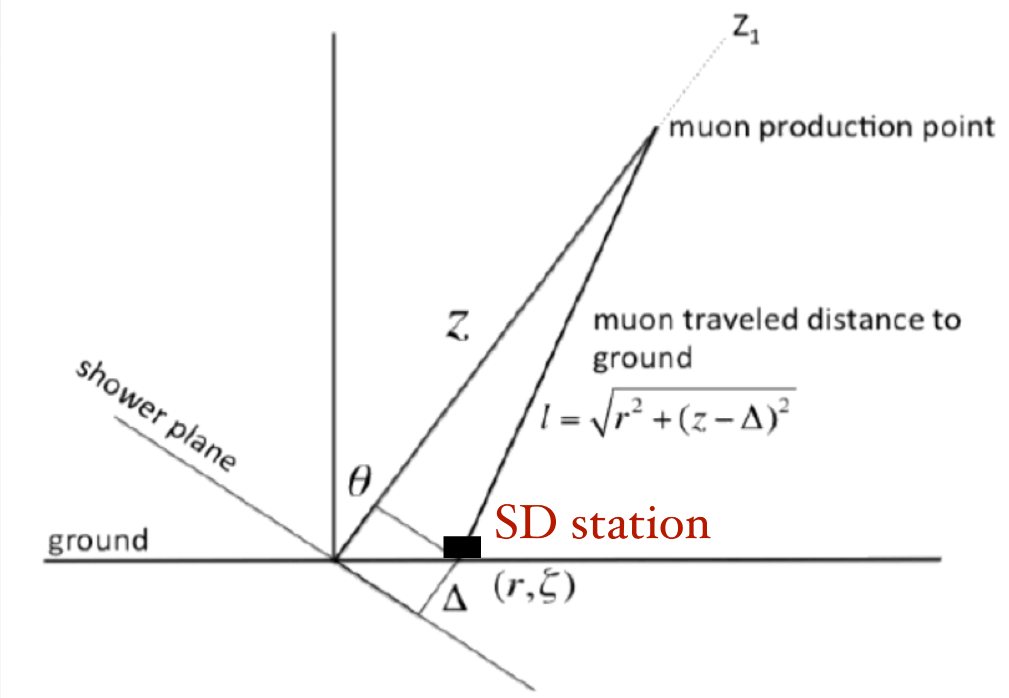
Muon Production Depth

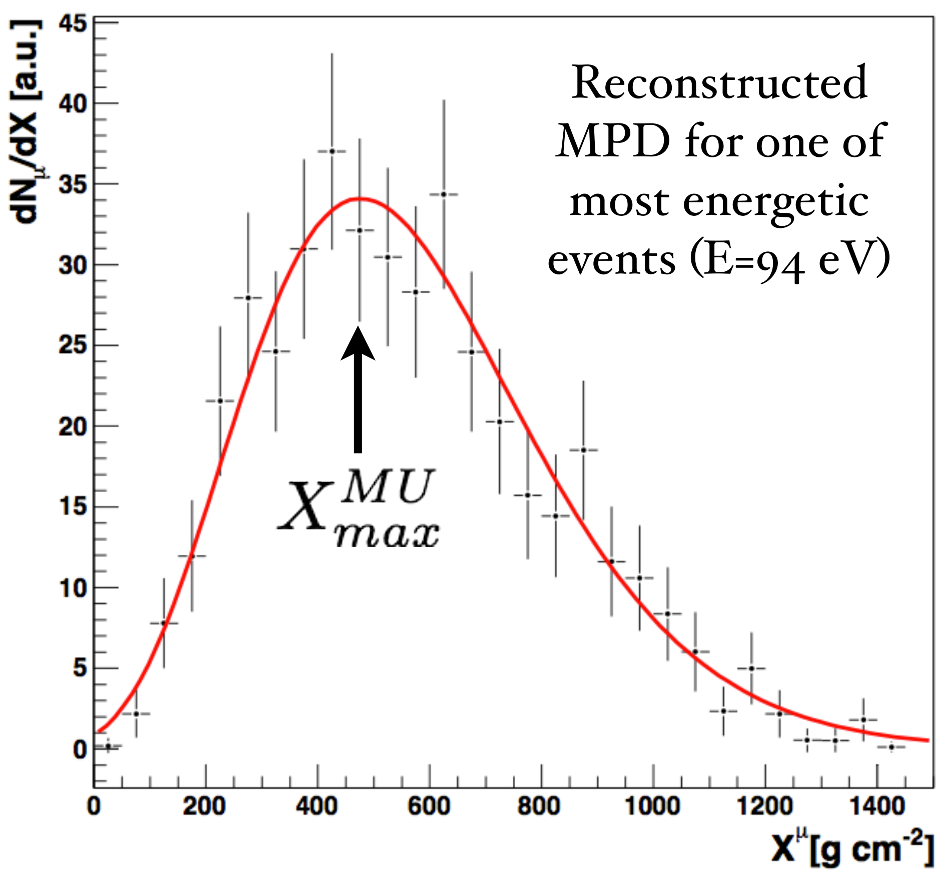
The muon longitudinal profile could be estimated from the muon time structure at ground **event-by-event**.

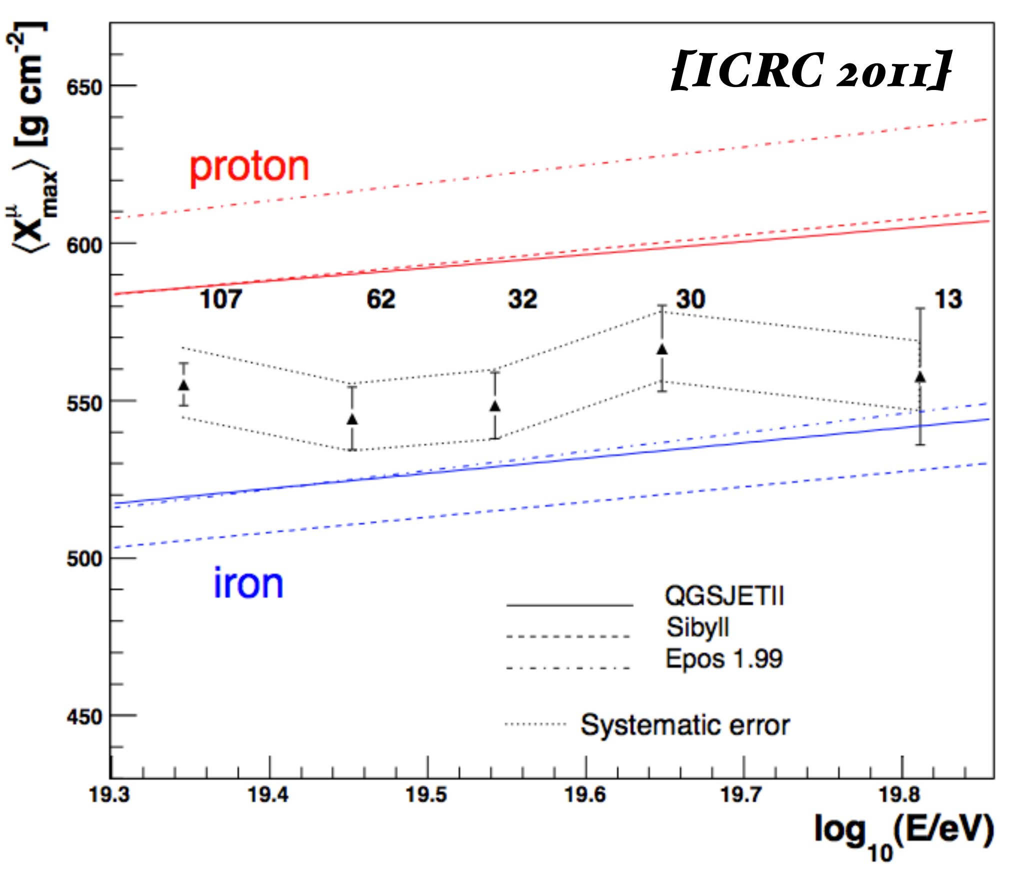
LIMIT:

Only for inclined showers (60°), traces from stations far from the core

➜ only 244 SD events (Jan'04-Dec'10)



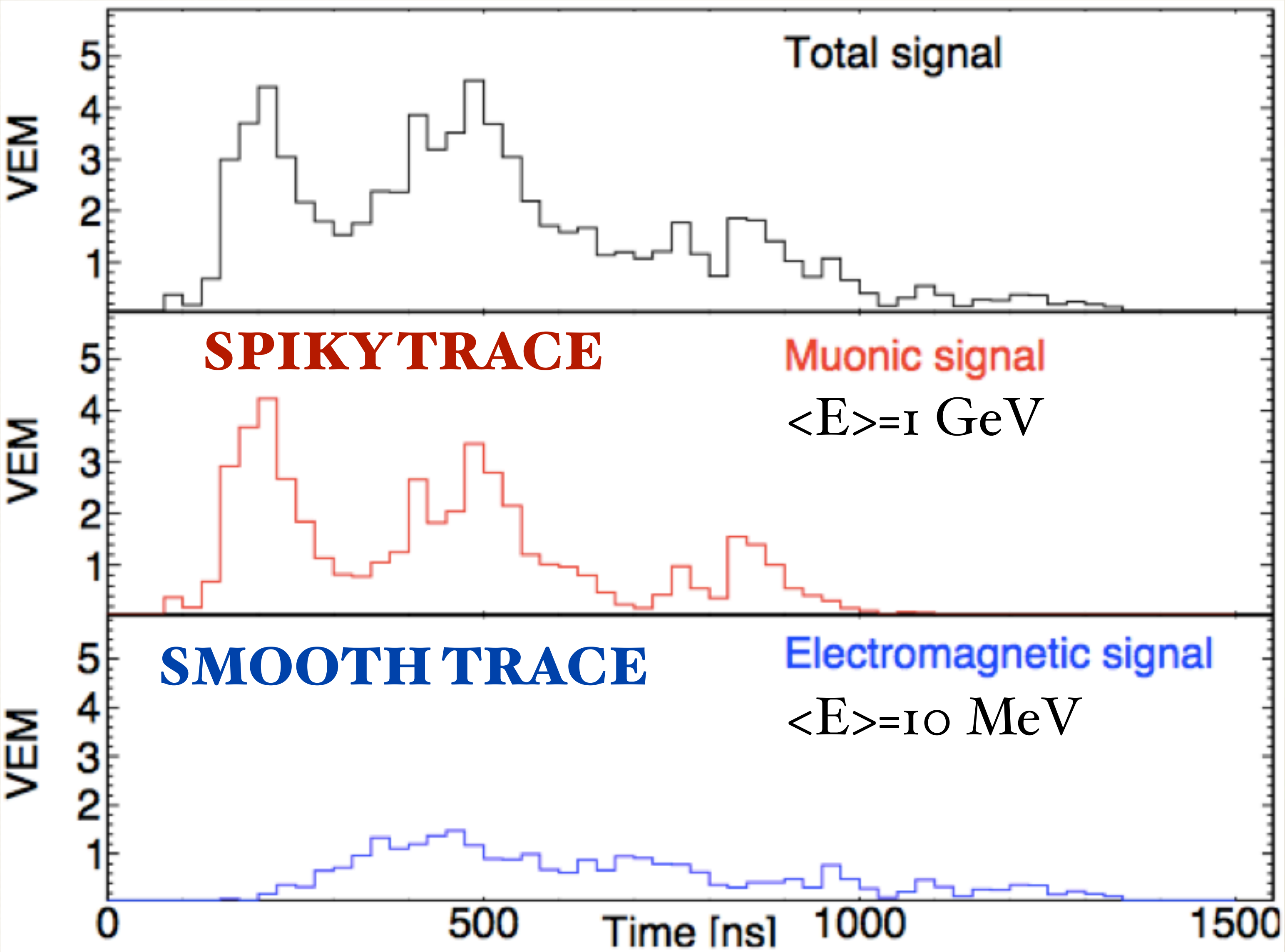

Reconstructed MPD for one of most energetic events (E=94 eV)


[ICRC 2011]

How could we use more events for MPD analysis?

Time Structure of the signals in the SD stations

Each station is a Water Cherenkov detector, read by 3 PMTs, with electronics that digitize the signals at 40 MHz sampling rate.



SPIKY TRACE

<E>=1 GeV

SMOOTH TRACE

<E>=10 MeV

From MC simulation:

High energy release

Low number density

Narrow arrival time spread

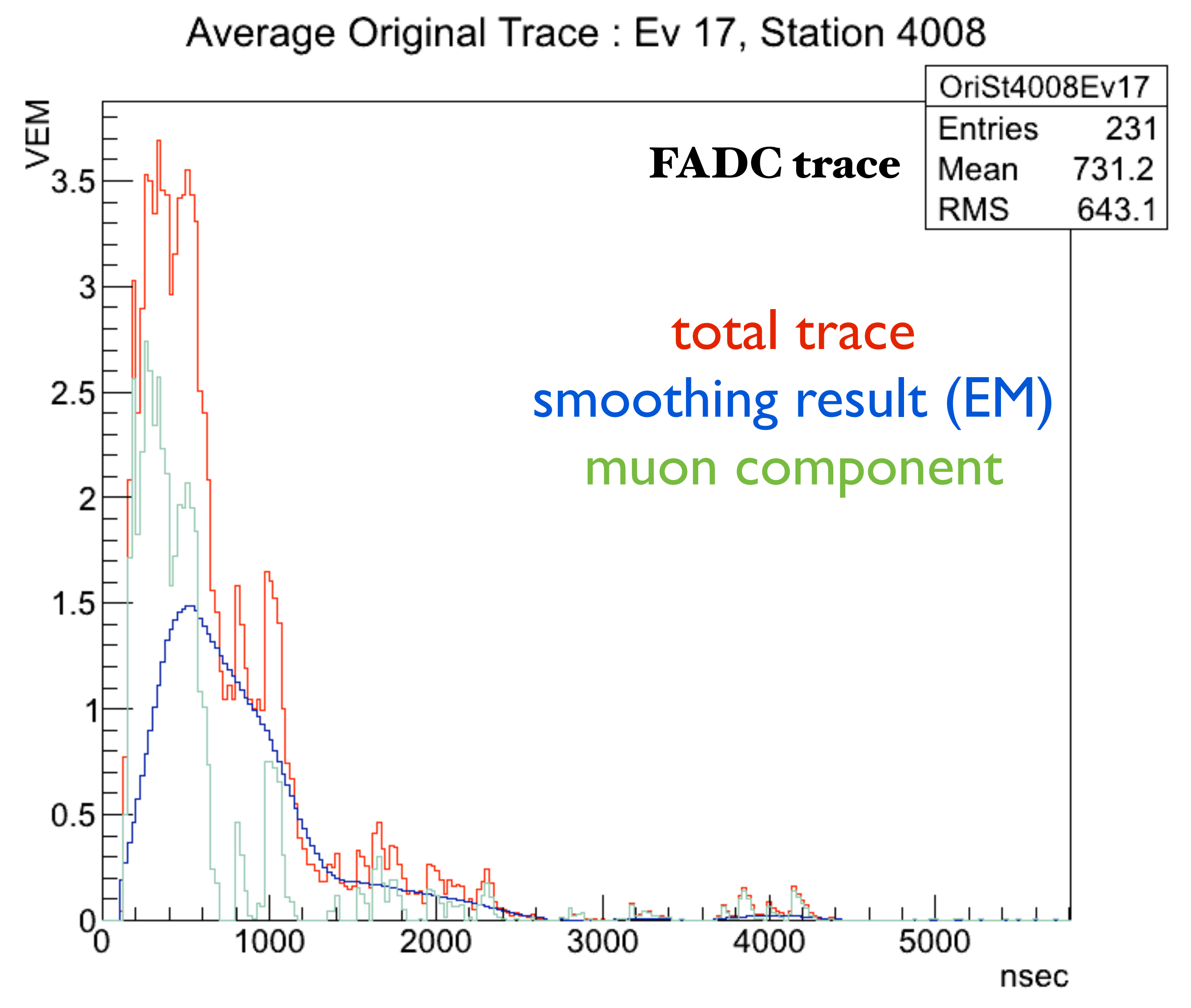
Small energy release

High number density

Large arrival time spread

Electromagnetic particles and muons leave signals with different time structure in the Flash ADC

Smoothing Technique: measuring muons



Extraction of the EM component of traces in FADC through a moving average algorithm.

The filter produces for each station:

S_{EM} directly from the smoothing

$$S_{nonEM} = S_{tot} - S_{EMsmooth}$$

$\Downarrow$ (nuclear component < 2%)

S_{MU} muon component

Muon component and its trace are derived event-by-event with systematic bias <10% and resolution <20% in the region between 700 and 1300 m from the core and zenith angles up to 60°.

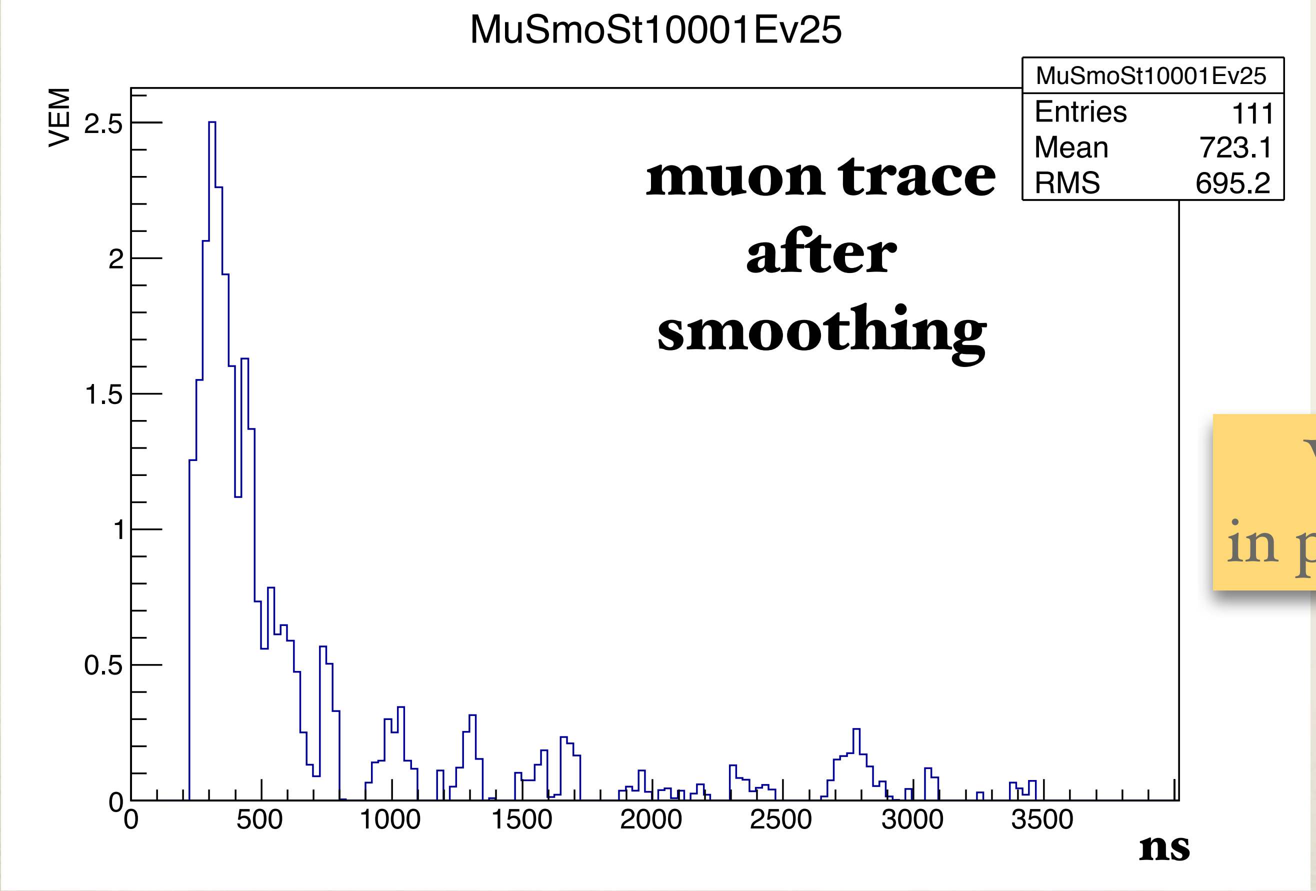
MPD estimation with the smoothing algorithm

By exploiting the smoothing method

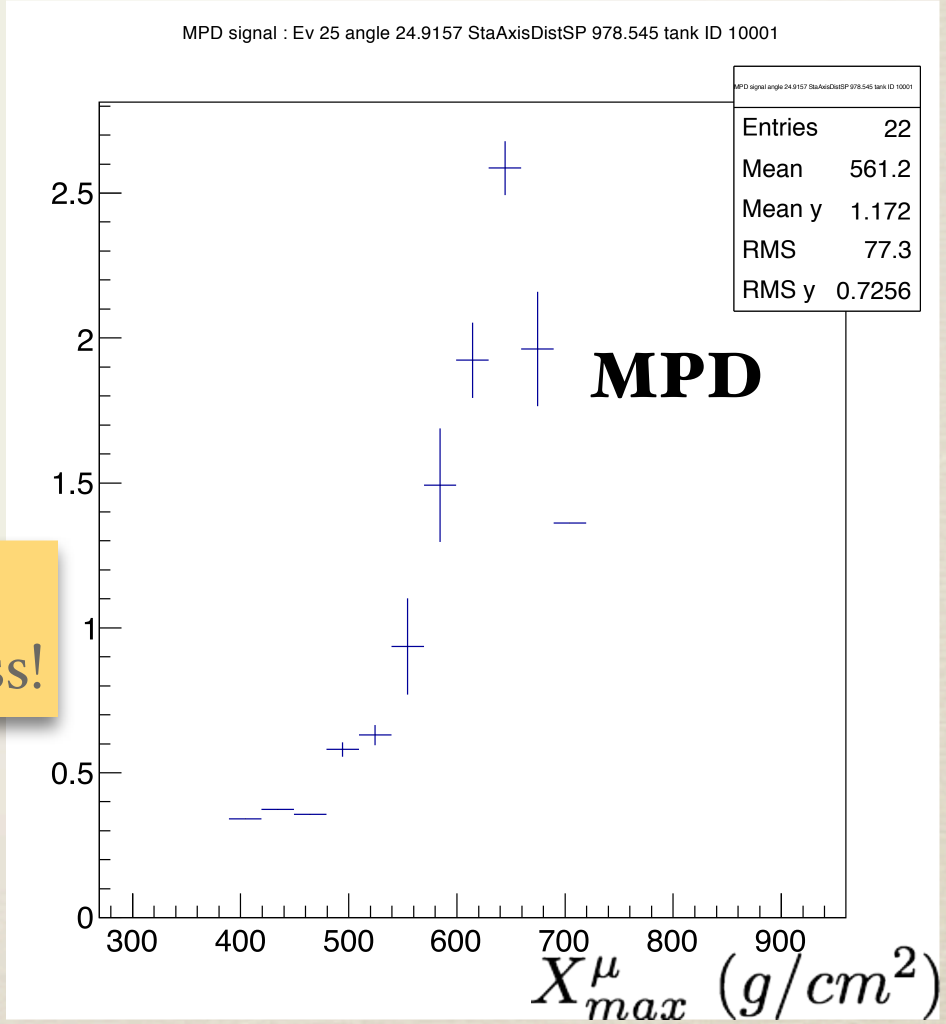
MPD can be reconstructed in a wider range of zenith angles and distances from the core:

$0<\theta<60, \; 700<d(m)<1300$

IRON, 25°, 25 EeV, 978 m from the core

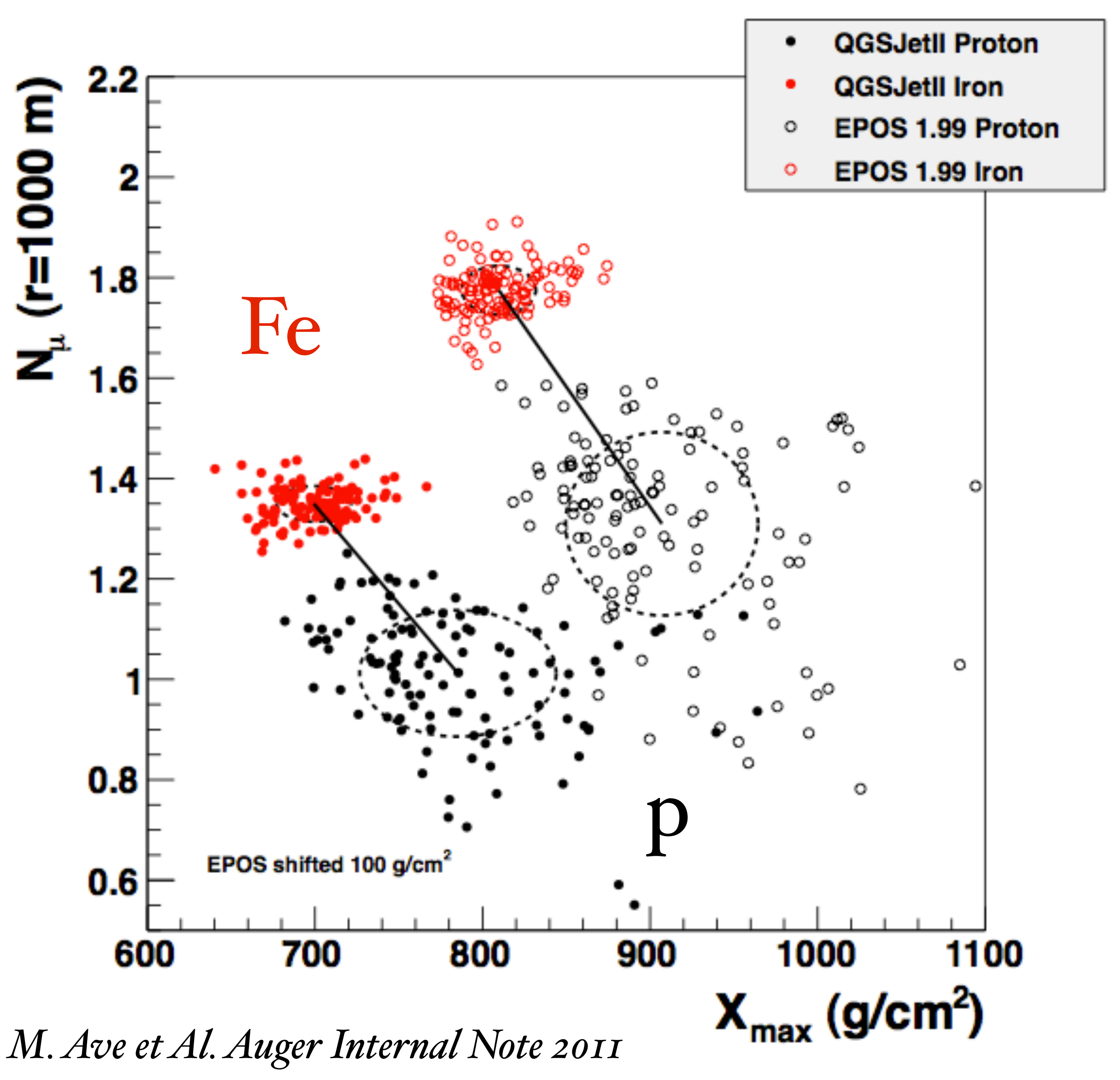


Work in progress!



Number of Muons with the smoothing algorithm

MC simulations, log(E/eV) = 19



M. Ave et Al. Auger Internal Note 2011

From smoothing I can estimate the muon number event-by-event:

$$N_{mu} = \frac{\overset{\text{MU signal integral}}{\boxed{S_{mu}}}}{1VEM * K(\theta)} \qquad K(\theta) = \frac{\pi R^2}{\pi R^2 cos\theta + 2Rhsin\theta}$$

<u>Muon number is sensitive to composition</u>

$$N_{\mu}^{proton} < N_{\mu}^{iron}$$

➜ break degeneracy between hadronic models and discriminate better the primary mass

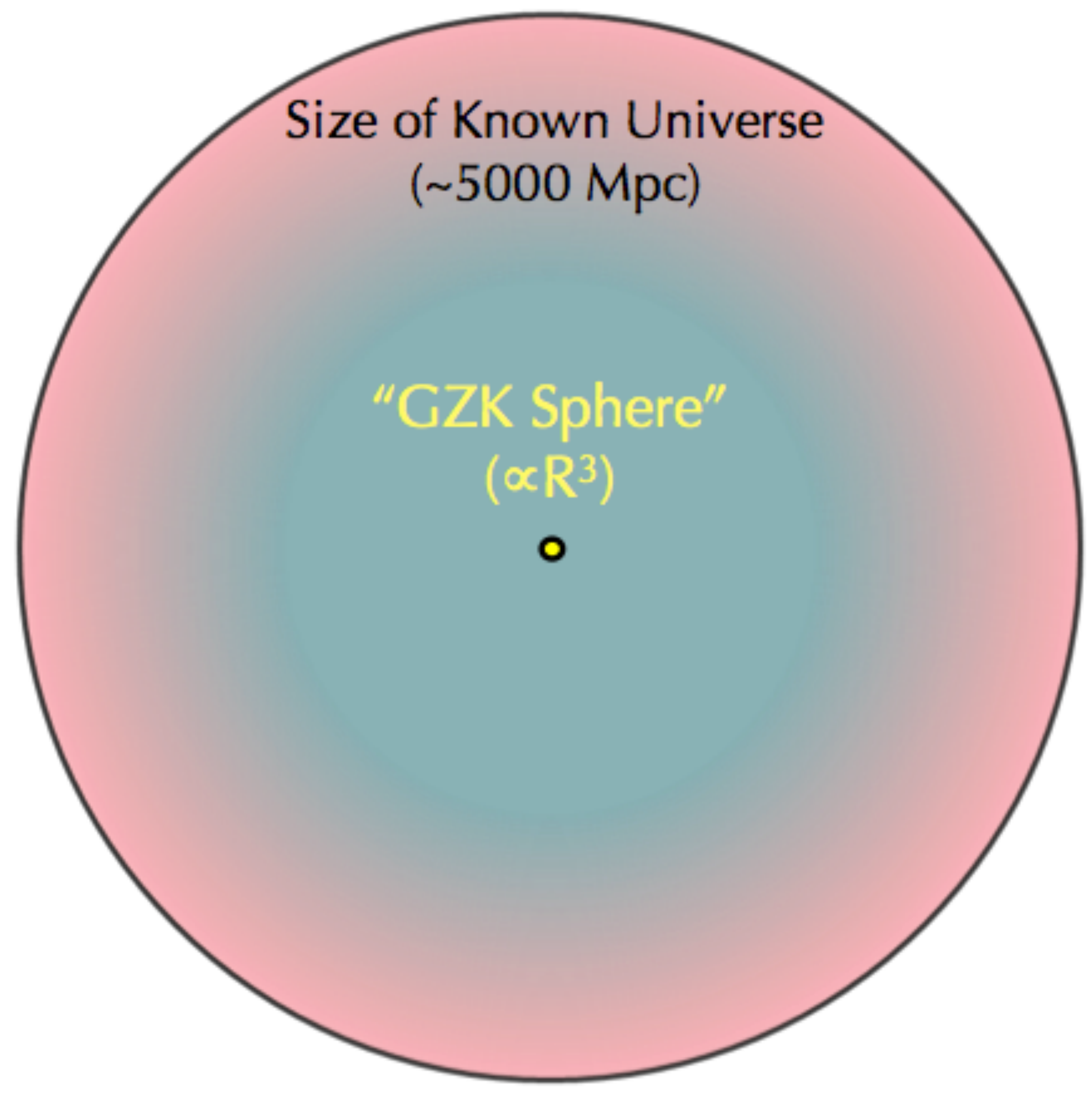
Conclusions and Outlook

- The Pierre Auger Observatory is studying the universe's highest energy particles with the goal to understand the physics behind the end of the spectrum.
- To achieve this goal, mass composition studies are crucial and in particular SD-based observables are necessary to exploit the full potentiality of PAO.
- In my PhD I am studying SD observables which allow to measure the UHECR composition: the **muon production depth**, and the **number of muons at ground**.
  - I applied the smoothing algorithm to different samples of MC simulations with the aim of extending the analysis range and of quantifying the systematics.
  - In my future work I will develop a deconvolution algorithm, an inverse filter complementary to the smoothing and I will apply the Multi-Variate Analysis to combine FD and SD observables together.

Thanks for your attention!

BACKUP SLIDES

GZK mechanism



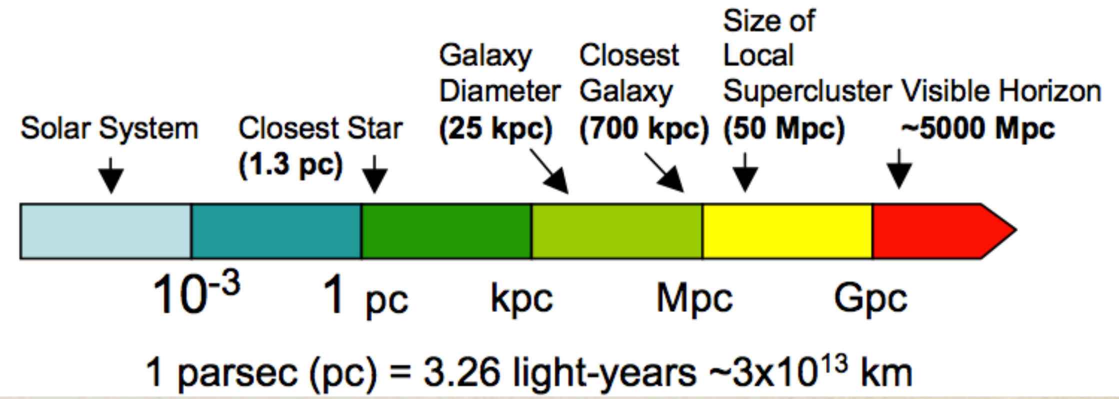
Given the GZK limit, only "nearby" sources (within 10-100 Mpc) are responsible for the observed UHECRs!

➜ Universe will be partially opaque to UHECRs, limiting them to a mean free path of about 50 Mpc if they are above the cut-off energy

Sources are nearby!

Extragalactic UHECRs source candidate:

Active Galactic Nuclei
Gamma Ray Burst
Black Hole



Sources of UHECRs

- UHECR are **extragalactic**

  e.g. in the Galaxy: B~3 μG, E=10^20 eV
  ➜ Larmor Radius >30 kpc

- UHECRs source such to reach the observed intensities

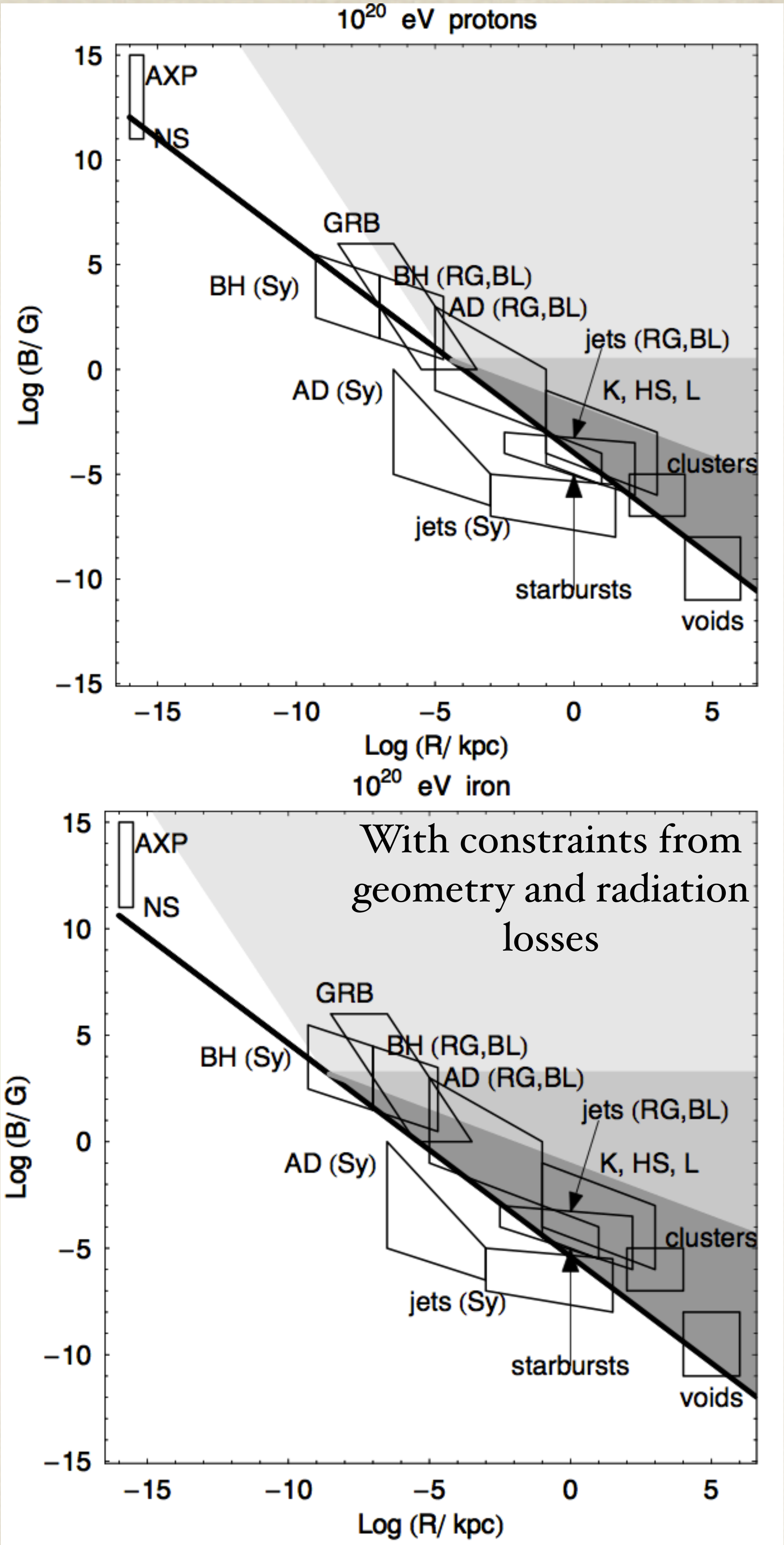
- acceleration mechanism able to reach 10^20 eV

- Hillas criterion: the particle's Larmor radius should not exceed the linear size of the accelerator.

Extragalactic UHECRs source candidate:

Active Galactic Nuclei
Gamma Ray Burst

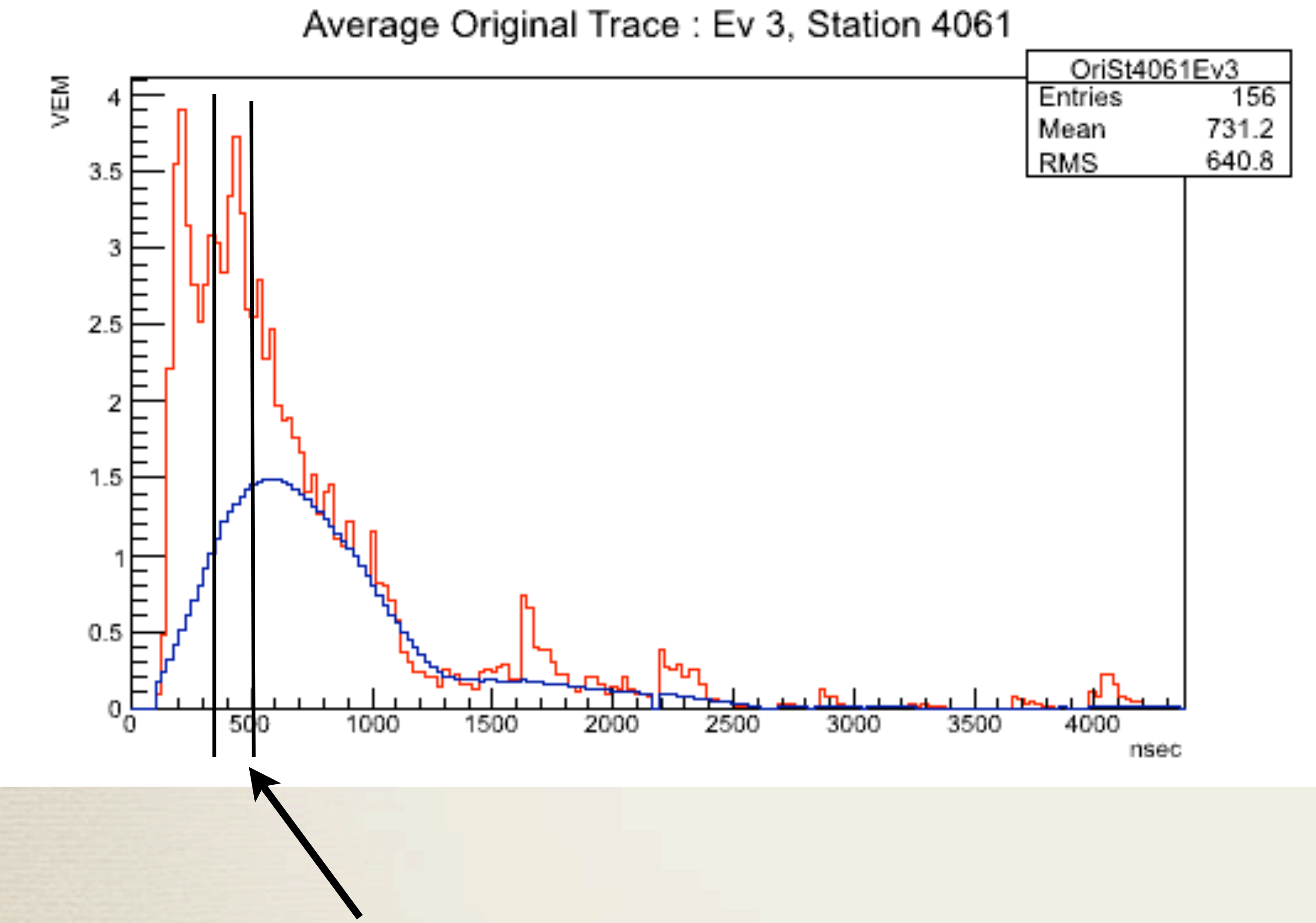
Evidence of anisotropies in the arrival directions of cosmic rays:
the largest excess around the position of the radio galaxy Centaurus A (d=3.5 Mpc)



With constraints from geometry and radiation losses

[Ptitsyna & Troitsky, Phys. Usp. 53, 691 (2010)]

Smoothing Technique: moving average algorithm with variable range



$$t_{start} < j < t_{end}$$

$$S_{ave} = \sum_{i=0}^{i=N_{bin}} \frac{S_{tot}(i)}{N_{bin}} \qquad S_{mu} = S_{tot}(j) - S_{ave}$$

$$N_{iter} = 4 \qquad N_{bin} \propto \theta$$

An interval, called *convolute range*, is moved stepwise through the trace and the central point of the interval is replaced by the value of the average estimated over the interval.

<u>The convolute range is chosen variable,</u> according to the functional dependence of the peak broadening.

In this way the technique is independent on zenith angle!

Smoothing Technique: physical background

Hadronic background is negligible:

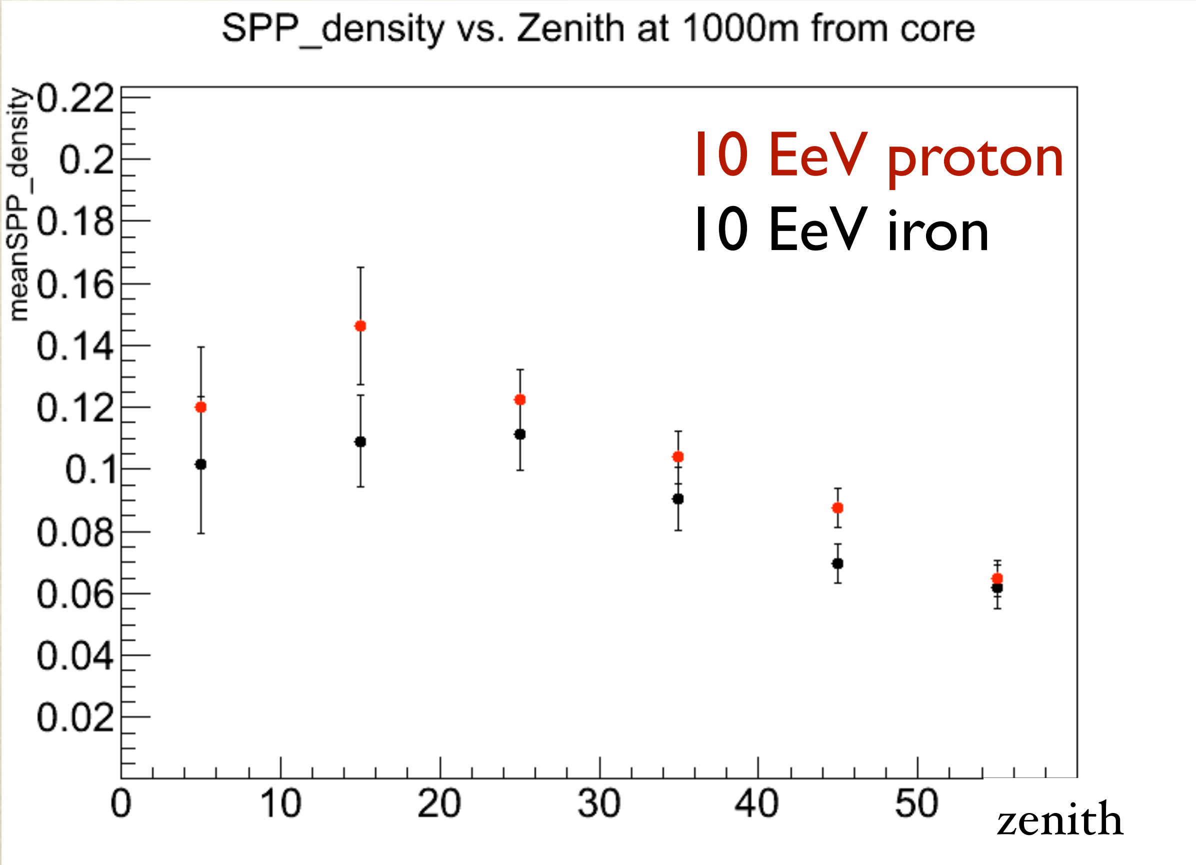
about 1% and 2% for 10 EeV proton and iron showers, arriving at ground with 0-10 zenith angle, smaller for large angles.

HE em particles background is significant:

Spike Producing Particles (SPP) are photons and electrons with E>300 MeV, muons with E>400 MeV **[GAP 2009-031]**

$$\frac{Spike\ Em}{Spike\ total} = \frac{SPPphoton + SPPelectron}{SPPelectron + SPPphoton + SPPmuon} = 10\%$$

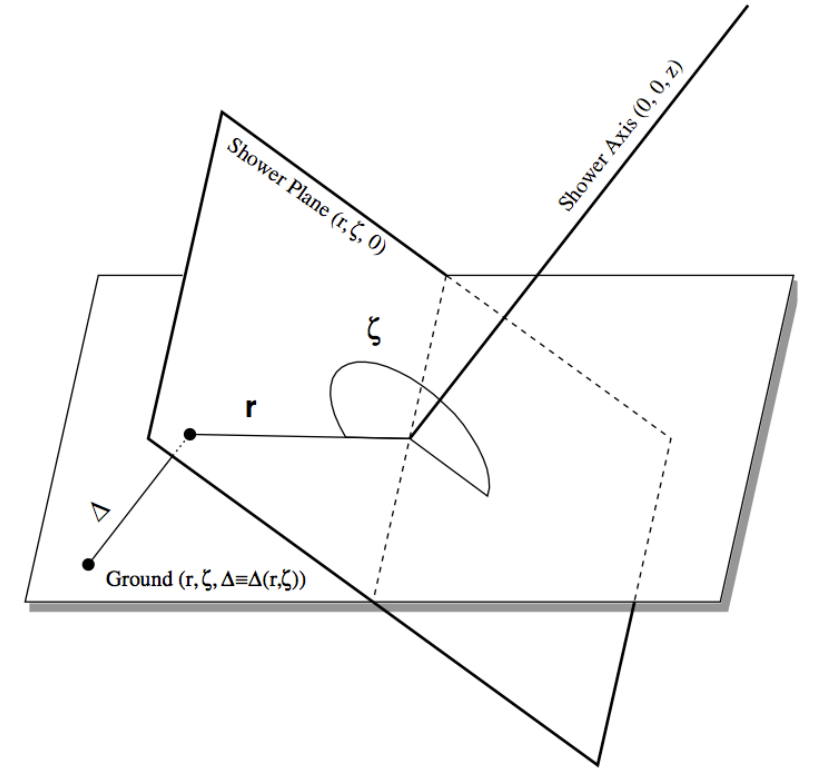
In the case of 10 EeV proton shower, zenith=26, 1km distance from core (SENECA, with QGSJETII)



COMPATIBLE WITH THE PREVIOUS RESULTS

SPP density < 15%
for proton and iron showers

Muon Production Depth



The MPD could be reconstructed using the FADC traces of tanks:
the arrival time structure observed in muons is a transformation of the muon production distance distribution.

The MPD z for each muon is

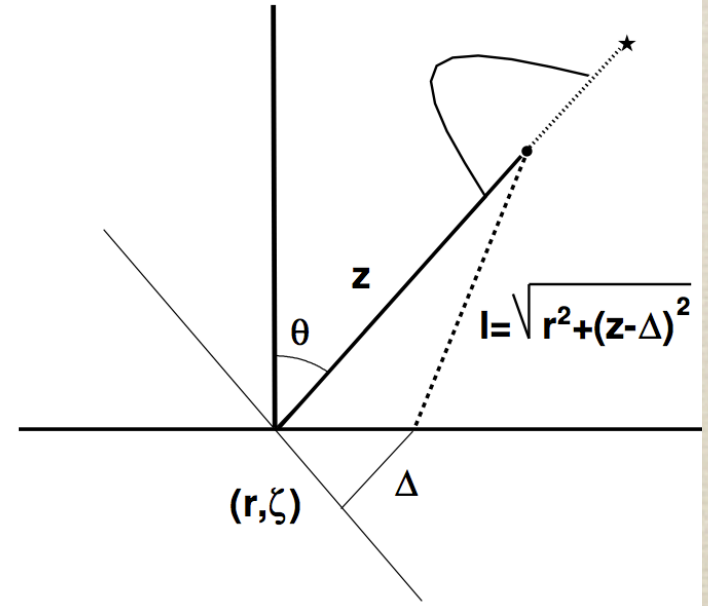
$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$

where:
r is the distance tank-SA
Δ is the distance tank-SP
is the geometrical delay

GEOMETRICAL DELAY

The delay wrt the shower front plane (⊥ SA, moving at *c*)

$$ct_g = \sqrt{r^2 + (z-\Delta)^2} - (z-\Delta)$$



KINEMATIC DELAY

The delay which takes into account the muon finite energy E
Dominant near the core, at r>600 m acts as a correction

MPD DISTRIBUTION

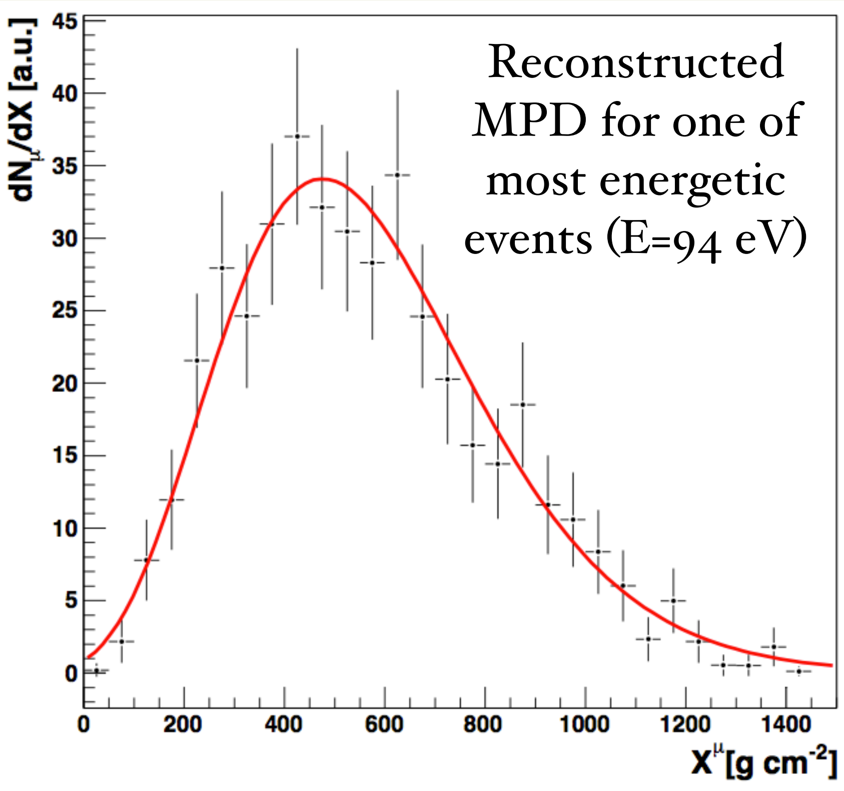
The production distance can be related to the total amount of traversed matter

$$X^{\mu} = \int_{z}^{\infty} \underset{\text{atmosphere density}}{\rho(z')}dz' \xrightarrow{\text{Gaisser-Hillas function fit}} X^{\mu}_{max}$$

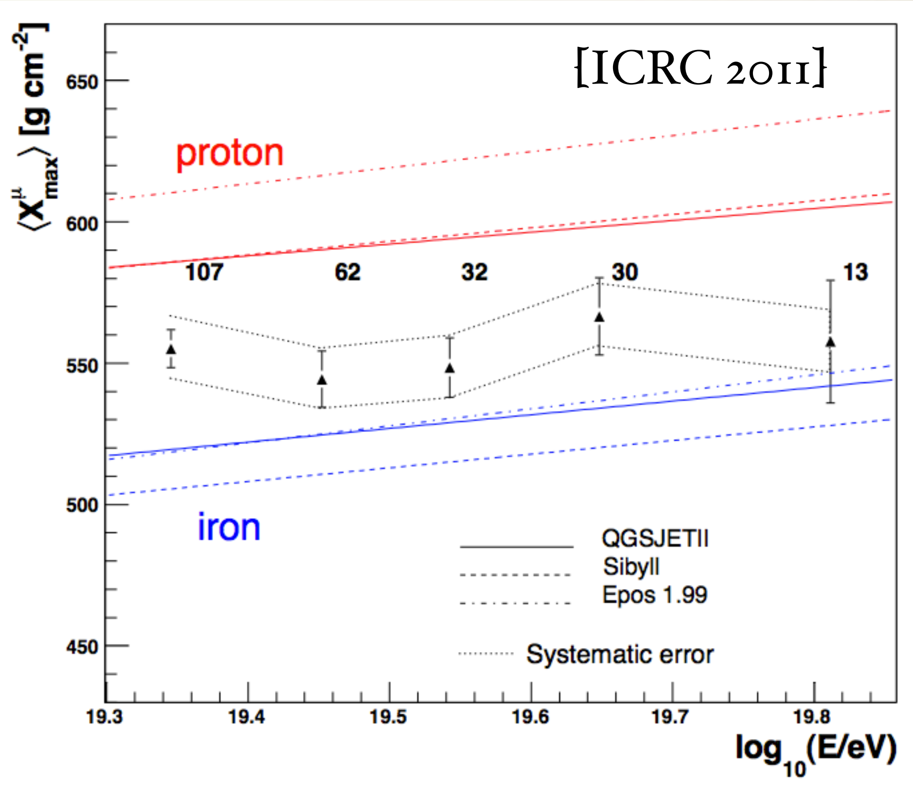
LIMIT:

MPD can be estimated only for events with E>20 EeV and zenith angle around 60°

➜ only 244 SD events (Jan'04-Dec'10)



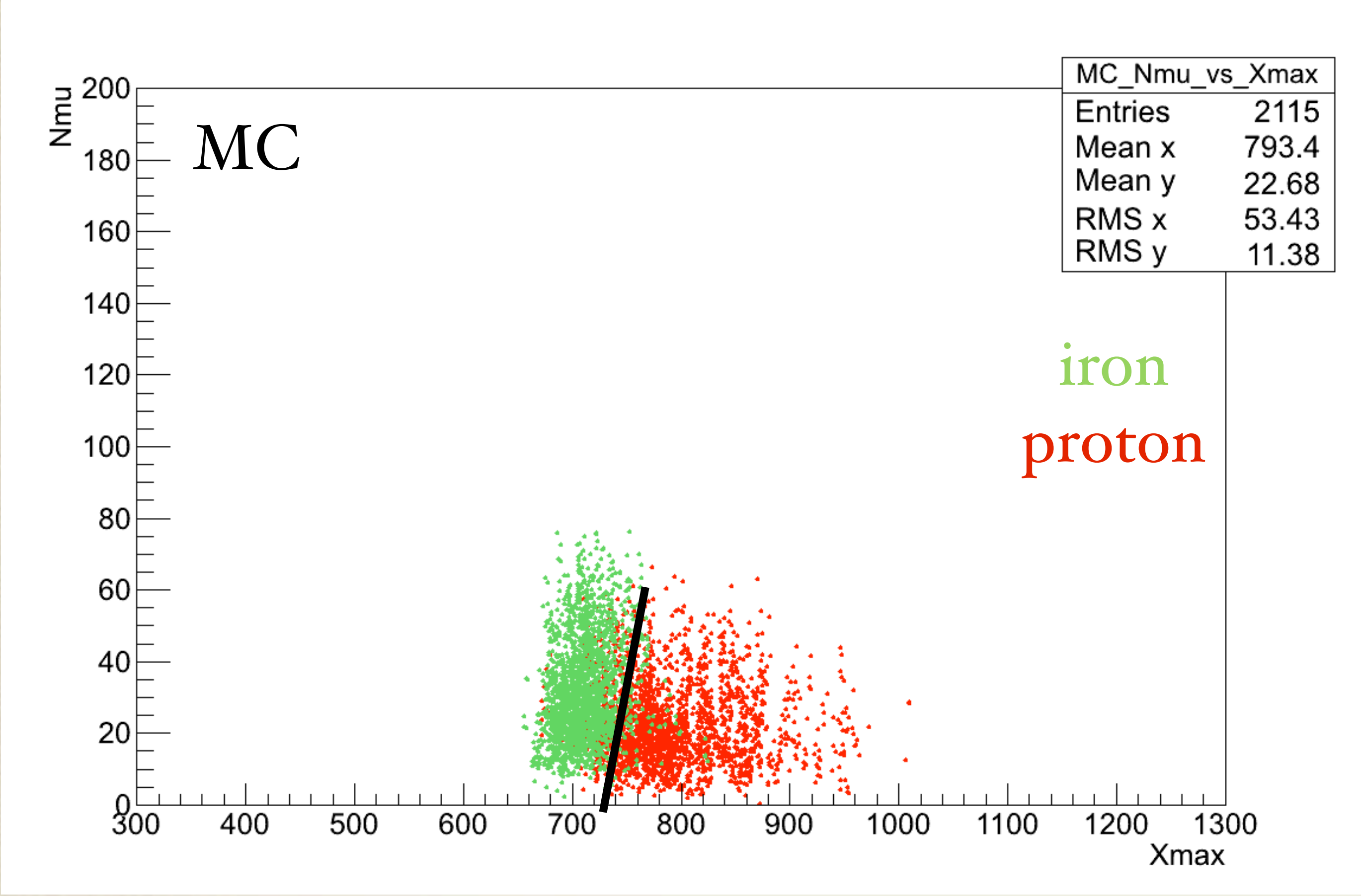
Reconstructed MPD for one of most energetic events (E=94 eV)



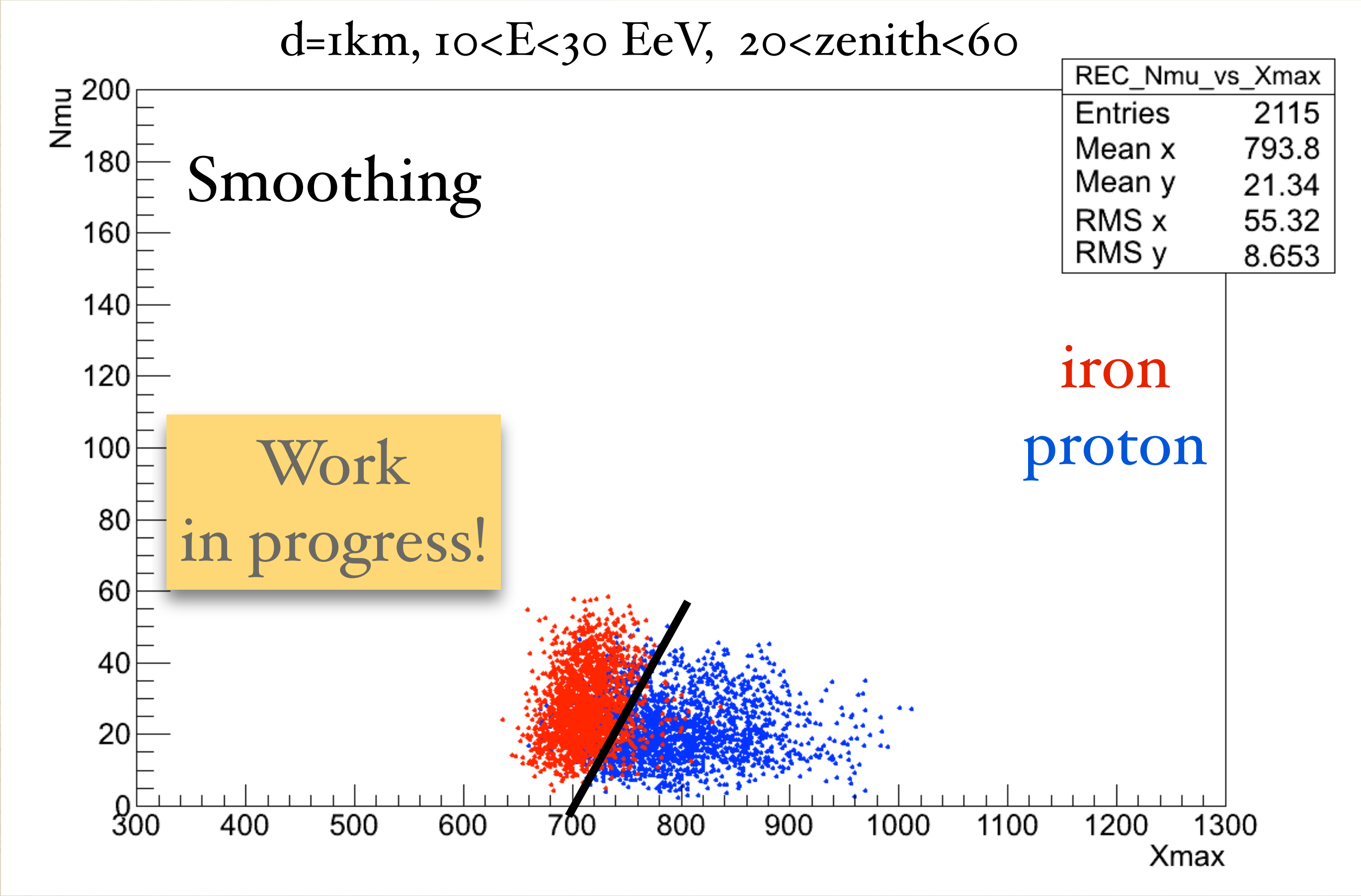
[ICRC 2011]

total systematic uncertainty 11%

Study of the correlation between Nmu vs. Xmax, for composition analysis



$$X_{max}^{proton} > X_{max}^{iron} \qquad N_{mu}^{proton} < N_{mu}^{iron}$$



Work in progress!

Taking into account the effective detector area

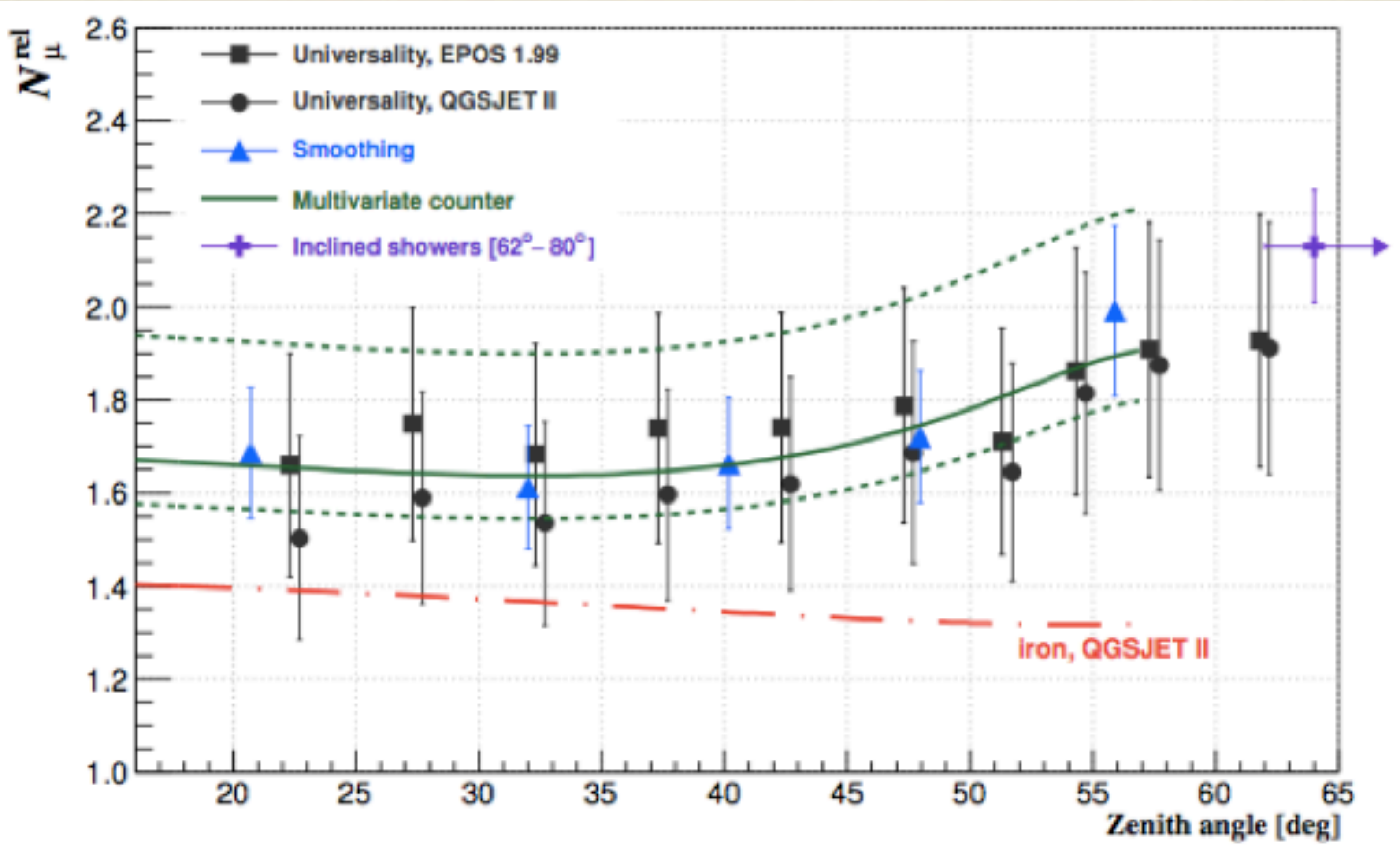
from smoothing

$$N_{mu} = \frac{\boxed{S_{mu}}}{1VEM * K(\theta)} \qquad K(\theta) = \frac{\pi R^2}{\pi R^2 cos\theta + 2Rhsin\theta}$$

R=1.8 m, tank radius; ***h***=1.2m, tank height;
Smu, muon signal integral

⇨ **Multi-Variate Analysis**

Muon puzzle



None of the existing models can consistently reproduce the measured muon number:

$$N_\mu^{rel} \approx 1.9 - 2.0 \quad for\ \theta > 55$$

$$N_\mu^{rel} \approx 1.6 - 1.7 \quad for\ \theta < 45$$

...need for more muons in simulations!