Mass Composition Study at the Pierre Auger Observatory

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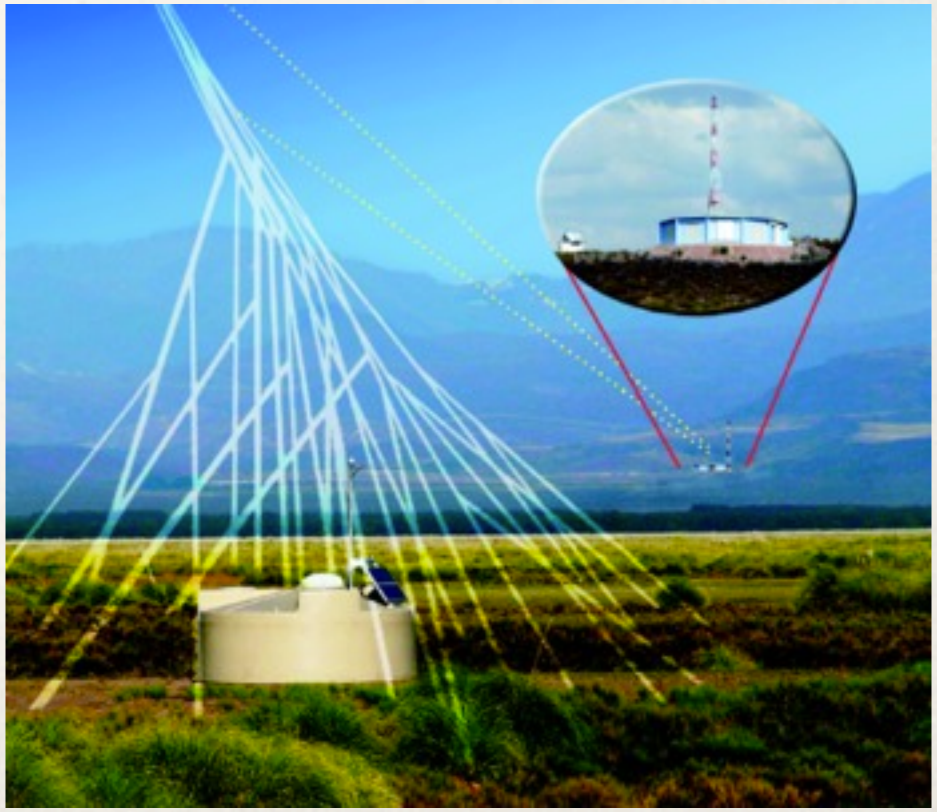
Outline

The physics:

- The UHECR spectrum
- Extensive Air Showers

The Pierre Auger Observatory:

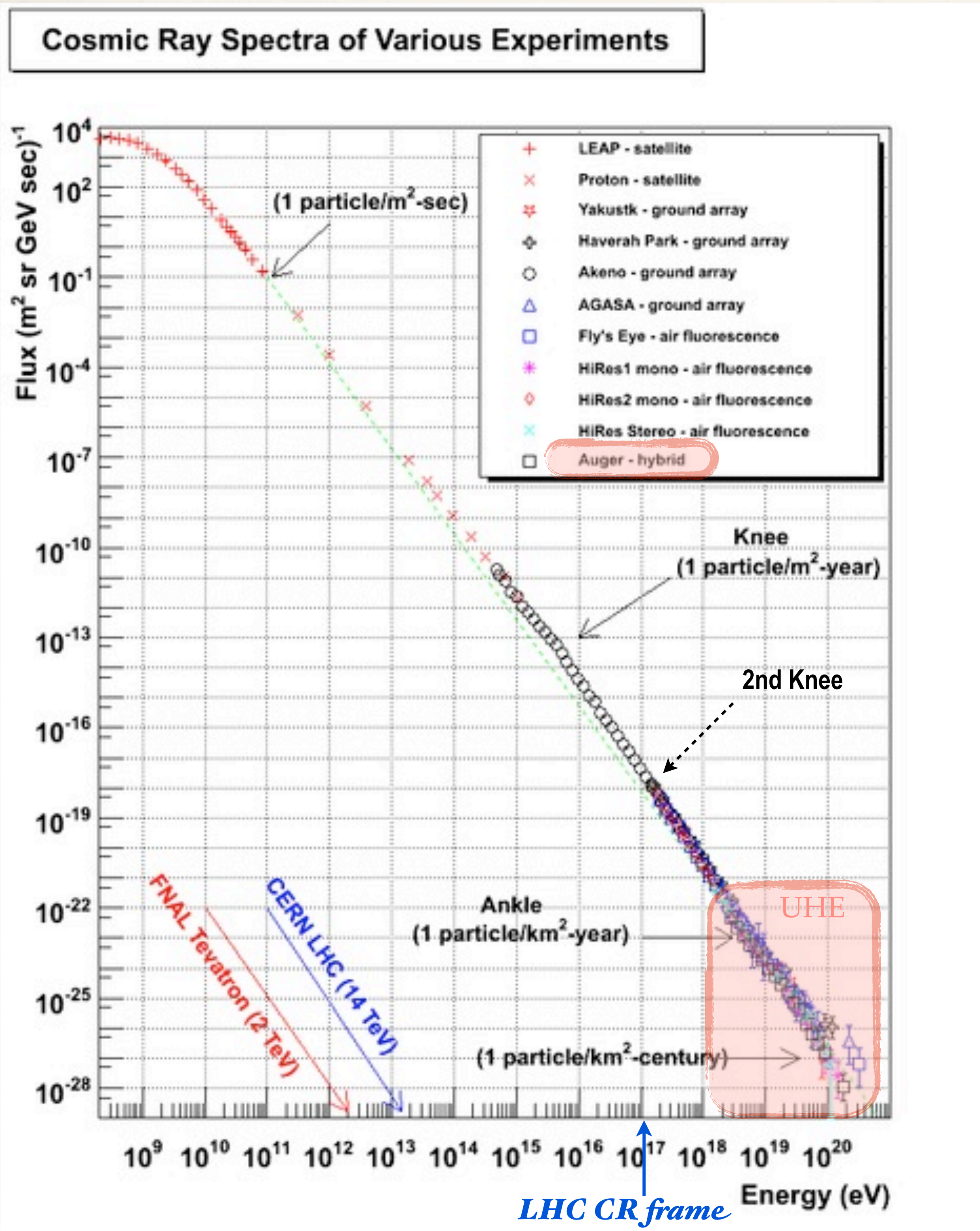
- Fluorescence Detector
- Surface Detector



UHECRs Mass Composition:

- Observables
- Experimental Results
- My work

Ultra-High Energy Cosmic Rays

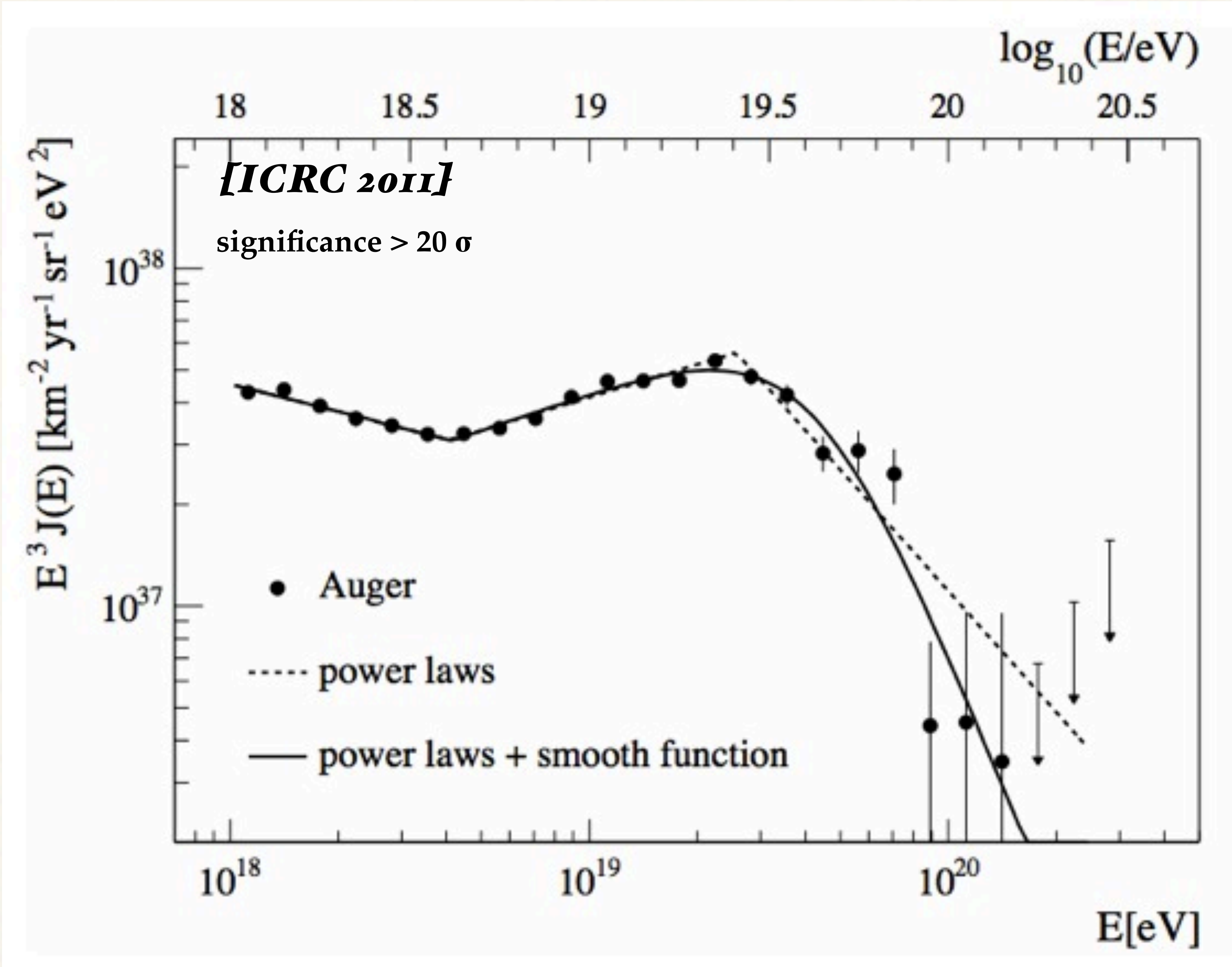


- UHECR are energetic particles which originate from outer space. E>10^19 eV
- Clear identification of the UHECRs sources not possible yet.
- Power-law flux over 12 orders of magnitudes in energy.
- 4 features:

knee:	slope steepening	γ~ 2.7 → 3.1
2nd knee:	small slope steepening	γ~ 3.1 → 3.2
ankle:	spectrum hardening	γ~ 3.2→ 2.7
flux suppression		

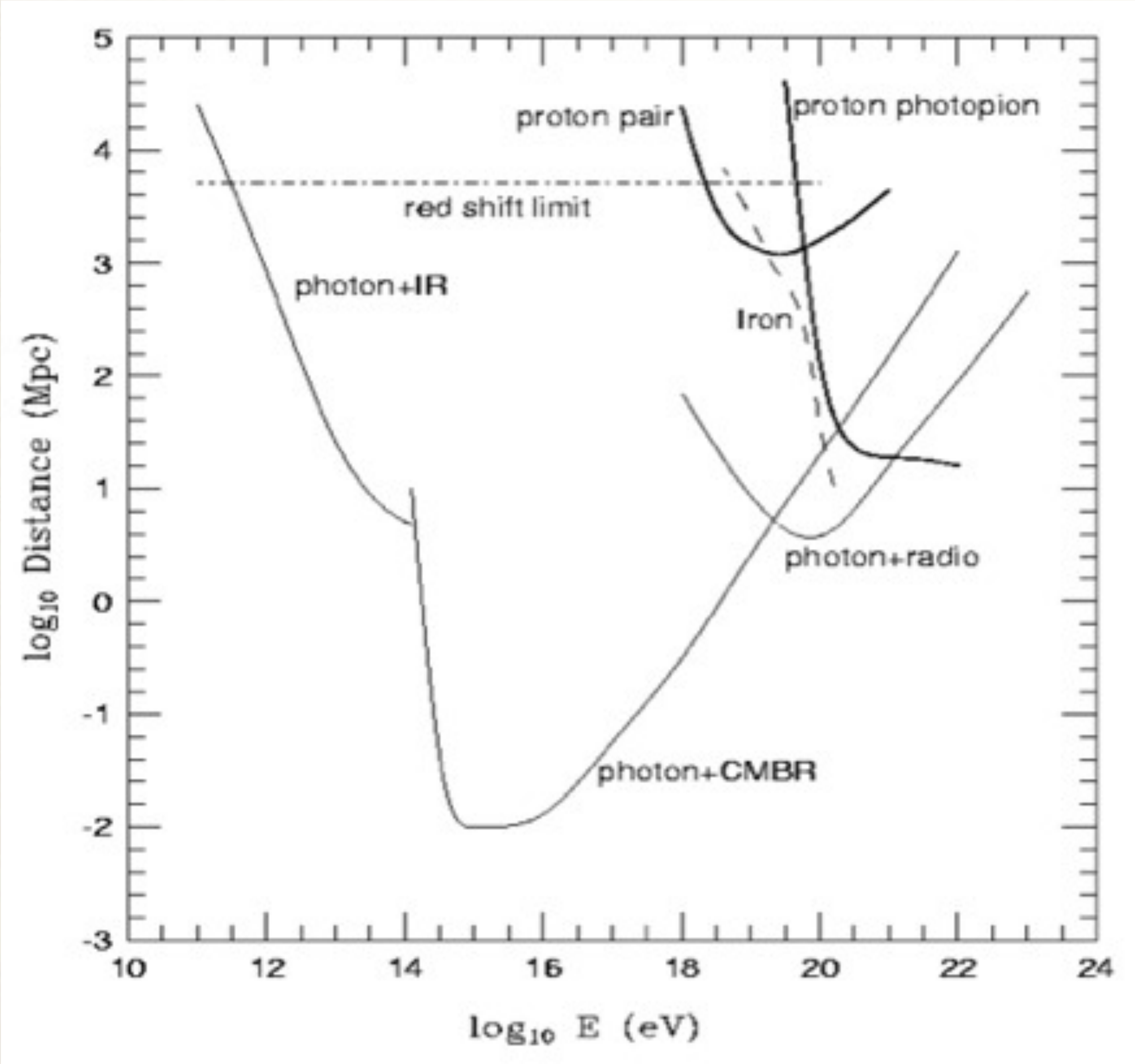
→ information on sources , propagation, composition

End of the CR spectrum



GZK effect or exhaustion of the sources?

GZK mechanism



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

Proton:

$$\gamma_{CMB} + p \rightarrow p + e^+ + e^- \qquad E \geq 7 \cdot 10^{17} eV$$

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

Nuclei: Photo-disintegration and pair production on CMB

"horizon" ~ 100 Mpc (at E~10^20 eV)

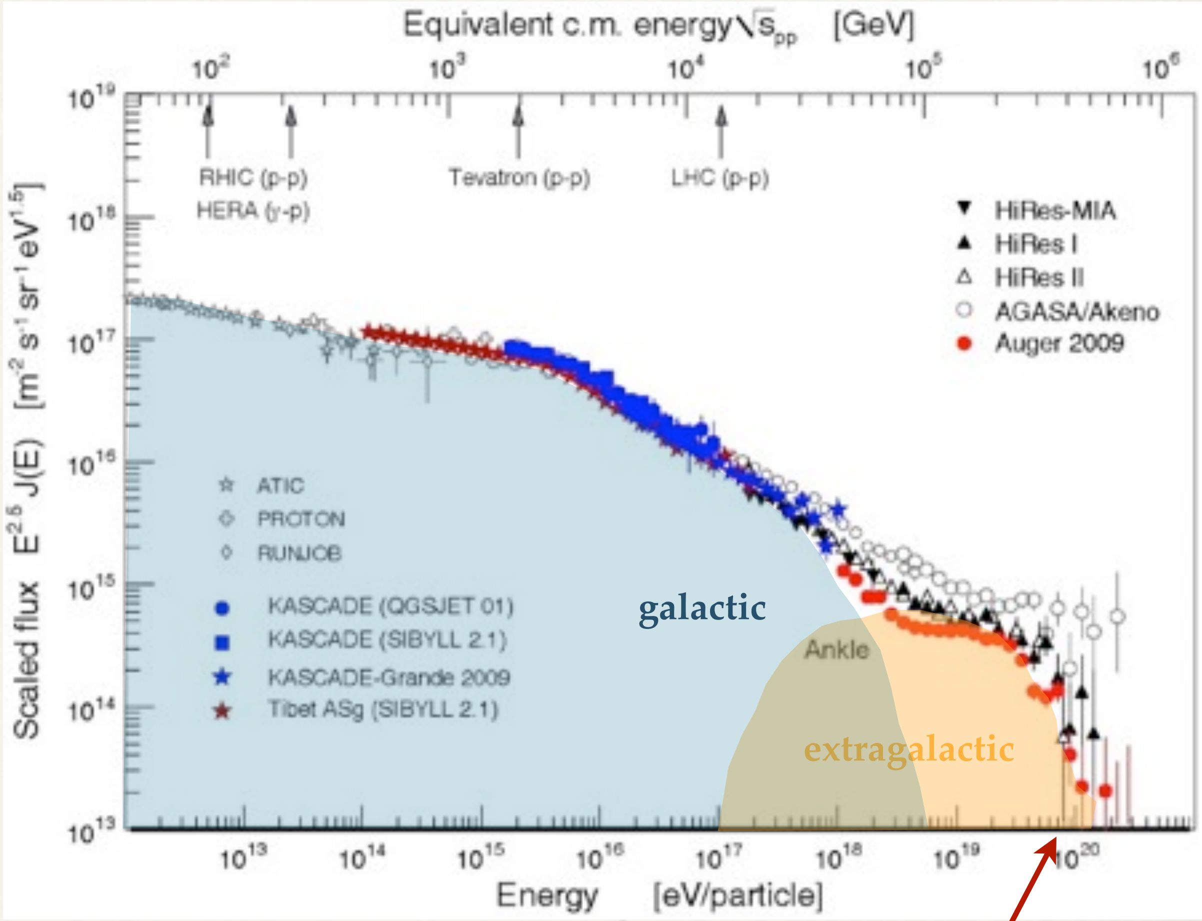
➜ Universe will be partially opaque to UHECRs

➜ Only "nearby" sources (within 10-100 Mpc) are responsible for the observed UHECRs!

Sources of UHECRs

In order to reach such energies, *Cosmic Accelerators* are needed.

Main ingredients:
- Shock waves
- Magnetic Fields
- Charge Particle injection



Galactic source

Pulsar
Supernovae Remnants

Extragalactic UHECRs source candidate:

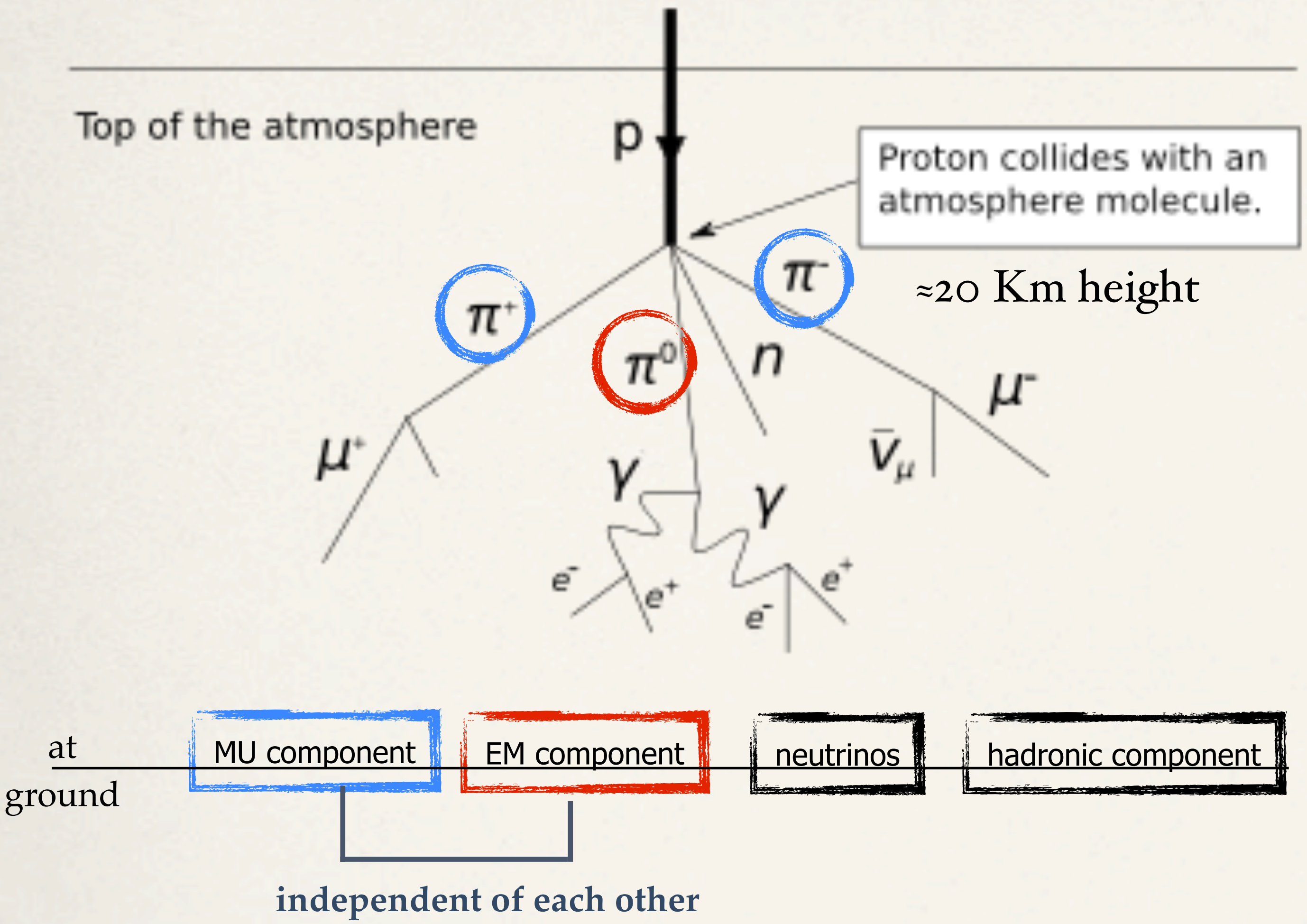
Active Galactic Nuclei
Gamma Ray Burst

Suppression of the UHECRs Spectrum: we may observe the end of the source fuel

$$E_{max} \propto ZBR$$

→ The knowledge of UHECRs composition and its energy evolution are the main challenge for near future!

UHECR Detection via Extensive Air Showers



- Direct measurements of CR only below 10^15 eV.
- EAS=only way to study UHECRs due to their low flux (< 1 particle/km^2/year)

  → Earth detectors with huge collection area!

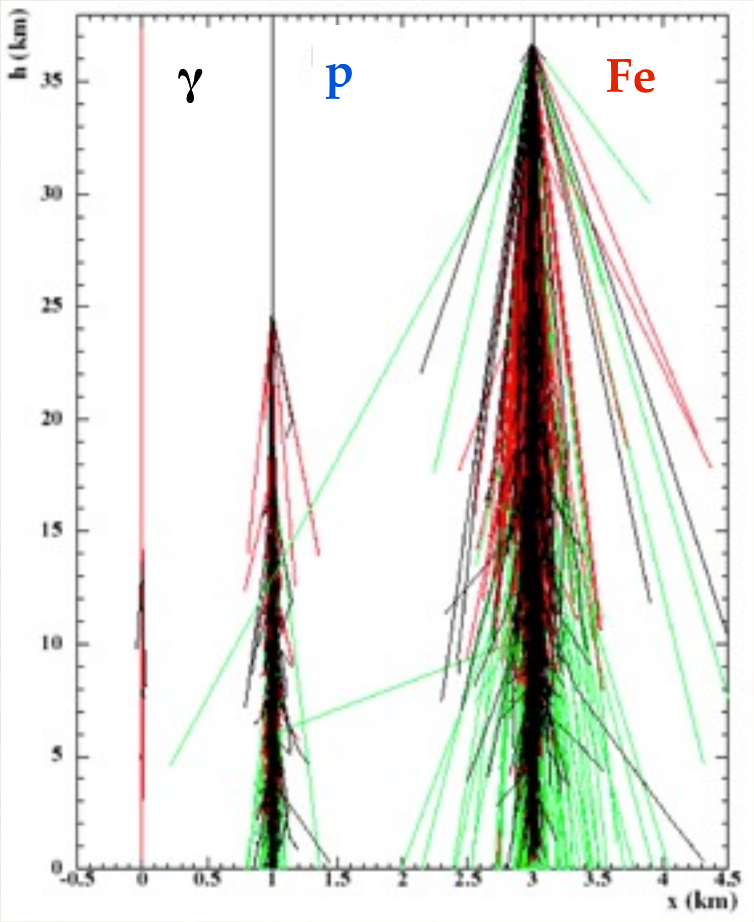
- Detection techniques developed in order to measure the energy deposit in the atmosphere and the particle density at ground

Mass composition studies are the most difficult:

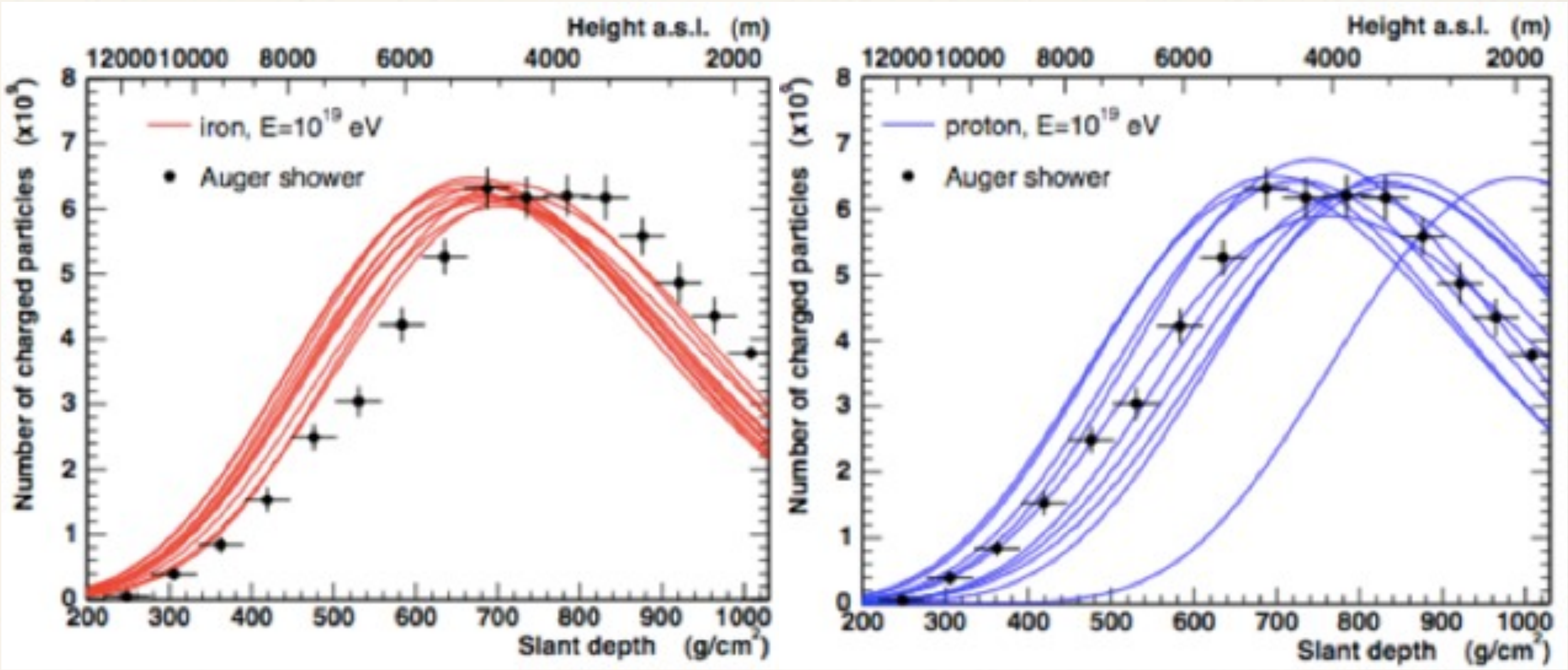
- Data-MC comparison is needed
- The hadronic cross sections used in EAS simulations are extrapolated from accelerator data

→ the uncertainties in the models are the main source of systematics

Showers from different primaries



Longitudinal Profile



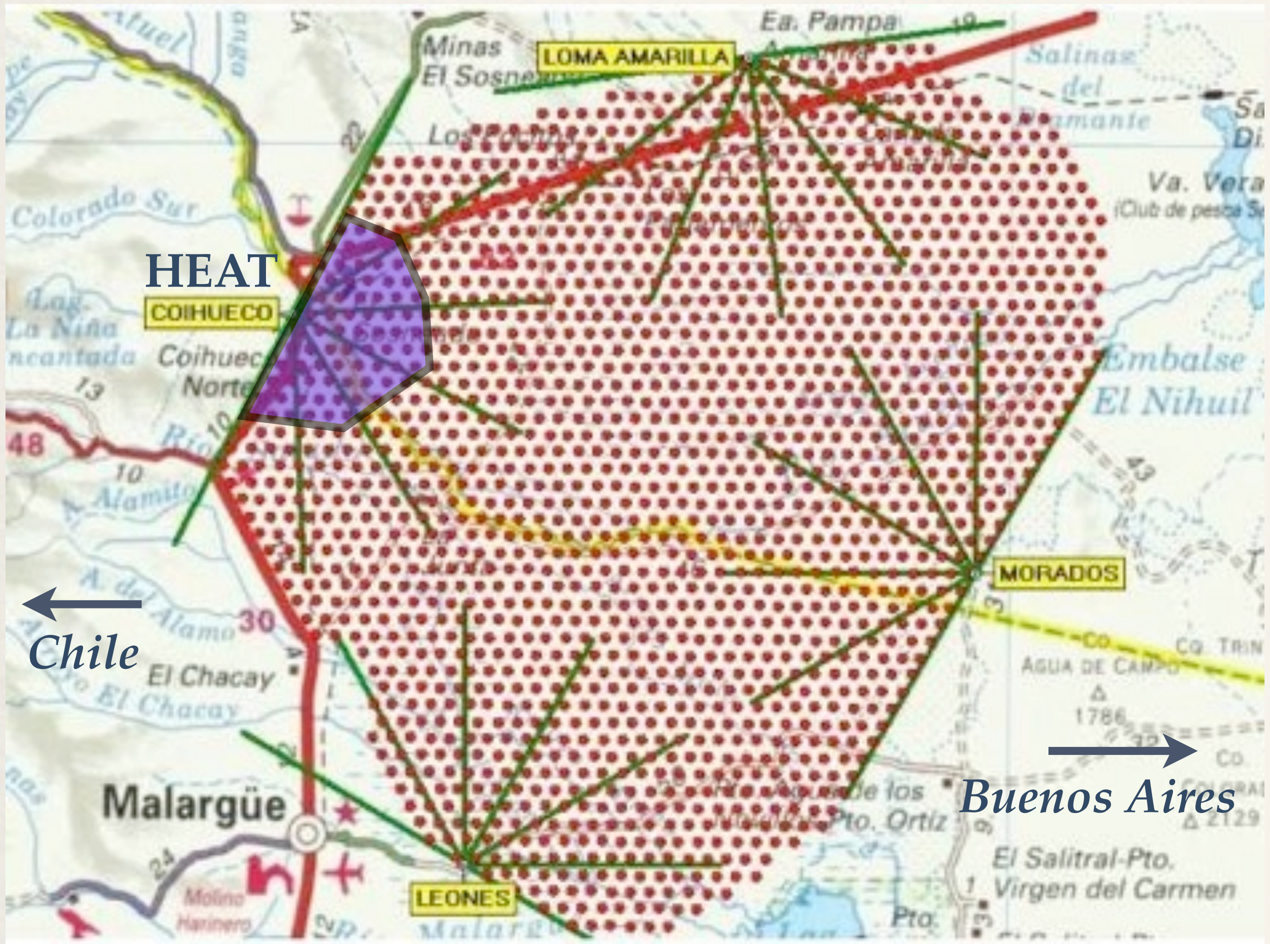
Iron shower compared to **proton** shower:

- develop early in the atmosphere (cross section higher)
- more secondaries
- more muons at ground
- less electrons at ground
- the shower to shower fluctuations are smaller (superposition of 56 sub-showers)

→ need to measure the longitudinal profile and muons at ground

The Pierre Auger Observatory

Mendoza Province (AR), 1420 m a.s.l.



Study UHECR with E>10^18 EeV

Operative since 2004

Surface Detector

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

Fluorescence Detector

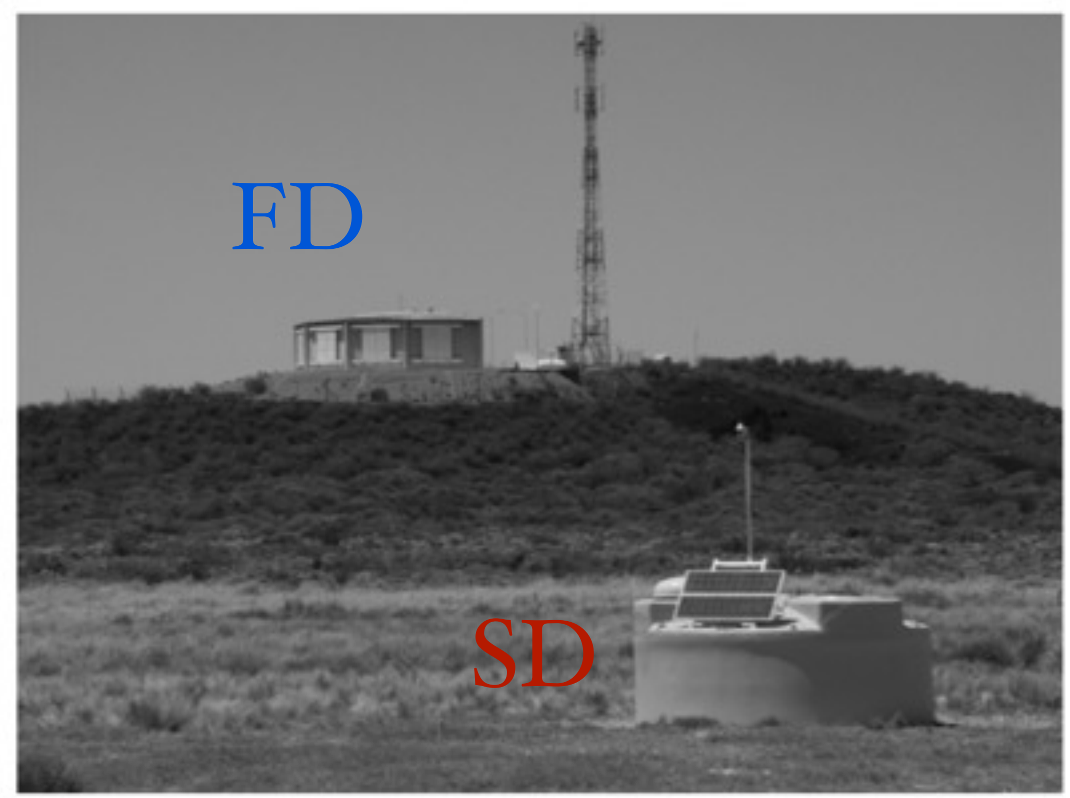
24 UV telescopes grouped in 4 buildings overlooking SD array

Low energy enhancement to study 2nd knee:

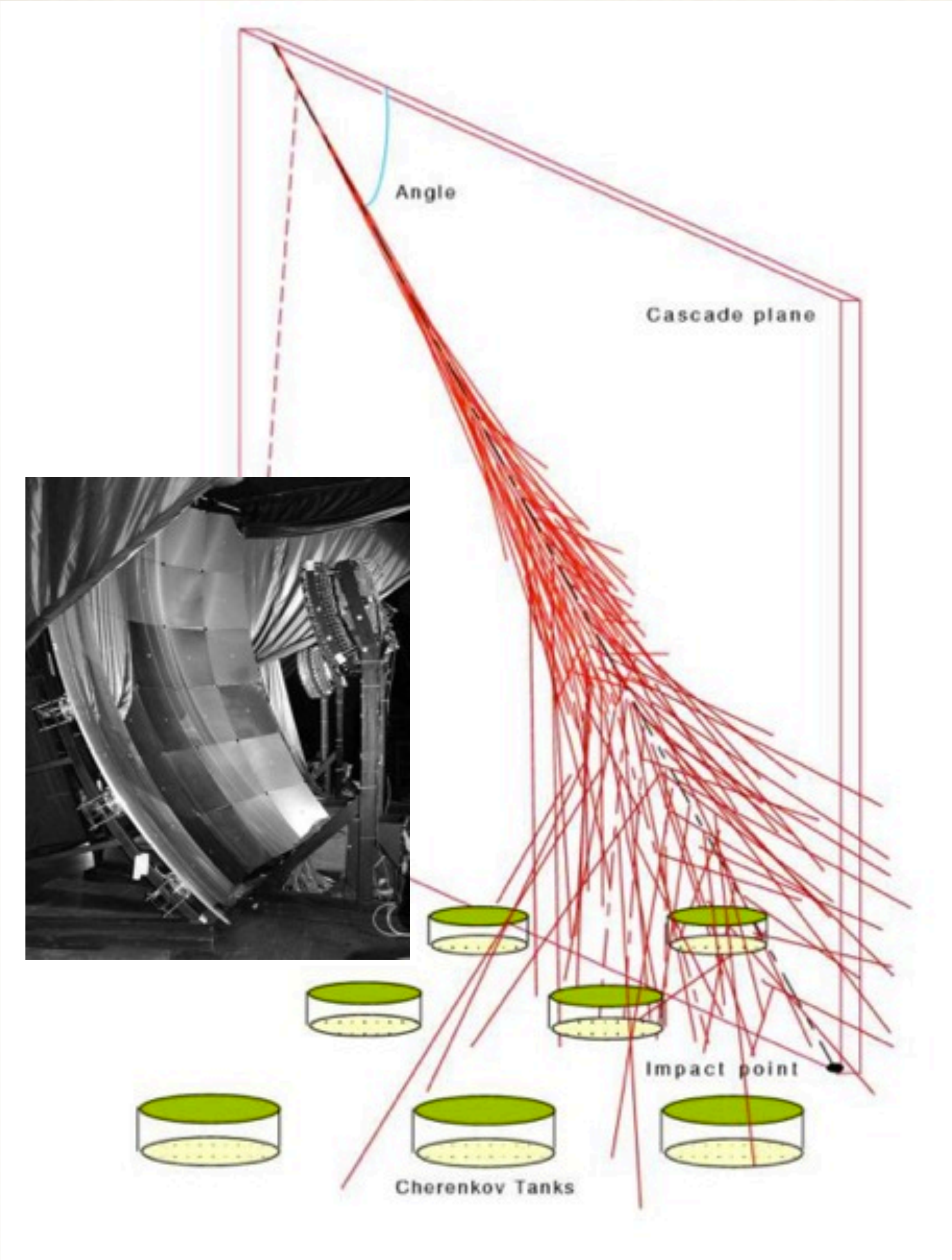
INFILL: 61 stations, 750 m triangular grid

HEAT: three high-elevation FD telescopes

AMIGA *[prototype phase]*:
infill array + buried muon detectors



Hybrid detection technique



SD observables:

signals at ground level and shower temporal profile
~100% duty cycle

➜ lateral distribution of particles

FD observables:

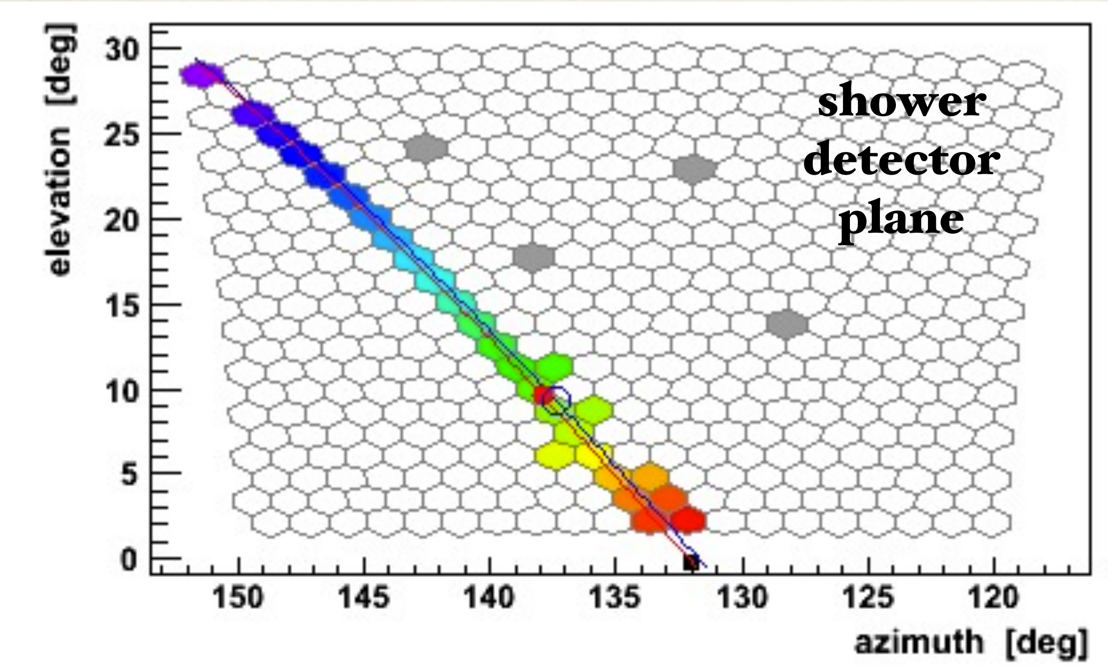
nitrogen fluorescence emission and time sequence on PMTs
~15% duty cycle (operative during moonless night)

➜ longitudinal profile, calorimetric energy measurement, SD energy calibration

accurate energy and arrival direction measurement

SD sensitive to muons
FD sensitive to em components of the shower

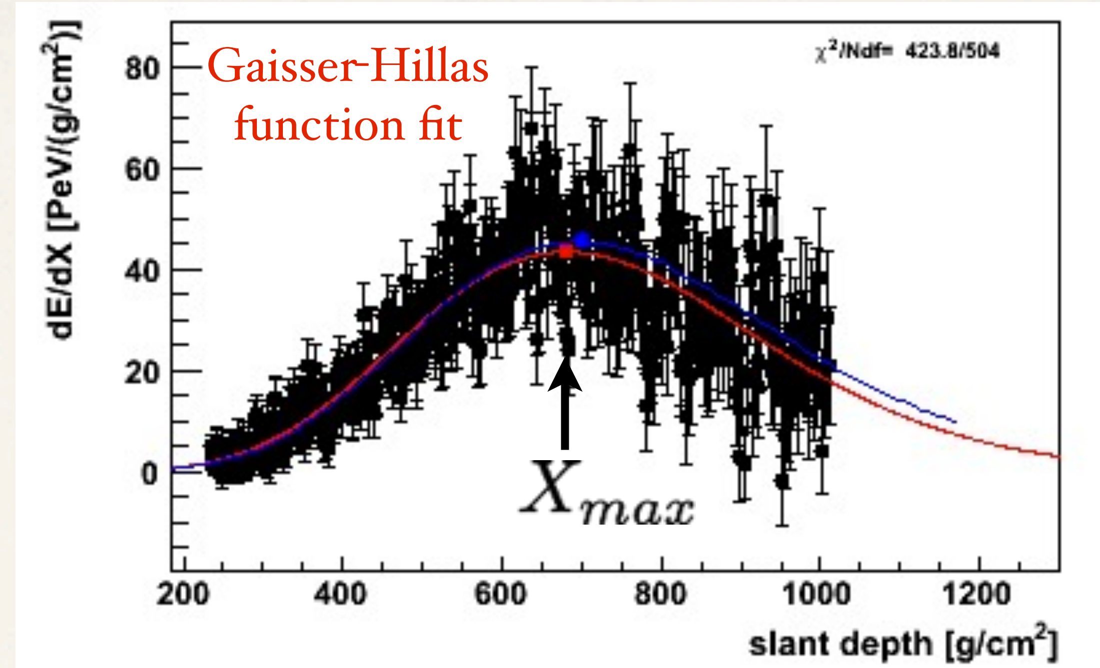
Observation of longitudinal profile with FD



1 event seen by Loma Amarilla telescope

Hybrid reconstruction of geometry

Atmosphere attenuation correction



X_{max} determined by

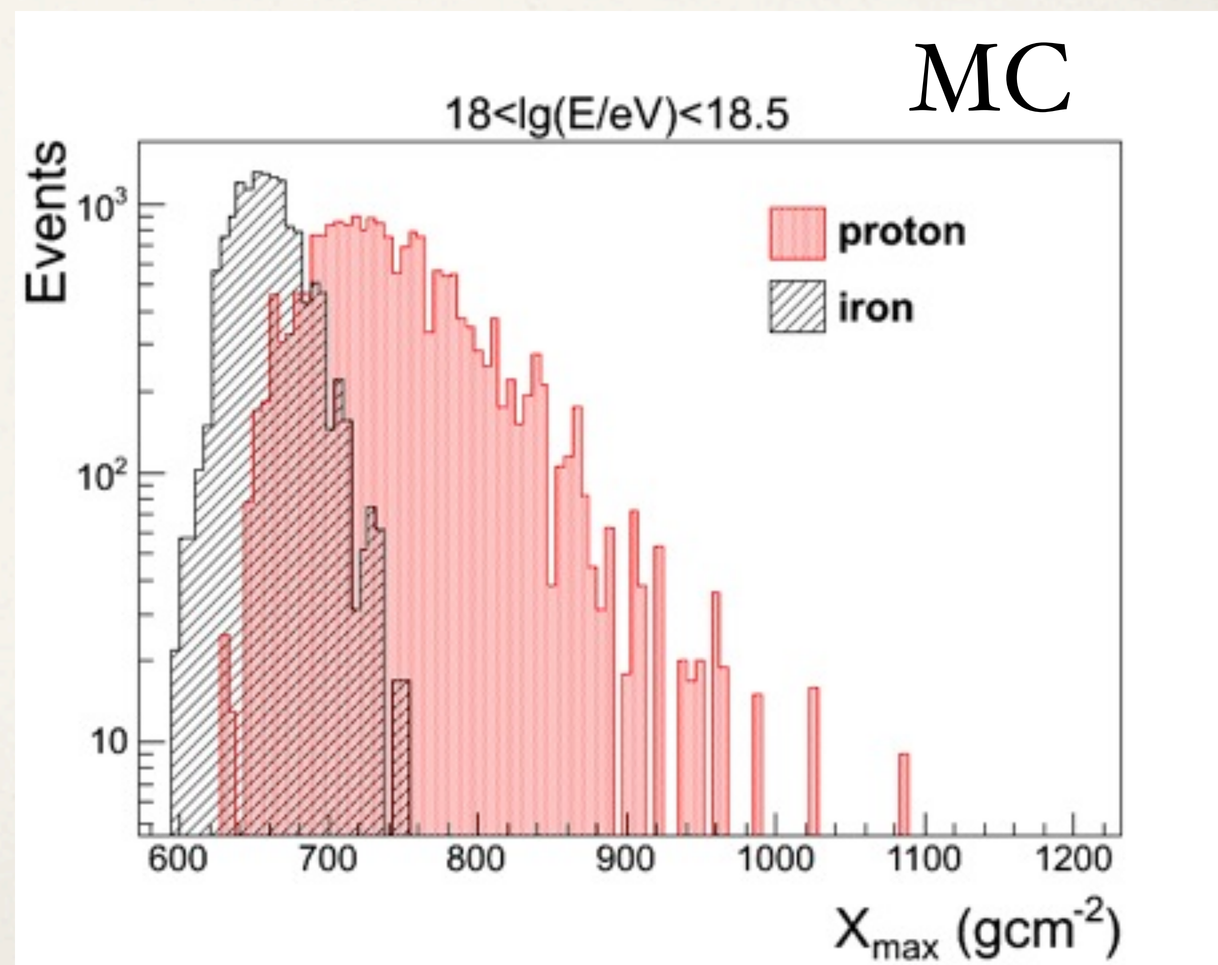
the depth of the first interaction

the depth that it takes the cascade to develop

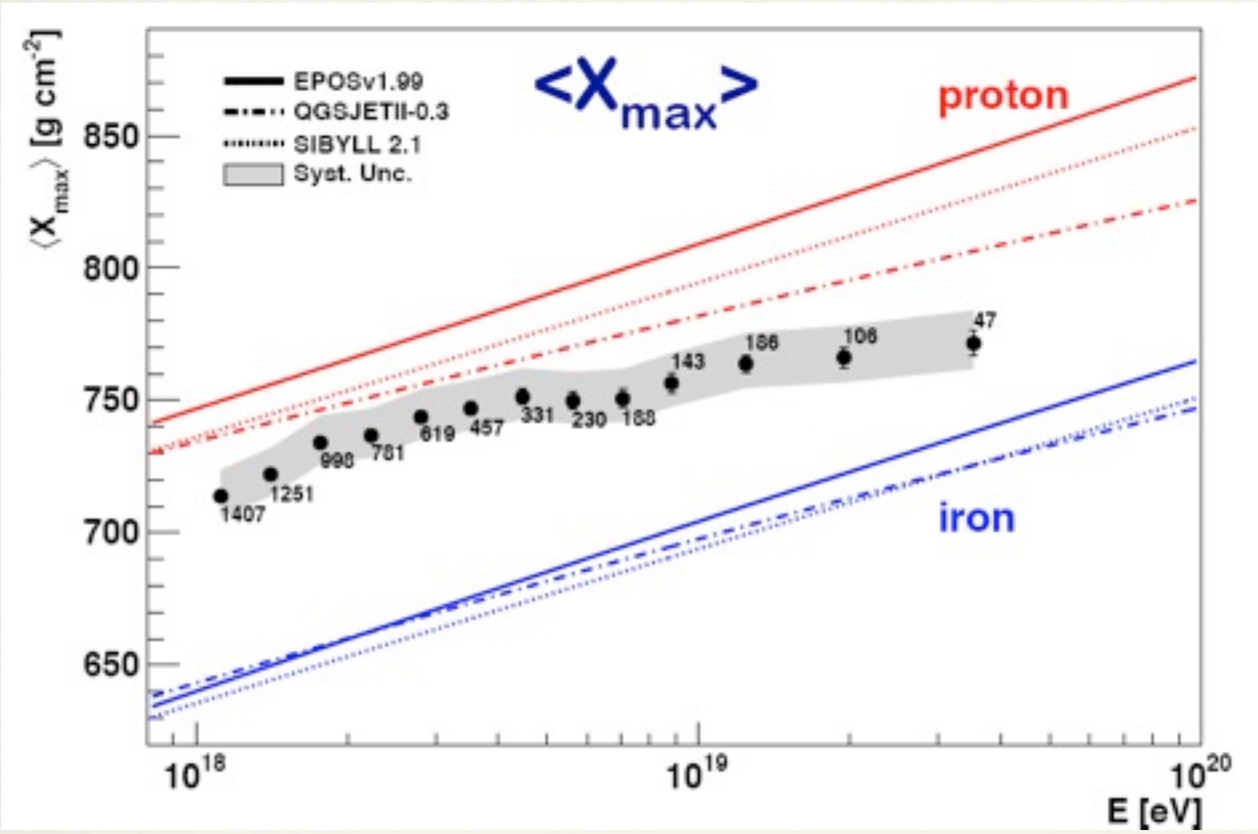
$$< X_{max} >= \alpha(lnE- < lnA >) + \beta$$

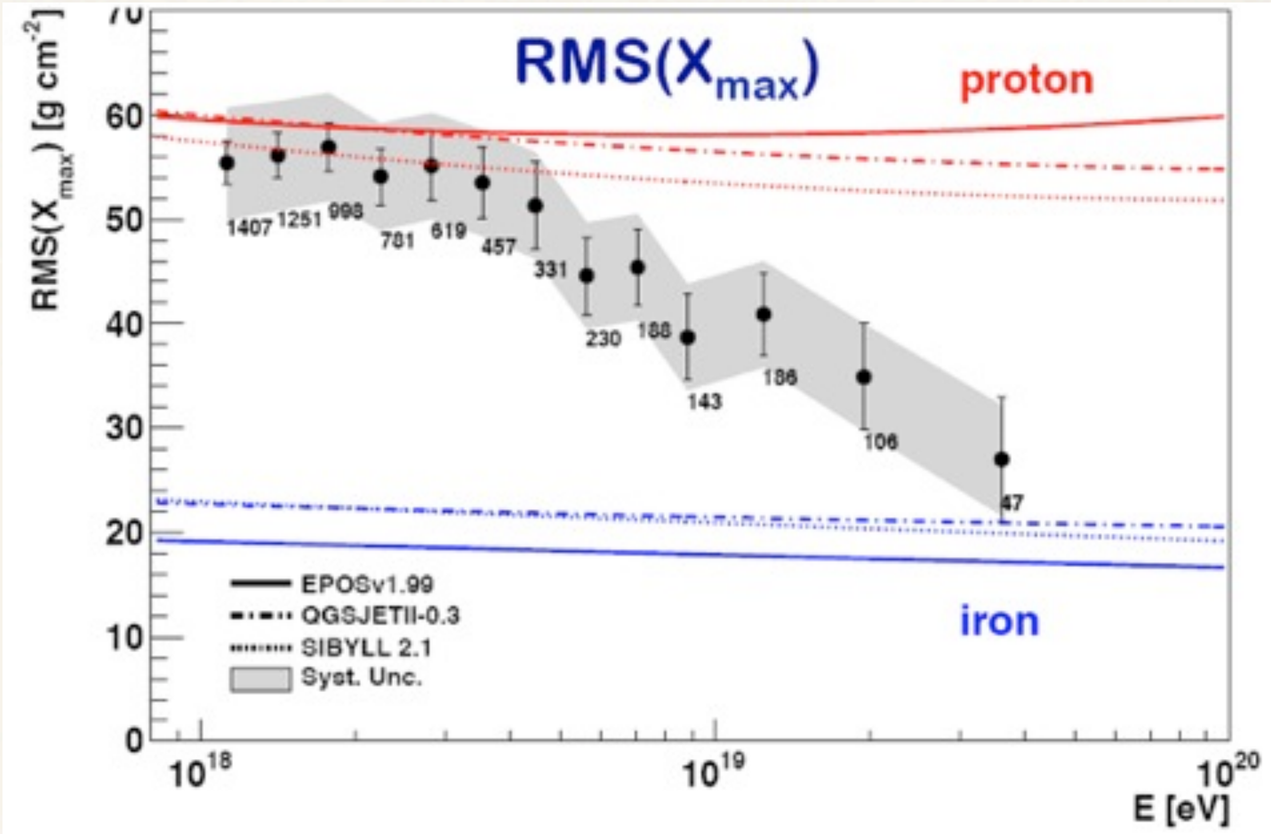
$$RMS(X_{max}) \propto A^{-1}$$

$X_{max}, RMS(X_{max})$ SENSITIVE TO MASS COMPOSITION



Composition with FD





Syst uncertainty < 13 g cm^{-2}

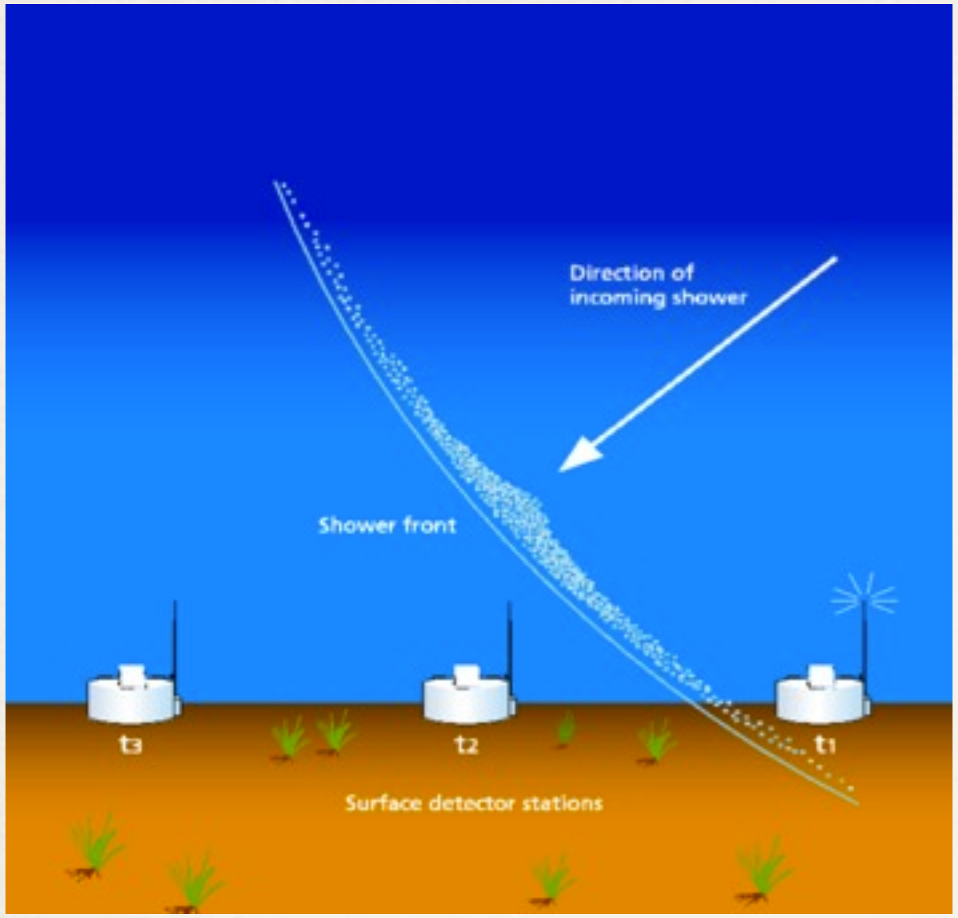
Xmax resolution ~ 20 g cm^{-2}

➜results suggest that composition gets heavier as E increases

➜ interpretation depends on hadronic interaction models

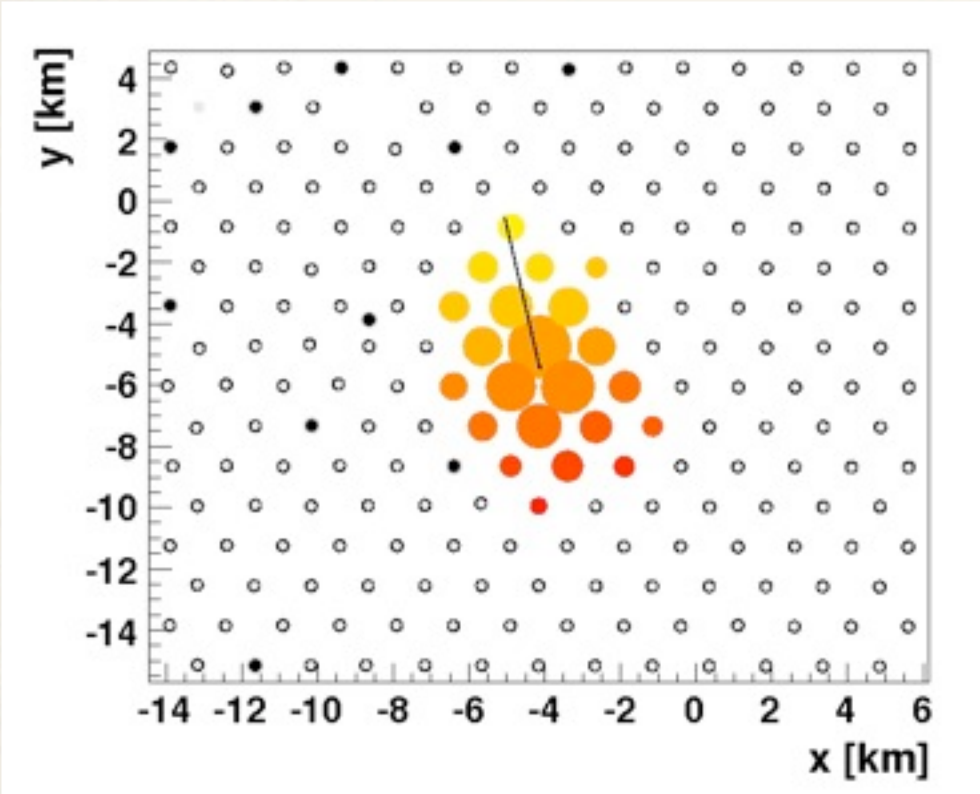
LIMIT: low statistics at UHE (FD duty cycle ~13%)
- collect more statistics
- SD mass sensitive observables

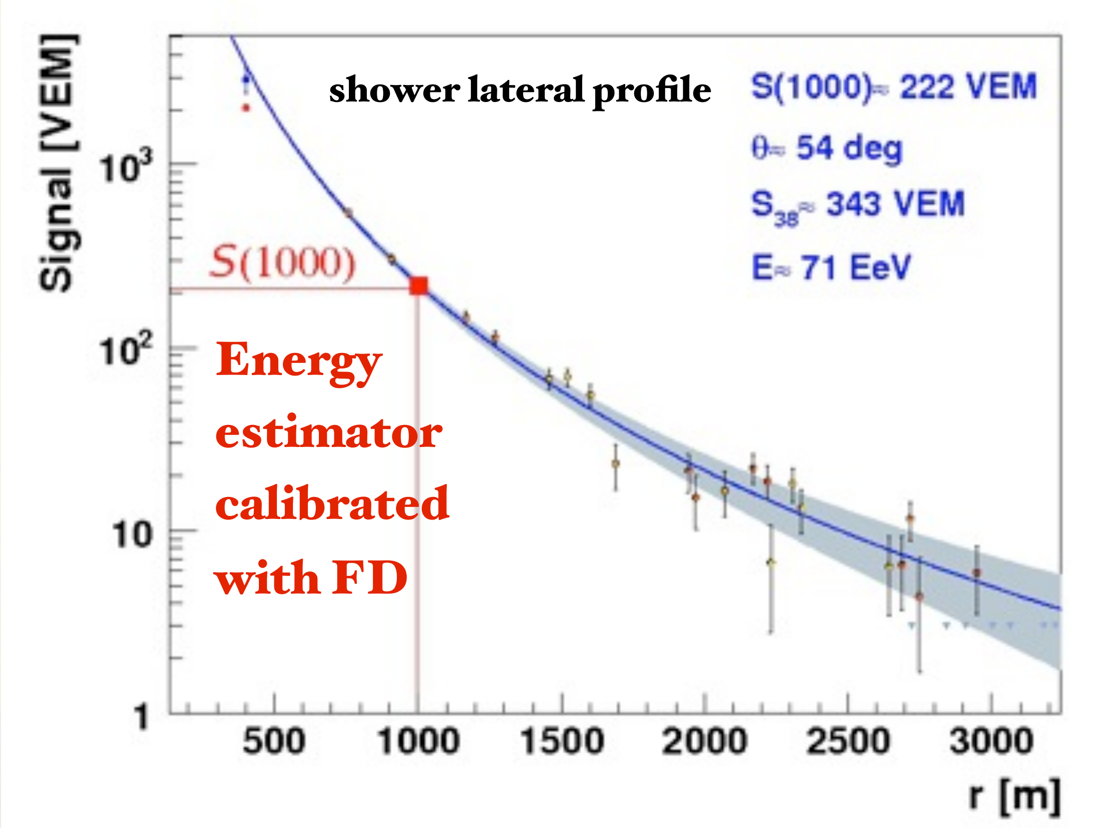
UHECRs Observation with SD



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

Angular resolution
E > 10^18 eV, ~ 3 stations, < 2°
E > 10^19 eV, ~ 6 stations, < 1°

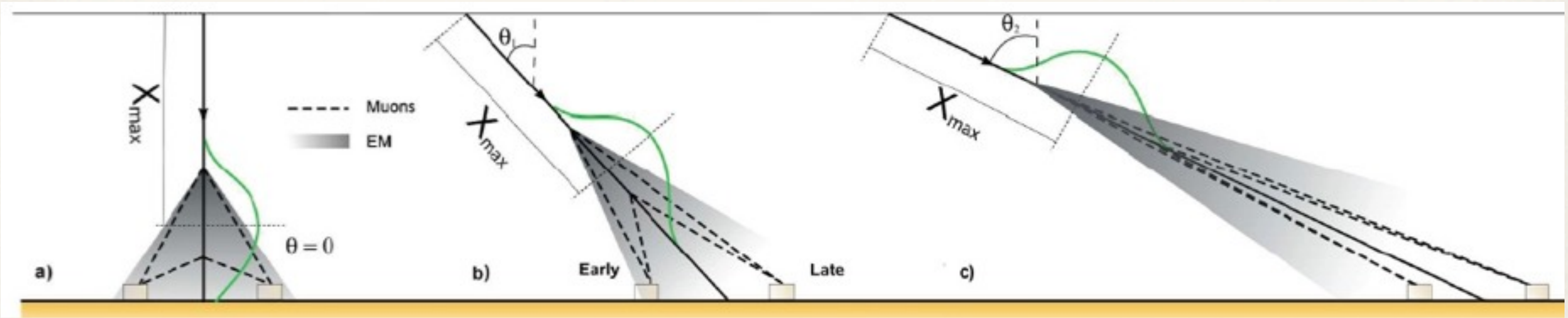




Composition with SD: Rise Time Asymmetry

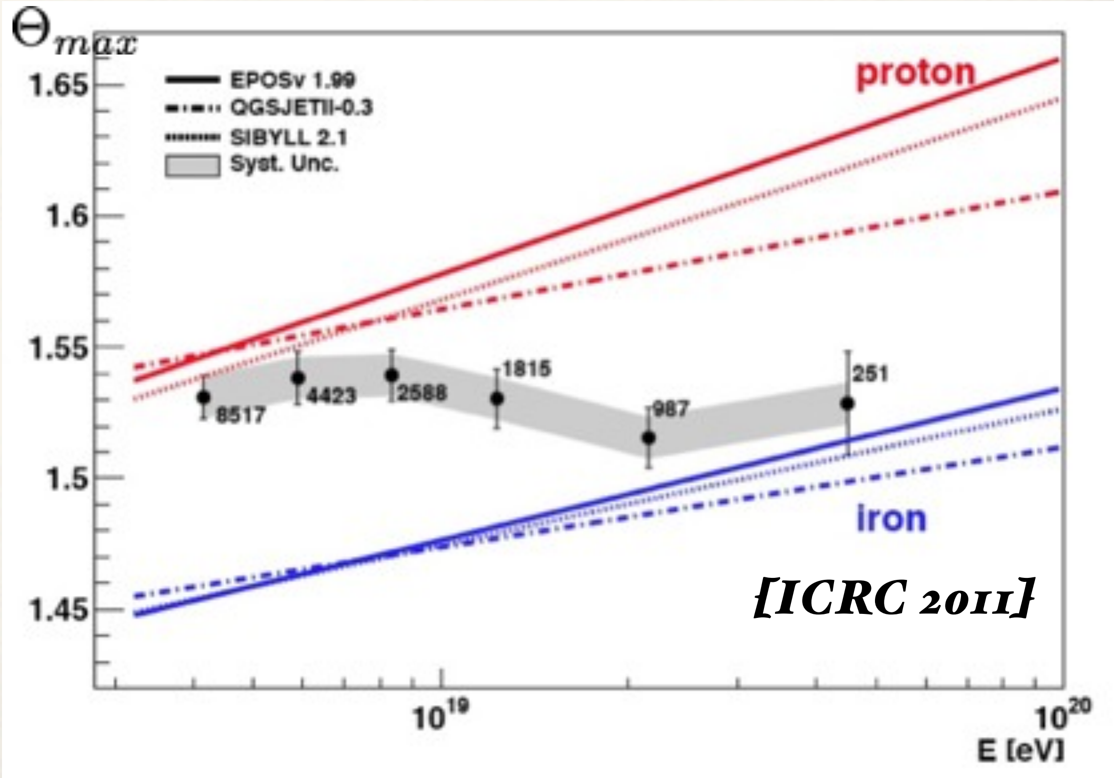
Rise Time of the tank signals (10% to 50%) related to the muon content of the shower

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



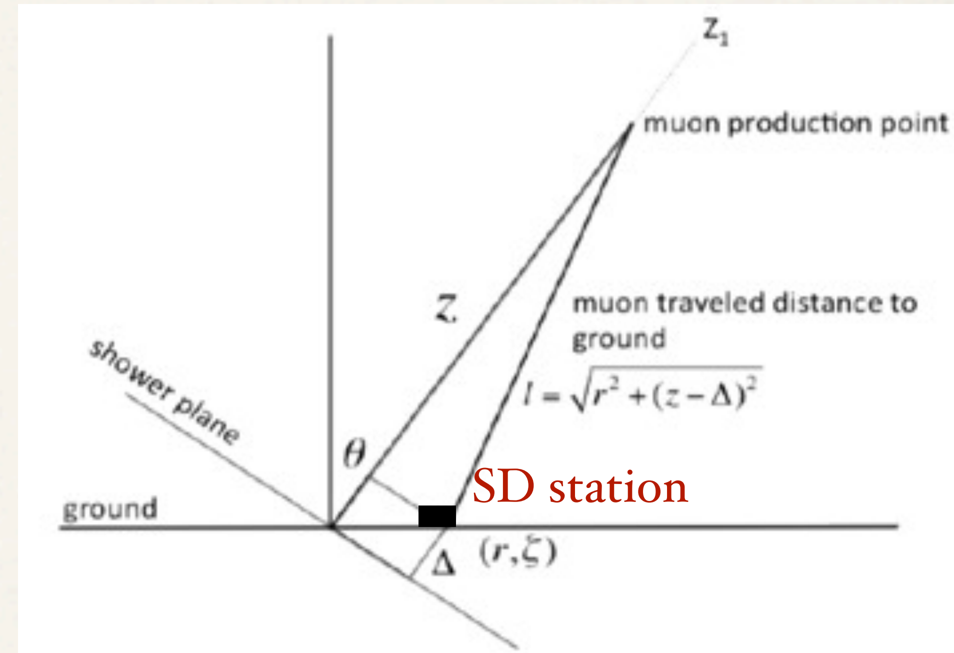
Rise time asymmetry:
the zenith angle at which the asymmetry becomes maximum is related to the shower development

LIMIT:
Only for non-vertical shower (30°-60°)
<u>Not on an event-by-event basis</u>



Composition with SD: Muon Production Depth

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



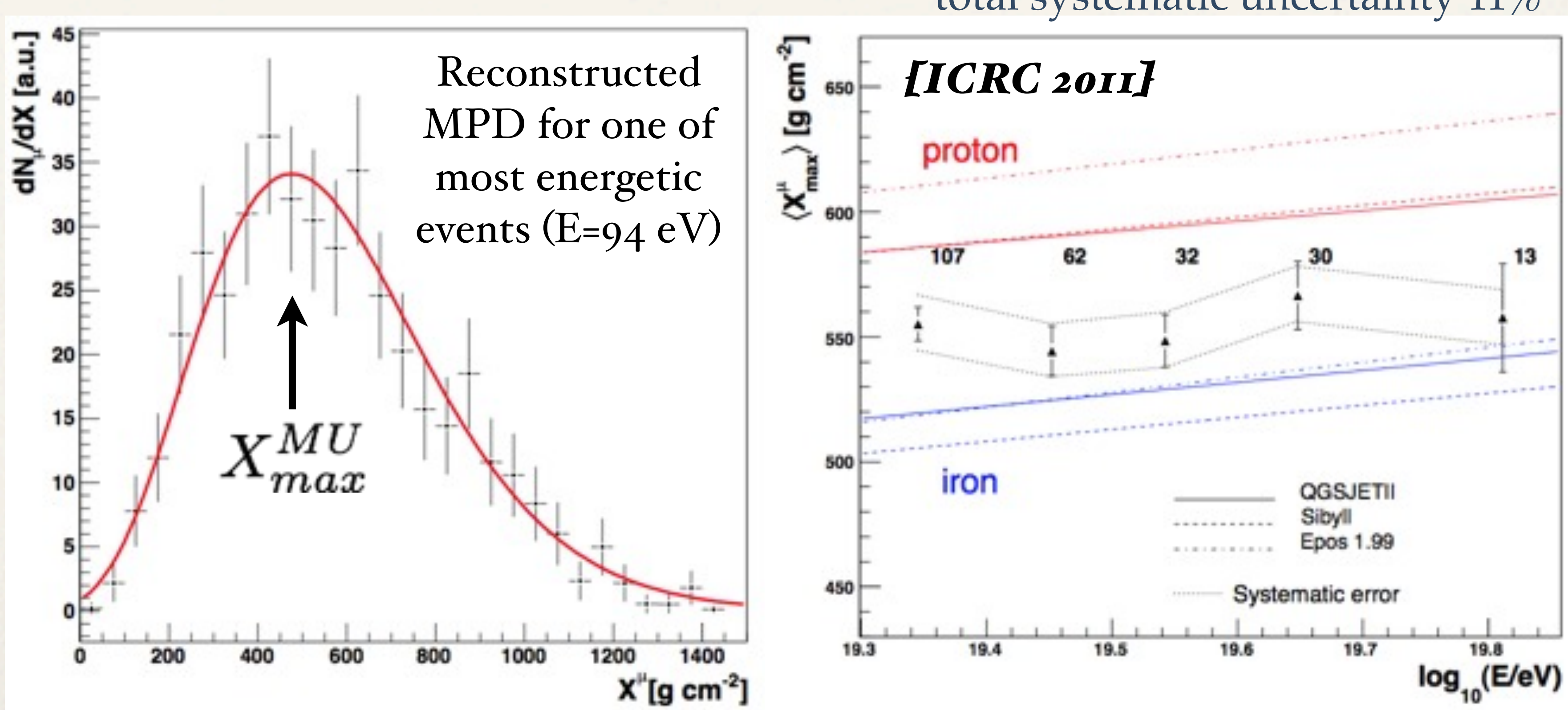
In these conditions:

- inclined showers: 55°-65°
- stations far from the core (r>1800 m)

it is possible to assume that the total signal in the station is due to muons

➜ only 244 SD events (Jan'04-Dec'10)

total systematic uncertainty 11%



How could we extend the analysis range for MPD studies?

Limitations in the MPD reconstruction

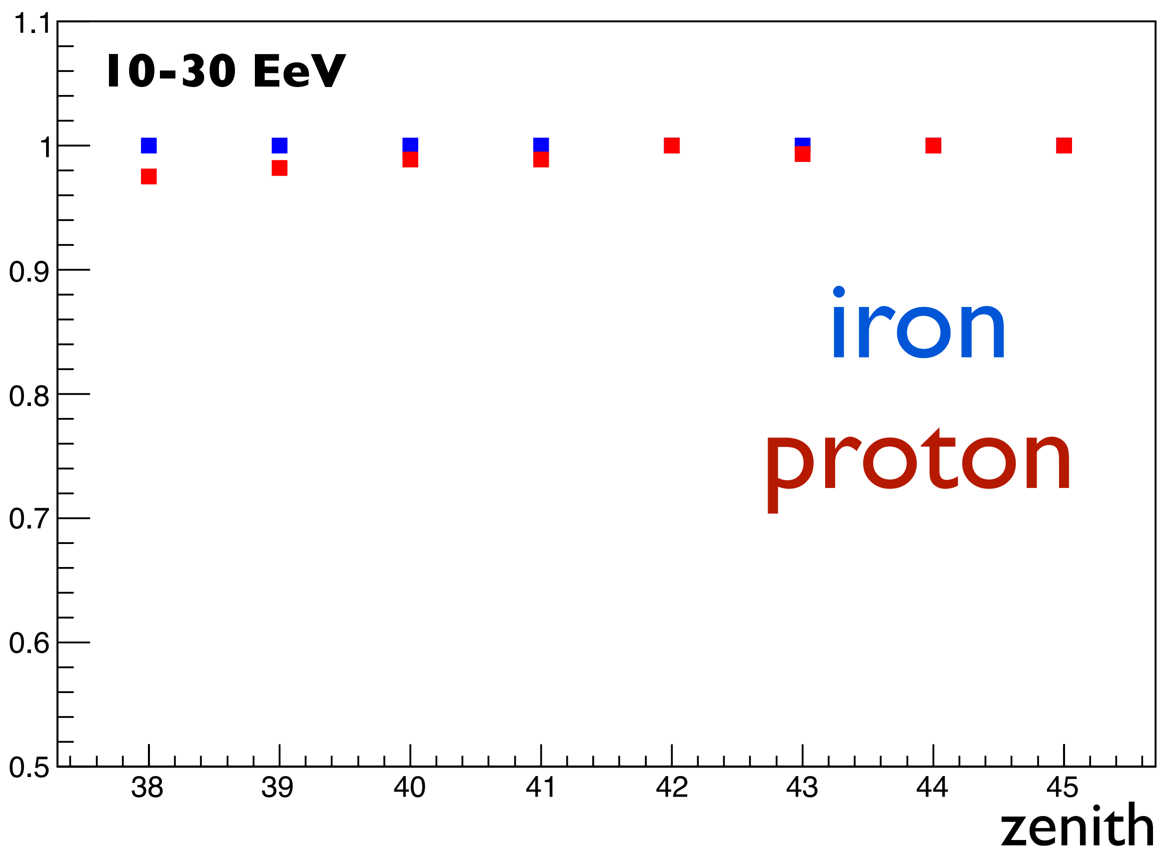
Dependence on θ

→ maximum visible for θ≥40° at PAO observation level

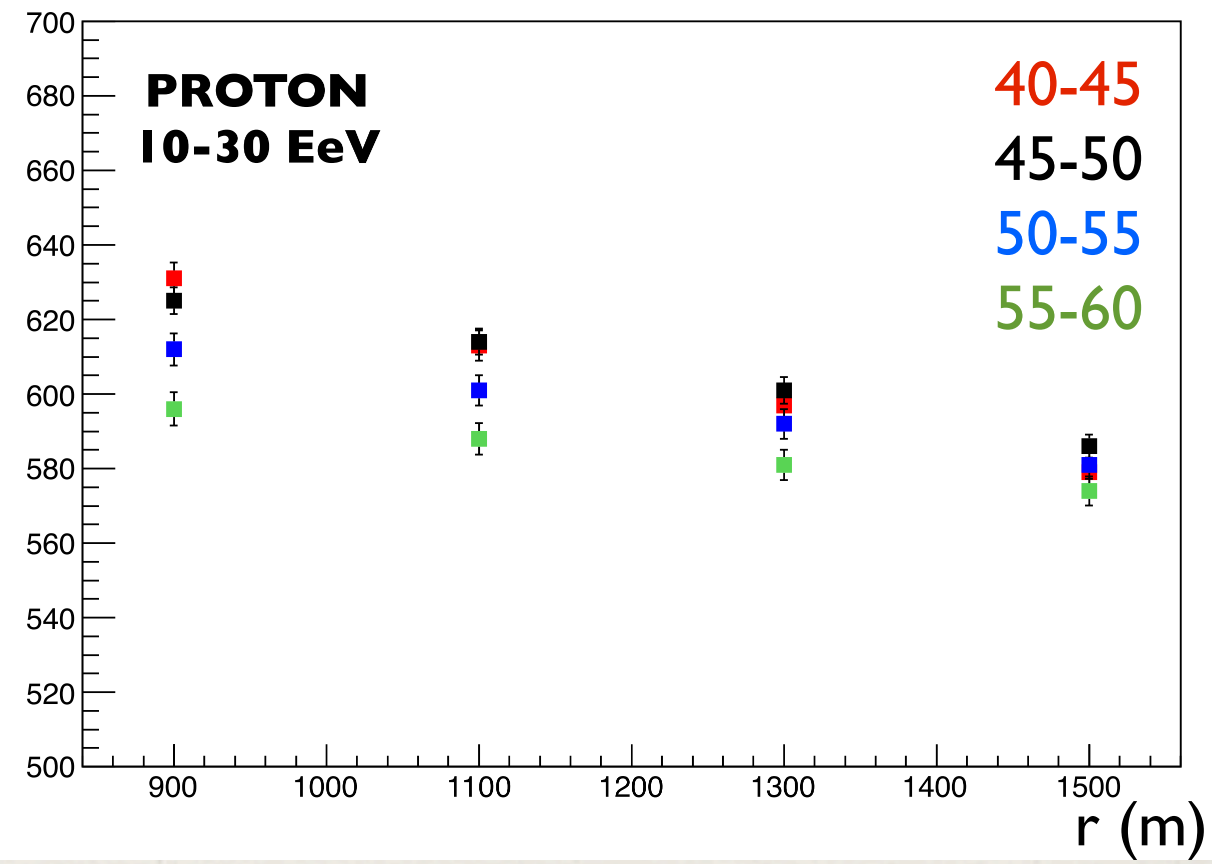
Dependence on the core distance at which the reconstruction is performed

→ maximum r-dependence for θ<60°

visibility of the maximum



r-dependence

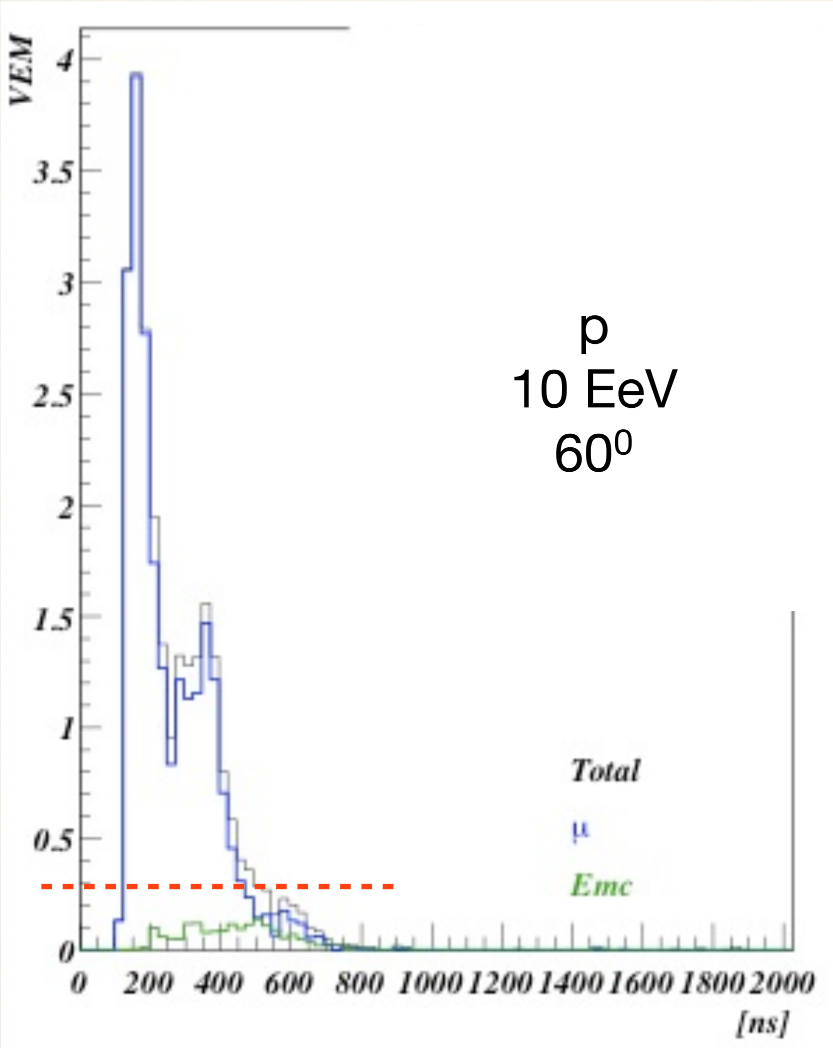


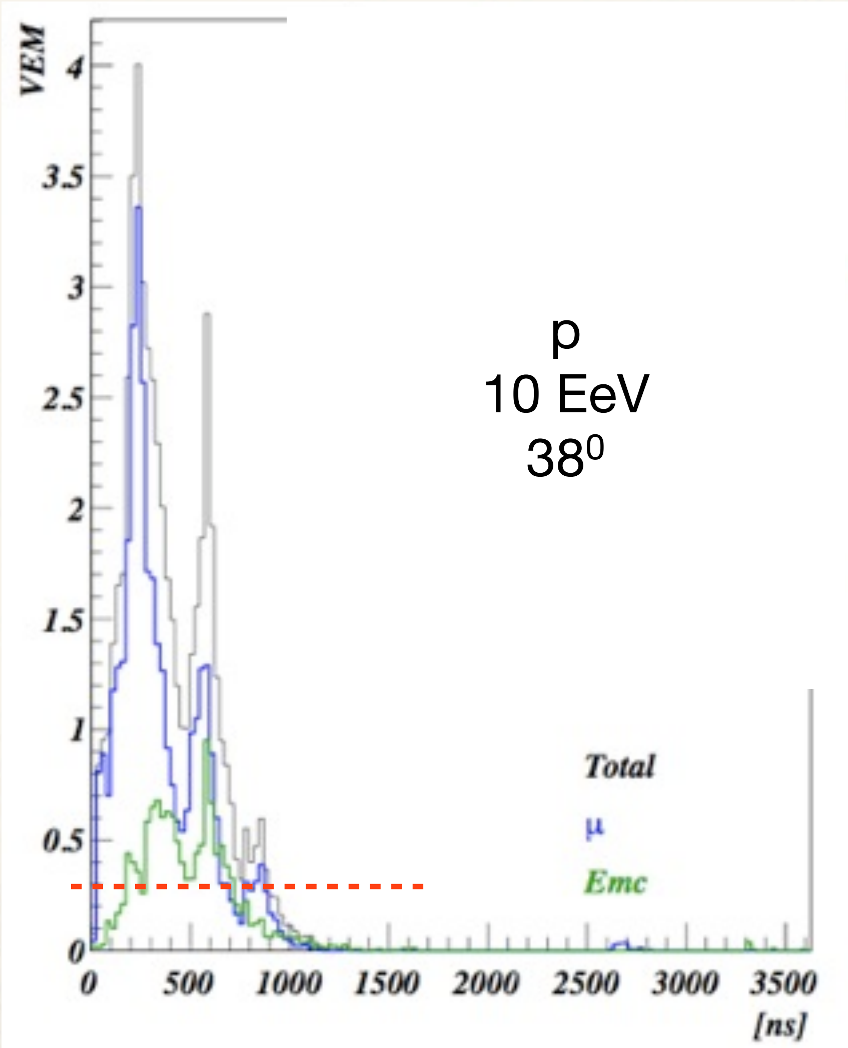
Limitations in the MPD reconstruction

Dependence on the EM component

- can be subtracted by using a simple cut for large θ (S[bin]>0.3 VEM)

- more refined technique in a larger zenith range

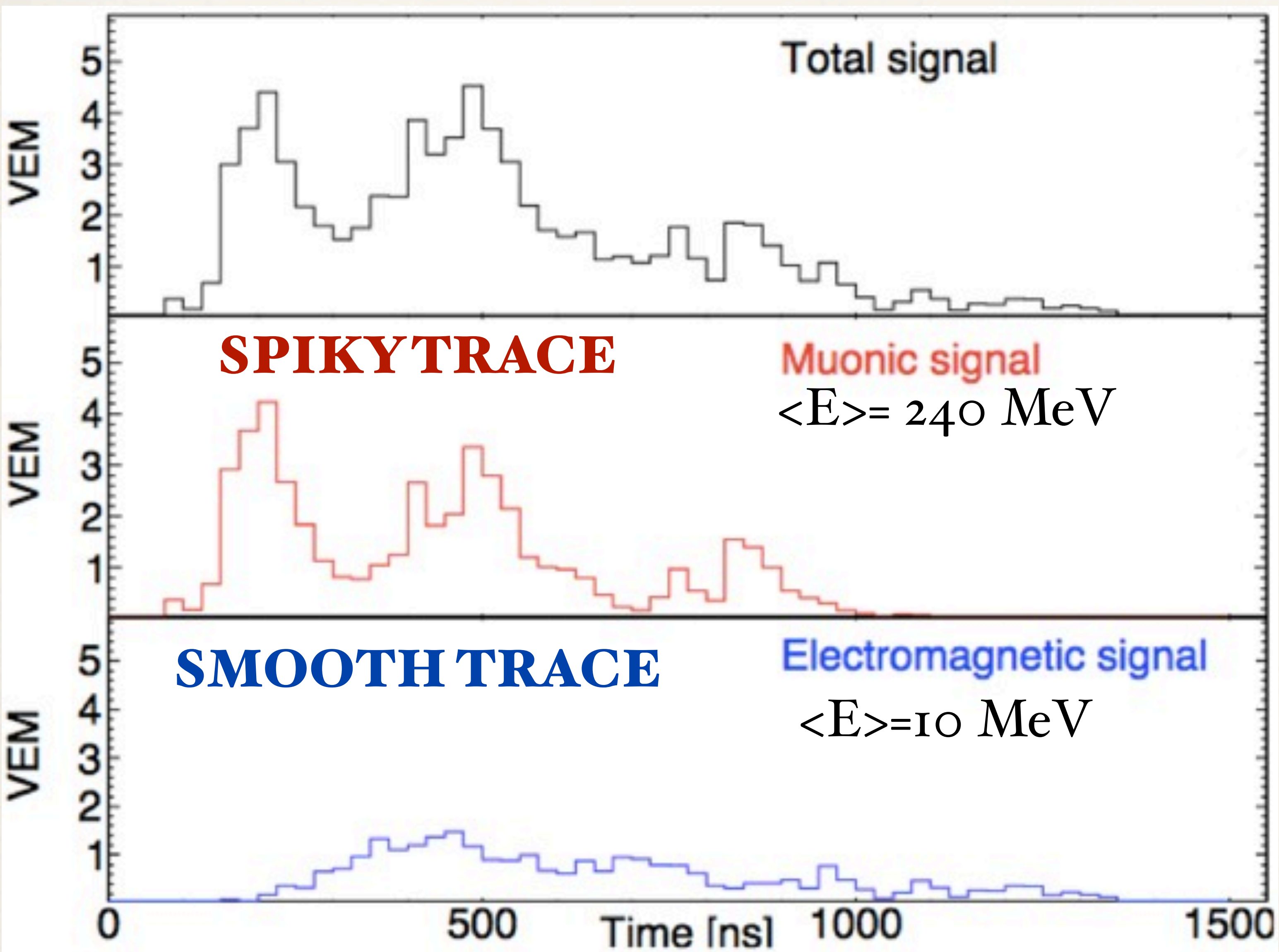




Time Structure of the signals in the SD stations

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

From MC simulation



High energy release

Low number density

Narrow arrival time spread

Small energy release

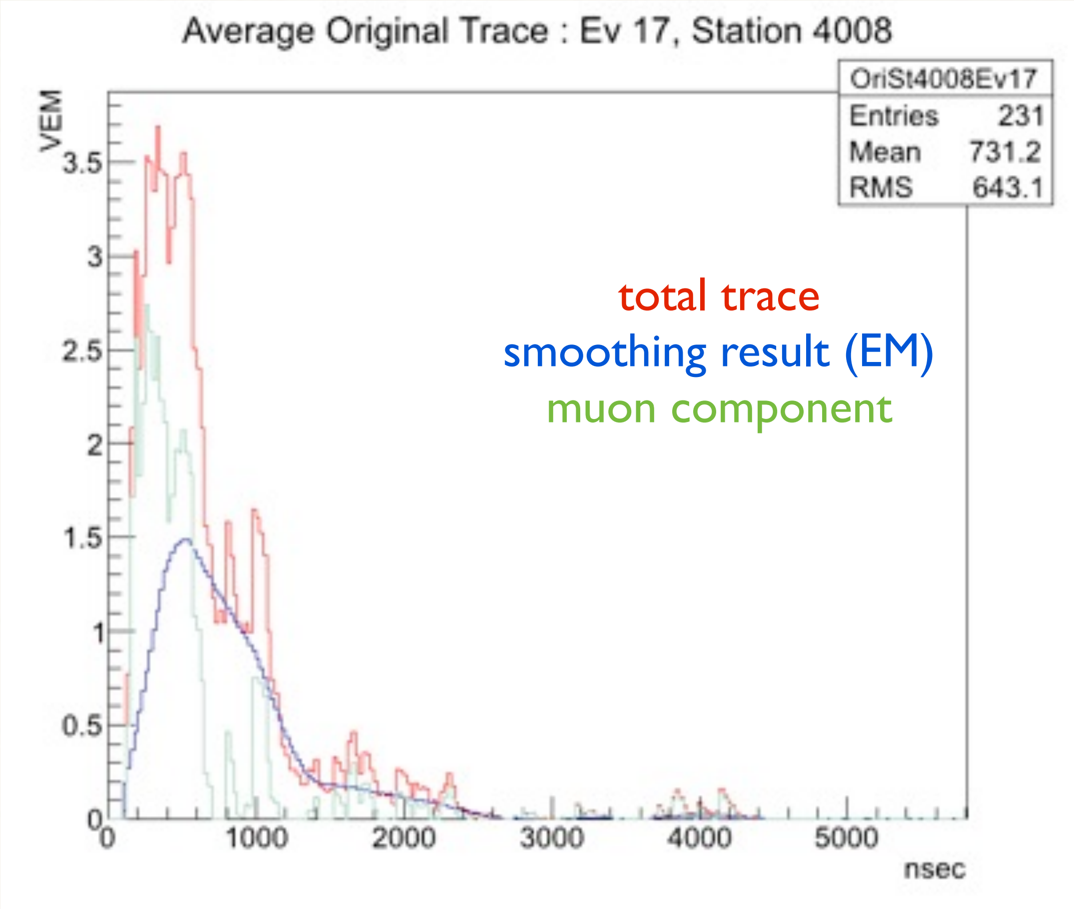
High number density

Large arrival time spread

Electromagnetic particles and muons leave signals with different time structure

The smoothing technique

A. Castellina, Auger Torino Group



Based on the different characteristics of the two components

$< E_{EM} >$ $about\ 10MeV$ smooth signal

$< E_{MU} >$ $about\ 240MeV$ spiky signal

The temporal distribution of the total signal S(t) in each station is smoothed using a moving average over a variable convolute range

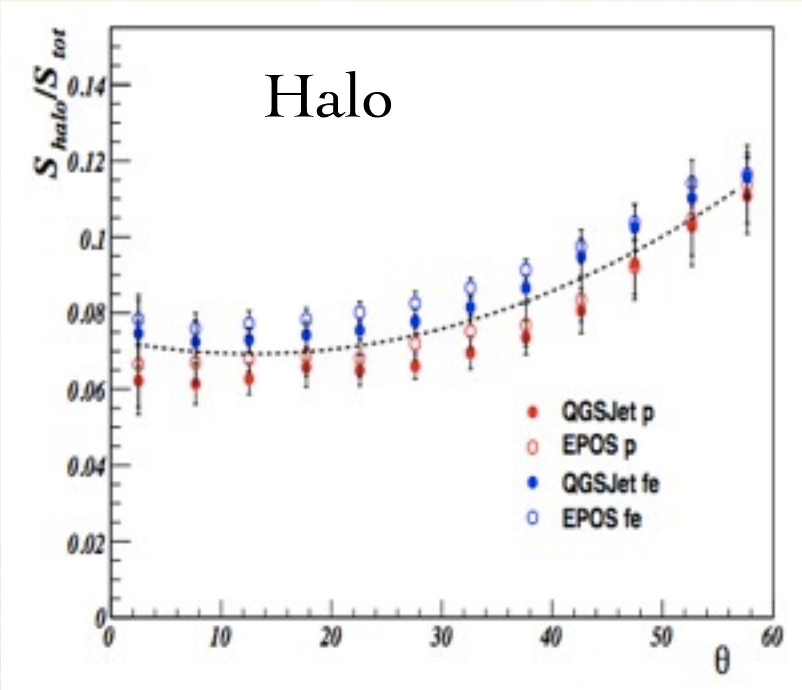
$$S = S_{EM} + S^{MU}_{halo} + S_{MU} + S_{nucl}$$

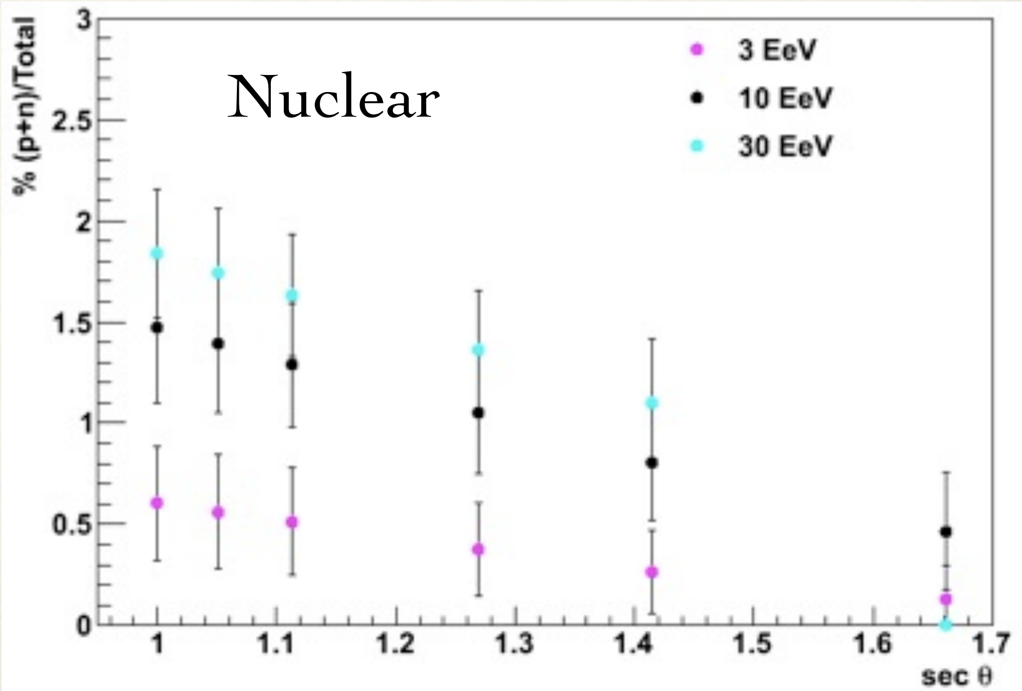
directly from smoothing ($S_{EM} + S^{MU}_{halo}$)

by difference from smoothing ($S_{MU} + S_{nucl}$)

700-1500 m
E> 3 EeV
0-60° zenith angle

systematic bias <10%
resolution <20%

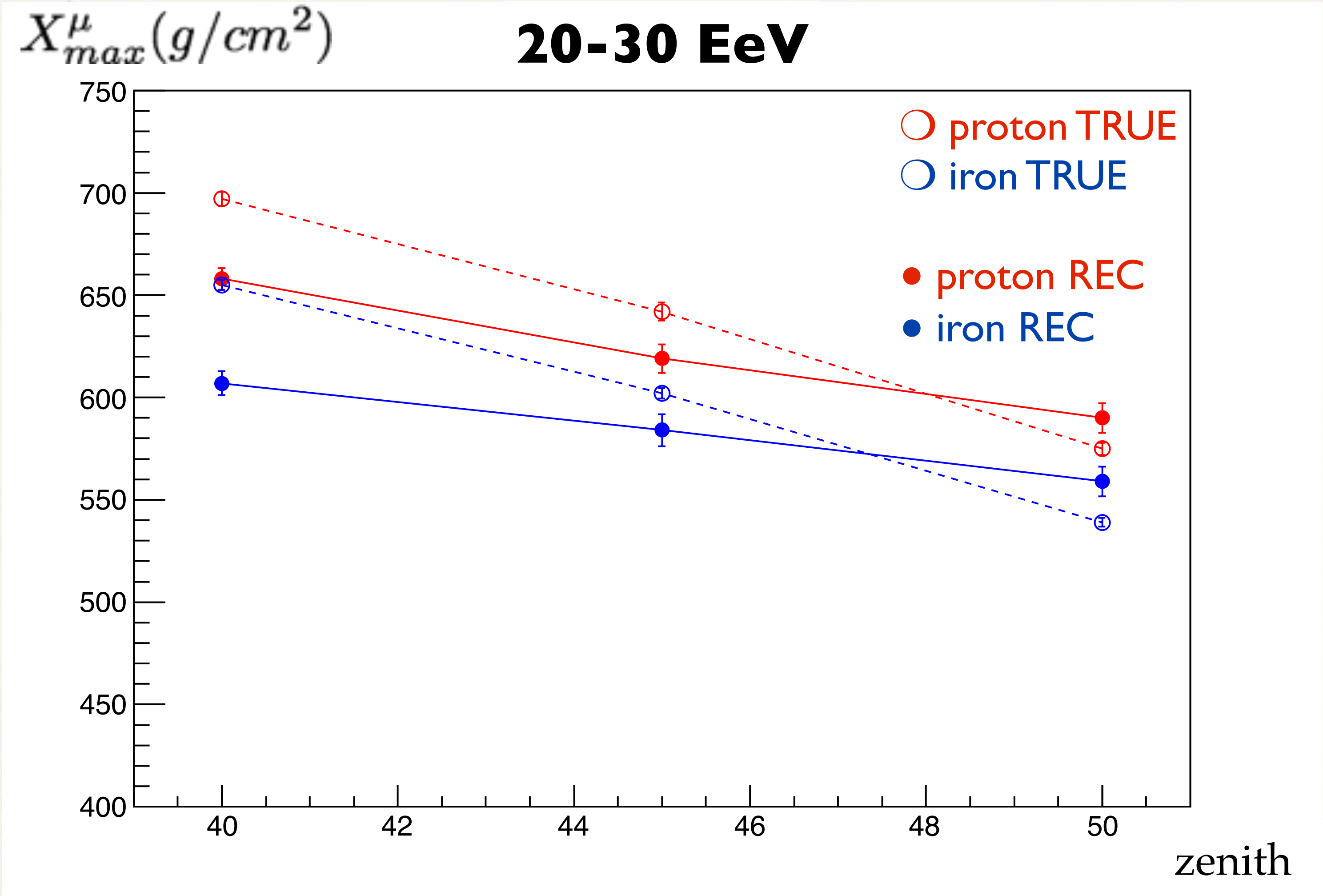




MPD reconstruction

- The smoothing technique is exploited in order to estimate the muon trace between 1000 and 1500 m from the core

- an average r-dependence correction is applied at the reconstructed shower maximum for the different zenith angle bins



The reconstructed shower maximum is underestimated in the range 40°- 50°

→ need to study a correction on a event-by-event basis

Conclusions and Outlook

- The Pierre Auger Observatory is studying the universe's highest energy particles and one of the physics goal is to understand the physics behind the end of the spectrum.

- To achieve this goal, mass composition studies are crucial in order to break degeneracy between astrophysical models.

- In this context, MPD analysis has great potentiality but the applicability range has to be extended.

- The Smoothing technique could help to reach this goal, but there is still much work to do...

STAY TUNED

☺