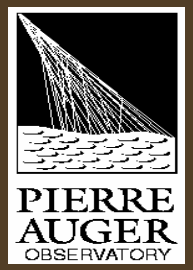
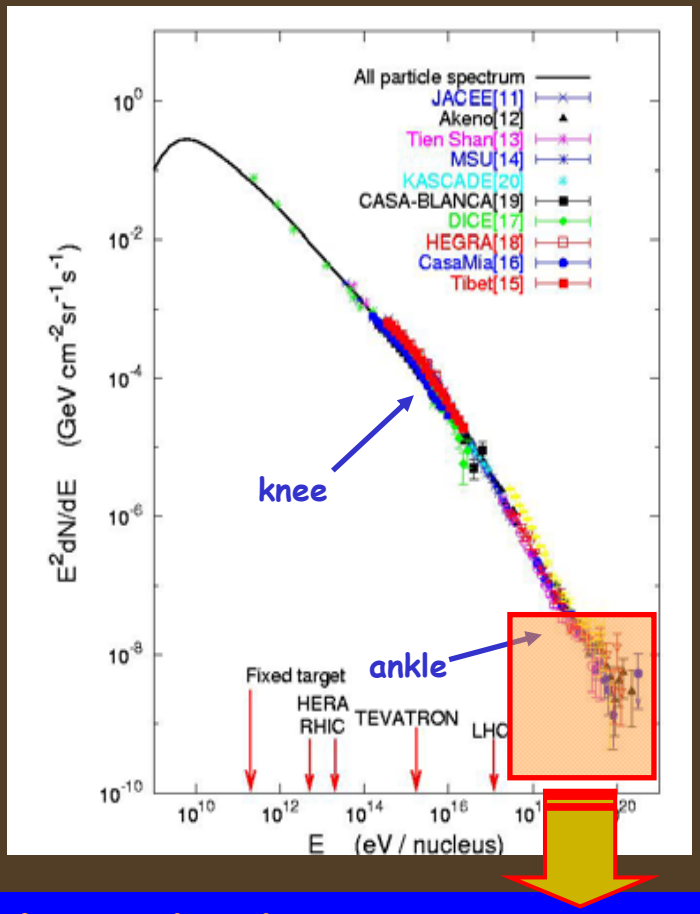


Pierre Auger Observatory status and results

XLIId Rencontres de Moriond on
Electroweak interactions and unified theories
La Thuile, 10-17 March 2007

Véronique Van Elewyck
[for the AUGER Collaboration]
Institut de Physique Nucléaire d'Orsay (France)



The cosmic ray spectrum:

❖ **power-law spectrum** (nearly-) **uniform** over 12 decades in E and 32 in flux !

...BUT

❖ **structures: knee, ankle**

change in nature of the sources ?
change in composition ?
galactic-extragalactic transition ?
new physics ?

❖ **above ankle:**

GZK cutoff ? (p^+ on CMB photons)
sources ?
...small fluxes, intricated experimental situation

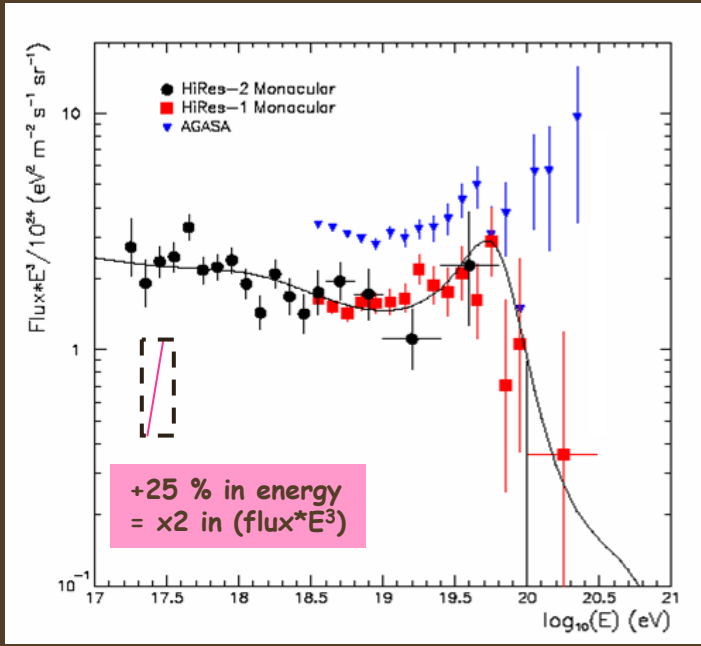
Ultra-high energy cosmic rays (UHECR):

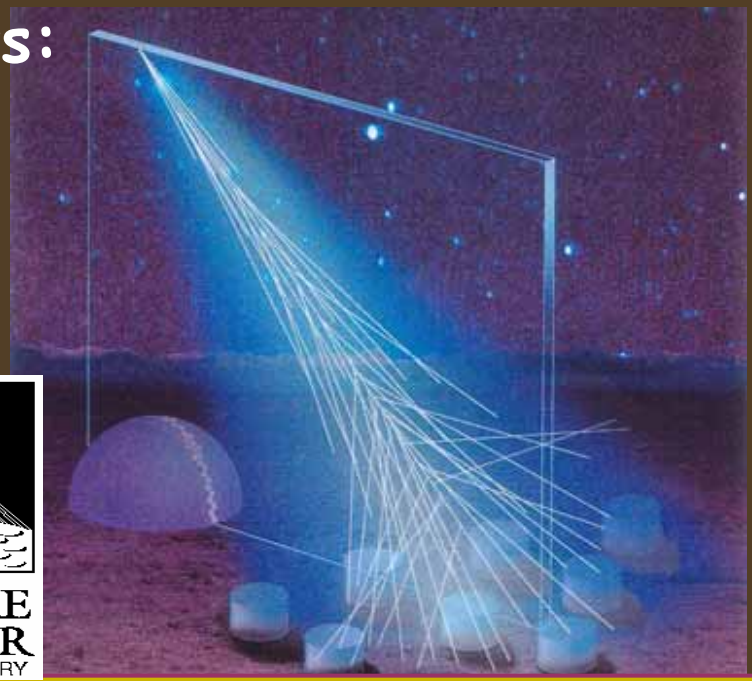
❖ Spectrum ?

❖ Arrival direction ?

❖ Composition ?

Ultra-High Energy Cosmic Rays:





PIERRE AUGER OBSERVATORY

The Pierre Auger Observatory:
A hybrid detector designed for a high statistics study of the UHECR

Ultra-high energy cosmic rays (UHECR):

- Spectrum ?
- Arrival direction ?
- Composition ?

…a hybrid strategy

…anisotropy studies

…limit on photon fraction

…UHE Earth-skimming tau neutrinos

The Pierre Auger Observatory

Fluorescence detector (FD)

4 telescopes with 6 "eyes" (all active)
Mirrors: d=3.4 m, 30° x 30° FOV
440 PMTs per mirror, 1.5° aperture
10 MHz sampling rate

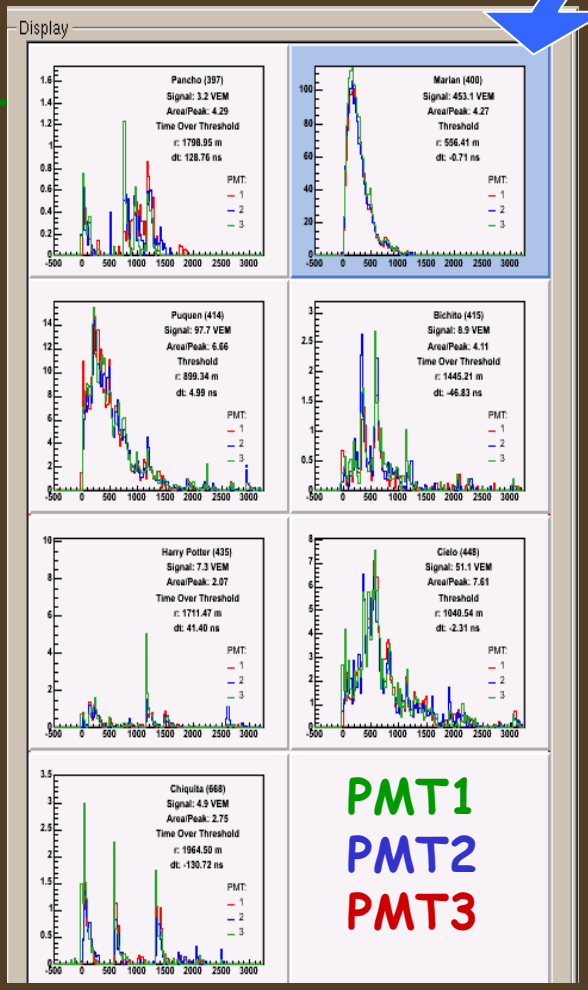
Surface detector (SD)

1600 Cherenkov water tanks (>1000 active)
3 PMTs per tank, 40 MHz sample rate
triangular array (d = 1,5 km)
total surface: 3000 km²

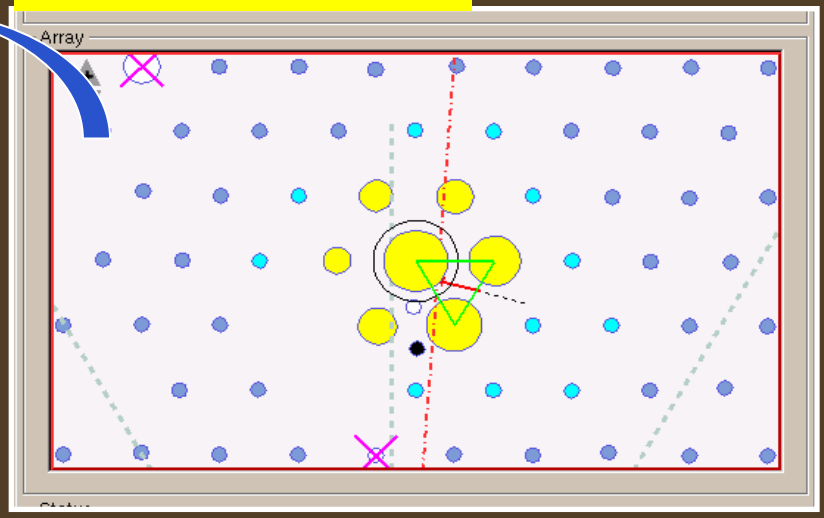
~ 70 km

Detection of Air Showers by the SD

FADC traces:



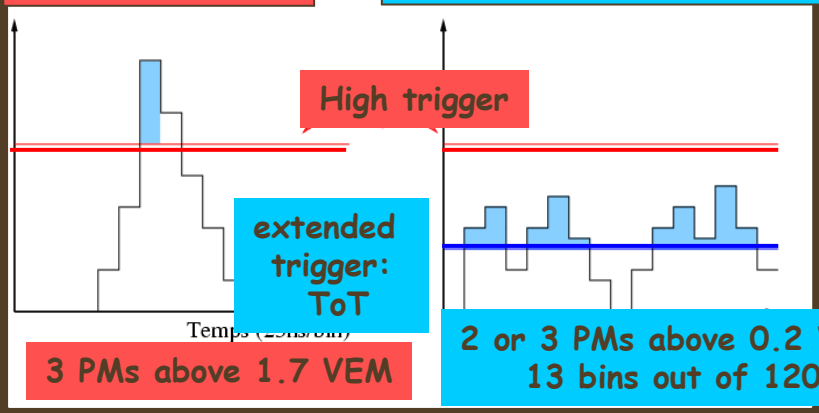
E ~ 8 EeV, θ ~ 30°



Local trigger conditions

Threshold (Th)
~ 100 Hz

Time Over Threshold (ToT)
~ 1 Hz

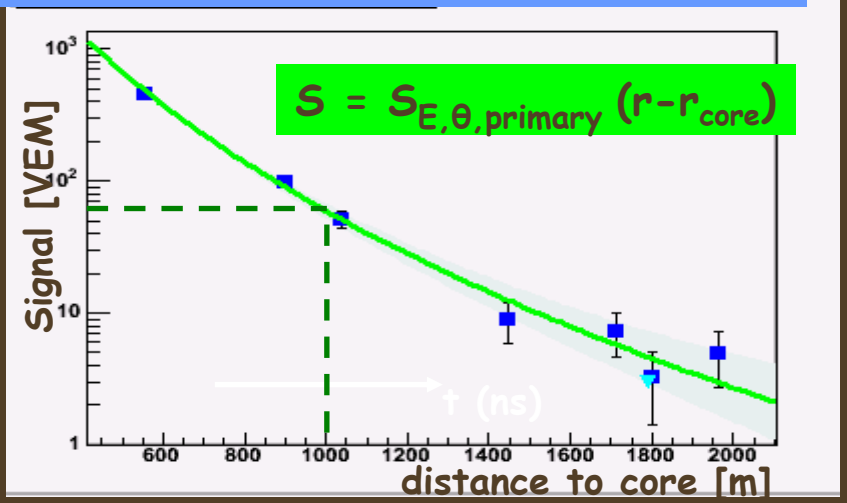


3 PMs above 1.7 VEM

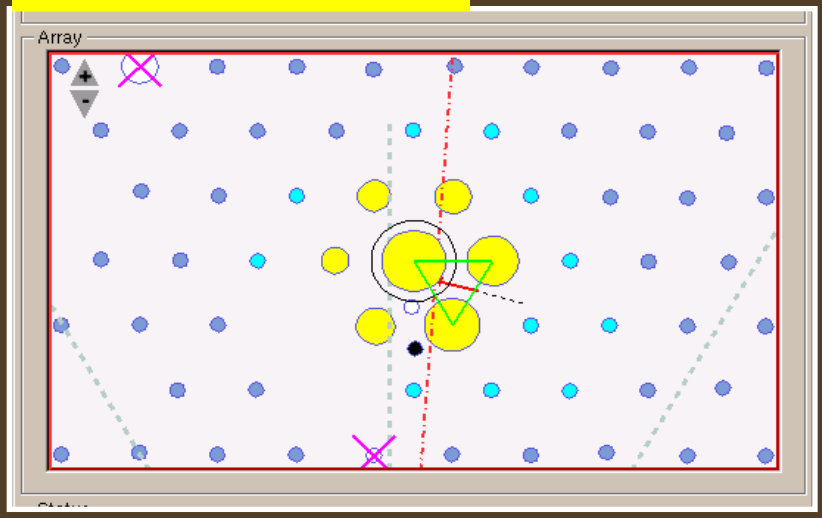
2 or 3 PMs above 0.2 VEM
13 bins out of 120

Detection of Air Showers by the SD

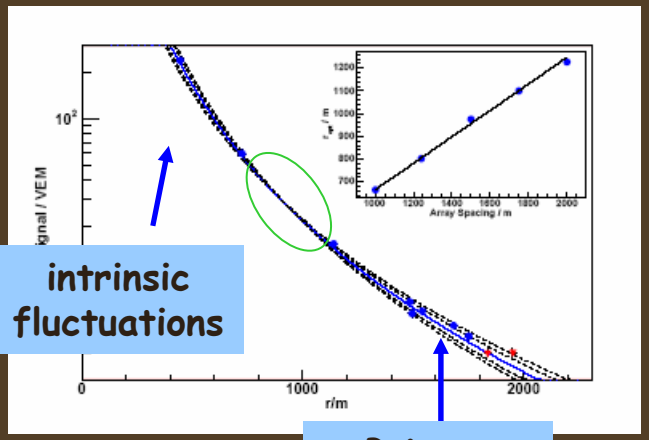
Lateral distribution function (LDF) fit



E ~ 8 EeV, θ ~ 30°



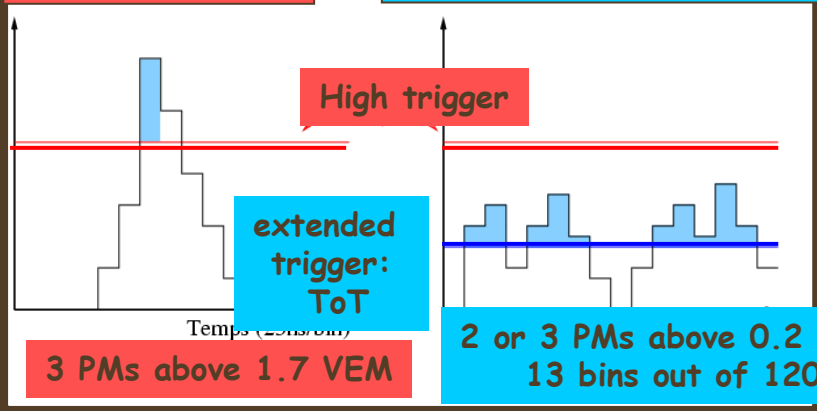
$S_{1000} = S_{1000}(E,\theta)$: good estimator of the shower energy for Auger SD



Local trigger conditions

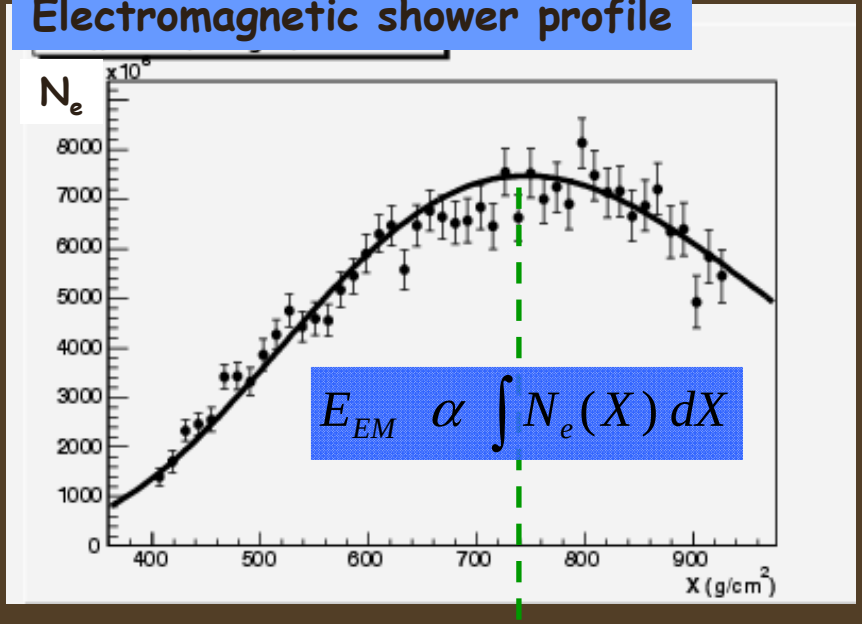
Threshold (Th) ~ 100 Hz

Time Over Threshold (ToT) ~ 1 Hz



Detection of air showers by the FD

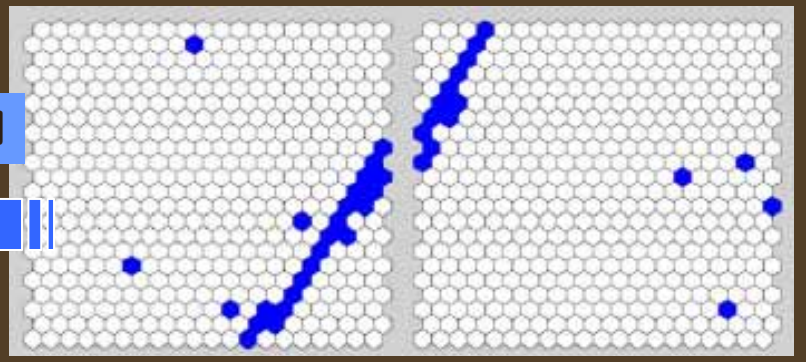
Electromagnetic shower profile



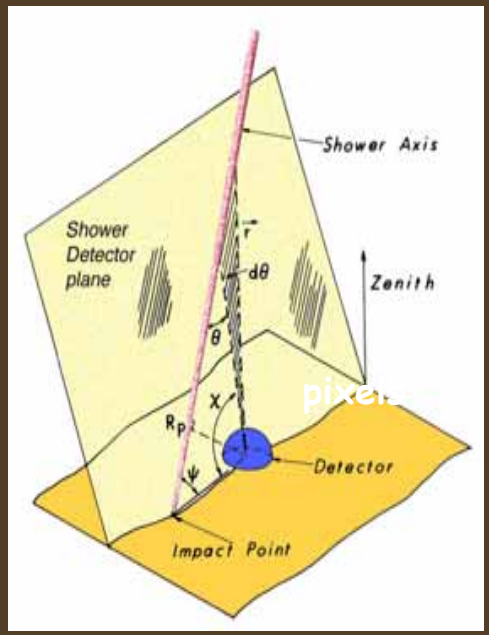
X_{max}: elongation rate

calorimetric measurement of the energy: independant from hadronic models

signal

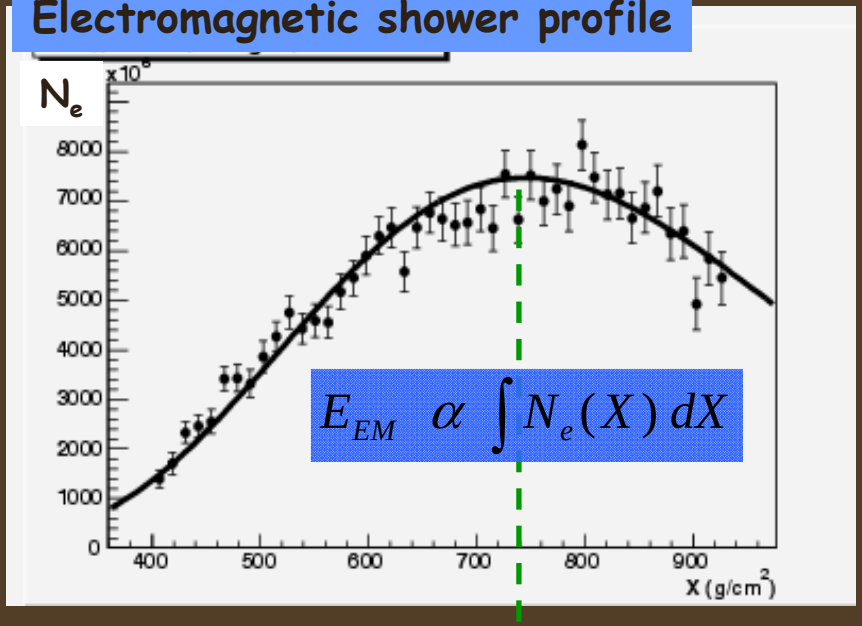


timing



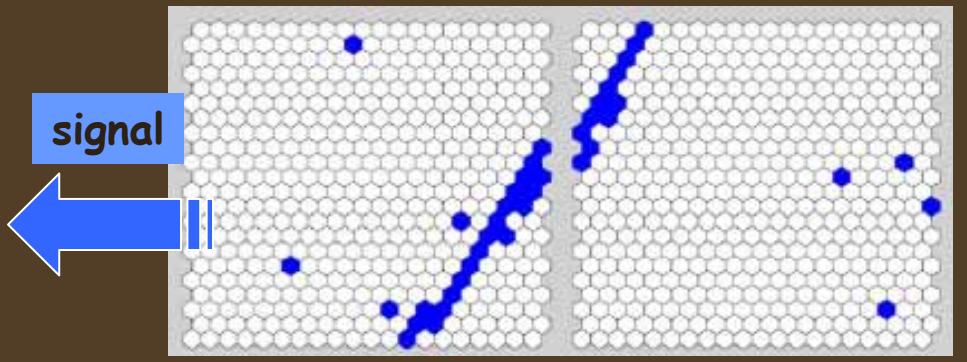
Detection of air showers by the FD

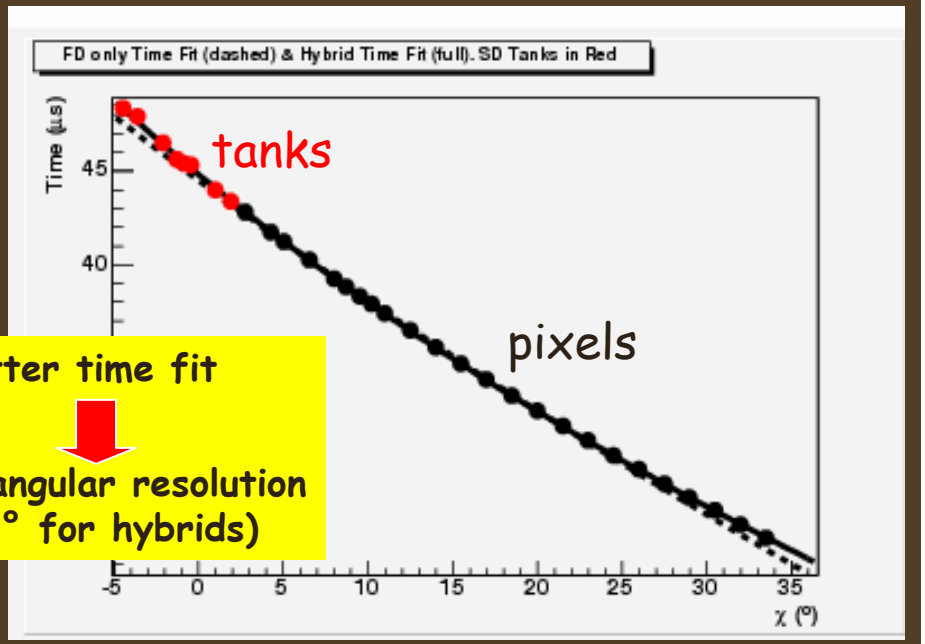
Electromagnetic shower profile



X_{max}: elongation rate

calorimetric measurement of the energy: independant from hadronic models





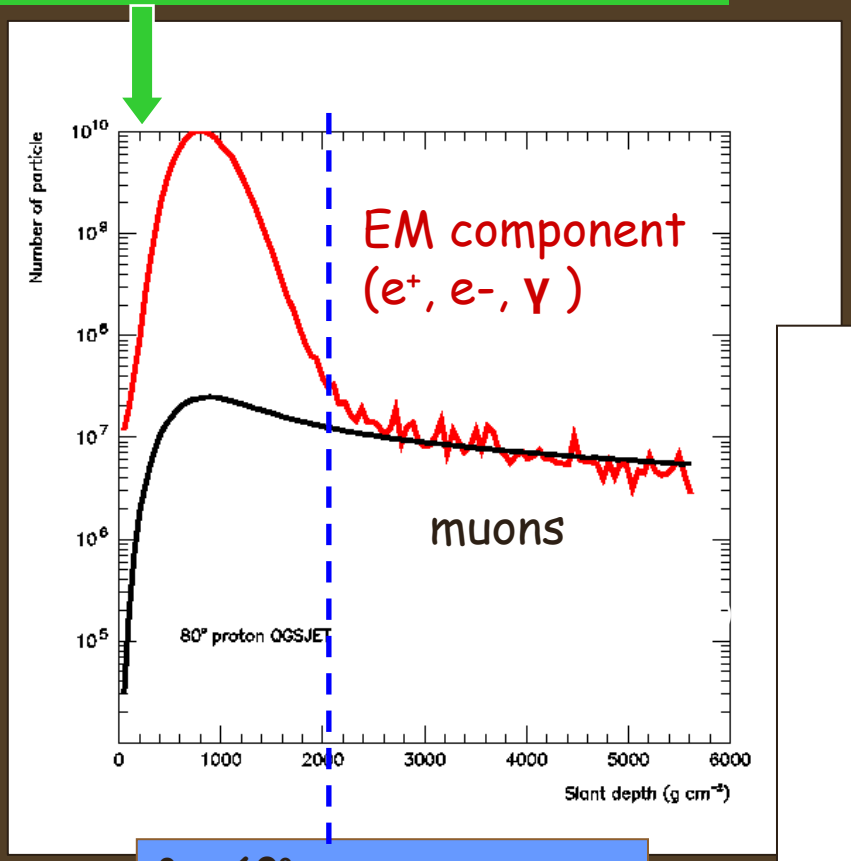
better time fit

better angular resolution (~0.6° for hybrids)

Inclined showers

Shower developpement and composition

Interaction of hadronic primaries: Within first ≈100 gr/cm²



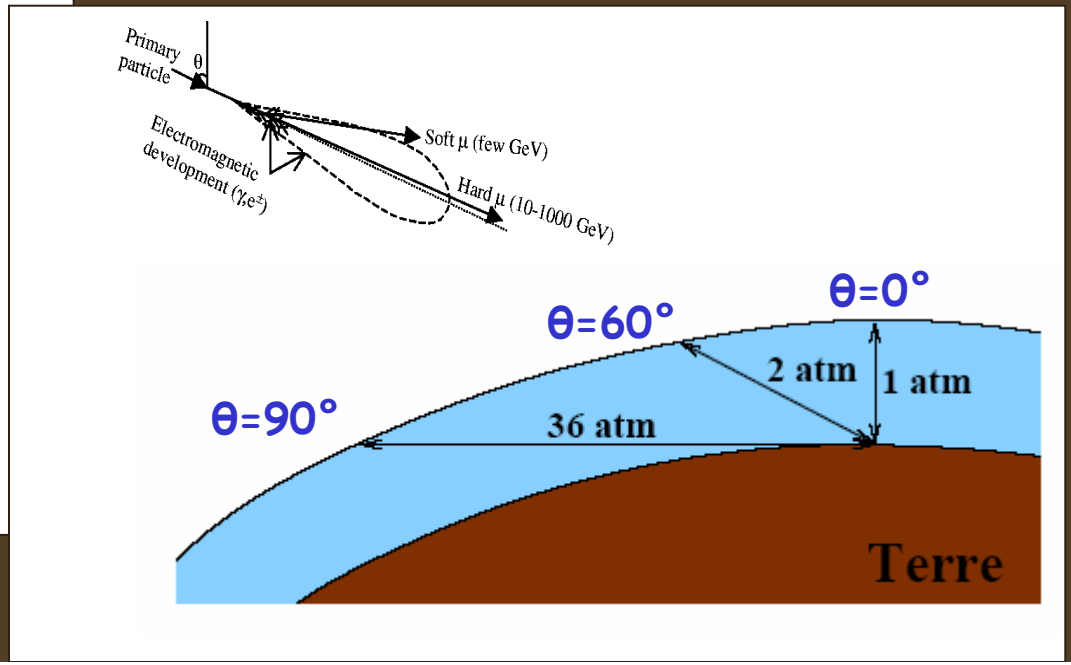
θ = 60° :
X_{sl} = 2 atm ≈ 2000 gr/cm²

θ ≤ 60° : "young" showers

- important EM component (π° decay)
- muons (π± decay)

θ > 60° : "old" showers

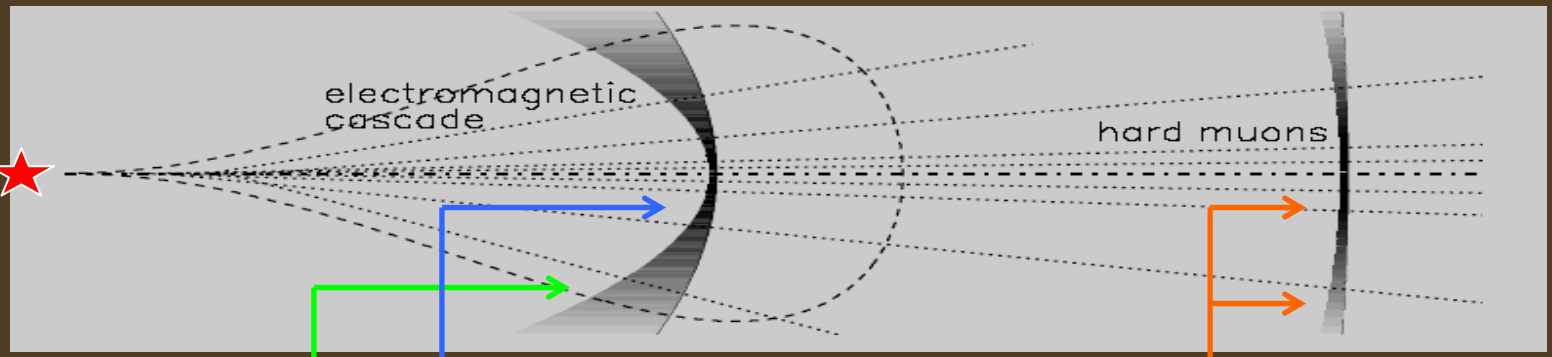
- essentially energetic muons
- EM halo (decay, bremsstrahlung)



Inclined showers

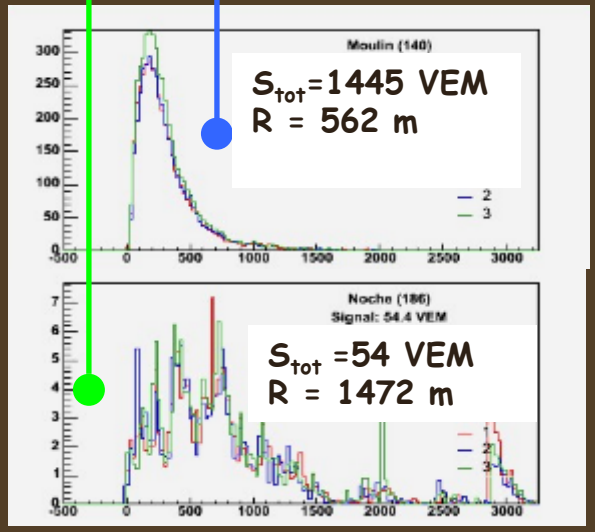
Structure of the signal:

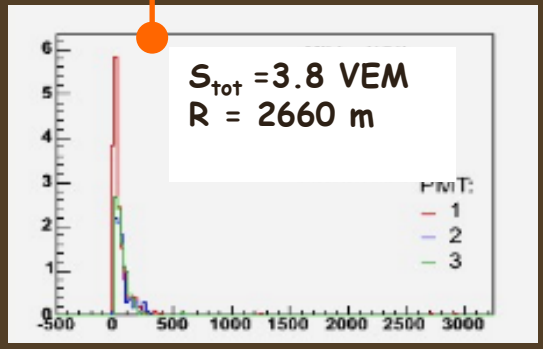
1 atm. 3 atm.



close to the core

far from the core





any distance from core

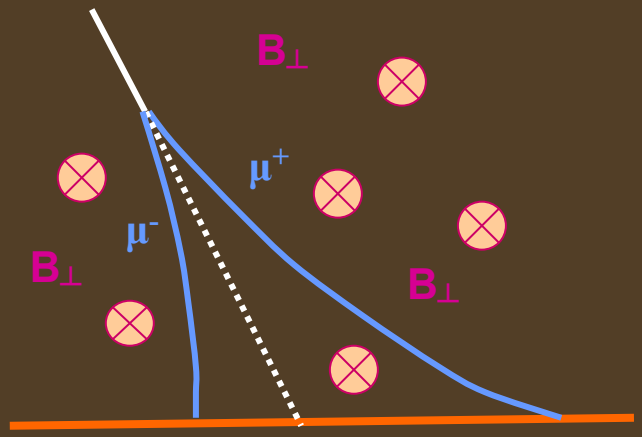
"young" shower :
Curved and thick front
trigger: Th + ToT

"old" shower :
Thin and (nearly-) plane front
trigger: Th only

Inclined showers

- elongated footprint
- early/late asymmetry (geometry & shower development)
- influence of geomagnetic field: lobular structure

…specific analysis tools required… work in progress

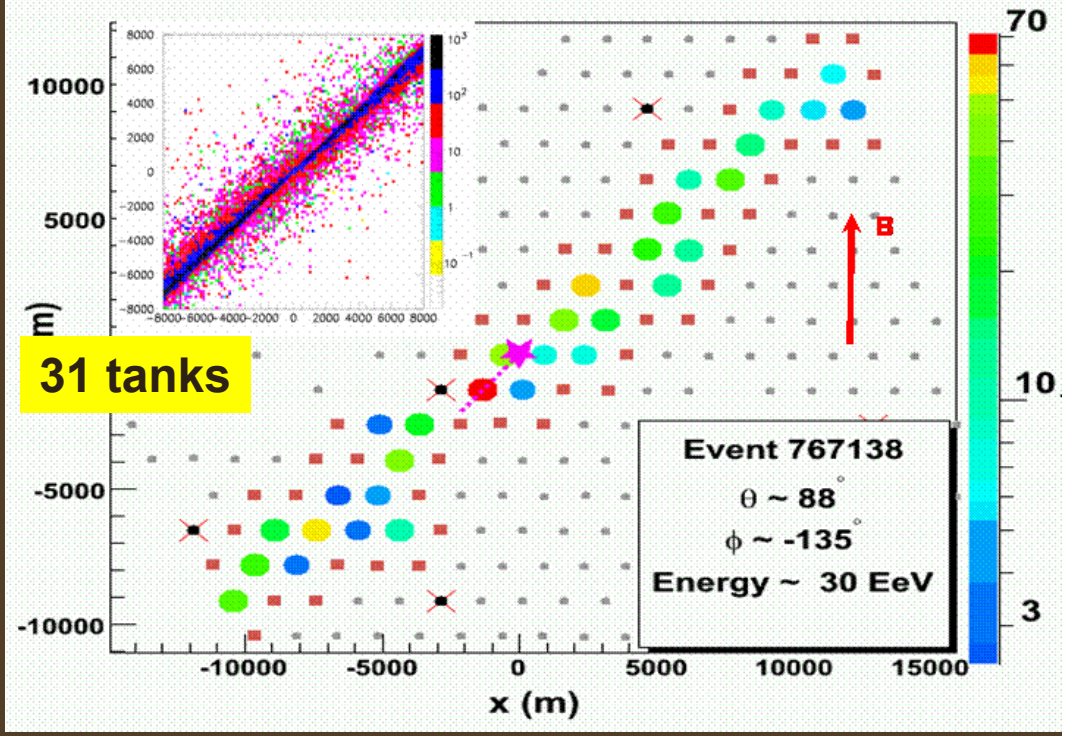


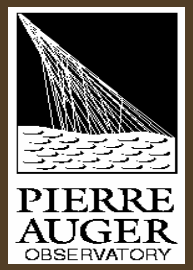
direct access to the muonic component of the shower:

- composition studies
- test of hadronic models

background for neutrino showers (see later)

muon density map (from simulations)
energy estimator = number of muons ("N_{19}")

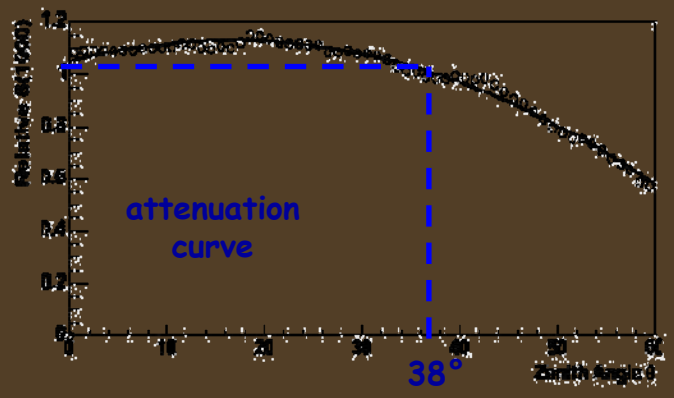




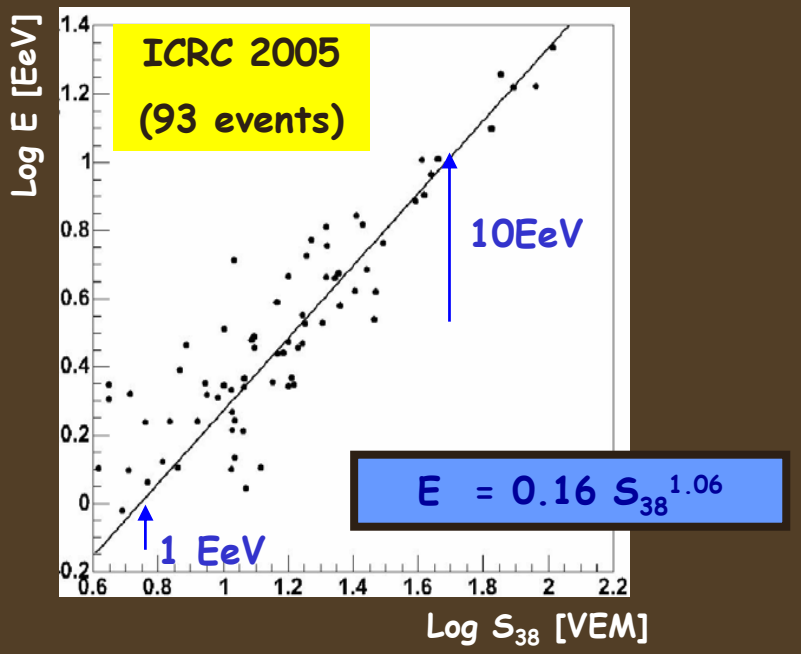
Physics results

The spectrum of cosmic rays above $10^{18.5}$ eV

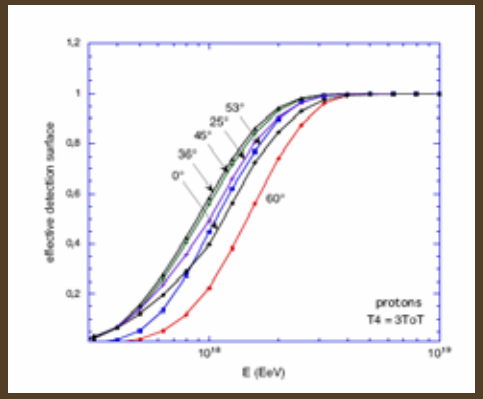
1/ S_{1000} normalized to a reference value:
$S_{38} = S_{1000}(\theta=38°)$
Constant Intensity Cut:



2/ calibration of the SD estimator on the FD energy with good events



❖ SD acceptance saturated above $10^{18.5}$ eV:



with quality cuts:
ICRC 2005:
A = 1750 km² sr yr
end 2006:
A > 4000 km² sr yr

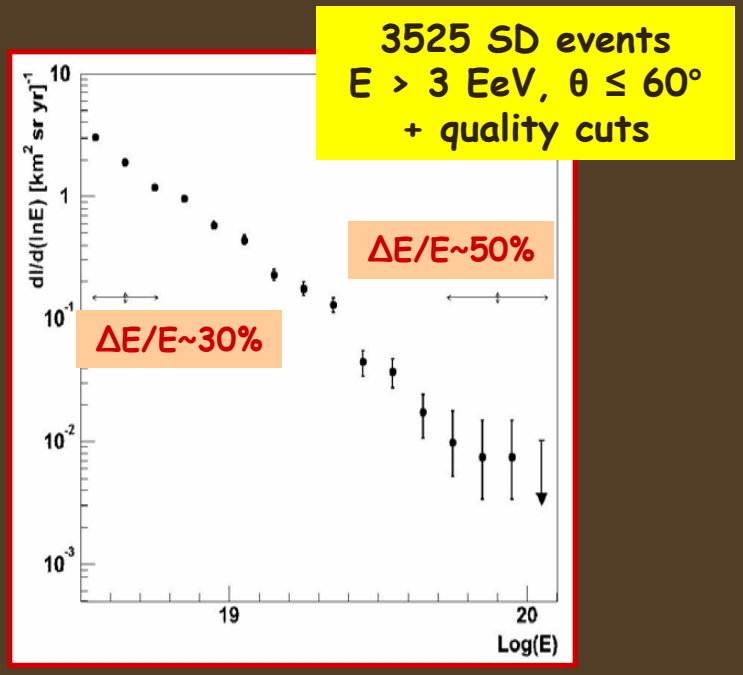
"Golden Hybrid" events:

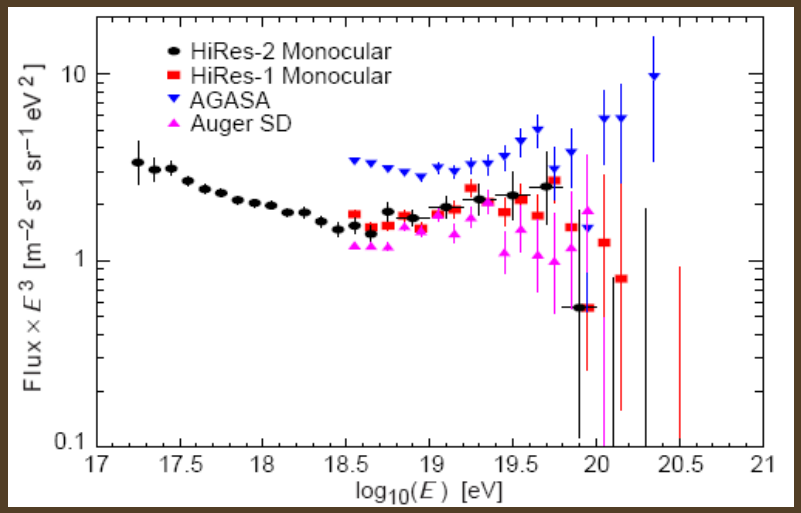
SD
- well-reconstructed core
- θ < 60°

FD
- E_{FD} > 3 x 10^{18} eV
- X_{max} observed
- limited Cherenkov contamination

The spectrum of cosmic rays above $10^{18.5}$ eV

as of ICRC 2005:





- Need more statistics
- Need better estimate of systematic errors:

~25% { FD calibration
atmospheric monitoring
FD energy estimation

  - integrate new data on fluorescence yield (AIRFLY, MACFLY)

~25% { S_{38} -FD conversion

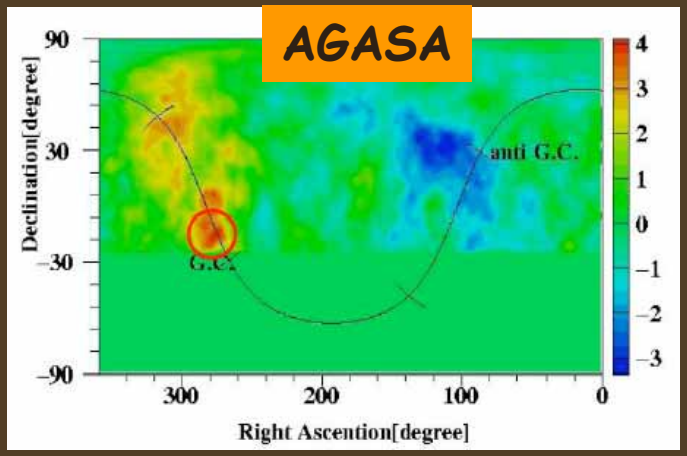
  - validity of "CIC+FD" calibration at high energies ?

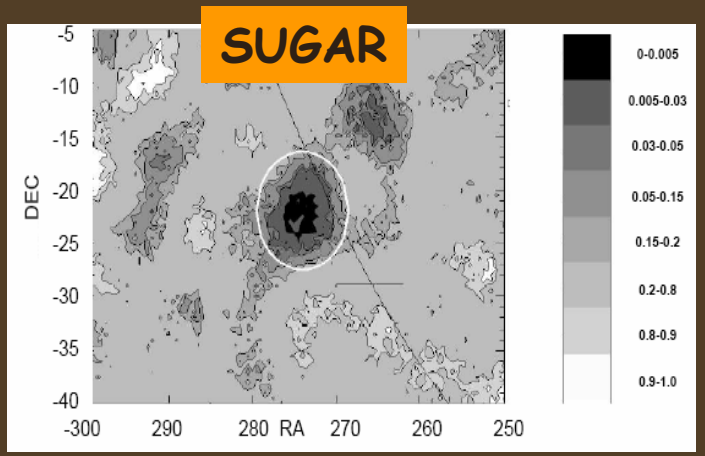
astro-ph/0507150
Proc. 29th ICRC (2005)

Anisotropy searches

❖ E ~ 10^{18} eV: UHE cosmic rays of galactic origin

→ large/small-scale anisotropies associated with Galactic Center or Plane ?





1 EeV < E < 2.5 EeV

20° cone around (-15°,280°)

obs/exp = 506/413.6

22% excess (4.5 σ)

→

0.8 EeV < E < 3.2 EeV

5,5° cone around (-22°,274°)

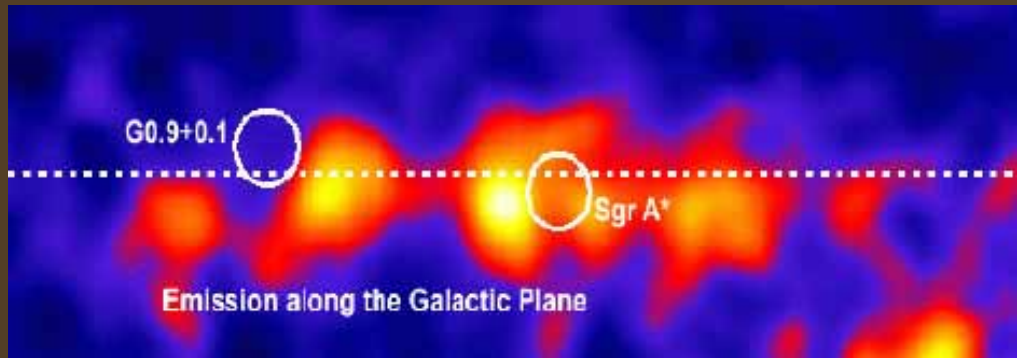
obs/exp = 21.8/11.8

85% excess (2.9 σ)

❖ HESS 2004: observation of TeV gamma-ray emission near GC

→ prediction of associated UHE neutron flux

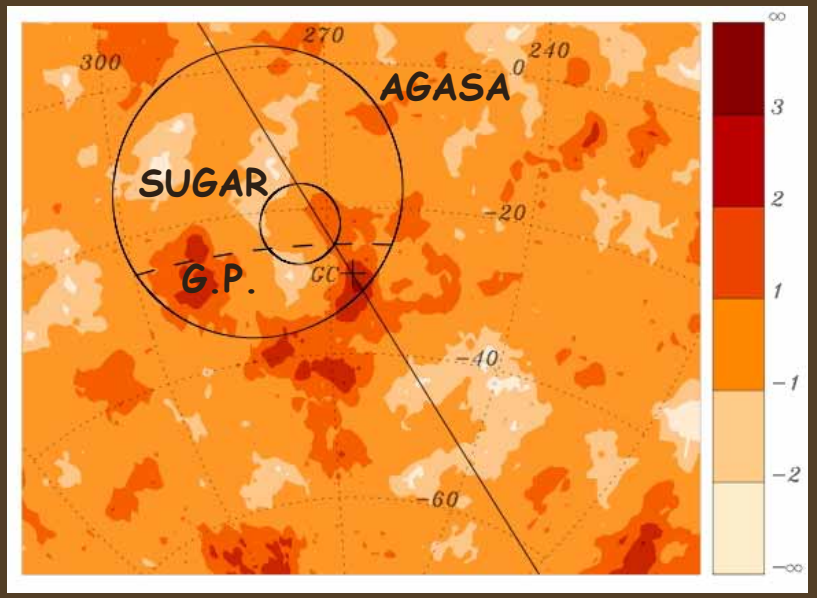
(λ_n ~ distance(GC-Earth) at E~EeV)



Anisotropy searches

❖ **Around the Galactic Center/Plane:**

5°, top-hat



- test of AGASA: obs/exp = 2116/2159.5
  R = 0.98 ± 0.02 ± 0.01
  NOT CONFIRMED (with 3x more stats)
- test of SUGAR: obs/exp = 286/289.7
  R = 0.98 ± 0.06 ± 0.01
  NOT CONFIRMED (with 10x more stats)
- Galactic Center as a point source (σ=1.5°):
  obs/exp = 53.8/45.8
  R = 1.17 ± 0.10 ± 0.01
  NO SIGNIFICANT EXCESS

upper limit on the flux of neutrons coming from GC:

$\Phi_s < 0.08\ \xi\ km^{-2}\ yr^{-1}$ at 95% C.L.

astro-ph/0607382
(Astropart. Phys., 2007)

- Galactic Plane: NO SIGNIFICANT EXCESS

❖ **All-sky blind searches:** NO EXCESS FOUND

❖ **Other searches on prescriptions:** NO EXCESS FOUND
(predefined targets & statistical significance: NGC253, NGC3256, Cen A)

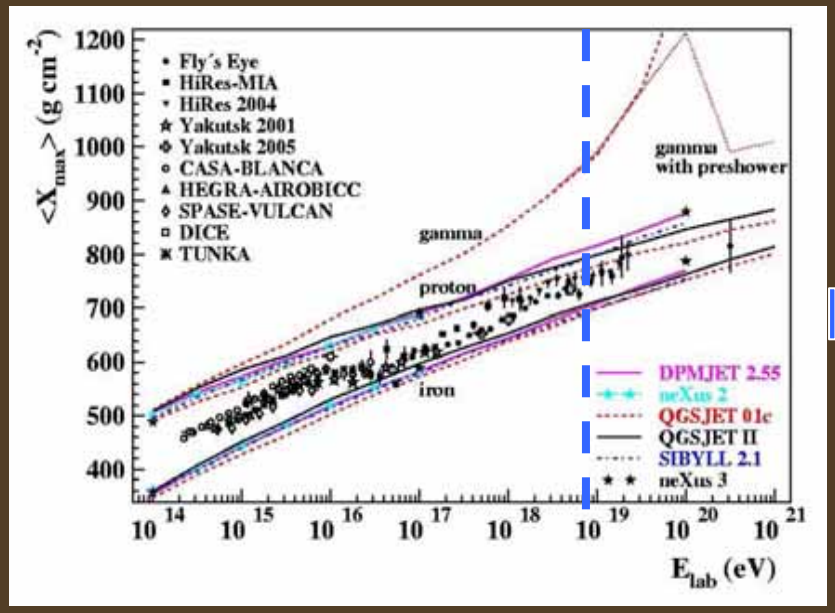
Limit on the UHE photon fraction

❖ **Top-down models predict abundant fluxes of UHE photons (& neutrinos)**
existing limits from Surface Detectors only (Haverah Park, AGASA)

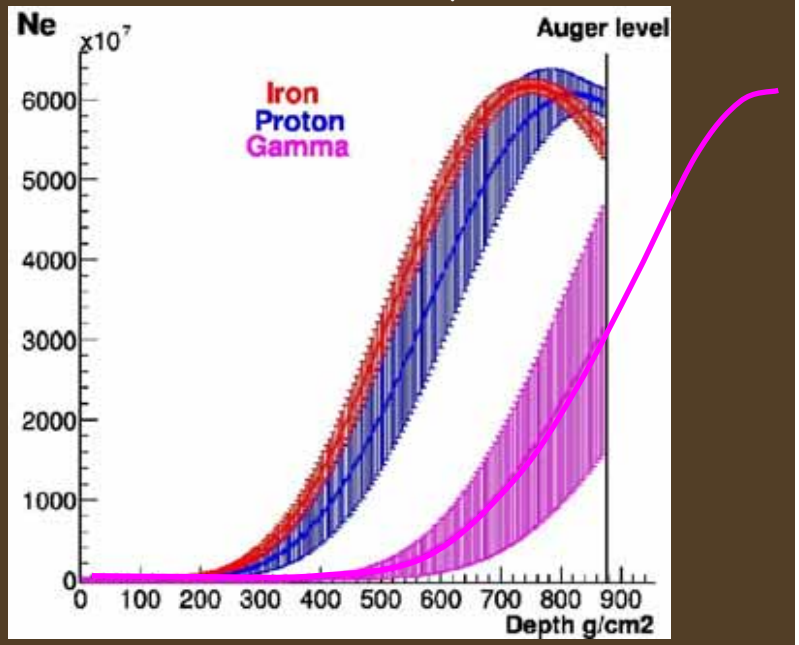
Auger approach: use hybrid events
direct observation of the **shower longitudinal profile**

discriminating variable:
X_{max} = **elongation rate** (depth of the shower maximum)
depends on primary **energy** and **composition**

photon shower delayed w.r.t. hadron one:
$\Delta x_{max} > 200$ gr/cm^2 at 10^{19} eV



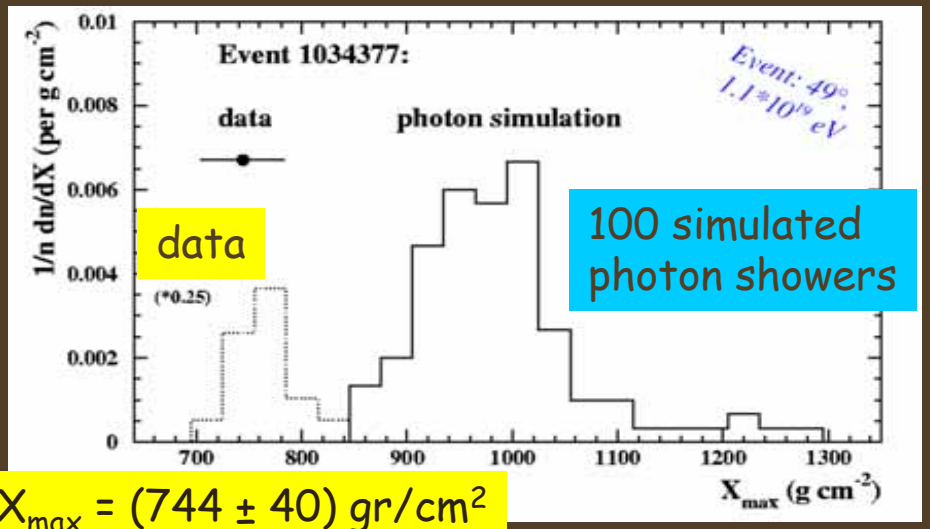
Shower at E = 10^{19} eV, θ = 0° :



Limit on the UHE photon fraction

Dataset: hybrid events, $E_{FD} > 10^{19}$ eV
+ $35° \leq \theta \leq 60°$
+ quality cuts

16 selected events (Jan 2004 – Feb 2006)

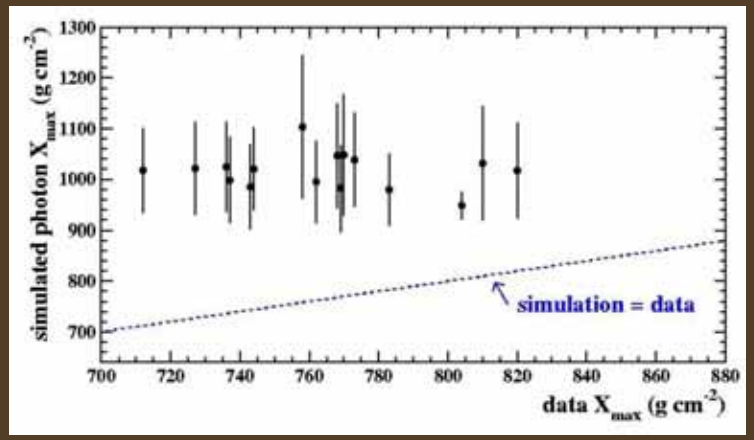


data

100 simulated photon showers

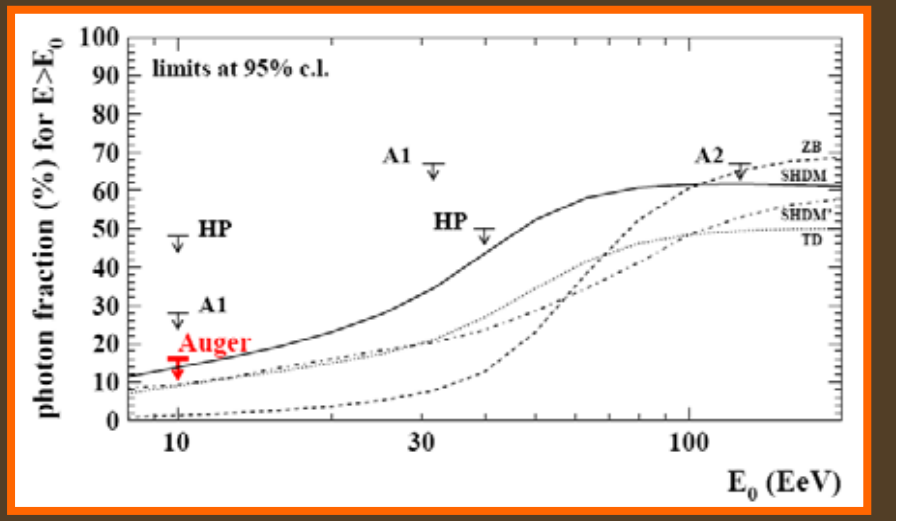
X_{max} = (744 ± 40) gr/cm^2

$\langle X_{max} \rangle$ = (1020 ± 80) gr/cm^2



No candidate photon:
strongest limit for $E \geq 10^{19}$ eV

F(photon) < 0.16 at 95% C.L.



astro-ph/0606619
Astropart. Phys.27, 155-168 (2007)

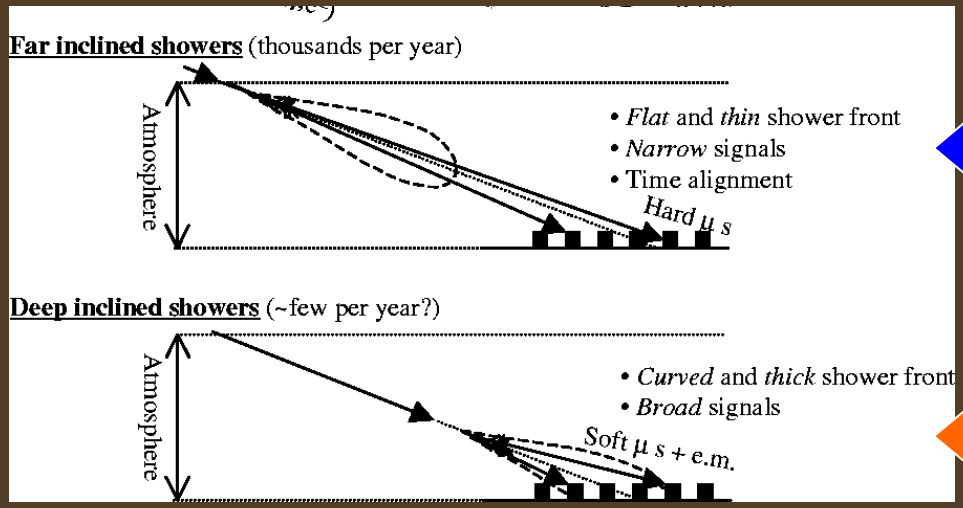
UHE neutrinos in Auger

Principle of detection:

- UHE Cosmic neutrinos: by-product in most acceleration and exotic models
  "guaranteed" flux : cosmogenic neutrinos (< 10 km^{-2} sr^{-1} yr^{-1} at 10^{18} eV)
  (GZK interactions of UHE cosmic rays)

small cross-section: uniform interaction probability at all depths

→ look for YOUNG and INCLINED showers:
easy identification at large θ



↔ Hadron (or photon) primary:
only energetic muons

↔ Neutrino primary:
muons + large EM component

at production site:
ν_e & ν_μ

oscillations →

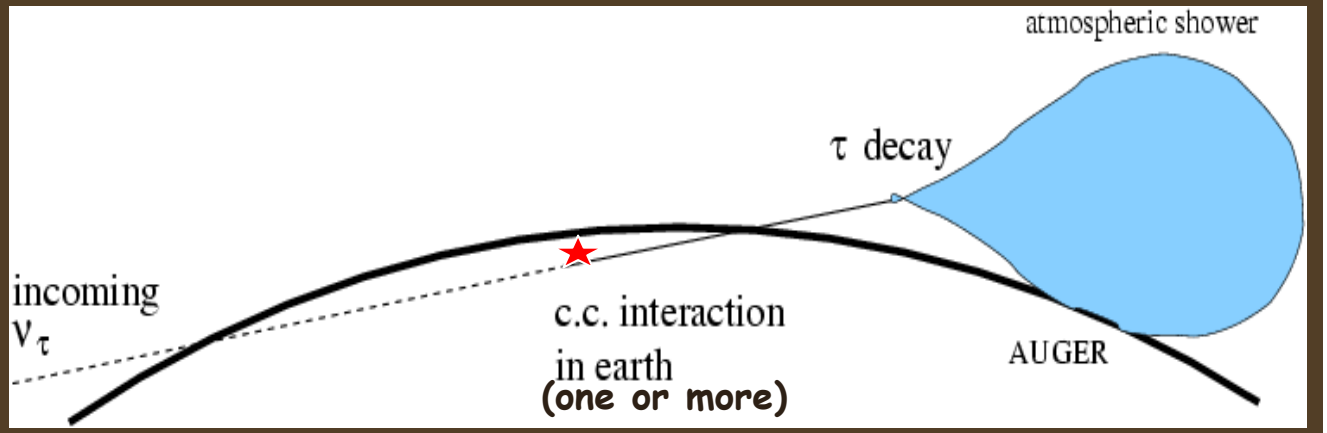
on Earth:
ν_e & ν_μ & ν_τ
1 : 1 : 1

UHE Earth-skimming tau neutrinos

Most promising signal:

upward-going ("Earth-skimming") ν_τ

~15% more sensitivity than down-going ν's in the range 10^{17} – 10^{19} eV



at 1 EeV: $L_{int}(\nu) \sim 500$ km $L_{decay}(\tau) \sim 50$ km $L_{Eloss}(\tau) \sim 30$ km

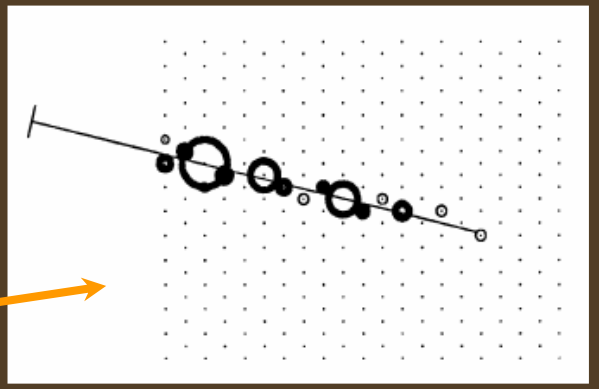
☹ **limited range in θ: Earth opaque for θ≥95°**

☺ **possibility of ν_τ regeneration**

ν_τ simulation chain:

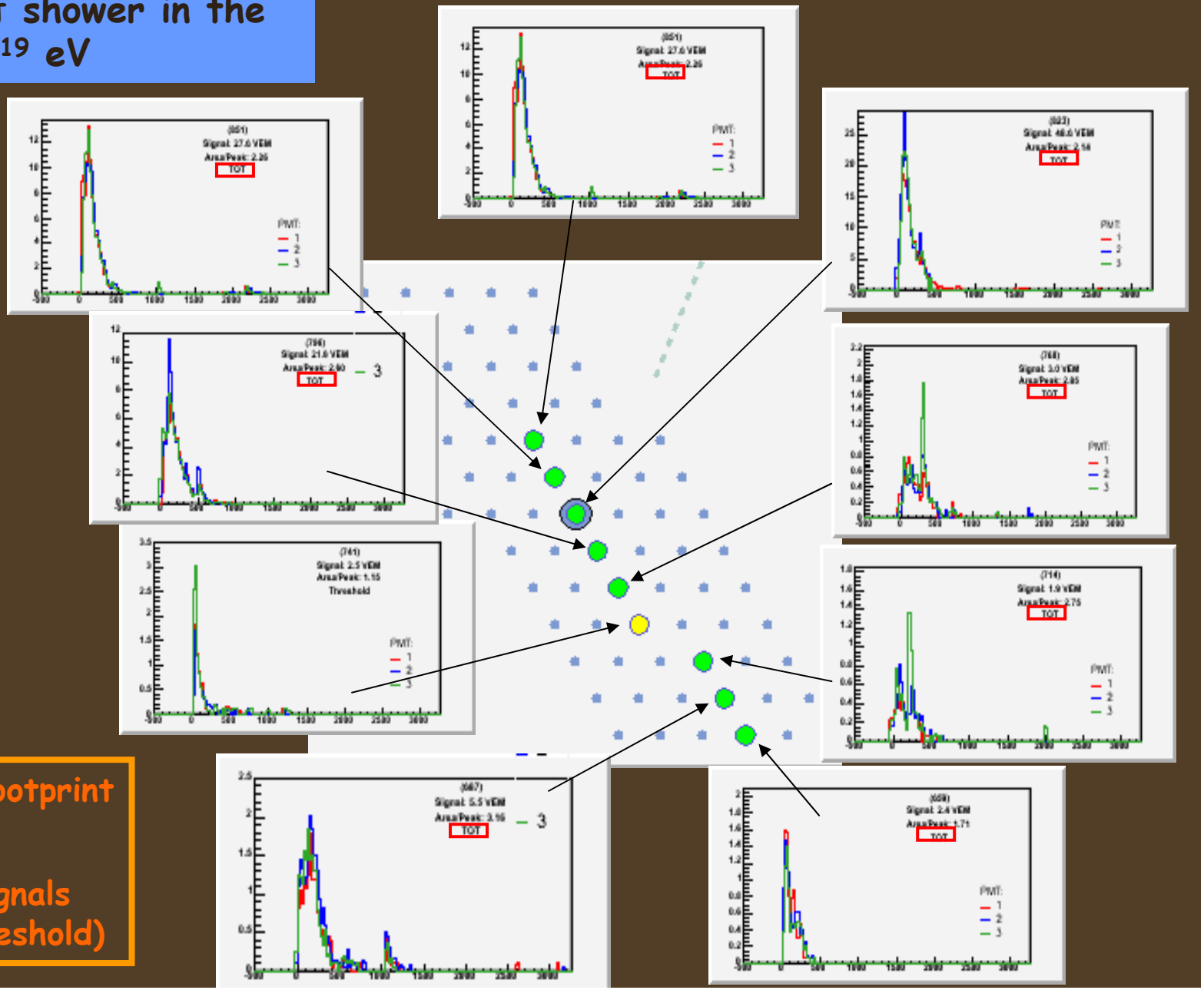
- incident flux at 10^{17} eV ≤ E ≤ 10^{20} eV, θ ≈ 90° (within few degs.)
- coupled transport equations for τ/ν_τ propagation across the Earth crust:
  - ν_τ NC/CC interactions
  - τ NC/CC interactions, decay and energy losses

  (allows for multiple τ/ν_τ regeneration)
- if τ emerges: simulate decay in atmosphere



UHE Earth-skimming tau neutrinos

A simulated τ shower in the θ=91°, E=10^{19} eV

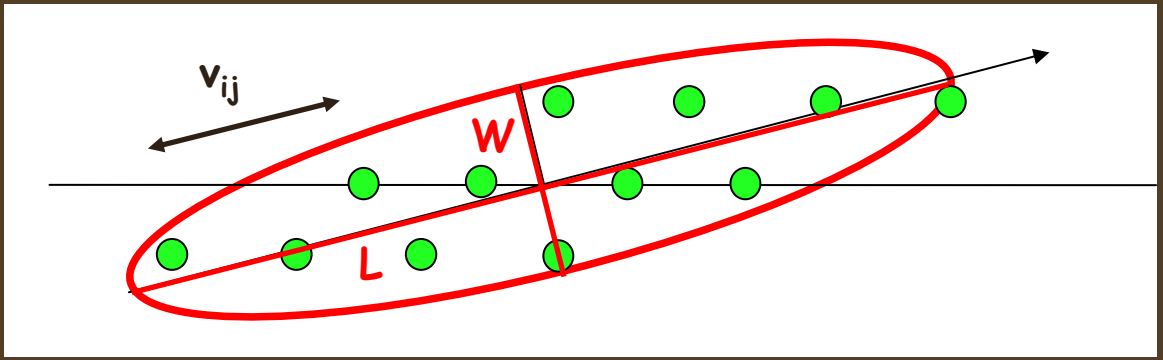


- elongated footprint with "holes"
- extended signals (time over threshold)

UHE Earth-skimming tau neutrinos

SD selection criteria

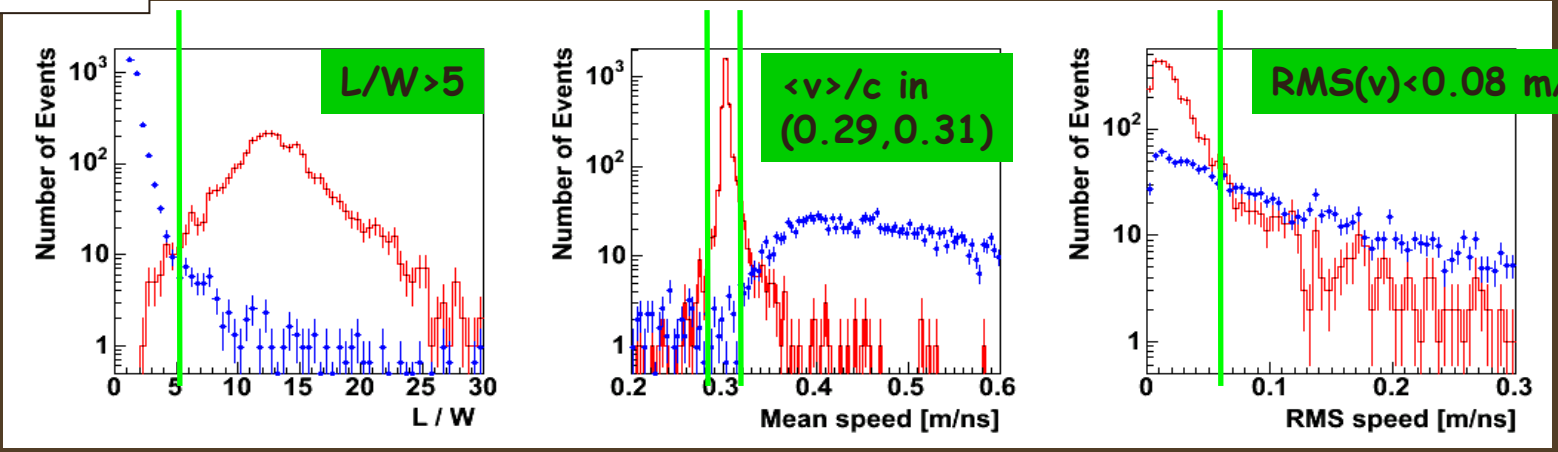
- ❖ presence of ToT-triggering stations
- ❖ elongated shape of the footprint



- Moments of inertia (weighted by signal)→ minor (W) and major (L) axis
- Signal transmission compatible with a plane front moving at the speed of light: <v>~c

data
simulated
tau showers

~80-90% selection efficiency on raw data + excellent discrimination power !



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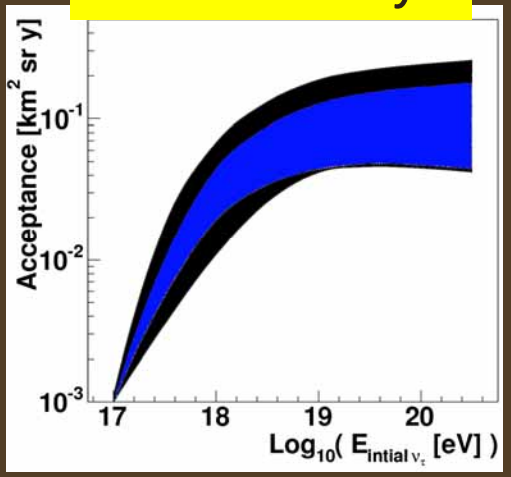
Systematics factor ~6.3 between worse/best estimations…

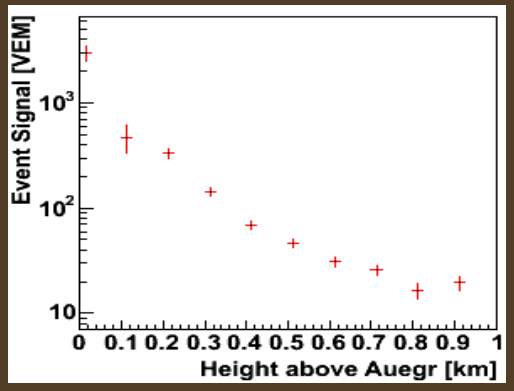
➢ MC simulations:	- propagation in Earth	5%
	- shower development	17%
	- detector	5%
➢ Detector:	- geography	20%
	- acceptance	3%
➢ Theory:	- tau polarisation	30%
	- cross-sections	15%
	- tau energy losses	263%

! Preliminary !

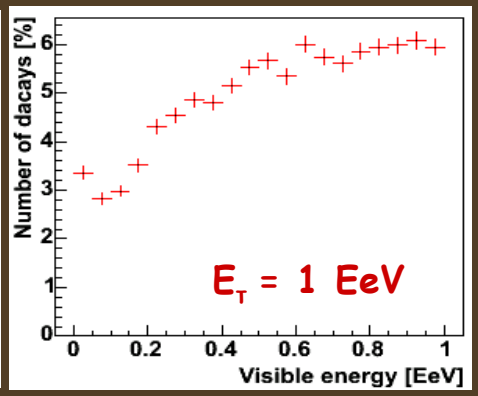


❖ No energy reconstruction procedure (yet ?):

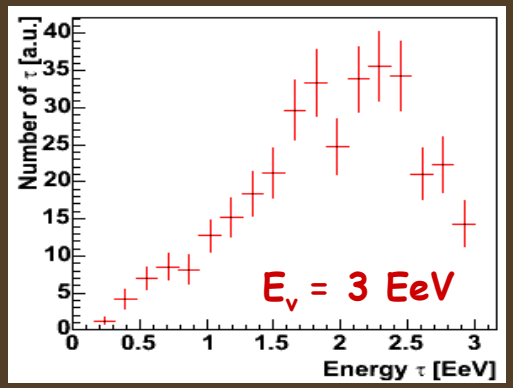
Uncertainty in position of the shower axis



uncertainty in visible energy of shower



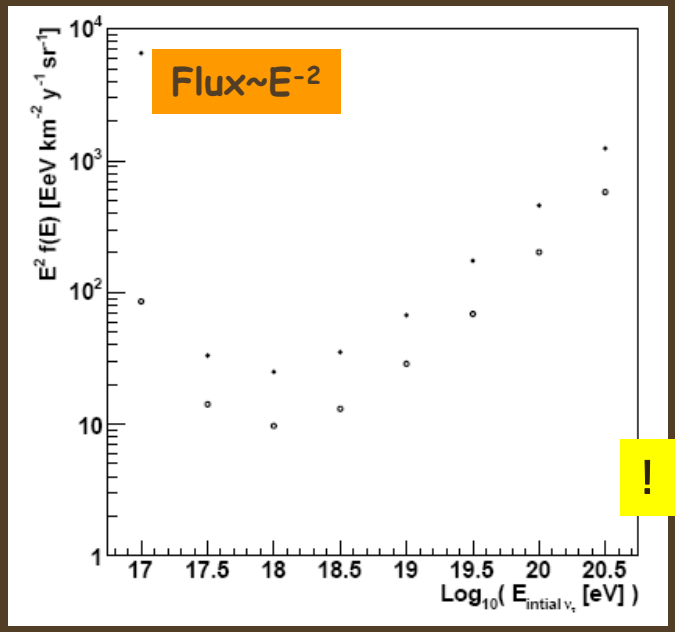
dispersion in energy of emerging tau



Shower energy → Tau energy → Neutrino energy

UHE tau neutrinos in Auger

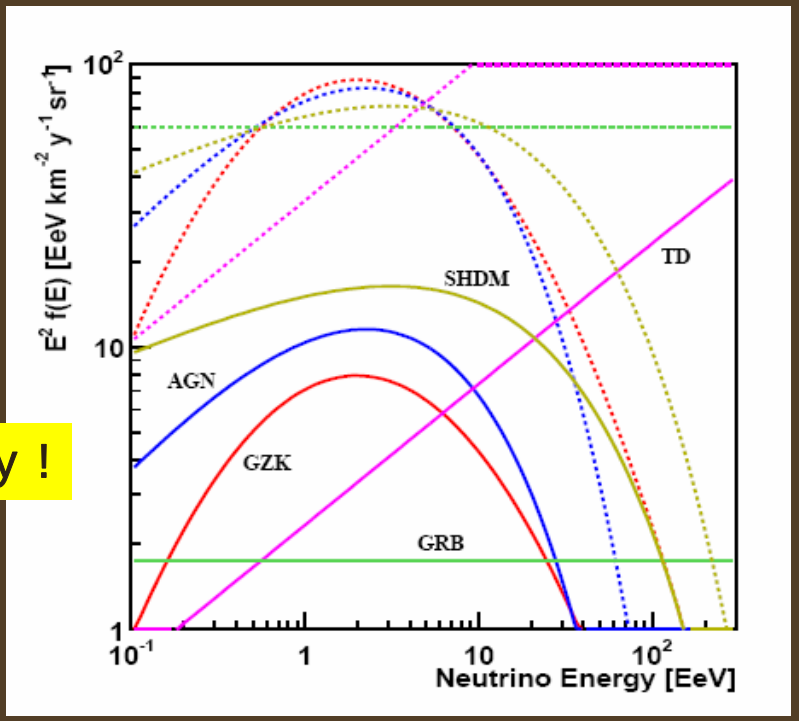
Sensitivity



1 event/yr/decade of energy

! Preliminary !

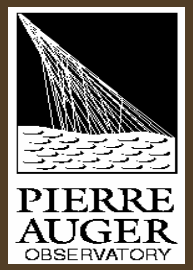
Projected bound



0 event

dashed: upper bounds at 90% C.L. for 1 yr of full Auger

most pessimistic evaluation of systematic errors...



Conclusions

- More than 2/3 Southern Auger Observatory now active

→ …expected completion in 2007; statistics x7 in 2 years

- Less than a full Auger-year exposure led to first physics results:
  - a strategy for an empirical study of the UHECR spectrum (CIC+FD)

→ improve energy assignment

→ start studies in GZK region

→ interpret the difference between SD/hybrid spectra

  - small-scale anisotropy studies

→ affine the anisotropy searches and extend to all scales; (AUGER North needed !!)

  - limit on photon fraction

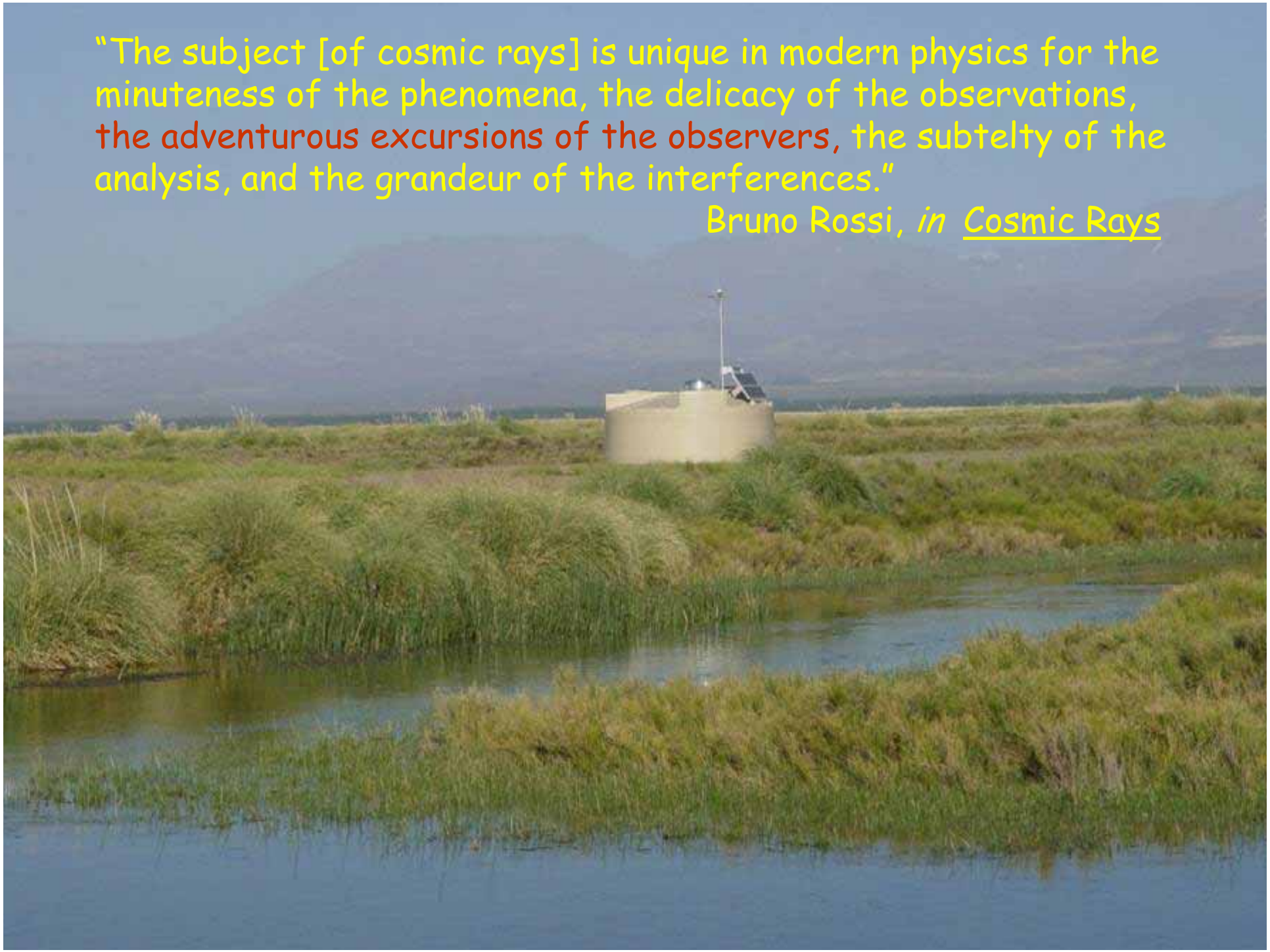
→ improve & develop methods for composition studies (with SD/FD)

- Inclined/horizontal events demonstrated physical relevance:

-Auger is sensitive to UHEv !!!

→ improve selection/reconstruction procedures for hadrons & v's

use inclined showers muon content for composition studies ?


"The subject [of cosmic rays] is unique in modern physics for the minuteness of the phenomena, the delicacy of the observations, the adventurous excursions of the observers, the subtelty of the analysis, and the grandeur of the interferences."
Bruno Rossi, *in* Cosmic Rays