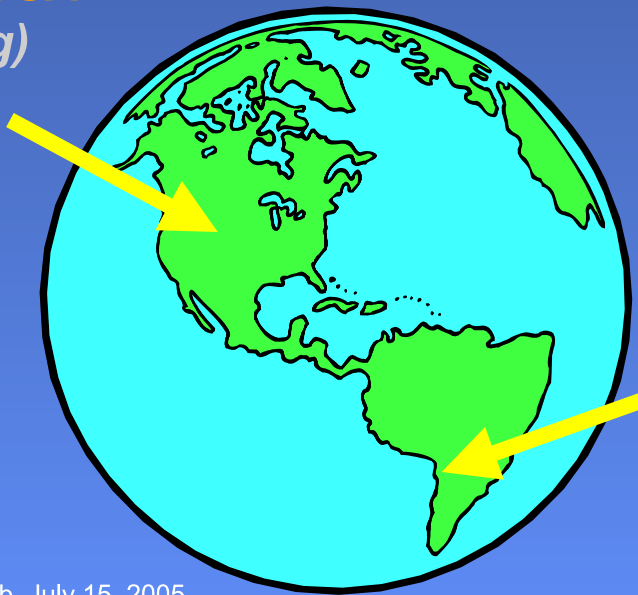
First Results from the Pierre Auger Project

A new cosmic ray observatory designed for a high statistics study of the **the Highest Energy Cosmic Rays.**

Aaron S. Chou (FNAL)
for the Pierre Auger Collaboration

Colorado, USA
(in planning)



Mendoza, Argentina
(construction underway)

Outline

- Description of the Experiment
  - Goals
  - Operation
  - Performance
- The Model-Independent Energy Spectrum
- Anisotropy results
- Photon fraction limit

The Auger Collaboration

Participating Countries

Argentina
Australia
Bolivia*
Brazil
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Slovenia
Spain
United Kingdom
USA
Vietnam*

****Associate***

63 Institutions,
369 Collaborators

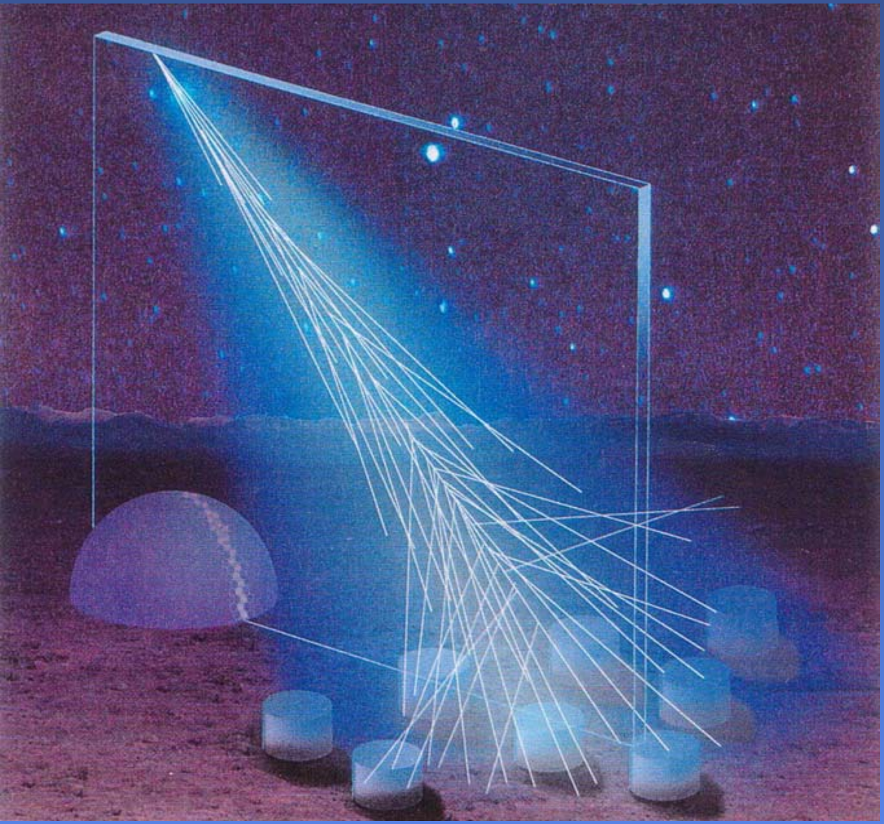
Science Objectives

- Cosmic ray spectrum above 10^{19} eV (= 10 EeV)
  - *Measure the shape of the spectrum in the region of the GZK feature*
    - Spectrum is predicted to be sharply attenuated at E>5 10^{19} eV due to scattering on CMB photons
- Arrival direction distribution
  - *Search for departure from isotropy – point sources*
- Composition
  - *Light or heavy nuclei, photons, exotics?*

Design Features

- High statistics (aperture >7000 km^2 sr above 10^{19}eV in each hemisphere) → Actual threshold 3 10^{18}eV
- Hybrid configuration –surface array with fluorescence detector coverage
- Full sky coverage with uniform exposure

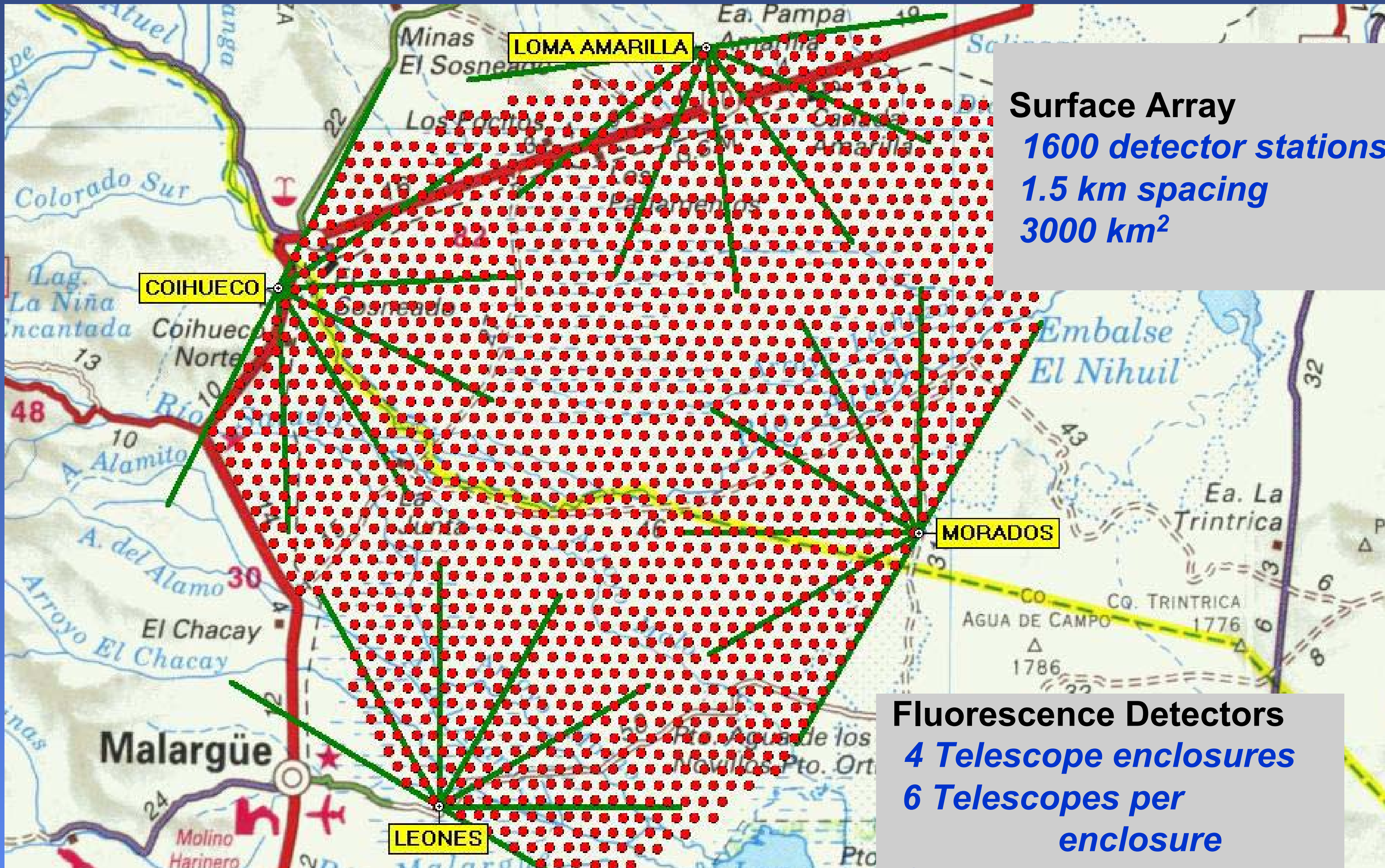
The Hybrid Design



*A large **surface detector array** combined with **air fluorescence detectors** results in the unique and powerful design*

- **Simultaneous shower measurement allows for transfer of the nearly calorimetric energy calibration from the fluorescence detector to the event gathering power of the surface array.**
  - **FD duty cycle ~10%**
  - **SD duty cycle ~100%**
- **Different measurement techniques force understanding of systematic uncertainties in each.**
- **Reconstruction synergy for precise measurements in hybrid events.**
- **A complementary set of mass sensitive shower parameters contributes to the identification of primary composition.**

The Observatory Plan



Surface Array

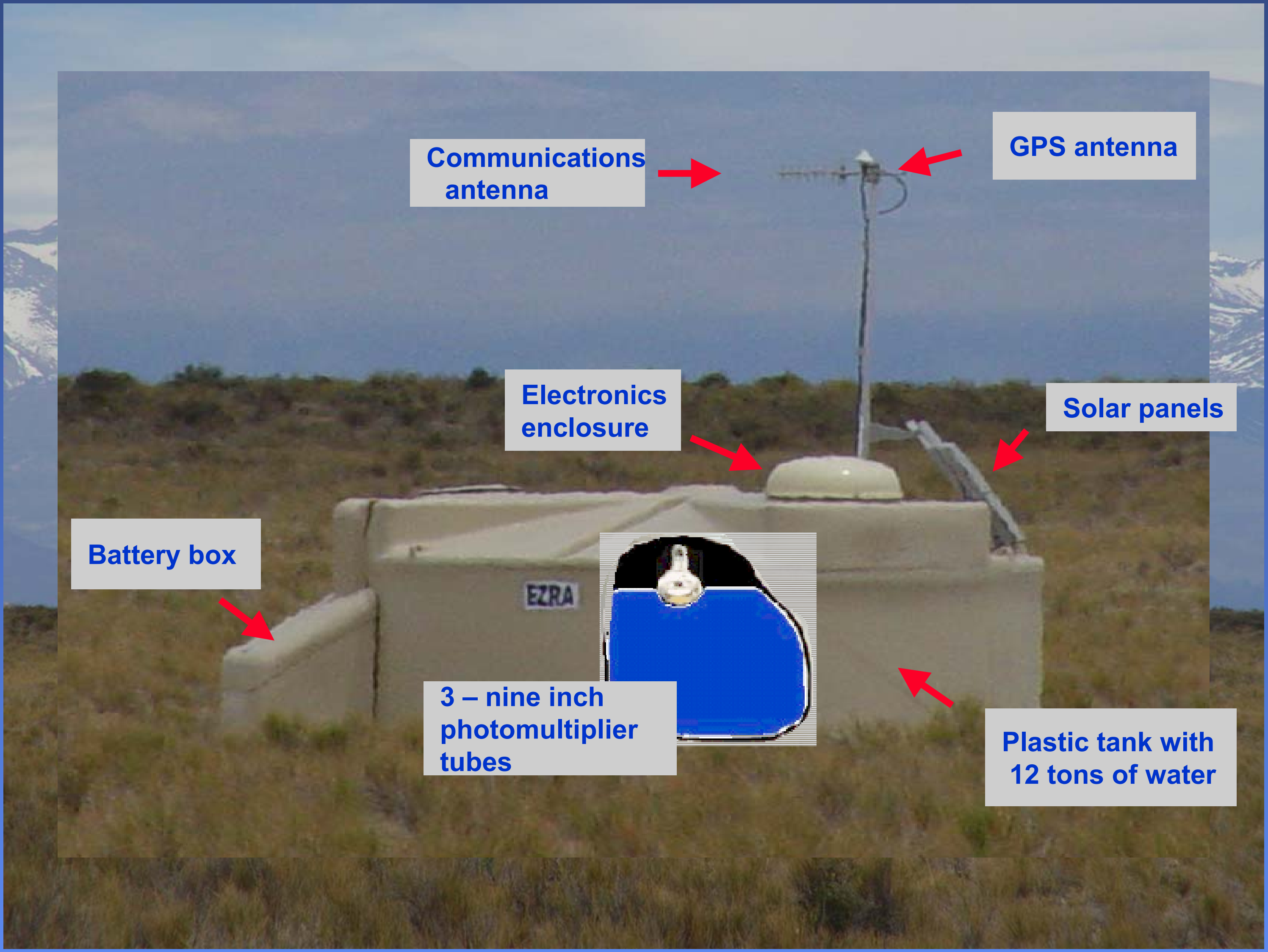
- ***1600 detector stations***
- ***1.5 km spacing***
- ***3000 km^2***

Fluorescence Detectors

- ***4 Telescope enclosures***
- ***6 Telescopes per enclosure***
- ***24 Telescopes total***

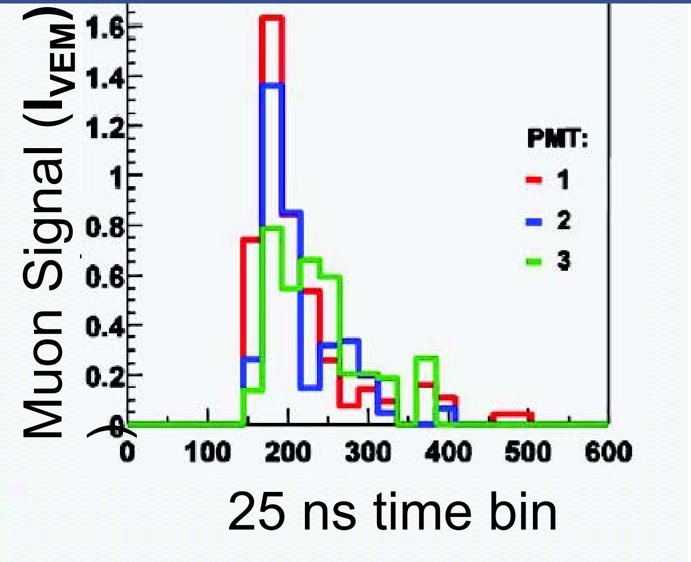
The Surface Array

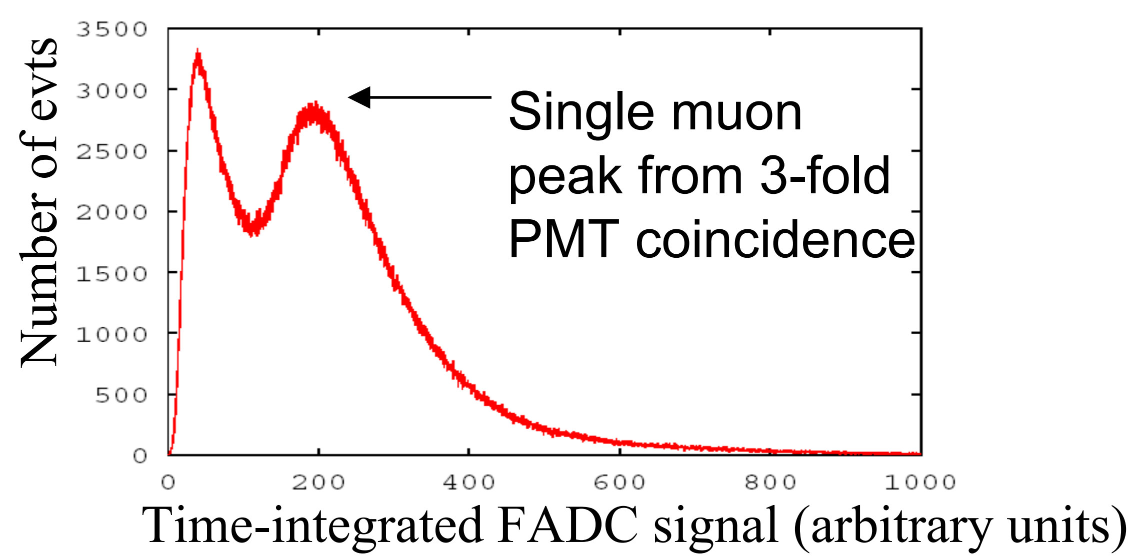
Detector Station



Surface Detector Deployment

SD tanks are self-calibrating (Atmospheric muons used as a standard candle)

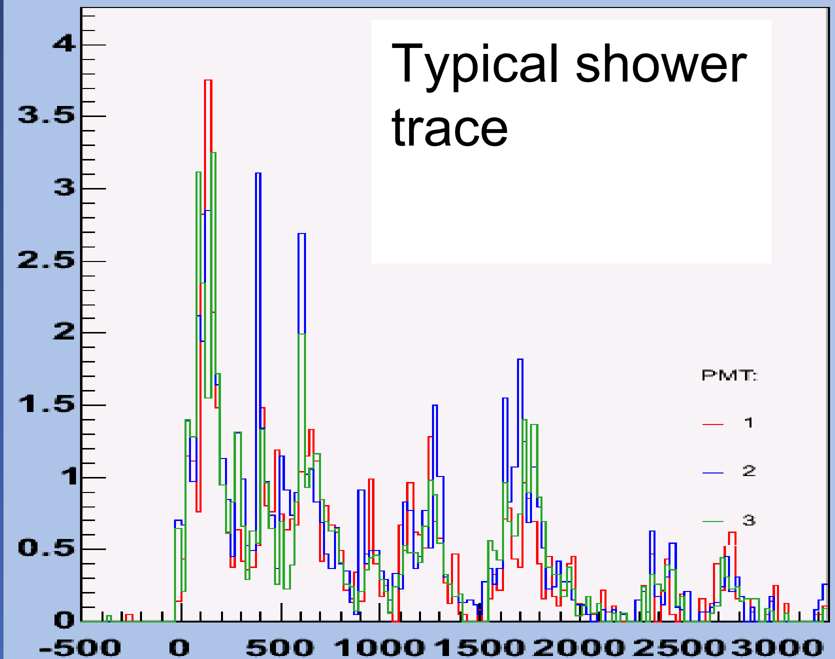


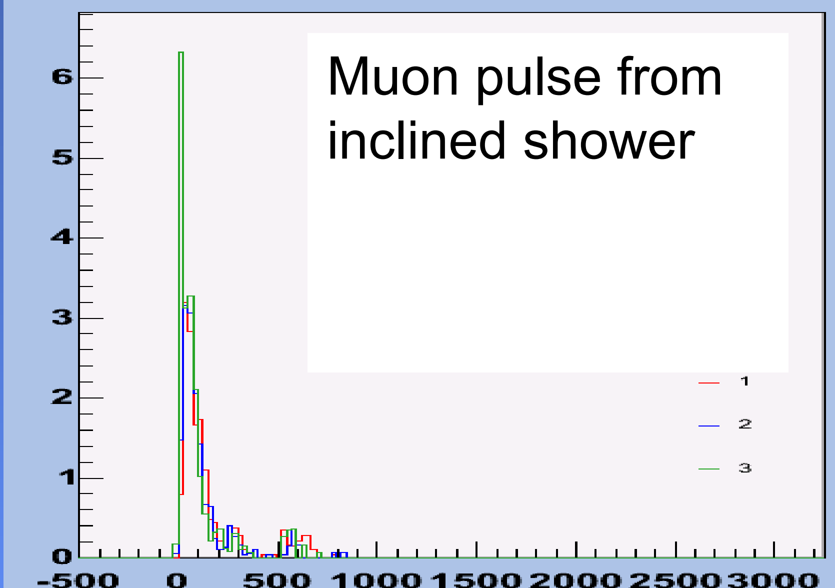


- Measure all signals in Vertical Equivalent Muon units (VEM).
- Trigger thresholds expressed in instantaneous current I_{VEM}
  - Dynamic range 0-700 I_{VEM}
- Time-integrated signals for energy measurement expressed in Q_{VEM}

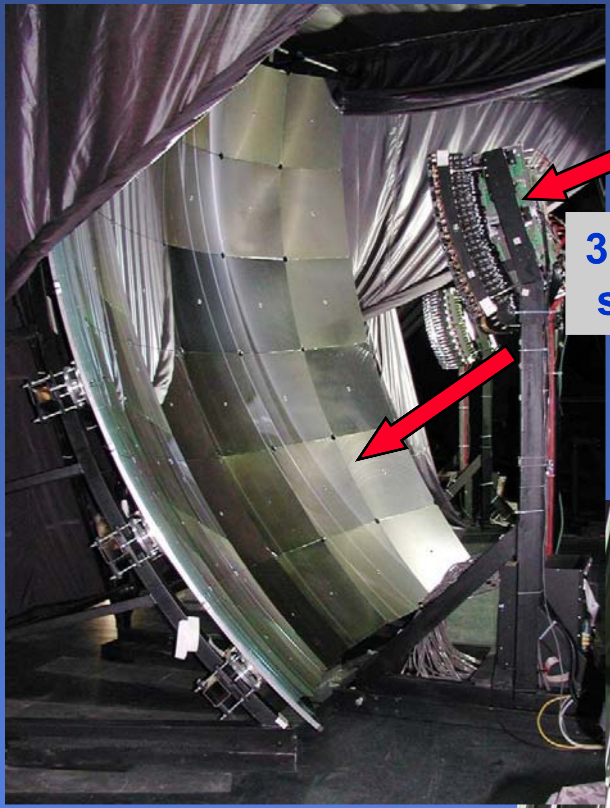
SD triggers

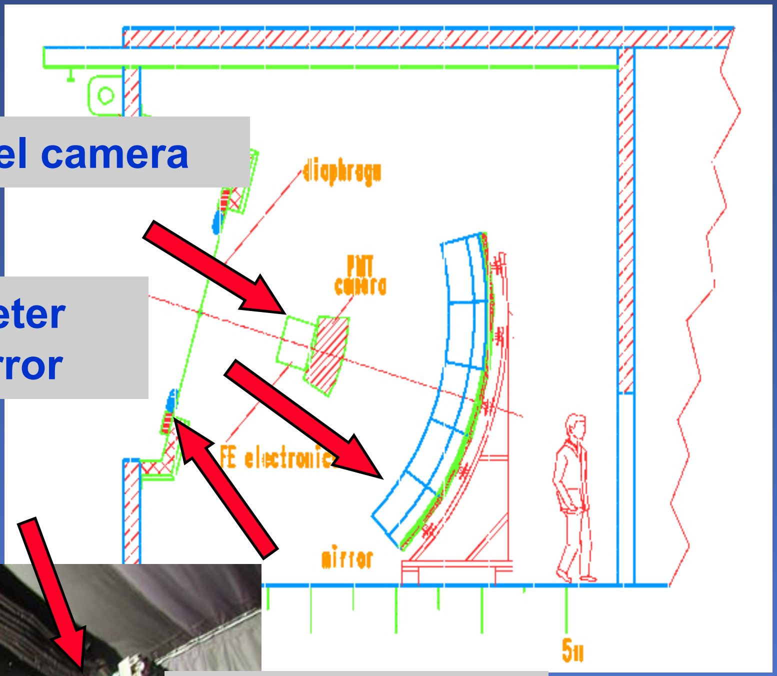
- Time-over-threshold (TOT) 1-5Hz
  - Long signals
- Threshold 20Hz
  - Fast signals (inclined showers)
- Central trigger, rate~3000/day
  - look for topologically clustered triggered tanks
- Event selection (for current spectrum analysis)
  - look for at least 3 TOT triggers in a compact configuration
  - ~600/day   (~0.9/tank/day)





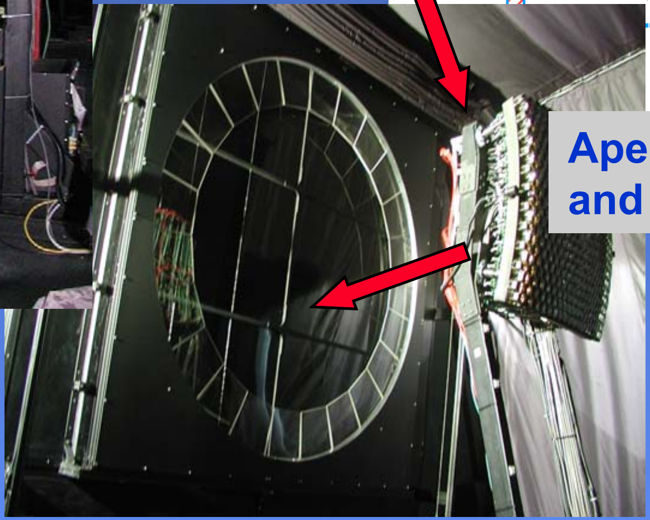
The Fluorescence Detector





440 pixel camera

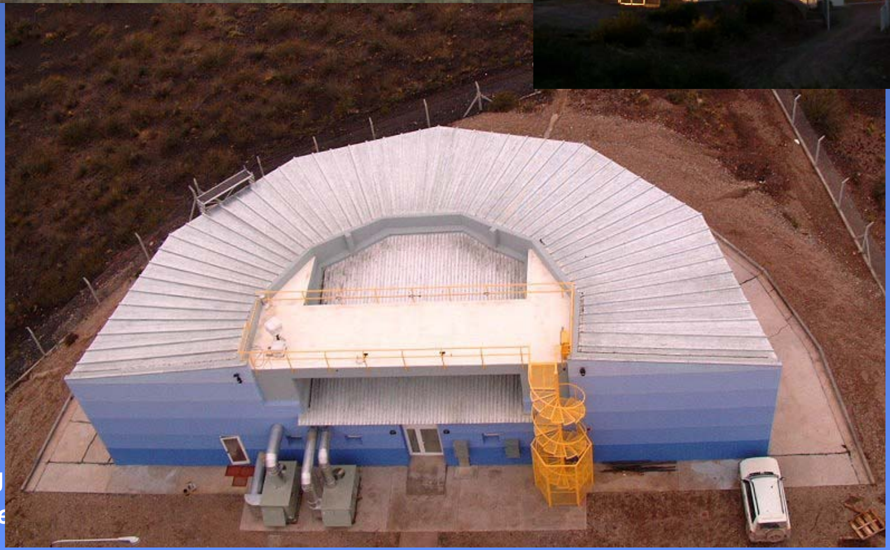
3.4 meter diameter segmented mirror



Aperture stop and optical filter

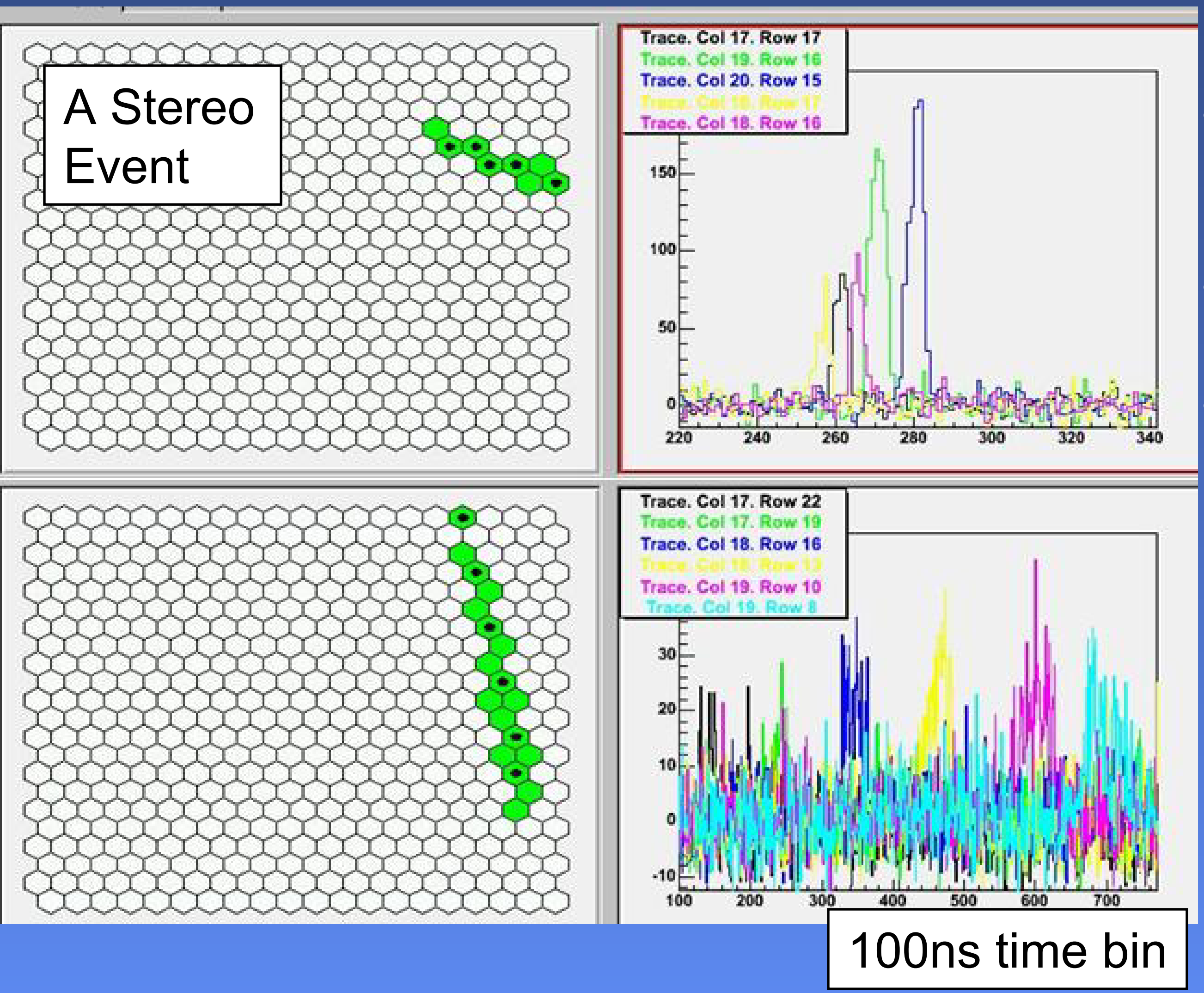
The Fluorescence Detector

Los Leones



30 deg x 30 deg x 30 km field of view per eye

FD Triggers



- Threshold trigger on individual pixels
- Look for “tracks”
  - 1 Hz trigger rate per 6 cameras
- Multi-camera events merged within 2 sec
- Geometry recon within 5 sec, and passed to central data acquisition system
  - Induces SD readout of tanks within range.
  - Obtain “Hybrid” events with both longitudinal and transverse shower information.

Atmospheric Monitoring and Fluorescence Detector Calibration

Atmospheric Monitoring

Central Laser Facility (laser optically linked to adjacent surface detector tank)

- Atmospheric monitoring
- Calibration checks
- Timing checks

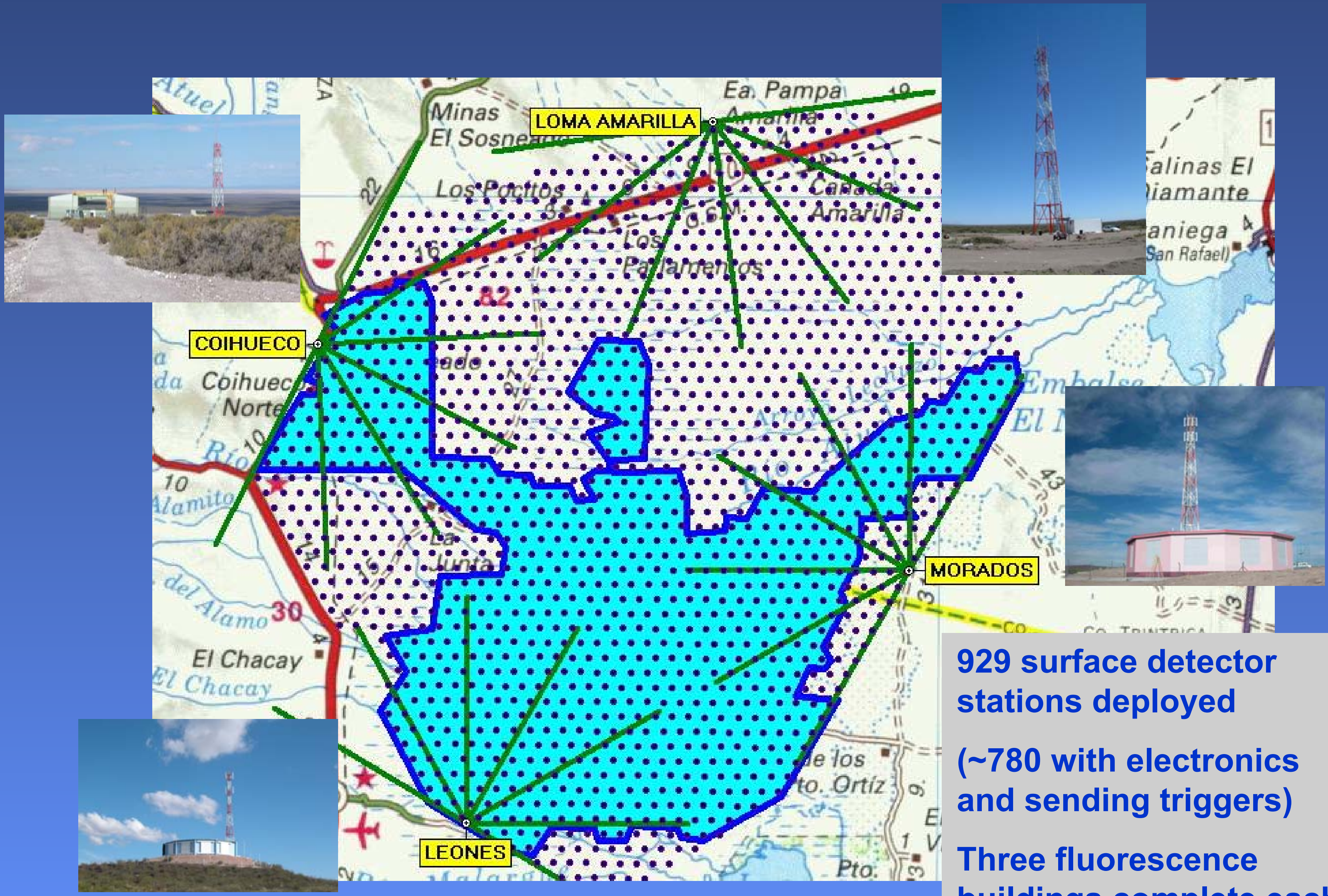
Absolute Calibration

Drum for uniform illumination of each fluorescence camera

Radiosondes for atm profile

Lidar at each fluorescence eye for atmospheric profiling - "shooting the shower"

Construction Progress



929 surface detector stations deployed

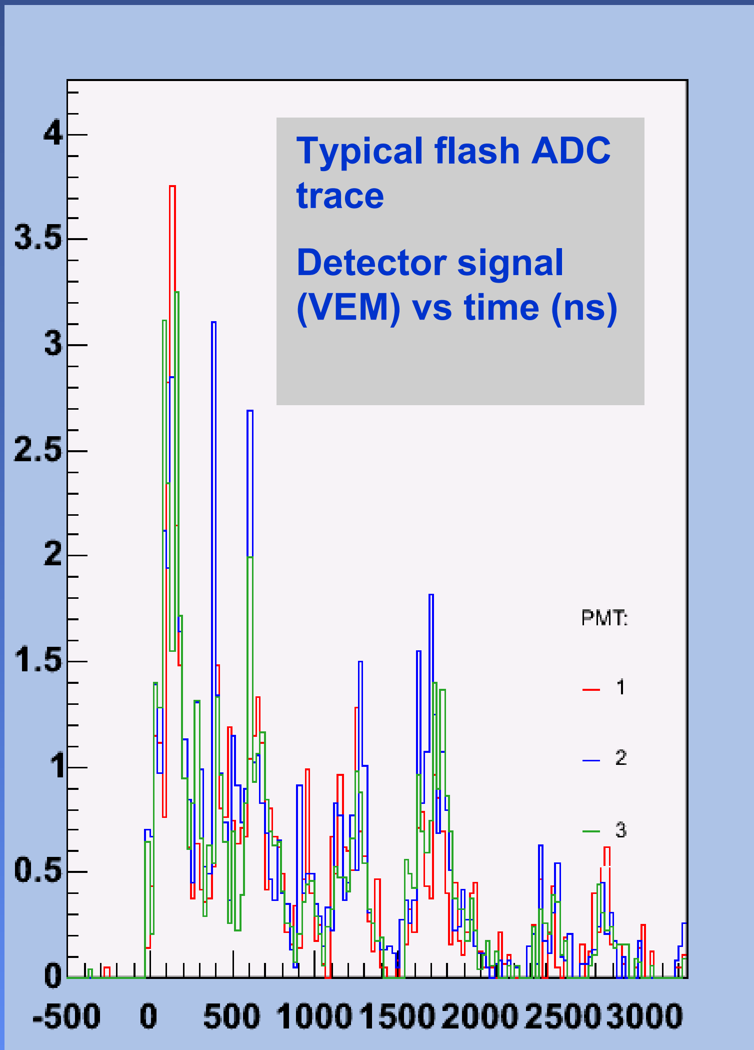
(~780 with electronics and sending triggers)

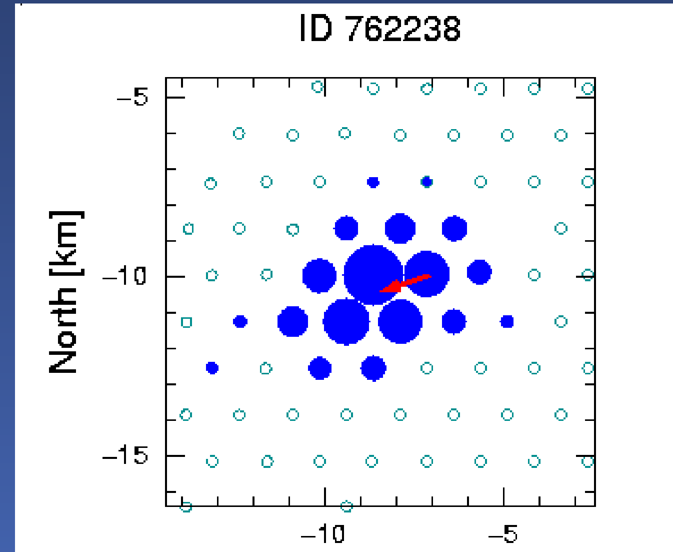
Three fluorescence buildings complete each with 6 telescopes

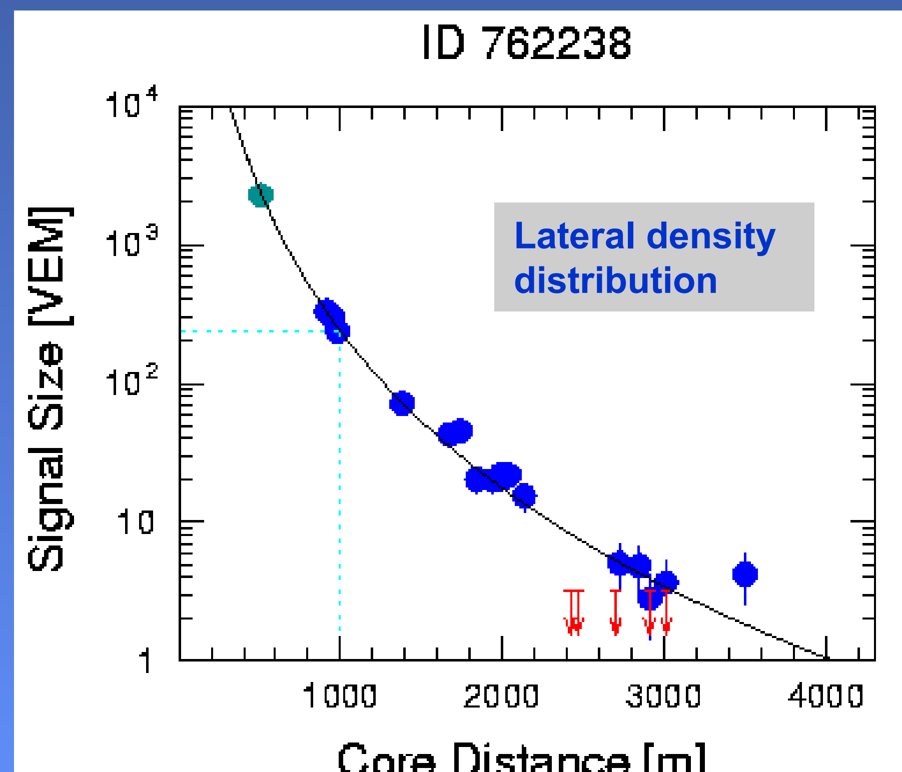
Example Event 1

A moderate angle event - 762238

Zenith angle ~ 48º, Energy ~ 70 EeV

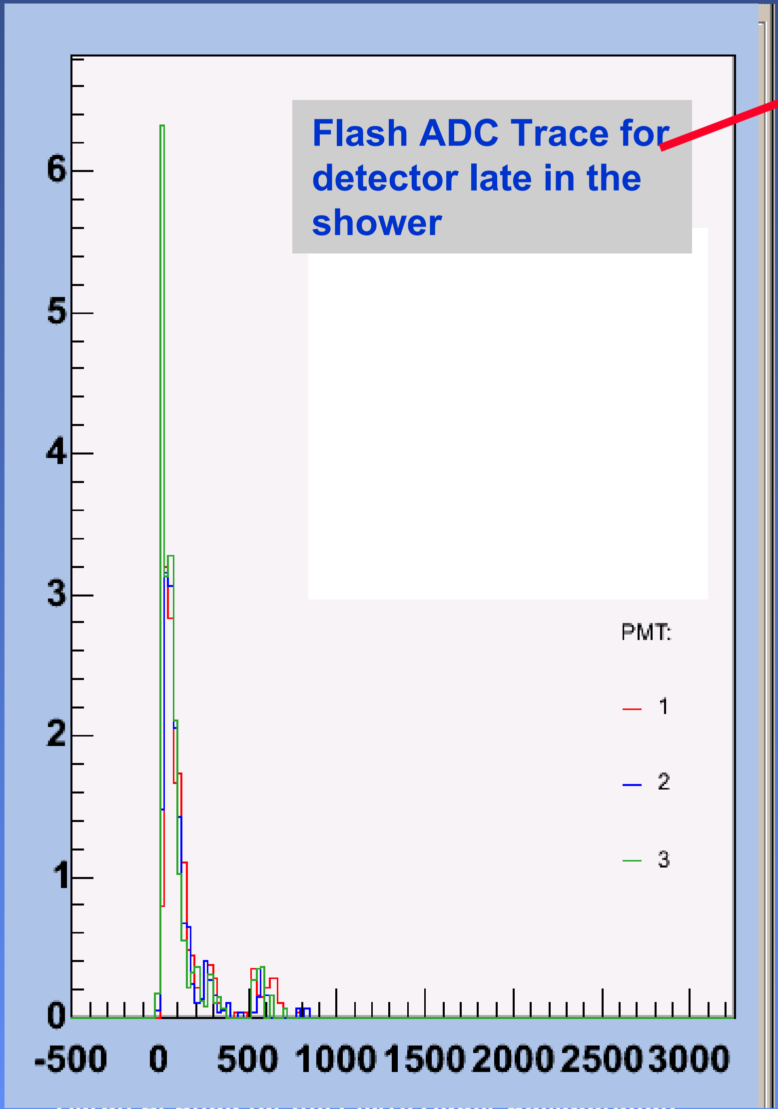


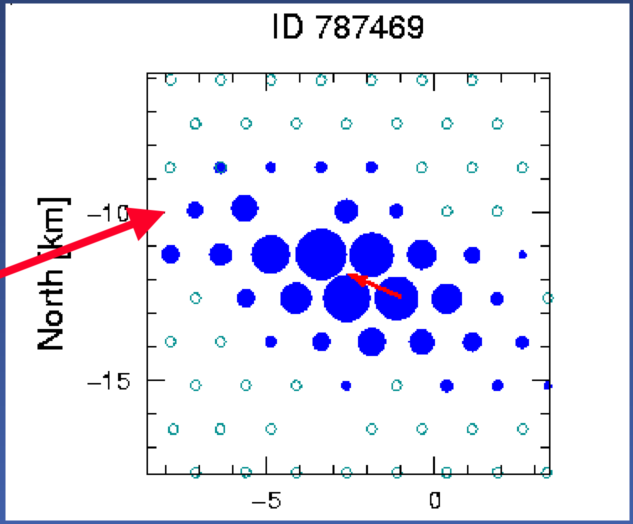


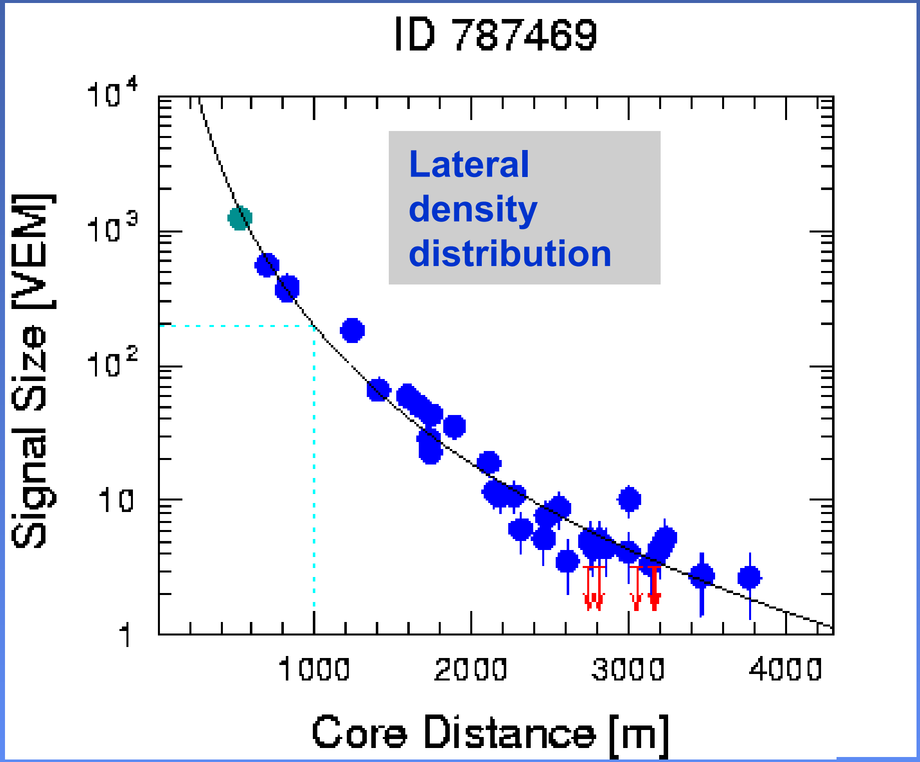


Example Event 2

A high zenith angle event - 787469
Zenith angle ~ 60º, Energy ~ 86 EeV



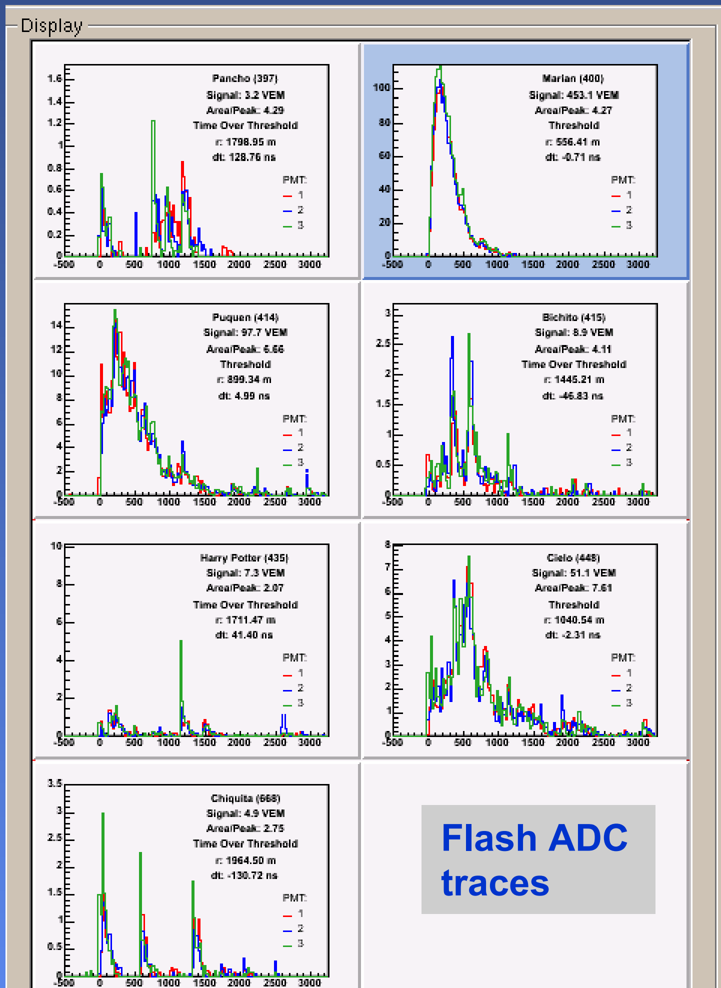


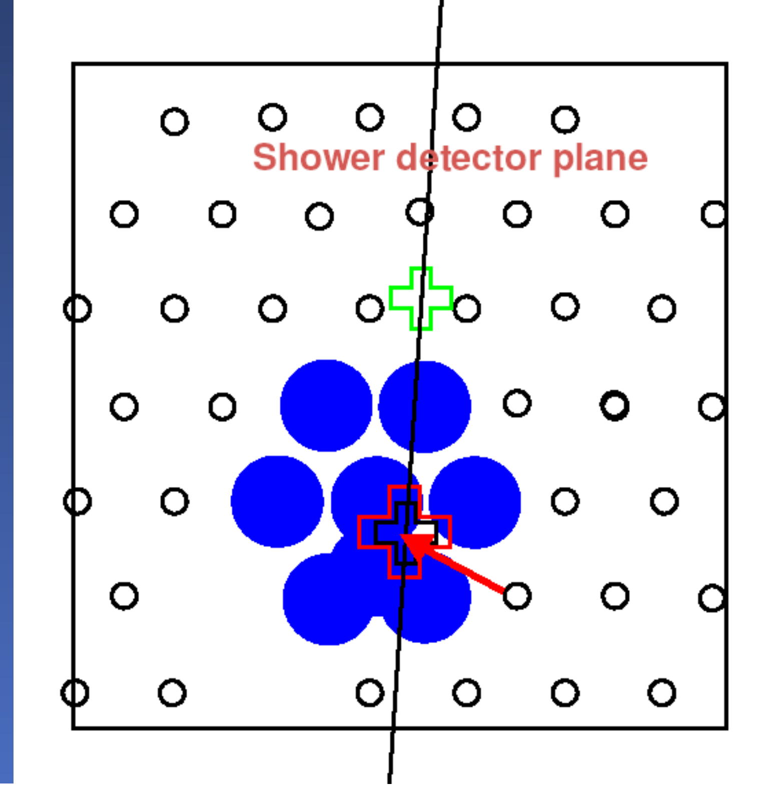


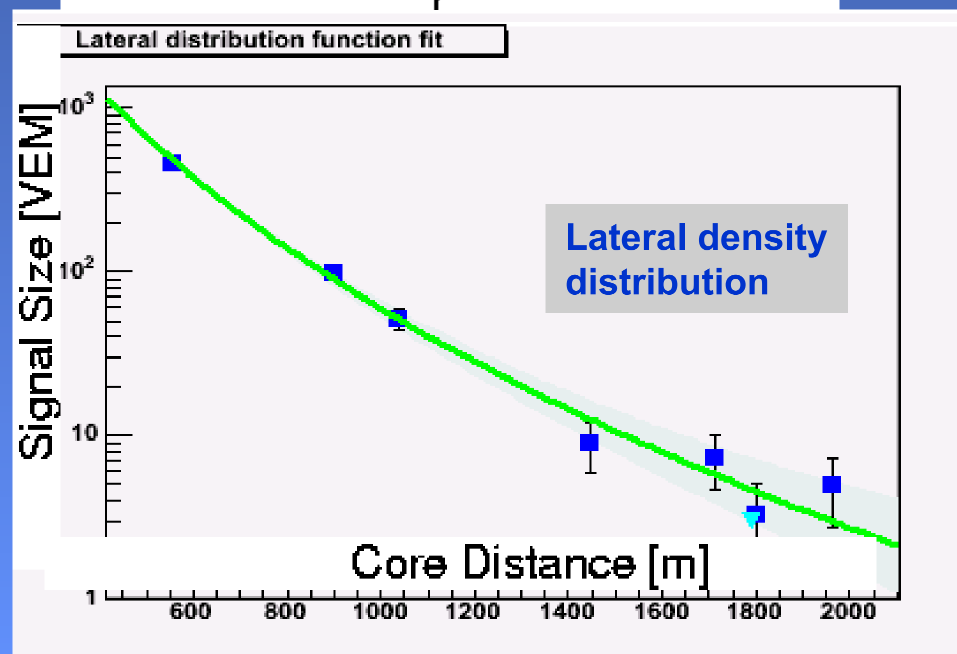
Example Event 3

A hybrid event – 1021302

Zenith angle ~ 30º, Energy ~ 10 EeV





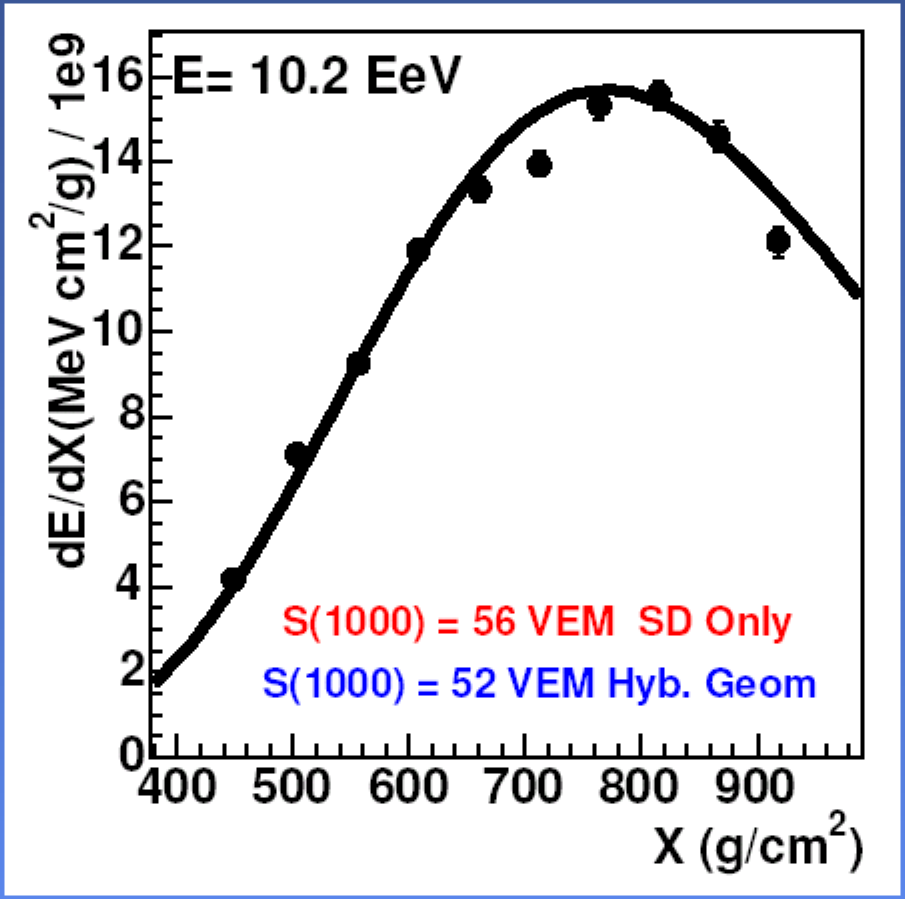


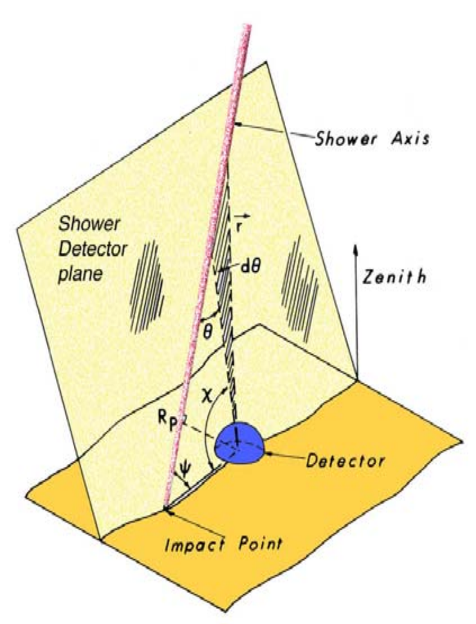
Wine&Cheese, Fermilab, July 15, 2005

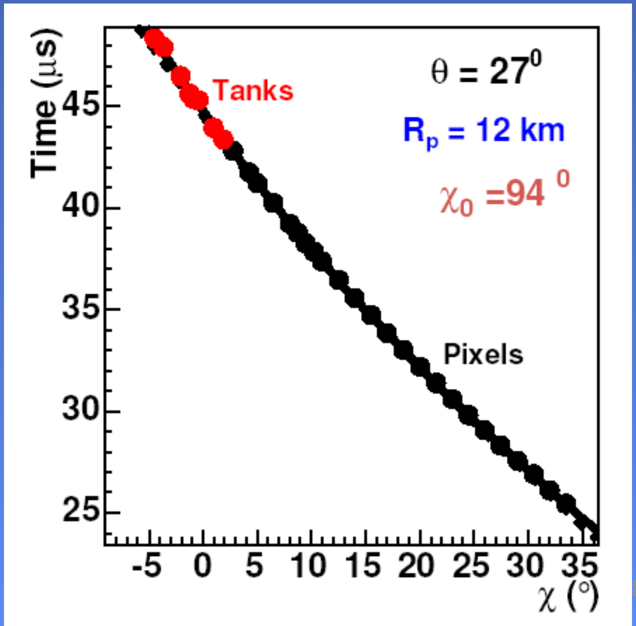
Aaron S. Chou for the Pierre Auger Collaboration

Example Event 3

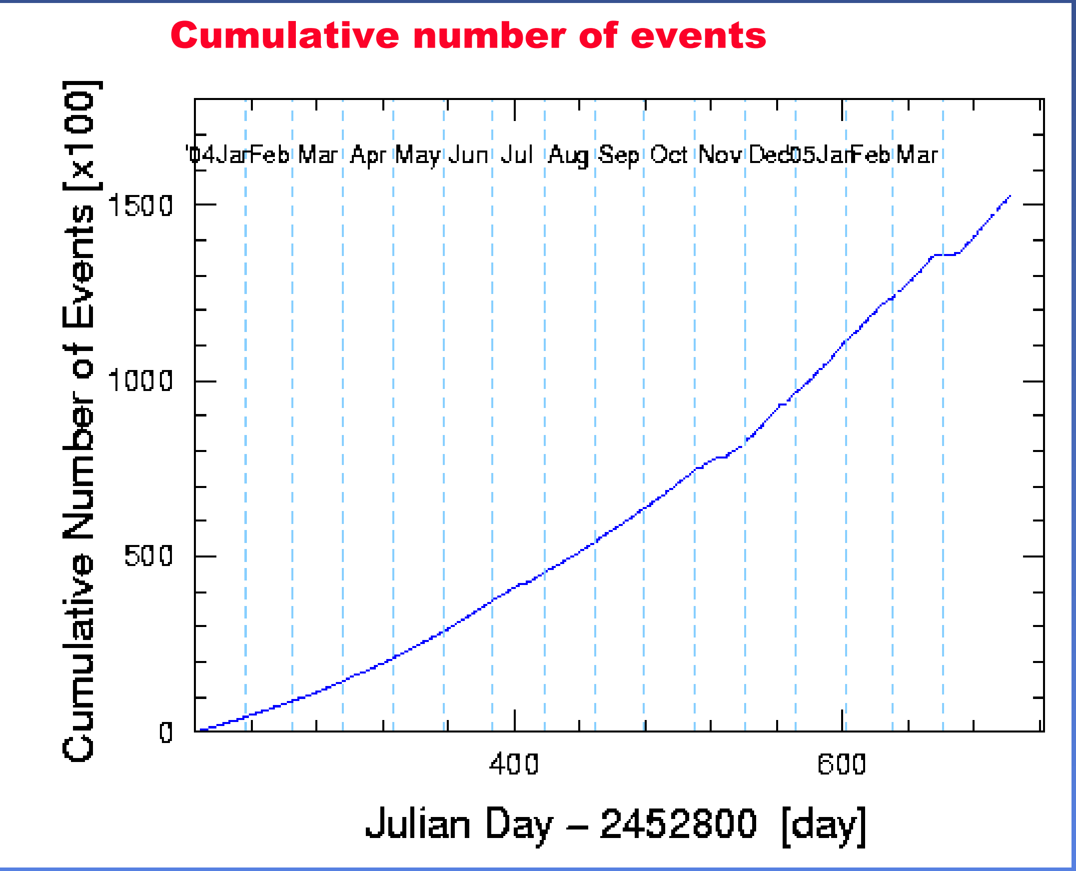
A hybrid event – 1021302
Zenith angle ~ 30º, Energy ~ 10 EeV







The First Data Set



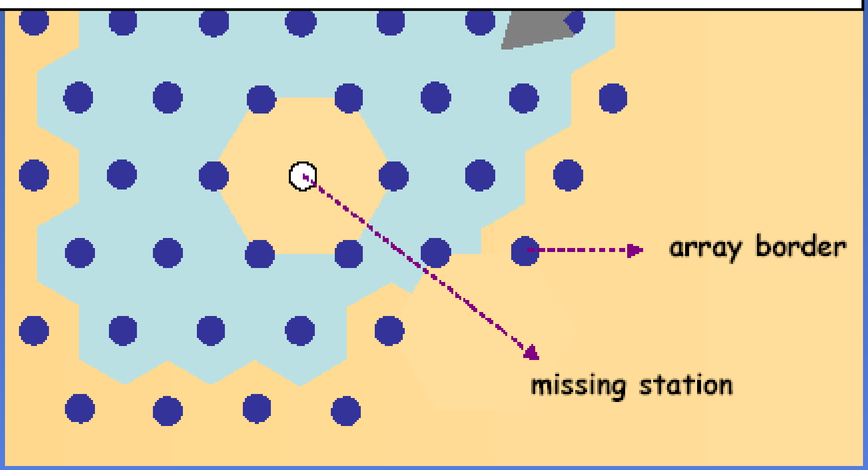
- Collection period – 1 Jan 2004 to 5 June 2005
- Zenith angles - 0 - 60º
- Total acceptance – 1750km^2 sr yr (~ 1.07 * AGASA)
- Surface array events (after quality cuts)
  - Current rate - 18,000 / month
  - Total - 150,000

The SD Exposure Computation

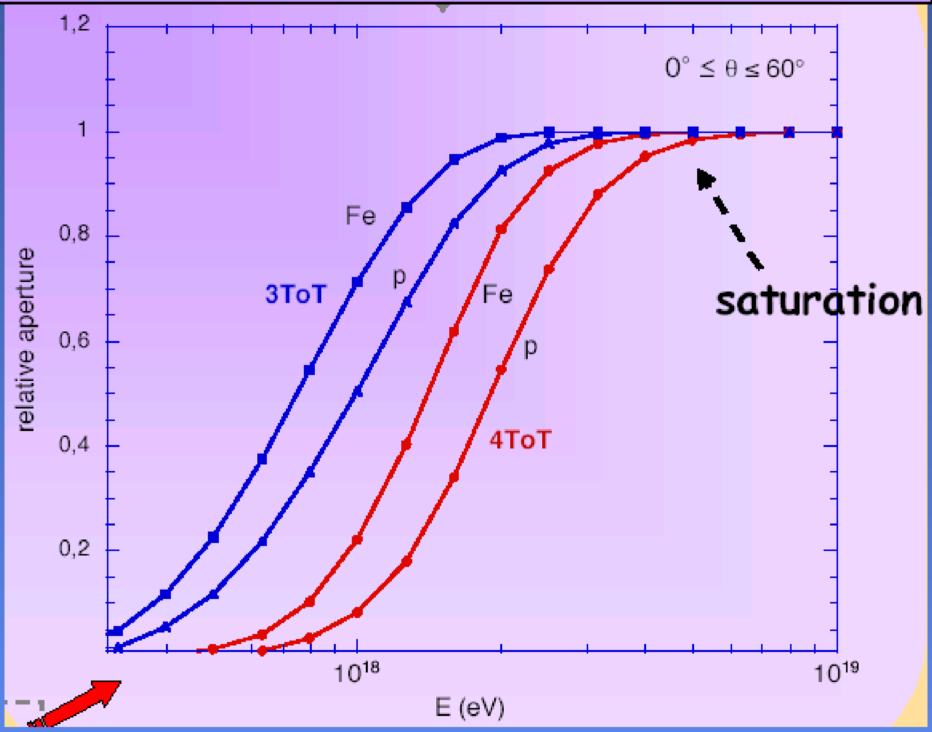
- **Determine the instantaneous effective surface area by monitoring the detector status in real-time.**

Multiply the trigger efficiency by the effective surface area of the array.

Integrate over solid angle and time.

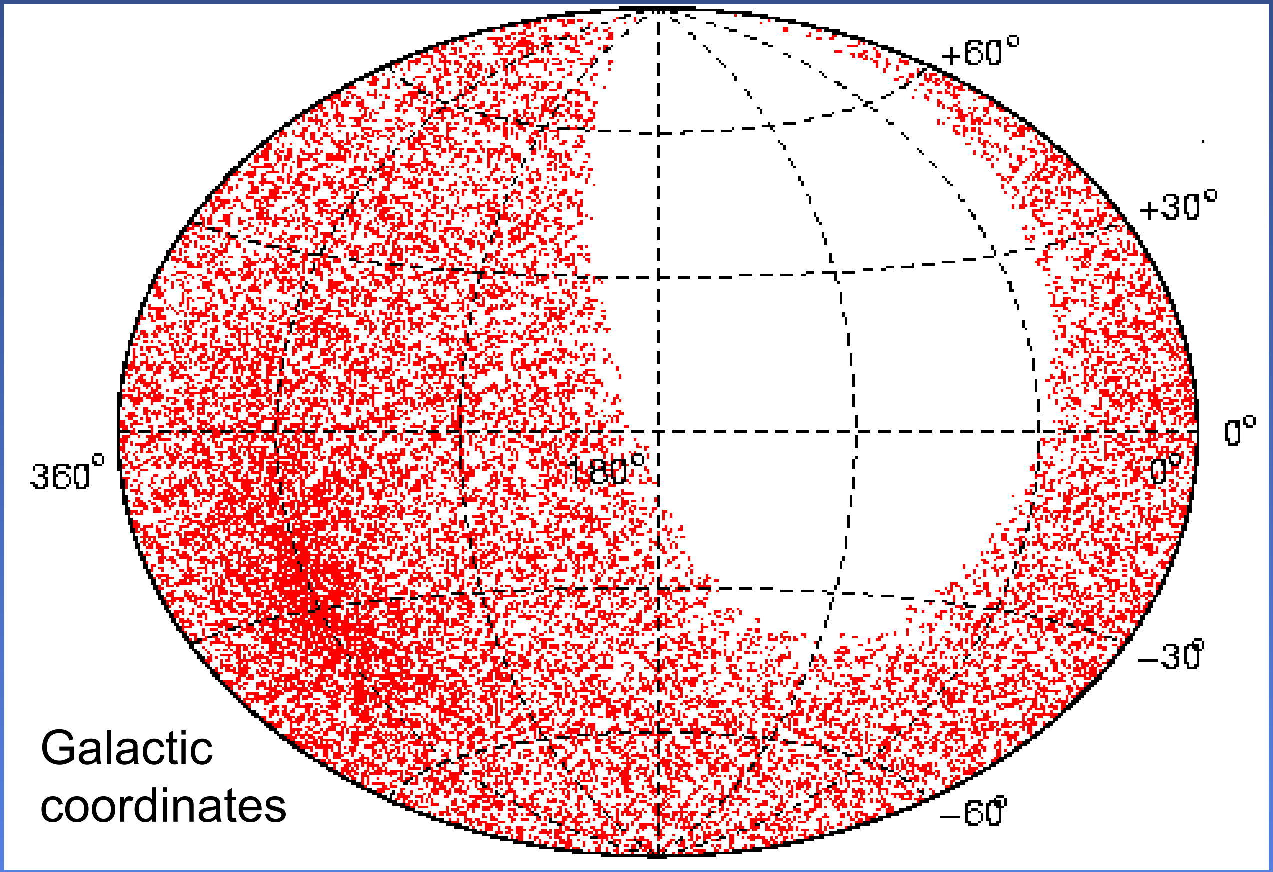


Solid angle-averaged trigger efficiency from simulations



Exposure=1750 km^2 sr yr
= AGASA*1.07

Sky Map of Data set



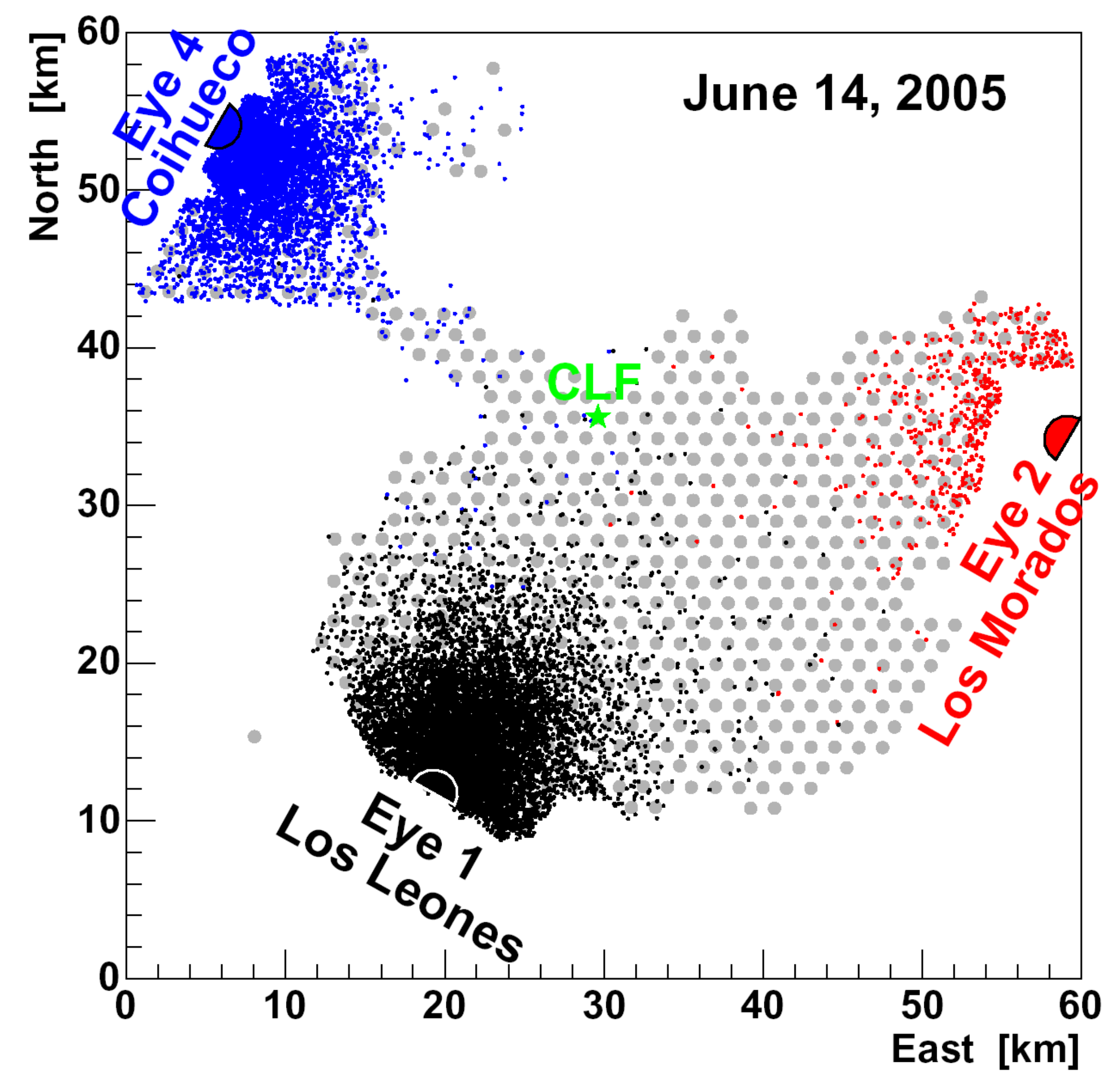
Auger latitude= -36.

Always looking towards South.

Limited coverage in Northern region.

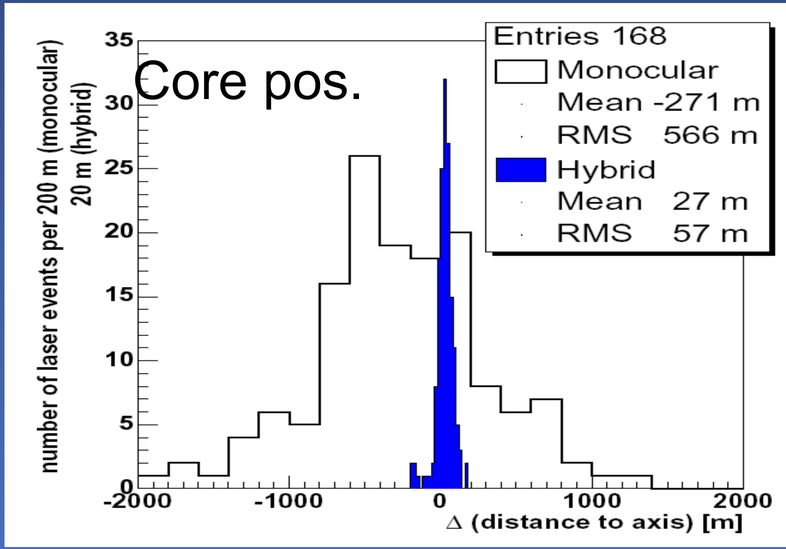
We mainly measure properties of the Southern sky flux!

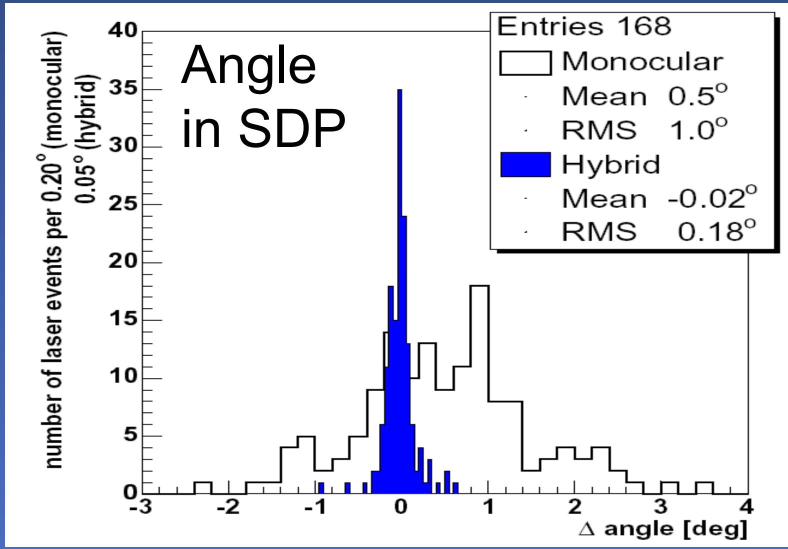
Hybrid Events

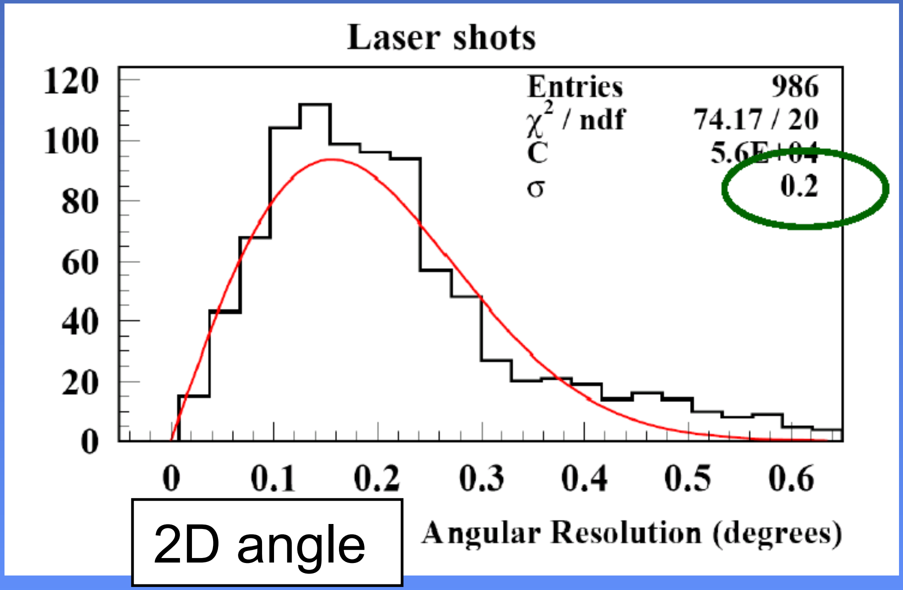


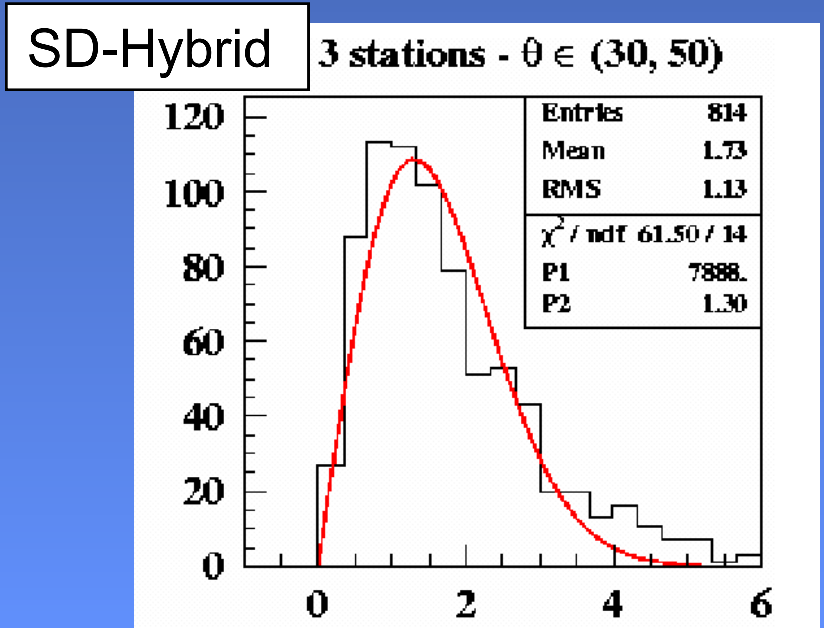
- Reconstructed
  - 1800/month
  - Total = 10,000
  - Mostly at low energies near eyes
  - ~2000 (>1 EeV)

Hybrid Core position and direction resolution is measured with CLF Laser shots

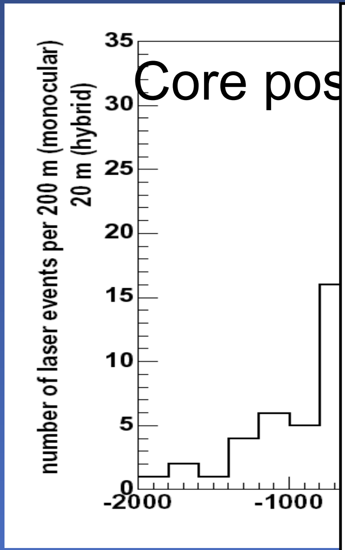




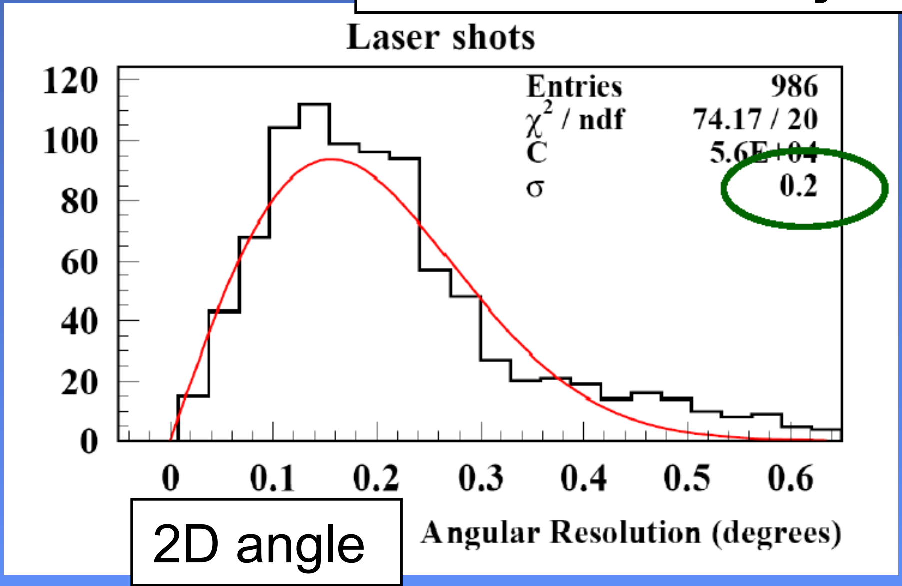


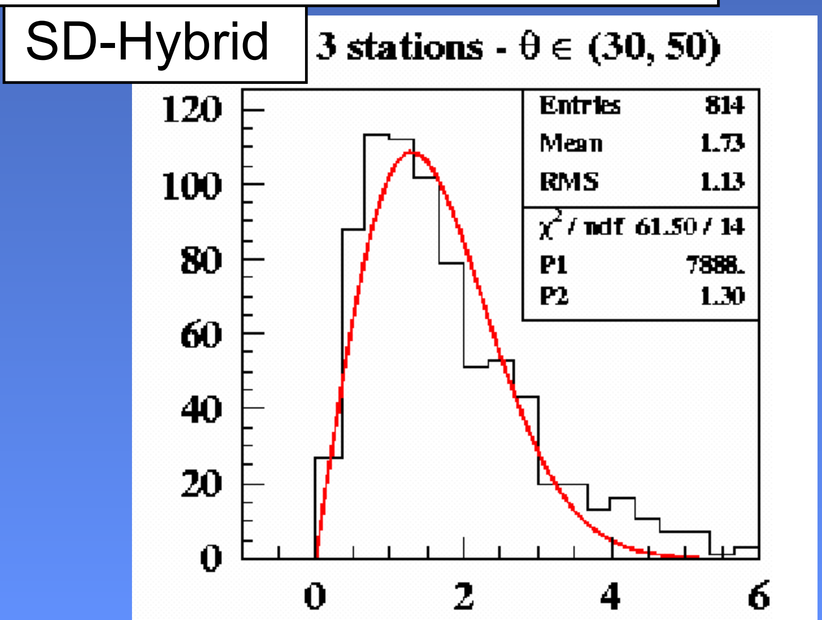


Hybrid core position and direction resolution is measured with CLF Laser shots

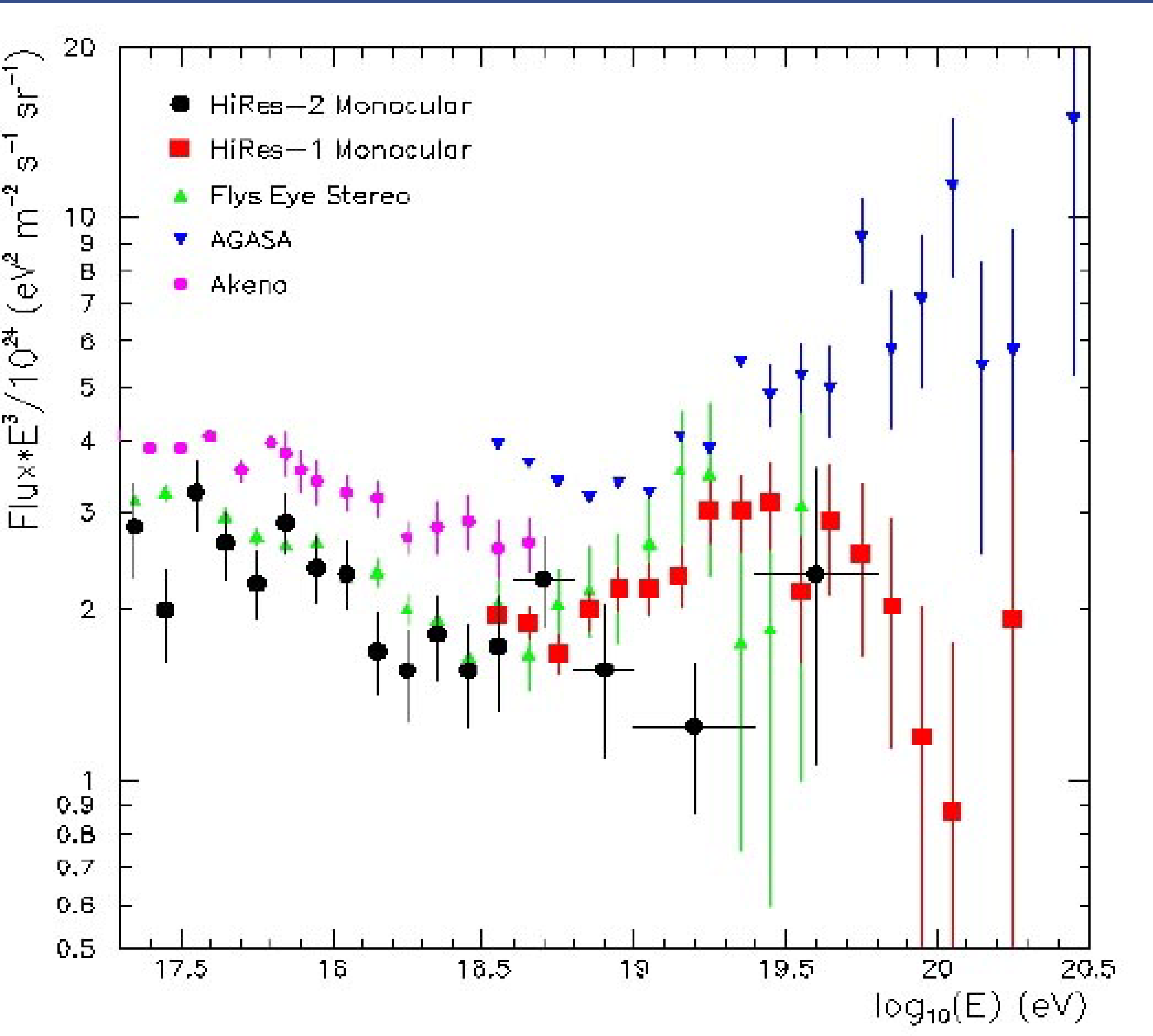


- **Angular resolution (68% CL):**
  - **Hybrid – *0.6 degrees***
  - **Surface array**
    - ***2.2º for 3 station events (E< 4 EeV, θ < 60º).***
    - ***1.7º for 4 station events (3<E<10 EeV)***
    - ***<1.4º for 5 or more station events (E>8 EeV)***
- **Core position**
  - **Hybrid – *60 meters***
  - **Surface array: < 200 meters**





The GZK Feature?



- **AGASA (SD) sees the apparent continuation of the spectrum**
- **HiRes (FD) sees a dropoff in the spectrum above 10^19.5eV.**

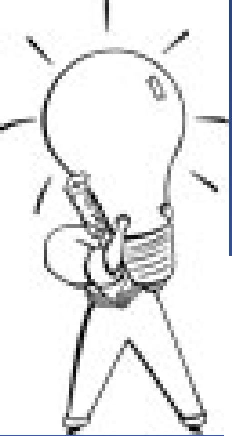
FD-alone Energy Measurement

- **Pro: The energy measurement is calorimetric.**
  - **Energy~ionization loss~tracklength~fluorescence emission**
- **Cons:**
  - **Low duty cycle**
  - **The aperture is not easily determined. For example, if the atmosphere is dirtier than expected:**
    - ***Energy is underestimated.***
    - ***Exposure (integrated trigger efficiency) is overestimated.***
    - ***With enough time and modest money spent on atmospheric monitoring, this difficulty can be overcome***

SD-alone Energy Measurement

- Con: The energy measurement technique relies on MC simulations of the expected signal level
  - Assumed hadronic interaction model requires extrapolations of collider data to higher energies and rapidities. Uncertainties are difficult (impossible) to estimate.

- Pros:
  - high duty cycle
  - Exposure is easily estimated
    - *The array trigger efficiency is 100% for large showers!*
  - self-calibration with atmospheric muons



The Auger Model-Independent Approach

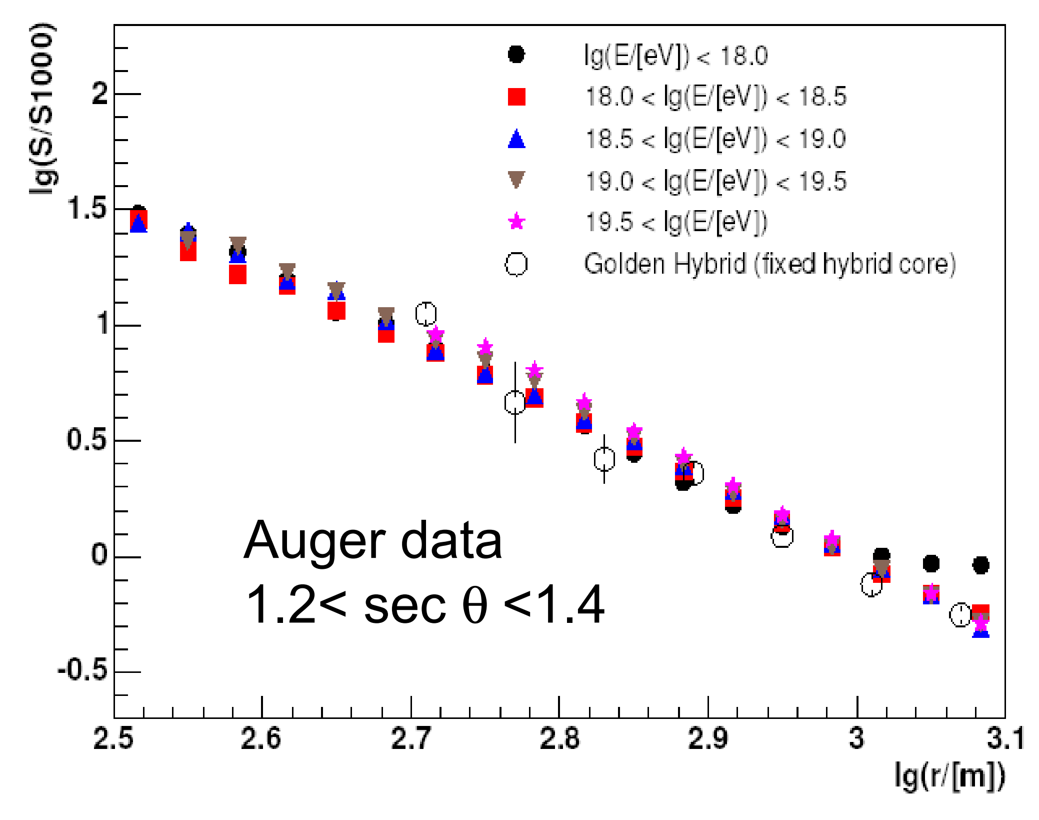
Use the strengths from each technique:
FD(Hybrid) energy, SD statistics, SD exposure.

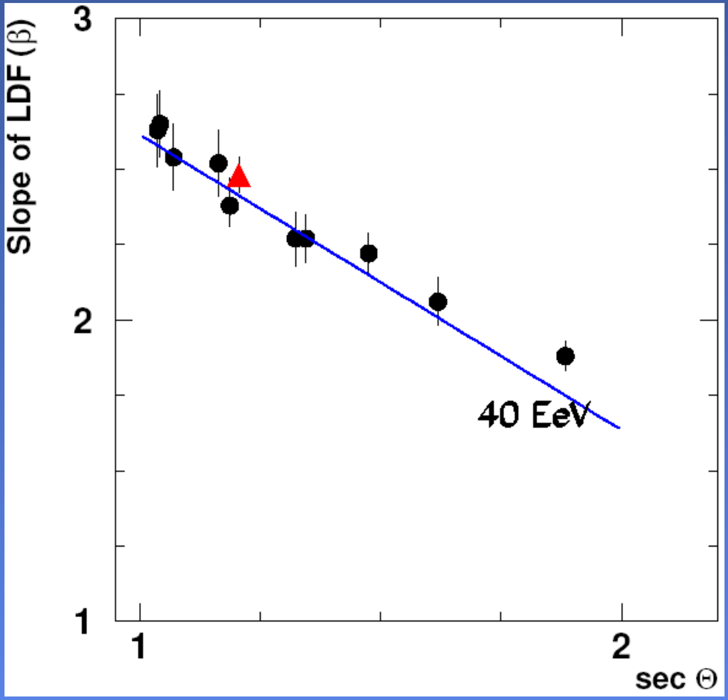
- **From SD data, reconstruct a stable ground parameter S(1000) (SD signal at 1000m) which is correlated with shower energy**
- **Empirically determine the S(1000)→Energy conversion**
  - **Measure the zenith angle dependence of the converter using SD data, and also using Hybrid data**
  - **Use Hybrid data to:**
    - ***Normalize the converter assuming the FD (hybrid) energy scale***
    - ***Determine the energy dependence of the converter***
- **Divide the SD energy histogram by the SD exposure to obtain the measured spectrum.**

The SD fitting function is determined from the data

- LDF: Distribution of signals versus the core distance r (transverse distance of detector to the shower axis)

Use a "NKG-like" LDF ~ r $^{-\beta}$





Measured β(E,θ) directly from the data.

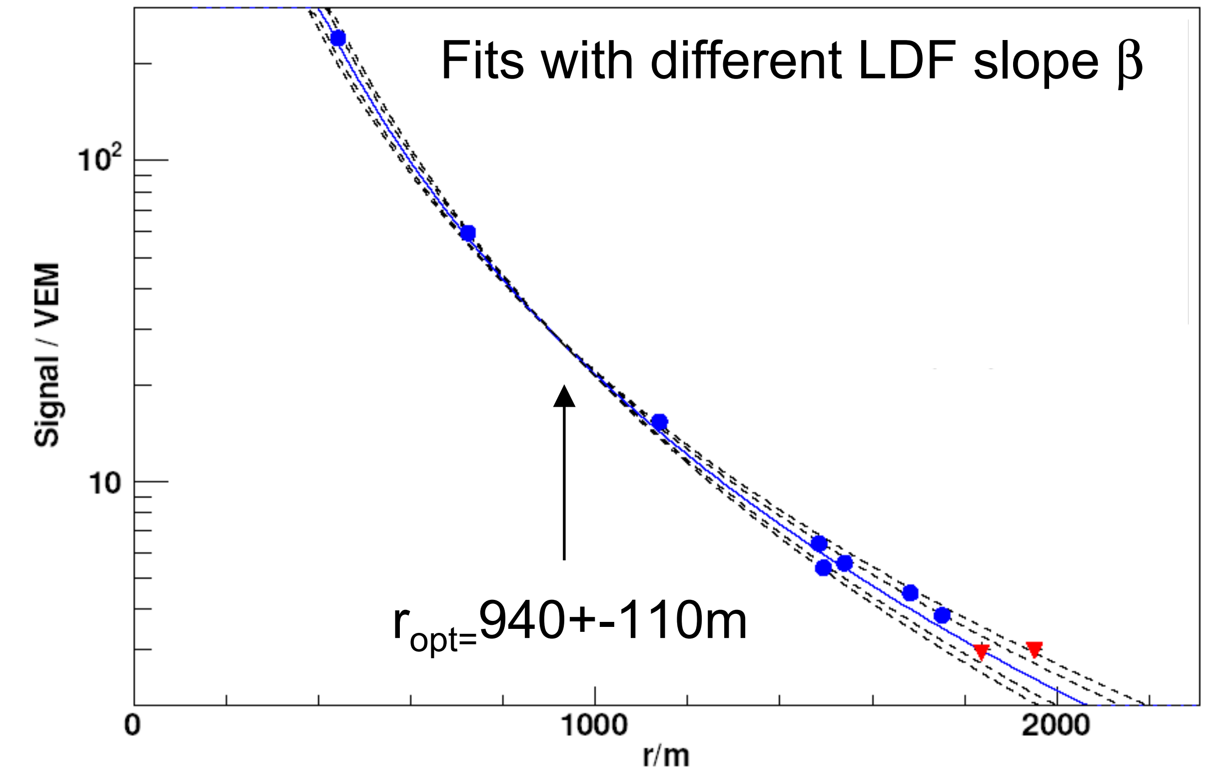
σ_β ~ 10% from previous exps.

The Ground Parameter S(1000)

- **To determine the shower energy, a single ground parameter S(r) is traditionally chosen to minimize the effects of reconstruction errors, and shower-to-shower fluctuations**

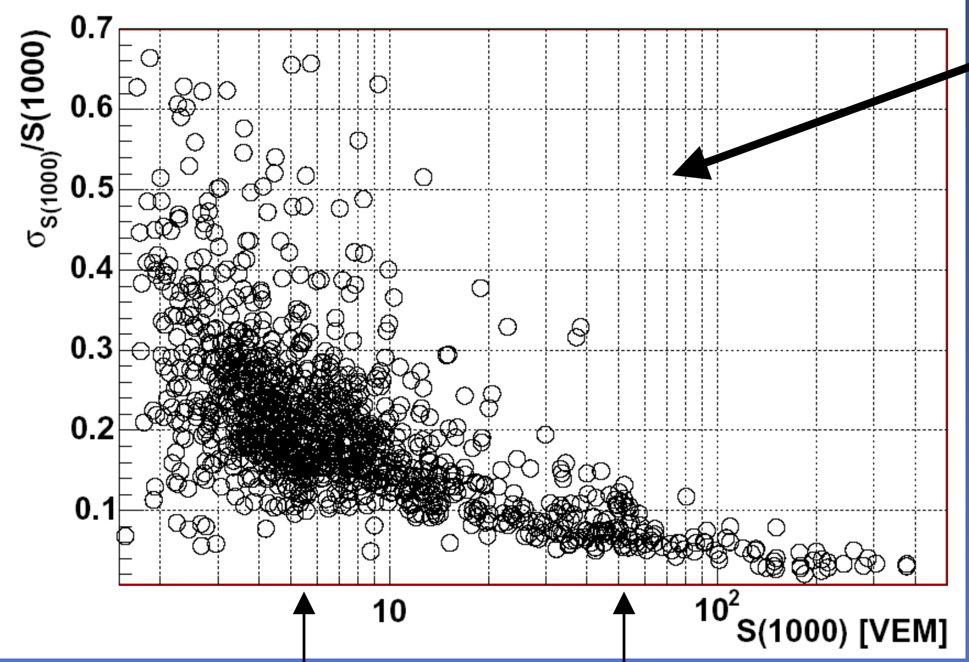
S(r) is determined from interpolating the data using a LDF with fixed β.

However, for most events, precise knowledge of the LDF shape is not important because there exists an optimal core distance $\mathbf{R_{opt}}$ at which the different fitted LDFs cross-over.



S(r_{opt}) is a stable ground parameter.

A fit to a NKG-like LDF function is used to extract simultaneously S(1000) and the core position

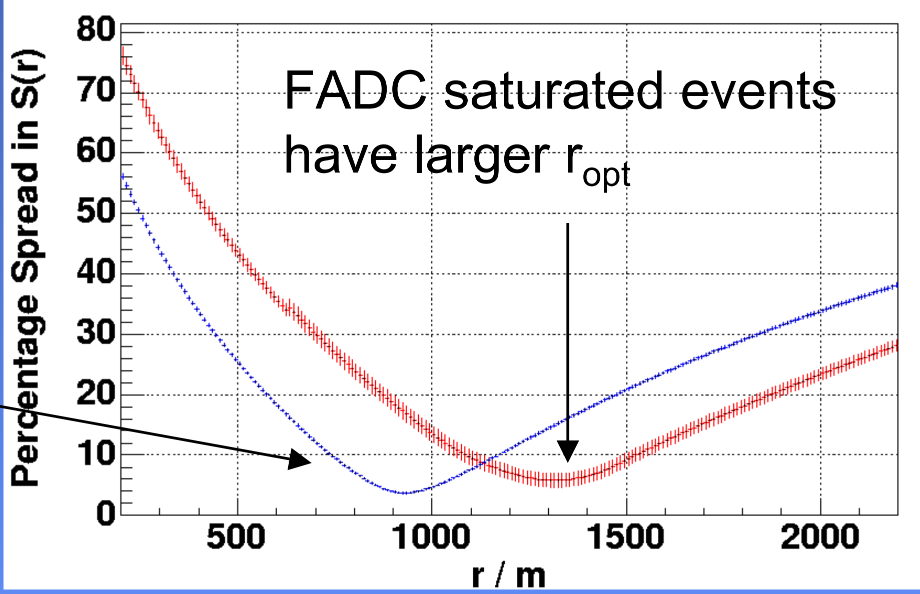


Statistical reconstruction error on S(1000).

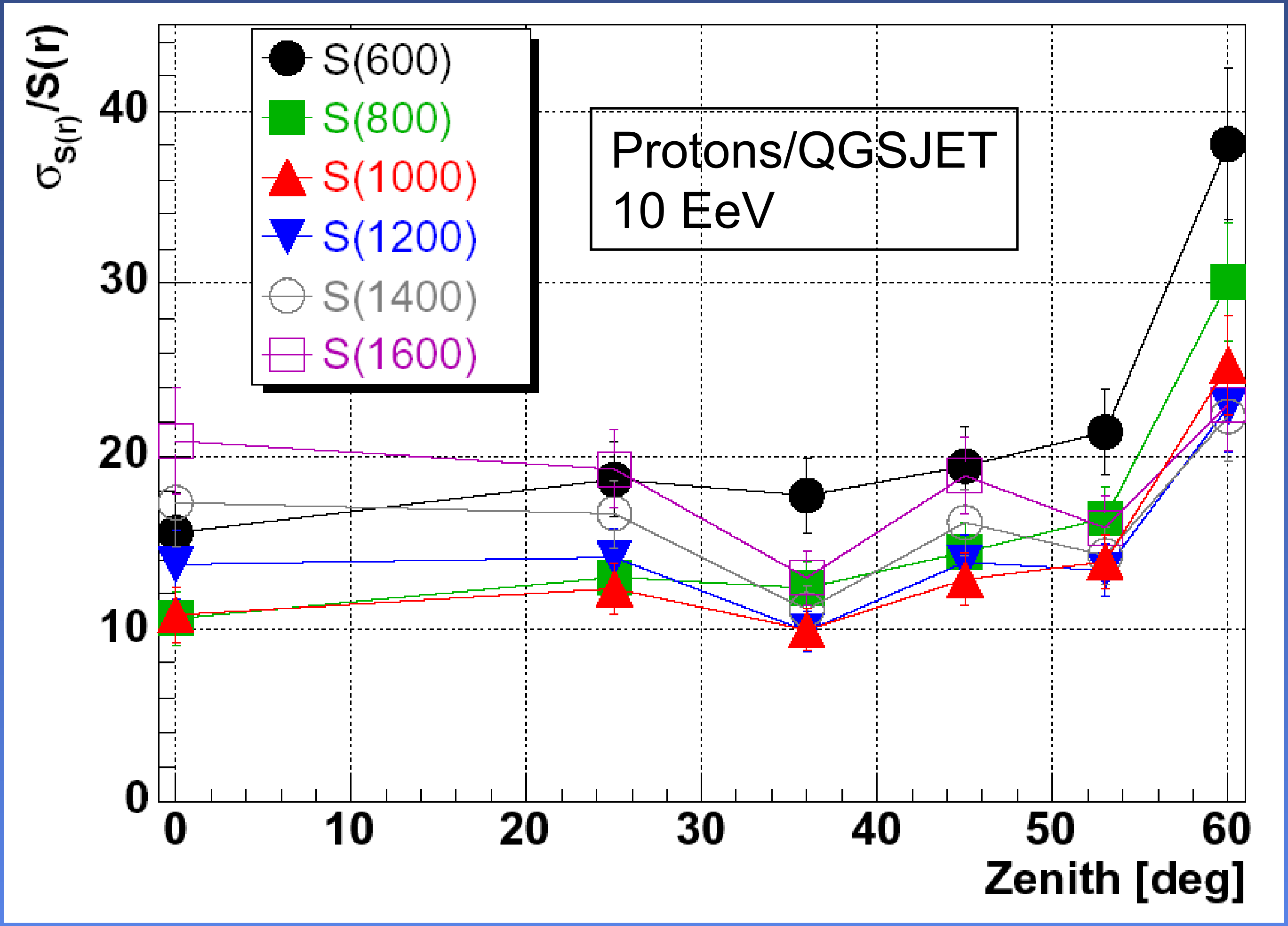
~1 EeV

~10 EeV

Systematic error from LDF shape <4%, estimated by varying LDF slope by +-10%.

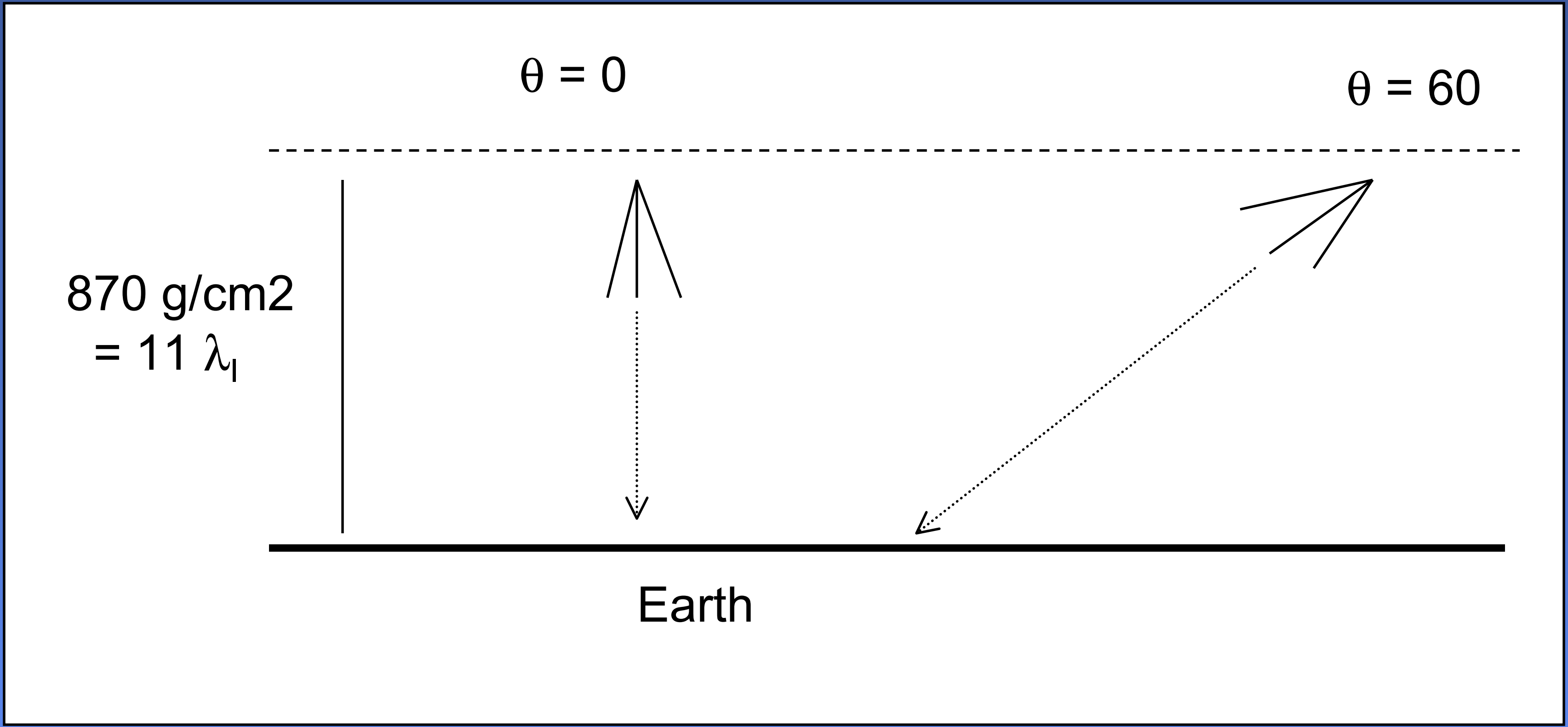


The total statistical fluctuations of S(1000) including shower-to-shower can be estimated with simulations



- **S(1000) is optimal for a 1.5km spacing array.**

Showers coming from different zenith angles give very different signals due to flux attenuation in the atmosphere

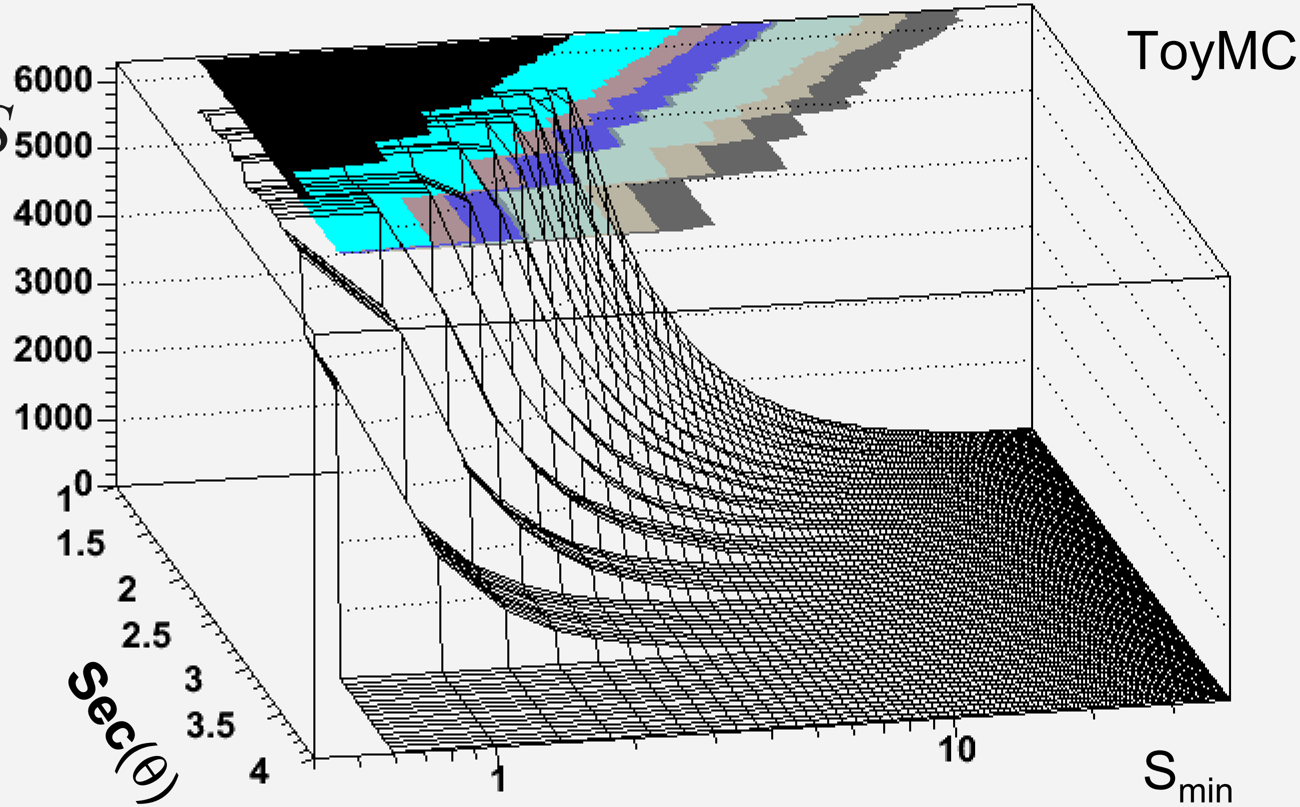


The "slant depth" is 870g/cm2 * sec(θ)

Measure the θ Dependence directly from the data

$$\int_{S_{min}}^{\infty} \frac{dN}{dS \cdot d\sin^2\theta} dS$$

$\propto \cos\theta \cdot d\Omega$
(acceptance correction)



- The flux dN/dS can in principle be measured independently in each zenith angle bin.
- Because dN/dS falls monotonically with increasing S, and because the CR flux is isotropic to a good approximation, the contours of constant integrated flux intensity give the θ dependence of the S(1000)→Energy relationship.

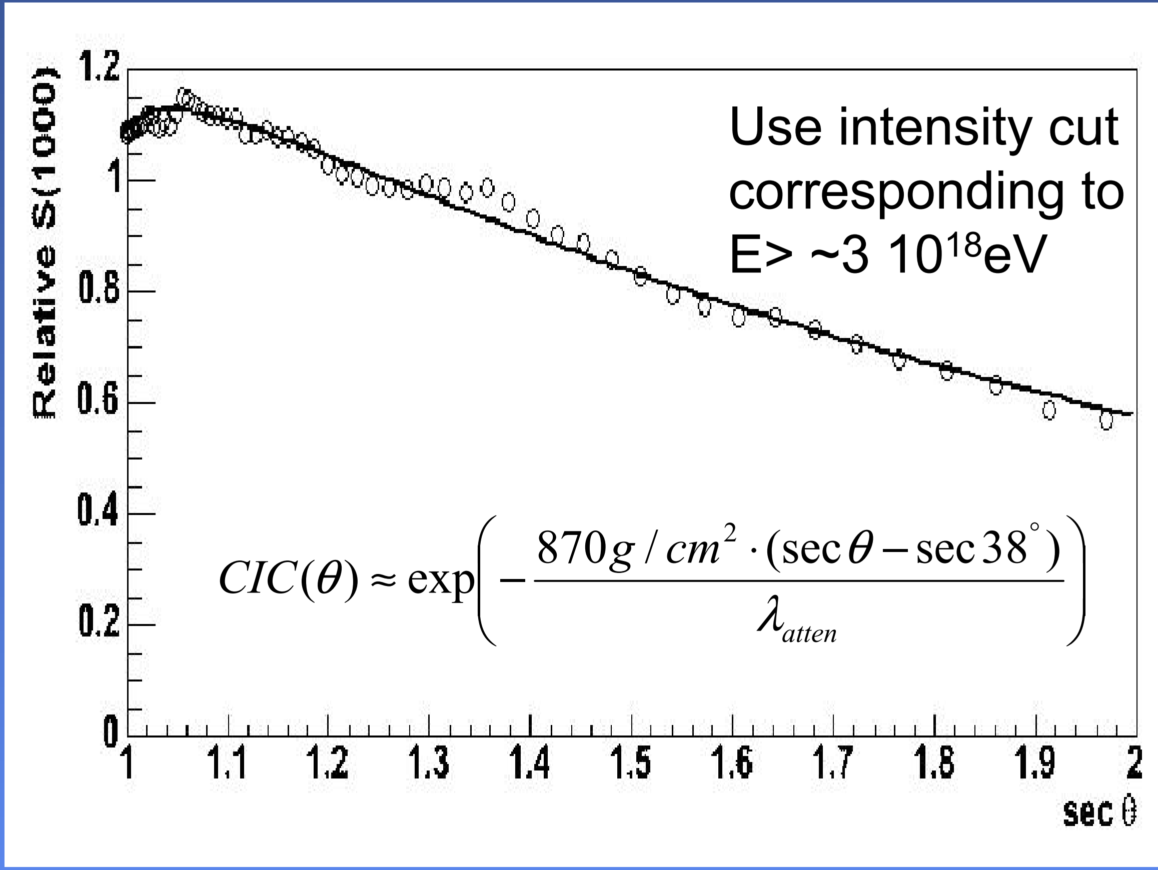
The SD-measured θ dependence (Constant Intensity Cut method)

- Shape is scanned in θ using bins of $\Delta\sin^2(\theta)=0.1$
- Normalize at the median zenith angle of 38 degrees.

$$S(1000)_\theta = S_{38}(E)\times CIC(\theta)$$

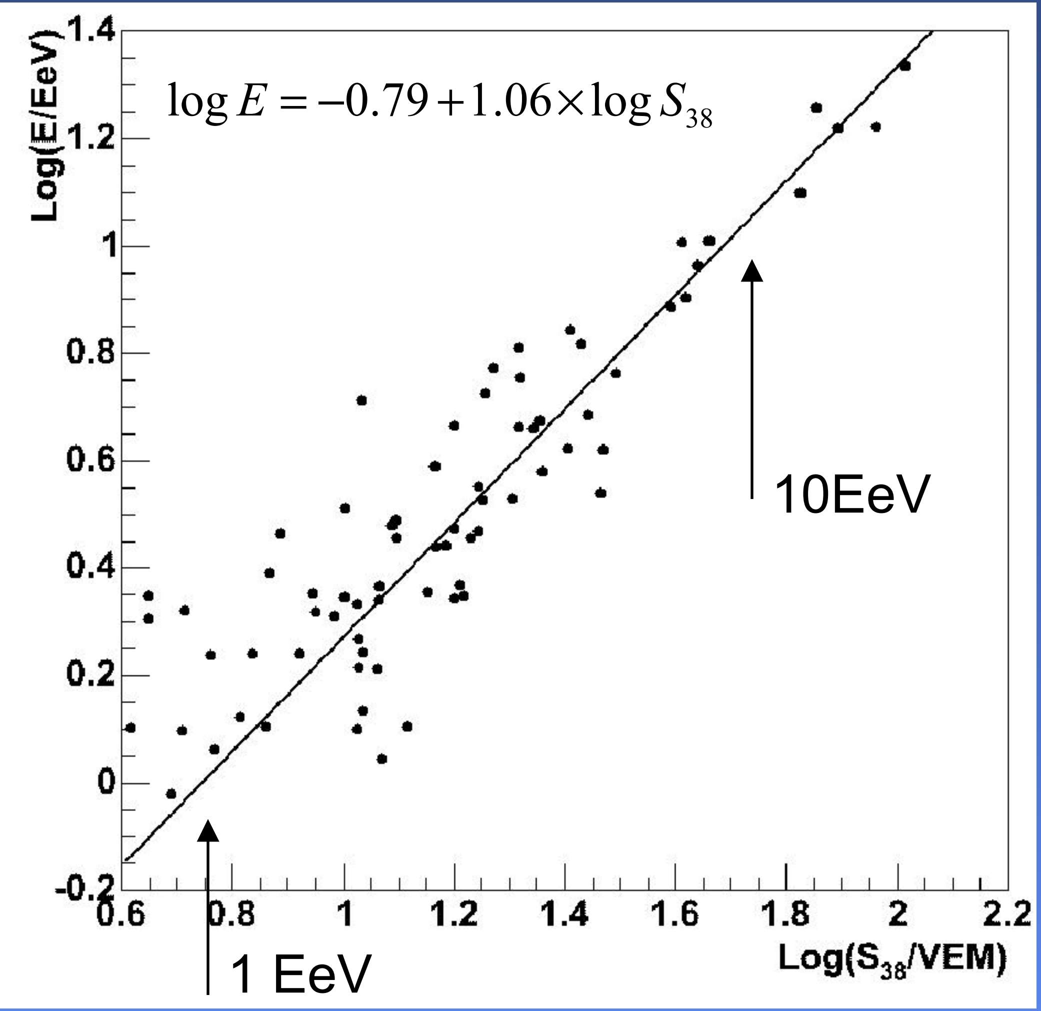
- **Assume for now that CIC(θ) is independent of energy.**

Note: bins are correlated!



$$CIC(\theta) \approx \exp\left(-\frac{870 g/cm^2 \cdot (\sec\theta - \sec 38^\circ)}{\lambda_{atten}}\right)$$

Obtain the S38→Energy Correlation with Fluorescence energies from hybrid events



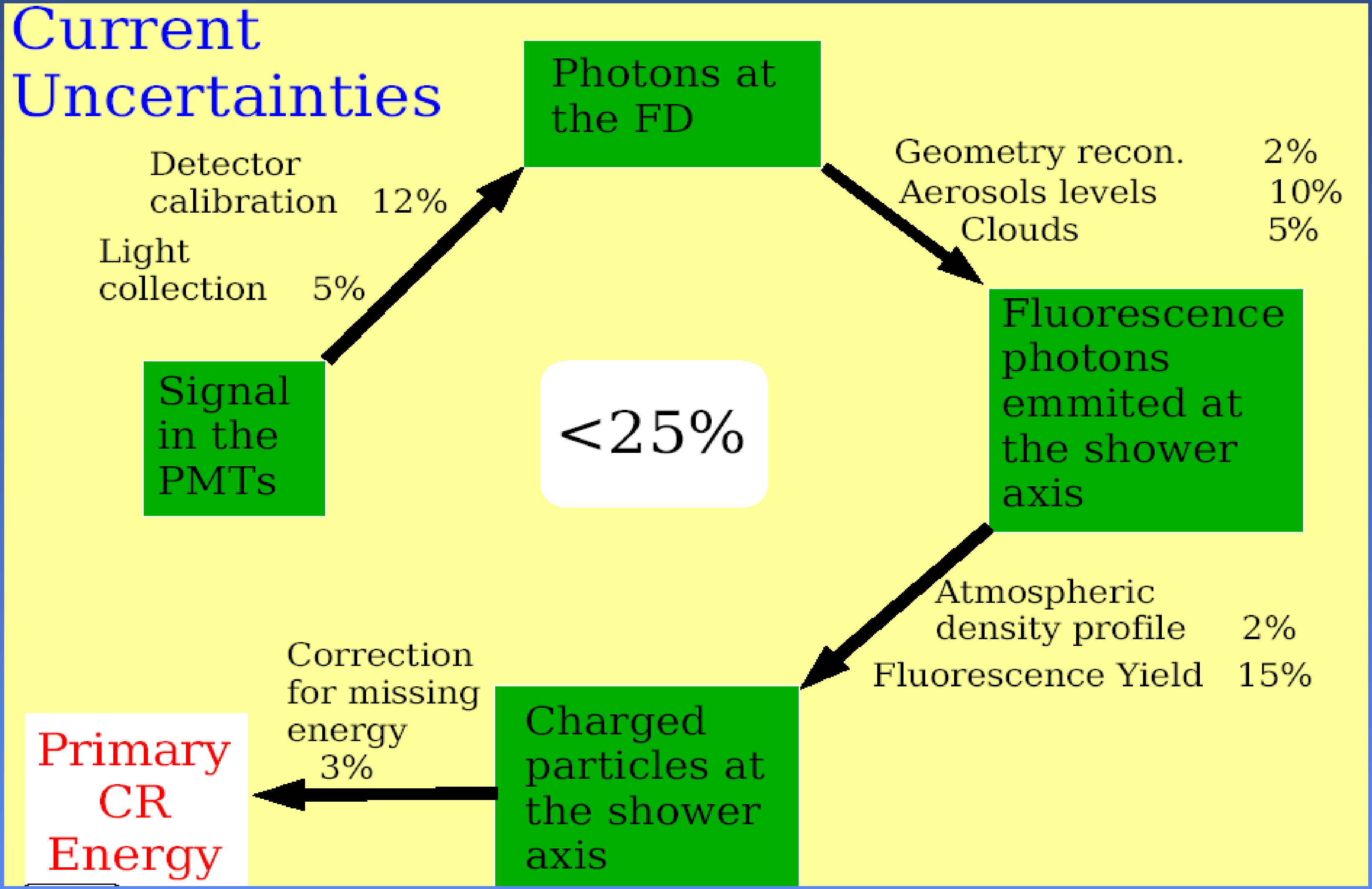
- Strict event selection:
  - tracklength >350g/cm^2
  - Cherenkov contamination<10%

- Obtain converter:

$$E/EeV = 0.16 \times \left(\frac{S(1000)/VEM}{CIC(\theta)} \right)^{1.06}$$

- **Note: systematic error grows when extrapolating this rule to 100 EeV!**

Systematic Errors in the FD(Hybrid) Energy Normalization



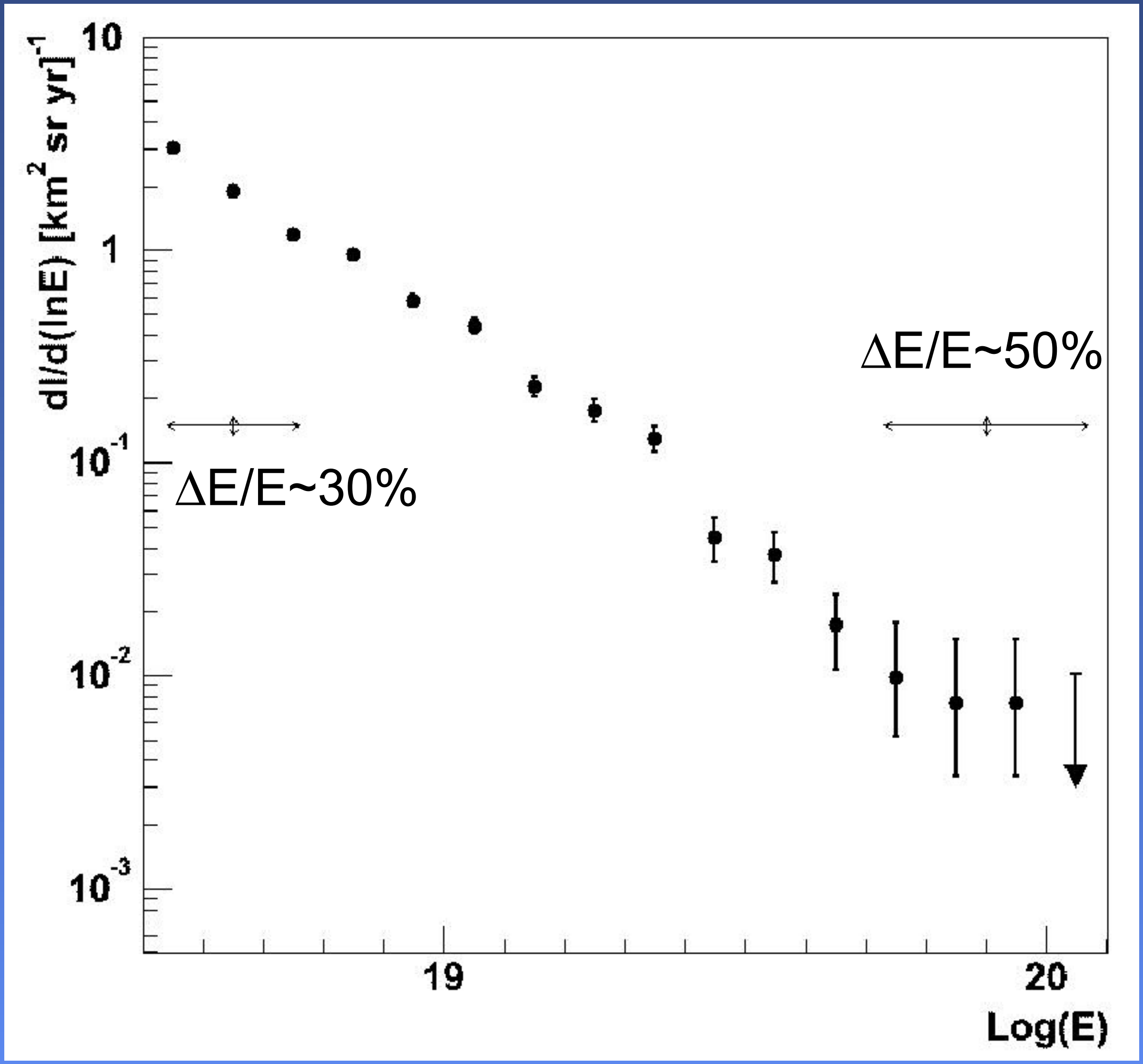
Summary of procedure

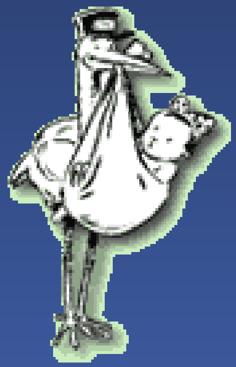
- Reconstruct the ground parameter S(1000)
- Correct for the zenith angle dependence by converting S(1000) to S38 using the measured CIC curve.
- Convert S38 to Energy using the correlation determined with hybrid data

Tank signals → S(1000) → S38 → Energy

Each step is empirically determined!

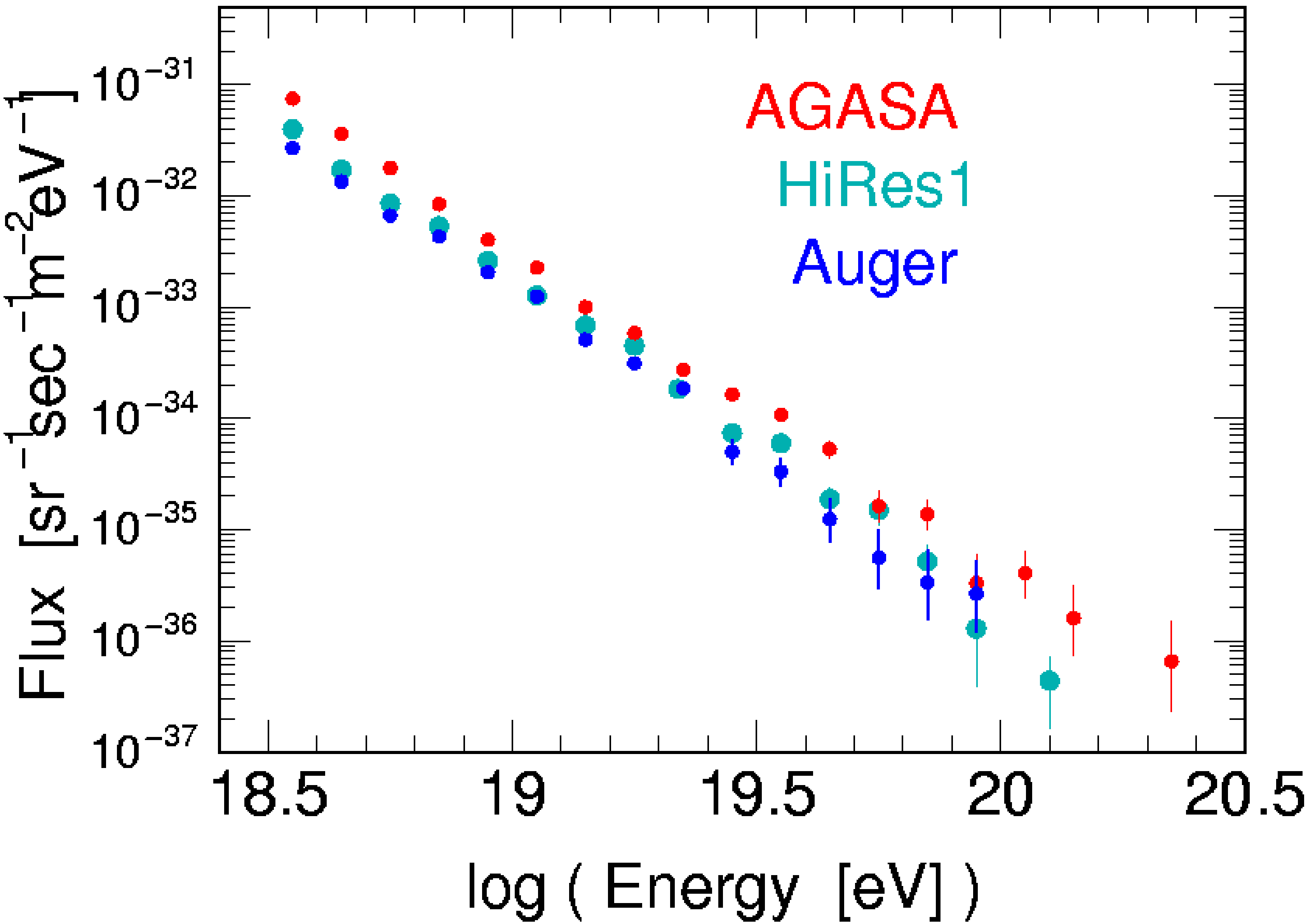
The Auger Southern Sky Energy Spectrum



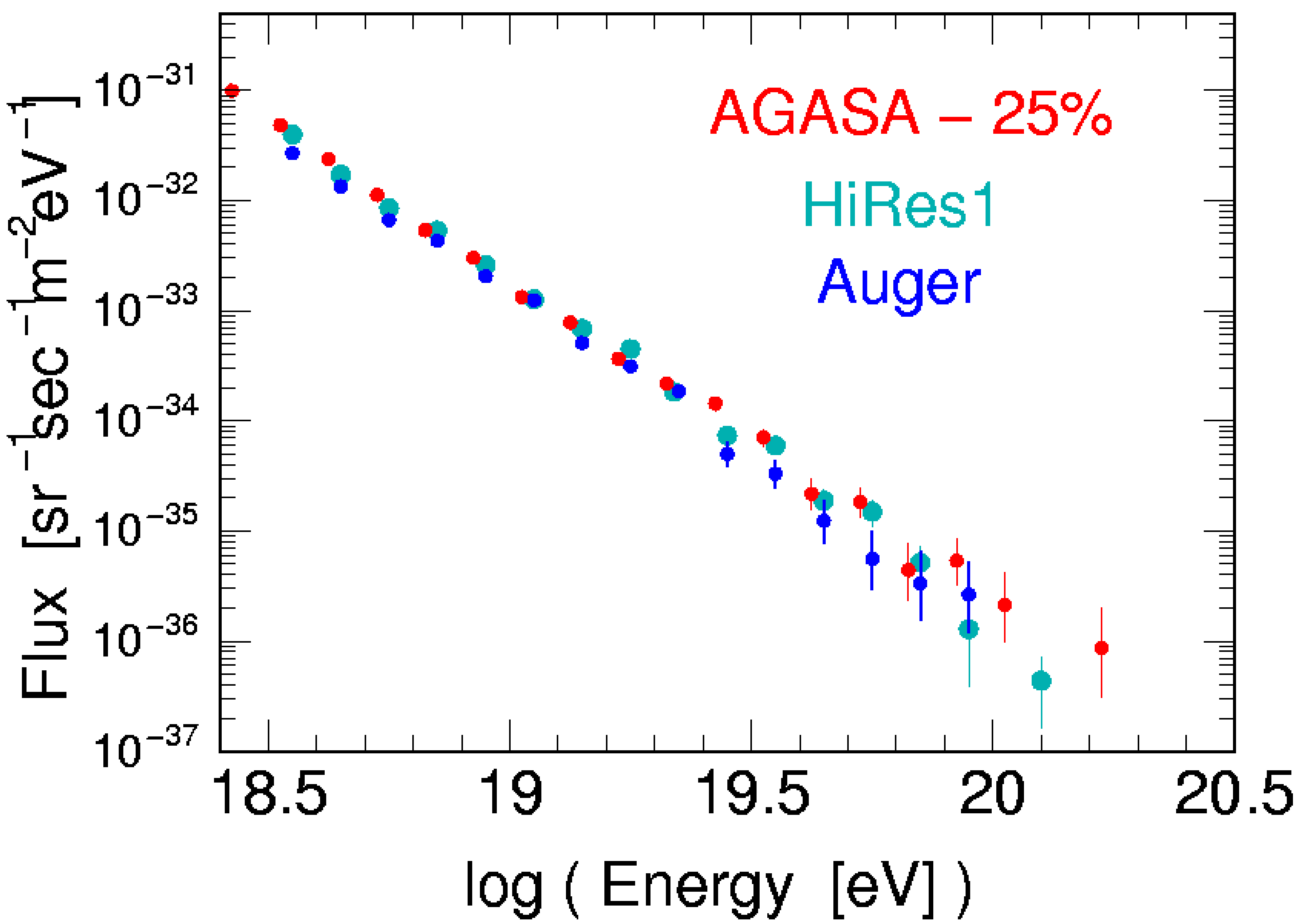


- dN/d(lnE) = E*dN/dE
- Errors on points are Statistical only
- Systematic errors are estimated at two energy regions
  - Energy measurement (horizontal)
  - Exposure determination (vertical)

Comparison with HiRes1, AGASA

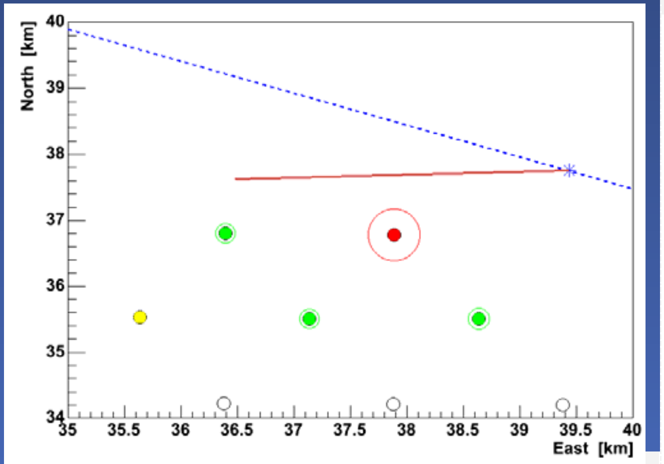


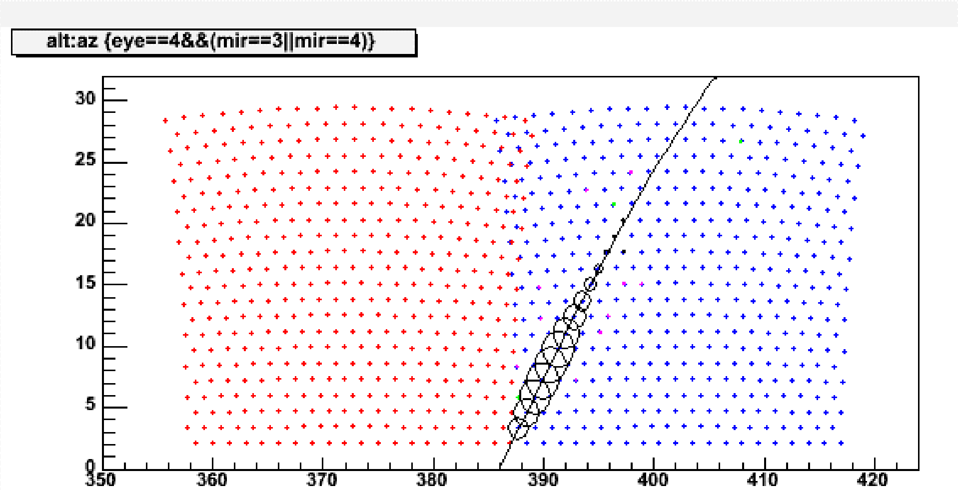
Comparison with HiRes1, AGASA-25%

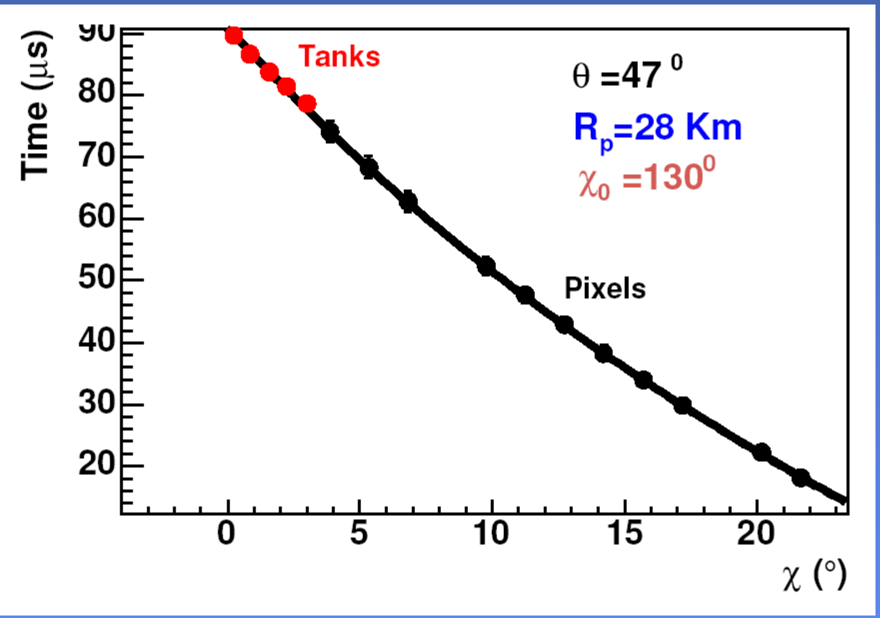


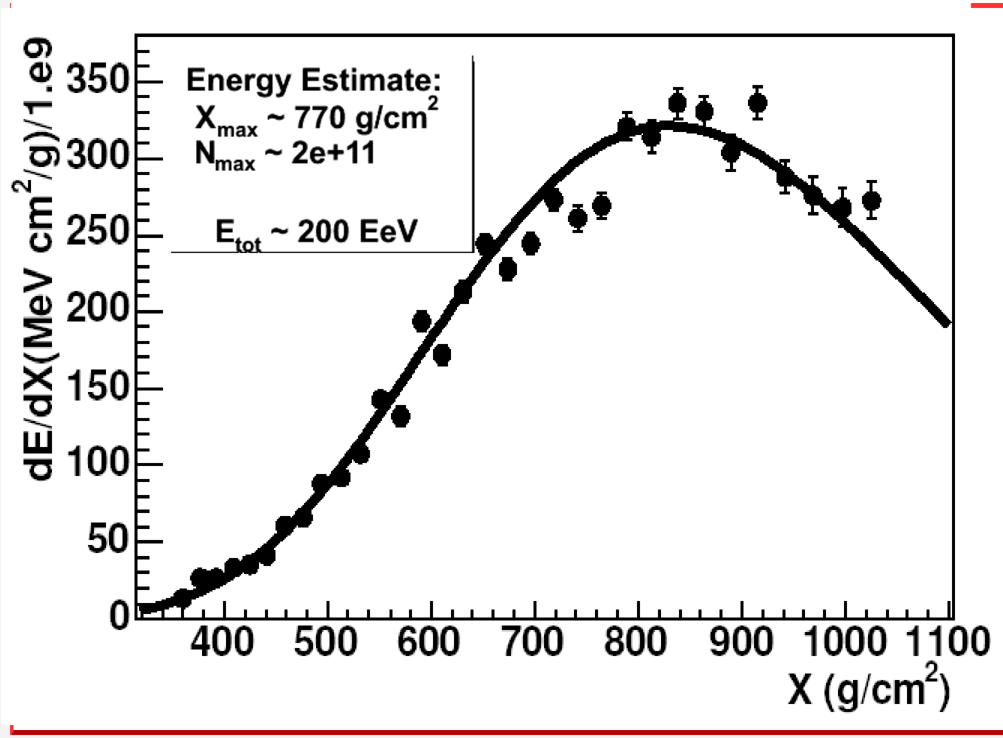
Our Highest Energy Event E_{FD}~2 10^{20}eV

Landed just outside the array, so not used in spectrum!









The Top 10 SD events

Event Id	θ	S(1000)	Multiplicity	r_{opt}	β	E(EeV)
1096757	45.1 ± 0.2	$344 \pm 15 \pm 33$	21	1322	—	86 ± 9
1225537	34.4 ± 0.2	$364 \pm 10 \pm 13$	14	909	2.48 ± 0.06	79 ± 4
787469	59.7 ± 0.2	$204 \pm 8 \pm 11$	31	1173	2.03 ± 0.06	76 ± 5
762238	47.3 ± 0.2	$248 \pm 11 \pm 12$	18	1135	2.22 ± 0.07	64 ± 4
1102721	23.8 ± 0.2	$318 \pm 22 \pm 52$	12	1467	—	63 ± 11
1233429	54.3 ± 0.2	$201 \pm 9 \pm 16$	21	1261	—	63 ± 6
1018639	26.9 ± 0.2	$294 \pm 19 \pm 26$	10	1196	2.93 ± 0.13	59 ± 6
1264145	16.3 ± 0.2	$289 \pm 12 \pm 11$	11	910	2.65 ± 0.11	56 ± 3
1263529	20.7 ± 0.2	$264 \pm 20 \pm 34$	7	1470	—	51 ± 8
634746	51.6 ± 0.2	$174 \pm 9 \pm 12$	14	1203	—	48 ± 4

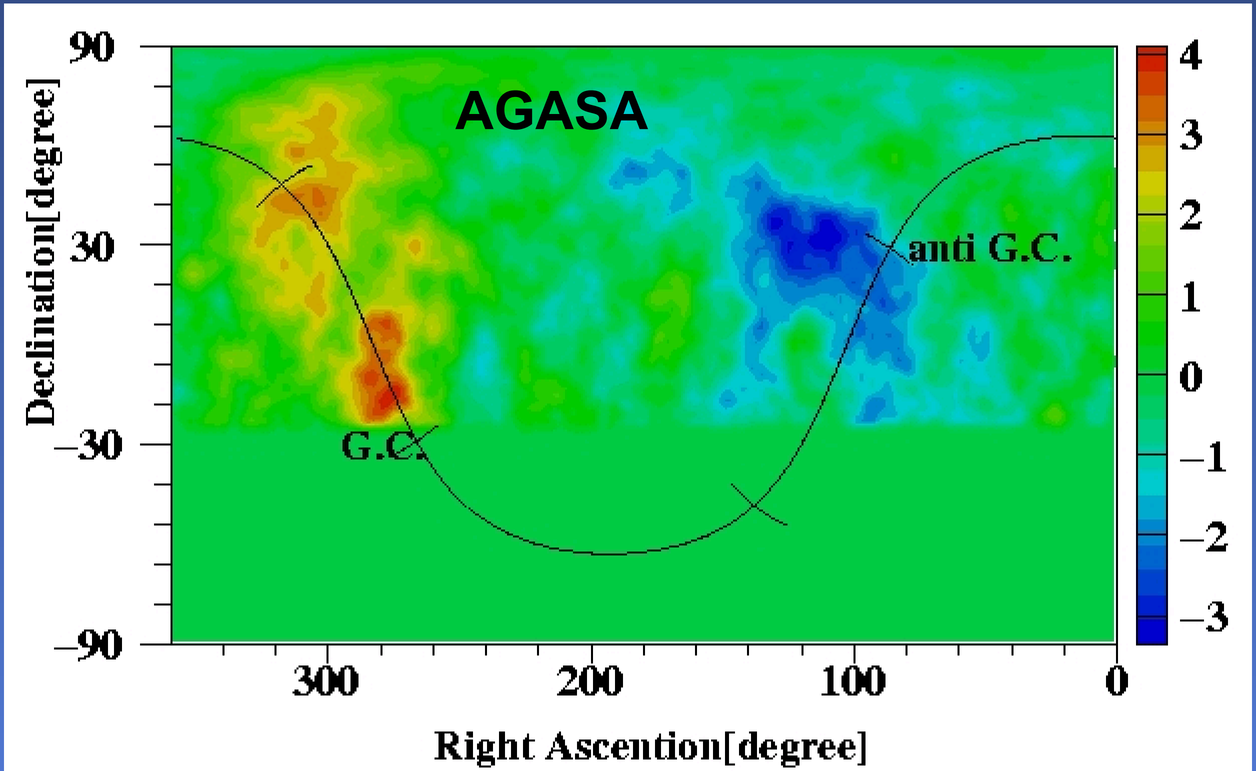
Reconstruction errors only

Anisotropies

- **It is extremely difficult to measure anisotropies in the sky which populate a narrow energy band in a rapidly falling energy spectrum.**
  - The energy search window must be carefully tuned to coincide with the true energy band of any excess. Otherwise the isotropic lower energy background swamps the signal.
  - Systematic errors in the energy measurement can easily contaminate the population of the energy window.
  - Precise angular resolution is needed to detect sources with small intrinsic angular scales. Otherwise the off-source background flux dominates.

- **Furthermore, low statistics require that the energy and angular windows be pre-defined so that the statistical significance of excesses can be evaluated**

Previous Observations of the Galactic Center



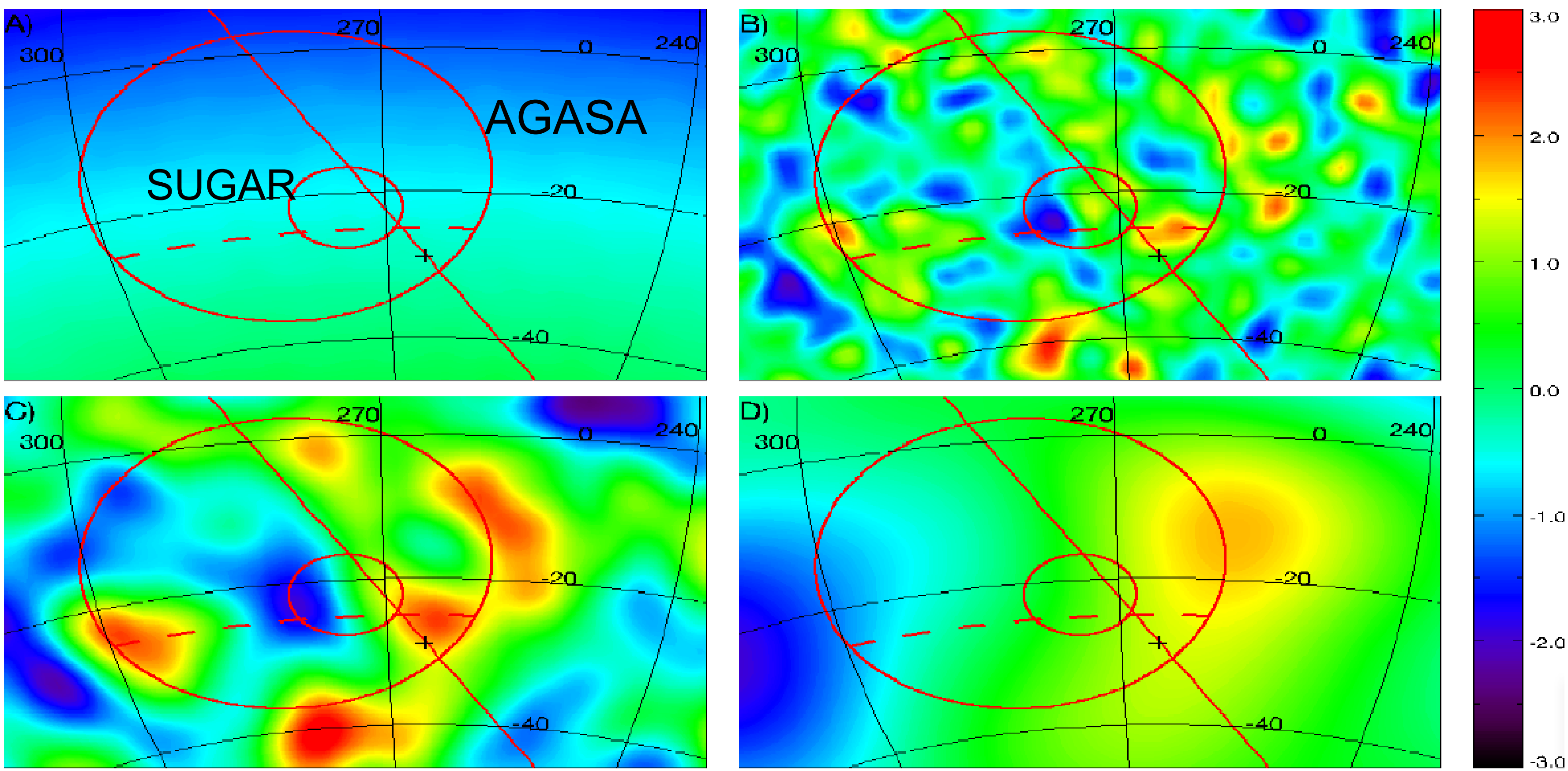
- 22% excess seen at 4.5σ by AGASA with a partial 20 degree tophat window (centered near the GC) with E=1-2.5EeV.
- SUGAR sees a 2.9σ excess with a 5.5 degree window at a slightly different location near the GC with E=0.8-3.2EeV.

•To propagate through the Galactic magnetic fields, the particles are postulated to be neutral, and perhaps to be neutrons from p-p scattering.

Auger: No excess seen in either region

Our coverage map by shuffling event zenith, day, hour

Events smoothed with true resolution, Energy = 0.8-3.2 EeV



Significance of excess or deficit

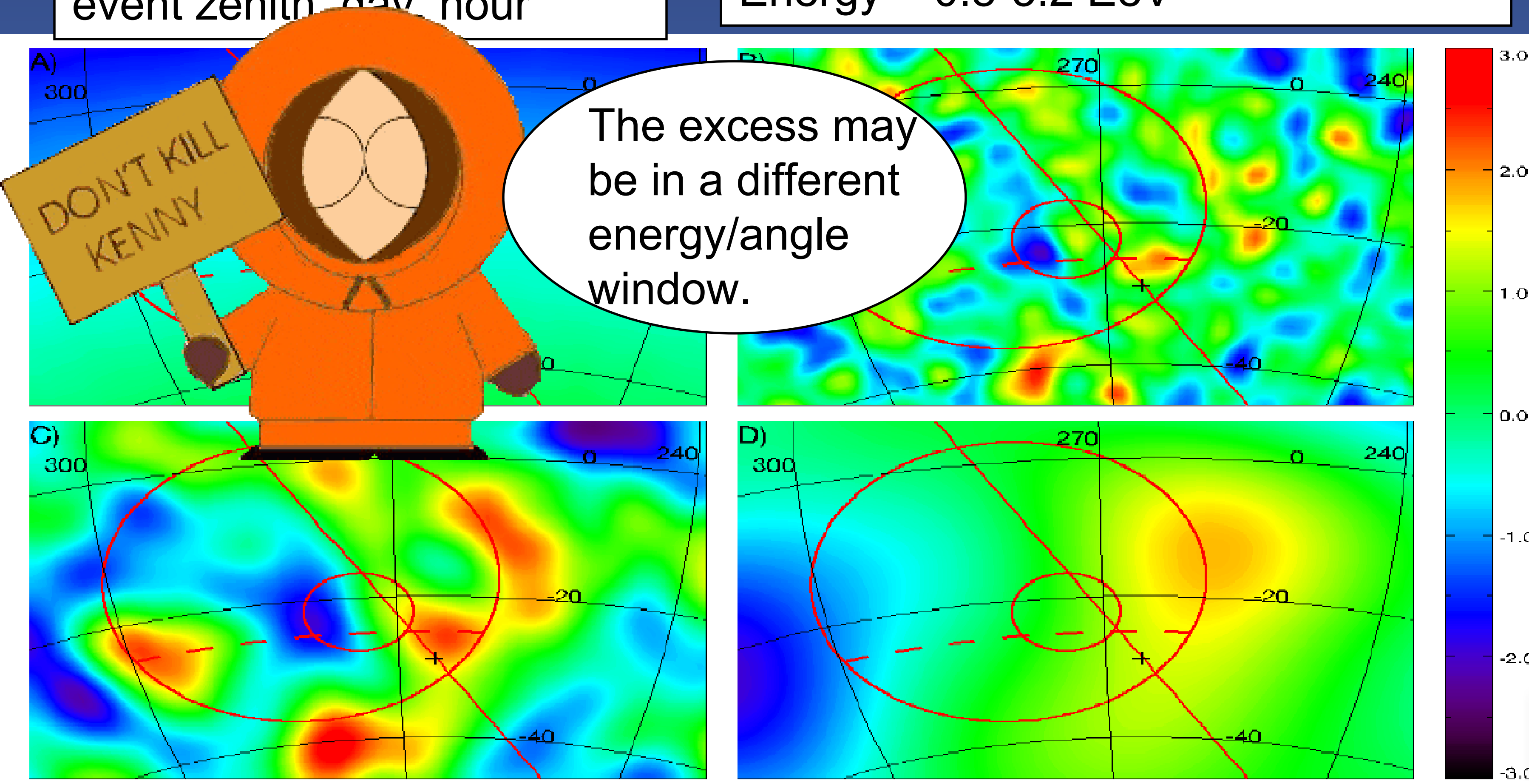
Smoothed at SUGAR scale, SUGAR energy window

Smoothed at AGASA scale, AGASA energy window

Auger: No excess seen in either region

Coverage map by shuffling event zenith, day, hour

Events smoothed with true resolution, Energy = 0.8-3.2 EeV



Significance of excess or deficit

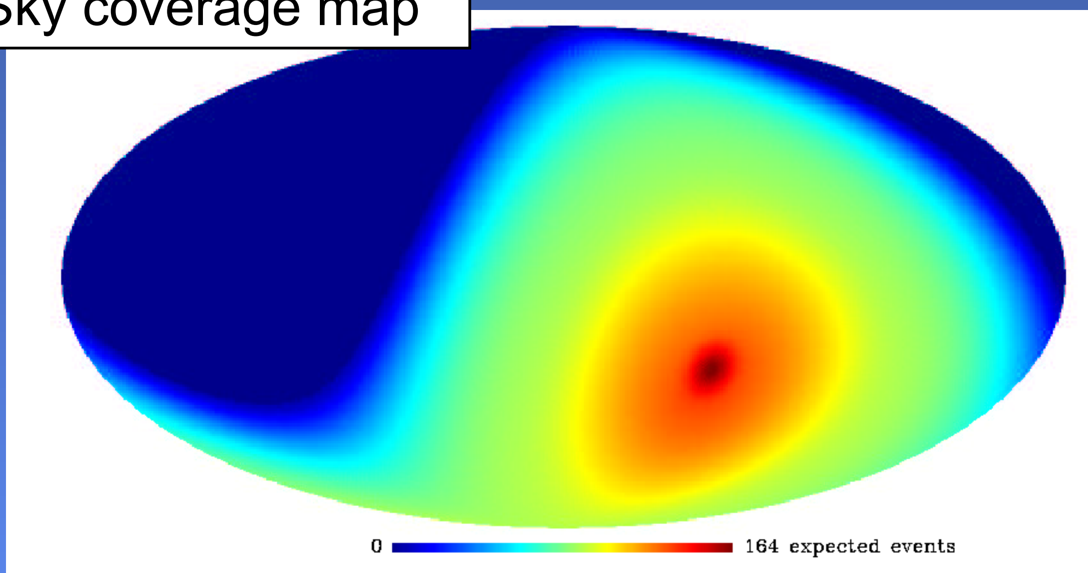
Smoothed at SUGAR scale, SUGAR energy window

Smoothed at AGASA scale, AGASA energy window

Search for localized excesses

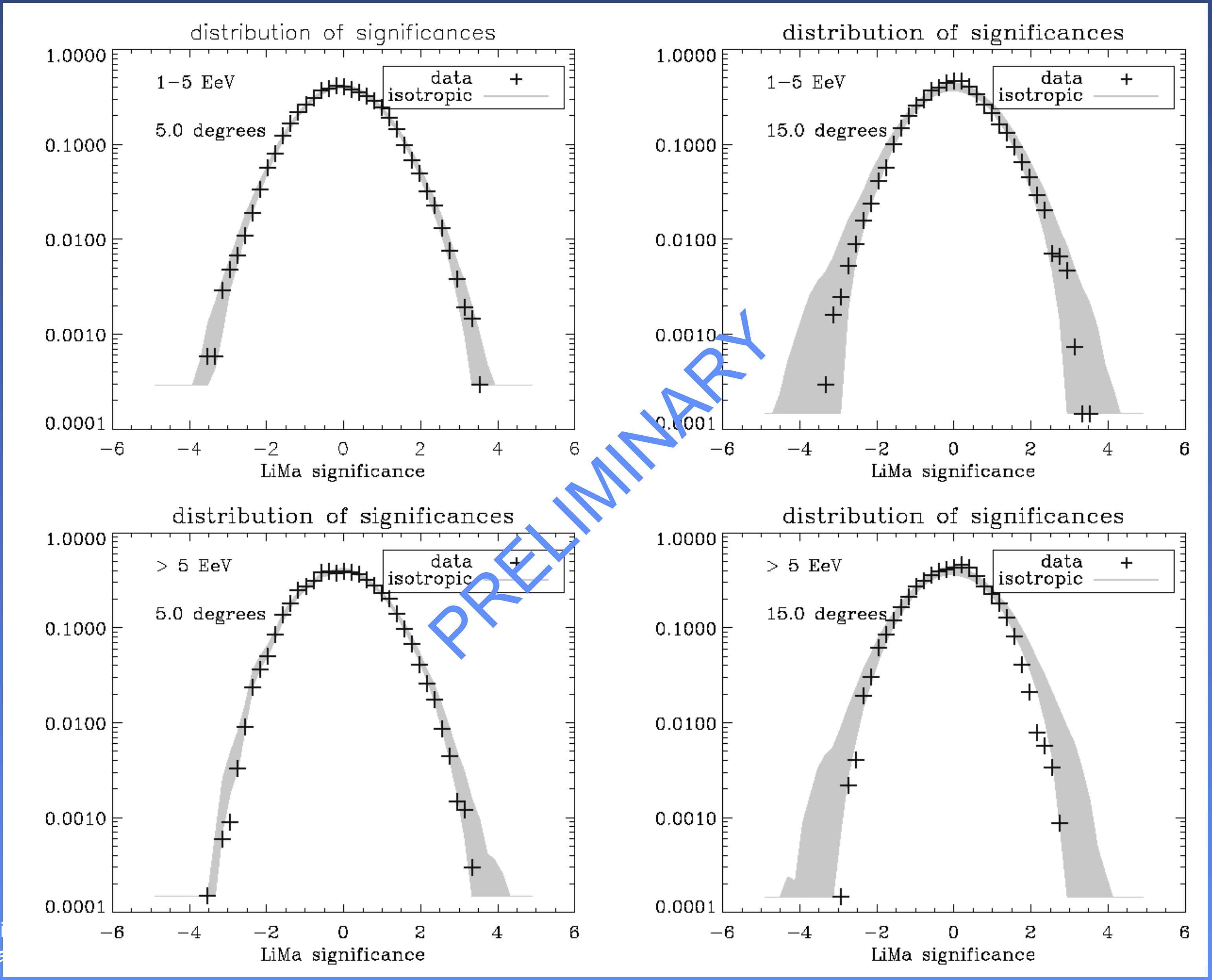
- Predefined search parameters:
  - E=1-5 EeV, or E>5 EeV
  - Angular scale=5 degrees, or 15 degrees (tophat)
  - Uses Monte Carlo energy converter instead of CIC (for now)

Sky coverage map



Look for excesses with tophats centered on each of 50K HEALPIX pixels (1 square degree)

So far, the data is consistent with isotropy



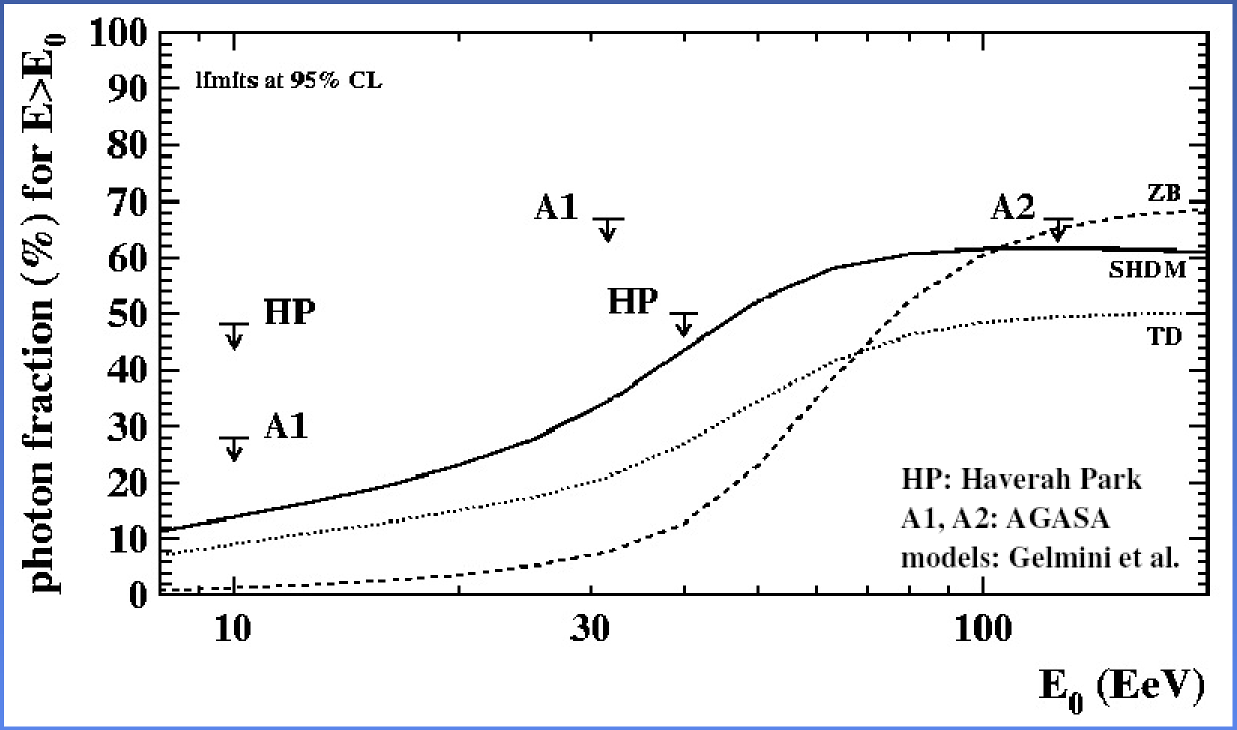
Other pre-defined targets not seen either with any large significance.

Target	$\ell(°)$	$b(°)$	Radius	$\log(E/\text{EeV})$	Found	Exp.	Prob	Req. Prob
GC 1	0.00	0.00	15°	$\geqslant 18$	155	167.3	-	0.0035
GC 2	0.00	0.00	Point (2°)	$18 - 18.5$	2	2.5	-	0.00025
AGASA SUGAR	7.00	0.00	Point (2°)	$18 - 18.5$	3	2.69	0.43	0.00025
NGC0253	88.92	-87.80	5°	$\geqslant 19.5$	0	0.01	-	0.00005
NGC3256	277.56	11.49	5°	$\geqslant 19.5$	0	0.01	-	0.00005
Centaurus A	309.43	19.44	5°	$\geqslant 19.5$	0	0.01	-	0.00005

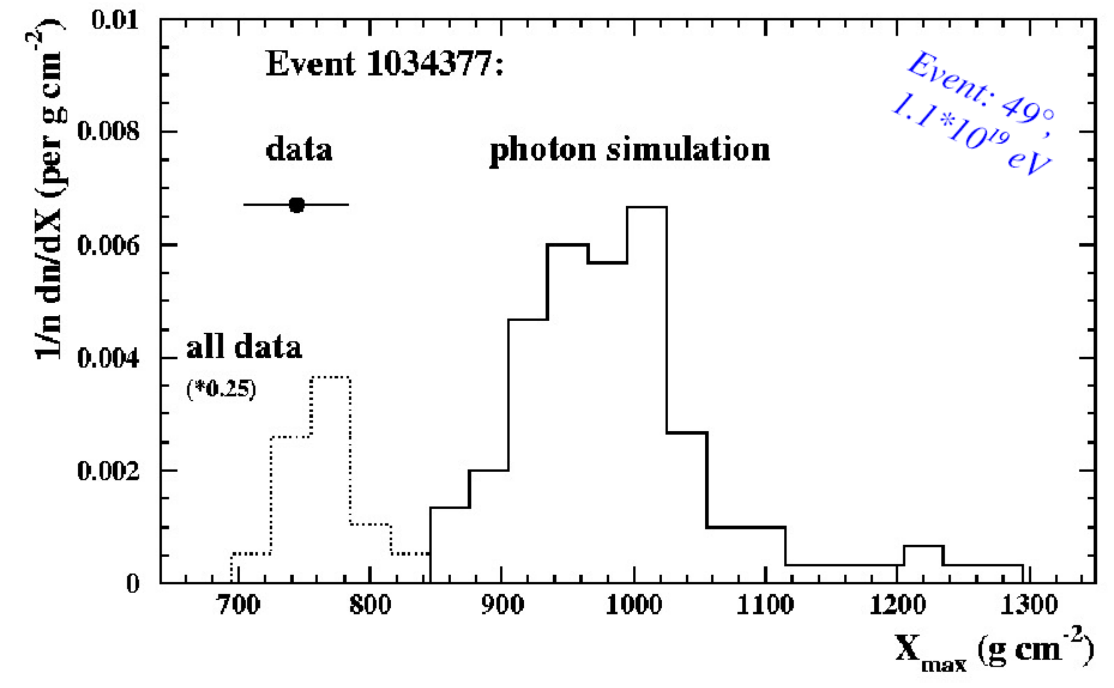
Caveats: This analysis still uses the old MC-derived energy converter. Empirical CIC analysis is in progress, and should in principle improve the significance of excesses due to true sources.

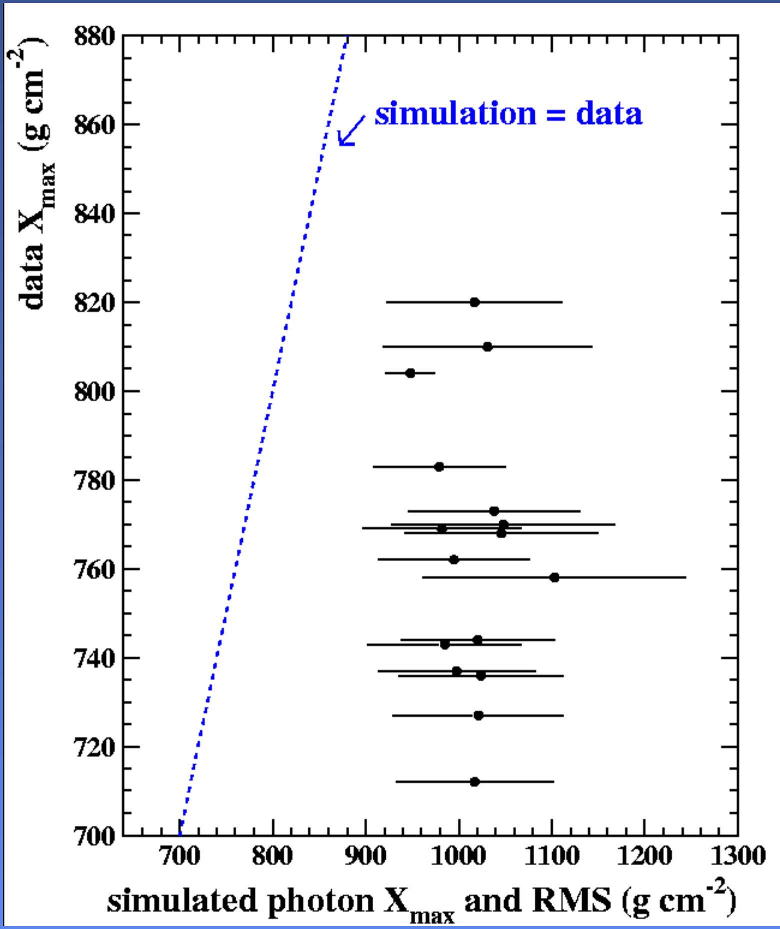
Photon Limit

- All top-down models predict a large flux of photon primaries at some energy scale



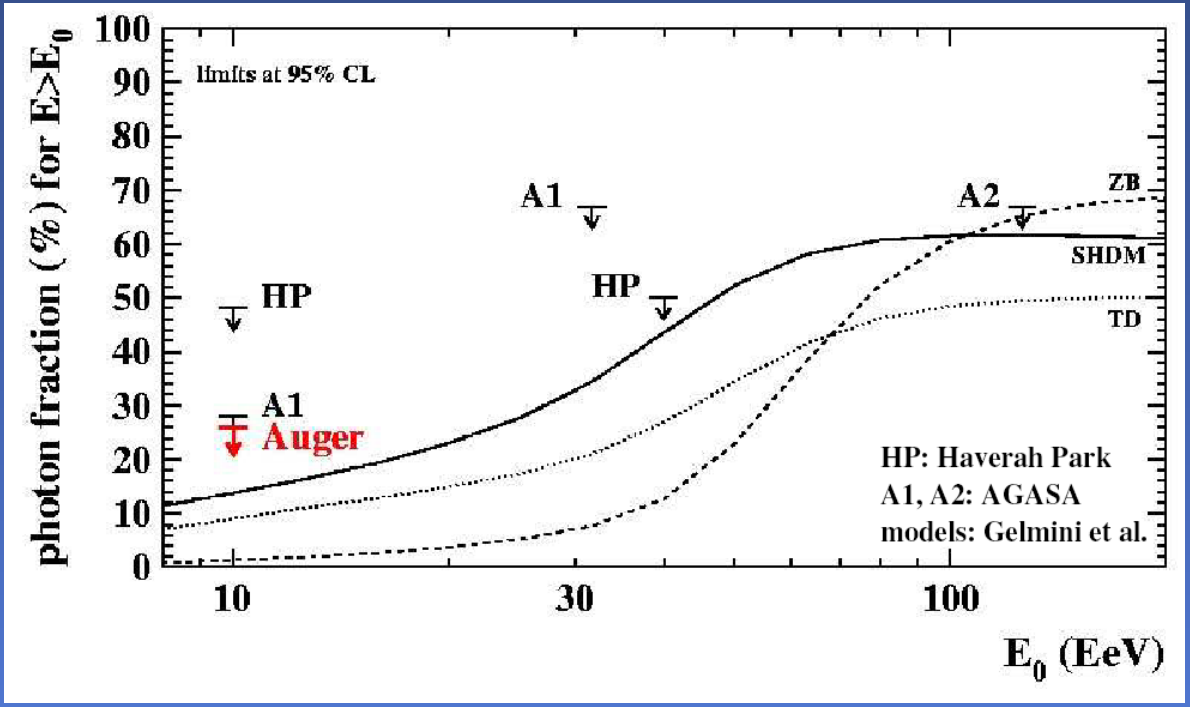
For each of 16 selected hybrid events (tracklength>450g/cm2), simulate 100 photon showers



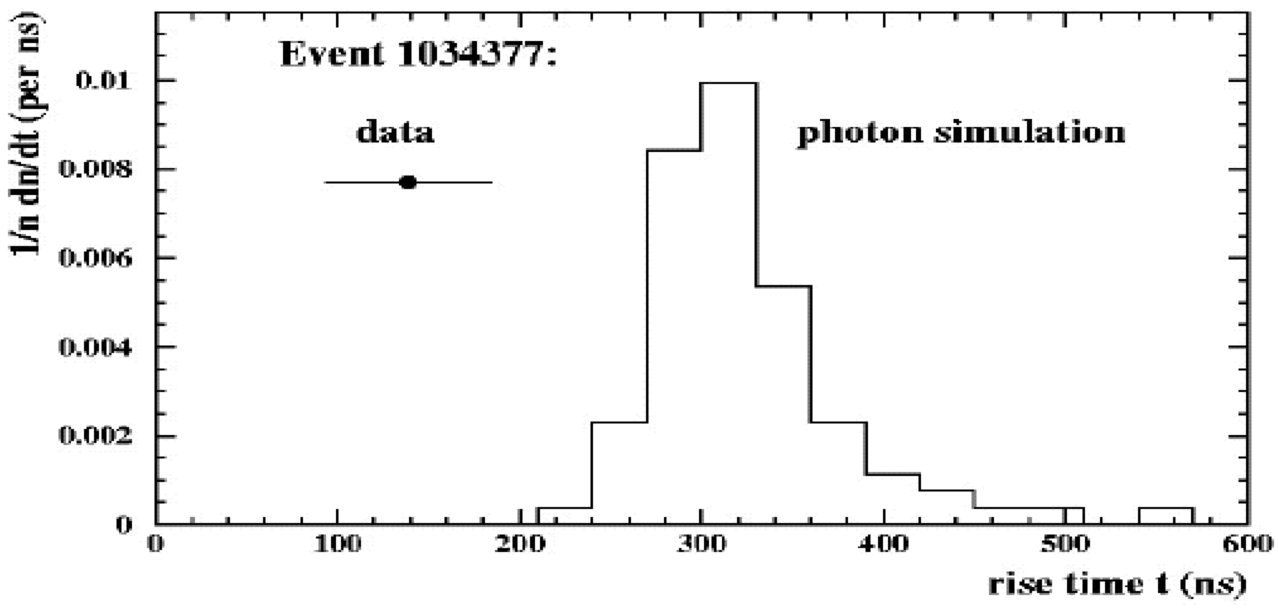


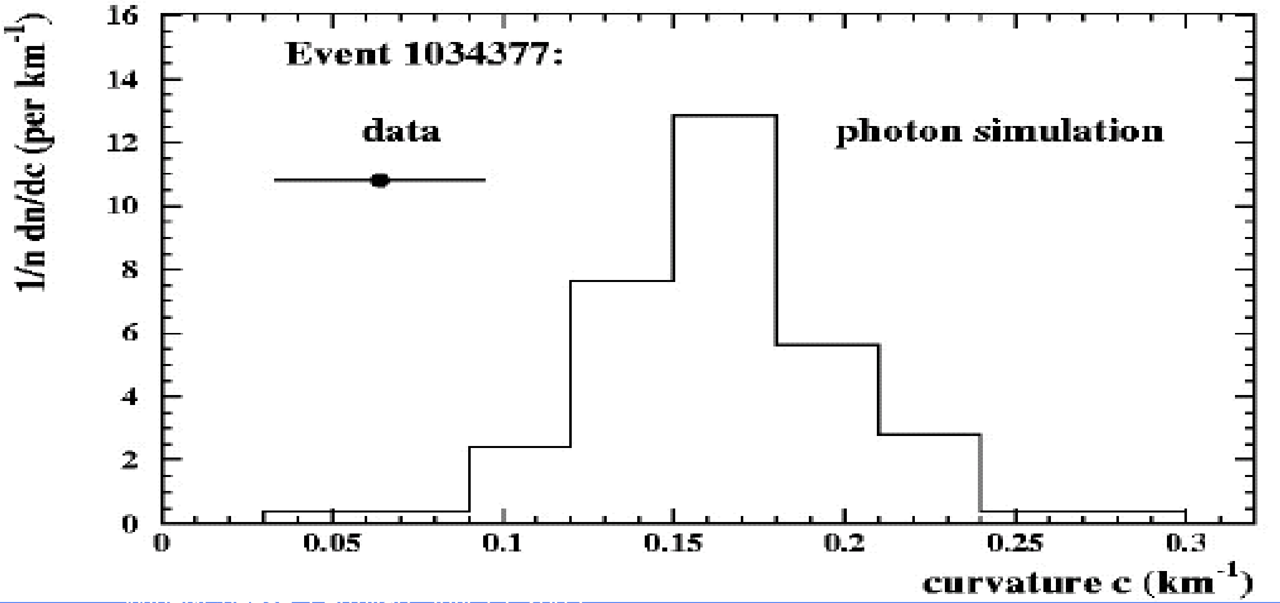
- Sample the distributions to compute the limit such that in 95% of mock experiments, a better limit is set.

Photon Fraction Limit Result



- Photon Fraction <26% at 95%CL for the integrated flux of cosmic rays with E > 10 EeV.
- Technique is applicable for low statistics datasets at high E.





Composition Sensitive SD observables

Risetime→ Muon flux

Curvature→Xmax

Summary

- **With only 25% of a full Auger-year exposure, we have already:**
  - **Defined our empirical spectrum analysis strategy and produced our first model-independent spectrum**
  - **Performed first studies of anisotropies in the sky**
  - **Defined a procedure for setting photon fraction limits with low statistics.**

Future Plans

- Complete Auger South by mid 2006 (funding dependent)
  - Full aperture > 7000 km2 sr
- Fully understand our instruments.
- Use rapidly expanding data set (x7 in two years) to enable
  - Improved energy assignment
    - *Improve LDF measurements → Reduce systematic errors in reconstructing events*
    - *Energy dependent CIC functions*
    - *Reduce error from extrapolating converter to high energies*
  - High statistics study of the trans-GZK spectrum
  - Anisotropy studies and point source searches.
  - Primary composition and hadronic interaction studies
- Exploit events beyond a zenith angle of 60º
  - search for neutrinos and exotics
- Begin work on Auger North