The analysis of hybrid events in Auger

Francesco Salamida
University of L'Aquila & INFN

for the Pierre Auger Collaboration

RICAP 07

June 21, 2007

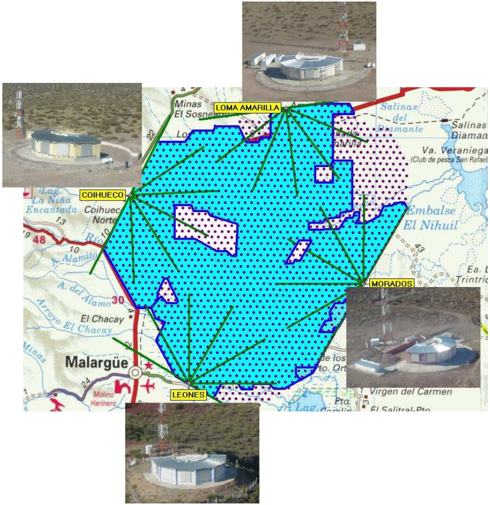
PIERRE
AUGER
OBSERVATORY

Outline

- The Pierre Auger Observatory
- The Hybrid Concept
- Performance of the Hybrid Detector
- Brass Hybrid Events
- Selection of Hybrid Data Sample
- The Hybrid Exposure Calculation
- Conclusions

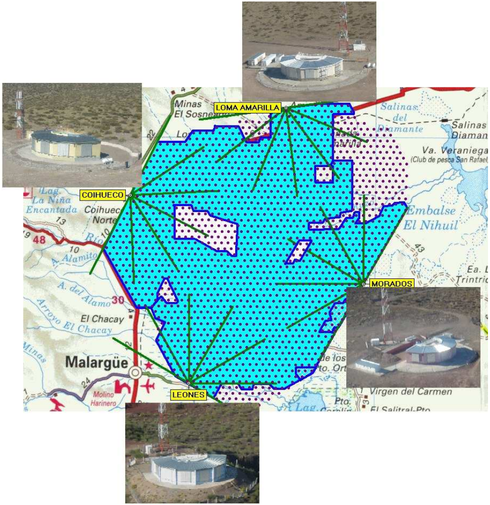
The Pierre Auger Observatory

Malargüe (Argentina) 1400 m a.s.l ($\simeq$ 875 g/cm^2)
35° S latitude - 69° W longitude
Low population density ($< 0.1/\text{km}^2$), good atmospheric conditions (clouds, aerosol ...)



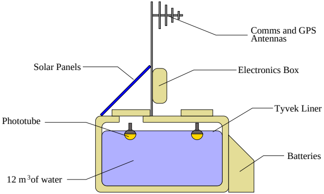
The Pierre Auger Observatory

Malargüe (Argentina) 1400 m a.s.l ($\simeq$ 875 g/cm^2)
35° S latitude - 69° W longitude
Low population density (< 0.1/km^2), good atmospheric conditions (clouds, aerosol ...)



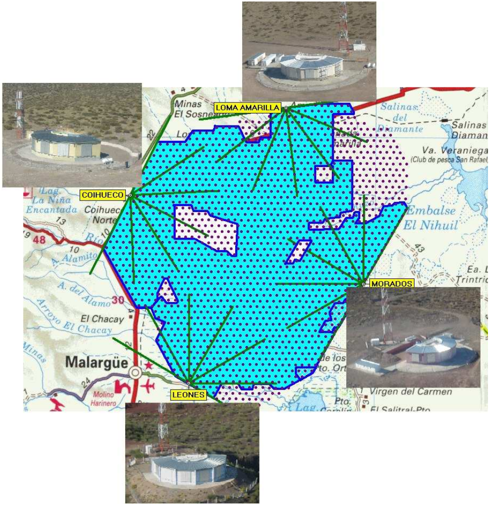
Surface Array(SD)

1600 Cerenkov Detectors - 1307 working
1.5 km spacing
3000 km^2



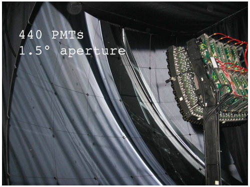
The Pierre Auger Observatory

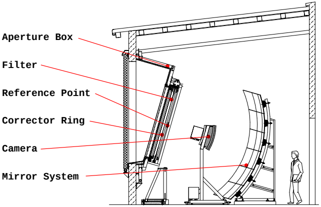
Malargüe (Argentina) 1400 m a.s.l ($\simeq$ 875 g/cm^2)
35° S latitude - 69° W longitude
Low population density (< 0.1/km^2), good atmospheric conditions (clouds, aerosol ...)



Fluorescence Detector(FD)

4 fluorescence buildings(Eyes) - 4 working
6 telescopes per eye
telescope f.o.v 30° × 30°





PIERRE AUGER OBSERVATORY

The Hybrid Concept I

Three Detection Strategies:

SD Only

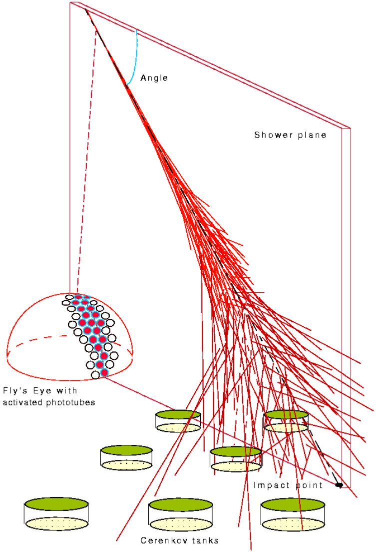
- Lateral Distribution → Energy
- Time → direction

FD Only

- Longitudinal development → Energy
- Fluorescence Image + Time → direction

(SD + FD) → Hybrid

- Better geometric reconstruction
- then a more reliable energy measurement
- mass composition studies from X_{max}.



PIERRE AUGER OBSERVATORY

The Hybrid Concept I

Three Detection Strategies:

SD Only

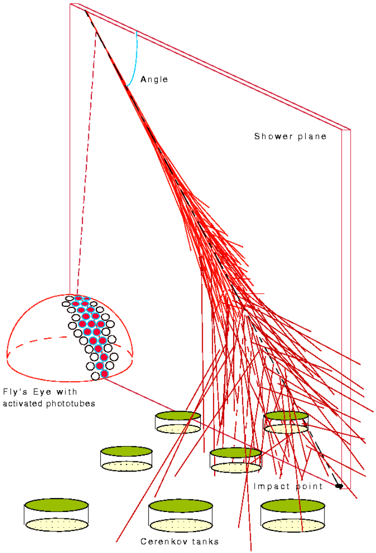
- Lateral Distribution → Energy
- Time → direction

FD Only

- Longitudinal development → Energy
- Fluorescence Image + Time → direction

(SD + FD) → Hybrid

- Better geometric reconstruction
- then a more reliable energy measurement
- mass composition studies from X_{max}.



PIERRE AUGER OBSERVATORY

The Hybrid Concept I

Three Detection Strategies:

SD Only

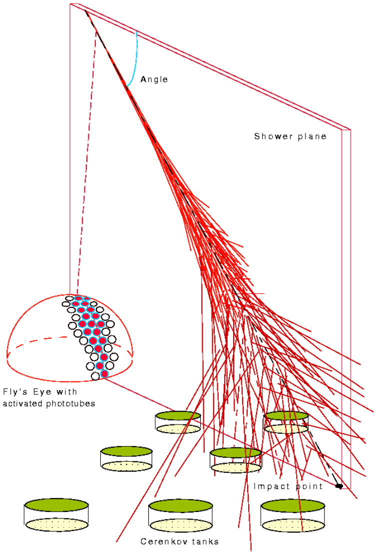
- Lateral Distribution → Energy
- Time → direction

FD Only

- Longitudinal development → Energy
- Fluorescence Image + Time → direction

(SD + FD) → Hybrid

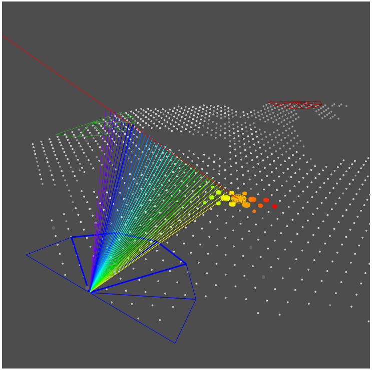
- Better geometric reconstruction
- then a more reliable energy measurement
- mass composition studies from X_{max}.

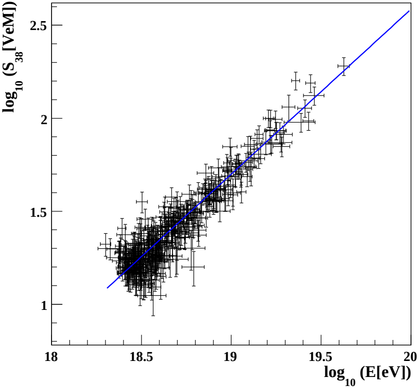


The Hybrid Concept II - Golden Hybrid Events

Events with independent SD and Hybrid trigger and reconstruction

SD absolute Energy Calibration from FD





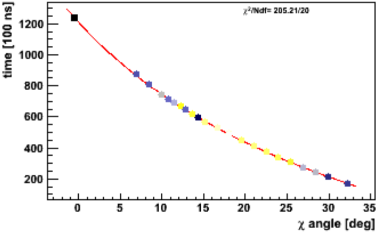
S_{38} is the particle density at 1000 m from the core referred to 38° with the CIC method.

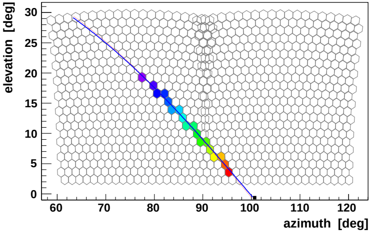
$$
\begin{aligned}
\lg E_{FD} &= A + B \cdot \lg S_{38} \\
A &= 17.8 \pm 0.03;\ B = 1.13 \pm 0.02
\end{aligned}
$$

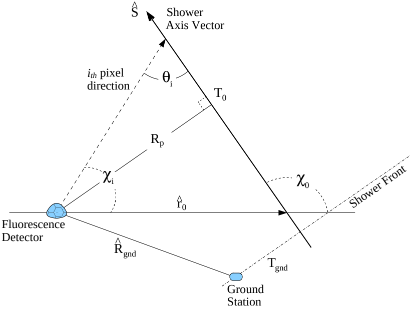
PIERRE AUGER OBSERVATORY

The Hybrid Concept III - Brass Hybrid Events

Hybrids events with at least one triggered tank







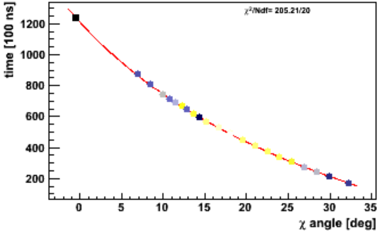
$$\chi^2 = \sum_i w_1(\vec{r}_i \cdot \vec{n})^2;$$

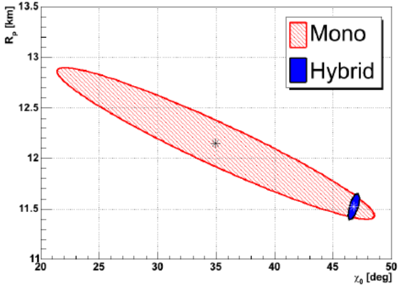
$$\hat{t}_i = T_0 + \frac{R_p}{c}\tan\left(\frac{\chi_0 - \chi_i}{2}\right);$$

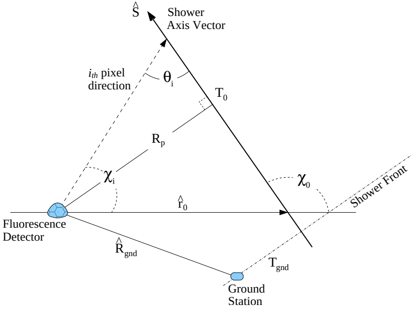
PIERRE
AUGER
OBSERVATORY

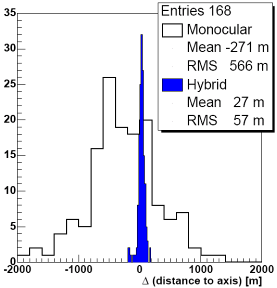
The Hybrid Concept III - Brass Hybrid Events

Hybrids events with at least one triggered tank









PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - Data Selection

December 2004 - February 2007

Cuts to improve the quality of the sample

geometry

- zenith angle $< 60^\circ$
- axis-tank distance $< 750m$
- energy dependent fiducial volume (ICRC 07)

profile

1816 events surviving $\Rightarrow \sim 26\%$

Analysis of Brass Hybrid Events - Data Selection

December 2004 - February 2007

Cuts to improve the quality of the sample

geometry

- zenith angle $< 60^\circ$
- axis-tank distance $< 750m$
- energy dependent fiducial volume (ICRC 07)

profile

1816 events surviving $\Rightarrow \sim 26\%$

PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - Data Selection

December 2004 - February 2007

Cuts to improve the quality of the sample

geometry

- zenith angle $< 60^\circ$
- axis-tank distance $< 750m$
- energy dependent fiducial volume (ICRC 07)

profile

- X_{max} observed
- energy reconstruction uncertanties $< 20\%$
- Cherenkov contamination $< 50\%$
- profile fit quality $\chi^2/ndof < 2.5$

1816 events surviving $\Rightarrow \sim 26\%$

PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - Data Selection

December 2004 - February 2007

Cuts to improve the quality of the sample

geometry

- zenith angle $< 60^\circ$
- axis-tank distance $< 750m$
- energy dependent fiducial volume (ICRC 07)

profile

- X_{max} observed
- energy reconstruction uncertanties $< 20\%$
- Cherenkov contamination $< 50\%$
- profile fit quality $\chi^2/ndof < 2.5$

1816 events surviving $\Rightarrow \sim 26\%$

PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - Data Selection

December 2004 - February 2007

Cuts to improve the quality of the sample

geometry

- zenith angle $< 60^\circ$
- axis-tank distance $< 750m$
- energy dependent fiducial volume (ICRC 07)

profile

- X_{max} observed
- energy reconstruction uncertanties $< 20\%$
- Cherenkov contamination $< 50\%$
- profile fit quality $\chi^2/ndof < 2.5$

1816 events surviving $\Rightarrow \sim 26\%$

PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - Hybrid Exposure Calculation I

For a given Detector configuration:

$\mathcal{E}(E) = \mathcal{A}(E) \cdot T$

$\mathcal{A}(E) = \int_{\Omega} \int_{A_{gen}} \varepsilon \mathrm{d}S \cos\theta \mathrm{d}\Omega$

Hybrid detector configuration continuosly change

End-to-End Exposure

Simulate a sample of events that reproduce the exact conditions of the experiment in the selected time interval.

PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - Hybrid Exposure Calculation I

For a given Detector configuration:

$\mathcal{E}(E) = \mathcal{A}(E) \cdot T$

$\mathcal{A}(E) = \int_{\Omega} \int_{A_{gen}} \varepsilon \mathrm{d}S \cos\theta \mathrm{d}\Omega$

Hybrid detector configuration continuosly change

End-to-End Exposure

Simulate a sample of events that reproduce the exact conditions of the experiment in the selected time interval.

PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - Hybrid Exposure Calculation I

For a given Detector configuration:

$$\mathcal{E}(E) = \mathcal{A}(E) \cdot T$$

$$\mathcal{A}(E) = \int_{\Omega} \int_{A_{gen}} \varepsilon \mathrm{d}S \cos\theta \mathrm{d}\Omega$$

Hybrid detector configuration continuosly change

End-to-End Exposure

Simulate a sample of events that reproduce the exact conditions of the experiment in the selected time interval.

Analysis of Brass Hybrid Events - Hybrid Exposure Calculation I

For a given Detector configuration:

$\mathcal{E}(E) = \mathcal{A}(E) \cdot T$

$\mathcal{A}(E) = \int_{\Omega} \int_{A_{gen}} \varepsilon \mathrm{d}S \cos\theta \mathrm{d}\Omega$

Hybrid detector configuration continuosly change

- SD configuration (DAQ, Array Status)
- FD configuration (eyes, telescopes, pixels)
- Environmental effects on detector response (Moon, atmosphere ...)

$\mathcal{E}(E) = \int_{T} \int_{\Omega} \int_{A_{gen}} \varepsilon(E, T) \mathrm{d}S \cos\theta \mathrm{d}\Omega \mathrm{d}T$

End-to-End Exposure

Simulate a sample of events that reproduce the exact conditions of the experiment in the selected time interval.

Analysis of Brass Hybrid Events - Hybrid Exposure Calculation I

For a given Detector configuration:

$\mathcal{E}(E) = \mathcal{A}(E) \cdot T$

$\mathcal{A}(E) = \int_{\Omega} \int_{A_{gen}} \varepsilon \mathrm{d}S \cos\theta \mathrm{d}\Omega$

Hybrid detector configuration continuosly change

- SD configuration (DAQ, Array Status)
- FD configuration (eyes, telescopes, pixels)
- Environmental effects on detector response (Moon, atmosphere ...)

$\mathcal{E}(E) = \int_{T} \int_{\Omega} \int_{A_{gen}} \varepsilon(E, T) \mathrm{d}S \cos\theta \mathrm{d}\Omega \mathrm{d}T$

End-to-End Exposure

Simulate a sample of events that reproduce the exact conditions of the experiment in the selected time interval.

PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - Hybrid Exposure Calculation I

For a given Detector configuration:

$$\mathcal{E}(E) = \mathcal{A}(E) \cdot T$$
$$\mathcal{A}(E) = \int_{\Omega} \int_{A_{gen}} \varepsilon \mathrm{d}S \cos\theta \mathrm{d}\Omega$$

Hybrid detector configuration continuosly change

- SD configuration (DAQ, Array Status)
- FD configuration (eyes, telescopes, pixels)
- Environmental effects on detector response (Moon, atmosphere . . .)

$$\mathcal{E}(E) = \int_{T} \int_{\Omega} \int_{A_{gen}} \varepsilon(E, T) \mathrm{d}S \cos\theta \mathrm{d}\Omega \mathrm{d}T$$

End-to-End Exposure

Simulate a sample of events that reproduce the exact conditions of the experiment in the selected time interval.

PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - Hybrid Exposure Calculation I

For a given Detector configuration:

$$\mathcal{E}(E) = \mathcal{A}(E) \cdot T$$
$$\mathcal{A}(E) = \int_\Omega \int_{A_{gen}} \varepsilon \mathrm{d}S \cos\theta \mathrm{d}\Omega$$

Hybrid detector configuration continuosly change

- SD configuration (DAQ, Array Status)
- FD configuration (eyes, telescopes, pixels)
- Environmental effects on detector response (Moon, atmosphere . . .)

$$\mathcal{E}(E) = \int_T \int_\Omega \int_{A_{gen}} \varepsilon(E, T) \mathrm{d}S \cos\theta \mathrm{d}\Omega \mathrm{d}T$$

End-to-End Exposure

Simulate a sample of events that reproduce the exact conditions of the experiment in the selected time interval.

Analysis of Brass Hybrid Events - Hybrid Exposure Calculation I

For a given Detector configuration:

$\mathcal{E}(E) = \mathcal{A}(E) \cdot T$
$\mathcal{A}(E) = \int_\Omega \int_{A_{gen}} \varepsilon \mathrm{d}S \cos\theta \mathrm{d}\Omega$

Hybrid detector configuration continuosly change

- SD configuration (DAQ, Array Status)
- FD configuration (eyes, telescopes, pixels)
- Environmental effects on detector response (Moon, atmosphere ...)

$\mathcal{E}(E) = \int_T \int_\Omega \int_{A_{gen}} \varepsilon(E, T) \mathrm{d}S \cos\theta \mathrm{d}\Omega \mathrm{d}T$

End-to-End Exposure

Simulate a sample of events that reproduce the exact conditions of the experiment in the selected time interval.

PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - Hybrid Exposure Calculation I

For a given Detector configuration:

$\mathcal{E}(E) = \mathcal{A}(E) \cdot T$
$\mathcal{A}(E) = \int_{\Omega} \int_{A_{gen}} \varepsilon \mathrm{d}S \cos\theta \mathrm{d}\Omega$

Hybrid detector configuration continuosly change

- SD configuration (DAQ, Array Status)
- FD configuration (eyes, telescopes, pixels)
- Environmental effects on detector response (Moon, atmosphere ...)

$\mathcal{E}(E) = \int_{T} \int_{\Omega} \int_{A_{gen}} \varepsilon(E, T) \mathrm{d}S \cos\theta \mathrm{d}\Omega \mathrm{d}T$

End-to-End Exposure

Simulate a sample of events that reproduce the exact conditions of the experiment in the selected time interval.

PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - Hybrid Exposure Calculation II

Time Dependent MonteCarlo Simulation

FD Simulation

- Conex Shower Profiles ⇒ proton an iron form 10^{17} up to 10^{21} eV
- Uptime Information
- Complete FD Trigger Response

SD Simulation

- Fast Simulation - timing of the closest tank
- Actual SD configuration (active tank)
- Parameterization of Hybrid Trigger Response

PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - Hybrid Exposure Calculation II

Time Dependent MonteCarlo Simulation

FD Simulation

- Conex Shower Profiles ⇒ proton an iron form 10^{17} up to 10^{21} eV
- Uptime Information
- Complete FD Trigger Response

SD Simulation

- Fast Simulation - timing of the closest tank
- Actual SD configuration (active tank)
- Parameterization of Hybrid Trigger Response

Analysis of Brass Hybrid Events - Hybrid Exposure Calculation II

Time Dependent MonteCarlo Simulation

FD Simulation

- Conex Shower Profiles ⇒ proton an iron form 10^{17} up to 10^{21} eV
- Uptime Information
- Complete FD Trigger Response

SD Simulation

- Fast Simulation - timing of the closest tank
- Actual SD configuration (active tank)
- Parameterization of Hybrid Trigger Response

PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - Uptime Evaluation I

Efficiency of hybrid data taking

Hybrid Uptime Contributions

- Probability of open shutters
- DAQ deadtime
- Telescope in DAQ
- Lidar activity rejection
- CDAS protection veto
- SD *"bad periods"*

Probability for a telescope to be in DAQ

$$p(i,t) = \varepsilon_{shutters}(i,t) \cdot \varepsilon_{DAQ}(i,t) \cdot \delta(i,t) \cdot \varepsilon_{Lidar}(e,t) \cdot \varepsilon_{T3-veto}(e,t) \cdot \varepsilon_{CDAS}(t)$$

Analysis of Brass Hybrid Events - Uptime Evaluation I

Efficiency of hybrid data taking

Hybrid Uptime Contributions

- Probability of open shutters
- DAQ deadtime
- Telescope in DAQ
- Lidar activity rejection
- CDAS protection veto
- SD *"bad periods"*

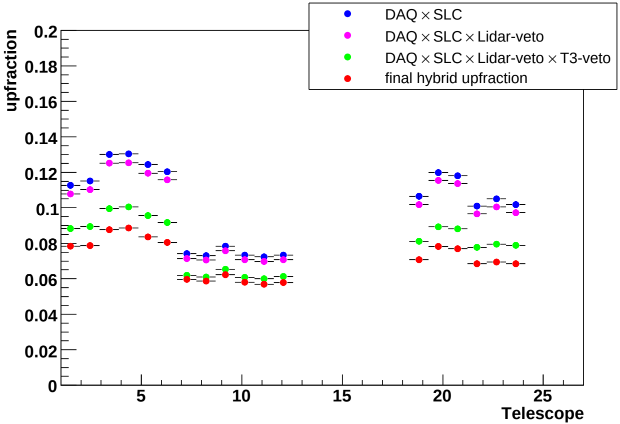
Probability for a telescope to be in DAQ

$$p(i,t) = \varepsilon_{shutters}(i,t) \cdot \varepsilon_{DAQ}(i,t) \cdot \delta(i,t) \cdot \varepsilon_{Lidar}(e,t) \cdot \varepsilon_{T3-veto}(e,t) \cdot \varepsilon_{CDAS}(t)$$

PIERRE AUGER OBSERVATORY

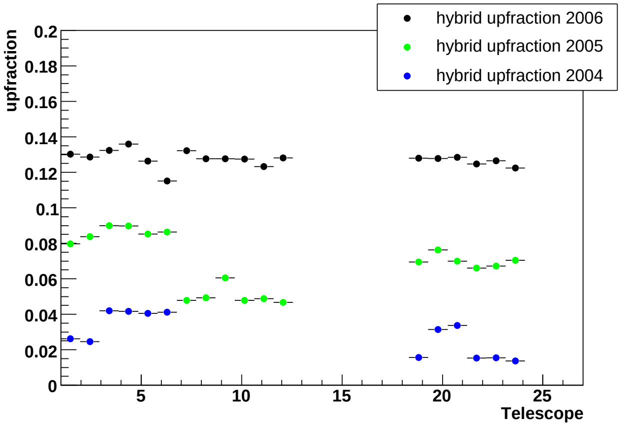
Analysis of Brass Hybrid Events - Uptime Evaluation II

Hybrid Uptime Contributions



Analysis of Brass Hybrid Events - Uptime Evaluation II

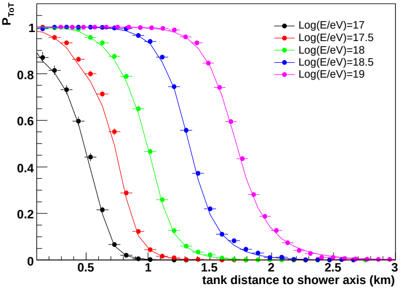
Hybrid Uptime Time Evolution



Analysis of Brass Hybrid Events - Hybrid Trigger Simulation

Parameterization based on the Lateral Trigger Probability (ICRC 05)

- For each active tank within a given radius the ToT probability is calculated based on LTPs
- The event Hybrid Trigger probability is evaluated OR-ing the single tank probabilities
- Hit-or-Miss is used to accept or reject the event



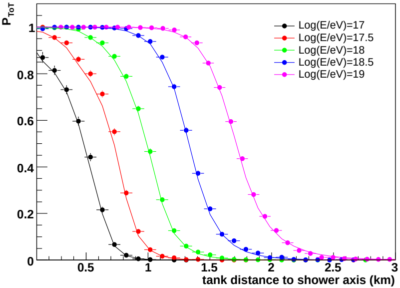
Single tank trigger probabilities as a function of tank-to-axis distance (CORSIKA+Geant4 Offline Full Hybrid Simulation vs parameterization)

PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - Hybrid Trigger Simulation

Parameterization based on the Lateral Trigger Probability (ICRC 05)

- For each active tank within a given radius the ToT probability is calculated based on LTPs
- The event Hybrid Trigger probability is evaluated OR-ing the single tank probabilities
- Hit-or-Miss is used to accept or reject the event

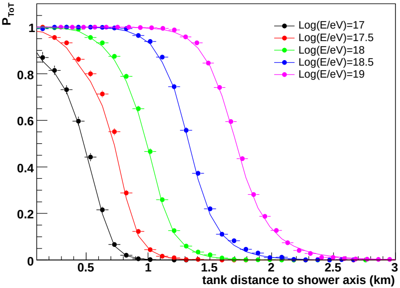


Single tank trigger probabilities as a function of tank-to-axis distance (CORSIKA+Geant4 Offline Full Hybrid Simulation vs parameterization)

Analysis of Brass Hybrid Events - Hybrid Trigger Simulation

Parameterization based on the Lateral Trigger Probability (ICRC 05)

- For each active tank within a given radius the ToT probability is calculated based on LTPs
- The event Hybrid Trigger probability is evaluated OR-ing the single tank probabilities
- Hit-or-Miss is used to accept or reject the event

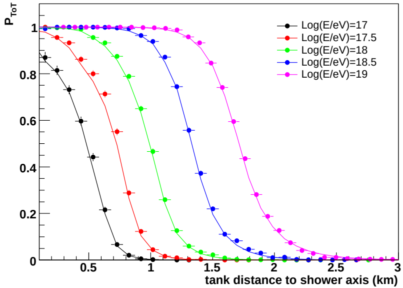


Single tank trigger probabilities as a function of tank-to-axis distance (CORSIKA+Geant4 Offline Full Hybrid Simulation vs parameterization)

Analysis of Brass Hybrid Events - Hybrid Trigger Simulation

Parameterization based on the Lateral Trigger Probability (ICRC 05)

- For each active tank within a given radius the ToT probability is calculated based on LTPs
- The event Hybrid Trigger probability is evaluated OR-ing the single tank probabilities
- Hit-or-Miss is used to accept or reject the event



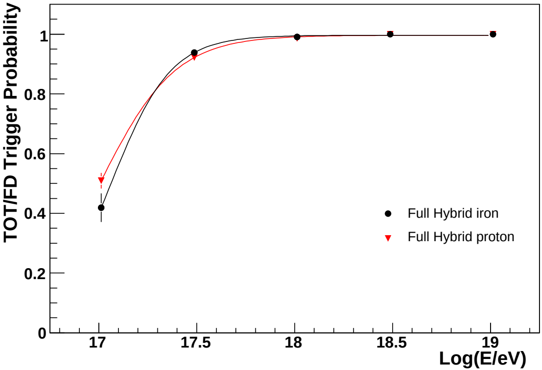
Single tank trigger probabilities as a function of tank-to-axis distance (CORSIKA+Geant4 Offline Full Hybrid Simulation vs parameterization)

PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - LTP vs Full Simulation

ToT trigger efficiency relative to FD

For Log(E/eV) $\gtrsim$ 18:



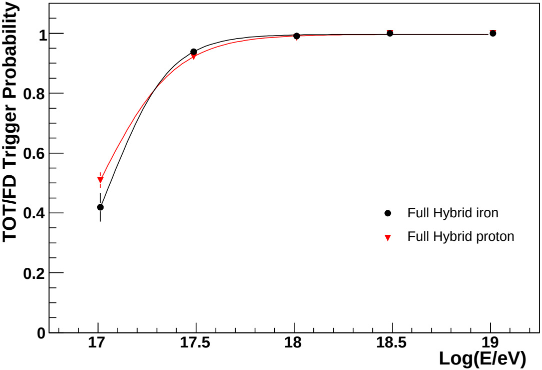
PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - LTP vs Full Simulation

ToT trigger efficiency relative to FD

For Log(E/eV) $\gtrsim$ 18:

- each FD is hybrid
- NO bias due to mass composition



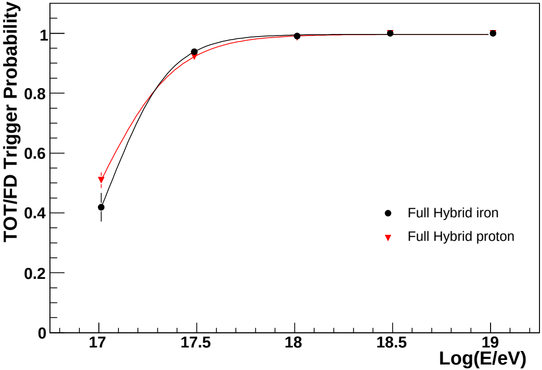
PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - LTP vs Full Simulation

ToT trigger efficiency relative to FD

For Log(E/eV) $\gtrsim$ 18:

- each FD is hybrid
- NO bias due to mass composition



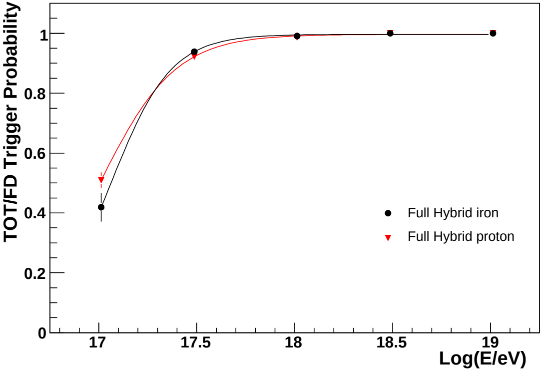
PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - LTP vs Full Simulation

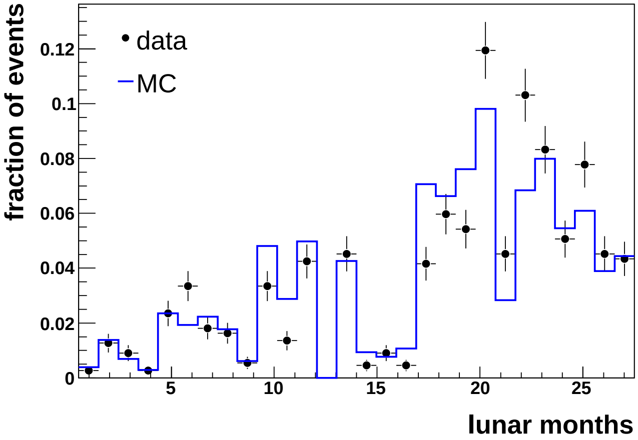
ToT trigger efficiency relative to FD

For Log(E/eV) $\gtrsim$ 18:

- each FD is hybrid
- NO bias due to mass composition



Analysis of Brass Hybrid Events - Time Dependent Simulation I

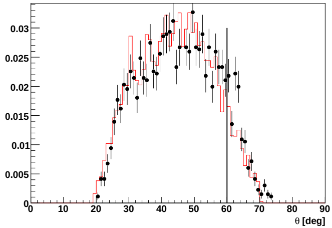


The dependence of detector configurations on time is well reproduced by the simulation

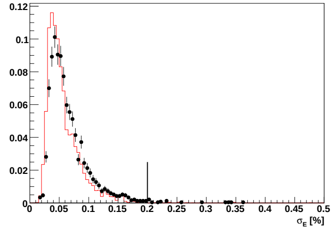
PIERRE AUGER OBSERVATORY

Analysis of Brass Hybrid Events - Data Selection

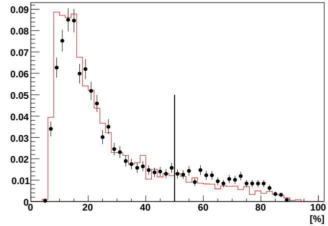
Data - MonteCarlo Comparison



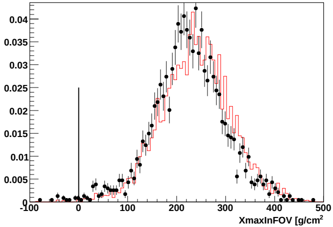
zenith angle $< 60^\circ$



energy reconstruction uncertanties $< 20\%$

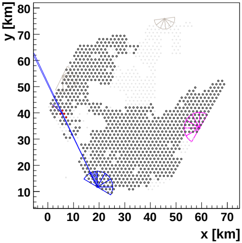


Cherenkov contamination $< 50\%$

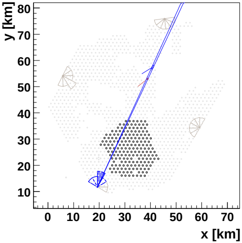


X_{max} observed

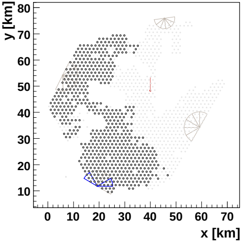
Analysis of Brass Hybrid Events - Time Dependent Simulation II



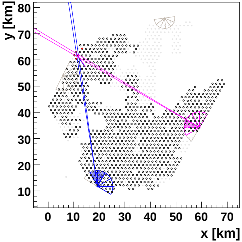
2005/12/08



2004/02/19



2006/01/25

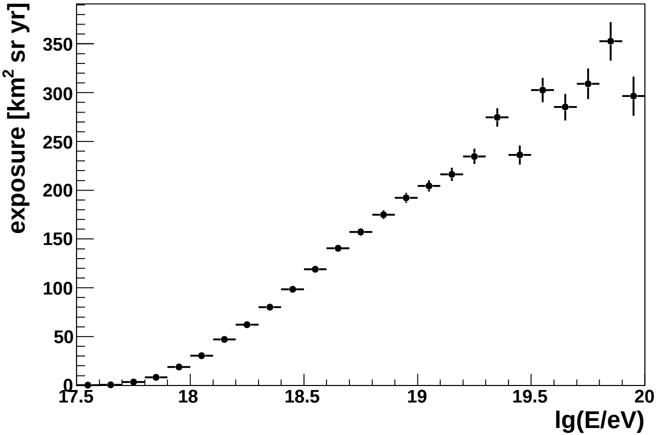


2006/04/28

PIERRE AUGER
OBSERVATORY

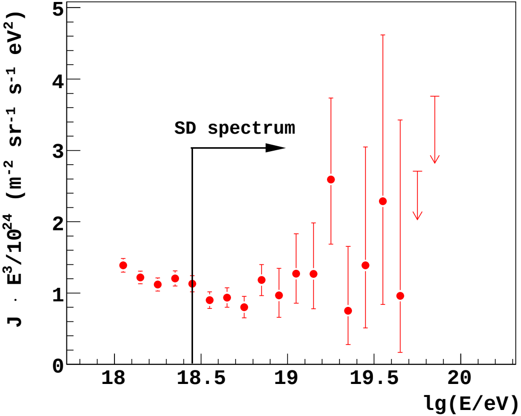
Analysis of Brass Hybrid Events - Hybrid Exposure

Applying all the data selection cuts on the Montecarlo one gets the Hybrid Exposure at Reconstruction Level.



Analysis of Brass Hybrid Events - The Hybrid Spectrum

$$J(E) = \frac{1}{\Delta E} \frac{N^D(E)}{\mathcal{E}(E)}$$



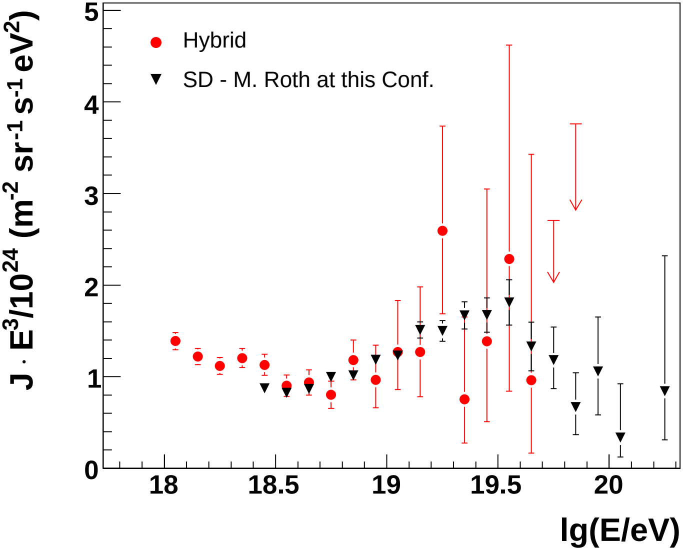
PIERRE AUGER OBSERVATORY

Conclusions

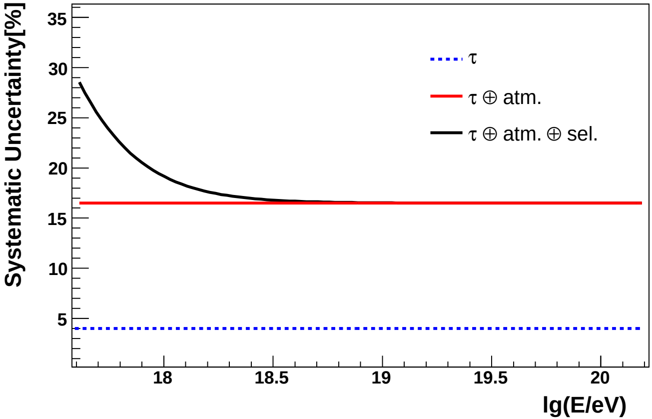
- A class of events "Brass Hybrids" has been characterized as a suitable sample for physics analysis;
- the spectrum of Ultra High Energy Cosmic Rays has been evaluated "for the first time" in the energy region above 10^{18} eV;
- in spite of the low statistics the use of Brass Hybrid events allows to extend the Auger spectrum below $10^{18.5}$ eV;
- these events allow a robust determination of X_{max} and consequently a more reliable mass composition study(see H. Geenen at this conference)

PIERRE AUGER OBSERVATORY

FD - SD Comparison



Hybrid Spectrum Systematics



Uptime 4%, Atmosphere 16%, energy scale 22% → selection 15% at 10^{18} eV.

PIERRE AUGER OBSERVATORY