Search for sources of cosmic rays through anisotropy and chemical composition in the highest energy data of the Pierre Auger Observatory

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PLANNING

INTRODUCTION

- Ultra-high energy cosmic rays
- The Pierre Auger Observatory

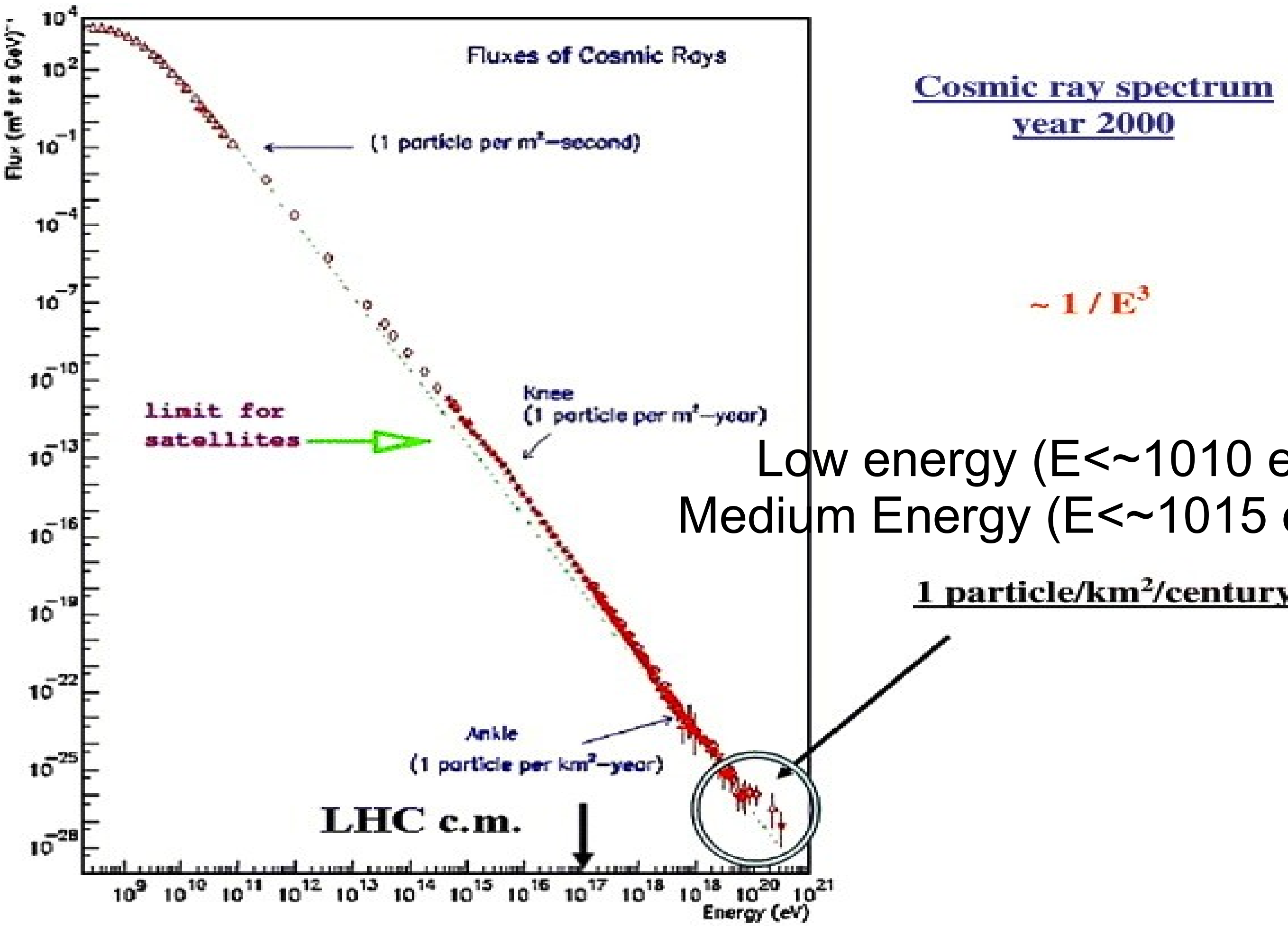
MY WORK

- **Search for point sources:**
  - VCV update
  - CenA
  - New catalogs
  - TA comparison
- **Mass discrimination**
  - Mass-sensitive observables
  - Multi-variate Analyisis
  - Beyond 2015
- **Detector understanding**
  - PMTs issues
  - Event selection
  - Stability in time

INTRODUCTION

Cosmic Rays

Cosmic rays are mainly **charged particles** observed with energies up to ~10^{20} eV (~100 EeV).



Low energy (E<~1010 eV) → Solar origin

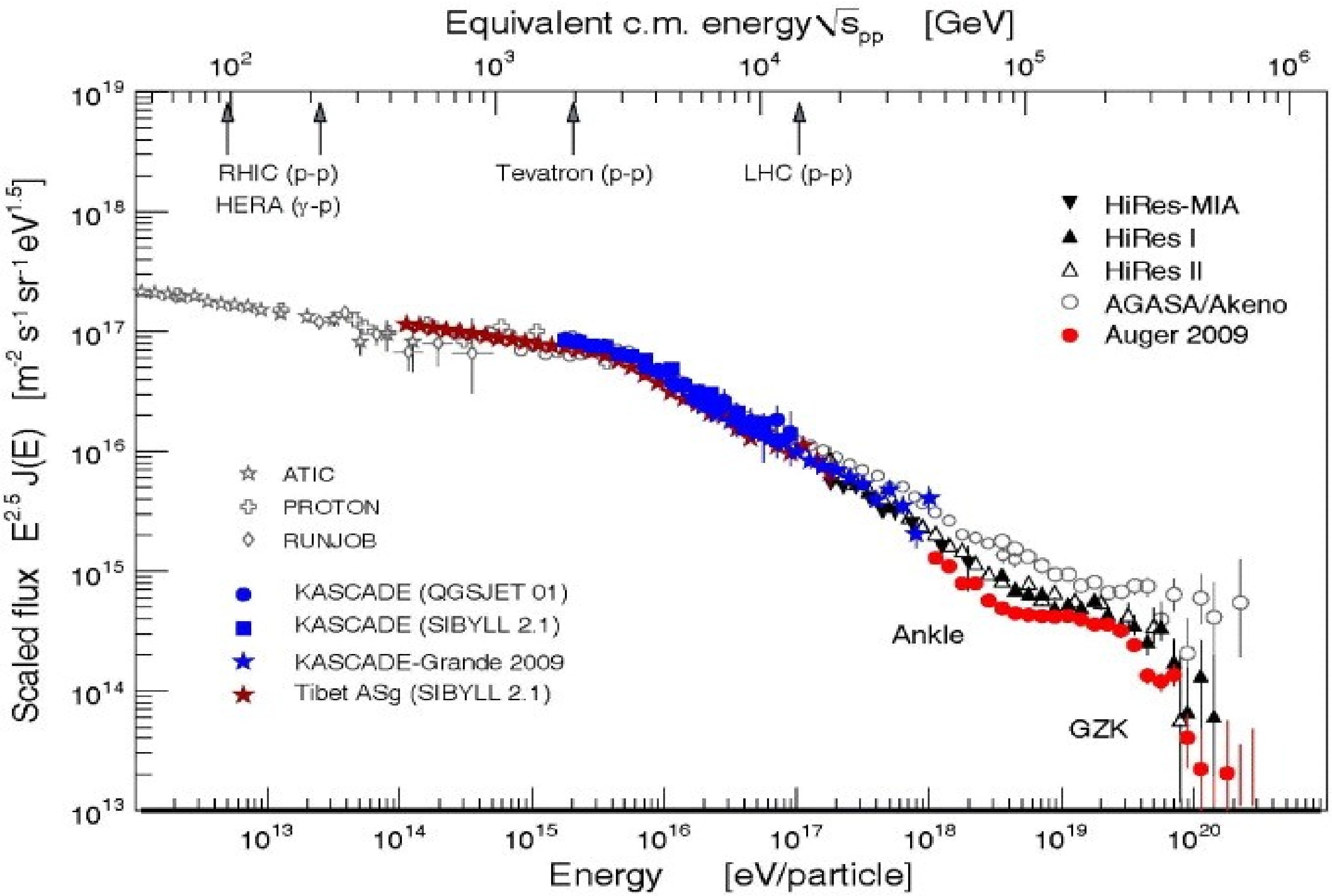
Medium Energy (E<~1015 eV) → Galactic origin

(SNR, Fermi Science 2013)

Ultra-High Energy Cosmic Rays

The **sources** of the Ultra-High Energy Cosmic Rays (UHECRs, $E>10^{18}$ eV) are still unknown.

Discovering the sources of such energetic particles would be an important leap forward in the understanding of the most extreme astrophyisical objects

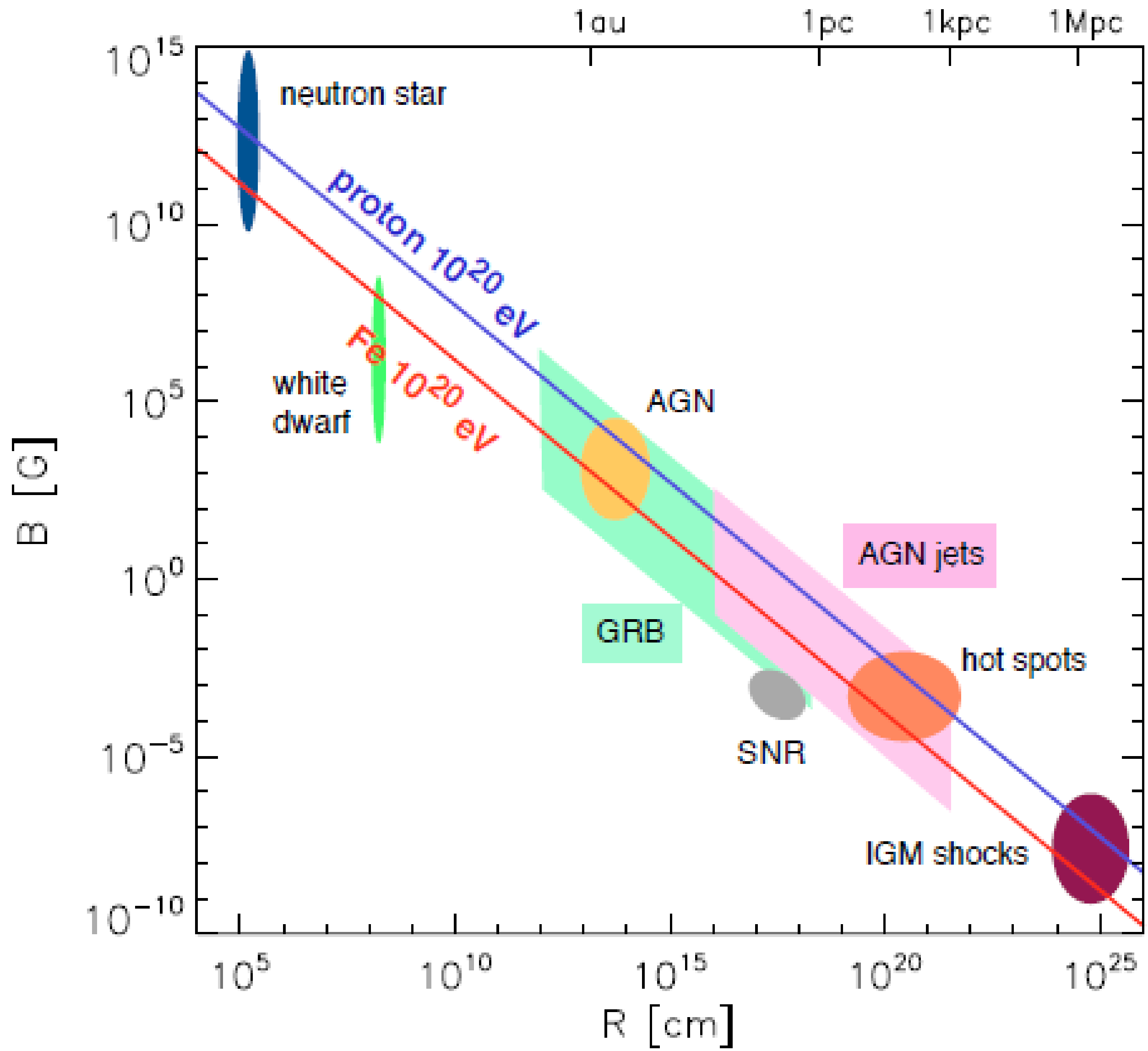


UHECRs candidate sources

To accelerate particles to such high energies **strong magnetic fields** on **large scale** are needed

Candidate sources for UHECRs are **AGNs, jets, lobes, galaxy clusters** and particular neutron stars (**magnetars**)

Hillas plot



UHECRs propagation

Beyond a certain threshold cosmic rays can interact with the **cosmic backgrounds** and decrease their energy

$$p+\gamma_{CMB} \rightarrow p+\pi^0 \quad E_{th} \approx 5\cdot 10^{19} eV$$
$$p+\gamma_{CMB} \rightarrow n+\pi^+ \quad E_{th} \approx 5\cdot 10^{19} eV$$
$$p+\gamma_{CMB} \rightarrow p+e^+ + e^- \quad E_{th} \approx 10^{17} eV$$

GZK effect

$$A+\gamma_{CMB} \rightarrow (A-1)+N$$
$$A+\gamma_{CMB} \rightarrow (A-2)+2N$$
$$A+\gamma_{CMB} \rightarrow A+e^+ + e^-$$

Nuclei photodisintegration

Mean free path → "GZK Horizon":

no CR with E> ~50 EeV should come from further than ~100-200 Mpc.

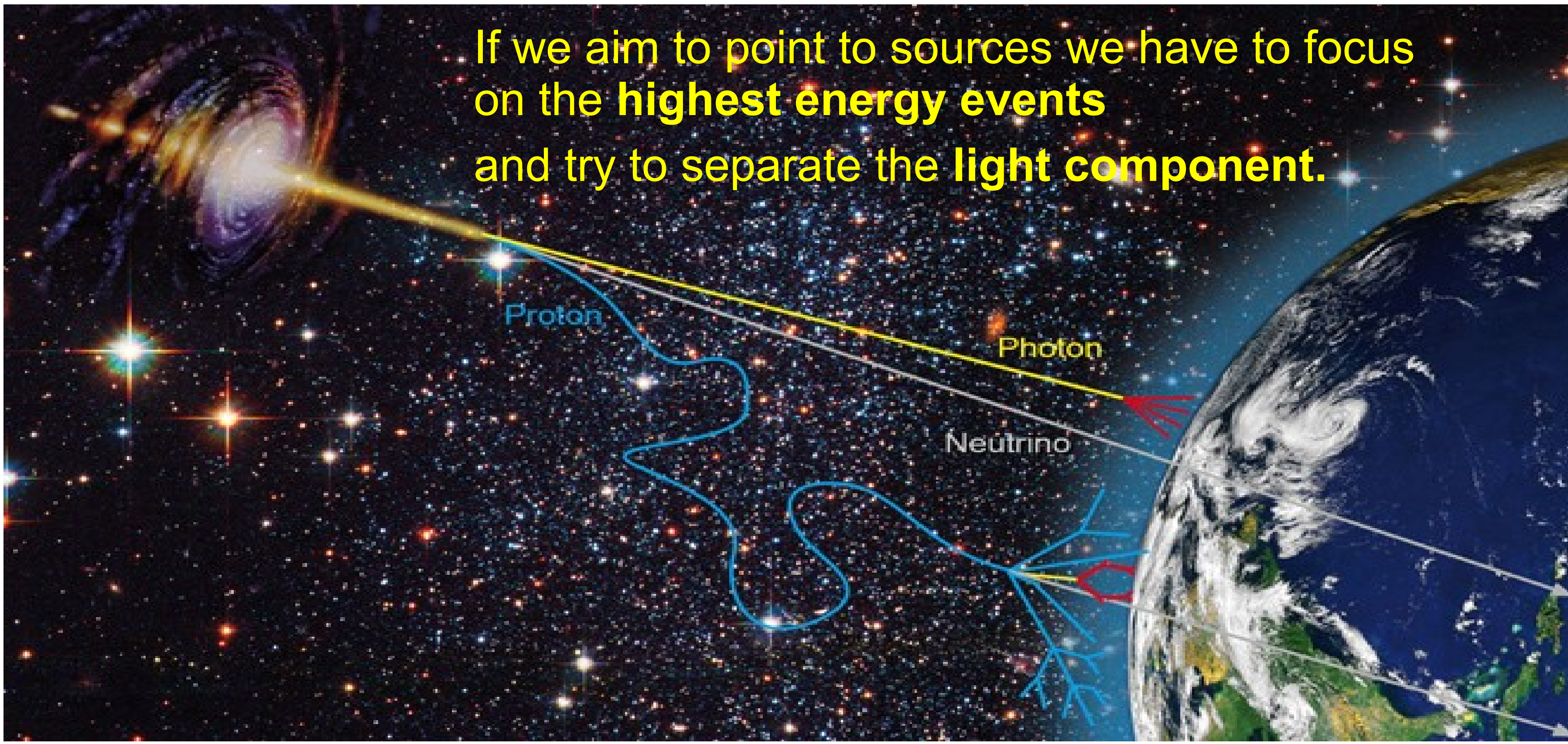
This **helps us** reducing the number of **candidate sources**.

UHECRs astronomy

Doing astronomy with UHECRs is not simple:

UHECRs are **charged particles:** deflected by the (mostly unknown) **galactic** and **extragalactic** magnetic fields.

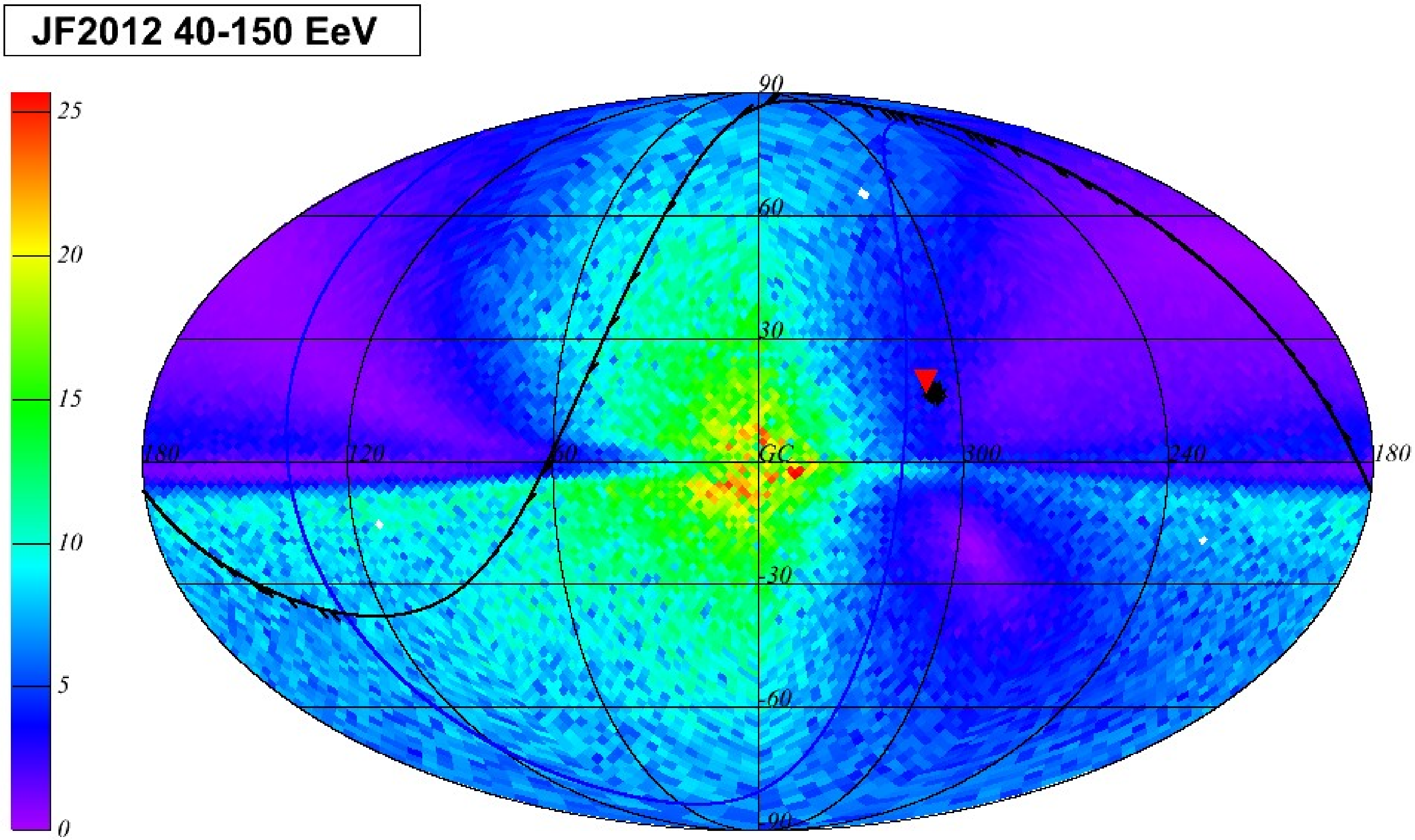
The deflection is proportional to the charge and inversely proportional to the energy.



The Galactic Magnetic Field

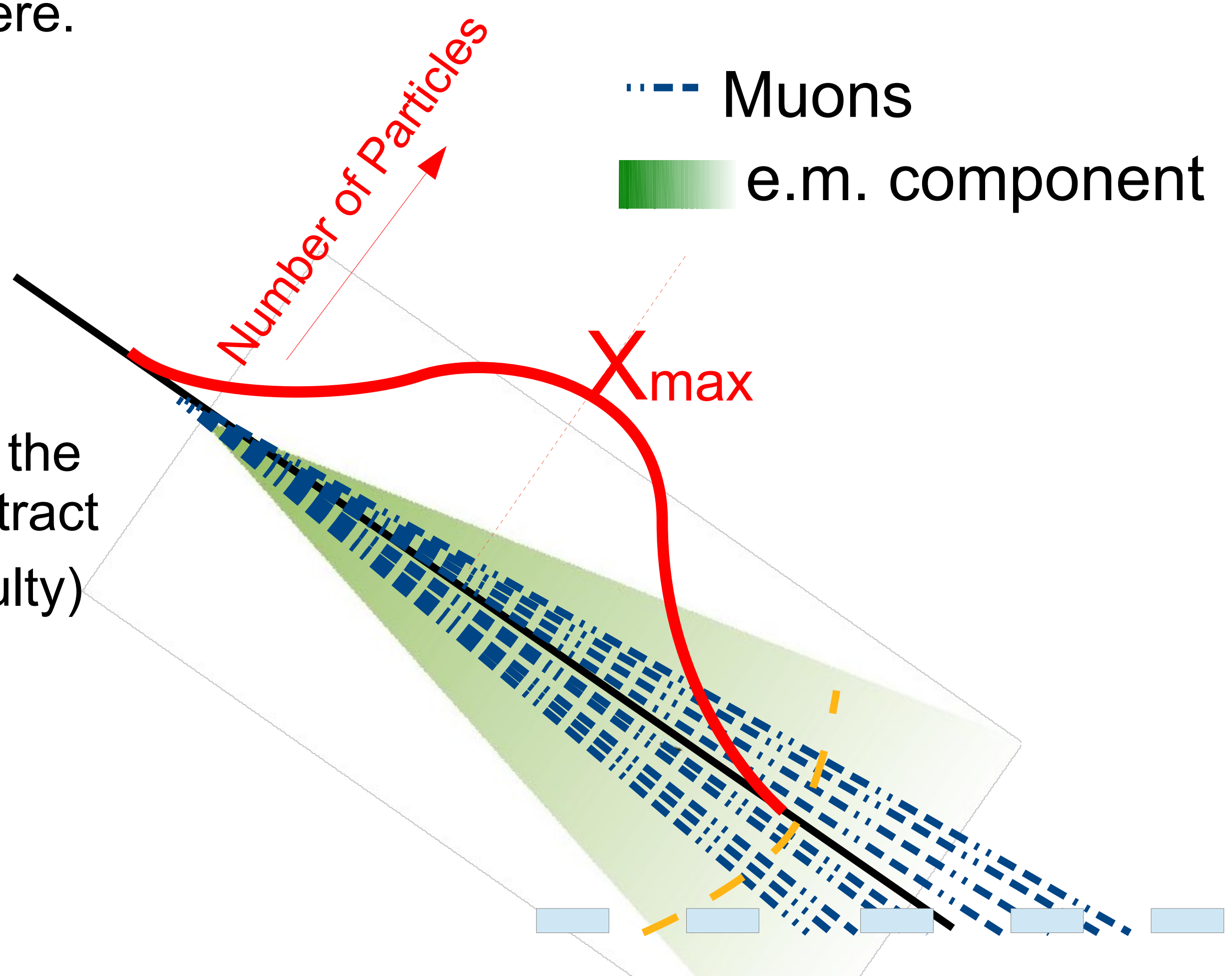
Mean deflection (for protons with E>50 EeV in galactic coordinates)

In the Jensson-Farrar 2012 model (regular field only)



UHECRs Detection

The flux of cosmic rays at high energy is too low to allow direct detection. We observe instead the showers of particles (called **Extensive Air Showers**) that the cosmic rays create as they interact in the atmosphere.



From the characteristics of the EAS we can in principle extract (sorted by increasing difficulty)

Direction

Energy

Mass

Of the primary

The Pierre Auger Observatory

The Pierre Auger Observatory is the biggest UHECRs detector in the world. It is located in Argentina, in the Mendoza province.

Taking data since 2004, It is the first Hybrid detector: it uses both an array of water Cherenkov detectors (Surface Detector, SD) and UV telescopes (Fluorescence detector, FD) to detect the EAS produced by UHECRs

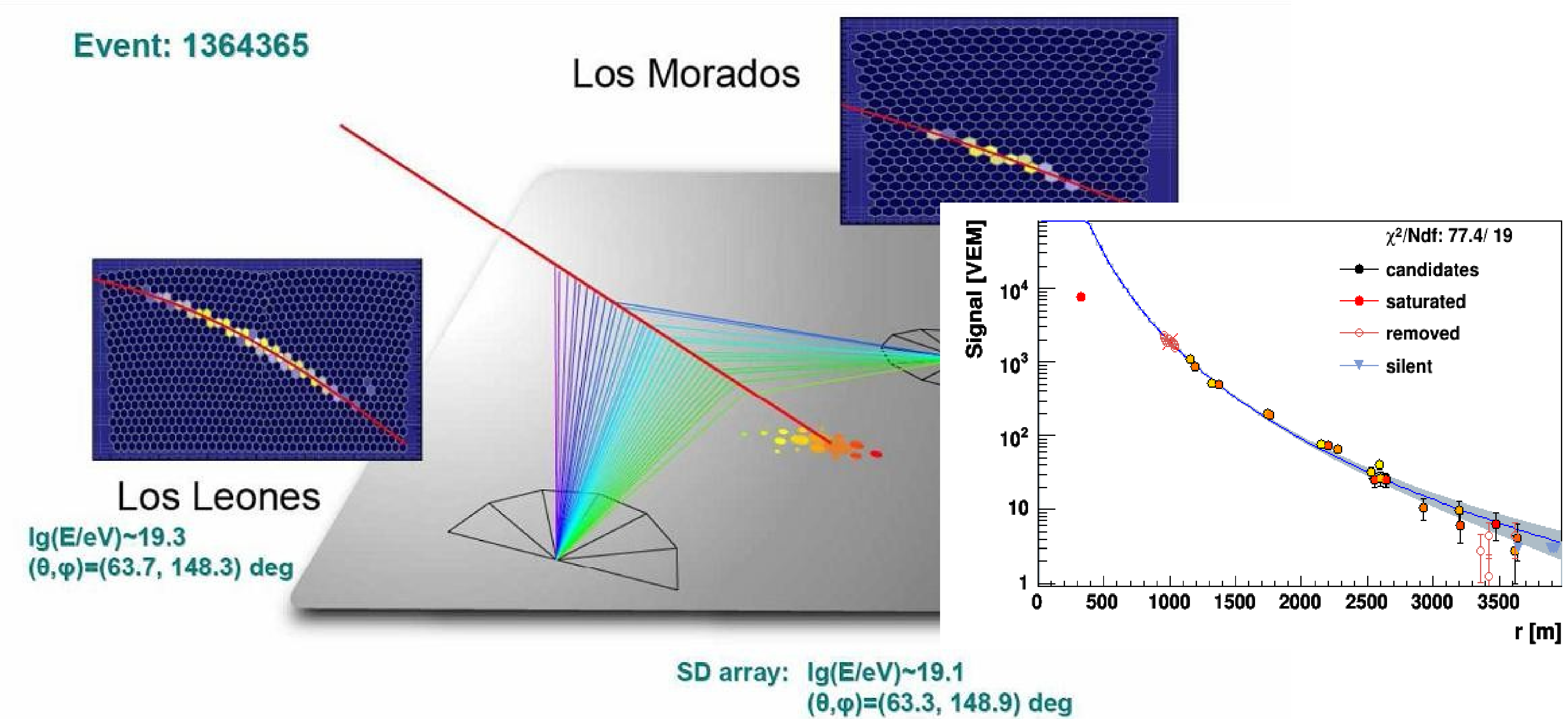
SD: 1660 water Cherenkov detectors (3 PMTs each) on 3000 km2 (~100% duty cycle)

FD: 27 telescopes on 4 sites (~10% duty cycle)

The Pierre Auger Observatory

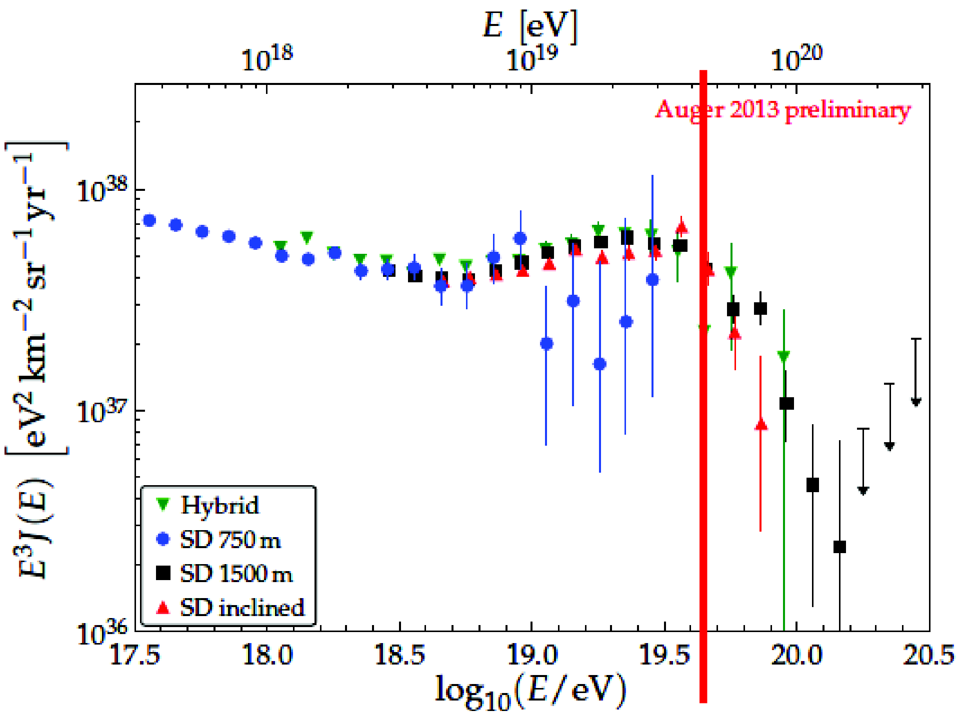
The Pierre Auger Observatory

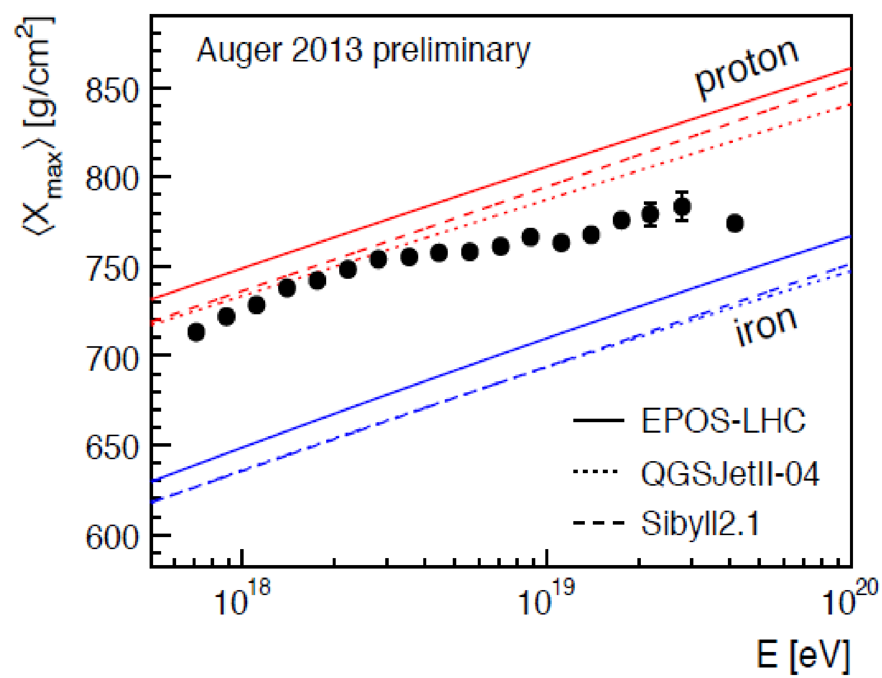
The key feature of the Pierre Auger Observatory is its being an **hybrid detector**: it allows the SD energy (**~100%** duty cycle, no direct access to the energy of the shower) to be **calibrated** through the FD (**~10%** duty cycle, direct measurement of the calorimetric energy).



The Pierre Auger Observatory – Key results

When the observatory was built the prejudice in the community was that cosmic rays were mainly protons at the highest energies. In this scenario we would expect a suppression of the flux compatible with the **GZK effect**





Results does not favor a clear scenario

GZK-compatible suppression → ← **Trend towards heavier components at high energies**

The Pierre Auger Observatory - Key results (2)

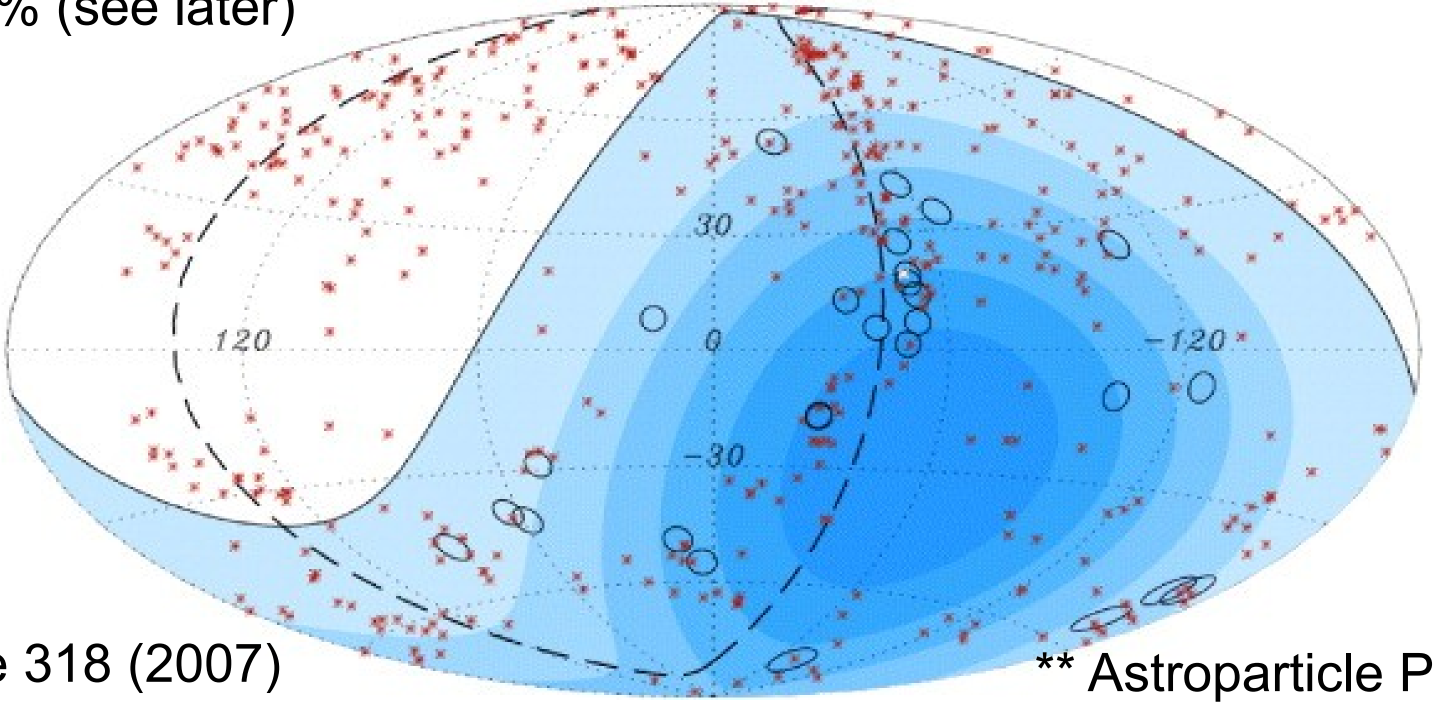
2006: Anisotropy in correlation with AGNs in the VCV. Prescription started

2007: 9 out of the 13 (70%) new events correlated (3 expected from isotropy): prescription fulfilled.*

2010: 12 out of the 42 (29%) new events correlated: decrease of the correlation signal**

2011: Total: 28/84 ~ 33% - ICRC 2011

2014: 28% (see later)



*Science 318 (2007) 938

** Astroparticle Physics 34 (2010) 314–326

MY WORK

My Work – Overview

The purpose of my PhD thesis is to exploit at his best the highest energy dataset of the Pierre Auger Observatory to search for candidate sources of UHECRs.

- **Search for point sources:**
  - VCV update
  - CenA
  - New catalogs
  - TA comparison
  - Likelihood method
- **Mass discrimination**
  - Mass-sensitive observables
  - Multi-variate Analysis
  - Beyond 2015
- **Detector understanding**
  - PMTs issues
  - Event selection
  - Stability in time

SEARCH FOR POINT SOURCES

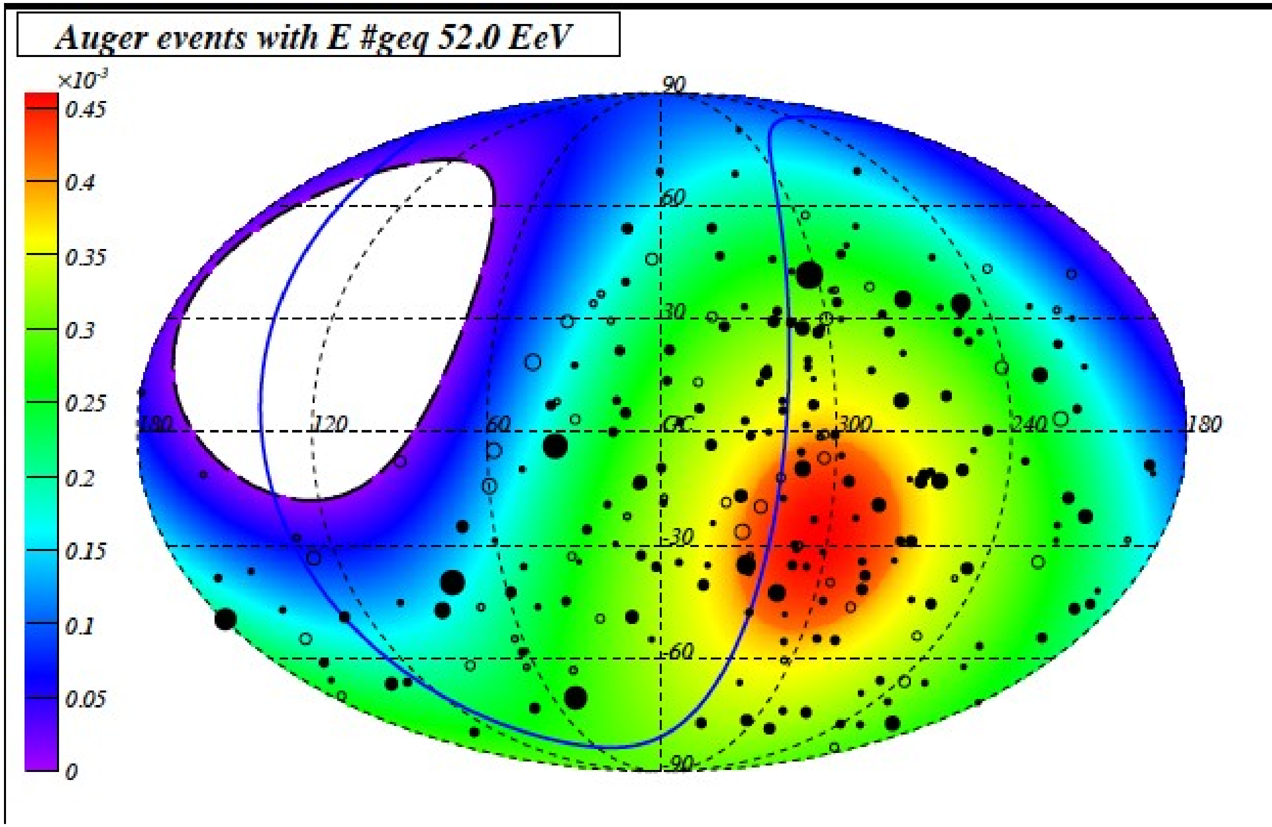
Search for point sources: the dataset

In the following the results are using the highest energy dataset (E>40 EeV) up to the end of march 2014.

454 **vertical (up to 60°)** events inspected one by one in order to check for any unknown problem (→ see third part).

For the first time using also **horizontal** events (up to 80°) in order to increase our statistics (148 events more).

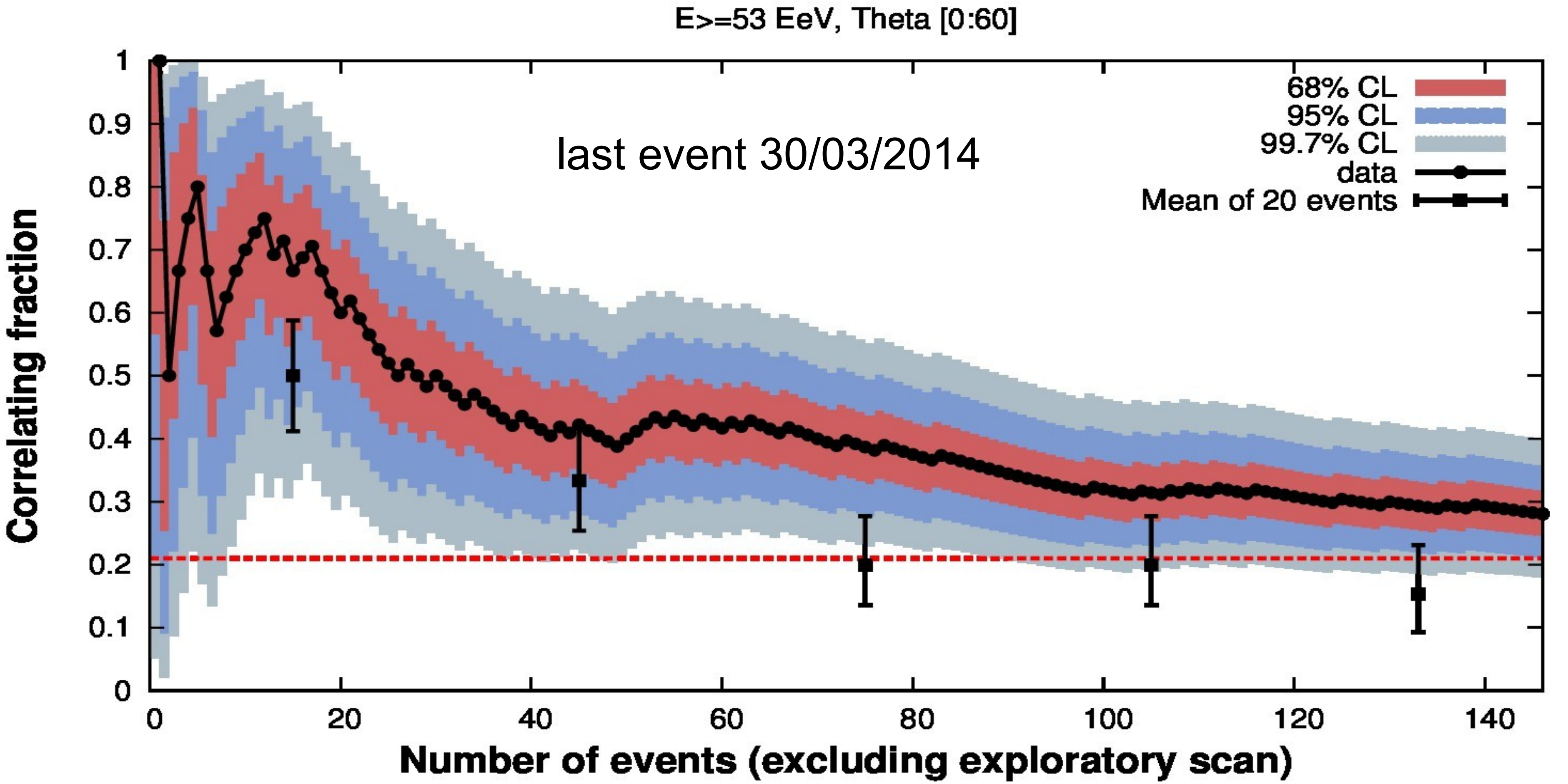
With a **total exposure** of ~66500 km^2 sr yr it is the biggest dataset of cosmic rays at the highest energies.



Search for point sources: VCV update

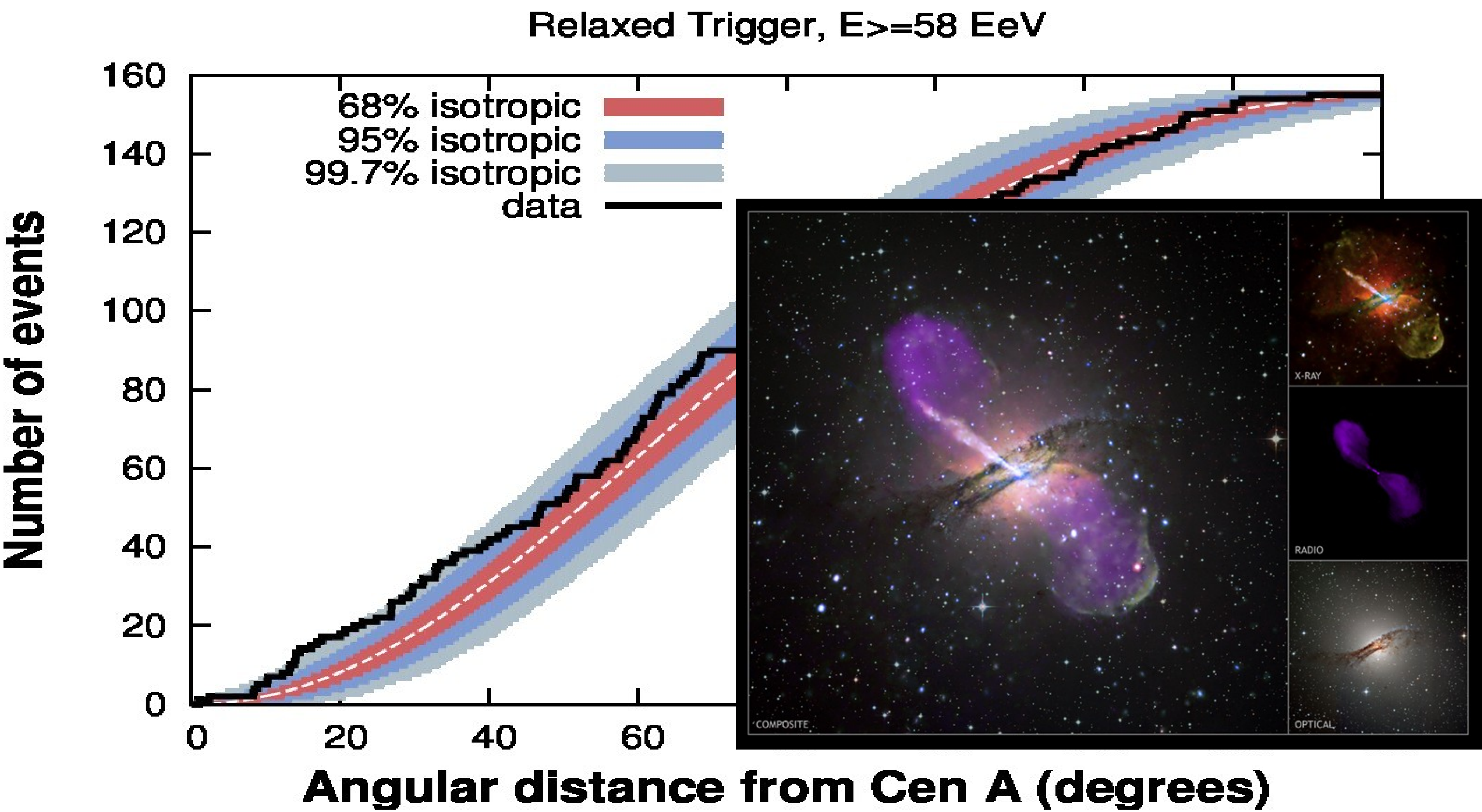
Scan to search for correlation with a catalog. Varying **Emin**, **zmax** (GZK) and ψ (deflection) to find the maximum deviation from isotropic expectation.

The prescription in 2006 fixed these parameters at Emin= 57 EeV (52.8 EeV in the **new energy scale**), zmax=0.018 and ψ=3.1° with the VCV 2006 catalog.



Search for point sources: CenA

The closest radio galaxy is Centaurus A (NGC 5128, 3.6 Mpc). It lies well within Auger FOV.



Search for point sources: other catalogs

The VCV AGN catalog is a collection of all the galaxies that shows at least an hint of some form of activity (Even M31 is in there!).

We now focus on more restricted catalogs to search for specific sources candidates, such as:

- **radio galaxies**.
- **2MRS IR:** maps mainly the distribution of stars (nearby matter).
- **Swift-Bat:** X observation in the full BAT energy range

Objects	E_{th} [EeV]	Ψ [°]	D [Mpc]	$\mathcal{L}_{min}$ [erg/s]	f_{min}	$\mathcal{P}$
2MRS Galaxies	52	9	90	-	1.5×10^{-3}	24%
Swift AGNs	58	1	80	-	6×10^{-5}	6%
Radio galaxies	72	4.75	90	-	2×10^{-4}	8%
Swift AGNs	58	18	130	10^{44}	2×10^{-6}	1.3%
Radio galaxies	58	12	90	$10^{39.33}$	5.6×10^{-5}	11%
Centaurus A	58	15	-	-	2×10^{-4}	1.4%

Search for point sources – TA comparison

Telescope Array is an UHECRs observatory located in Utah, in the northern emisphere.

- In May 2012*, the Telescope Array collaboration published results on UHE correlation with extragalactic objects using Auger scan parameters.

- In June 2013**, the Telescope Array collaboration published its own scan results on UHE correlation with extragalactic objects.

The Pierre Auger Observatory has larger area and longer operation time: we can check their results on 12 independent datasets equivalent to TA exposure

Using their scan parameters we have almost always **less correlation** then they do.

Re-doing the scan showed however compatible results using the **VCV catalog**, while they seem to obtain still **stronger correlation** then us with the **Swift-Bat** catalog.

*SEARCH FOR ANISOTROPY OF ULTRA-HIGH ENERGY COSMIC RAYS WITH THE TELESCOPE ARRAY EXPERIMENT arXiv:1205.5984v1

**Search for correlation of the arrival directions of ultra-high energy cosmic rays with extragalactic objects as observed by the telescope array experiment arXiv:1306.5808

Search for point sources: outlook

The search for point sources isn't a simple task.

Our plan for the future includes:

- Continuous update with new statistics, possible “prescription” on Swift and CenA

- New catalogs coming from new observations or new scenarios

- Search for correlation with other observations even if unidentified (e.g. Ice Cube Neutrinos) → Joint work with IceCube and TA

- New search methods that consider detector uncertainties, galactic magnetic field deflections and, when (if?) available, mass indicators (→ **see second part of this talk**)

MASS DISCRIMINATION

Mass discrimination

Possible predominant **heavy fraction** in the highest energy events.

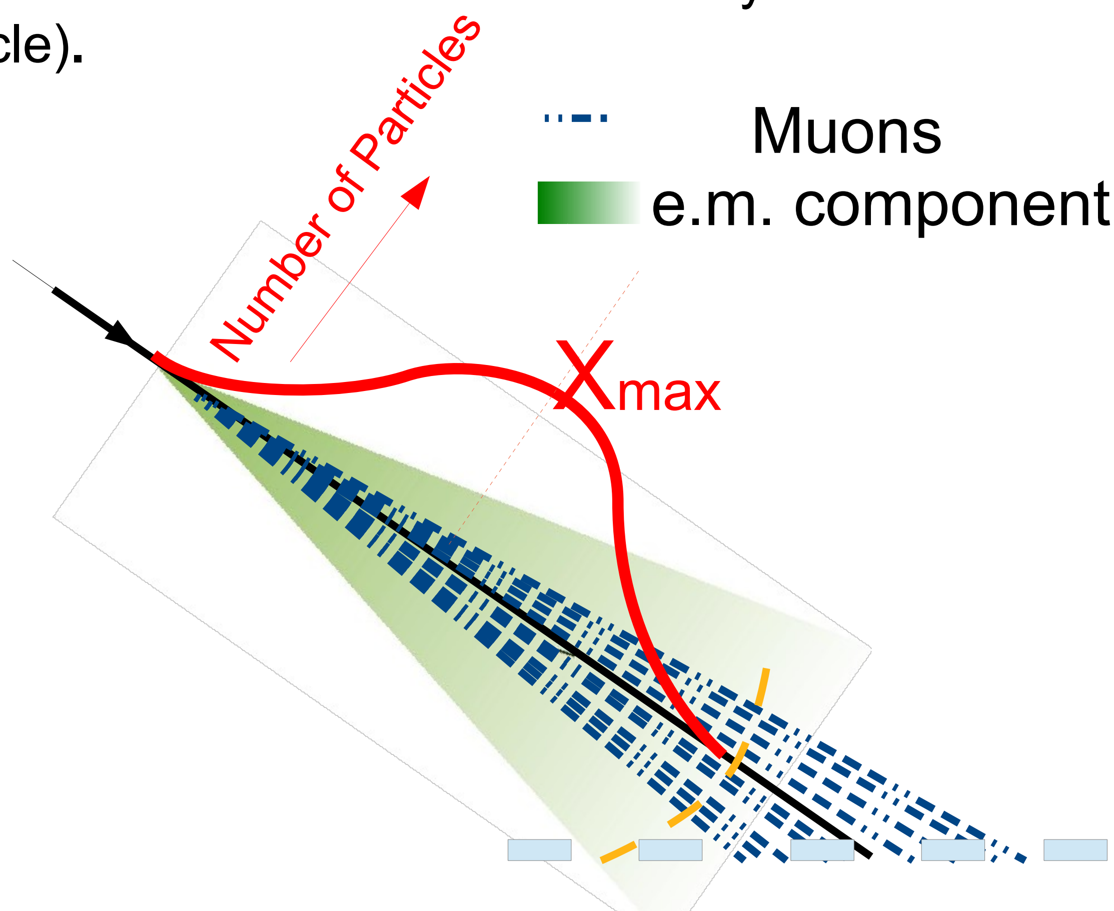
Lots of effort in the collaboration are devoted to finding a way to discriminate light from heavy component on an event-by-event basis.

We need to find mass-sensitive observables accessible by the **surface detector** (100% duty cycle).

- **Longitudinal profile** (i.e. number of particles as a function of shower depth)

- **Shower width** (i.e. Number of particles as a function of the distance from the axis)

- Number of **muons** and depth of muon production.



Mass discrimination: shower depth

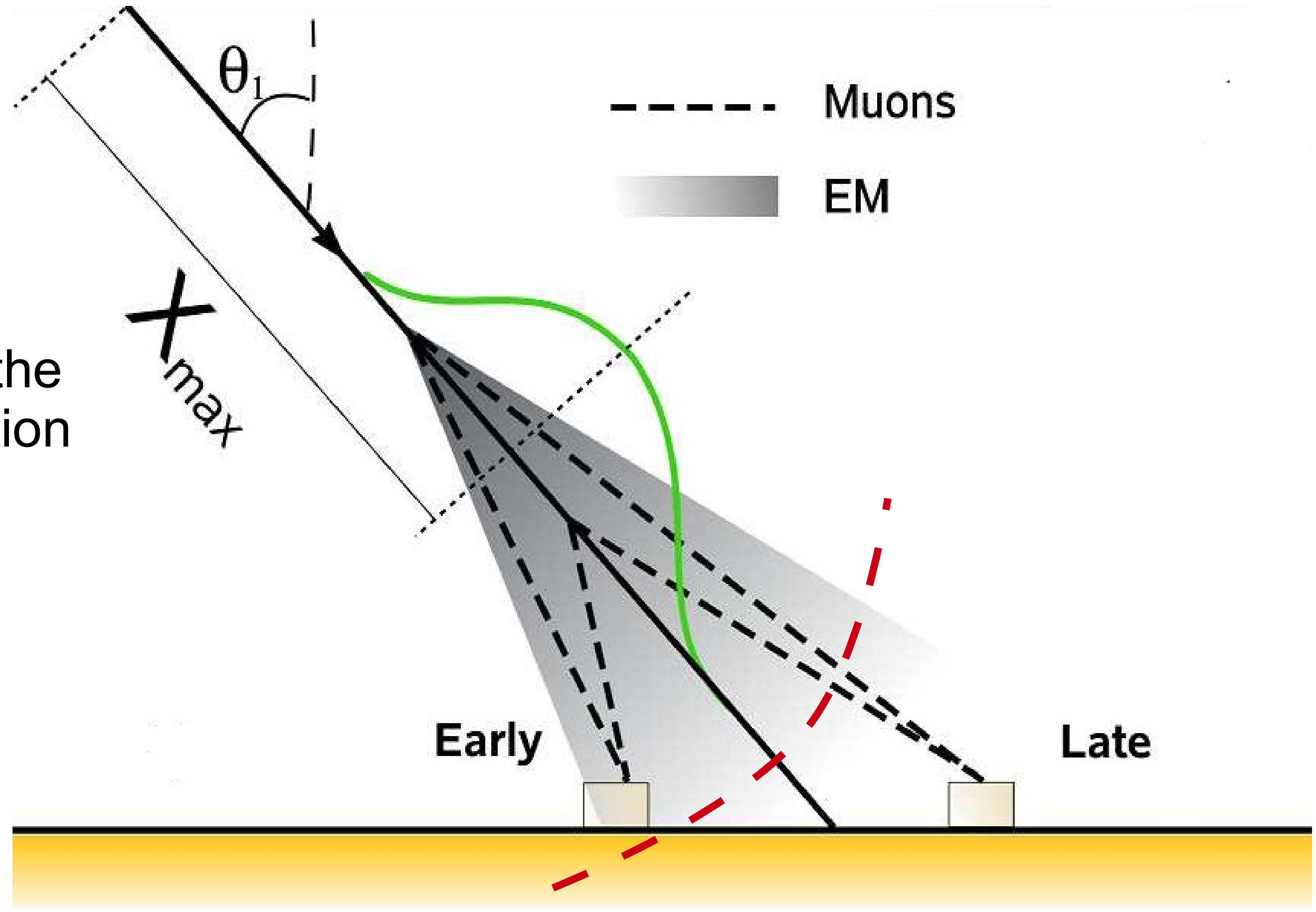
X_{max} , the depth of the shower maximum, is probably the best mass-sensitive variable but itis not directly accessible through SD

→ it is possible to build Xmax related observables

From timing information in **SD traces** we extract:

- the asymmetry of the **rise time** of the station signal (sensitive to em/mu ratio)

- the **curvature** of the shower front



Mass discrimination: shower width

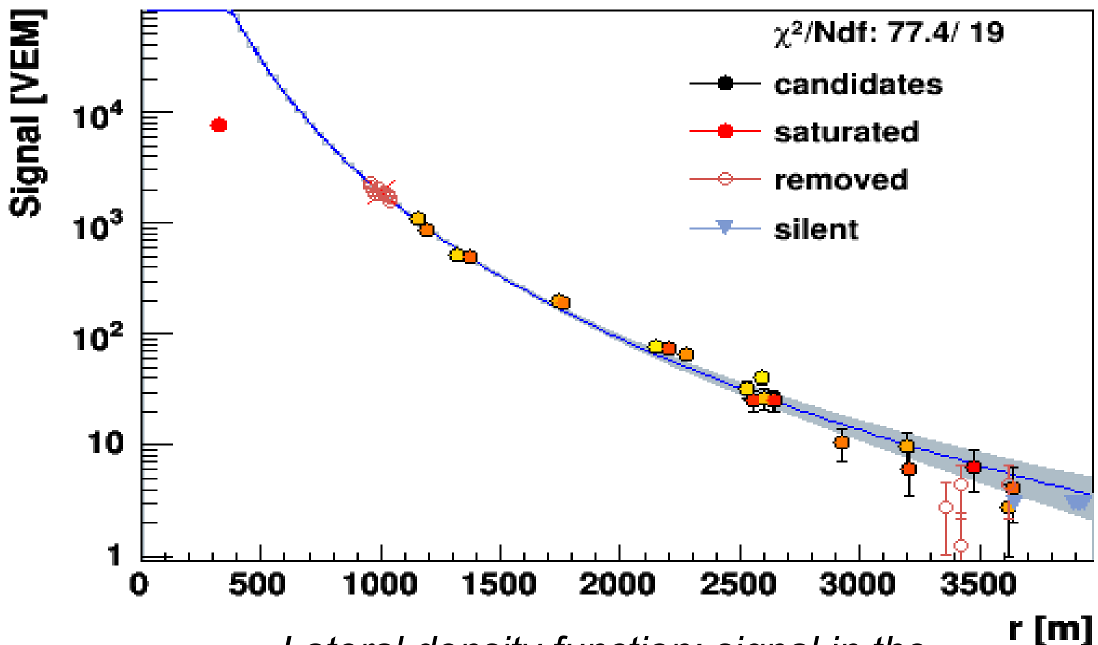
The information on the shower width can be extracted by the Lateral Density Function (LDF)

- **Slope** of the LDF

- distance-weighted sum of the signals

$$S_b = \sum_i \left[S_i \cdot \left(\frac{r}{1000\text{m}} \right)^b \right]$$

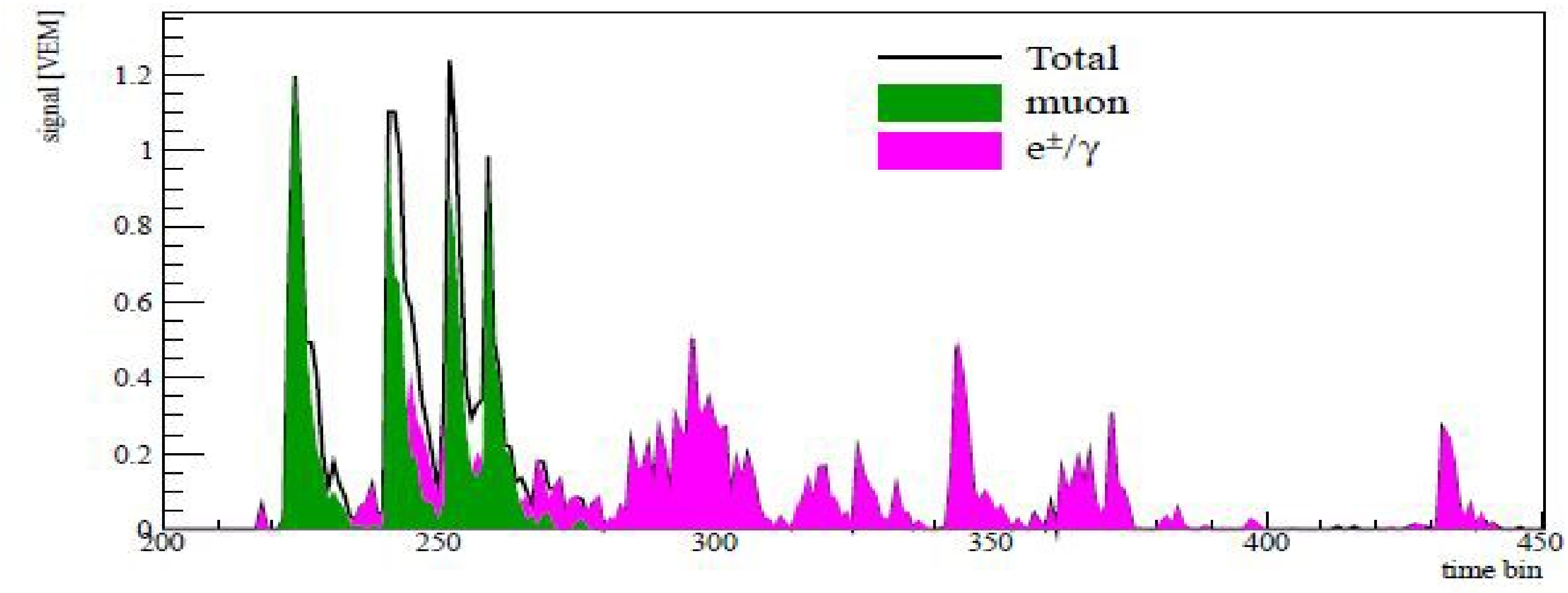
- **Number of Triggered Stations**: footprint of the shower at ground



Lateral density function: signal in the stations as a function of distance from the shower impact point.

Mass discrimination: Number of muons

In principle we can both try to compute the real number of muons or just use a variable *related* to that number



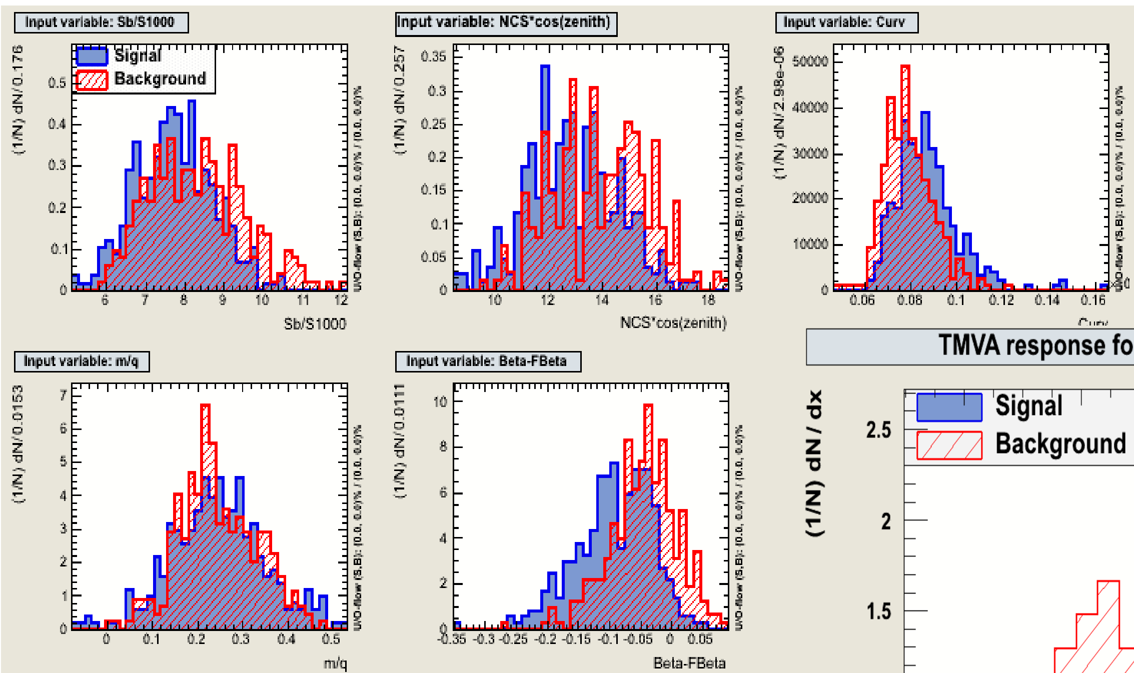
- Number of muons (or muon signal) with the **smoothing technique on the signal traces**

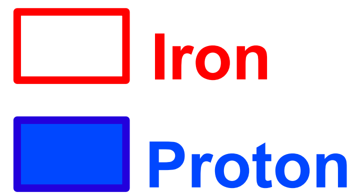
→ **possibly biased**

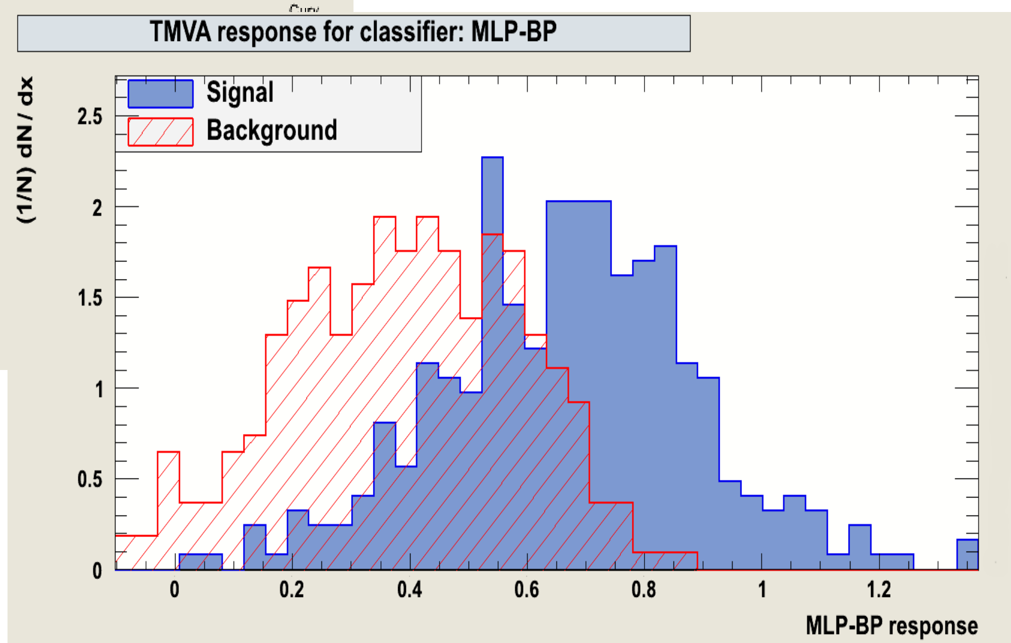
- Rise time at 1000m wrt a parametrization (**delta variable**)

Mass discrimination: MVA

At the moment there is not a single mass-sensitive variable that is discriminating enough to be use by her own.
A stronger approach is needed: **Multi-Variate Analysis**

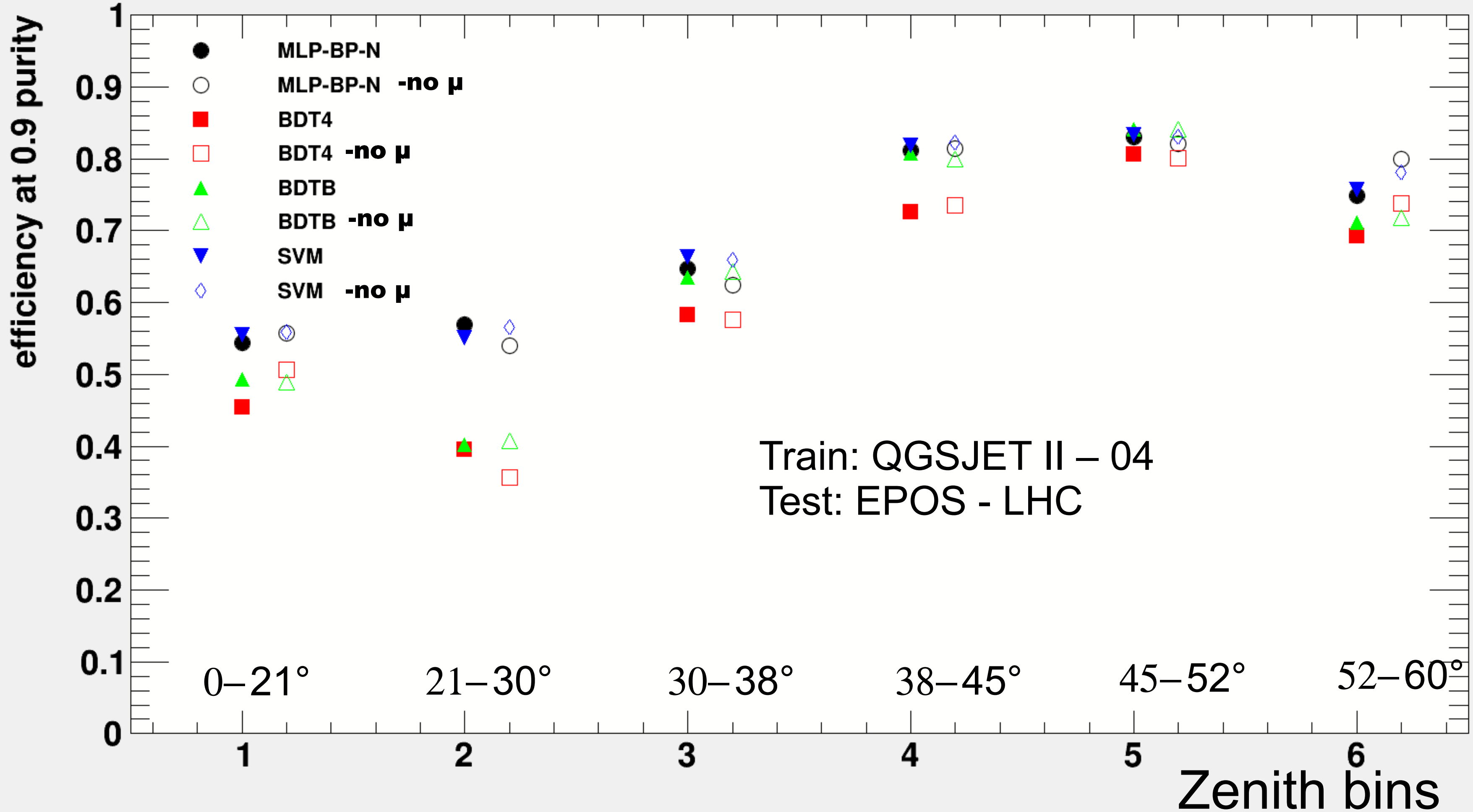






MVA results

To avoid the intrinsic zenith angle dependencies of variables we bin in zenith and produce different MVA in each bin

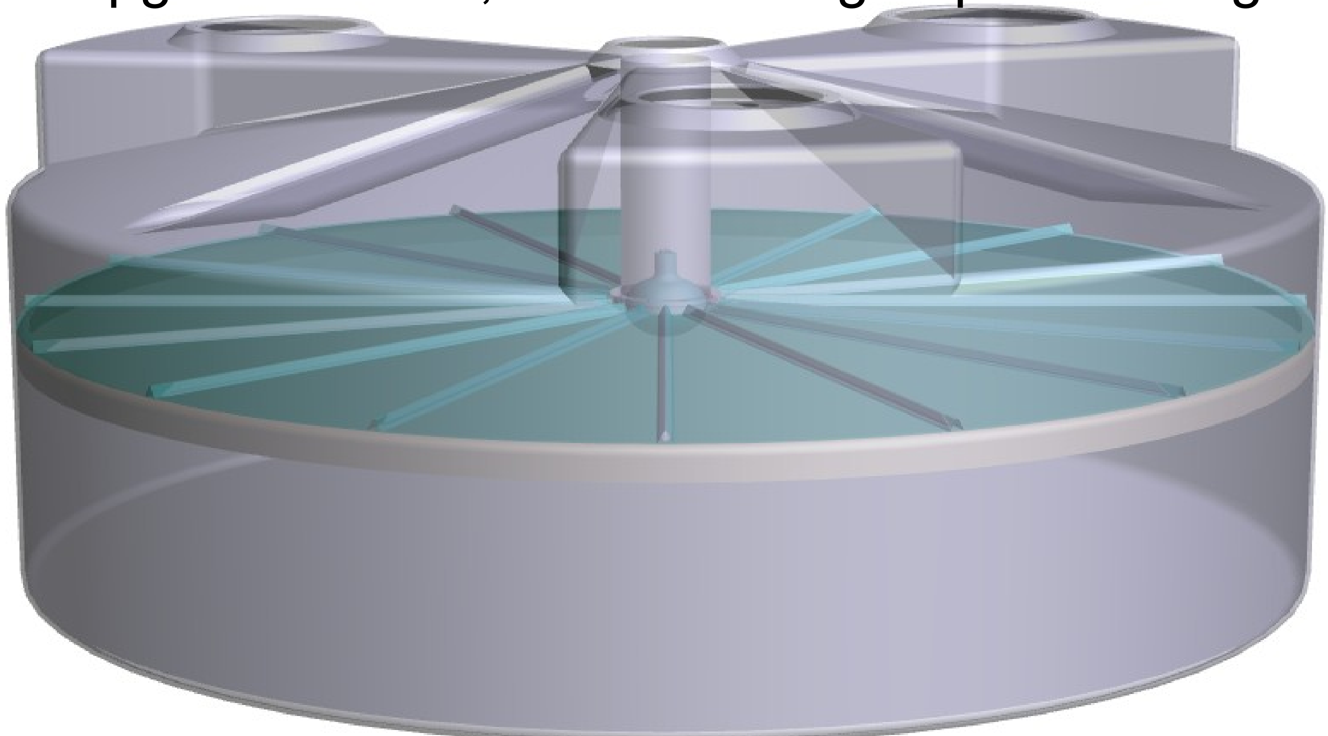


The future of the detector: Beyond 2015

An upgrade of the Pierre Auger Observatory is scheduled for 2015.

The aim is to achieve a better mass discrimination.

One of these upgrade is LSD, and LPHNE group is working on its R&D



Segmenting the tank the em signal is deposited mainly In the **upper part.** Measuring the signal in the 2 segments, with a simple inversion of a matrix we could in principle separate the em and the μ components

Mass discrimination: outlook

Mass discrimination is a key point for the Observatory: all the main R&D efforts of the collaboration are in this direction.

Focusing on the present detector, in the near future we're planning to

- Apply the results to the real data in order to obtain a "proton enriched sample" → anisotropy studies on that

- add new variables to the analysis, in particular related to the muon content production depth in the showers.

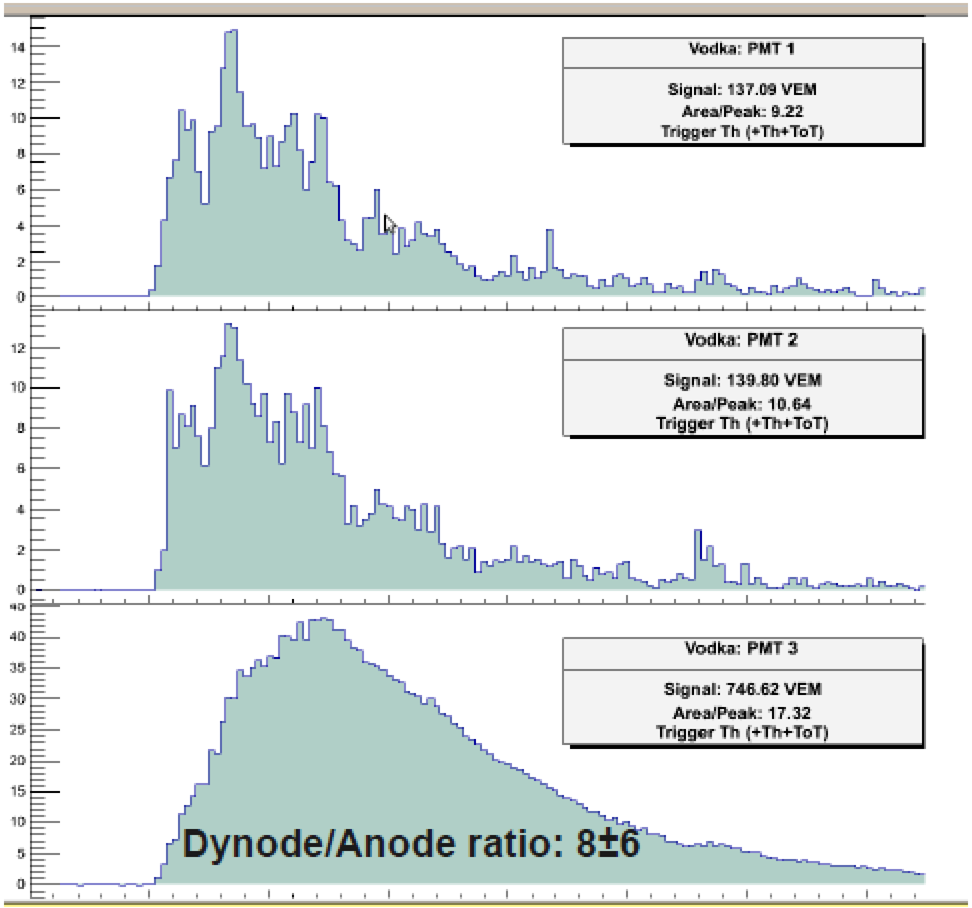
DETECTOR UNDERSTANDING

Mass discrimination: a new challenge for the detector

The search for mass-sensitive observables pushes further the exploitation of the detector. For this reason a better understanding and control of its behavior is needed.

Example: Many of the muon-counting algorithms are based on the PMT traces.

“bad” PMTs.
A small fraction of PMTs have some problem that translates into a deformation of the signal traces.

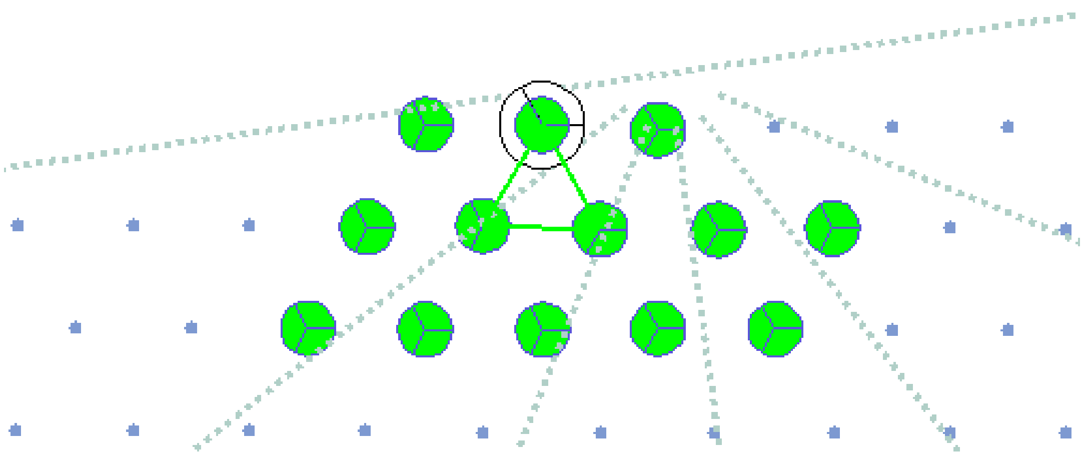


Building the ultimate dataset: event selection

Statistics is a key point in such correlation and anisotropies studies, in particular if only a few percent of the dataset is exploitable, being the "**proton-like**" part.

Auger has strict quality selection cuts on its data that in principle can be relaxed, in particular at the highest energies:

- **Zenith Angle<60°** → methods are being developed in order to include horizontal showers (thus extending the achievable sky!)
- **5 (6) active tanks around the hottest** → The highest energy events usually have enough tanks to relax this request

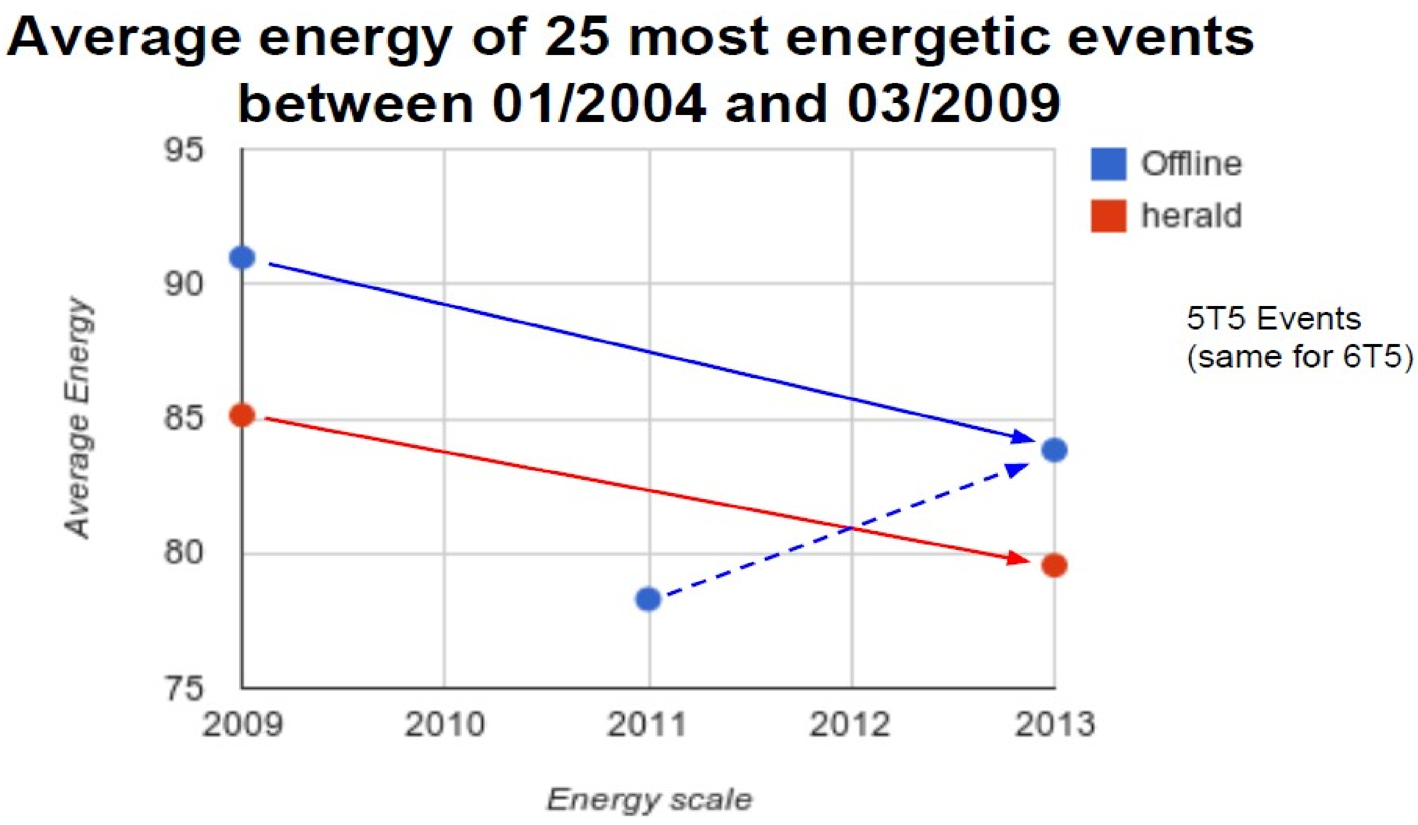


Increase the statistics of about ~30%

Energy reconstruction

At the end of my thesis the detector will be running for more than 12 years: does it behaves steadily?

In Auger we have 2 different reconstruction software: **Herald** and **Offline**: do they behave the same when a new energy calibration is released?

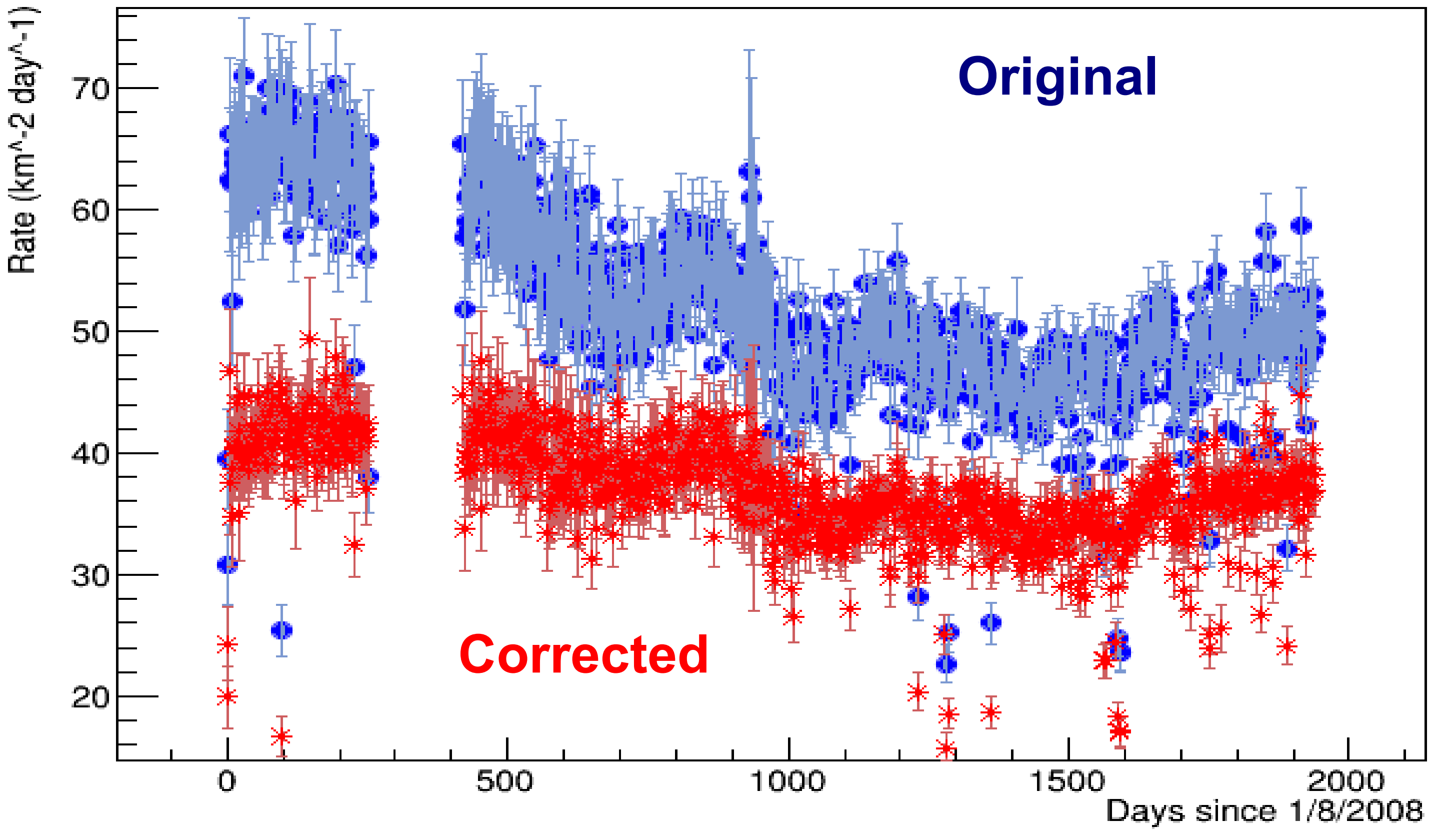


Stability in time

There is a possible drift in the average flux of events in time?.

Maybe due to the aging of the tanks → less reflectivity of light

Implement a correction of the shape of the signal that reports everything to the “worst case” (oldest tanks)



Infill array

Detector understanding: Outlook

The Pierre Auger Observatory is a complex detector in an uncontrolled environment.
It is pushed to its maximum capabilities by the recent analysis, so it has to be known and kept under control

To do this we will:

- Do further studies (possibly on the field) on the PMTs

- Do further studies on the aging

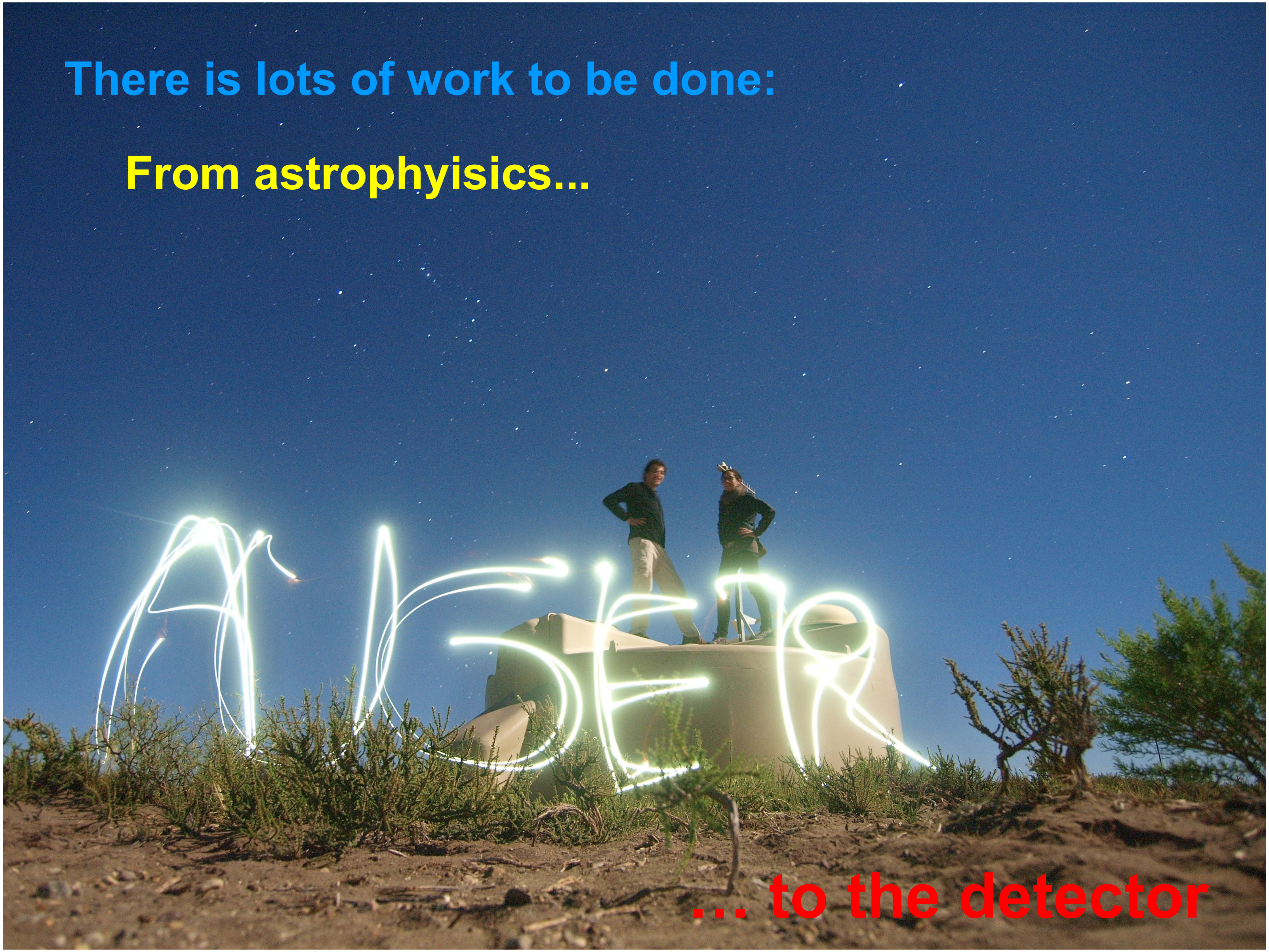
- Check also the arrival direction reconstruction stability, using hybrid data.

AUGER

LEGO

MODEL

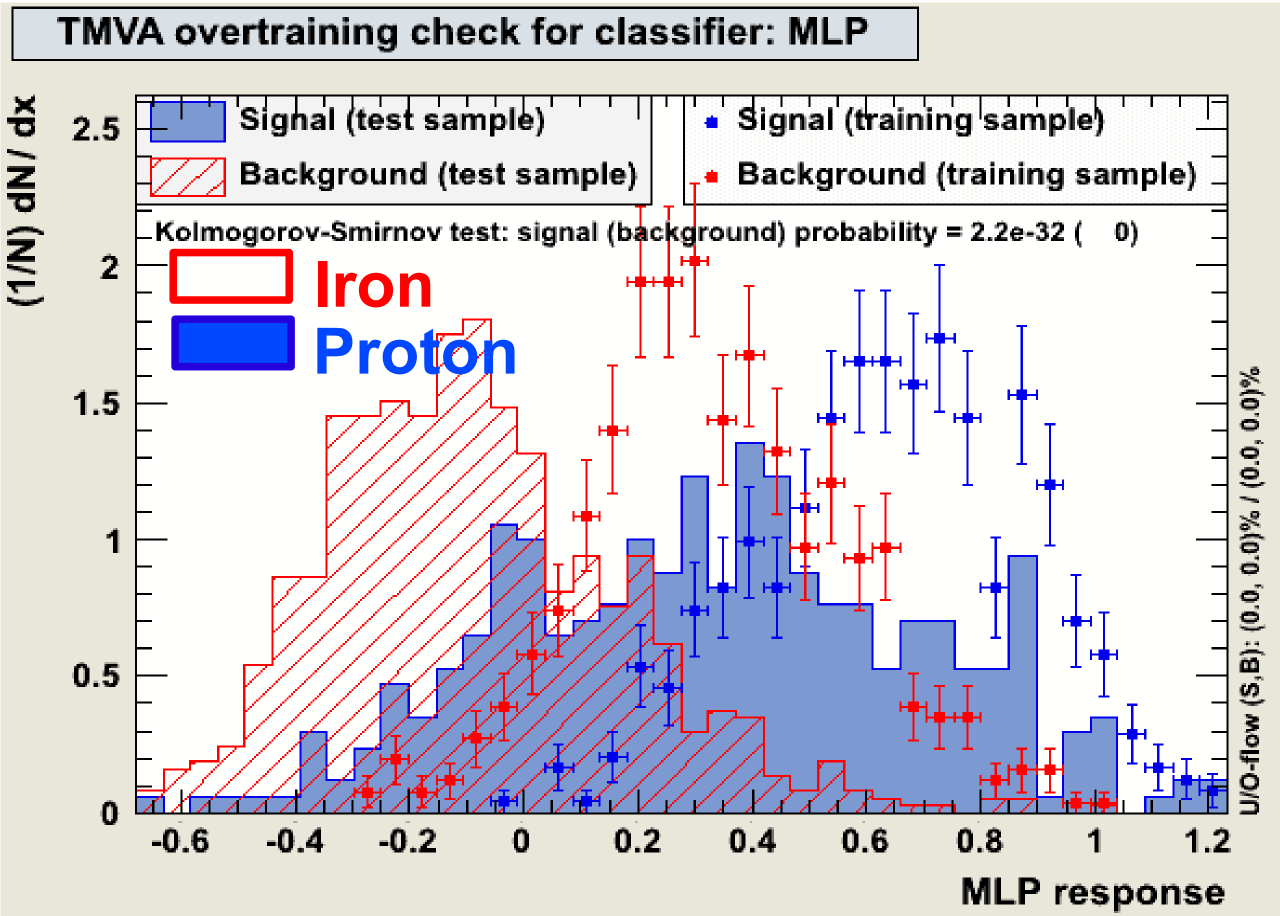
Conclusions

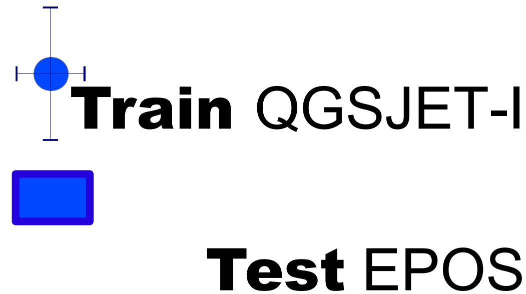


BACKUP

Mass discrimination: MVA

The problem with MVA is its being **strongly model dependent**

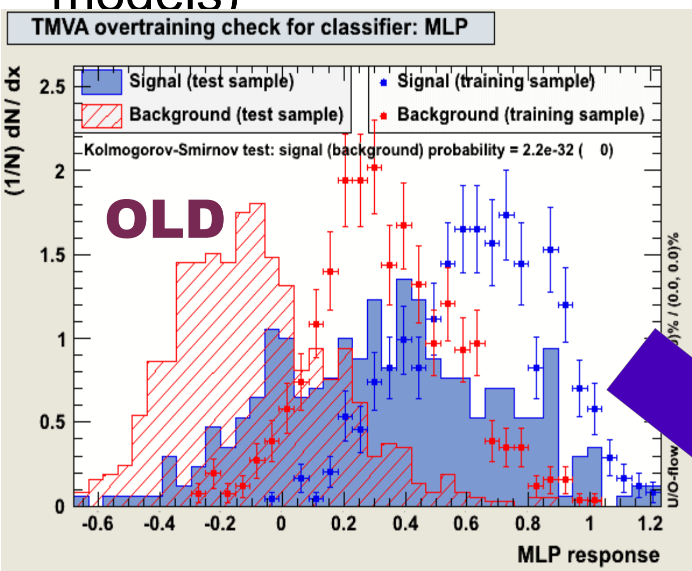




MVA WITH NEW MODELS

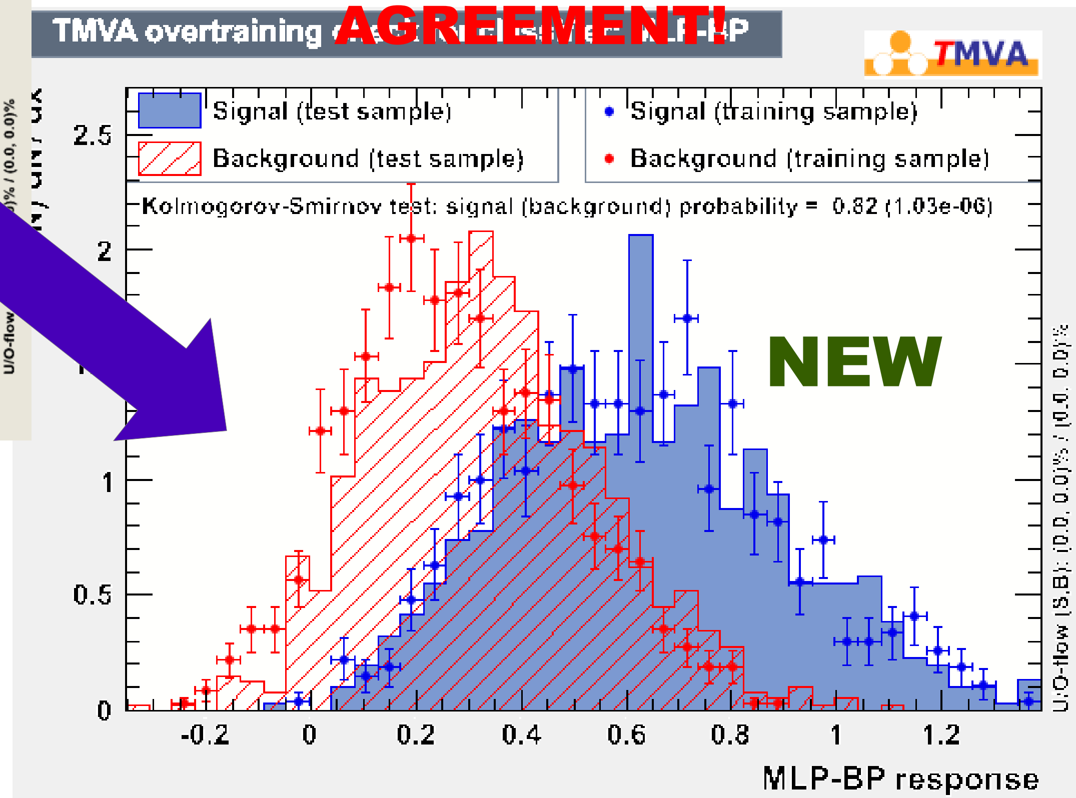
A quick update of the MVA results with the new models.

NO fine tuning (using the same MVA parameters used for the old models)



4th Bin

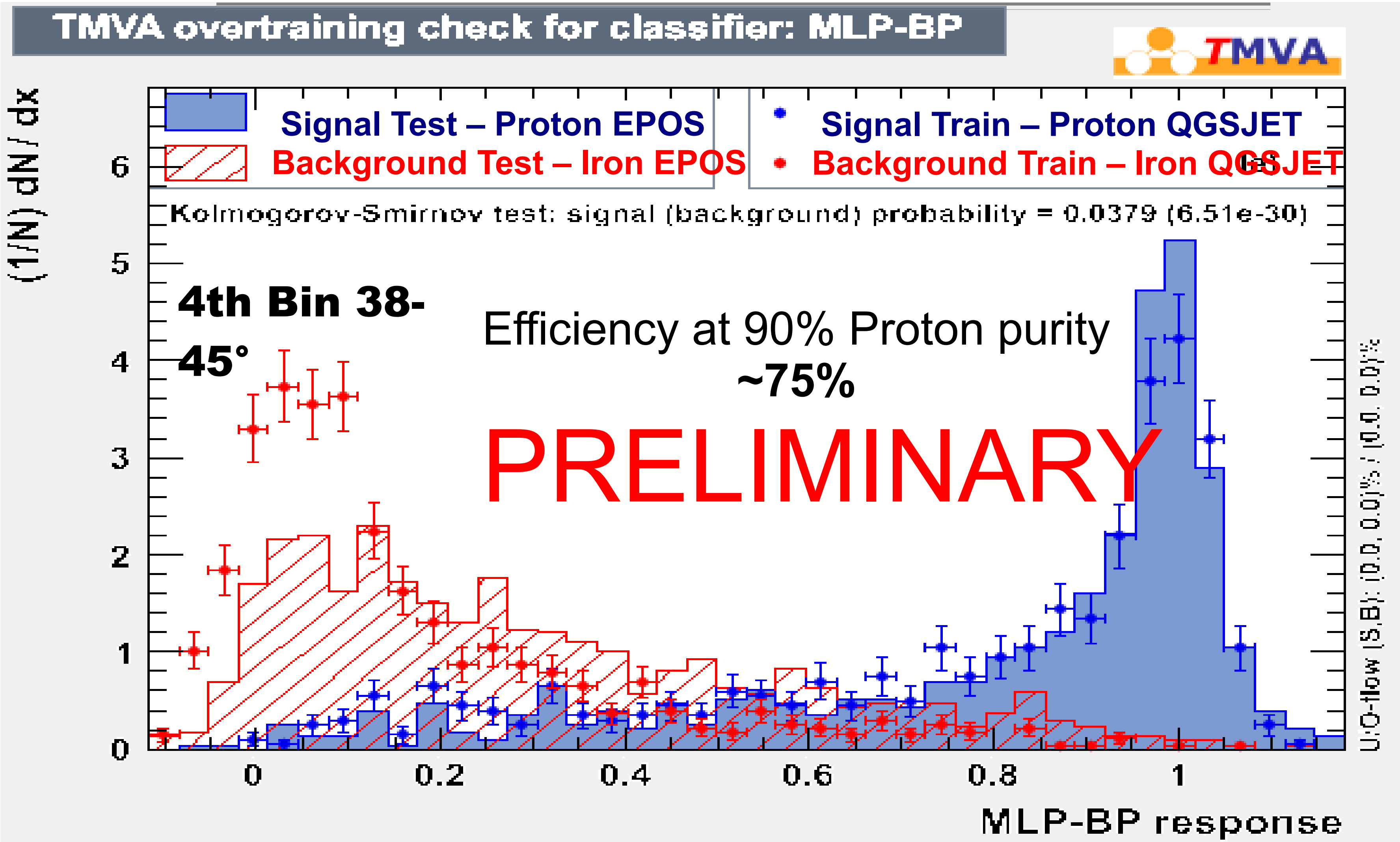
MUCH BETTER AGREEMENT!



Train QGSJET

Test EPOS.

MVA-ANN BIN 4 WITH NEW VARIABLES

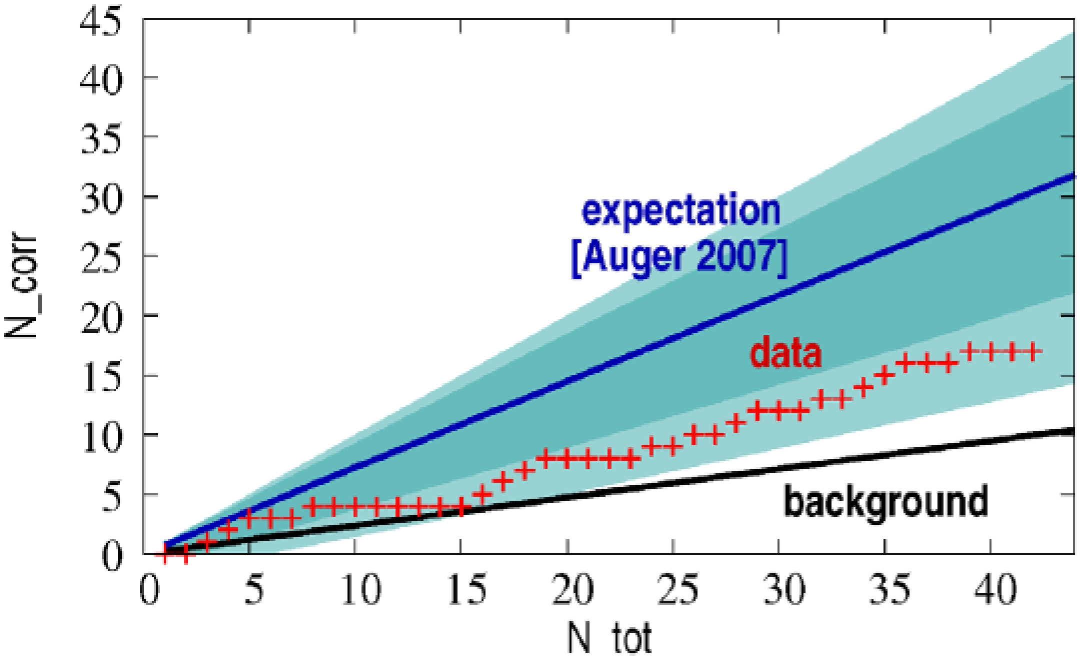


Impressive separation but slight model dependence in Irons.

Telescope Array results

Correlations with AGN

- Probability to hit AGN with a single event $p_o = 0.24$
- 17 events correlate out of 42 $\Longrightarrow$ $p = 0.014$



Search for point sources: VCV update

Scan to search for correlation with a catalog. Varying Emin, zmax (GZK) and the angle ψ (deflection) to find the maximum deviation from isotropic expectation.

The prescription in 2006 fixed these parameters at Emin= 57 EeV, zmax=0.018 and ψ=3.1° with the VCV 2006 catalog. Updating this with our full dataset (last event 28/11/2013)

Period:	SCAN	Science 2007	Update 2010	2010	2011	2012	2013
# of Events	12	15	42	21	20	11	13
Correlating	6	8	12	4	4	1	3
corr. Fraction	50%	53%	29%	19%	20%	9%	23%

Total percentage correlating without period I: 26%