The Pierre Auger Observatory: results and prospects

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for the Pierre Auger Collaboration

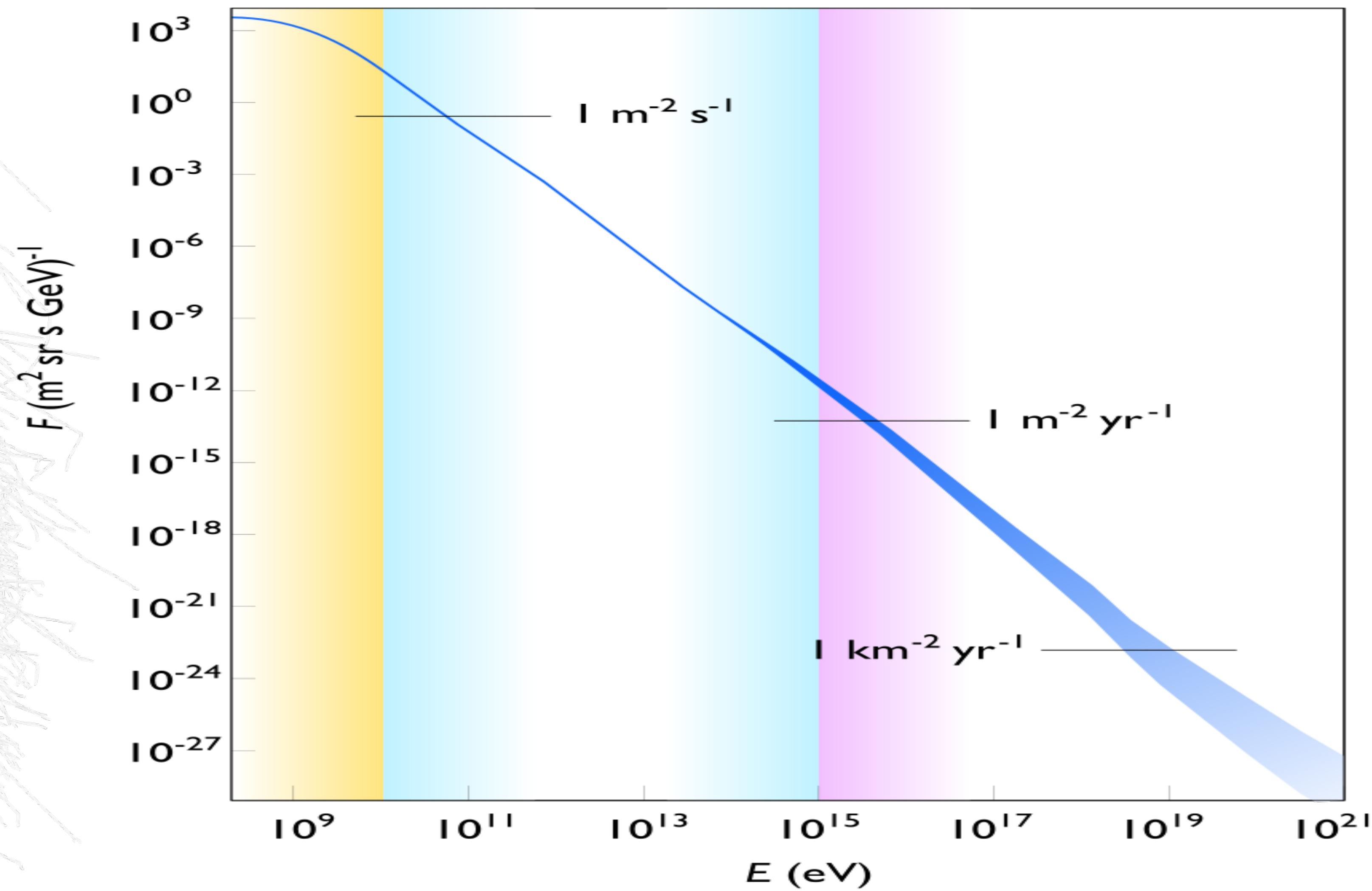
LIP

PIERRE AUGER OBSERVATORY

LHC days, Split, September 23rd 2016

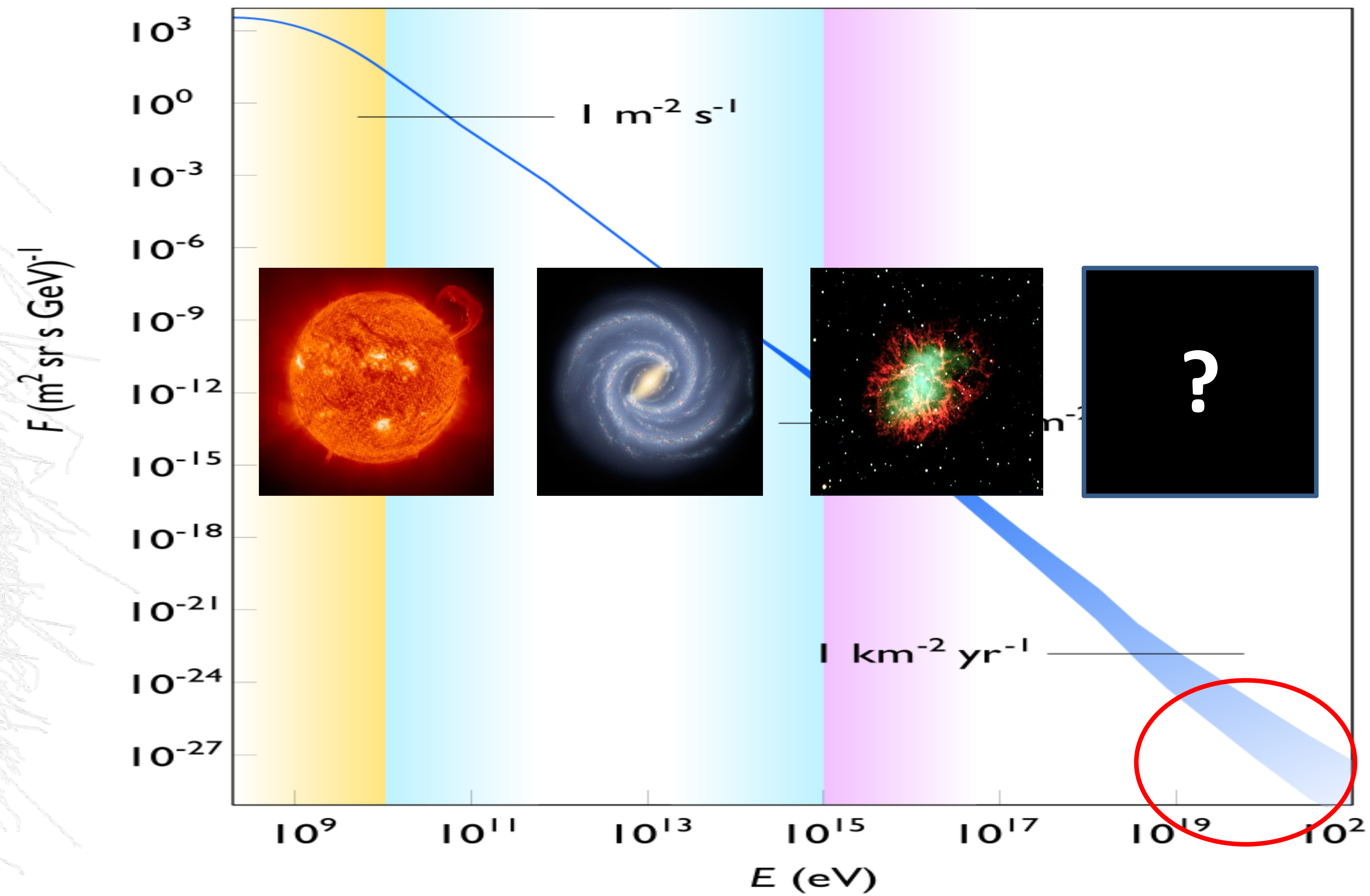
Ultra High Energy Cosmic Rays

Cosmic ray energy spectrum



Ultra High Energy Cosmic Rays

Cosmic ray energy spectrum



Ultra High Energy Cosmic Rays

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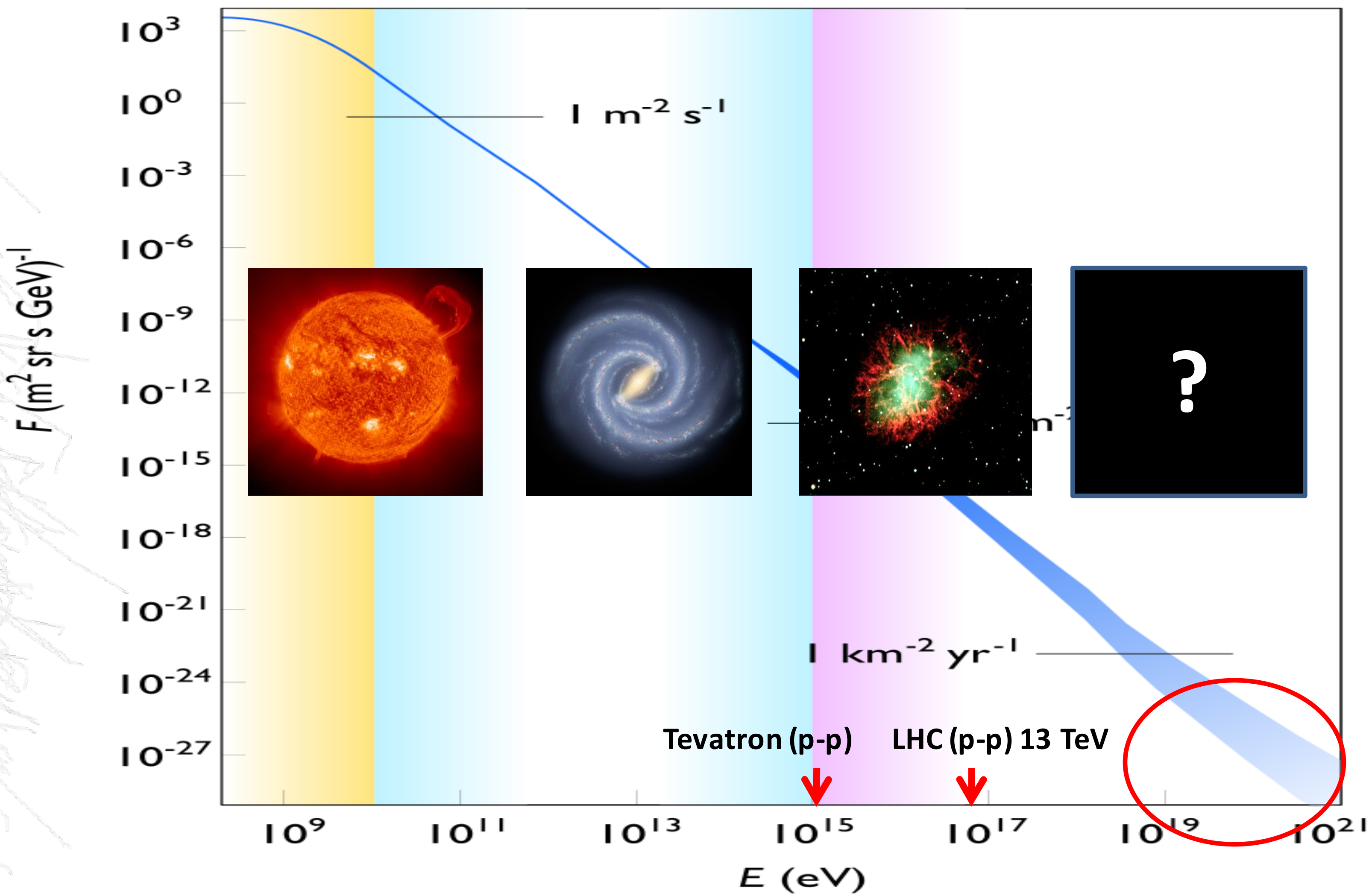
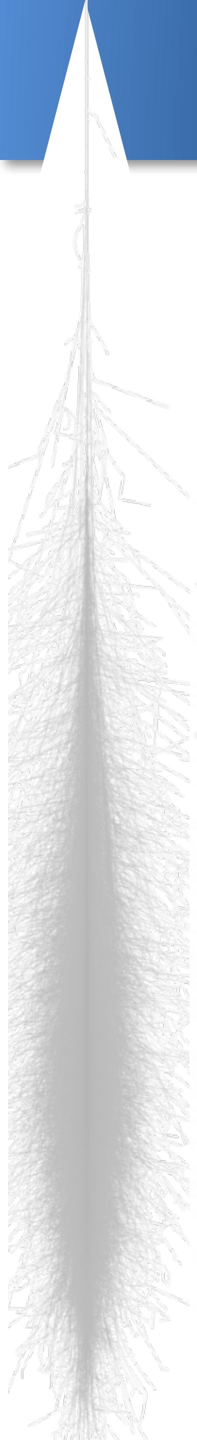
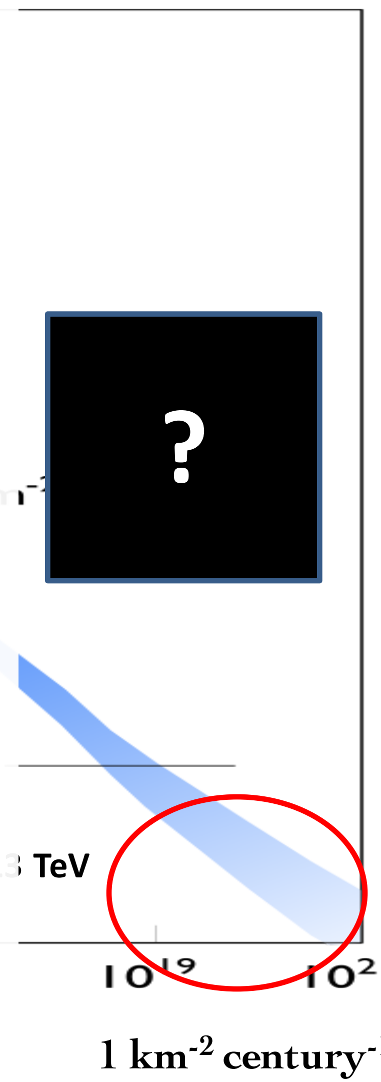


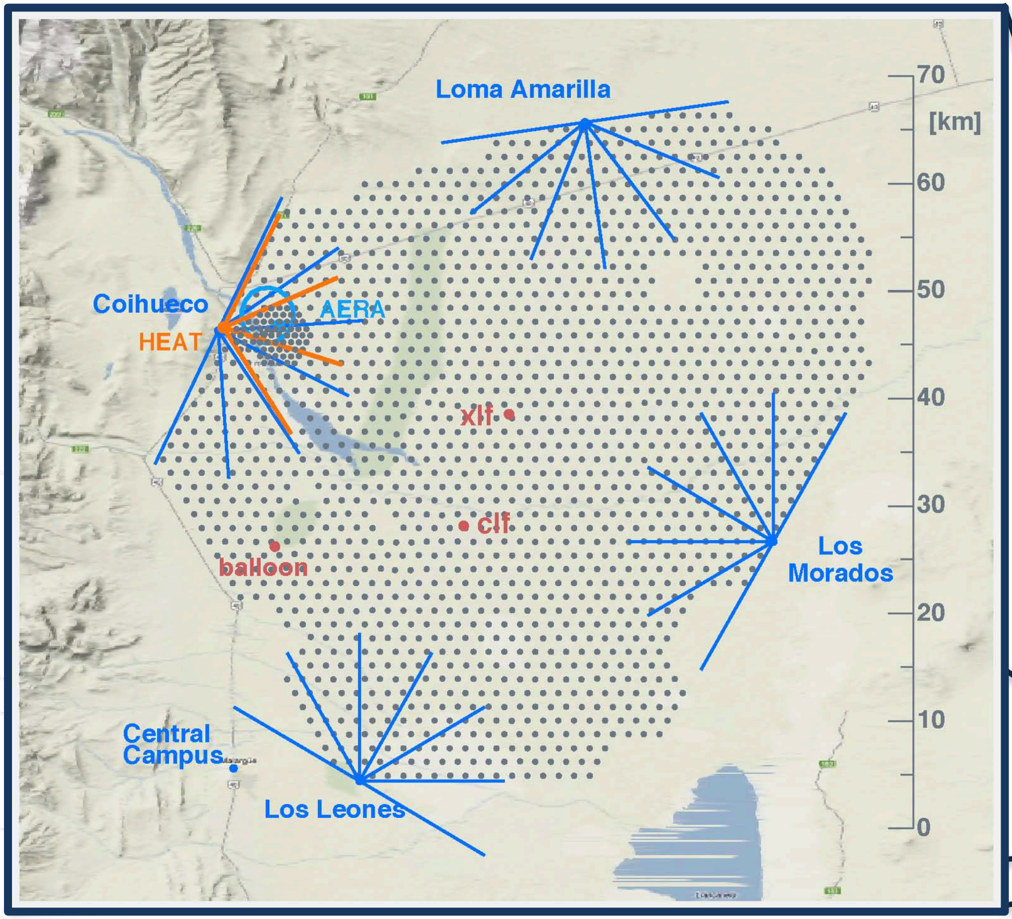
Ultra High Energy Cosmic Rays



- Opportunity to understand **high-energy Universe**
  - Production (sources; acceleration mechanisms…)
  - Propagation (Magnetic fields…)
- Opportunity to test **particle physics** at energies above the LHC
  - High-energy interactions
    - E = 10^{19} eV => sqrt(s) ~ 130 TeV
  - Different kinematic regimes
    - E_{beam} up to 10^8 TeV



Pierre Auger Observatory

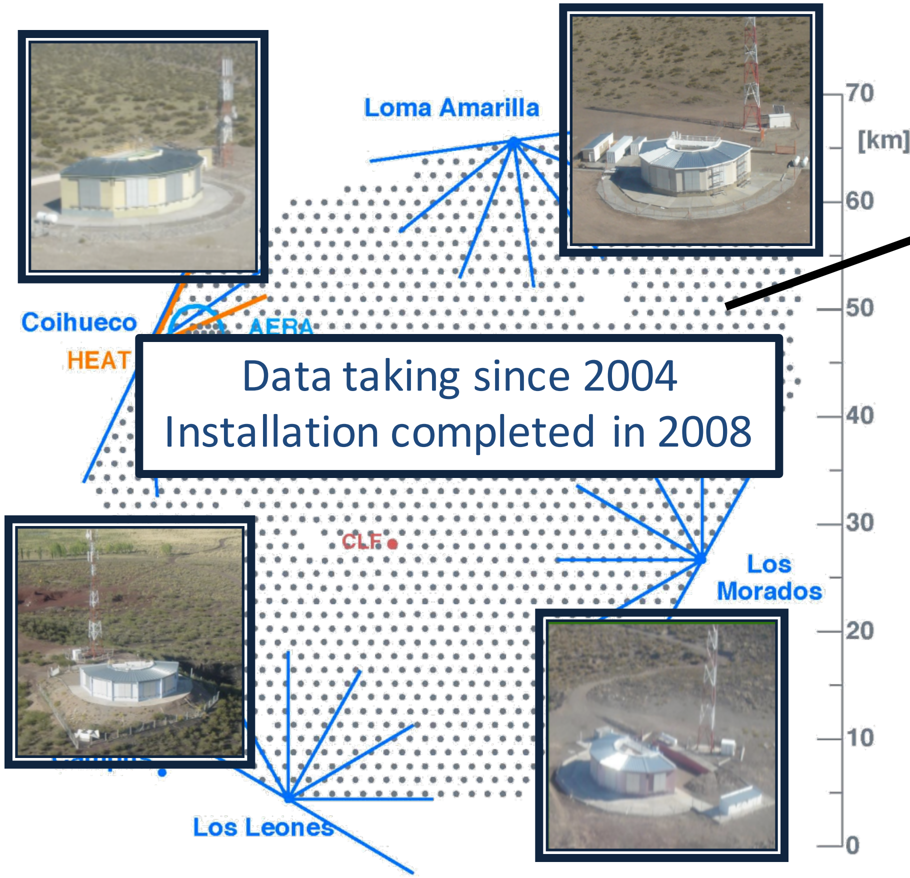


Area: 3000 km²

Located in the Pampa Amarilla, Mendoza, Argentina

Altitude: 1400 m a.s.l.

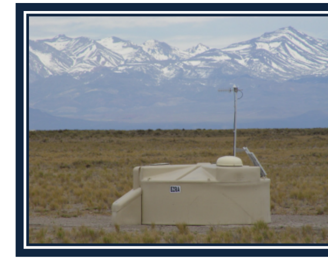
Pierre Auger Observatory



Data taking since 2004
Installation completed in 2008

~ 60 km

- **4 Fluorescence Detectors** (FD)
- 6 x 4 Fluorescence Telescopes



- ~ 1600 Surface Detector (SD) Stations
- 1.5 km spacing
- 3000 km^2

Low energy extension

- Aim to E ≈ 10^{17} eV
- AMIGA
  - Denser array plus muon detectors
- HEAT
  - 3 additional FD telescopes with a high elevation FoV

Pierre Auger Collaboration

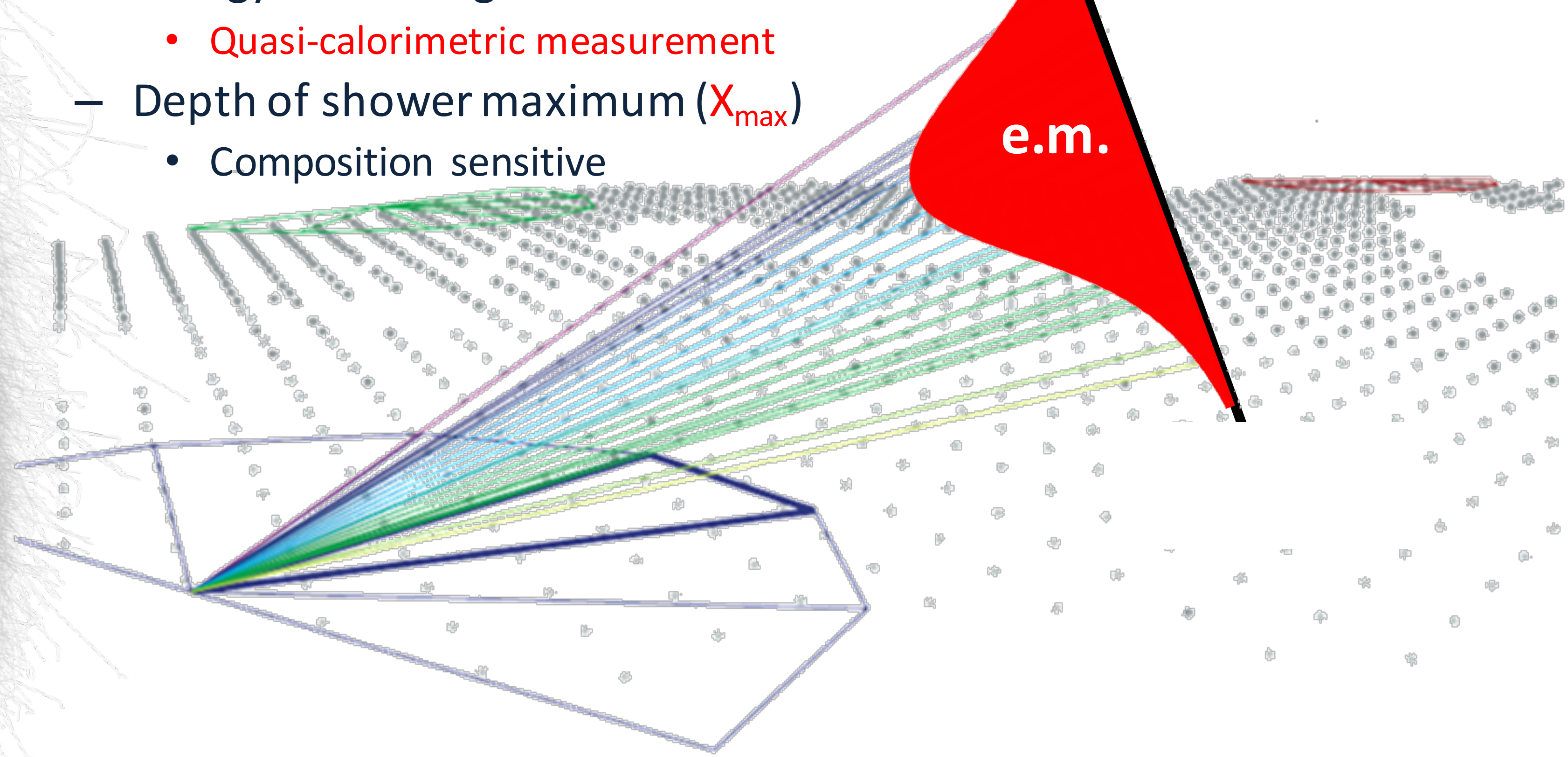
16 countries, ≈ 90 institutions, ≈ 500 authors

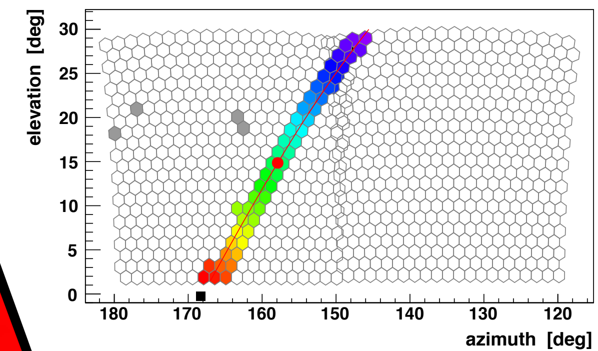
Argentina
Australia
Brasil
Colombia*
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
USA

*associated

What is measured?

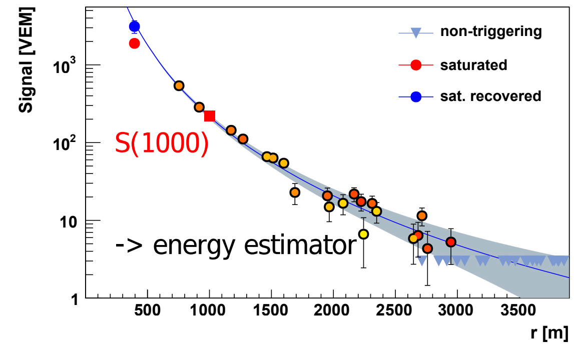
- FD: Collects the fluorescence light produced by the e.m. shower component in moonless nights
  - ~15% duty cycle
  - Energy from integral
    - Quasi-calorimetric measurement
  - Depth of shower maximum (X_{max})
    - Composition sensitive

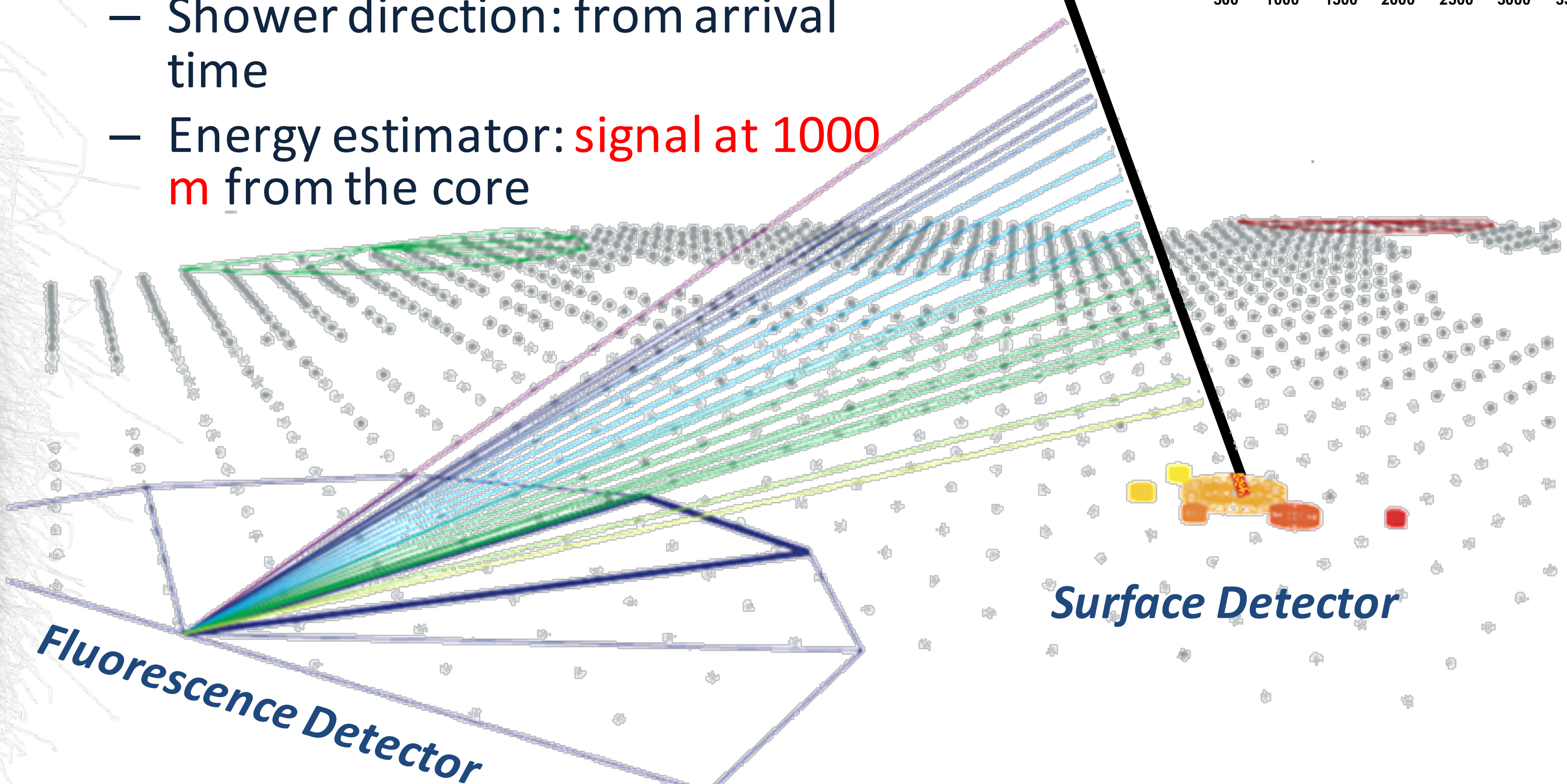




What is measured?

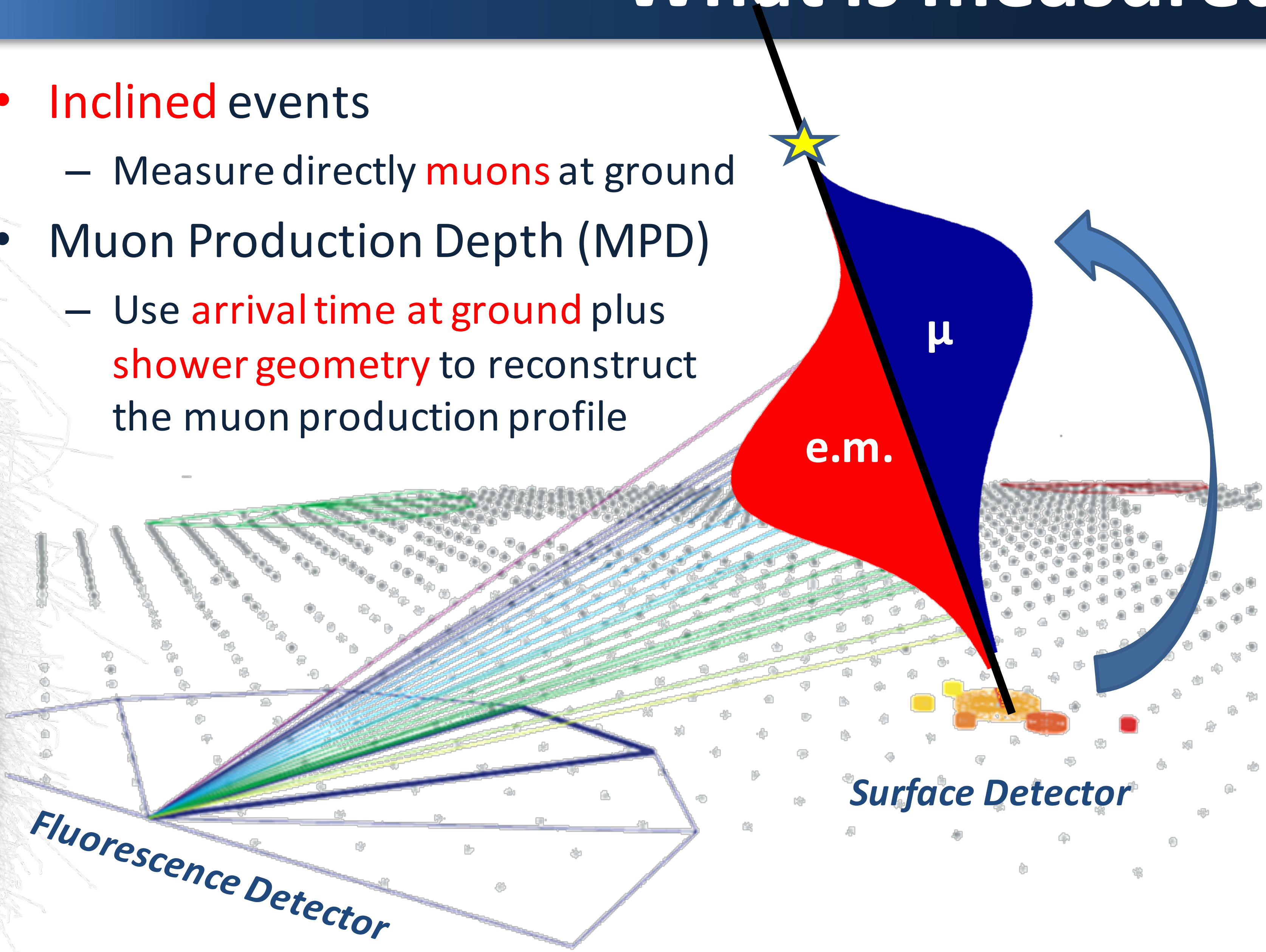
- SD: Sample the charged secondary particles that arrive at ground
  - 100% duty cycle
  - Shower direction: from arrival time
  - Energy estimator: signal at 1000 m from the core





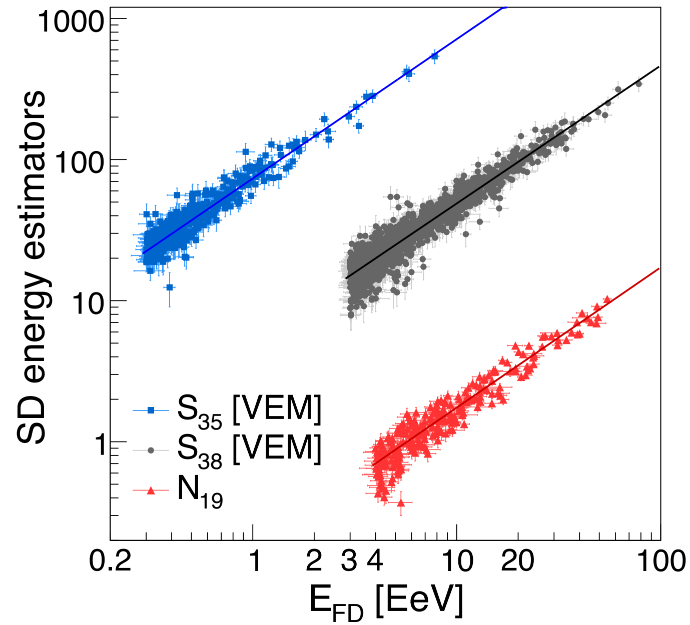
What is measured?

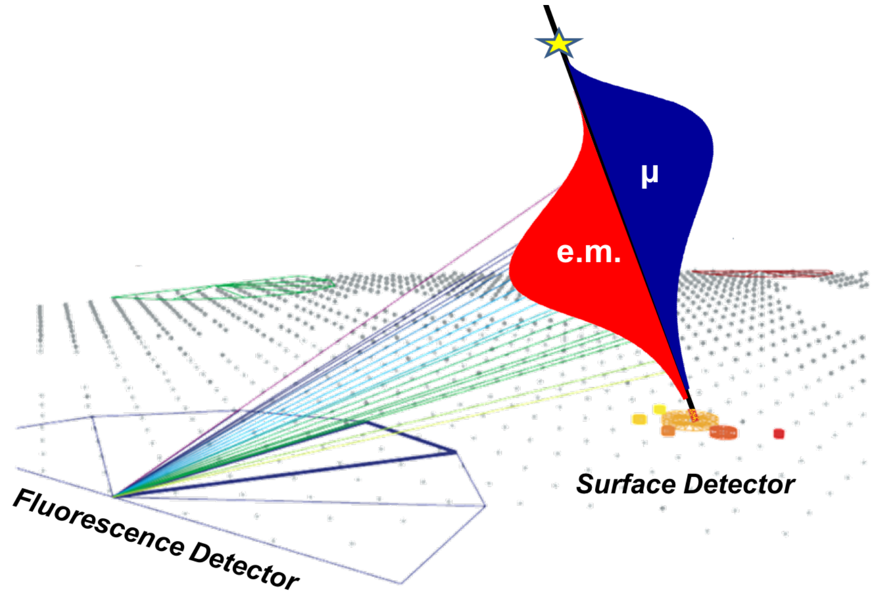
- Inclined events
  - Measure directly muons at ground
- Muon Production Depth (MPD)
  - Use arrival time at ground plus shower geometry to reconstruct the muon production profile



Hybrid technique advantages

- Calibration of SD with FD
  - FD provides a quasi-calorimetric energy measurement
- Improve geometry reconstruction
  - For hybrid events
- Different insights of the shower
  - Access different shower components
  - Test shower consistency



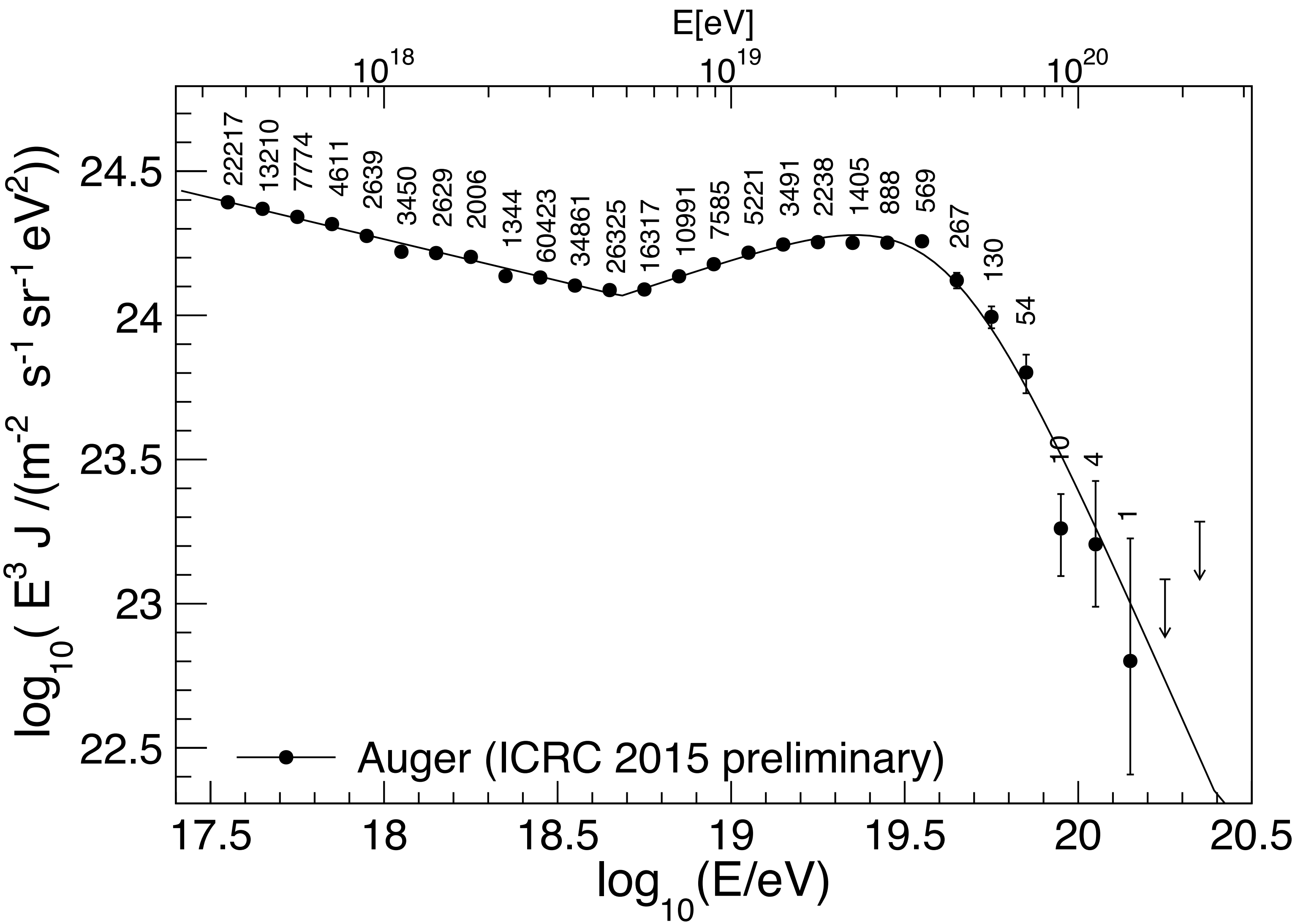


Pierre Auger Observatory Results

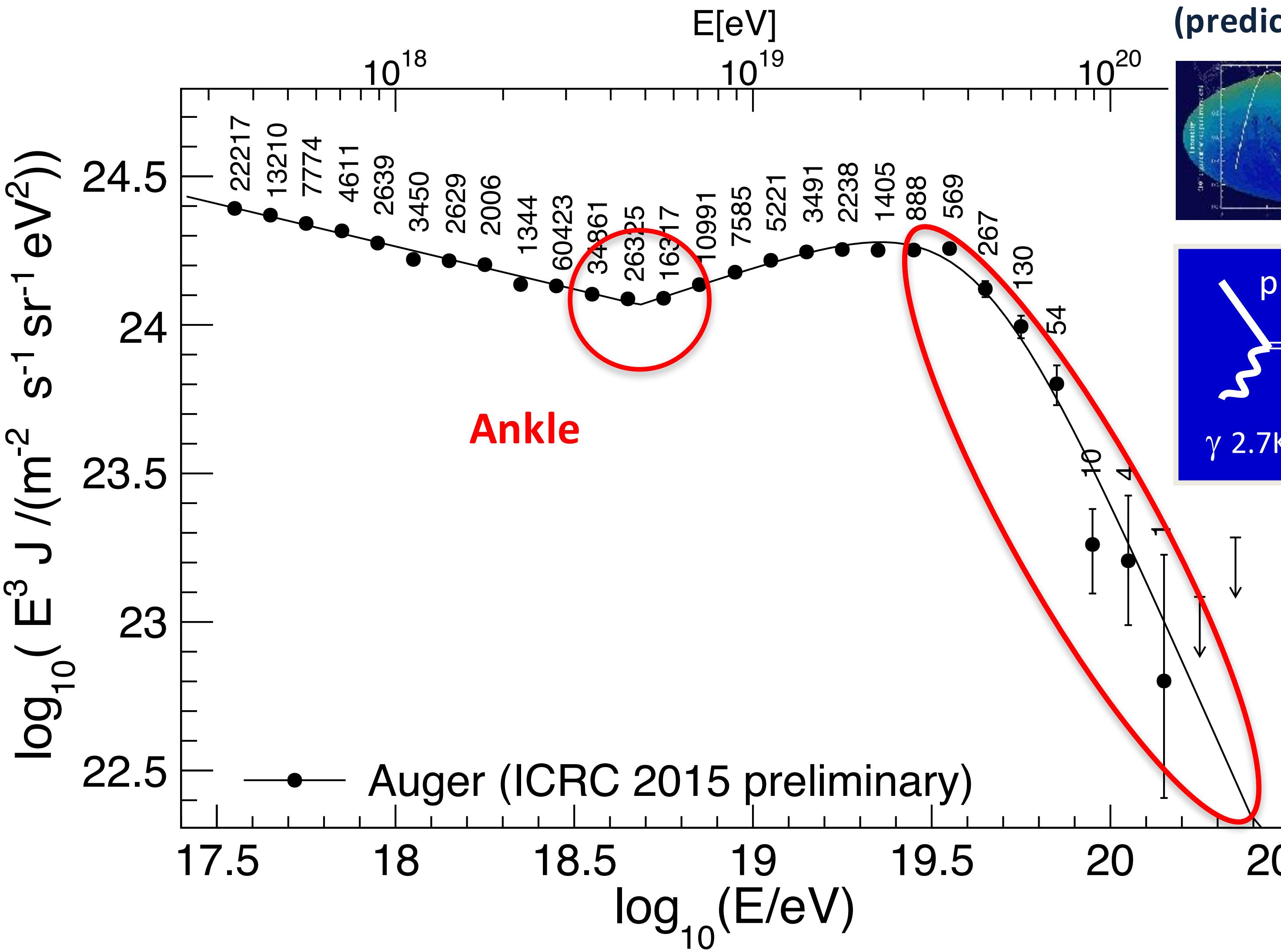
A small selection of the observatory results

UHECRs Energy Spectrum

I. Valiño for the Pierre Auger Coll., Proc. 34th ICRC (2015)

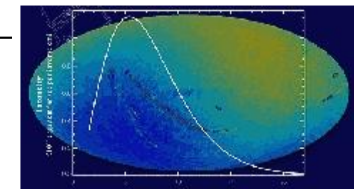


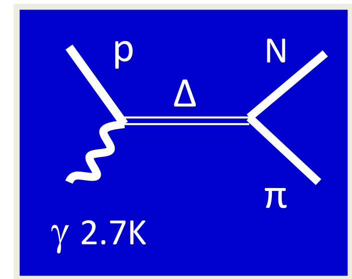
UHECRs Energy Spectrum



GZK effect

(predicted in 1966)

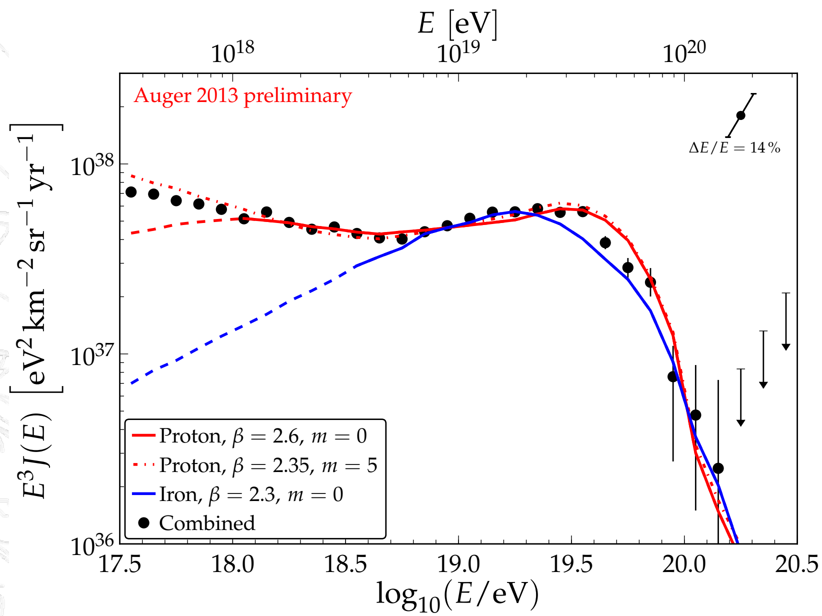




Two possible scenarios

Pure proton or Fe nuclei at source

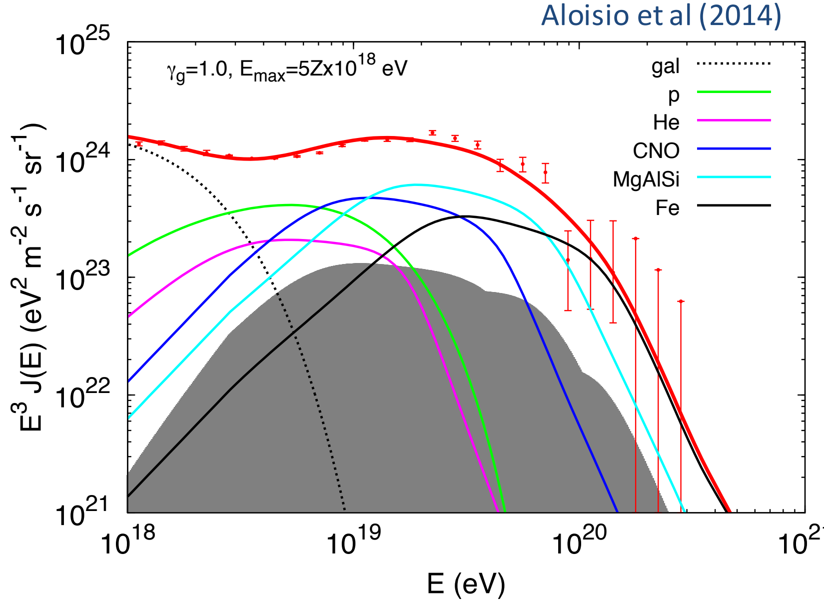
Cutoff caused by **GZK or photo-disintegration**



Mixed composition at source

Cutoff caused by **source energy exhaustion**

Aloisio et al (2014)

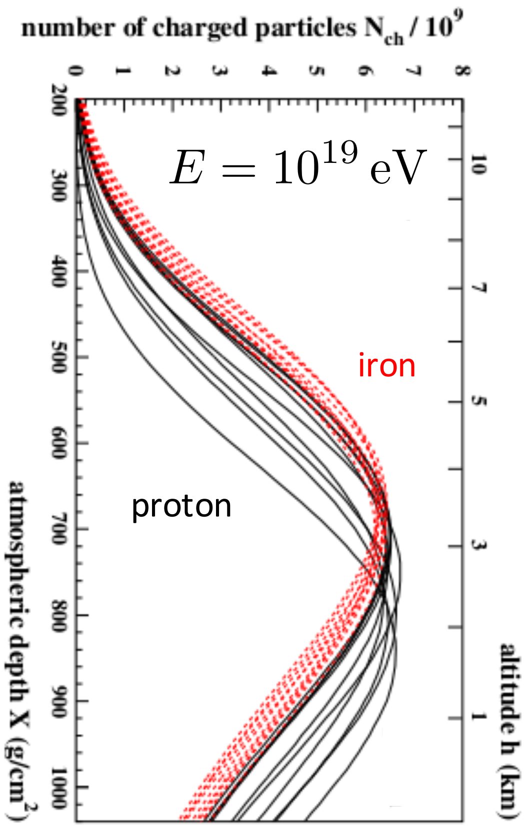


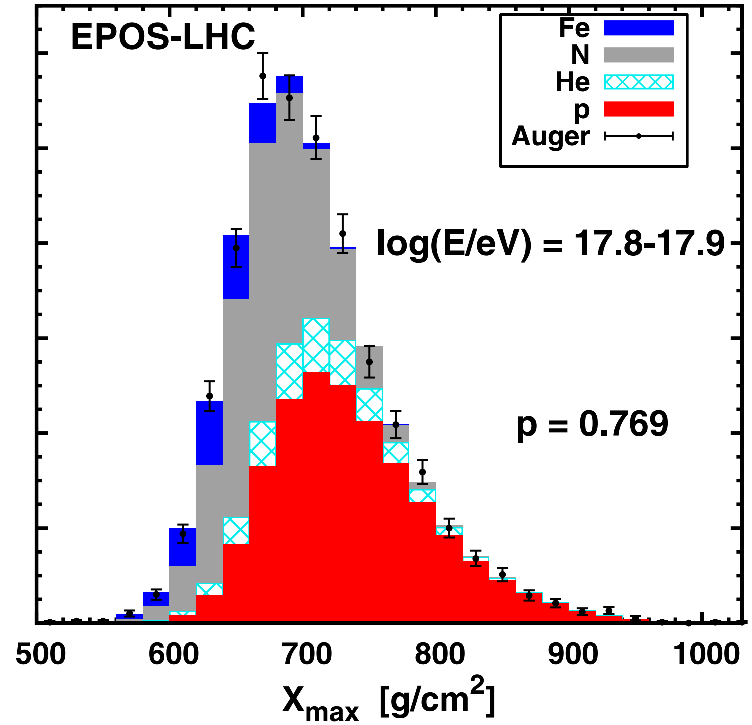
The UHECR composition is essential to understand the spectrum features cause

Nature of UHECRs

Depth of the shower maximum

Phys.Rev. D90 (2014) 12, 122006

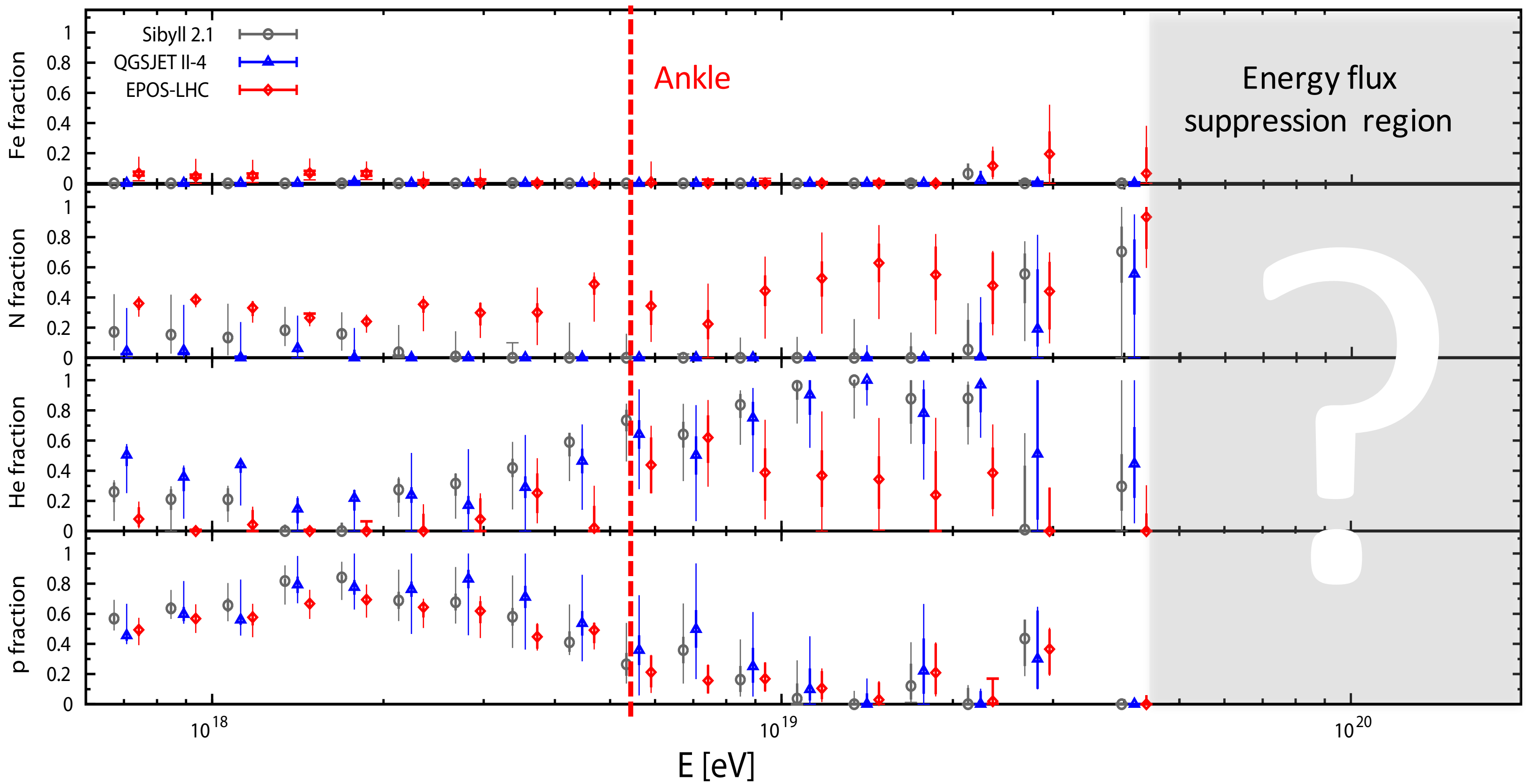




- Interpretation of the X_{max} distribution in terms of mass composition
  - Proton showers have in average deeper X_{max} than iron induced showers
  - X_{max} fluctuates more for proton induced showers

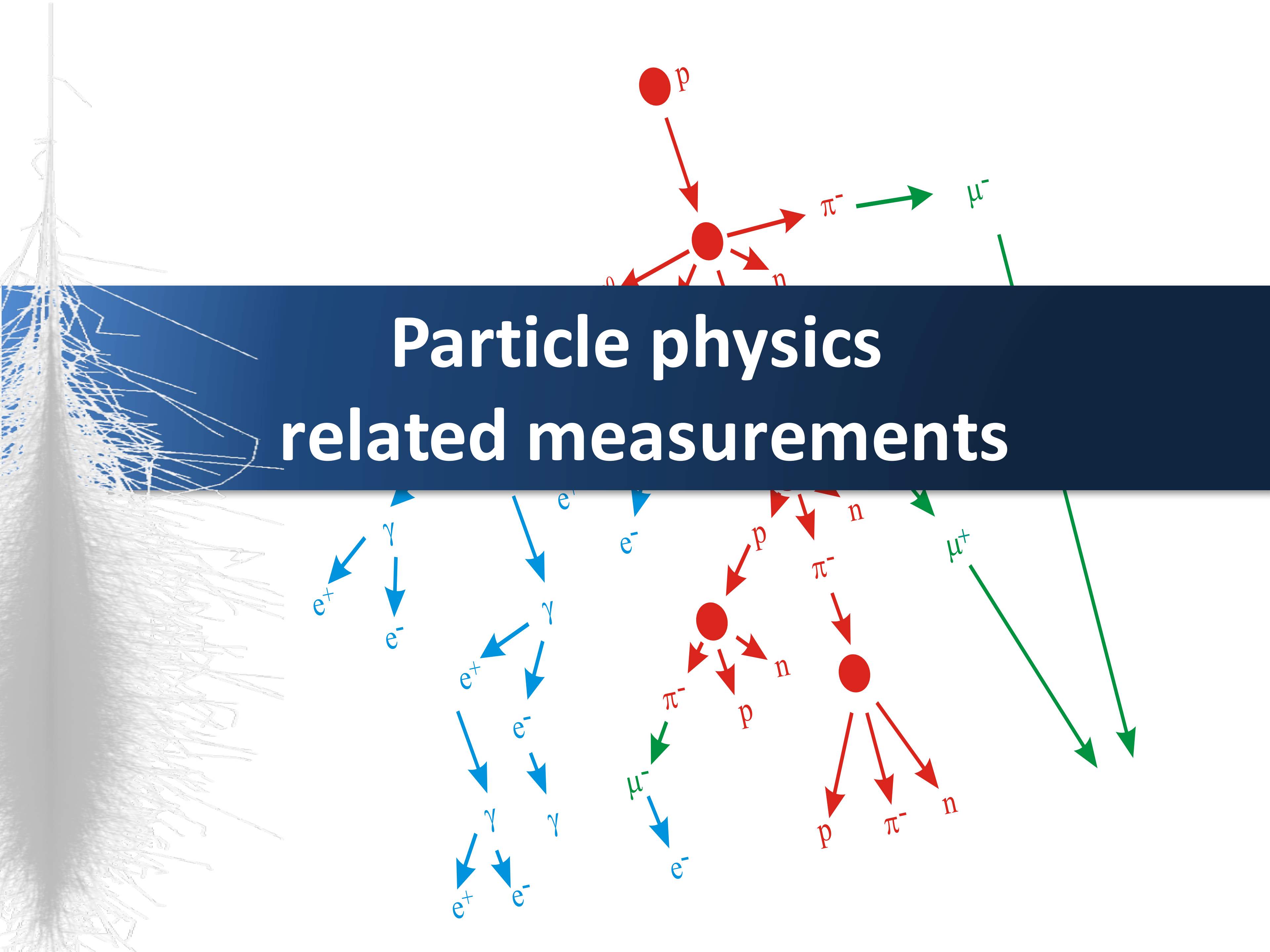
Mass composition interpretation

Phys.Rev. D90 (2014) 12, 122006



- Interpretation of the X_{max} distribution in terms of mass composition
  - Depends on the performance of hadronic interaction models
    - Mostly proton at low energies
    - Intermediate mass states at the highest available energies
    - Nearly no iron

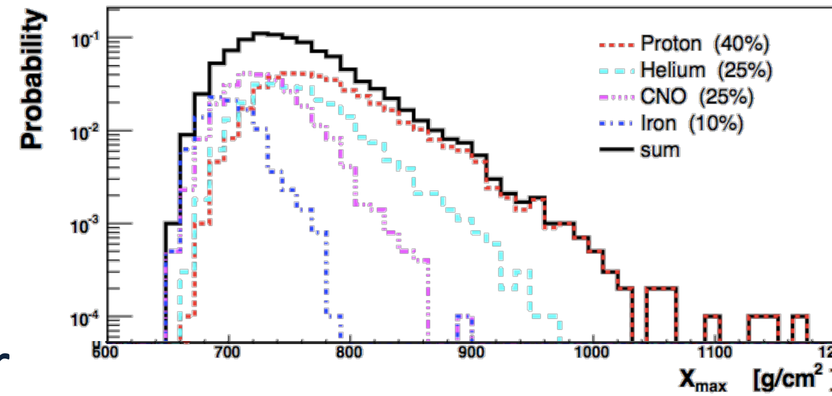
Particle physics related measurements

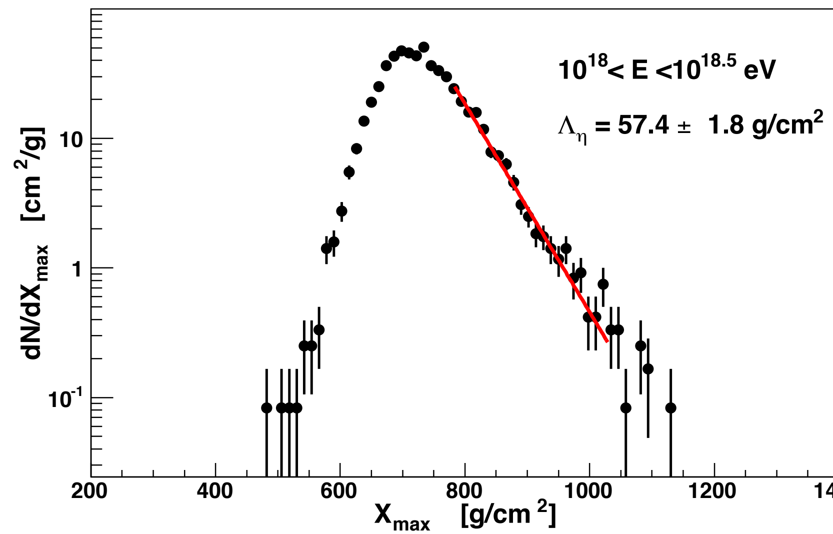


Proton-air cross-section

R. Ulrich for the Pierre Auger Coll., Proc 34th ICRC (2015)

- X_{max} distribution tail is sensitive to the primary cross-section
- If there is enough proton it is possible to measure the p-air cross-section at very high energies





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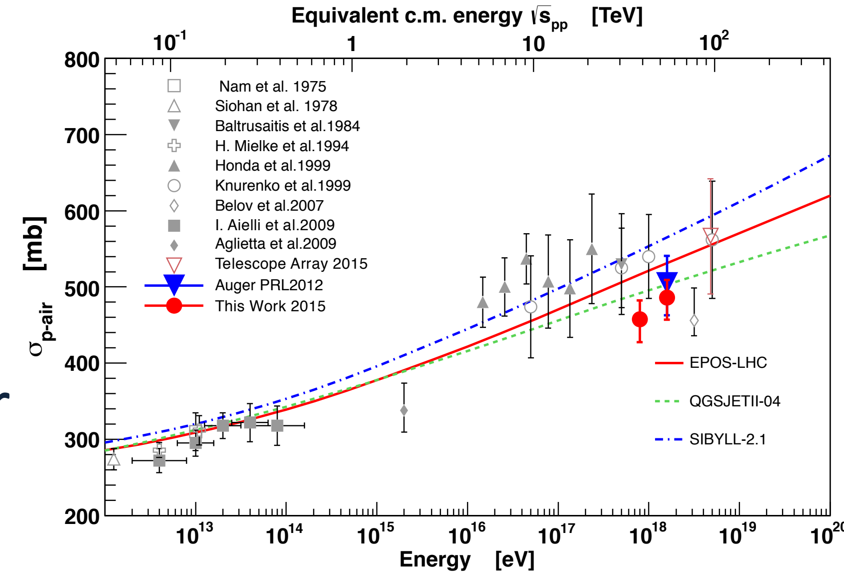
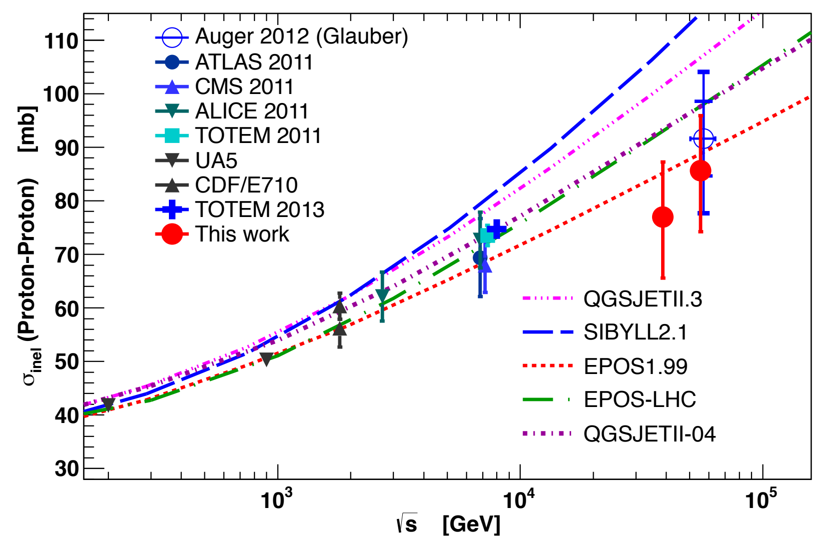
R. Ulrich for the Pierre Auger Coll., Proc 34th ICRC (2015)

- X_{max} distribution tail is sensitive to the primary cross-section
- If there is enough proton it is possible to measure the p-air cross-section at very high energies
- Measurement performed at:
  - $E = 10^{17.90}, 10^{18.22}$ eV
  - $\sqrt{s}$ = 38.7, 55.5 TeV
- Using Glauber theory is possible to translate this result into p-p cross-section



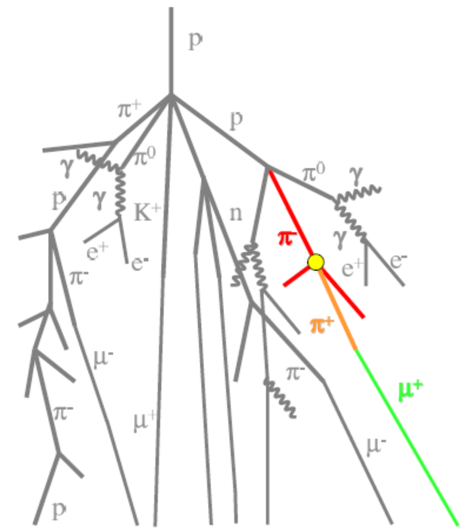


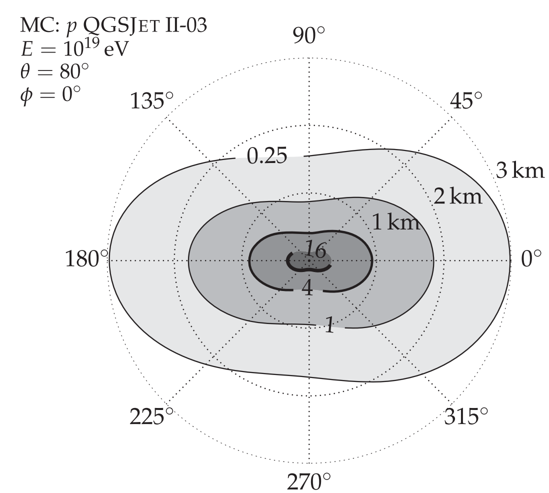
Muon content in air showers

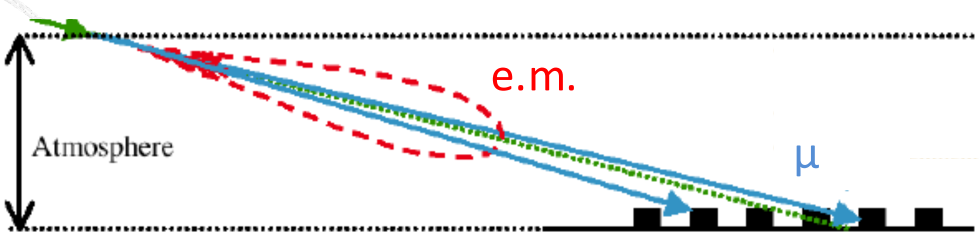
Phys.Rev. D91 (2015) 3, 032003

- Muon EAS content is directly related with the hadronic shower component

- Through inclined showers is possible to measure directly the muon content (R_μ) in the SD
  - Electromagnetic shower component gets attenuated

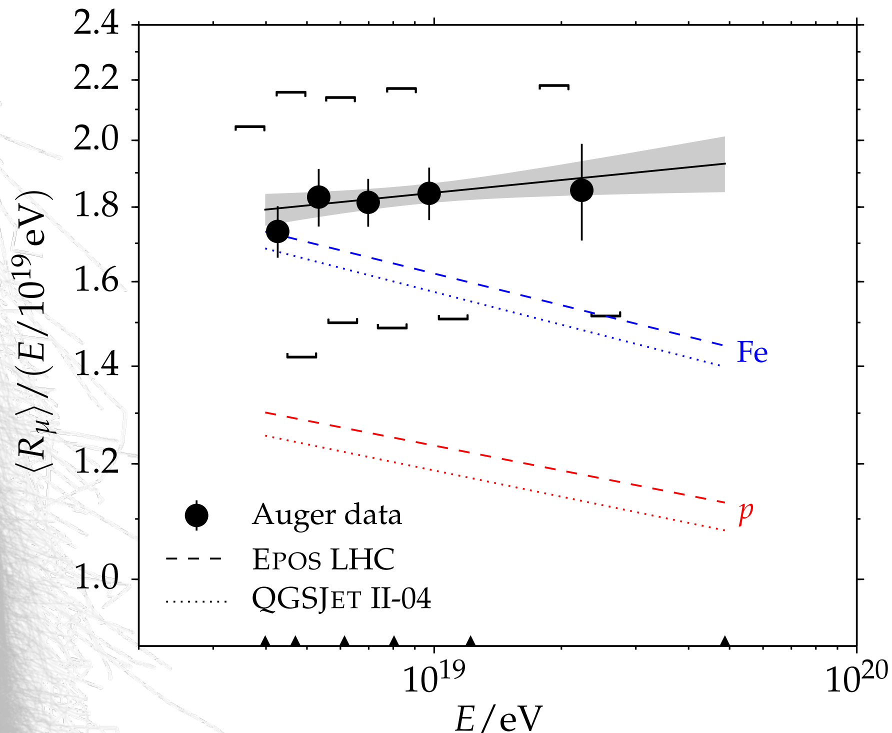


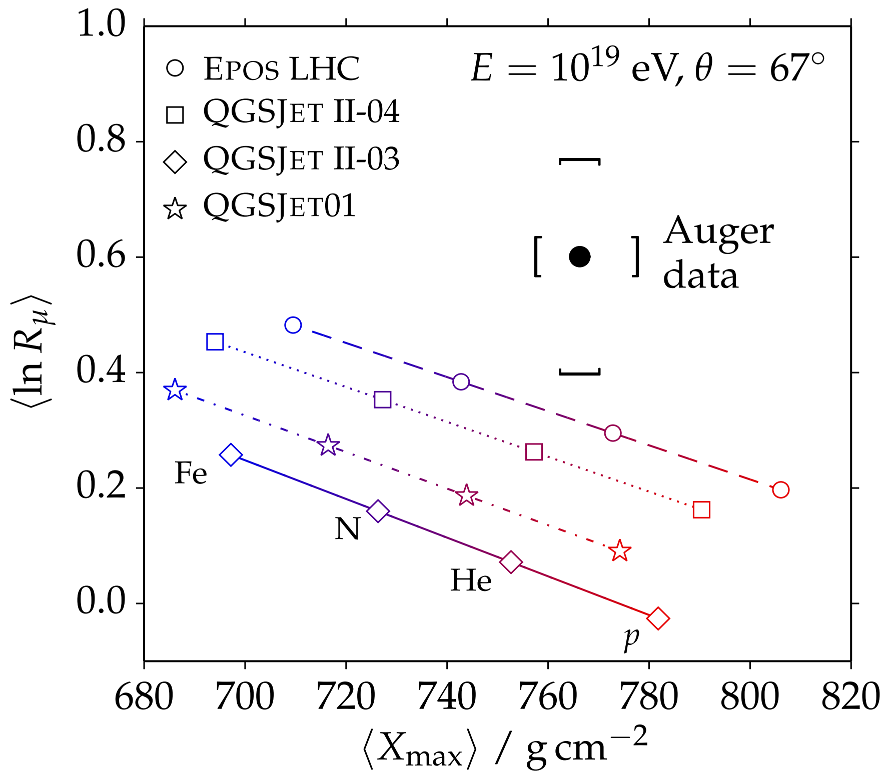




Muon content in air showers

Phys.Rev. D91 (2015) 3, 032003





- Mean muon number compatible with iron showers within systematic uncertainties
- Combination of the R_μ with X_{max} shows tension between data and all hadronic interaction models

Explore hybrid events

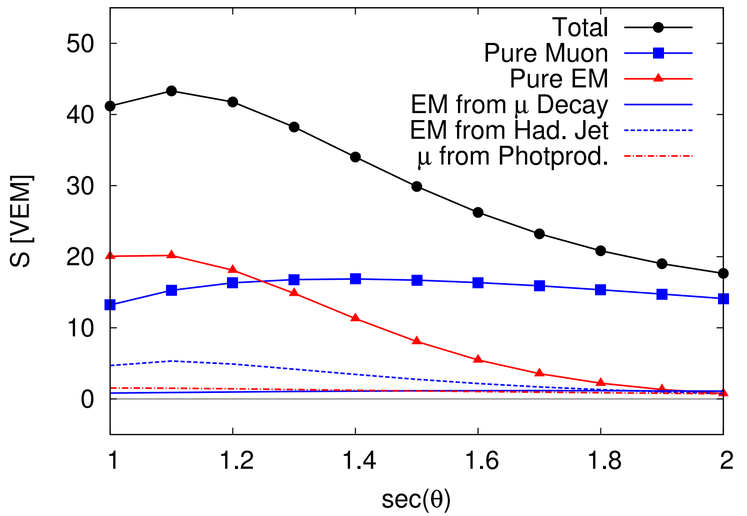
Accepted in Phys. Rev. Lett.

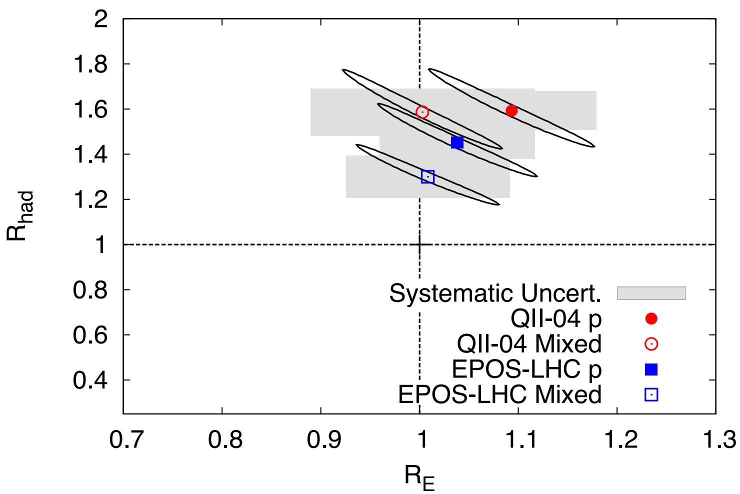
- Combined fit of energy scale (R_E) and hadronic component rescaling (R_{had})

$$S_{\text{resc}}(R_E, R_{\text{had}})_{i,j} \equiv R_E\, S_{EM,i,j} + R_{\text{had}}\, R_E^{\alpha}\, S_{\text{had},i,j}$$

- Findings:
  – No need for an energy rescaling
  – Hadronic signal in data is significantly larger with respect to simulations

Model	R_E	R_{had}
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 Mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS Mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

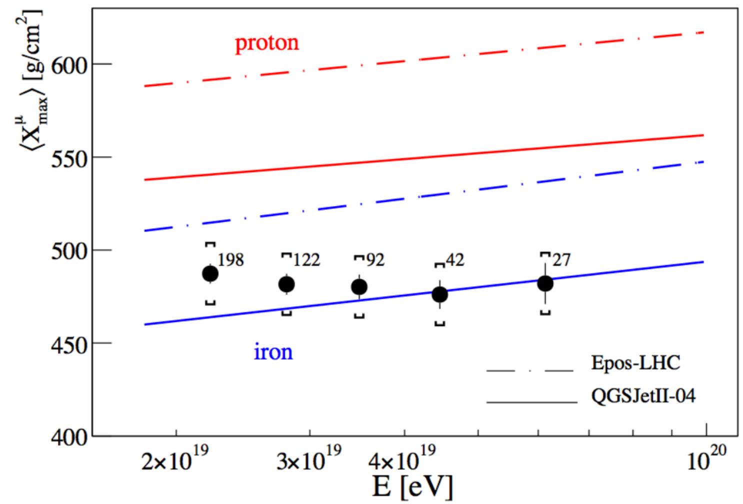


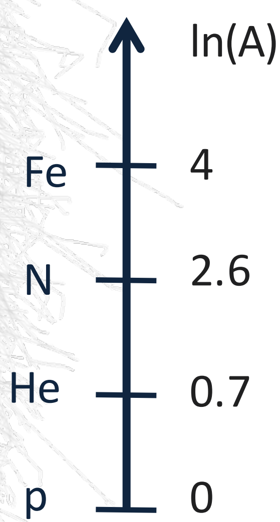


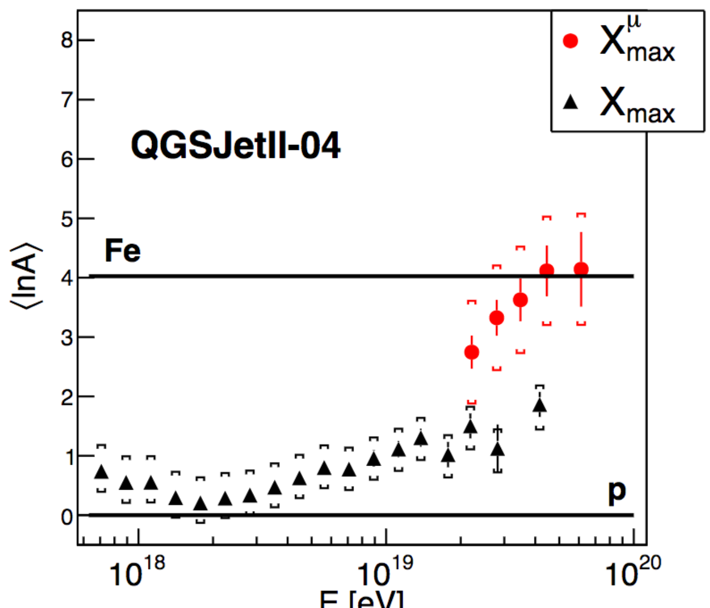
Muon Production Depth

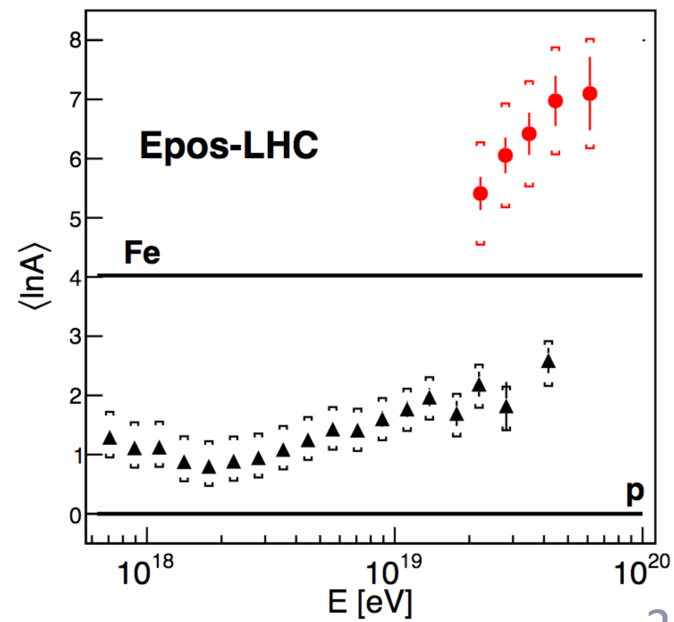
Phys.Rev. D90 (2014) 1, 012012

- Muon Production Depth
  - Sensitive to composition
- Mean X_{max} and X^{μ}_{max} should give the same average mass composition
  - EPOS-LHC fails to provide a consistent solution





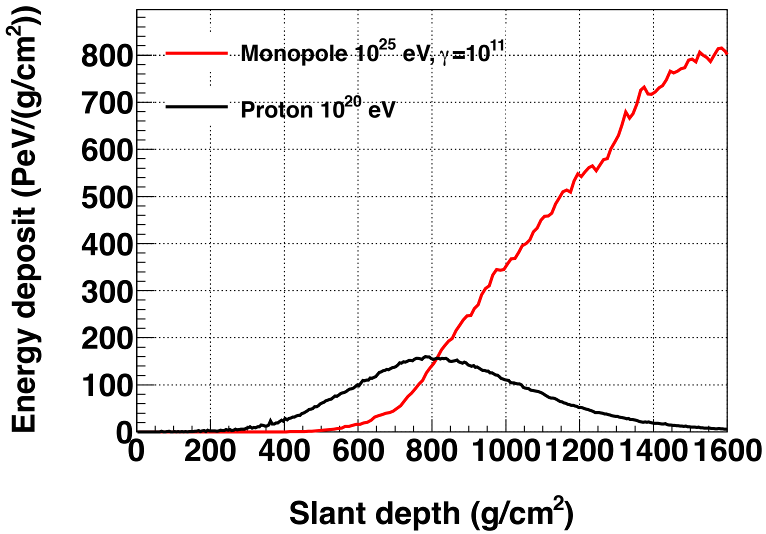


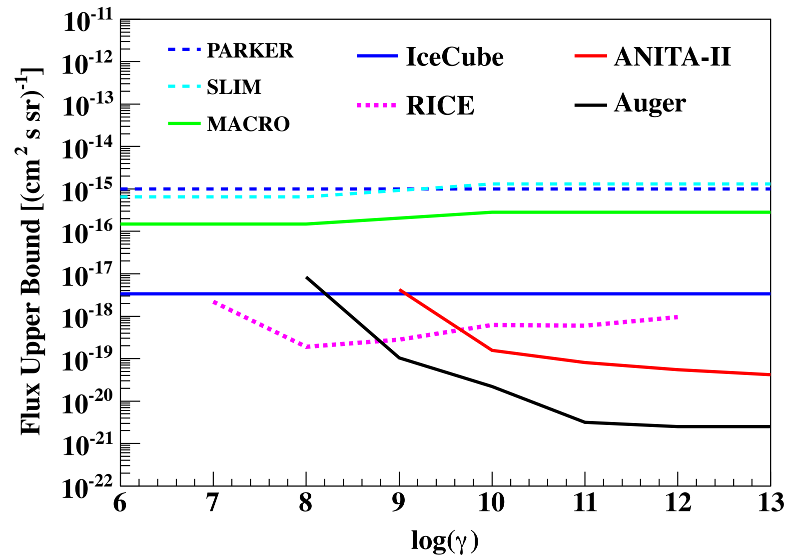


Testing exotic scenarios

Accepted in Phys. Rev. D, arXiv:1609.04451

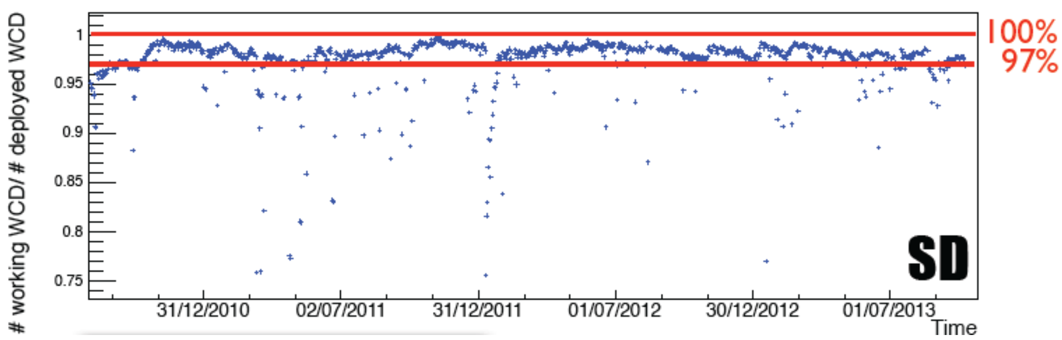
- Put the strongest limits on the existence of ultra-relativistic magnetic monopoles
  - Test on fundamental particle physics exotic scenarios
    - Relics of phase transitions in the early universe
  - MM produce air showers with a distinct signature from standard ones
    - $E_{mon} \approx 10^{25}\,\mathrm{eV}$
    - $M_{mon} \in [10^{11}; 10^{16}]\,\mathrm{eV/c^2}$

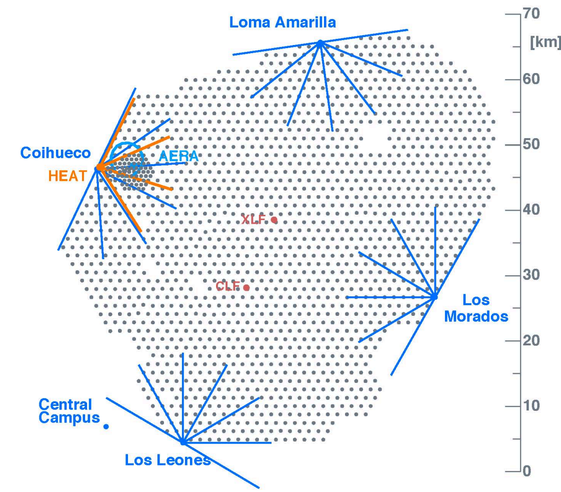




The future of the Observatory

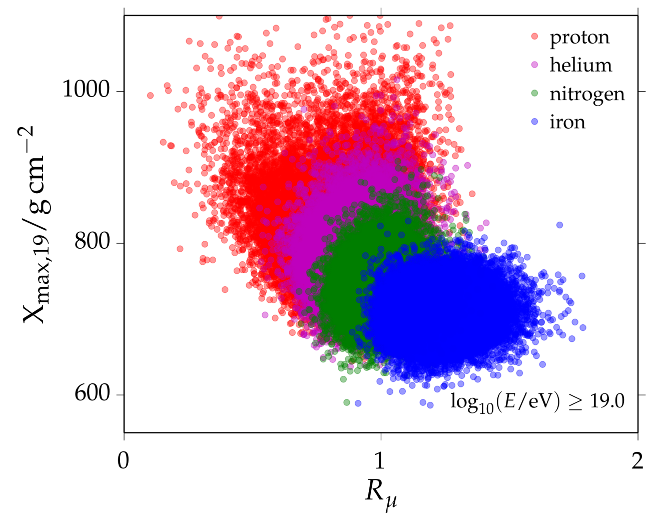
Fraction of Cherenkov tanks in operation





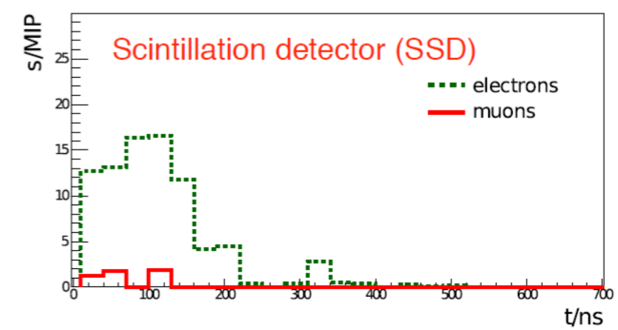
- Observatory is running smoothly and its operation was approved until 2025

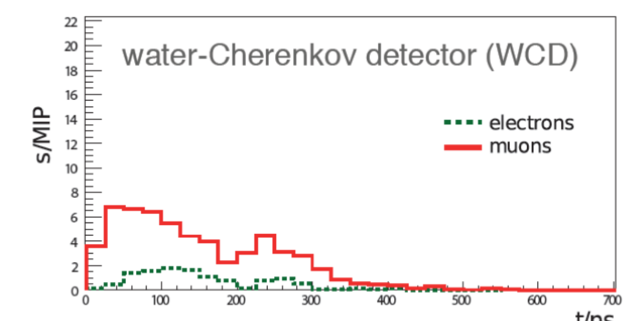
- Upgrade to measure separately the e.m. and muonic shower component at the ground



The future of the Observatory

- Auger PRIME
  - "Primary cosmic Ray Identification through Muons and Electrons"
  - Two complementary detectors:
    - Scintillator on top of the tank: signal dominated by e.m. component
    - WCD sensitive to e.m. + muons
  - The goal:
    - Enhance primary identification
    - Improve shower description
    - Reduce systematic uncertainties



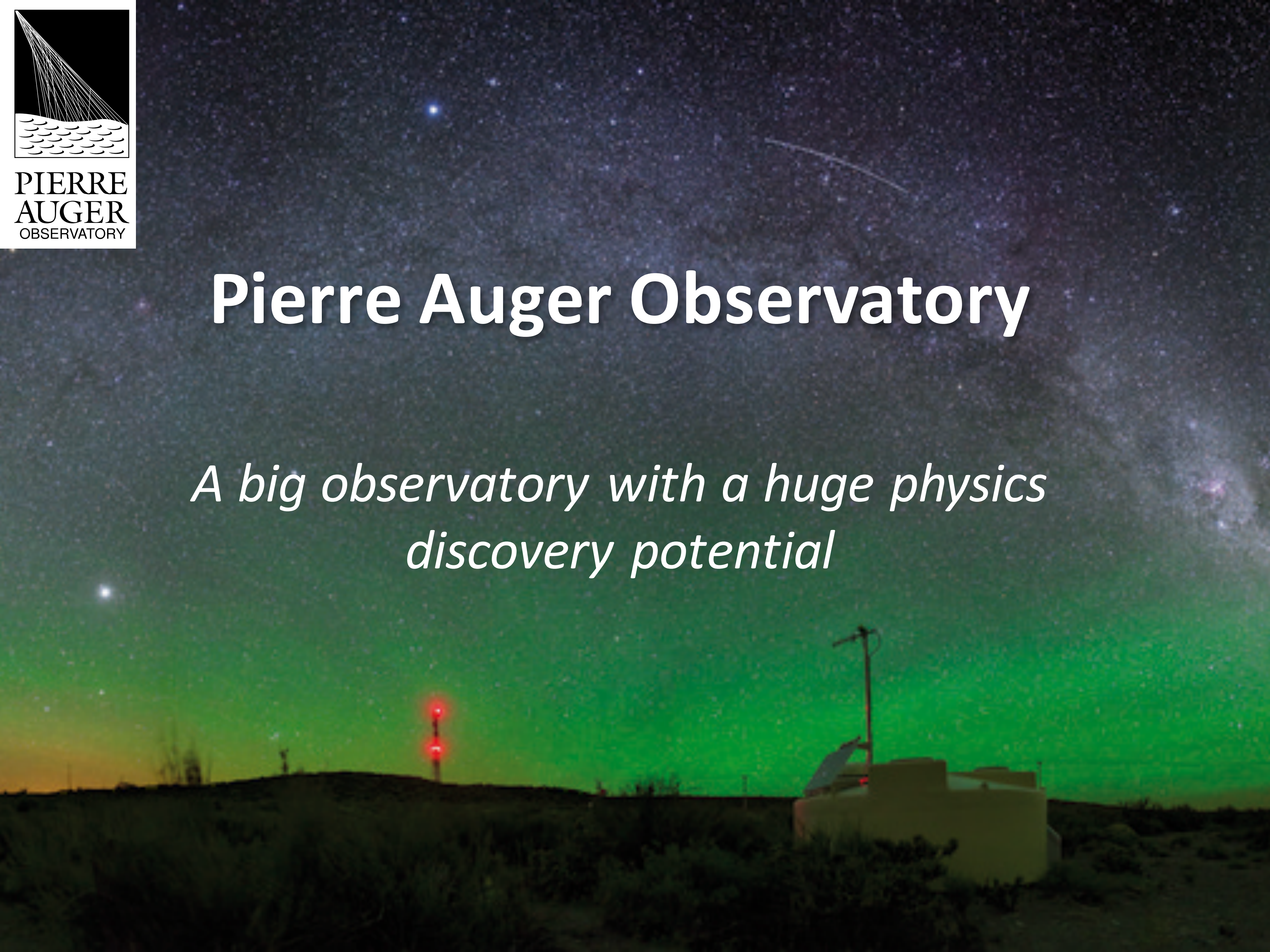


Summary

- UHECRs measured at Pierre Auger Observatory
  - Opportunity to study the **high-energy Universe** and **Particle Physics** at the highest energies
- Pierre Auger Observatory has delivered many important results
  - GZK-like suppression established
  - Complex primary mass composition scenarios
  - Current hadronic interaction models not able to describe consistently the air shower observables
- Upgrade: Auger PRIME
  - Measure independently the e.m. and muonic component at ground

Pierre Auger Observatory

A big observatory with a huge physics discovery potential



Acknowledgments

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

COMPETE
PROGRAMA OPERACIONAL FACTORES DE COMPETITIVIDADE

QREN
QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL
PORTUGAL 2007.2013

UNIÃO EUROPEIA
Fundo Europeu de Desenvolvimento Regional

LIP

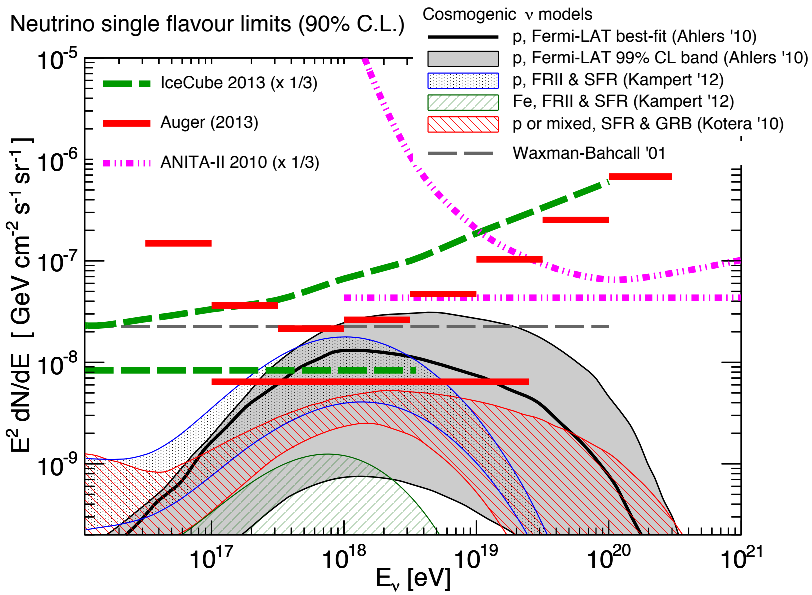
TÉCNICO LISBOA

BACKUP SLIDES

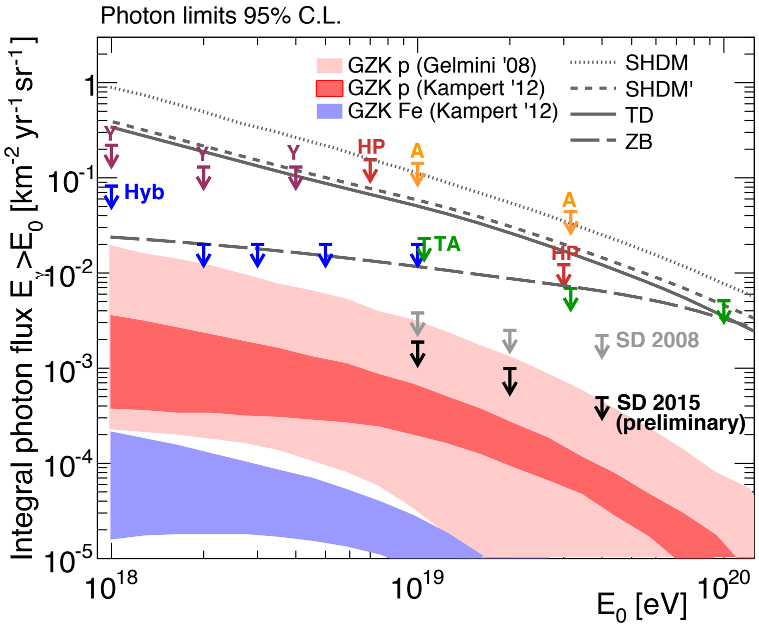
Neutrino and photon limits

C. Bleve for the Pierre Auger Coll., Proc 34th ICRC (2015)

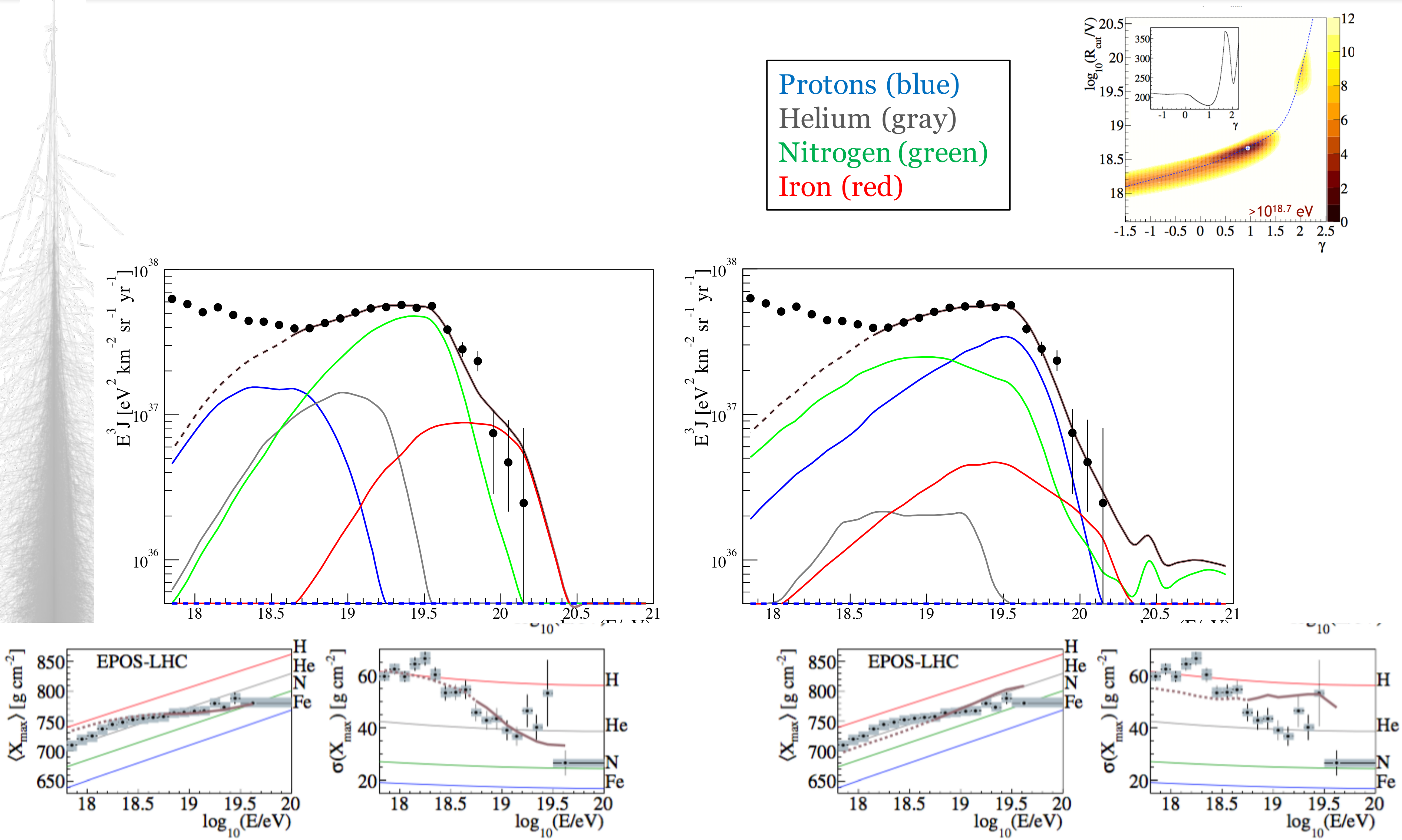
Neutrino limits



Photon limits

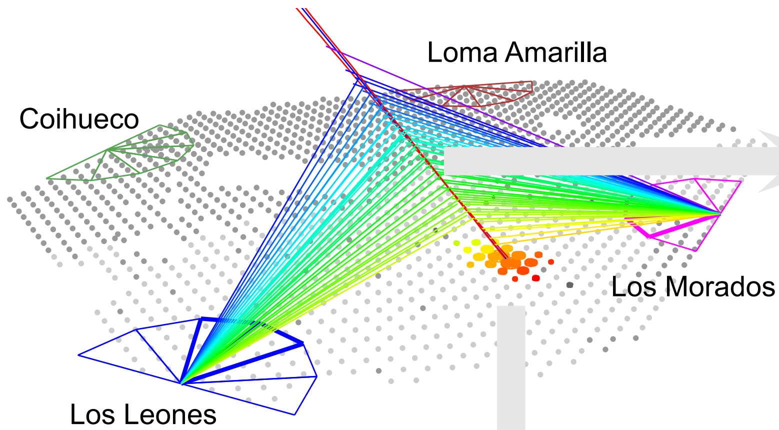


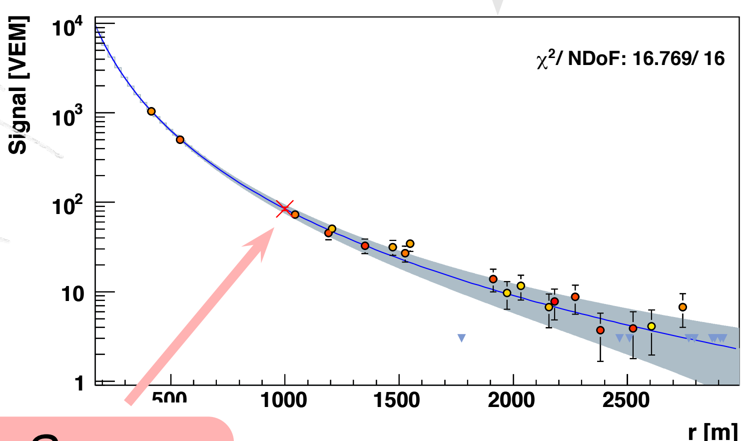
Combined spectrum + comp fits



A. di Matteo for the Pierre Auger Coll., Proc 34th ICRC (2015)

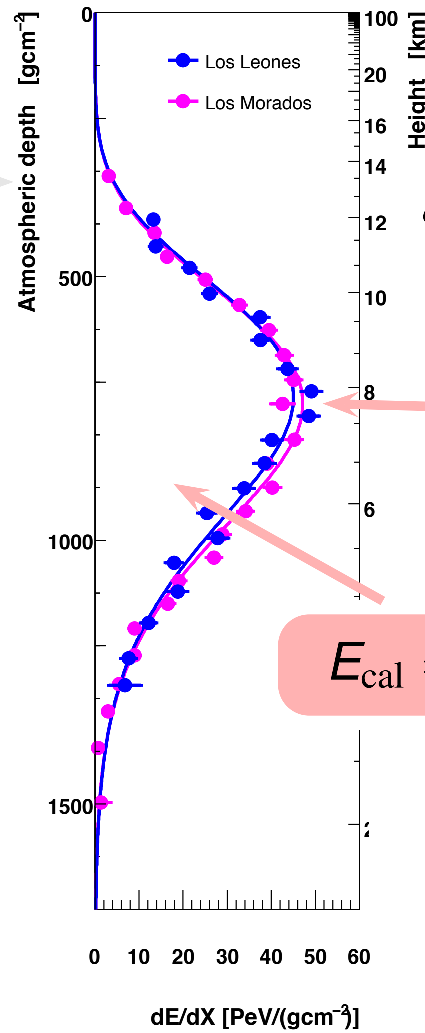
Hybrid Technique





S_{1000}

$E_{\mathrm{surface}} = f(S_{1000},\ \theta)$



$\sigma X_{\mathrm{max}} \lesssim 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \lesssim 10\,\mathrm{g/cm^2}$

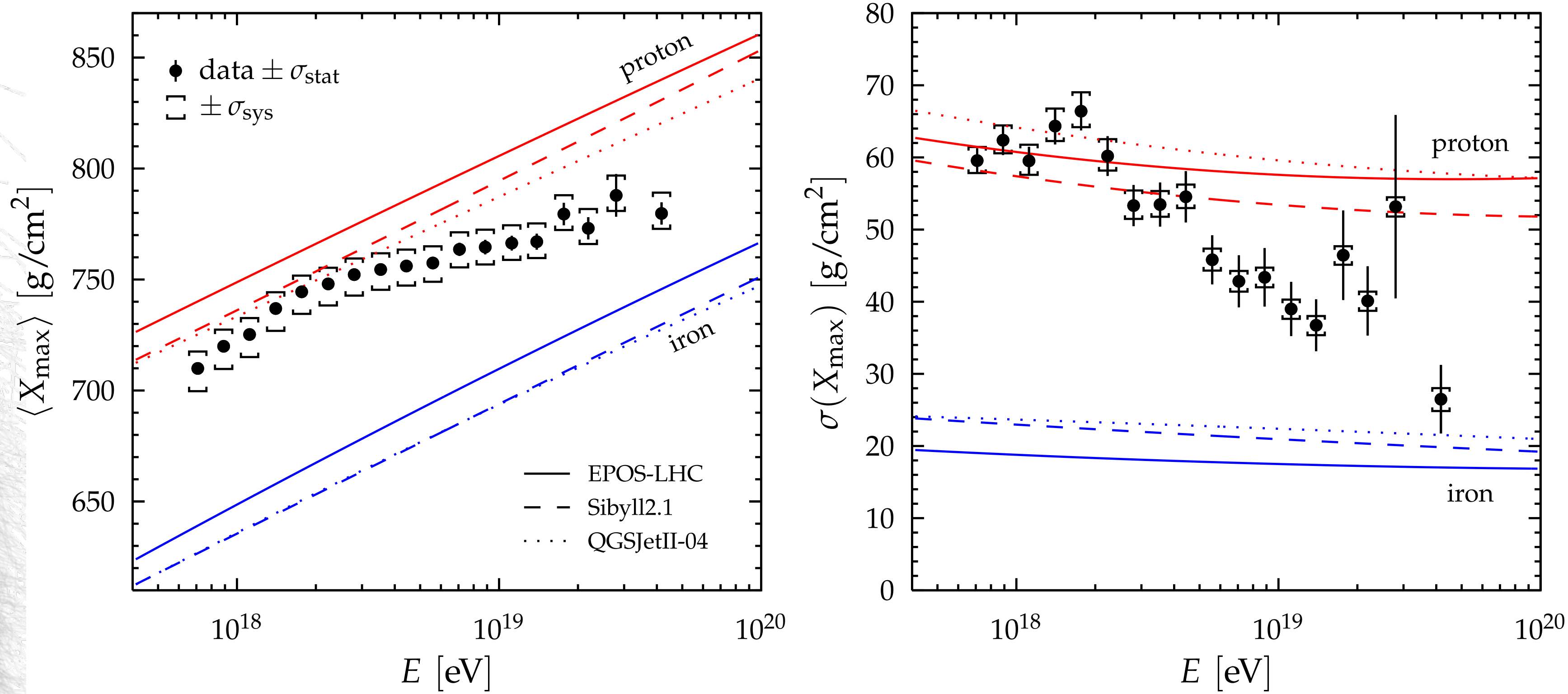
X_{max}

$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 15\,\%$

Depth of Shower Maximum (X_{max})

Phys.Rev. D90 (2014) 12, 122005

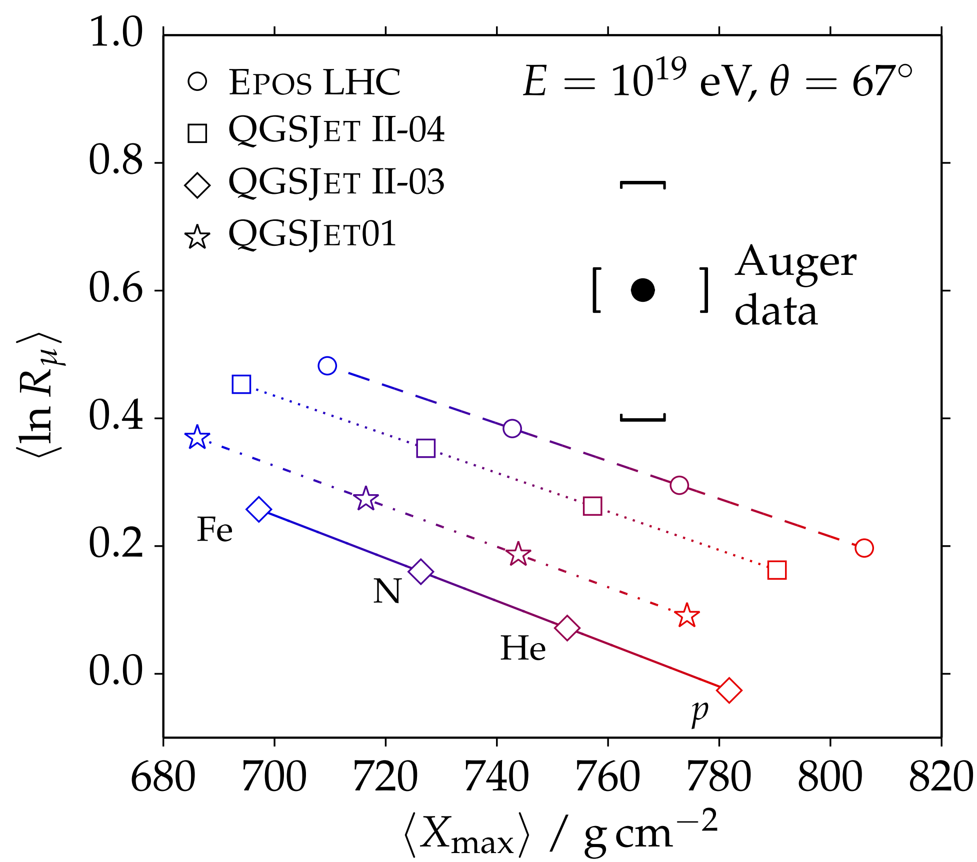


- Average X_{max} and its RMS consistent with a lighter(heavier) composition at lower(higher) energies
- Change on elongation rate around log(E/eV) = 18.2

Muon content in air showers

Phys.Rev. D91 (2015) 3, 032003

Surface Detector



Fluorescence Detector

Combination of the number of muons R_μ with X_{max} reveals tension between data and all hadronic interaction models