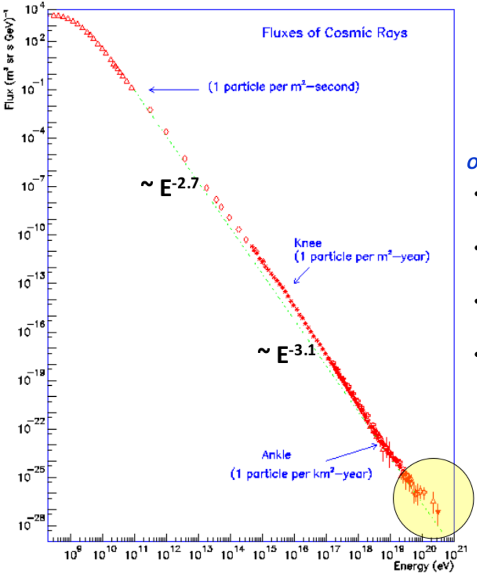
Auger: Showers and Physics

F. Diogo on behalf of the Auger Group

Jornadas LIP

20^{th} February 2016

Cosmic Ray Energy Spectrum



Ultra High Energy Cosmic Rays

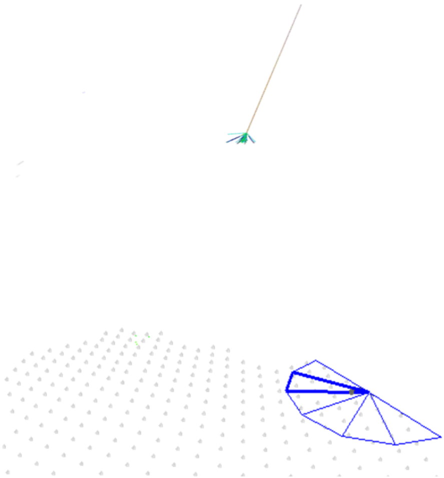
Open (and interconnected) questions

- Determine the **sources** of these cosmic rays
- Study the **propagation** through the intergalactic medium
- Determine the **elemental composition** of cosmic rays
- Study extensive air showers -> **particle interactions**

Above 10^{20} eV (50 Joules!):

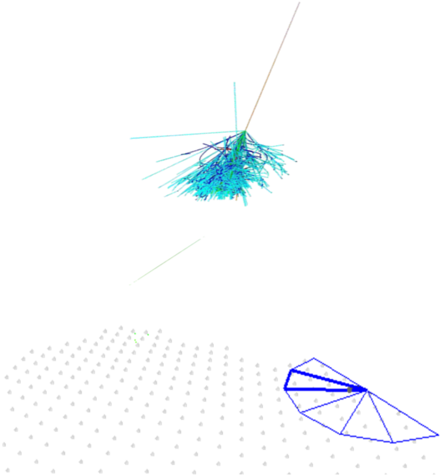
$\Phi \approx 1$ per km^2 per century

Extensive Air Shower



- High energy cosmic rays interact with the atmosphere, multiplying and creating an air shower

Extensive Air Shower



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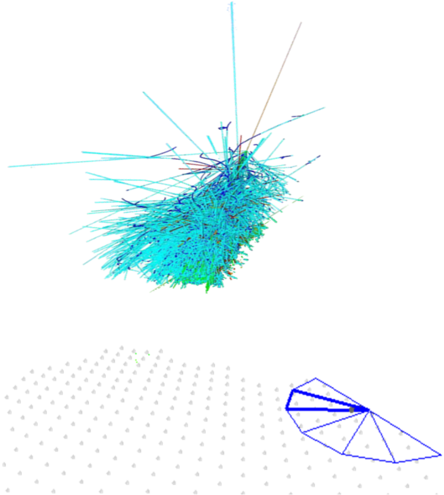

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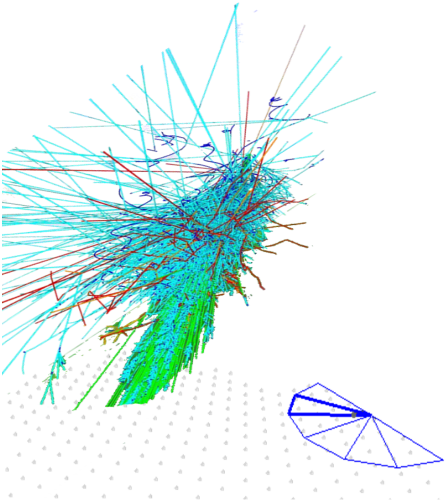
- Shower keeps developing until particles reach a minimum critical energy - Shower maximum

Extensive Air Shower



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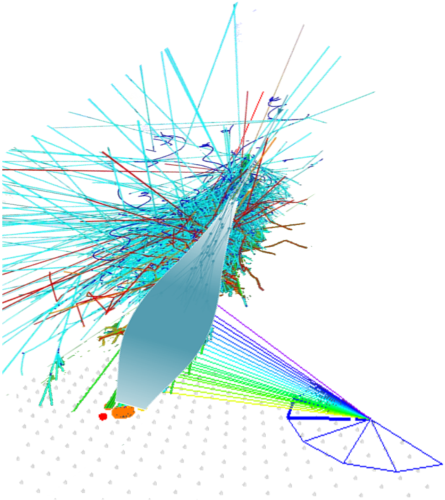


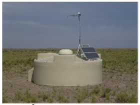
- High energy cosmic rays interact with the atmosphere, multiplying and creating an air shower
- Shower keeps developing until particles reach a minimum critical energy - Shower maximum
- Two methods of (indirect) detection
  - sample the particles hitting the ground
  - detection of fluorescence light from de-excitation of atmospheric molecules

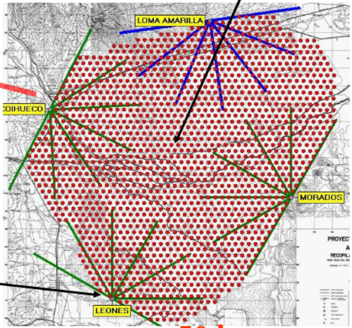
Pierre Auger Observatory

Malargue - Argentina

3000 km^2

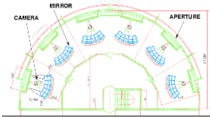
SD 1600 water Cherenkov detec. on a 1.5 km hexagonal grid





50 km

FD 4 x 6 fluorescence telescopes



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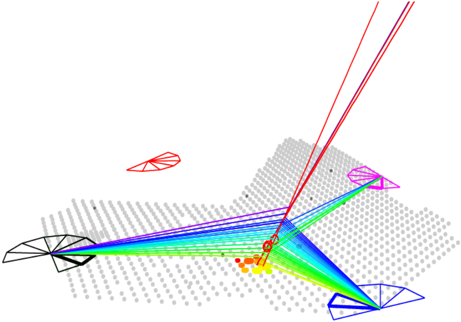

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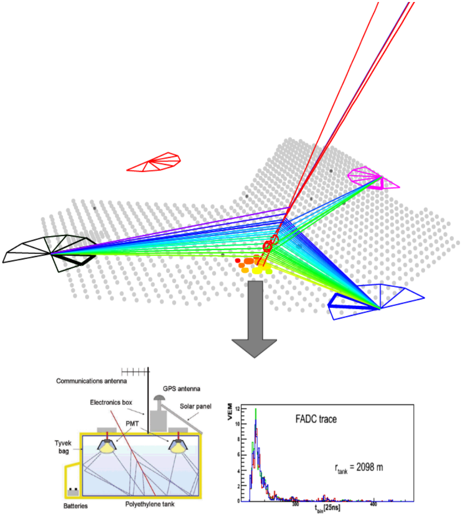

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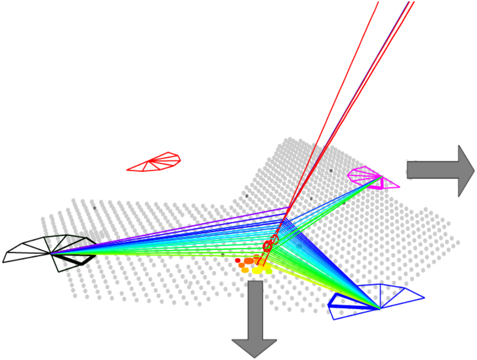

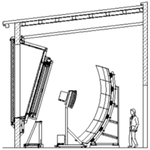

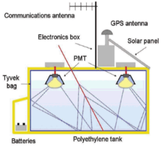

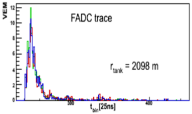

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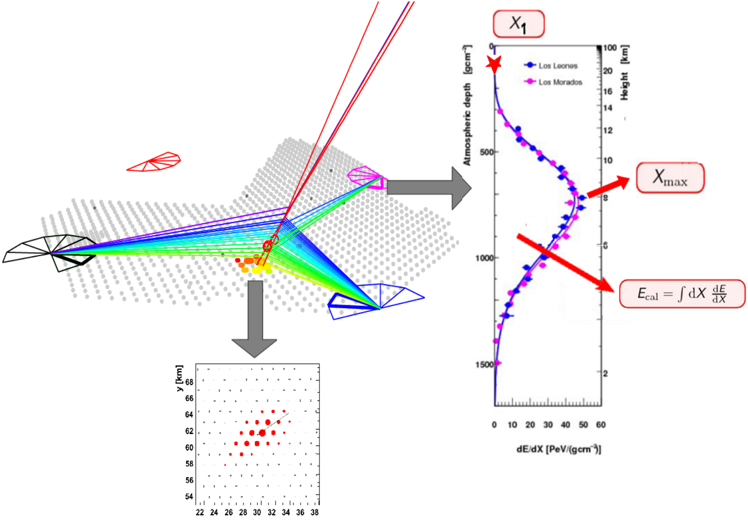
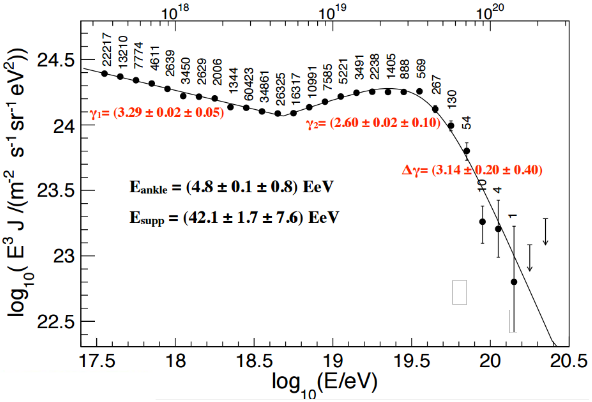
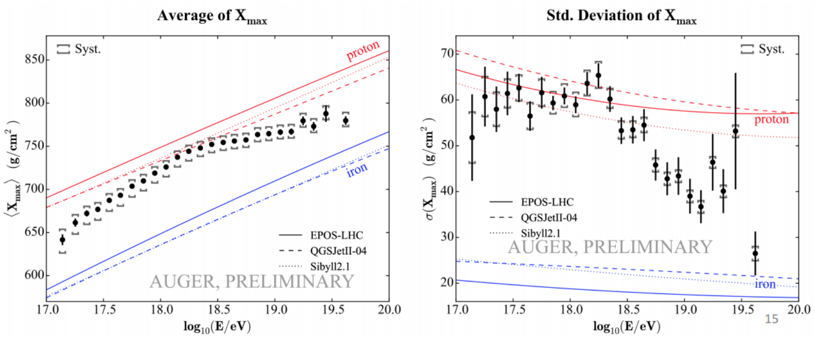


Auger Results - Spectrum



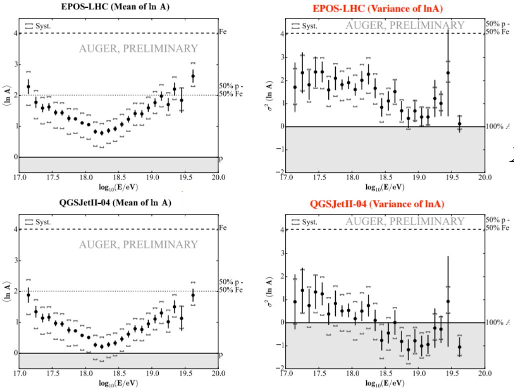
- Precise spectrum in almost 3 decades in energy
  - SD (1500m) + SD (750m) + FD
- Suppression at around $10^{19.6}$ eV
  - compatible with the GZK prediction

Shower maximum



- Main composition variable in UHECR is X_{max}
- Auger has the most precise measurement, now in a larger energy range
  - HEAT extends the energy range down to 10^{17} eV

Combining X_{max} and $\sigma(X_{max})$



X_{max} decreases linearly with $\ln[A]$:

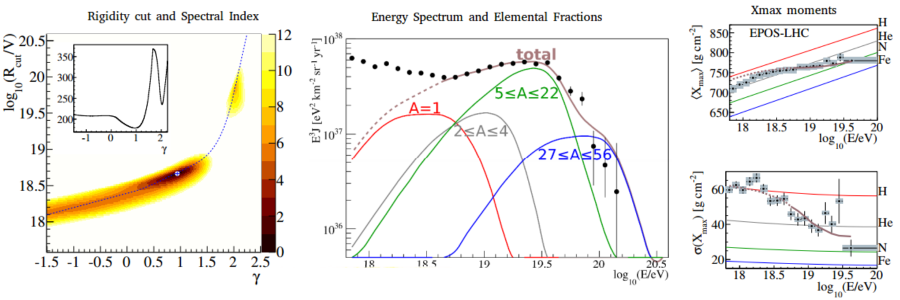
- $\langle X_{max} \rangle = \langle X_{max} \rangle_p + f_E \langle \ln[A] \rangle$
- X_{max}, $\sigma(X_{max}) \rightarrow \ln[A]$, $\sigma(\ln[A])$

- EPOS-LHC infers a mostly pure composition above $10^{18.5}$ eV
- QGSJETII04 infers an unphysical $RMS(\ln[A])$ at 1.5σ

Combining Spectrum and X_{max}

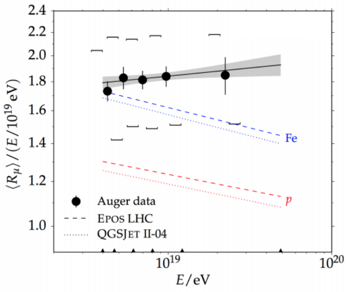
Fit parameters: source flux, p-He-N-Fe fractions, spectral index γ and rigidity cutoff R_{cut}

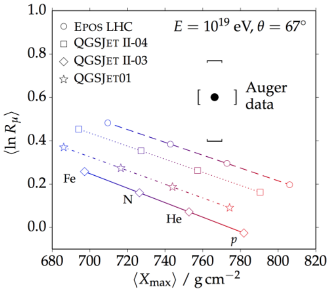
Homogeneous distribution of sources



- Very mixed composition between $10^{18.5}$ and 10^{20} eV is favoured
- Best fit has unexpectedly very hard injection spectra: $\gamma < 1$
  - Fermi mechanism $\rightarrow \gamma > 2$
- Flux limited by exhaustion at sources (instead of GZK?)
- But still many fit parameters and astrophysical assumptions...

Muon content





Data incompatible with **all** current hadronic interaction models

- deficit of muons in models between 30% and 80%

Effect is more pronounced in the $X_{max} : N_\mu$ plane

- observables from FD **and** SD provide tighter constraints
    - accessing different components of the shower

Auger status

Astrophysical interpretations of Auger data (X_{max}+Spectrum) indicate

- transition towards heavier composition
- but completely unexpected injection spectrum at the sources

However, the combined interpretation of all variables show that post-LHC hadronic interaction models cannot provide a consistent description of the shower

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Astrophysical interpretations of Auger data (X_{max}+Spectrum) indicate

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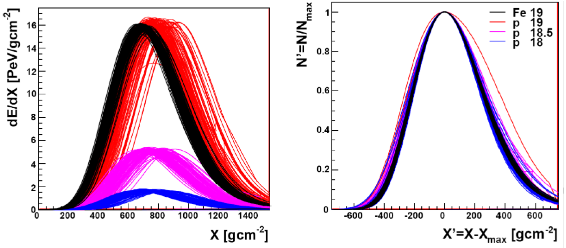
At LIP we are focused on studying the shower physics

- understand the shower dynamics
- explore new shower variables
- develop new analysis
- improve systematics
- develop new technologies for shower detection

Measuring the electromagnetic profile shape



- N_{max} (energy) and X_{max} (composition) have been measured before
- We normalize and translate each profile by them respectively
- The shape can be parametrized by a Gaisser-Hillas (GH) function with two variables:

$$N' = \underbrace{\exp\Big(-\frac{1}{2}\Big(\frac{X'}{L}\Big)^2\Big)}_{\text{Gaussian(L)}} \times \underbrace{\prod_{n=3}^{\infty} \exp\Big(-\frac{R^{n-2}}{n}\Big(-\frac{X'}{L}\Big)^n\Big)}_{\text{Distortion(R)}}$$

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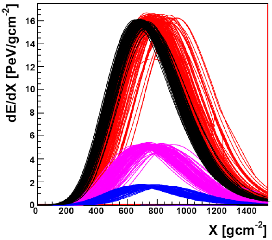

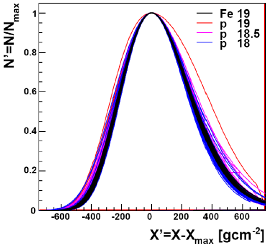

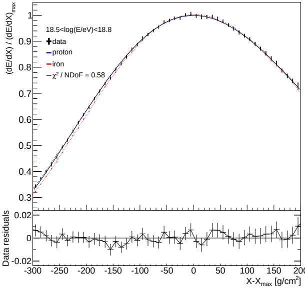

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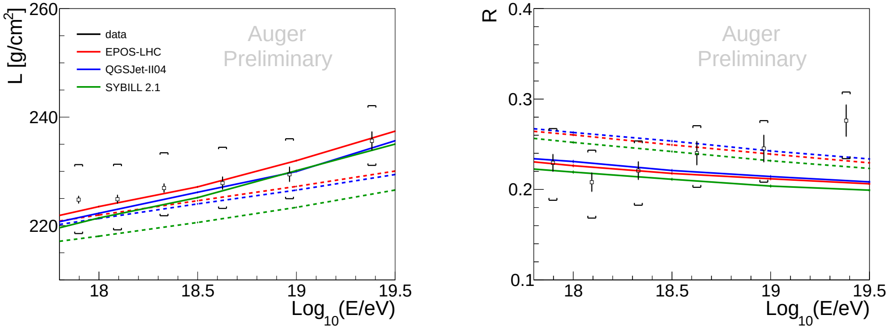
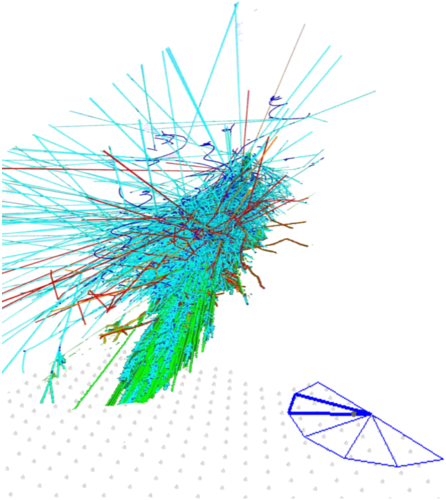
First proof that average profiles in data are described by a GH!

Shape parameters - energy evolution



- Proton full lines, Iron in dashed lines
- dominated by systematic uncertainties - atmospheric aerosols
- L - measurement compatible with models
- R - e.m. shower develops faster with increasing energy
  - opposite of model predictions
  - indication of changes in interaction properties!

Extensive Air Shower - Muonic Component



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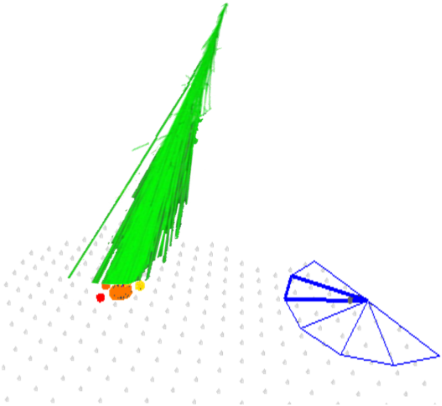

Muonic

- hard to measure: no signal in FD, hard to disentangle from e.m signal in SD
- muons interact scarcely with the atmosphere
- preserve information from their production point

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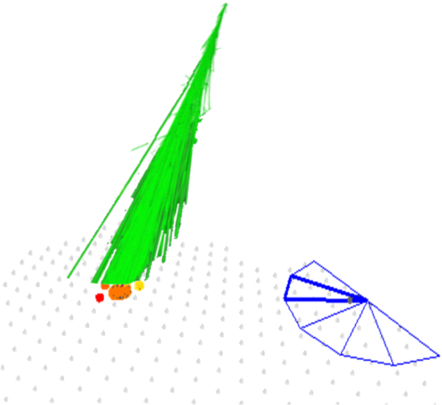

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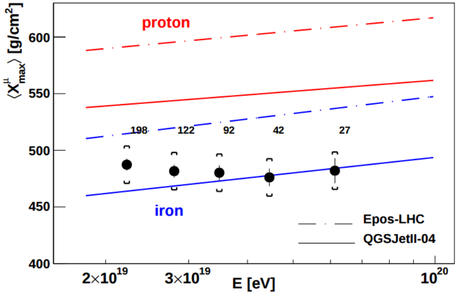
LIP plays a leading role in the muon analysis at Auger

- coordination of this task
- data analysis and phenomenology

Muon Production Depth (MPD)



Muon production point can be calculated $\rightarrow X^{\mu}_{max}$

- Bracketed by QGSJetII, incompatible with EPOS

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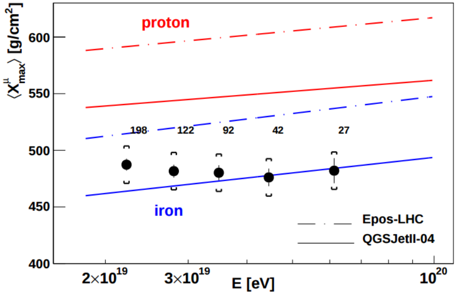
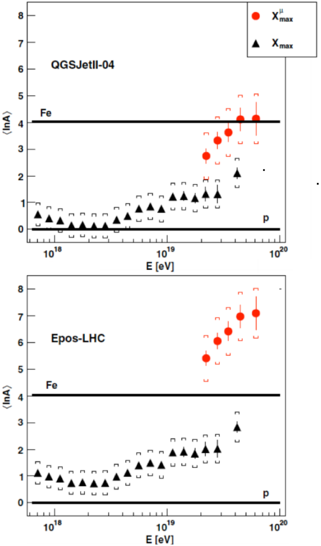




Muon production point can be calculated $\rightarrow X^{\mu}_{max}$

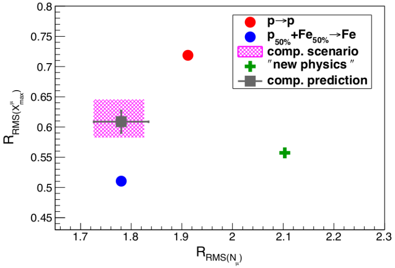
- Bracketed by QGSJetII, incompatible with EPOS

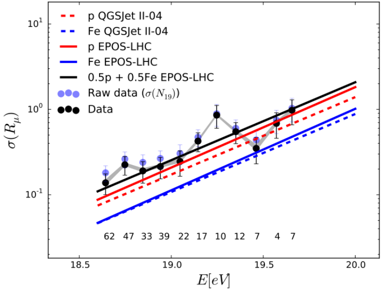
X^{μ}_{max} predicts different $\ln[A]$ than X_{max} in both models!

- 1.5σ for QGSJETII04 and $> 6\sigma$ for EPOS-LHC

$RMS(N_\mu)$ - Fluctuations of the shower muon content

Phenomenological studies show that this is the most powerful variable to test new physics

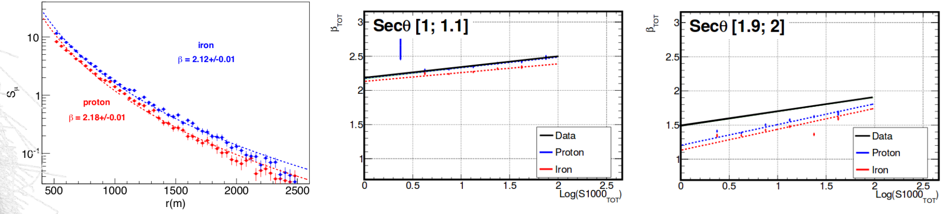




- Preliminary measurement of the $RMS(N_\mu)$ done at LIP

Lateral Distribution Function shape in SD

The lateral distribution of files at ground is also composition dependent It is sensitive to both muonic and electromagnetic components

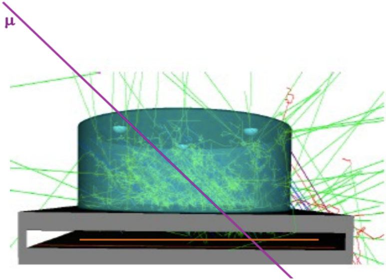


Event-to-event we do not have enough resolution to separate composition

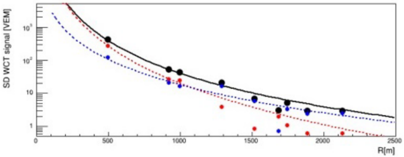
- but building the average LDF we can measure the slope
- comparing with models - ok at low angles, larger β in data at high angles
  - muon spectrum problem, not normalization
- preliminary results

Our current path

To really understand Auger data we need to reduce systematics and access the muonic component independently!



- proposal for a dedicated muon detector (MARTA)
- N_μ independent from energy
- prototypes already working in the pampa (R. Luz talk)



Understand air showers dynamics and the e.m./muon interplay

- they come from the same primary so are not independent
- but each process affect with in a different way

Conclusion

New results from Auger are at odds with current hadronic/astrophysical models:

- particularly, the muon sector is poorly predicted
- disagreement increases with energy

The Auger group is pursuing three (complementary) ways to go forward:

- measuring new independent variables
- parametrize and model the different shower components
- decrease systematics - new generation detectors (R. Luz talk)