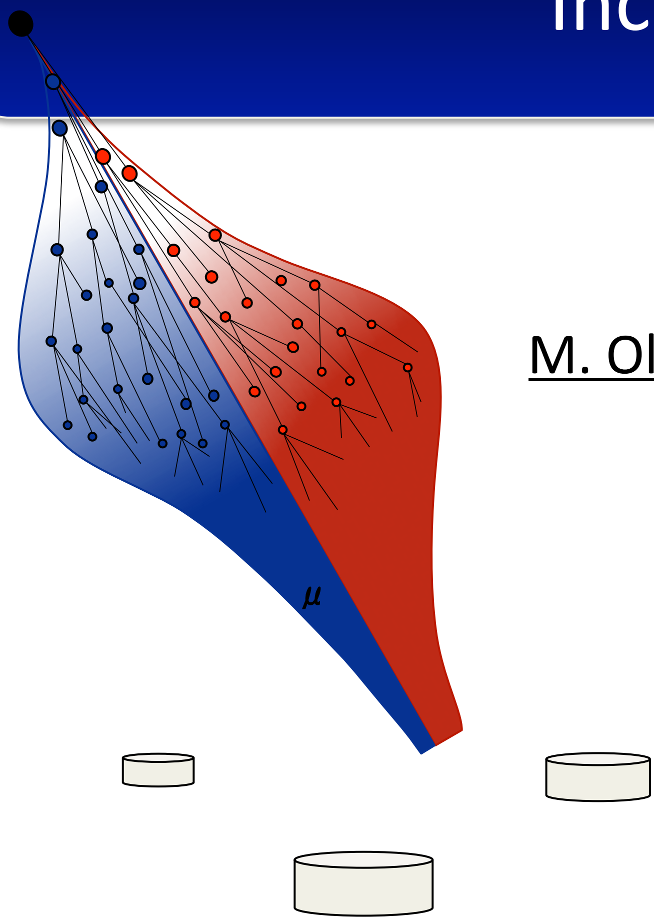
Measurement of the Number of Muons in Inclined Showers



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TÉCNICO LISBOA

LIP

PIERRE AUGER OBSERVATORY

Outline

- Reconstruction Mehod
- EM contamination
- Calibration
- Bias and Resolution
- Application to Data
- Conclusions and Prospects

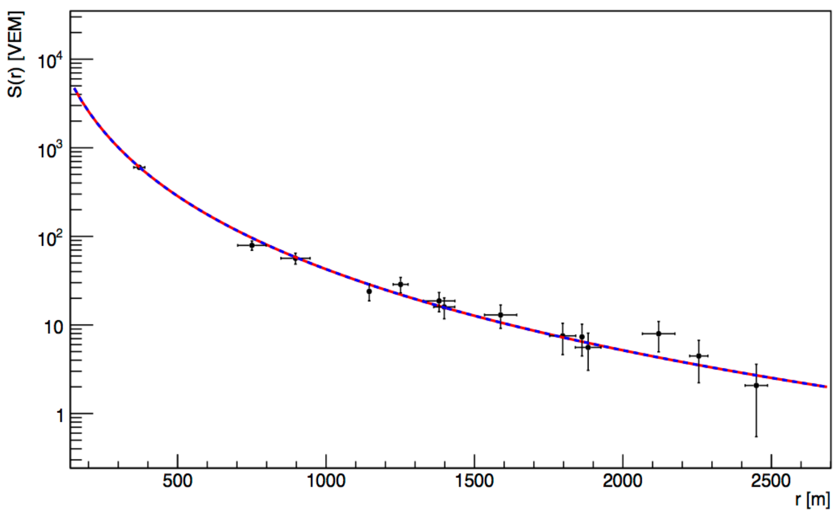
Reconstruction Method

- Method to recover the number of muons on the ground from the LDF

Signal on the ground is due to various components:

$$S_{total} = S_\mu + S_{em} + S_{\mu/em}$$

Signal as a function of r the distance to the shower core in the perpendicular plane



- At theta=60 the EM component is small, the signal in the tanks is **dominated by muons**
- Muons give signals proportional to their tracks
- The muonic signal in the tanks can be expressed as:

$$S_\mu = N_\mu \hat{t}_\mu$$

NKG: $$S_\mu = S_{1000}\left(\frac{r}{r_{1000}}\right)^\beta \left(\frac{r+r_{700}}{r_{1000}+r_{700}}\right)^{\beta+\gamma}$$

Reconstruction Method

Averaging the Signal:

$$S_\mu(\theta) \quad = \quad N_\mu \, \langle t_\mu(\theta) \rangle = \rho_\mu \, A_\theta \, \langle t_\mu(\theta) \rangle$$

And from the projected area:

$$\begin{aligned} \langle t_\mu(\theta) \rangle &= \frac{\int t_\mu \, dA_\theta}{\int dA_\theta} \\ &= \frac{V_{station}}{A_\theta} \end{aligned}$$

Finally we get the number of muons on the ground from the Signal:

$$\begin{aligned} N_\mu &= \int_0^{2\pi} \int_R \rho_\mu \, r dr \, d\phi \\ &= \frac{2\pi}{A_0} \int S_\mu \, r dr \end{aligned}$$

Number of muons from the fit to the signal sampled by the SD

Simulations

The integral of the LDF will be evaluated for **various r-cuts**

- Assess the best r-cuts for the resolution and bias
- Good separation between the Proton and Iron muon distributions

- 50 Shower Simulations with CORSIKA for proton and iron **QGSJET-II.03**
- Energy = $10^{18.6} - 10^{19.5}$ eV
- Theta = 60°
- random Phi
- 5 different realizations for each CORSIKA simulation
- Total of 250 Reconstructed events for **Proton** and **Iron**

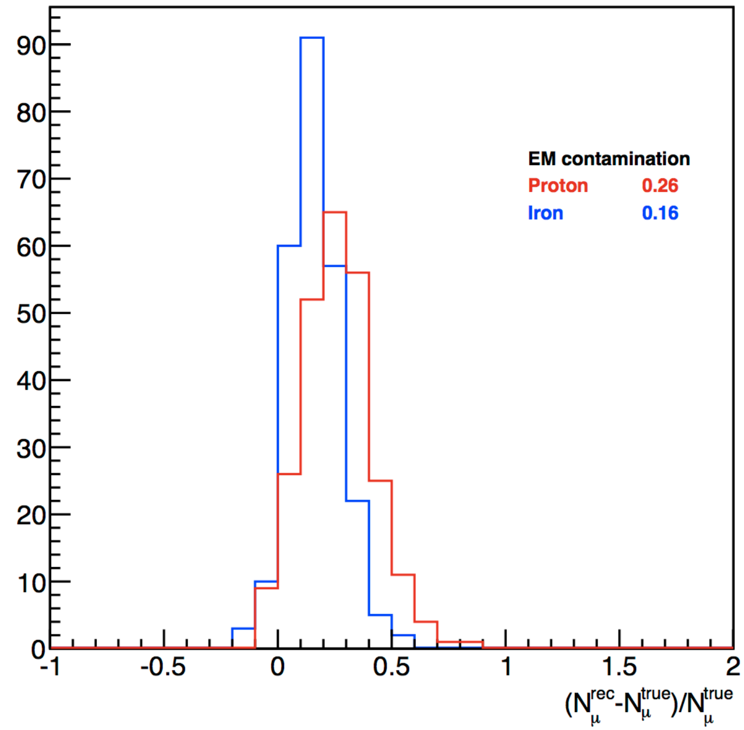
N_μ TRUE: Number of Muons obtained from the CORSIKA simulated files

N_μ REC: Number of Muons obtained from our reconstruction using the LDF

Signal Contamination

- Electromagnetic halo decreases with the distance to the shower core
- The method considers all the signal in the stations, EM halo included
- Need for a Calibration in order to attenuate the electromagnetic halo

- EM contamination: **15% - 30%**
- Depends on Primary Energy
- Depends on zenith angle

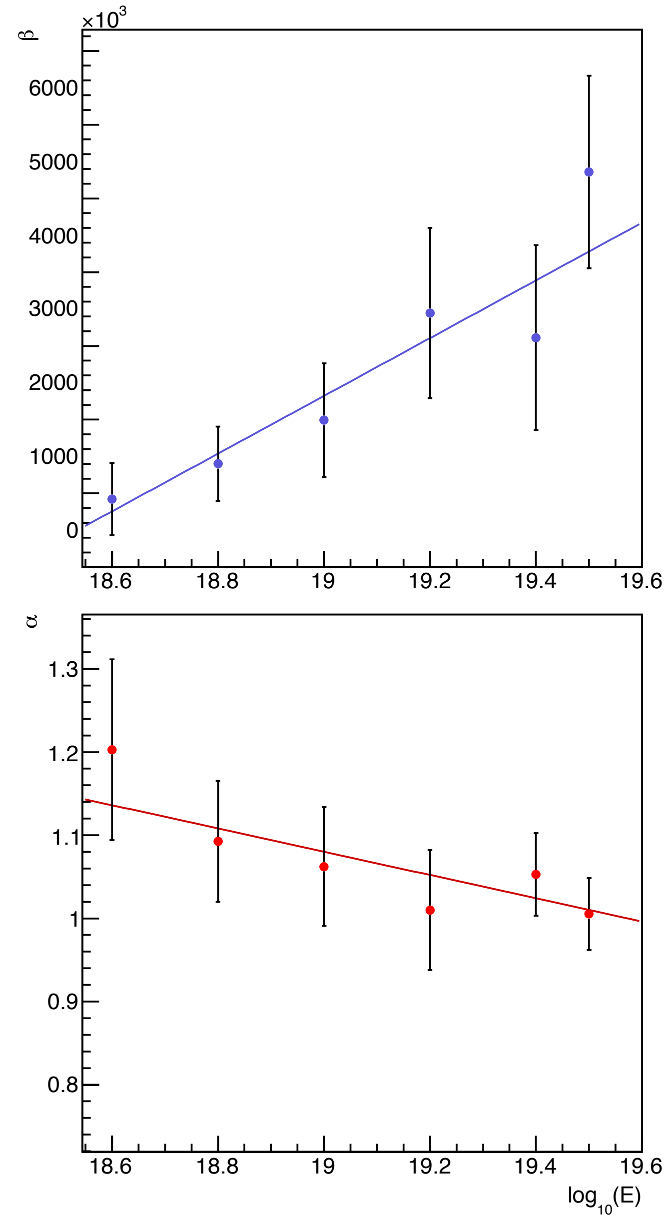


Calibration

Fit to **N_μ(Rec) vs N_μ(True)** to get parameters in order to attenuate the EM component.

$$N_\mu^{rec} = \frac{N_\mu^{rec'} - \beta}{\alpha}$$

- Calibration relative to the True number of muons
- Number of muons without the EM component
- alpha an beta are the **calibration parameters**
- Fit to alpha an beta in order to recover values for all energies

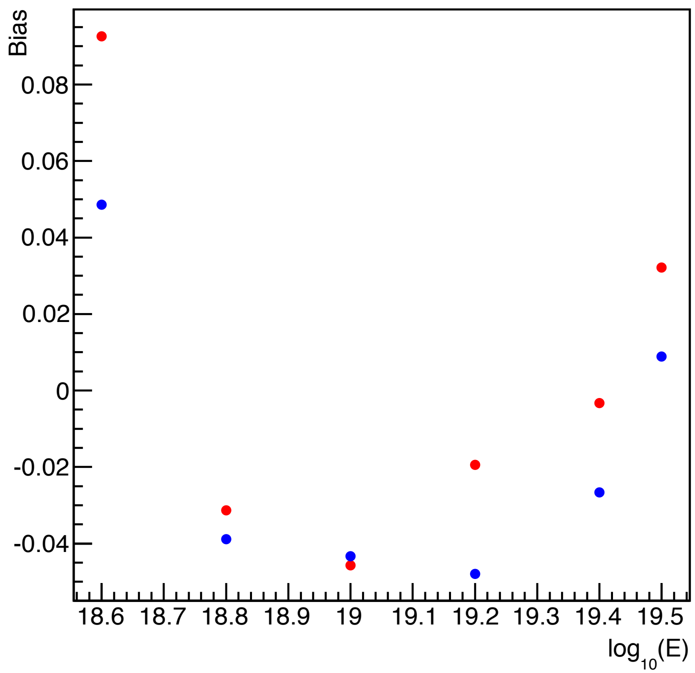


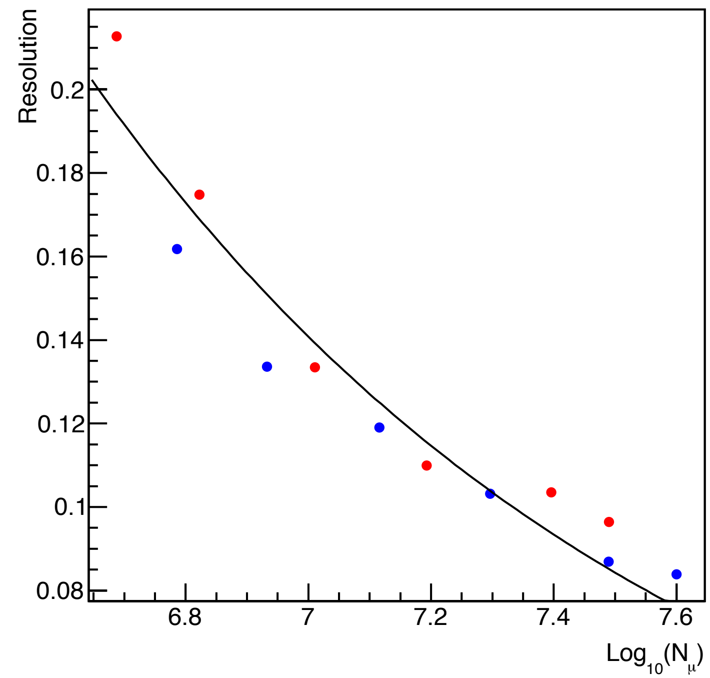
Bias & Resolution

- We apply the Proton primary calibration to Proton and Iron primaries

After the calibration:

- Pull Distributions give the **Bias and the Resolution** of the Method
- Fit in order to determine the distribution for any given energy





Application to Data

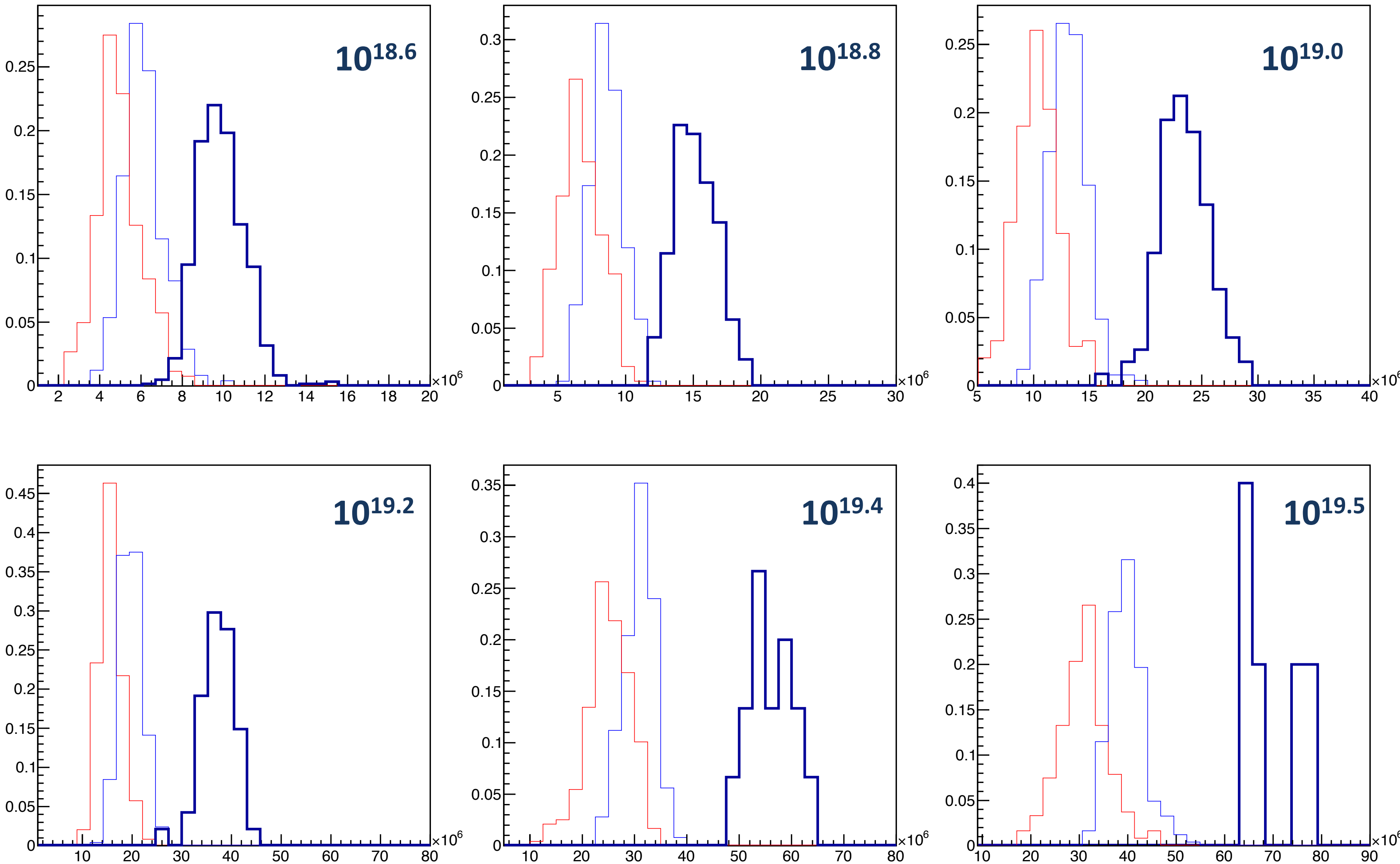
Application to **SDHASRec Data** (2004-2012 except 2009)

Cuts:

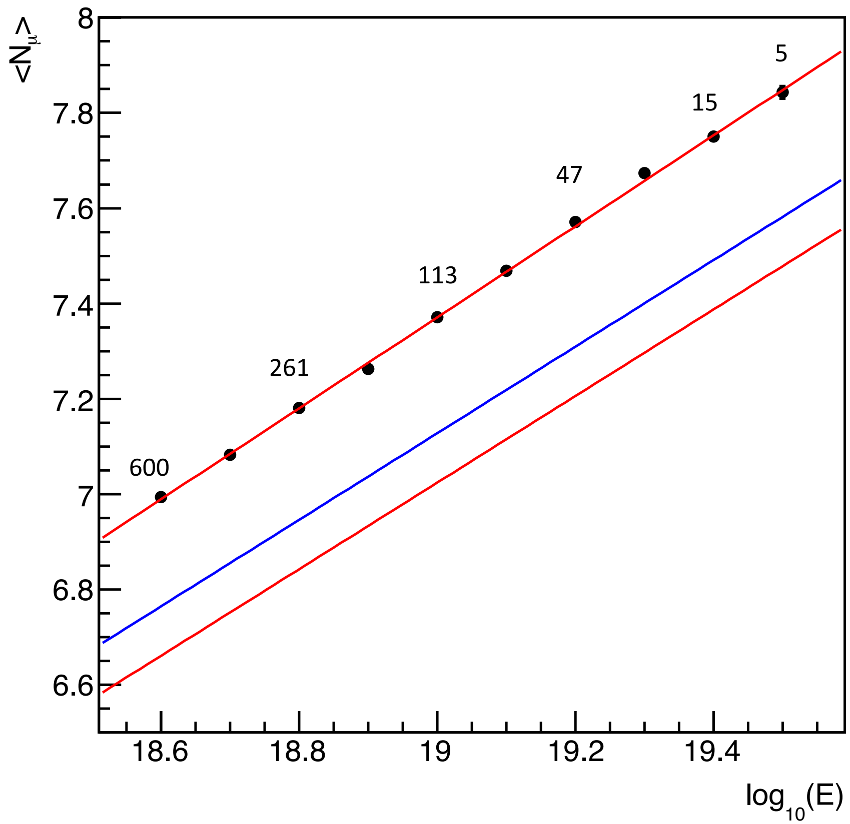
- Energy [E +/- 0.05]
- Theta [**58.5 – 61.5**]
- **T5 Trigger**

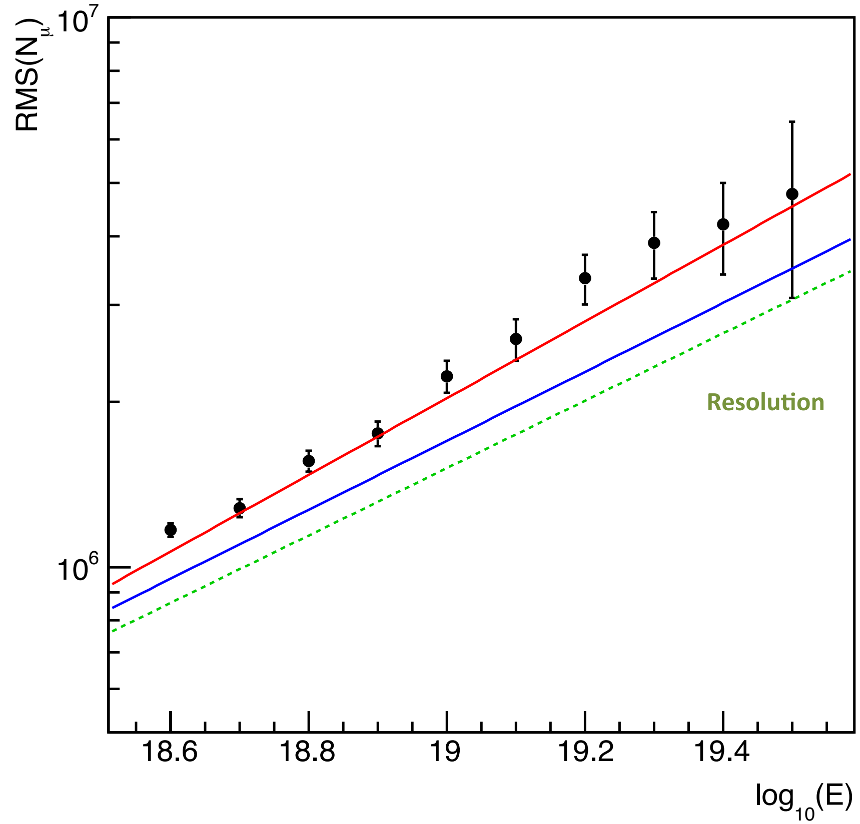
ENERGY	18.6		18.8		19.0		19.2		19.4		19.5	
EVENTS	**600**		**261**		**113**		**47**		**15**		**5**	
	MEAN $\times 10^6$	RMS $\times 10^6$										
P	4.96	1.08	6.72	1.54	10.2	1.94	15.6	2.33	25.0	4.11	30.9	5.02
FE	6.13	0.97	8.60	1.21	13.1	1.70	19.8	2.34	30.9	2.89	39.8	3.61
DATA	**9.85**	**1.17**	**15.2**	**1.56**	**23.5**	**2.23**	**37.3**	**3.35**	**56.3**	**4.20**	**69.7**	**4.78**

Muonic Distributions



Elongation Rate





β (proton) = 0.91
β (iron) = 0.91
β (data) = 0.95

Preliminary

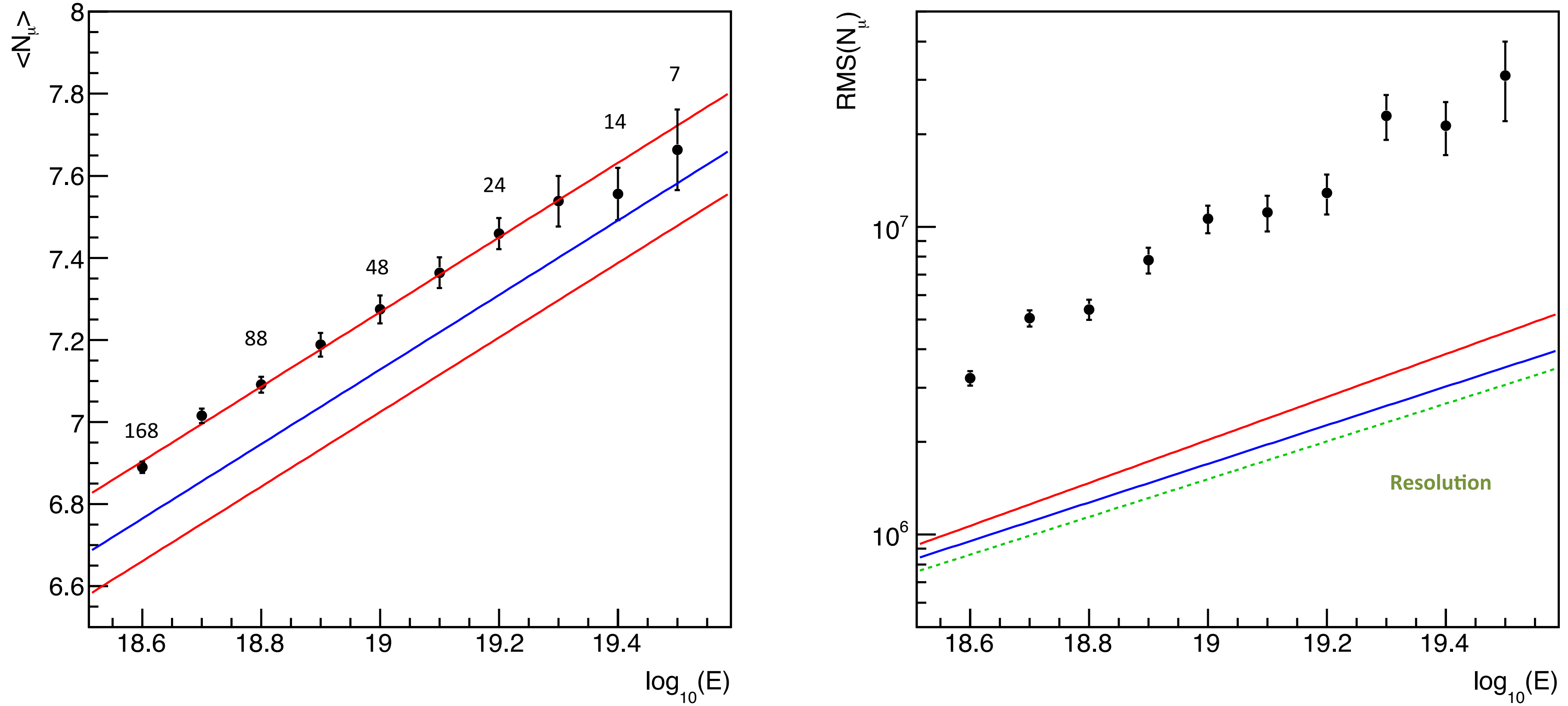
Application to Data

Application to **GoldenRec Data** (2004-2012 except 2009)
Cuts:

- Energy [E +/- 0.05]
- Theta [**57. – 63.**]
- **T5 Trigger**
- **FD HasEnergy**

ENERGY	18.6		18.8		19.0		19.2		19.4		19.5	
EVENTS	**168**		**88**		**48**		**24**		**14**		**7**	
	MEAN $\times10^6$	RMS $\times10^6$										
P	4.96	1.08	6.72	1.54	10.2	1.94	15.6	2.33	25.0	4.11	30.9	5.02
FE	6.13	0.97	8.60	1.21	13.1	1.70	19.8	2.34	30.9	2.89	39.8	3.61
DATA	**7.75**	**3.22**	**12.6**	**5.13**	**19.2**	**10.4**	**30.1**	**11.6**	**47.5**	**8.65**	**66.9**	**11.3**

Elongation Rate

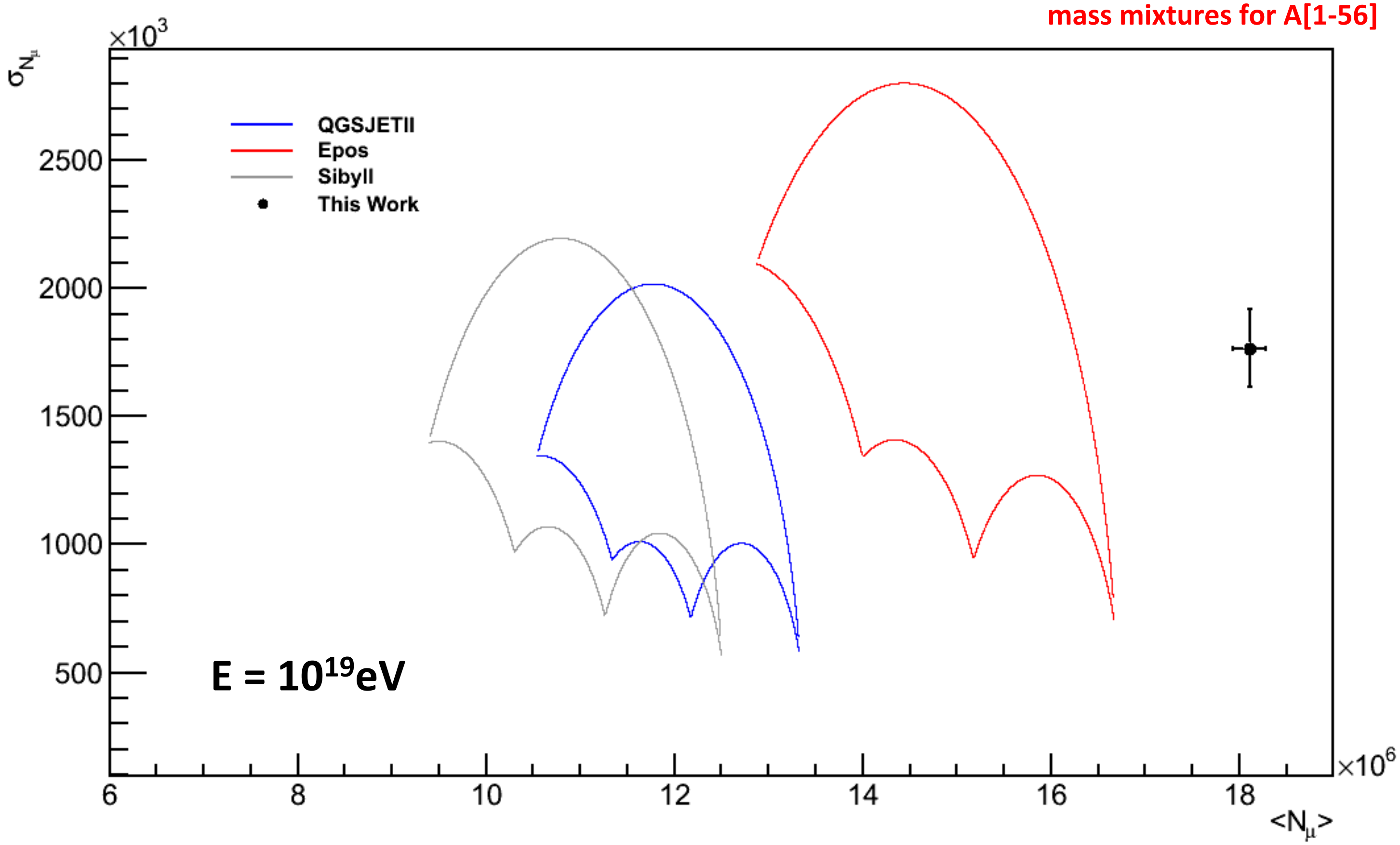


β (proton) = 0.91
β (iron) = 0.91
β (data) = 0.91

Preliminary

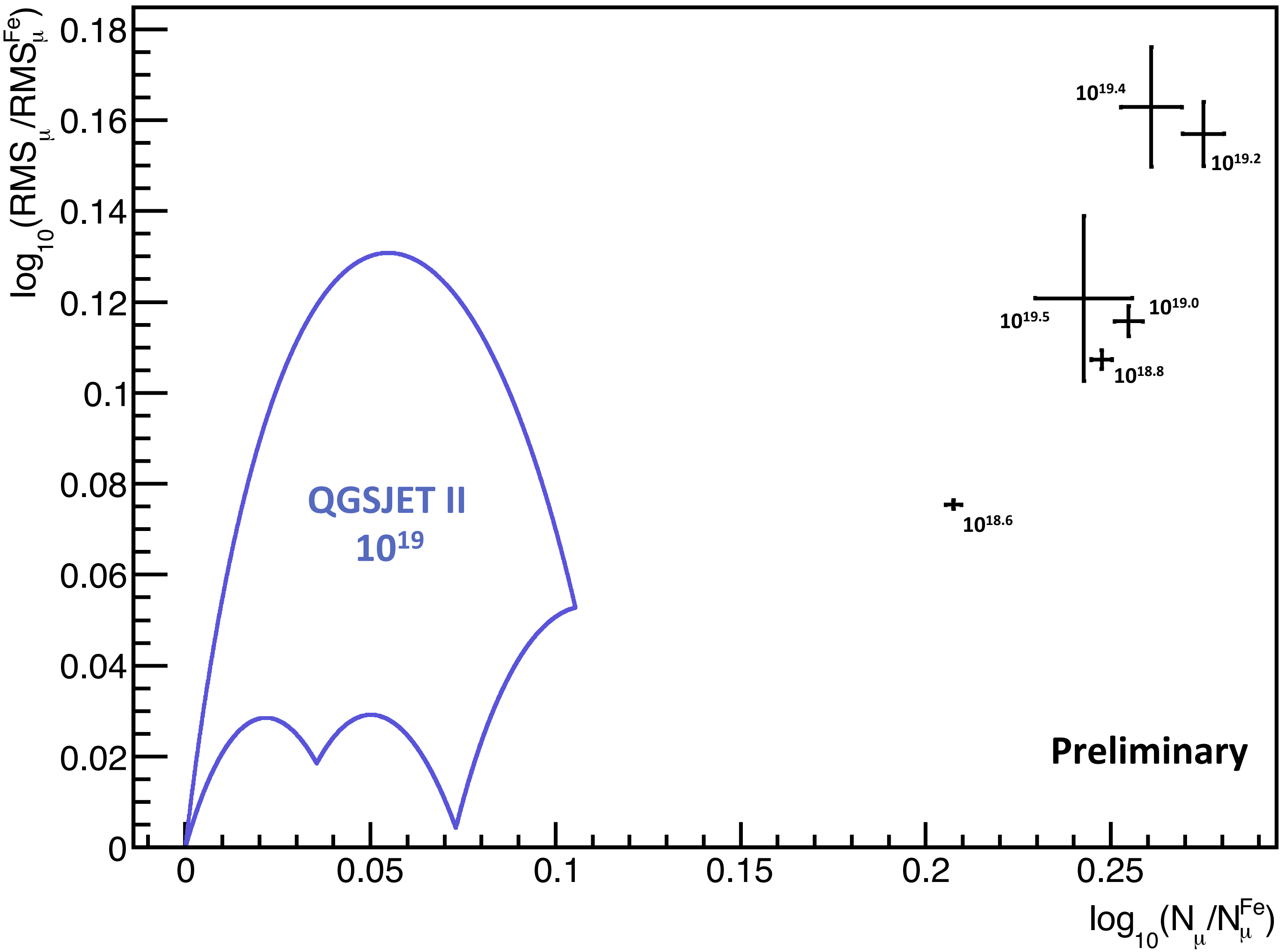
Umbrella

These parabolas define a closed contour that contain all possible combinations of mass mixtures for A[1-56]



- Two first momenta of the distribution N_μ and RMS(N_μ)
- The result obtained is **not compatible** with any of the hadronic interaction models
- Systematics to be included

Umbrella



$\log_{10}(RMS_\mu/RMS_\mu^{Fe})$
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
$10^{19.4}$
$10^{19.2}$
$10^{19.5}$
$10^{19.0}$
$10^{18.8}$
$10^{18.6}$
QGSJET II
10^{19}
Preliminary
0
0.05
0.1
0.15
0.2
0.25
$\log_{10}(N_\mu/N_\mu^{Fe})$

Conclusions and Prospects

- Encouraging **preliminary results**
- Simple method that allows to obtain the distribution of the number of muons
- Study of their shape, analysis of the momenta of the distribution
- Measure more muons than the previsions of the models, in accordance with previous works
- None of the models gives an accurate description of the number of muons in Auger data
- Integrate the X^{μ}_{max}, obtain a better resolution

Better understanding of the hadronic models
High Precision measurements of the muonic component of the EAS, Detector Enhancements

Thank You!