Electromagnetic and muonic shower development:
breaking degeneracy in mass composition/hadronic models interpretation

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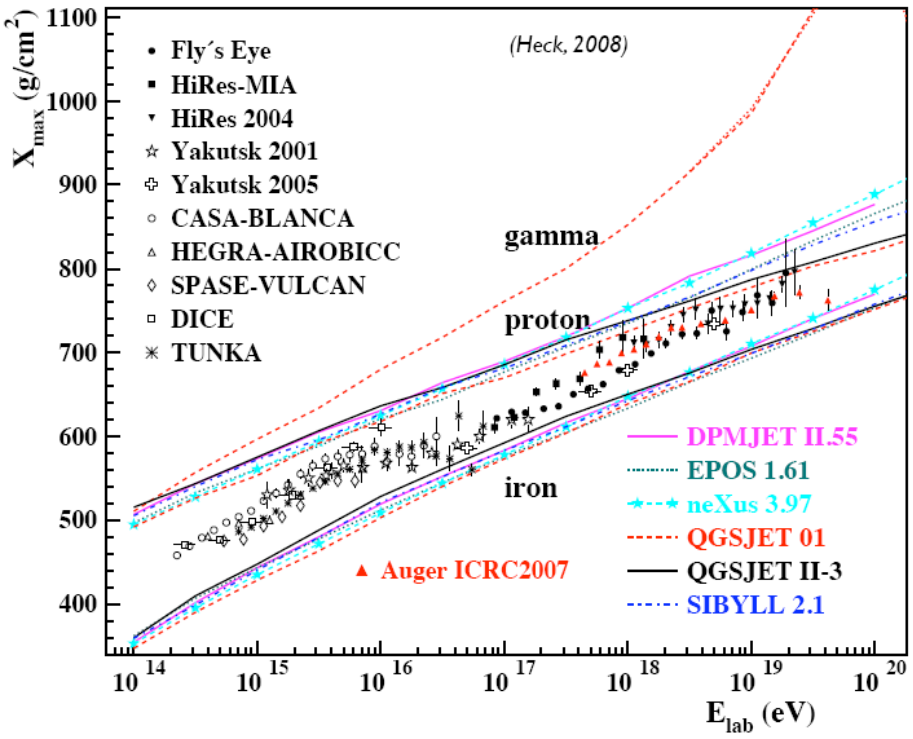
LIP, Lisboa

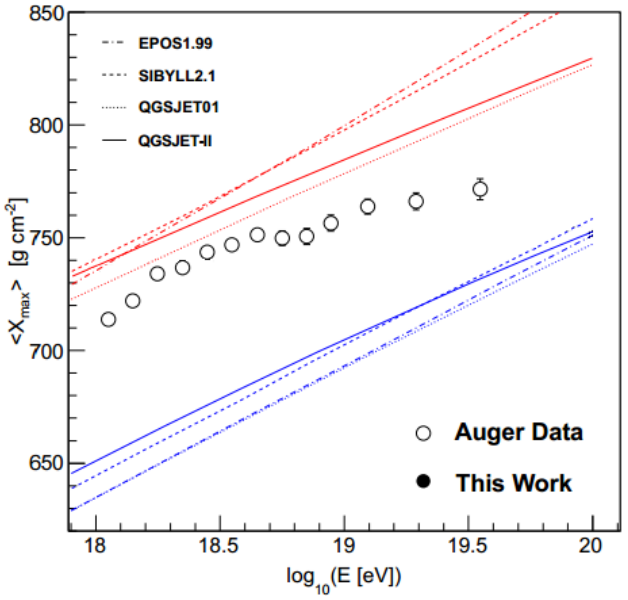
Ultra High Energy Cosmic Rays – what are they?

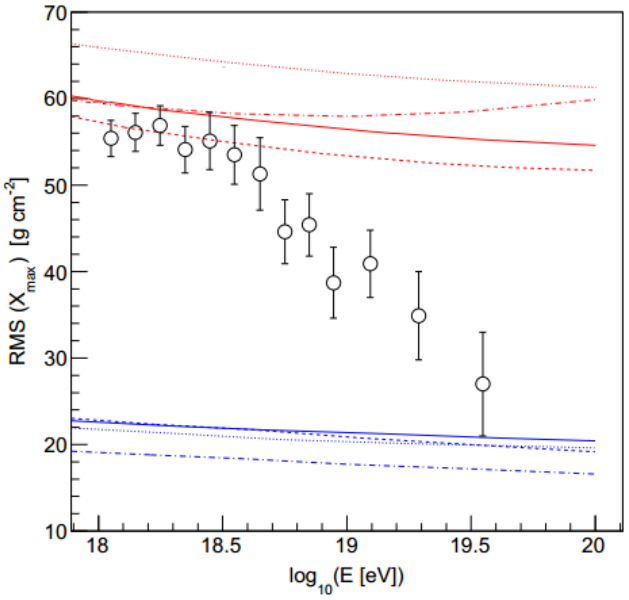


- UHECR composition is one of the main open questions in astrophysics today
  - Essential to understand sources and acceleration mechanisms

- Right now the main composition variable is Xmax
- But there is a degeneracy in interpretation between mass composition and uncertainty in hadronic interactions

<Xmax> and RMS(Xmax) – proton and iron?





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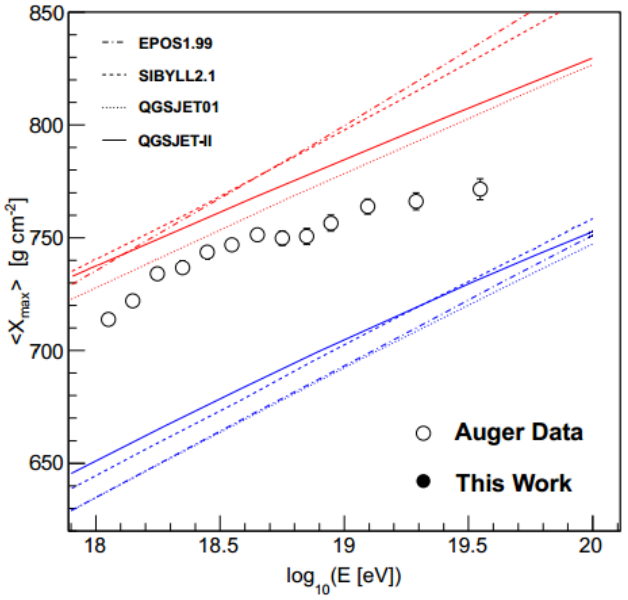
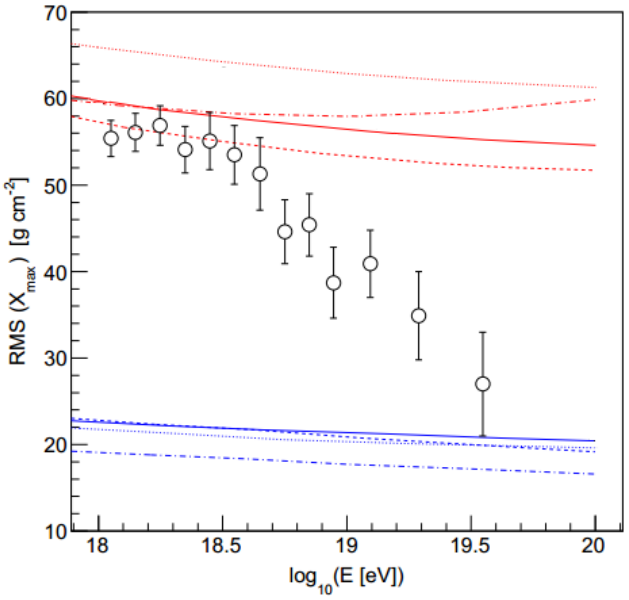
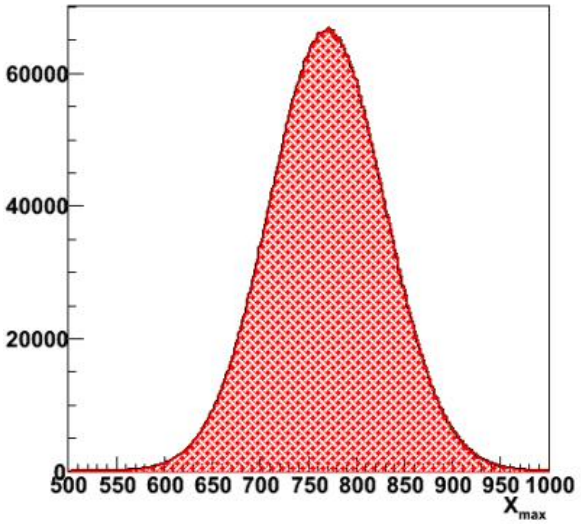
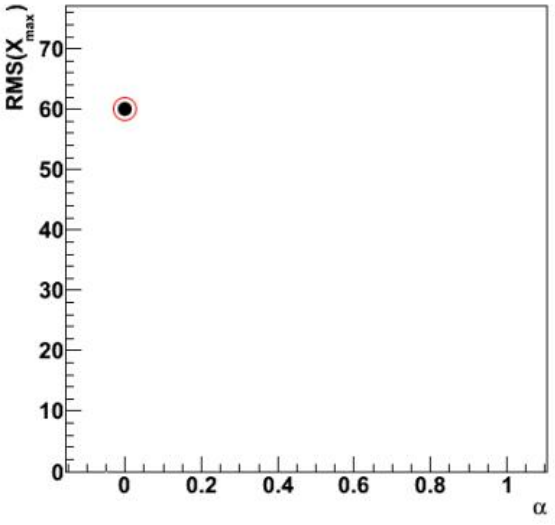




- But the rms is non-linear for transitions between composition





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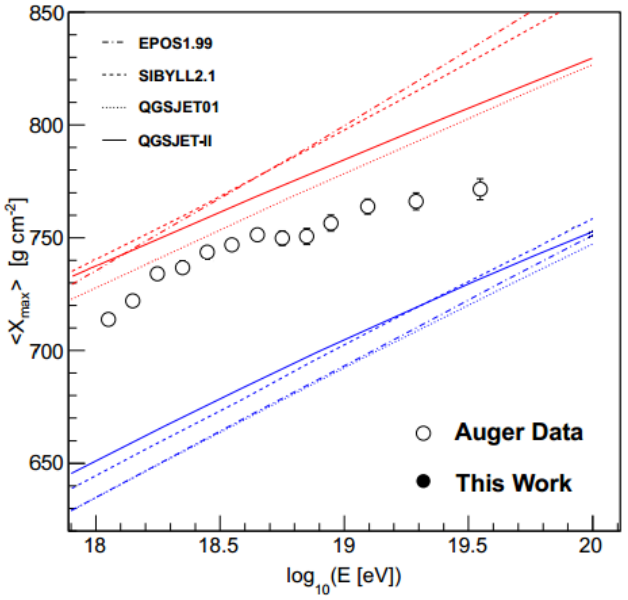

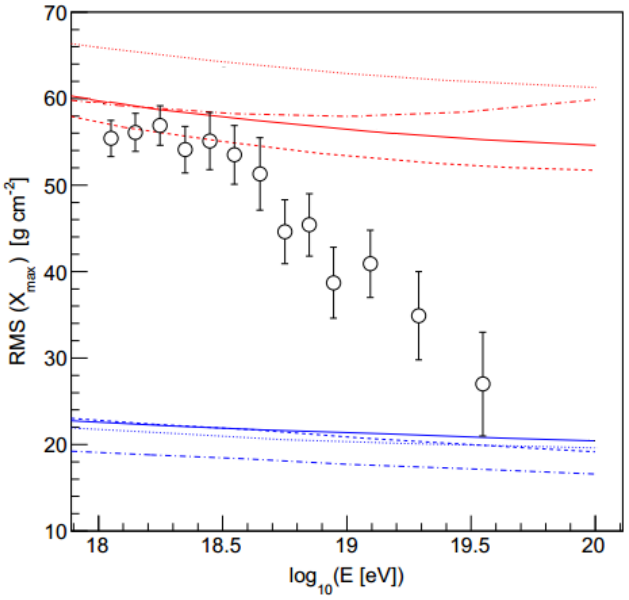

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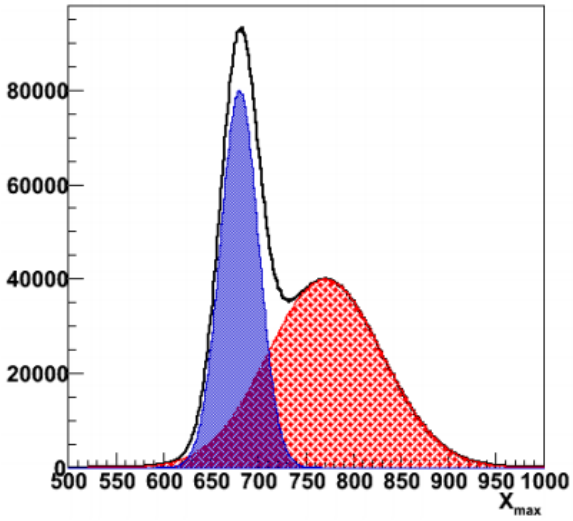

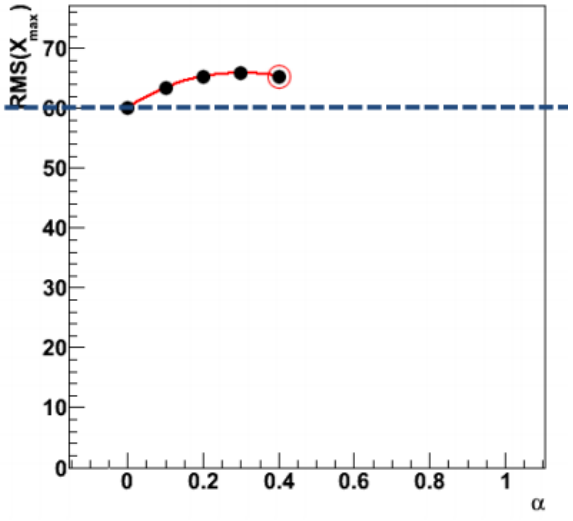

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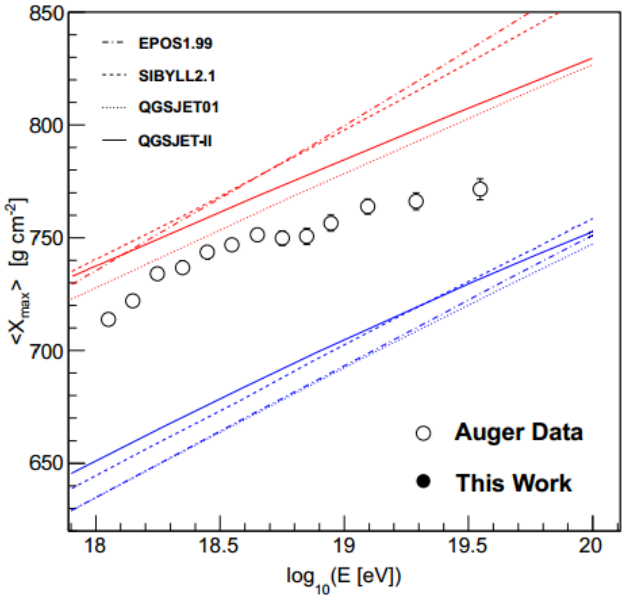

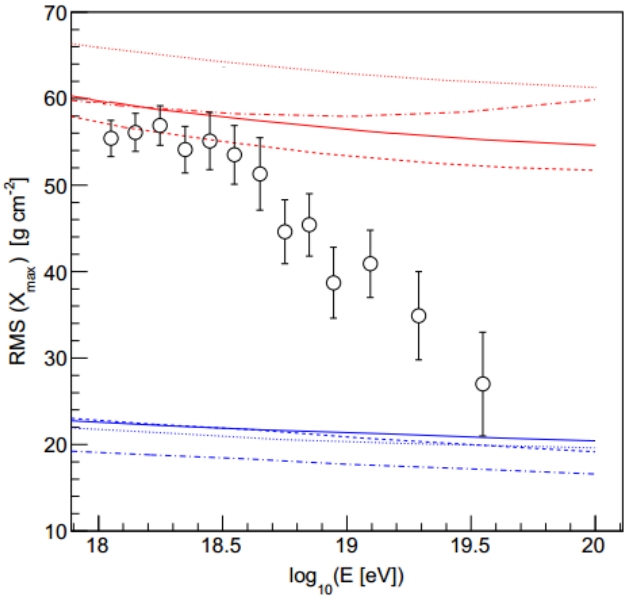

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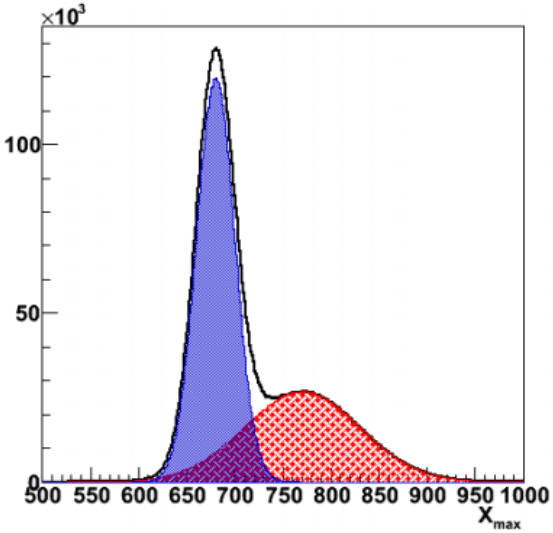

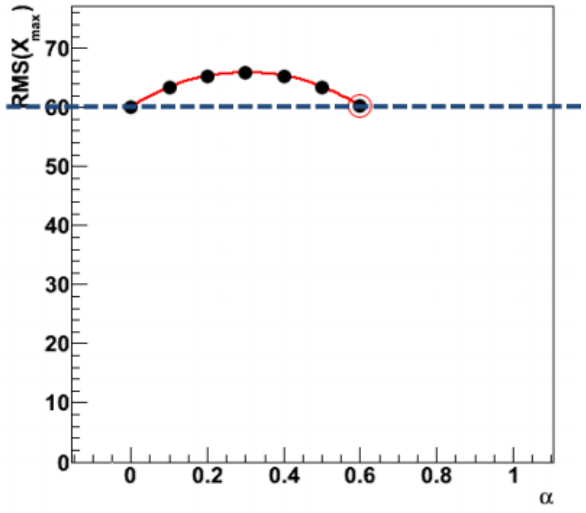

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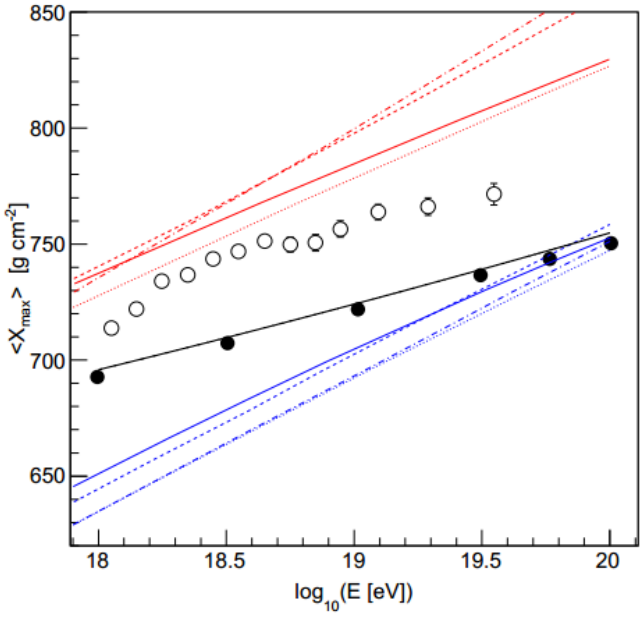
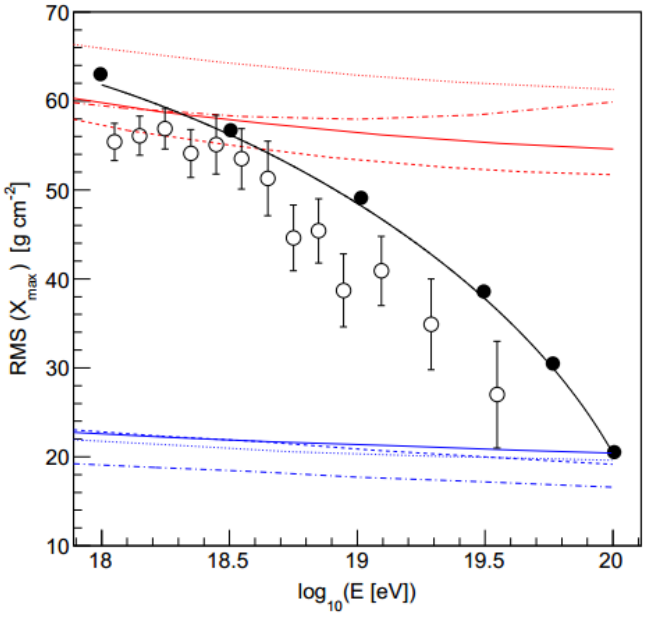
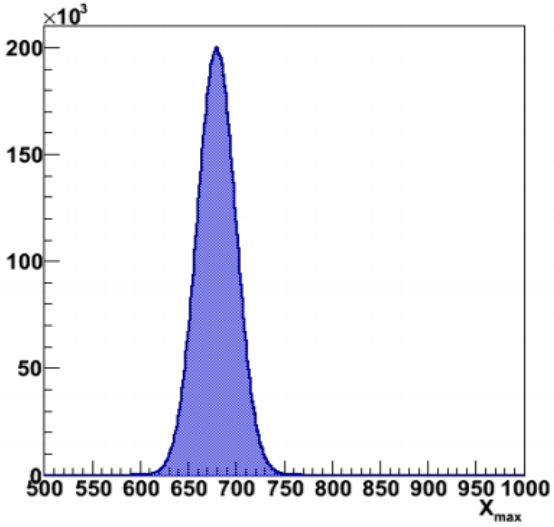
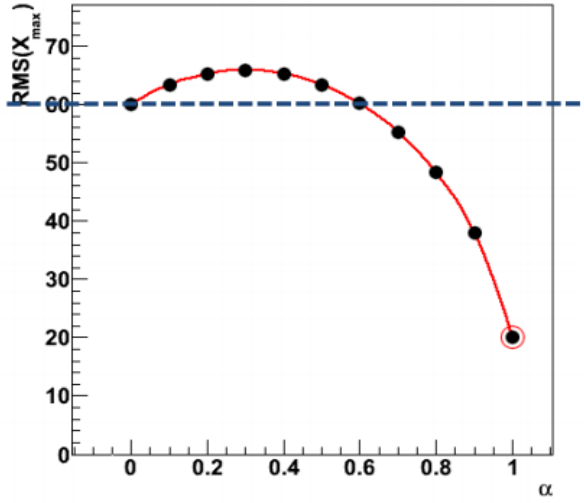


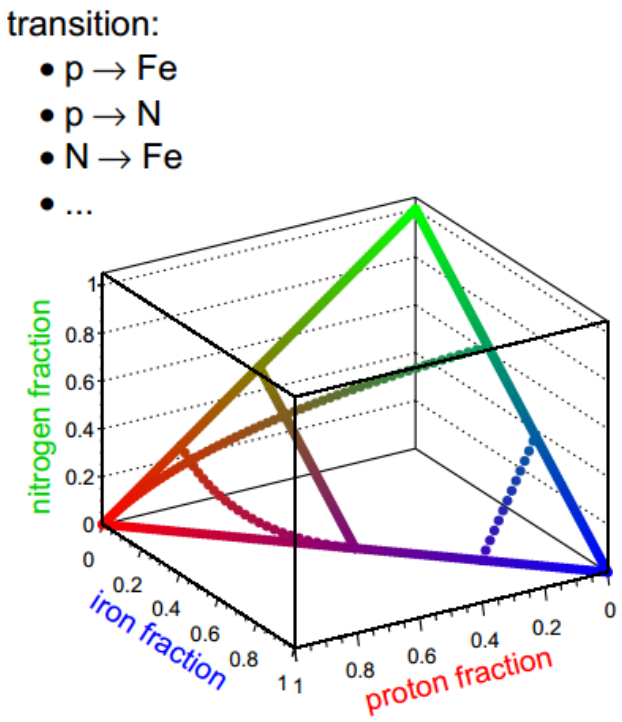


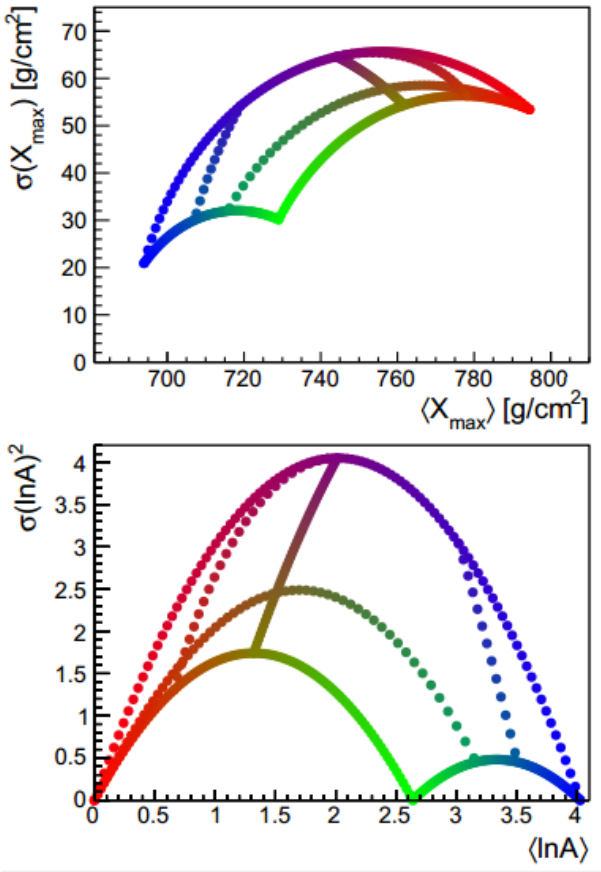
- The rms is non-linear for transitions between composition
- We cannot fit both curves with just proton and iron primaries and usual high energy hadronic models





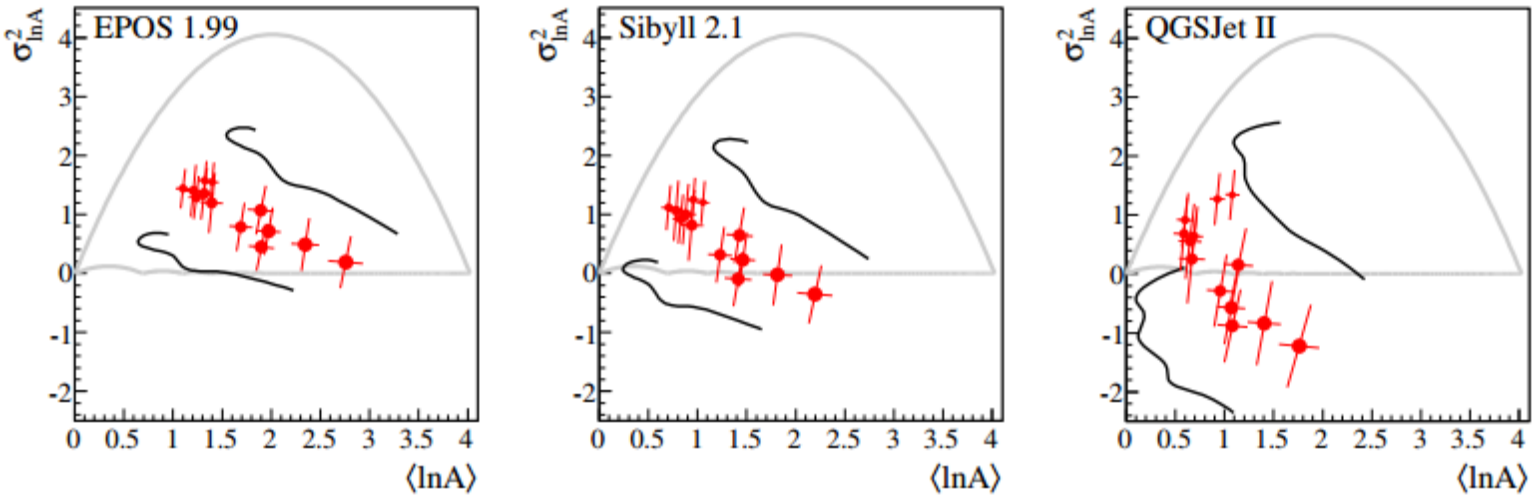
Scenario 1: intermediate primaries



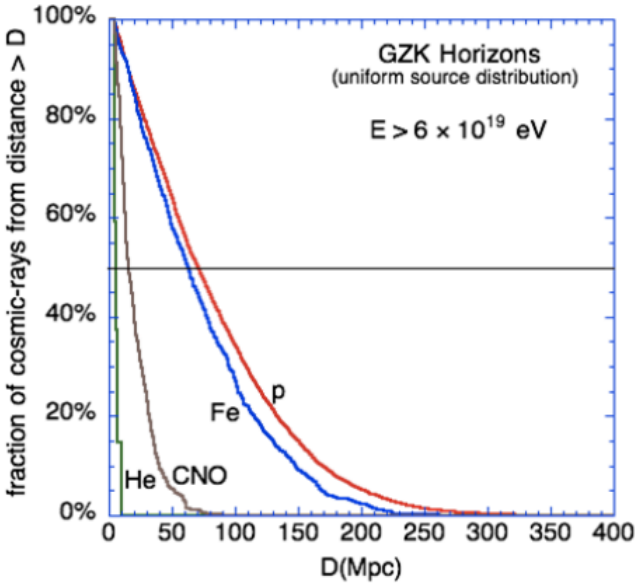


- We can scan all possible combinations of Xmax and its RMS to build umbrella plots
  - Gives all the phase space occupied by a given hadronic model

Scenario 1: intermediate primaries

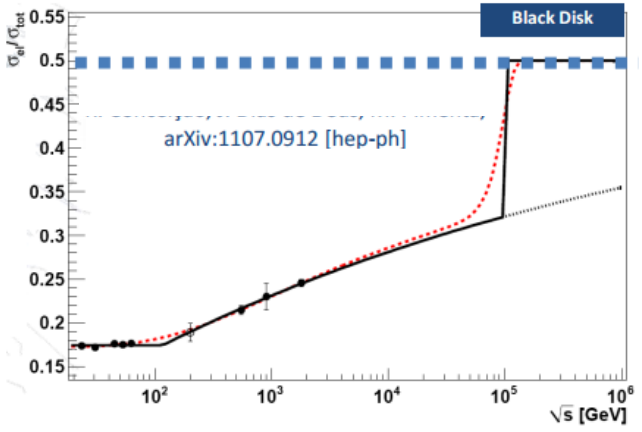


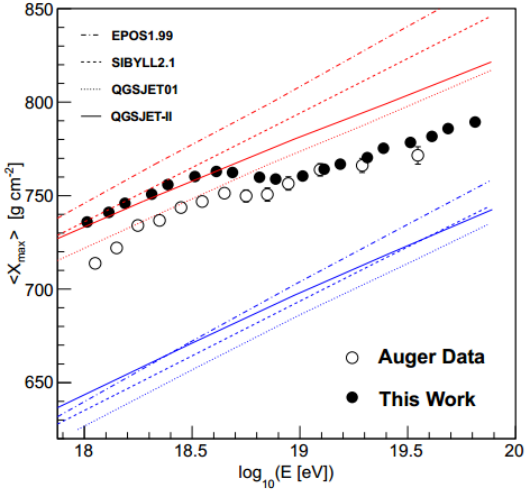
- Consistent with models within systematics for Auger data

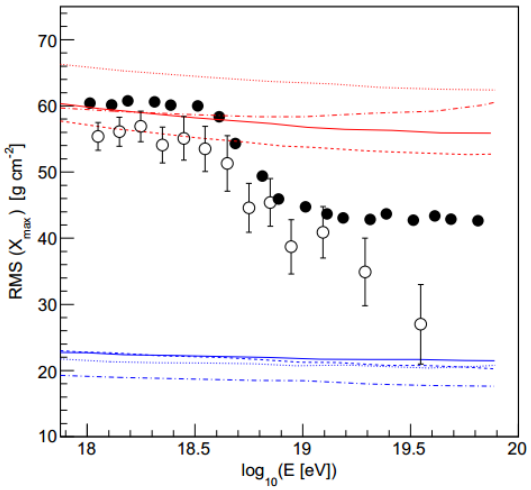


But having intermediate primaries gives constraints on the distance of sources and acceleration mechanisms!

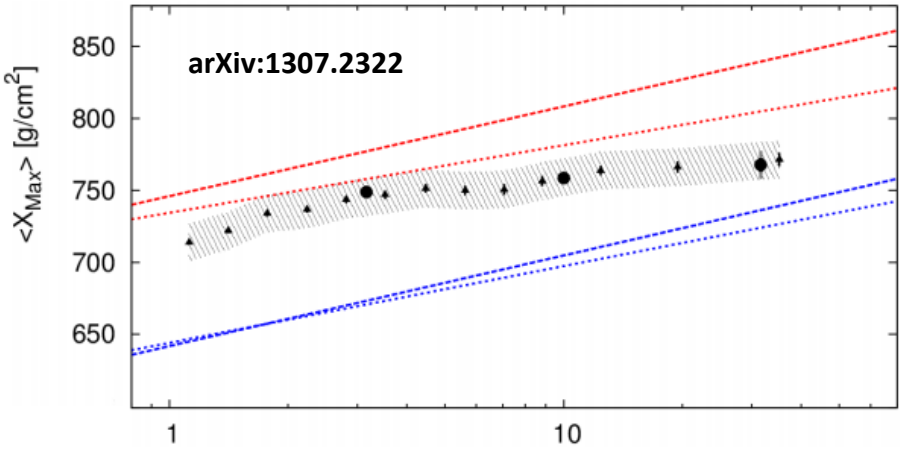
Scenario 2: new physics

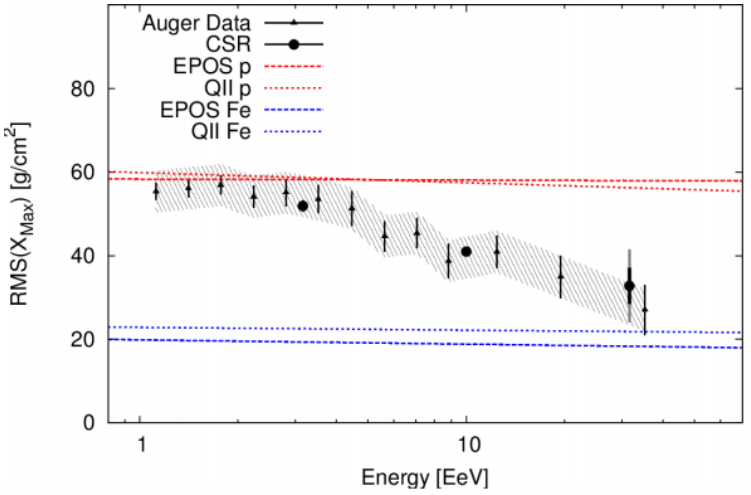






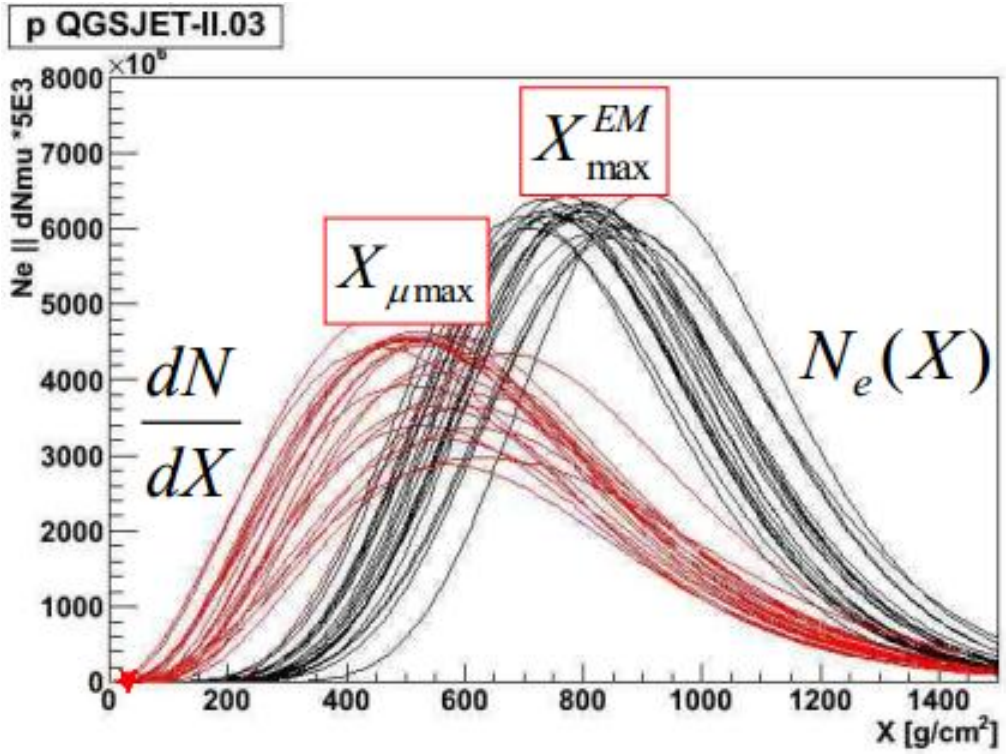
- Changing high energy hadronic interactions affects the resulting Xmax distribution
  - Two examples (non-extensive!) – Chiral symmetry restoration and black disk model





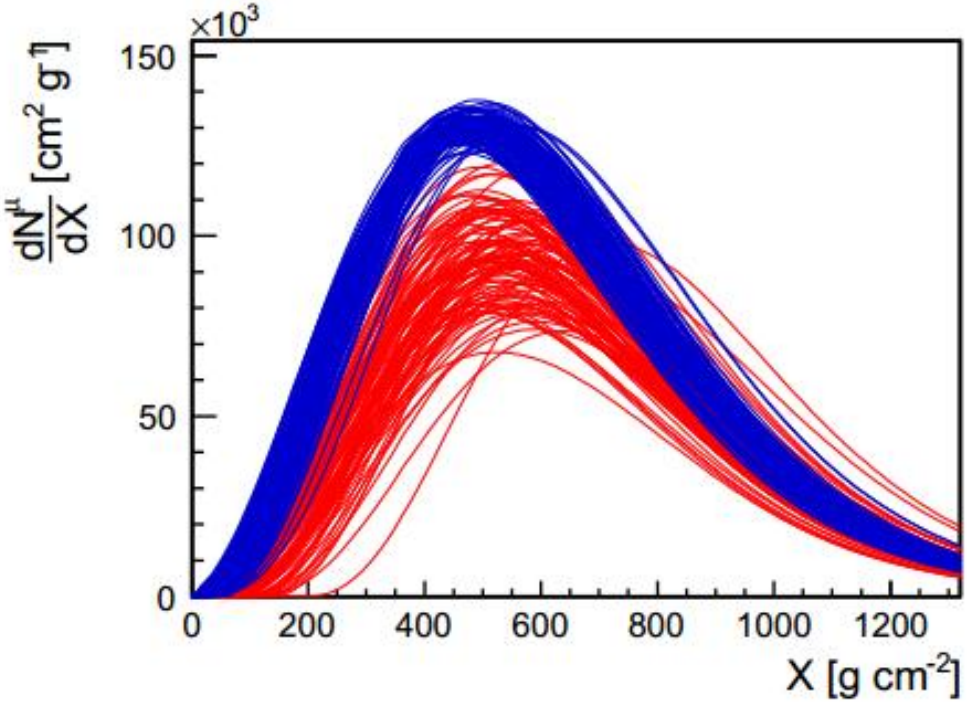
We need more variables to break this degeneracy in interpretation!

EM and Muon Production Depth (MPD) profiles



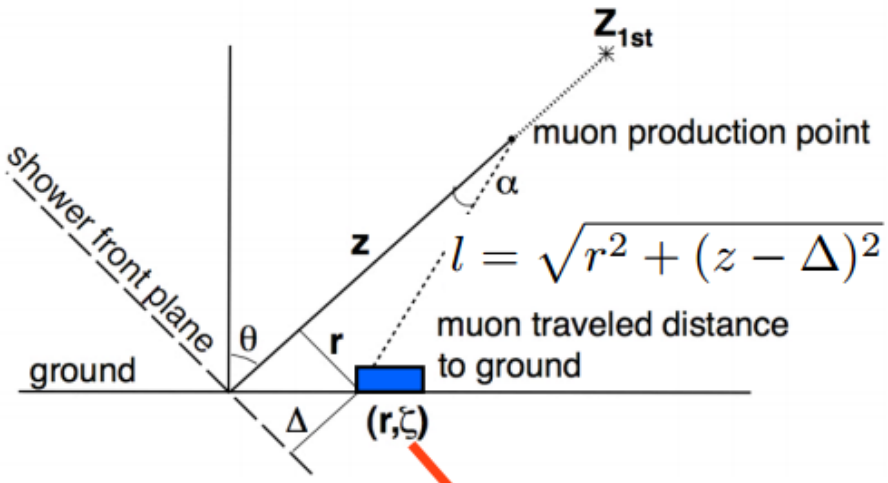
- Both profiles are experimentally accessible
  - Electromagnetic profile is measured in fluorescence detectors usually
  - MPD can be reconstructed with surface detector measurements
  - In hybrid detectors the measurement may be independent

Muon Production Depth (MPD) profiles



- Very difficult to obtain with current detectors, but carries valuable information on the highest energy hadronic interactions
- As with the electromagnetic profiles, we have 4 variables:
  - Nmu, Xmumax and two shape parameters
  - We will try to maximize the separation between scenarios using a combination of variables

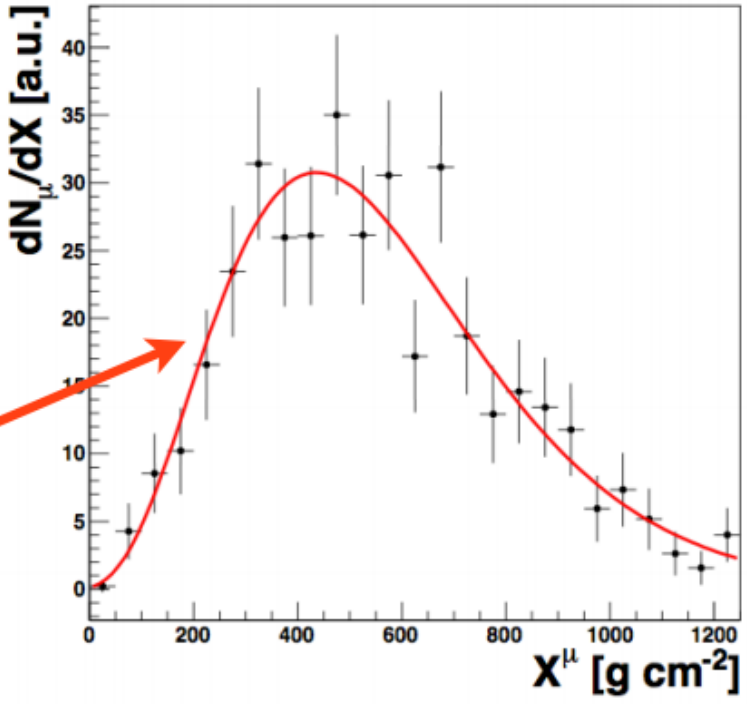
Measuring the MPD



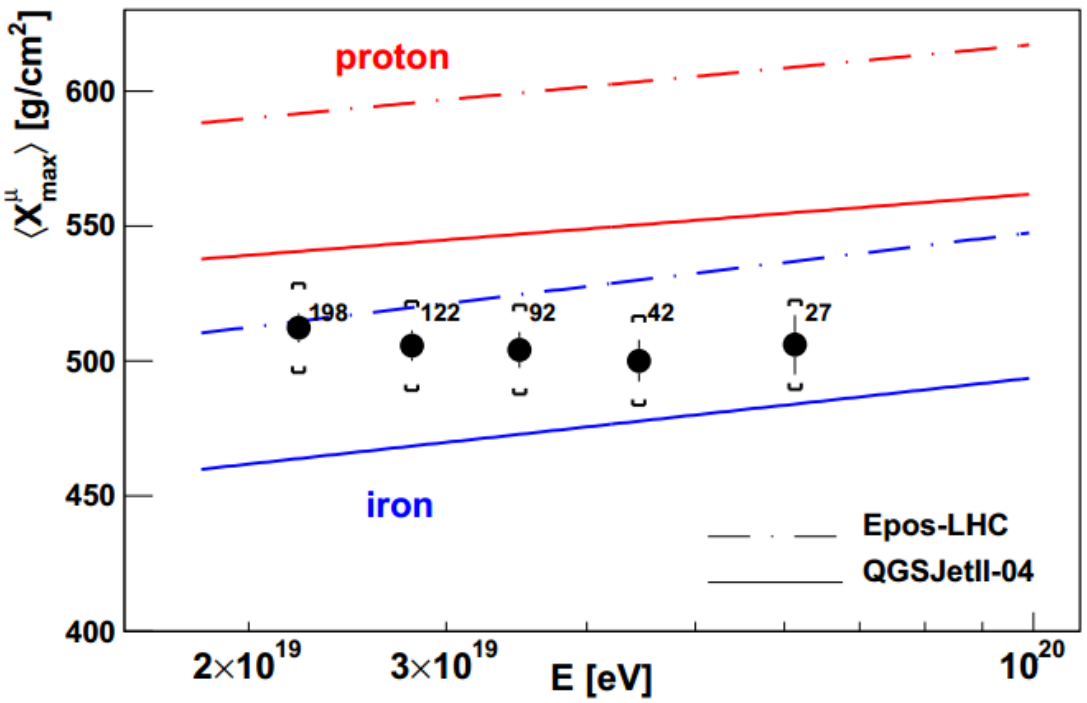
Measured

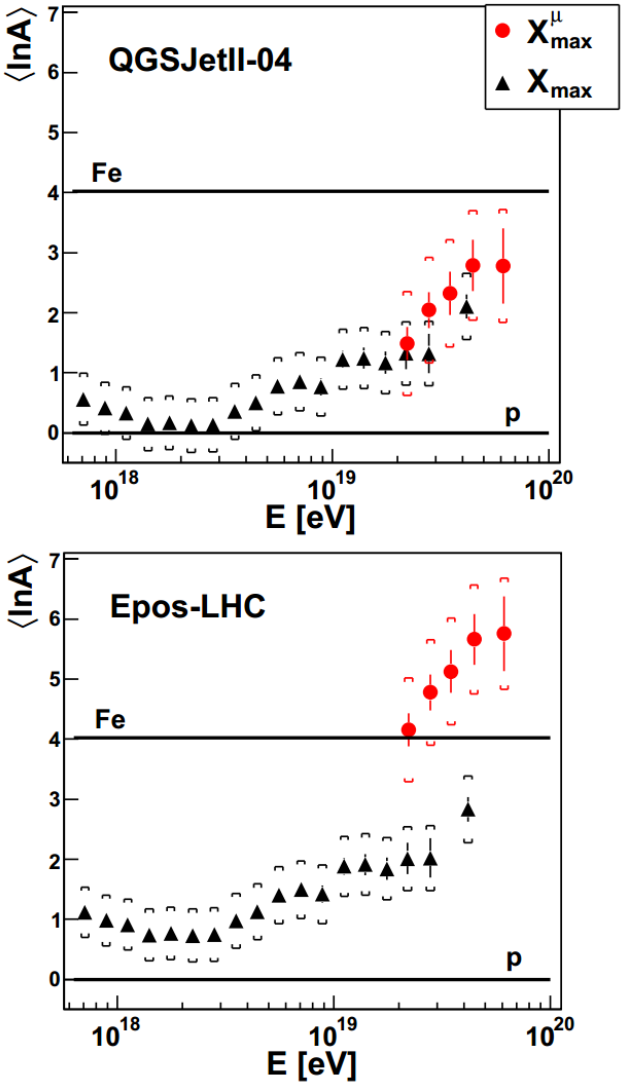
Obtained

$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$



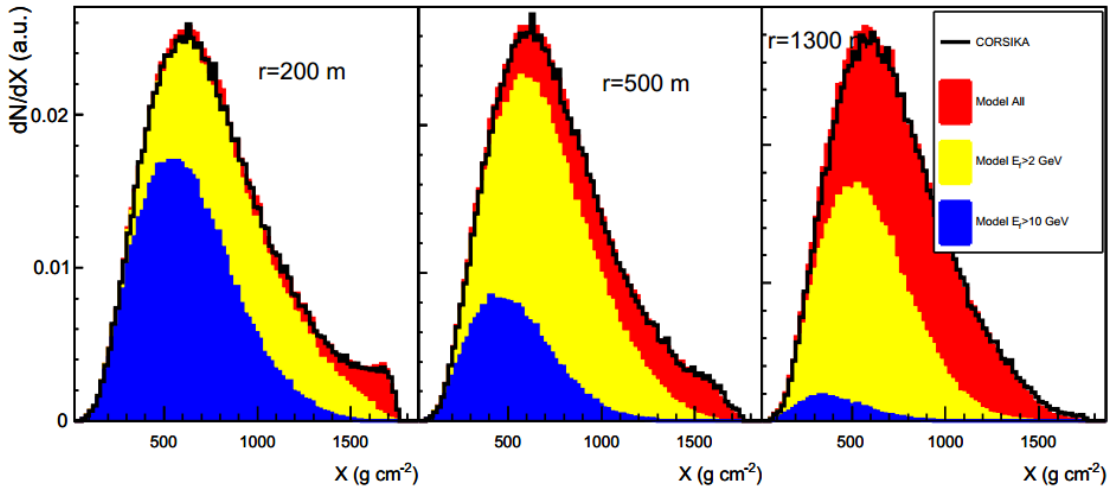
$X_\mu max$



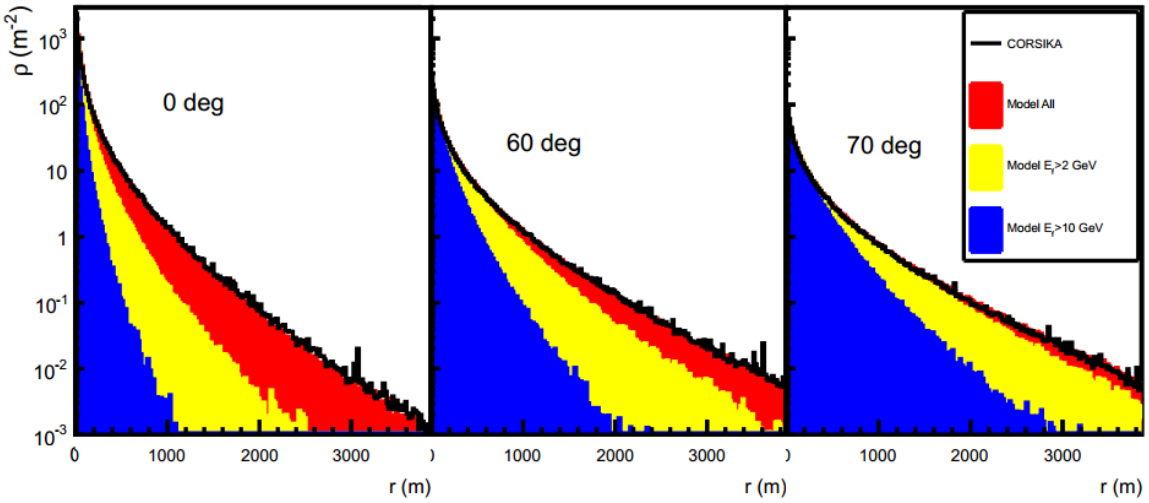


- $X_\mu max$ has been measured in Auger
- Clear disagreement between measurements in EPOS-LHC
  - Measuring just one of them could have led to composition interpretations (?)

Apparent MPD – threshold dependent



Cazon et al: arXiv:1201.5294v2

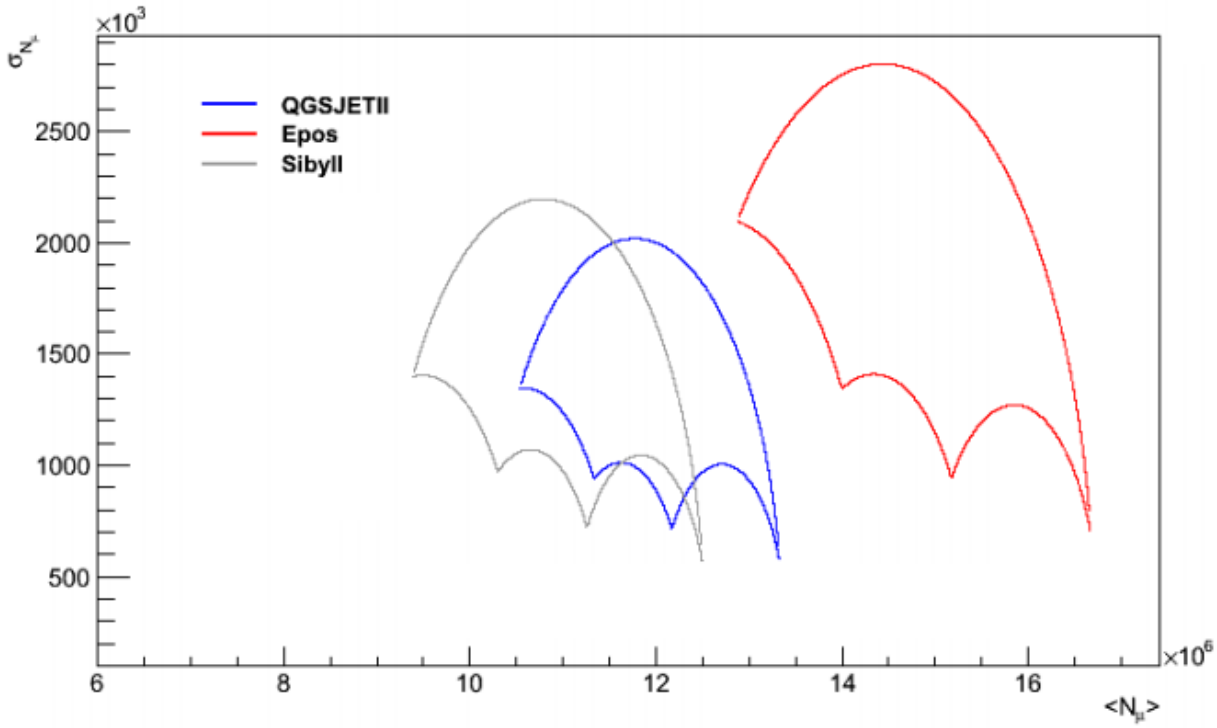


E>5GeV, E>2GeV, all

The apparent MPD shape depends on the energy threshold of muons, and it is a convolution of the MPD of all muons, the propagation effects, and the energy and pt spectrum

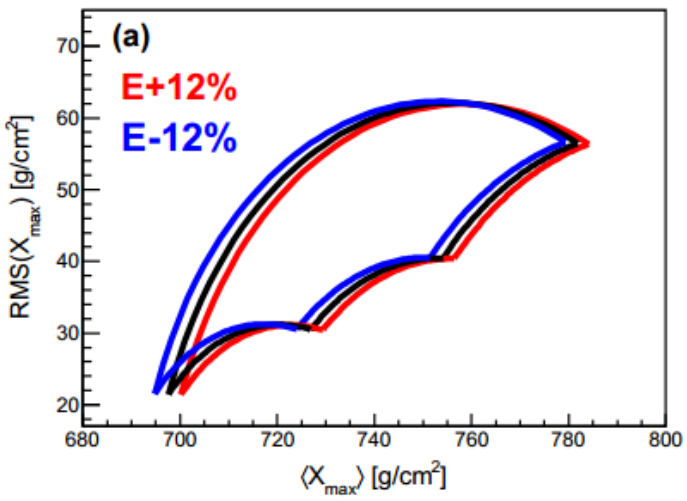
This is also an opportunity – measuring profiles at different energy cutoffs allows estimation of pt spectrum

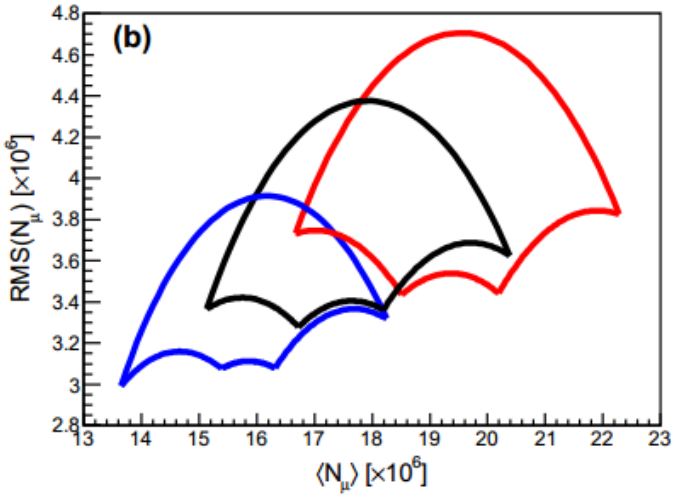
N_μ

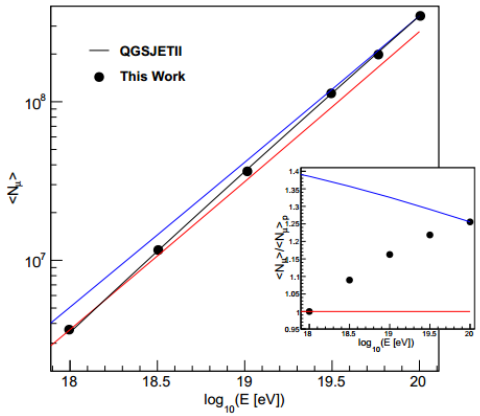


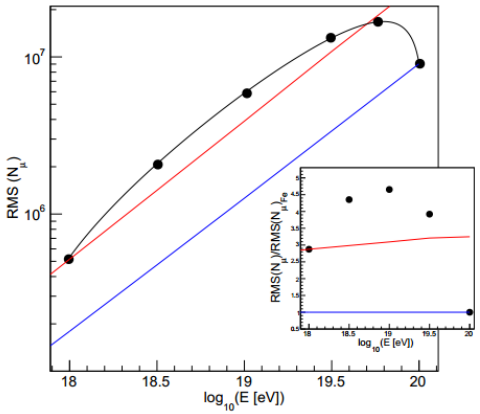
- N_μ is the best separation variable at generator level
  - EPOS number much higher than other models
  - "New physics" models tend to have even higher numbers
  - Important to measure full distribution and not only mean
    - RMS has very different features for pure and mixed compositions

Nmu correlation wih energy







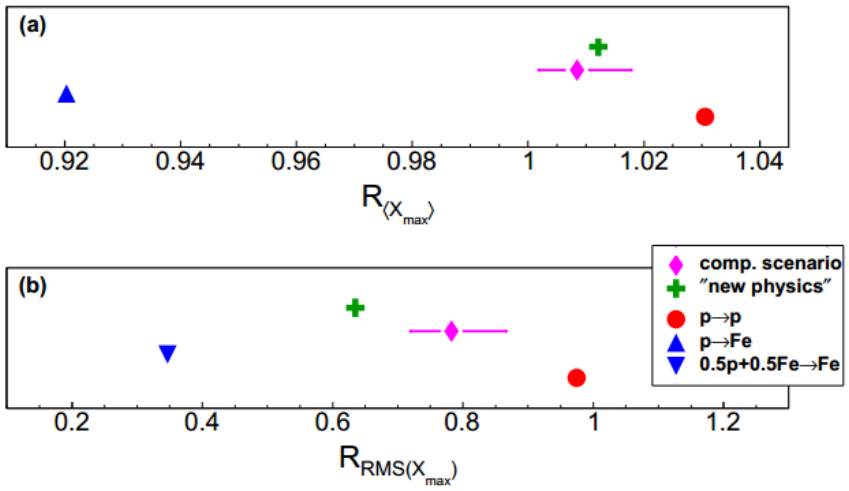


- We can get further separation using the fact that energy evolution is different between pure and mixed samples

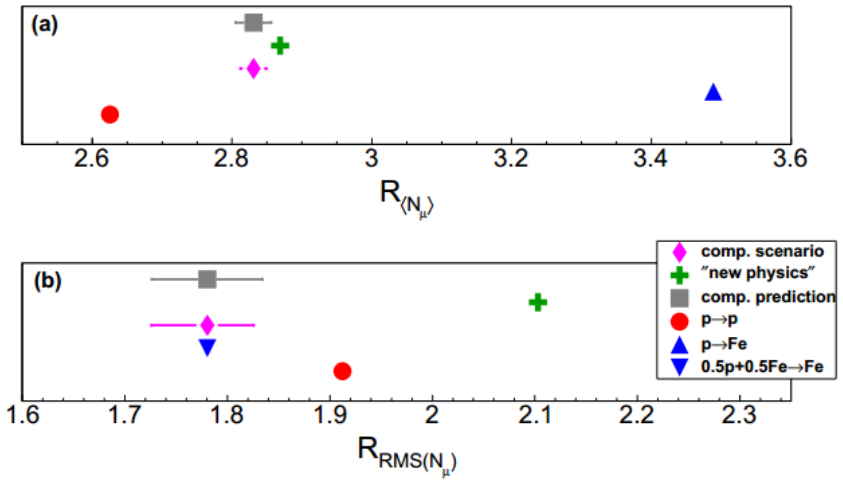
Nmu and Xmax - differential analysis

- We define R which is the ratio between a variable at 2 different energies
  - Independent of (a constant) energy uncertainty

Xmax

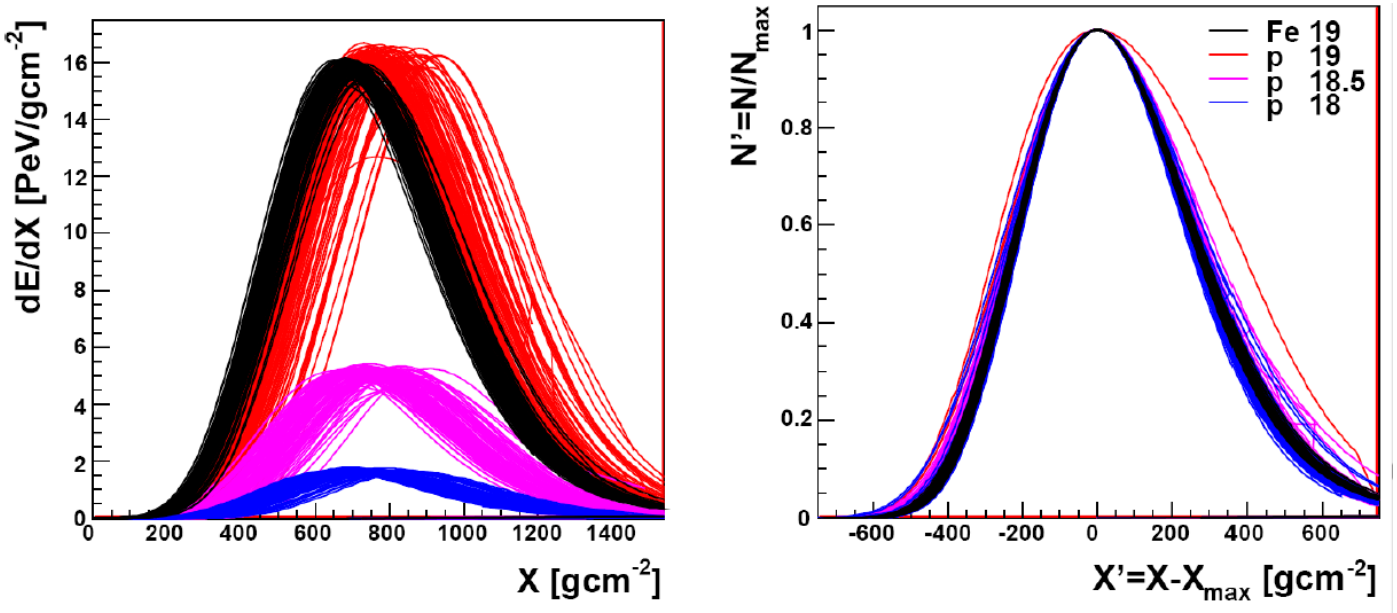


Nmu



- The ratio that we found best separates the “new physics” scenario from a mixed composition is RMS(Nmu)

Electromagnetic profiles

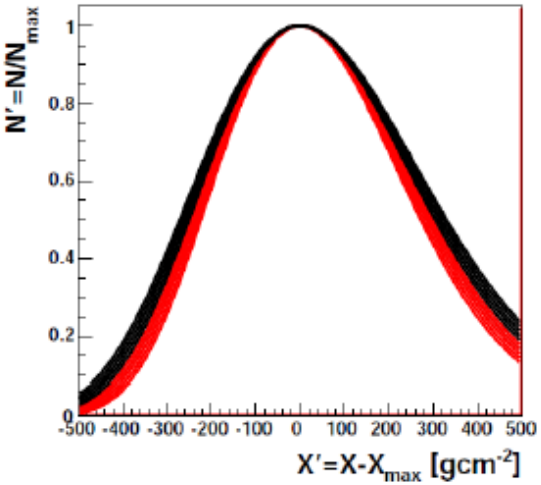


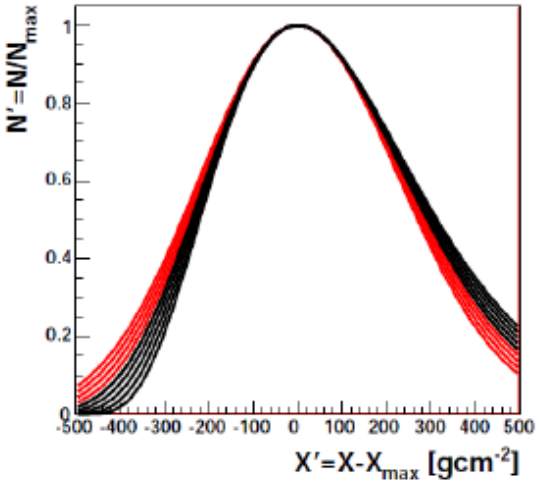
- Nmax gives energy and Xmax is primary dependent
- After normalizing for these two variables, shape is (almost) universal

Profile shape parametrization

E.M profiles are known to be well described by a Gaisser Hillas function

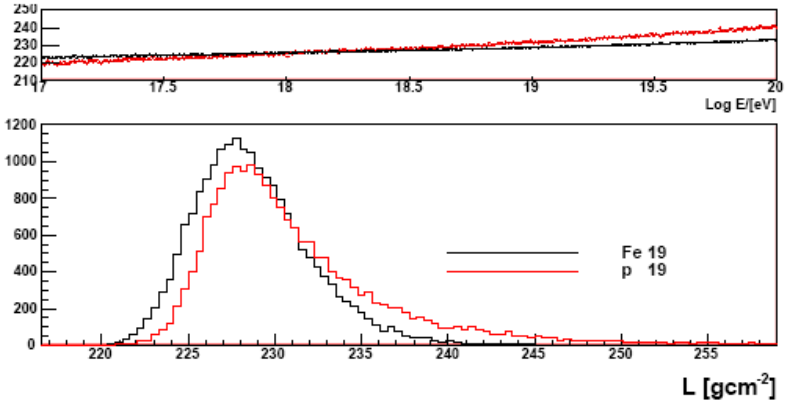
We write the shape variables as $R = \sqrt{\lambda/(X_{\max} - X_0)}$ and $L = \sqrt{\lambda \cdot (X_{\max} - X_0)}$

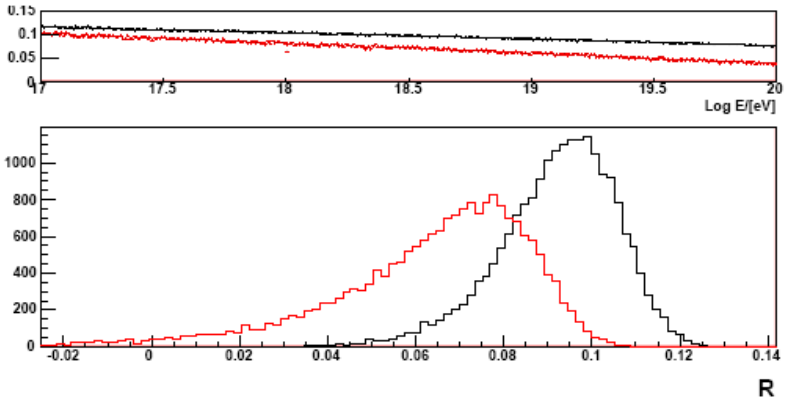




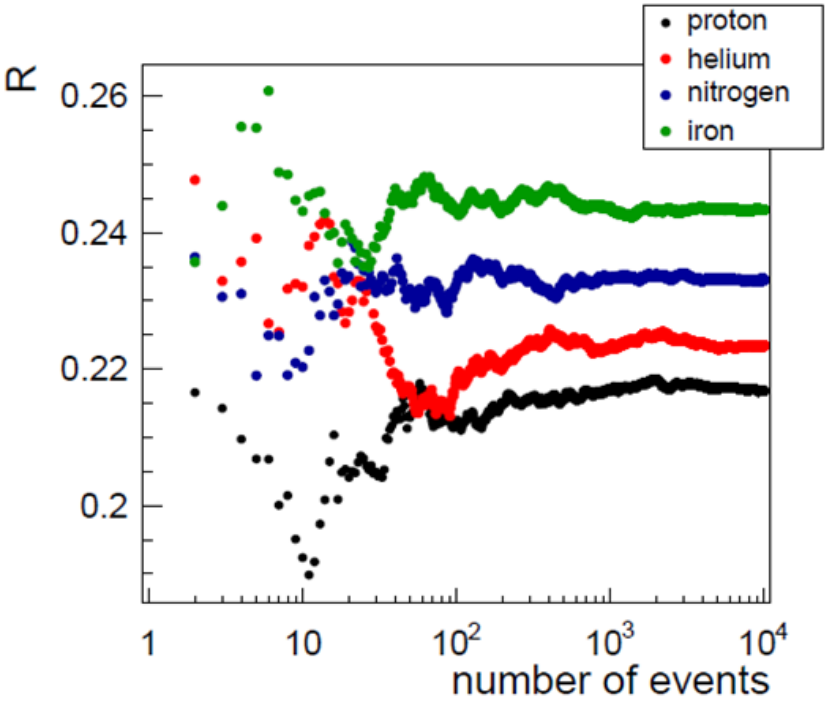
L is a gaussian width: $E \propto \sqrt{2\pi} \cdot N_{\max} \cdot L$

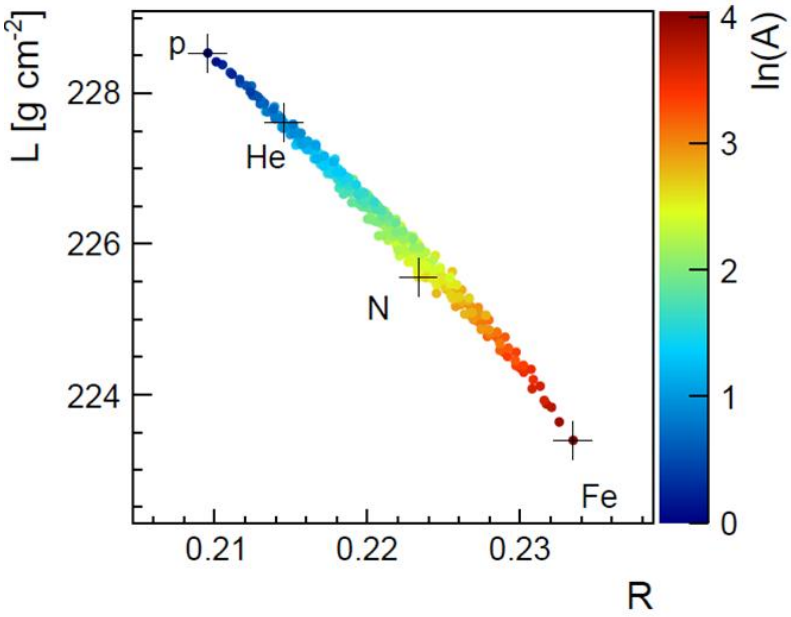
R is a measure of speed of shower development





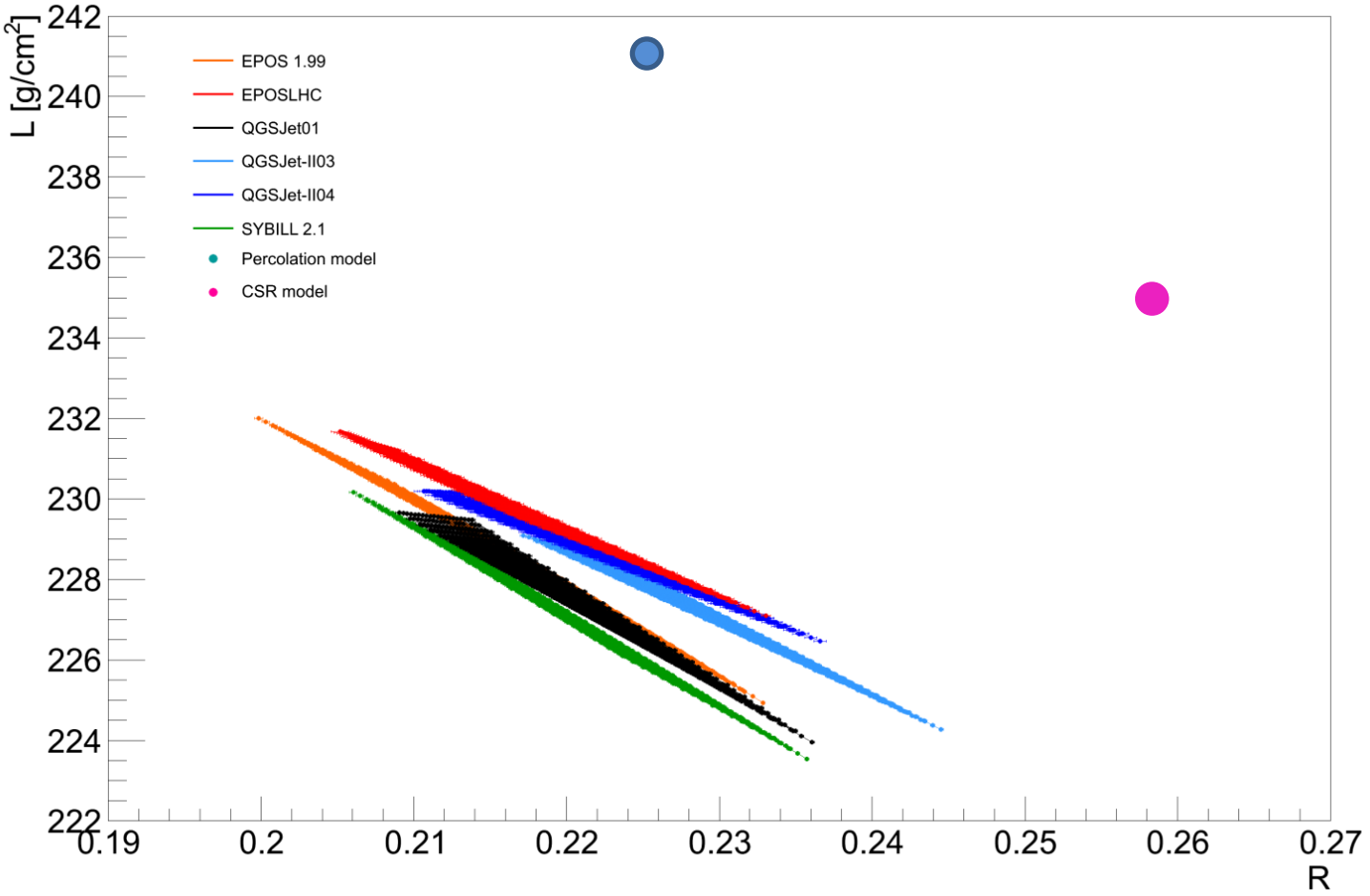
Building an average profile





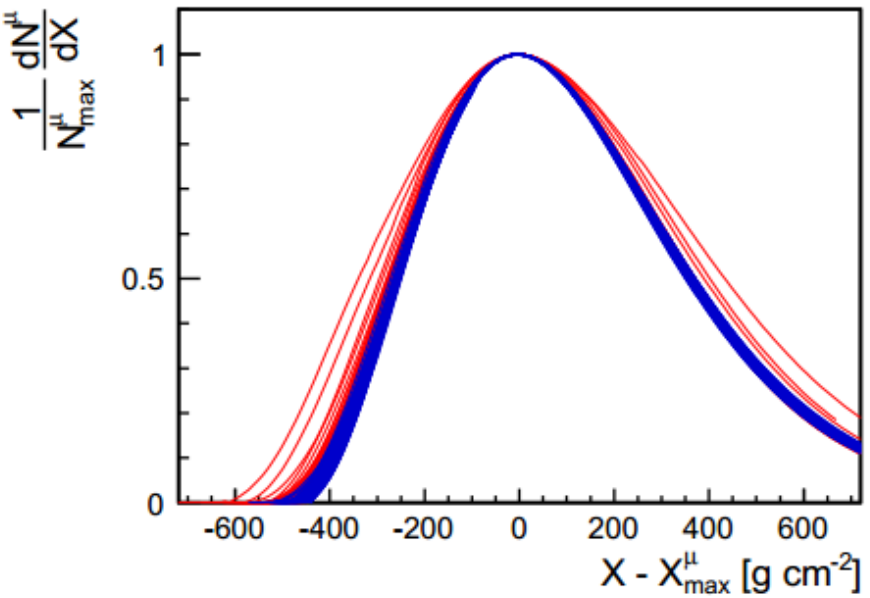
- Shape parameters difficult to measure event-by-event: wide distributions dependent on constraints and fit limits
- For each energy bin we first build an average profile and then fit R and L unconstrained
- Just a practical way to cope with errors in current profiles; event by event shape determination would be clearly better and allow estimation of X_1

R vs L

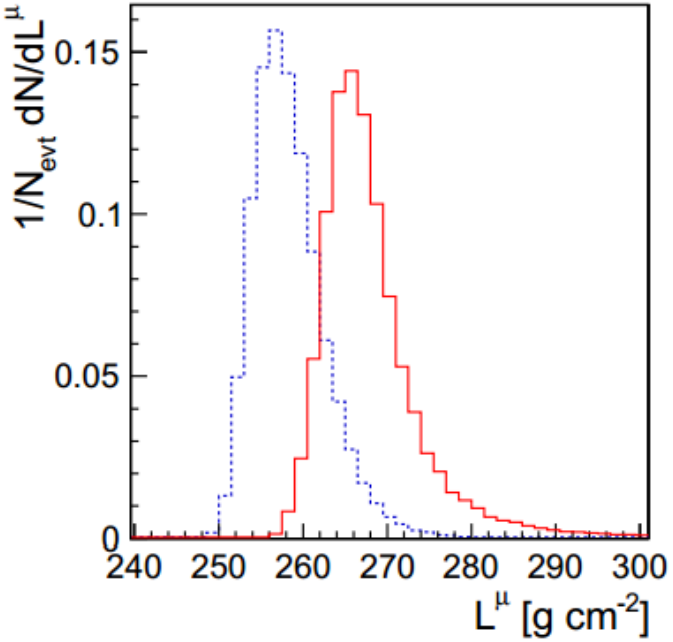


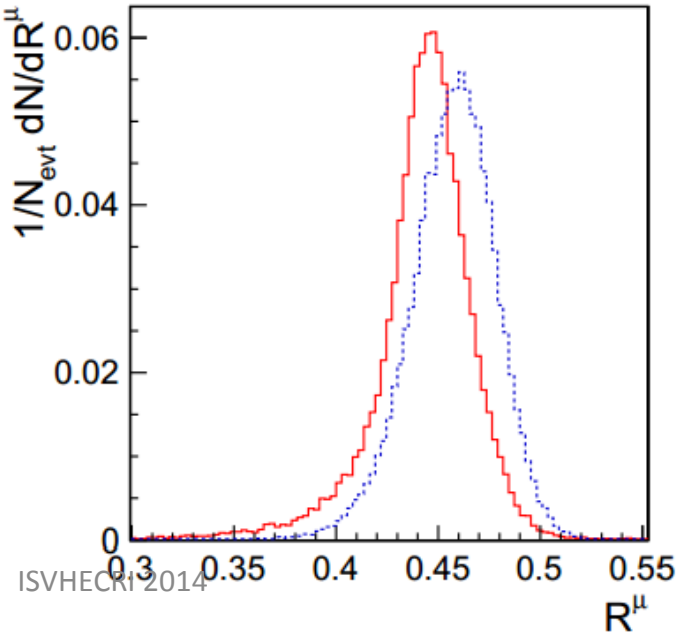
- "New physics" high energy interaction models give a very different shape while maintaining Xmax consistent with results
  - Testing hadronic interaction models at the highest energies
  - Constraining new physic scenarios

MPD shape



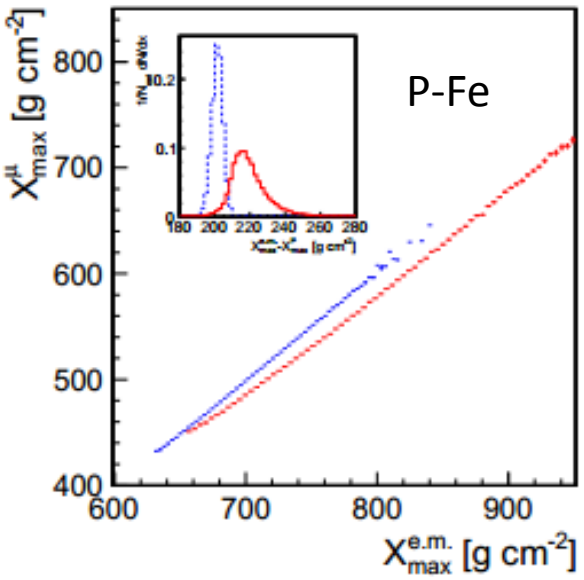
- As with the EM profile, after normalizing to Nmumax and Xmumax we see there is still some difference between primaries

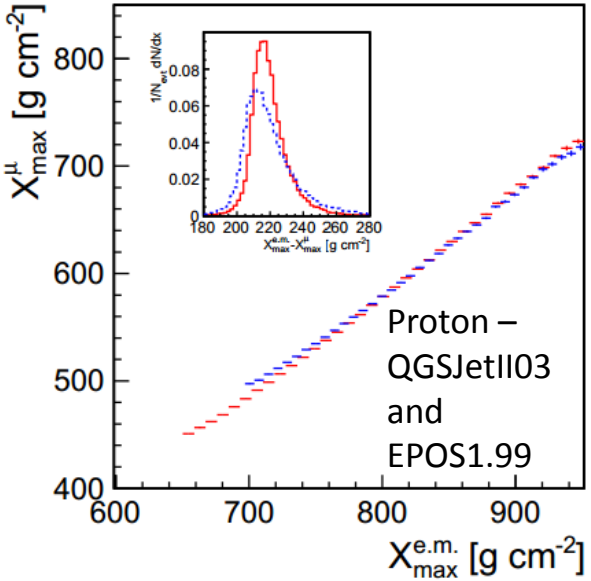


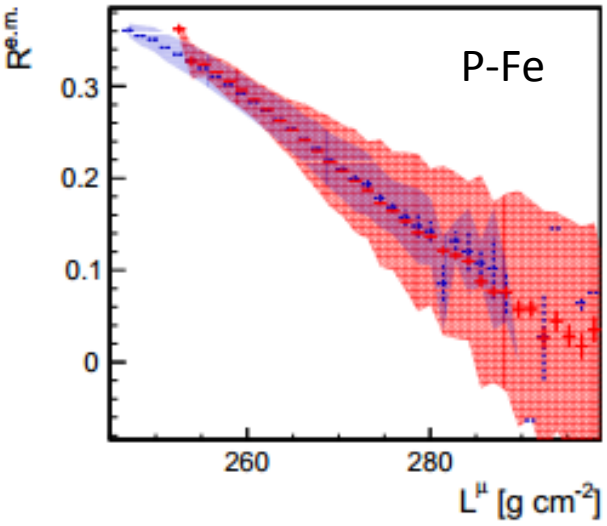


Correlation between profiles

arXiv:1111.1424



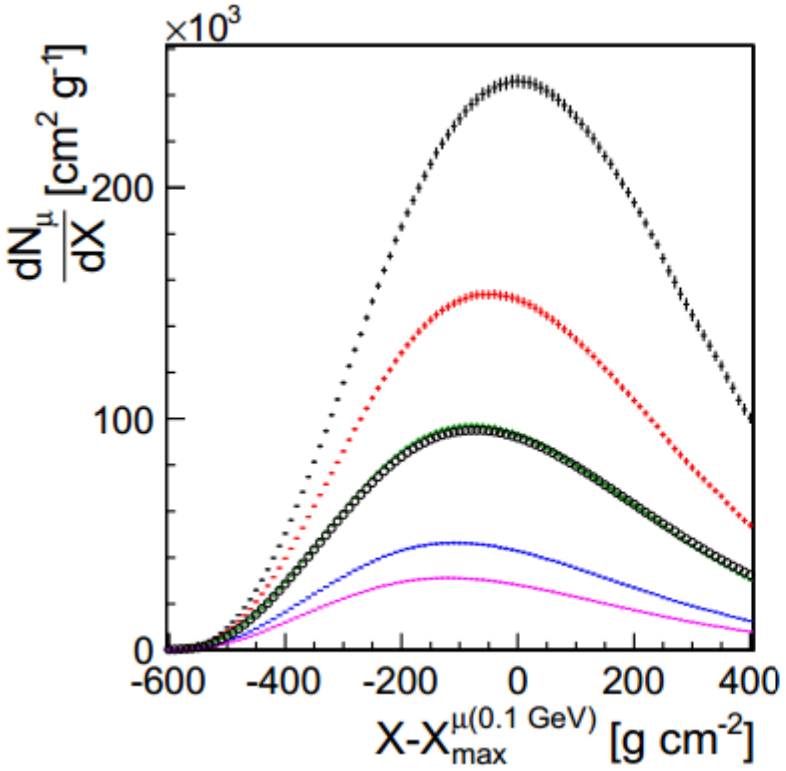


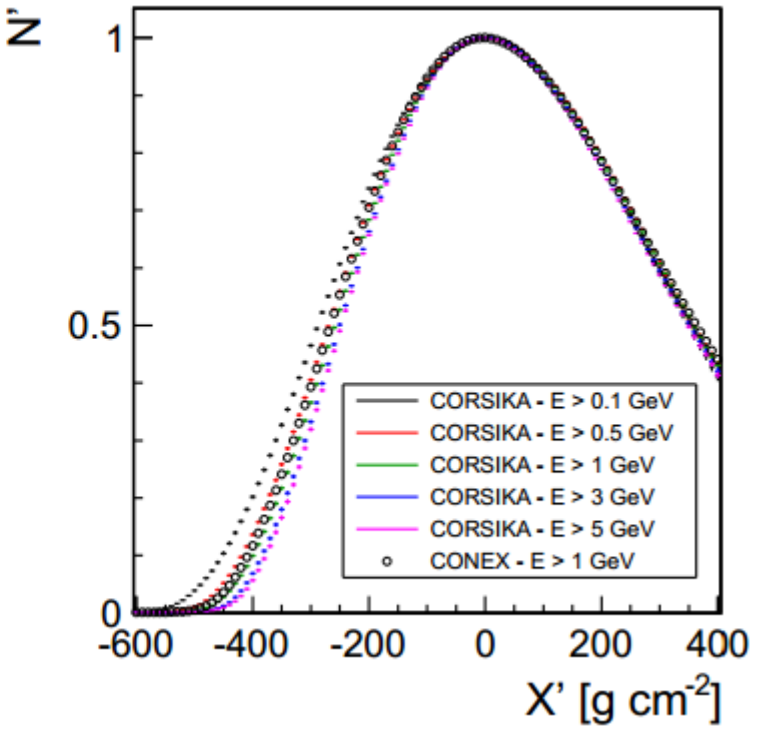


- Correlation between muonic and electromagnetic profiles – Xmax and shape
  - Possible to test the agreement between measurements in the overlapping energy region

Conclusions

- Today we do composition analysis mostly with Xmax and its RMS
  - degeneracy in interpretation between composition and hadronic models – more variables than data
- There is more experimentally accessible information in electromagnetic and muonic profiles
  - Nmu and its rms are the best composition separation variables
  - The shape variables are very important – changes in cross-section do not affect shape while changing Xmax
  - Also, there are correlations in shape of both profiles – useful for cross calibration in the energy region where there is overlap


×10^3
dN_μ/dX [cm^2 g^-1]
200
100
0
-600
-400
-200
0
200
400
X-X_max^μ(0.1 GeV) [g cm^-2]


N'
1
0.5
0
-600
-400
-200
0
200
400
X' [g cm^-2]
CORSIKA - E > 0.1 GeV
CORSIKA - E > 0.5 GeV
CORSIKA - E > 1 GeV
CORSIKA - E > 3 GeV
CORSIKA - E > 5 GeV
CONEX - E > 1 GeV