The interplay between the electromagnetic and the muonic longitudinal profile at production

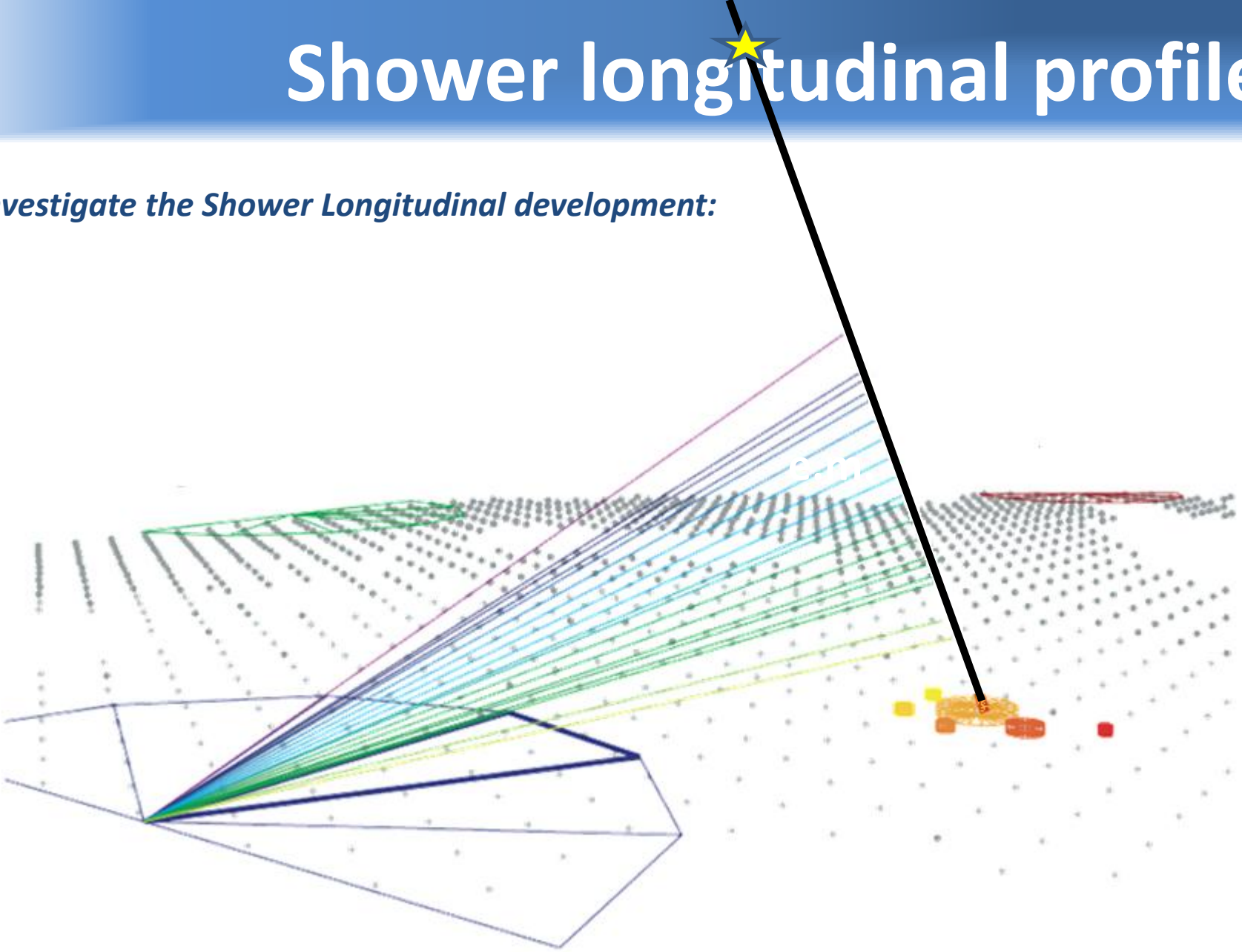
Ruben Conceição

Sofia Andringa, Lorenzo Cazon, Mário Pimenta

ISVHECRI, Berlin, 11th August 2011

Shower longitudinal profiles

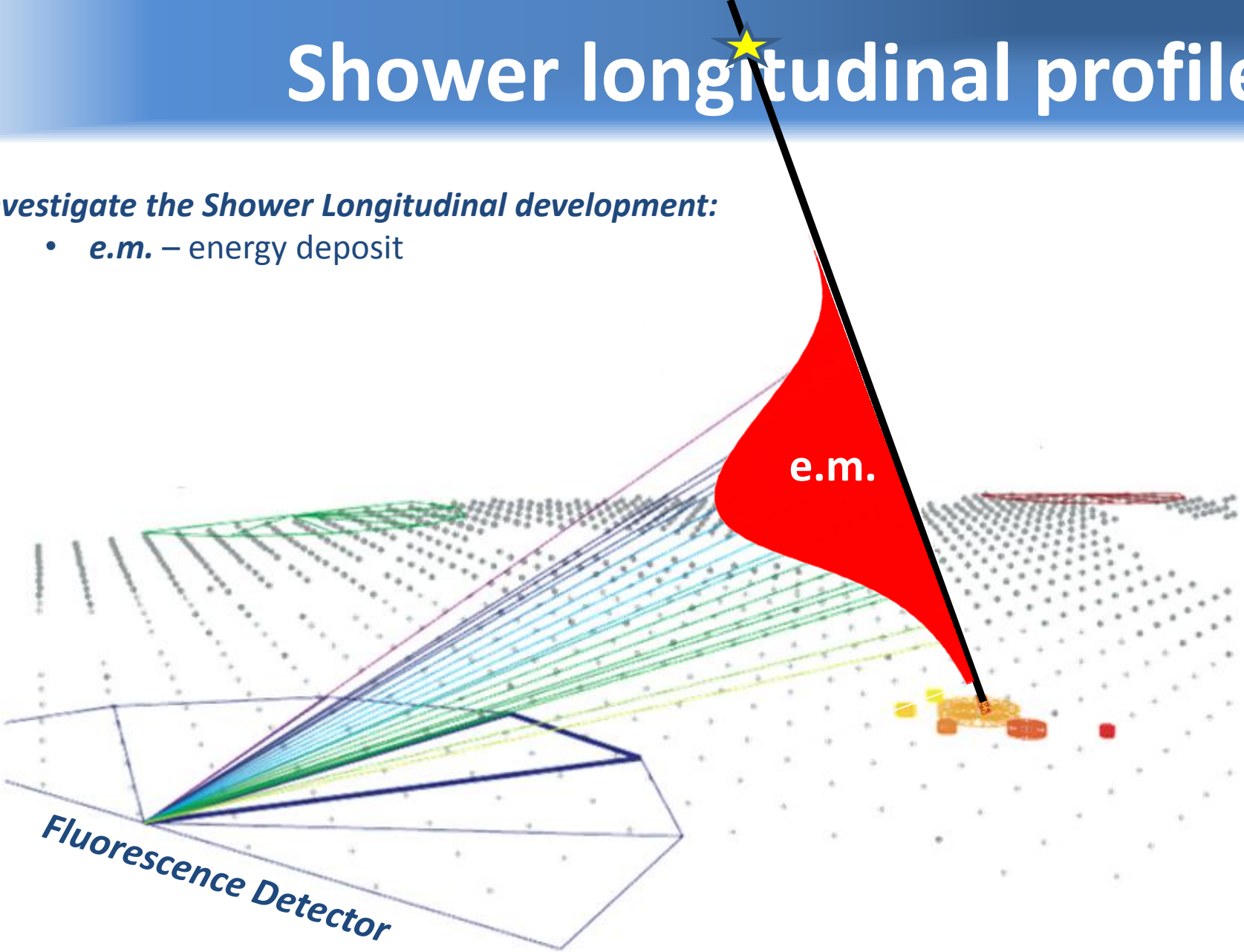
Investigate the Shower Longitudinal development:



Shower longitudinal profiles

Investigate the Shower Longitudinal development:

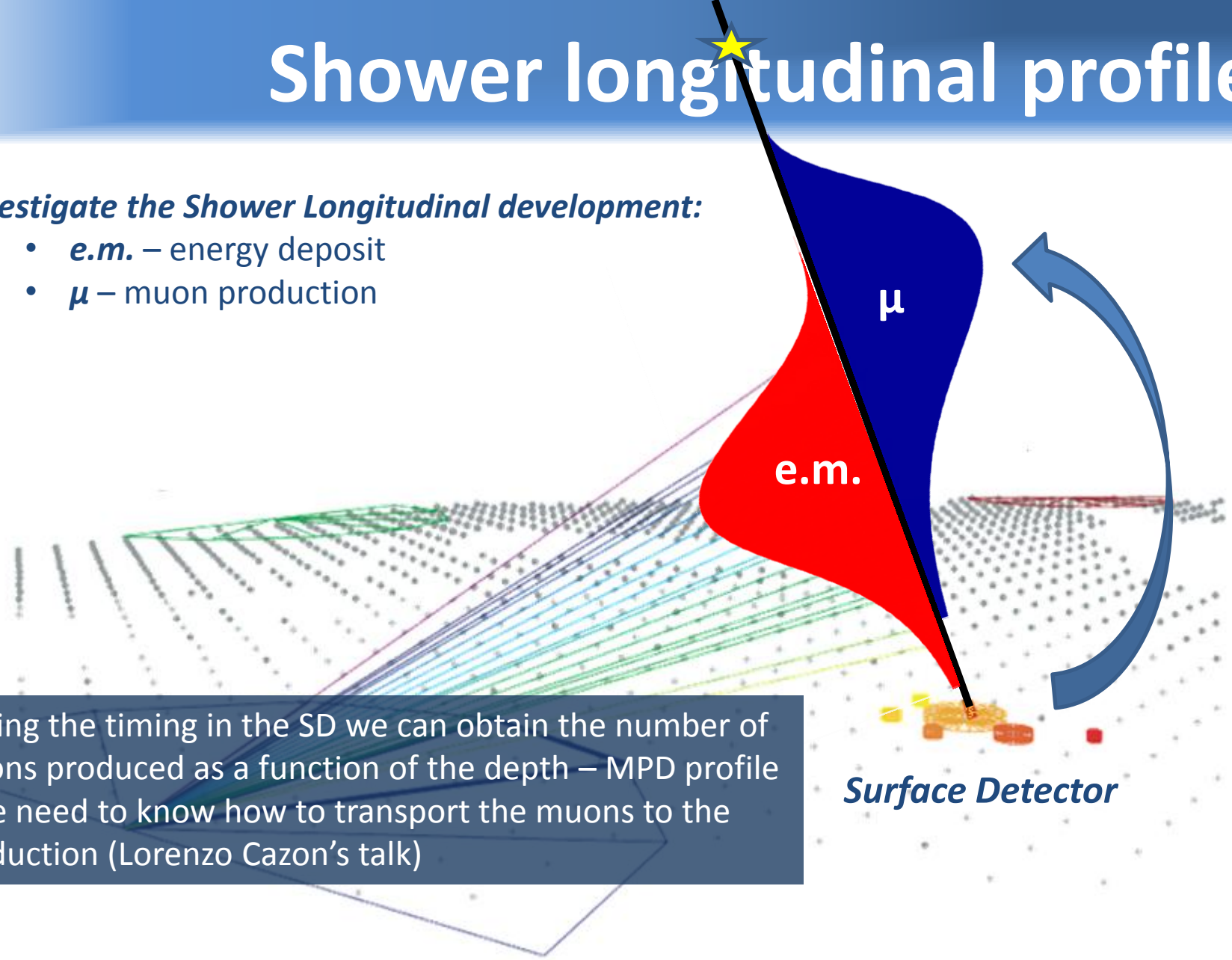
- ***e.m.*** – energy deposit



Shower longitudinal profiles

Investigate the Shower Longitudinal development:

- ***e.m.*** – energy deposit
- ***μ*** – muon production

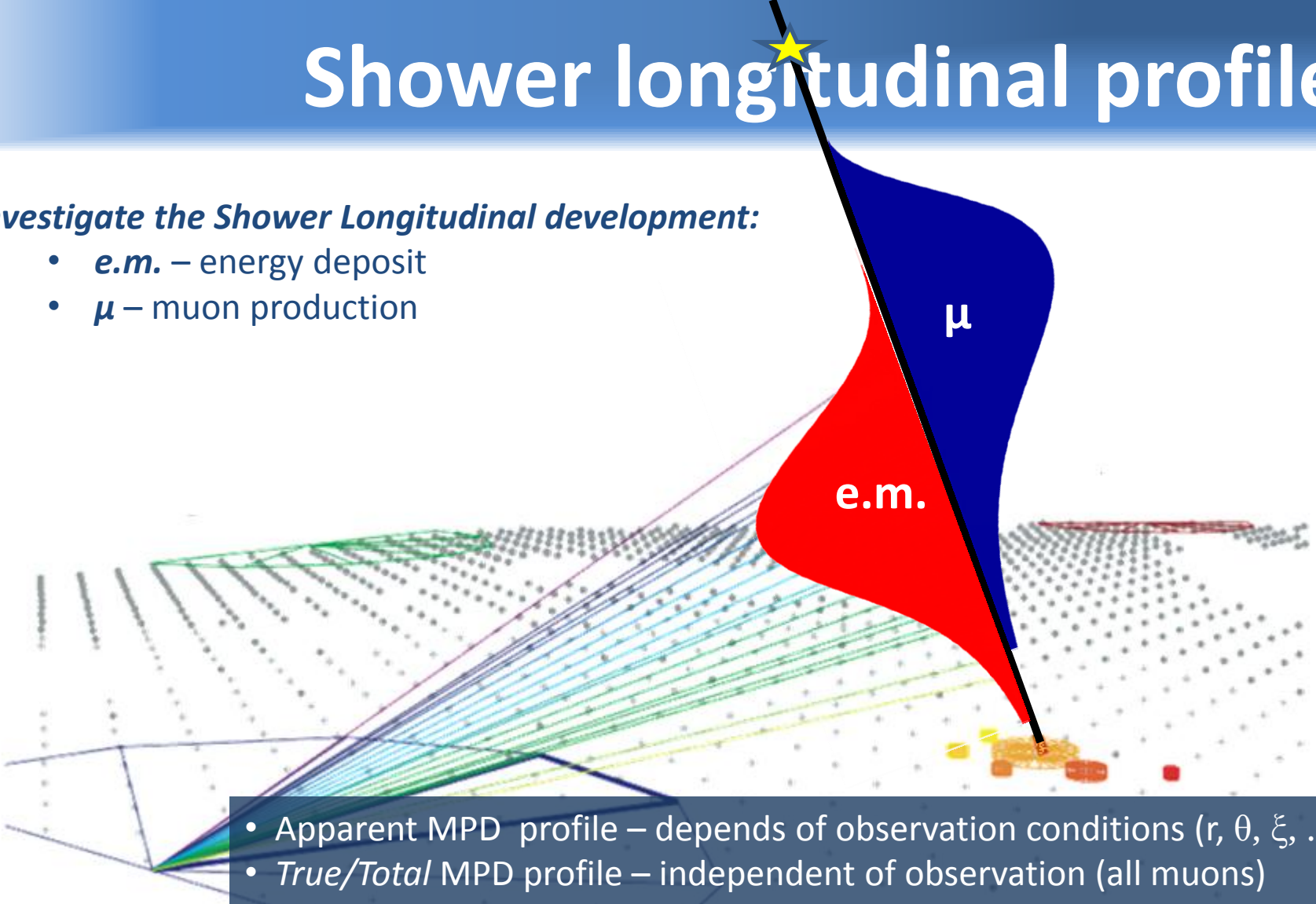


• Using the timing in the SD we can obtain the number of muons produced as a function of the depth – MPD profile
• We need to know how to transport the muons to the production (Lorenzo Cazon's talk)

Shower longitudinal profiles

Investigate the Shower Longitudinal development:

- ***e.m.*** – energy deposit
- ***μ*** – muon production

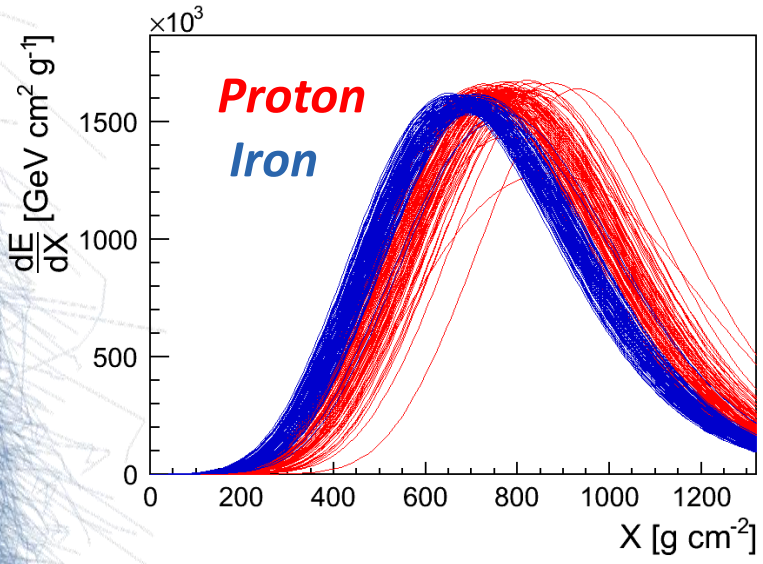


- Apparent MPD profile – depends of observation conditions (r, θ, ξ, ...)
- *True/Total* MPD profile – independent of observation (all muons)

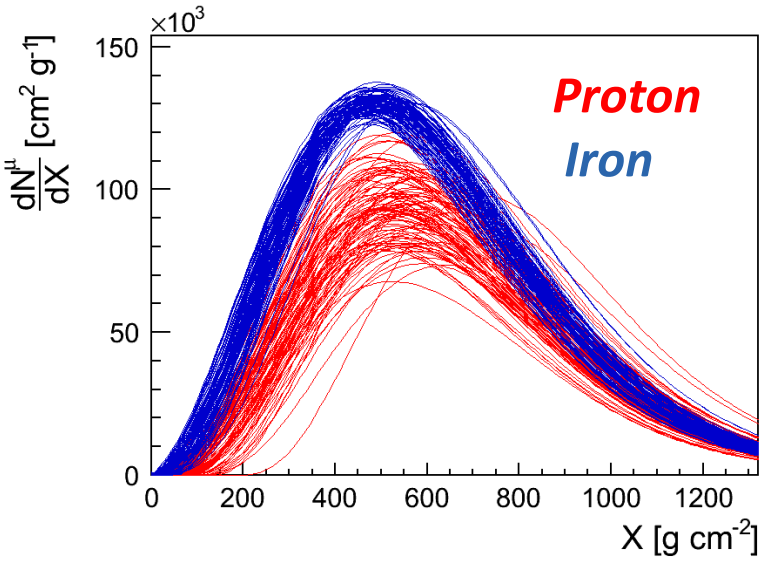
Characterization of the total MPD and comparison with the electromagnetic profile

Shower Longitudinal profiles

Electromagnetic



Muon Production

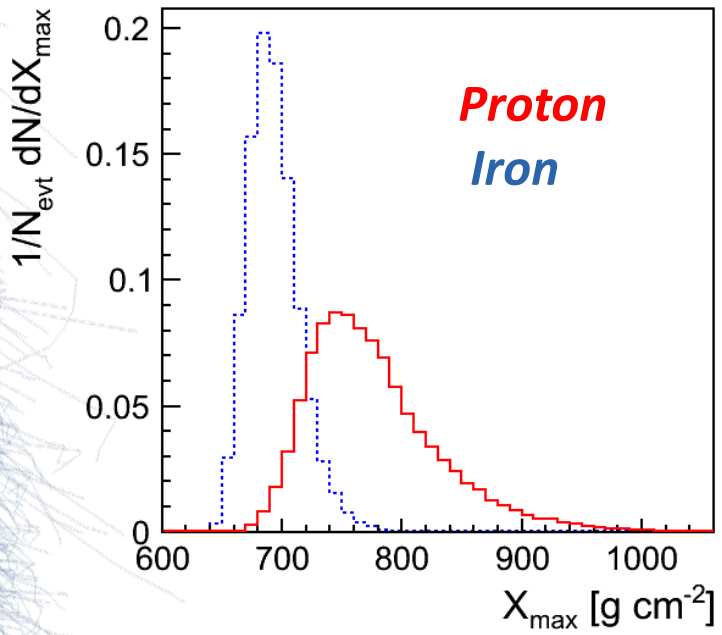


$E = 10^{19}$ eV ; $\theta = 40^{o}$

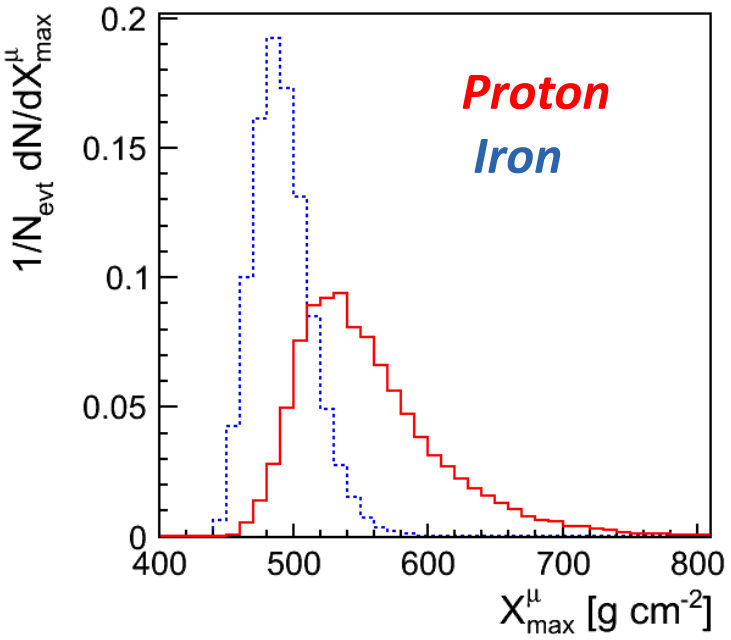
- N_{max} of the e.m. profile is related to the primary energy
- N_{max} fluctuates more in the Muon Production Depth profile
  - Related with the total number of muons
  - Sensitive to primary mass

Depth of maximum (X_{max})

Electromagnetic



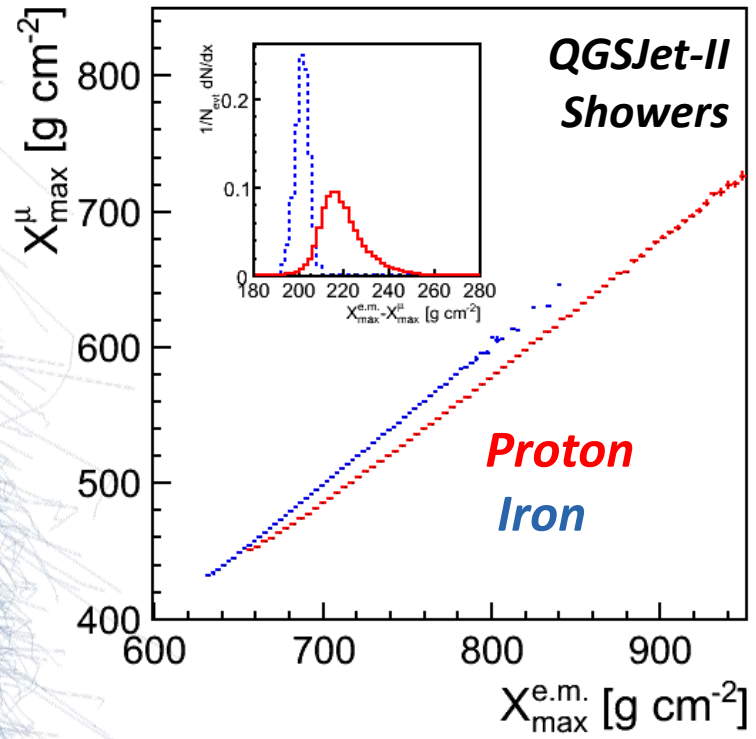
Muon Production



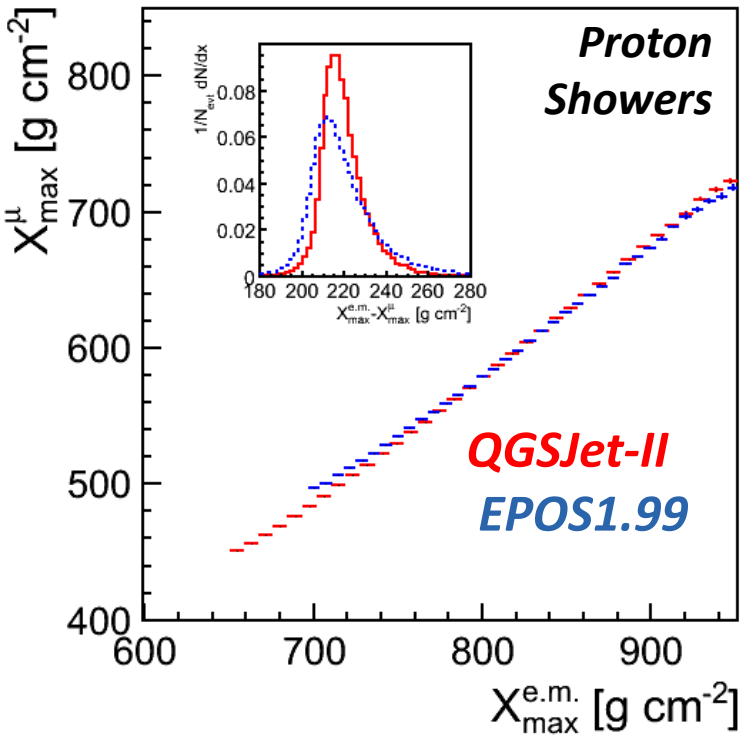
- Both average X_{max} of MPD profile and its fluctuations are sensitive to the primary mass composition
- The distributions have the same features although the muonic X_{max} occurs about 200 g cm^{-2} before

Relation between X_{max}

Primary mass



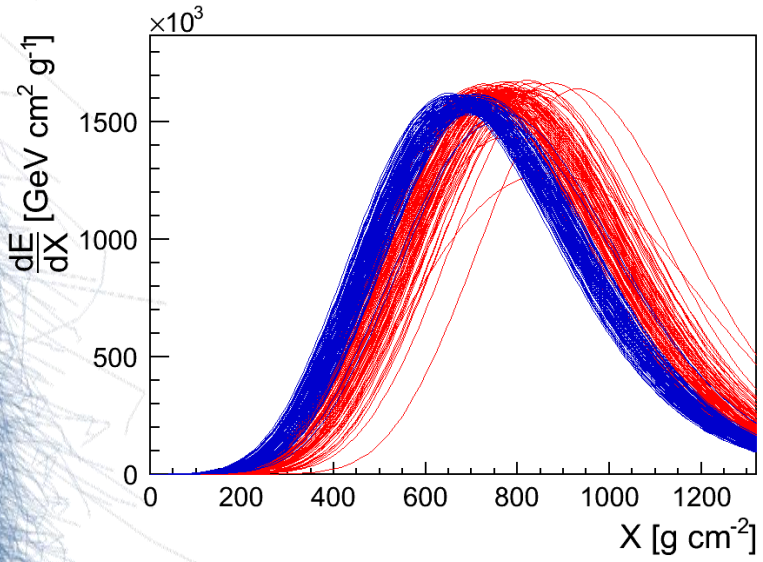
Hadronic int. model



- $X^{e.m.}_{max}$ correlates with X^{μ}_{max}
- ($X^{e.m.}_{max} - X^{\mu}_{max}$) is sensitive to mass composition
  - $X^{e.m.}_{max} - X^{\mu}_{max} = \Delta X^{e.m.} + X_1 - \Delta X^{\mu} - X_1$
  - This variable is completly independent of the first interaction point, i.e, primary cross-section

Universal Shower Profile

Electromagnetic



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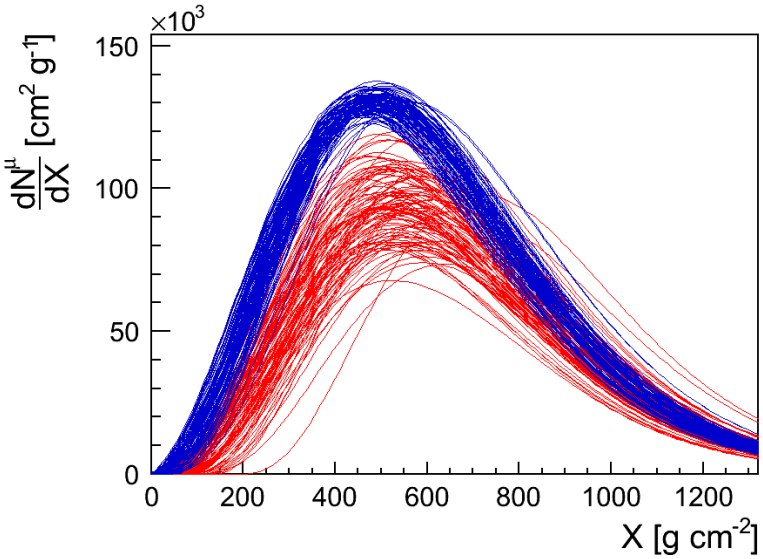
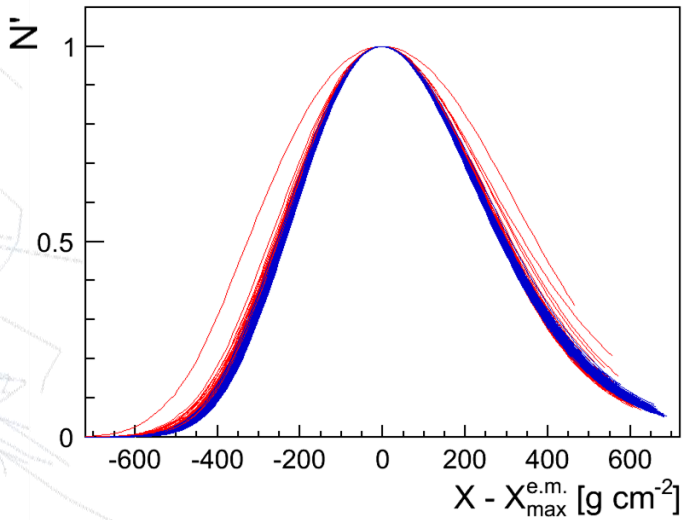


Proton Iron

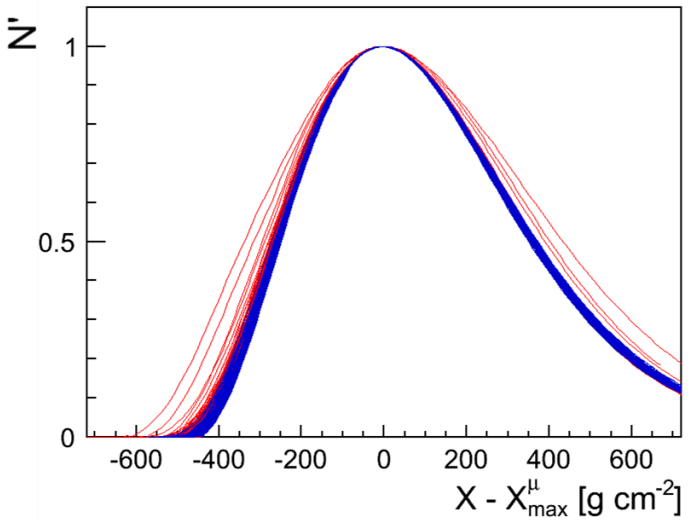
- $X' = X - X_{max}$; $N' = N/N_{max}$

Universal Shower Profile

Electromagnetic



Muon Production

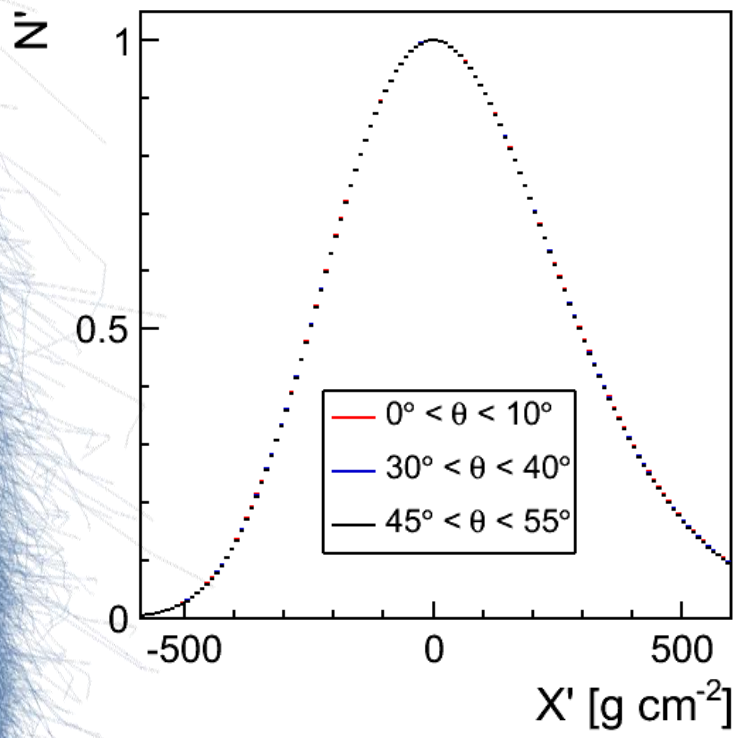


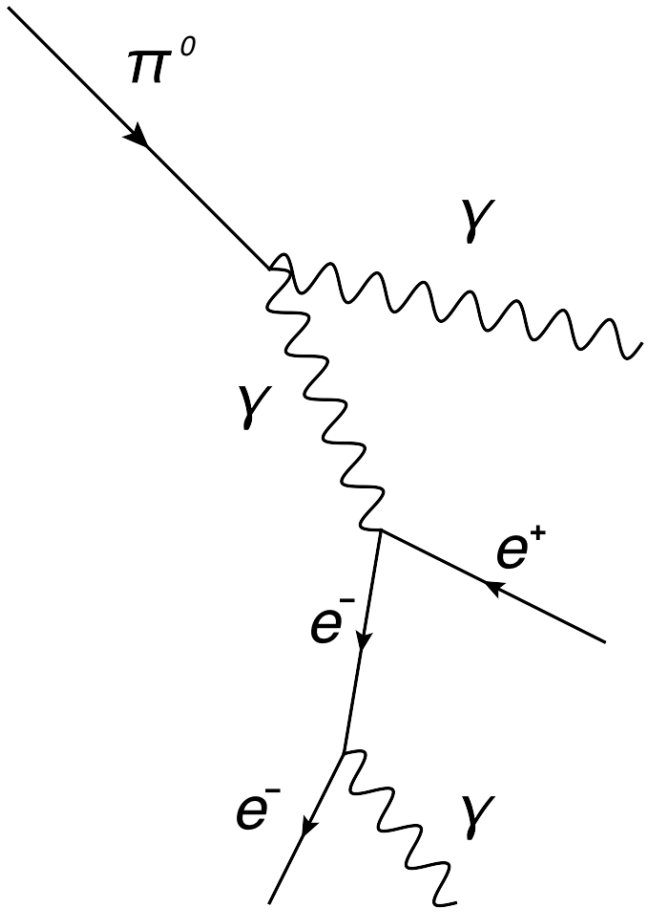
Proton Iron

- $X' = X - X_{max}$; $N' = N/N_{max}$
- **The shape of the muon production longitudinal profile is universal**

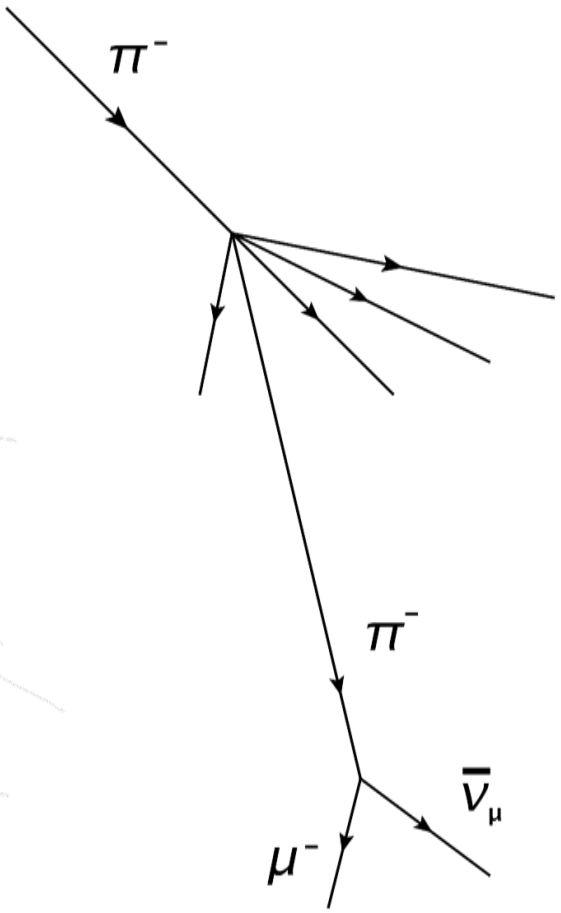
Dependence with the zenith angle

Electromagnetic

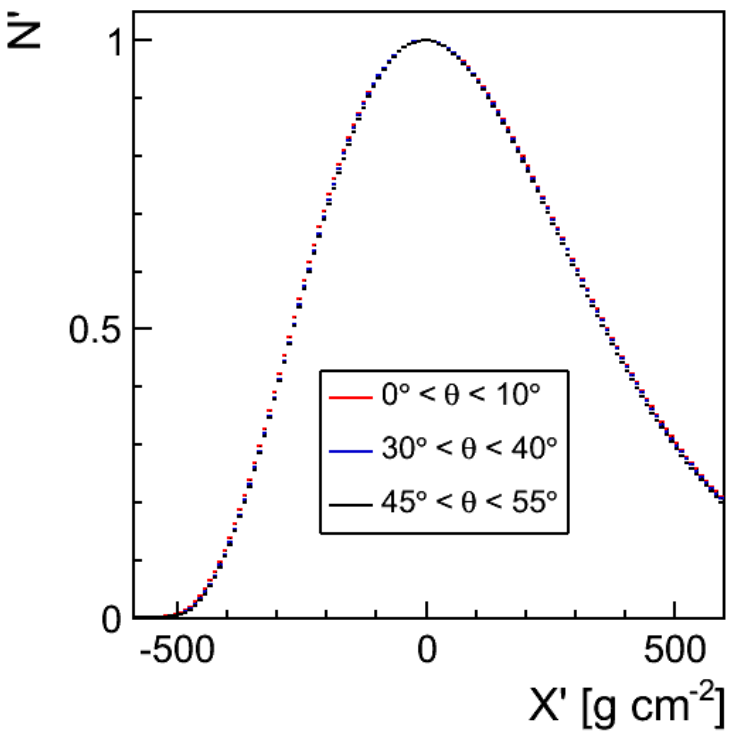




Dependence with the zenith angle

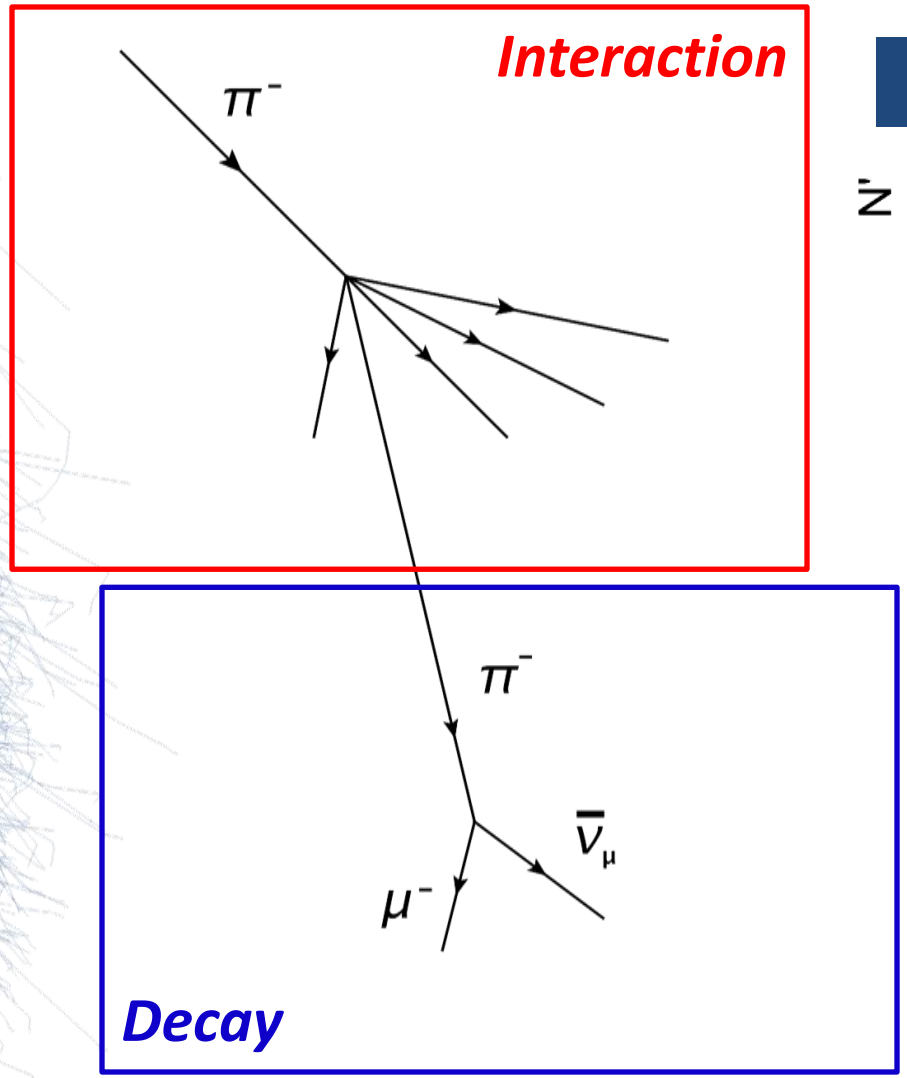


Muon Production

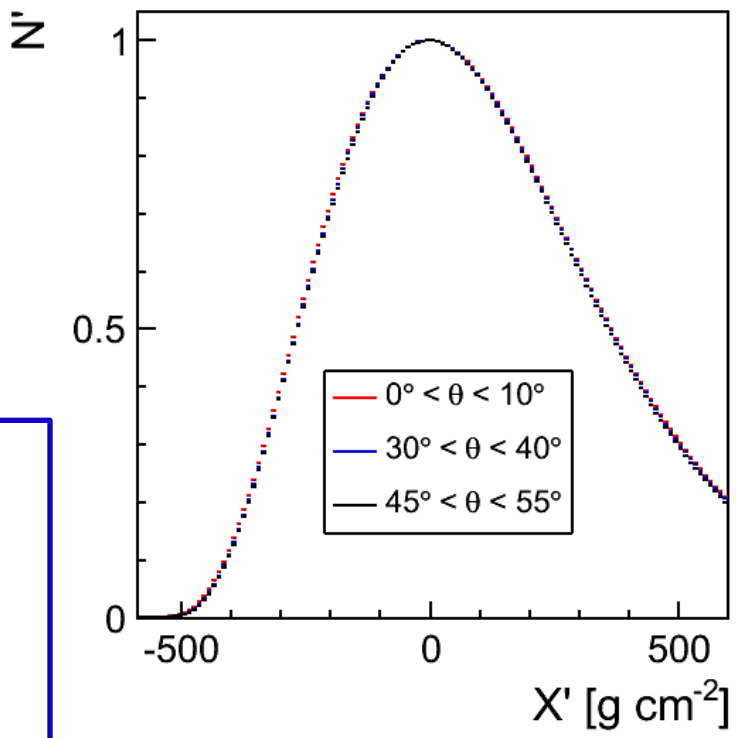


- There are some minor universality violation with the zenith angle

Dependence with the zenith angle



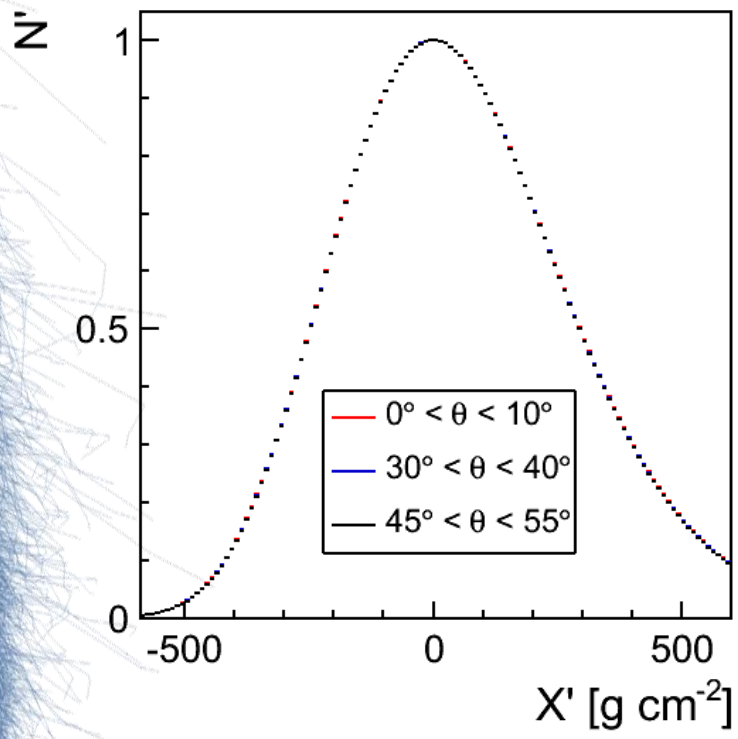
Muon Production



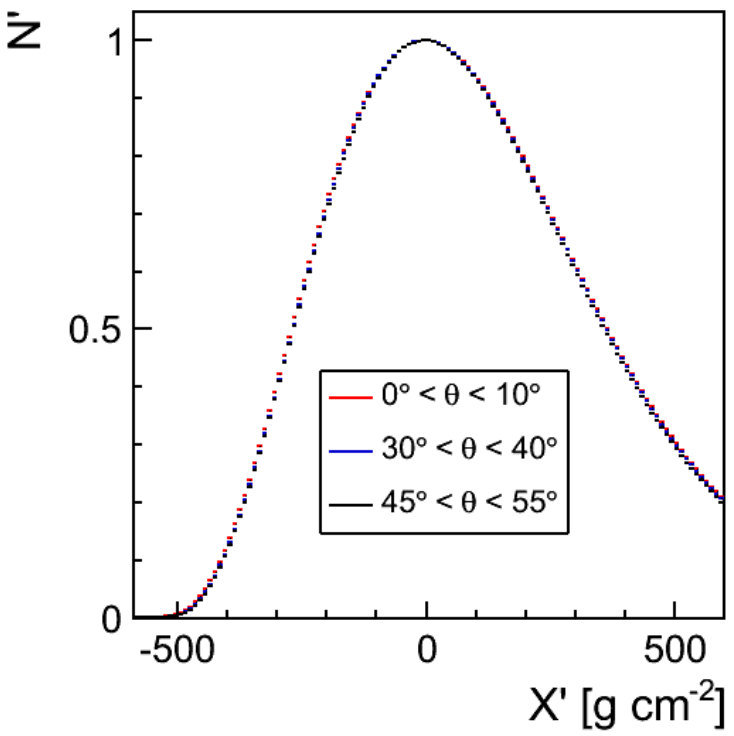
- There are some minor universality violation with the zenith angle

Dependence with the zenith angle

Electromagnetic



Muon Production



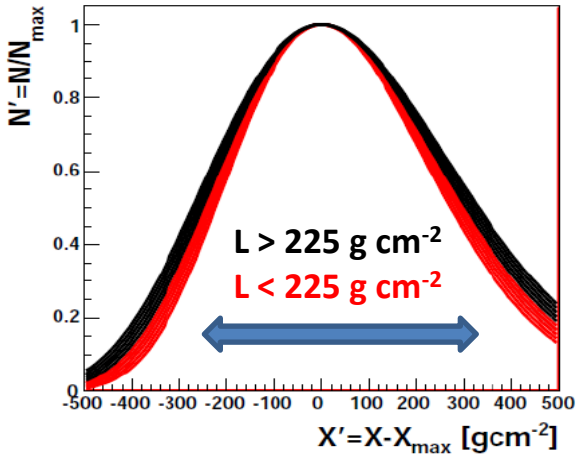
- *The shape of the USP is rather universal with the zenith angle*

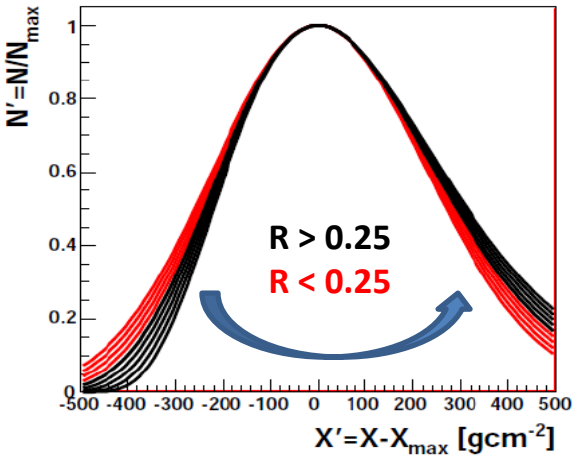
Shape Variables for the USP

S. Andringa et. al., Astropart. Phys. 34 (2011) 360–367

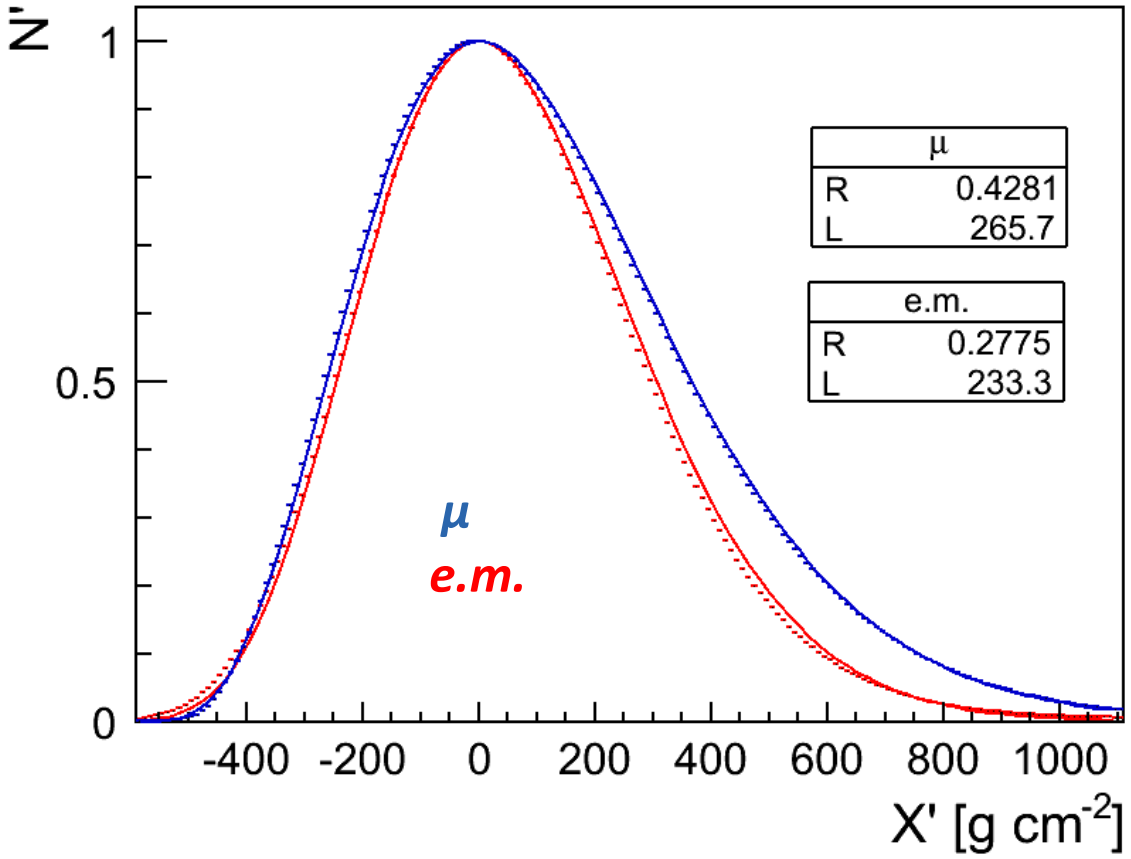
$$N' = \underbrace{\exp\left(-\frac{1}{2}\left(\frac{X'}{L}\right)^2\right)}_{\text{Gaussian(L)}} \times \underbrace{\prod_{n=3}^{\infty} \exp\left(-\frac{R^{n-2}}{n}\left(-\frac{X'}{L}\right)^n\right)}_{\text{Distortion(R)}}$$

- Gaisser-Hillas rewritten in terms of **R** and **L**:
- **$L^2 = \lambda \cdot |X_0'|$**
- Measurement of the width of the profile
- **$R^2 = \lambda / |X_0'|$**
- Measurement of the asymmetry of the profile





Fitting Gaisser-Hillas



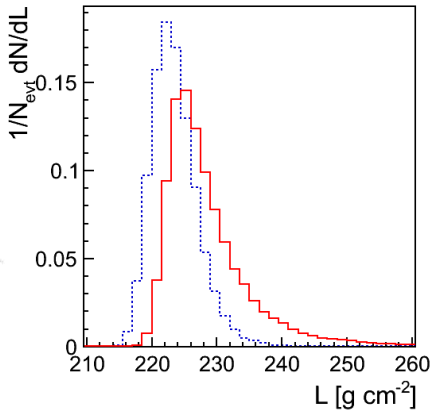
- **L –** width **e.m. –** energy **μ –** related with number of muons
- **R –** asymmetry **e.m. & μ –** shower development

- ***The Muon Production profile is described by a Gaisser-Hillas function***

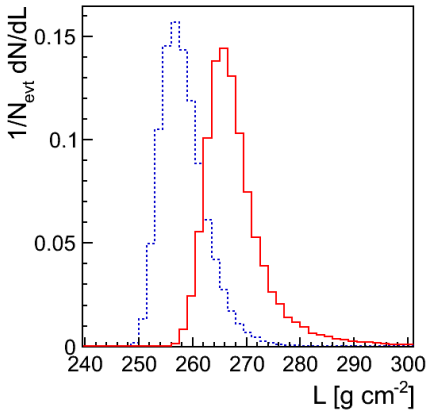
Profile Shape Parameters

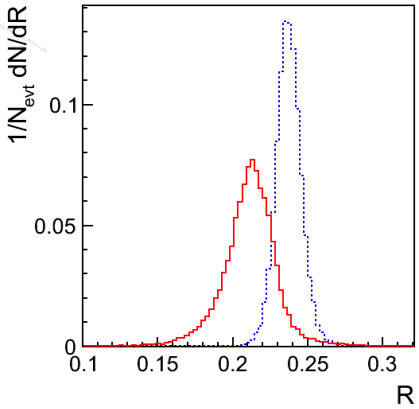
Electromagnetic

Muon Production

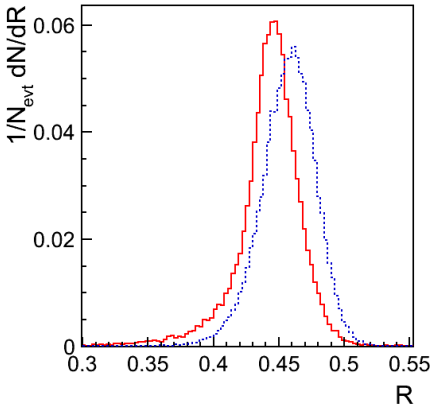


L





R

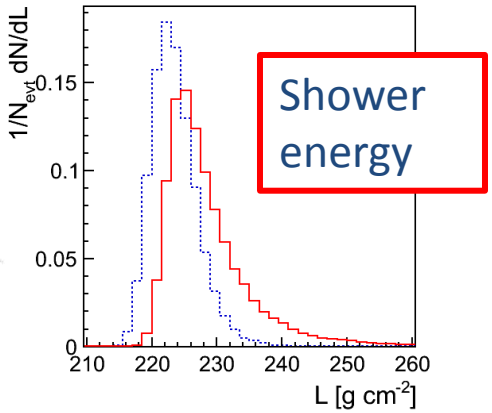


Proton ***Iron***

Profile Shape Parameters

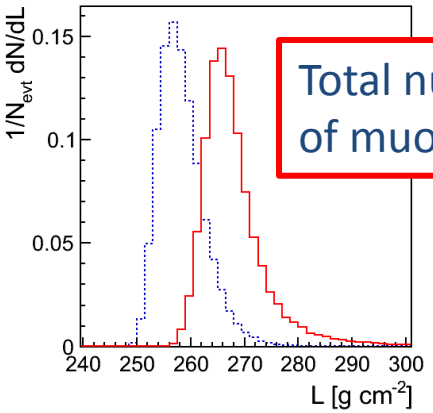
Electromagnetic

Muon Production



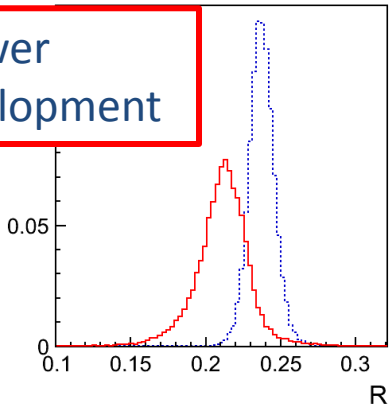
Shower energy

L



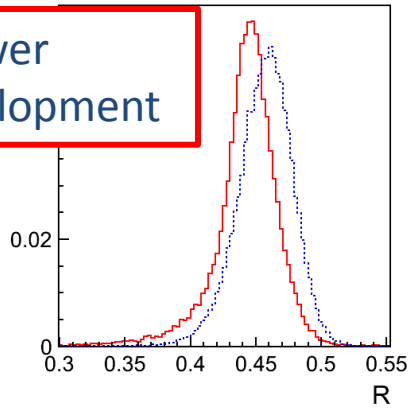
Total number of muons

Shower development



R

Shower development



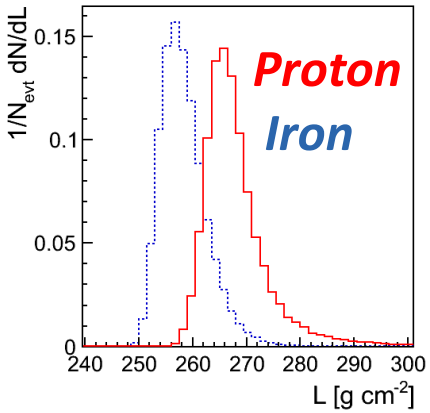
Proton ***Iron***

Profile Shape Parameters

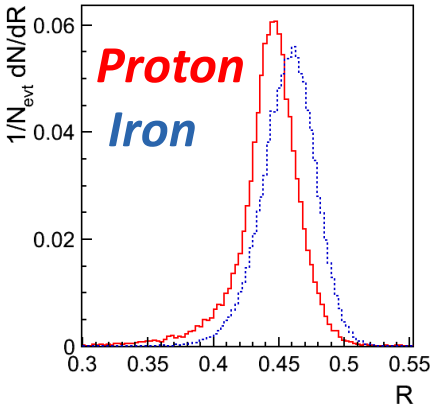
- The shape of the Muon Prod. profile is sensitive to the primary mass
  - Additional information independent of X_{max} and N_{max}
  - Related to the total number of muons produced in the shower
- L^{μ} is the most sensitive shape parameter
- R^{μ} can be fixed to enhance the proton/iron separation

Muon Production

L

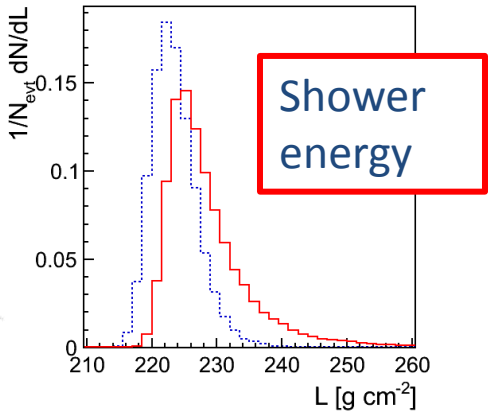


R



Profile Shape Parameters

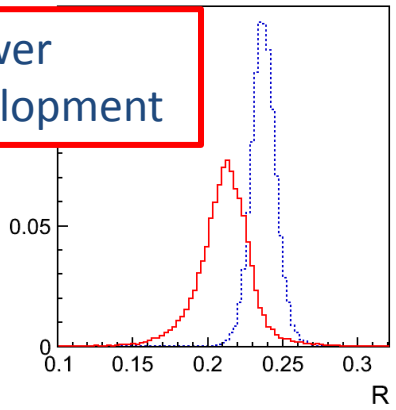
Electromagnetic



Shower energy

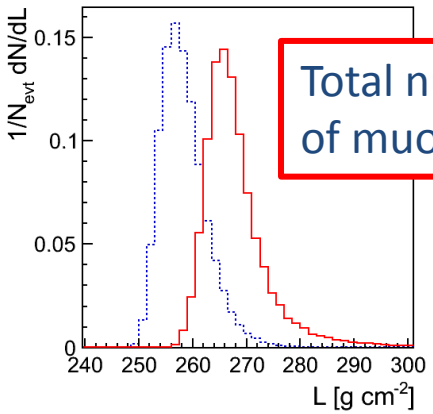
L

Shower development



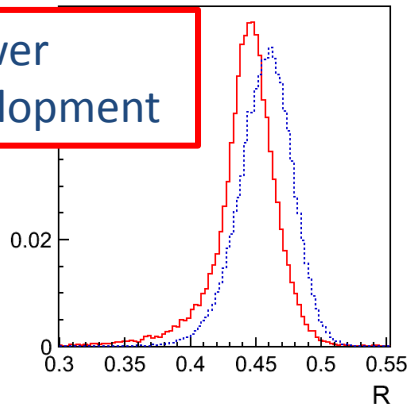
R

Muon Production



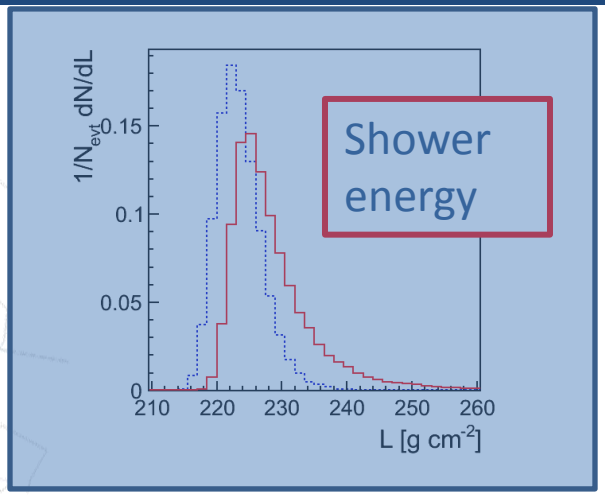
Total number of muons

Shower development

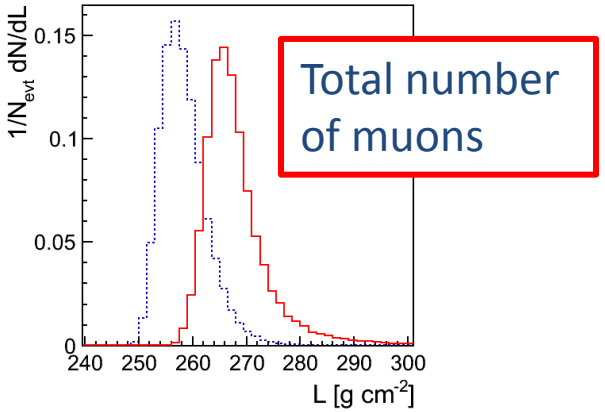


Profile Shape Parameters

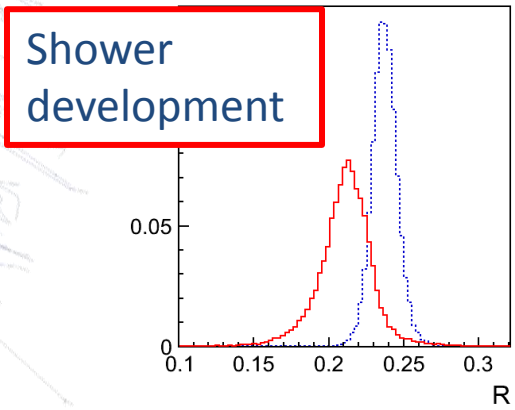
Electromagnetic



Muon Production



L



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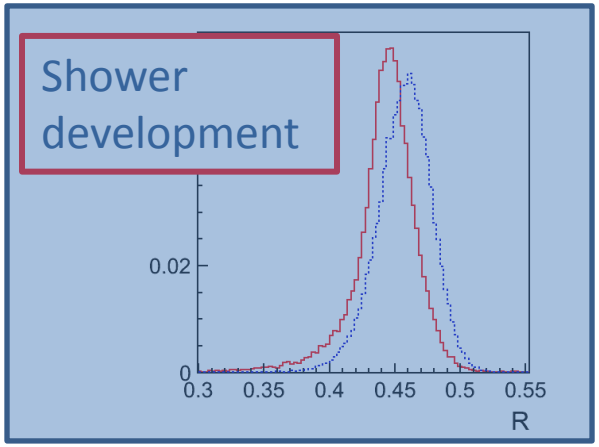
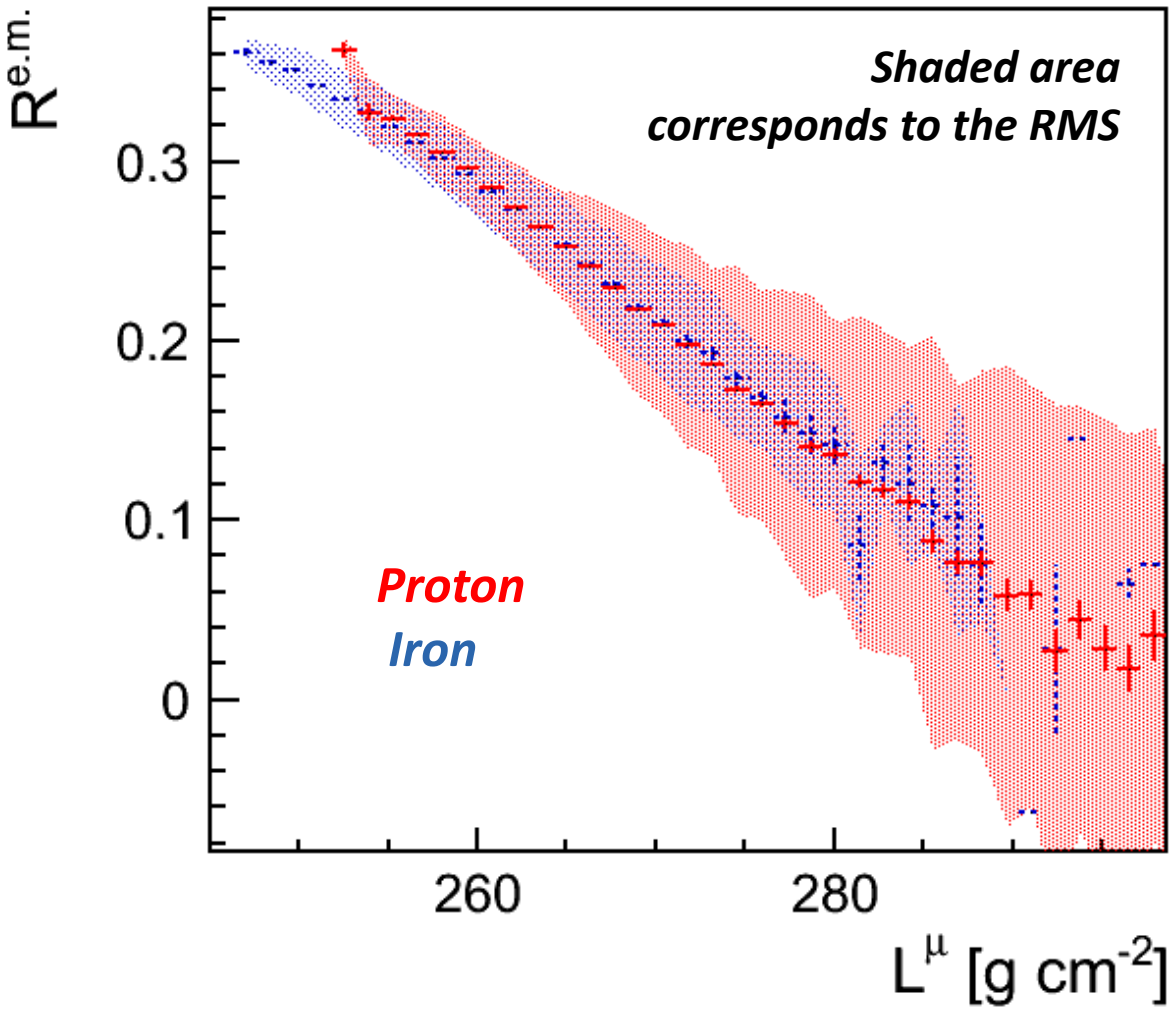
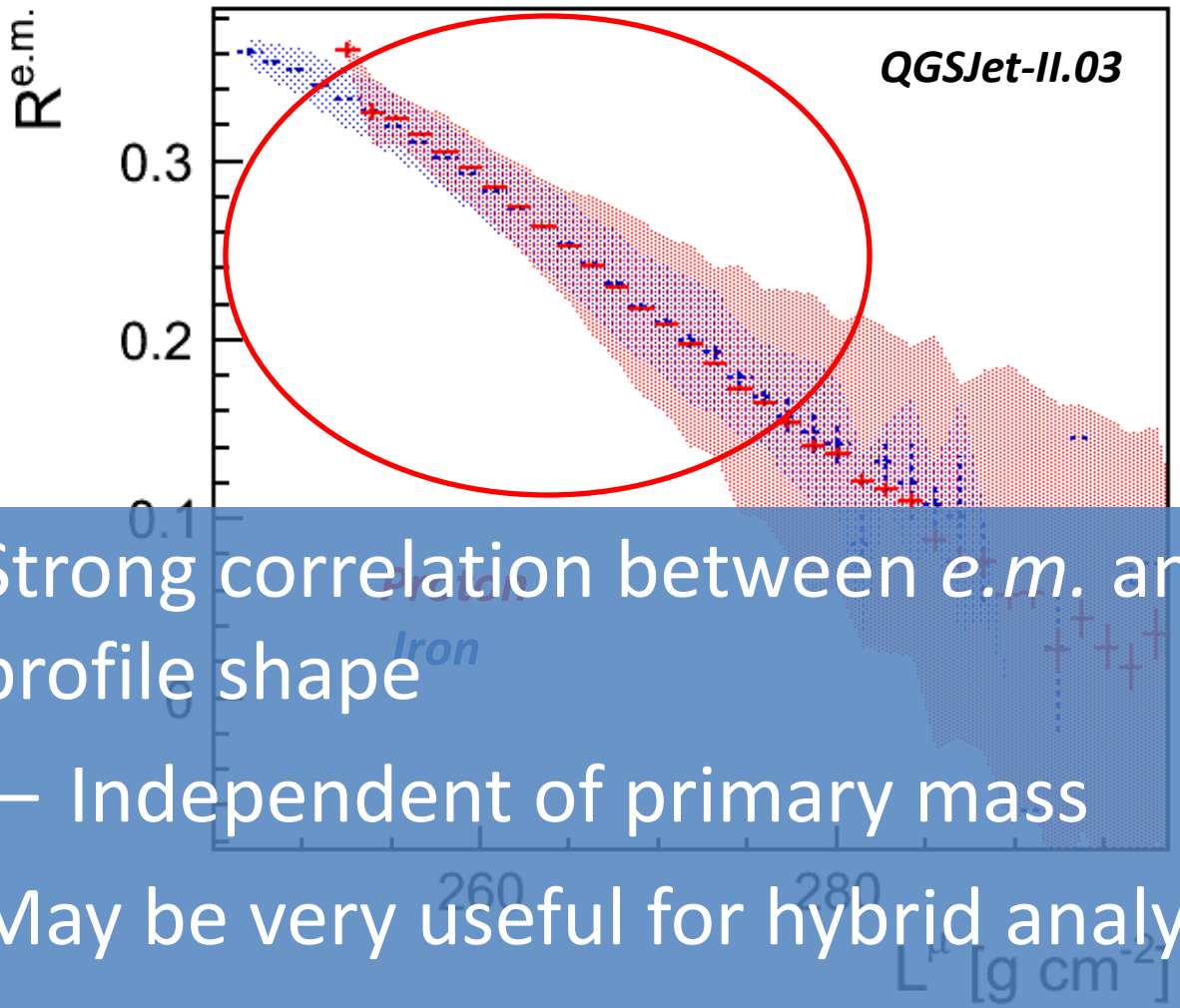


R^{μ} and $L^{e.m.}$ can be fixed enhancing the proton/iron separation

Shape Parameters Correlation



Shape Parameters Correlation



- Strong correlation between *e.m.* and μ profile shape
  - Independent of primary mass
- May be very useful for hybrid analysis

First Conclusions

- MPD profile provides several independent mass composition variables
  - N_{max}, X_{max}, Shape (L^{μ})
- X_{max} and the shape of e.m. and MPD profile correlates
  - Useful for hybrid analysis
  - ($X^{e.m.}_{max} - X^{\mu}_{max}$) is a mass composition variable independent of the primary cross-section
- MPD profile has an universal shape that can be described with a Gaisser-Hillas function

More info in ***Astropart.Phys. 35 (2012) 821-827*** *(arXiv:1111.1424)*

Electromagnetic Longitudinal Profile

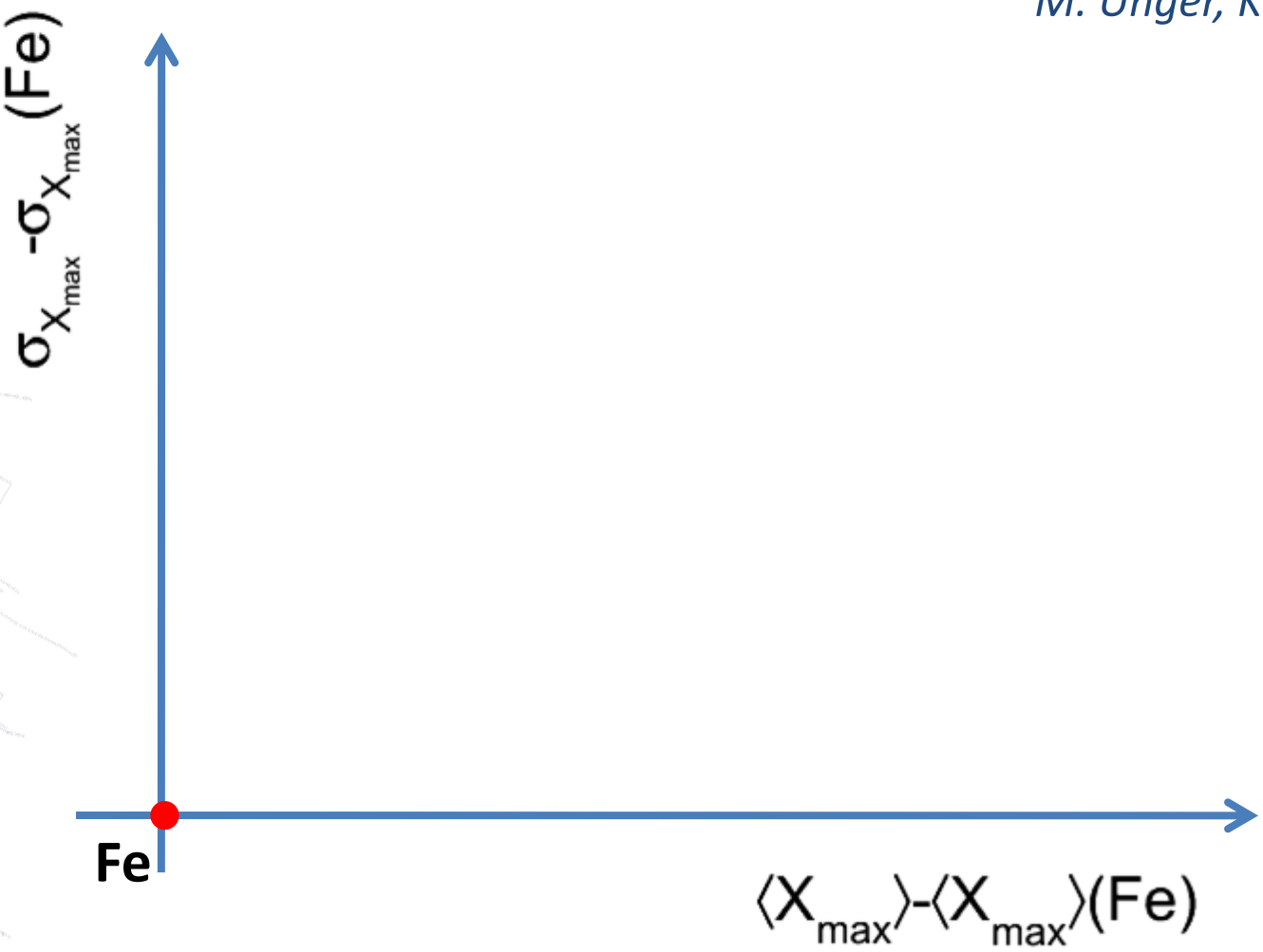
Muonic Longitudinal Profile at Production

WHY IS THIS IMPORTANT?

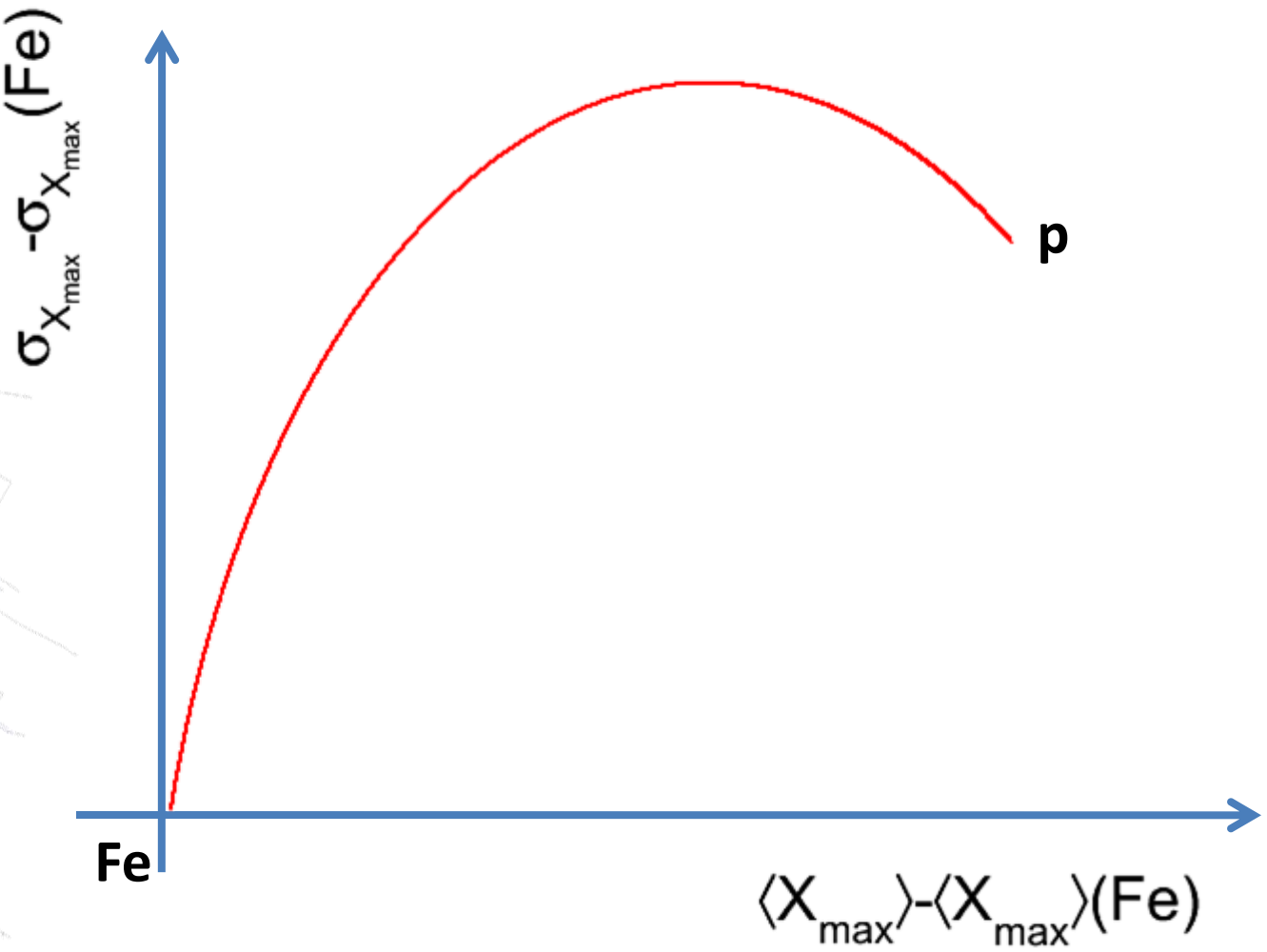
“Umbrella Plots”

J. Linsley

M. Unger, K. H. Kampert



“Umbrella Plots”



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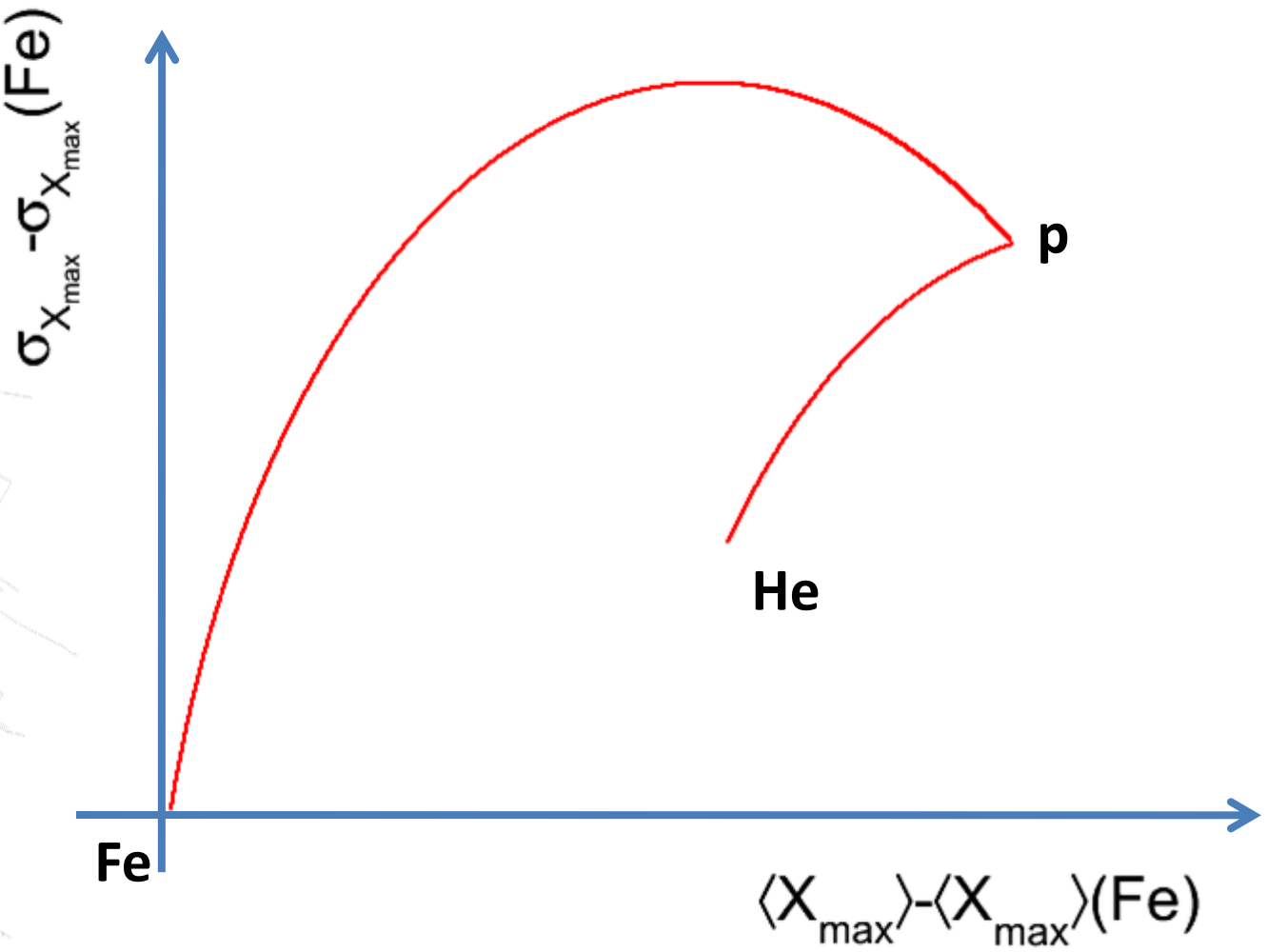

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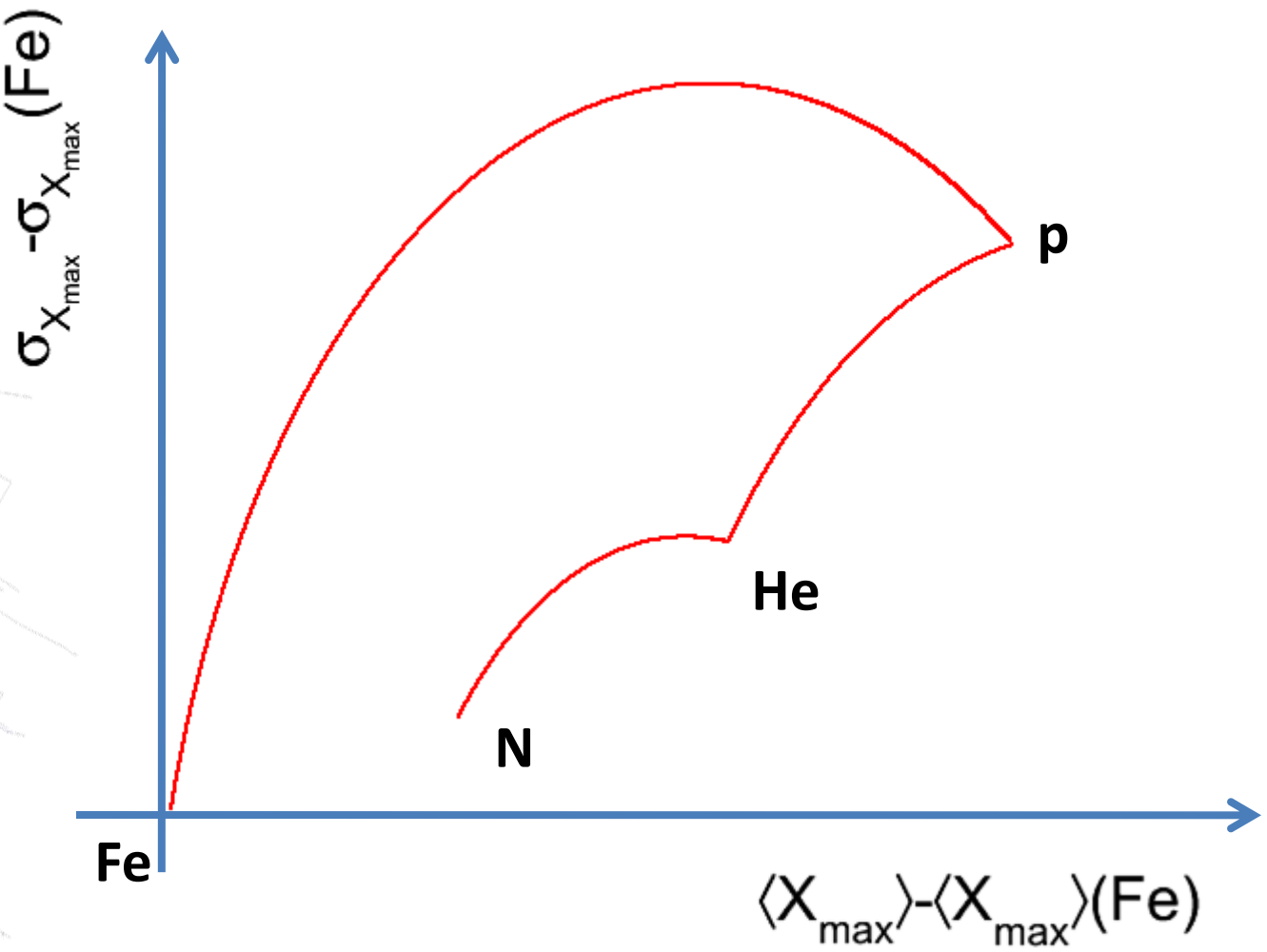

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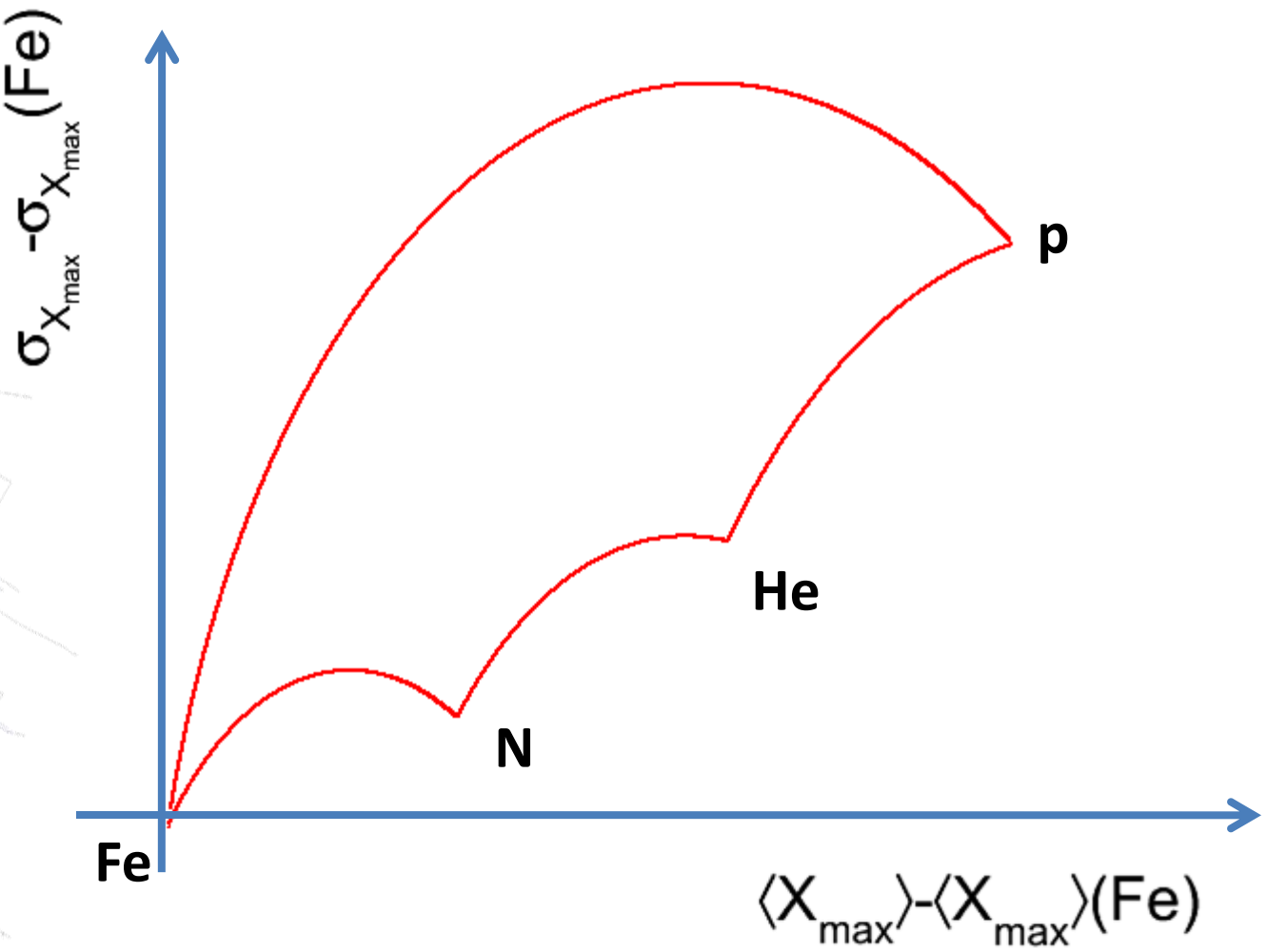

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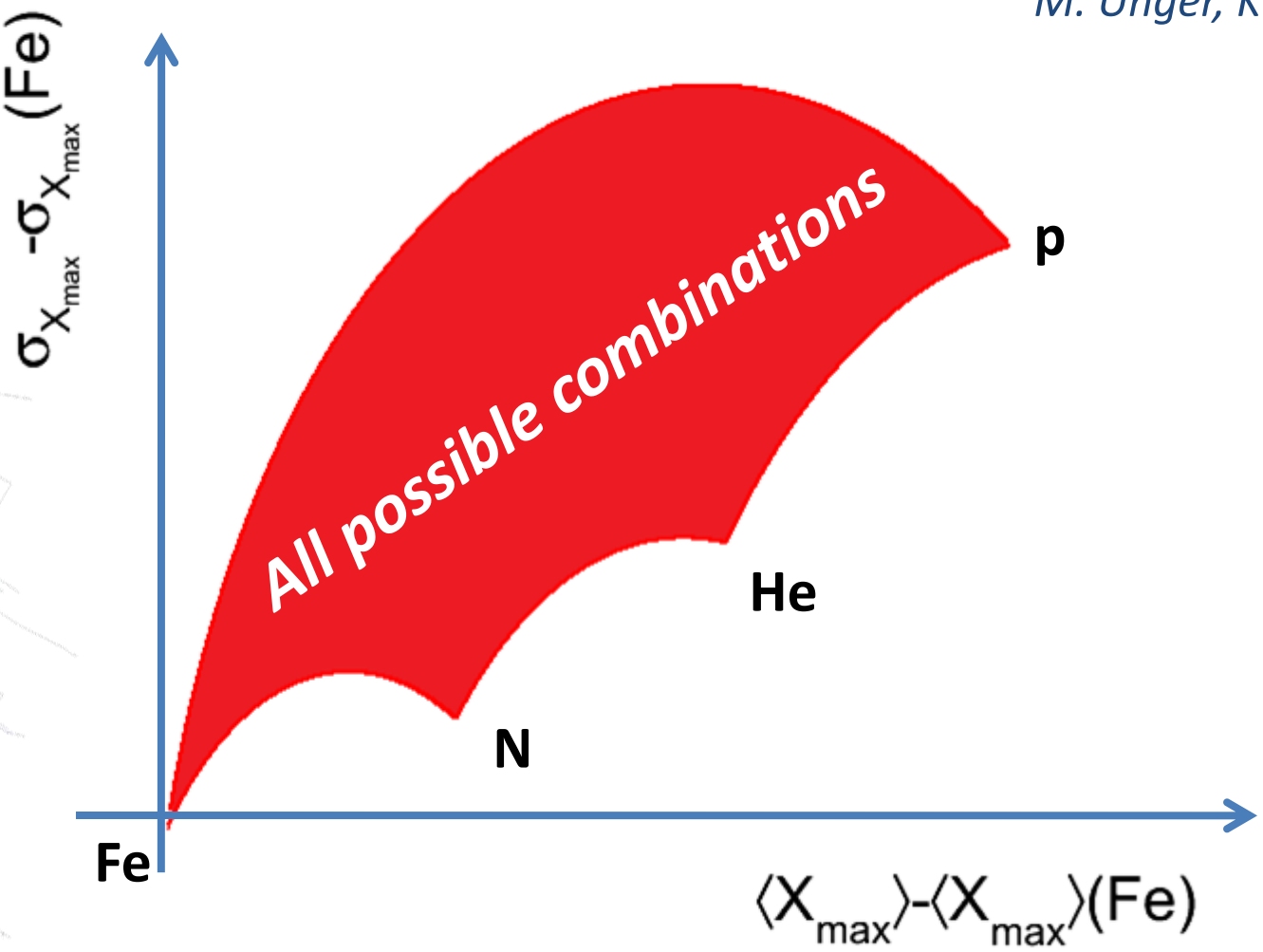
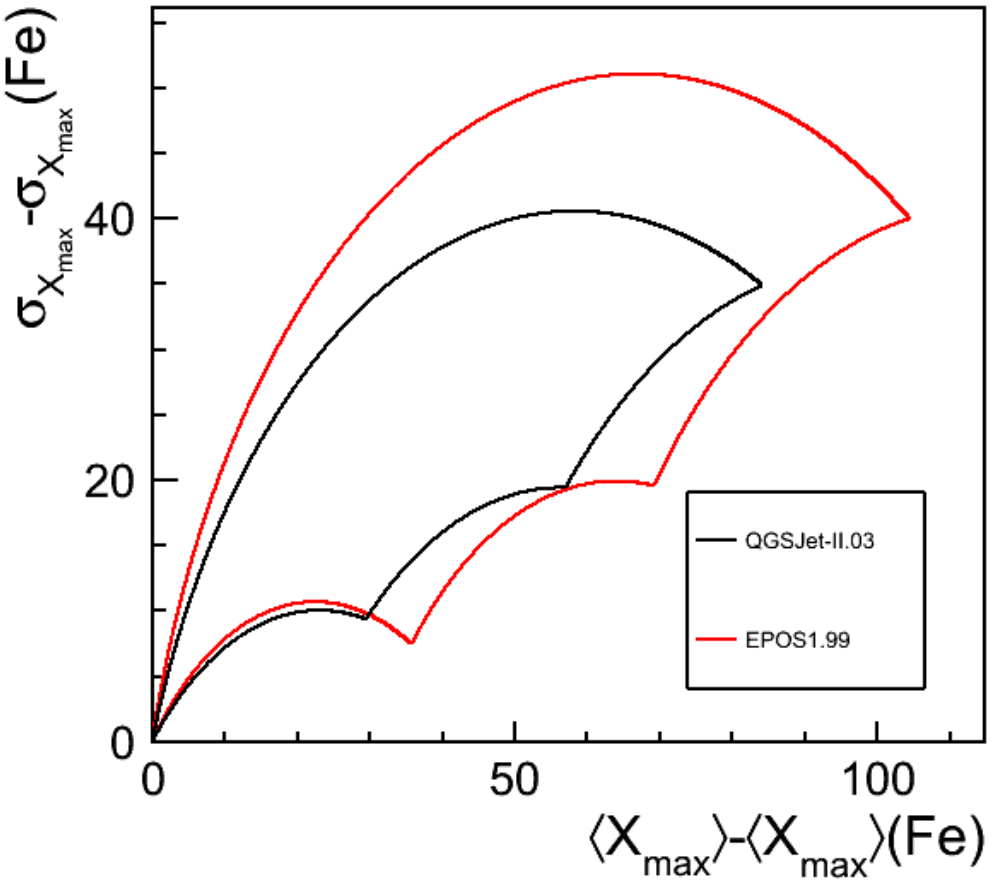
J. Linsley

M. Unger, K. H. Kampert



RMS(X_{max}) vs. X_{max}

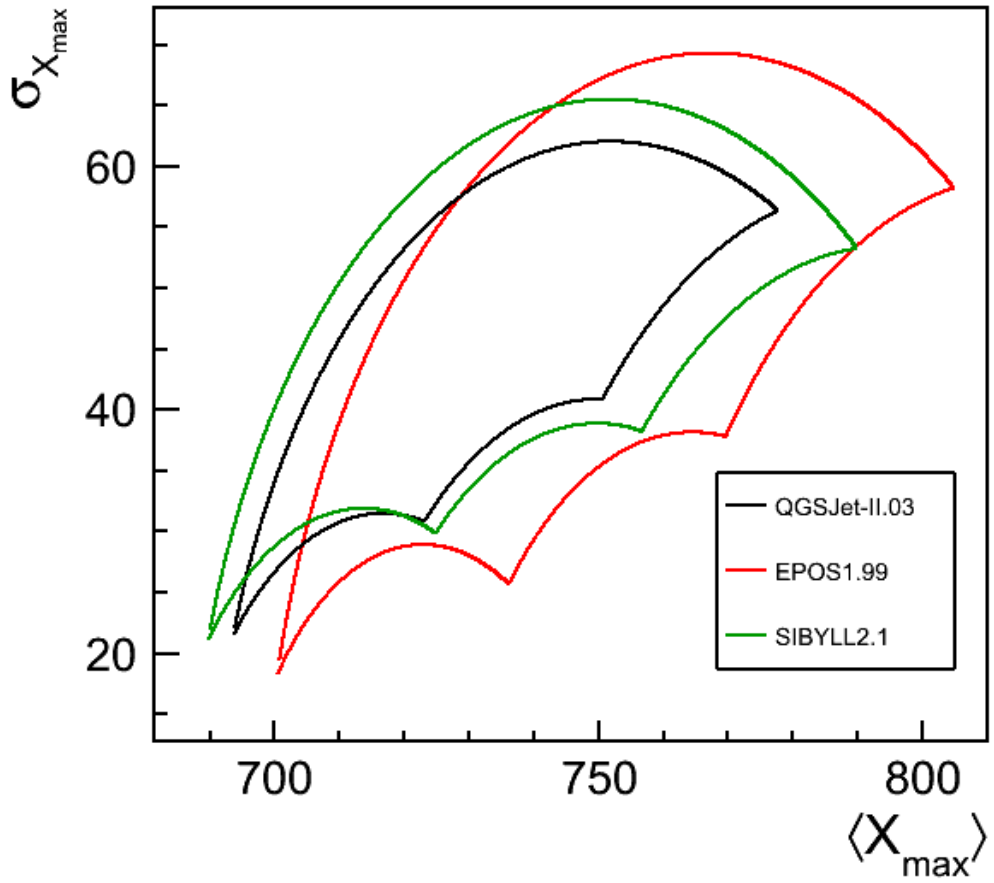
for the electromagnetic profile



- All mass composition scenarios are considered
- Subtraction by Iron momenta to be quasi-independent of the energy evolution

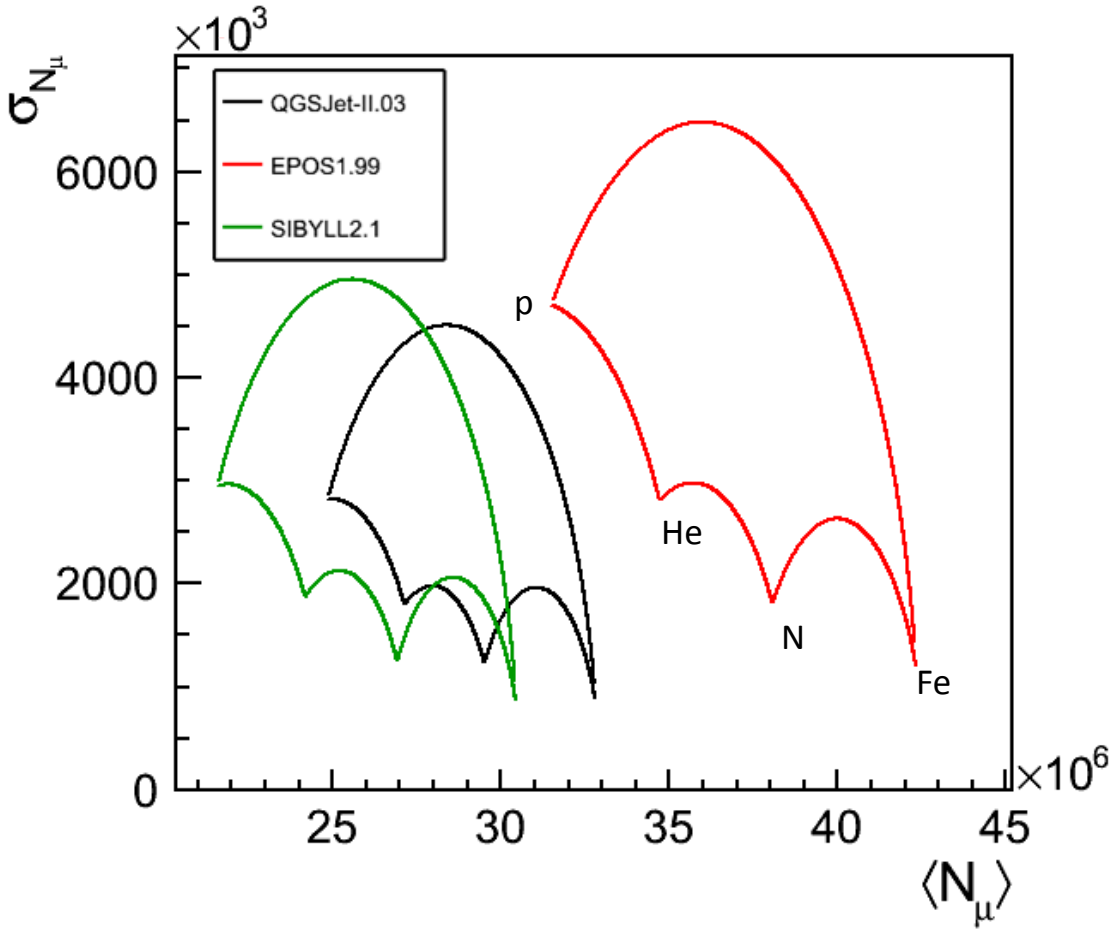
RMS(X_{max}) vs. X_{max}

for the electromagnetic profile



- At fixed energy (E = 10^{19} eV) hadronic interaction models may be distinguished independently of mass composition through the combining the X_{max} momenta

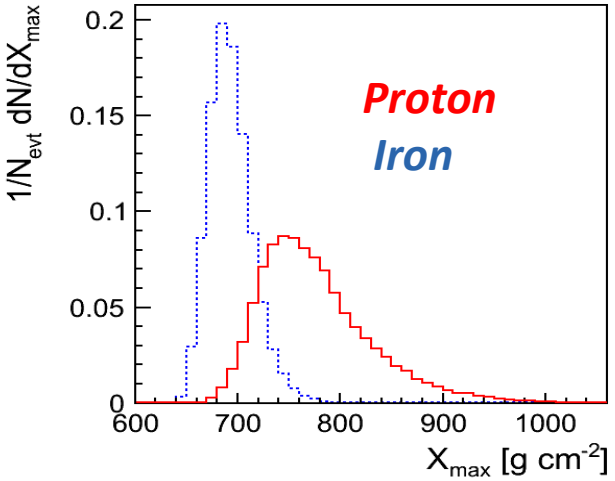
Muons and Hadronic Models

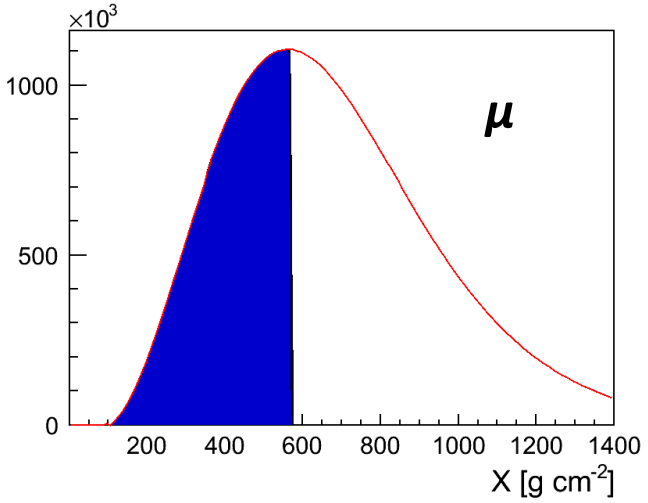


- Average number of muons at ground vs. its fluctuations
- Muons are very sensitive to Hadronic Interaction Models

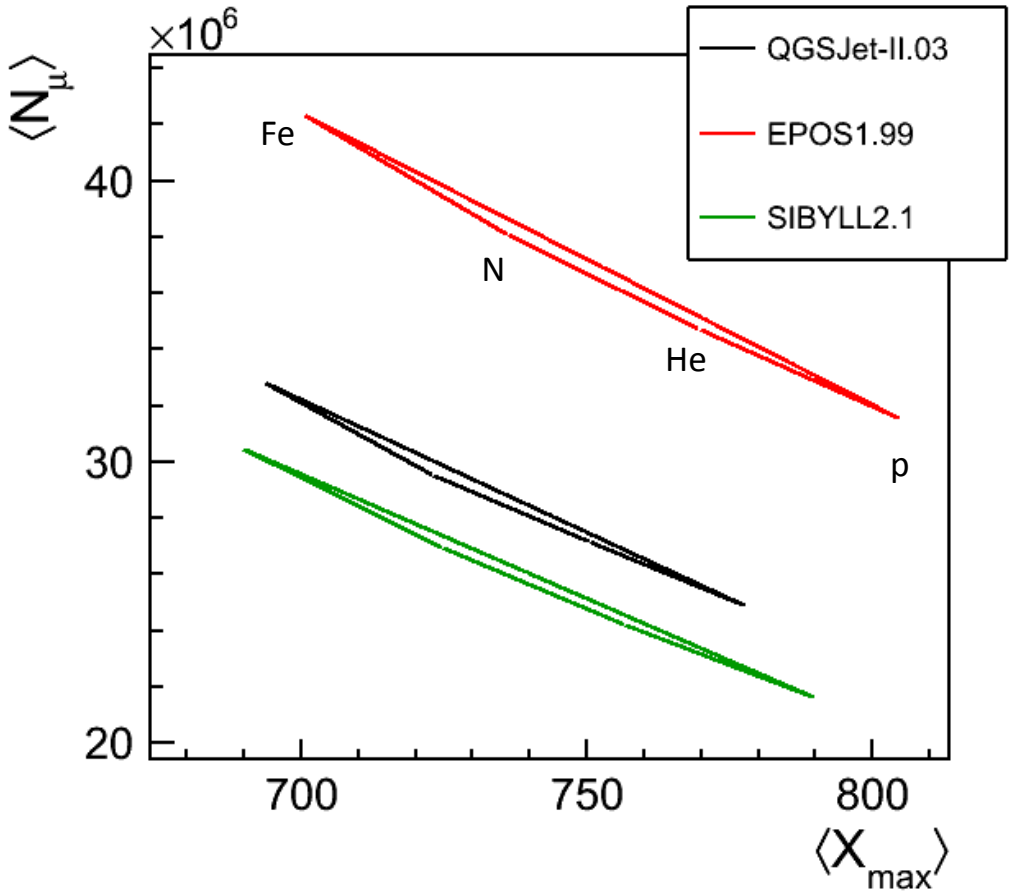
Building a plot…

- Use the average e.m. X_{max}
  - Measured by the Fluorescence Detector
  - Small uncertainties w.r.t. the surface detectors
- Integral of the MPD-total up to its maximum
  - Number of muons produced in the shower
  - Avoid problems with the ground
- Combine information from the hadronic (muonic) and electromagnetic shower components





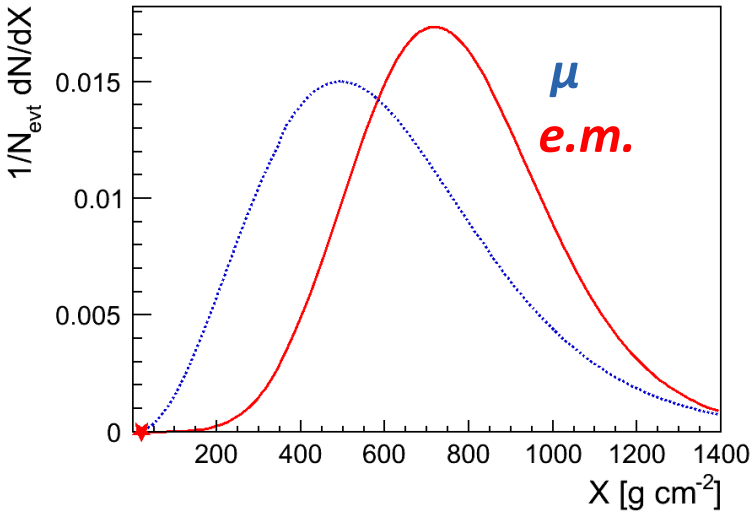
Particle physics with UHECRs



- Hadronic interaction models can be constrained combining the average X_{max} with the average number of muons

Conclusions

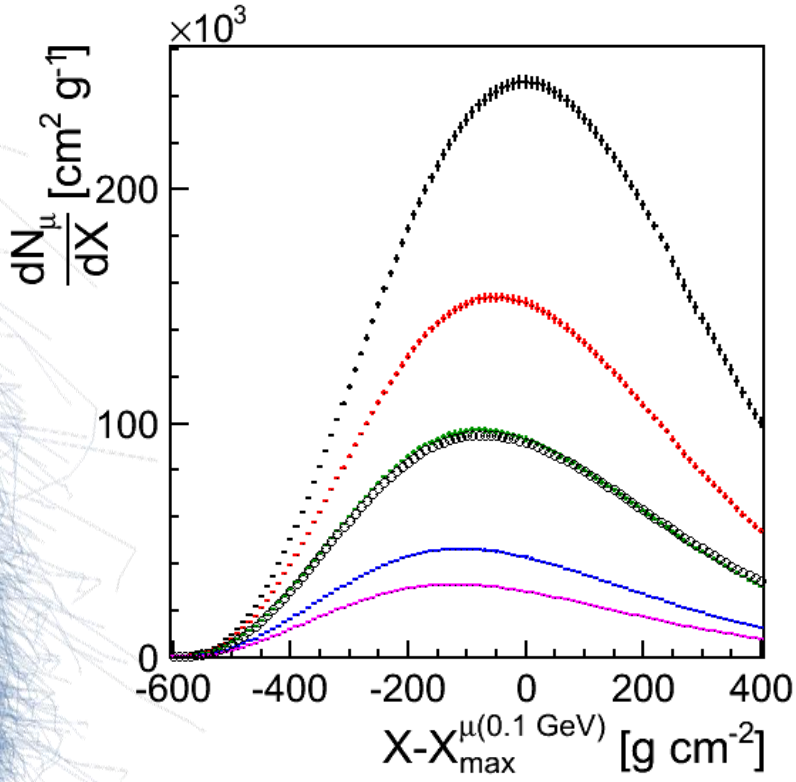
- MPD profile has as many variables for composition as the electromagnetic profile
- Advantages of combining the e.m. with the muonic profile:
  - Constrain shower physics mechanism
  - Improve hybrid analyses
- With a more complete insight of the shower and through Multivariate Analysis we might be able to do particle physics with UHECRs

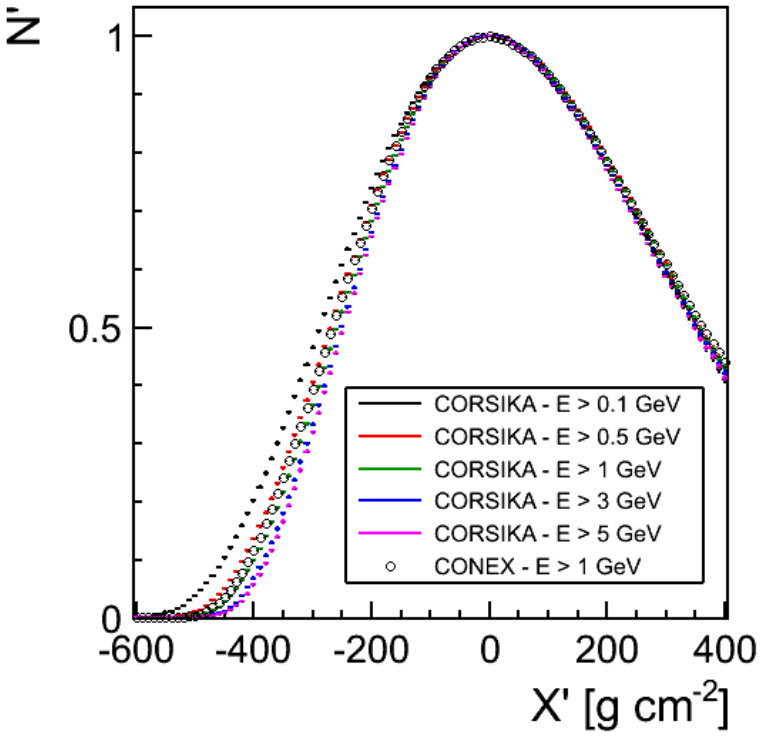


END

BACKUP SLIDES

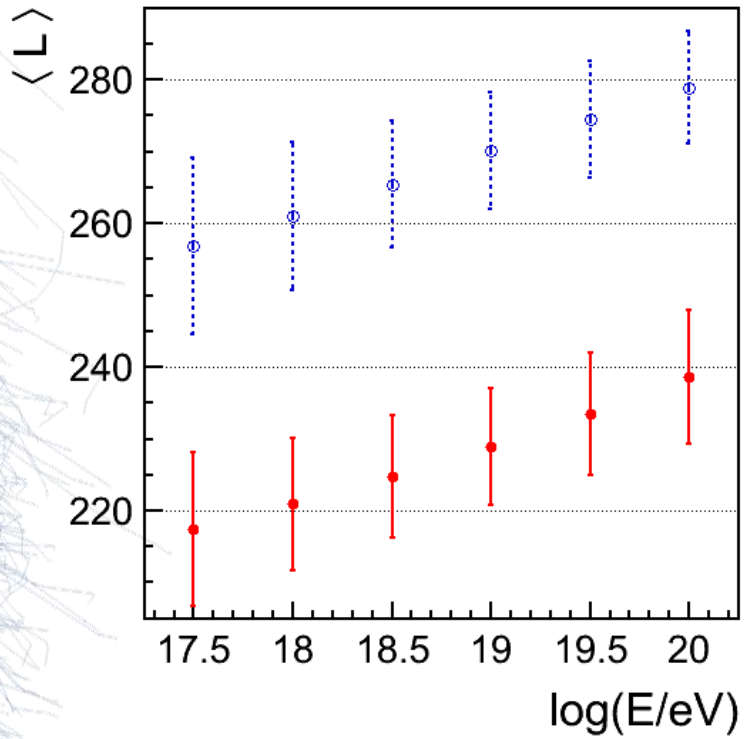
MPD Energy cutoff dependence

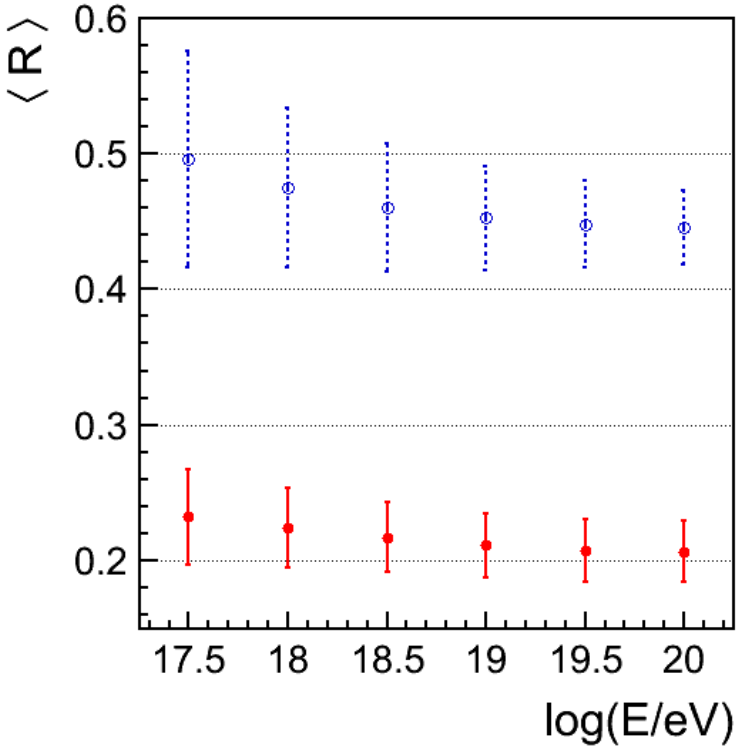




- The muon production profile depends on the muons energy cutoff:
  - Normalization, X_{max} and even the shape
  - Sensitivity to the muon energy spectrum

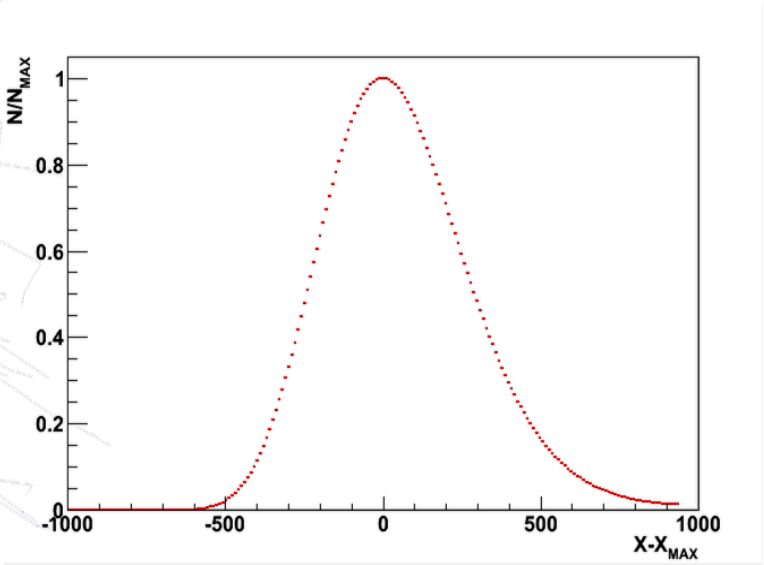
L and R energy dependence



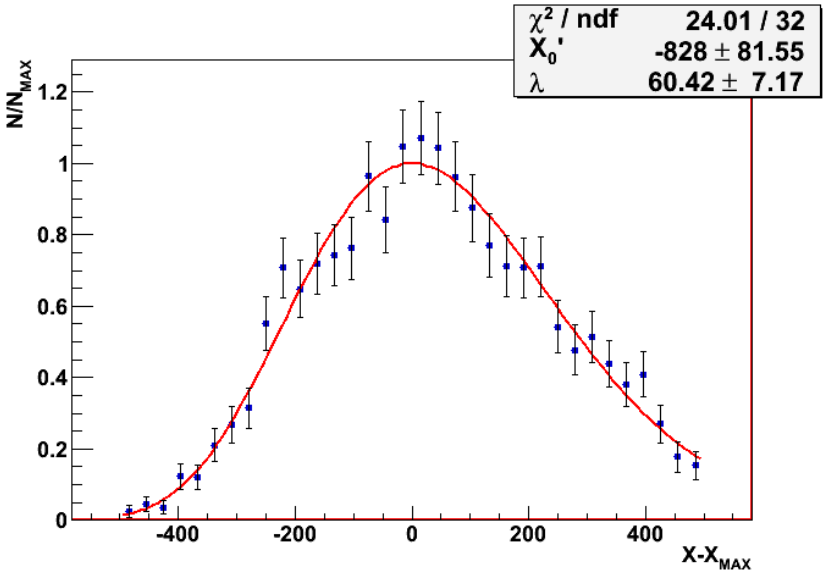


Gaisser-Hillas shape parameters

Ideal longitudinal profile

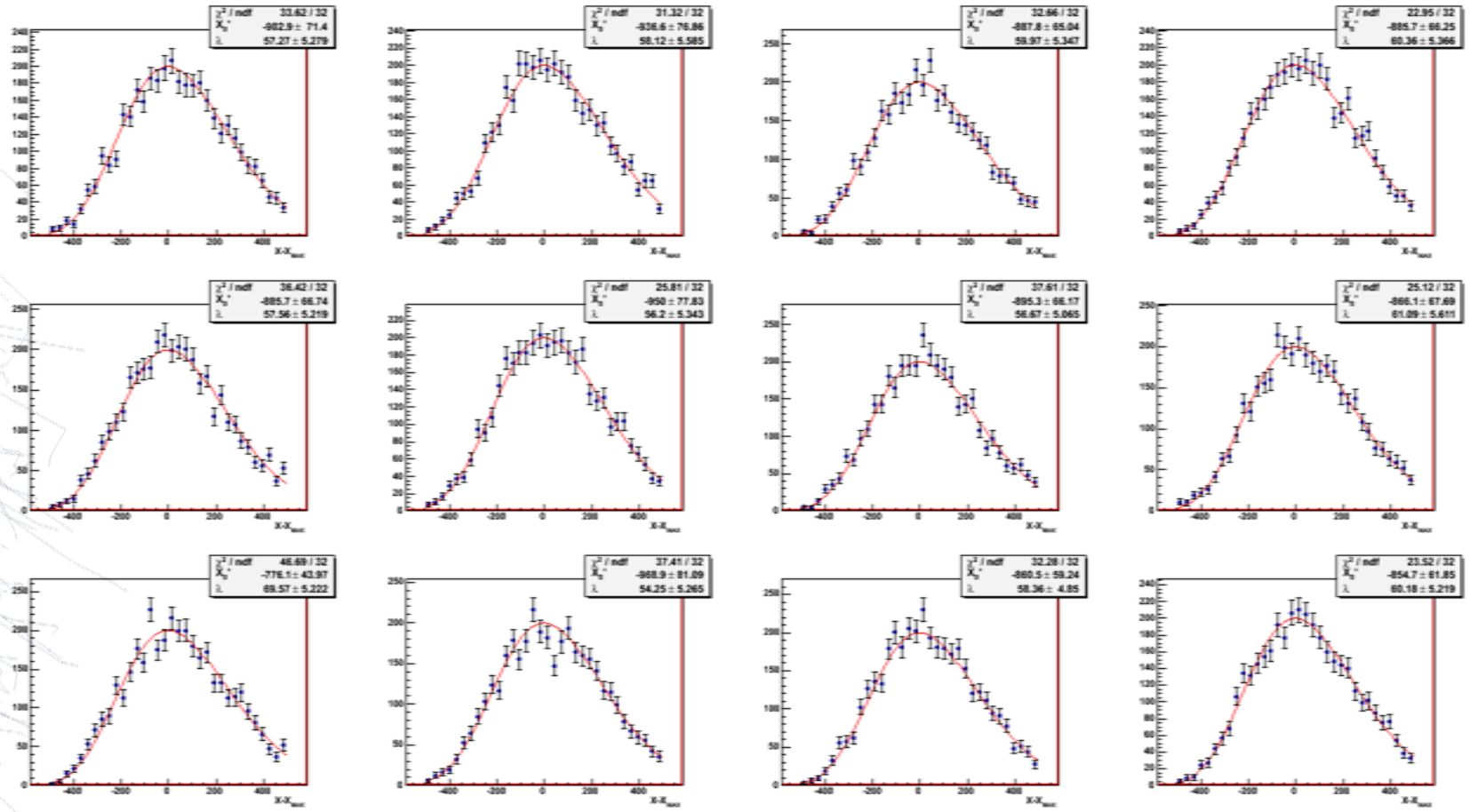


"Real" profile
(N_{max}=200 photons)



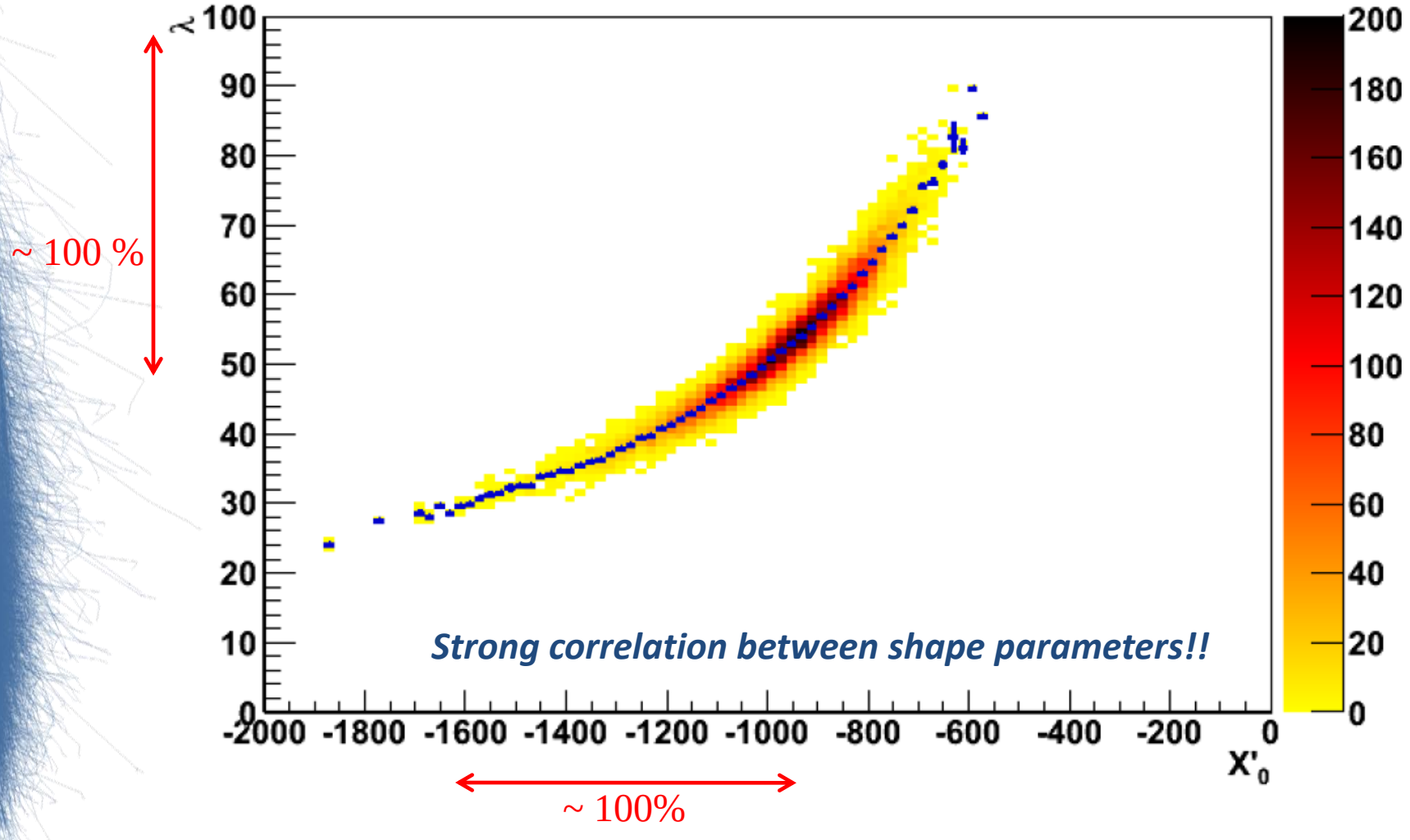
Fit using a Gaisser-Hillas function (λ,X_0')

Gaisser-Hillas shape parameters

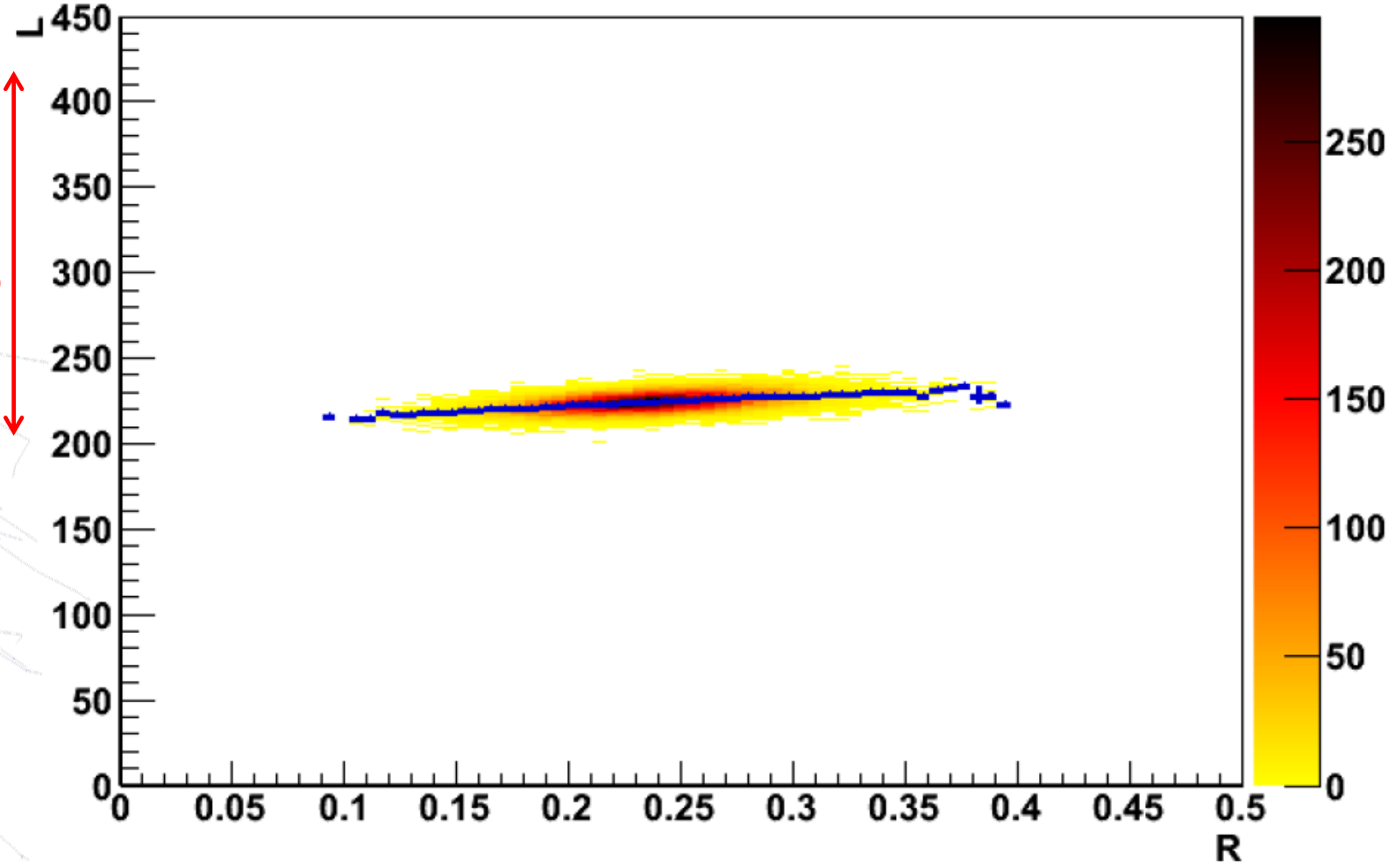


Check the resulting shape parameters (λ, X_0')

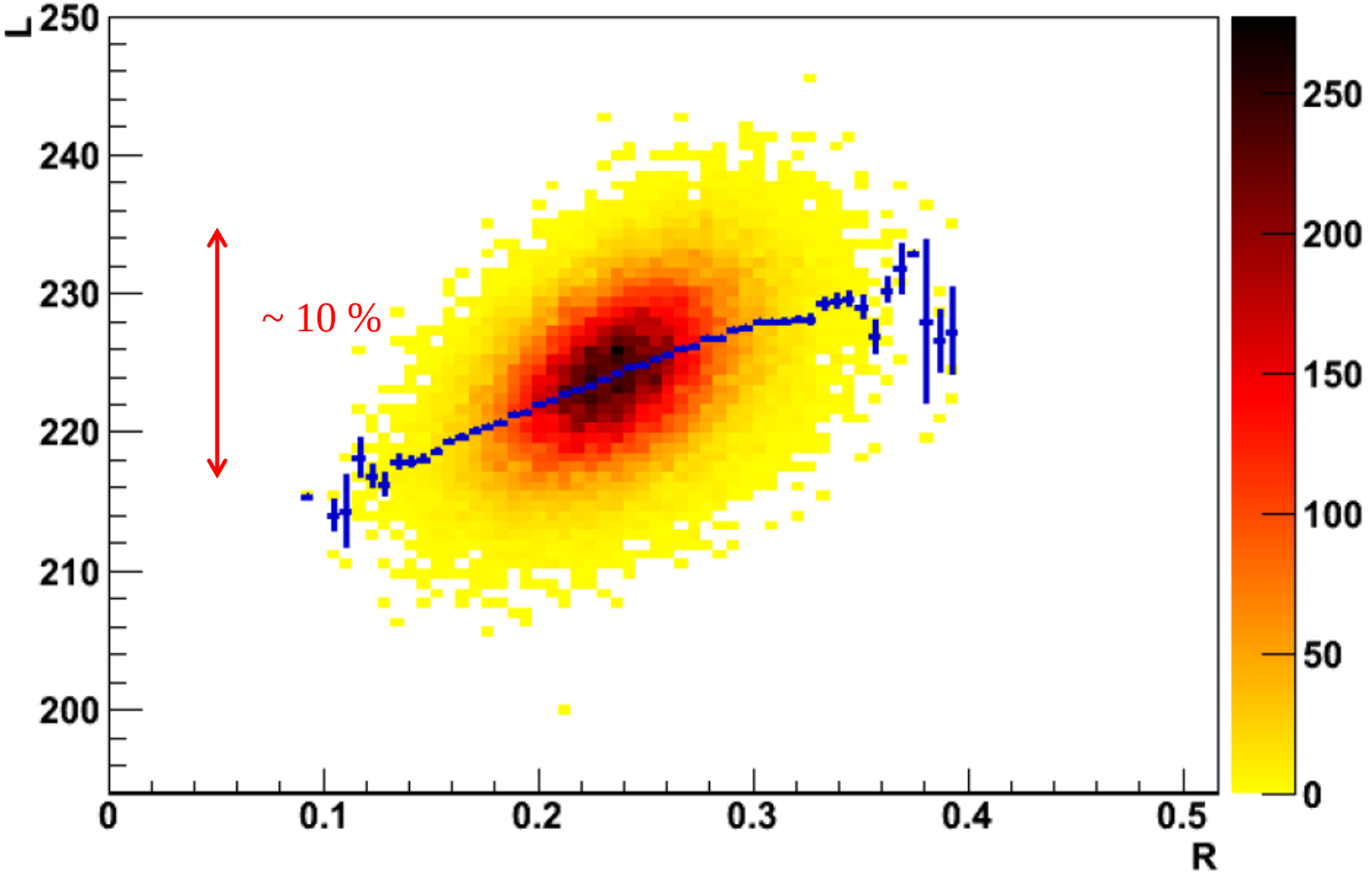
Correlation between X_0' and λ



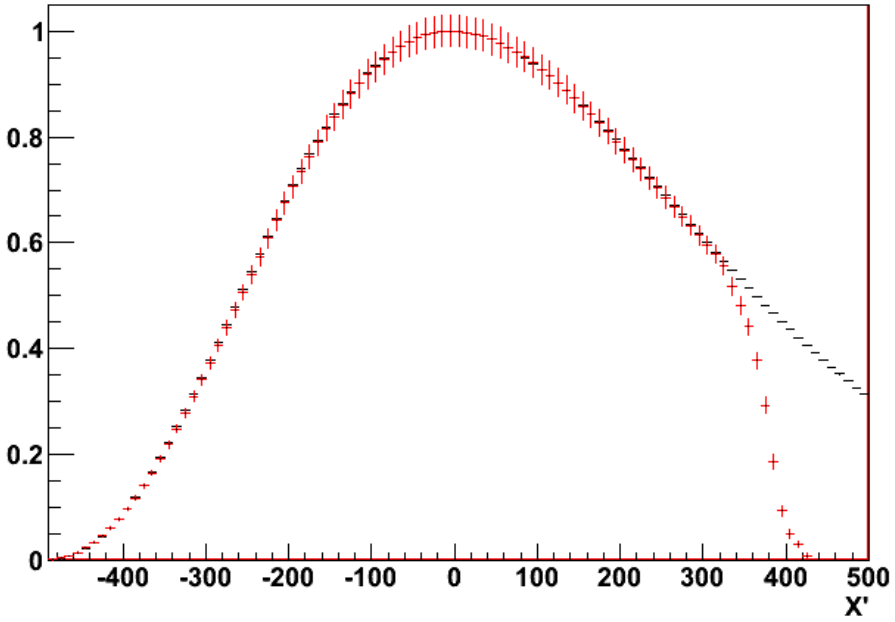
Correlation between L and R



Correlation between L and R

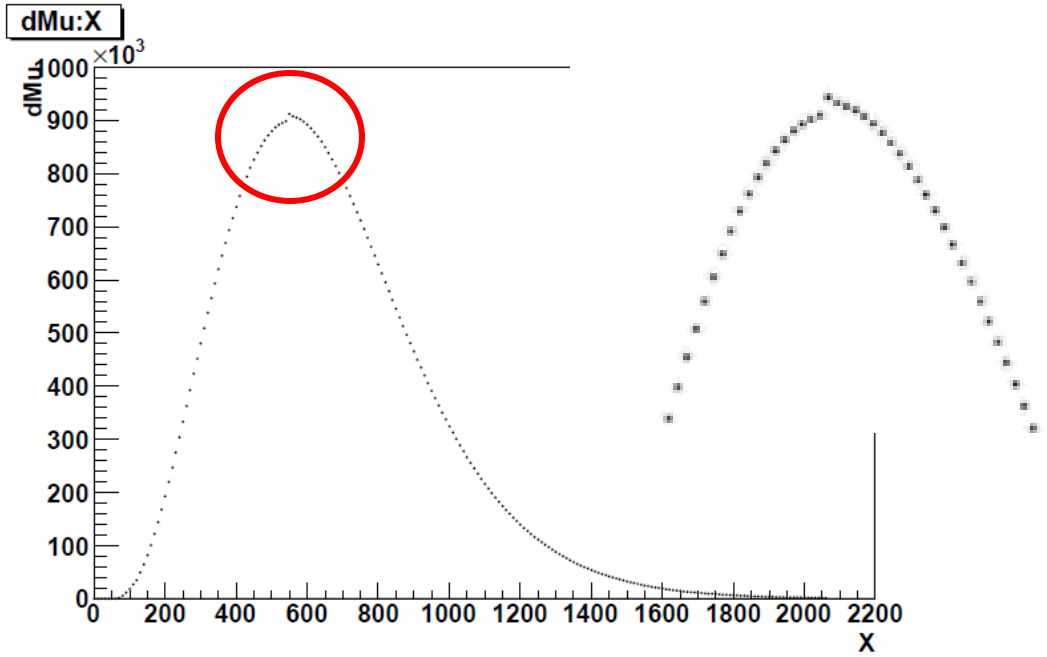


Conex vs. Corsika



- Longitudingal distribution (1D) => CONEX
- Cross-check with CORSIKA for:
  - Xmax
  - Number of muons at the ground
  - Shape of the profile
- Compatible up to $\theta = 60°$

Conex vs. Corsika



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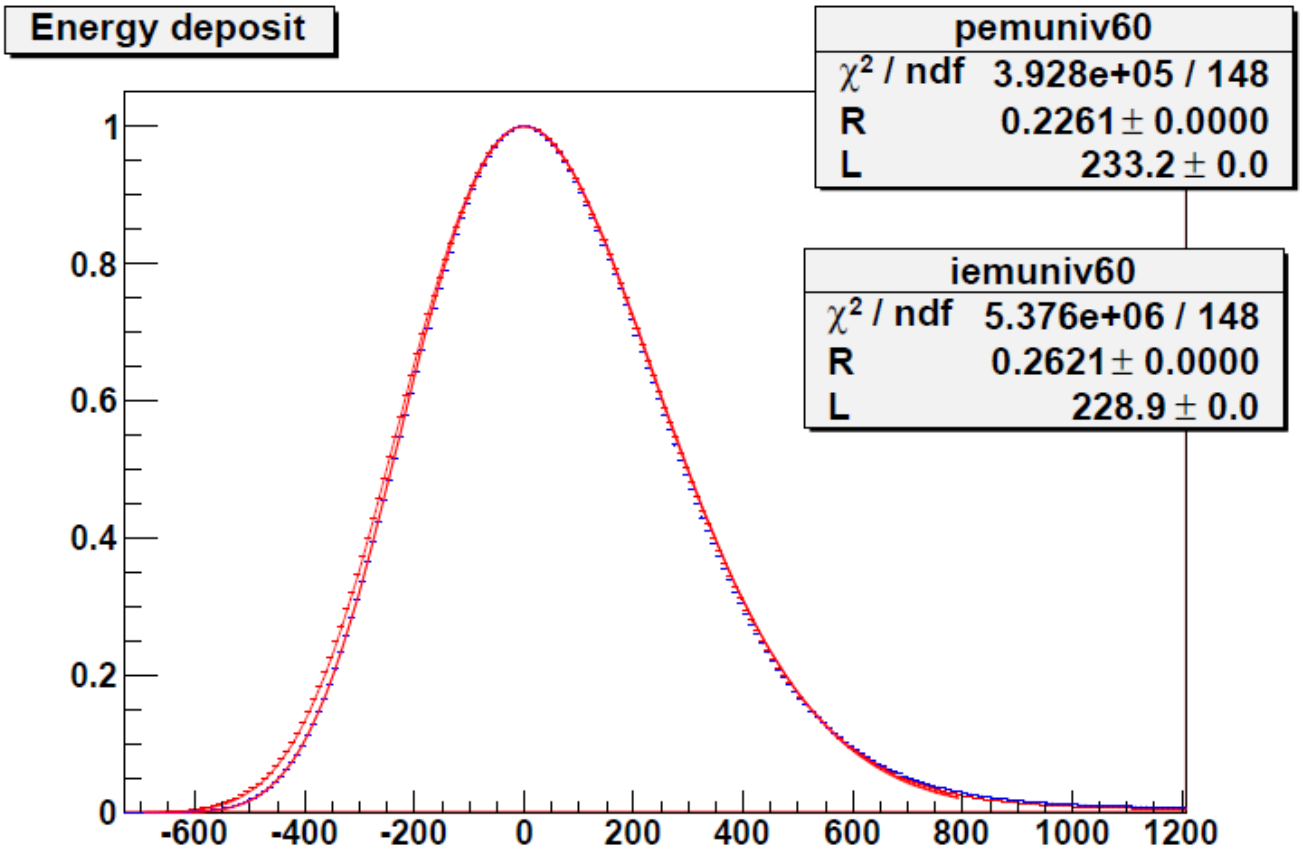
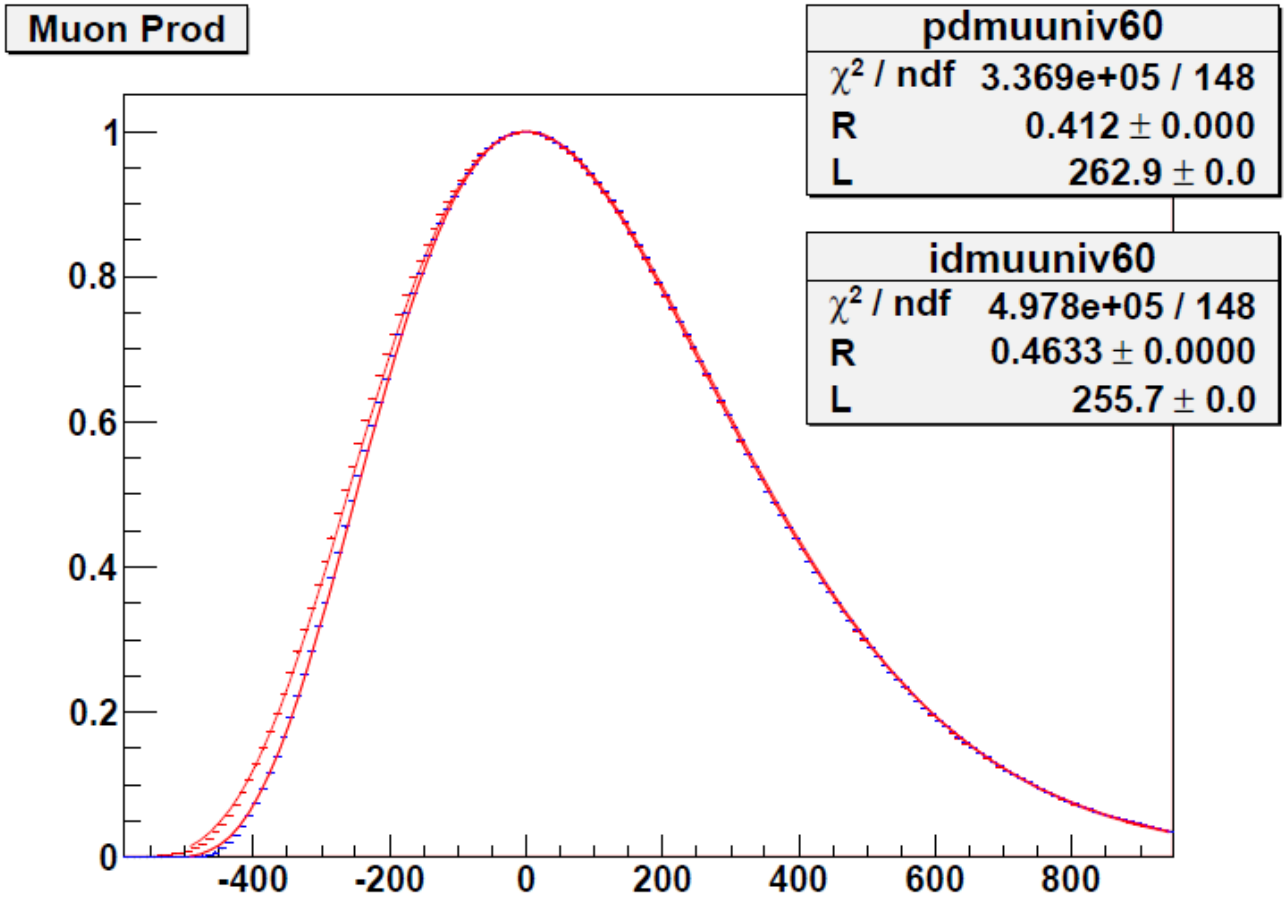
Fit Gaisser-Hillas (e.m.)



Proton / Iron

Fit Gaisser-Hillas (muons)



Proton / Iron