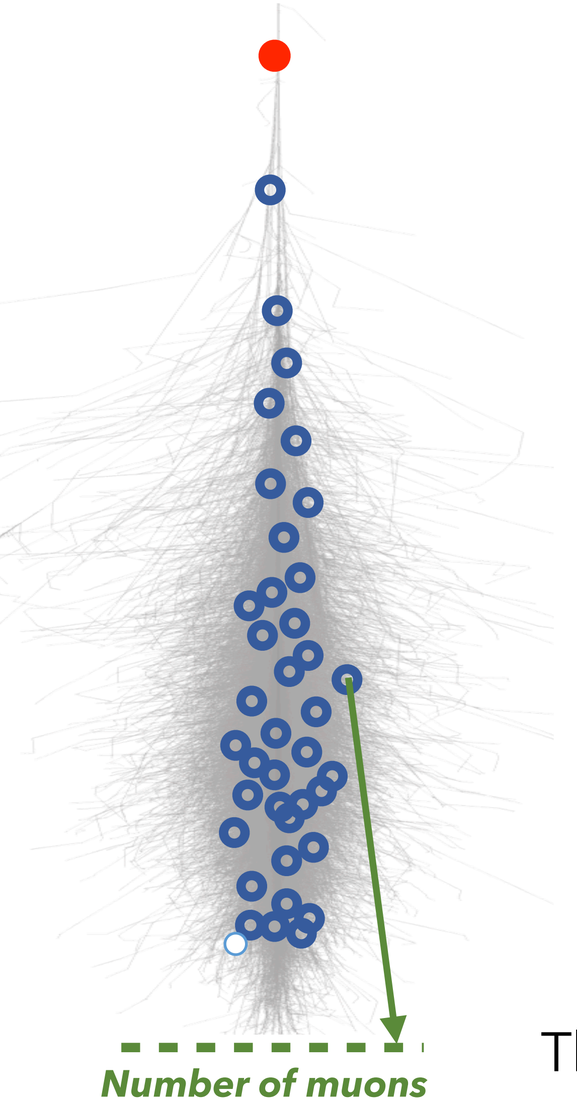
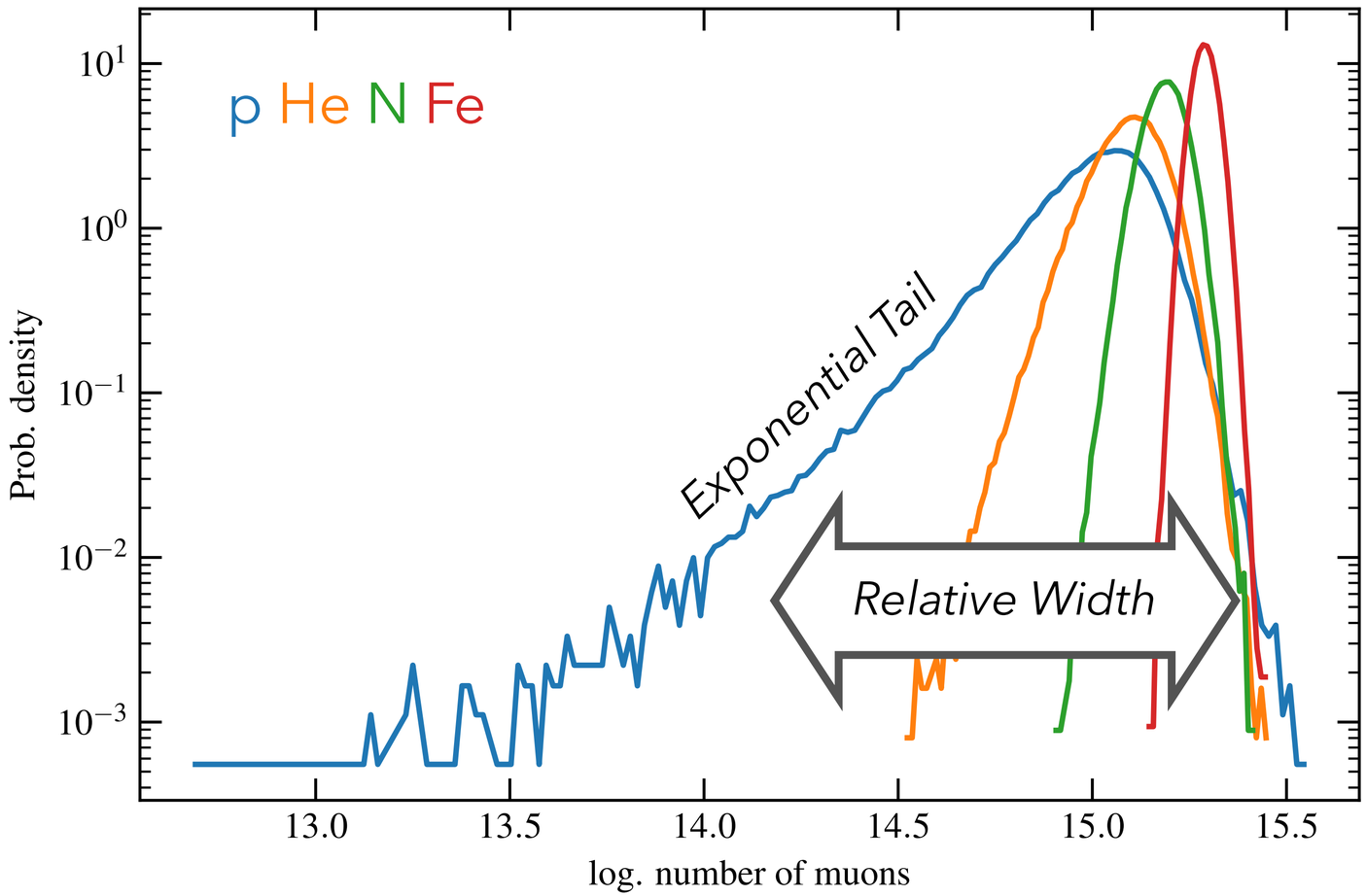
Probing the high-energy spectrum of neutral pions in ultra-high-energy proton-air interaction

Lorenzo Cazon, Ruben Conceição, Felix Riehn, Miguel Martins

36th ICRC, Madison, July 31st 2019

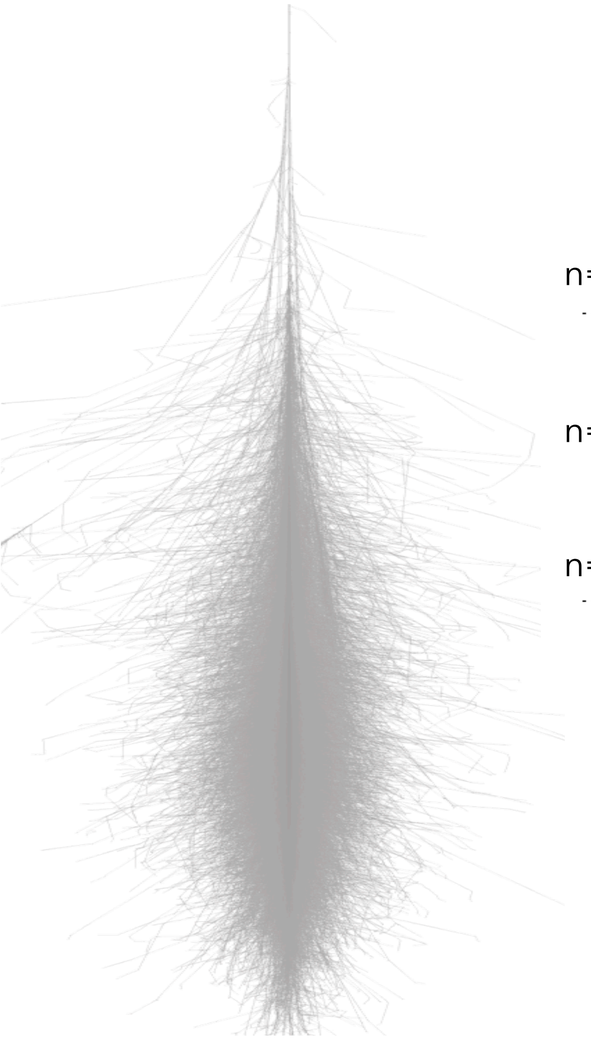
Conclusion



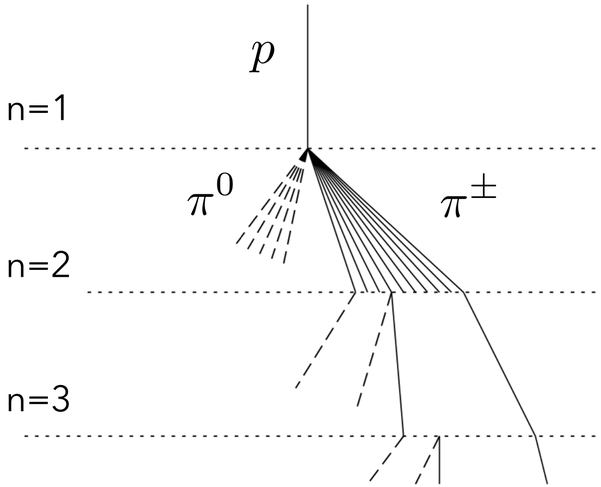


The shape of the muon number distribution gives access to the properties of the **FIRST hadronic interaction**

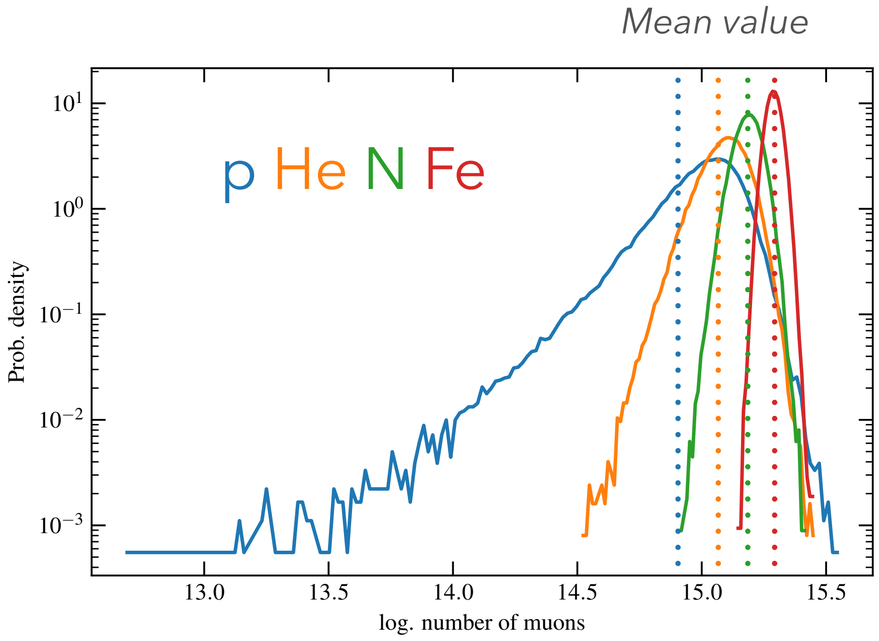
Origin of the fluctuations of the muon number distribution



Heitler-Matthews model

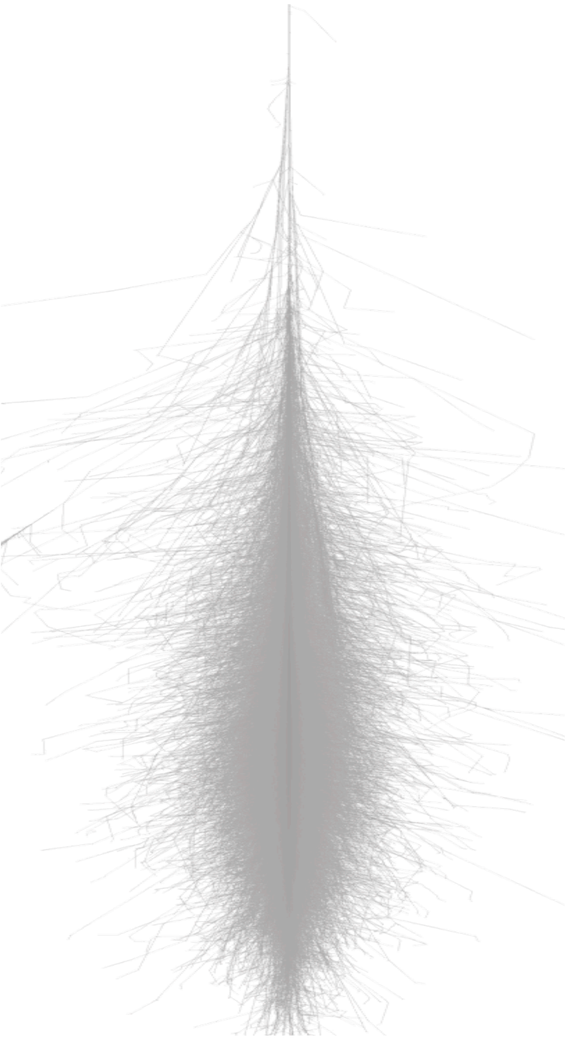


$$\langle N_\mu \rangle \sim E^\beta$$



How to explain the higher moments of the N_μ distribution?

Origin of the fluctuations of the muon number distribution



Heitler-Matthews model

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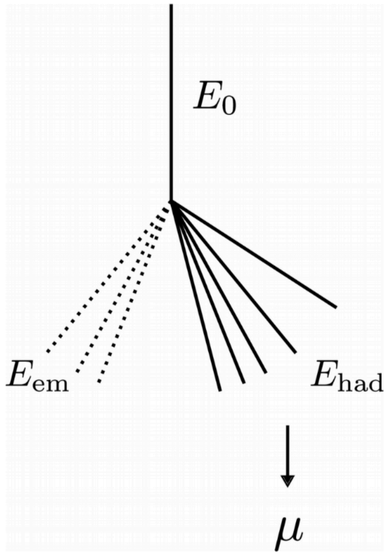
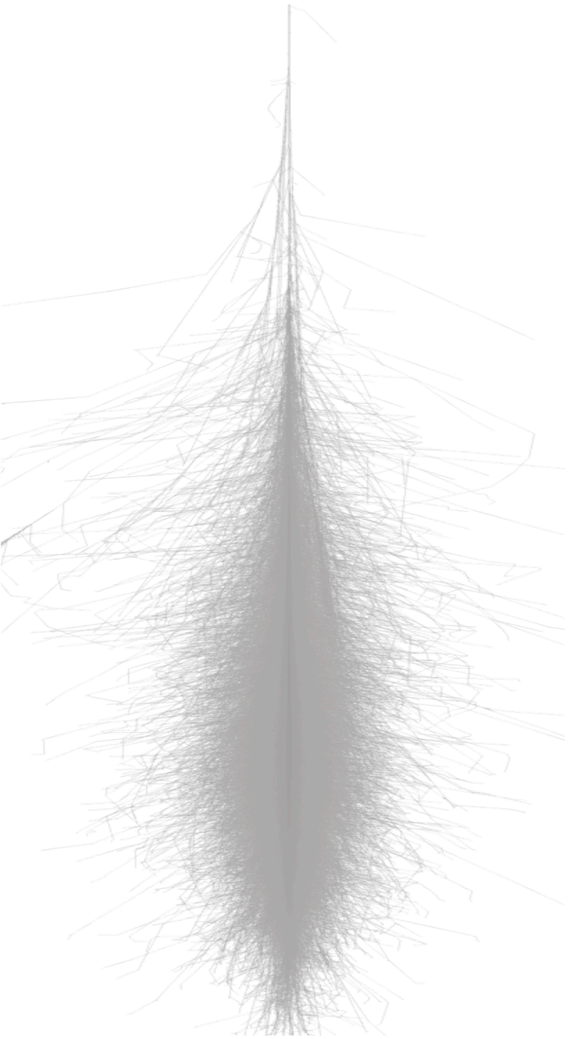
New model



$$N_\mu \sim E_{\mathrm{had}}$$

Origin of the fluctuations of the muon number distribution



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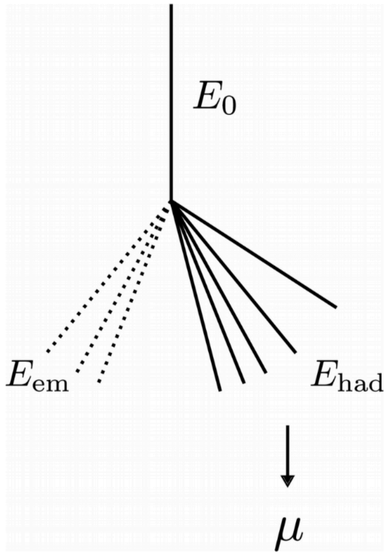

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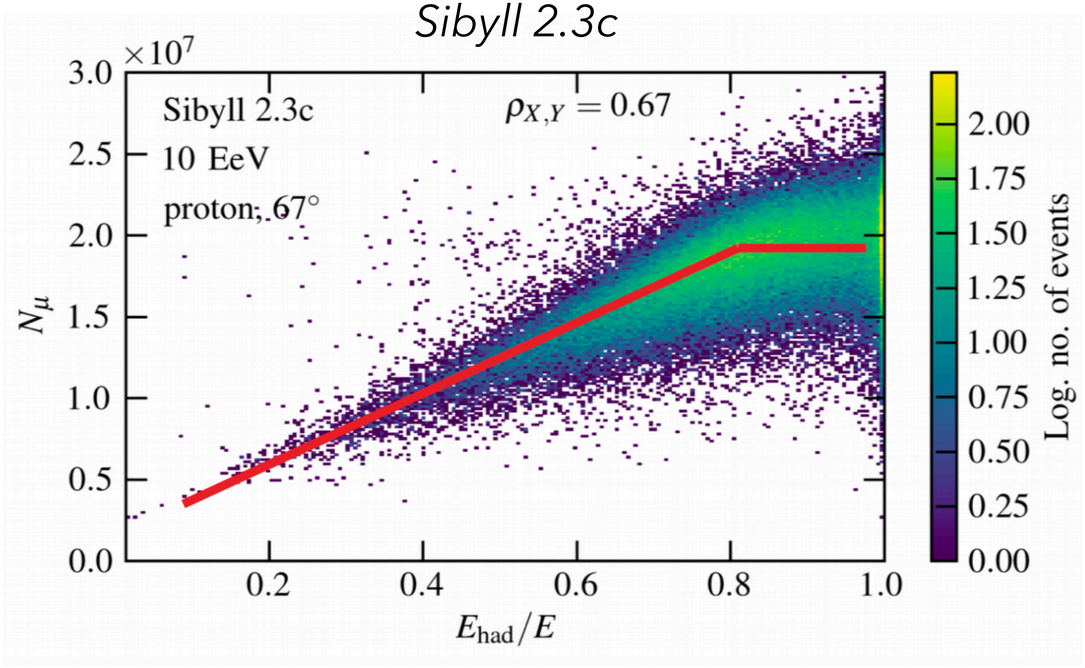
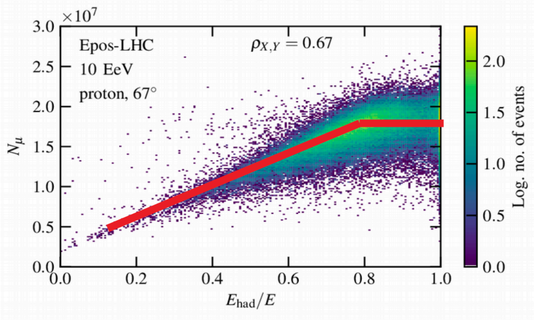
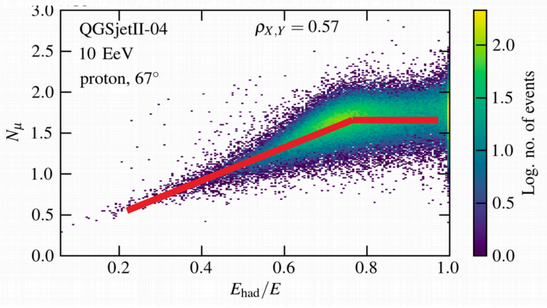
Sibyll 2.3c



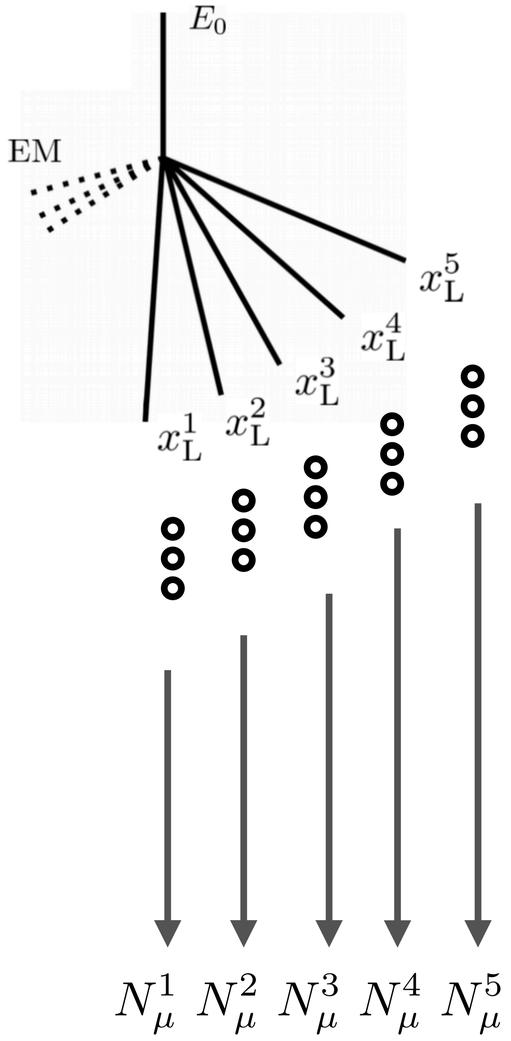
EPOS-LHC



QGSJet-II.04



Origin of the fluctuations of the muon number distribution



New model

$$x_L^i = E_i / E_0 \qquad E_{had} = E_0 \sum_i x_L^i$$

Since

$$N_\mu = \sum_i N_\mu^i \approx \sum_i \langle N_\mu(E_i) \rangle$$

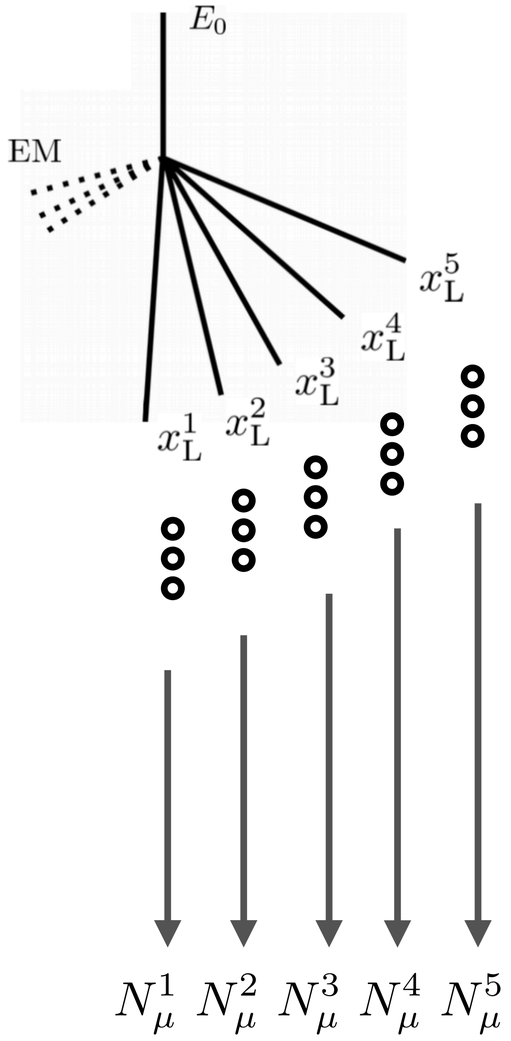
And

$$\langle N_\mu \rangle \sim E^\beta$$

Then

$$N_\mu = a \sum_i (x_L^i)^\beta = a\,\alpha_1$$

Origin of the fluctuations of the muon number distribution



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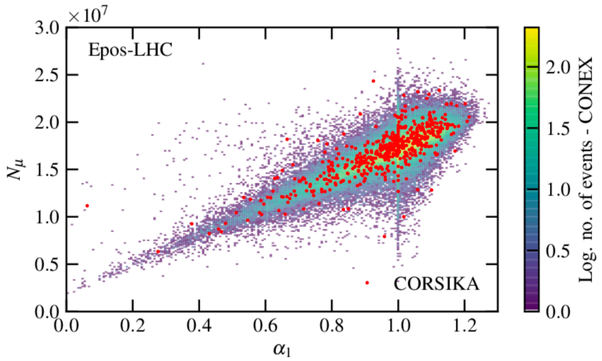
$$\alpha_1 \equiv \sum_i^{m_{had}} (x_L^i)^\beta$$



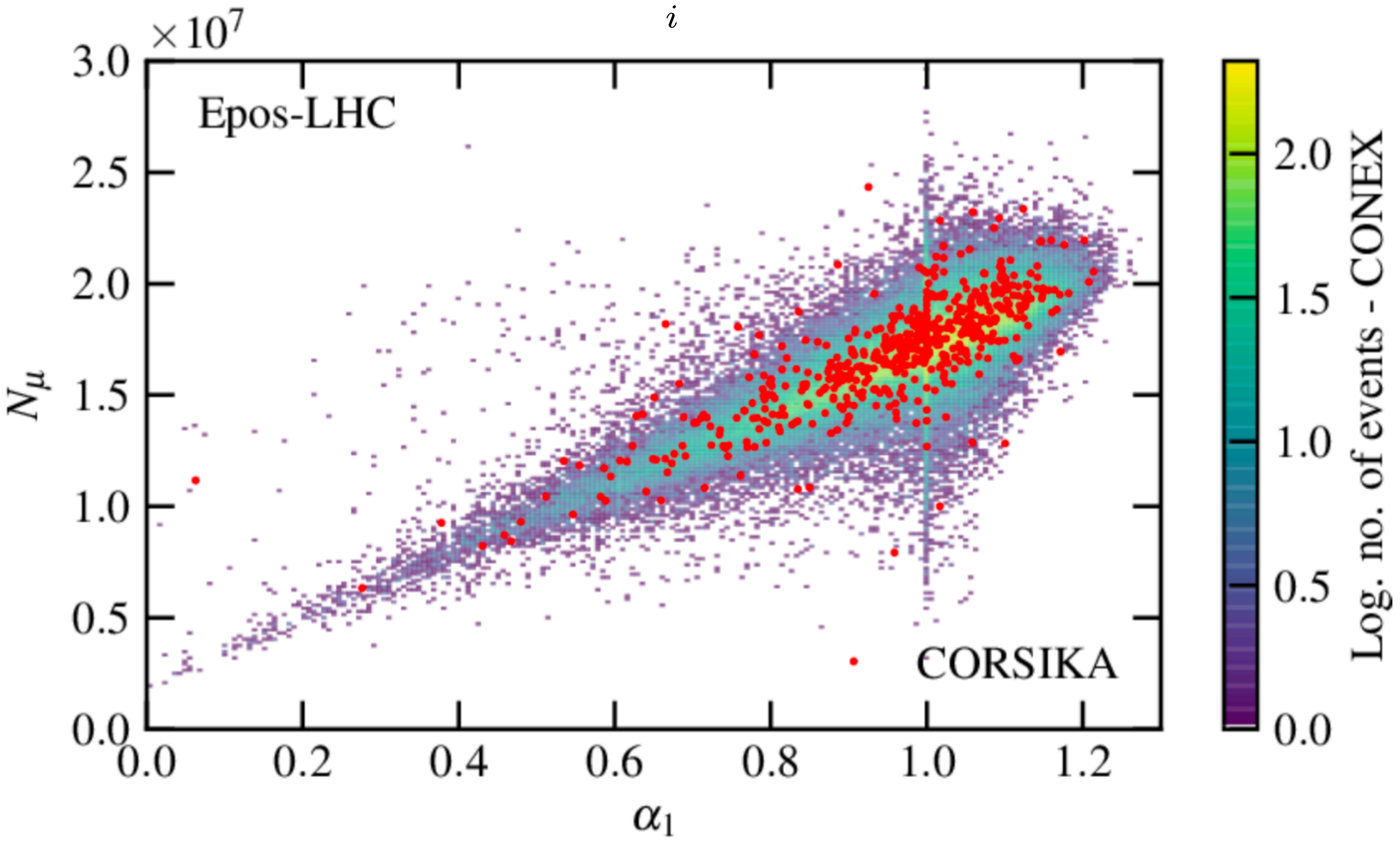
$$\sigma(\alpha) \to 70\%\,\sigma(N_\mu)$$

β is a parameter related with the first Interaction multiplicity

Origin of the fluctuations of the muon number distribution

$$\alpha_1 \equiv \sum_i^{m_{had}} (x_L^i)^\beta$$

L. Cazon, RC, F. Riehn, PLB 784 (2018) 68-76

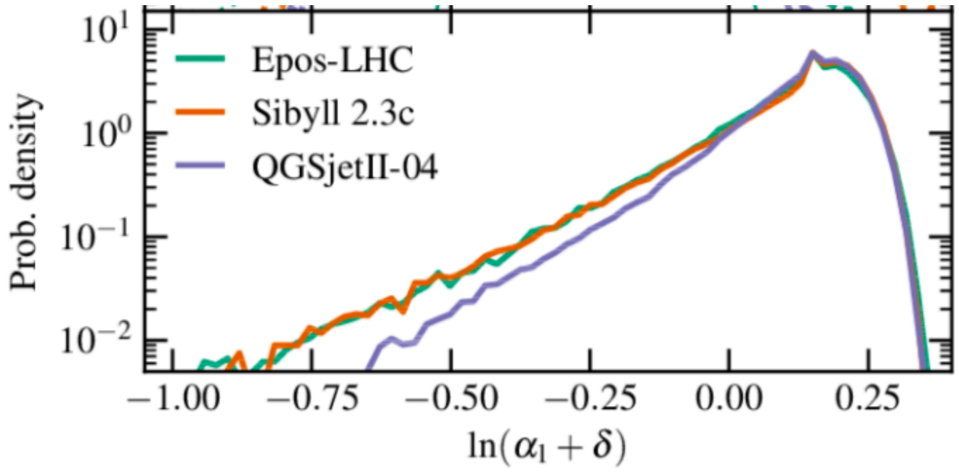


The number of muons strongly correlates with the fraction of hadronic energy of the first interaction

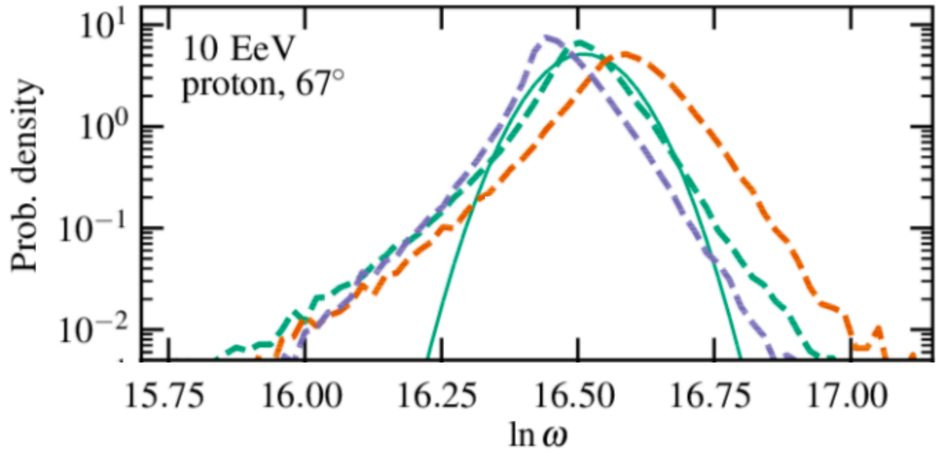
- Independently of interaction model, primary energy, primary zenith angle

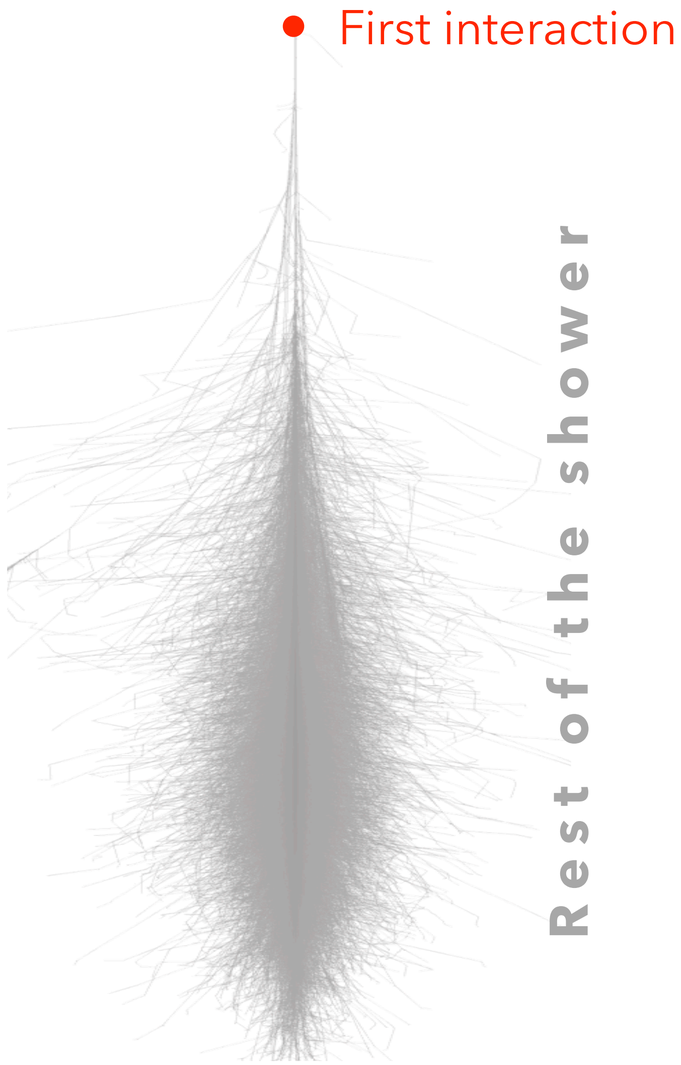
Understanding the N_μ distribution

First interaction



Rest of the shower





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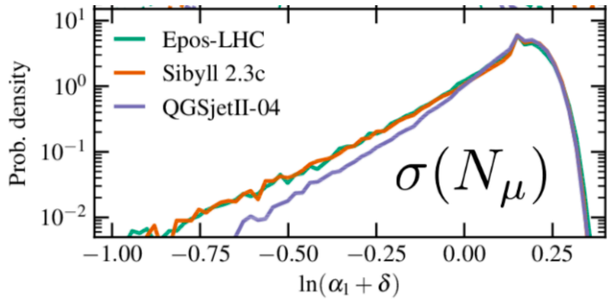
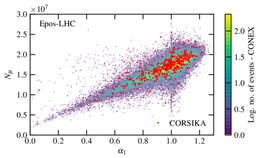
First interaction

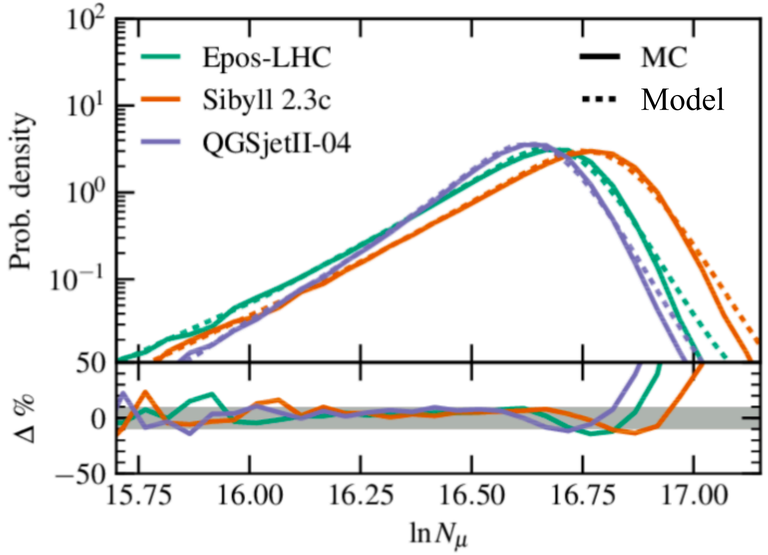


Model

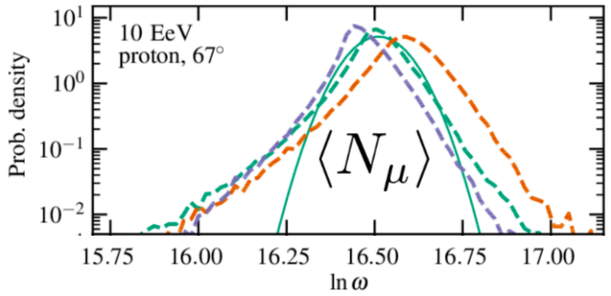


$$\ln(N_\mu) = \ln(\alpha_1 + \delta) + \ln(\omega)$$

Convolution



Rest of the shower

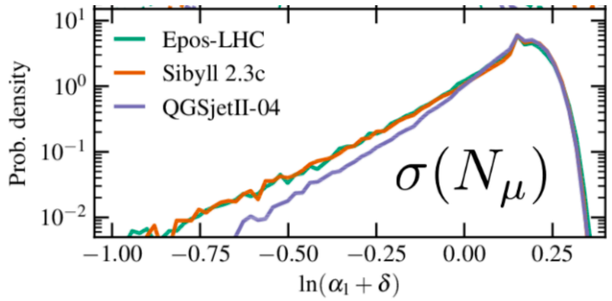


$\boldsymbol{\alpha}$ is the main parameter that controls the shape of N_μ dist

$\boldsymbol{\delta}$ is a small contribution from photopion production, ~10%

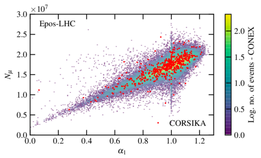
Understanding the N_μ distribution

First interaction



Controls N_μ fluctuations event-by-event

Model



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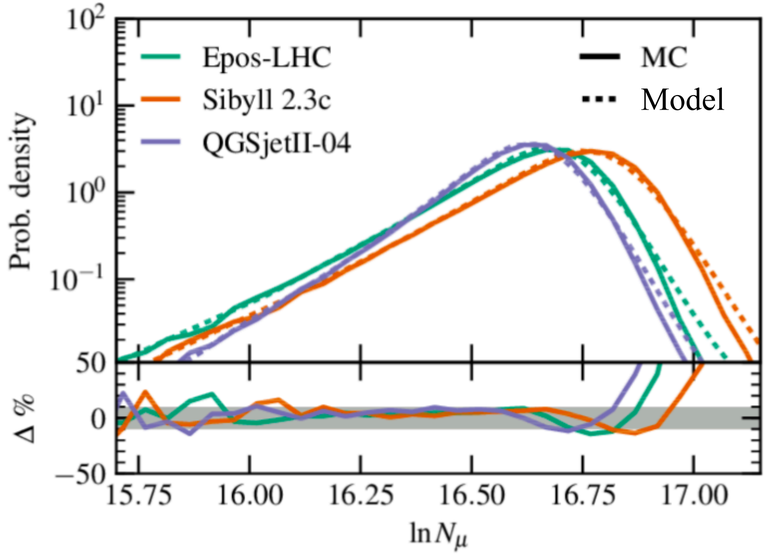
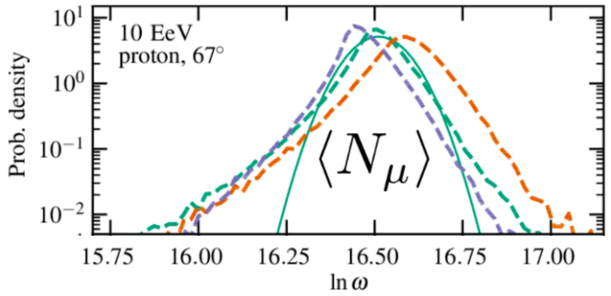
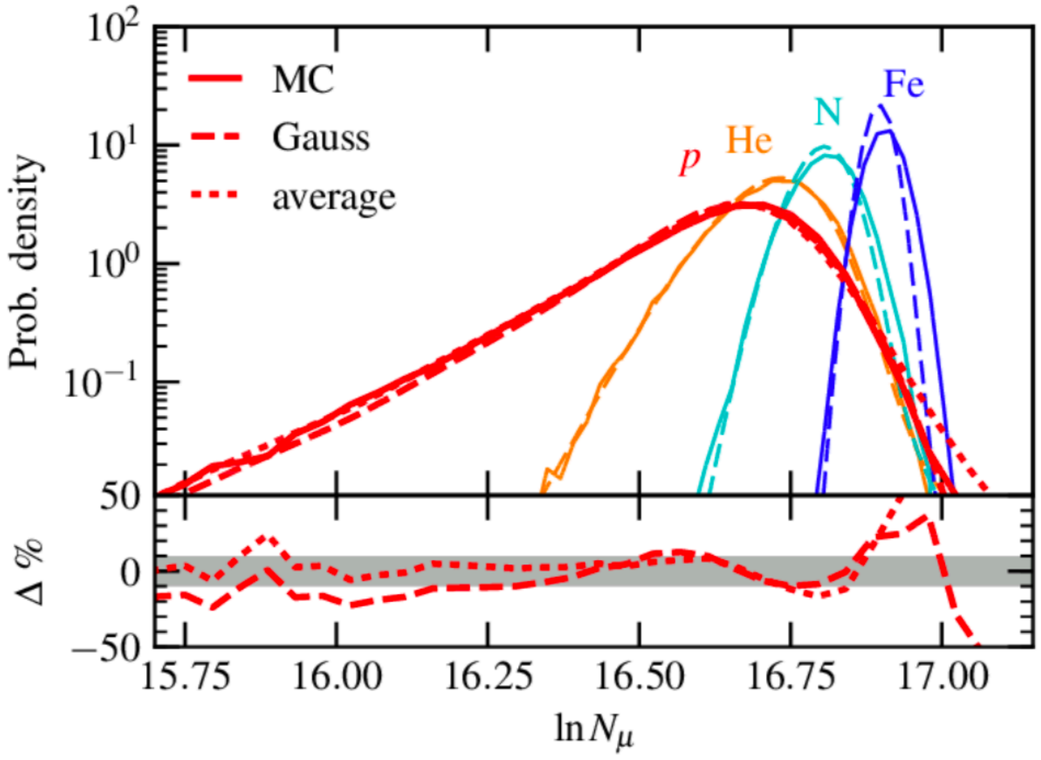


Rest of the shower



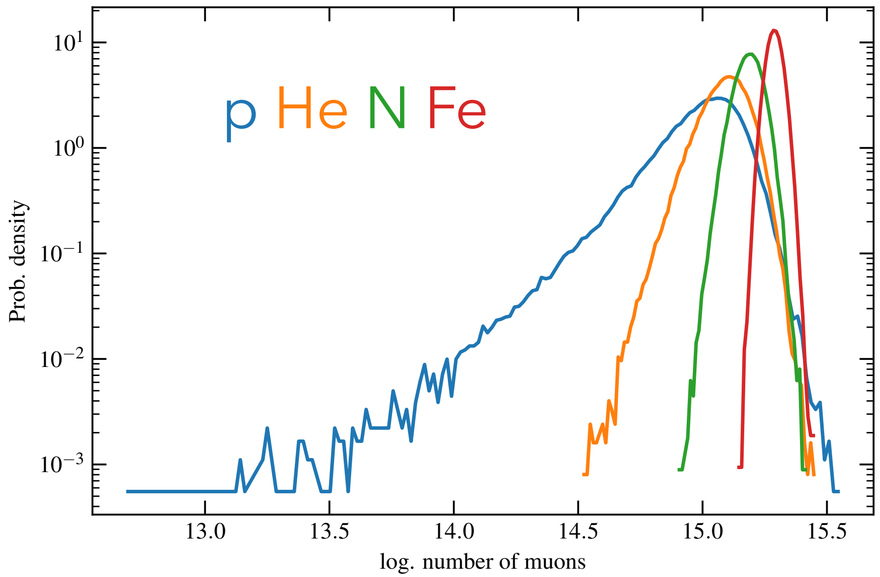
Controls overall number of muons

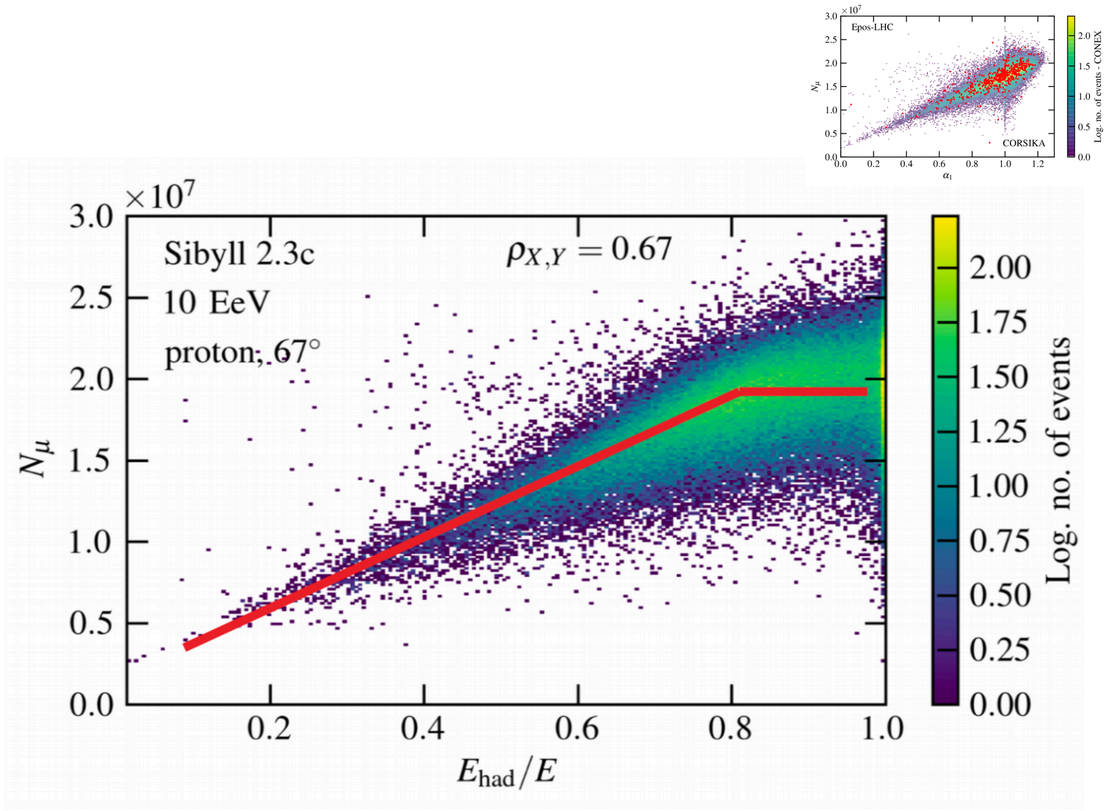


What is the proton low N_μ tail?

To which property of the first interaction is it related to?

On the origin of the proton N_μ distribution tail



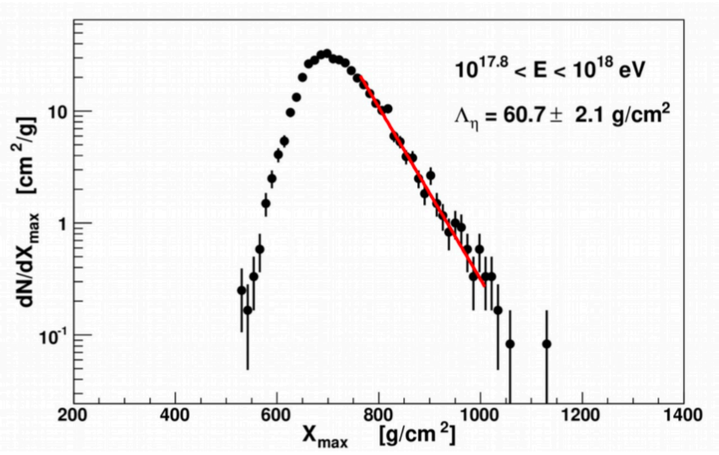


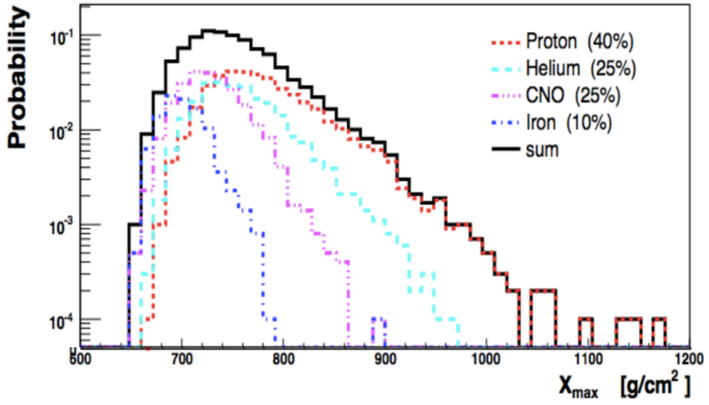
N_μ distribution tail has a very high correlation with the **hadronic energy of the first interaction**

Can it be measured?

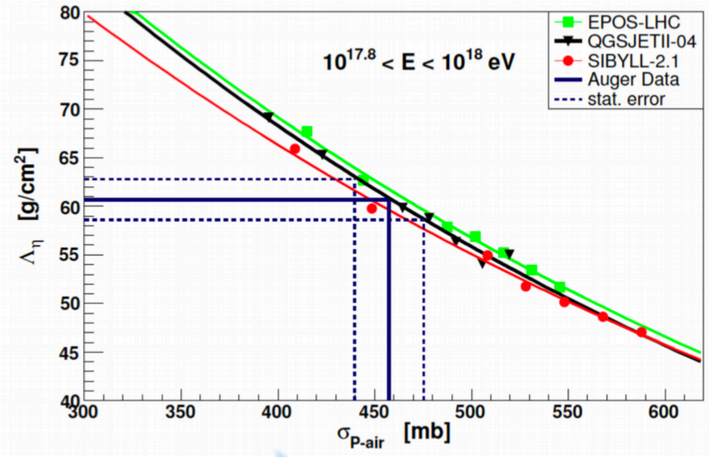
Phys.Rev.Lett. 109 (2012) 062002

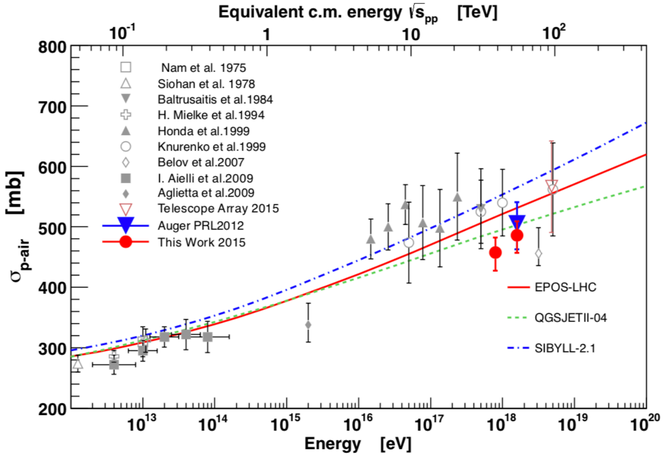
34th ICRC, PoS (2015) 401



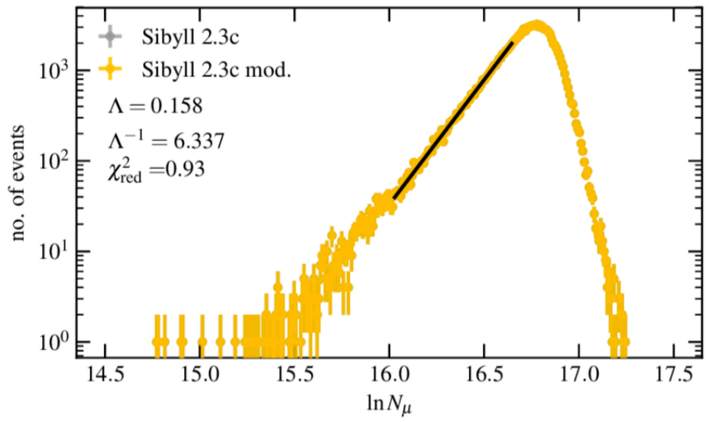


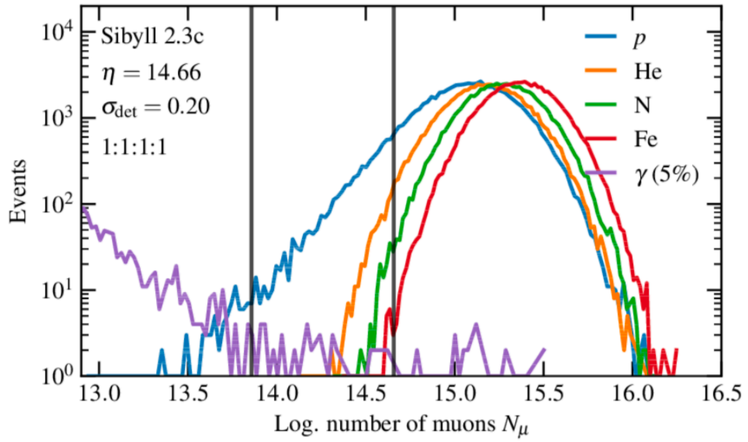
proton-Air cross-section measurement



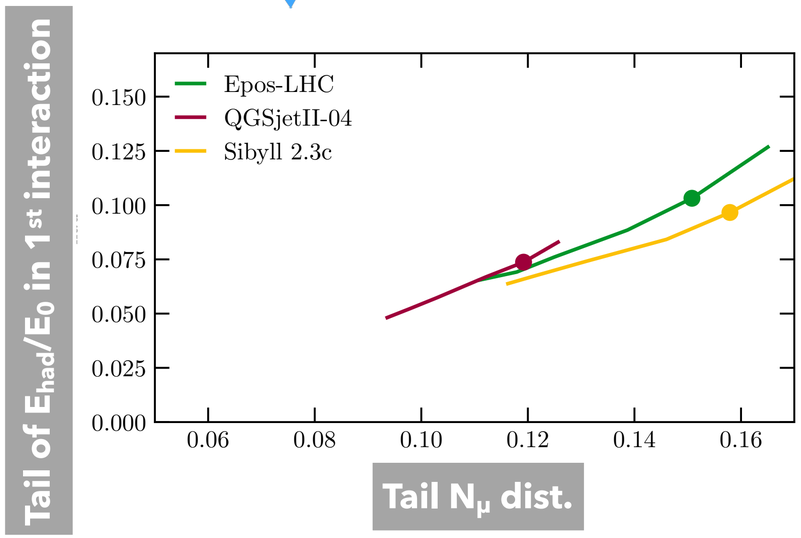


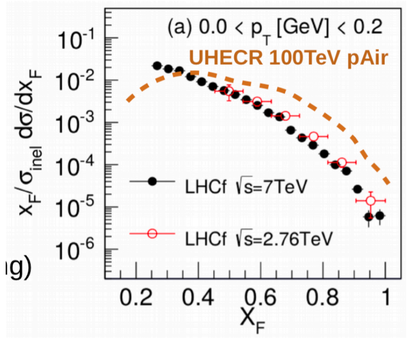
Paper to be published soon…



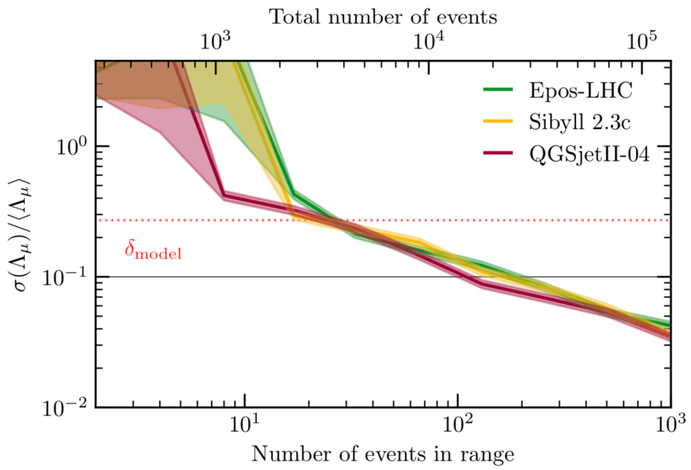


Possible measurement of the hadronic energy @100TeV c.m.





Cross-check
with LHC measurements



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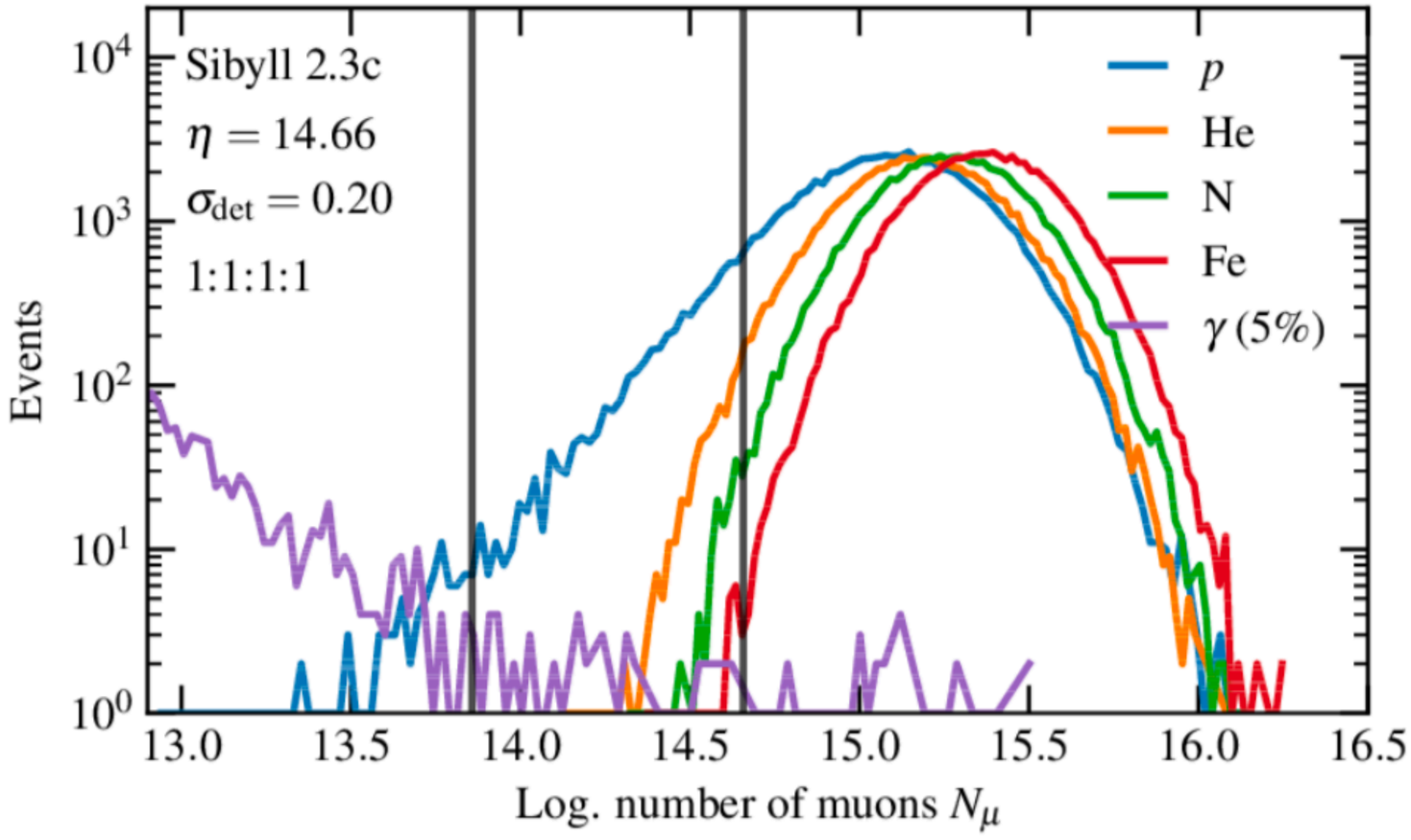
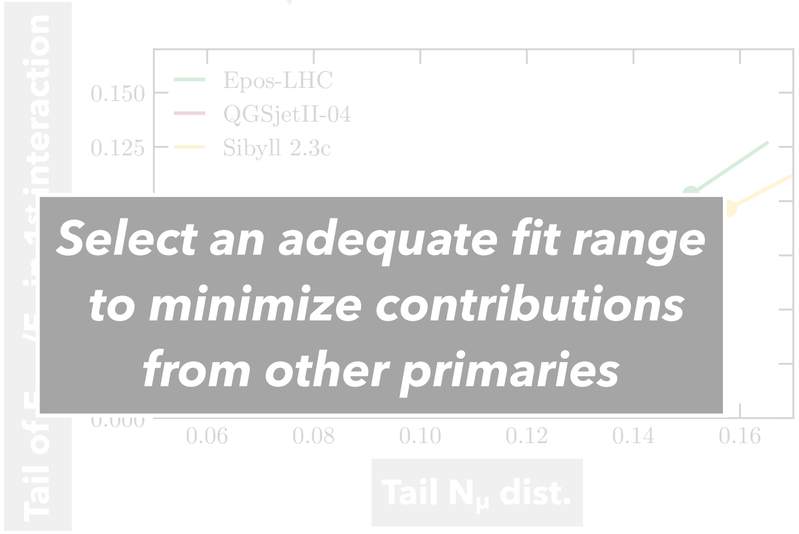
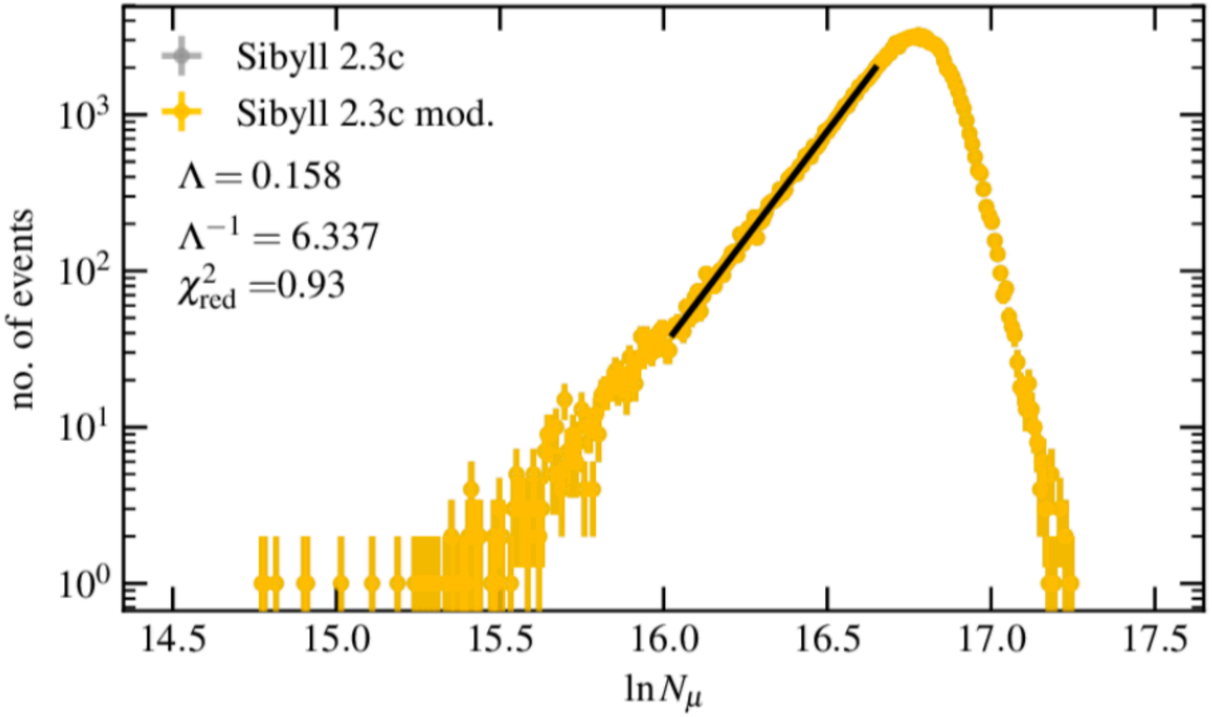


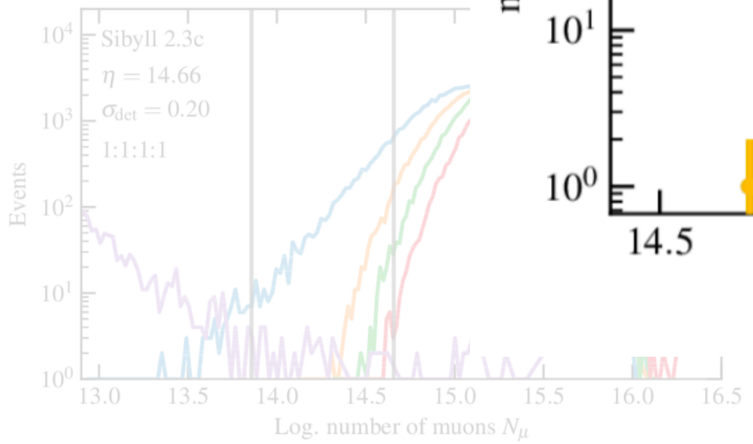


Select an adequate fit range to minimize contributions from other primaries

with LHC measurements

aper to be published soon…





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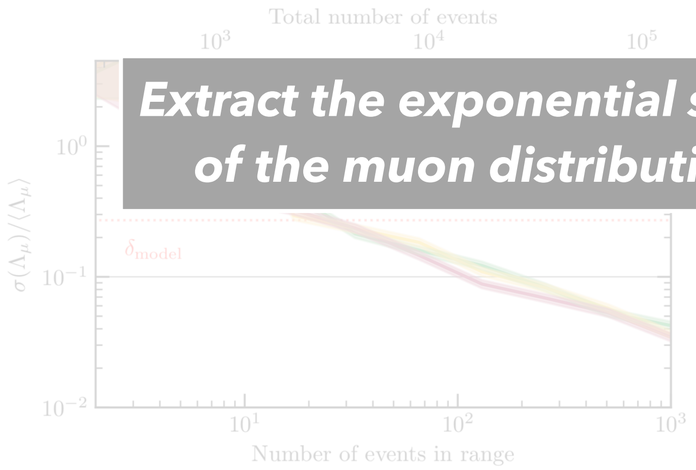
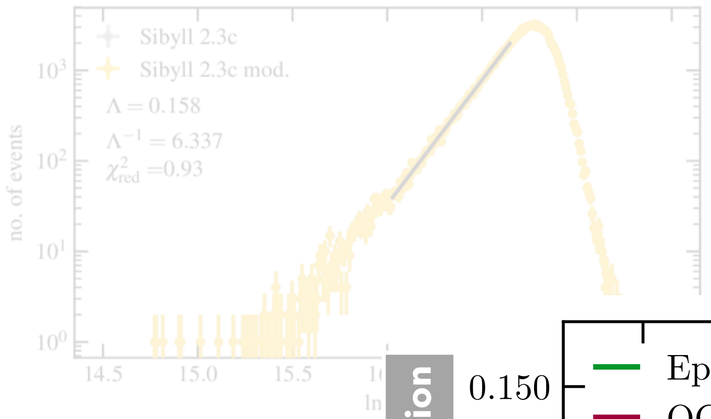
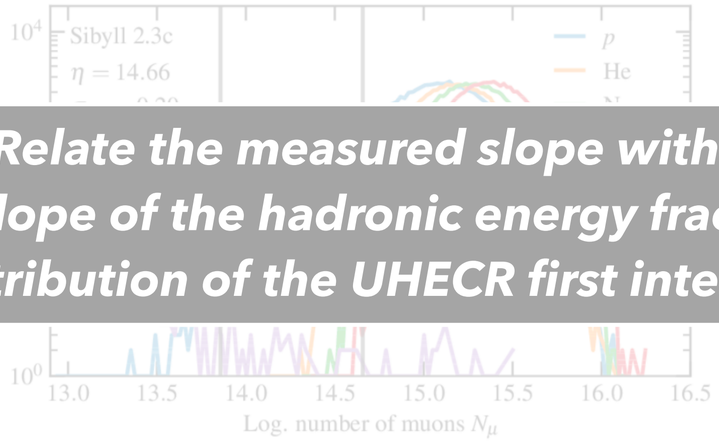


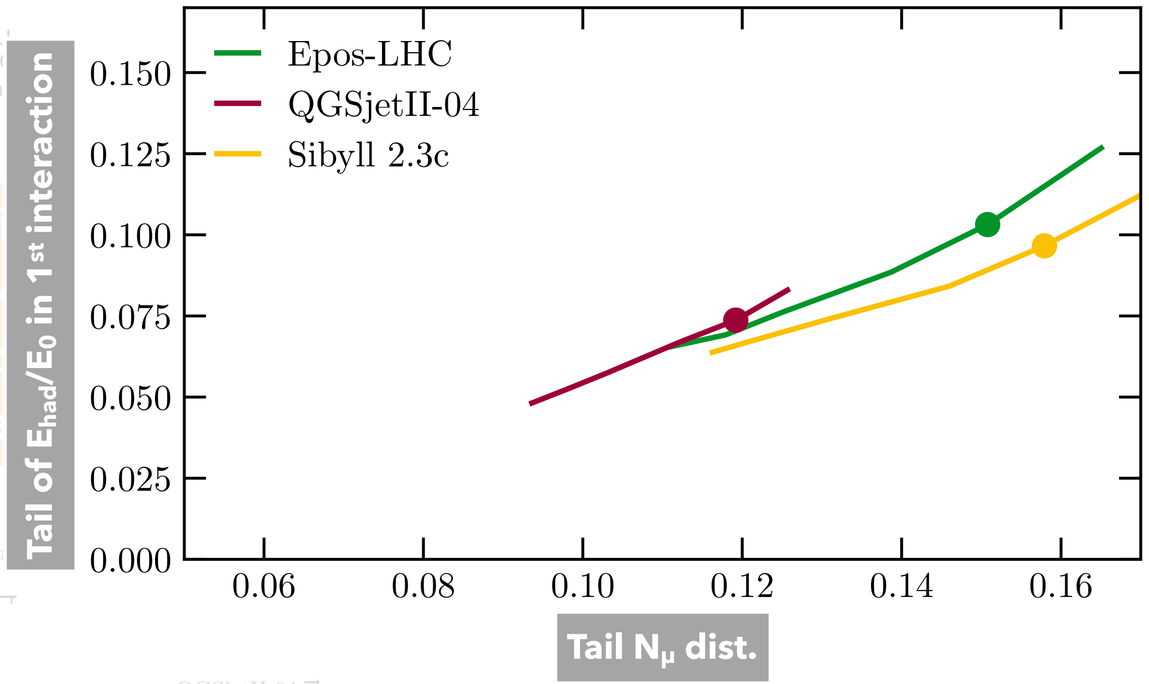
Extract the exponential slope of the muon distribution

Paper to be published soon…





Relate the measured slope with the slope of the hadronic energy fraction distribution of the UHECR first interaction



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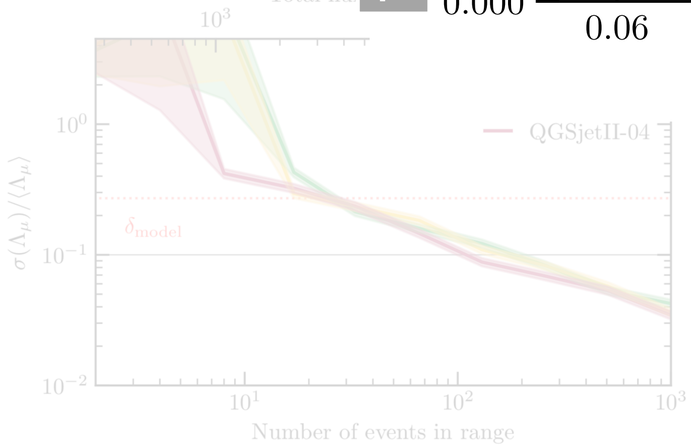
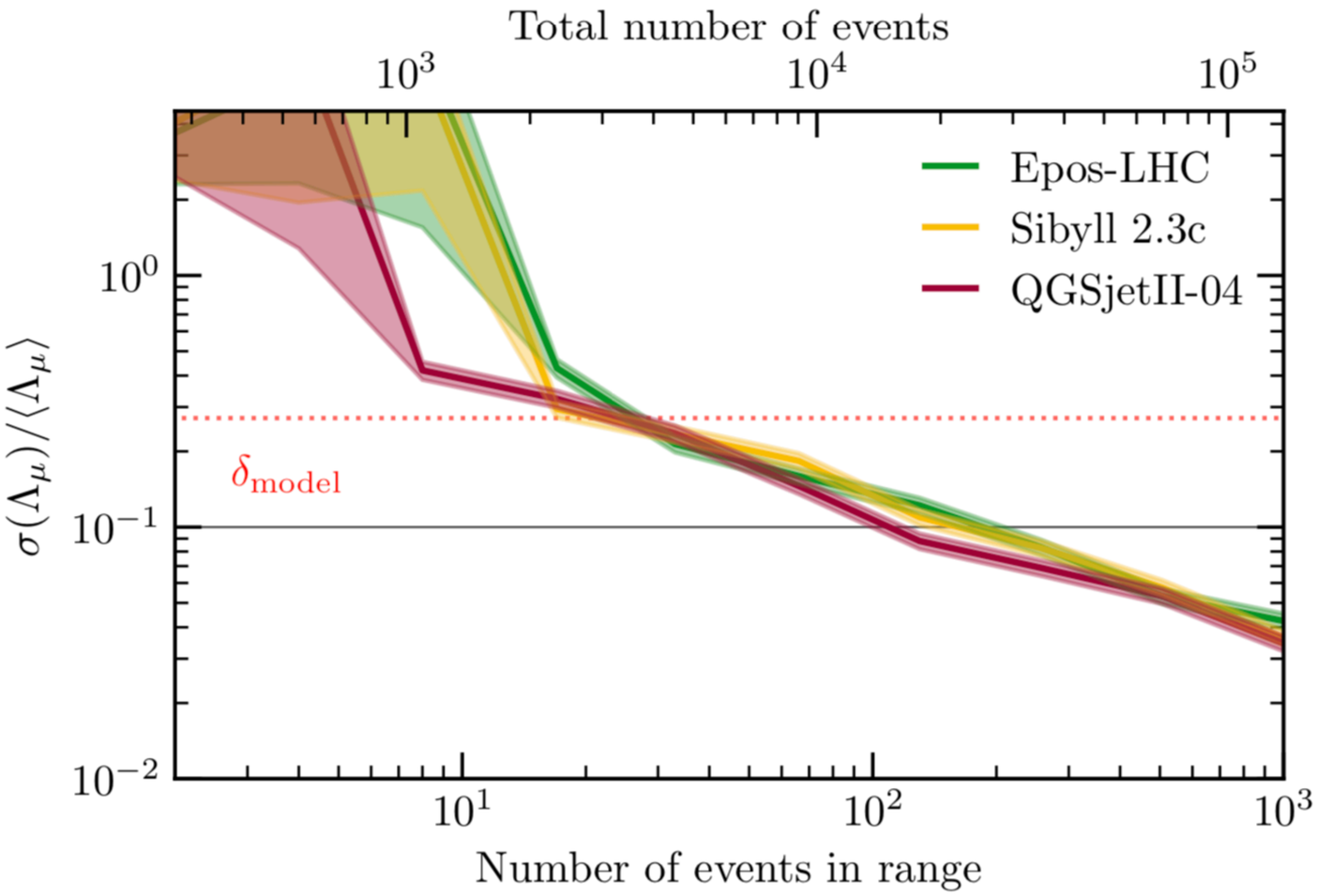


Paper to be published soon…

Number of shower events necessary to have a meaningful result



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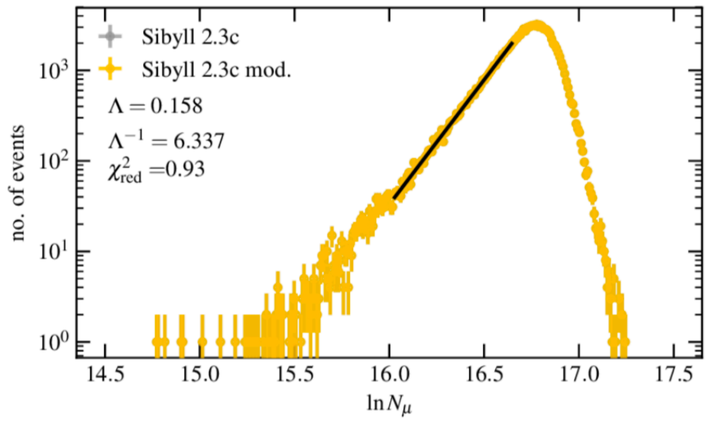

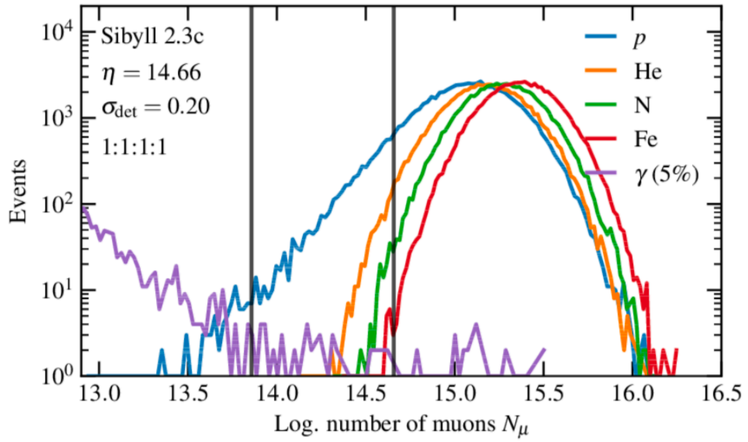

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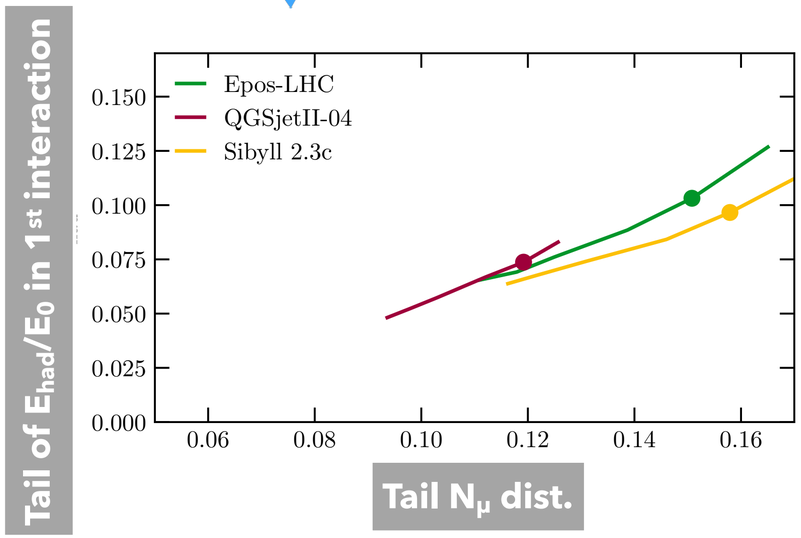

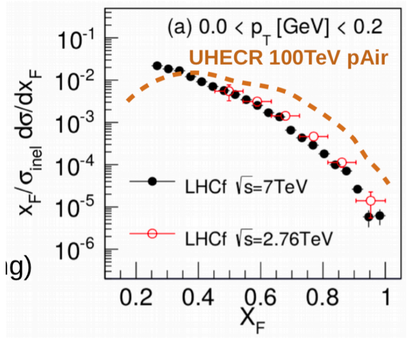

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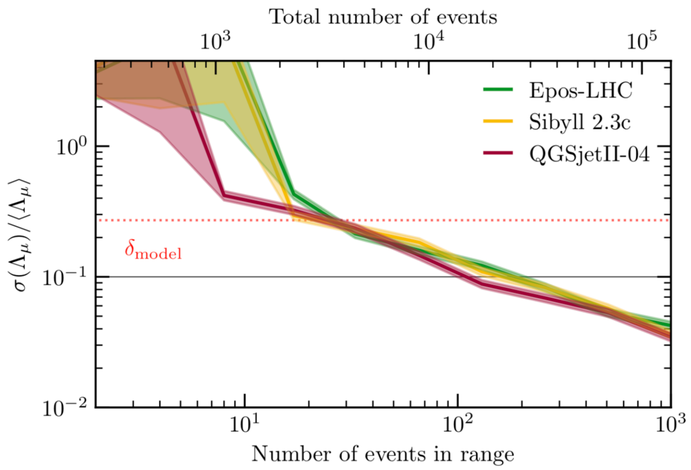
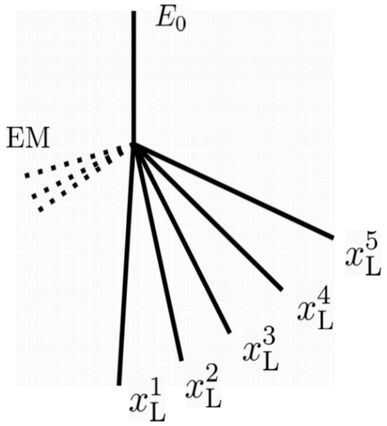


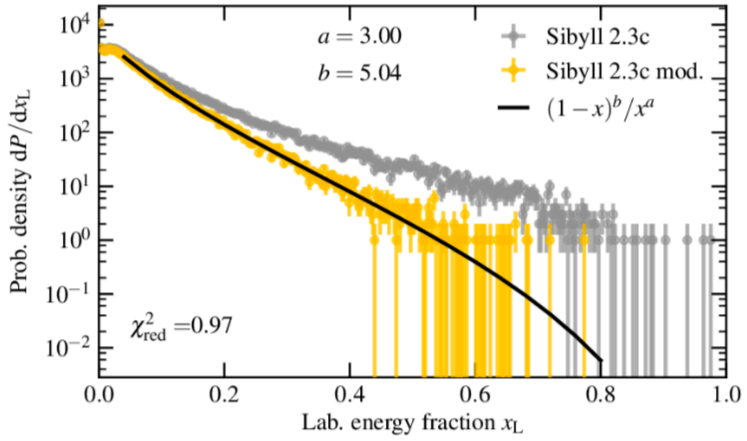
Access the pion energy spectrum of the first interaction

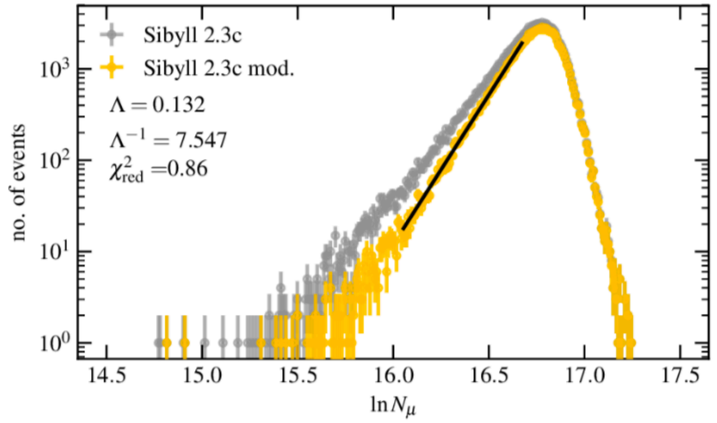


$$\frac{E_{had}}{E_0} = \sum_i x_{had}^i = 1 - \frac{E_{EM}}{E_0}$$

π^0

$$p + \text{Air} \rightarrow \pi^0 + X$$





- Change the high-energy tail of the inclusive production cross-section
- Check impact in the slope of muon distribution low-tail

Slope of muon distribution ⇔ Shape of inclusive production cross-section at high-x

Summary

- Fluctuations of the N_μ distribution are sensitive to the first interaction properties
  - *PLB 784 (2018) 68-76*

- The slope of the low-tail of the proton N_μ distribution is sensitive to the pion energy spectrum of the first interaction
  - *Paper to be published soon*

Acknowledgements

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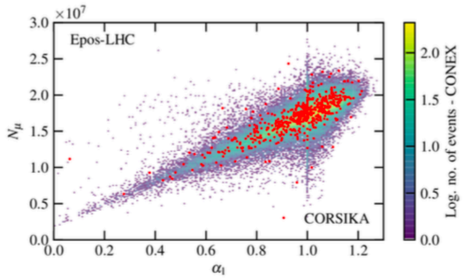
Backup slides

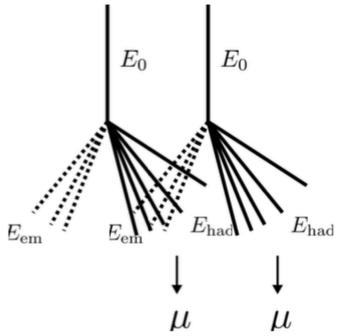
Different primaries

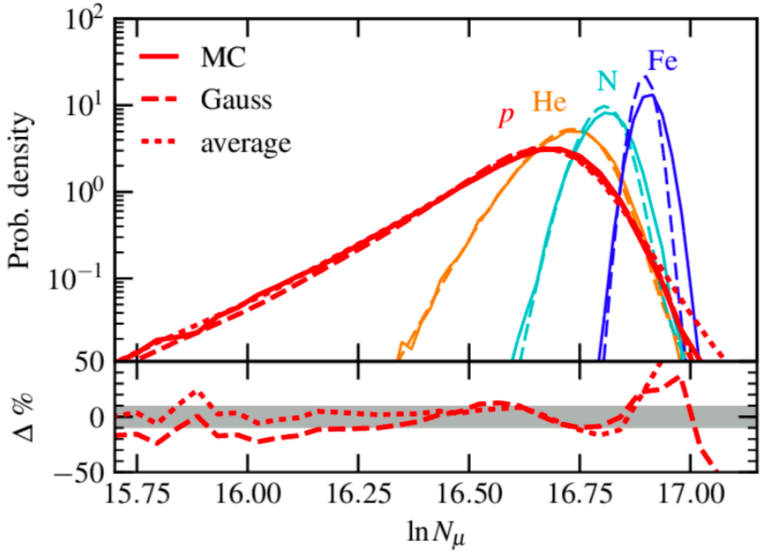
* Energy fluctuations p-Air



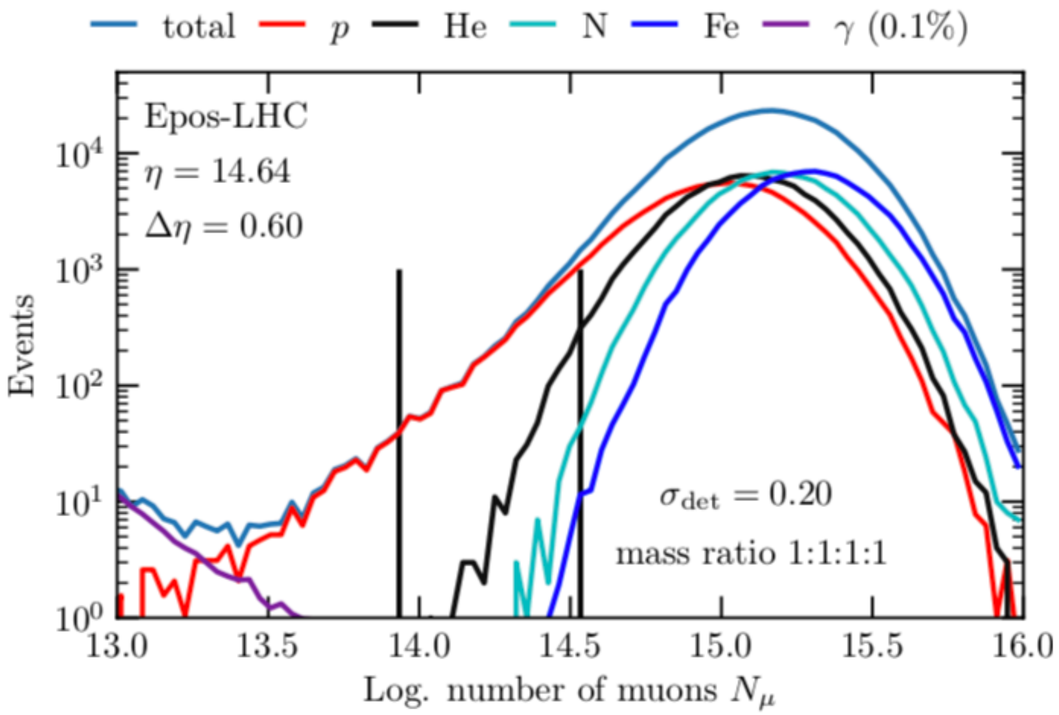
* Superposition model

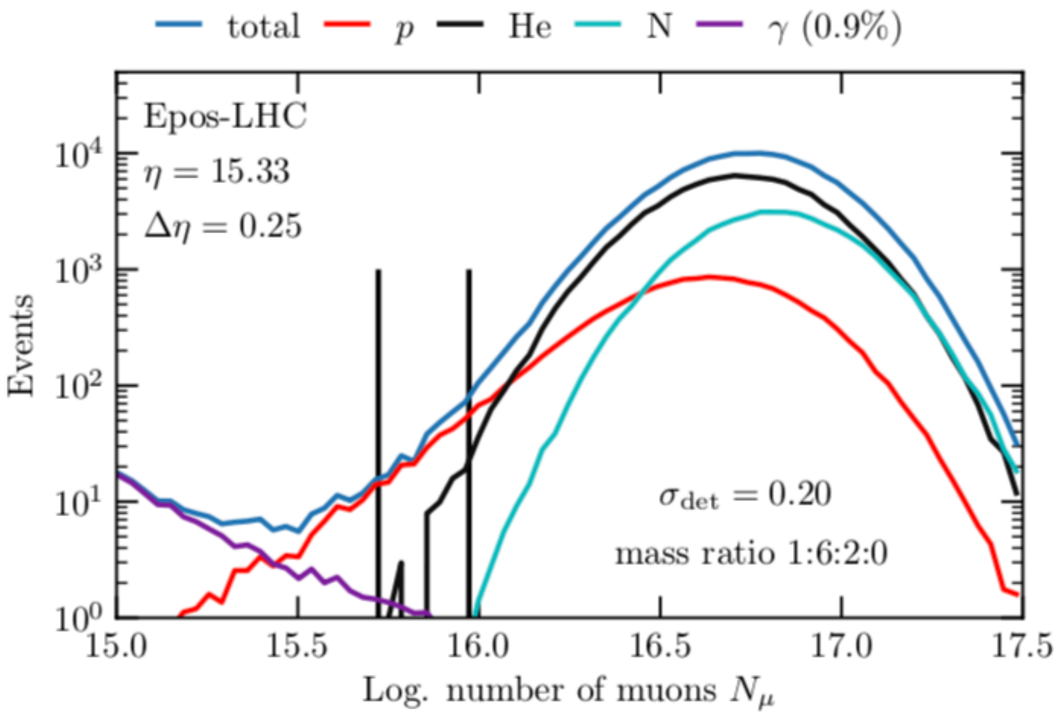
$$N_\mu(E, A) = A \cdot N_\mu(E/A)$$



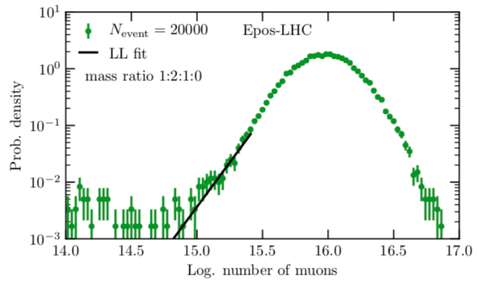


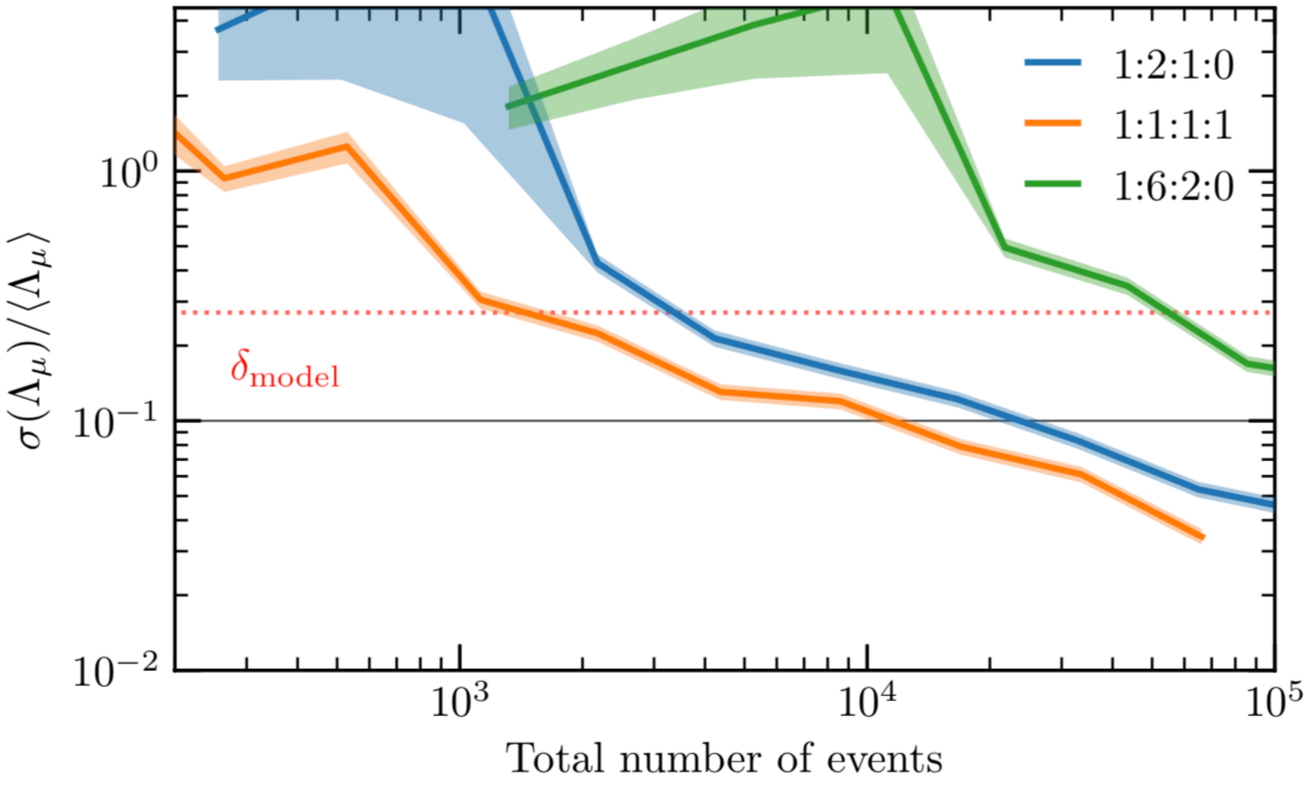
Different mass composition scenarios





Different mass composition scenarios





Fitting the pion energy spectra tail