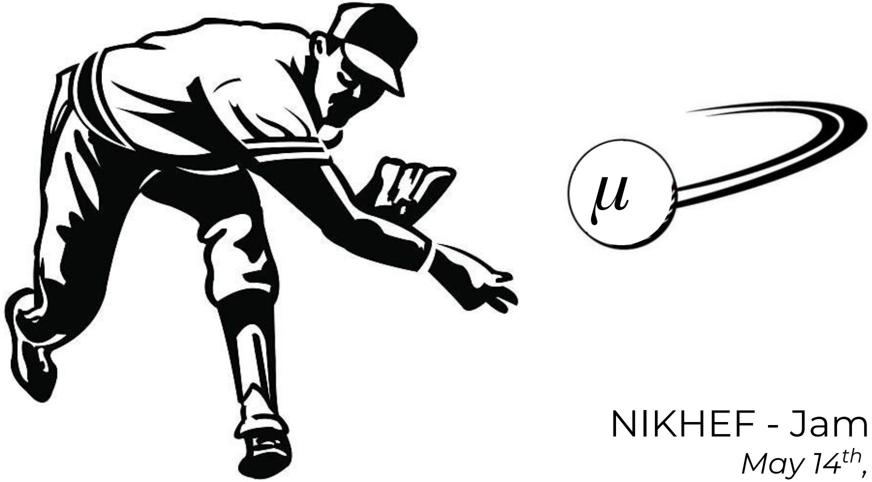
Radboud Universiteit

PIERRE AUGER OBSERVATORY

Nikhef

The **M**uon **P**uzzle: Nature's curveball at **UHECR** physics

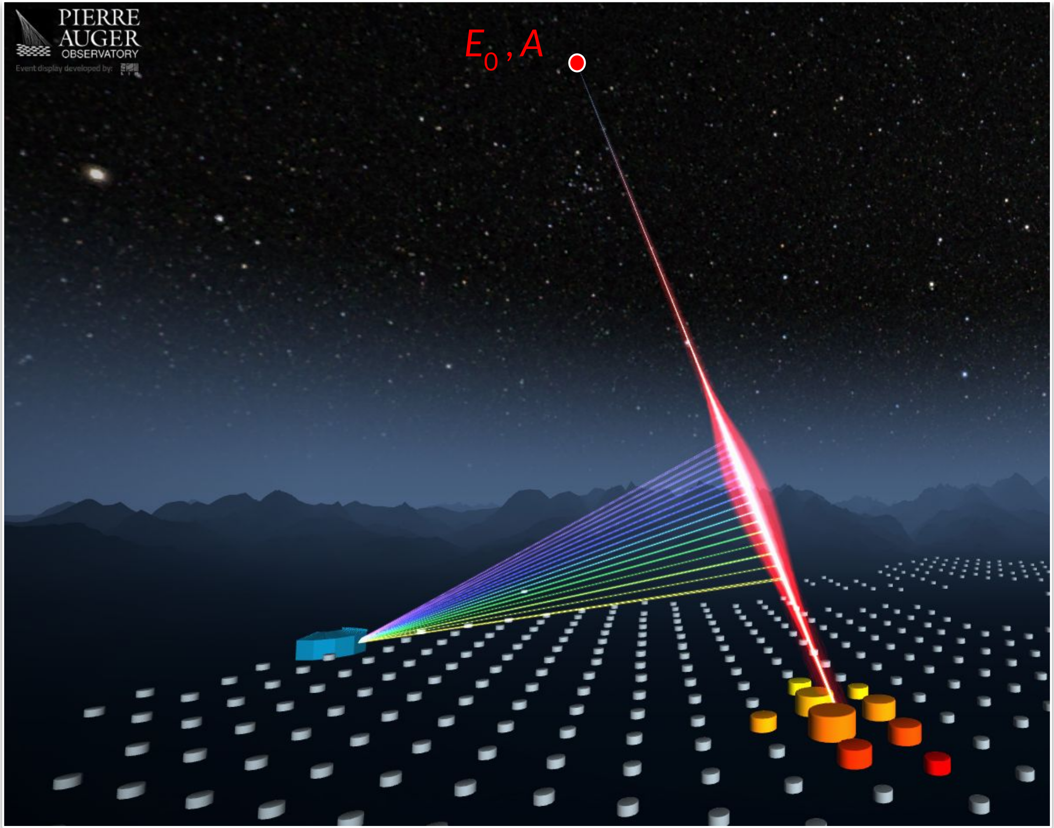
Kevin Almeida Cheminant



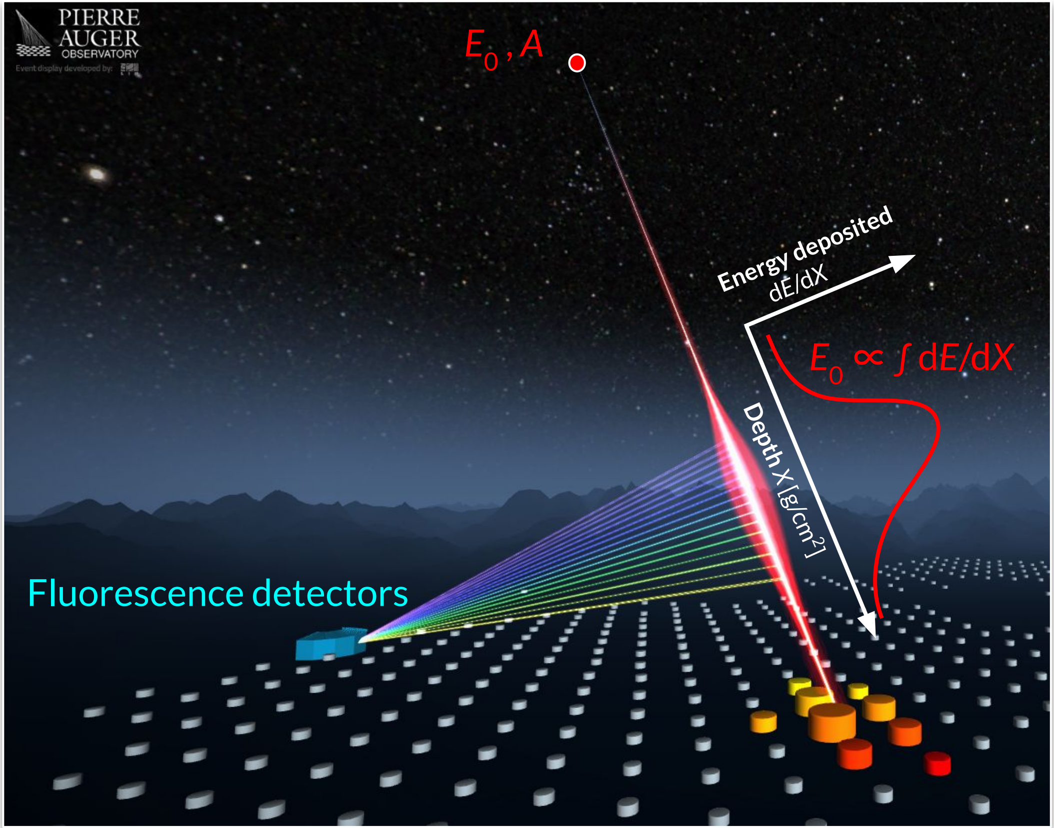
NIKHEF - Jamboree 2024

May 14th, 2024

Measuring Extensive Air Showers



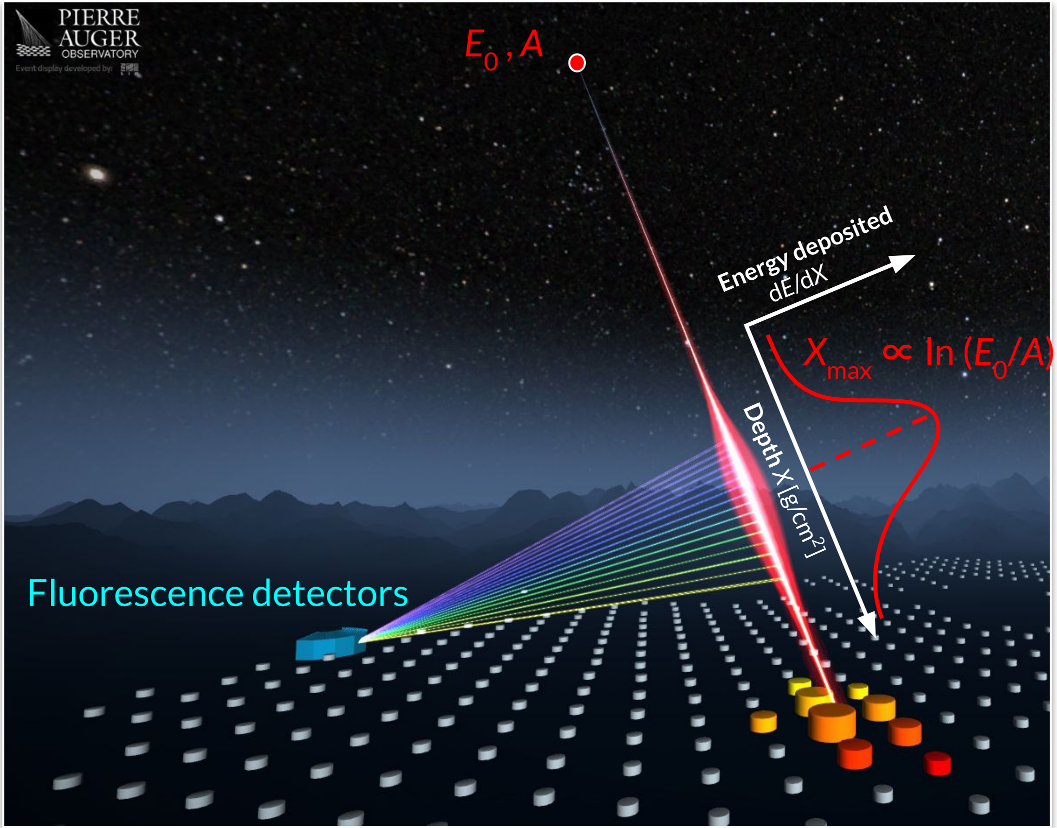
Measuring Extensive Air Showers



Longitudinal profile

- EM component formed by the decay of π^0
  - ***calorimetric energy***

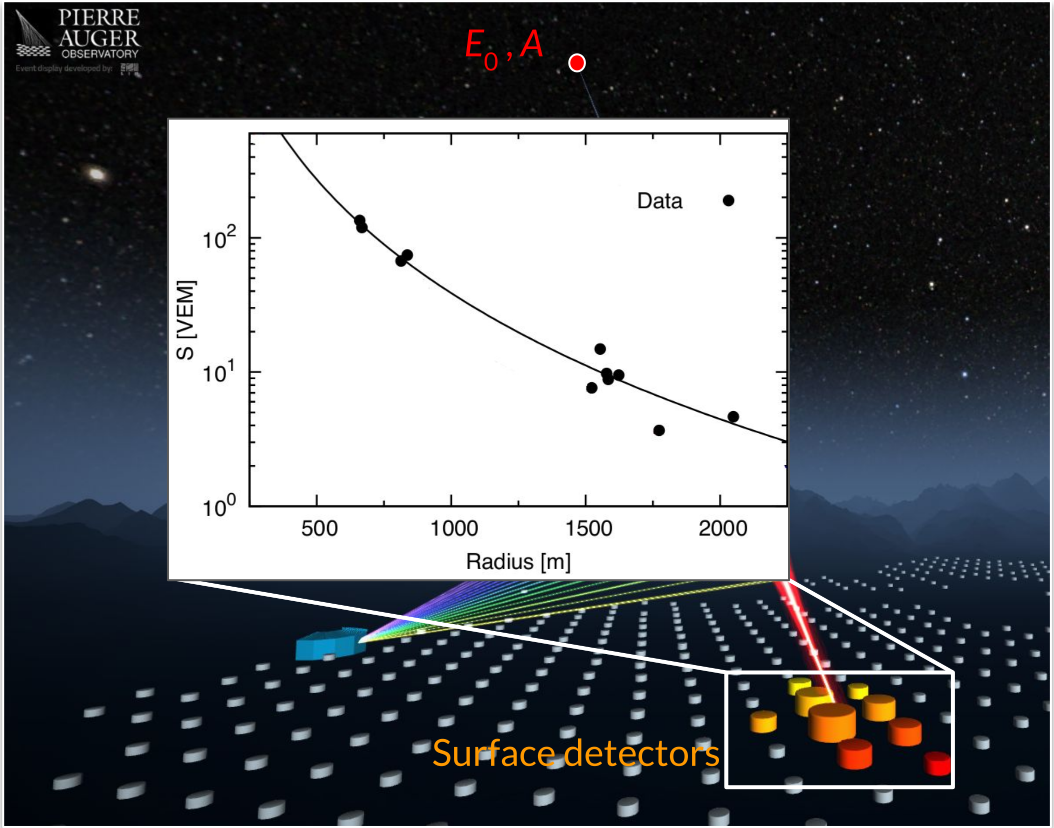
Measuring Extensive Air Showers



Longitudinal profile

- EM component formed by the decay of π^0
  - calorimetric energy
  - ***depth of maximum development X_{max}***

Measuring Extensive Air Showers



Longitudinal profile

- EM component formed by the decay of π^0
  - calorimetric energy
  - ***depth of maximum development X_{max}***

Ground distribution

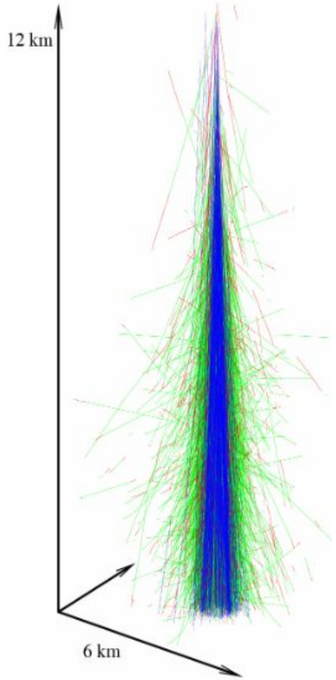
- Muonic component* formed by the decay of $\pi^{+/-}$ and $K^{+/-}$.
  - ***lateral distribution***

  → tracer of hadronic interactions.

* also EM

Hadronic Interaction Models

Monte-Carlo simulations of air showers are needed to describe particle interactions and decays, energy losses, magnetic fields, etc...

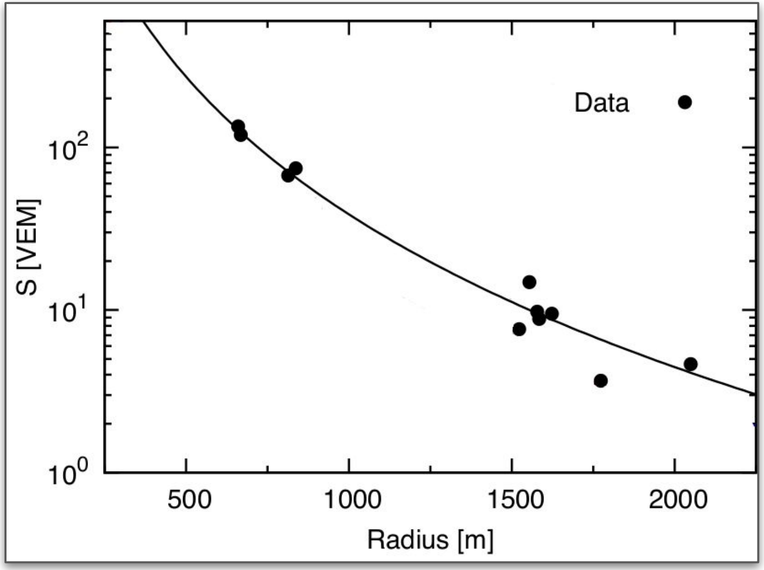


Hadronic Interaction Models

Monte-Carlo simulations of air showers are needed to describe particle interactions and decays, energy losses, magnetic fields, etc...

➢ Below ~100 GeV: Such as **UrQMD, FLUKA** and **GHEISHA** models.

→ large influence on the **lateral profile of muons** at ground level.



Hadronic Interaction Models

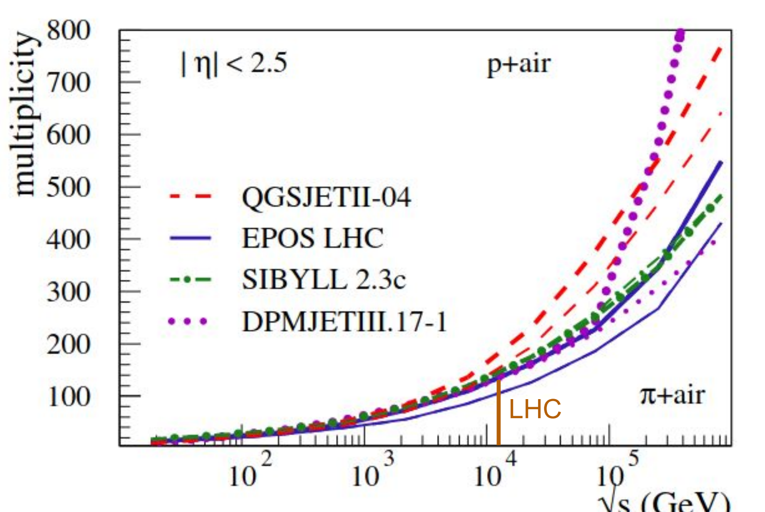
Monte-Carlo simulations of air showers are needed to describe particle interactions and decays, energy losses, magnetic fields, etc...

- Below ~100 GeV: Such as **UrQMD, FLUKA** and **GHEISHA** models.
  → large influence on the **lateral profile of muons** at ground level.
- Above ~100 GeV: **EPOS-LHC**, **QGSJetII**, **SIBYLL** and others...
  → tuned to LHC data.
  → influence on the **number of muons** at ground level.

Hadronic Interaction Models

Monte-Carlo simulations of air showers are needed to describe particle interactions and decays, energy losses, magnetic fields, etc...

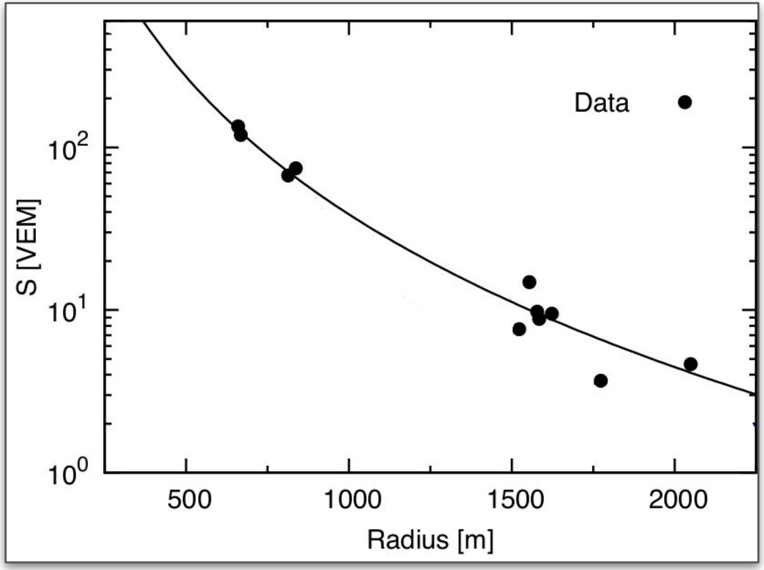
- Below ~100 GeV: Such as **UrQMD, FLUKA** and **GHEISHA** models.
  → large influence on the **lateral profile of muons** at ground level.
- Above ~100 GeV: **EPOS-LHC**, **QGSJetII**, **SIBYLL** and others...
  → tuned to LHC data.
  → influence on the **number of muons** at ground level.
- Uncertainties:
  - Extrapolation at highest energies.
  - No *air* target in terrestrial accelerators.
  - Air showers in the forward direction.



T. Pierog, EPJ Web Conf. 208 (2019) 02002

Hadronic Interaction Models

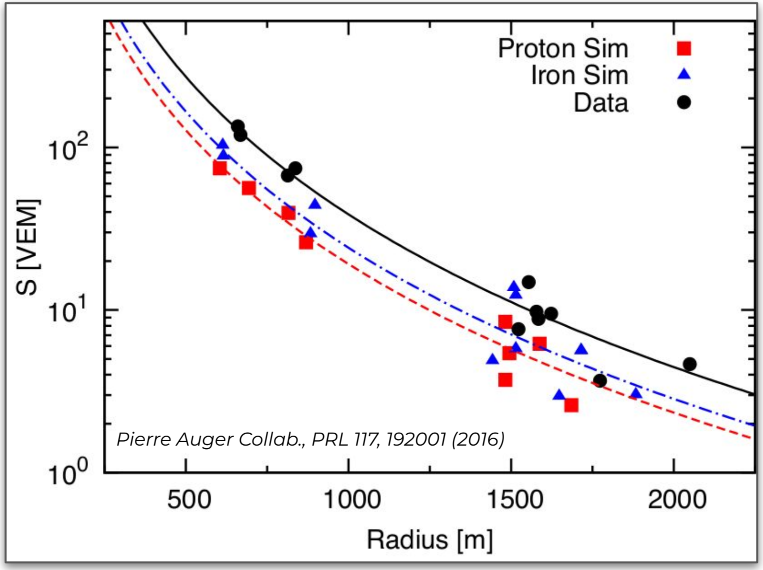
Monte-Carlo simulations of air showers are needed to describe particle interactions and decays, energy losses, magnetic fields, etc...



Hadronic Interaction Models

Monte-Carlo simulations of air showers are needed to describe particle interactions and decays, energy losses, magnetic fields, etc...

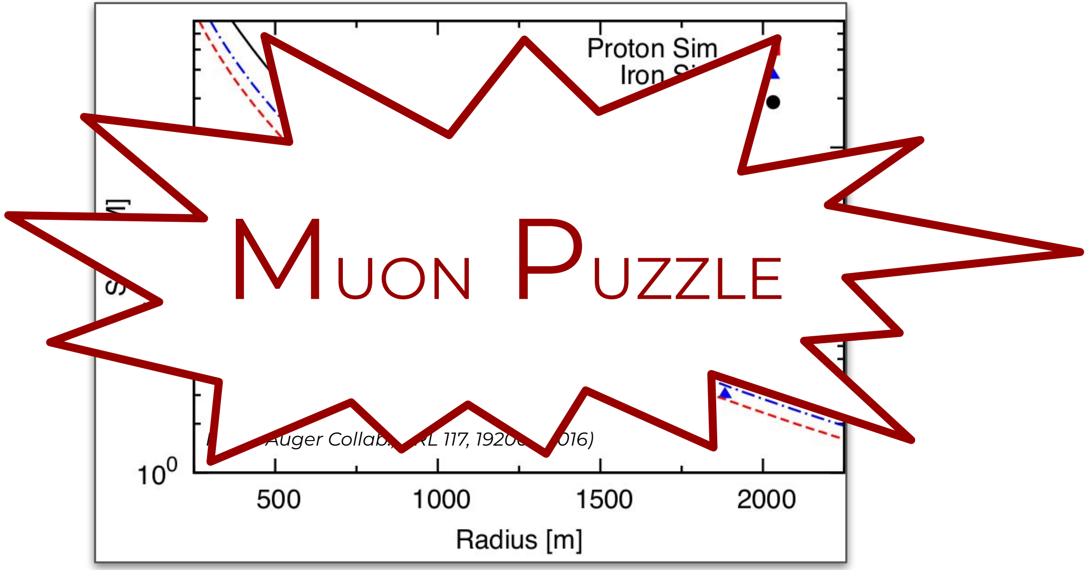
Simulations predict the **right shape of the lateral distribution** but **fail to produce enough muons** to match the data.



Hadronic Interaction Models

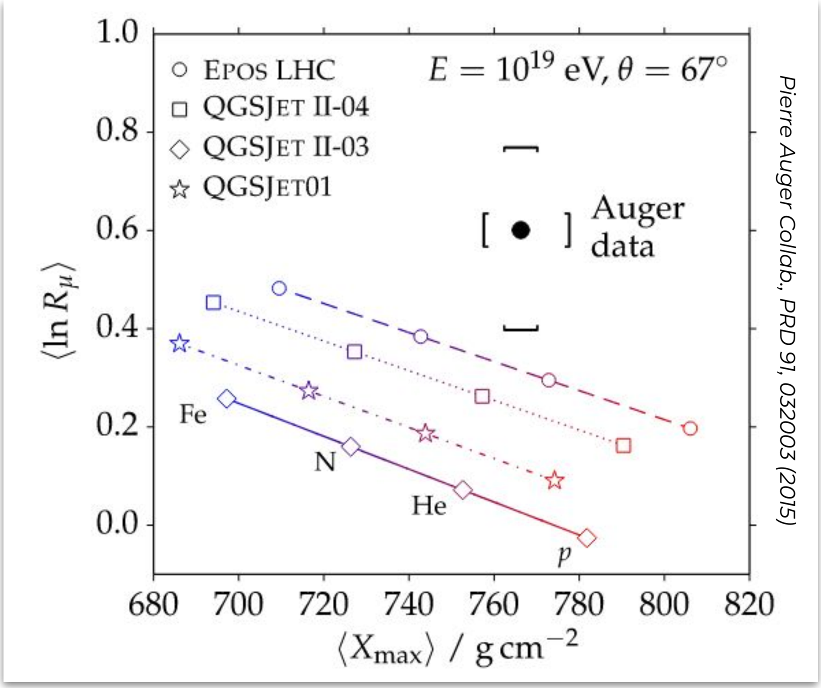
Monte-Carlo simulations of air showers are needed to describe particle interactions and decays, energy losses, magnetic fields, etc...

Simulations predict the **right shape of the lateral distribution** but **fail to produce enough muons** to match the data.



At the Pierre Auger Observatory...

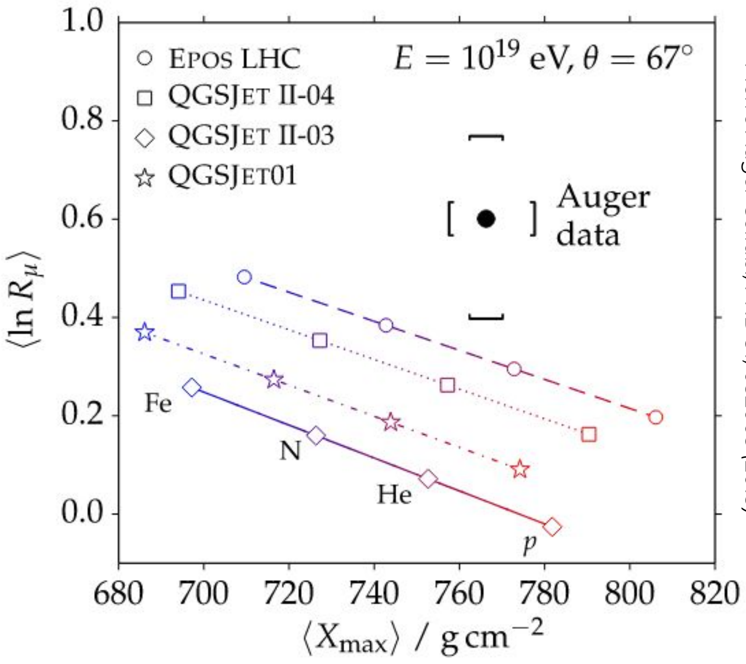
Inclined showers



Pierre Auger Collab., PRD 91, 032003 (2015)

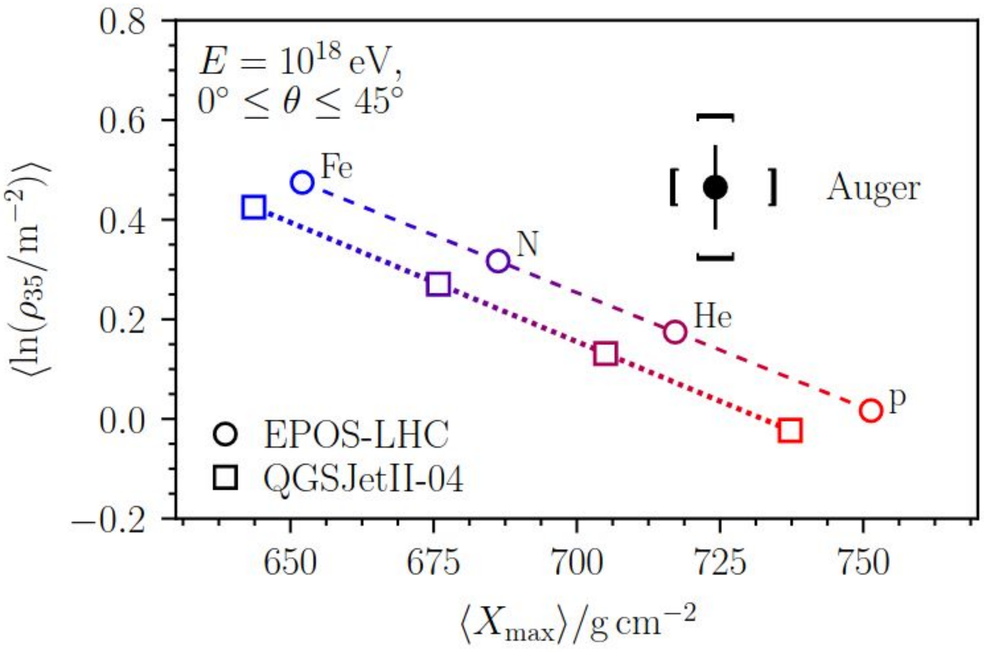
At the Pierre Auger Observatory...

Inclined showers



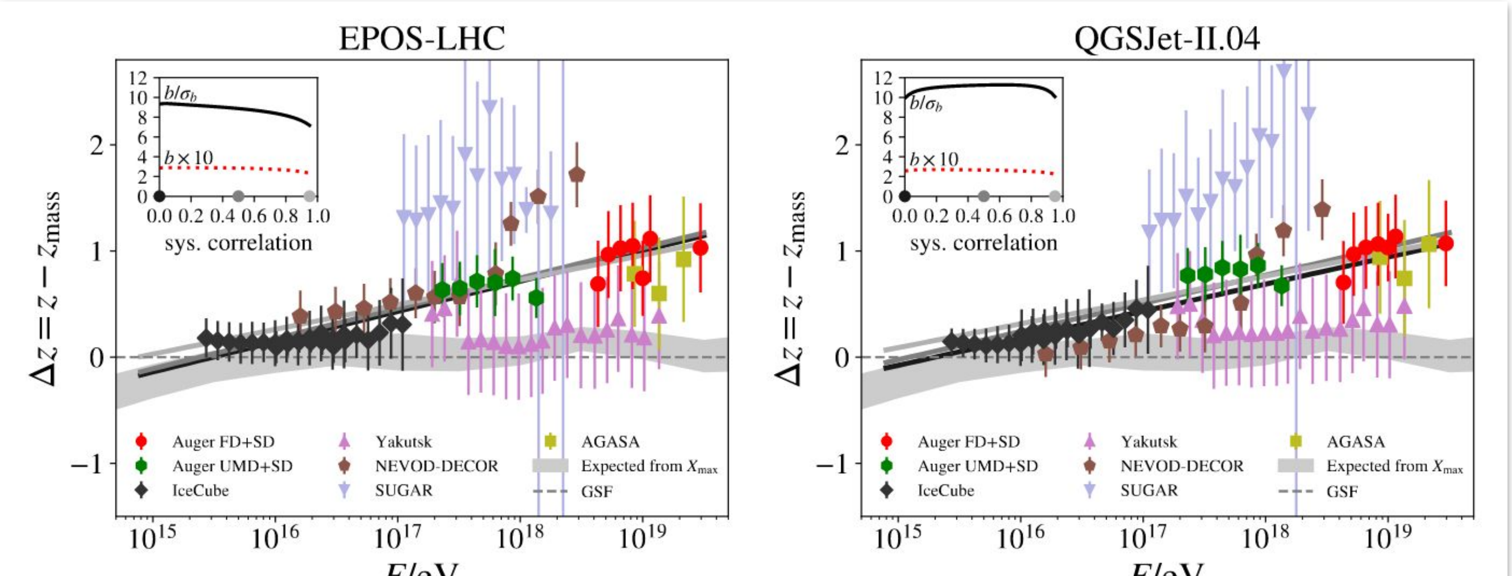
Pierre Auger Collab., PRD 91, 032003 (2015)

Underground detectors



Pierre Auger Collab., Eur. Phys. J. C (2020) 80:751

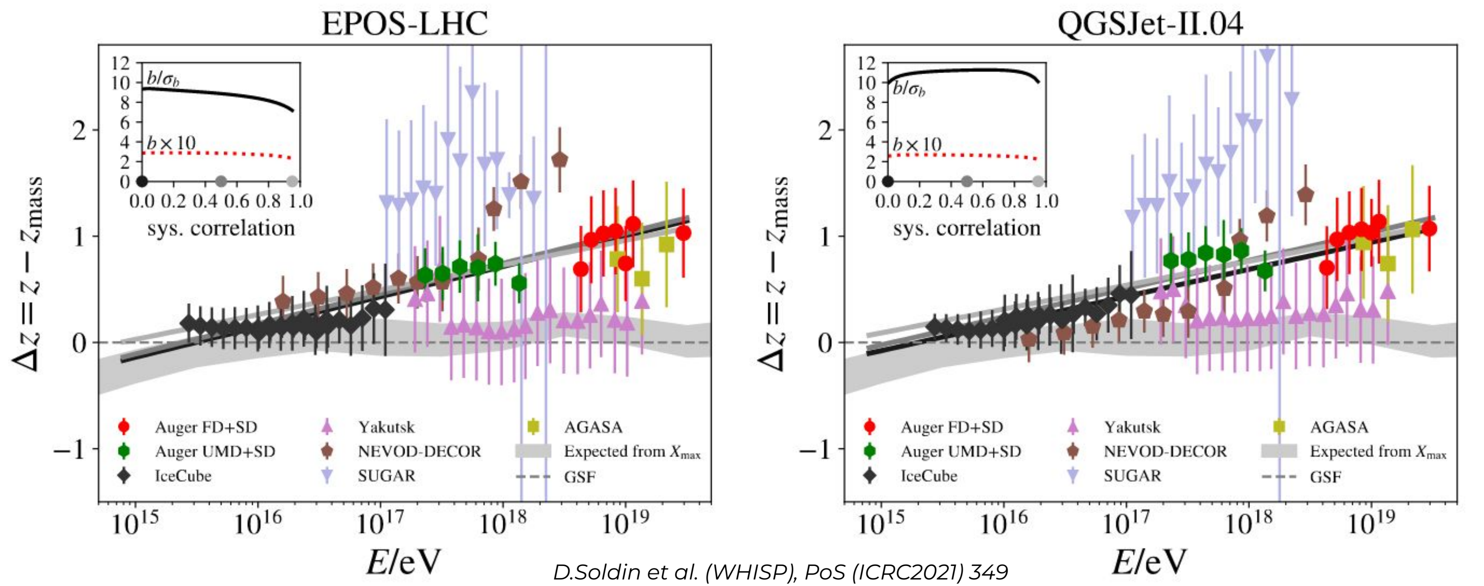
… and in other experiments



D.Soldin et al. (WHISP), PoS (ICRC2021) 349

➢ Departure from 0 highlights a discrepancy between data and simulations at 8 sigma level.

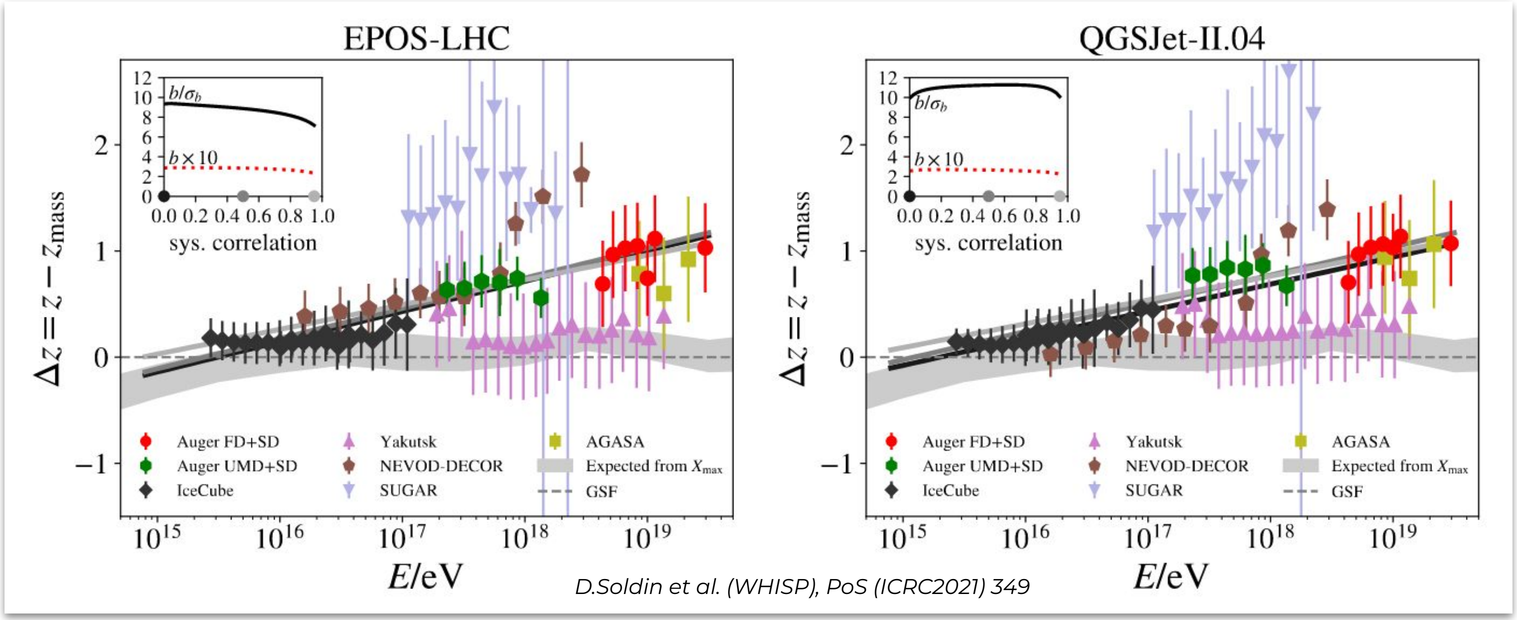
… and in other experiments



D.Soldin et al. (WHISP), PoS (ICRC2021) 349

- ➢ Departure from 0 highlights a discrepancy between data and simulations at 8 sigma level.
- ➢ Deficit seen across a large range of experiments.

… and in other experiments

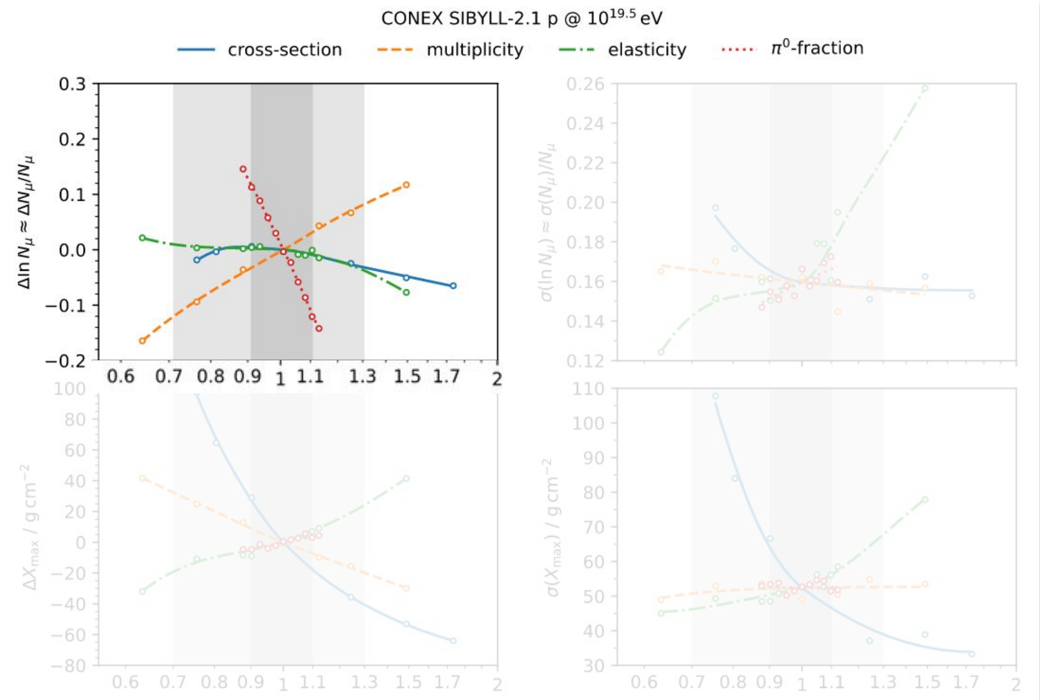


D.Soldin et al. (WHISP), PoS (ICRC2021) 349

- ➢ Departure from 0 highlights a discrepancy between data and simulations at 8 sigma level.
- ➢ Deficit seen across a large range of experiments.
- ➢ Other experiments recently reported similar observations (KM3NeT - arXiv:2403.11946).

… and in other experiments

What can we do to increase the muon content of simulations?

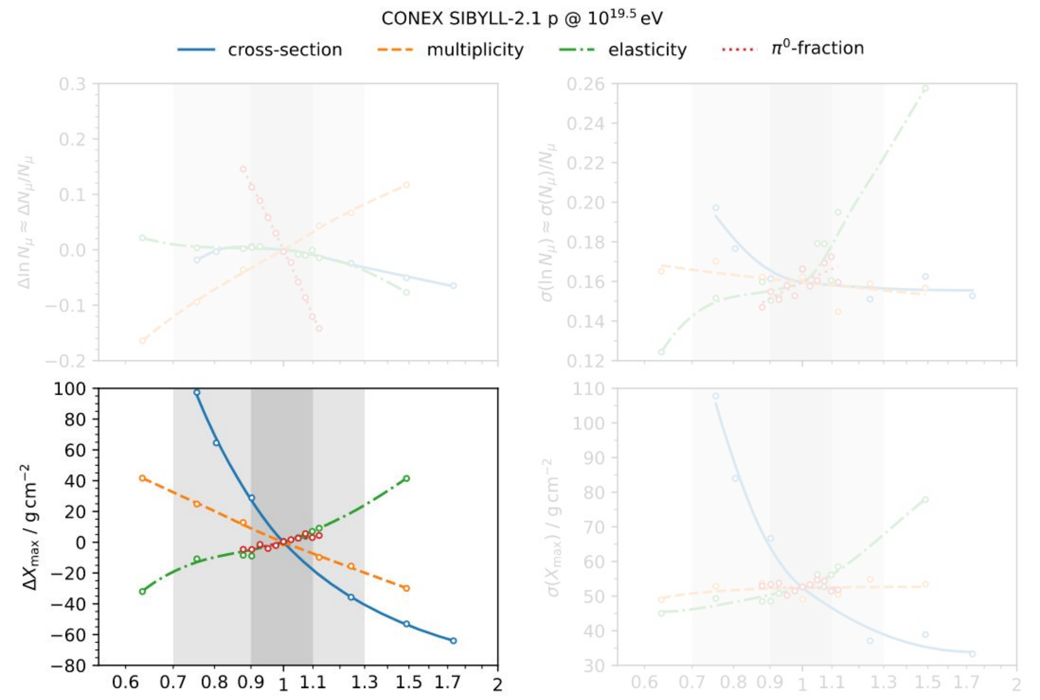


R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026

- The number of muons is sensitive to:
  - the cross-section
  - the π-ratio

... and in other experiments

What can we do to increase the muon content of simulations?

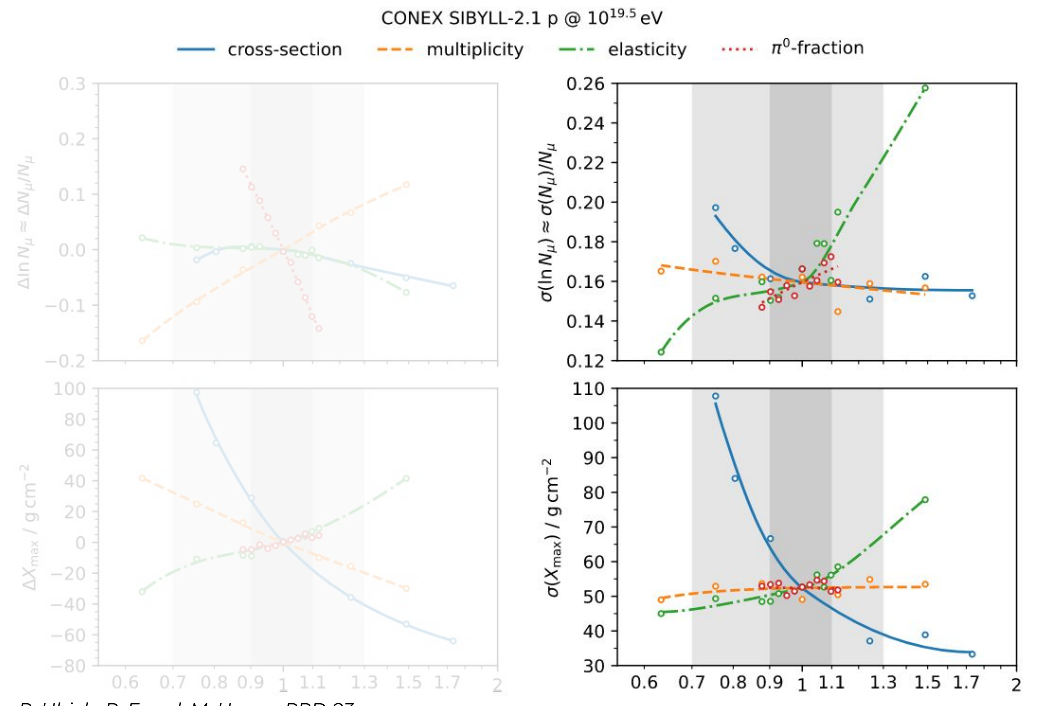


R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026

- ➢ The number of muons is sensitive to:
  - ○ the cross-section
  - ○ the π-ratio
- ➢ X_{max} sensitive to:
  - ○ the cross-section

… and in other experiments

What can we do to increase the muon content of simulations?

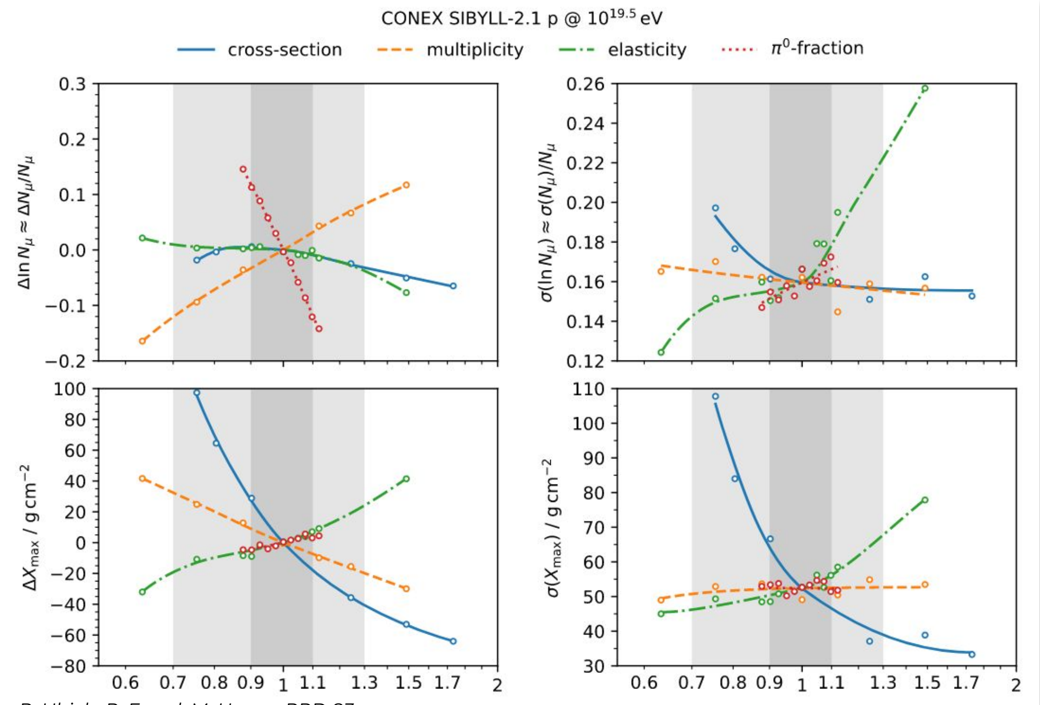


R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026

- The number of muons is sensitive to:
  - the cross-section
  - the π-ratio
- X_{max} sensitive to:
  - the cross-section
- Fluctuations NOT sensitive to the π-ratio.

… and in other experiments

What can we do to increase the muon content of simulations?



R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026

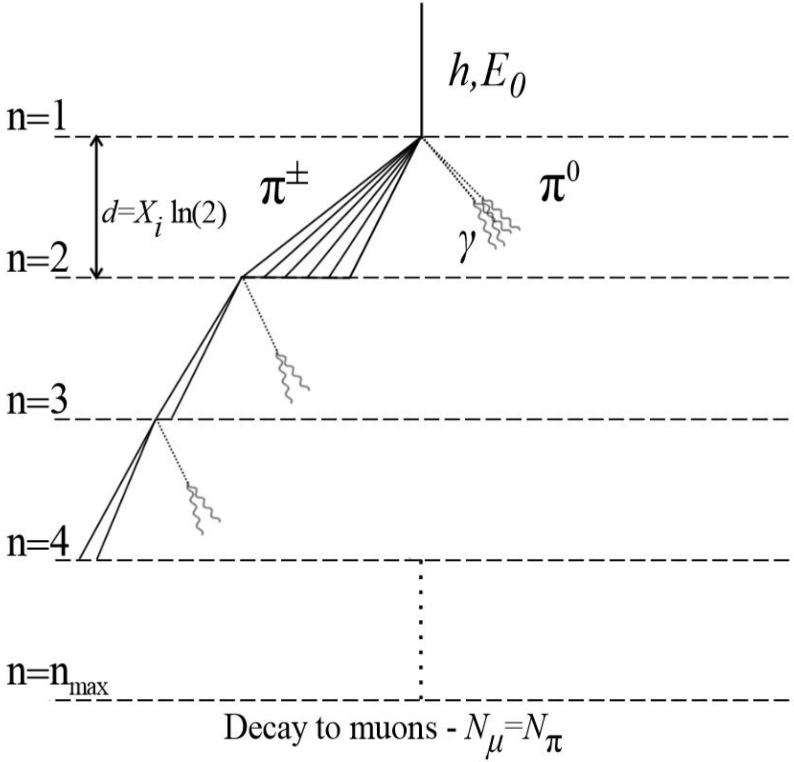
- ➢ The number of muons is sensitive to:
  - the cross-section
  - the π-ratio
- ➢ X_{max} sensitive to:
  - the cross-section
- ➢ Fluctuations NOT sensitive to the π-ratio.

π-ratio modification most promising direction!

Heitler-Matthews Model of Extensive Air Showers

How to constrain the π-ratio?

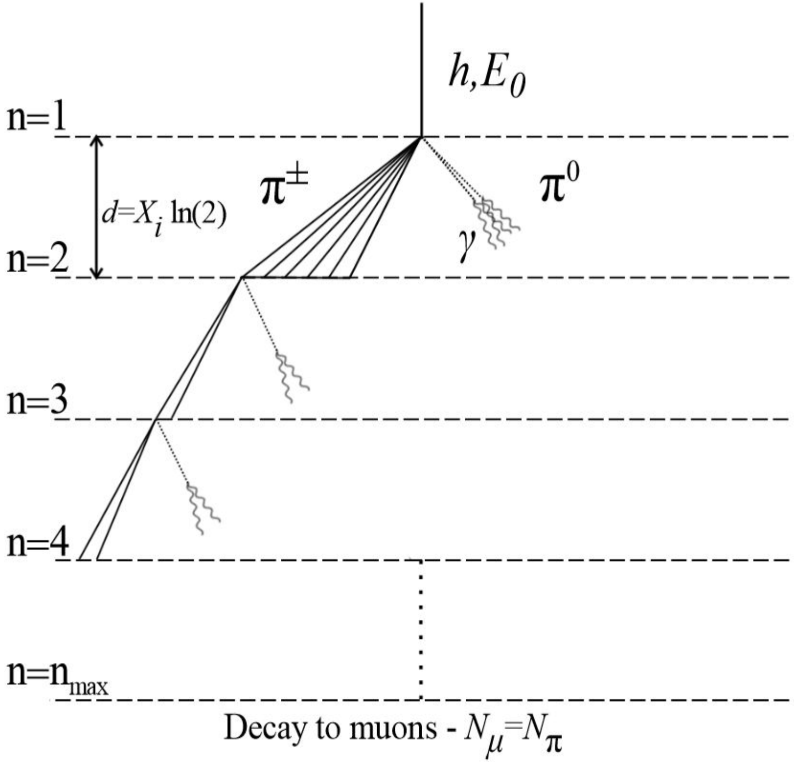
- ➢ Toy-model describing the development of hadronic air showers.



Heitler-Matthews Model of Extensive Air Showers

How to constrain the π-ratio?

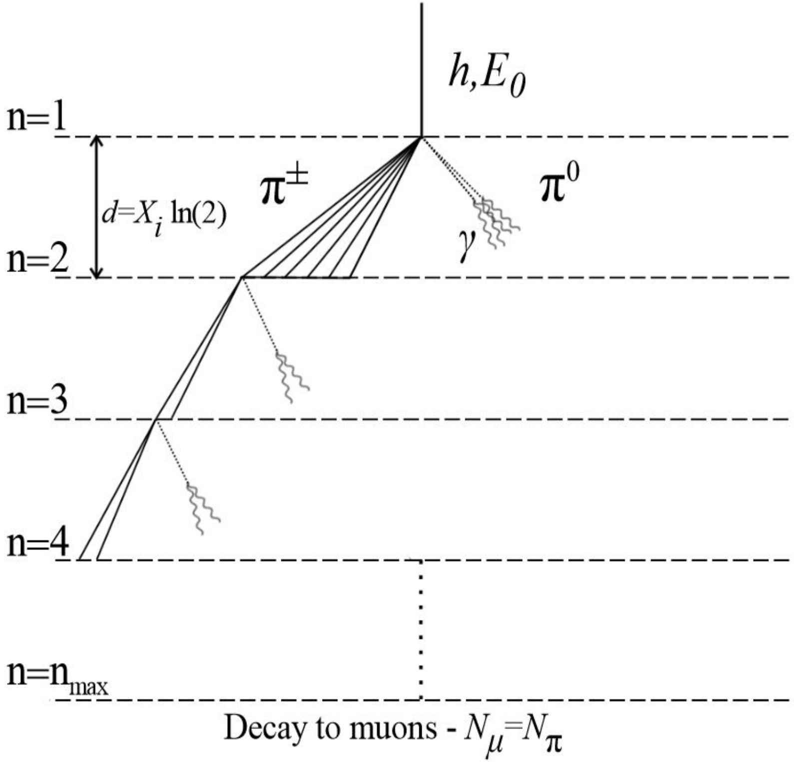
- Toy-model describing the development of hadronic air showers.
  - **2:1** ratio of charged to neutral π.



Heitler-Matthews Model of Extensive Air Showers

How to constrain the π-ratio?

- ➢ Toy-model describing the development of hadronic air showers.
  - ❖ **2:1** ratio of charged to neutral π.
  - ❖ Decay to muons when $\mathbf{E_{\pi,c}}$ **~ 20 GeV**



Heitler-Matthews Model of Extensive Air Showers

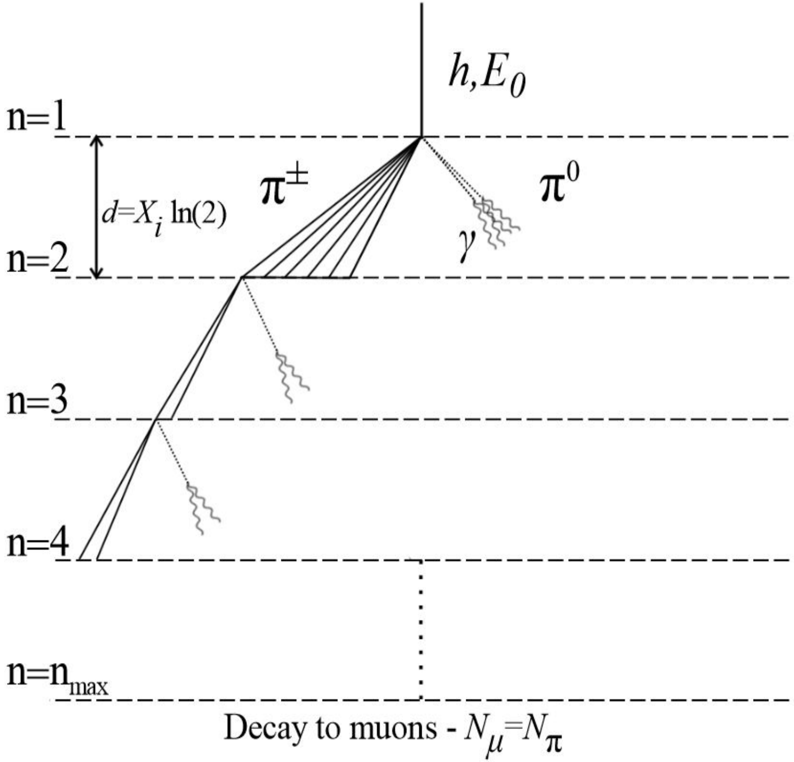
How to constrain the π-ratio?

➢ Toy-model describing the development of hadronic air showers.

❖ **2:1** ratio of charged to neutral π.

❖ Decay to muons when $\mathbf{E_{\pi,c}}$ **~ 20 GeV**

Number of muons: $N_\mu \simeq A\left(\frac{E/A}{\epsilon_c^\pi}\right)^\beta$



Heitler-Matthews Model of Extensive Air Showers

How to constrain the π-ratio?

➢ Toy-model describing the development of hadronic air showers.

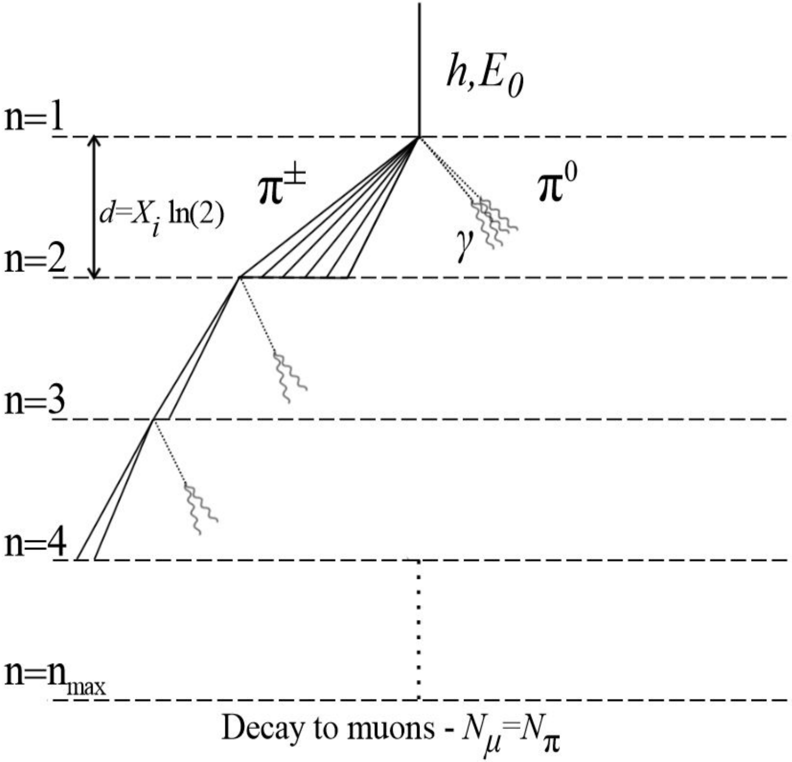
❖ **2:1** ratio of charged to neutral π.

❖ Decay to muons when $\mathbf{E_{\pi,c}}$ **~ 20 GeV**

Number of muons: $$N_\mu \simeq A\left(\frac{E/A}{\epsilon_c^\pi}\right)^\beta$$

$$\beta = \frac{\ln r\, n_{\mathrm{mult}}}{\ln n_{\mathrm{mult}}}$$

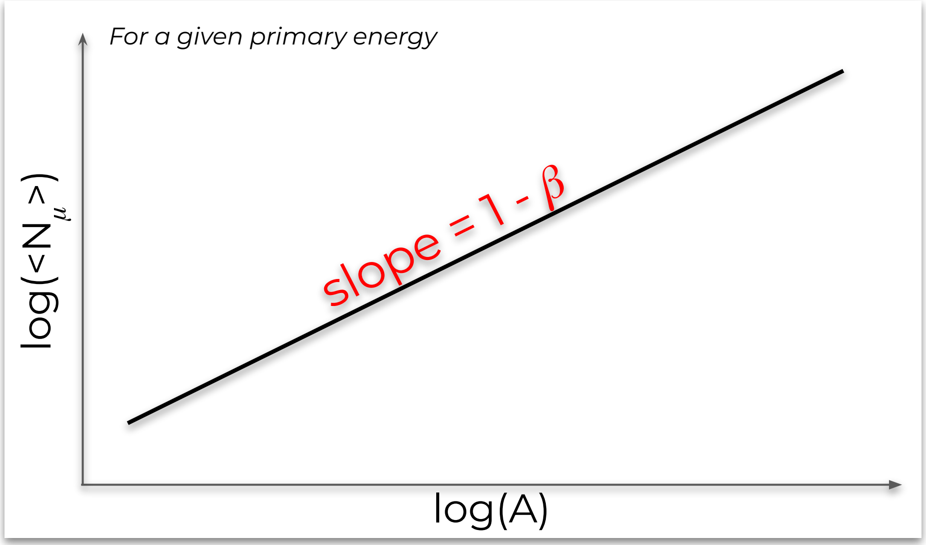
(typically ~0.92 for all hadronic models)



Heitler-Matthews Model of Extensive Air Showers

How to calculate the Heitler-Matthews β coefficient?

The β coefficient represents the slope of the change in the muon content as a function of the primary mass (in logarithmic scale).



The Top-Down Method

For showers with zenith angles below 60 degrees, disentangling the muon component from the electromagnetic one can be challenging…

The Top-Down Method

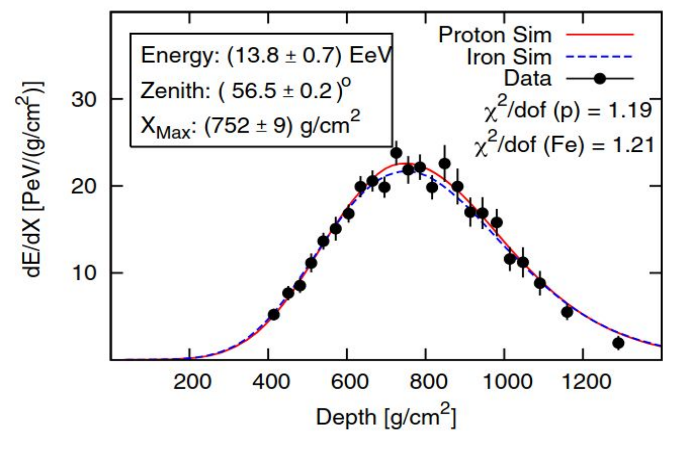
For showers with zenith angles below 60 degrees, disentangling the muon component from the electromagnetic one can be challenging...

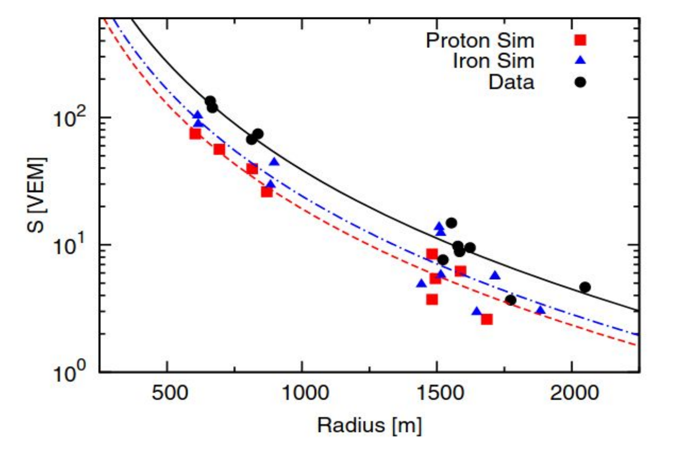
Top-Down simulations: estimating the muon content of an input dataset of observed* air showers and quantifying the discrepancy with hadronic model predictions of simulated air showers, by matching their longitudinal profiles.

The Top-Down Method

For showers with zenith angles below 60 degrees, disentangling the muon component from the electromagnetic one can be challenging...

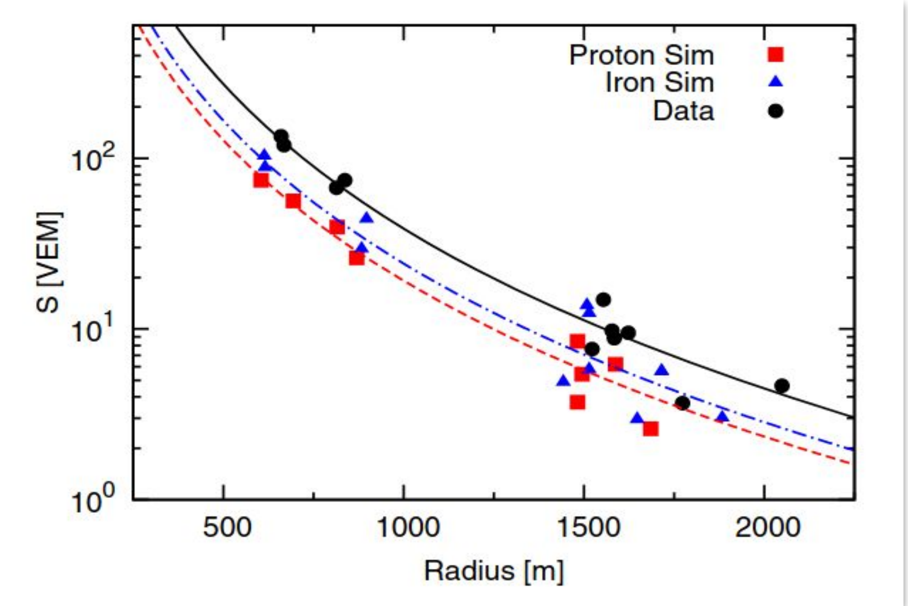
Top-Down simulations: estimating the muon content of an input dataset of observed* air showers and quantifying the discrepancy with hadronic model predictions of simulated air showers, by matching their longitudinal profiles.





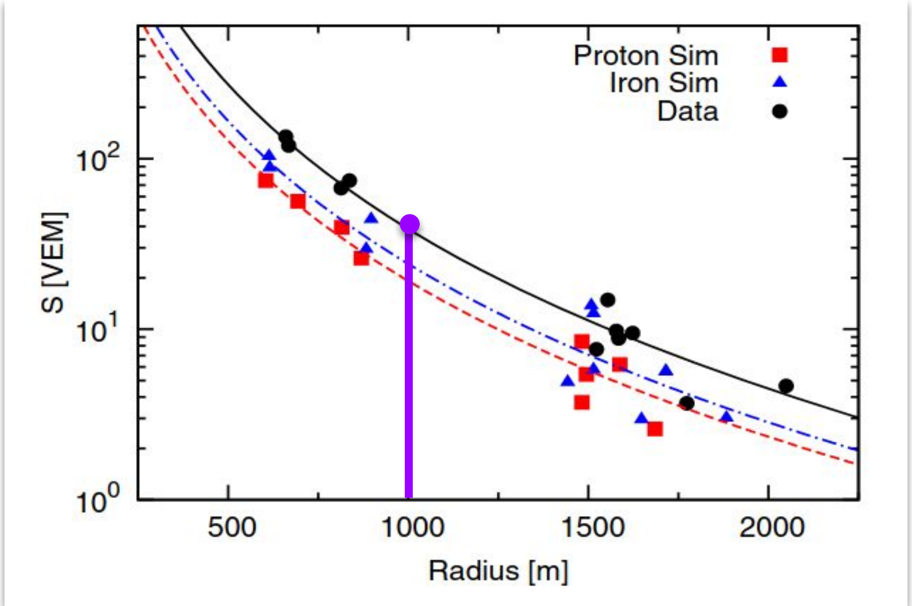
The Top-Down Method

How to rescale the Monte-Carlo simulations?



The Top-Down Method

How to rescale the Monte-Carlo simulations?



For a simulated primary *k*:

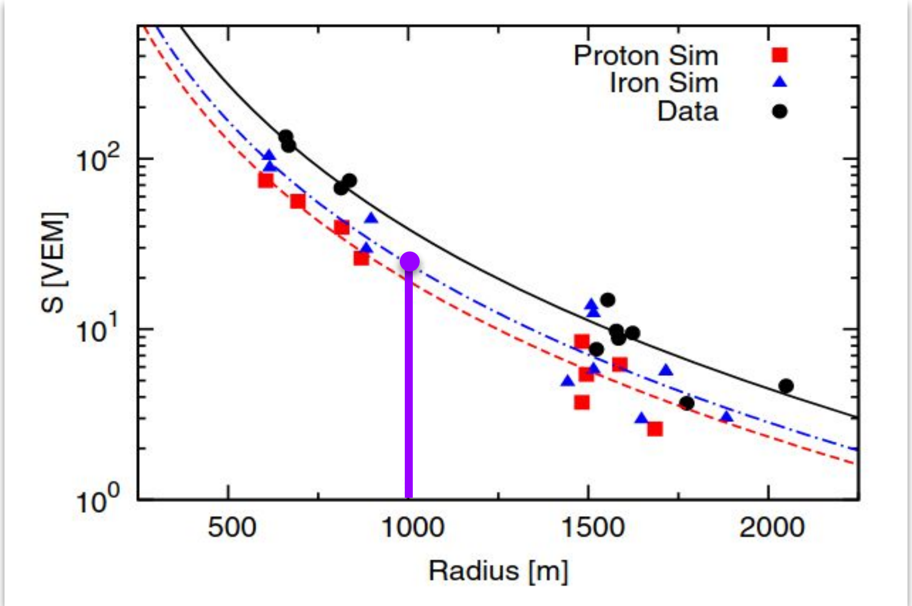
$$S - \bar{S}_k = \varepsilon_{\mu,k} \bar{S}_{\mu,k} \; ^*$$

data total signal

* signal at 1000 meters

The Top-Down Method

How to rescale the Monte-Carlo simulations?



For a simulated primary k:

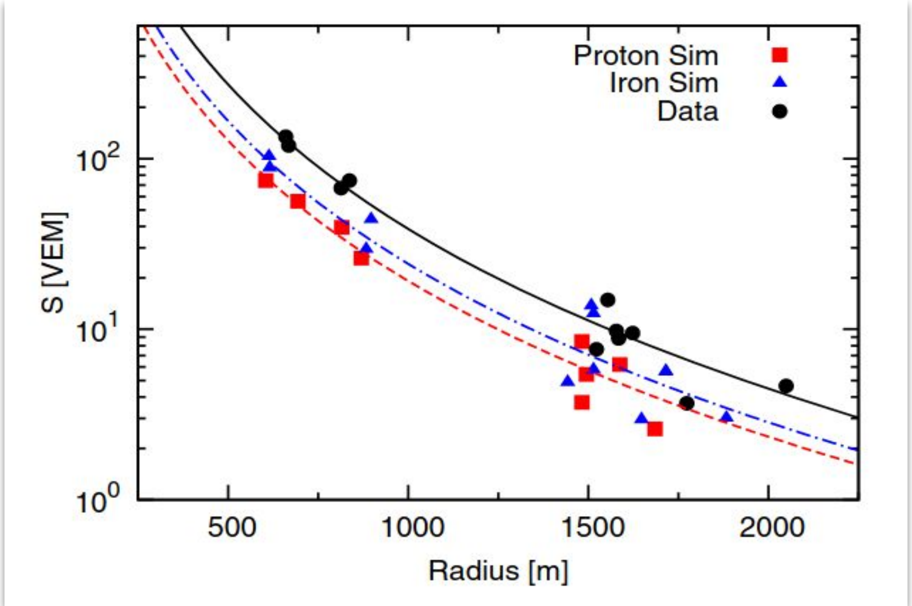
$$S - \bar{S}_k = \varepsilon_{\mu,k} \bar{S}_{\mu,k} \; ^*$$

MC total signal

* signal at 1000 meters

The Top-Down Method

How to rescale the Monte-Carlo simulations?



For a simulated primary *k*:

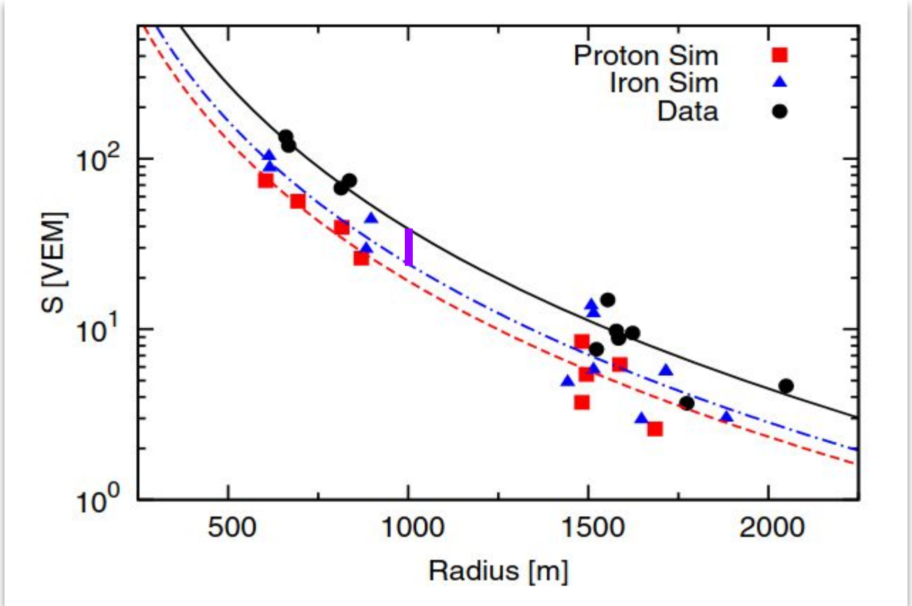
$$S - \bar{S}_k = \varepsilon_{\mu,k} \bar{S}_{\mu,k}^{*}$$

MC muon signal

* signal at 1000 meters

The Top-Down Method

How to rescale the Monte-Carlo simulations?



For a simulated primary *k*:

$$S - \bar{S}_k = \varepsilon_{\mu,k} \bar{S}_{\mu,k} \; *$$

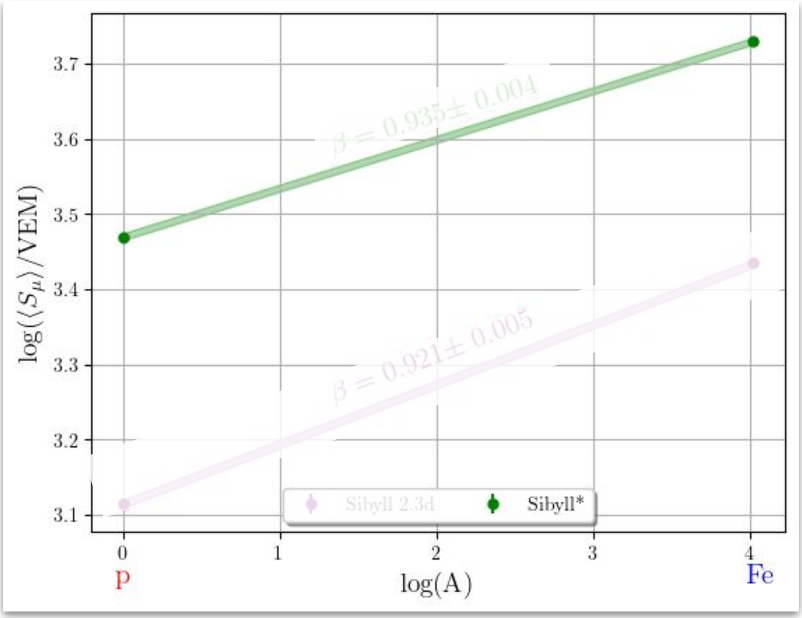
Rescaling of the MC muon signal

* signal at 1000 meters

The Top-Down Method

Application to a mock-up dataset of known composition

10^{19}eV - θ < 60 degrees

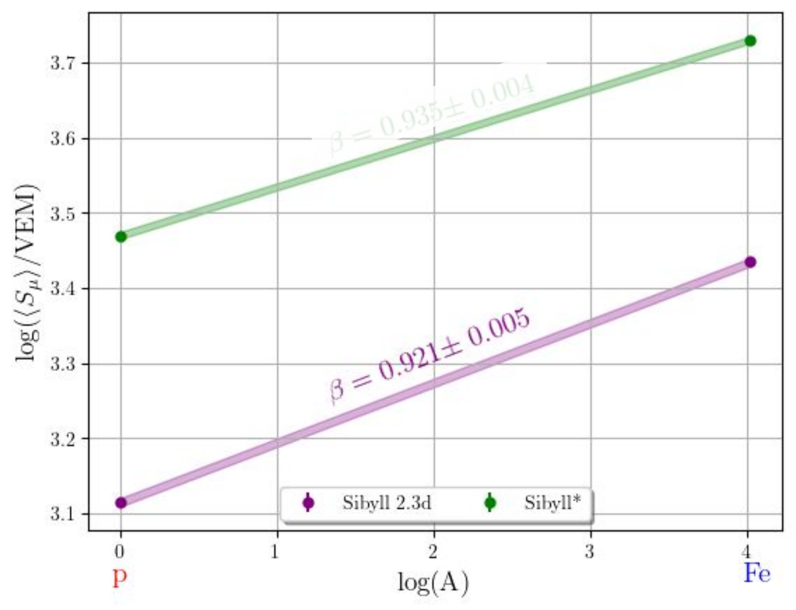


- Mock-up data: **Sibyll*** hadronic model→ modification* of Sibyll 2.3d to artificially **increase the number of muons by ~30%**.

The Top-Down Method

Application to a mock-up dataset of known composition

10^{19}eV - θ < 60 degrees

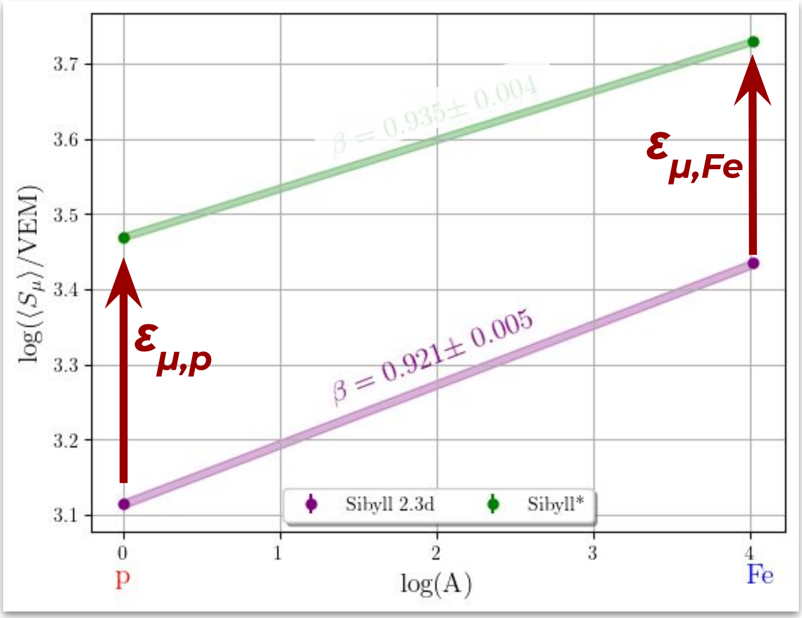


- Mock-up data: **Sibyll*** hadronic model→ modification* of Sibyll 2.3d to artificially **increase the number of muons by ~30%**.
- Match the longitudinal profiles with **Sibyll 2.3d**.

The Top-Down Method

Application to a mock-up dataset of known composition

10^{19}eV - θ < 60 degrees

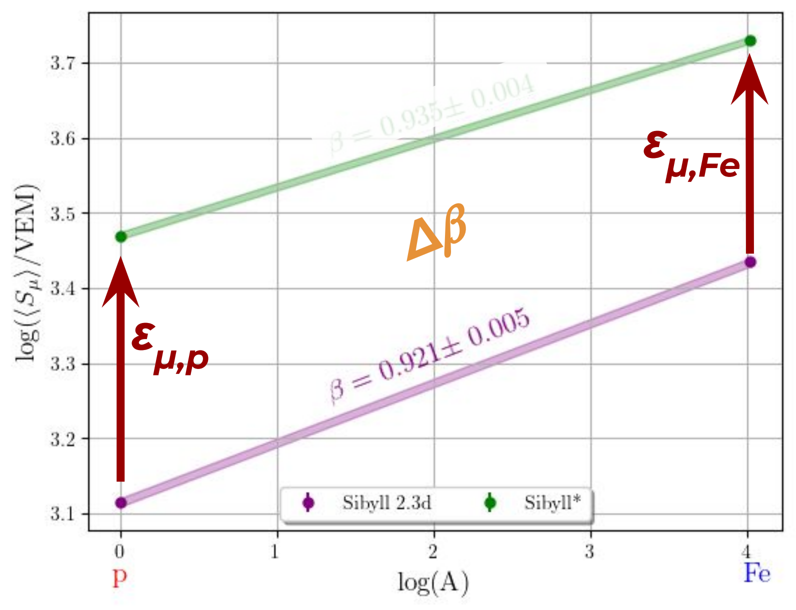


- ➢ Mock-up data: **Sibyll*** hadronic model→ modification* of Sibyll 2.3d to artificially **increase the number of muons by ~30%**.
- ➢ Match the longitudinal profiles with **Sibyll 2.3d**.
- ➢ Determine the **rescaling factors**.

The Top-Down Method

Application to a mock-up dataset of known composition

10^{19}eV - θ < 60 degrees

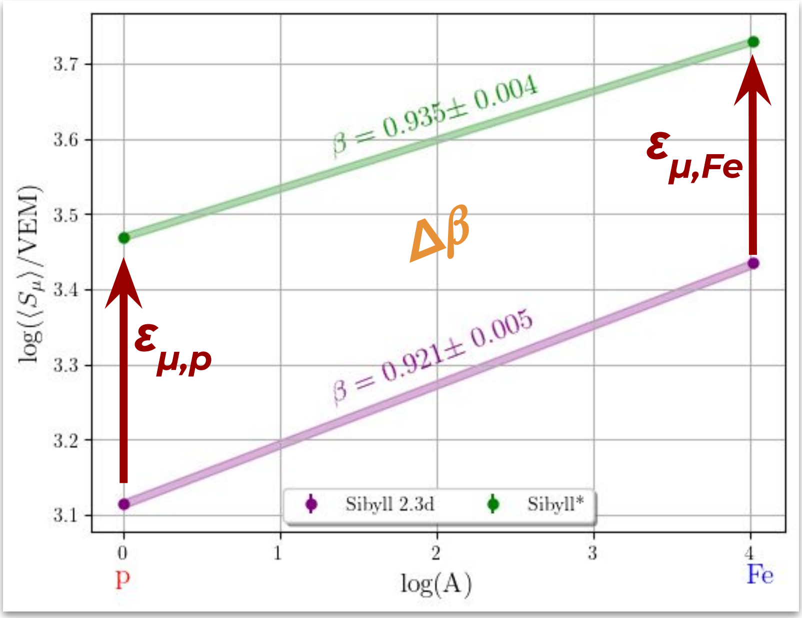


- Mock-up data: **Sibyll*** hadronic model→ modification* of Sibyll 2.3d to artificially **increase the number of muons by ~30%**.
- Match the longitudinal profiles with **Sibyll 2.3d**.
- Determine the **rescaling factors**.
- Deduce the required **change in β**.

The Top-Down Method

Application to a mock-up dataset of known composition

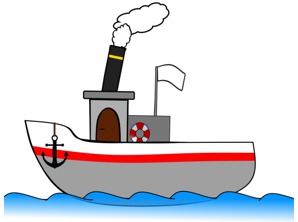
10^{19}eV - θ < 60 degrees



- <u>Mock-up data:</u> **Sibyll*** hadronic model→ modification* of Sibyll 2.3d to artificially **increase the number of muons by ~30%**.
- Match the longitudinal profiles with **Sibyll 2.3d**.
- Determine the **rescaling factors**.
- Deduce the required **change in β**.
- Do we retrieve the true β ?

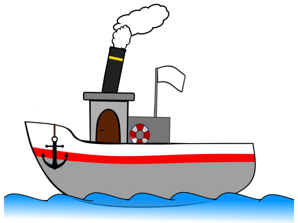
The Top-Down Method

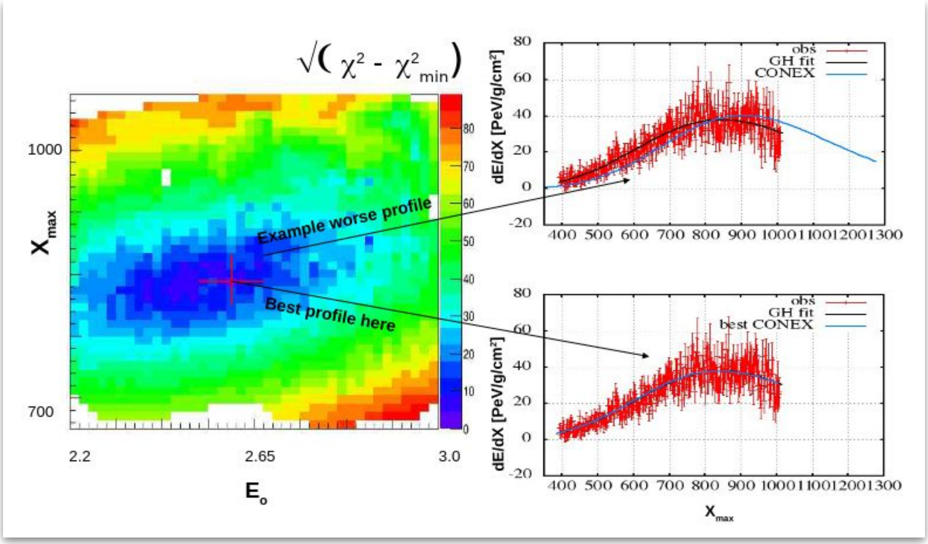
- Extensive simulations currently being performed on **Stoomboot**.



The Top-Down Method

- Extensive simulations currently being performed on **Stoomboot**.
- Finding a simulated shower with a matching longitudinal profile is a <u>time-consuming task</u>.

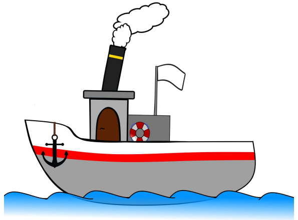




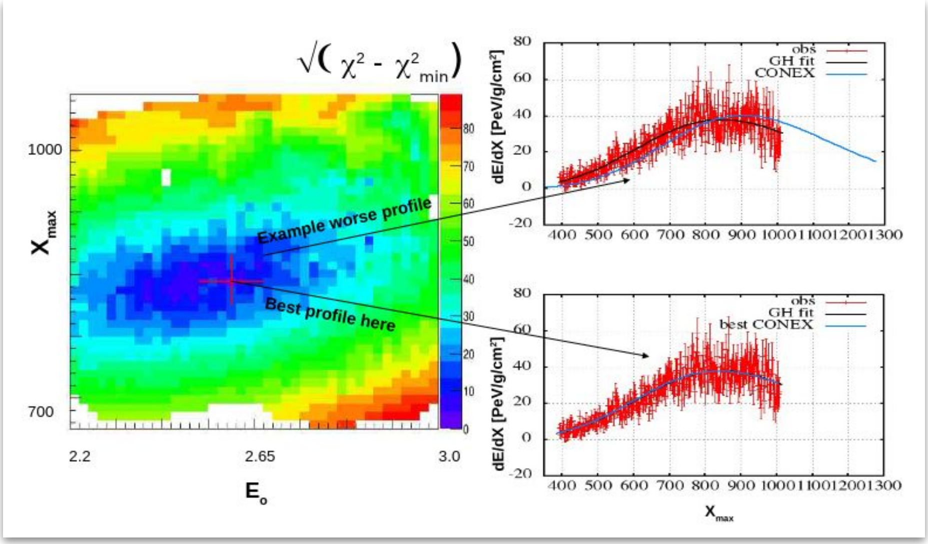
The Top-Down Method

- ➢ Extensive simulations currently being performed on **Stoomboot**.

- ➢ Finding a simulated shower with a matching longitudinal profile is a time-consuming task.

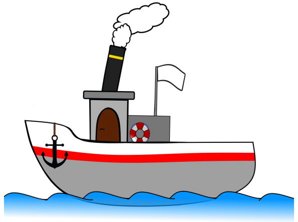


- ➢ Previous cross-checks of the method have shown **good results**.

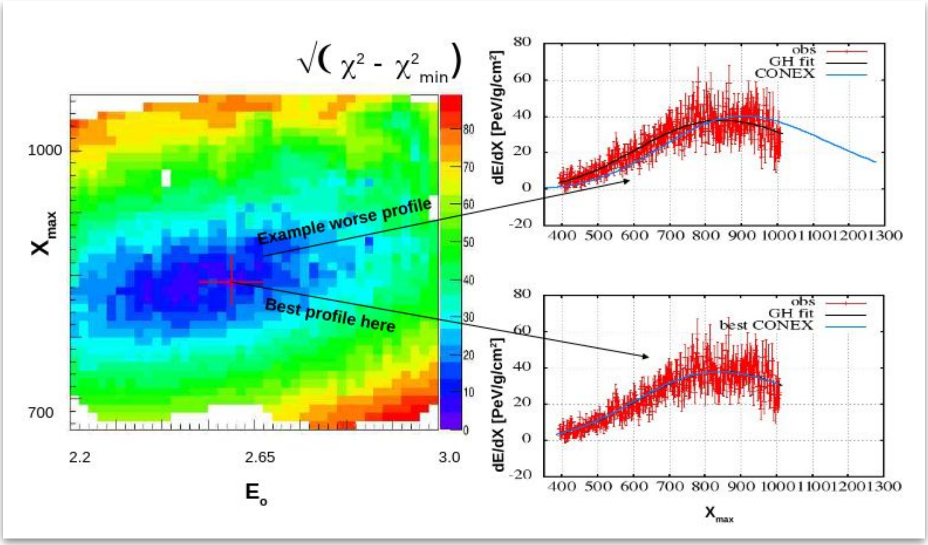


The Top-Down Method

- Extensive simulations currently being performed on **Stoomboot**.
- Finding a simulated shower with a matching longitudinal profile is a time-consuming task.



- Previous cross-checks of the method have shown **good results**.
- This should be the final one (hopefully...) before application to the real Auger data.



Summary

- The Heitler-Matthews β **coefficient** could be the key to understand how the hadronic models need to change to solve the Muon Puzzle.

Summary

- The Heitler-Matthews β **coefficient** could be the key to understand how the hadronic models need to change to solve the Muon Puzzle.

- **Top-Down Method**: matching of the longitudinal profile to understand how the muon signal of MC simulations must be rescaled.

Summary

- The Heitler-Matthews β **coefficient** could be the key to understand how the hadronic models need to change to solve the Muon Puzzle.

- **Top-Down Method**: matching of the longitudinal profile to understand how the muon signal of MC simulations must be rescaled.

- Preliminary results on Auger hybrid data could have significant impact on AugerPrime mass discrimination power $\rightarrow$ **need several cross-checks**!

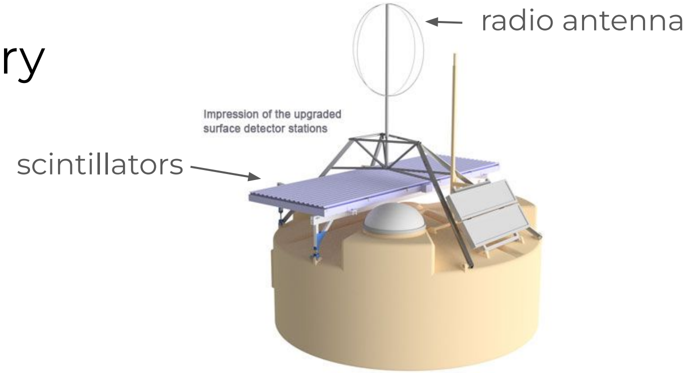
Summary

➢ The Heitler-Matthews β **coefficient** could be the key to understand how the hadronic models need to change to solve the Muon Puzzle.

➢ **Top-Down Method**: matching of the longitudinal profile to understand how the muon signal of MC simulations must be rescaled.

➢ Preliminary results on Auger hybrid data could have significant impact on AugerPrime mass discrimination power → **need several cross-checks**!

➢ The **upgrade** of the Pierre Auger Observatory will allow us to look into very inclined events and to better isolate the muonic component so...



Stay tuned!

Thank you!