Top-Down reconstruction of extensive air showers

A method to quantify the rescaling of the muon signal of hadronic interaction models.

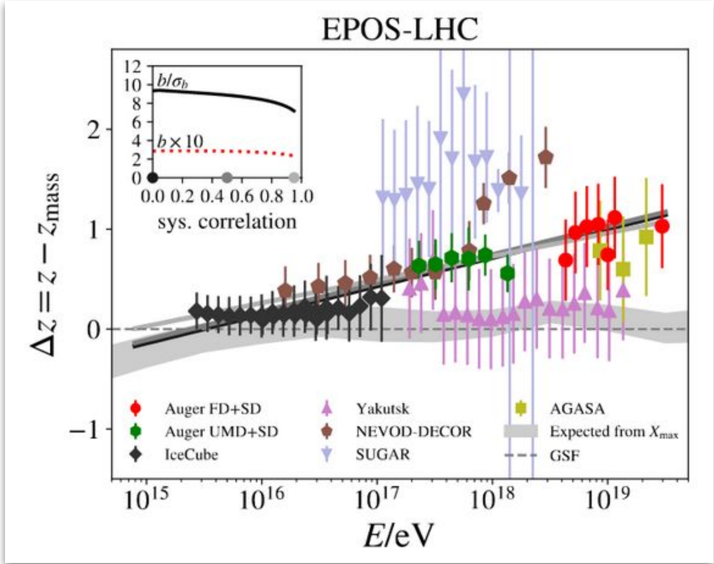
K. Almeida Cheminant, N. Borodai, R. Engel, D. Góra, T. Pierog, J. Pękala, M. Roth, M. Unger, D. Veberic and H. Wilczyński

Many thanks to the *Pierre Auger Collaboration* for the help and support!

(Highlights by A. Castellina on Wednesday morning)

Motivations

Muon deficit in simulations



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

*Update this afternoon by Juan Carlos Arteaga

➢ Quantify the discrepancy between data and hadronic models predictions in the context of the **muon puzzle**.

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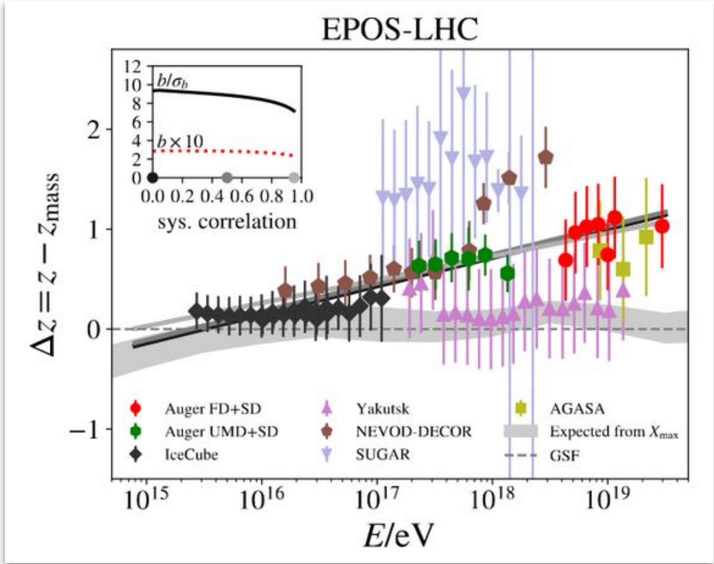


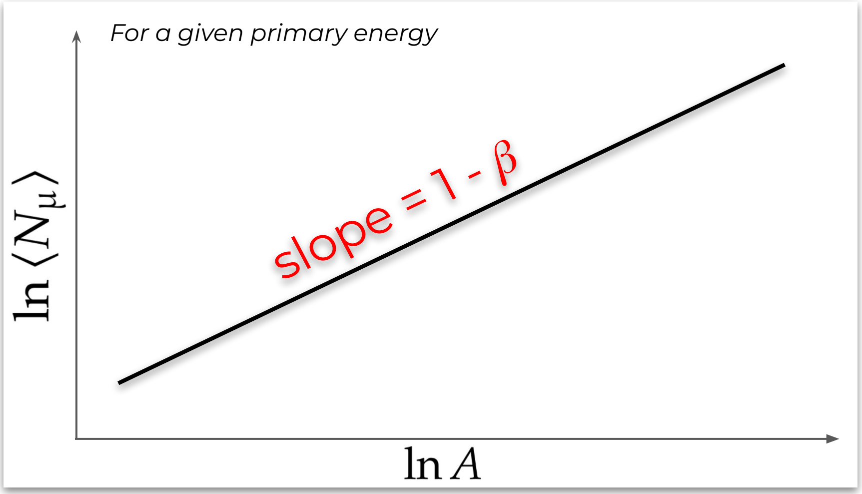
D. Soldin et al. (WHISP), PoS (ICRC2021) 349

**Update this afternoon by Juan Carlos Arteaga*

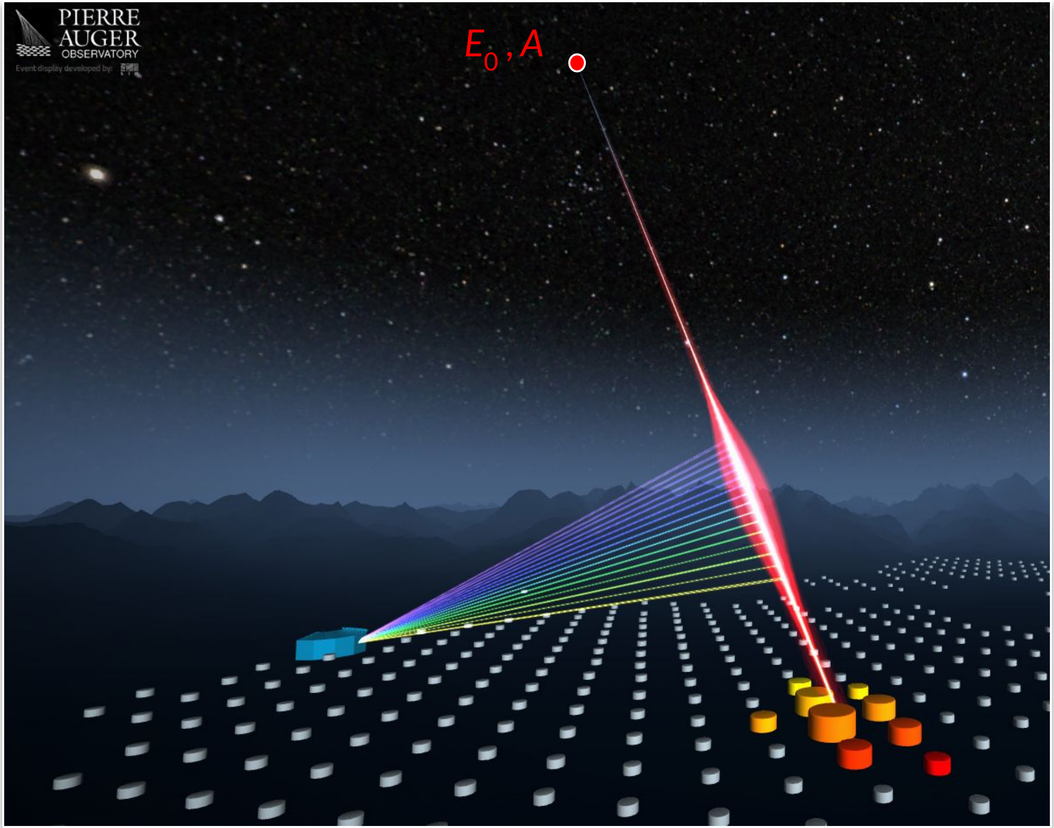
- ➢ Quantify the discrepancy between data and hadronic models predictions in the context of the **muon puzzle**.

Heitler-Matthews β coefficient

- ➢ Represents the **slope of the change in the muon content** of EAS as a function of the primary mass.
- ➢ Can help **constrain the amount of energy** carried away by the hadronic component.
- ➢ Determines the **mass discrimination power** of muons.



Measuring Extensive Air Showers



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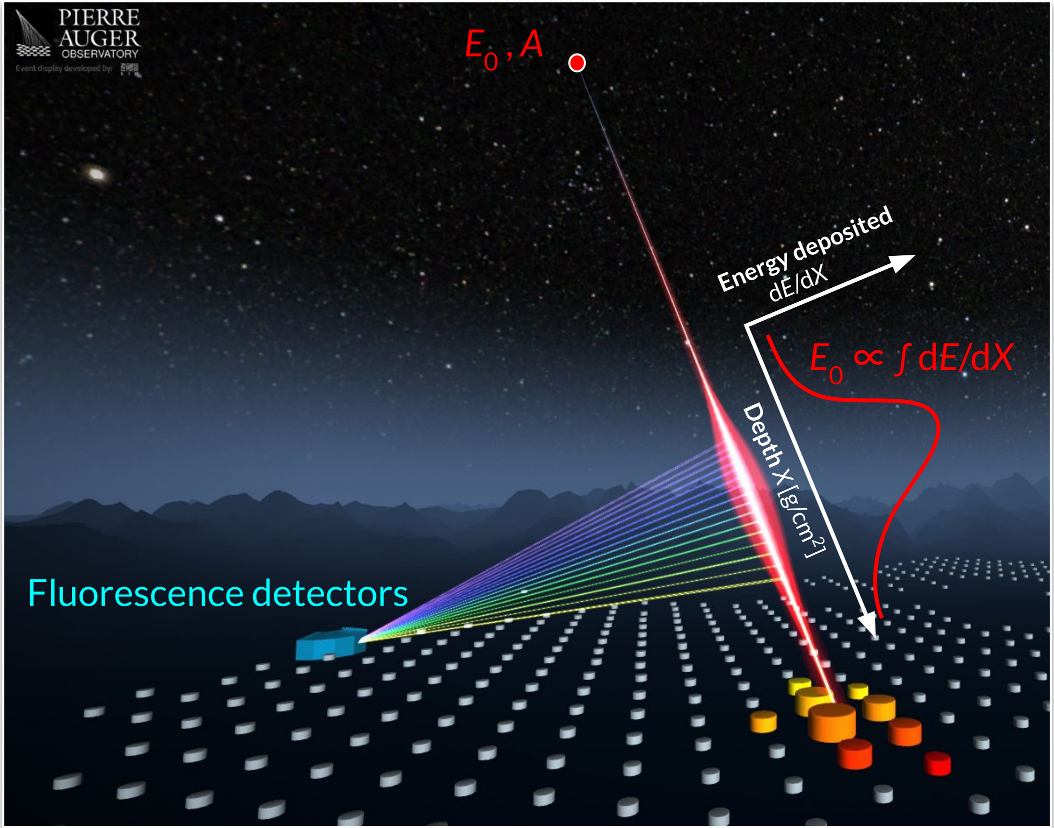
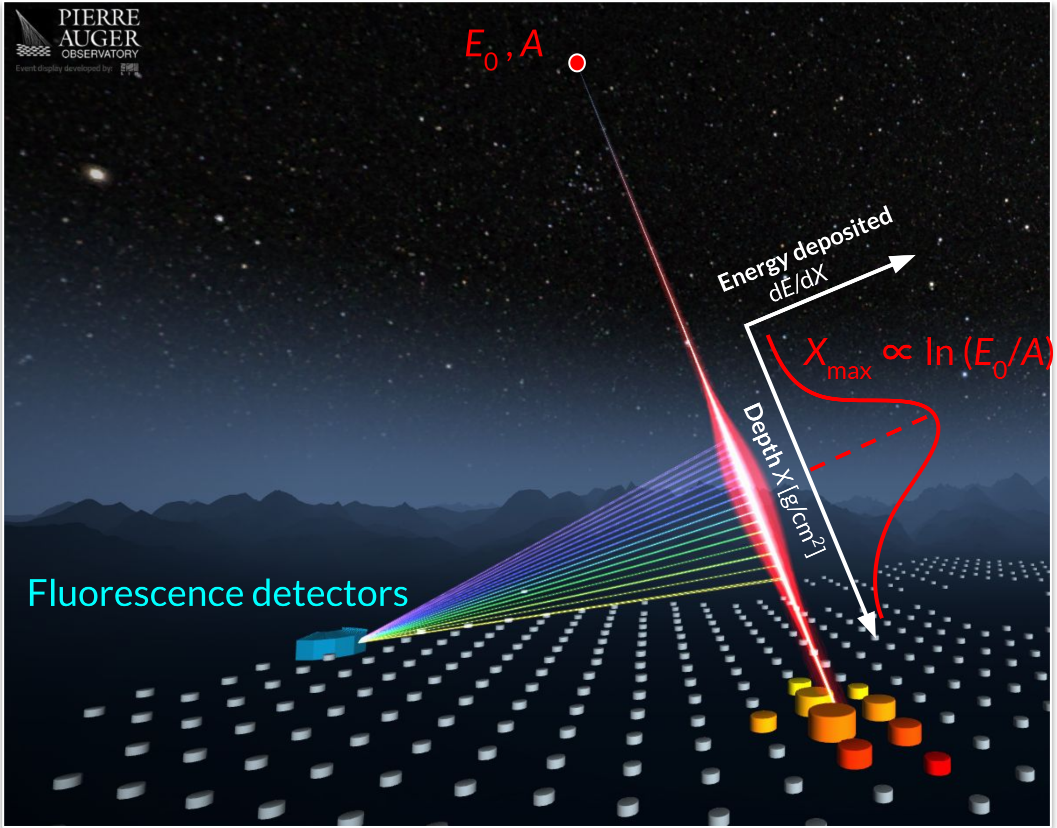


Longitudinal profile

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

Measuring Extensive Air Showers



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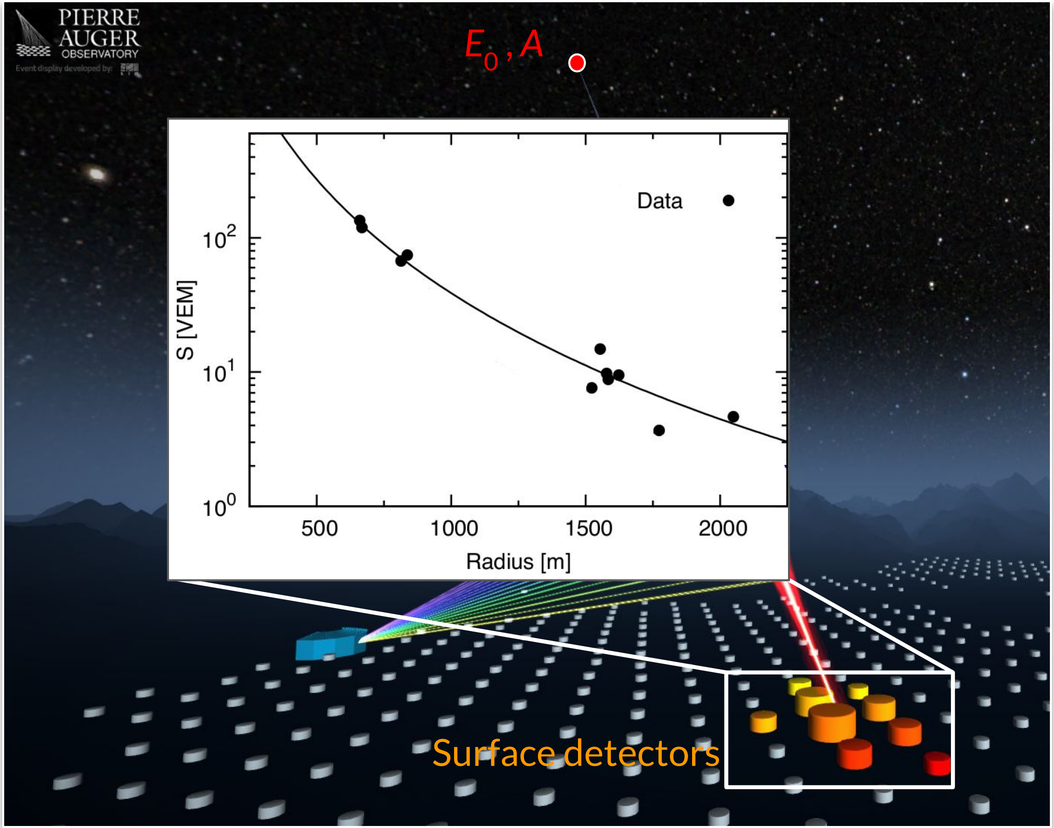

Longitudinal profile

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Ground distribution

- EM and muonic components formed by the decay of $\pi^{+/-}$ and $K^{+/-}$.
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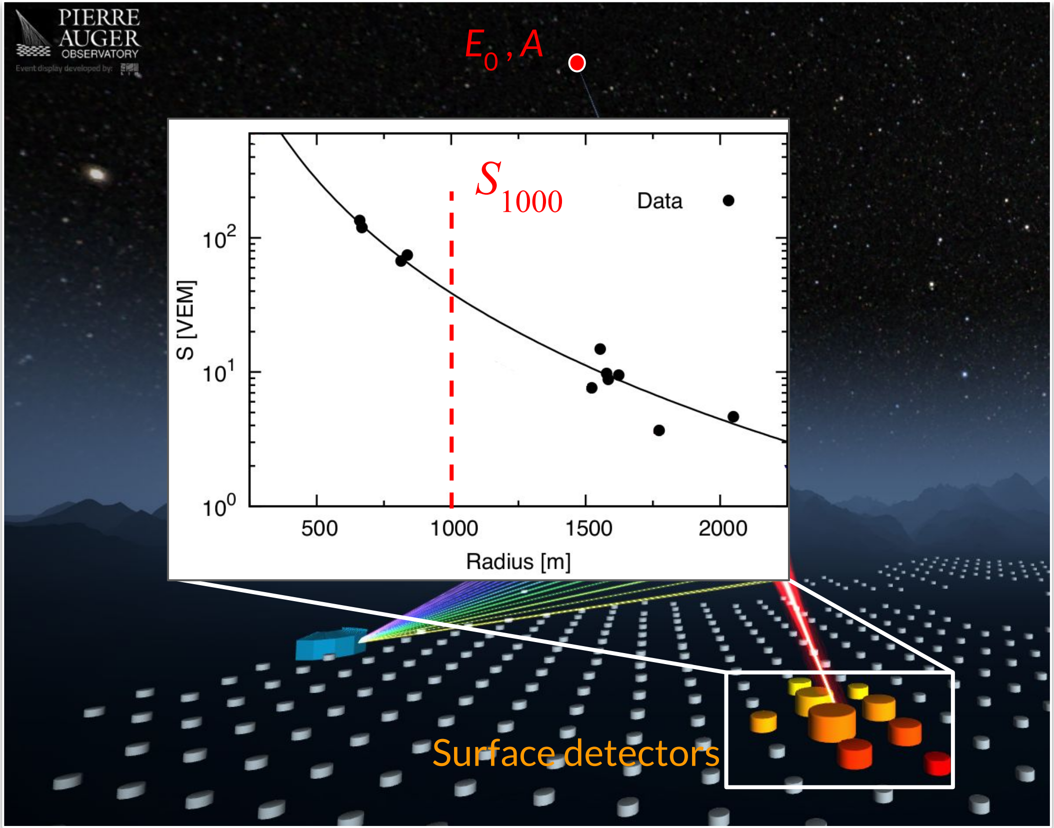

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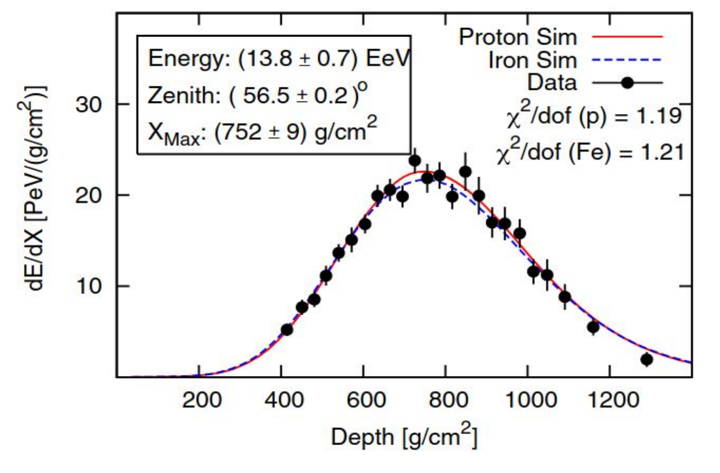
The Top-Down Method

For an **observed shower** of a given *energy* and *arrival direction*

➢ Find a simulated shower that has a **similar longitudinal profile** in order to constrain the electromagnetic component.



Pierre Auger Collab., PRL 117, 192001 (2016)

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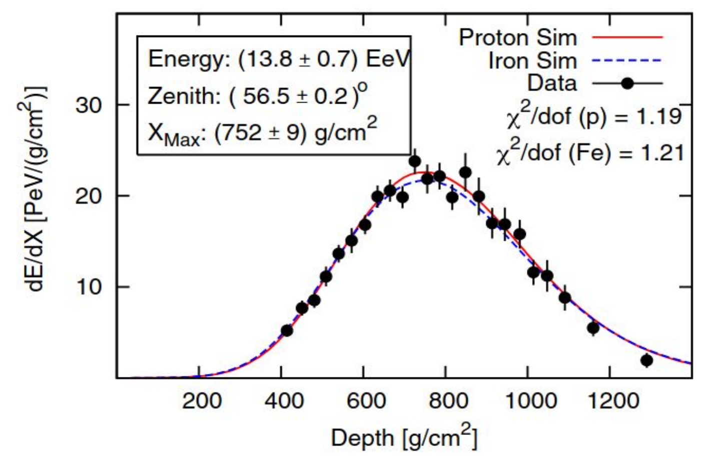

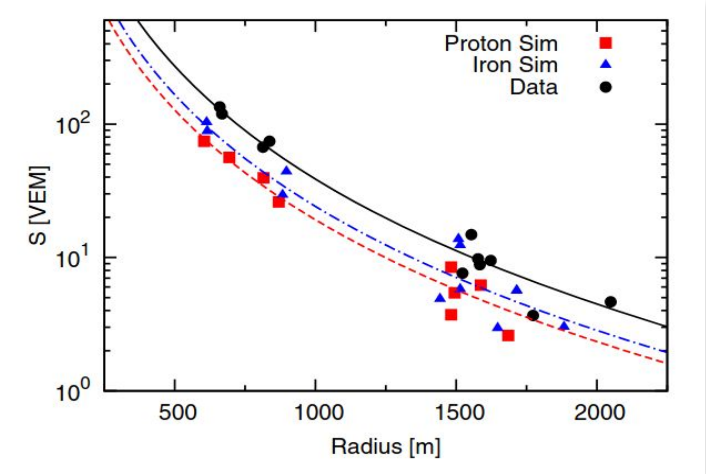

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CONEX

Simulation and single Offline FD **reconstruction** of CONEX showers

Objective: find a simulated shower with the **best longitudinal profile match**.

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→

CORSIKA

Full MC simulation of the best CONEX shower and **hybrid** reconstruction

Objective: obtain the **ground signal**.

→ **Reconstructed showers** with LP matched to the observed one.

The Sibyll* mockup dataset

- <u>Mock-up data:</u> **Sibyll*** hadronic model→ modification of Sibyll 2.3d to artificially **increase the number of muons.**

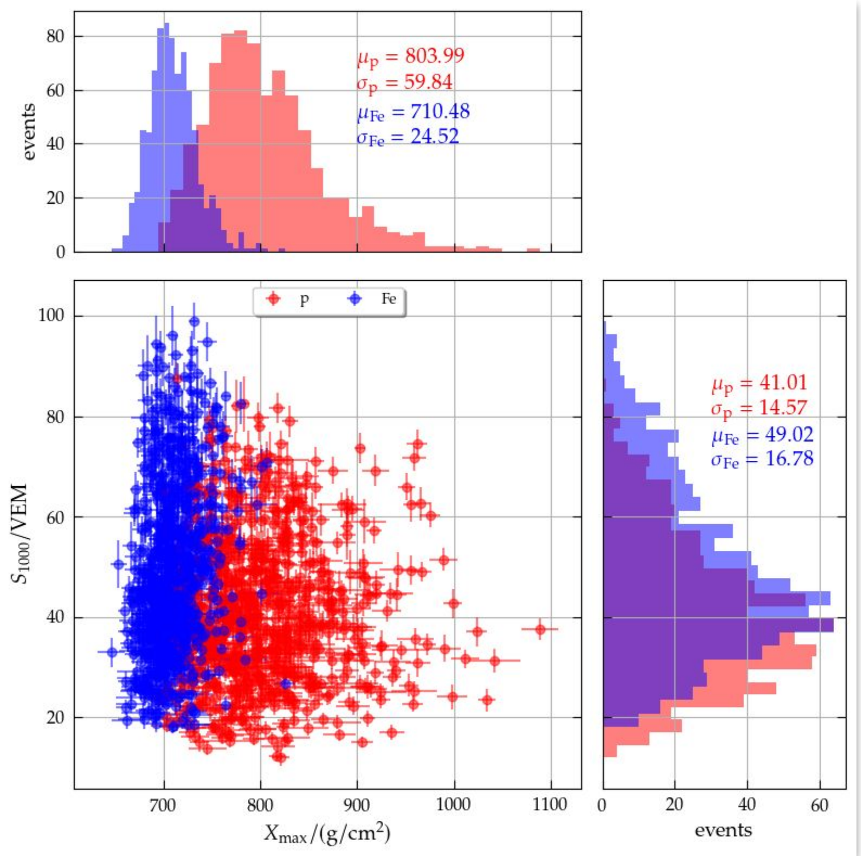
(Talk by F. Riehn on Thursday morning.)

The Sibyll* mockup dataset

➢ <u>Mock-up data:</u> **Sibyll*** hadronic model→ modification of Sibyll 2.3d to artificially **increase the number of muons.**

(Talk by F. Riehn on Thursday morning.)

- Primary particles: **proton** & **iron**
- Energy range: **18.8 < lg(E/eV) < 19.2**
- Zenith angle: θ **< 60 deg**
- Quality cuts applied to obtain events with well-measured longitudinal profiles.
- Number of showers: **800 proton** & **800 iron**.



CONEX simulations

Finding a simulated shower whose longitudinal profile matches the one of the input shower.

- We select the **Sibyll 2.3d** model to try and match the Sibyll* mockup dataset.
- **Same CORSIKA, low-energy hadronic model** and **detector reconstruction software** versions as the one used to produce the Sibyll* mockup dataset are chosen.
- Simulation input specifying **energy** & **direction** of the shower to be matched.
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Best CONEX selection

- Run and reconstruct **thousands** of CONEX showers.
- Select the CONEX shower producing the **best fit with the longitudinal profile of the input shower** and whose reconstructed X_{max} , E_{cal} , dE/dX_{max} are within uncertainties of the input shower.

CONEX simulations

Finding a simulated shower whose longitudinal profile matches the one of the input shower.

- Test → 800 **proton** showers from mockup dataset and matched with CONEX showers simulated with **proton** primaries.

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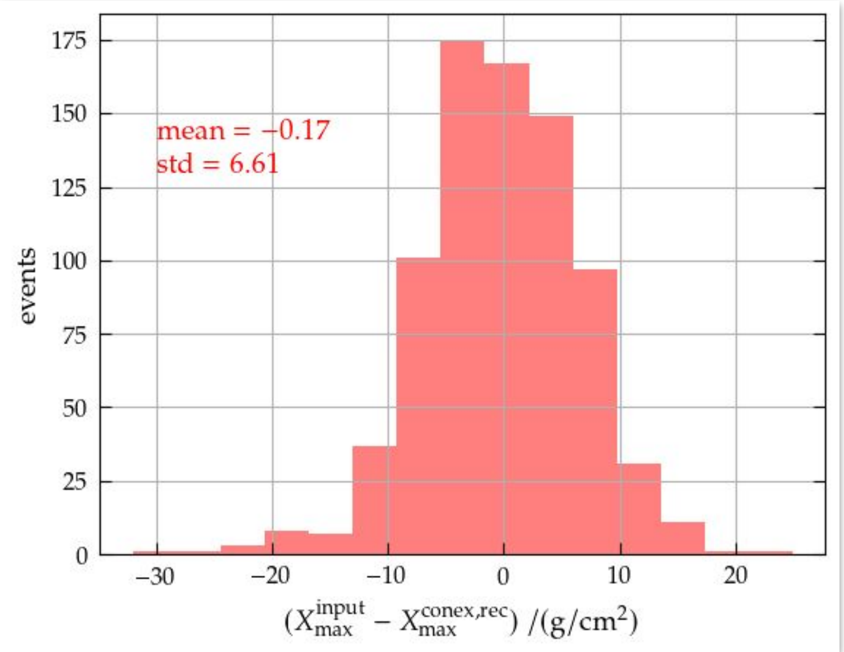

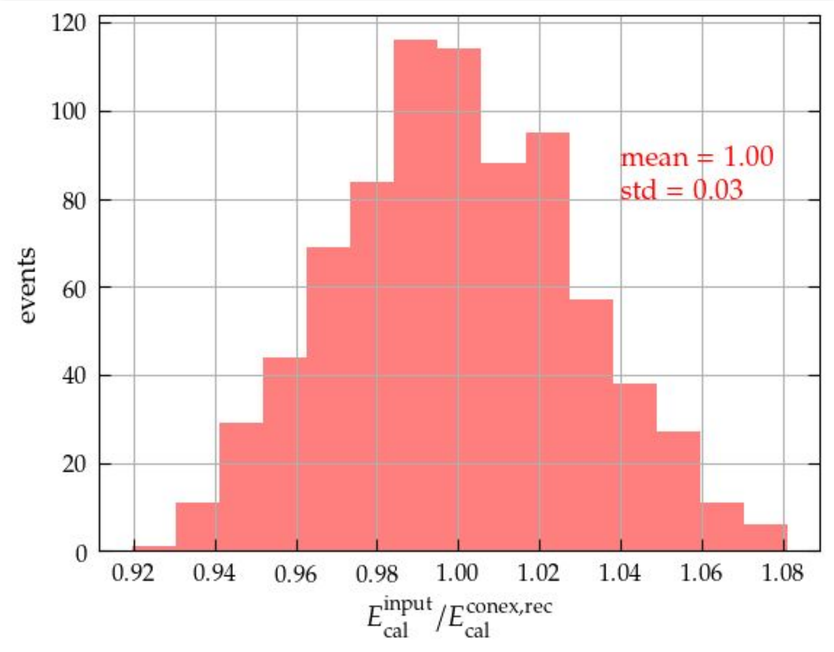

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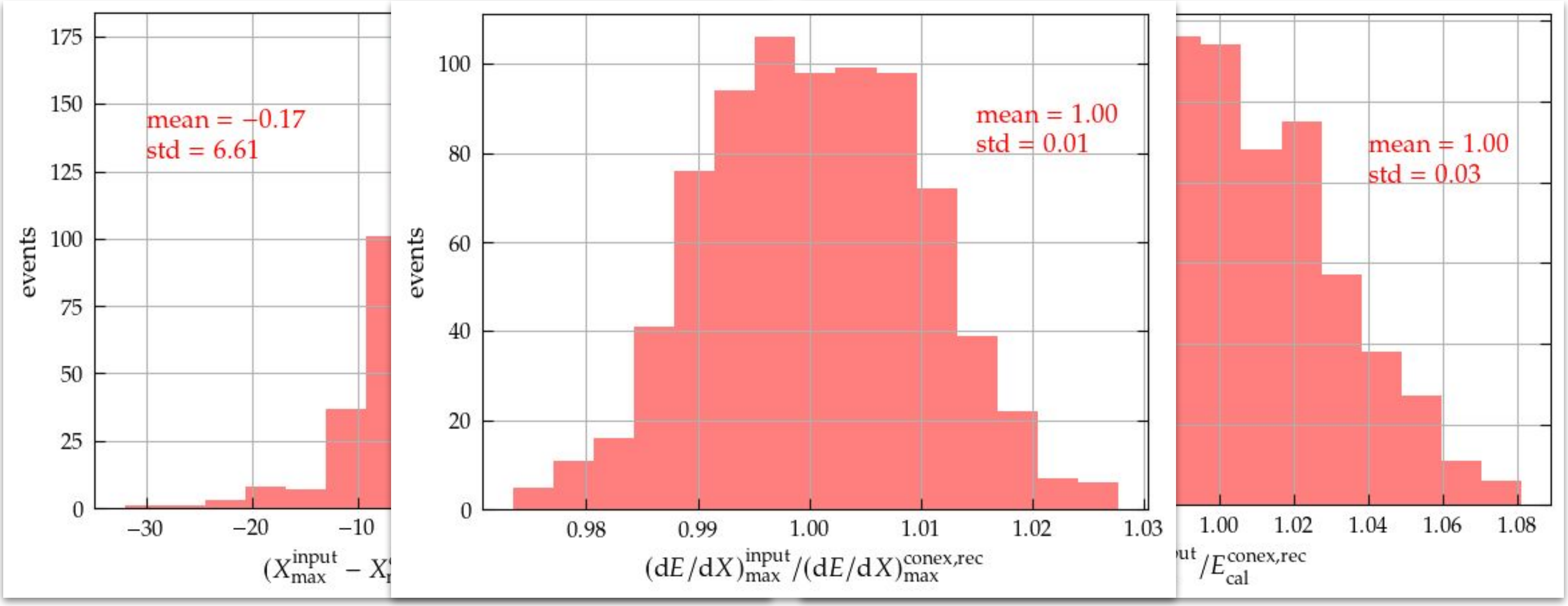


CORSIKA simulations

Full Monte Carlo simulation and Offline reconstructions of the best CONEX shower.

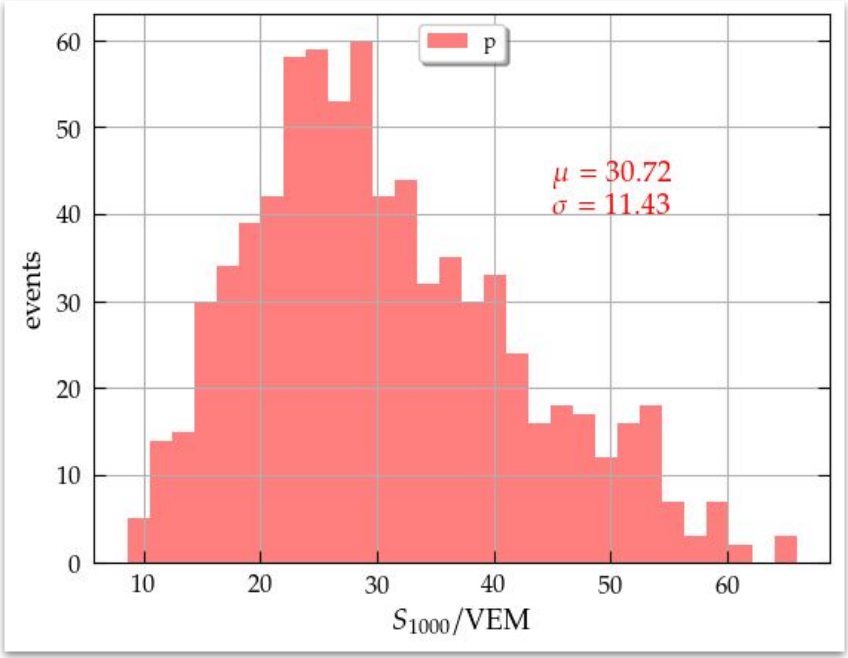
- Input card similar to the CONEX one - **same SEEDS**.
- **Full Monte Carlo simulation** with information on the ground distribution of particles retrieved.
- Multiple **hybrid** reconstructions (SD +FD).
- The **best reconstruction** is selected using the same method as the one used to find the best CONEX.

NOTE: the transition from CONEX to full Monte Carlo simulations preserve the simulated longitudinal profile.

CORSIKA simulations

Full Monte Carlo simulation and Offline reconstructions of the best CONEX shower.

Distribution of the signal at a 1000 m from the shower core



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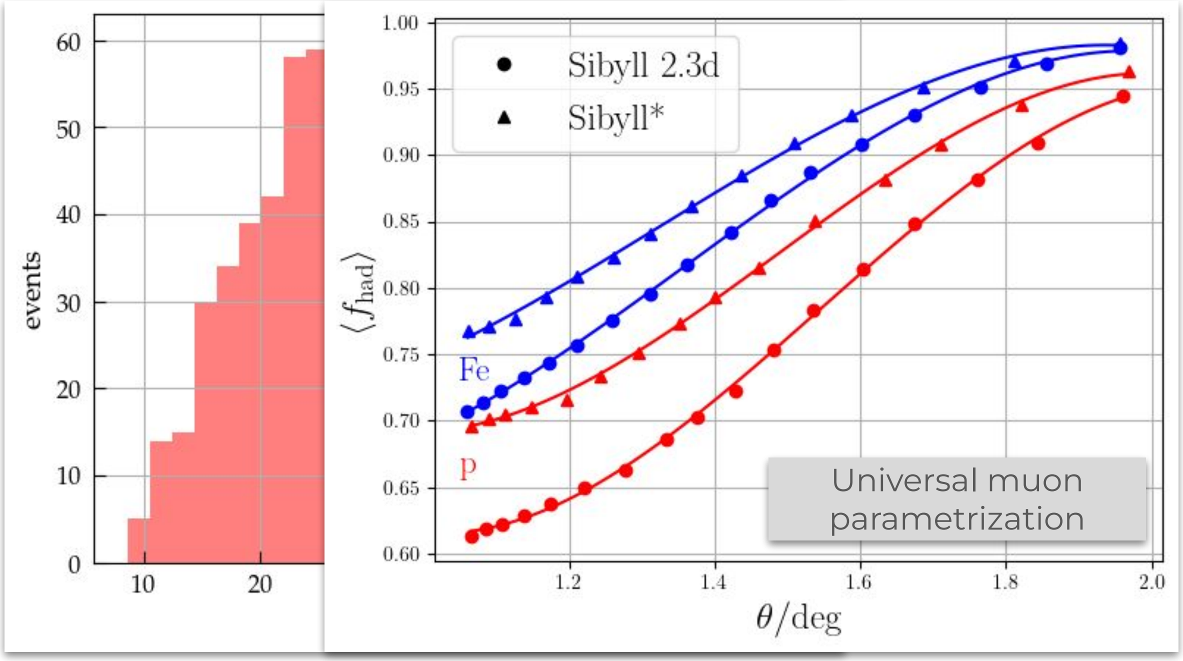

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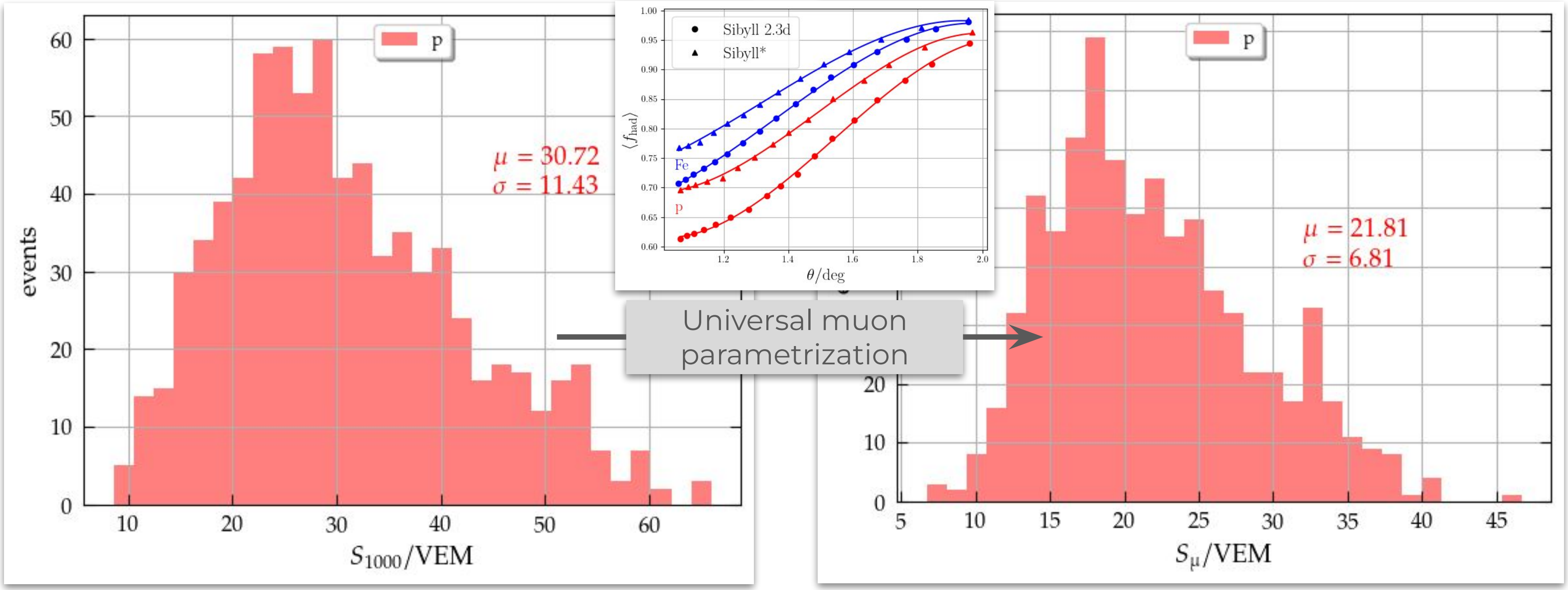

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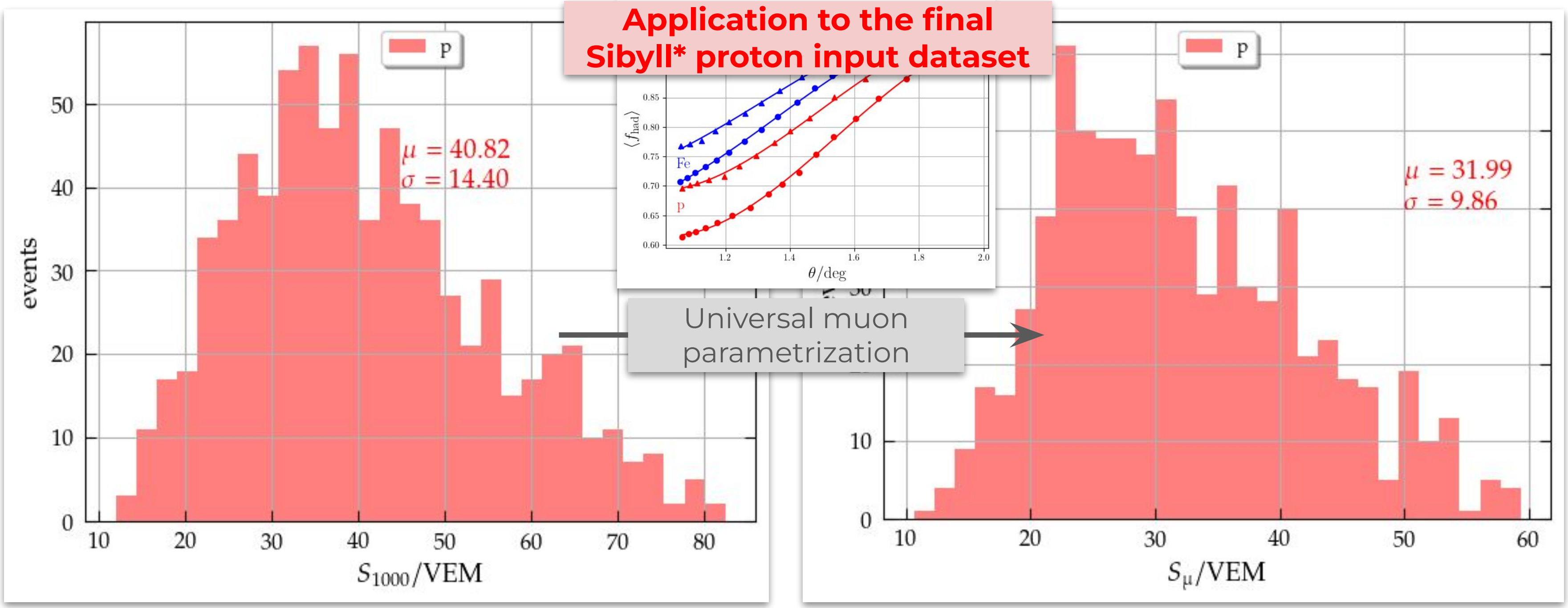

Results

Summary and rescaling factors

protons

	$\langle S_{1000} \rangle$ [VEM]	$\langle S_{\mu} \rangle$ [VEM]
Sibyll 2.3d (TD)	30.72 ± 0.41	21.81 ± 0.25
Sibyll* (mockup)	40.82 ± 0.52	31.99 ± 0.36

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- ➢ The true muon signal ratio is **1.47 ± 0.02**.
- ➢ In reality, this **quantity** is not accessible when dealing with real hybrid events since we do not know the composition on an event-by-event basis.
- ➢ **BUT**, the Top-Down paradigm and the matching of the longitudinal profile allows us to write the **rescaling factor**:

*Sibyll**

$$r_\mu = 1 + \frac{S_{1000}^{\mathrm{input}} - S_{1000}^{\mathrm{MC}}}{S_\mu^{\mathrm{MC}}}$$

Sibyll 2.3d

(derivation in back-up)

which gives us a ratio of **1.46 ± 0.03**.

Results

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iron

	$\langle S_{1000} \rangle$ [VEM]	$\langle S_{\mu} \rangle$ [VEM]
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- ➢ Rescaling factor:

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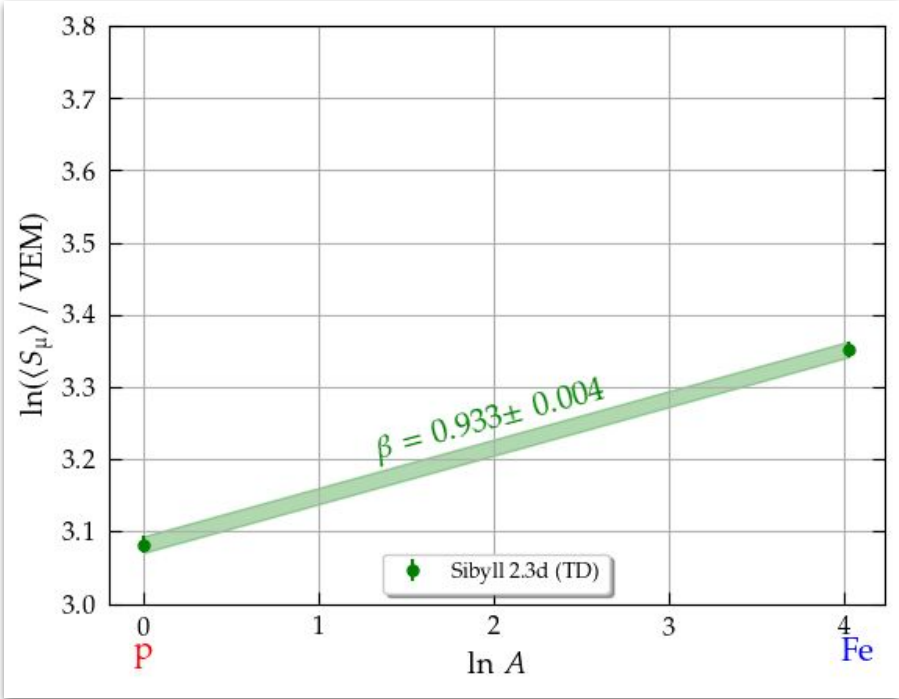
Heitler-Matthews coefficient

- The **Heitler-Matthews β** coefficient represents the slope of the change in the muon content as a function of the primary mass.

$$\beta = 1 - \frac{\ln \langle S_\mu^{\mathrm{p}} \rangle - \ln \langle S_\mu^{\mathrm{Fe}} \rangle}{\ln A^{\mathrm{p}} - \ln A^{\mathrm{Fe}}}$$



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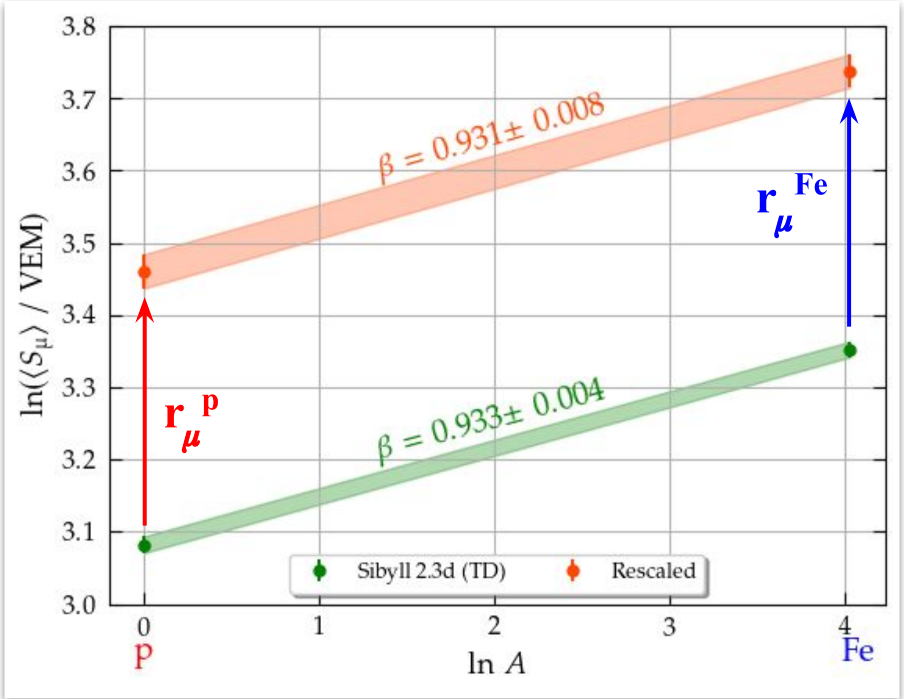
- We apply the rescaling factor and obtain the **rescaled model trend**.



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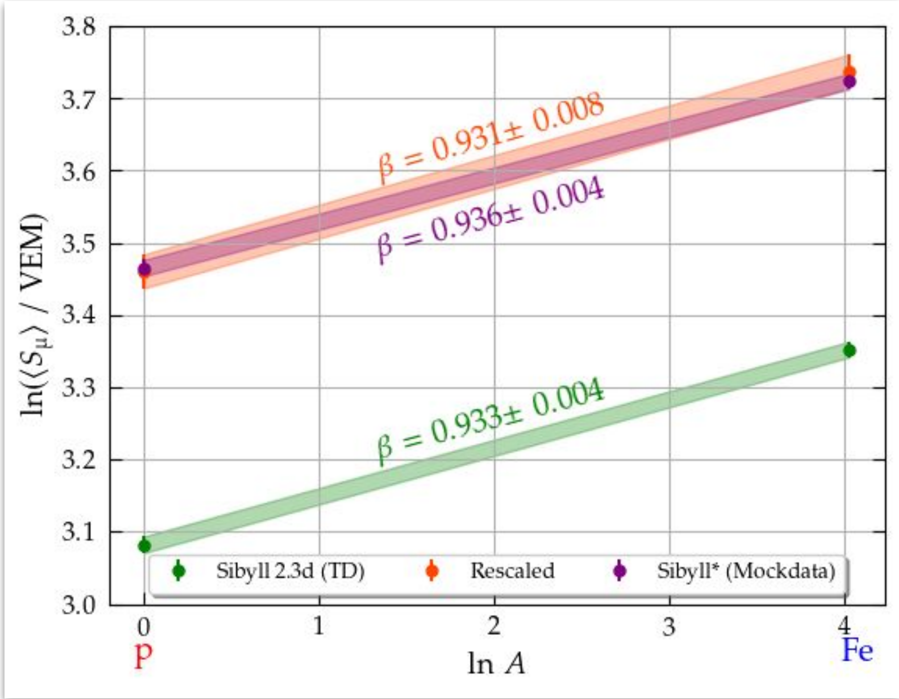
- ➢ We can compare to the true trend from our **mockup dataset**.



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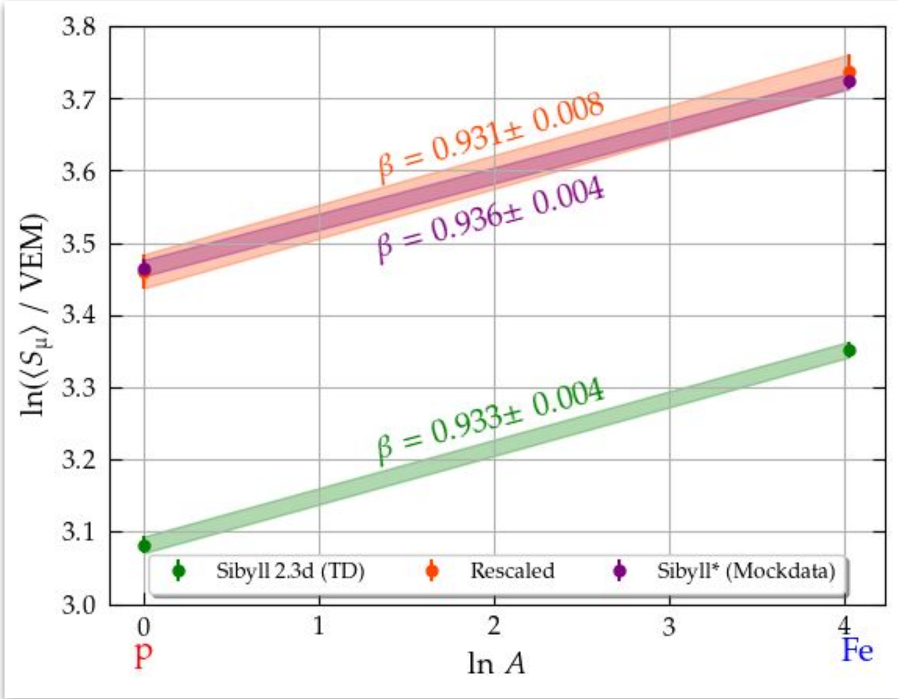
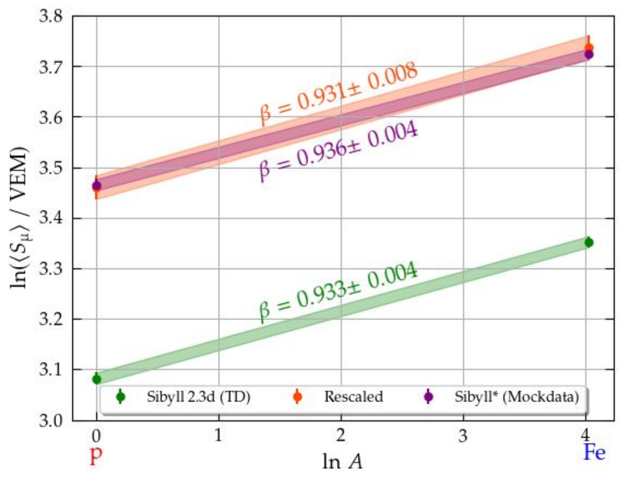
Very good agreement between the true and the rescaled model trends!



Summary

- Application of the **Top-Down method** to the muon-rich Sibyll* hadronic model, using Sibyll 2.3d simulations.
- The **average muon signals** of Sibyll* proton and iron primaries are well recovered with the rescaled Sibyll 2.3d.
- The calculated $\boldsymbol{\beta}$ **coefficient** of the rescaled Sibyll 2.3d is well within the uncertainties of the true β coefficient of Sibyll*.



Summary & Outlook

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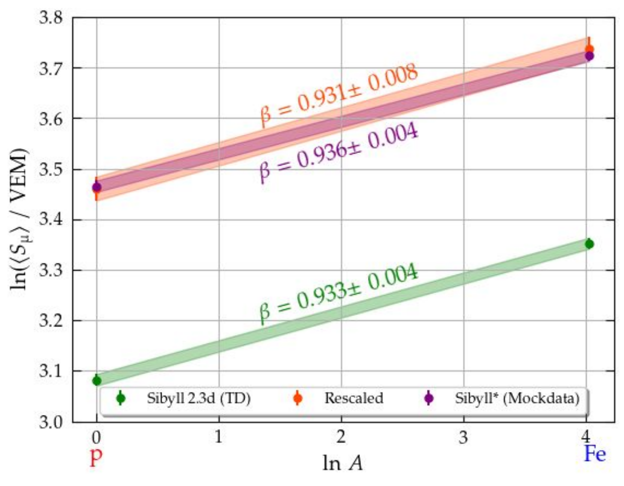
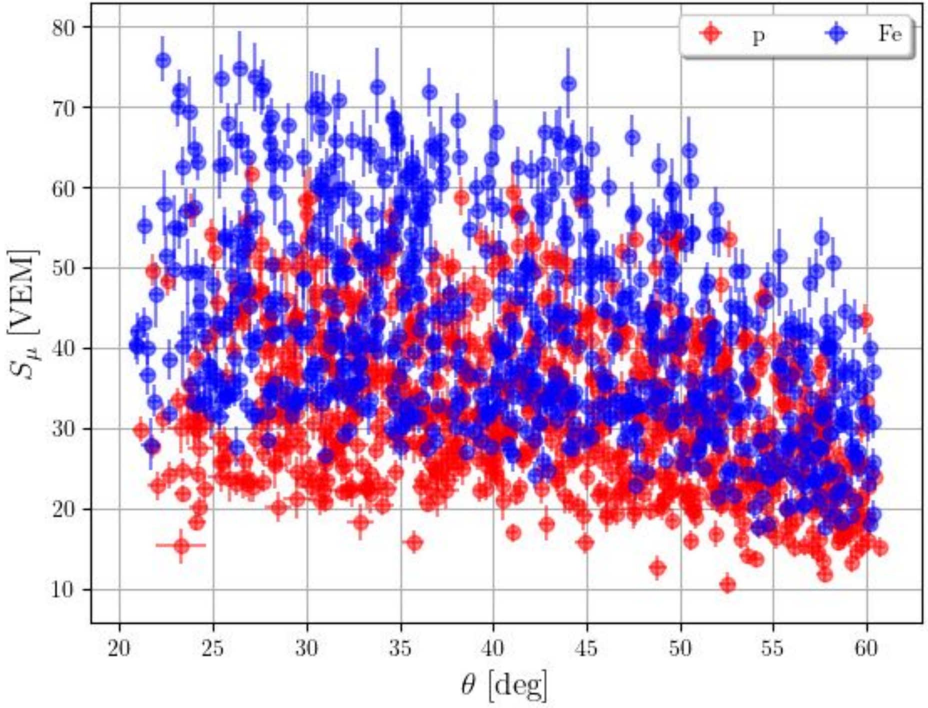
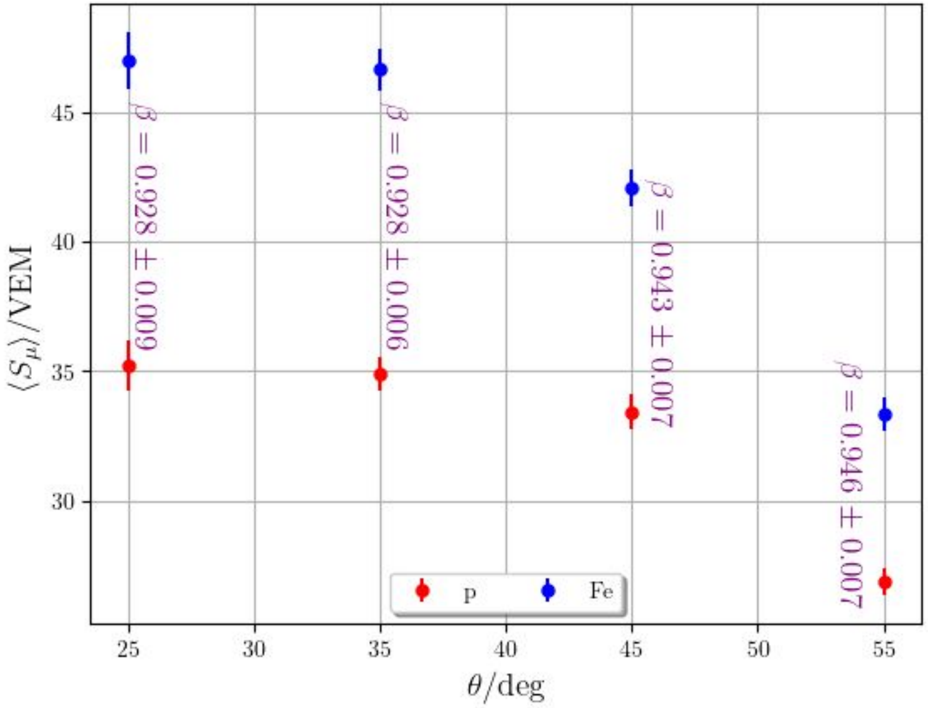


- Extend the input dataset to include **intermediate mass** primaries.
- For a dataset of unknown event-by-event composition: implement the **probability of an observed shower to have a given primary mass** based on its X_{max} and on composition fraction measurements.
- Apply the method to **real hybrid events**.

Back-up

The Sibyll* mockup dataset





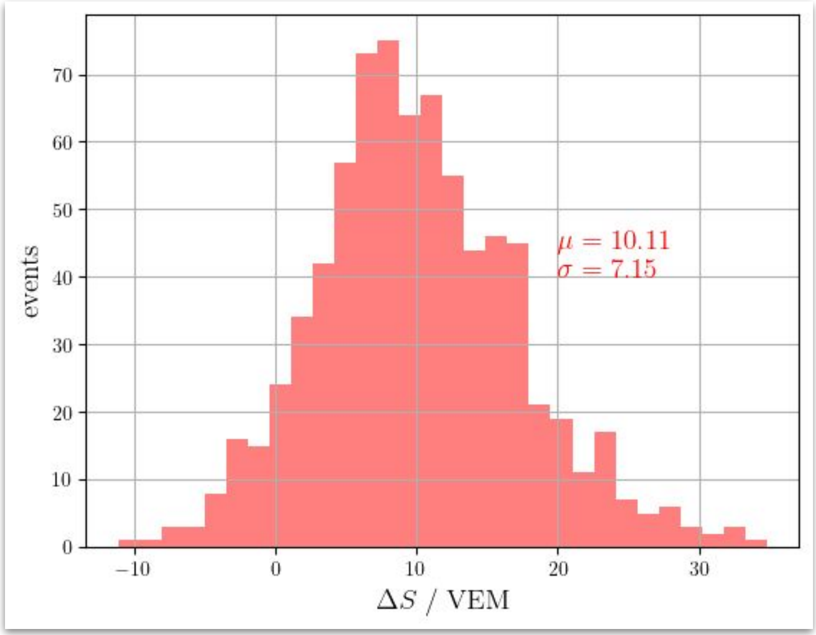
Results

- We define:

$$\Delta S = S_{1000}^{\mathrm{Sib}^*} - S_{1000}^{\mathrm{Sib2.3}}$$

Input dataset → $S_{1000}^{\mathrm{Sib}^*}$

TD simulations → $S_{1000}^{\mathrm{Sib2.3}}$



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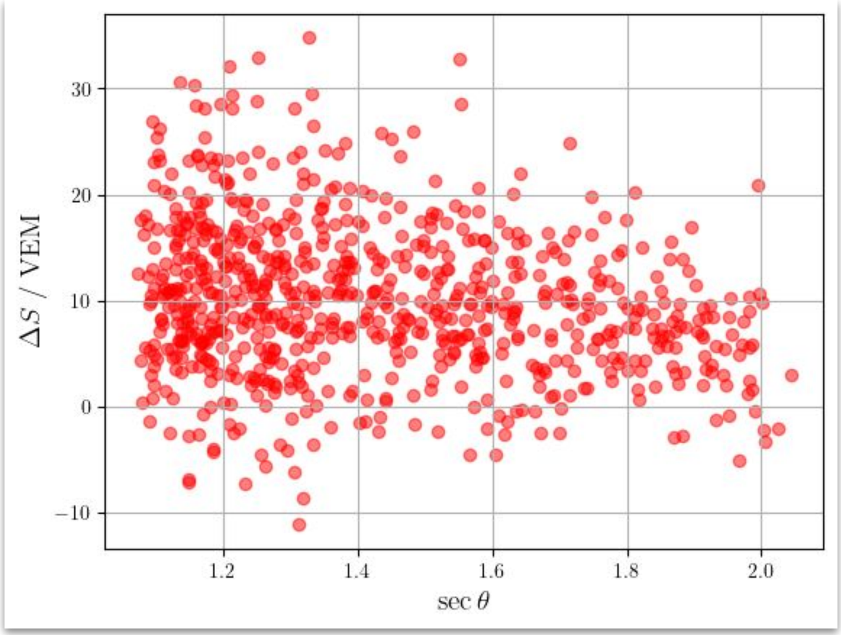
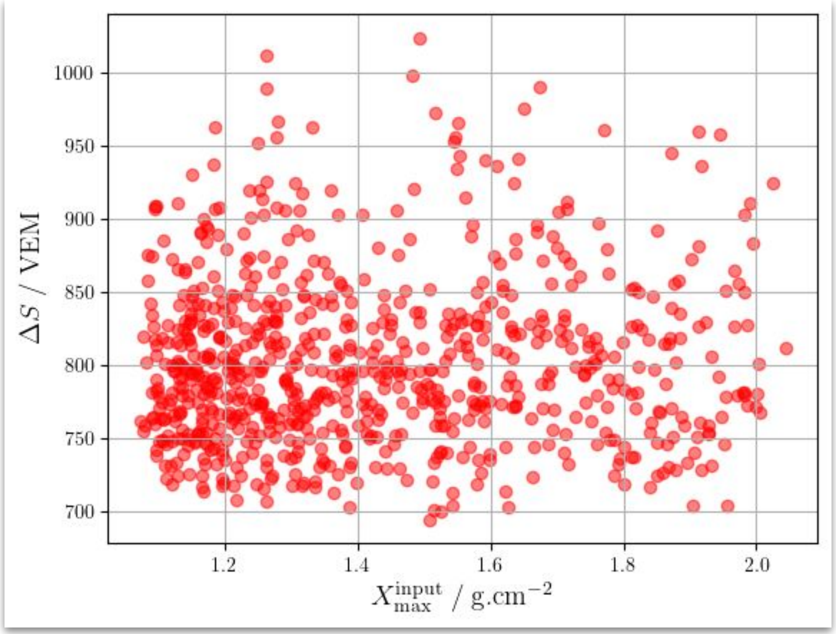

ΔS / VEM
30
20
10
0
−10
1.2
1.4
1.6
1.8
2.0
sec θ


ΔS / VEM
1000
950
900
850
800
750
700
1.2
1.4
1.6
1.8
2.0
X_{max}^{input} / g.cm^{-2}

Rescaling factor

The total signal is the sum of the EM and muonic component:

$$\begin{cases} S_{1000}^{\text{input}} = S_{1000,\mu}^{\text{input}} + S_{1000,\text{EM}}^{\text{input}} \\ S_{1000}^{\text{MC}} = S_{1000,\mu}^{\text{MC}} + S_{1000,\text{EM}}^{\text{MC}} \end{cases}$$

Rescaling MC to get the input signal gives:

$$S_{1000}^{\text{input}} = r_\mu S_{1000,\mu}^{\text{MC}} + r_{\text{EM}} S_{1000,\text{EM}}^{\text{MC}}$$

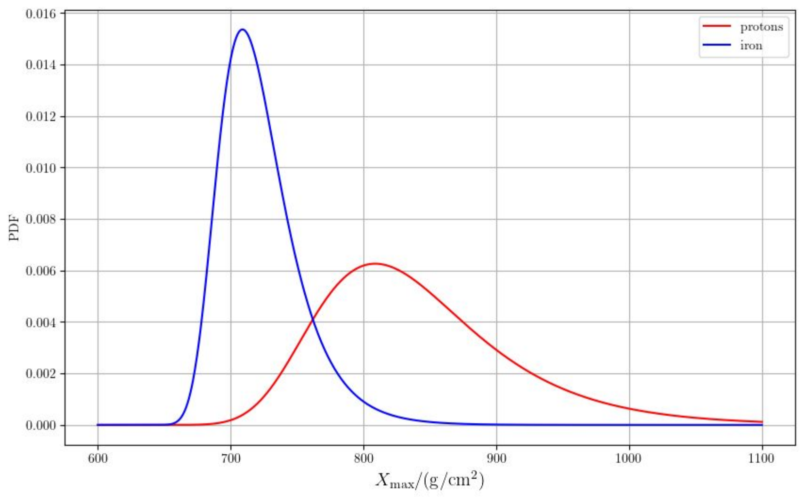
$$\rightarrow \quad S_{1000}^{\text{input}} - S_{1000}^{\text{MC}} = (r_\mu - 1) S_{1000,\mu}^{\text{MC}} + (r_{\text{EM}} - 1) S_{1000,\text{EM}}^{\text{MC}}$$

Matching the longitudinal profiles gives: $r_{\text{EM}} = 1$

Hence: $r_\mu = 1 + \dfrac{S_{1000}^{\text{input}} - S_{1000}^{\text{MC}}}{S_{1000,\mu}^{\text{MC}}}$

The new way to calculate the rescaling factors

- We want to take into account the **probability** of a given event to be an proton or an iron primary based on its X_{max} value → Use **Gumbel functions** to estimate these probabilities.



➢ For an input event n, the rescaling factor for a simulated primary i must be weighted by its probability of having the mass i:

$$\bar{r}_{\mu,i} = \frac{1}{\sum_n p_i(X_{\max,n})} \sum_n p_i(X_{\max,n})\, r_{\mu,i,n}$$

where

$$p_i(X_{\max,n}) = \frac{f_i\, P_i(X_{\max,n})}{\sum_i f_i\, P_i(X_{\max,n})}$$

P_i = Gumbel PDF

is "the **prior on the probability** that an event *n* with $X_{\max,n}$ has mass *i*, given the mass fractions f_i in the interval 10^{19} eV".

and

$$r_{\mu,i,n} = 1 + \frac{S^{\text{input}}_{1000,n} - S^{\text{MC}}_{1000,i,n}}{S^{\text{MC}}_{\mu,i,n}}$$