Sibyll*

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Workshop on the tuning of hadronic interactions
Wuppertal – Germany

Muon discrepancy in Sibyll

30% enhancement in number of muons from 2.1 → 2.3d

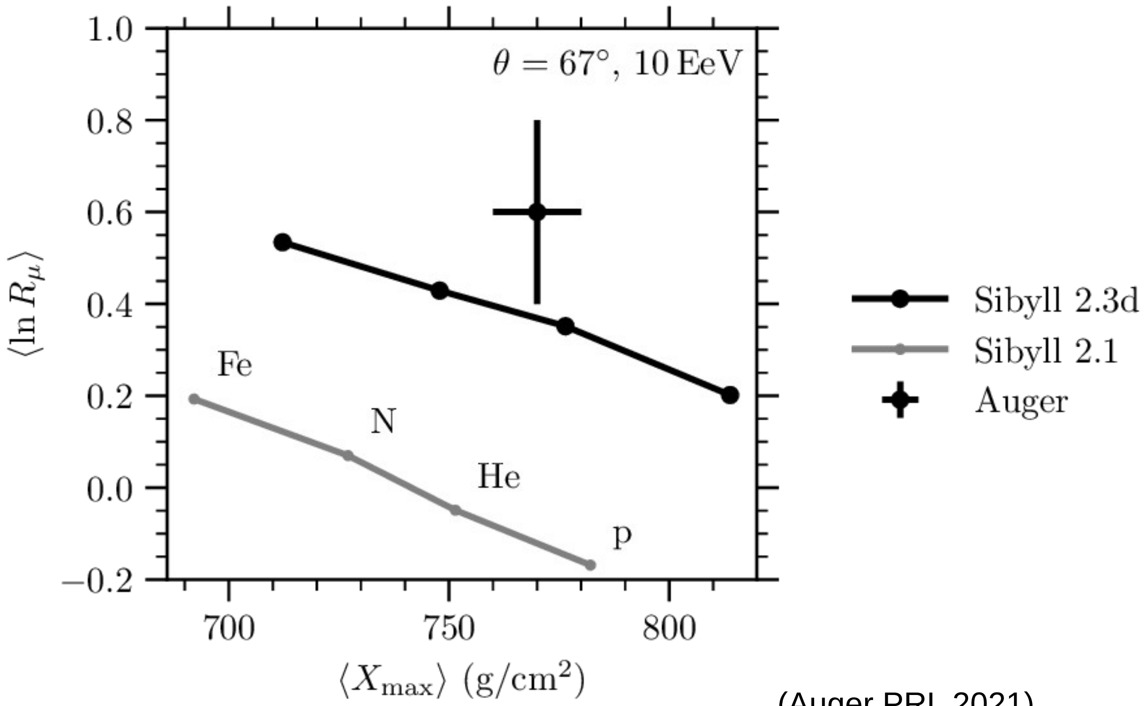
Achieved through:
- baryon production
- Forward Rho meson production

Data driven (LHC,NA22/NA61) !

NOT ENOUGH MUONS !

Is there more room within standard physics ?

→ **Sibyll***



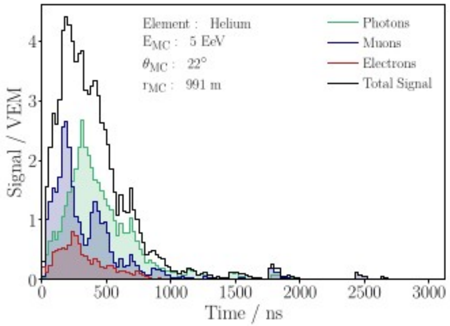
(Auger PRL 2021)

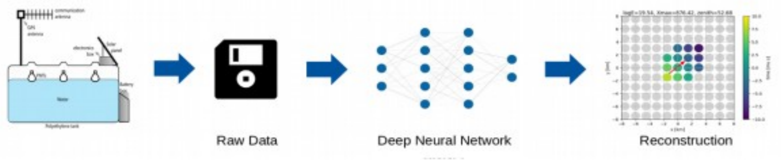
In addition, **ML** analyses require detailed simulations that are consistent with data

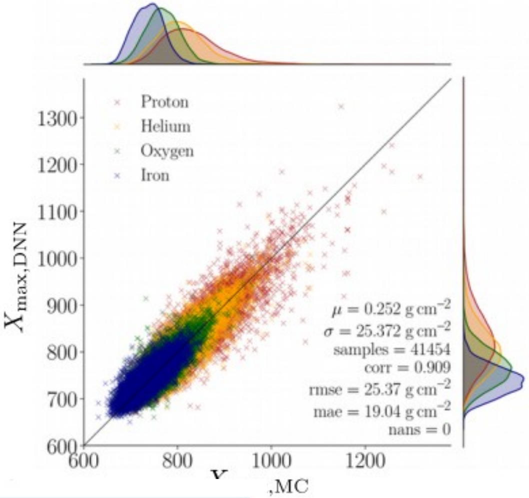
Discrepancy is limiting factor in many applications

One example:

Training of DNN with MC simulations



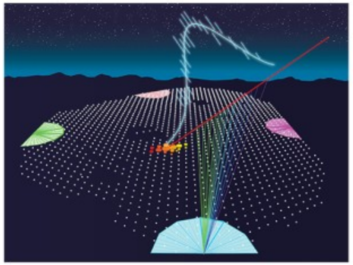


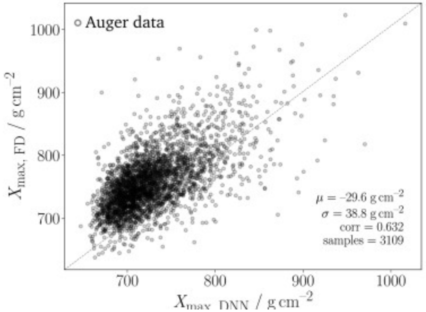


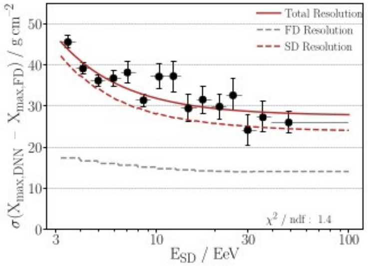
(Auger, JINST 16 (2021) 07, P07019)

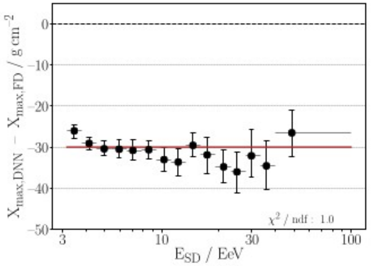
Reconstructing Xmax: ultimate check with data

Very good resolution, unexpected offset of ~30 g/cm²









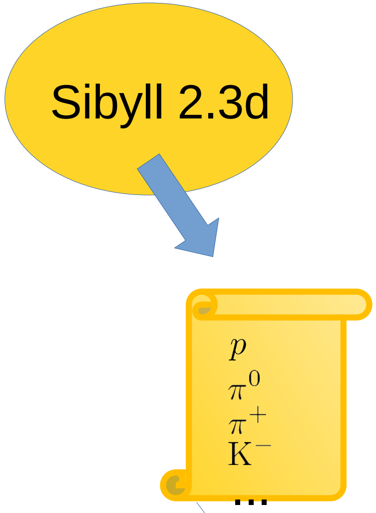
Sibyll*

We want:

* test different scenarios
* simple adjustable parameters
* physically consistent events

(energy/momentum + Q,B,S conservation)

Therefore leave Sibyll unmodified, but alter final state.



List of particle names & momenta

Post-processing

1) Replace *suitable* pairs/tripels of pions with desired hadrons at a **specific rate P**
   Example: for rho-meson replace (pi0,any) with (rho0,any)

2) Recalculate momenta

Energy- and phasespace dependent modifications

Start from Sibyll 2.3d and only change events **outside** of phasespace covered by accelerator experiments

$$P_i = P_{i,0} \cdot |x_F|^{\epsilon_i} \cdot f(\sqrt{s}, E_{\mathrm{thr}})$$

Base rate

Longitudinal phasespace dependence

Epsilon → 1 max. change in forward phasespace

Epsilon → 0 no change

Energy dependence

* linear in log(s)
* zero at thresh.
* unity at 10**19eV

Four variants

We test 4 scenarios:

- $S^\star(\bar{p})$
- $S^\star(\rho^0)$
- $S^\star(K^{\pm,0})$
- $S^\star(\text{mix})$

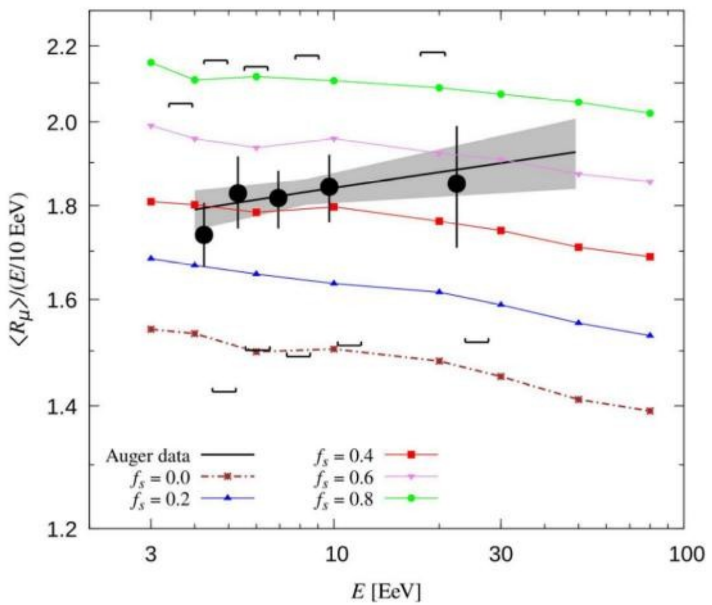
Sibyll 2.3d

$\bar{p} + \rho^0$

Enhancements fine-tuned

(first three featured in
Sibyll ad-extremum at UHECR 2022)

Kaon/strangeness enhancement



(Anchordoqui et al. 2017,
Manshanden 2022,
Sciutto et al. 2022,
Baur et al. 2023)

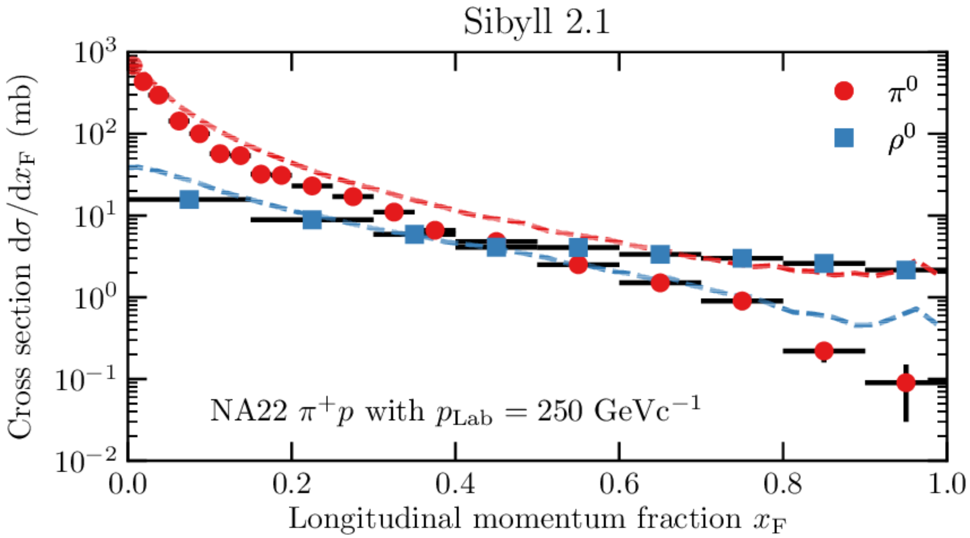
A detailed example: Rho0 enhancement

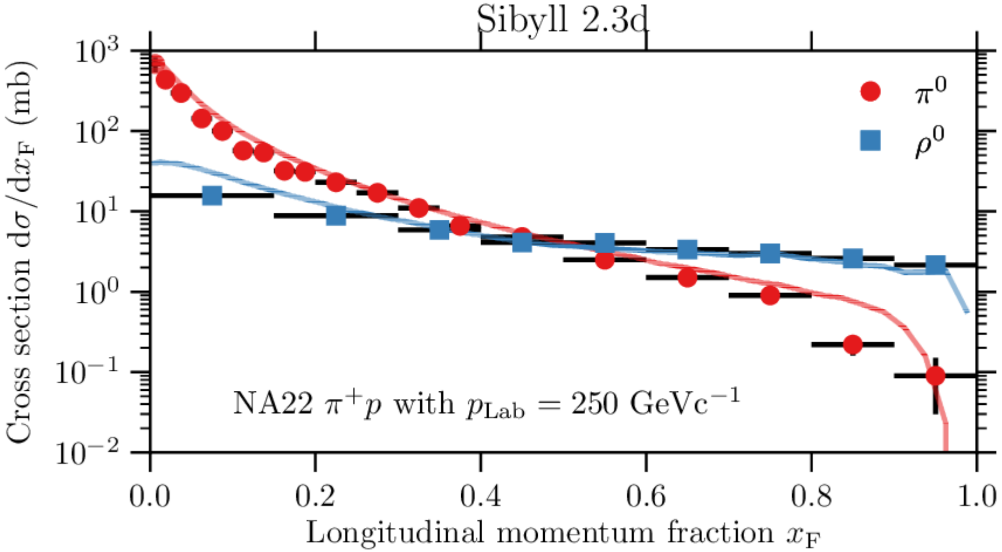
* constrained by NA22,NA61 data in pi-p and pi-C
* specific to pion projectiles
* very efficient!

$$\pi^+ + X \to \rho^0 + X^{*+}$$

vs

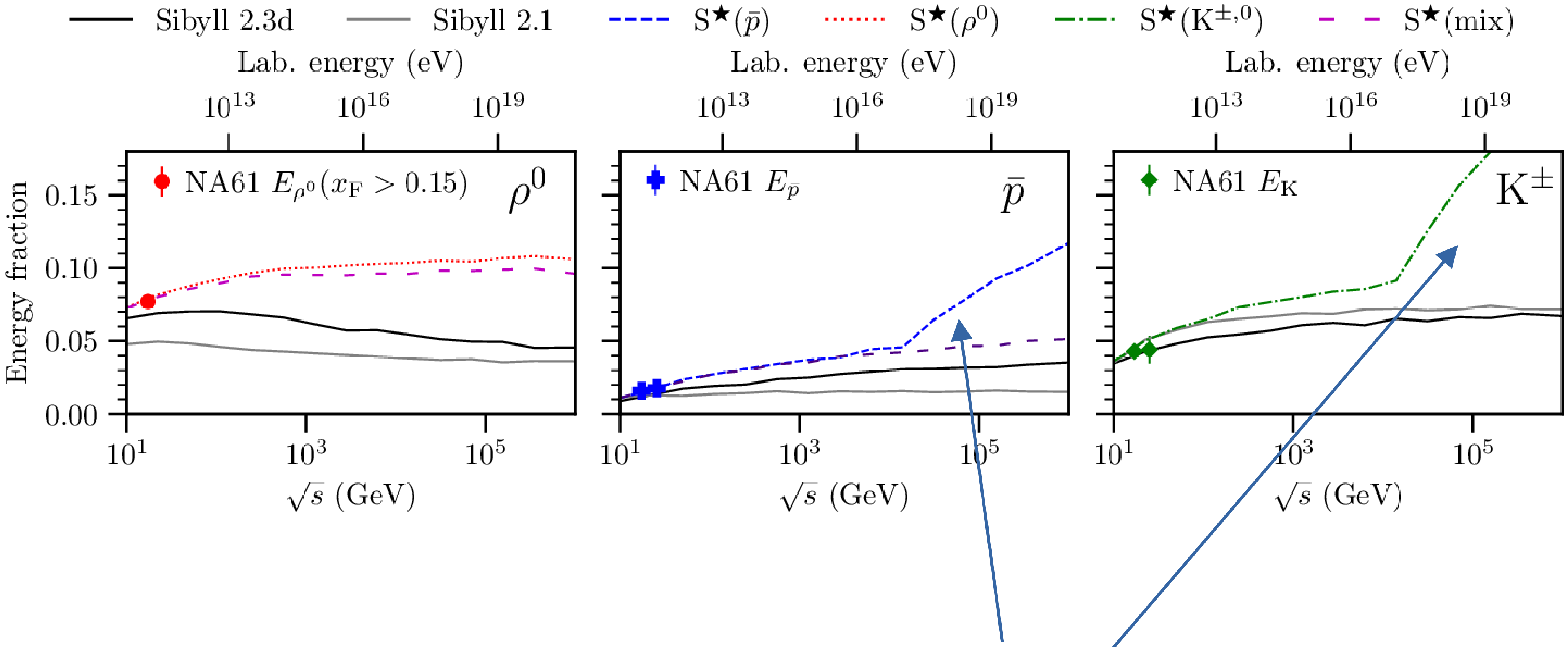
$$\pi^+ + X \to \pi^0 + X^{*+}$$





Enhancement: $P = 0.8 \cdot |x_\mathrm{F}|^{0.3} \cdot f(\sqrt{s}, 5\,\mathrm{GeV})$

Sibyll* variants in pion-carbon

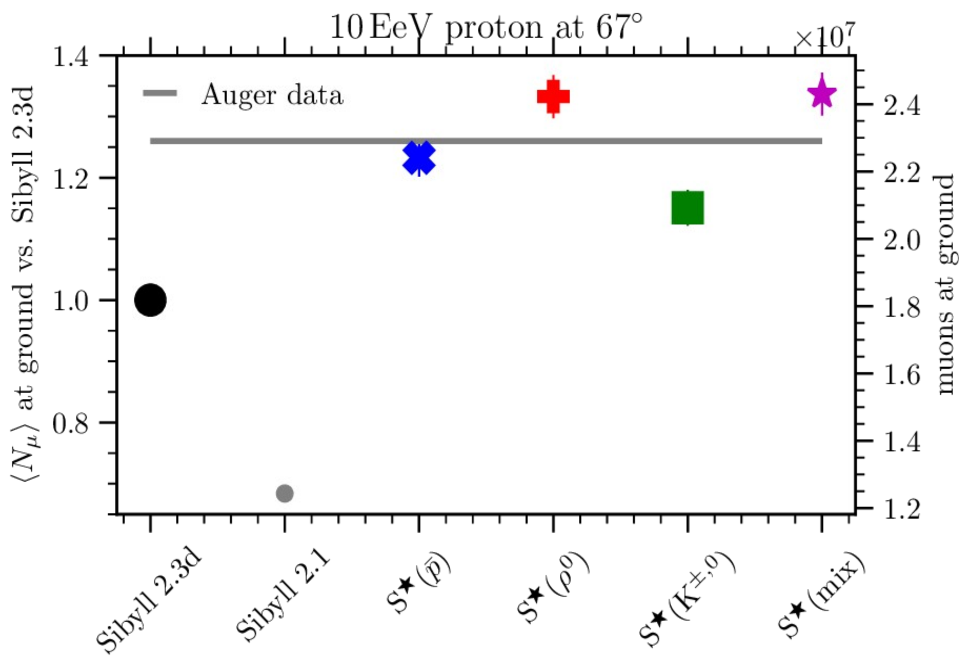


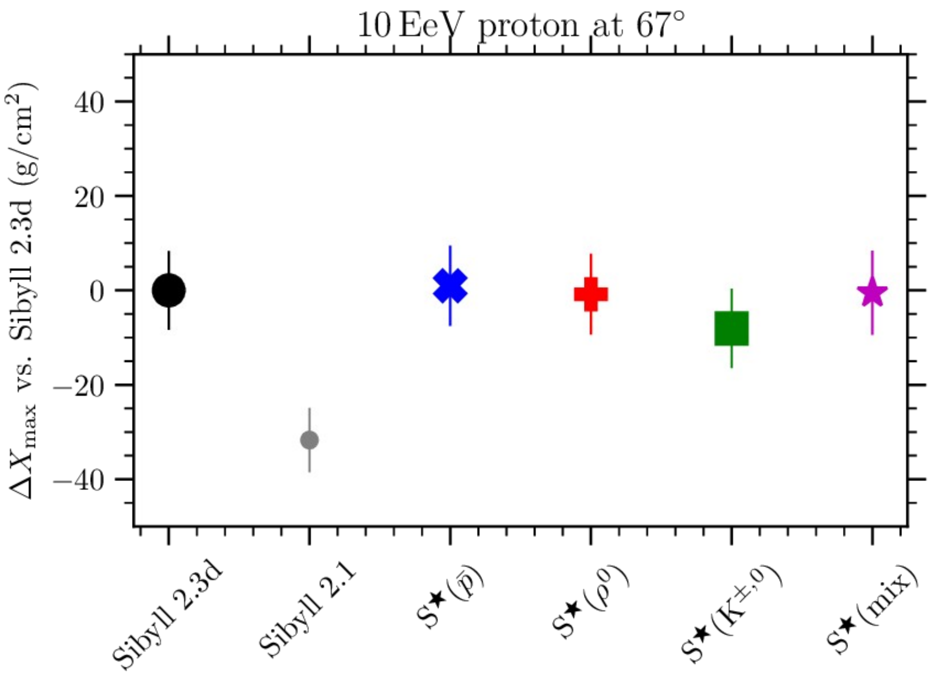
Similar for pp

Extreme enhancement above LHC energies

EAS predictions for protons

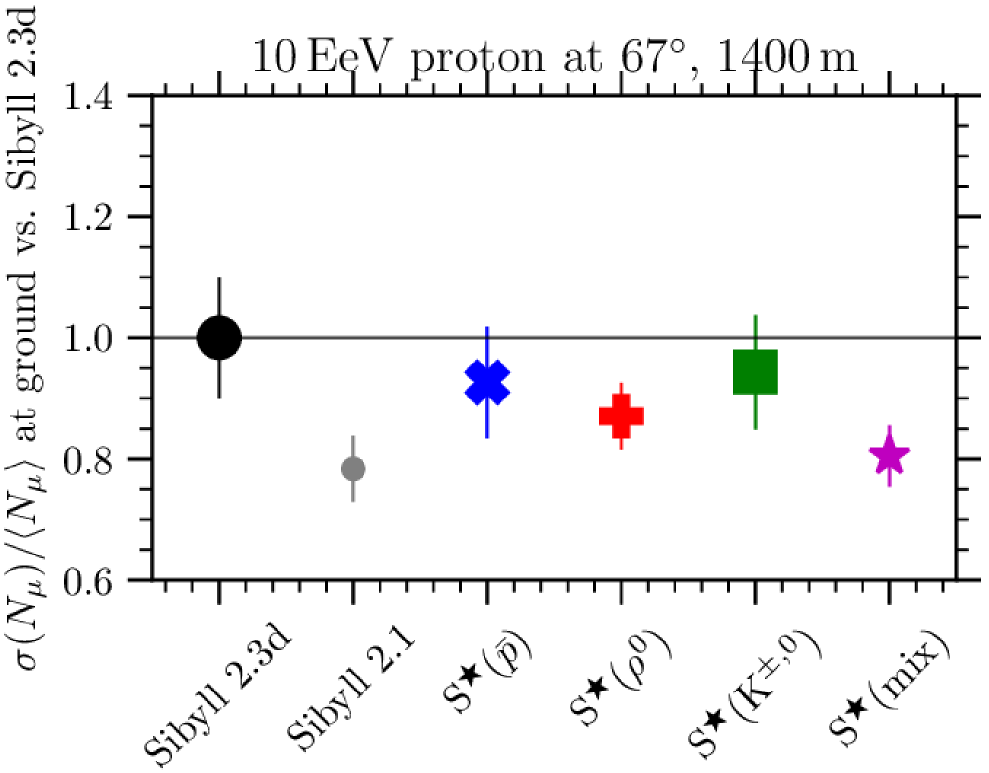
Looking good...

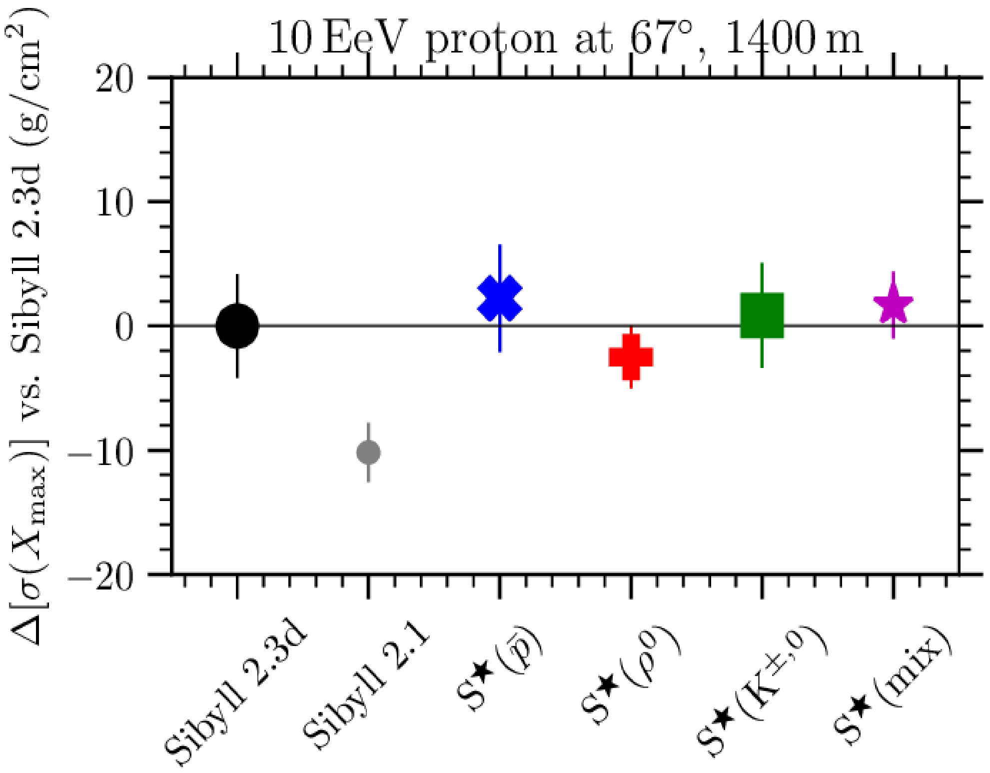




Enough for Auger data?

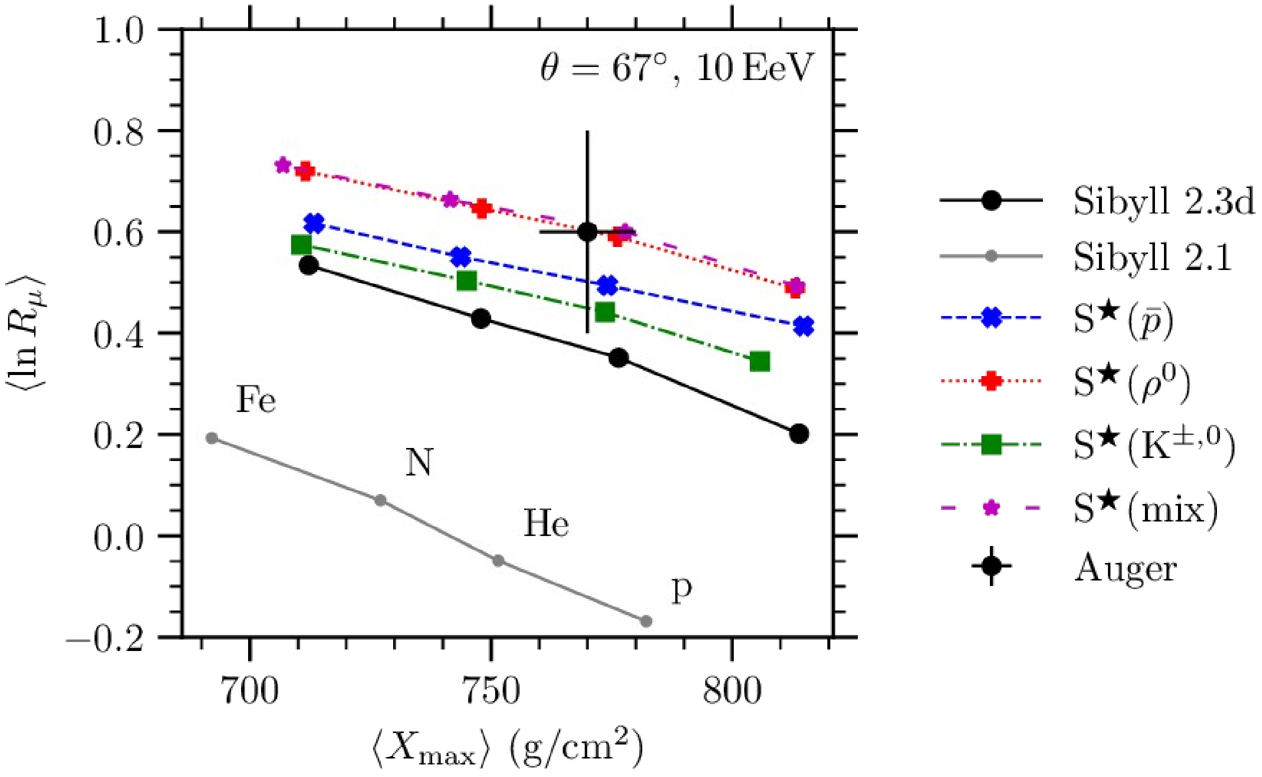
Fluctuations





Sibyll* vs Auger inclined

YES!
Finally
sufficient
muons
(sometimes..)



Sibyll* vs Auger inclined

Superposition:

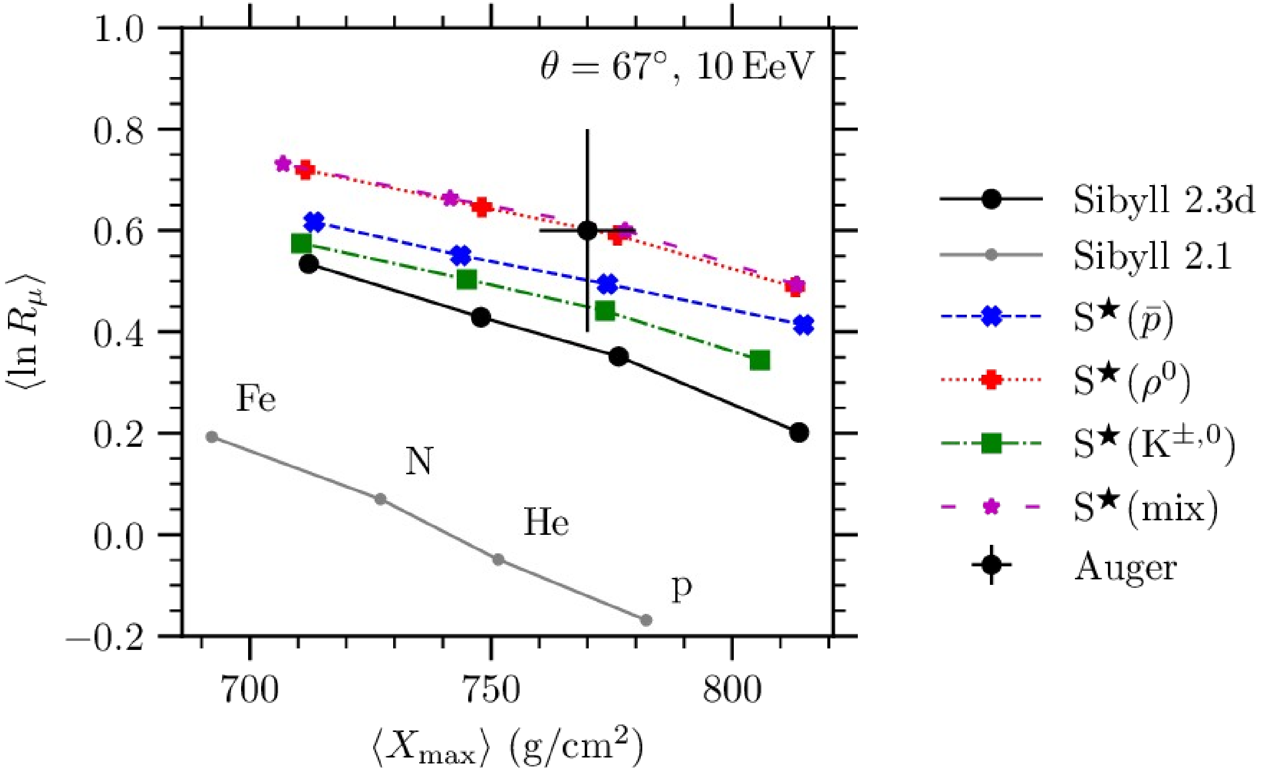
$$N_\mu = A \cdot \left(\frac{E}{A \cdot E_{\mathrm{dec}}}\right)^\beta$$

$$\frac{\mathrm{d}\ln N_\mu}{\mathrm{d}\ln A} \sim 1 - \beta$$

Heitler-Matthews:

$$\beta \sim \frac{\ln N_{\mathrm{ch}}}{\ln N_{\mathrm{tot}}}$$

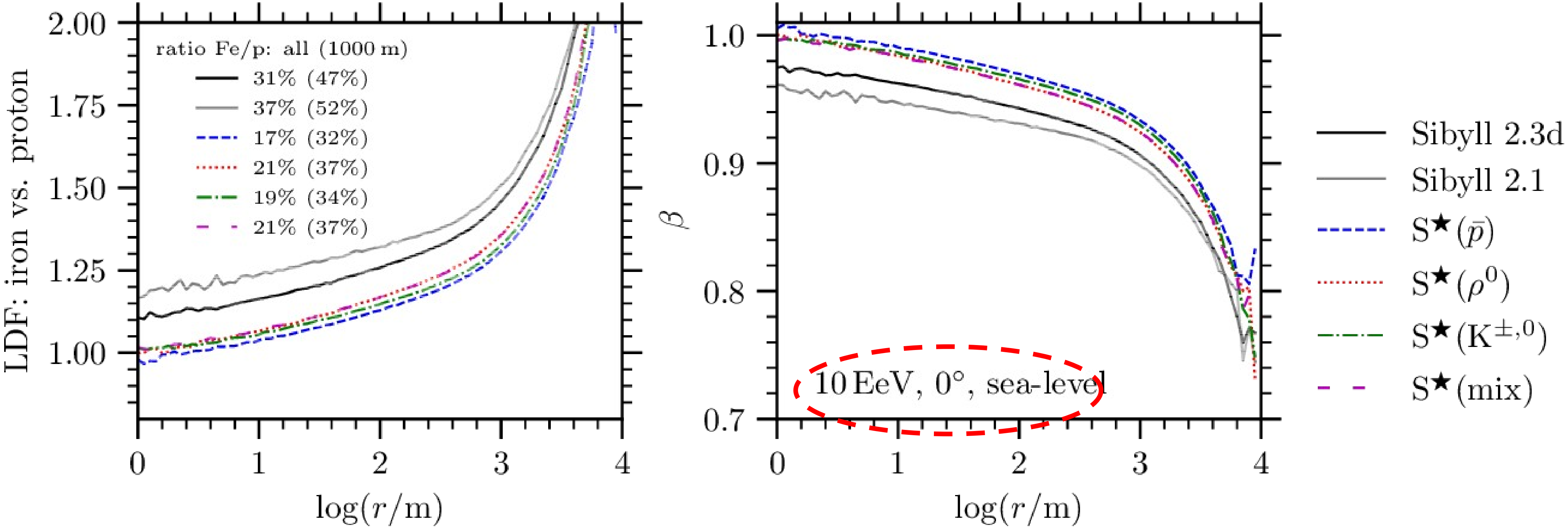
Modified in **Sibyll* !!**



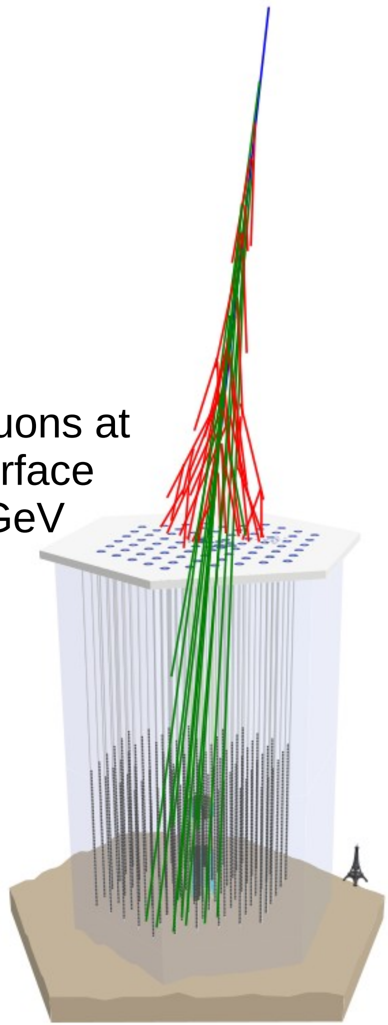
→ mass discrimination power is reduced in **all variants !**

but...

Mass discrimination depends on many aspects



IceCube



* high & low energy muons!

* mostly vertical showers

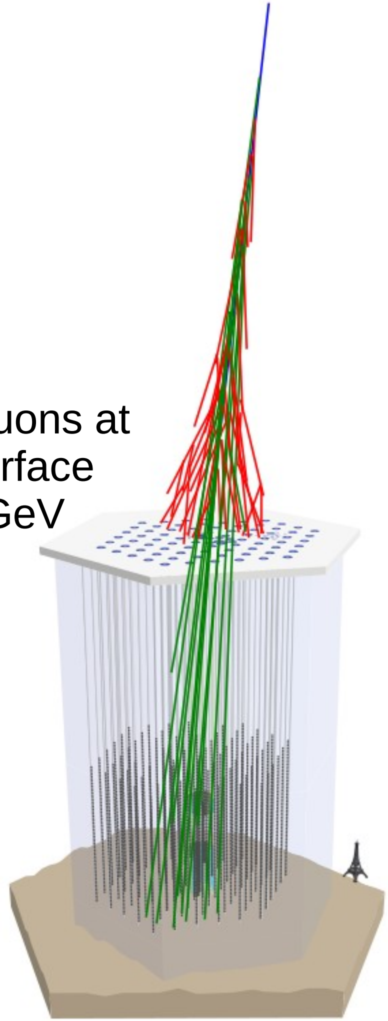
* ~ 10^15eV - 10^17eV

* high altitude! Low grammage ! ~ 680g/cm2

→ close to shower maximum

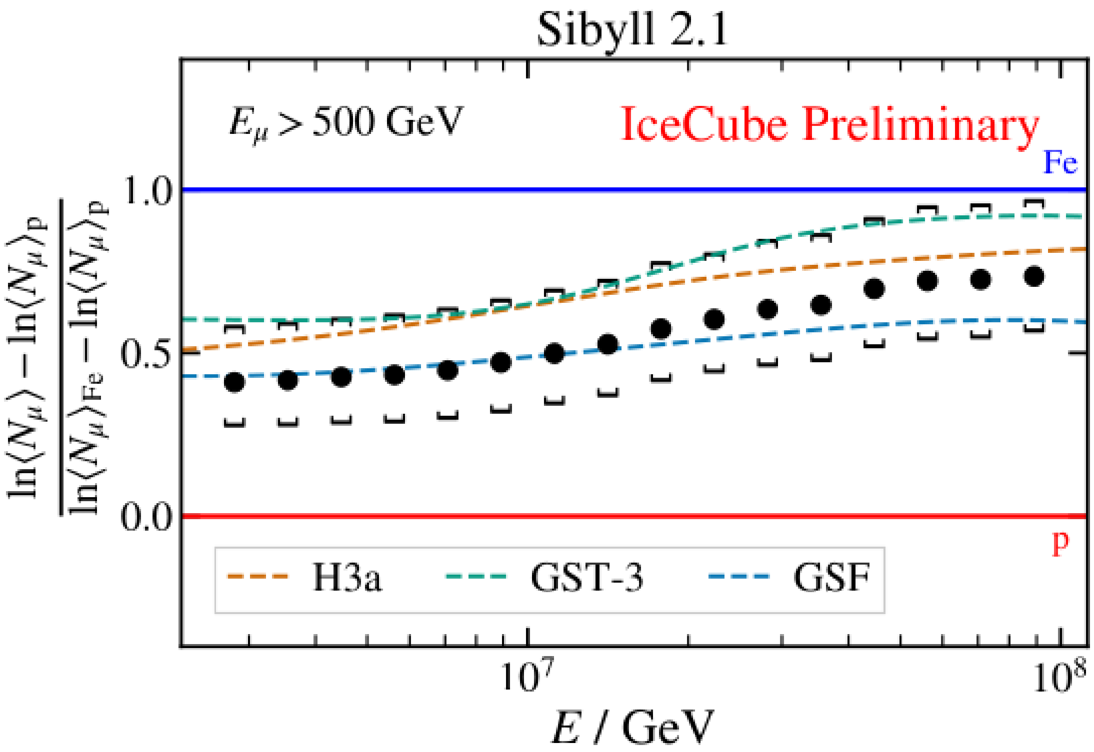
==> Sibyll 2.1 is found to be mostly consistent with data

IceCube TeV muons



Muons at surface ~GeV

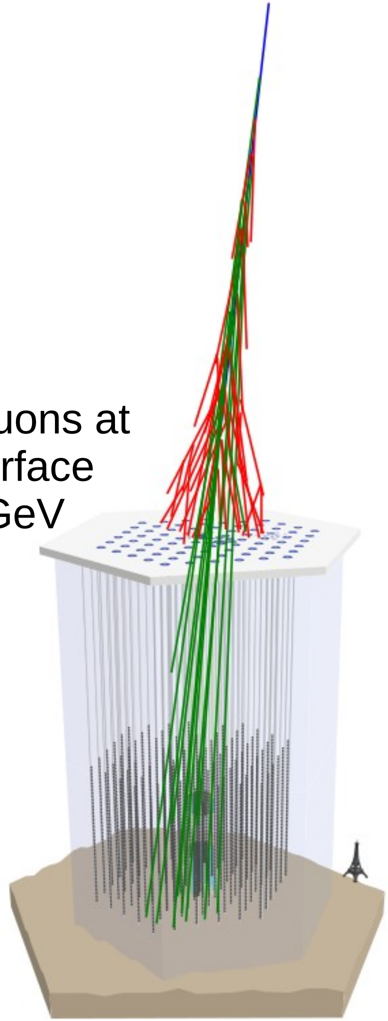
Muons under ice ~TeV



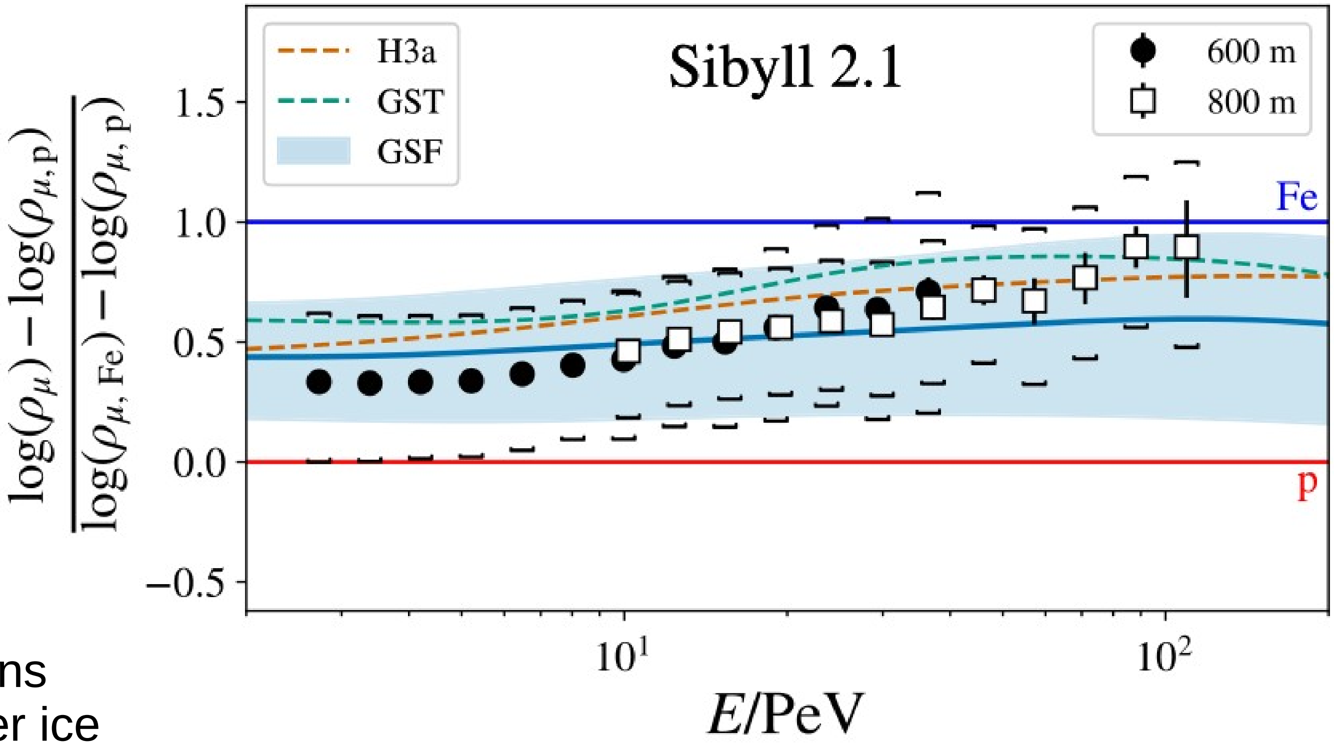
IceCube, Verpoest (ICRC 2023)

IceCube GeV muons

Muons at surface ~GeV

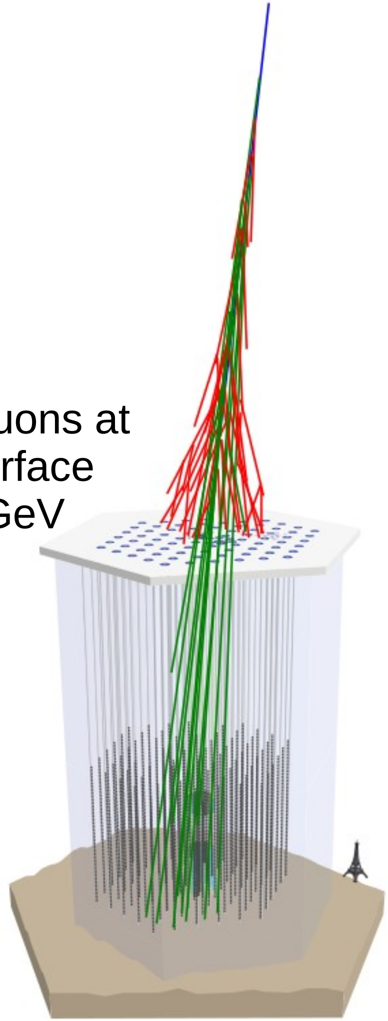


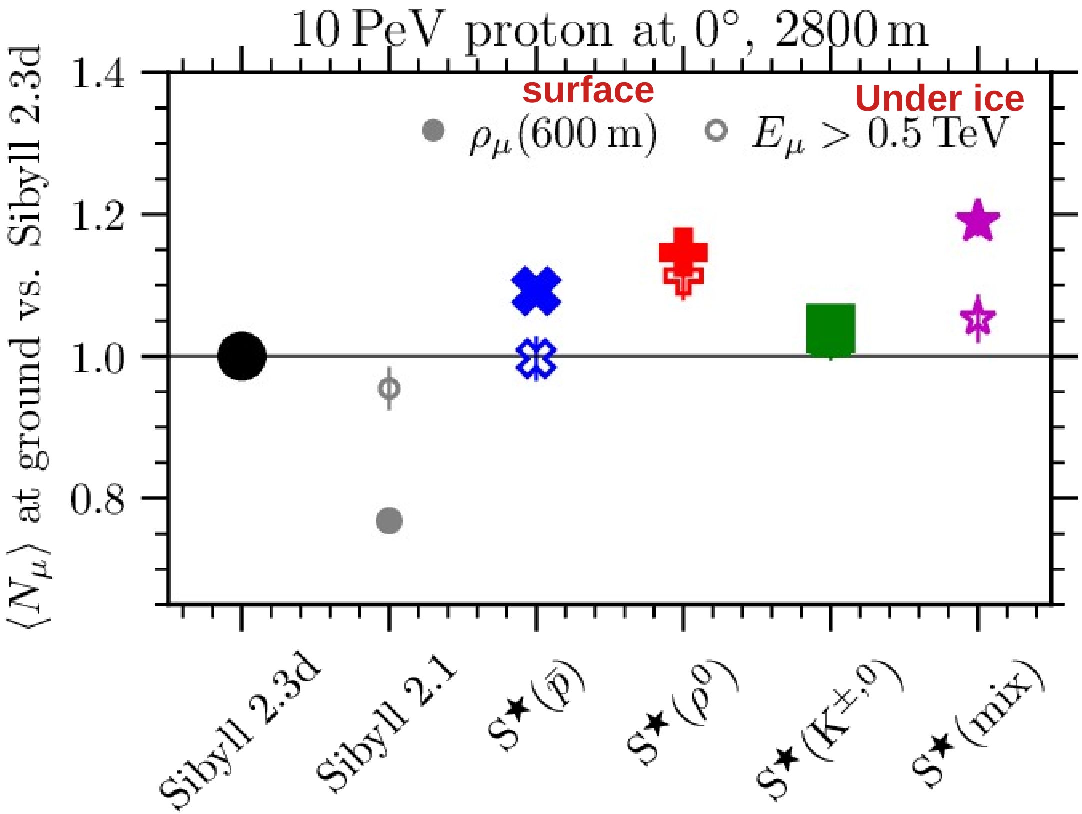
Muons under ice ~TeV



(IceCube PRD 2022)

Sibyll* for IceCube





Sibyll* ~40% more GeV muons than Sibyll 2.1

Summary & Outlook

* set of Sibyll variants with sufficient muon production (Auger inclined)
  → best choice: **mixed** model
* Xmax (average & fluctuations) unchanged, slight change in muon fluctuations
* **strangeness** & **baryon** enhancement **disfavored**. Require extreme modification
* in superposition model, enhanced total muon production means reduced mass separation
* **no** significant impact on inclusive fluxes, only kaon enhancement leads to 5% change in neutrino flux (IceCube, KM3NeT, FPF!)
* models freely available now! (replace source code of Sibyll 2.3d with Sibyll*, recompile, done)

Need to:
* test against more available muon data (KM3NeT, WHISP..), seems inconsistent with prel. IceCube data
* employ in experimental data analysis (template fits, **machine learning**)
* theoretical basis for present ad-hoc modifications?

Acknowledgments

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UNIÓN EUROPEA

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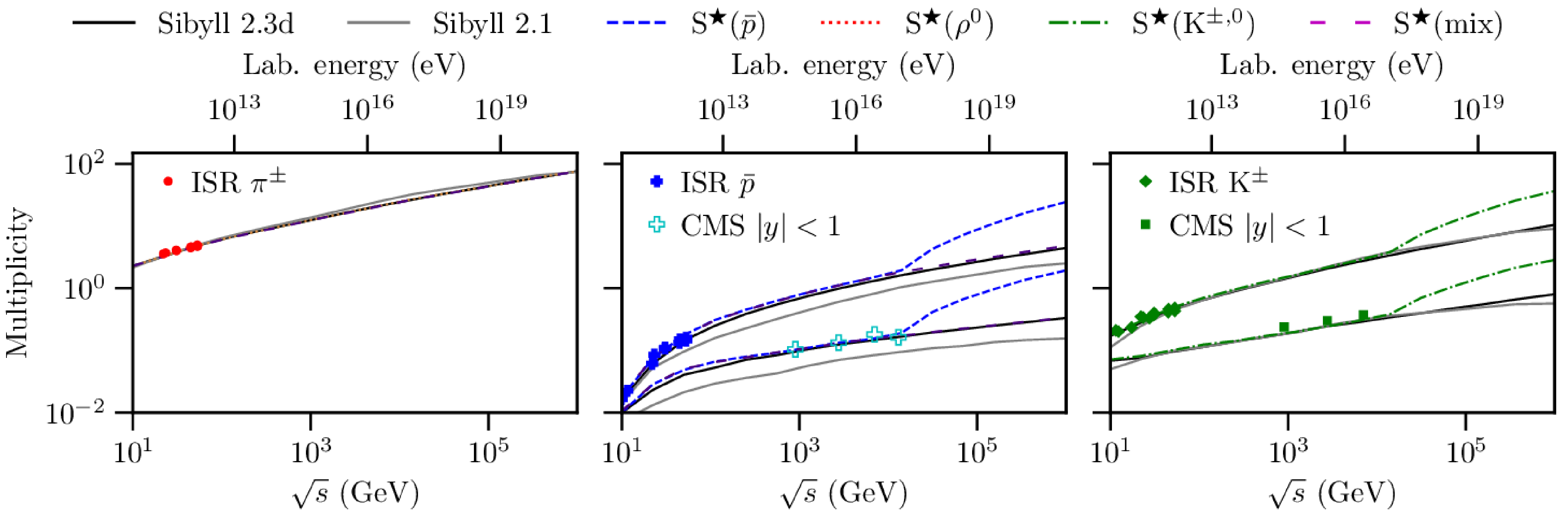
Backup

Sibyll* variants in proton-proton



Hadron energy fraction

Fraction of beam energy that is carried by all hadrons except *neutral pions*
= energy available in EAS to produce muons