An explanation of the muon puzzle of ultrahigh-energy cosmic rays and the role of the Forward Physics Facility for model improvement

Luis A. Anchordoqui, Carlos A. García Canal, Felix Kling,
Sergio J. Sciutto, Jorge F. Soriano.

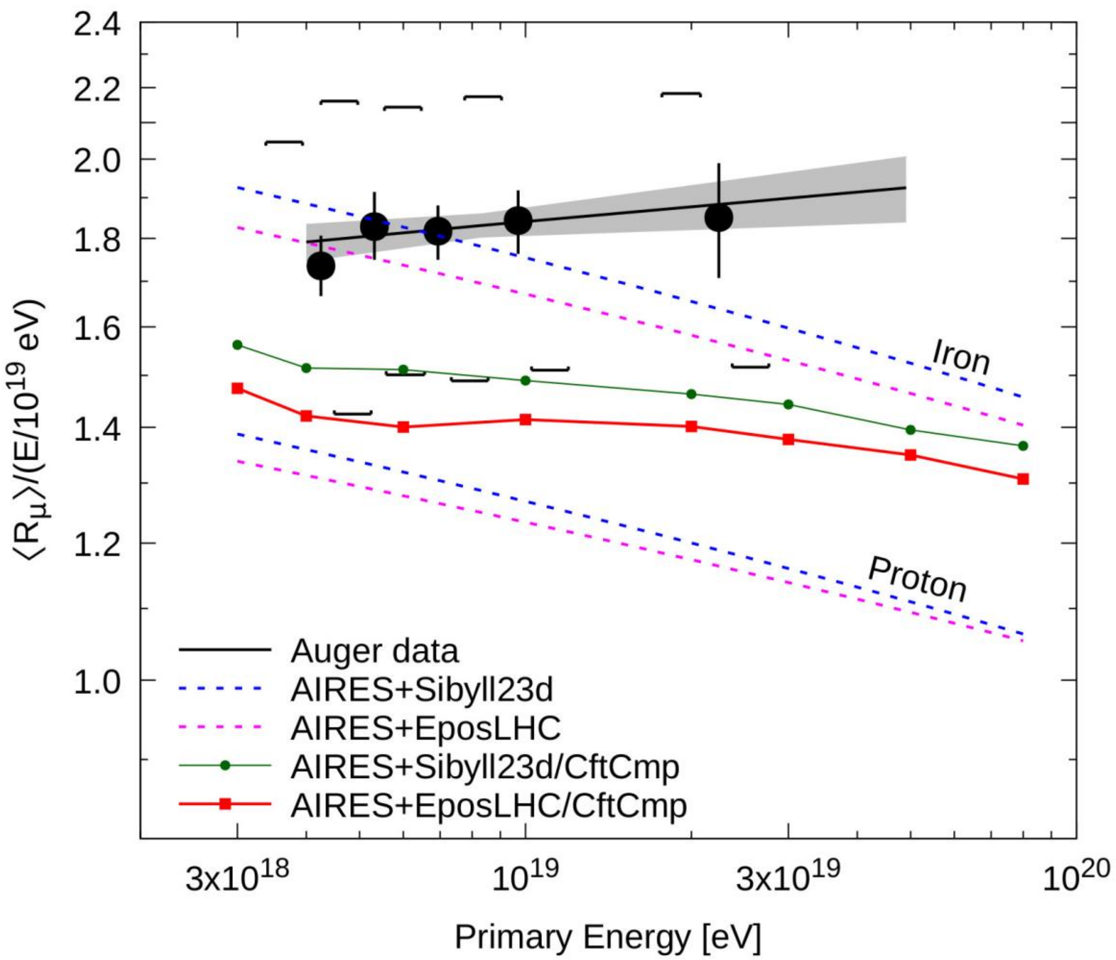
4TH FORWARD PHYSICS FACILITY MEETING – JAN 31, 2022.

A hybrid cosmic ray detector

- The ***Fluorescence Detector*** measures the air fluorescence light produced during the development of the air shower initiated by the primary cosmic ray. The main observables that can be measured are:
  - X_{max}, position of the point of maximum shower development.
  - N_{max}, number of charged partices at the shower máximum.
- The ***Surface Detector*** signals allow to evaluate a quantitative estimation of the shower particles that reached the ground. In particular, it can provide a measure of the *total number of muons at ground*:

$$R_\mu = \frac{\text{Total number of muons at ground}}{N_\mu^{(\mathrm{ref})} \text{ (fixed reference number)}}$$

The muon puzzle



- The ***muon puzzle***, deficit between simulation and data, starts at $E{\sim}10^{17}$ eV increasing noticeably as primary energy grows, with a slope which was found to be significant at about 8σ.
- The analysis of Auger data suggests that the hadronic component of showers with primary energy $10^{18.8} < E/\mathrm{eV} < 10^{19.2}$ contains about 30% to 60% more muons than expected. The significance of the discrepancy is above 2.1σ.
- Predictions obtained using **Sibyll 2.3d** or **EPOS-LHC** are quite similar.

Auger data after *Phys. Rev. D*, **91**, 032003 (2015). Combined fit composition based on Auger *JCAP*, **04**, 038 (2017).

Strangeness production enhancement: The key to solve the muon puzzle?

- There is experimental evidence (ALICE) of an enhancement of the yield ratio of strange and multi-strange hadrons to charged pions in N-N scattering. Current versions of hadronic collision generators fail to correctly reproduce such results.

- So, let's assume that this is the key to solve the muon puzzle, and let's set up a simple model capable of giving a quantitative estimation of the impact of strangeness enhancement on the number of ground muons in air showers initiated by the highest energy cosmic rays…

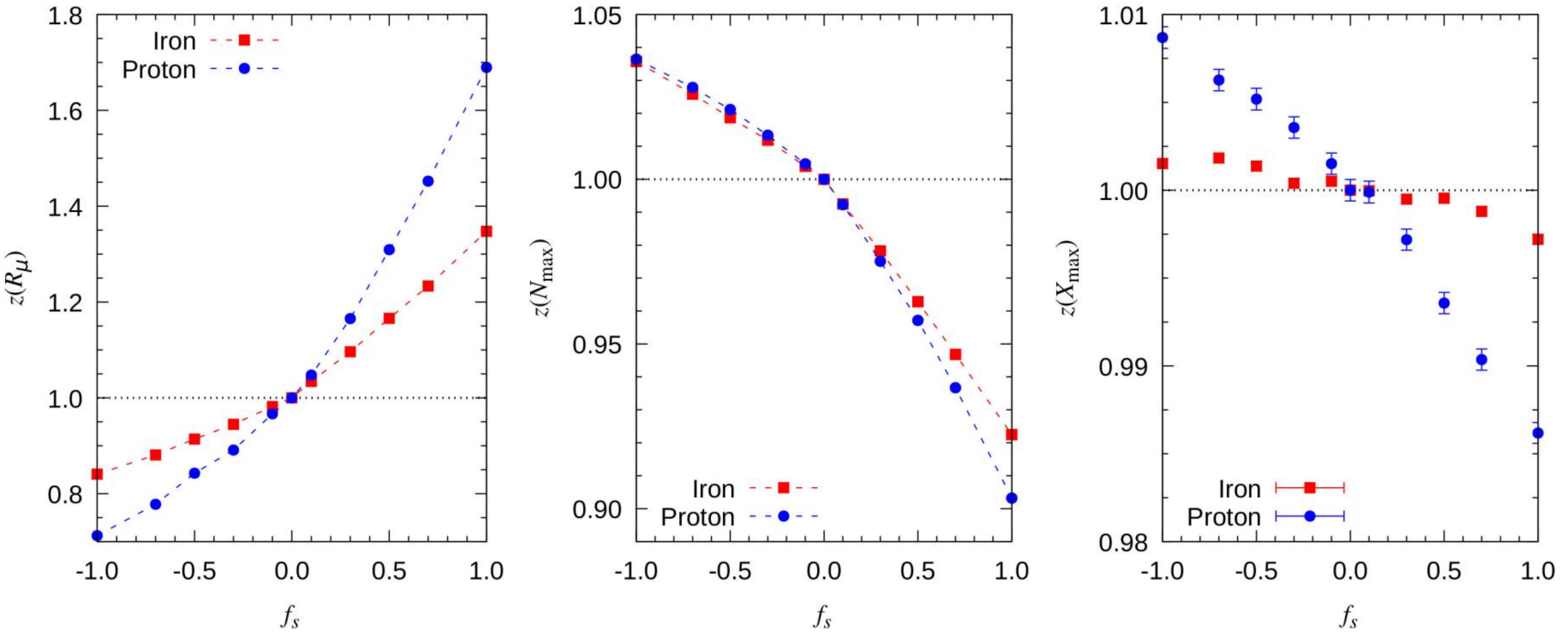
$\pi \leftrightarrow K$ swap: the toy model

Process the secondary particles returned from the hadronic collision generator (Sibyll 2.3d in our case), and eventually change the identity of some of them before of continuing their propagation with the AIRES engine, accordingly with the following ***toy model***:

1. If the ***swapping fraction*** f_s is not zero, and $E_{\text{pmin}} < E_{\text{proj}} < E_{\text{pmax}}$ (Lab system), then
   a. If $f_s > 0$, all the secondary **pions** with kinetic energy $E_{\text{sec}} \in [E_{\text{smin}}, E_{\text{smax}}]$ (Lab system) are considered for being transformed onto **kaons**, after being selected with probability $|f_s|$.
   b. If $f_s < 0$, all the secondary **kaons** with kinetic energy $E_{\text{smin}} \in [E_{\text{smin}}, E_{\text{smax}}]$ are considered for being transformed onto **pions**, after being selected with probability $|f_s|$.
2. Both original and transformed secondaries have the same electrical charge.
3. Both original and transformed secondaries have the same total energy.
4. If $f_s = 0$, or $E_{\text{proj}} \notin [E_{\text{pmin}}, E_{\text{pmax}}]$, **no action is taken**: all the secondaries remain unchanged.

Evaluate impact on observables ($\mathcal{O}$) via: $z(\mathcal{O}) = \langle \mathcal{O}(f_s) \rangle / \langle \mathcal{O}(f_s = 0) \rangle$.

$\pi \longleftrightarrow K$ swap: toy model results.

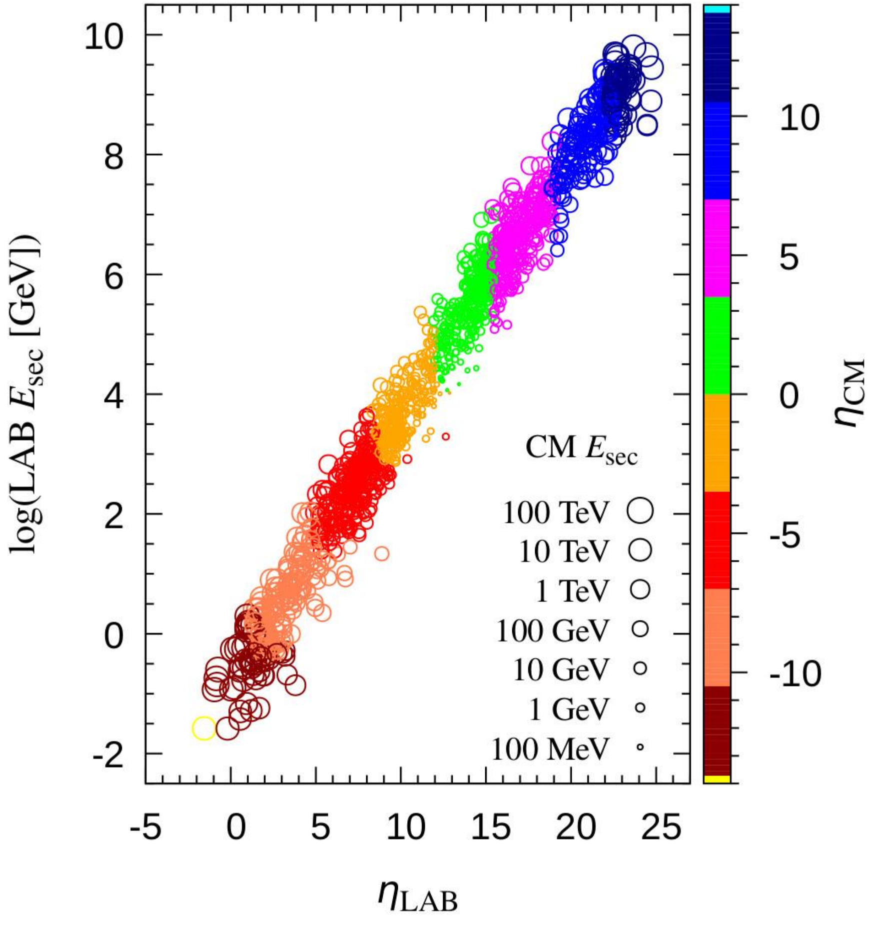


Results from AIRES+ Sibyll 2.3d + $\pi \longleftrightarrow K$ swap, for varying swapping fractions f_s.
10^{19} eV proton and iron showers inclined 67°.

$E_{\text{pmin}} = 1$ PeV, $E_{\text{smin}} = 1$ TeV, $E_{\text{pmax}} = E_{\text{smax}} = \infty$. With these settings, the swapping algorithm is applied to only 3.8% of the hadronic collisions, and only 0.54% ($f_s = 0.7$) of the secondaries are actually swapped.

R_μ **increases up to more than 60%** (that's what was needed!),
with moderate ($\lesssim 10\%$) and not significant ($\lesssim 1.5\%$) impact on $N_{\max}$ and $X_{\max}$, respectively.

CM (@FPF) and LAB (@Auger) frames.



10^{19} eV (LAB) *pp* collisions. $\sqrt{s} = 137$ GeV (CM).

CM and LAB reference frames related via Lorentz transforms. The total energy of a secondary emerging after the collision is transformed via:

$$E_{LAB} = \gamma\left(E_{CM} + \beta p_{l_{CM}}\right)$$

(β = speed of CM with respect to LAB)

In the ultrarrelativistic case:

$\beta \approx 1,\ p_{l_{CM}} \approx E_{CM} \cos\theta_{CM}$, so

$$E_{LAB} \approx \gamma E_{CM}(1 + \cos\theta_{CM})$$

For *emerging secondaries*, $\cos\theta_{CM}$ can take any value within $[-1,1]$.

Note: $\eta_{CM} = -\log[\tan(\theta_{CM}/2)]$

The refined model
(Pseudorapidity dependent swapping fraction)

Process the secondary particles returned from the hadronic collision generator (Sibyll 2.3d in our case), and eventually change the identity of some of them, accordingly with the following:

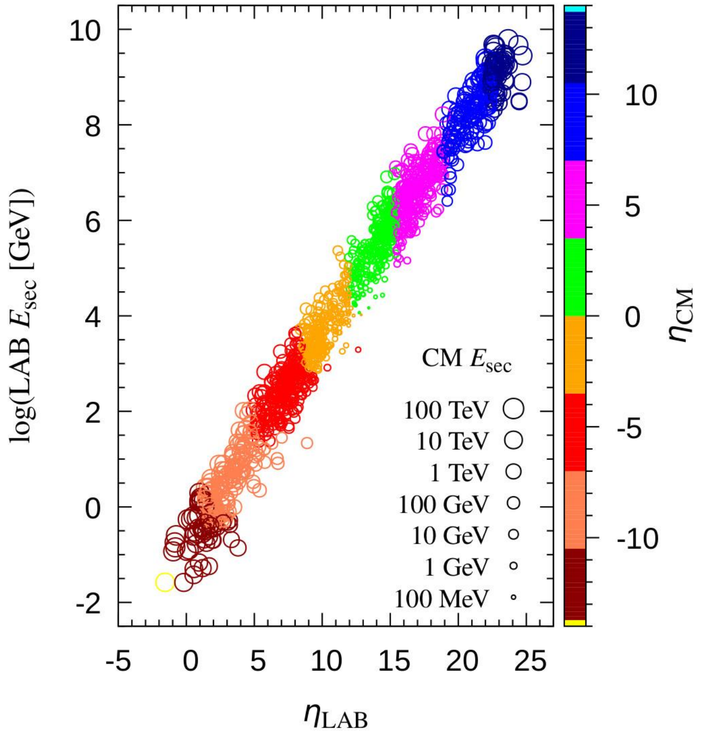
1. If the ***swapping fraction*** F_s is greater than zero, and $E_{\mathrm{proj}} \geq E_{\mathrm{pmin}}$ (Lab system), then all the secondary **pions** are considered for being transformed onto **kaons**, after being selected with probability $F_s(\eta)$, where η is the pion pseudorapidity (Centre of Mass system).
2. Both original and transformed secondaries have the same electrical charge.
3. Both original and transformed secondaries have the same total energy.
4. If $F_s(\eta) \equiv 0$ or $E_{\mathrm{proj}} < E_{\mathrm{pmin}}$, no action is taken: all the secondaries remain unchanged.

The refined model (cont.)

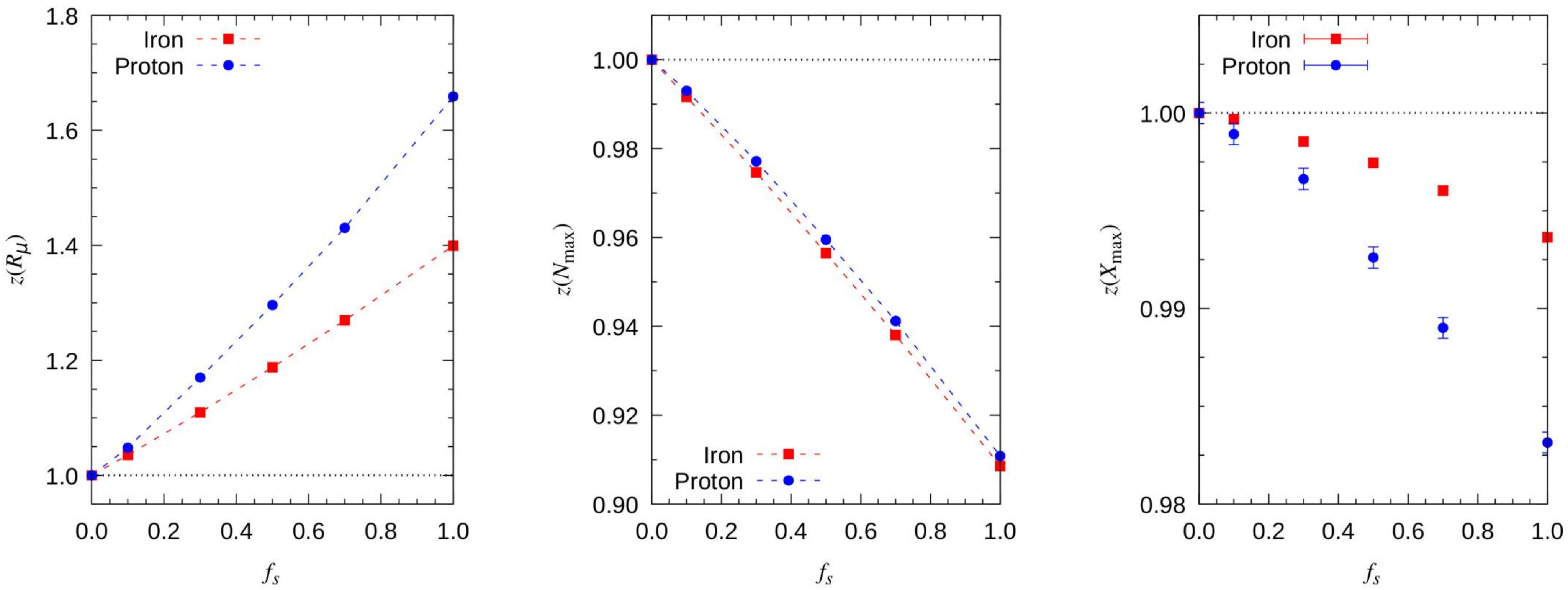
The ***swapping fraction function*** used in most of our analysis with the refined model is:

$$F_s(\eta_{\mathrm{CM}}) = \begin{cases} f_s & \text{if} \quad -\infty < \eta_{\mathrm{CM}} < -\eta_0 \\ 0 & \text{if} \quad -\eta_0 \le \eta_{\mathrm{CM}} \le \eta_0 \\ f_s & \text{if} \quad \eta_0 < \eta_{\mathrm{CM}} < \infty \end{cases}$$

where $\eta_0 = 4$ unless otherwise specified.



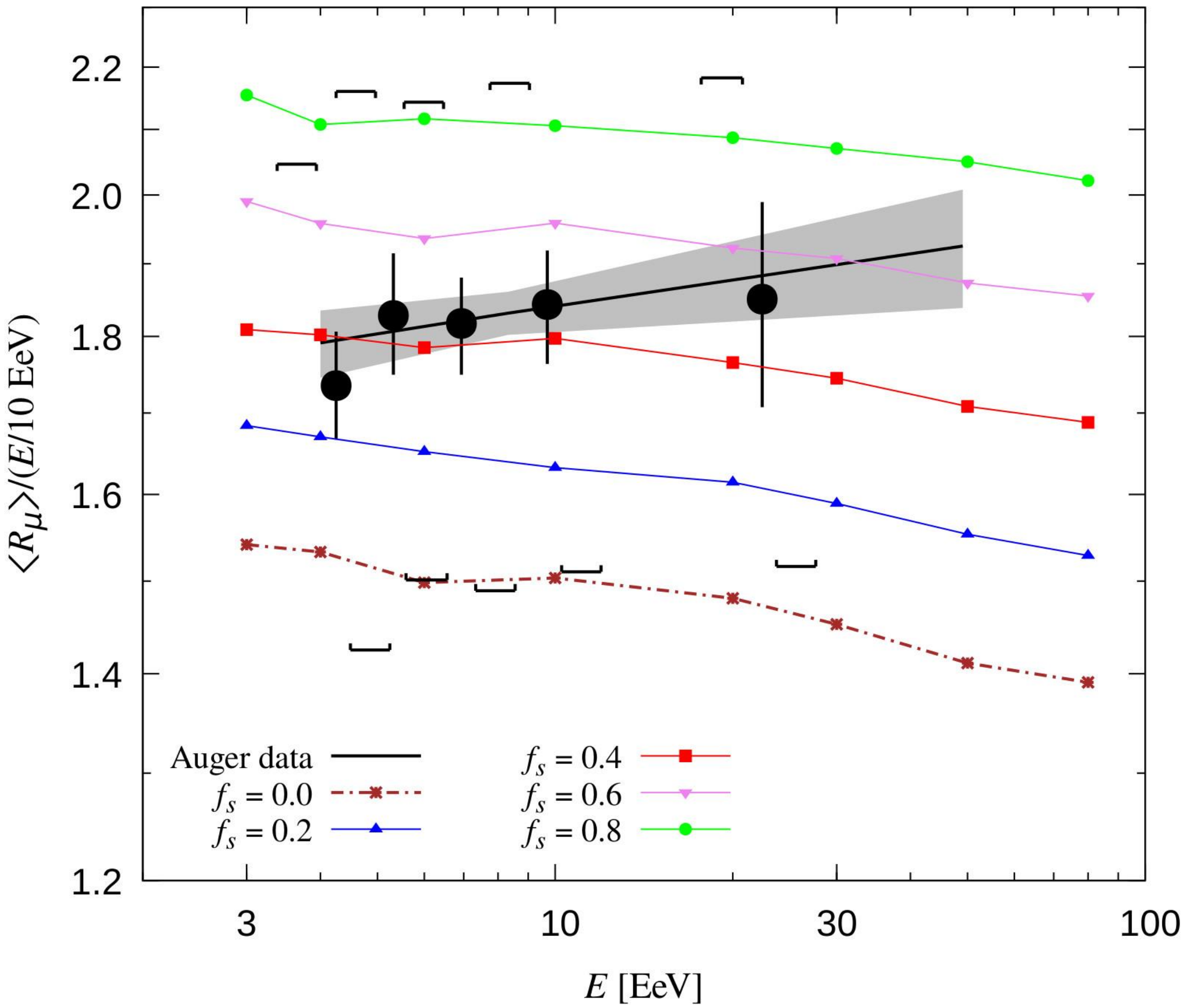
$\pi \longrightarrow K$ swap: refined model results.



Results from AIRES+ Sibyll 2.3d + $\pi \longrightarrow K$ swap, for varying swapping probabilities f_s. 10^{19} eV proton and iron showers inclined 67°. $E_{\mathrm{pmin}} = 1$ PeV.

Results are almost identical to the ones obtained with the first toy model.

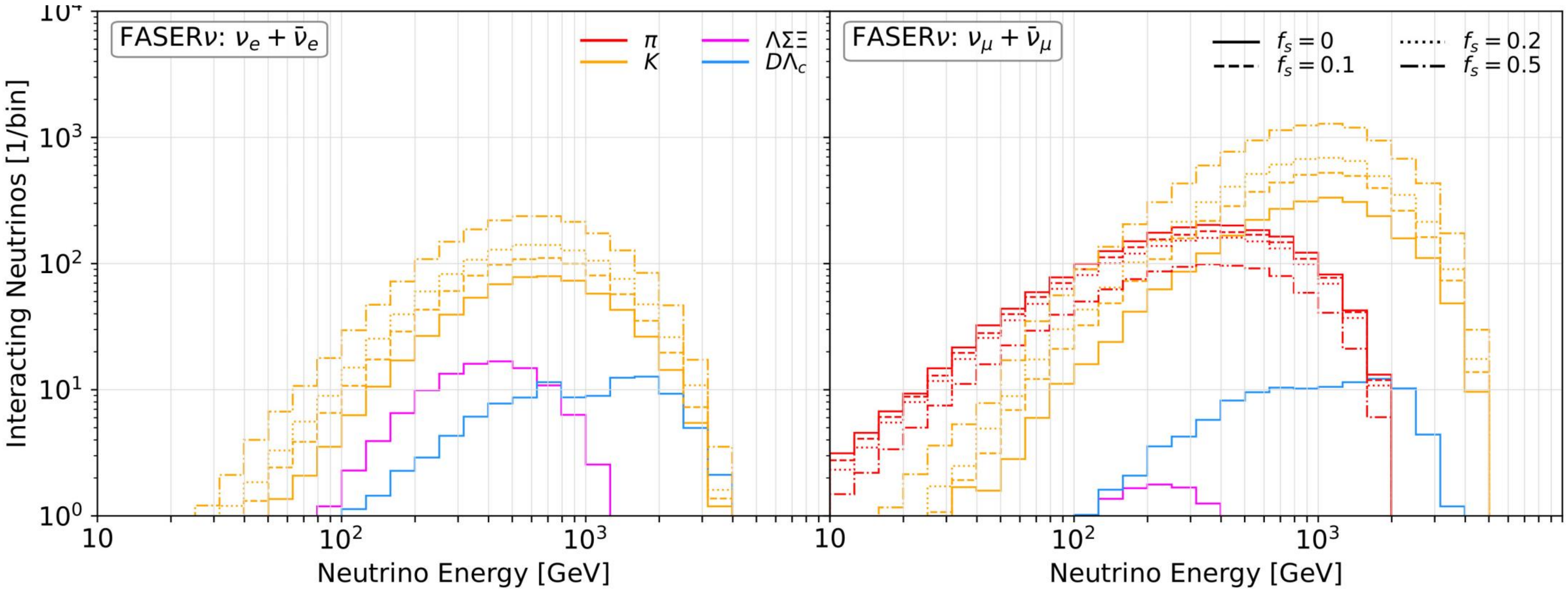
The muon puzzle (again!?)



Auger data after *Phys. Rev. D*, **91**, 032003 (2015).

Combined fit composition based on Auger *JCAP*, **04**, 038 (2017).

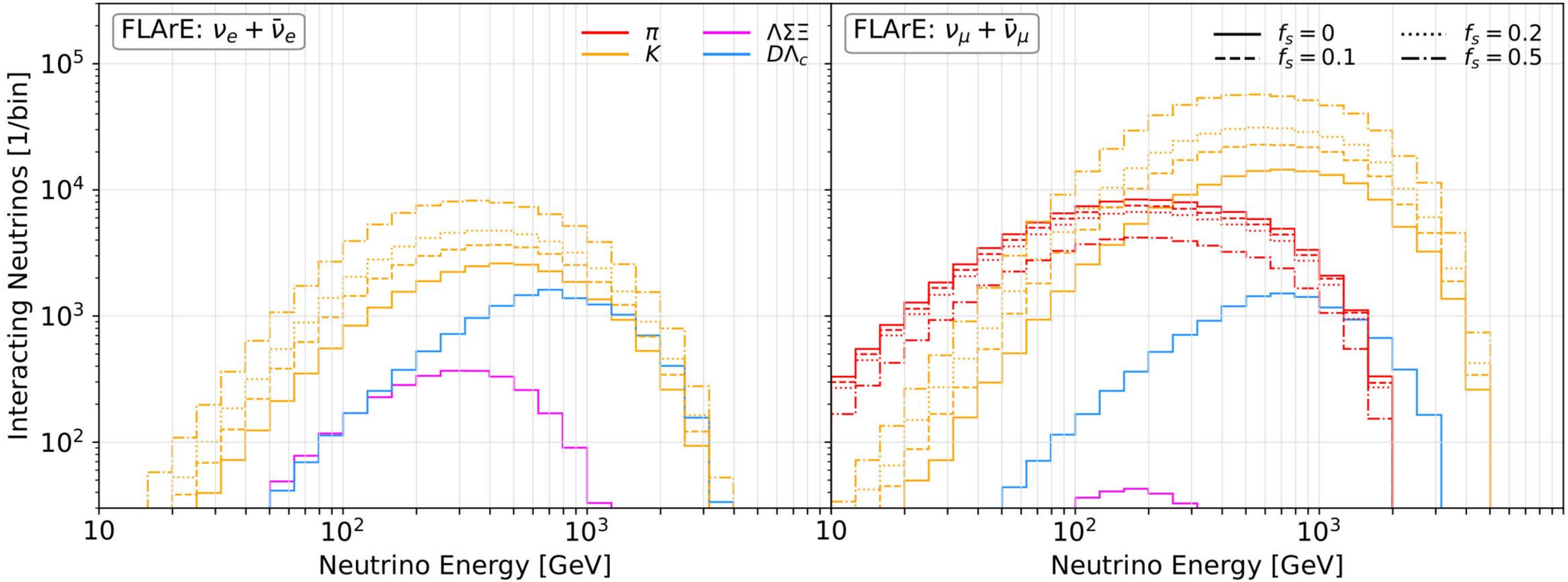
The refined model and FPF



FPF neutrino flux simulated with Fast Neutrino Flux Simulation (arXiv:2105.08270 [hep-ph]), for the experiment FASERν.

It shows up clearly that even small f_s lead to sizable changes in the neutrino flux contribution from kaons.

The refined model and FPF (cont.)



FPF neutrino flux simulated with Fast Neutrino Flux Simulation (arXiv:2105.08270 [hep-ph]), for the projected experiment FLARrE.

Again, it shows up that even small f_s lead to sizable changes in the neutrino flux contribution from kaons.

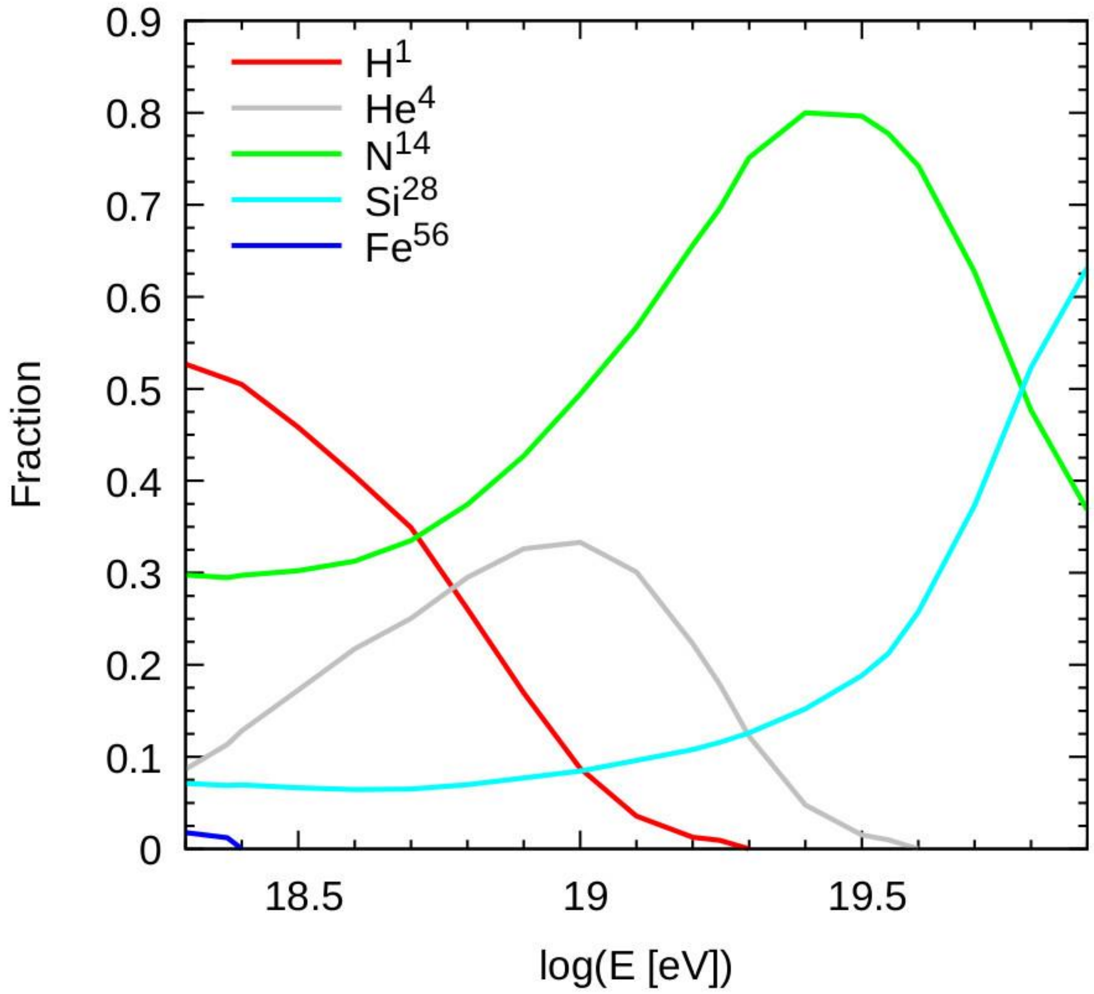
Conclusions and final remarks

- We constructed an **empirical model**, based on ALICE observations of strangeness enhancement in high-energy collisions, that **can accomodate the muon deficit between simulations and Auger data**, while maintaining complete agreement with measurements of longitudinal development observables.
- The $\pi \longrightarrow K$ **swapping probability** is parameterized in terms of the **pseudorapidity**.
- The predictions for the **FPF neutrino flux** obtained from simulations indicate that even small swapping probabilities can lead to **sizable changes** in the corresponding contribution from kaons. This can be understood taking into account that converting even a small fraction of the very large number of pions produced in the collisions, will significantly increase the flux of kaons (the difference is larger than the expected experimental uncertainties). As a result, **both FLArE and FASERν** should be **sensitive to constraint f_s**, especially if it is large ($f_s \sim 50$ %).
- The first generation experiment FASERν will start to take data in a few months, so we can expect some exciting results soon! ☺

THANK YOU!

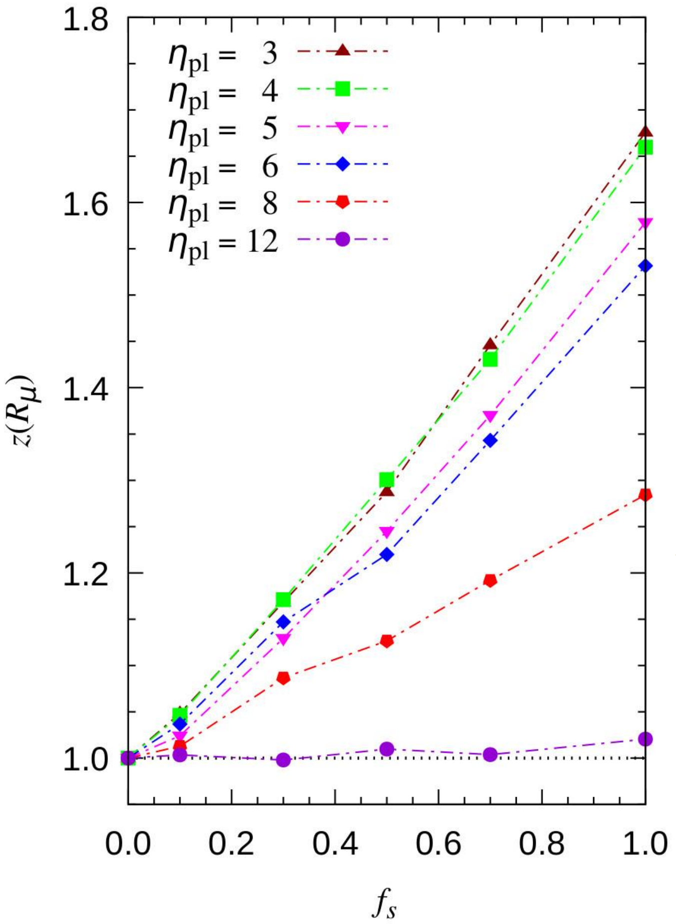
Backup slides

Combined fit composition



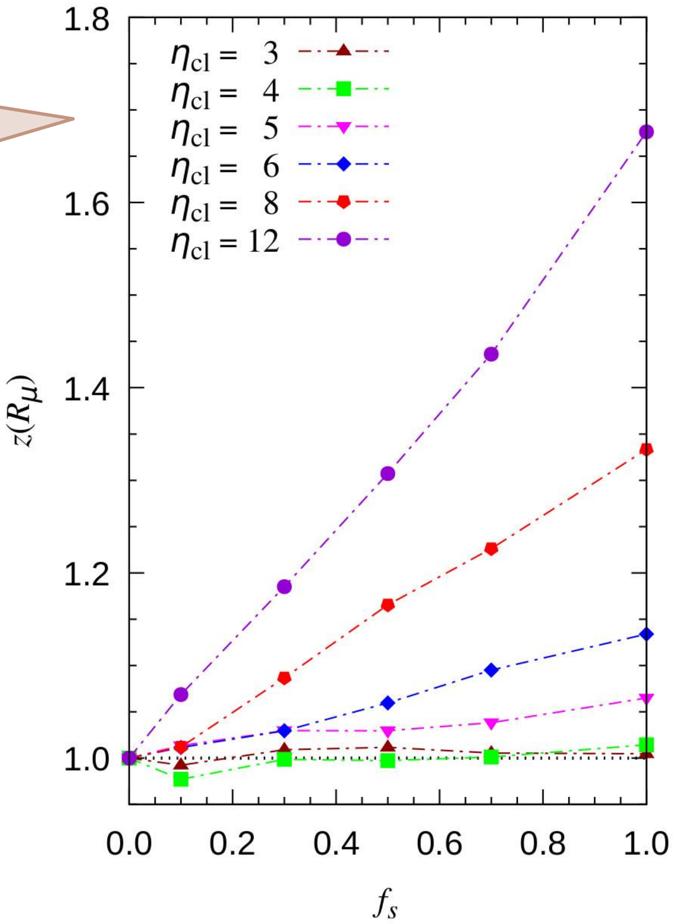
- The partial fluxes of different nuclei that add up to the measured total flux of highest energy cosmic rays that reach the Earth, are found to be primary energy dependent. They are estimated via simultaneous fits to Auger $X_{\max}$ and $\sigma X_{\max}$ data.
- For the detailed analysis see: Auger Collab., *JCAP* **04**, 038 (2017).; erratum: *JCAP* **03**, E02 (2018).

“Central” and “Peripheral” swapping



Swapping **only *“central”*** pions
(“peripheral” pions left unchanged)

Swapping **only *“peripheral”*** pions
(“central” pions left unchanged)



$$F(\eta_{CM}) = \begin{cases} f_s & \text{if } |\eta_{CM}| \geq \eta_{pl} \\ 0 & \text{if } |\eta_{CM}| < \eta_{pl} \end{cases}$$

$$F(\eta_{CM}) = \begin{cases} 0 & \text{if } |\eta_{CM}| \geq \eta_{cl} \\ f_s & \text{if } |\eta_{CM}| < \eta_{cl} \end{cases}$$