Proton-air interactions at ultra-high-energies in muon-depleted air showers with different depths

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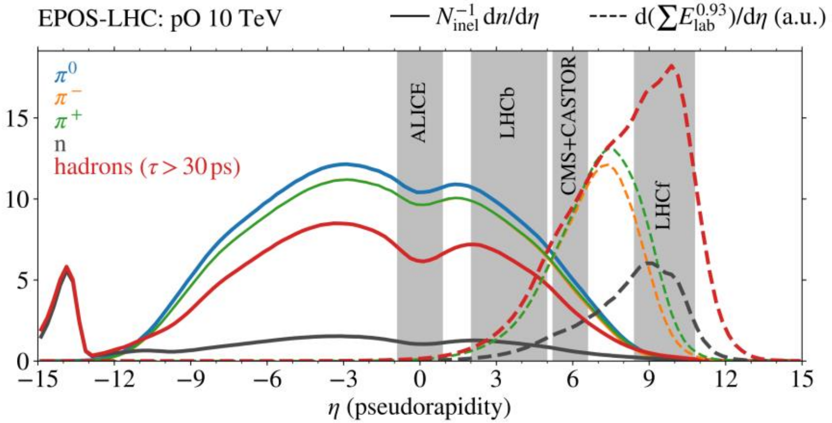
TeVPA 2024 – Chicago, 26 August 2024

LIP USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA IGFAE INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS 25 1999 2024 Fundación "la Caixa"

Motivation

- Ultra-high energy cosmic rays ($E_0 > 100\,\mathrm{PeV}$) measured through extensive air showers $\Longrightarrow$ opportunity to probe hadronic interactions at center-of-mass energies and rapidity regions not covered by human-made accelerators.



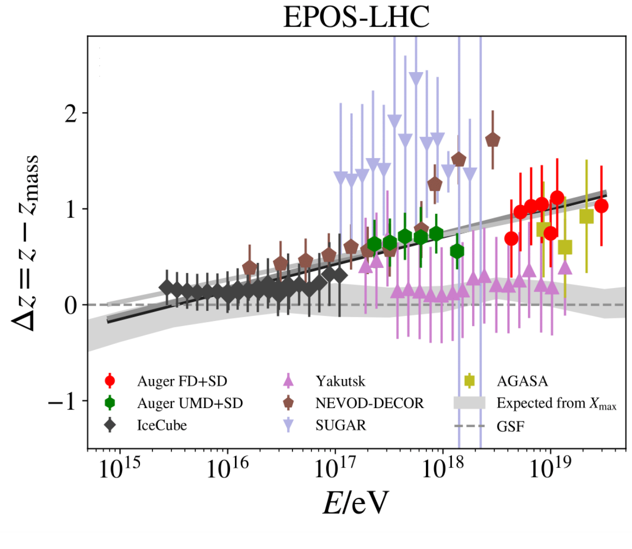
Astrophys Space Sci **367**, 27 (2022)

A degenerate problem:

- Unknown mass composition at highest energies;
- Lack of accelerator data in relevant kinematic phase space regions of CR-air interaction $\Longrightarrow$ hamper interpretation of mass composition.

A few current issues with air shower simulations:

- Muon puzzle: underestimation of muon scale in air shower simulations given mass composition from $X_{\max}$ (but fluctuations compatible!)
- Inconsistent description of electromagnetic and muonic components of EAS

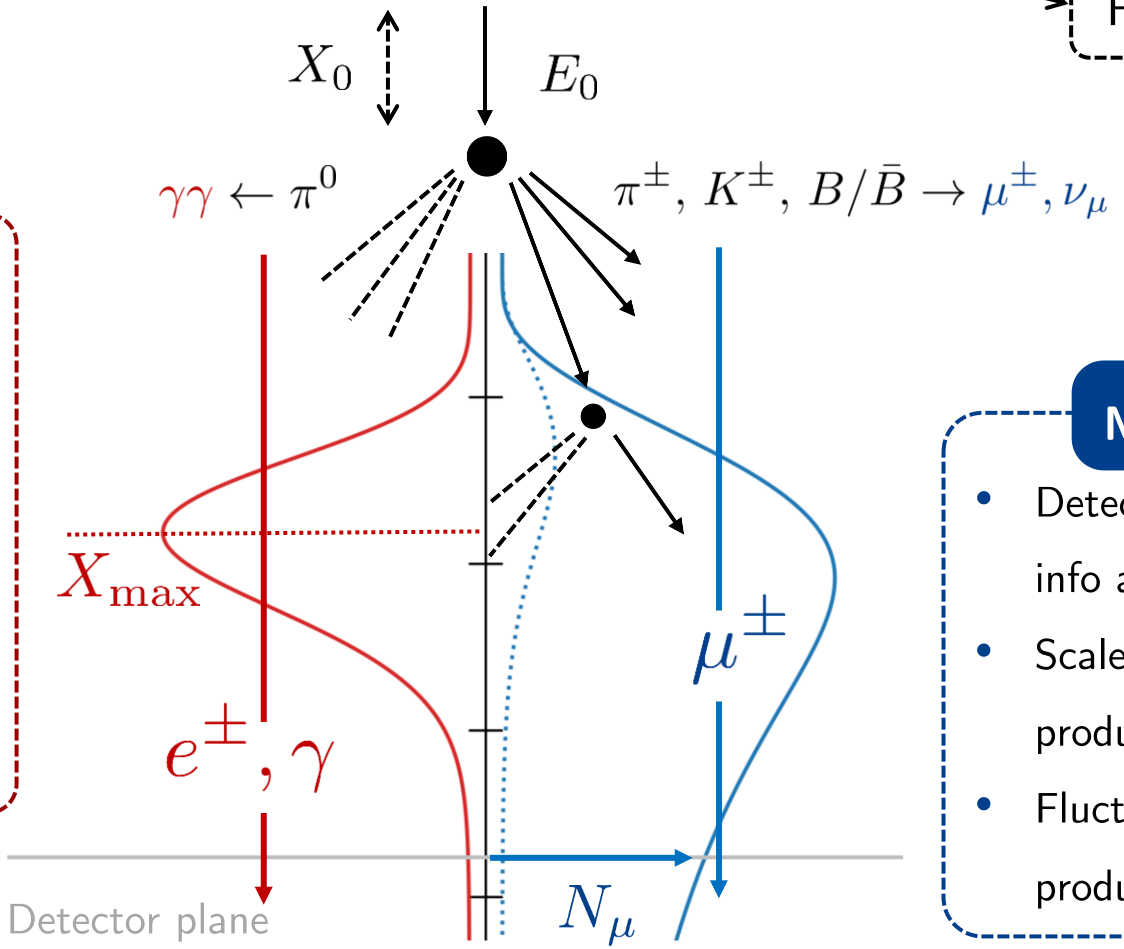


Use full distributions of shower observables to probe particle production in model independent way from data!

Cascade physics for fixed primary composition

Mostly coupled through 1st interaction

Hadronic component



Meson decay

Electromagnetic component

Maximum reached at X_{max};

X_{max} scale dominated by first few interactions; [Phys.Rev.D 93 (2016) 5, 051501]

Fluctuations dominated by:

- $\sigma(X_0) \propto 1/\sigma_{p-air}$;
- Fluctuations in particle production in first few interactions

Muonic component

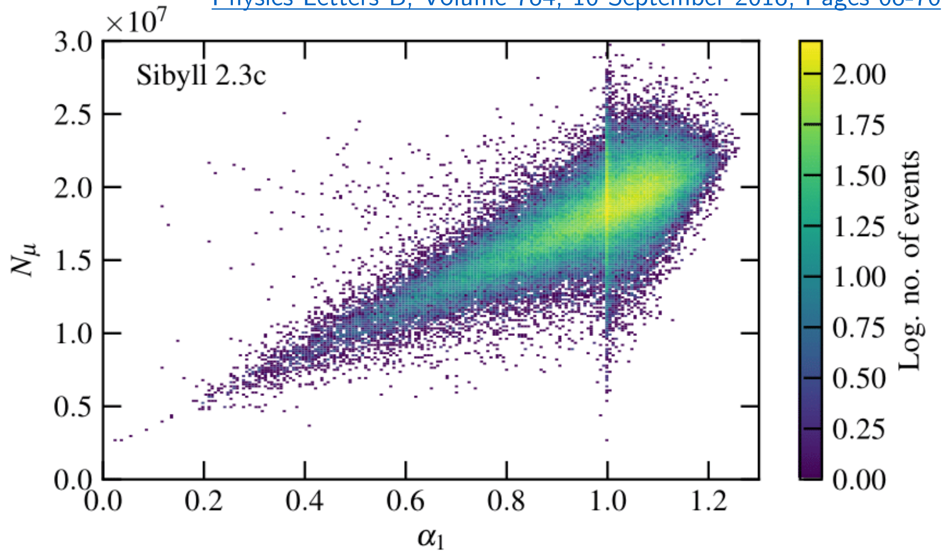
- Detected at ground $\Longrightarrow$ carries info about hadronic interactions;
- Scale depends on hadron production history;
- Fluctuations sensitive to particle production in first interactions.

Physics Letters B, Volume 784, 10 September 2018, Pages 68-76

- Shower-to-shower distributions of X_{max} and N_μ sensitive to particle production at the highest energies.

Hadronic physics from tail of distribution of N_μ

Physics Letters B, Volume 784, 10 September 2018, Pages 68-76

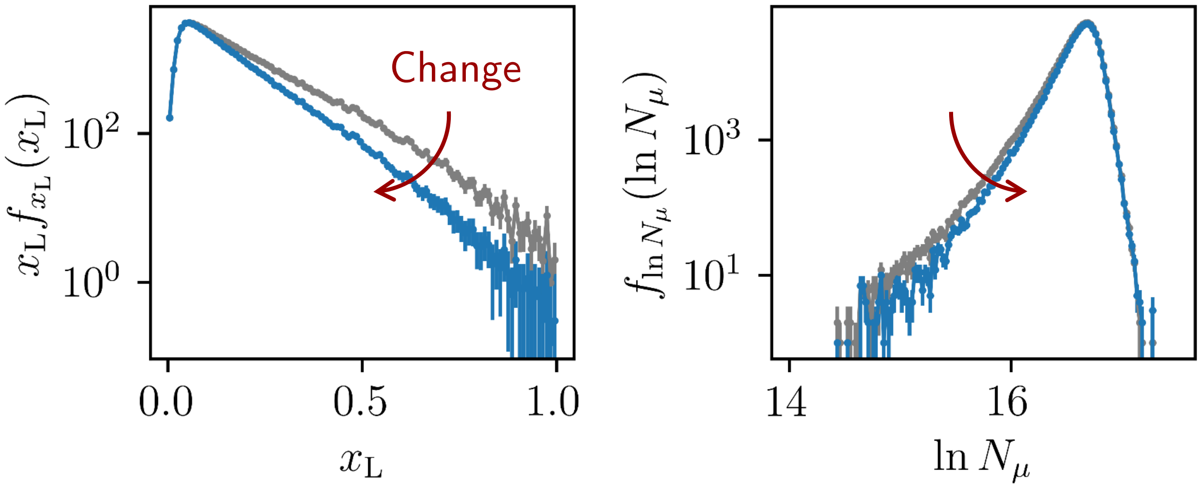


- N_μ highly correlated with fraction of primary energy in hadronic sector of the 1st CR-air interaction α_1;
- $\sigma(N_\mu)/N_\mu \simeq \sigma(\alpha_1)/\alpha_1$;
- Shape of distribution of N_μ sensitive to hardness of energy spectrum of hadrons of 1st CR air interaction;

$$\alpha_1 = \sum_{\text{hadrons } i} \left(\frac{E_{\text{had } i}}{E_0} \right)^\beta$$

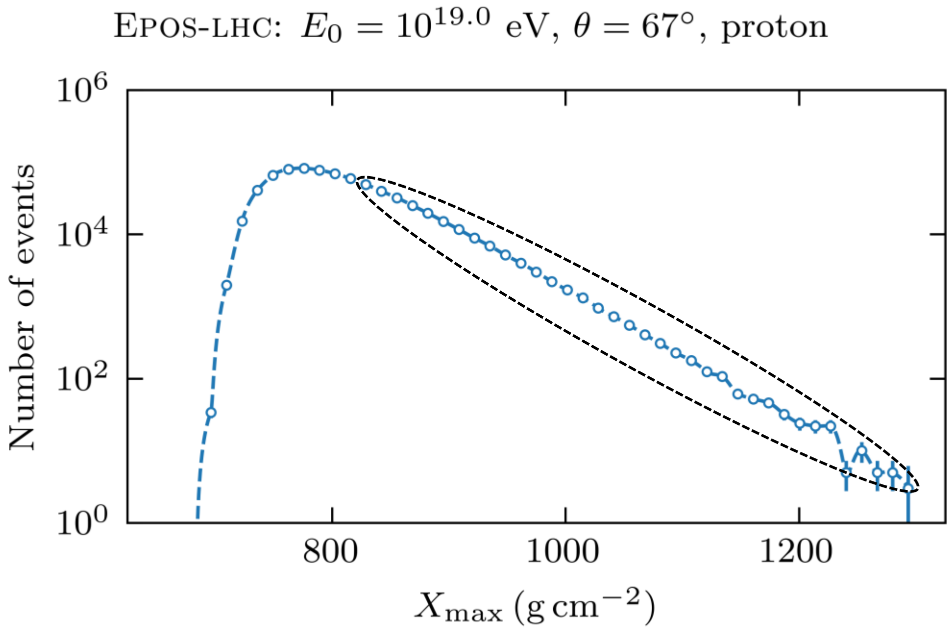
Energy spectrum of π^0 of 1st p-air int.

Phys.Rev.D 103 (2021) 2, 022001



- Softer energy spectrum of π^0 of 1st p-air interaction $\Longrightarrow$ steeper tail of N_μ $\Longrightarrow$ probe production cross-section of π^0 in p-air interactions above LHC through measurement of tail of distribution of N_μ

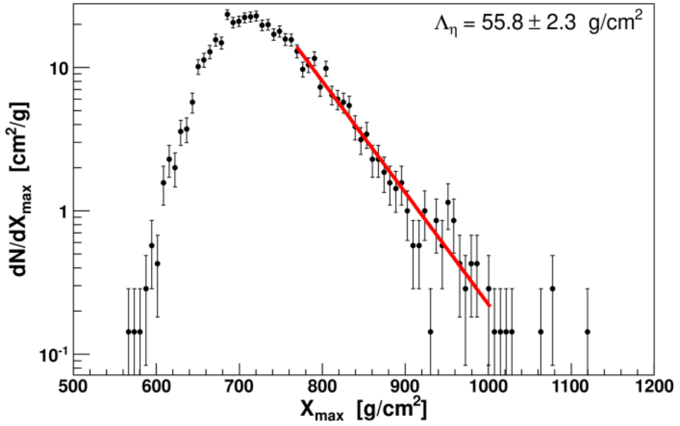
Hadronic physics from tail of distribution of $X_{\max}$

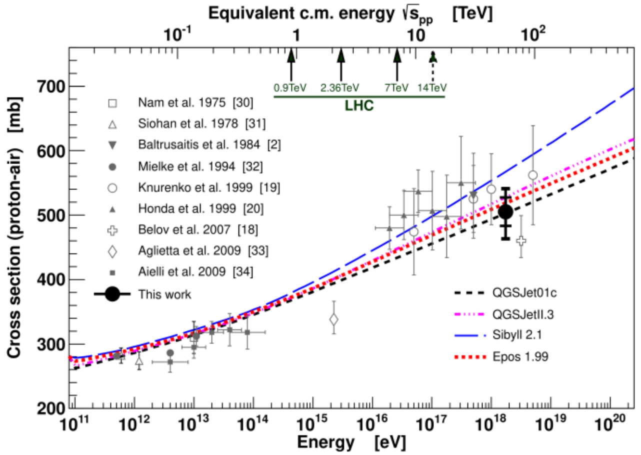


- Exponential tail from exponential distribution of depths of first interaction:

$$X_0 \sim \exp\left(-\frac{X_0}{\lambda_{p-\text{air}}}\right) \text{ with } \lambda_{p-\text{air}} \propto 1/\sigma_{p-\text{air}}$$

- Measurement of p-air cross-section with Auger at $\sqrt{s} > 57\,\text{TeV}$:





Phys. Rev. Lett. **109**, 062002

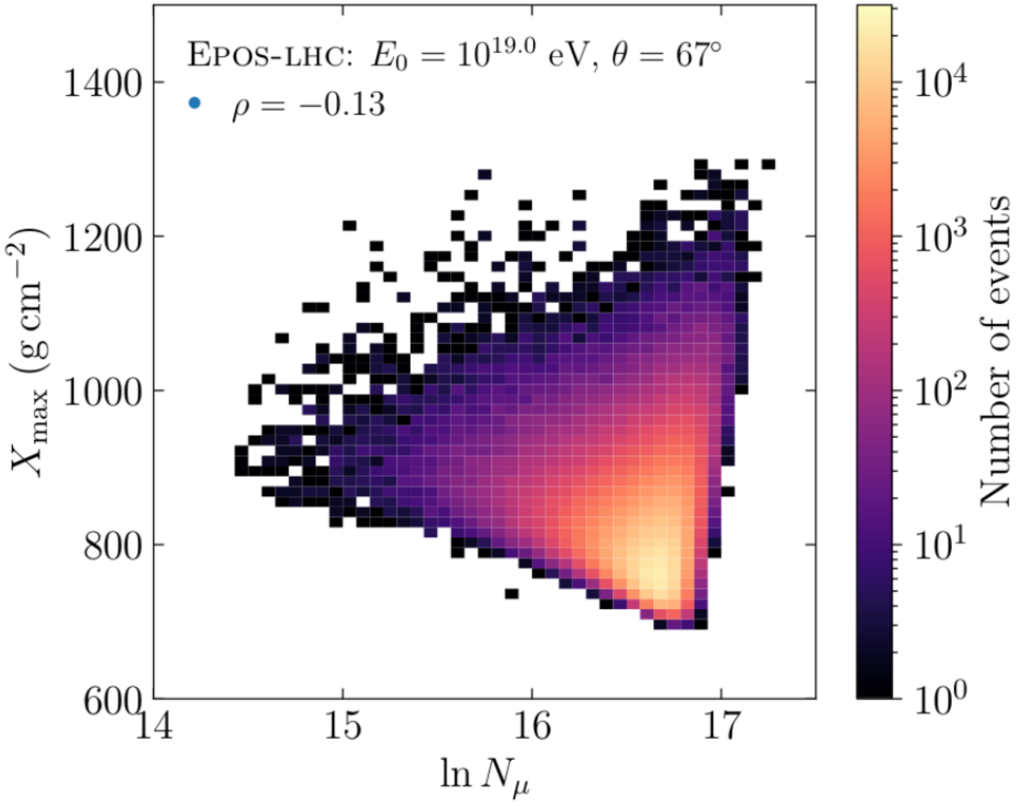
- Remaining fluctuations from fluctuations of $\Delta X_{\max} = X_{\max} - X_0$ $\Longrightarrow$ dominated by fluctuations in particle production in the highest energy interactions $\Longrightarrow$ possibility to probe such interactions above LHC energies.

Hadronic physics from the $\ln N_\mu - X_{\max}$ plane

Proton primaries $\Longrightarrow$ mild anti-correlation between $X_{\max}$ and N_μ from highest energy interactions.

Anti-correlation decreased by:

- Fluctuations of depth of first interaction X_0 uncorrelated with N_μ;
- Increased muon attenuation in shallower showers $\Longrightarrow$ positive correlation with $X_{\max}$;



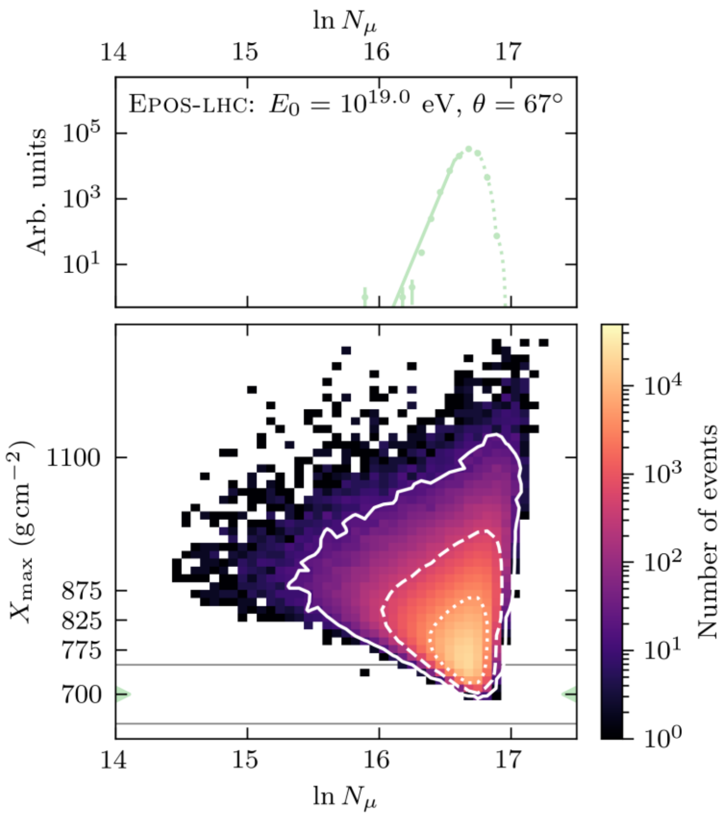
Conex simulations for proton primary!

Objective:

How much more information about 1st p-air interaction in joint distribution of $N_\mu - X_{\max}$?

Tail of muon number distribution as a function of $X_{\max}$

arXiv:2406.08620



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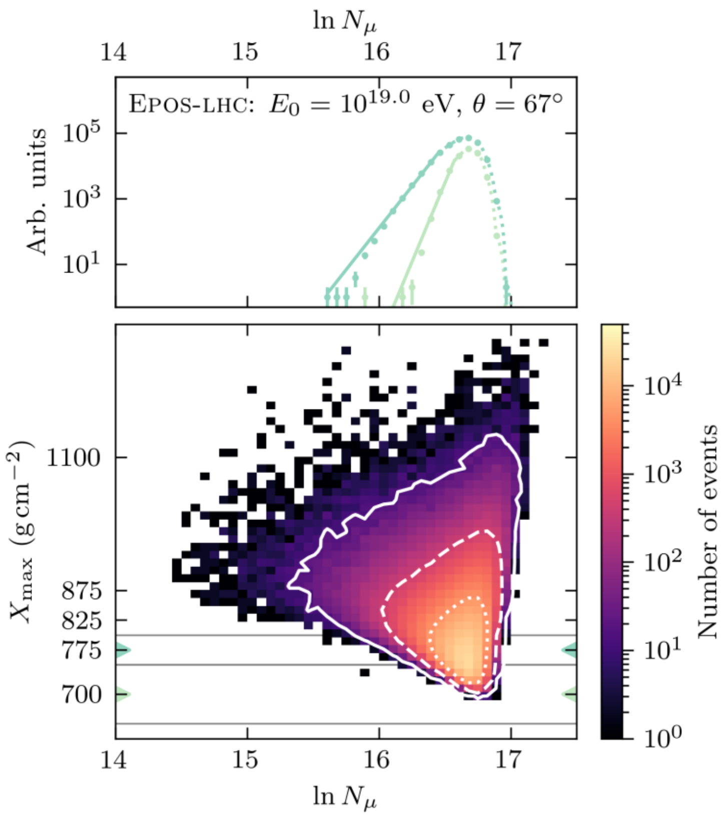

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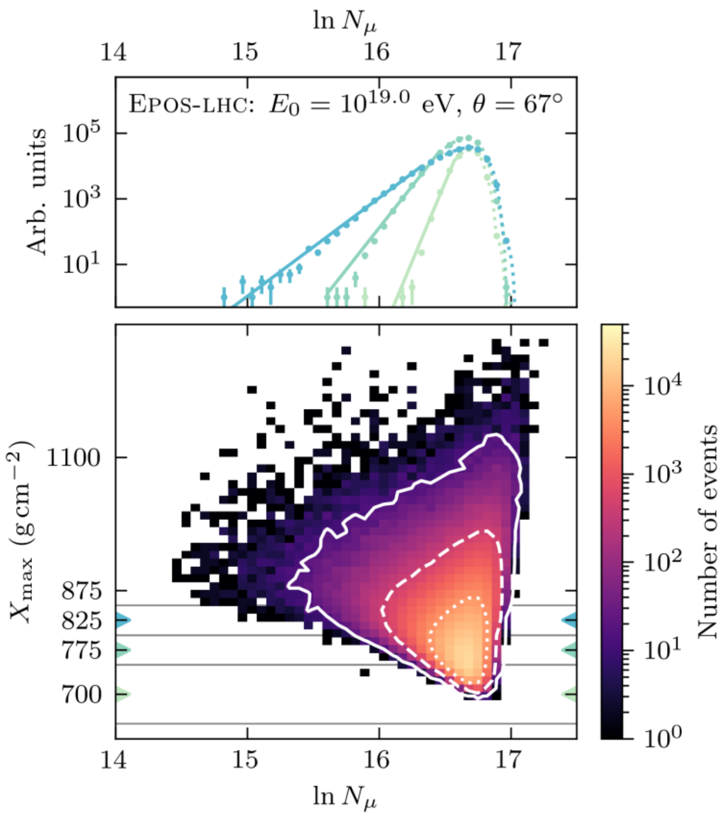

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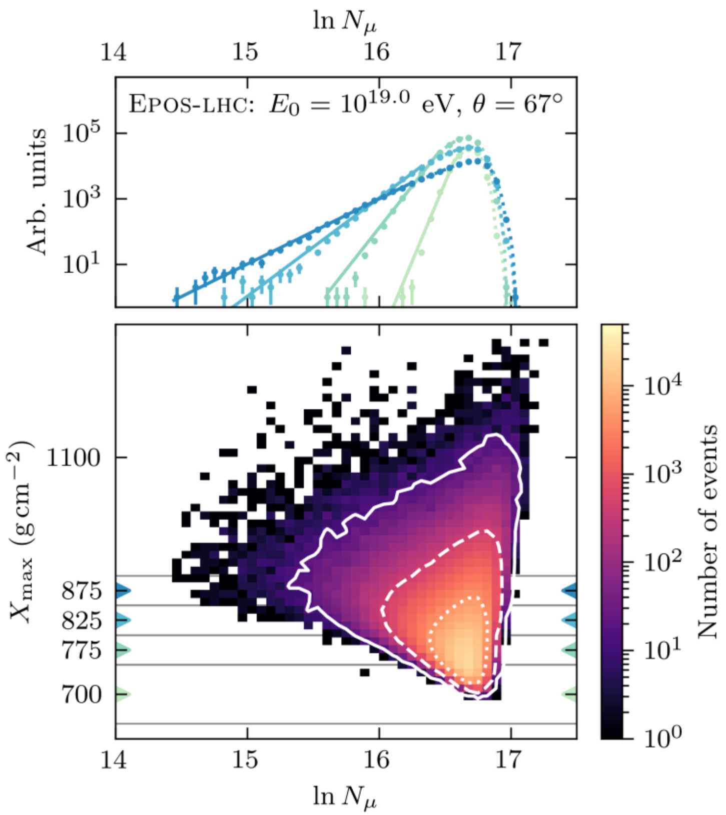

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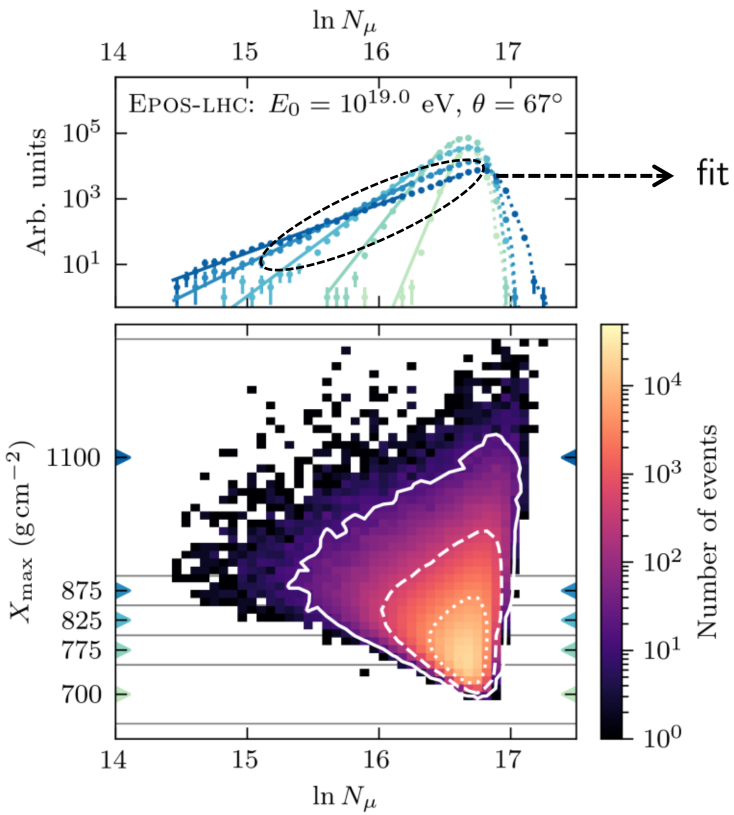
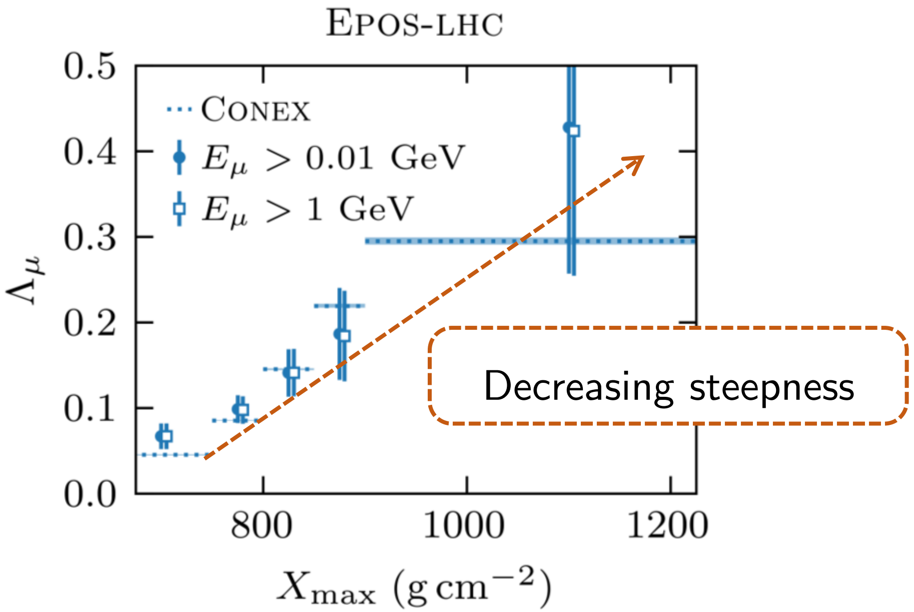




- Steepening of tail of N_μ distribution with increasing $X_{\max}$;
- Agreement between CORSIKA (full 3D Monte Carlo) and CONEX (MC + Cascade Equations) simulations $\Longrightarrow$ trend independent of energy threshold of muons.

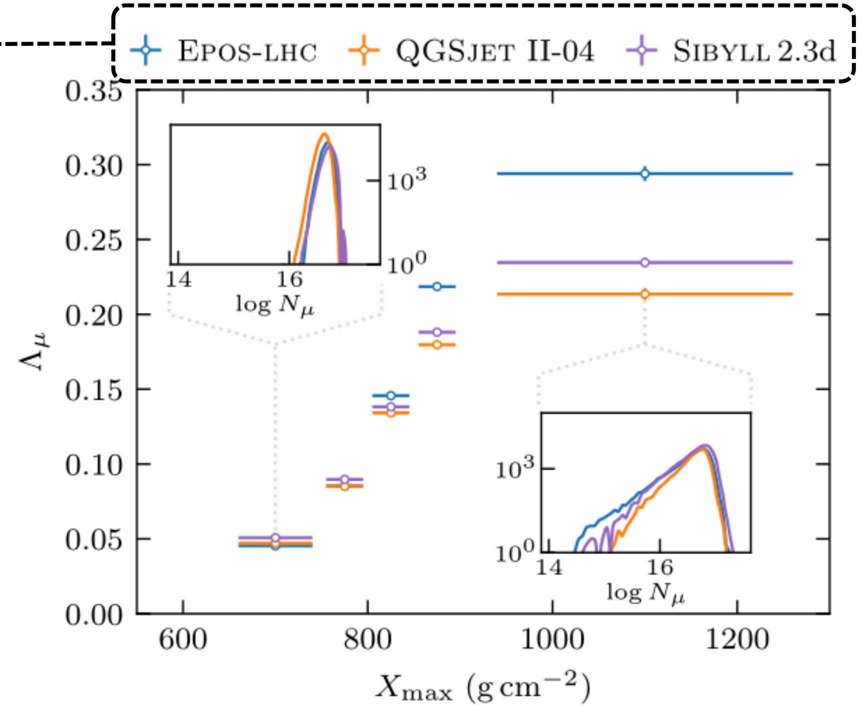
Take home message

- Measuring evolution of Λ_μ with $X_{\max}$ $\Longrightarrow$ stronger constraints on particle production in the 1st p-air interaction

Hadronic model dependence of Λ_μ evolution with $X_{\max}$

arXiv:2406.08620

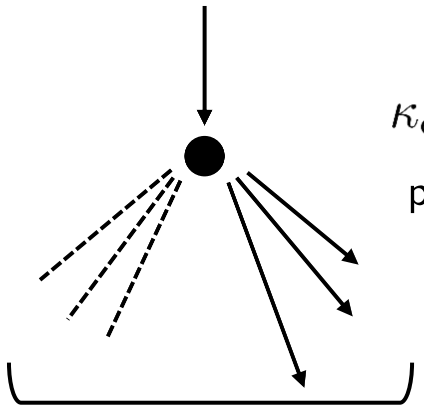
Different high energy hadronic interaction models



- Λ_μ evolution with $X_{\max}$ is model dependent;
- Shallow showers: hadronic interaction model predictions are universal ($<$ 10 % model dependence);
- Deep showers: enhanced model dependence of Λ_μ reaching 30 %

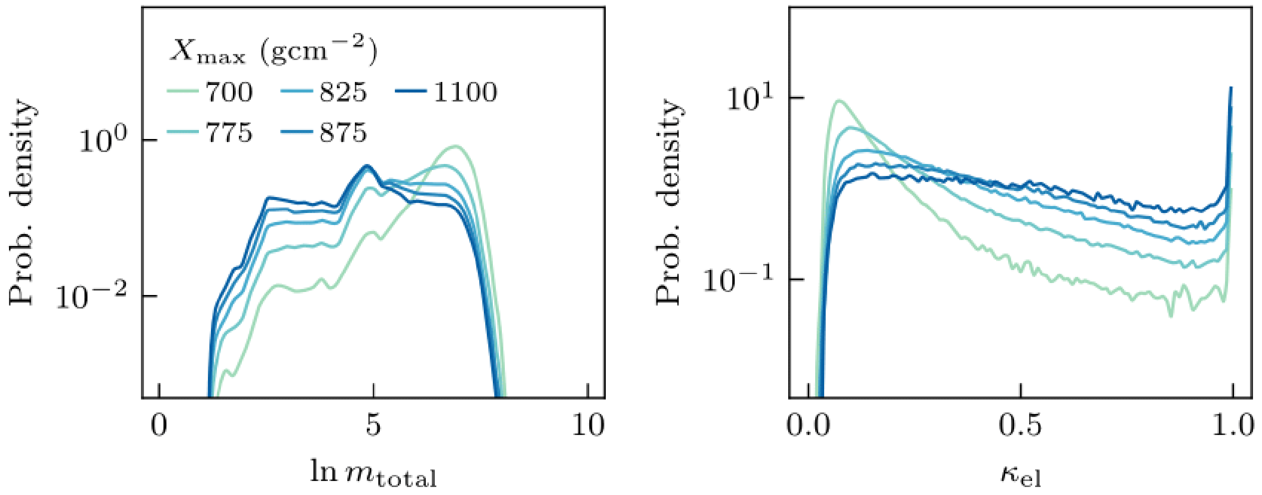
Multiparticle production variables of 1st interaction per X_{max} bin

arXiv:2406.08620



$\kappa_{el} \equiv$ elasticity: fraction of primary energy carried by leading

$m_{total} \equiv$ multiplicity: total number of secondaries



- Shallower showers: tendency for very inelastic 1st p-air interaction with high multiplicity (energy more evenly distributed among secondaries) $\Longrightarrow$ more hadronic activity $\Longrightarrow$ more universal tail.
- Deep showers: tendency for lower multiplicity + more elastic events $\Longrightarrow$ less hadronic activity

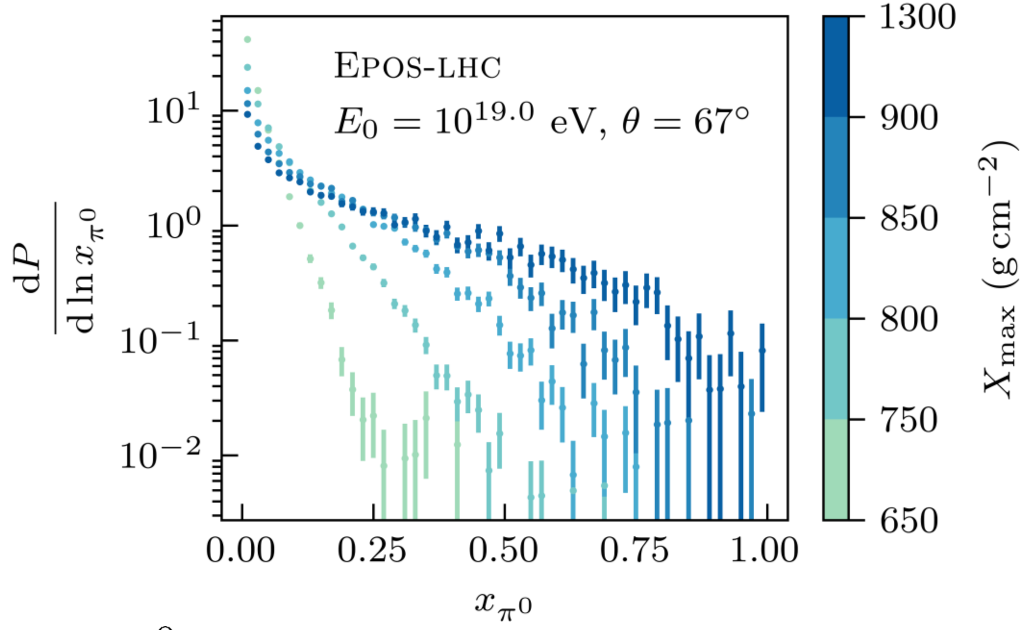
Take home messages

- Binning in $X_{max} \Longrightarrow$ probe continuously the hadronic activity of 1st interaction;
- $\Lambda_\mu(X_{max})$ evolution constrains models in different regions of the kinematic phase-space of 1st interaction.

Stronger constraints on neutral pion production cross section

arXiv:2406.08620

Recall that Λ_μ probes the hardness of the energy spectrum of neutral pions.



- Deep showers $\Longrightarrow$ events with fast π^0 of the 1st int. more likely $\Longrightarrow$ less muons $\Longrightarrow$ flattening of the muon tail.

Take home message:

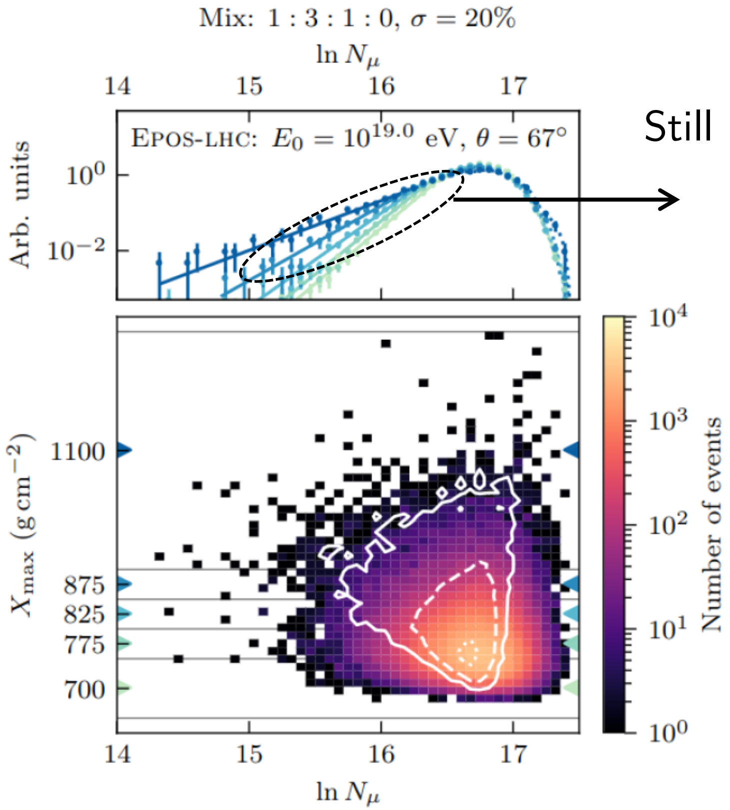
- Can probe the production cross-section of neutral pions of the 1st p-air collision as a function of the hadronic a activity outside phase-space covered by human-made accelerators!

Feasibility of measurement of Λ_μ: the case of Auger

arXiv:2406.08620

Is it possible to measure $\Lambda_\mu(X_{max})$ with Auger, given:

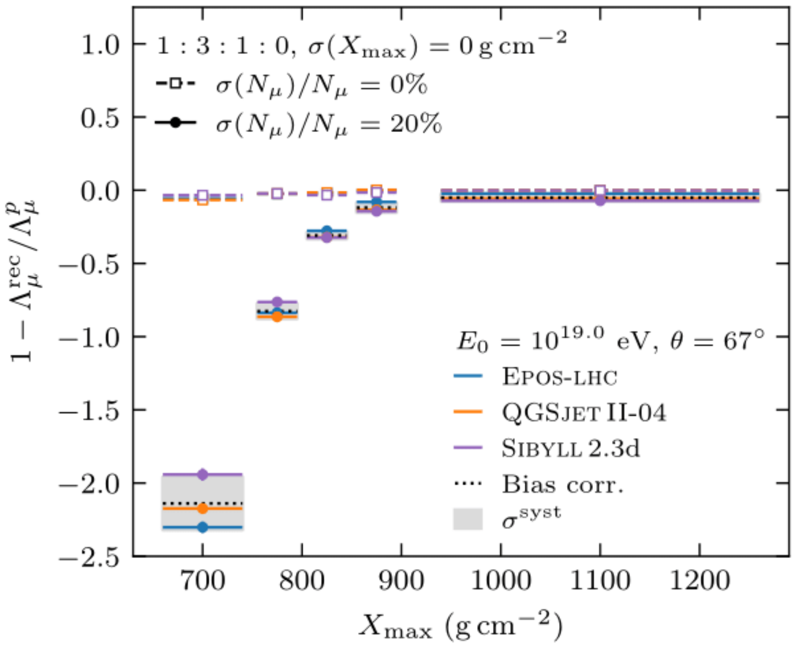
- Mixed mass composition: p: He : N : Fe?
- Resolution in X_{max}, N_μ and E_0?



Still has exponential tail!

Is Λ_μ biased?

- Proton-rich and proton-poor composition scenarios estimated from Auger data with $1 < E_0 < 3$ EeV



- Mixed mass comp. does not bias Λ_μ , BUT resolution in N_μ and X_{max} does!
- Bias is model dependent $\Longrightarrow$ apply average bias correction and consider model systematic.

Feasibility of measurement of Λ_μ: needed statistics

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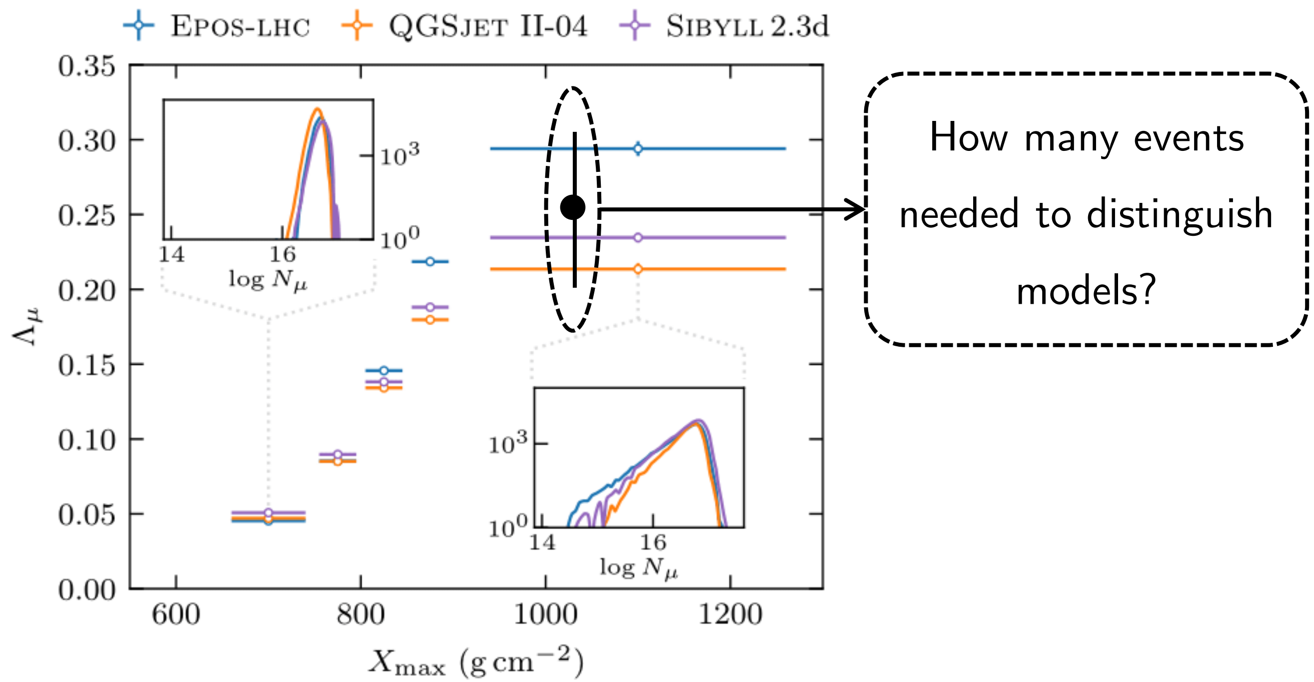

Proton poor: p :He: N = 1:3:1

$X_{\max}$ bin low edge	$n_{\min}\,(1\,\sigma)$	$n_{\min}\,(3\,\sigma)$
850	3 927	29 015
900	2 835	24 300

Proton rich: p :He: N = 7:1:2

$X_{\max}$ bin low edge	$n_{\min}\,(1\,\sigma)$	$n_{\min}\,(3\,\sigma)$
850	4 034	47 640
900	1 556	15 191

- Model distinction at 1 sigma possible with golden hybrids, regardless of the composition;
- AugerPrime and/or DNNs $\Longrightarrow$ able to exclude models with 3 sigma significance.

Take home message:

- $\Lambda_\mu(X_{\max})$ measurement feasible with Auger statistics!

Conclusions and outlook:

Conclusions:

- Model independente value of Λ_μ for shallow showers but highly dependent for deep showers;
- Binning in $X_{\mathrm{max}} \Longrightarrow$ continuously probe the hadronic activity of the first interaction;
- $\Lambda_\mu(X_{\mathrm{max}})$ evolution constrains models in different regions of the kinematic phase-space of 1st interaction $\Longrightarrow$ probe production cross-section of neutral pions in p-air interactions as a function of hadronic activity
- $\Lambda_\mu(X_{\mathrm{max}})$ measurement feasible with statistics of a typical UHECR observatory!
- Measuring Λ_μ as a function of the primary energy by combining different experiments would probe the cross section for neutral pion production as a function of projectile energy $\Longrightarrow$ compare with/ extrapolate safely from accelerator data.
- More details in: arXiv:2406.08620

Outlook:

- Fully explore the joint $N_\mu - X_{\mathrm{max}}$ distribution to constrain particle production in the highest energies.