New multiparticle production variables: Bridging the gap between air-shower observables and accelerator measurements

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Seminar – Dortmund, 24 April 2025

Ultra-high-energy cosmic rays

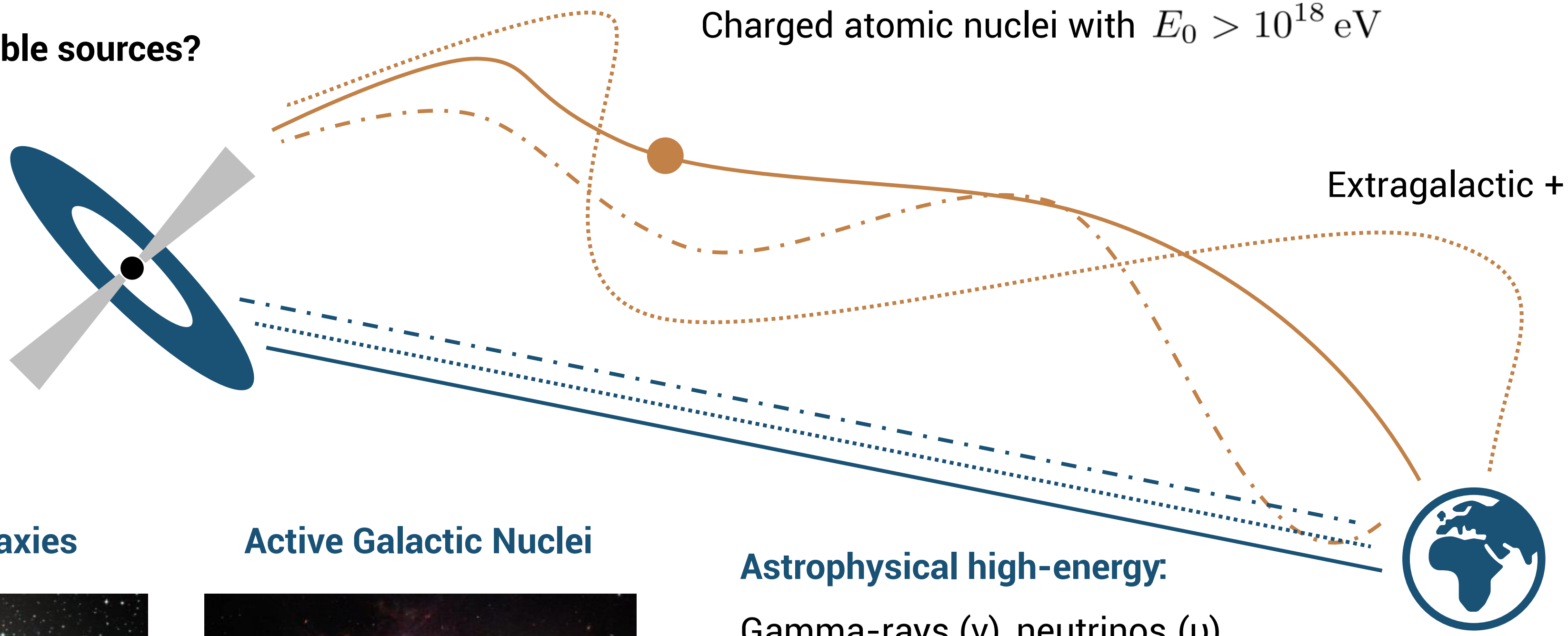
Possible sources?

Ultra-high-energy cosmic rays (UHECRs):

Charged atomic nuclei with $E_0 > 10^{18}\,\mathrm{eV}$

Extragalactic + galactic magnetic fields:

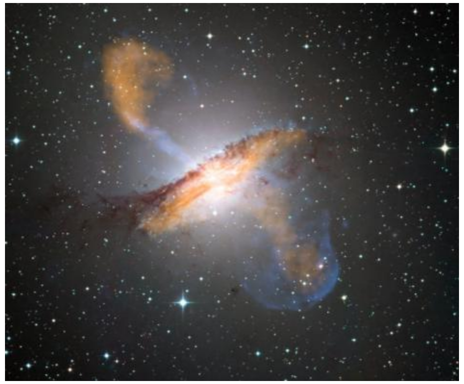
$\mathbf{B}$



Astrophysical high-energy:

Gamma-rays (γ), neutrinos (υ), ...

Starburst Galaxies



Active Galactic Nuclei

Open questions:

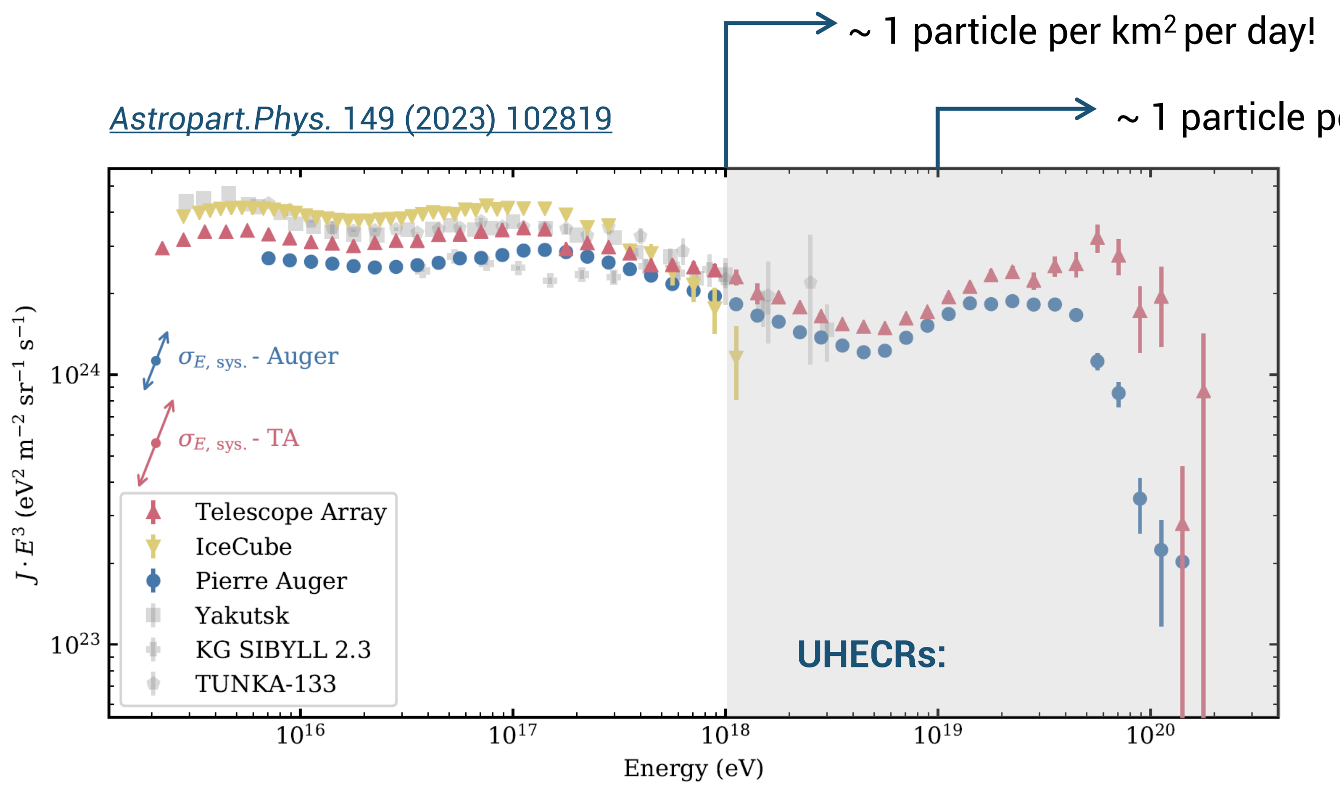
1. What is the mass composition of UHECRs
2. What are the sources of UHECRs

?

The cosmic ray flux at the highest energies

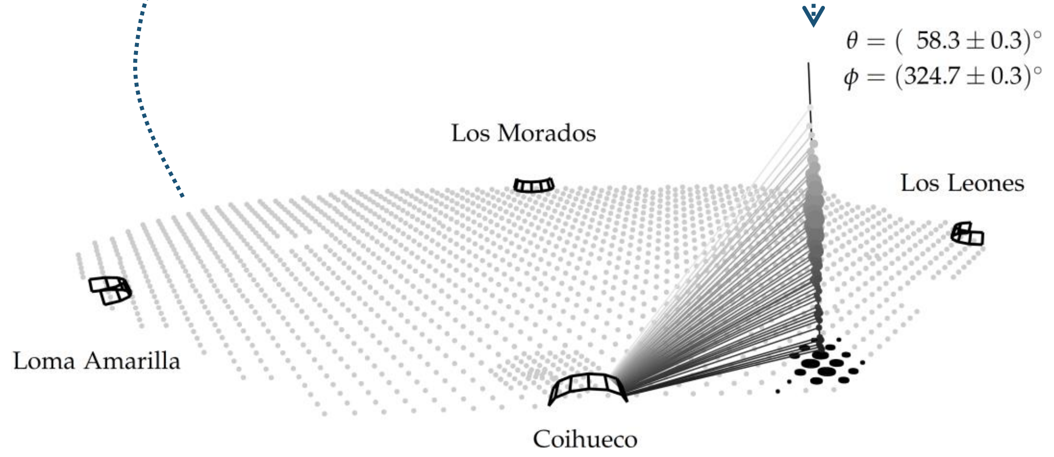
Cosmic-Ray Flux

Astropart.Phys. 149 (2023) 102819



$\Longrightarrow$ Extremely low flux $\Longrightarrow$ indirect detection in ground arrays (~1000 km²) through **Extensive Air Showers (EAS)**

Ground array (e.g. the Pierre Auger Observatory)



Phys.Rev.D 90 (2014) 12, 122005

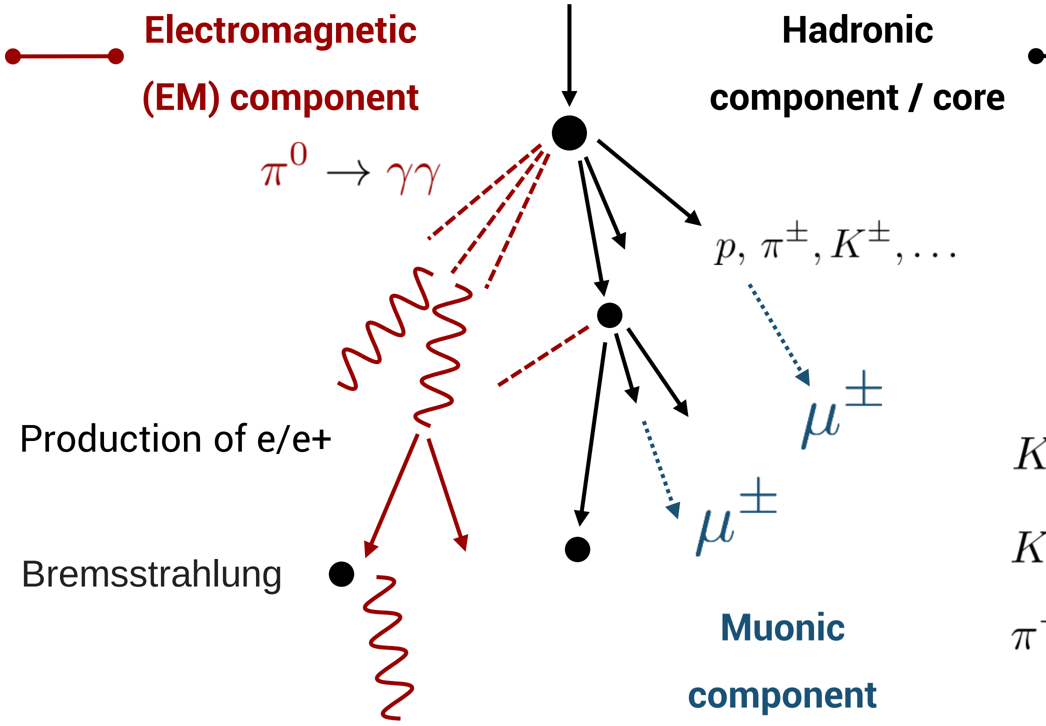
Take home message:

Indirect detection $\Longrightarrow$ **mass composition** of the cosmic ray (primary) **must be inferred** from EAS observables!

Extensive Air Showers

$$E_0 \sim 10^{18}\,\mathrm{eV} \iff \sqrt{s_{\mathrm{NN}}} \sim 100\,\mathrm{TeV}$$

Grows up to critical energy ξ_c^e below which ionization losses dominate over radiative processes



Grows up to critical energy ξ_c at which meson decay becomes more likely than further interaction

Muonic component mostly from meson decay:

$$K^+ \to \mu^+ + \nu_\mu \; (\Gamma \simeq 63.5\%)$$

$$K^+ \to \pi^+\pi^0 \to \mu^+ + \nu_\mu + \gamma\gamma \; (\Gamma \simeq 20.7\%)$$

$$\pi^+ \to \mu^+ + \nu_\mu \; (\Gamma \simeq 99\%)$$

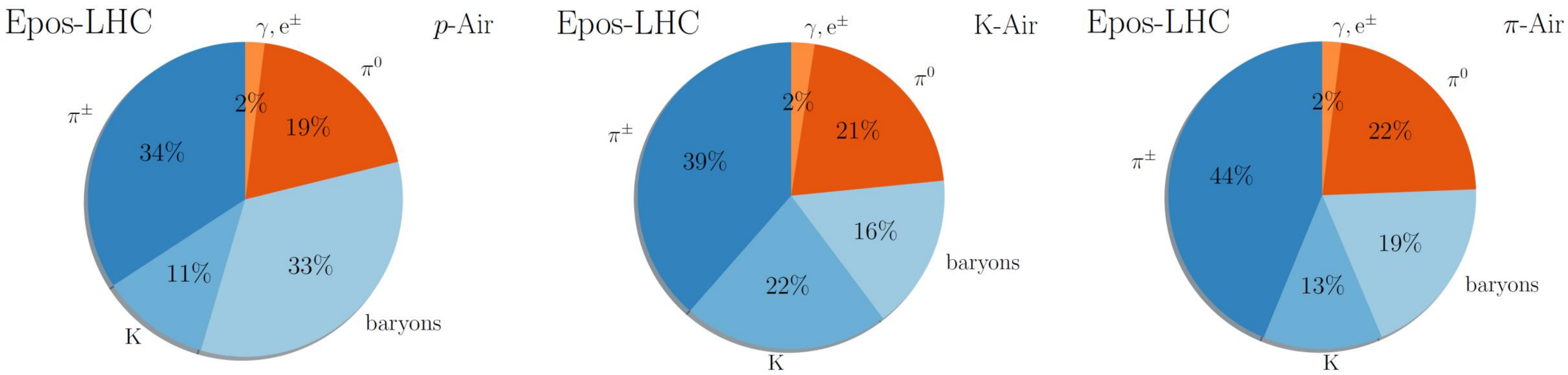
Decay of low energy muons:

$$\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$$
$$\mu^- \to e^- + \overline{\nu}_e + \nu_\mu$$

- Most particles reaching the ground level are muons (carry ~10 % of E_0) and electromagnetic particles (carry ~90 % of E_0)
- EM and hadronic components mostly decoupled after primary interaction

Review of particle physics, Phys.Rev.D 110 (2024) 3, 030001

Energy partition among secondary hadrons



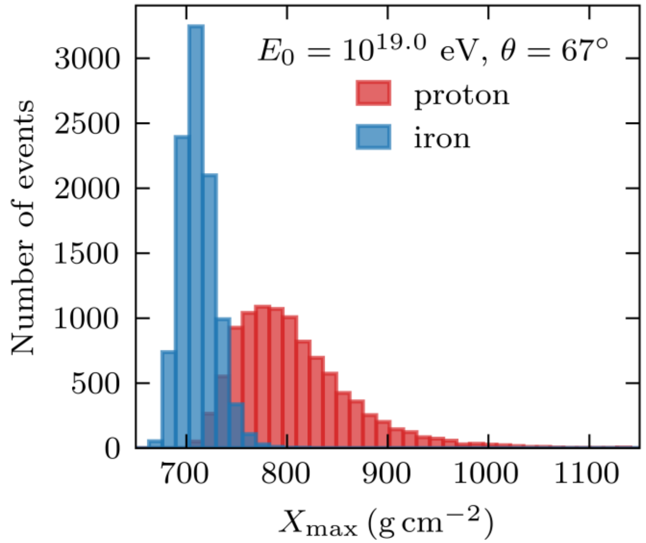
L. Cazon, PoS ICRC2019 (2020) 005

Take home messages:

- Electromagnetic component mostly fed by decay of neutral pions
- Energy in hadronic component mostly carried by charged pions and kaons and light long-lived baryons

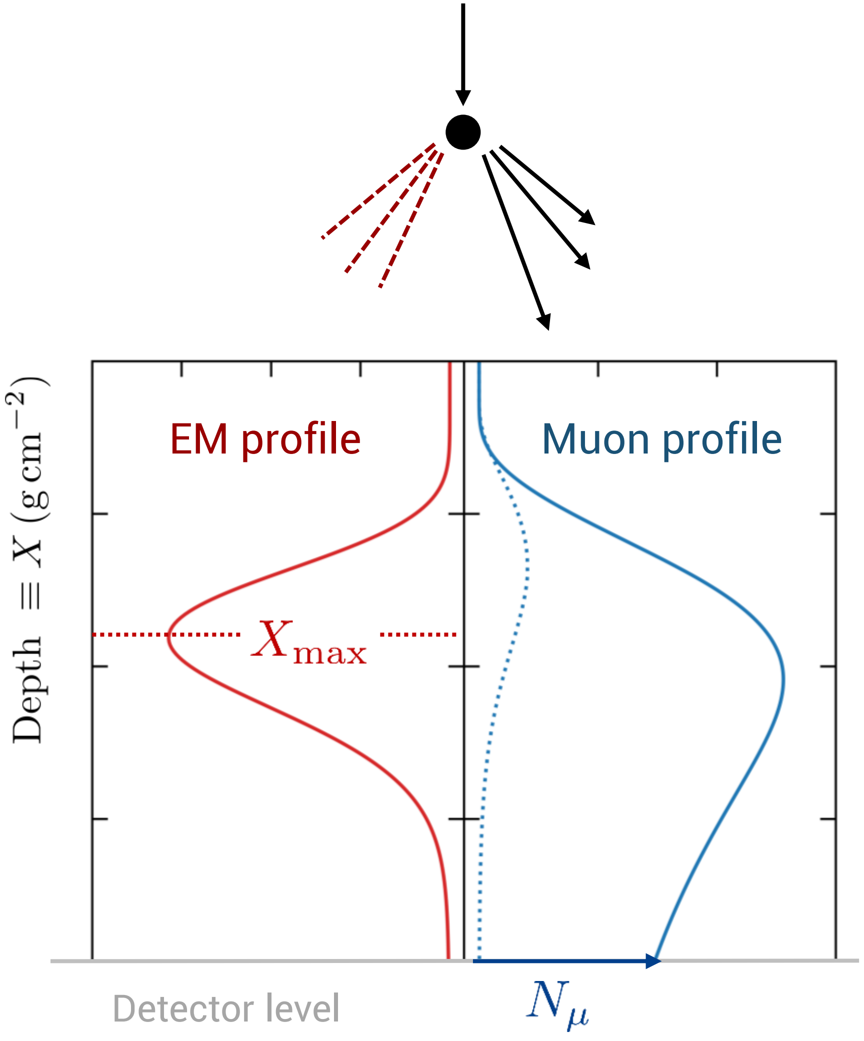
Main air-shower observables as probes of the primary composition

X_{max}

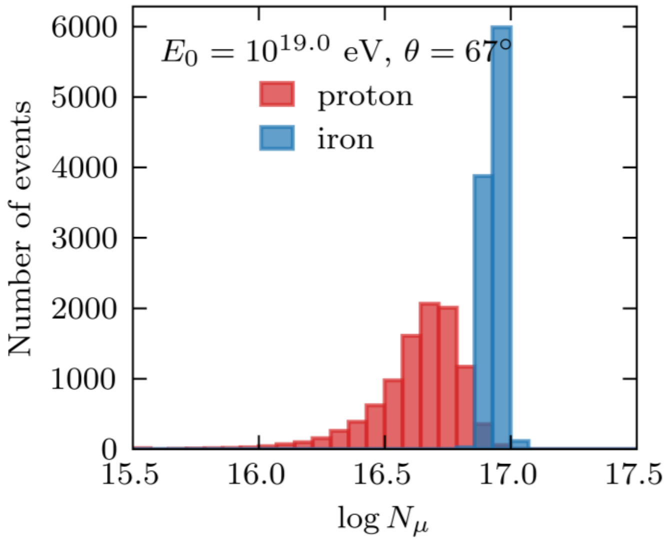


Shape of X_{max} distribution highly sensitive to primary mass number $A \Longrightarrow$ allows mass discrimination

Issue: primaries with similar $A \Longrightarrow$ overlapping X_{max} distributions $\Longrightarrow$ poor event-by-event mass discrimination



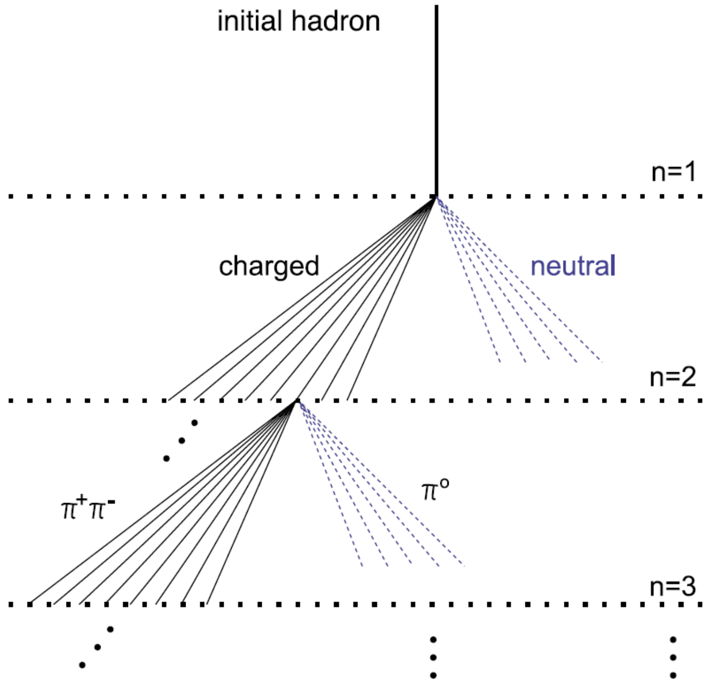
N_μ



Shape of N_μ distribution highly sensitive to primary mass number $A \Longrightarrow$ allows mass discrimination

Issue: sensitive to hadron production in all stages of cascade $\Longrightarrow$ highly dependent on description of hadronic interactions

EAS as splitting processes: the Heitler-Matthews model



[Astropart.Phys. 22 (2005) 387-397](#)

Heitler-Matthews framework for proton showers:

1. In each interaction, energy is equipartitioned between secondaries
2. Ratio between neutral and charged pions is constant
3. Number of secondaries is fixed in all interaction
4. All mesons decay into muons at the same critical energy
5. For X_{max}, only consider neutral pions from primary-air interaction

$$N_\mu \propto \left(\frac{E_0}{\xi_c^\pi}\right)^\beta \qquad X_{\max} \propto \ln(E_0/\xi_c^e)$$

Superposition: nucleus with energy E and A nucleons = A nucleons each carrying energy E / A

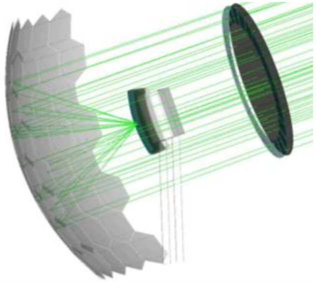
Predicts correct mass evolution!

$$\boxed{N_\mu(A) \propto A^{1-\beta}\left(\frac{E_0}{\xi_c^\pi}\right)^\beta \qquad X_{\max}(A) - X_{\max}(1) \propto \ln A}$$

Precise mass inference requires modeling of hadronic interactions!

Measuring / Estimating X_{max} and N_μ

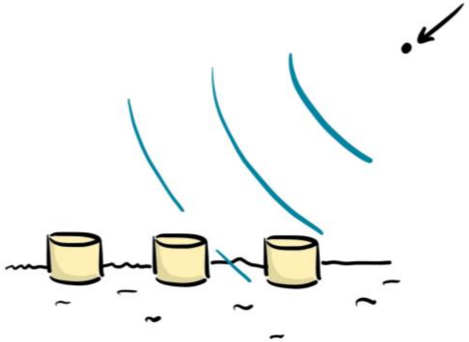
Nucl.Instrum.Meth.A 798 (2015) 172-213

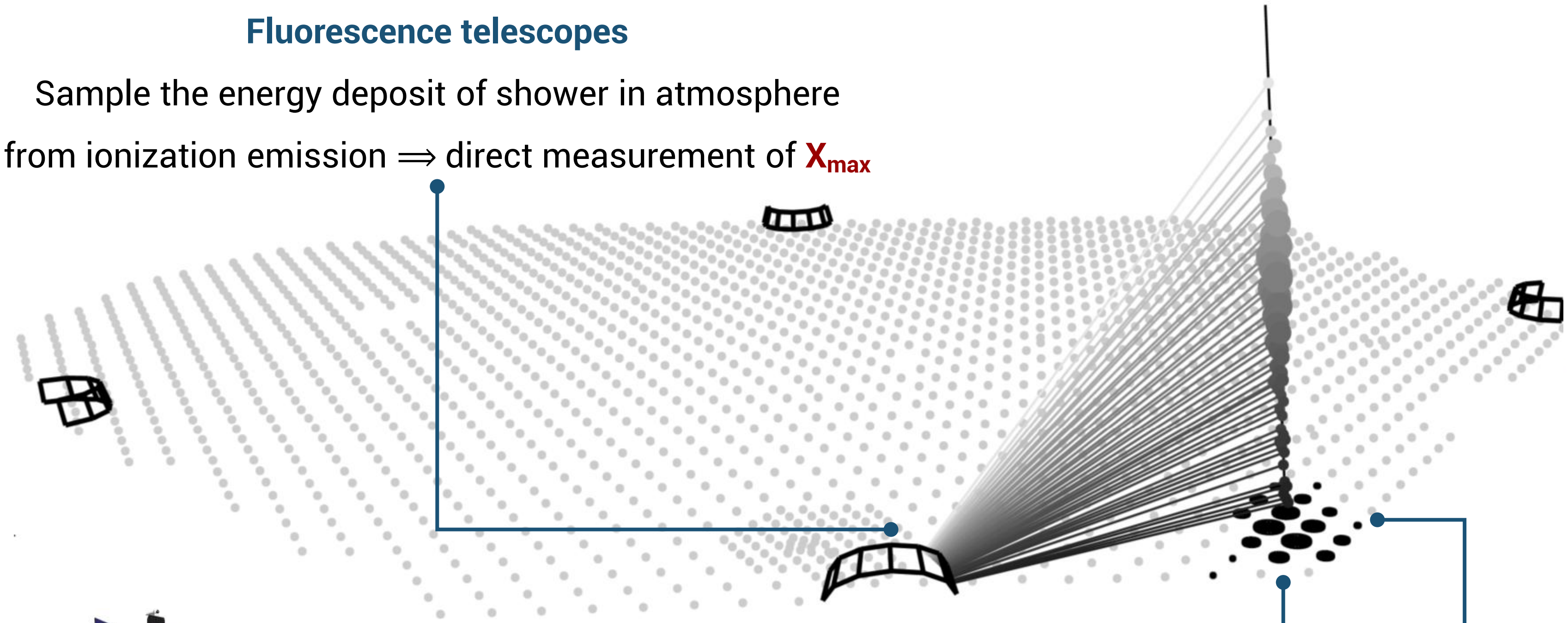


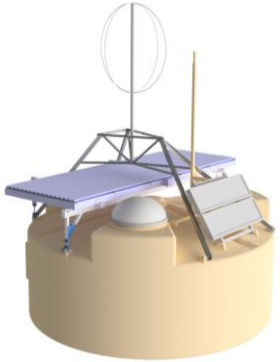
Fluorescence telescopes

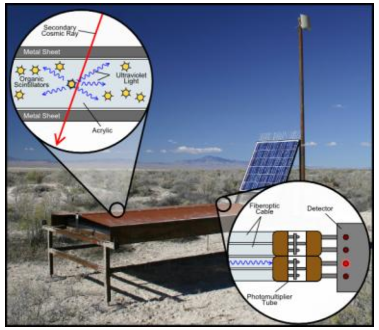
Sample the energy deposit of shower in atmosphere

from ionization emission $\Longrightarrow$ direct measurement of X_{max}





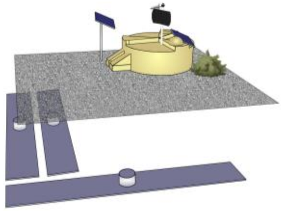




Water-Cherenkov detectors, Scintillators, ...

Sample the shower front of a large area $\Longrightarrow$

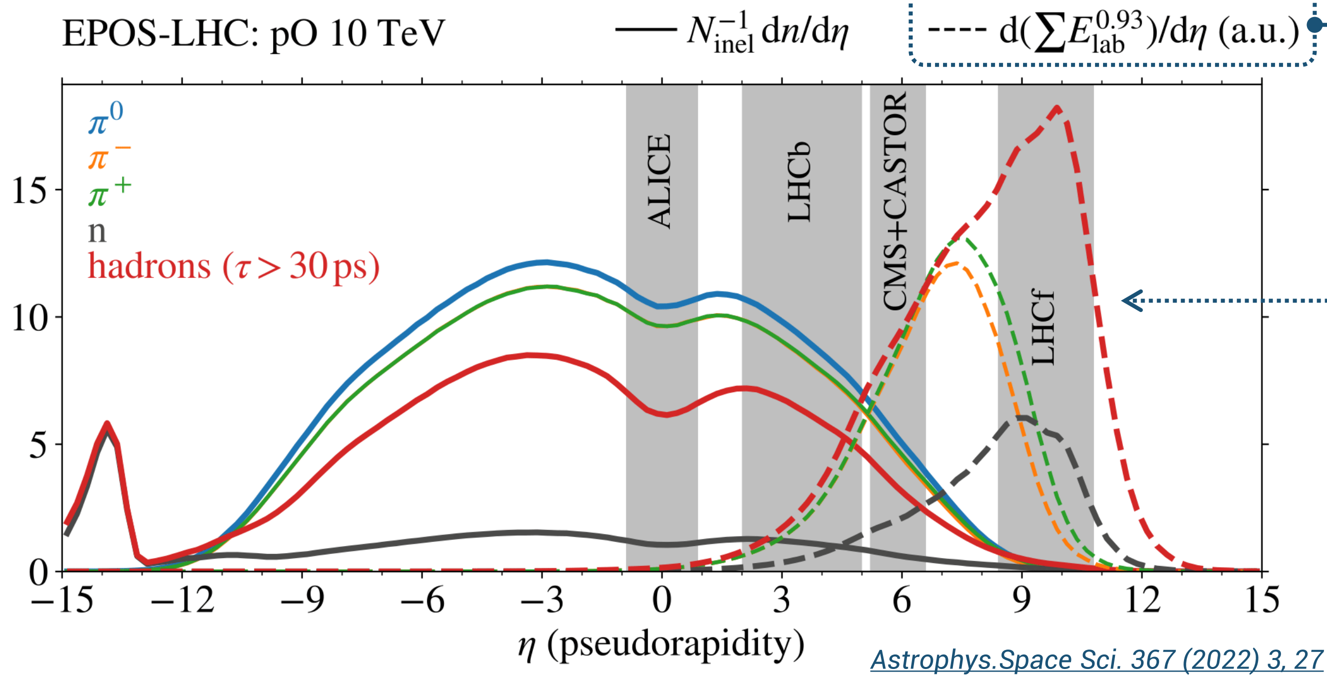
allow inference of N_μ and X_{max}



Underground Muon Detectors

Direct measurement of N_μ above a certain energy threshold

Modelling hadronic interactions: Hadronic Interaction Models



Normalized energy flow

Peaks of energy flow in far forward region (η > 7)

Astrophys.Space Sci. 367 (2022) 3, 27

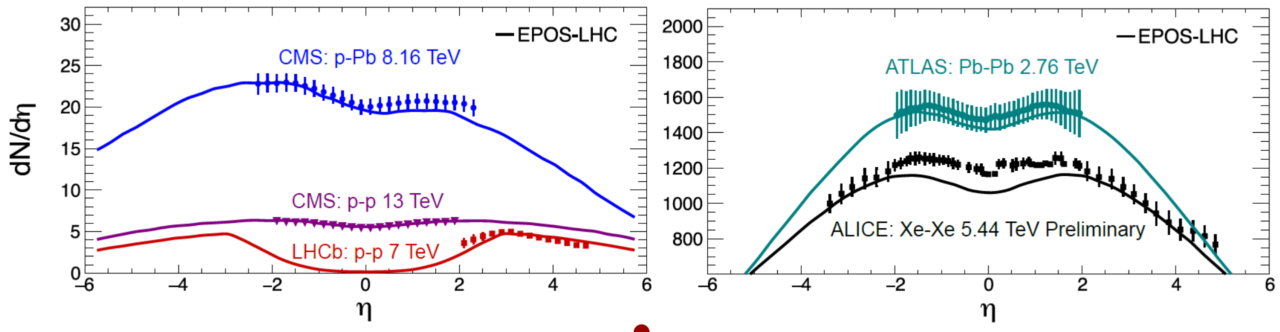
Extensive air showers driven by hadronic interactions with low momentum transfer $\Longrightarrow$ Hadron production cannot be calculated from first principles using perturbative QCD $\Longrightarrow$ Use effective theories / phenomenology (e.g Gribov-Regge theory) to compute particle spectra and interaction rates

Hadronic interactions in showers must be simulated with phenomenological hadronic interaction models (HIMs): Epos LHC, Epos LHC-R, QGSjetII04, QGSjetIII01, Sibyll23d !

Inference challenge in EAS physics

From the collider physics side

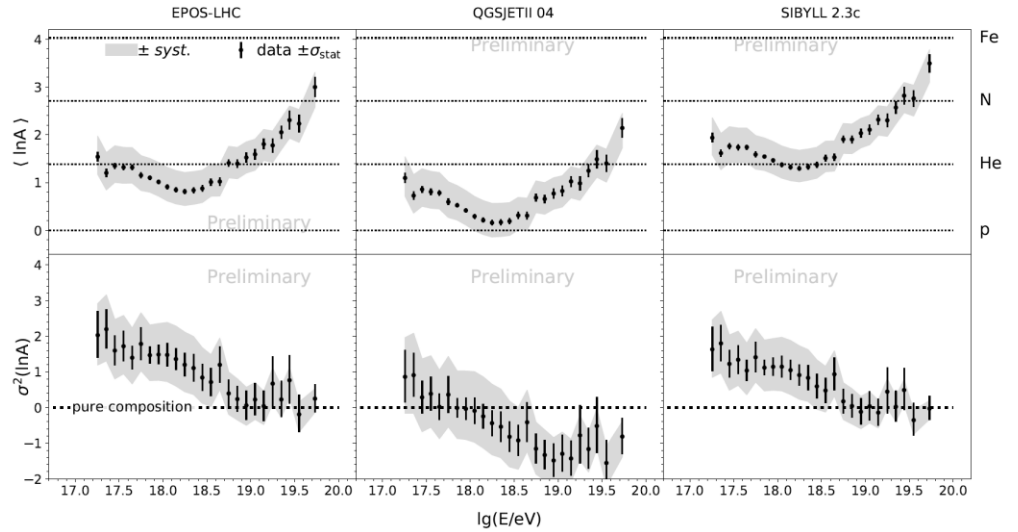
Phenomenological HIMs must be tuned to accelerator data **BUT** lack of data in relevant phase-space



CERN Yellow Rep.Monogr. 7 (2019) 1159-1410

From the astroparticle physics side

Mass interpretation of EAS observables **highly dependent** on HIM



Alexey Yushkov for the Pierre Auger Collaboration, PoS ICRC2019 (2020) 482

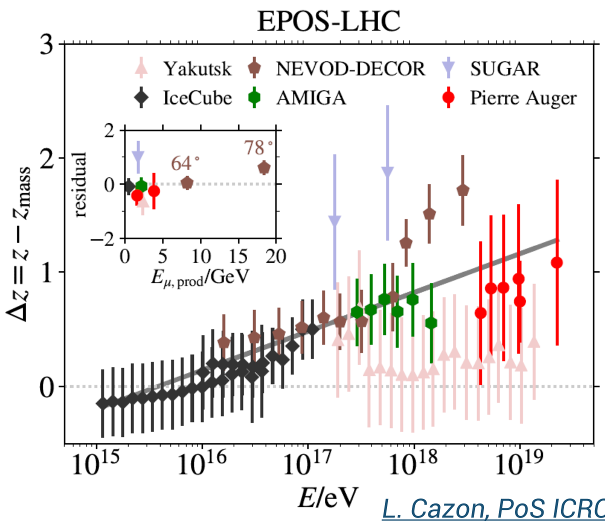
! **Inconsistent description of EAS observables!**

Tuning of HIMs using EAS data is **challenging** because the primary mass is unknown!

Inconsistences in interpretation of air-shower observables

Muon puzzle

EAS simulations **underestimate** N_μ given X_{max}-derived composition

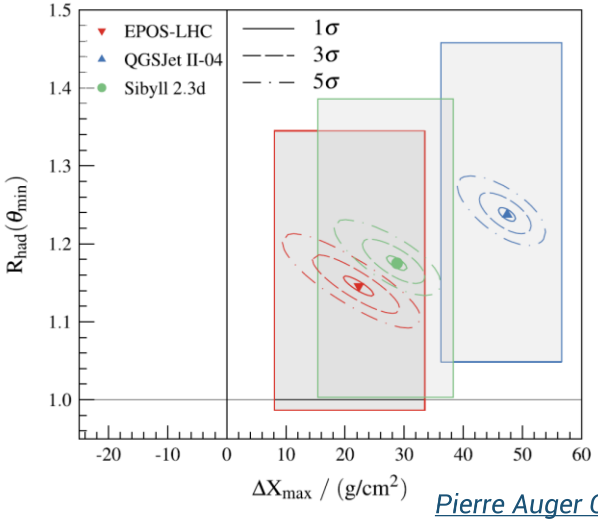


[L. Cazon, PoS ICRC2019 (2020) 005]

[Astrophys.Space Sci. 367 (2022) 3, 27]

"X_{max} puzzle"

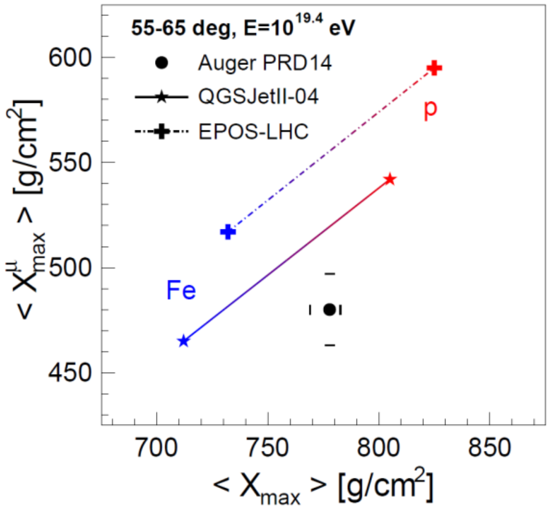
X_{max} and N_μ **need to increase** in simulations to describe EAS data



[Pierre Auger Collaboration, Phys.Rev.D 109 (2024) 10, 102001]

"X^μ_{max} puzzle"

Primary composition derived from peak of muon production **incompatible** with X_{max}

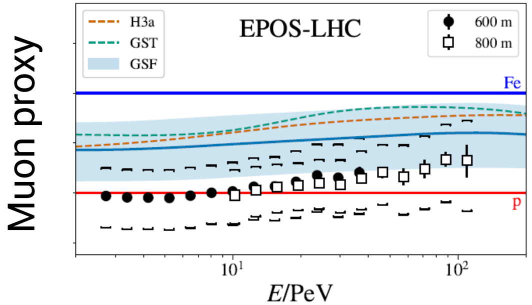


[L. Cazon, PoS ICRC2019 (2020) 005]

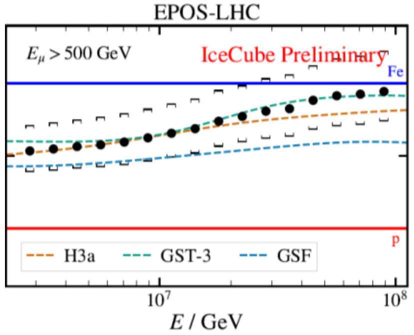
Need to constrain hadron production in the relevant phase-space for air-shower development!

!

GeV muons



TeV muons



Energy spectrum of muons

Compositions derived from GeV and TeV muons **incompatible**!

[S. Verpoest for the IceCube Collaboration, PoS UHECR2024 (2025) 035]

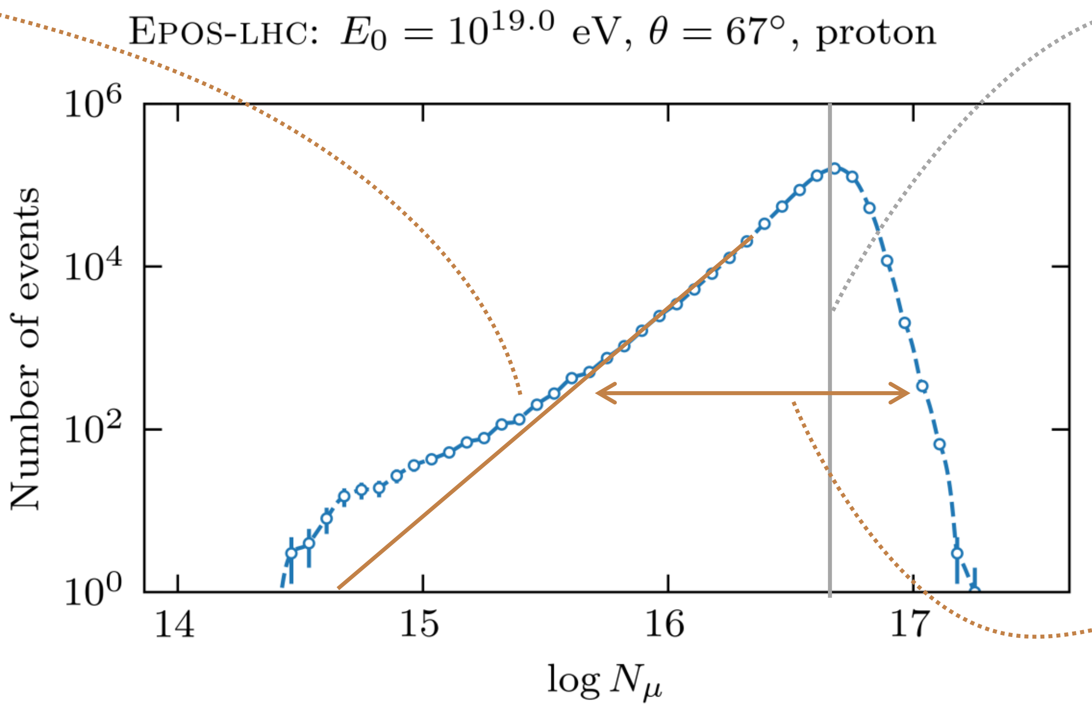
Probing hadronic interactions using N_μ

The shower-to-shower distribution of the muon content

Distribution of log N_μ over an ensemble of 10^6 proton-induced showers

Λ_μ

Steepness of N_μ distribution for muon-depleted showers $\Longrightarrow$ mostly determined by hardness of π^0 energy spectrum in primary-air interaction



$\langle N_\mu \rangle$

Average number of muons at ground $\Longrightarrow$ revealed the **muon puzzle**

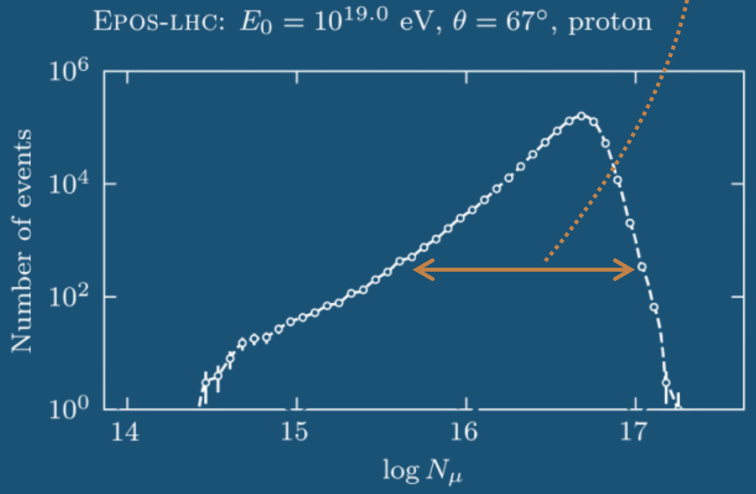
$\dfrac{\sigma(N_\mu)}{N_\mu}$

Standard deviation of N_μ $\Longrightarrow$ mostly determined by the shape of the energy spectrum of hadrons of the primary-air interaction

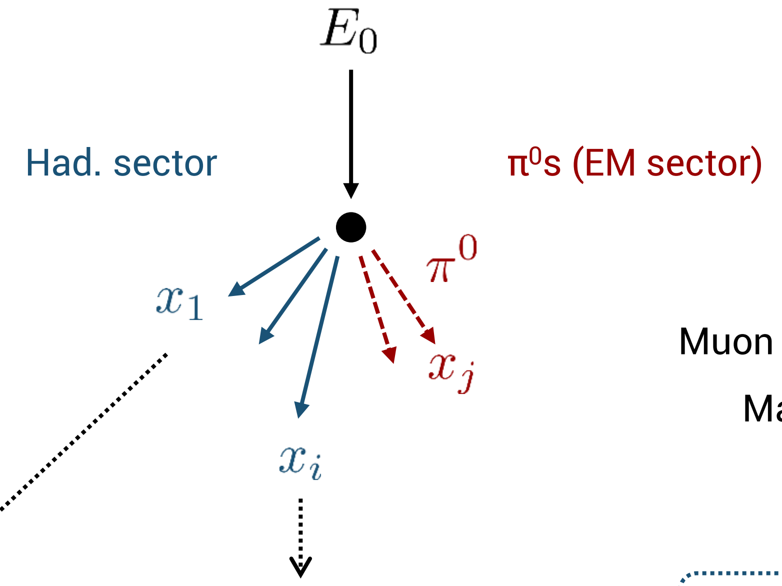
Probing the hadron energy spectrum via σ(N_μ)

Variable deduction

$$\frac{\sigma(N_\mu)}{N_\mu}$$



Estimate the muon yield of each secondary of 1st interaction allowing for fluctuations of the lab. energy fraction of each hadron: x_i



Muon yield from Heitler-Matthews model

$$N_\mu = N_\mu^{(1)} \propto x_1^\beta + \cdots + N_\mu^{(i)} \propto x_i^\beta + \cdots + \boxed{N_\mu^{(m_{\mathrm{had}})} \propto x_{m_{\mathrm{had}}}^\beta}$$

$$N_\mu \propto \boxed{\sum_{i=1}^{m_{\mathrm{had}}} x_i^\beta = \alpha_1}$$

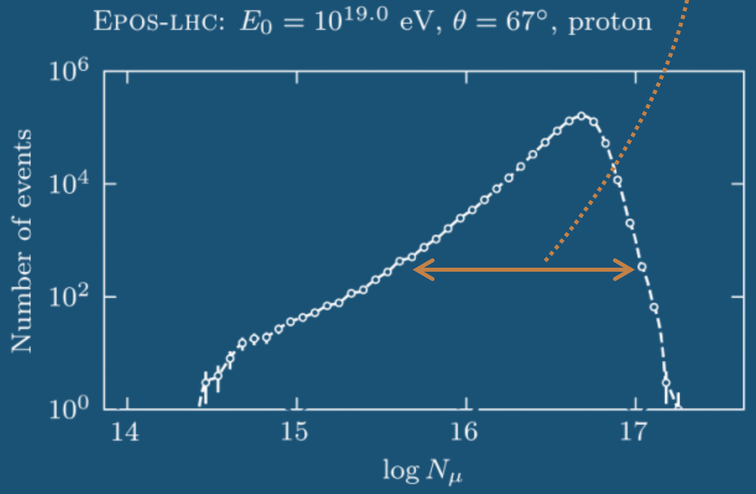
Shower-by-shower estimator of N_μ from primary-air interaction

L. Cazon, R. Conceição, F. Riehn, Phys.Lett.B 784 (2018) 68-76

Probing the hadron energy spectrum via $\sigma(N_\mu)$

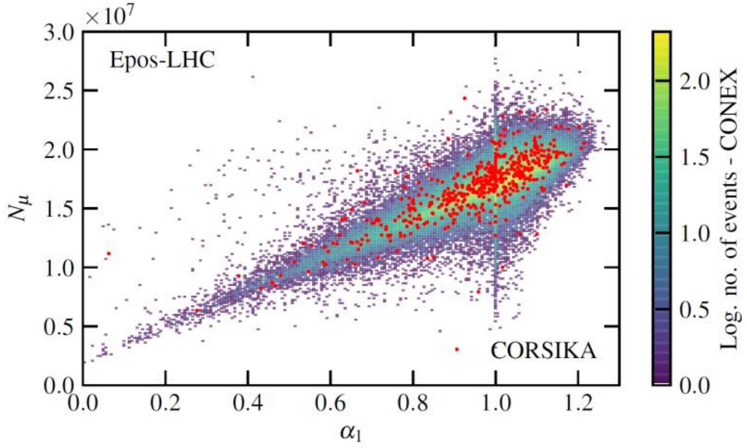
Validation with MC simulations

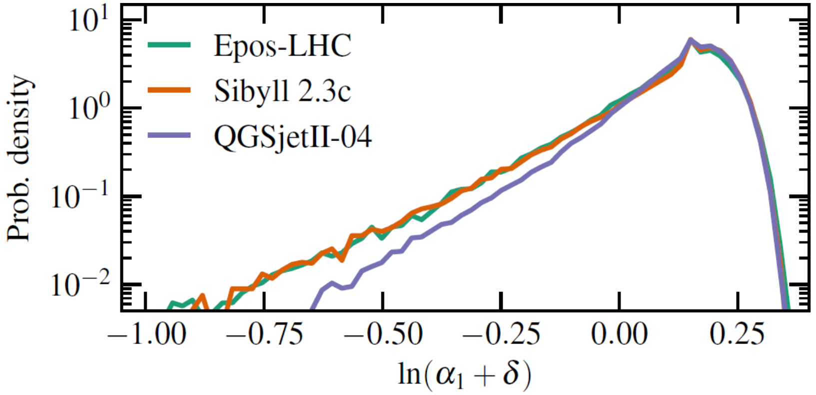
$$\frac{\sigma(N_\mu)}{N_\mu}$$



- Pearson correlation coefficient ~ 0.80
- $\sigma^2(N_\mu)$ ~ 70 % $\sigma^2(\alpha_1)$

Shape α_1-distribution sensitive to differences in energy spectrum predicted by had. int. models



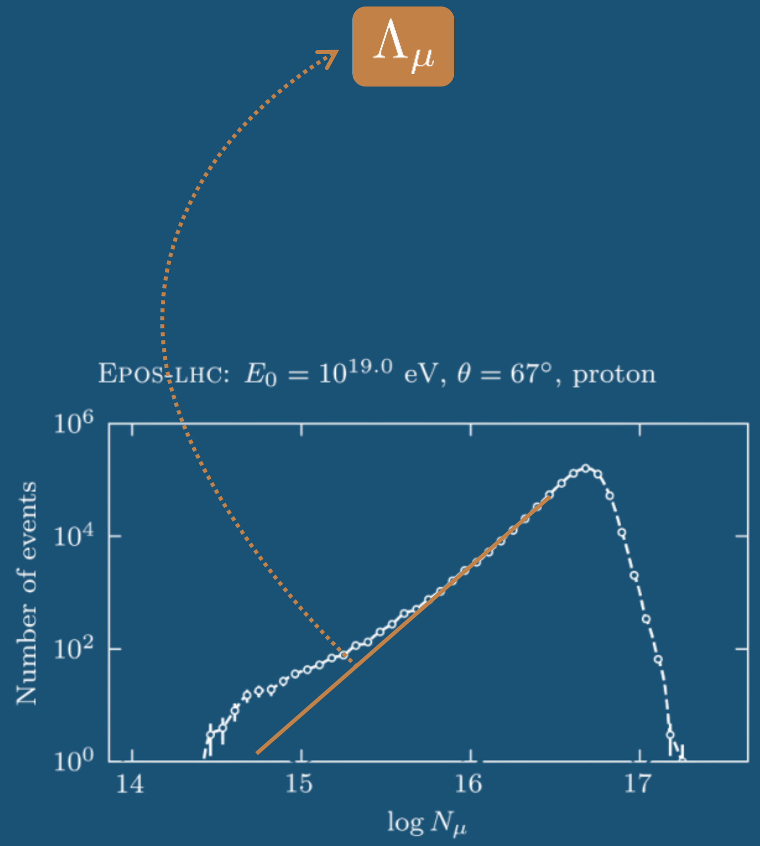


Take home message:

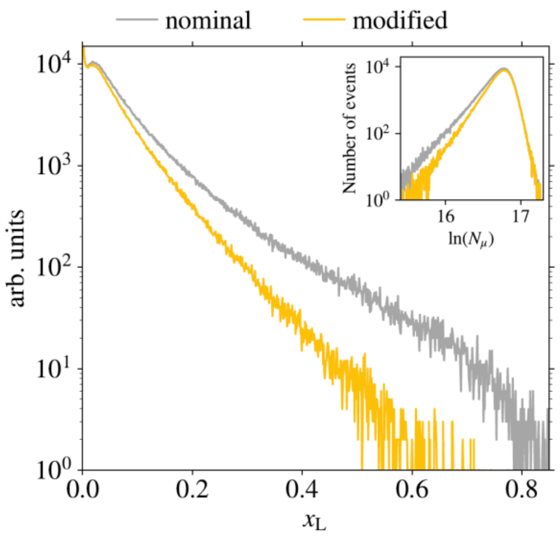
- Shower-to-shower fluctuations of N_μ mostly determined by energy spectrum of hadrons of the primary-air interaction

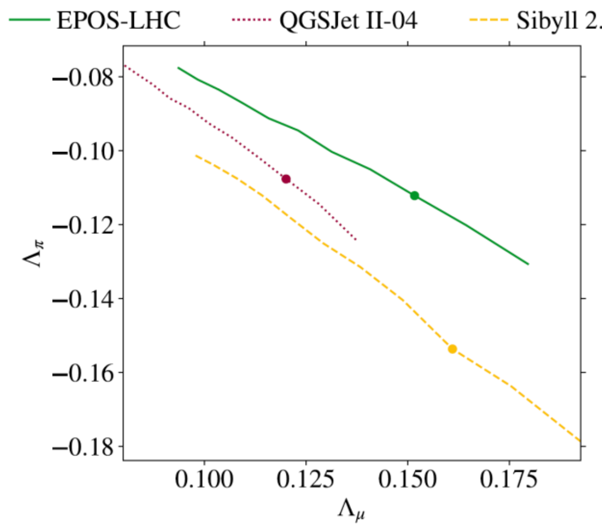
L. Cazon, R. Conceição, M. A. Martins, F. Riehn, Phys.Rev.D 103 (2021) 2, 022001

Probing the energy spectrum of neutral pions through Λ_μ



1. Higher energy π^0 $\Longrightarrow$ less energy available for muon production
2. Harder π^0-energy spectrum in primary-air interaction $\Longrightarrow$ greater chance of muon-depleted showers





Take home message:

- Shape of N_μ-distribution in muon depleted showers sensitive to hardness of neutral pion spectrum in primary-air interaction

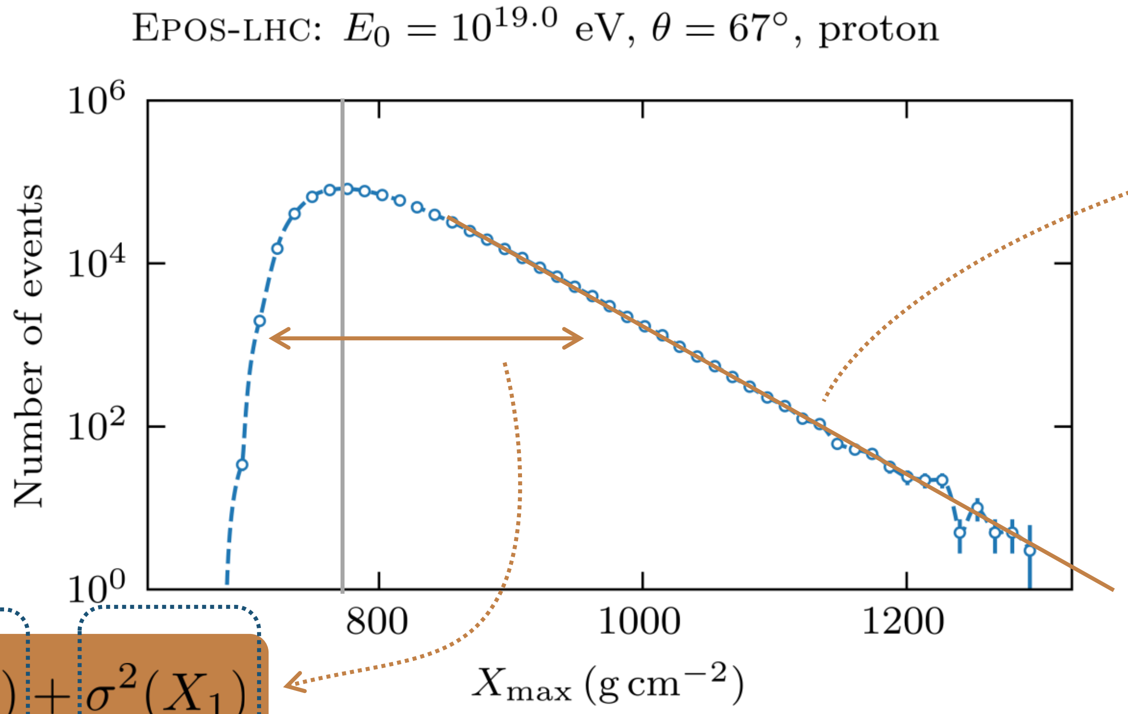
PROBING HADRONIC INTERACTIONS USING X_{max}

The shower-to-shower distribution of X_{max}

$\langle X_{\mathrm{max}} \rangle$

Average in tension with the latest Auger results $\Longrightarrow$ X_{max} puzzle?

Distribution of X_{max} over ensemble of 10^6 proton-induced showers



cite the papers + write down the variables

Λ_η

Proxy of the proton air cross-section

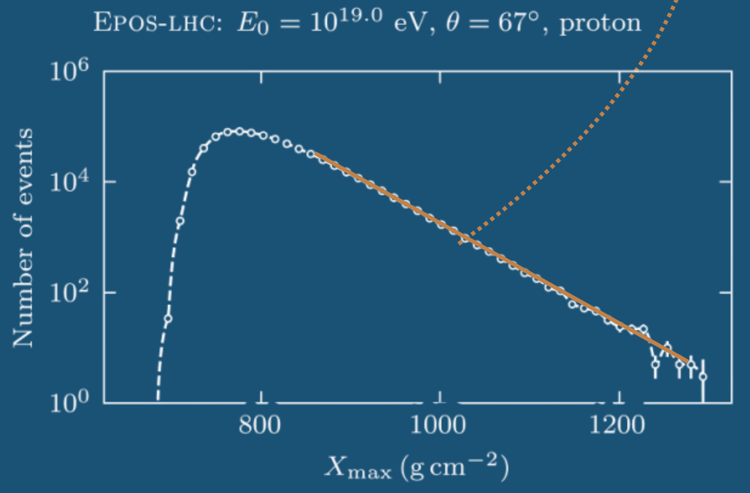
$$\sigma^2(X_{\mathrm{max}}) = \sigma^2(X_{\mathrm{max}} - X_1) + \sigma^2(X_1)$$

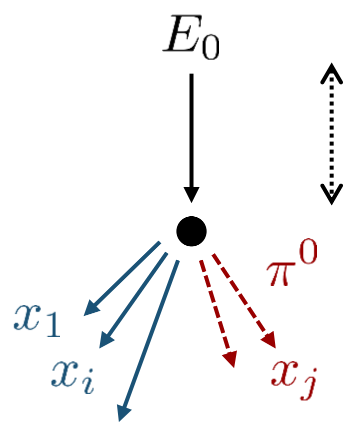
Connected with hadron production and propagation in the early stages of EAS

For proton showers: $\sigma^2(X_1) = \lambda^2_{p-\mathrm{air}} \propto \dfrac{1}{\sigma^2_{p-\mathrm{air}}}$

Measurement of the proton-air cross section

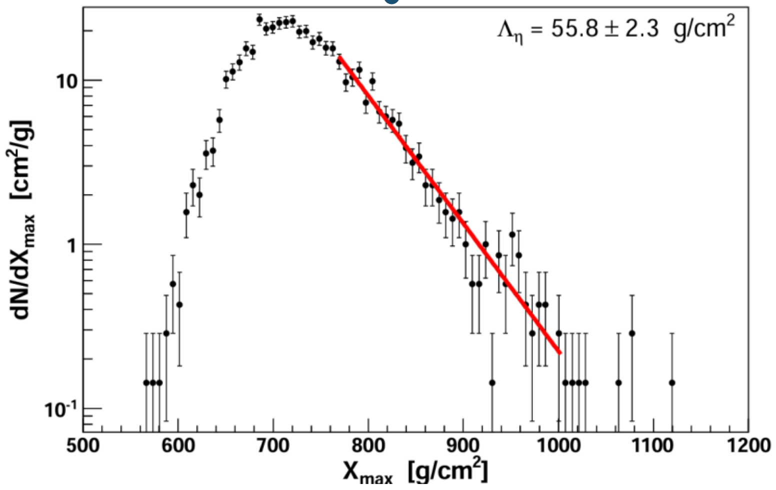
Λ_η

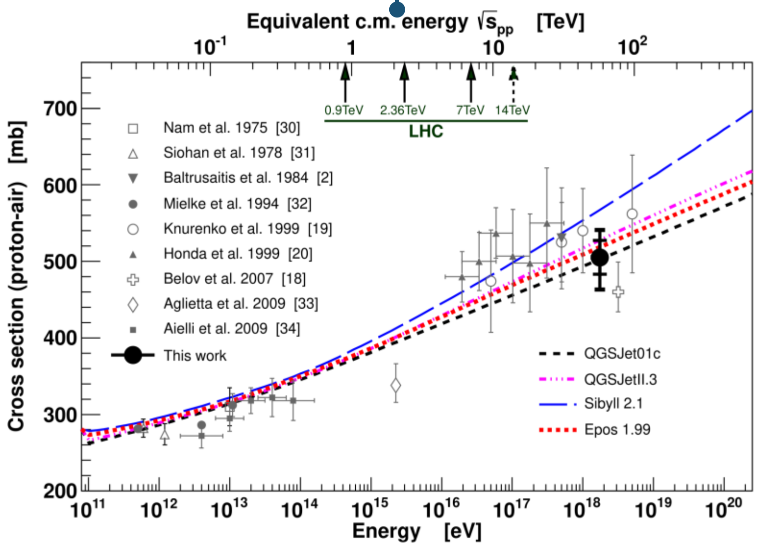




$$X_1 \implies p(X_1) = \frac{1}{\lambda_{p-\mathrm{air}}} \exp\left\{-\frac{X_1}{\lambda_{p-\mathrm{air}}}\right\}$$

Λ_η is probe of $\lambda_{p-\mathrm{air}} \propto \dfrac{1}{\sigma_{p-\mathrm{air}}}$



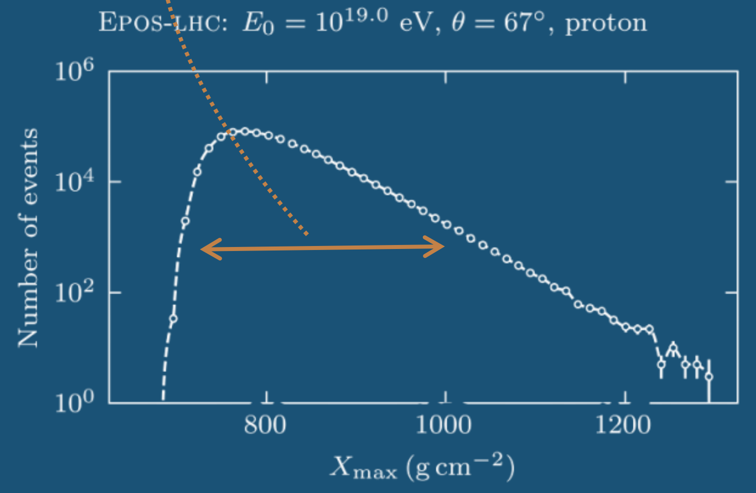


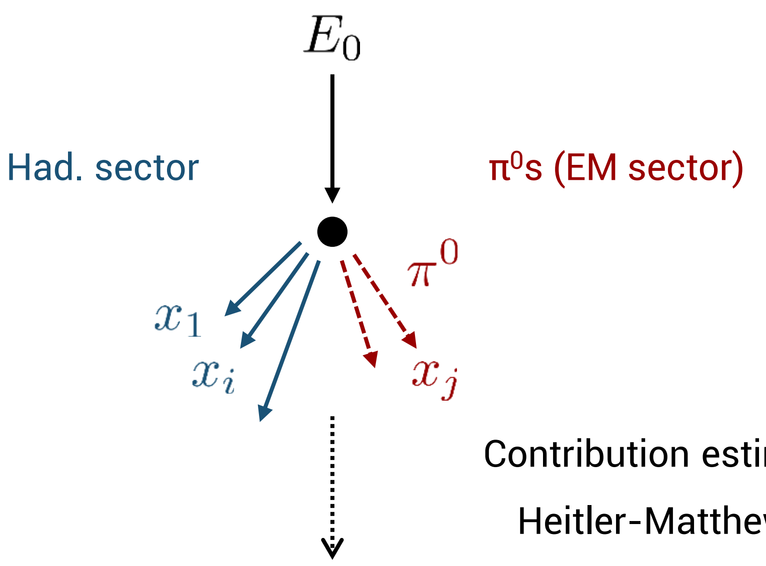
[Pierre Auger Collaboration, Phys.Rev.Lett. 109 (2012) 062002]

Estimator of $X_{max} - X_1$ from primary interaction

Estimate the contribution of each secondary of 1st interaction to $X_{max} - X_1$

$\sigma(X_{\mathrm{max}})$





Contribution estimated from Heitler-Matthews model

Primary interaction estimator of $X_{max} - X_1$

$$\lambda_r^{-1}\xi = \ln\left(\frac{E_0}{2\xi_c^e}\right) + \left[\mathcal{C}_0 - (1-\omega)\ln\left(\frac{E_0}{2\xi_c^e}\right)\right]\alpha_{\mathrm{had}} - \omega\zeta_{\mathrm{had}} - \zeta_{\mathrm{EM}}$$

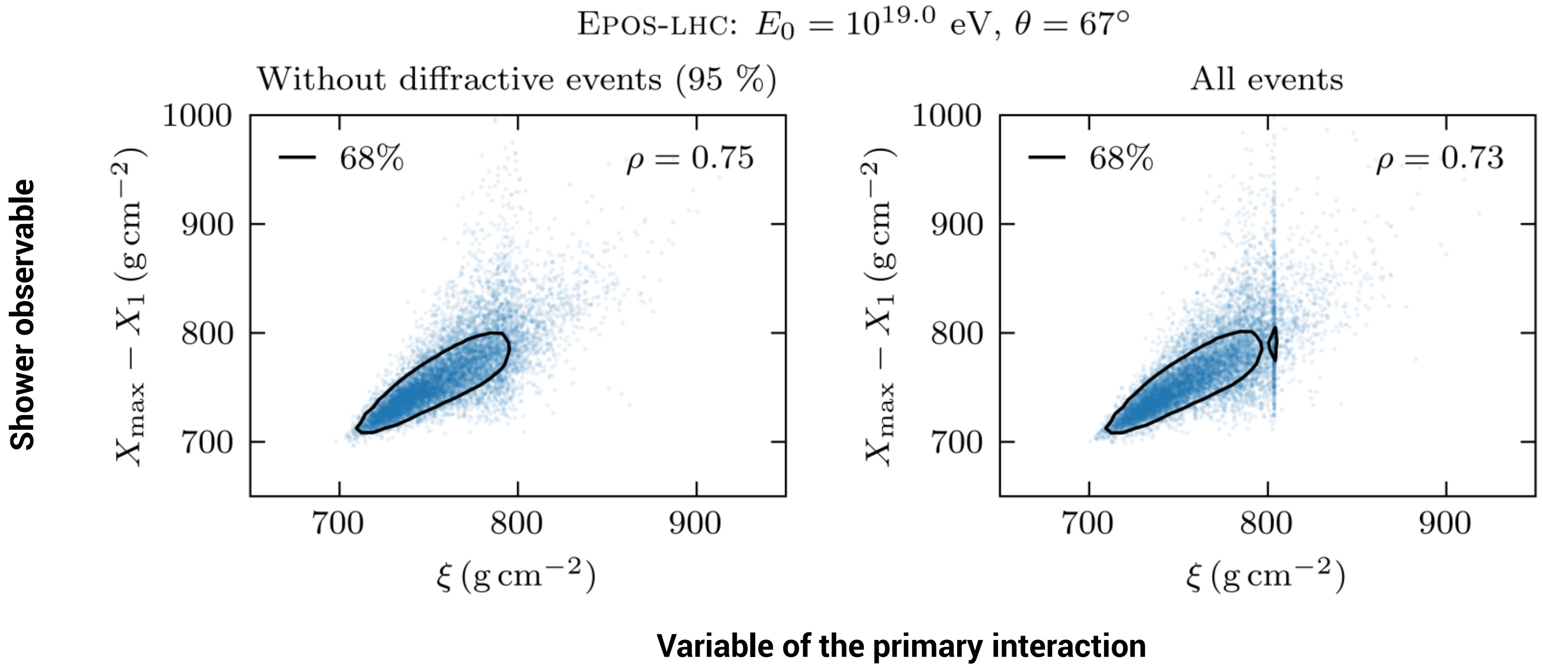
Primary interaction variables

$$\alpha_{\mathrm{had}} = \sum_{i=1}^{m_{\mathrm{had}}} x_i \qquad \zeta_{\mathrm{had}} = -\sum_{i=1}^{m_{\mathrm{had}}} x_i \ln x_i \qquad \zeta_{\mathrm{EM}} = -\sum_{j=1}^{m_{\mathrm{EM}}} x_j \ln x_j$$

Note : $\omega = p_1 \left\langle \frac{\zeta_{\mathrm{EM}}}{1-\alpha_{\mathrm{had}}} \right\rangle + p_0$

L. Cazon, R. Conceição, M. A. Martins, F. Riehn, 2504.08610 [astro-ph.HE]

Validating ξ as estimator of $X_{max} - X_1$



Take home messages:

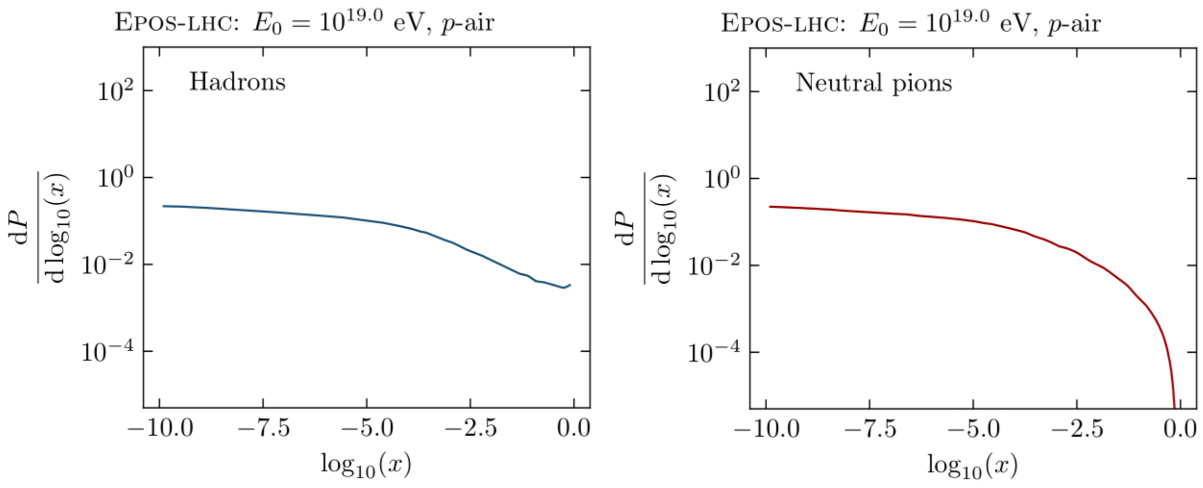
- Fluctuations in ξ determine > 50 % of fluctuations in X_{max} -X_1 ⟹ 80 % of the maximum variability in (X_{max} -X_1) from stochasticity of primary interaction
- Strength of causal connection between ξ and (X_{max} -X_1) independent of Had. Int. Model

!

Understanding a new set of primary variables: ζ_{had}, ζ_{EM} and α_{had}

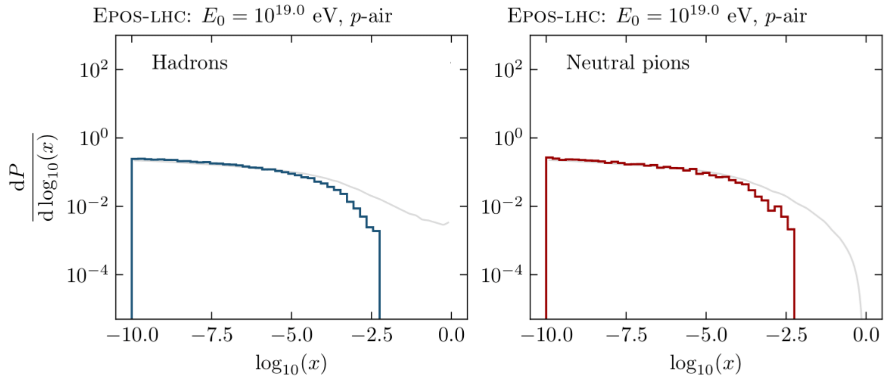
Average hadron-energy spectra

$$\langle\alpha_{\rm had}\rangle = 0.80\ ;\ \langle\zeta_{\rm had}\rangle = 1.93\ ;\ \langle\zeta_{\rm EM}\rangle = 0.68$$



Examples of Monte Carlo primary interactions

Highly Inelastic



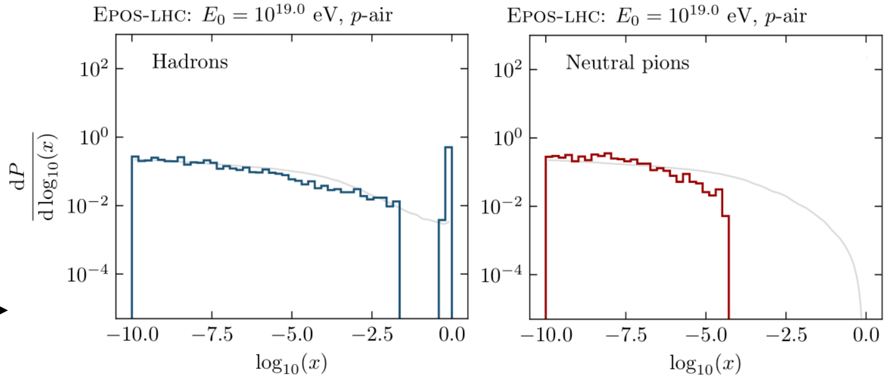
$$\alpha_{\rm had} = 0.71 \quad \zeta_{\rm had} = 3.32 \quad \zeta_{\rm EM} = 1.32$$

Increased α_{had}

Decreased ζ_{had} , ζ_{EM}

$$\alpha_{\rm had} = 1.00 \quad \zeta_{\rm had} = 0.08 \quad \zeta_{\rm EM} = 0.01$$

Highly Elastic



Probabilistic model of the rest of the shower

Removing dependence on the hadronic interaction model: step 1

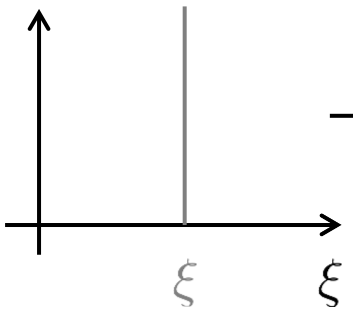
Determined by energy spectra of secondaries of primary int.

Response of the shower, which depends on the hadronic interaction model *M*

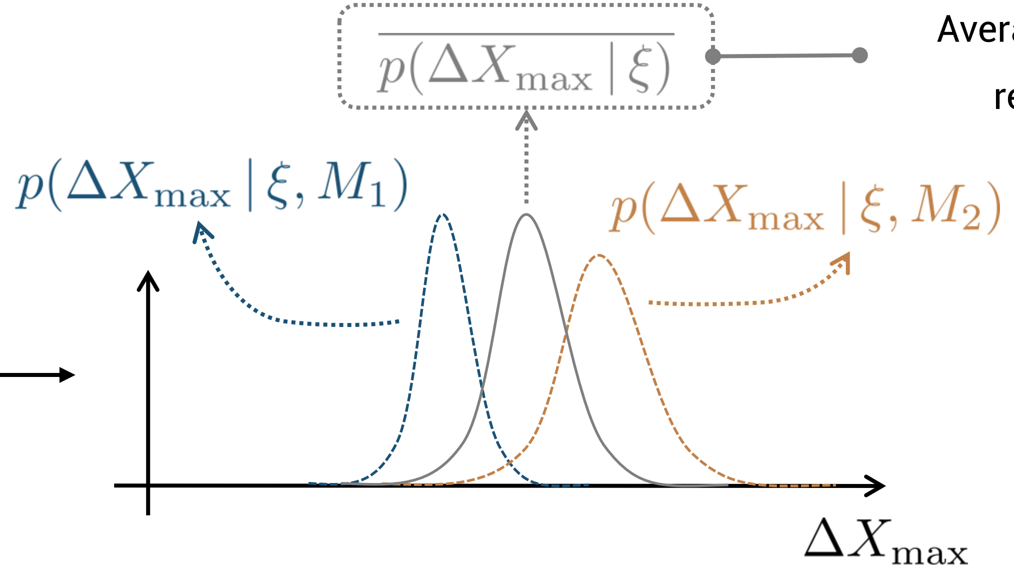
$$p(\Delta X_{\max}) = \int p(\xi)\, p(\Delta X_{\max} \,|\, \xi, M)\, \mathrm{d}\xi$$

Is it possible to remove the dependence on the hadronic interaction model?

Step 1:



Primary interaction



Probabilistic response of shower

Average shower response

$$\overline{p(\Delta X_{\max})} = \int p(\xi)\, \overline{p(\Delta X_{\max} \,|\, \xi)}\, \mathrm{d}\xi$$

Issues:

- Unrealistic assumption that the primary interaction could **change** while leaving rest of shower **unchanged**
- Induce bias in $\Delta X_{\max}$ distribution

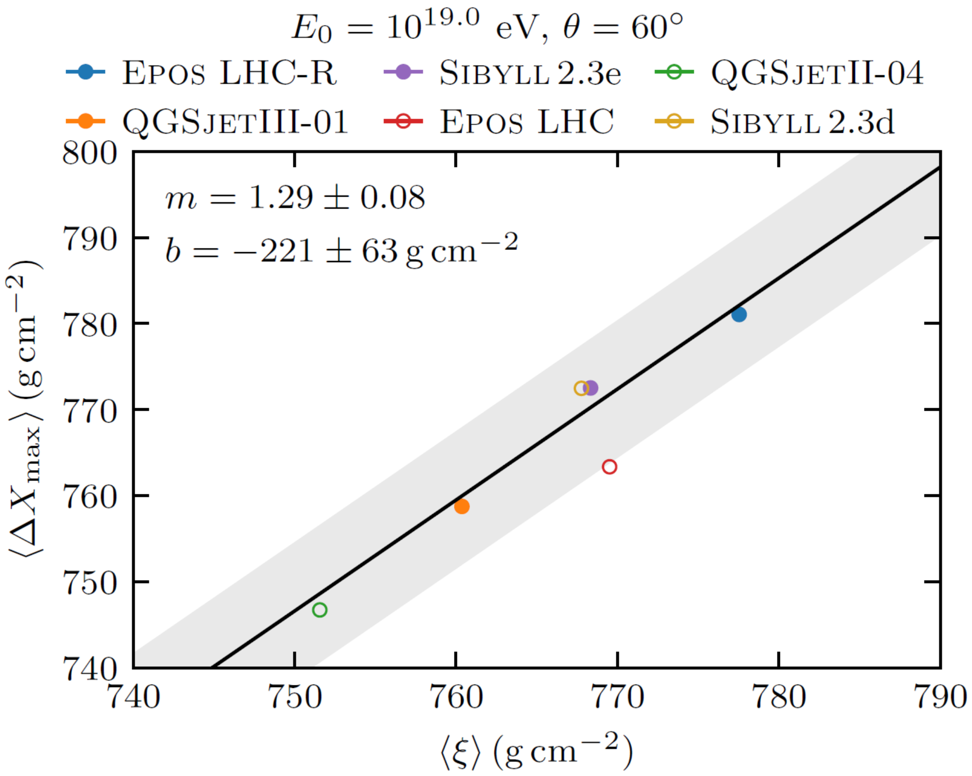
!

Probabilistic model of the rest of the shower

Removing dependence on the hadronic interaction model: step 2

L. Cazon, R. Conceição, M. A. Martins, F. Riehn, 2504.08610 [astro-ph.HE]

- Change in **ξ** in primary interaction ⟹ change energy spectra in deeper interactions ⟹ change in $\langle X_{max} \rangle$
- Consistently propagate changes in the energy spectra in primary interaction using hadronic interaction models



Take home messages:

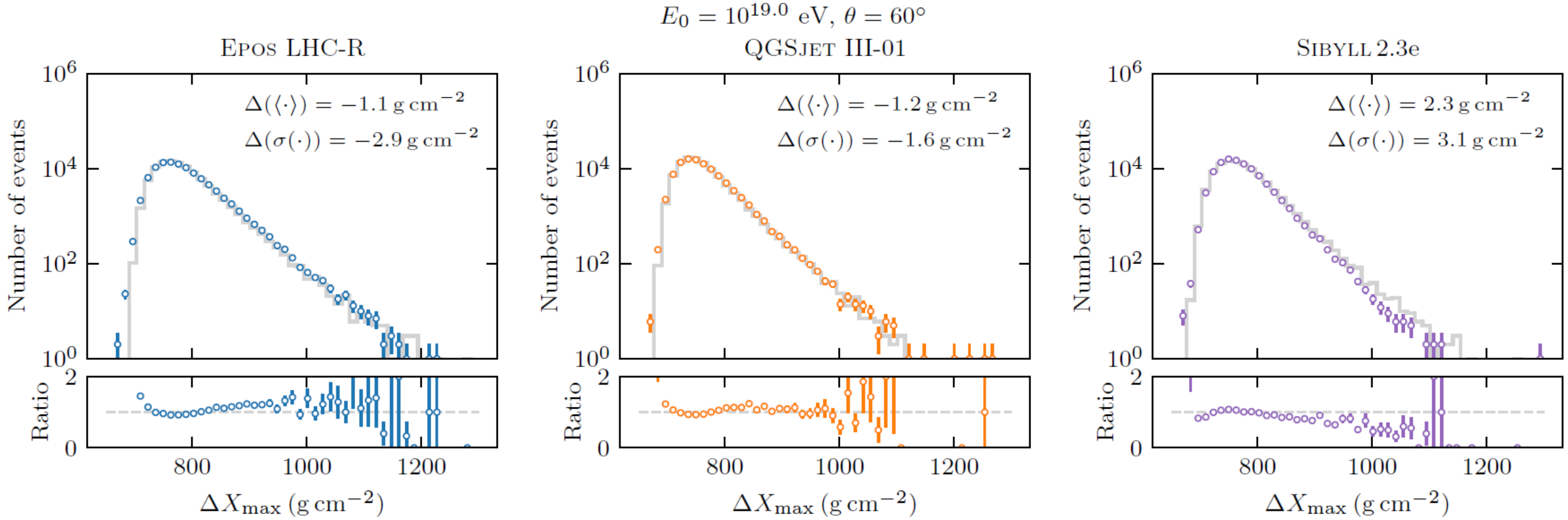
- Linear evolution of $\langle \mathbf{X_{max} - X_1} \rangle$ with $\langle \boldsymbol{\xi} \rangle$ with ~ 7 g cm^{-2} systematic uncertainty due to Had. Int. Model.
- Substitute the residual model dependence of the shower response by its dependence on $\langle \boldsymbol{\xi} \rangle$:

$$p(\Delta X_{\max} \,|\, \xi, M) \rightarrow \overline{p(\Delta X_{\max} \,|\, \xi)} \rightarrow p(\Delta X_{\max} \,|\, \xi, \langle \xi \rangle)$$

Reconstructing the distribution of ΔX_{max}

L. Cazon, R. Conceição, M. A. Martins, F. Riehn, 2504.08610 [astro-ph.HE]

$$p(\Delta X_{\max}) = \int p(\xi) p(\Delta X_{\max} \,|\, \xi, \langle \xi \rangle)\, \mathrm{d}\xi$$



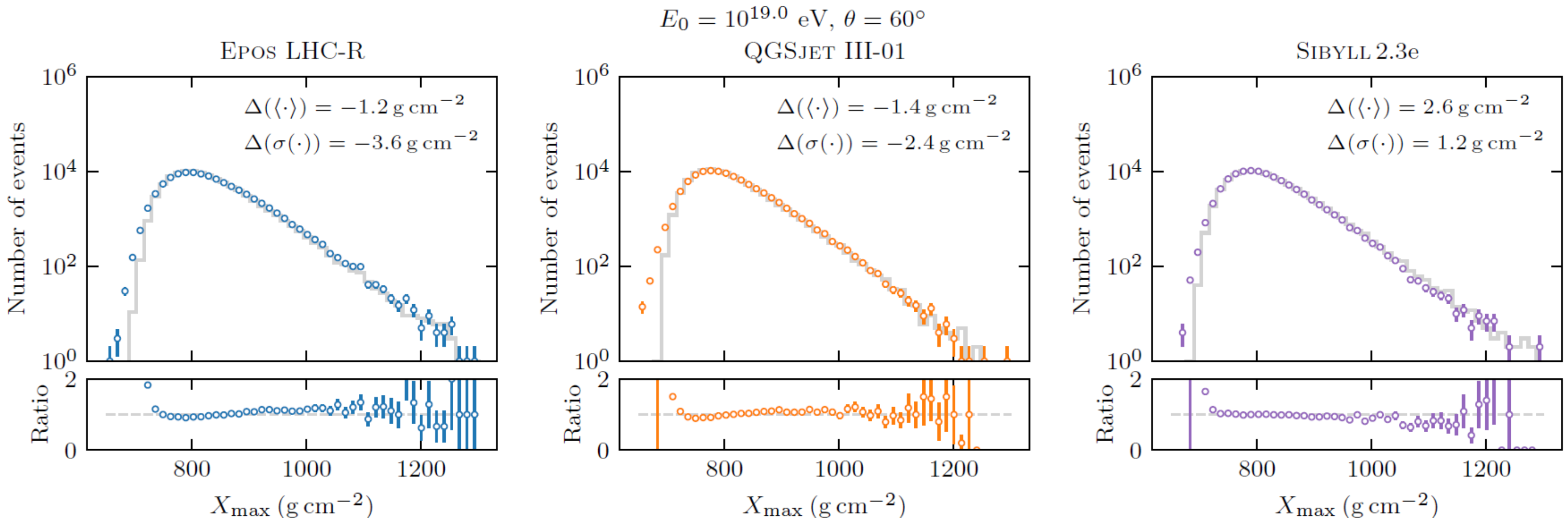
Take home messages:

- Systematic ~ 3 g cm^{-2} in reconstruction of first and second moments of ΔX_{max}-distribution using universal probabilistic shower response $\Longrightarrow$ differences in ΔX_{max}-distribution attributed to differences in energy spectra of primary interaction!

Reconstructing the distribution of X_{max}

L. Cazon, R. Conceição, M. A. Martins, F. Riehn, 2504.08610 [astro-ph.HE]

$$p(X_{\max}) = \int p(\xi) p(X_{\max} \,|\, \xi, \langle\xi\rangle)\, \mathrm{d}\xi$$



Take home messages:

- Systematic ~ 3 g cm^{-2} in the reconstruction of $\langle X_{max}\rangle$, $\sigma(X_{max})$ and Λ_η using universal probabilistic shower response $\Longrightarrow$ can use the shape of X_{max}-distribution to probe the energy spectra secondaries of the primary interaction!

PROBING HADRONIC INTERACTIONS USING (N_μ, X_{max})

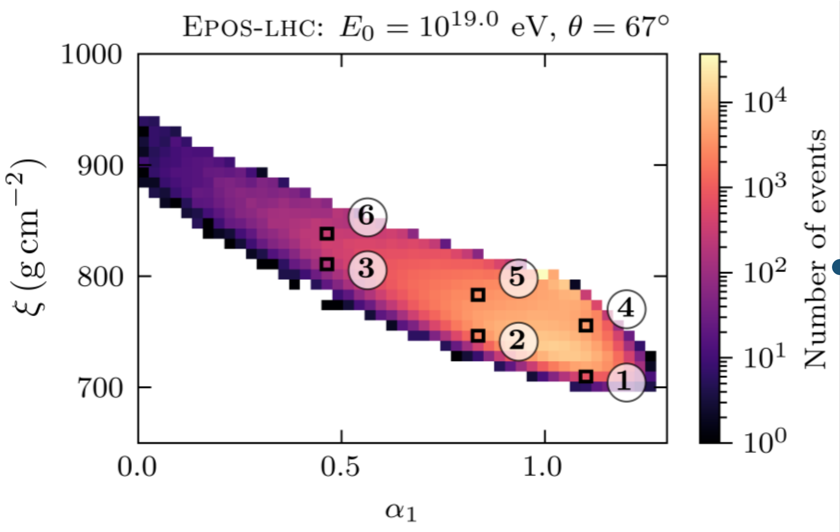
Present the 2d model with the 2d kernel

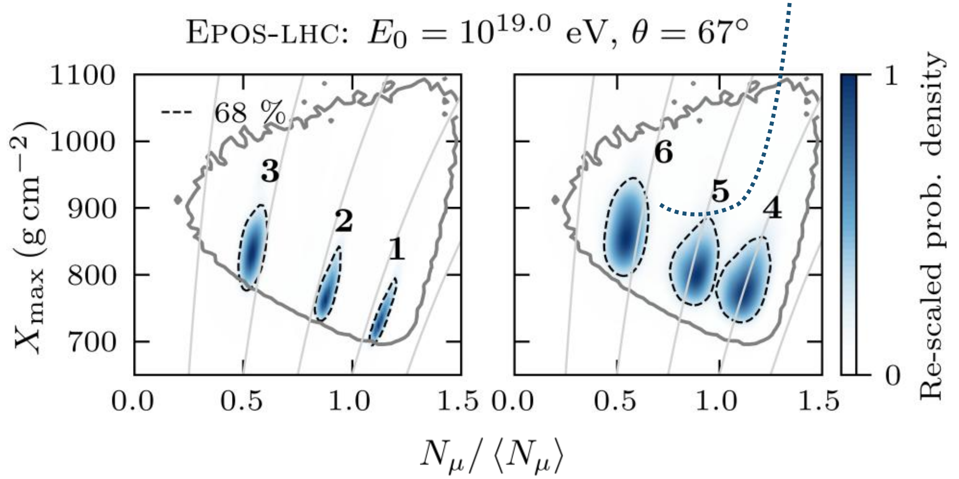
L. Cazon, R. Conceição, M. A. Martins, F. Riehn, PoS UHECR2024 (2025) 101

Extend the formalism to describe 2-dimensional (N_μ, X_{max}):

$$p(N_\mu, X_{\max}) = \int p(\alpha_1, \xi) p(N_\mu, X_{\max} \mid \alpha_1, \xi, \langle \xi \rangle)\, \mathrm{d}\xi$$

Exponential fluctuations of 1st int. point + muon attenuation $\Longrightarrow$ slanted dispersion

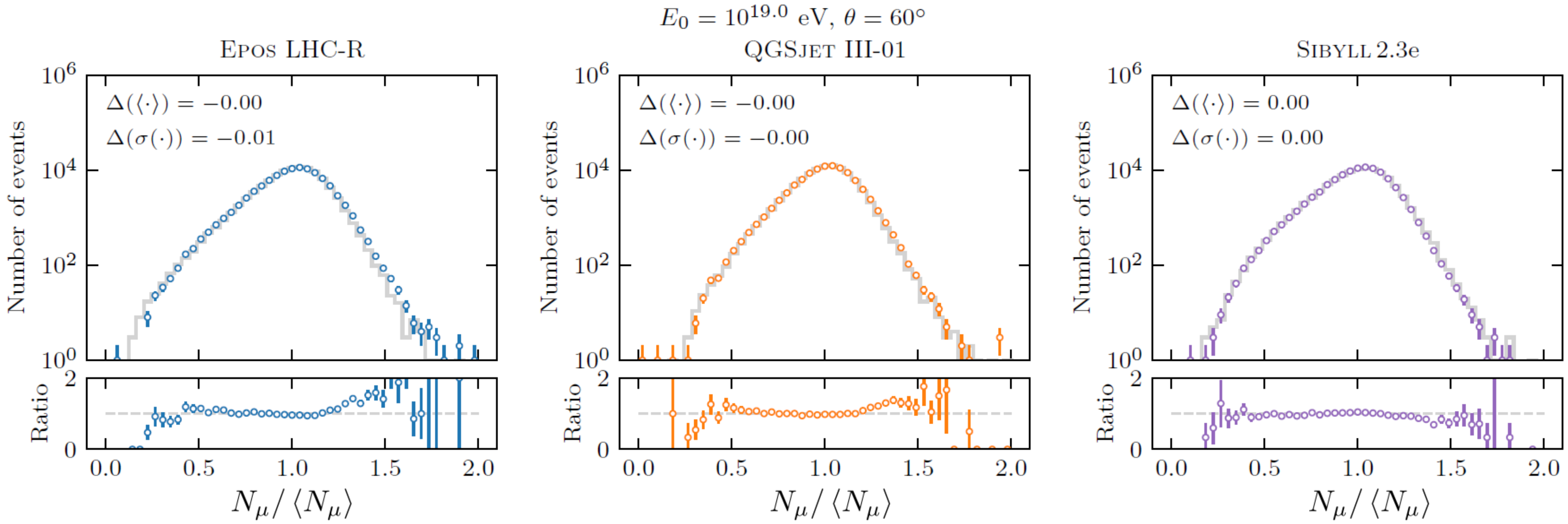




Take home message:

- Information about the energy spectrum of the primary interaction retained in the (N_μ, X_{max}) via the probabilistic mapping between (α_1, ξ_1) $\longrightarrow$ (N_μ, X_{max})

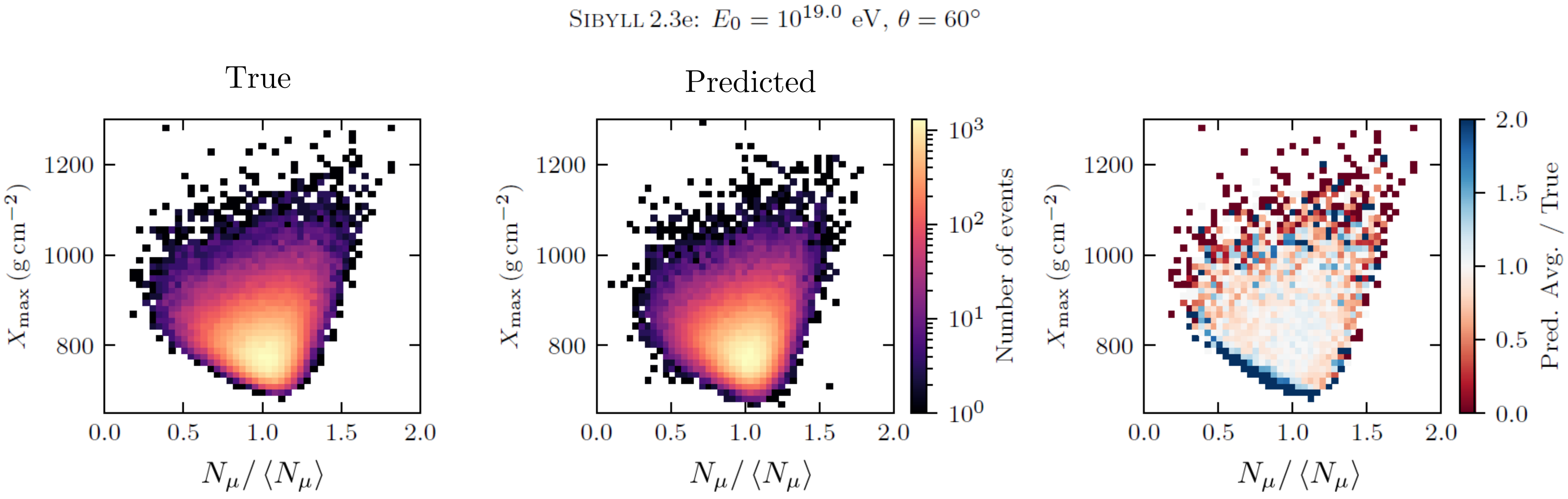
Reconstructing the distribution of N_μ



Take home message:

- Negligible bias in the reconstruction of the first and second moments of the distribution of $N_\mu / \langle N_\mu \rangle$ using universal probabilistic shower response $\Longrightarrow$ differences in shape of N_μ distribution only due to differences in energy spectra of the primary interaction!

Reconstructing the joint distribution of (N_μ, X_{max})



Take home message:

Promising reconstruction of joint distribution of (N_μ, X_{max}) using the universal shower response

Outlook:

Change the energy spectra of the primary interaction and quantity the differences in the obtained distribution of (N_μ, X_{max})

New production variables

Distributions of new interaction variables in extensive air showers

Multi-particle production variables:

$$\zeta_{\text{had}} = -\sum_{i=1}^{m_{\text{had}}} x_i \ln x_i \qquad \zeta_{\text{EM}} = -\sum_{j=1}^{m_{\text{EM}}} x_j \ln x_j \qquad \alpha_{\text{had}} = \sum_{i=1}^{m_{\text{had}}} x_i$$

Increase in hadronic activity!

Increase in EM activity!

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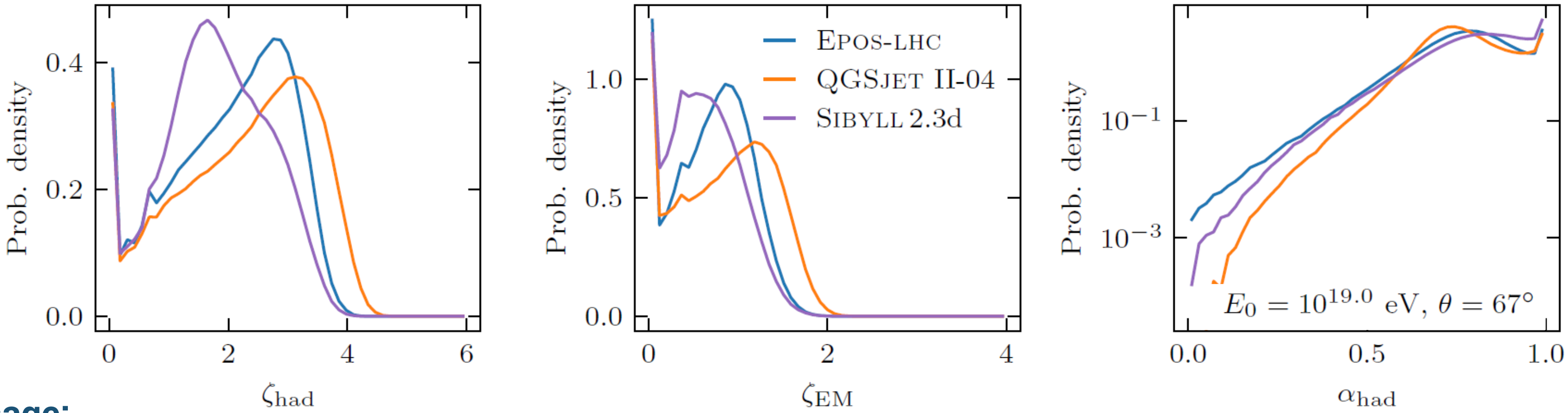
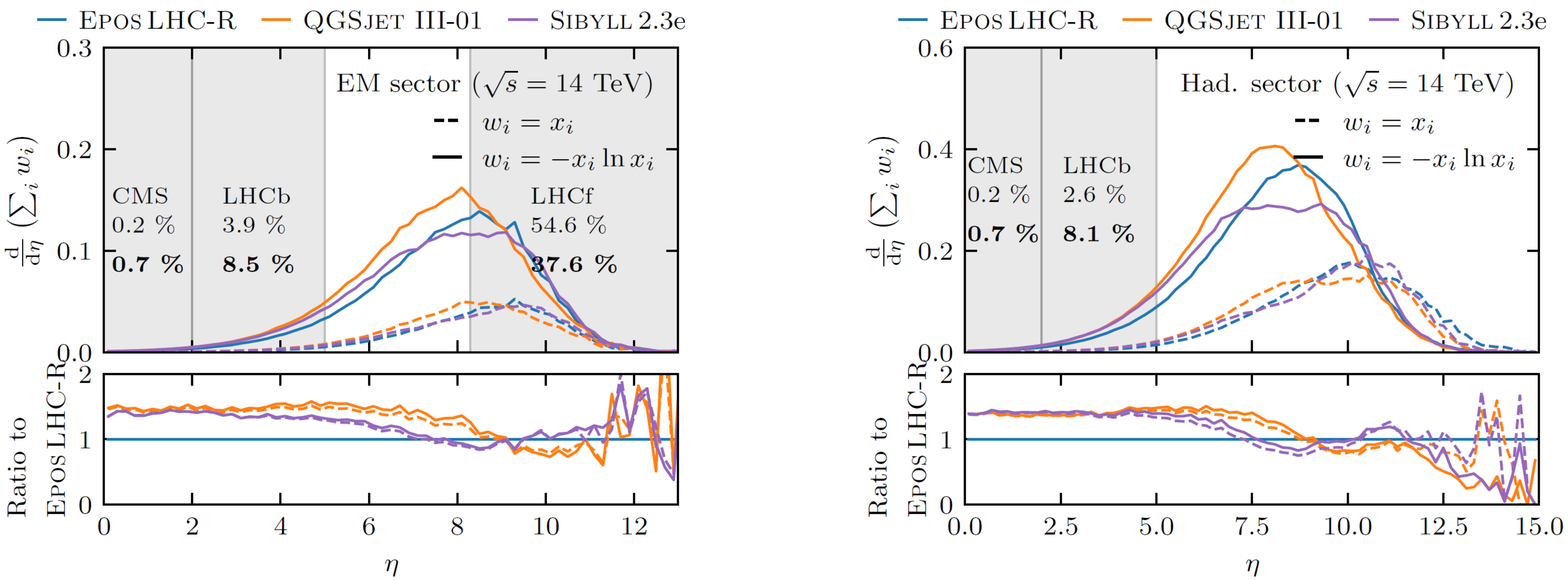


Take home message:

Shapes of distributions of ζ_{had}, ζ_{EM} and α_{had} highly dependent on hadronic interaction model $\Longrightarrow$ great constraining power!

Under investigation: explicit relation between shape of energy spectrum of secondaries and features of p.d.fs of ζ_{had} and ζ_{EM}

Relevant phase-space for EAS production variables



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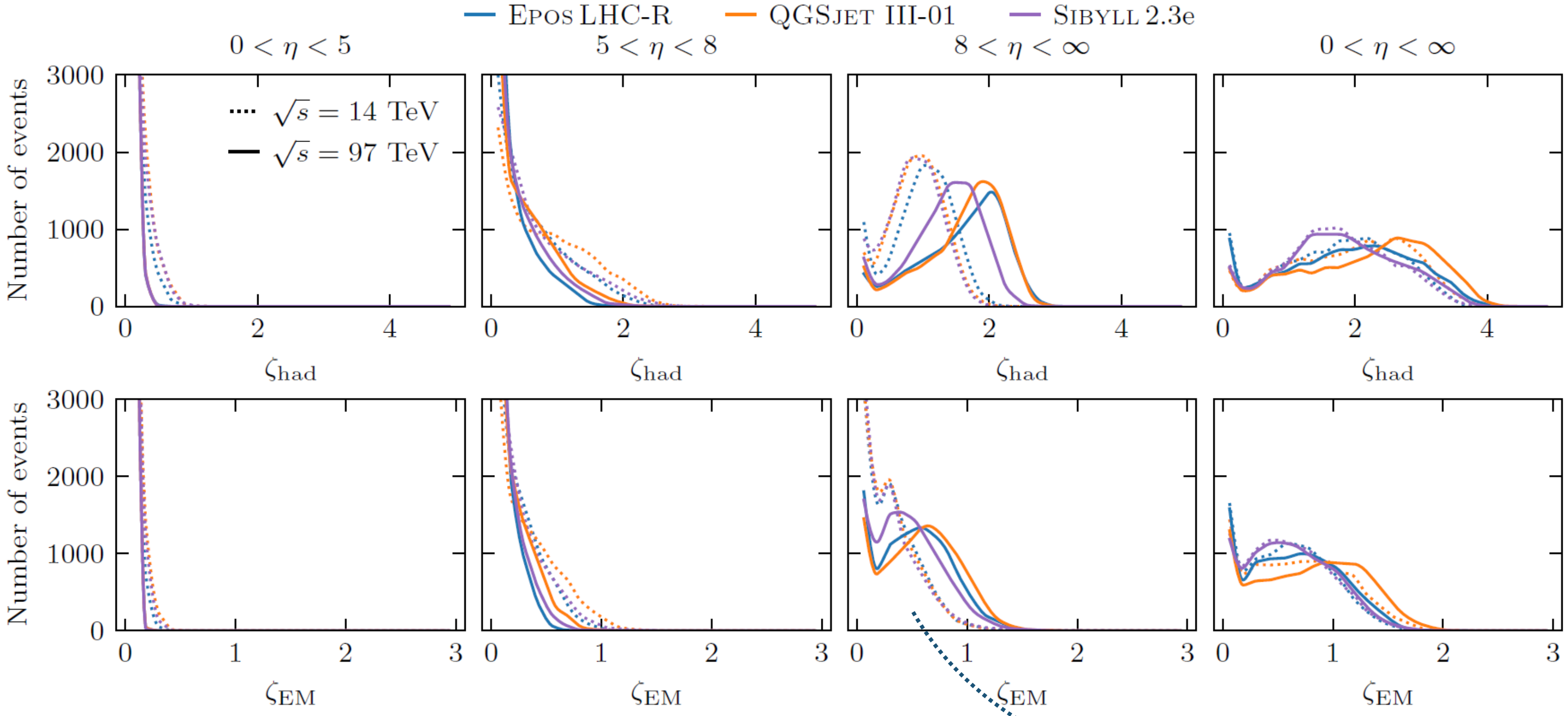
Distributions of production variables at different rapidities

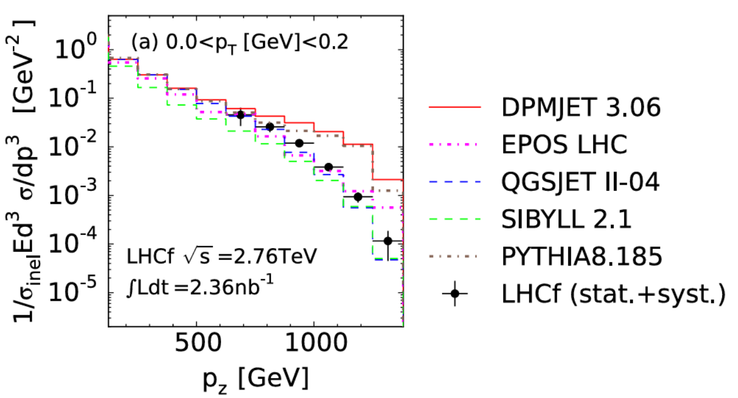
[*The LHCf Collaboration, Phys.Rev.D 94 (2016) 3, 032007]



[L. Cazon, R. Conceição, M. A. Martins, F. Riehn, 2504.08610 [astro-ph.HE]]

- Model disagreement greater at higher rapidity and incident energies
- Distributions of production variables most distinguishable in the kinematic space relevant for EAS development

Measured at LHCf*



- Need p-O collisions at LHC to provide data to tune Had. Int. Models for air showers
- Need a way to constrain the production spectra of charged pions and kaons in forward region $\Longrightarrow$ Forward Physics Facility

Conclusions

Conclusions:

1. Developed a probabilistic framework linking the energy spectra of secondary hadrons with the main observables of Extensive Air Showers
2. The energy spectra can be measured in accelerator experiments in the far-forward region
3. Combined EAS and accelerator data can mitigate series of inconsistences in EAS description
4. Improve description of hadronic interactions at the highest energies

Thank you!

Additional acknowledgments

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XUNTA DE GALICIA

CENTROS CiGUS

Cofinanciado por la Unión Europea

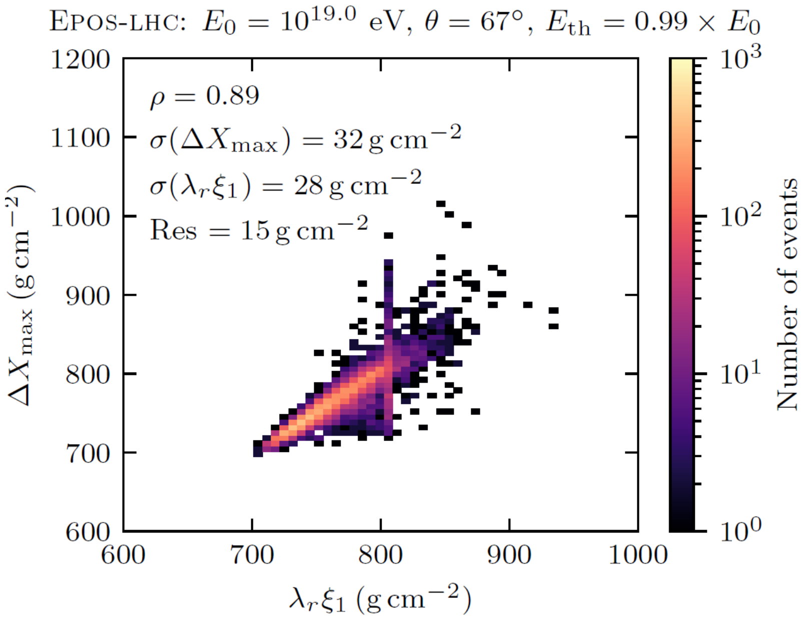
Fondos Europeos

Backup Slides

Validating the approximations taken in derivation of ξ_1

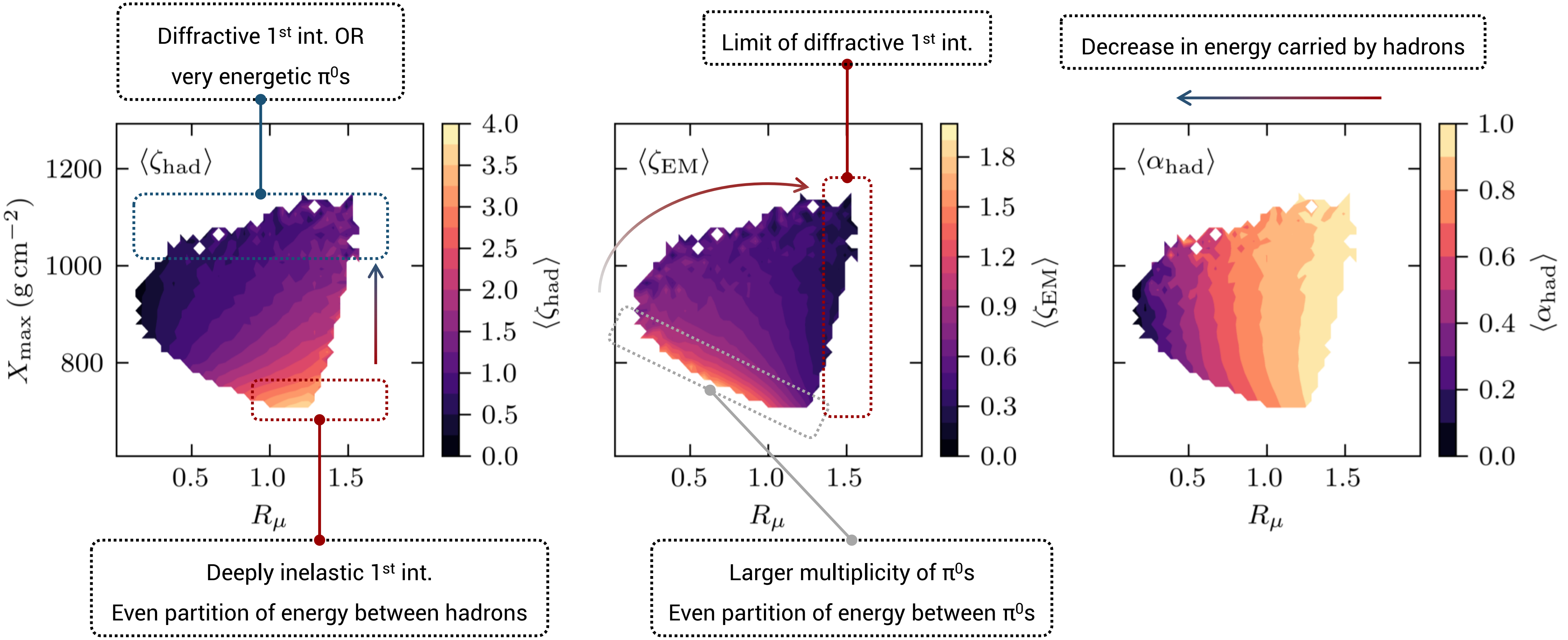
Idea:

1. Increase the transition energy between MC and CE in Conex $\Longrightarrow$ isolate fluctuations of 1st interaction
2. Compare obtained value of ΔX_{max} and ξ_1 $\Longrightarrow$ validation of ξ_1 as predictor of shower-to-shower ΔX_{max}



Take home message: Shower to shower values of ΔX_{max} and ξ_1 extremely correlated $\Longrightarrow$ validate ξ_1 as estimator of ΔX_{max} from 1st interaction fluctuations

New variables in the ΔX_{max}-N_μ plane



Take home message:

- ζ_{had}, ζ_{EM} and α_{had} offer a natural interpretation of the different regions of (N_μ, X_{max}) plane in terms of 1st interaction

!