Opportunities and Future directions for Astroparticle physics

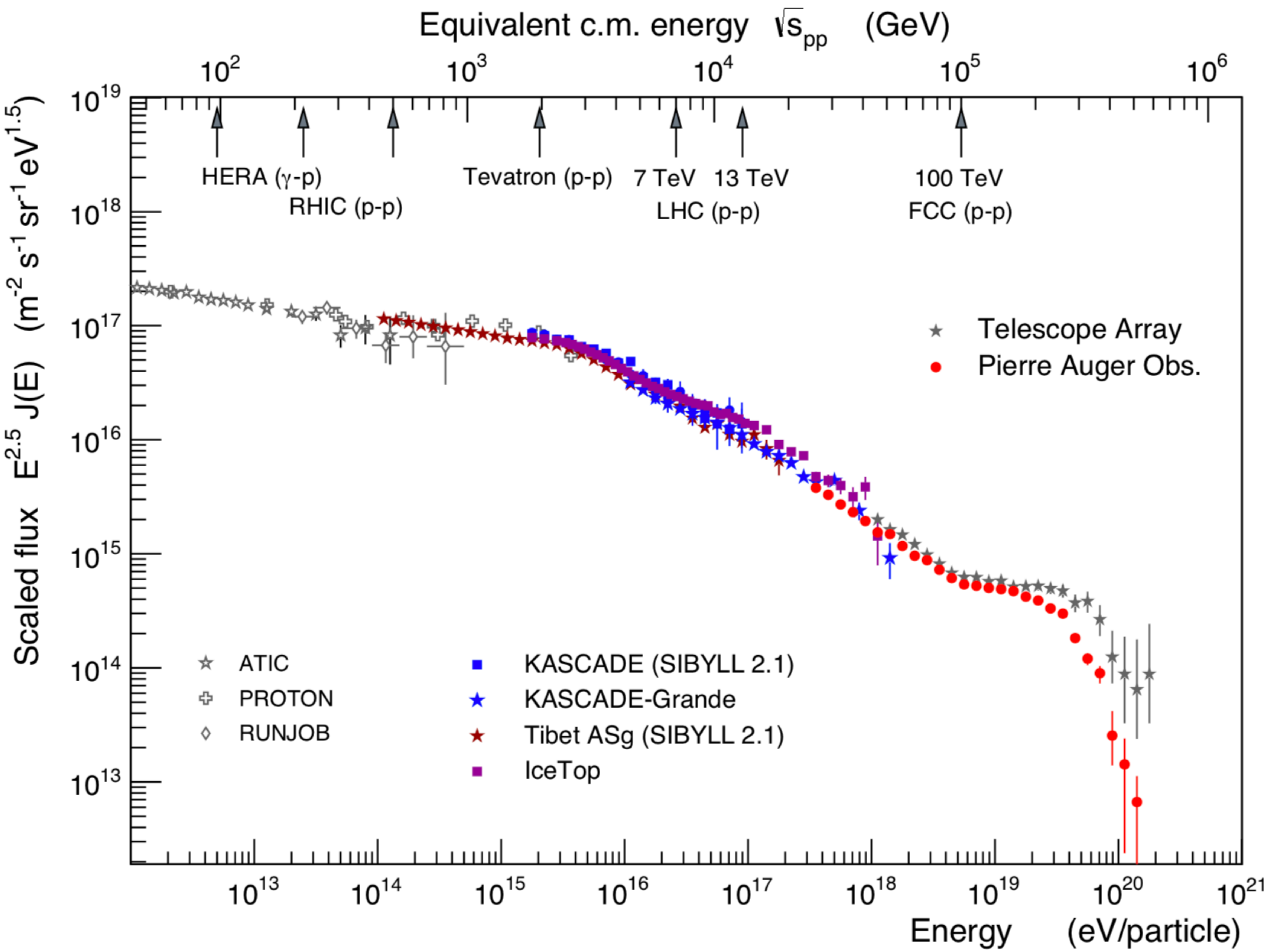
Ruben Conceição

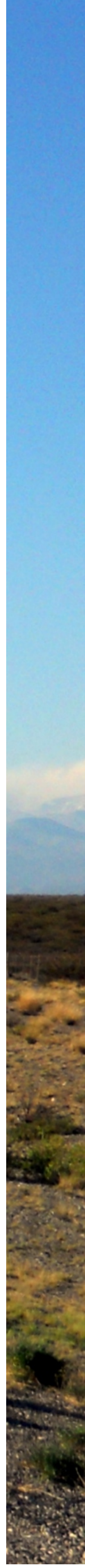
LIP

TÉCNICO LISBOA

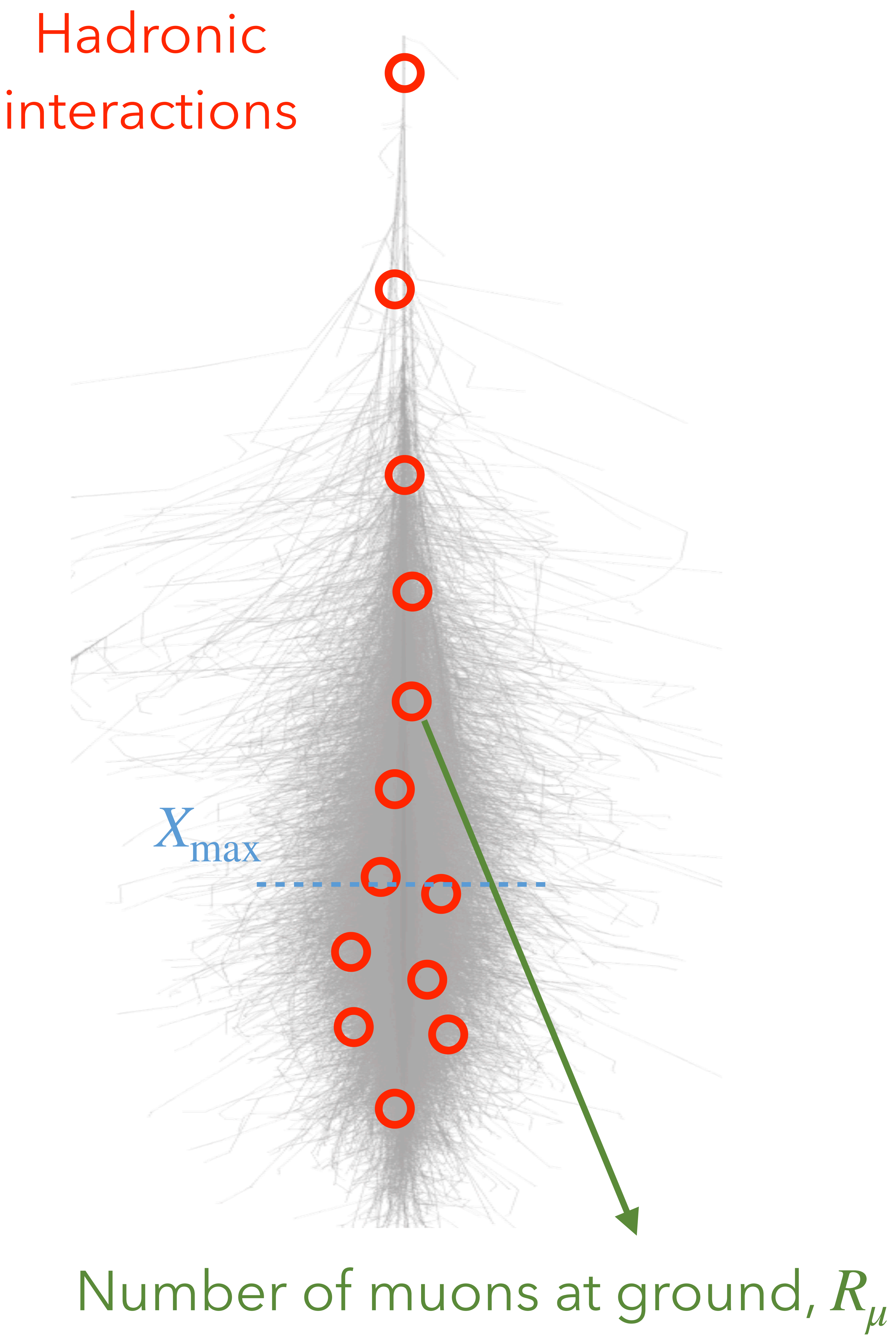
European Strategy Discussion, Lisbon, January 20th 2025

Study of cosmic rays at the highest energies

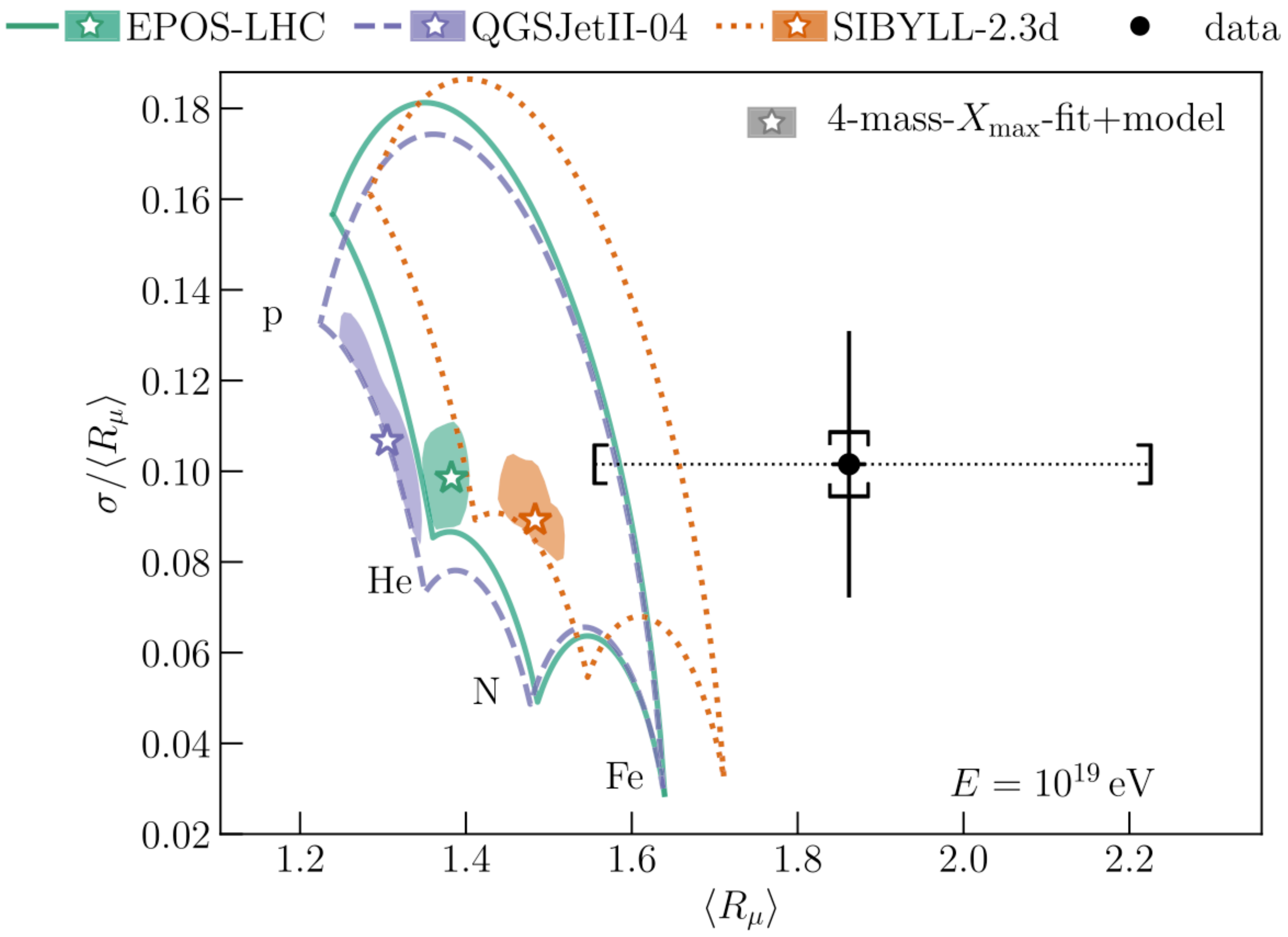




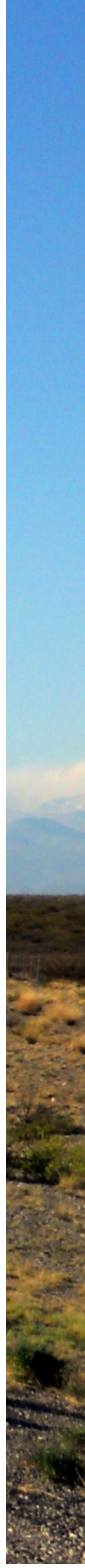
EAS Muon Puzzle



Pierre Auger Coll., Phys.Rev.Lett. 126 (2021) 15, 152002



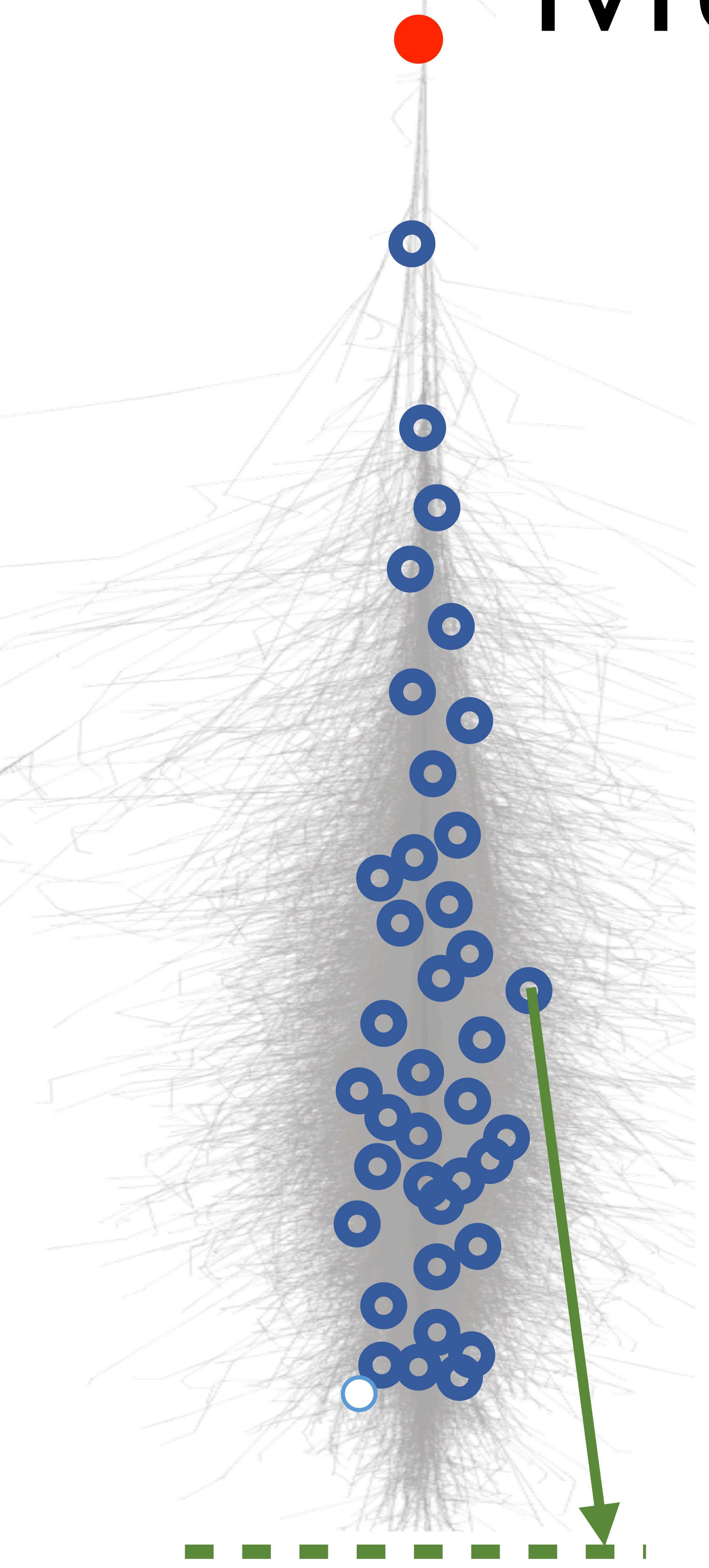
Models unable to consistently describe the average EAS muon content but its relative fluctuations agree with X_{max} expectations!!

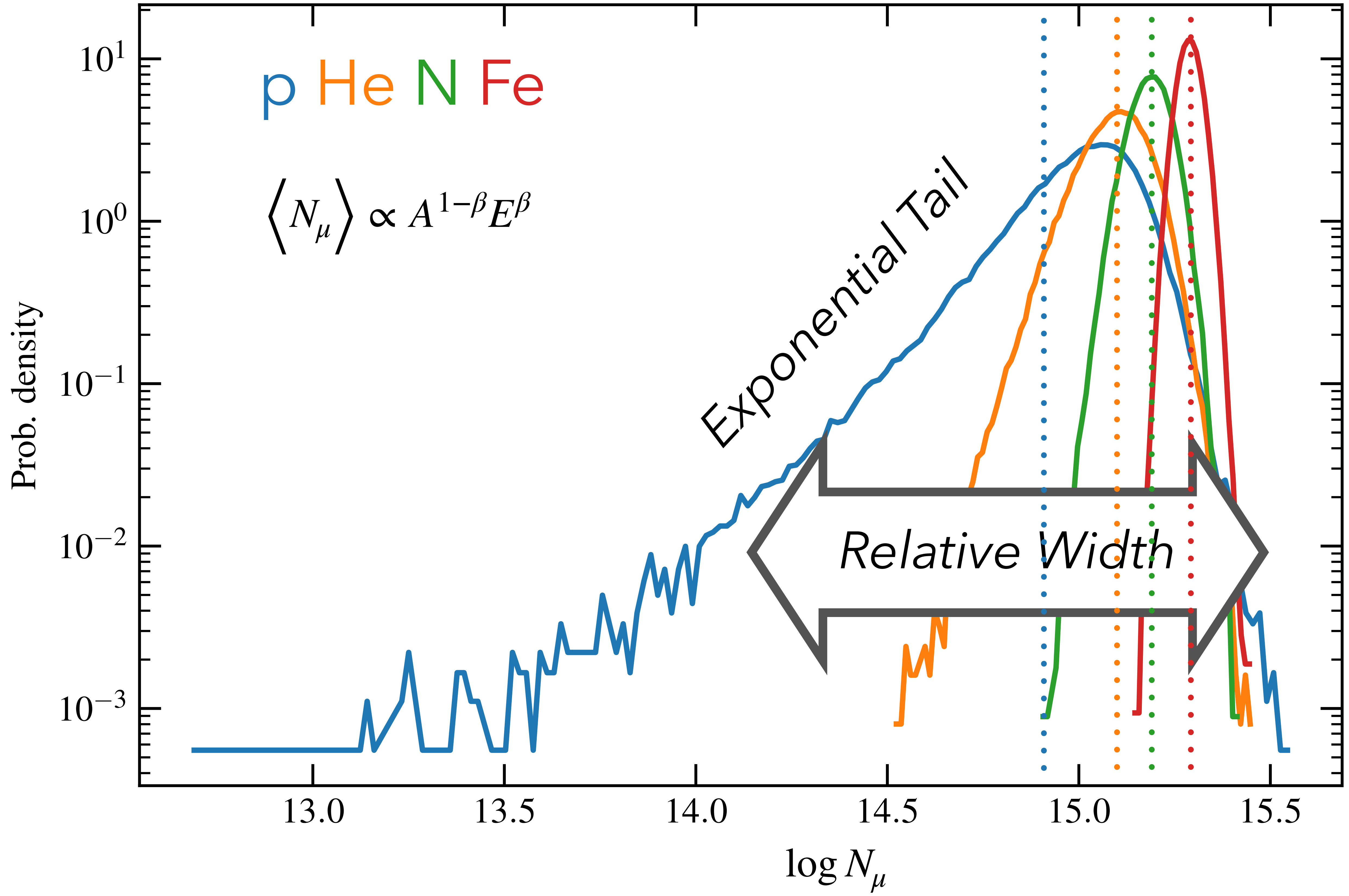


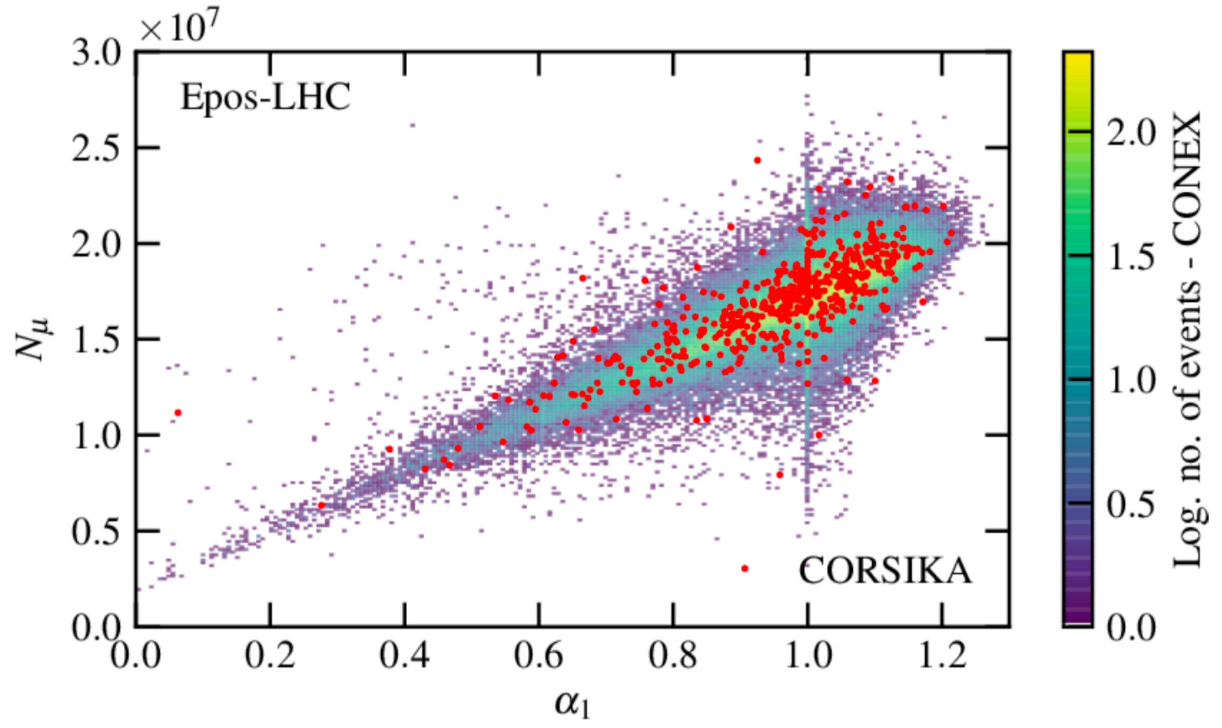
(see also, Pierre Auger Coll., Phys.Rev.D 109 (2024) 10, 102001)

Muon number distribution features

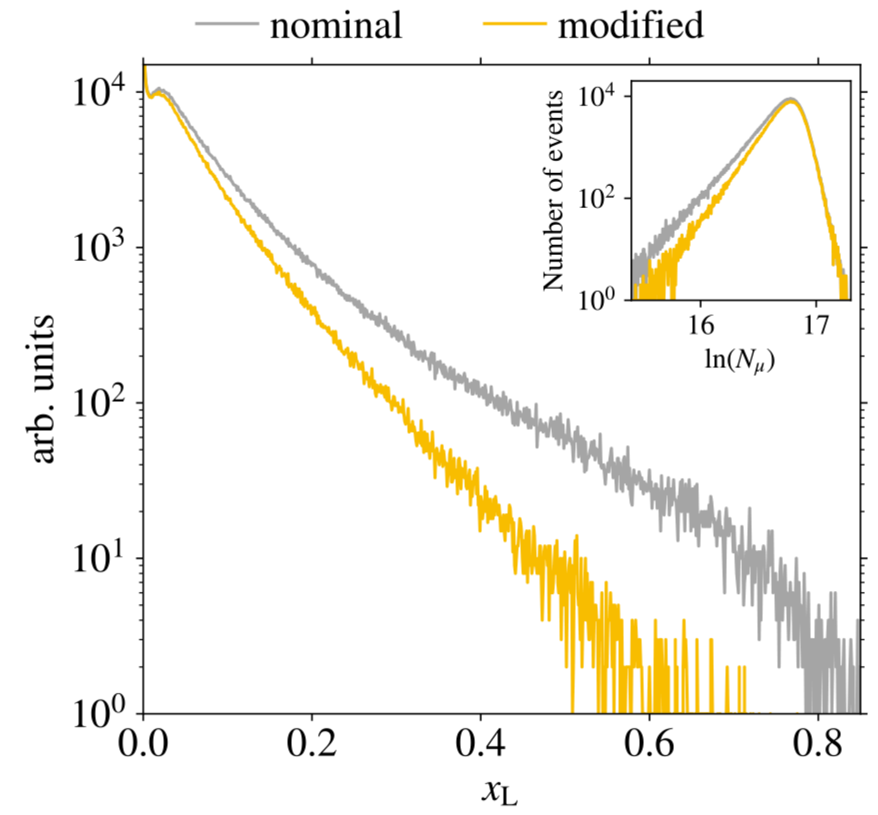
L. Cazon, RC, F. Riehn, Phys.Lett.B 784 (2018) 68-76
L. Cazon, RC, M. Martins, F. Riehn, Phys.Rev.D 103 (2021) 2, 022001
L. Cazon, RC, M. Martins, F. Riehn, Phys.Lett.B 859 (2024) 139115







1^{st} *interaction* π^0 *energy spectrum*



The shape and relative fluctuations of the muon number distribution gives access to the properties of the **FIRST hadronic interaction** (fraction of energy carried by neutral pions - α_1)

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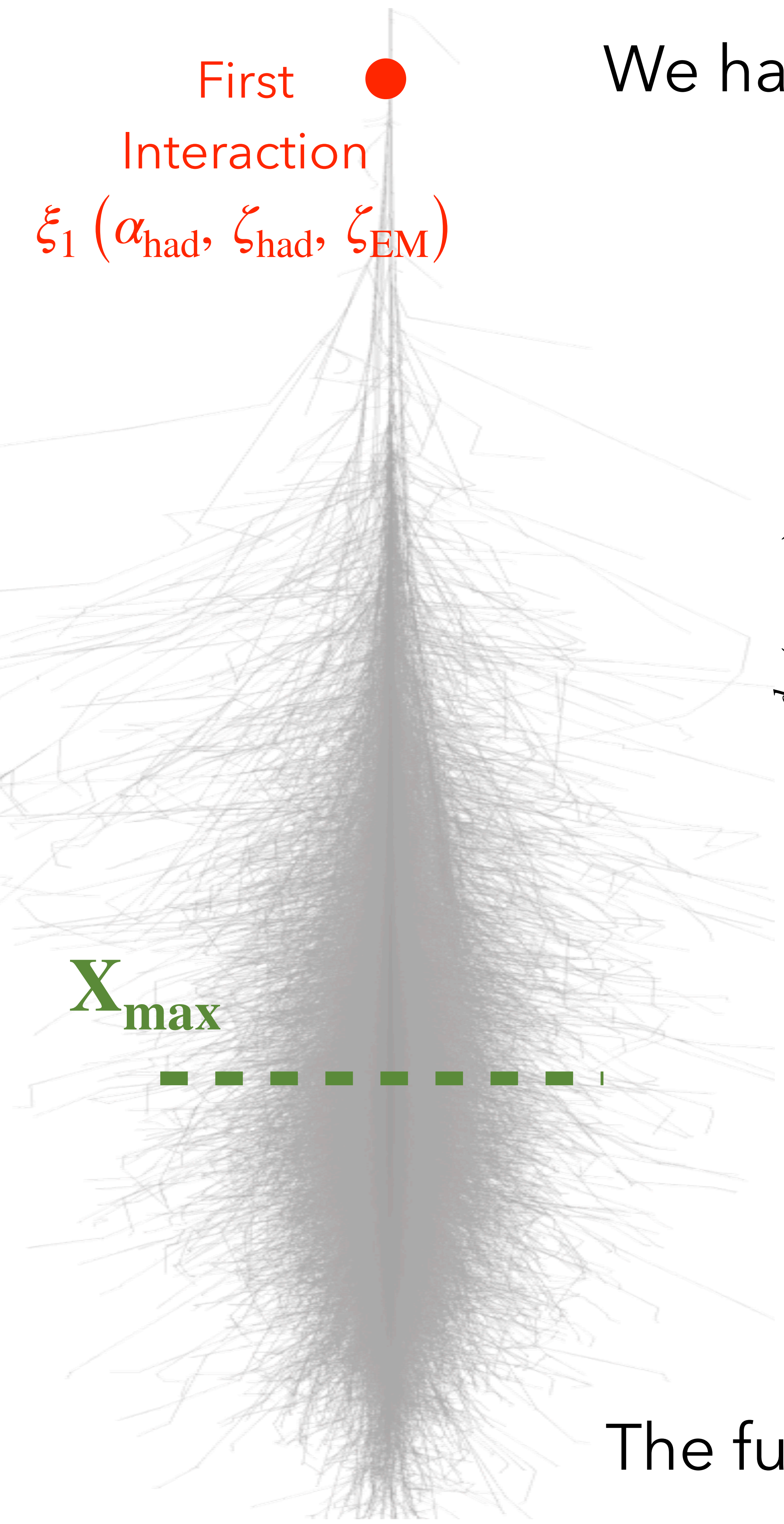
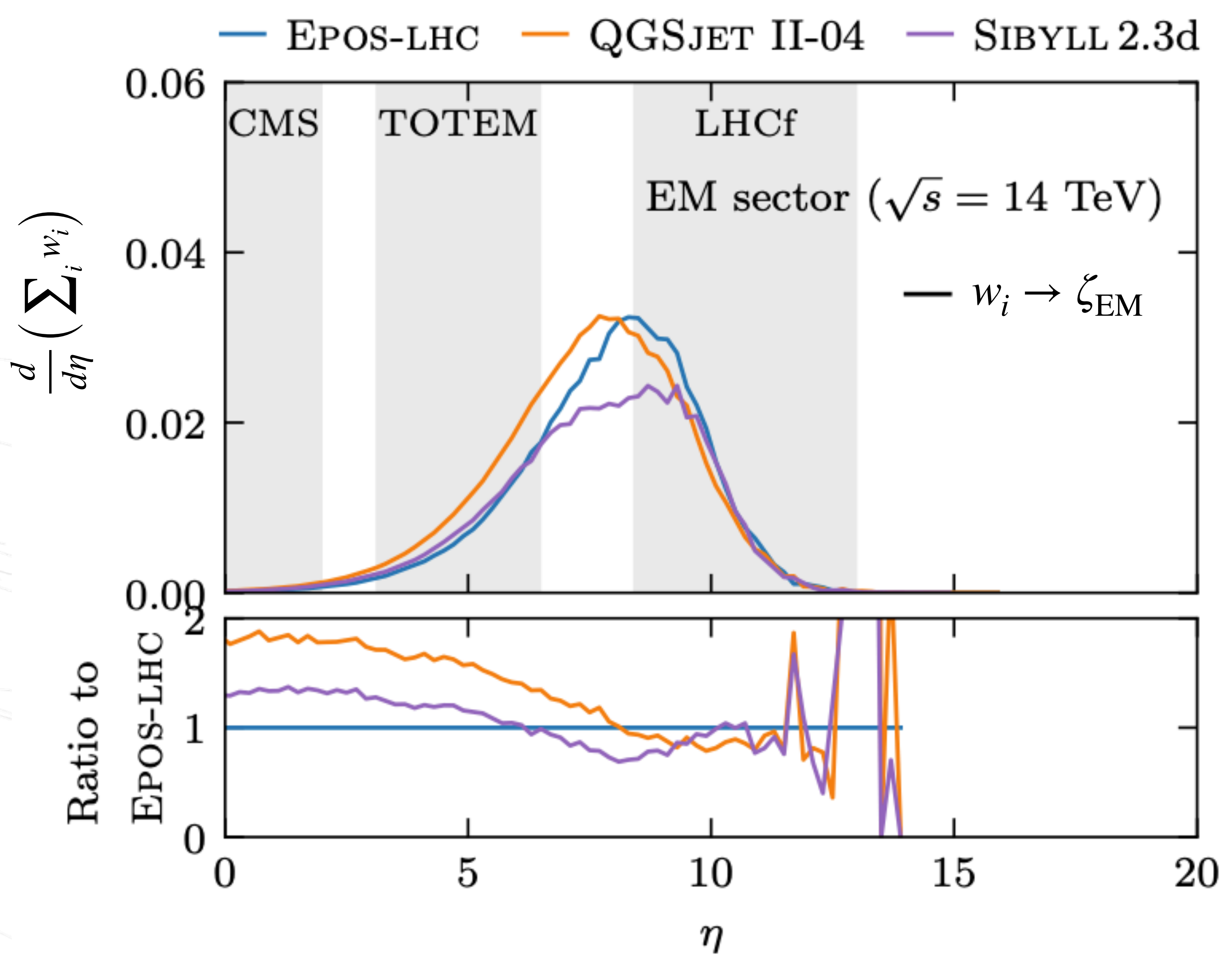
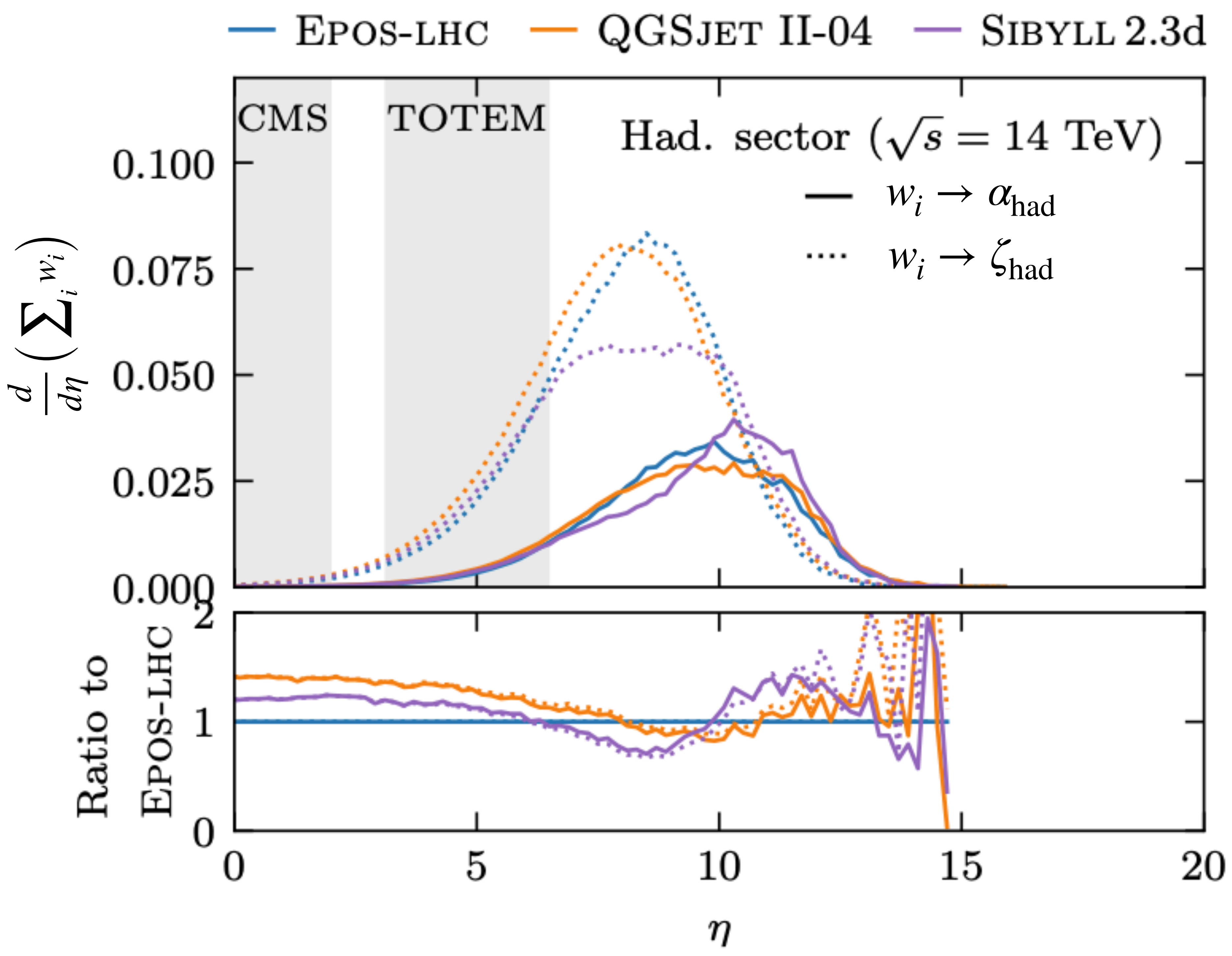
Depth of the shower maximum

L. Cazon, RC, M. Martins, F. Riehn, soon to be submitted to Phys. Rev. D



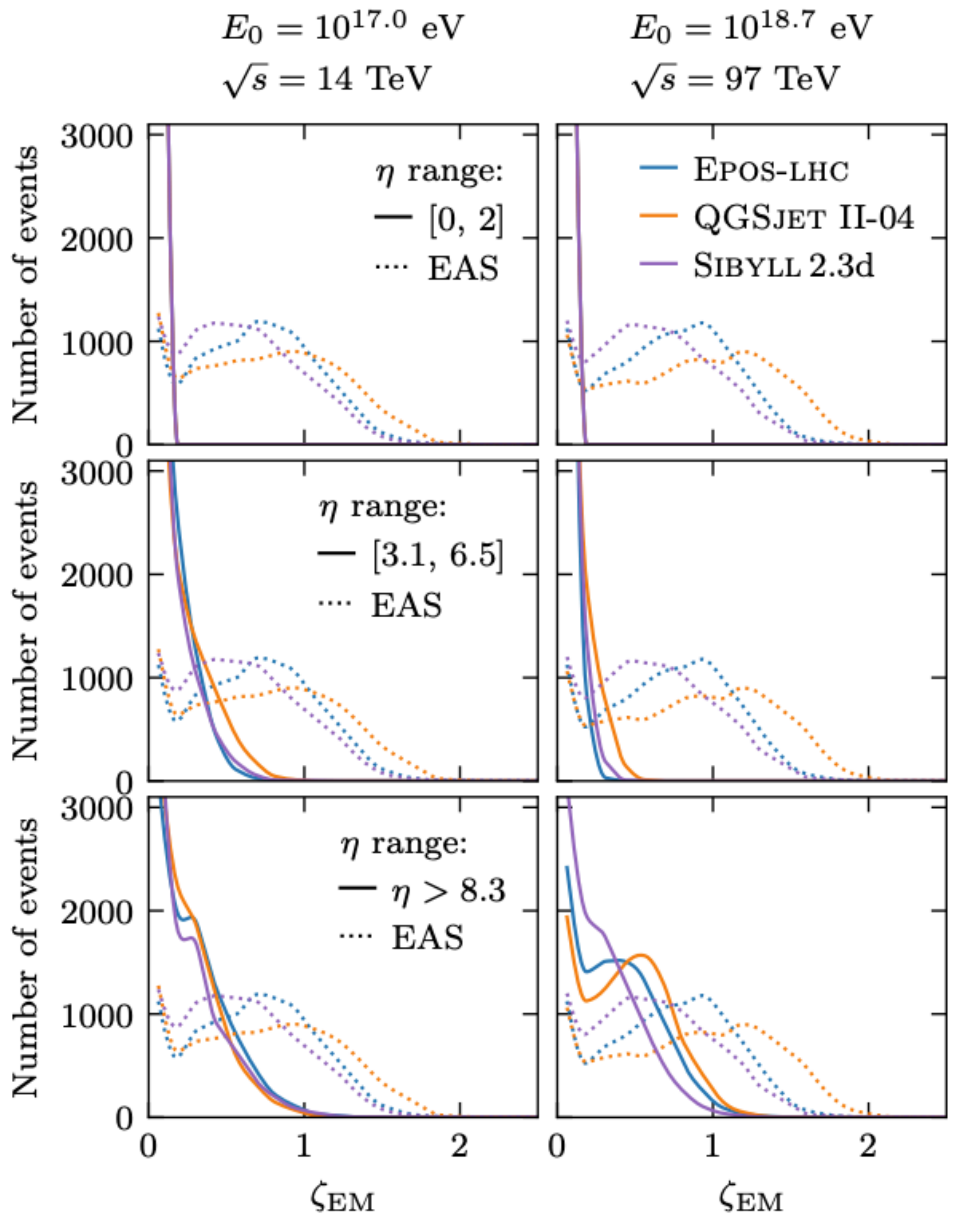
We have shown that X_{max} can be predicted solely from the energy spectra of secondaries by using linear combinations of the following multiparticle production quantities $\alpha_{had}, \zeta_{had}, \zeta_{EM}$.





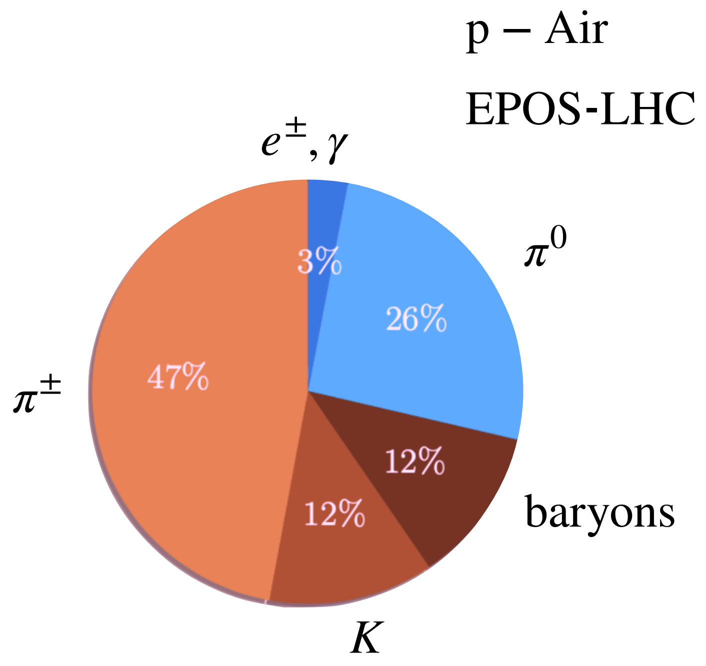
The functional form of $\alpha_{had}, \zeta_{had}, \zeta_{EM}$ is independent of the hadronic interaction models and the particle contribution to these quantities can be explored at the HL-LHC to exclude models

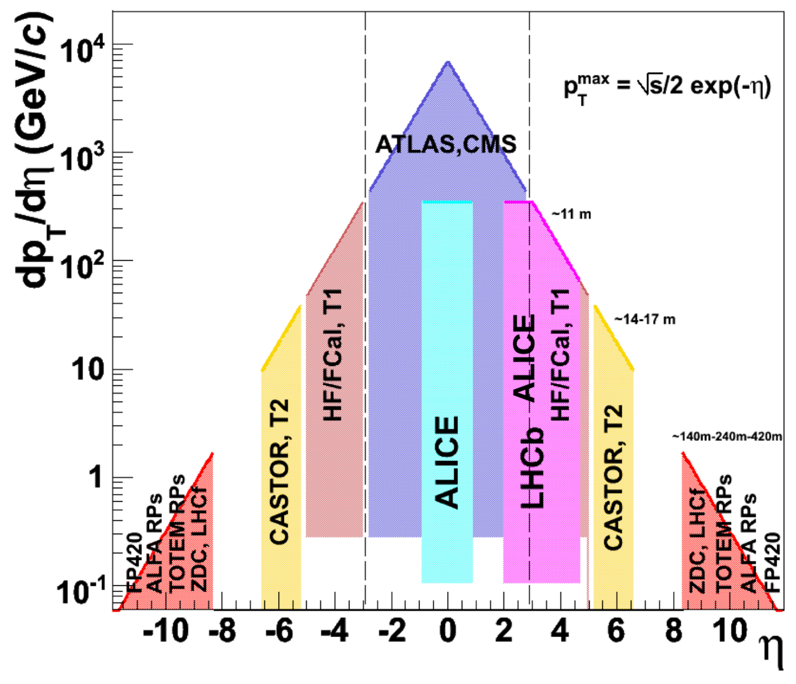
The functional form of ζ_{EM} and ζ_{had}

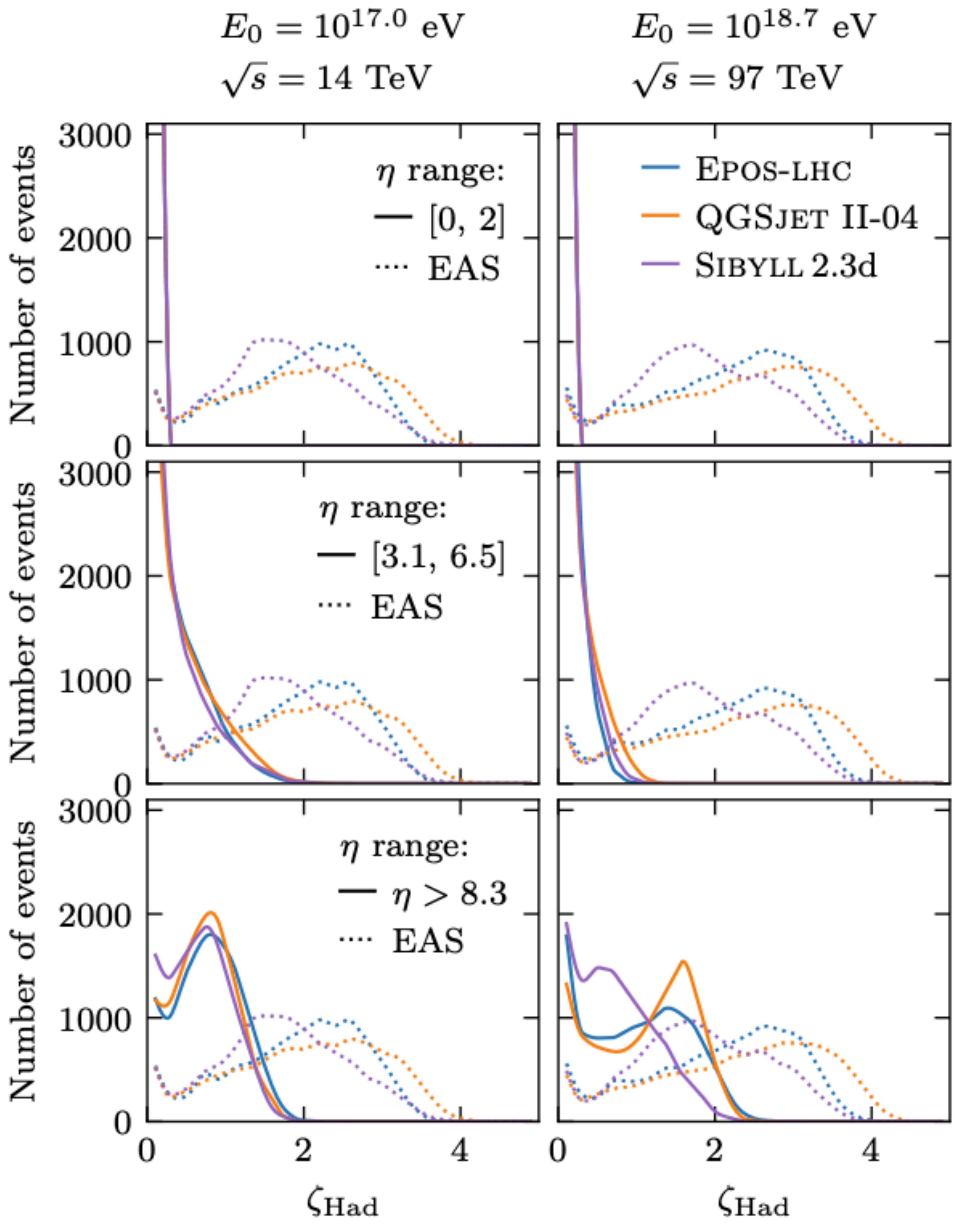


Shower electromagnetic sector

The **shape** of ζ_{EM} and ζ_{had} can only be differentiated across models in **Cosmic Ray experiments** or at the **FCC-hh**







Shower hadronic sector

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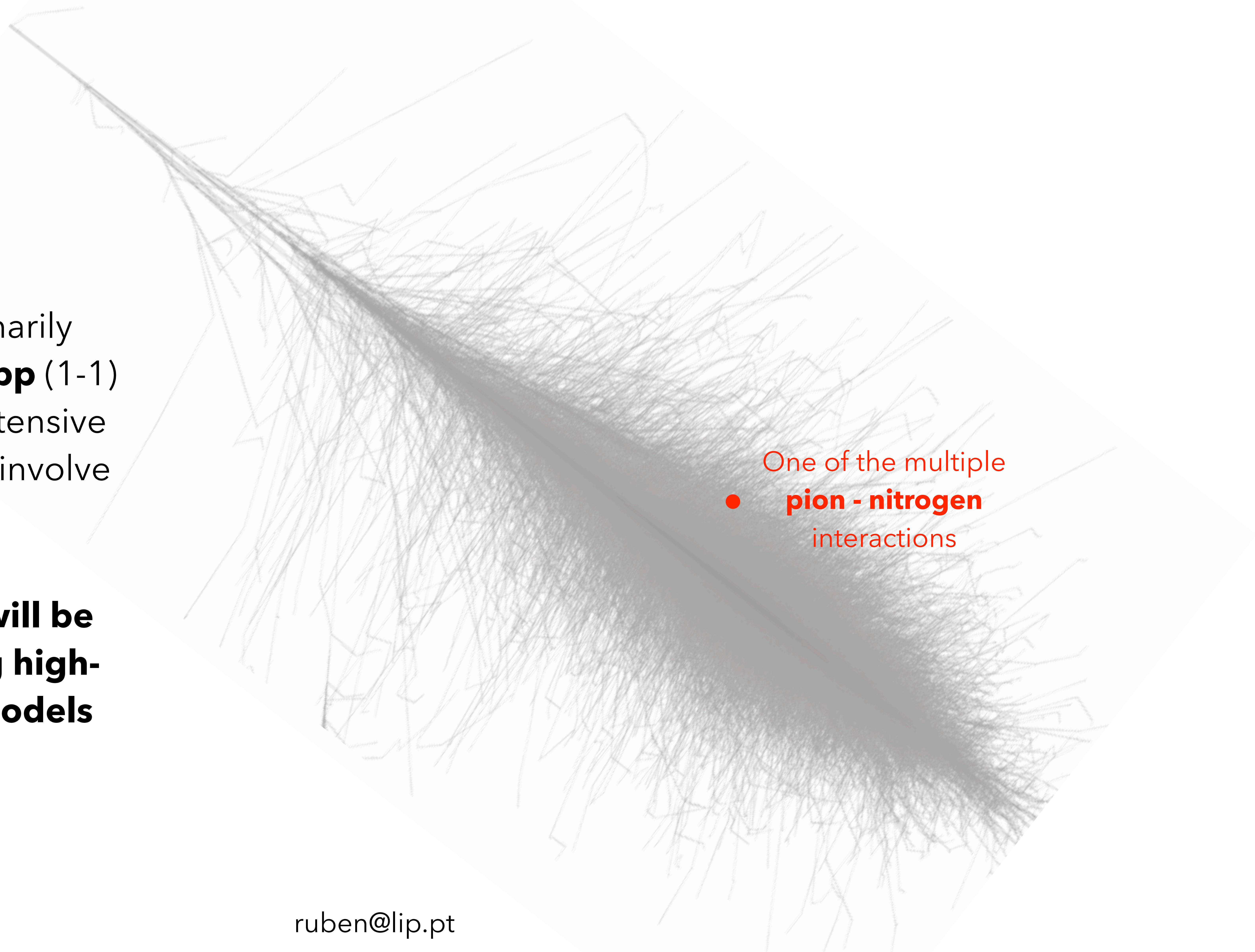
Extensive Air Showers

Available accelerator data primarily cover collisional systems such as **pp** (1-1) and **PbPb** (208-208), whereas extensive air showers (EAS) predominantly involve **p/$\pi^{\pm}$-N** (1-14) interactions

The upcoming p-O collisions will be highly valuable in constraining high-energy hadronic interaction models



Extensive Air Showers

How well do we understand them?

Acknowledgements

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

REPÚBLICA PORTUGUESA

LIP

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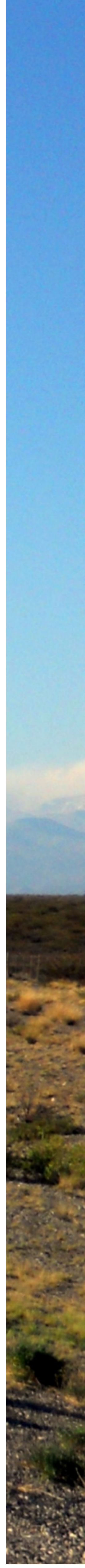
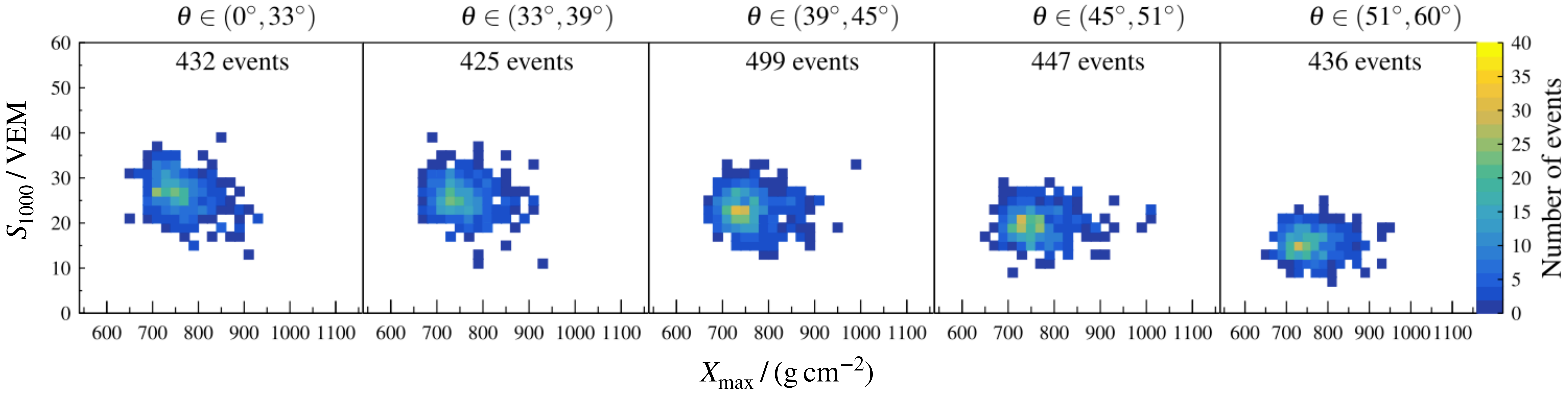


Backup slides

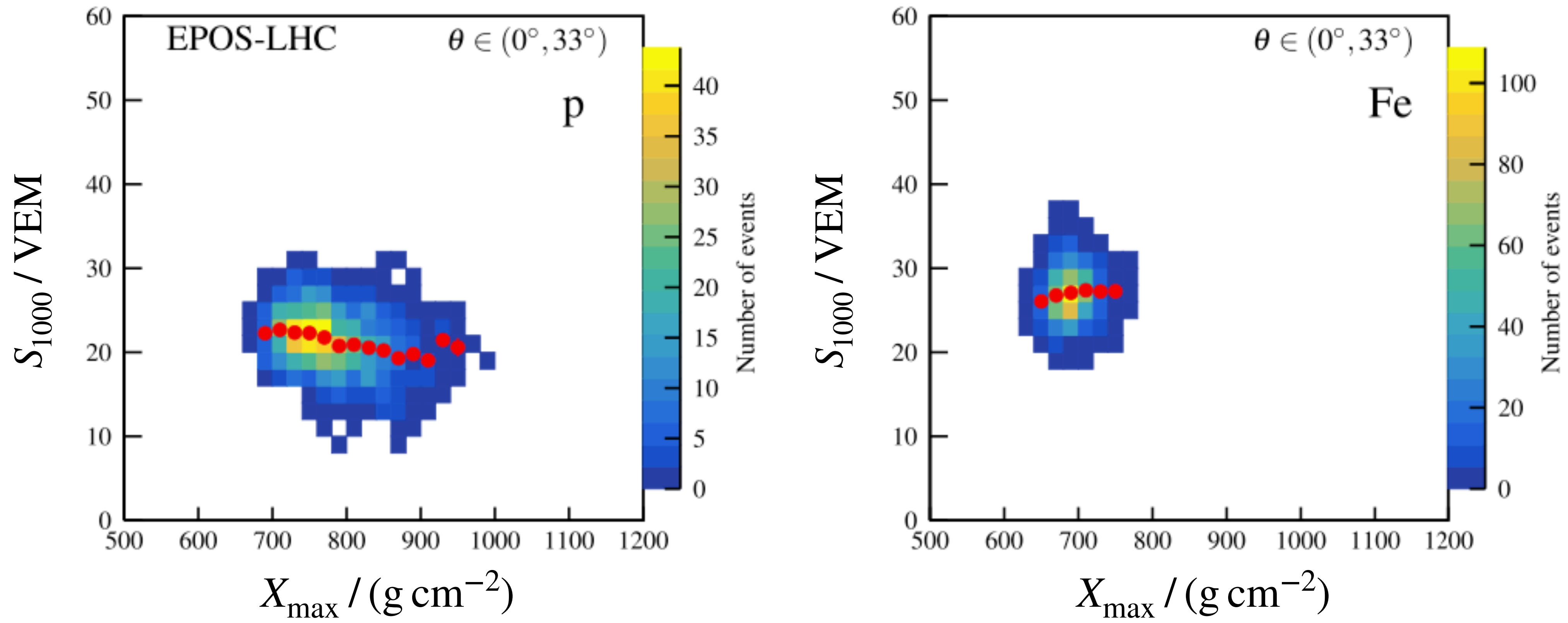
Analysis of the (X_{max}, S_{1000}) distribution

Pierre Auger Coll., Phys.Rev.D 109 (2024) 10, 102001

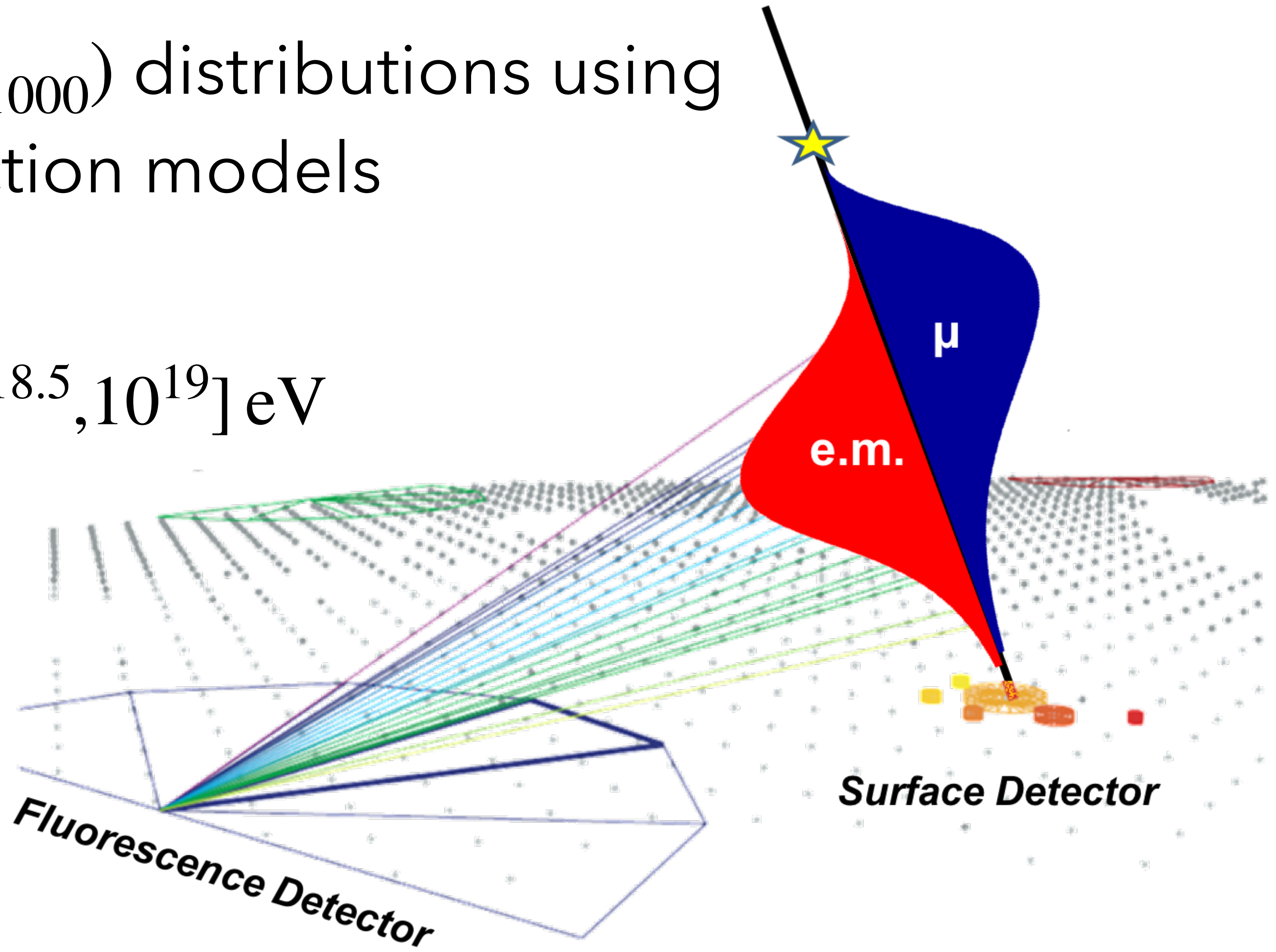


Explore hybrid FD-SD events and **fit the measured two-dimensional** (X_{max}, S_{1000}) distributions using templates for simulated air showers produced with hadronic interaction models

Example of MC templates

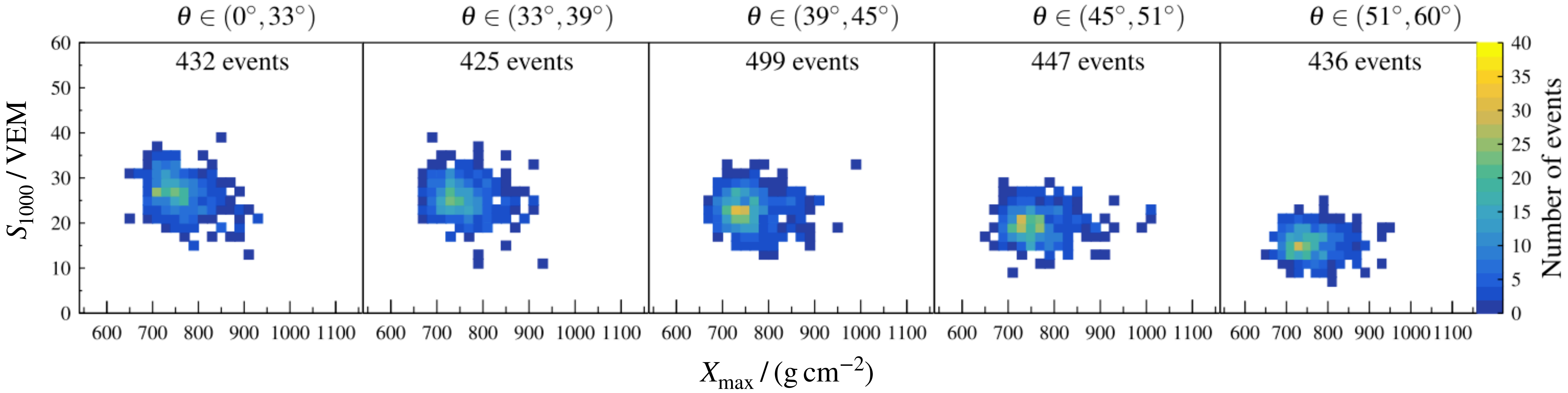


$E \in [10^{18.5}, 10^{19}]$ eV



Analysis of the (X_{max}, S_{1000}) distribution

Pierre Auger Coll., Phys.Rev.D 109 (2024) 10, 102001



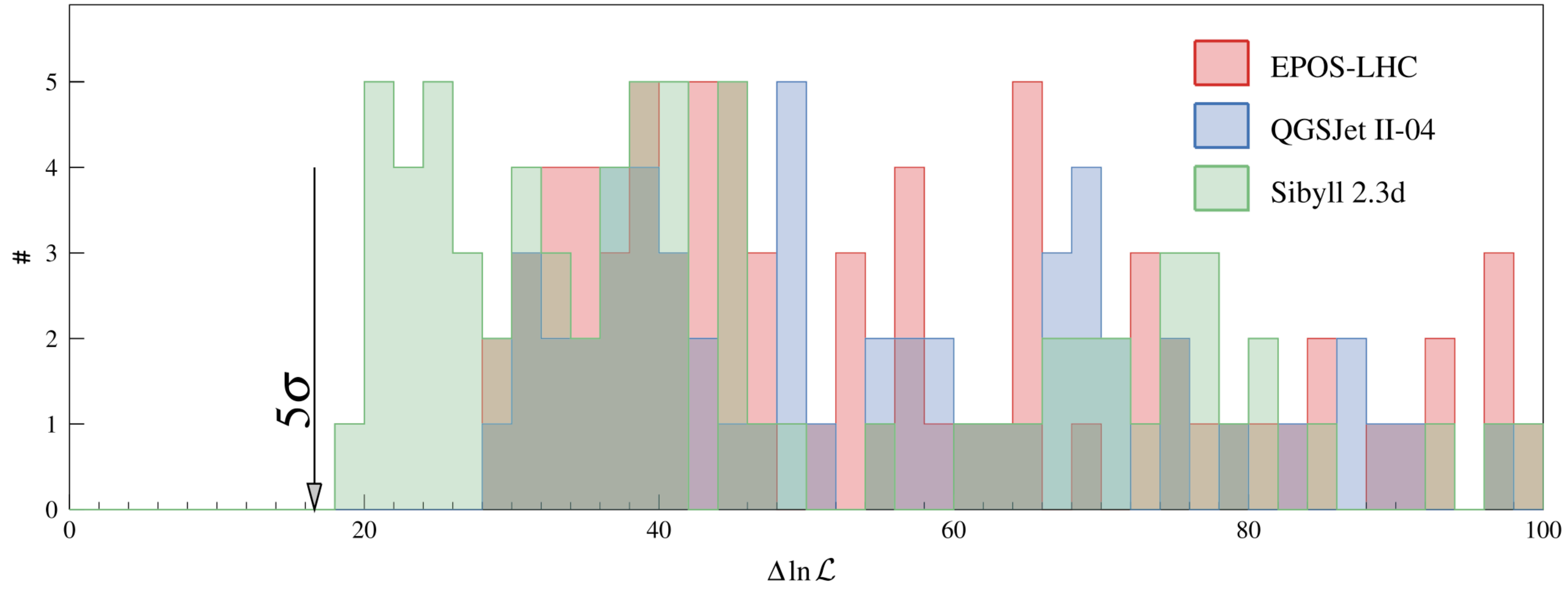
Systematic uncertainties

$E - 14\%$

$E + 14\%$

$X_{max} - 9 g/cm^2$

$X_{max} + 8 g/cm^2$



Systematic uncertainties

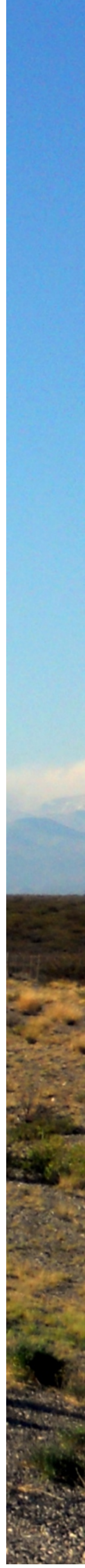
S(1000) − 5%

S(1000) + 5%

Method

None of the post-LHC hadronic interaction models can describe the Auger (X_{max}, S_{1000}) data, even considering the systematic uncertainties

More details in J. Vicha's talk



Hadronic Interaction Models

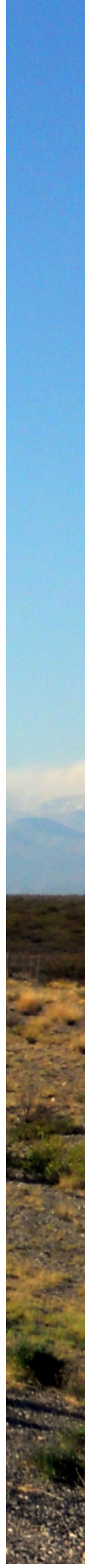
- Most based on the simple parton model associated with the Gribov-Regge multiple scattering approach
- Various approaches in the physics treatment
- Phenomenological models with parameters tuned to available accelerator data

See T. Pierog talk for latest results on EPOS LHC-R

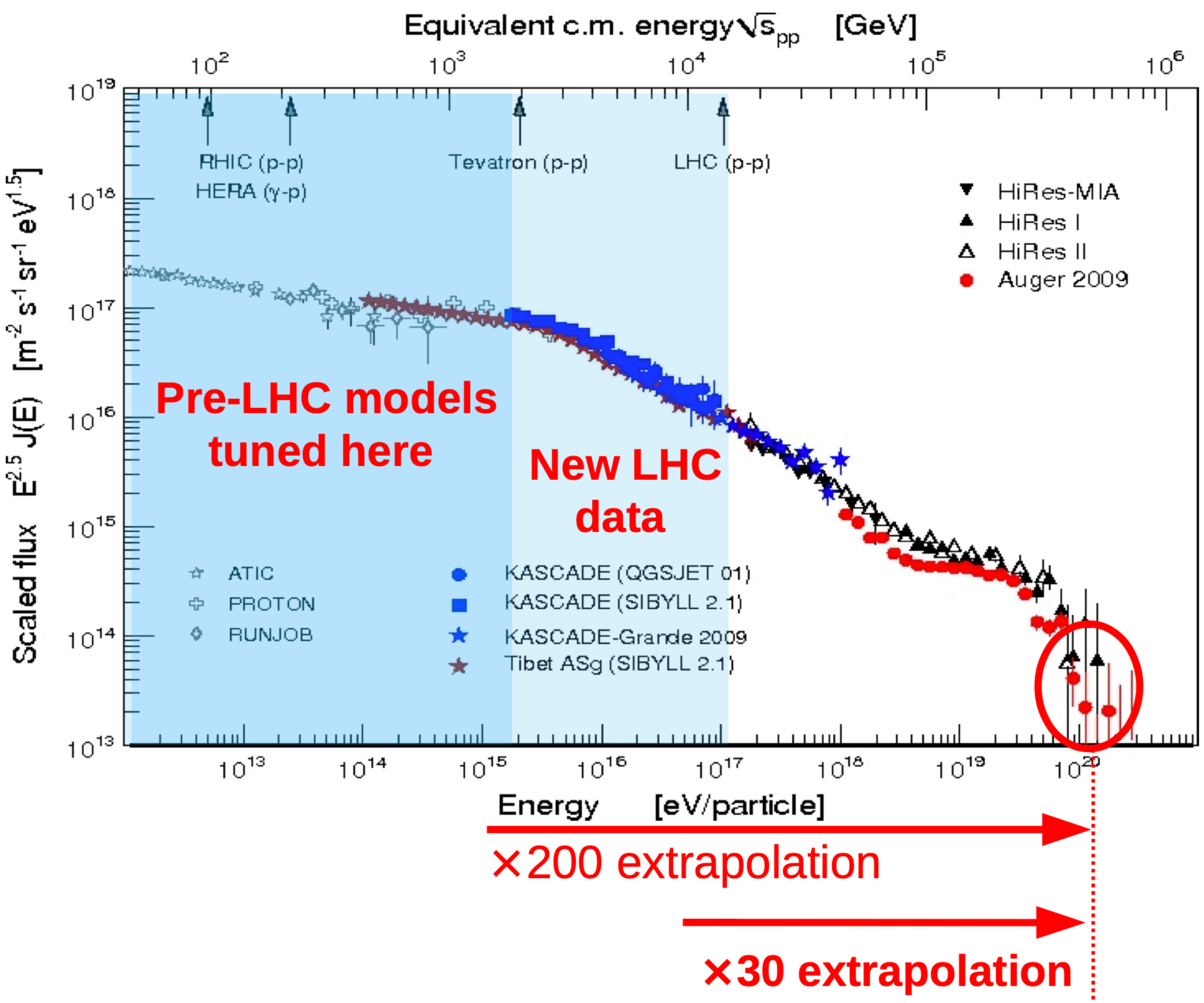
EPOS-LHC ↓ QGSJet-II.04 ↓

	EPOS4	EPOS LHC-R	QGSJETIII	Sibyll 2.3d	PYTHIA8
Primary domains	HIC, HEP	EAS, HIC	EAS	EAS	HEP
Theoretical basis	parton-based GRT, pQCD, energy sharing, saturation	parton-based GRT, pQCD, energy sharing	GRT, pQCD (DGLAP+HT)	GRT, pQCD (minijet)	MPI, pQCD, ISR, FSR
Nuclear collisions	idem	idem	idem	extended superposition	Glauber via Angantyr
Pomeron	semi-hard, dynamical saturation	semi-hard	semi-hard	soft+hard	soft+hard
Parton distributions	generated	custom (GRV for valence)	Pomeron PDFs + DGLAP + HT	GRV	various
Diffractive dissociation (low mass)	diffractive Pomeron	diffractive Pomeron	Good-Walker (3-channel eikonal)	Good-Walker (2-channel eikonal)	longitudinal strings
Diffractive dissociation (high mass)	Pomeron exchange	Pomeron exchange	cut-enhanced graphs	Pomeron exchange	MPI
String fragmentation	area law	area law	early Lund type	Lund	Lund
Forward-central correlation	strong	strong	strong	weak	strong
Charm production	pQCD	parameterised + intrinsic	—	parameterised + intrinsic	pQCD
Collective effects	core-corona, hydrodynamical flow, hadronic rescattering	core-corona, parameterised flow, hadronic rescattering	—	—	colour reconnection, rope fragm., string shoving, hadronic rescattering

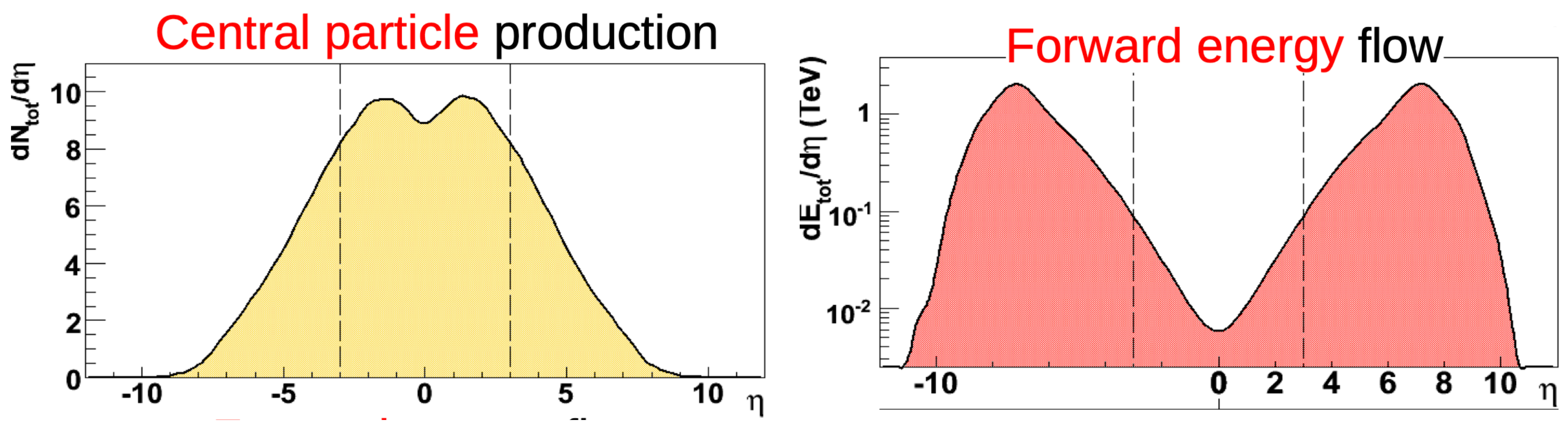
HIM typically used in EAS simulations

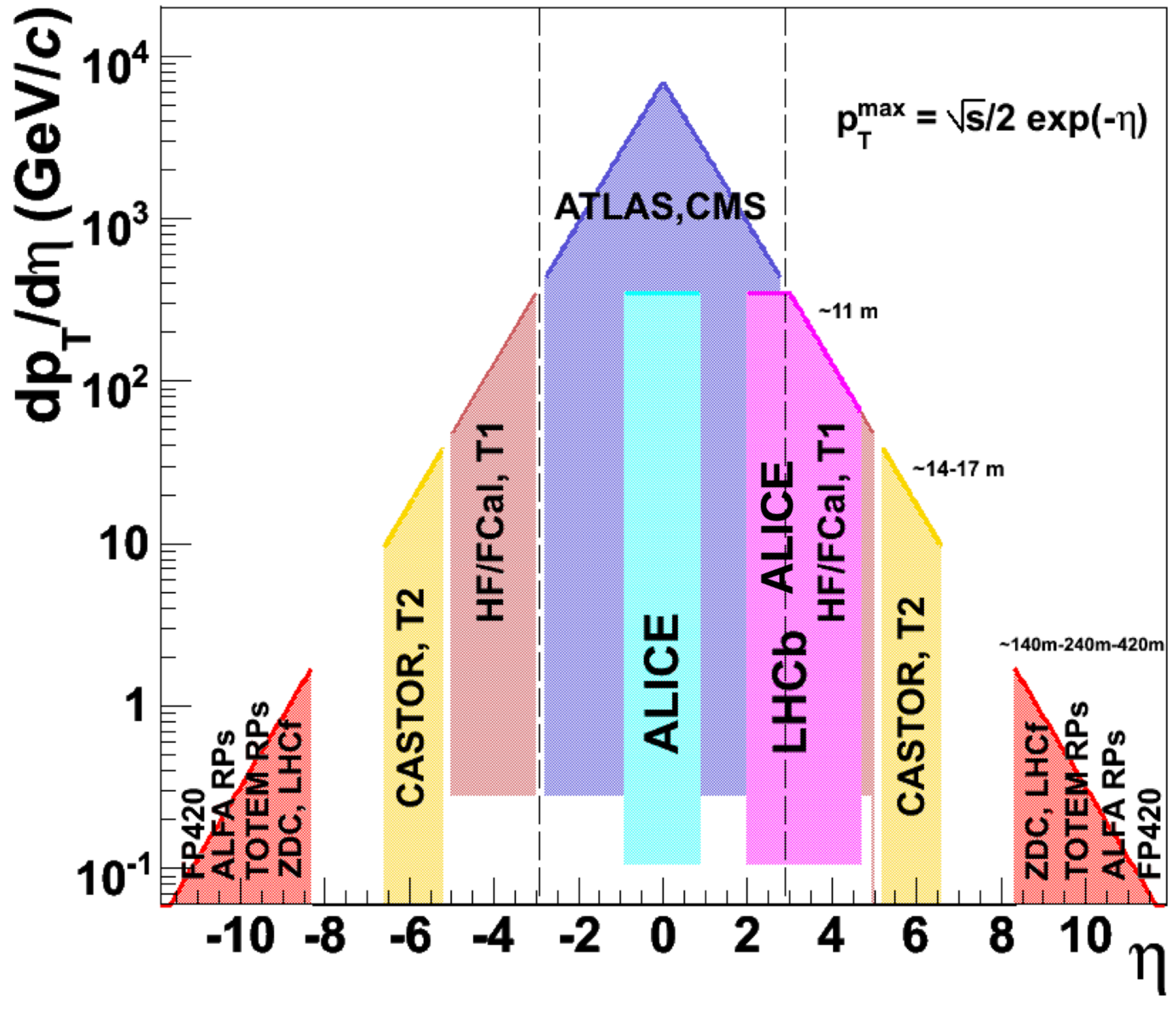


The challenge



p-p @ 14 TeV

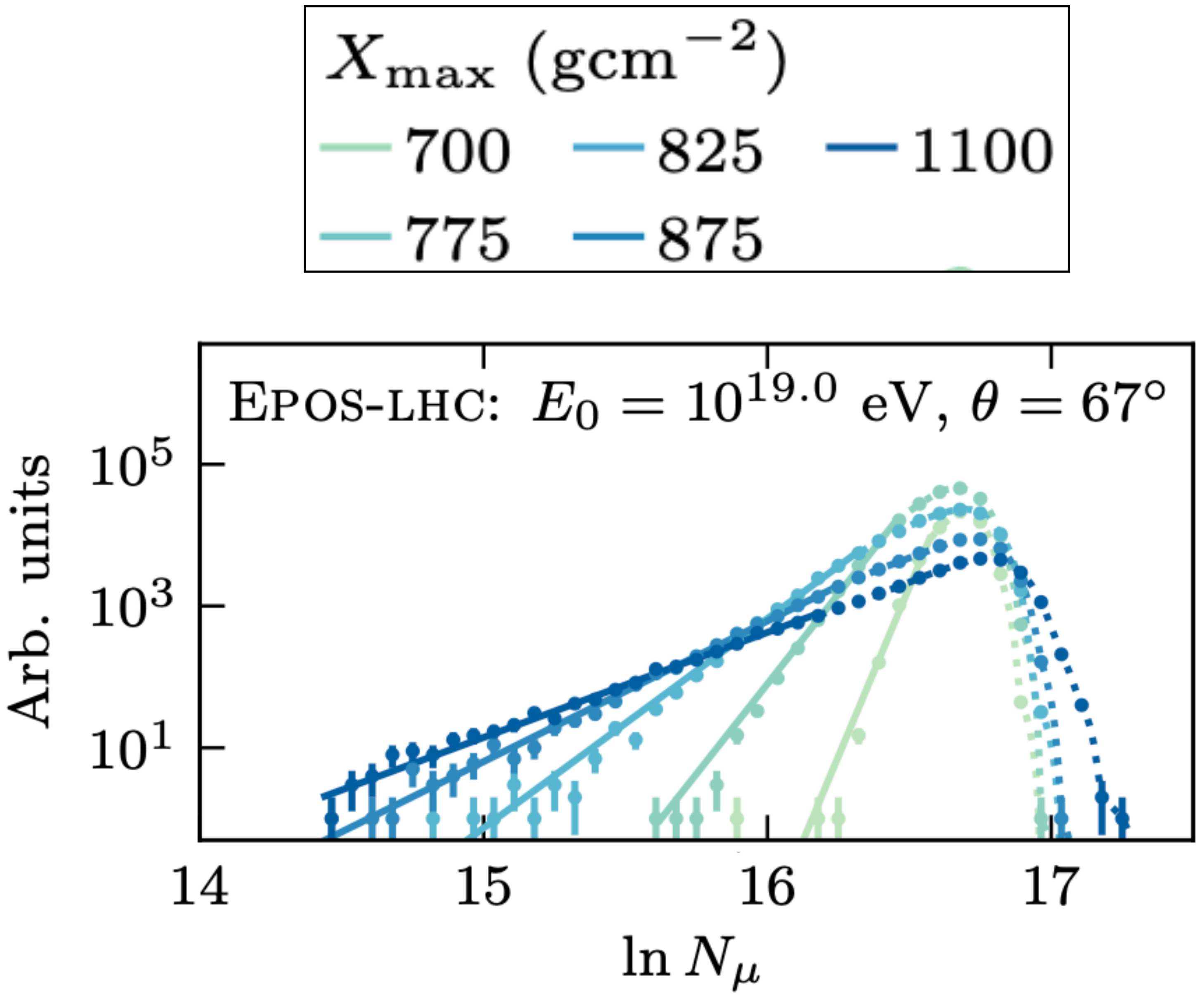




New insights!

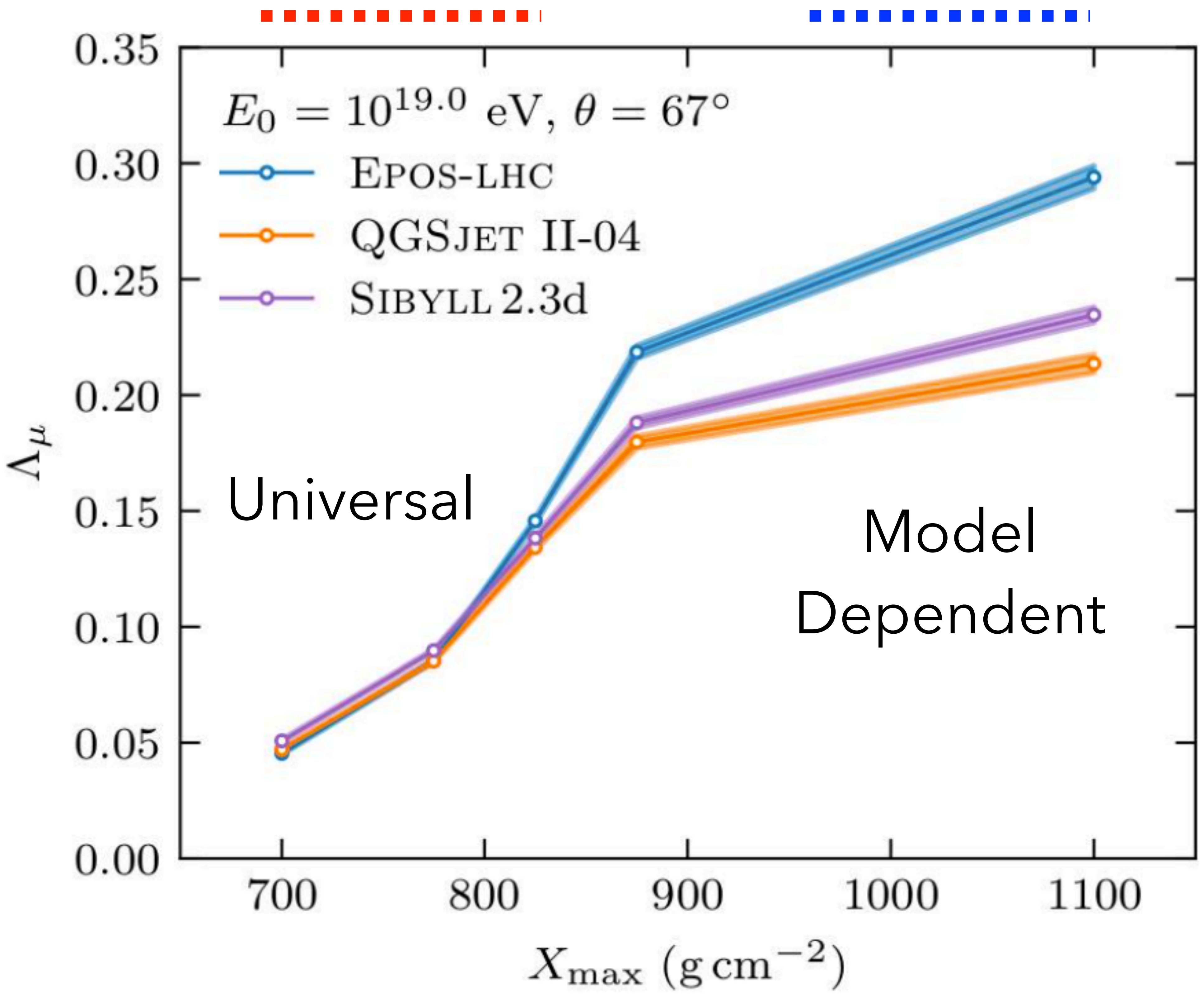
L. Cazon, RC, M. A. Martins, F. Riehn, Phys.Lett.B 859 (2024) 139115

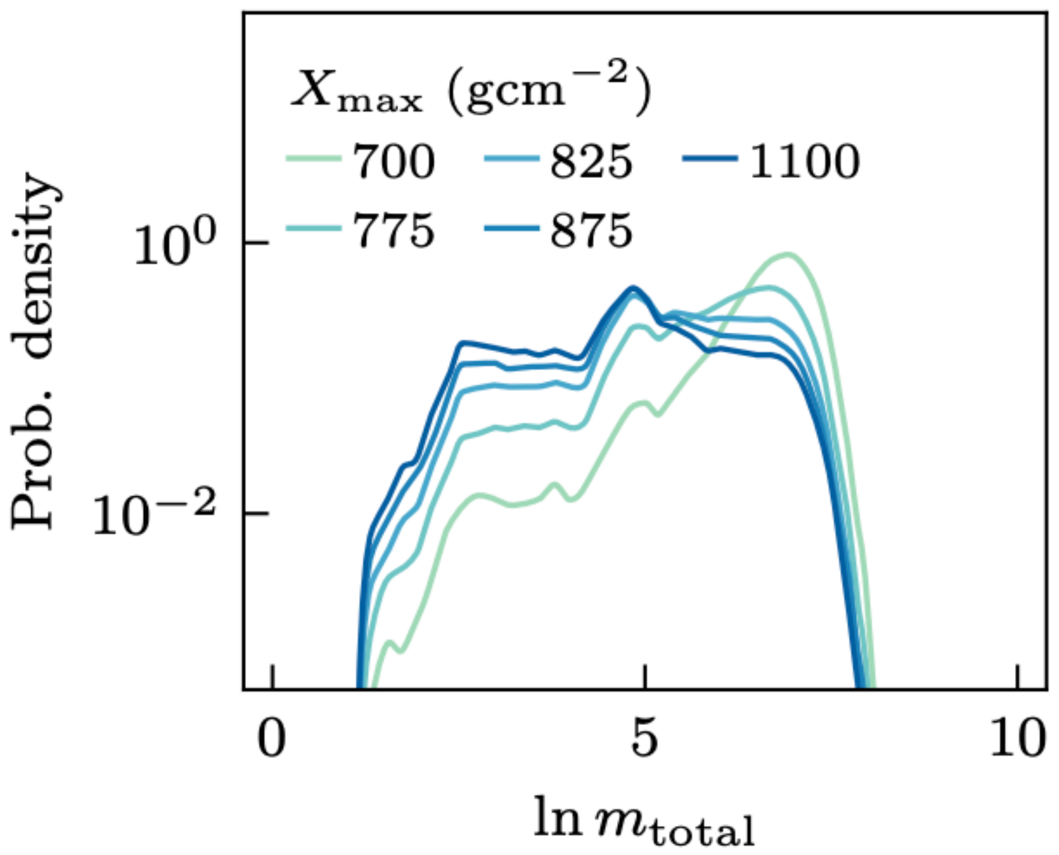
- ✧ Hadronic interaction models predict universal value of Λ_μ for shallow showers and highly distinct values for deep showers
- ✧ Binning in $X_{\max}$ ⇒ probe the hadronic activity of the first interaction



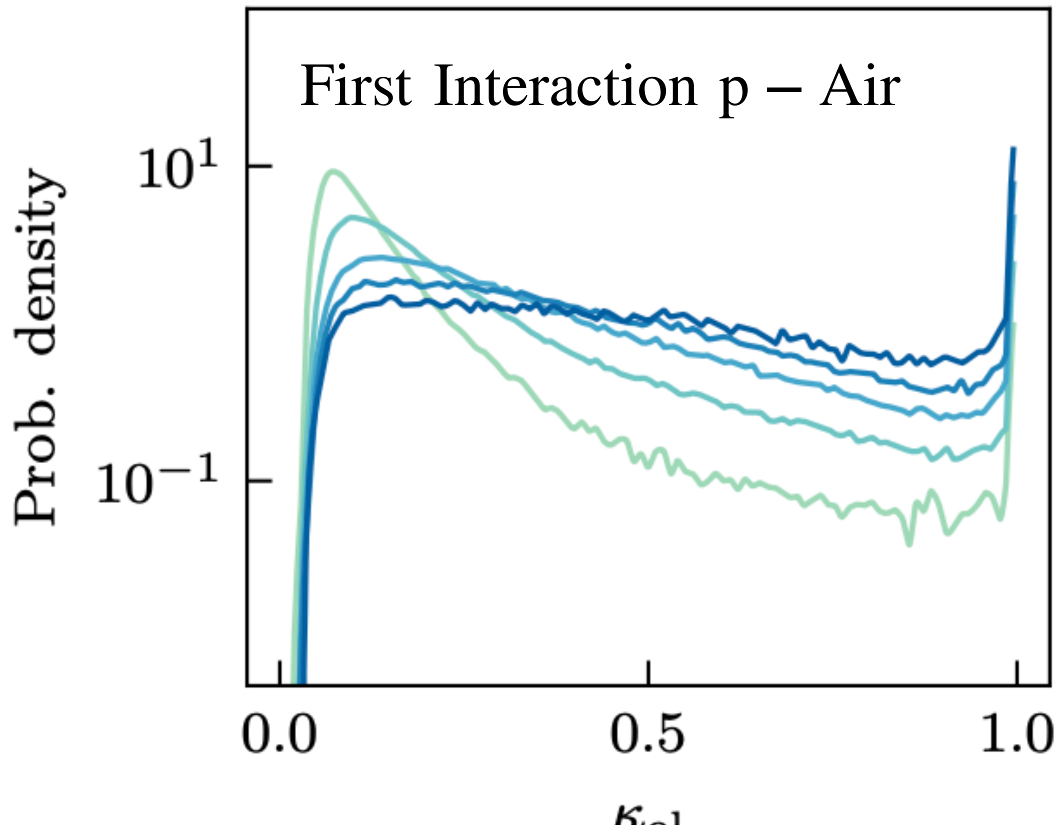
Low hadronic activity - diffractive events

Large hadronic activity - e.g. high multiplicity

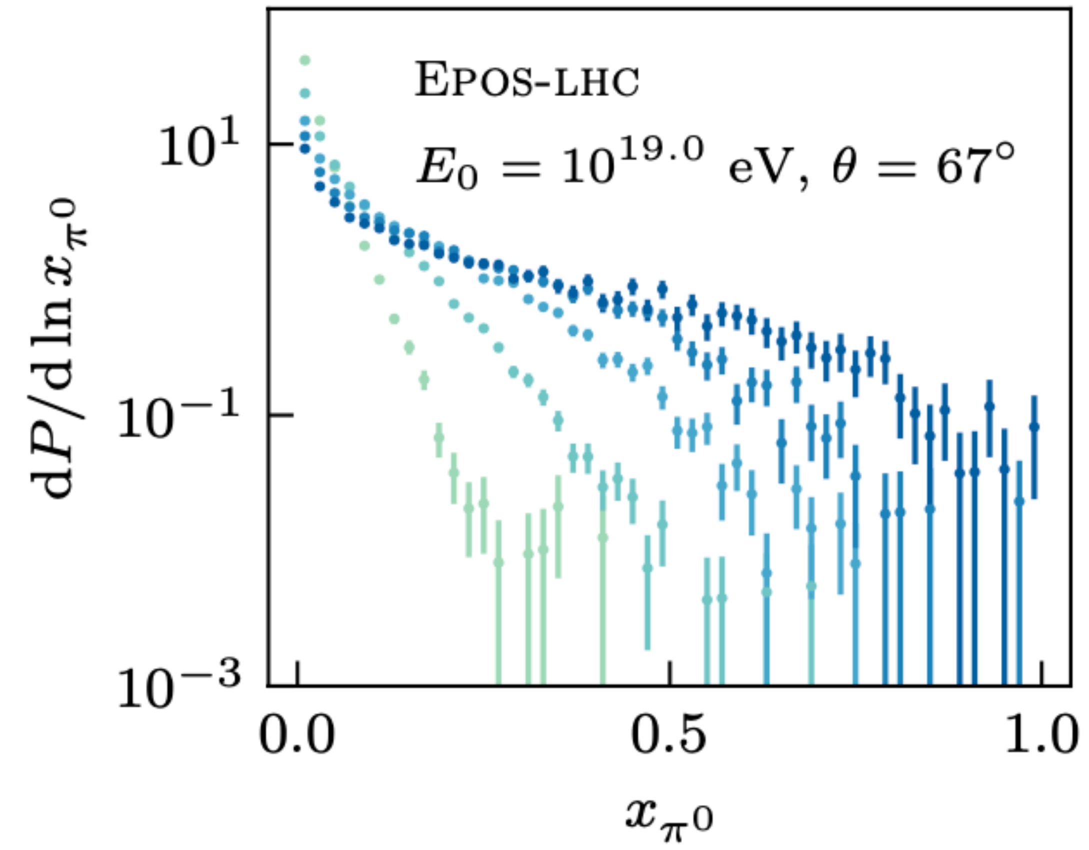




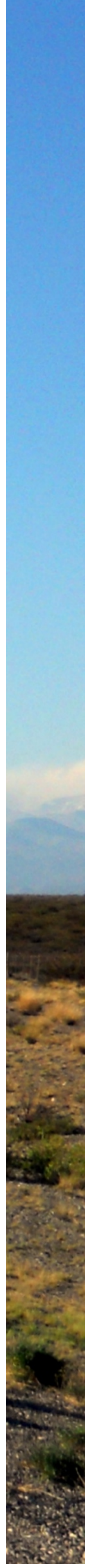
Multiplicity



Elasticity



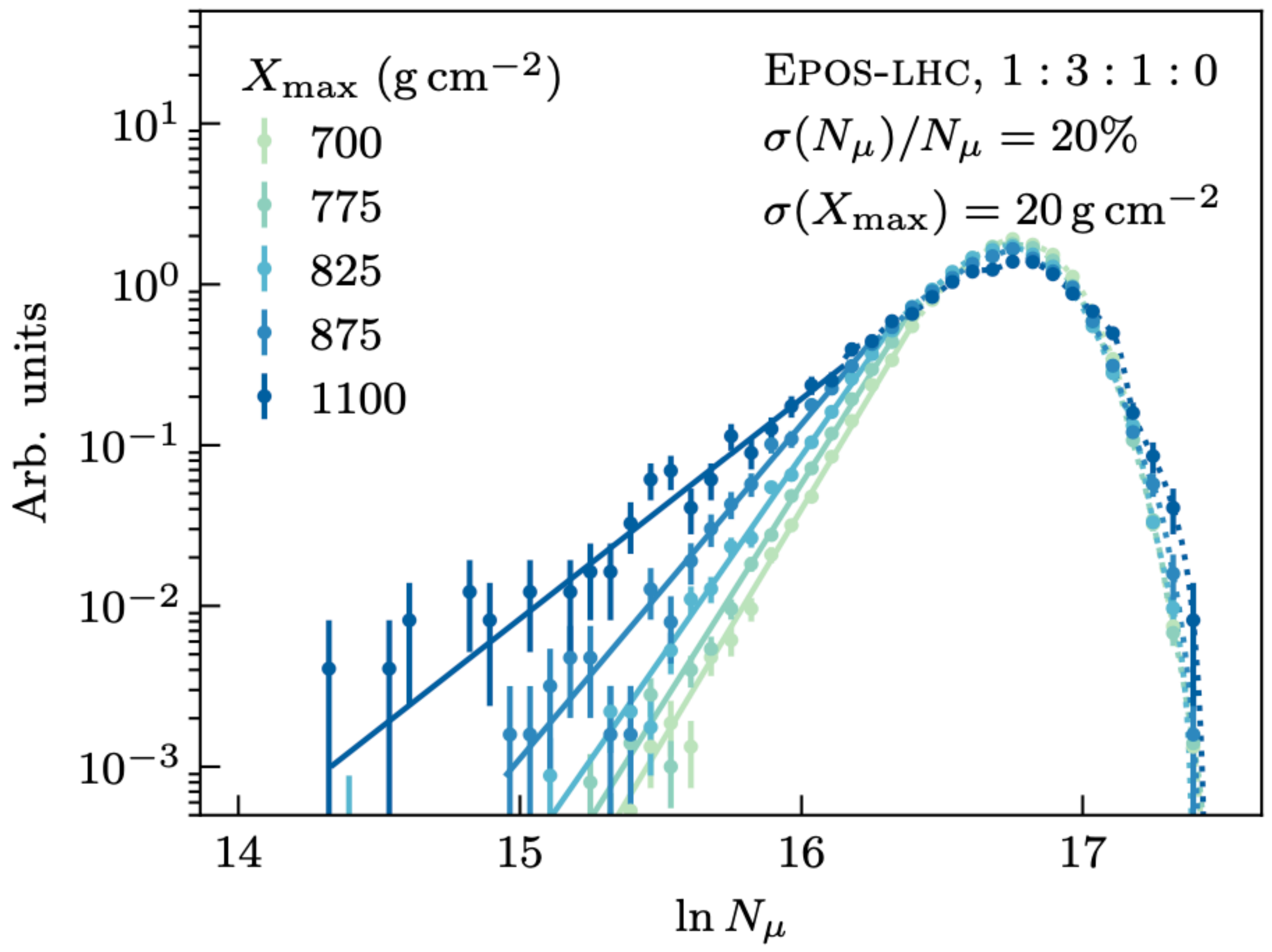
π^0 energy spectrum

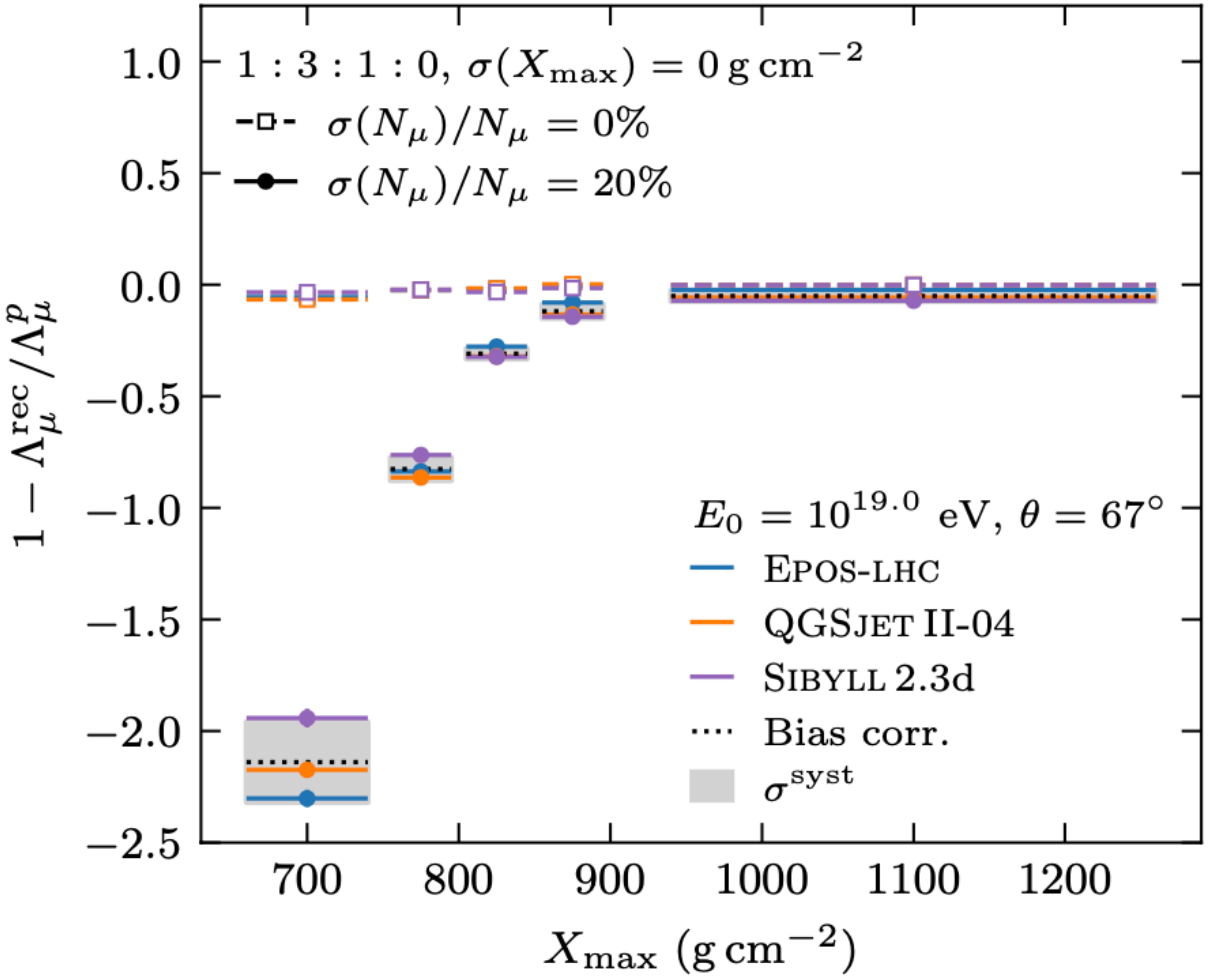


See also M. A. Martins's Poster

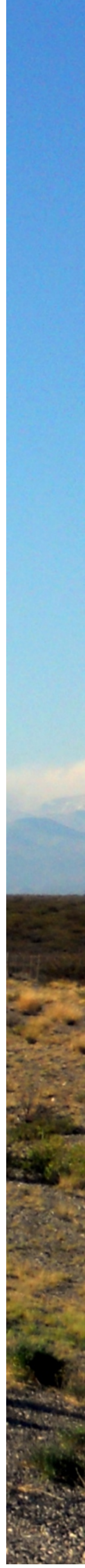
Experimental feasibility

Test applicability to data under several mass composition scenarios and experimental resolutions

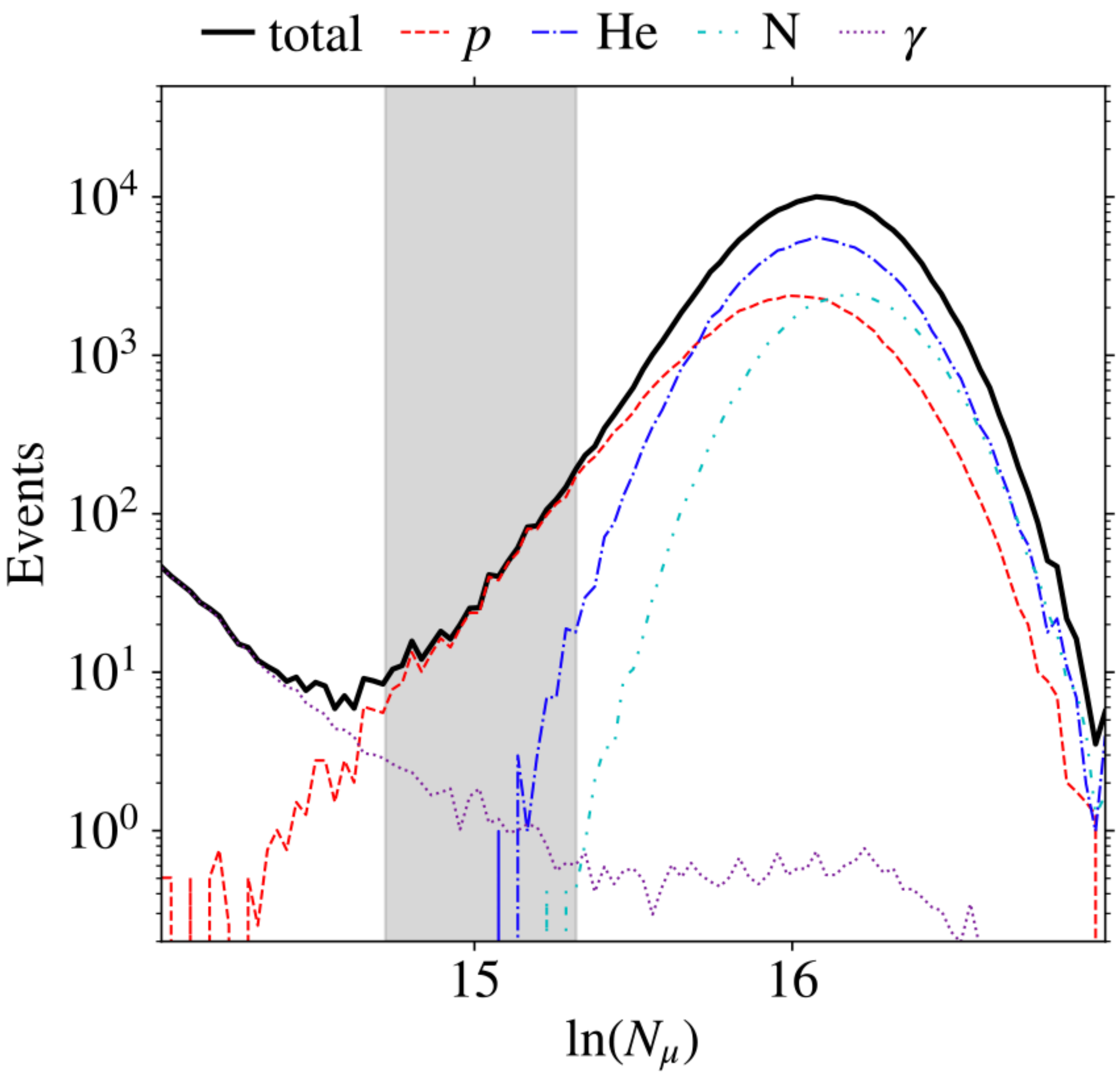


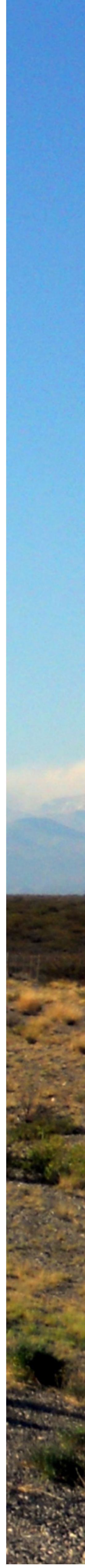


X_{max} (g cm^{-2})	1 : 3 : 1 : 0 $n_{min}^{1\sigma}$	1 : 3 : 1 : 0 $n_{min}^{3\sigma}$	7 : 1 : 2 : 0 $n_{min}^{1\sigma}$	7 : 1 : 2 : 0 $n_{min}^{3\sigma}$
700	–	–	–	–
775	–	–	–	–
825	13 030	100 000	18 478	100 000
875	5 080	54 393	3 519	29 587
1100	3 113	25 898	1 877	18 805



Measuring Λ_μ

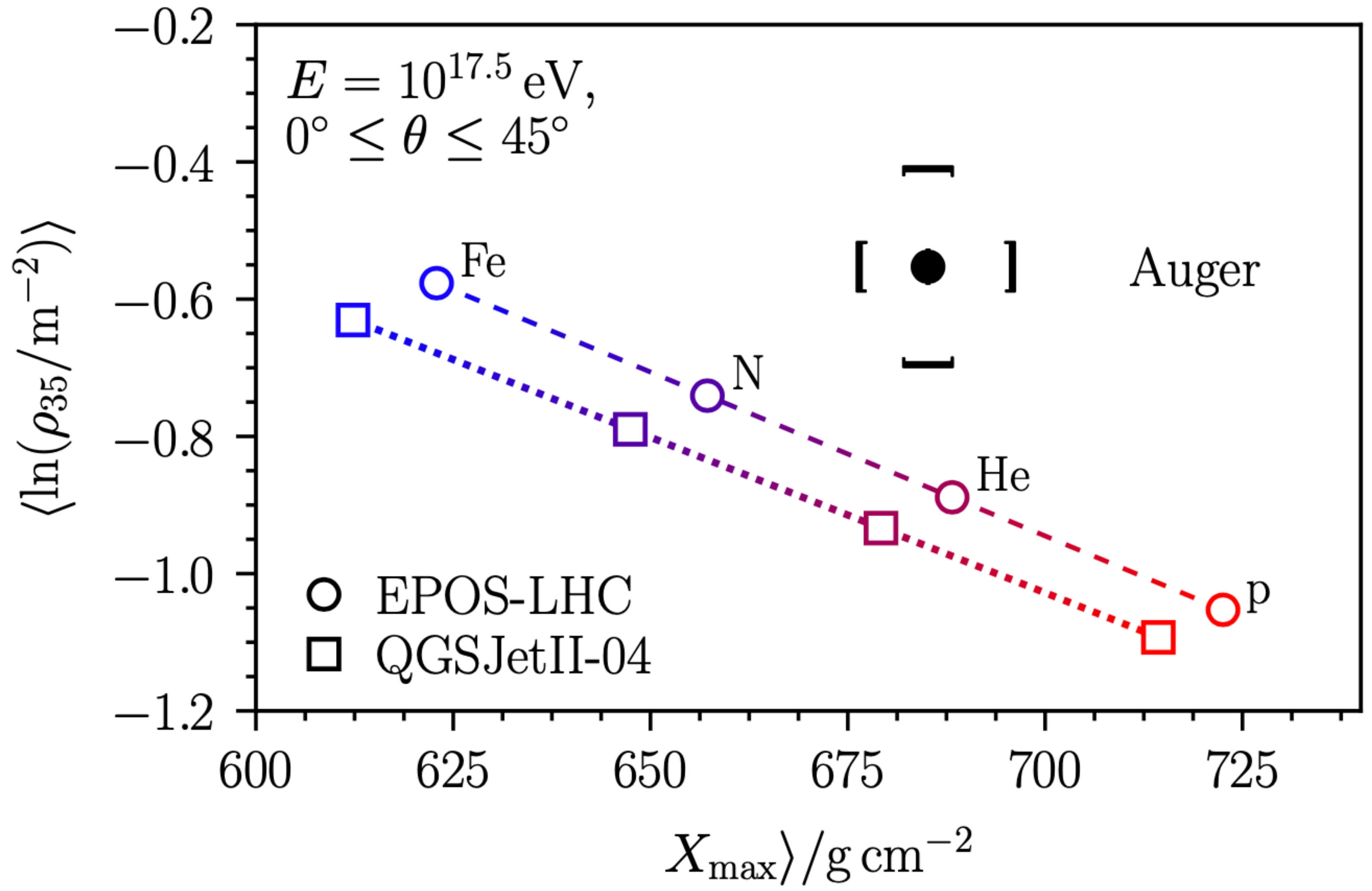




The EAS muon puzzle @ Auger

Eur.Phys.J.C 80 (2020) 8, 751

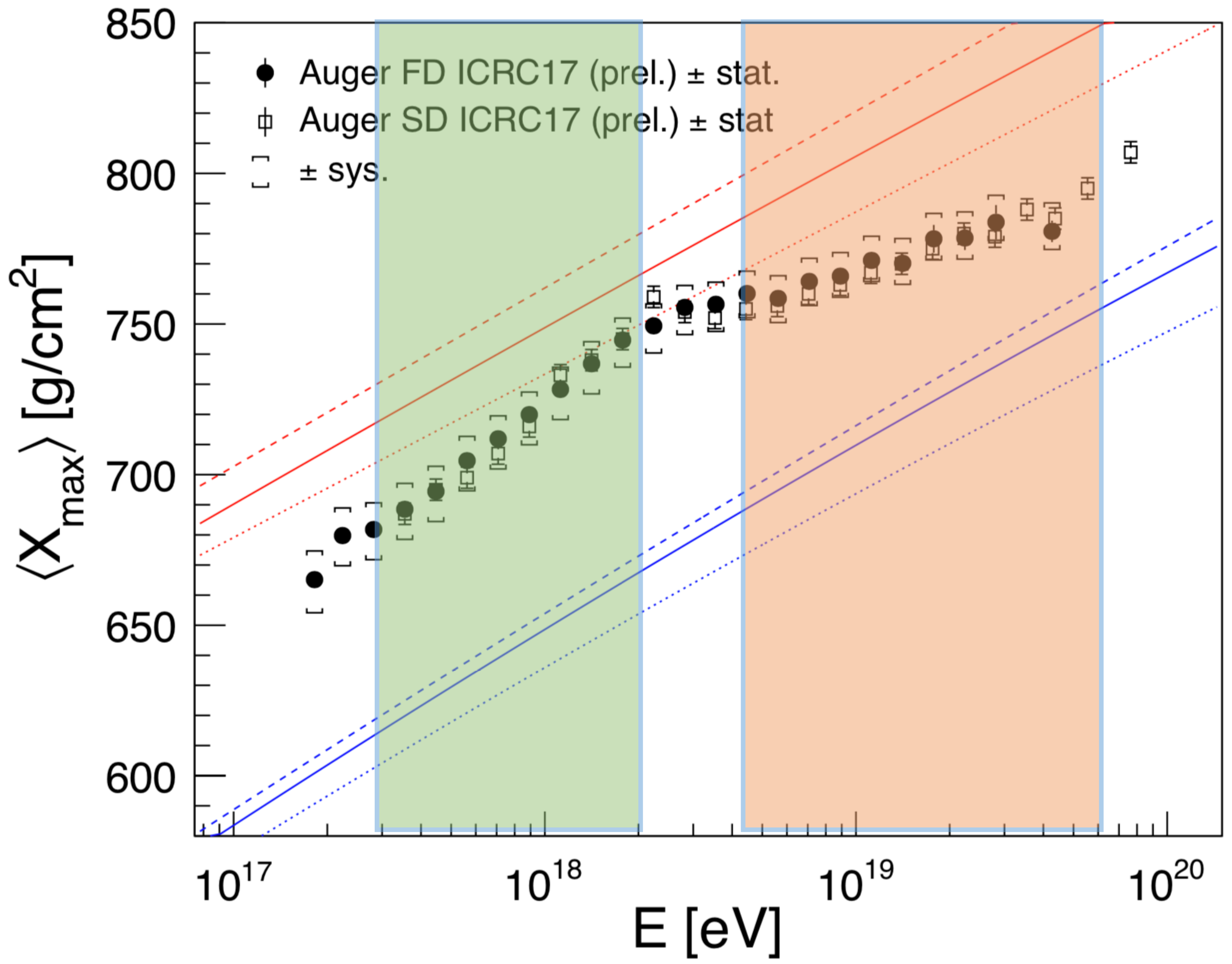
Phys.Rev.Lett. 126 (2021) 15, 152002

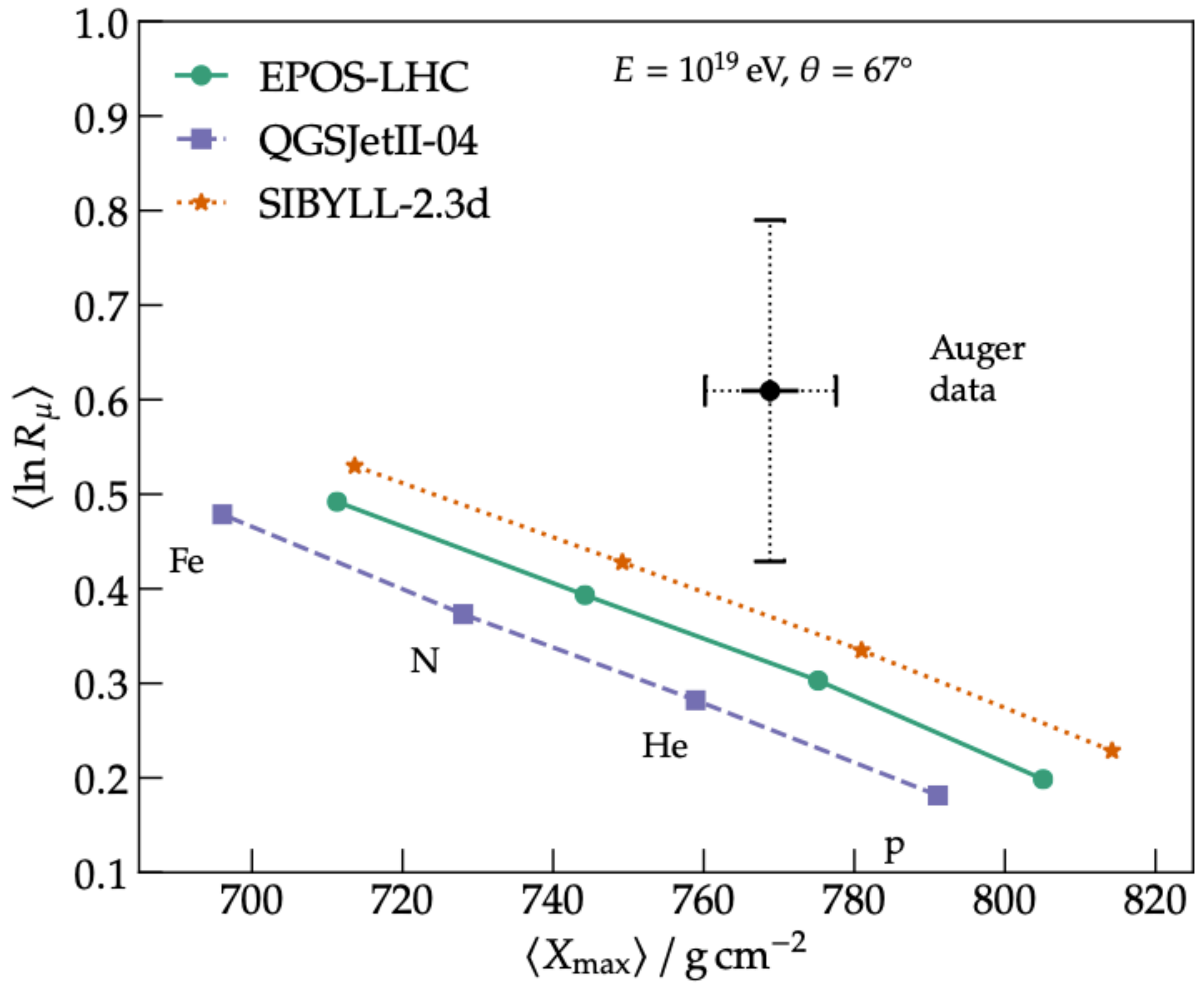


Buried Scintillators + FD

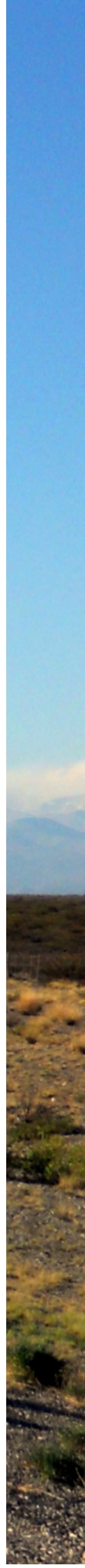
Muon excess present both at lower and higher energies if one takes into account preferred X_{max} composition

FD data





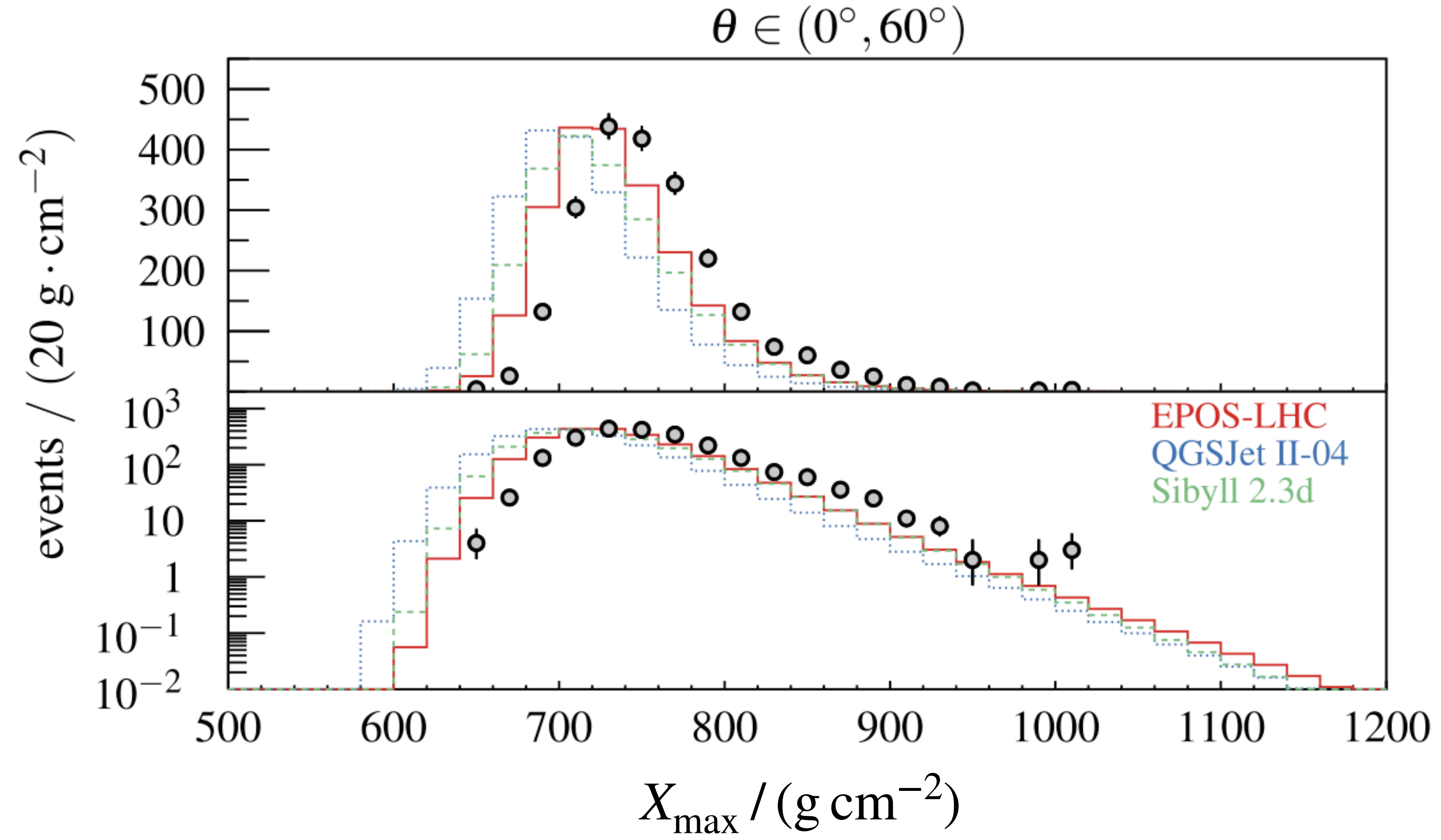
SD inclined + FD



Ruben Conceição

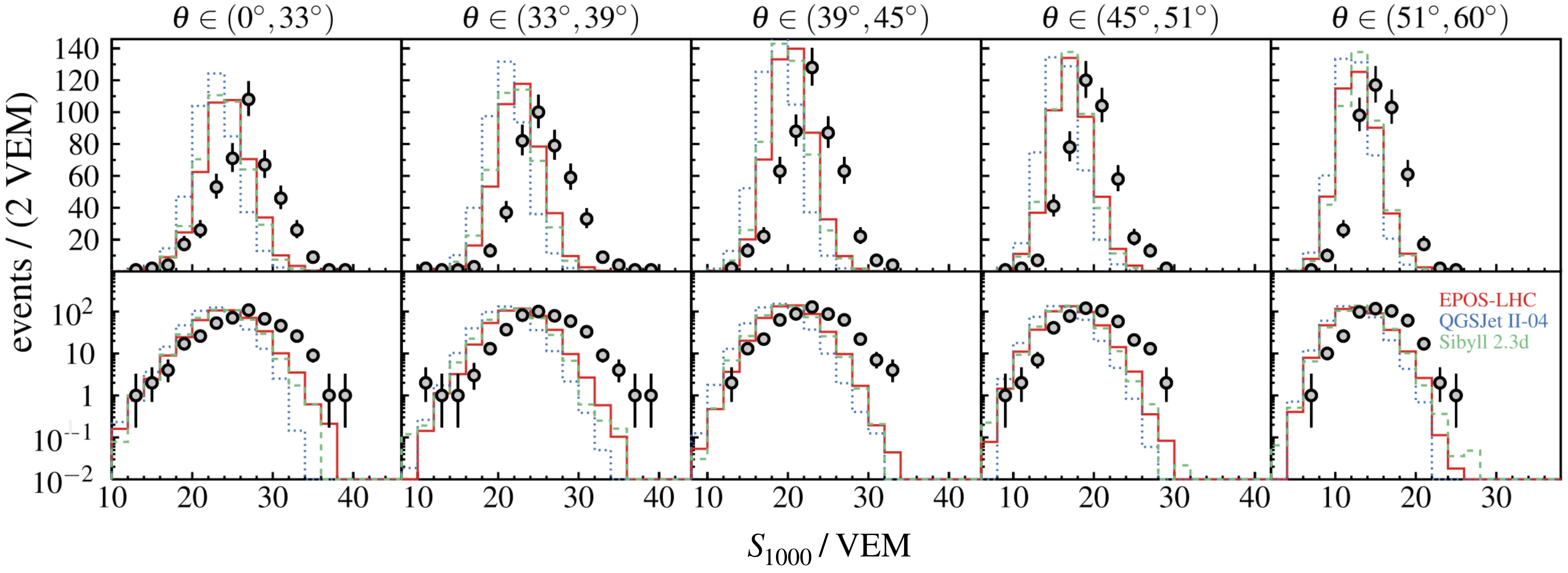
Muon puzzle

Phys.Rev.D 109 (2024) 10, 102001



Allow for a change in the rescaling of the **signal on the ground** produced by the **hadronic** shower component at 1000 m with a factor, R_{had}

$R_{had} > 1$ **for all tested hadronic interaction models - EAS muon puzzle**



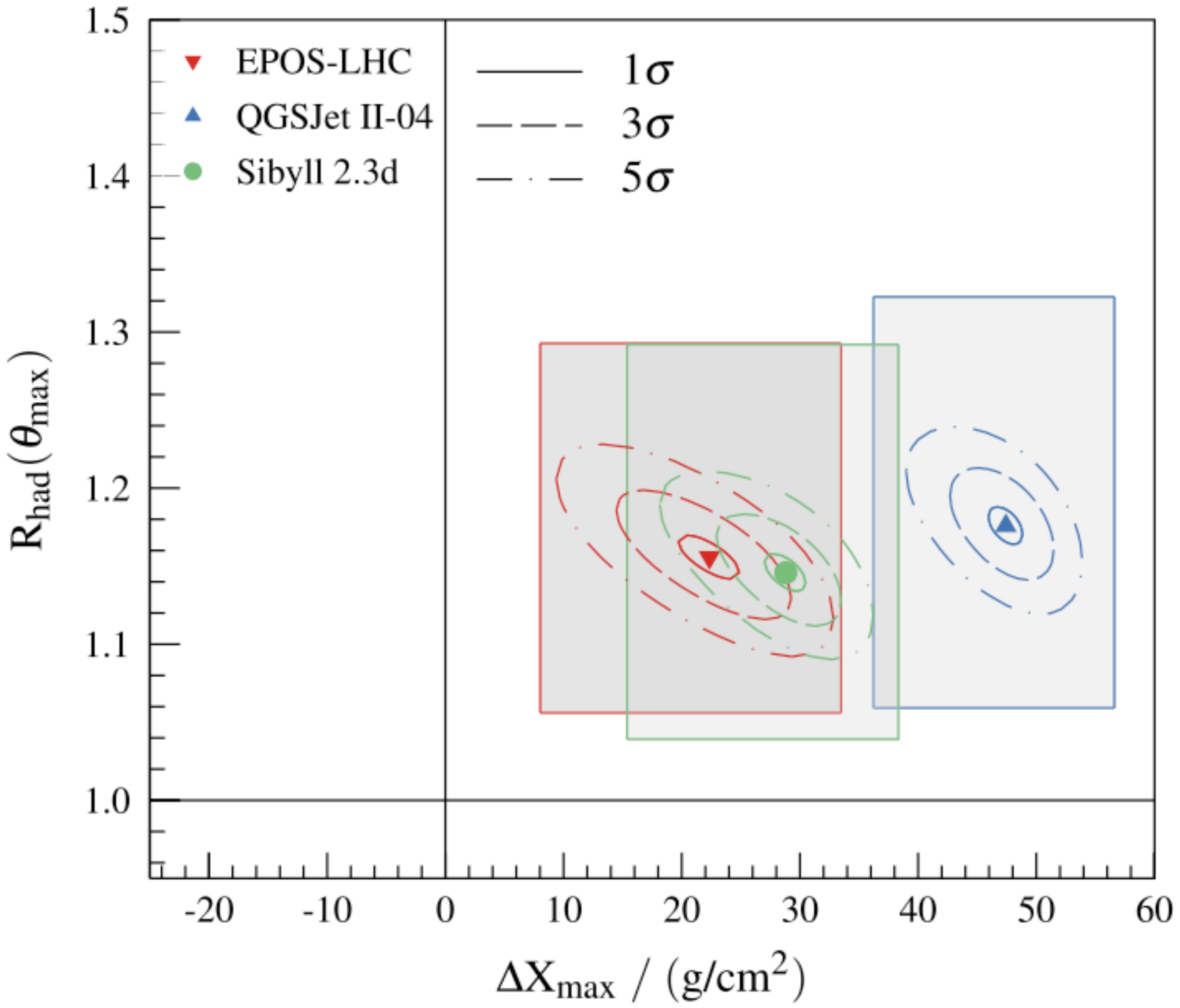
In accordance with previous Auger results
Phys.Rev.Lett. 117 (2016) 19, 192001

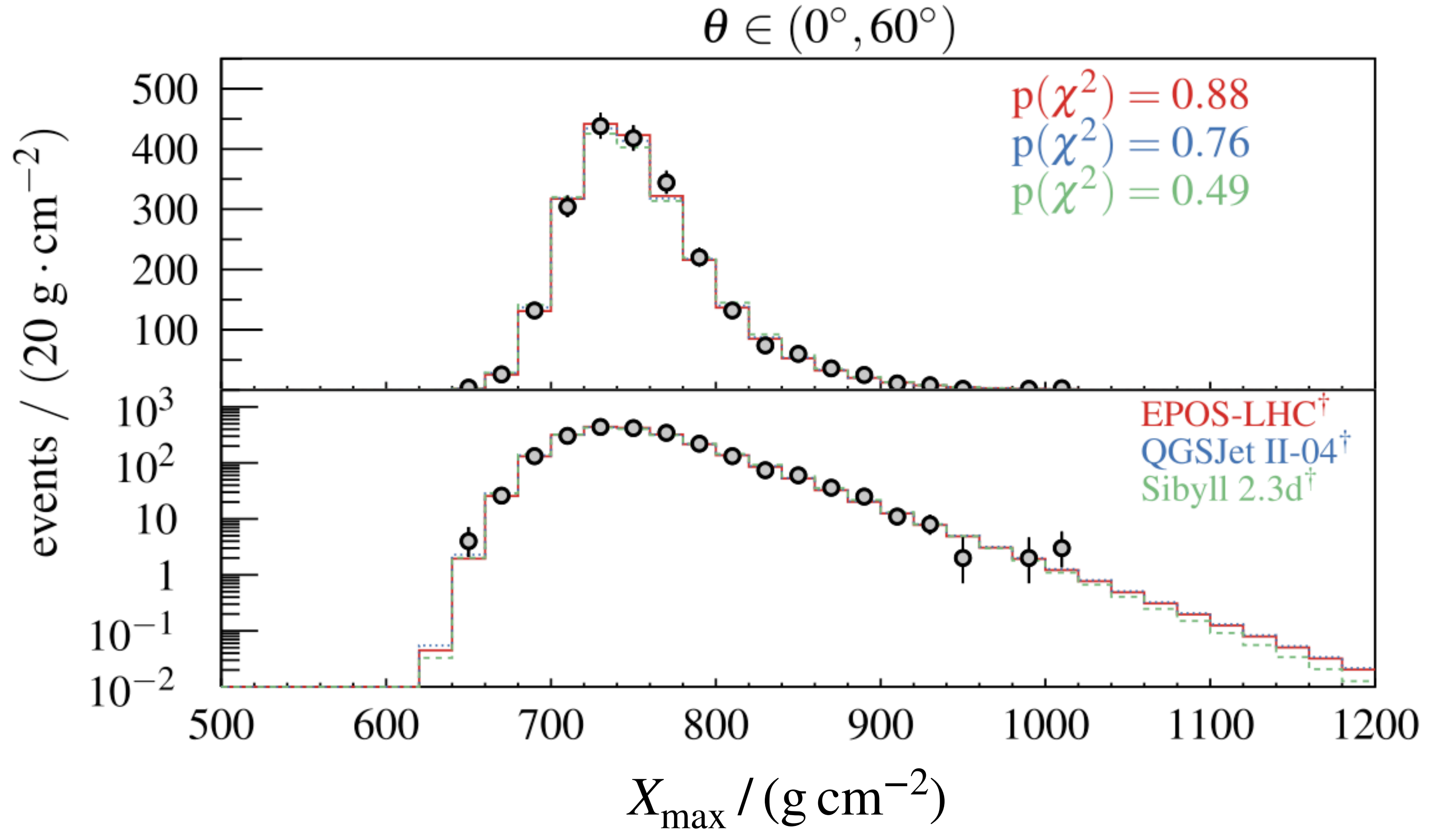
Poor agreement between data and simulations

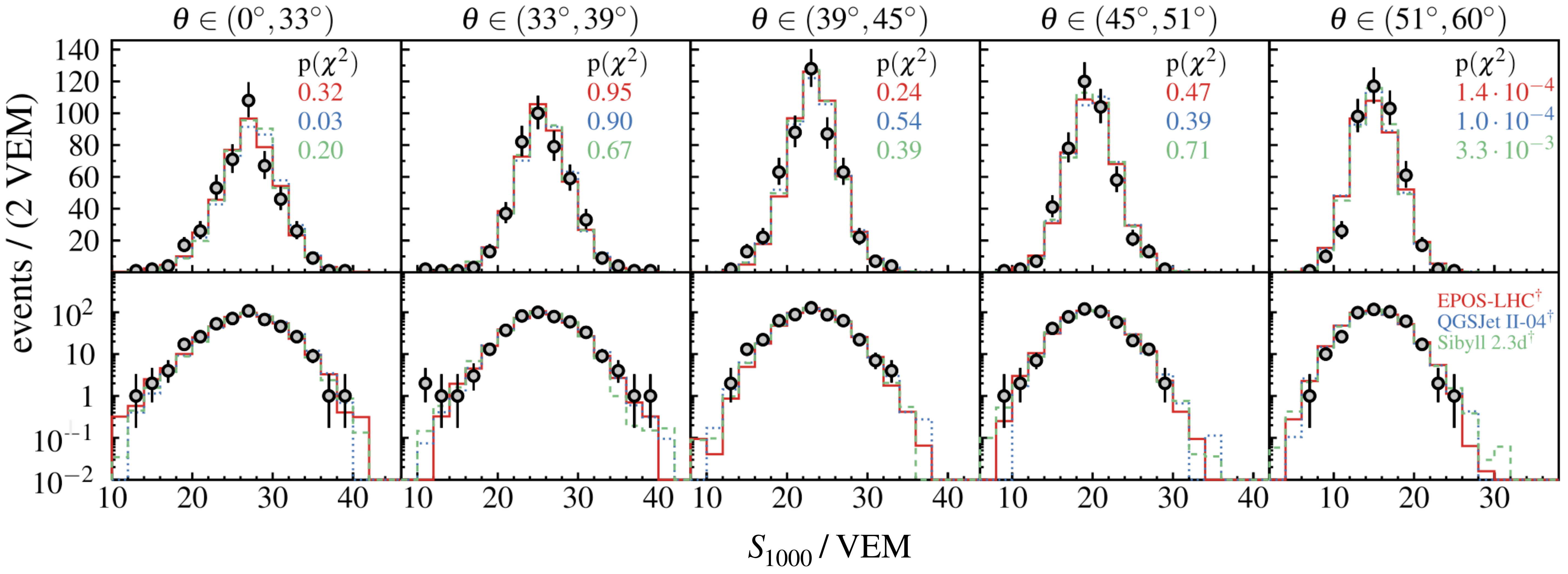
Muon puzzle + Shift in X_{max} scale

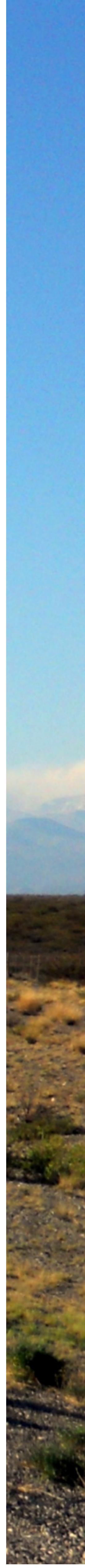
Phys.Rev.D 109 (2024) 10, 102001

Allow simultaneously for an ad-hoc **shift on the** X_{max} scale and a change in the rescaling of the **signal on the ground** produced by the **hadronic** shower component at 1000 m with a factor, R_{had}



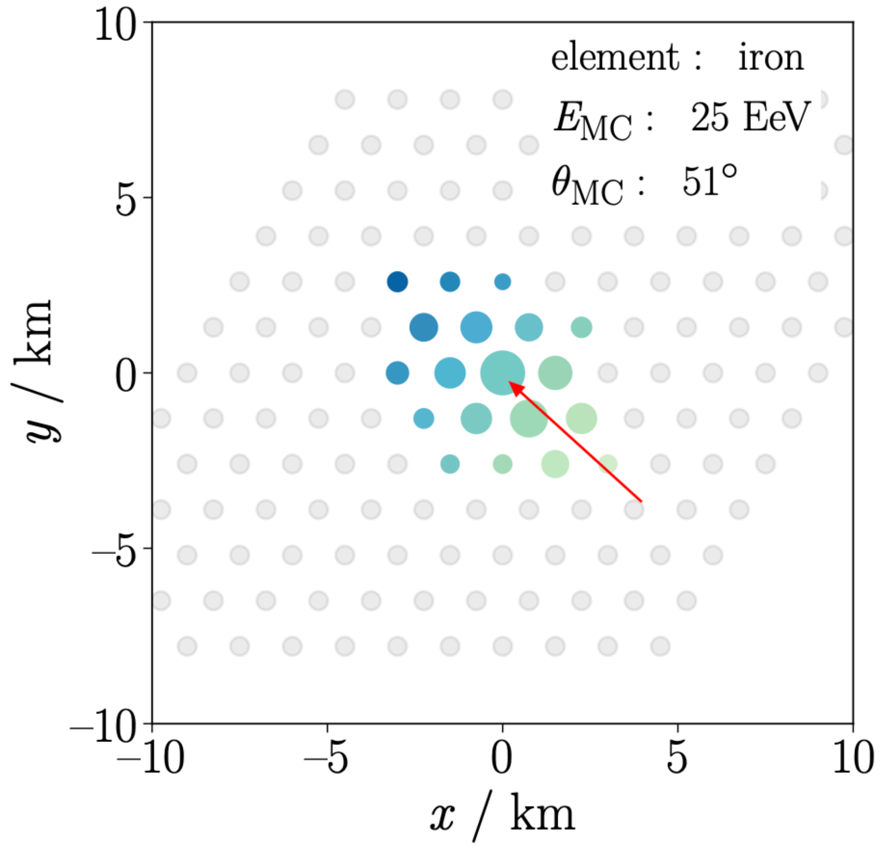


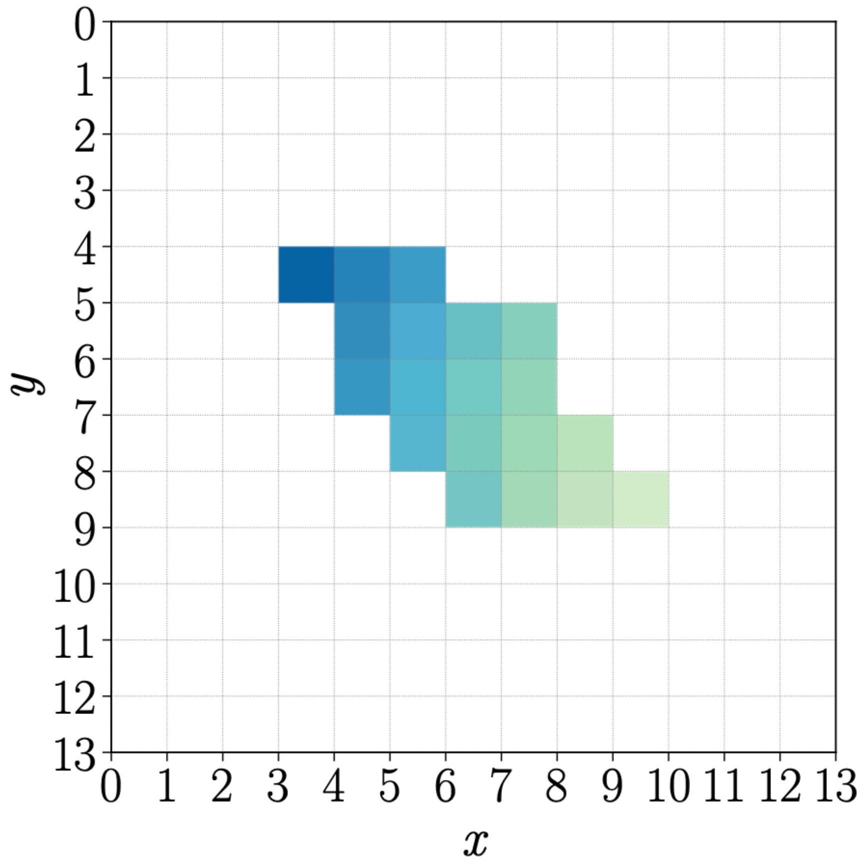


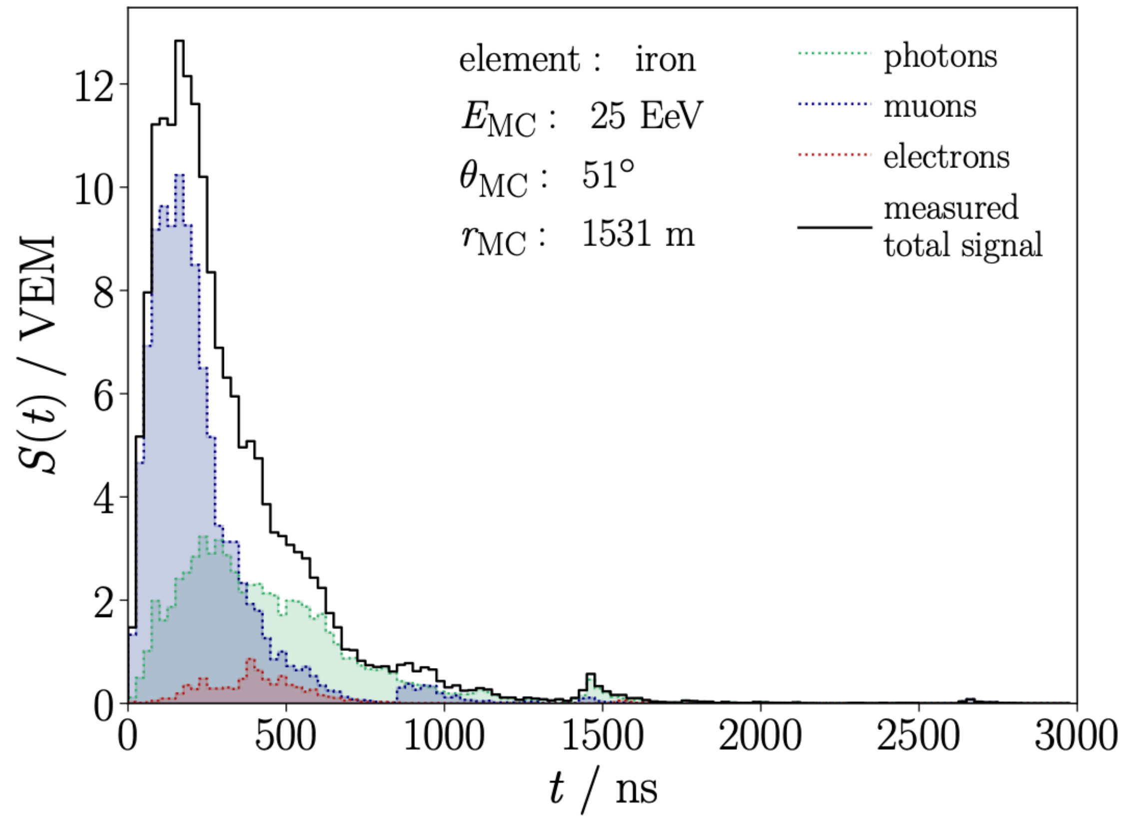


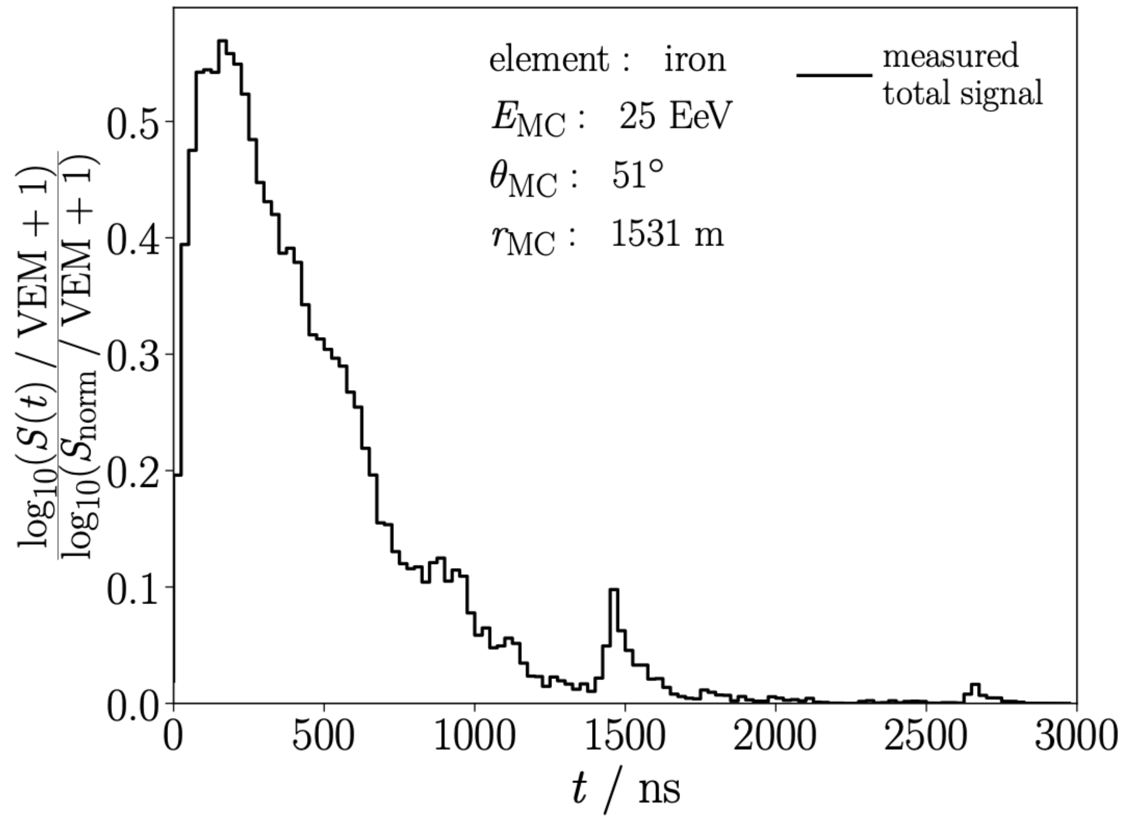
X_{max} from SD trace using a DNN

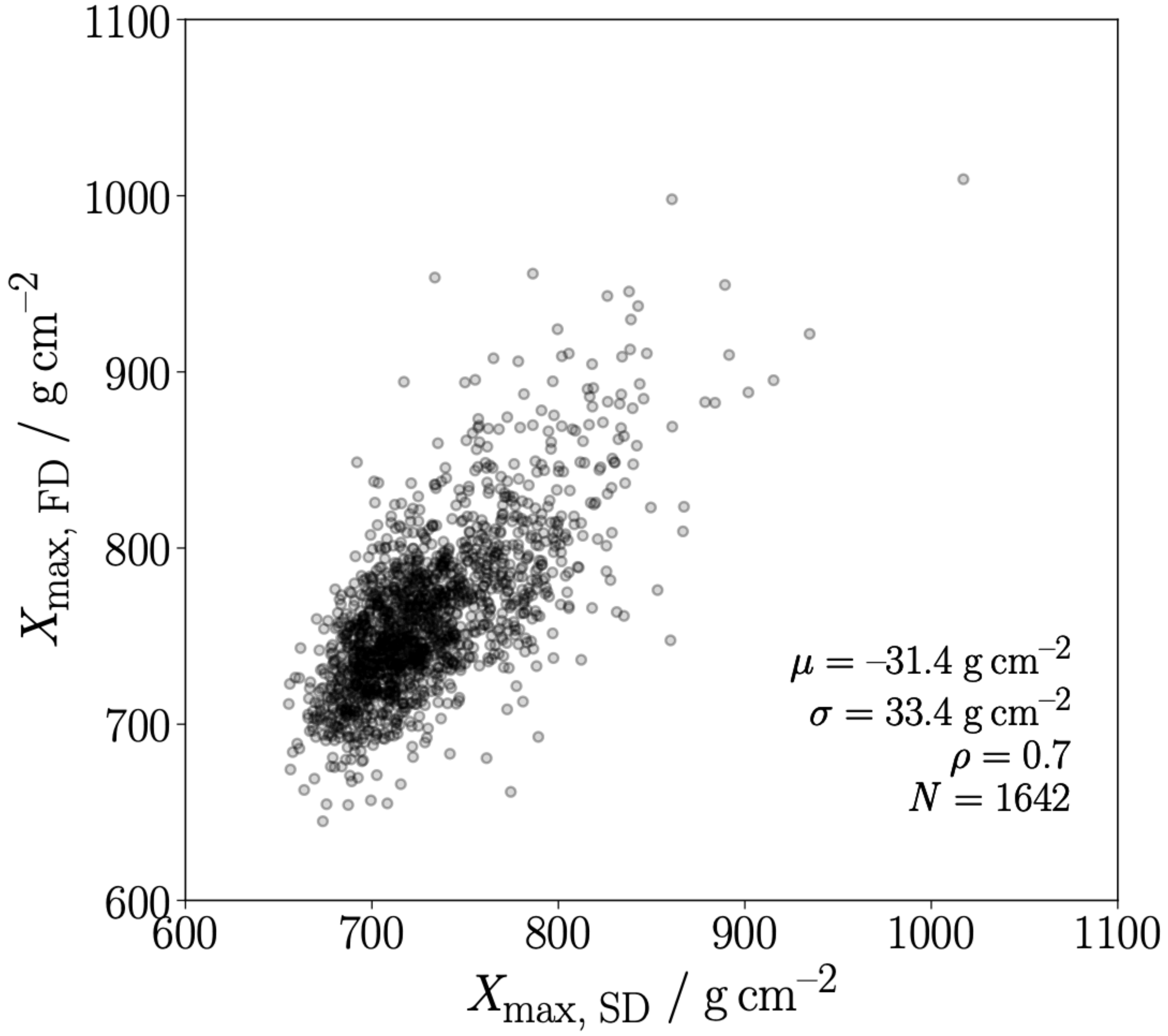
Accepted in PRL + PRD (2024)







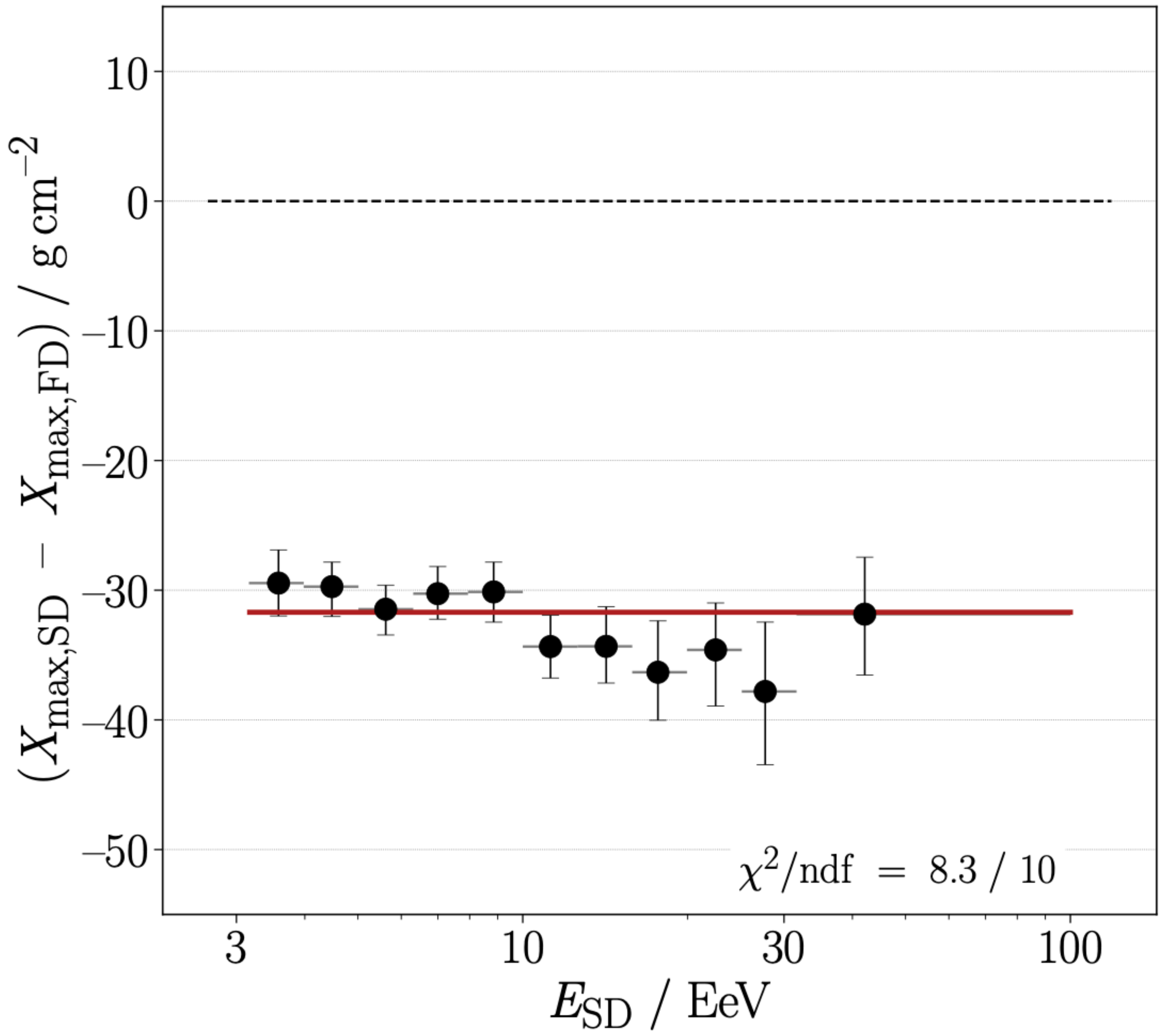


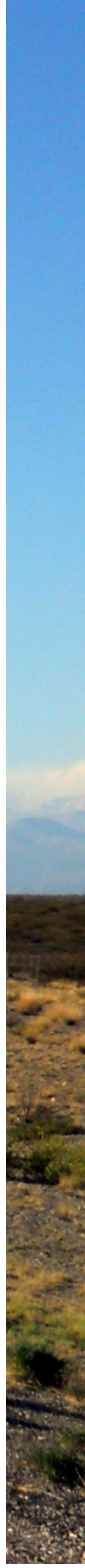


Extract the X_{max} from SD-only events

Exploit the SD traces using a Deep Neural Network

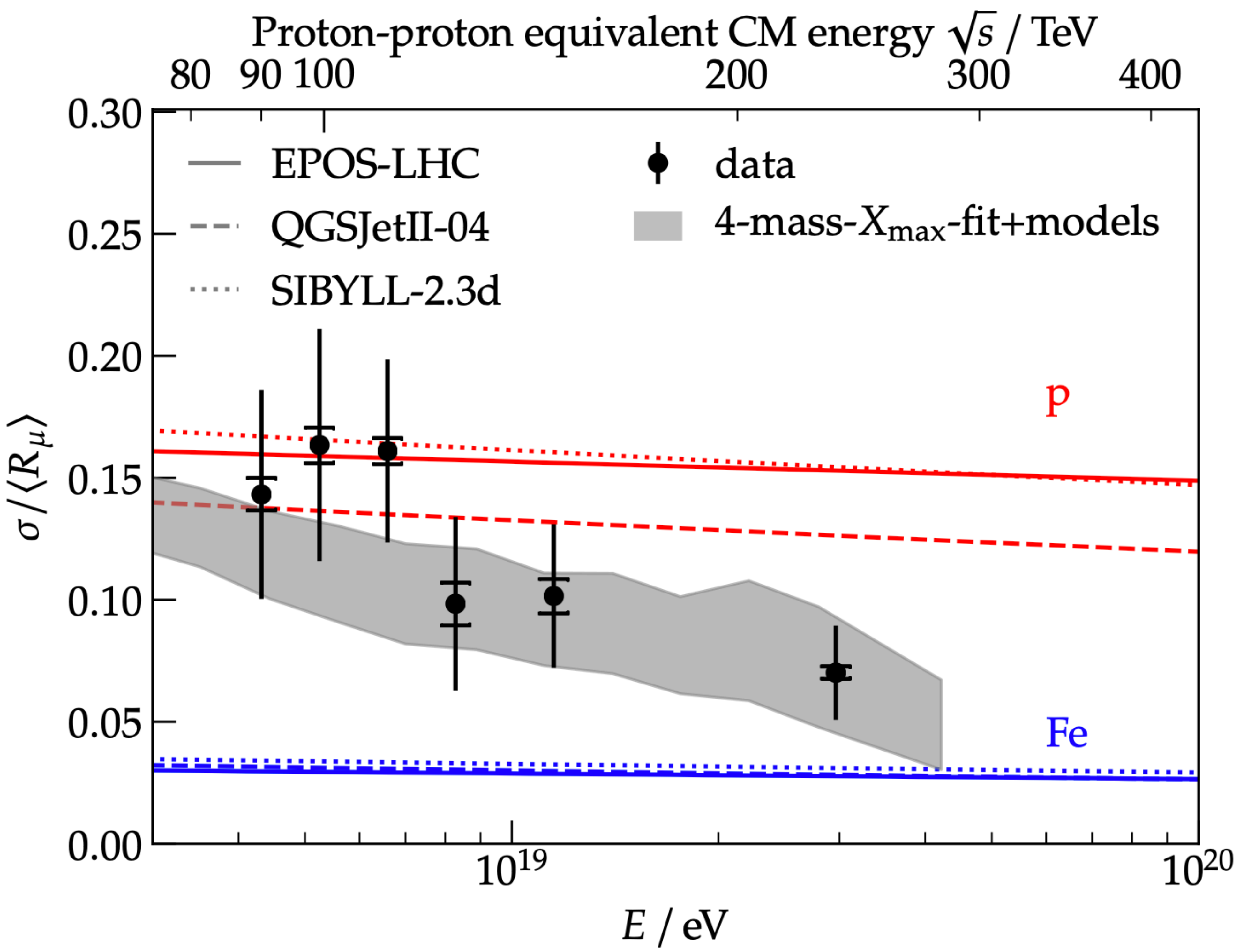
Test DNN performance using FD-SD **hybrid events**





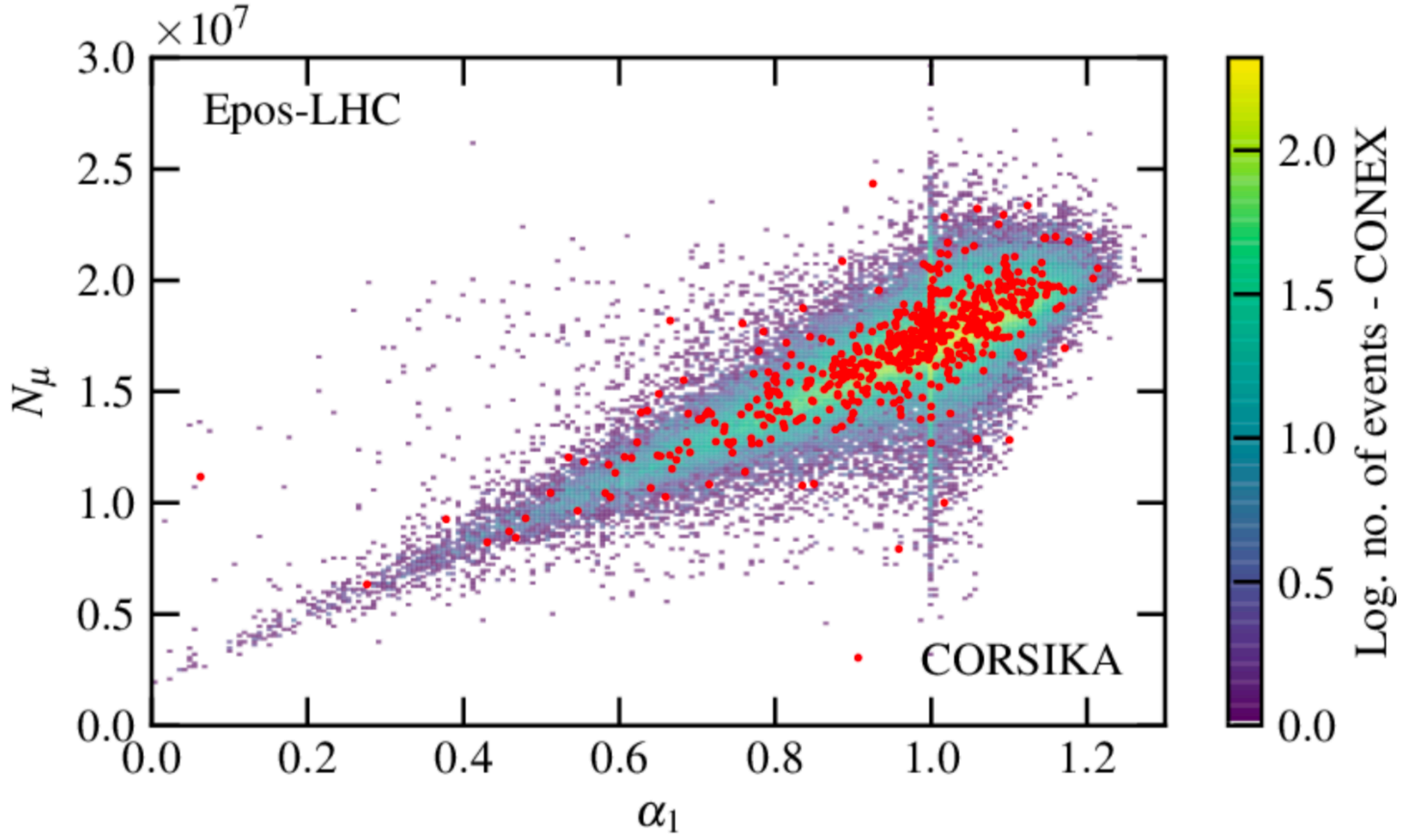
EAS muon fluctuations

Phys.Rev.Lett. 126 (2021) 15, 152002



The muon relative fluctuations are in agreement with the mass composition expectations derived from the analysis of X_{max} data

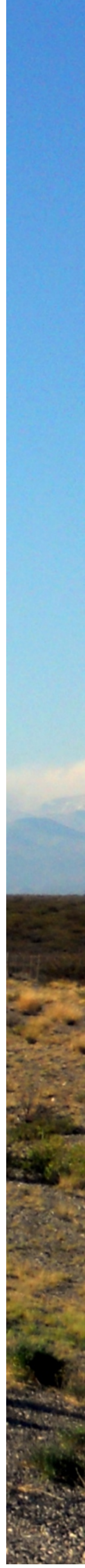
L. Cazon, RC, F. Riehn, PLB 784 (2018) 68-76



α_1 is the fraction of energy going into the hadronic sector in the first interaction

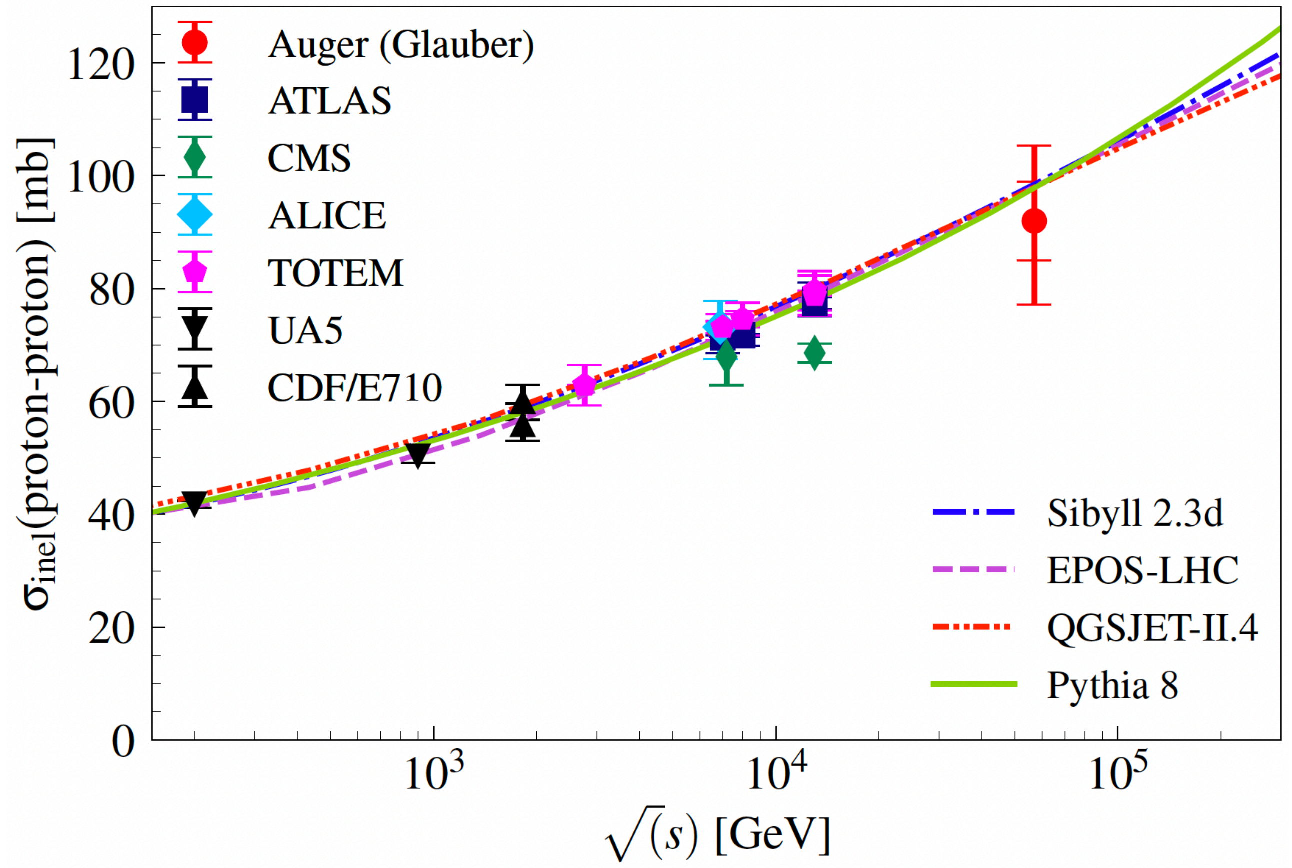
$$\sigma(\alpha_1) \rightarrow 70\,\%\,\sigma(N_\mu)$$

Suggestion that muon deficit might be related with description of low energy interactions

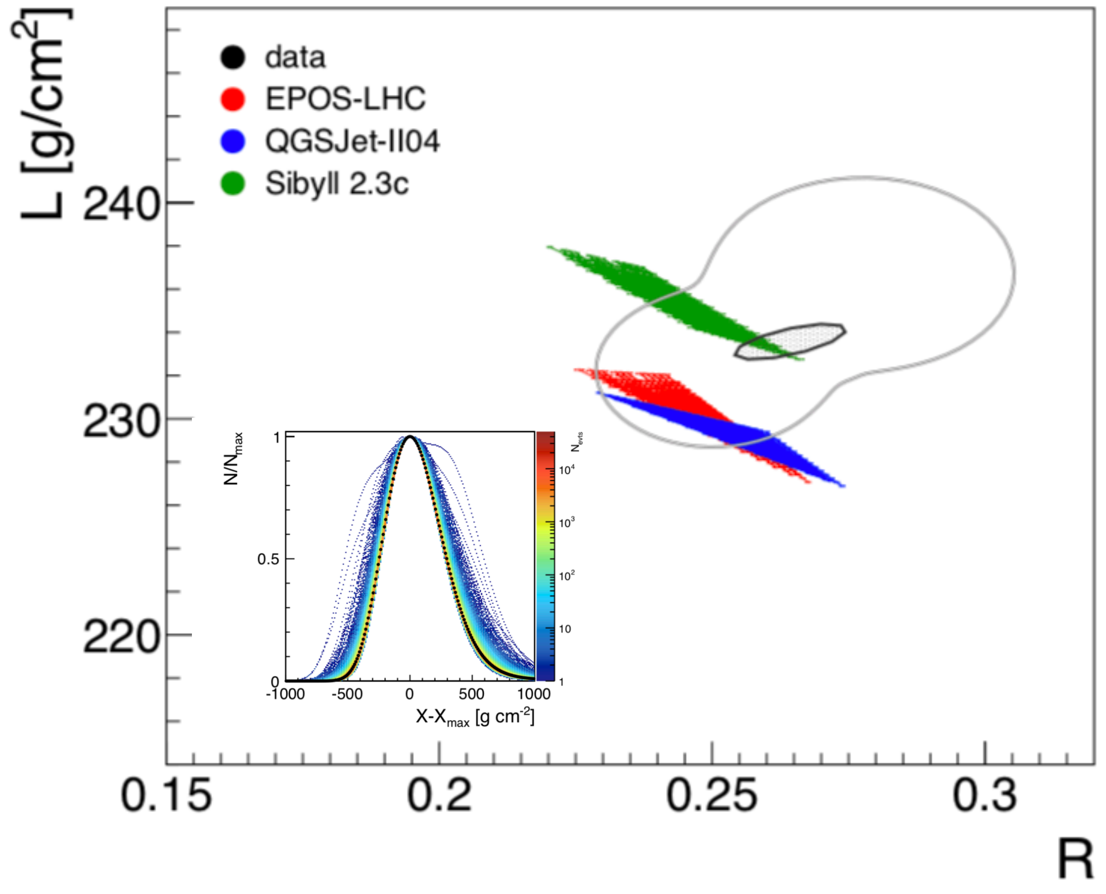


Many other EAS measurements…

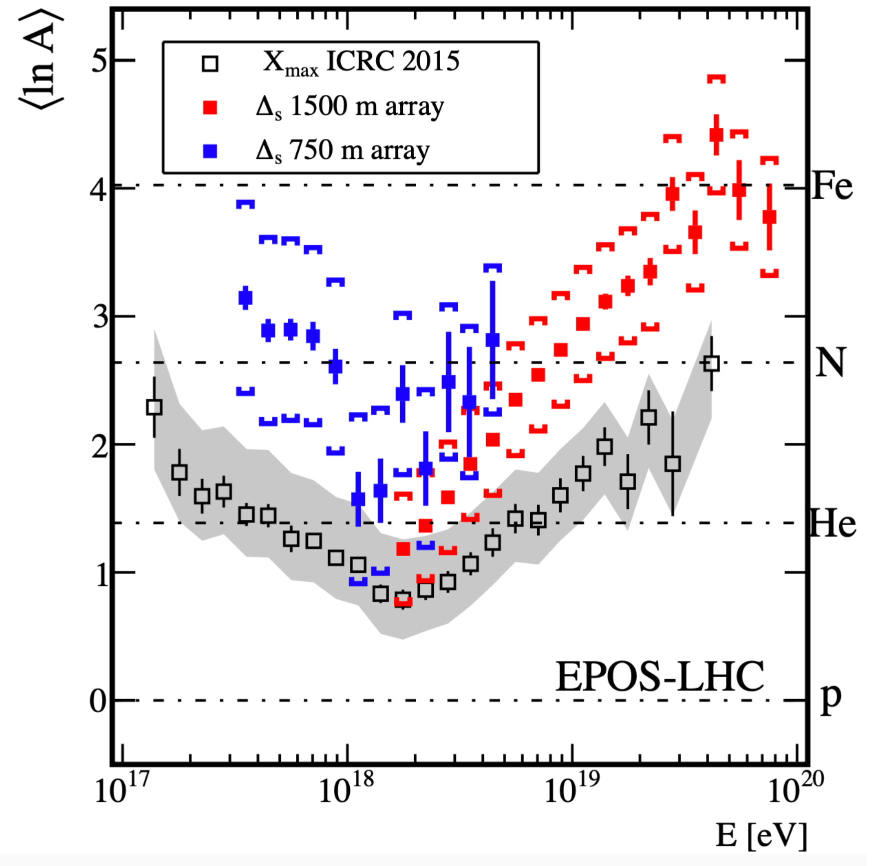
Phys.Rev.Lett. 109 (2012) 062002	*JCAP 1903 (2019) no.03, 018*	*Phys.Rev.D 96 (2017) 12, 122003*	*PoS (ICRC2023) 339*



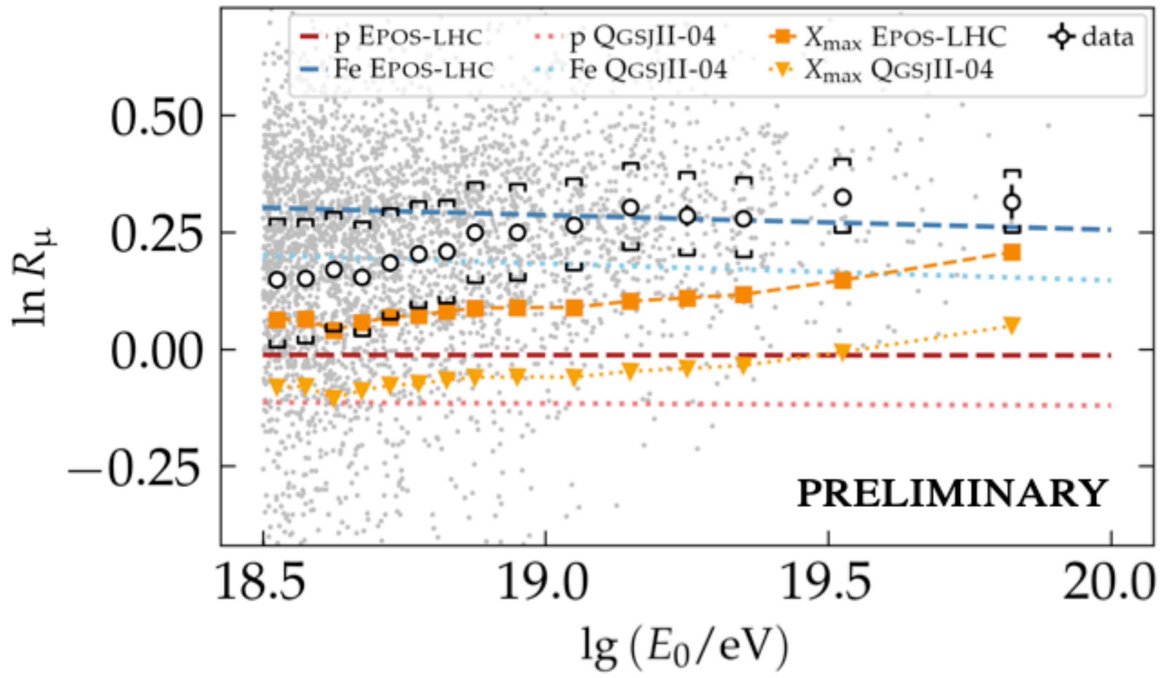
Measurement of the proton-air cross-section at E~10¹⁸ eV



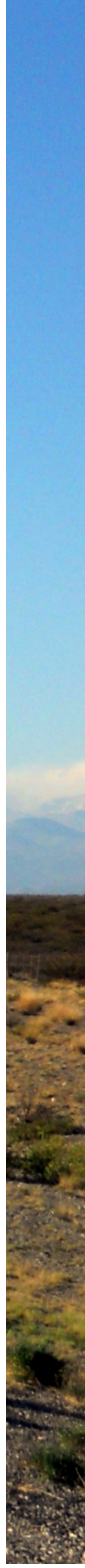
Measurement of average e.m. longitudinal profile shape



Measurement of time profiles of the signals recorded with the water-Cherenkov detectors

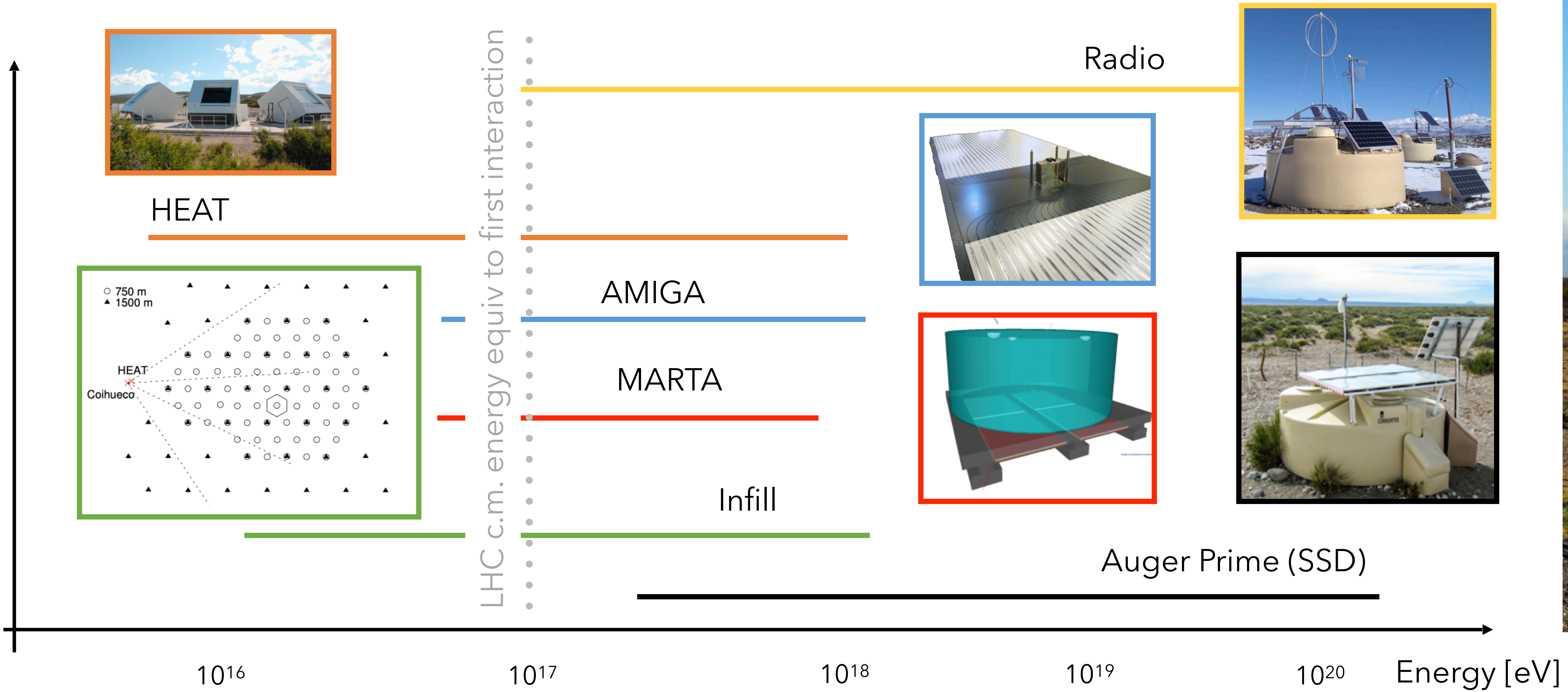


The number of muons measured in hybrid events

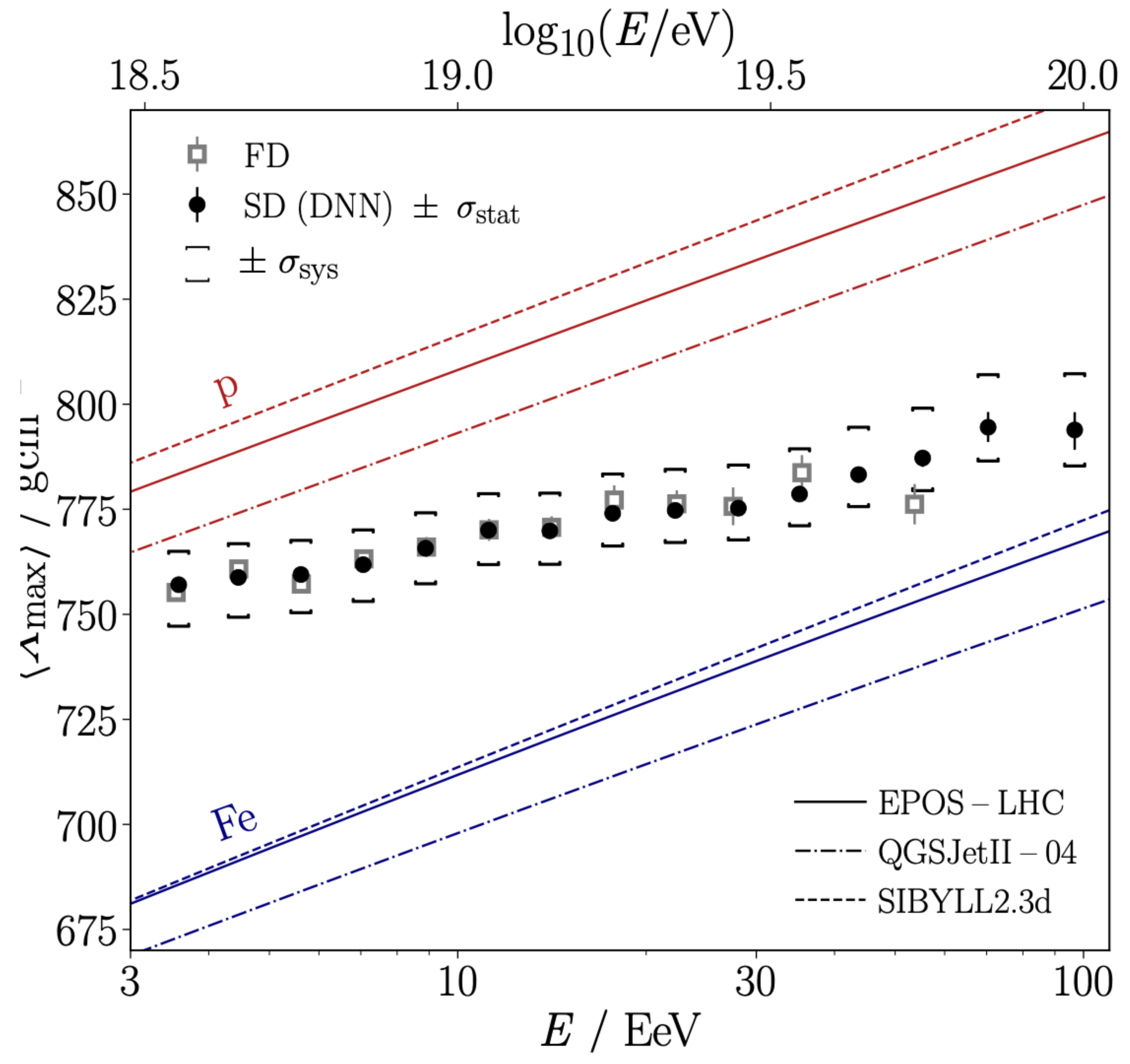


Multi-hybrid shower events

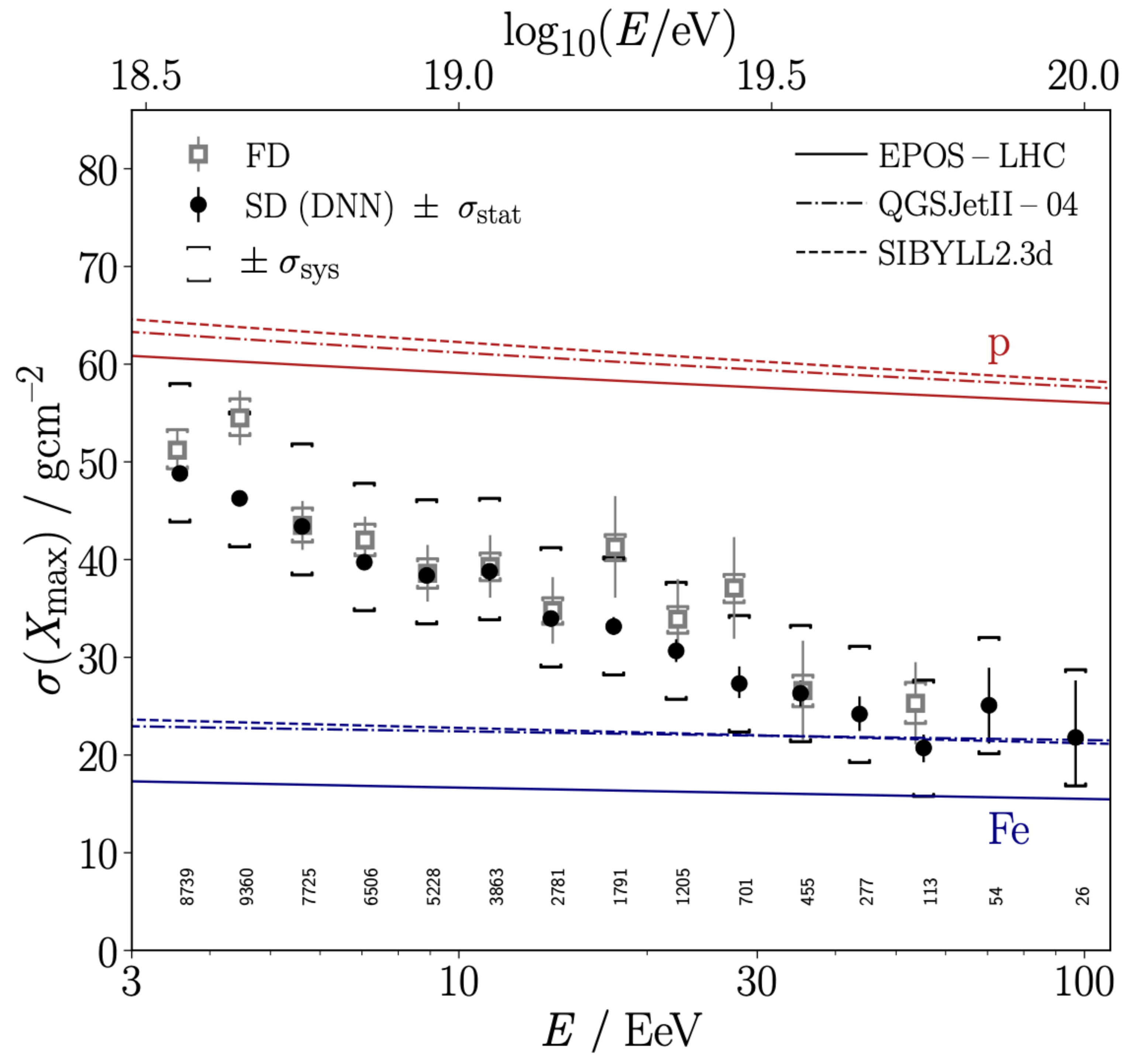
(A plethora of measurements to fully understand the shower)



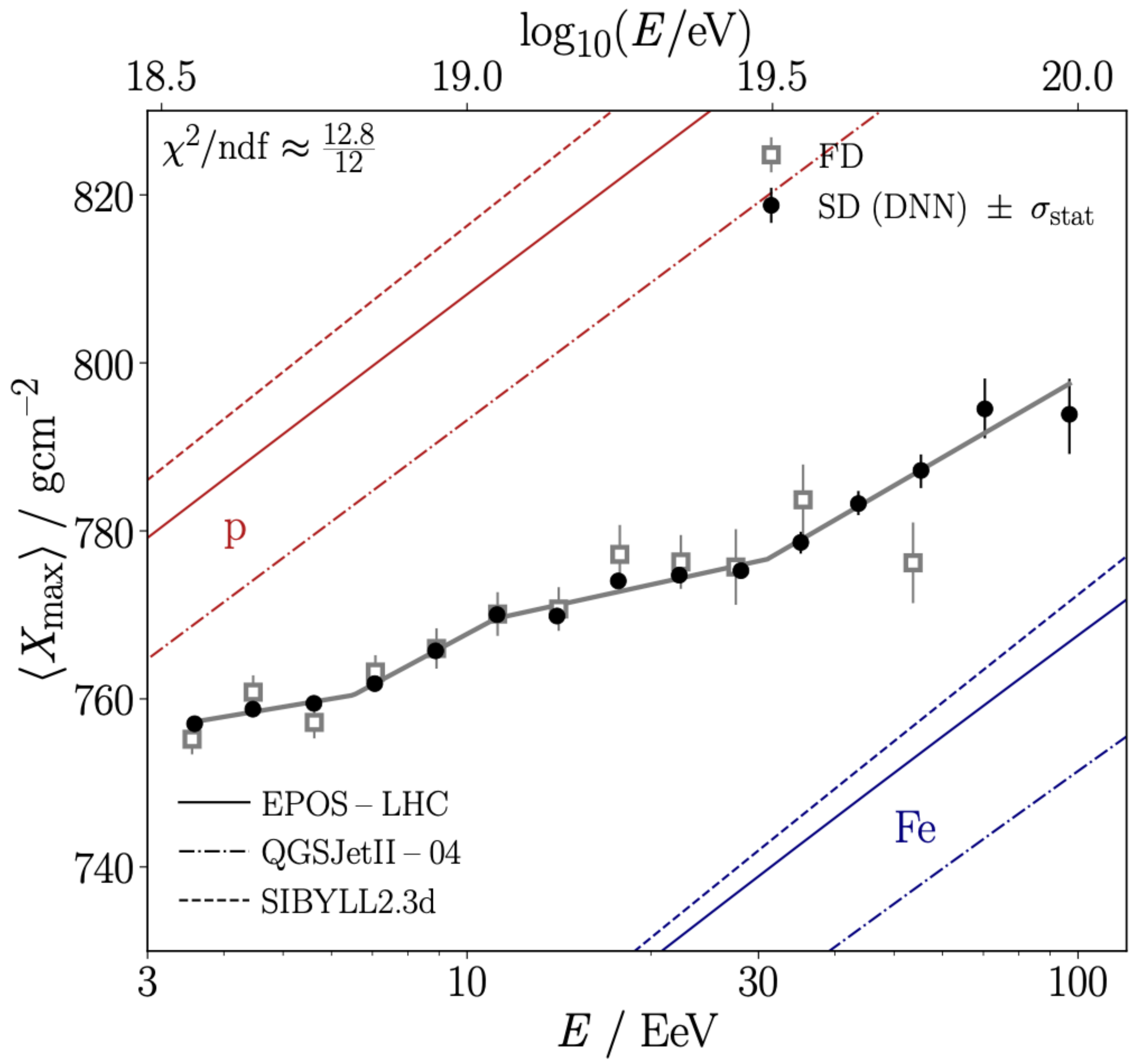
DNN



$\log_{10}(E/\mathrm{eV})$
FD
SD (DNN) $\pm\ \sigma_{\mathrm{stat}}$
$\pm\ \sigma_{\mathrm{sys}}$
p
Fe
EPOS – LHC
QGSJetII – 04
SIBYLL2.3d
E / EeV



$\log_{10}(E/\mathrm{eV})$
FD
SD (DNN) $\pm\ \sigma_{\mathrm{stat}}$
$\pm\ \sigma_{\mathrm{sys}}$
EPOS – LHC
QGSJetII – 04
SIBYLL2.3d
p
Fe
$\sigma(X_{\mathrm{max}})$ / gcm^{-2}
E / EeV



$\log_{10}(E/\mathrm{eV})$
$\chi^2/\mathrm{ndf} \approx \frac{12.8}{12}$
FD
SD (DNN) $\pm\ \sigma_{\mathrm{stat}}$
p
Fe
EPOS – LHC
QGSJetII – 04
SIBYLL2.3d
$\langle X_{\mathrm{max}}\rangle$ / gcm^{-2}
E / EeV