The road to understanding hadronic interactions at the highest energies

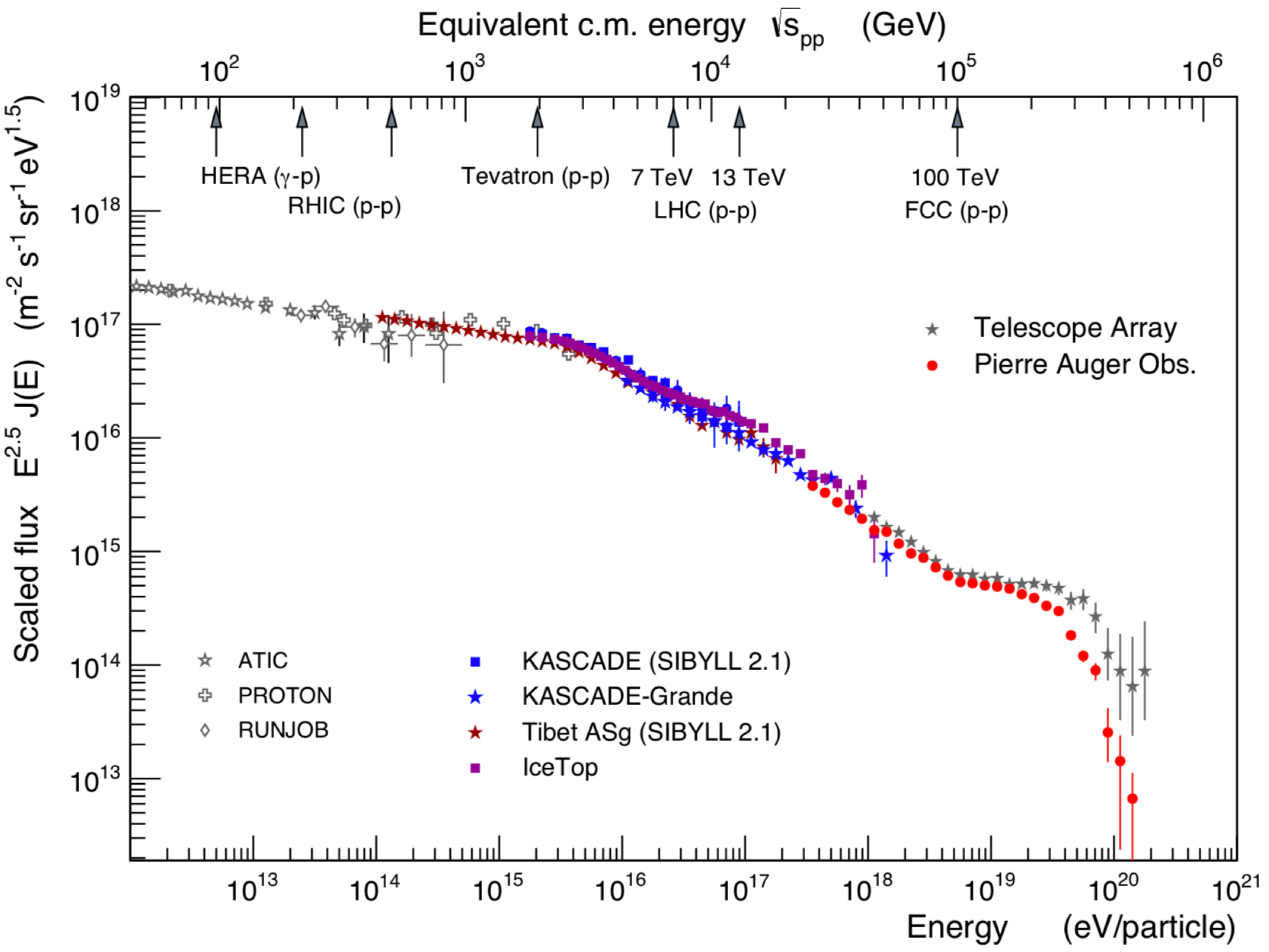
Ruben Conceição

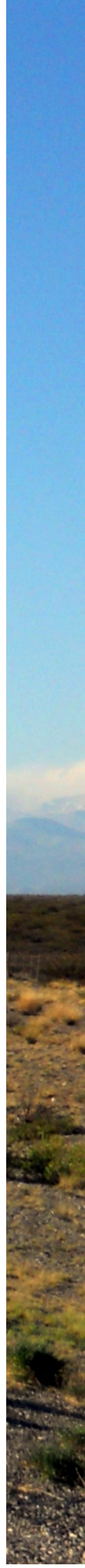
LIP

TÉCNICO LISBOA

UHECR 2024, Malargüe, November 20th 2024

Study of cosmic rays at the highest energies

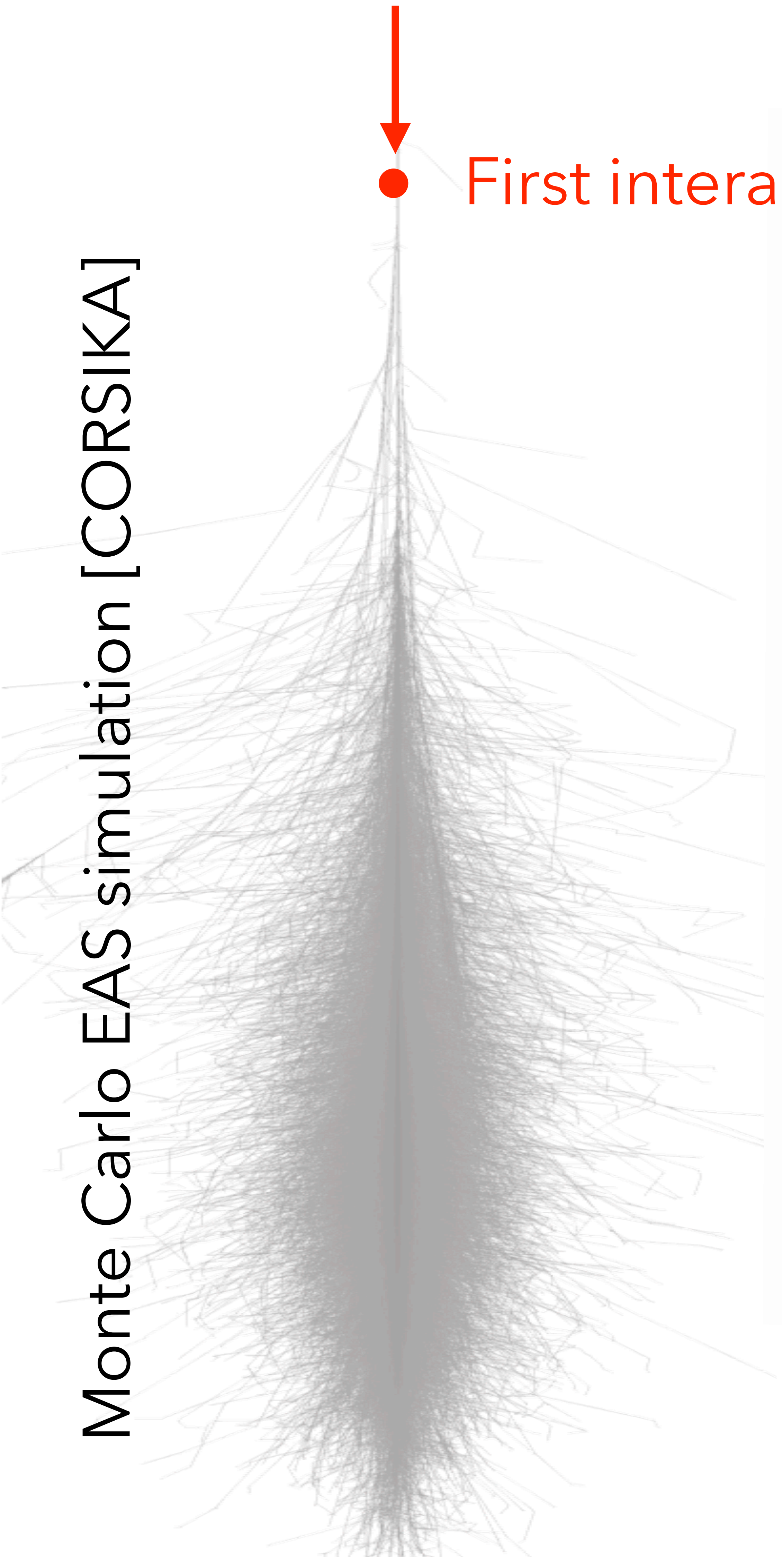


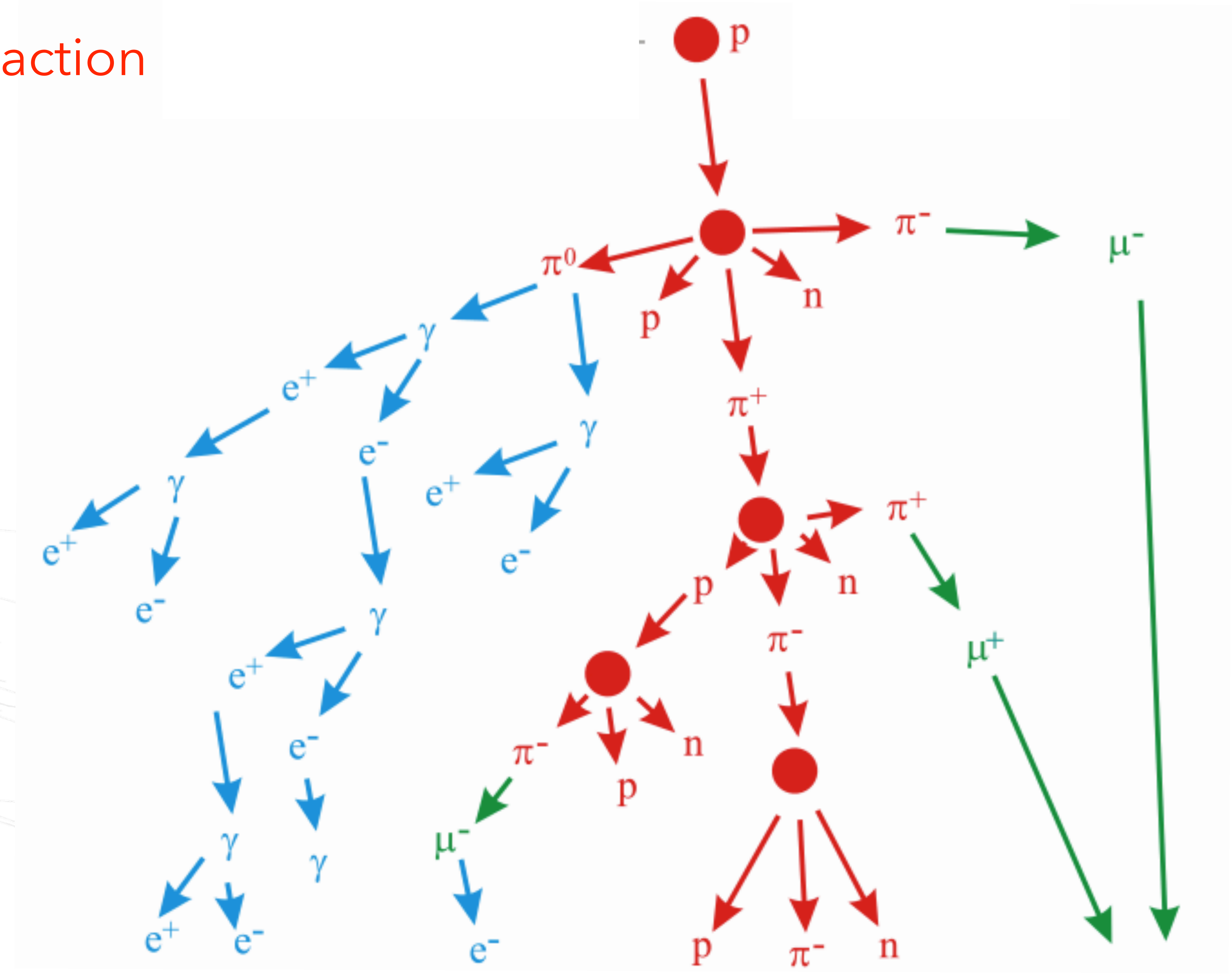


Air Shower Physics

Primary Particle

First interaction

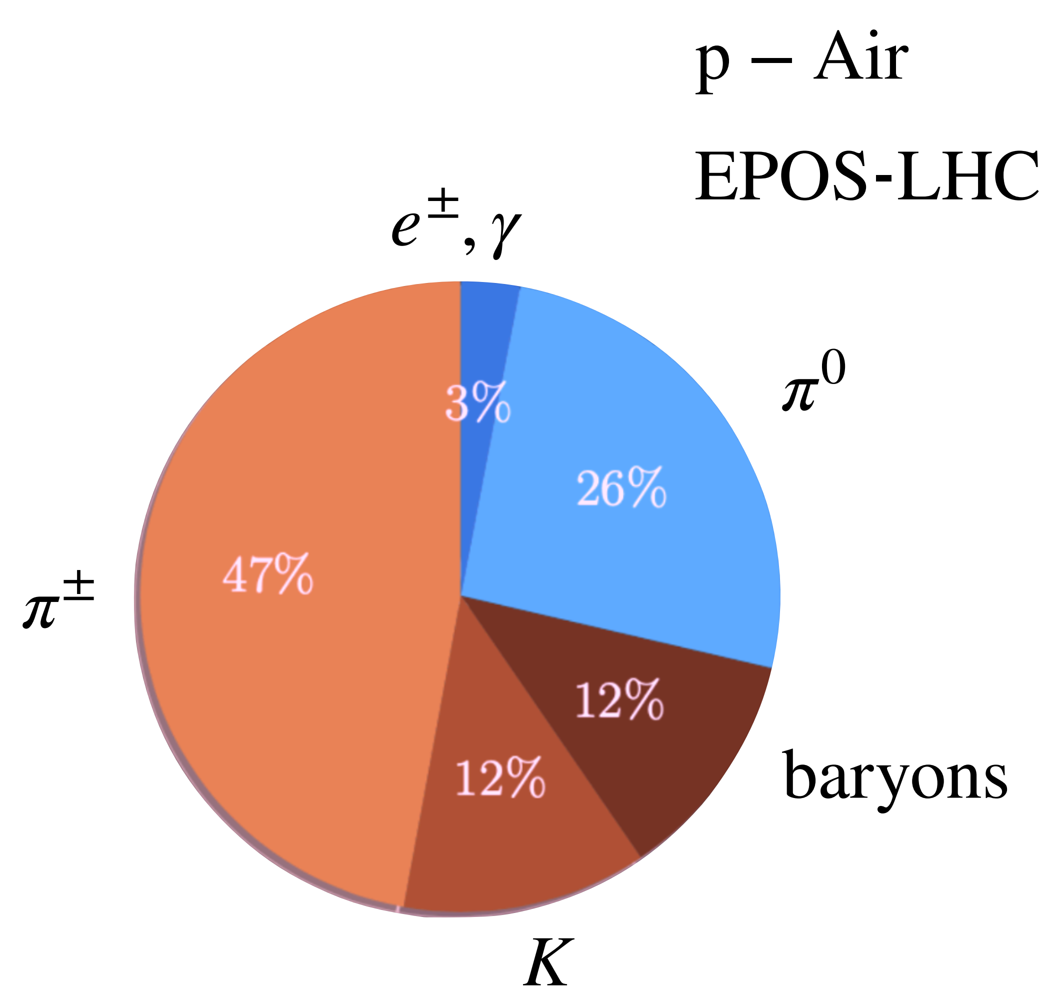


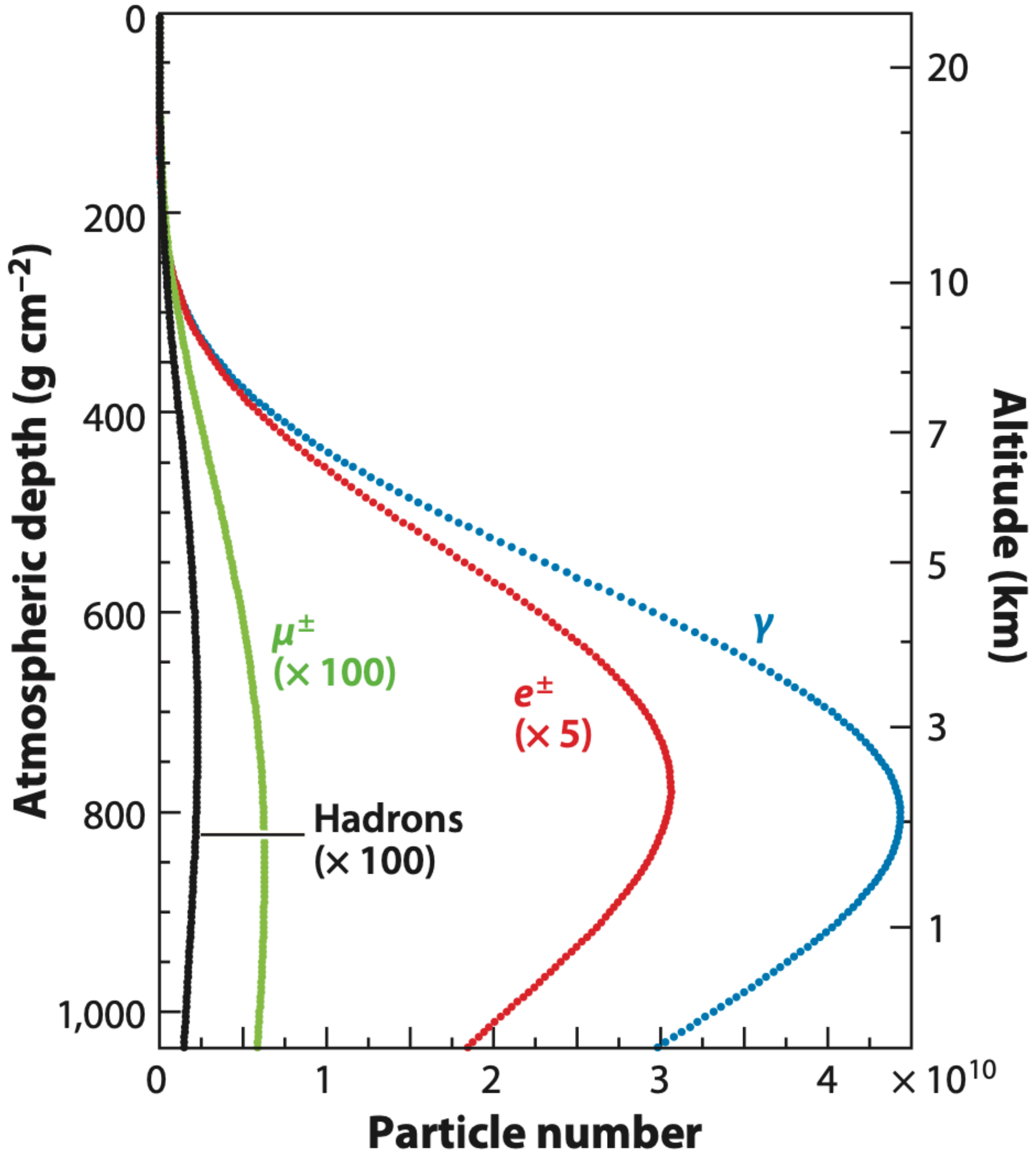


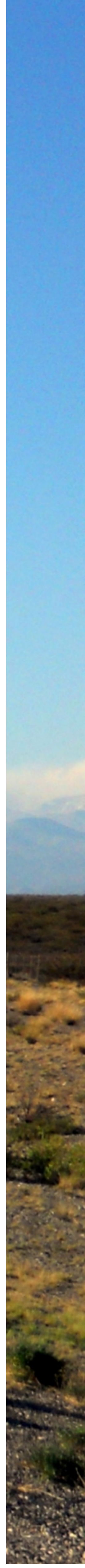
Electromagnetic component

Hadronic component

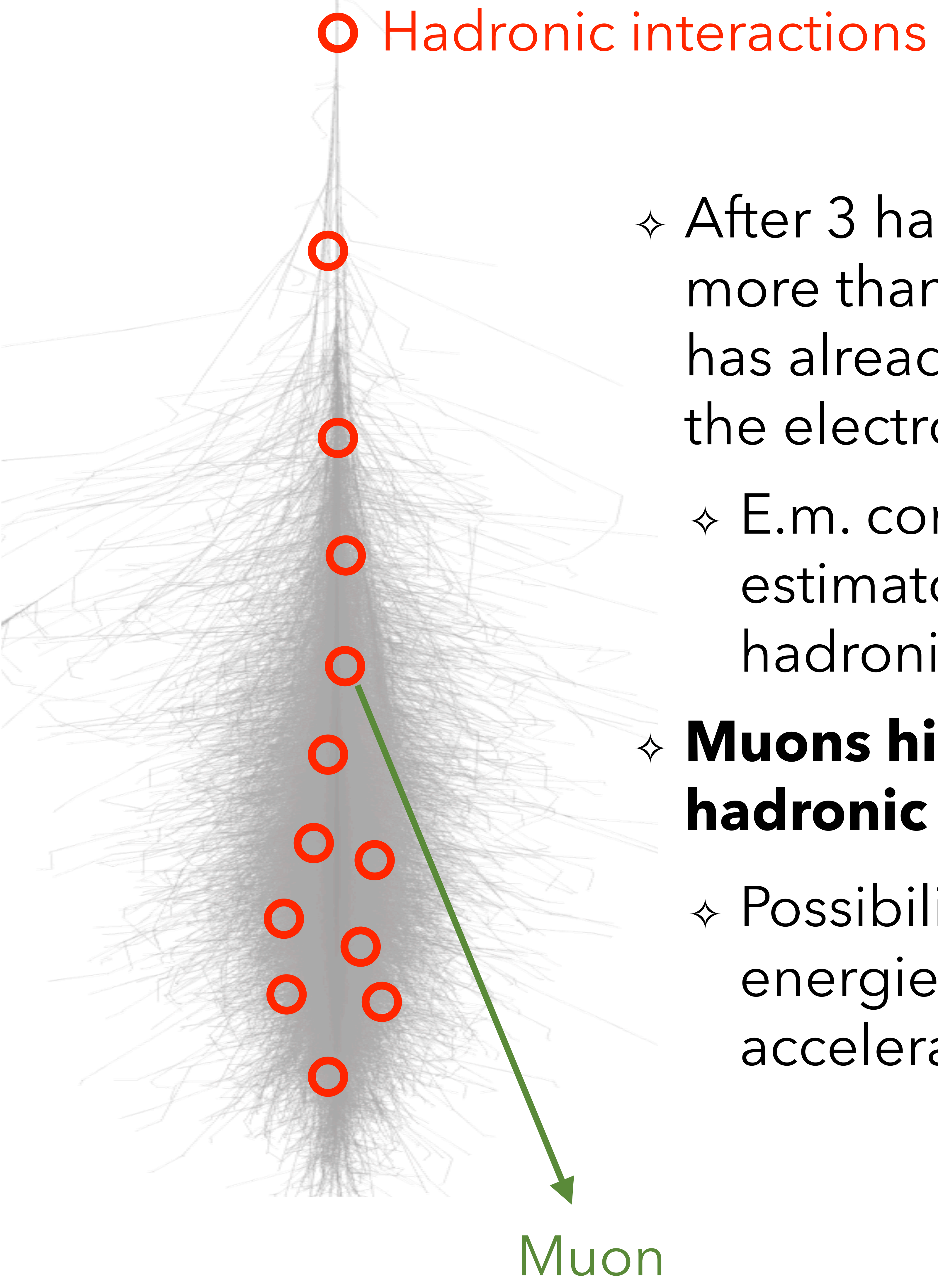
Muonic component



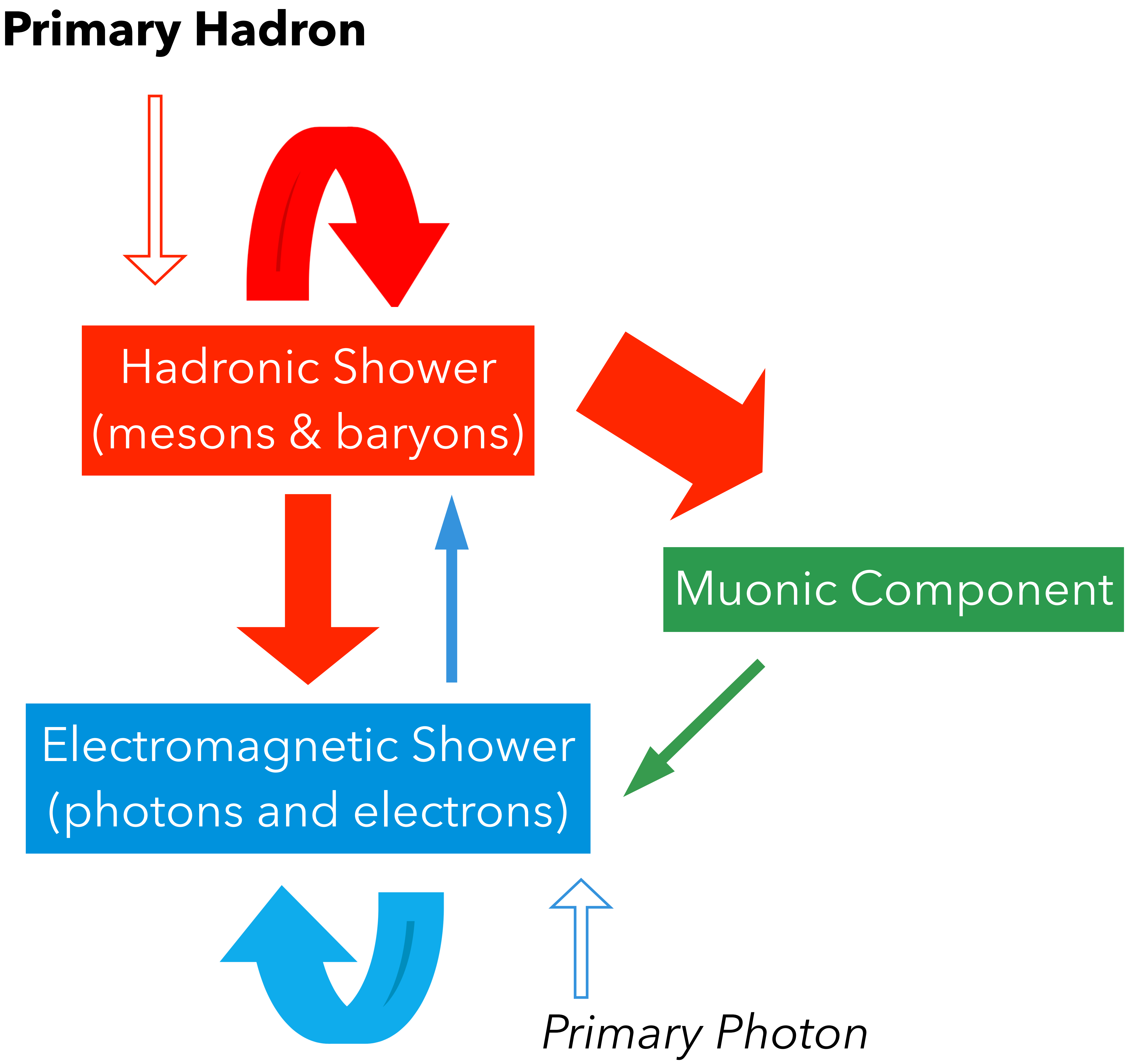




Air Shower Physics



- After 3 hadronic generations, more than 50% of the energy has already been transferred to the electromagnetic sector
  - E.m. component mass estimators less dependent of hadronic interaction details
- **Muons highly sensitive to hadronic interaction details**
  - Possibility to probe $\sqrt{s}$ energies above terrestrial accelerators



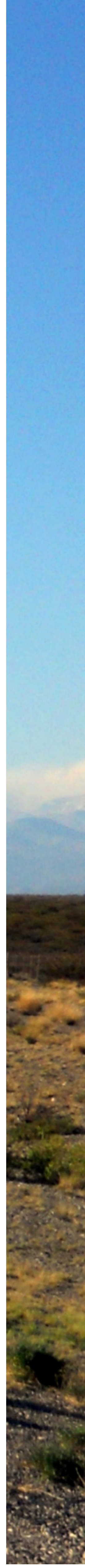
Primary Hadron

Hadronic Shower (mesons & baryons)

Muonic Component

Electromagnetic Shower (photons and electrons)

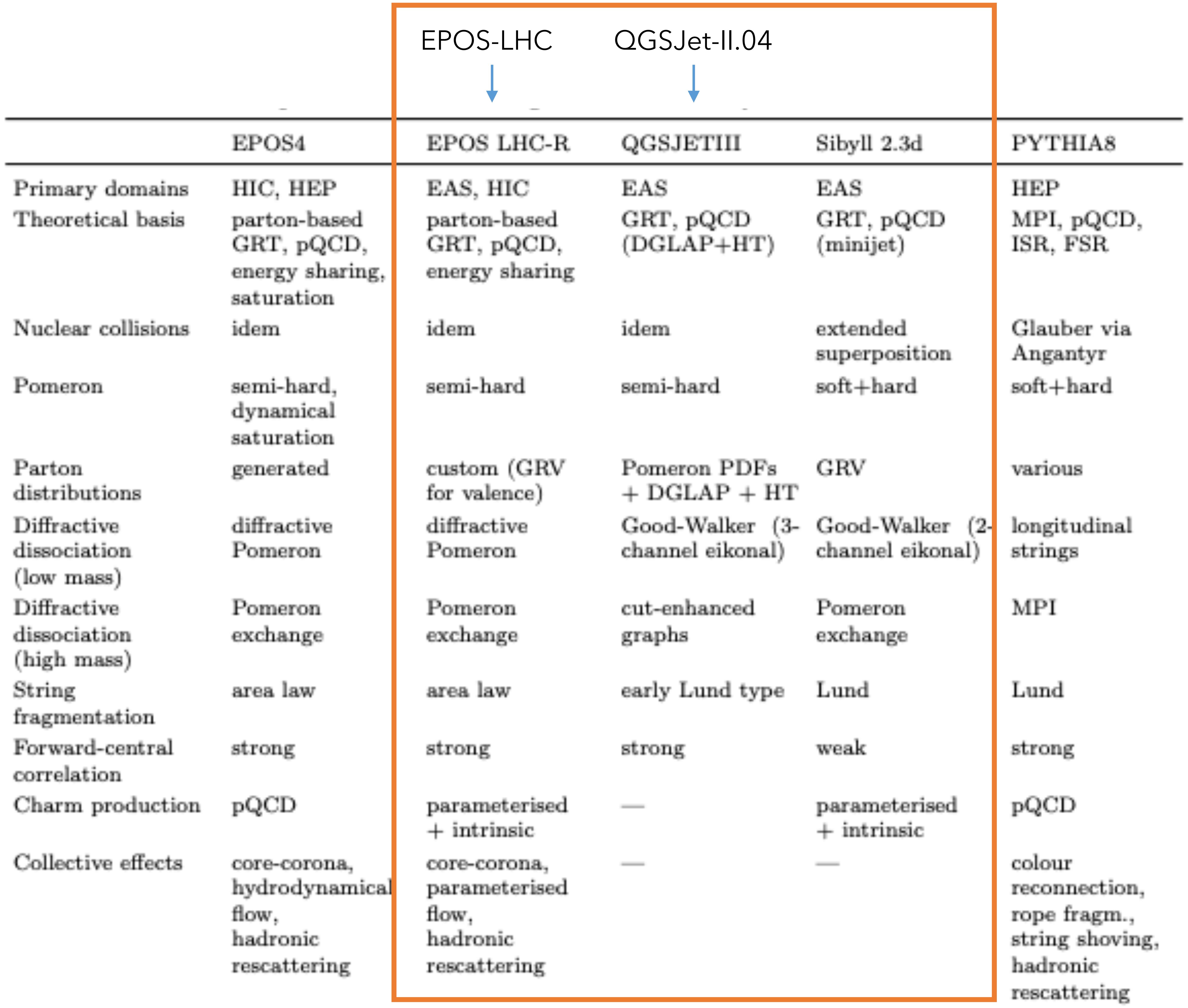
Primary Photon



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

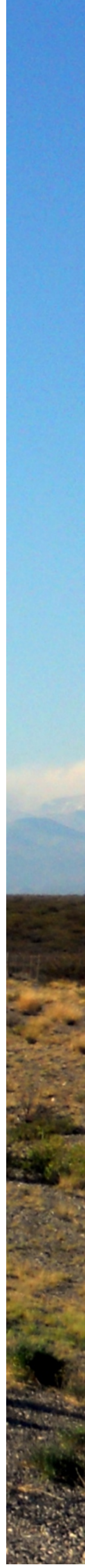


EPOS-LHC

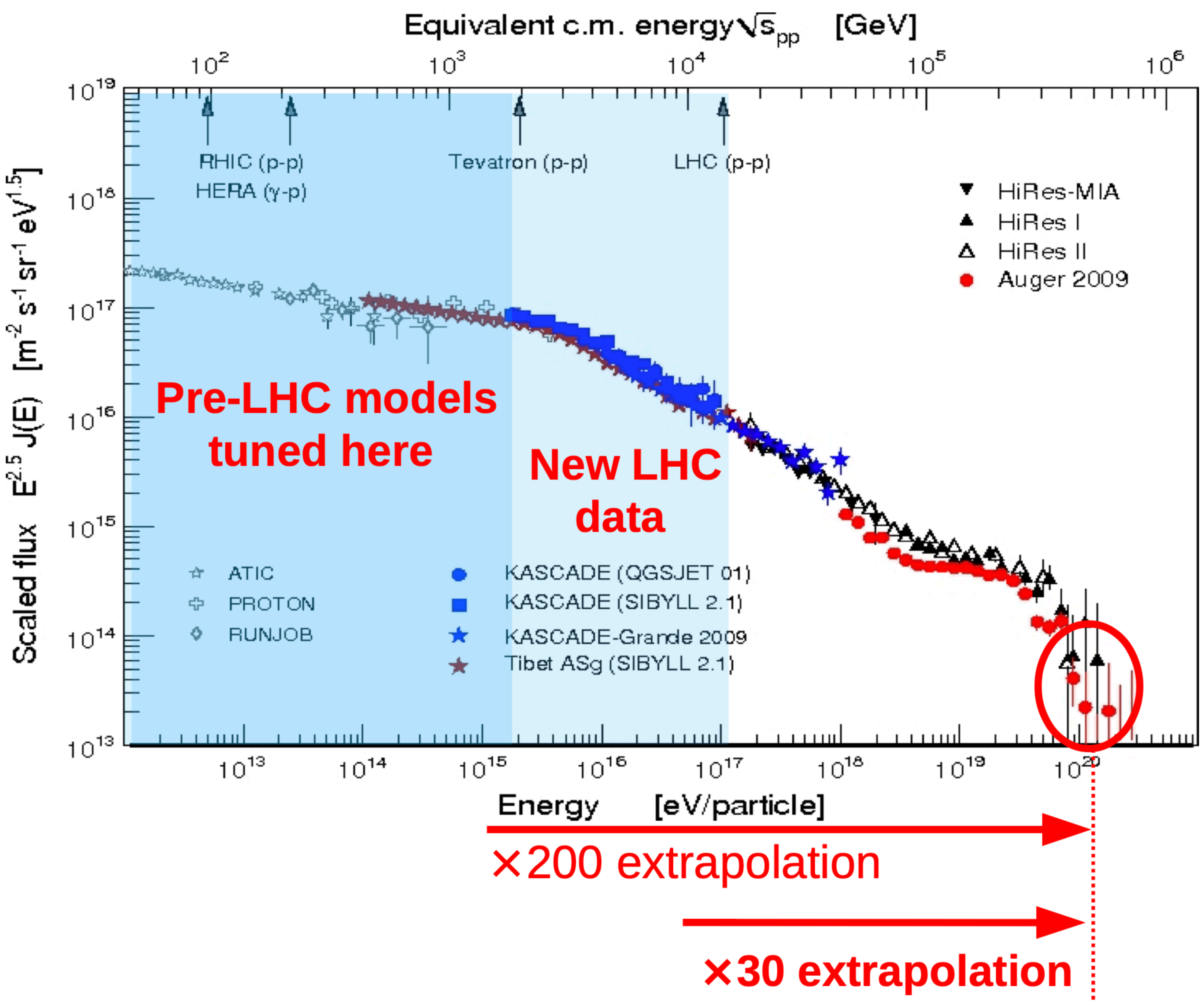
QGSJet-II.04

	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



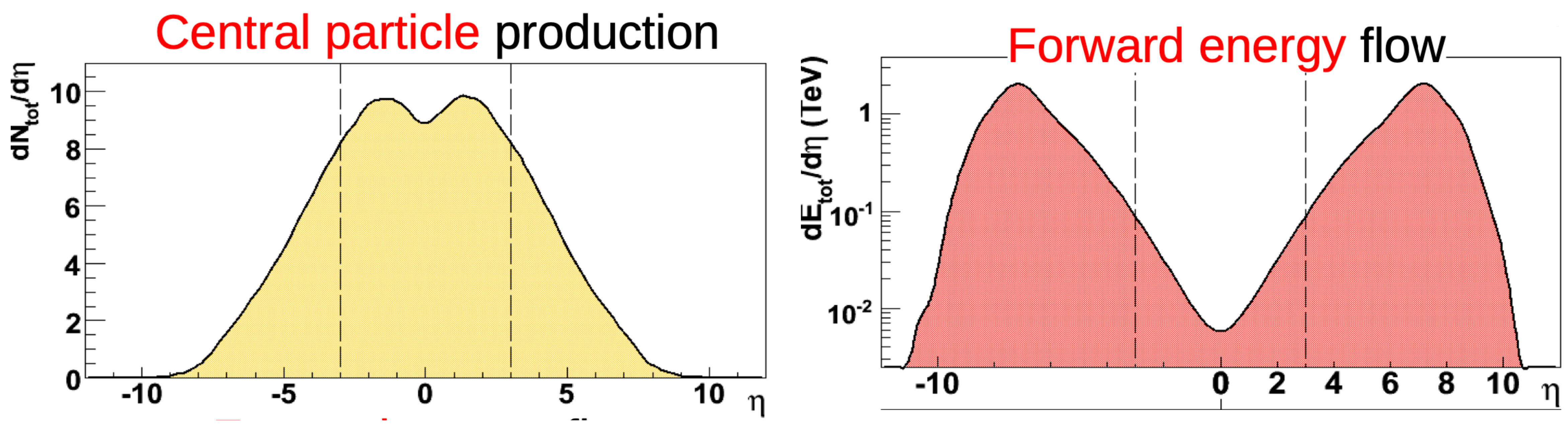
Pre-LHC models tuned here

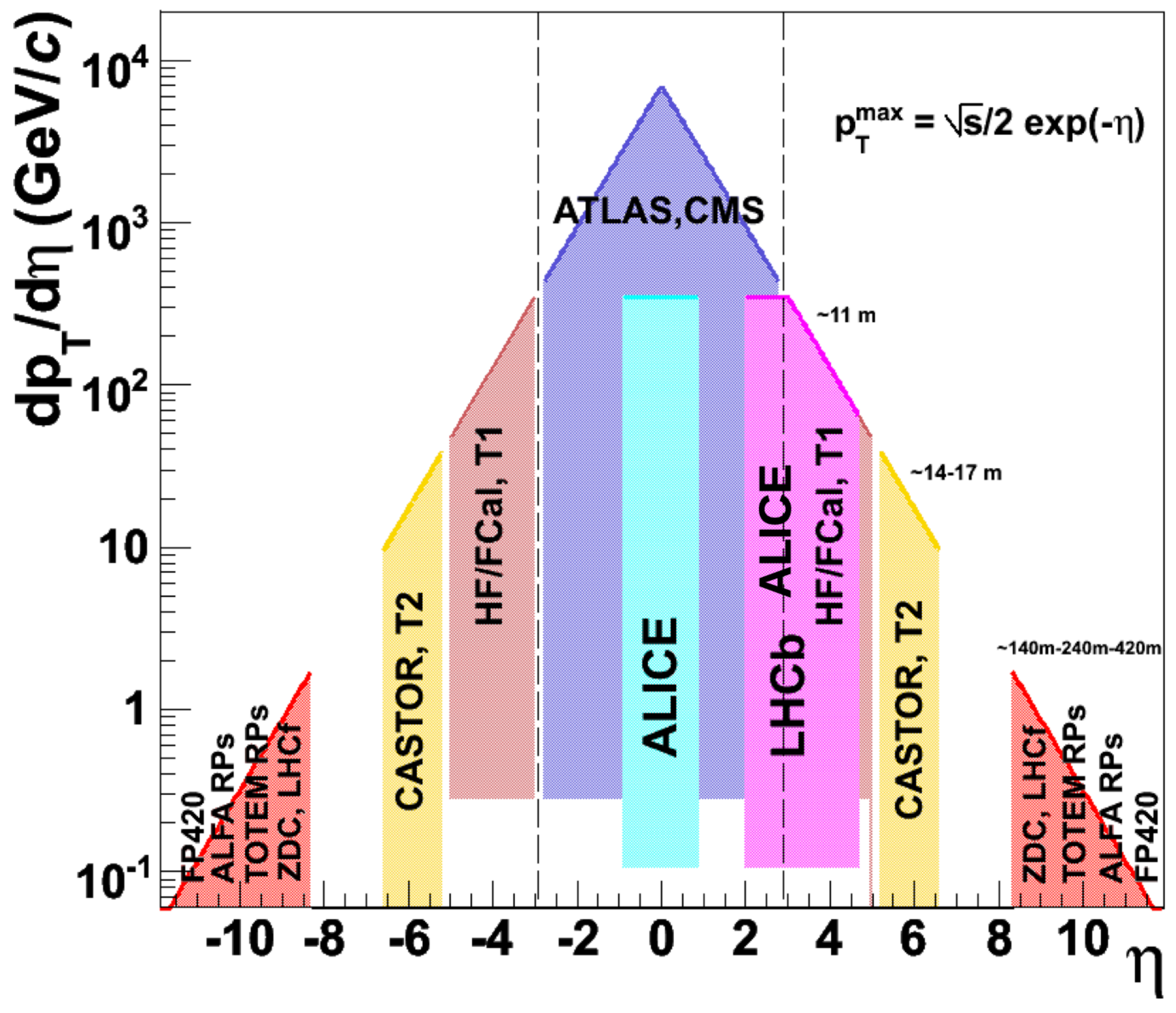
New LHC data

×200 extrapolation

×30 extrapolation

p-p @ 14 TeV





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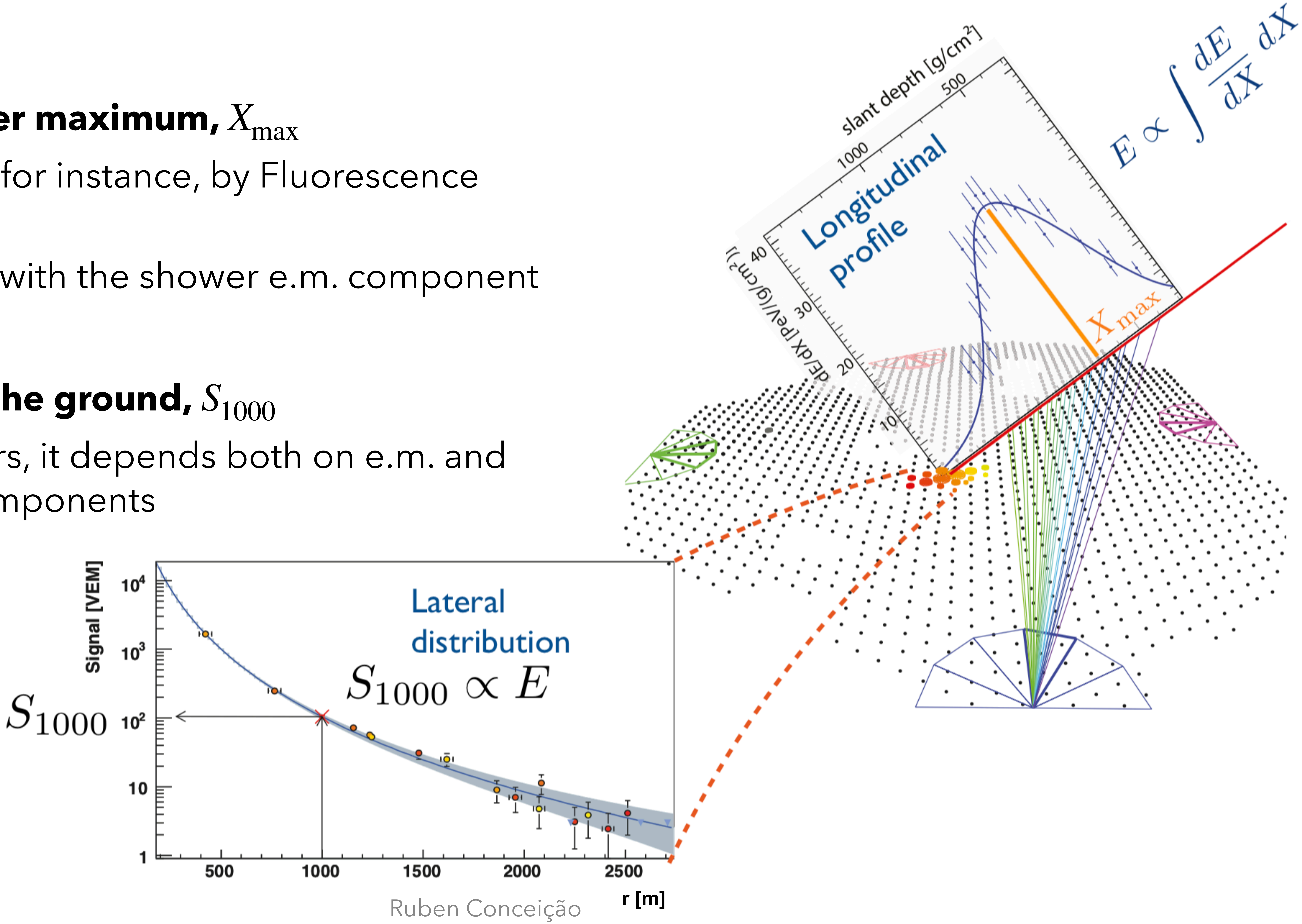
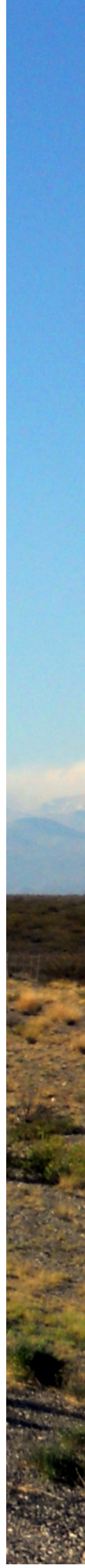
Extensive Air Showers

How well do we understand them?

Shower Observables

- **Depth of the shower maximum, X_{max}**
  - Directly accessed, for instance, by Fluorescence Telescopes
  - Mostly connected with the shower e.m. component
  - $X_{\mathrm{max}} \propto \ln A$
- **Signal intensity at the ground, S_{1000}**
  - For vertical showers, it depends both on e.m. and muonic shower components
  - $N_\mu \propto A^{1-\beta} E^\beta$





Shower Universality

- **Shower Universality**
  - *Shower observables display minimal dependence on primary mass composition or hadronic interaction models*

- **Electromagnetic component**
  - Universality of lateral distribution, energy distribution, angular distribution, and arrival time

S. Lafebre et al., Astropart. Phys. 31 (2009) 243-254
A. Smialkowski, M. Giller, Astrophys. J. 854 (2018) no.1, 48
M. Giller et al., Astropart. Phys. 60 (2015) 92

F. Nerling et al., Astropart. Phys. 24 (2006) 421
M. Guiller et al., J. Phys. G 30 (2004) 97
RC et al, J.Phys.Conf.Ser. 632 (2015) 1, 012087

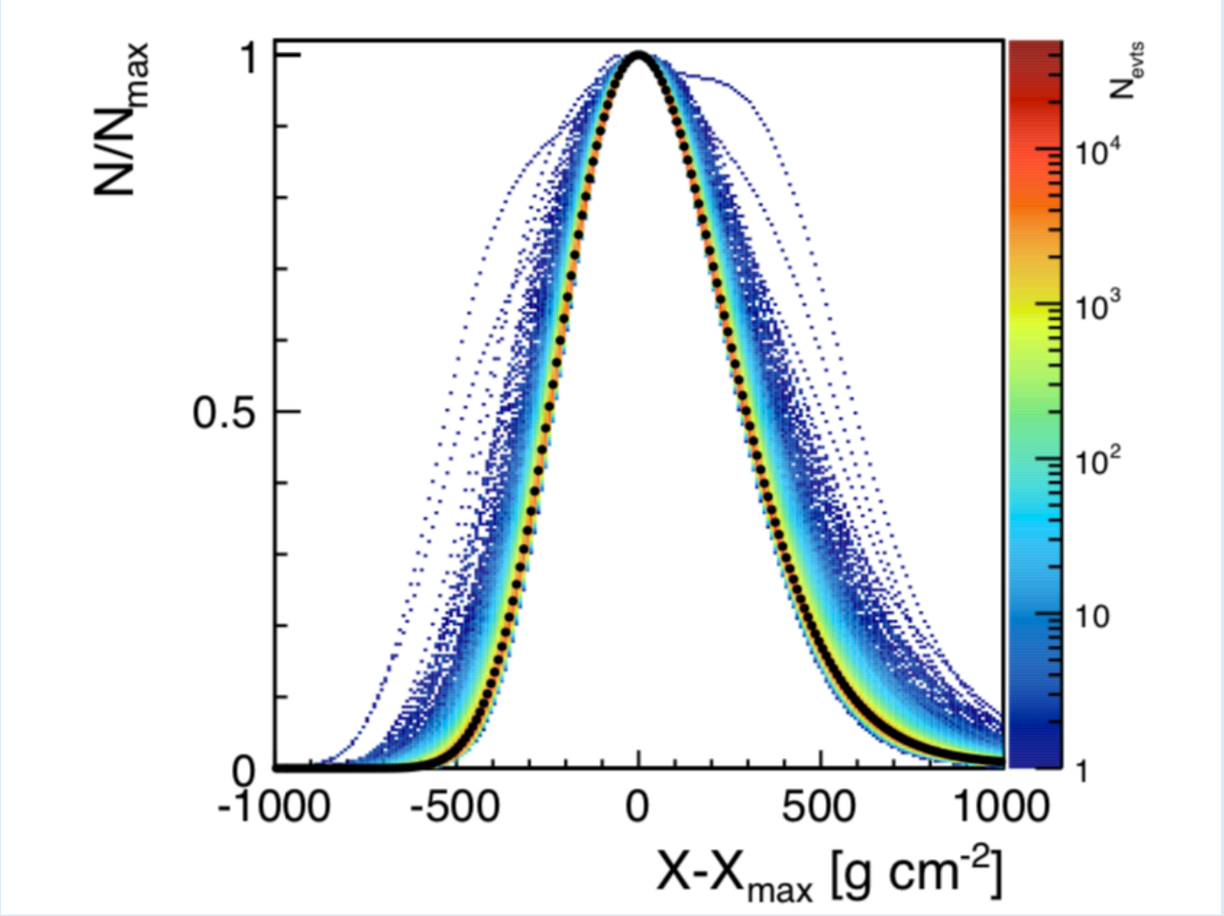
- **Muonic component**
  - Universal distribution at production

$$\frac{d^3N}{dX\,dE\,dcp_t} = N_\mu f\left(X - X^\mu_{\max}, E_i, cp_t\right)$$

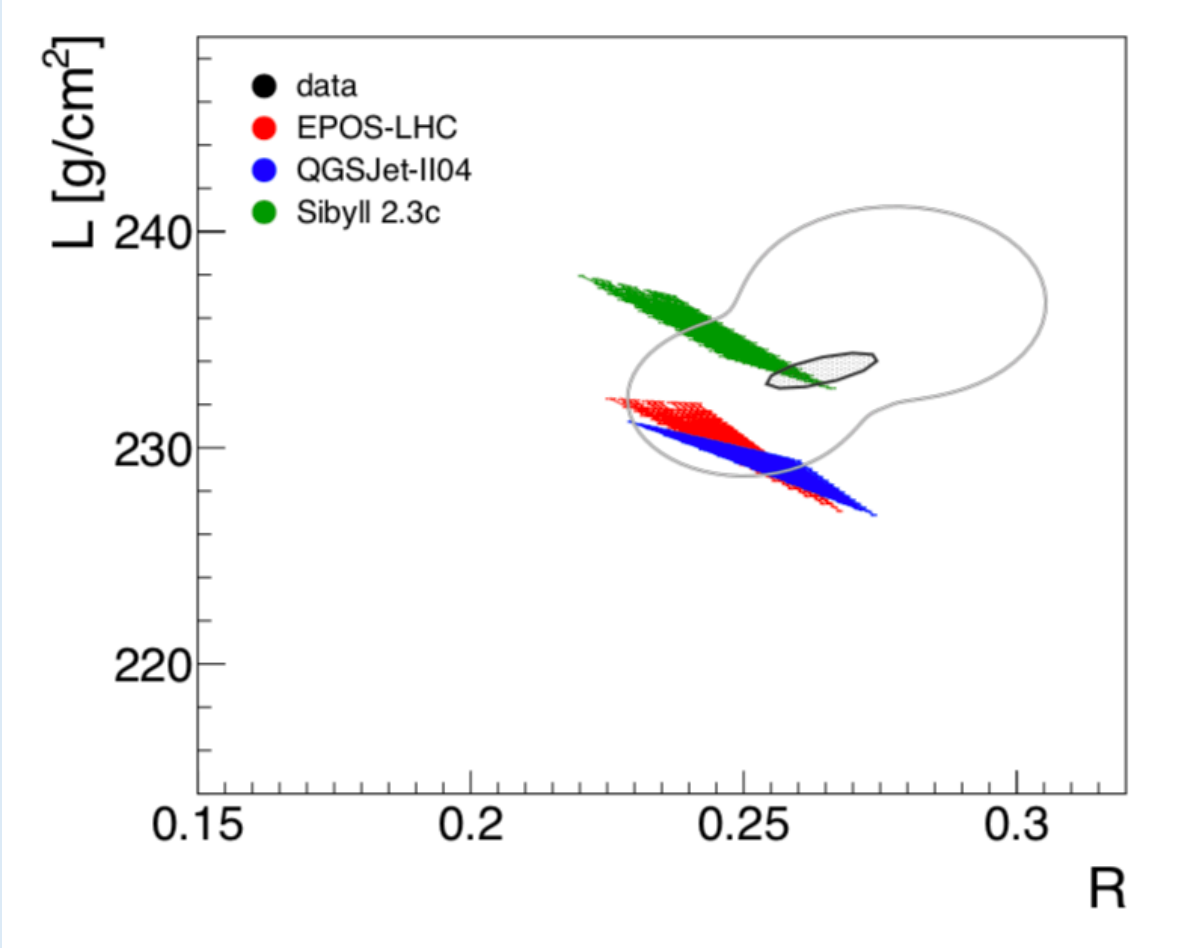
L. Cazon, RC et al. Astropart. Phys. 36 (2012) 211
M. Ave et al., Astropart. Phys. 88 (2017) 46

M. Ave et al., Astropart. Phys. 87 (2017) 23
L. Cazon, RC, F. Riehn, JCAP 03 (2023) 022

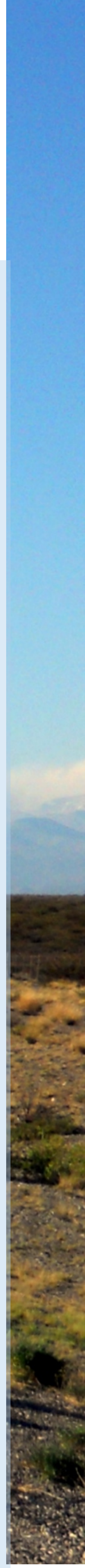
Universal Shower Profile (USP)



USP shape parameters



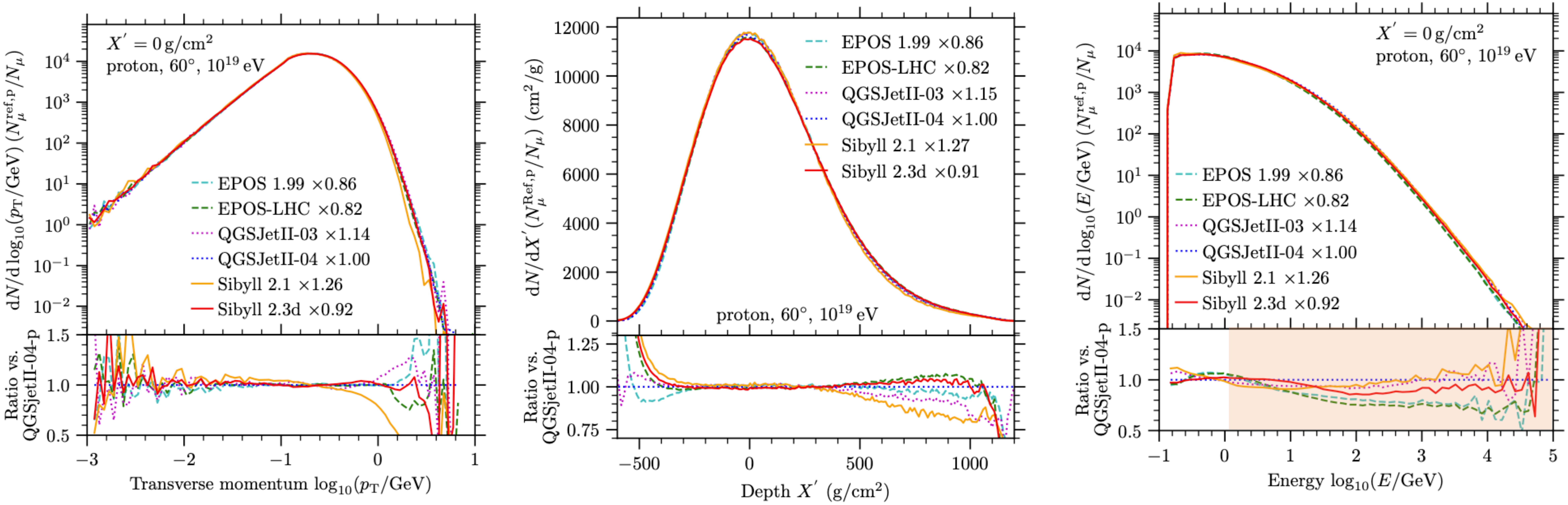
Pierre Auger Coll., JCAP 1903 (2019) no.03, 018



Universality of the muonic sector

L. Cazon, RC, F. Riehn, JCAP 03 (2023) 022

The muon distributions in air shower can be characterized using few key distributions



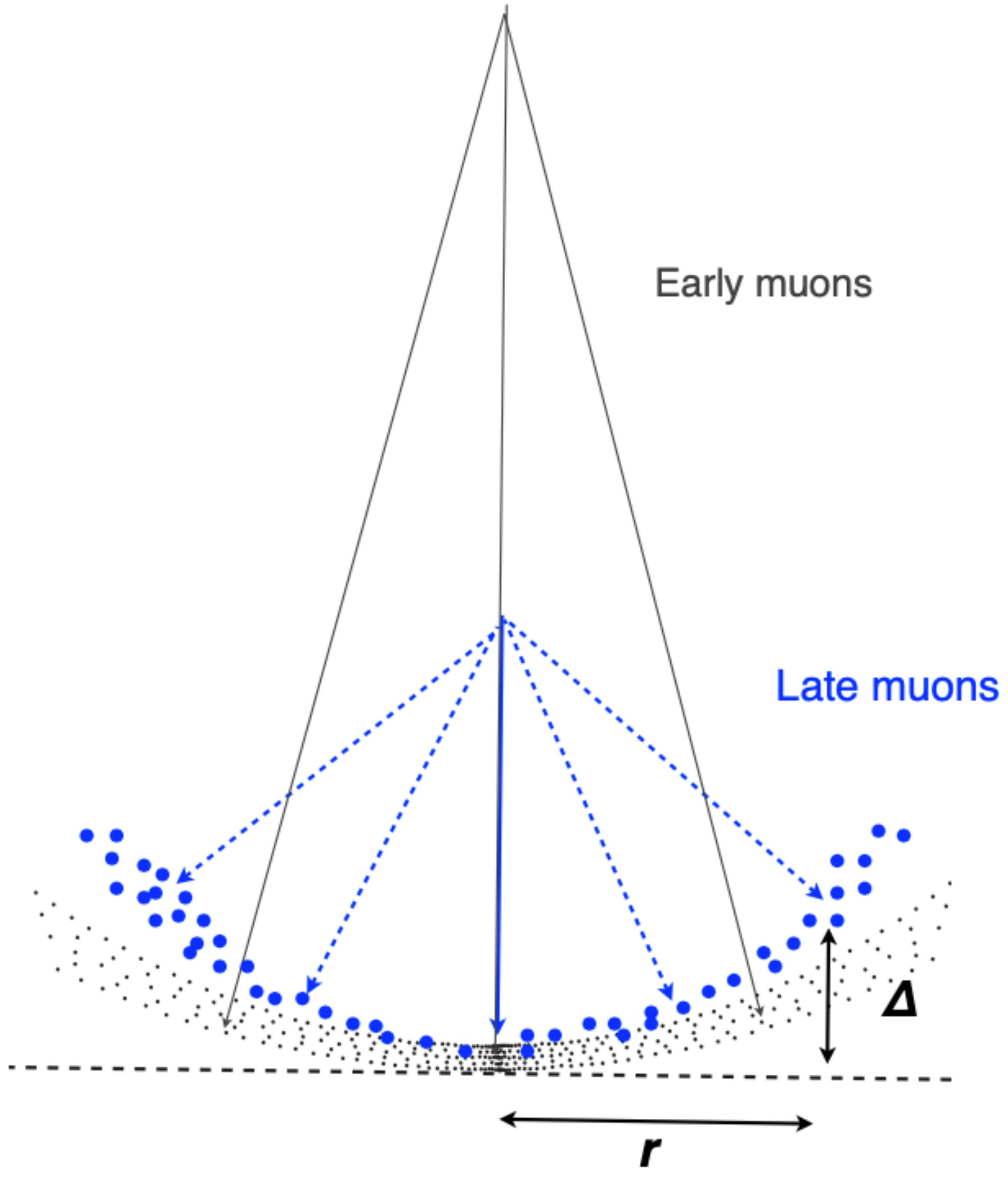
Most of these distributions are universal with the exception of the muon energy spectrum for $\mathrm{E}_\mu > 1\,\mathrm{GeV}$

New EPOS LHC-R addresses the muon puzzle predicting an increase of $1-10\,\mathrm{GeV}$ muons - T. Pierog

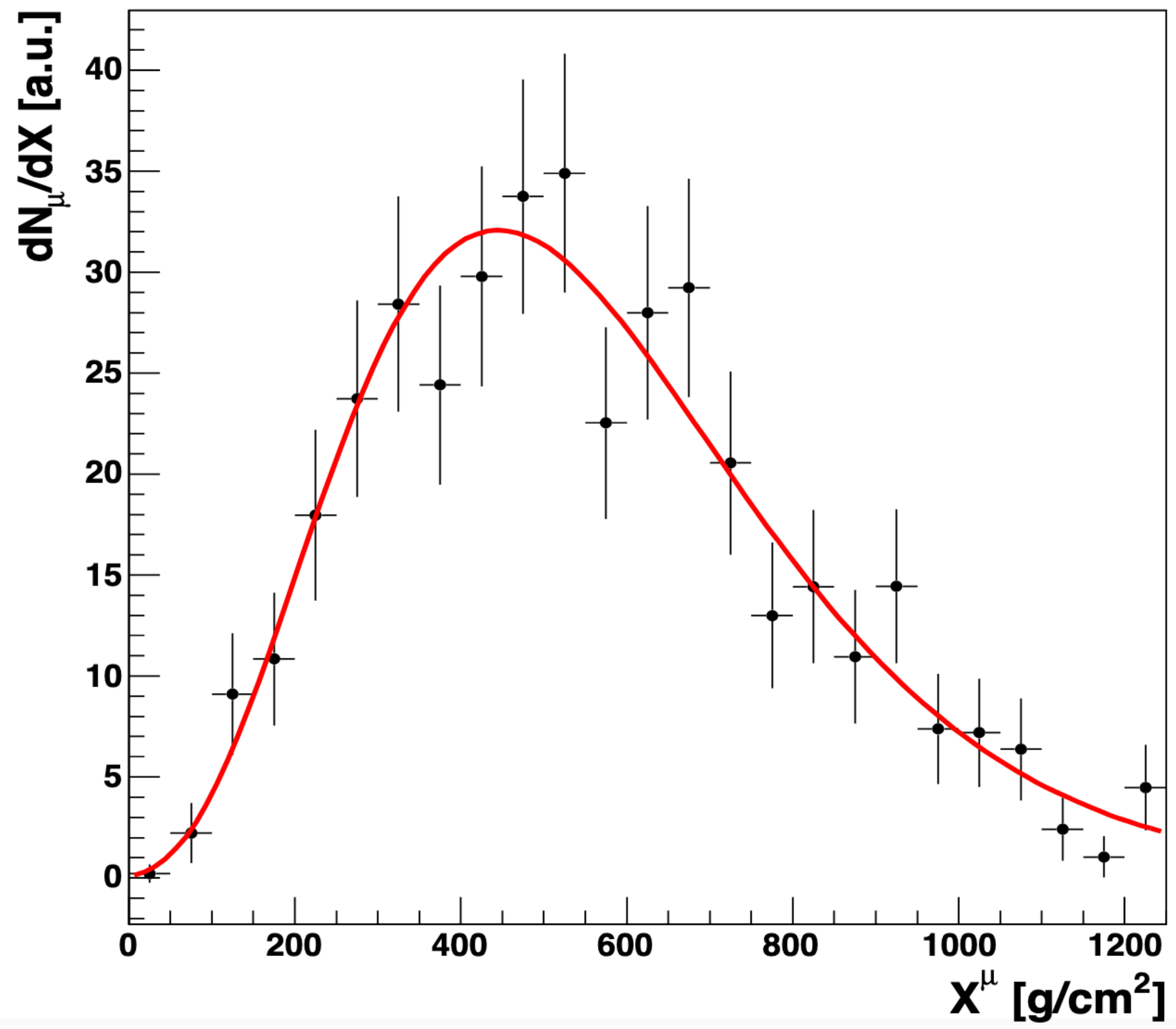
Muon Production Depth

L. Cazon et al. Astropart. Phys. 23, 2005

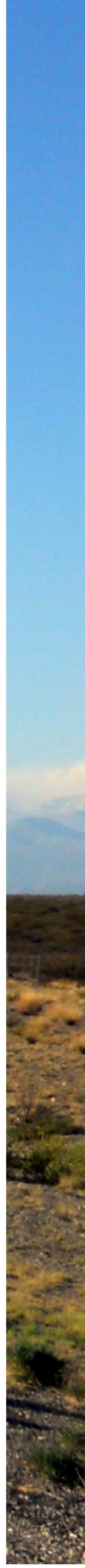
$$z \simeq \frac{1}{2}\left(\frac{r^2}{c\left(t-\langle t_\varepsilon\rangle\right)} - c\left(t-\langle t_\varepsilon\rangle\right)\right) + \Delta - \langle z_\pi\rangle$$



Pierre Auger Coll., Phys.Rev.D 90 (2014) 1, 012012



- Relation between **geometry of the shower** (shower front plane) and **muons arrival time** allow us to obtain the position of muons upon their creation - **MPD**
- ***Sensitive to pion-air interaction properties!*** L. Cazon, RC et al., Astropart.Phys. 35 (2012) 821-827 S. Ostapchenko, M. Bleicher, Phys.Rev.D 93 (2016) 5, 051501



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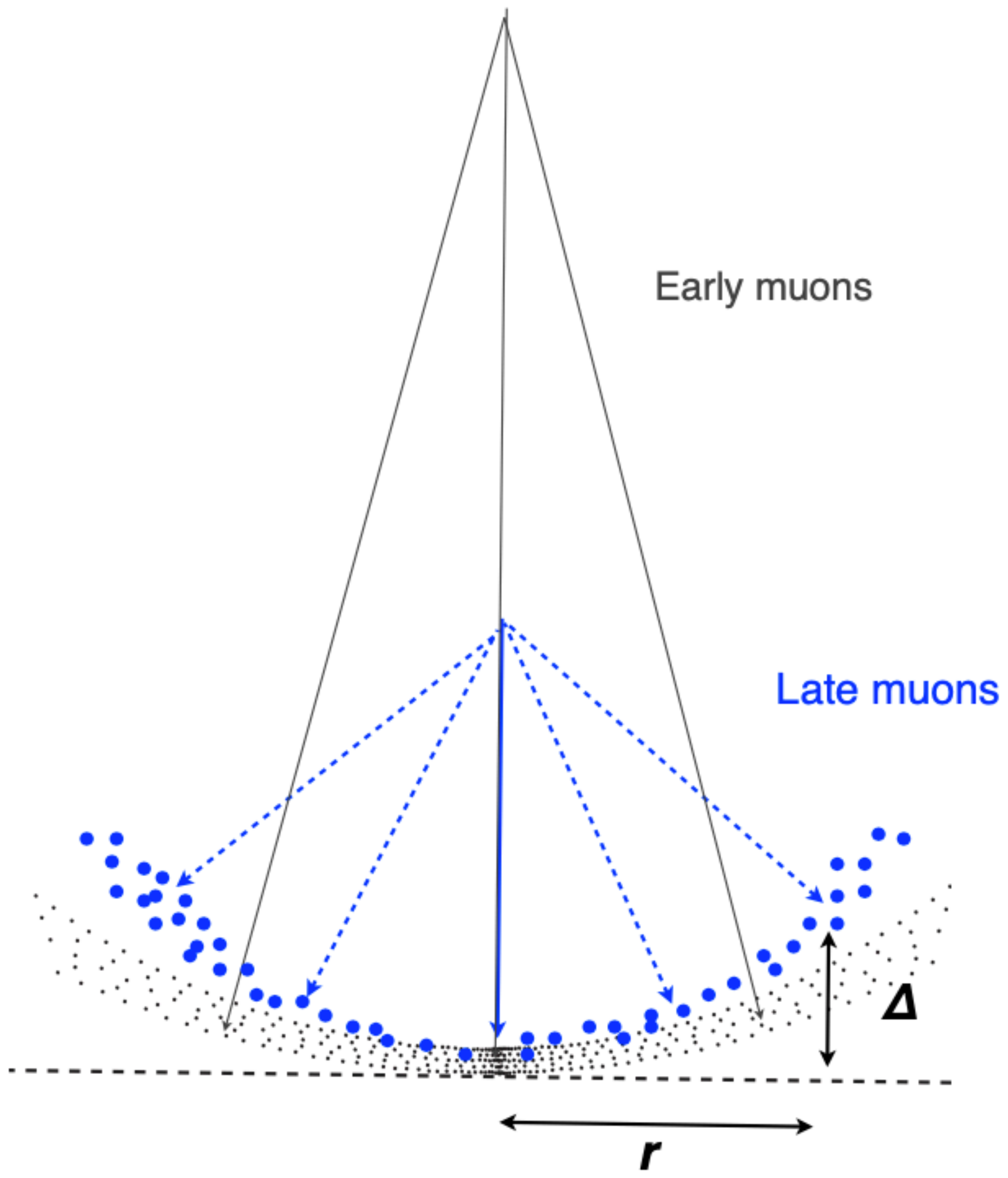
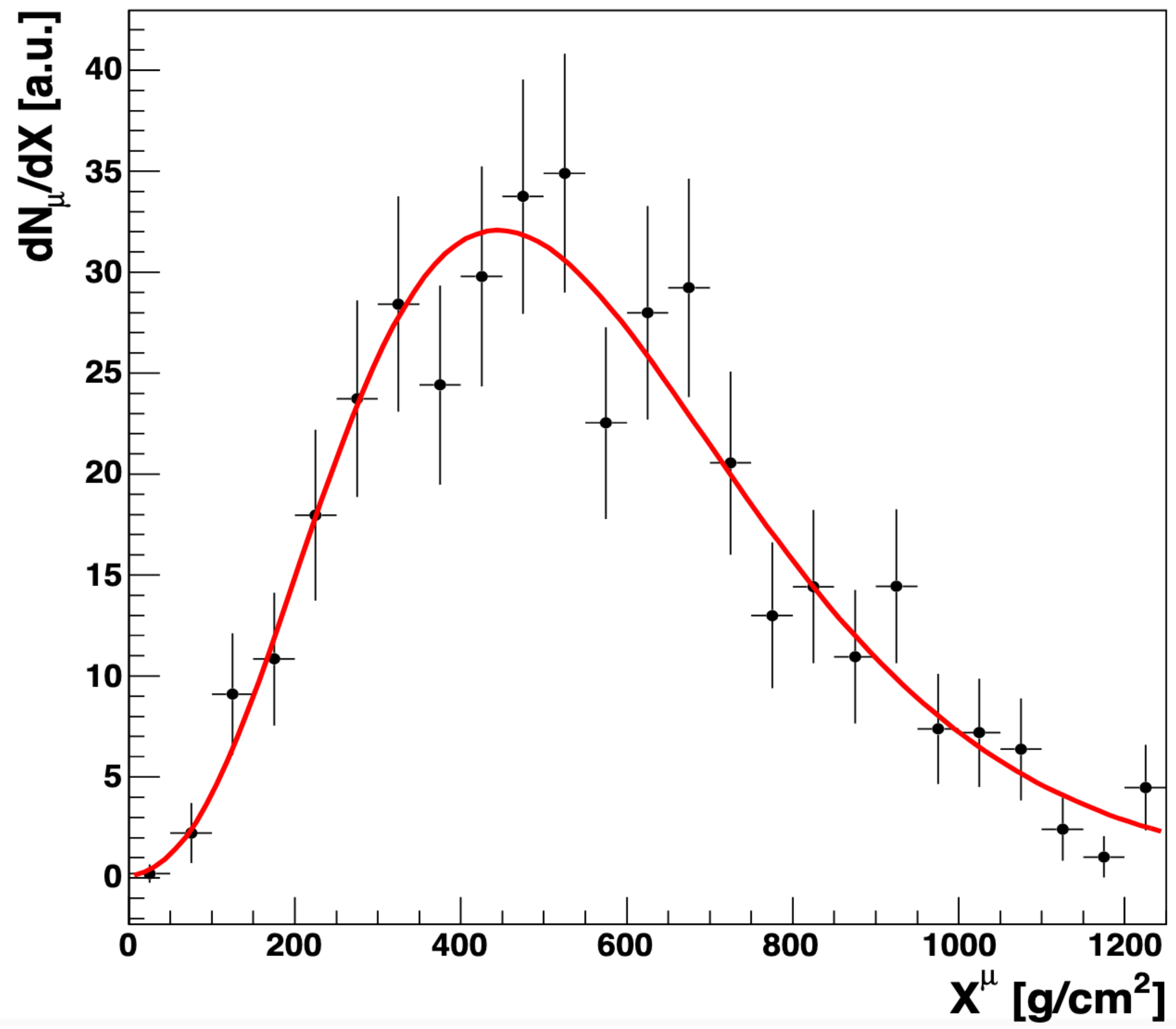
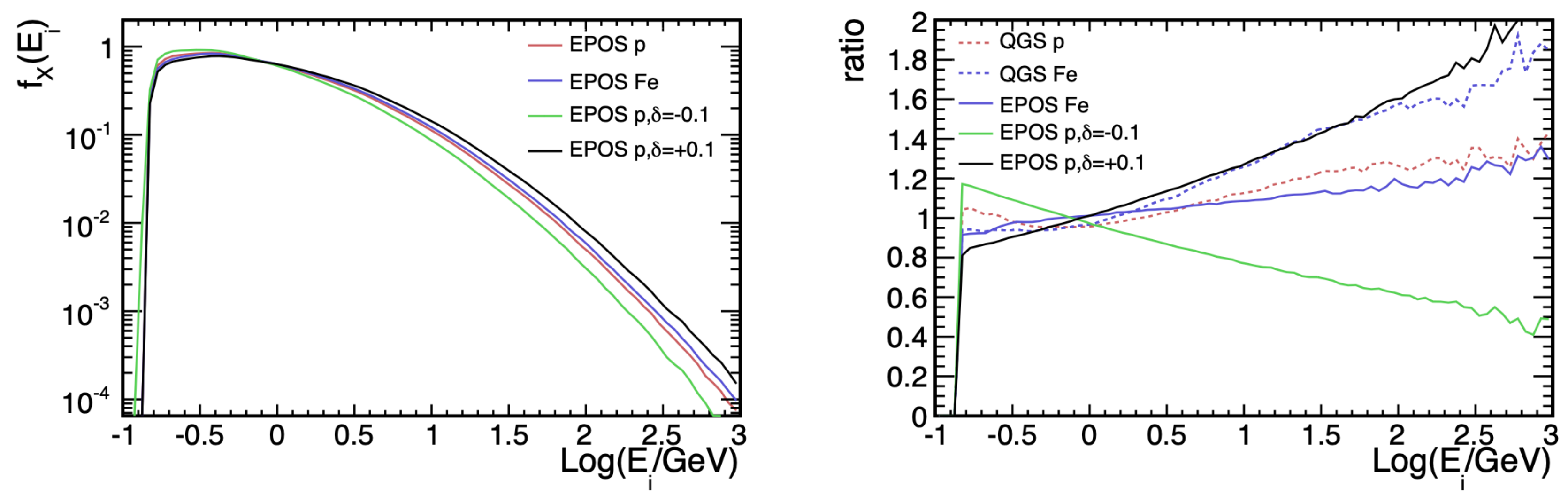
L. Cazon et al. Astropart. Phys. 23, 2005

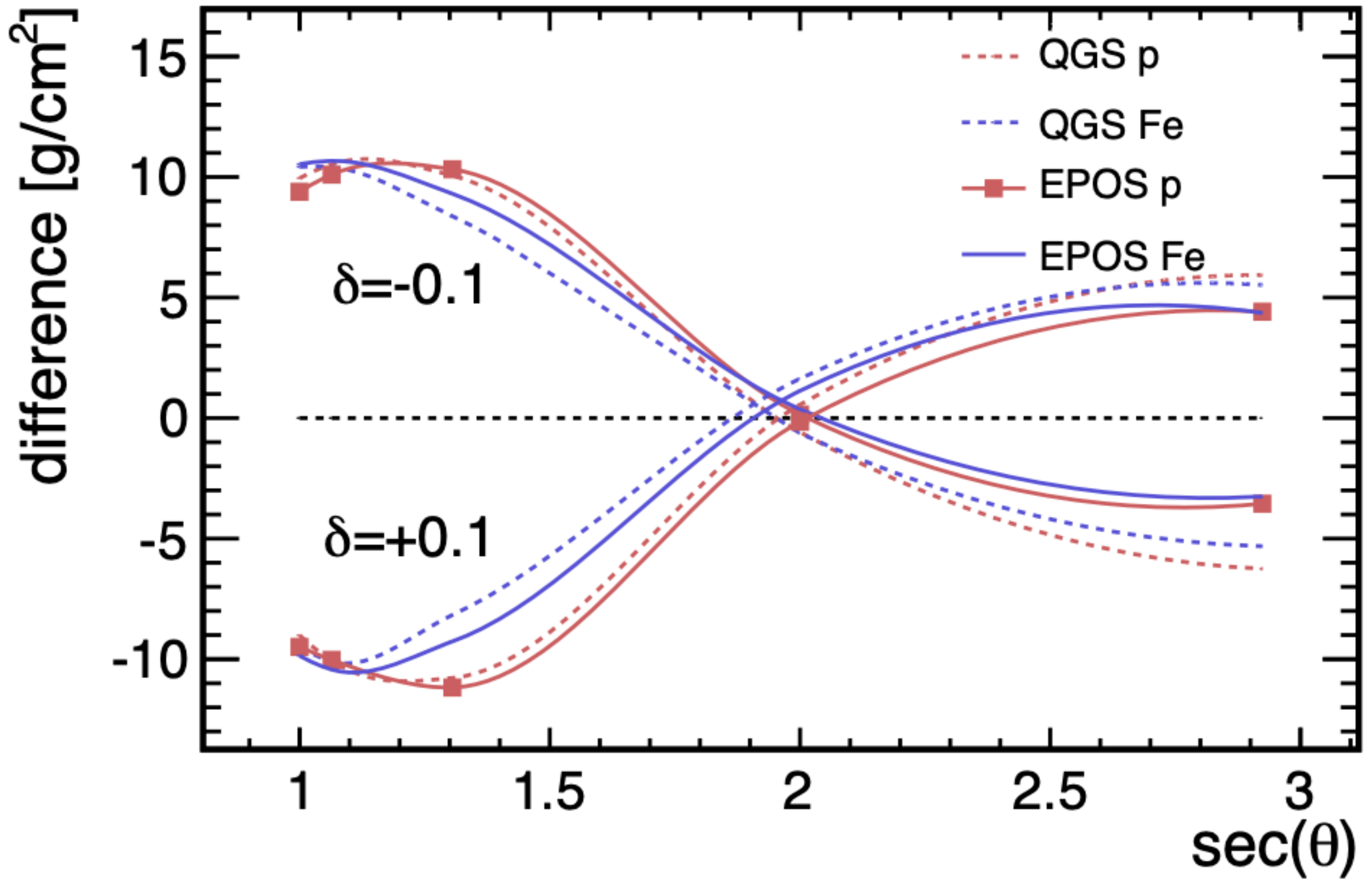


Pierre Auger Coll., Phys.Rev.D 90 (2014) 1, 012012



J. Espadanal, L. Cazon, RC, Astropart.Phys. 86 (2017) 32-40





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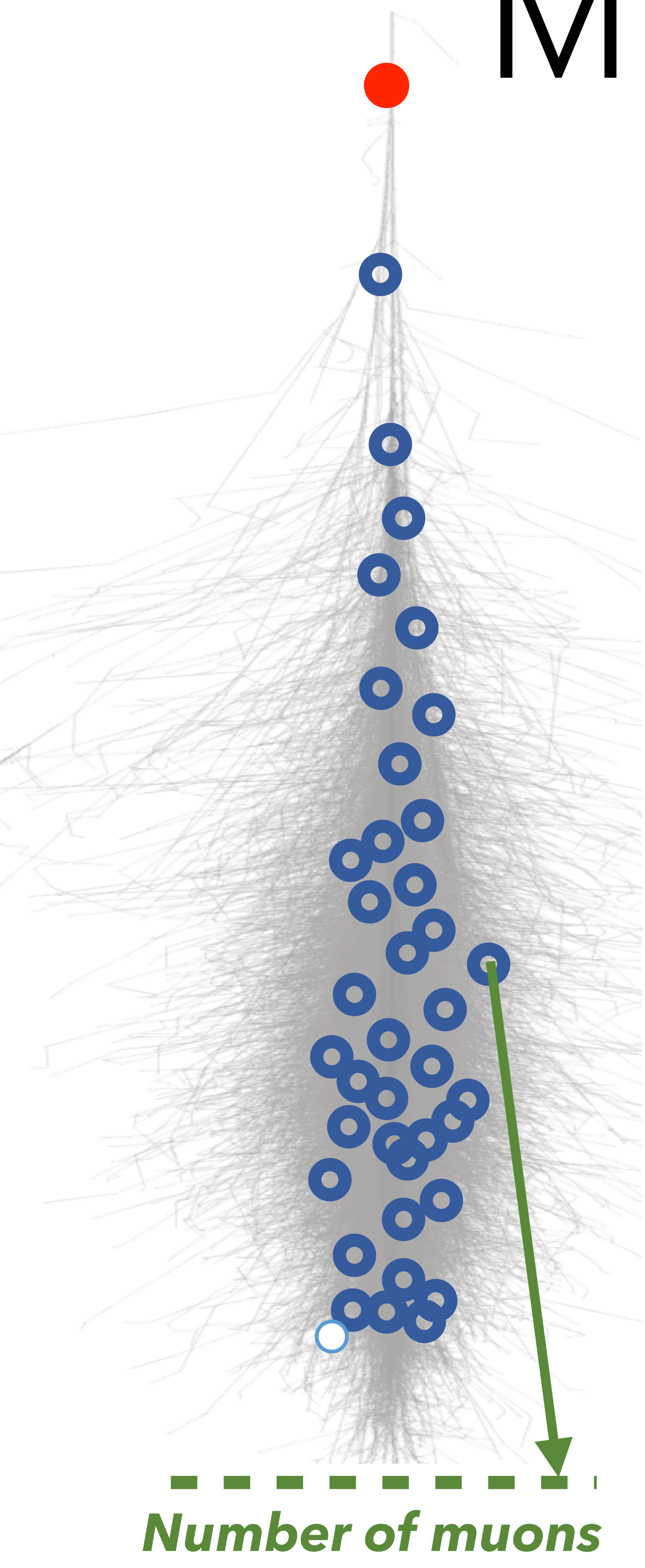
L. Cazon, RC et al., Astropart.Phys. 35 (2012) 821-827

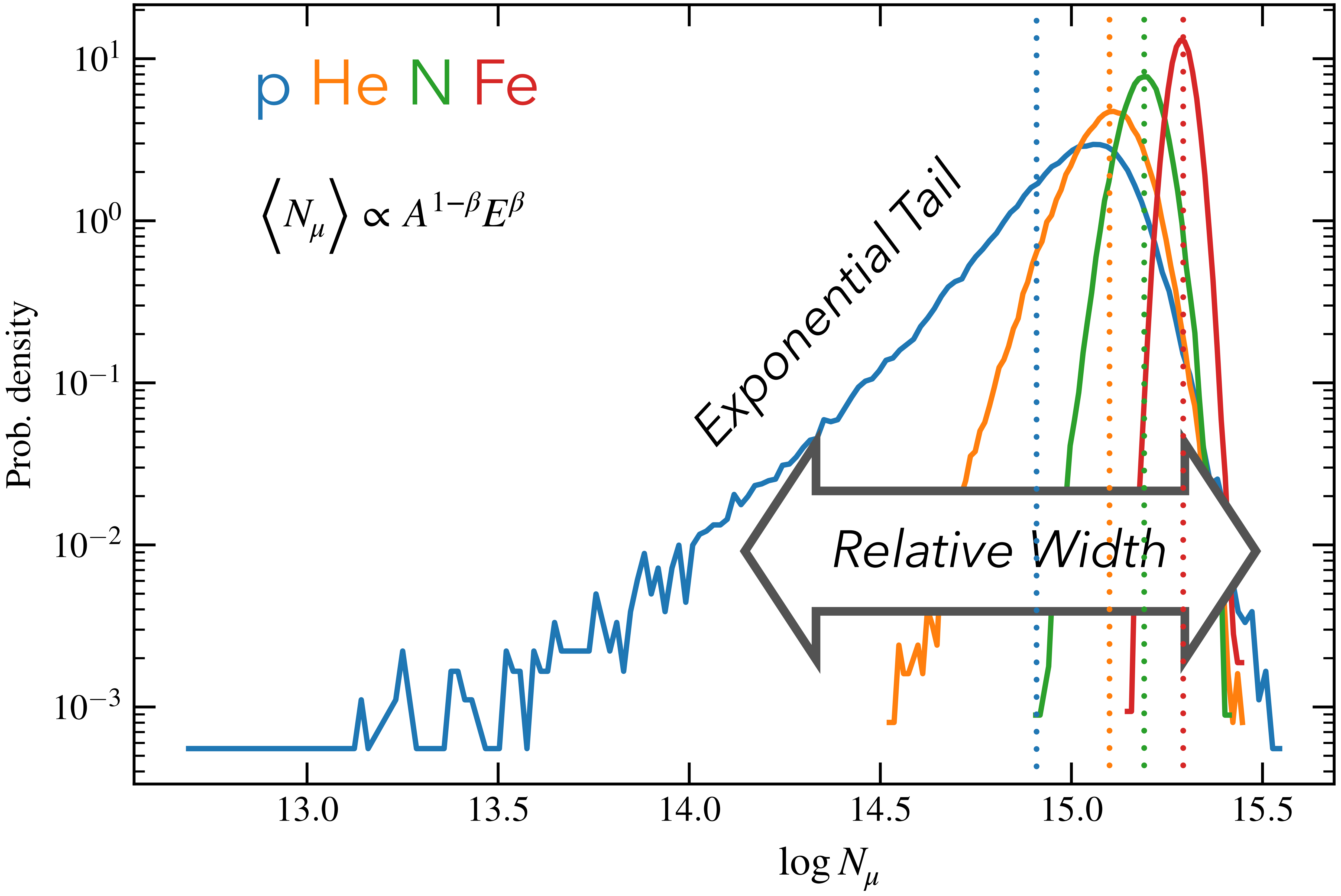
S. Ostapchenko, M. Bleicher, Phys.Rev.D 93 (2016) 5, 051501

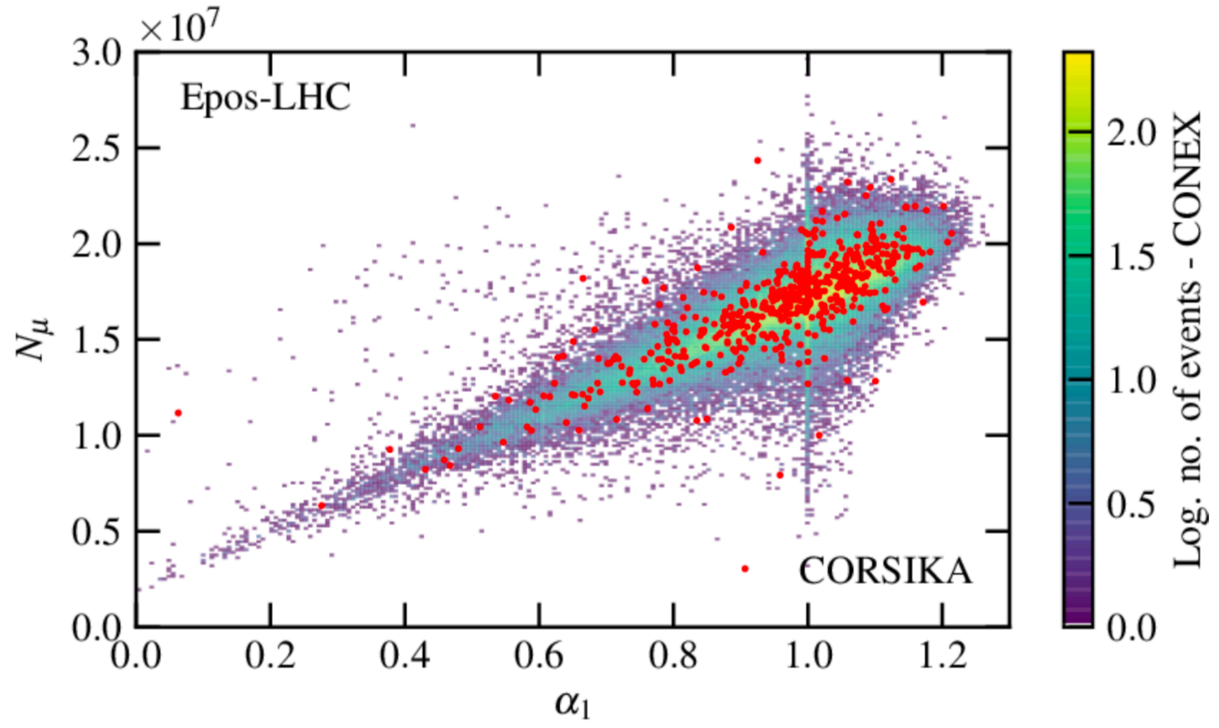
Muon number distribution features

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

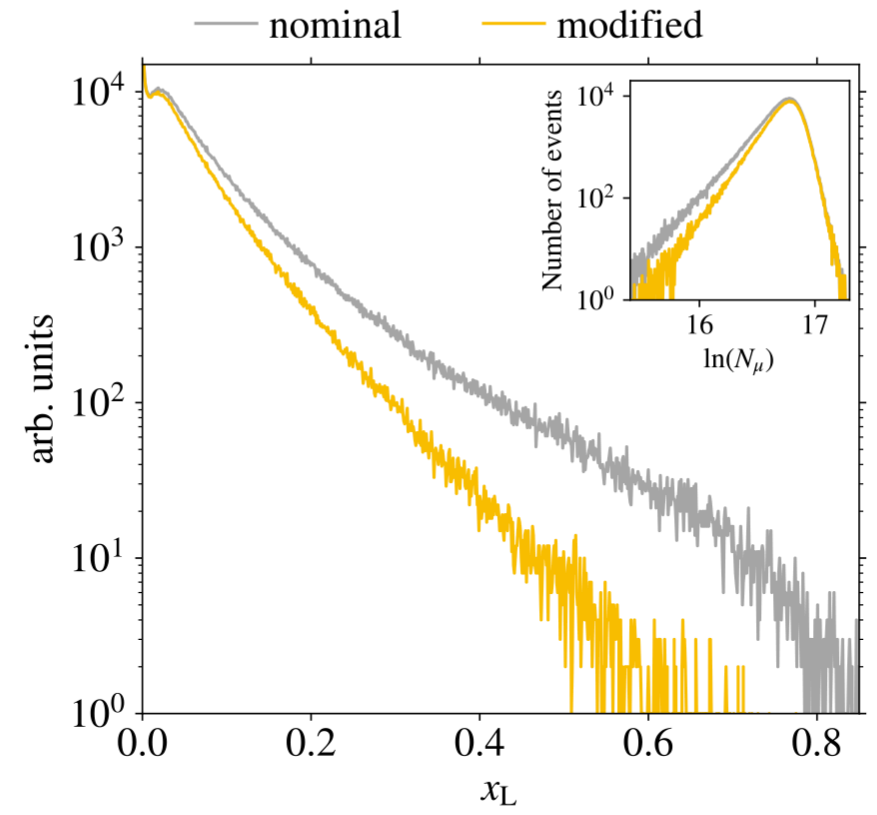
L. Cazon, RC, M. Martins, F. Riehn, Phys.Rev.D 103 (2021) 2, 022001







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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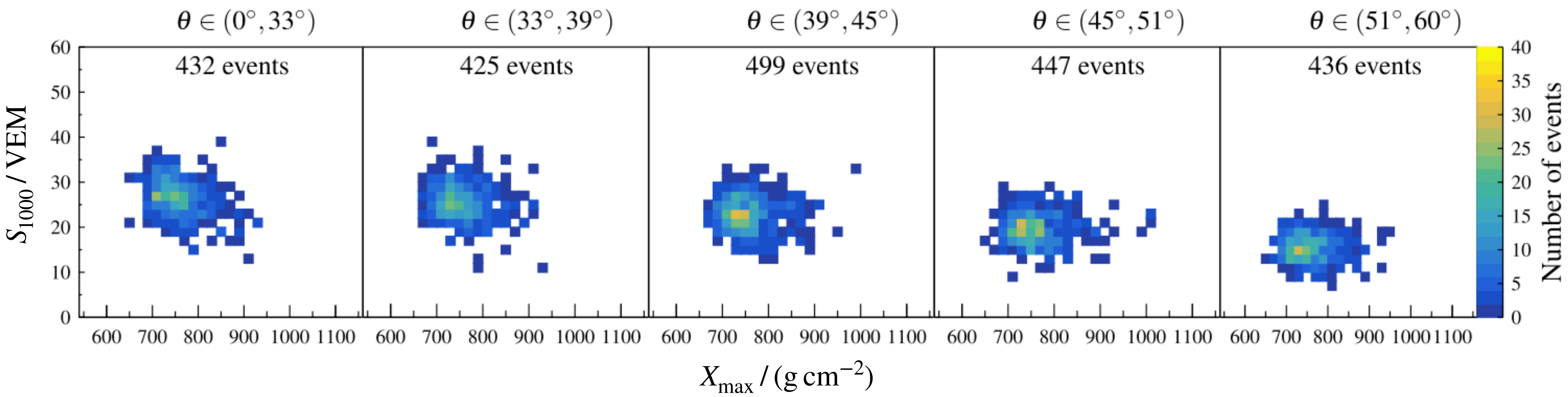
Hadronic Interaction Models

How well do we truly understand them?

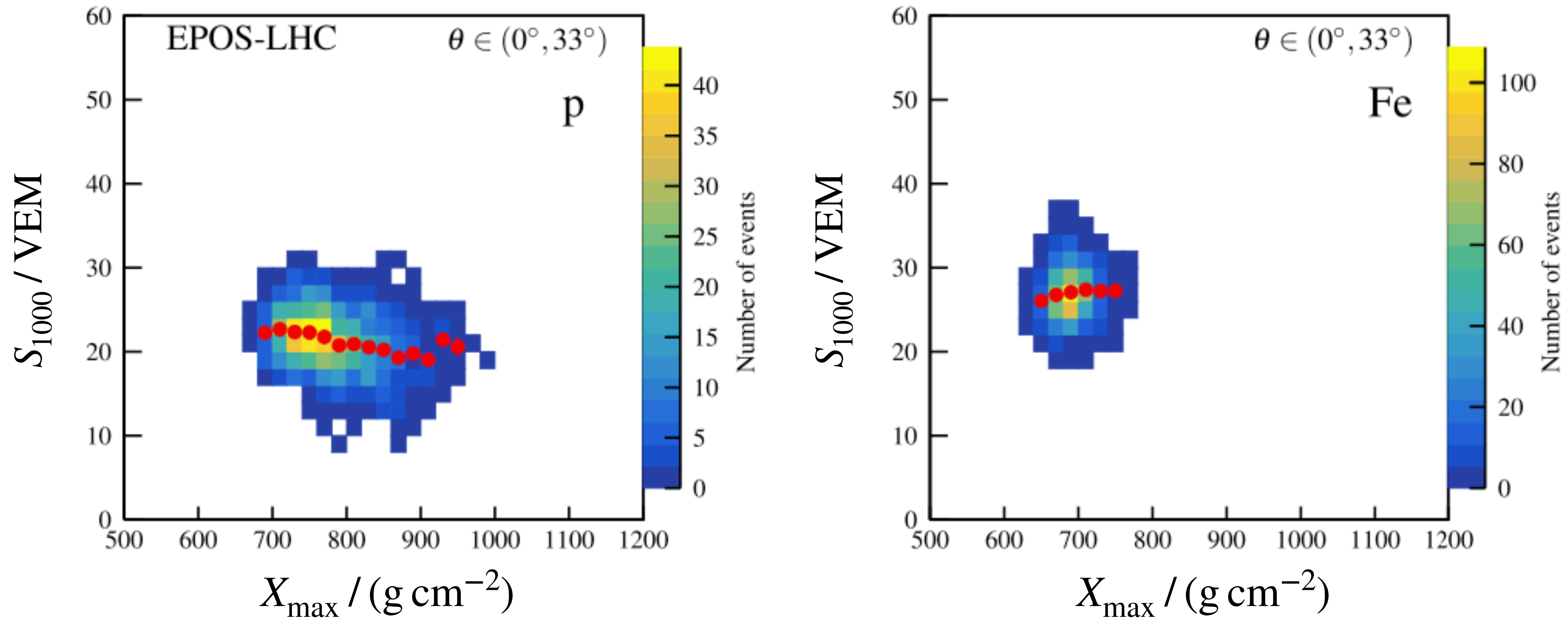
Analysis of the ($X_{\max}$, S_{1000}) distribution

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

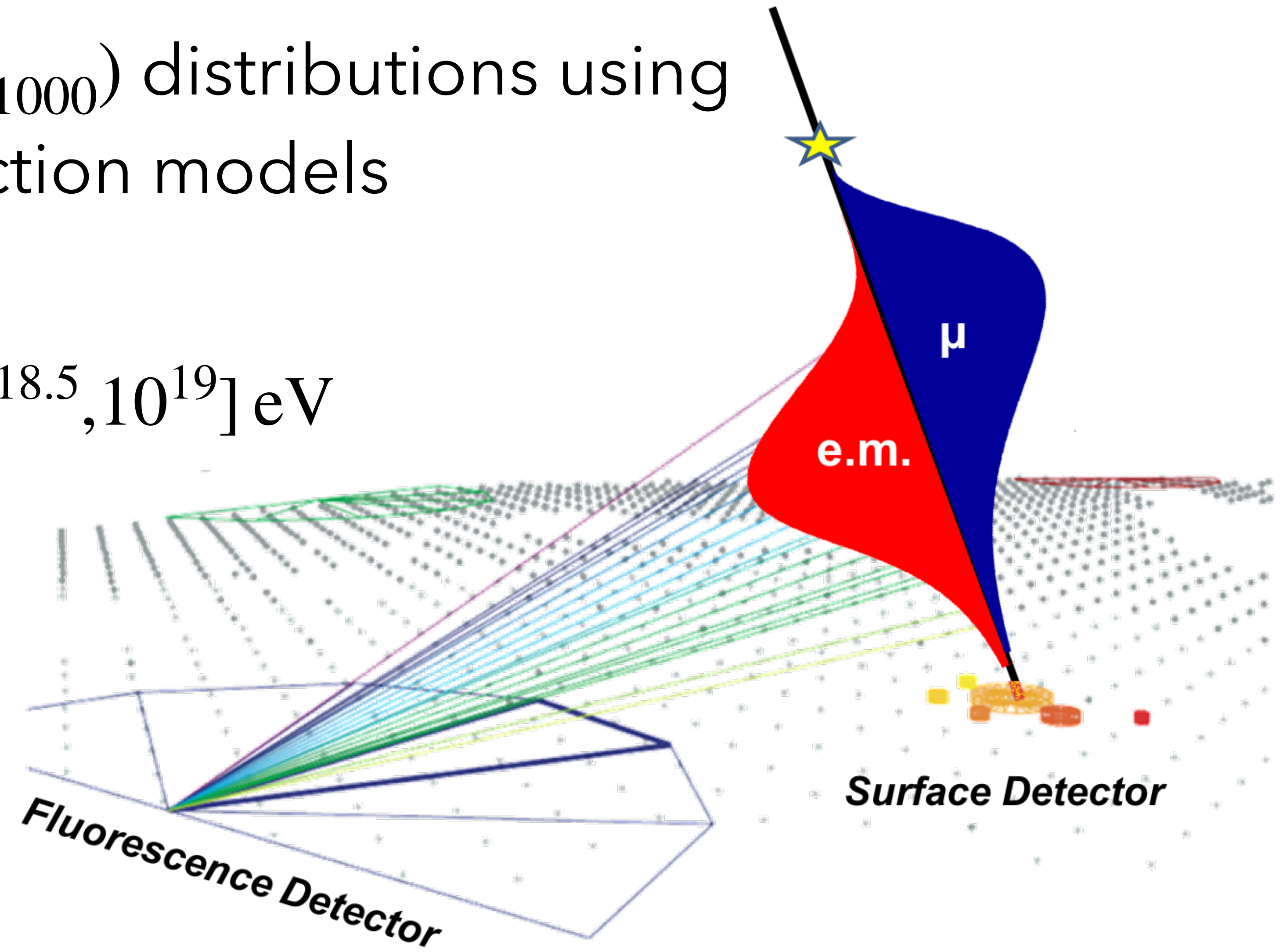


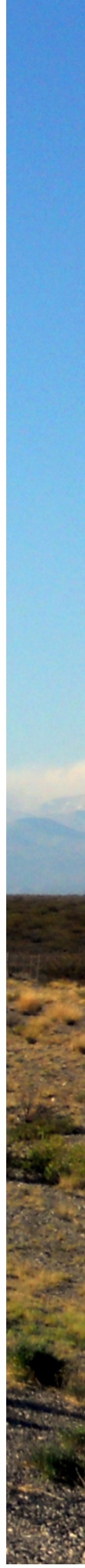
Explore hybrid FD-SD events and **fit the measured two-dimensional** ($X_{\max}$, S_{1000}) distributions using templates for simulated air showers produced with hadronic interaction models

Example of MC templates



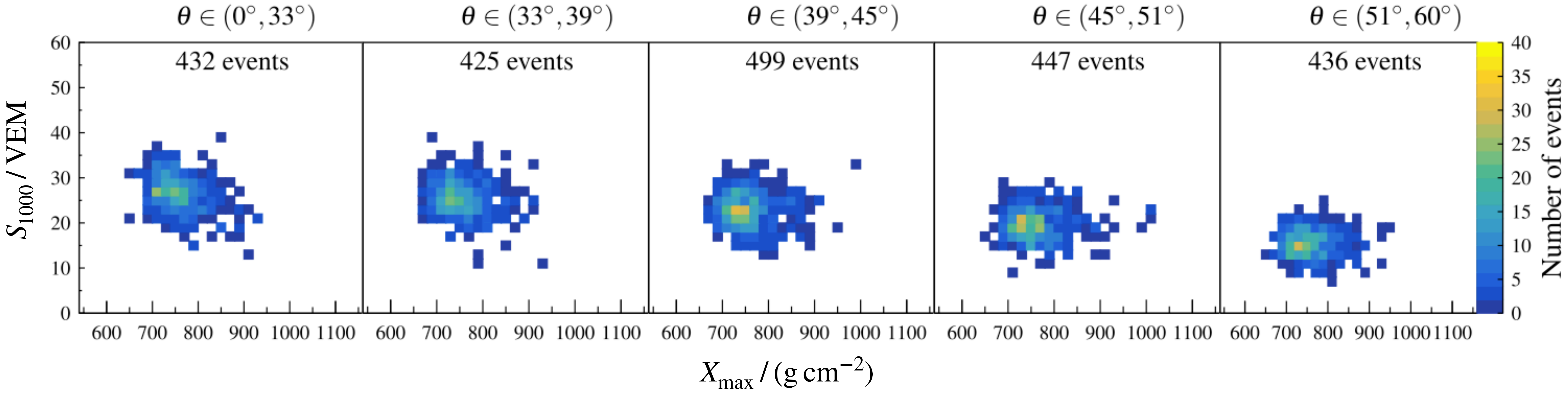
$E \in [10^{18.5}, 10^{19}]$ eV





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

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



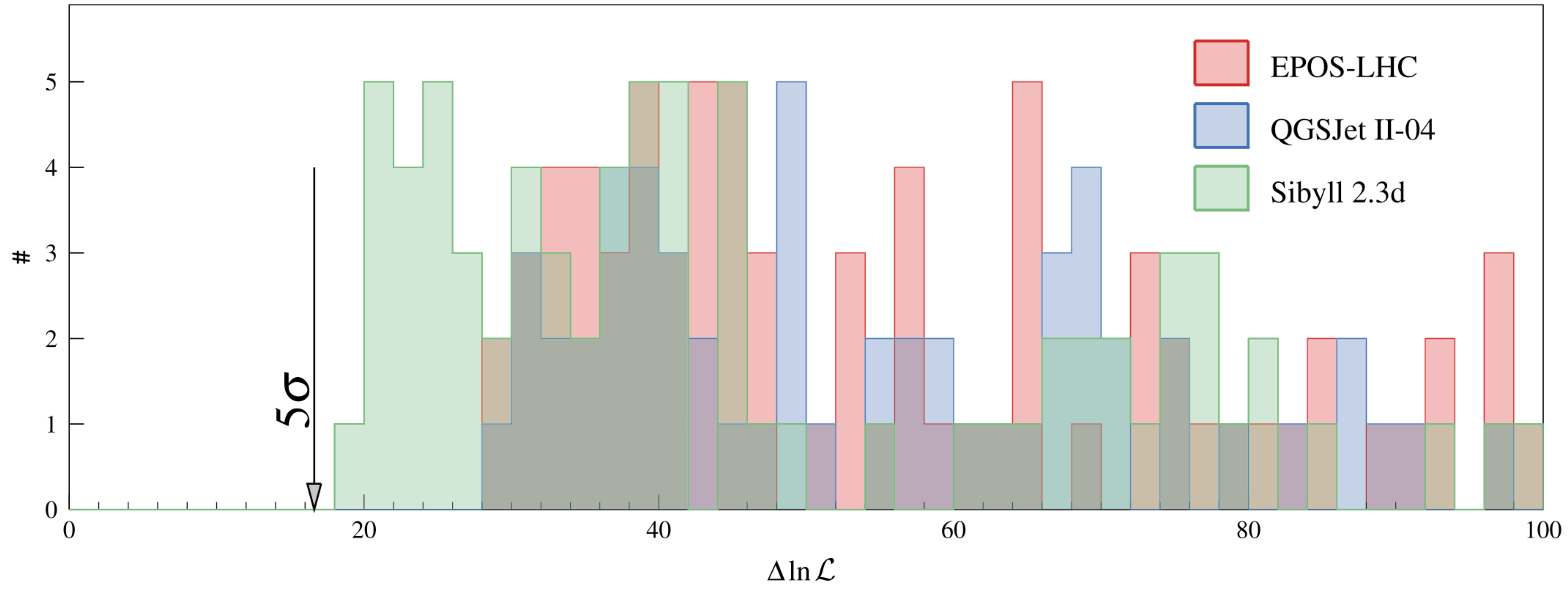
Systematic uncertainties

$E - 14\%$

$E + 14\%$

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

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



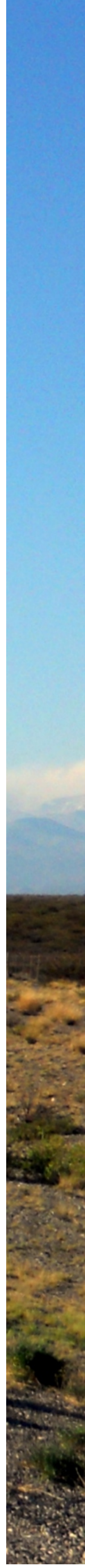
Systematic uncertainties

$S(1000) - 5\%$

$S(1000) + 5\%$

Method

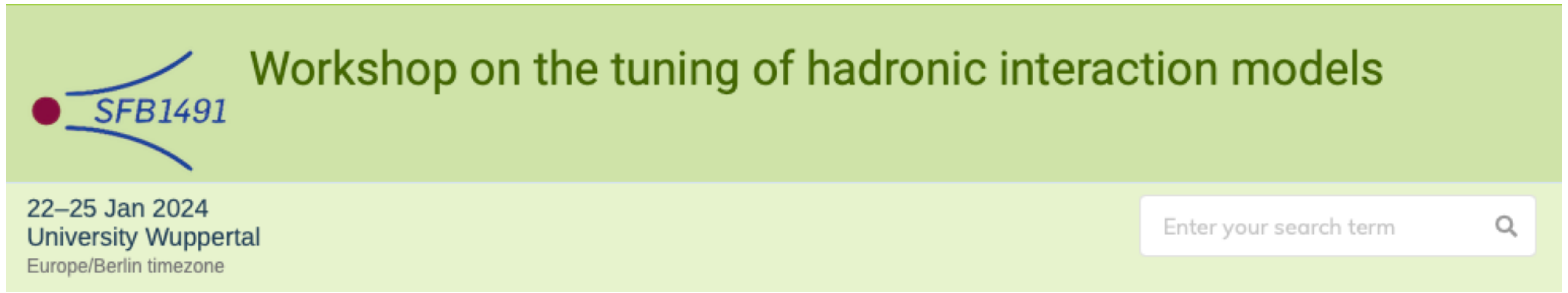
None of the post-LHC hadronic interaction models can describe the Auger ($X_{\max}, S_{1000}$) data, even considering the systematic uncertainties



More details in J. Vicha's talk

Models tuning efforts

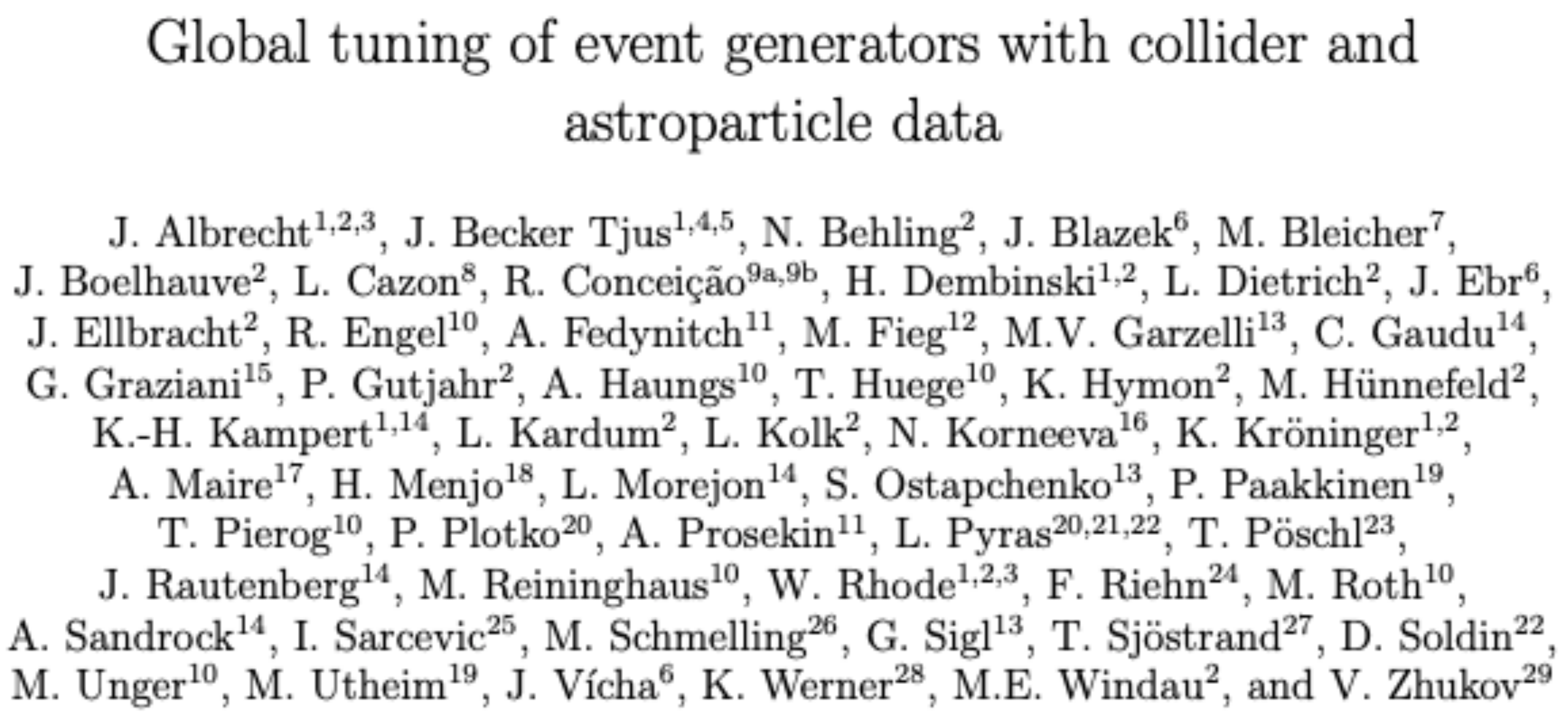
- Workshop on how to tune hadronic interaction models
  - **Integrate all available accelerator and astroparticle experiments data**
- Incoming **proton-Oxygen LHC run** in 2025 will significant boost our knowledge over the shower
- Efforts to integrate Pythia 8 + Angantyr model with CORSIKA8 to simulate air showers
  - Create a fixed-target tune (Wuppertal tune) to study EAS



Workshop on the tuning of hadronic interaction models

22–25 Jan 2024
University Wuppertal
Europe/Berlin timezone

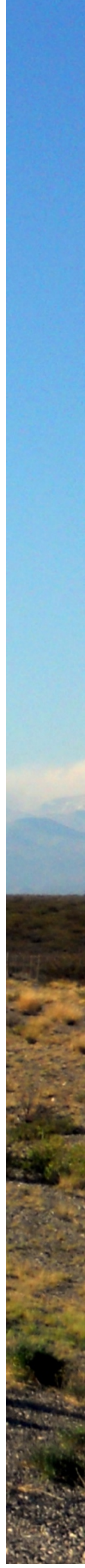
https://indico.uni-wuppertal.de/event/284/overview



Global tuning of event generators with collider and astroparticle data

J. Albrecht[1,2,3], J. Becker Tjus[1,4,5], N. Behling[2], J. Blazek[6], M. Bleicher[7], J. Boelhauve[2], L. Cazon[8], R. Conceição[9a,9b], H. Dembinski[1,2], L. Dietrich[2], J. Ebr[6], J. Ellbracht[2], R. Engel[10], A. Fedynitch[11], M. Fieg[12], M.V. Garzelli[13], C. Gaudu[14], G. Graziani[15], P. Gutjahr[2], A. Haungs[10], T. Huege[10], K. Hymon[2], M. Hünnefeld[2], K.-H. Kampert[1,14], L. Kardum[2], L. Kolk[2], N. Korneeva[16], K. Kröninger[1,2], A. Maire[17], H. Menjo[18], L. Morejon[14], S. Ostapchenko[13], P. Paakkinen[19], T. Pierog[10], P. Plotko[20], A. Prosekin[11], L. Pyras[20,21,22], T. Pöschl[23], J. Rautenberg[14], M. Reininghaus[10], W. Rhode[1,2,3], F. Riehn[24], M. Roth[10], A. Sandrock[14], I. Sarcevic[25], M. Schmelling[26], G. Sigl[13], T. Sjöstrand[27], D. Soldin[22], M. Unger[10], M. Utheim[19], J. Vícha[6], K. Werner[28], M.E. Windau[2], and V. Zhukov[29]

See C. Gaudu's poster



CORSIKA8 news in M. Gottowik's talk

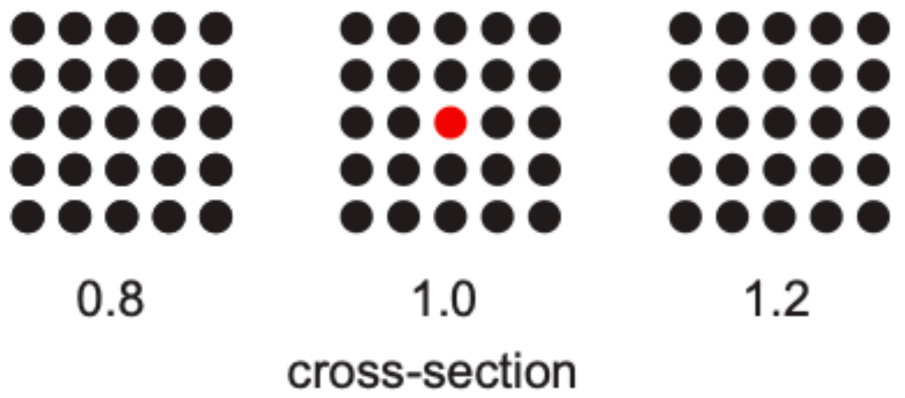
Understand the available phase space

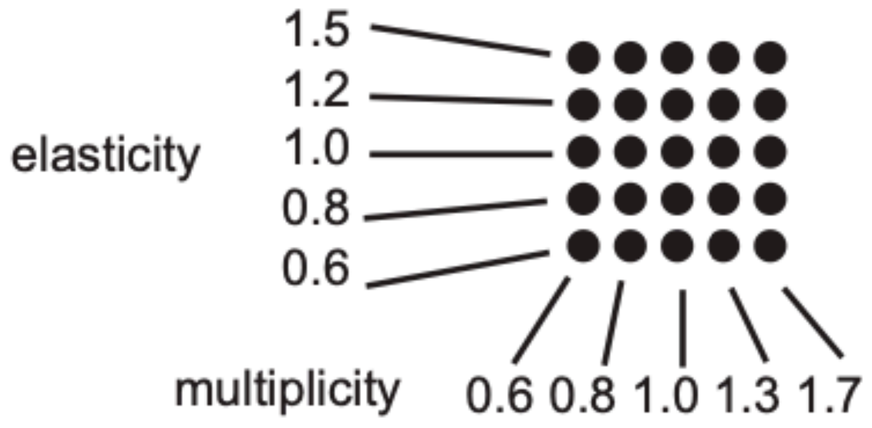
J. Ebr et al., PoS(ICRC2023)245

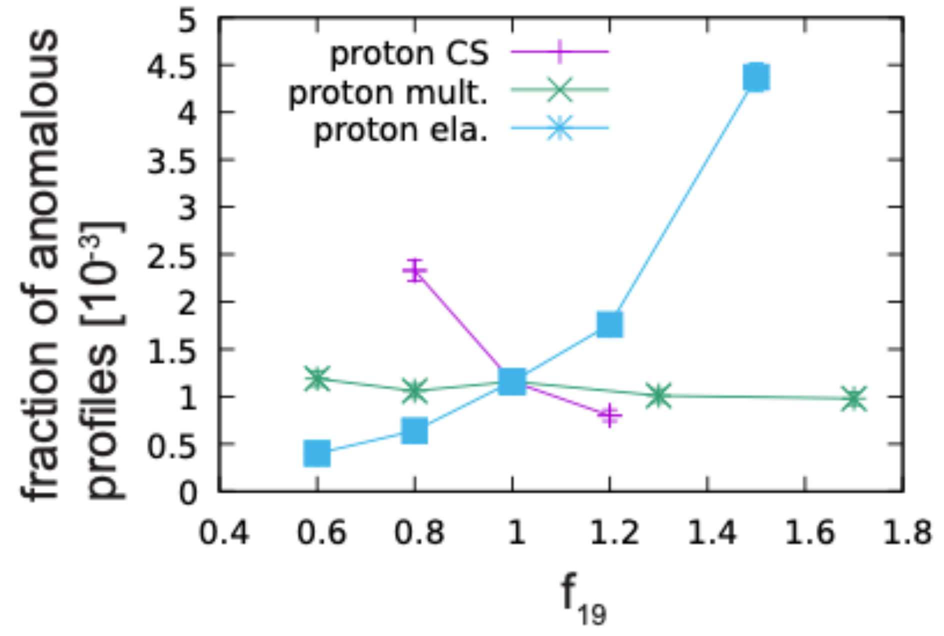
MOCHI

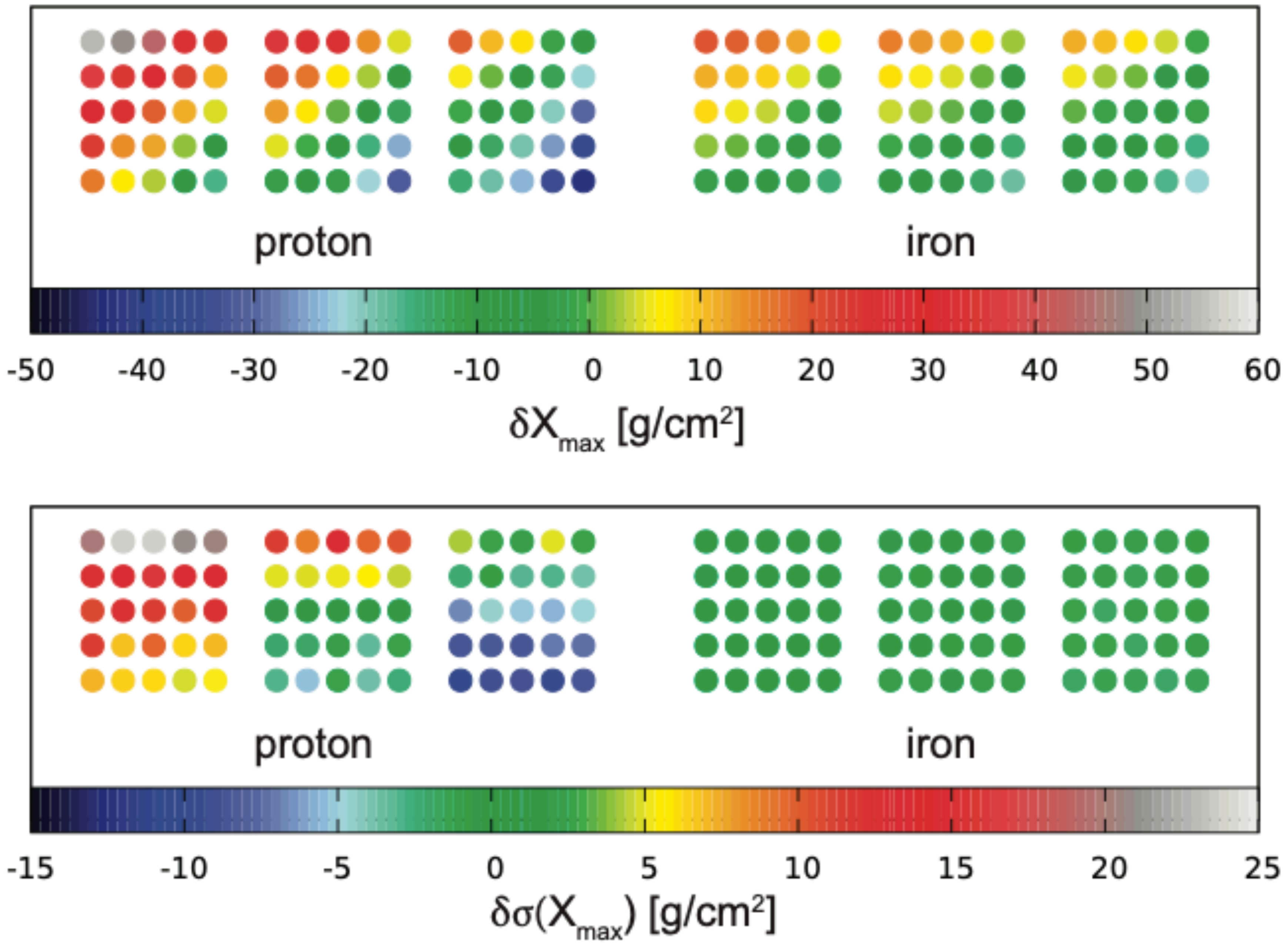
(**MO**dified **C**haracteristics of **H**adronic **I**nteractions)

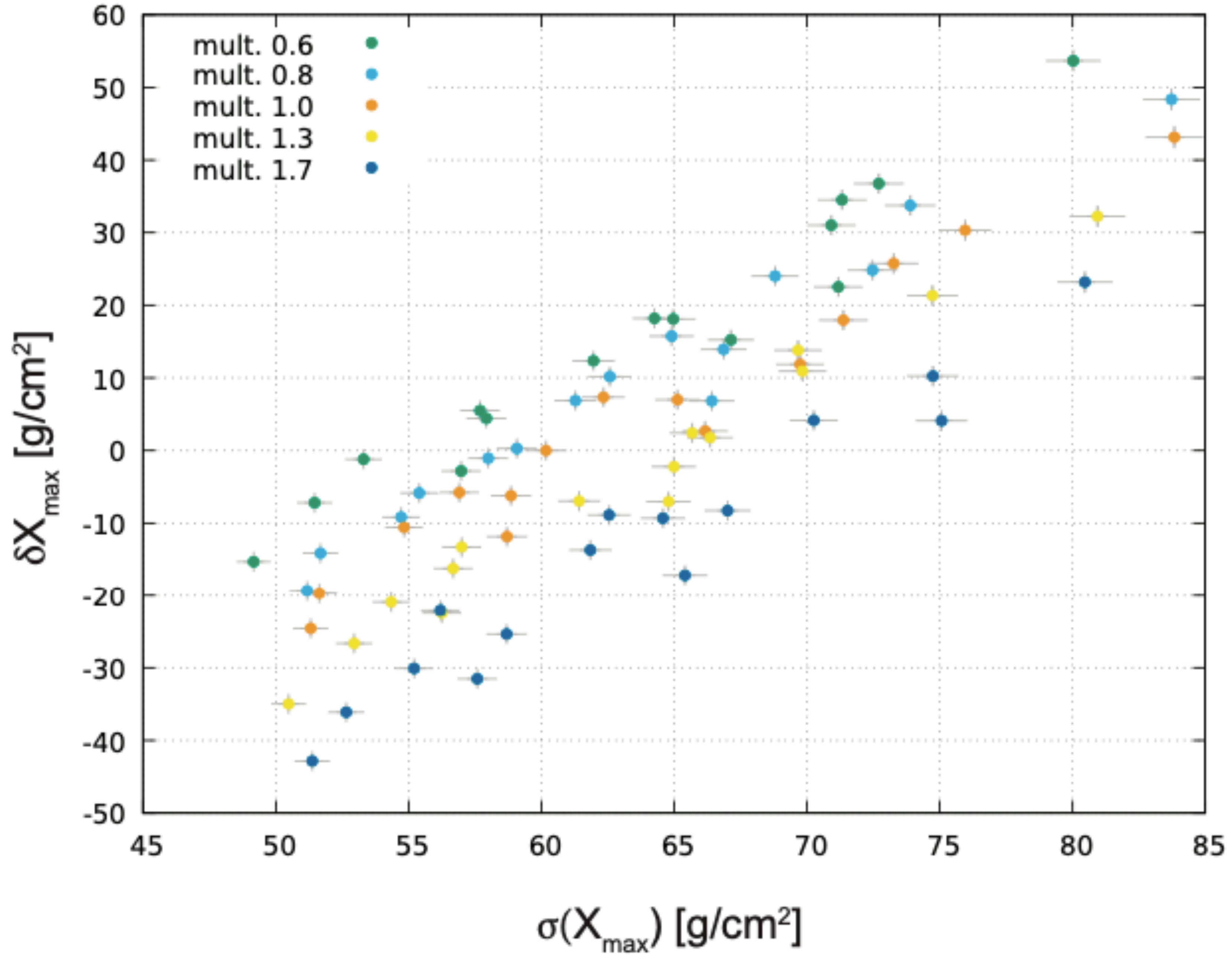
Explore the phase space to better understand impact of model parameters on shower observables

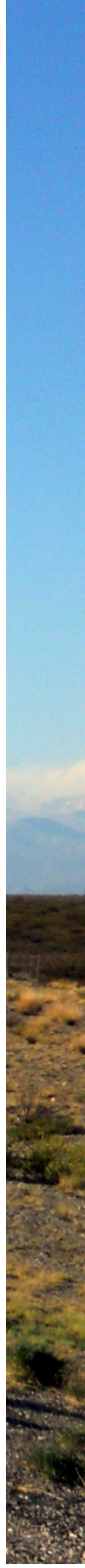








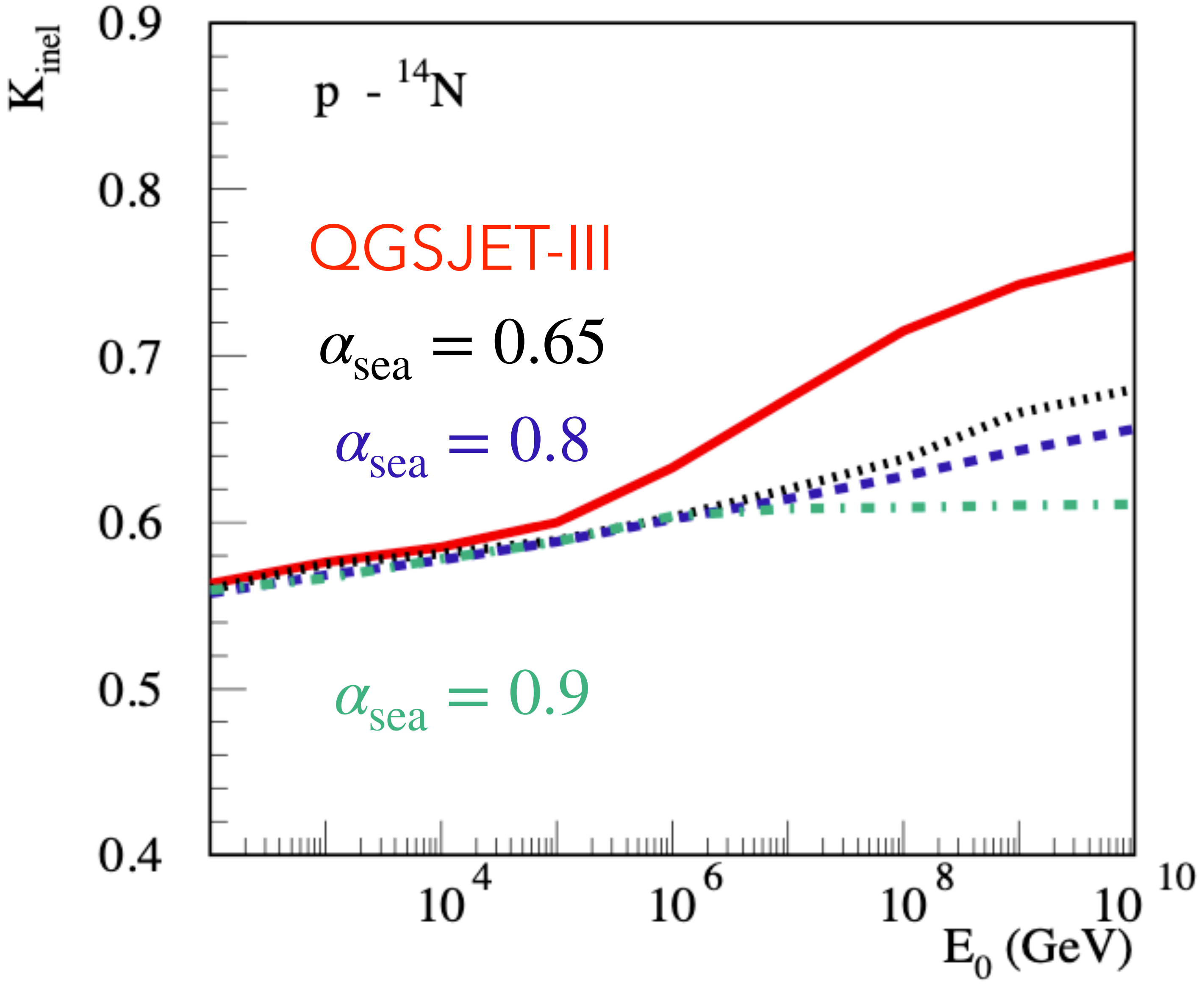


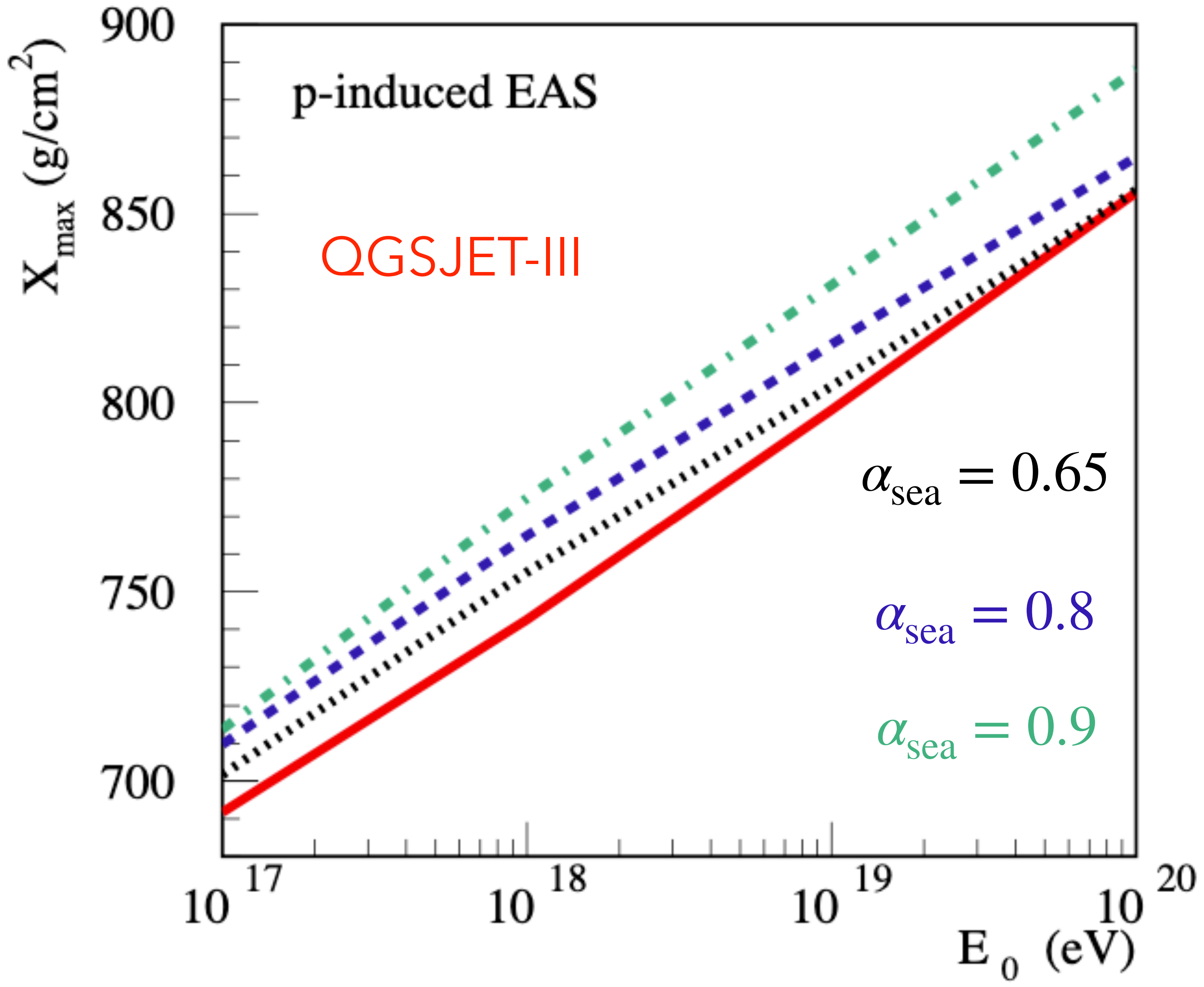


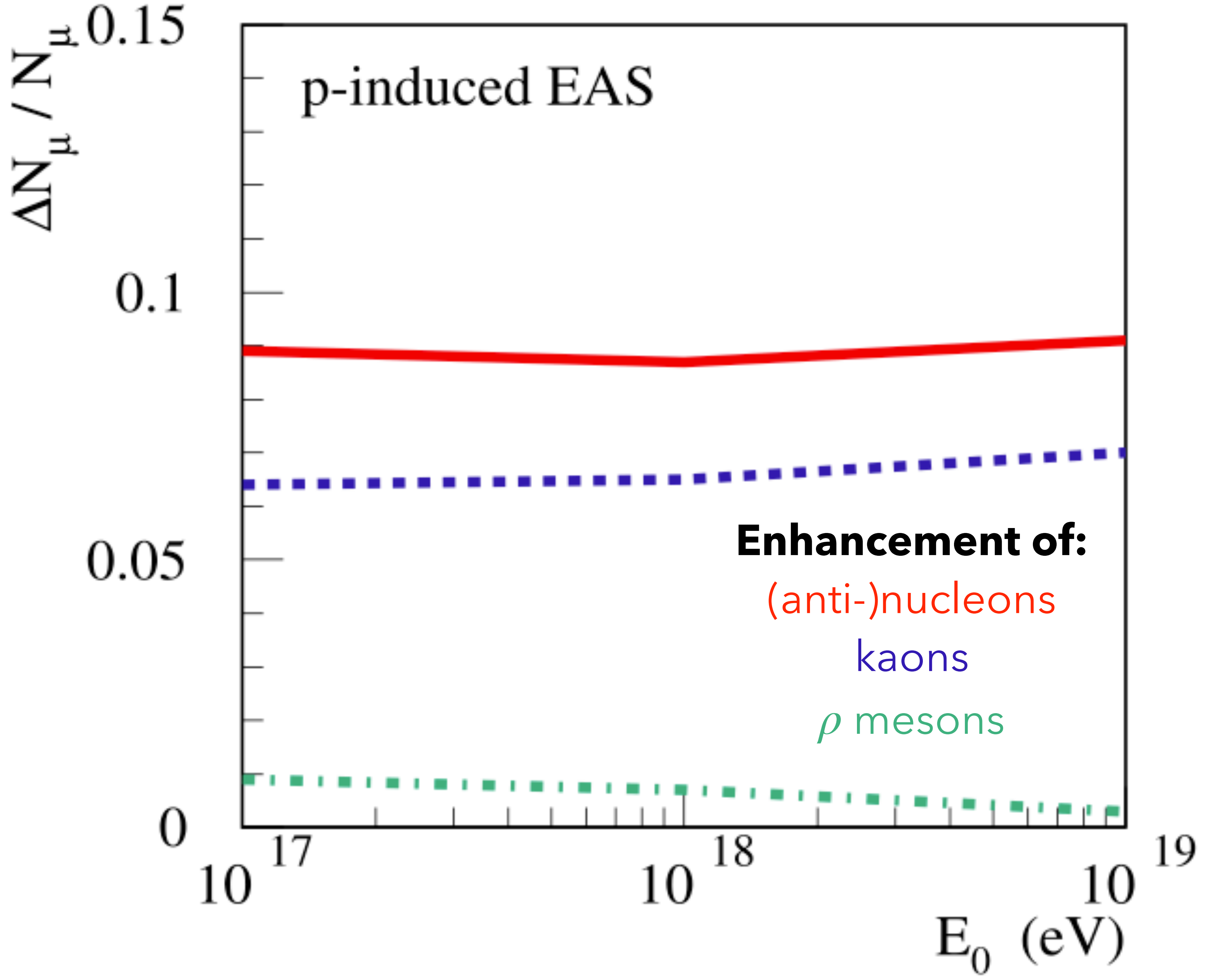
More details in J. Ebr's talk

Estimating the Model Uncertainties

S. Ostapchenko, G. Sigl, Phys.Rev.D 110 (2024) 6, 063041
S. Ostapchenko, G. Sigl, Astropart.Phys. 163 (2024) 103004





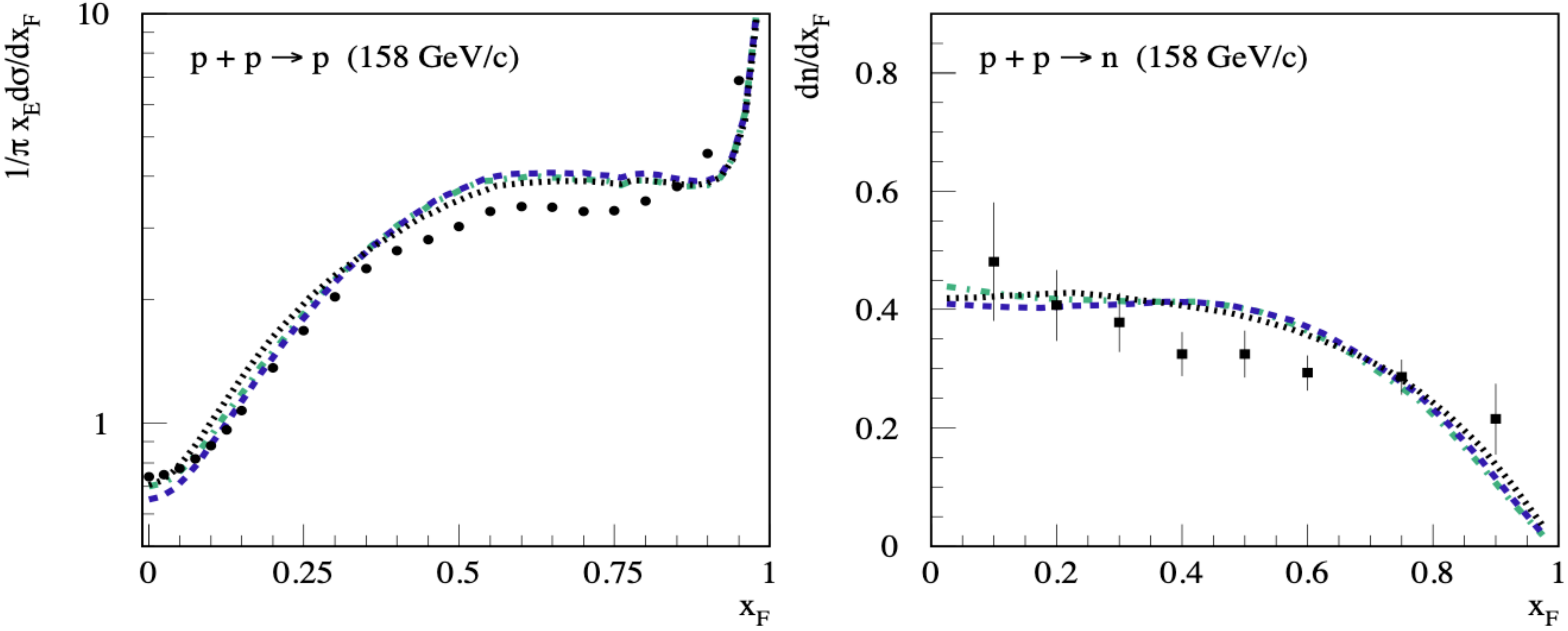


- Varying model parameters within experimental uncertainties results in:
  - X_{max} can vary up to $10\ \mathrm{g\,cm^{-2}}$ ($30\ \mathrm{g\,cm^{-2}}$ in exotic scenarios, disfavoured by accelerators)
  - N_μ can be increased in about $10\,\%$

Estimating the Model Uncertainties

S. Ostapchenko, G. Sigl, Phys.Rev.D 110 (2024) 6, 063041

S. Ostapchenko, G. Sigl, Astropart.Phys. 163 (2024) 103004



- While hadronic interaction models have had a great success describing and even predicting new accelerator data it's important to note that the agreement with data is not perfect
- **New unaccounted phenomena might change this picture**

A Quantum Leap is On the Horizon!

A few examples that illustrate how significantly the scrutiny of air showers is expected to intensify in the coming years

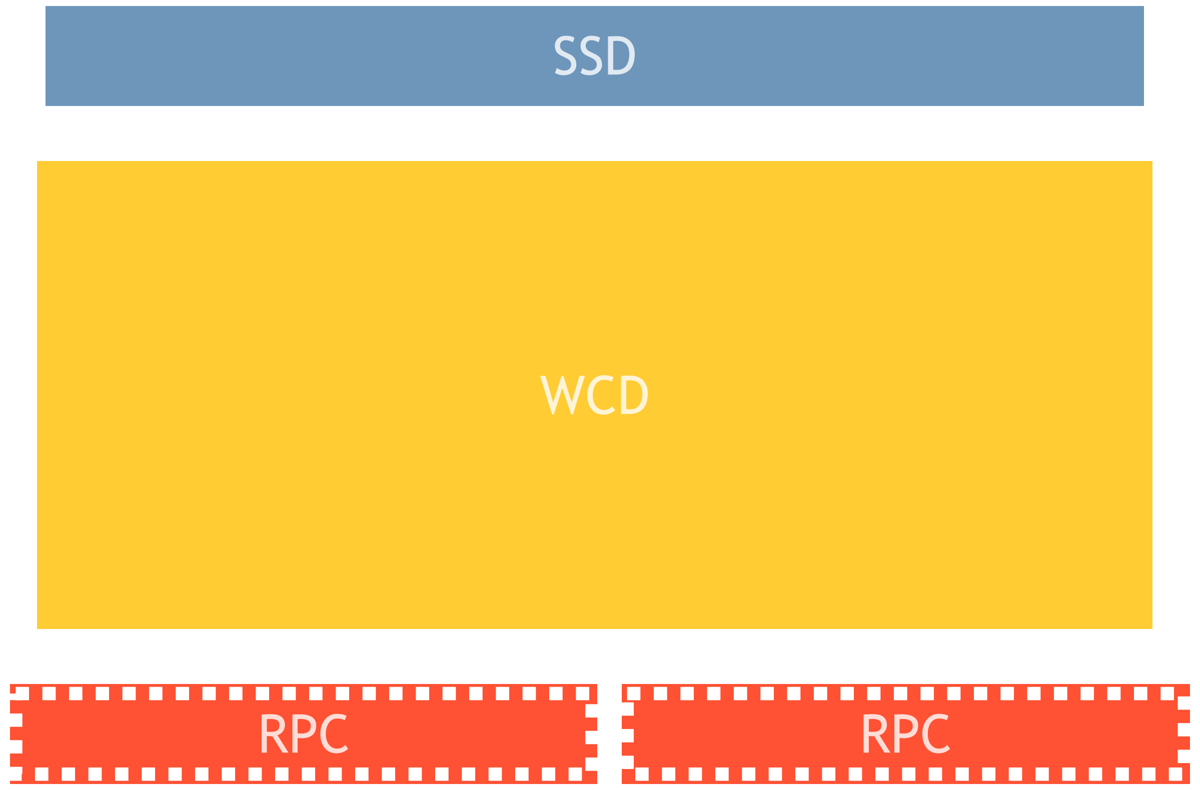
Multi-hybrid events

The capability to analyze the same air showers using multiple instruments

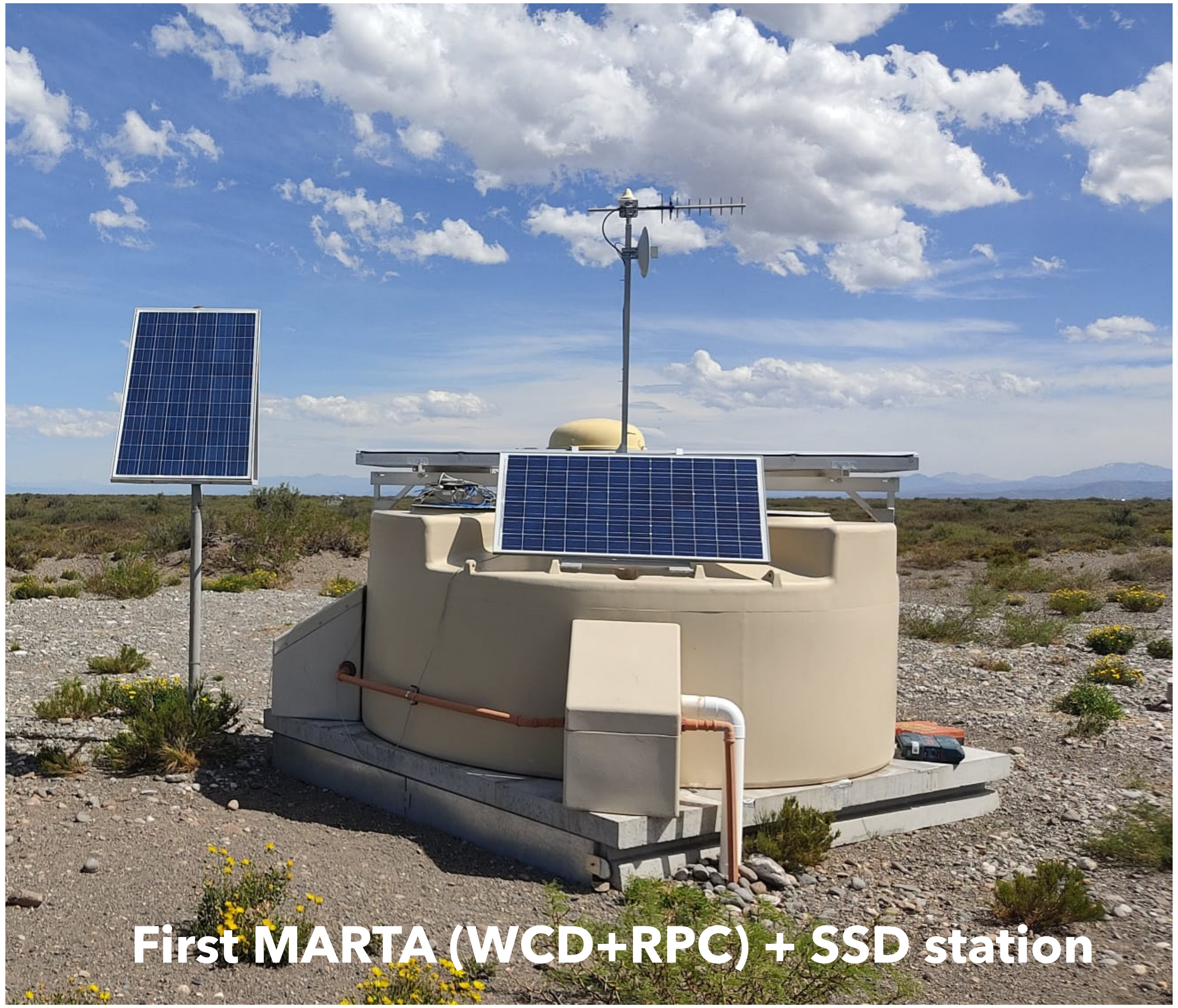
(see, for instance, talks and posters about AugerPrime in this conference)

Multi-hybrid stations

- Shower particles are crossing multiple detectors
- Detectors respond differently to particle type and energy
  - **SSD** (scintillator) is mainly counting particles (MIP)
  - **WCD** (water Cherenkov detector) sensitive to particle energy
    - E.m. component $\propto$ energy
    - Muons $\propto \beta \, (E_\mu \leq 1\,\mathrm{GeV})$ and tracklength in WCD
  - **RPC** (Resistive Plate Chambers) shielded by the WCD and the concrete precast
    - Due to its segmentation, it can identify regions dominated by muons from others

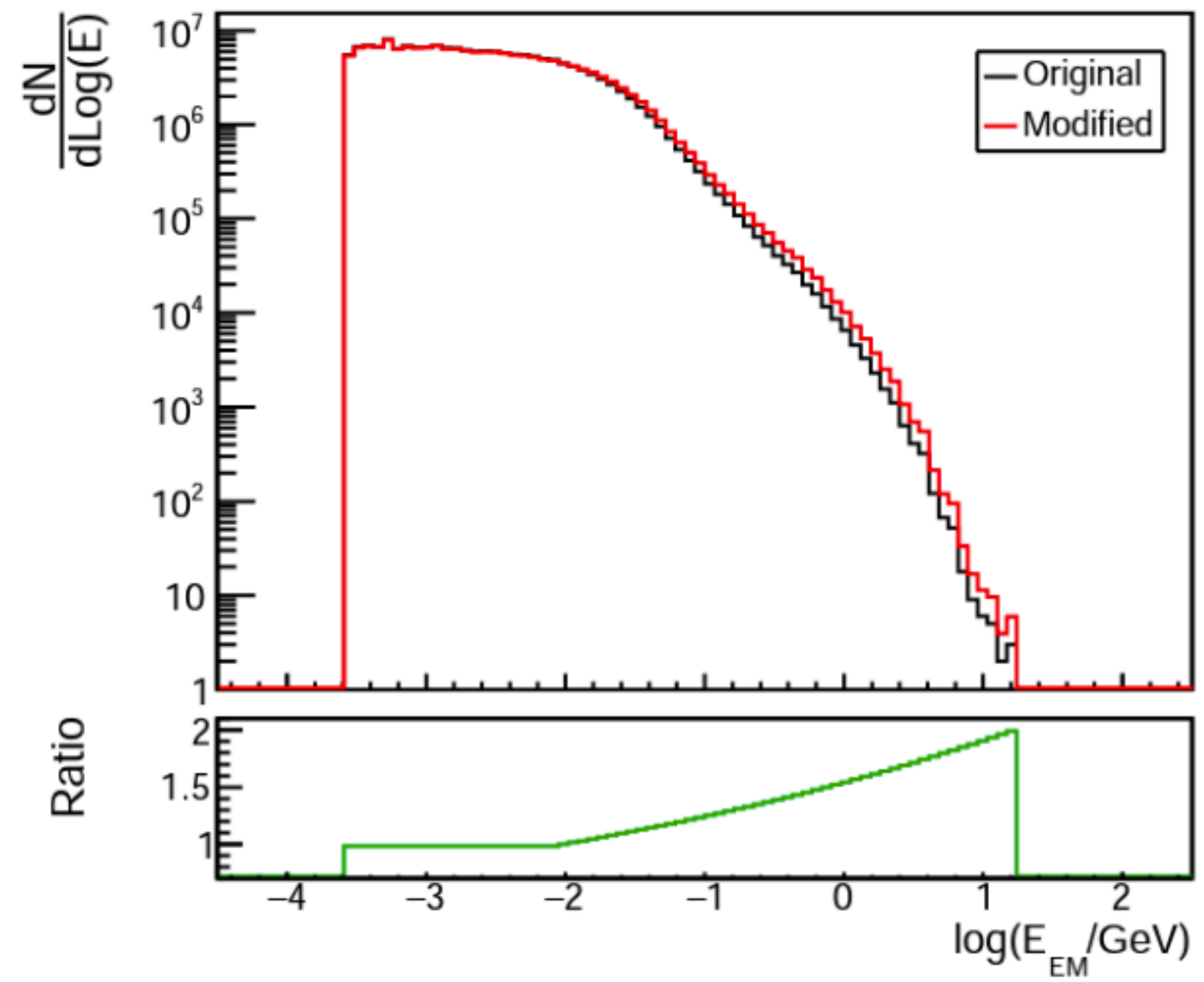


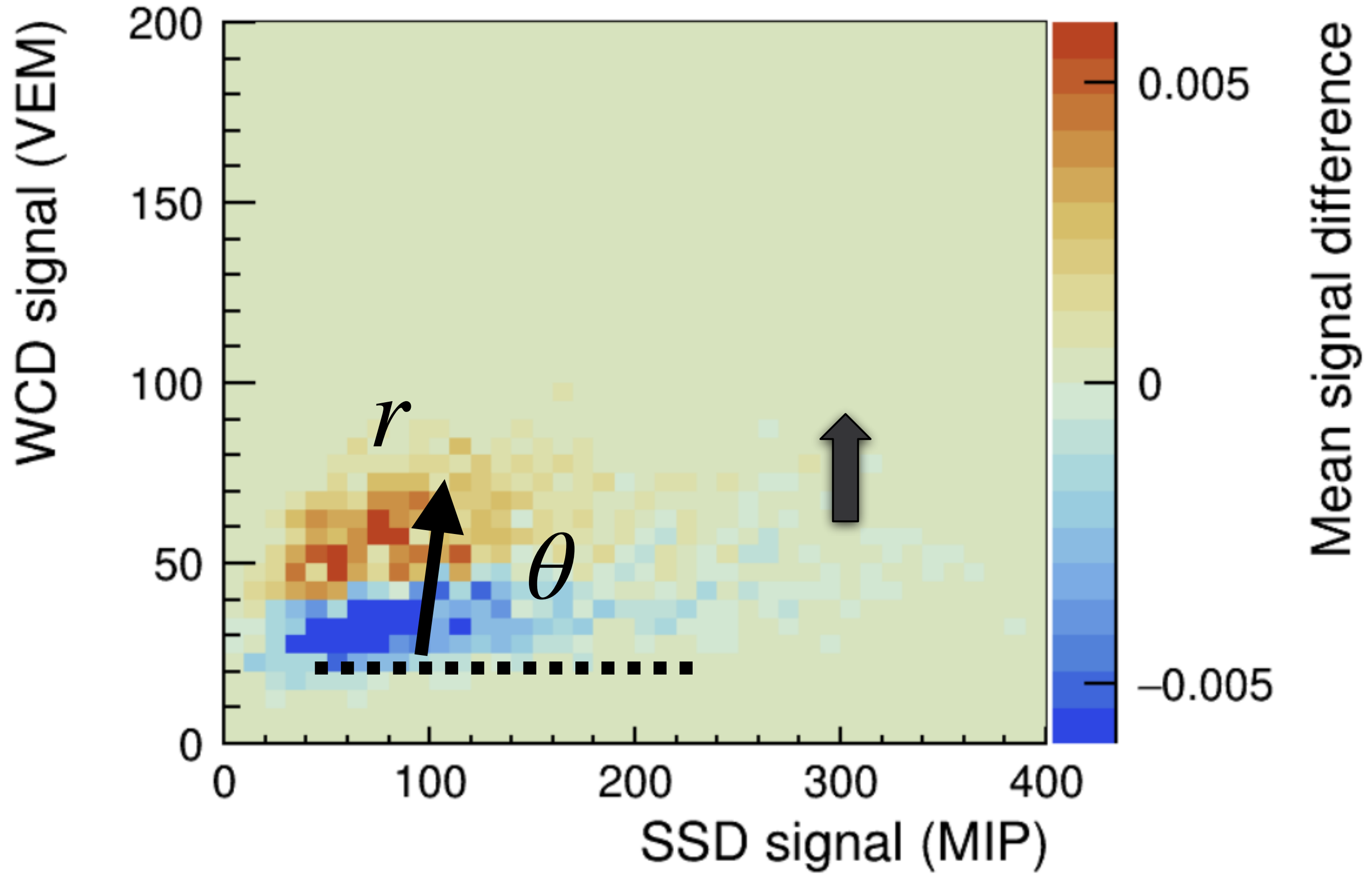
P. Assis, RC, et al Eur.Phys.J.C 78 (2018) 4, 333

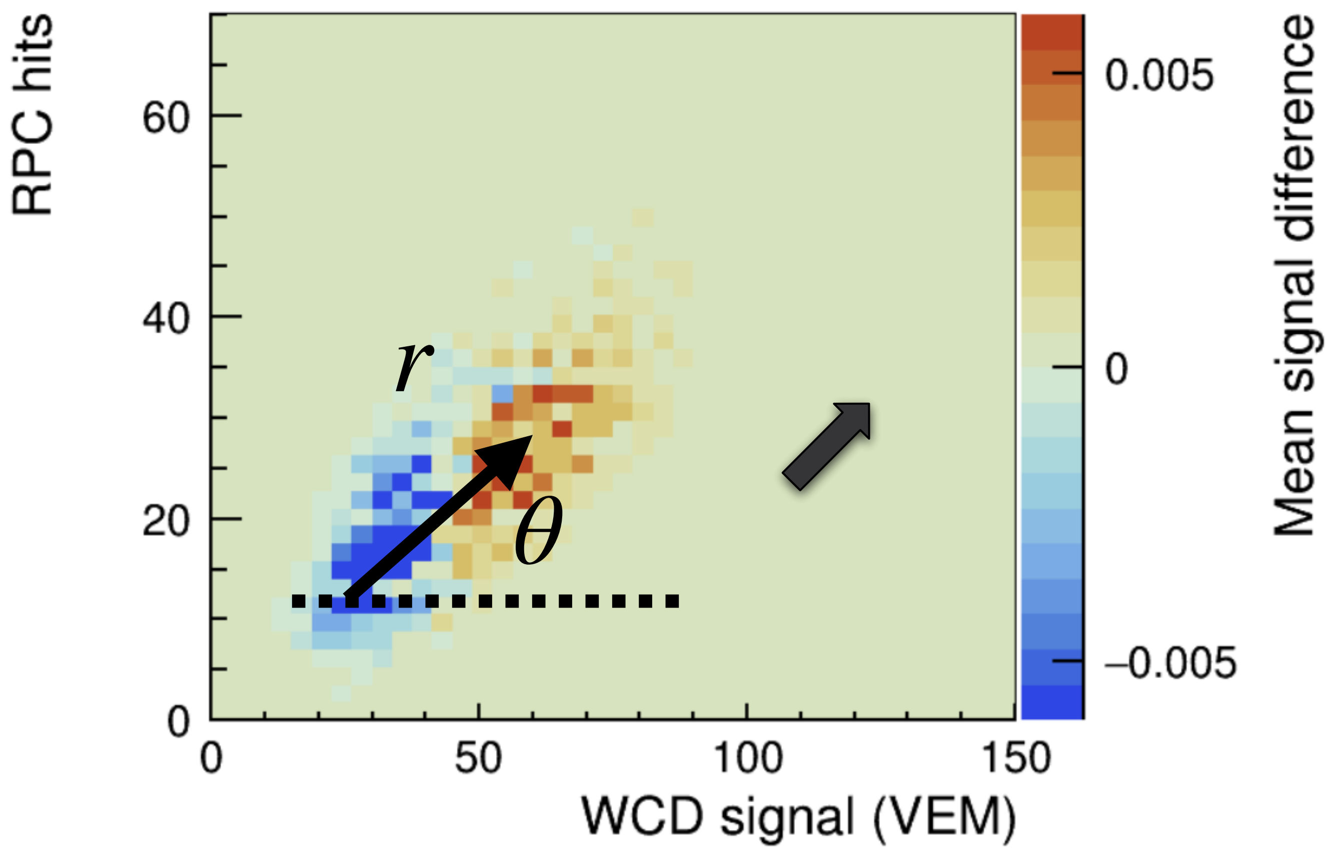


Multi-hybrid stations

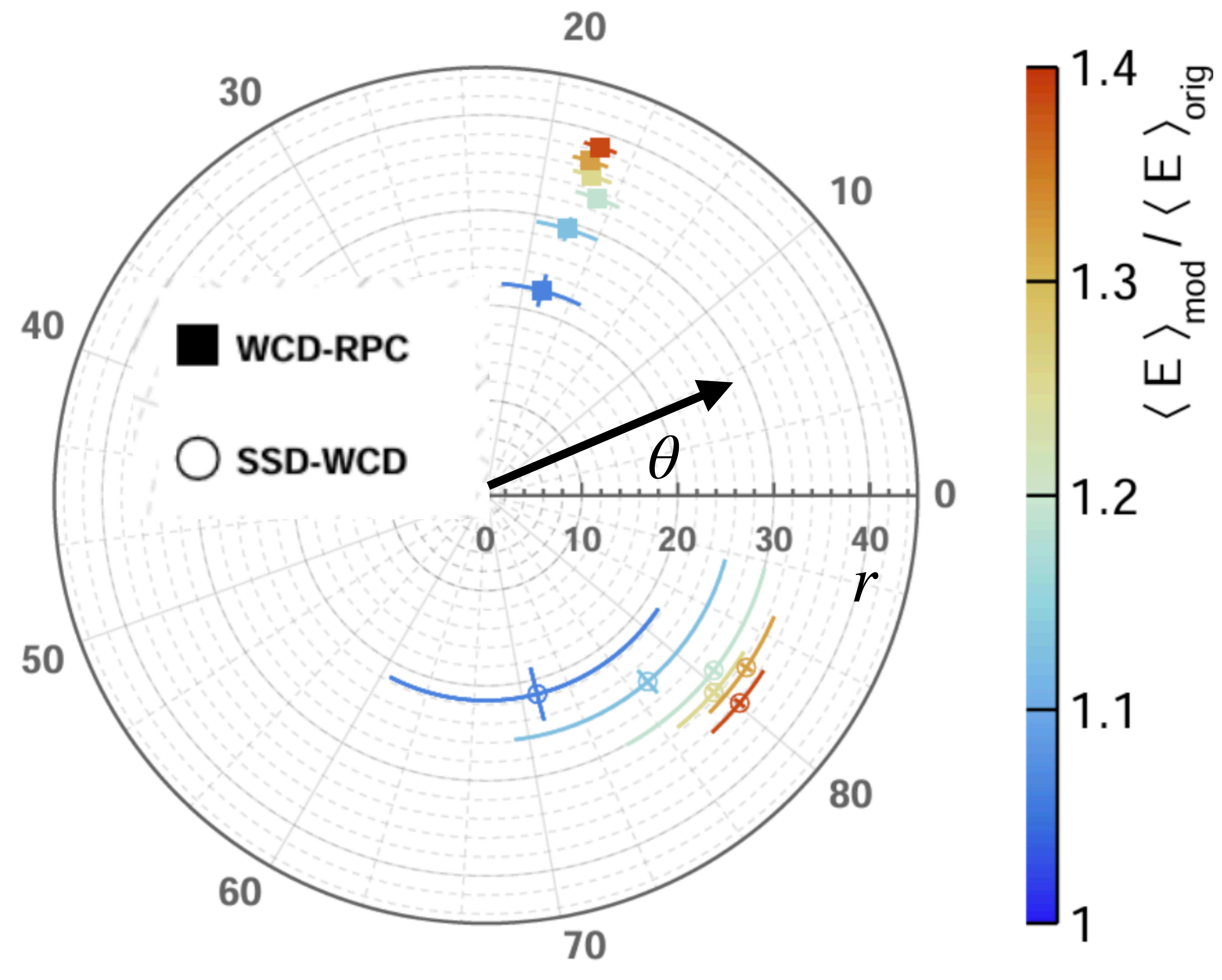
- Select a station close to the shower core ($r = 320\,\mathrm{m}$)
- Increase the high-energy tail of the e.m. energy spectrum of shower secondary particles
- **Sensitive to changes in the energy spectrum of e.m. secondary particles**
- **Insensitive** to detector **aging** effects





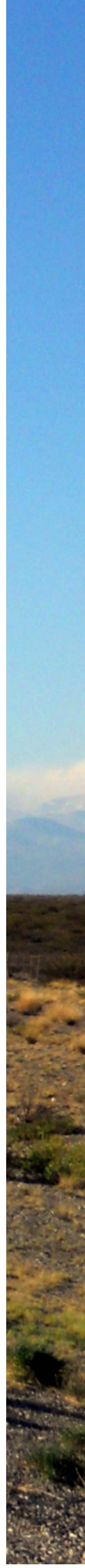


P. Assis, RC, M. Freitas et al., to be submitted soon



Energy Spectrum Estimator

Vector between positive and negative barycenters



The rise of machine learning in EAS physics

Unlocking previously inaccessible information

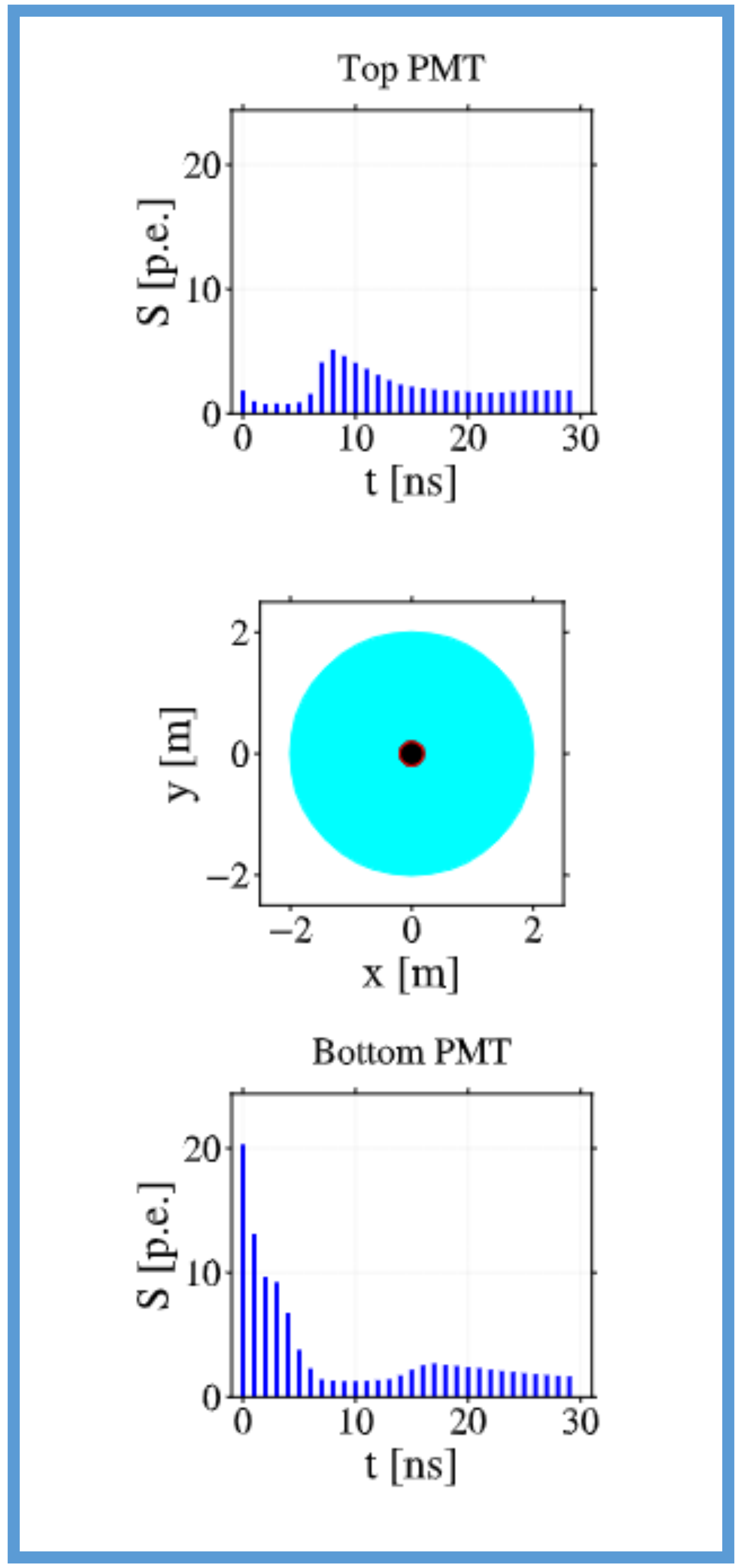
See, for instance, posters by:

S. Hahn for Pierre Auger Coll., L. Lavitola for SWGO Coll., E. Rodriguez for Pierre Auger Coll., M. Shahvar et al.

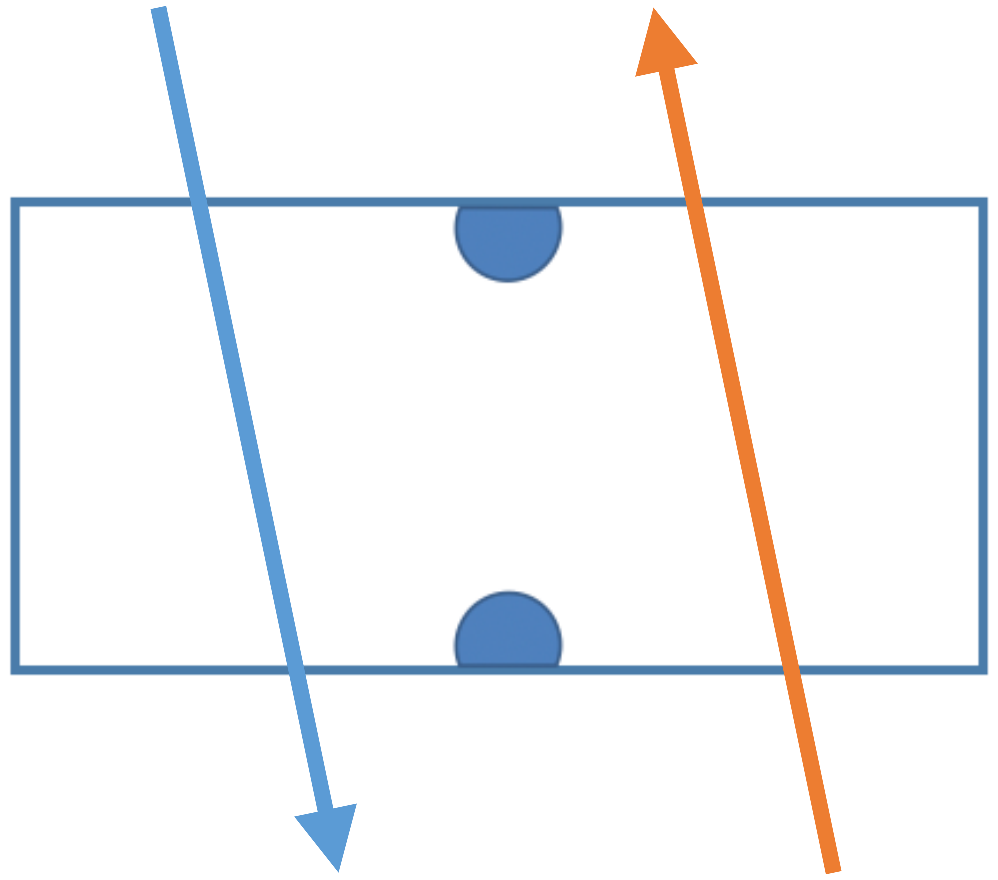
Catching neutrinos with a single WCD (I)

J. Alvarez-Muñiz, RC, B. S. González et al., Phys.Rev.D 110 (2024) 2, 023032

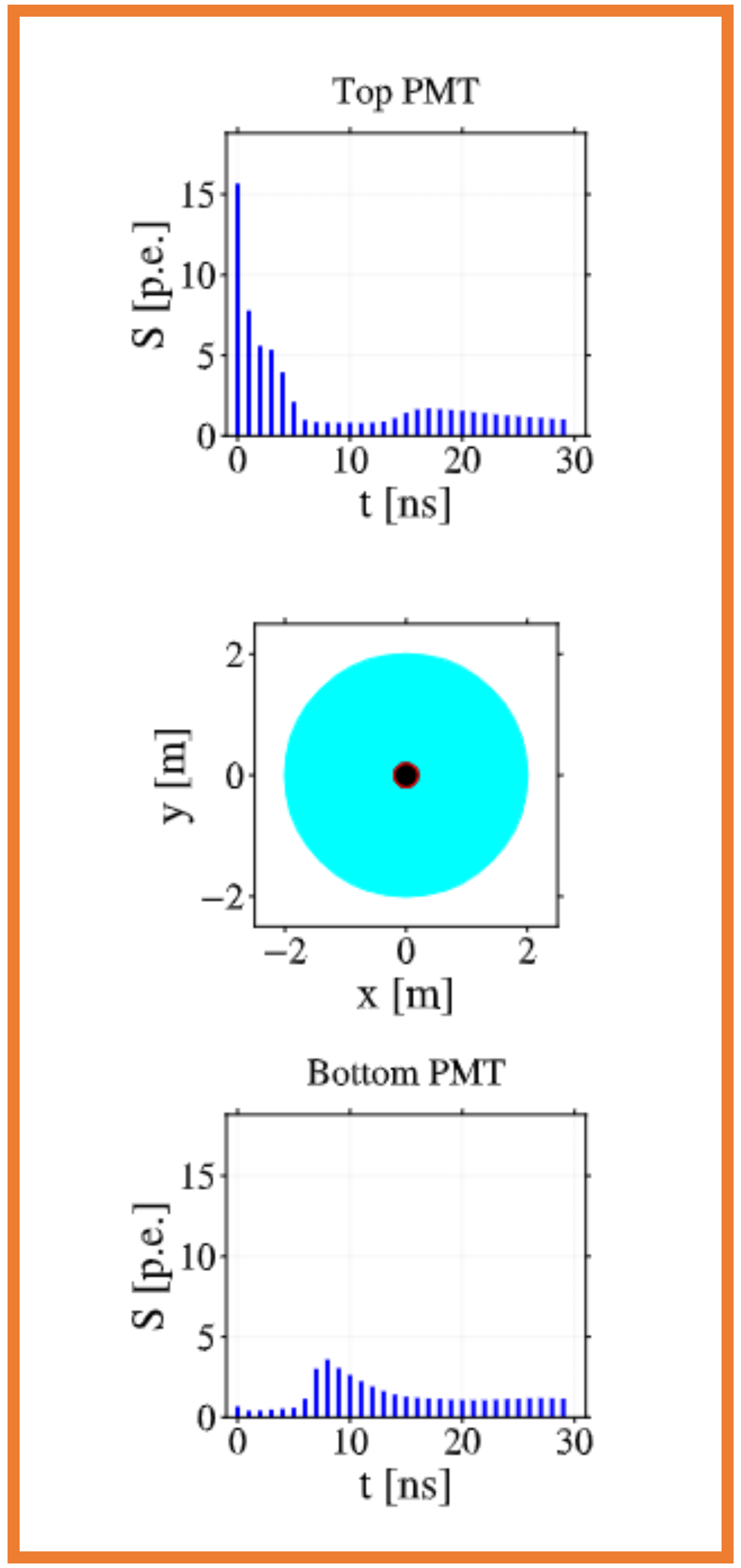
Background - cosmic ray events $(\theta < 40^\circ)$



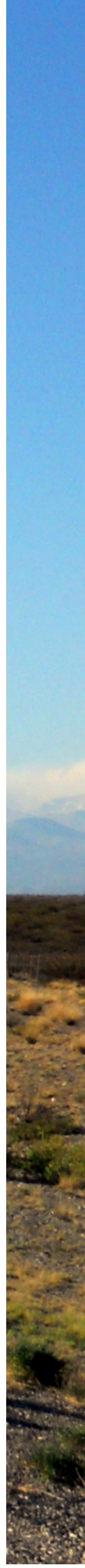
Down-going events



Signal - neutrino events $(\theta > 140^\circ)$

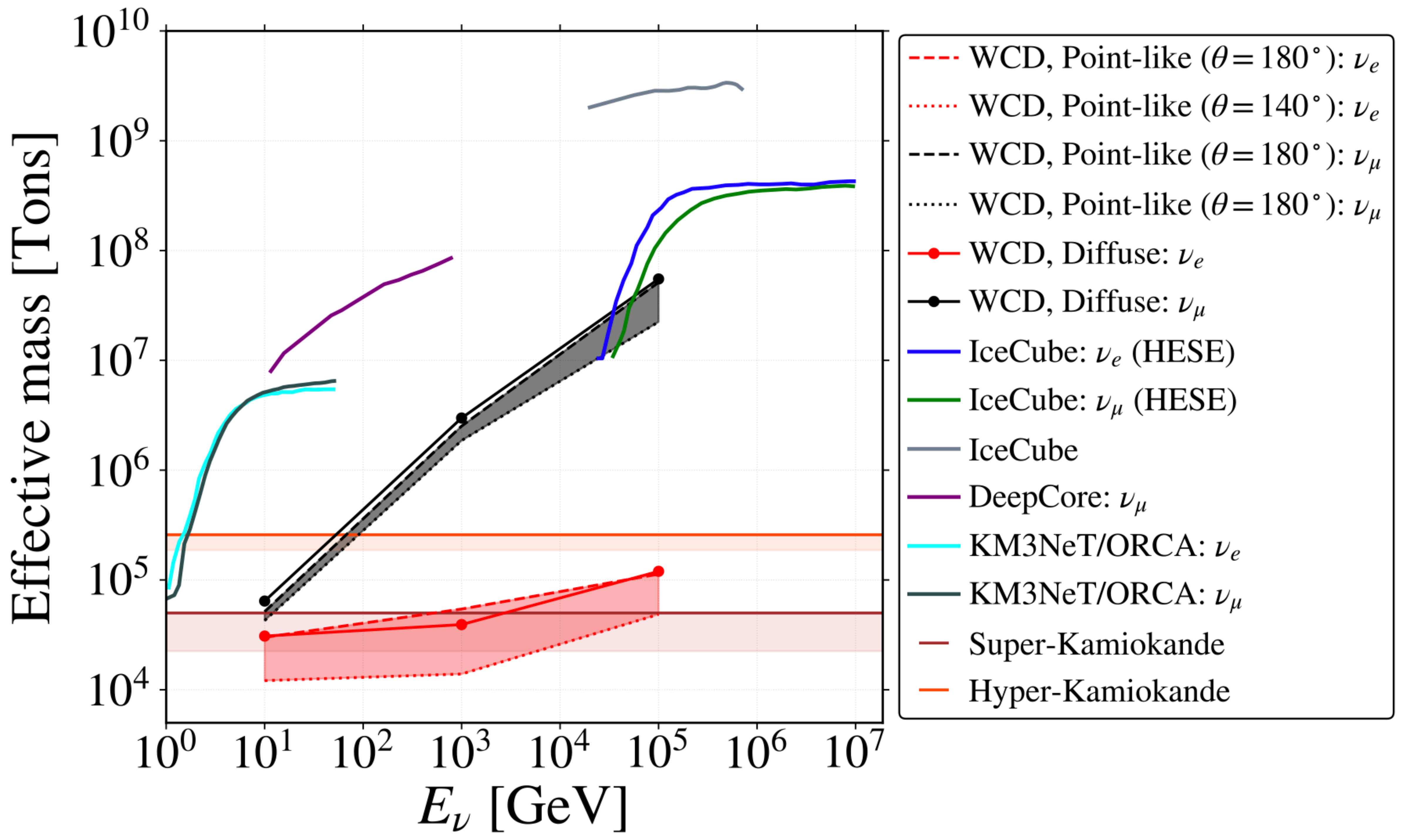


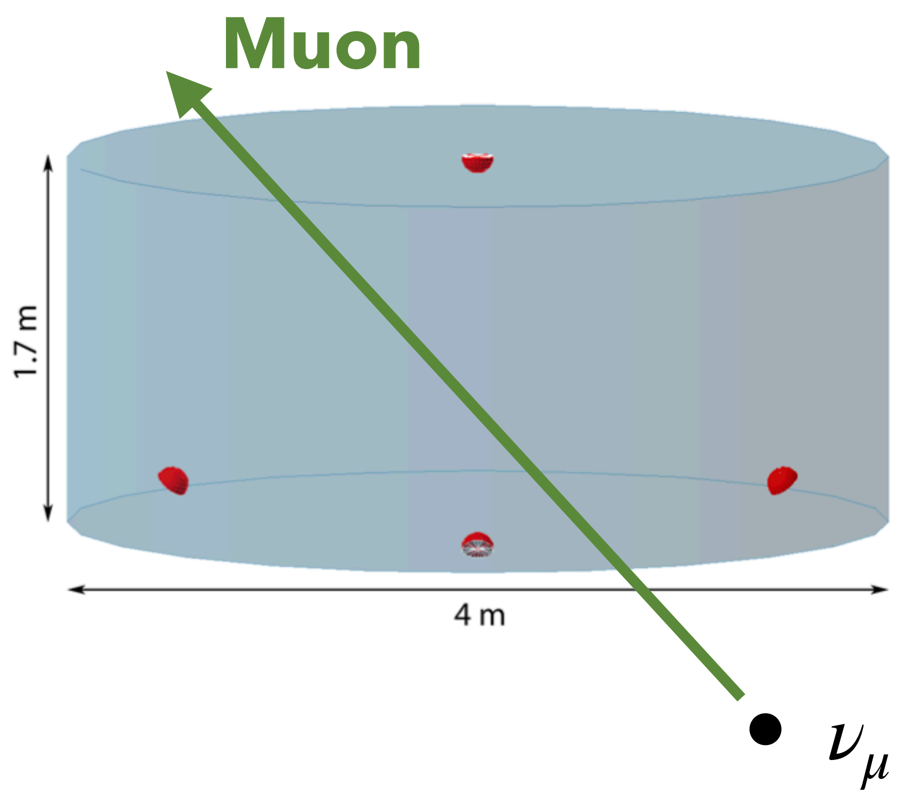
Up-going events

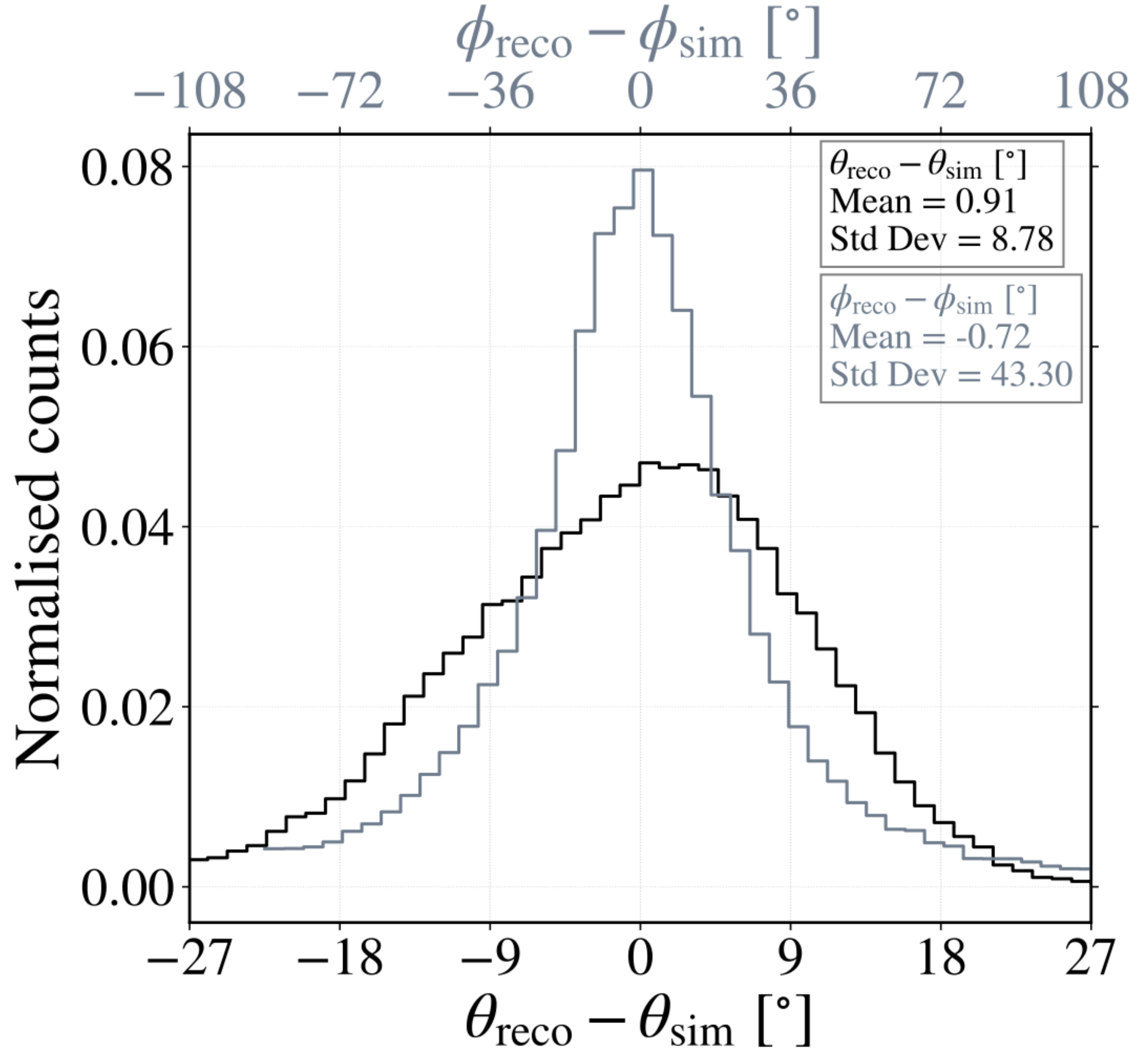


Catching neutrinos with a single WCD (II)

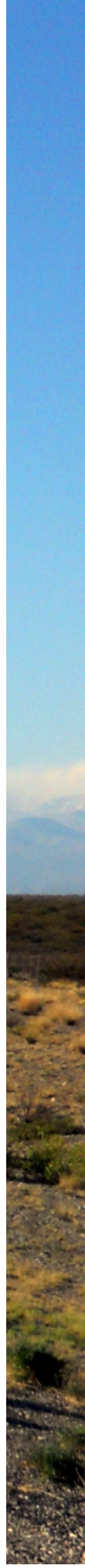
J. Alvazez-Muñiz, RC, B. S. González et al., Phys.Rev.D 110 (2024) 2, 023032





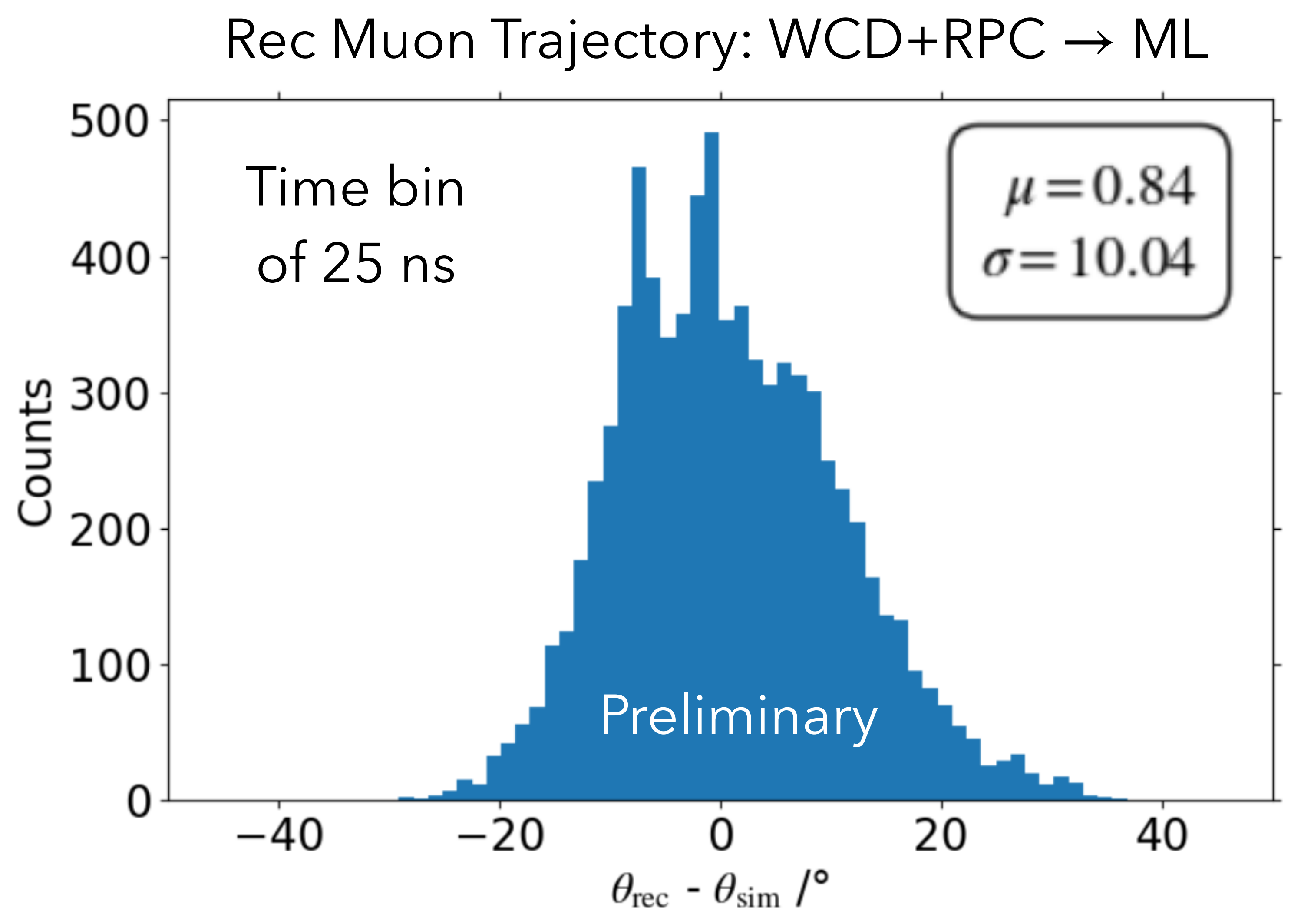


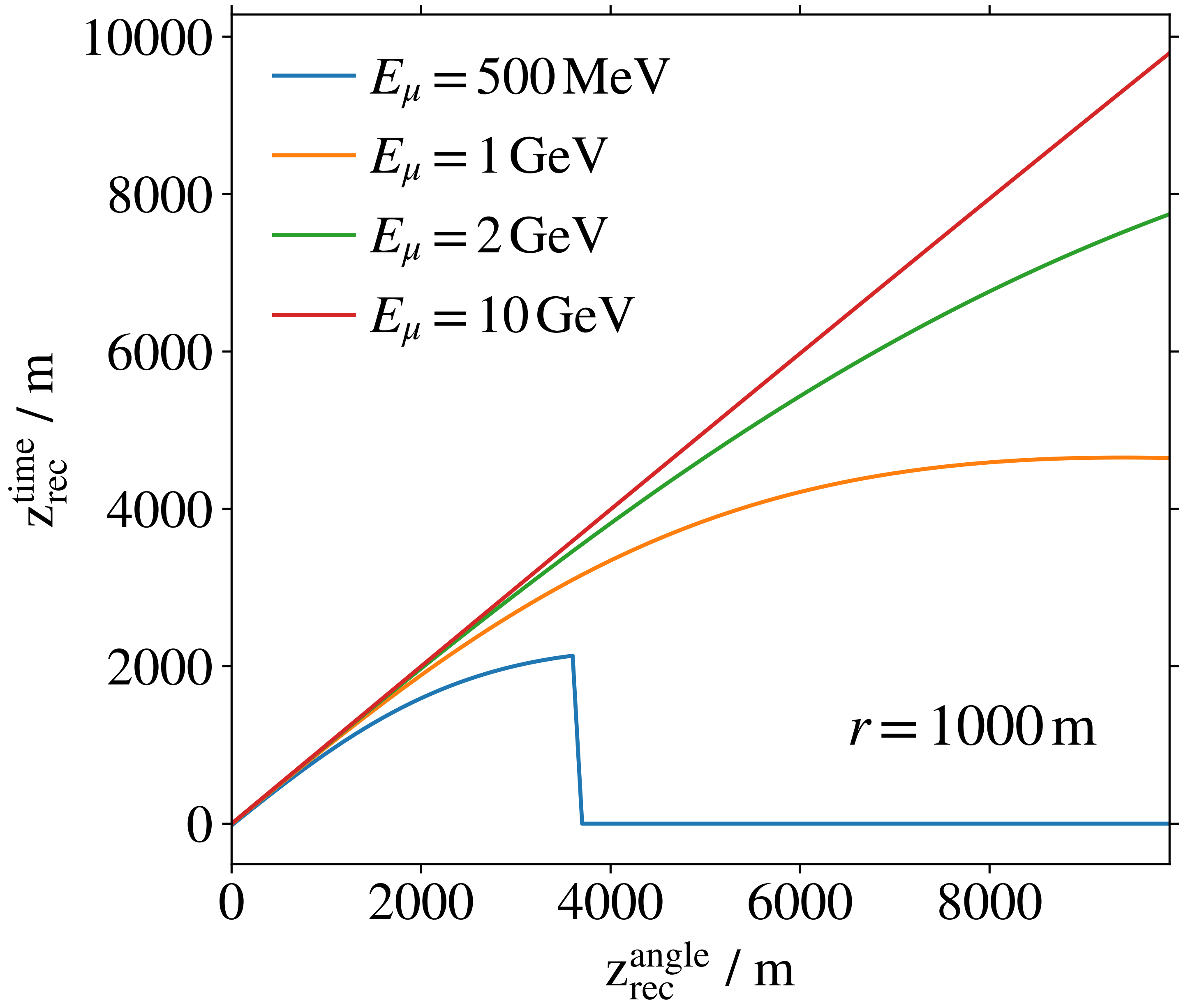
- ✧ Explore the PMT signal time trace structure recurring to ML algorithms:
  - ✧ Identify up-going ν from CR background
  - ✧ Use a CNN to reconstruct the direction of the neutrino (i.e. the muon traversing the WCD)



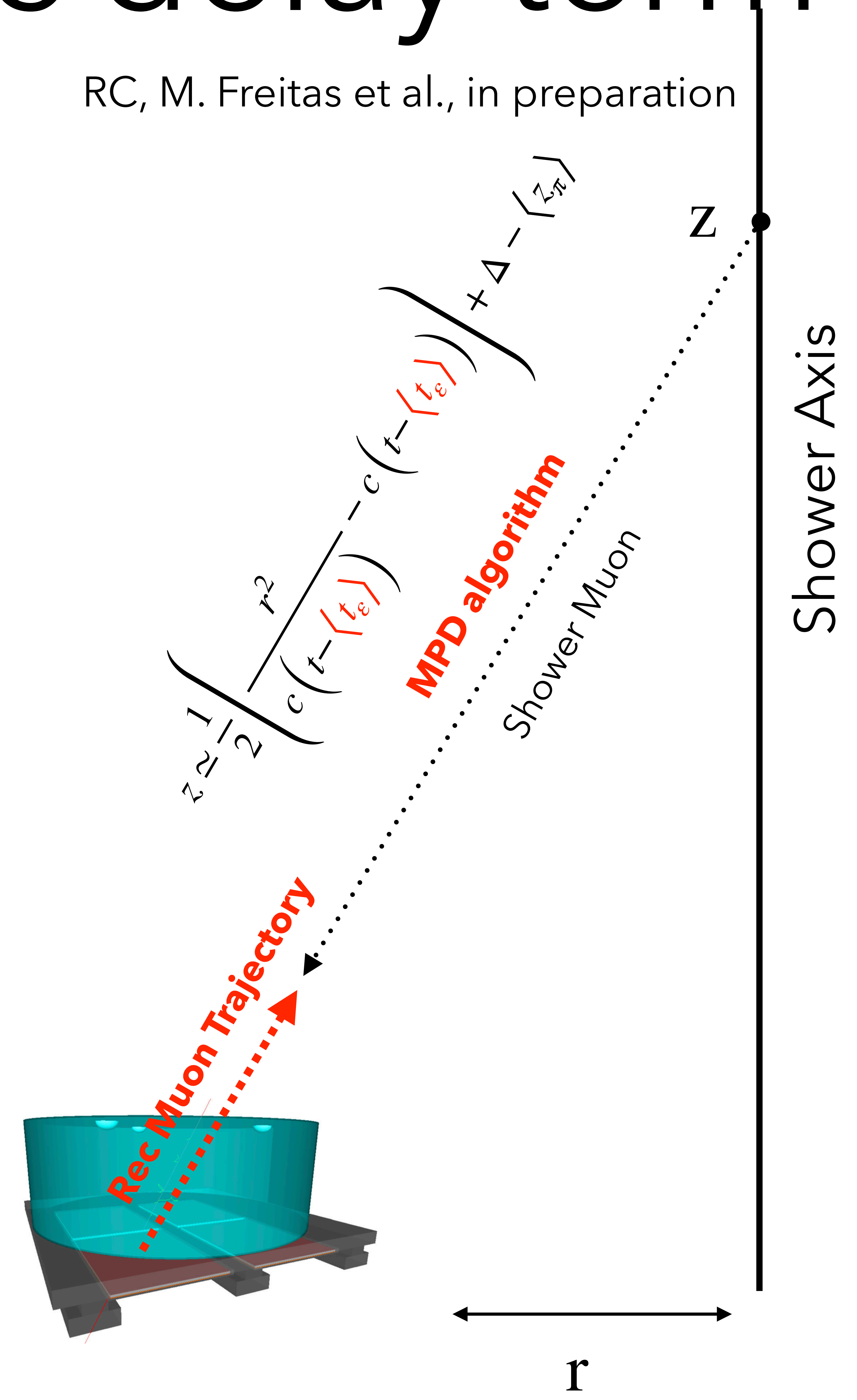
Accessing the MPD kinematic delay term

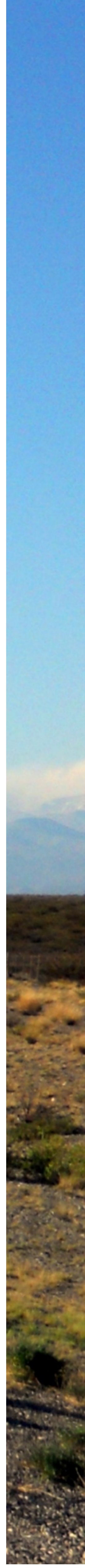
- Reconstruct muon trajectories by combining the active **RPC pad** and **WCD PMT signal time traces**, leveraging **machine learning** algorithms for enhanced accuracy - $z_{\rm rec}^{\rm angle}$
- Reconstruction of the muon production height (depth) with **arrival time delay of muon** w.r.t. shower from - $z_{\rm rec}^{\rm time}$
- *Integrate **muon direction** reconstruction with the **MPD** algorithm to capture the kinematic delay term, providing insights into the **muon energy spectrum***





RC, M. Freitas et al., in preparation





Understanding the first UHE interaction

Gaining insight into hadronic interactions at energies beyond the reach of human-made accelerators

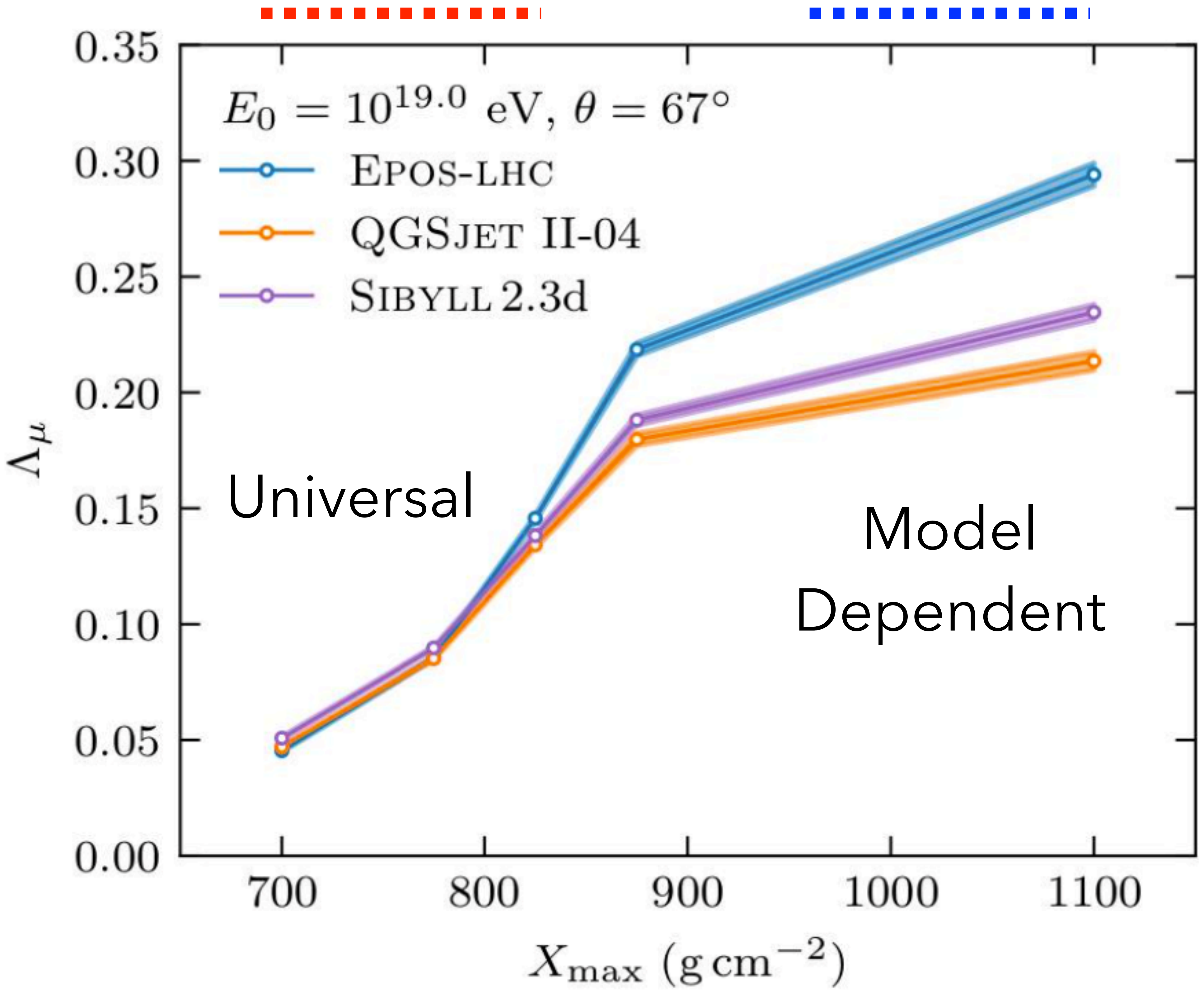
New insights!

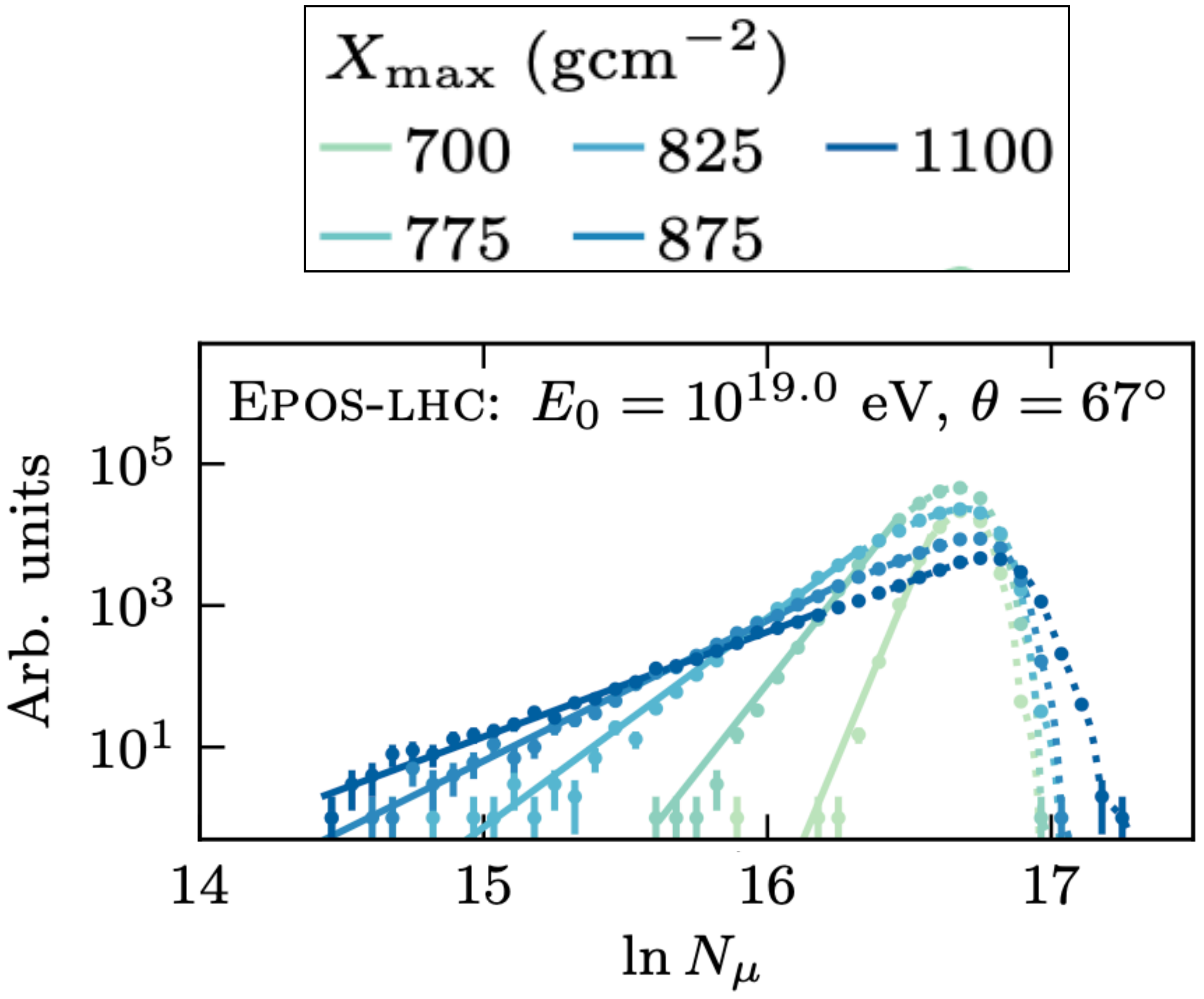
L. Cazon, RC, M. A. Martins, F. Riehn, Phys.Lett.B 859 (2024) 139115

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

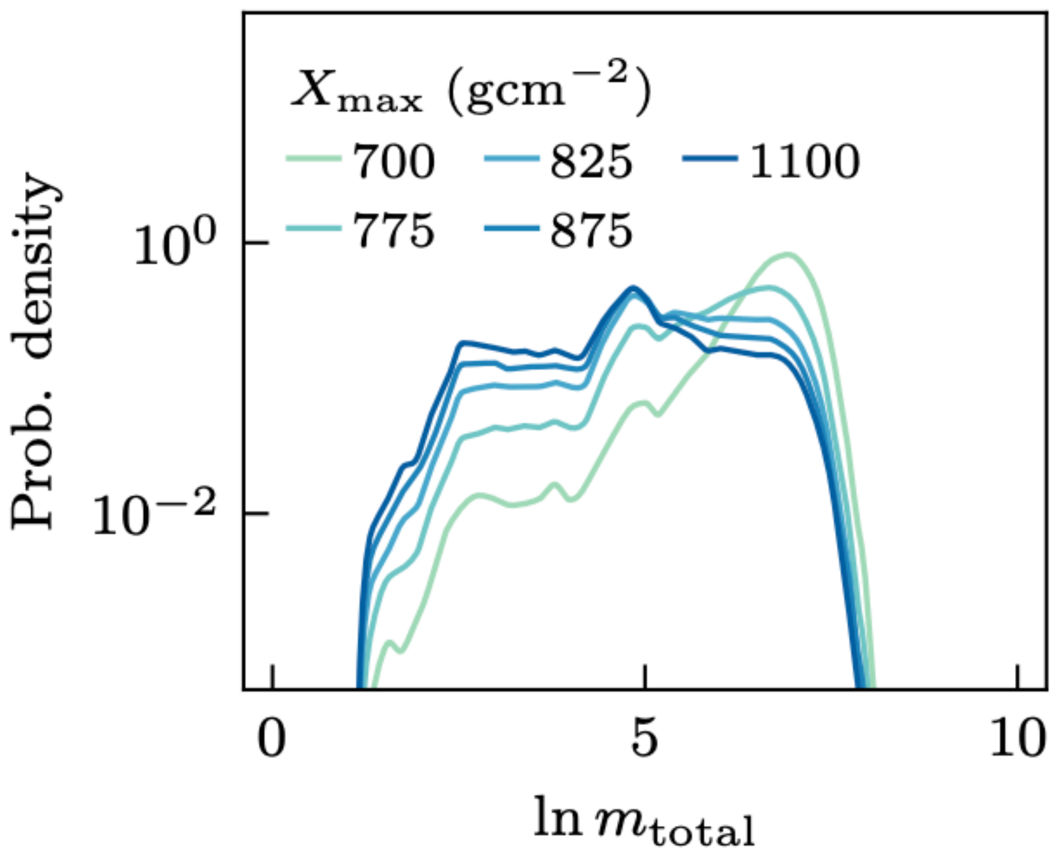
Low hadronic activity - diffractive events

Large hadronic activity - e.g. high multiplicity

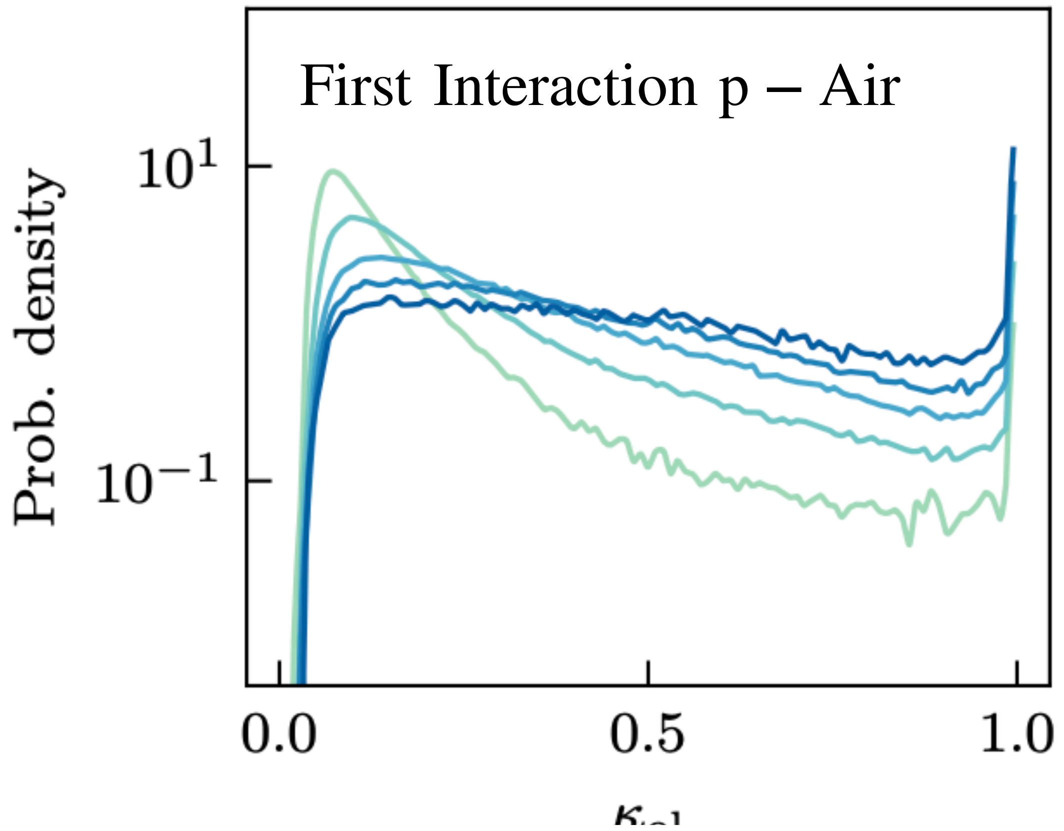




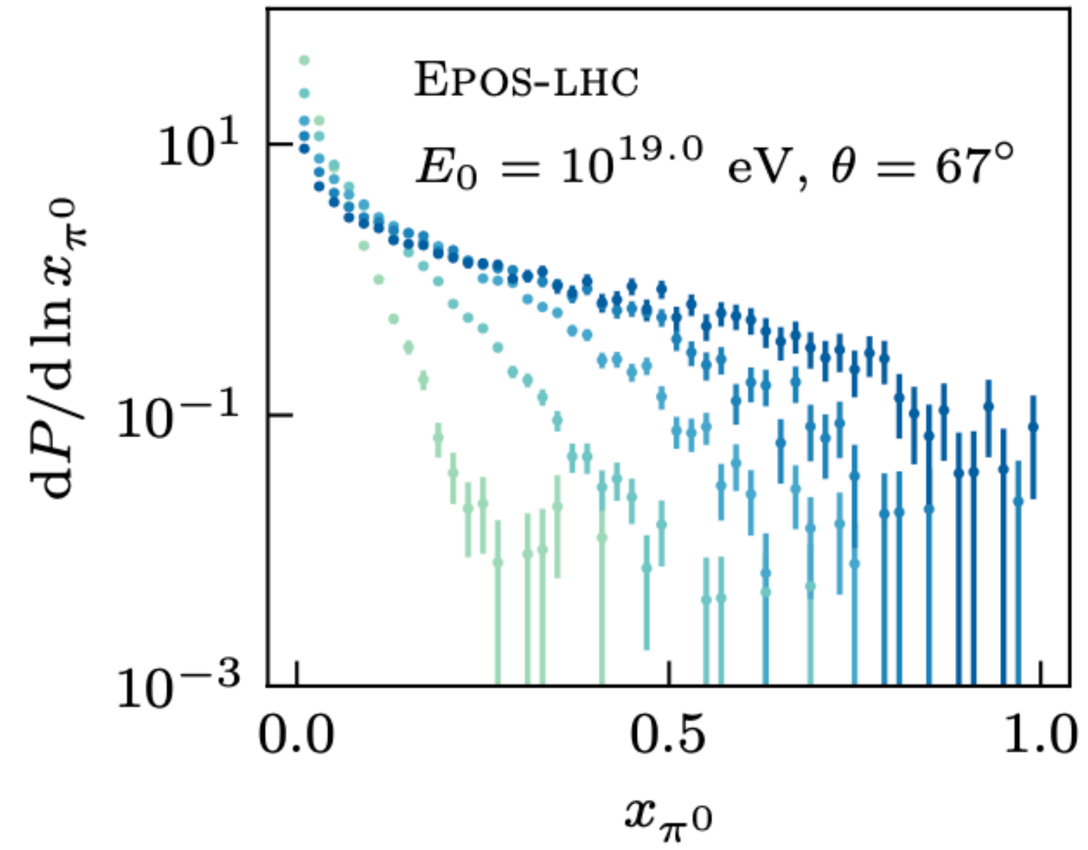
See also M. A. Martins's Poster



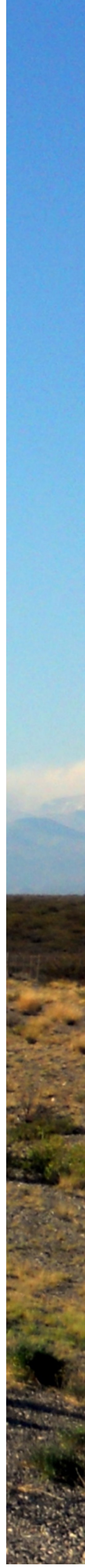
Multiplicity



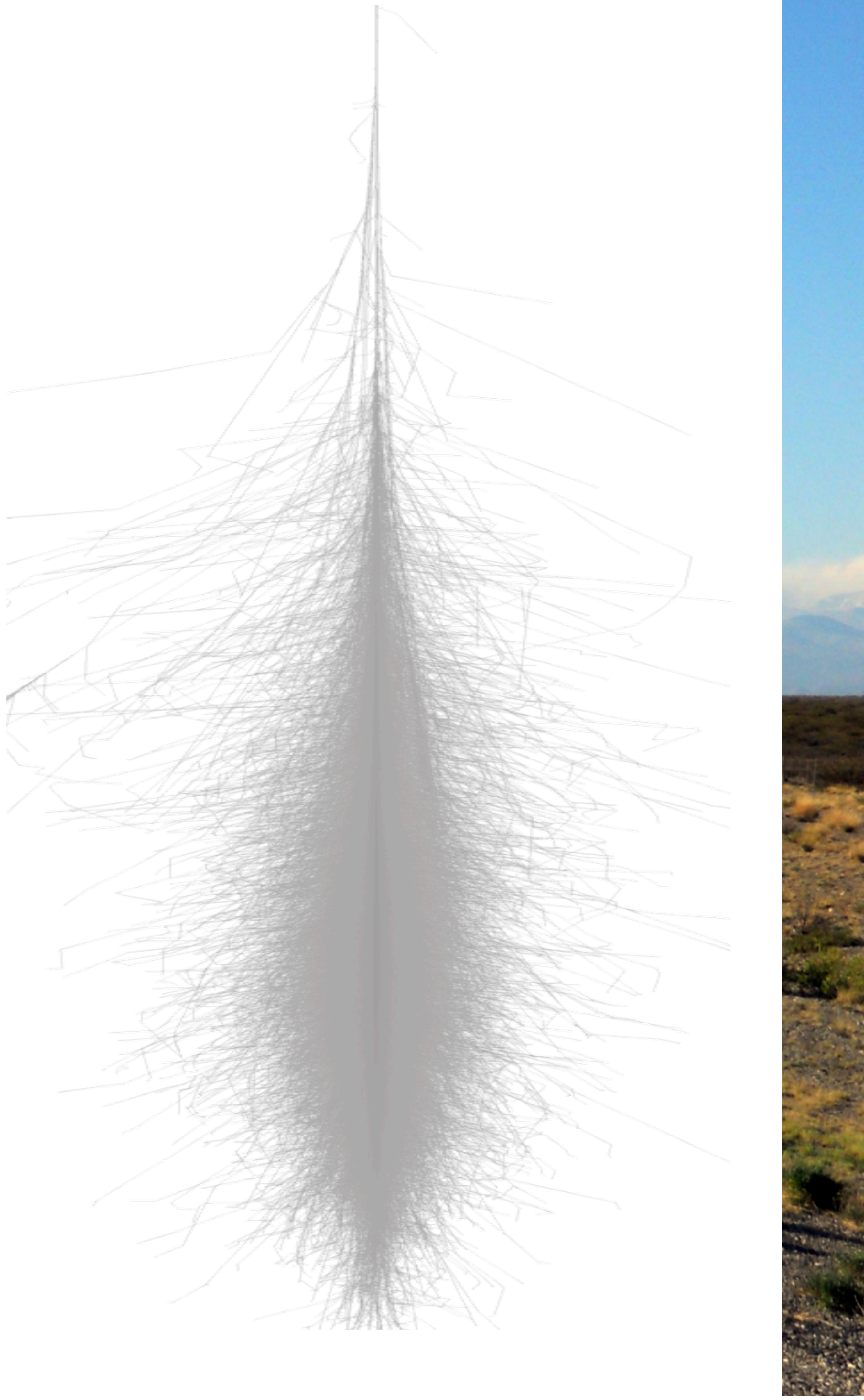
Elasticity



π^0 energy spectrum



Summary



- The **description of hadronic interactions** in extensive air showers (EAS) remains **incomplete**
- **Upcoming accelerator** and **astroparticle data** are essential for refining models and **testing** their **consistency**.
- **Multi-hybrid events** and **machine learning** algorithms will significantly boost this endeavour

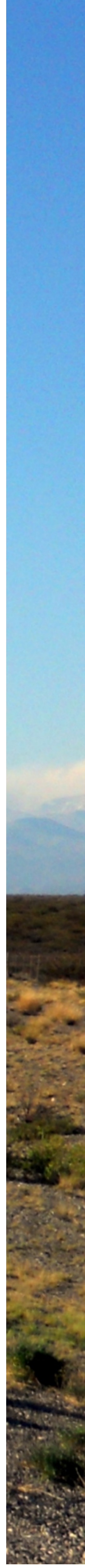
Acknowledgements

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

REPÚBLICA
PORTUGUESA

LIP

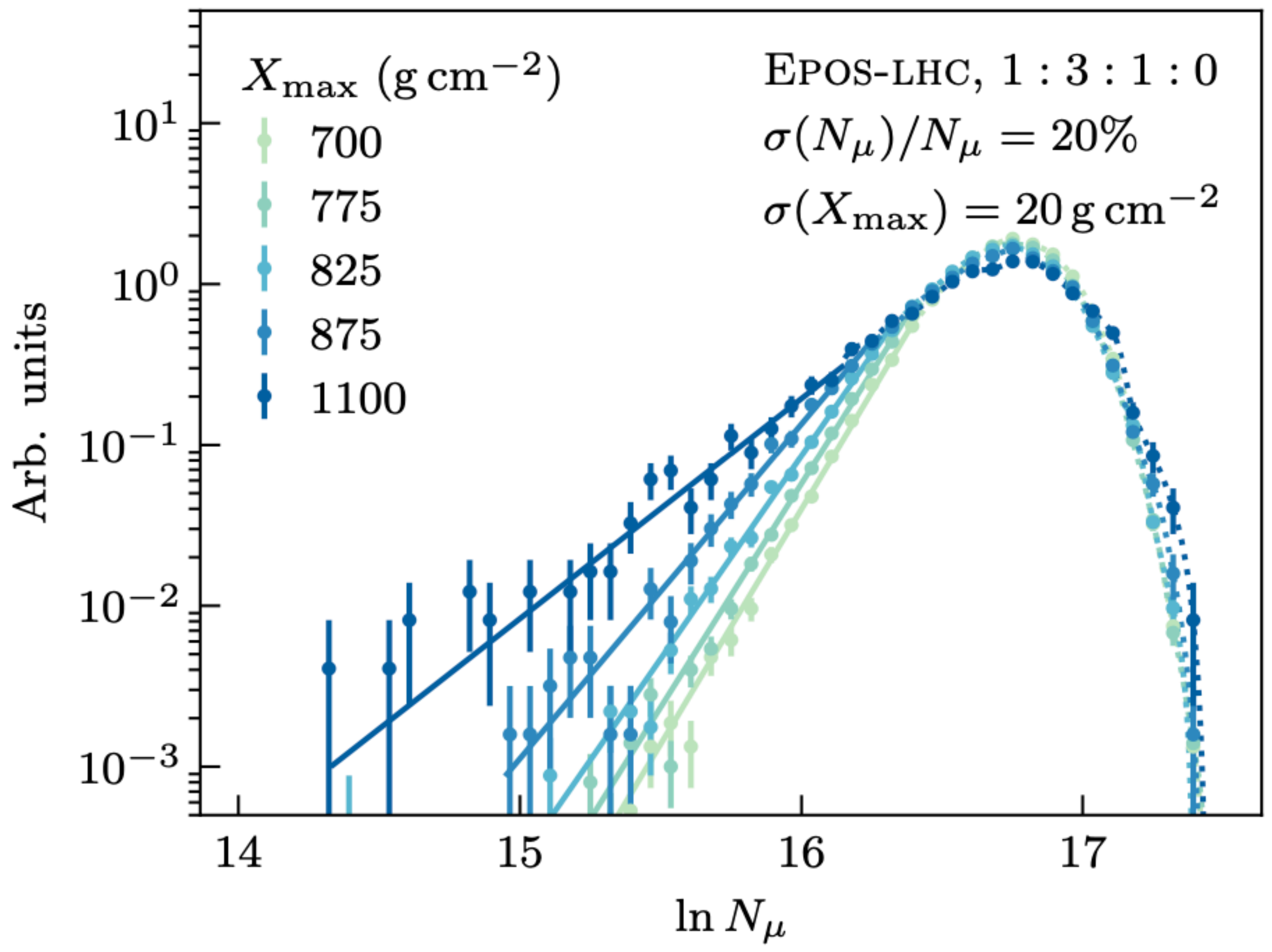
TÉCNICO
LISBOA

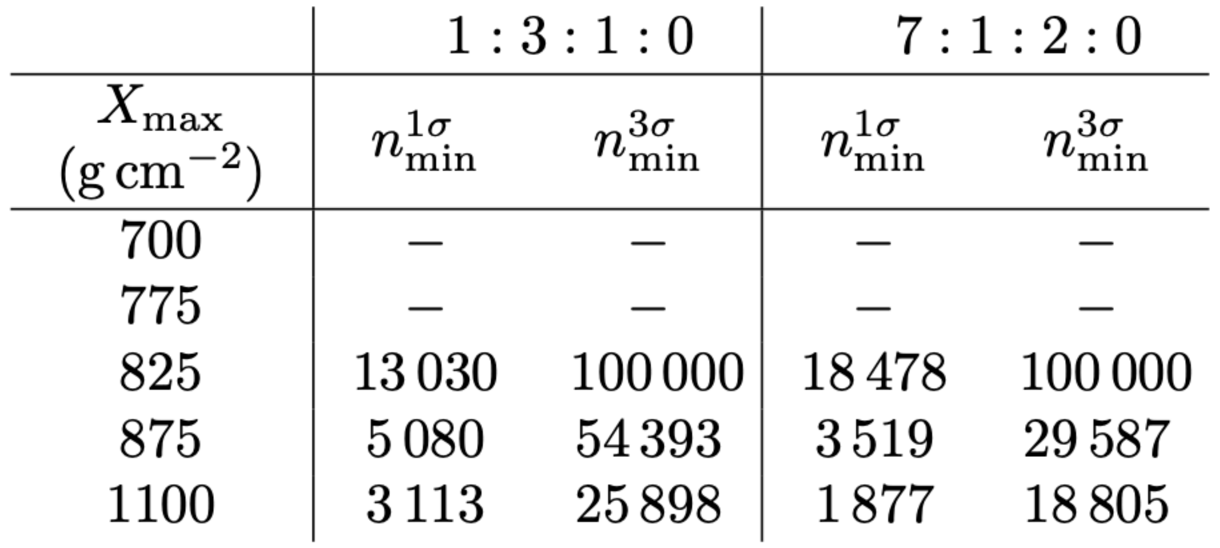


Backup slides

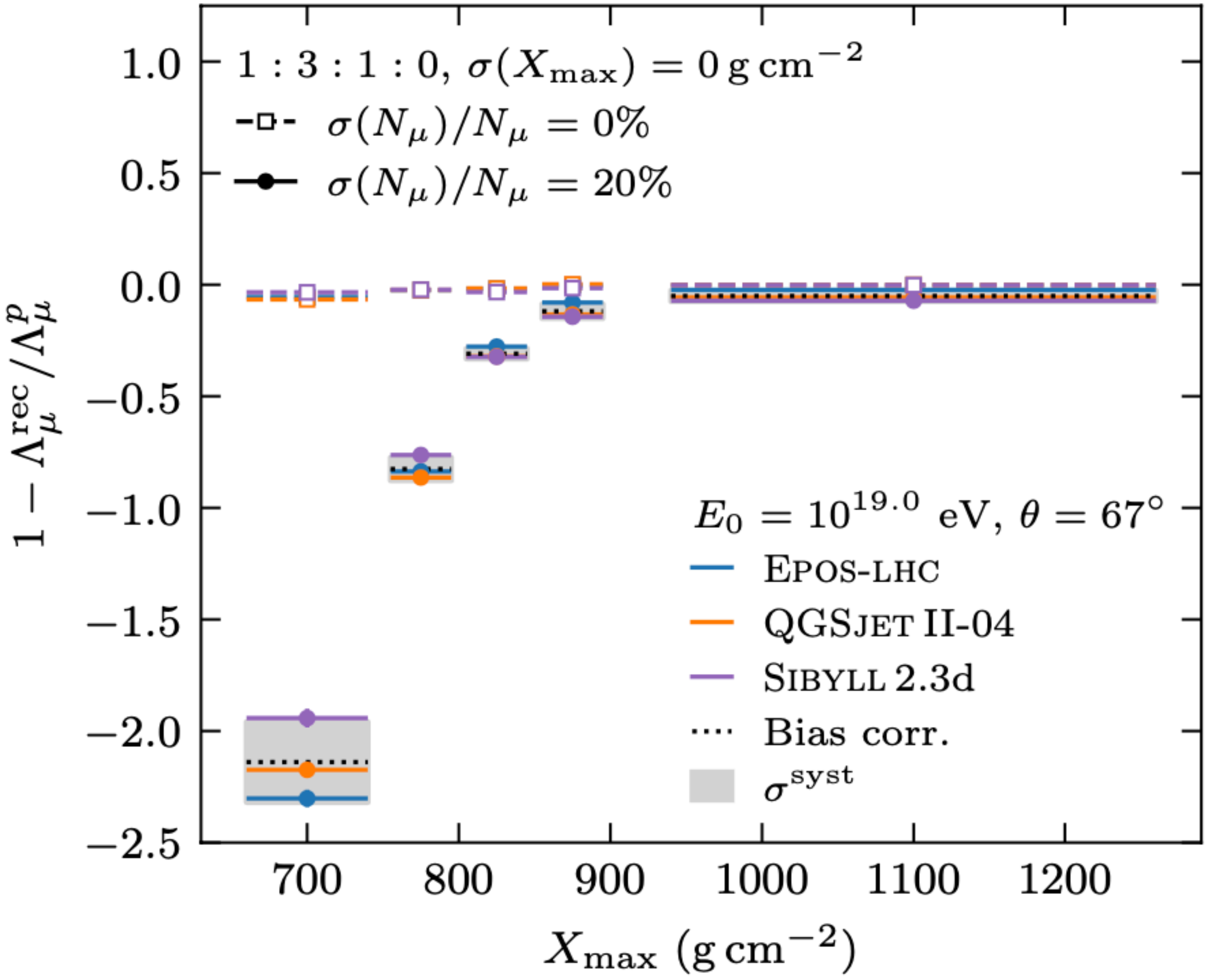
Experimental feasibility

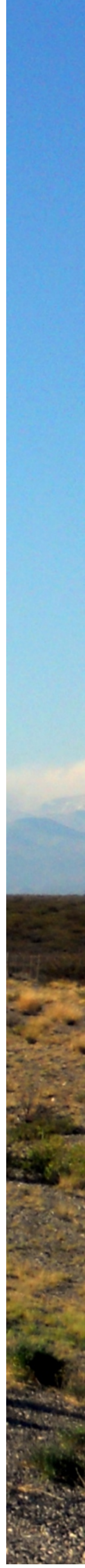
Test applicability to data under several mass composition scenarios and experimental resolutions



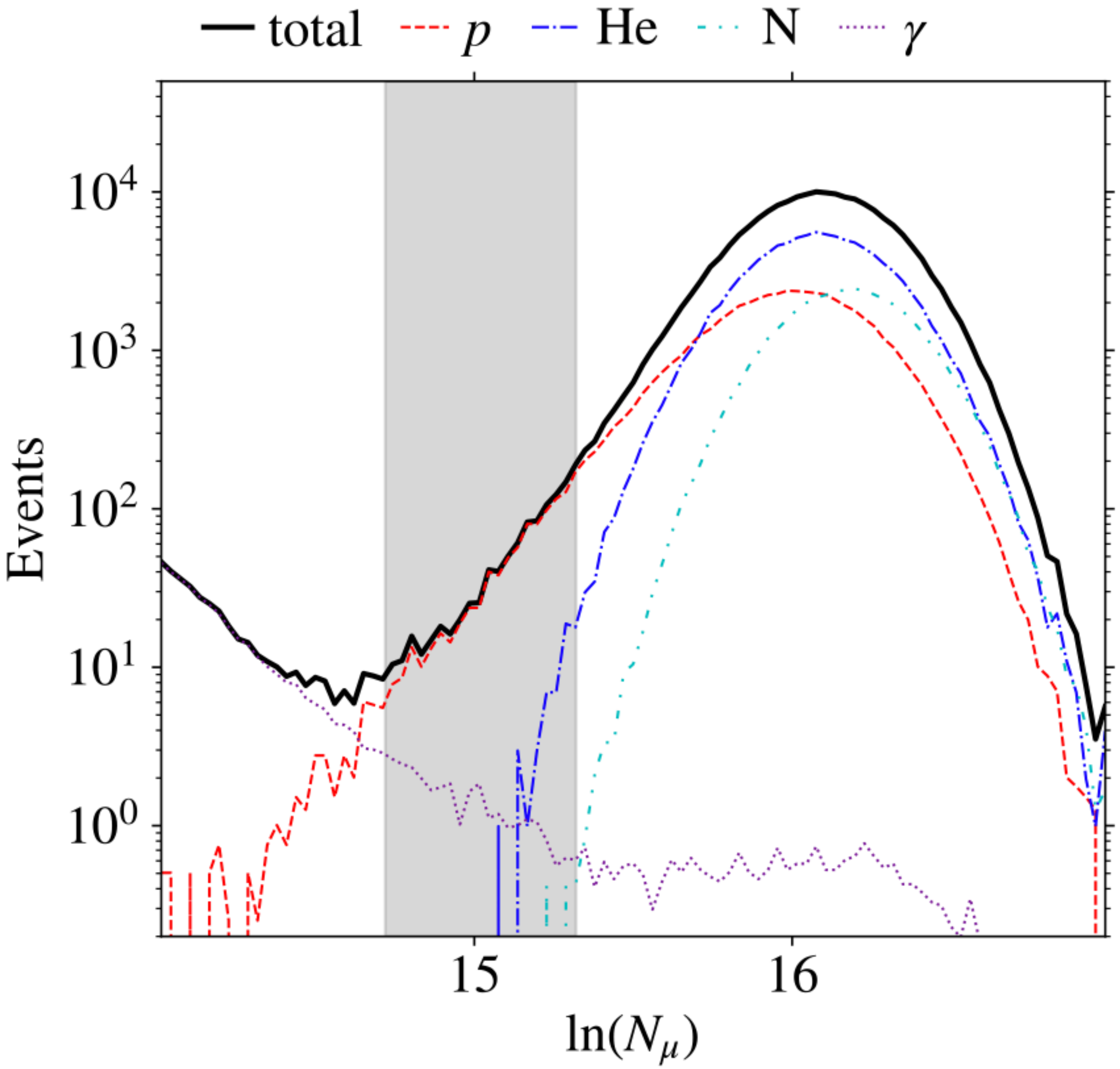


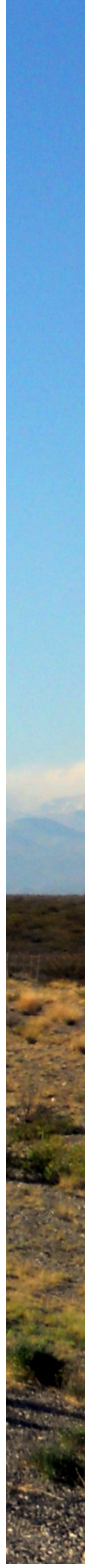
$X_{\max}$ (g cm^{-2})	1 : 3 : 1 : 0 $n_{\min}^{1\sigma}$	1 : 3 : 1 : 0 $n_{\min}^{3\sigma}$	7 : 1 : 2 : 0 $n_{\min}^{1\sigma}$	7 : 1 : 2 : 0 $n_{\min}^{3\sigma}$
700	–	–	–	–
775	–	–	–	–
825	13 030	100 000	18 478	100 000
875	5 080	54 393	3 519	29 587
1100	3 113	25 898	1 877	18 805





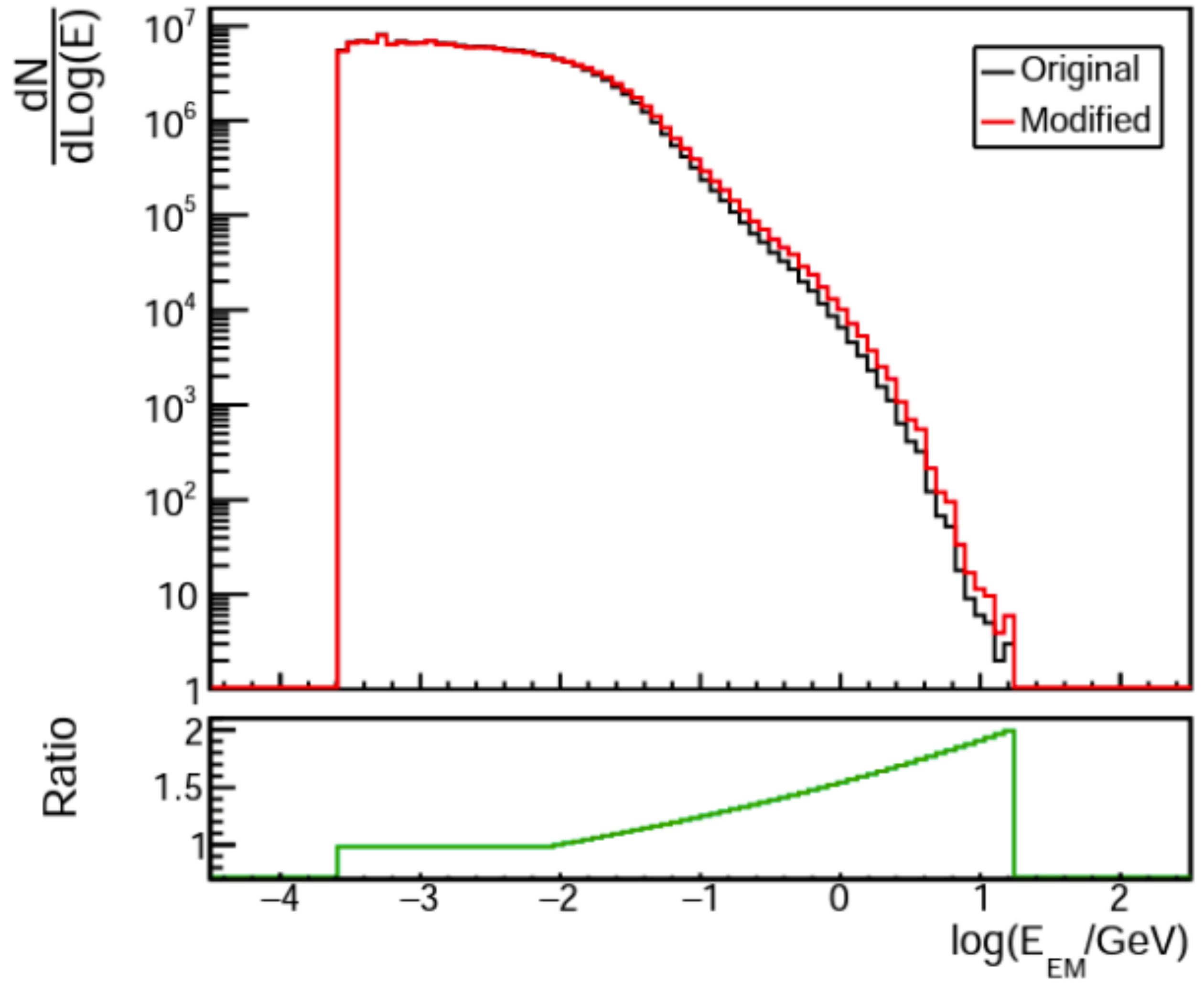
Measuring Λ_μ





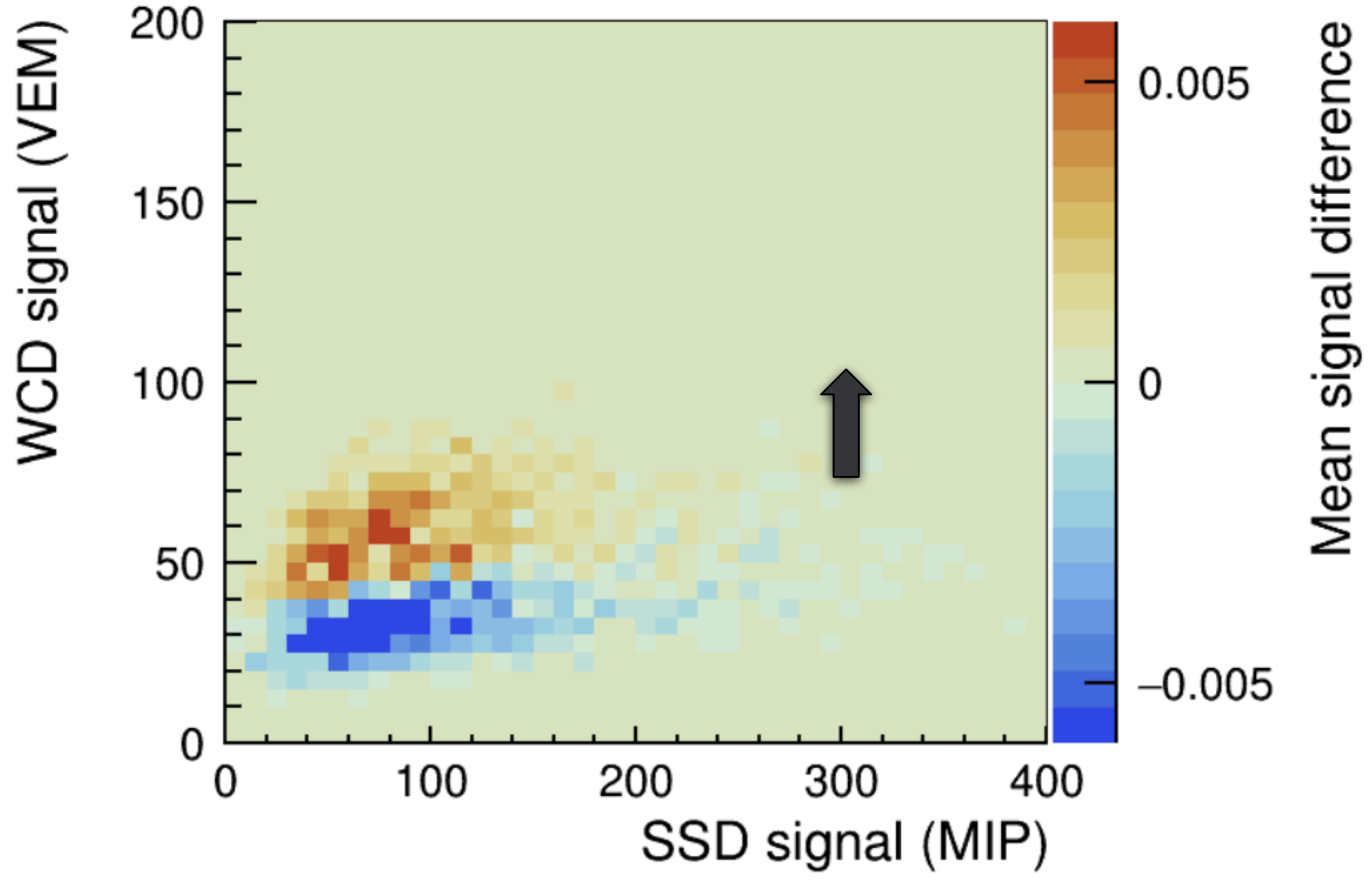
Multi-hybrid stations

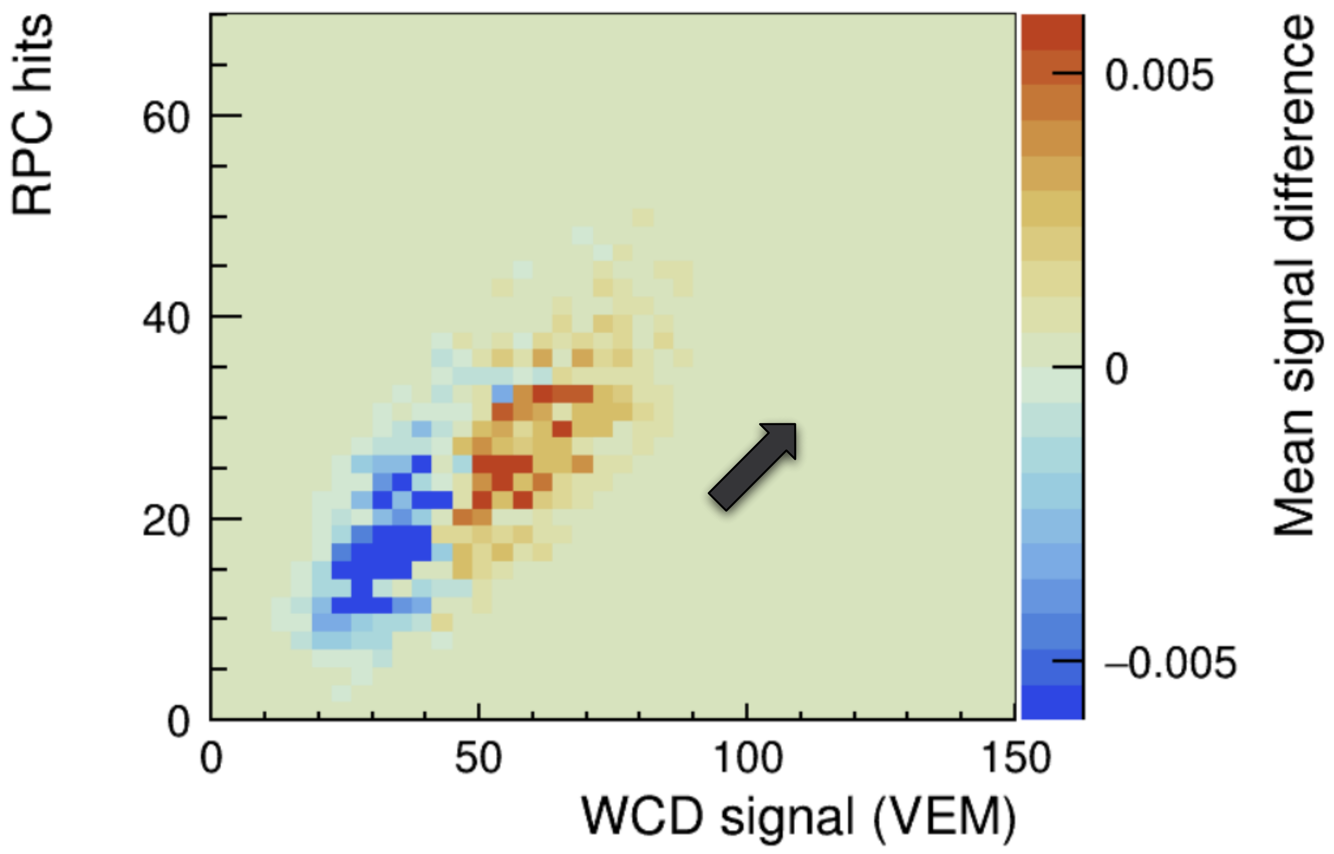
P. Assis, RC, M. Freitas++, to be submitted soon

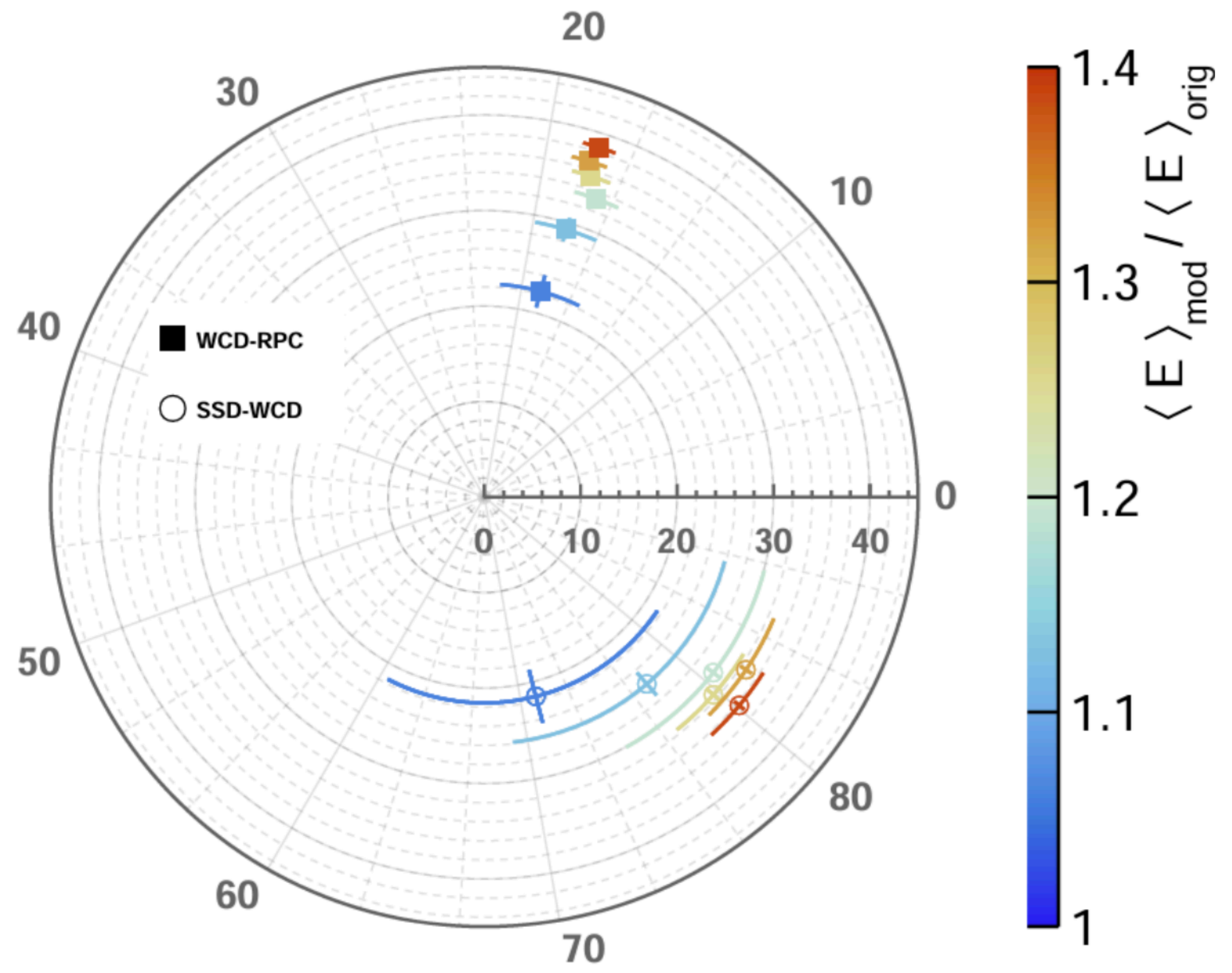


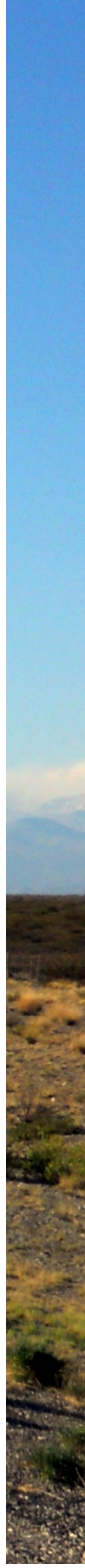
EM	High Energies			Low Energies		
	WCD	SSD	RPC	WCD	SSD	RPC
320 m	↑ 🟩	– 🟥	↑ 🟩	– 🟥	– 🟥	– 🟥
715 m	↑ 🟩	– 🟥	– 🟥	– 🟥	– 🟥	– 🟥
1060 m	↑ 🟩	– 🟥	– 🟥	– 🟥	– 🟥	– 🟥

Muon	High Energies			Low Energies		
	WCD	SSD	RPC	WCD	SSD	RPC
320 m	– 🟥	– 🟥	– 🟥	– 🟥	– 🟥	– 🟥
715 m	– 🟥	– 🟥	– 🟥	↓ 🟩	– 🟥	↓ 🟩
1060 m	– 🟥	– 🟥	– 🟥	↓ 🟩	– 🟥	↓ 🟩





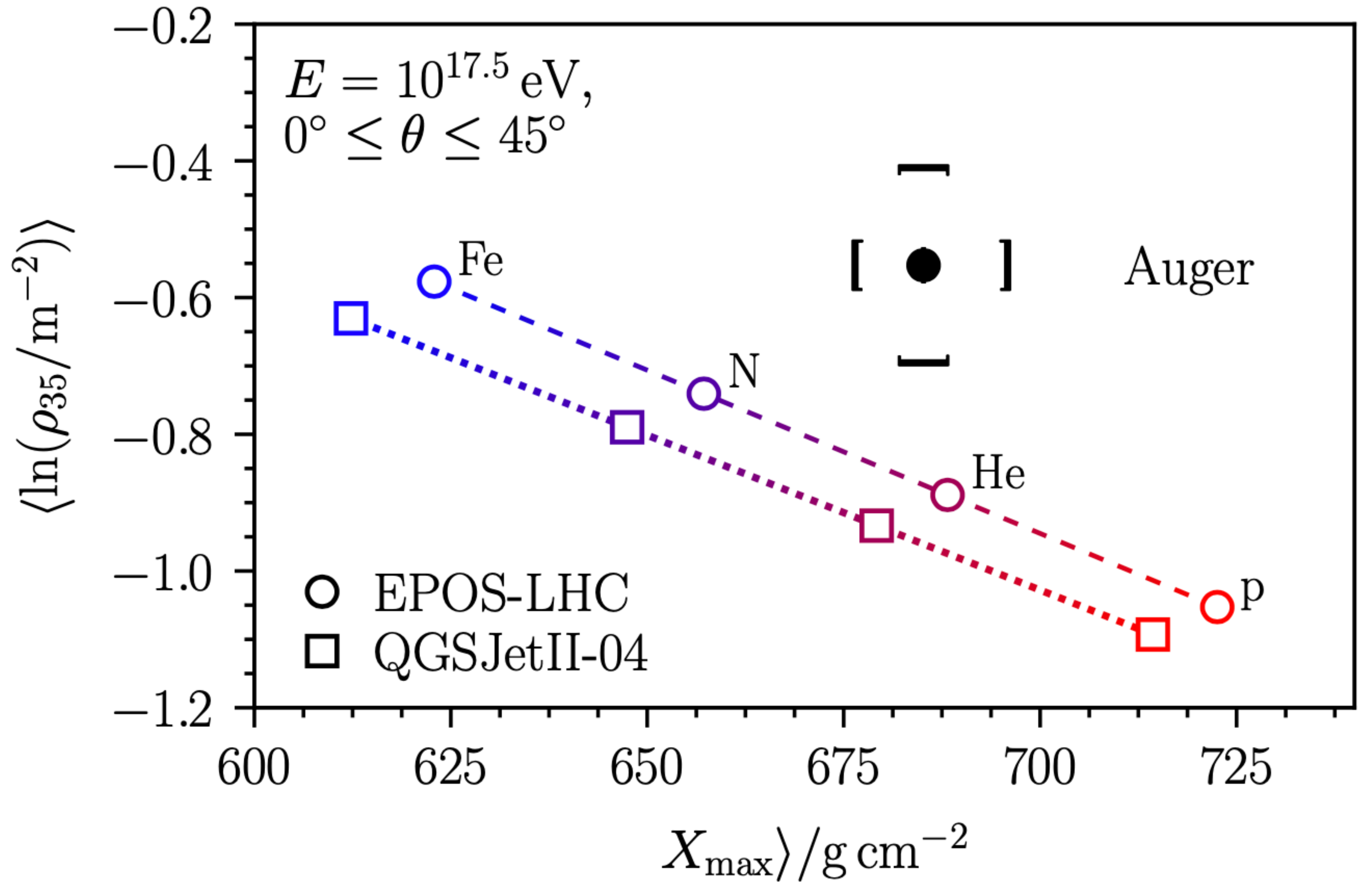




The EAS muon puzzle @ Auger

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

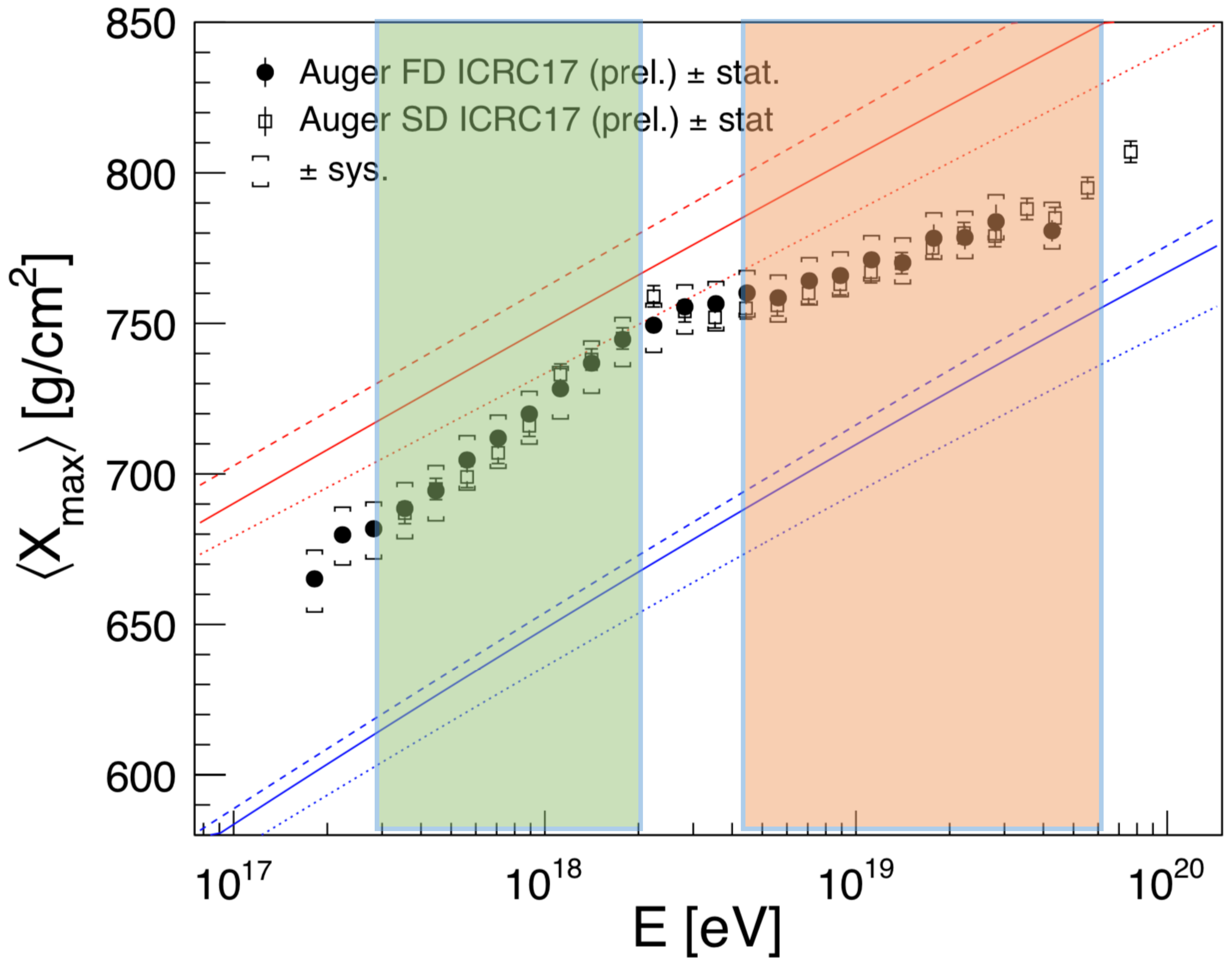
Phys.Rev.Lett. 126 (2021) 15, 152002

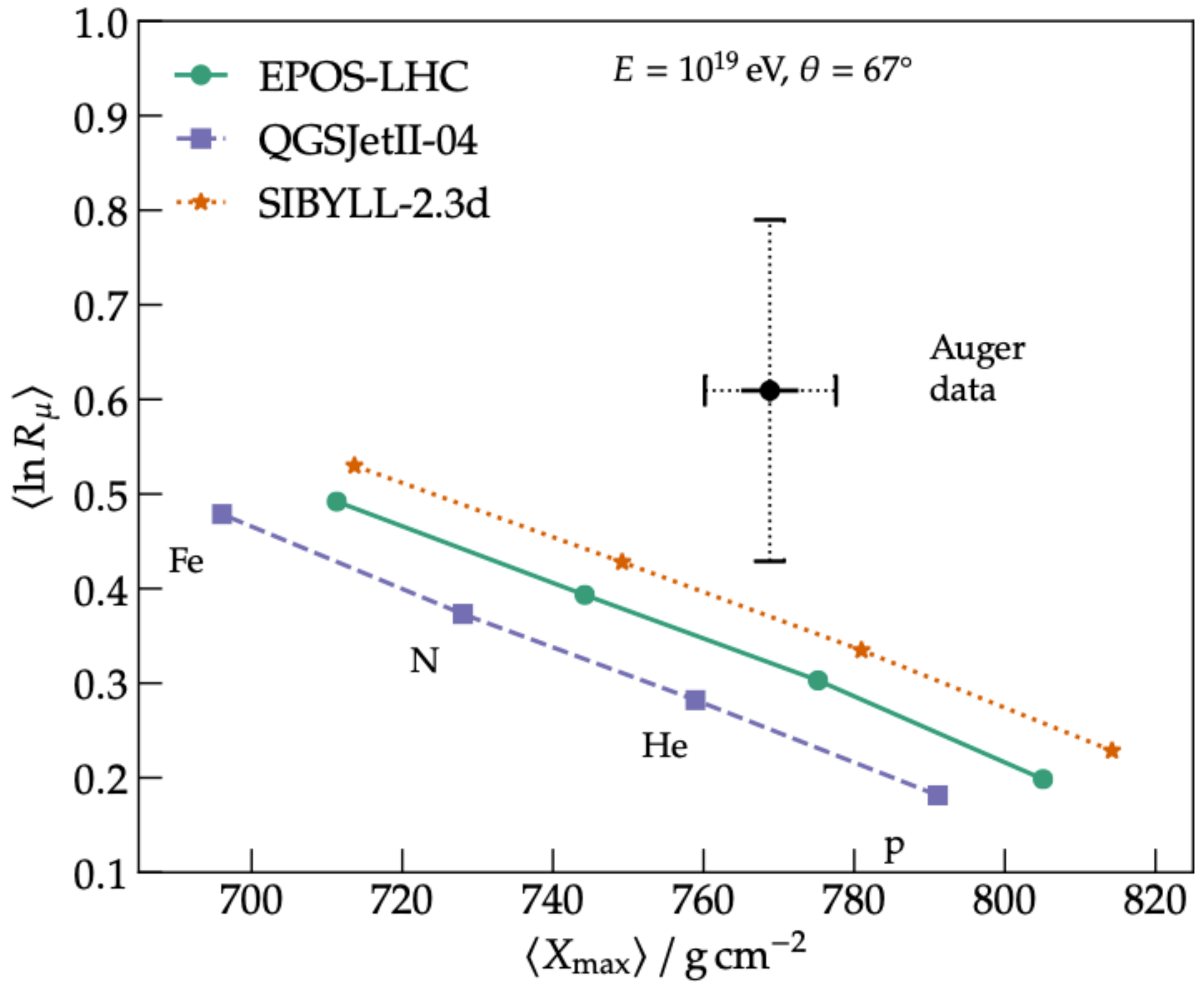


Buried Scintillators + FD

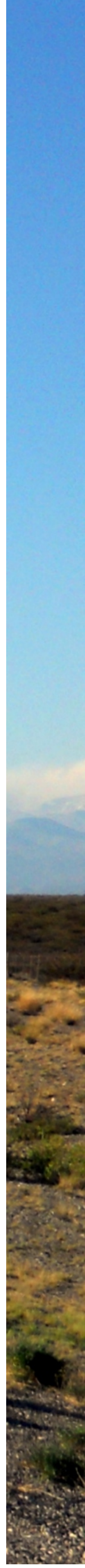
Muon excess present both at lower and higher energies if one takes into account preferred X_{max} composition

FD data



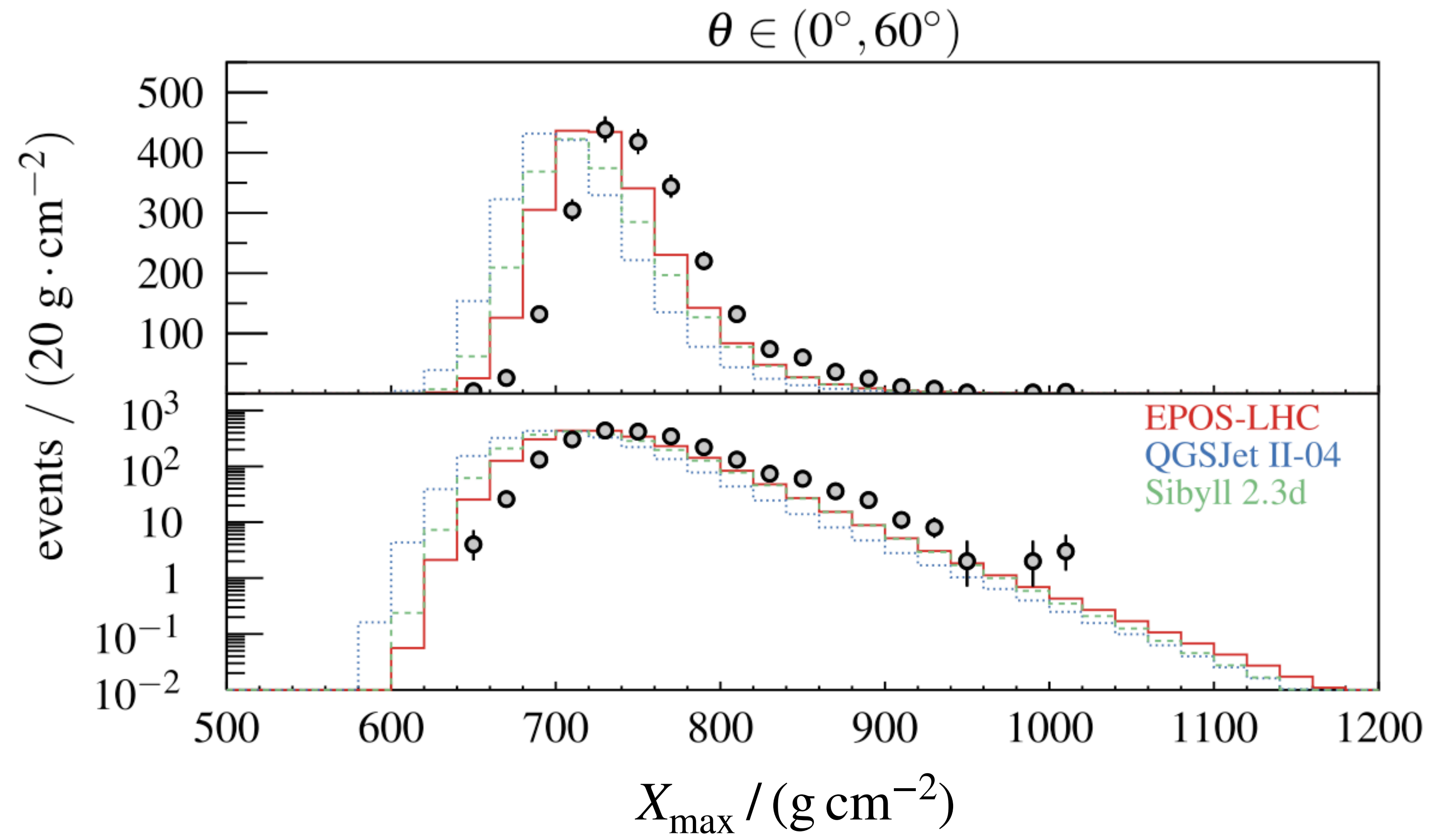


SD inclined + FD



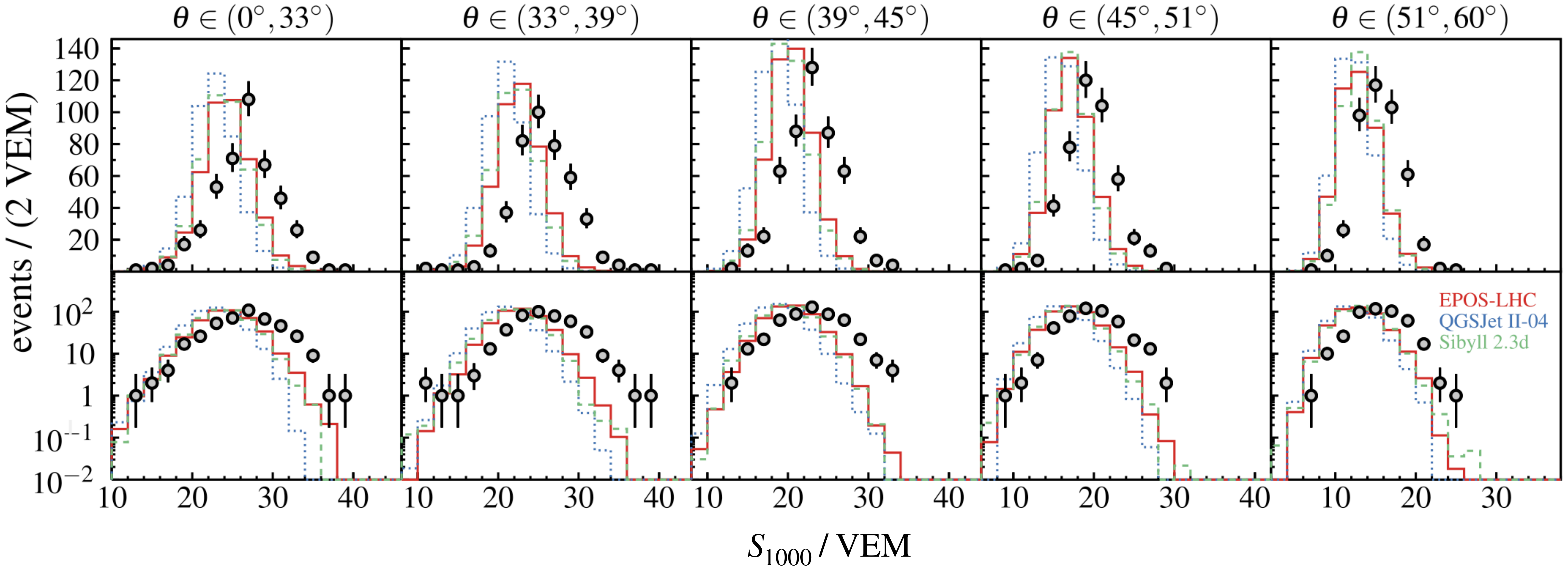
Muon puzzle

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



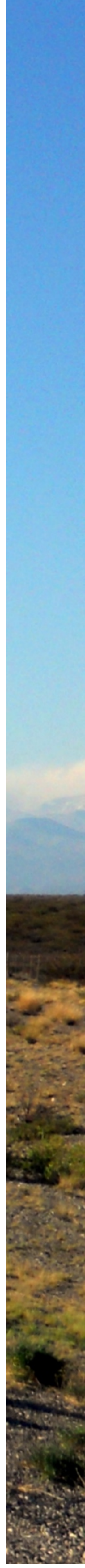
Allow for a change in the rescaling of the **signal on the ground** produced by the **hadronic** shower component at 1000 m with a factor, R_{had}

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



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

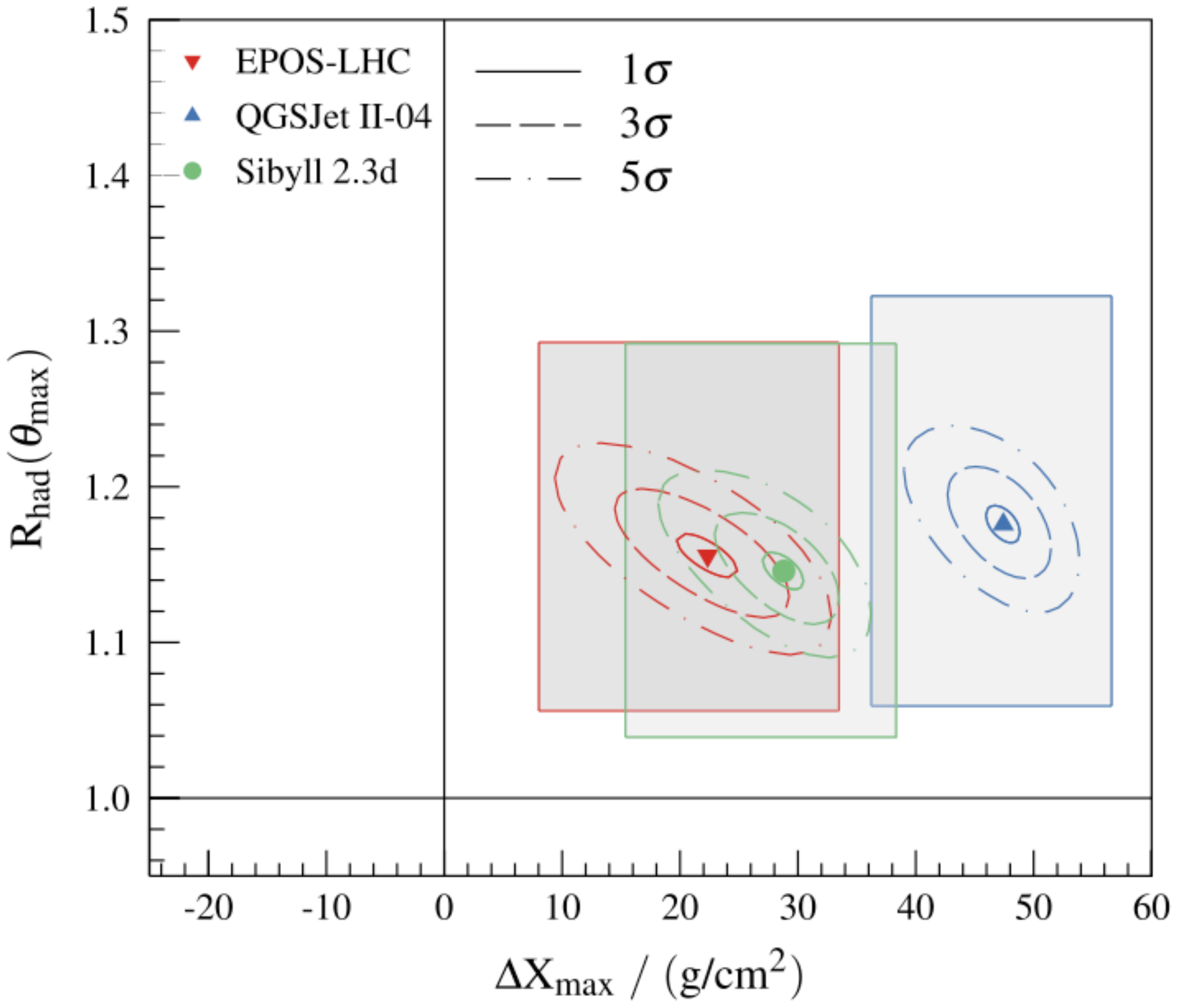
Poor agreement between data and simulations

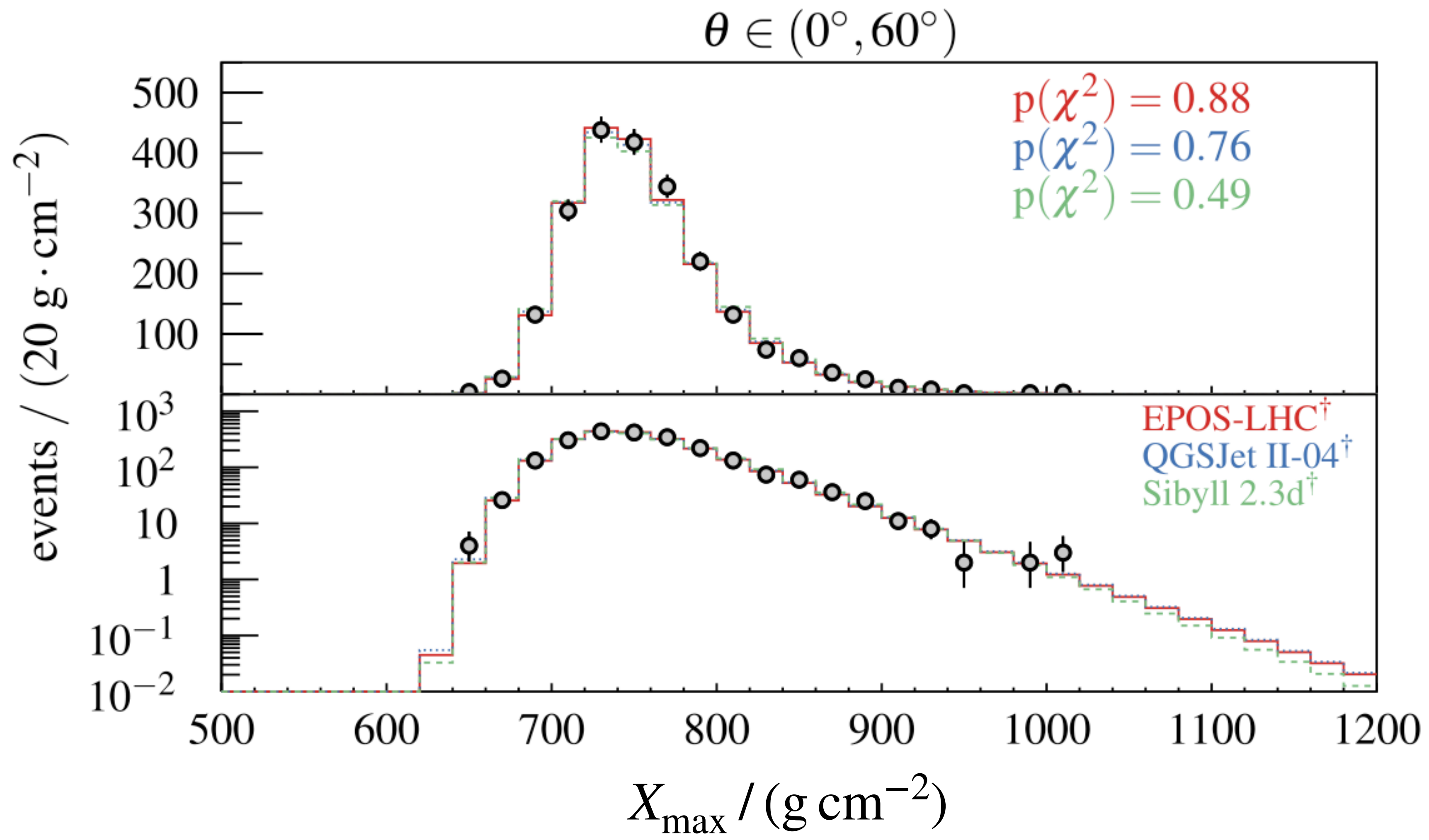


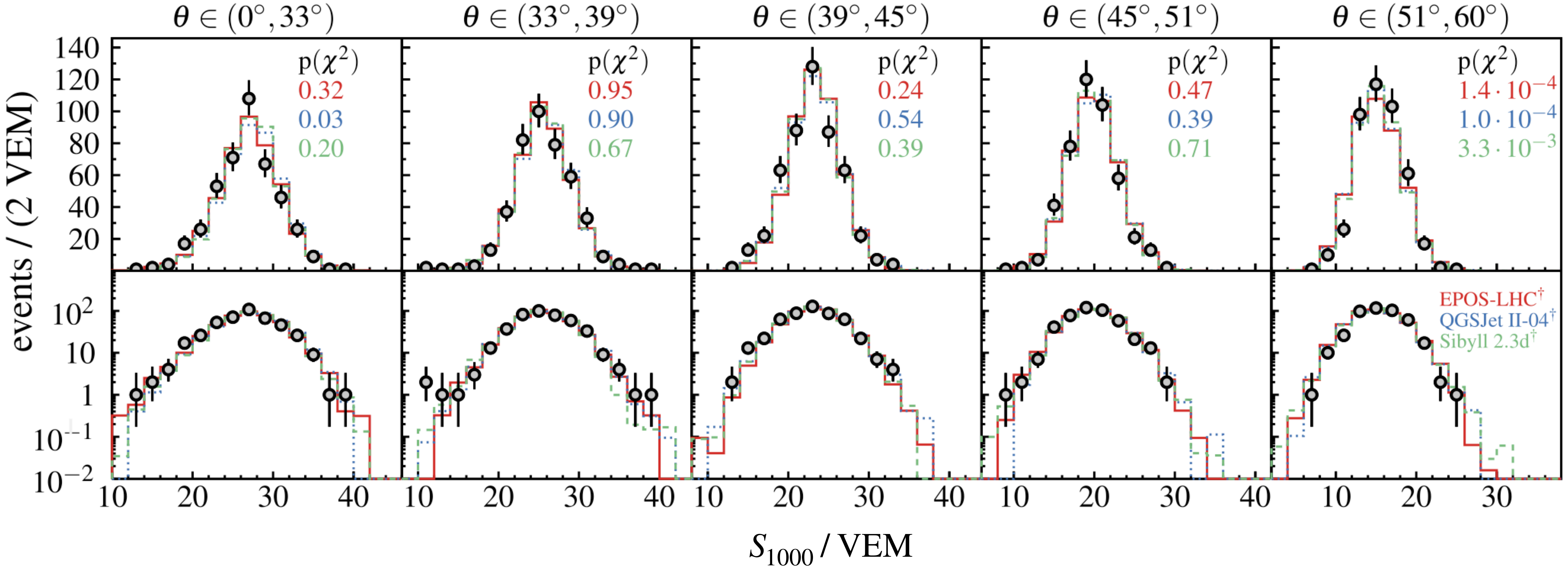
Muon puzzle + Shift in X_{max} scale

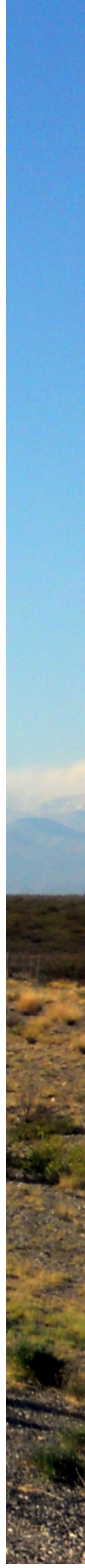
Phys.Rev.D 109 (2024) 10, 102001

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}



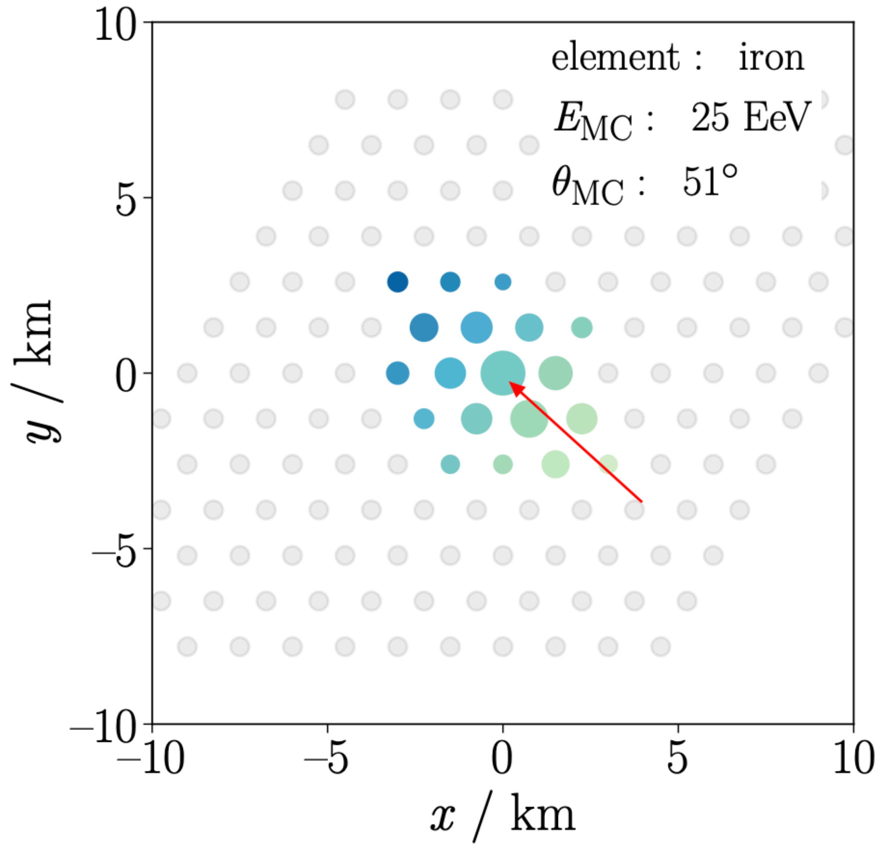


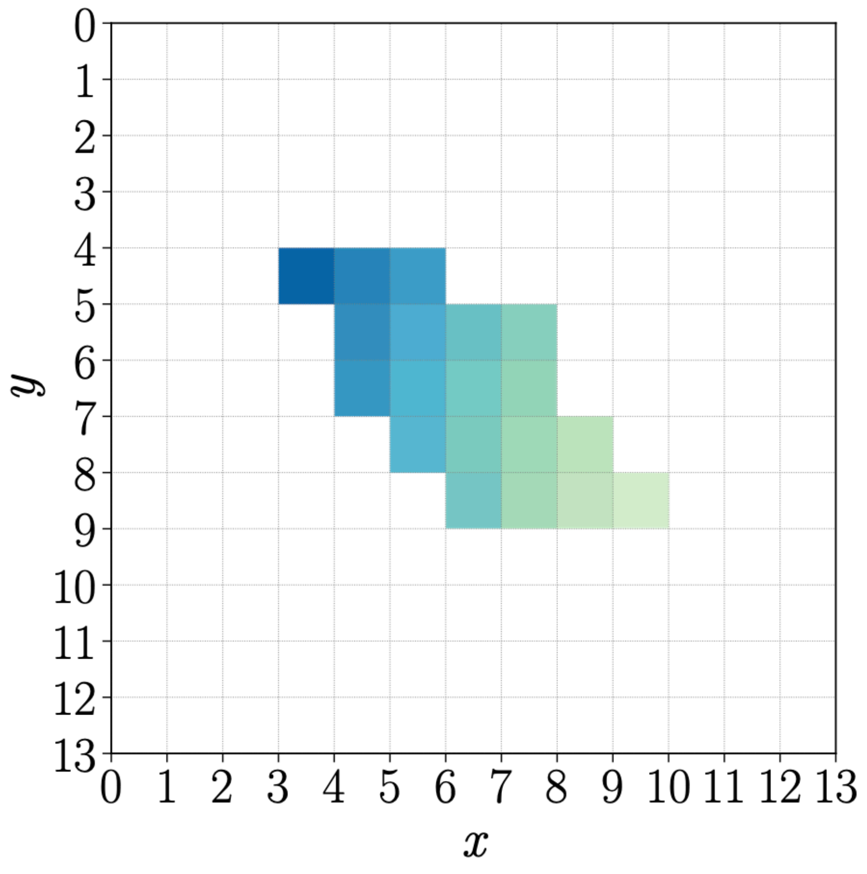


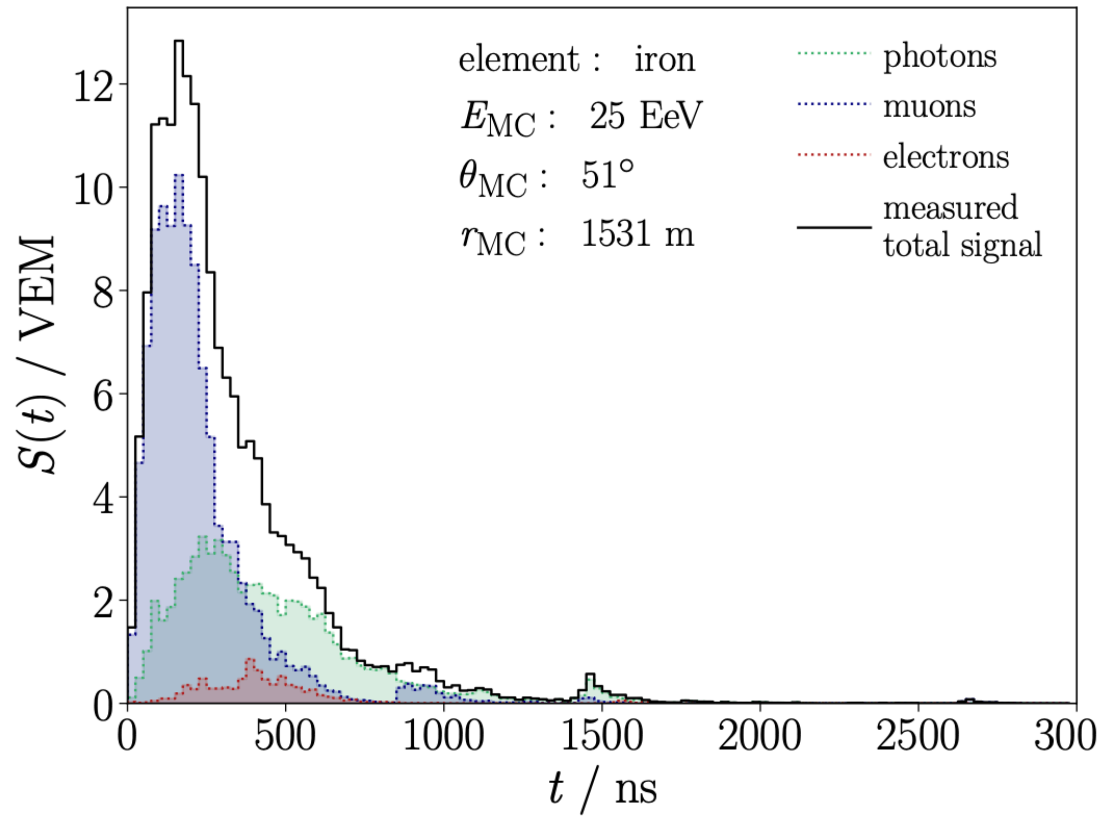


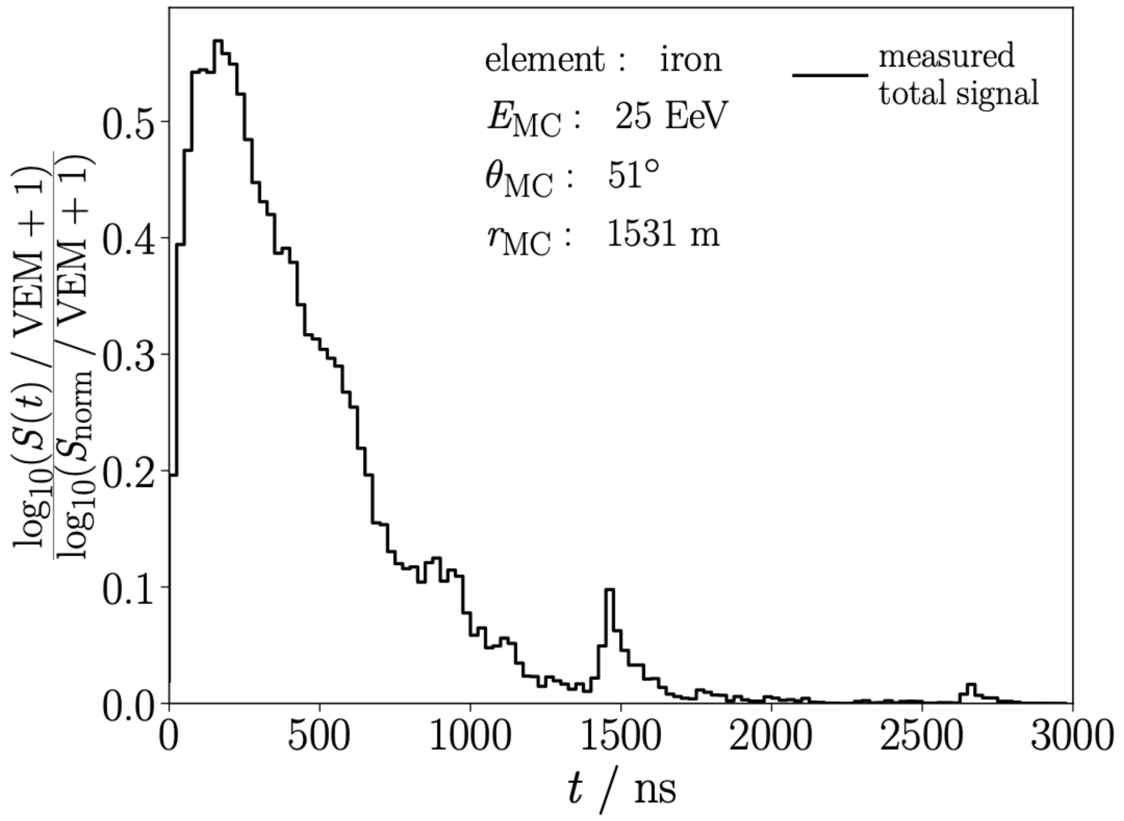
$X_{\max}$ from SD trace using a DNN

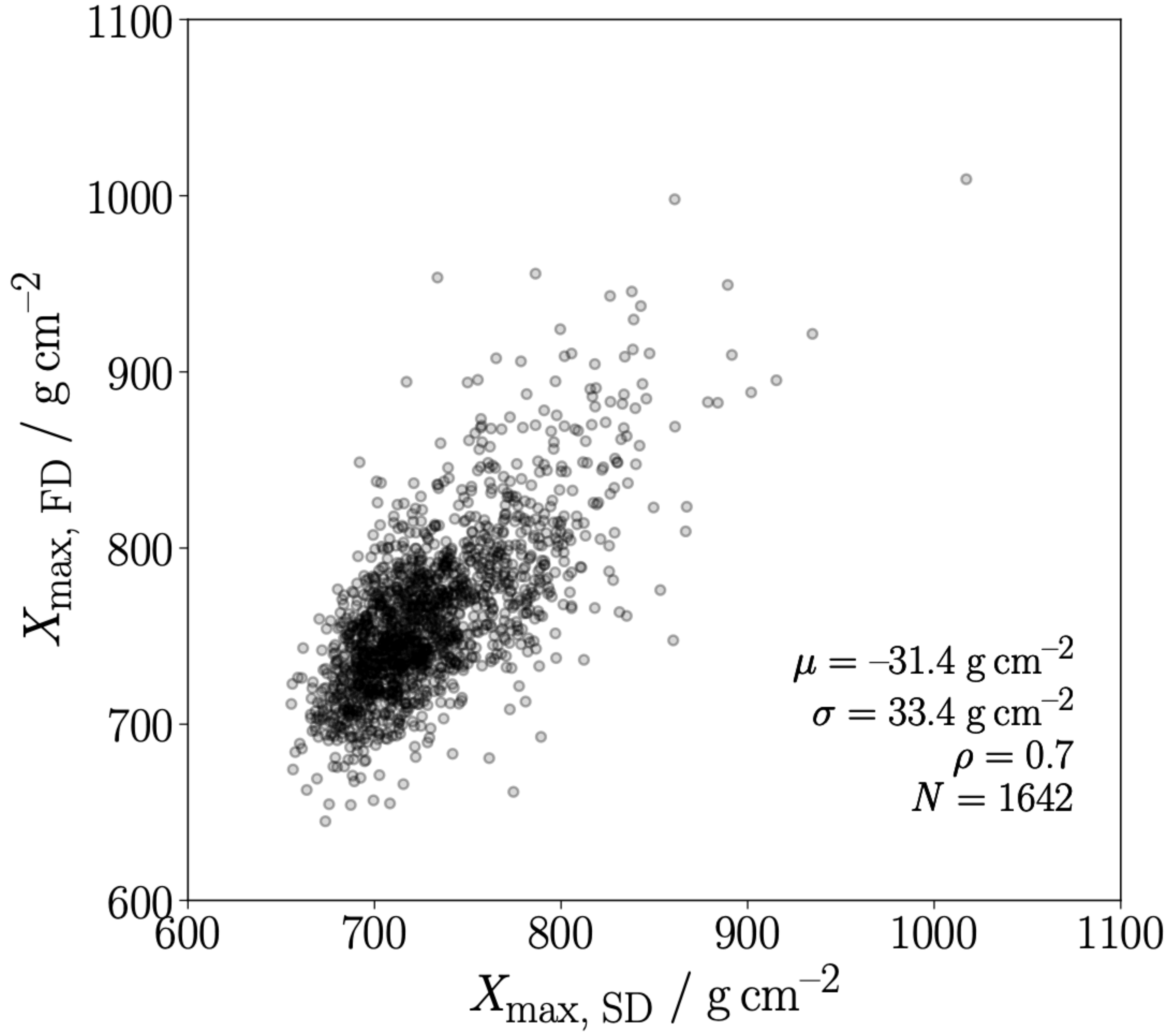
Accepted in PRL + PRD (2024)







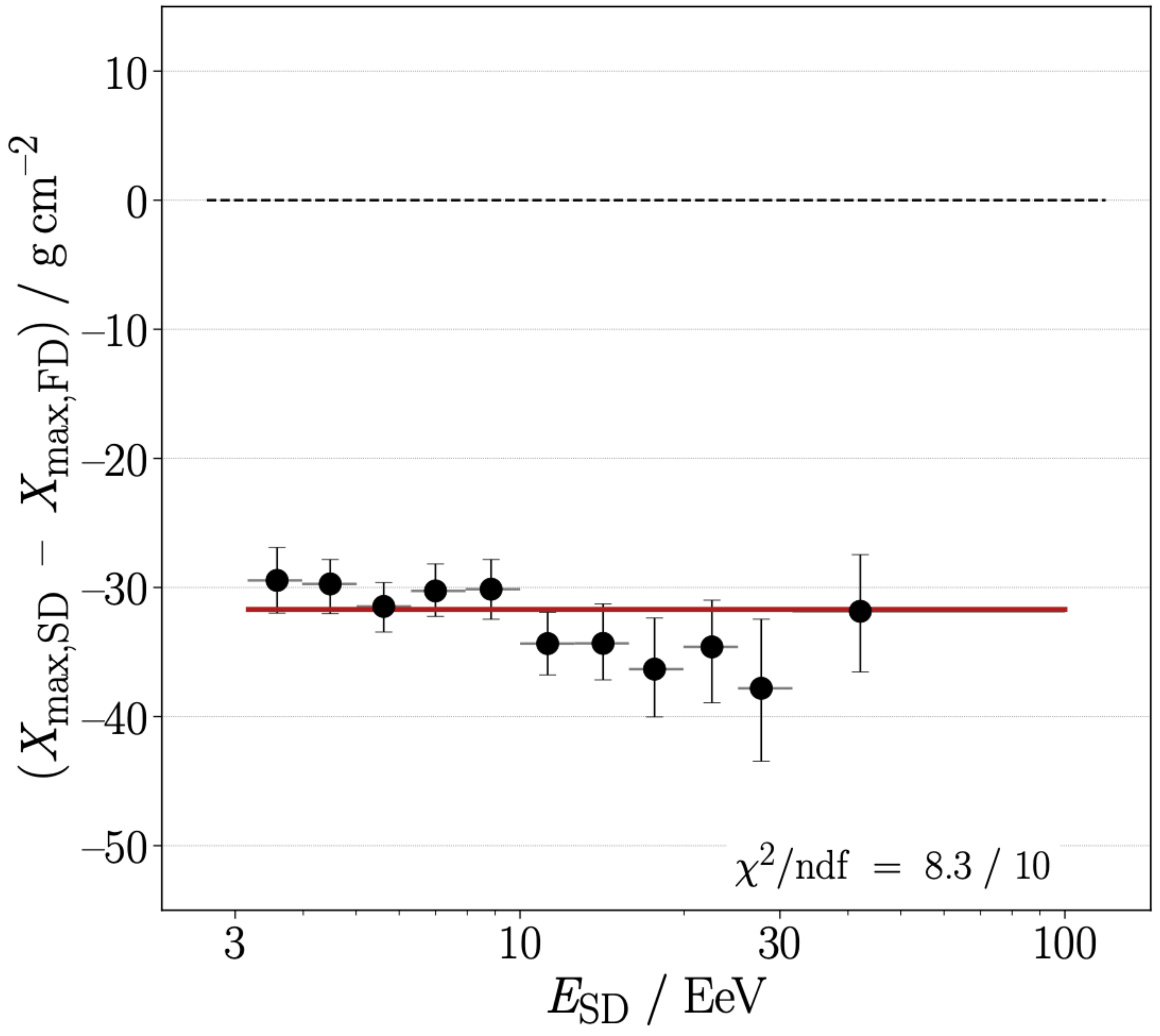


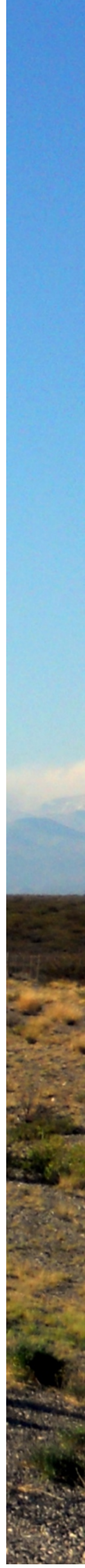


Extract the $X_{\max}$ from SD-only events

Exploit the SD traces using a Deep Neural Network

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

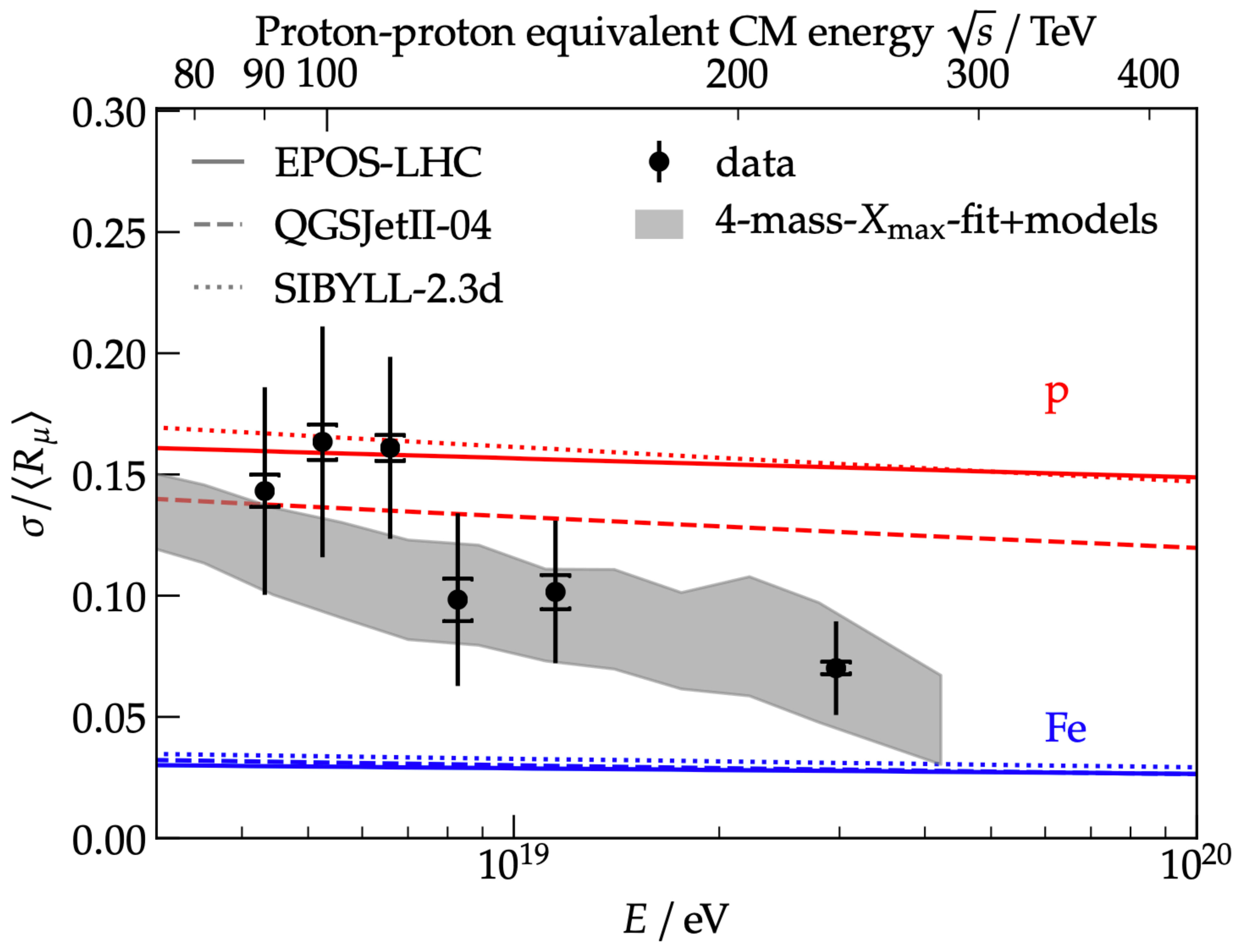




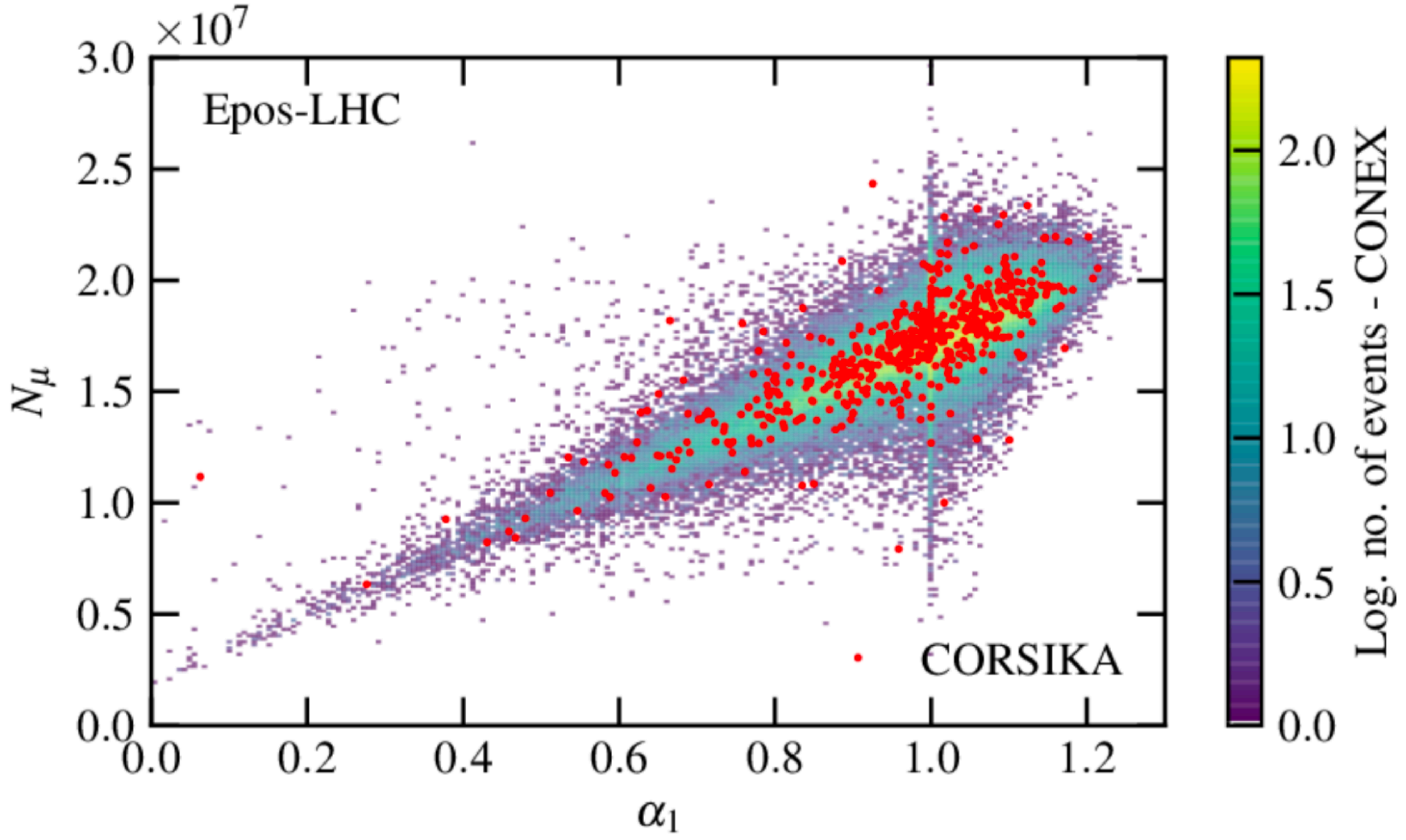
EAS muon fluctuations

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

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



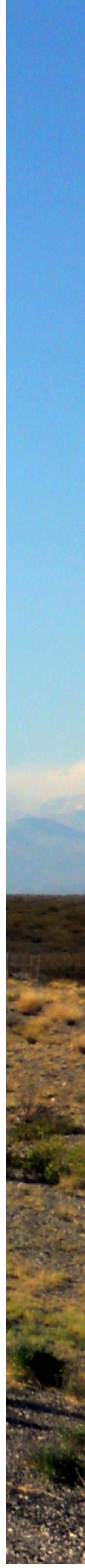
The muon relative fluctuations are in agreement with the mass composition expectations derived from the analysis of X_{max} data



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

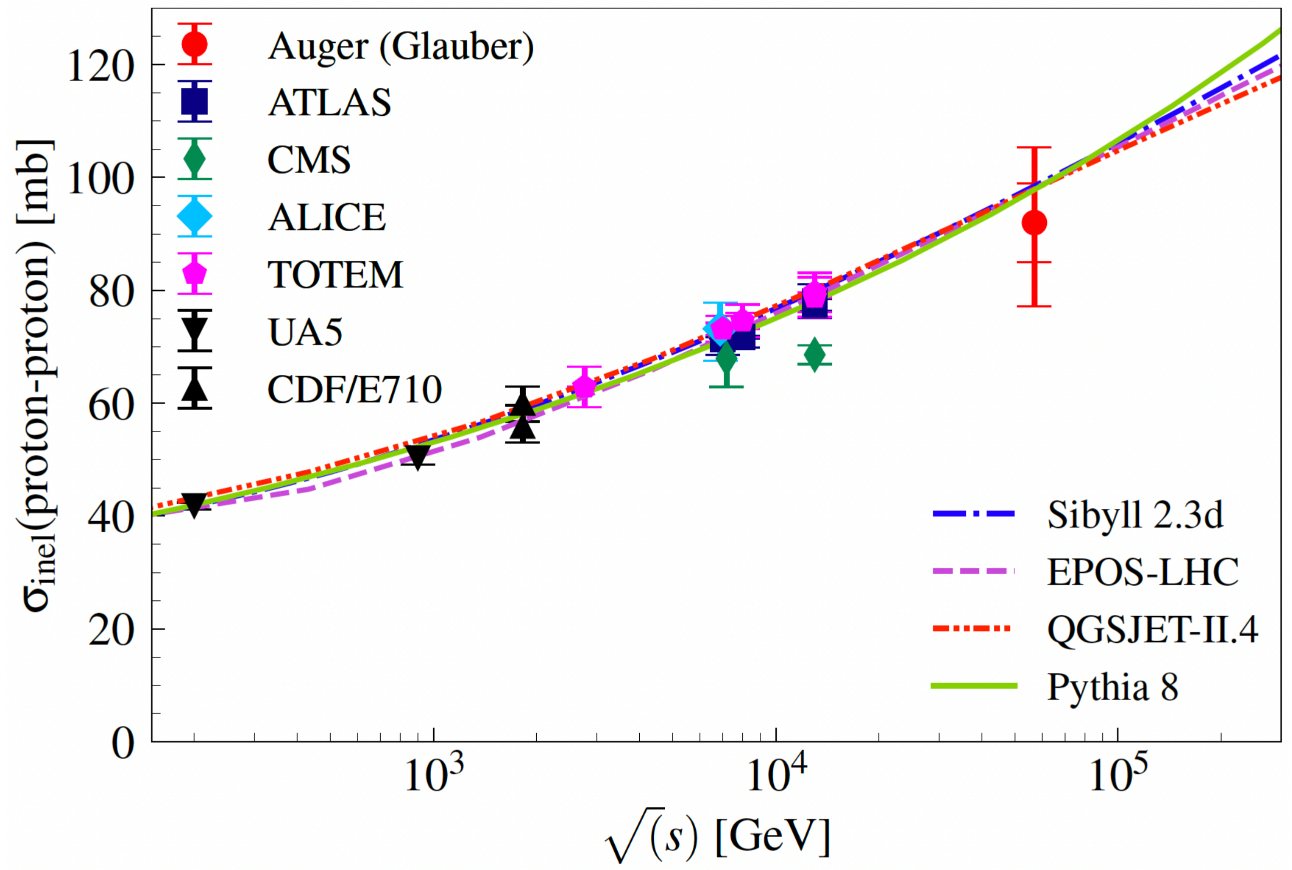
$$\sigma(\alpha_1) \rightarrow 70\,\%\,\sigma(N_\mu)$$

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



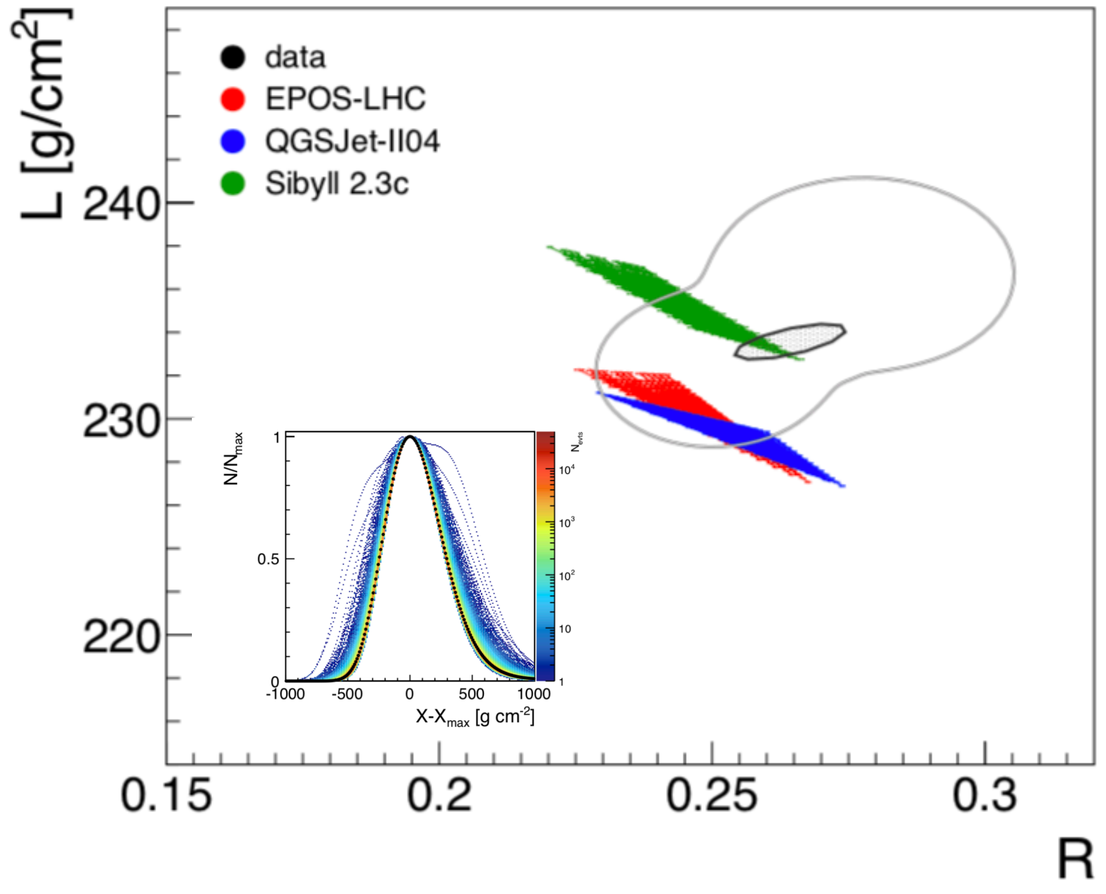
Many other EAS measurements…

Phys.Rev.Lett. 109 (2012) 062002



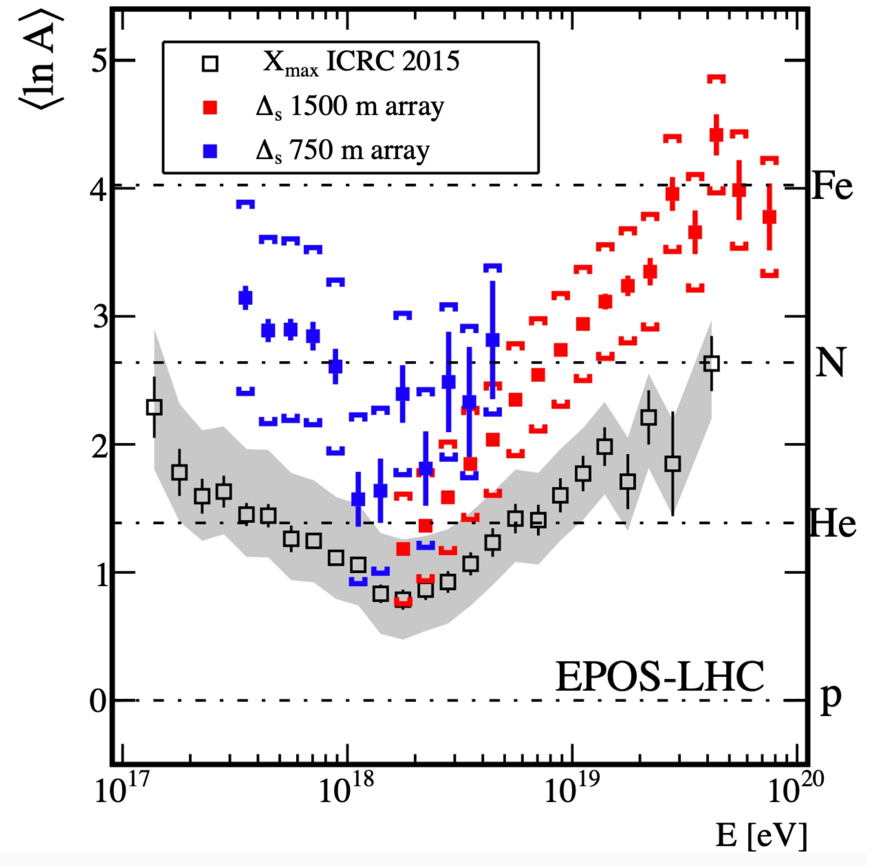
Measurement of the proton-air cross-section at E~10¹⁸ eV

JCAP 1903 (2019) no.03, 018



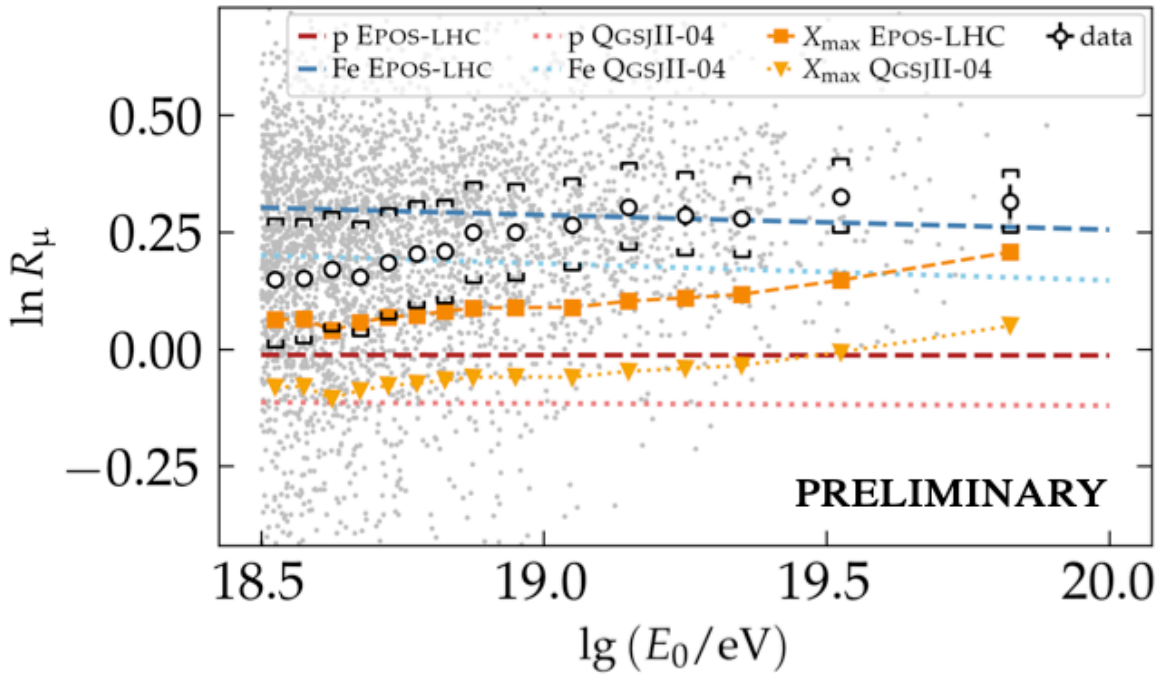
Measurement of average e.m. longitudinal profile shape

Phys.Rev.D 96 (2017) 12, 122003

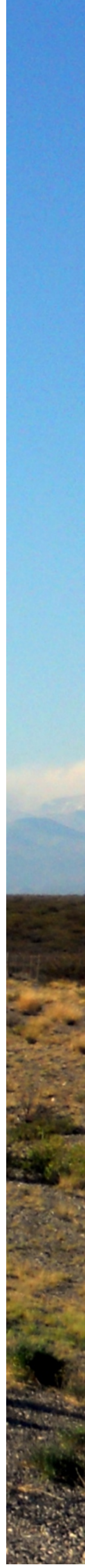


Measurement of time profiles of the signals recorded with the water-Cherenkov detectors

PoS (ICRC2023) 339

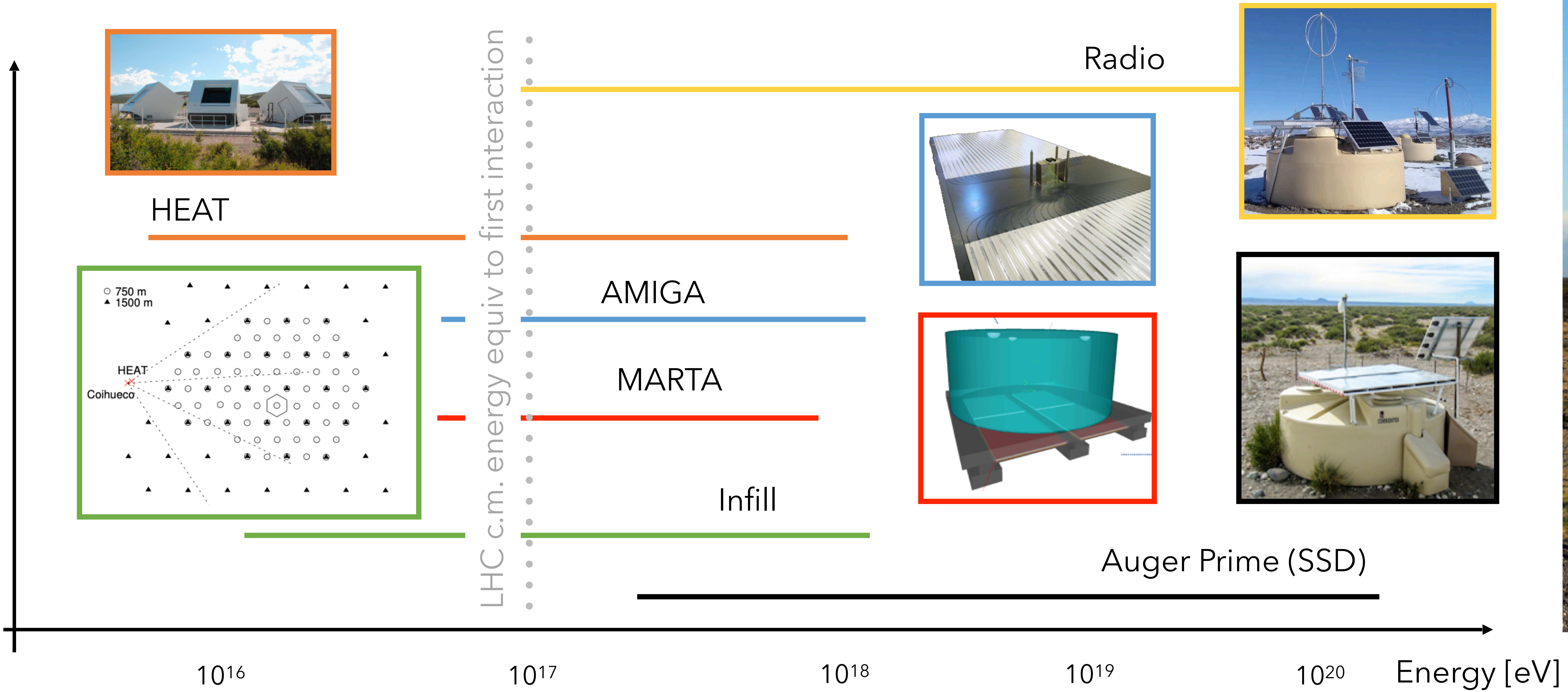


The number of muons measured in hybrid events

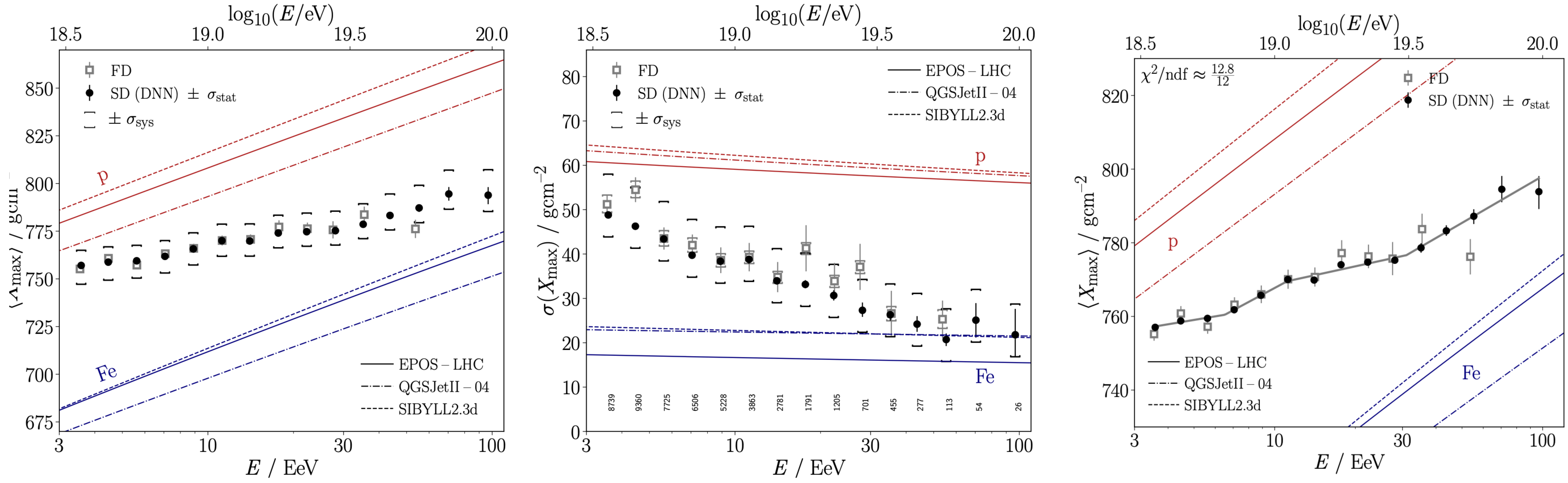


Multi-hybrid shower events

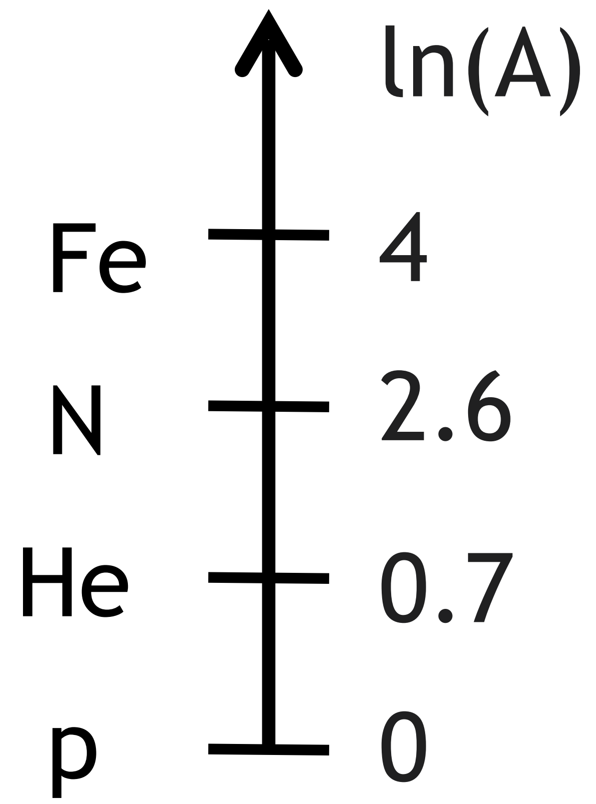
(A plethora of measurements to fully understand the shower)



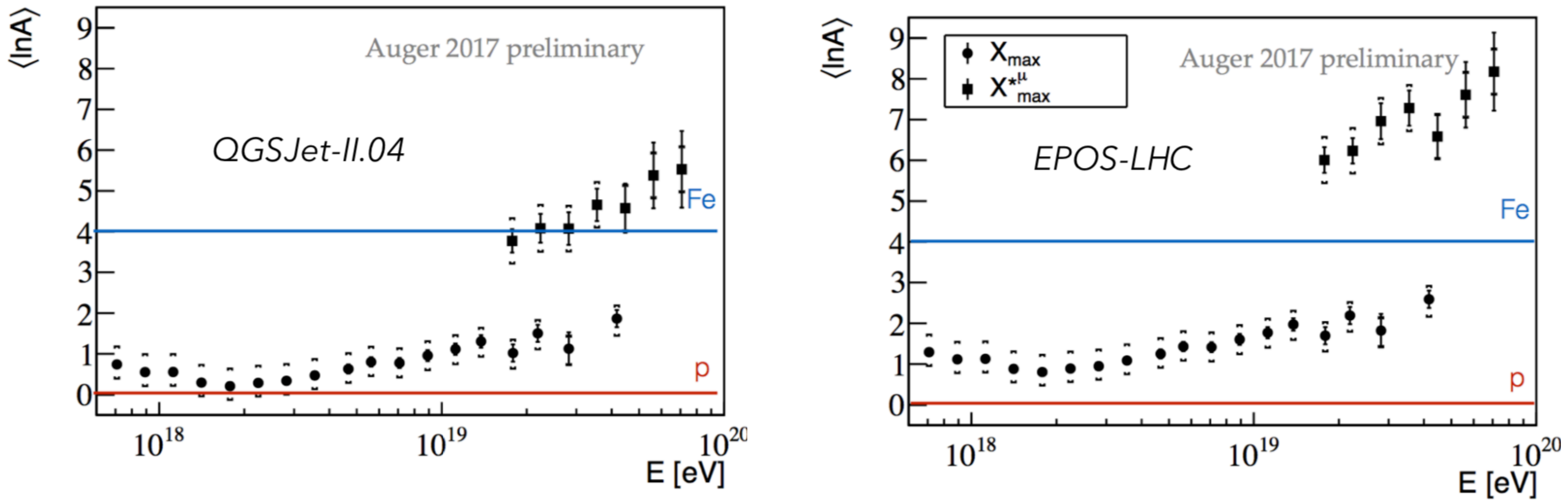
DNN


$\log_{10}(E/\mathrm{eV})$
18.5
19.0
19.5
20.0
$\langle X_{\max}\rangle$ / gcm^{-2}
850
825
800
775
750
725
700
675
FD
SD (DNN) ± σ_{stat}
± σ_{sys}
p
Fe
EPOS – LHC
QGSJetII – 04
SIBYLL2.3d
3
10
30
100
E / EeV
$\log_{10}(E/\mathrm{eV})$
18.5
19.0
19.5
20.0
$\sigma(X_{\max})$ / gcm^{-2}
80
70
60
50
40
30
20
10
0
FD
SD (DNN) ± σ_{stat}
± σ_{sys}
EPOS – LHC
QGSJetII – 04
SIBYLL2.3d
p
Fe
8739
9360
7725
6506
5228
3863
2781
1791
1205
701
455
277
113
54
26
3
10
30
100
E / EeV
$\log_{10}(E/\mathrm{eV})$
18.5
19.0
19.5
20.0
$\chi^2/\mathrm{ndf} \approx \frac{12.8}{12}$
FD
SD (DNN) ± σ_{stat}
$\langle X_{\max}\rangle$ / gcm^{-2}
820
800
780
760
740
p
Fe
EPOS – LHC
QGSJetII – 04
SIBYLL2.3d
3
10
30
100
E / EeV

Muon Production Depth



35th ICRC, PoS (2017) 398



- Depth of maximum of muon production depth ($X^{*\mu}_{max}$) in strong tension with FD measurements
- $X^{*\mu}_{max}$ measurement is highly dependent on details of hadronic interactions

J. Espadanal, L. Cazon, RC, Astropart.Phys. 86 (2017) 32-40