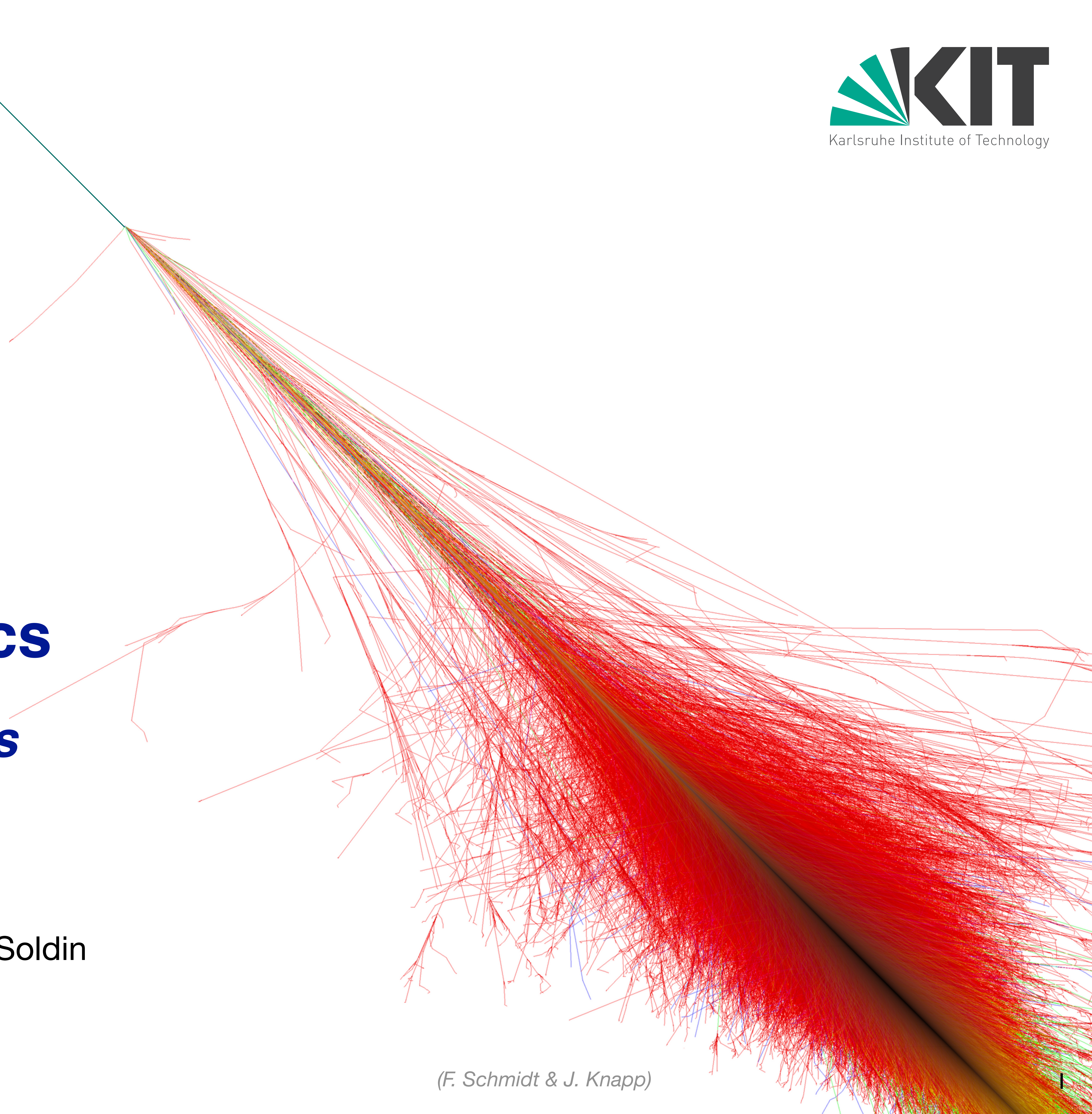
Forward Physics Facility

Karlsruhe Institute of Technology

FPF and Air Shower Physics

Some thoughts and suggestions

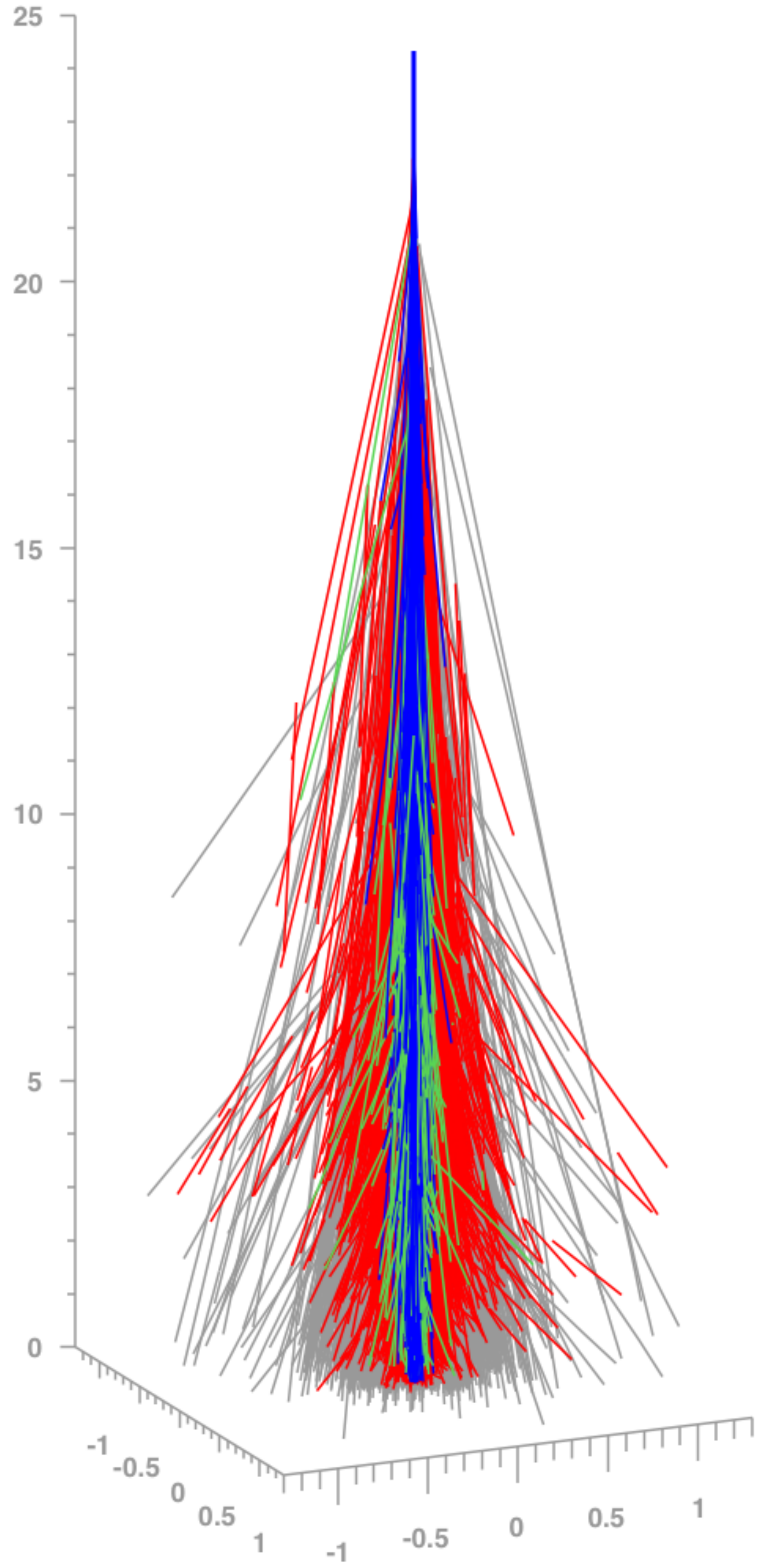
Ralph Engel, Anatoli Fedynitch, Felix Riehn, Dennis Soldin

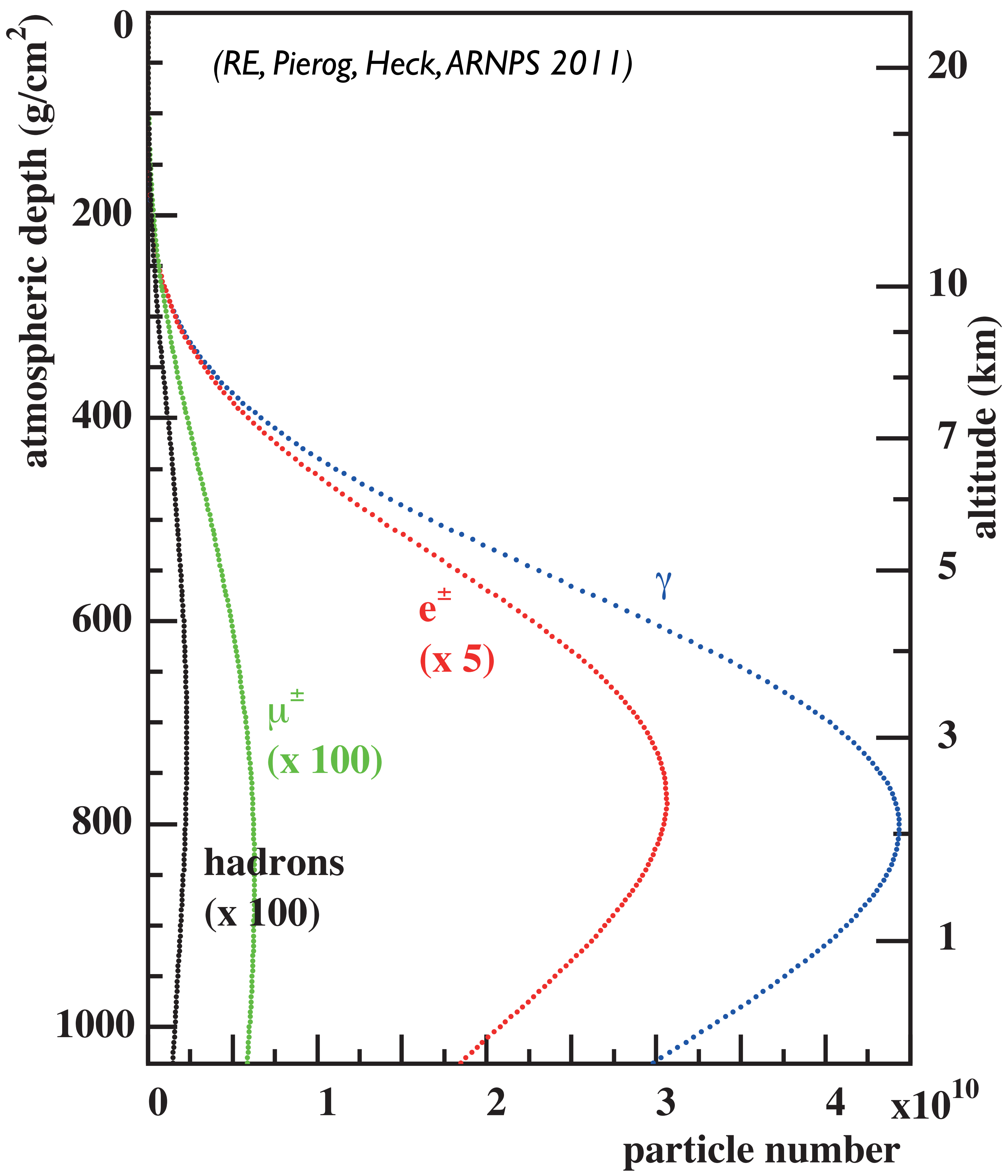


(F. Schmidt & J. Knapp)

The muon discrepancy

Air shower observables



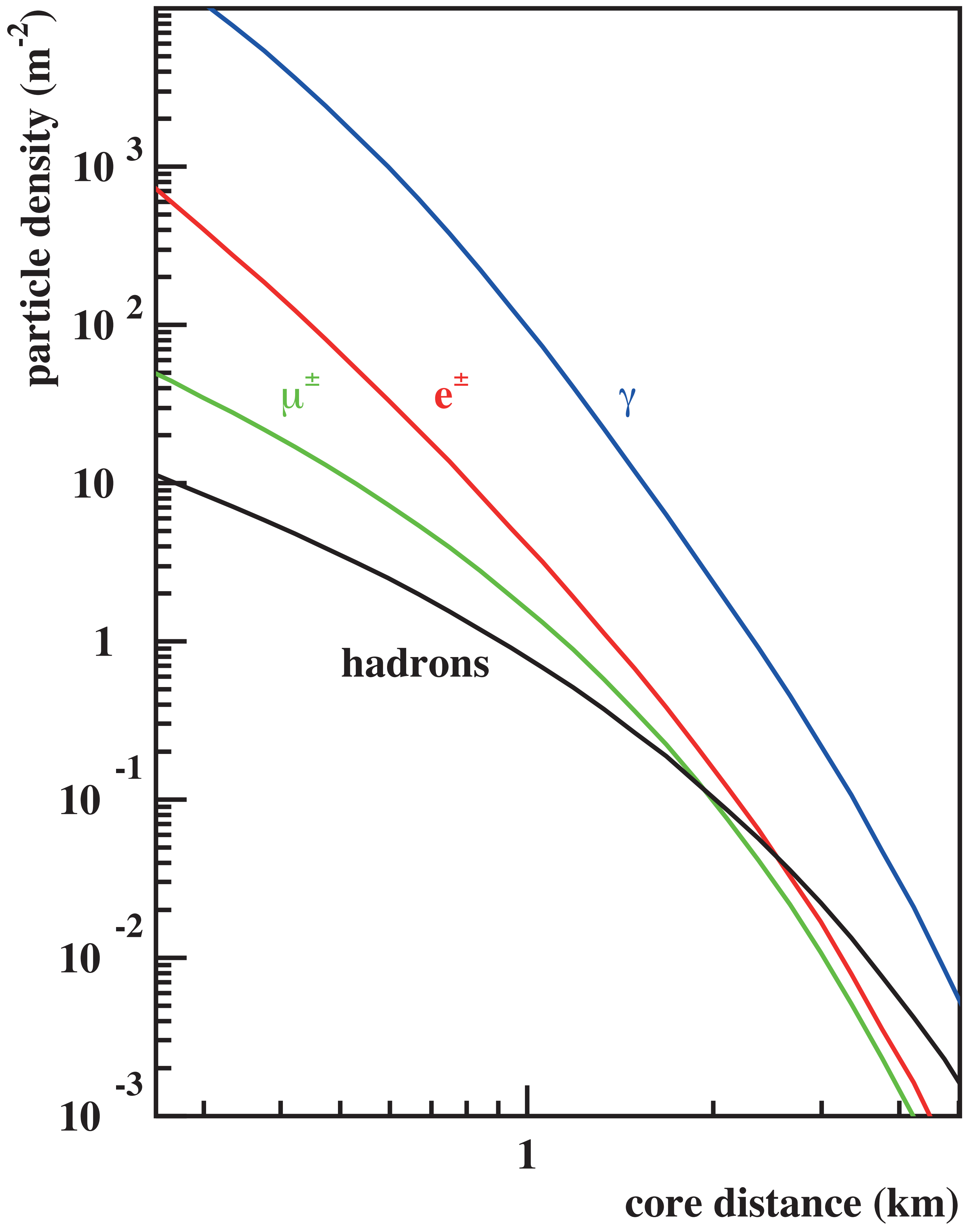


Longitudinal profile:

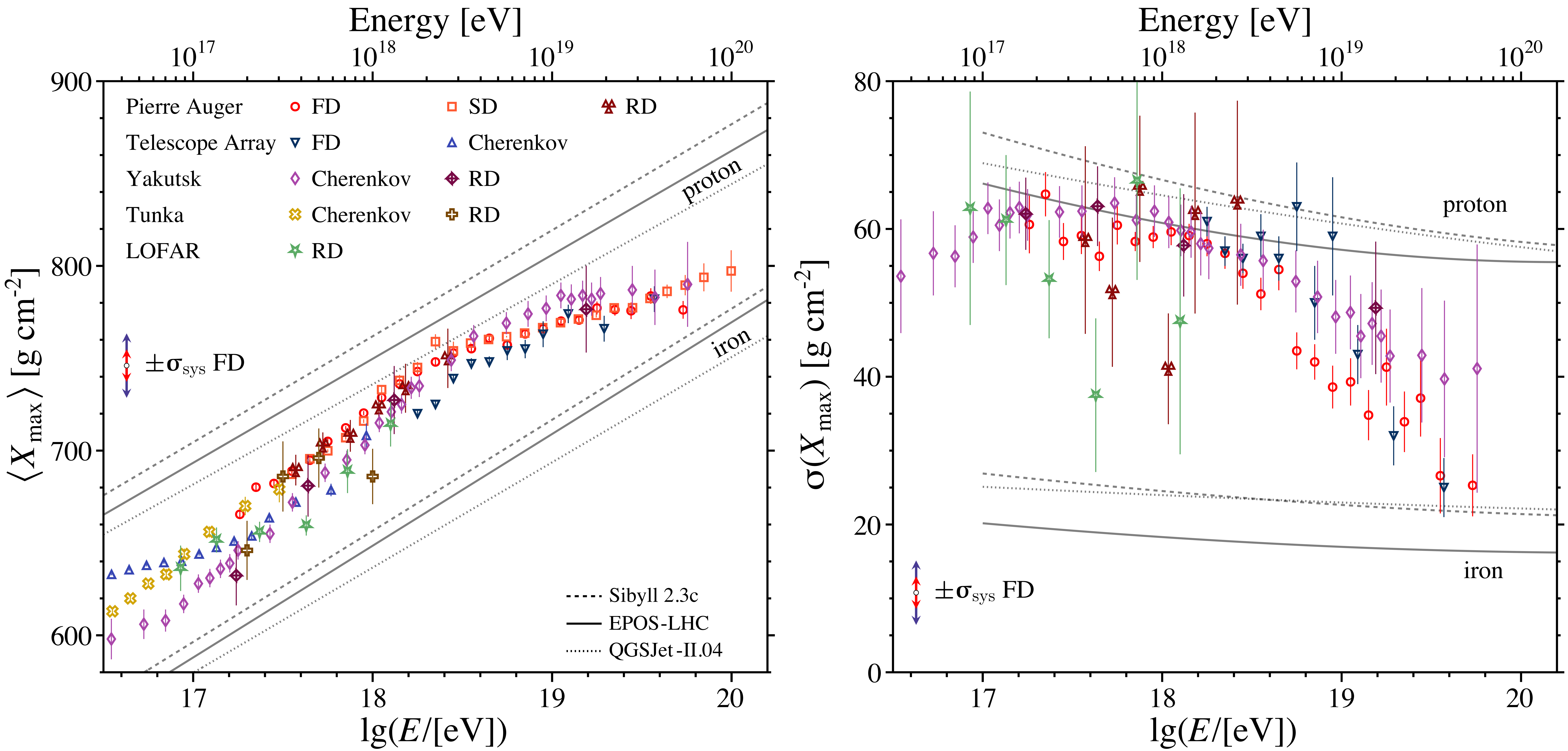
Cherenkov light
Fluorescence light
(bulk of particles measured)

Lateral profiles:

particle detectors at ground
(very small fraction of particles sampled)

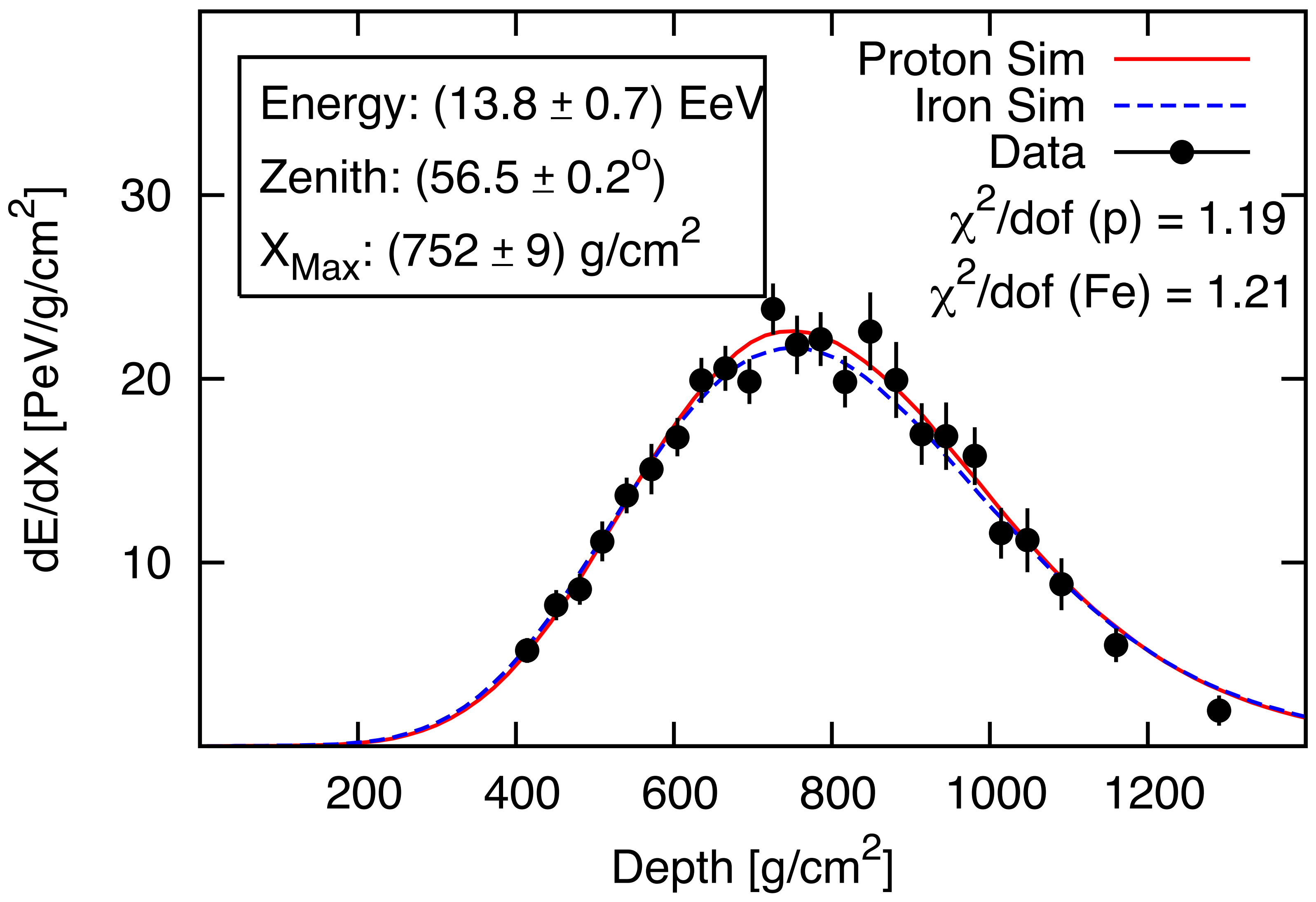


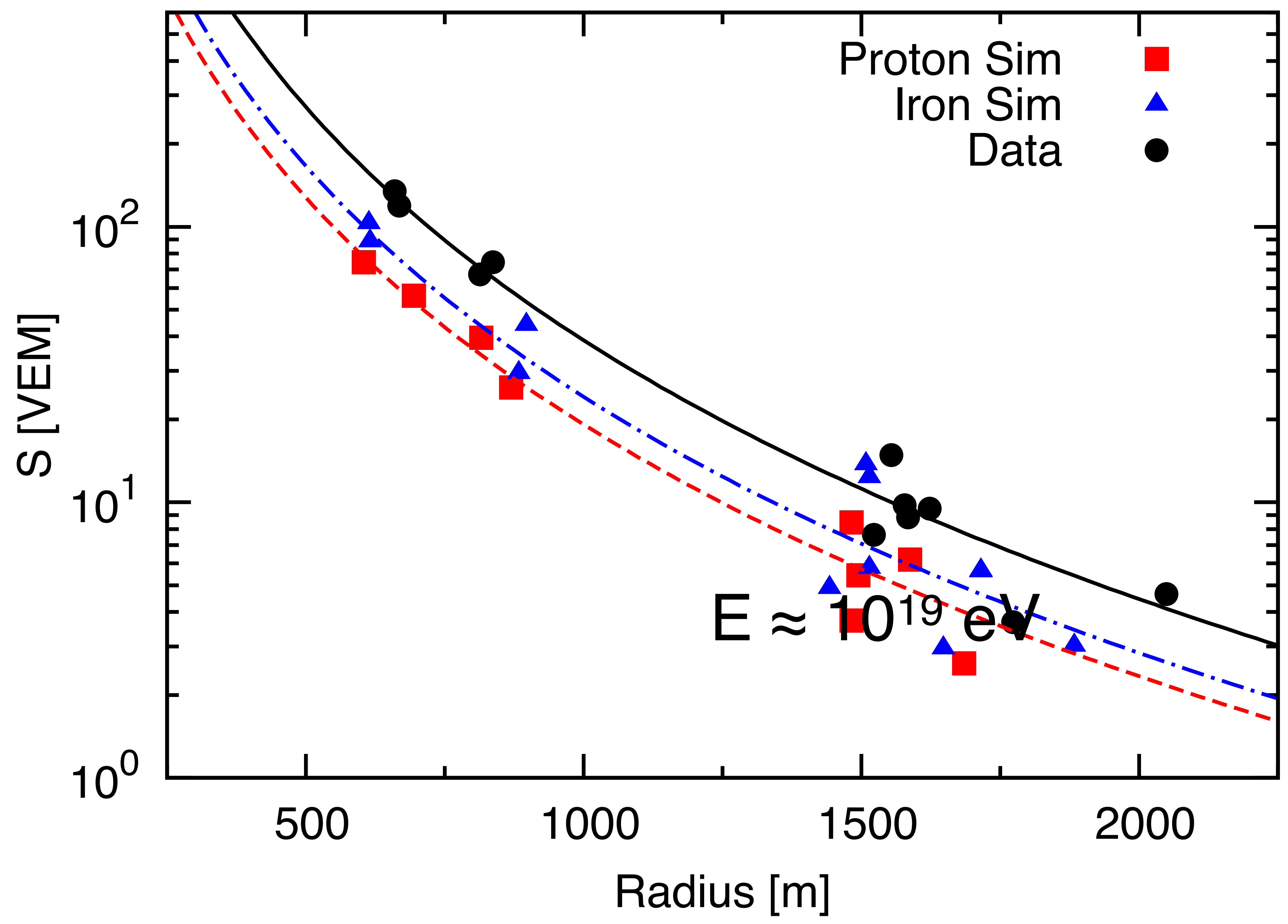
World data set on depth of shower maximum (X_{max})



(Coleman et al. Snowmass, Astroparticle Physics 147 (2023) 102794)

Auger muon measurement – vertical showers



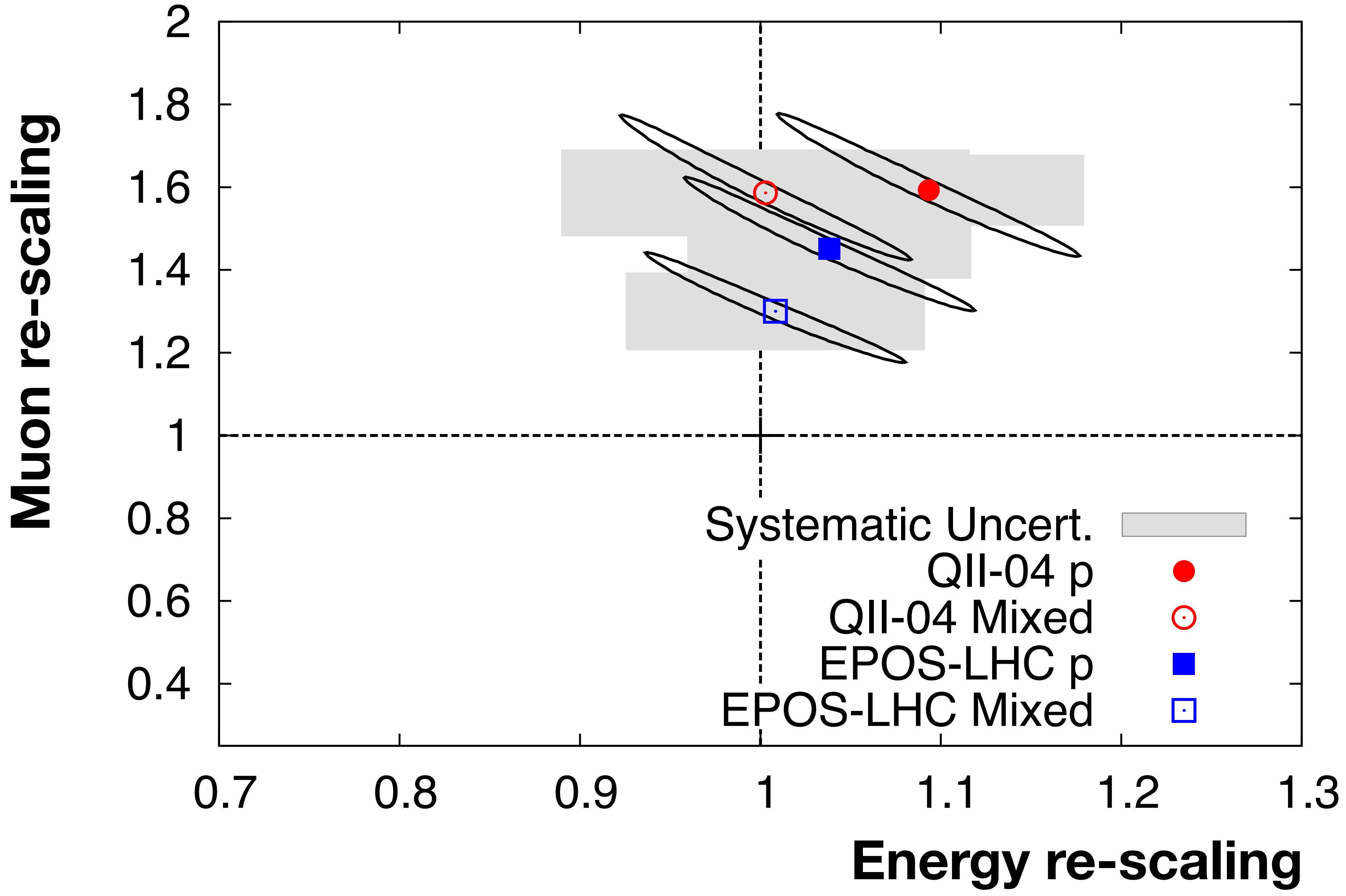


(Auger, PRL 117, 2016)

Energy scaling: em. particles and muons

Muon scaling: hadronically produced muons and muon interaction/decay products

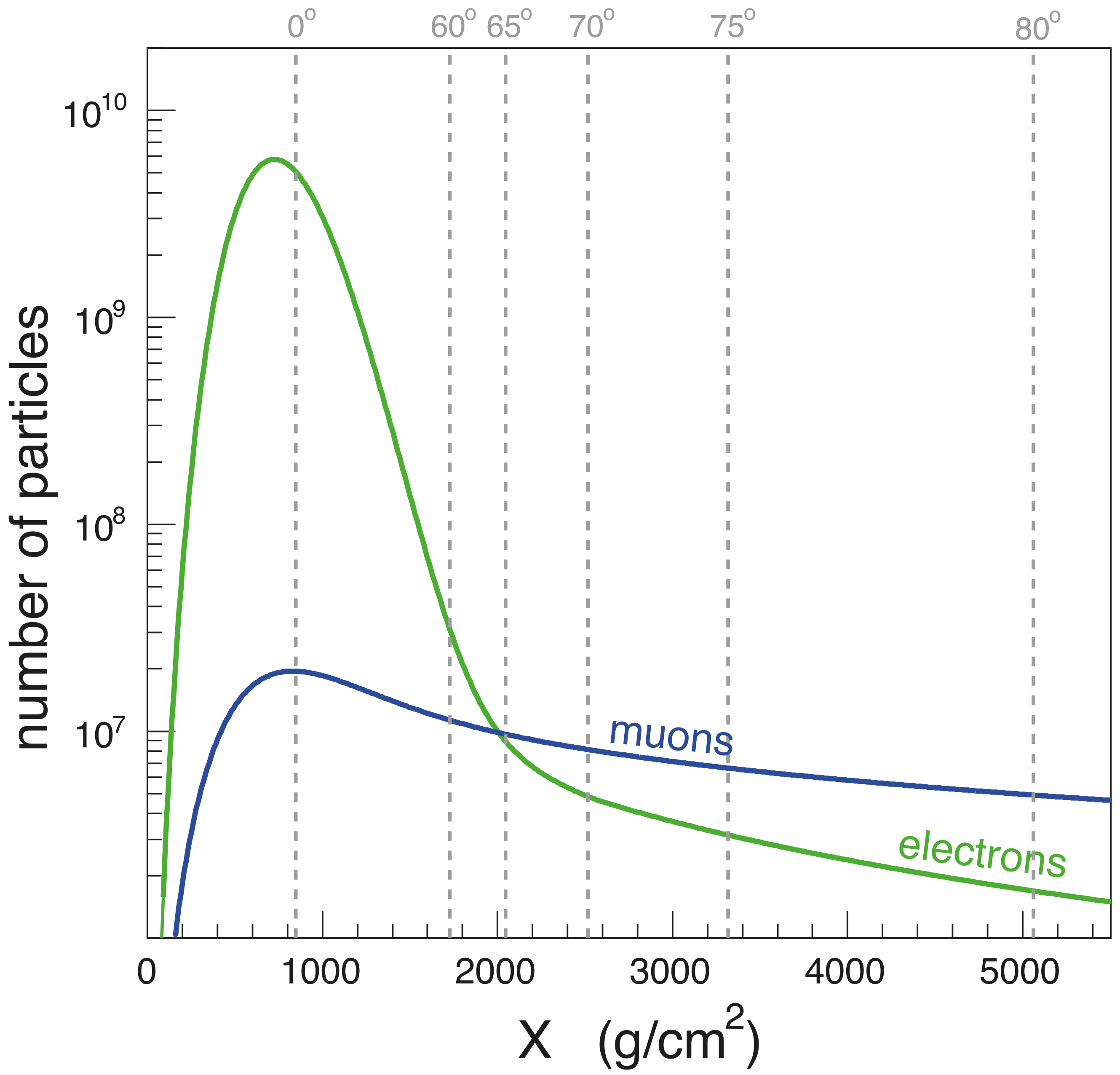
Use showers of different zenith angles



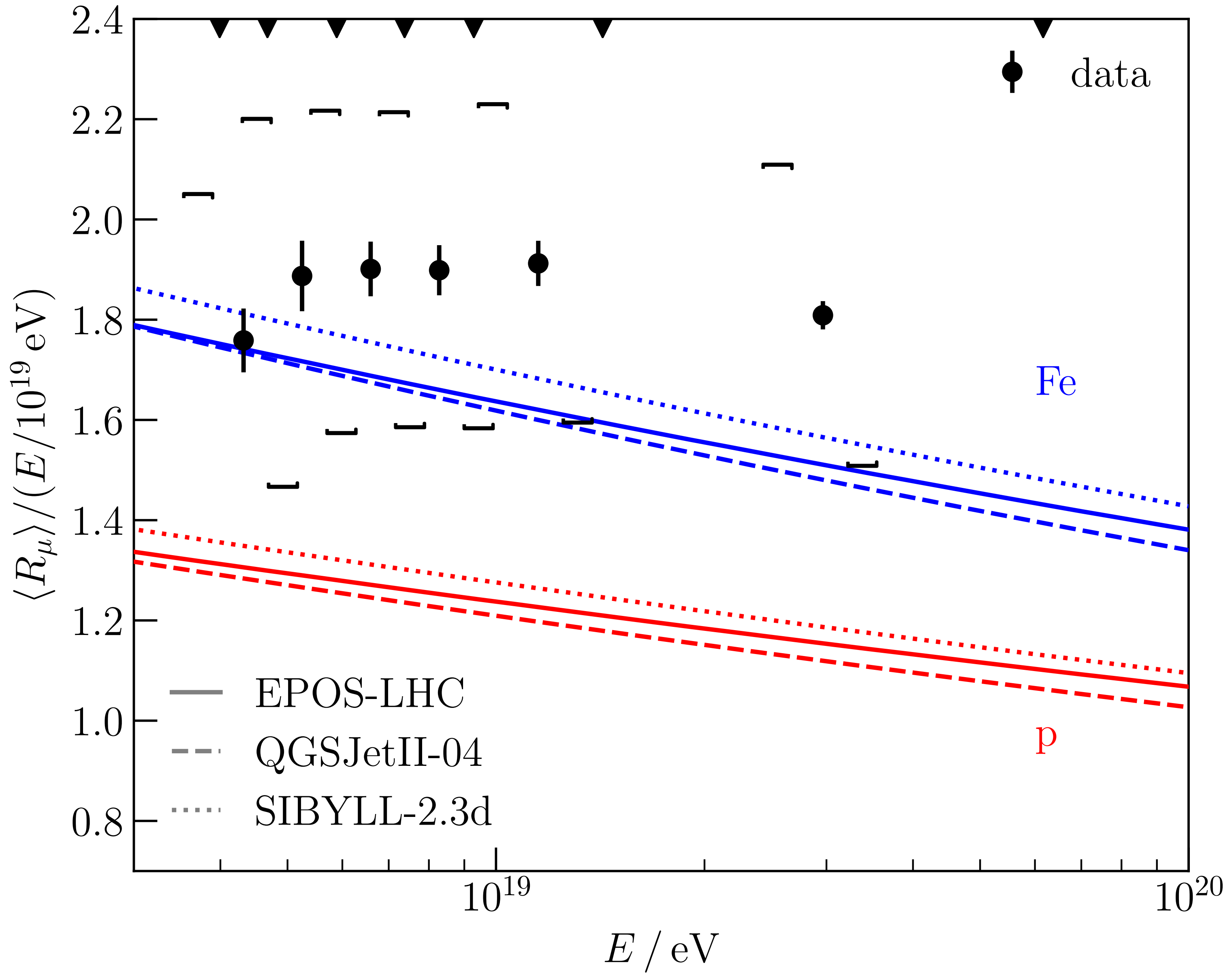
Consistently more muons in data than predicted

Auger muon measurement – inclined showers

Shower size attenuation

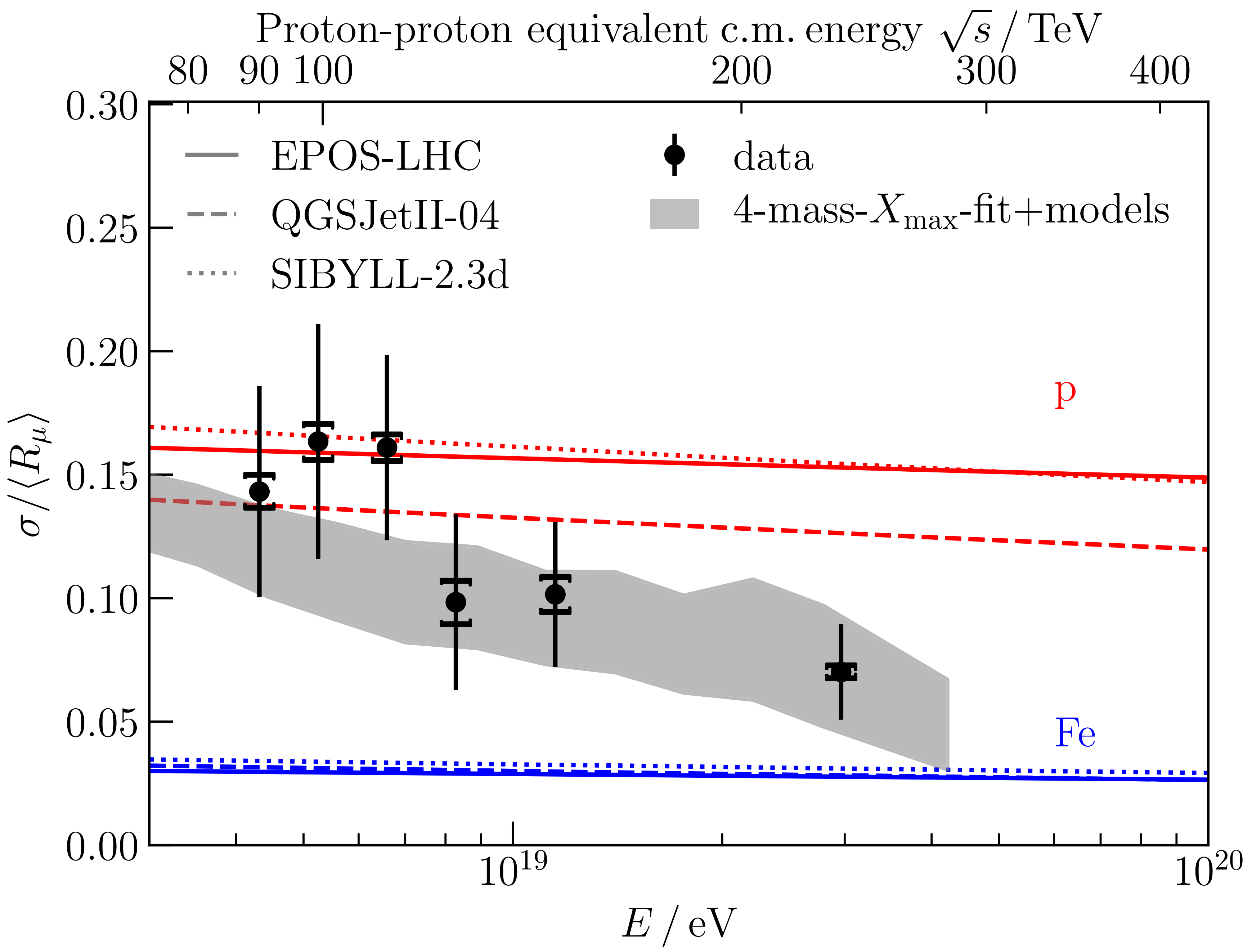


Number of muons in showers with θ>65°



(Auger PRD 2015, PRL 2021)

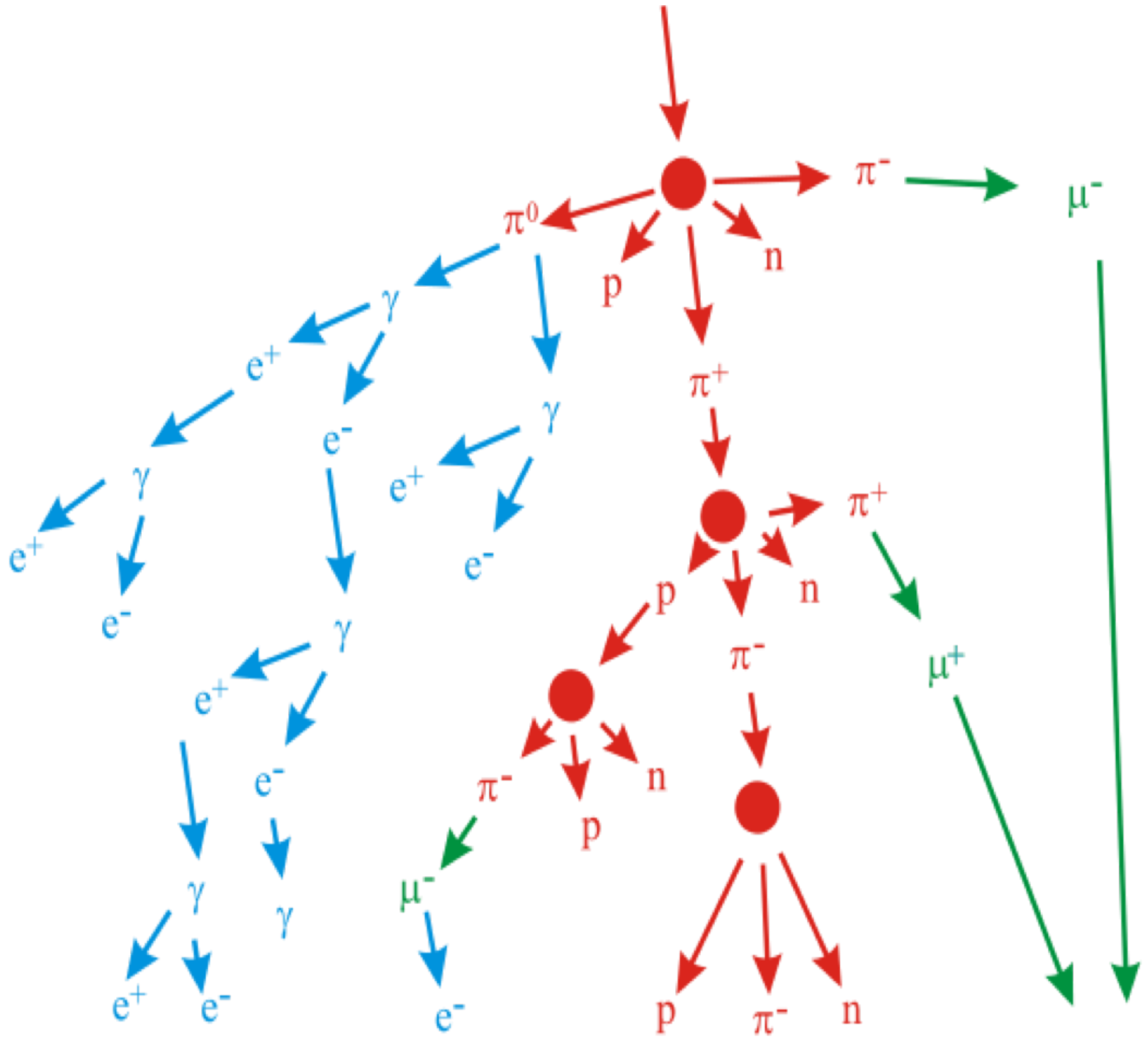
Shower-to-shower fluctuations

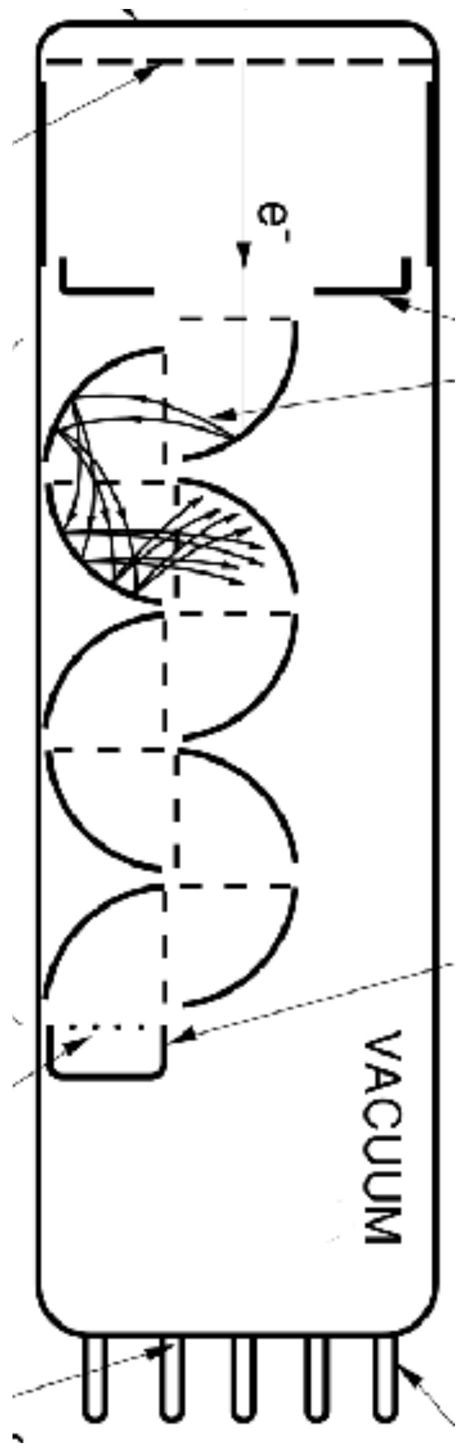


(Auger, ICRC 2019, PRL 2021)

Discrepancy of muon muon number, but no in relative shower-to-shower fluctuations

Importance of shower-to-shower fluctuations





Lorenzo Cazon et al.
Astropart. Phys. 36 (2012) 211
Phys. Lett. B784 (2018) 68
Phys. Rev. D103 (2021) 022001

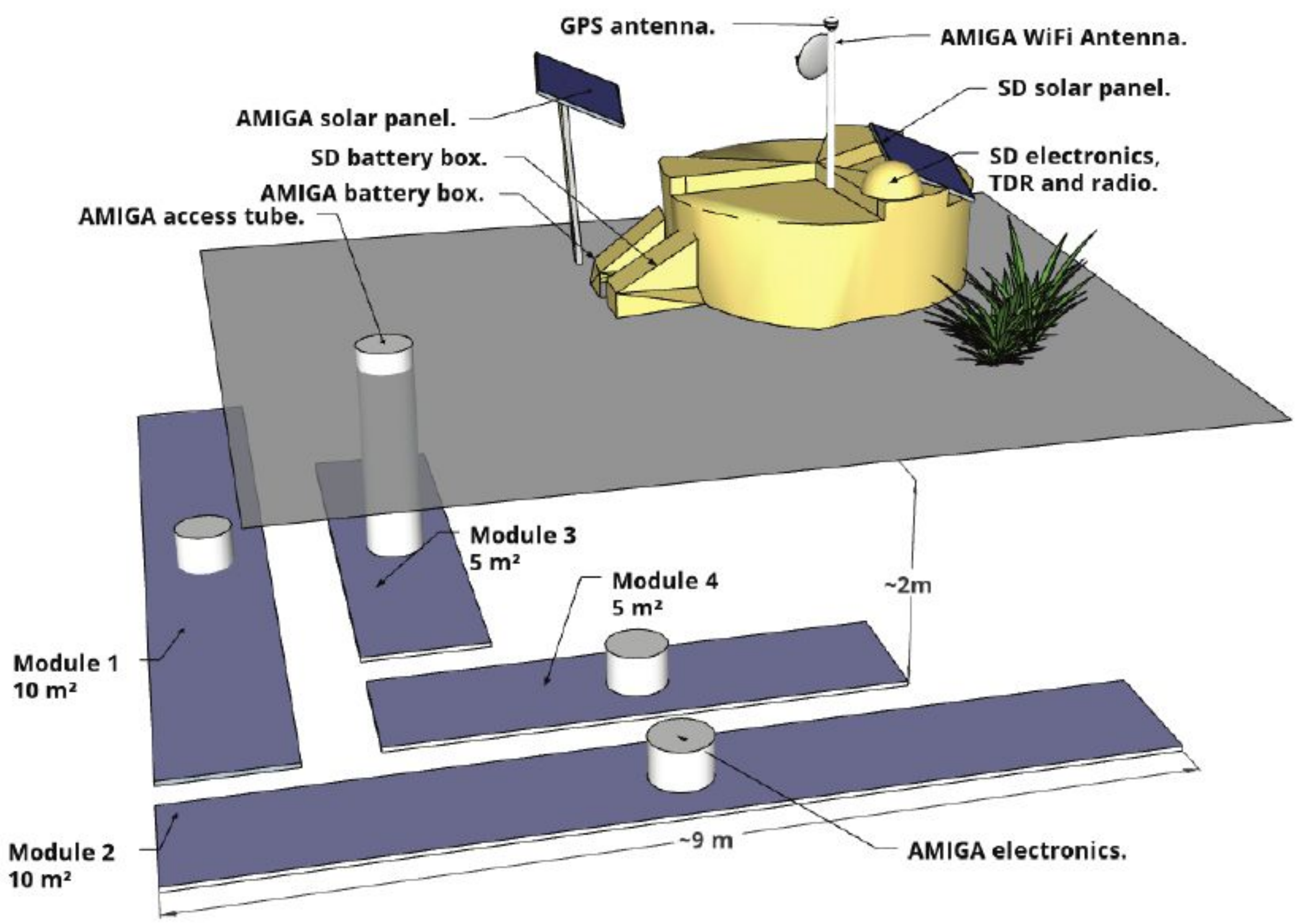
PMT analogy to shower

First interaction in air shower not exotic in terms of fluctuations

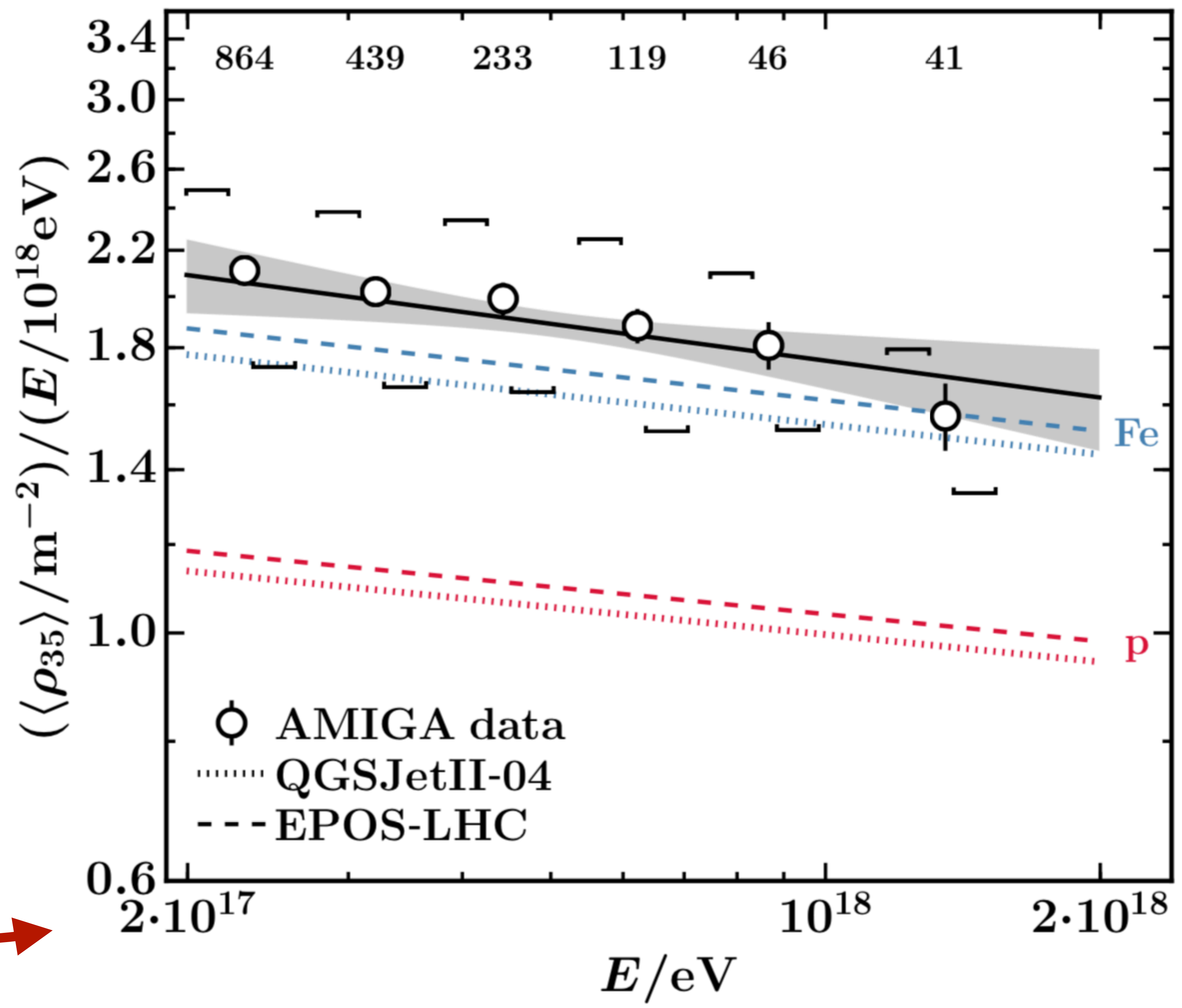
70% of fluctuations from first interaction

$$\left(\frac{\sigma(N_\mu)}{N_\mu}\right)^2 \simeq \left(\frac{\sigma(\alpha_1)}{\alpha_1}\right)^2 + \left(\frac{\sigma(\alpha_2)}{\alpha_2}\right)^2 + \ldots + \left(\frac{\sigma(\alpha_c)}{\alpha_c}\right)^2$$

At what energy does discrepancy begin?

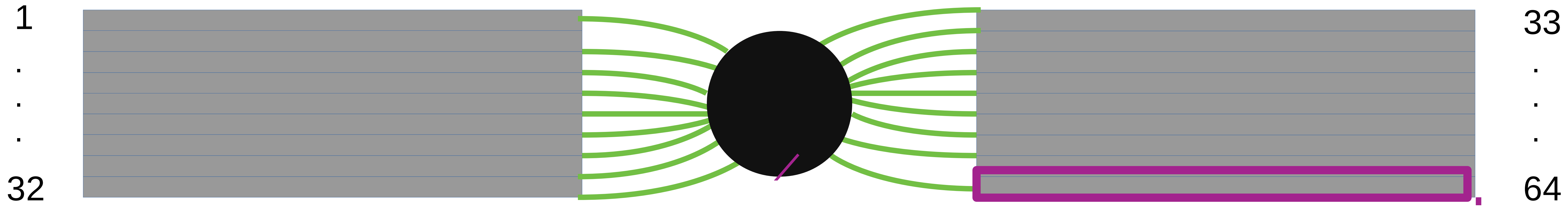


(Auger, EPJ 2020)



LHC energy

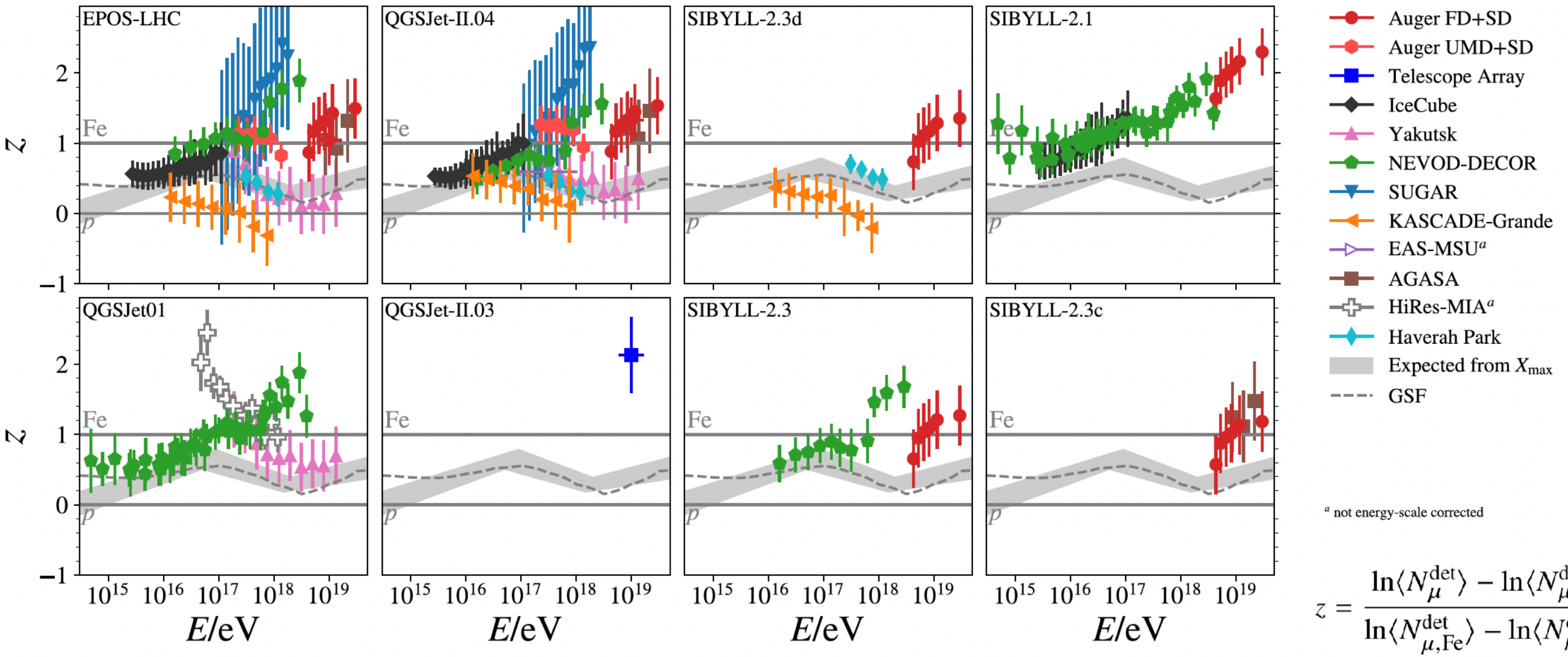
Scintillator strip detector, readout initially MAPMT, later SiPM



World data set on muon production in air showers

- The z-scale after applying the energy shifts for common energy calibration. Preliminary

(WHISP group, updated ICRC 2023, Cazon et al. HadInt tuning WS 2024)



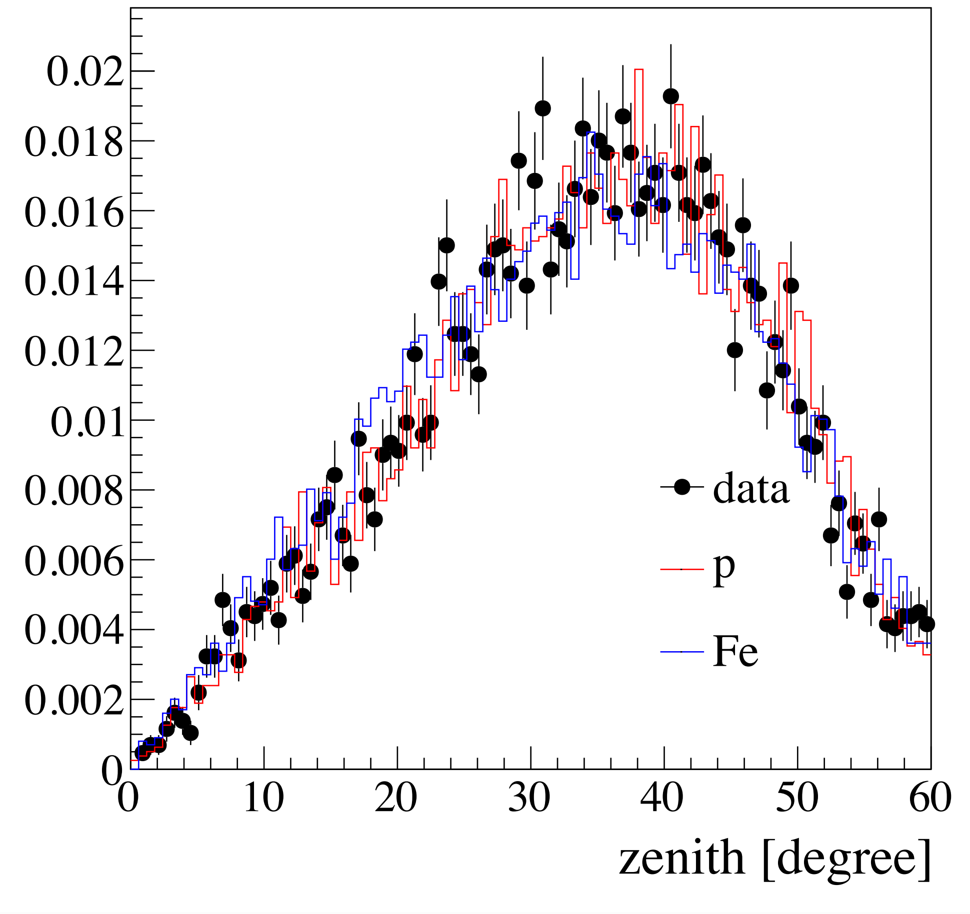
$$z = \frac{\ln\langle N_{\mu}^{det}\rangle - \ln\langle N_{\mu,p}^{det}\rangle}{\ln\langle N_{\mu,Fe}^{det}\rangle - \ln\langle N_{\mu,p}^{det}\rangle}$$

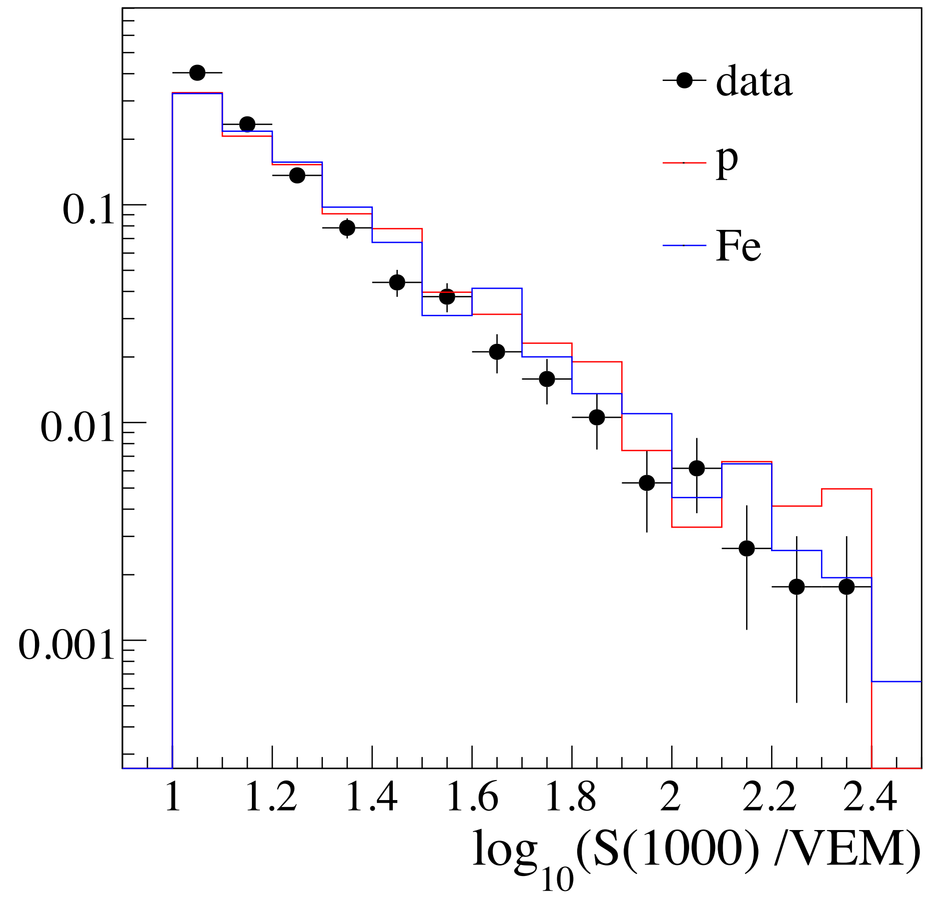
Data compilation appears inconclusive, sensitivity of many experiments debated

Sensitivity of individual observables

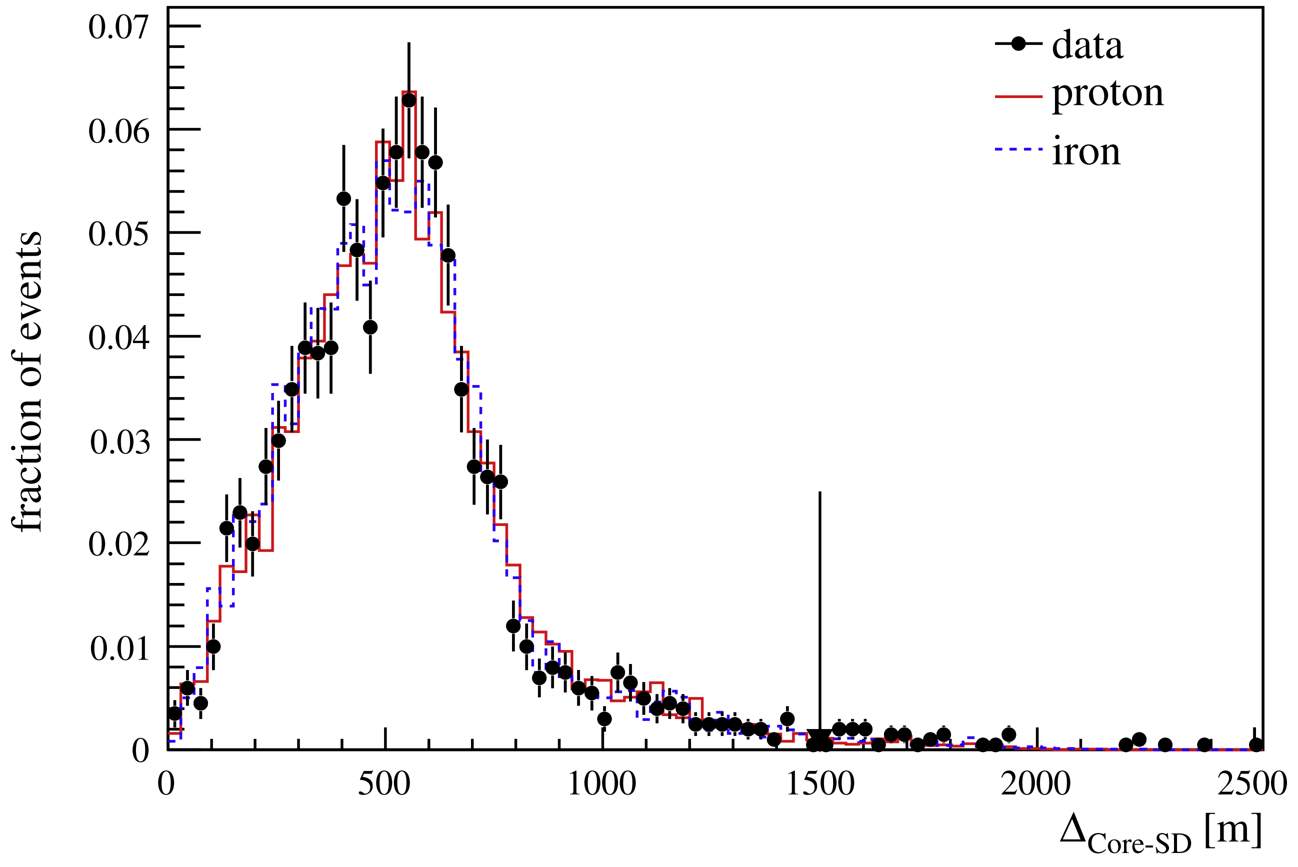
(*Auger, Astropart. Phys. 34, 2011*)

Zenith angle

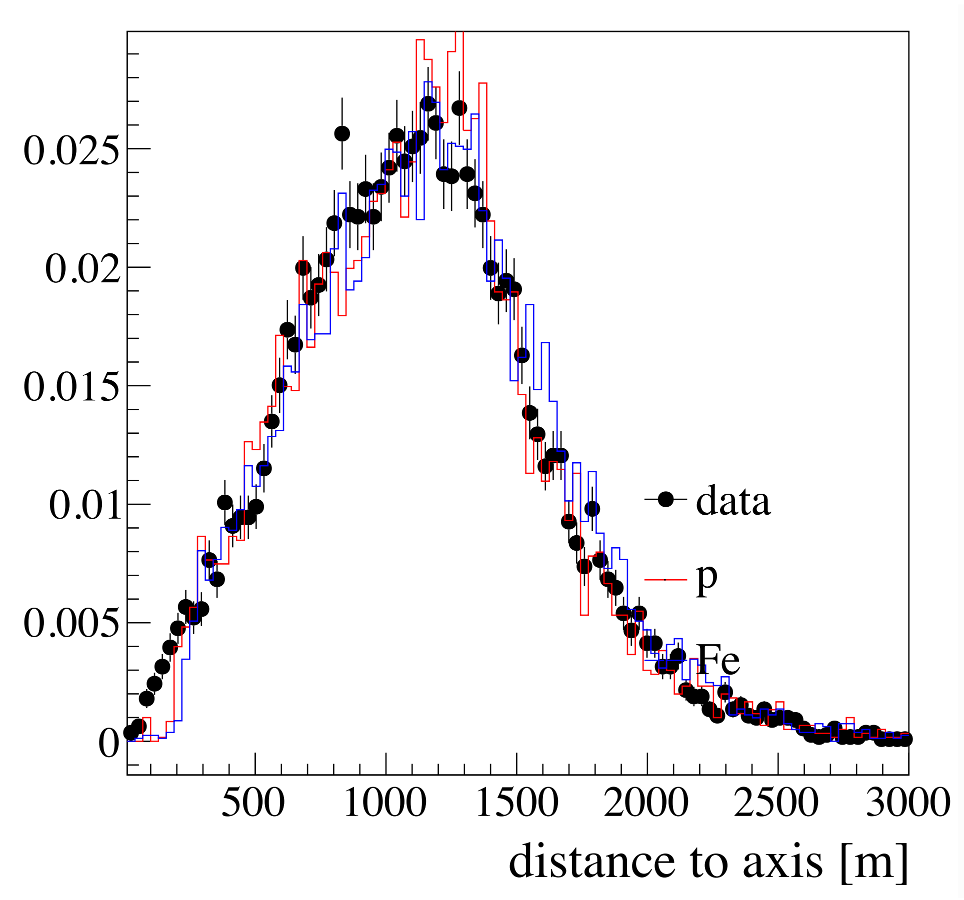


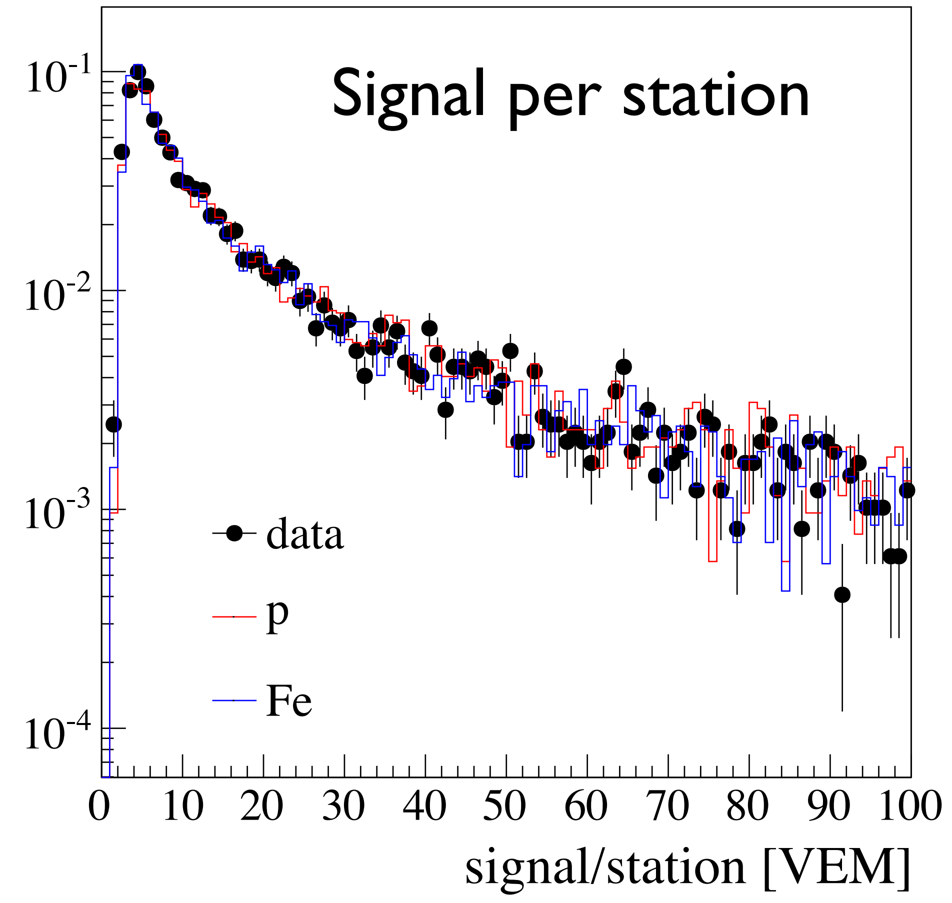


Core distance to closest station (FD)

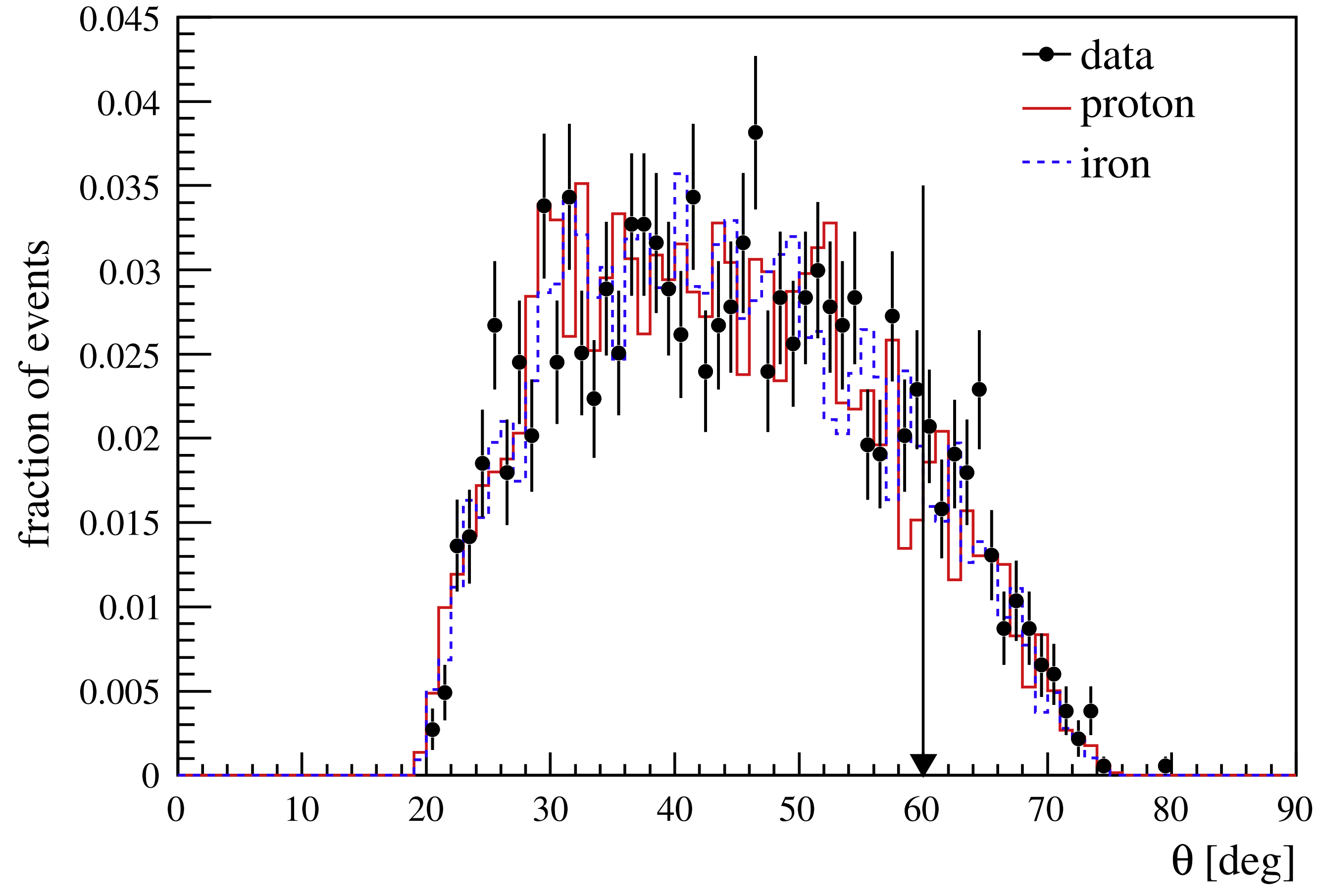


Distance of triggered stations





Zenith angle (FD, fluorescence data)



Data appear fully compatible with MC simulations if only one observable is considered

Physics of muon production

Electromagnetic energy and energy transfer

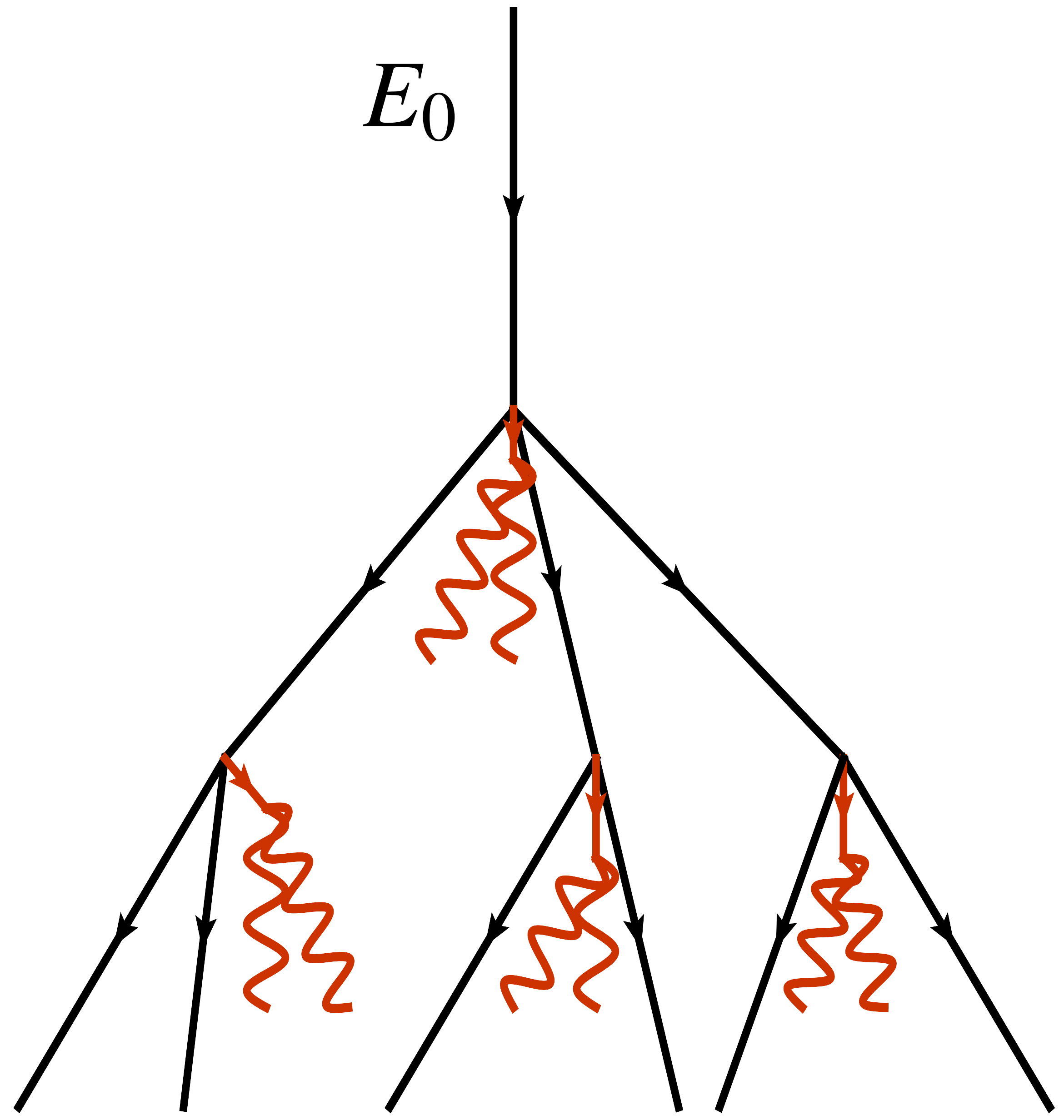
Hadronic energy

$$\frac{2}{3}E_0$$

$$\frac{2}{3}\left(\frac{2}{3}E_0\right)$$

$$\vdots$$

$$E_{\text{had}} = \left(\frac{2}{3}\right)^n E_0$$



After n generations ...

$$n = 5,\quad E_{\text{had}} \sim 12\%$$
$$n = 6,\quad E_{\text{had}} \sim 8\%$$

Electromagnetic energy

$$\frac{1}{3}E_0$$

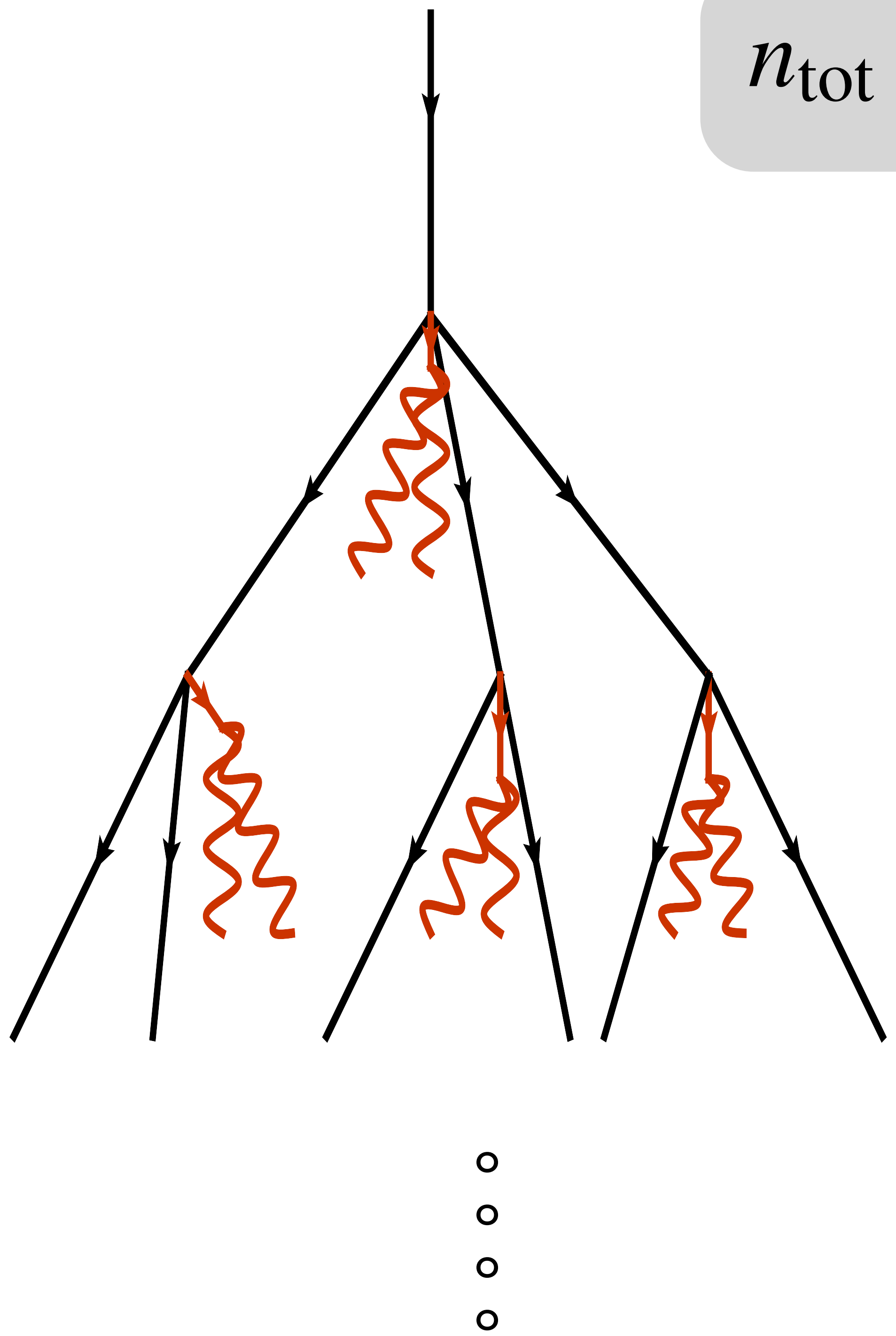
$$\frac{1}{3}E_0 + \frac{1}{3}\left(\frac{2}{3}E_0\right)$$

$$\vdots$$

$$E_{\text{em}} = \left[1 - \left(\frac{2}{3}\right)^n\right] E_0$$

Muon production in hadronic showers

$$n_{tot} = n_{\pi^0} + n_{ch}$$



Energy	Number of charged particles
E_0	
E_0/n_{tot}	n_{ch}
$E_0/(n_{tot})^2$	$(n_{ch})^2$
$E_0/(n_{tot})^n$	$(n_{ch})^n$

Primary particle proton

π^0 decay immediately

$\pi^\pm$ initiate new cascades

Pion decay energy ~30 GeV,
Typically 8-12 generations

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\beta$$

$$\beta = \frac{\ln n_{ch}}{\ln n_{tot}} \approx 0.82 \ldots 0.95$$

Assumptions:

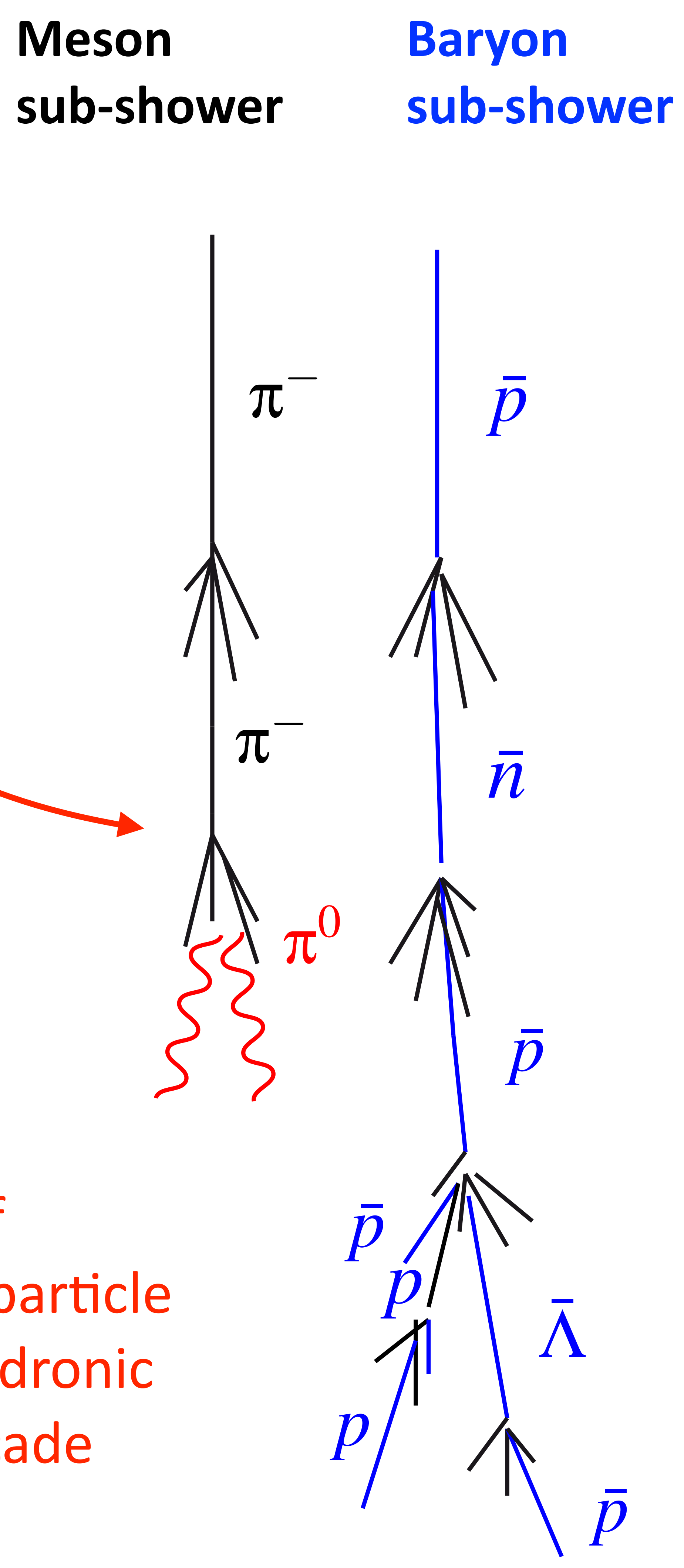
- cascade stops at $E_{part} = E_{dec}$
- each hadron produces one muon

(Matthews, Astropart.Phys. 22, 2005)

Possible solutions to muon problem and FPF

Muon production depends on hadronic energy fraction

30% chance to have π^0 as leading particle



$\pi^0 \to \gamma\gamma$

$\rho^0 \to \pi^+\pi^-$

Decay of leading particle stops hadronic sub-cascade

1 Baryon-Antibaryon pair production *(Pierog, Werner 2008)*

- Baryon number conservation
- Low-energy particles: large angle to shower axis
- Transverse momentum of baryons higher
- Enhancement of mainly **low-energy** muons

(Grieder ICRC 1973; Pierog, Werner PRL 101, 2008)

2 Enhanced kaon/strangeness production *(Anchordoqui et al. 2022)*

- Similar effects as baryon pairs
- Decay at higher energy than pions (~600 GeV)

3 Leading particle effect for pions *(Drescher 2007, Ostapchenko 2016)*

- Leading particle for a π could be ρ^0 and not π^0
- Decay of ρ^0 to 100% into two charged pions

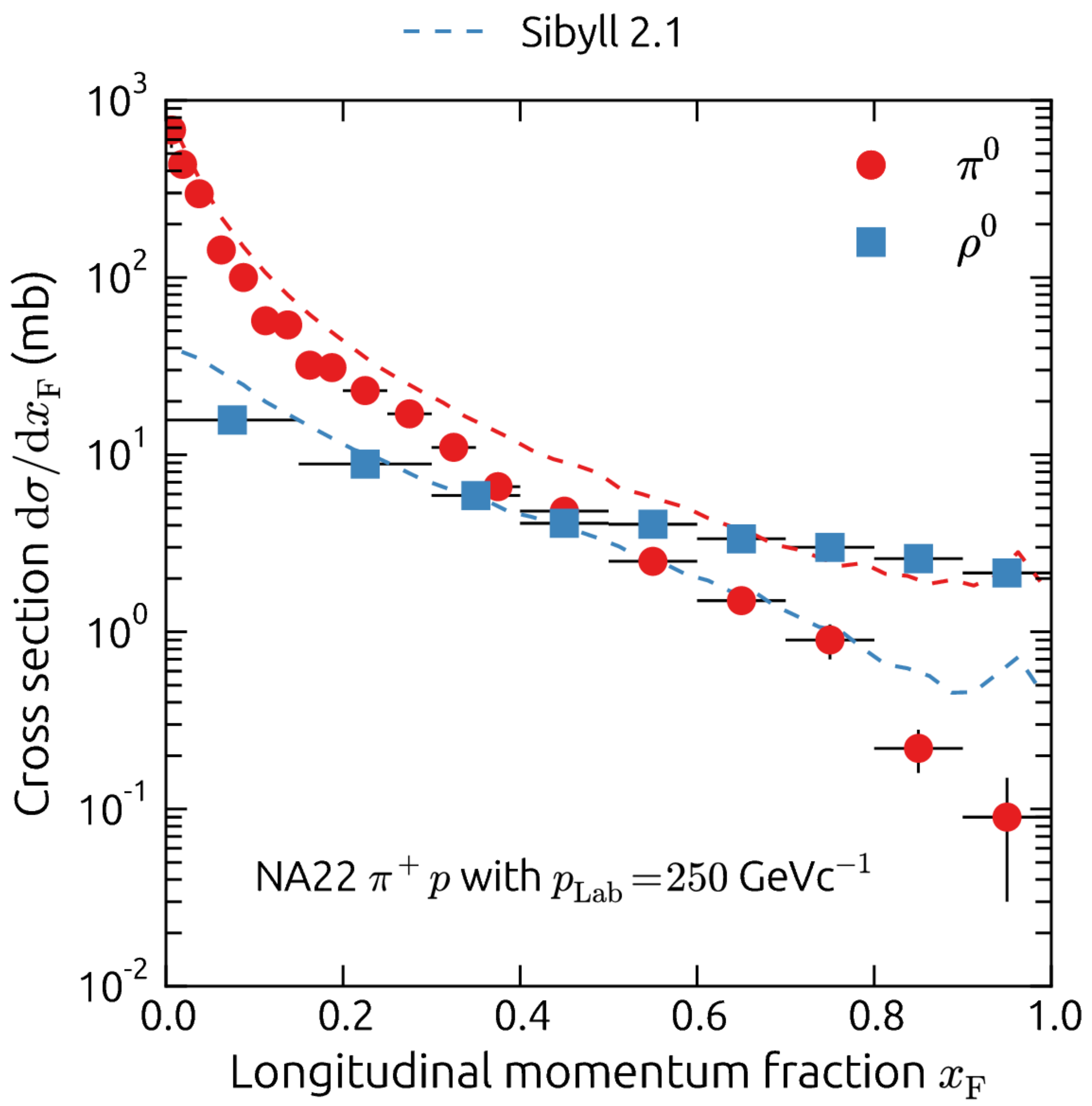
4 New hadronic physics at high energy *(Farrar, Allen 2012, Salamida 2009)*

- Inhibition of π^0 decay (Lorentz invariance violation etc.)
- Chiral symmetry restauration

Several of these effects: Core-Corona model (Pierog et al.)

Rho production in π-p interactions (Sibyll 2.1 → Sibyll 2.3)

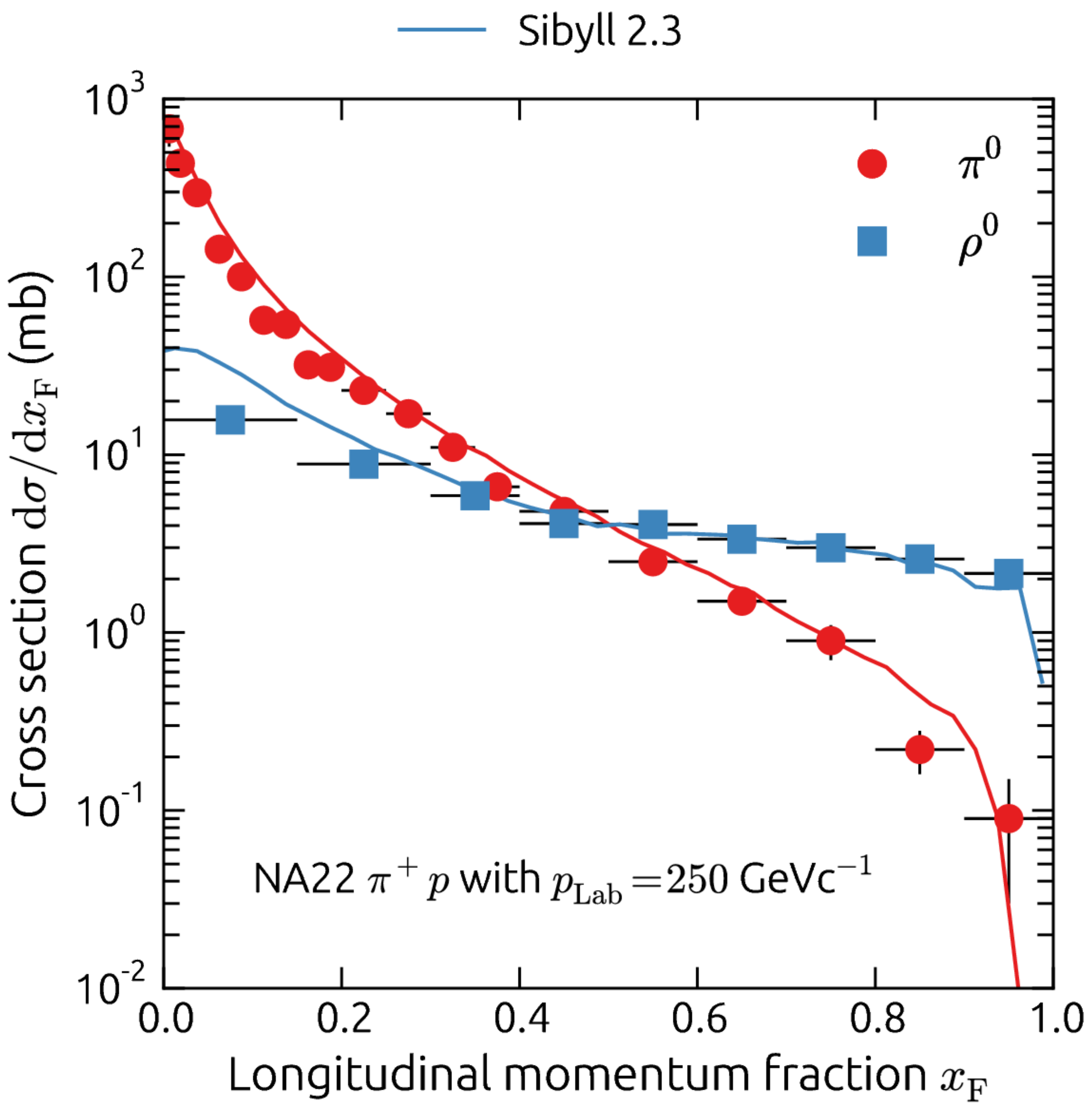
Leading particle production



$$\pi^+ p \rightarrow \pi^0 \rightarrow 2\gamma$$

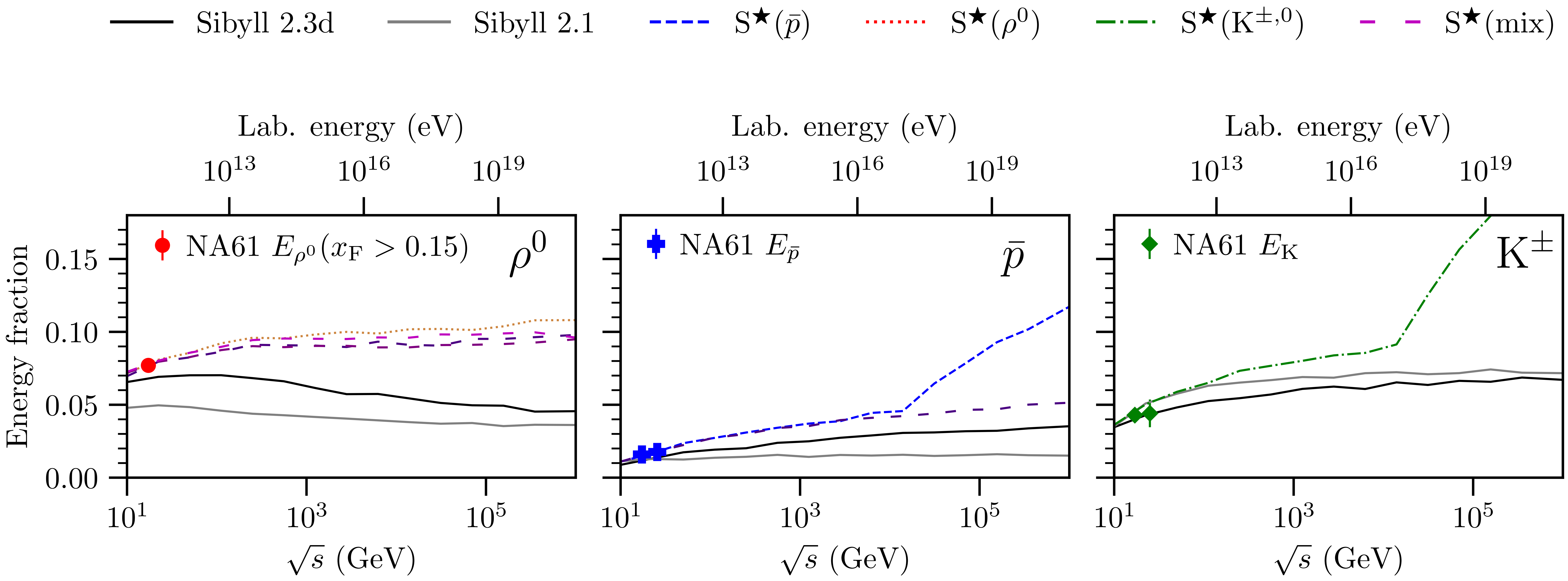
$$\pi^+ p \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$$

$$x_F = p_{\parallel}/p_{max}$$



(Riehn et al., ICRC 2015)

Simple and pragmatic approach – Sibyll 2.3d*

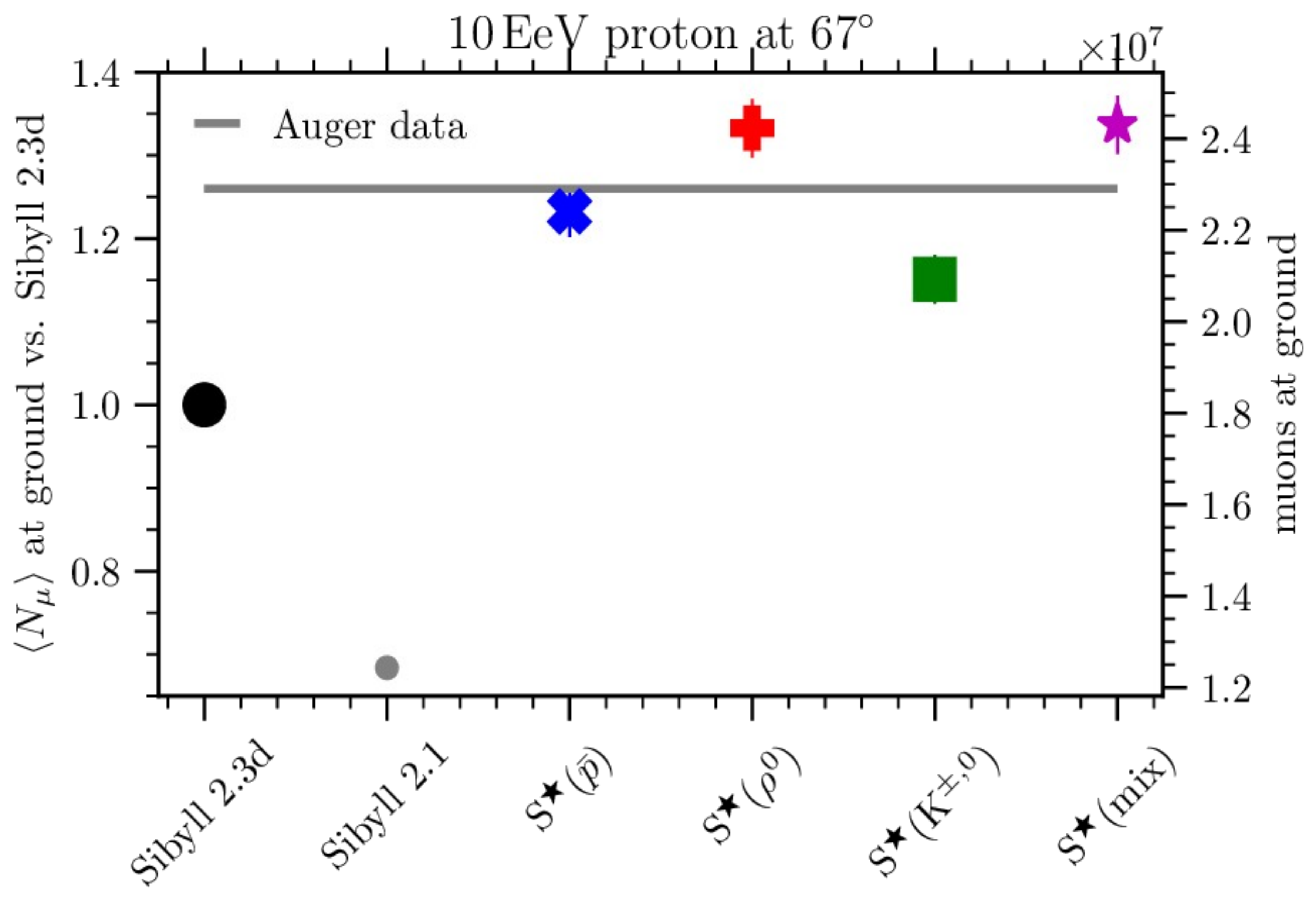


Modification of Sibyll 2.3d to study different versions of muon enhancement

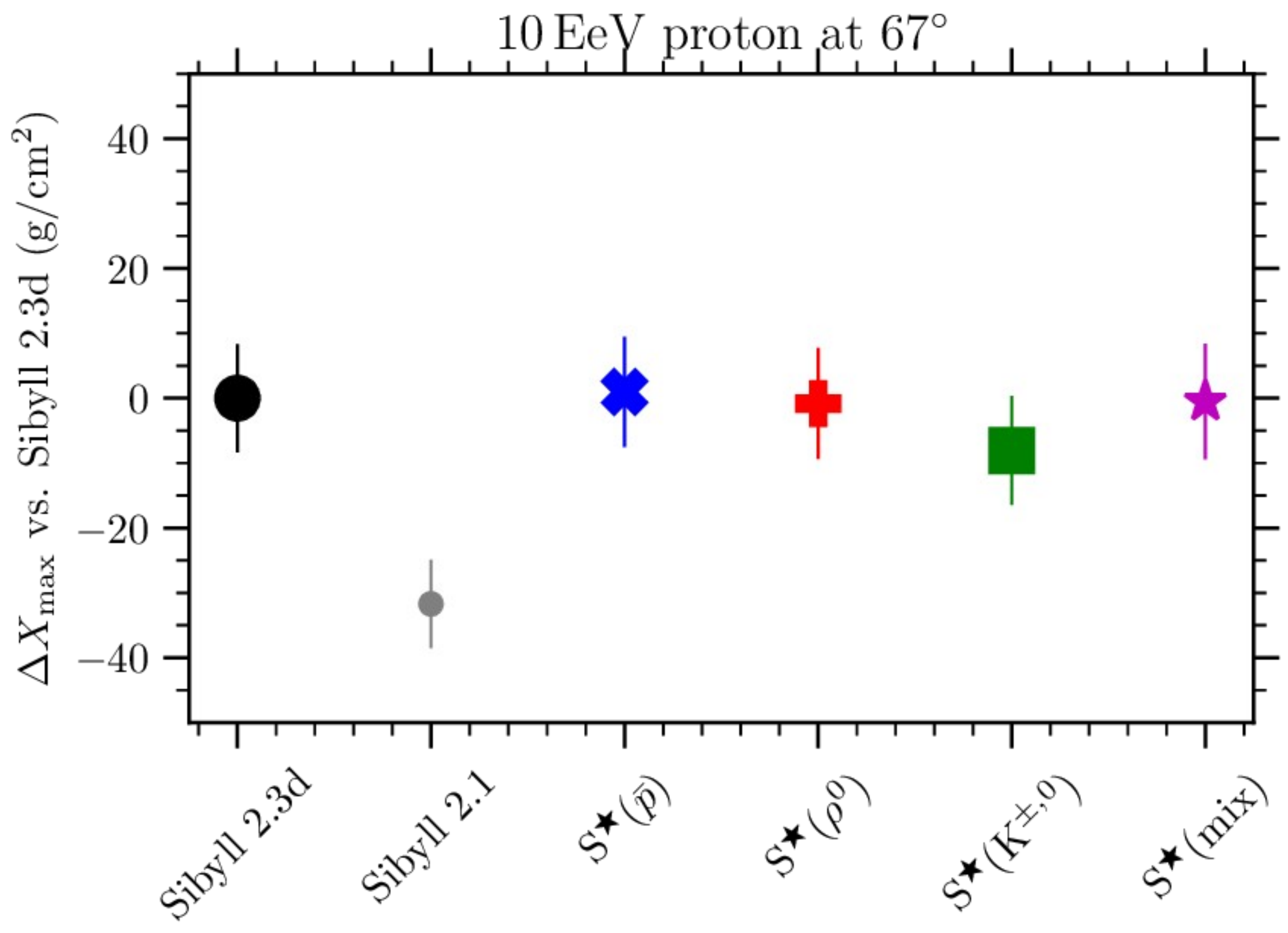
- Rho meson in pion interactions (leading particle effect only)
- Baryon pair production (all interactions)
- Kaon production (all interactions)

Simple and pragmatic approach – Sibyll 2.3d*

Muon number



Depth of maximum

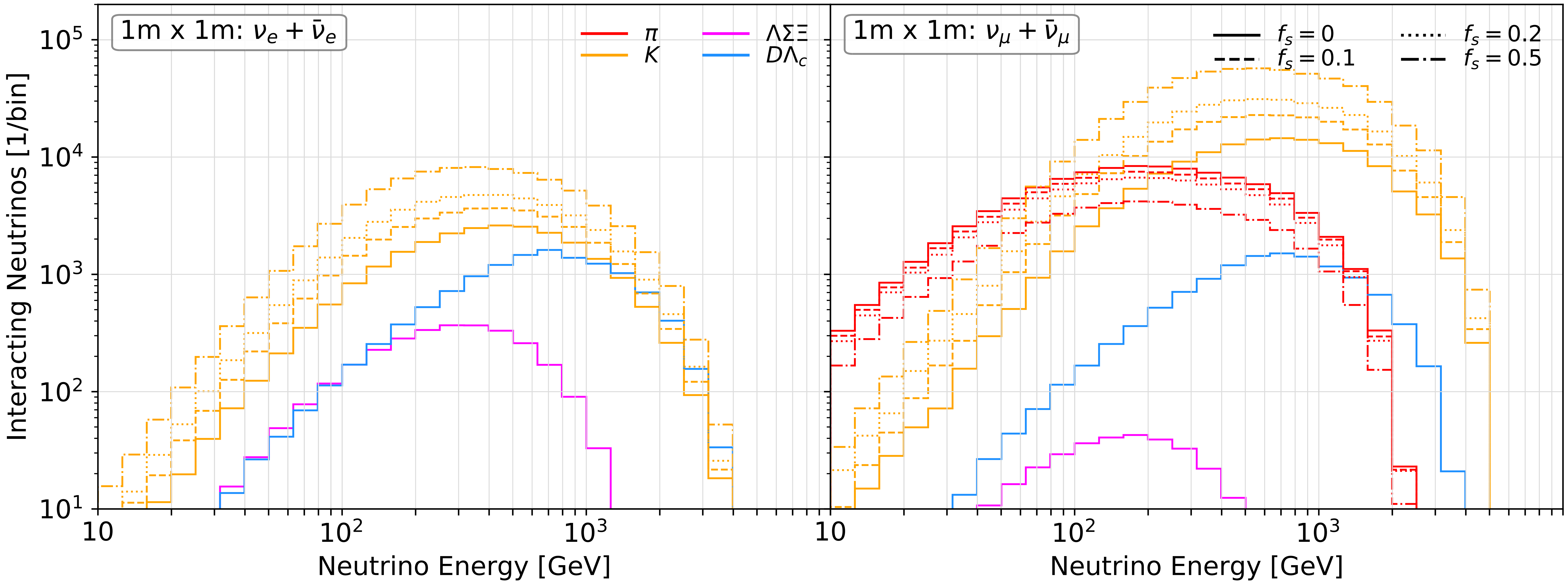


Good description of Auger data, detailed studies in progress

FPF sensitivity to modifications

Modification of Sibyll 2.3d to study different versions of muon enhancement

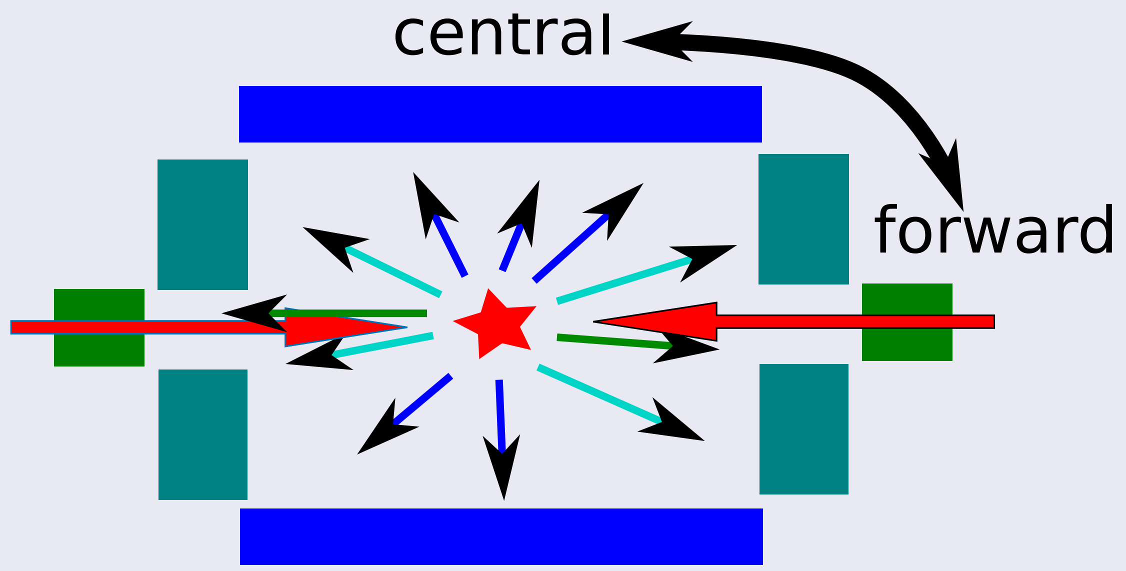
- Rho meson in pion interactions (leading particle effect only) → **not seen in FPF**
- Baryon pair production (all interactions) → **not seen in FPF**
- Kaon production (all interactions) → **directly seen in FPF**



(White Paper J. Phys. G: Nucl. Part. Phys. 50 (2023) 030501)

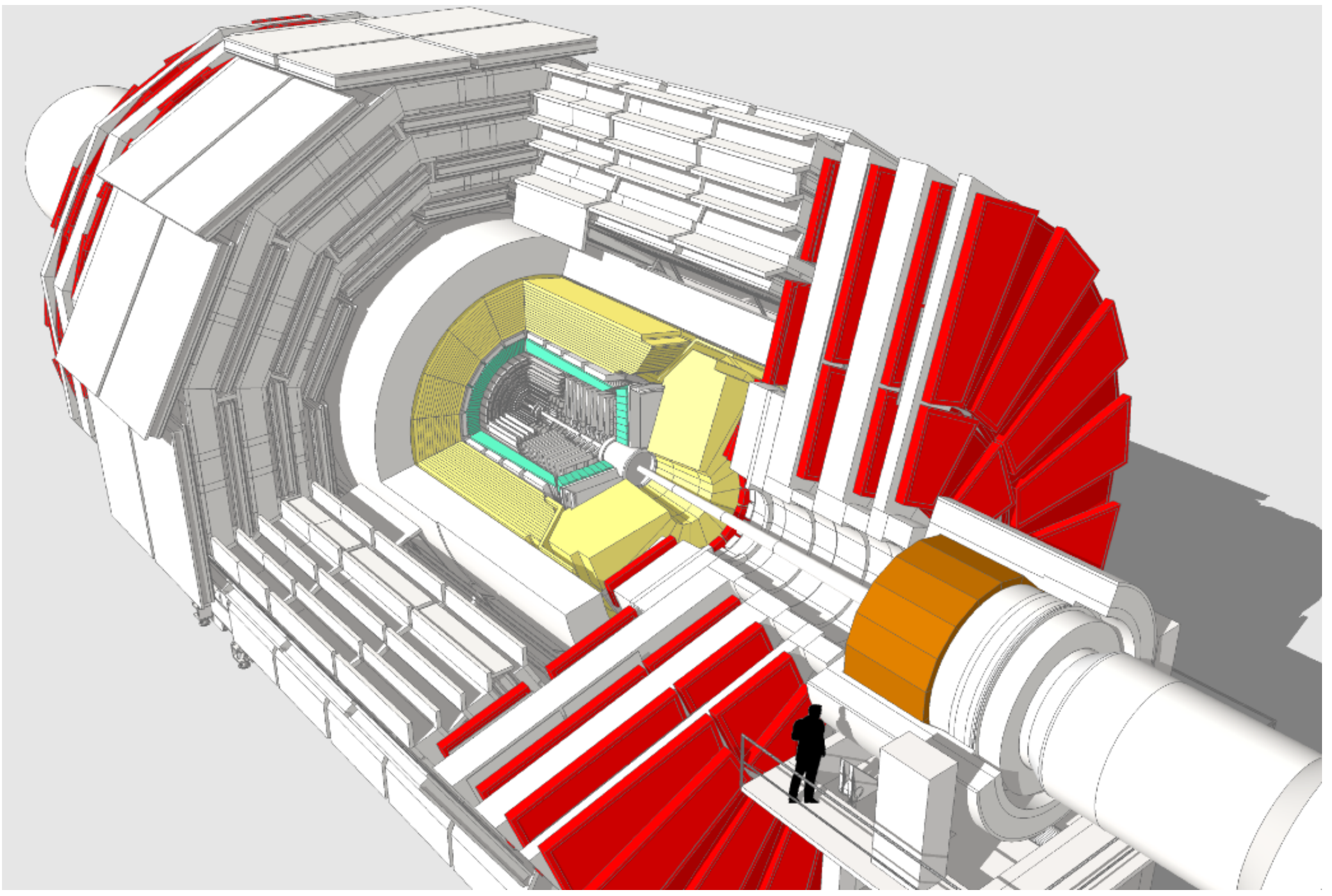
Forward meson production and FPF

Importance of forward phase space to air showers

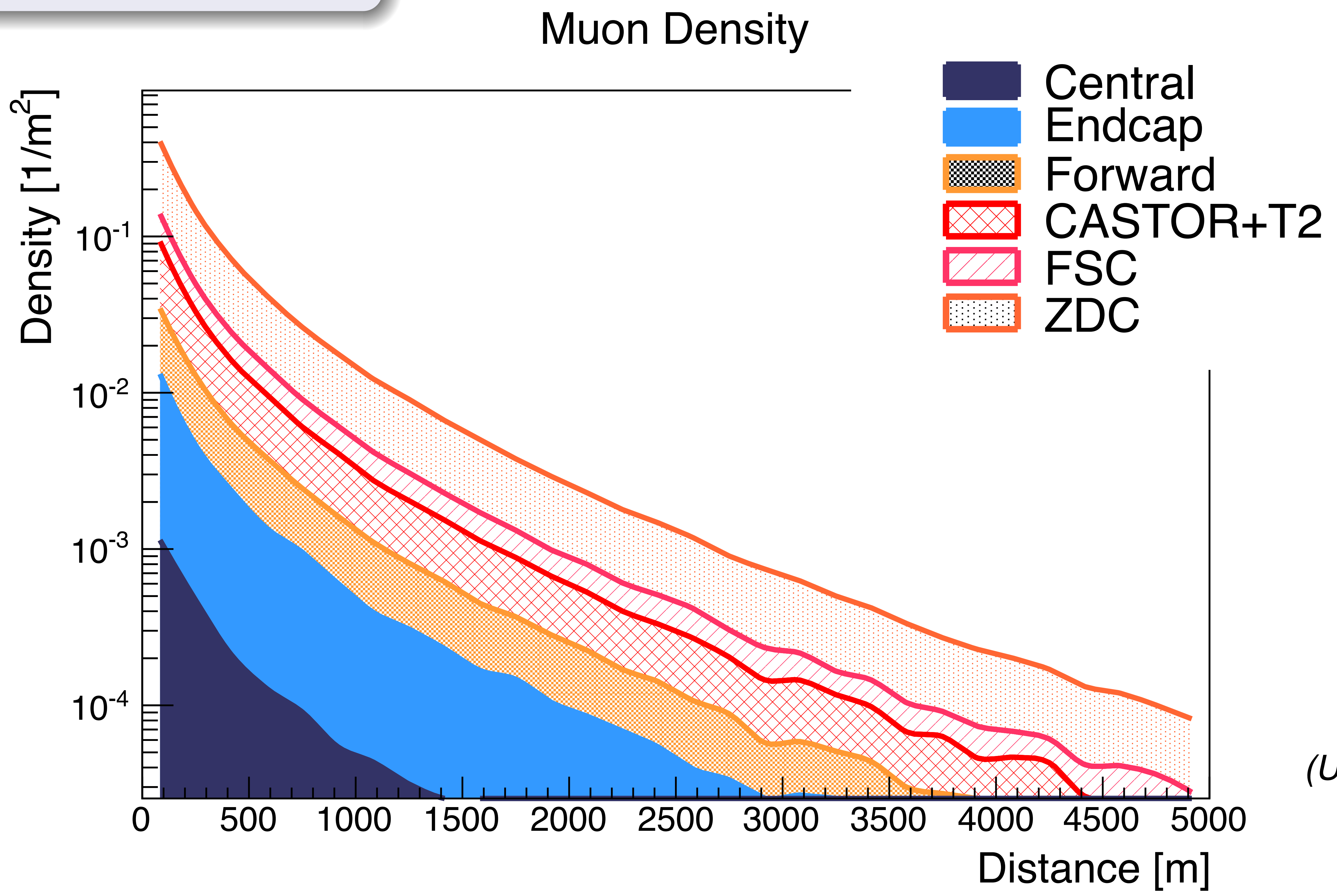


- Central ($|\eta| < 1$)
- Endcap ($1 < |\eta| < 3.5$)
- Forward ($3 < |\eta| < 5$), HF
- CASTOR+T2 ($5 < |\eta| < 6.6$)
- FSC ($6.6 < |\eta| < 8$)
- ZDC ($|\eta| > 8$), LHCf

Similar study for FPF possible?

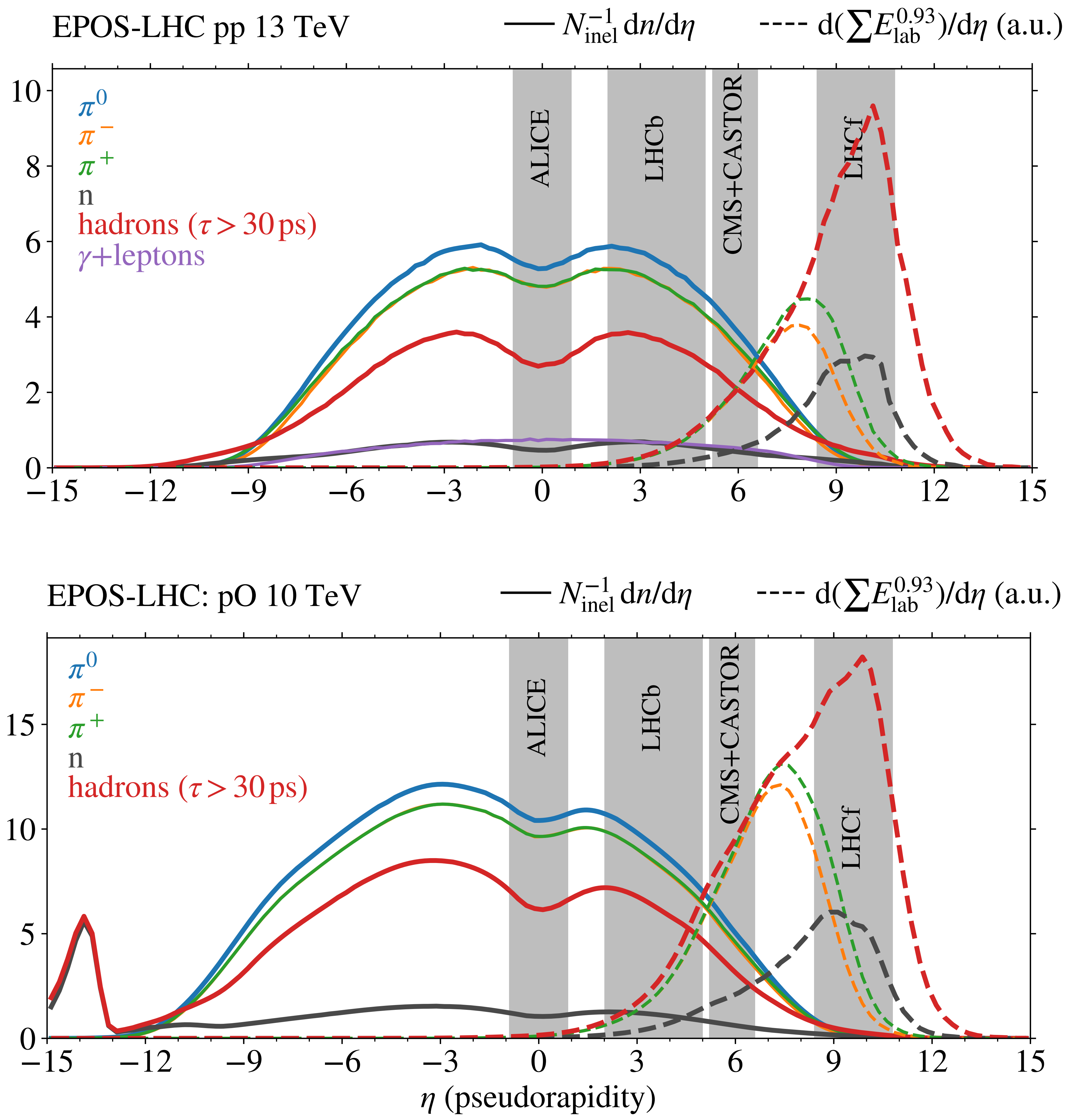


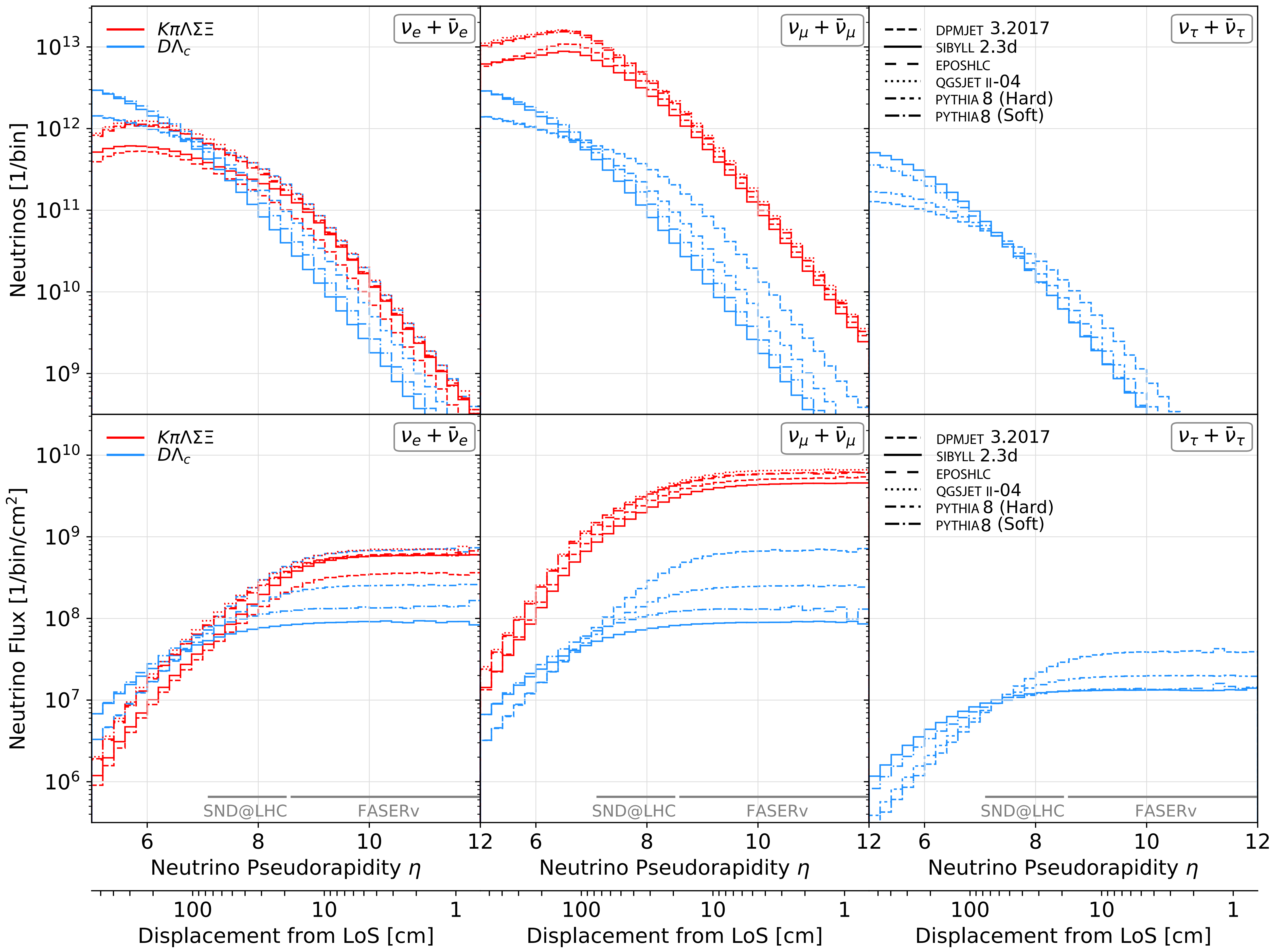
(data from all LHC experiments, CMS shown as example)



(Ulrich, DPG 2014)

Comparison of phase space coverage

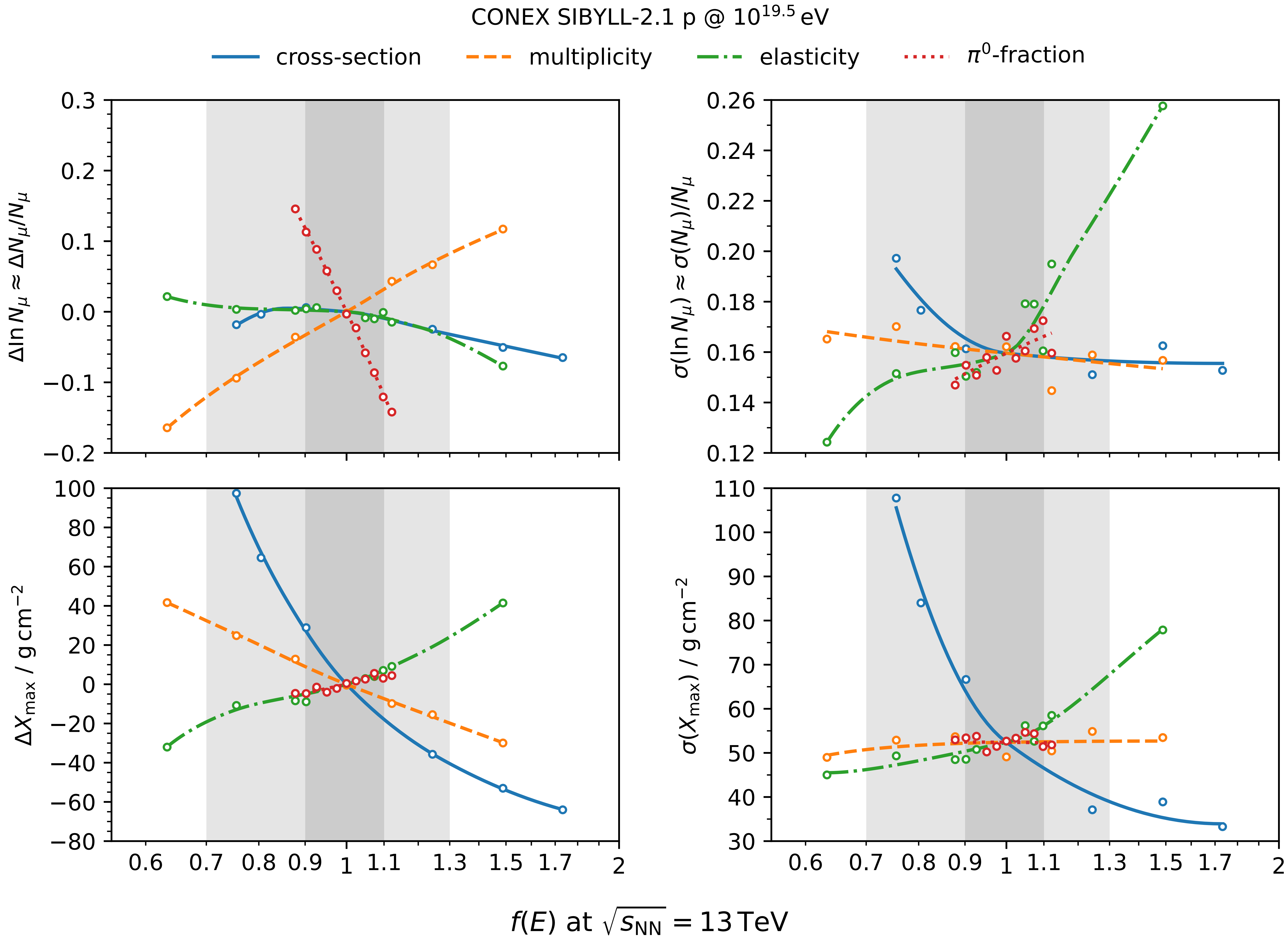


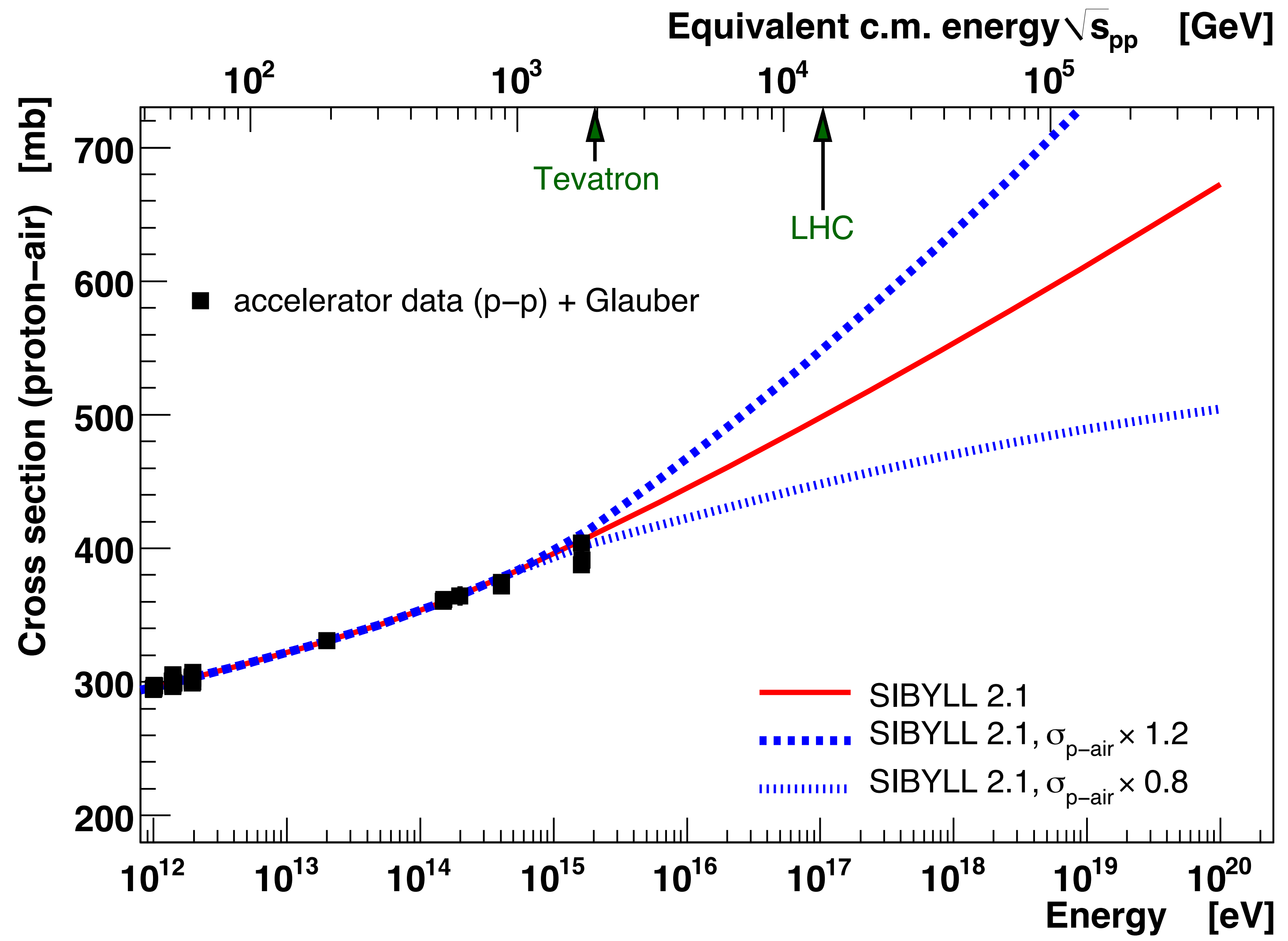


(Albrecht et al. Astrophys. Space Science 2022)

(Kling & Nevay, Phys. Rev. D 2021)

Systematic study of relation to interaction properties





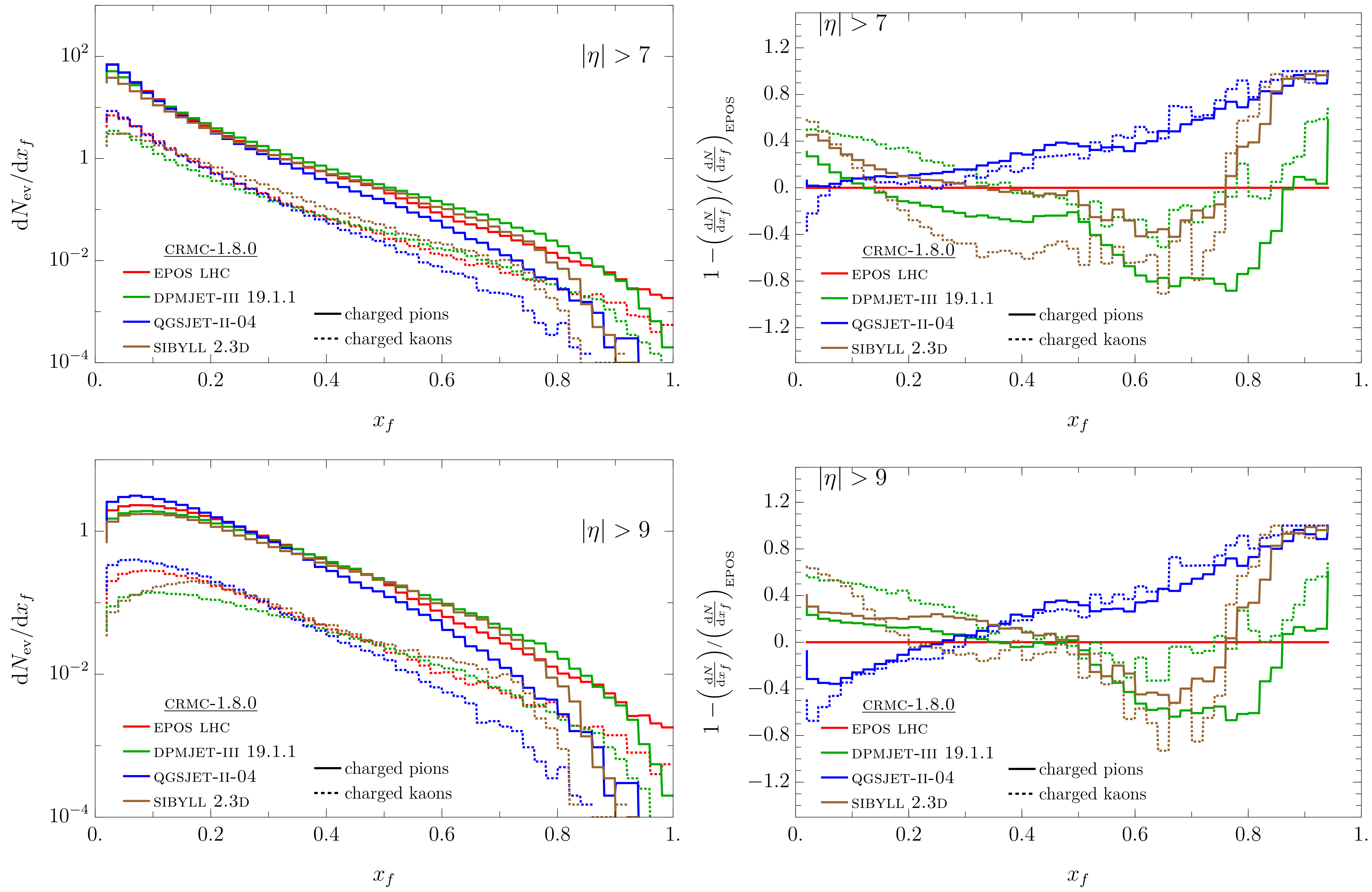
(Ulrich et al. Phys. Rev. D 83 (2011) 054026)

Combination of FPF and LHCf ideal for air shower physics

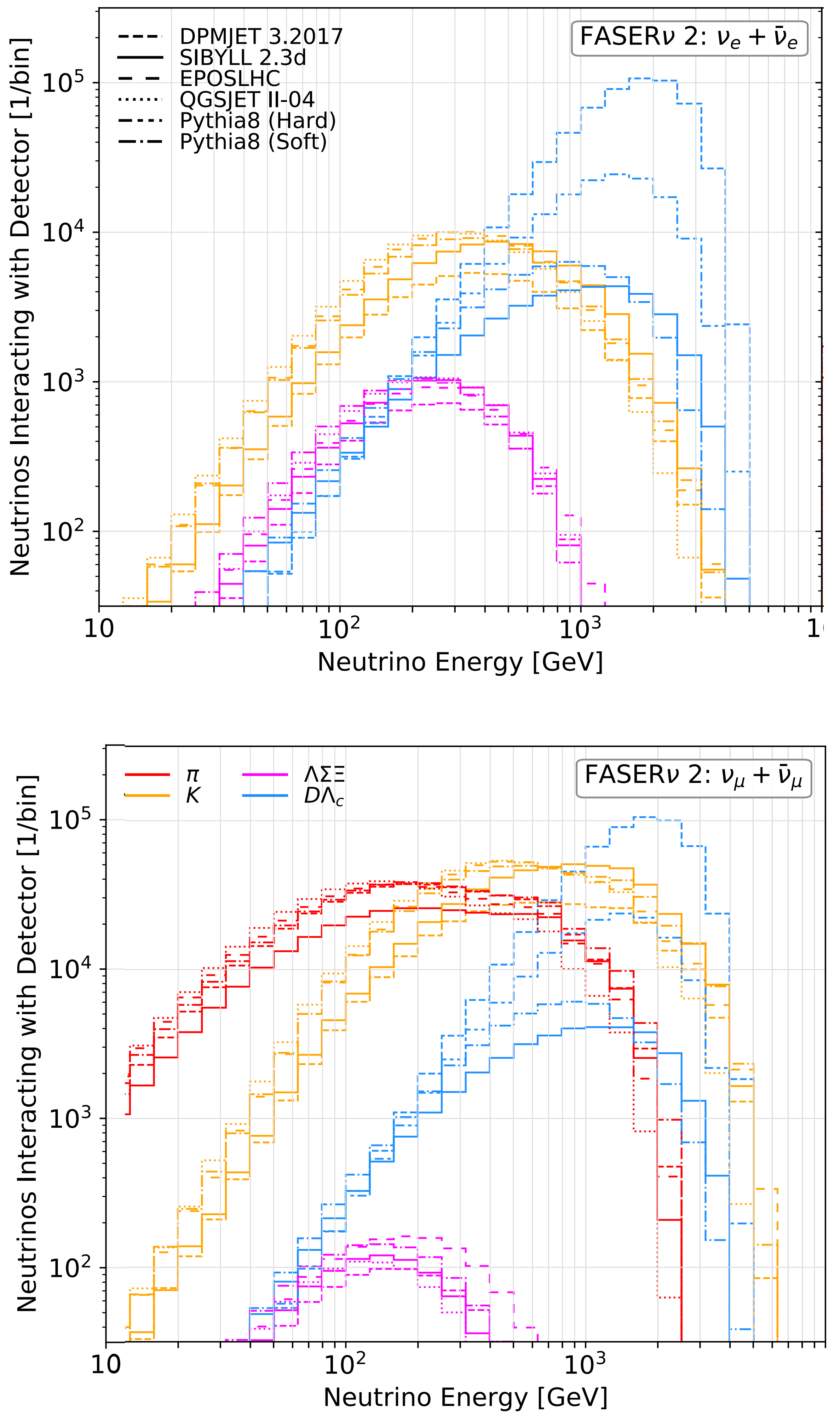
(Dembinski, ICRC 2021, Albrecht et al. Astrophys. Space Science 2022)

Qualitative picture of relation to neutrino fluxes

Pion and kaon spectra at production

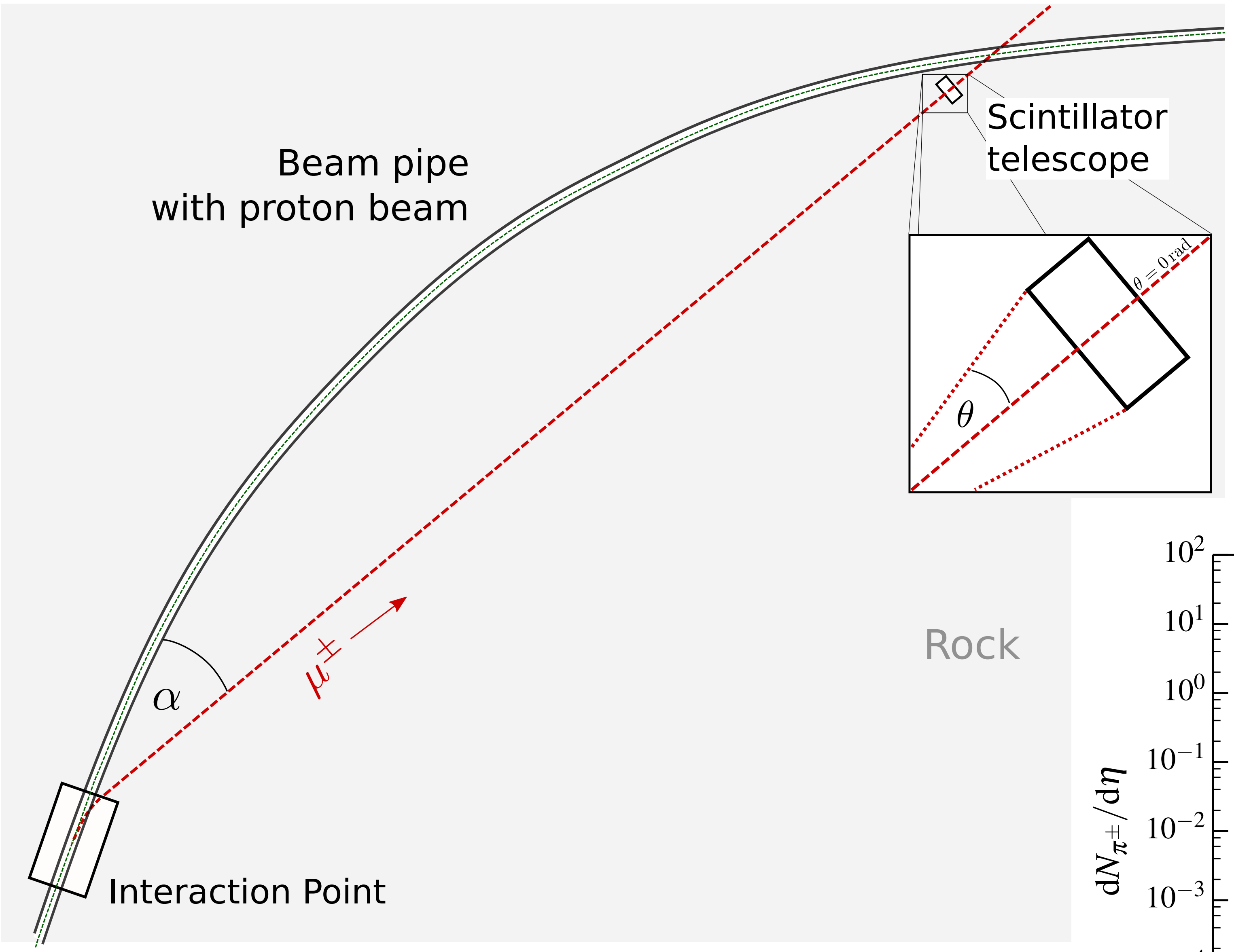


Neutrino interactions in detector

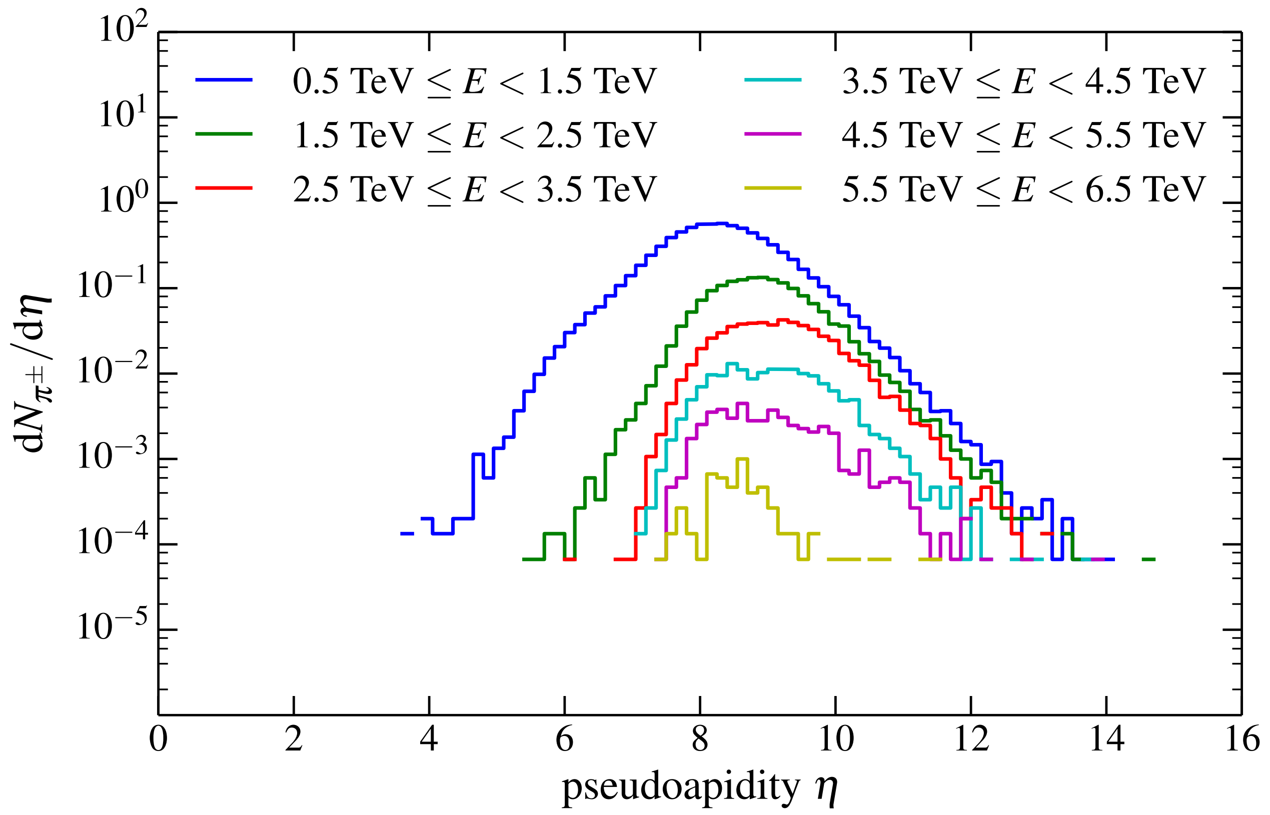


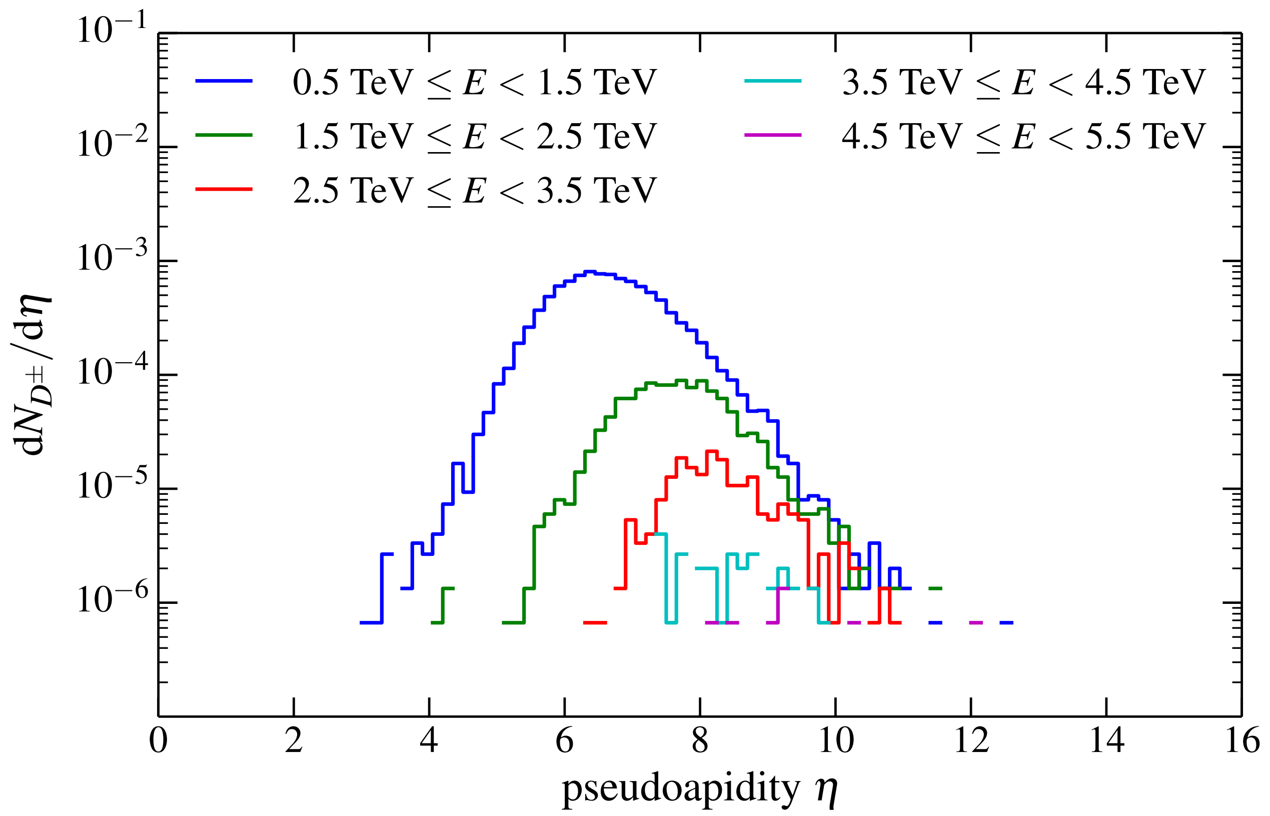
(White Paper J. Phys. G: Nucl. Part. Phys. 50 (2023) 030501)

Are muons useless for FPF?

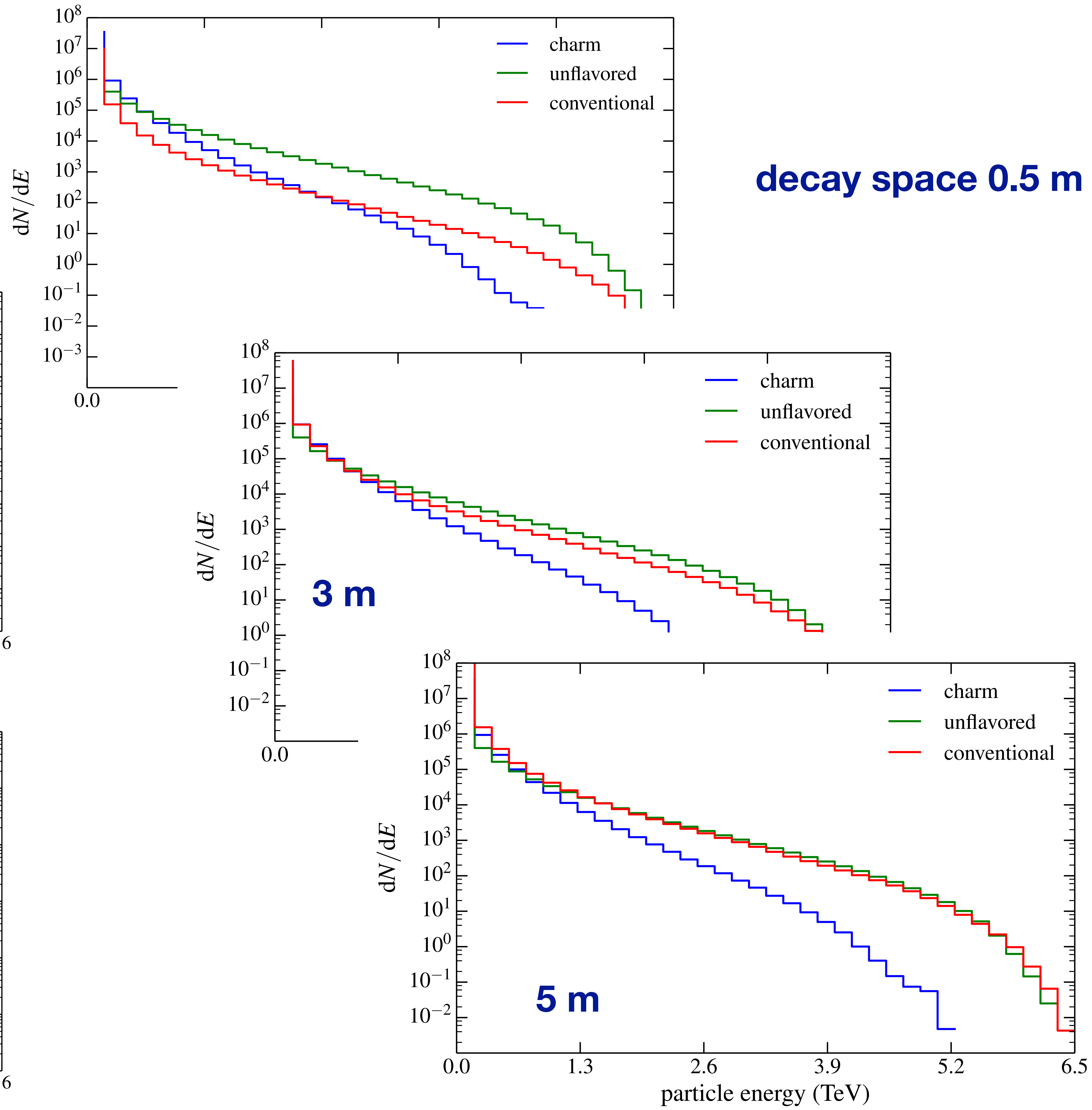


(Isabell Engeln,
Bachelor's thesis 2015)



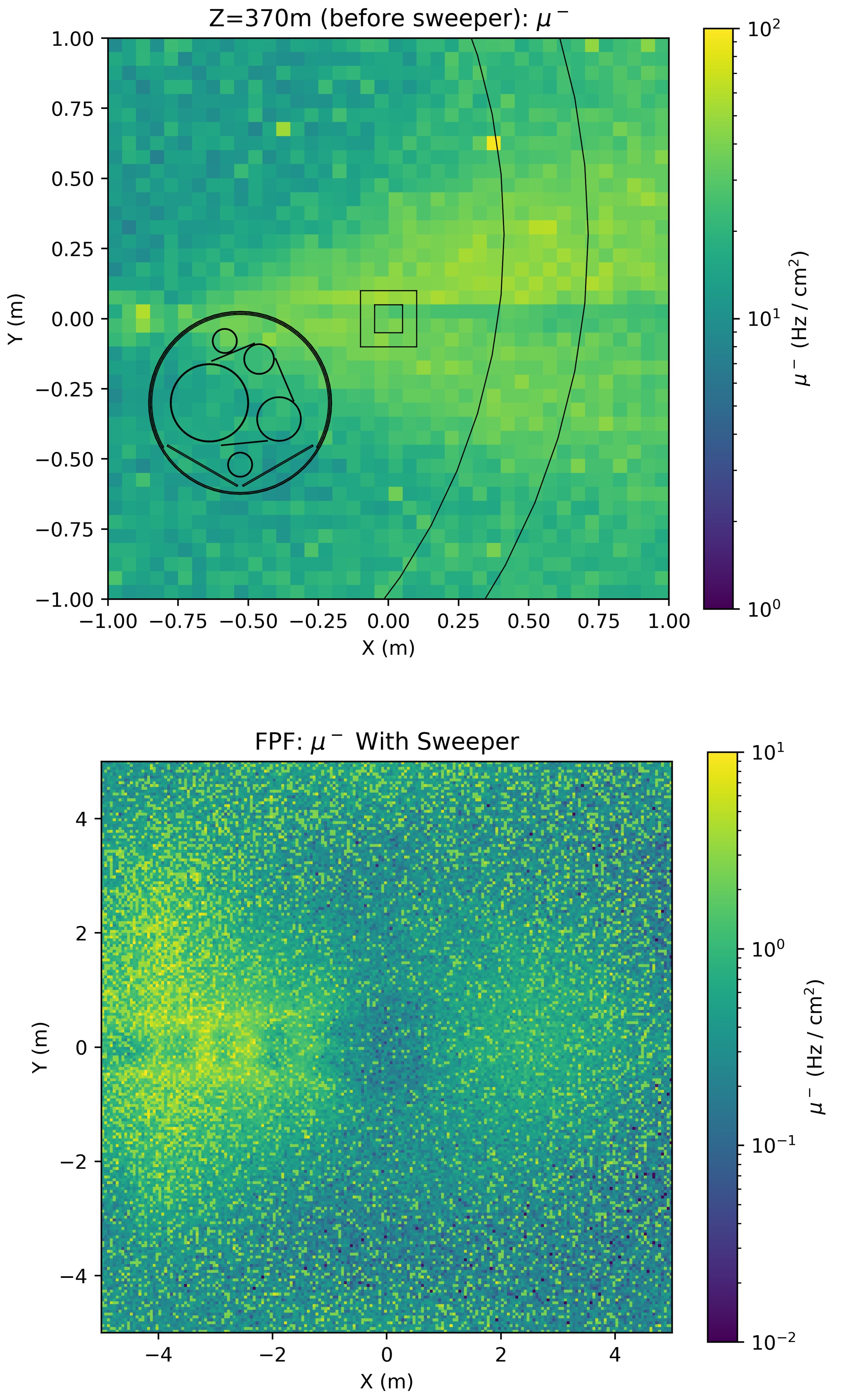


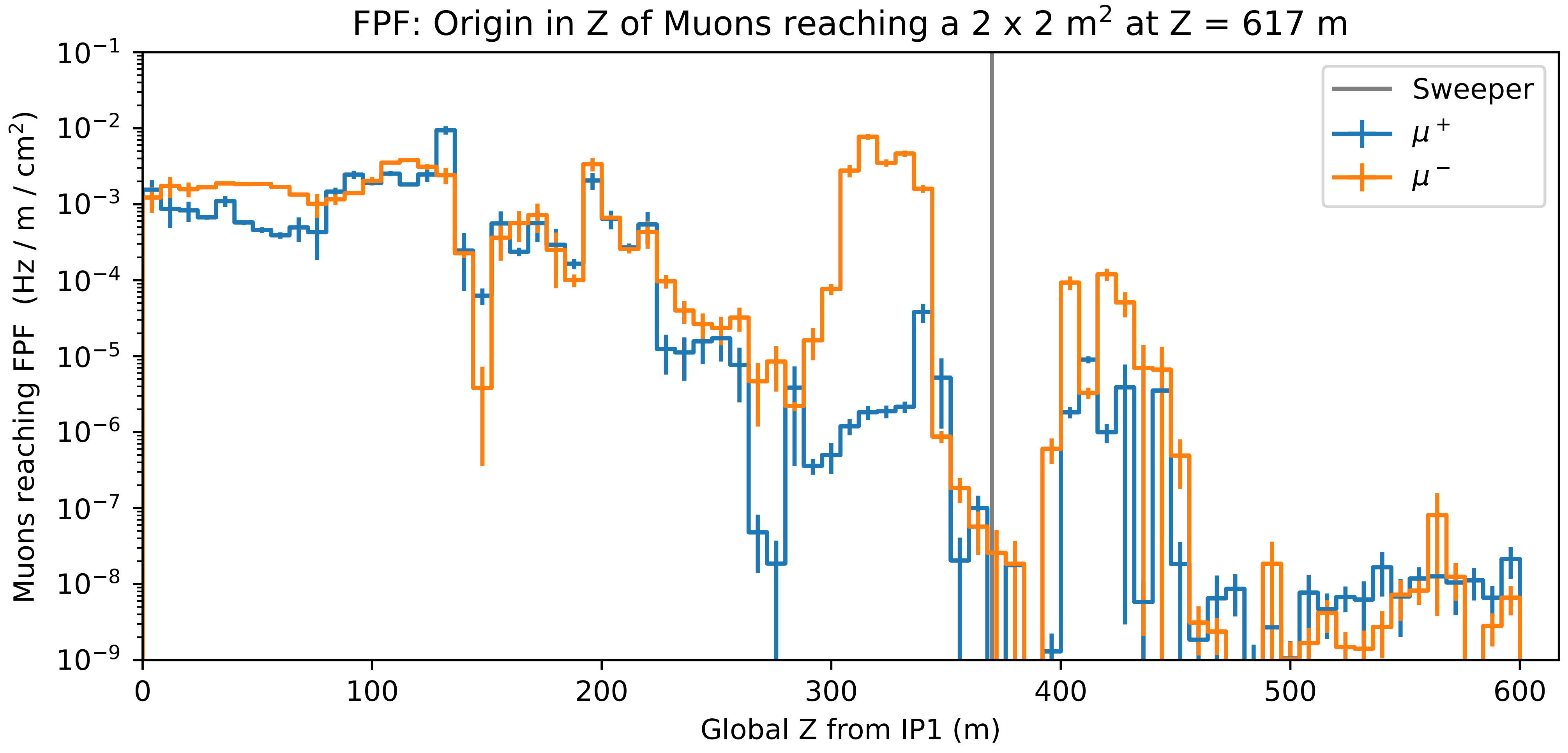
decay space 0.5 m

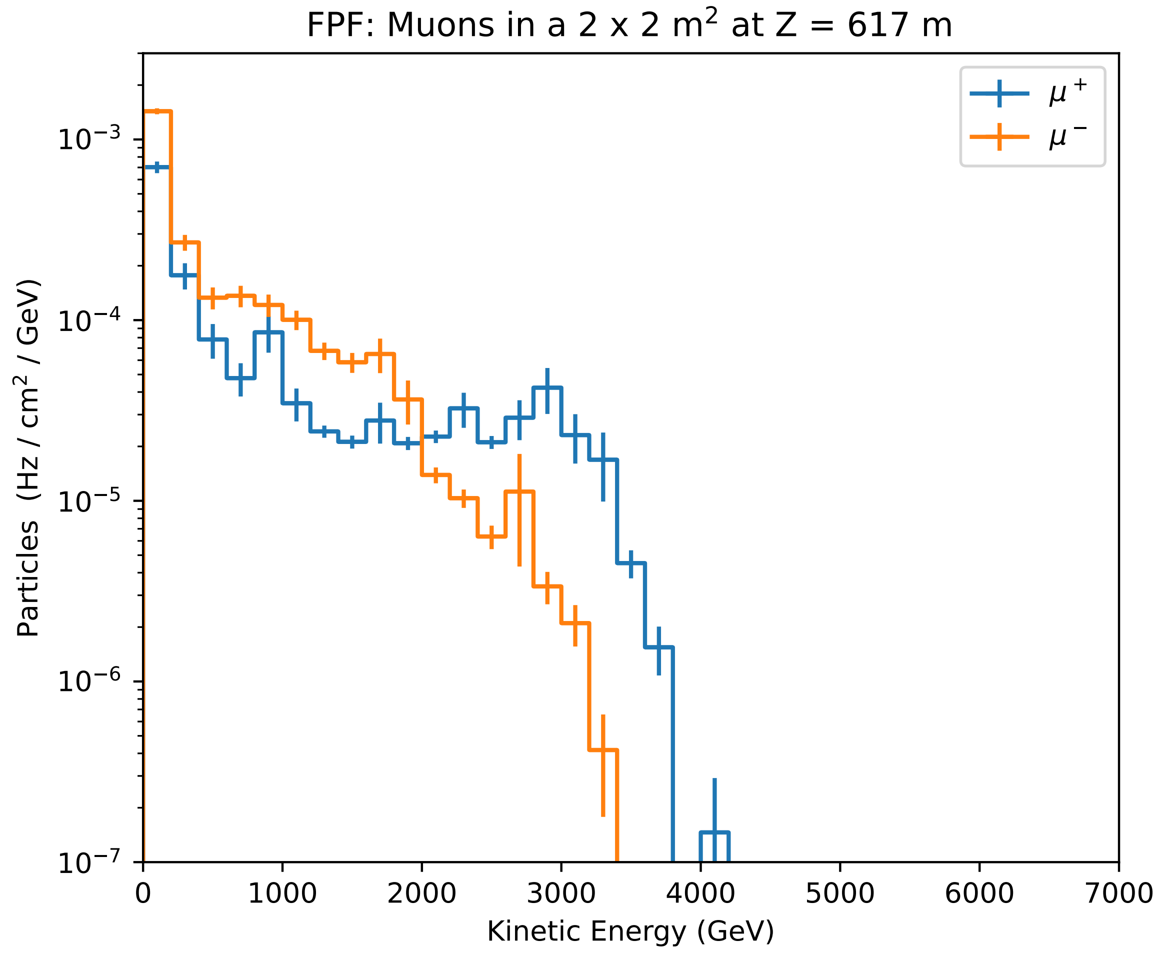


- Conventional contribution: $\pi^{\pm}$, $K^{\pm}$, K^0_L,
- Charm contribution: D^0, $D^{\pm}$, $D^{\pm}_s$, Λ^+_c,
- Unflavored contribution: ρ^0, η, ω, η'.

Simulation study for muons for FPF







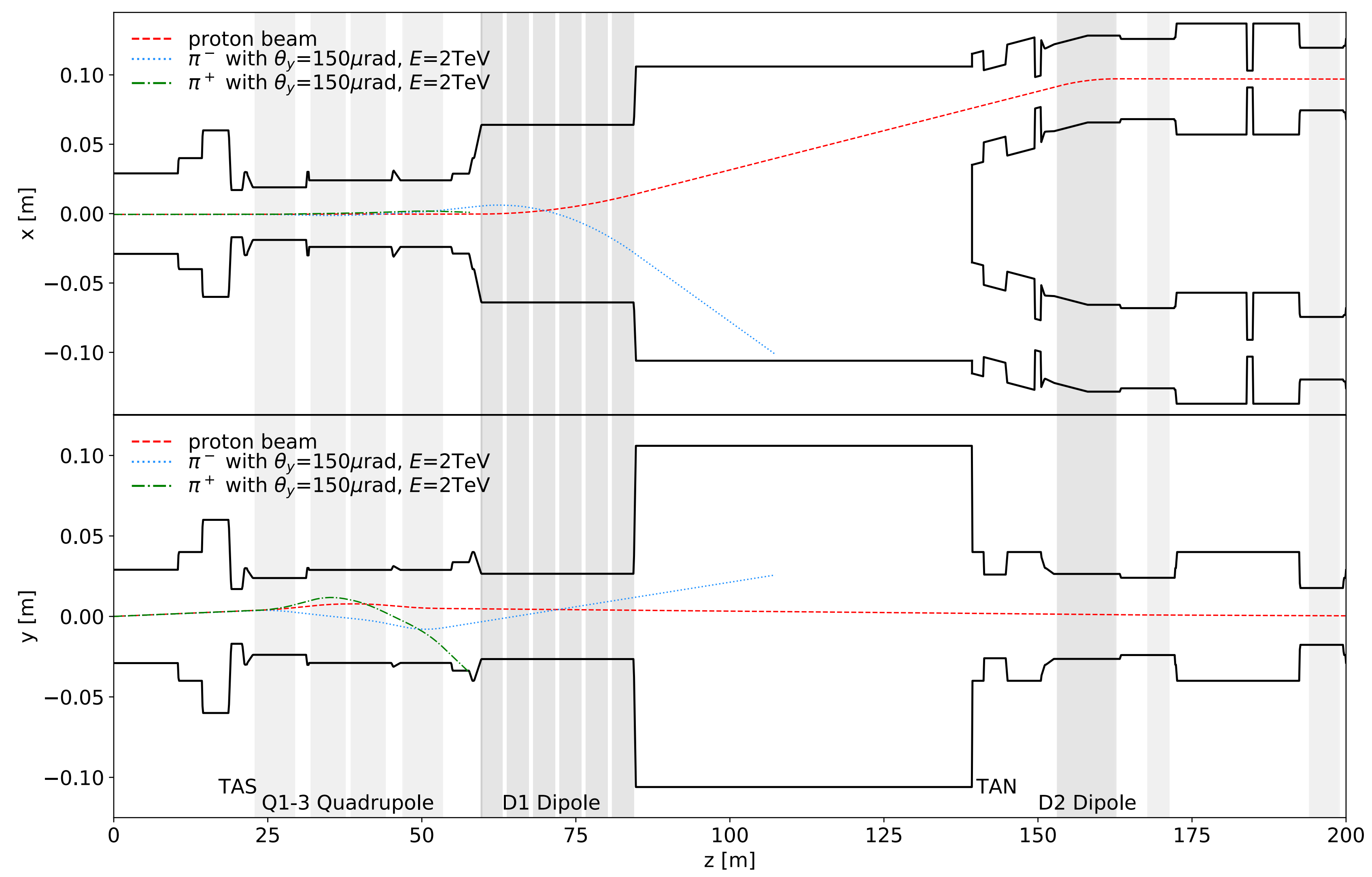
Take advantage of geometry of muon distribution (relative measurement)

(White Paper J. Phys. G: Nucl. Part. Phys. 50 (2023) 030501)

Very high rate, also useful for temporary detector locations, short p-O run

Summary

(Kling & Nevay, Phys. Rev. D 2021)



Muon discrepancy in air showers

- Experimental evidence at highest energies
- Energy range of onset still unclear
- Some conflicting data (due probably to limited sensitivity)
- FPF as key instrument for kaon enhancement scenario
  (already done in White Paper)
- Test Sibyll 2.3d* scenarios with direct FPF simulations?

Forward meson production for air shower physics

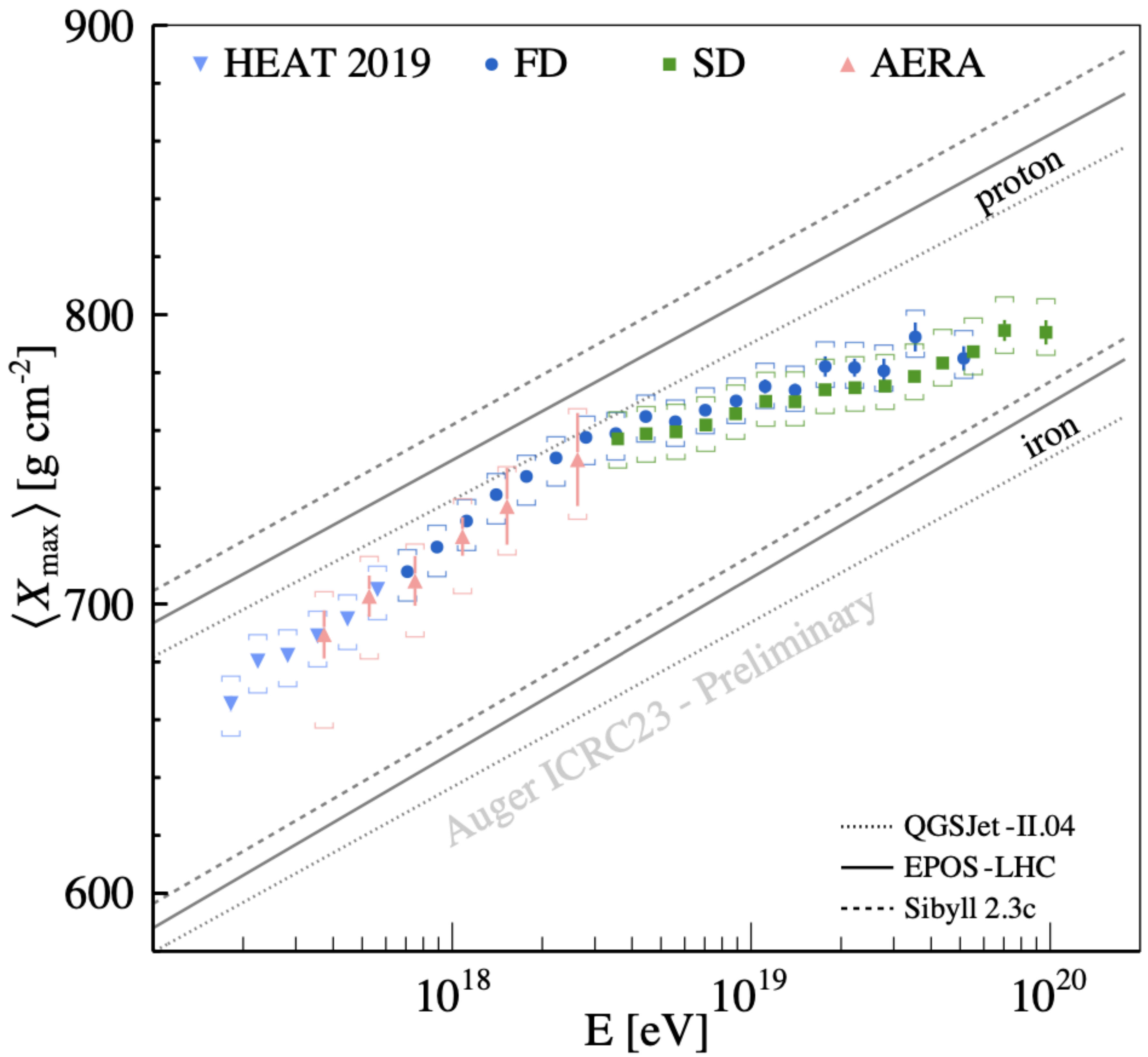
- Central input for composition interpretation of air shower data
  (model comparison already done in White Paper, but phase space discussion limited)
- Need to understand better link between production kinematics and observed neutrinos
- Perform simulations for air showers with FPF-like kinematics?

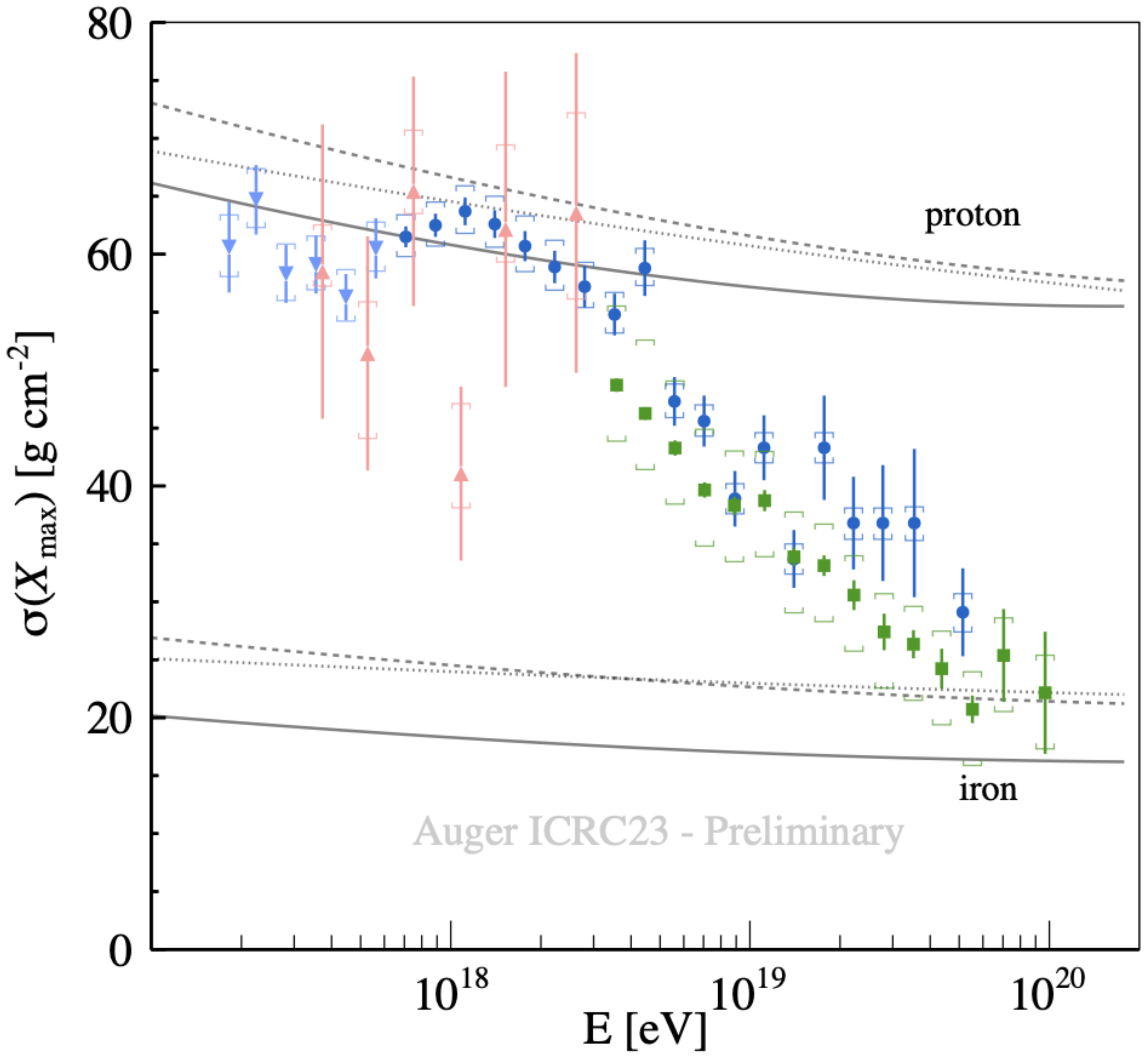
Use neutrino and muon data together for physics studies

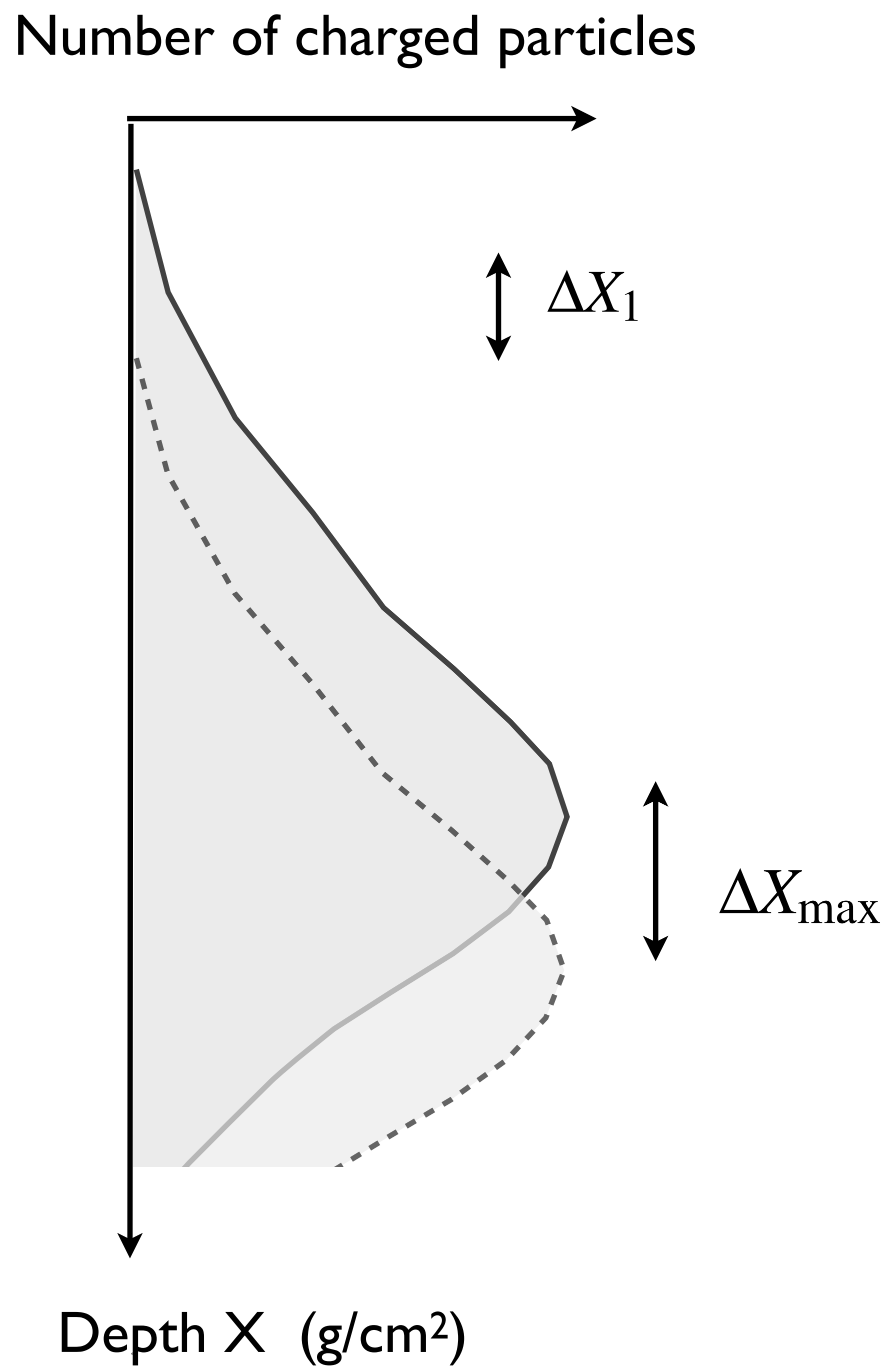
- Take advantage of very high muon rate (geometry of fluxes, temporary detector locations, p-O or other runs)
- Simulate expectation for muons for different interaction models
- Produce libraries that provide production (kinematics & location of muons and neutrinos) and detection information
- Distinguish between primary and secondary neutrinos and muons

Backup slides

Mass composition results of Auger Observatory







$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

$$\sigma_{X_1,p} \sim 45 - 55\,\mathrm{g/cm^2}$$
$$\sigma_{X_1,Fe} \sim 10\,\mathrm{g/cm^2}$$

$(E \sim 10^{18}\,\mathrm{eV})$

Important: LHC-tuned interaction models used for interpretation

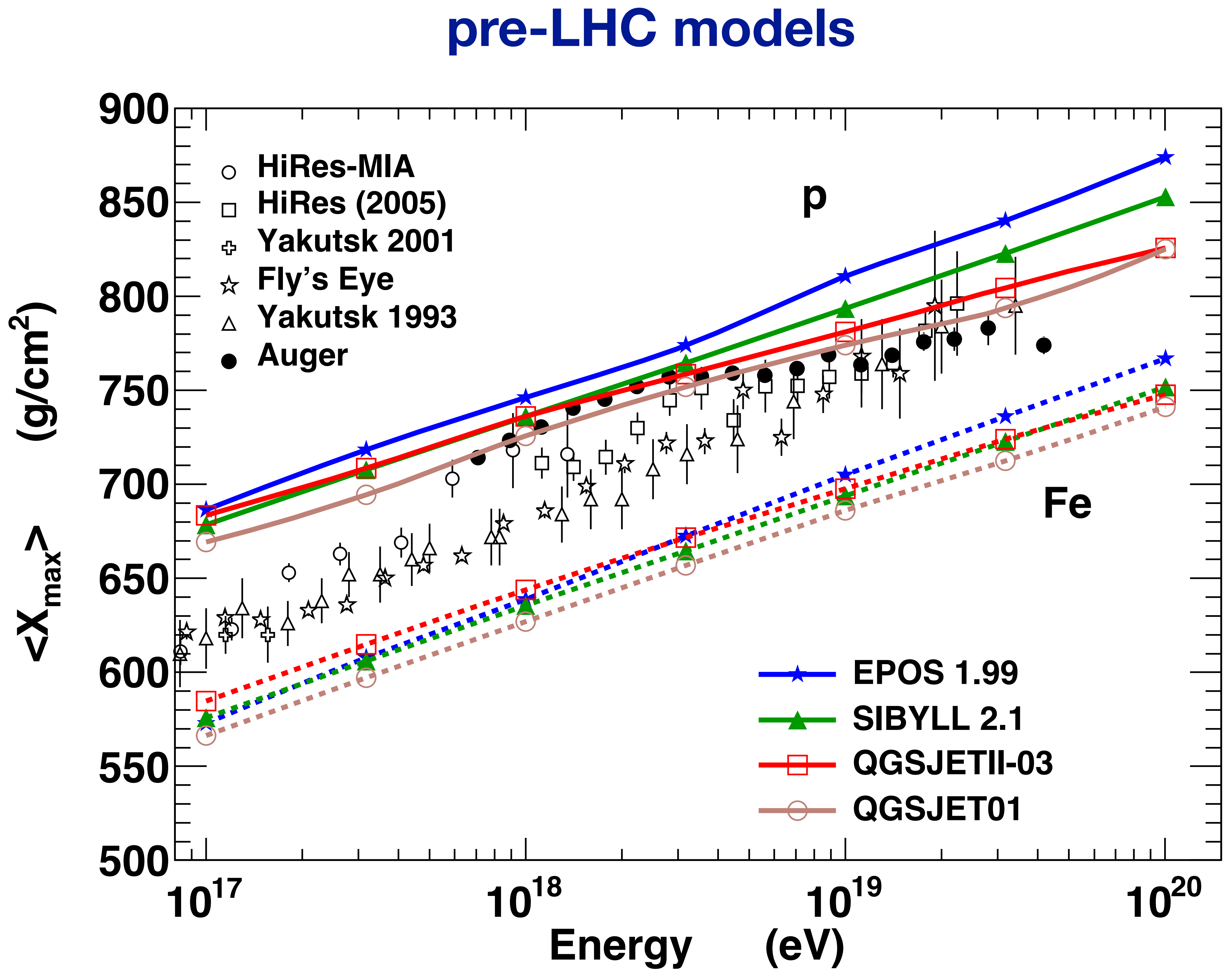
(FD telescopes: PRD 90 (2014), 122005 & 122005, updated ICRC 2023)

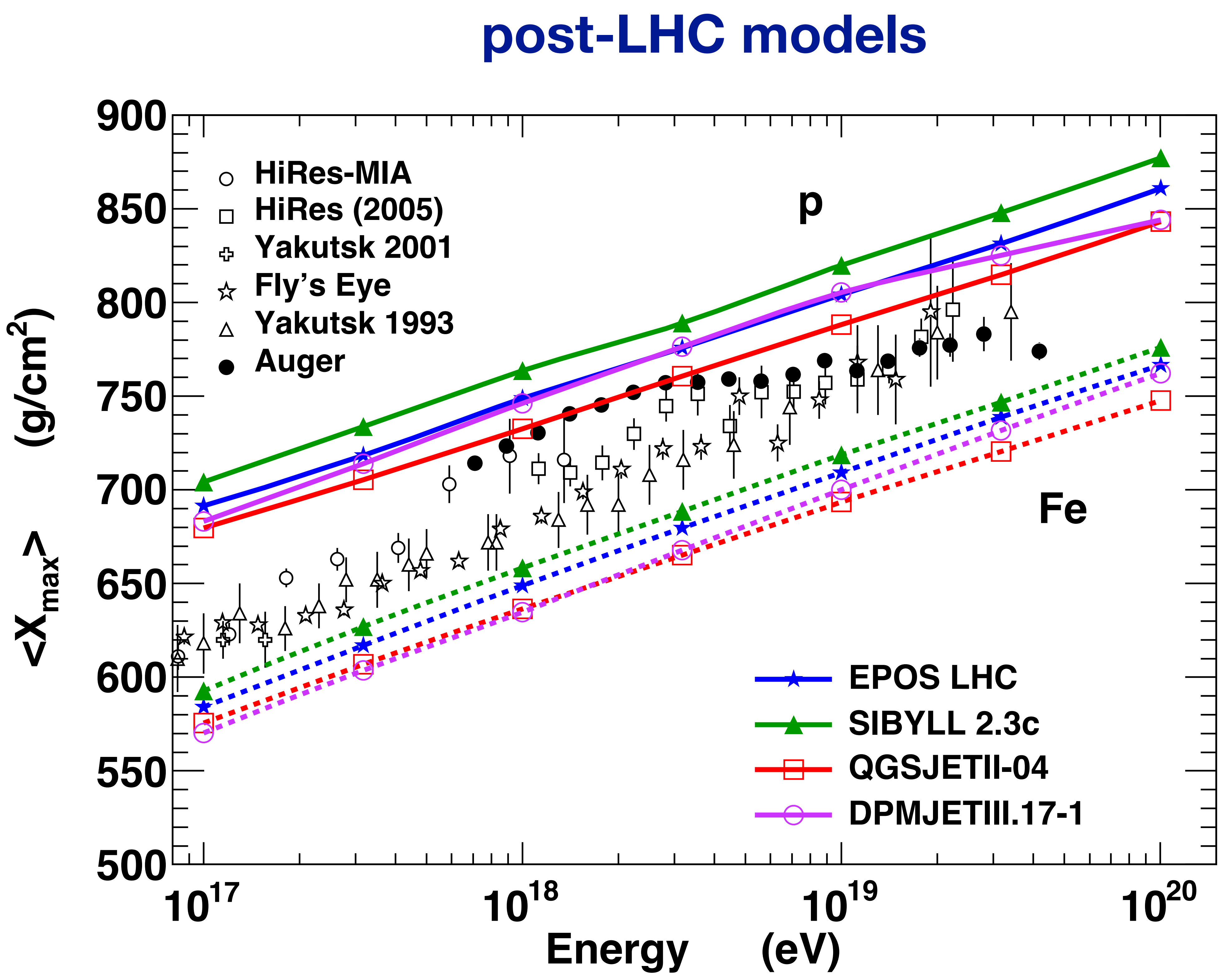
(SD risetime: Phys. Rev. D96 (2017), 122003)

(AERA/radio: PRL & PRD 2023)

(SD DNN: ICRC 2023, to be published)

Change of model predictions thanks to LHC data





(Pierog, ICRC 2017)

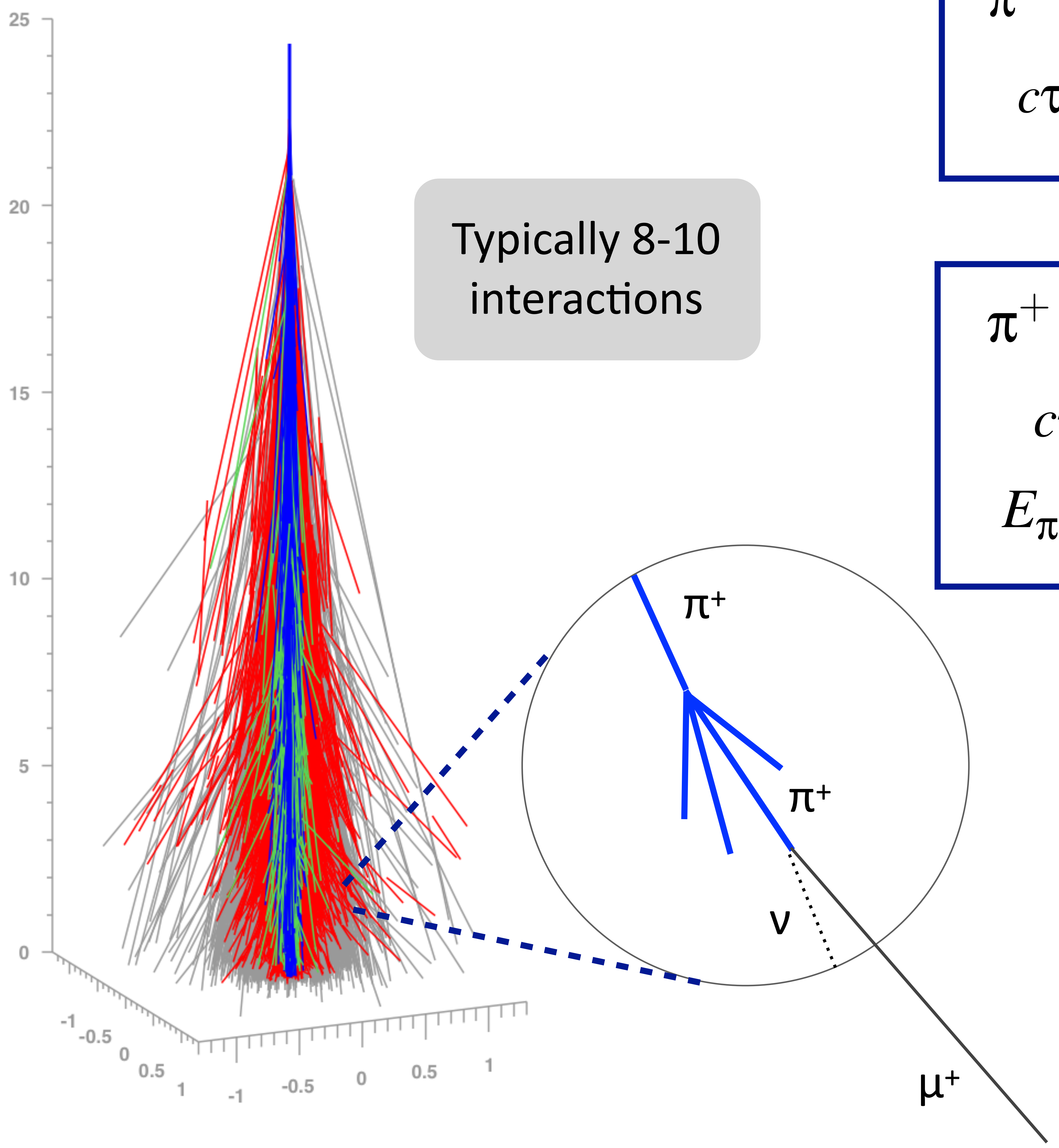
Sys. X_{max} uncertainty Auger: $\Delta X_{\mathrm{max}} = -10\,\mathrm{g/cm^2}\ +8\,\mathrm{g/cm^2}$

TA: $\Delta X_{\mathrm{max}} = \pm 20\,\mathrm{g/cm^2}$

LHC-tuned models should be used for data interpretation

(see also discussion Lipari, Phys.Rev.D 103 (2021) 103009)

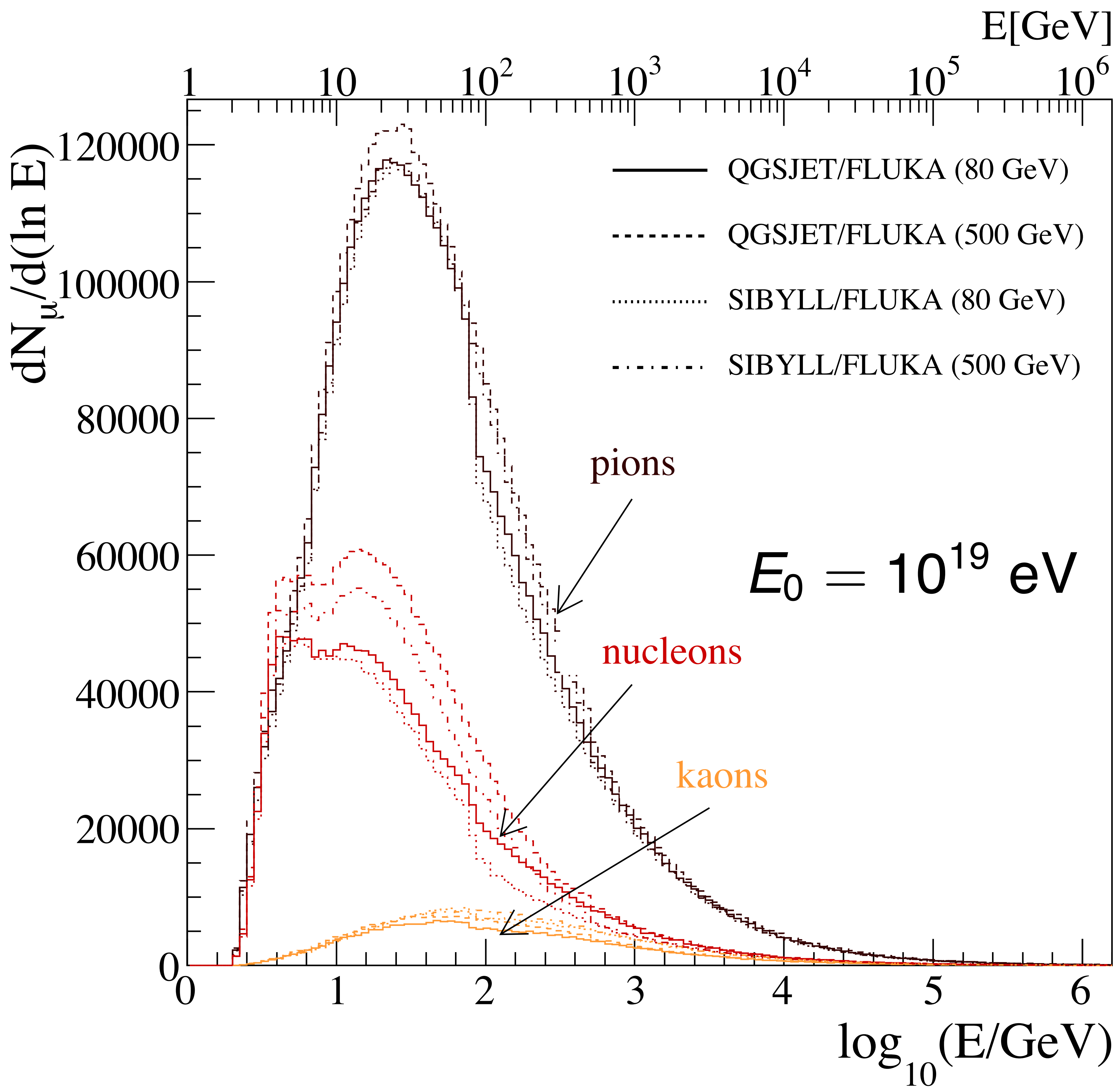
Muon production at large lateral distance



$$\pi^0 \rightarrow \gamma\gamma$$
$$c\tau_{\pi^0} = 25.1\,\mathrm{nm}$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$c\tau_{\pi^\pm} = 7.8\,\mathrm{m}$$
$$E_{\pi^\pm,\mathrm{dec}} \sim 30\,\mathrm{GeV}$$

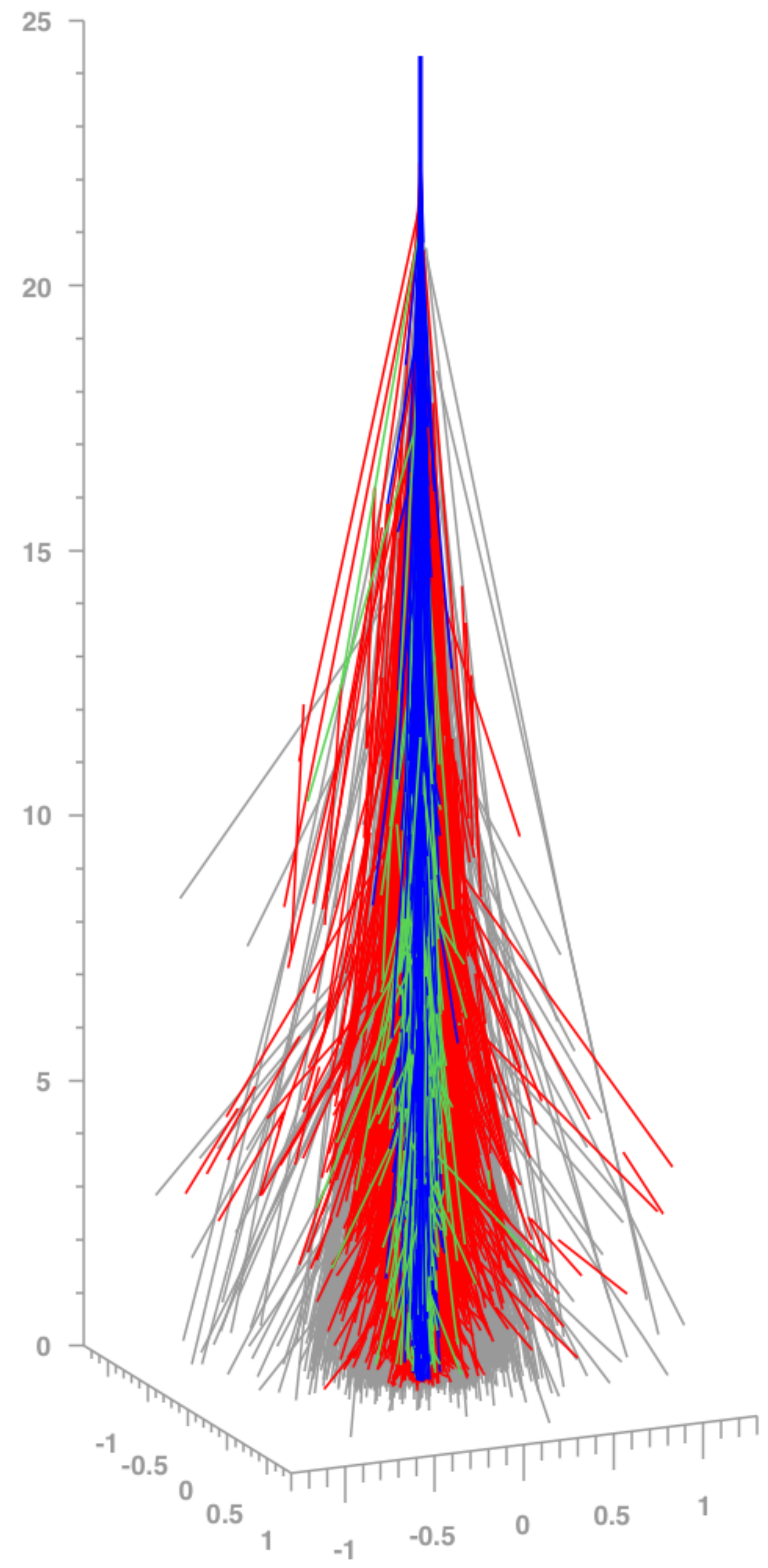
Energy distribution of **last interaction** that produced a detected muon

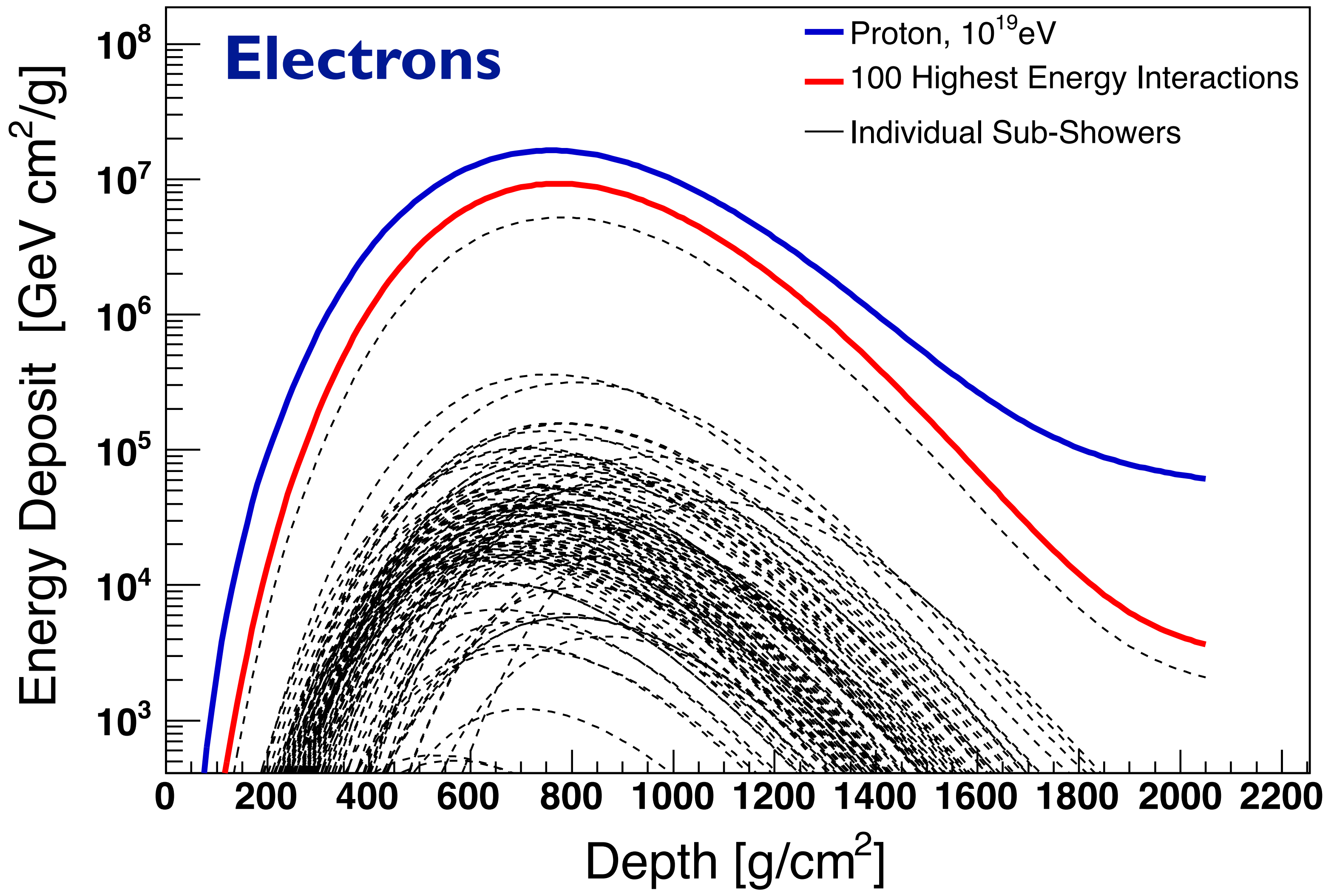


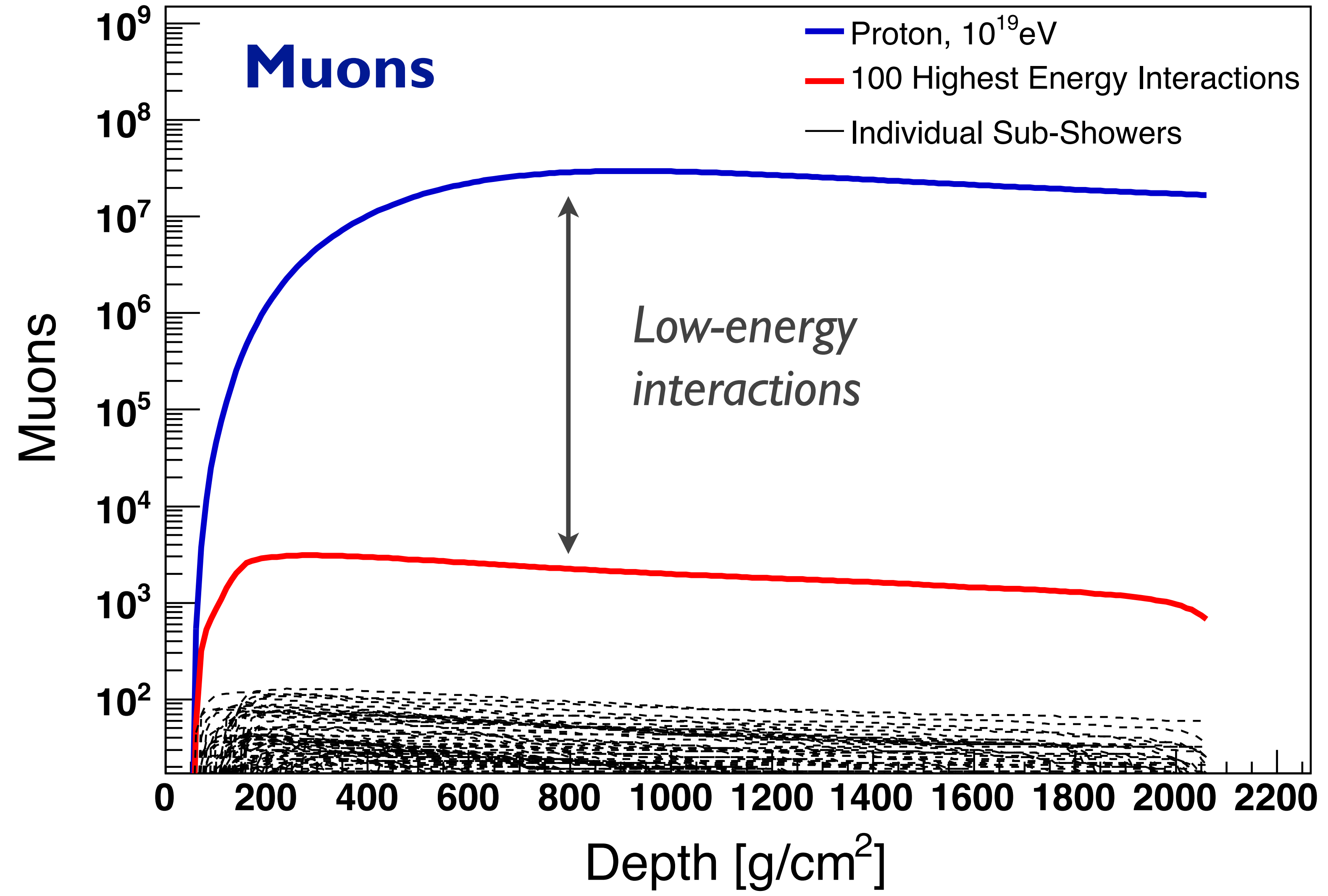
Muon observed at 1000 m from core

(Maris et al. ICRC 2009)

Importance of hadronic interactions at different energies







(Ulrich APS 2010)

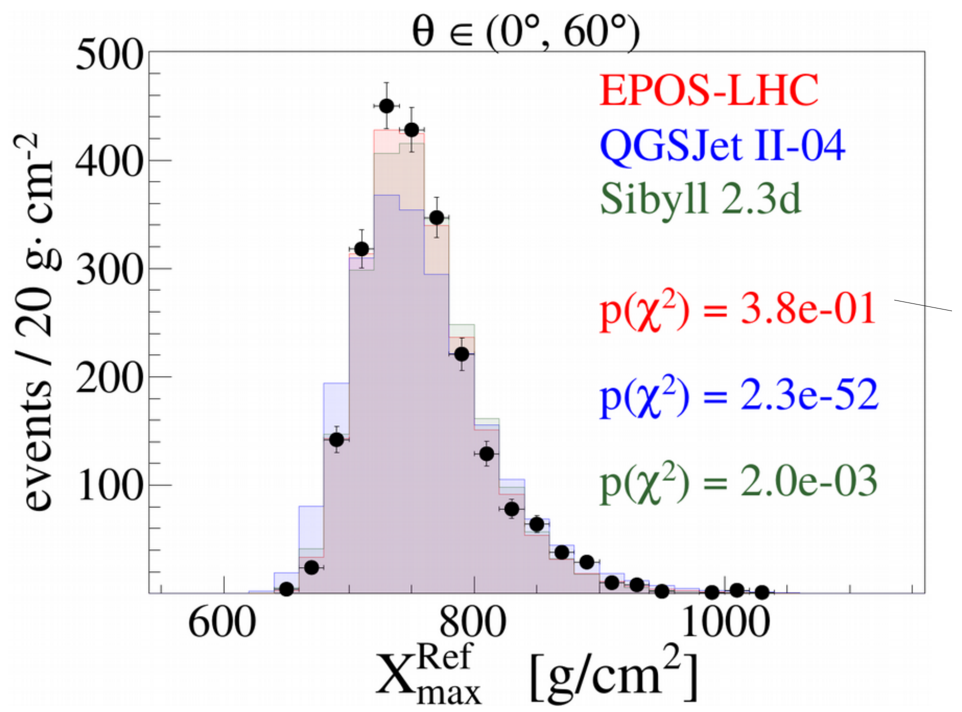
Shower particles produced in 100 interactions of highest energy

Electrons/photons:
high-energy interactions

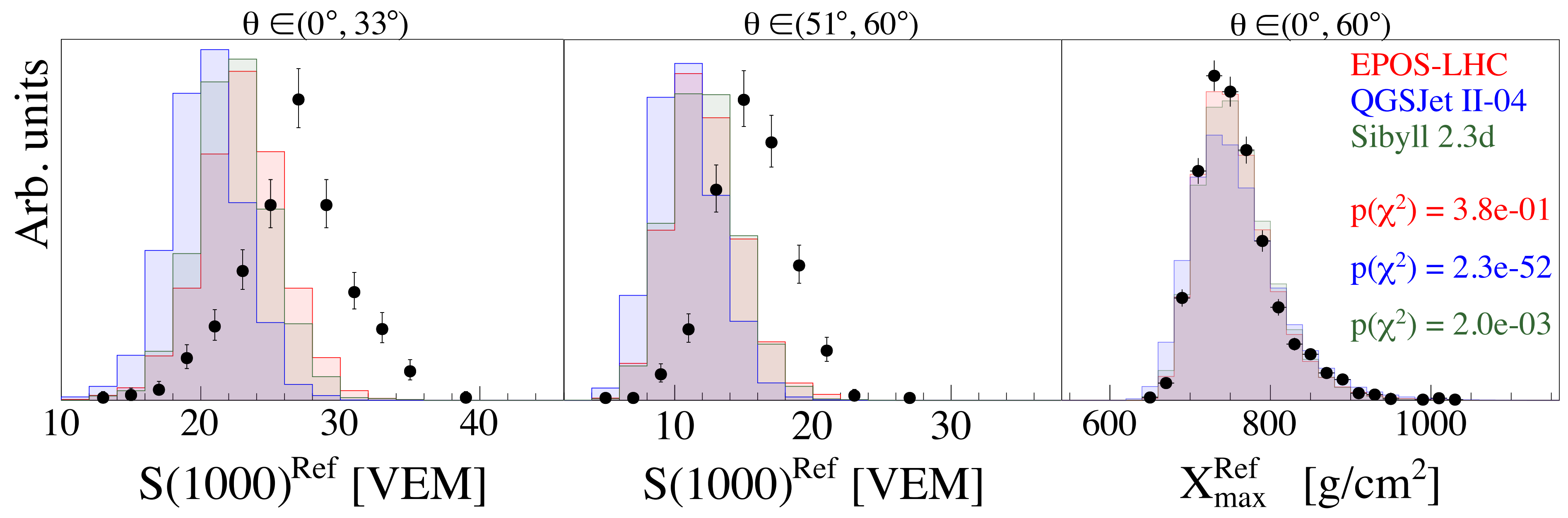
Muons/hadrons:
low-energy interactions

Muons: 8 – 12 generations, majority of muons produced in ~30 GeV interactions

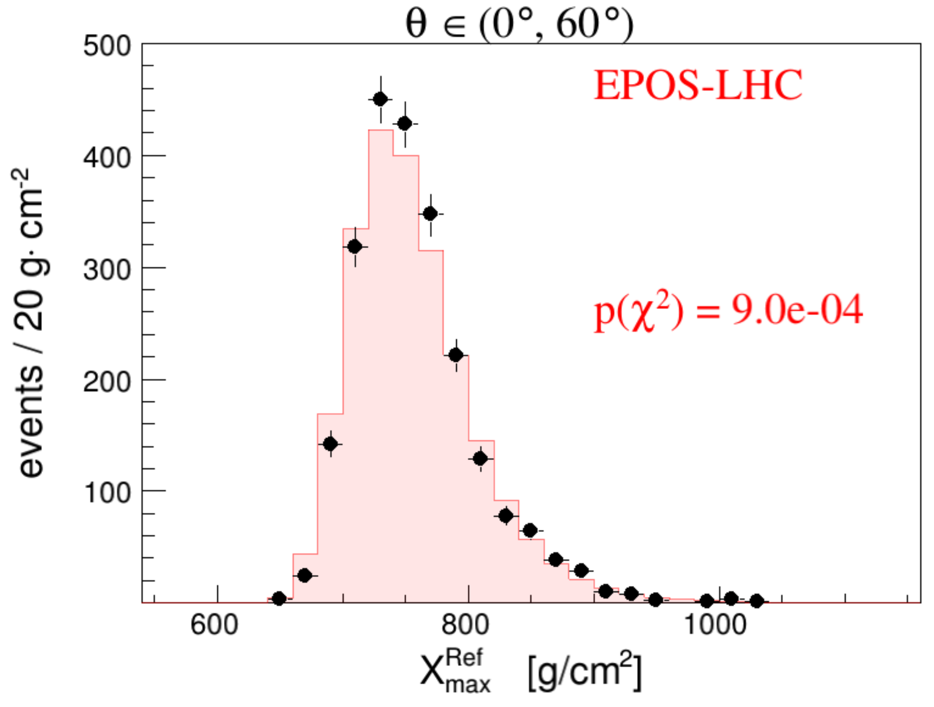
Test: modification of hadronic interaction models



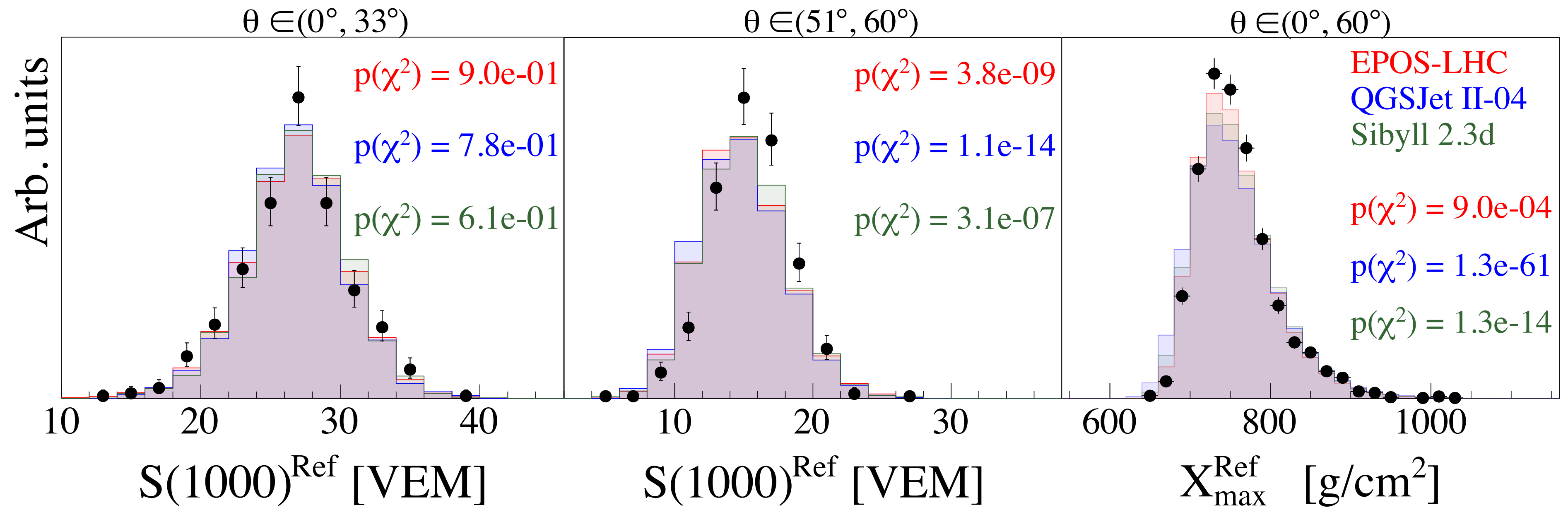
Combined fit of correlated Xmax distribution and S(1000) signal at ground



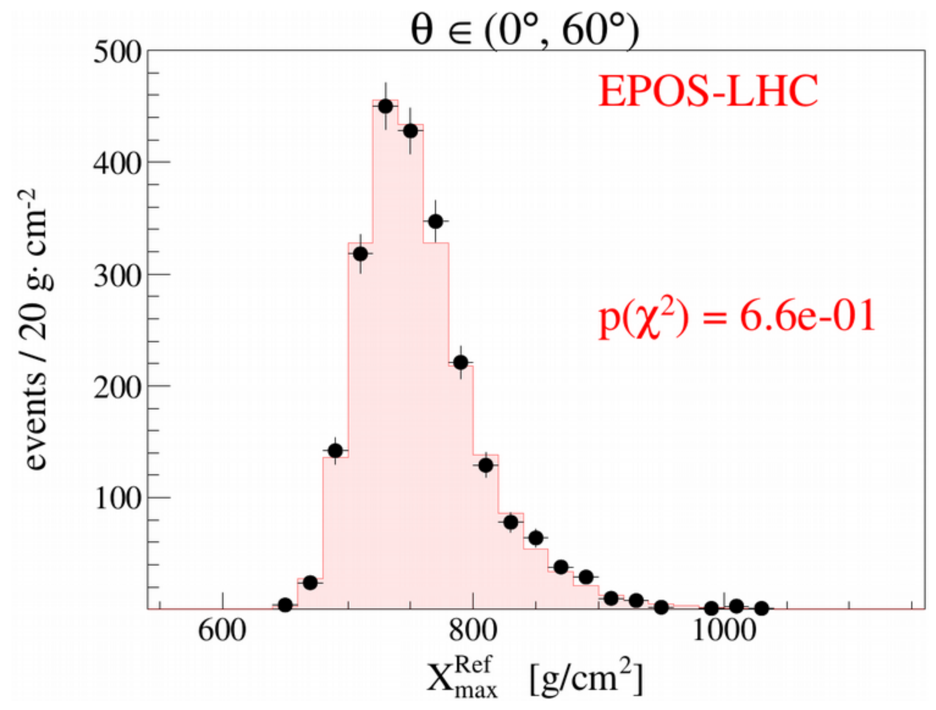
(a) No MC corrections



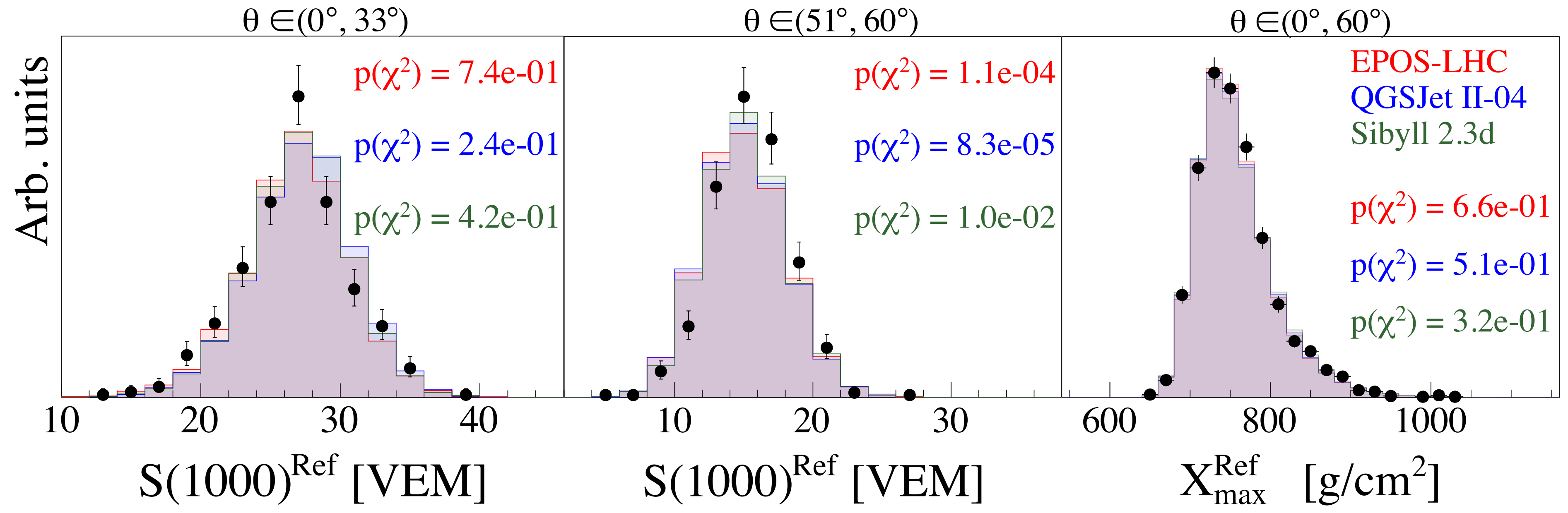
Combined fit of correlated Xmax distribution and S(1000) signal at ground allowing for an **angular-dependent muon re-scaling** (only mean muon number changed)



(b) MC corrections: $R_{\mathrm{Had}}(\theta)$



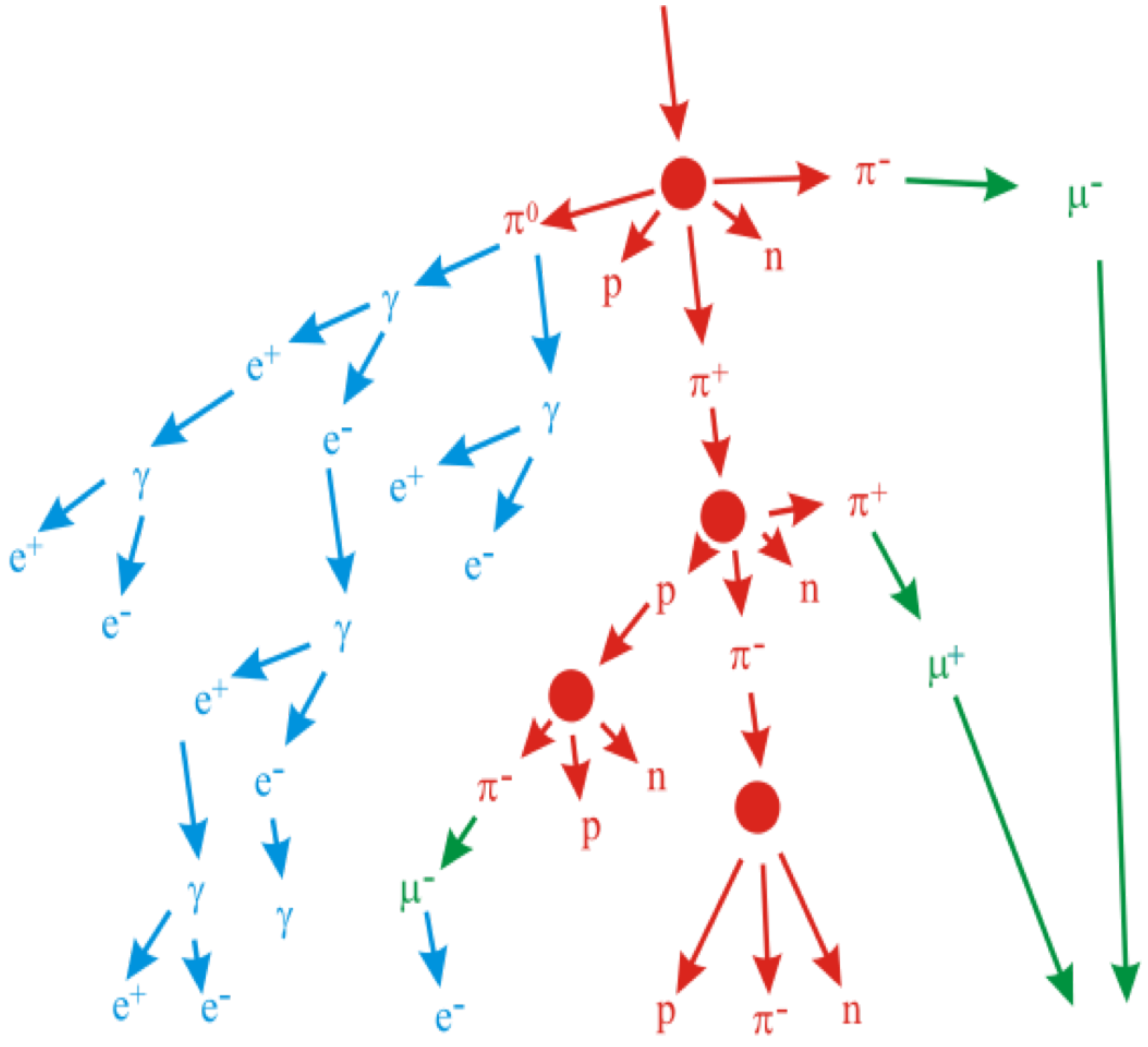
Combined fit of correlated Xmax distribution and S(1000) signal at ground allowing for an **angular-dependent muon re-scaling** (only mean muon number changed) and **shifting Xmax** of all primaries by fixed value

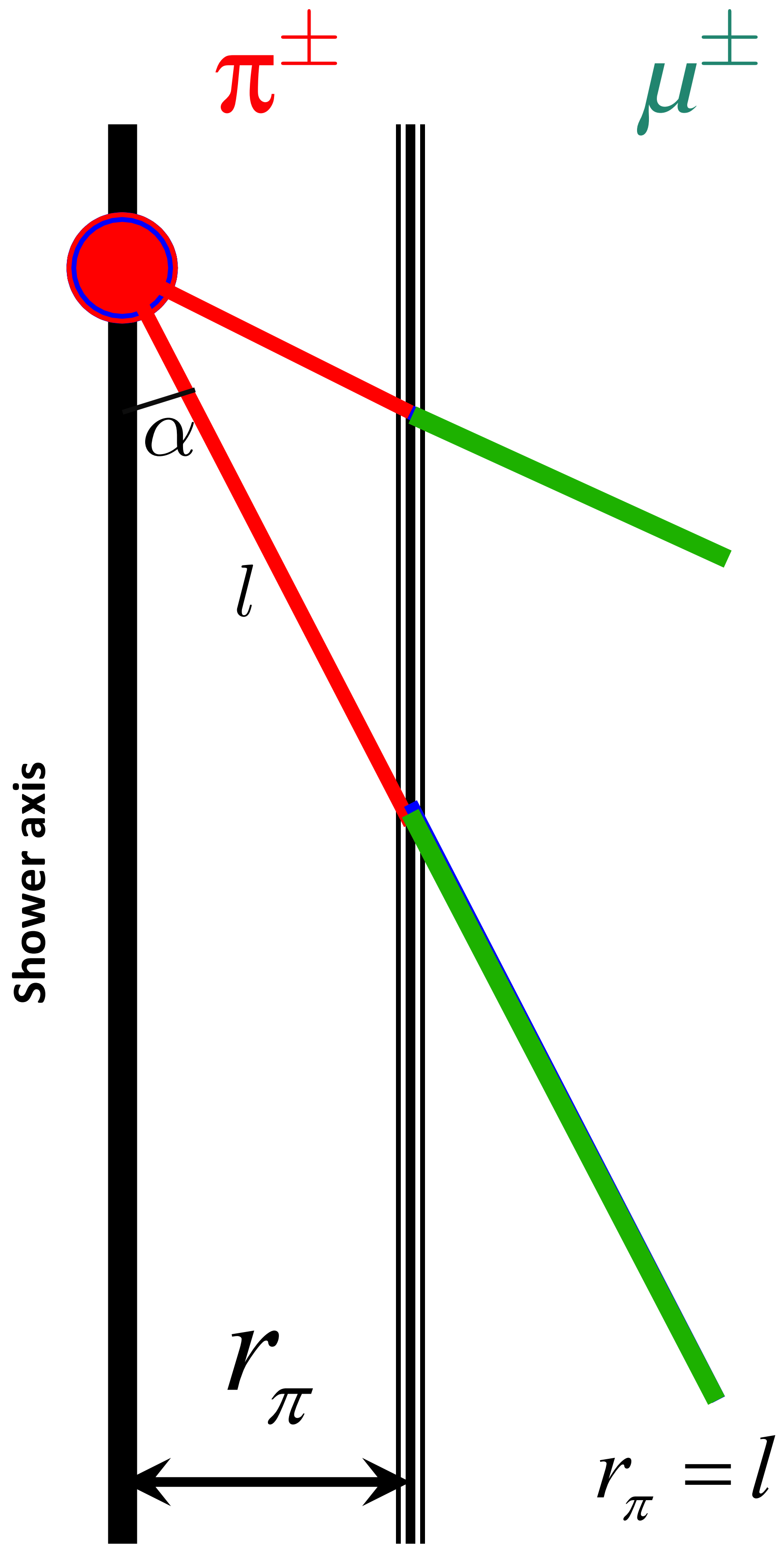


(c) MC corrections: ΔX_{max} and $R_{\mathrm{Had}}(\theta)$

(Auger, ICRC 2012)

Physics of muon production and number fluctuations





$$\sin\alpha = \frac{cp_t}{E}$$

$$l = \frac{E}{m_\pi c^2} c\tau_\pi$$

$$r_\pi = l\sin\alpha = \frac{\tau_\pi p_t}{m_\pi}$$

Lorenzo Cazon et al.
Astropart. Phys. 36 (2012) 211
Phys. Lett. B784 (2018) 68
Phys. Rev. D103 (2021) 022001

Lateral distance

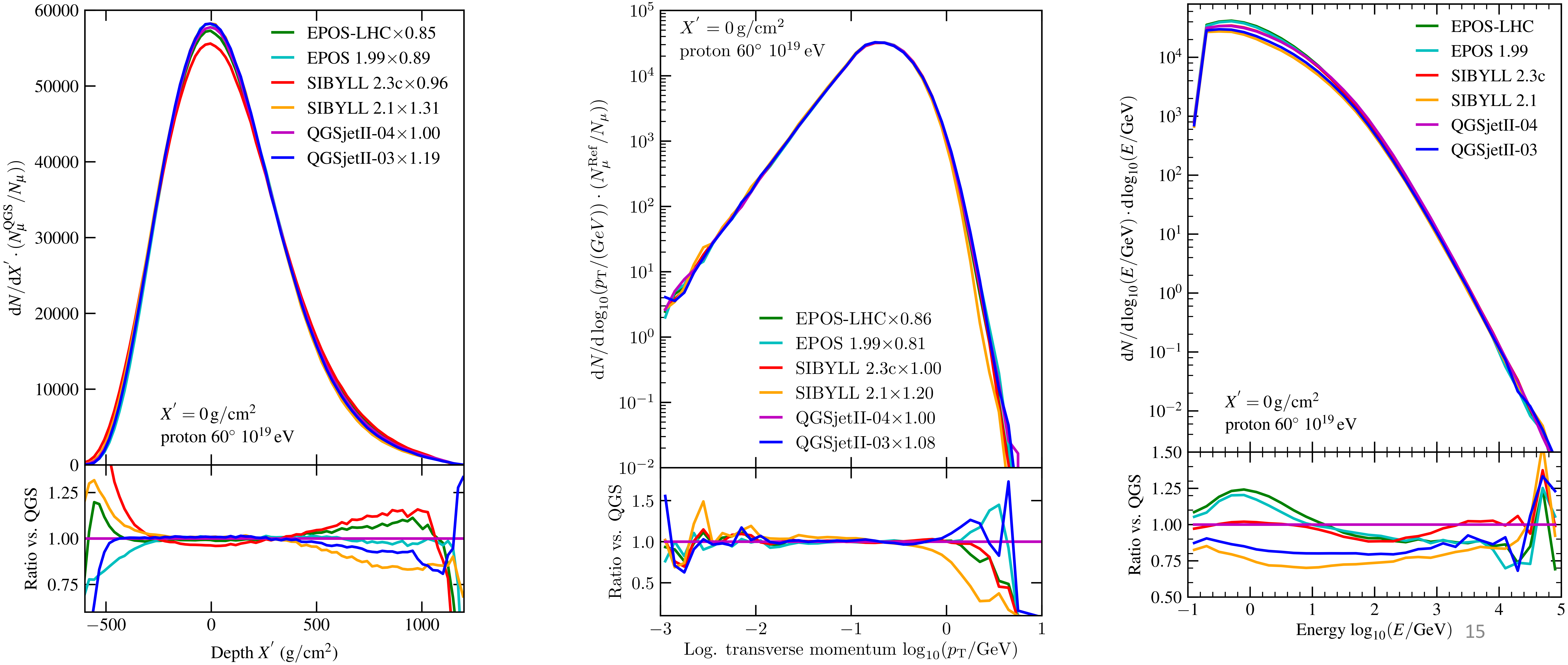
59% of all muons

$$r_\pi < 22\,\mathrm{m}$$

$$\left(\frac{\sigma(N_\mu)}{N_\mu}\right)^2 \simeq \left(\frac{\sigma(\alpha_1)}{\alpha_1}\right)^2 + \left(\frac{\sigma(\alpha_2)}{\alpha_2}\right)^2 + \ldots + \left(\frac{\sigma(\alpha_c)}{\alpha_c}\right)^2$$

70% of fluctuations from first interaction

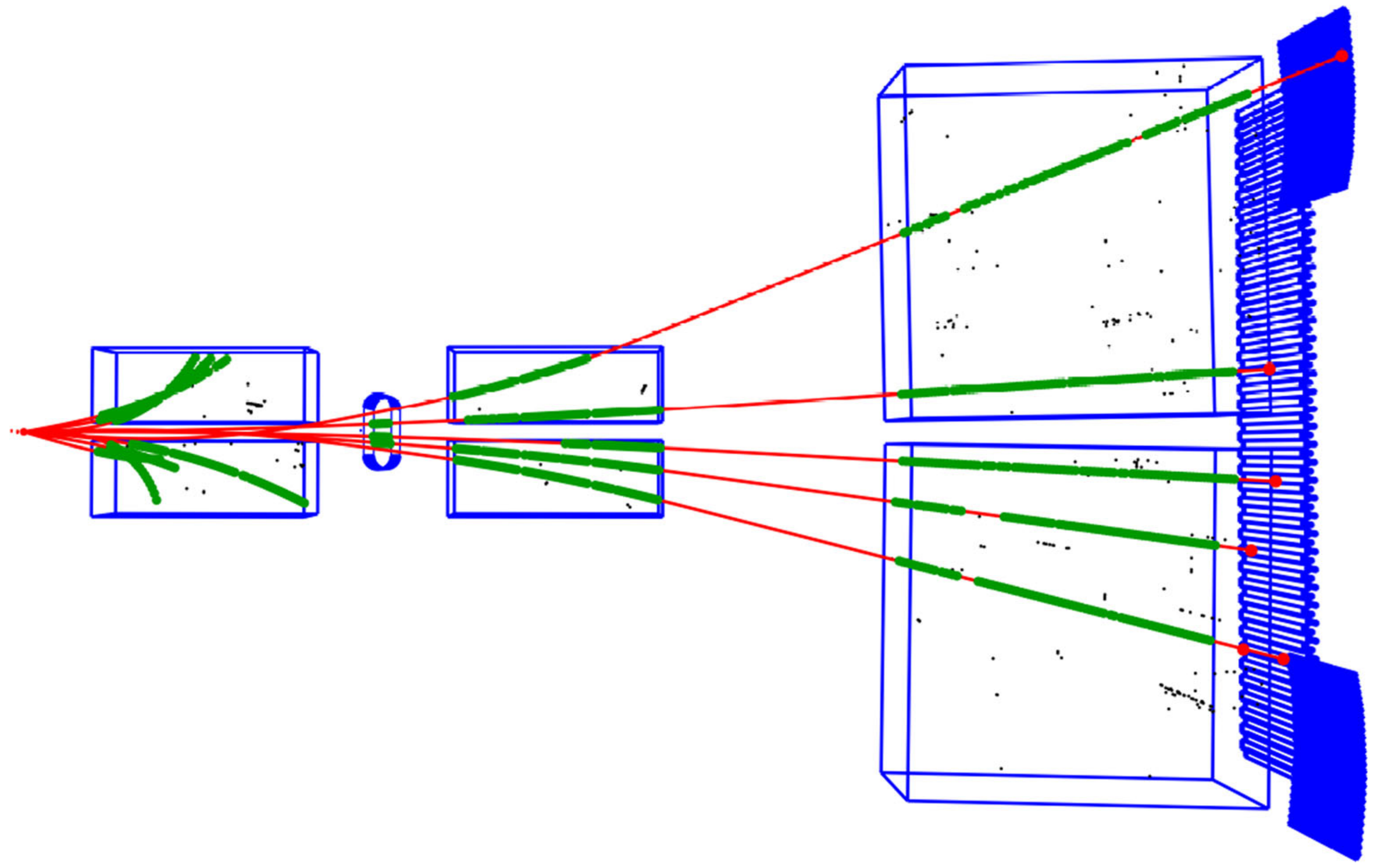
Universality features of muon production



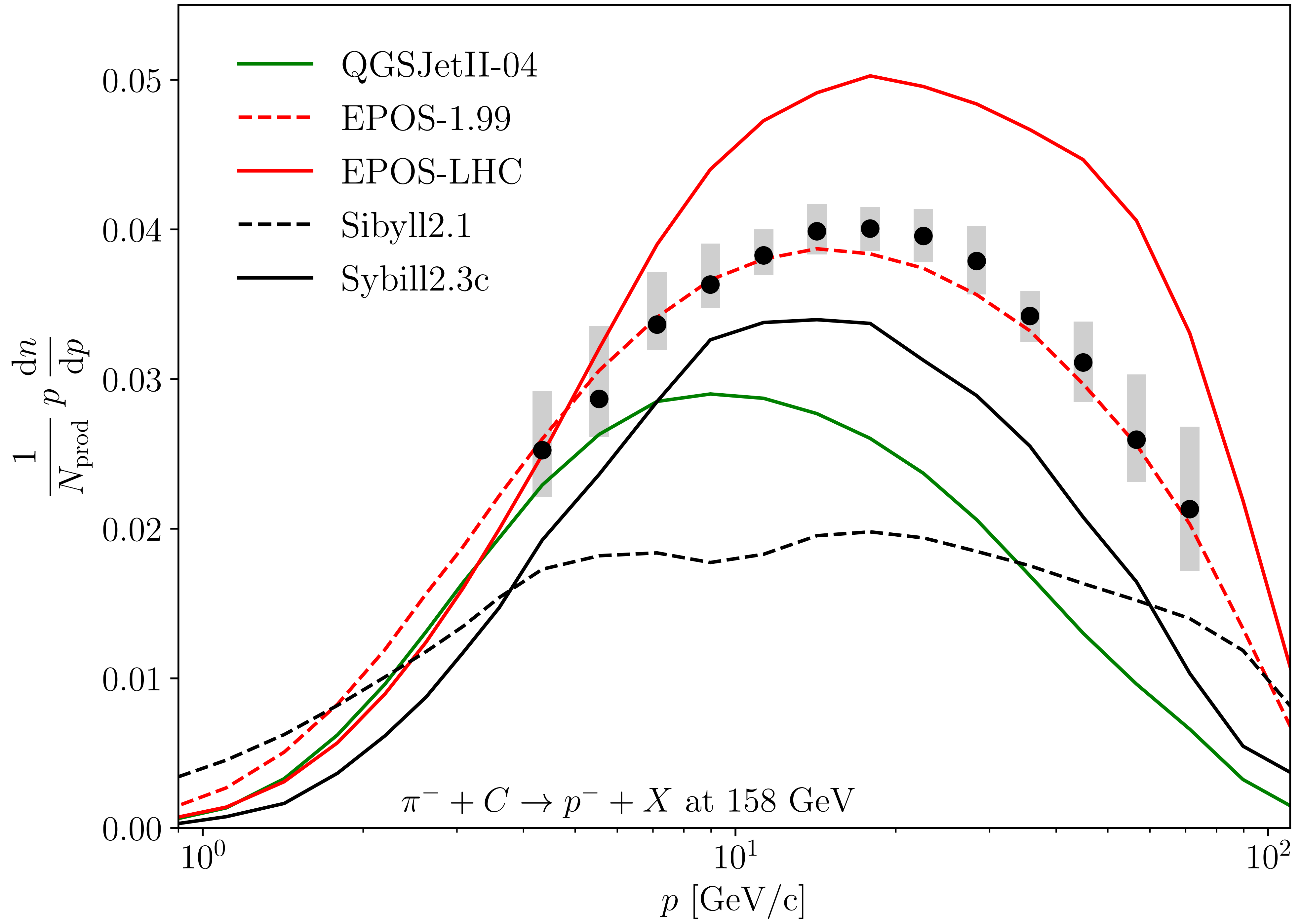
(Cazon, Epiphany Conference 2022, Cazon et al. JCAP 2023)

NA61 experiment at CERN SPS

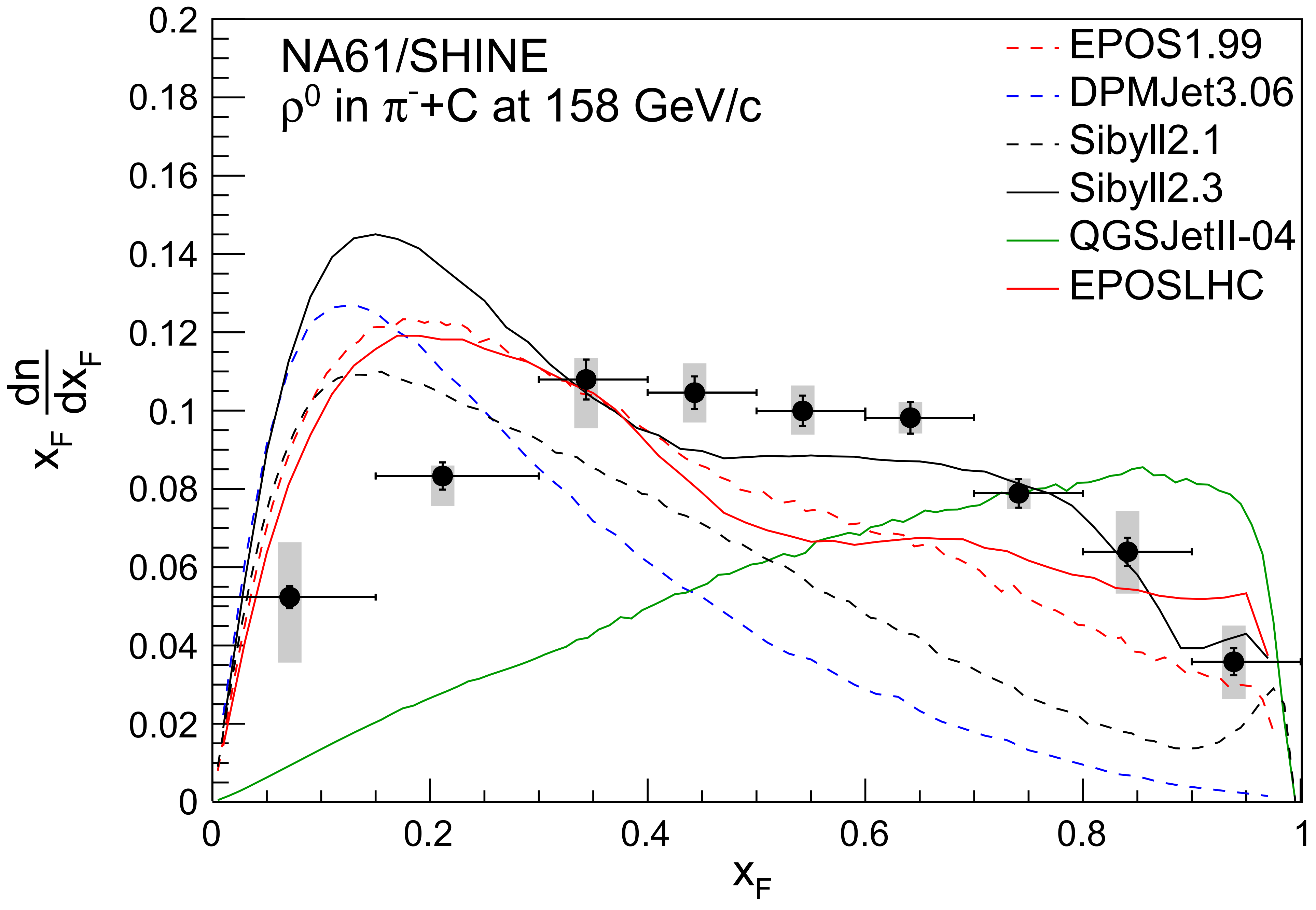
Dedicated cosmic ray runs
(π-C at 158 and 350 GeV)



$\pi^- C \rightarrow \bar{p}\, X$

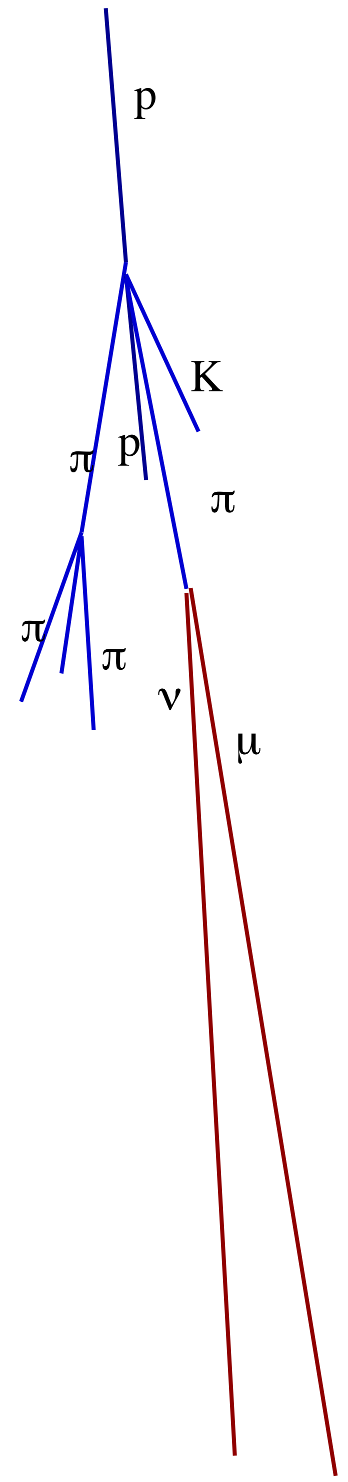


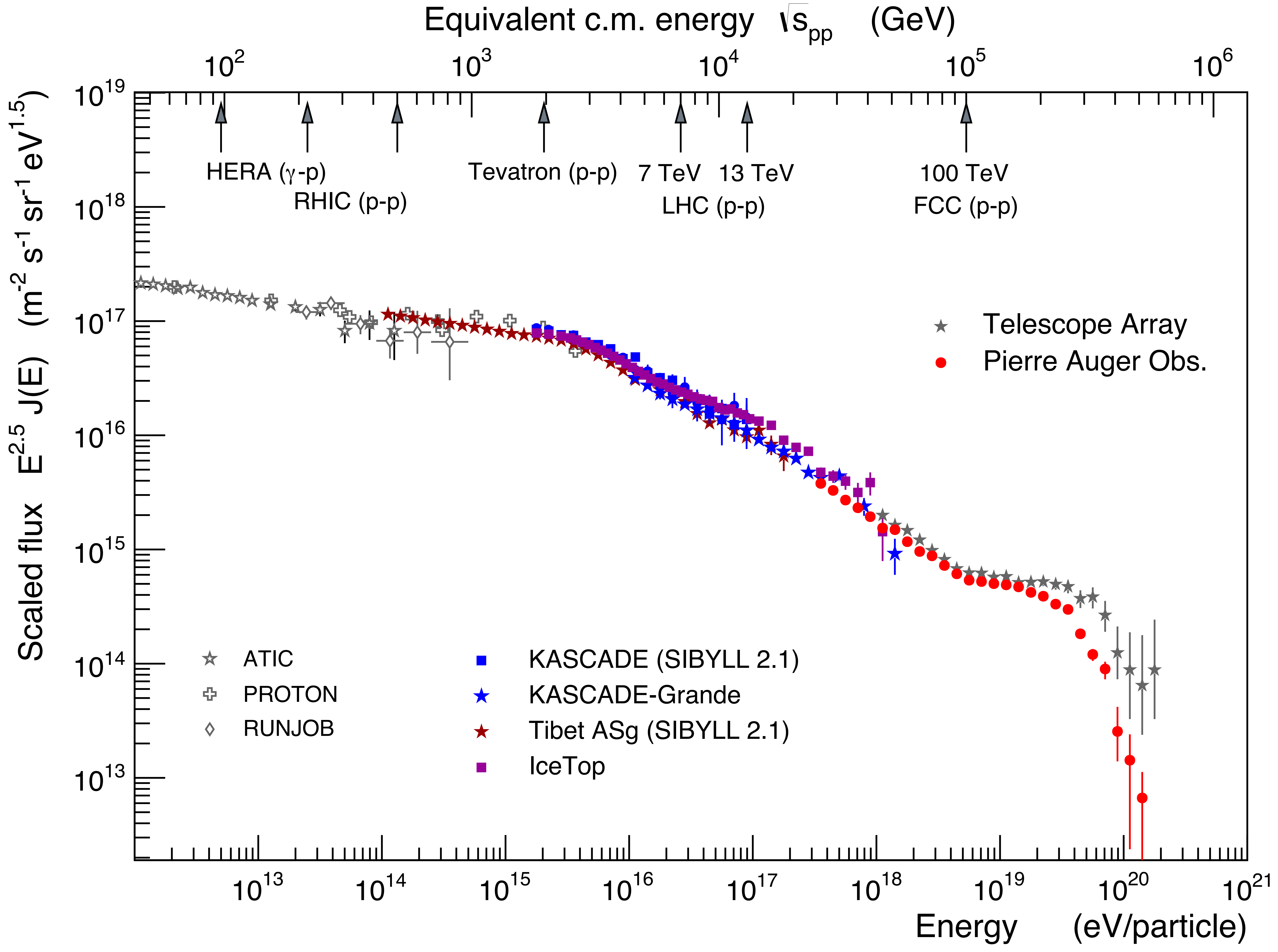
$\pi^- C \rightarrow \rho^0 X \rightarrow \pi^+\pi^- X$

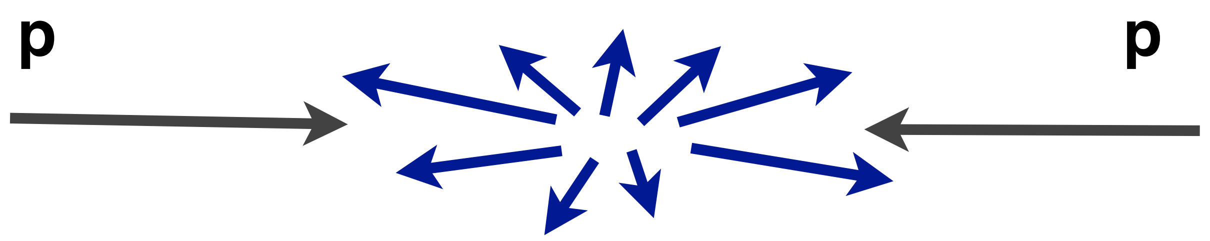


(NA61, Unger, Herve, Prado, et al. EPJ 77, 2017 & PRD 107, 2023)

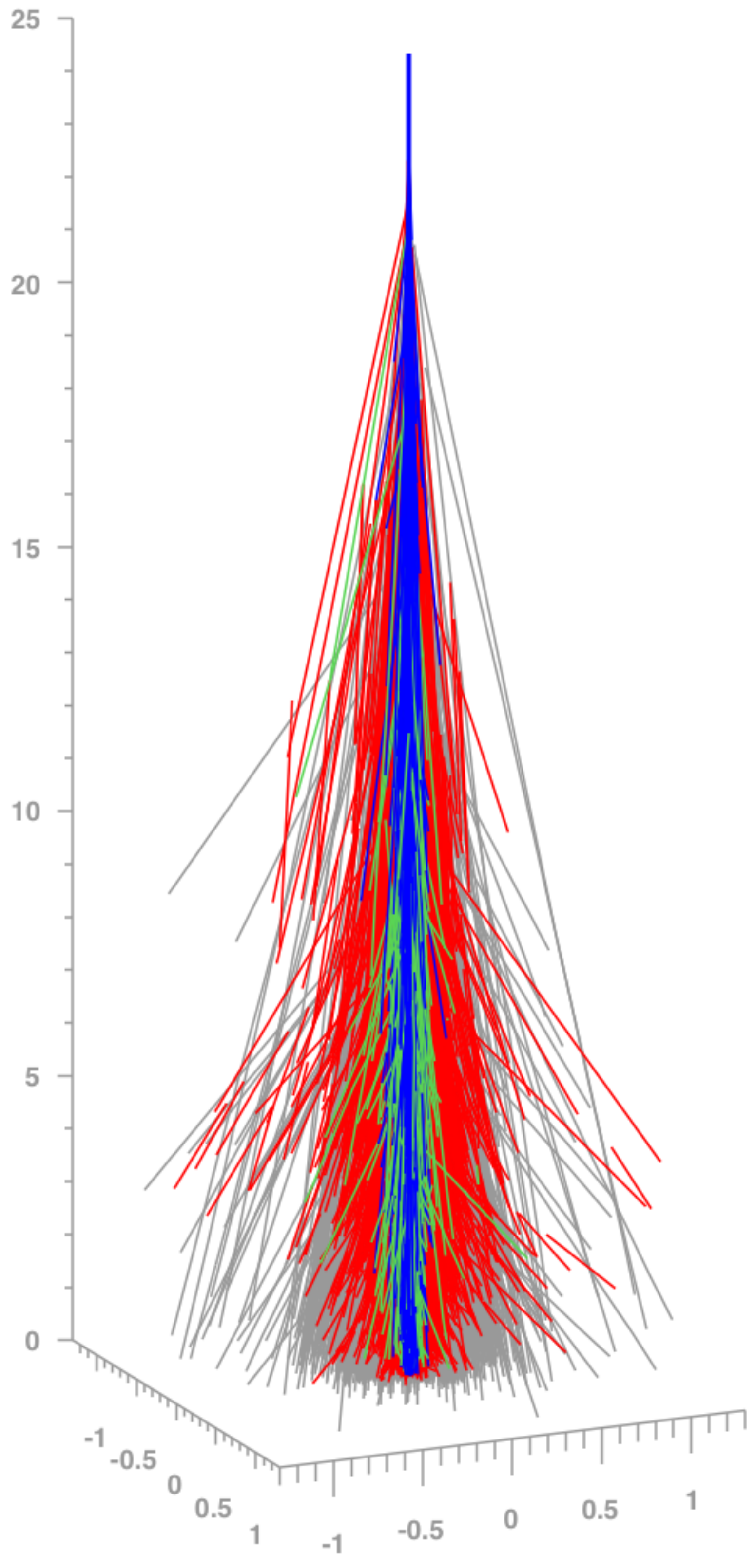
Cosmic ray flux and interaction energies







Center-of-mass energy



Laboratory energy