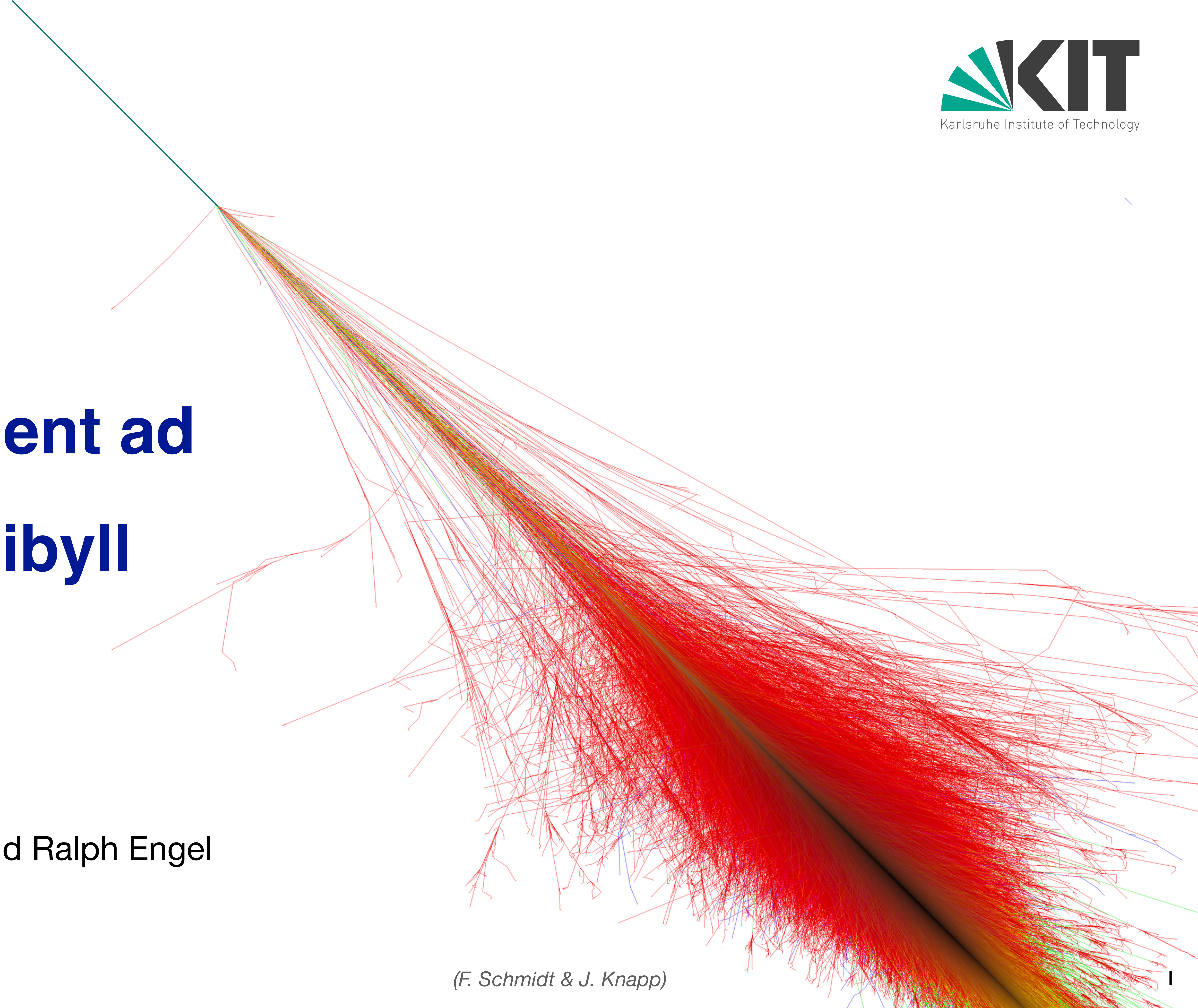
Muon enhancement ad extremum in Sibyll

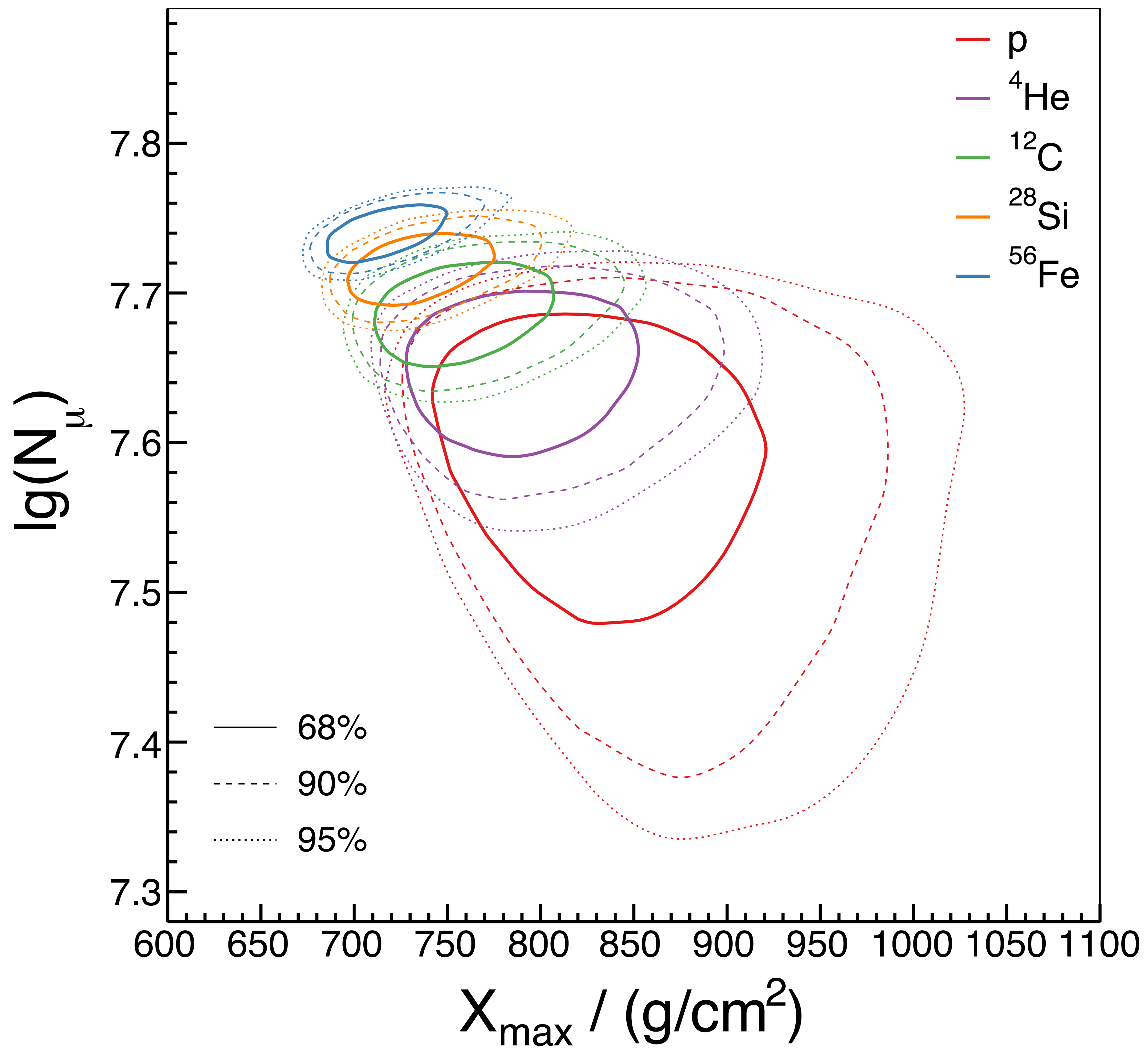
Felix Riehn, Anatoli Fedynitch, and Ralph Engel

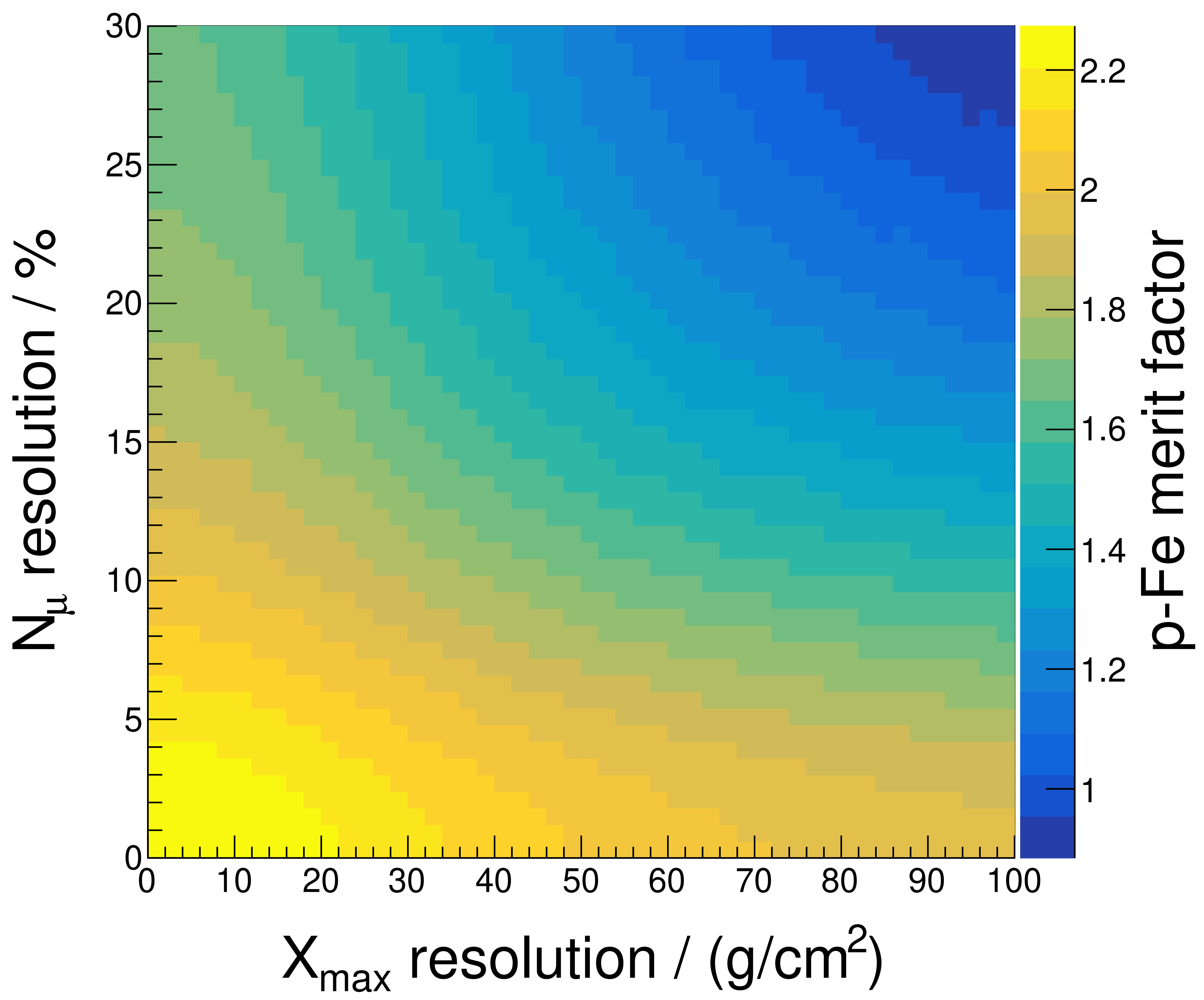


(F. Schmidt & J. Knapp)

Number of muons – a very important observable

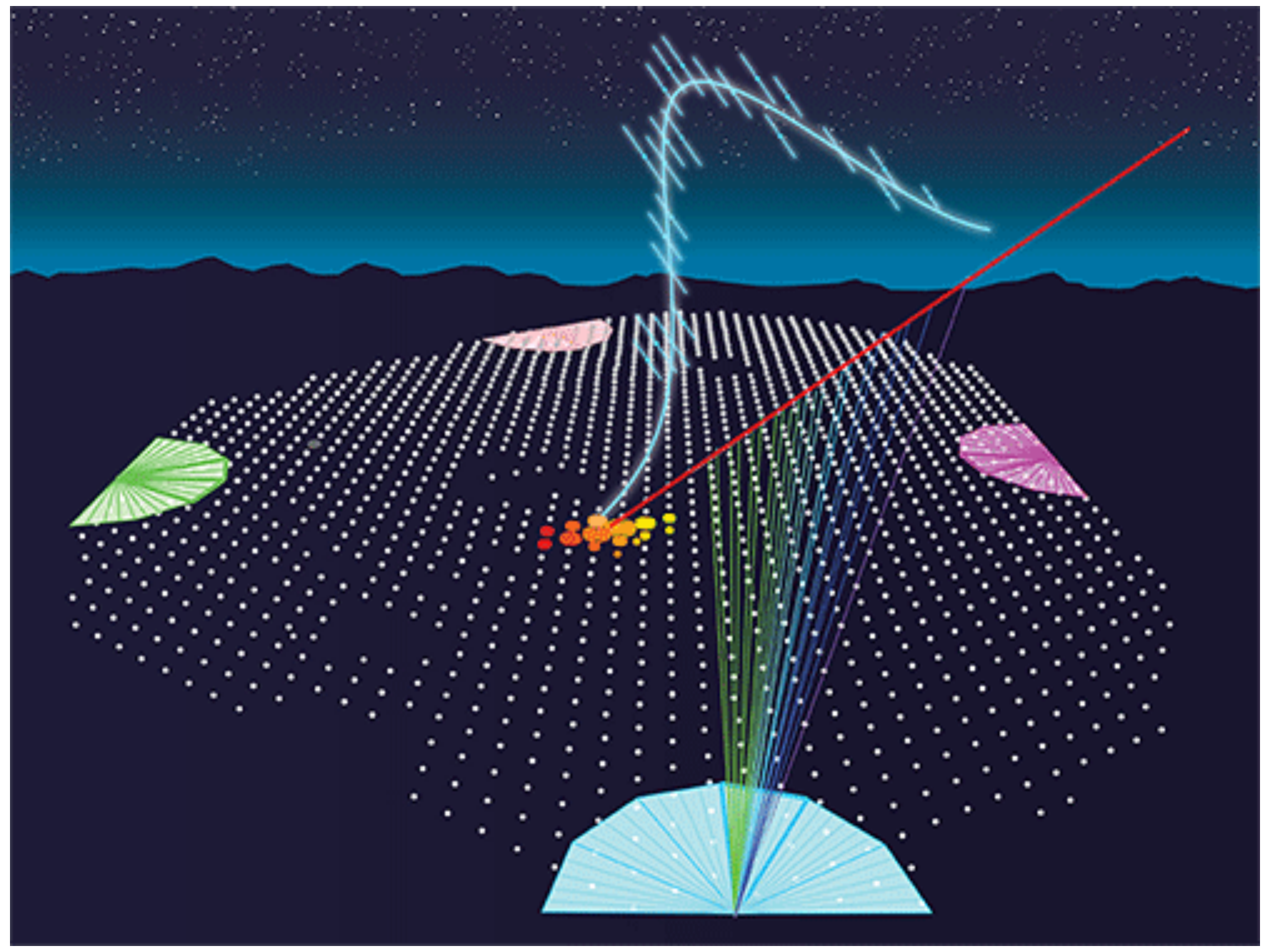
(UHECR Snowmass Summer Study, Coleman, 2205.05845)





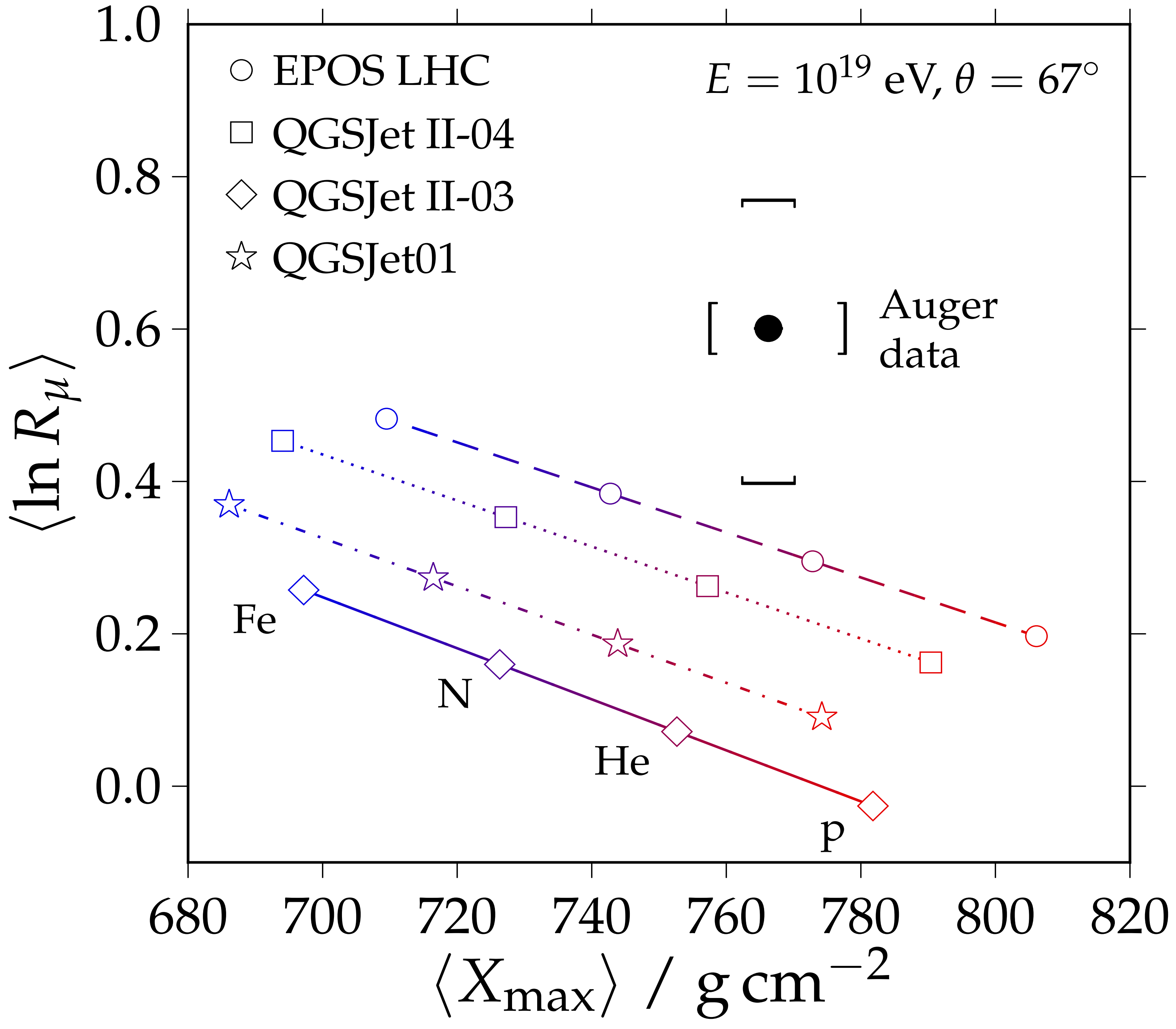
Muons have even better mass composition sensitivity than Xmax

Example of muon discrepancy – inclined showers

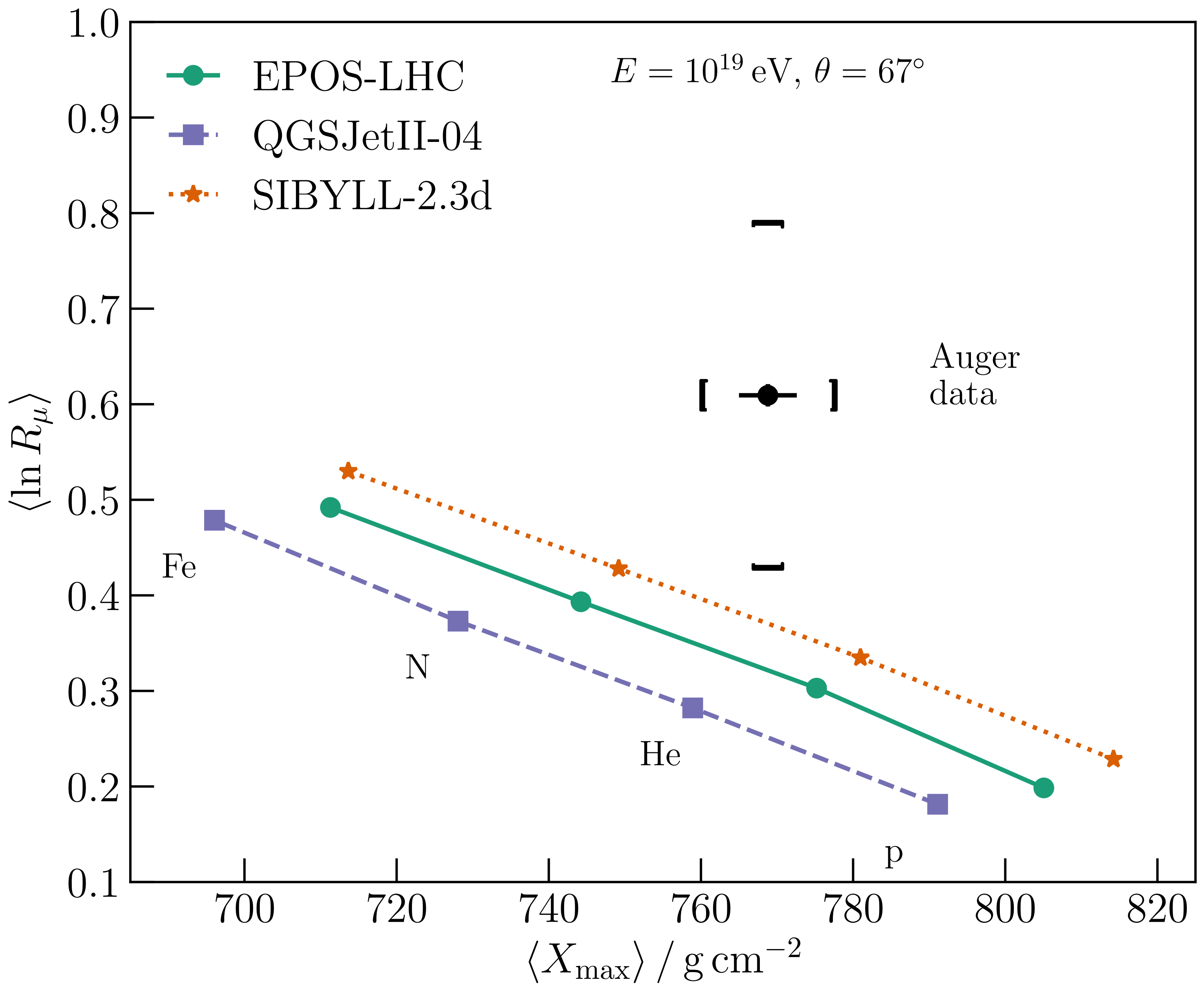


Relative number of muons in showers with θ>60°

(Auger, Phys. Rev. Lett. 117 (2016) 192001, Phys. Rev. D91 (2015) 032003)



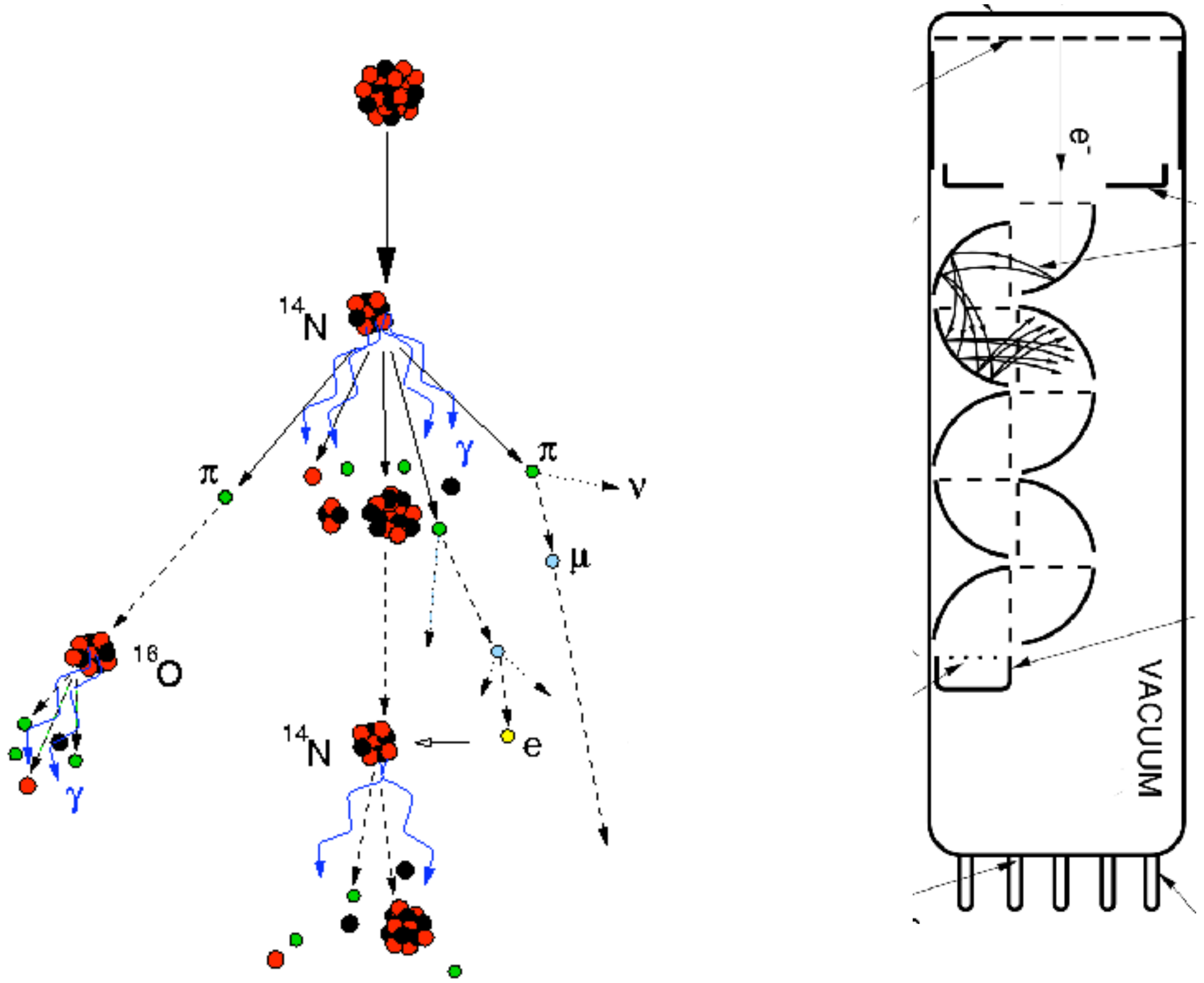
(Auger, Phys. Rev. Lett. 126 (2021) 152002)



Muon discrepancy known for long time, limited progress on side of model predictions

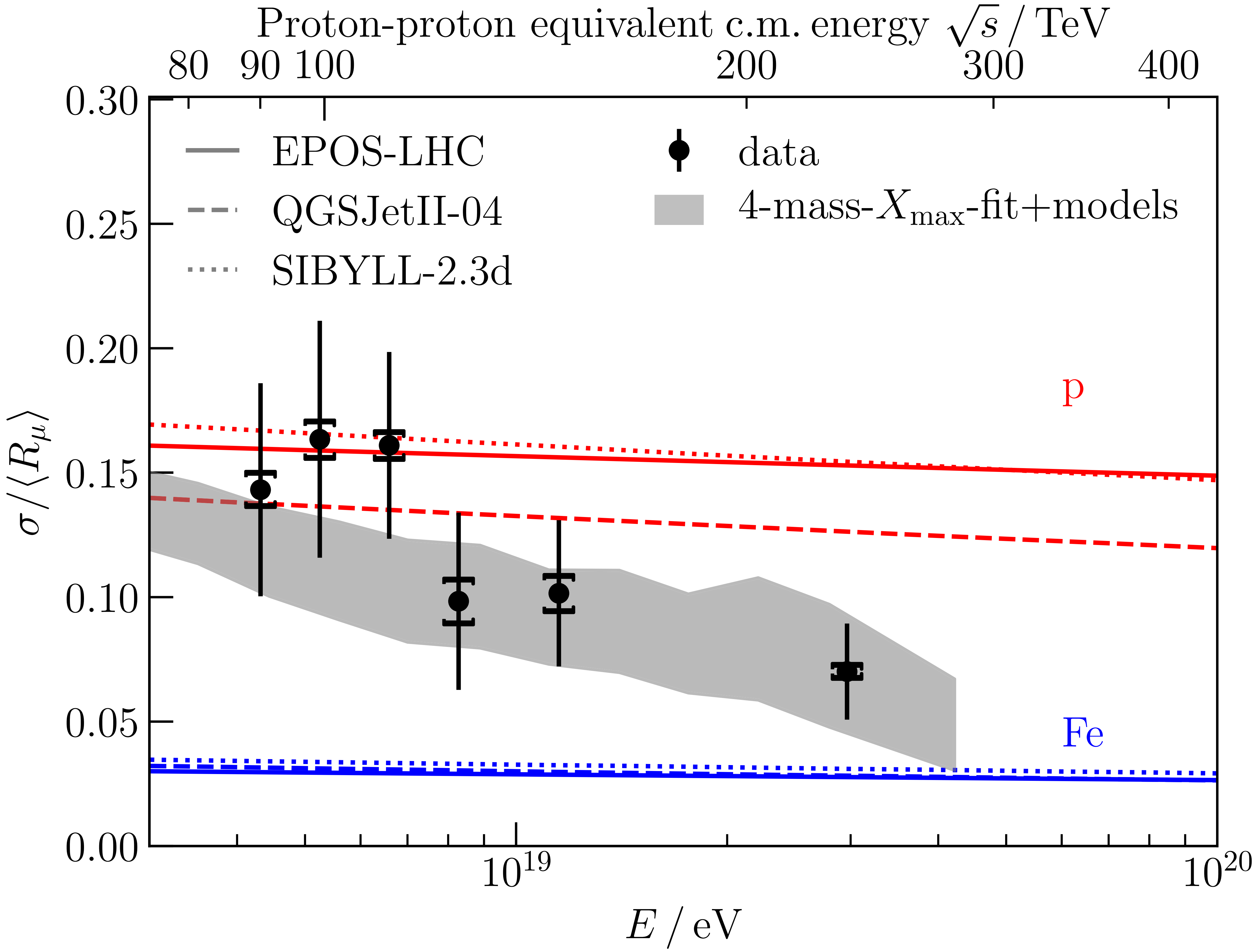
Relative fluctuations of muon number as expected

PMT analogy of air shower



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

Cazon et al. Phys. Lett. B784 (2018) 68

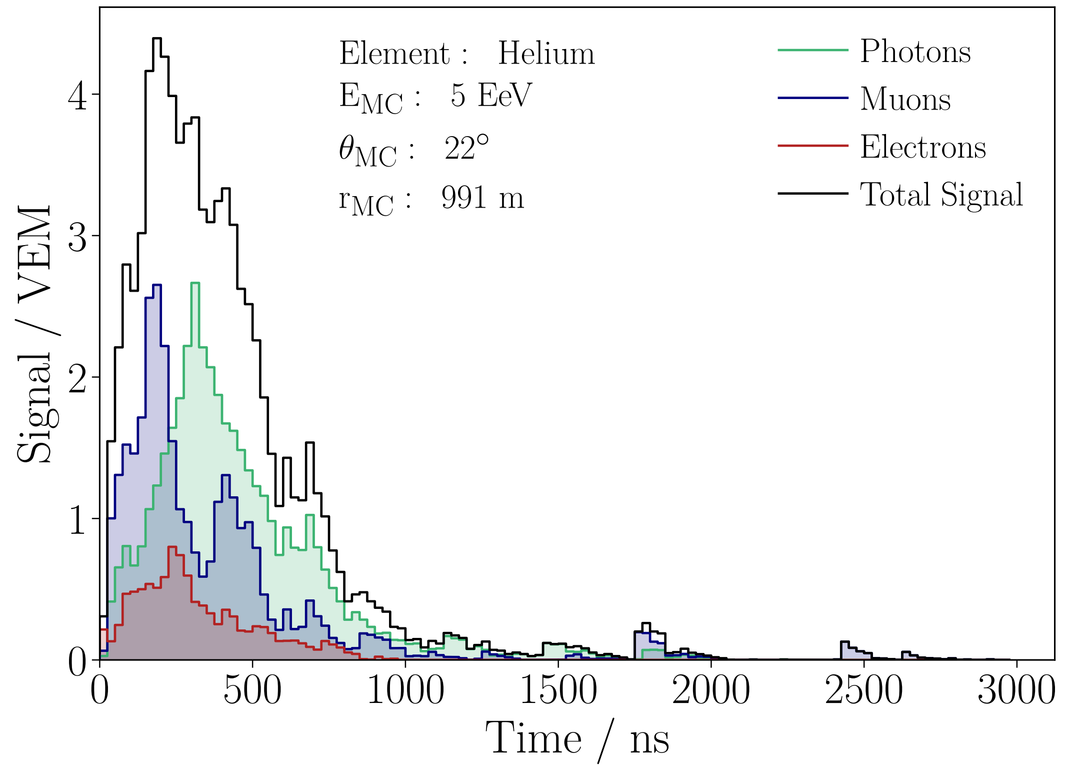


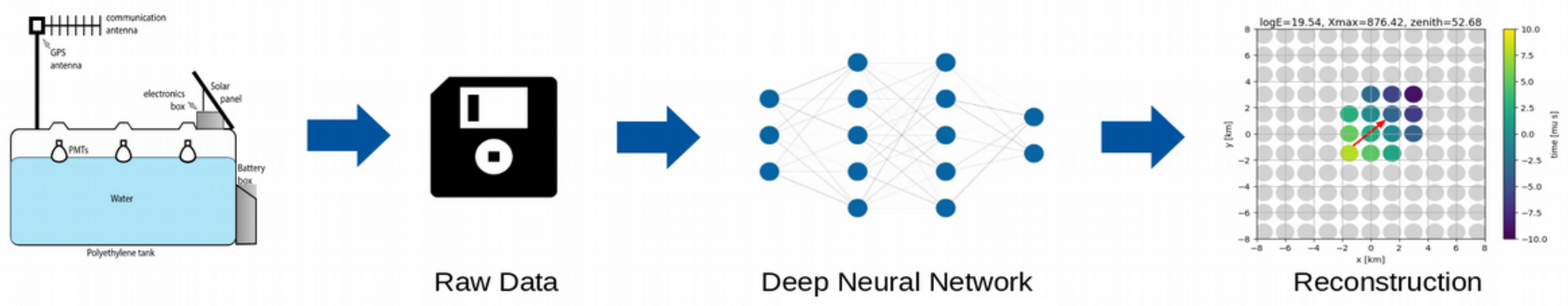
(Auger, Phys. Rev. Lett. 126 (2021) 152002)

70% of fluctuations from first interaction

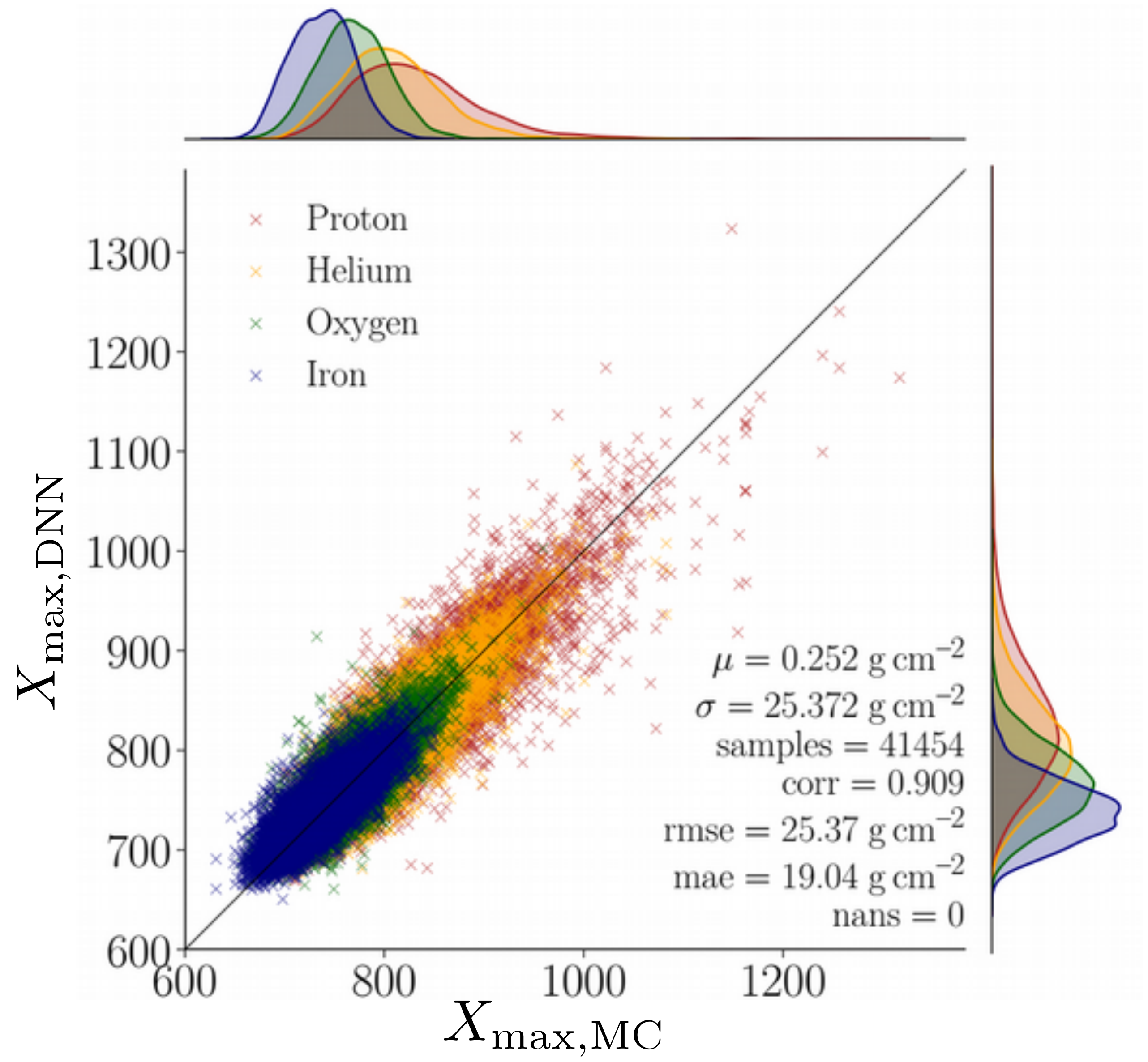
Muon discrepancy major obstacle in many applications

Training of DNN with MC simulations



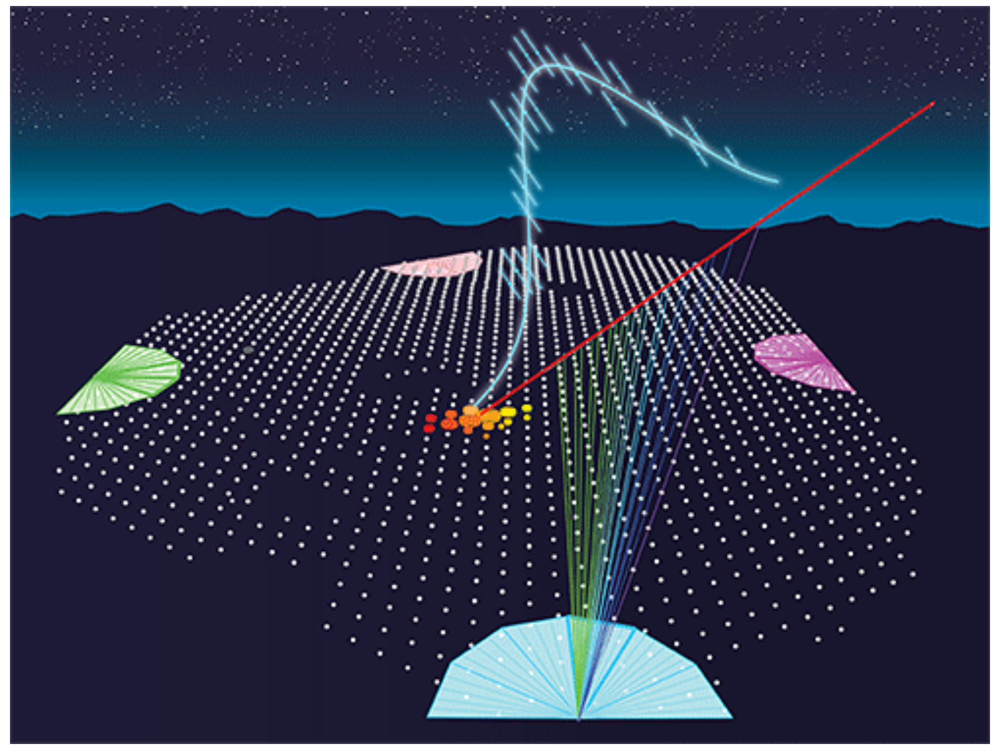


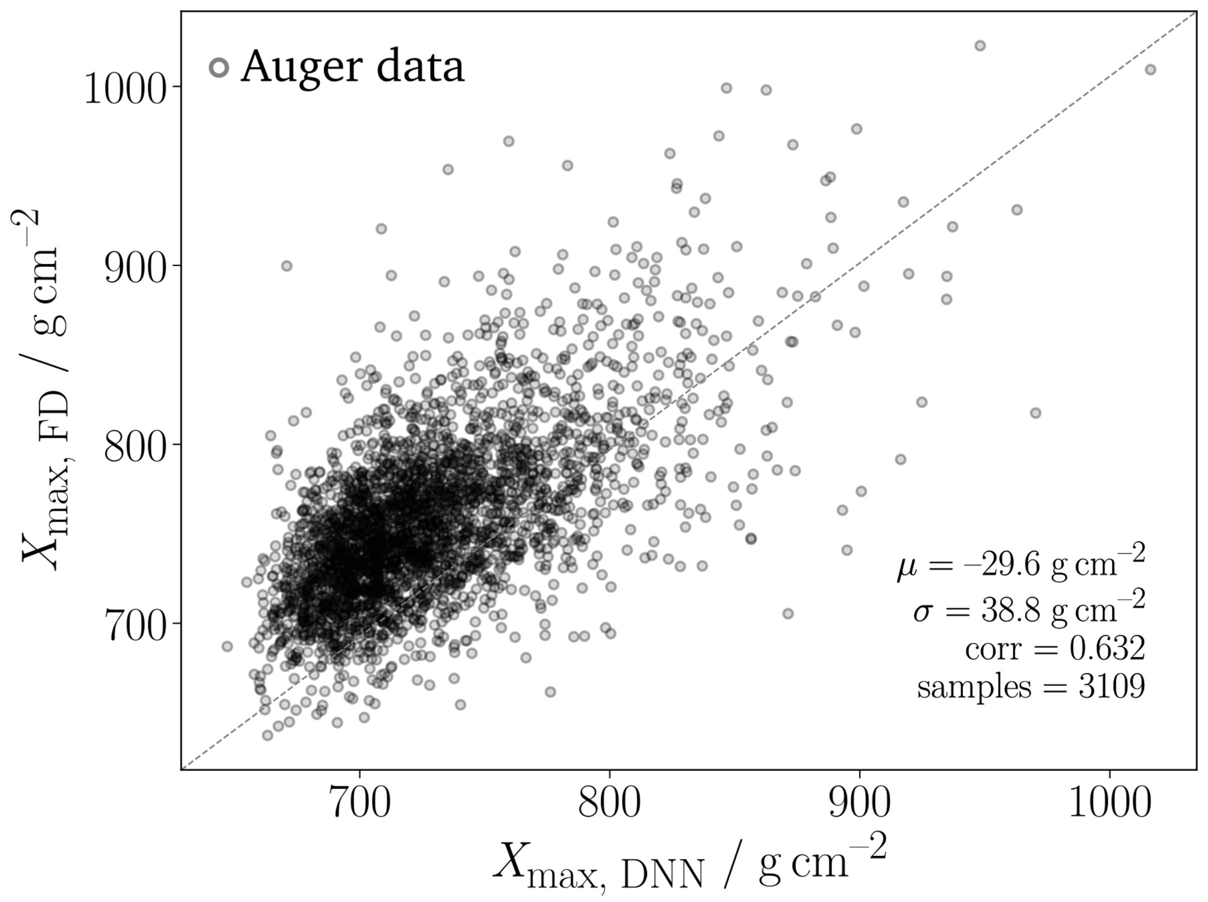
(Auger, JINST 16 (2021) 07, P07019)

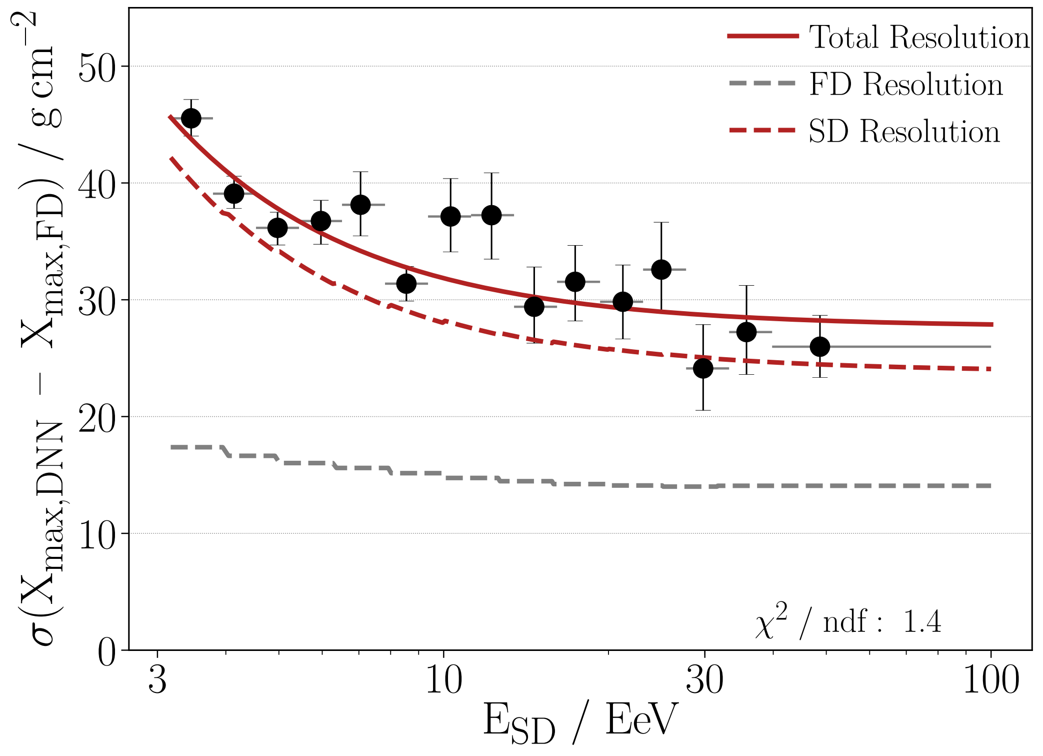


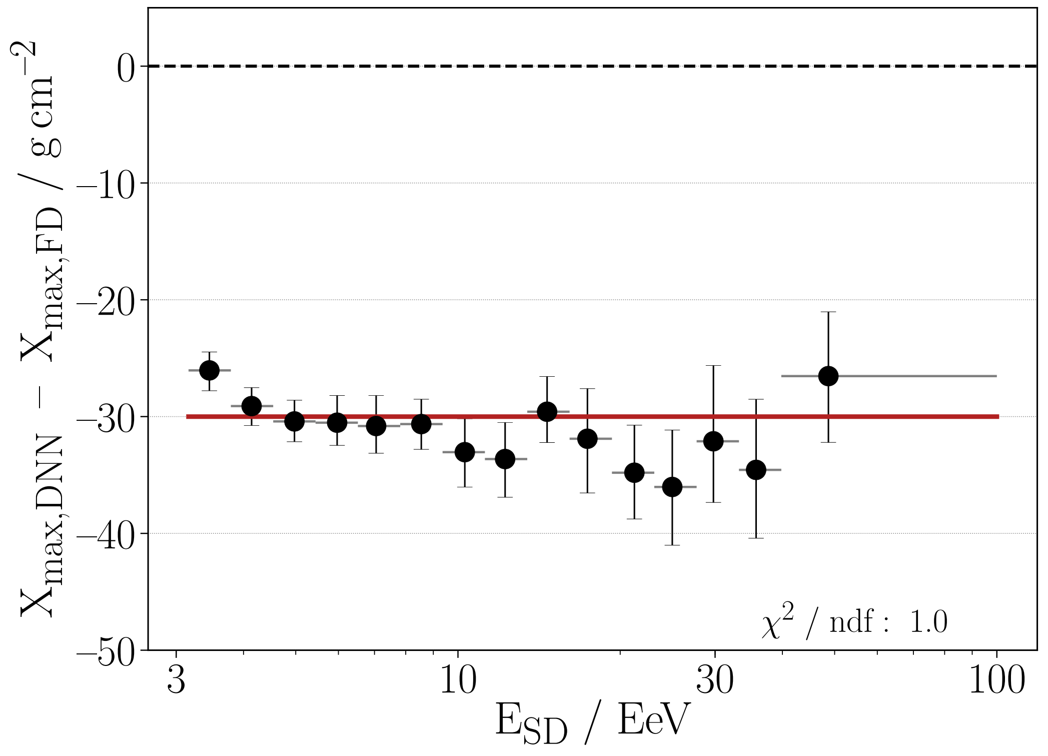
Reconstructing Xmax: ultimate check with data

Very good resolution, unexpected offset of ~30 g/cm²









Thoughts on how to make progress

Progress highly desirable, muon discrepancy impacts many fields

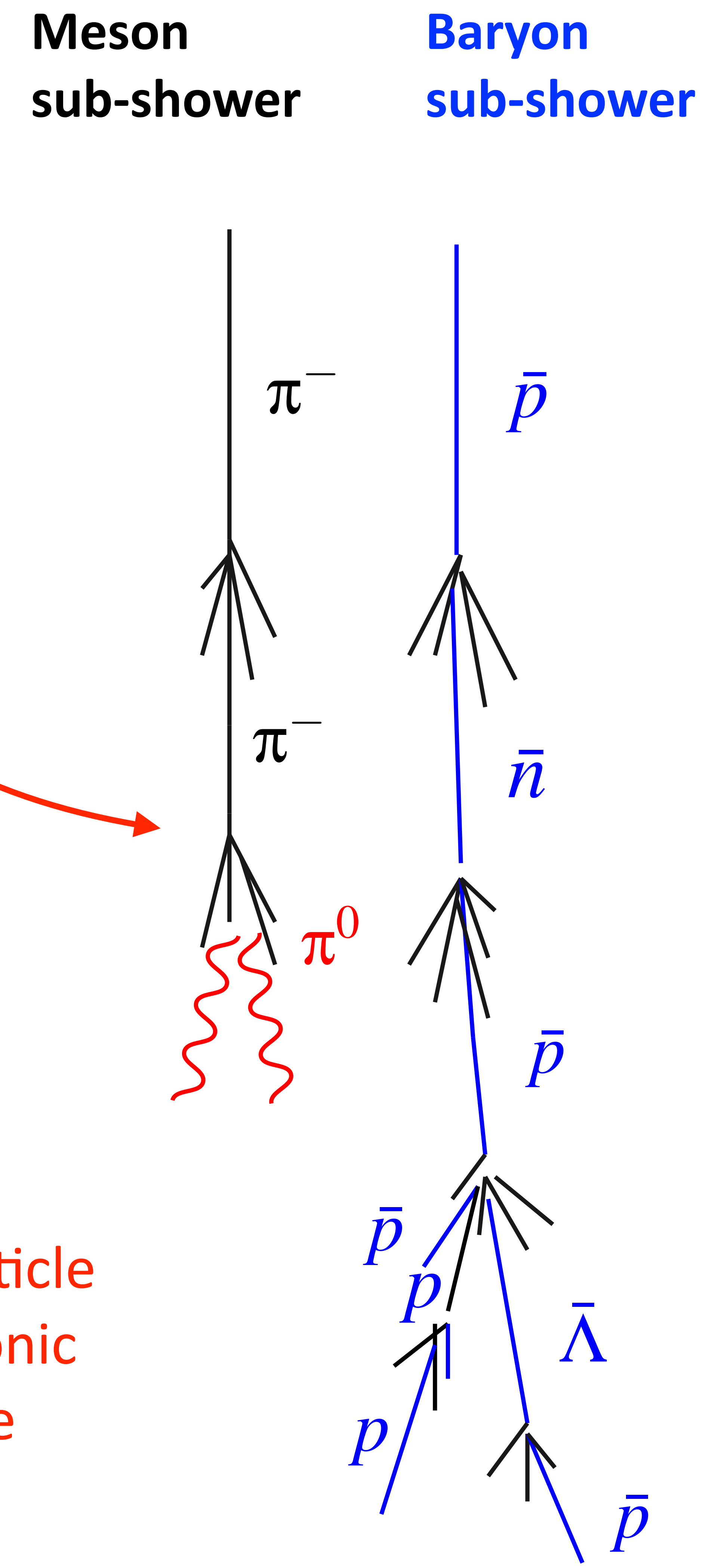
- Energy calibration with Monte Carlo predictions
- Use of SD data for composition studies (rise time, DNN, asymmetries)
- Calculation of efficiencies and trigger probabilities
- Search for photons and new phenomena, particle physics studies

Possible approaches and non-exclusive and complementary lines of work

- Wait and hope that model builders will produce a much better model based on accelerator data
- Wait and hope for new accelerator measurements that might help to solve problem
- Accept limited use of muon-sensitive observables and do not use full capabilities of observatories
- Accept contradictory composition results depending on used observables

- **Produce interaction models for different (extreme) physics scenarios to learn from EAS data**

Muon production depends on hadronic energy fraction



30% chance to have π^0 as leading particle

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. arXiv:2202.03095)*

- 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

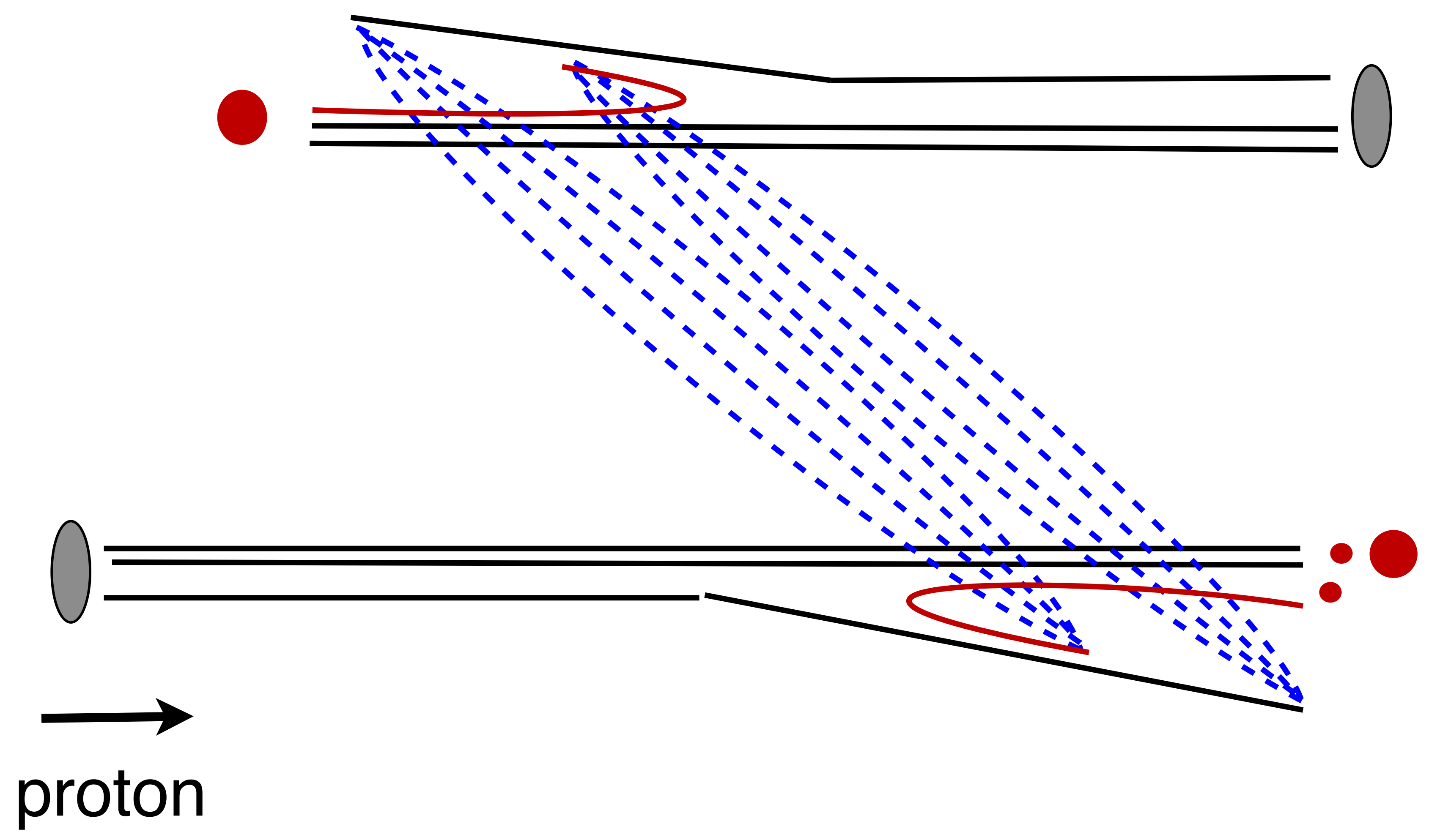
4 New hadronic physics at high energy *(Farrar, Allen 2012)*

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

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

Simple and pragmatic approach using Sibyll

- Only one process modified/enhanced per model scenario
- Changes transparent and minimalistic (tunable parameters)
- No or minimal change of other model predictions for accelerator and EAS data
- Satisfy all relevant conservation laws and implement expected universality



Central particle production not changed

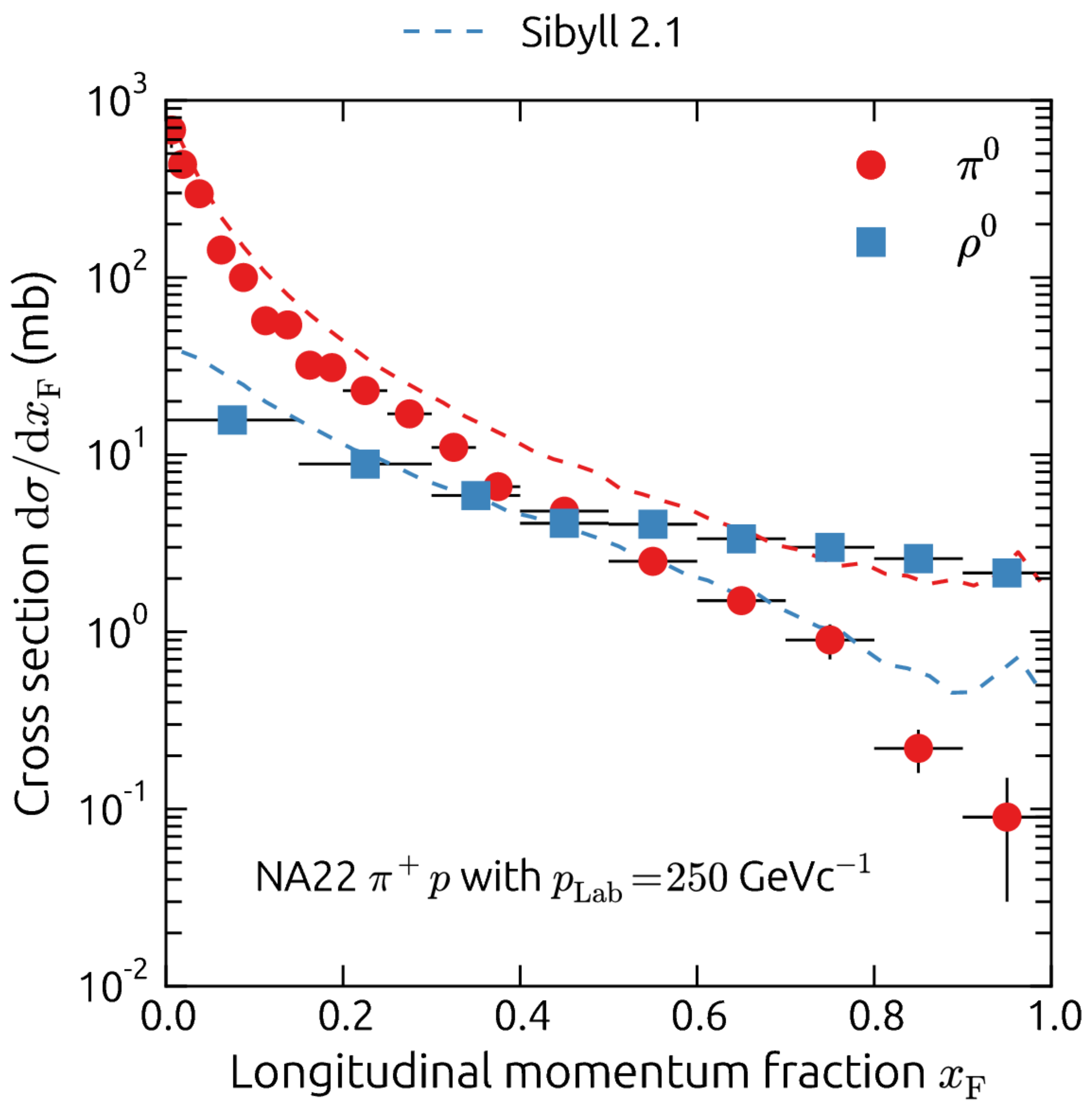
Modification of leading/forward particle production

Example:

$$P_{\pi^0 \to \rho^0} = 0.6 \times (x_F)^{0.4}$$

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

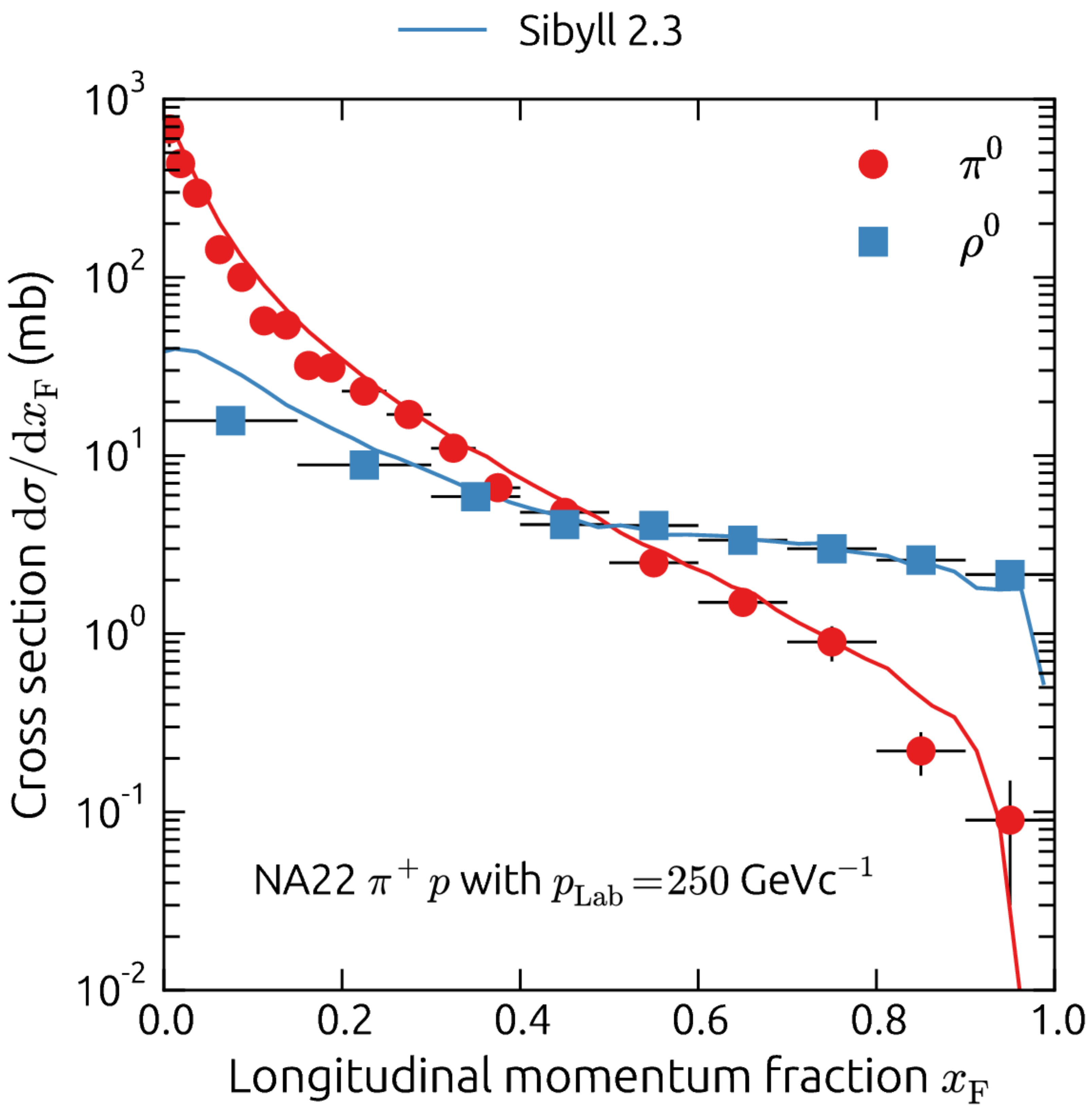
Leading particle production



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

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

$$E_{\rm lab} = 250\,{\rm GeV}$$

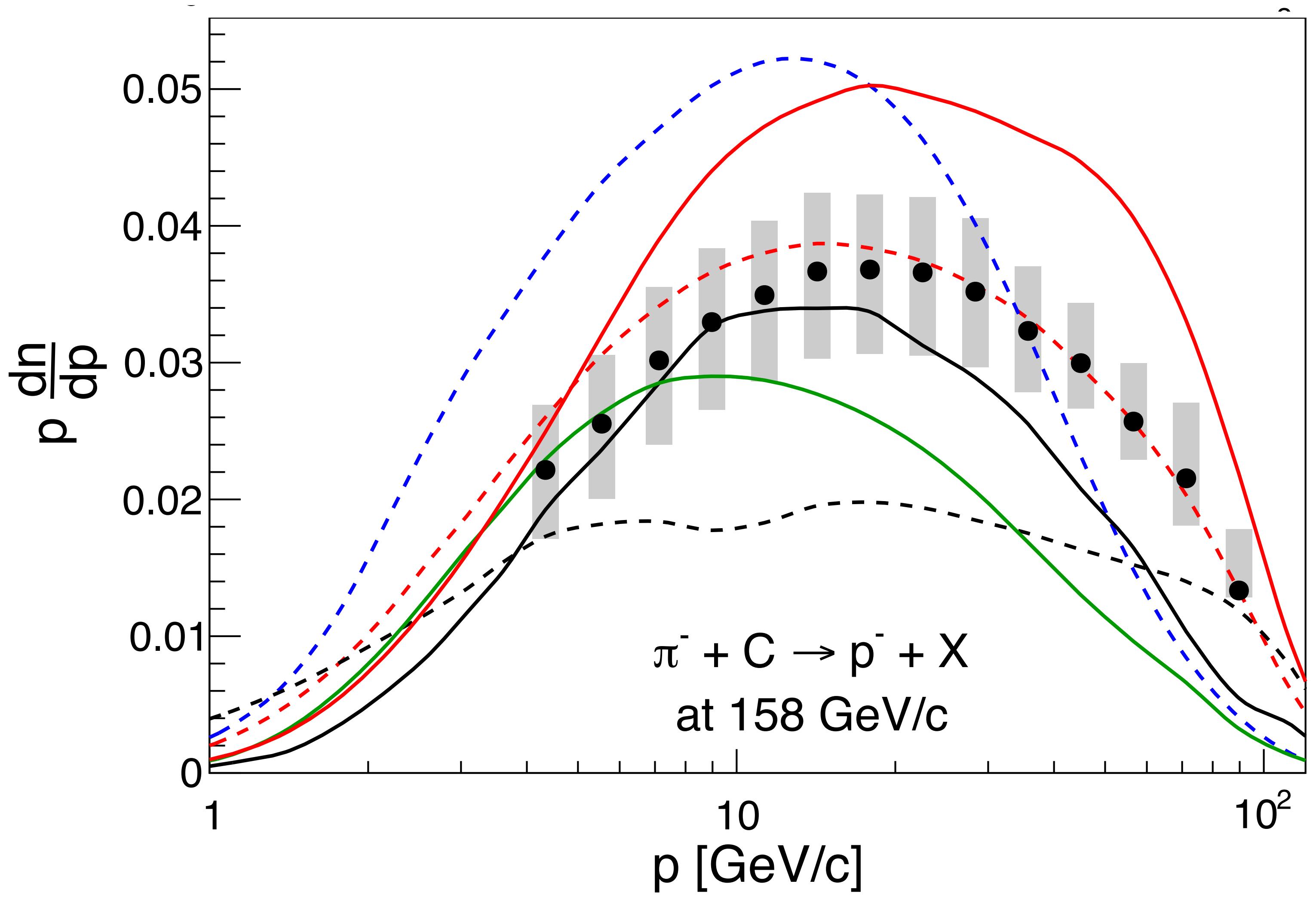


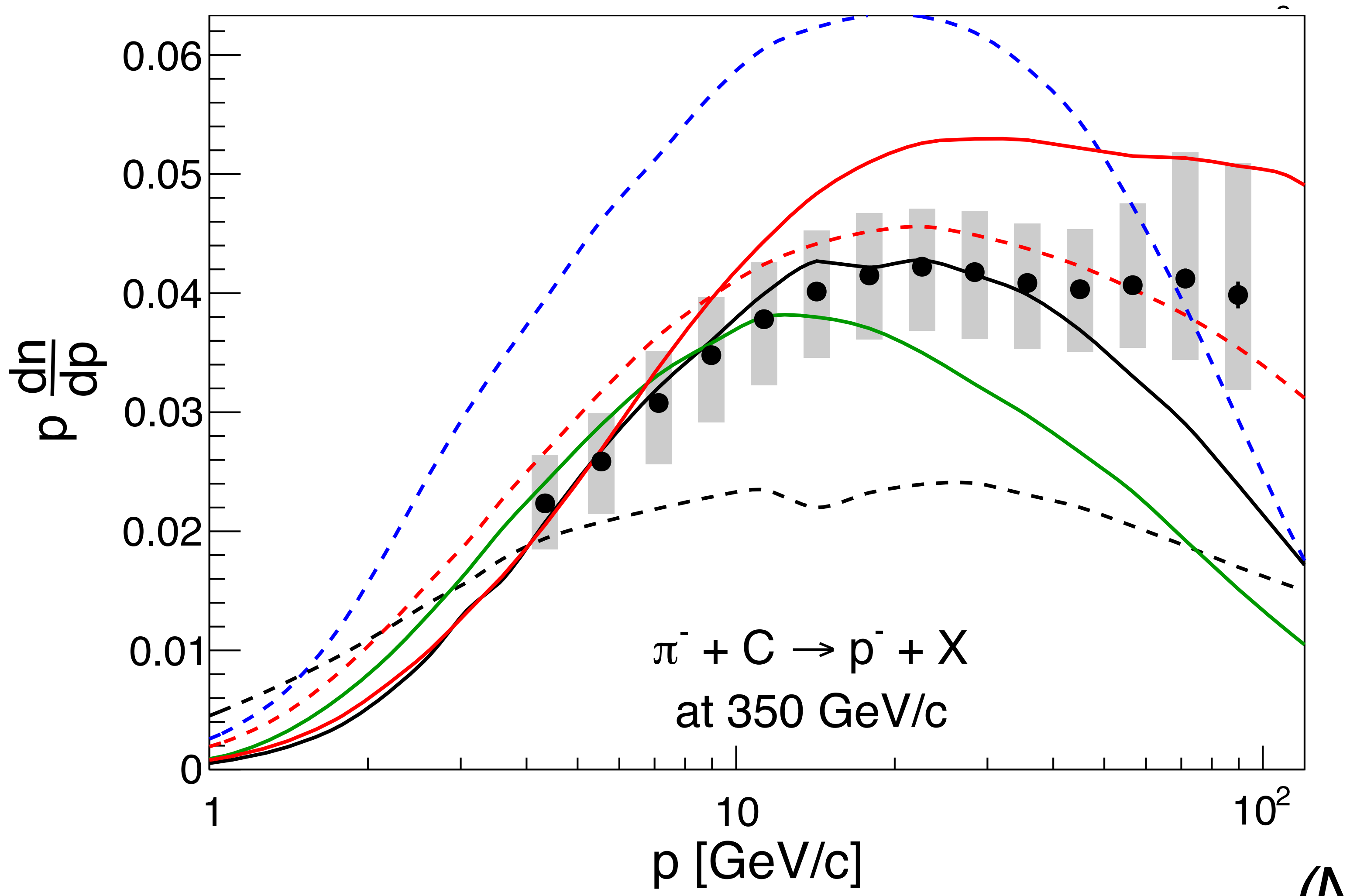
$$x_F = p_{\parallel} / p_{\max}$$

(Riehn et al., ICRC 2015)

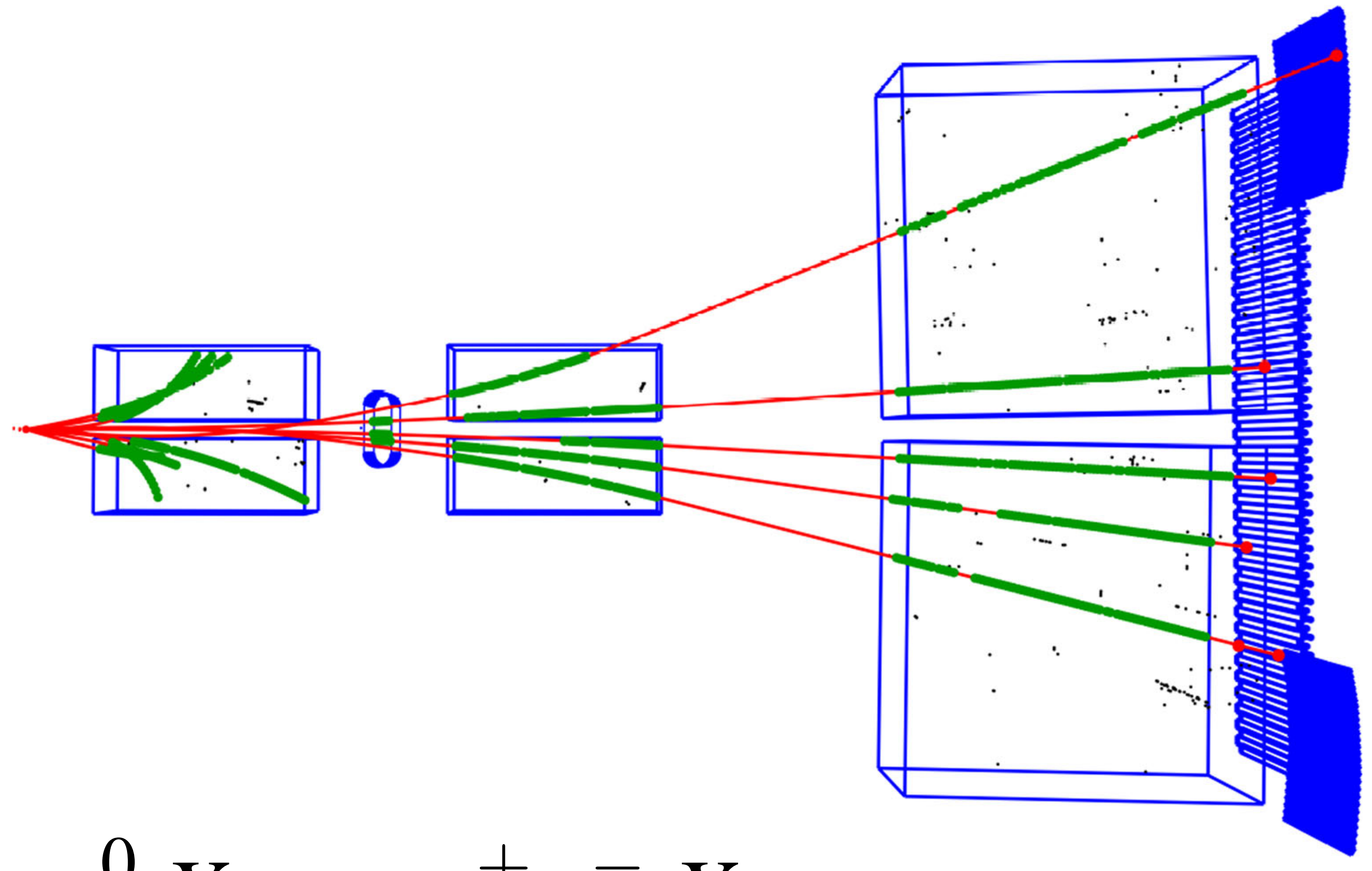
NA61 experiment at CERN SPS

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

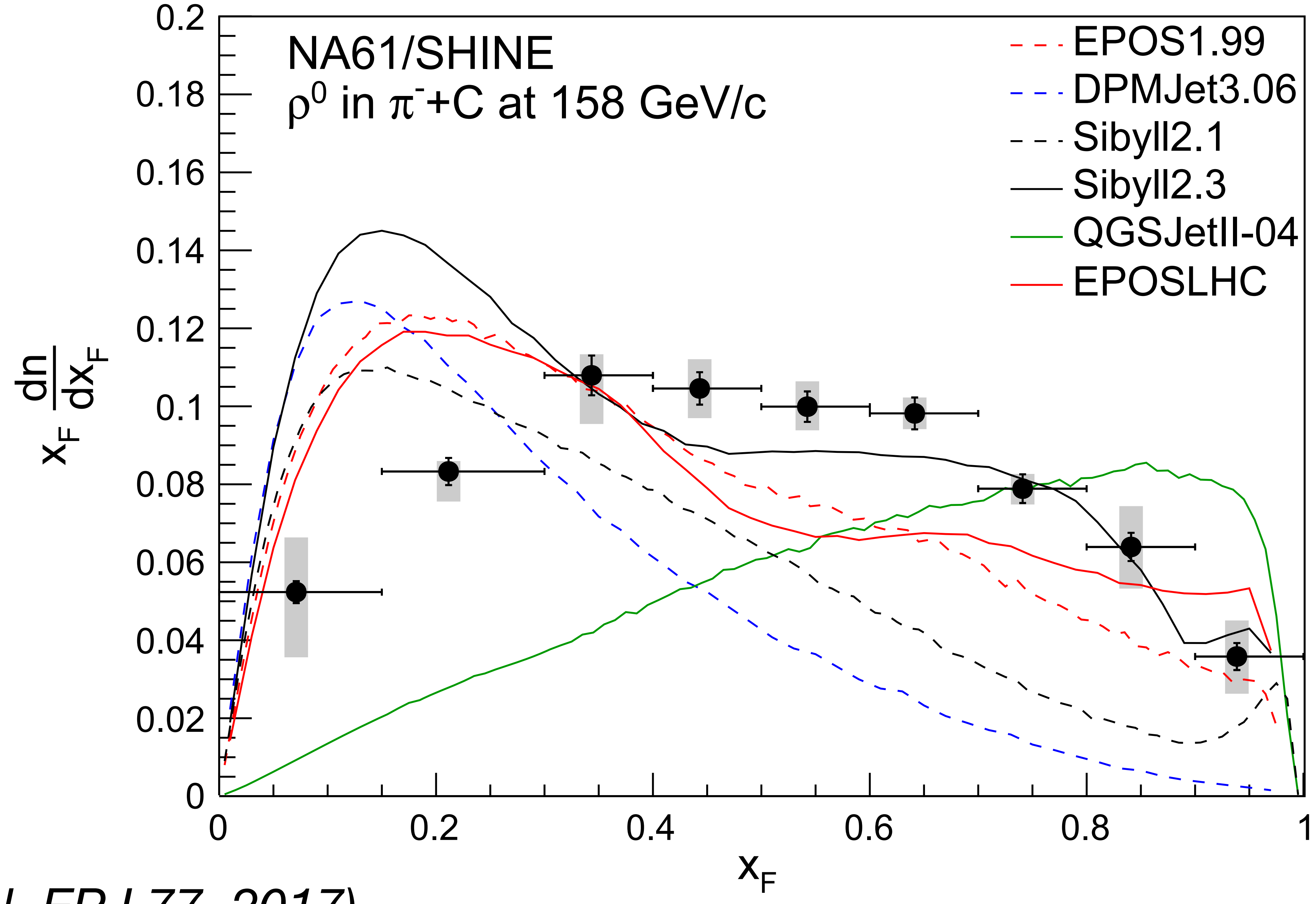




Dedicated cosmic ray runs
(π-C at 158 and 350 GeV)

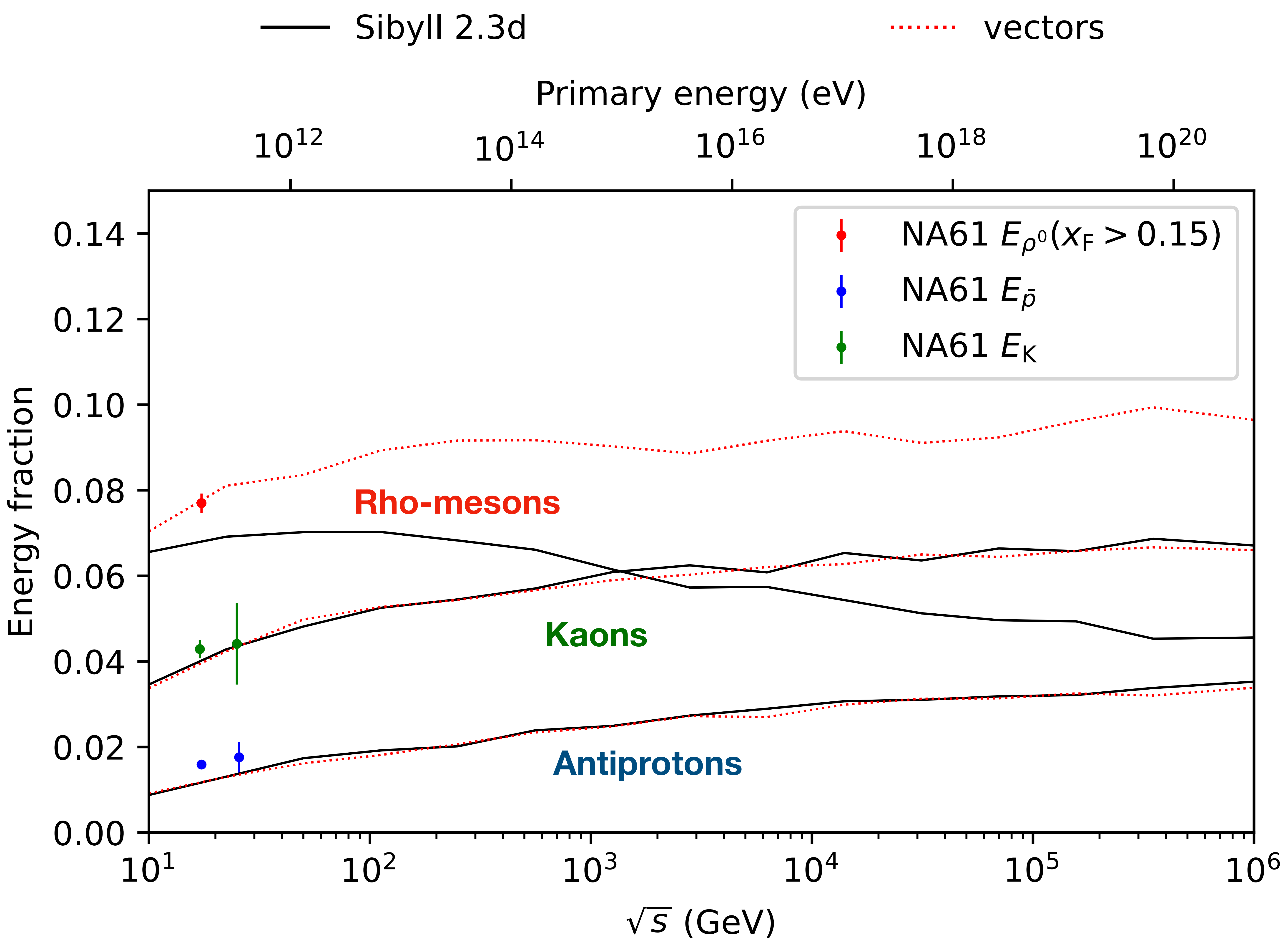


$\pi^- C \to \rho^0 X \to \pi^+\pi^- X$



(NA61, Unger, Herve, Prado, et al. EPJ 77, 2017)

Simple and pragmatic approach using Sibyll (i)

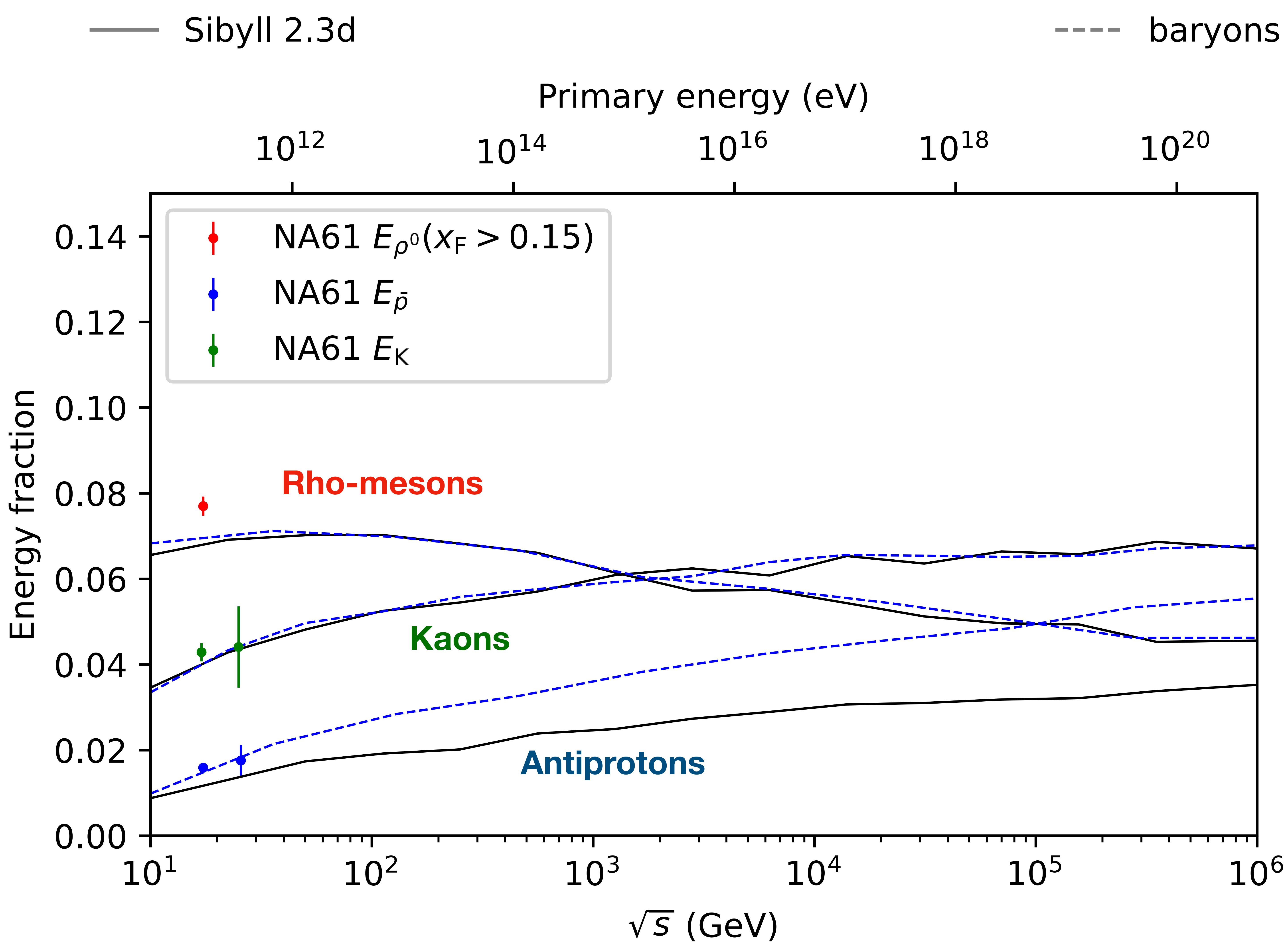


Modification of leading particle effect only for pion-air interactions

No change of p-air or nucleus-air

$$P_{\pi^0 \to \rho^0} = 0.6 \times (x_F)^{0.4}$$

Simple and pragmatic approach using Sibyll (ii-a)

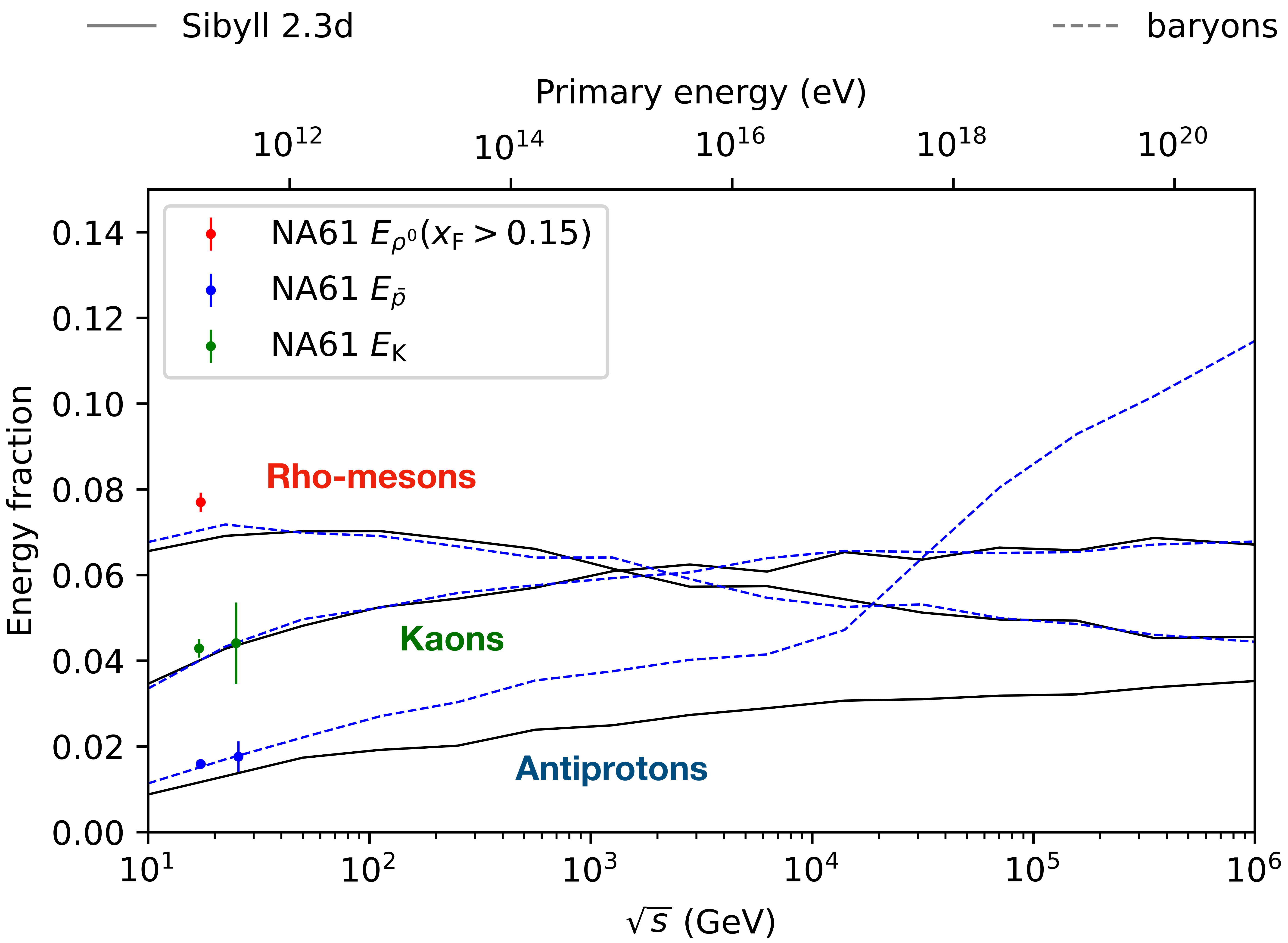


Baryon-pair production enhanced in all interactions (universality)

Only at large x_F, not visible at colliders (LHCf neutron data to be checked)

$$P_{\pi\pi \to p\bar{p}} = 0.5 \times (x_F)^{0.7}$$

Simple and pragmatic approach using Sibyll (ii-b)



Baryon-pair production enhanced in all interactions (universality)

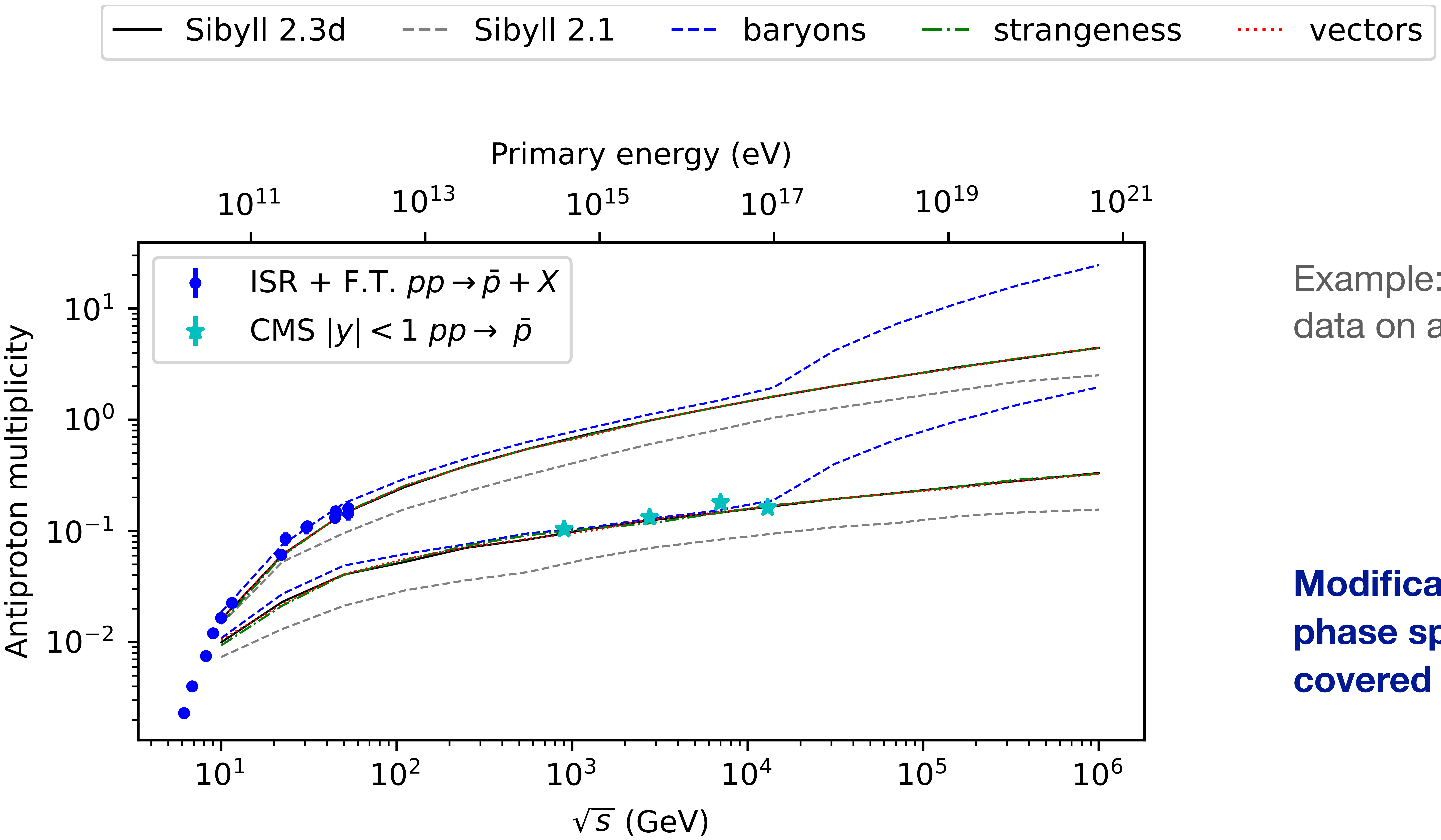
Only at large x_F, not visible at colliders (LHCf neutron data to be checked)

Pions of approx. same string used

$$P_{\pi\pi\to p\bar{p}} = 0.5 \times (x_F)^{0.7}$$

$$P_{\pi\pi\to p\bar{p}} = 0.25|_{E>E_{\rm LHC}}$$

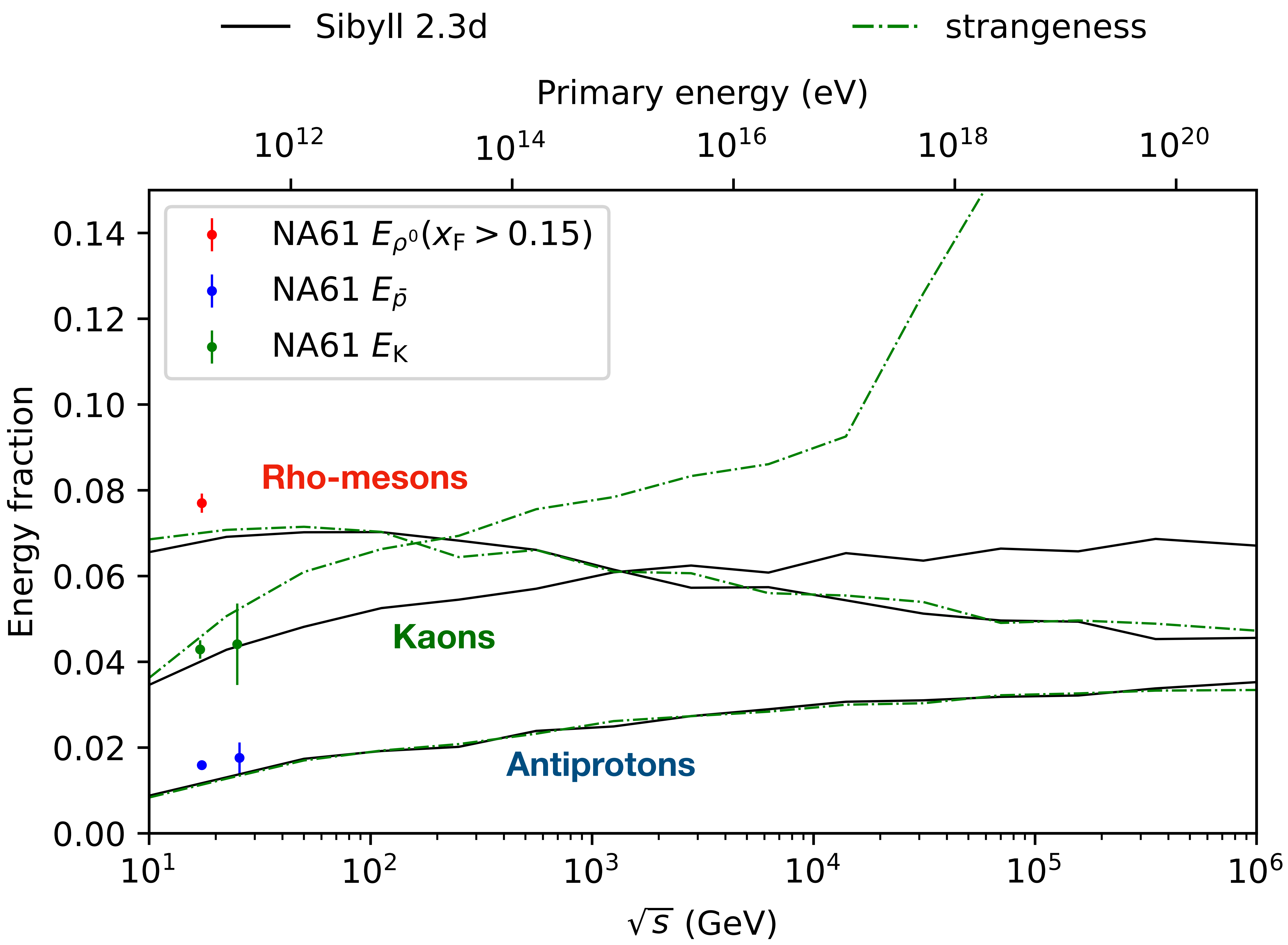
Simple and pragmatic approach using Sibyll (ii-b)



Example: comparison to collider data on antiproton production

Modification not visible in phase space / energy range covered by measurements

Simple and pragmatic approach using Sibyll (iii)



Kaon-pair production enhanced in all interactions (universality)

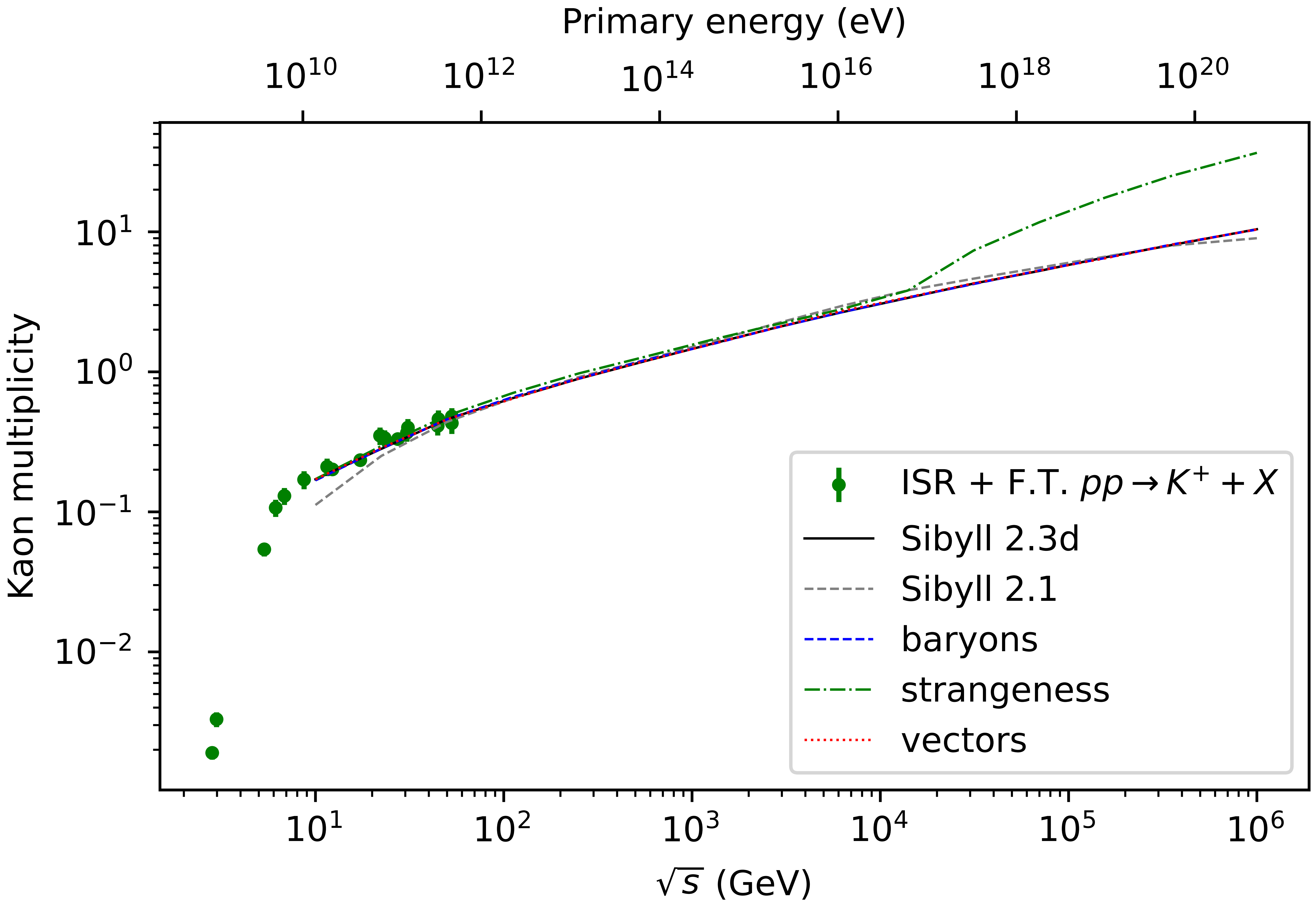
Only at large x_F, not visible at colliders

Pions of approx. same string used

$$P_{\pi\pi \to KK} = 0.5 \times (x_F)^{0.8}$$

$$P_{\pi\pi \to KK} = 0.3|_{E > E_{LHC}}$$

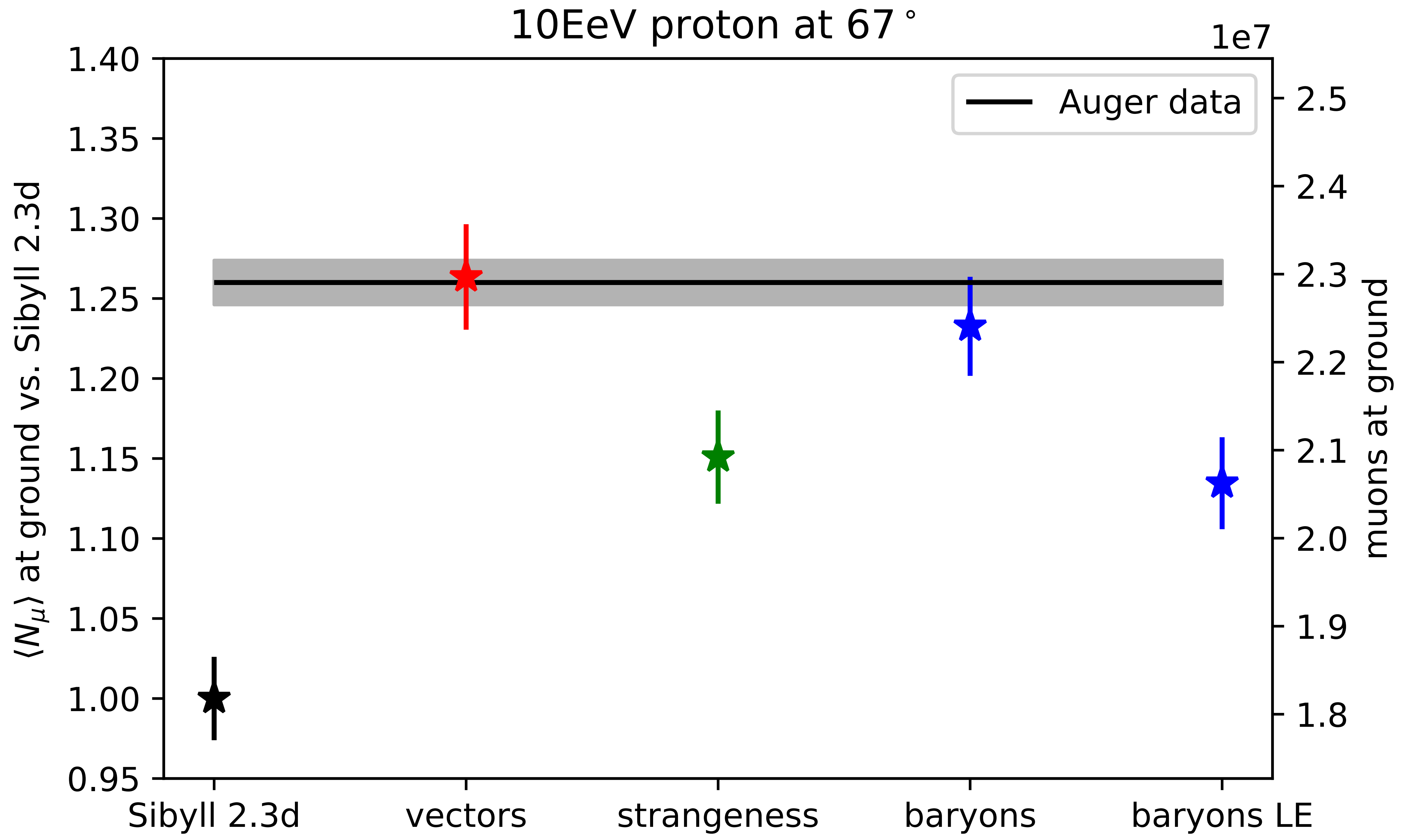
Simple and pragmatic approach using Sibyll (iii)

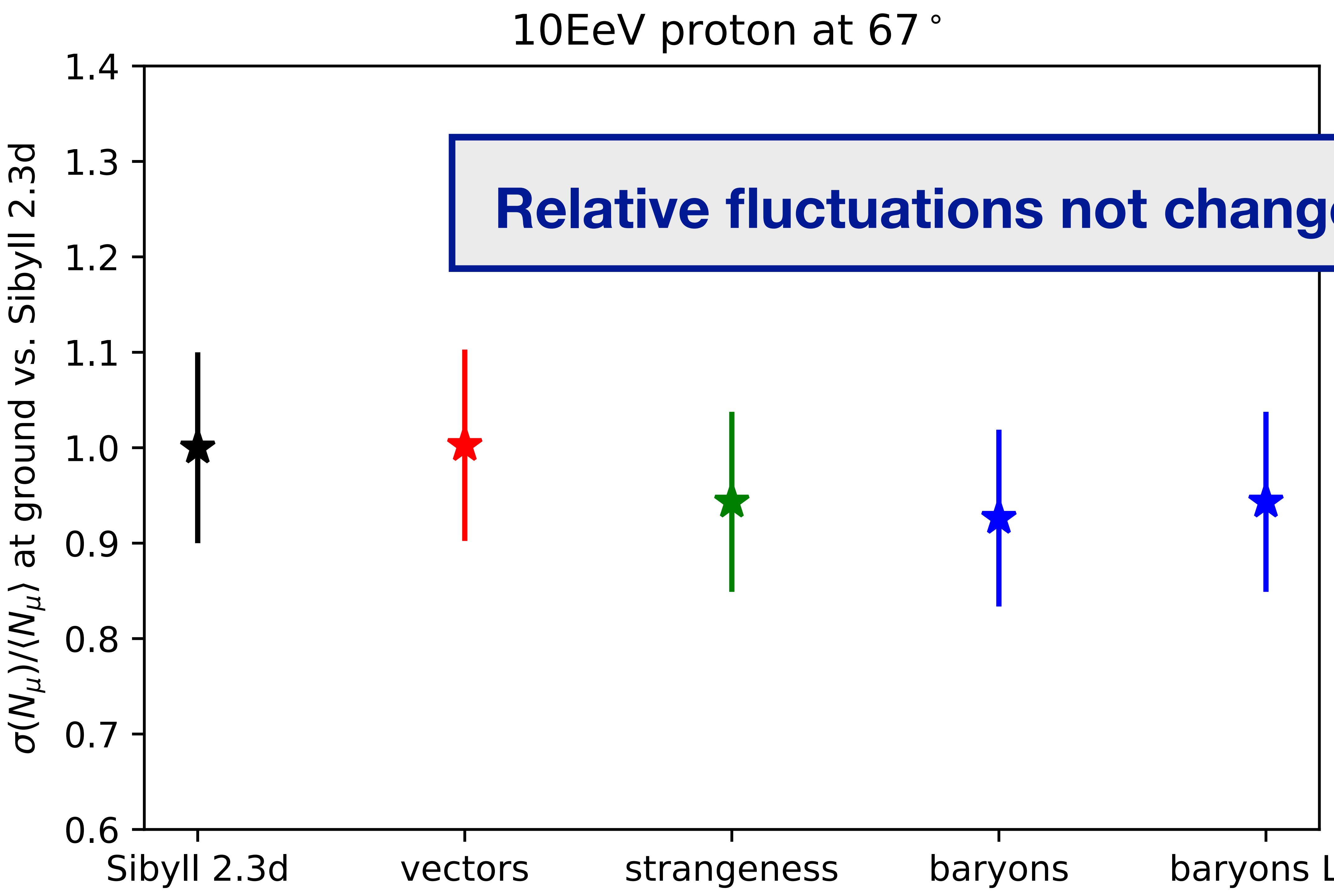


Example: comparison to collider data on kaon production

Modification not visible in phase space / energy range covered by measurements

Muon number in inclined showers (Auger)





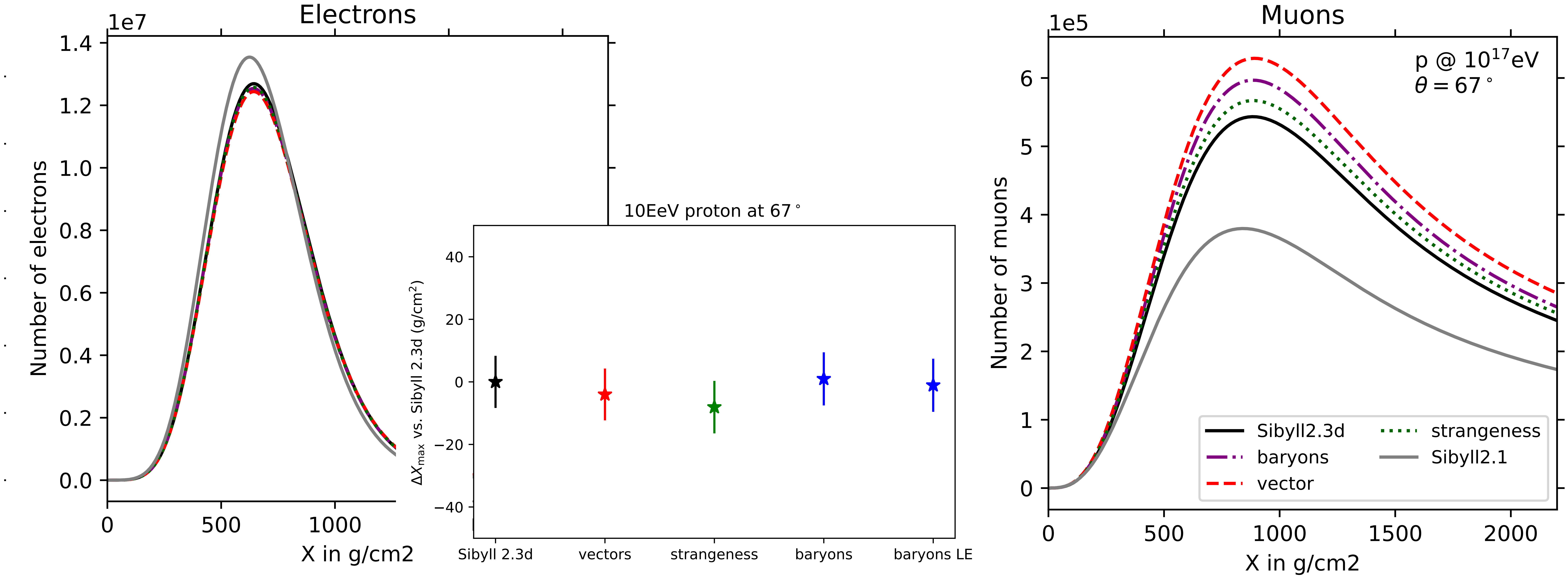
Relative fluctuations not changed

Rho-meson production can be easily modified to produce desired muon number

Only extreme scenario of baryon-pair-production efficient enough to match data

Kaon scenario alone not suited to describe Auger data

Depth of maximum of em. particles and muon production

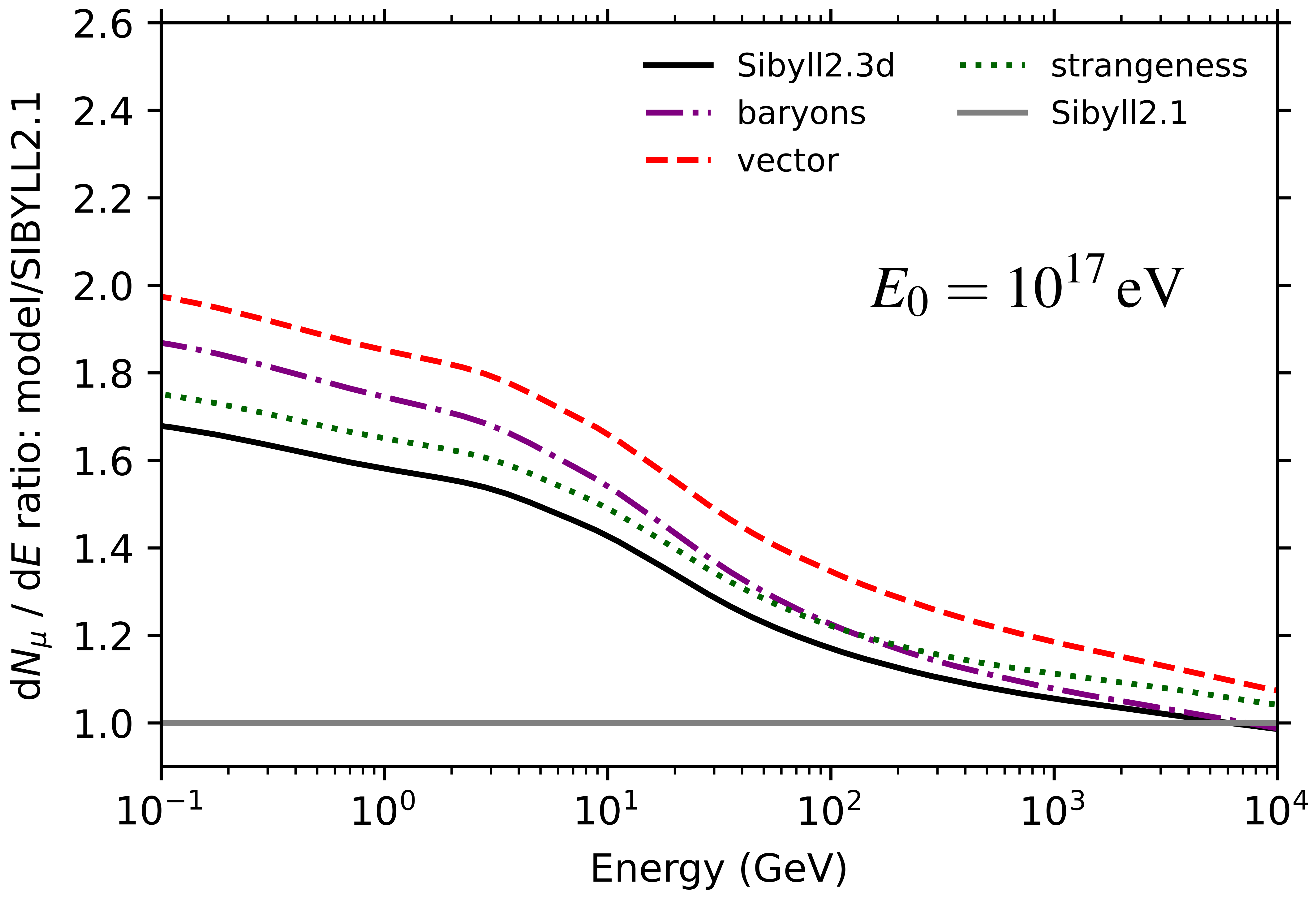


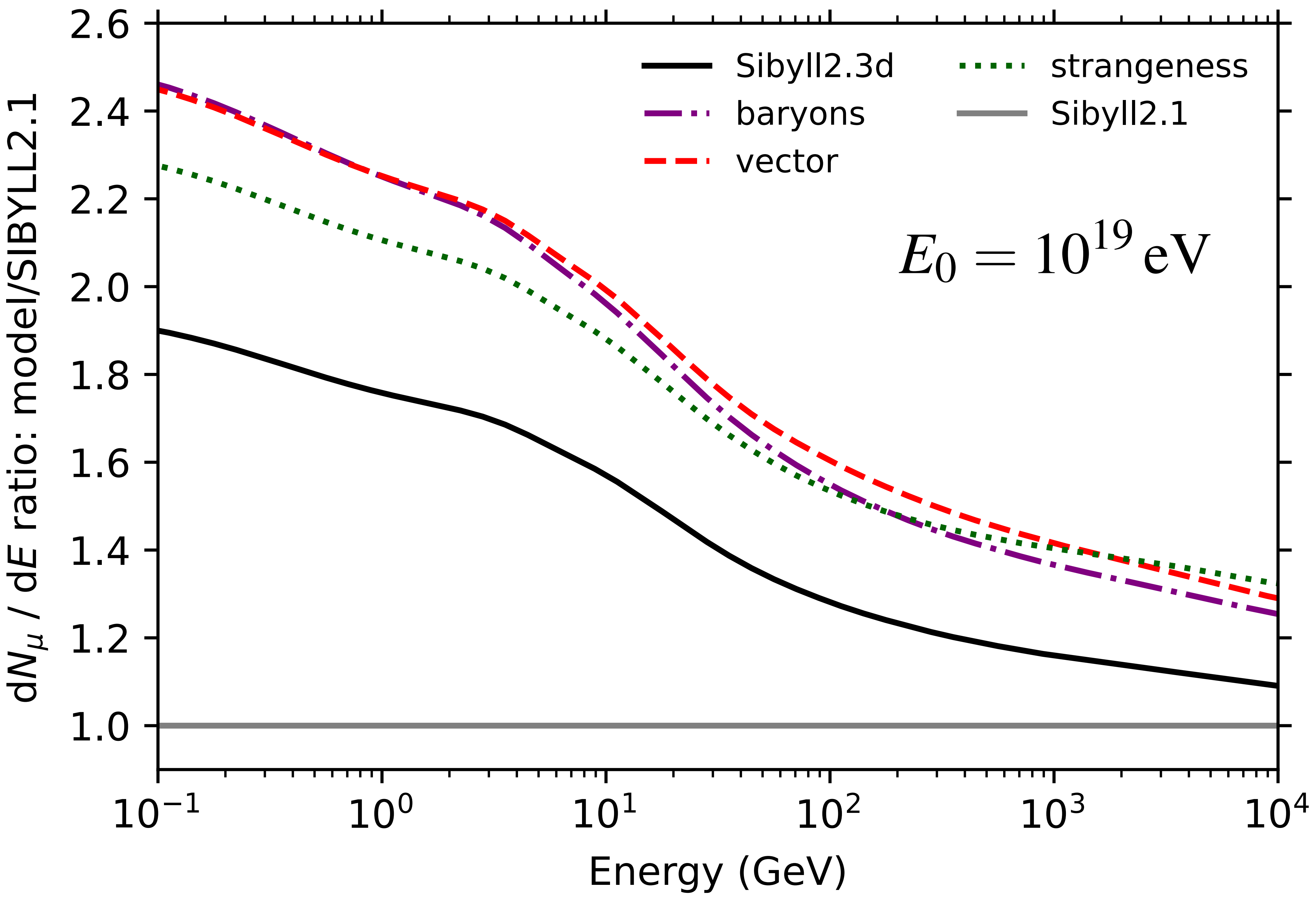
Maximum of em. particles not significantly changed (~5 g/cm²)

Maximum of muon production depth very similar to default model

Muon energy spectrum in air showers

Muon energy spectrum relative to Sibyll 2.1 prediction

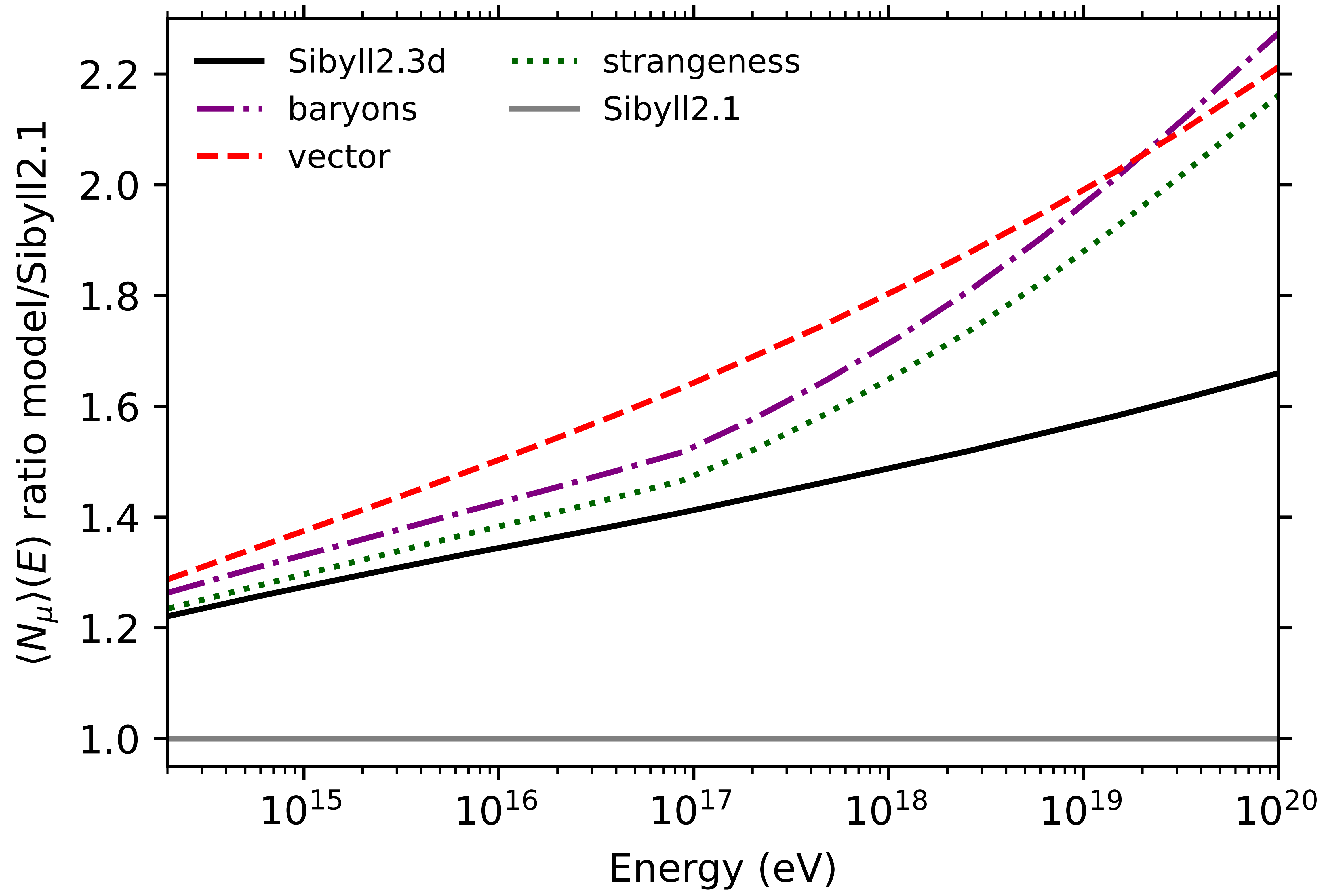




Muon energy spectrum sensitive to enhancement model

Extreme high-energy enhancement for baryon pairs similar to rho-meson scenario

Conclusion



- Model versions for individual scenarios
- Optimization of parameters possible
- Scenarios for tests and full-scale simulations

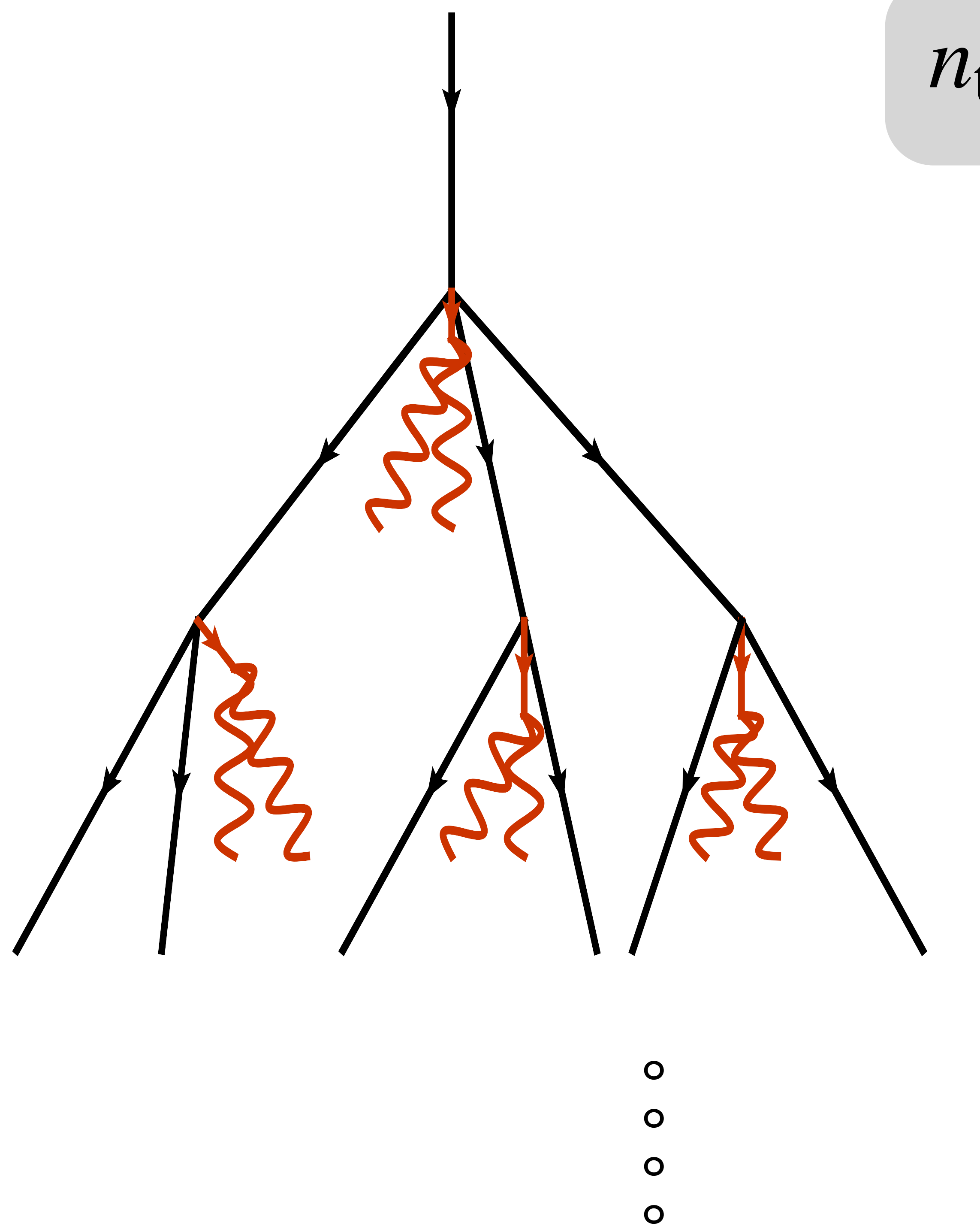
- Change of Xmax was not aim of this work

- Inclusive atm. lepton fluxes under investigation

Does any of these models provide a consistent description of SD data for hybrid events (risetime, DNN Xmax, etc.) or is an additional shift of Xmax or other physics needed?

Backup slides

Qualitative approach: Heitler-Matthews model



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

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

Primary particle proton

π^0 decay immediately

$\pi^{\pm}$ initiate new hadronic cascades

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

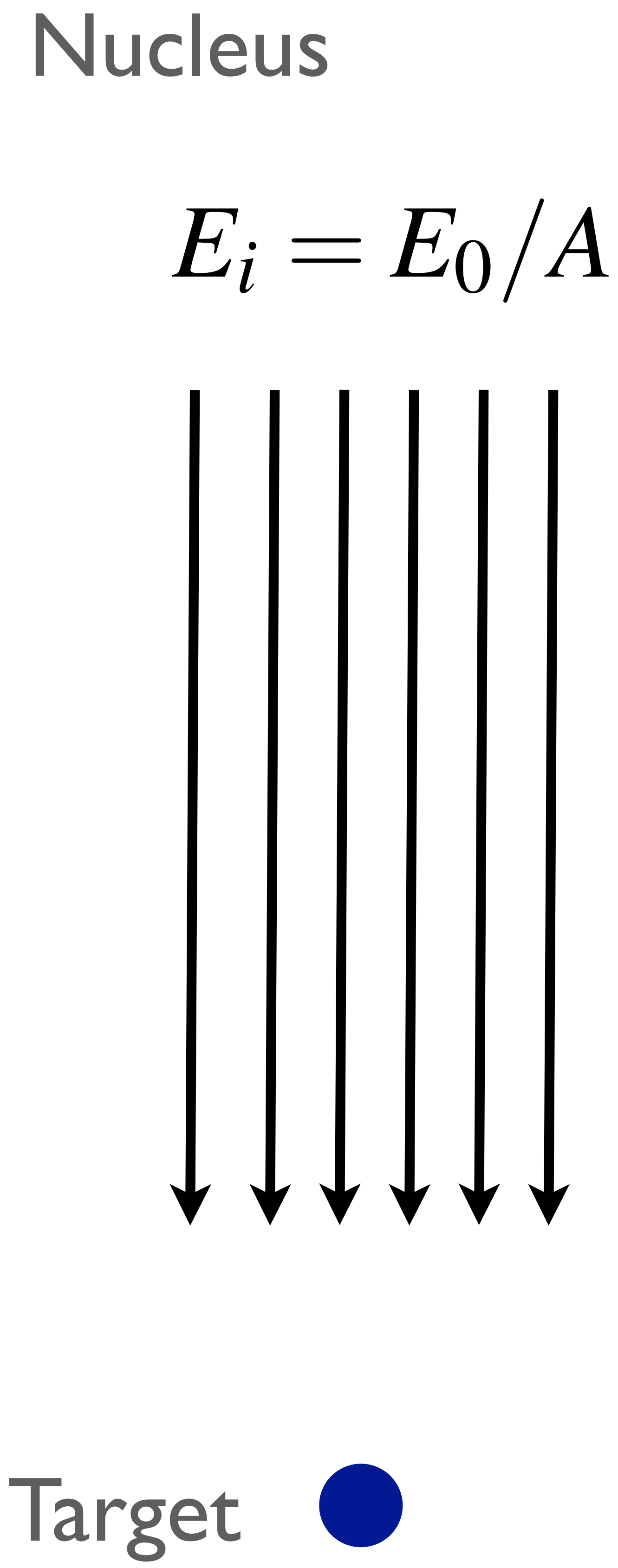
$$\alpha = \frac{\ln n_{ch}}{\ln n_{tot}} \approx 0.85 \ldots 0.95$$

Assumptions:

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

(Matthews, Astropart.Phys. 22, 2005)

Muon number and superposition model



Proton-induced shower

$$N_\mu = \left(\frac{E_0}{E_{\text{dec}}}\right)^{\alpha} \qquad \alpha \approx 0.9$$

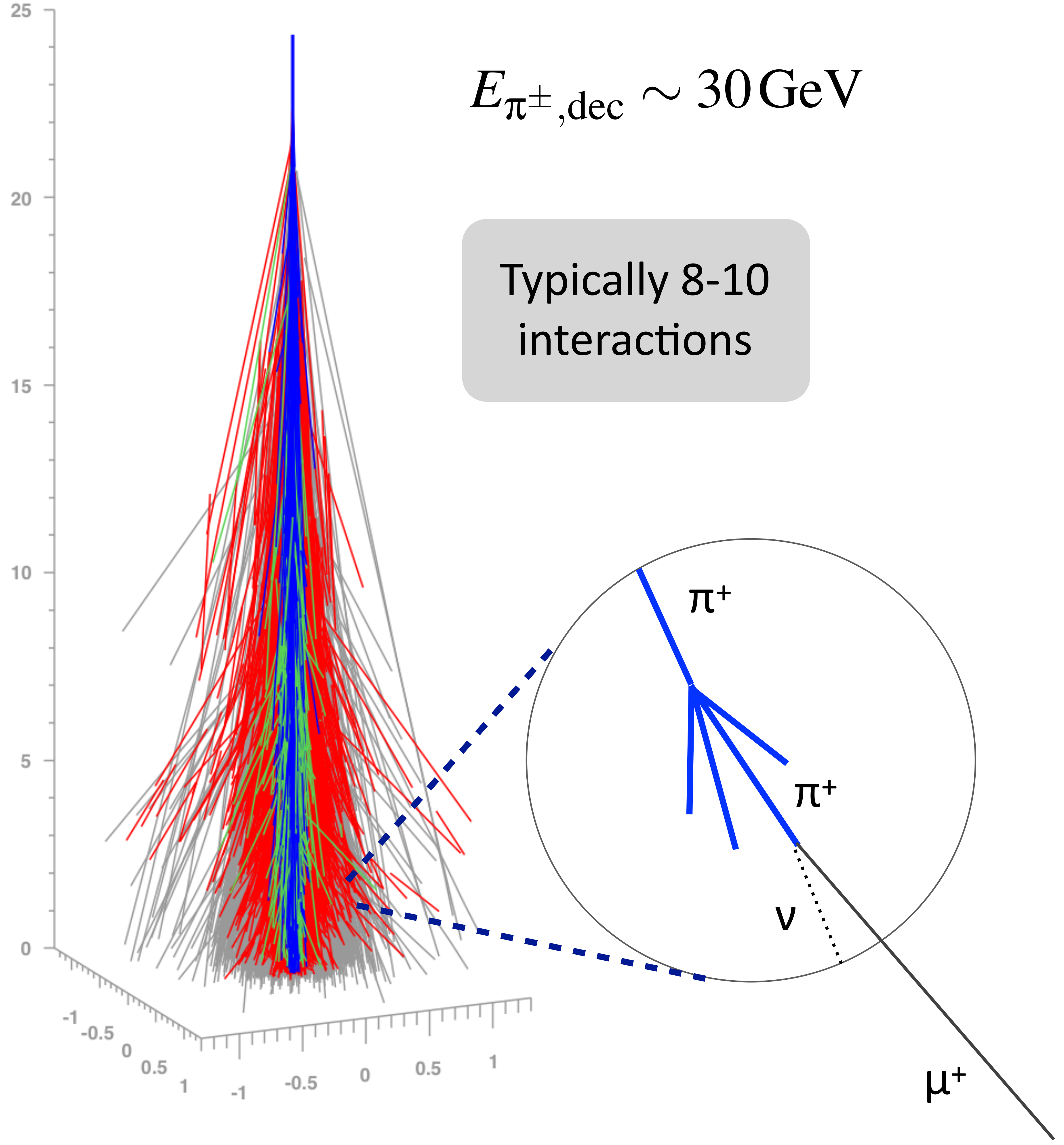
Assumption: nucleus of mass *A* and energy E_0 corresponds to *A* nucleons (protons) of energy $E_n = E_0/A$

$$N_{\text{max}}^A \sim A\left(\frac{E_0}{AE_c}\right) = N_{\text{max}}$$

$$N_\mu^A = A\left(\frac{E_0}{AE_{\text{dec}}}\right)^{\alpha} = A^{1-\alpha} N_\mu$$

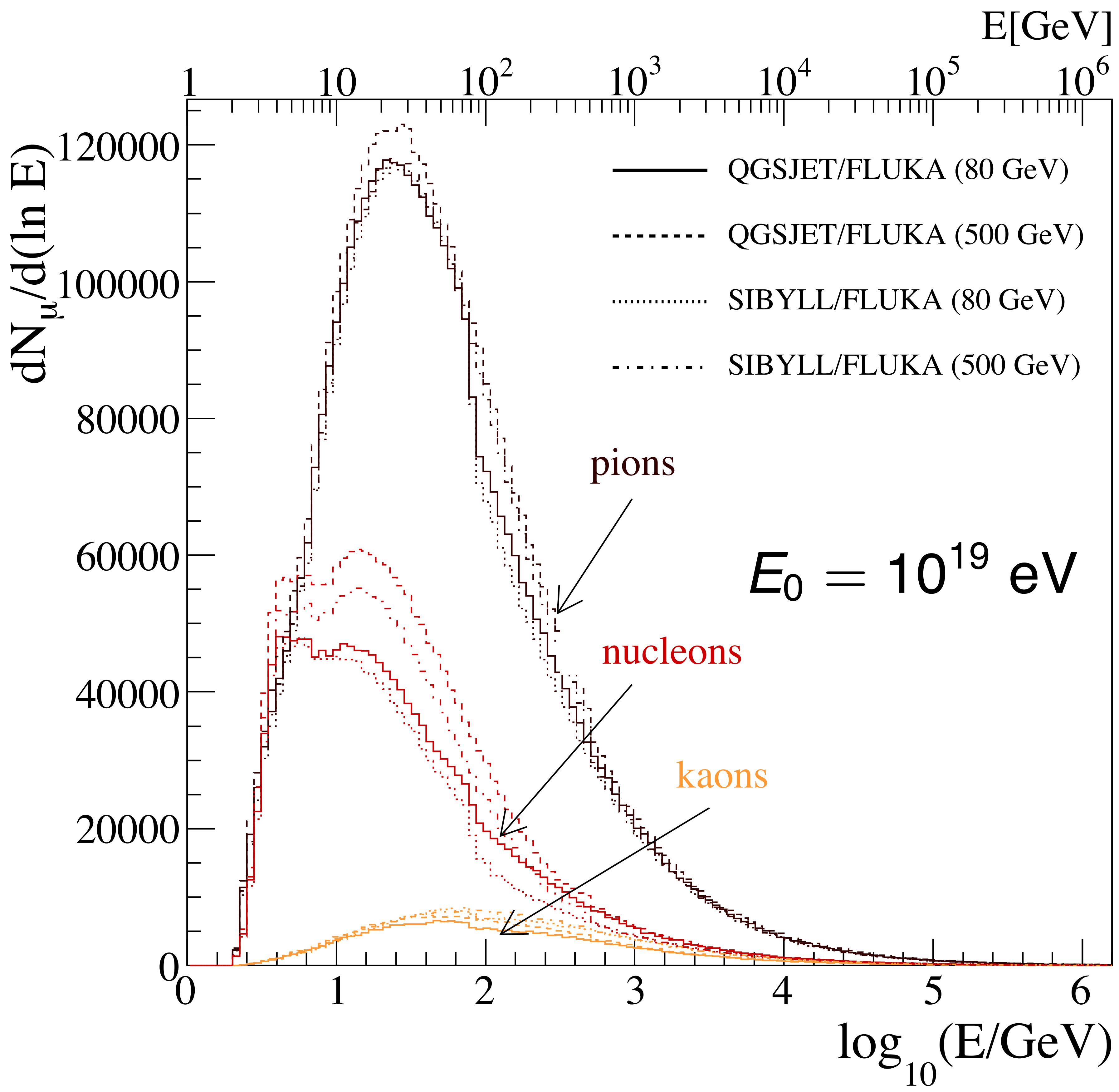
The larger alpha the smaller the difference between p … Fe

Muon production at large lateral distance



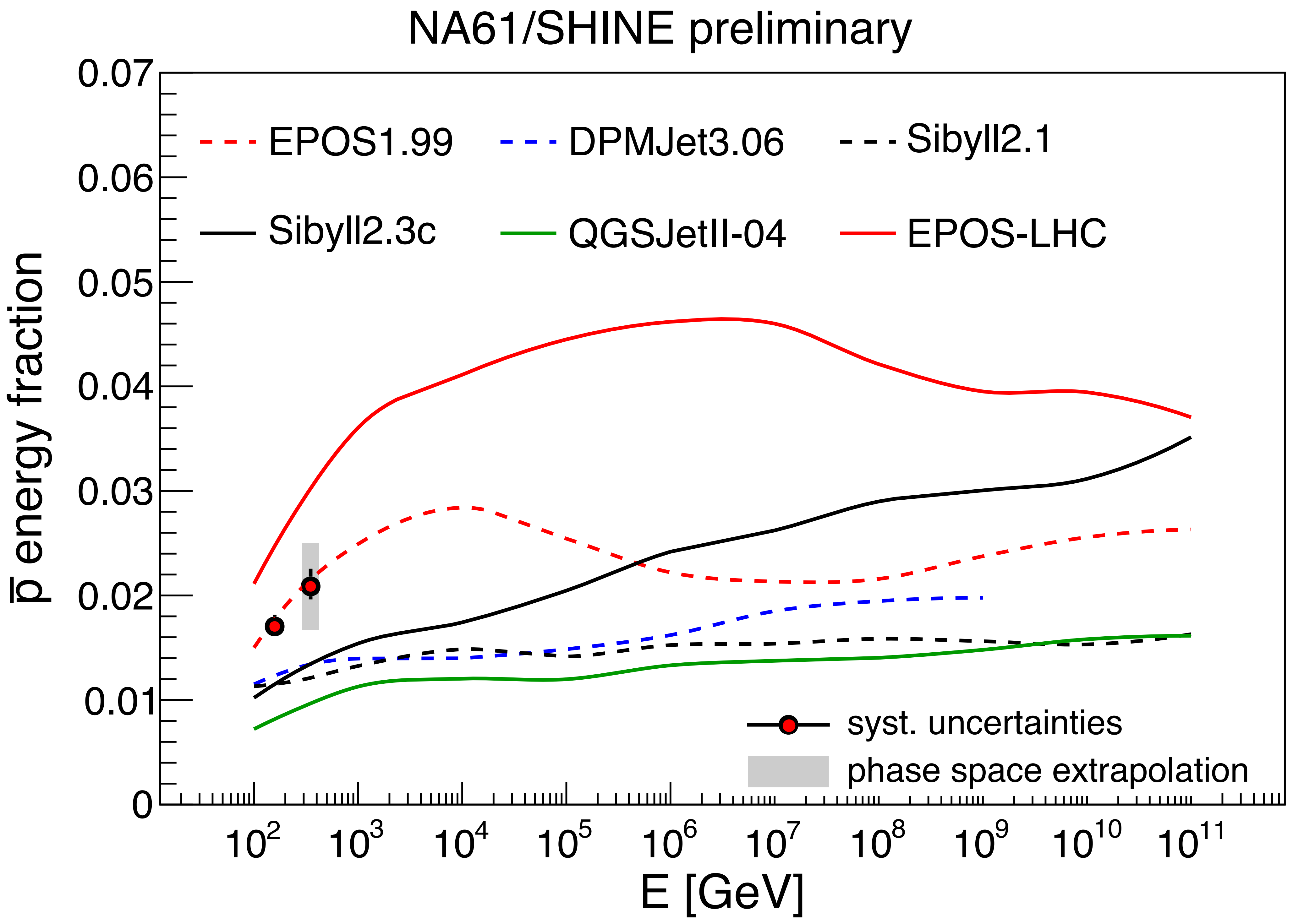
Muon observed at 1000 m from core

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

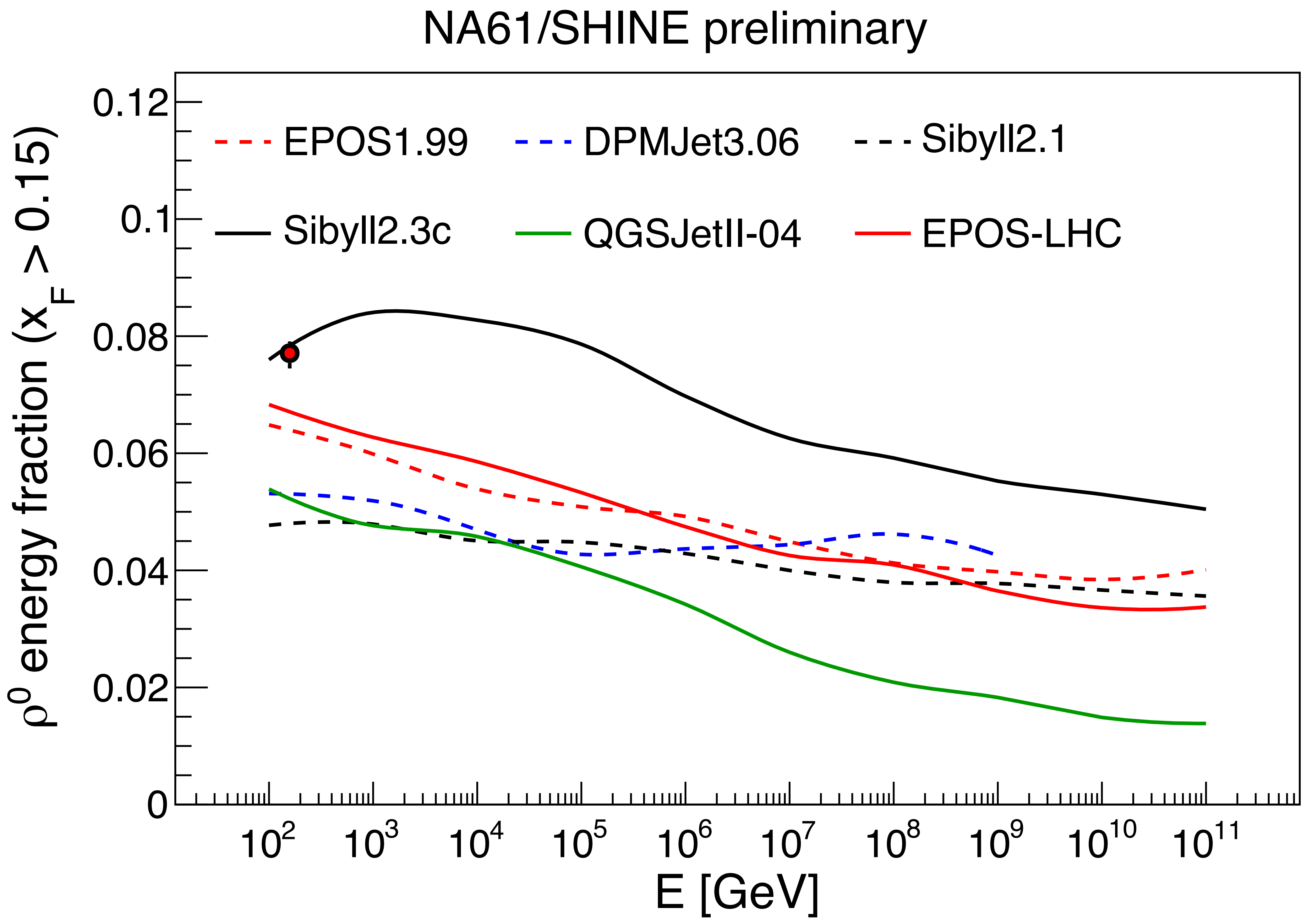


(Maris et al. ICRC 2009)

NA61 results and extrapolation to high energy



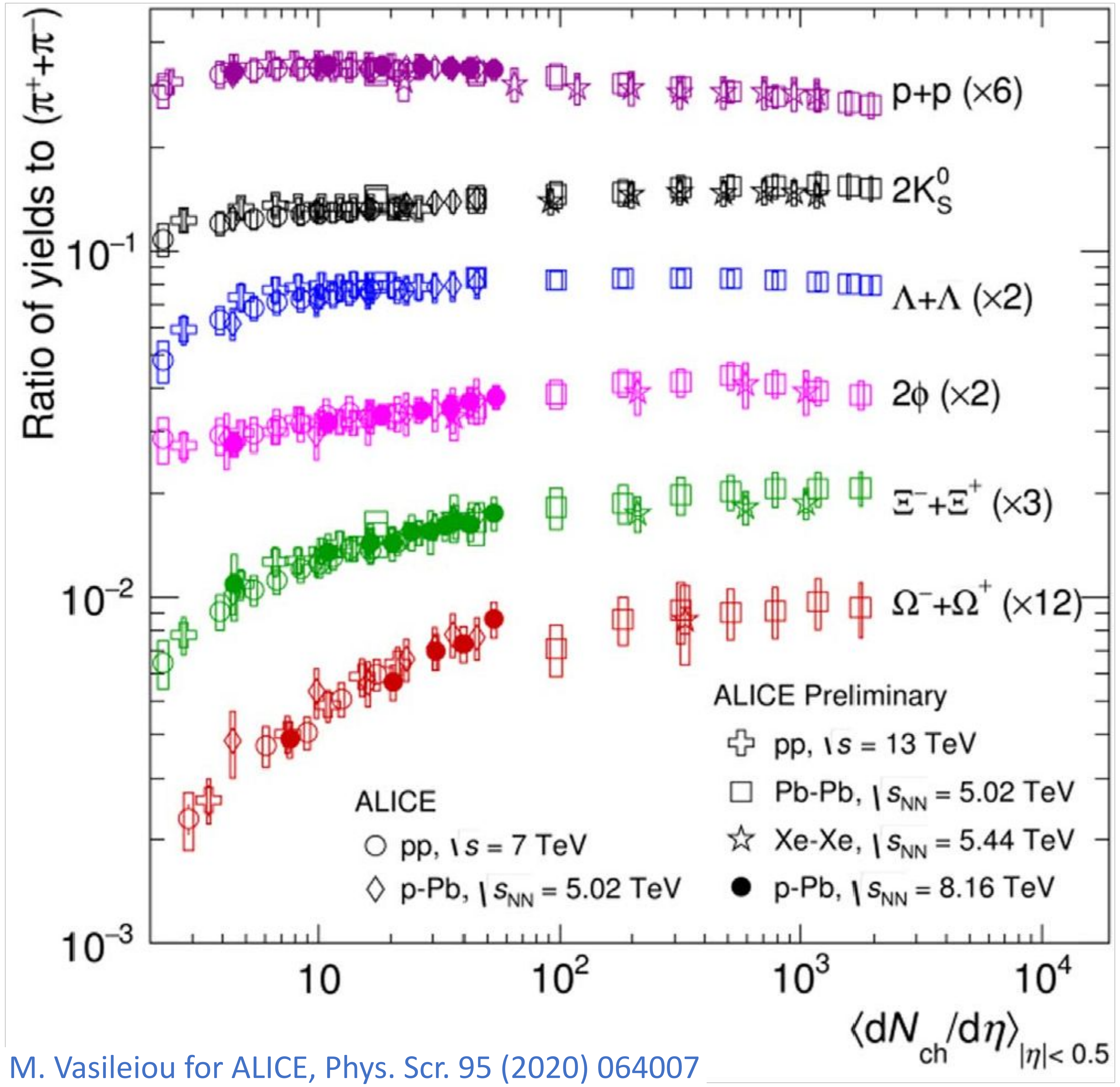
$\bar{p}$ energy fraction in π^-+C



ρ^0 energy fraction in π^-+C

(Prado, NA61, ICRC 2017)

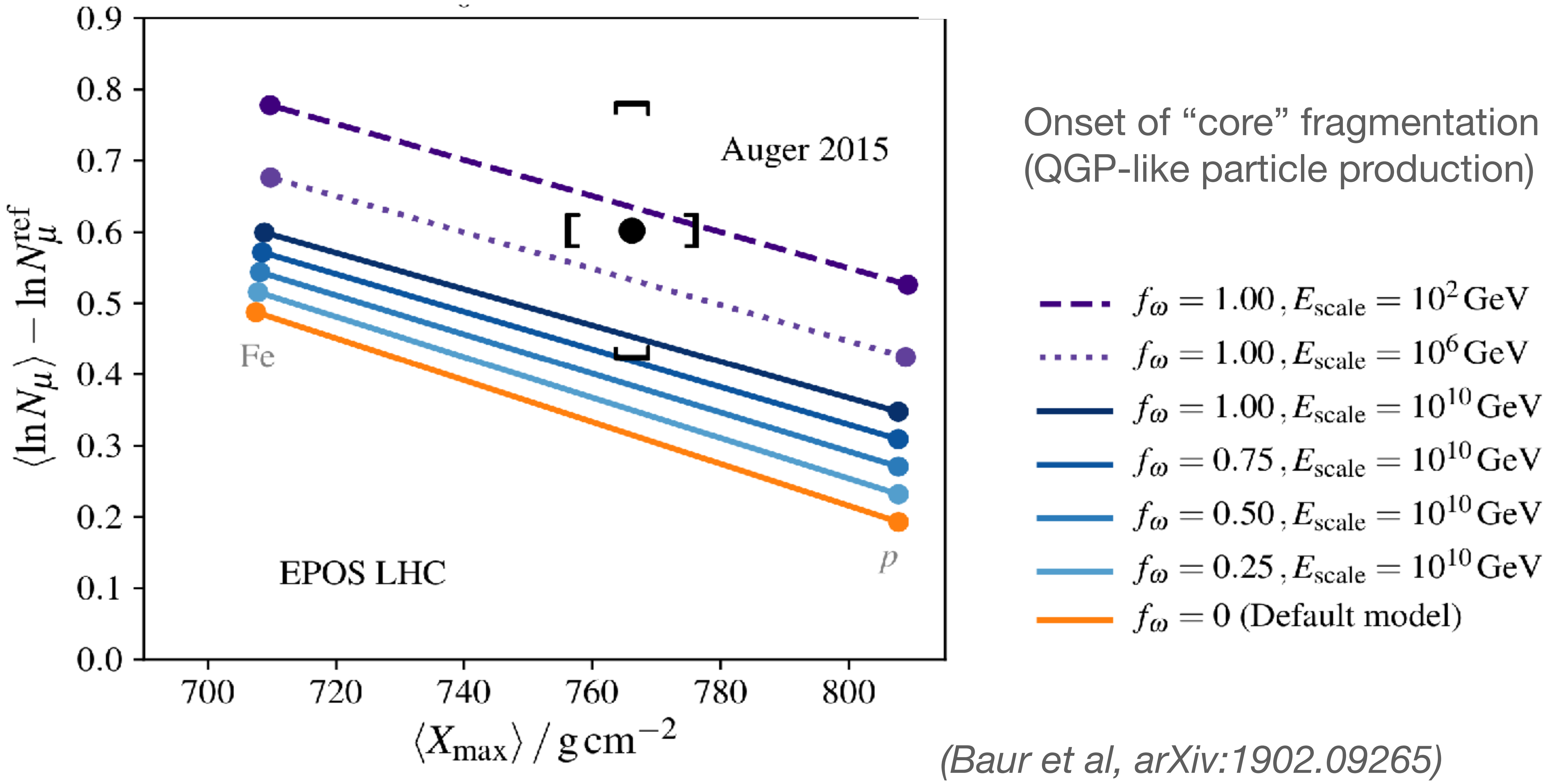
Universal particle scaling and core-corona model in EPOS



M. Vasileiou for ALICE, Phys. Scr. 95 (2020) 064007

ALICE: observation of **universal scaling of enhancement of heavy particles** with particle multiplicity or density *(Nature Phys. 13 (217) 535)*

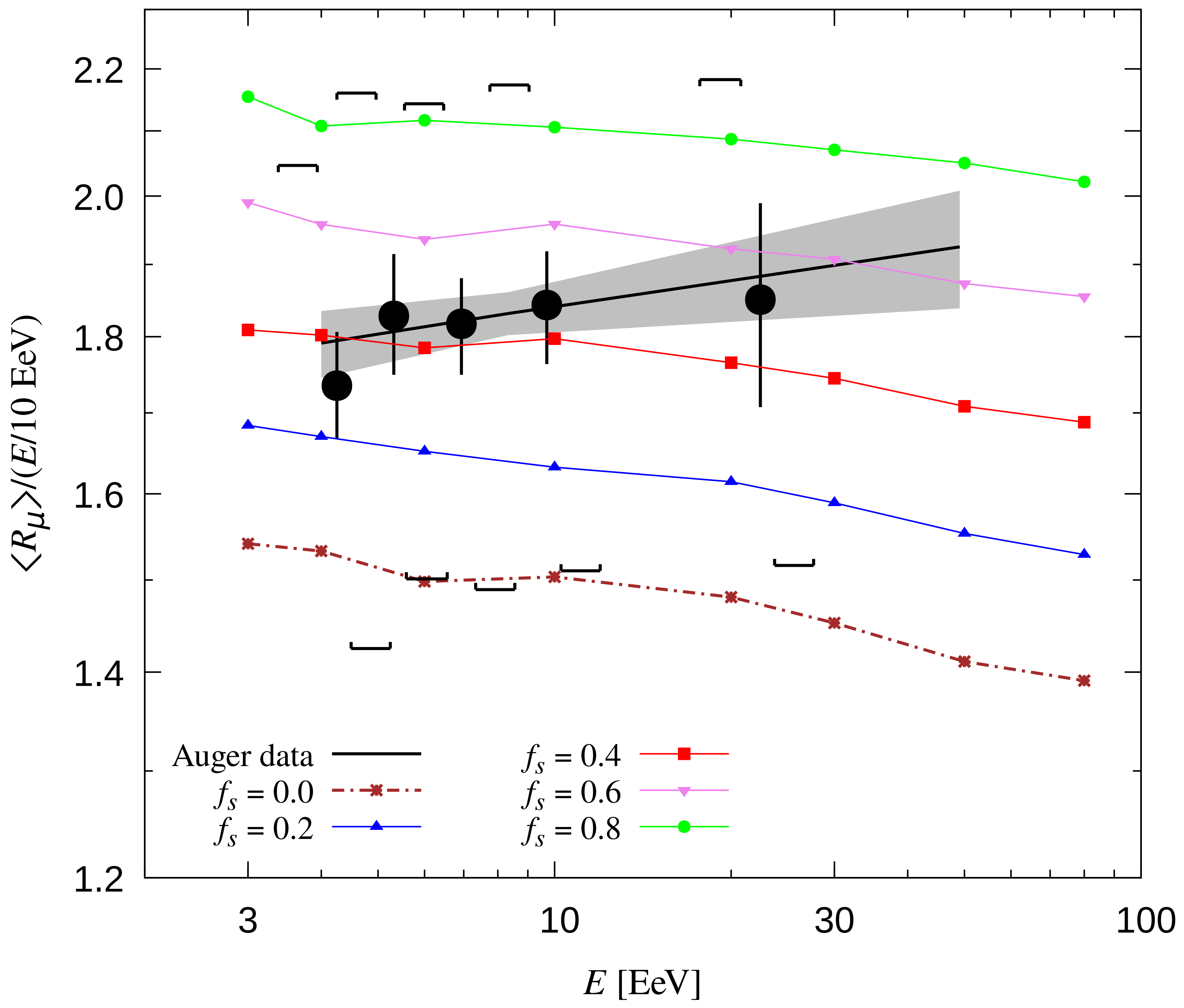
Does the same/similar scaling apply also in forward direction?



Onset of "core" fragmentation (QGP-like particle production)

(Baur et al, arXiv:1902.09265)

Phenomenological kaon enhancement model



(Anchordoqui et al. arXiv:2202.03095)

Probability f_s to change particles

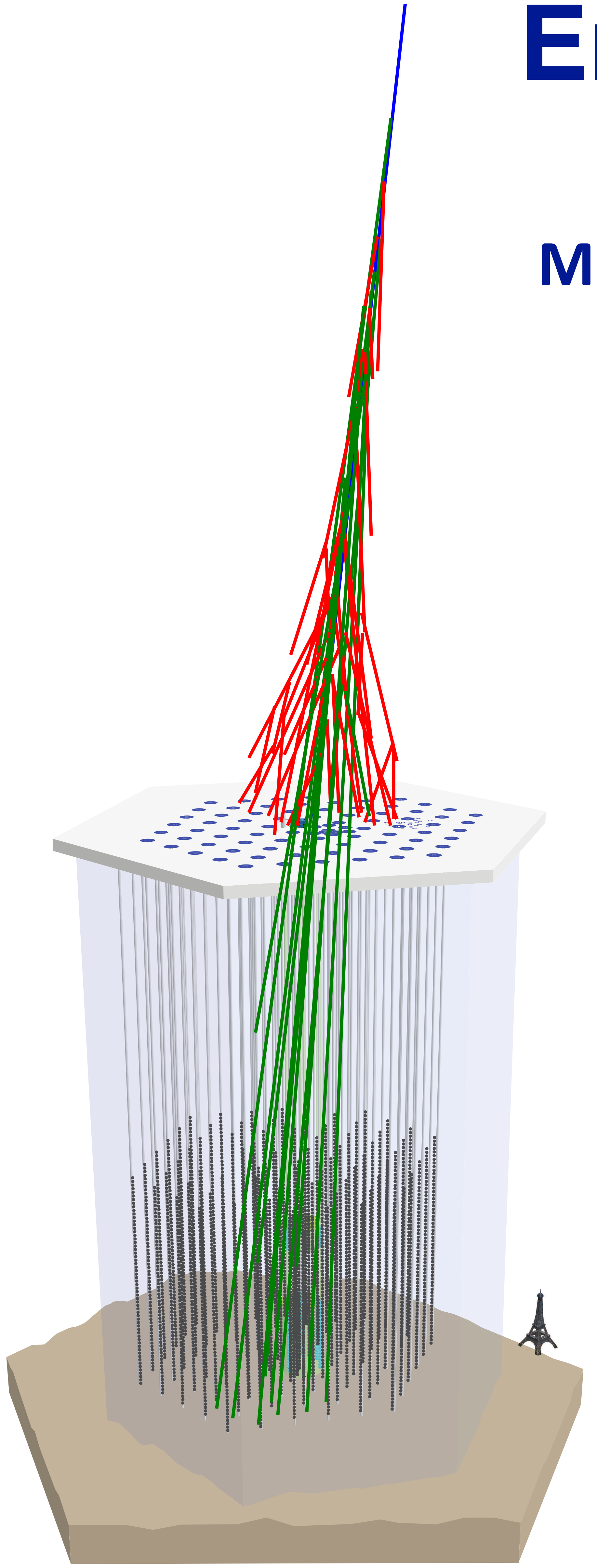
$$\pi^0 \longrightarrow K_S^0/K_L^0$$

$$\pi^\pm \longrightarrow K^\pm$$

TABLE II: Global counters for the refined model with $f_s = 0.7$, in the case of 10^{19} eV proton showers inclined 67°.

Total hadronic collisions per shower	264,600	100.00 %
Collisions with $E_{\text{proj}} < E_{\text{pmin}}$	262,070	99.04 %
Collisions with $E_{\text{proj}} > E_{\text{pmin}}$	2,530	0.96 %
Total number of secs. produced	6,806,244	100.00 %
Secs. from colls. with $E_{\text{proj}} < E_{\text{pmin}}$	6,544,194	96.15 %
Secs. from colls. with $E_{\text{proj}} > E_{\text{pmin}}$	262,050	3.85 %
Total number of pions scanned	134,060	1.97 %
Pions considered for swapping:		
Central ($\lvert\eta_{\text{CM}}\rvert < 4$)	99,790	1.47 %
Peripheral ($\lvert\eta_{\text{CM}}\rvert > 4$)	34,270	0.50 %
Total (central + peripheral)	134,060	1.97 %
Pions actually swapped	23,988	0.35 %

Energy spectrum of muons in air showers

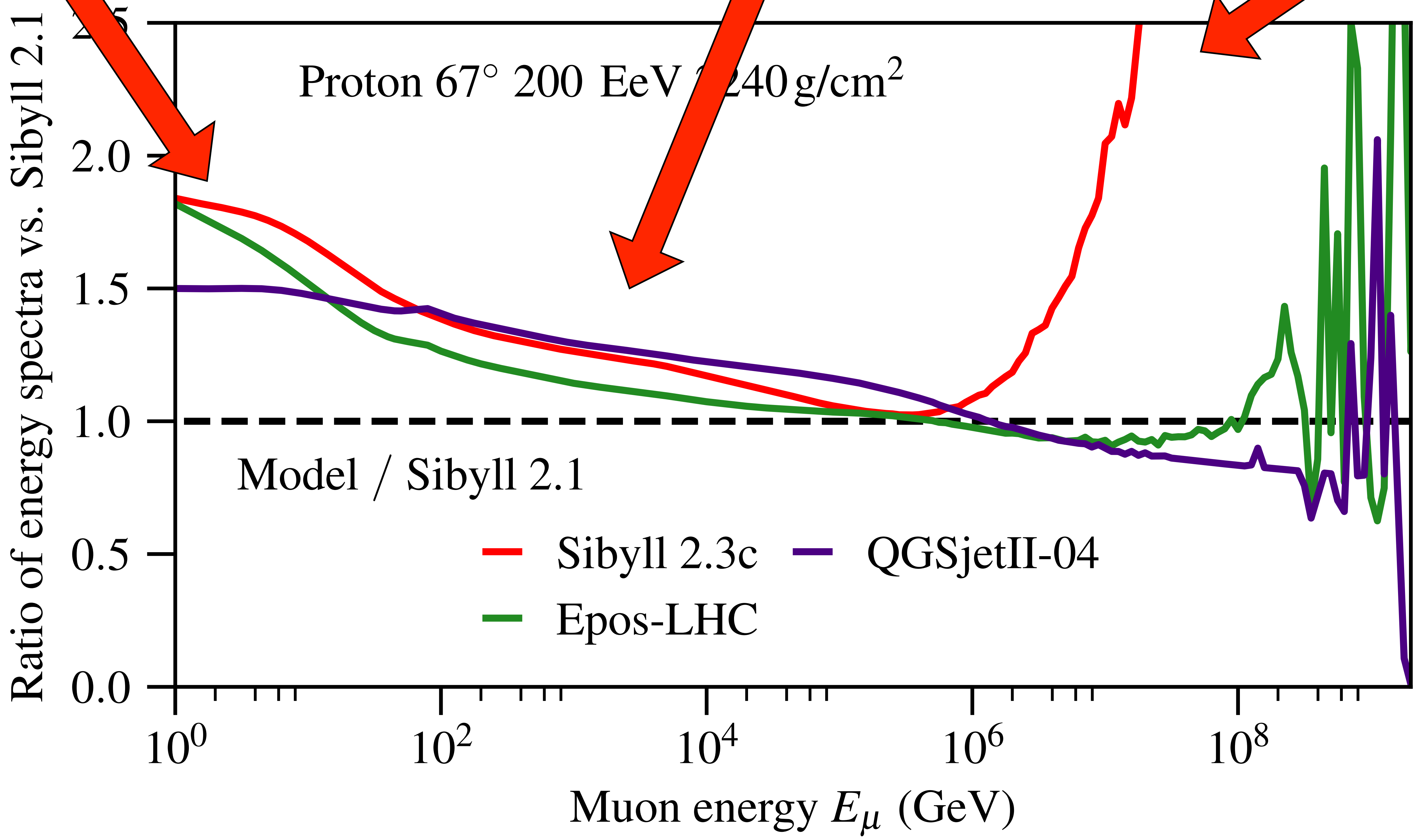


Muon energy spectrum in EAS relative to that of Sibyll 2.1

Low-energy enhancement due to baryon pair production

Rho-0 production

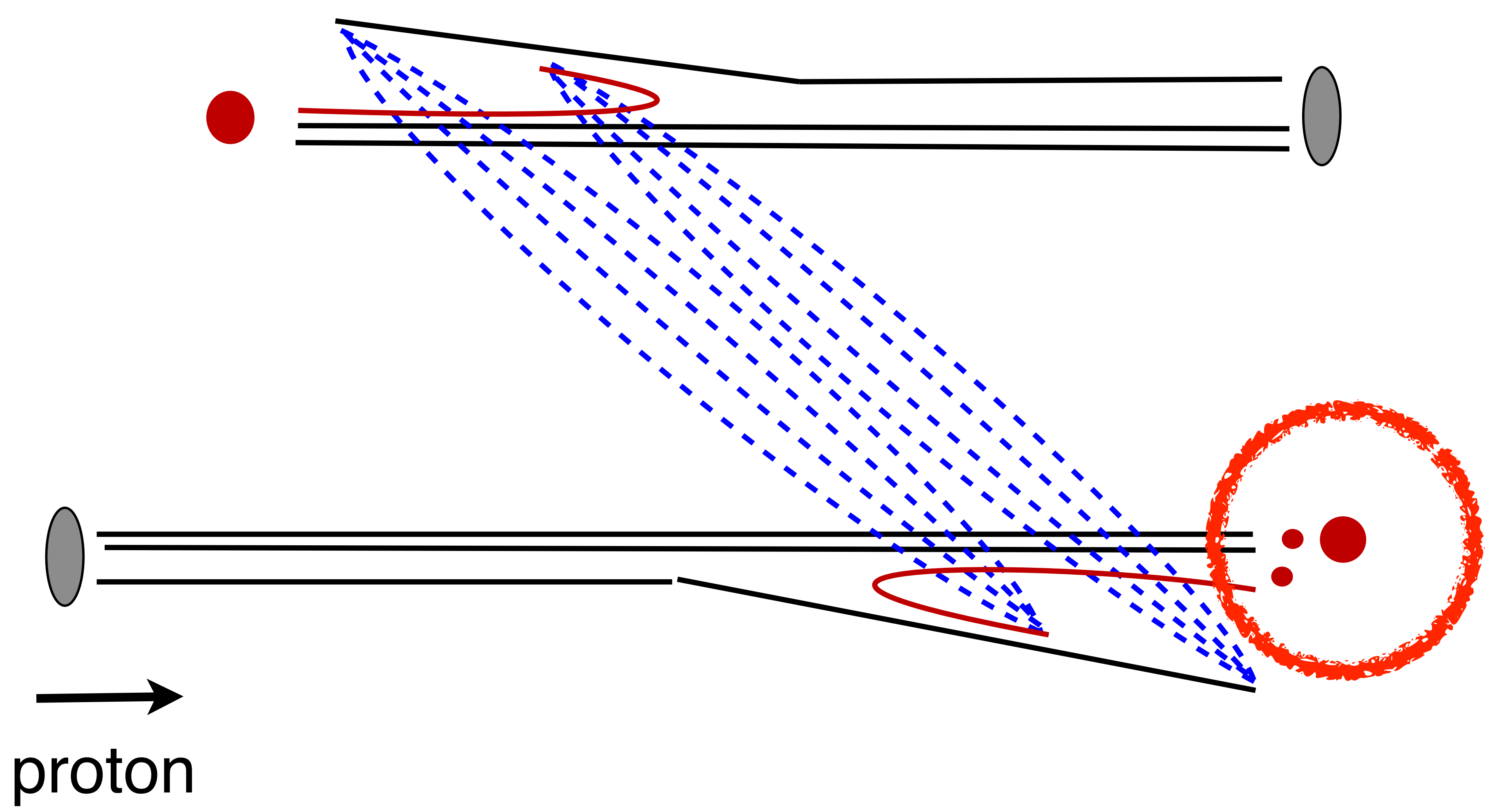
Charm particles (only Sibyll 2.3, and Sibyll 2.3c)



Correlation of low energy muons (surface ~ 1GeV) and in-ice (~500 GeV) muon bundles

Discrimination by IceCube possible (surface array and in-ice muon data)

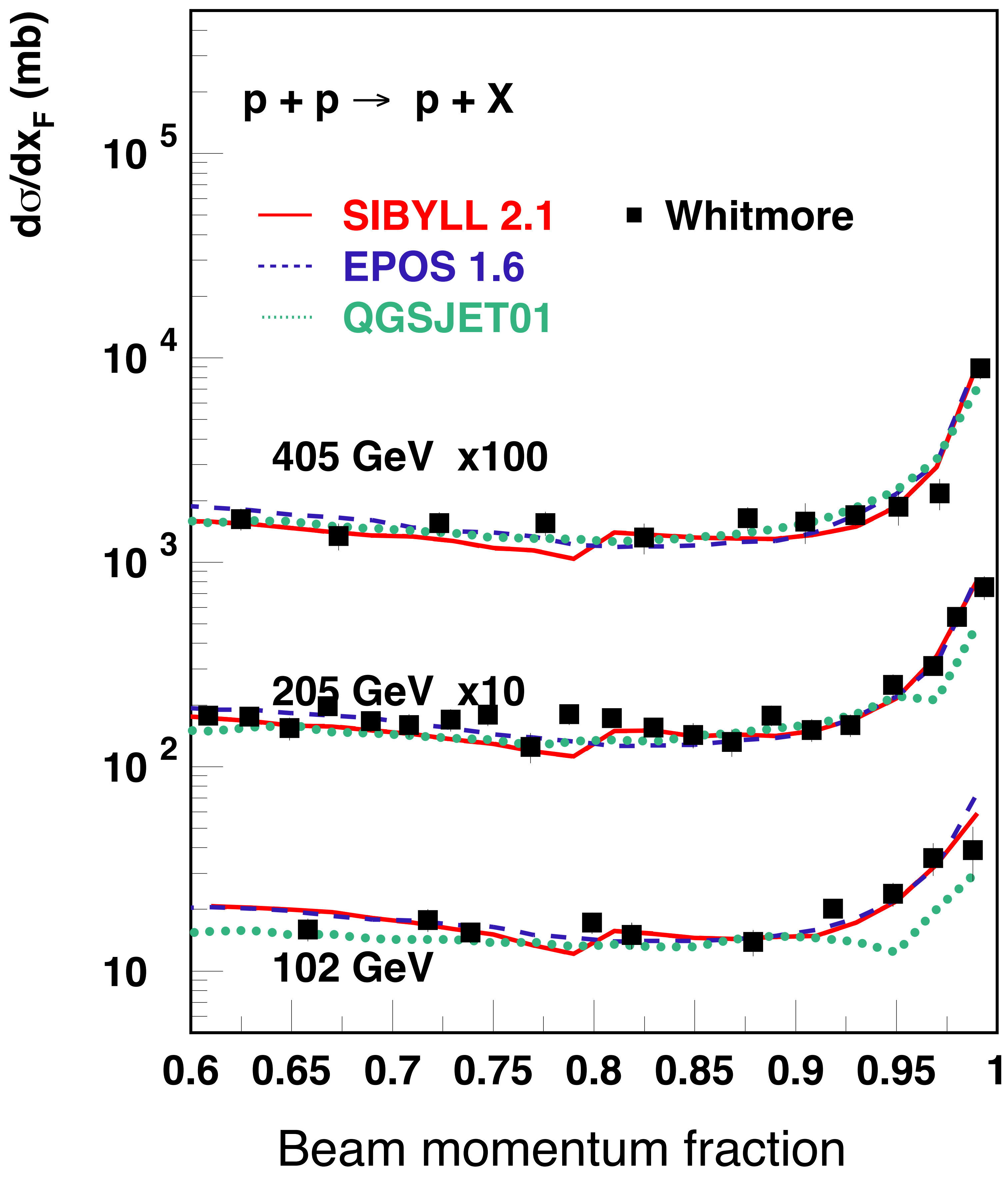
Particle production in hadronic interactions (i)



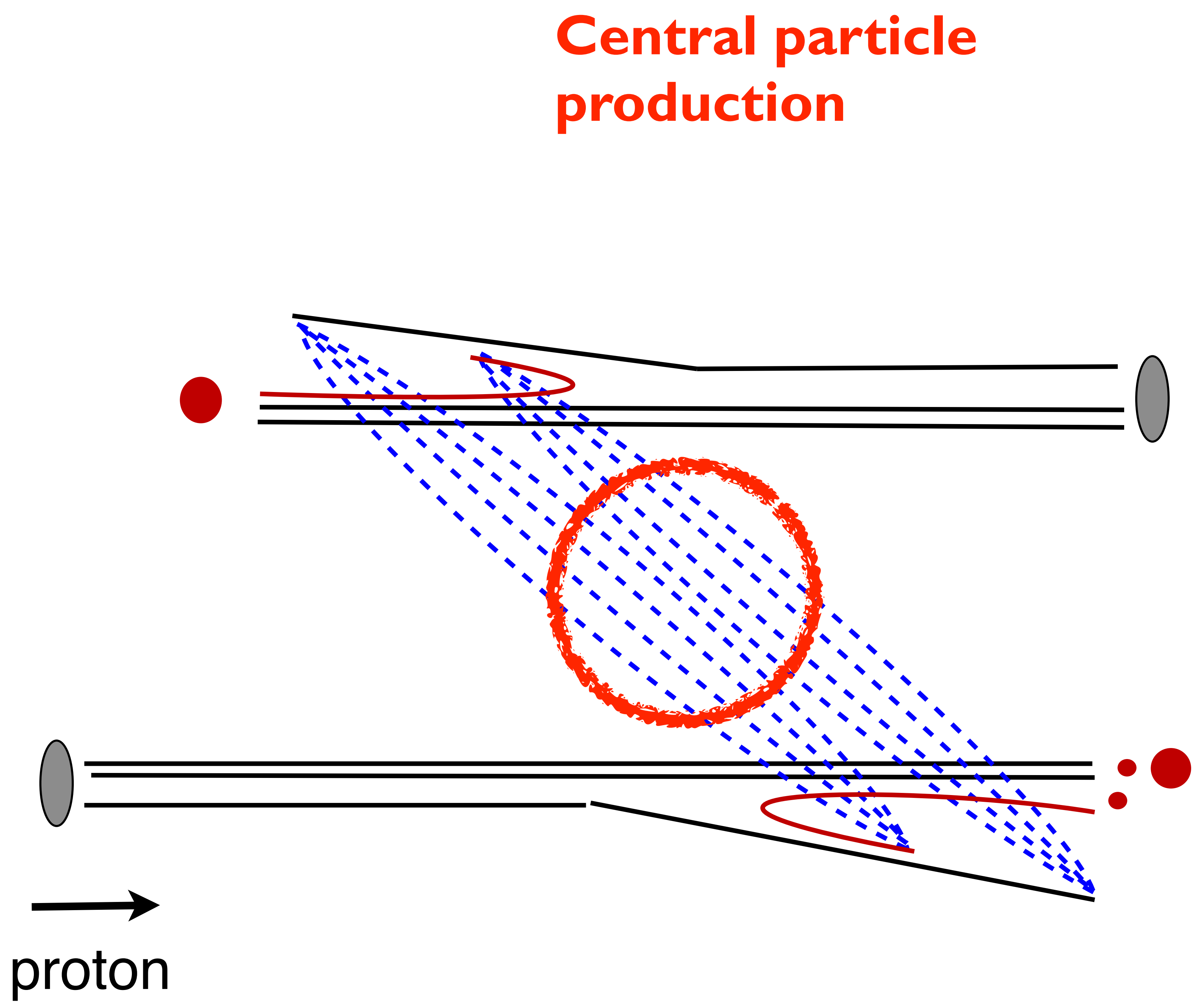
Fluctuations: generation of sea quark anti-quark pair and leading/excited hadron

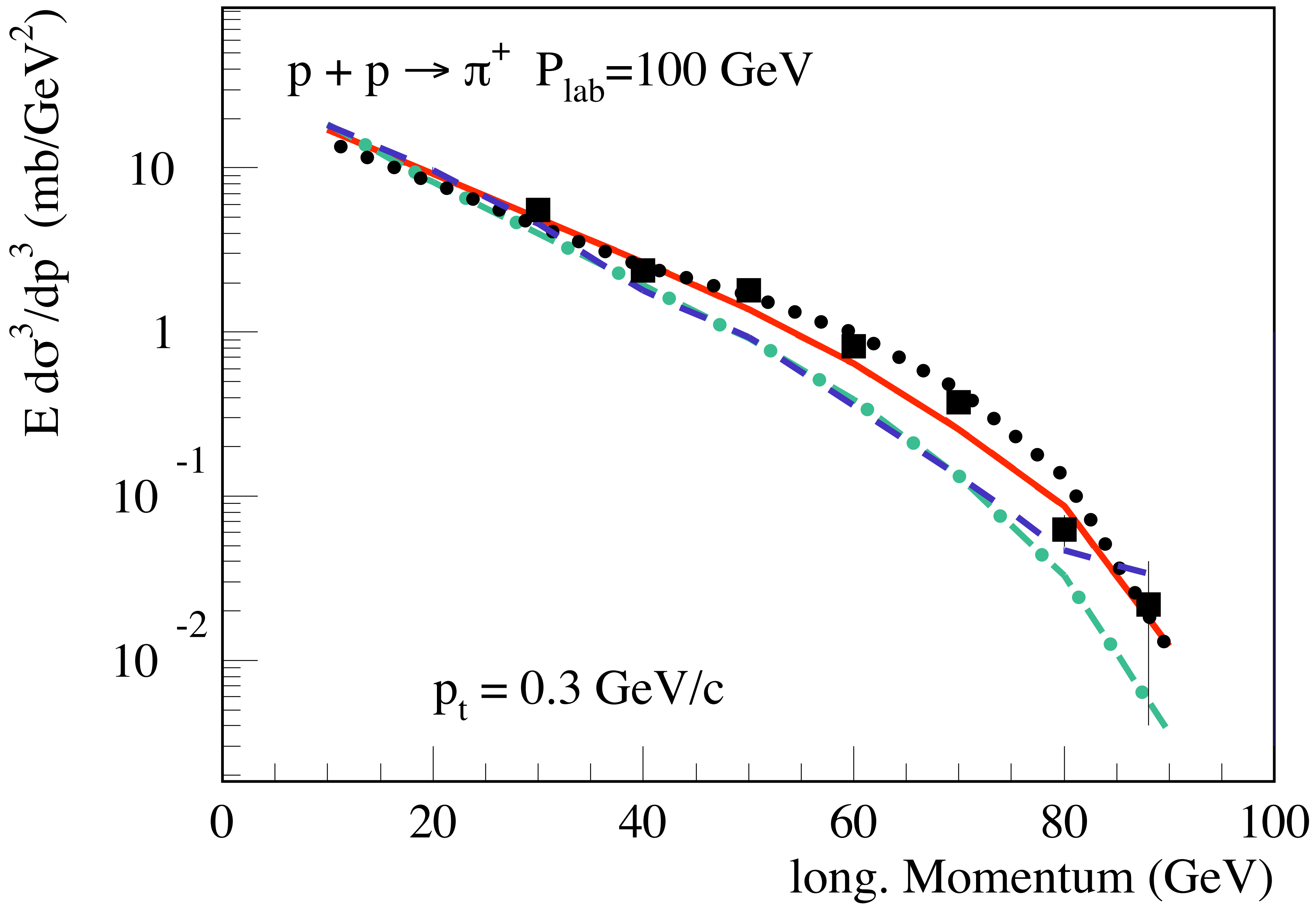
Leading particle effect:

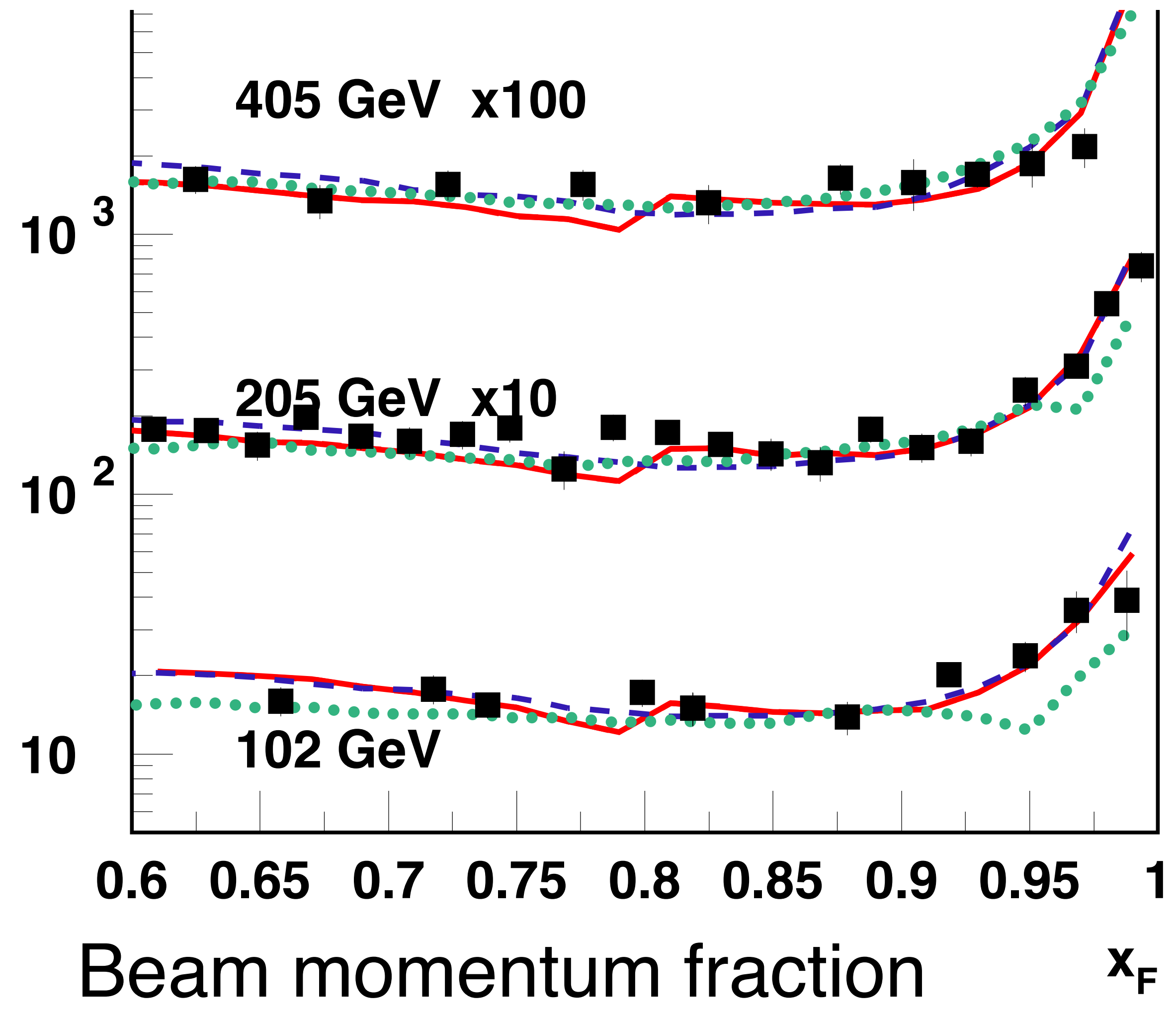
approx. 40–50% of energy of primary particle given to leading particle



Particle production in hadronic interactions (ii)







Fluctuations: generation of sea quark anti-quark pair and leading/excited hadron