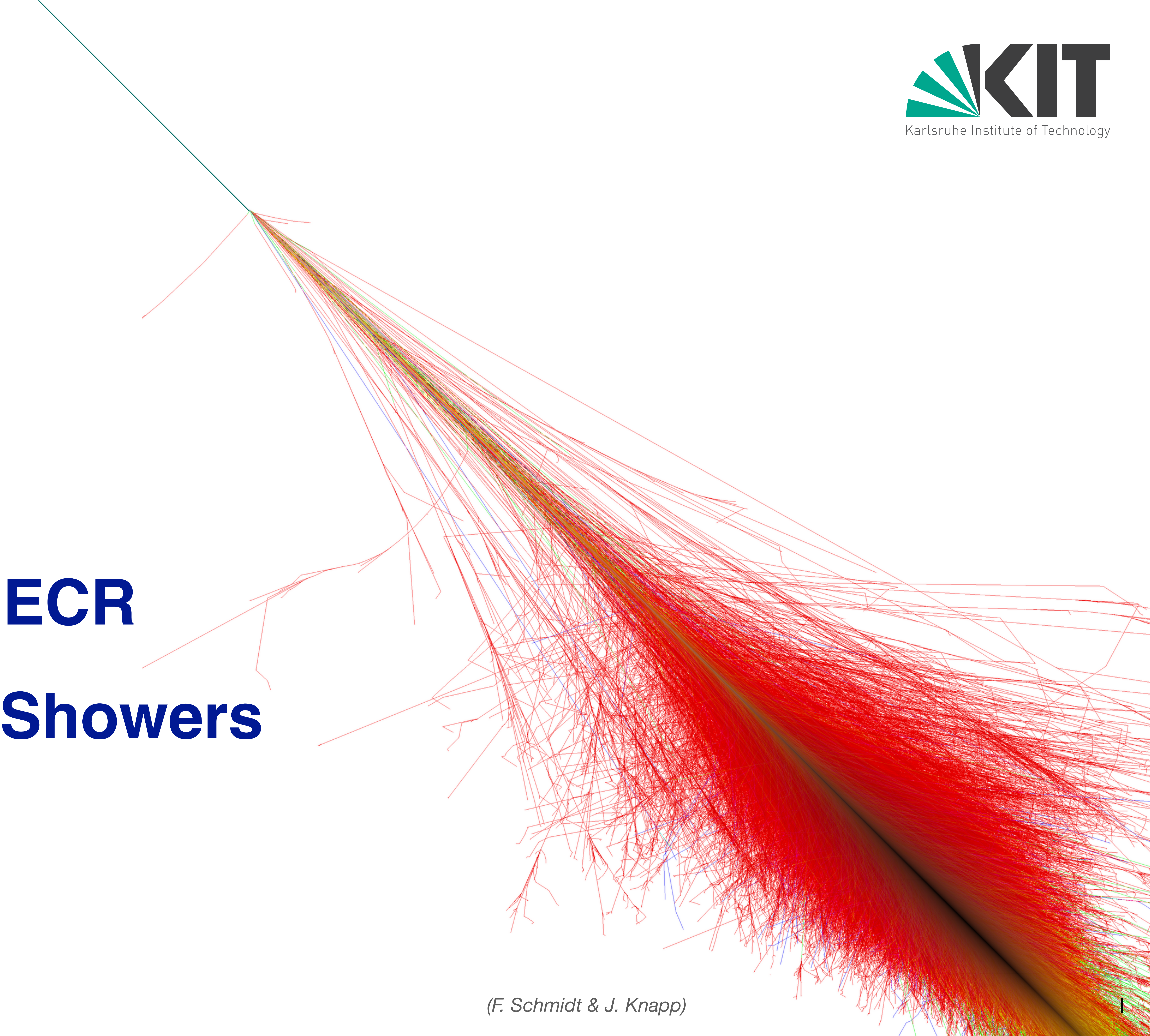


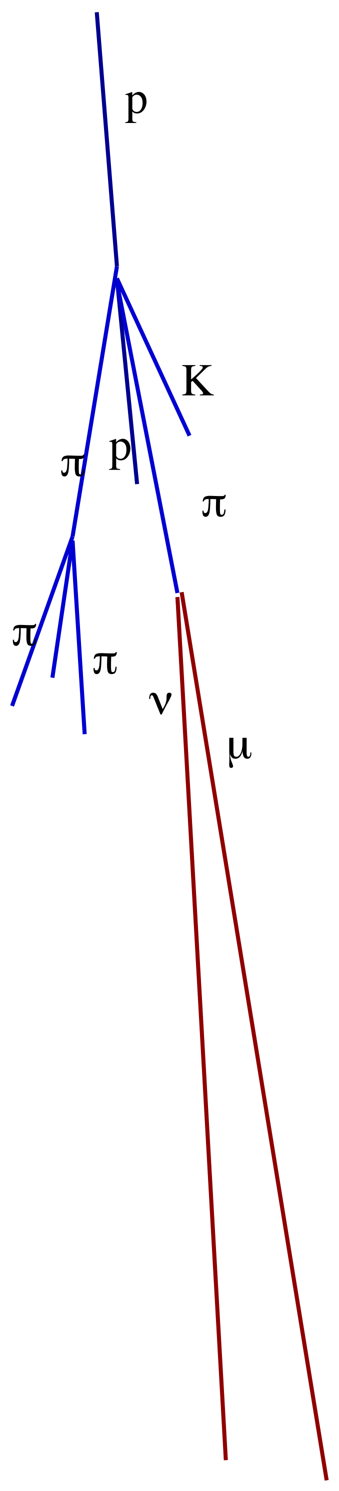
Overview on UHECR Interactions and Air Showers

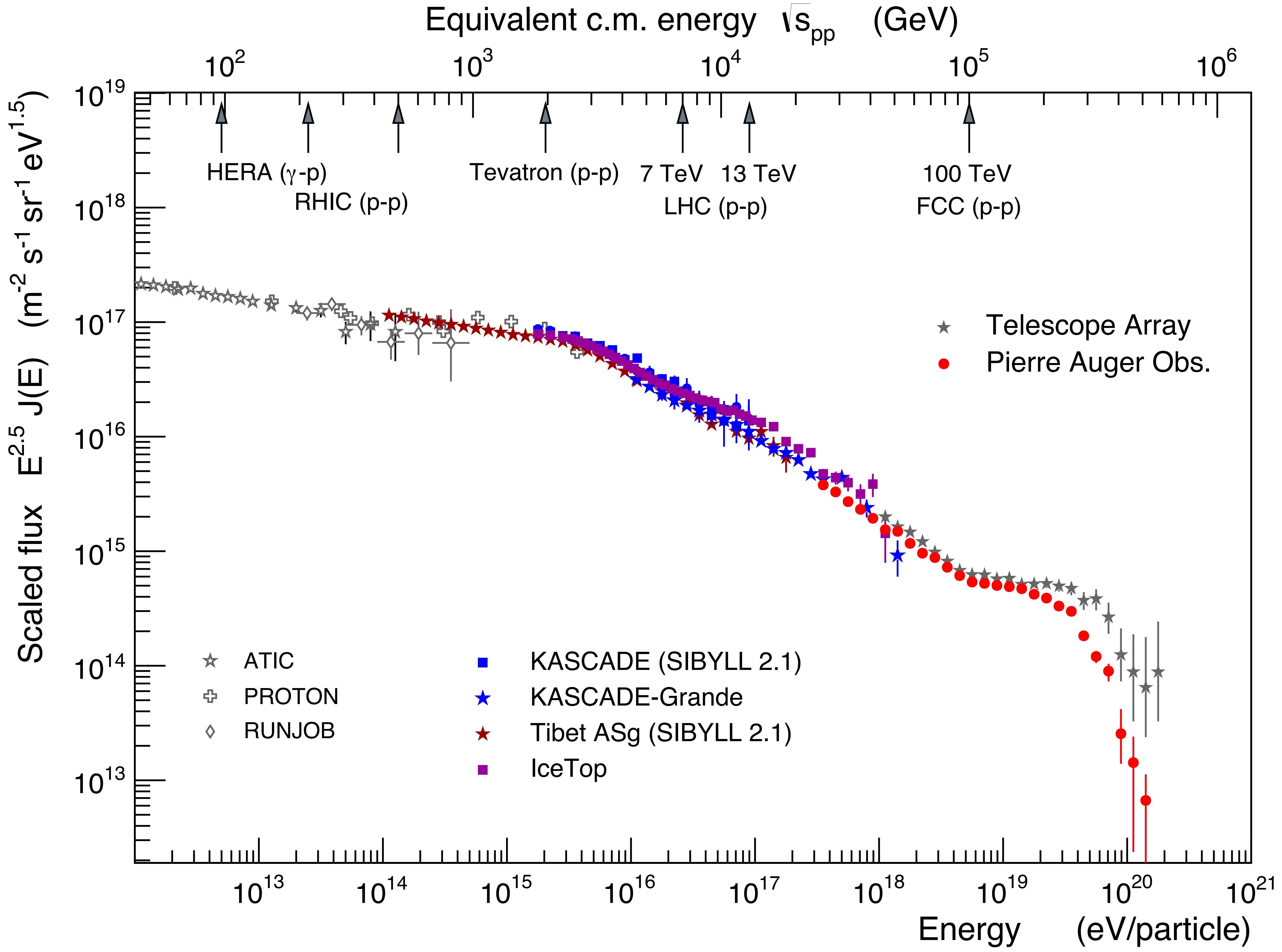
Ralph Engel

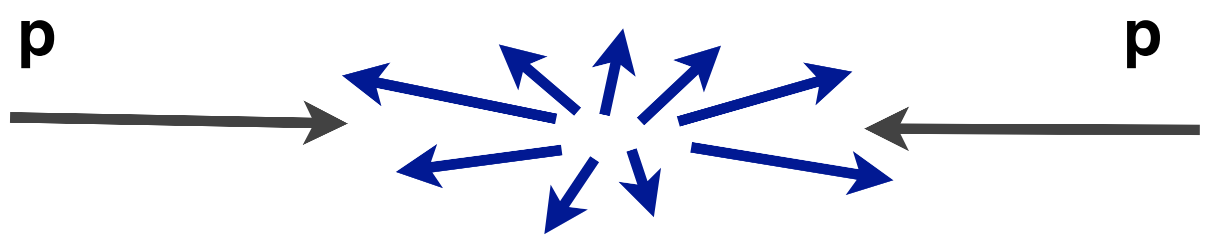
Karlsruhe Institute of Technology (KIT)

(F. Schmidt & J. Knapp)

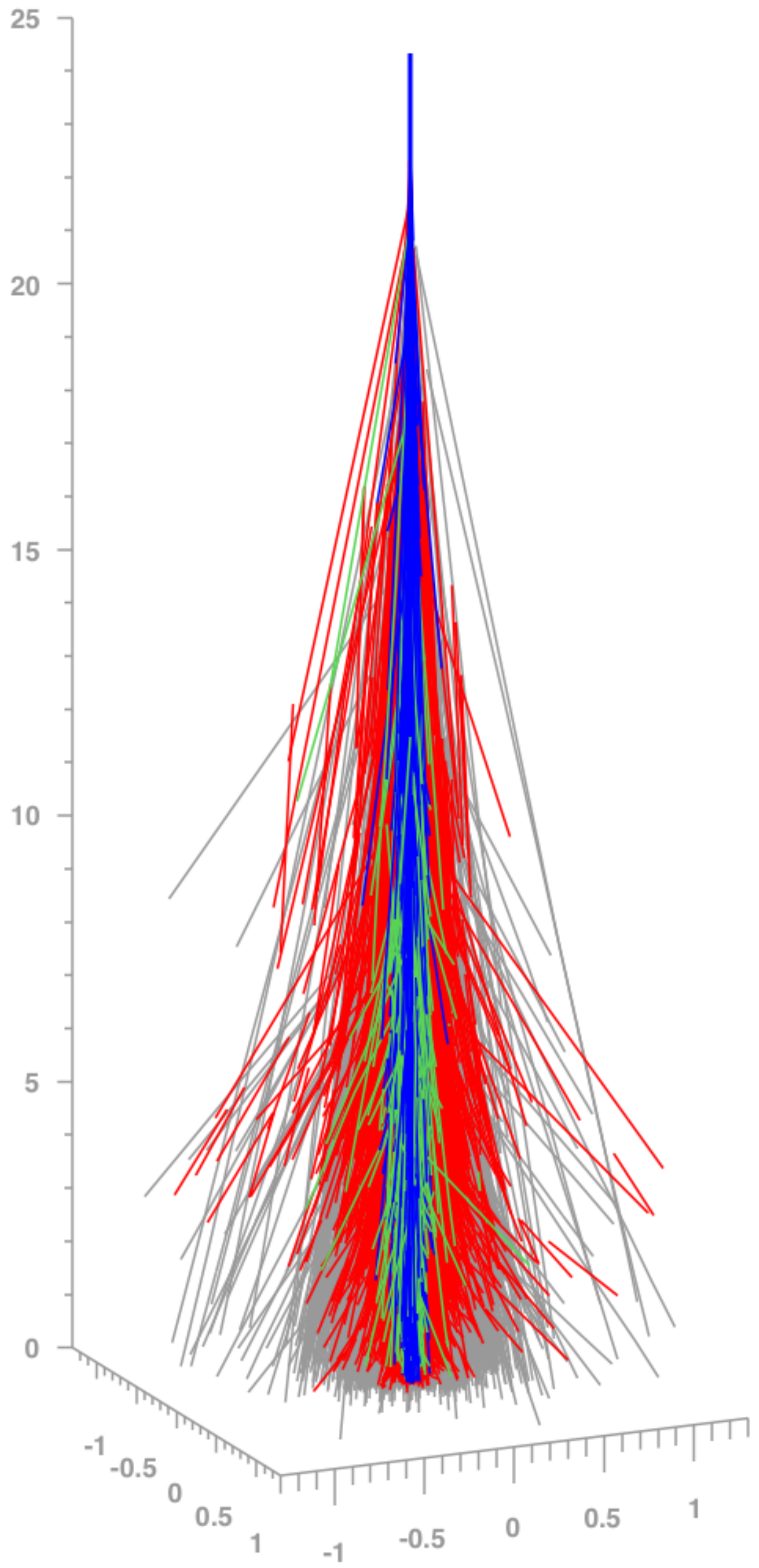
Cosmic ray flux and interaction energies



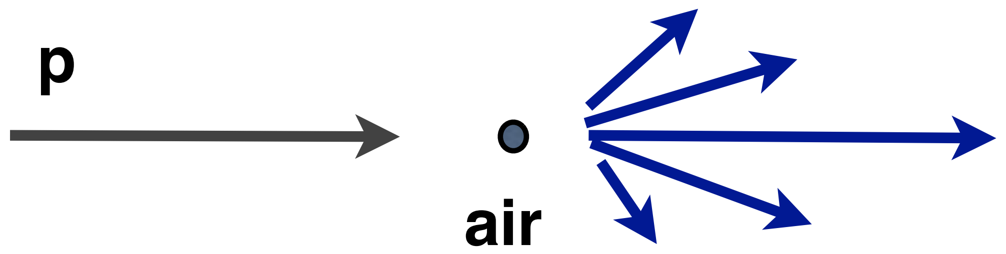




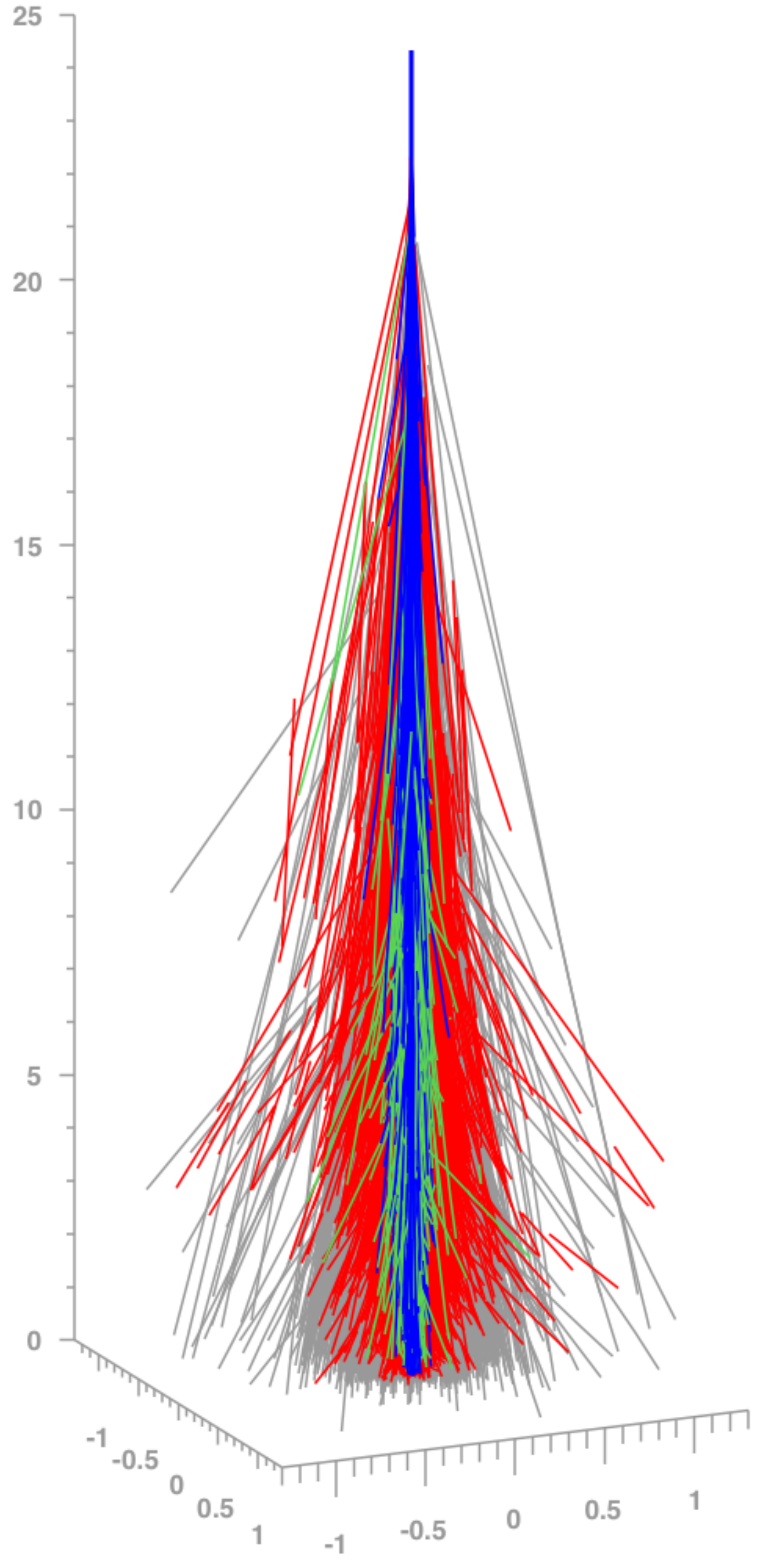
Center-of-mass energy

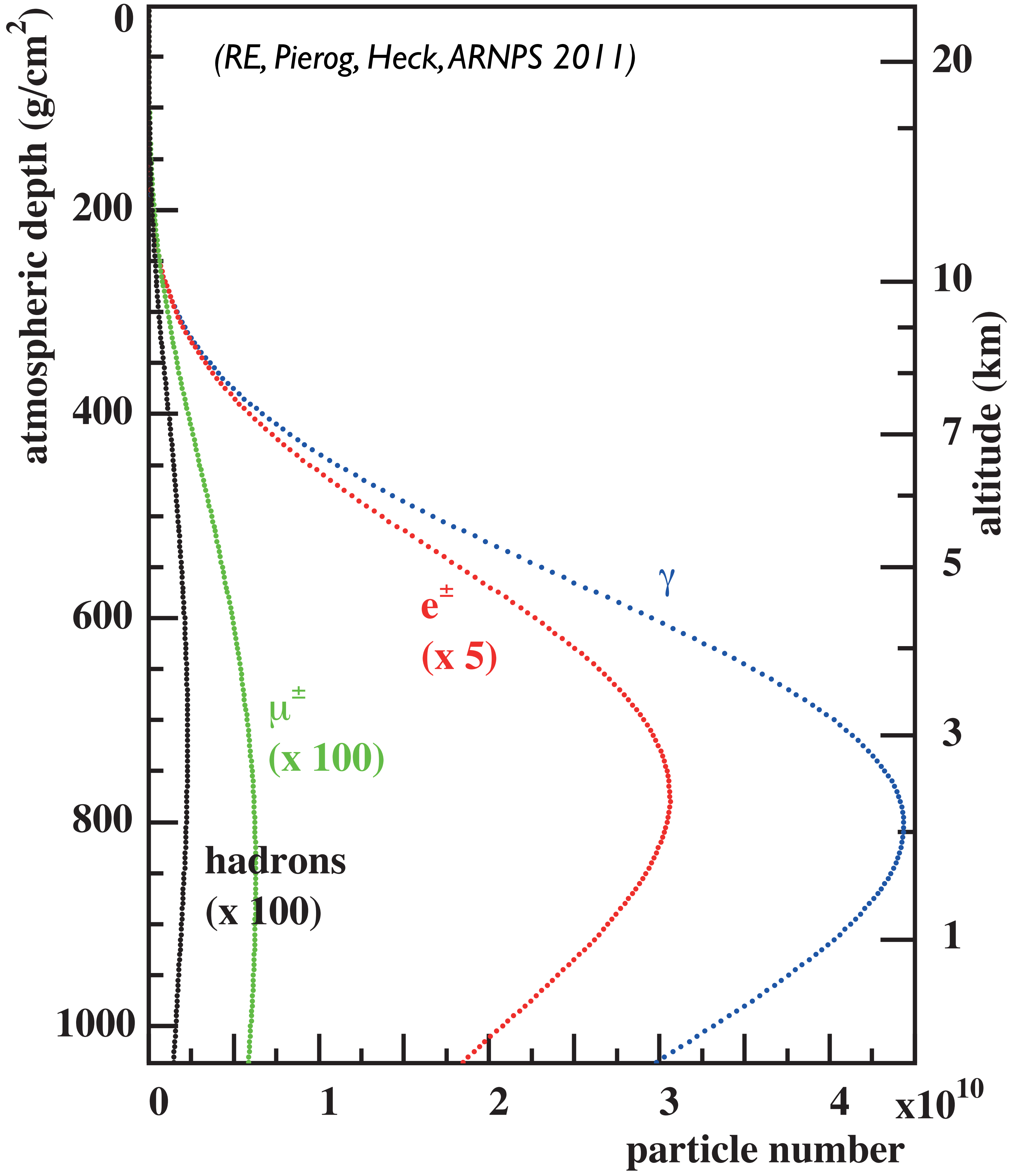


Laboratory energy



Expectation from simulations



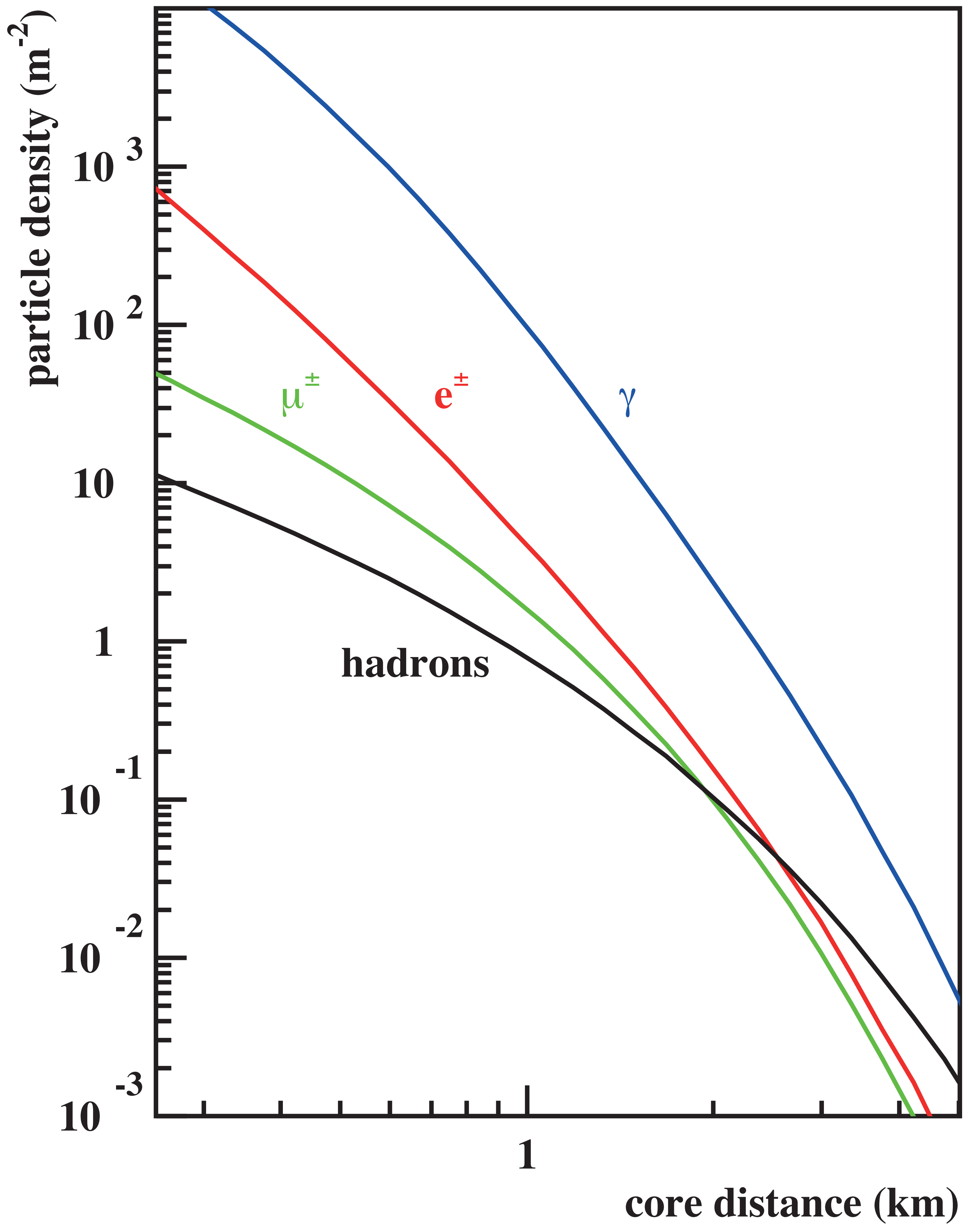


Longitudinal profile:

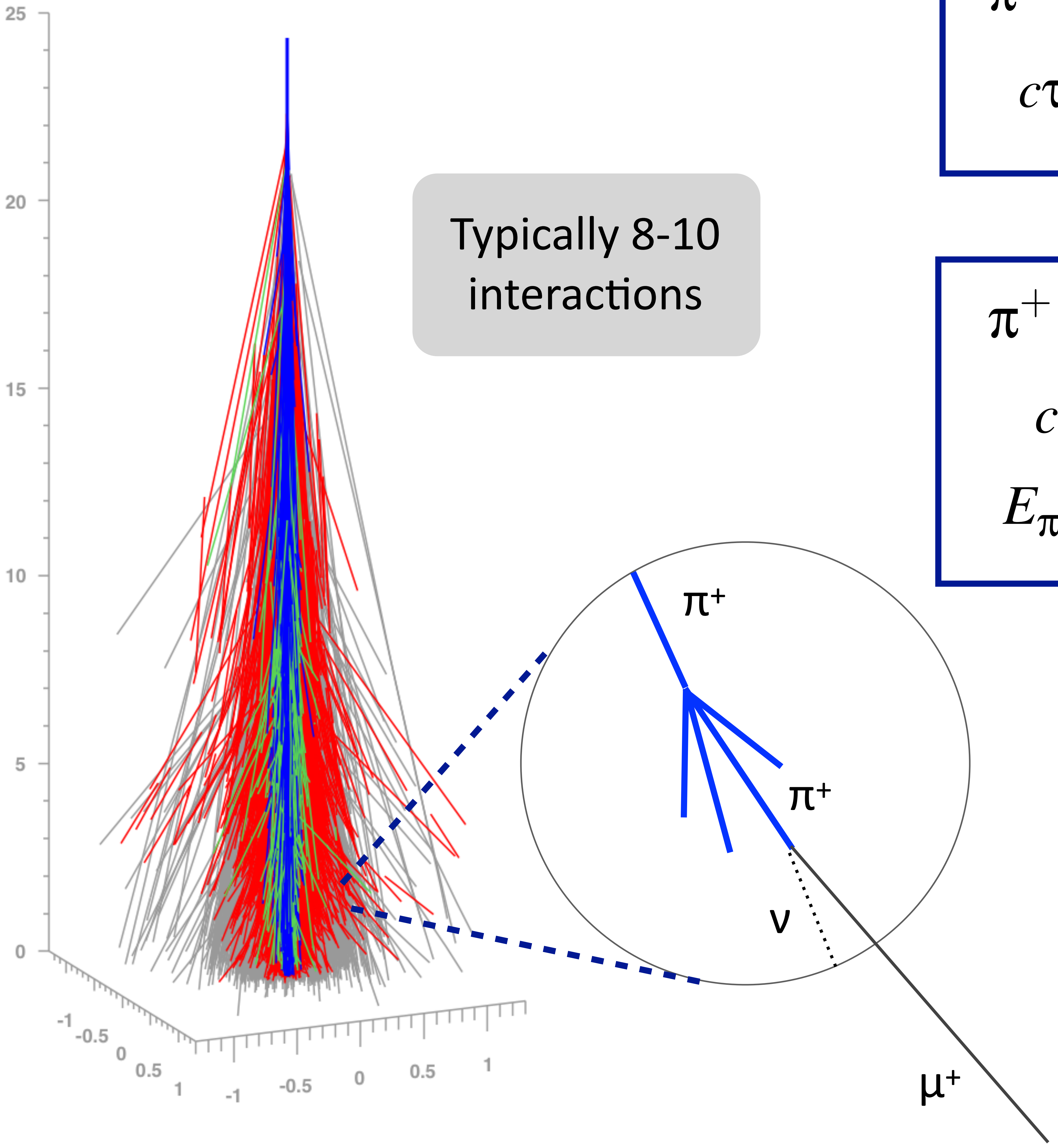
Cherenkov light
Fluorescence light
(bulk of particles measured)

Lateral profiles:

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



Muon production at large lateral distance

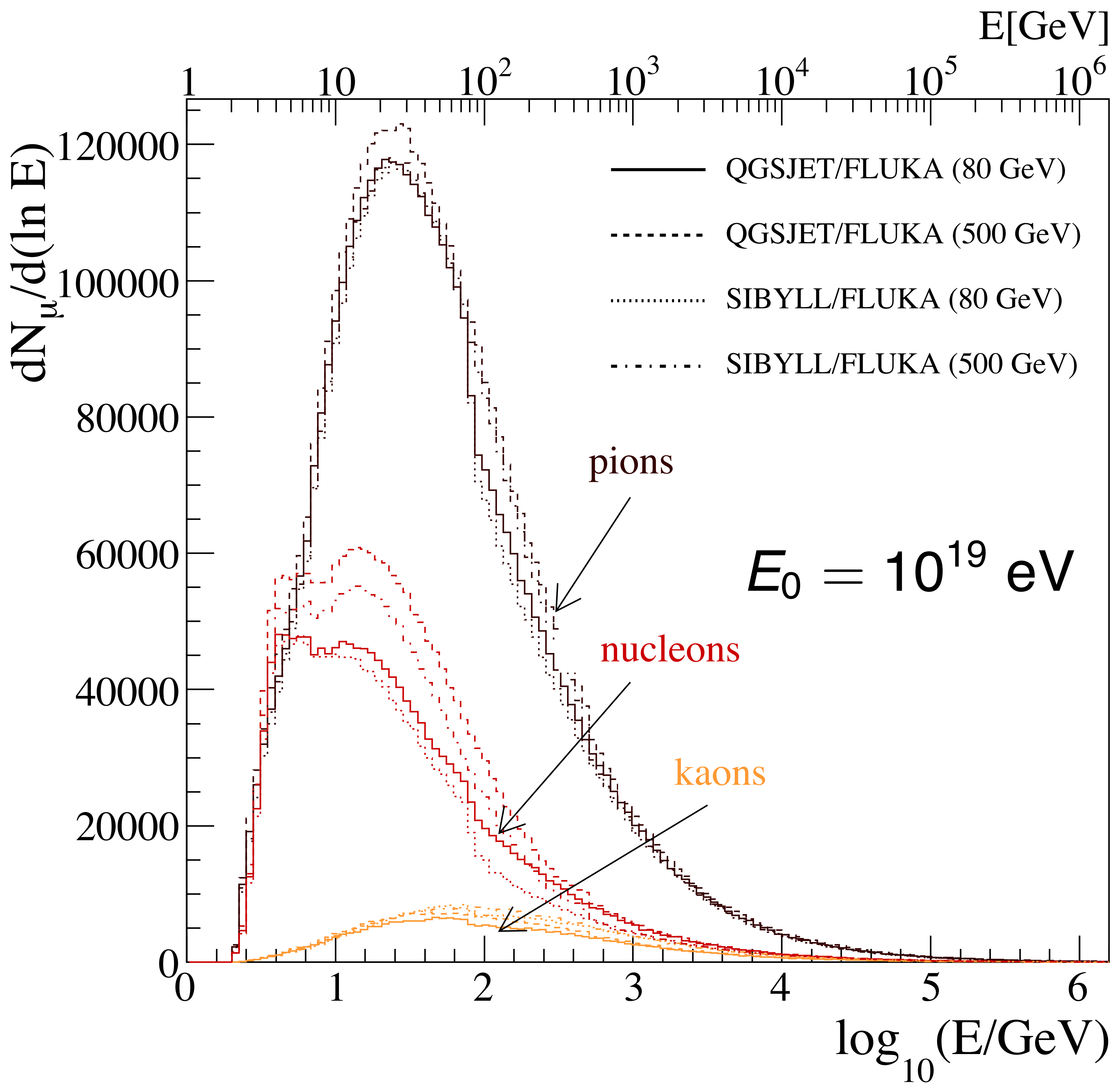


Typically 8-10 interactions

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

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

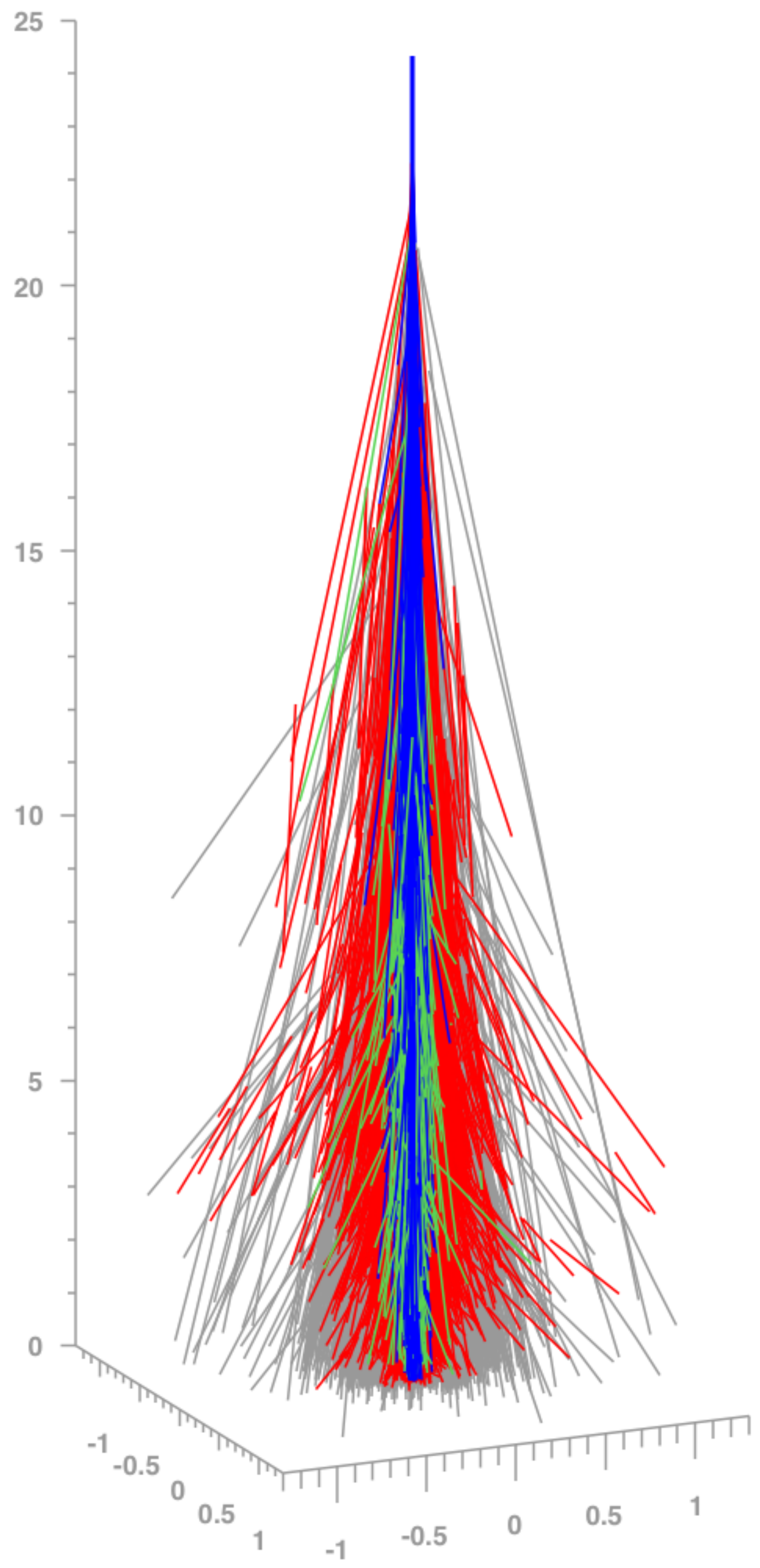
Energy distribution of **last interaction** that produced a detected muon



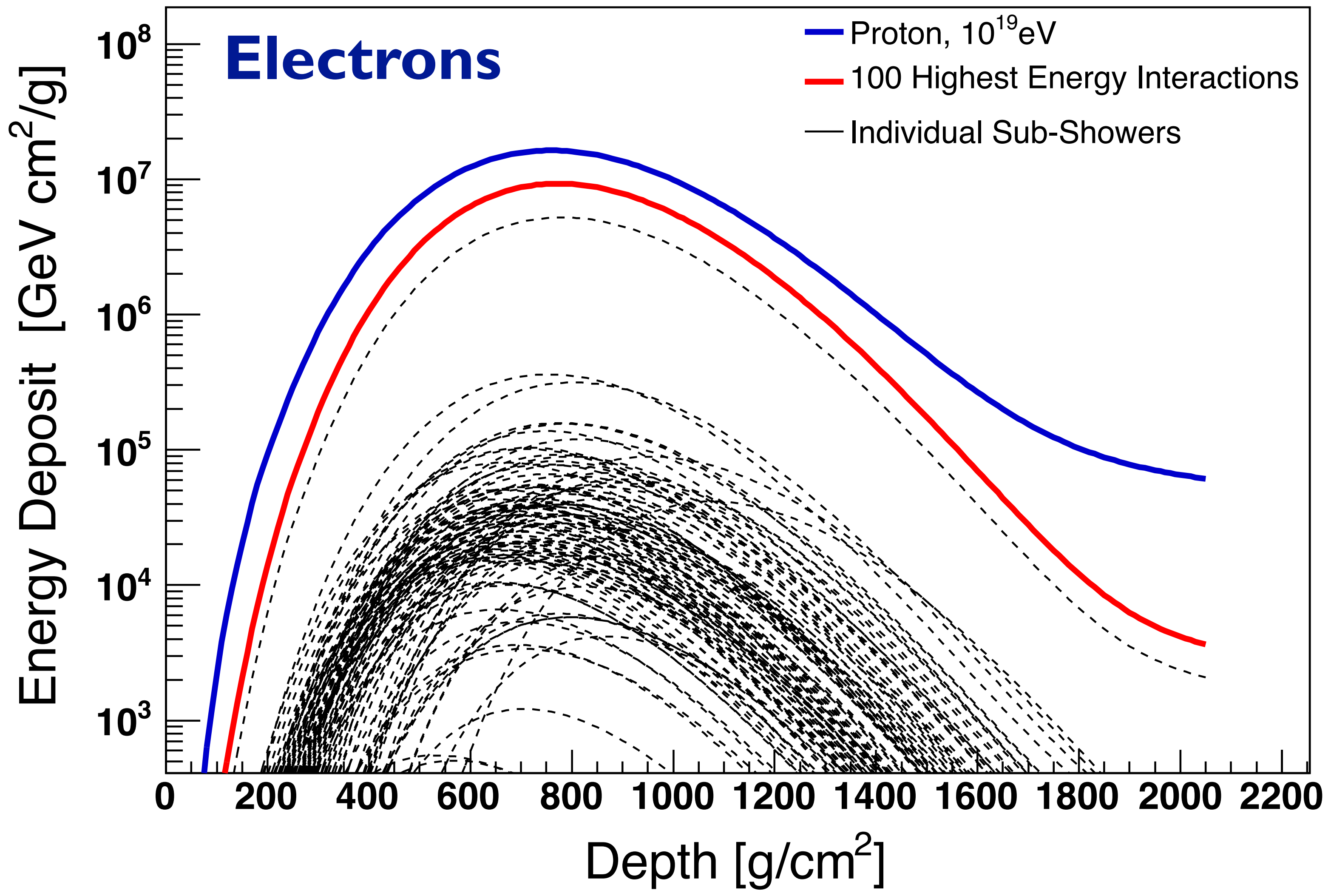
(Maris et al. ICRC 2009)

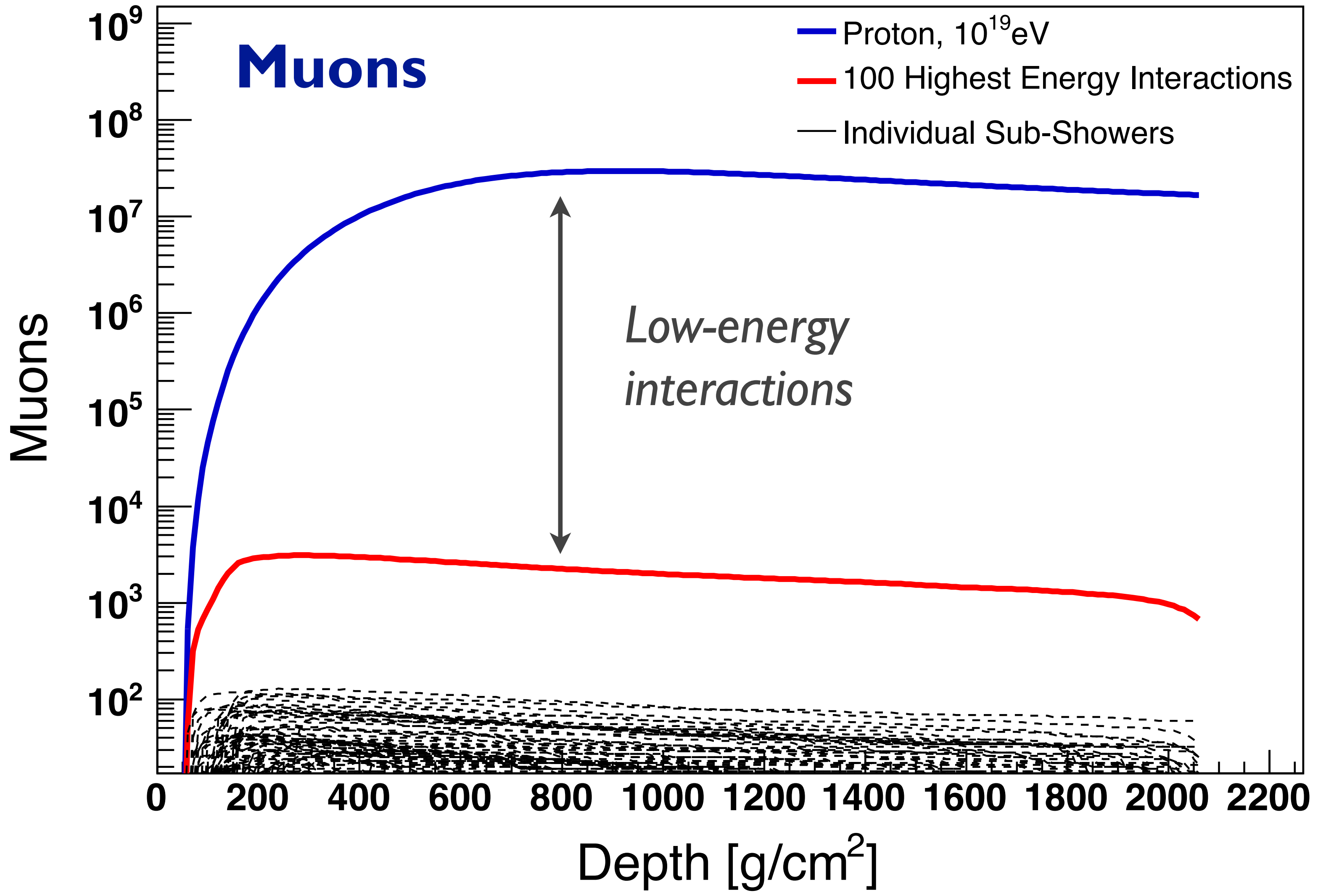
Muon observed at 1000 m from core

Importance of hadronic interactions at different energies



(Ulrich APS 2010)





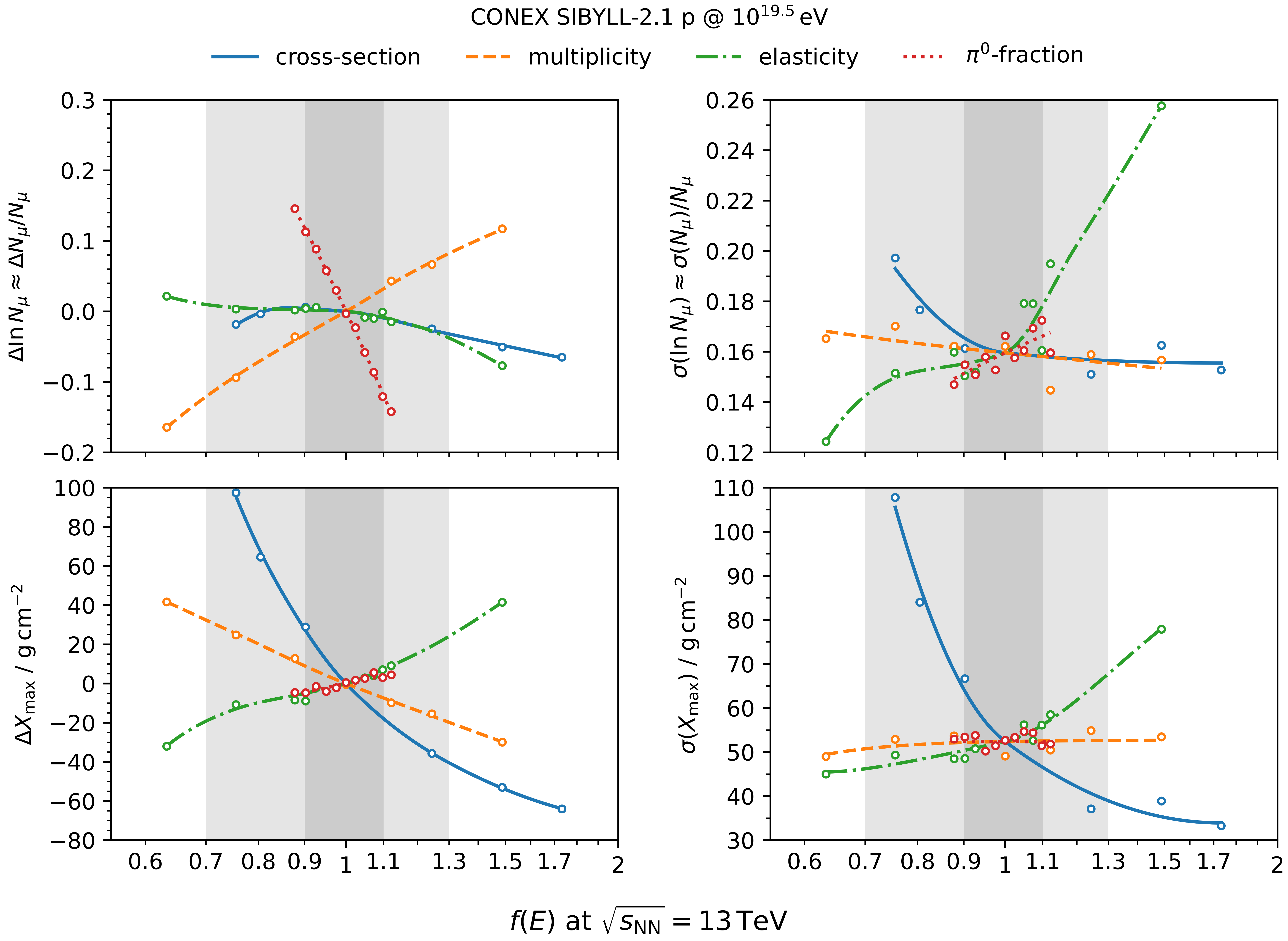
Shower particles produced in 100 interactions of highest energy

Electrons/photons:
high-energy interactions

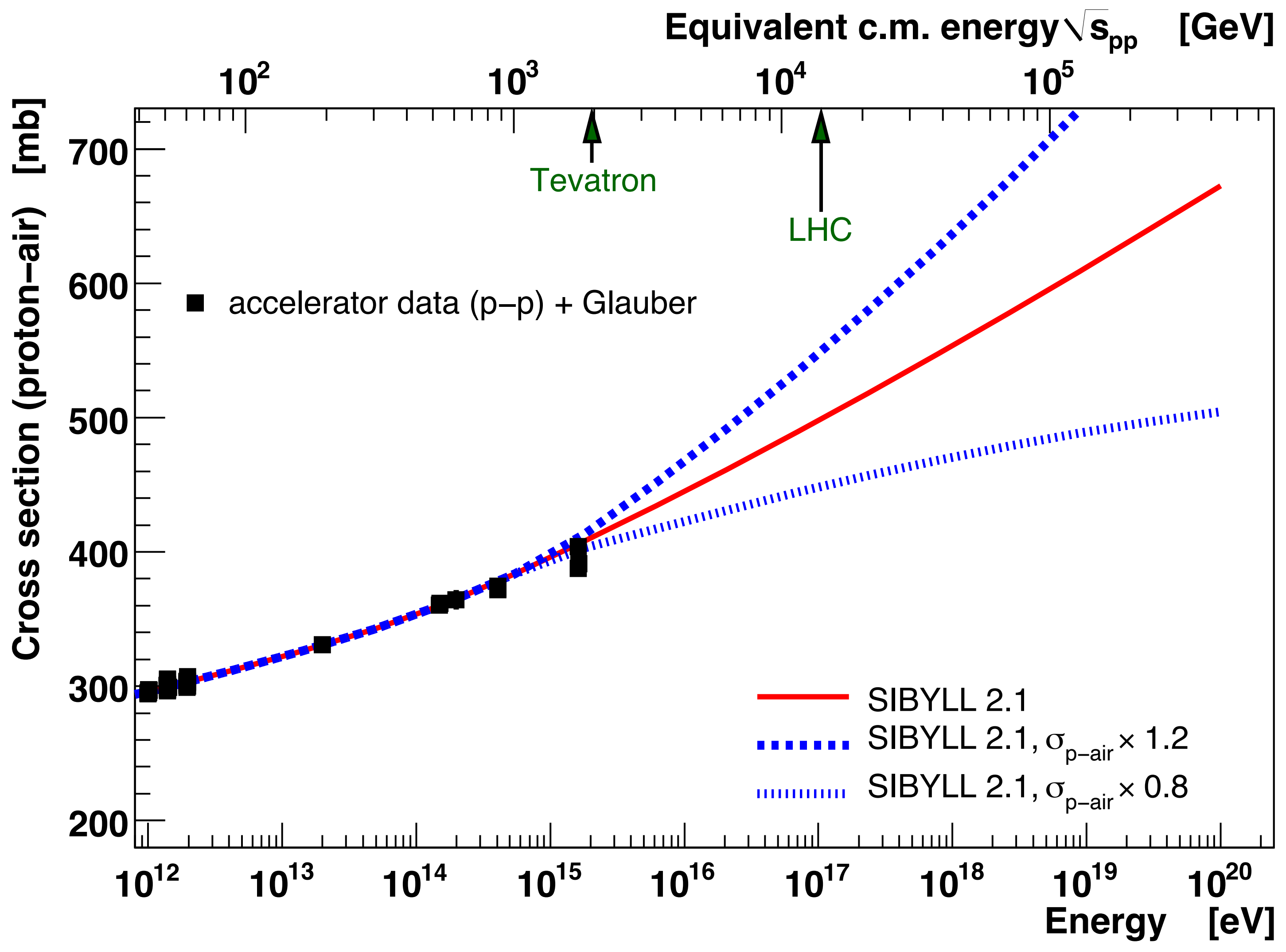
Muons/hadrons:
low-energy interactions

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

Systematic study of relation to interaction properties

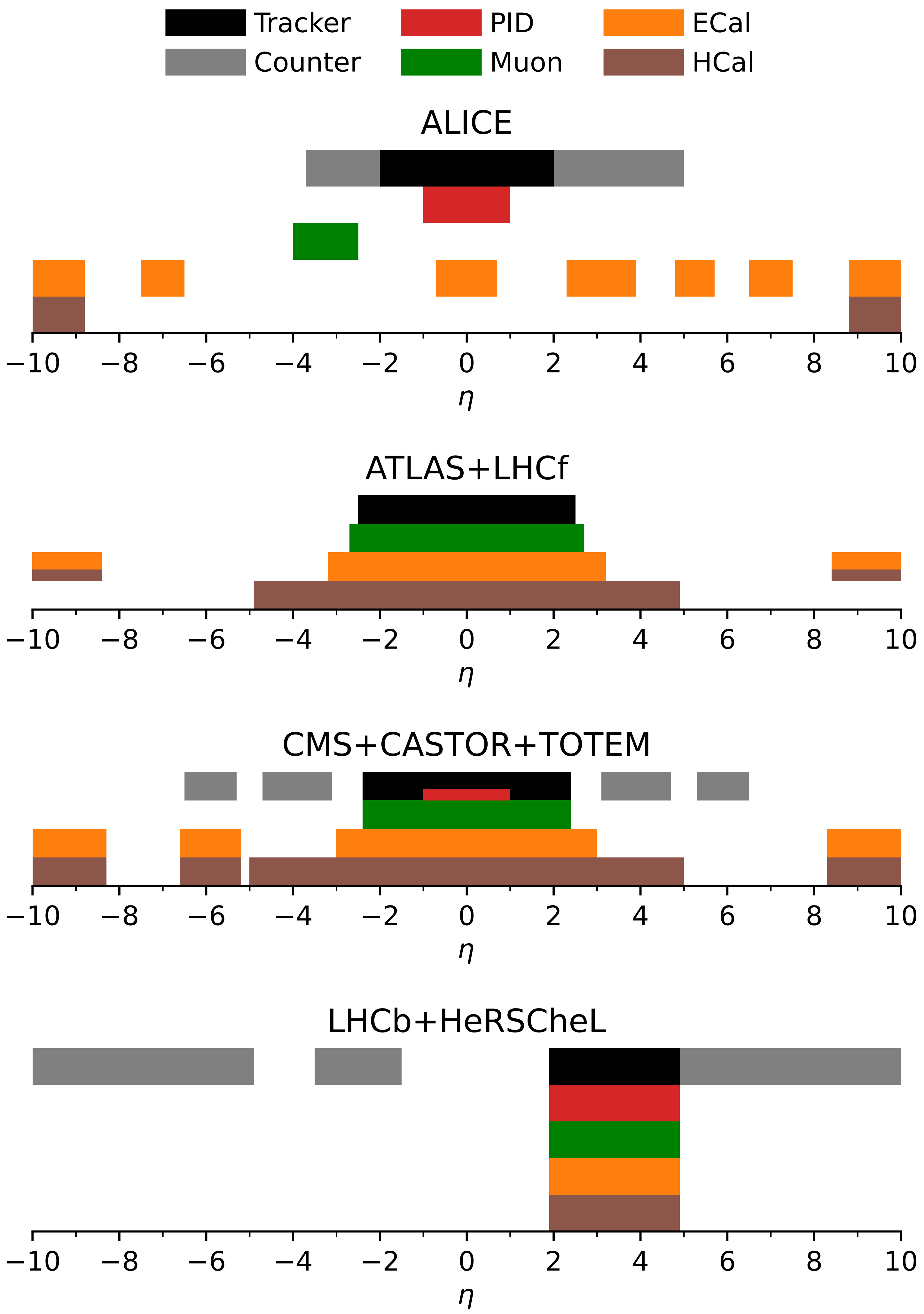


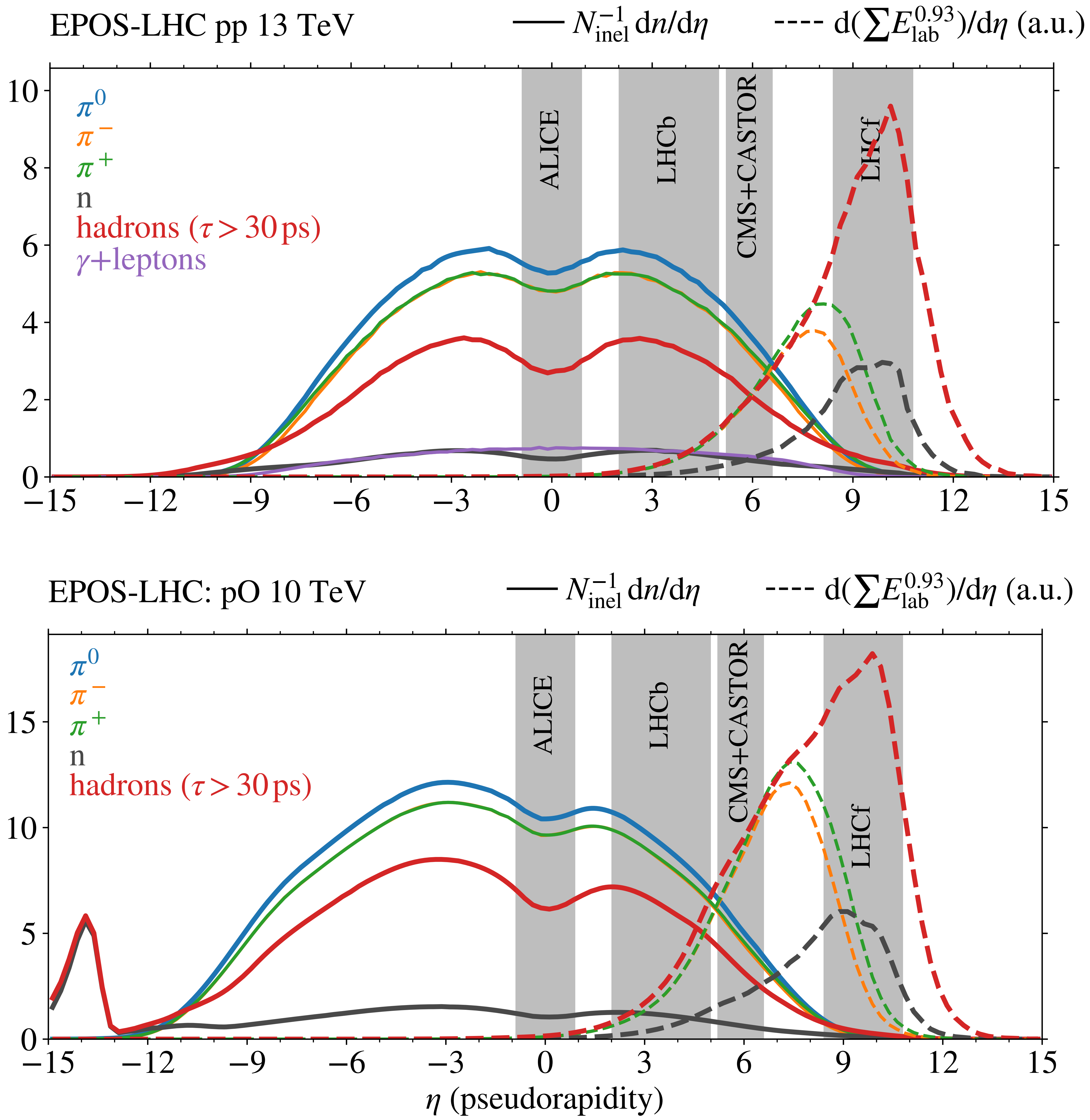
(Dembinski, ICRC 2021, Albrecht et al. Astrophys. Space Science 2022)



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

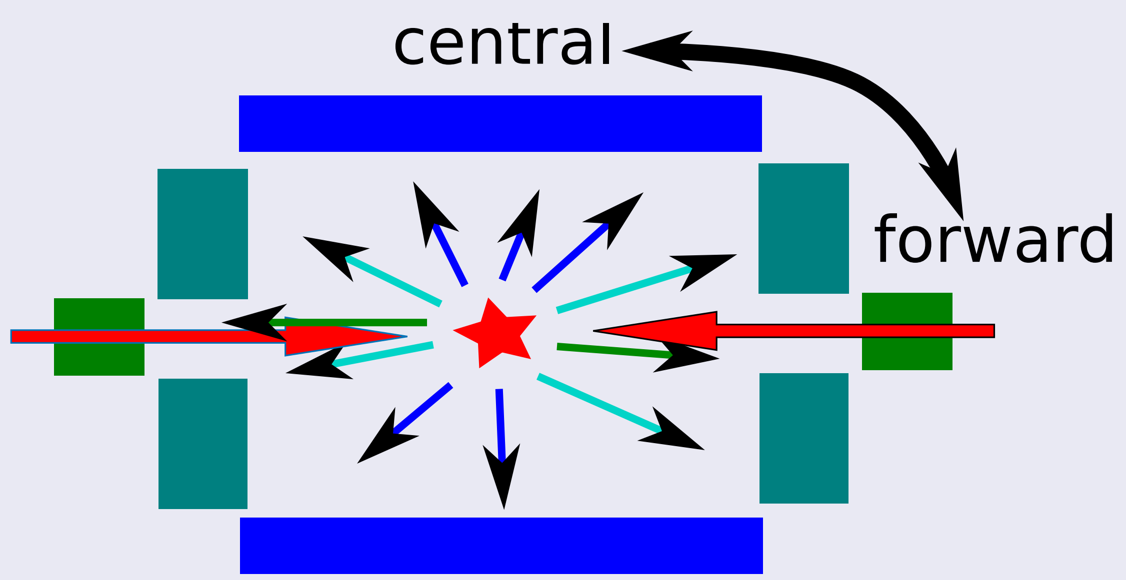
Challenge of limited phase space coverage





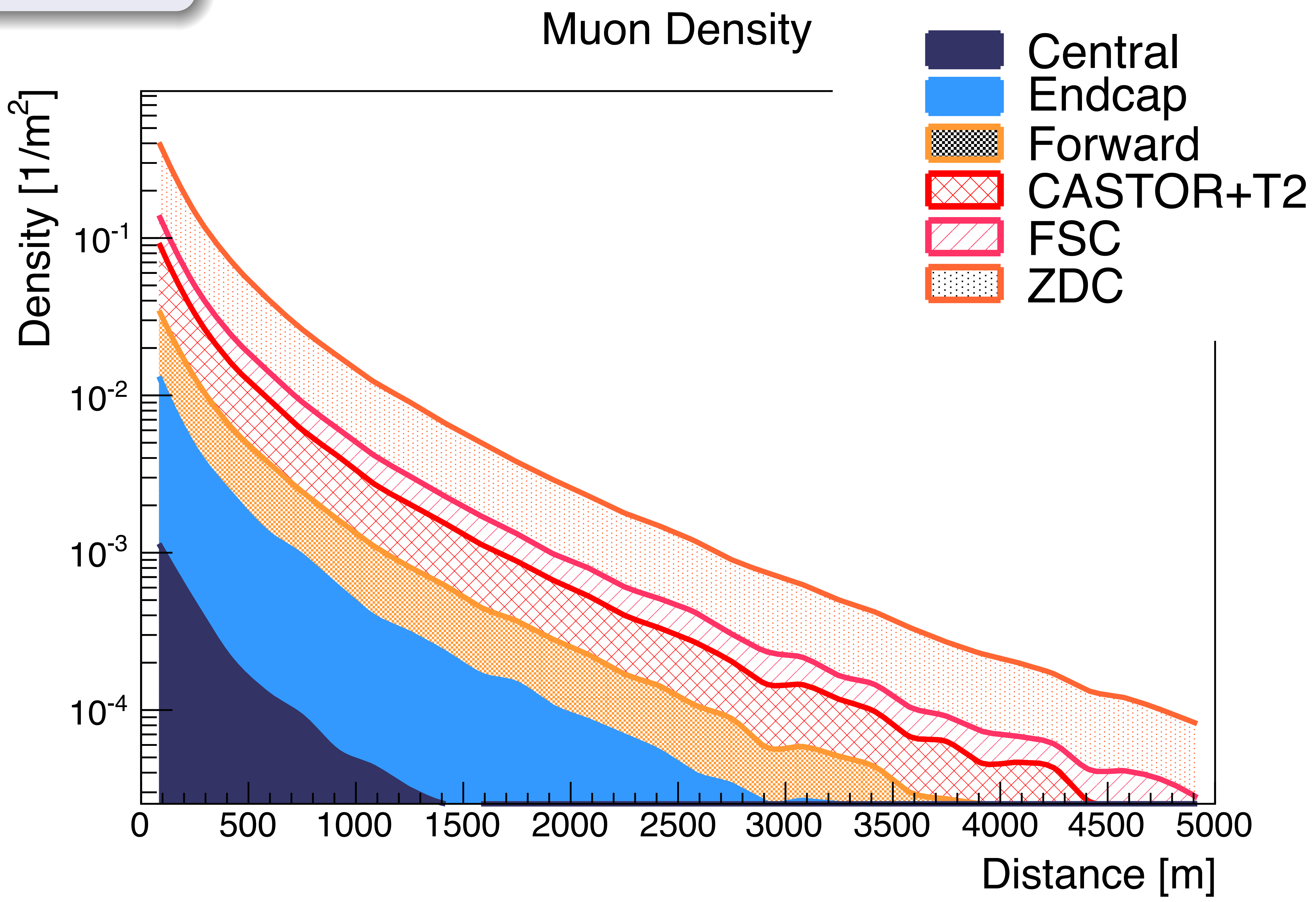
(Albrecht et al. Astrophys. Space Science 2022)

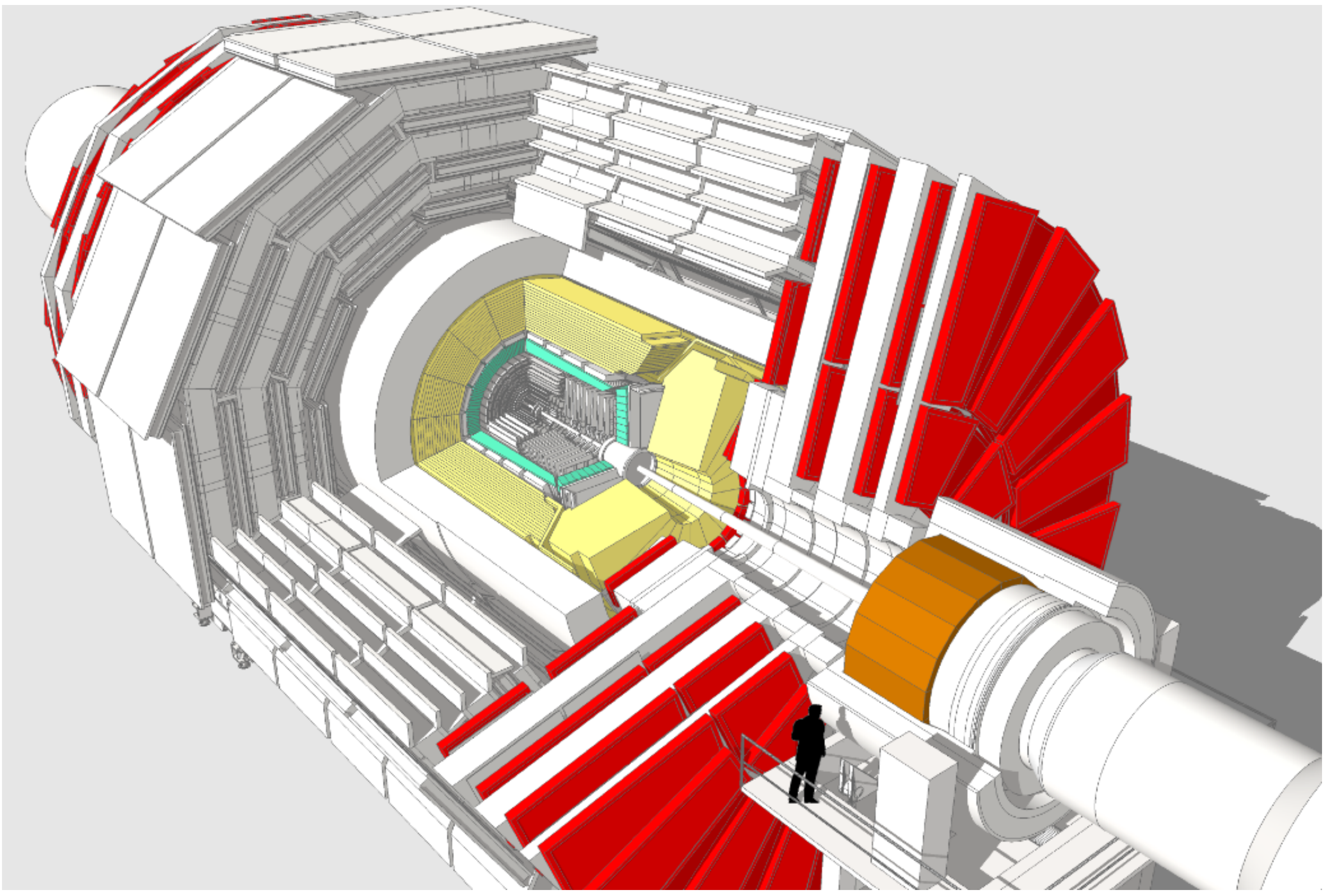
Challenge of limited phase space coverage



- 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

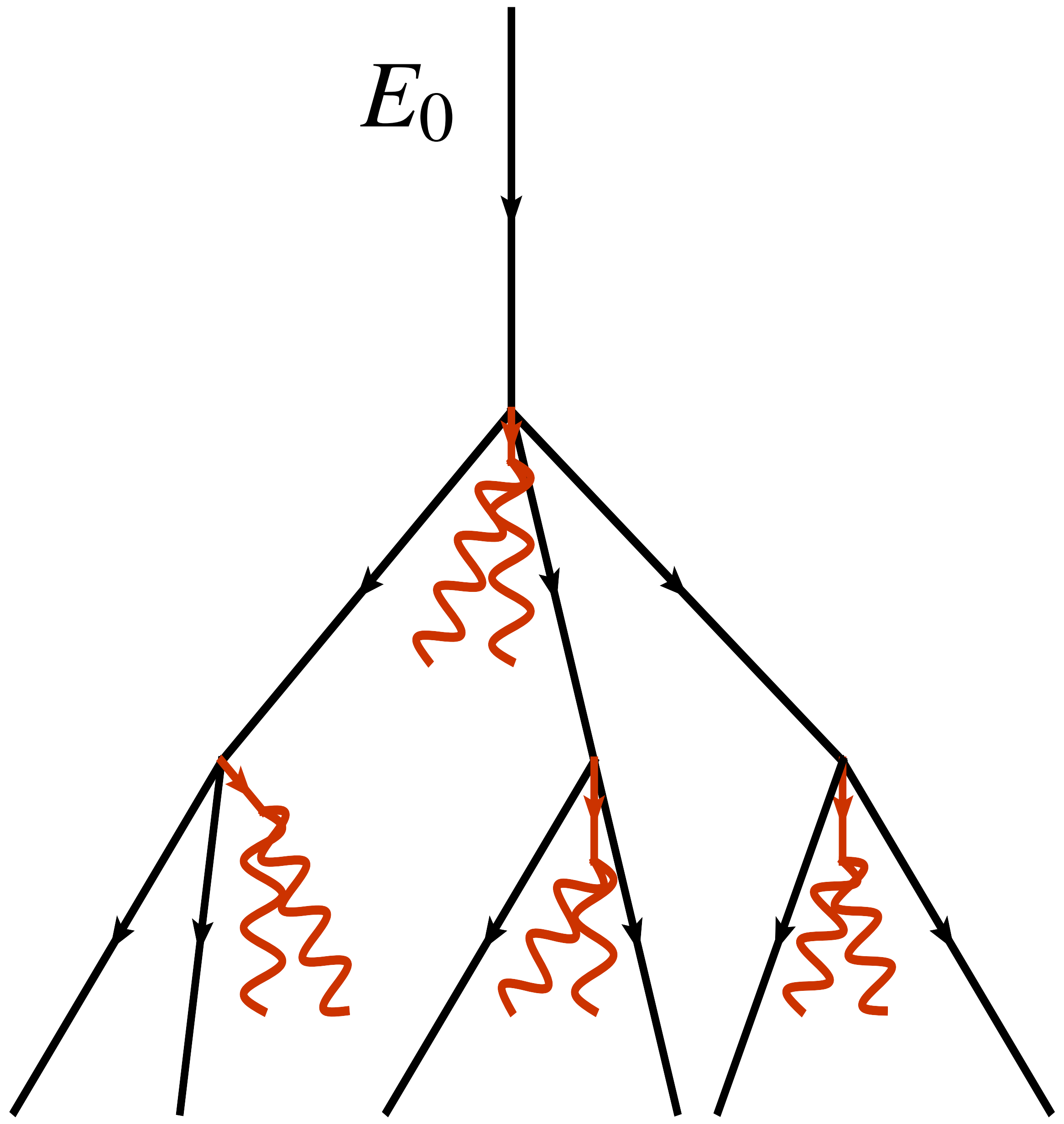
(Ulrich, DPG 2014)





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

Electromagnetic energy and energy transfer



Hadronic energy

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

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

∘
∘
∘
∘

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

After n generations ...

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

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

Electromagnetic energy

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

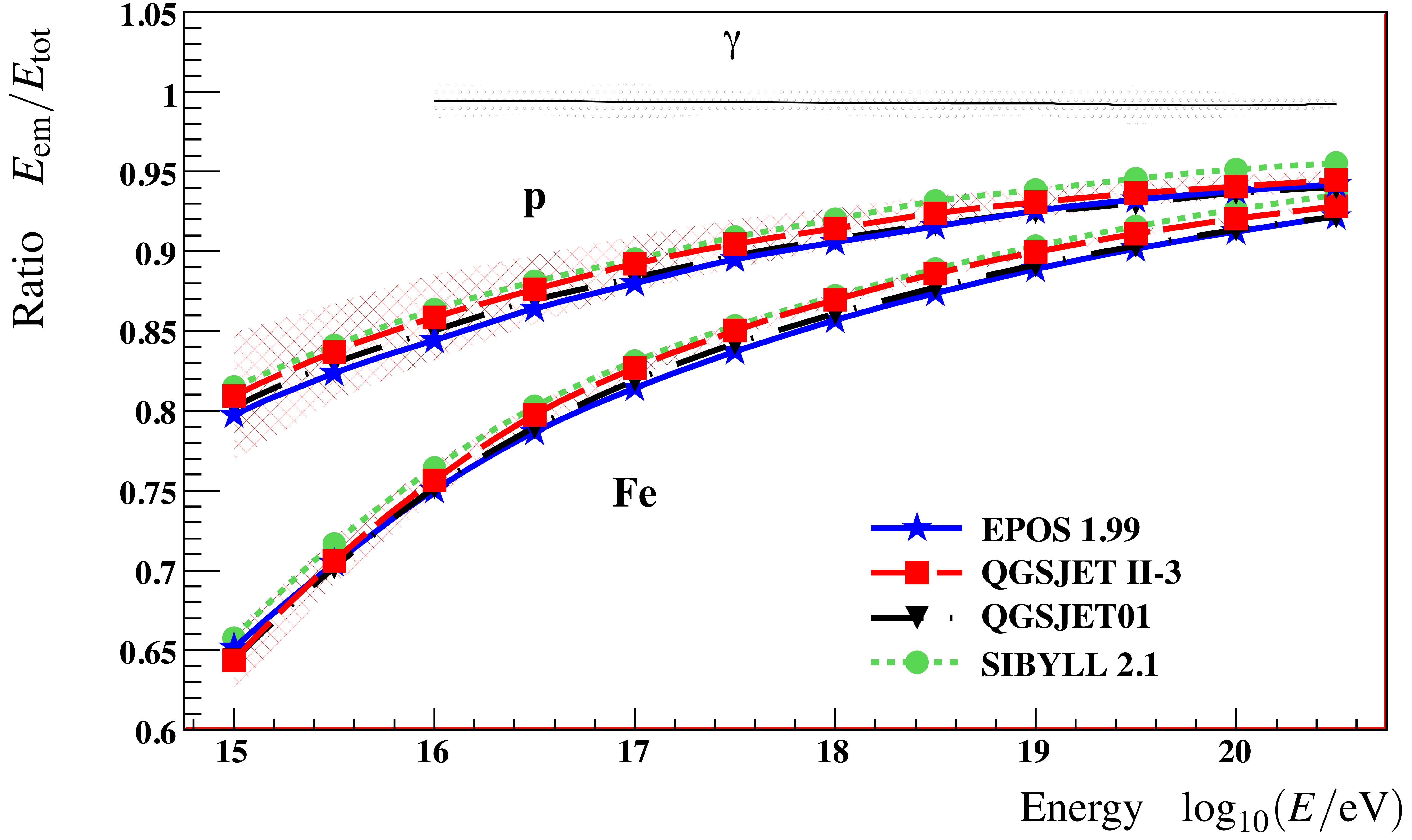
$$\frac{1}{3}E_0 + \frac{1}{3}\left(\frac{2}{3}E_0\right)$$

∘
∘
∘
∘

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

Energy transferred to electromagnetic component

(RE, Pierog, Heck, ARNPS 2011)



Ratio of em. to total shower energy

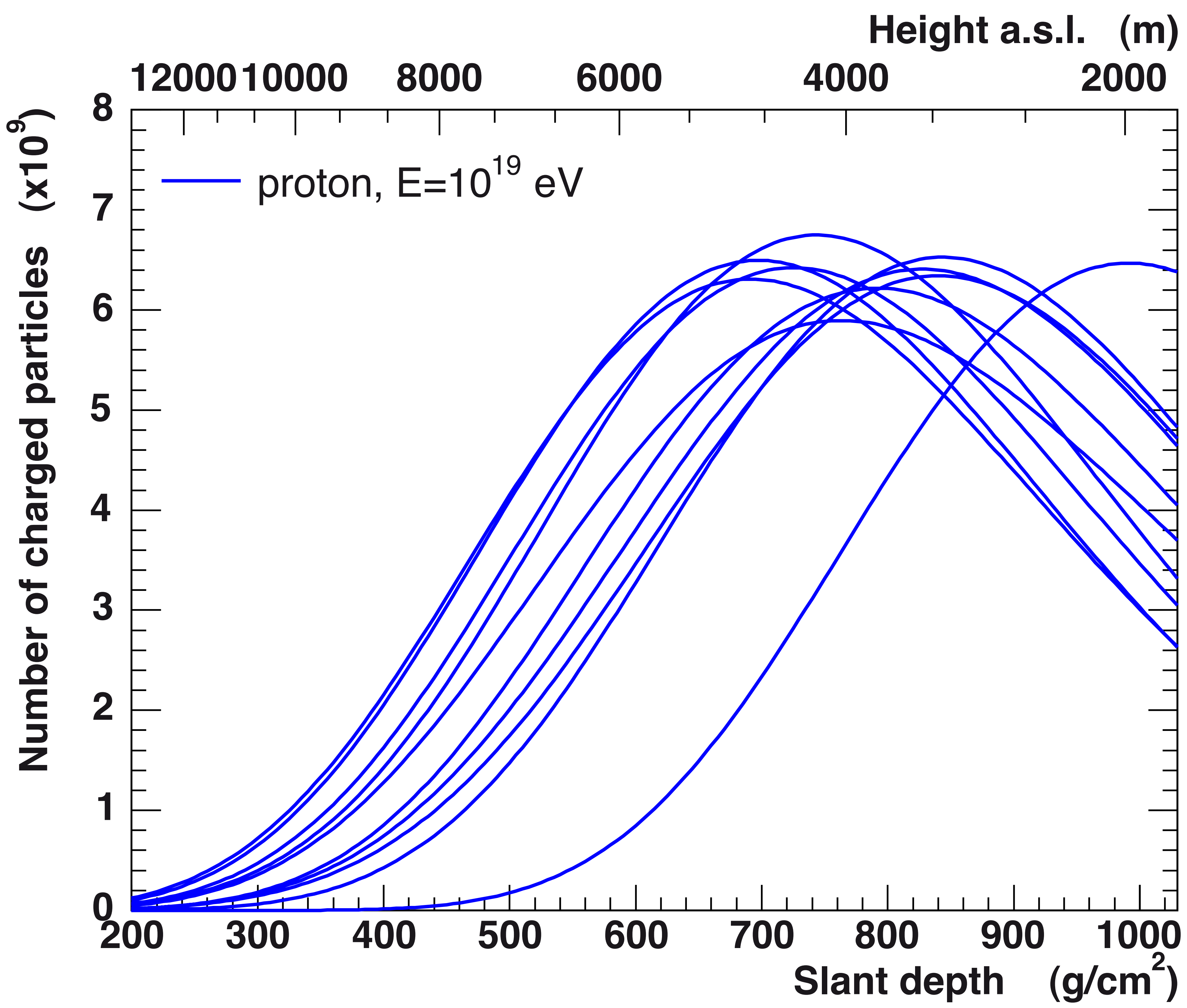
Detailed Monte Carlo simulation with CONEX

$$E_{\mathrm{inv}} = E_{\mathrm{tot}} - E_{\mathrm{em}}$$

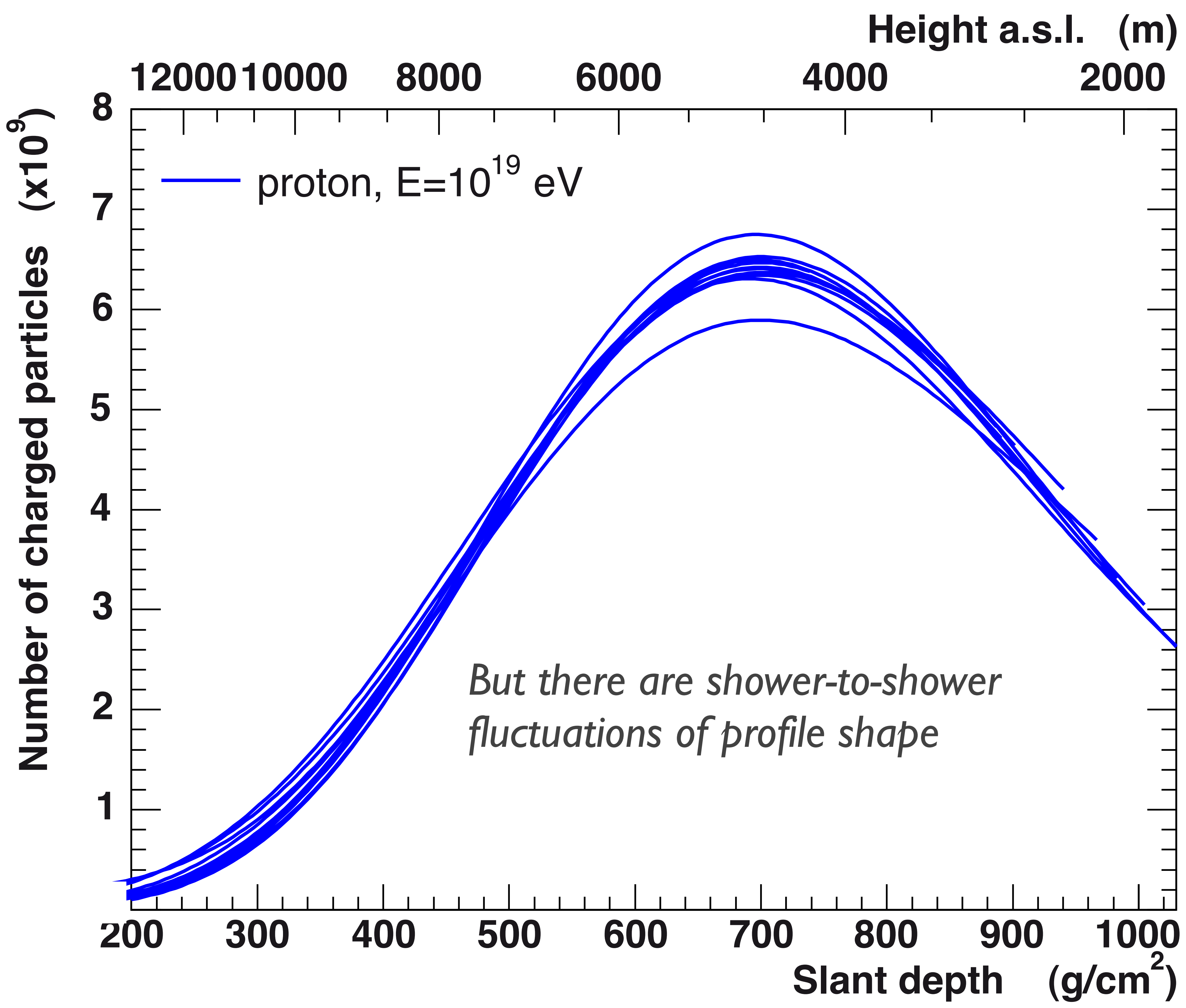
At high energy: model dependence of correction to obtain total energy small

Universality features of high-energy shower profiles

Simulated shower profiles



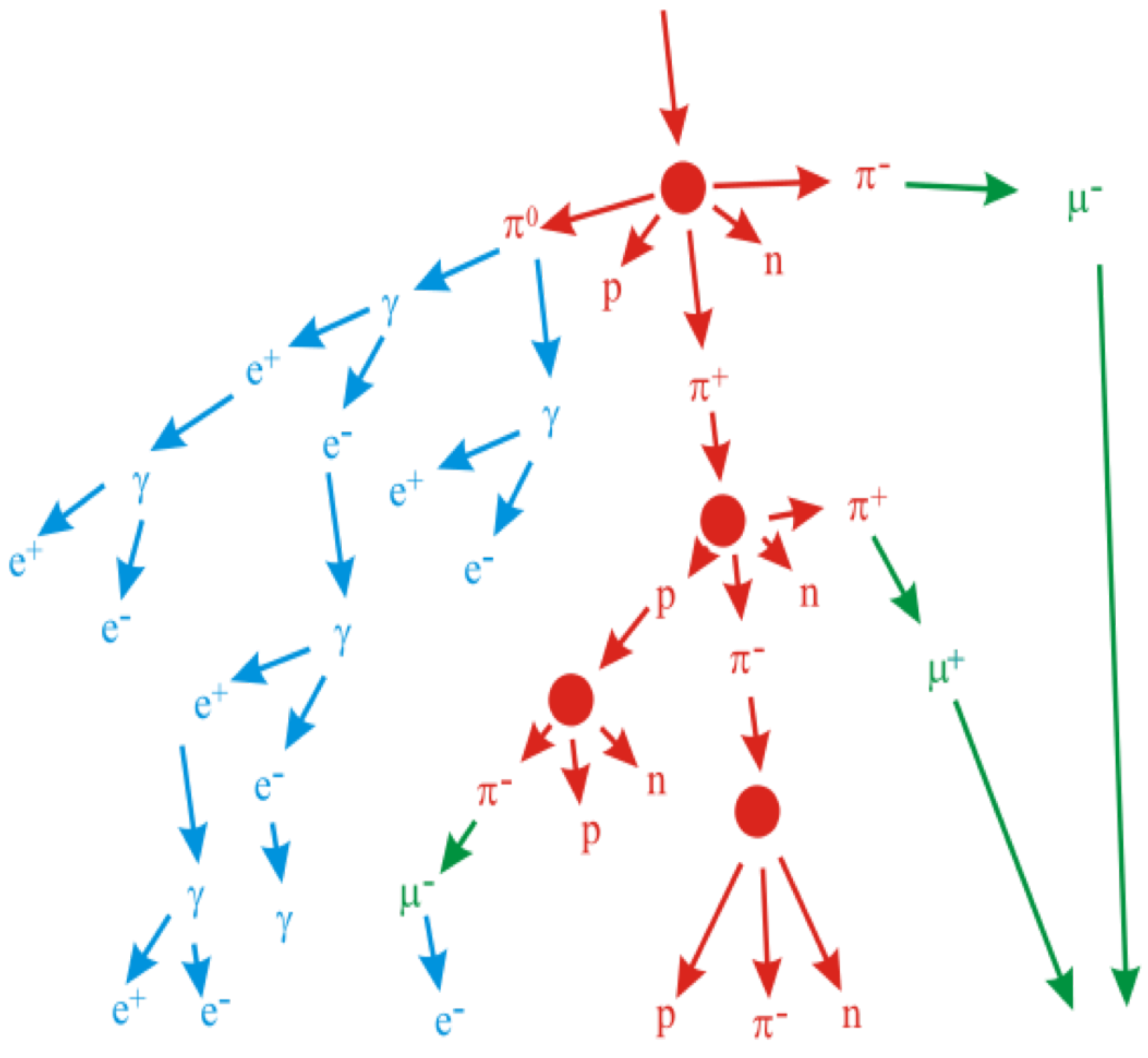
Profiles shifted in depth

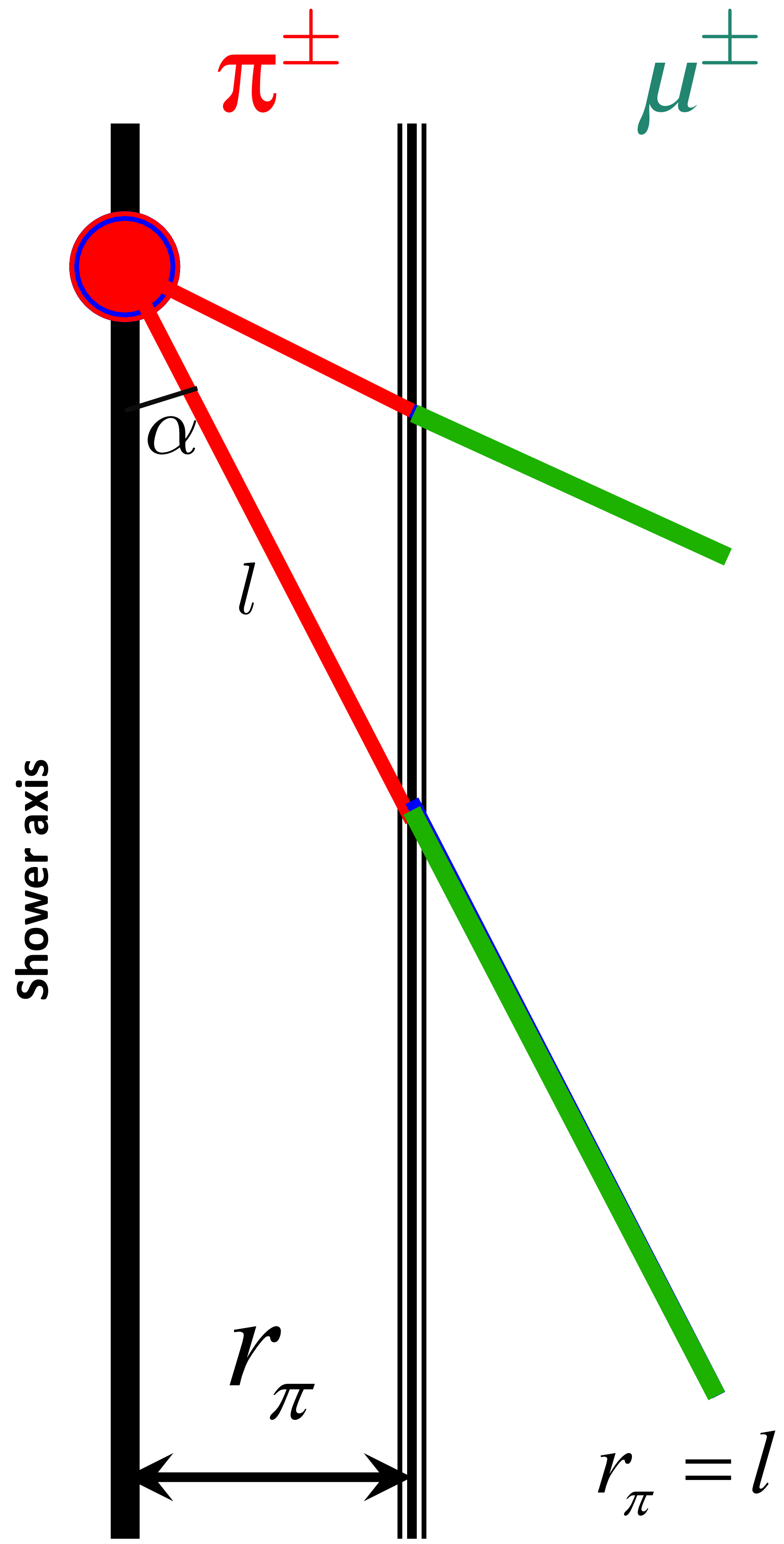


But there are shower-to-shower fluctuations of profile shape

Depth of first interaction X_I and X_{max} strongly correlated, use X_{max} for analysis

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

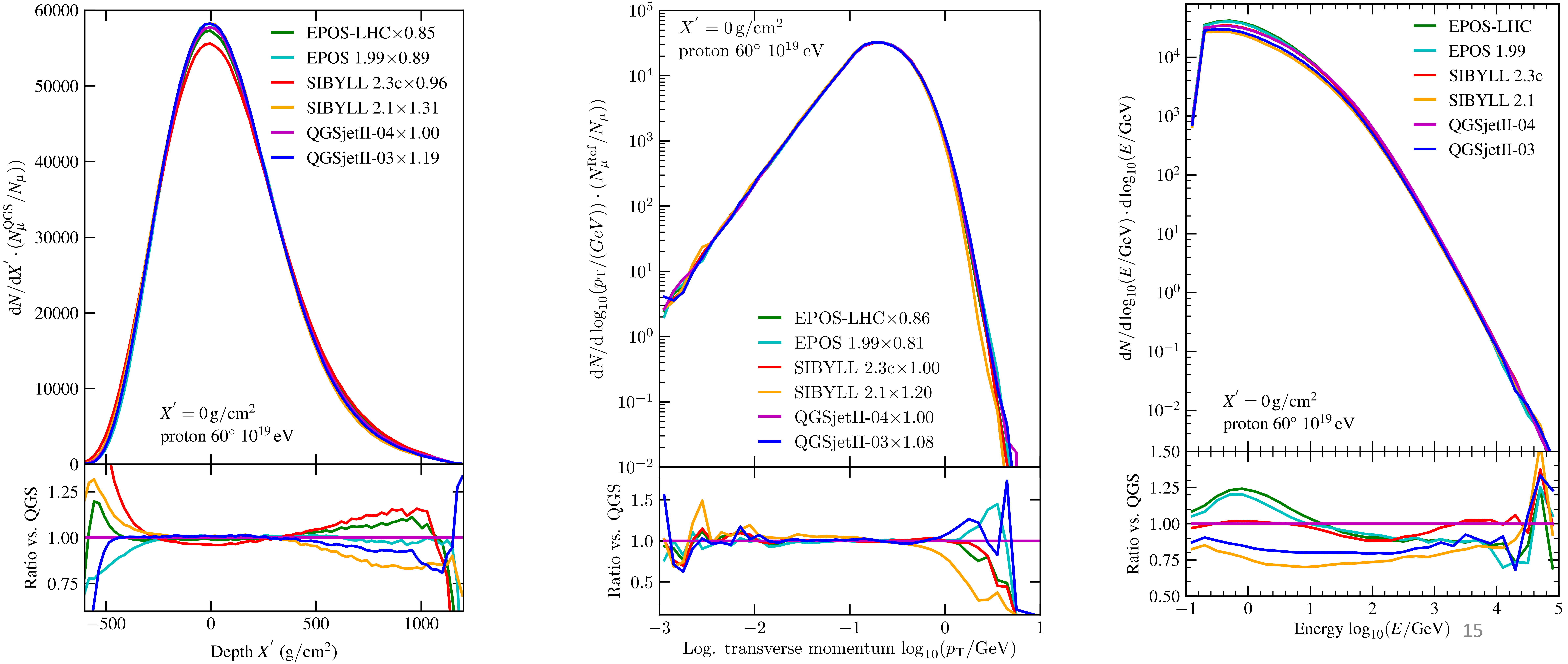
59% of all muons

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

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

70% of fluctuations from first interaction

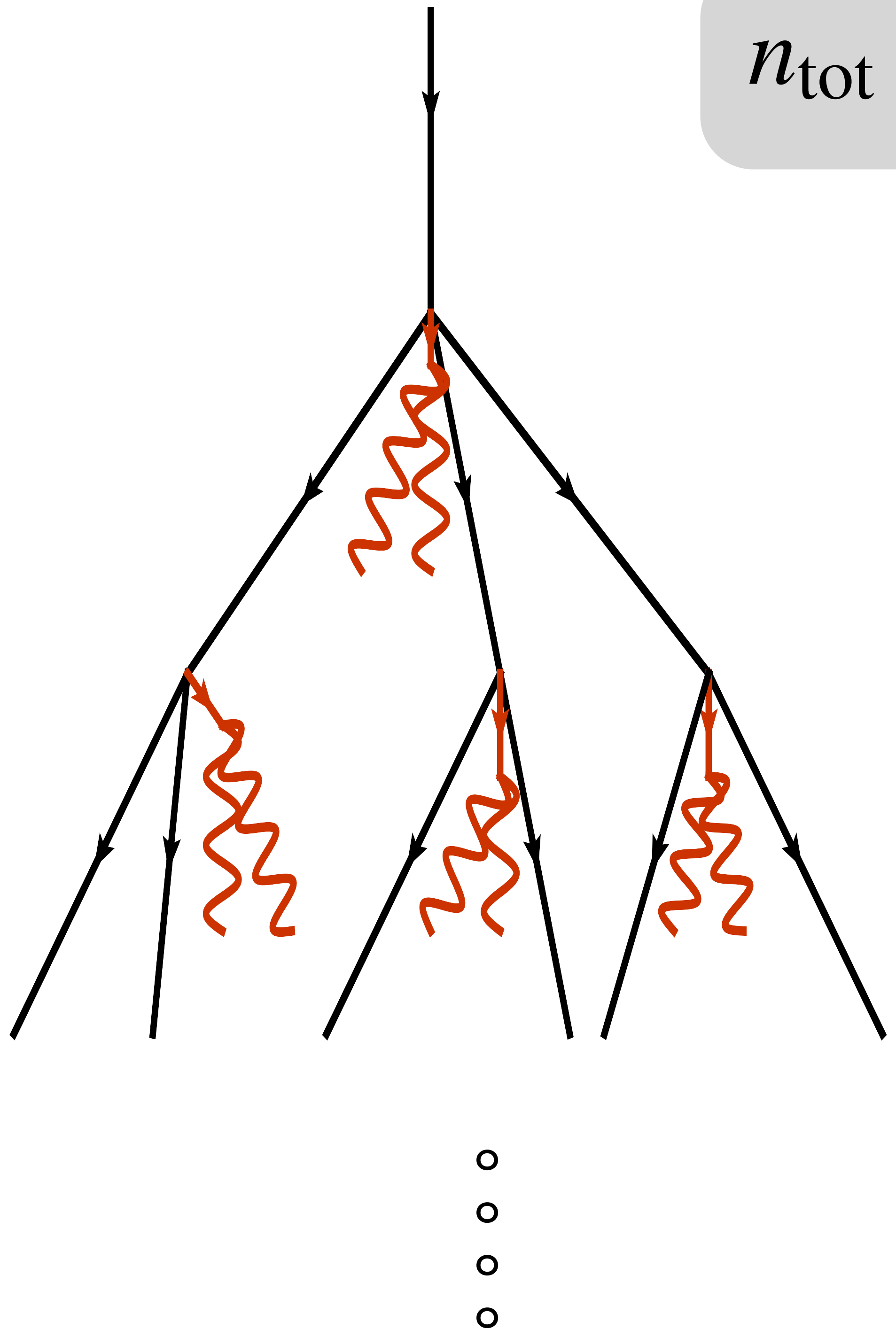
Universality features of muon production



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

Muon production in hadronic showers

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



E_0

E_0/n_{tot} $\qquad n_{\text{ch}}$

$E_0/(n_{\text{tot}})^2$ $\qquad (n_{\text{ch}})^2$

$E_0/(n_{\text{tot}})^n$ $\qquad (n_{\text{ch}})^n$

Primary particle proton

π^0 decay immediately

$\pi^\pm$ initiate new cascades

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

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

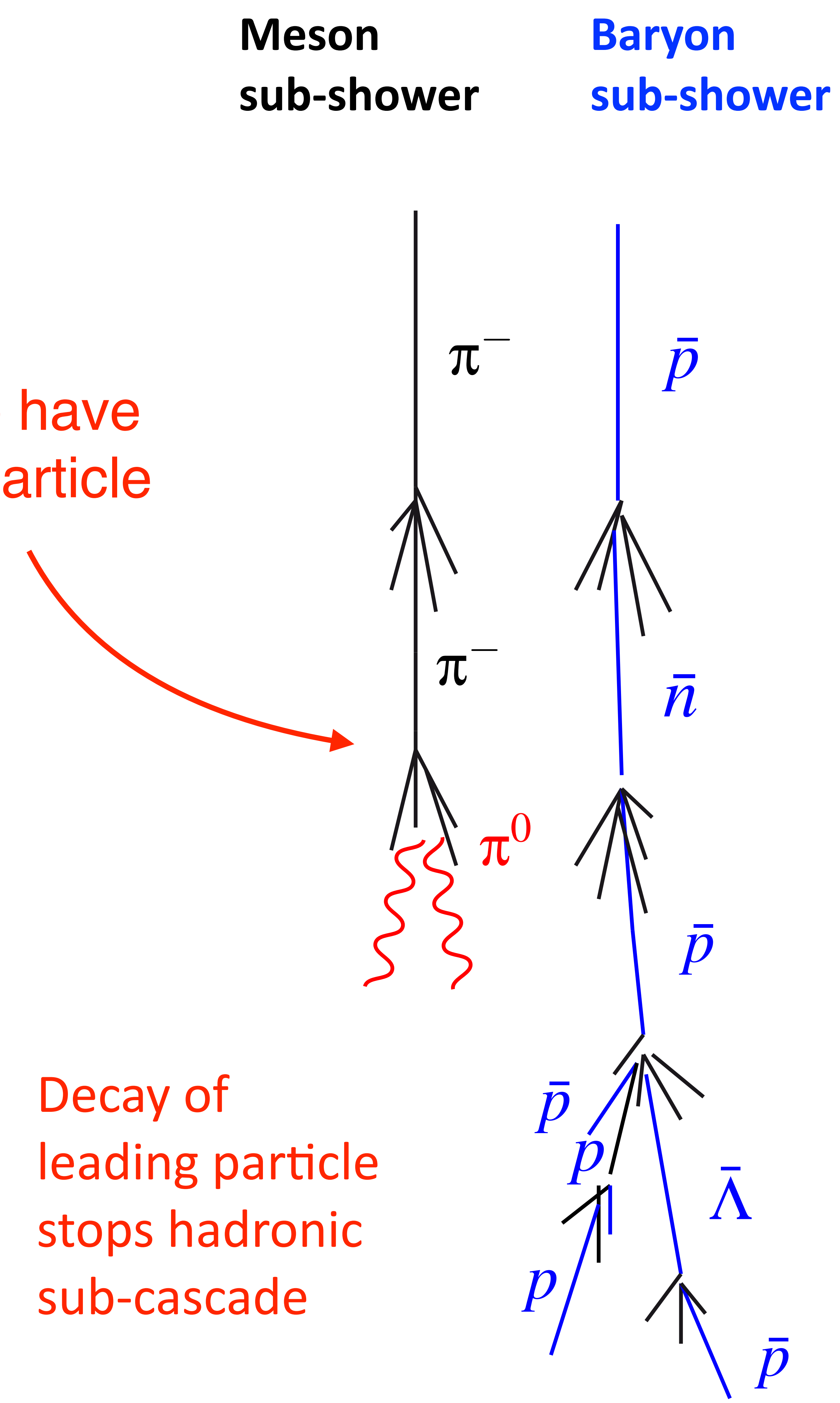
$$\beta = \frac{\ln n_{\text{ch}}}{\ln n_{\text{tot}}} \approx 0.82 \ldots 0.95$$

Assumptions:

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

(Matthews, Astropart.Phys. 22, 2005)

Muon production depends on hadronic energy fraction



30% chance to have π⁰ 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. 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

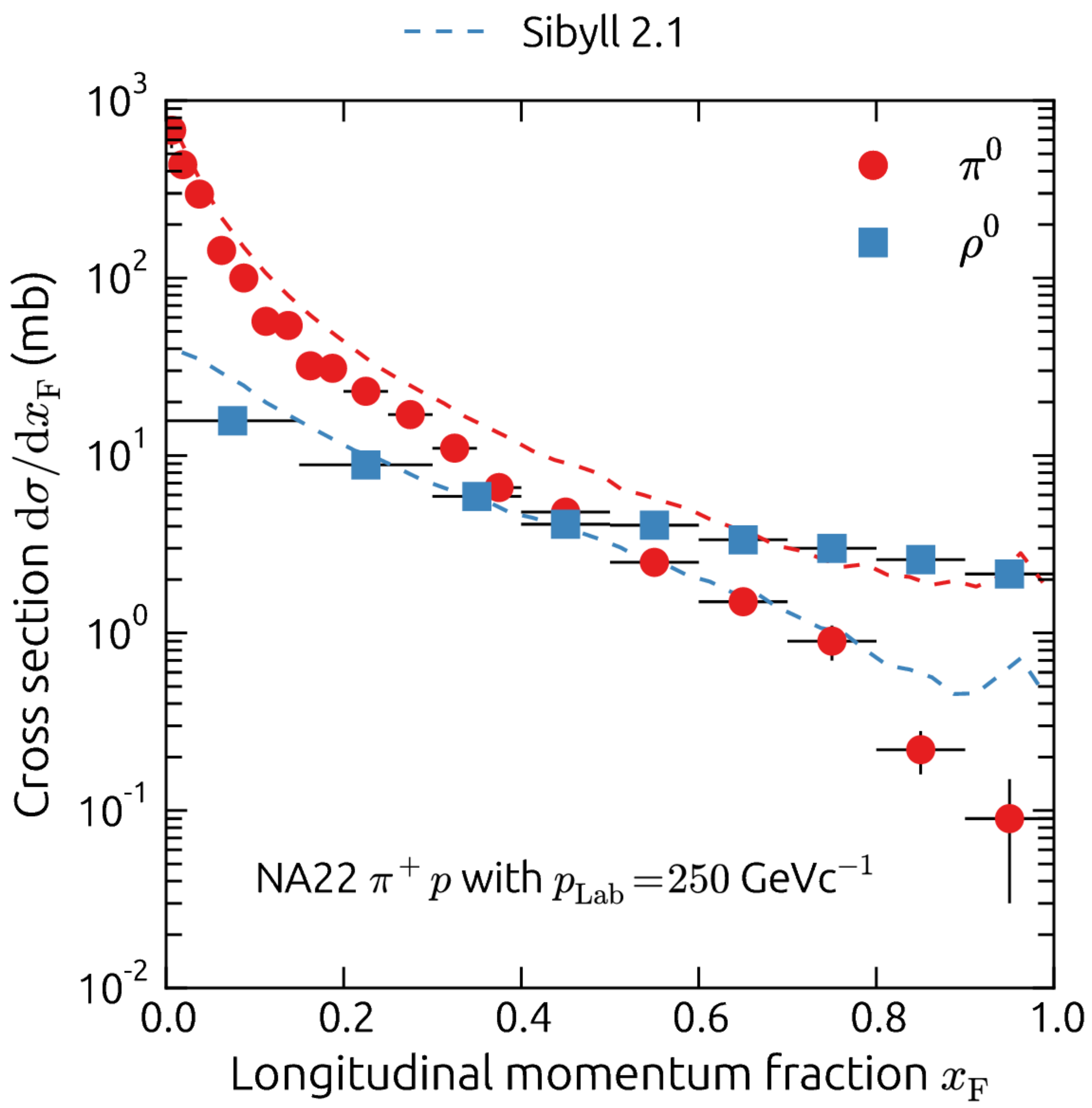
4 New hadronic physics at high energy *(Farrar, Allen 2012, Salamida 2009)*

- 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)

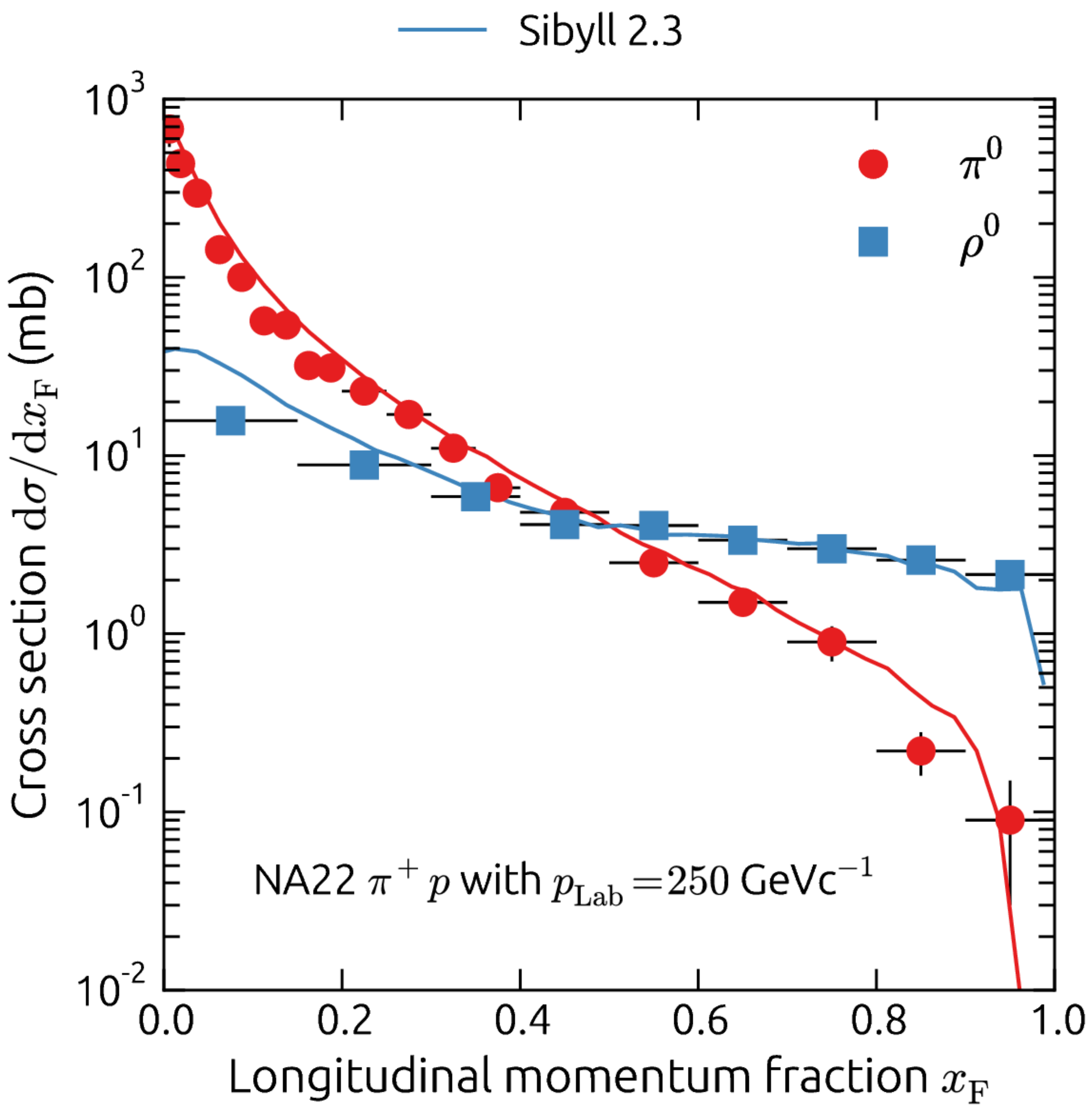
Leading particle production



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

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

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

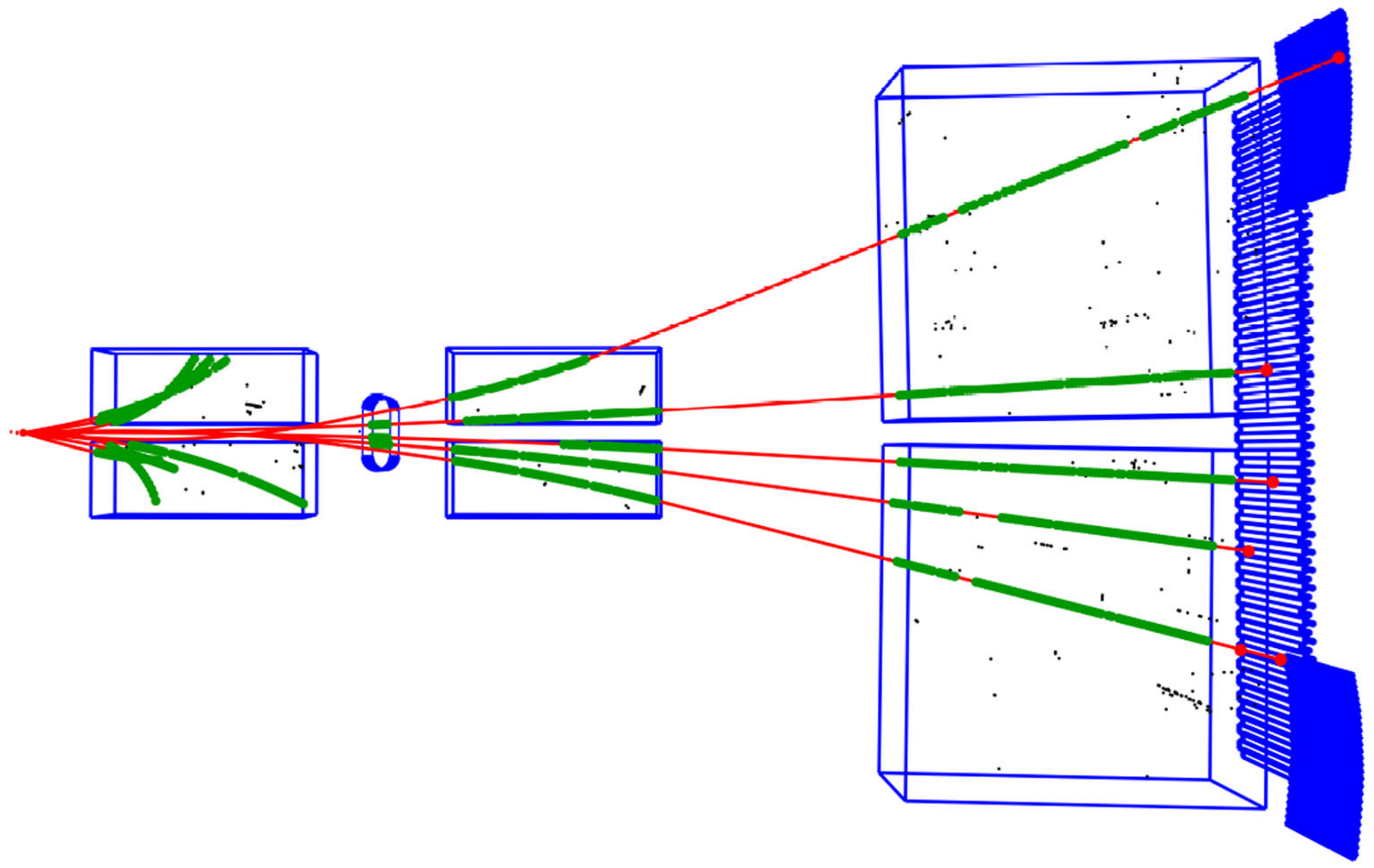


$$x_F = p_{\|} / p_{\max}$$

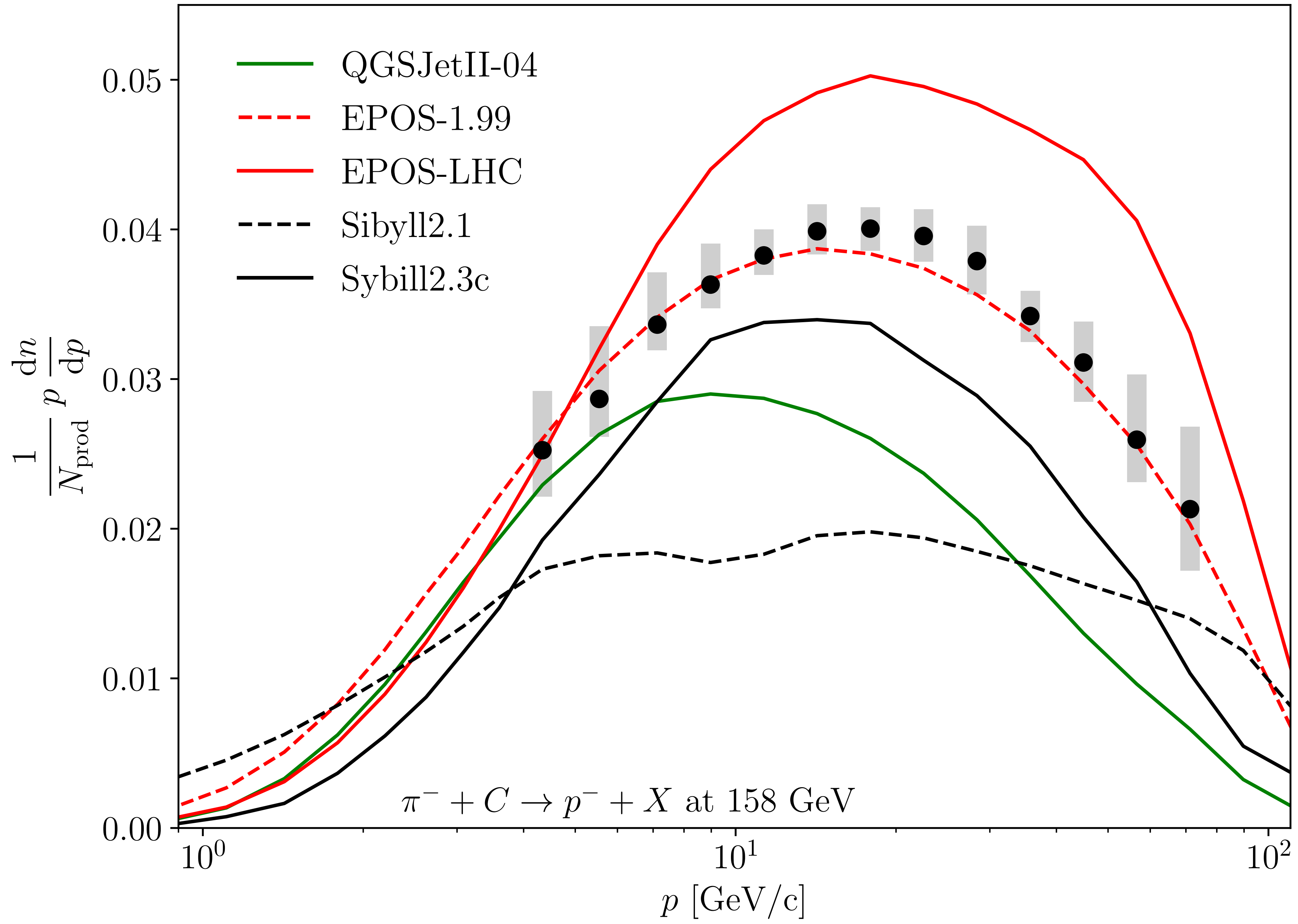
(Riehn et al., ICRC 2015)

NA61 experiment at CERN SPS

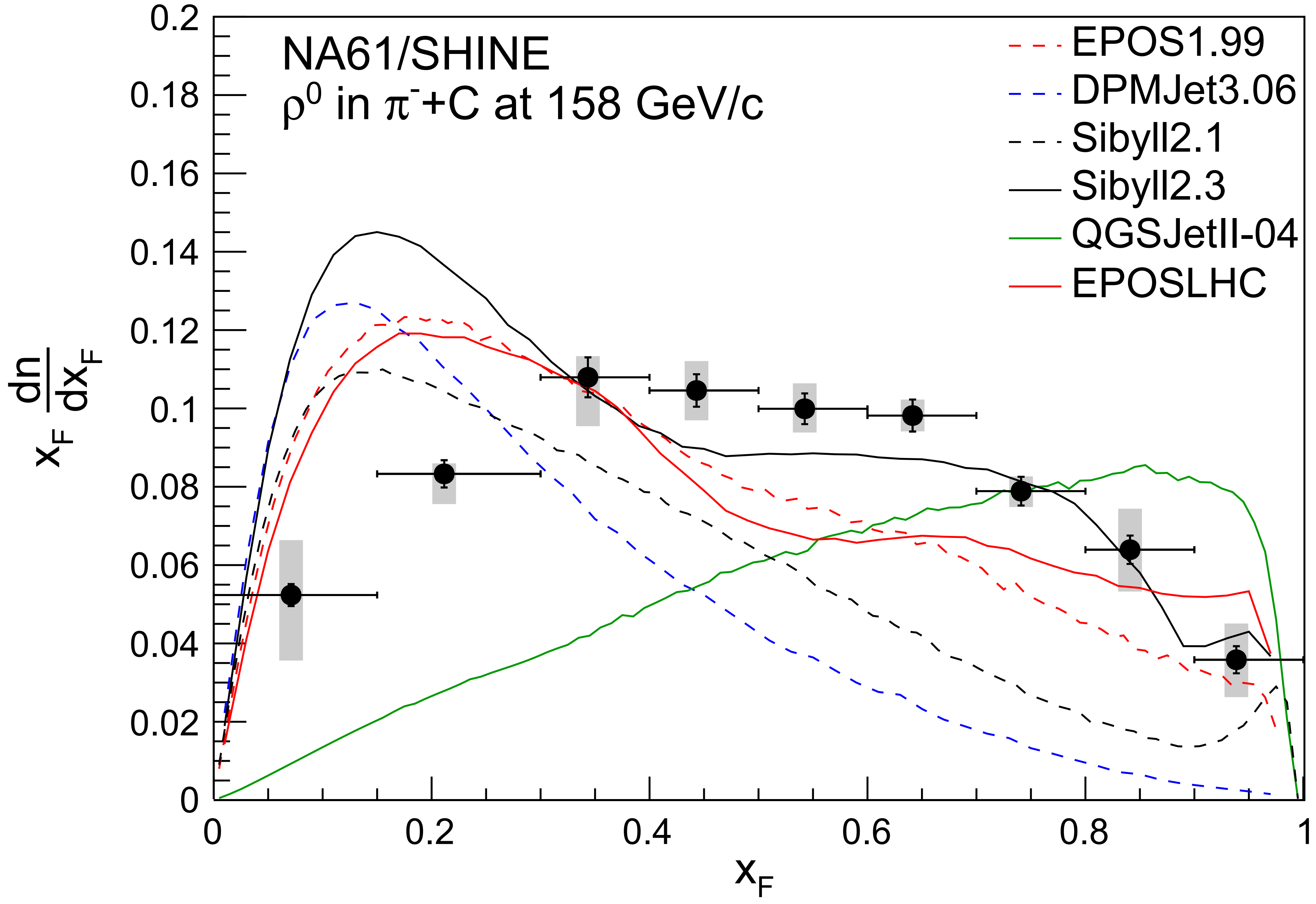
Dedicated cosmic ray runs
(π-C at 158 and 350 GeV)



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

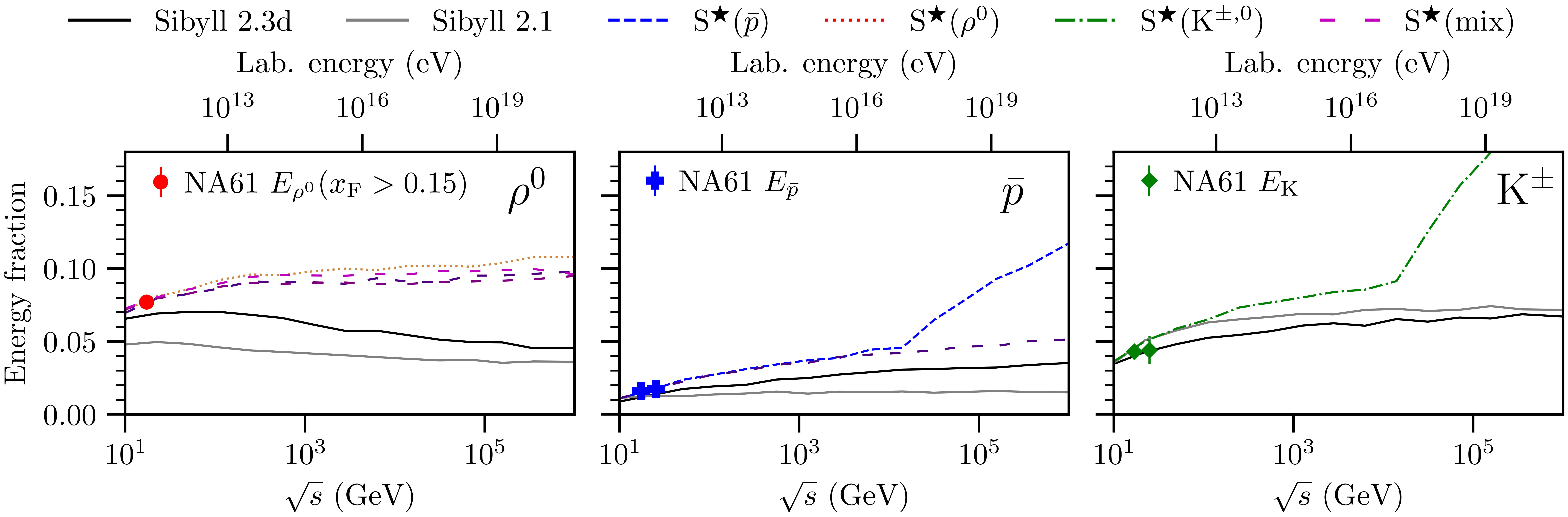


$\pi^- C \rightarrow \rho^0 X \rightarrow \pi^+\pi^- X$



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

Simple and pragmatic approach – Sibyll*



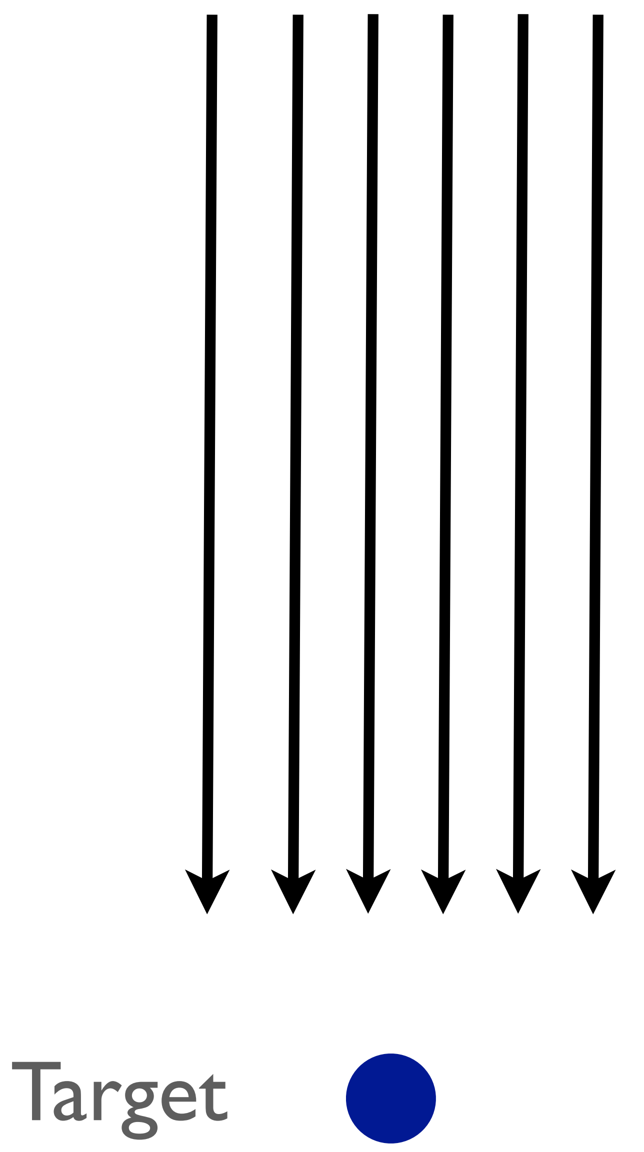
Modification of Sibyll 2.3d to study different versions of muon enhancement

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

Implications of the muon discrepancy

Superposition model

$$E_i = E_0/A$$



Energy dependence of muon production

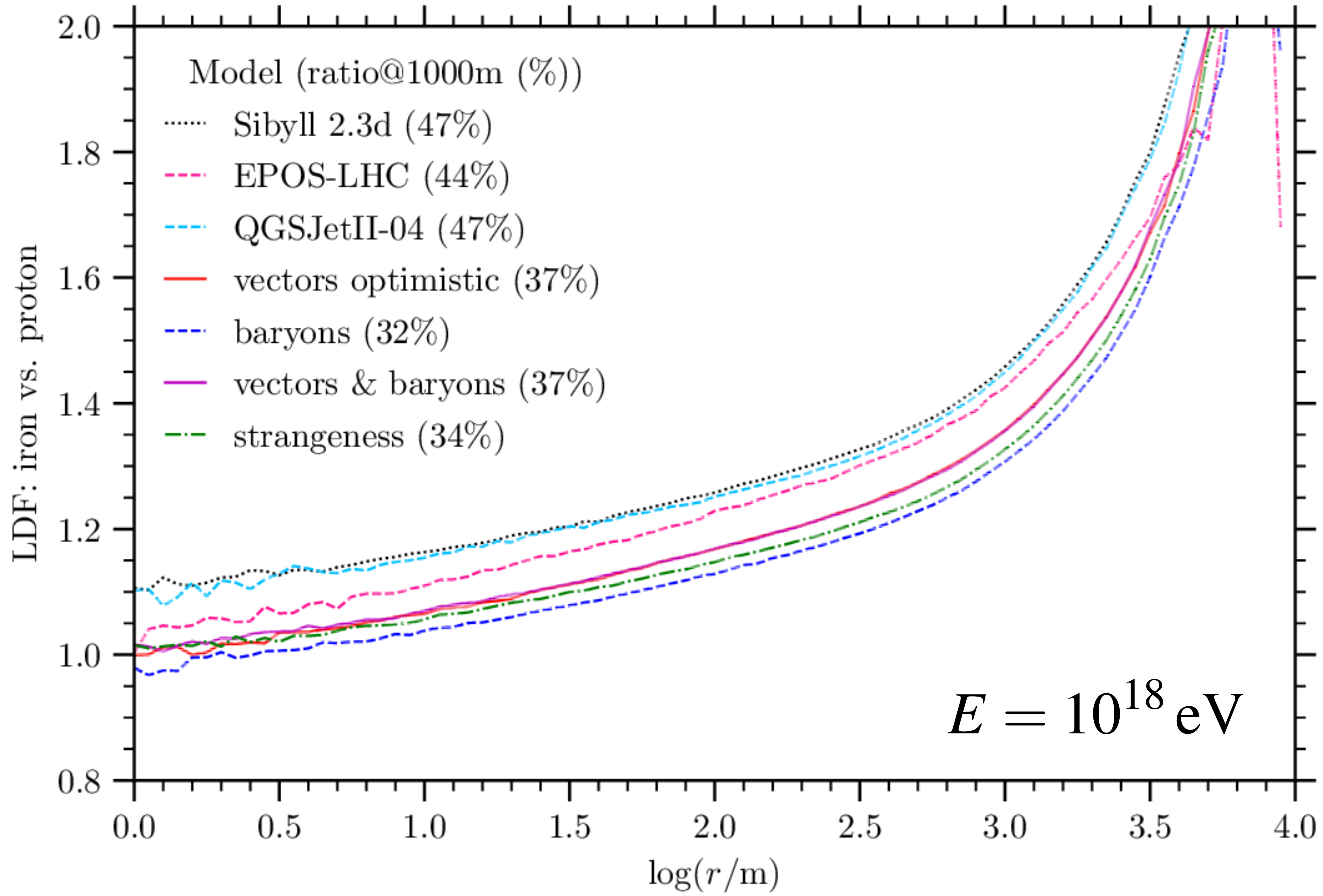
$$N_\mu = \left(\frac{E_0}{E_\mathrm{dec}}\right)^\beta \qquad \beta \sim 0.9$$

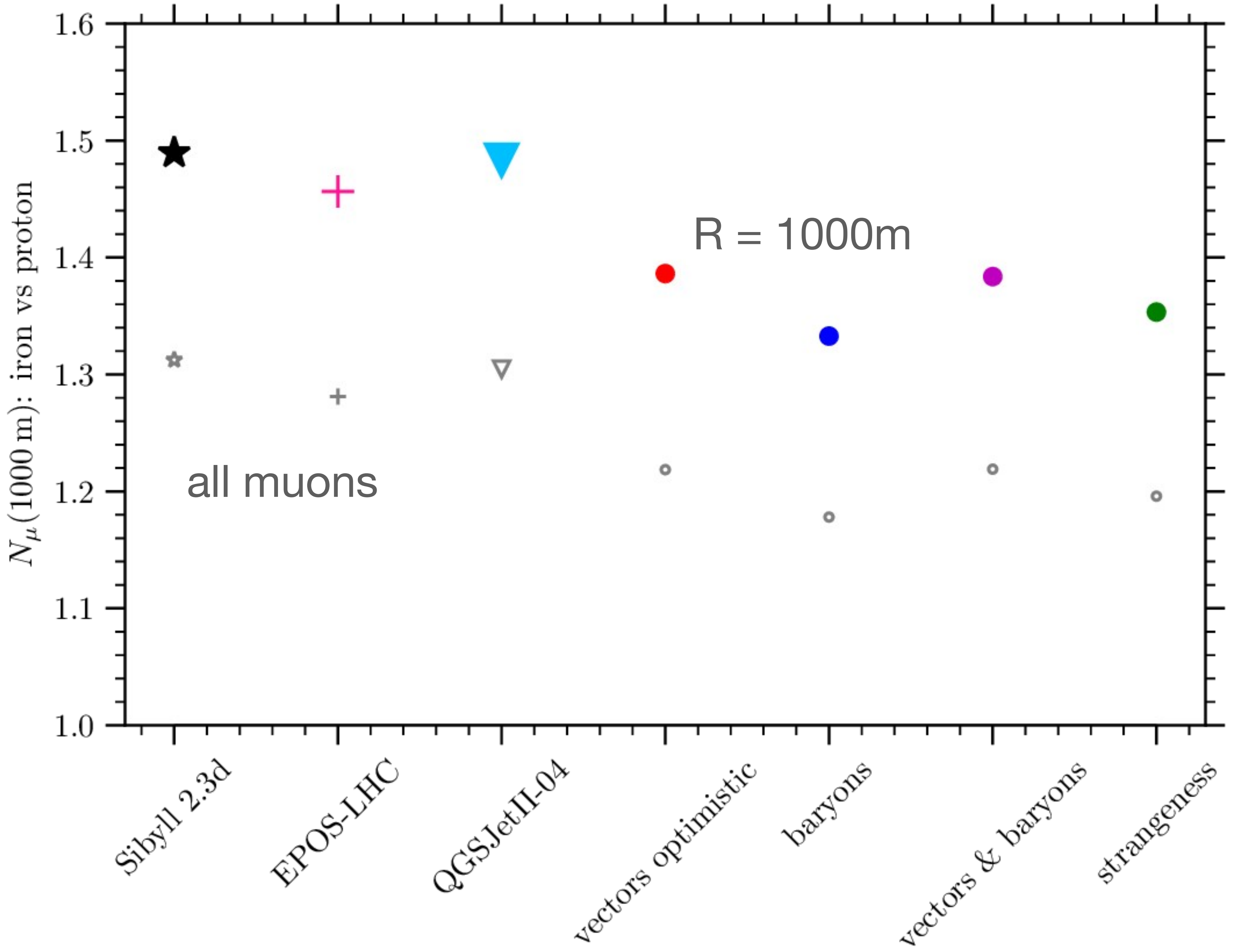
$$N_\mu^A = A\left(\frac{E_0}{AE_\mathrm{dec}}\right)^\beta = A^{1-\beta} N_\mu$$

To increase predicted muon number: increase hadronic fraction wrt π⁰

β	N_μ^A / N_μ
0.90	1.49
0.92	1.37
0.94	1.27
0.96	1.17

Model predictions for muon ratio of iron to proton



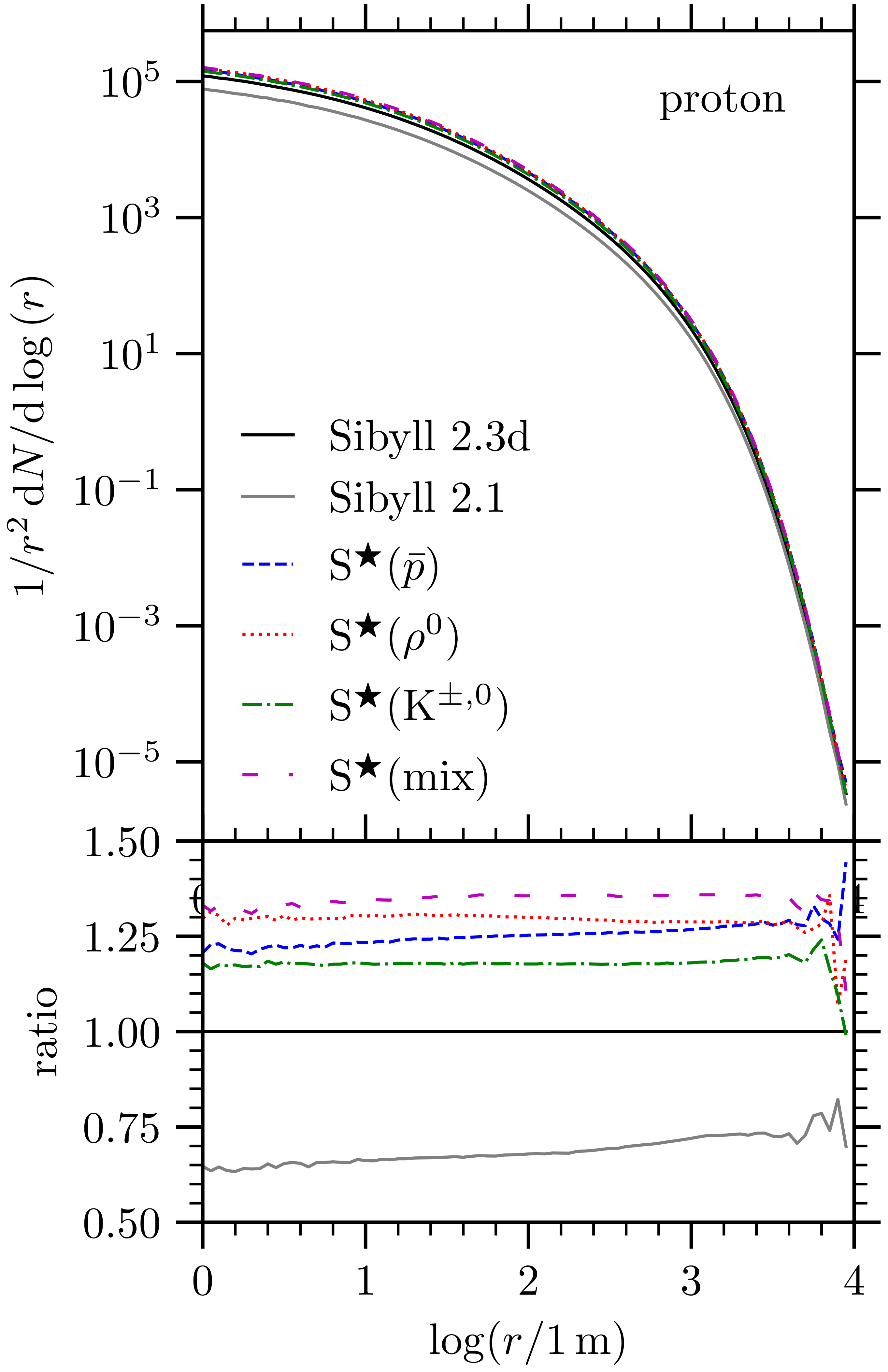


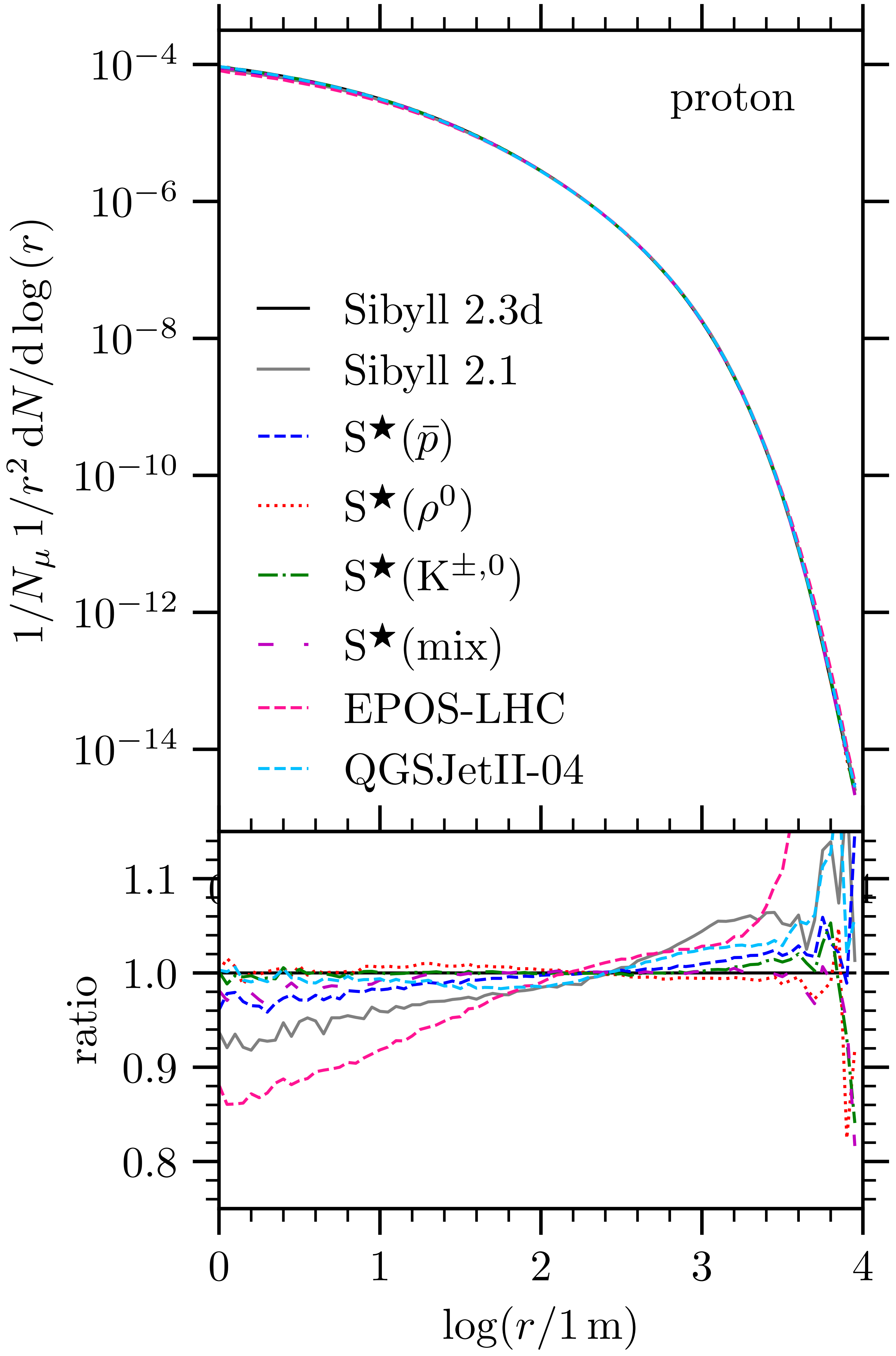
Old model versions
(parameters for all muons)

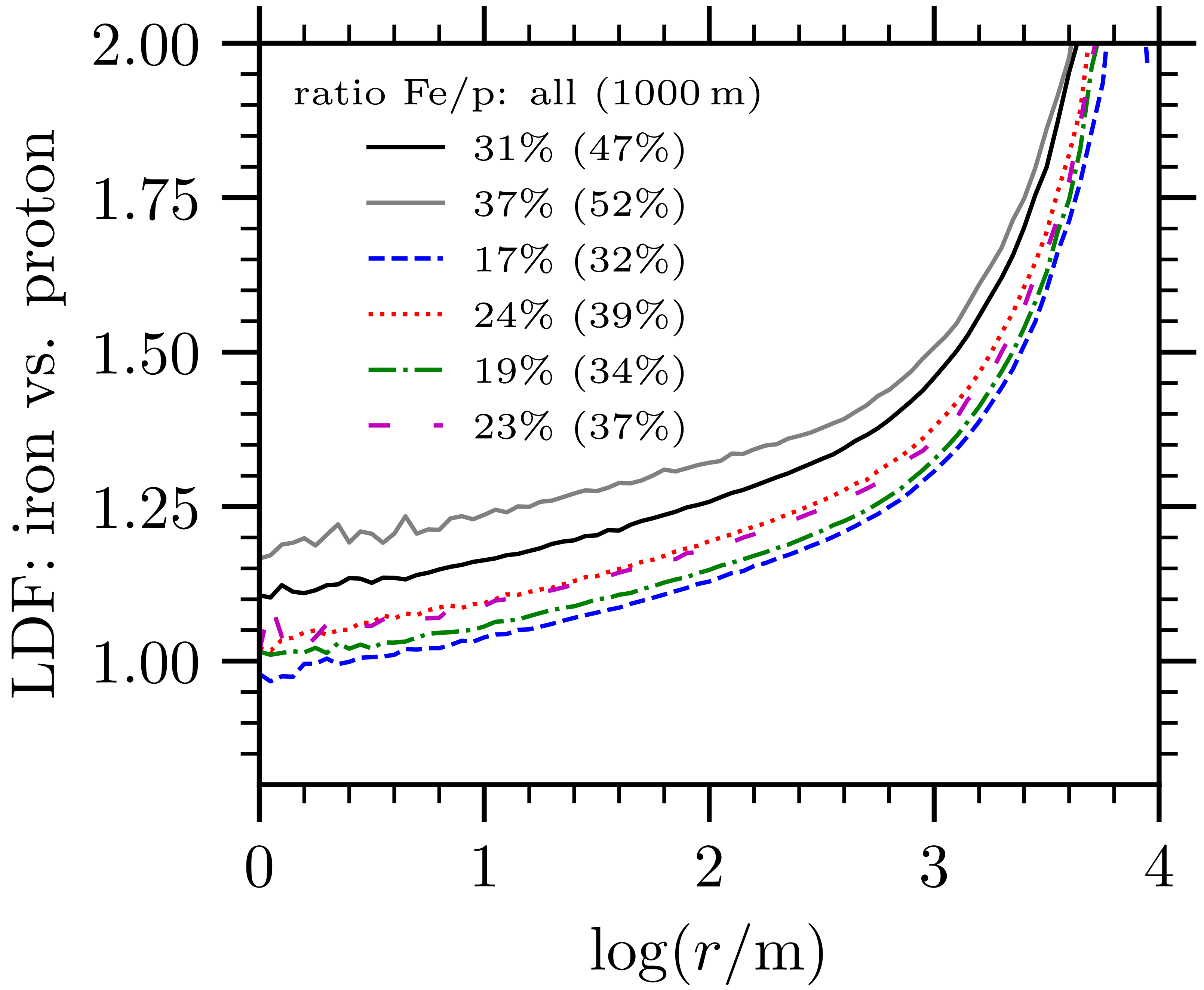
Model	SIBYLL 1.7					SIBYLL 2.1					QGSJET98				
E_μ^{thr} [GeV]	0.3	1	3	10	30	0.3	1	3	10	30	0.3	1	3	10	30
α	0.886	0.877	0.869	0.857	0.846	0.901	0.893	0.884	0.872	0.861	0.920	0.913	0.904	0.893	0.882
E_c [GeV]	35	43	67	162	594	39	47	70	161	555	44	53	79	182	638

(Felix Riehn et al.)

Importance of lateral distribution

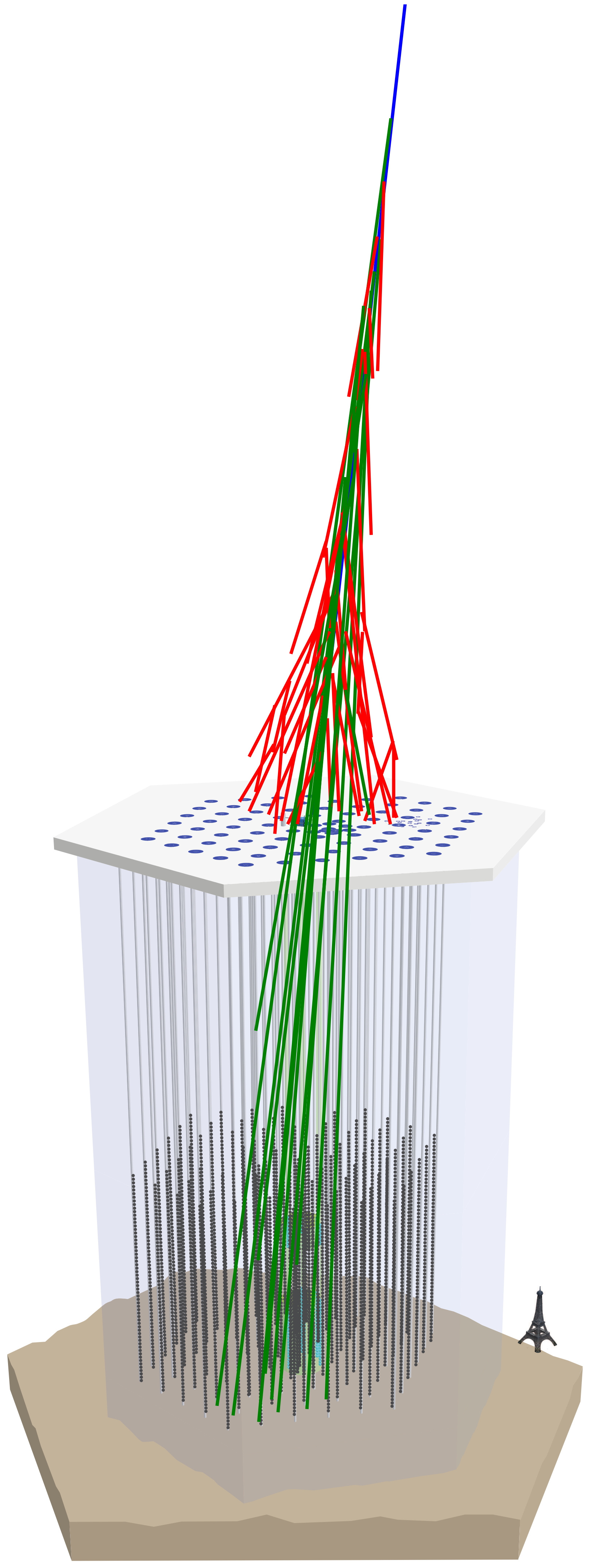






Importance of energy threshold (energy spectrum)

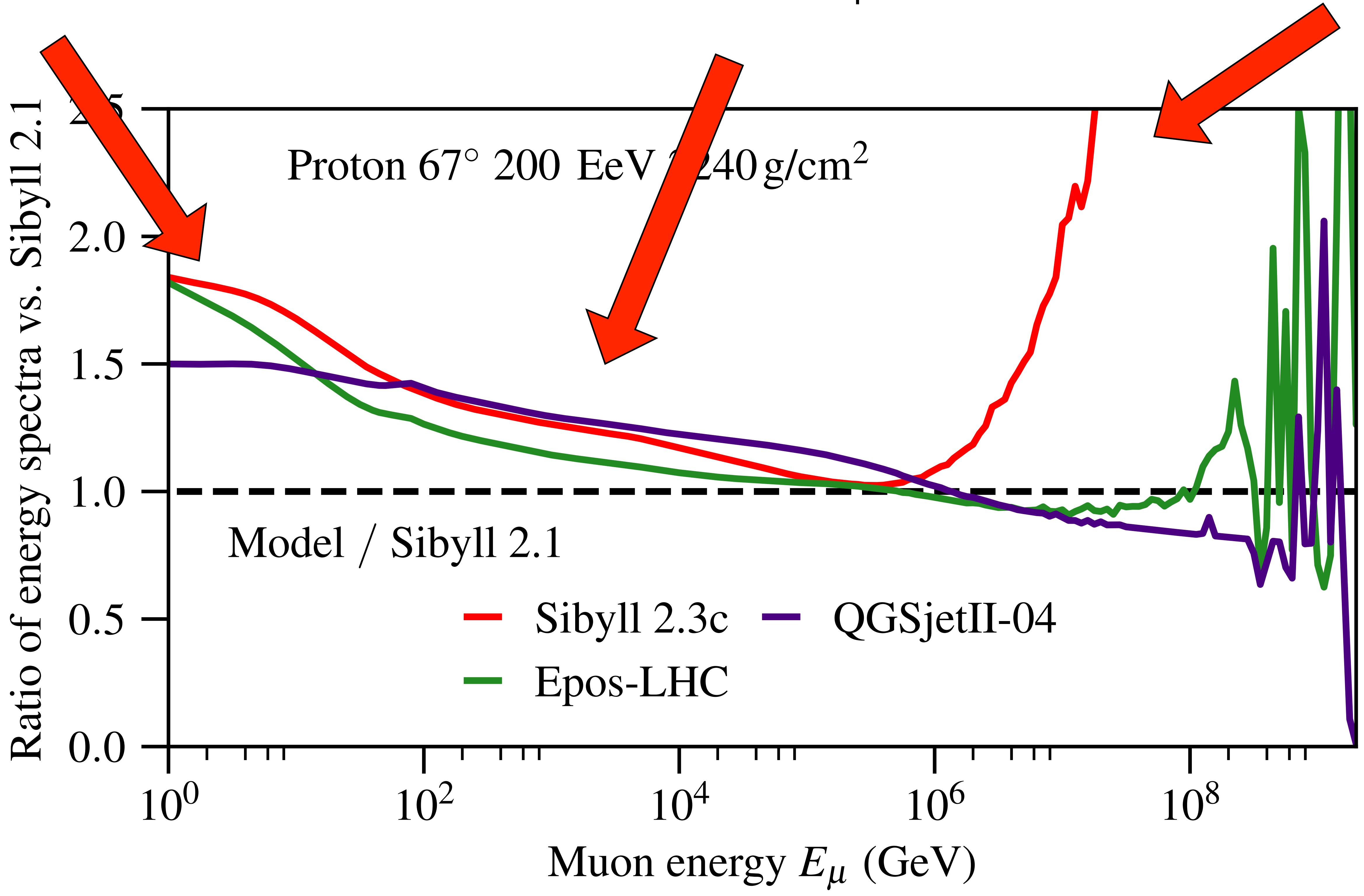
Muon energy spectrum in EAS relative to that of Sibyll 2.1



Low-energy enhancement due to baryon pair production

Rho-0 production

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

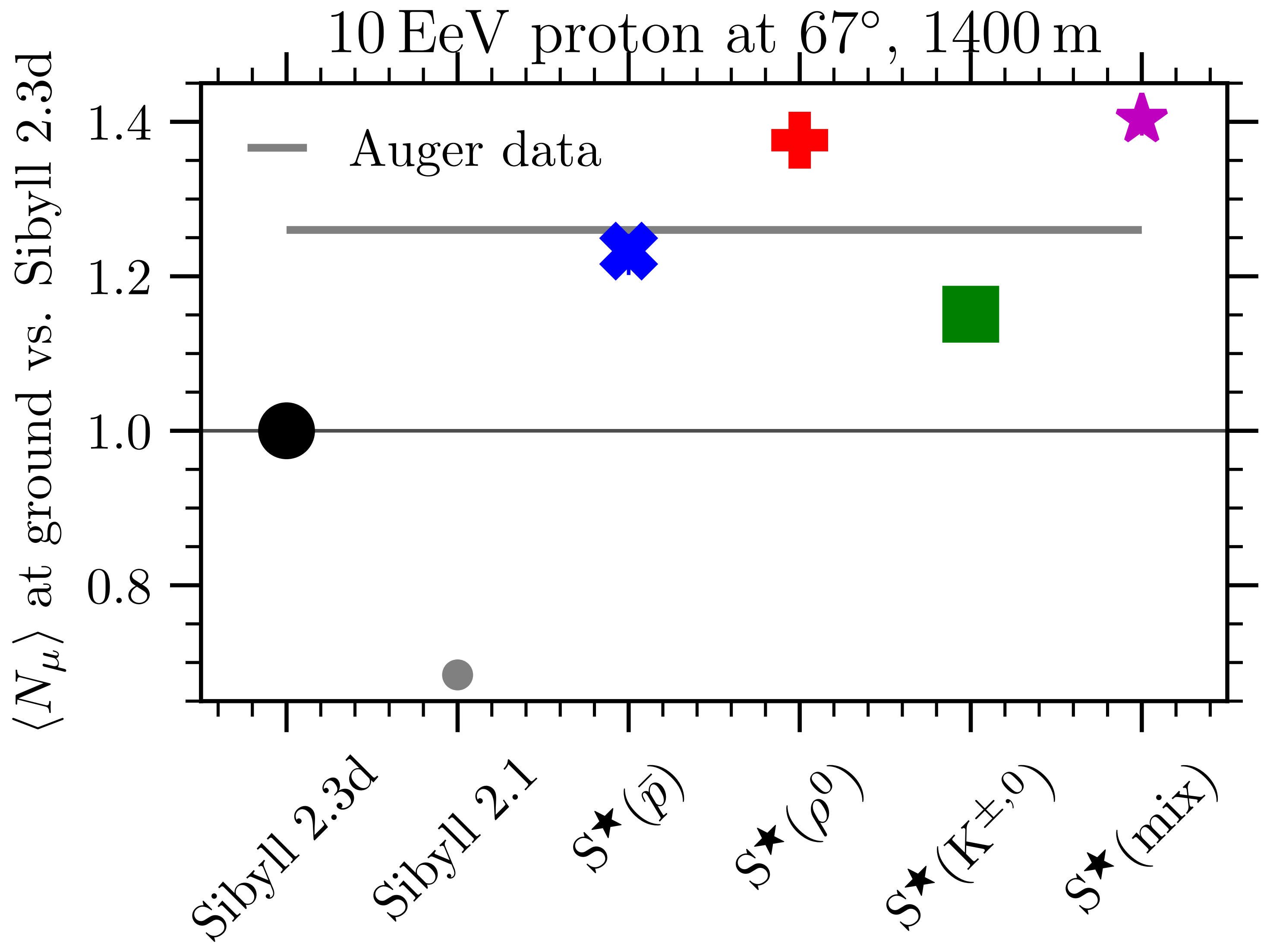


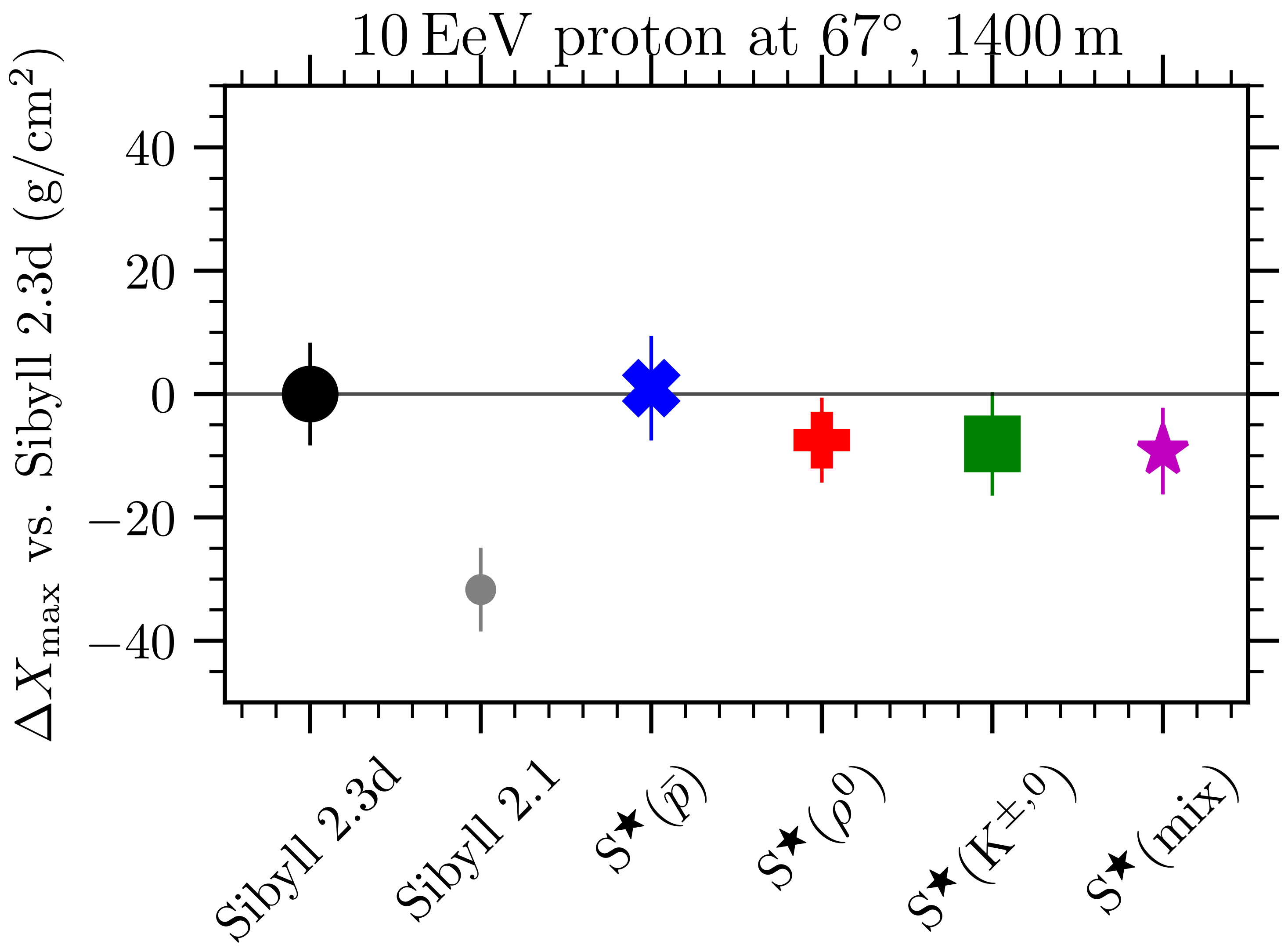
Correlation of low energy muons (surface ~ 1GeV) and in-ice (~500 GeV) muon bundles

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

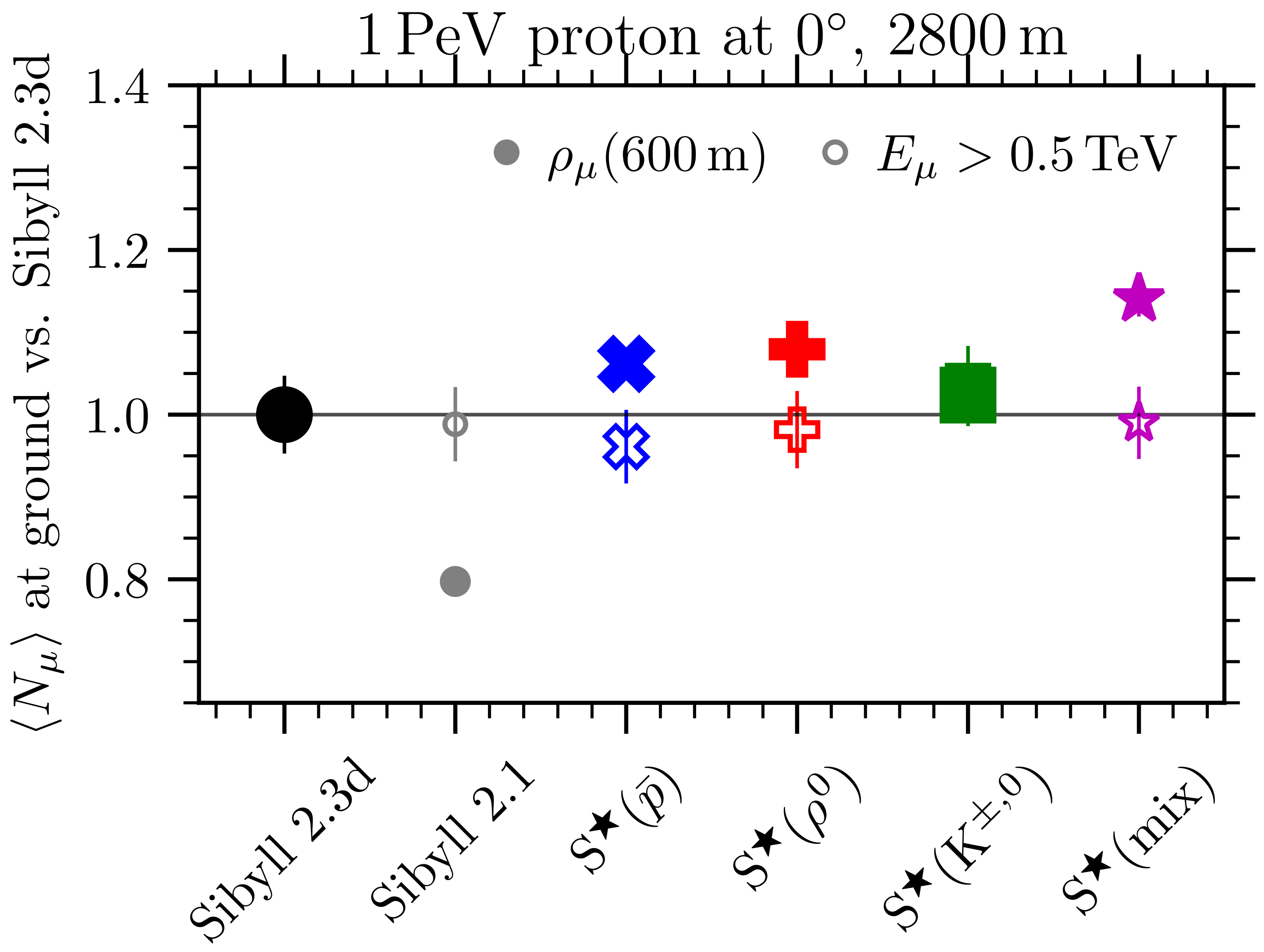
Shower predictions calculated with Sibyll*

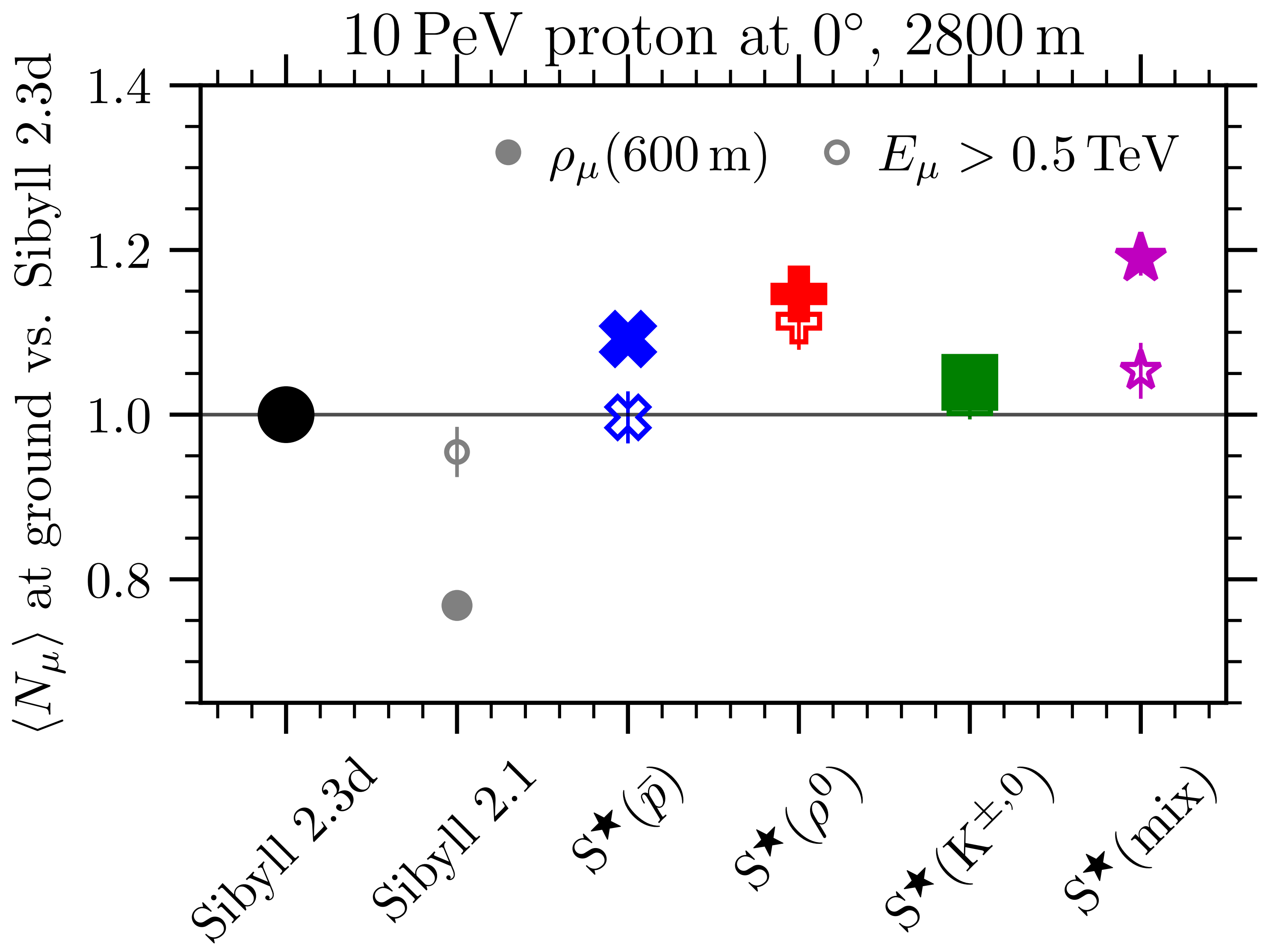
Auger Observatory





IceCube/IceTop

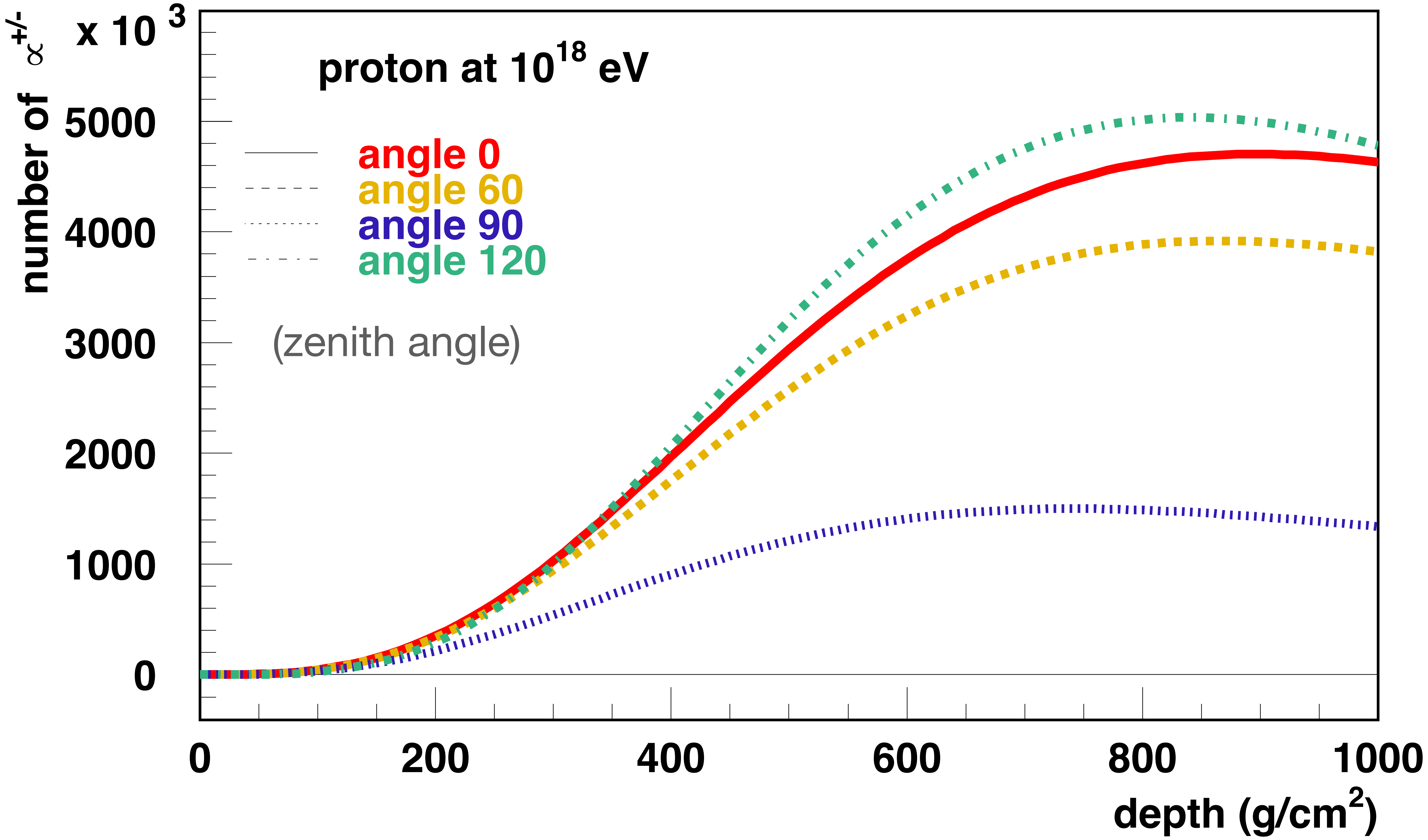




Importance of zenith angle (air density)

(Bergmann et al,
APP 26, 2007)

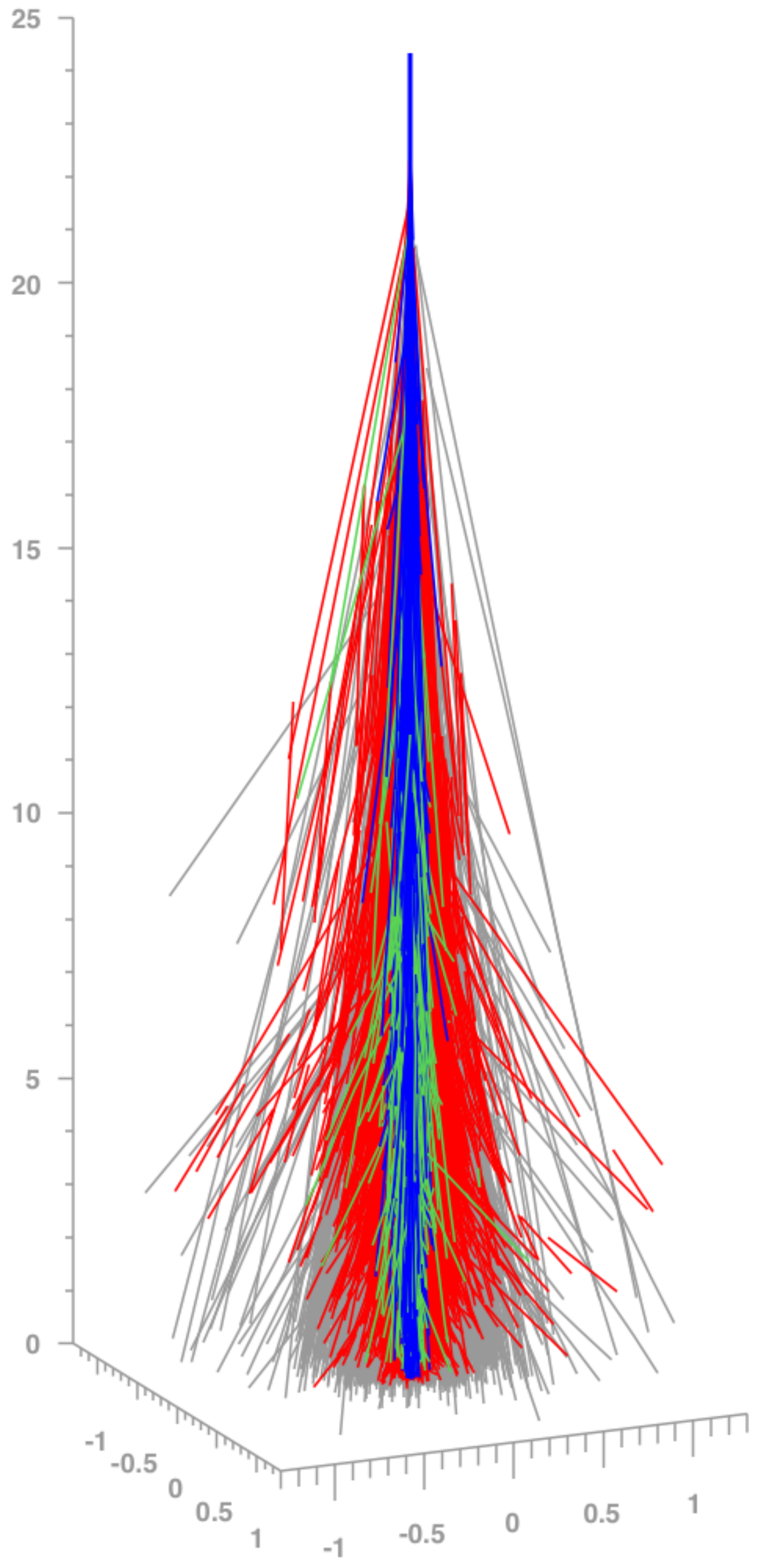
$$N_\mu = \left(\frac{E_0}{E_{\mathrm{dec}}}\right)^{\beta}$$



Pion decay energy depends on air density,
low density corresponds to large E_{dec}

Electromagnetic showers are independent of air density, hadronic showers not

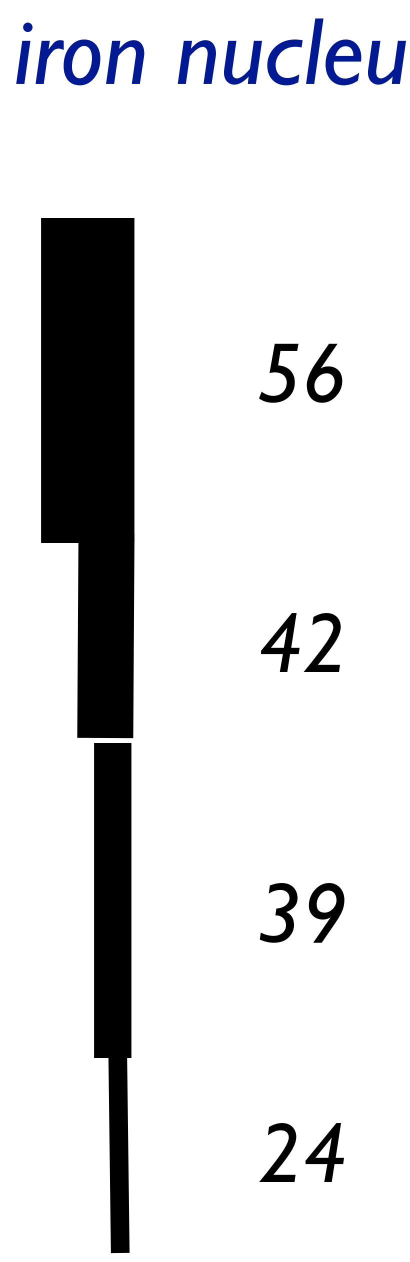
Summary

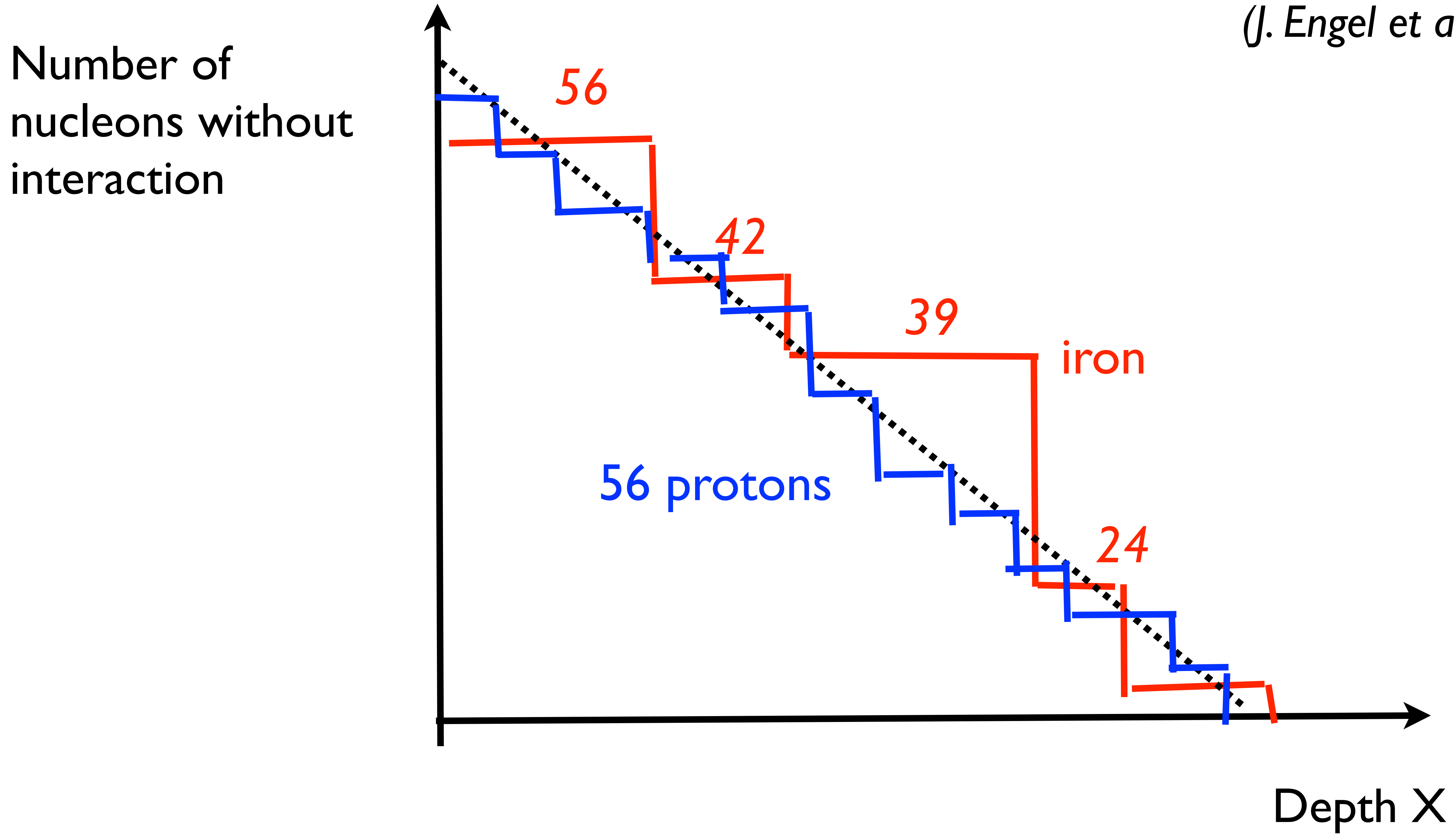


- Production of em. particles and muons very different
- Air showers mainly governed by energy sharing / energy flow
- Challenge of limited collider detector acceptance
- Many universality features (but also large fluctuations)
- Leading particle composition and energy distribution most important
- Detailed simulation of had. interactions needed for ~10–20% level
- Larger number of muons reduces muon composition sensitivity
- Different muon energy thresholds could be key to understanding

Backup slides

Fundamental nature of superposition model





(J. Engel et al. PRD D46, 1992)

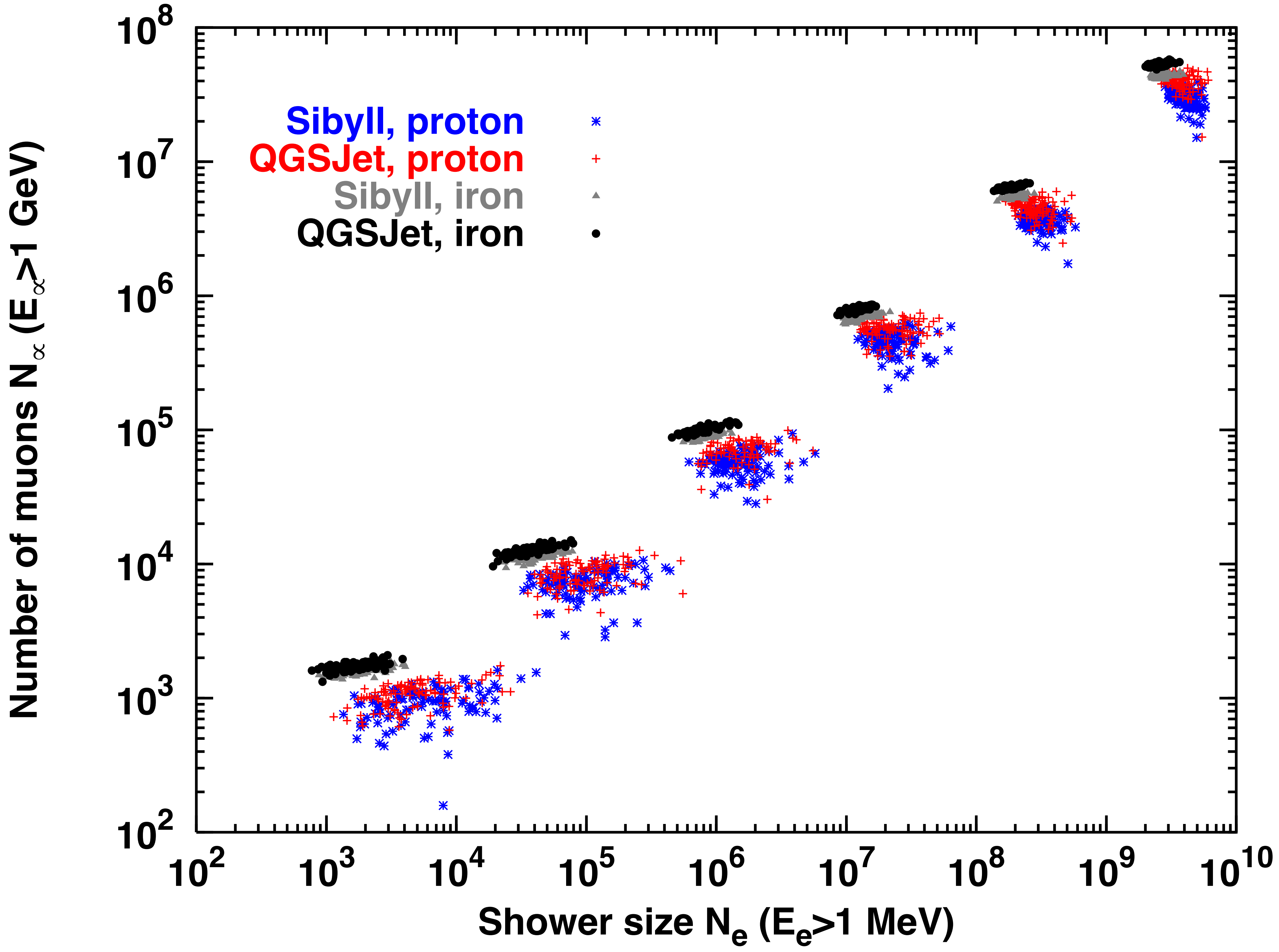
Glauber approximation (unitarity)

$$\sigma_{\text{Fe}-\text{air}} = \left(\frac{A}{n_{\text{part}}}\right) \sigma_{\text{p}-\text{air}}$$

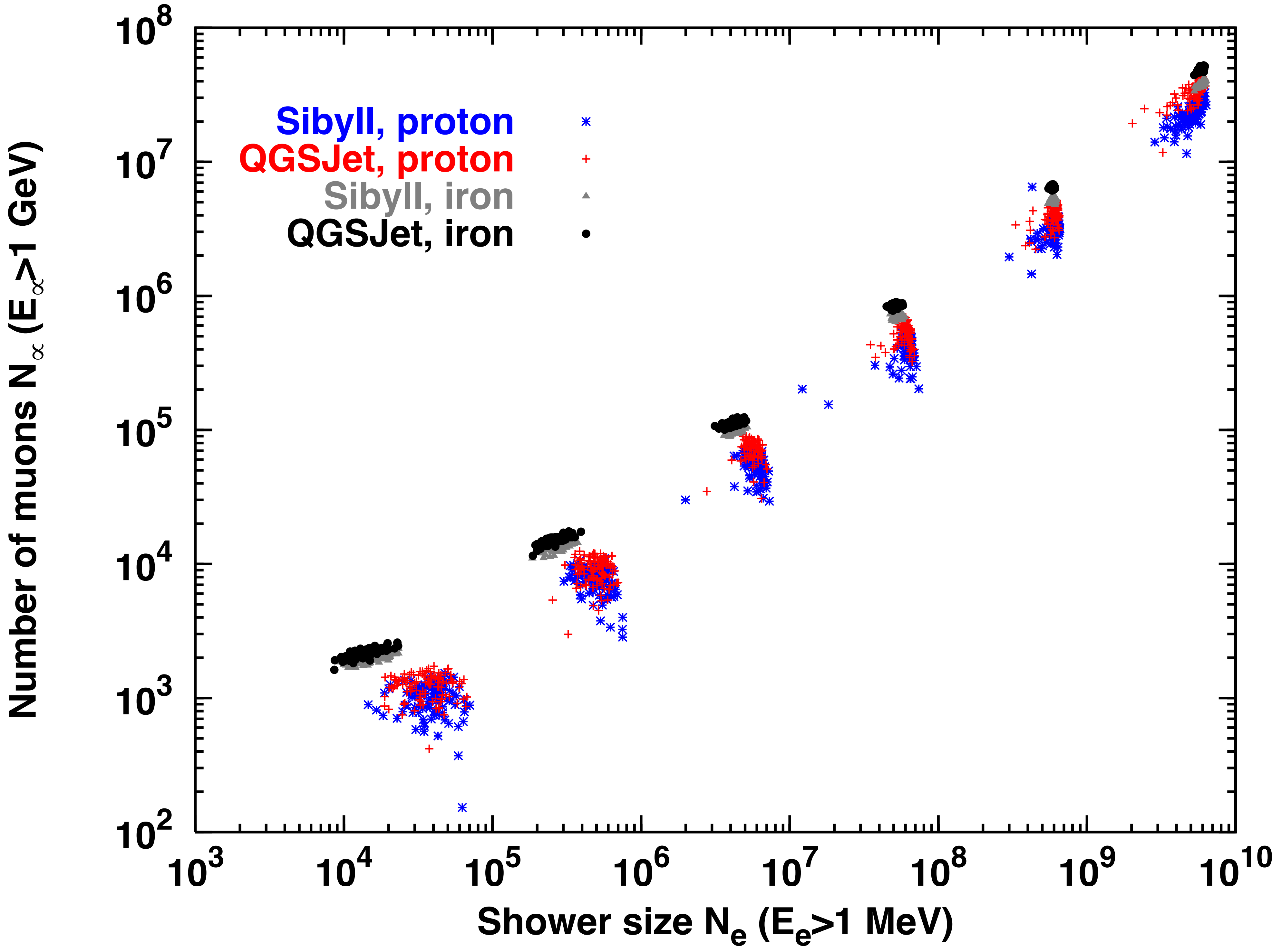
Average depth distribution of nucleon interaction points correctly described

Air shower ground arrays: N_e and N_μ

(RE, Aspen 2005)



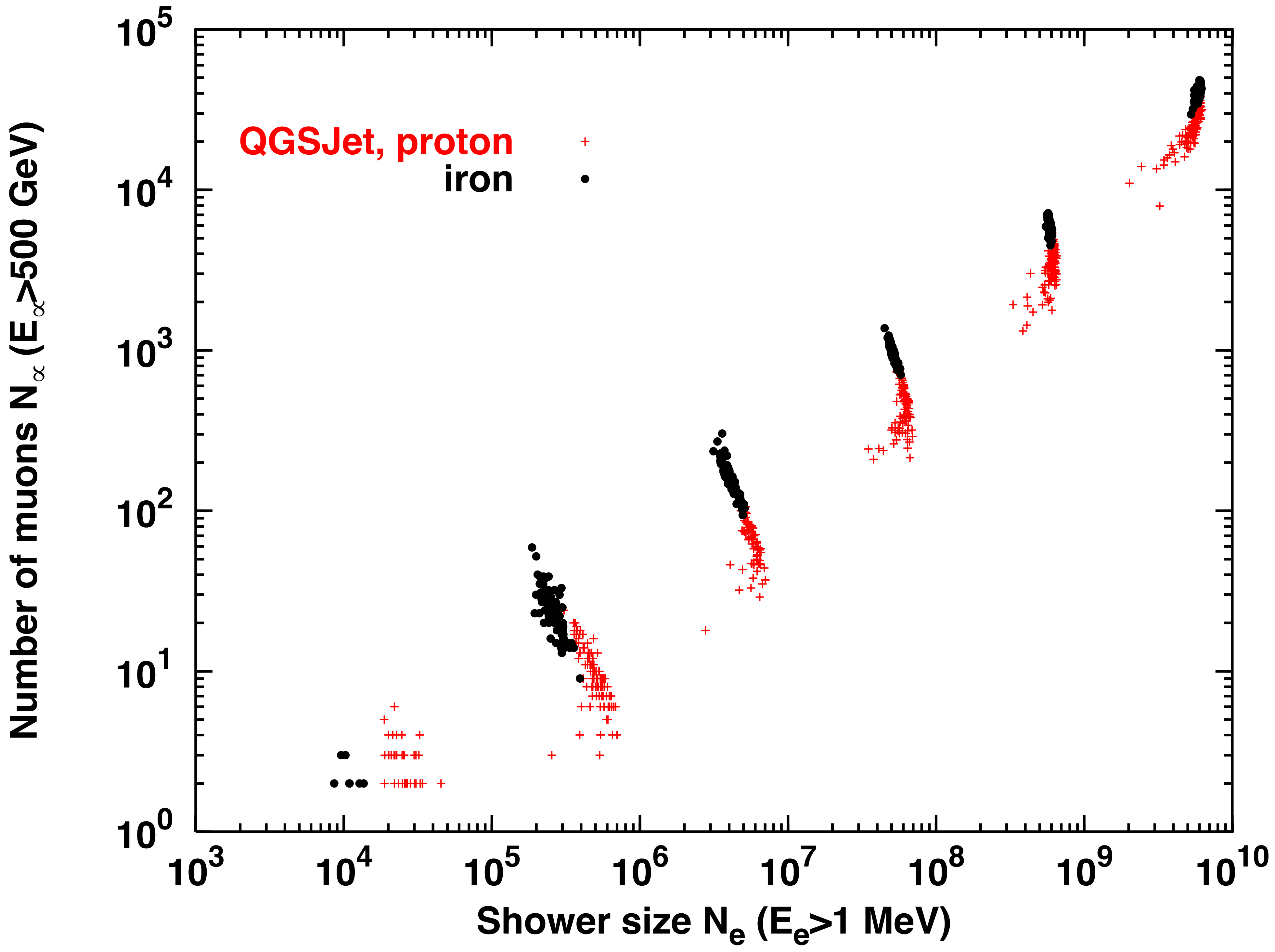
KASCADE and KASCADE-Grande
(sea level 1032 g/cm2, muon threshold 1 MeV)

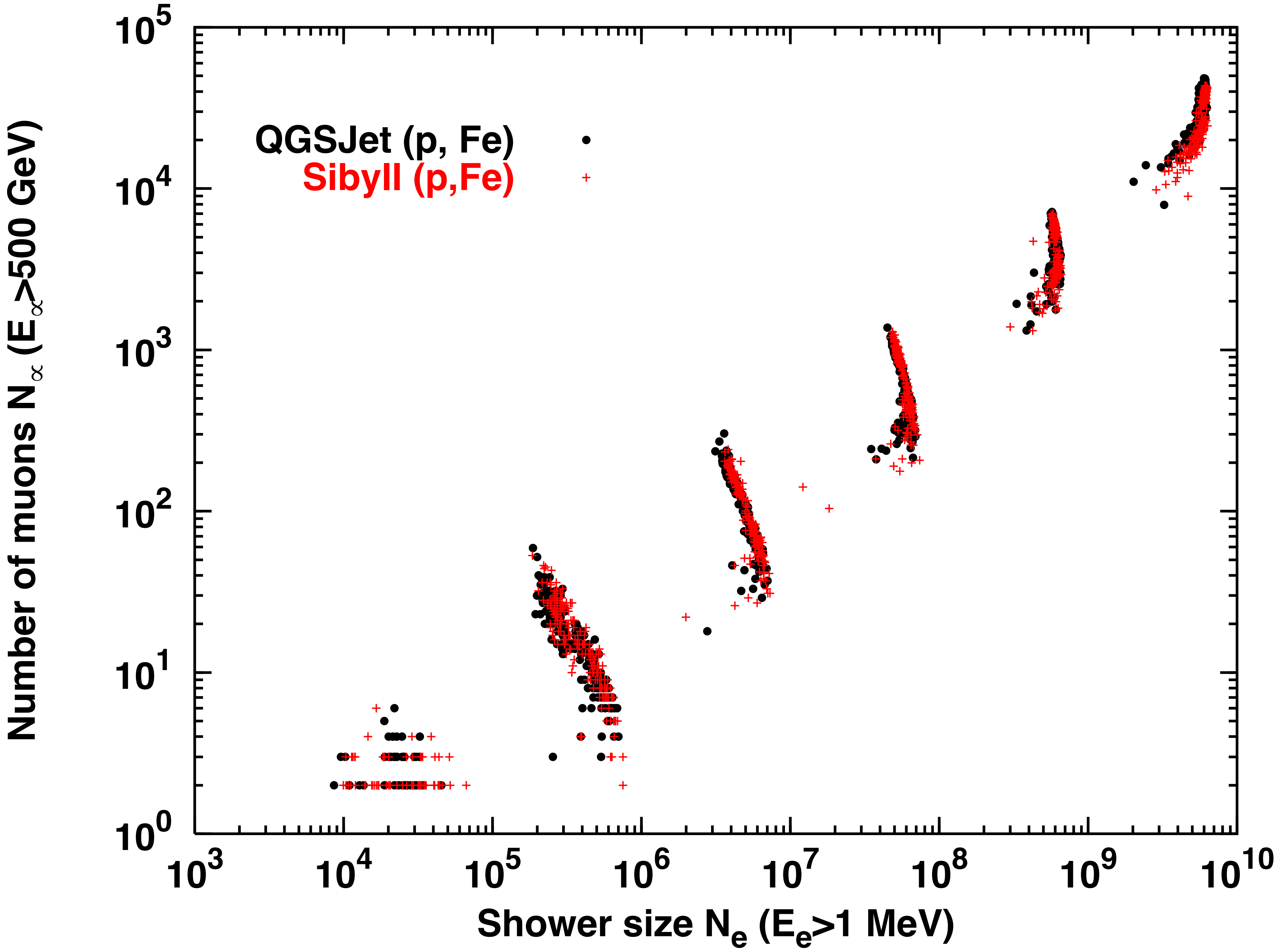


IceCube with IceTop
(South Pole 670 g/cm2, muon threshold 1 MeV)

Air shower ground arrays: N_e and N_μ

(RE, Aspen 2005)

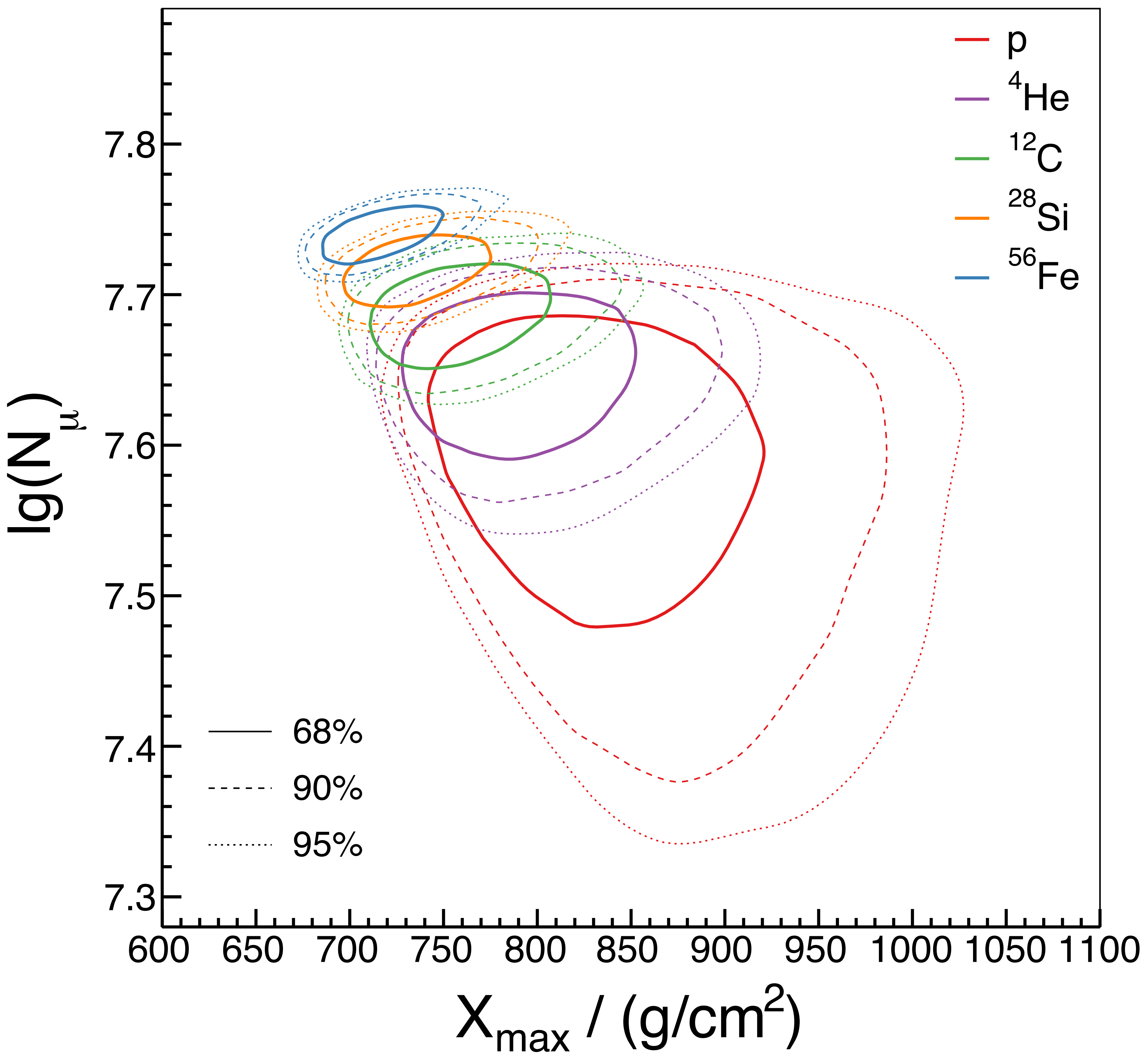


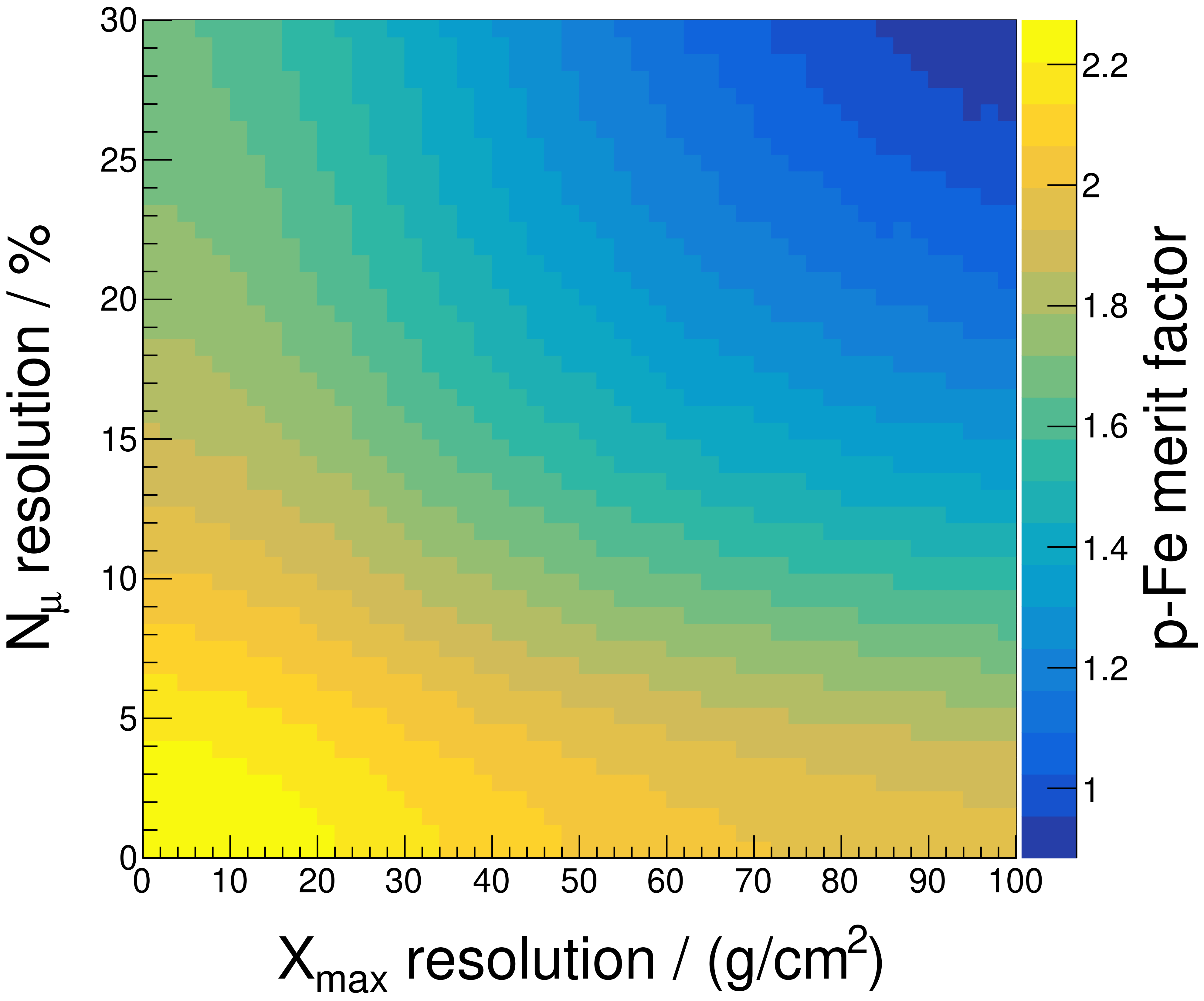


IceCube with IceTop
(South Pole 670 g/cm2, muon threshold 500 GeV)

Number of muons – a very important observable

(UHECR Snowmass Summer Study, Coleman, 2205.05845)





Muons have even better mass composition sensitivity than Xmax

Competing processes of interaction and decay

Interaction length

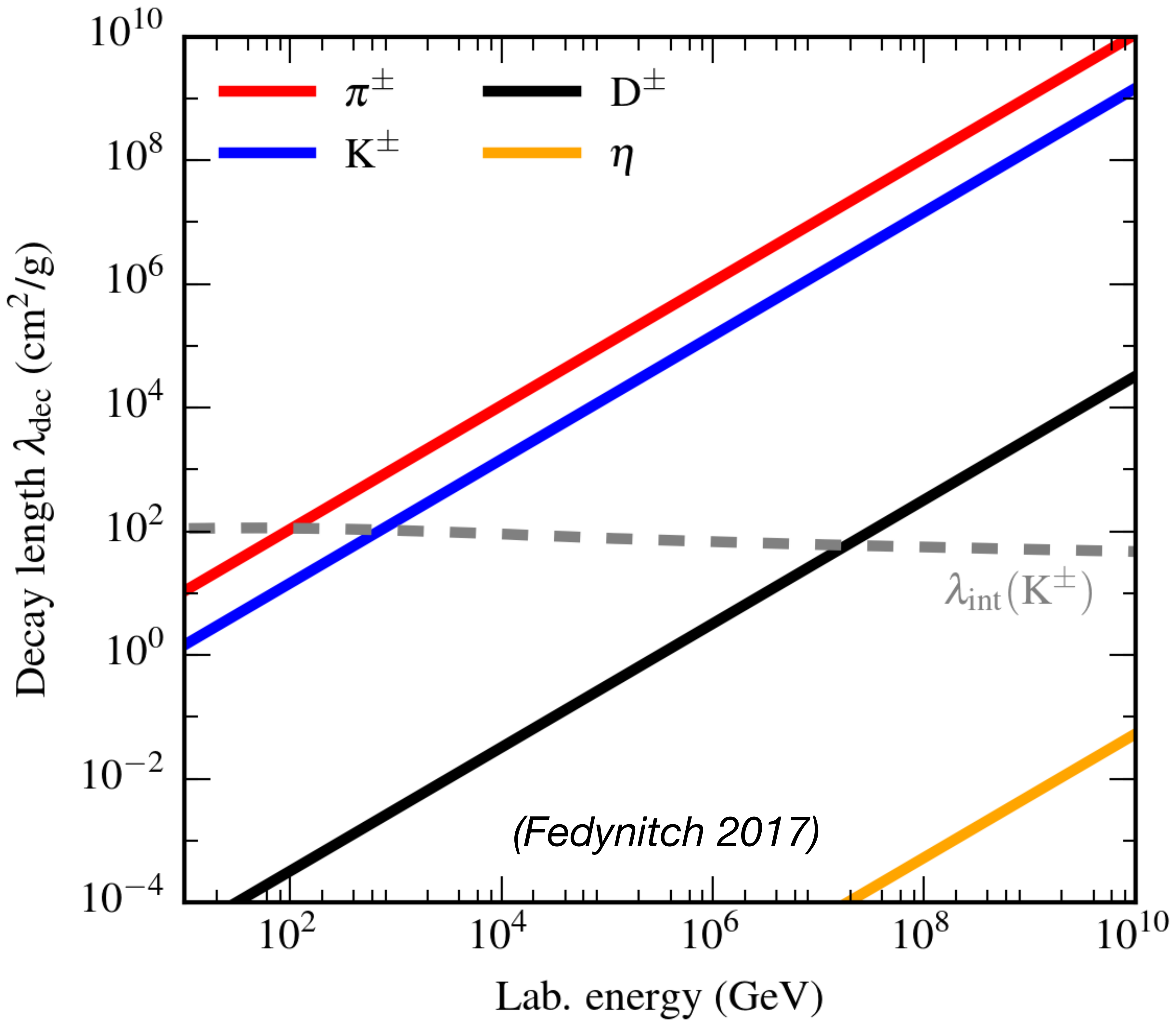
$$\lambda_{\text{int}} = \frac{\langle m_{\text{air}} \rangle}{\sigma_{\text{int}}}$$

$$\lambda_\pi \approx \lambda_K \approx 120\,\text{g/cm}^2$$

Decay length

$$\lambda_{\text{dec}} = \rho\, l_{\text{dec}} \approx c\tau\rho\frac{E}{m}$$

air density



(Fedynitch 2017)

Air at altitude of 8 km

$$c\tau_{\pi^\pm} = 7.8\,\text{m}$$

$$c\tau_{\pi^0} = 25.1\,\text{nm}$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\pi^0 \rightarrow \gamma\gamma$$

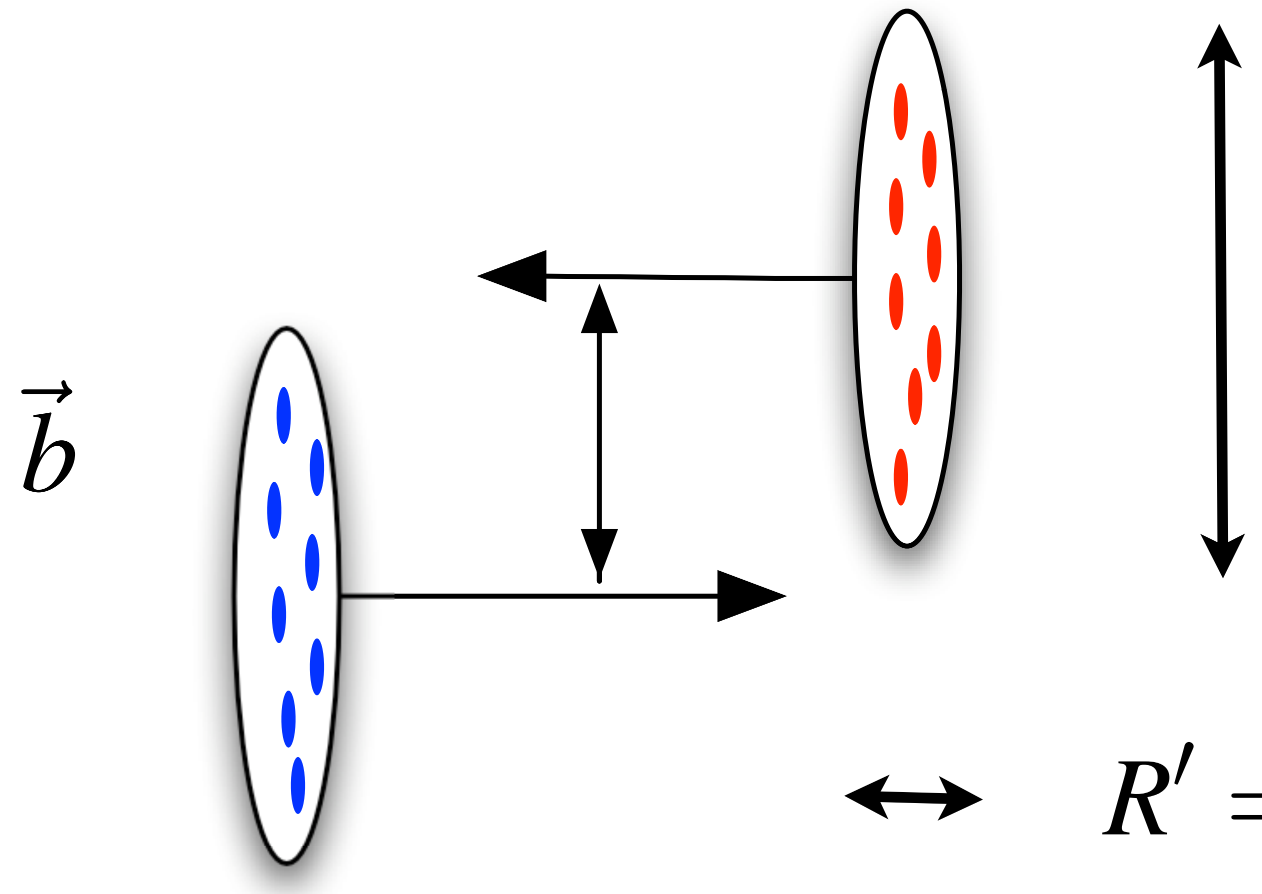
Charged pions interact E > 30 GeV

Neutral pions always decay

Expectations from uncertainty relation

Assumptions:

- hadrons built up of partons
- partons deflected/liberated in collision process, small momentum
- partons fragment into hadrons (pions, kaons,...) after interaction
- interaction viewed in c.m. system (other systems equally possible)



$$R \approx 1\text{fm} \approx 5\text{GeV}^{-1}$$

Heisenberg uncertainty relation

$$\boxed{\Delta x \, \Delta p_x \simeq 1}$$

$$\leftrightarrow \quad R' = R/\Gamma = R\,\frac{m_p}{E_p}$$

Longitudinal momenta of secondaries

$$\boxed{\langle p_{\parallel}\rangle \sim \Delta p_{\parallel} \approx \frac{1}{R'} \approx \frac{1}{5}E_p}$$

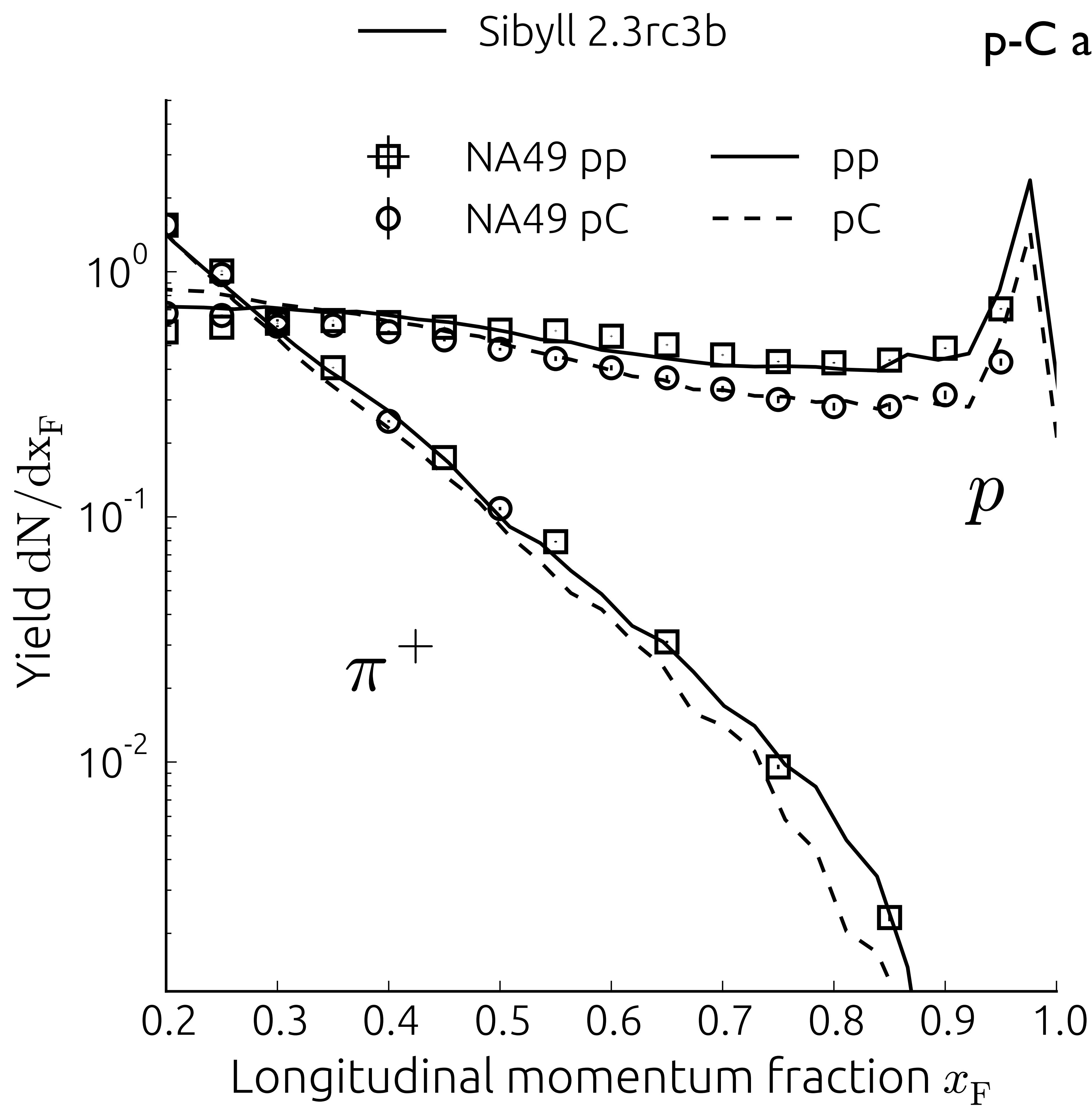
$$\Gamma = E_p/m_p$$

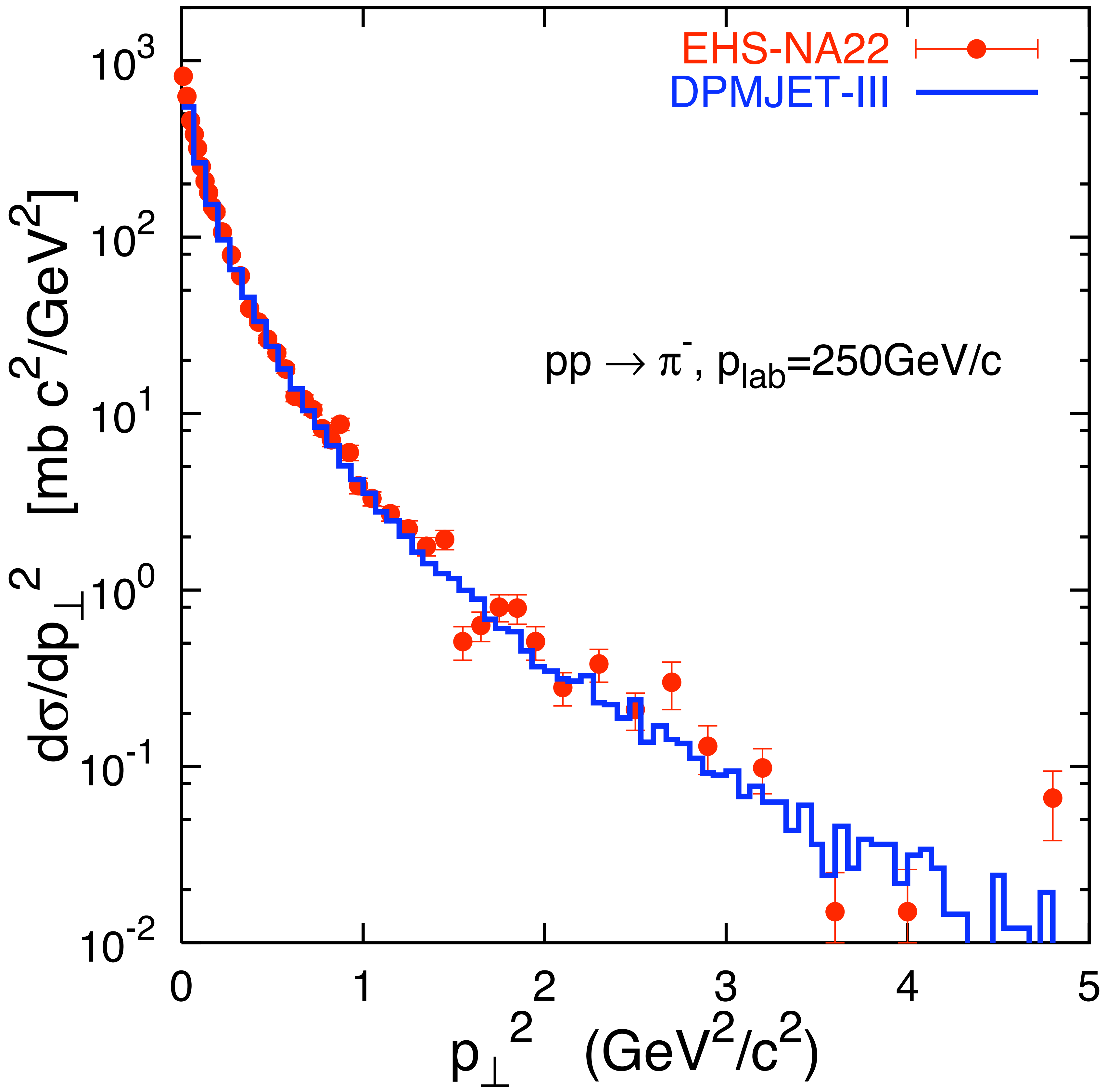
Transverse momenta of secondaries

$$\boxed{\langle p_{\perp}\rangle \sim \Delta p_{\perp} \sim \frac{1}{R} \approx 200\,\text{MeV}}$$

Typical hadronic final states

NA49 p-p and
p-C at 158 GeV





Feynman-x $$x_F = \left(\frac{p_\parallel}{p_{\max}}\right)_{\mathrm{CMS}}$$

Transverse momentum

(Riehn et al. ICRC 2017)

Secondary particle multiplicities

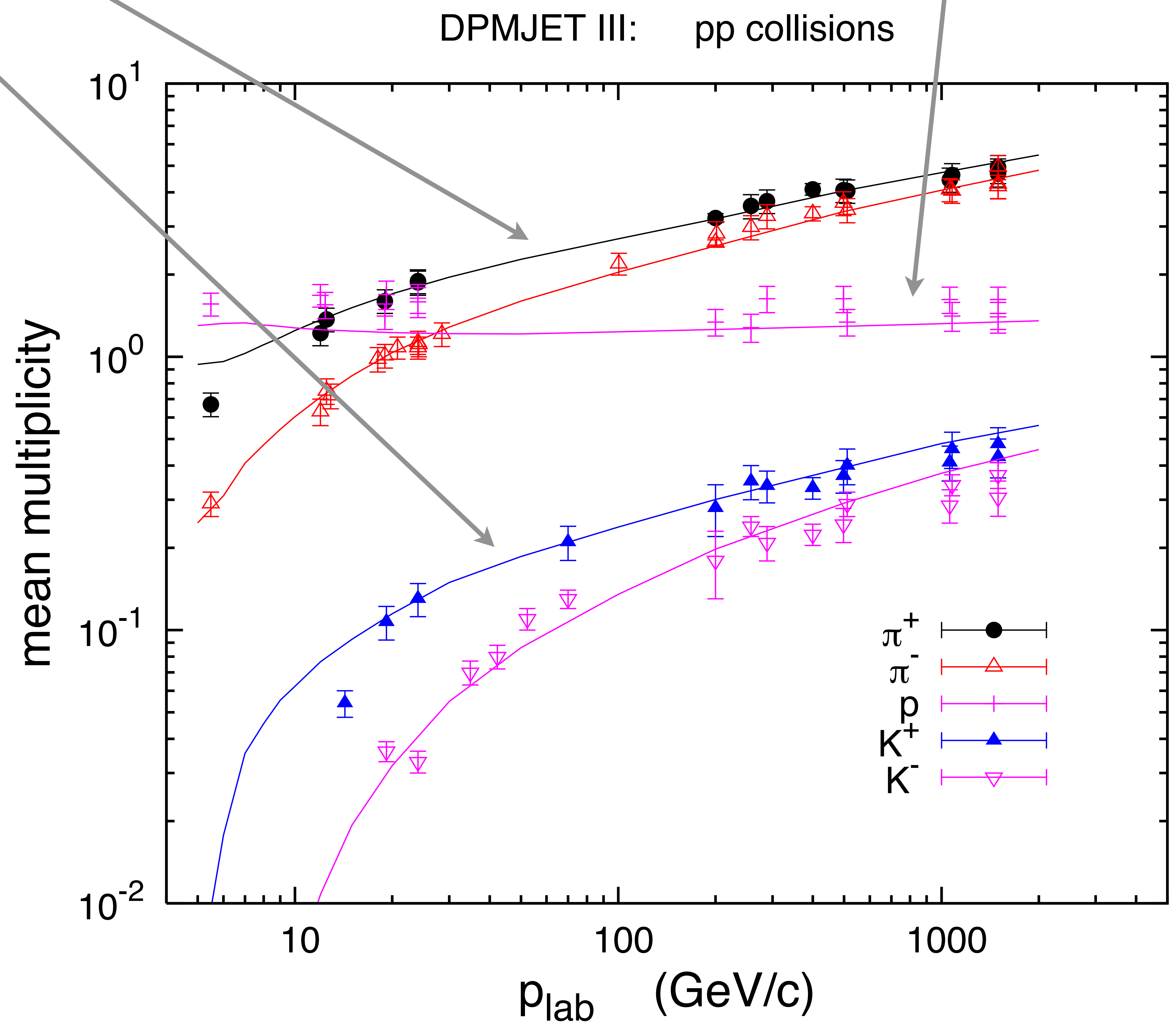
Power-law increase of number of secondary

Leading particles (multiplicity const.)

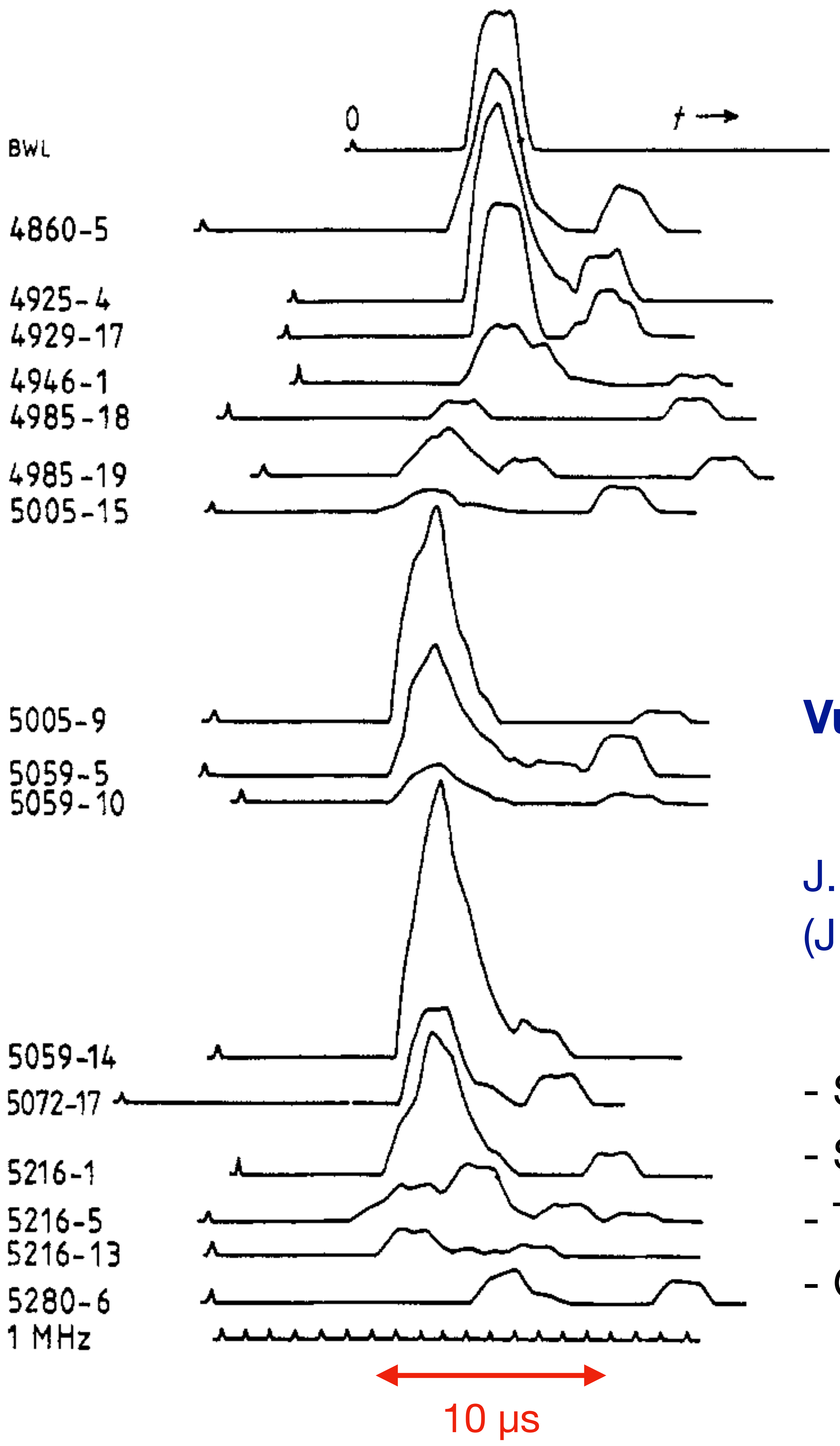
$$n_{\mathrm{ch}} \sim s^{0.1}$$

proton - proton, $E_{\mathrm{lab}} = 2 \times 10^{11}$ eV

	Exp.	DPMJET-III
charged	7.69 ± 0.06	7.64
neg.	2.85 ± 0.03	2.82
p	1.34 ± 0.15	1.26
n	0.61 ± 0.30	0.66
π^+	3.22 ± 0.12	3.20
π^-	2.62 ± 0.06	2.55
K^+	0.28 ± 0.06	0.30
K^-	0.18 ± 0.05	0.20
Λ	0.096 ± 0.01	0.10
$\bar{\Lambda}$	0.0136 ± 0.004	0.0105



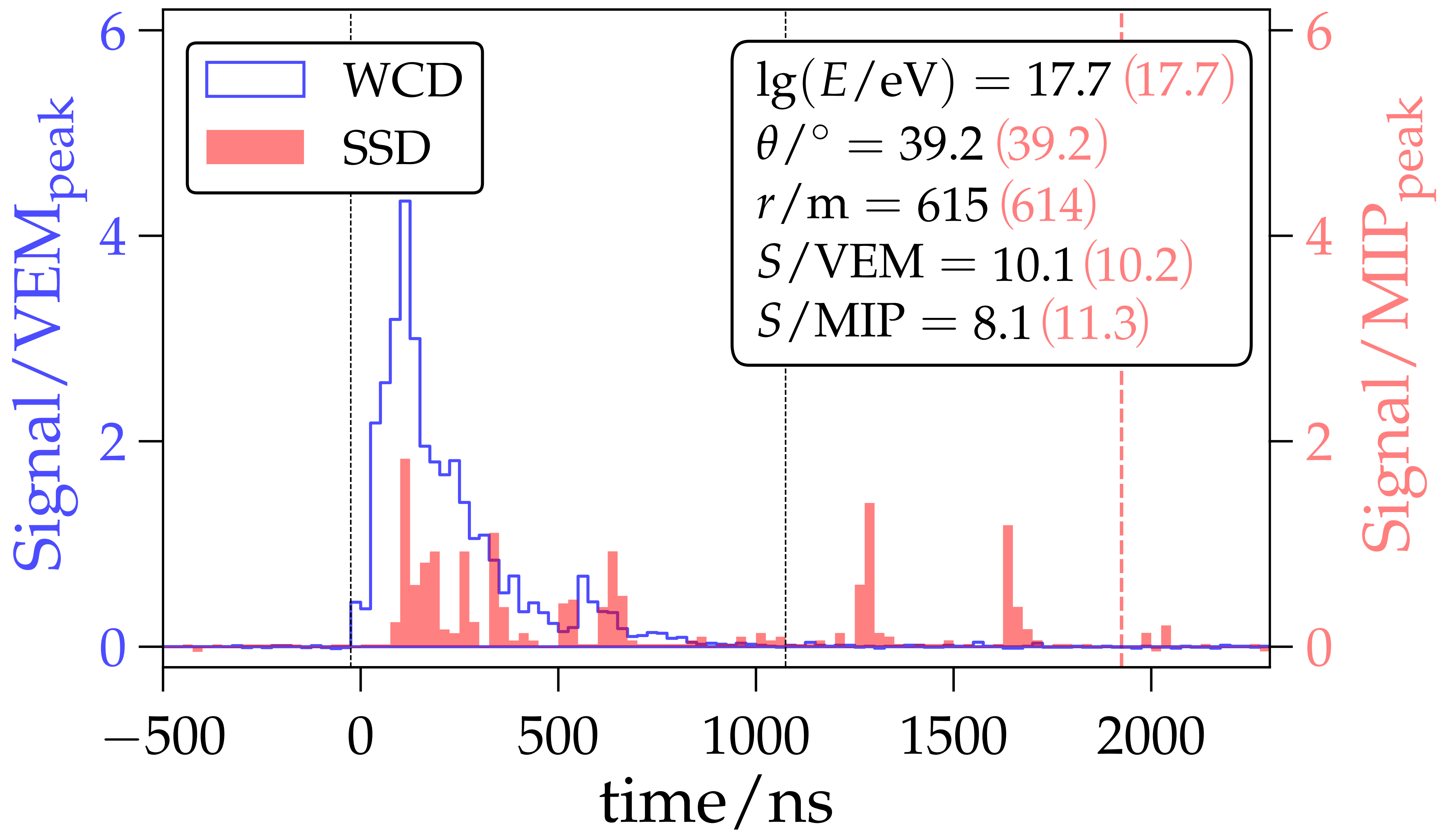
Sub-luminal neutrons in air showers



Vulcano Ranch (1962-63)

J. Linsley
(J. Phys. G: Nucl. Phys. 10 (1984) L191)

- Sub-luminal pulses with a delay of at least 3µs
- Sometimes several pulses observed
- Typically 1 km from core, high-energy showers
- Greisen: **neutrons** as sub-luminal particles

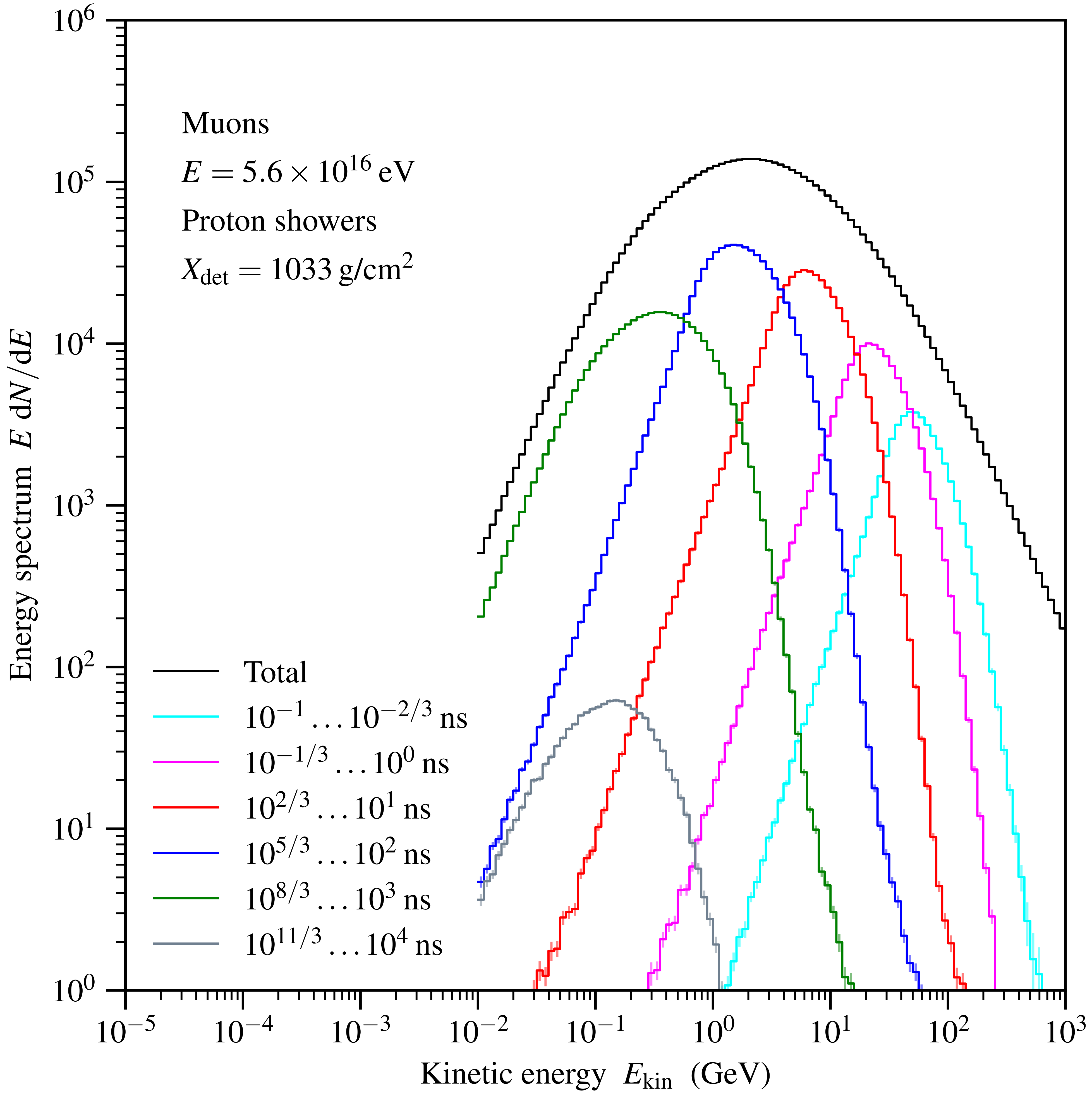


AugerPrime (2020-21)

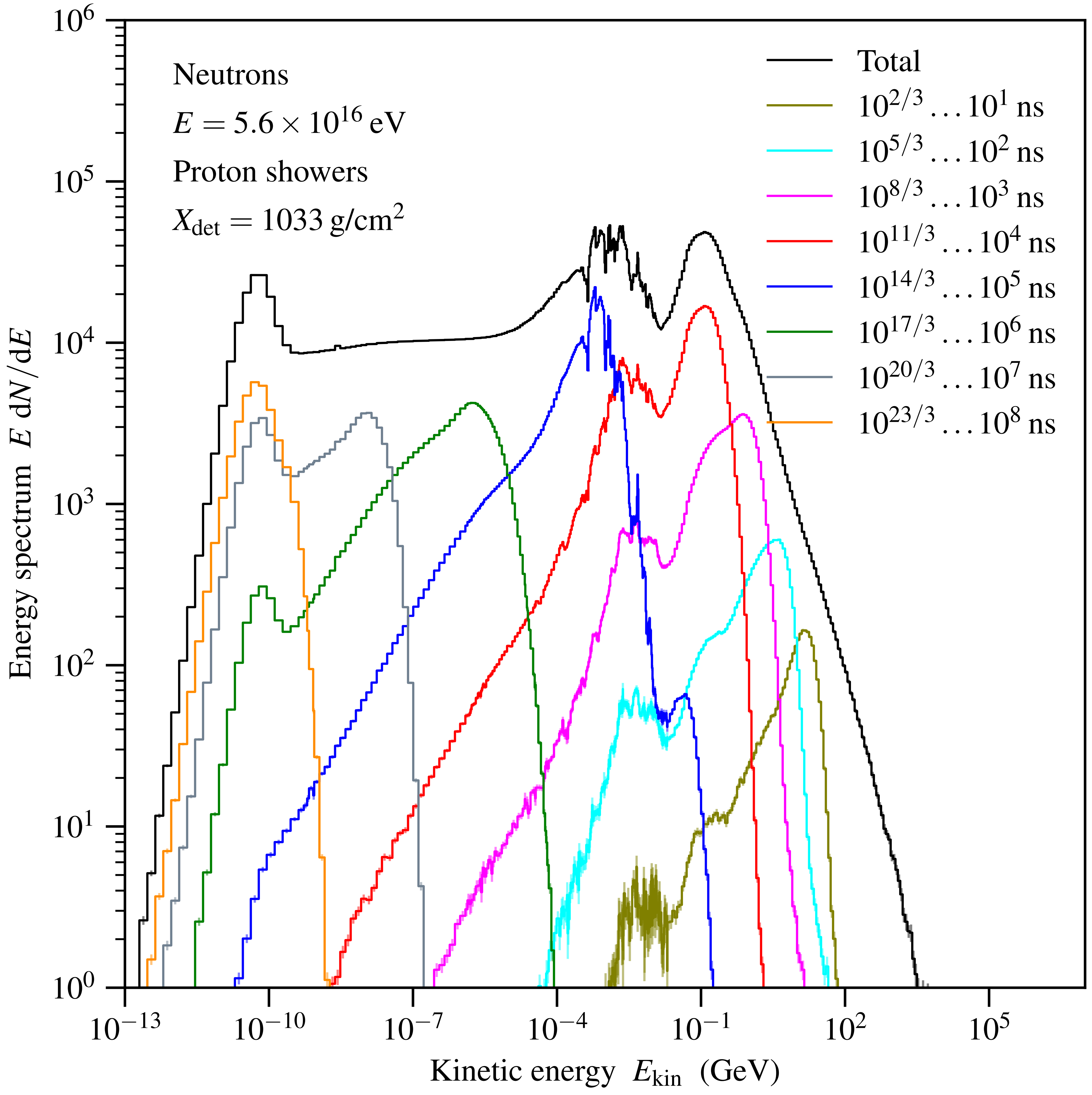
D. Schmidt, Pierre Auger Collaboration
(this conference)

- Late signals seen in scintillators (SSD)
- Late pulses have no coincident signal in water-Cherenkov detectors (WCD)
- Similar height distribution of late pulses?

Air shower results: time delay distribution



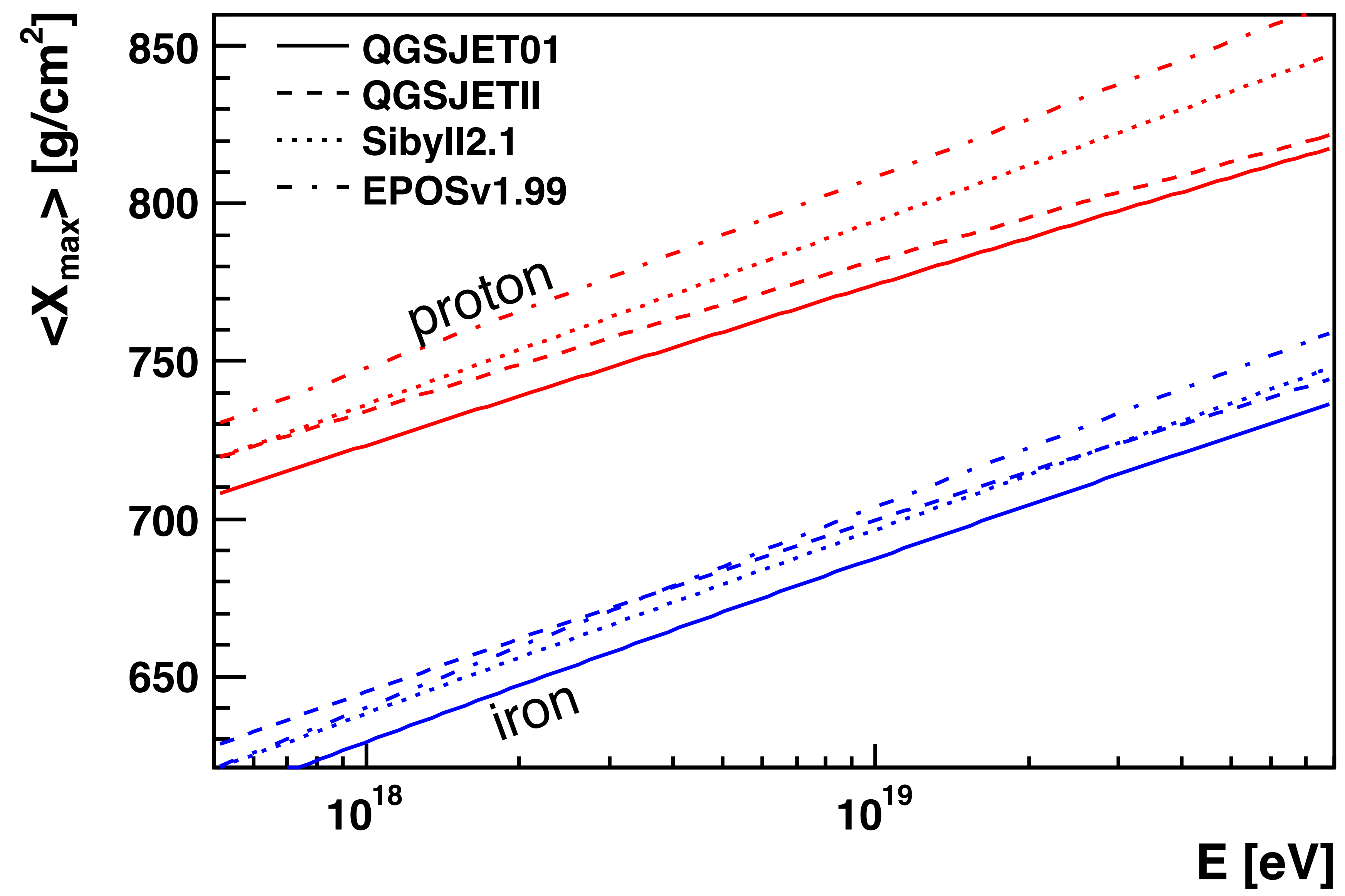
Muons: time delay of bulk of particles: 1 - 500 ns



Neutrons: time delay of high-energy particles: 1 - 20 μs,
slow (thermal) neutrons up to 100 ms

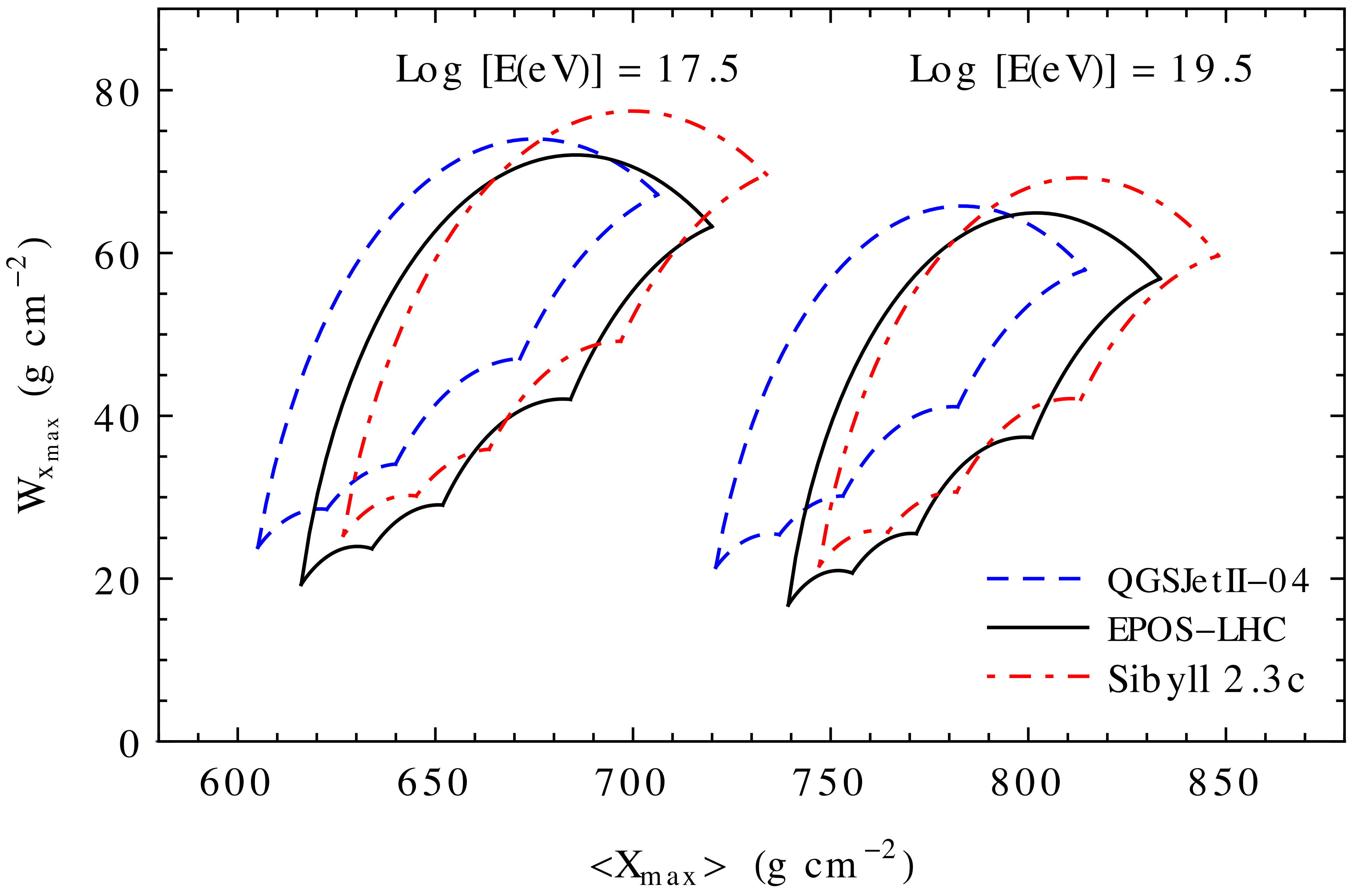
(RE & Ferrari et al. ICRC 2021)

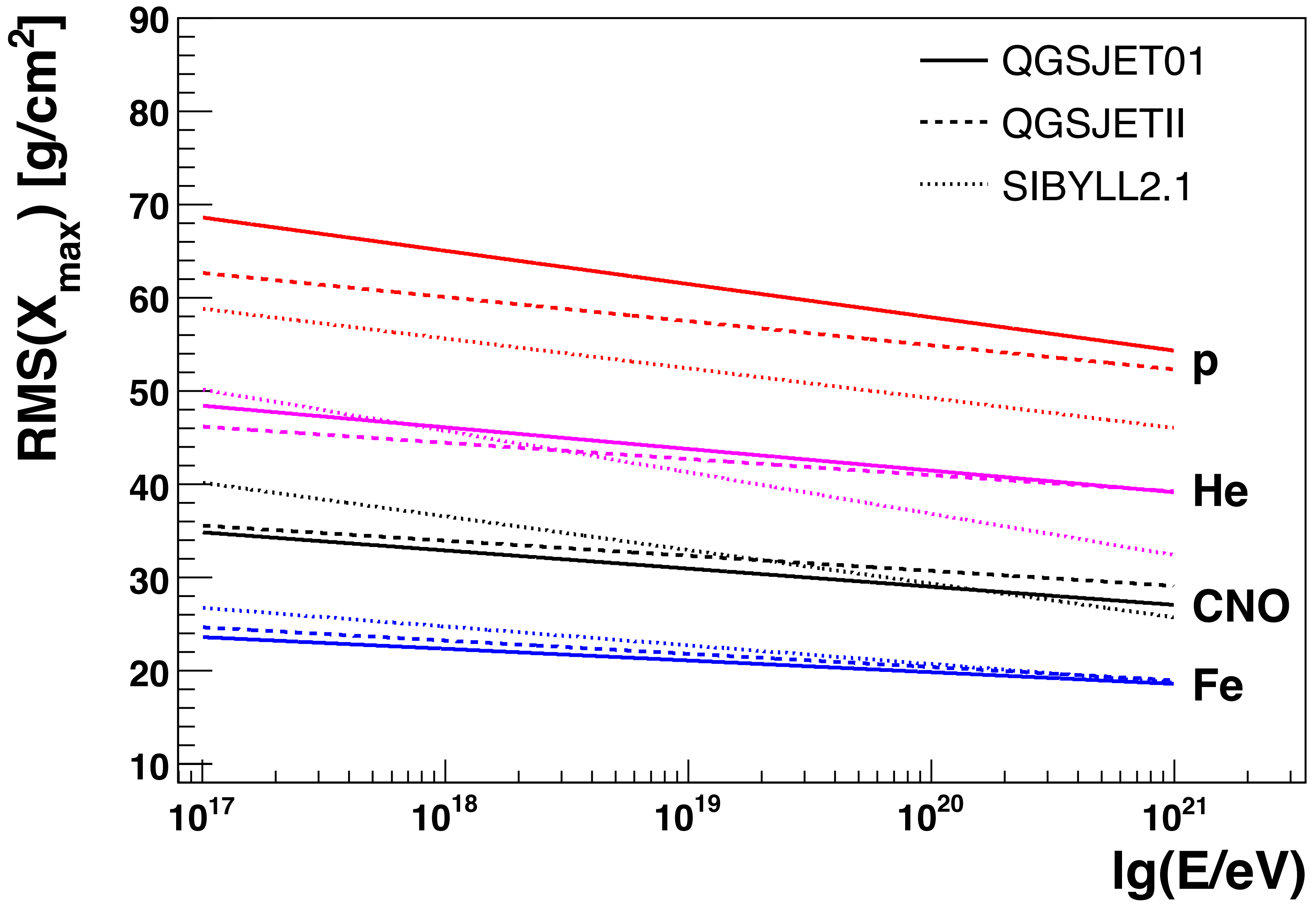
Information provided by Xmax fluctuations



superposition model

(Lipari, PRD 2021)

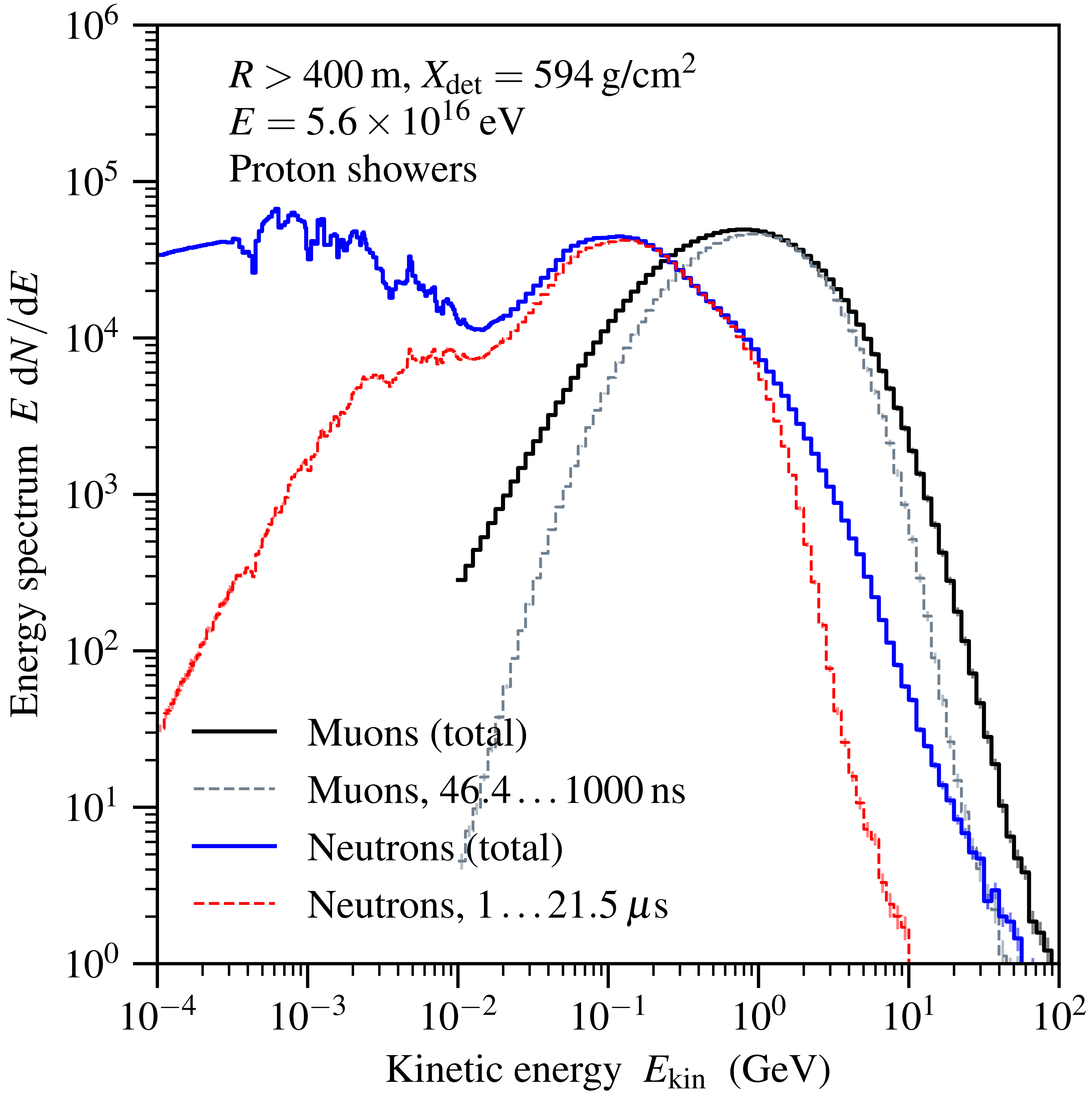


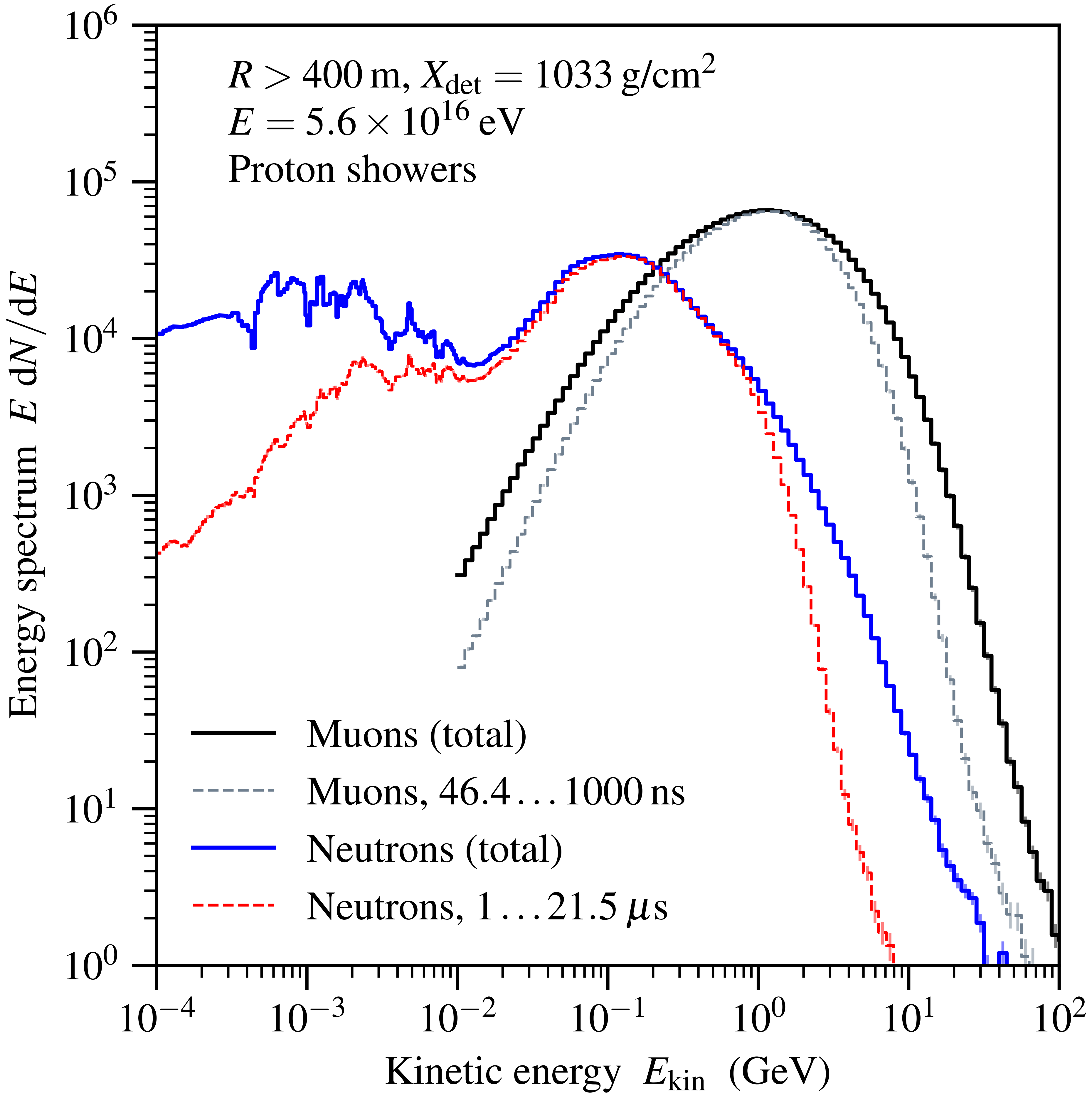


Model dependence of fluctuations seems small (for mixed composition)

(Unger, Solvay 2018)

Air shower results: muons vs. neutrons at large distance





Close to shower maximum: neutrons as abundant as muons

Past shower maximum: neutrons much less abundant than muons

(RE & Ferrari et al. ICRC 2021)

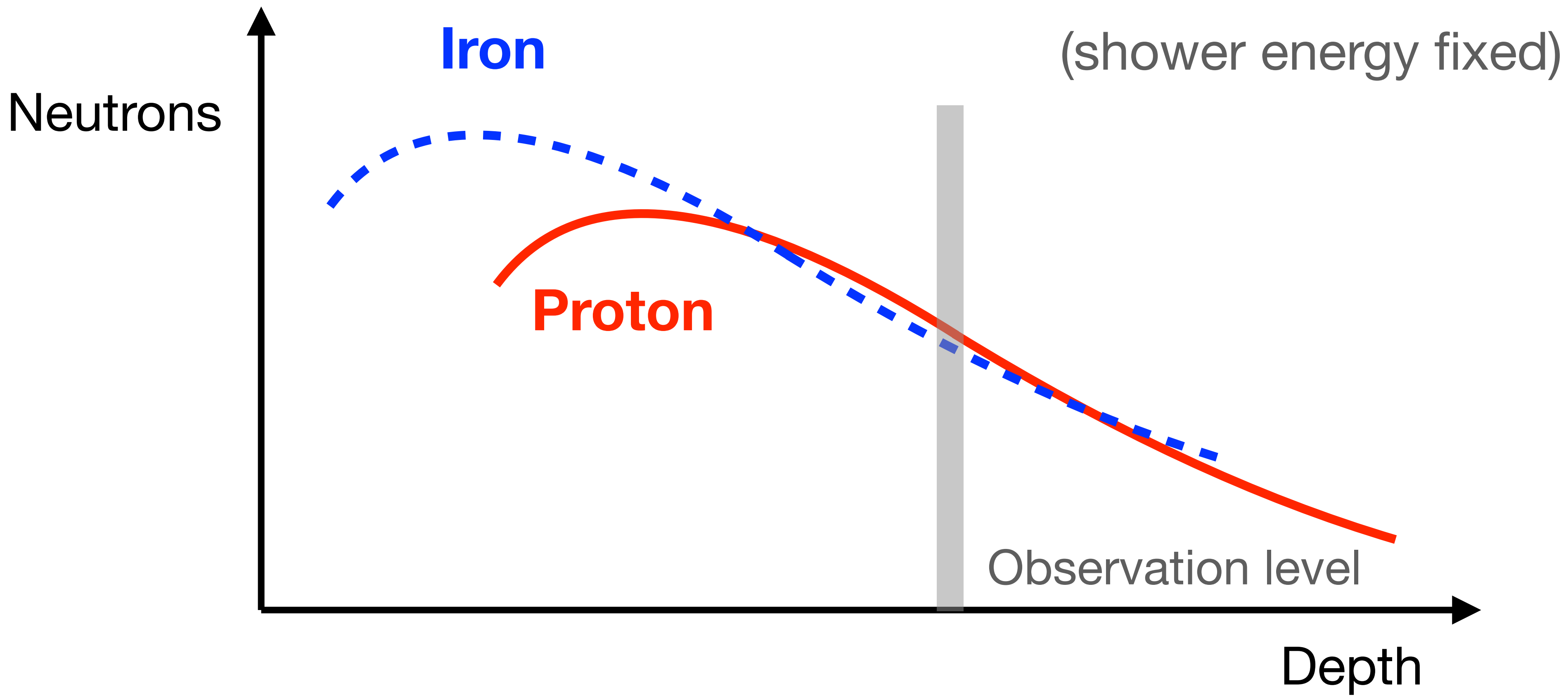
Do we learn anything from sub-luminal neutrons?

Neutrons

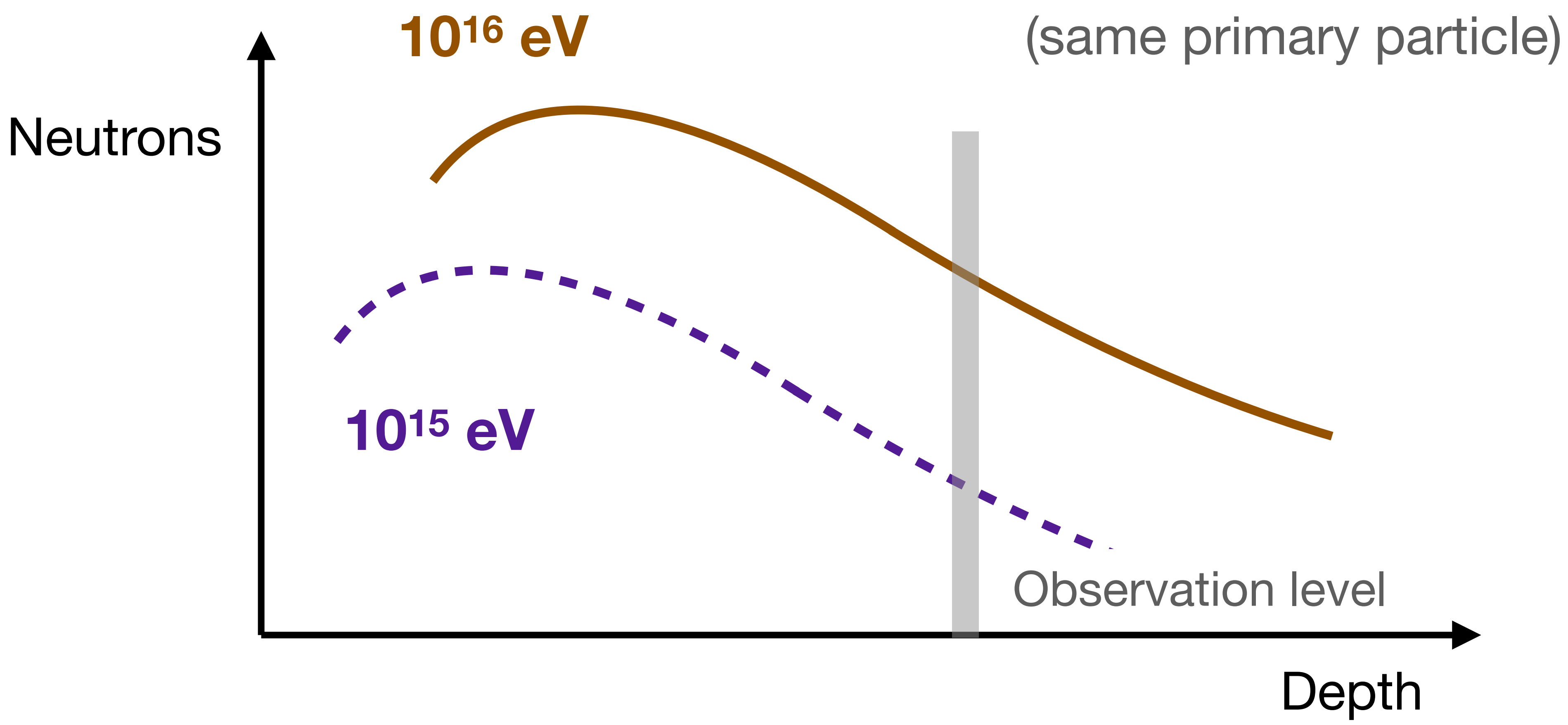
- Interesting sub-luminal particles
- Feature-rich and very wide energy spectrum
- Notoriously difficult to detect
- Very difficult to simulate accurately (environment)
- Expected to produce late pulses in scintillators

Scaling observations

- Energy scaling of production similar to muons
- Primary dependence of production like muons
- Attenuation (neutron removal) length 80 … 200 g/cm^2
- Very wide lateral distribution, wider than muons
- Typical delay in arrival time ~ 1 … 20 μs (E_{kin} > 20 MeV)
- Thermal neutrons up to ~ 100 ms



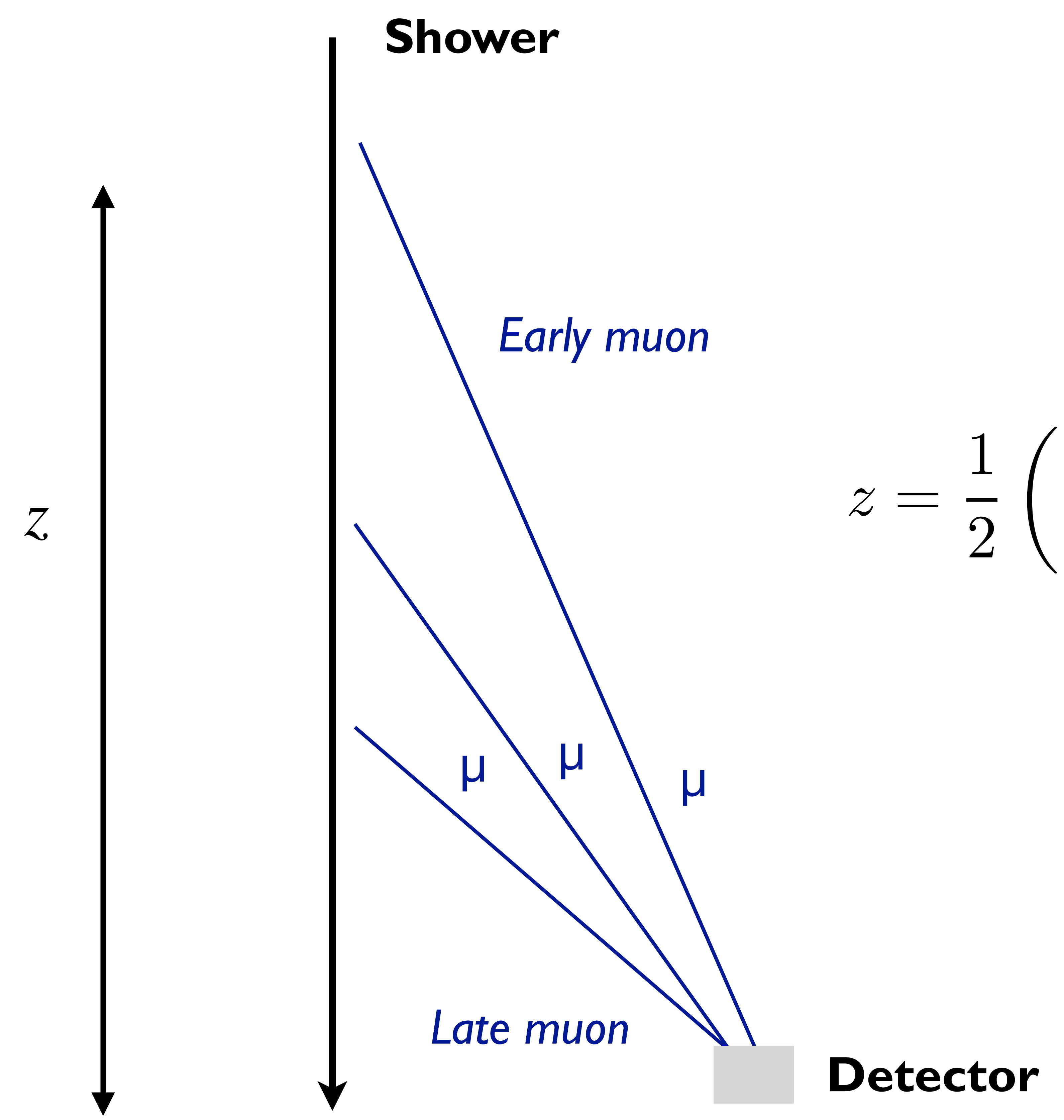
Reduced composition sensitivity?



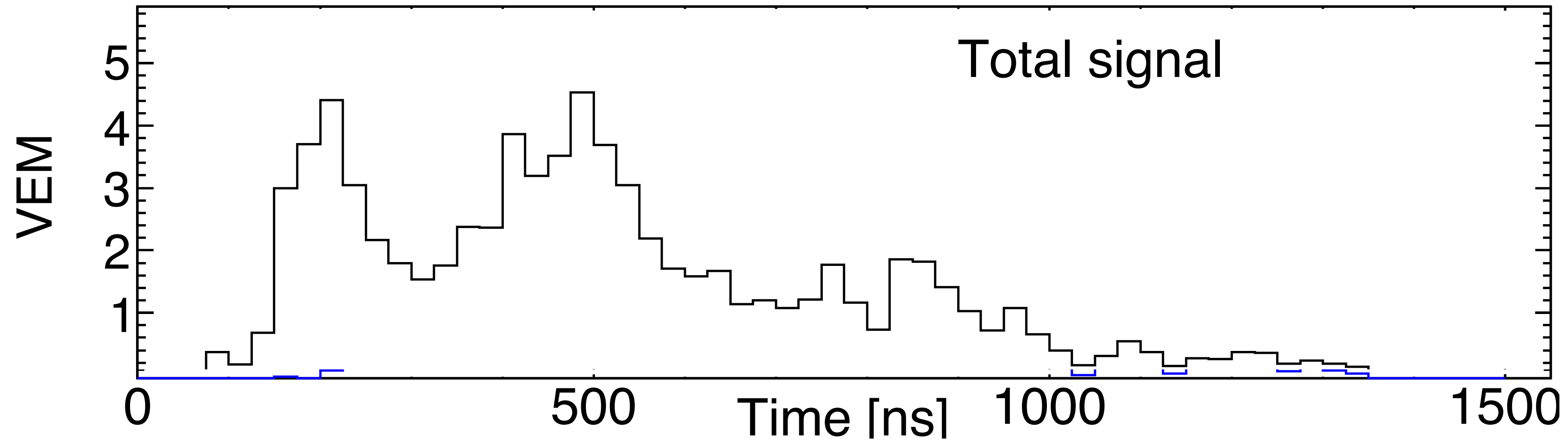
Scaling faster than ~ $E^{0.9}$

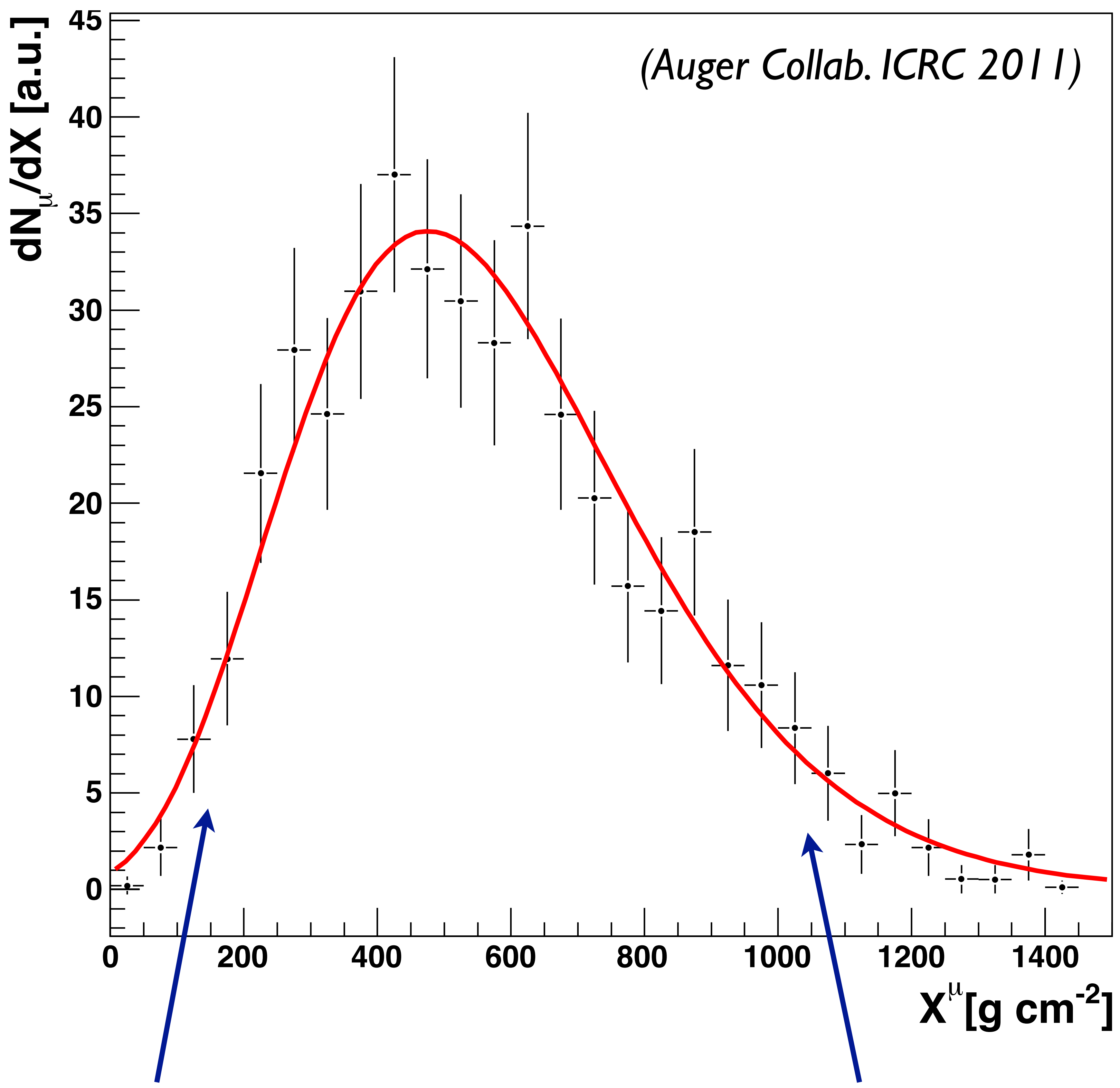
(RE & Ferrari et al. ICRC 2021)

Arrival time distribution – Muon production depth



$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$



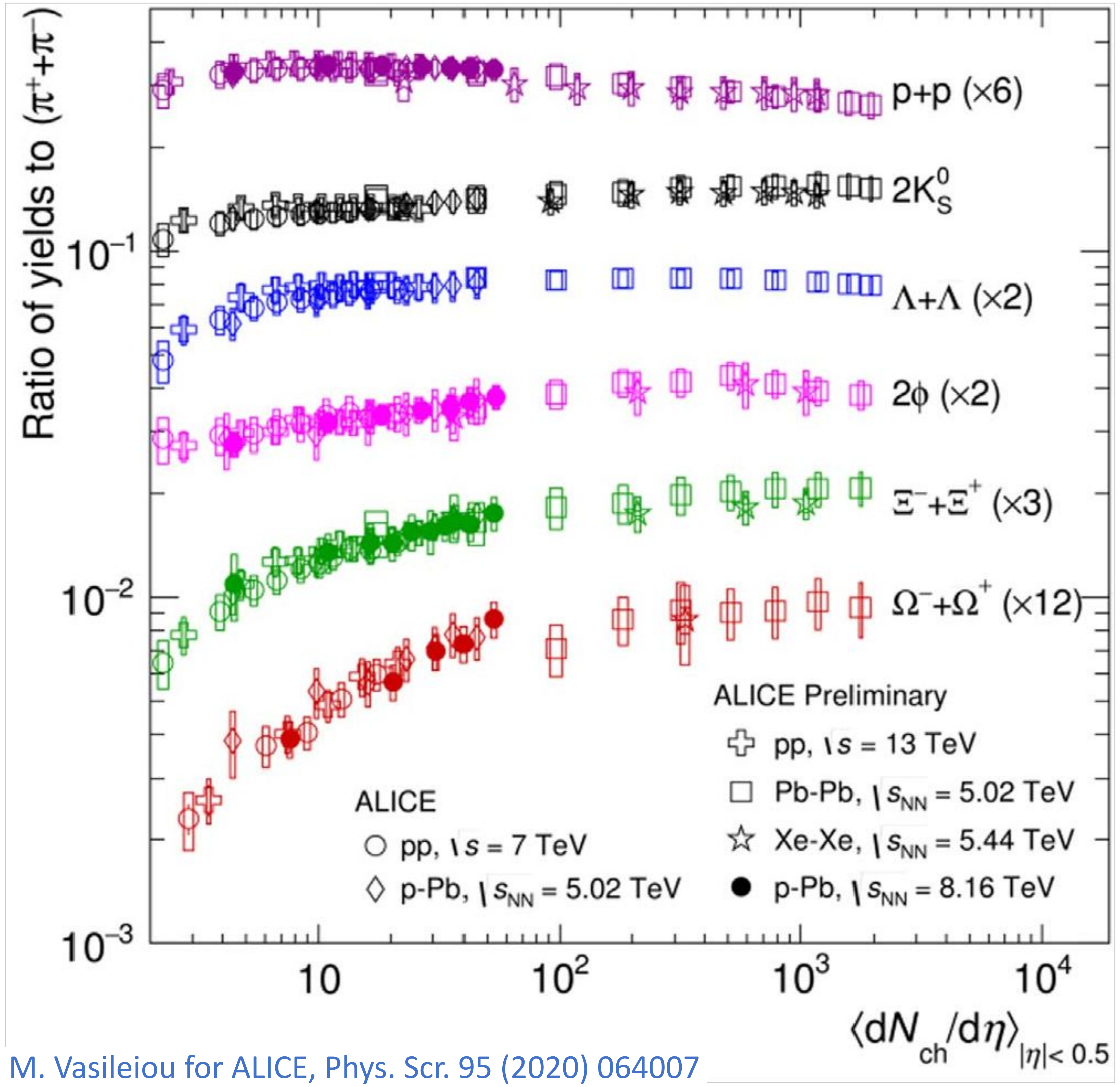


Muons from high-energy interactions

Muons from low-energy interactions

(Cazon et al. Astropart. Phys. 23, 2005 & 1201.5294)

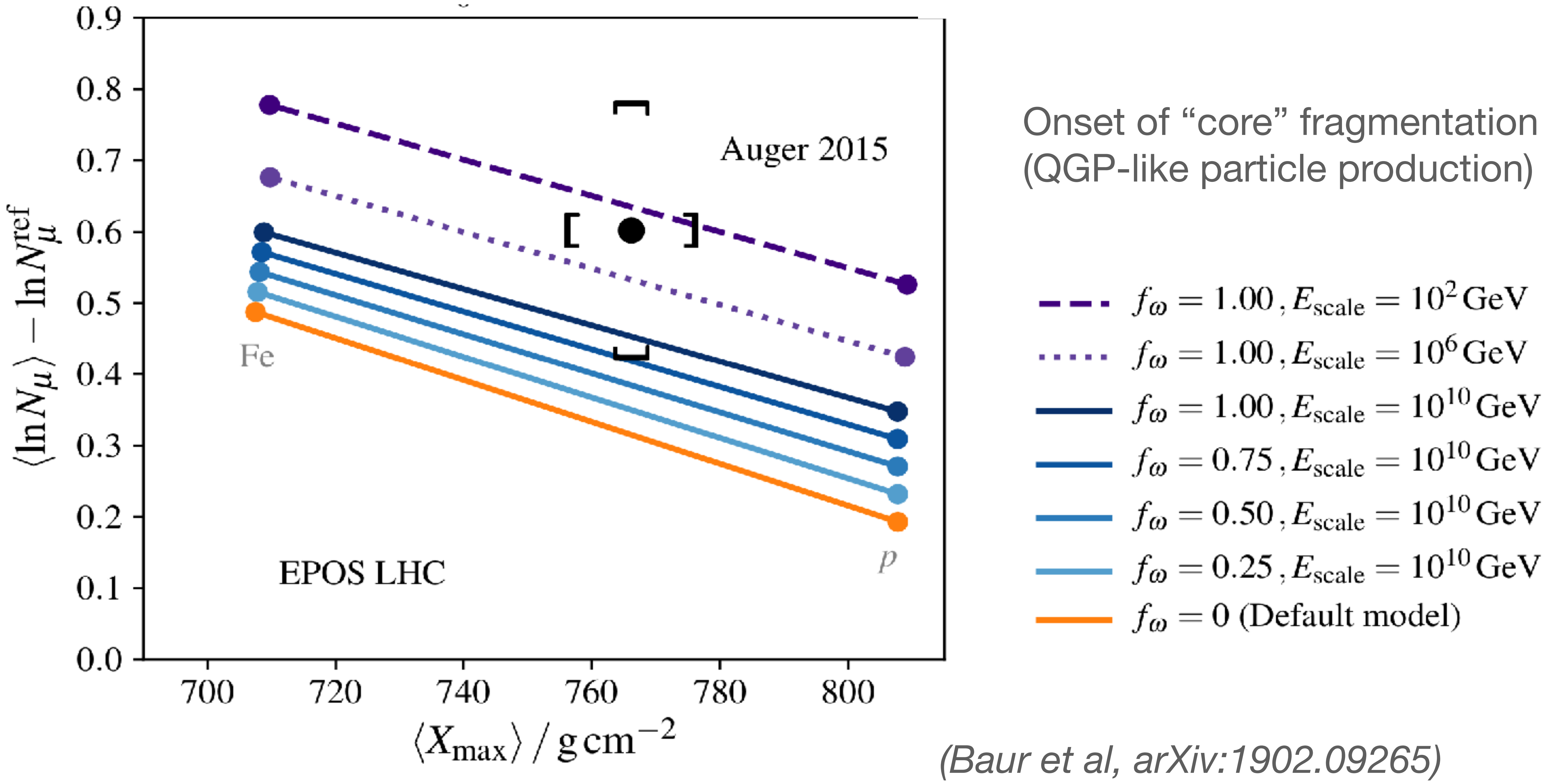
Universal particle scaling and core-corona model in EPOS



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?

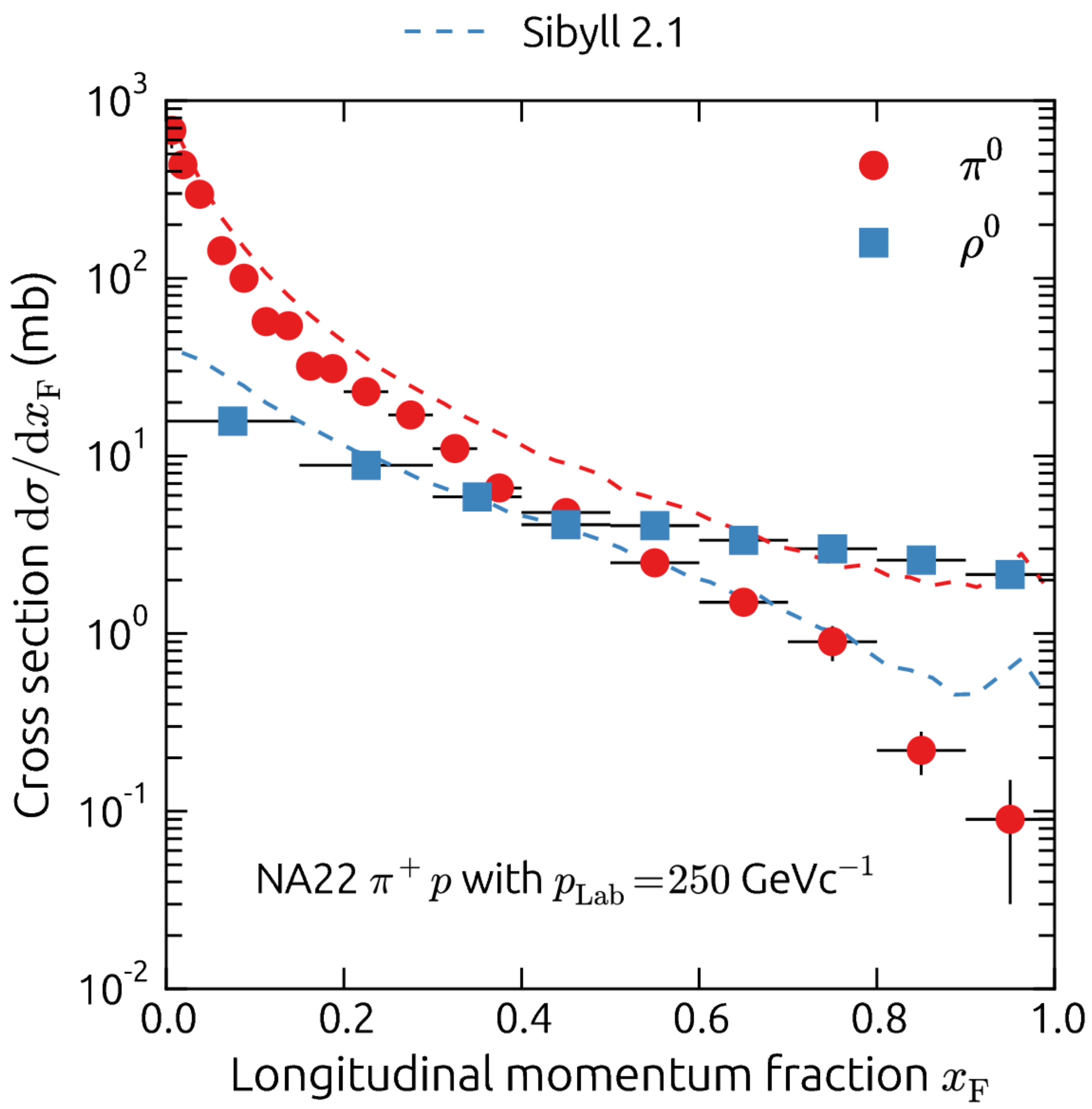


Onset of “core” fragmentation (QGP-like particle production)

(Baur et al, arXiv:1902.09265)

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

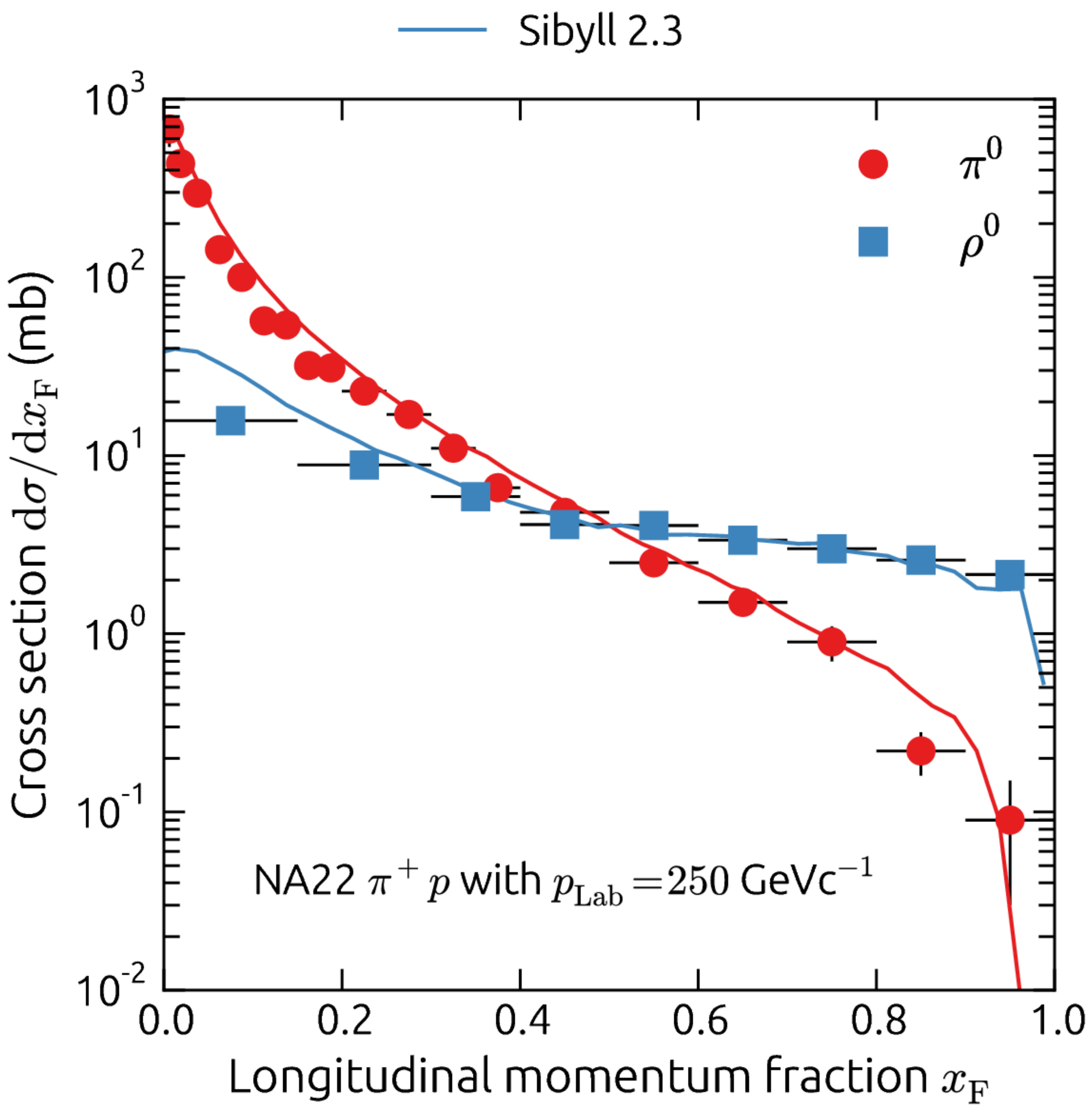
Leading particle production



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

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

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



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

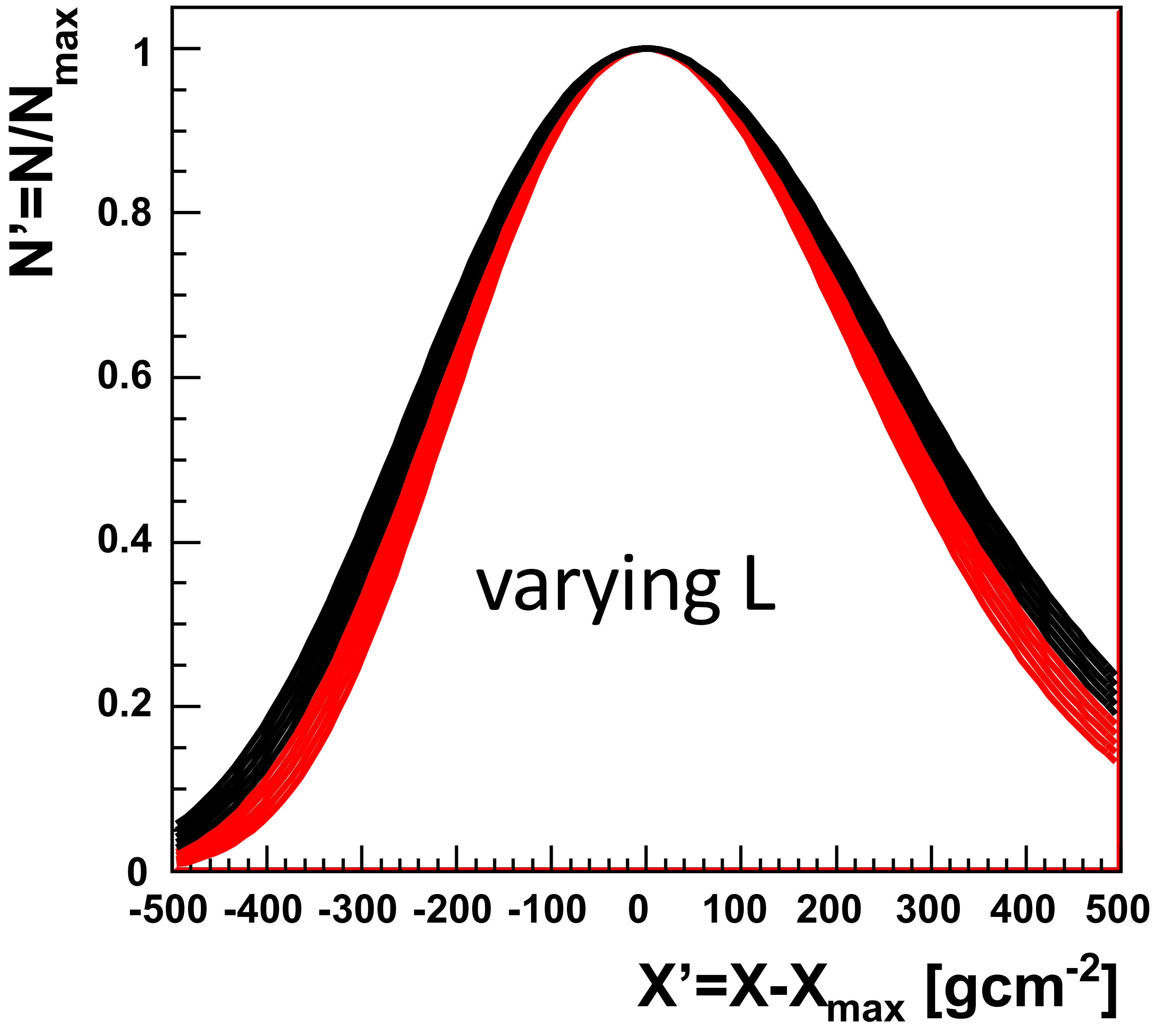
(Riehn et al., ICRC 2015)

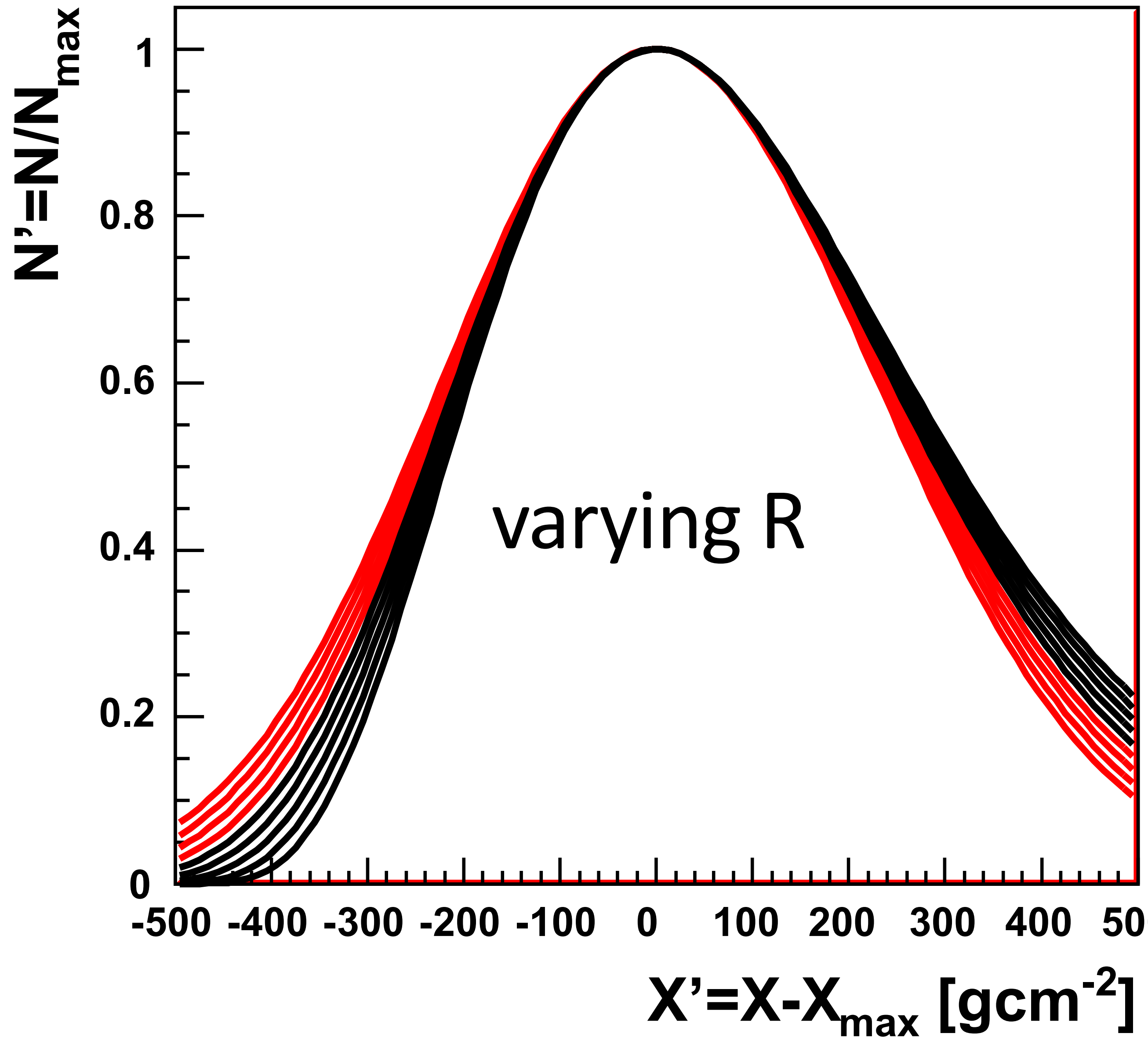
Alternative way of writing GH parametrization

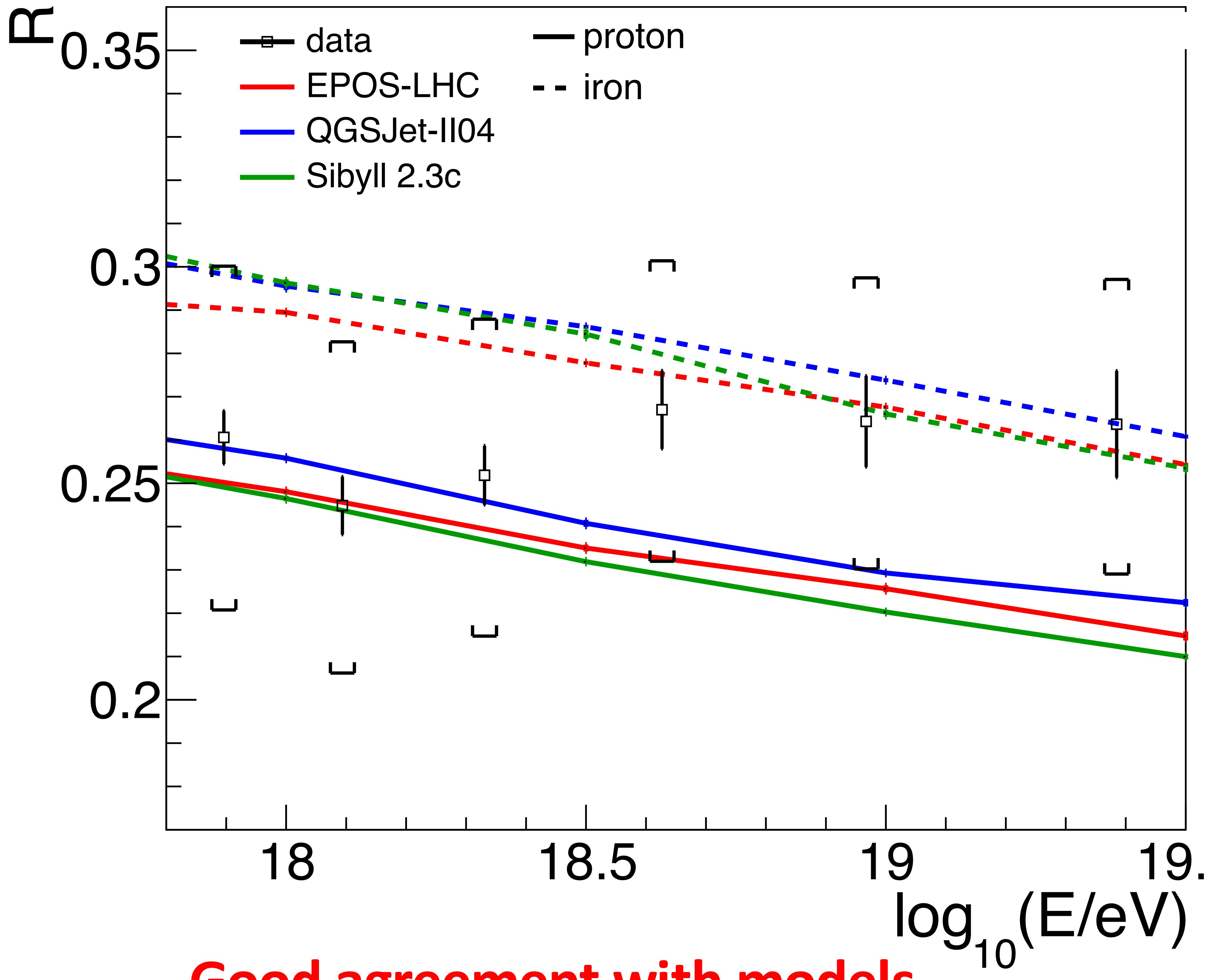
R is sensitive to the injection of **high energy π^0** in the start up of the shower.

$$R = \sqrt{\lambda/|X_0'|}, \qquad L = \sqrt{|X_0'|\lambda} \qquad X_0' = X_0 - X_{\max}$$

$$\frac{dE}{dX} = \left(1 + R\frac{X'}{L}\right)^{R^{-2}} \exp\left(-\frac{X'}{RL}\right)$$







Good agreement with models.

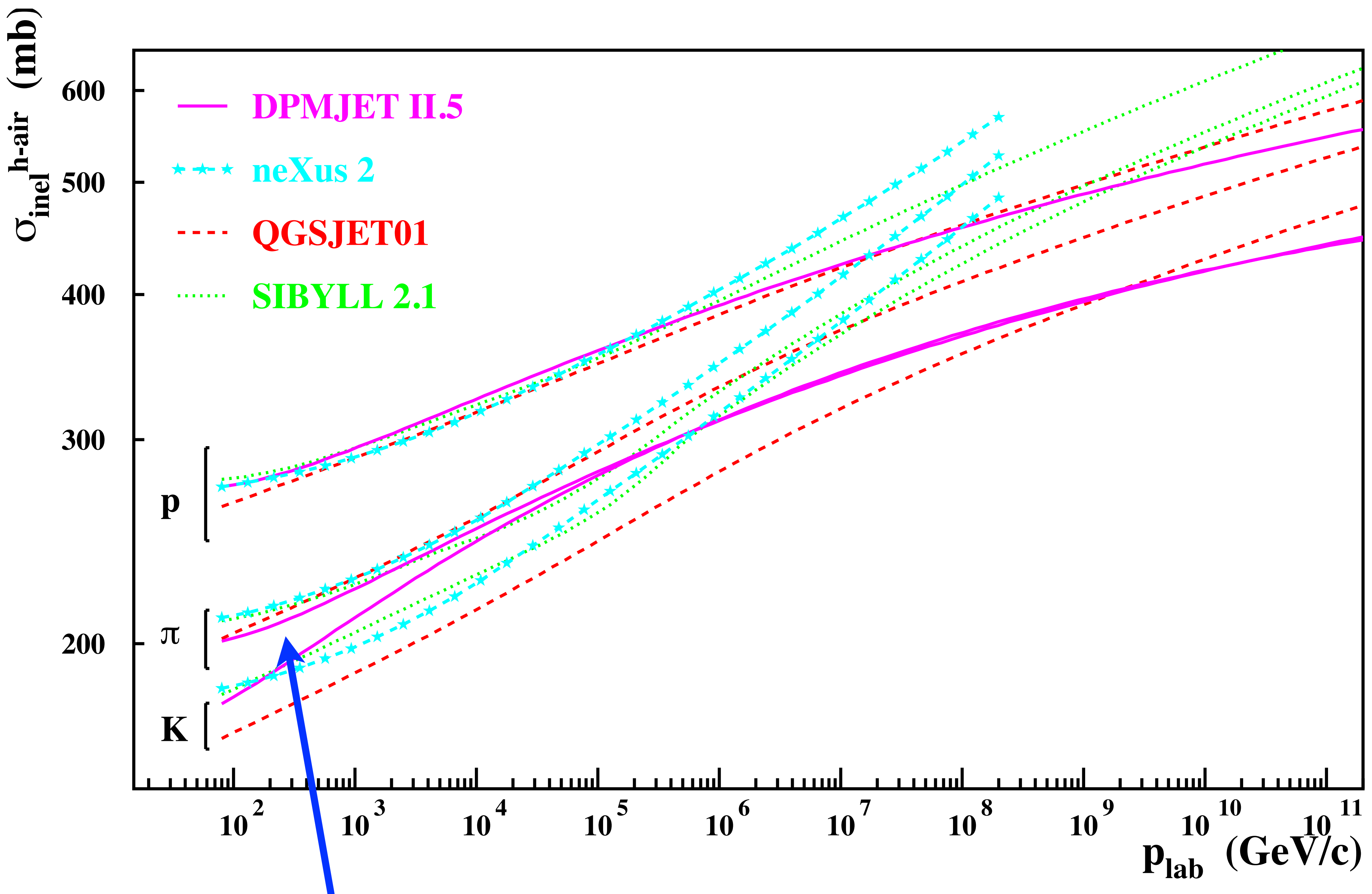
Too large systematics for hadronic physics, for the moment.

S. Andringa et al, Astropart.Phys. 34 (2011) 360

Slide by Lorenzo Cazon, Epiphany 2022

Auger JCAP 1903 (2019) 03 018

Interaction cross sections: mesons and nuclei

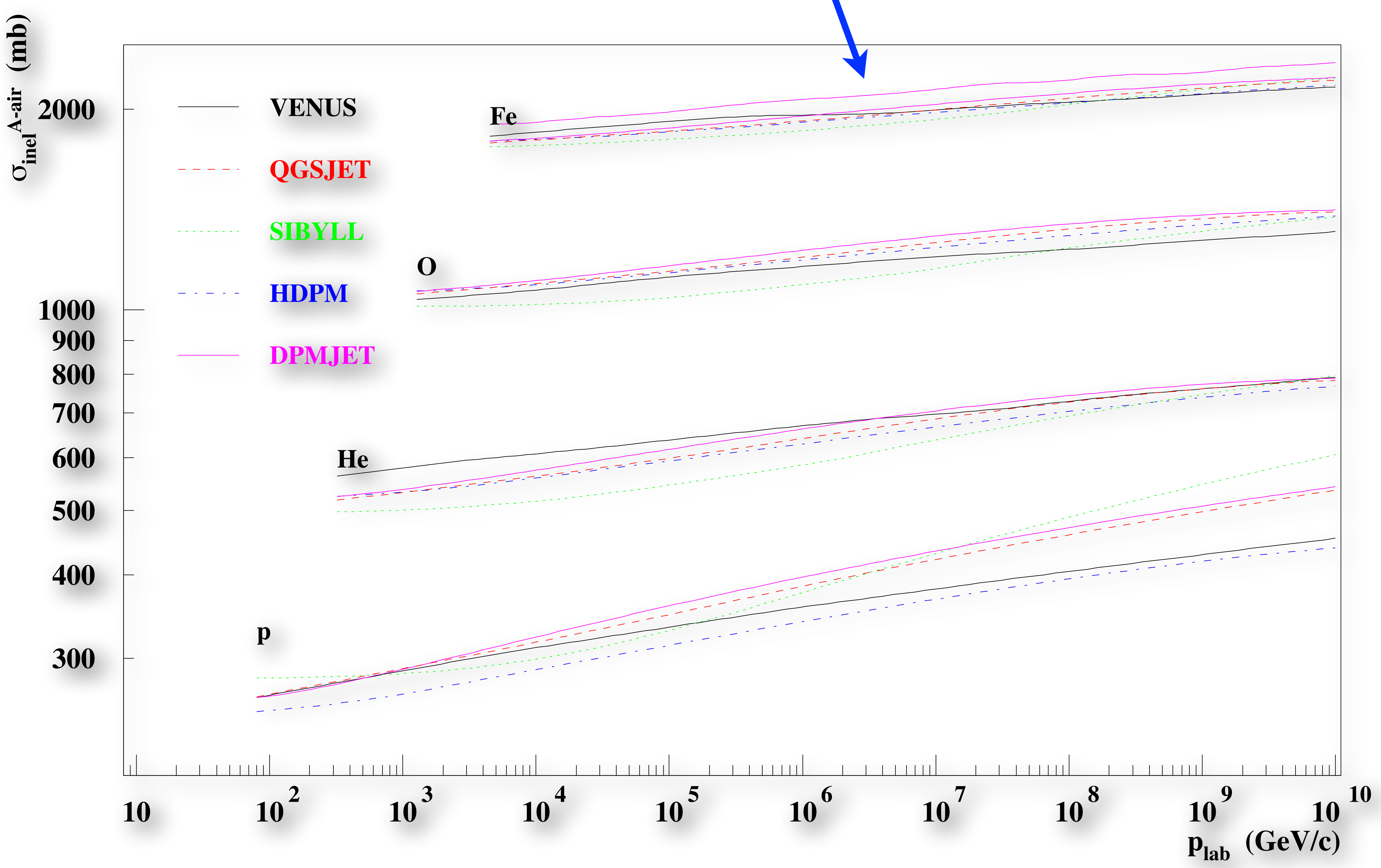


Pions: $\lambda_{\text{int}} \sim 120\ \text{g/cm}^2$

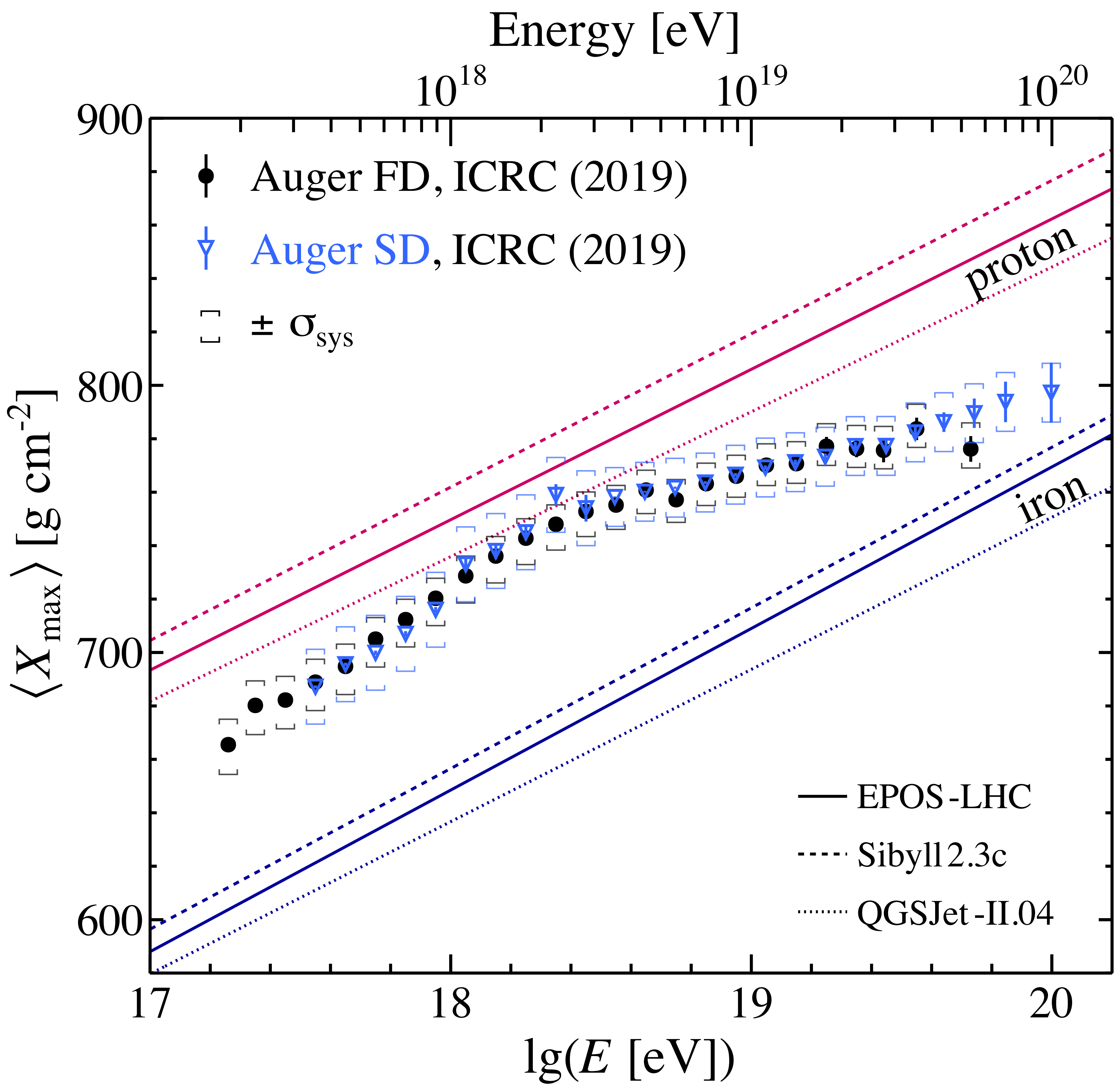
Protons: $\lambda_{\text{int}} \sim 75\ \text{g/cm}^2$

Photons: $\lambda_{\gamma,\text{pair}} = \frac{9}{7} X_0 \sim 50\ \text{g/cm}^2$

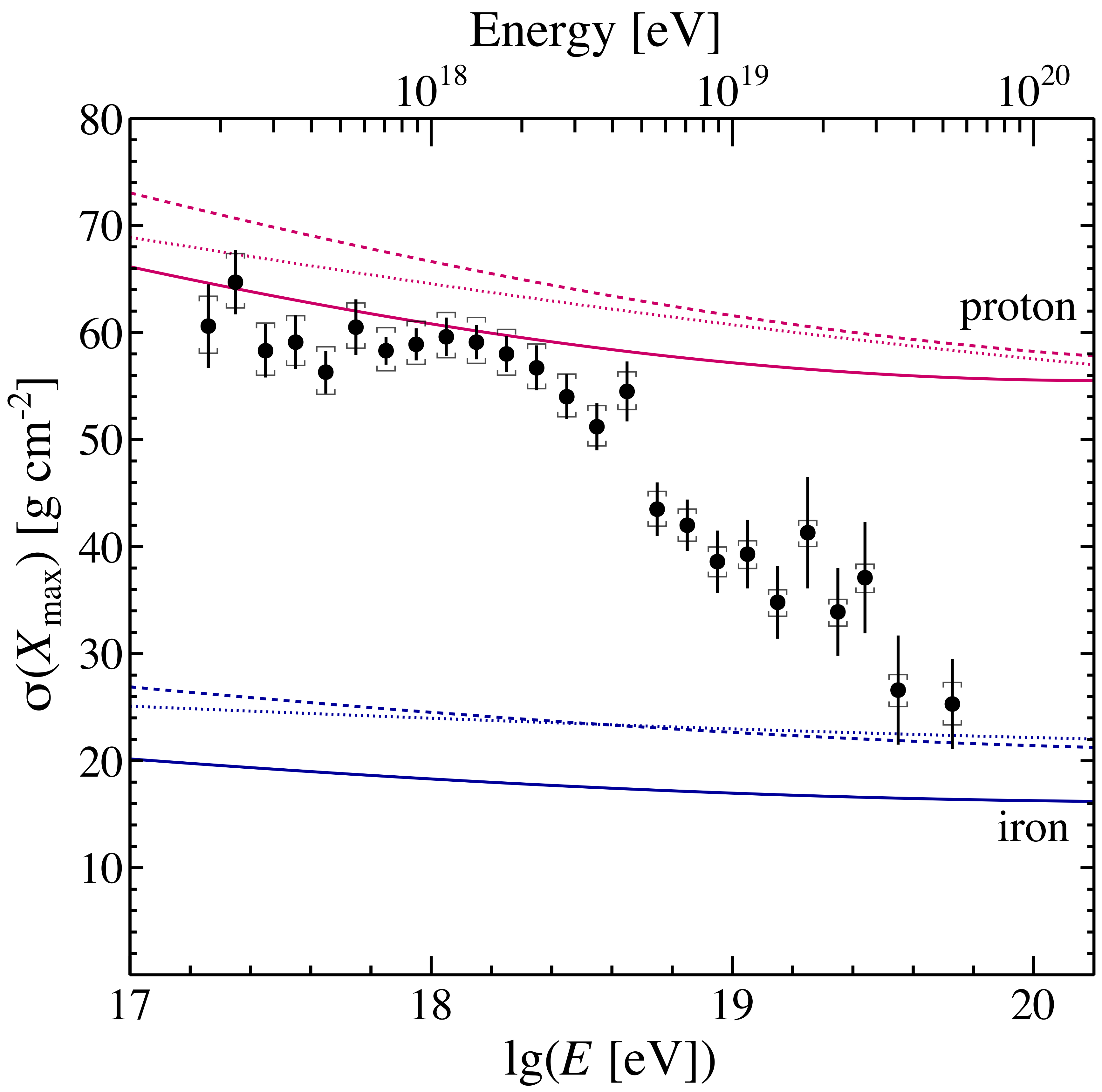
Iron nuclei: $\lambda_{\text{int}} \sim 12\ \text{g/cm}^2$



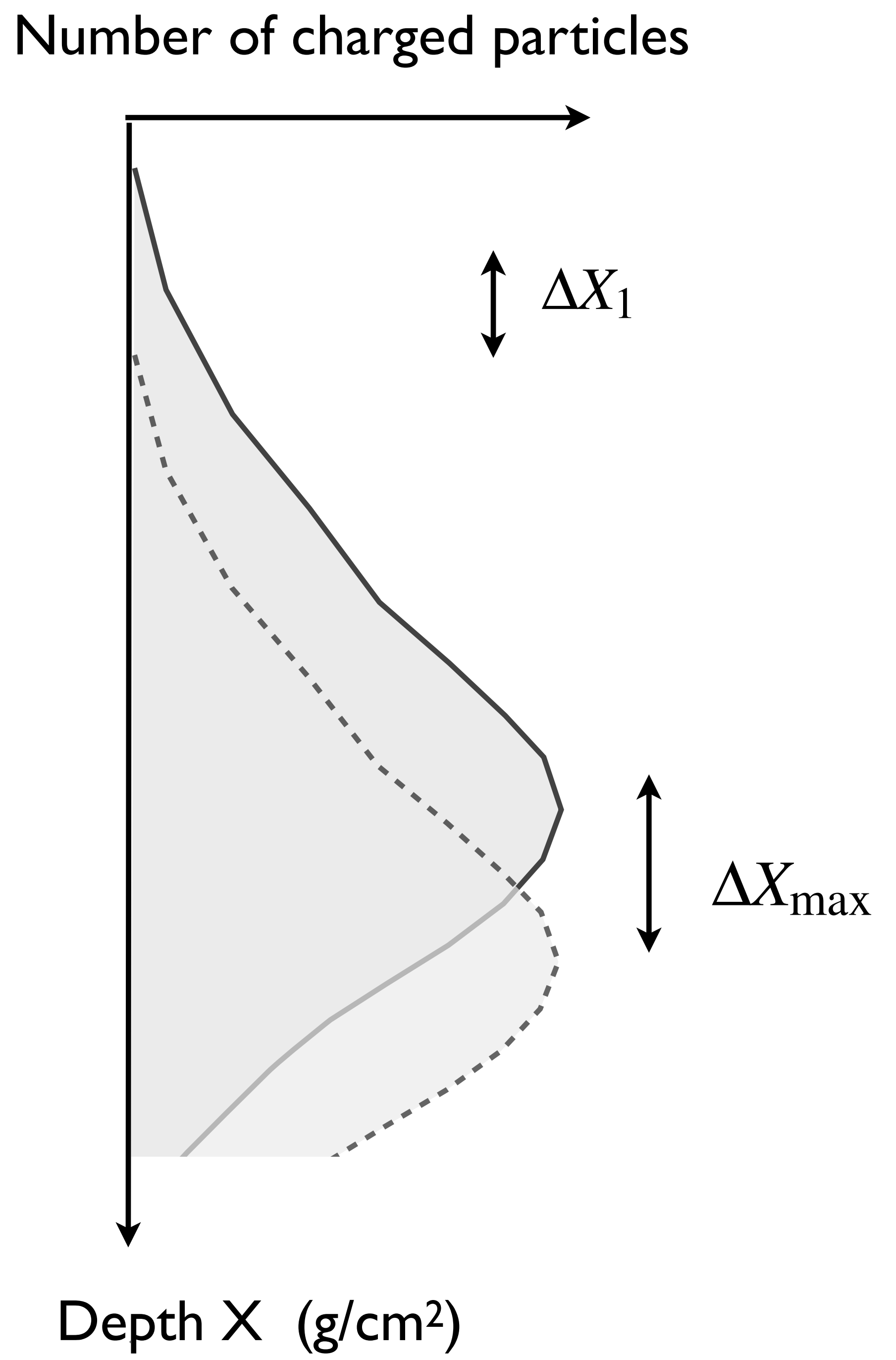
Mass composition results – Auger Observatory



(Phys. Rev. D90 (2014), 122005 & 122005, updated ICRC 2019)



(Phys. Rev. D96 (2017), 122003)



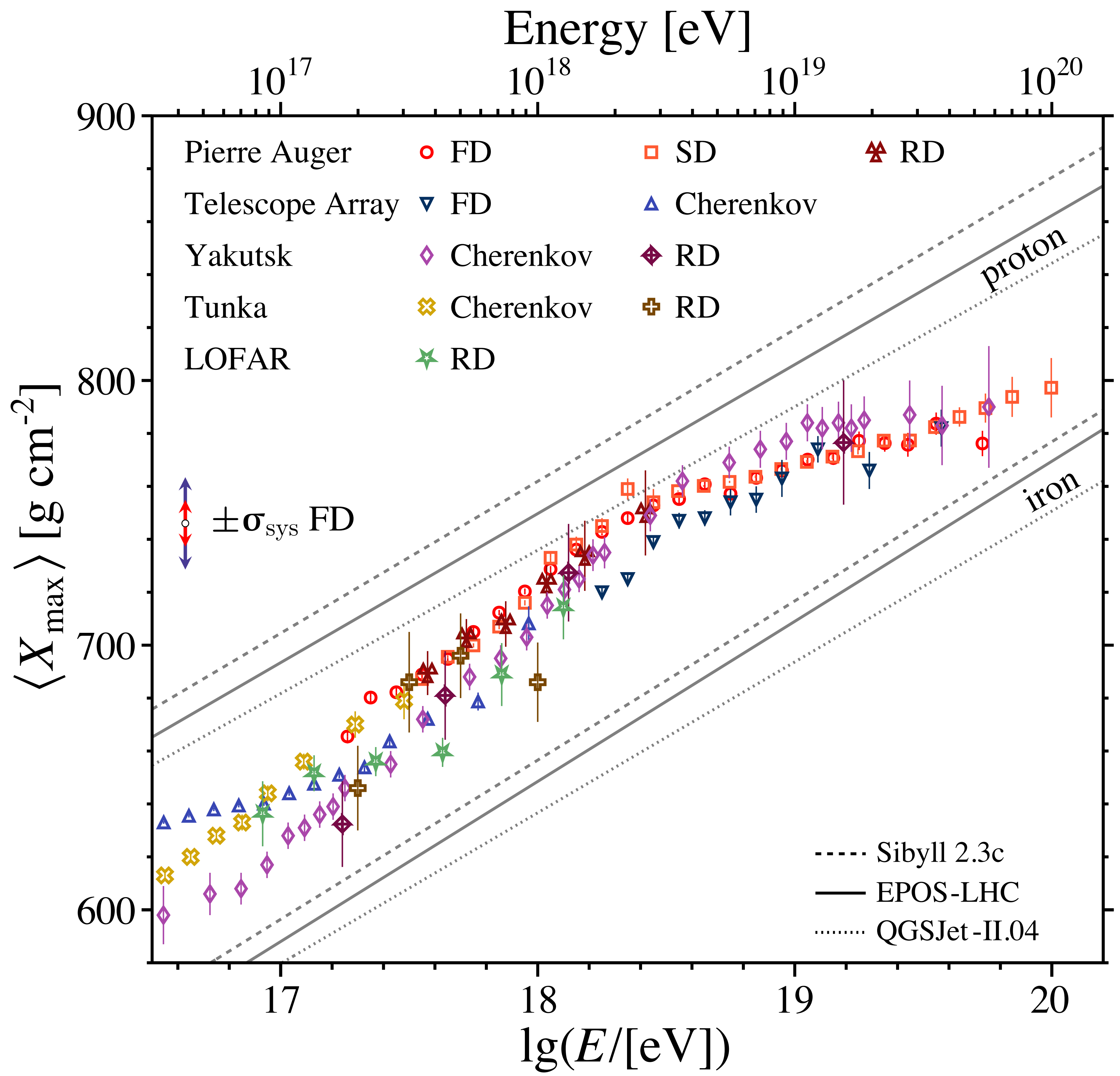
$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

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

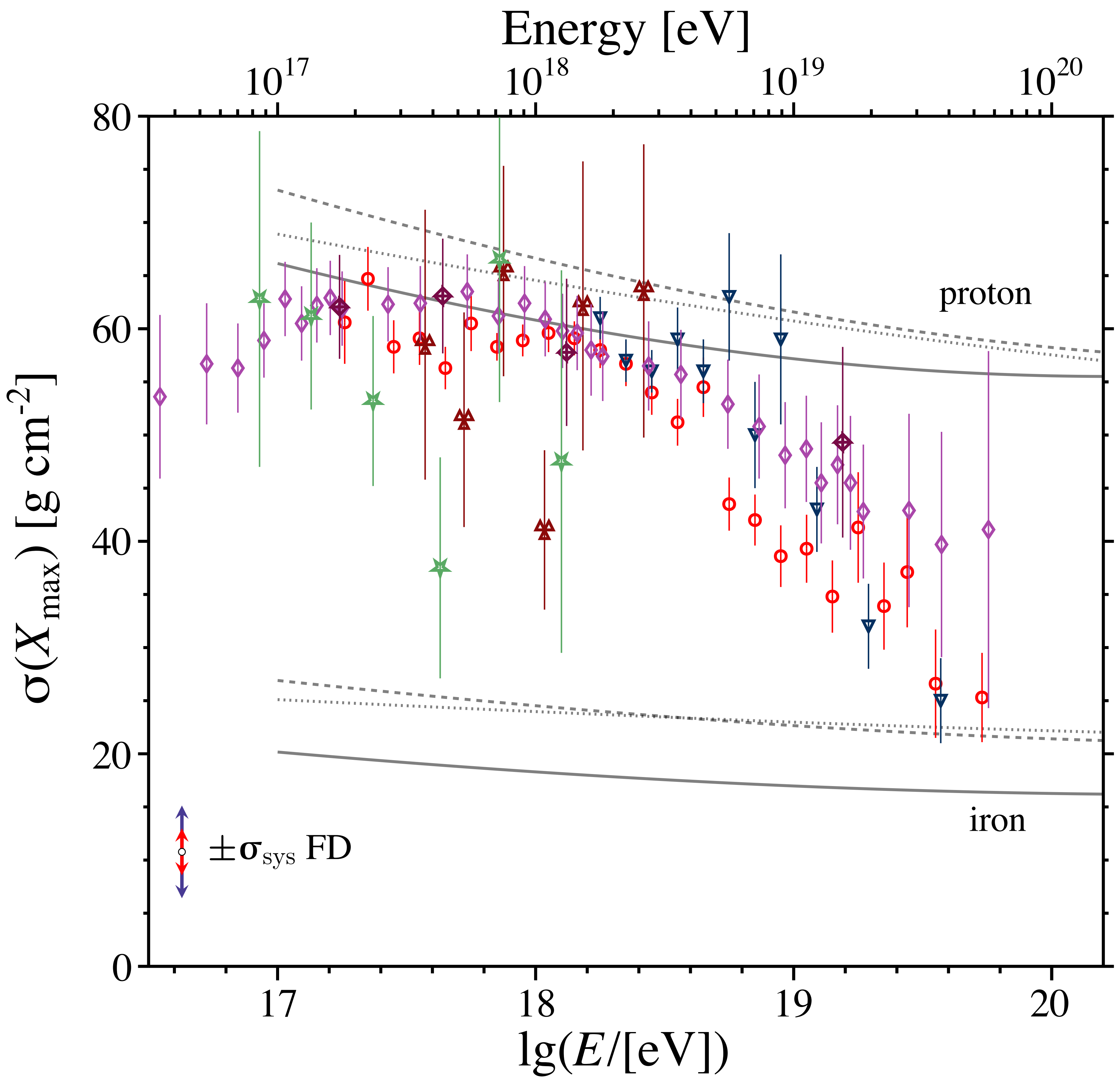
$(E \sim 10^{18}\,\mathrm{eV})$

Important: LHC-tuned interaction models used for interpretation

Mass composition results – world data

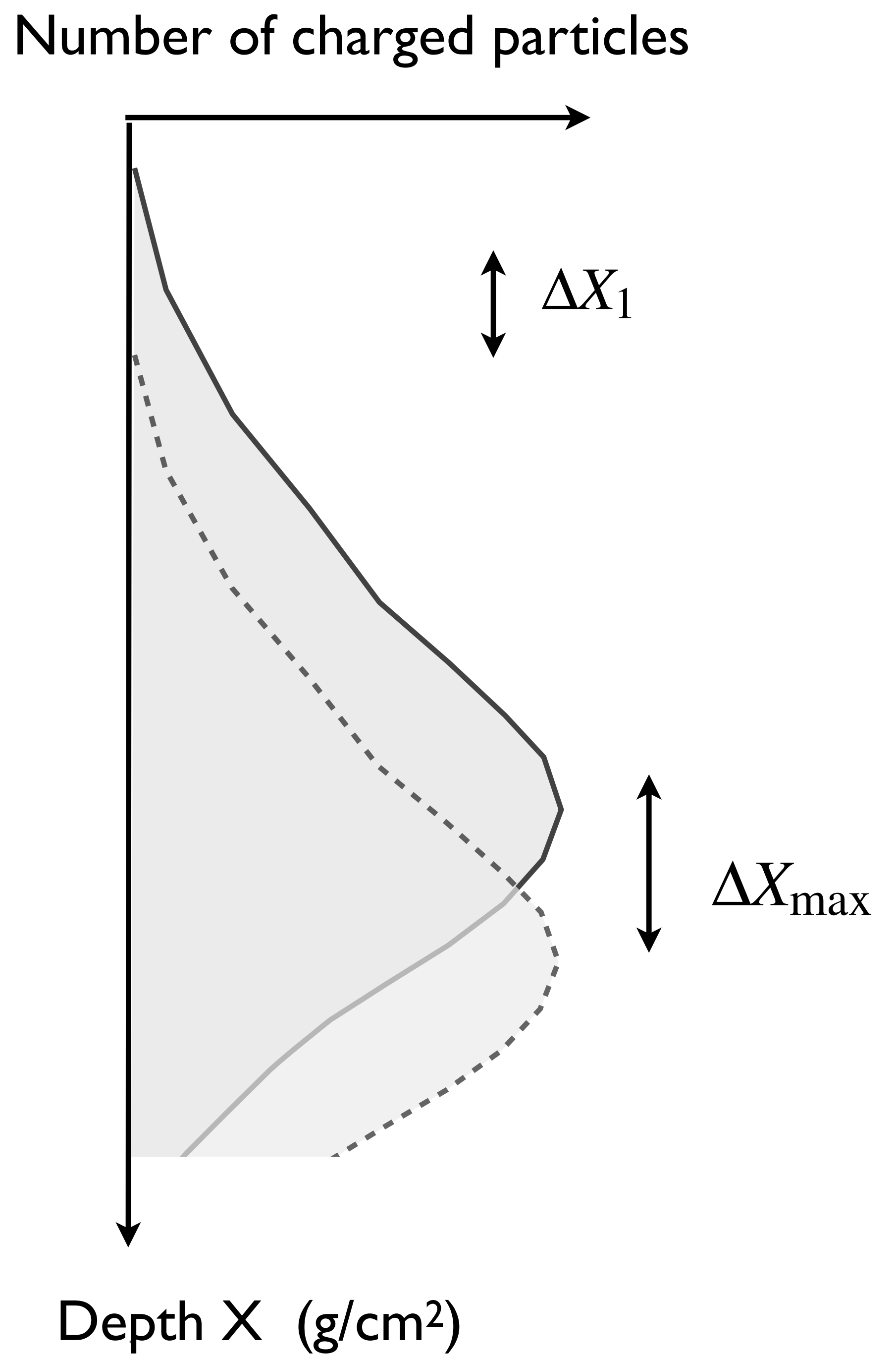


(Snowmass report UHECR composition, 2022)



(Phys. Rev. D96 (2017), 122003)

Important: LHC-tuned interaction models used for interpretation

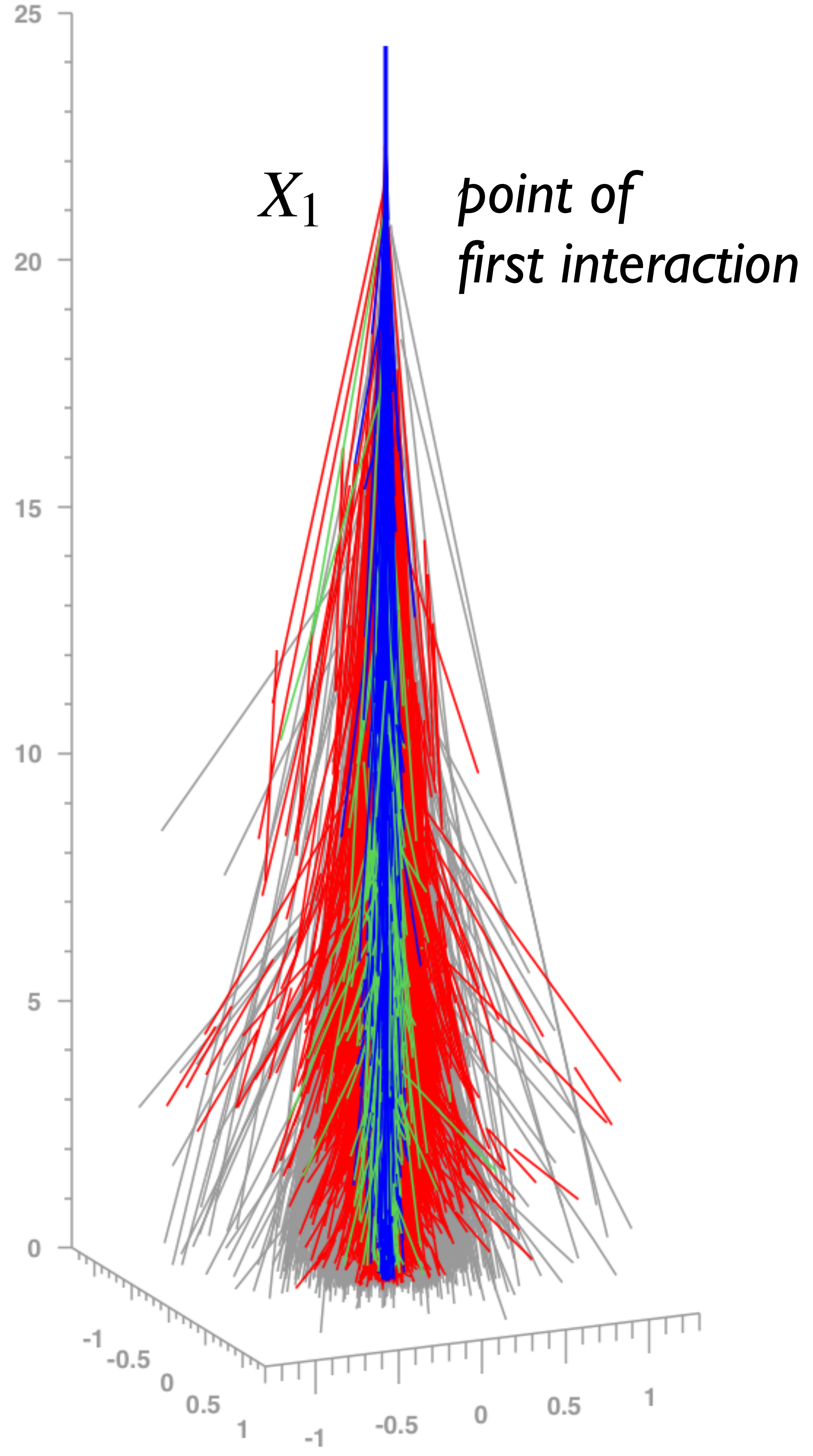


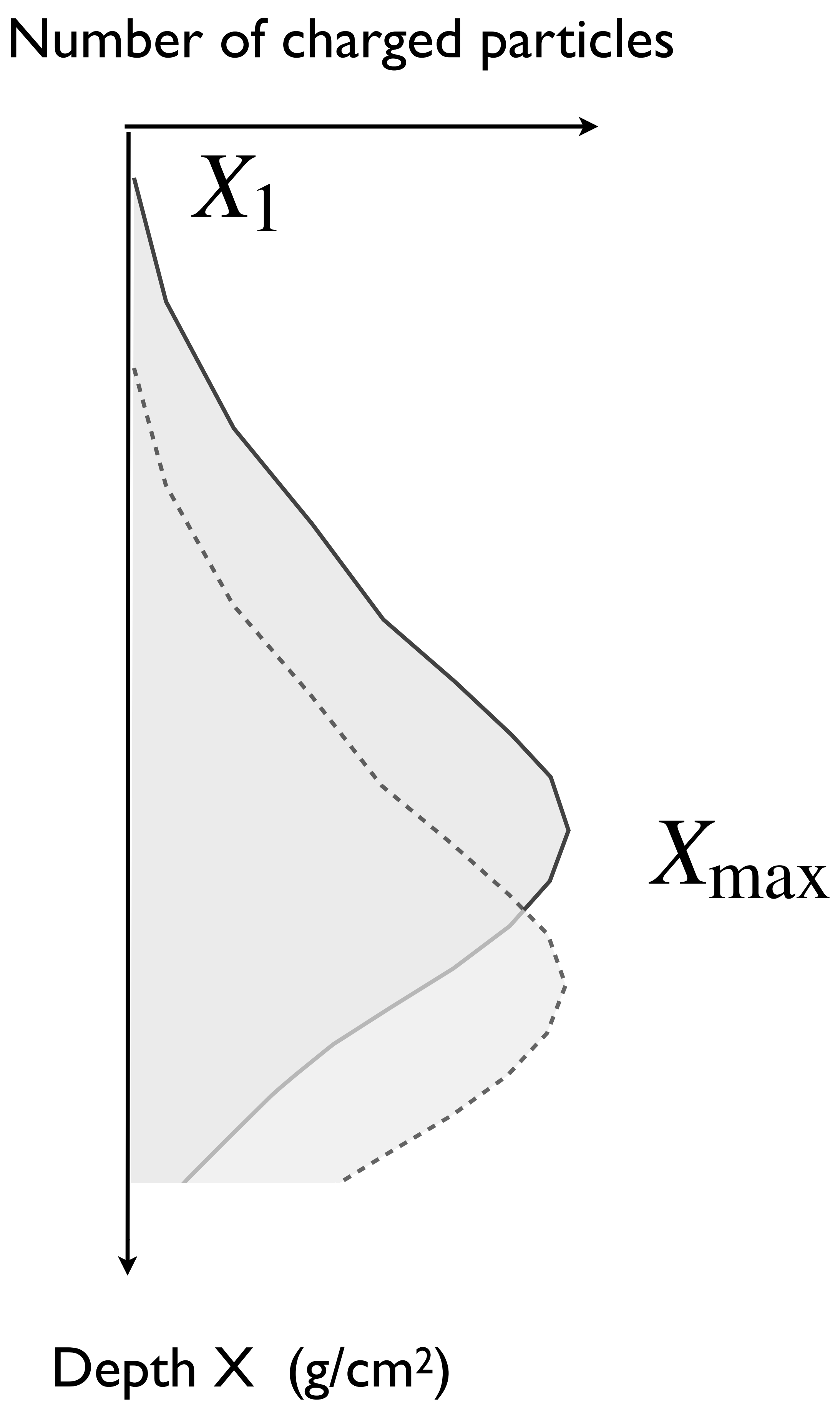
$$\frac{\mathrm{d}P}{\mathrm{d}X_1} = \frac{1}{\lambda_{\text{int}}} e^{-X_1/\lambda_{\text{int}}}$$

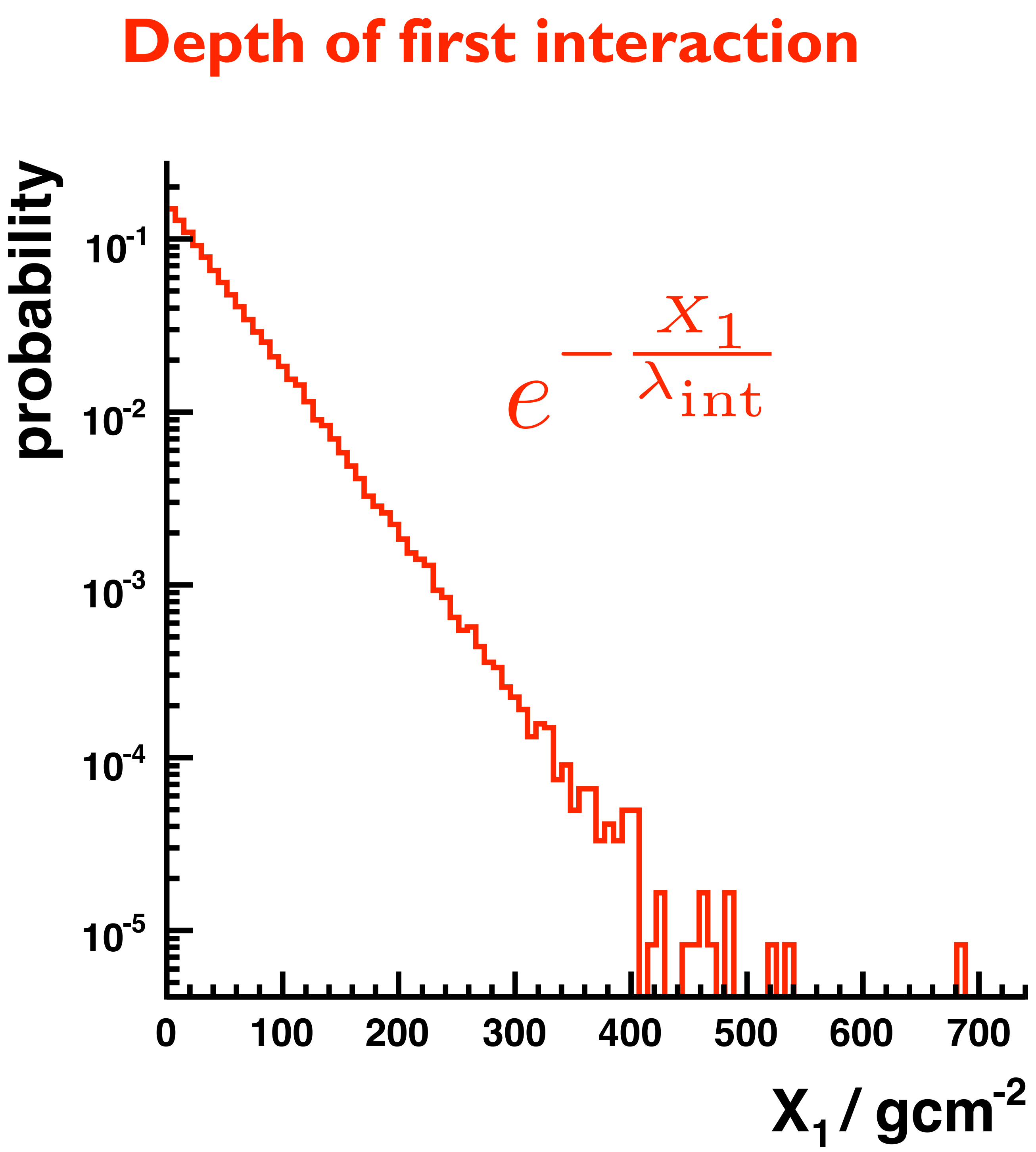
$$\sigma_{X_1,\mathrm{p}} \sim 45 - 55\,\mathrm{g/cm^2}$$
$$\sigma_{X_1,\mathrm{Fe}} \sim 10\,\mathrm{g/cm^2}$$

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

Depth distribution of point of first interaction





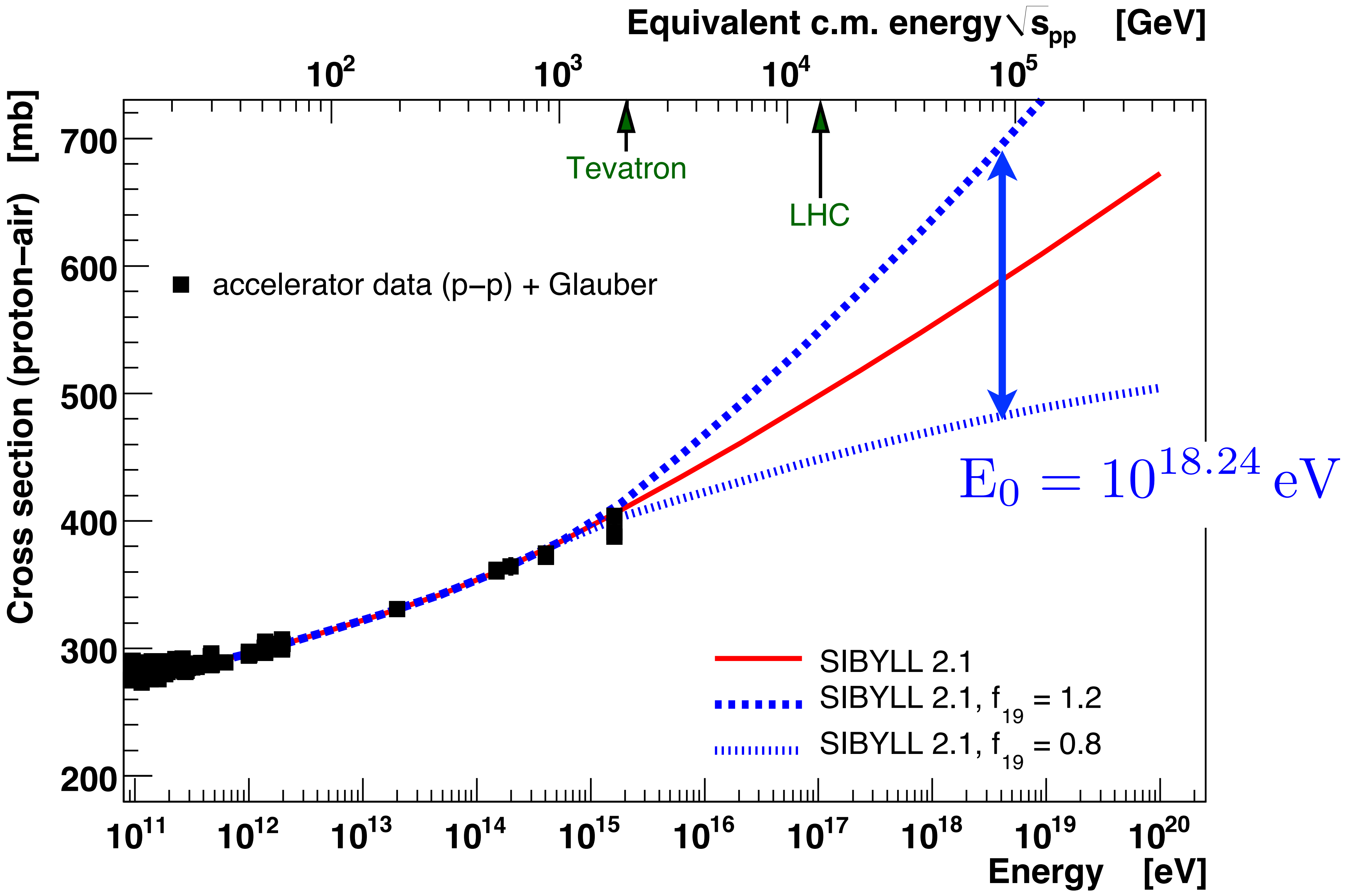


$$\langle X_1 \rangle = \lambda_{\rm int} \qquad \sigma(X_1) = \lambda_{\rm int}$$

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

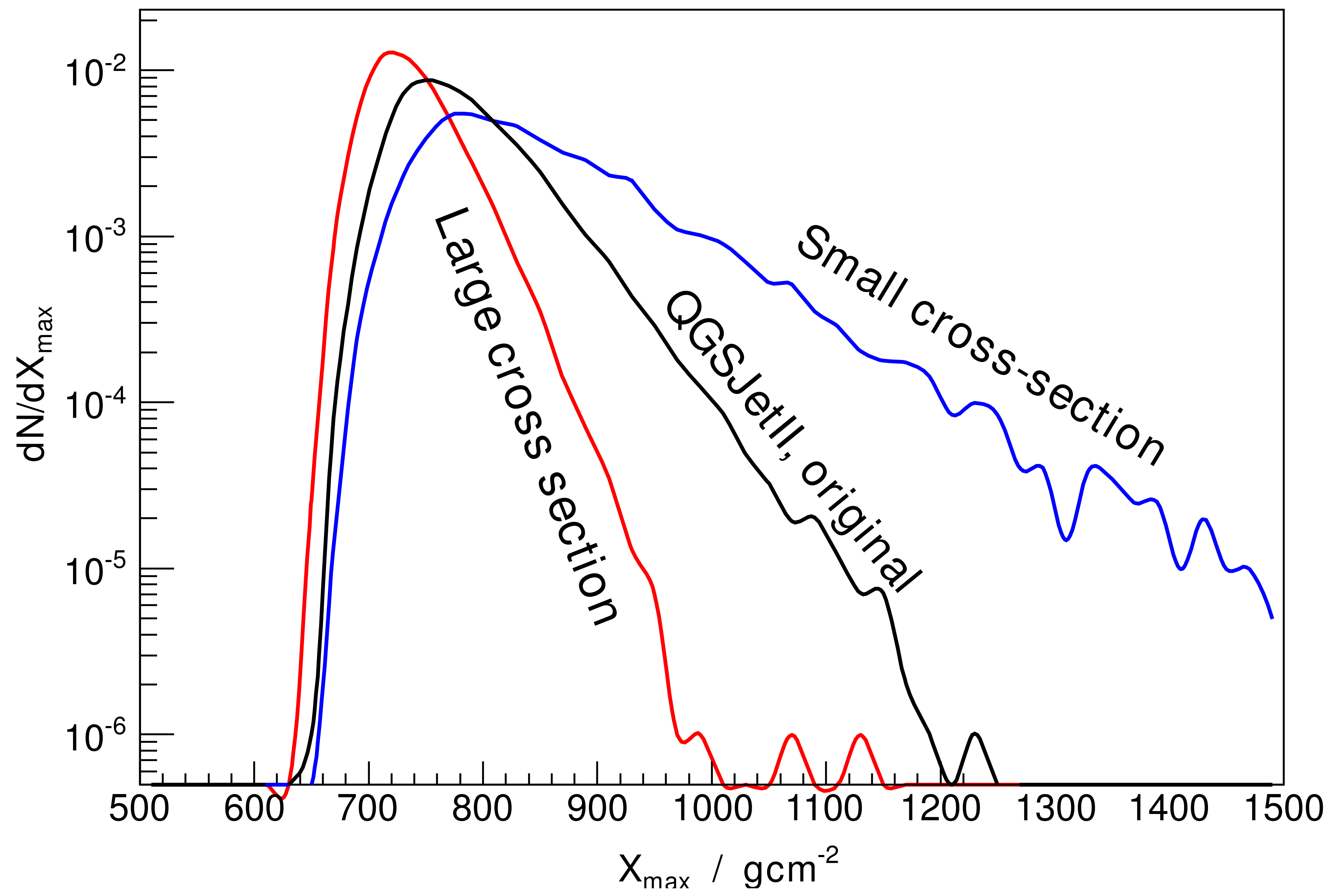
(R. Ulrich et al. NJP 11, 2009)

Cross section measurement: self-consistency



Simulation for proton showers with different cross sections:
very good sensitivity of tail of distribution

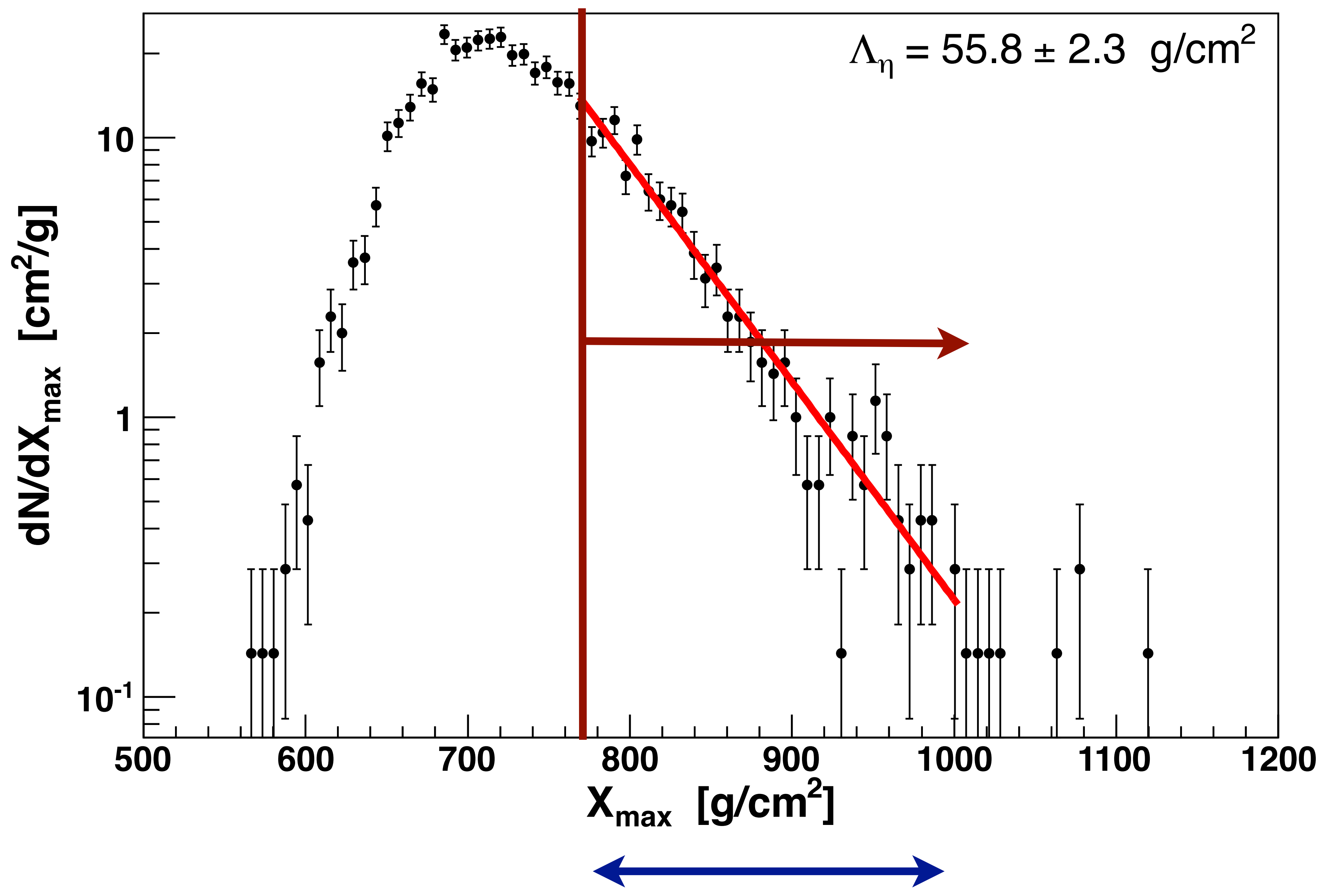
Simulated Xmax distributions



Cross section accepted if simulated slope fits measured slope of X_{max} distribution

(Auger Collab. 1107.4804)

Cross section measurement: composition bias?

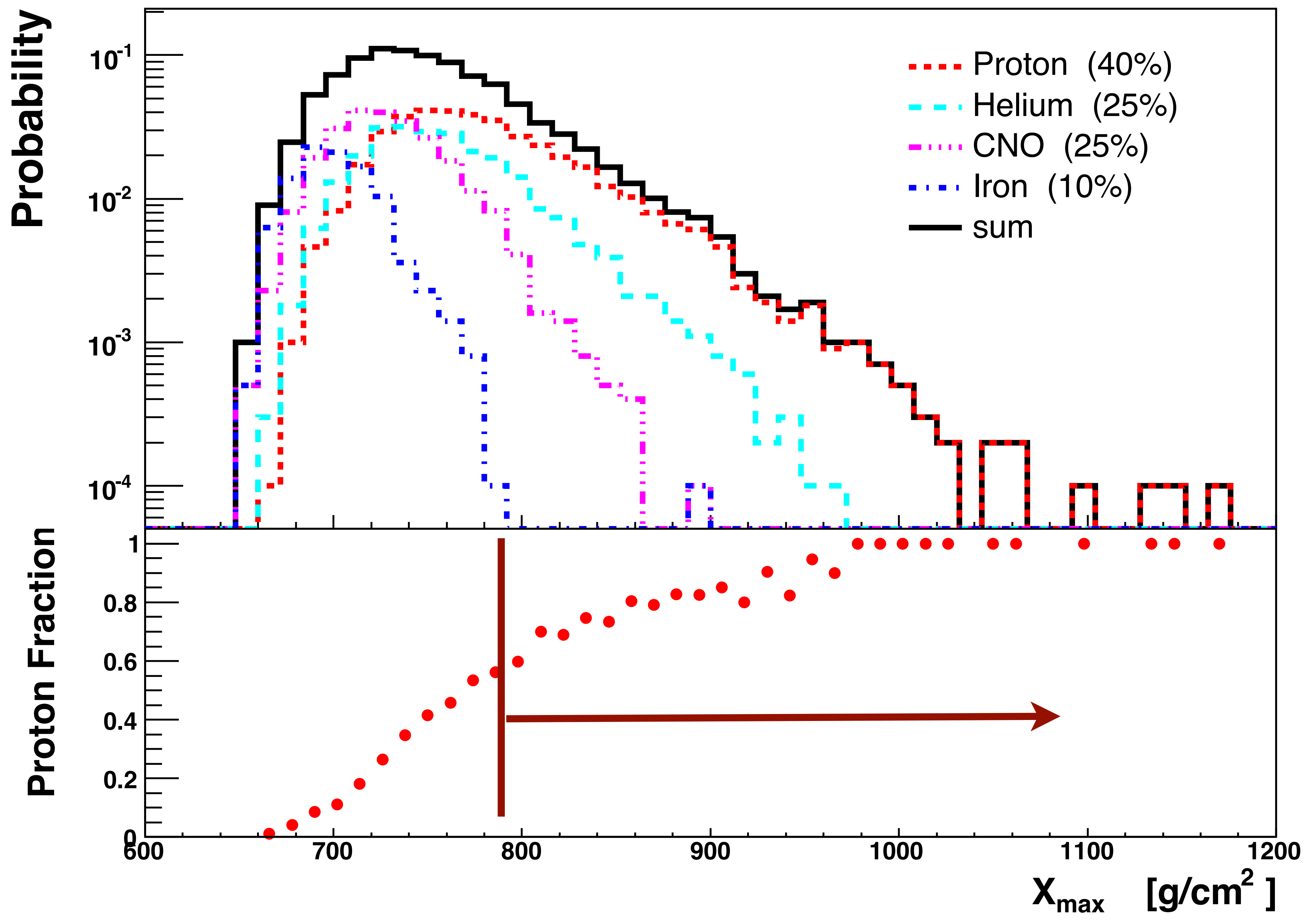


Effective slope of Xmax measured after event selection

Depth range of analysis

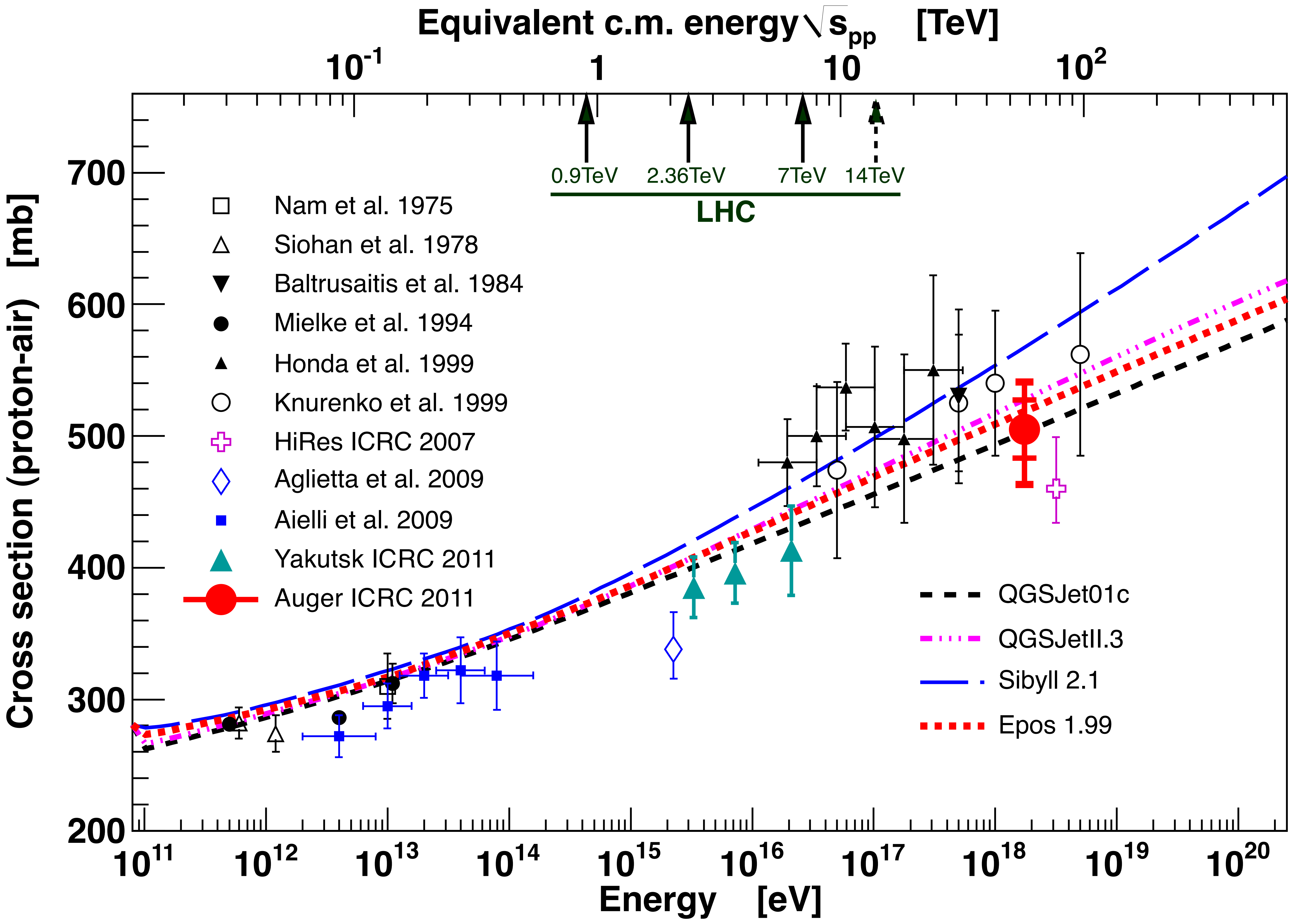
Only deep showers are used in analysis to enhance proton fraction in data sample

Simulated distribution of X_{max} for mixed composition



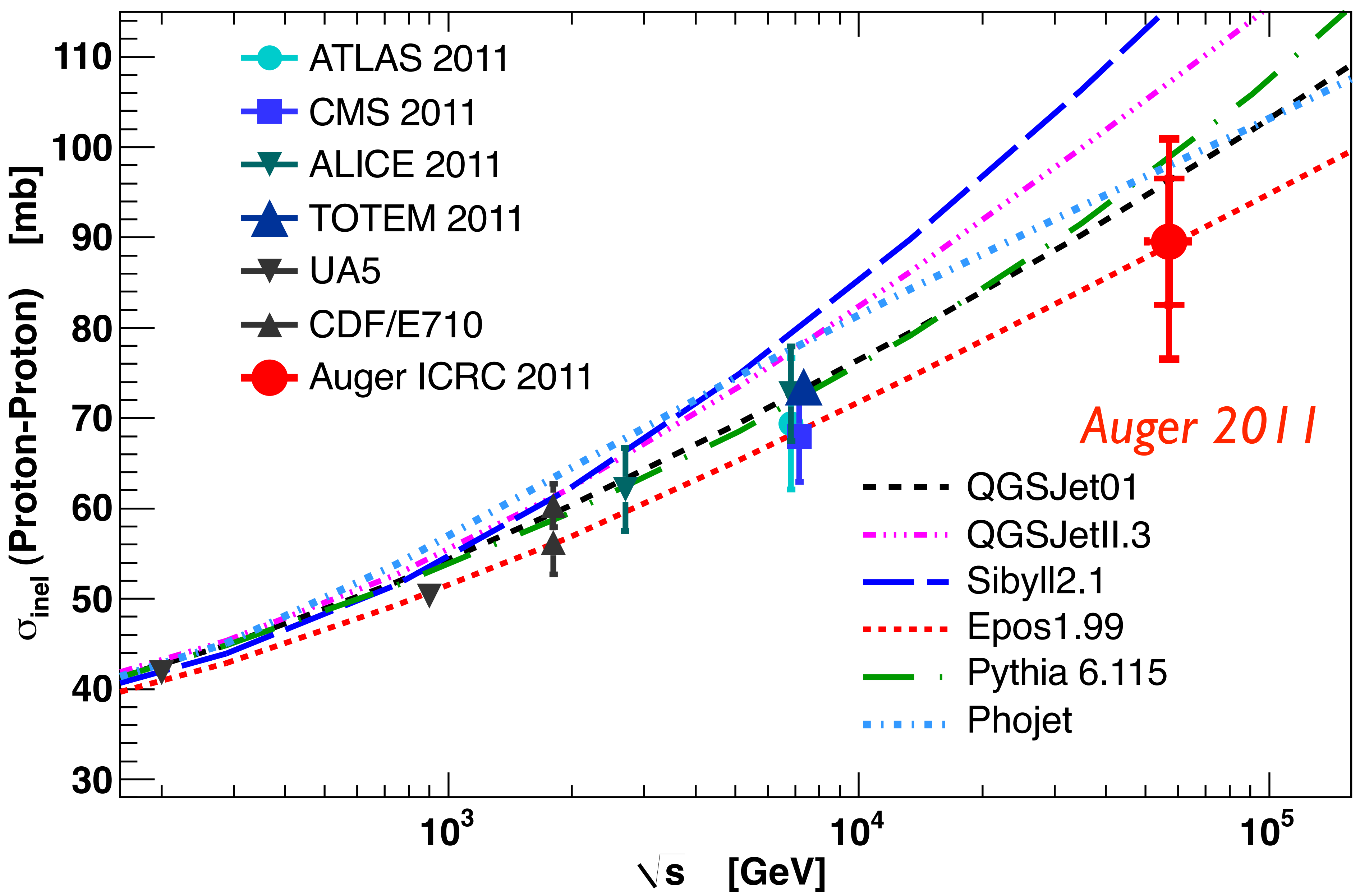
(Pierre Auger Collab. PRL)

High-energy frontier: proton-air cross section



Conversion from p-air to p-p cross section always model-dependent

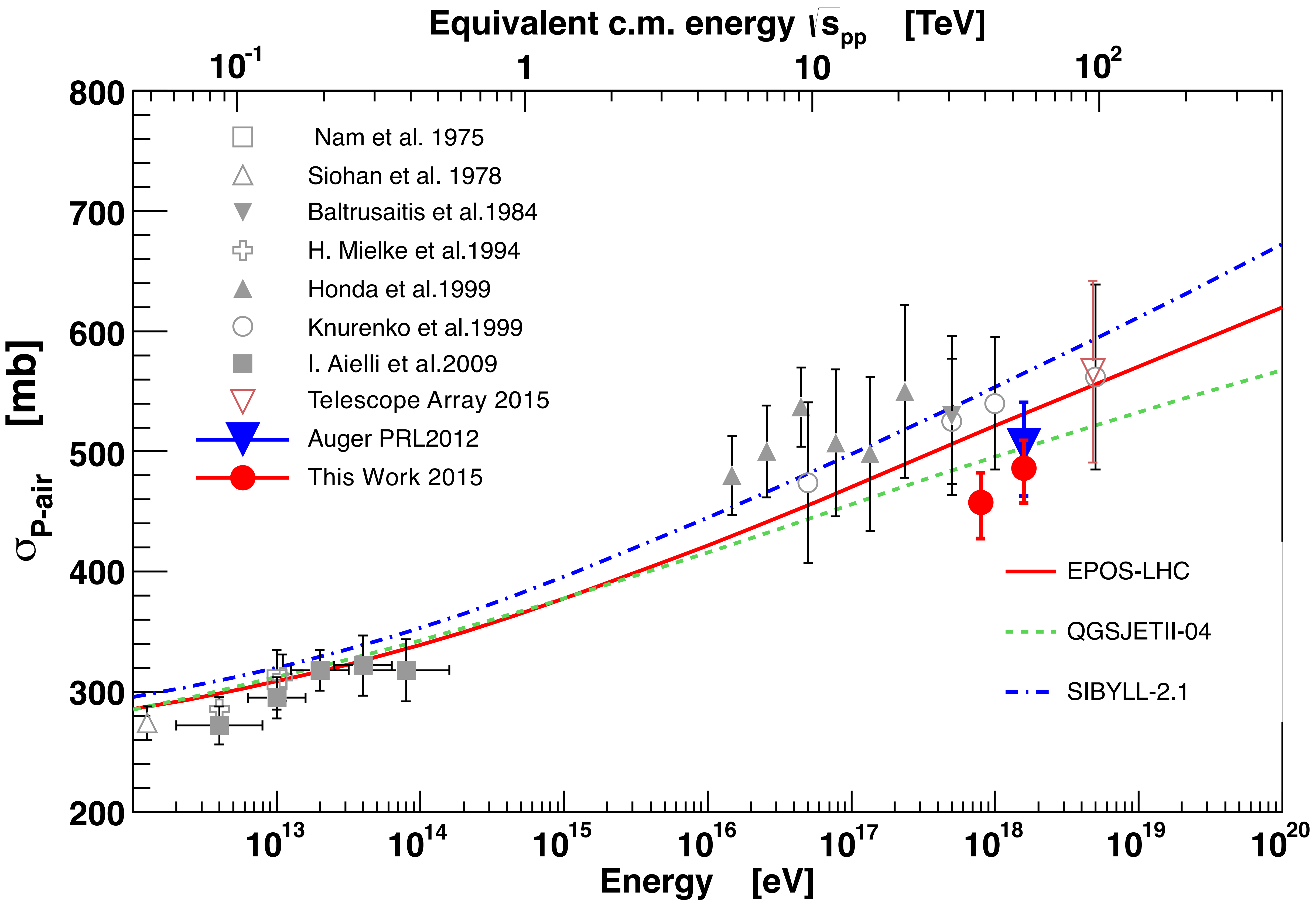
Glauber model



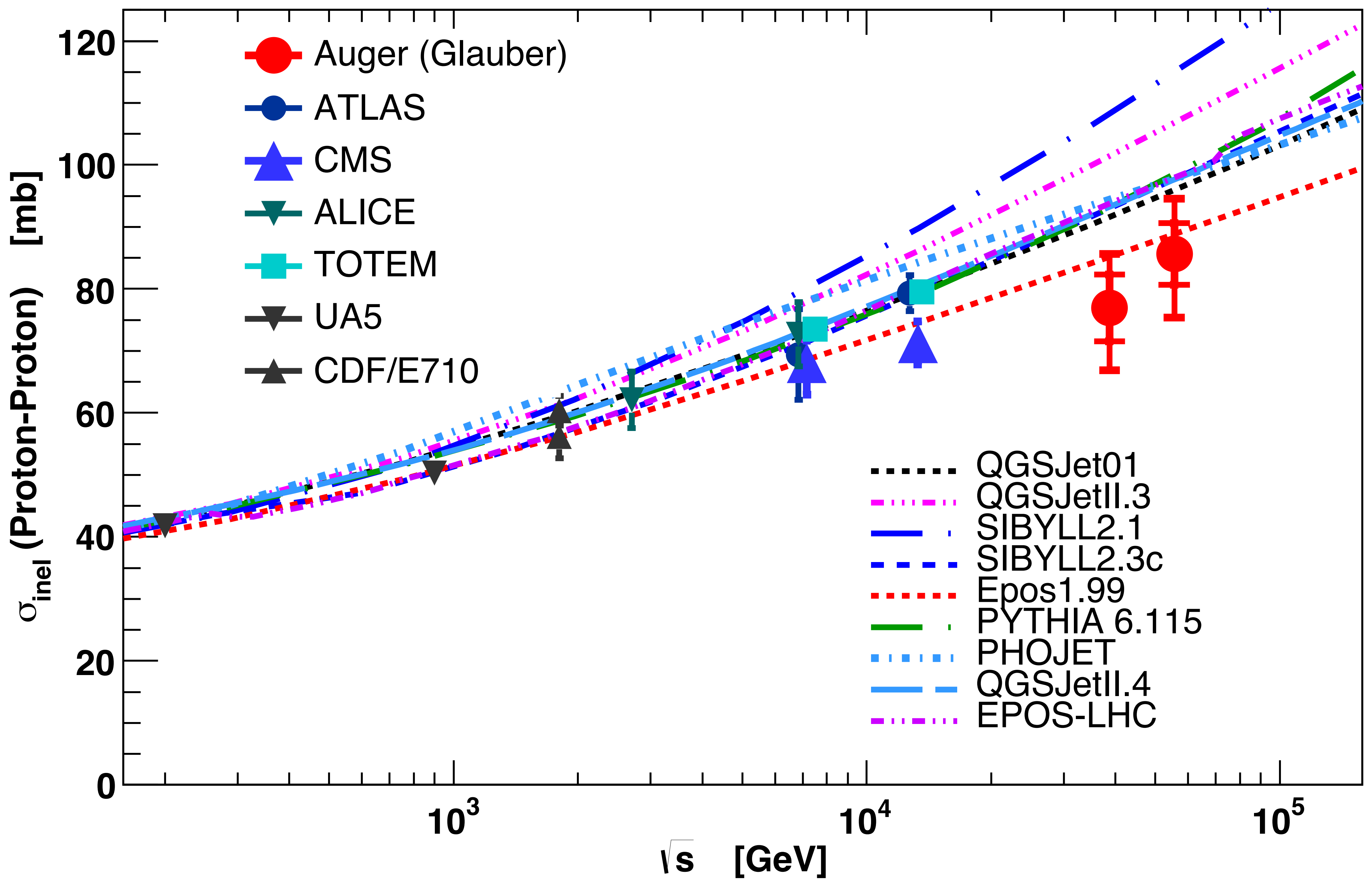
Cross section independent of LHC data,
very good agreement with extrapolated data

(Pierre Auger Collab. 1107.4804, Phys. Rev. Lett. 2012)

How to increase p-air cross section by factor 2



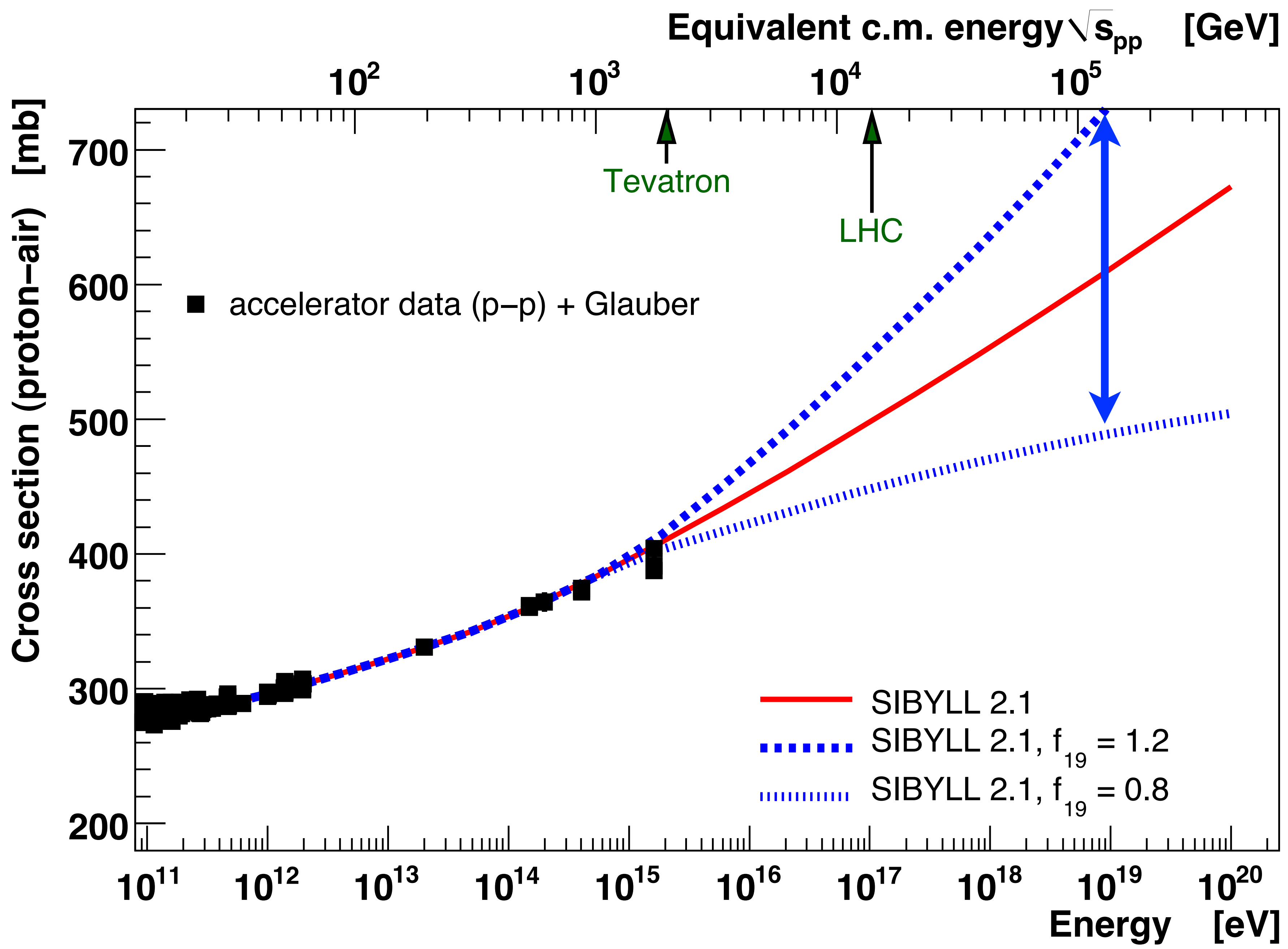
Glauber model (multiple scattering approximation)

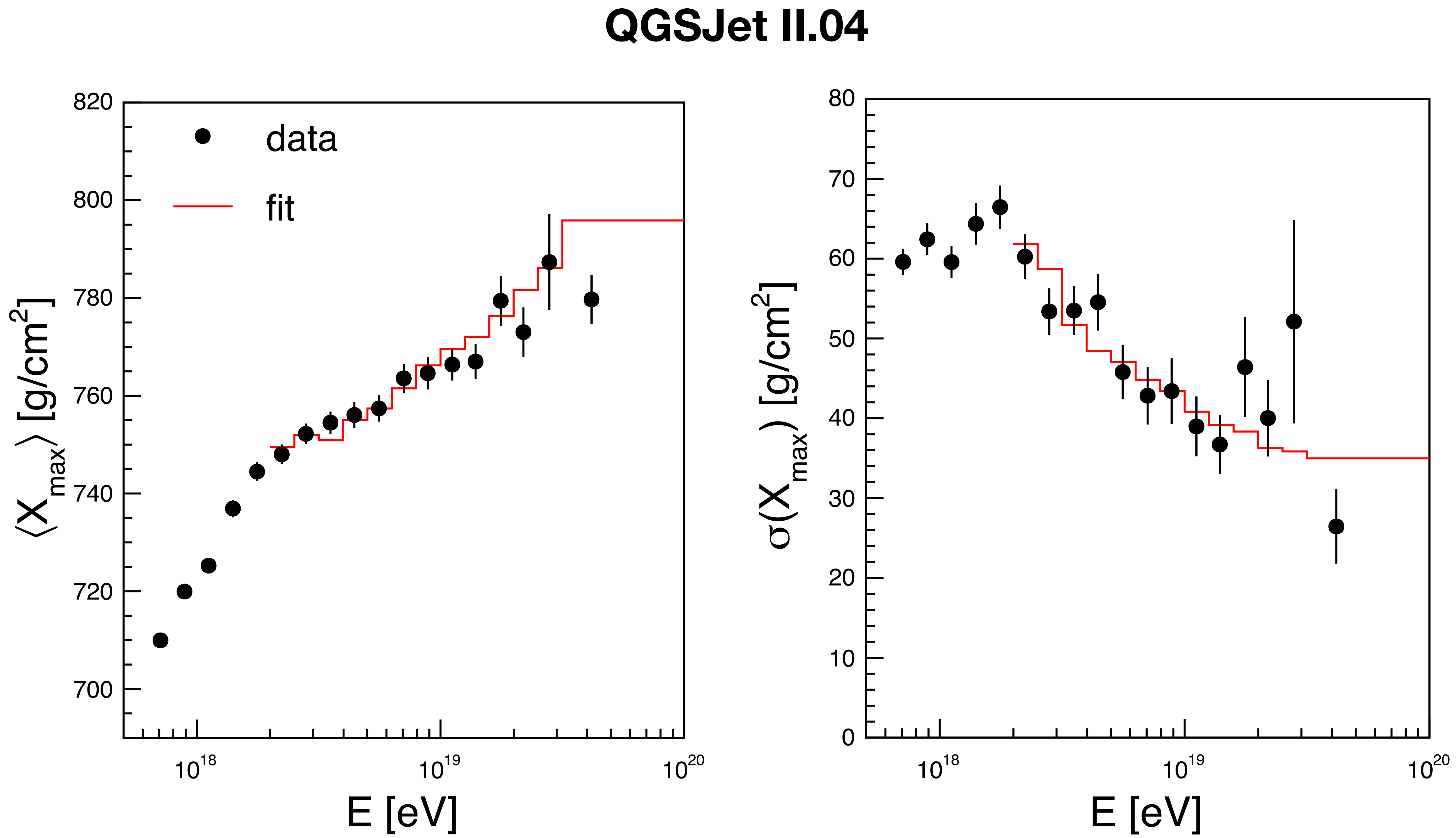


Models, recent collider data, Auger (derived) cross sections

(Ulrich, Auger, ICRC 2017)

Exotic scenario: change of interaction properties




QGSJet II.04

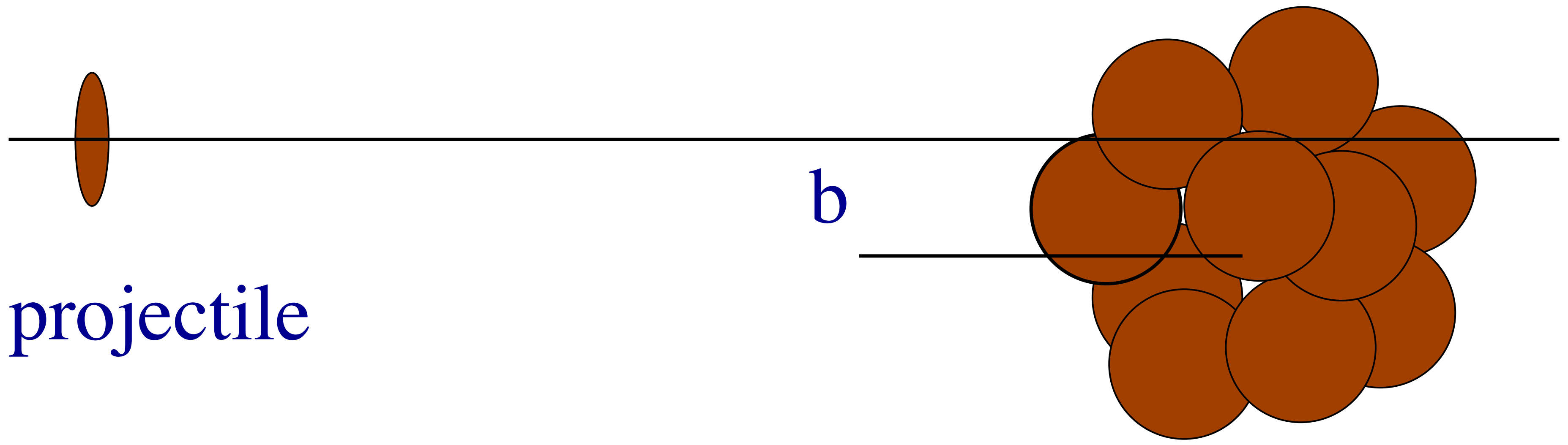
$$f(E, f_{19}) = 1 + (f_{19} - 1)\begin{cases} 0 & \lg E < 18.3 \\ (\lg(E) - 18.3)/0.7 & \lg E > 18.3 \end{cases}$$

Threshold for new physics scenario at $10^{18.3}$ eV

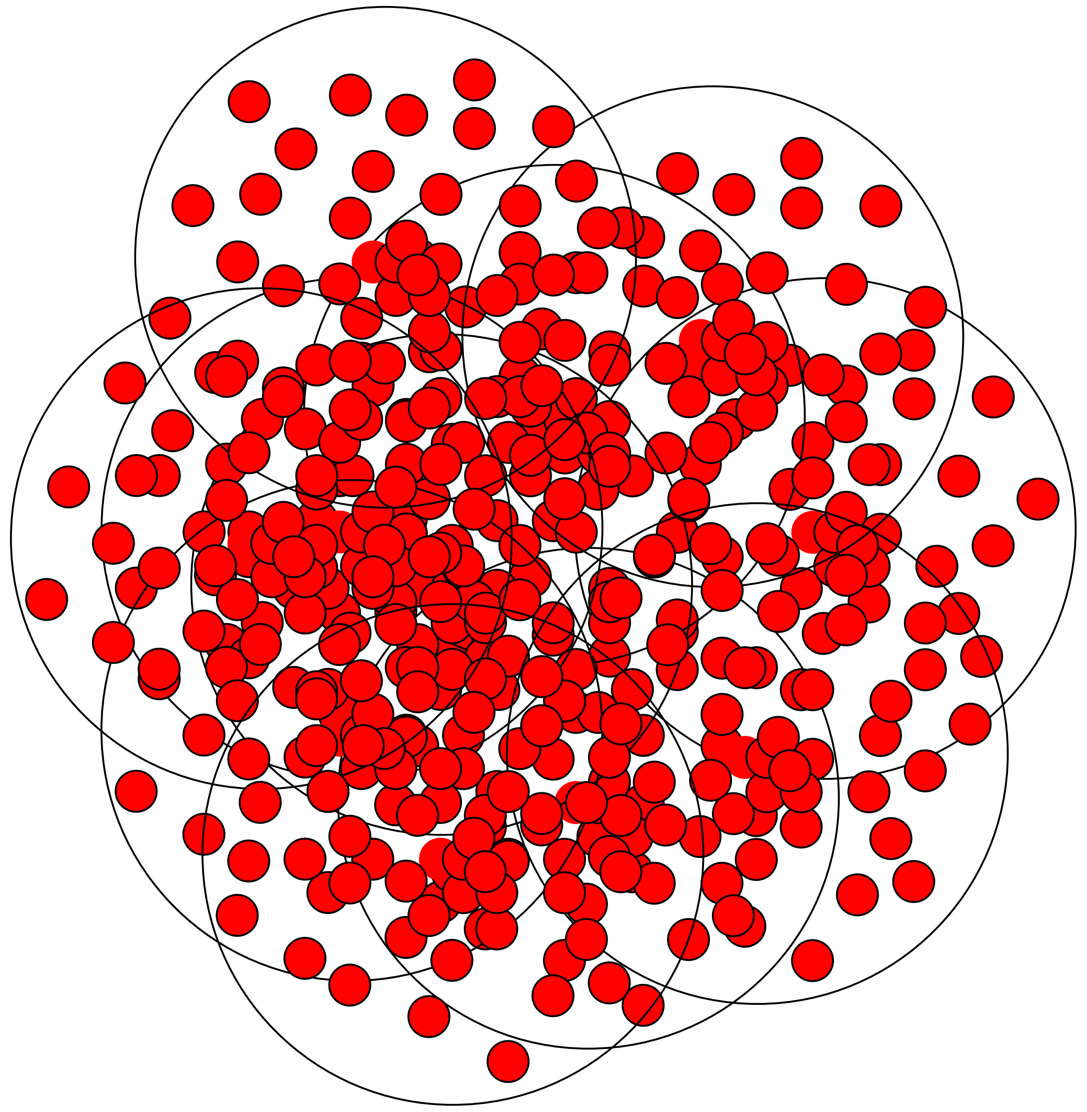
$$f_{\mathrm{mult}} = 0.82 \pm 0.01, \quad f_{\mathrm{cross}} = 2.06 \pm 0.02$$

(Unger, unpublished 2015)

Black disk limit reached at LHC energies for p-p scattering



$$\sigma_{\mathrm{prod}} \approx \int d^2\vec{b}\left[1-\exp\left\{-\sigma_{\mathrm{ine}}^{NN} T_A(\vec{b})\right\}\right]$$



LHC: p-p scattering
“black disk” at small
impact parameters

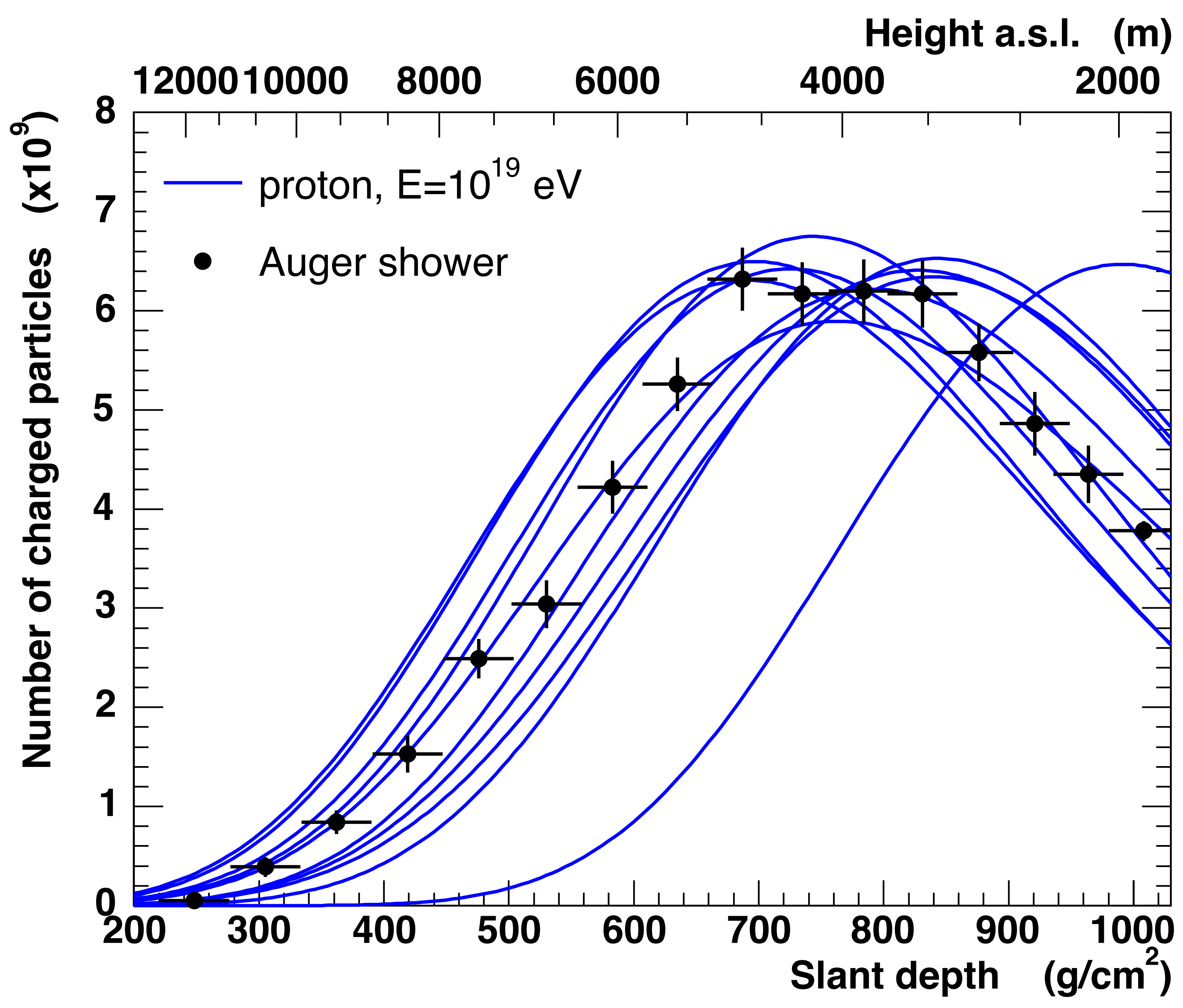
Cross section largely
determined by geometry
of nucleons in nucleus

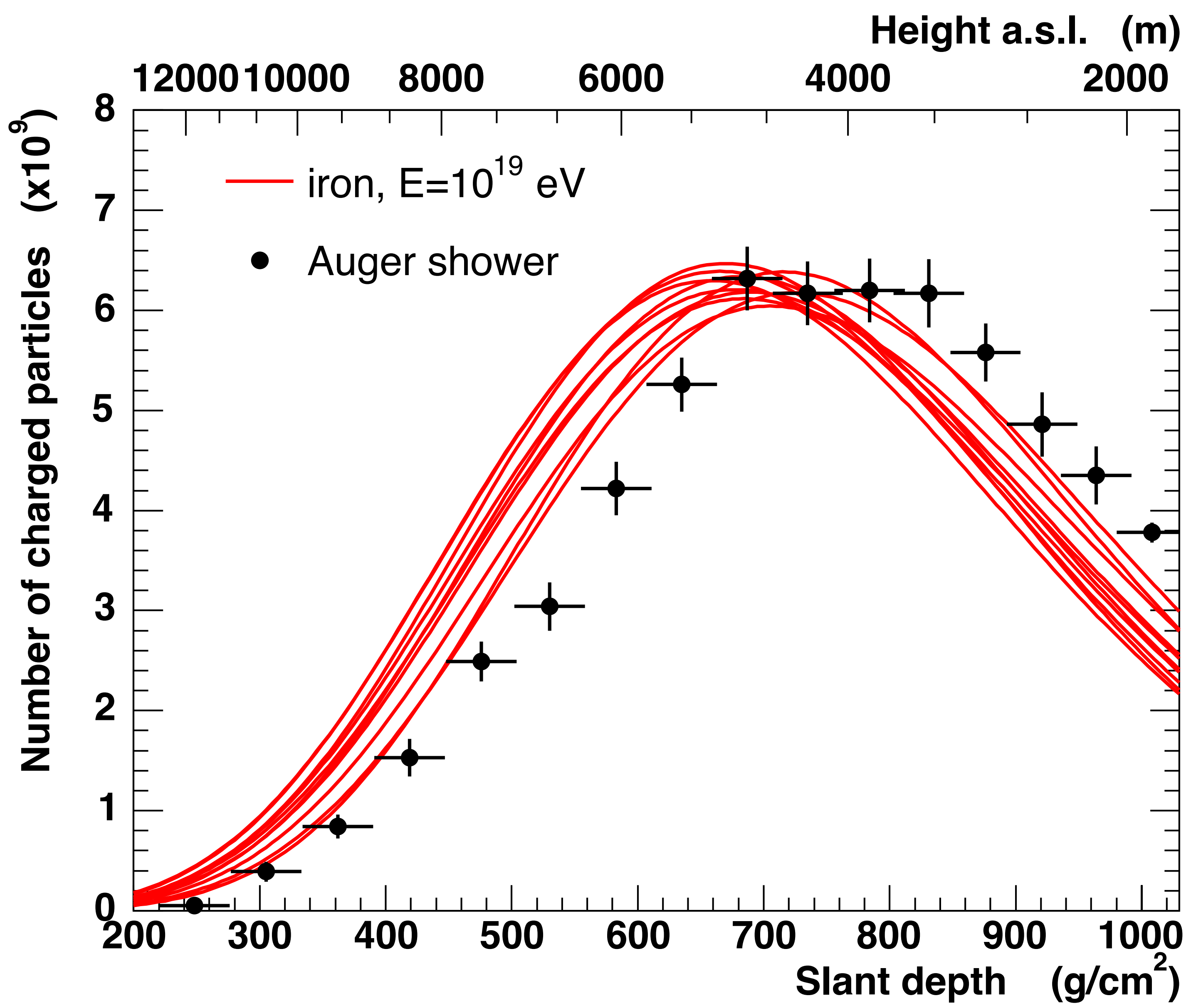
Cross section can
only grow at periphery

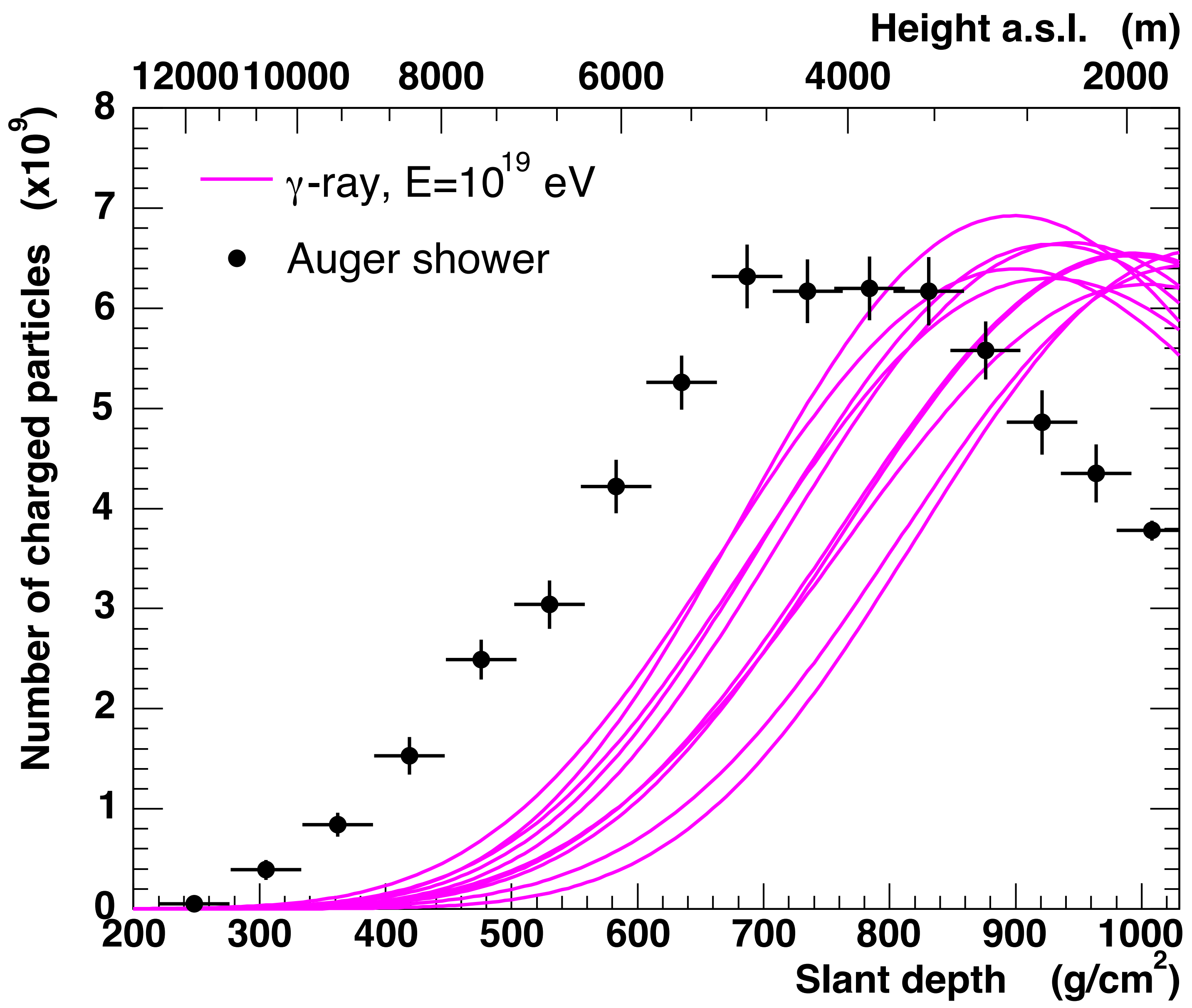
Example: total p-p cross section 160 mb, then p-air 560 mb
320 mb 630 mb (unitarity / black disk limit)

Rapid increase of transverse size of protons required, otherwise factor of 2 not possible

Longitudinal shower profiles: simulations and data







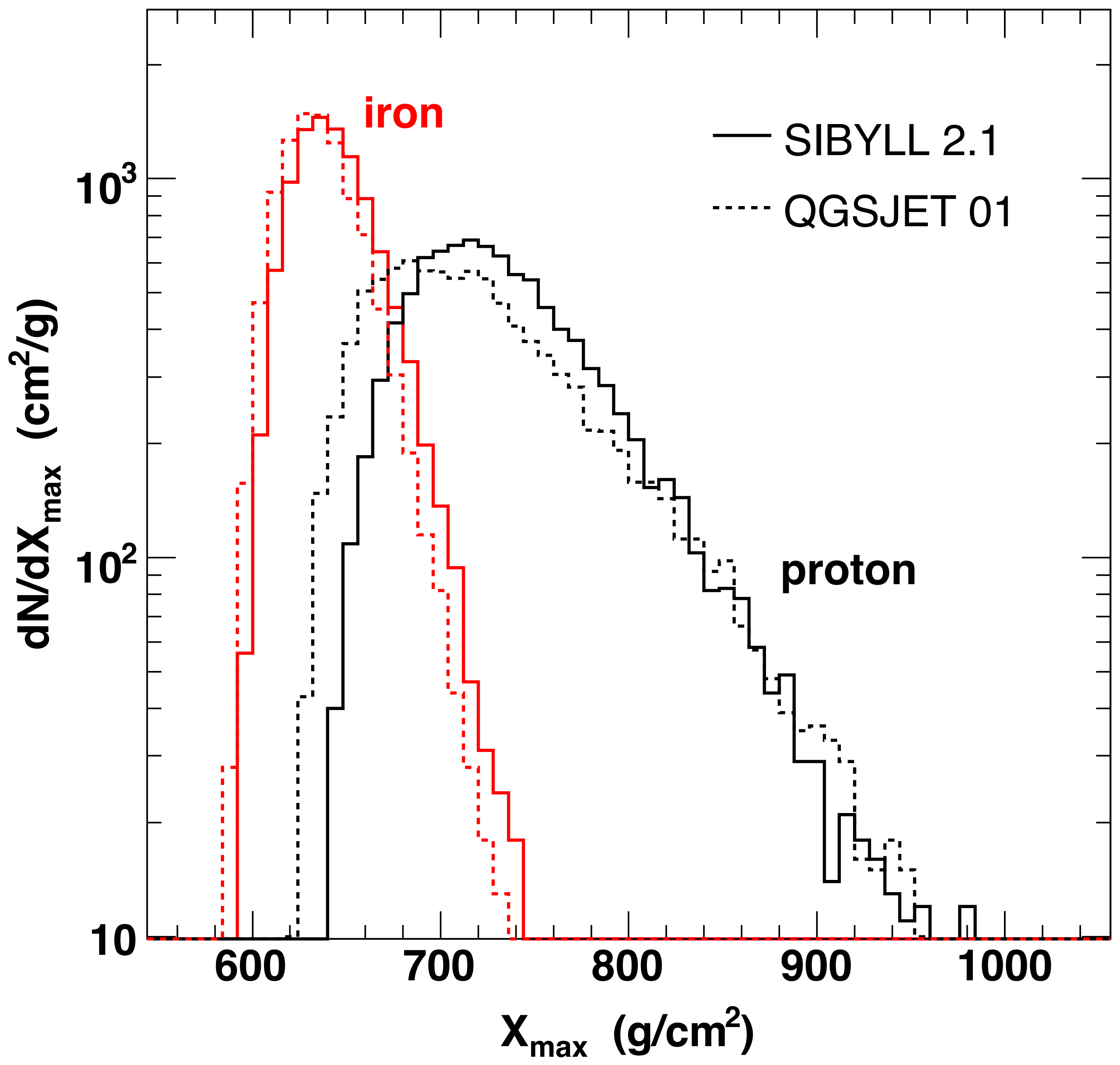
$$N_{\max} = E_0/E_c$$

$$X_{\max} \sim D_{\mathrm{e}} \ln(E_0/E_c)$$

Superposition model:

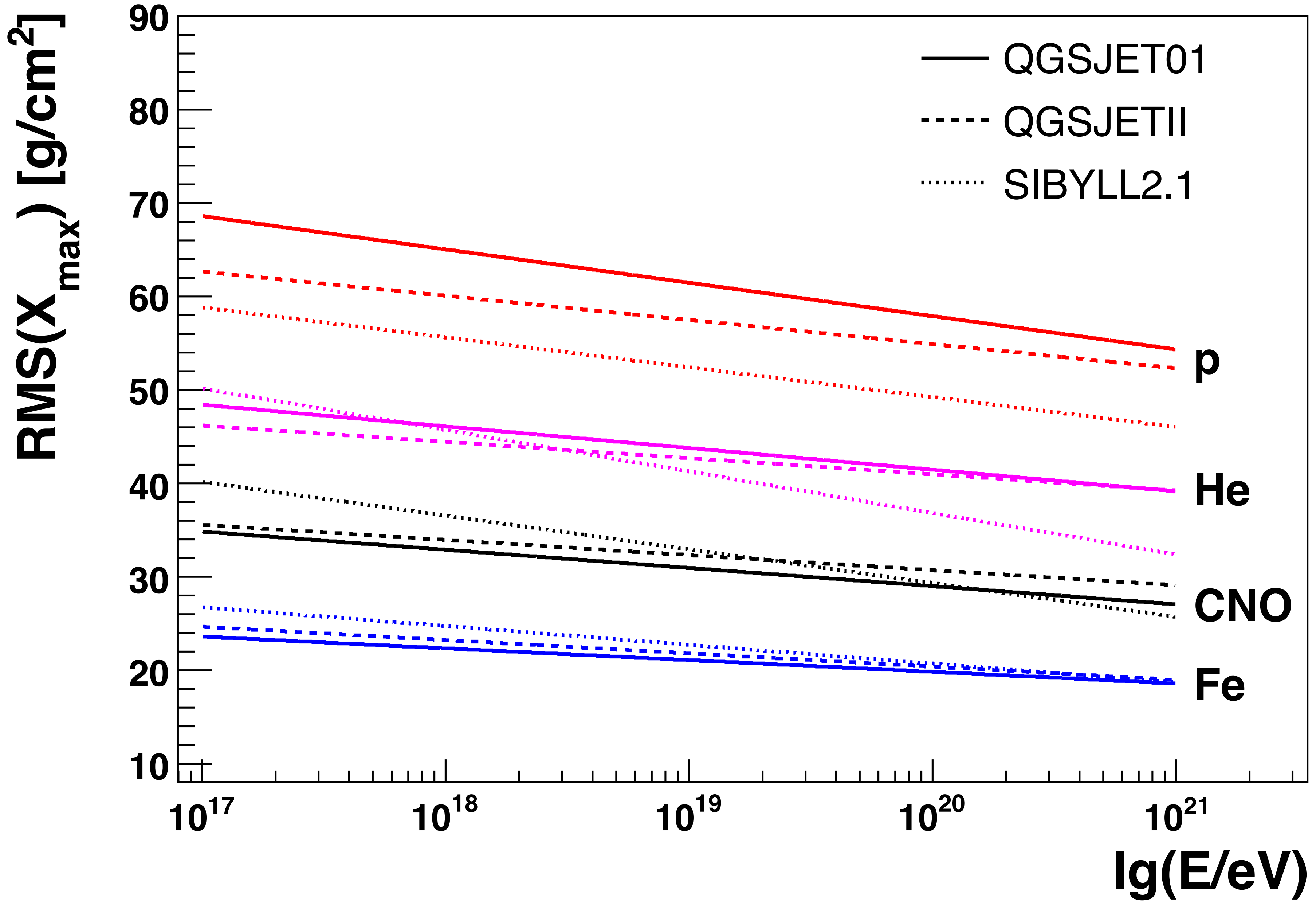
$$X^A_{\max} \sim D_e \ln(E_0/AE_c)$$

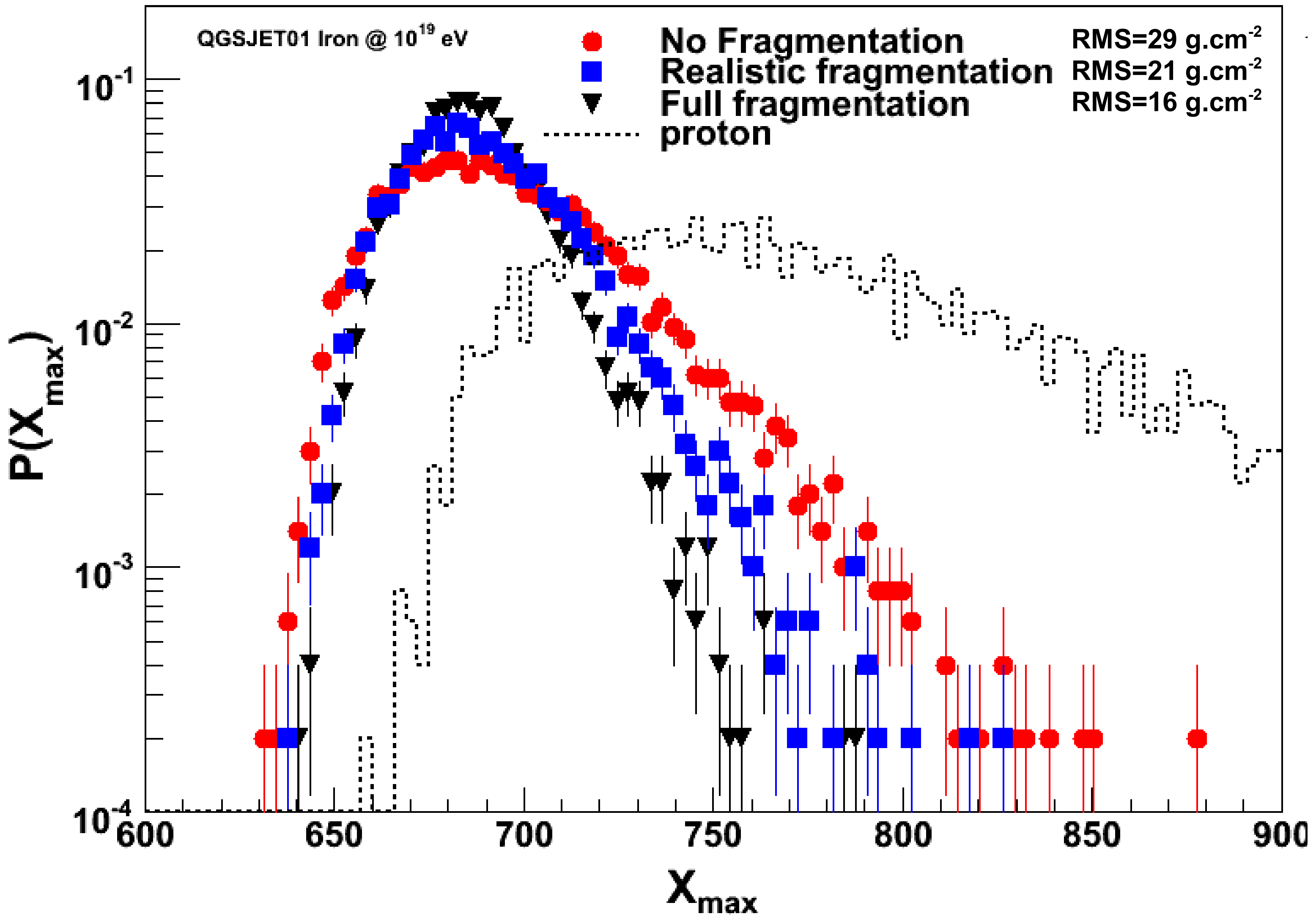
Fluctuations of X_{max} to study hadronic fragmentation ?



$E = 10^{19}$ eV

(Pierog, NUFRA 2009)





Doubled cross section:
Protons look like CNO