What do we learn about particle physics from high-energy cosmic ray measurements

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PIERRE AUGER OBSERVATORY

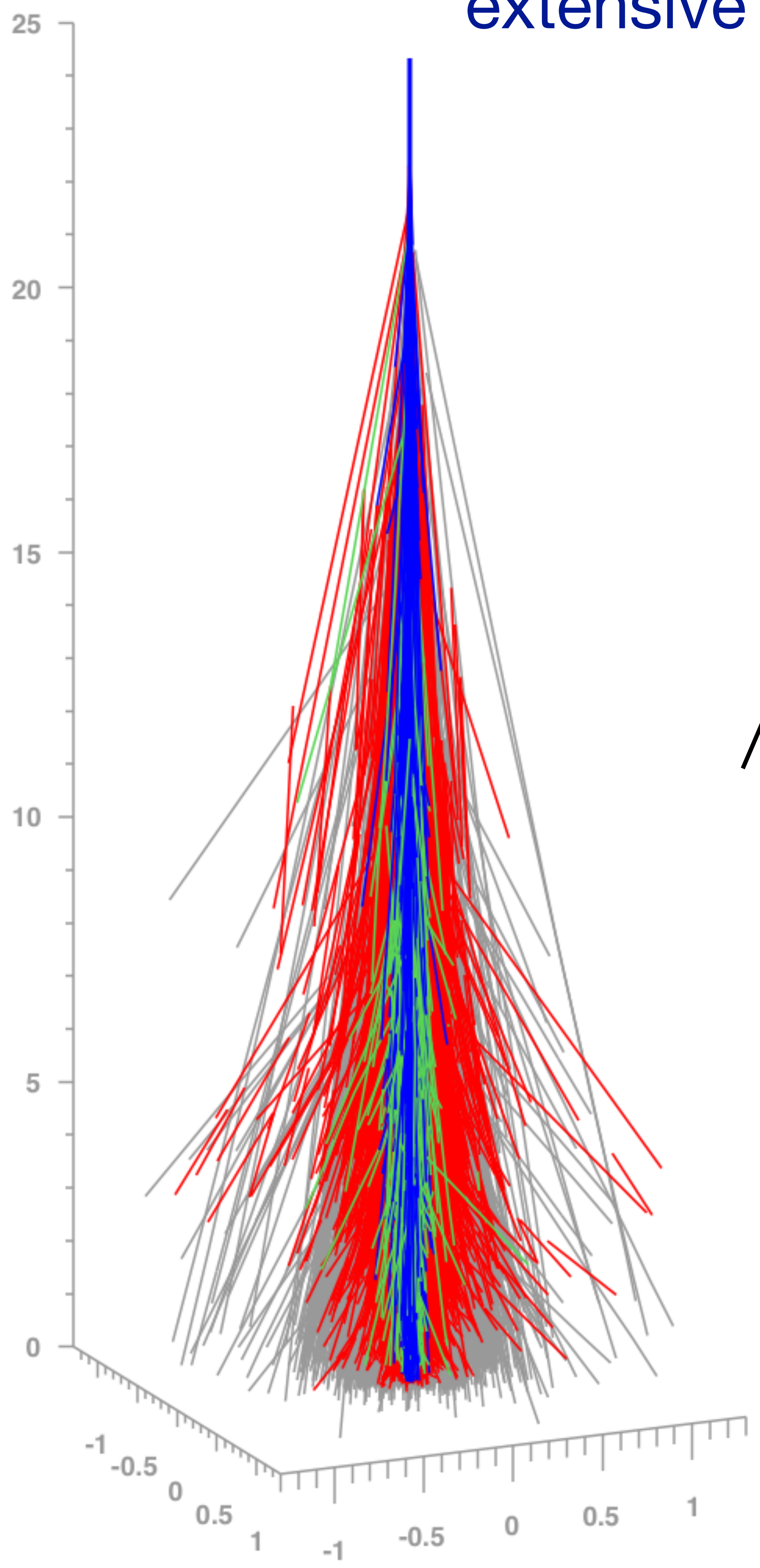
The first cosmic particle of ultra-high energy

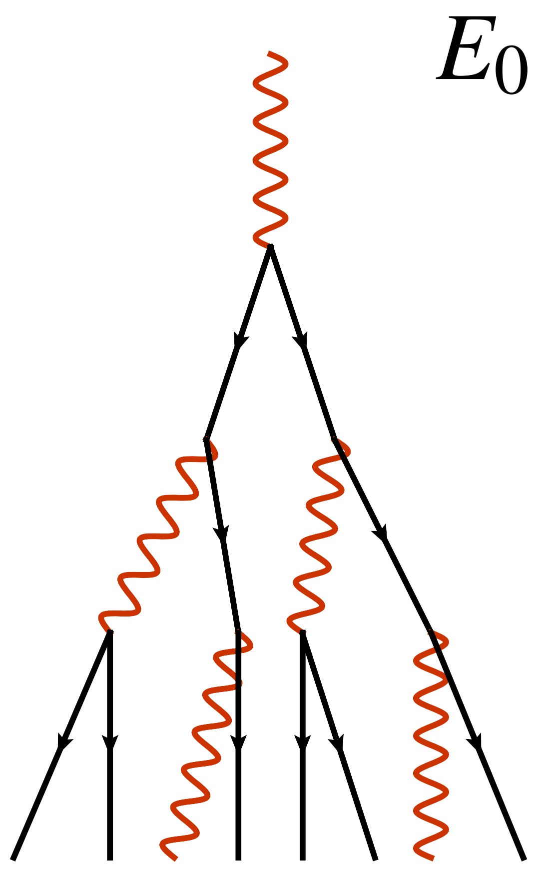
VOLUME 10, NUMBER 4 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1963

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

Cascade of secondary particles: extensive air shower





$$E = E_0/2^n$$

Energy conservation, overall energy estimate robust

E = 10^{20} eV

Cosmic rays of 10^{20} eV energy exist !

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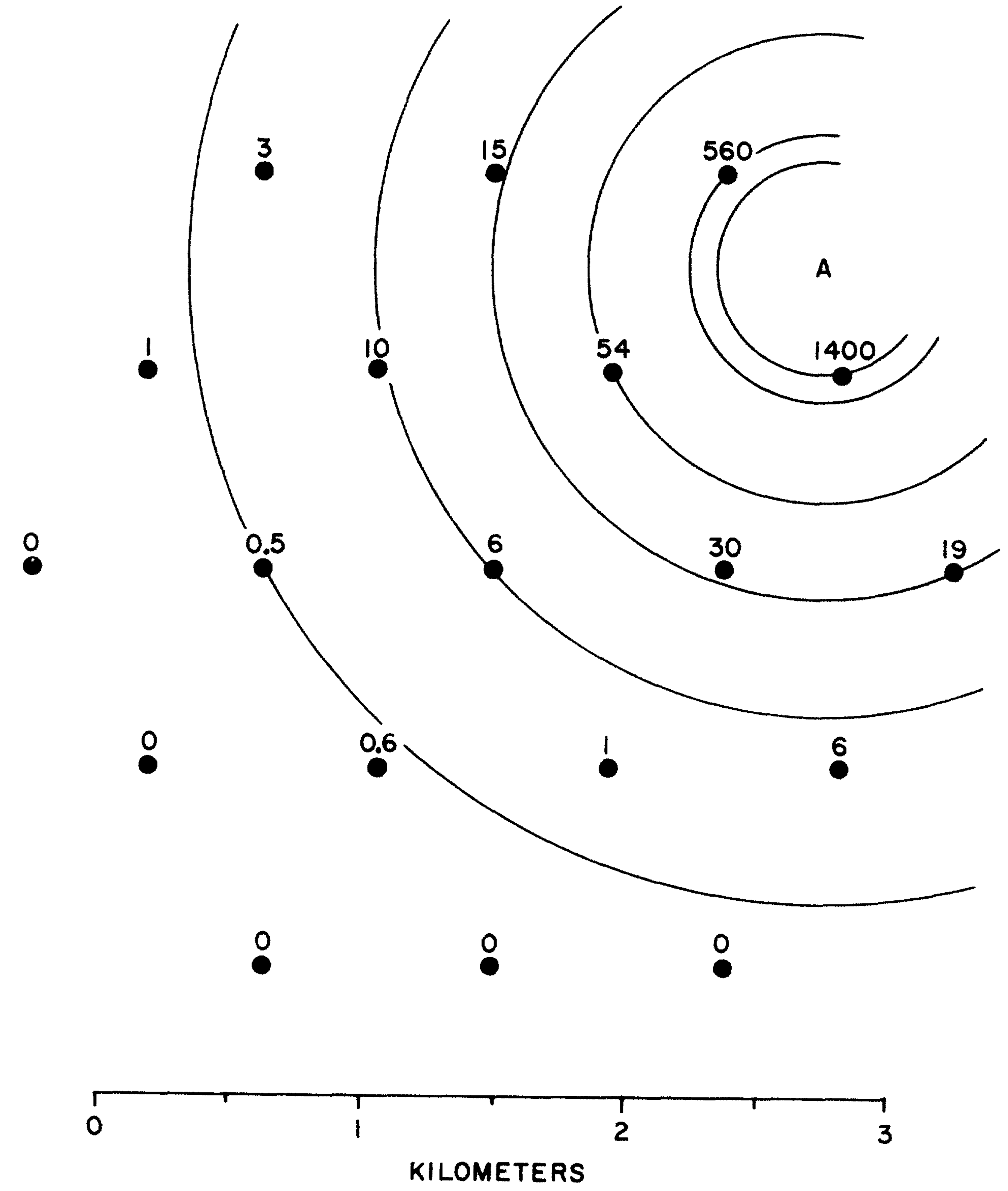
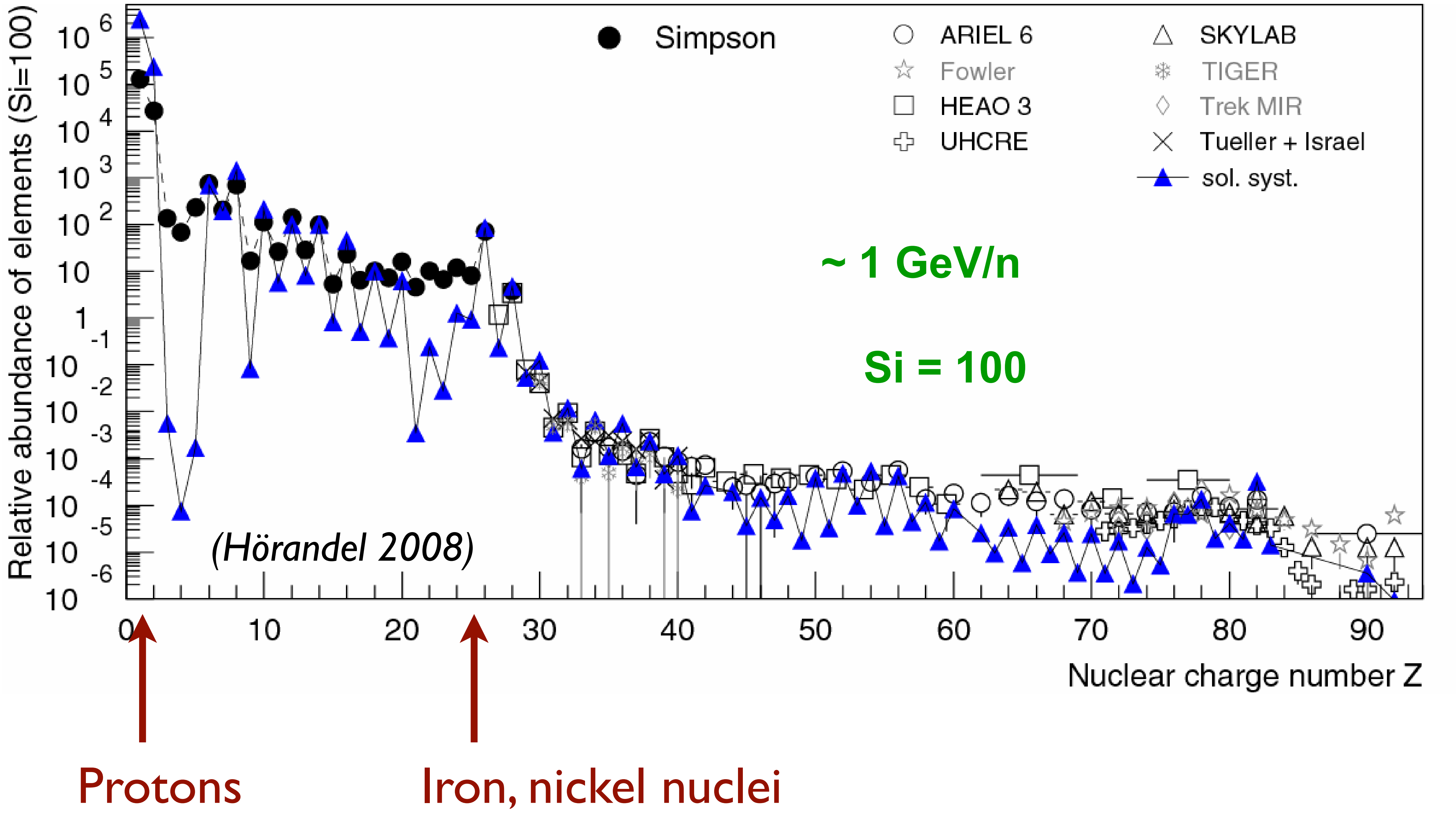
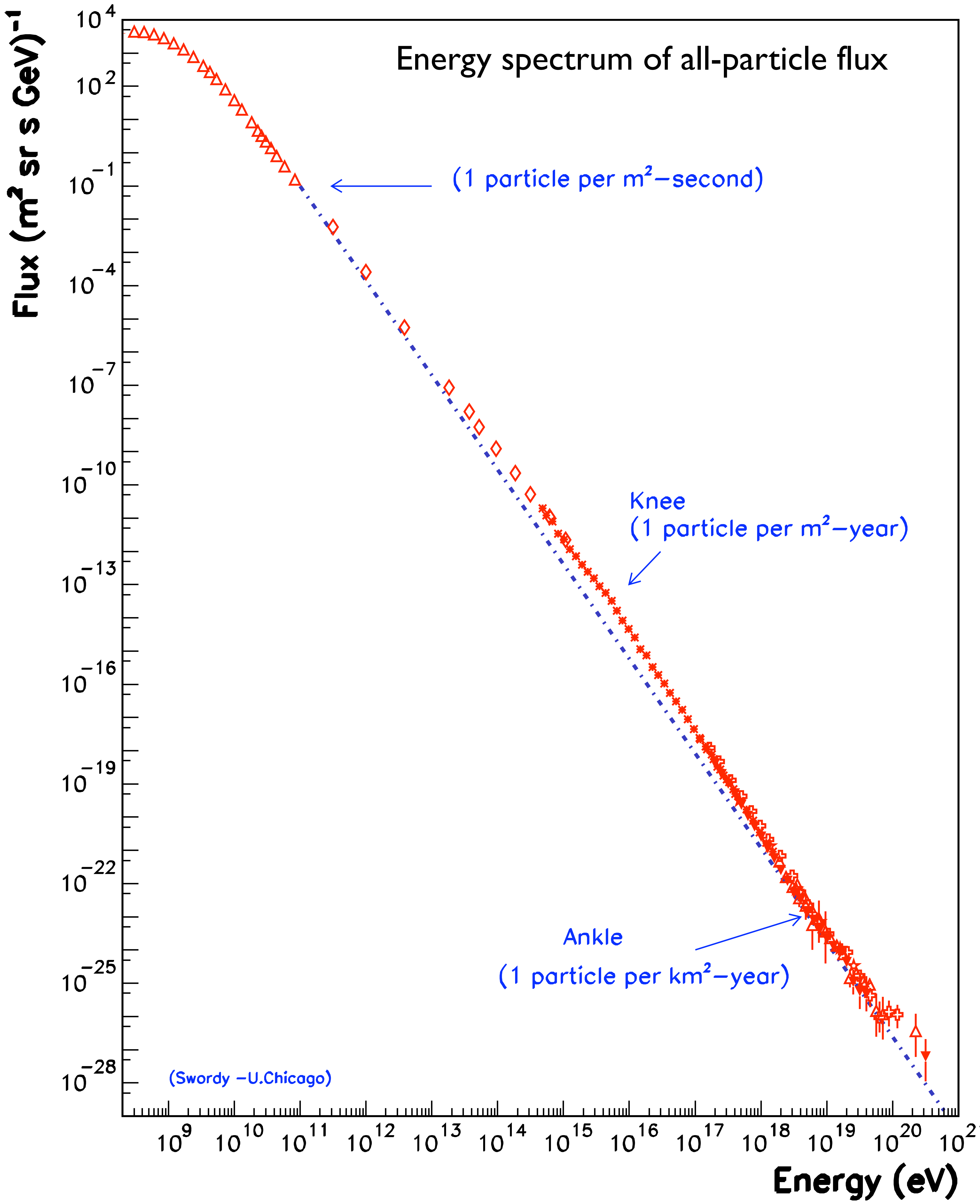


FIG. 1. Plan of the Volcano Ranch array in February 1962. The circles represent 3.3-m^2 scintillation detectors. The numbers near the circles are the shower densities (particles/m^2) registered in this event, No. 2-4834. Point "*A*" is the estimated location of the shower core. The circular contours about that point aid in verifying the core location by inspection.

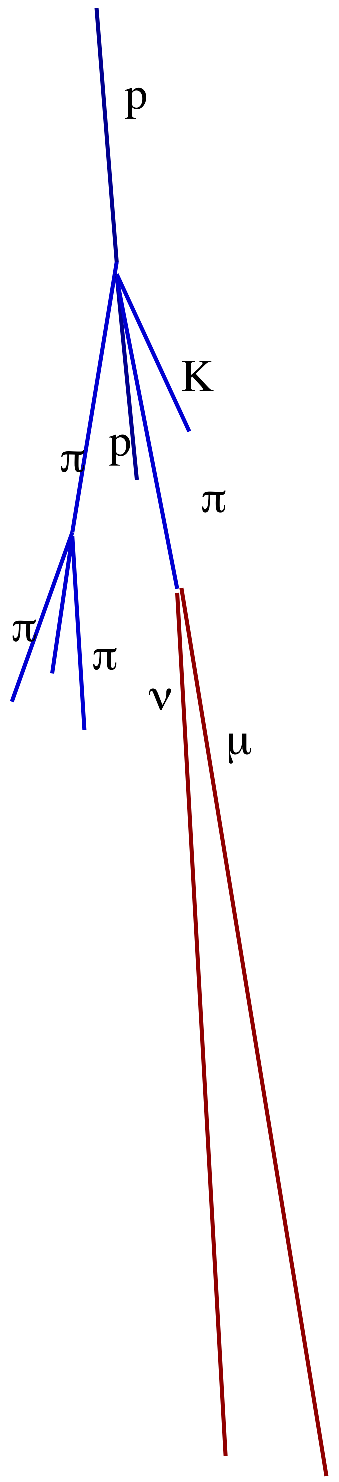
Flux of cosmic rays

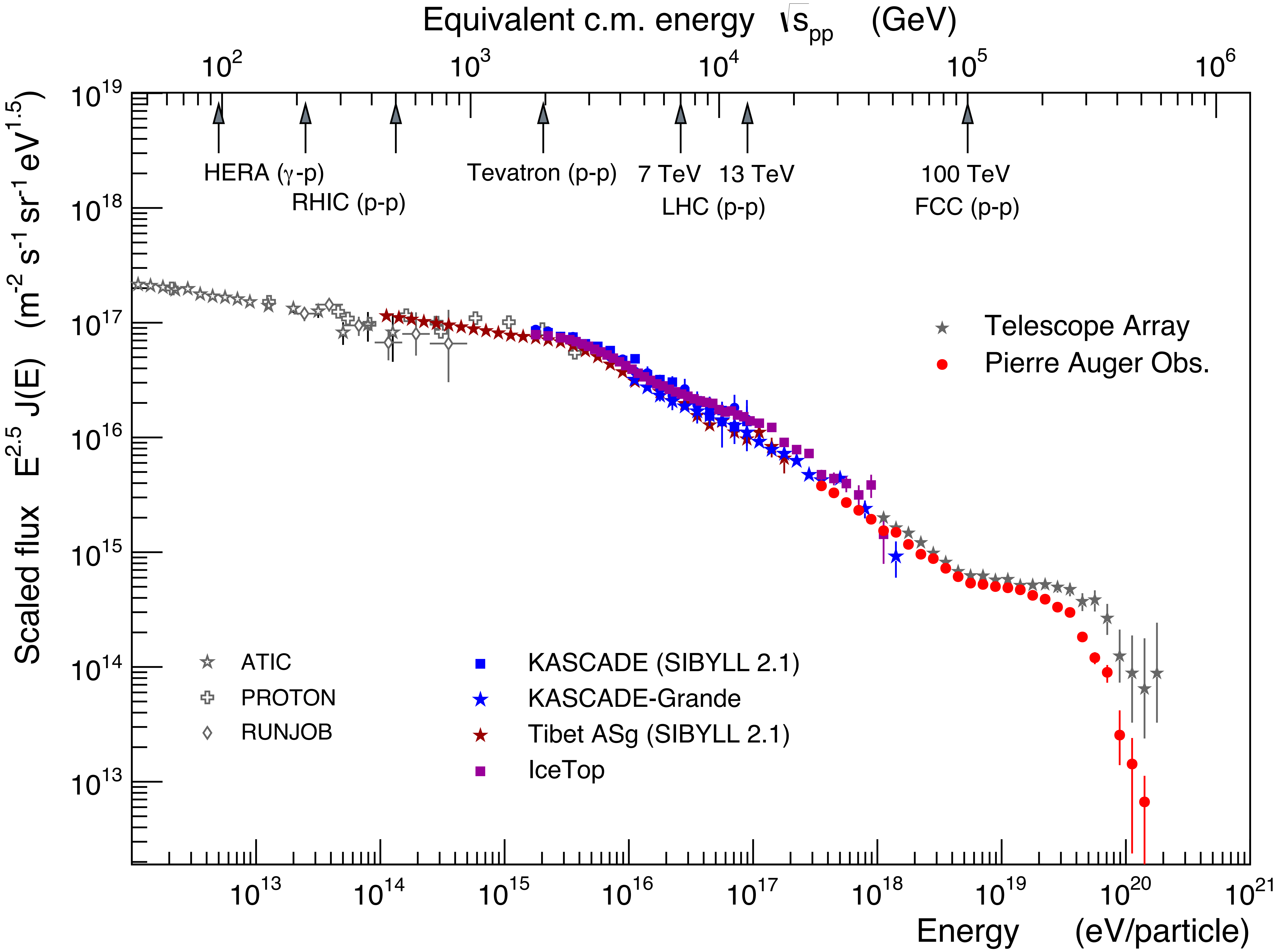
Mass composition at low energy

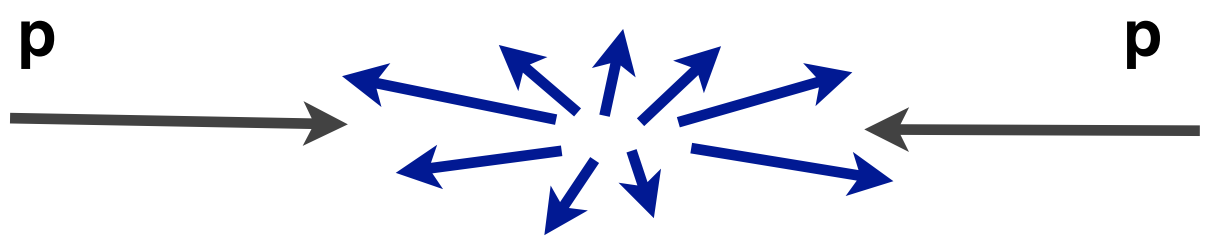




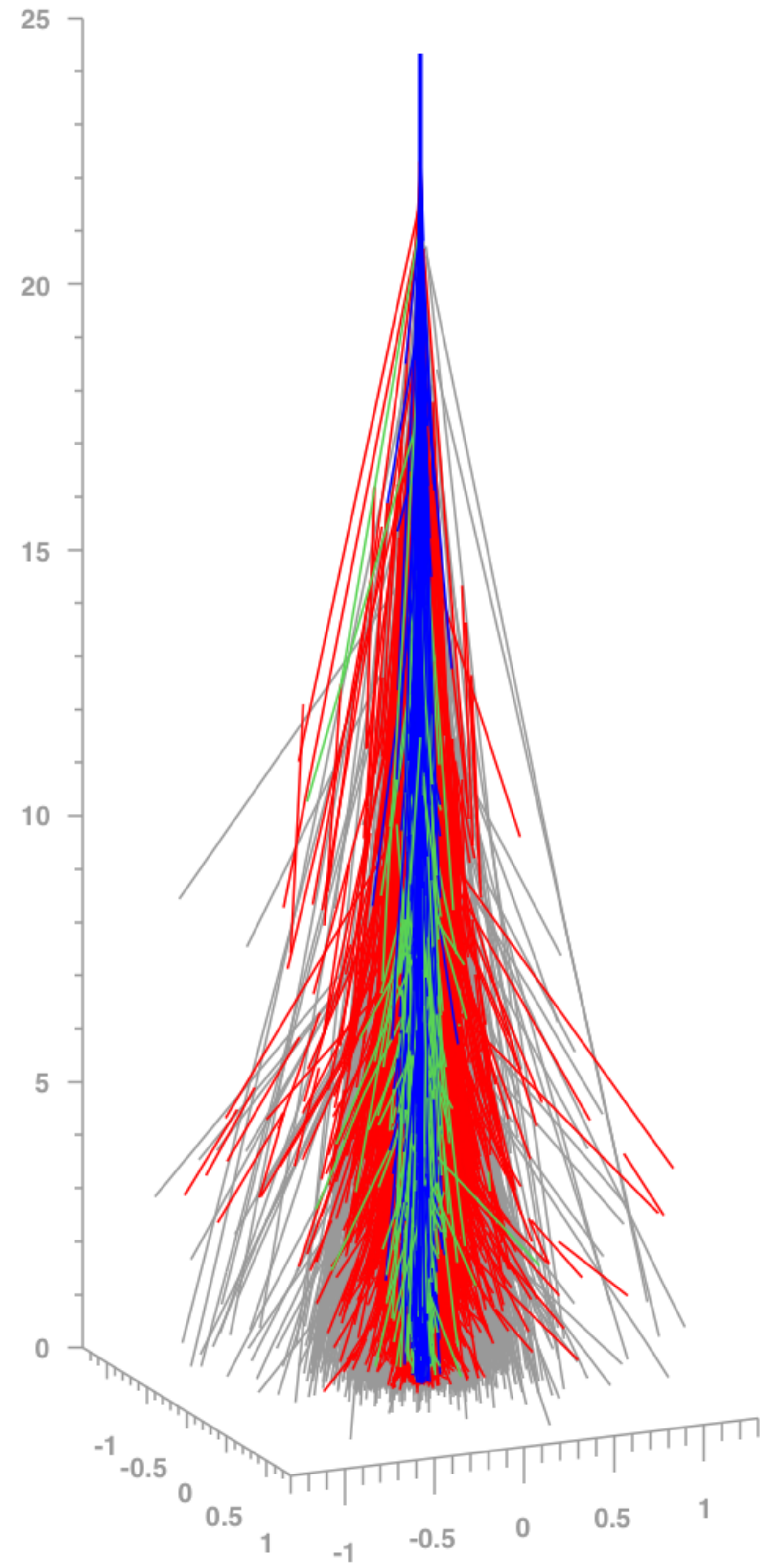
Cosmic ray flux and interaction energies



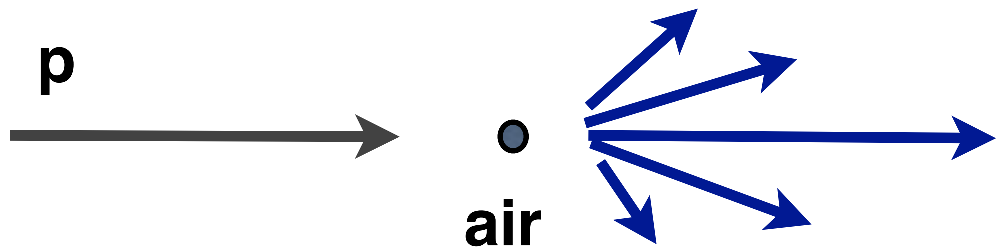




Center-of-mass energy



Laboratory energy



Fermi acceleration – a simplified view

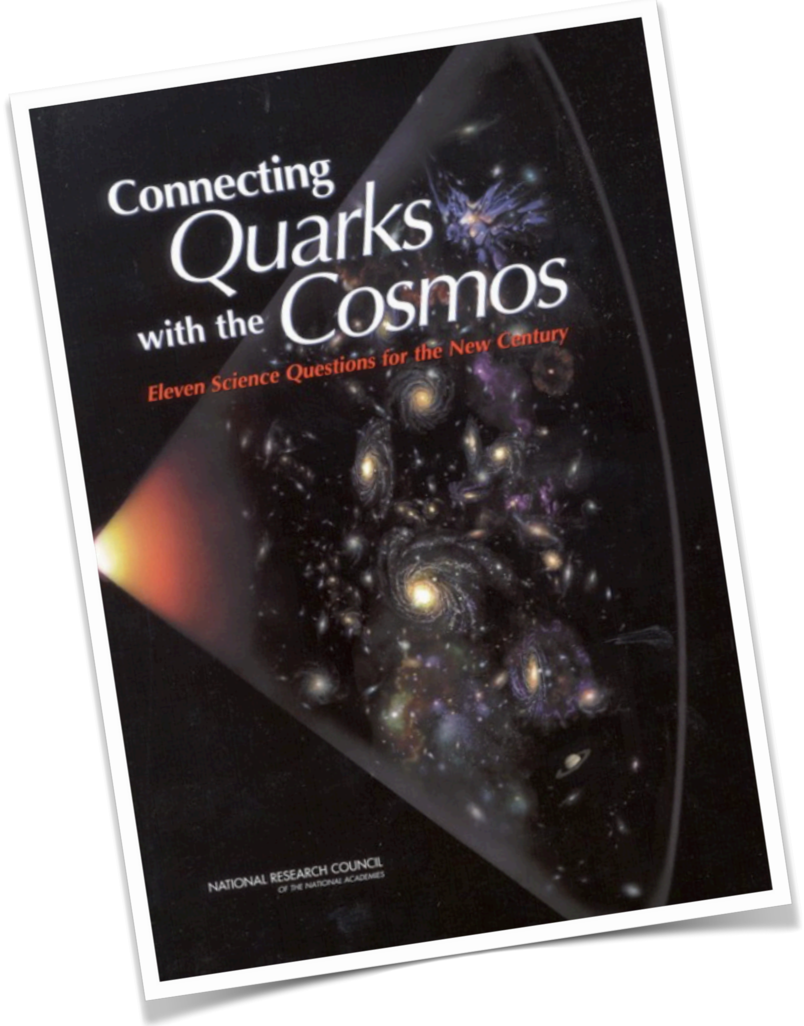
First order Fermi acceleration at large-scale shock fronts

(shown is second order Fermi acceleration)

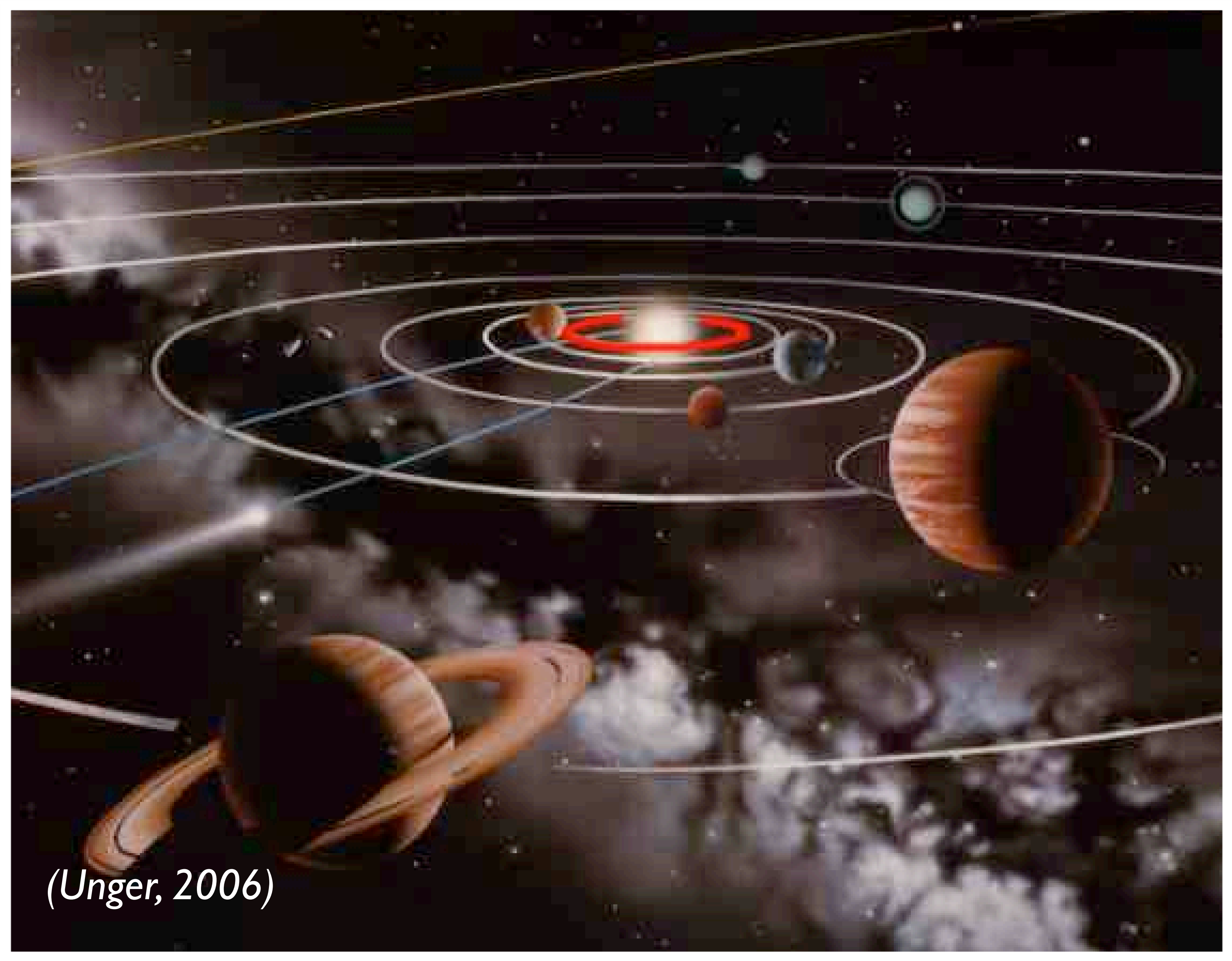
$$\frac{dN_{inj}}{dE} \sim E^{-2}$$

Does nature accelerate particles to 10^{20} eV?

Large Hadron Collider (LHC),
27 km circumference,
superconducting magnets



National Research Council, USA, 2002



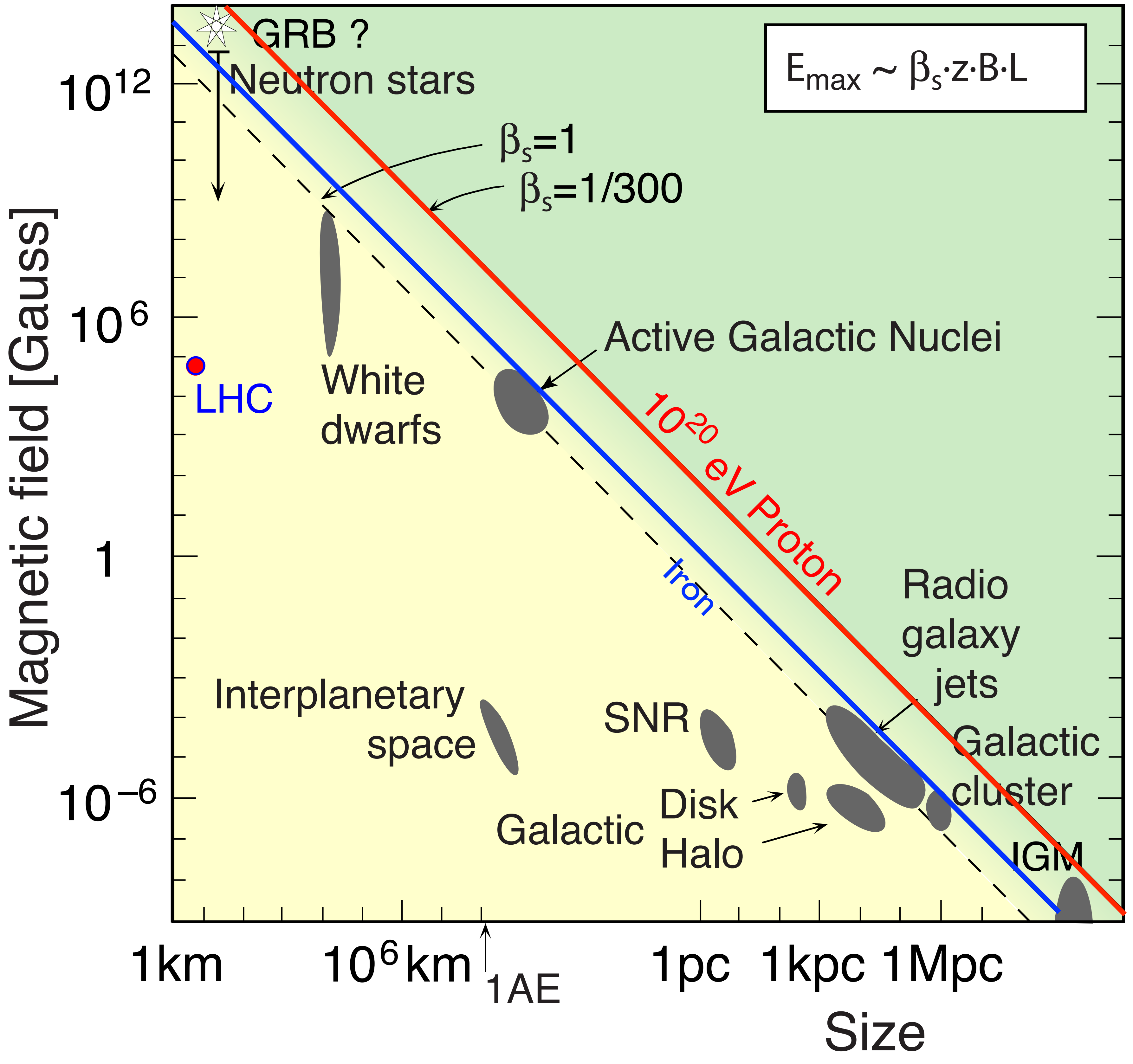
(Unger, 2006)

Need accelerator of size of Mercury orbit to reach 10^{20} eV with LHC technology

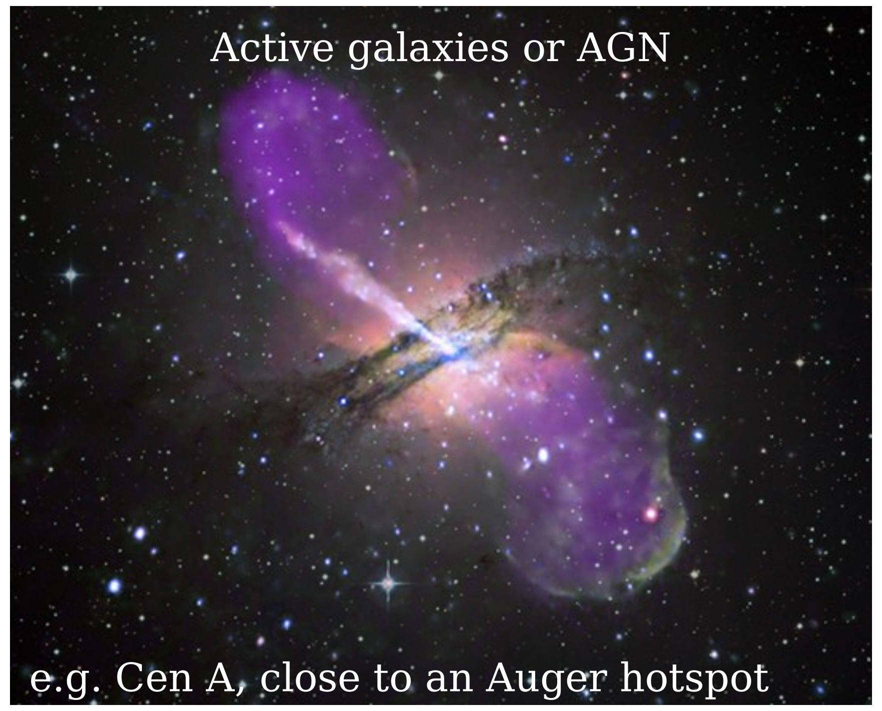
Maximum energy: Hillas plot (1984)

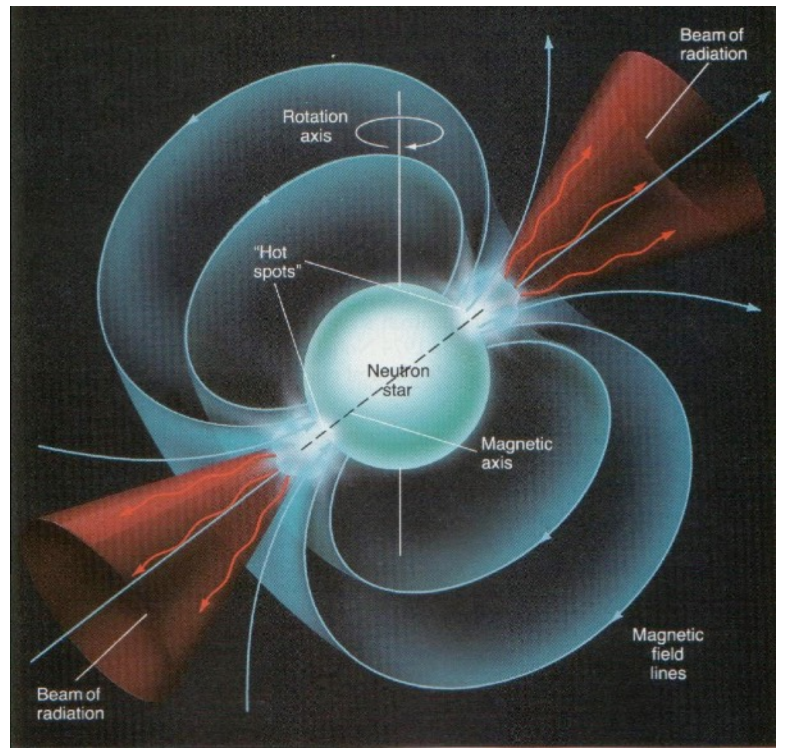
Constrained by Lamor radius and acc. time

$$E_{\max} \sim \beta_s Z B R$$



Examples of source scenarios





Astrophysical shock fronts exist in many objects

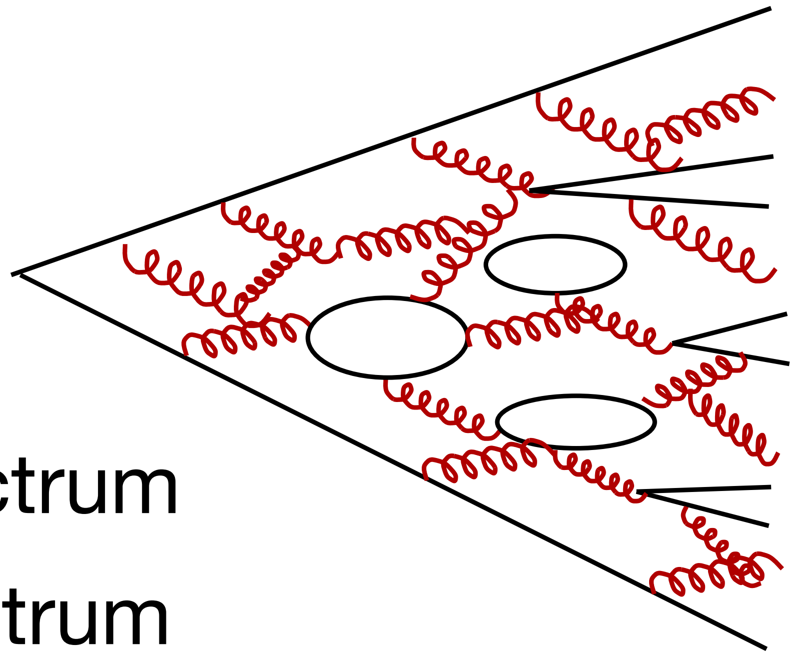
	Process	Distribution	Injection flux
AGNs, GRBs, … (☆)	Diffuse shock acceleration	Cosmological	p … Fe
Young pulsars (☆☆)	EM acceleration	Galaxy & halo	mainly Fe
X particles (☆☆☆)	Decay & particle cascade	(a) Halo (SHDM) (b) Cosmological	ν, γ-rays and p
Z-bursts (☆☆☆☆)	Z^0 decay & particle cascade	Cosmological & clusters	ν, γ-rays and p

X particles from:
- topological defects
- monopoles
- cosmic strings
- cosmic necklaces
- .....

Big Bang:
super-heavy particles, topological defects:
$M_X \sim 10^{23}$ - 10^{24} eV

QCD: ~ $E^{-1.5}$ energy spectrum

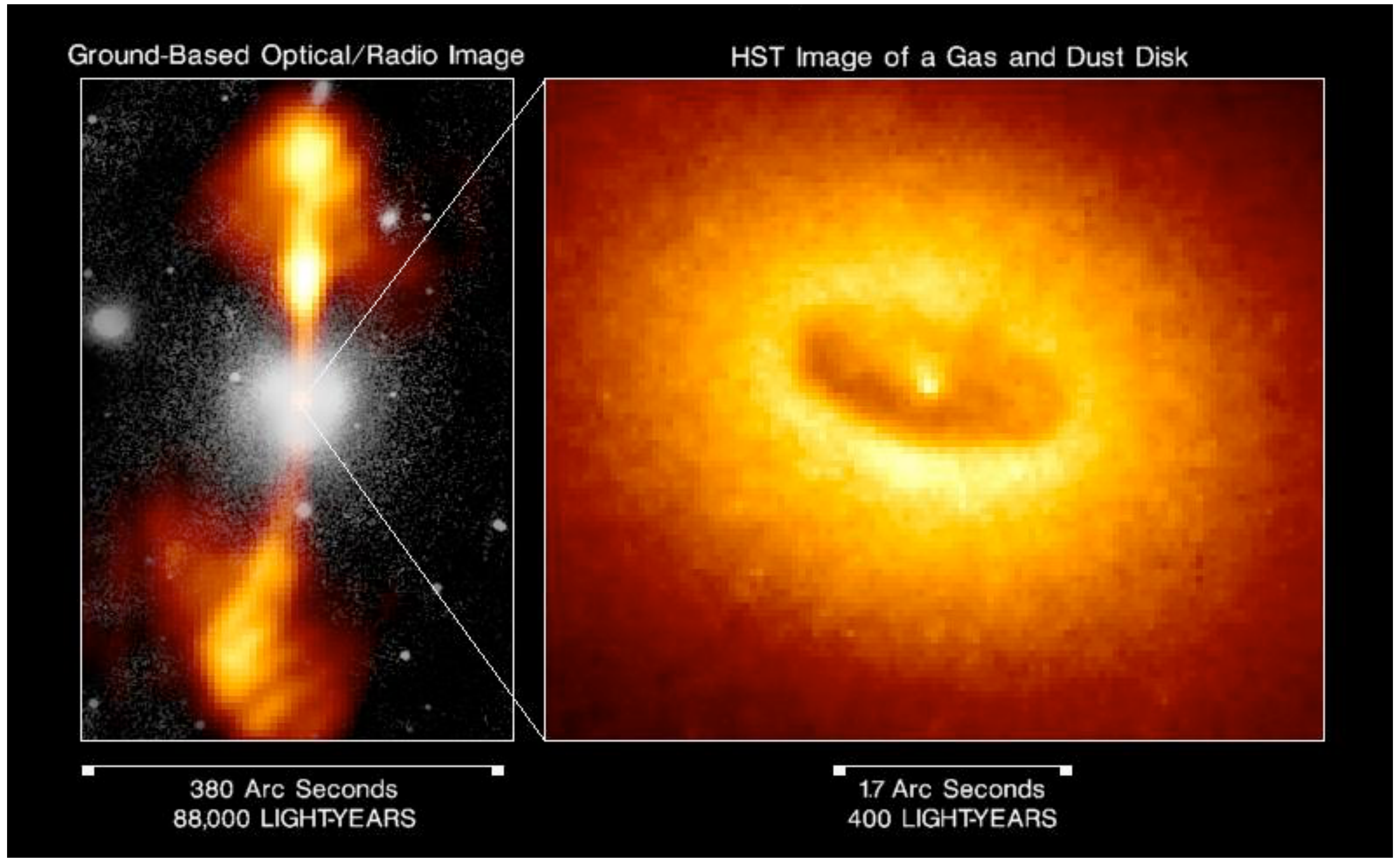
QCD+SUSY: ~ $E^{-1.9}$ spectrum



large fluxes of photons and neutrinos

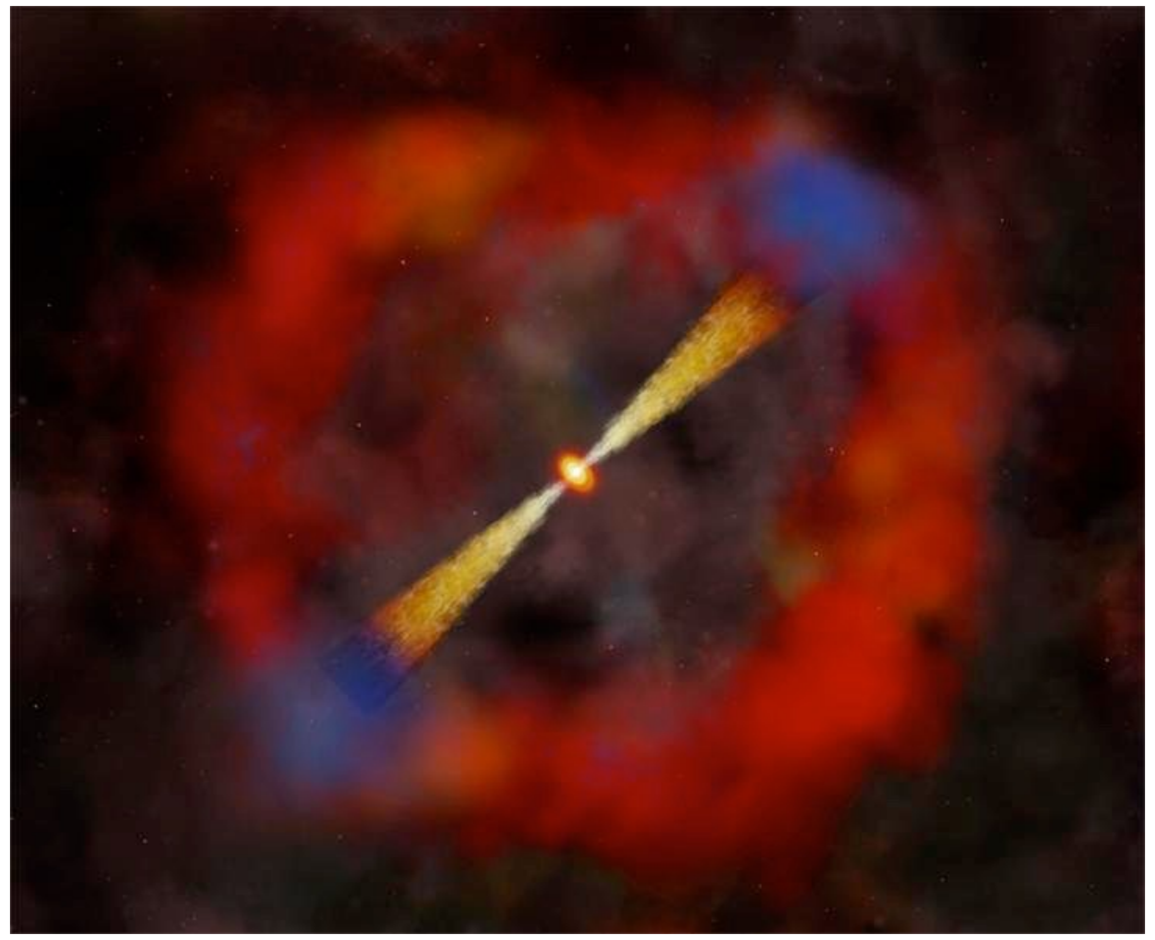
Acceleration scenarios and source candidates

Diffusive shock acceleration



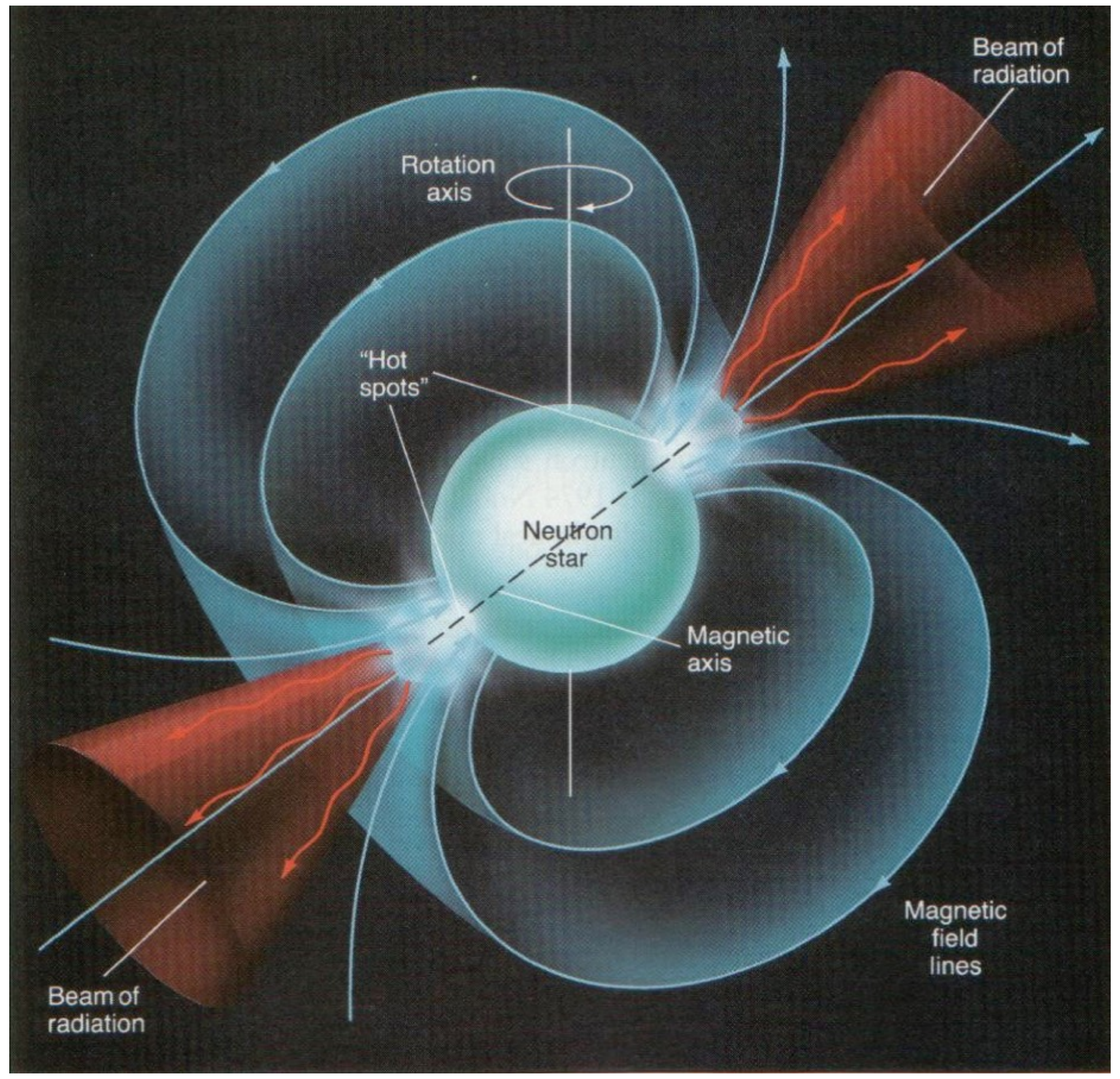
Active Galactic Nuclei
(in jets or in radio lobes)

$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim E^{-2}$$



Gamma ray bursts (GRBs)

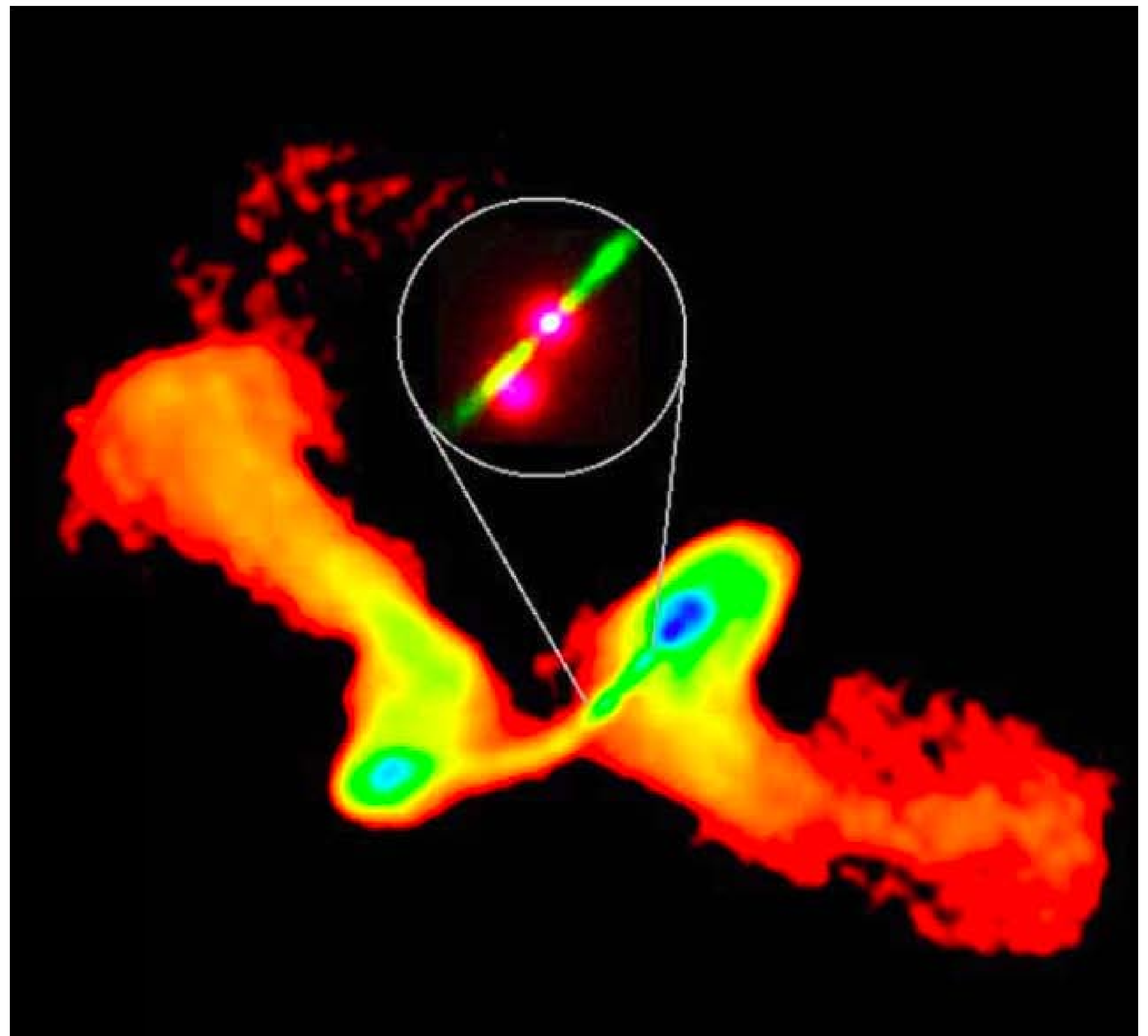
Inductive acceleration



Rapidly spinning neutron stars

$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim E^{-1}\left(1+\frac{E}{E_g}\right)^{-1}$$

Single (relativistic) reflection


National Radio Astronomy Observatory / AUI, Murgia et al.; STScI (for the inset).

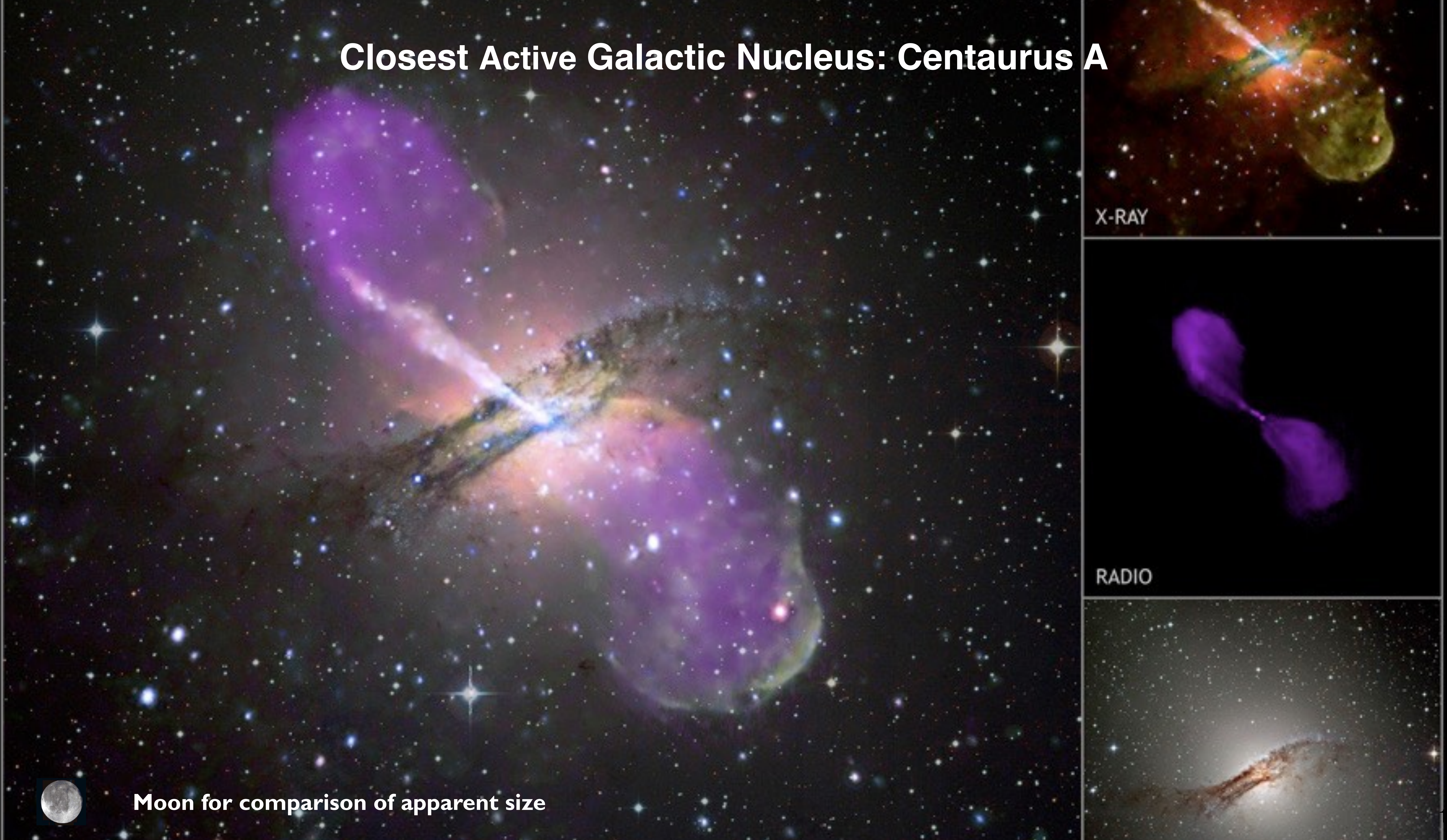
Spin flip of BH in AGN

Tidal disruption events (TDEs)

$$E_{\max} \sim \Gamma^2\, E_{\mathrm{inj}}$$

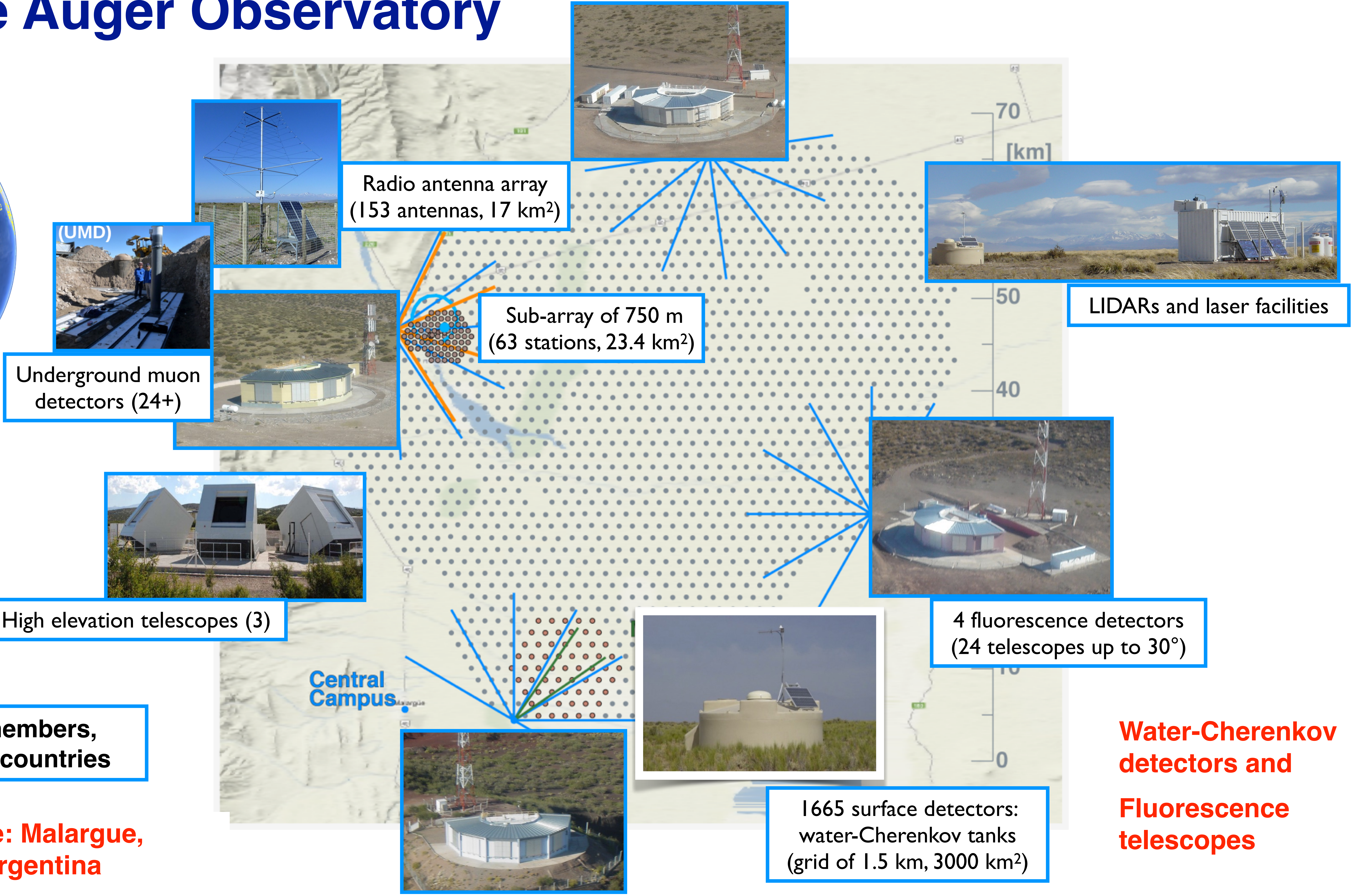
One-shot acceleration by re-connection
Wake-field acceleration in plasma jets

Closest Active Galactic Nucleus: Centaurus A



The Pierre Auger Observatory

Pierre Auger Observatory
Province Mendoza, Argentina



More than 400 members,
98 institutes, 17 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina

Water-Cherenkov detectors and

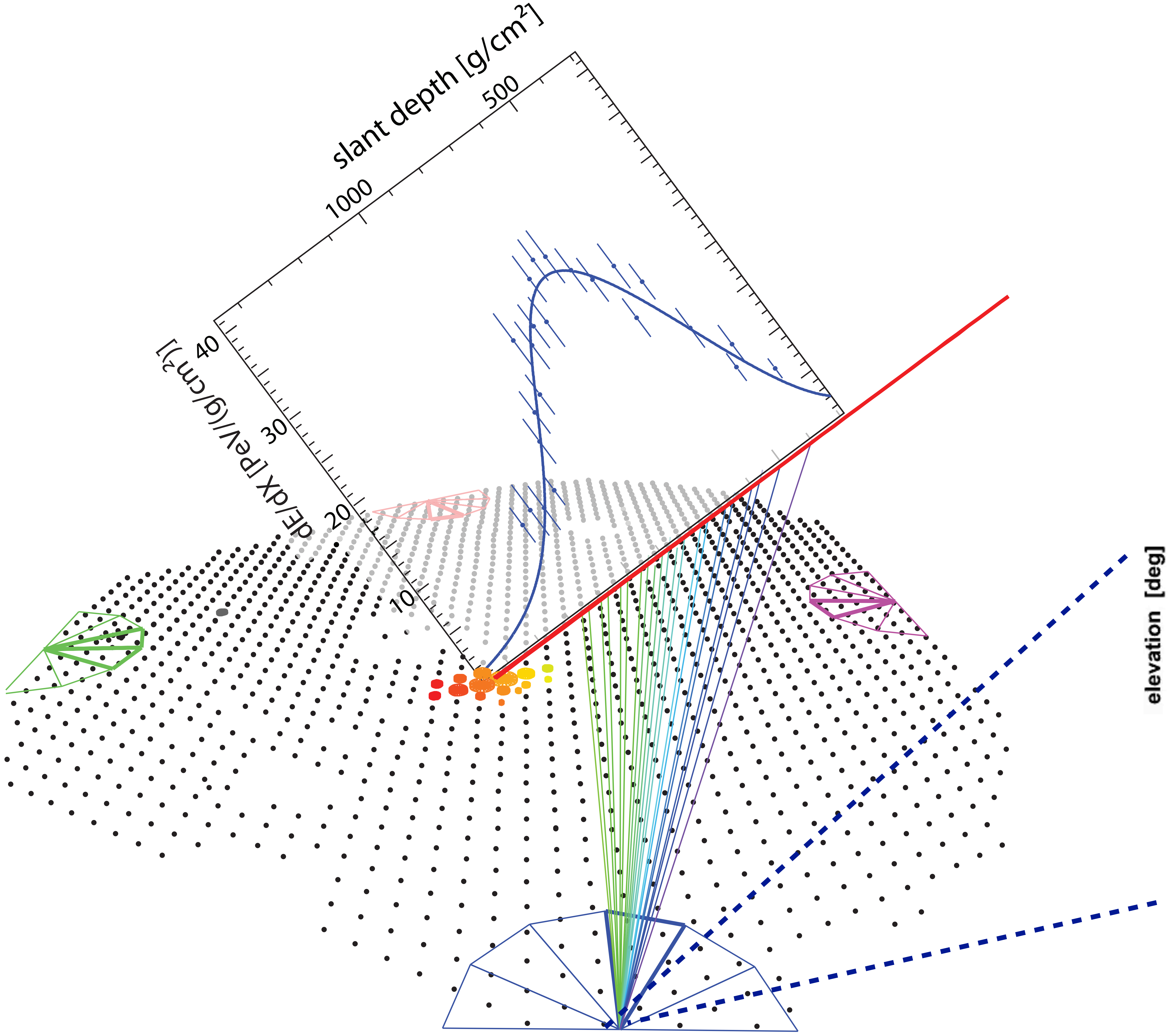
Fluorescence telescopes


1.5 km

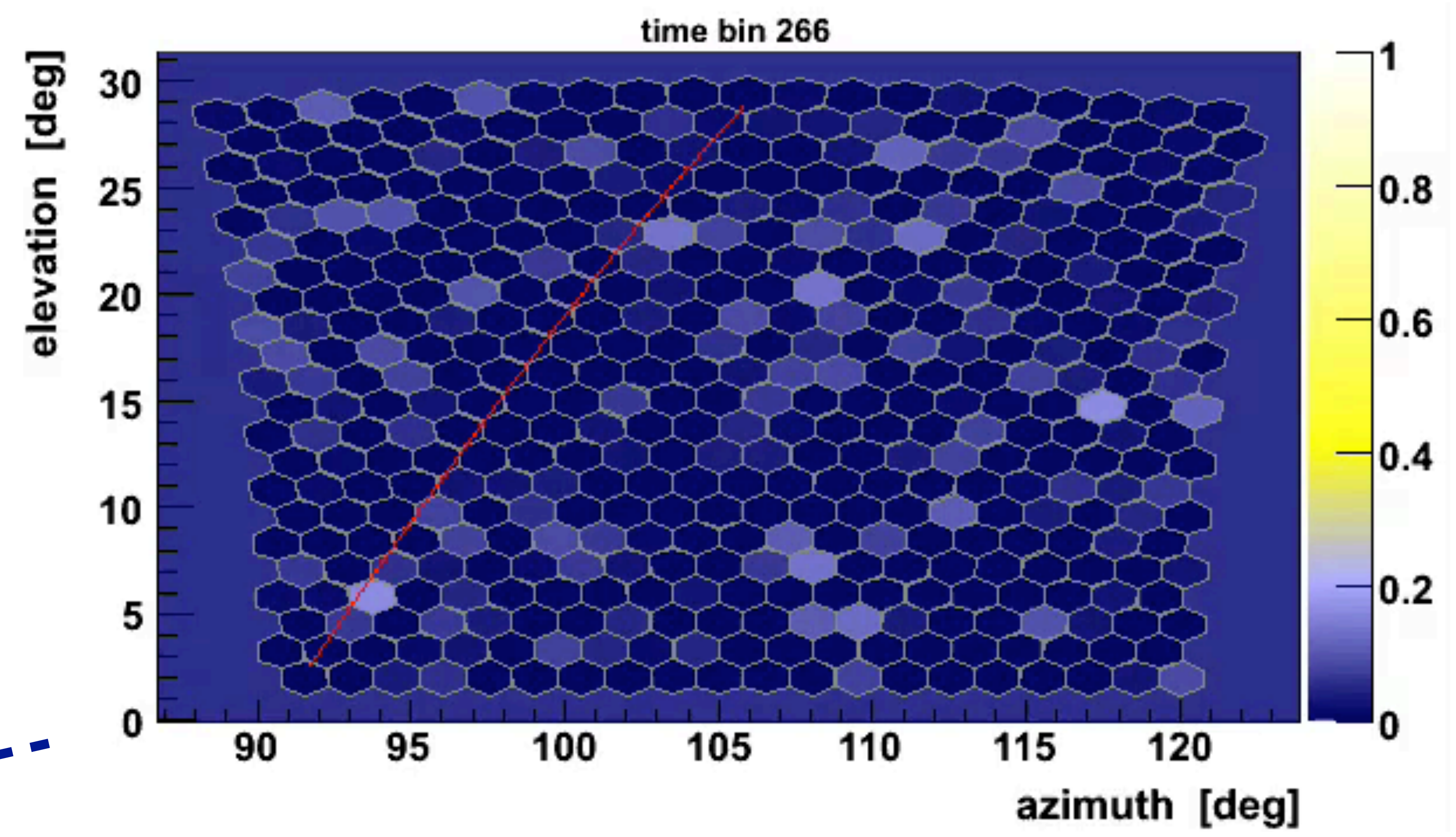

Fluorescence telescopes
Particle detectors
10 m² area, 1.20 m high
12 tons of water


PMT camera with
440 pixels, 1.5° FoV
per pixel, 10 MHz
UV transmitting
filter, corrector
lens, safety curtain
3.4 m segmented mirror
(aluminum alloy, glass)

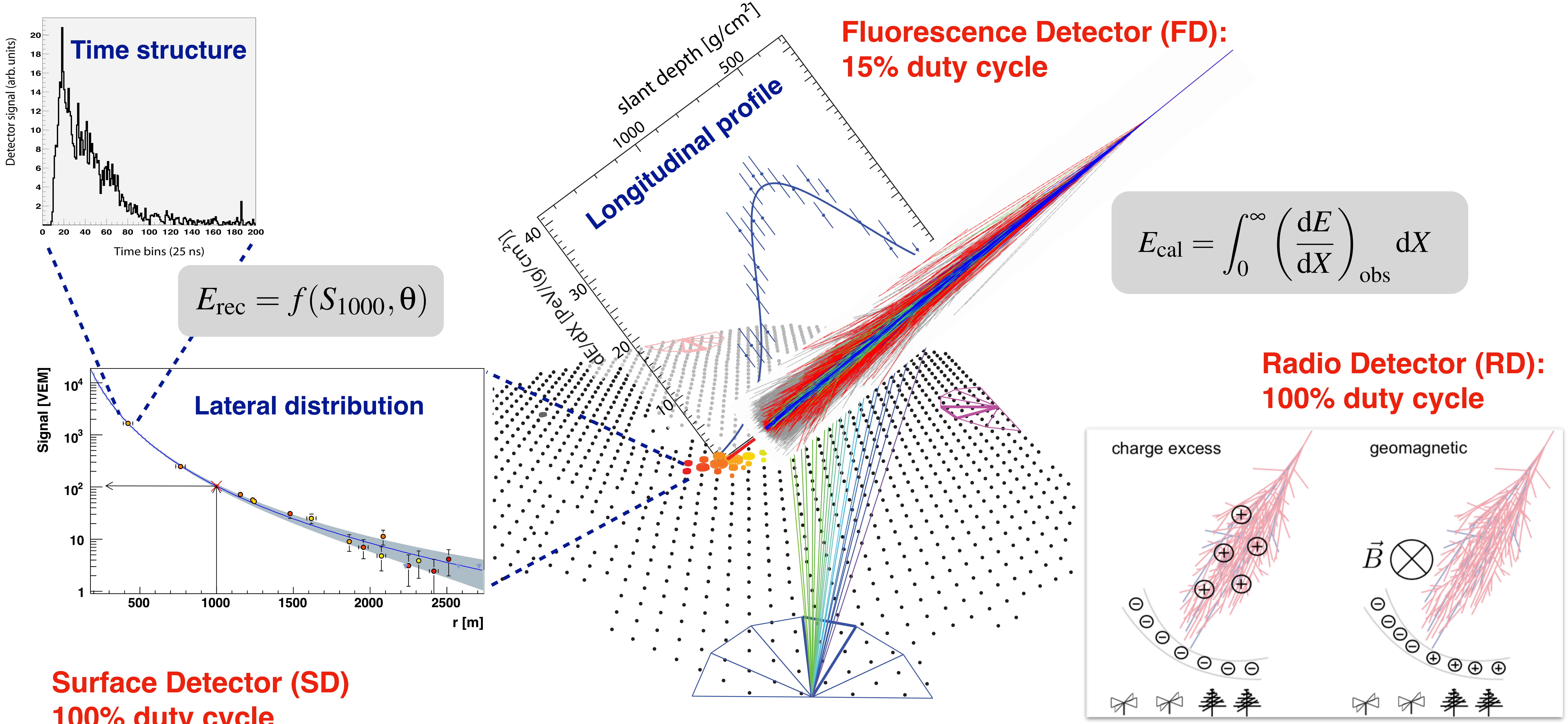
Fluorescence telescopes: longitudinal shower profile



Camera image
(10 million pictures per second)



Air shower observables (hybrid observation)



$$E_{\rm rec} = f(S_{1000}, \theta)$$

$$E_{\rm cal} = \int_0^\infty \left(\frac{dE}{dX}\right)_{\rm obs} dX$$

Fluorescence Detector (FD):
15% duty cycle

Radio Detector (RD):
100% duty cycle

Surface Detector (SD)
100% duty cycle

All-particle flux (energy spectrum)

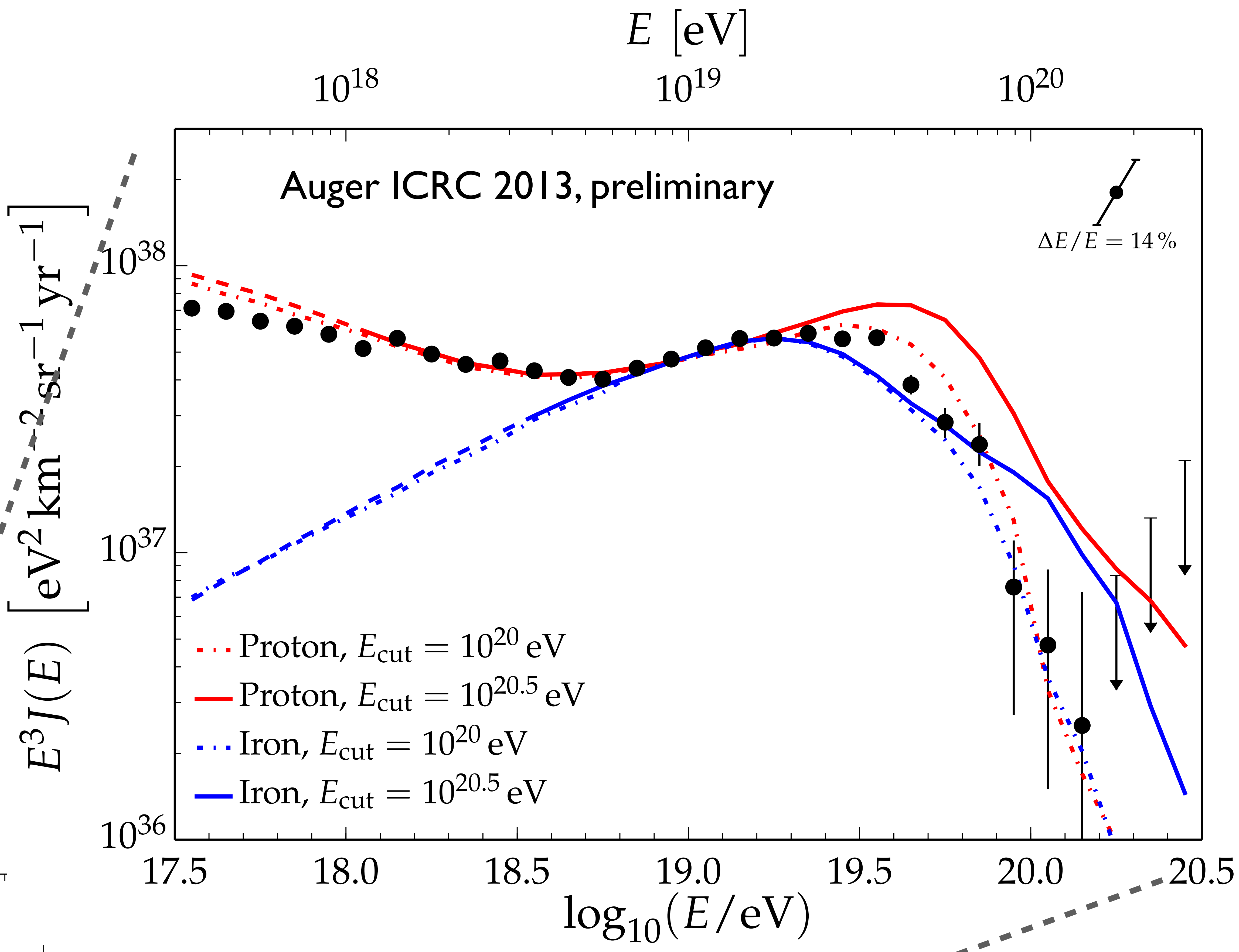
Energy spectrum 2013 and GZK suppression

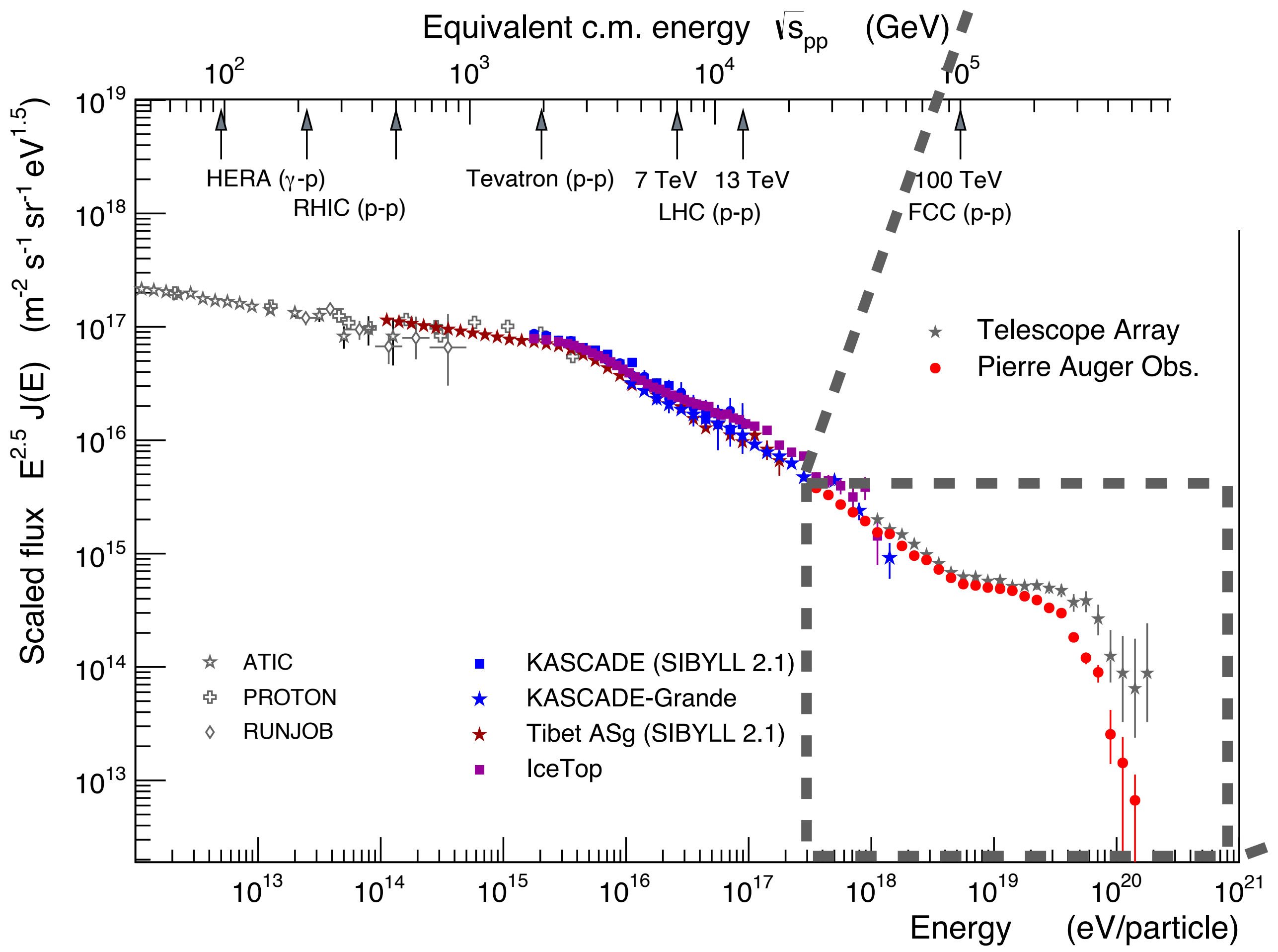
Proton dominated flux

Suppression: delta resonance

Ankle: e^+e^- pair production

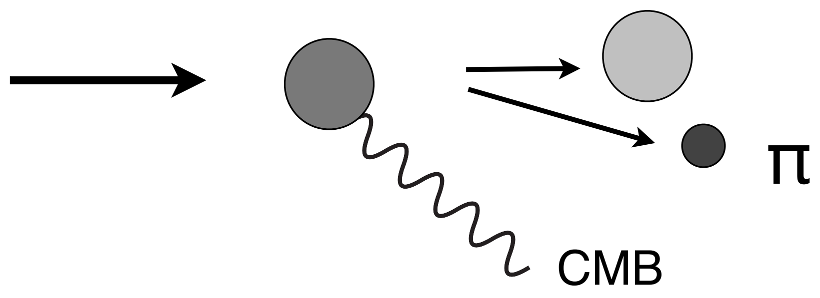
$$\frac{dN_{\mathrm{inj}}}{dE} \sim E^{-\gamma} \exp\left(-\frac{E}{E_{\mathrm{cut}}}\right)$$





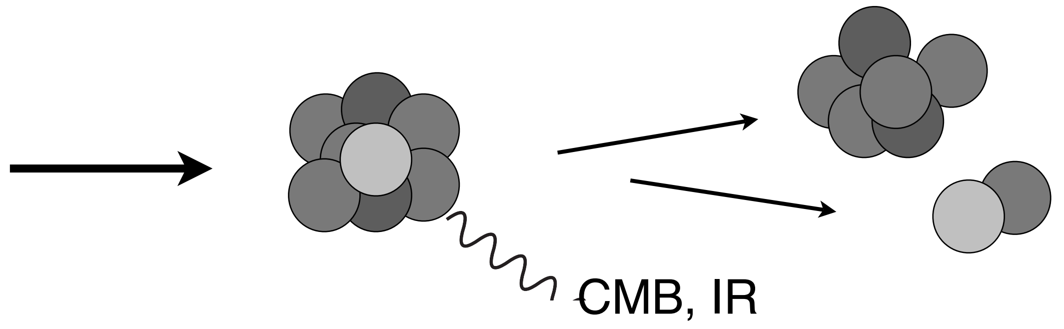
Greisen-Zatsepin-Kuzmin (GZK) effect

Photo-pion production (mainly Δ resonance)



GZK secondaries
- Photons
- Neutrinos

Photo-dissociation (giant dipole resonance)



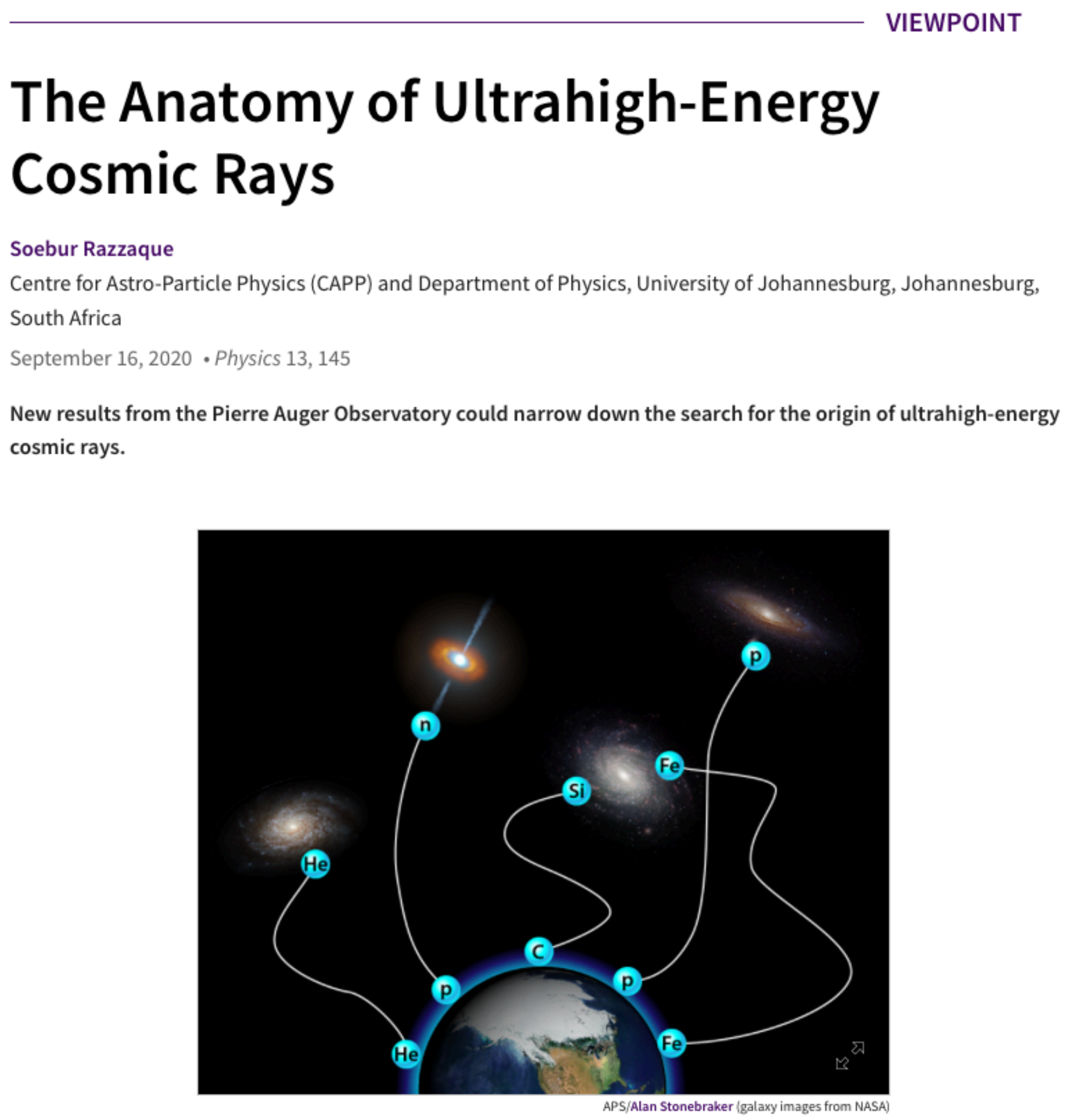
Iron dominated flux

Suppression: giant dipole resonance

Ankle: transition to galactic sources

Energy spectrum 2021

Simple fit with power-law spectrum at source and one primary mass does not work anymore


VIEWPOINT

The Anatomy of Ultrahigh-Energy Cosmic Rays

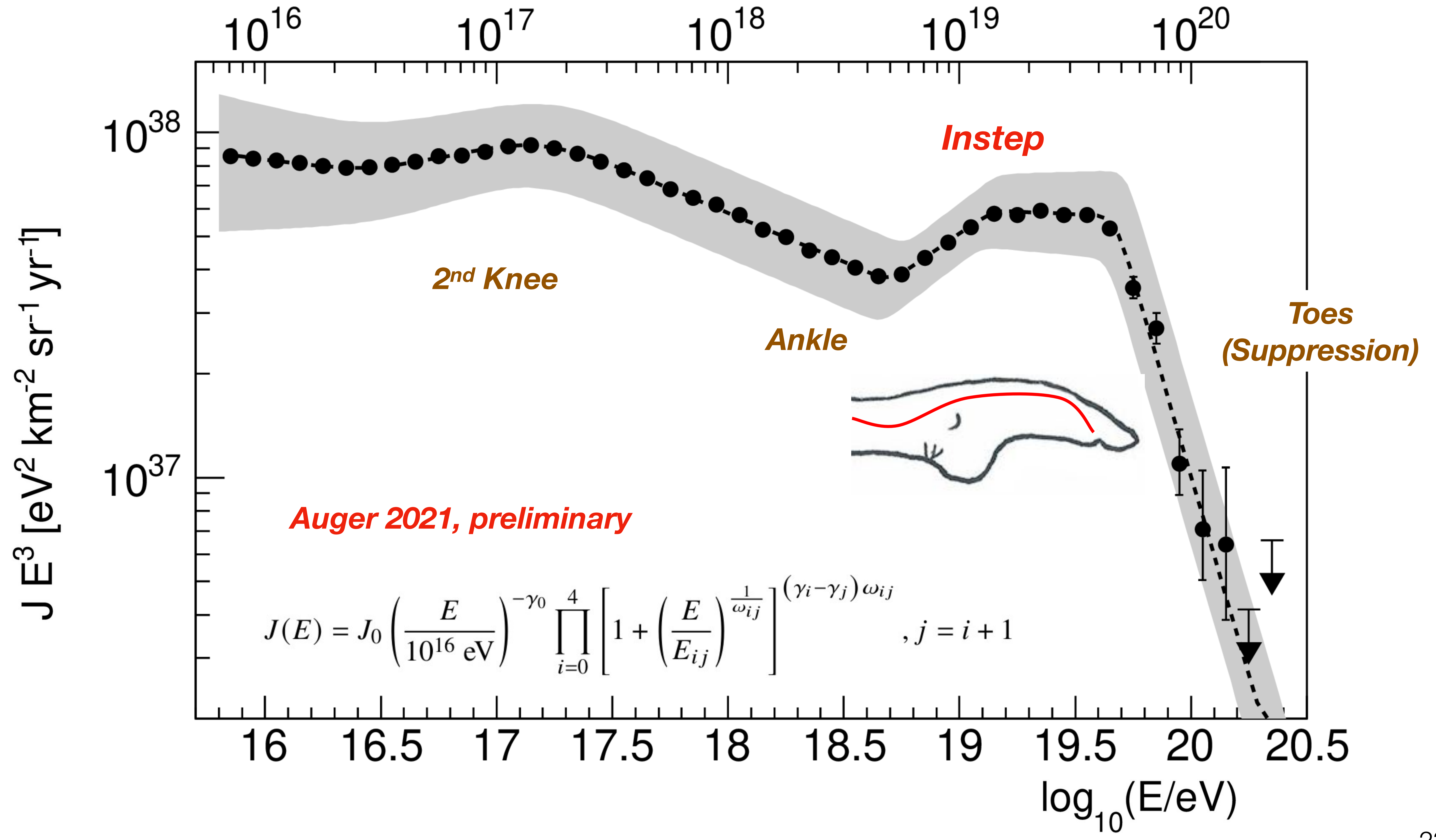
Soebur Razzaque

Centre for Astro-Particle Physics (CAPP) and Department of Physics, University of Johannesburg, Johannesburg, South Africa

September 16, 2020 • *Physics* 13, 145

New results from the Pierre Auger Observatory could narrow down the search for the origin of ultrahigh-energy cosmic rays.

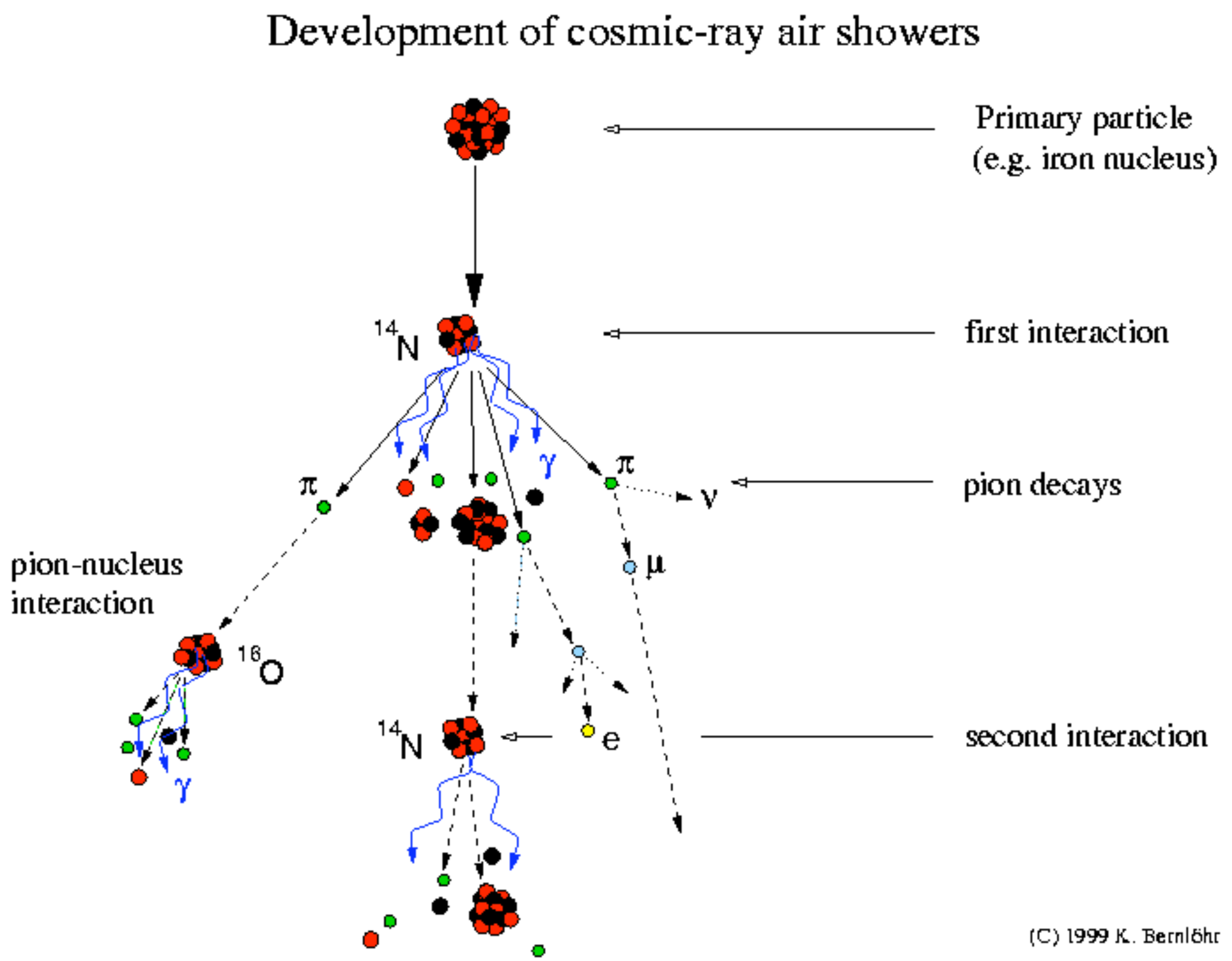
APS/Alan Stonebraker (galaxy images from NASA)

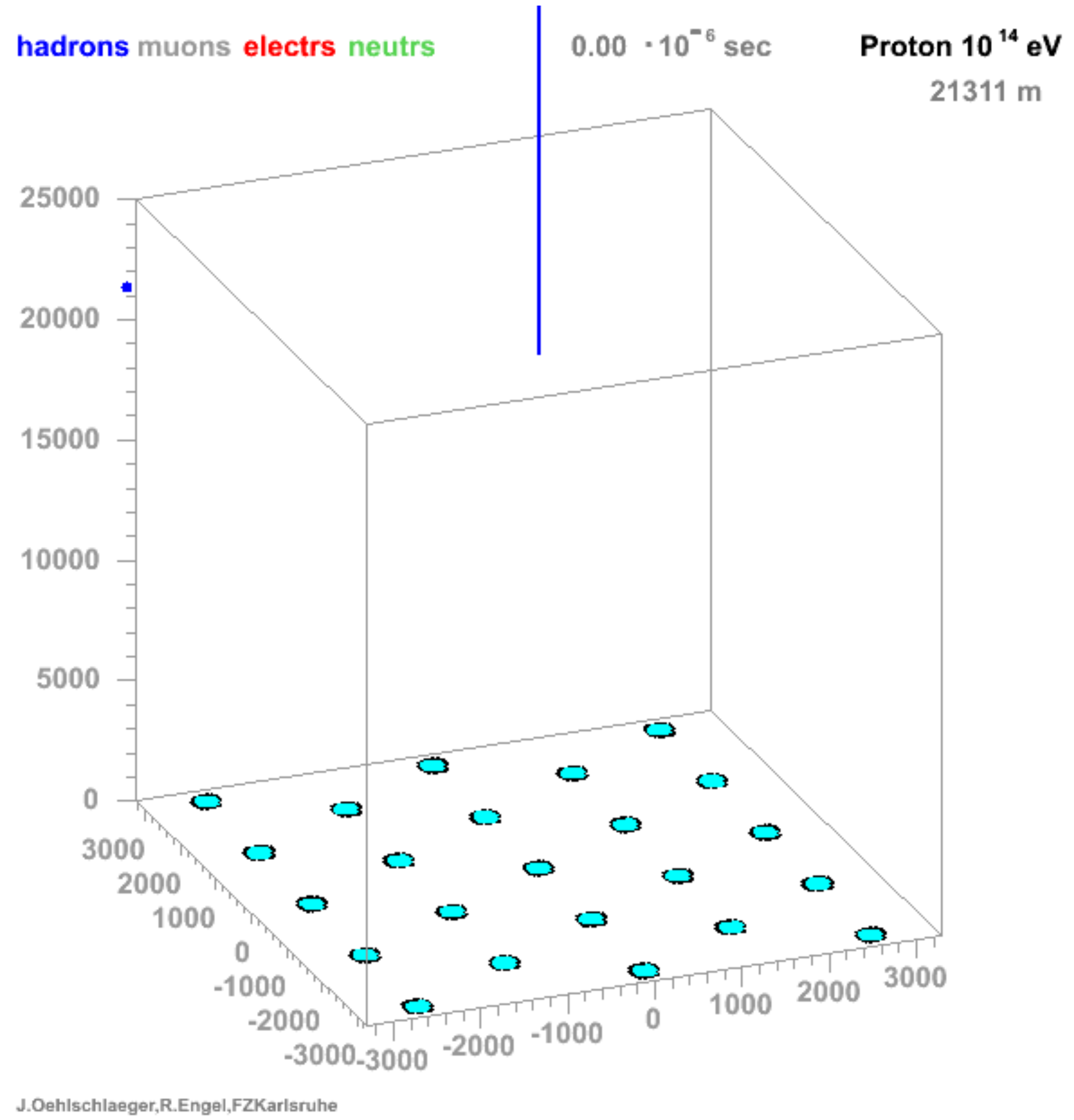


Phys. Rev. Lett. 125 (2020) 121106
Phys. Rev. D102 (2020) 062005
Eur. Phys. J. C (2021) 966

Mass sensitivity and fraction of photons

Basics of extensive air showers



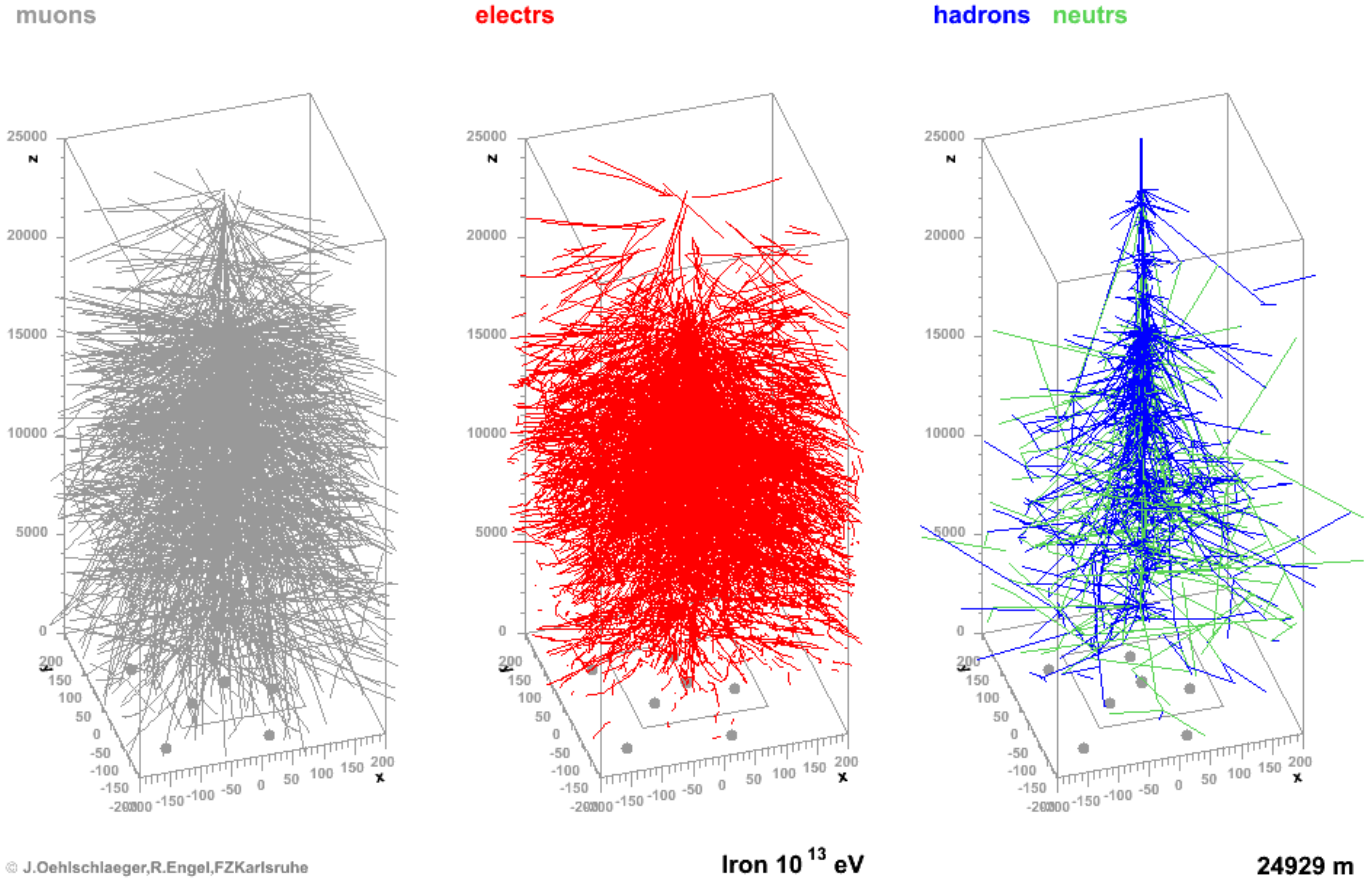


Decay of neutral pions feeds **em. shower component**

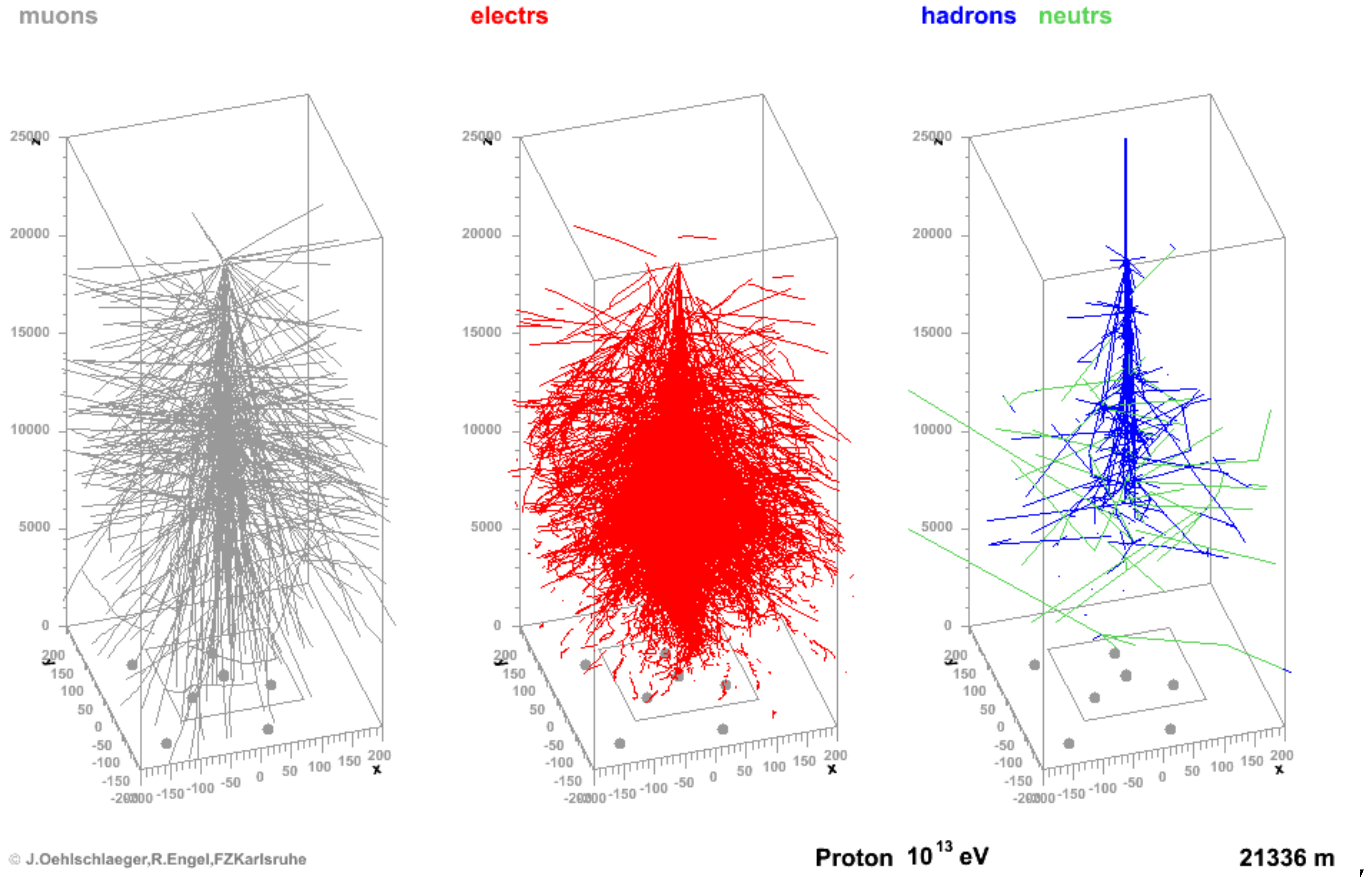
Decay of charged pions (~30 GeV) feeds **muonic component**

Animation of shower of lower energy (10^{14} eV)

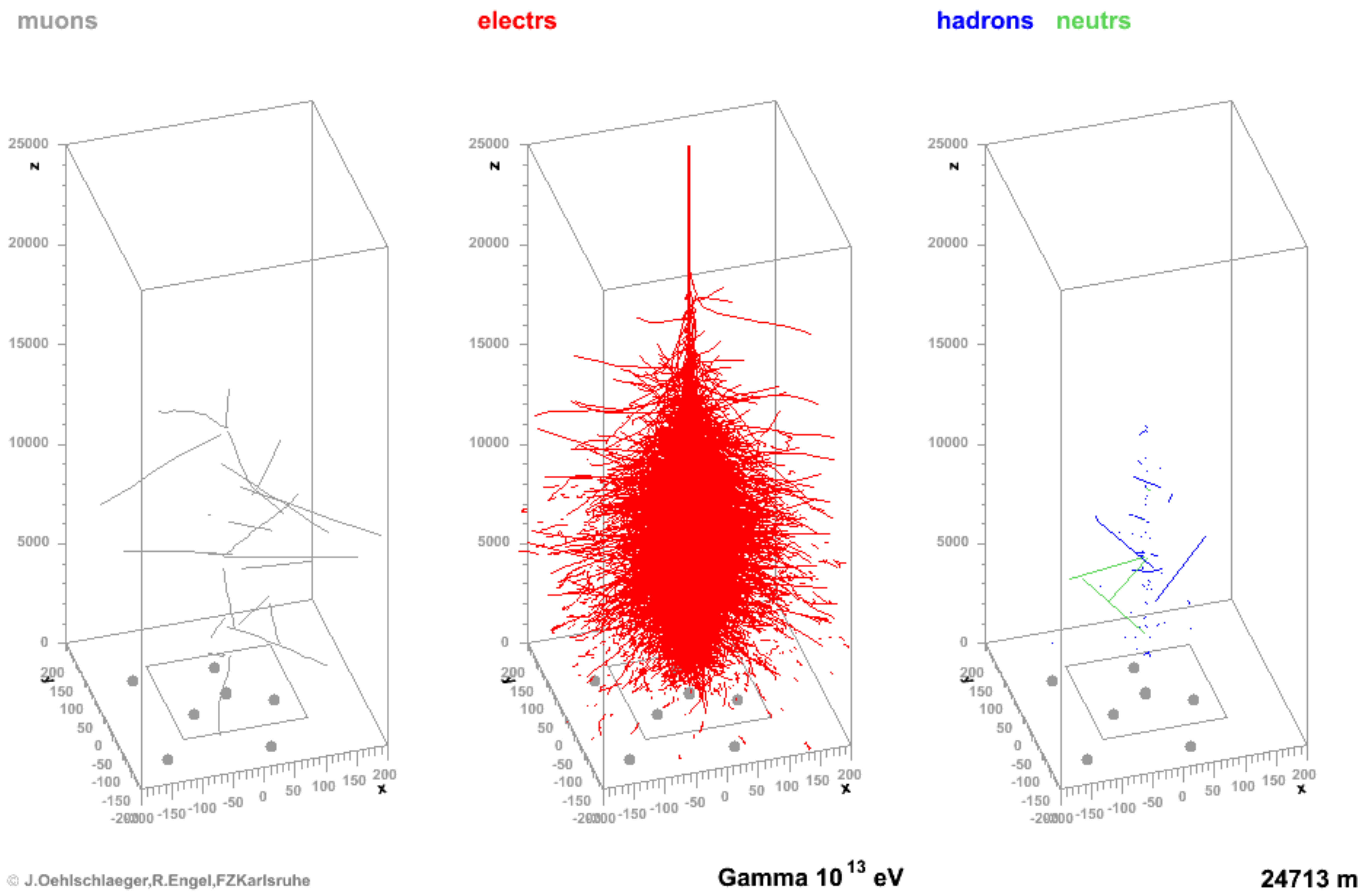
Particles of an iron shower



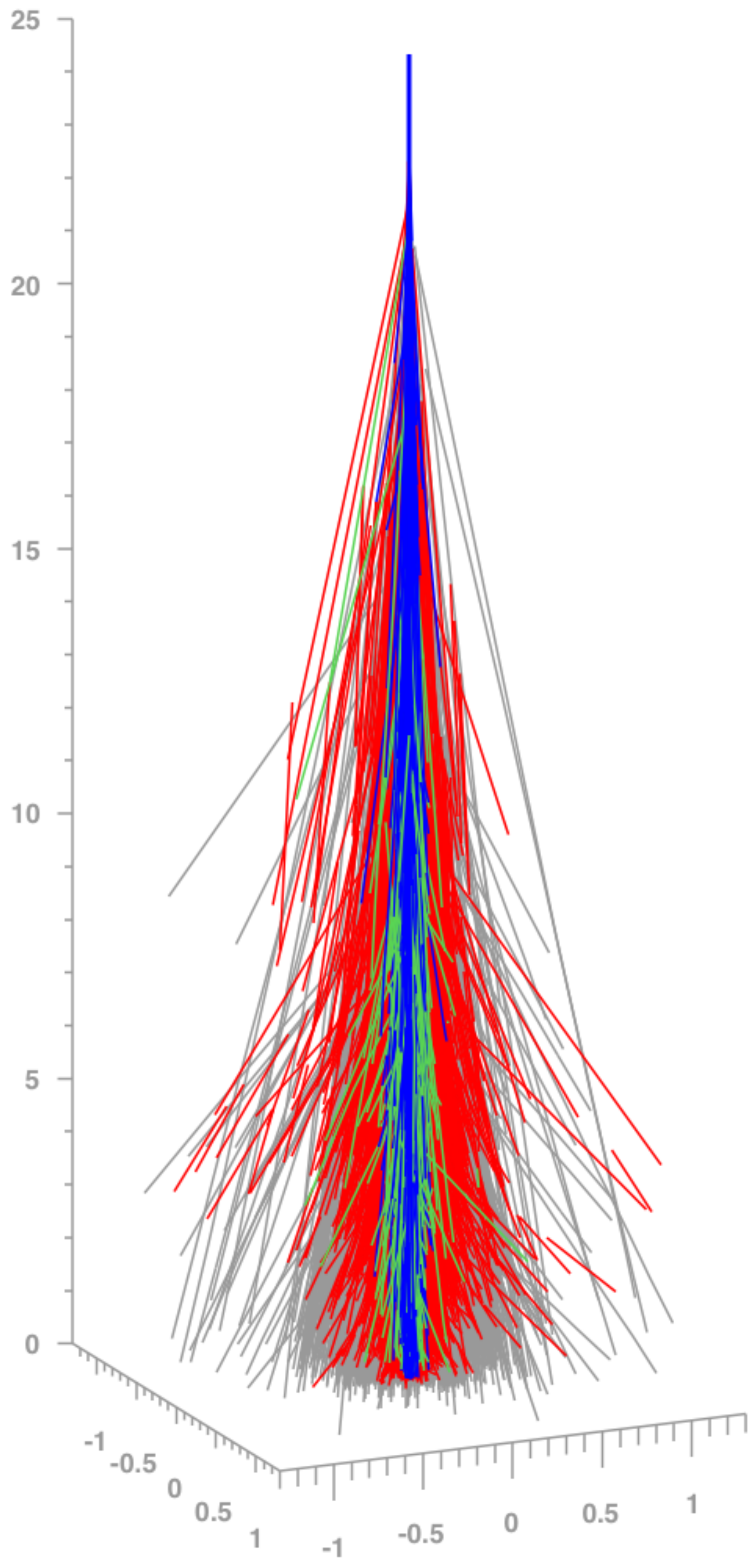
Particles of an proton shower

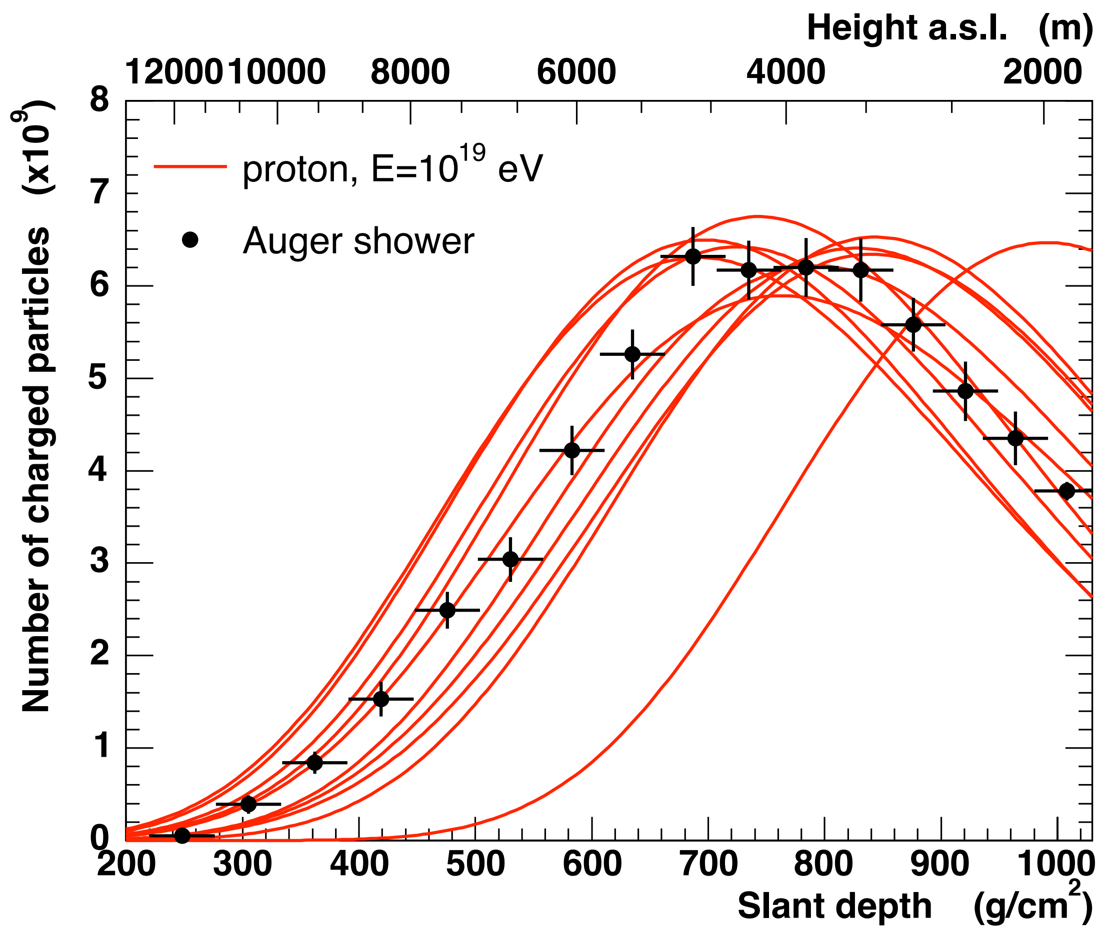


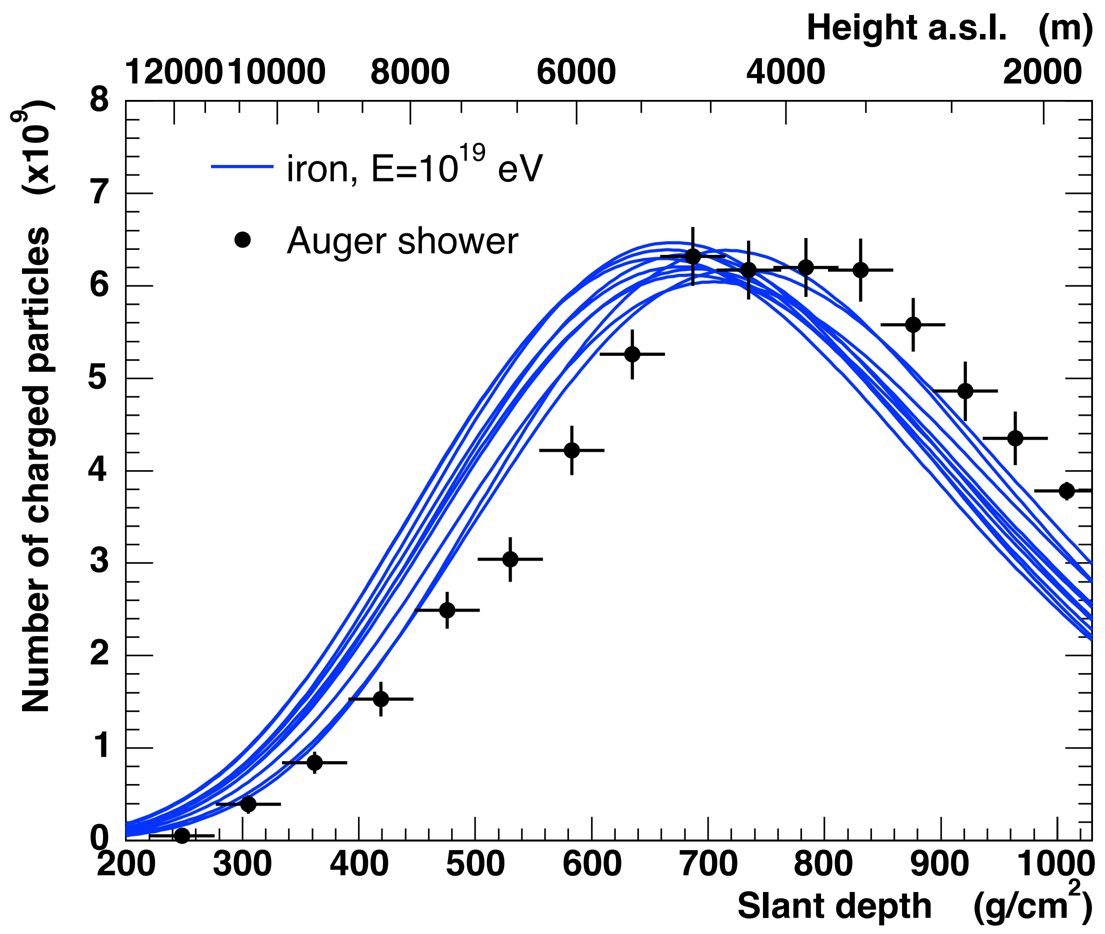
Particles of a gamma-ray shower



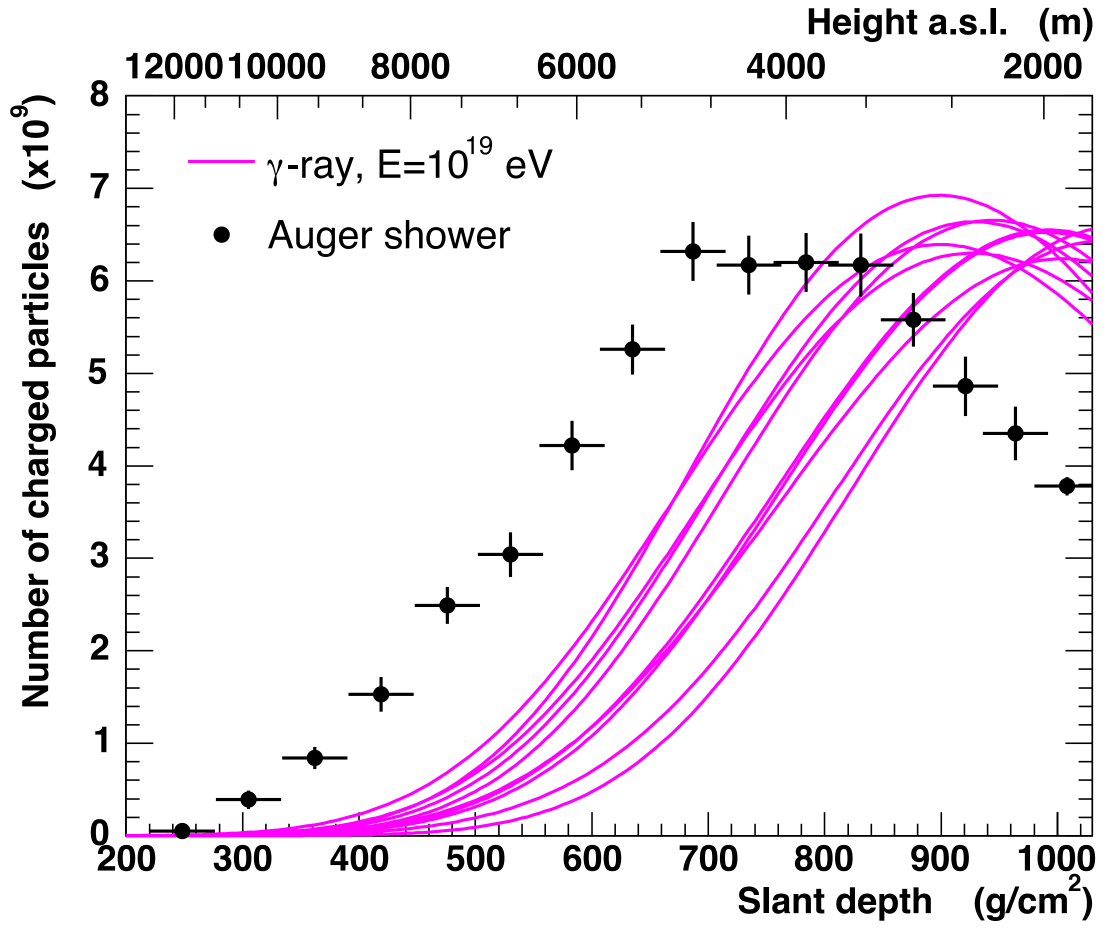
Mass composition from longitudinal shower profile

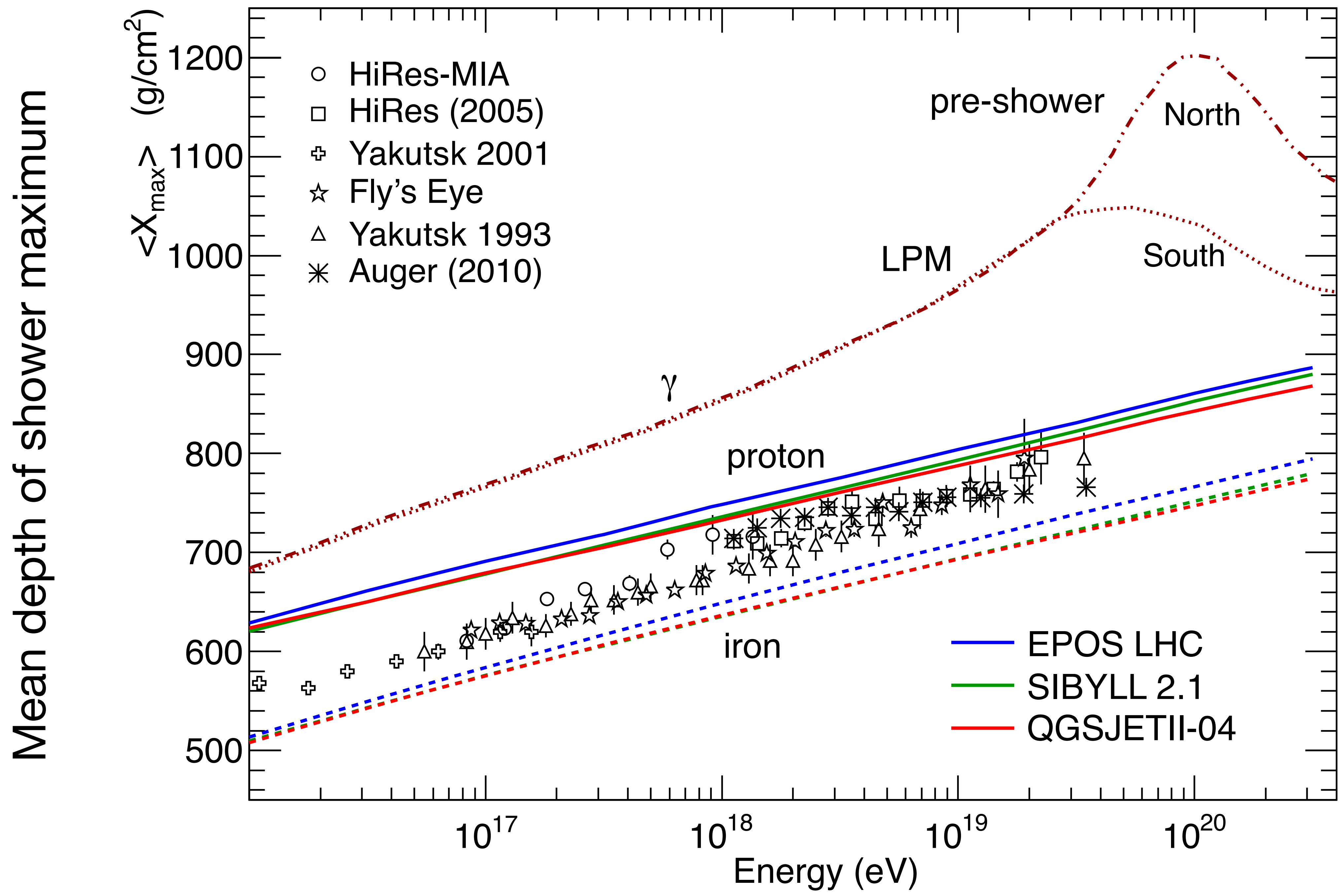






Simulations with CORSIKA and Sibyll



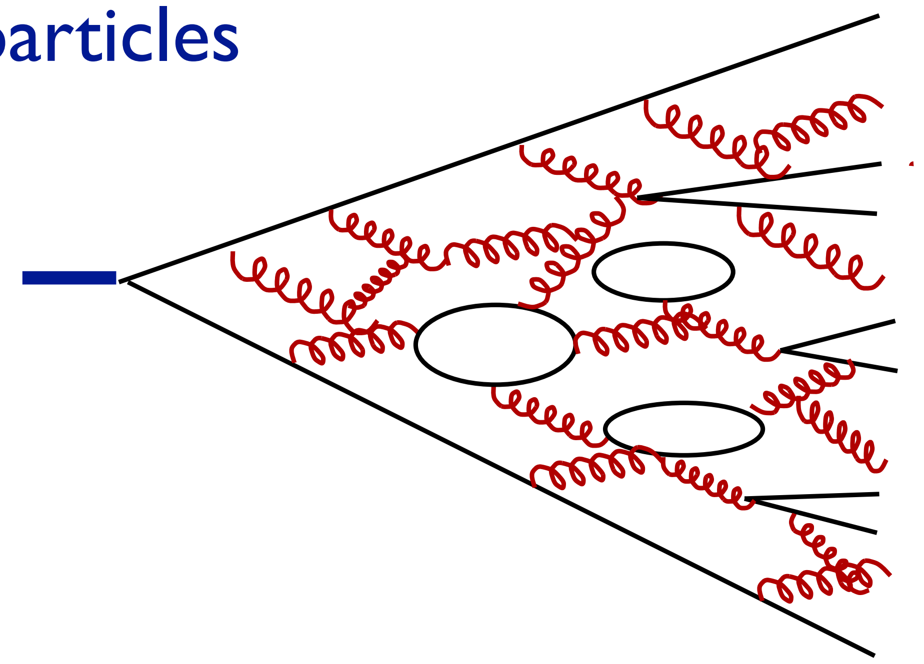


Example: event measured by Auger Collab.

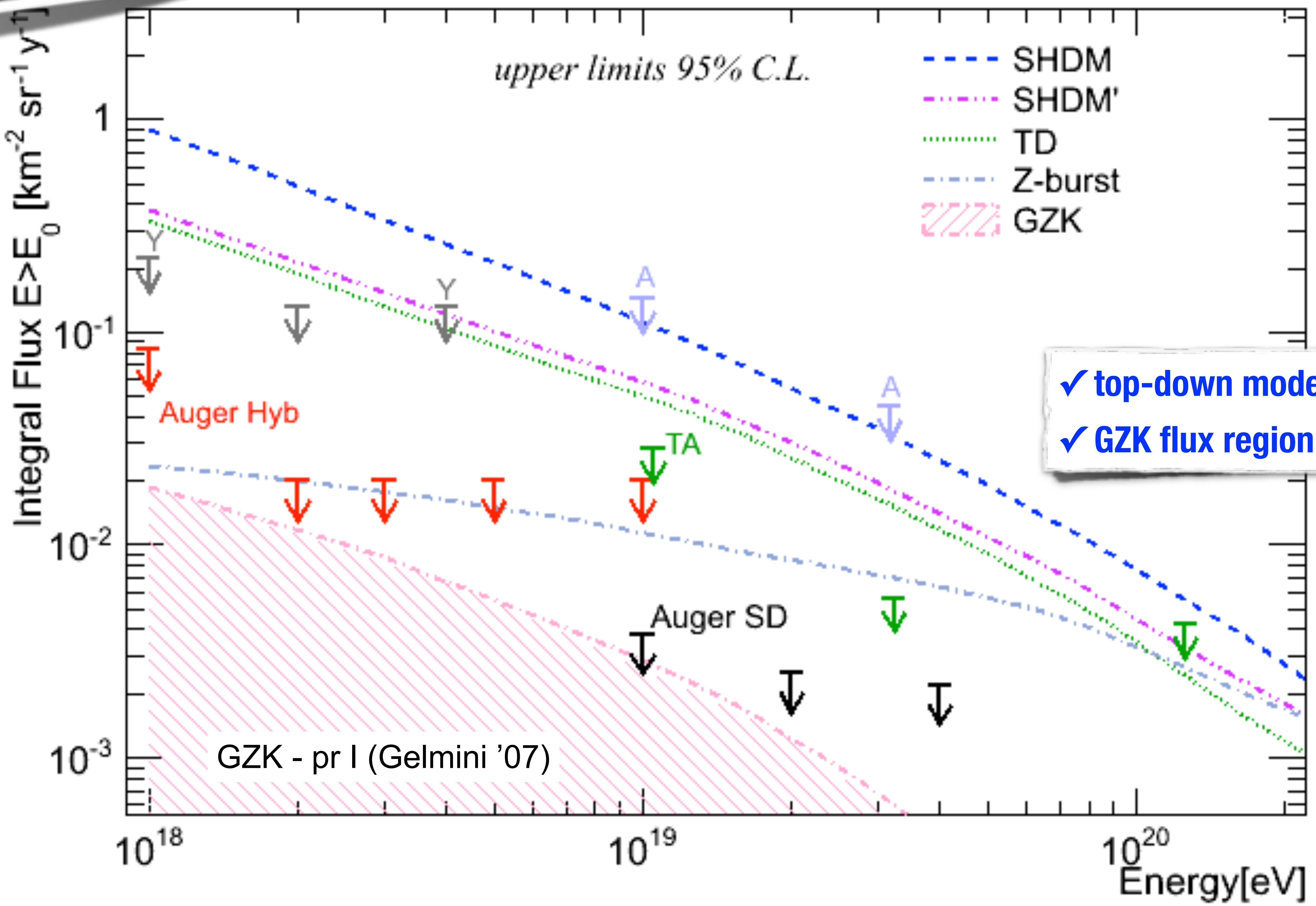
Most exotic source models excluded

No UHE photons identified so far!!

Super-heavy particles

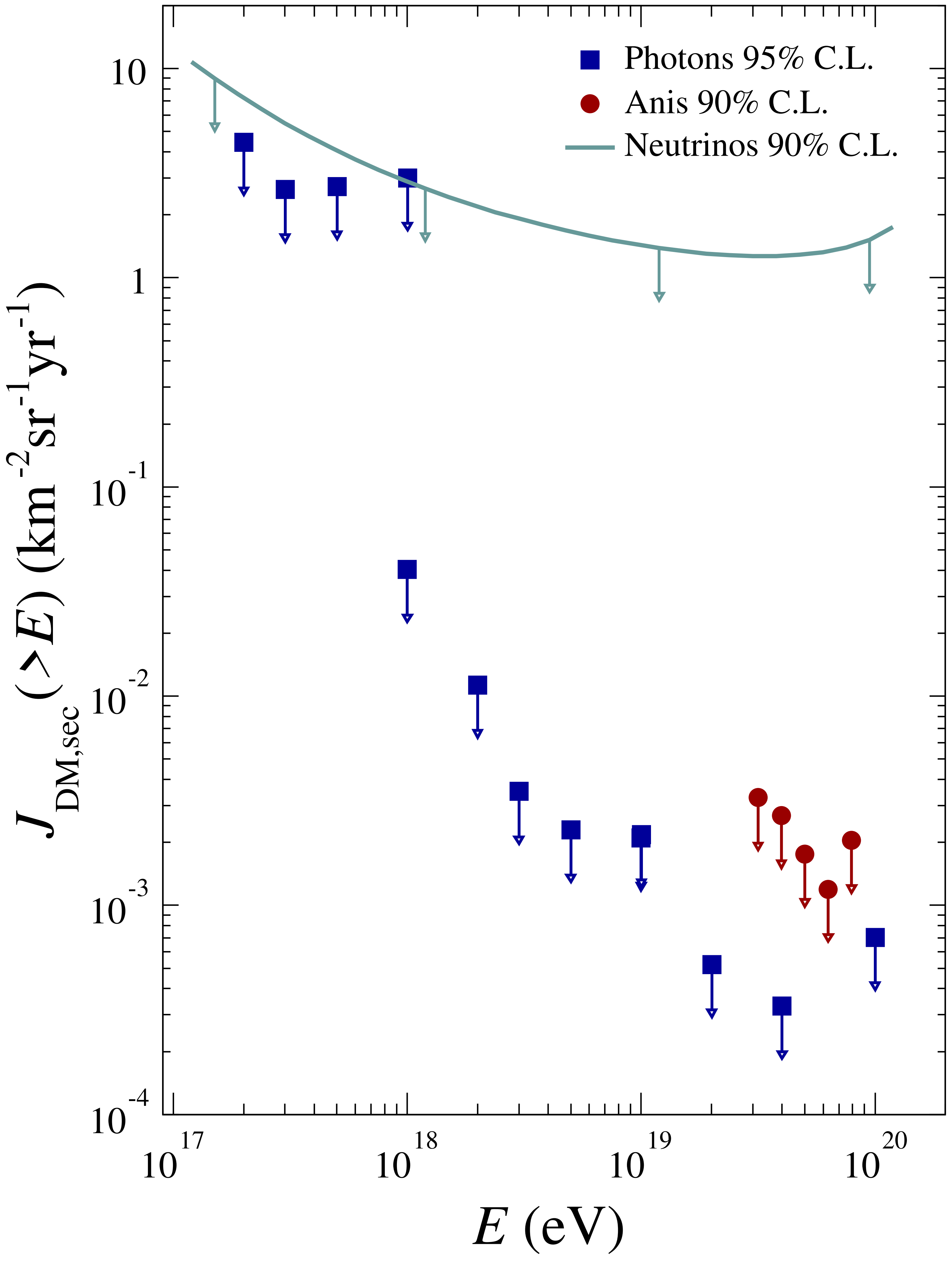


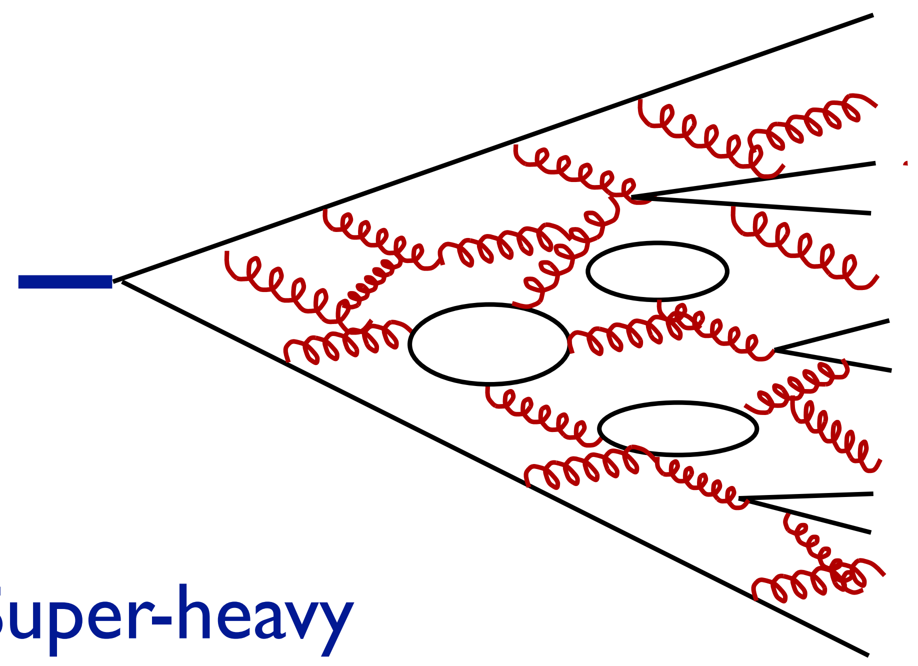
large fluxes of photons and neutrinos



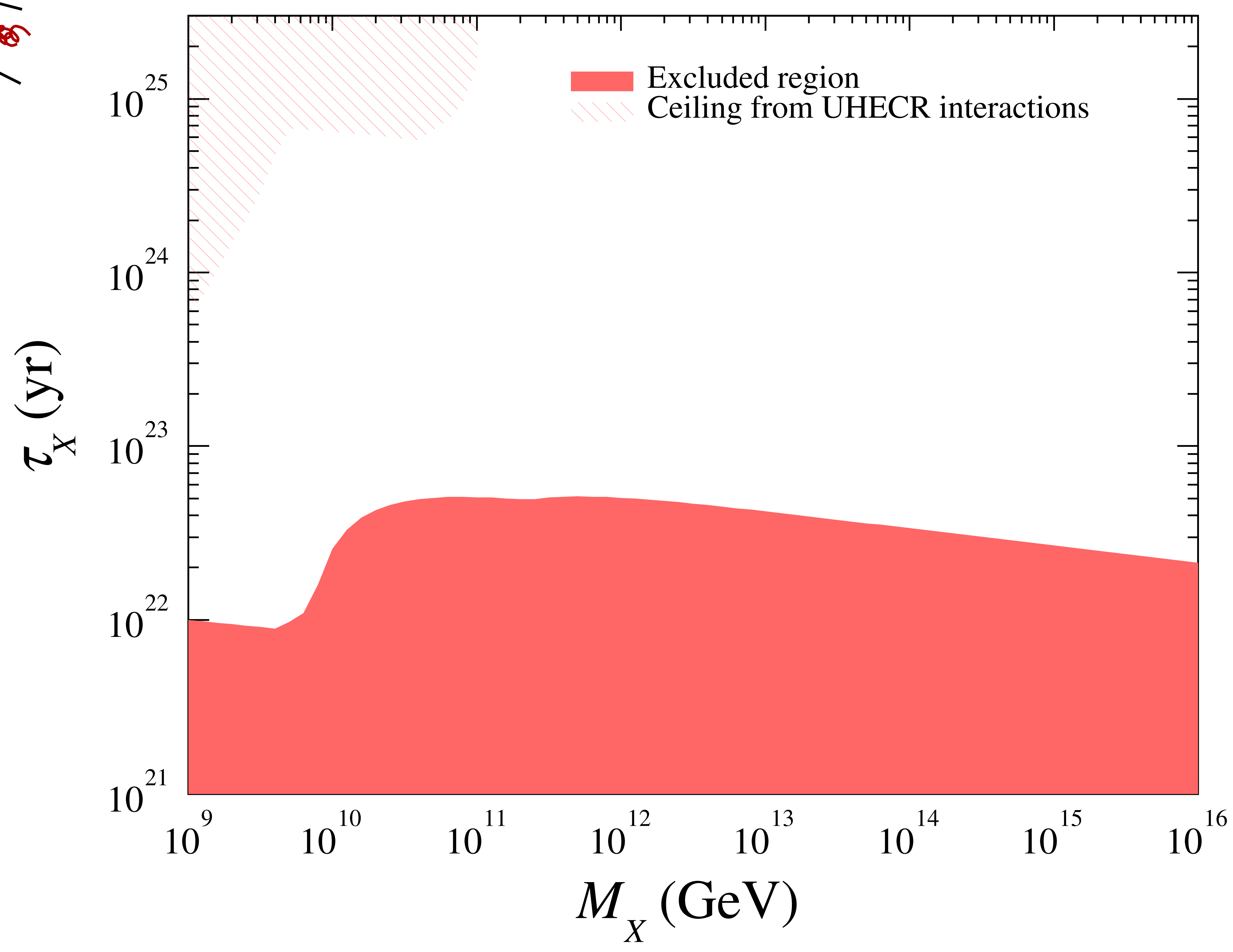
- ✓ top-down models disfavored
- ✓ GZK flux region within reach

Limits on super-heavy dark matter models





Super-heavy particles

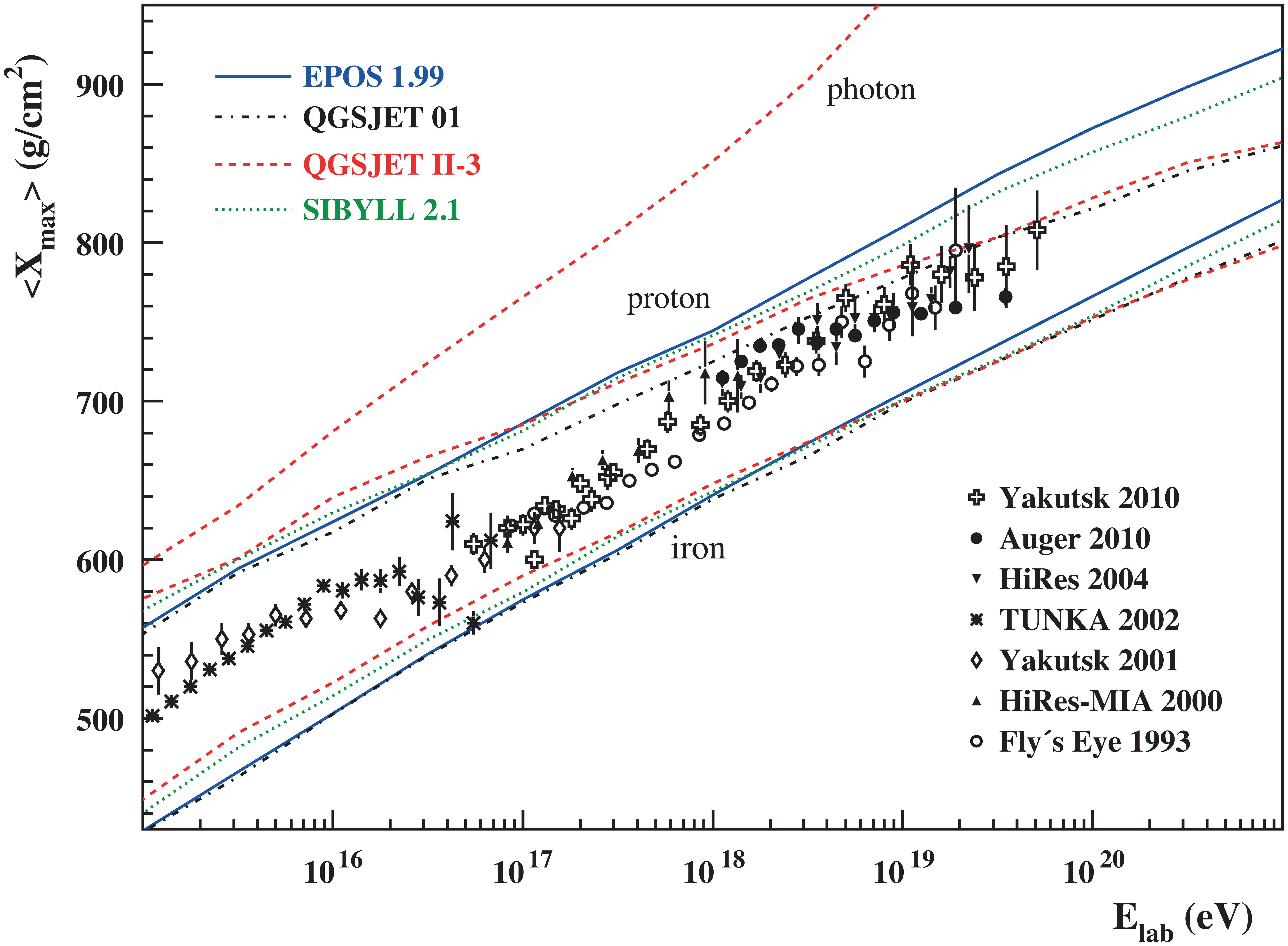


Anchordoqui, Deligny et al. Astropart.Phys. 132 (2021) 102614

Large uncertainty of model predictions for shower observables

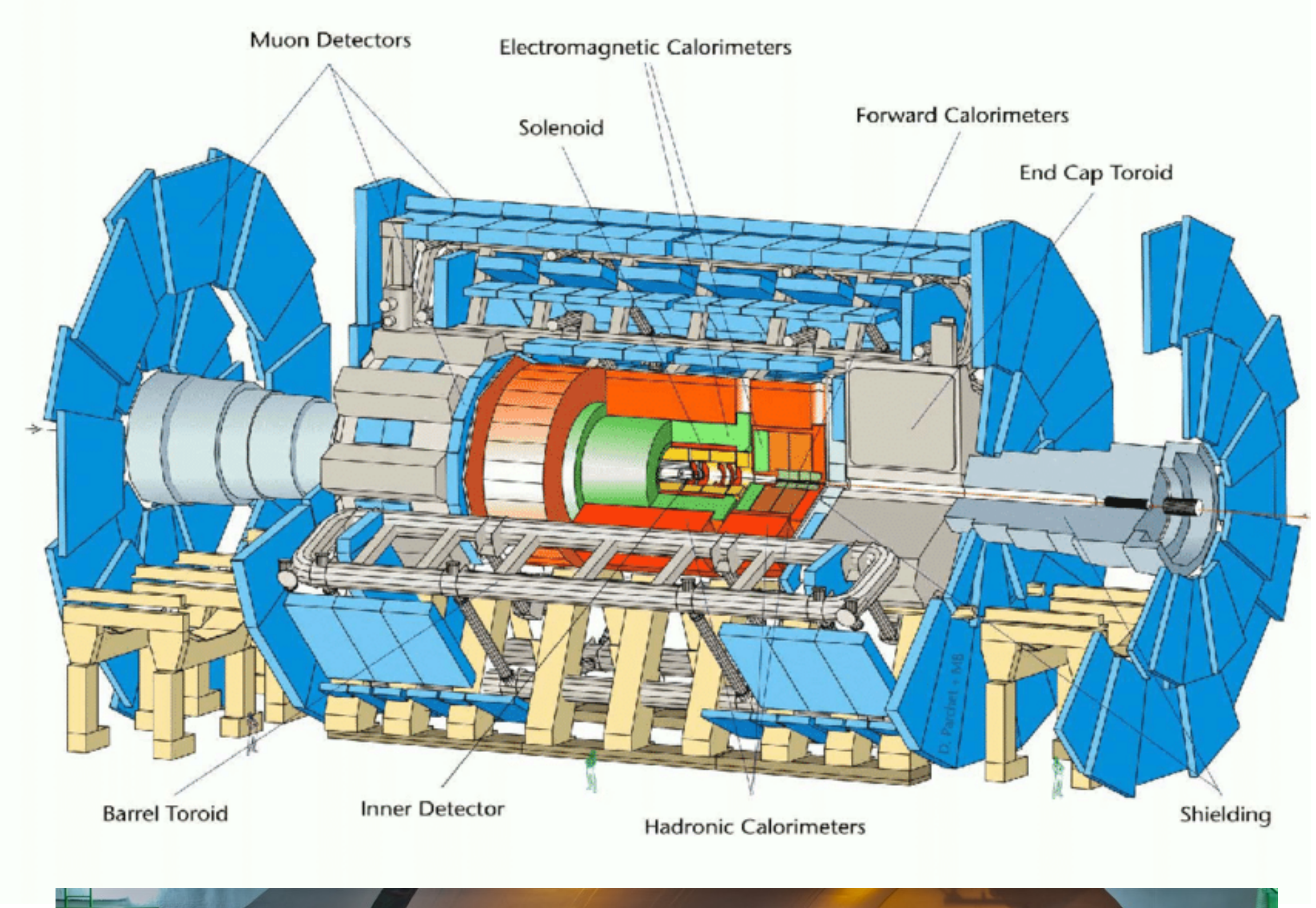
(RE, Pierog, Heck, ARNPS 2011)

Mean depth of shower maximum

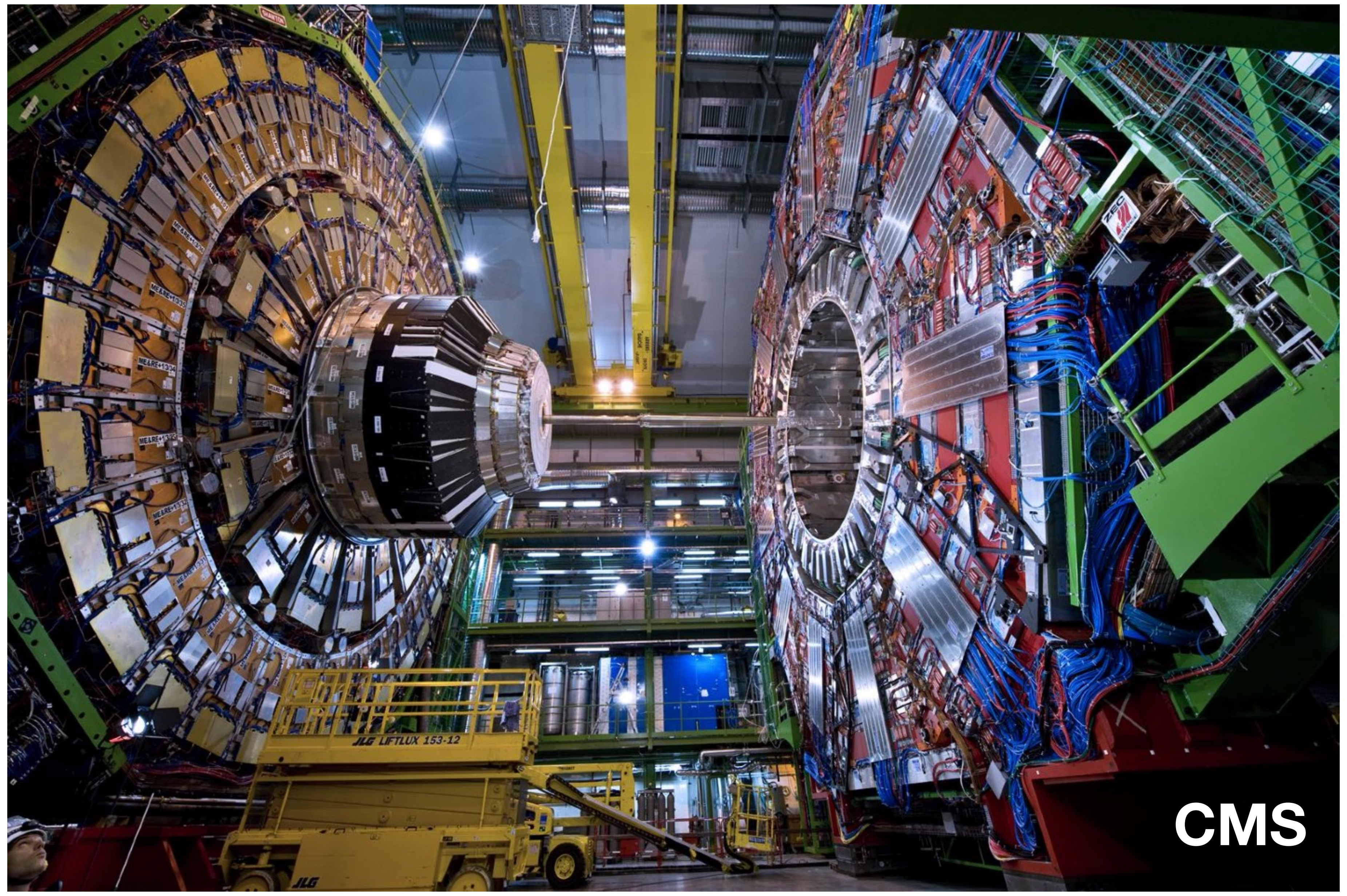


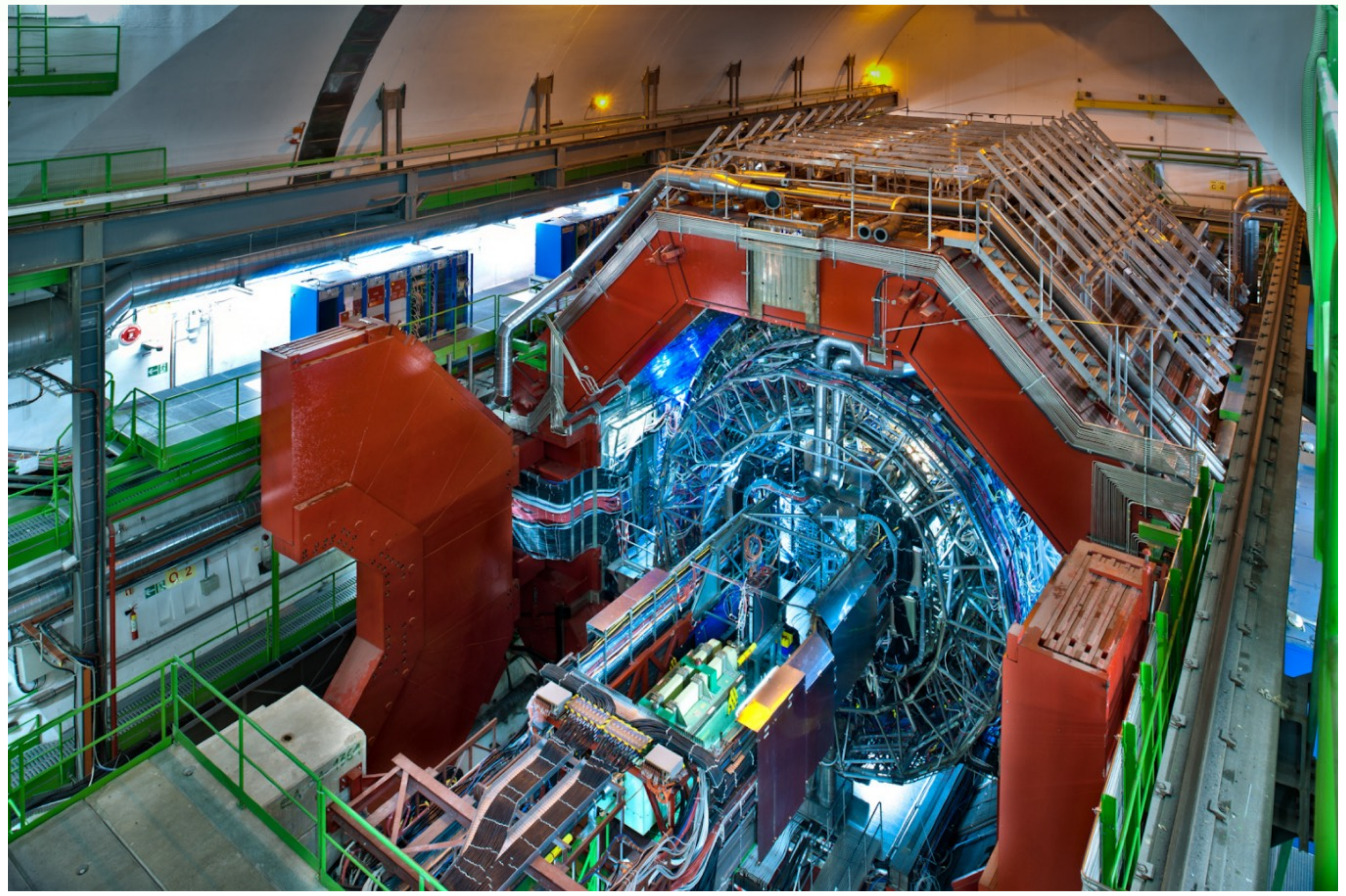
The importance of LHC

LHC and its experiments ($E_{equiv} \sim 10^{17}$ eV)

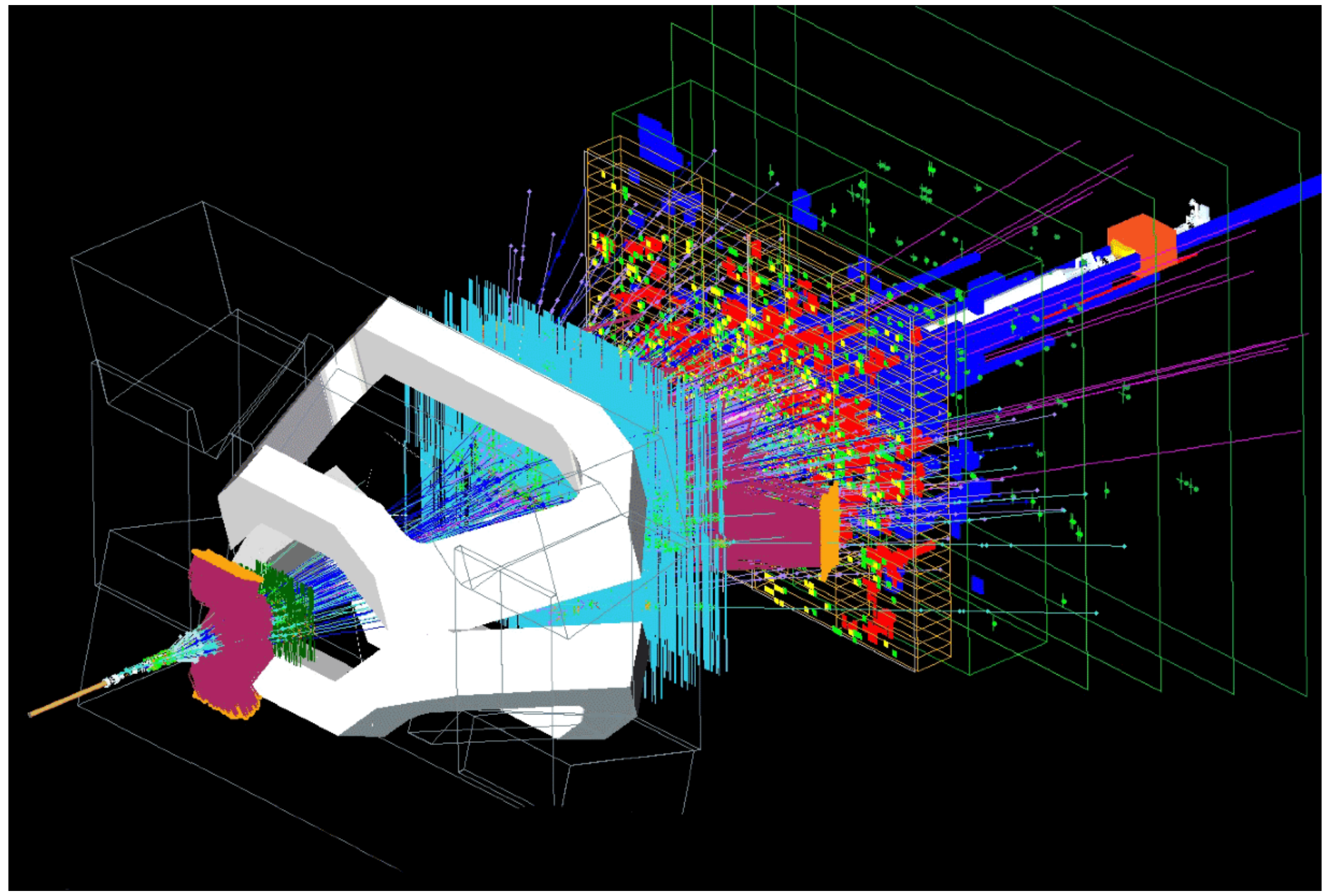


ATLAS



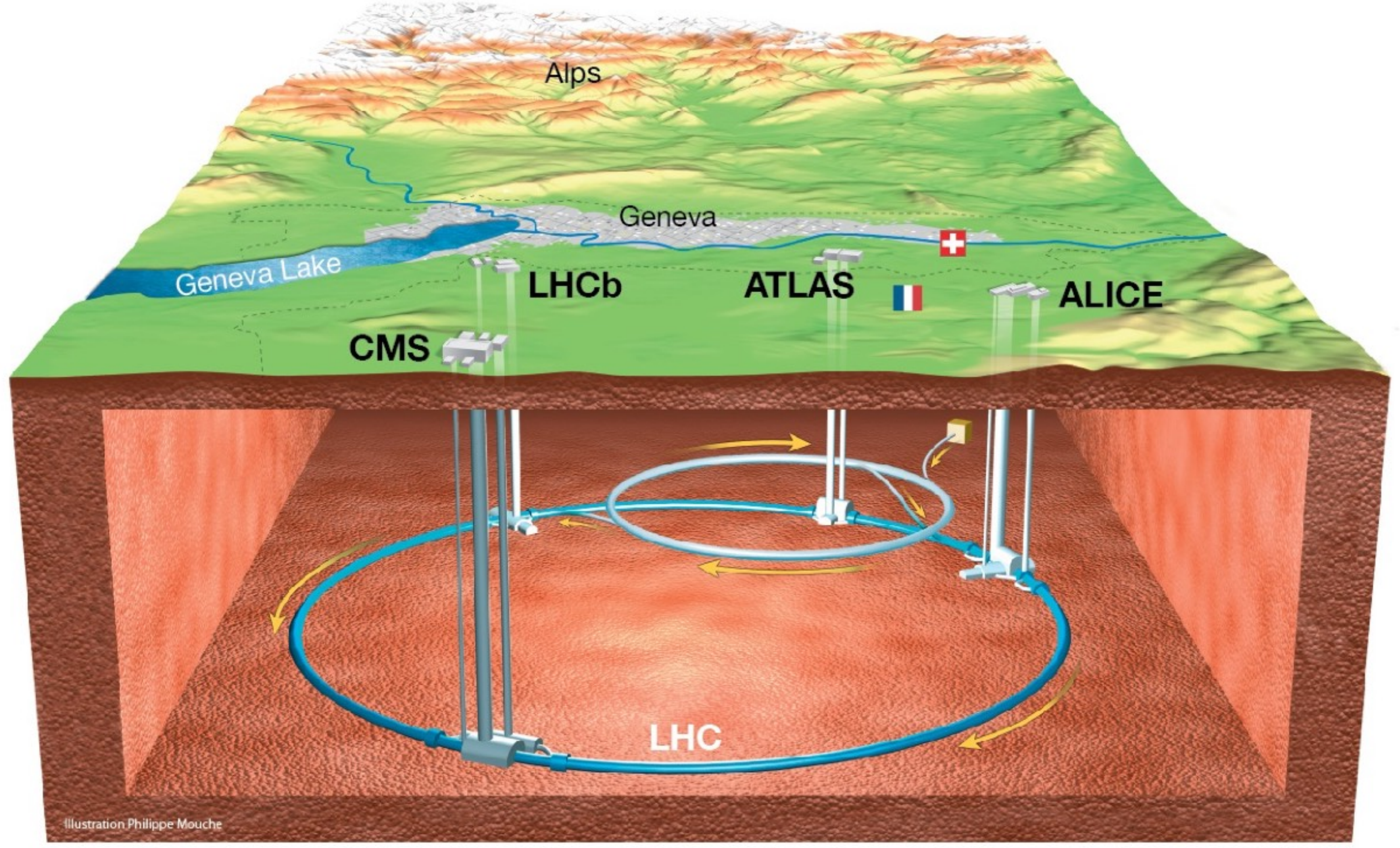


ALICE



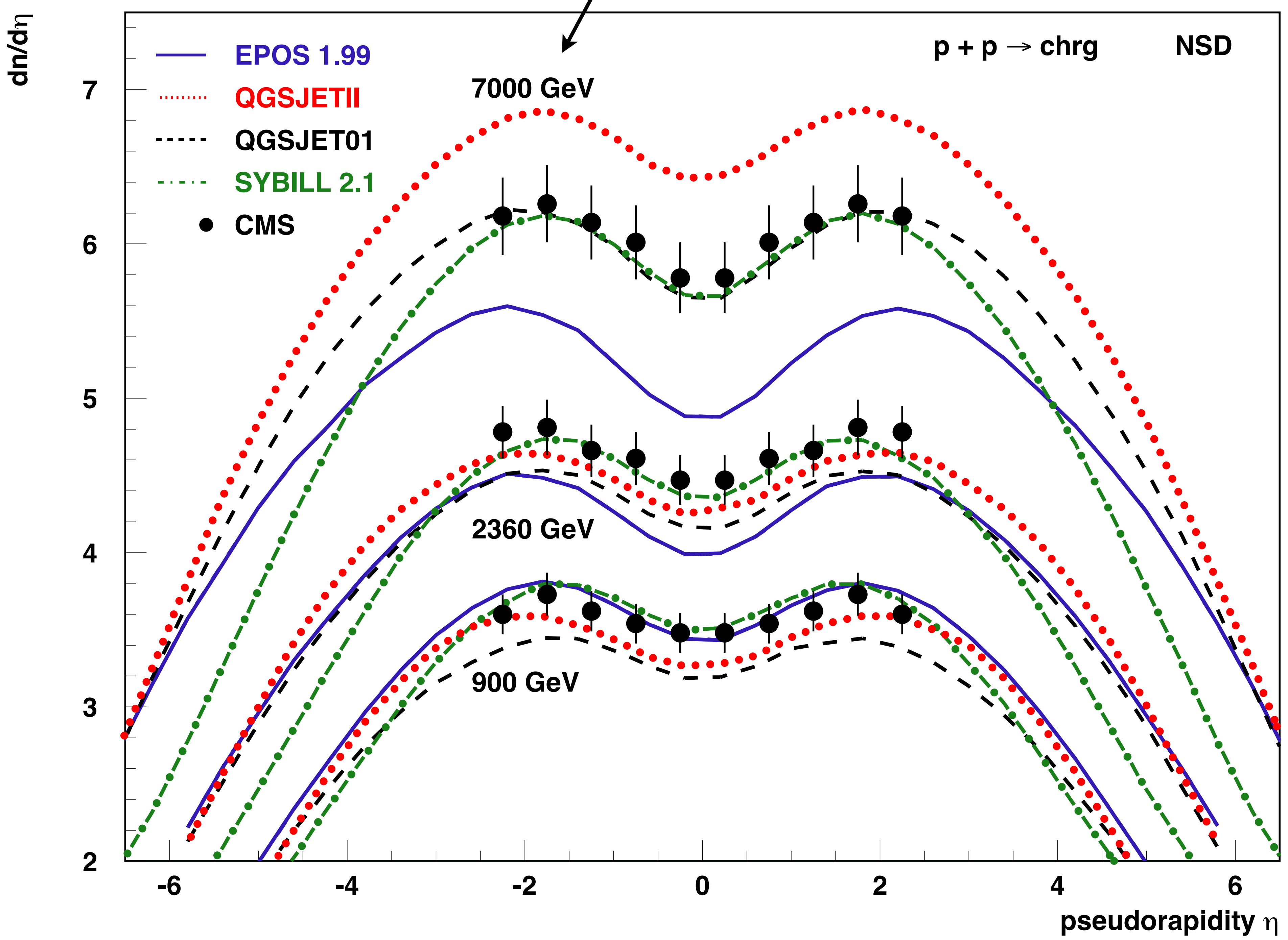
LHCb

Charged particle distribution in pseudorapidity

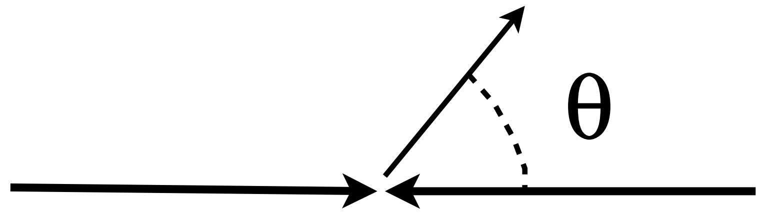


η	deg.	mrad.
3	5.7	97
5	0.77	10
8	0.04	0.7
10	0,005	0,009

Protons: $E_{lab} = 3 \times 10^{16}$ eV

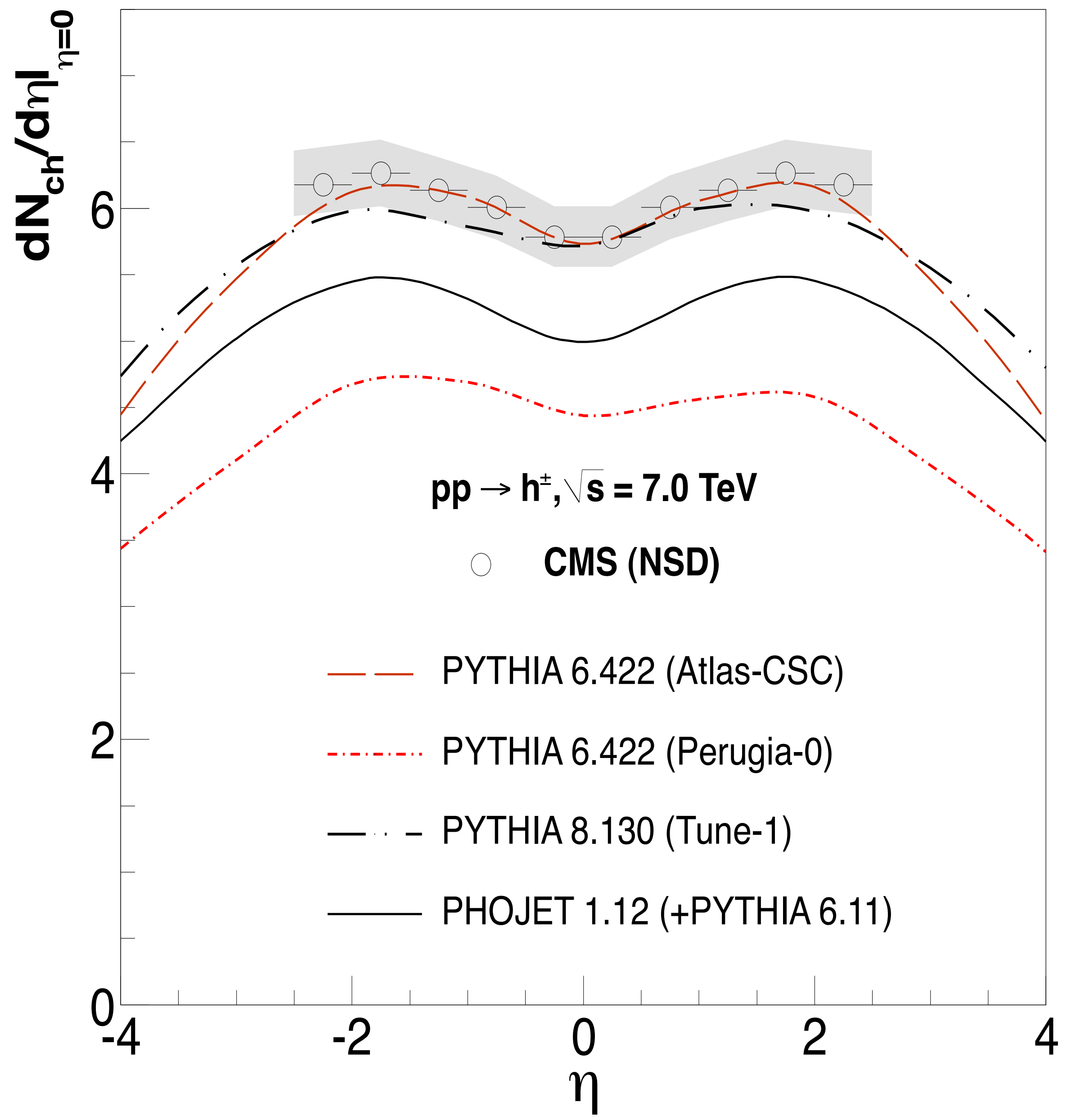


$$\eta = -\ln \tan \frac{\theta}{2}$$



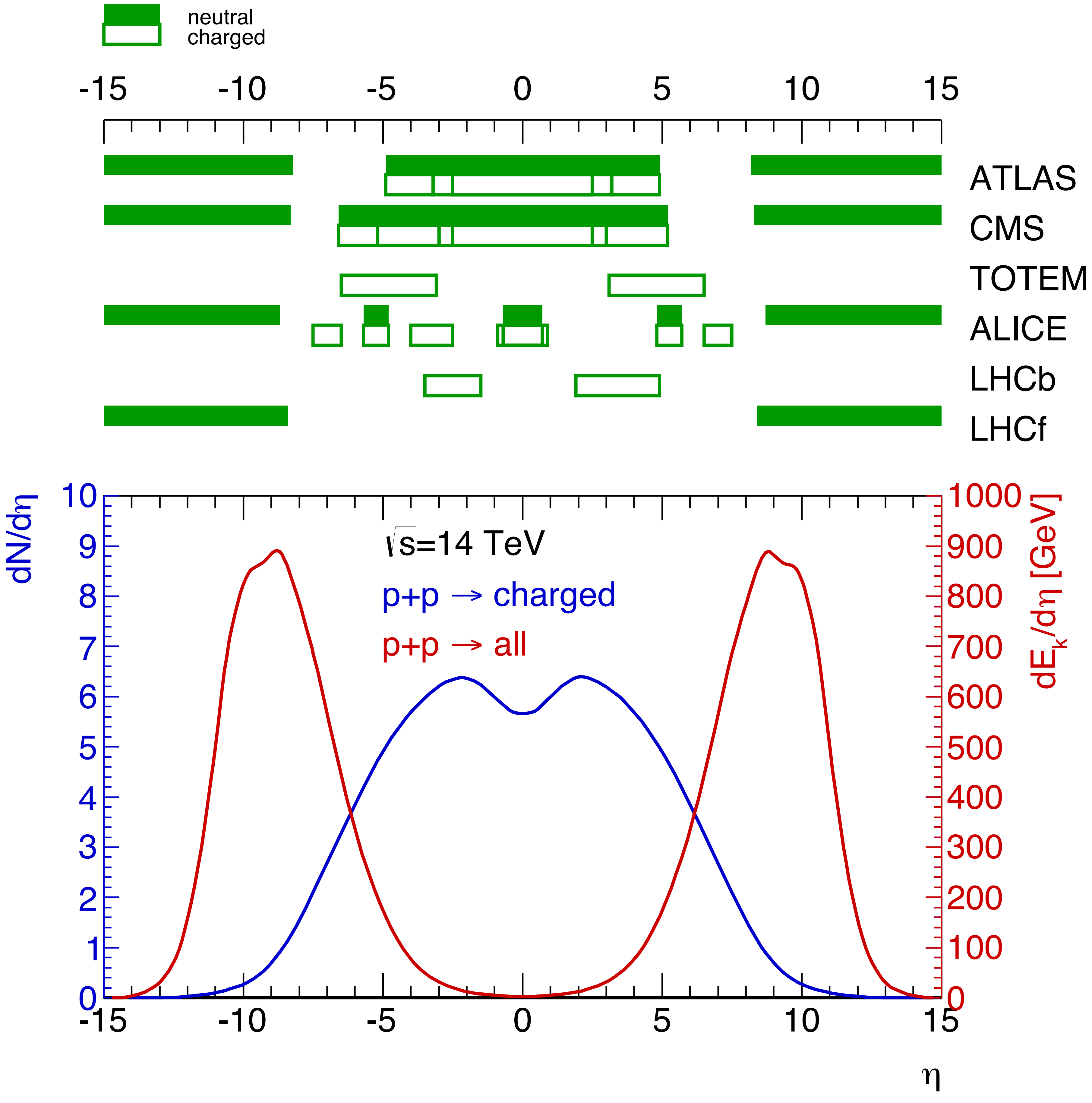
Detailed LHC comparison

(D'Enterria et al., APP 35, 2011)

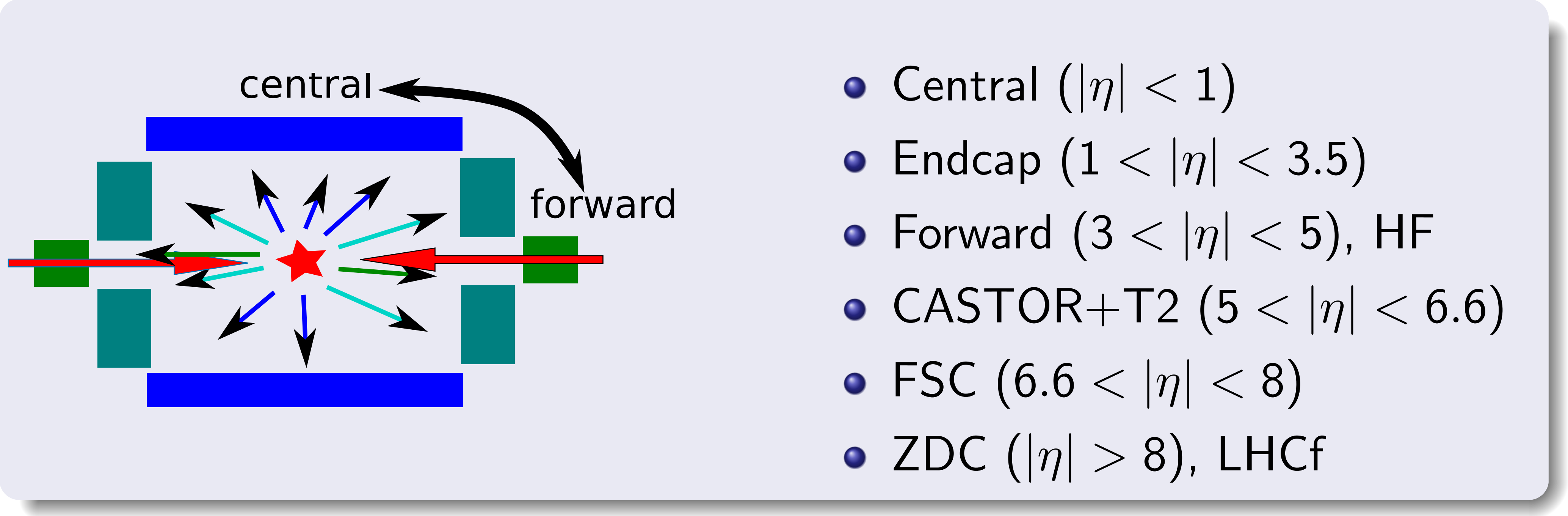


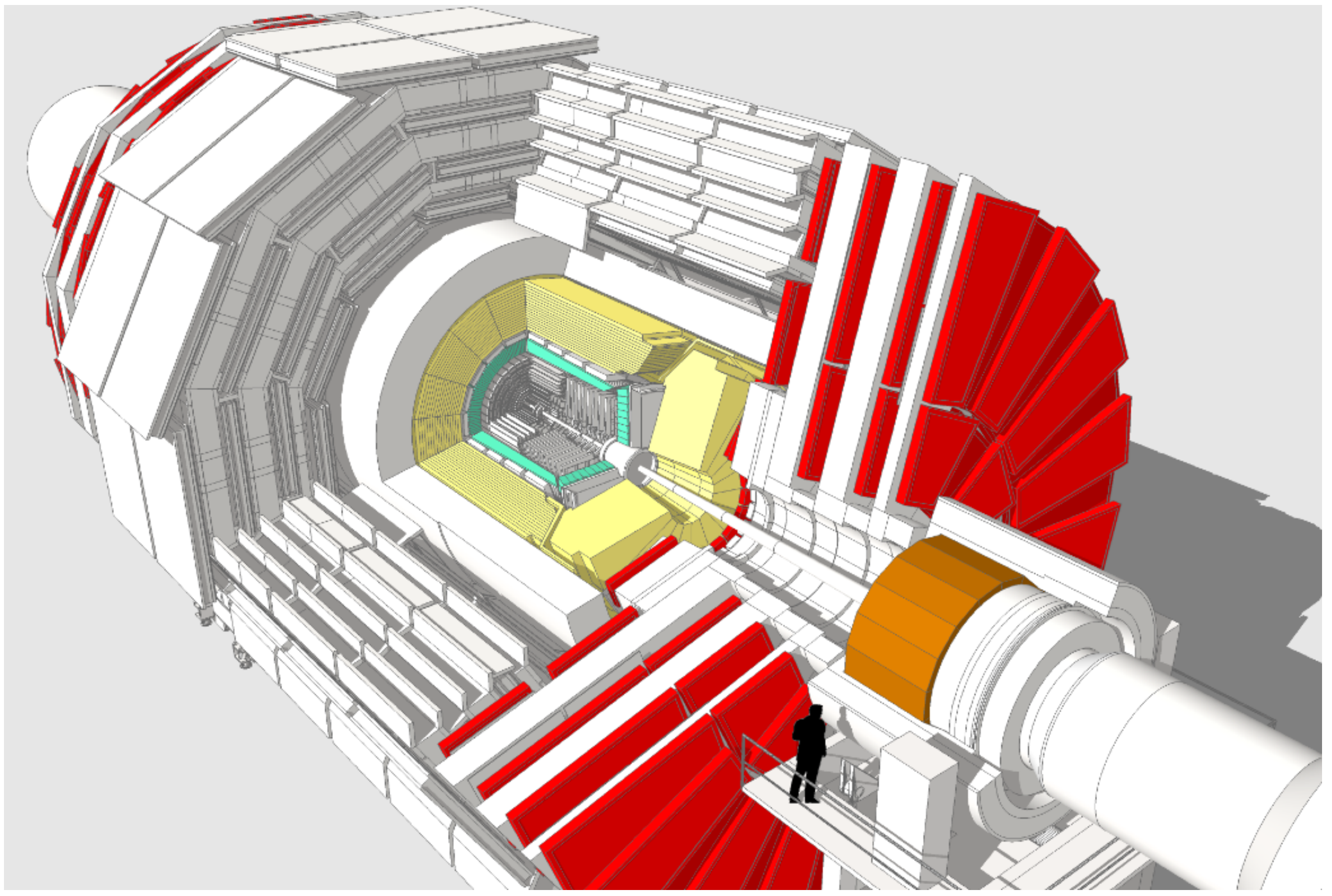
Models for air showers typically better in agreement with LHC data

Challenge of limited phase space coverage

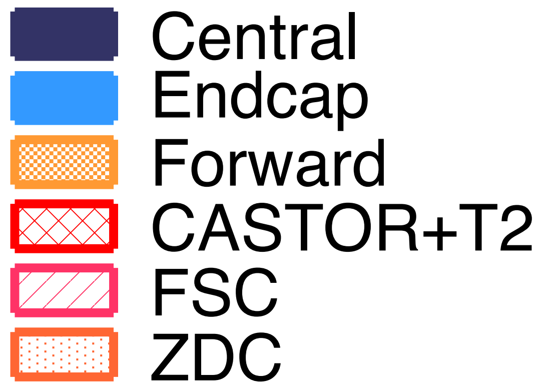


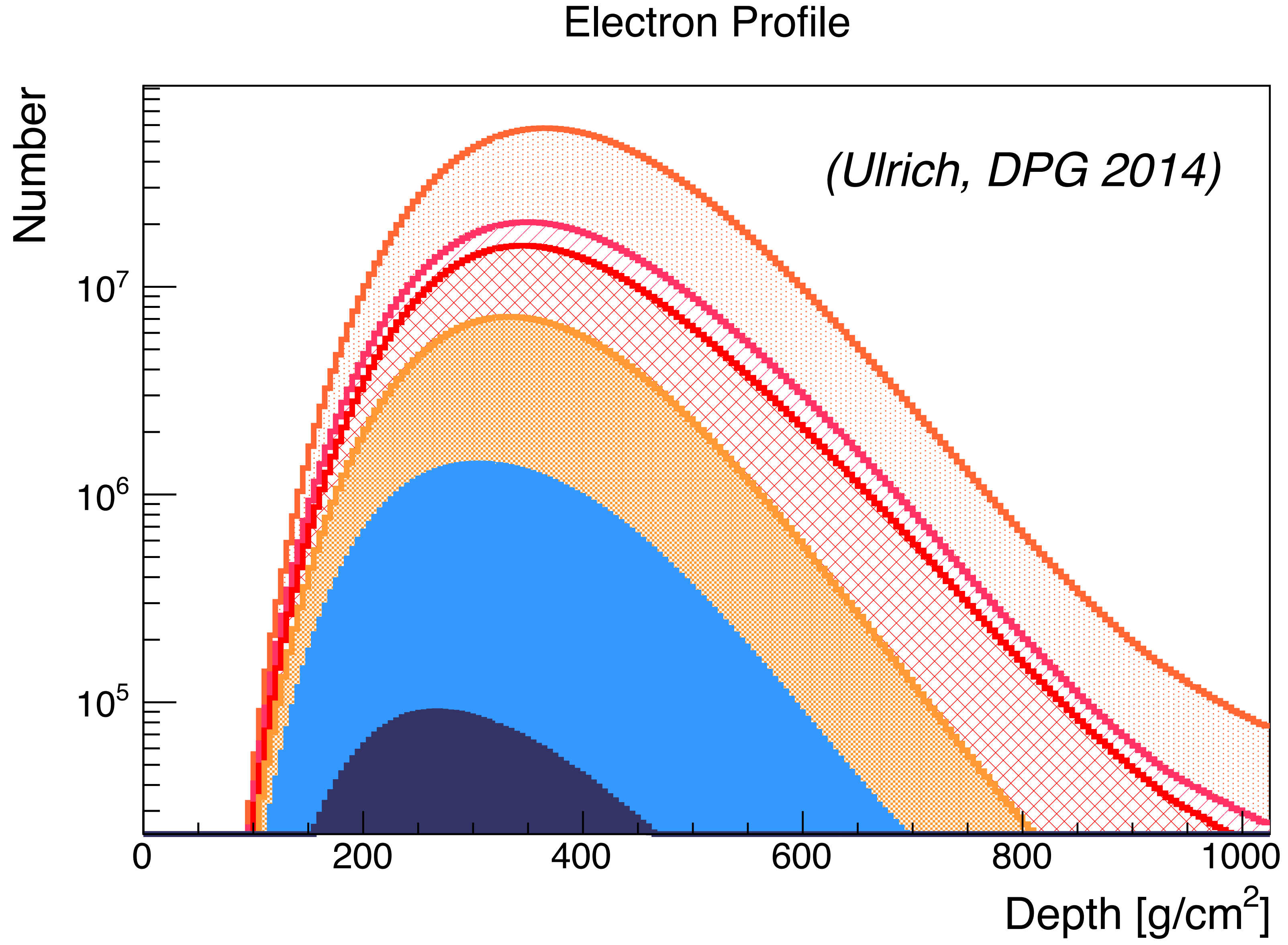
(Salek et al., 2014)





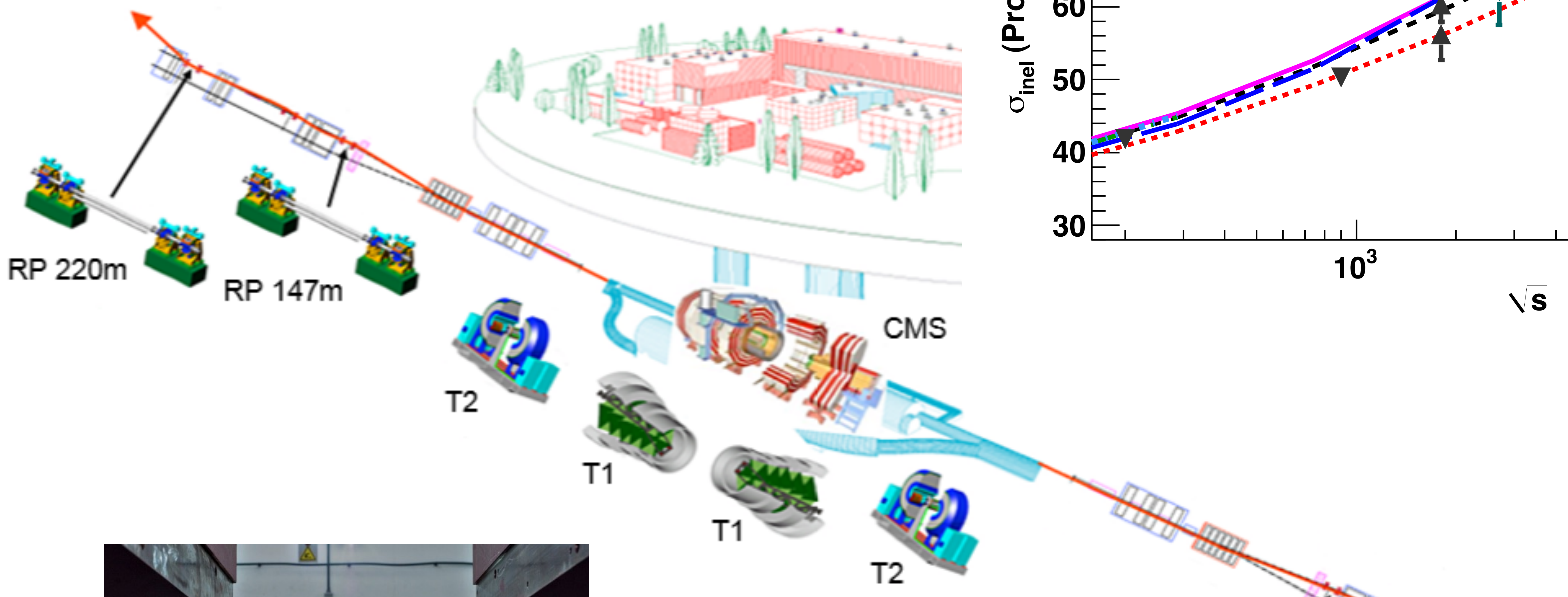
(data from all LHC experiments, CMS shown as example)

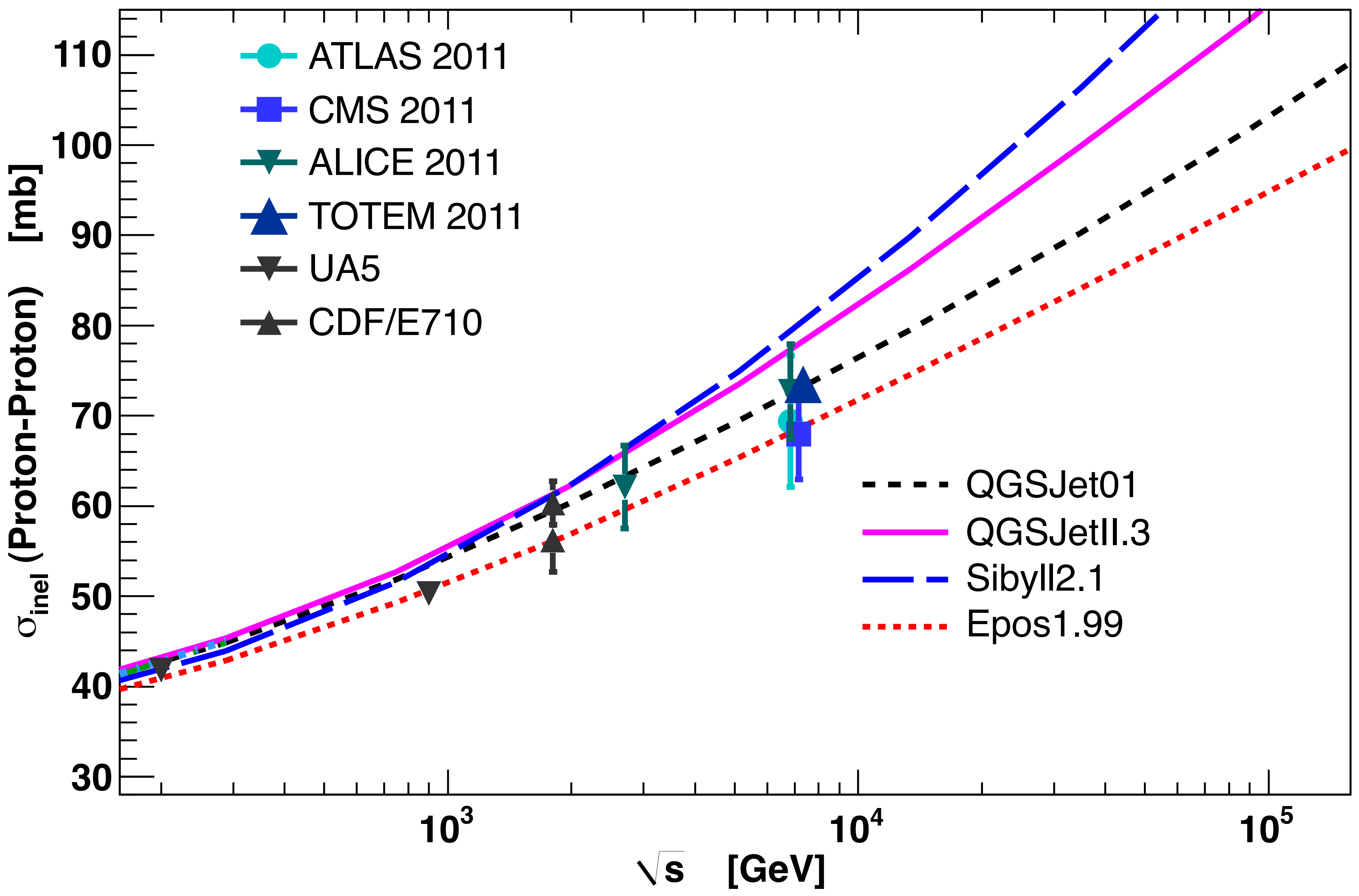


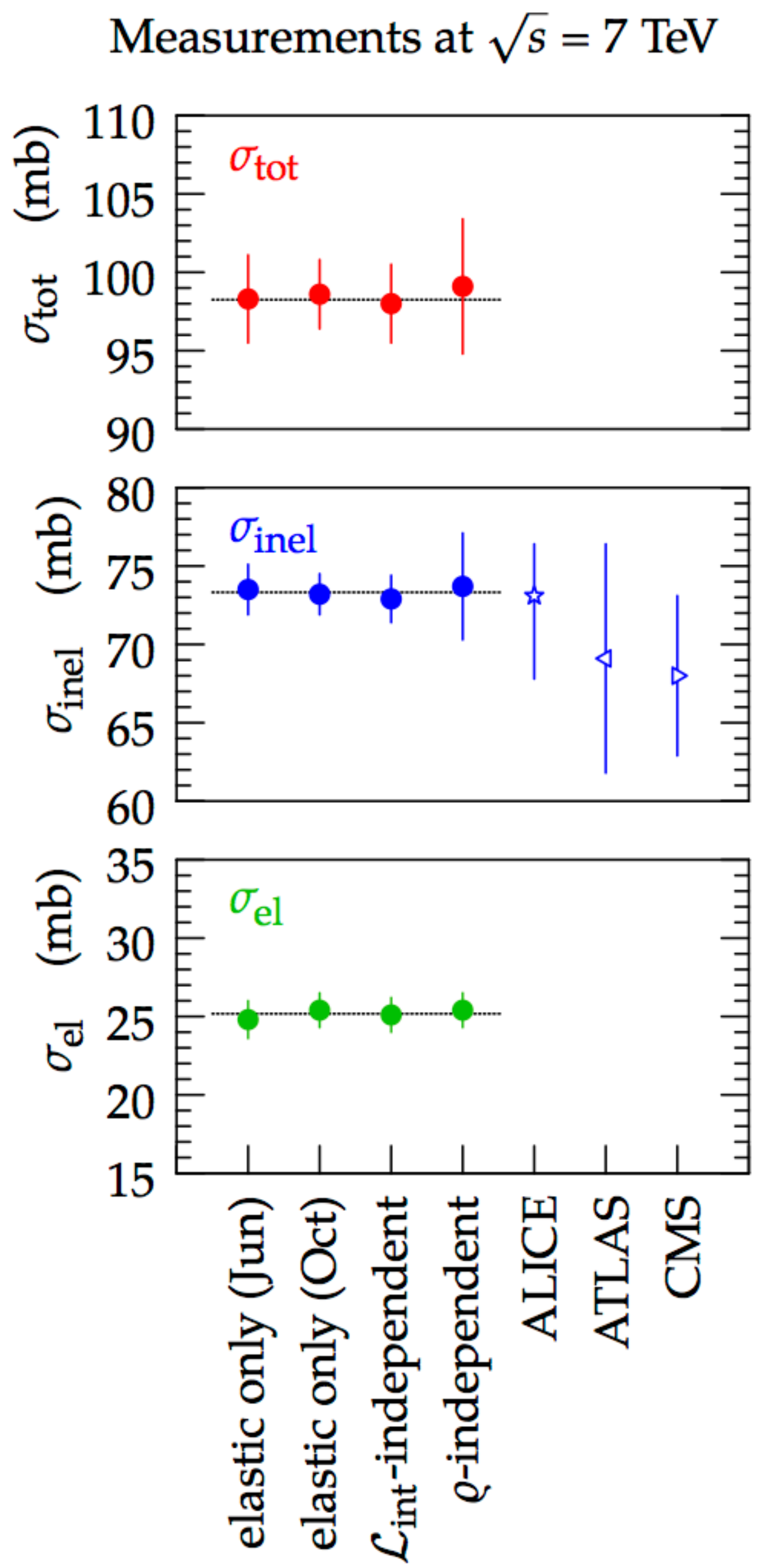


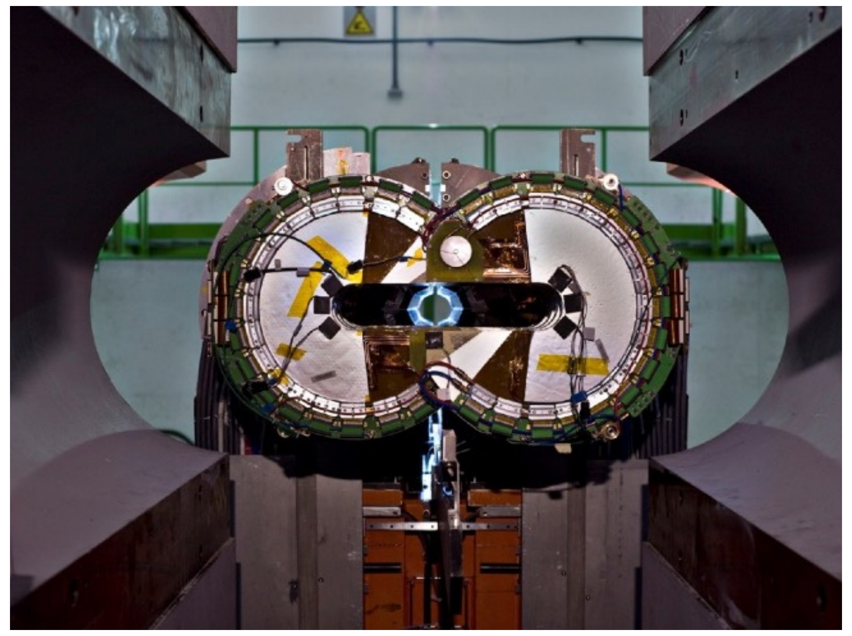
More than 50% of shower from η > 8

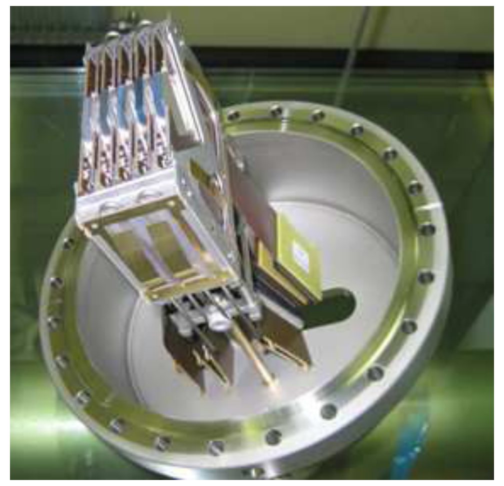
Cross section measurements at LHC

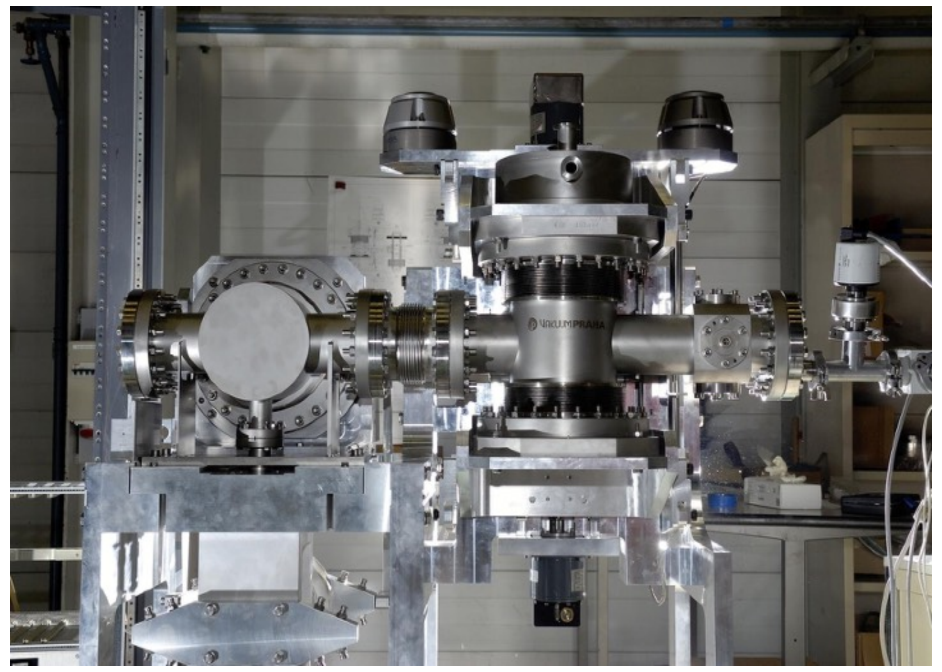




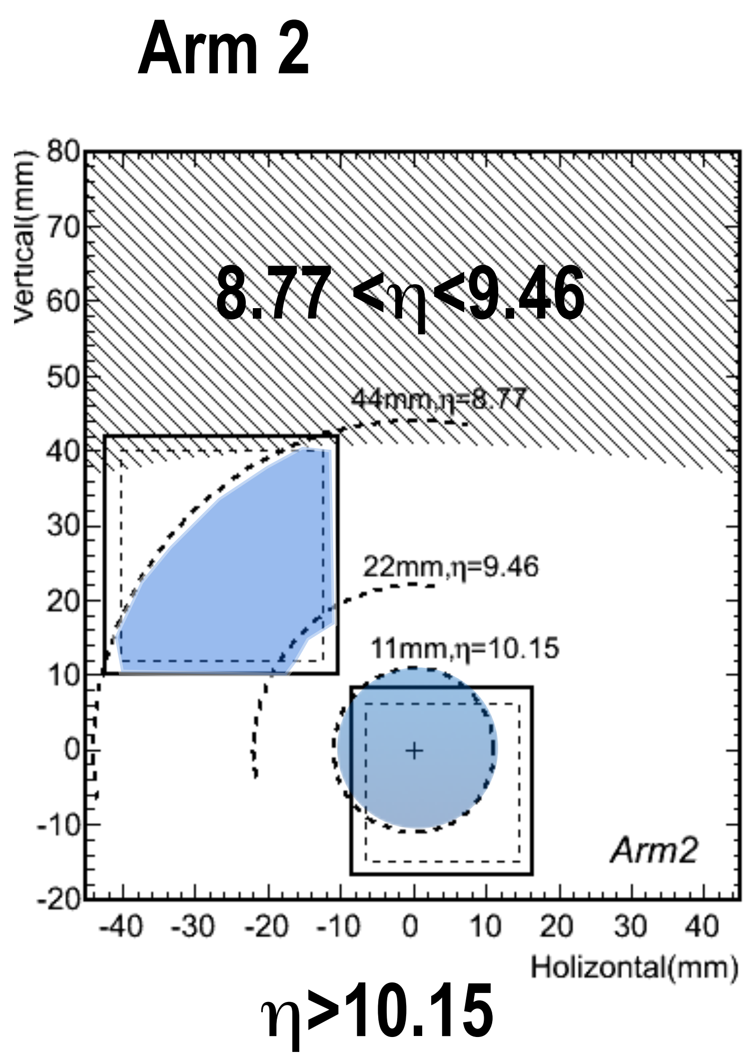


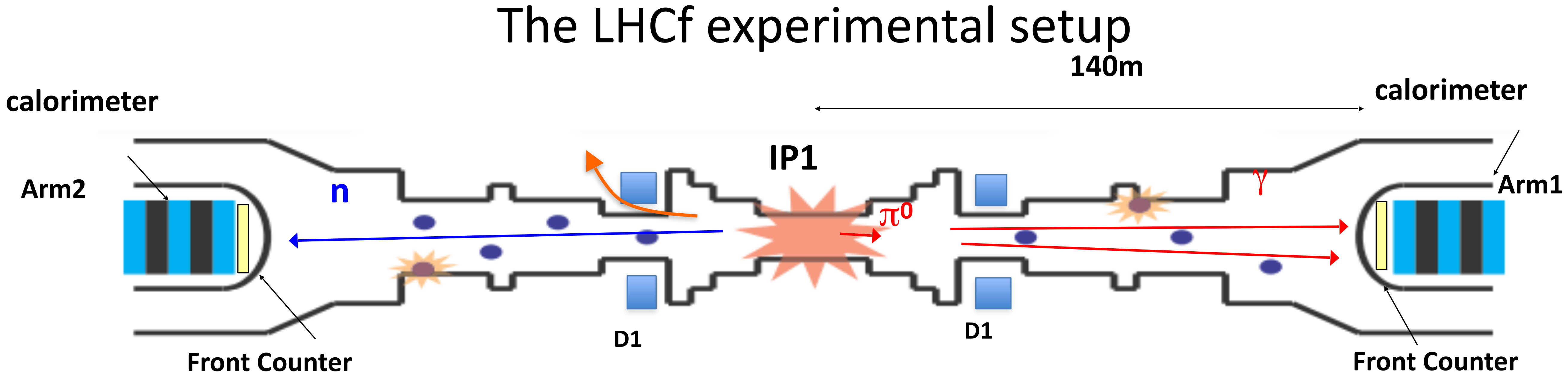


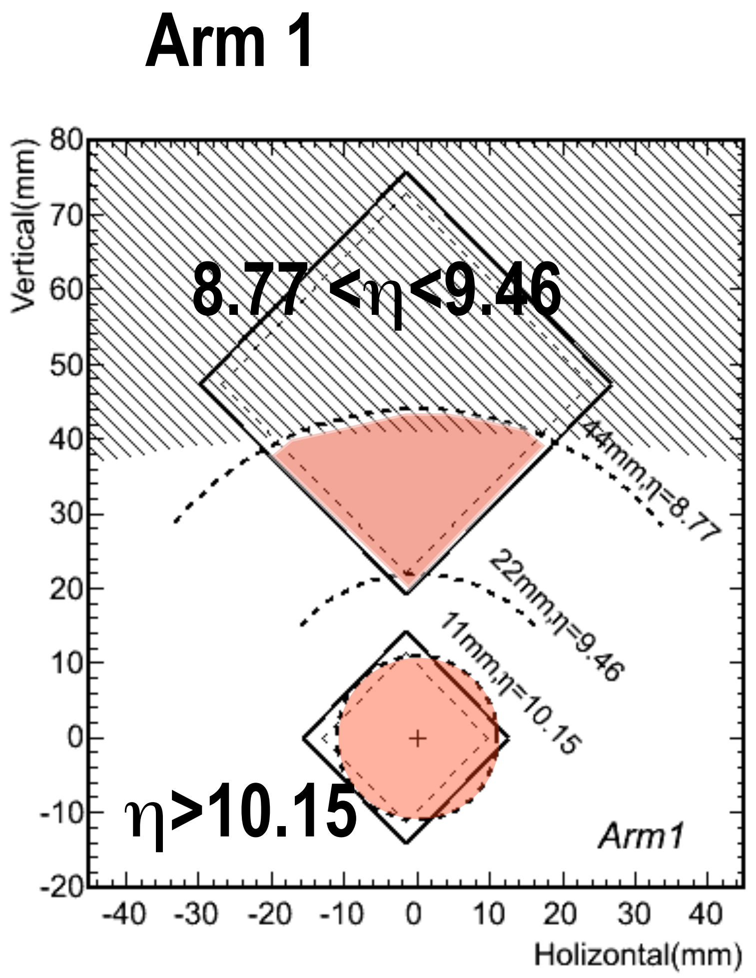




LHCf: very forward photon production at 7 TeV

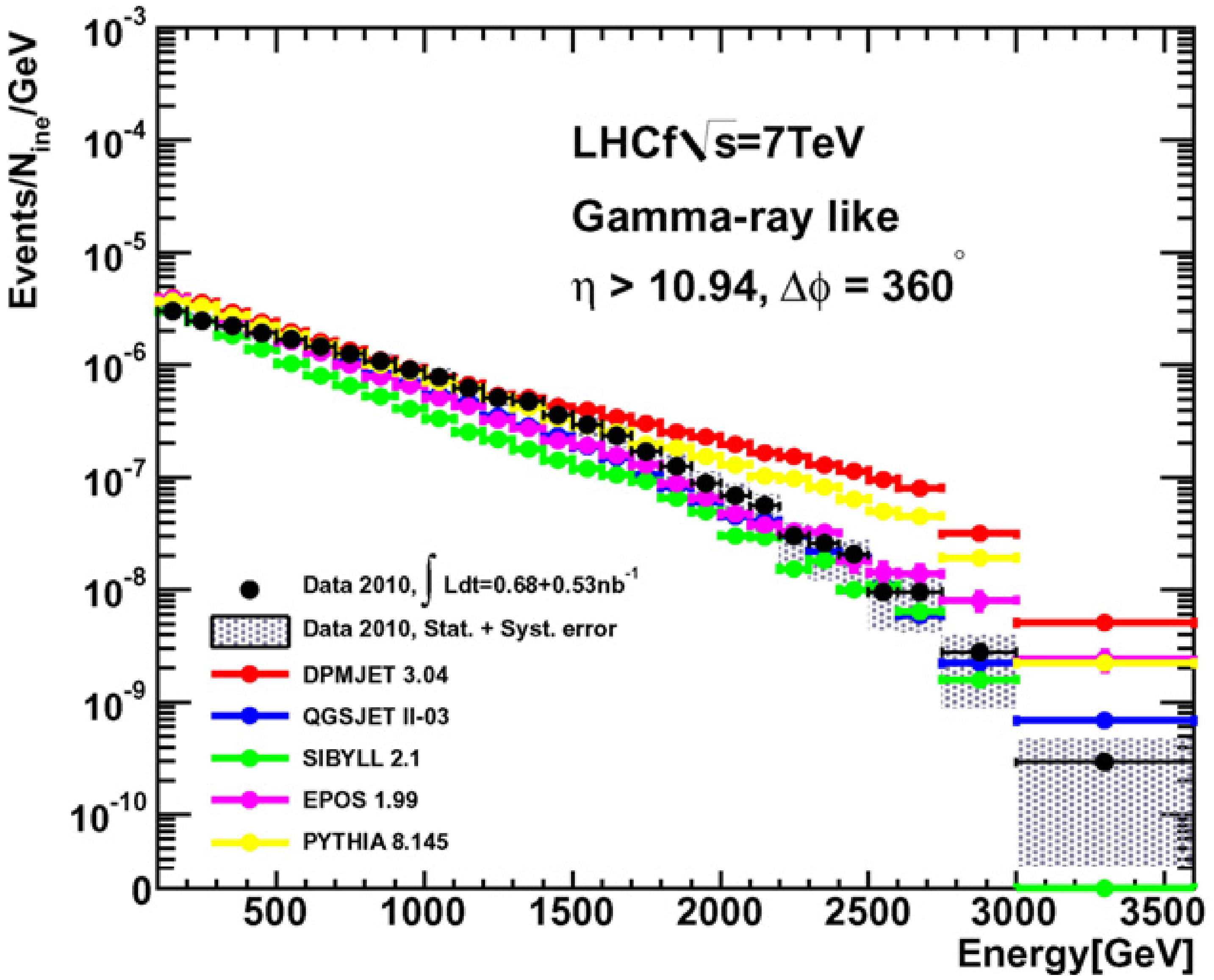


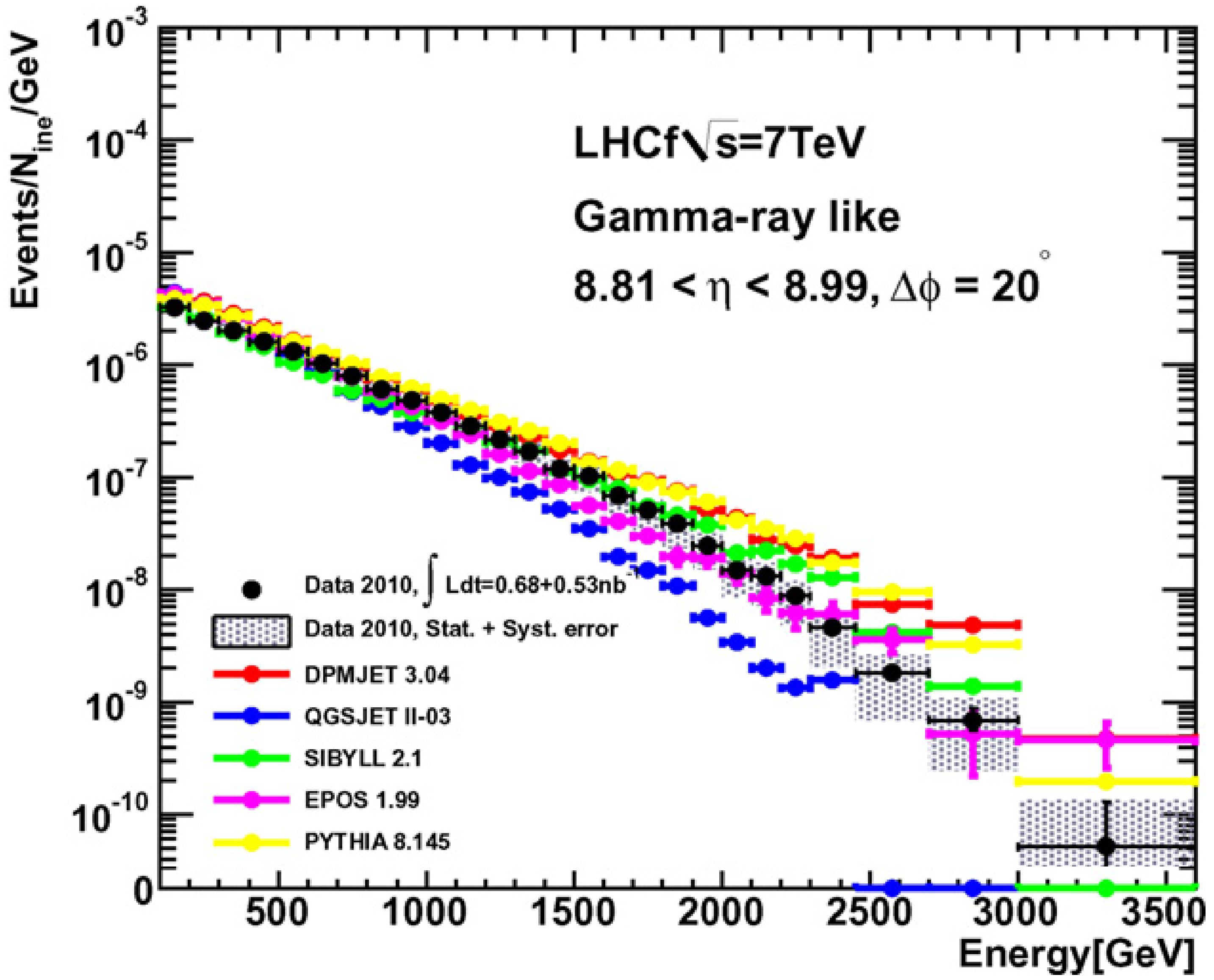


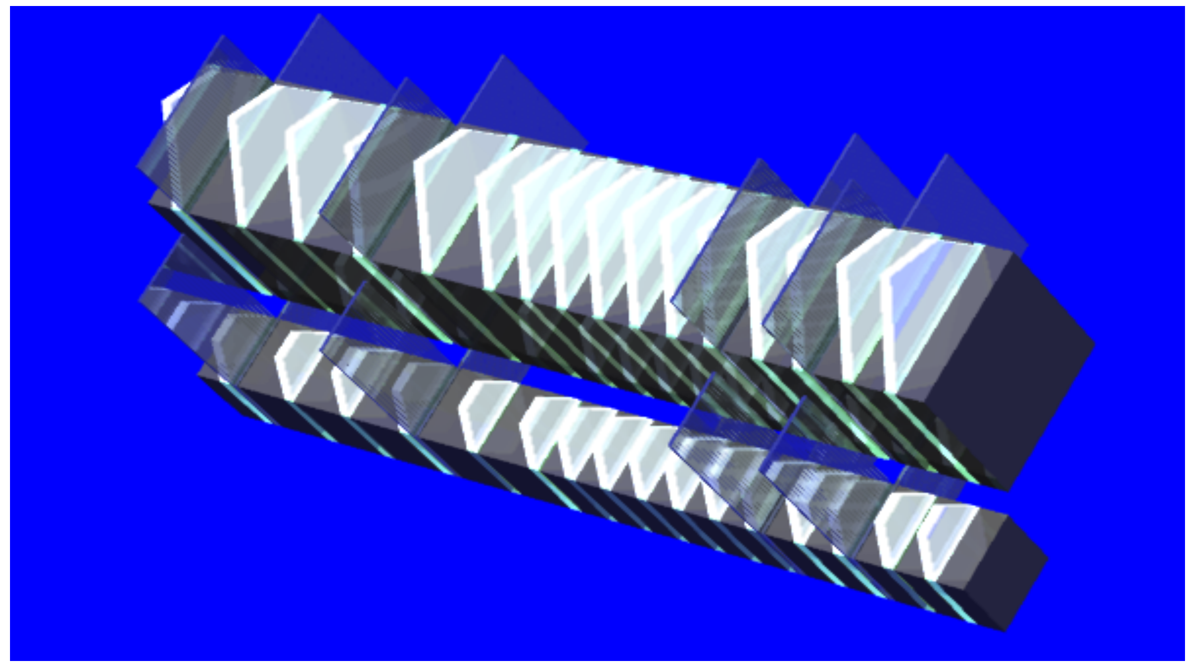


$$pp \to \gamma X$$

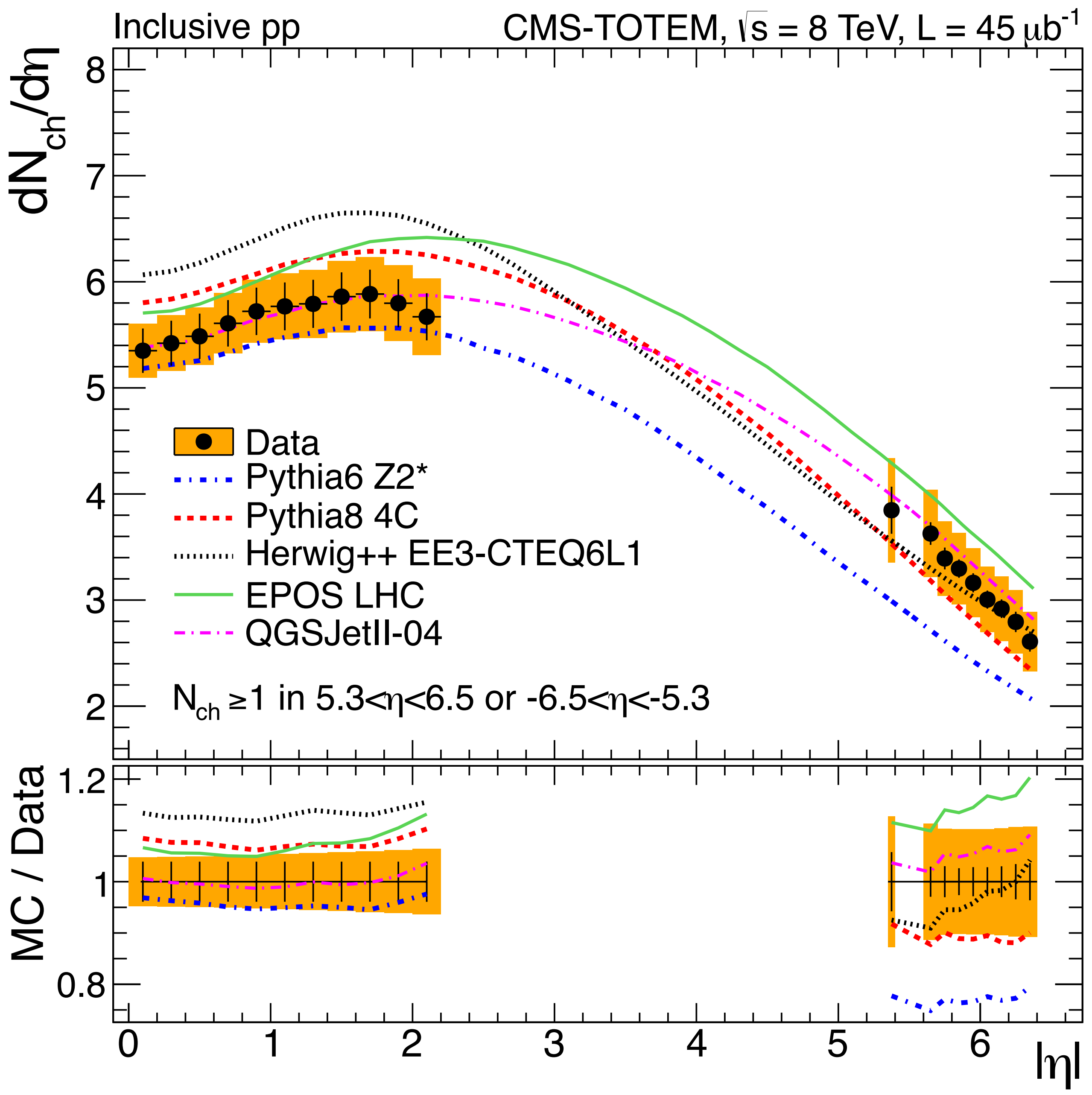
(LHCf Collab., Phys. Lett. B 703, 2011)

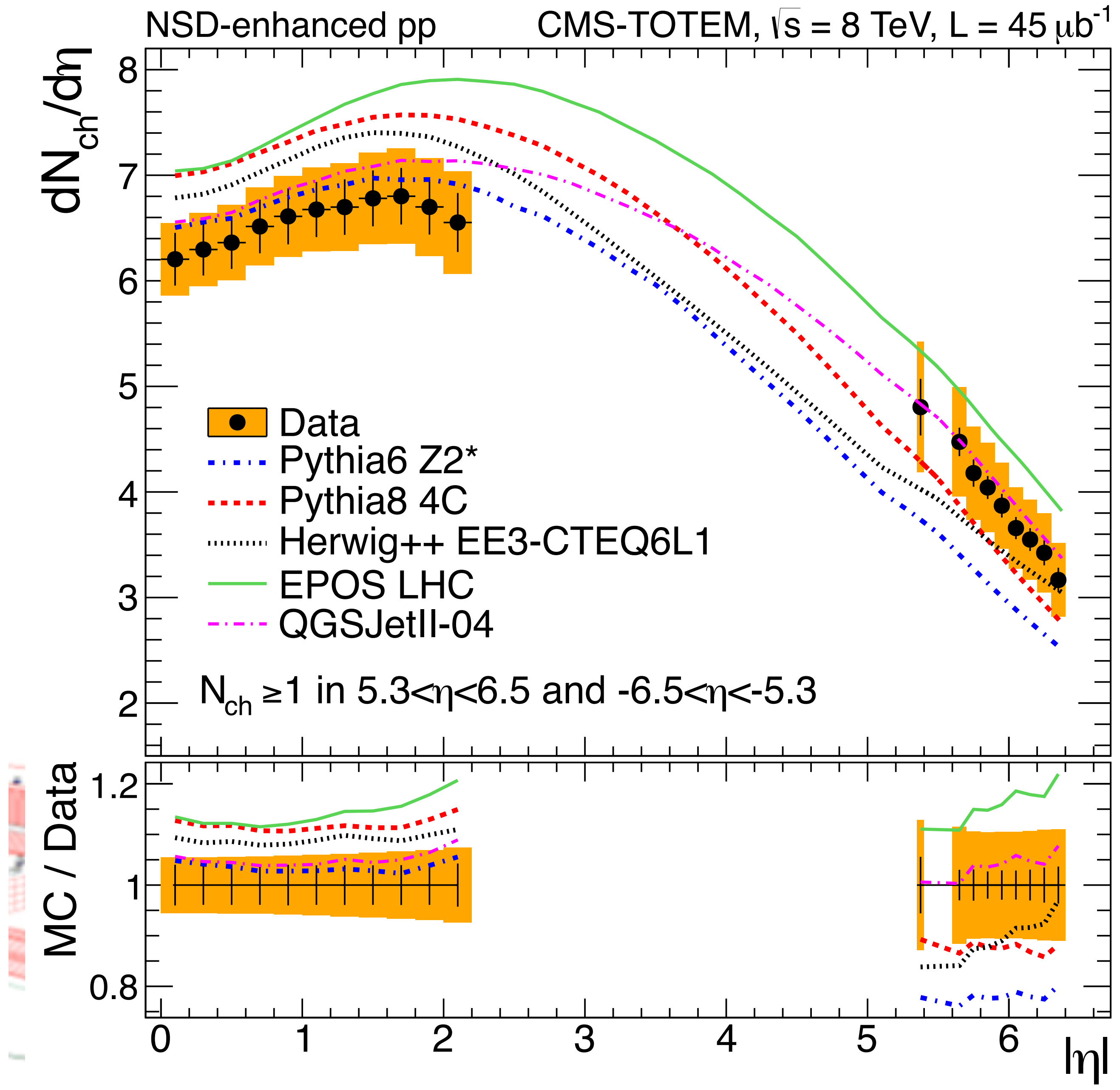


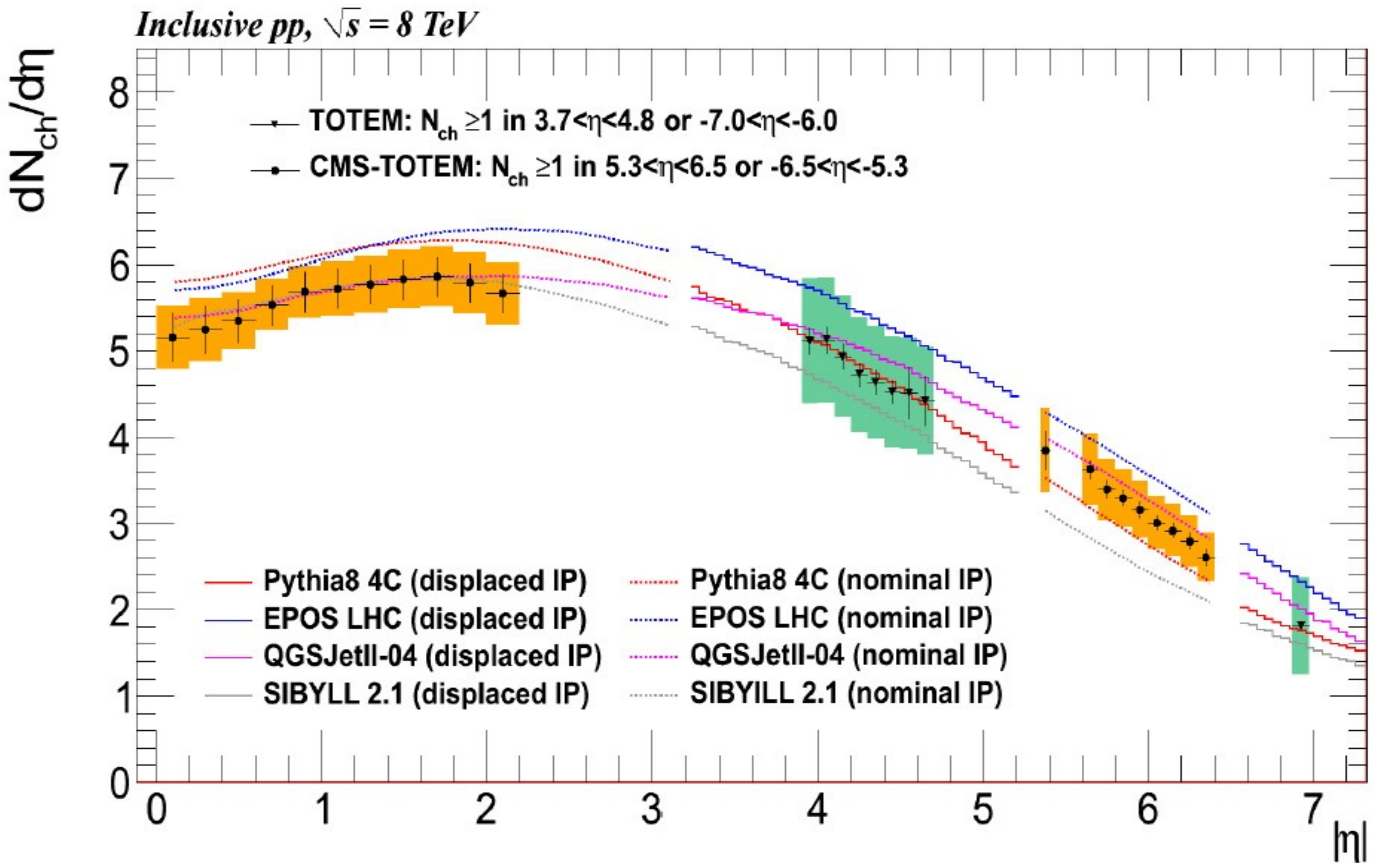


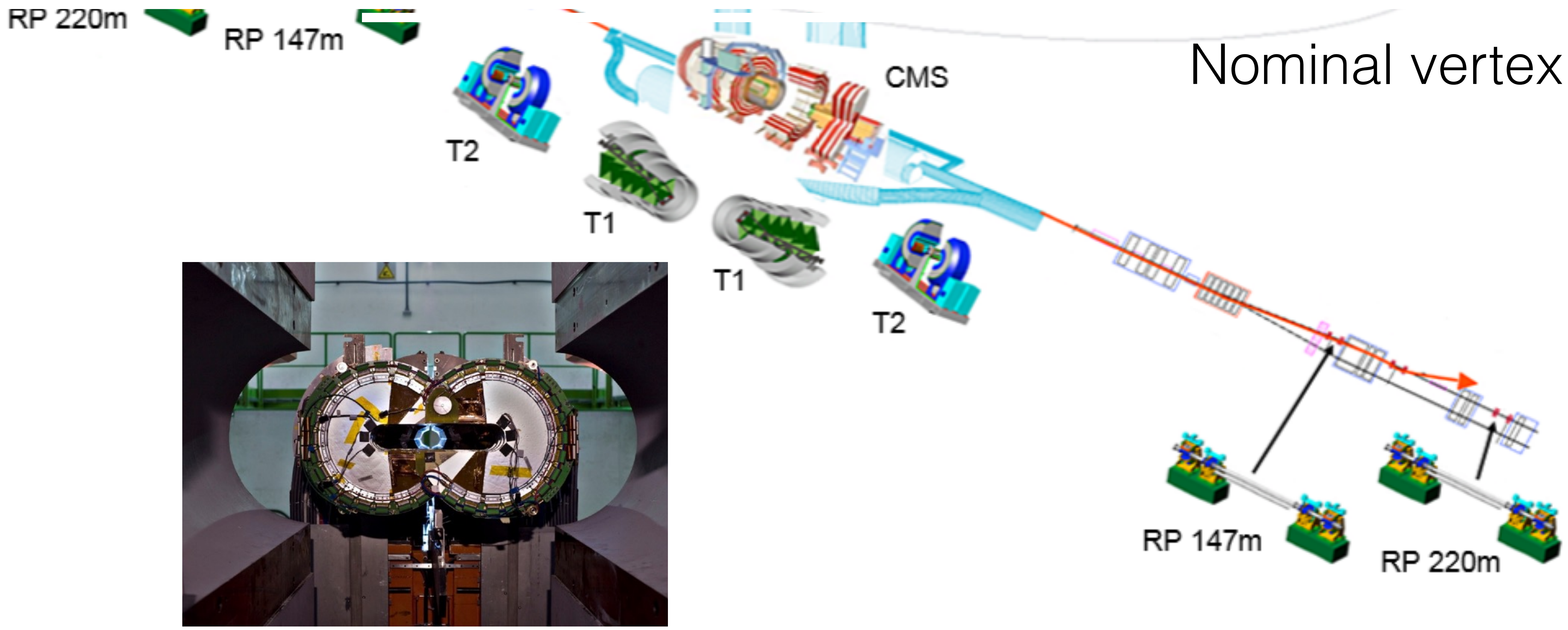


Combined CMS and TOTEM measurements



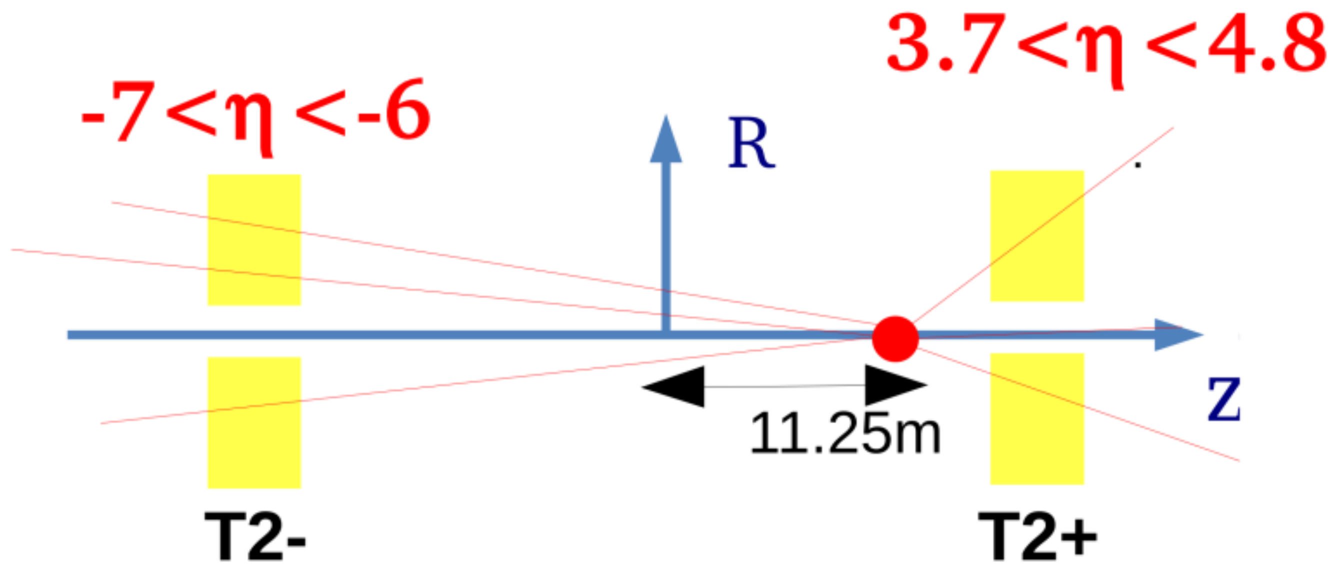




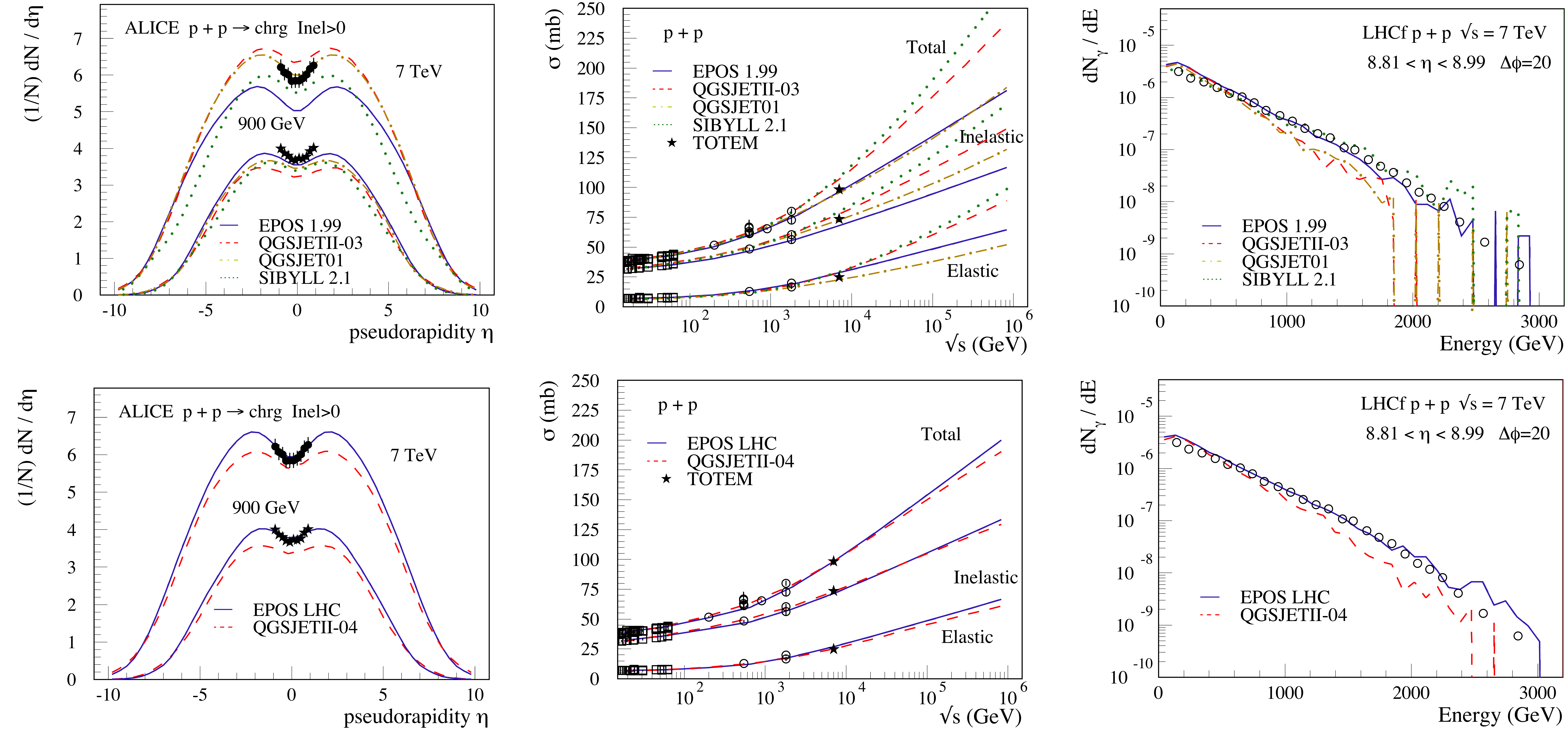


Nominal vertex

Shifted vertex

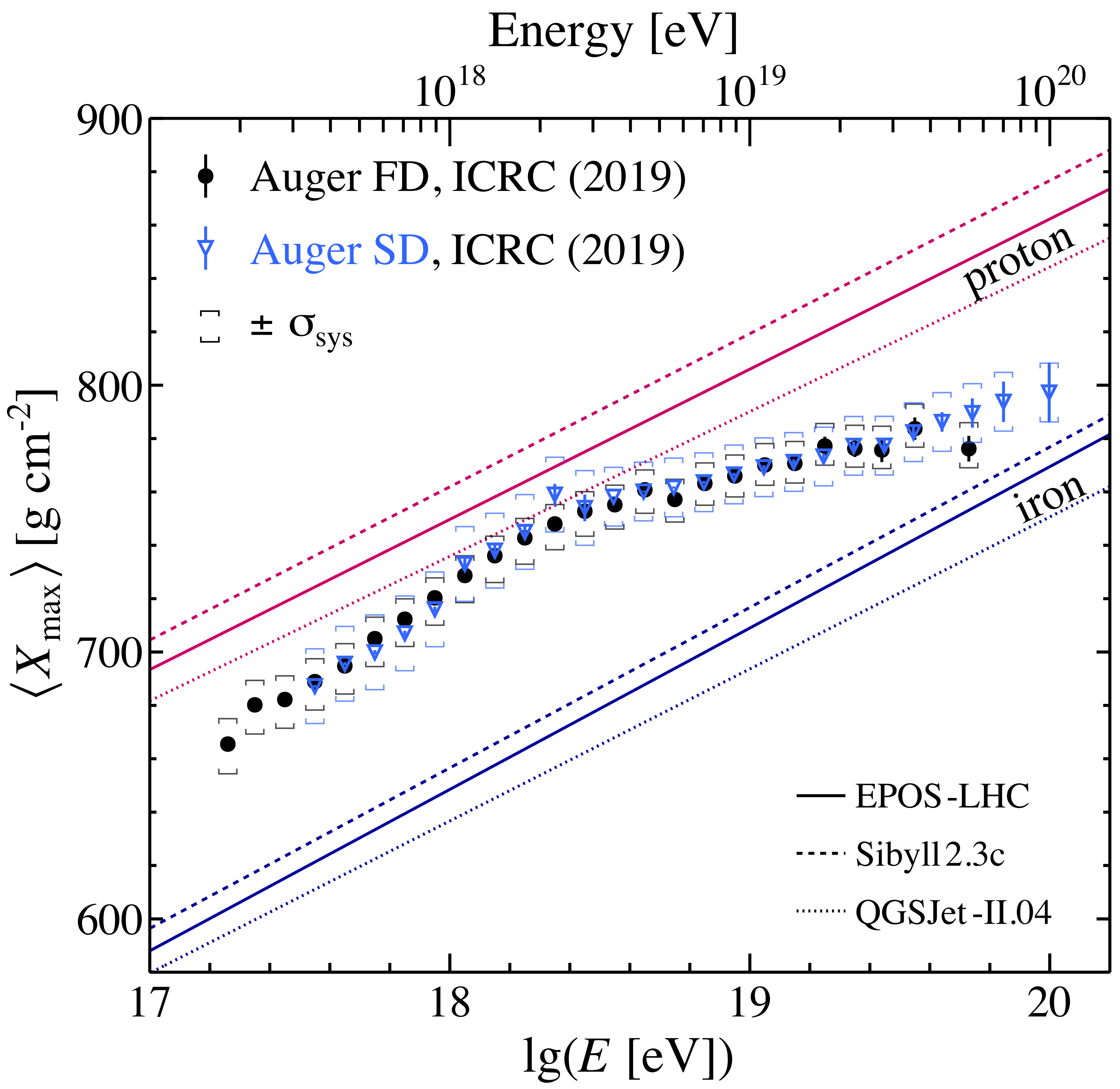


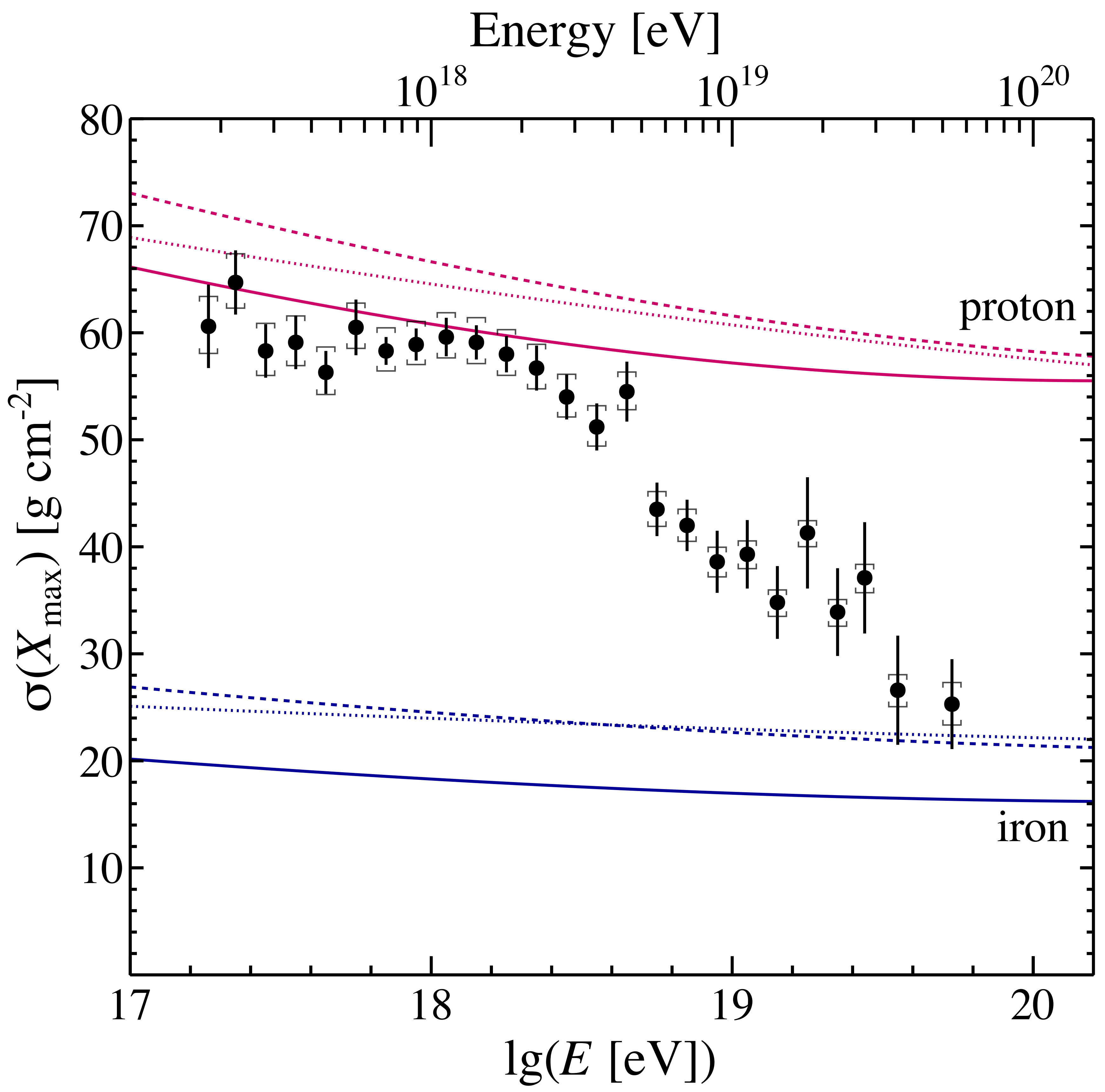
Examples of tuning interaction models to LHC data

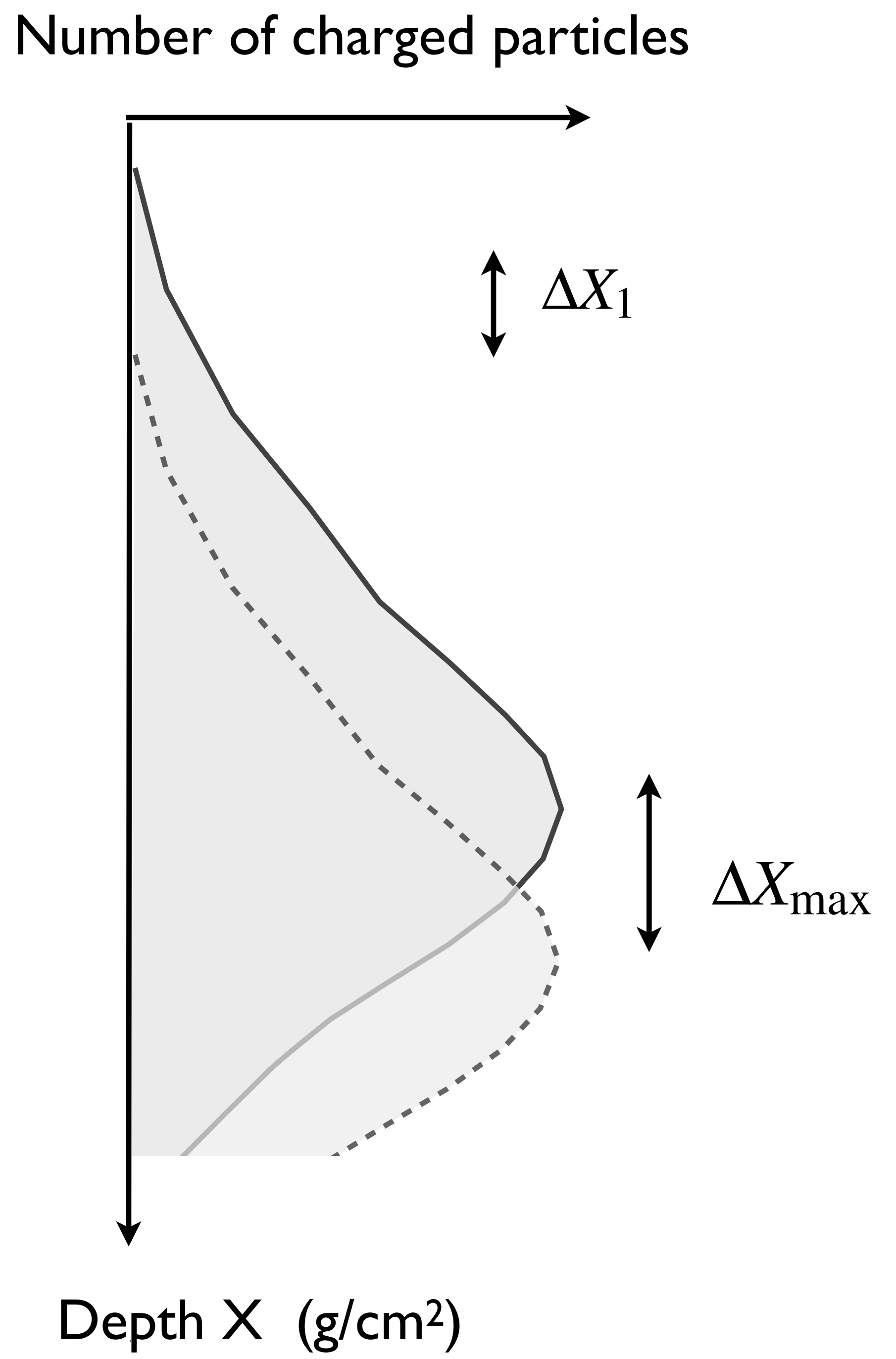


(Pierog 2013, 2014)

Mass composition (LHC-tuned models)







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

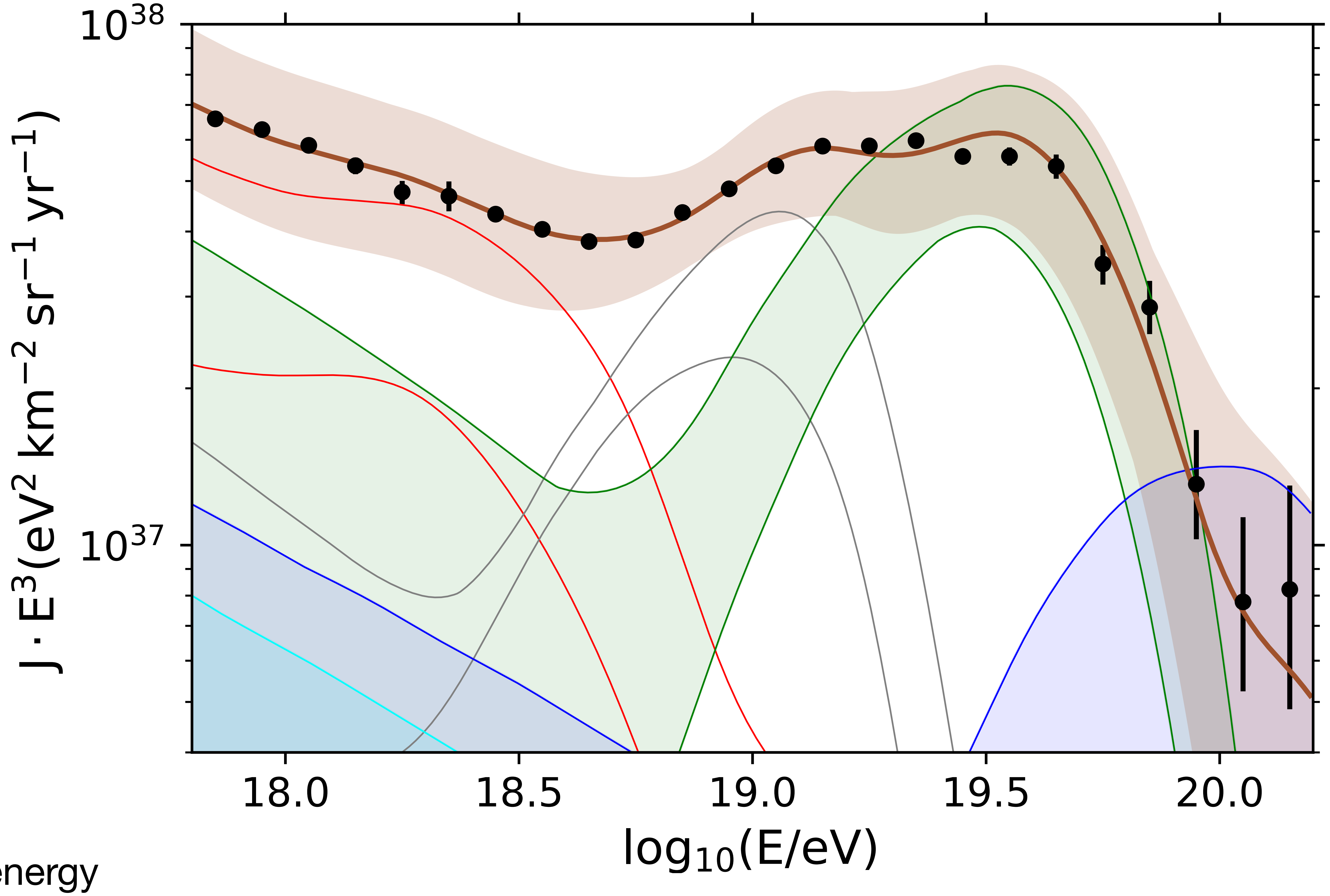
$$\sigma_{X_1,p} \sim 45 - 55\,\mathrm{g/cm^2}$$
$$\sigma_{X_1,Fe} \sim 10\,\mathrm{g/cm^2}$$

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

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

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

Interpretation of flux and composition data



Mass composition at Earth

A = 1
1 < A < 5
4 < A < 23
22 < A < 39
38 < A < 57

Bands:
Experimental uncertainties
(model uncertainties smaller)

Energy scale: $\sigma_{sys}(E)/E = 14\,\%$

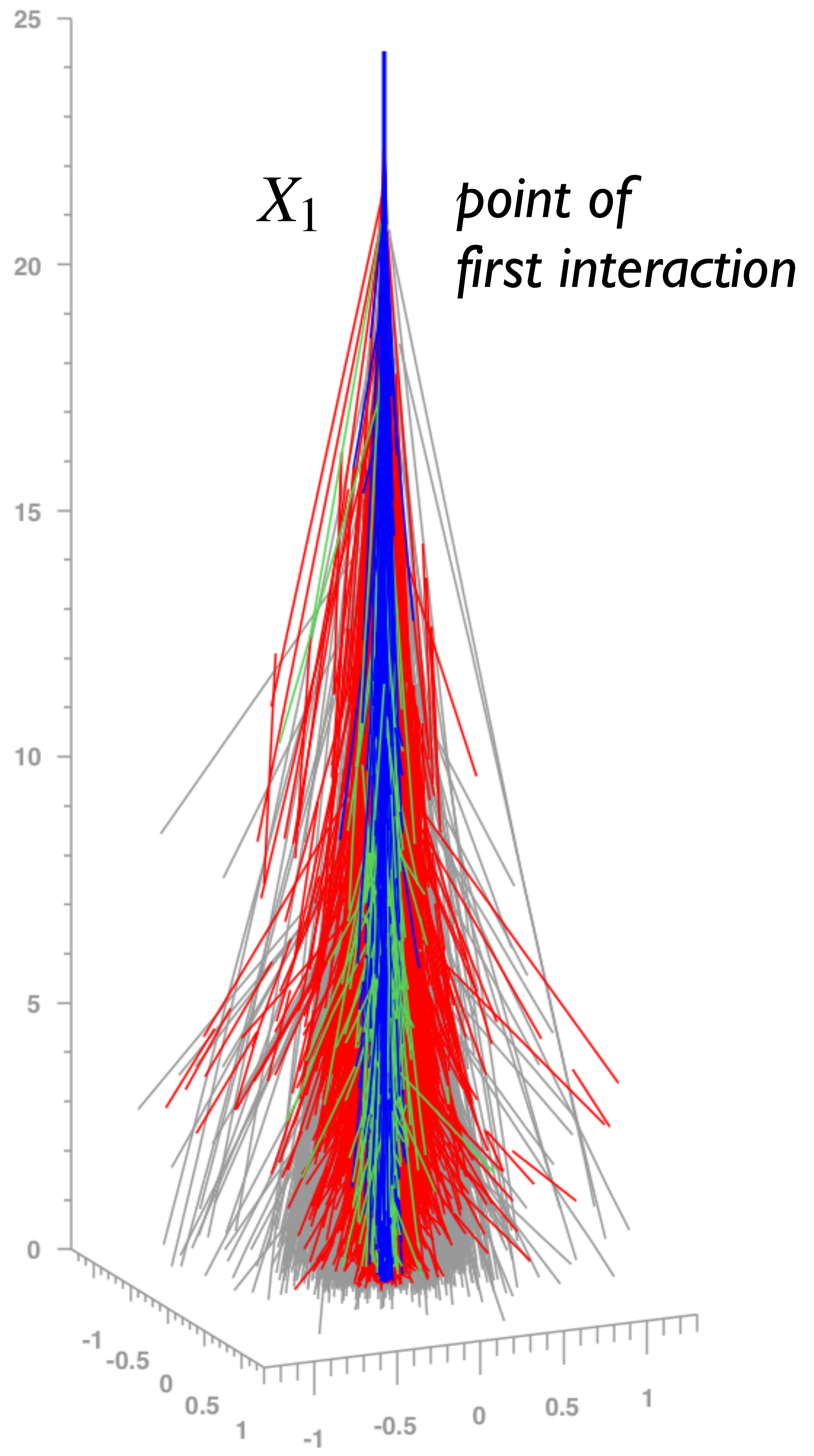
X_{max} scale: $\sigma_{sys}(X_{max}) = 6 \div 9\ g\ cm^{-2}$

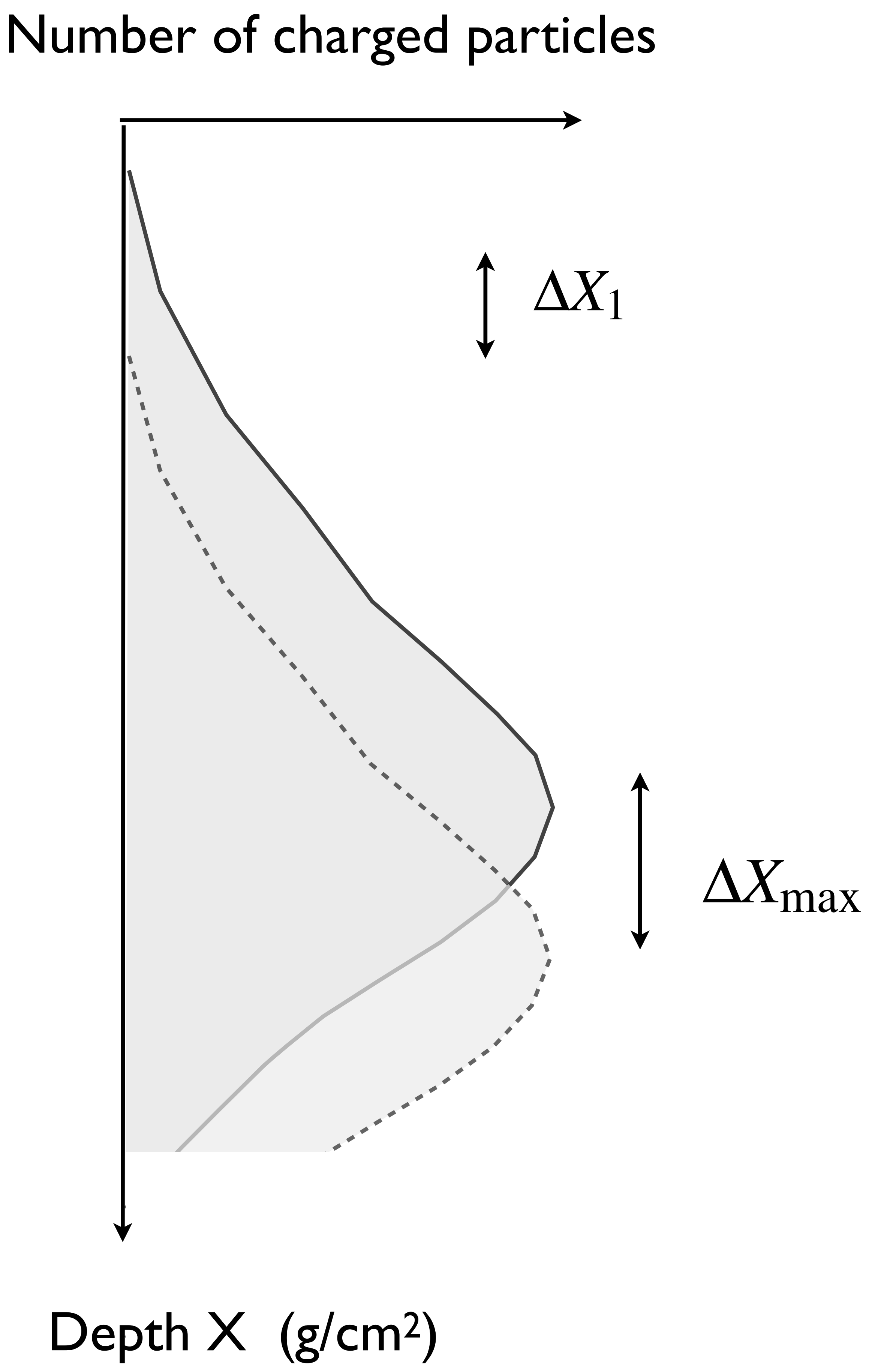
Surprising mass composition:
very hard spectra and almost
mono-elemental fluxes at high energy

Flux suppression superposition of injection maximum energy and propagation energy losses

$$E_{A,cut} = Z_A \cdot (1.4 \ldots 1.6) \times 10^{18}\, eV$$

Measurement of proton-air cross section (i)



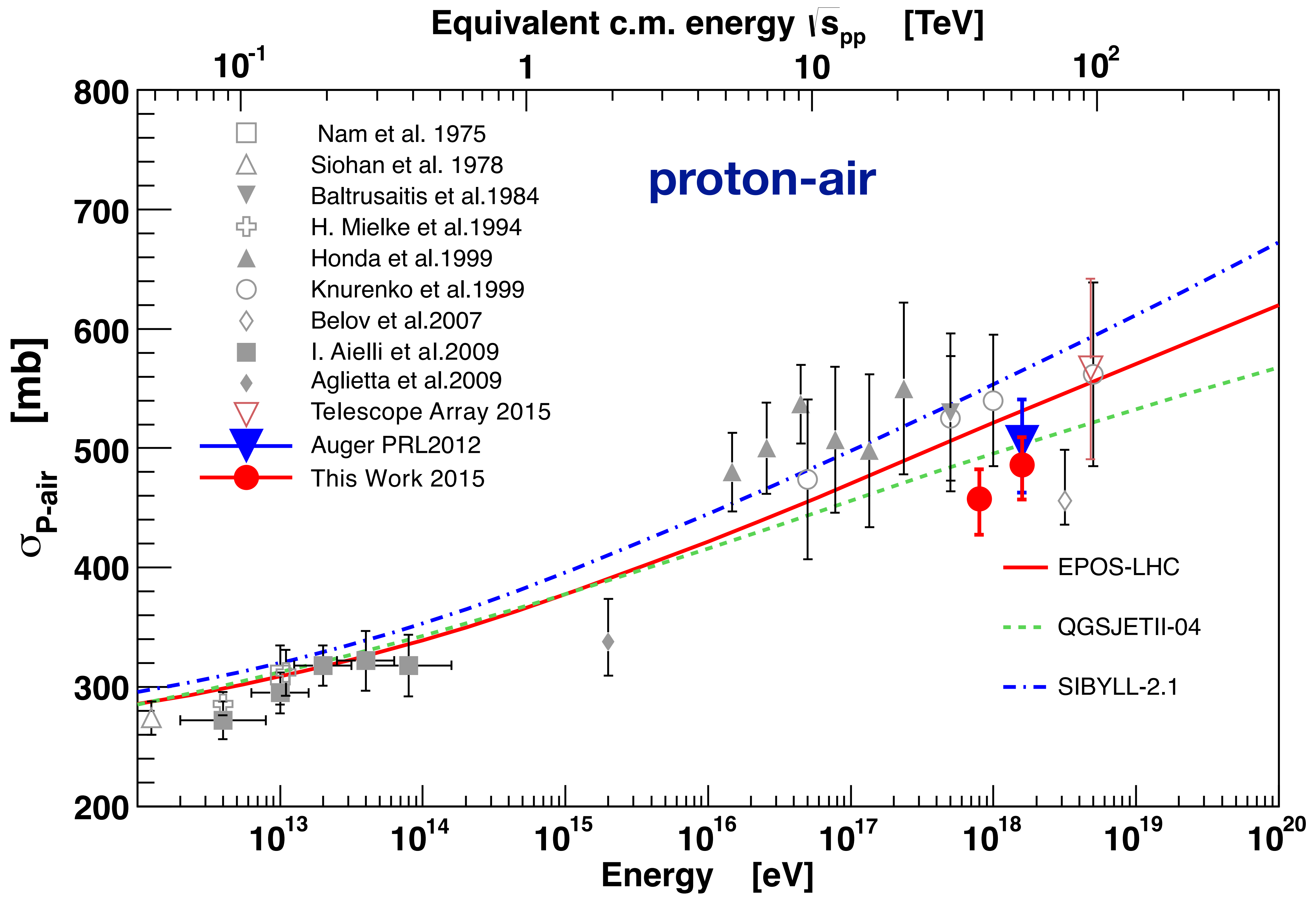


$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

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

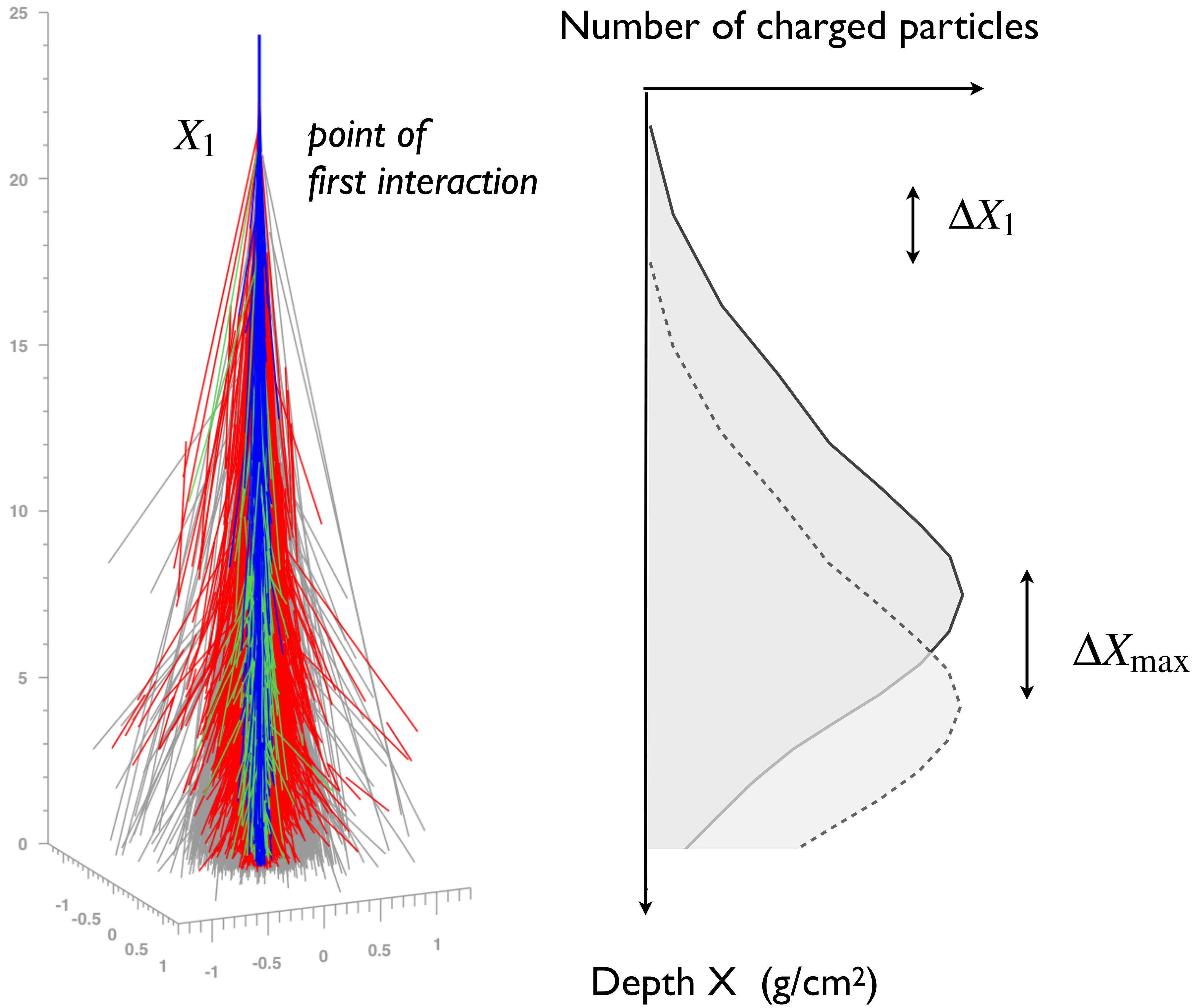
Difficulties

- mass composition
- fluctuations in shower development (model needed for correction)



(Auger PRL 109, 2012; Telescope Array PRD 92, 2015)

Measurement of proton-air cross section (ii)

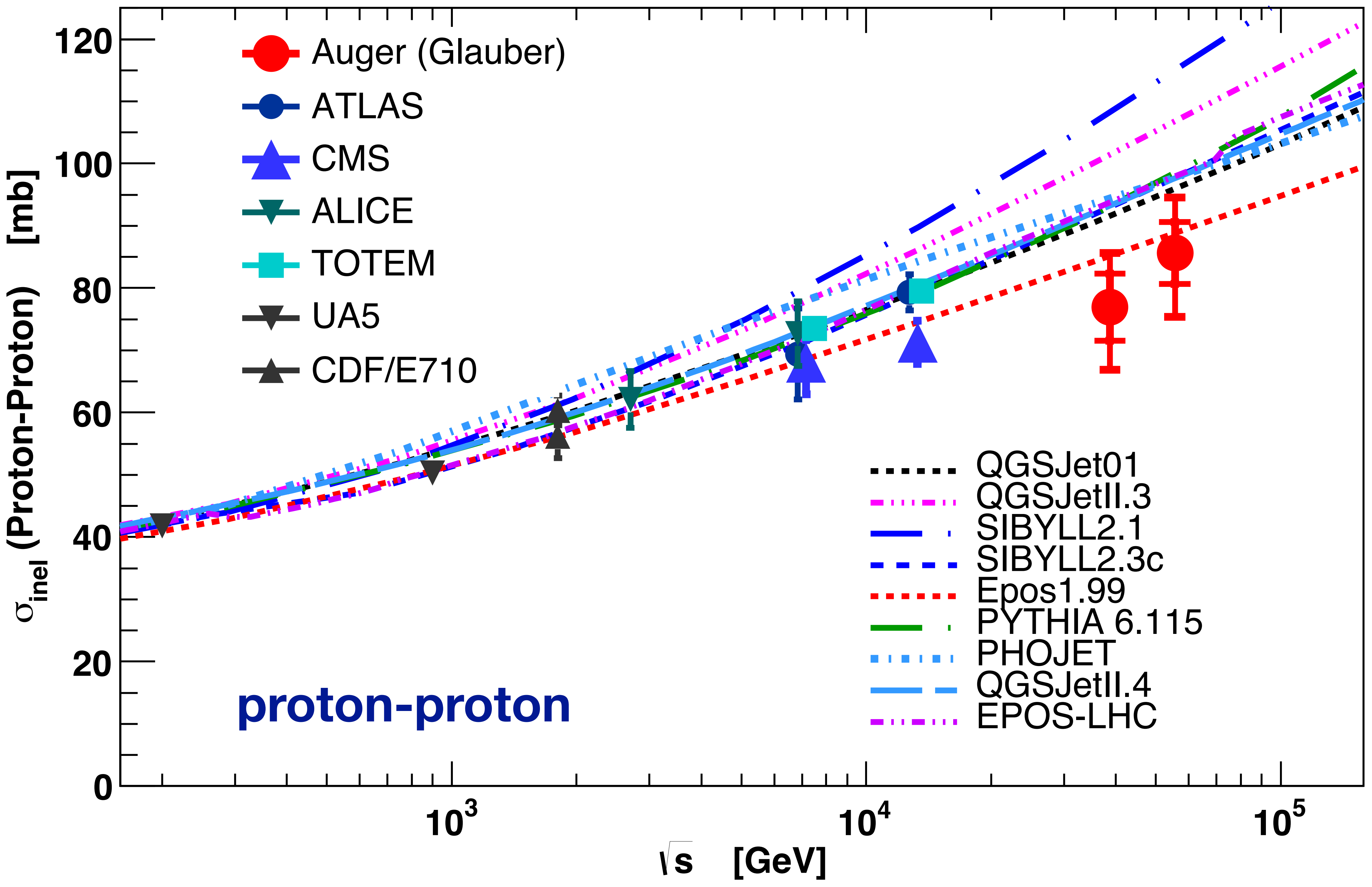


$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

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

Difficulties

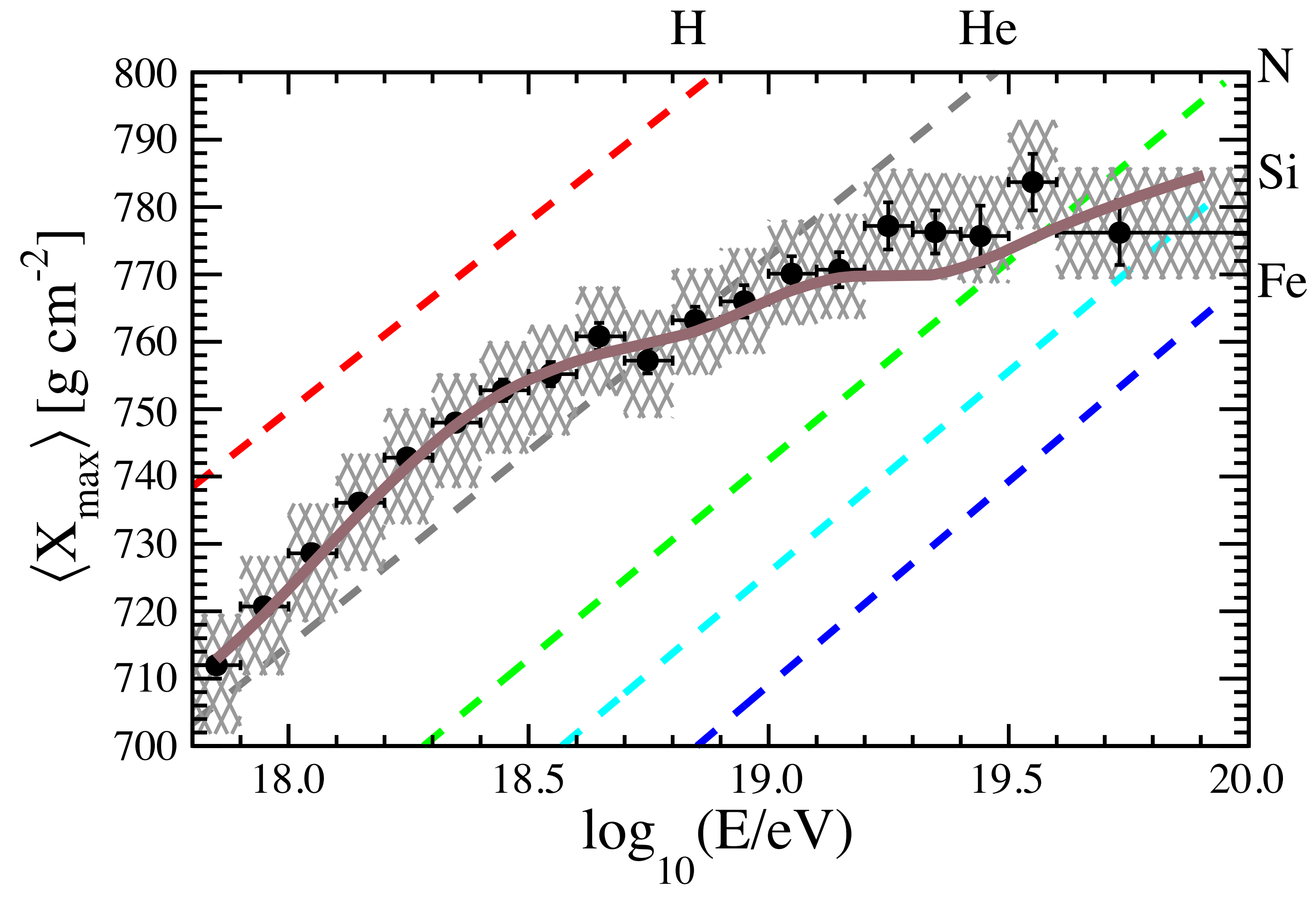
- mass composition
- fluctuations in shower development (model needed for correction)

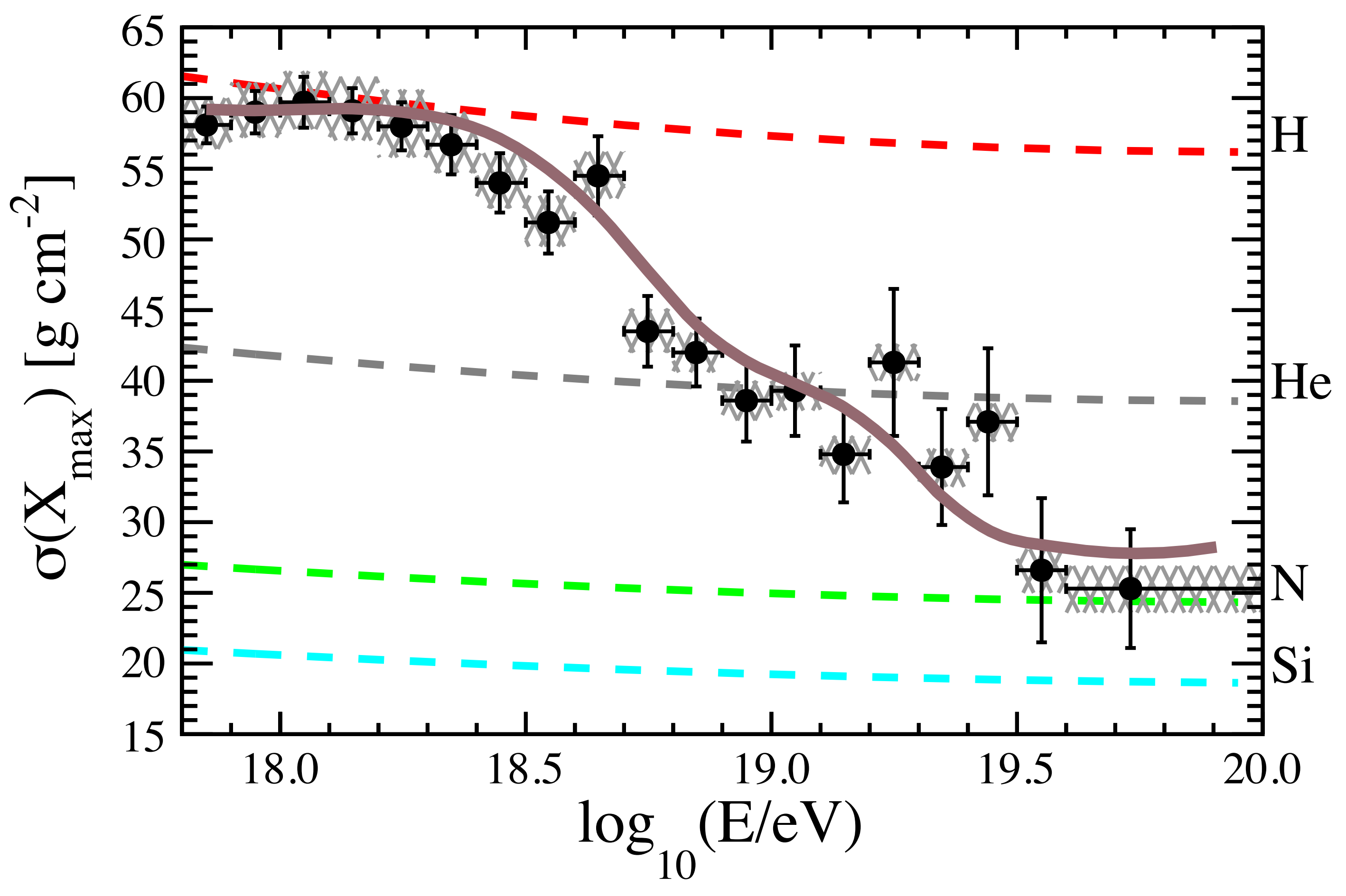


(Auger PRL 109, 2012; Telescope Array PRD 92, 2015)

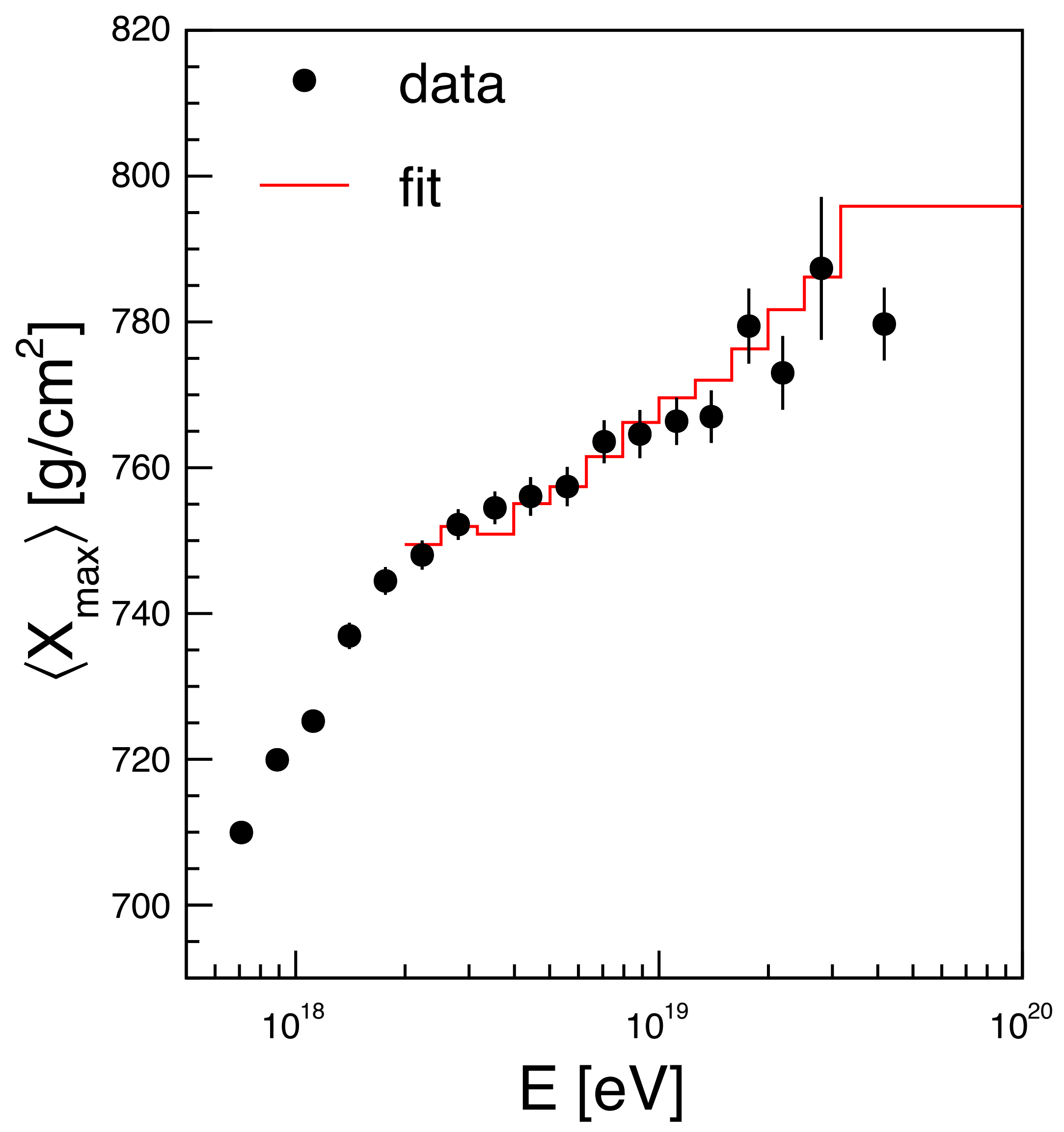
Hypothesis: change of proton-air interactions (i)

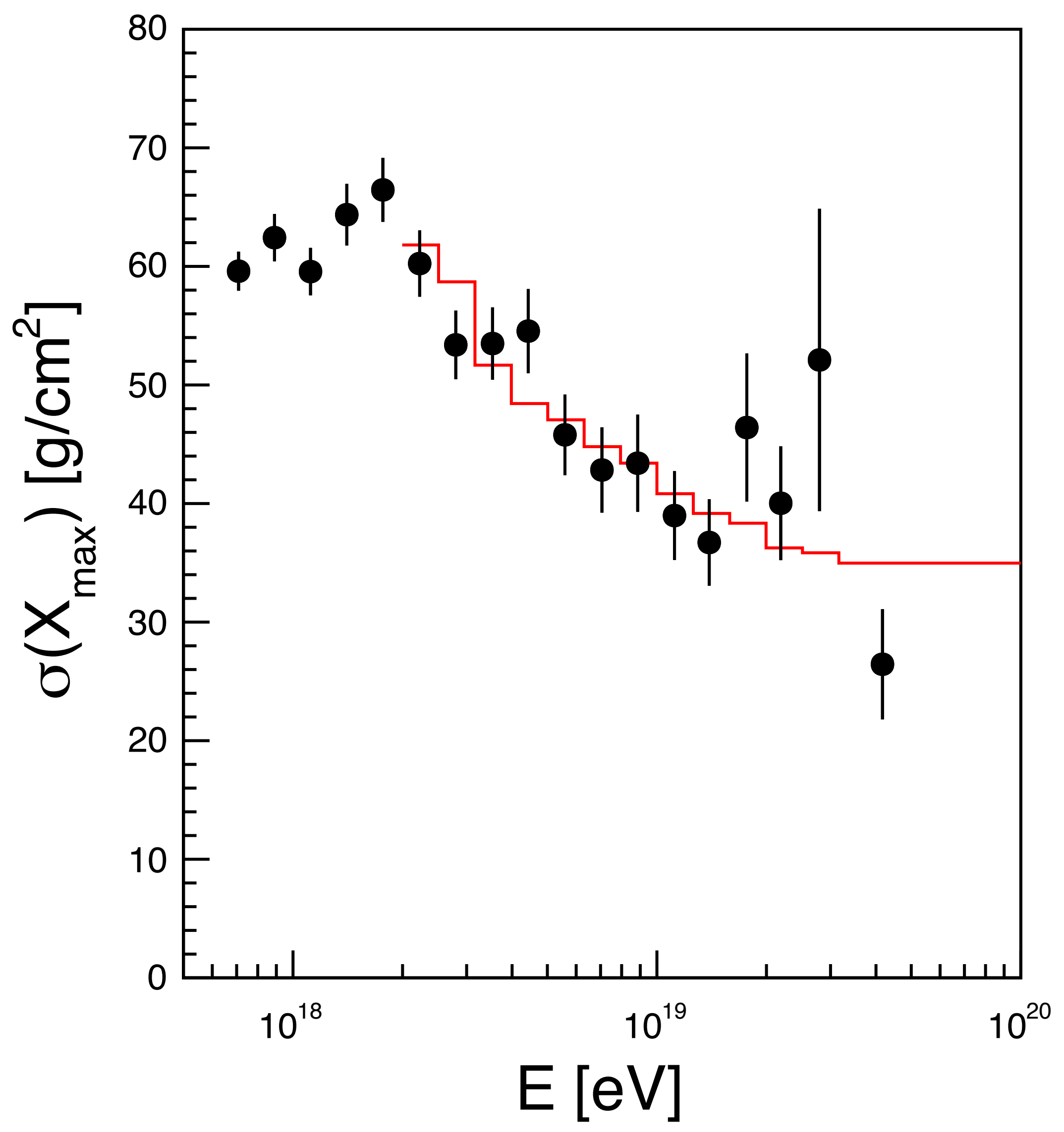
Data description by previously shown fit





Data description after modifying proton-air interactions

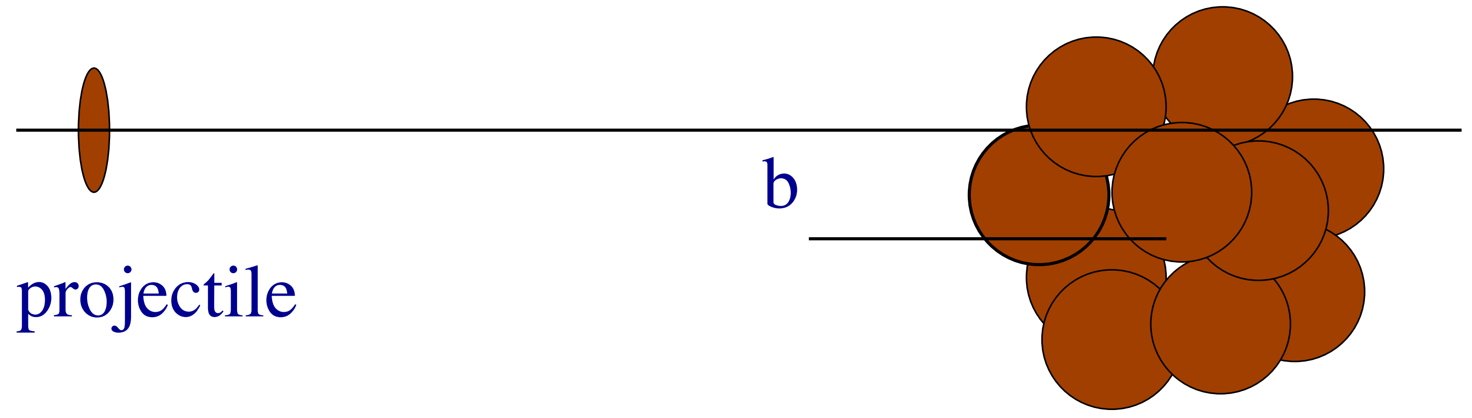


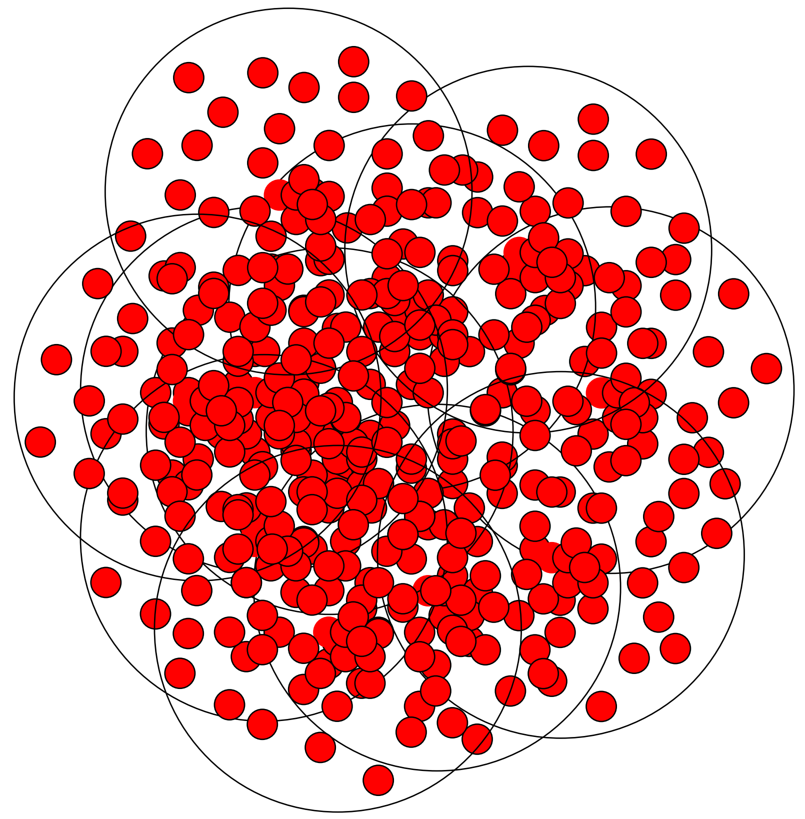


Required change from $10^{18.5}$ eV to 10^{19} eV

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

Hypothesis: change of proton-air interactions (ii)

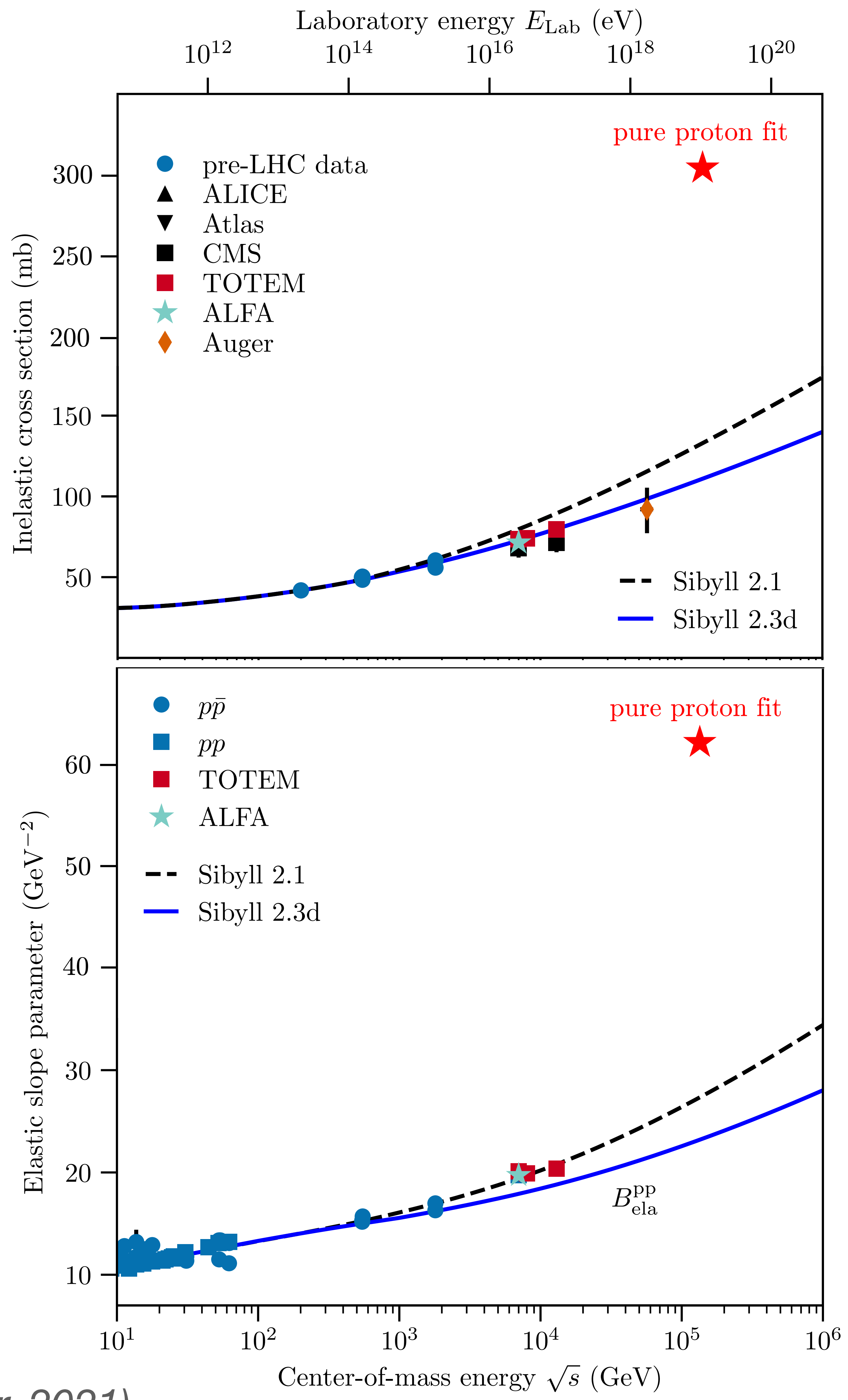




$$\sigma_{\text{prod}} \approx \int d^2\vec{b} \left[1 - \exp\left\{-\sigma_{\text{ine}}^{NN} T_A(\vec{b})\right\}\right]$$

Cross section largely determined by geometry of nucleons in nucleus

Cross section can only grow at periphery



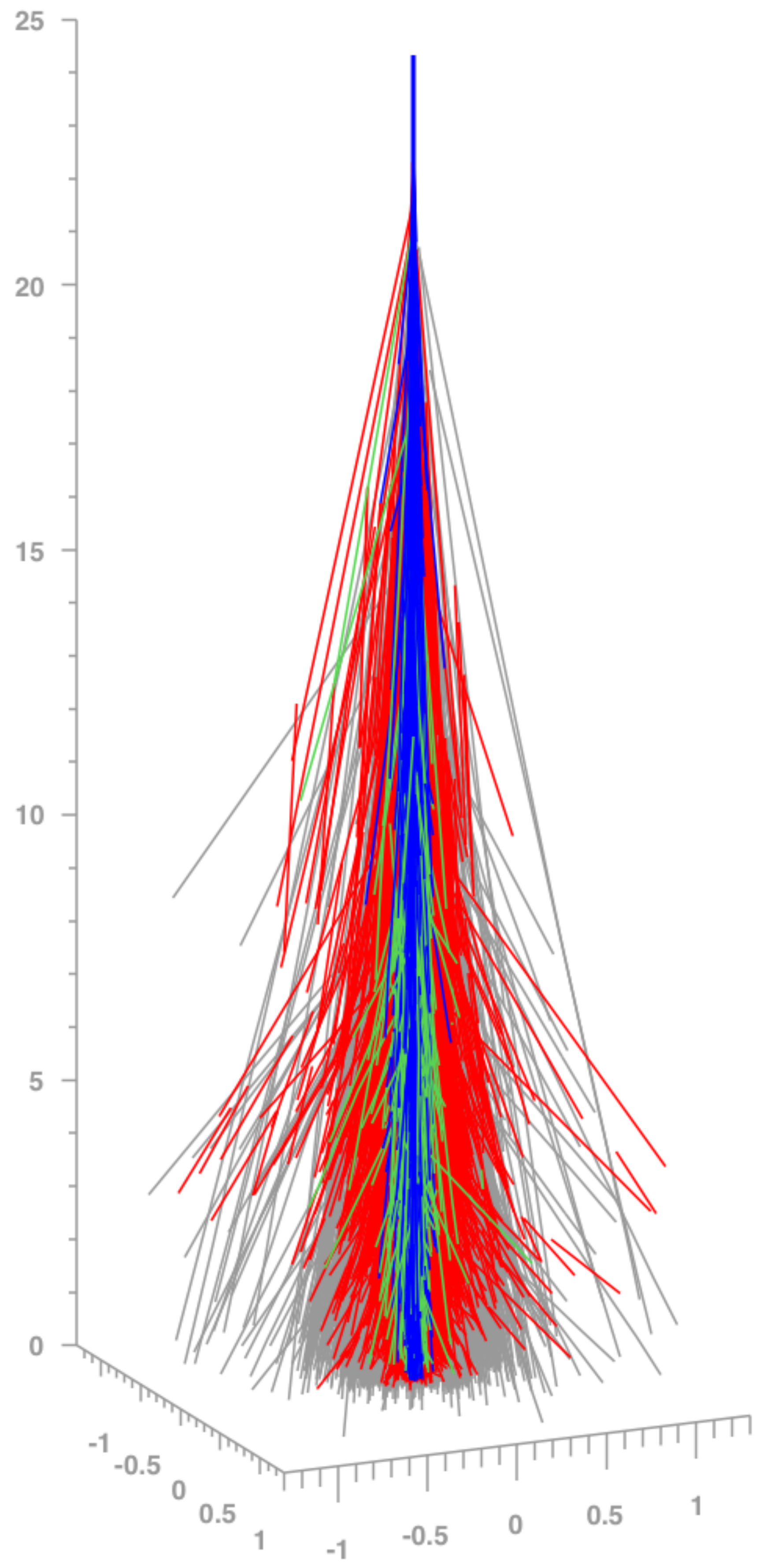
(Unger, 2021)

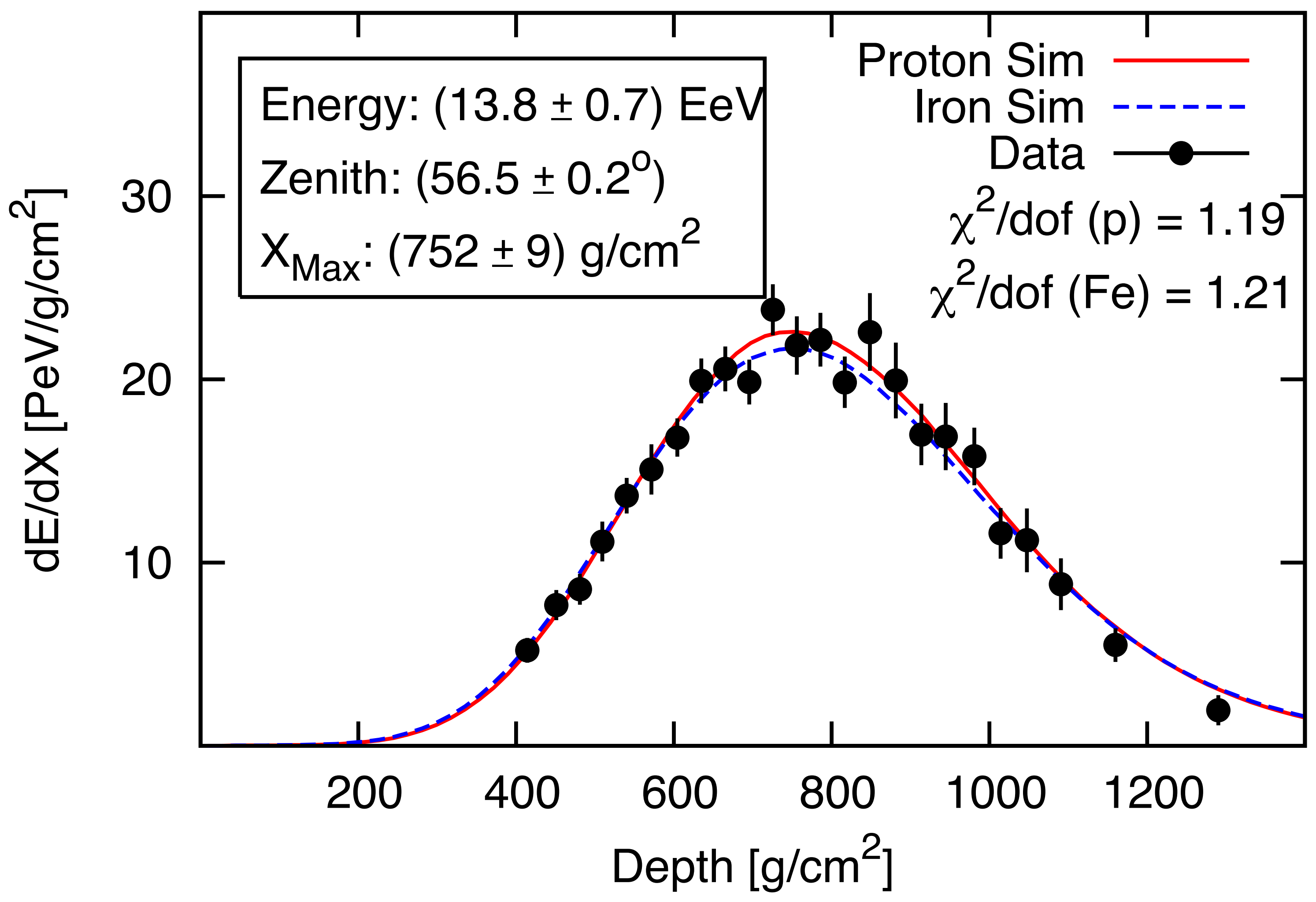
Example: total p-p cross section 160 mb, then p-air 560 mb
320 mb 630 mb (unitarity?)

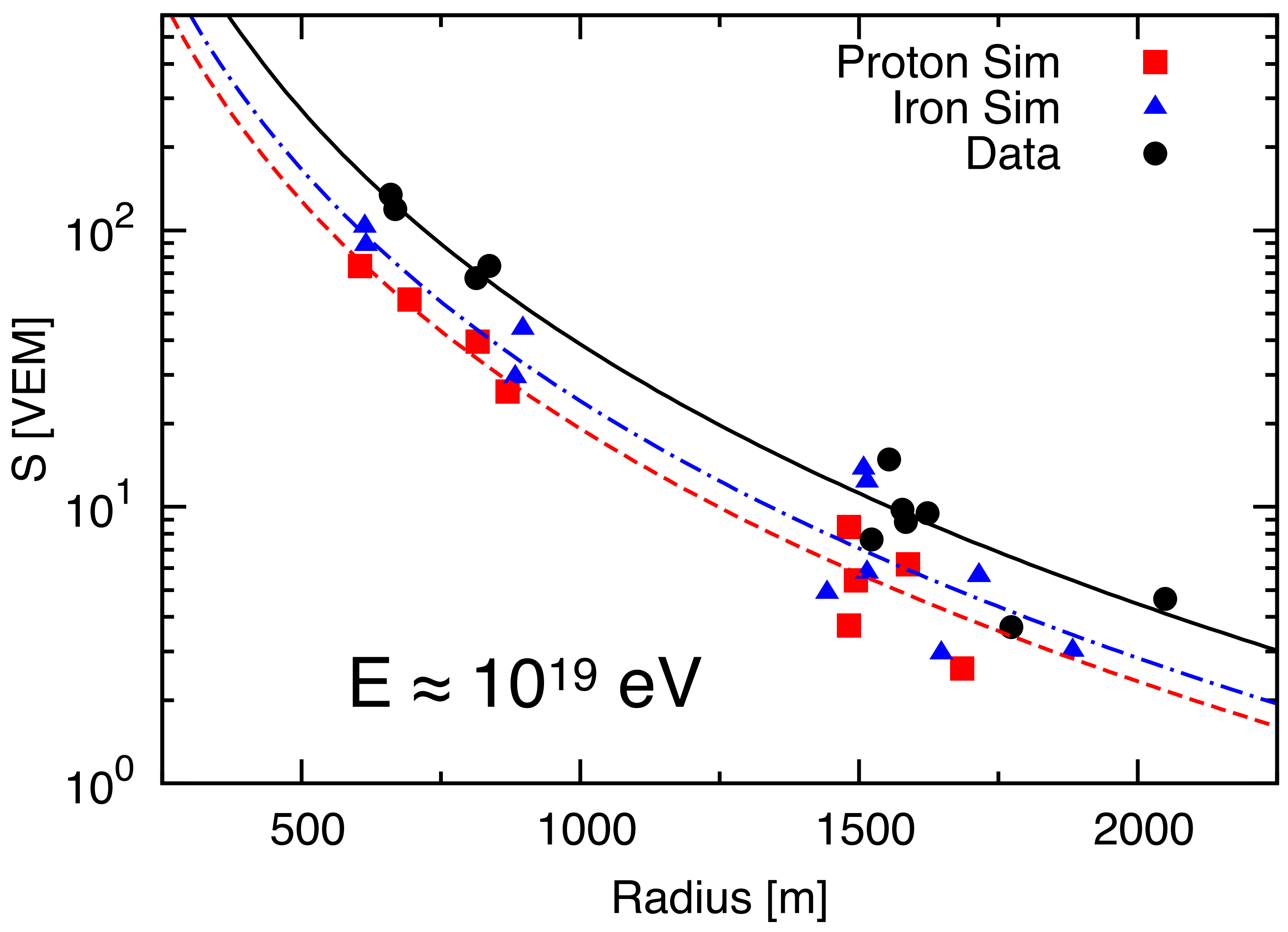
Rapid increase of transverse size of protons required, otherwise increase by factor of 2 not possible

The muon puzzle

Comparison of longitudinal and lateral shower profiles



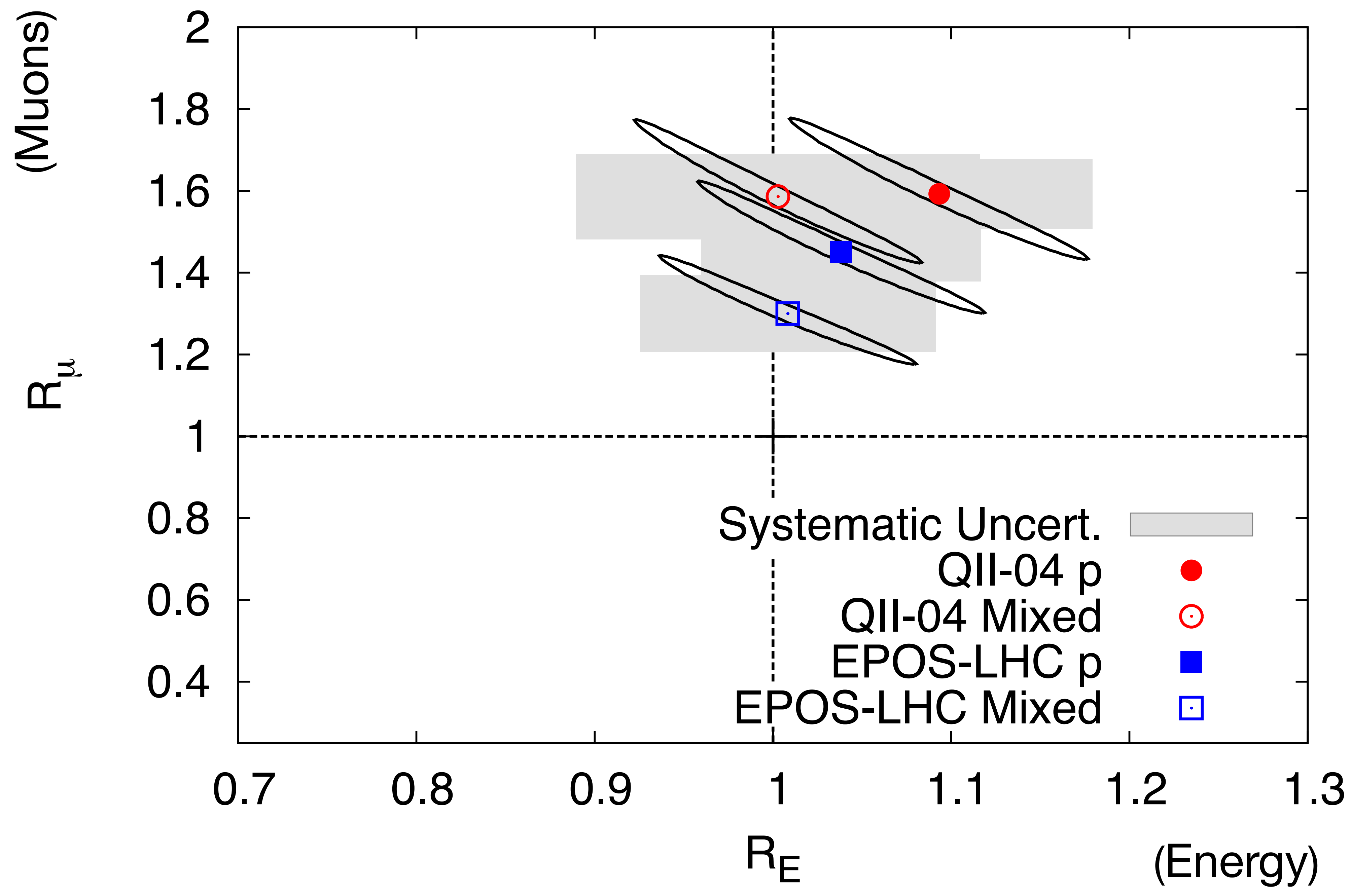




Phenomenological model ansatz

Energy scaling: em. particles and muons

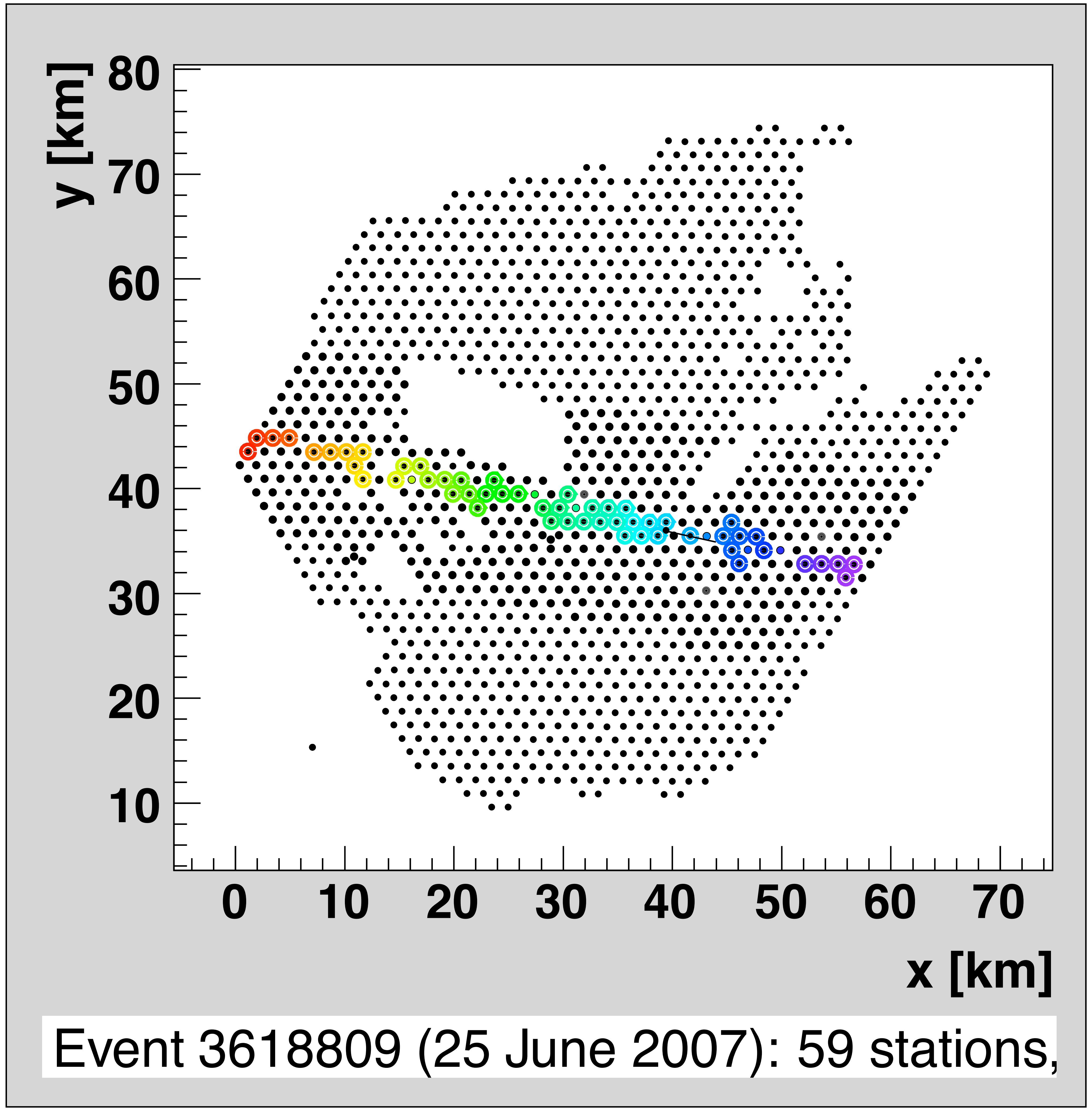
Muon scaling: hadronically produced muons and muon interaction/decay products

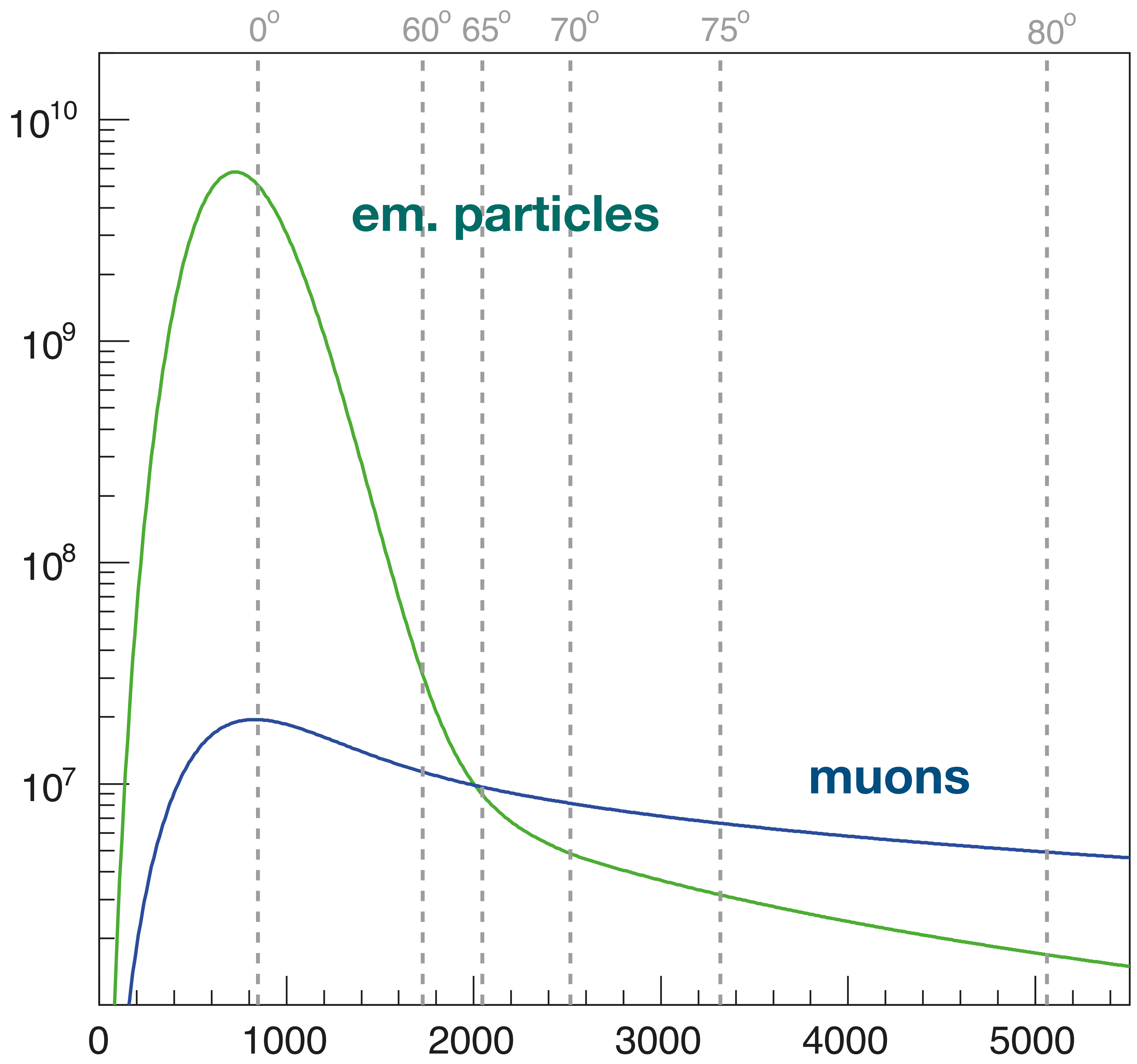


Rescaling factors

(Auger, ICRC 2013, PRL 2016)

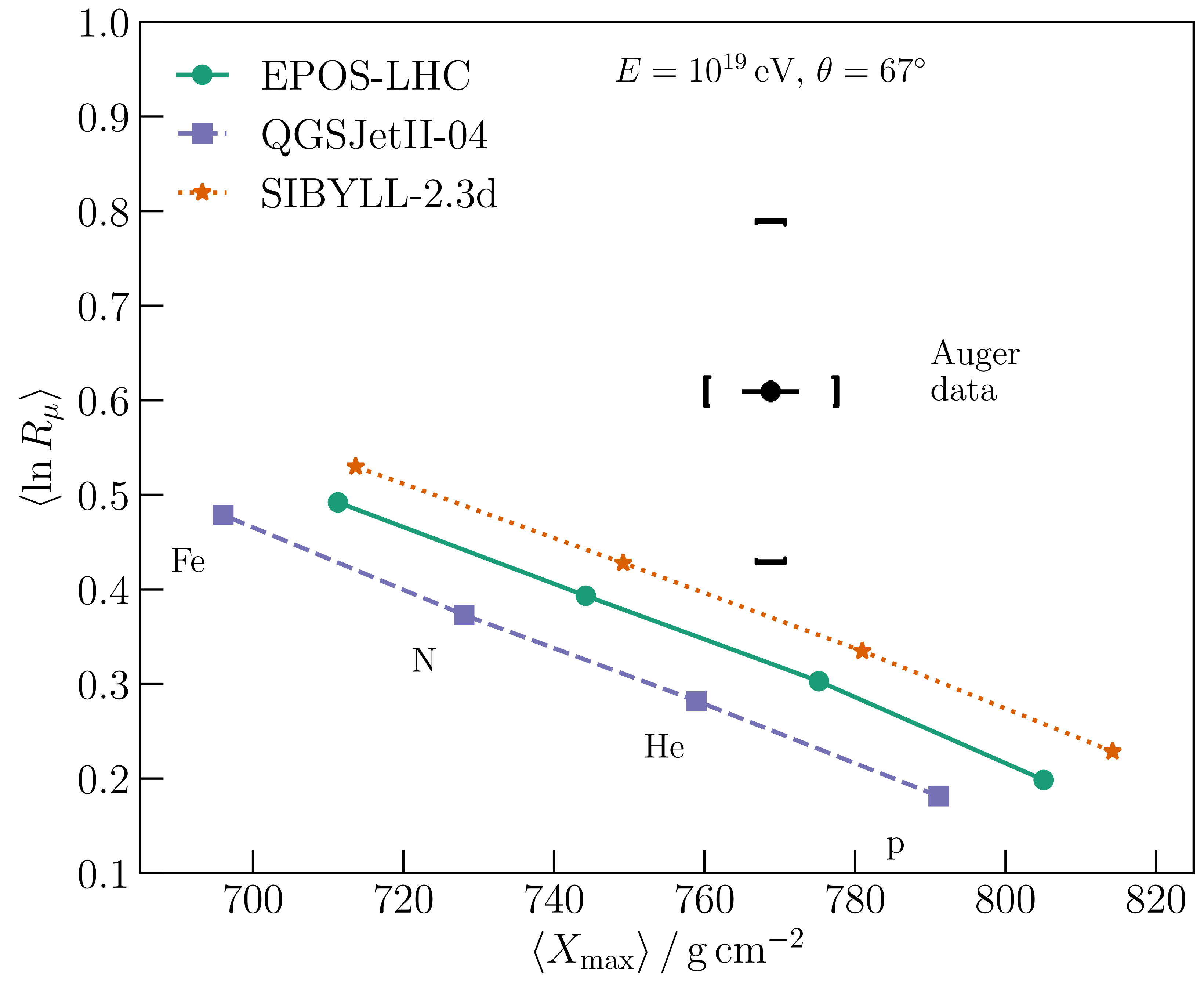
Spectacular inclined showers (θ > 60°)

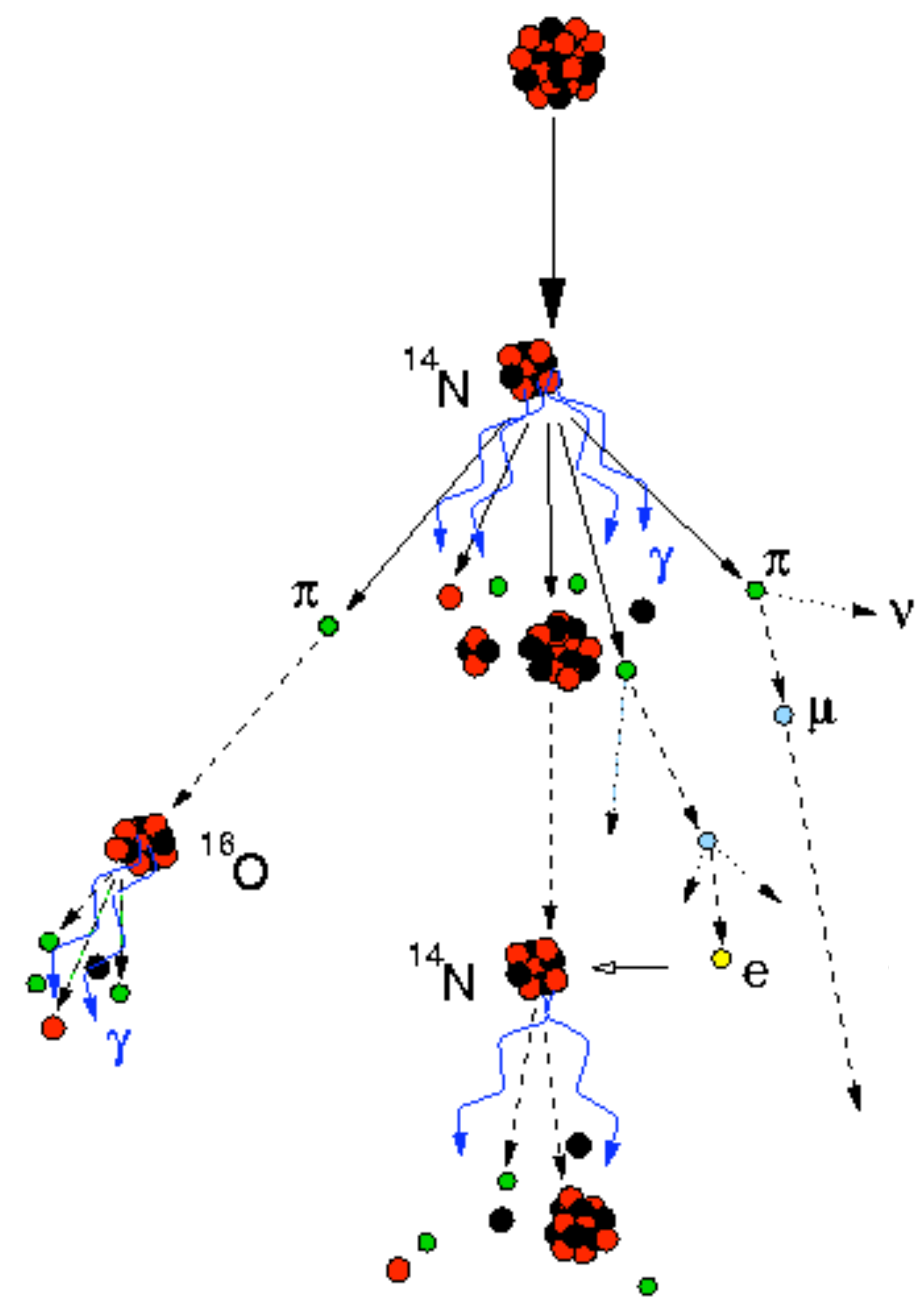


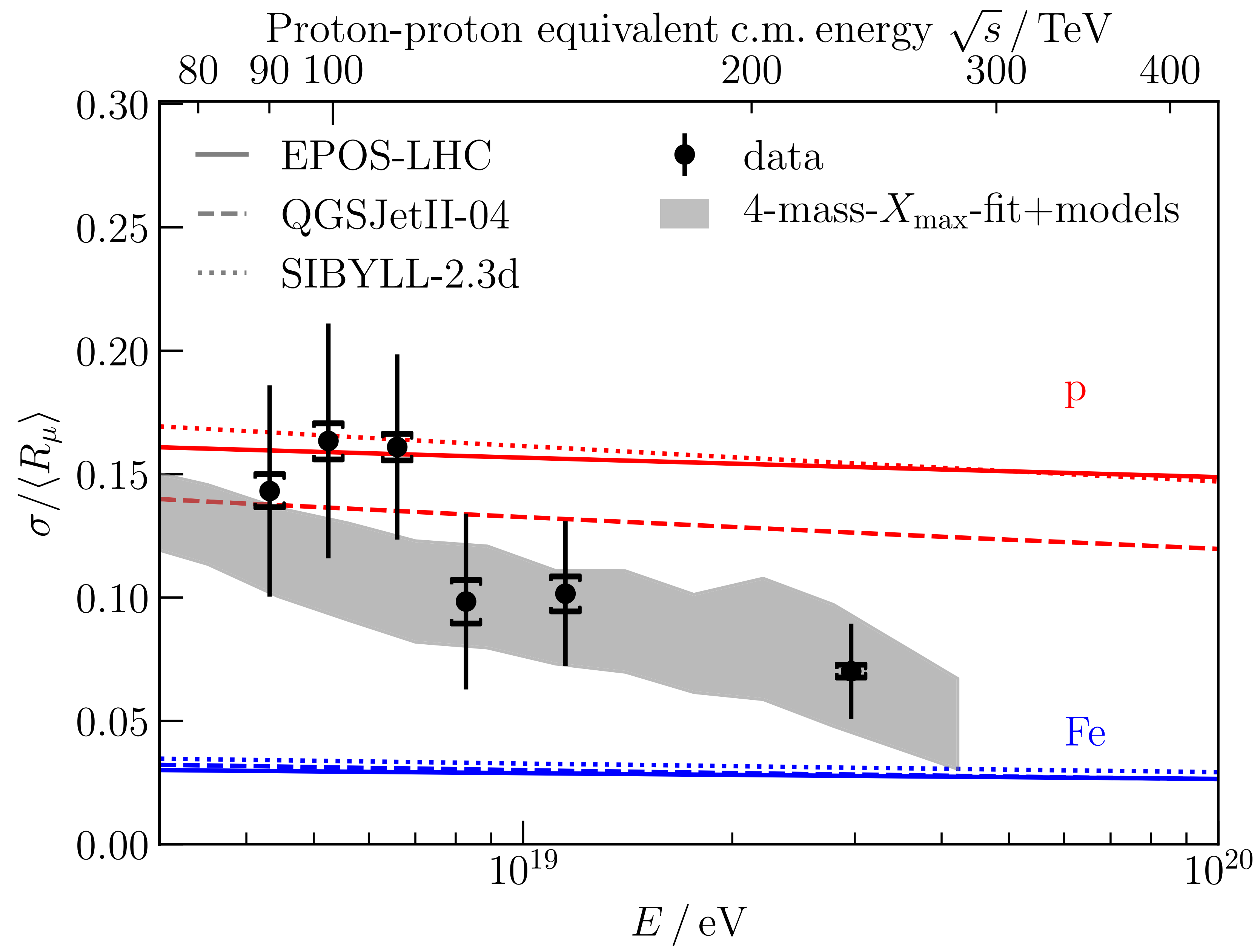


Muon number in inclined showers (θ > 60°)

Hybrid events and inclined showers





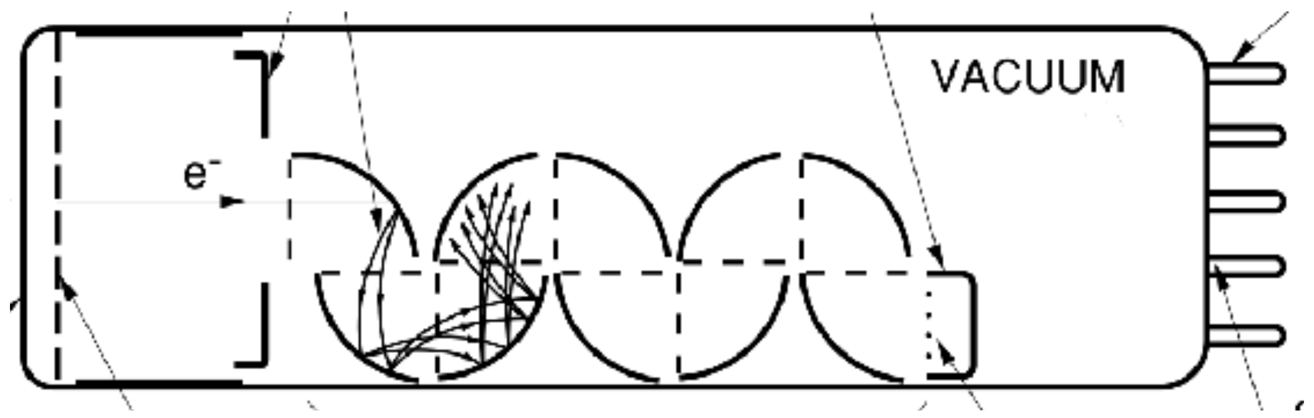


(Phys. Rev. Lett. 117 (2016) 192001,
Phys. Rev. D91 (2015) 032003)

Discrepancy in number of muons

Relative fluctuations as expected

PMT analogy of air shower

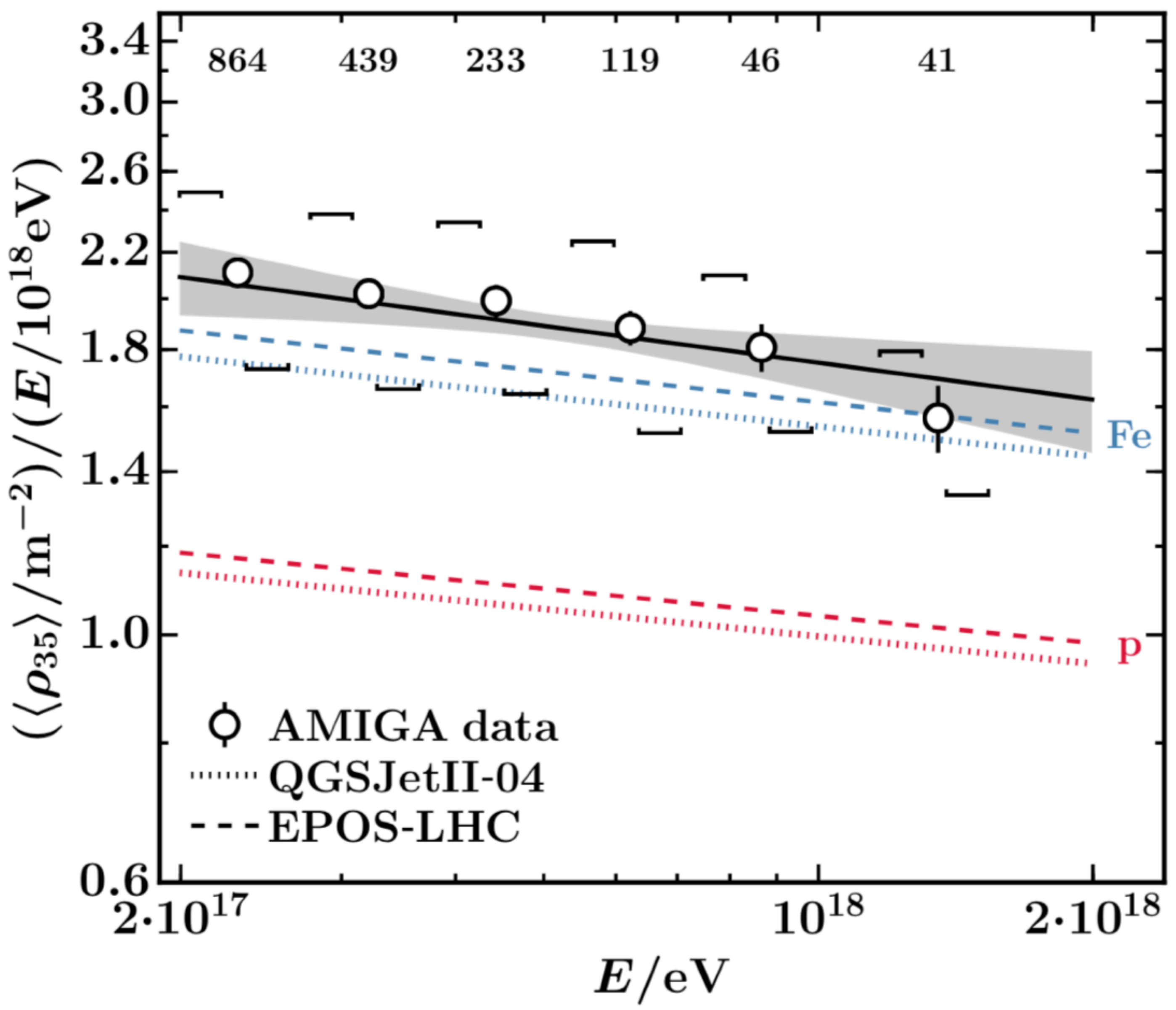


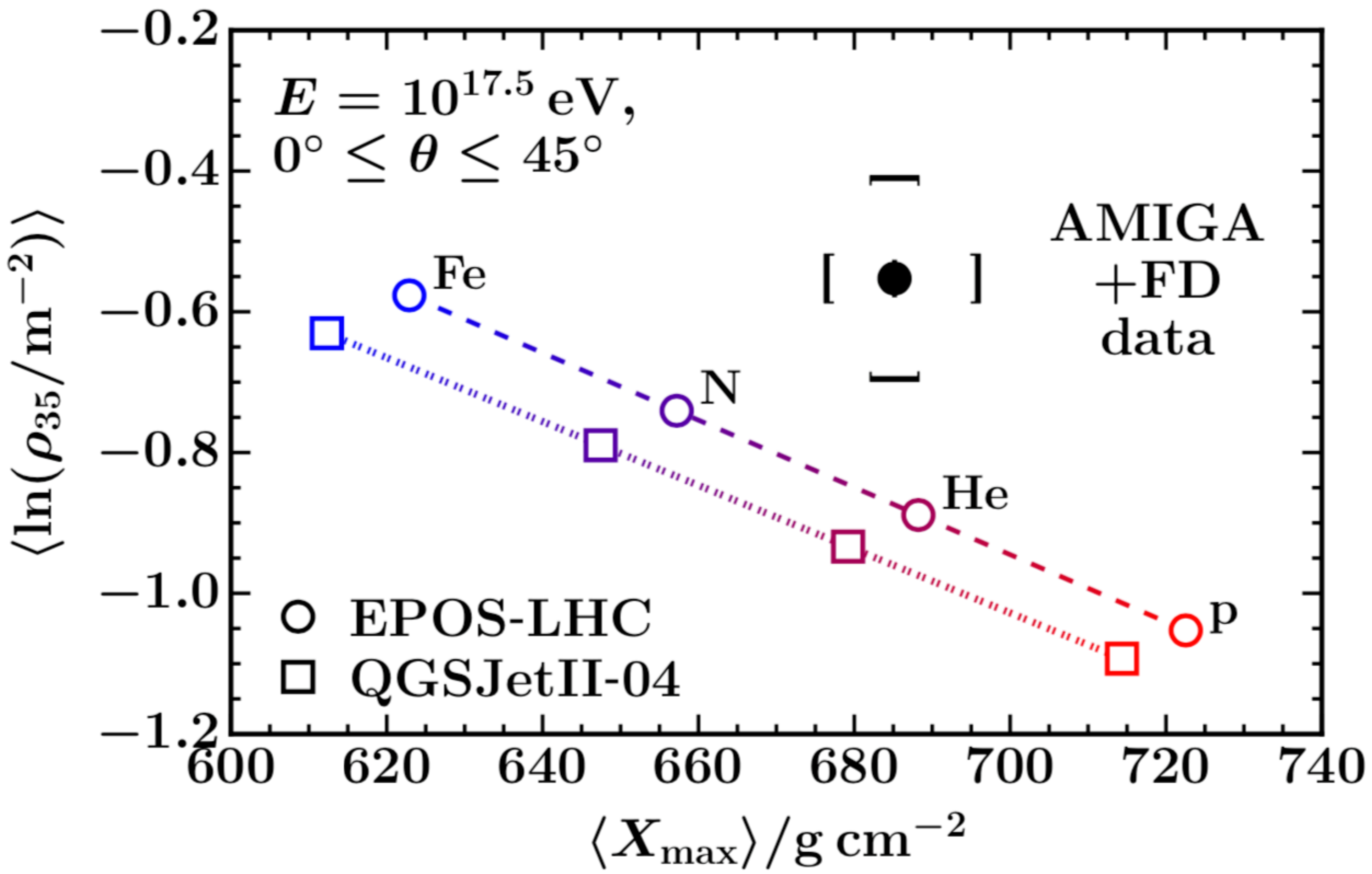
Muon fluctuations driven by first interactions

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

Direct measurement of muons at lower energy

Underground muon detectors
(2.3 m soil for shielding)



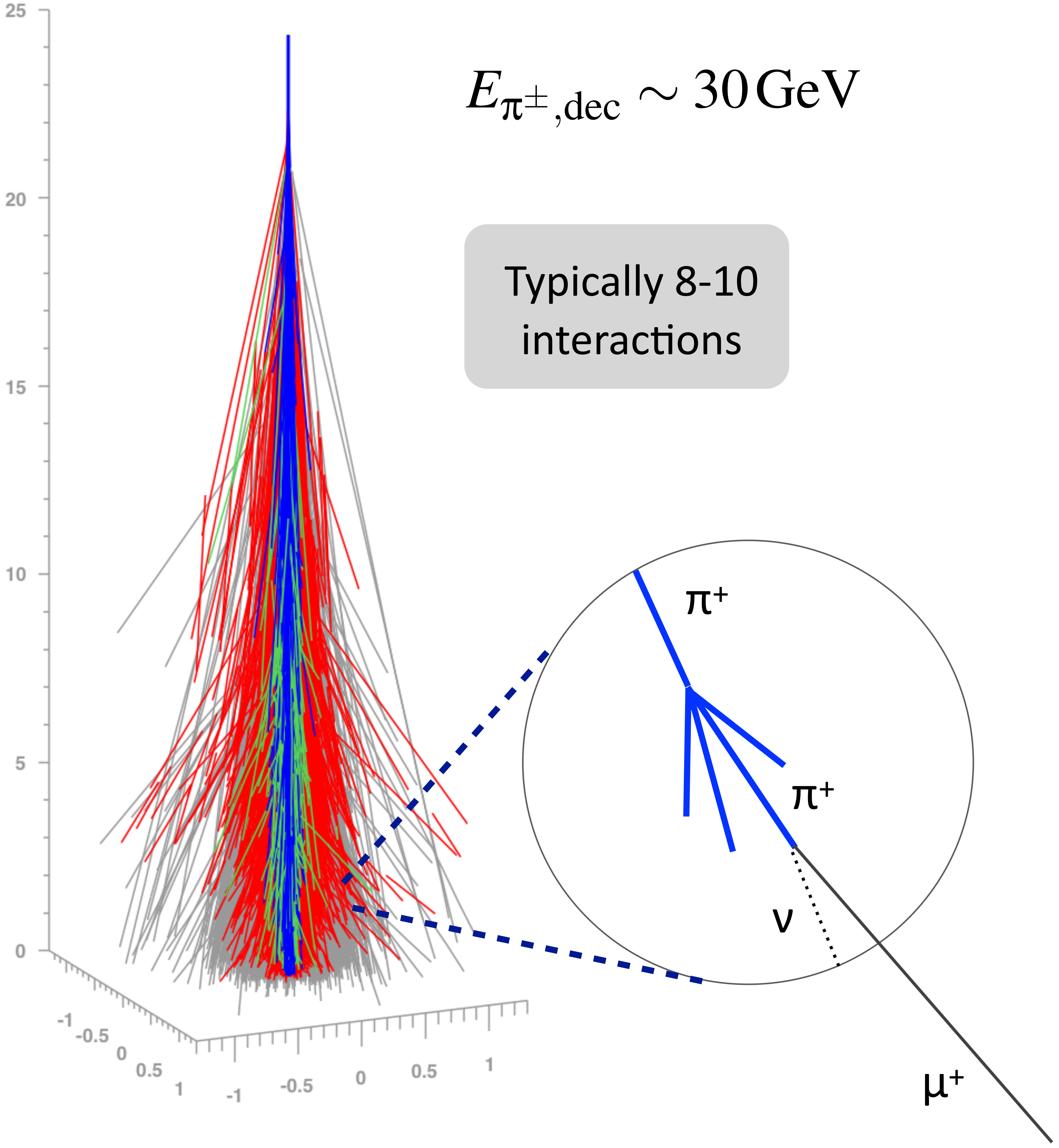


In range $3x10^{17}$ eV to $2x10^{18}$ eV simulations don't reproduce muon densities

38% (53%) increase in <N_μ> at 10^{18} eV needed for EPOS-LHC (QGSJetII-04)

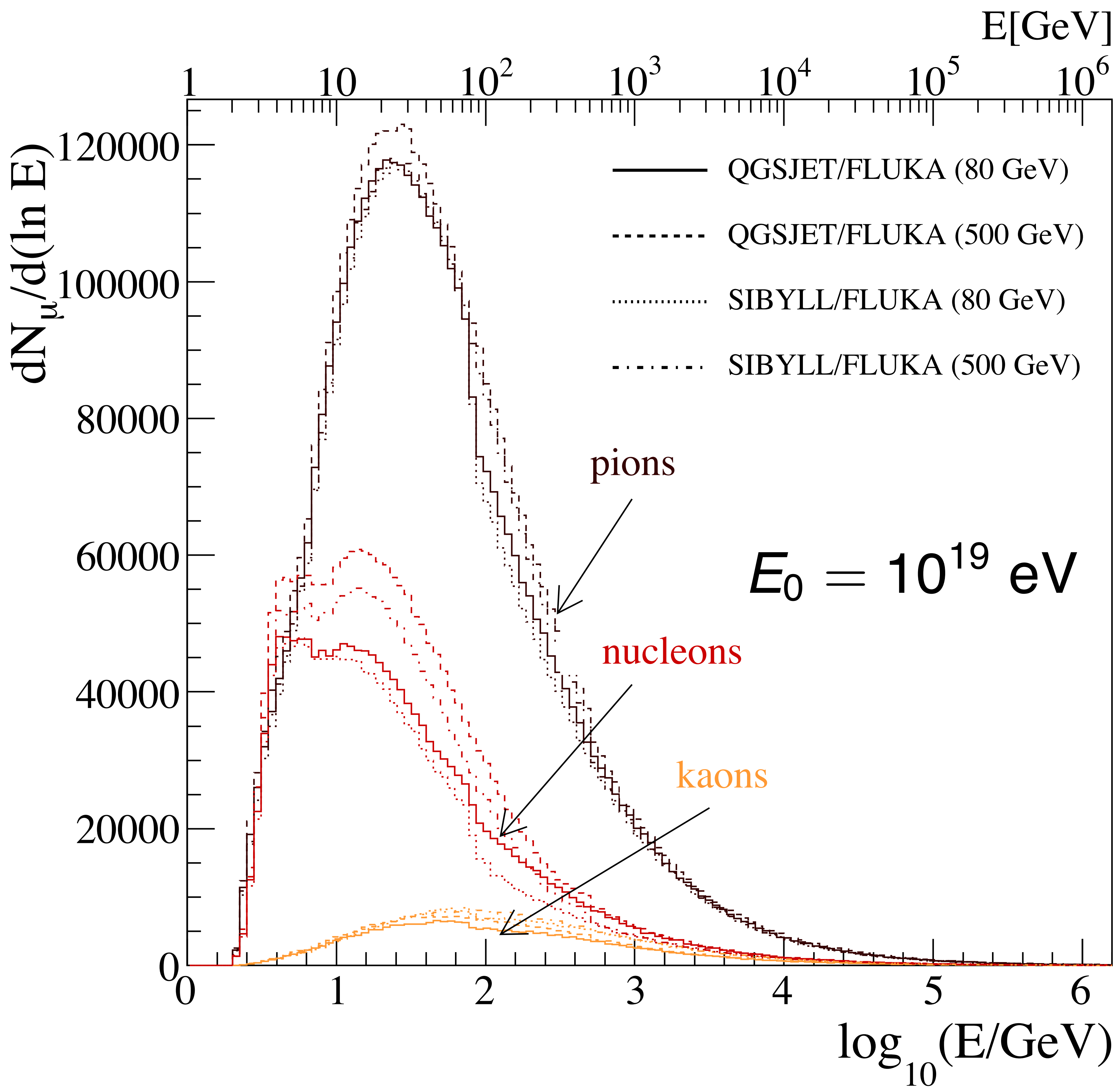
(Auger, Eur. Phys. J. C80 (2020) 751)

Muon production at large lateral distance



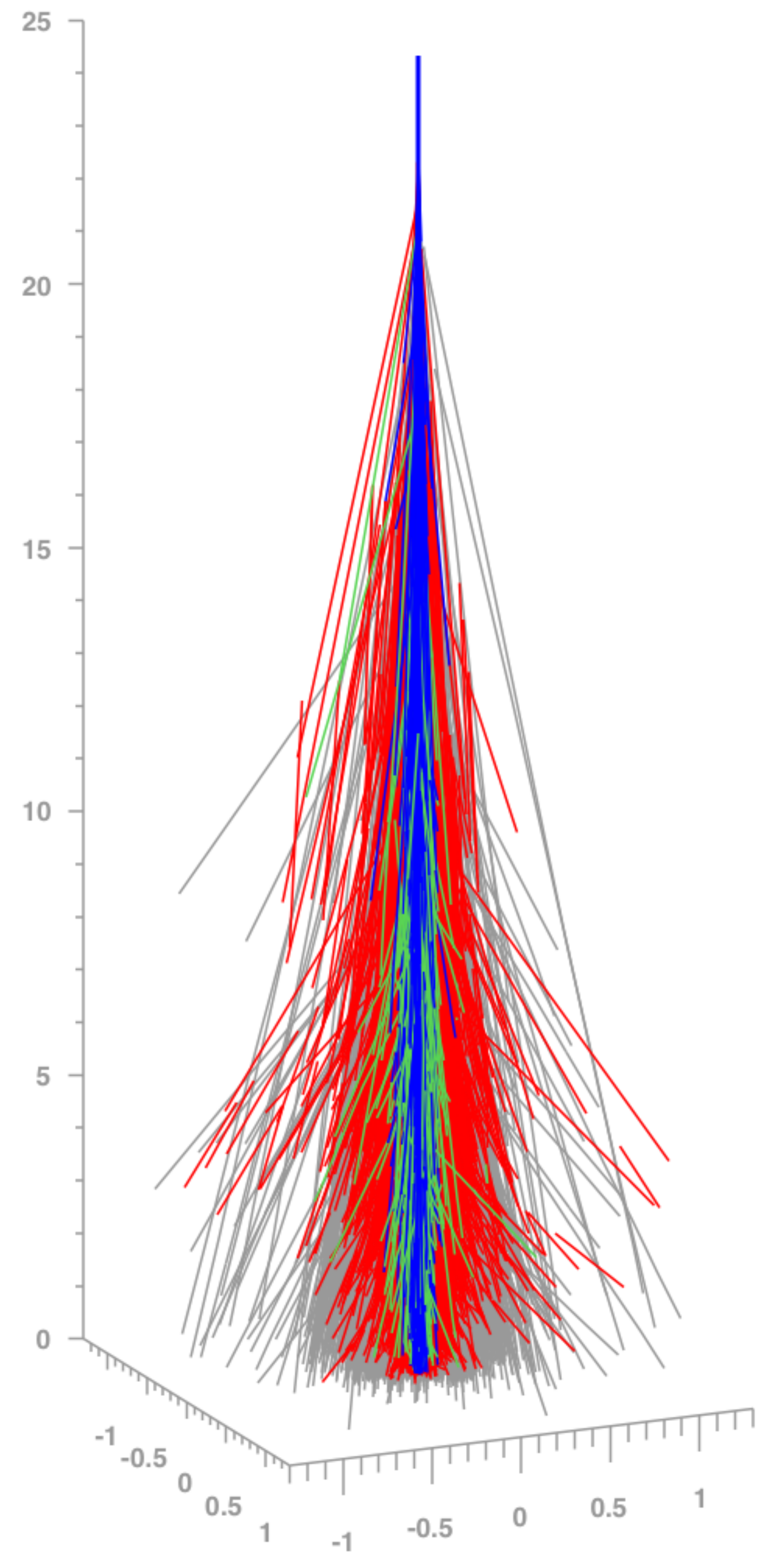
Muon observed at 1000 m from core

Energy distribution of last interaction that produced a detected muon

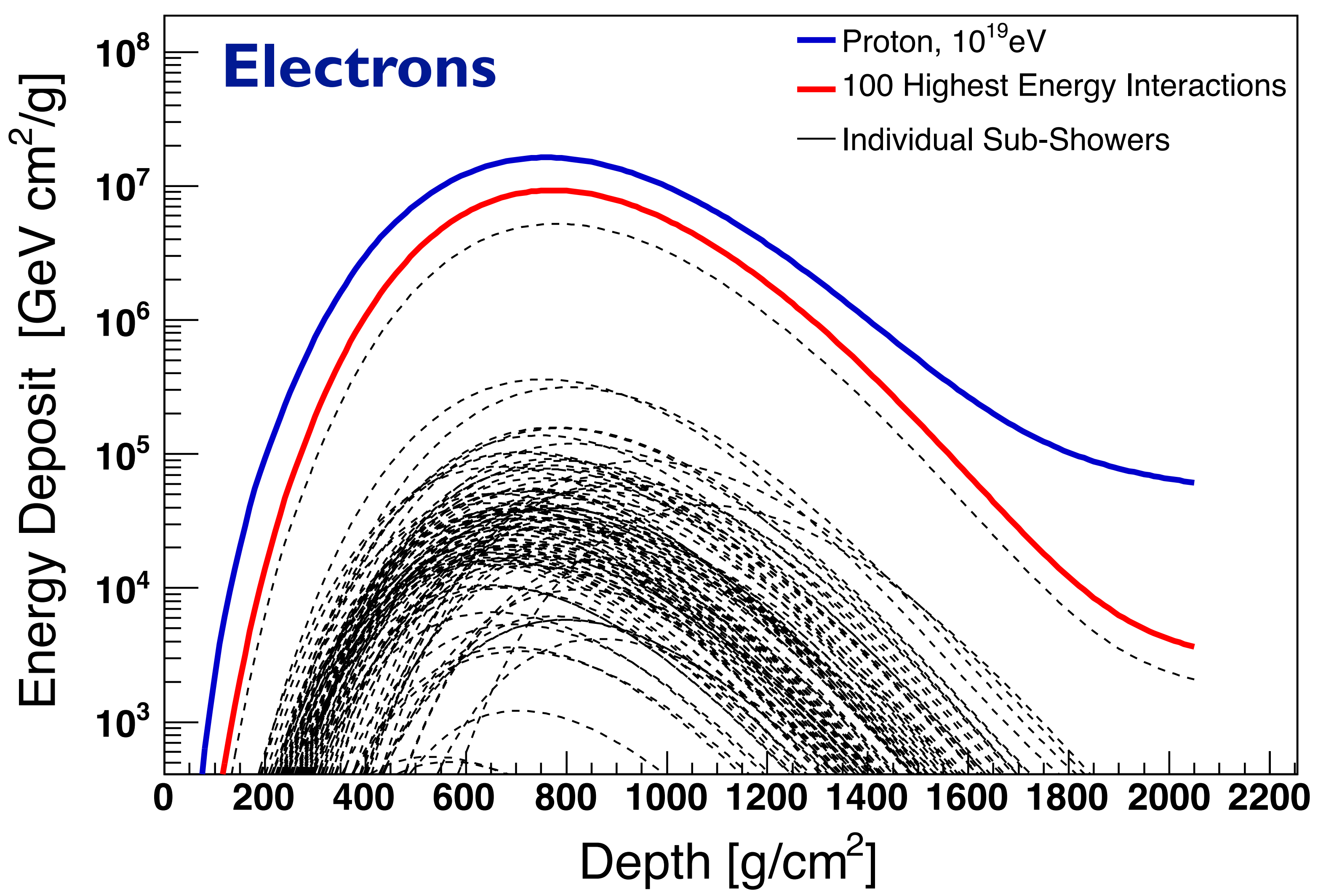


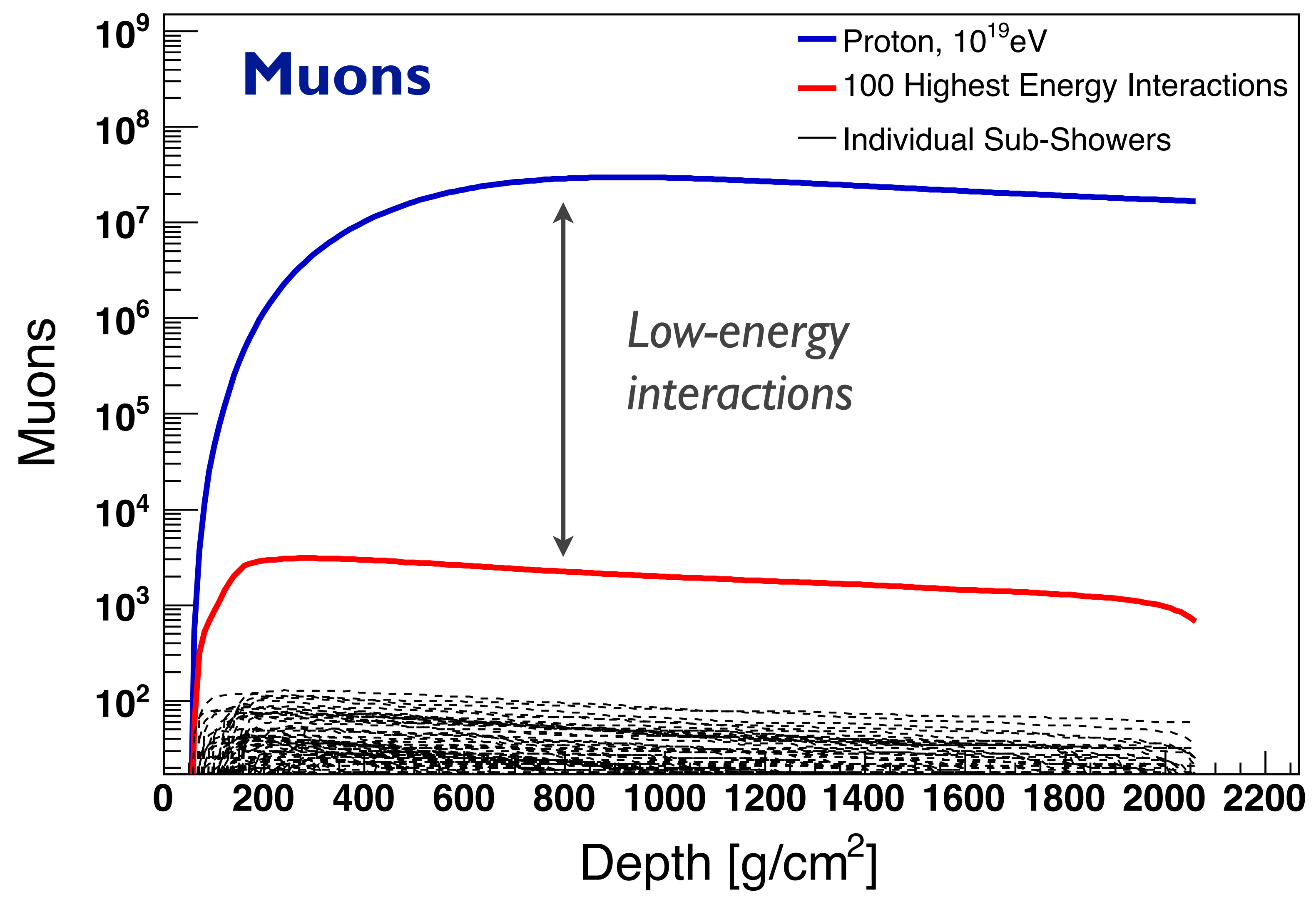
(Maris et al. ICRC 2009)

Importance of hadronic interactions at different energies



(Ulrich APS 2010)





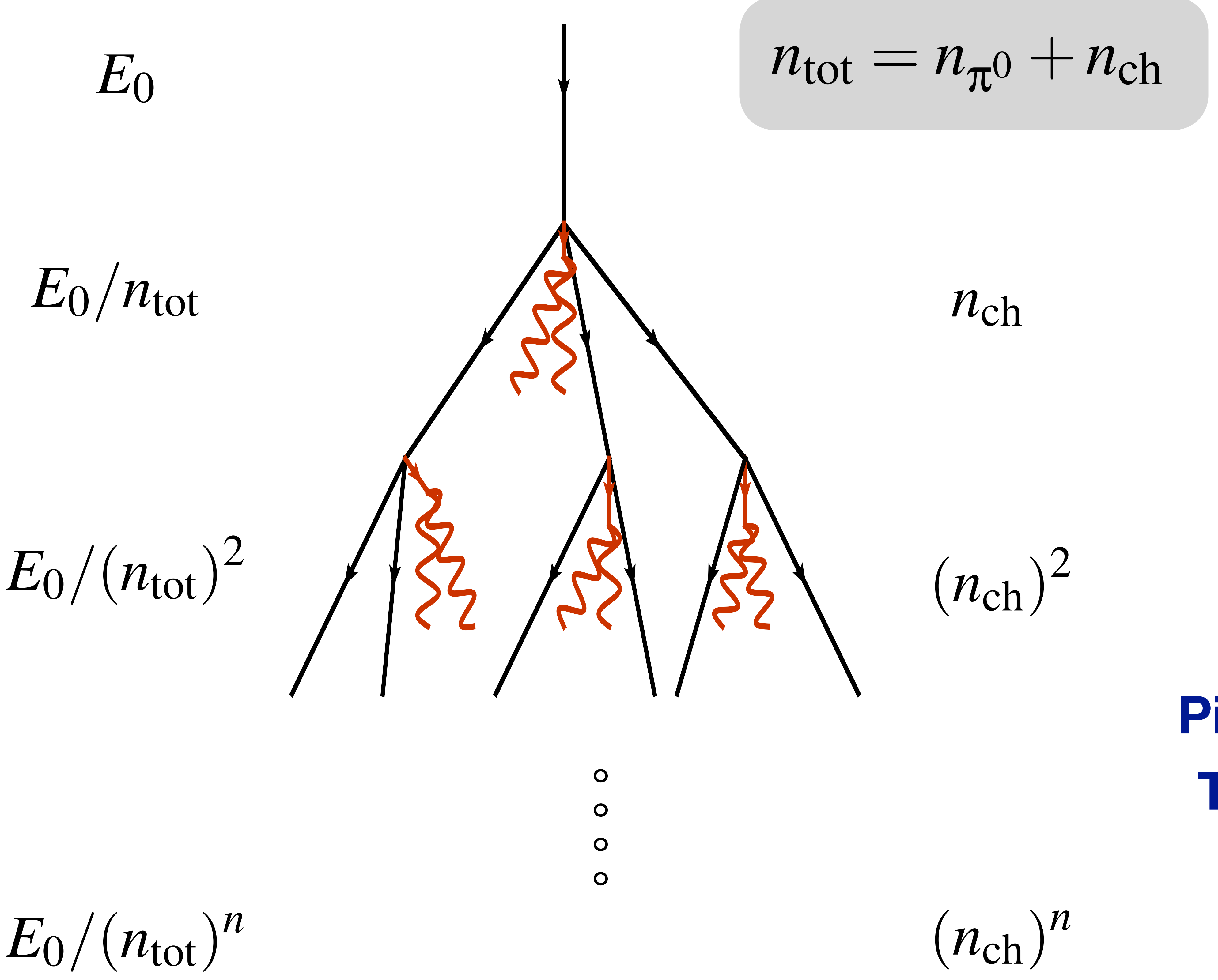
Shower particles produced in 100 interactions of highest energy

Electrons/photons: high-energy interactions

Muons/hadrons: low-energy interactions

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

Muon production in hadronic showers



Primary particle proton

π^0 decay immediately

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

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

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

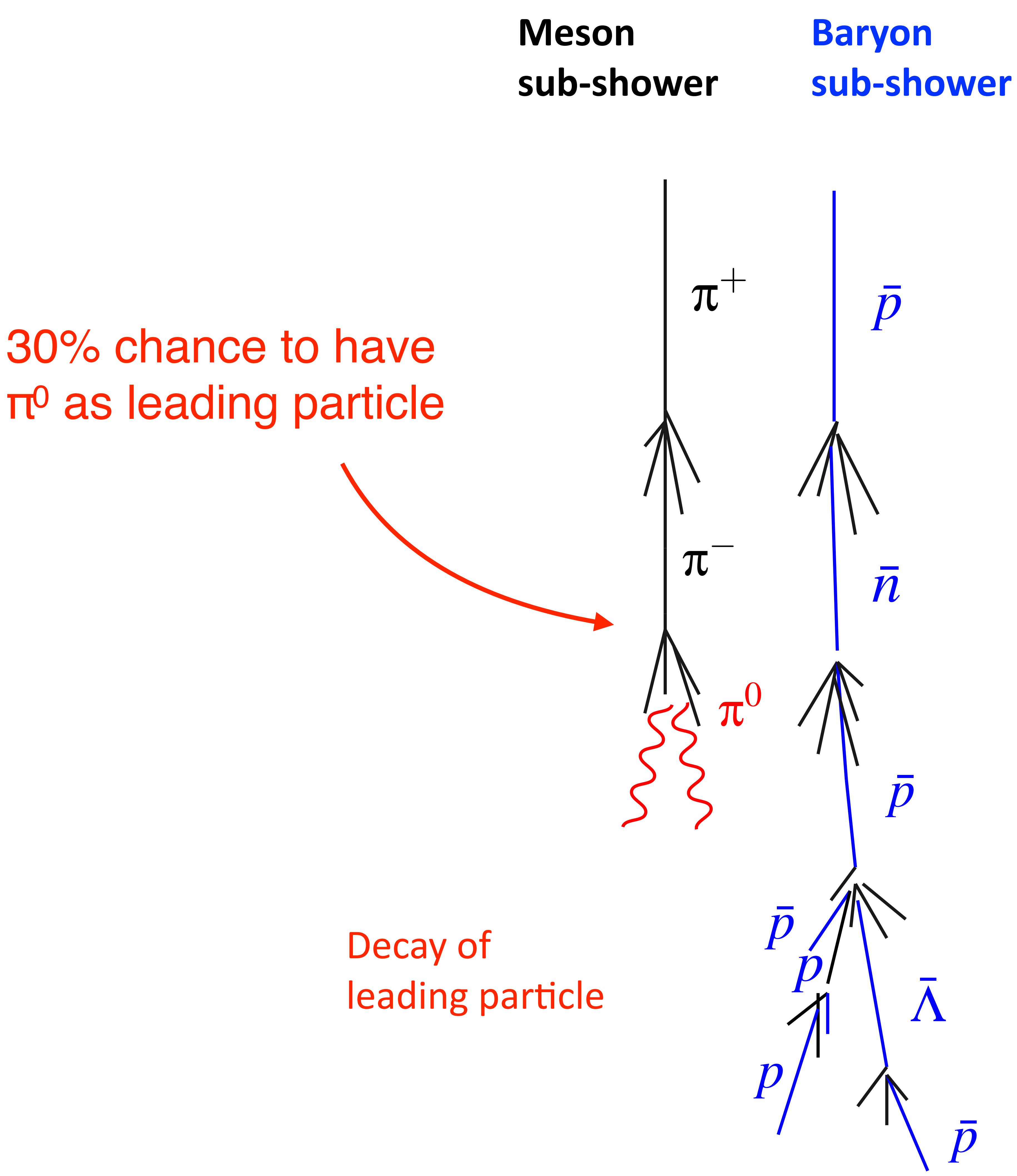
$$\alpha = \frac{\ln n_{ch}}{\ln n_{tot}} \approx 0.82 \ldots 0.95$$

Assumptions:

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

(Matthews, Astropart.Phys. 22, 2005)

Muon production depends on hadronic energy fraction



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 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

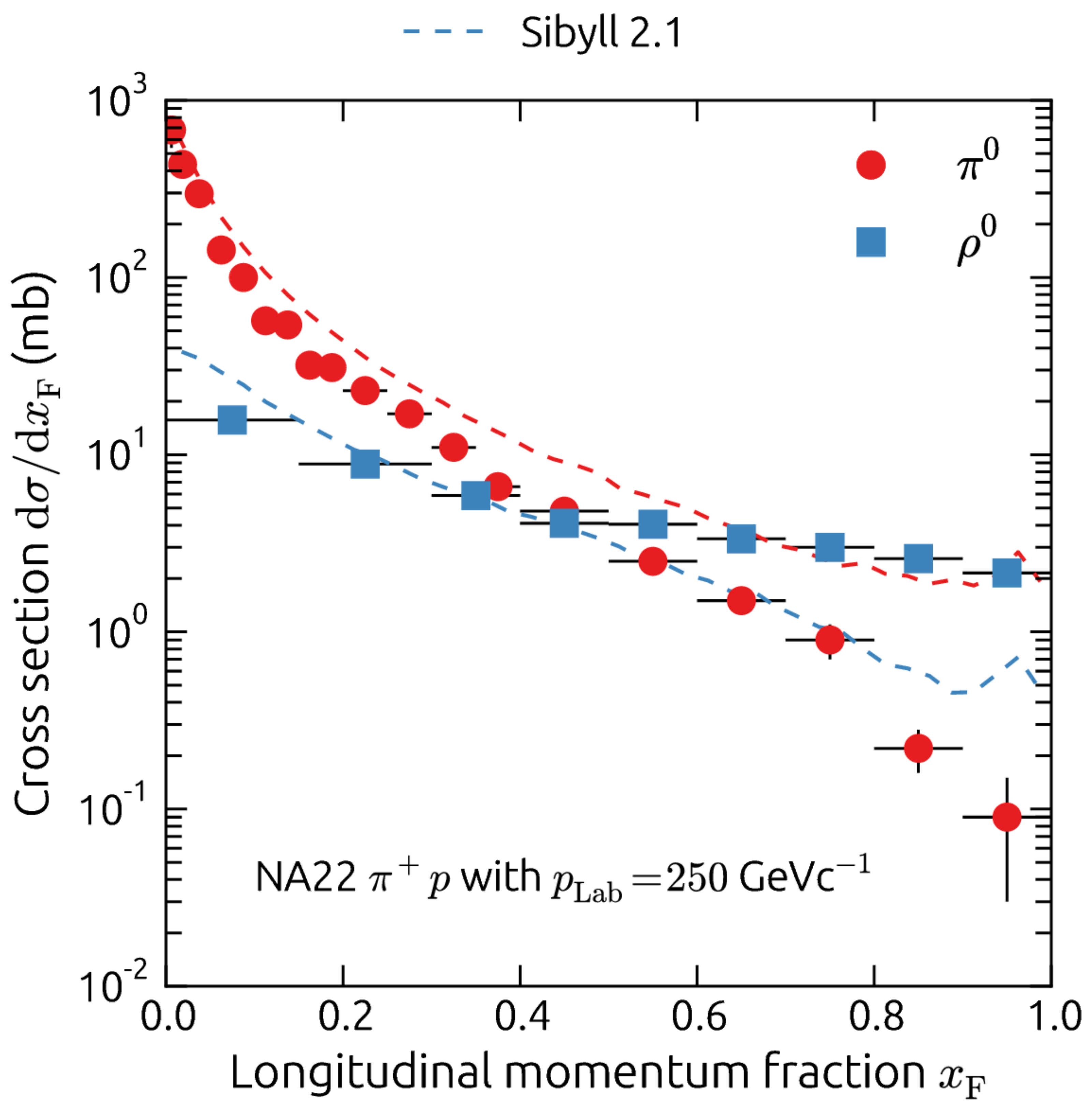
Core-Corona model (Pierog et al.)

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

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

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

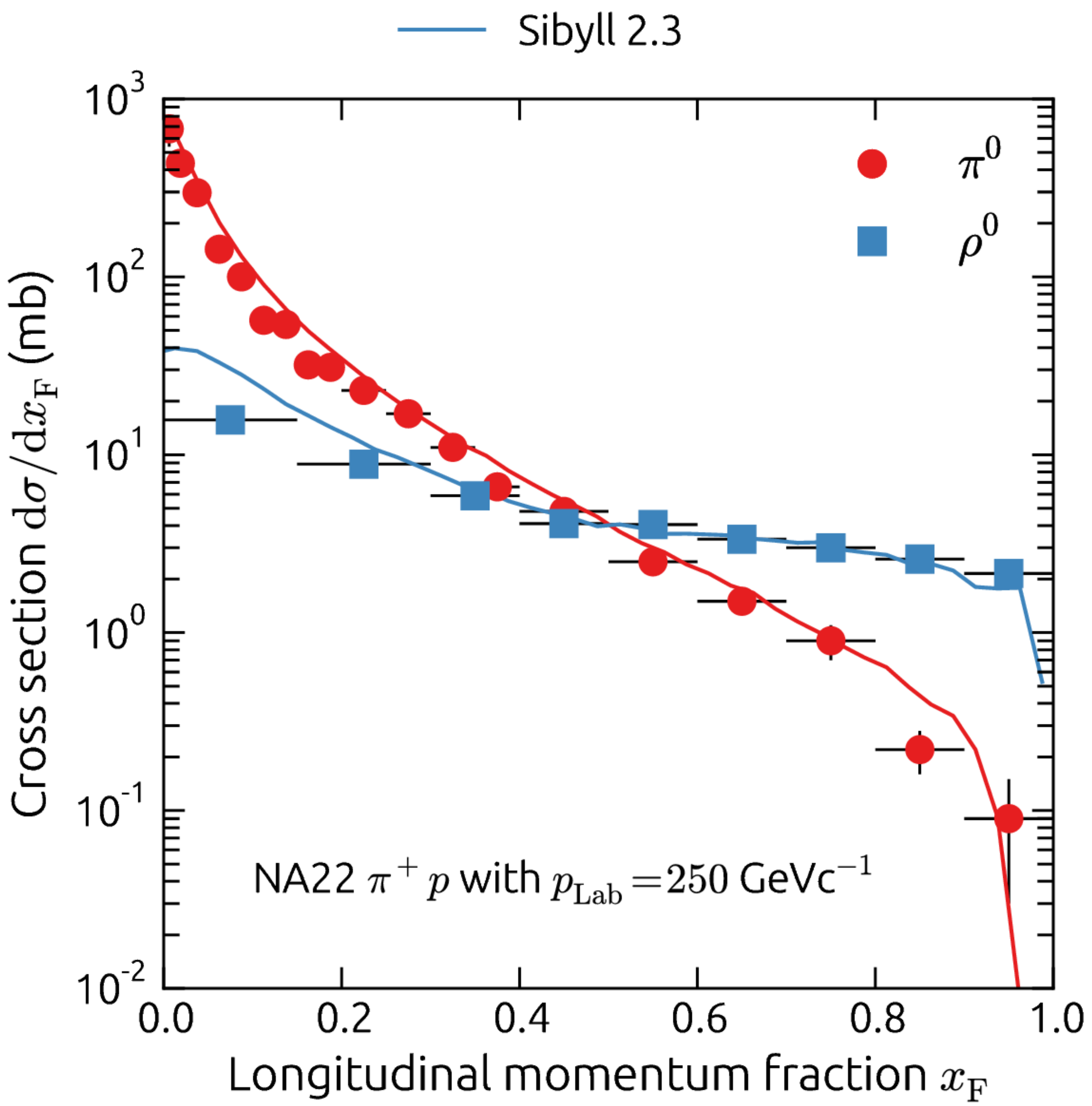
Leading particle production



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

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

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

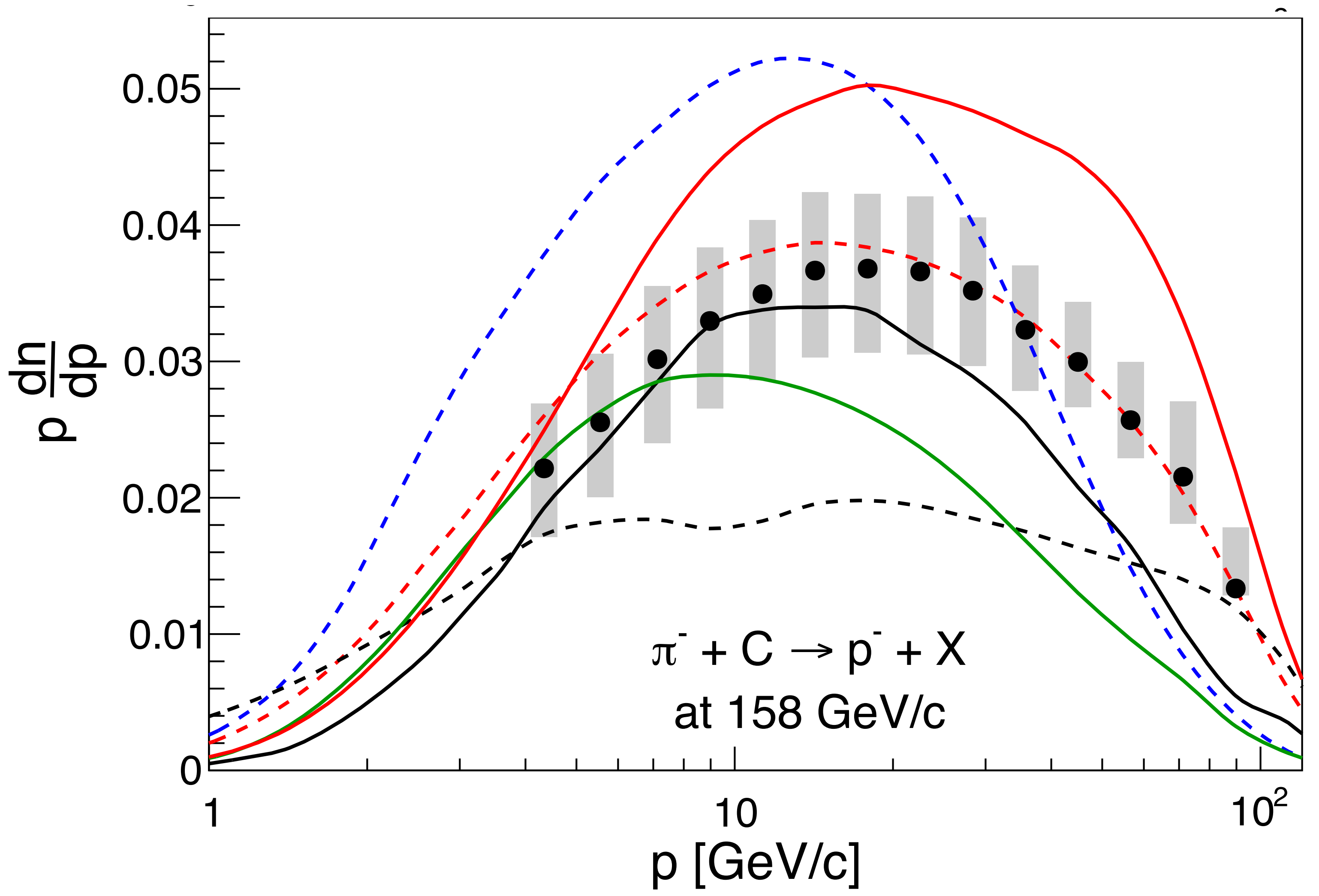


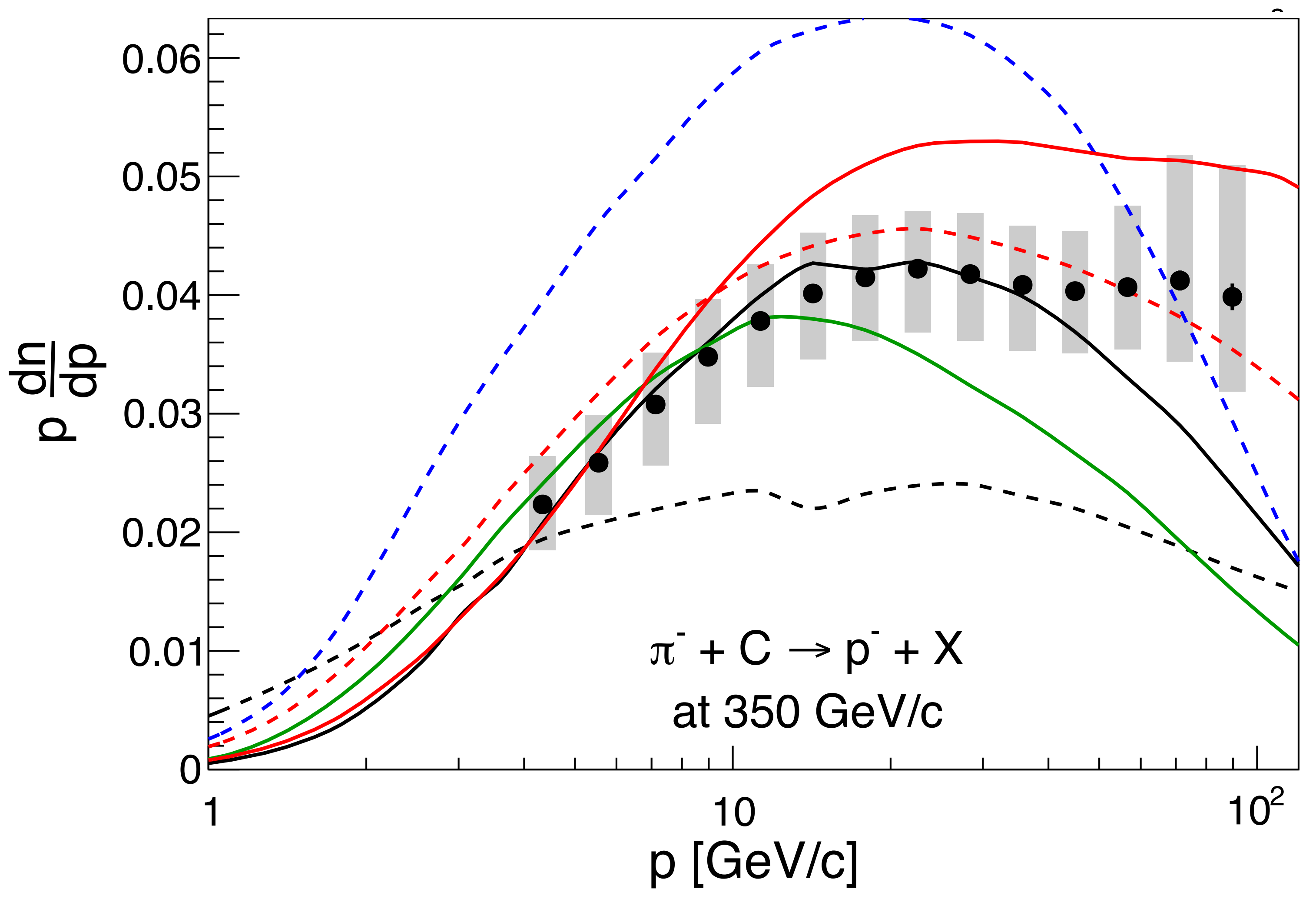
$$x_F = p_{\|} / p_{max}$$

(Riehn et al., ICRC 2015)

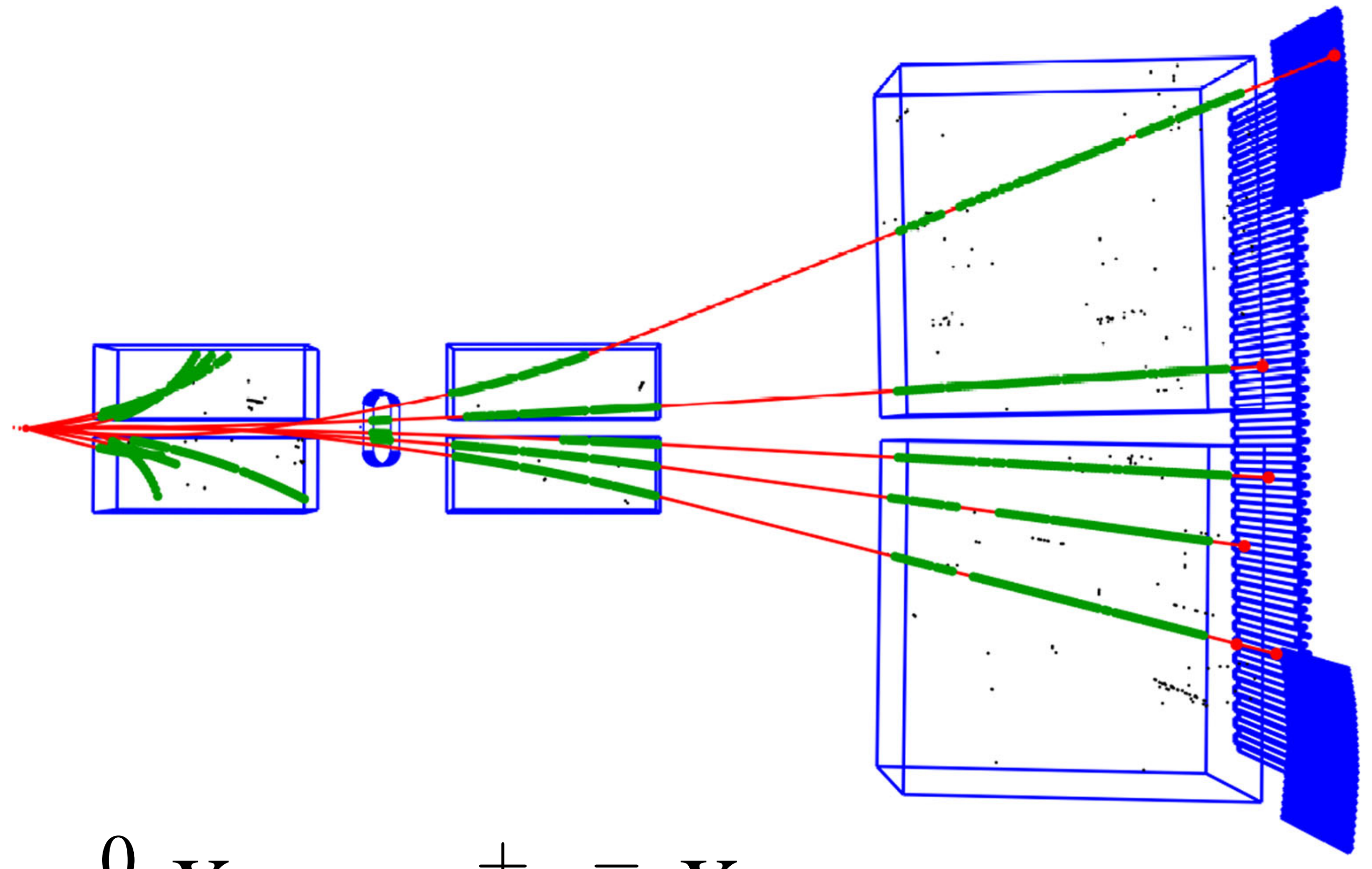
NA61 experiment at CERN SPS

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

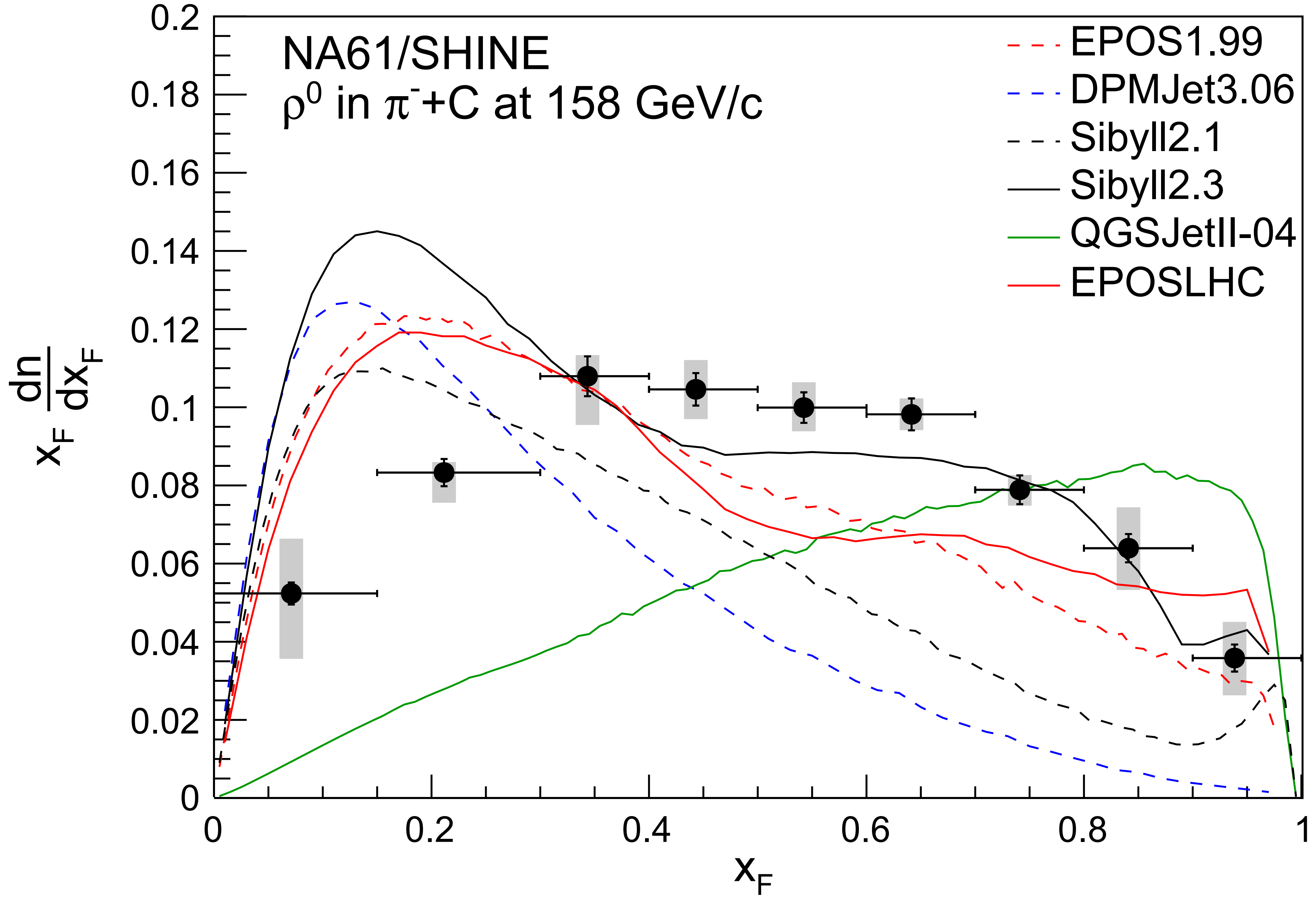




Dedicated cosmic ray runs
(π-C at 158 and 350 GeV)

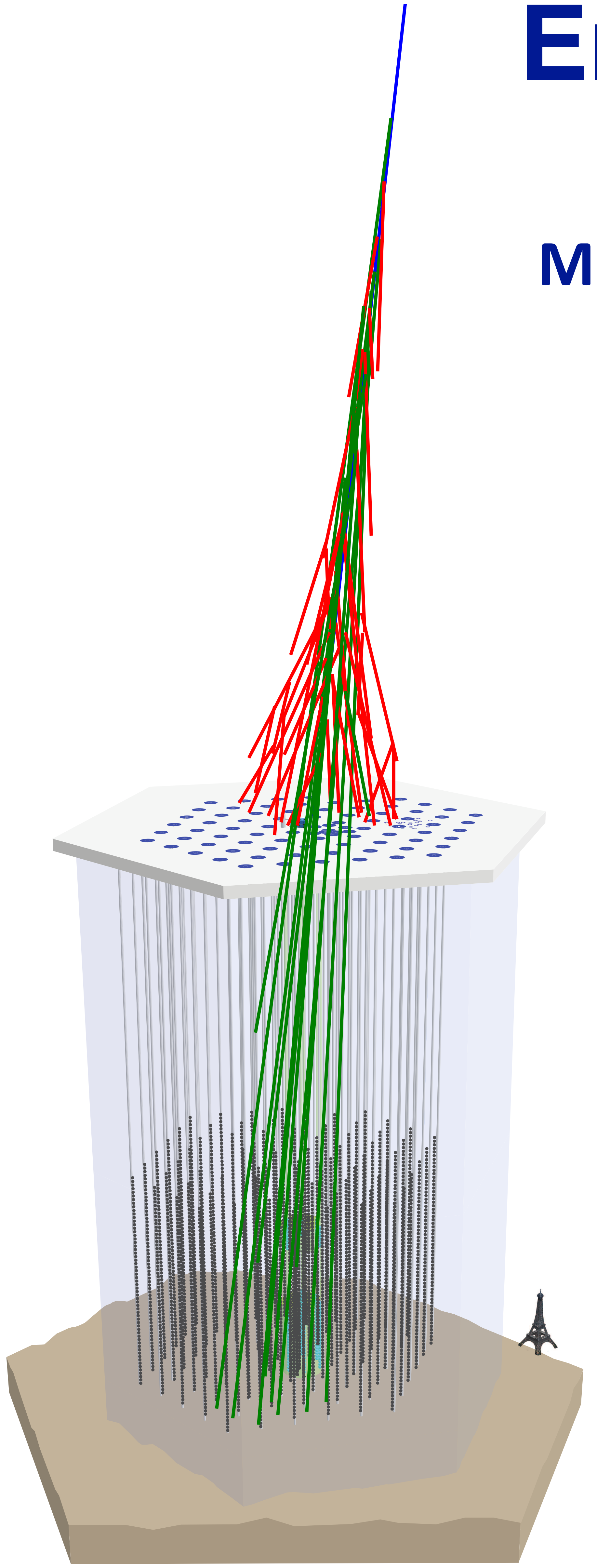


$\pi^- C \rightarrow \rho^0\, X \rightarrow \pi^+\pi^-\, X$



(NA61, EPJ 77, 2017)

Energy spectrum of muons in air showers

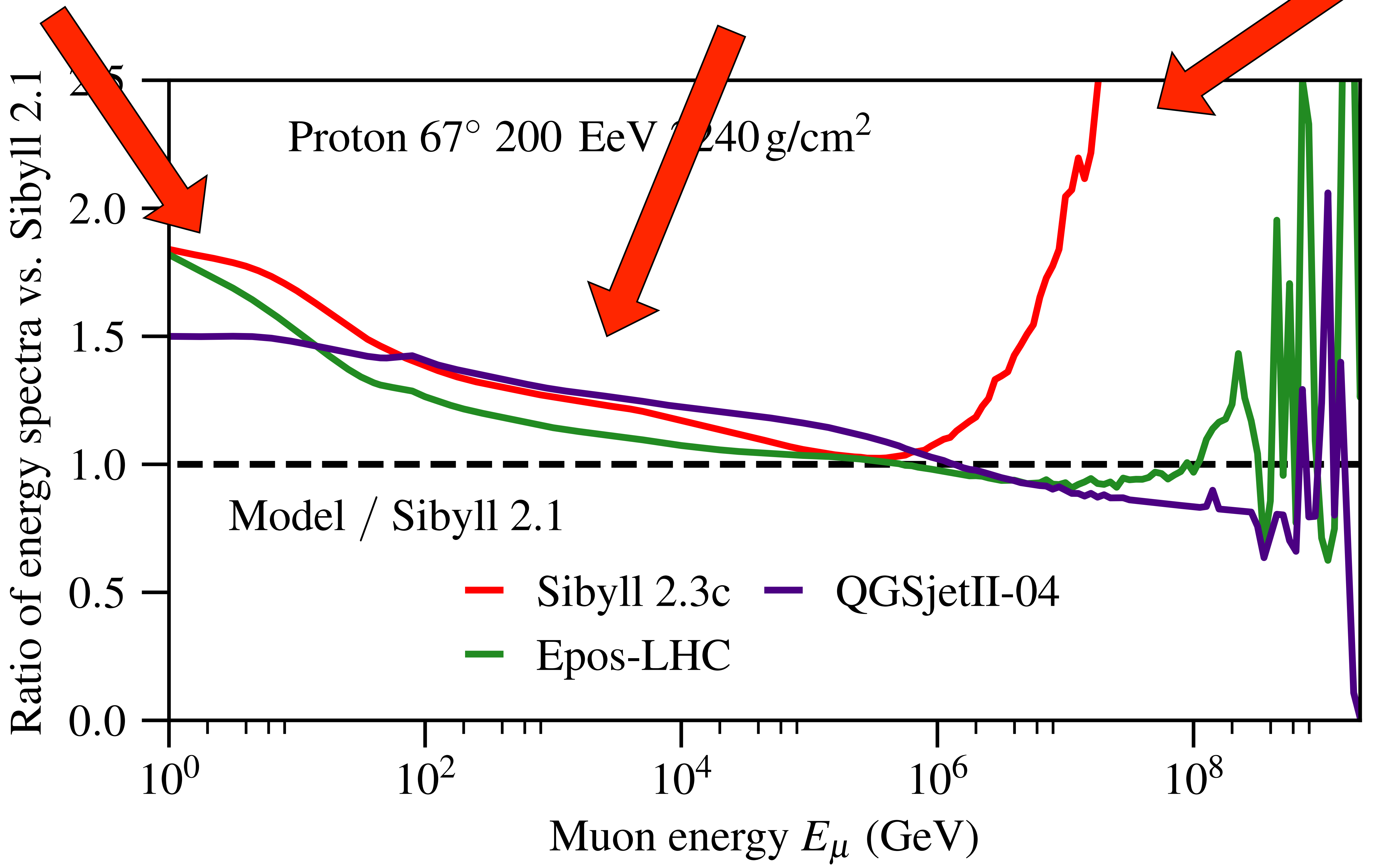


Muon energy spectrum in EAS relative to that of Sibyll 2.1

Low-energy enhancement due to baryon pair production

Rho-0 production

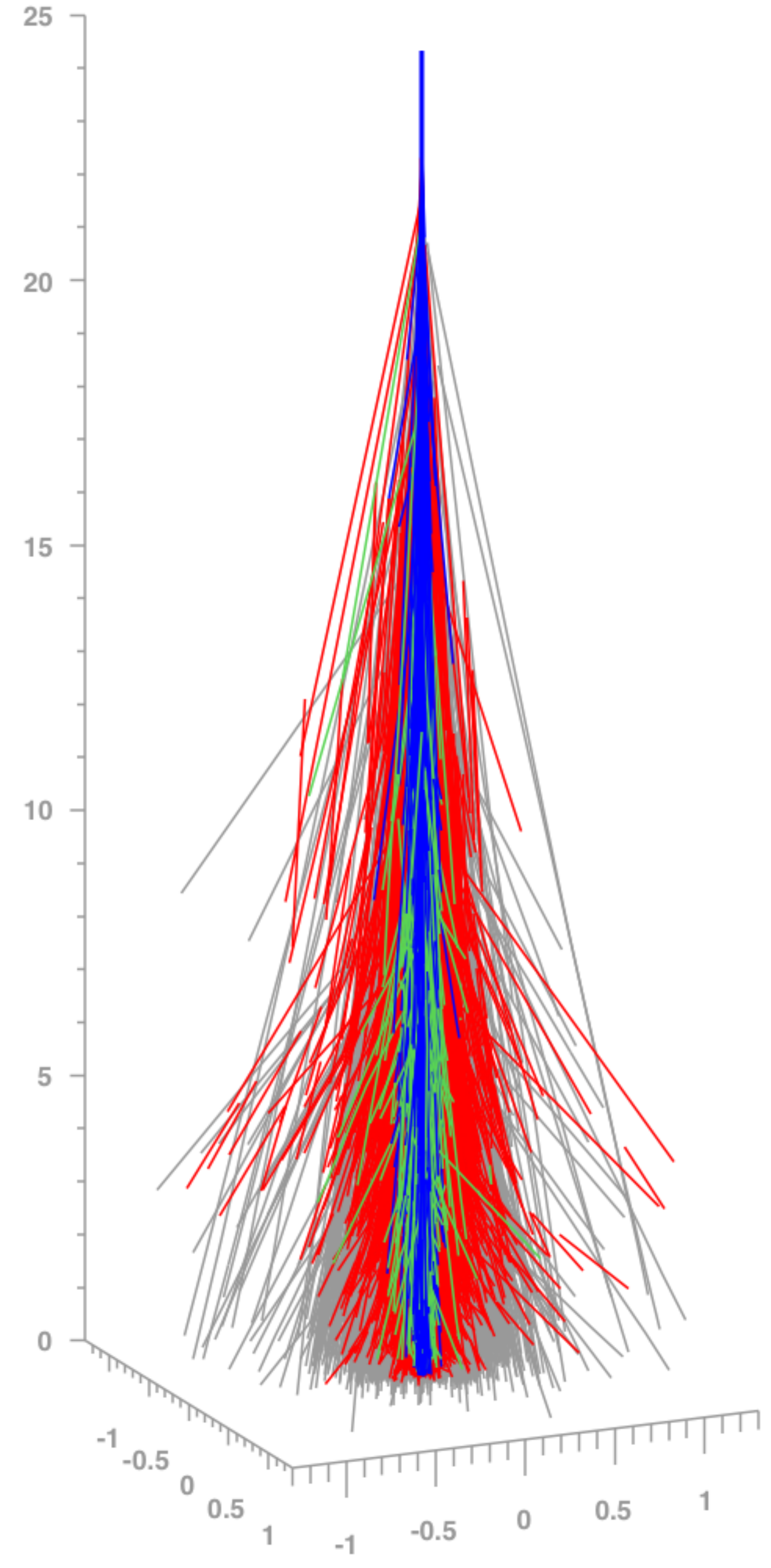
Charm particles (only Sibyll 2.3, and Sibyll 2.3c)



Correlation of low energy muons (surface) and in-ice muon bundles

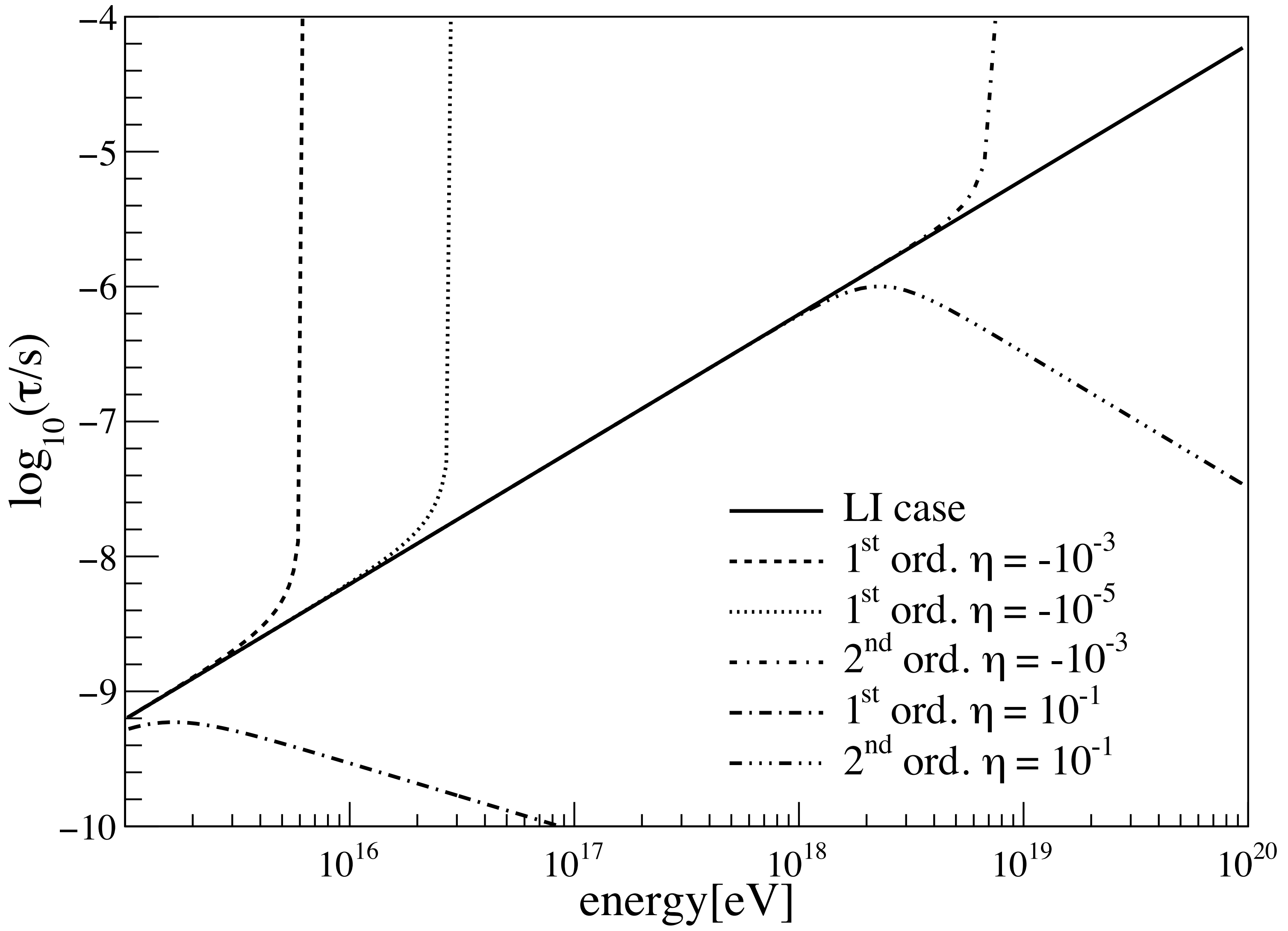
Discrimination by IceCube possible (surface array and in-ice muon data)

Lorentz invariance violation (LIV) and muon production



(Auger, ICRC 2021)

Lorentz-dilated lifetime of neutral pions



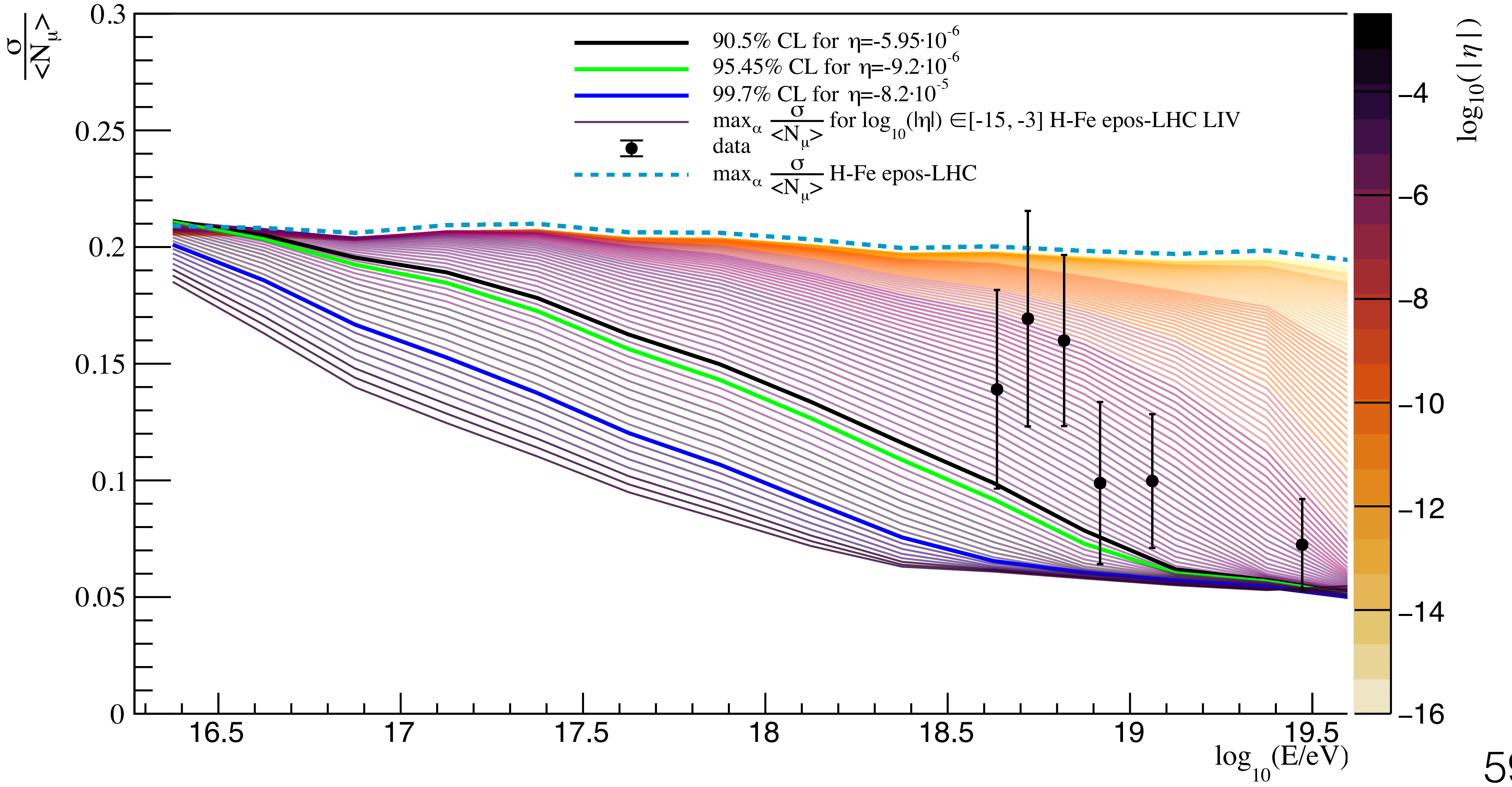
Comparison of model simulations with data on muon number fluctuations

Limits on LIV parameter η

$$E^2 - p^2 = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\rm Pl}^n}$$

$$\gamma_{\rm LIV} = E/m_{\rm LIV}$$

$$m_{\rm LIV}^2 = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\rm Pl}^n}$$

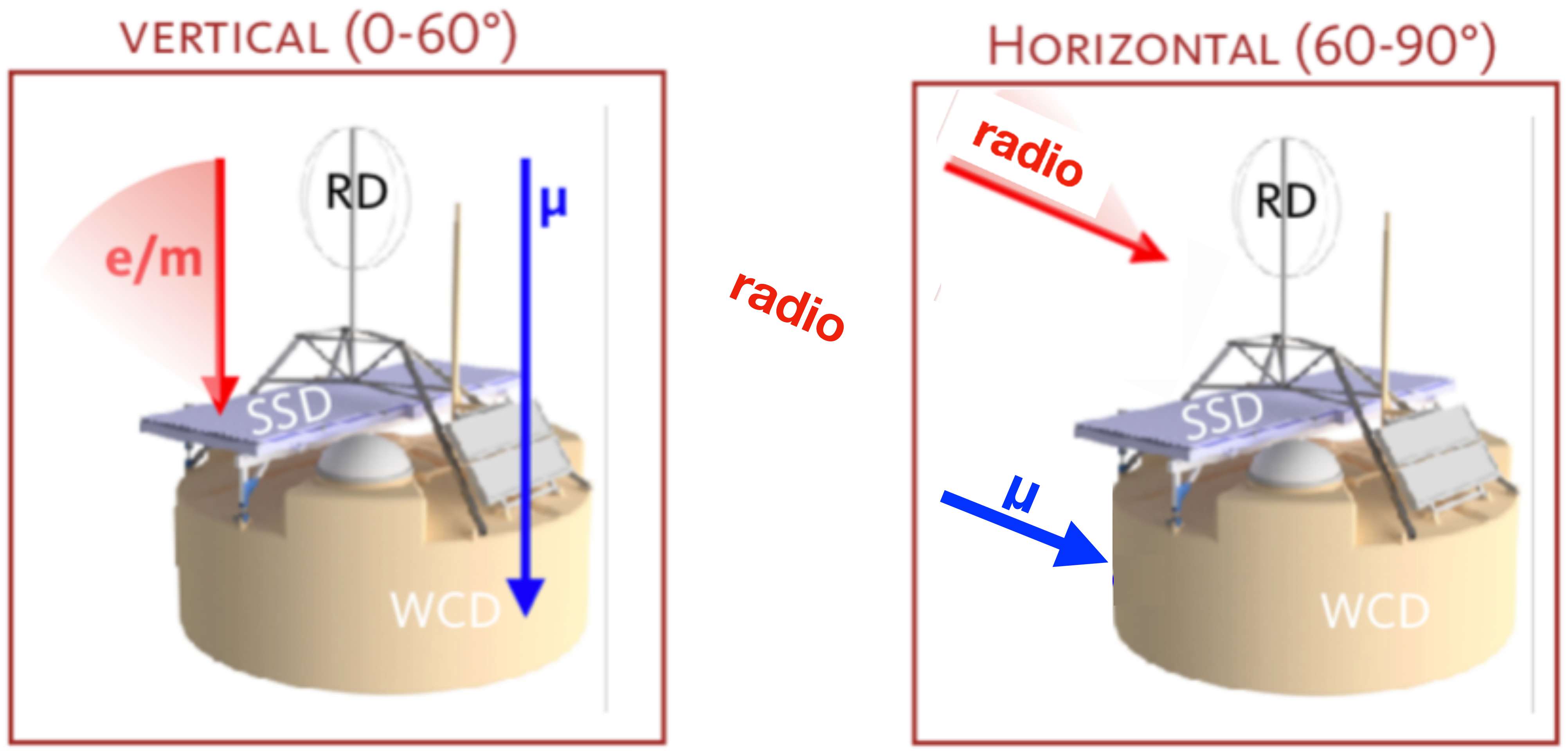


Upgrade of the Observatory – AugerPrime

Physics motivation

- Composition measurement up to 10^{20} eV
- Composition selected anisotropy
- Particle physics with air showers
- Much better understanding of **new and old** data

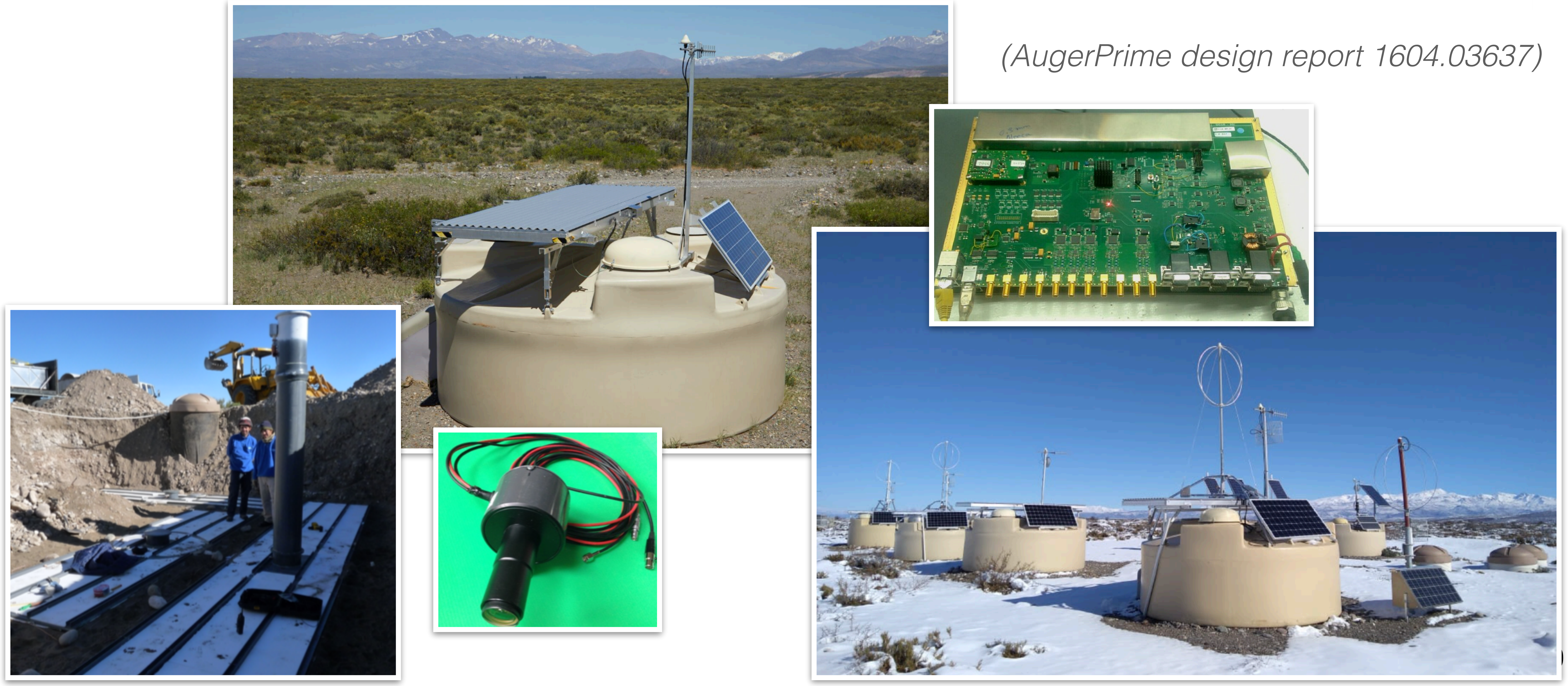
Composition sensitivity with 100% duty cycle



(AugerPrime design report 1604.03637)

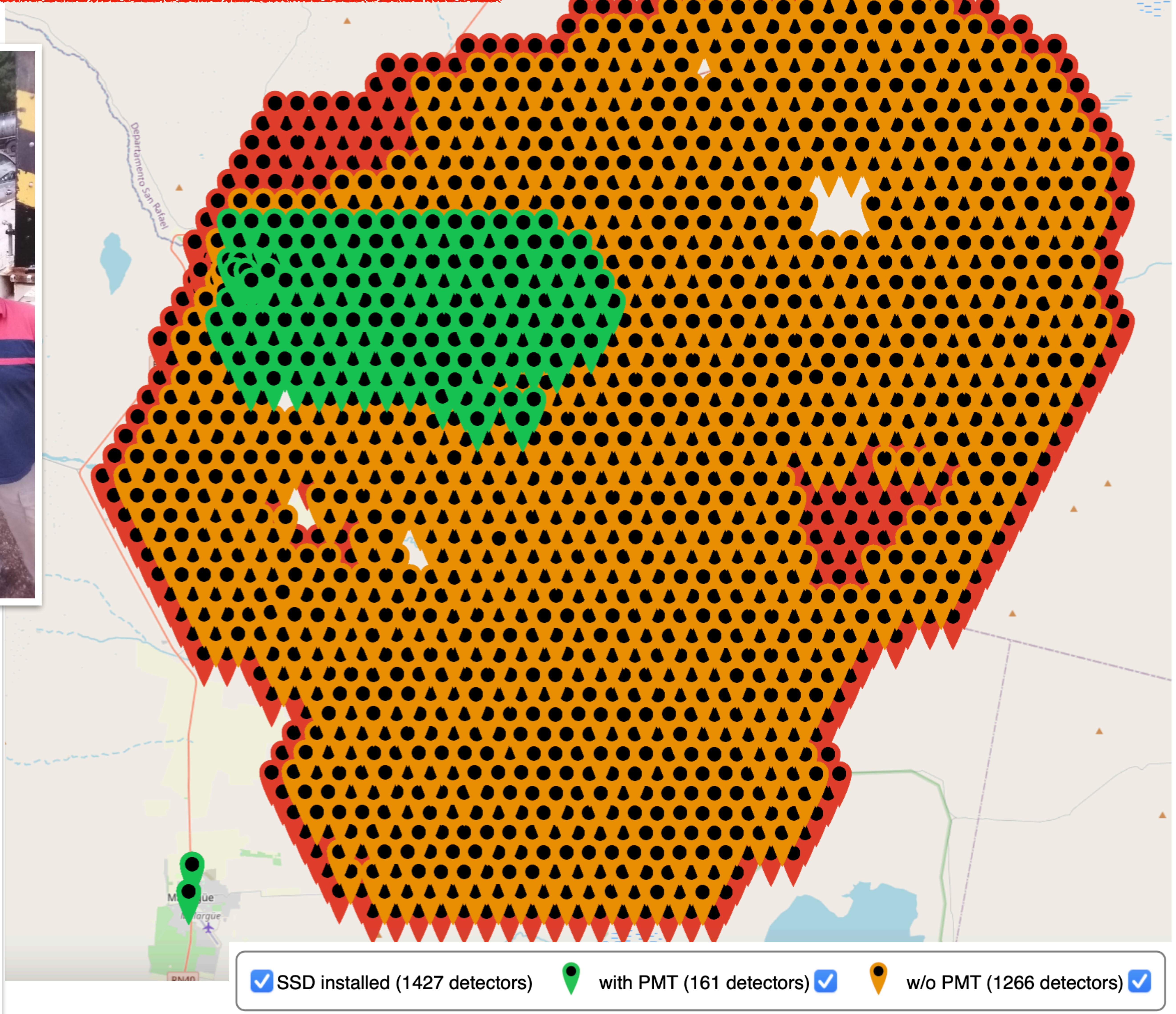
Components of AugerPrime

- 3.8 m^2 scintillator panels (SSD)
- New electronics (40 MHz -> 120 MHz)
- Small PMT (dynamic range WCD)
- Radio antennas for inclined showers
- Underground muon counters (750 m array, 433 m array)
- Enhanced duty cycle of fluorescence tel.

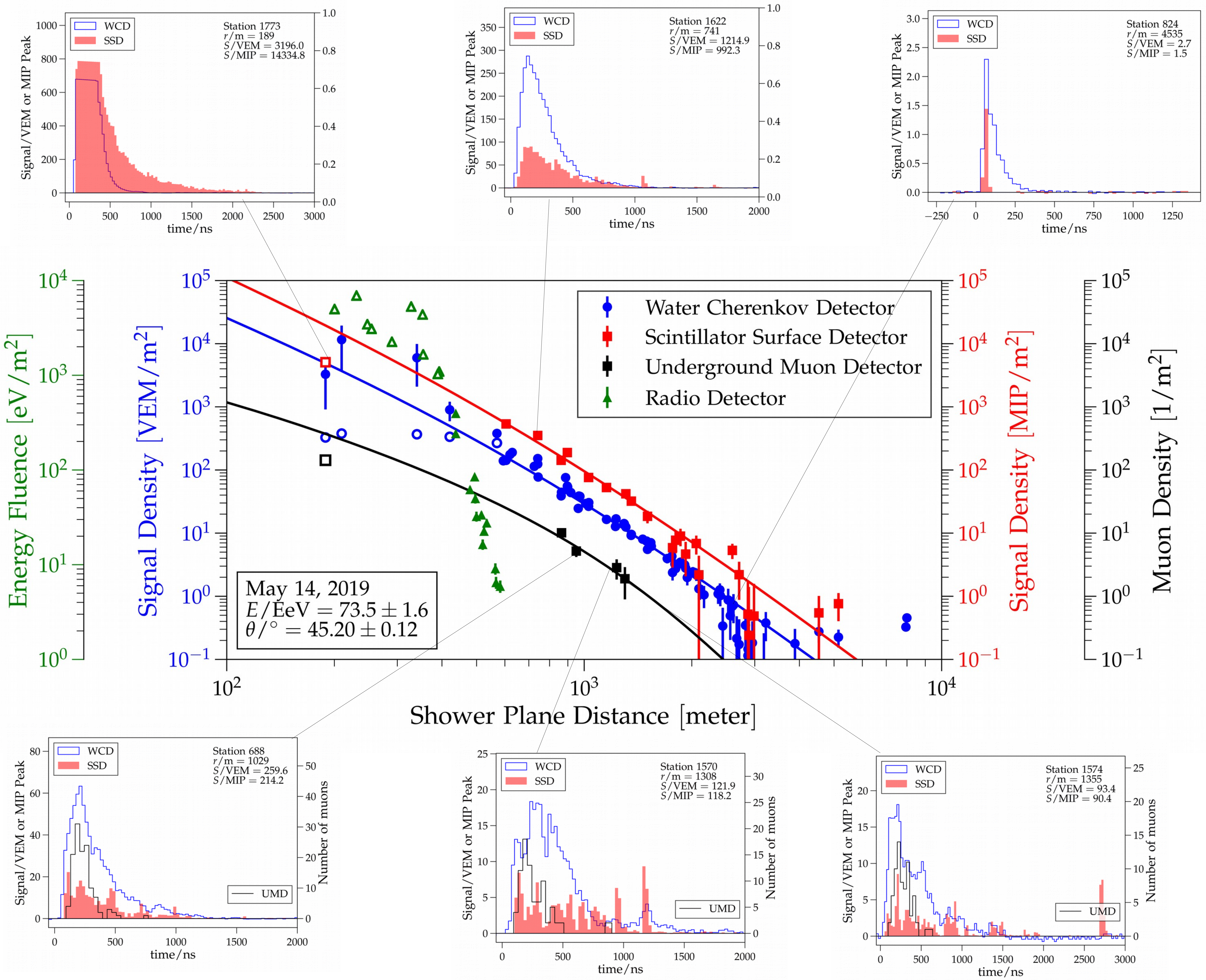


Progress of AugerPrime deployment

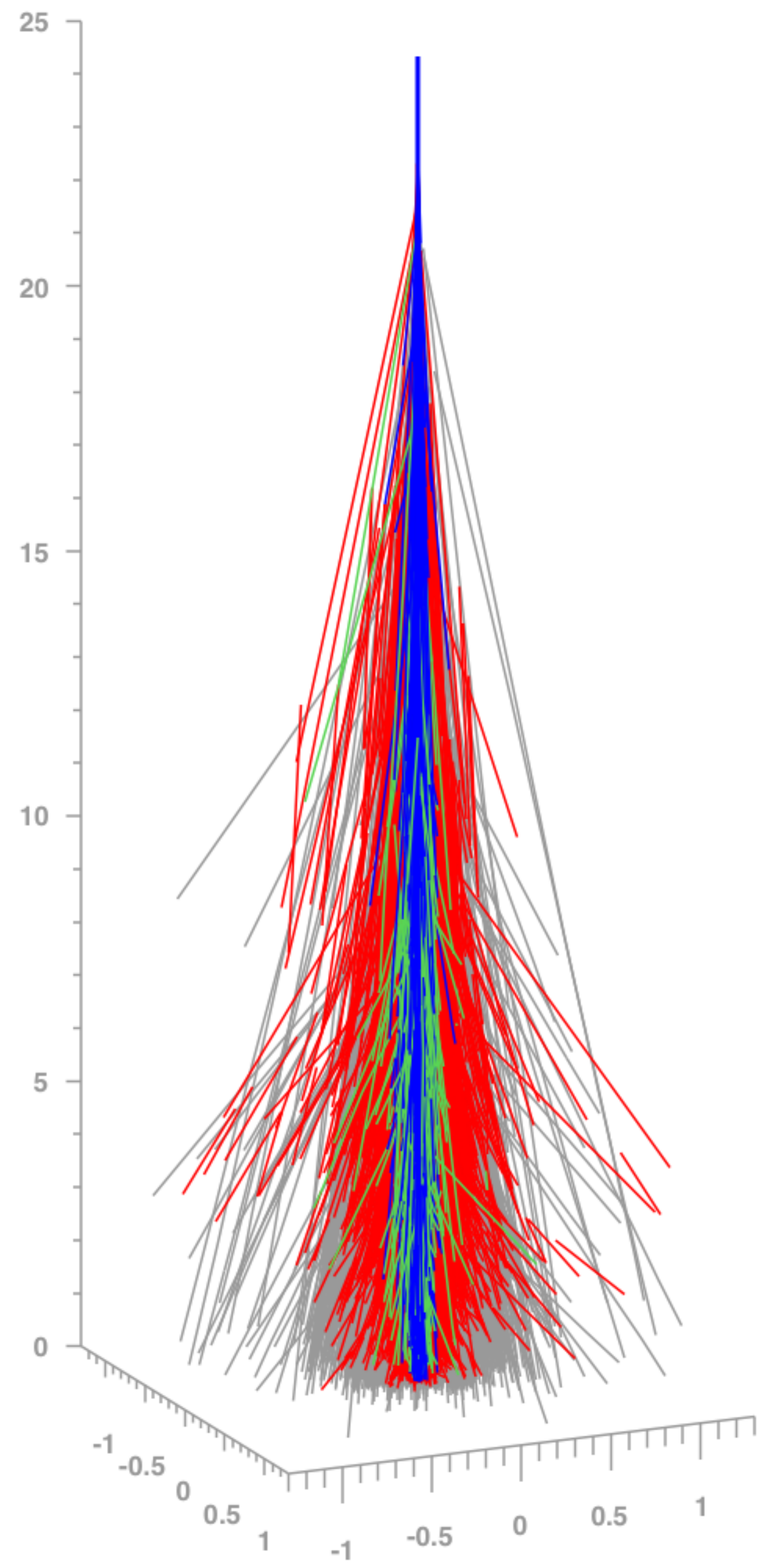
130 new stations are taking data



AugerPrime: New quality of data – multi-hybrid measurements

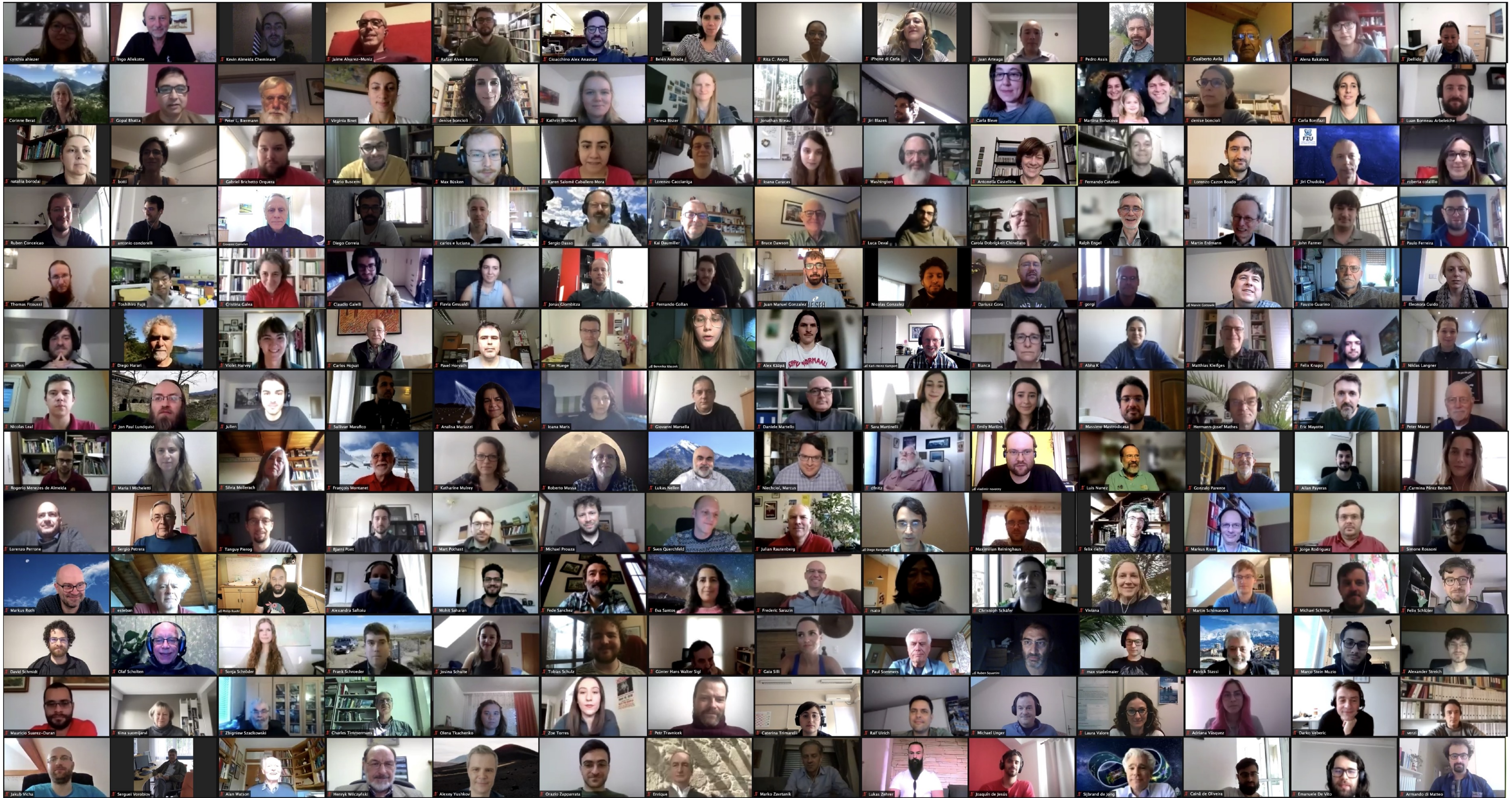


Summary



- Pierre Auger Observatory has very rich data set
- All-particle spectrum does not follow simple GZK suppression
- Flux suppression most likely superposition of maximum energy of injected particles and energy losses (GZK secondaries as tracers of composition)
- LHC data of fundamental importance for interpretation of cosmic ray data
  - *Only p-p data for far, p-O considered for Run 3*
  - *Need pion-proton and pion-oxygen data too (LHCf+ATLAS)*
- Very moderate increase of proton-air and proton-proton cross sections favored up to $10^{18.3}$ eV – conservative extrapolations favored
- Either unexpected (i.e. not predicted) source scenario for highest energies or very exotic particle physics (Auger will be like Münchhause)
- Apparently serious problem with muon production in air showers – new physics?
- Multiplicity fluctuations in first interactions seem to be “normal”
- Upgrade AugerPrime will increase sensitivity to mass composition and particle physics observables up to very highest energies

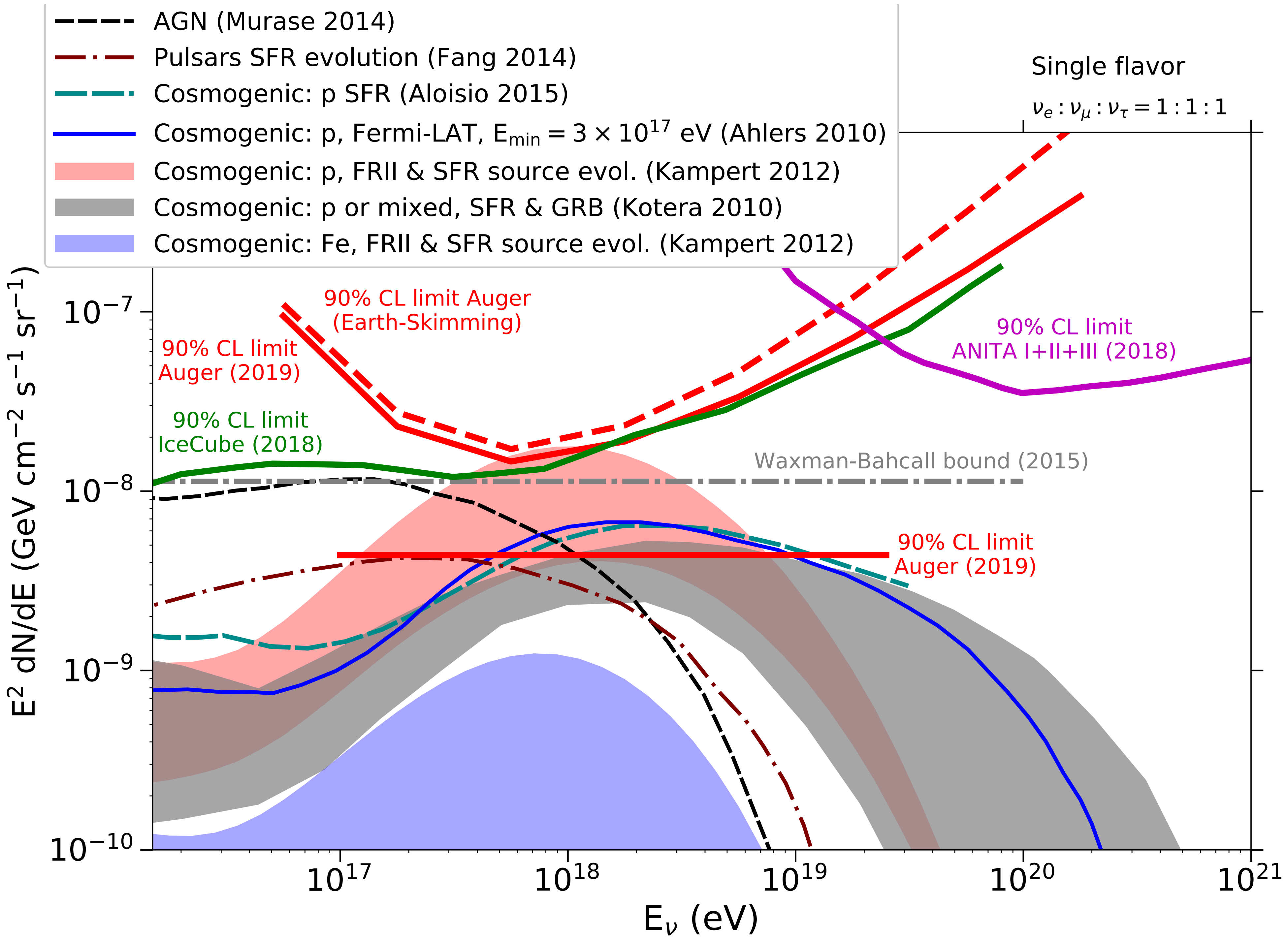
Zoom photograph of the Pierre Auger Collaboration

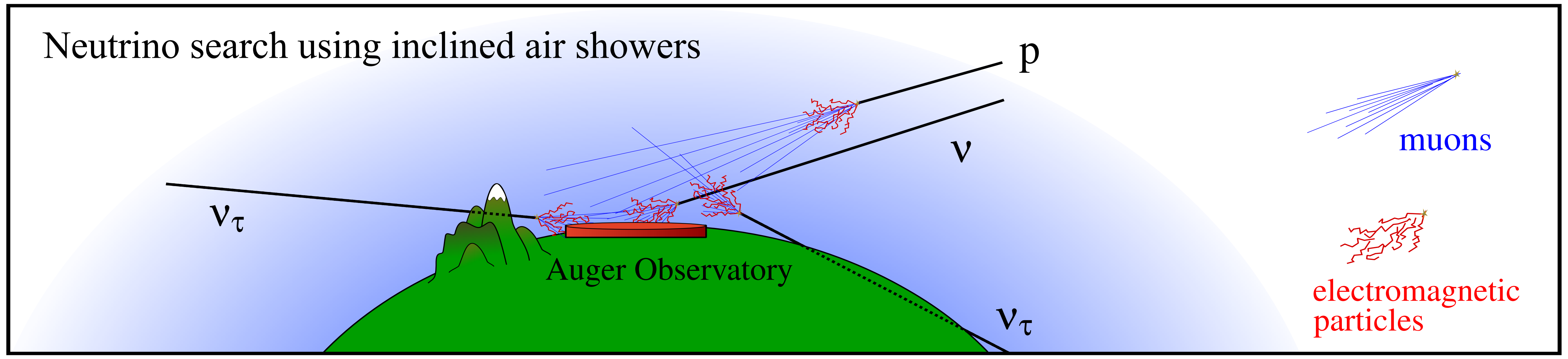


Science, Fun & Adventure

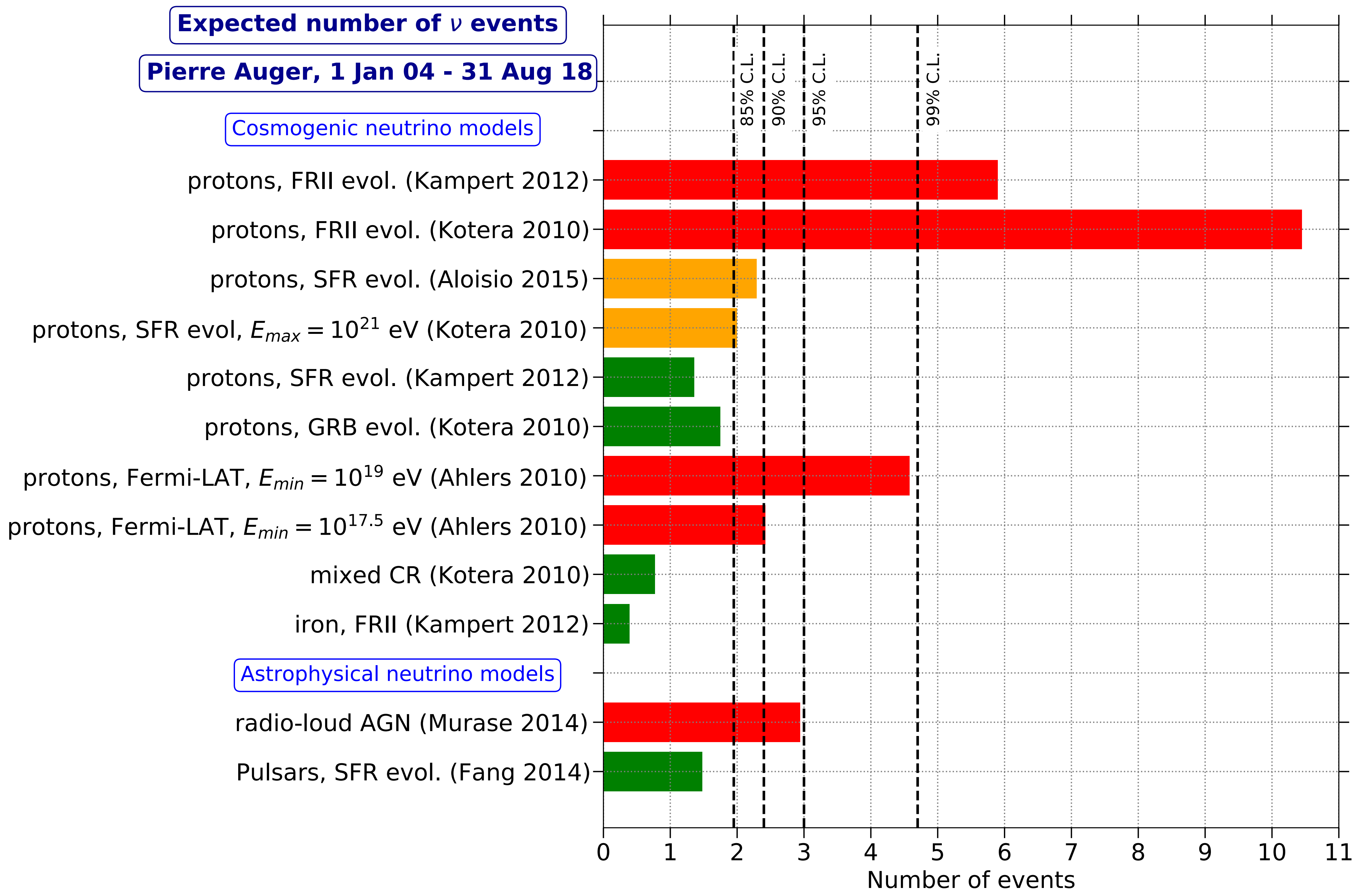
Backup slides

Searches: Ultra-high energy neutrinos





(JCAP 10 (2019) 022, JCAP 11 (2019) 004)



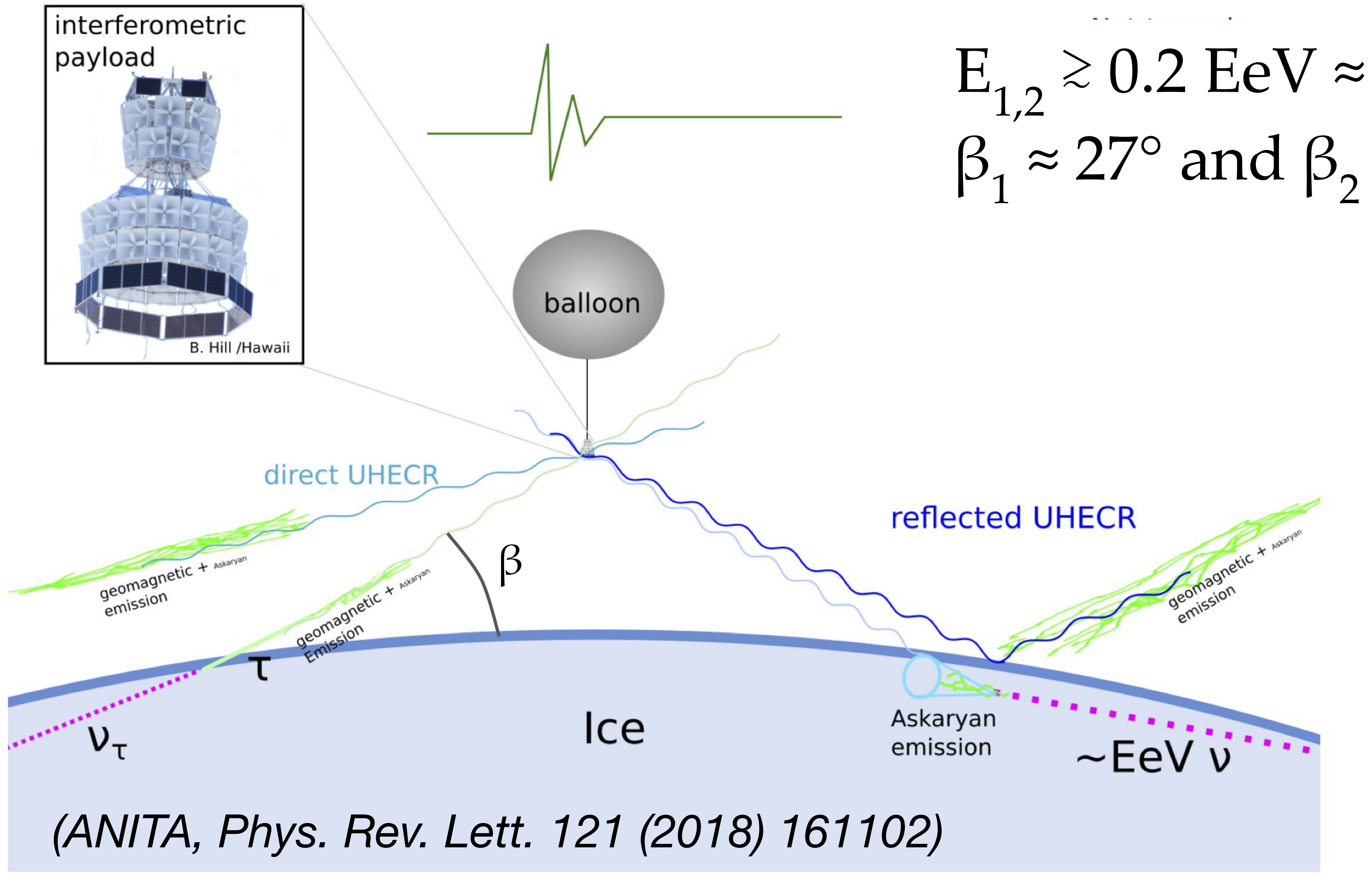
Aperture comparable to IceCube if direction of source is favorable
Multi-messenger: searches for neutrinos in coincidence with GW events
Phase II: lowering of detection threshold (new electronics)

(Michael Schimp)

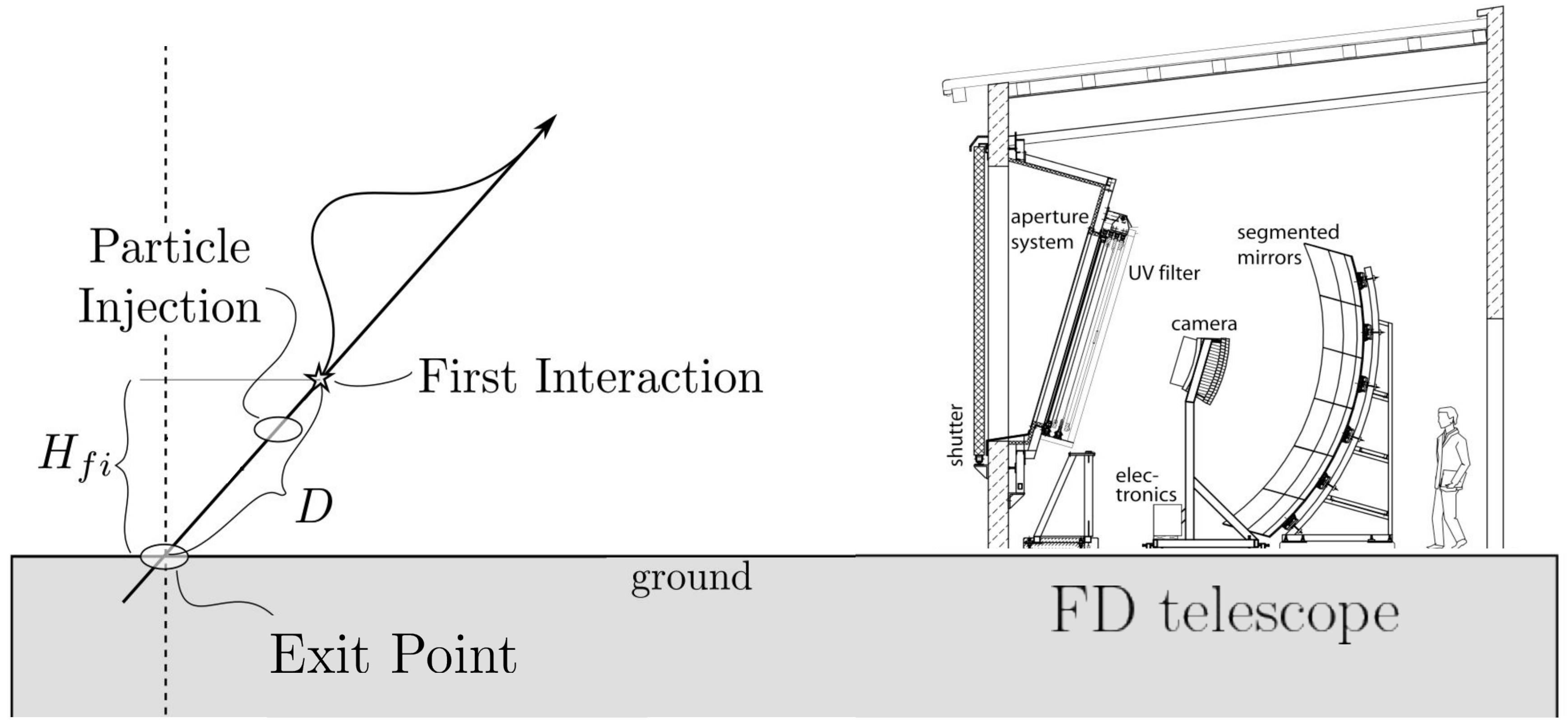
(UHECR 2018, updated)

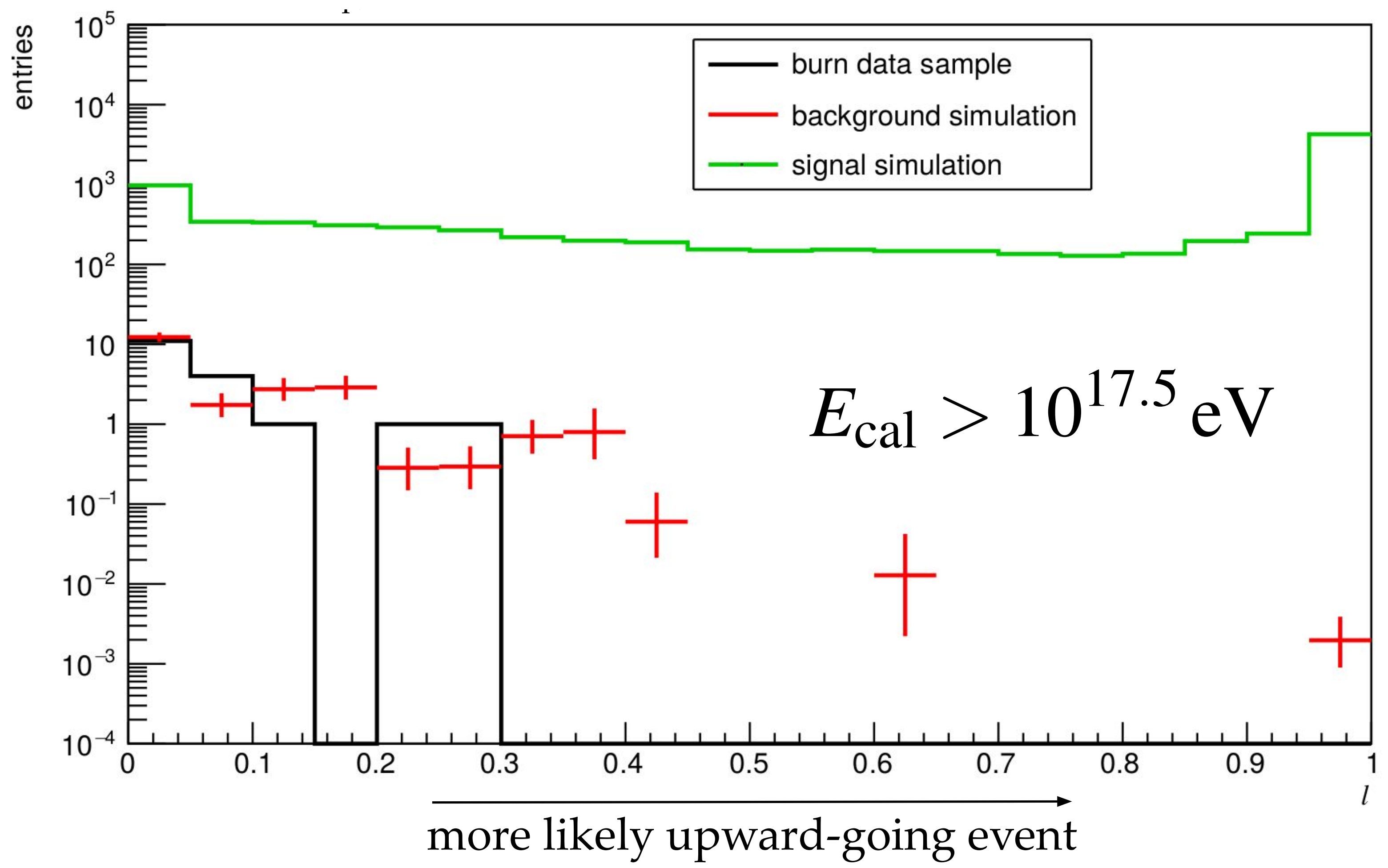
Searches: Upward-going events motivated by ANITA

$E_{1,2} \gtrsim 0.2$ EeV $\approx 10^{17.8}$ eV
$\beta_1 \approx 27°$ and $\beta_2 \approx 35°$



(ANITA, Phys. Rev. Lett. 121 (2018) 161102)

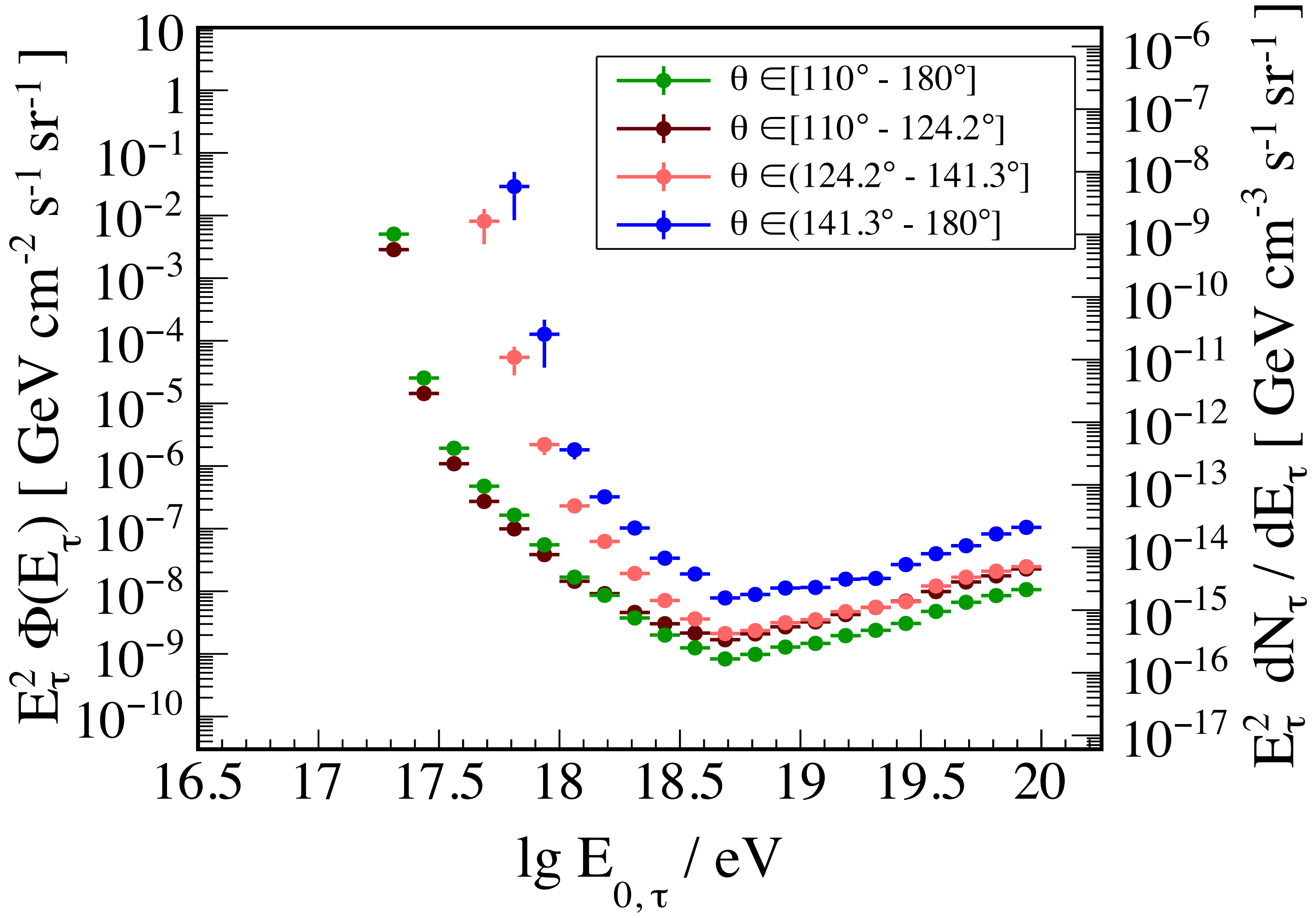




(Eva Santos)

Auger results:
Background 0.45 ± 0.18 expected
One event observed
Flux limits on anomalous events

Tau scenario



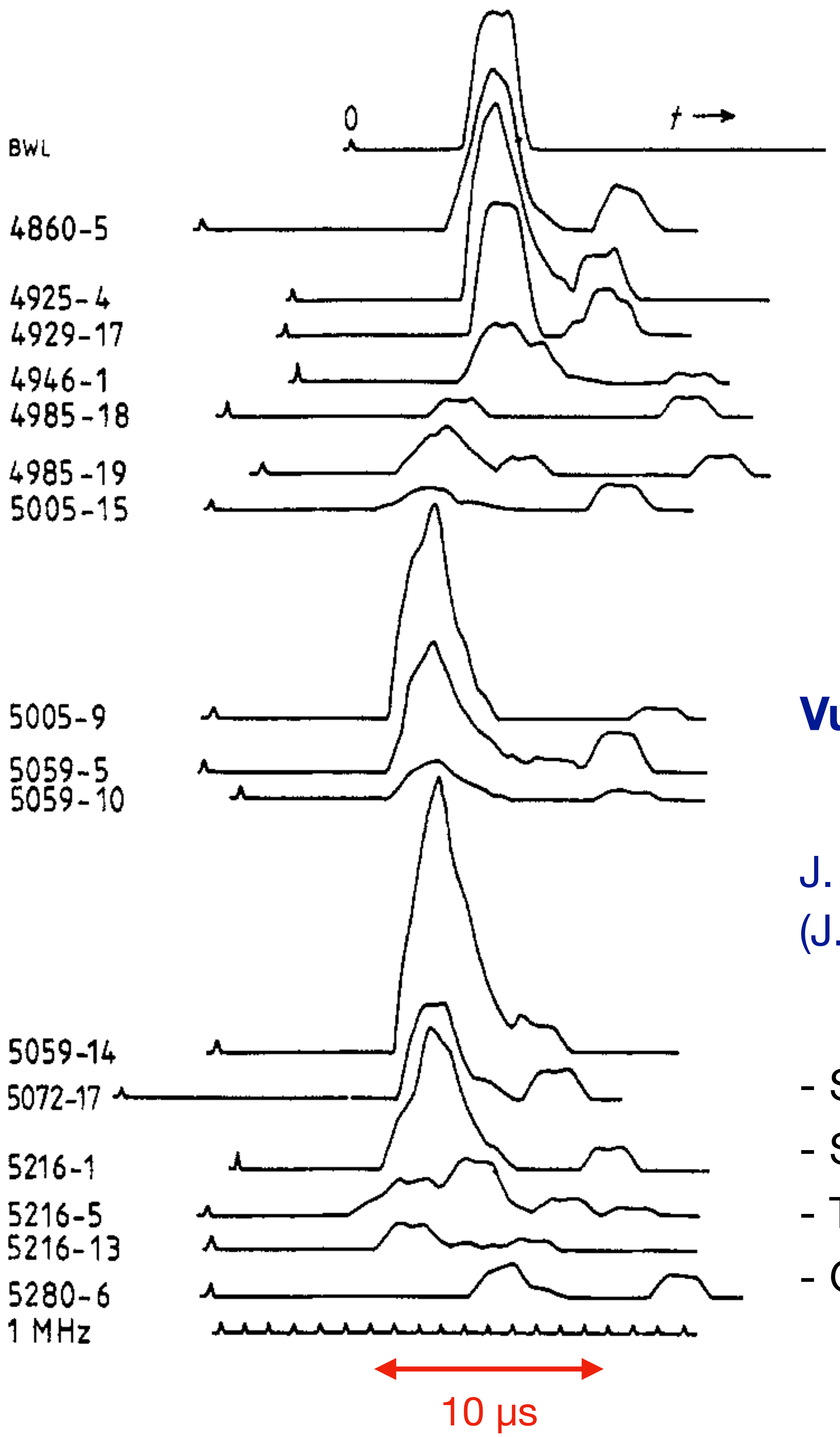
Uniform distribution

3.6×10^{-20} cm^{-2} sr^{-1} yr^{-1} if exposure is weighted with **E^{-1}**

8.5×10^{-20} cm^{-2} sr^{-1} yr^{-1} if exposure is weighted with **E^{-2}**

(Ioana Caracas) (Massimo Mastrodicasa)

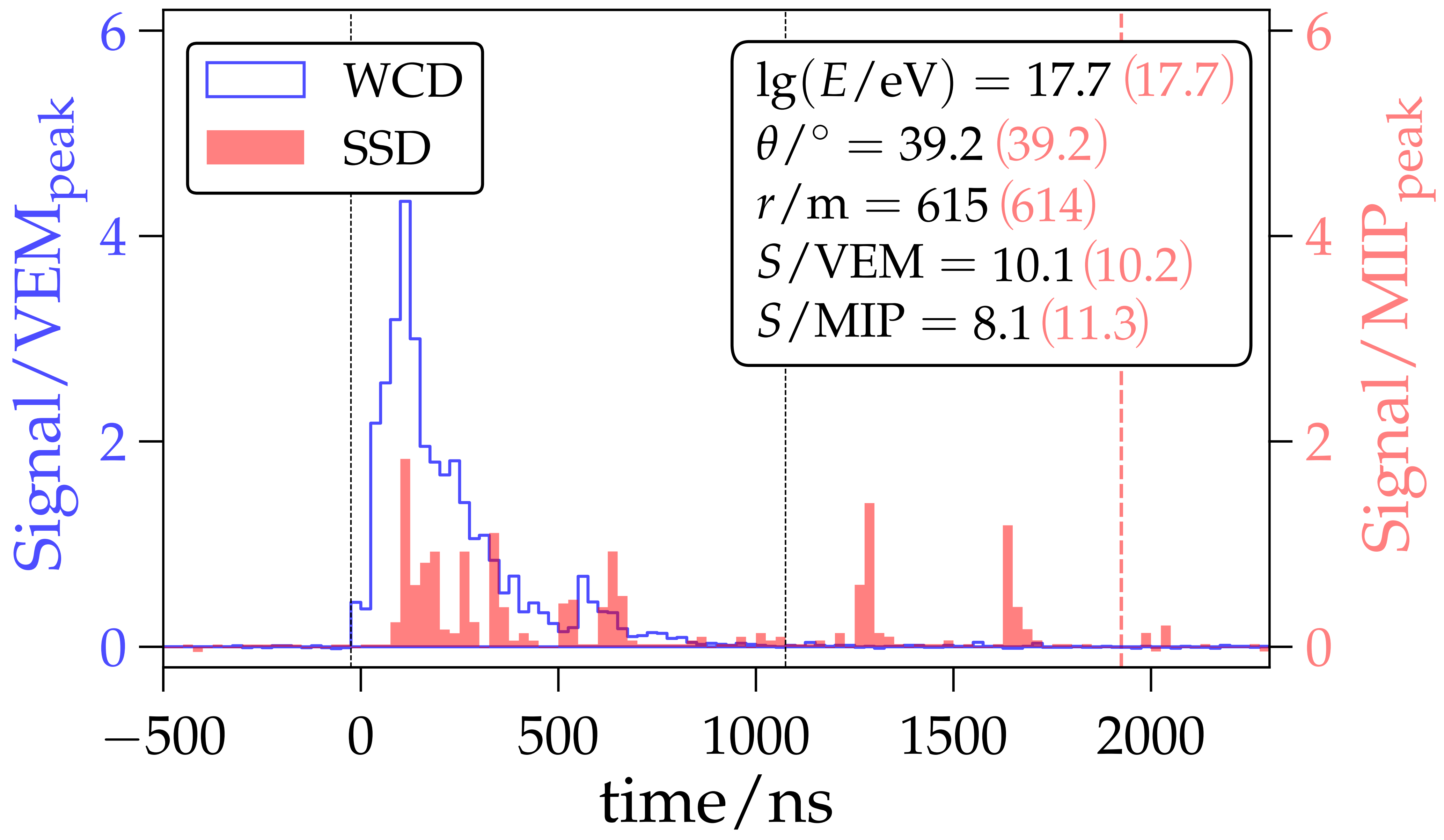
Sub-luminal neutrons in air showers



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

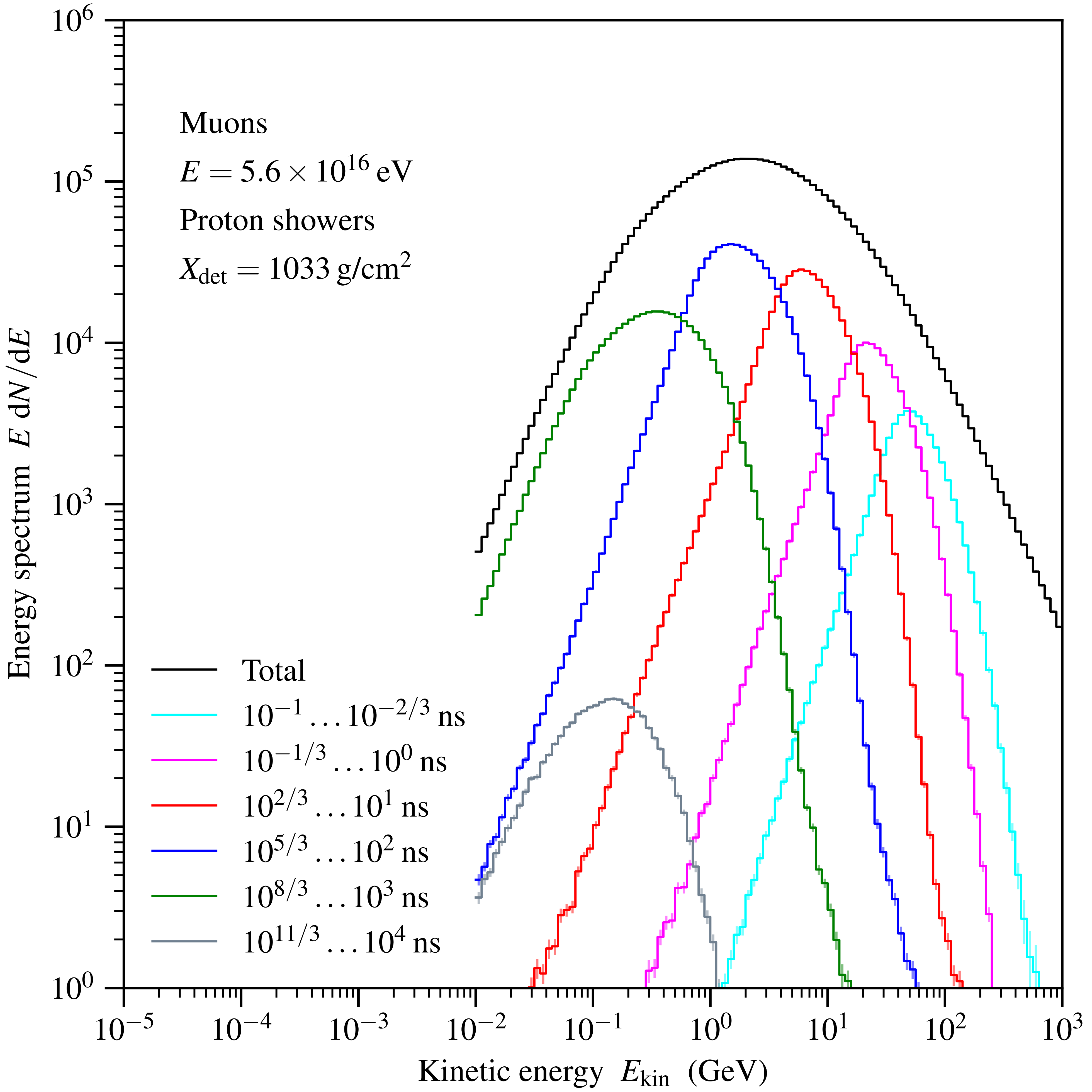


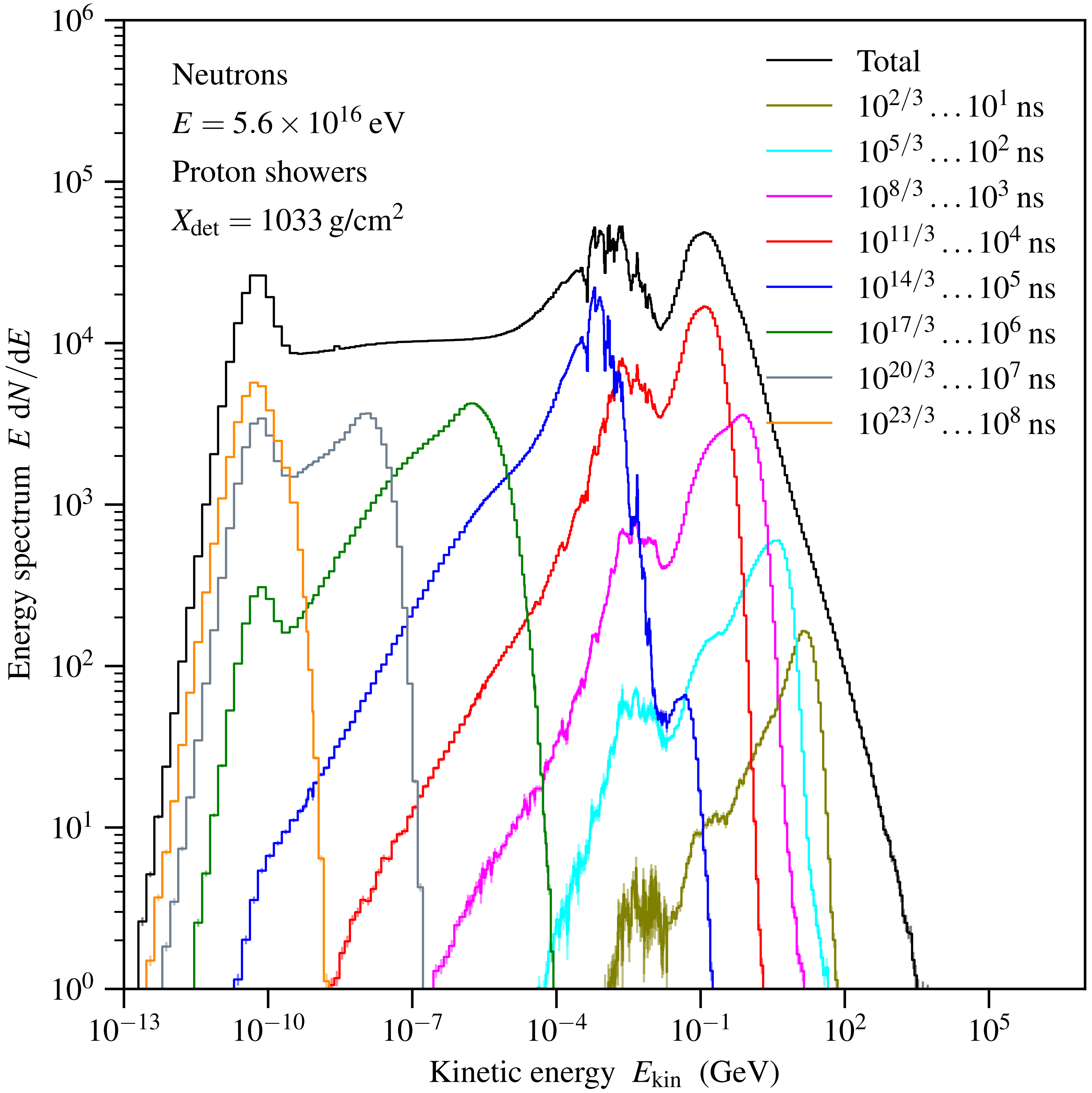
AugerPrime (2020-21)

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



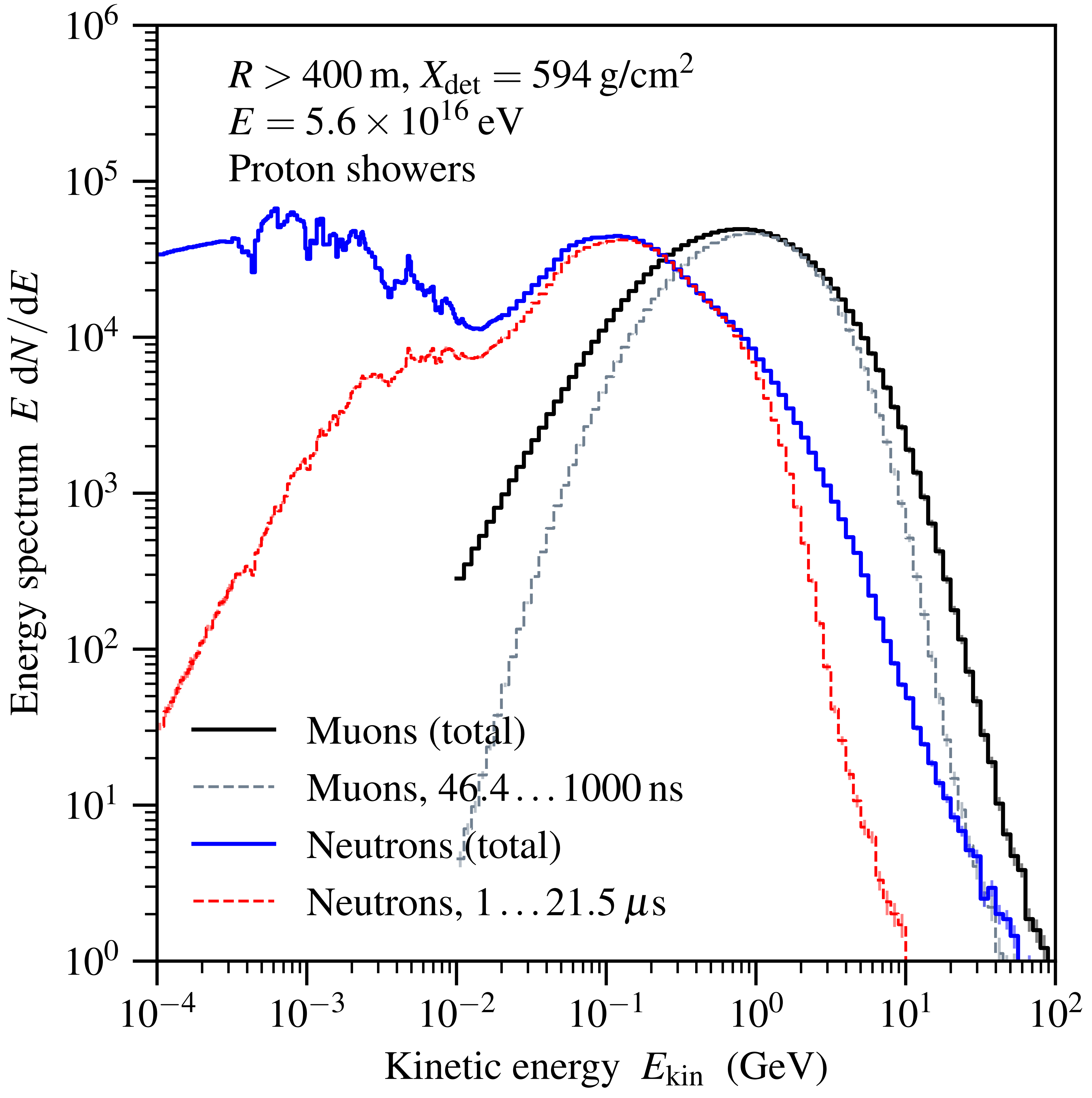


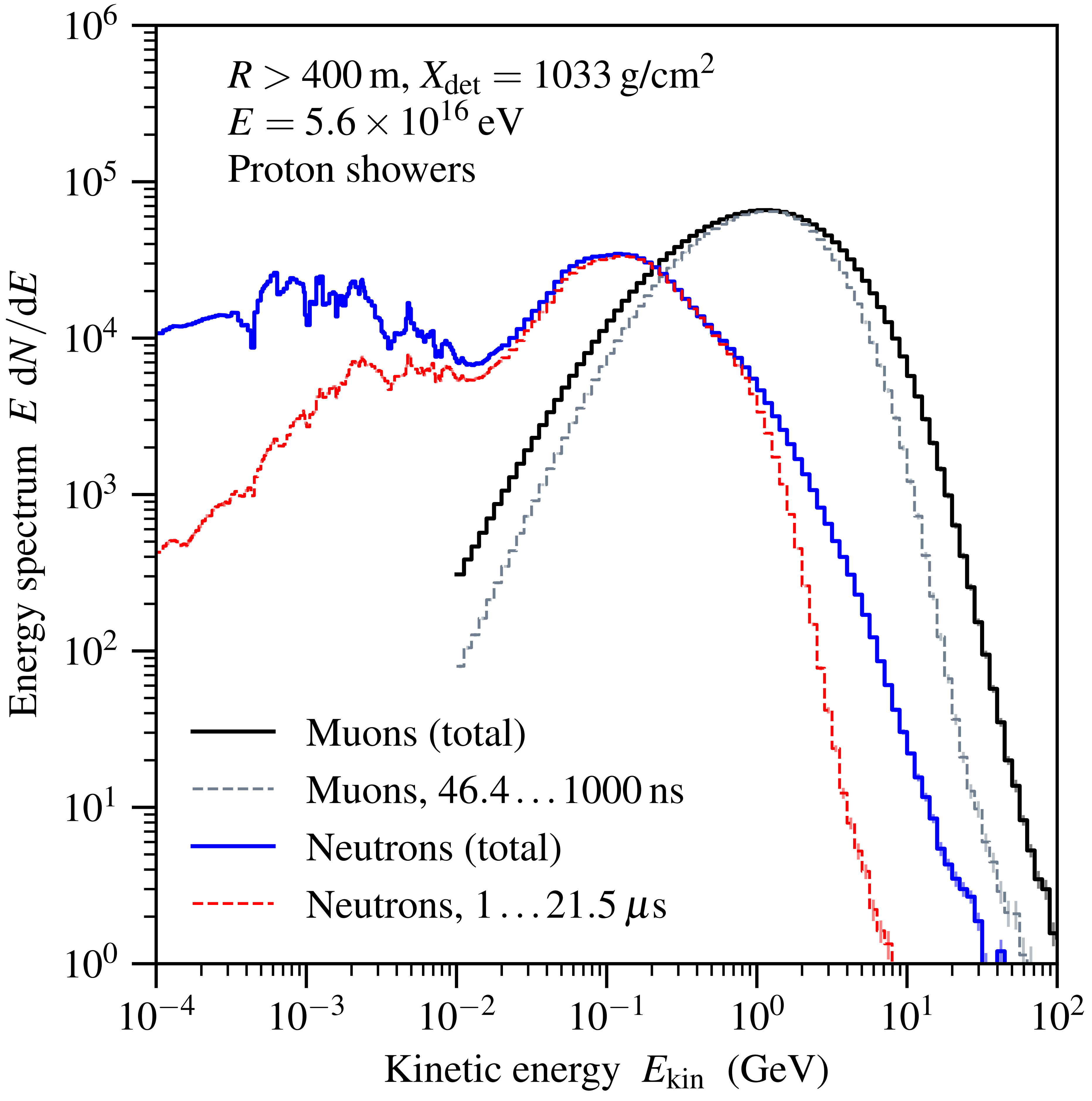
Muons: time delay of bulk of particles: 1 - 500 ns

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

(RE & Ferrari et al. ICRC 2021)

Air shower results: muons vs. neutrons at large distance





Close to shower maximum: neutrons as abundant as muons

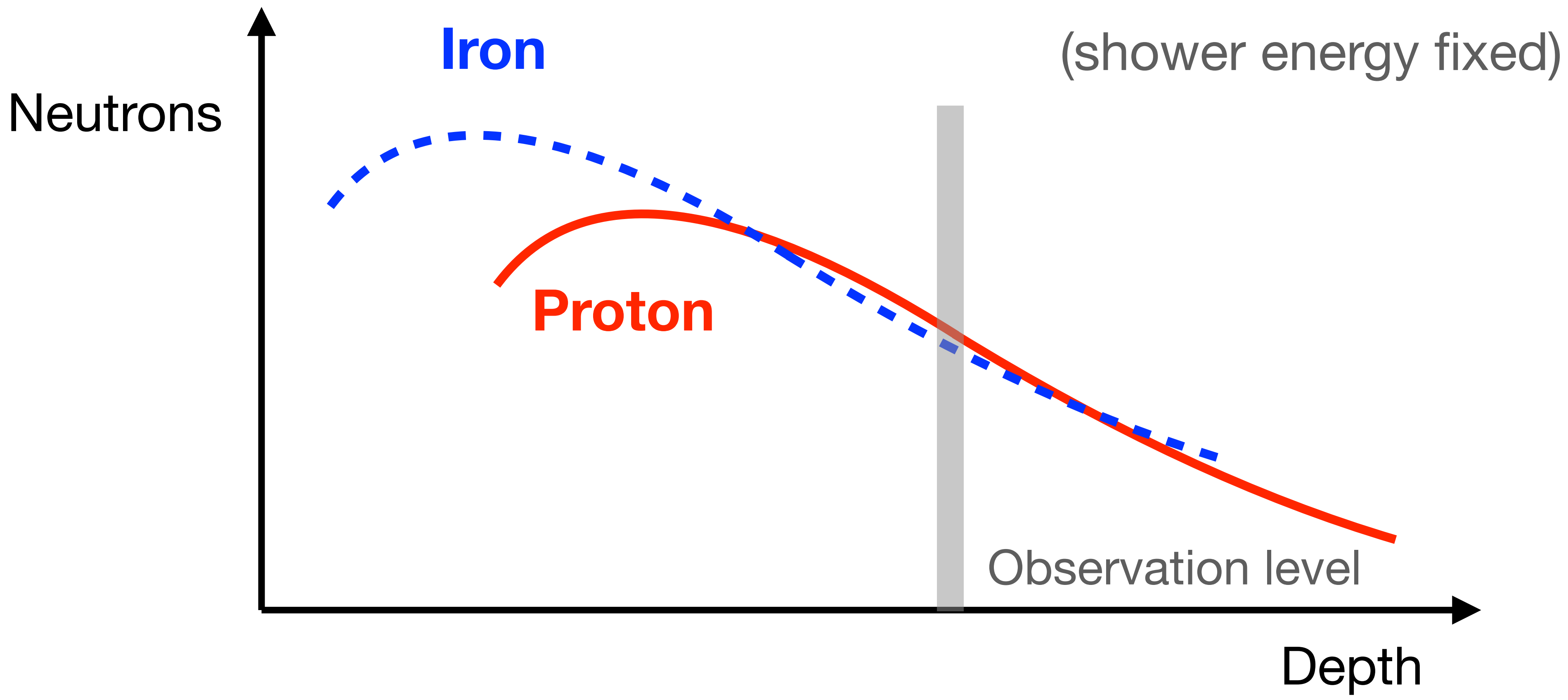
Past shower maximum: neutrons much less abundant than muons

(RE & Ferrari et al. ICRC 2021)

Do we learn anything from sub-luminal neutrons?

Neutrons

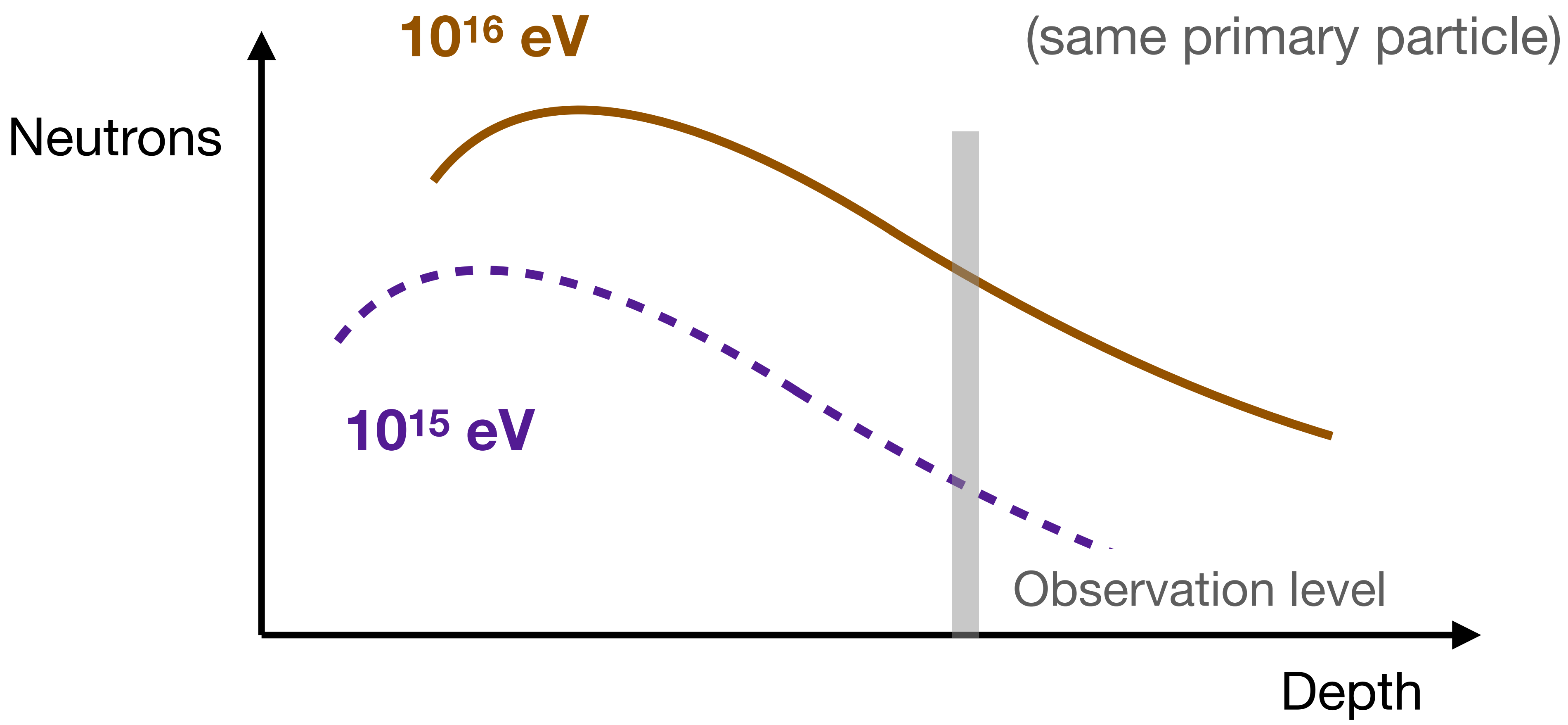
- Interesting sub-luminal particles
- Feature-rich and very wide energy spectrum
- Notoriously difficult to detect
- Very difficult to simulate accurately (environment)
- Expected to produce late pulses in scintillators



Reduced composition sensitivity?

Scaling observations

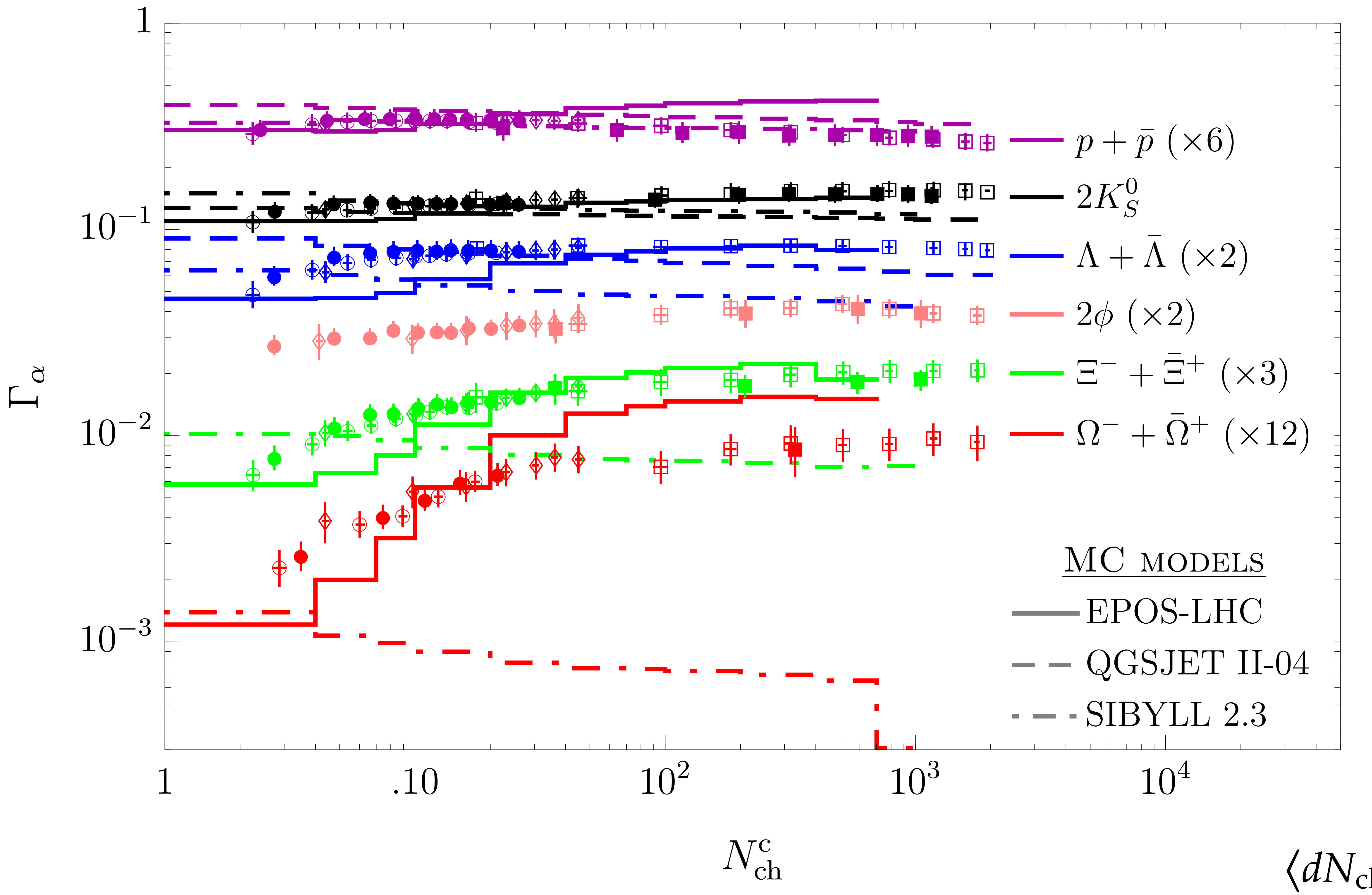
- Energy scaling of production similar to muons
- Primary dependence of production like muons
- Attenuation (neutron removal) length 80 … 200 g/cm^2
- Very wide lateral distribution, wider than muons
- Typical delay in arrival time ~ 1 … 20 μs (E_{kin} > 20 MeV)
- Thermal neutrons up to ~ 100 ms



Scaling faster than ~ $E^{0.9}$

(RE & Ferrari et al. ICRC 2021)

Empirical scaling of relative particle yields



$$\Gamma_{\alpha,i} \equiv \frac{N_{\alpha,i}}{N_{\pi,i}}$$

Data: ALICE Coll. 2019
p-p, p-Pb and Pb-Pb at LHC

$$\langle dN_{\rm ch}/d\eta \rangle_{|\eta|<0.5} = \frac{\int_{|\eta|<0.5} \frac{dN_{\rm ch}}{d\eta} d\eta}{\int_{|\eta|<0.5} d\eta} = N_{\rm ch}(|\eta| < 0.5)$$

$$\equiv N_{\rm ch}^{\rm c},$$

(Anchordoqui et al., Phys. Lett. B 810 (2020) 135837)