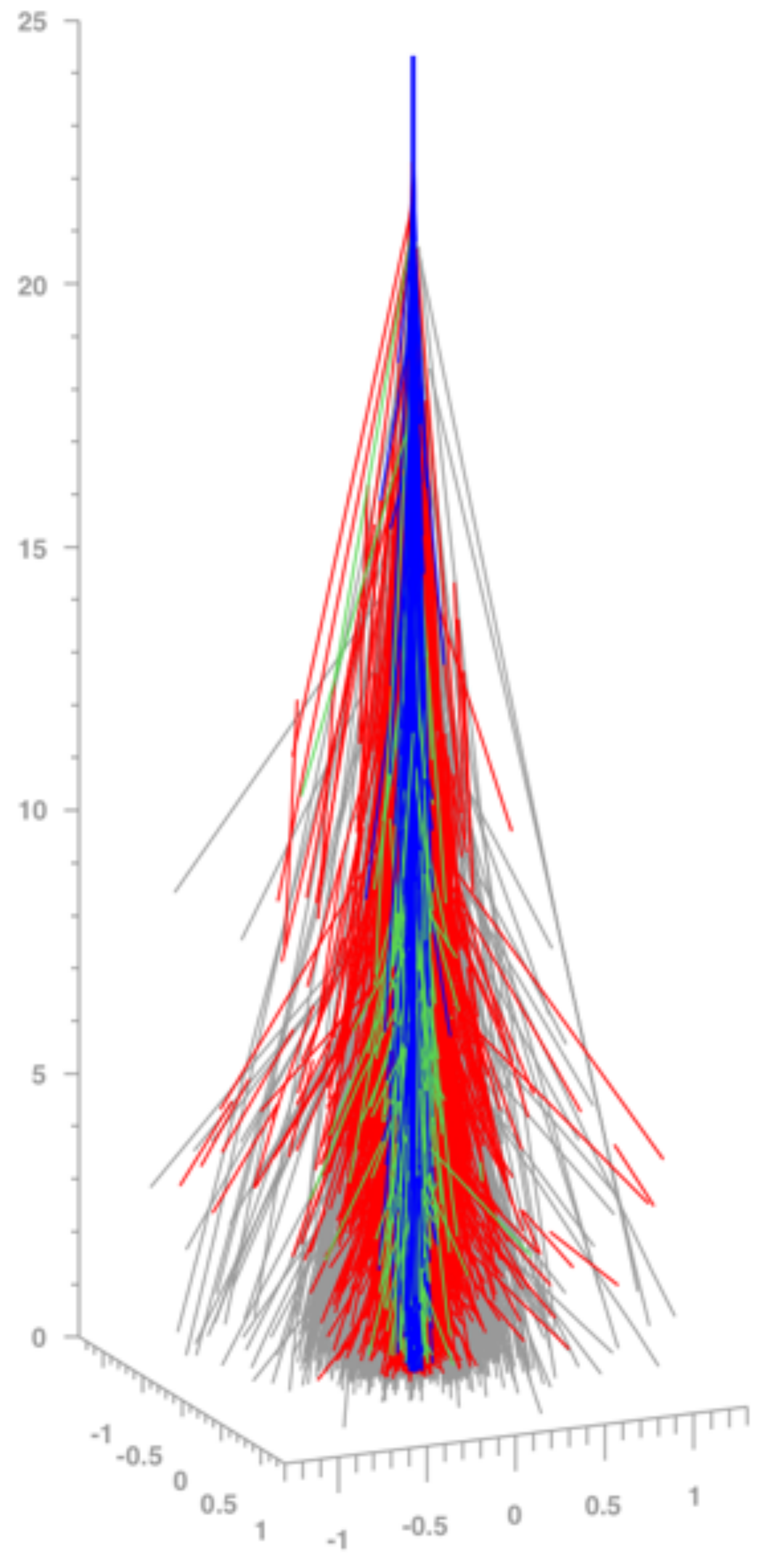
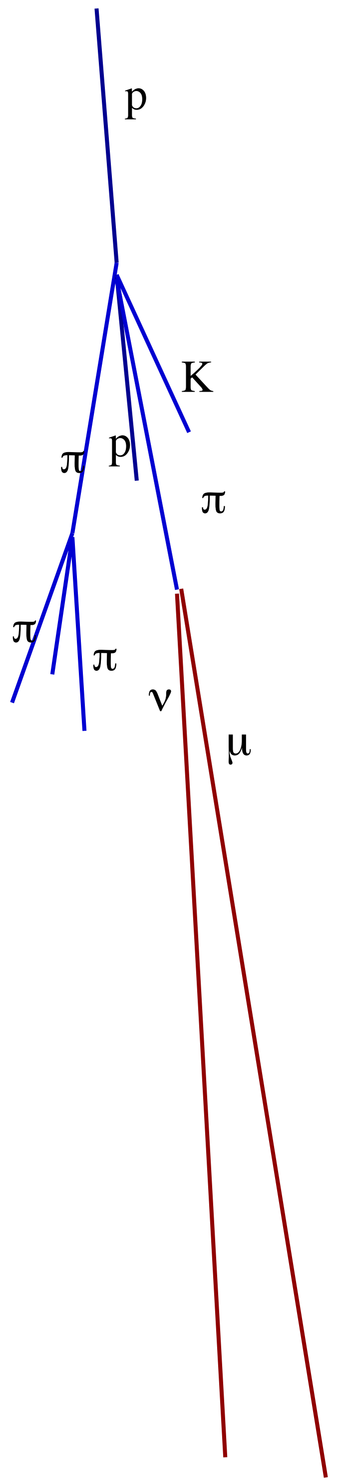
Relation between high energy particle and cosmic ray physics

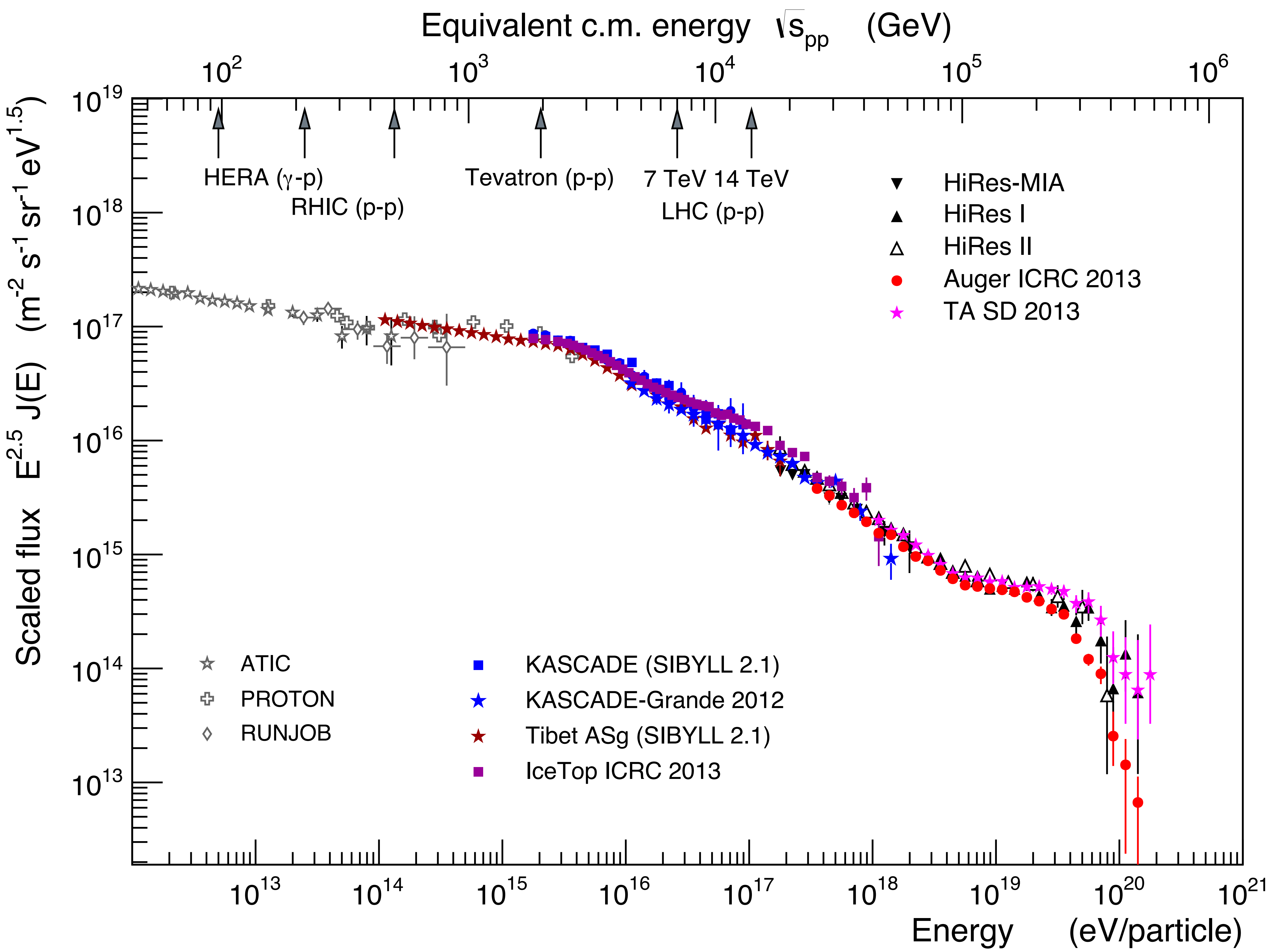


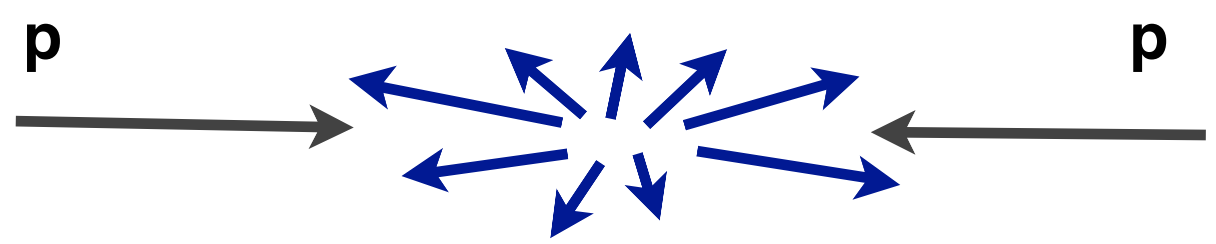
Ralph Engel *(Karlsruhe Institute of Technology)*

Karlsruhe Institute of Technology

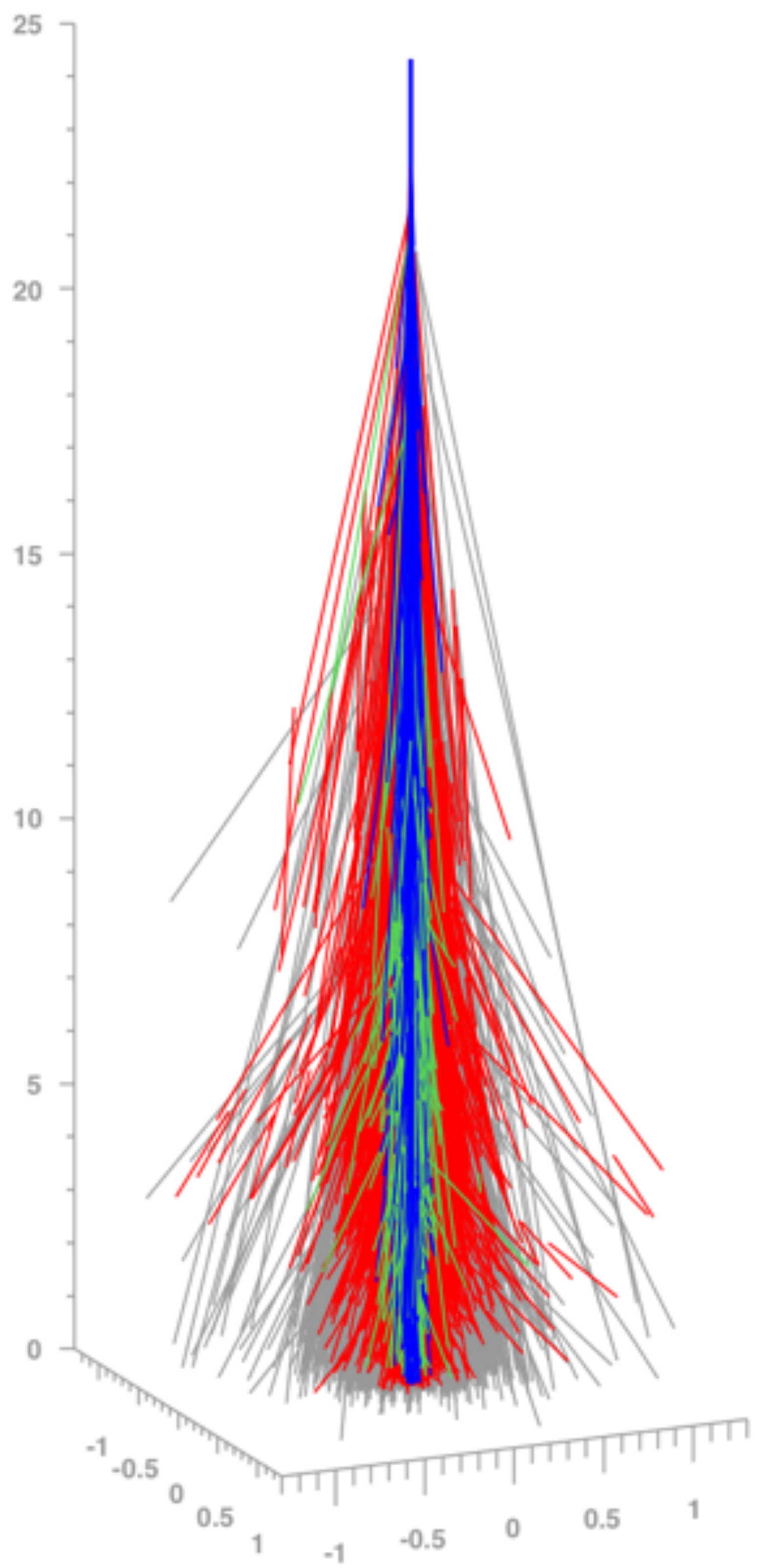
Cosmic ray flux and interaction energies



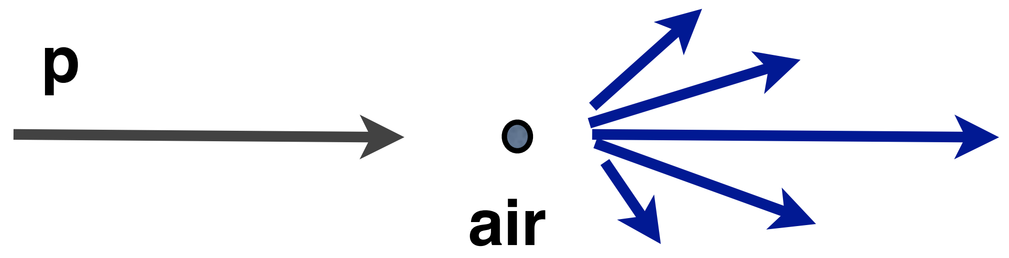




Center-of-mass energy

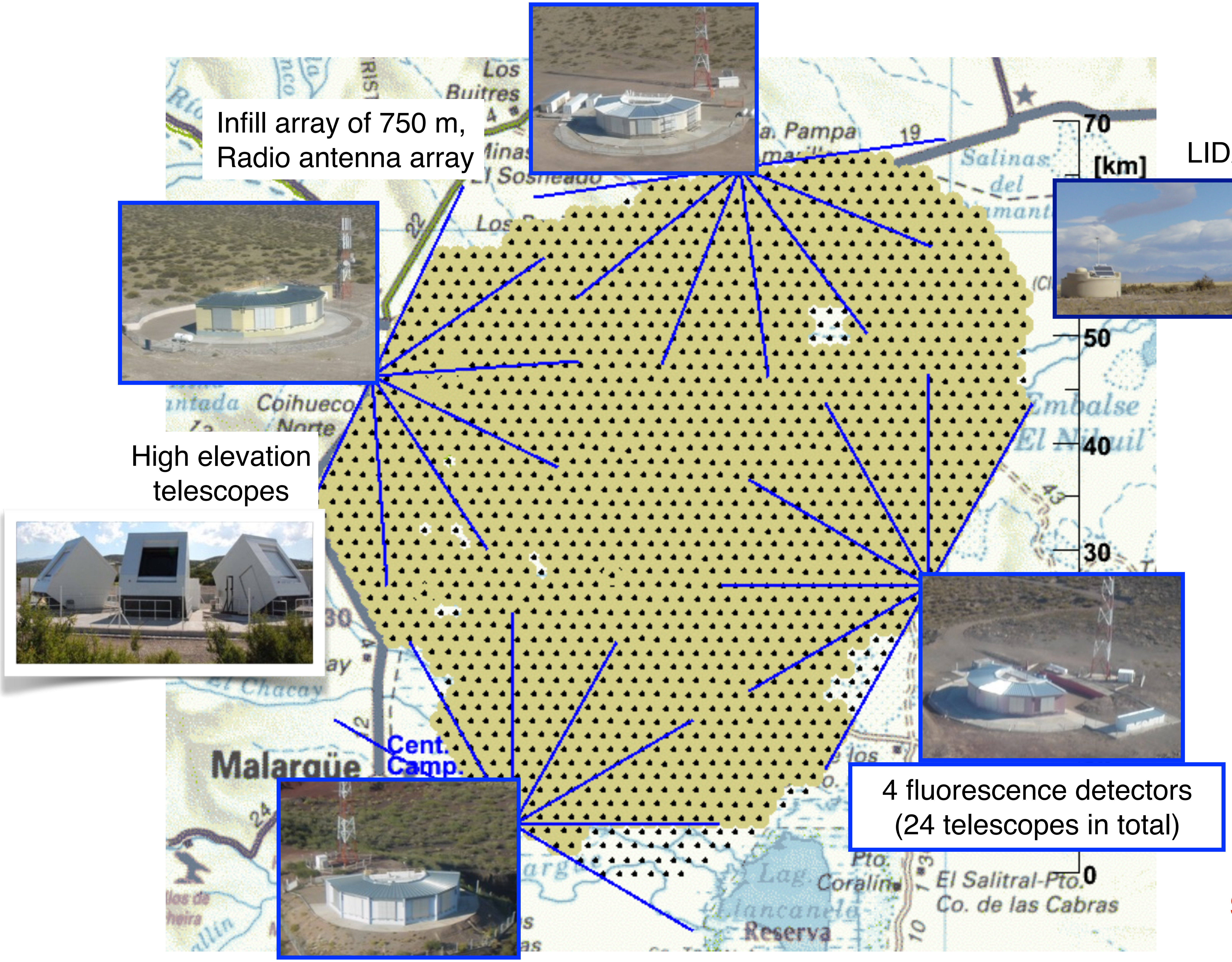


Laboratory energy



Example: cosmic-ray data at the highest energies

The Pierre Auger Observatory



LIDARs and laser facilities

1665 surface detectors:
water-Cherenkov tanks
(grid of 1.5 km, 3000 km²)

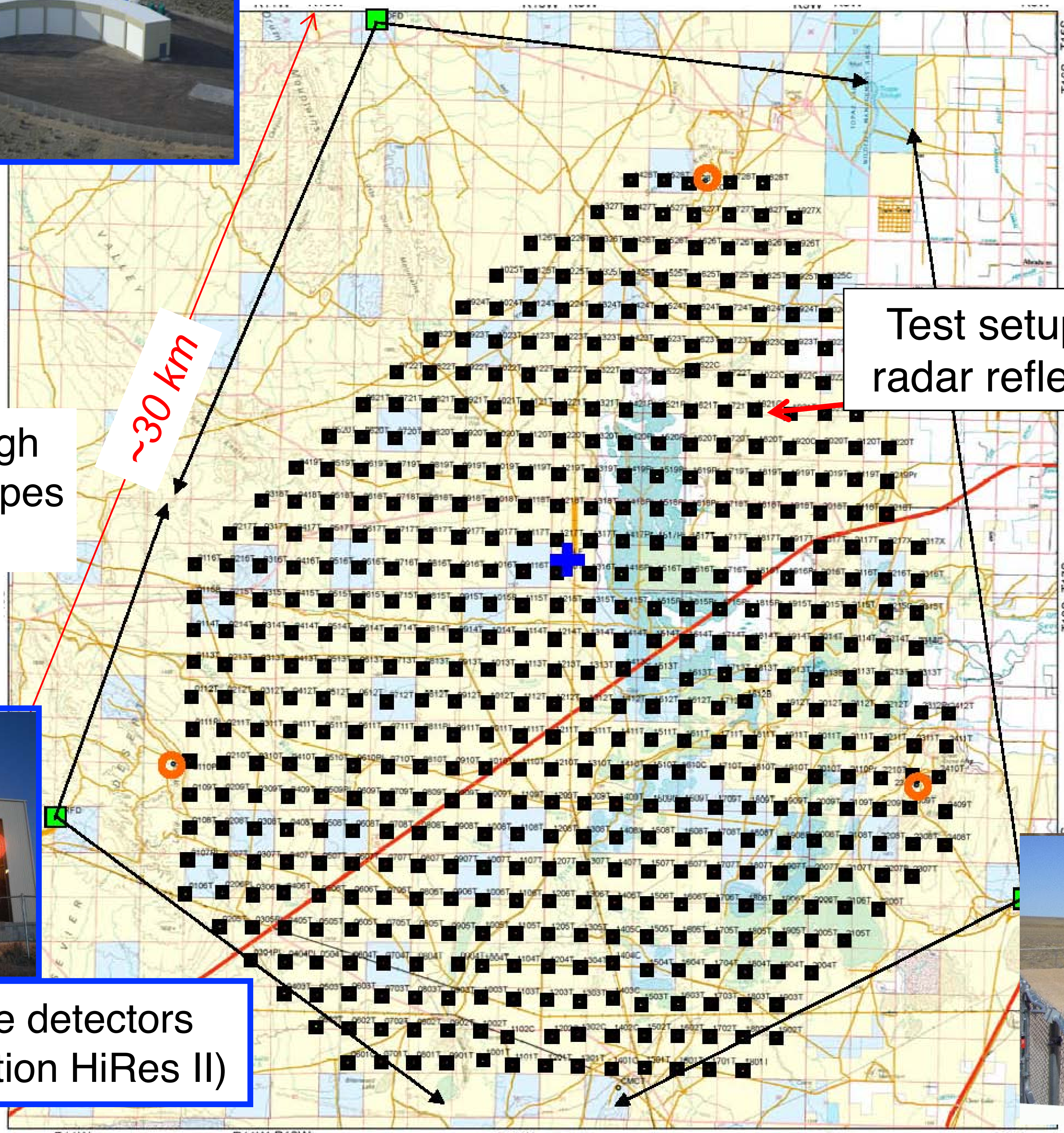
Southern hemisphere:
Province Mendoza, Argentina

Telescope Array (TA)

Middle Drum: based on HiRes II

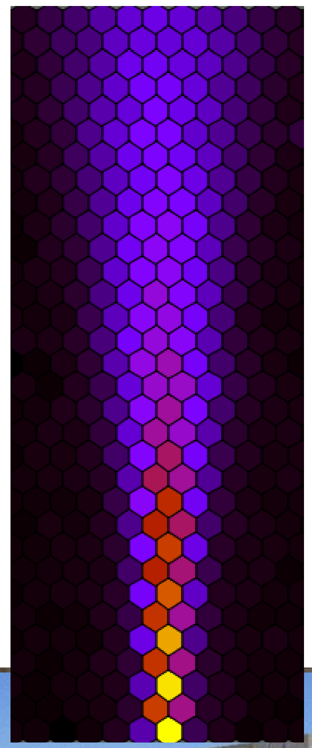
LIDAR
Laser facility

Infill array and high
elevation telescopes



3 fluorescence detectors
(2 new, one station HiRes II)

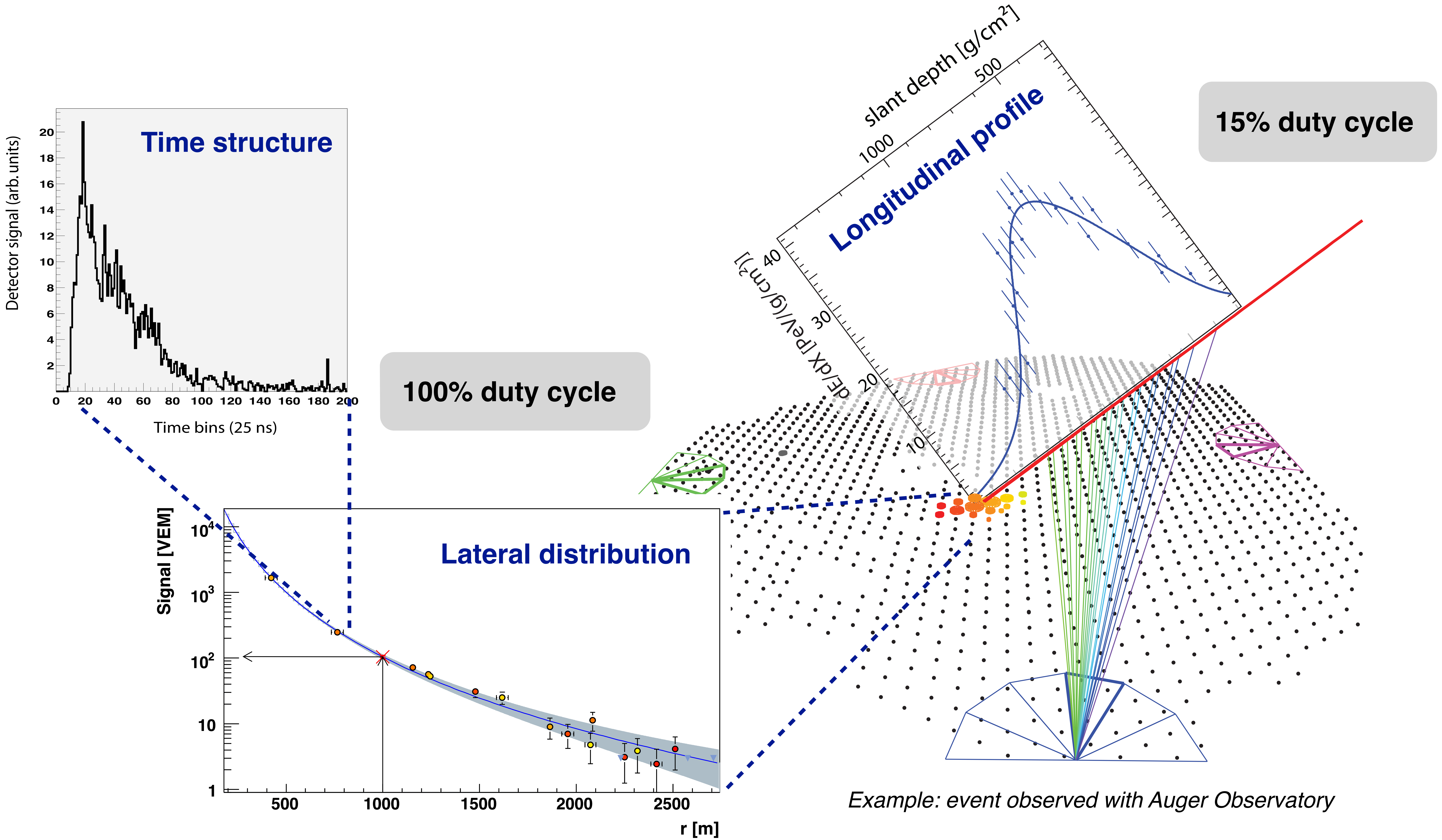
507 surface detectors:
double-layer scintillators
(grid of 1.2 km, 680 km²)



Electron light source
(ELS): ~40 MeV

Northern hemisphere: Utah, USA

Precision measurement of shower observables



Example: event observed with Auger Observatory

Air showers: electromagnetic and hadronic components

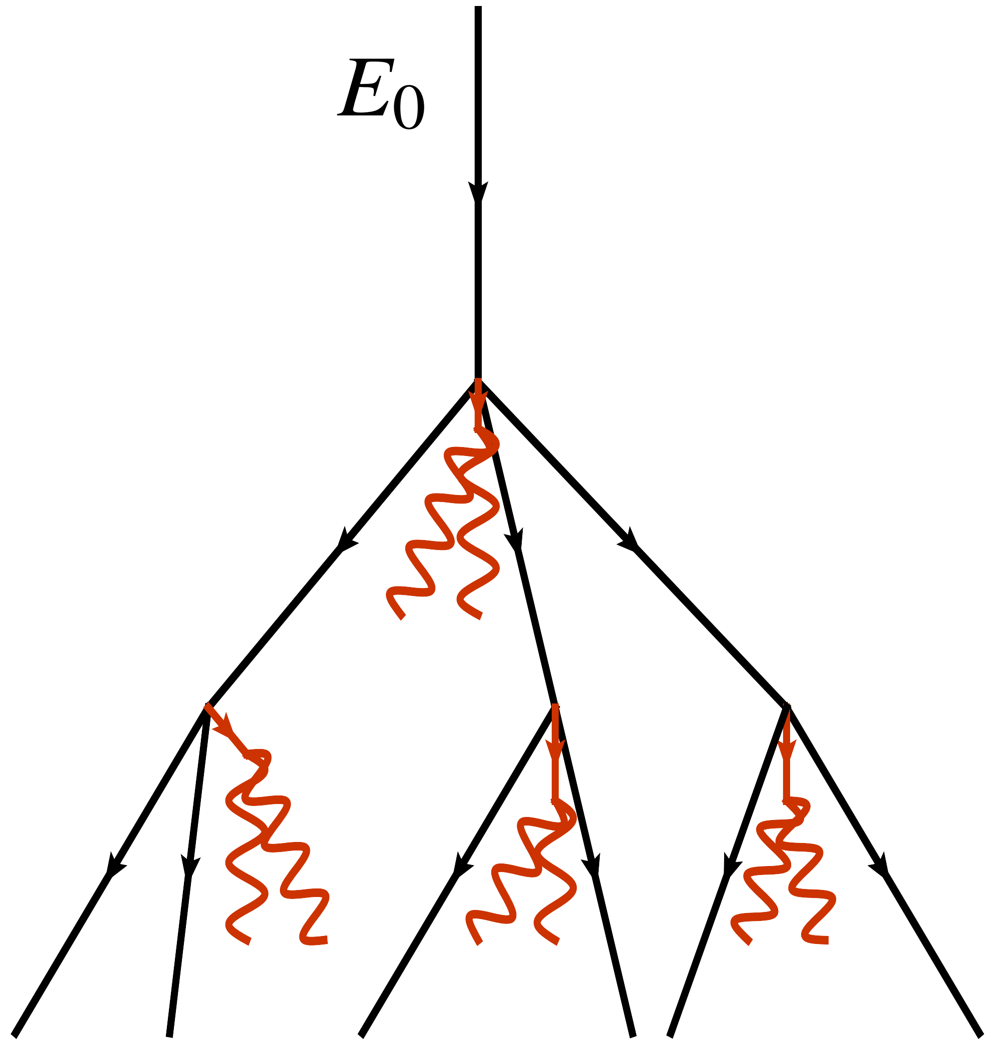
Hadronic energy

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

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

o
o
o

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



After n generations ...

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

Electromagnetic energy

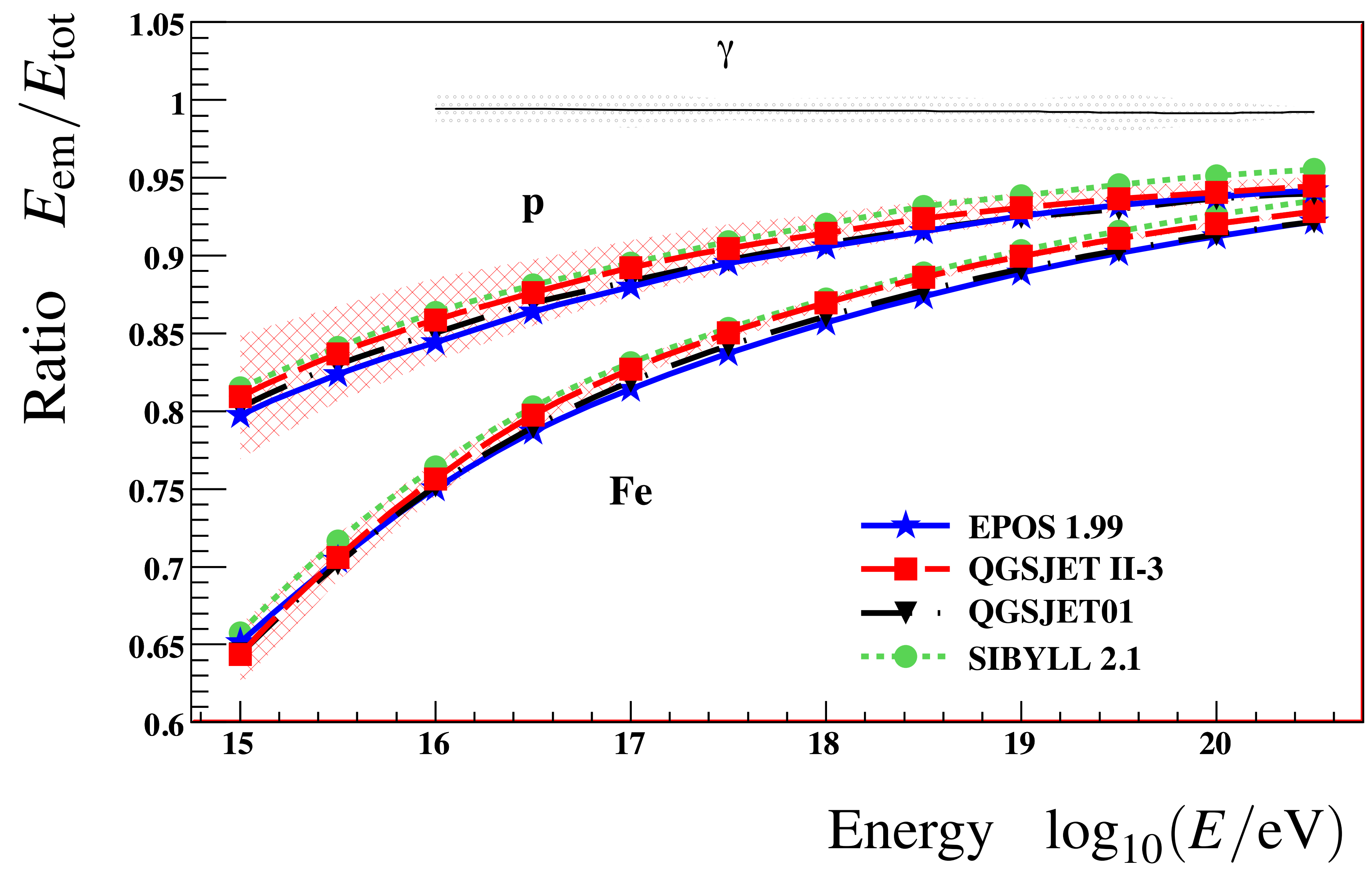
$$\frac{1}{3}E_0$$

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

o
o
o

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

(RE, Pierog, Heck, ARNPS 2011)

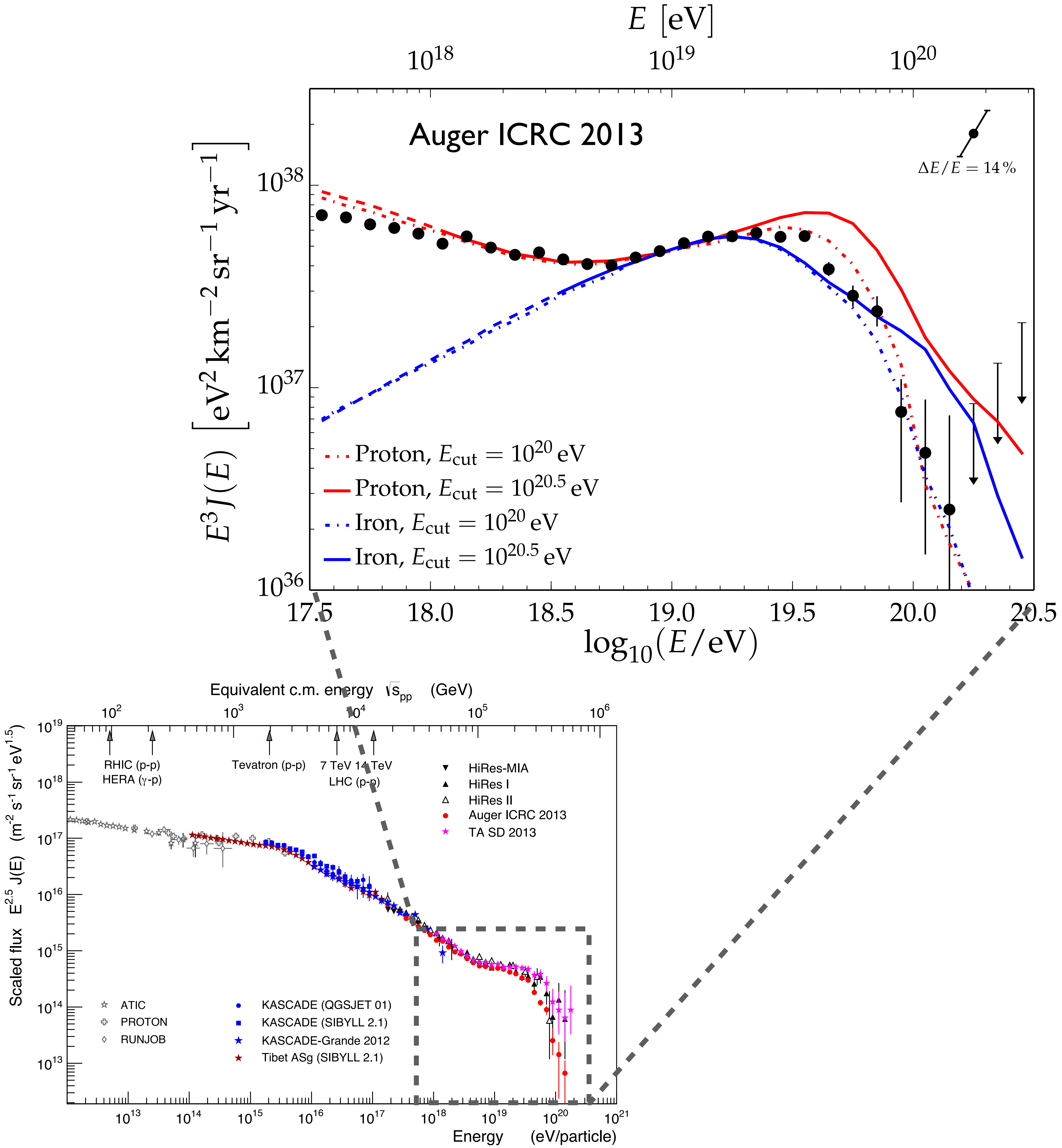


Very efficient transfer of hadronic energy to em. component

High-energy interactions most important

(Matthews, APP22, 2005)

All-particle energy spectrum: model independent (almost)

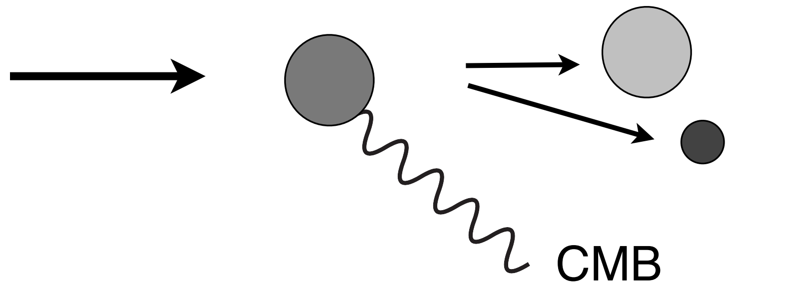


Proton dominated flux

Suppression: delta resonance

Ankle: e^+e^- pair production

(Dip model of Berezinsky et al.)



e+e- pair production and photo-pion production

Iron dominated flux

Suppression: giant dipole resonance

Ankle: transition to galactic sources

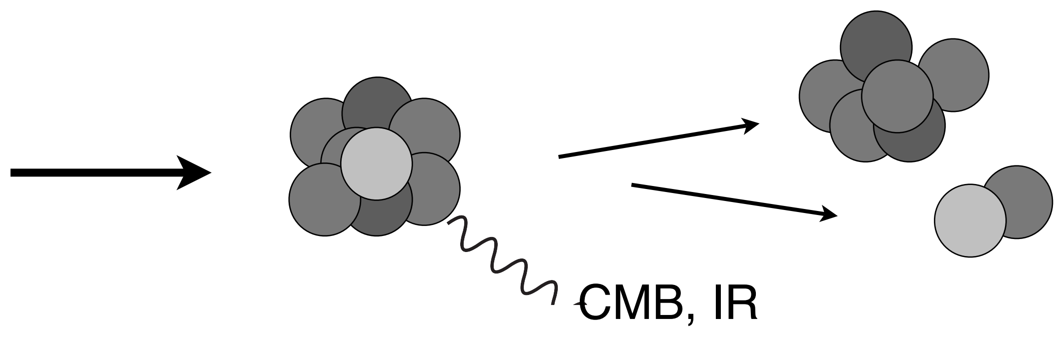
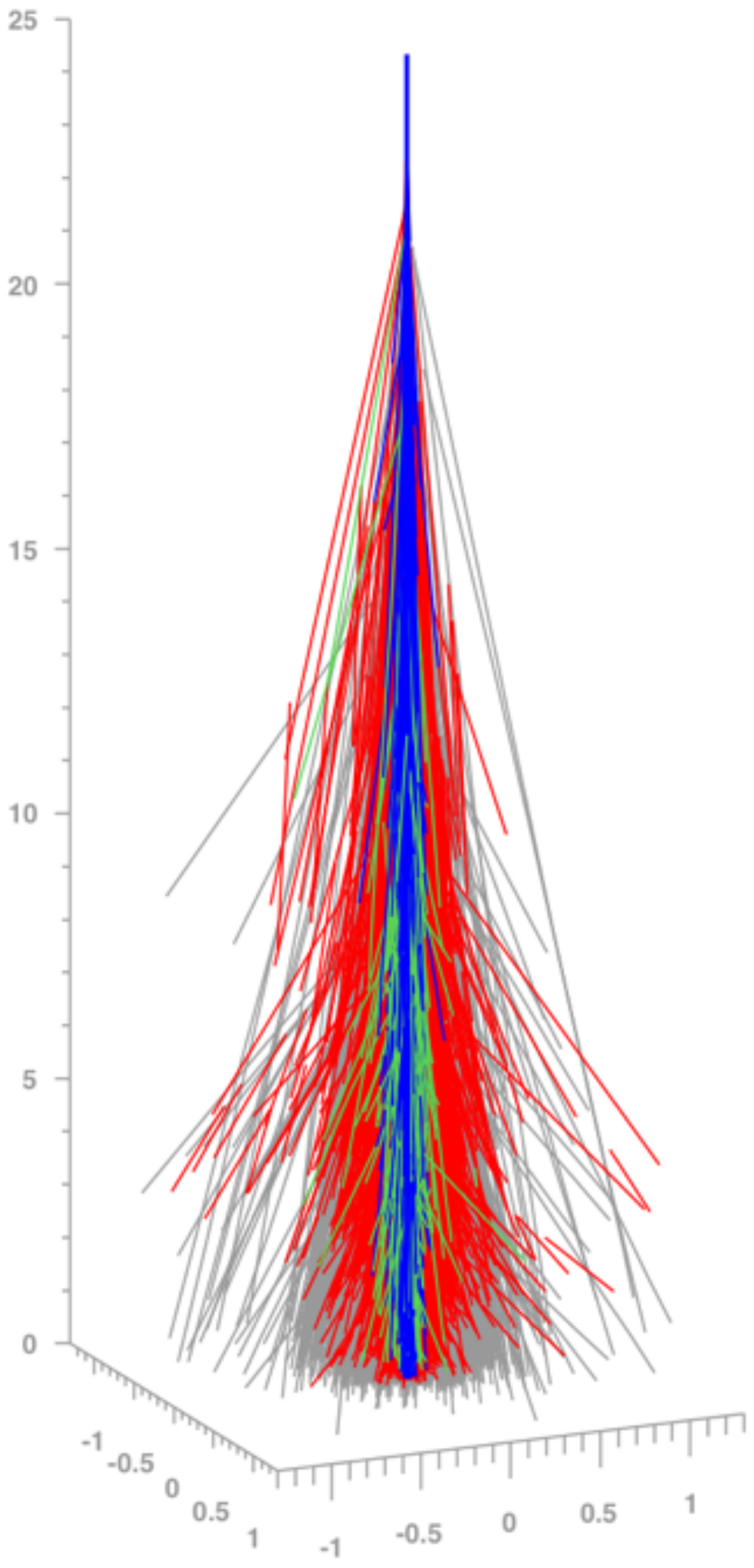
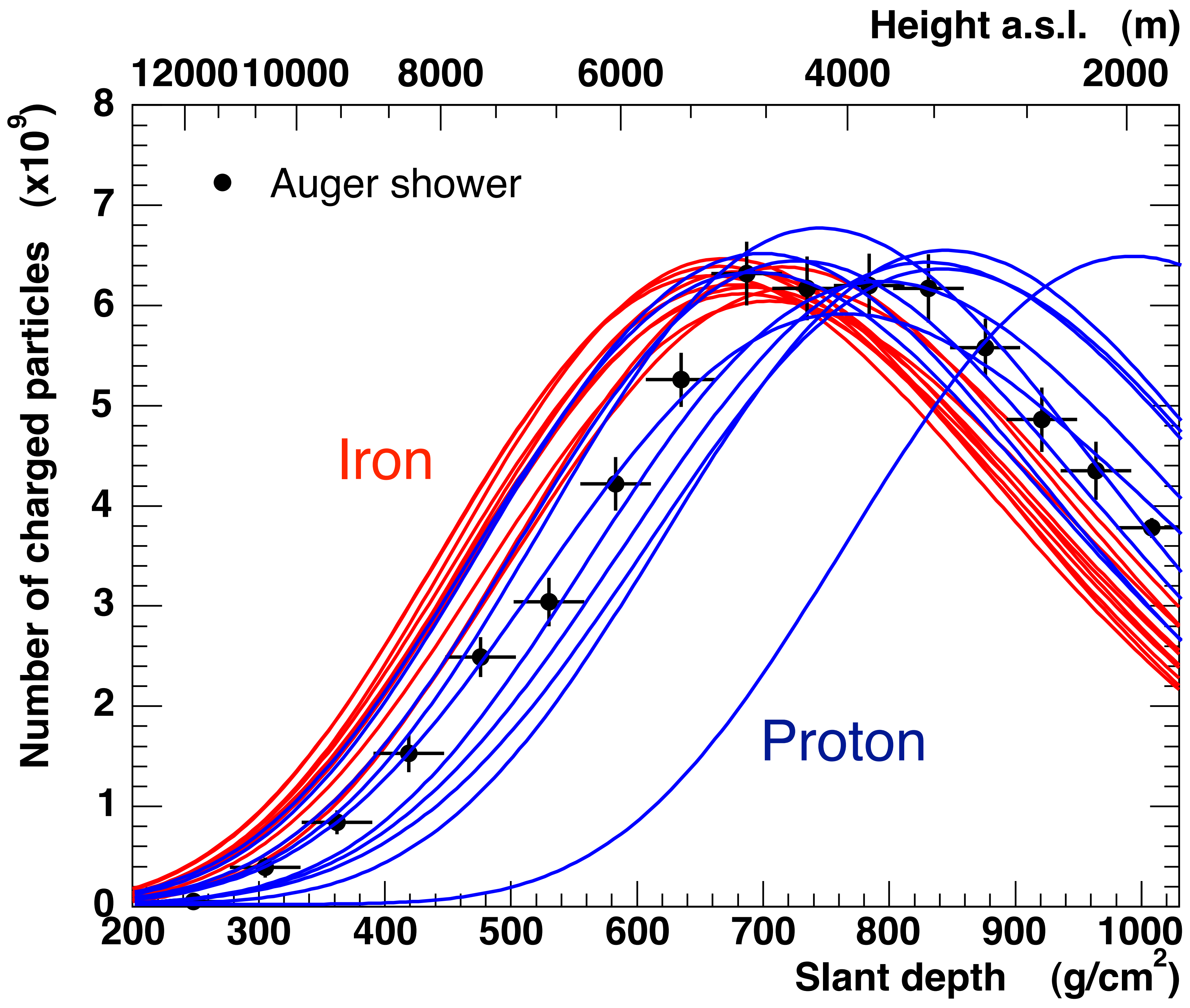


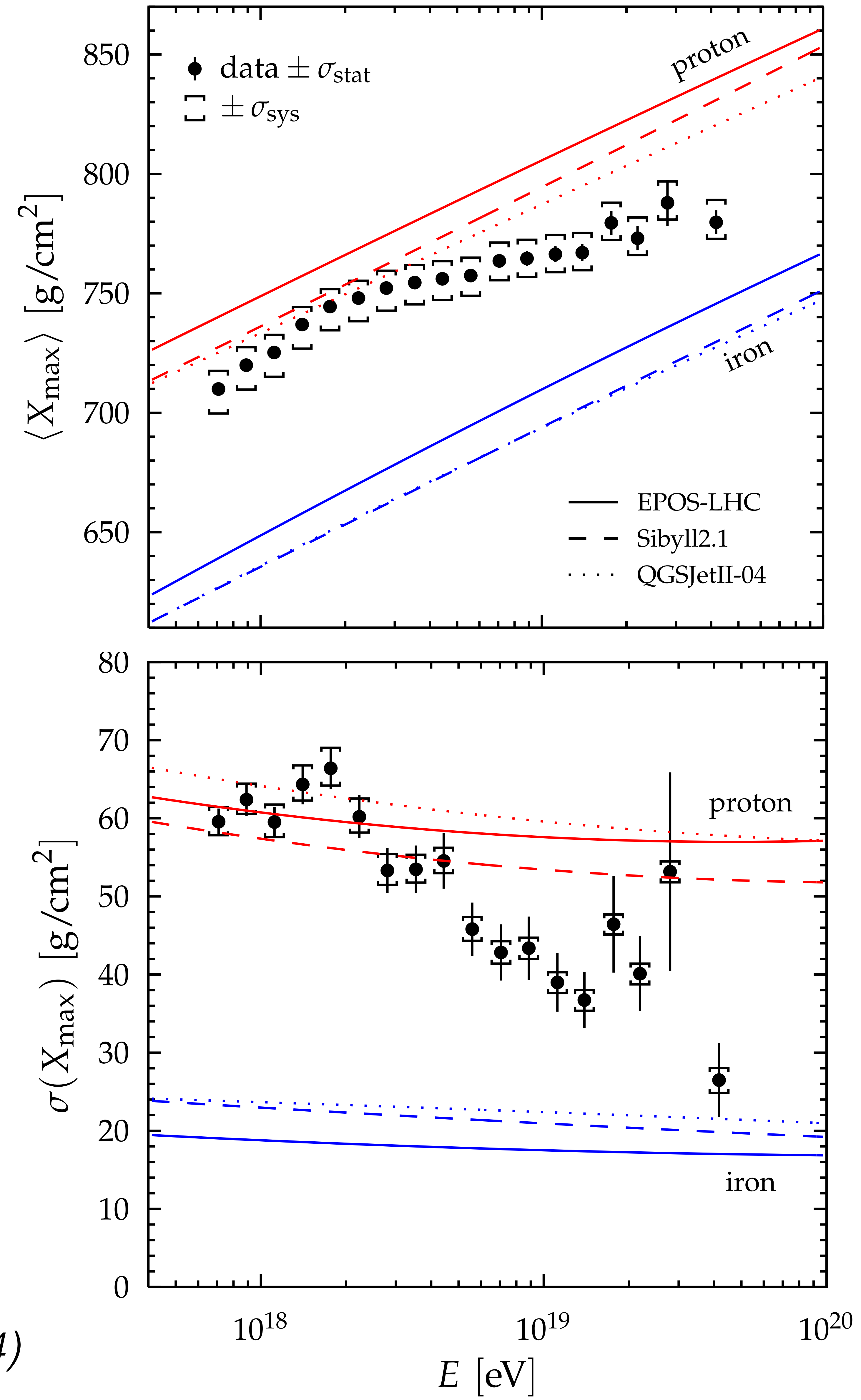
Photo-dissociation (giant dipole resonance)

Composition from longitudinal shower profile





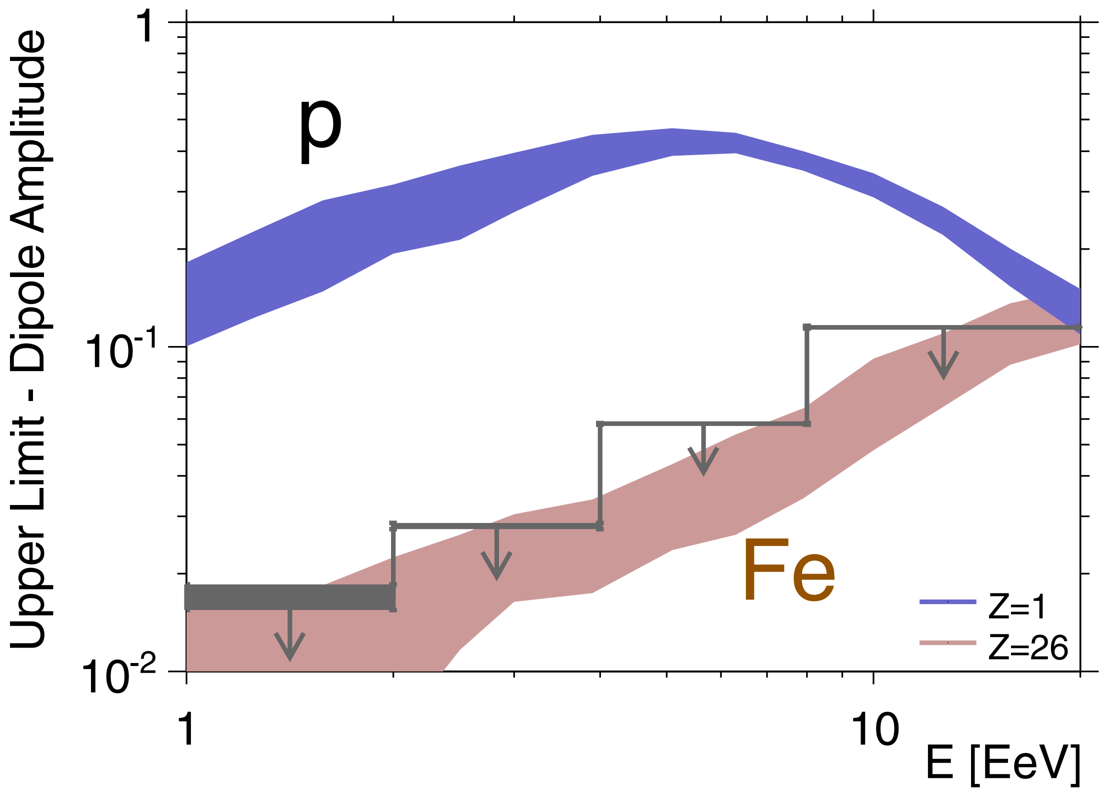
Example: event measured by Auger Collab.



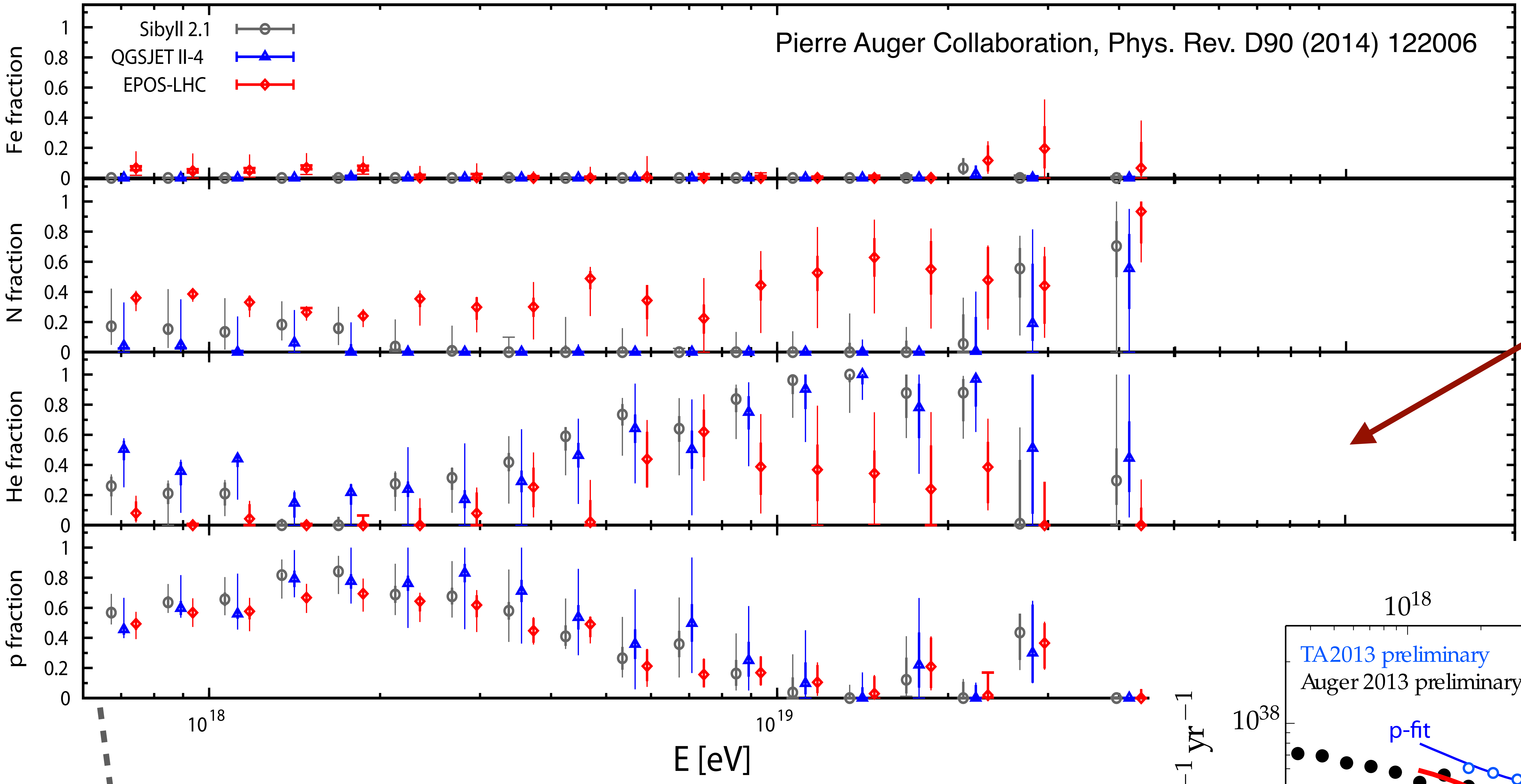
(Auger PRD90, 2014)

Composition: model dependent interpretation

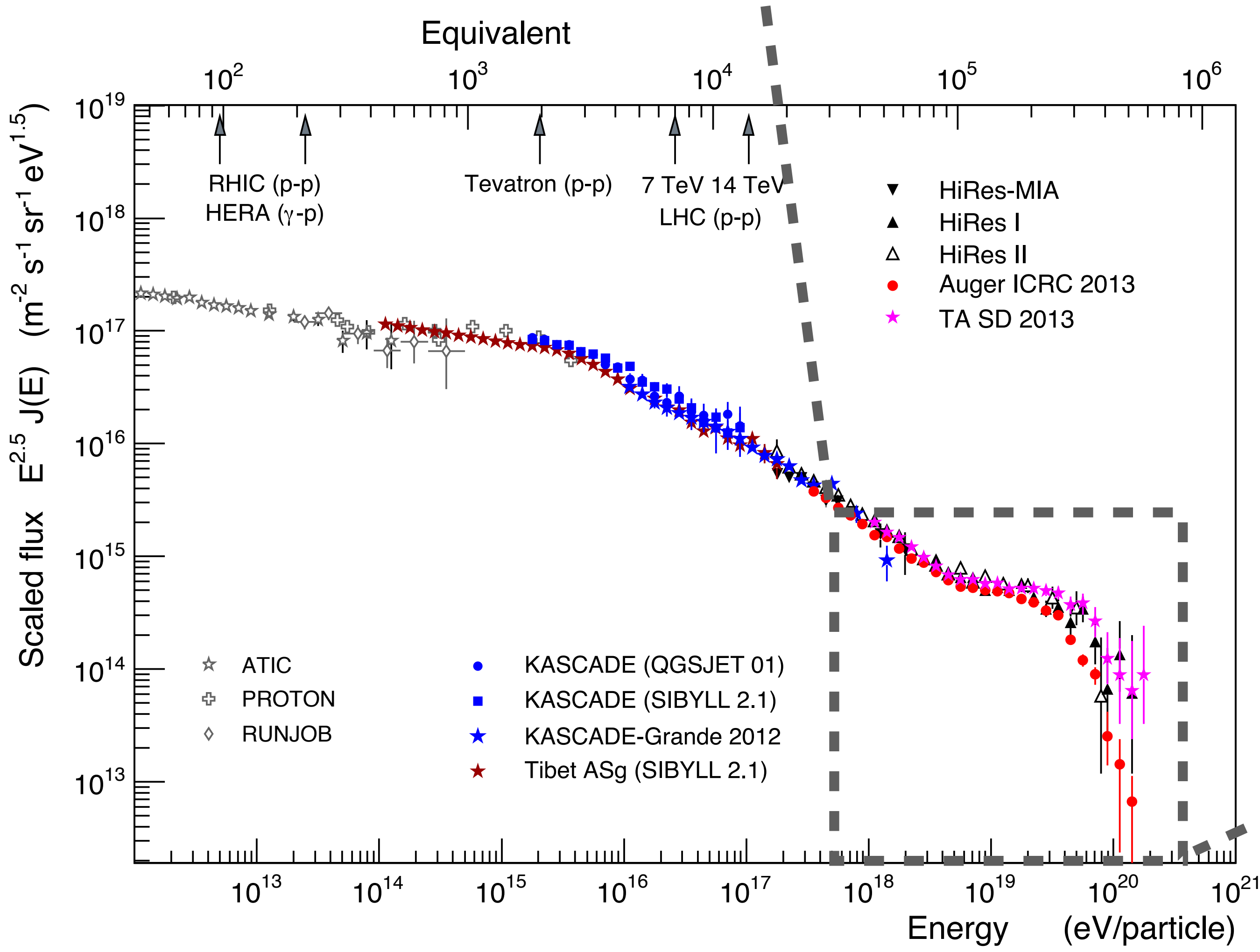
Sources in galactic plane

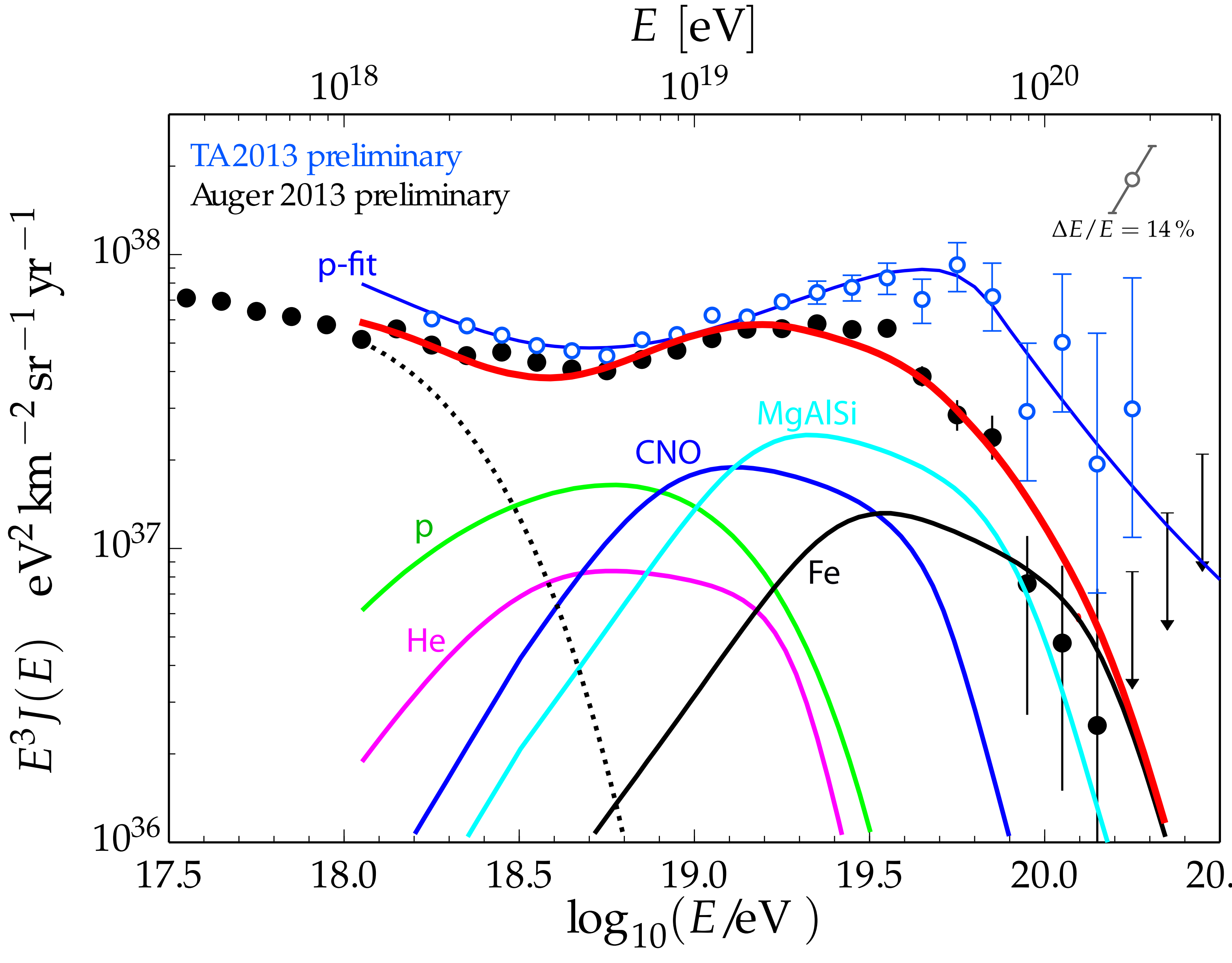


(Auger, ApJ 203, 2012)



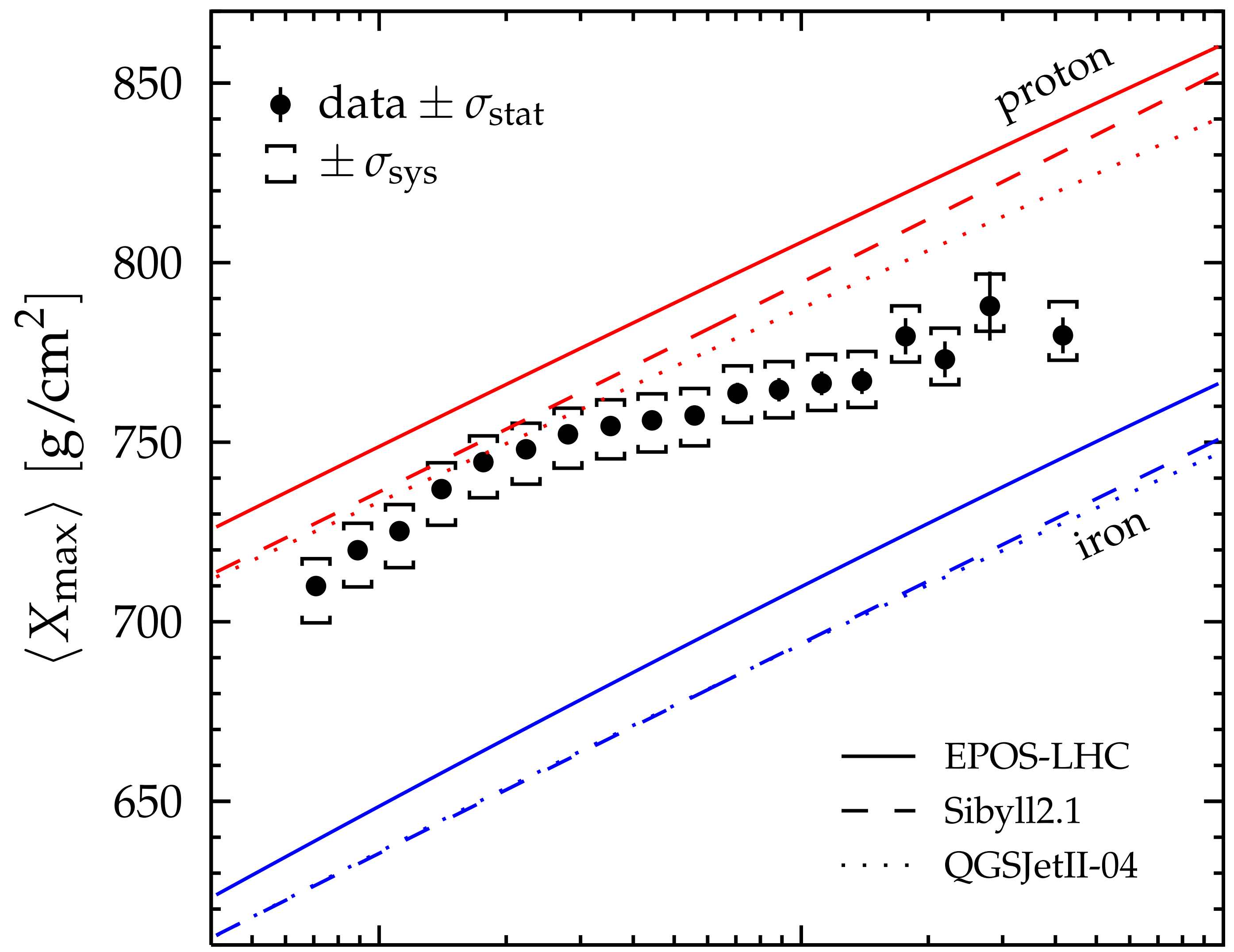
Proton fraction, anisotropy?

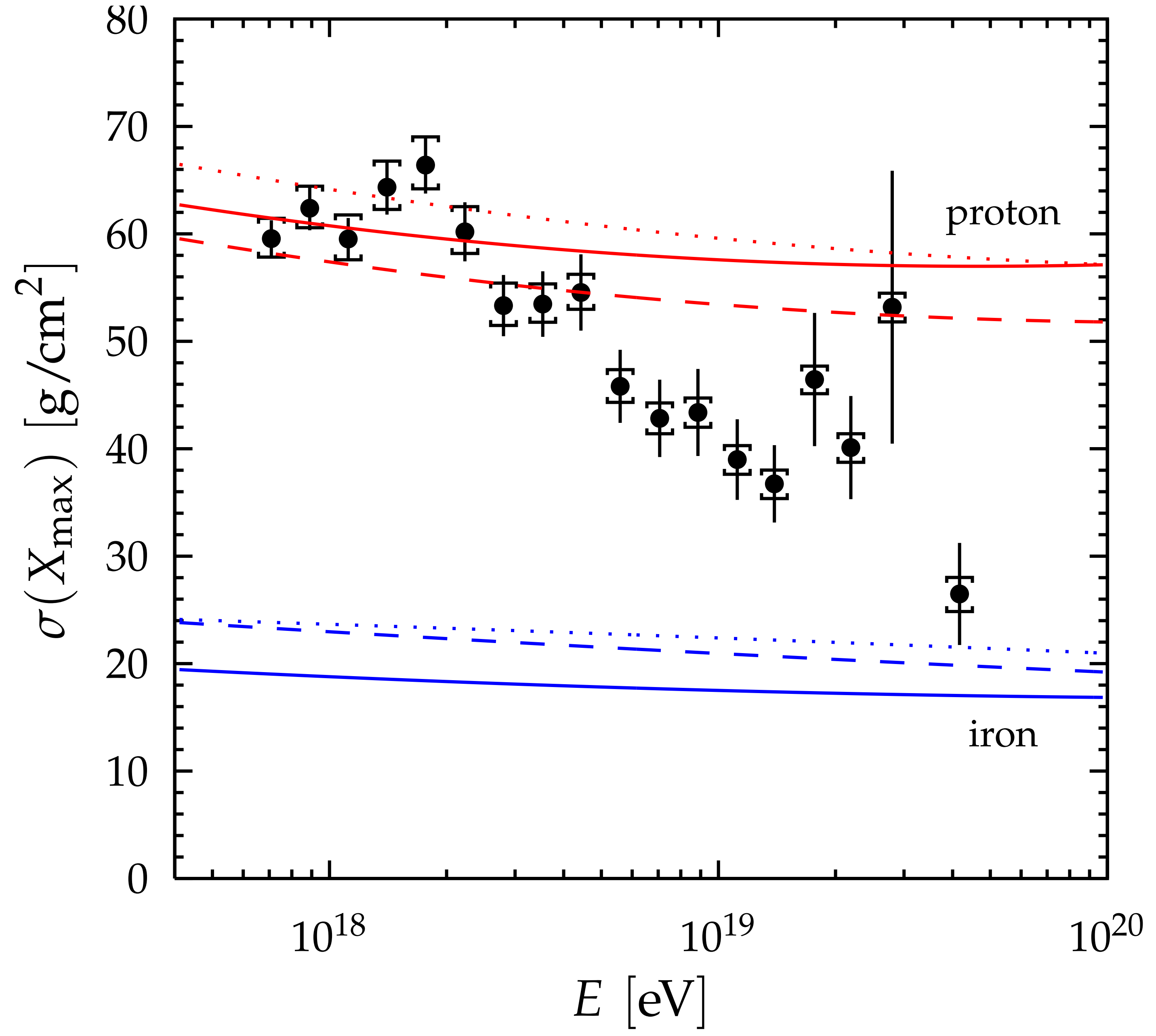




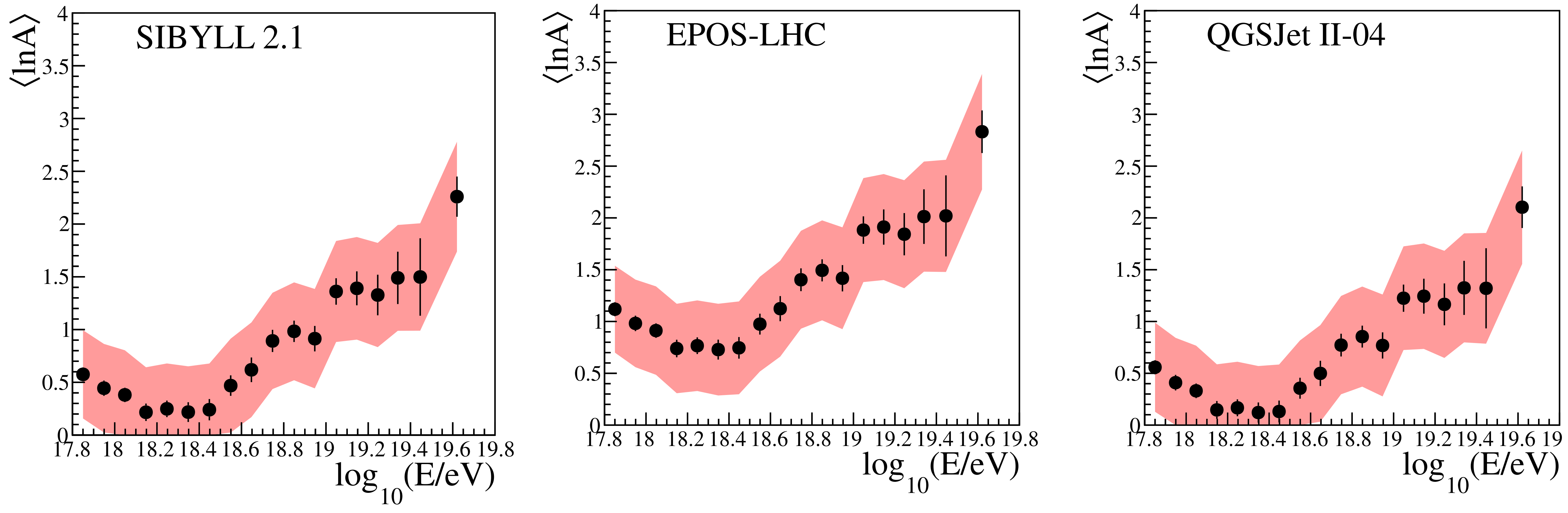
Kampert&Tinyakov, CRP **15** (2014) 318; Aloisio, Berezinsky & Blasi, JCAP 1410 (2014) 10, 02

Consistency constraint on interaction models





$$\langle X_{max}\rangle \approx \langle X^{p}_{max}\rangle - D_p \,\langle \ln A\rangle$$



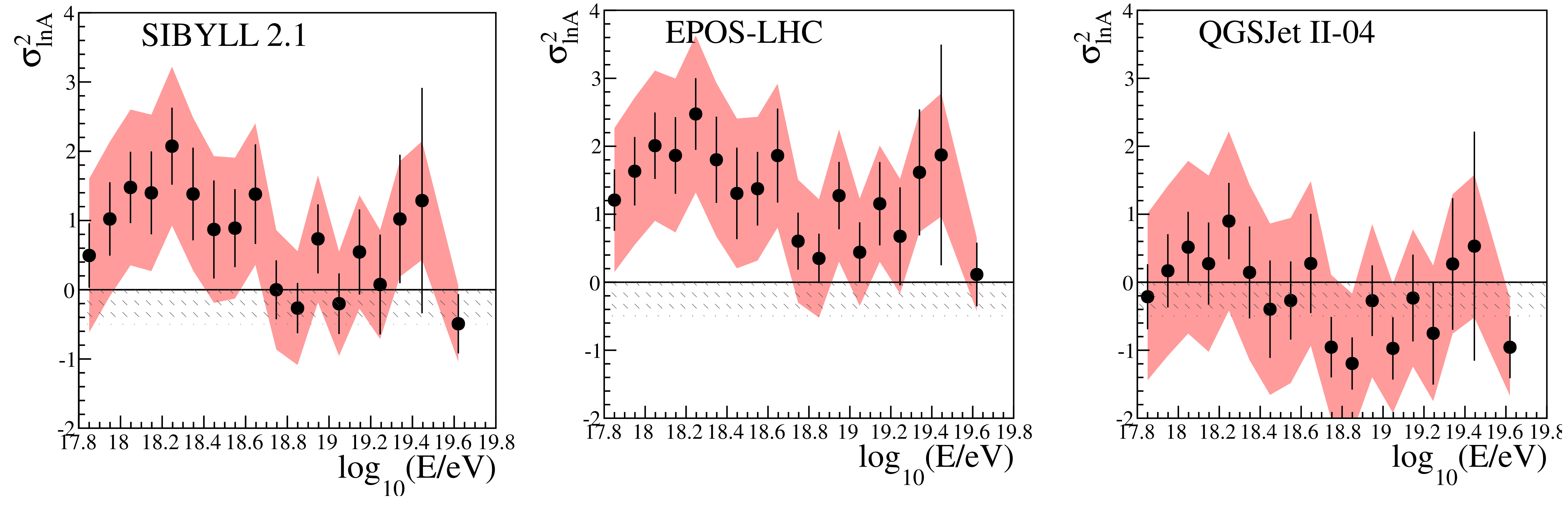
Fe

N

He

p

$$\sigma(X_{max})^2 \approx \langle \sigma_i^2\rangle + D_p^2 \,\sigma(\ln A)^2$$



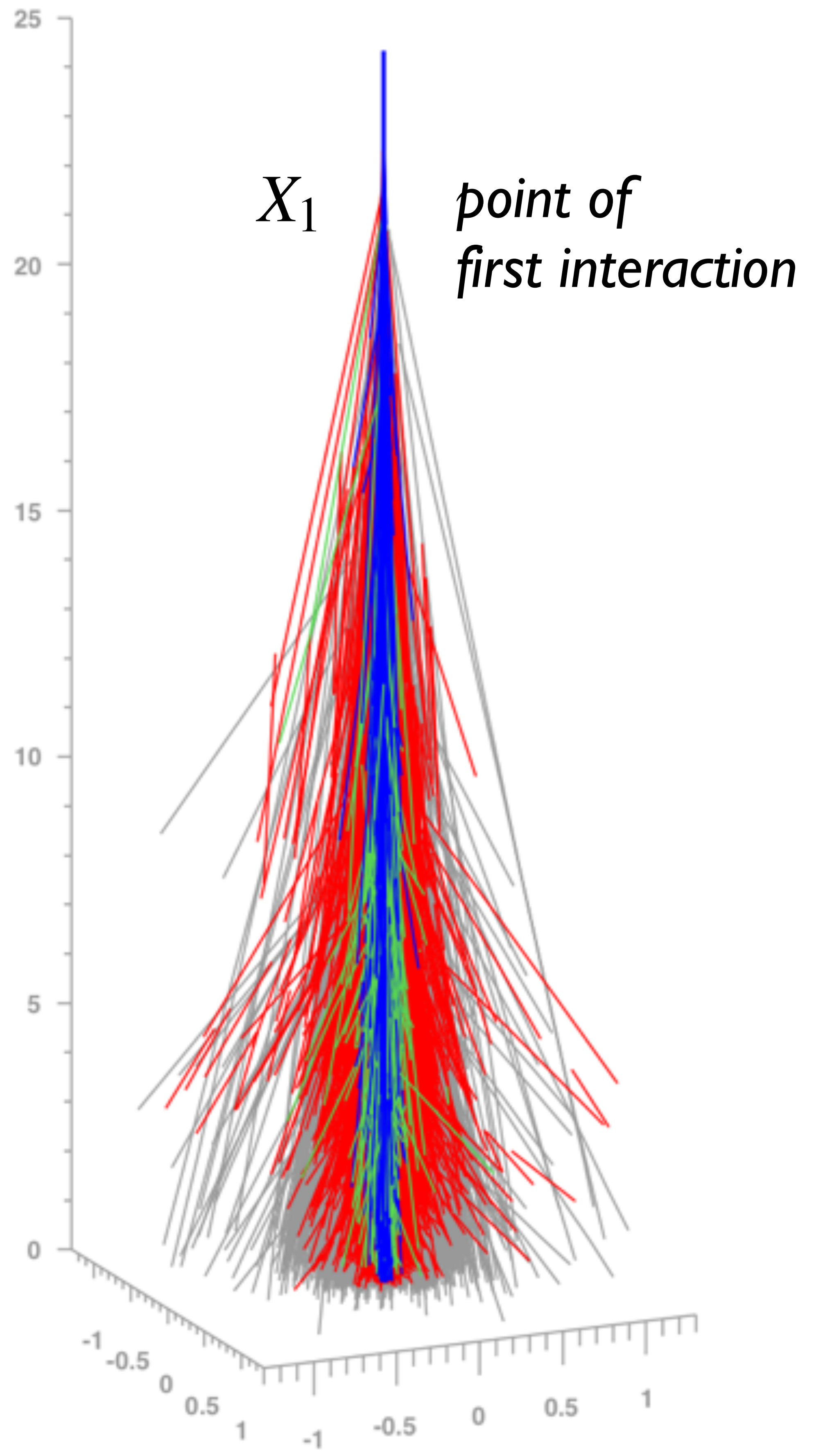
p/Fe 50:50

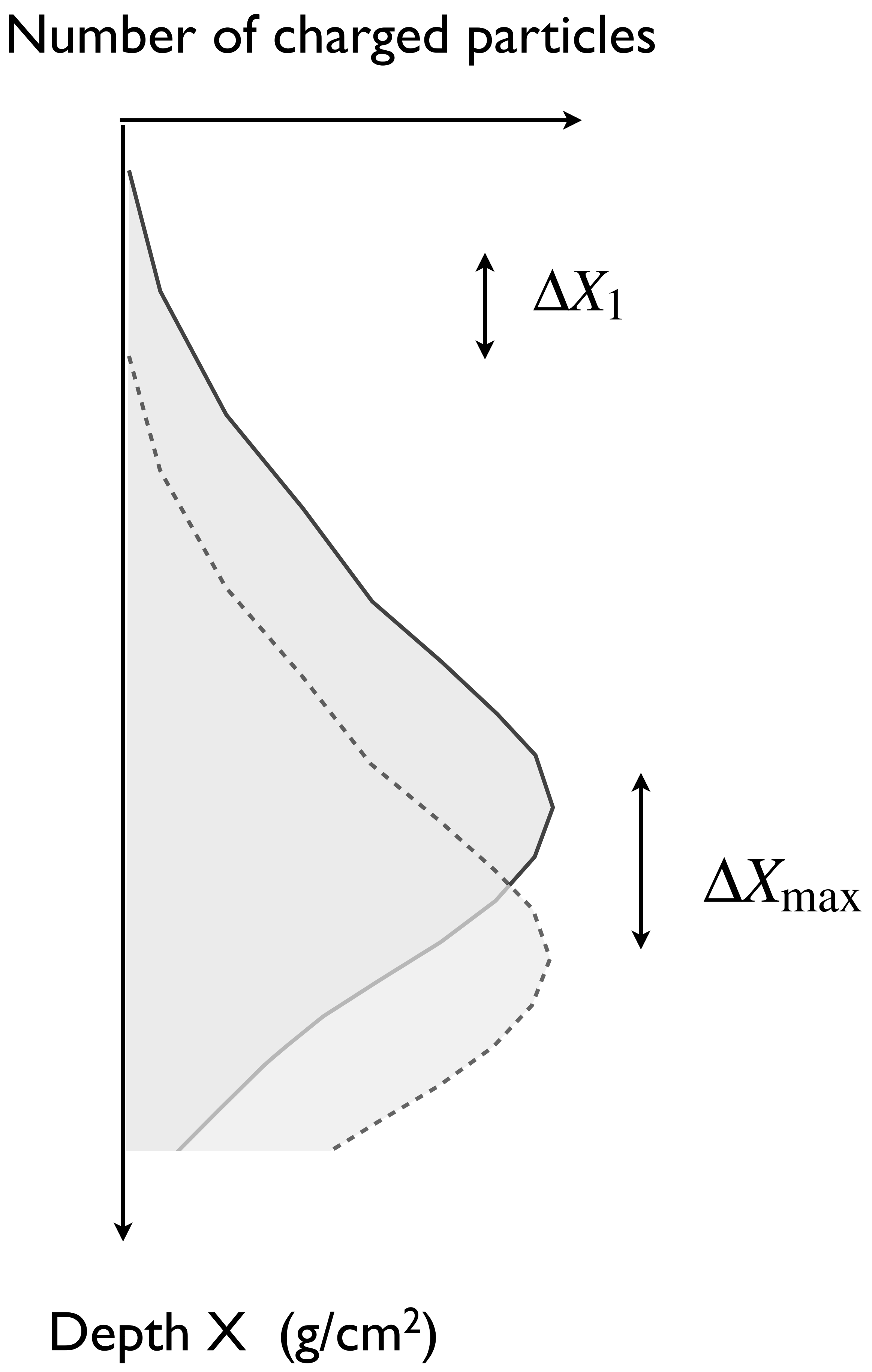
mono-elemental

(Auger, JCAP 02 (2013) 026; update: PRD 90 (2014) 122005)

QGSJet II.04 disfavored ?

Measurement of proton-air cross section



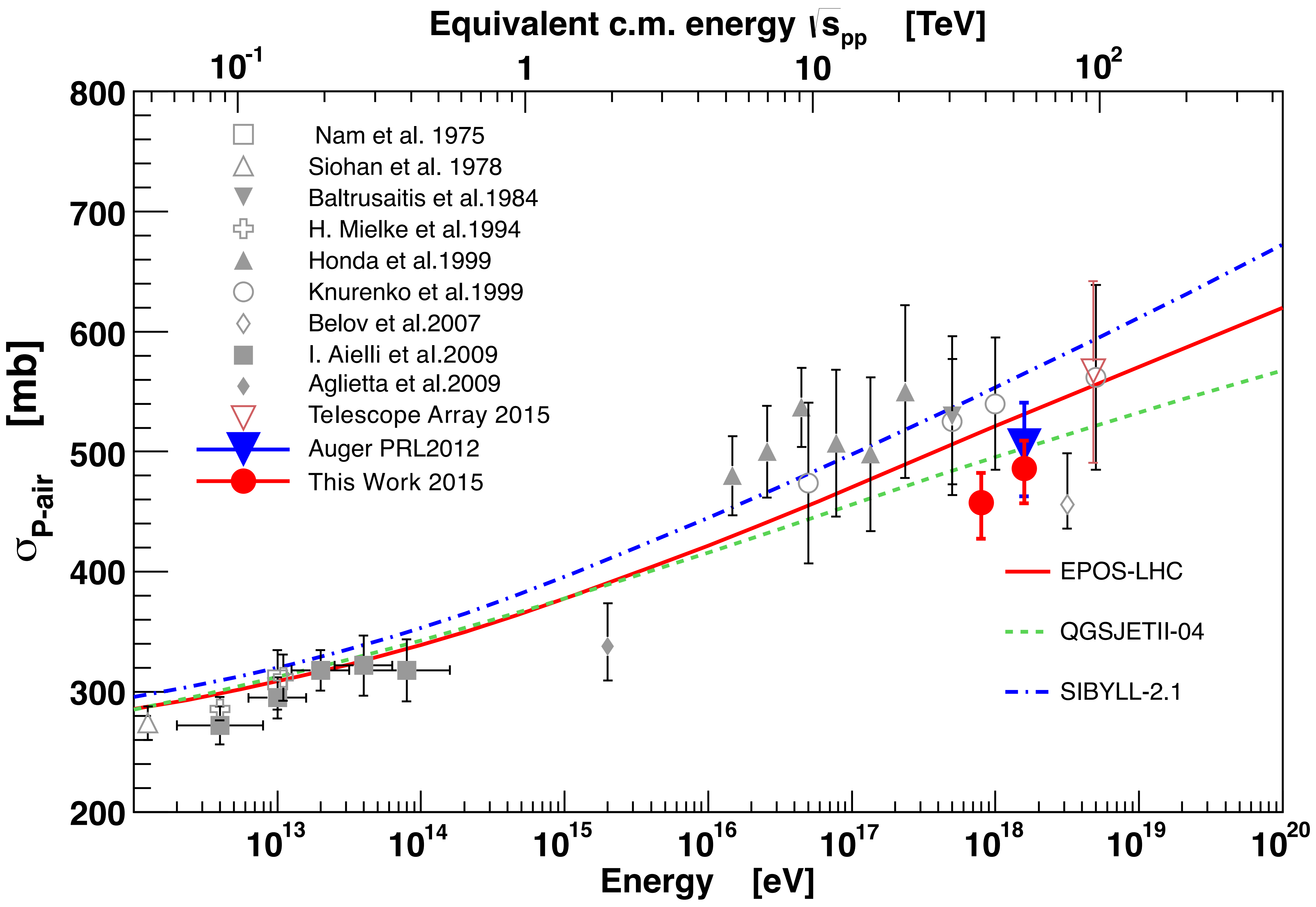


$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

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

Difficulties

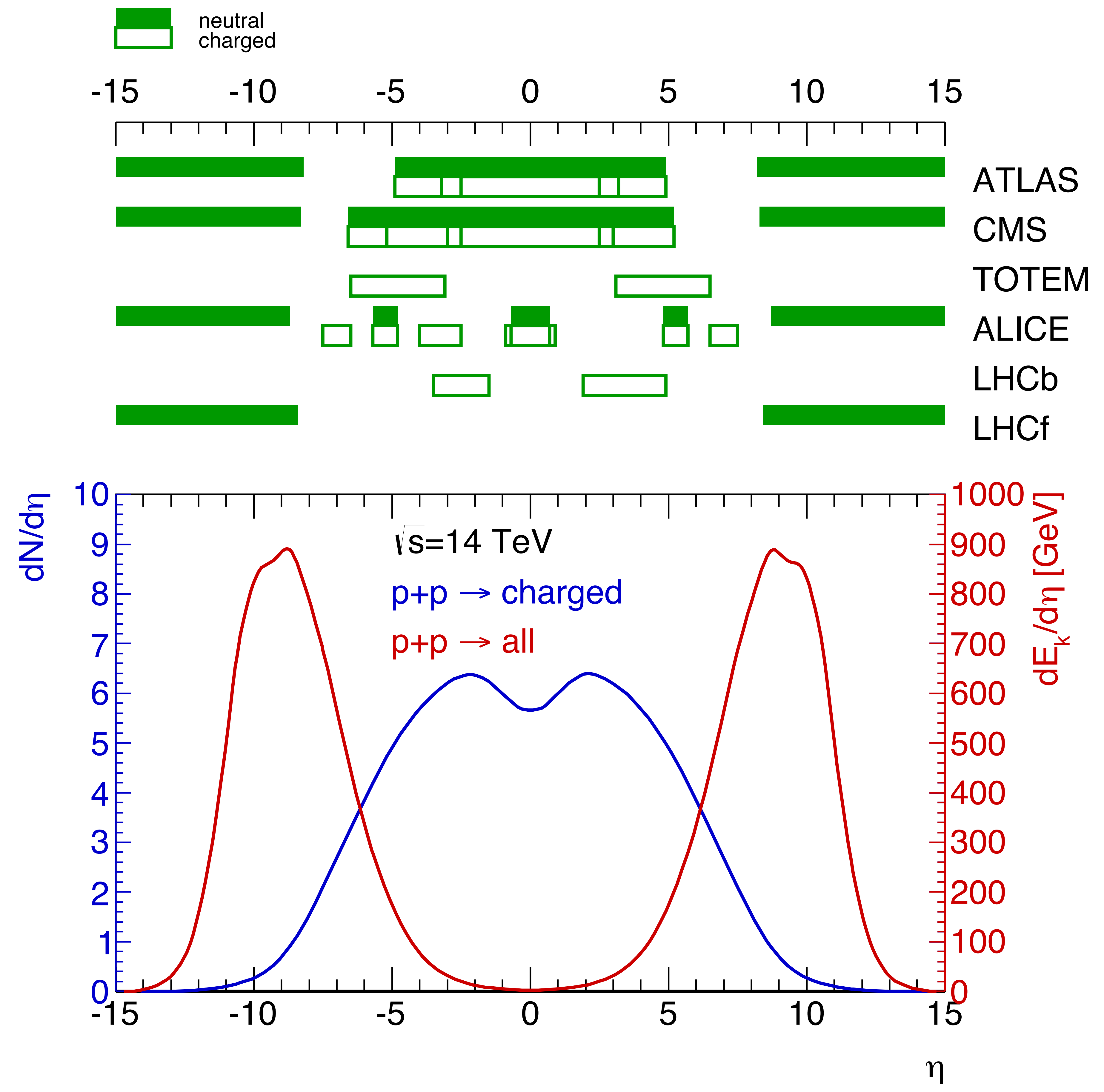
- mass composition
- fluctuations in shower development (model needed for correction)

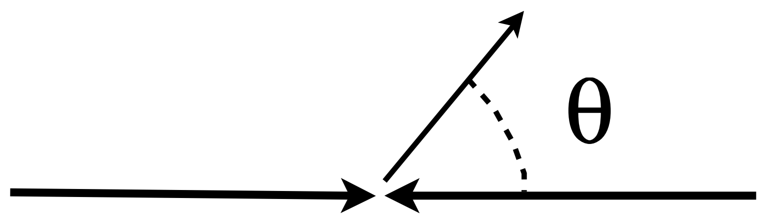


(Auger PRL 109, 2012; Telescope Array 1505.01860)

How reliable are the predictions of the interaction models ?

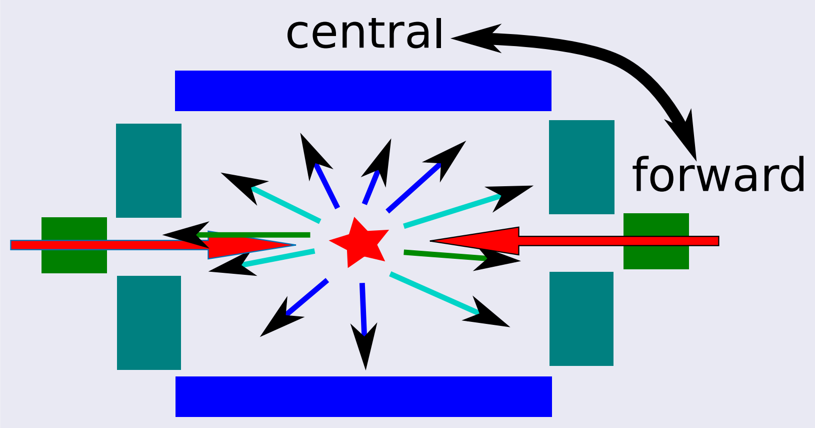
Challenge of limited phase space coverage



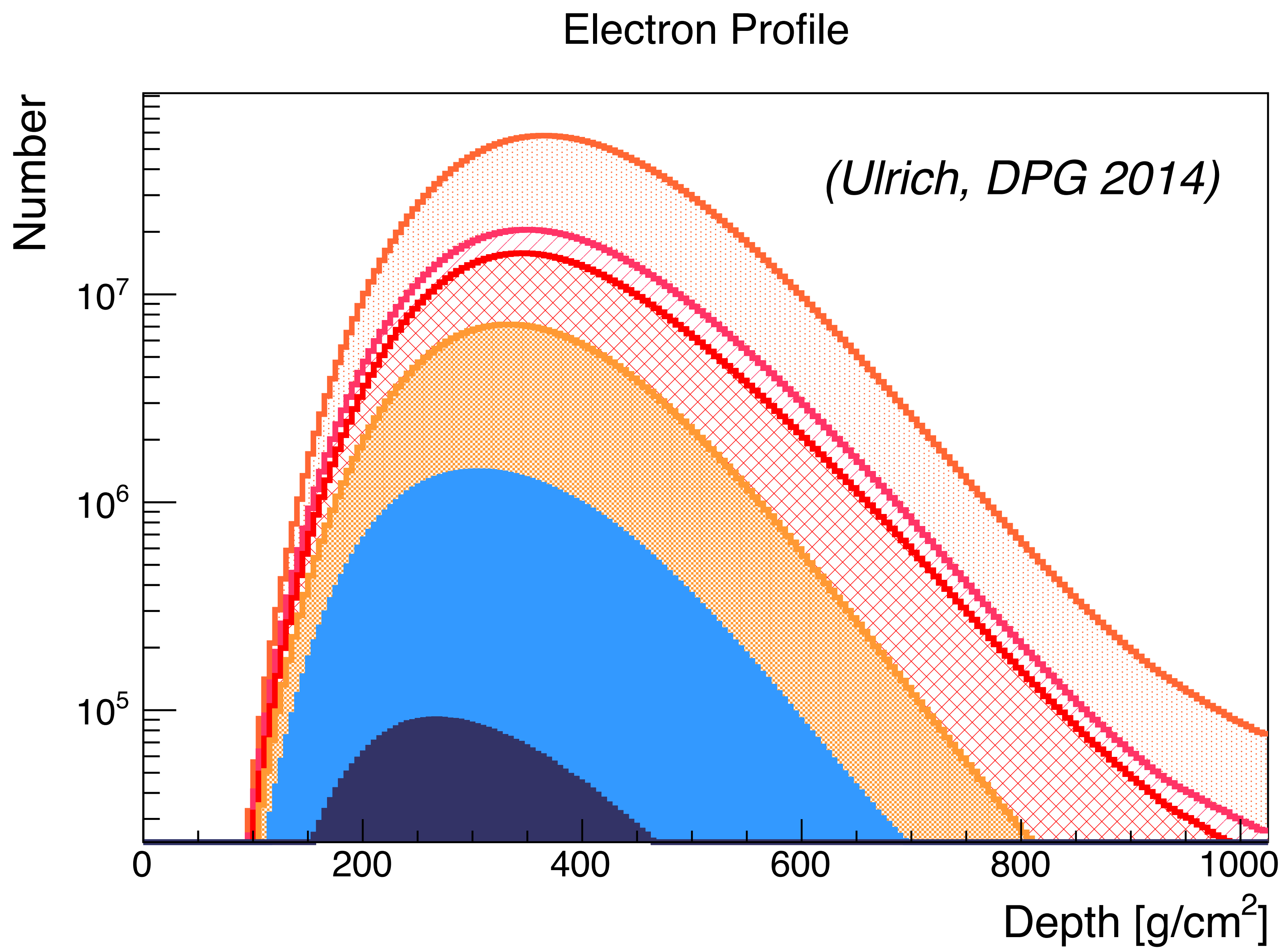


$$\eta = -\ln \tan \frac{\theta}{2}$$

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



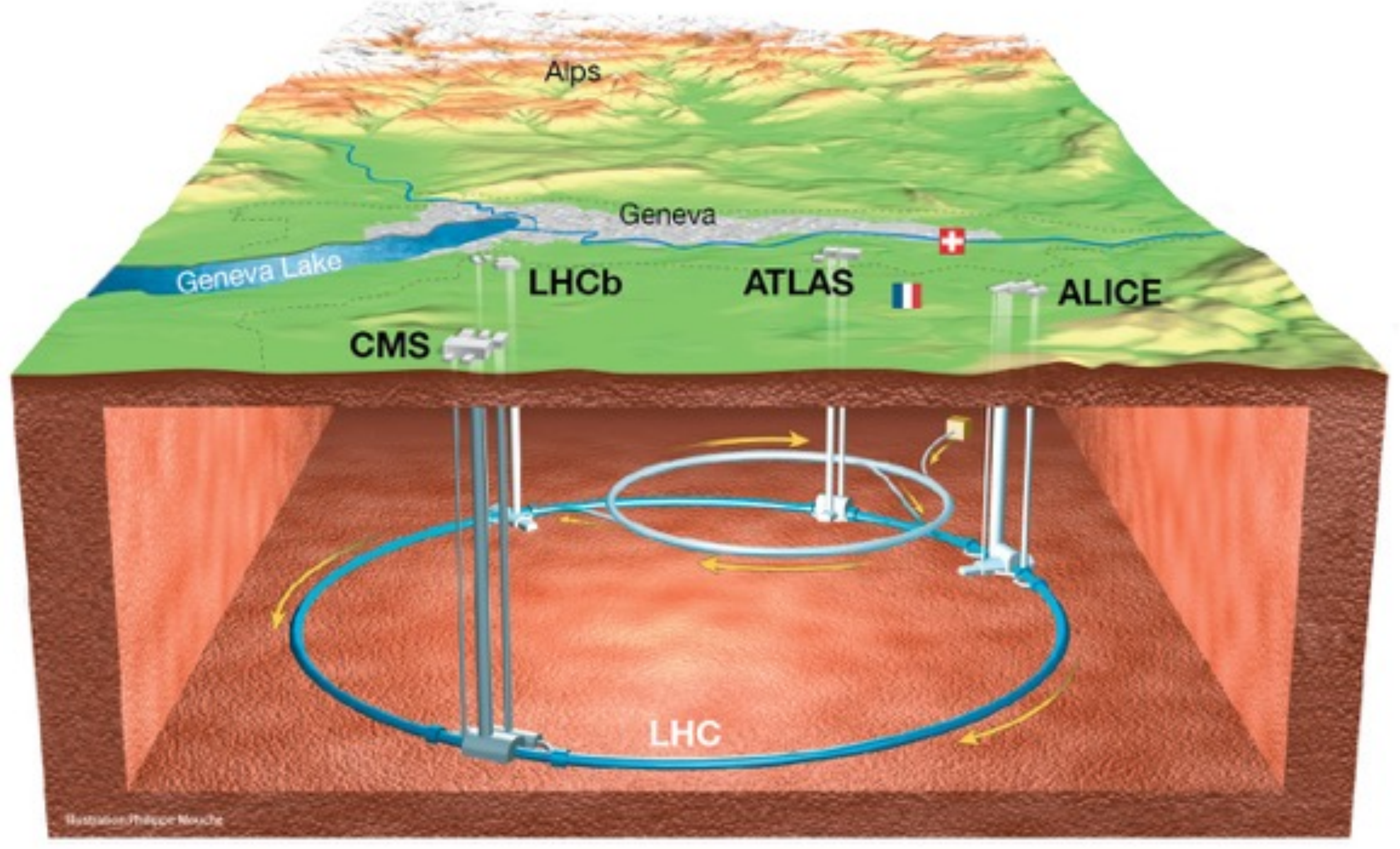
- Central ($|\eta| < 1$)
- Endcap ($1 < |\eta| < 3.5$)
- Forward ($3 < |\eta| < 5$), HF
- CASTOR+T2 ($5 < |\eta| < 6.6$)
- FSC ($6.6 < |\eta| < 8$)
- ZDC ($|\eta| > 8$), LHCf

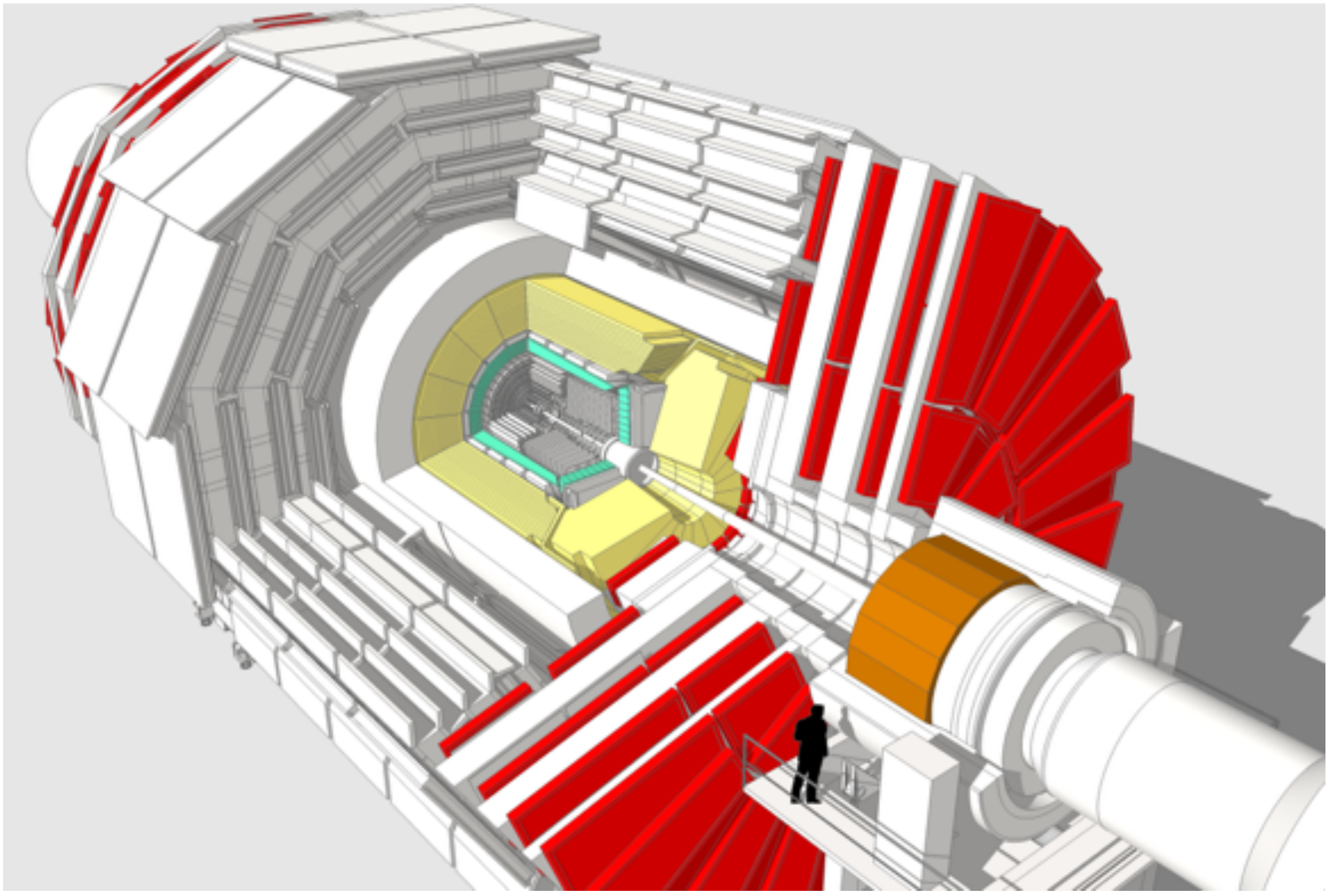


More than 50% of shower from η > 8

(Salek et al., 2014)

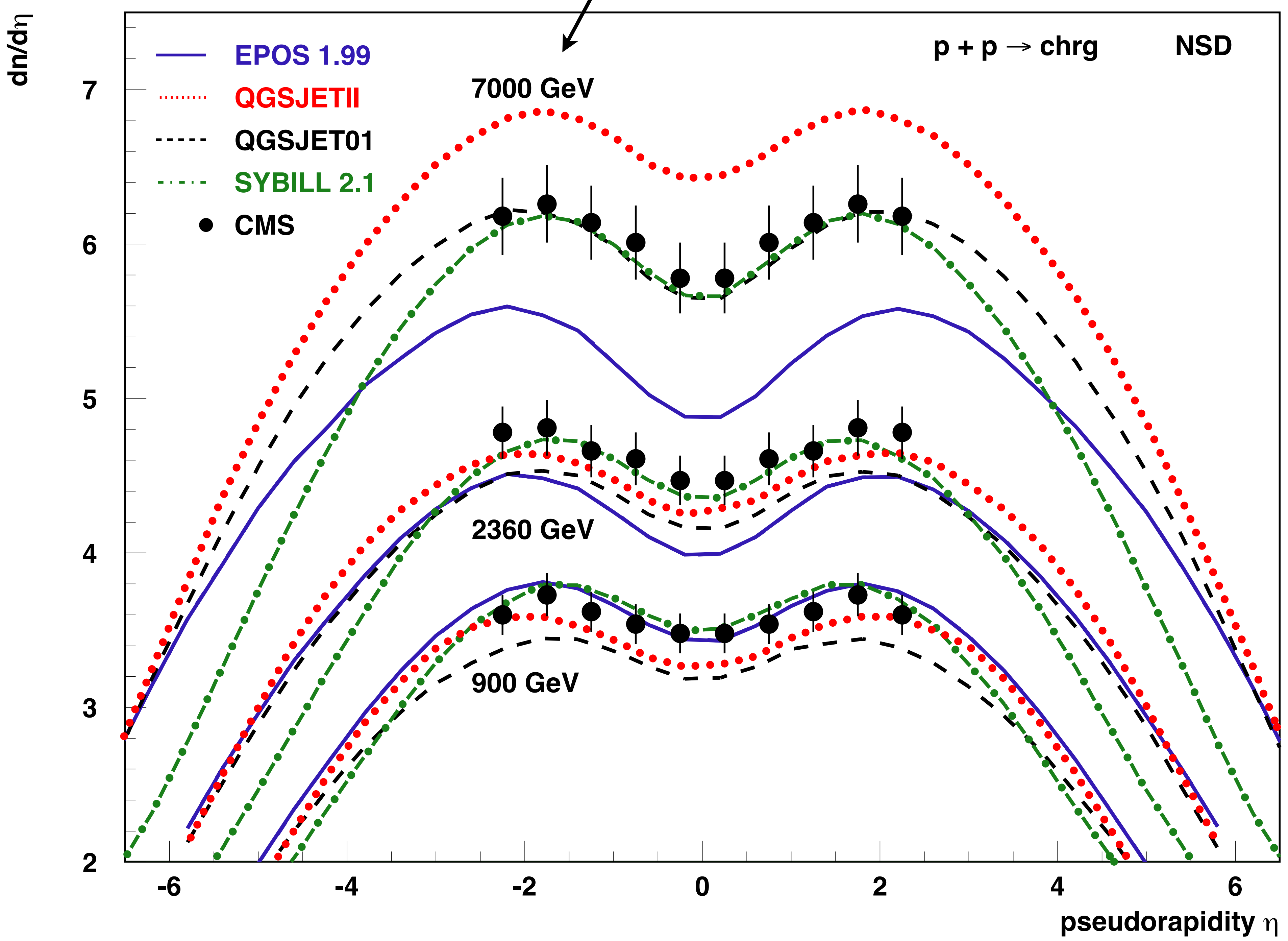
Charged particle distribution in pseudorapidity





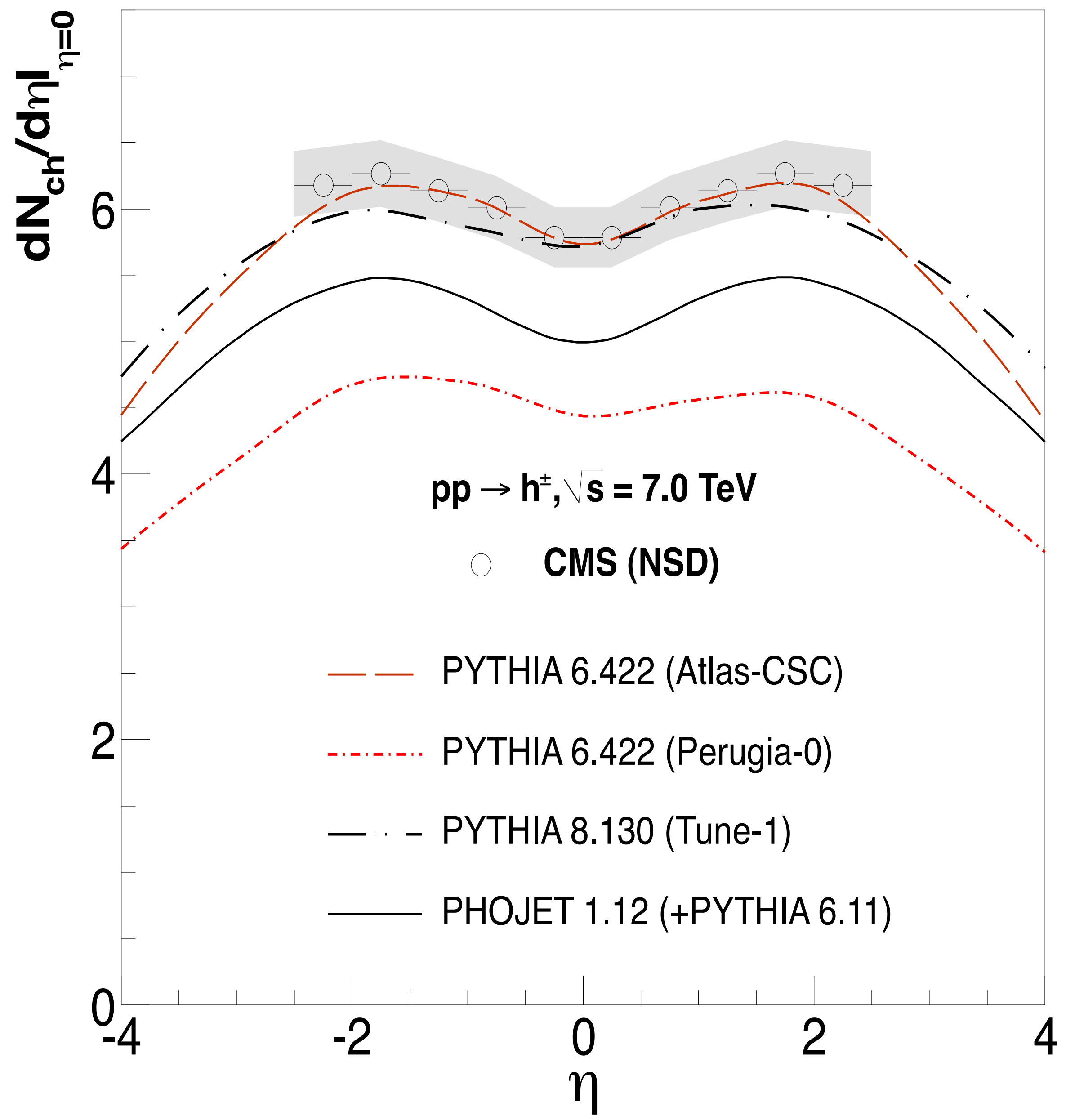
(data from all LHC experiments, CMS shown as example)

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



Detailed LHC comparison

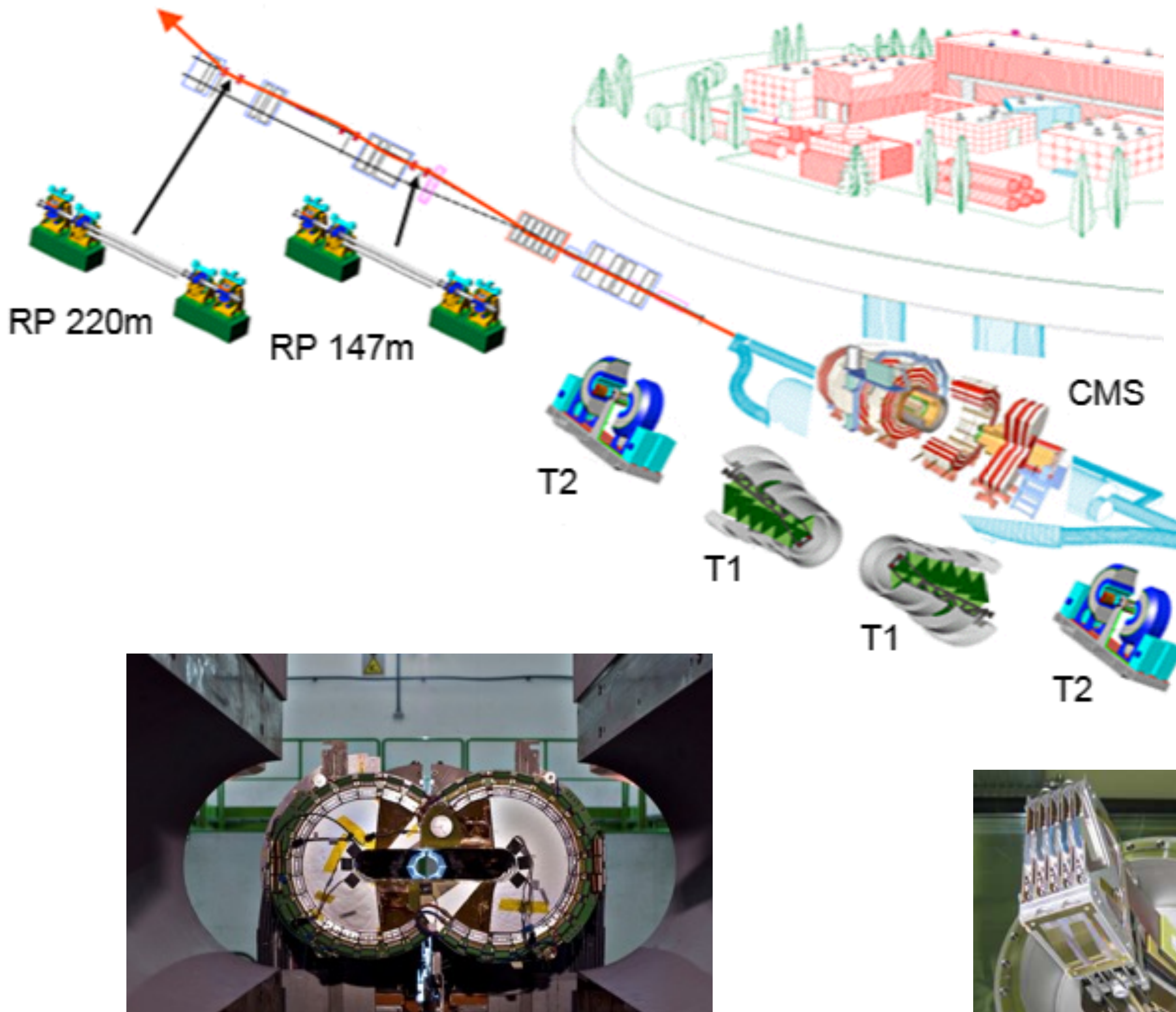
(D'Enterria et al., APP 35, 2011)

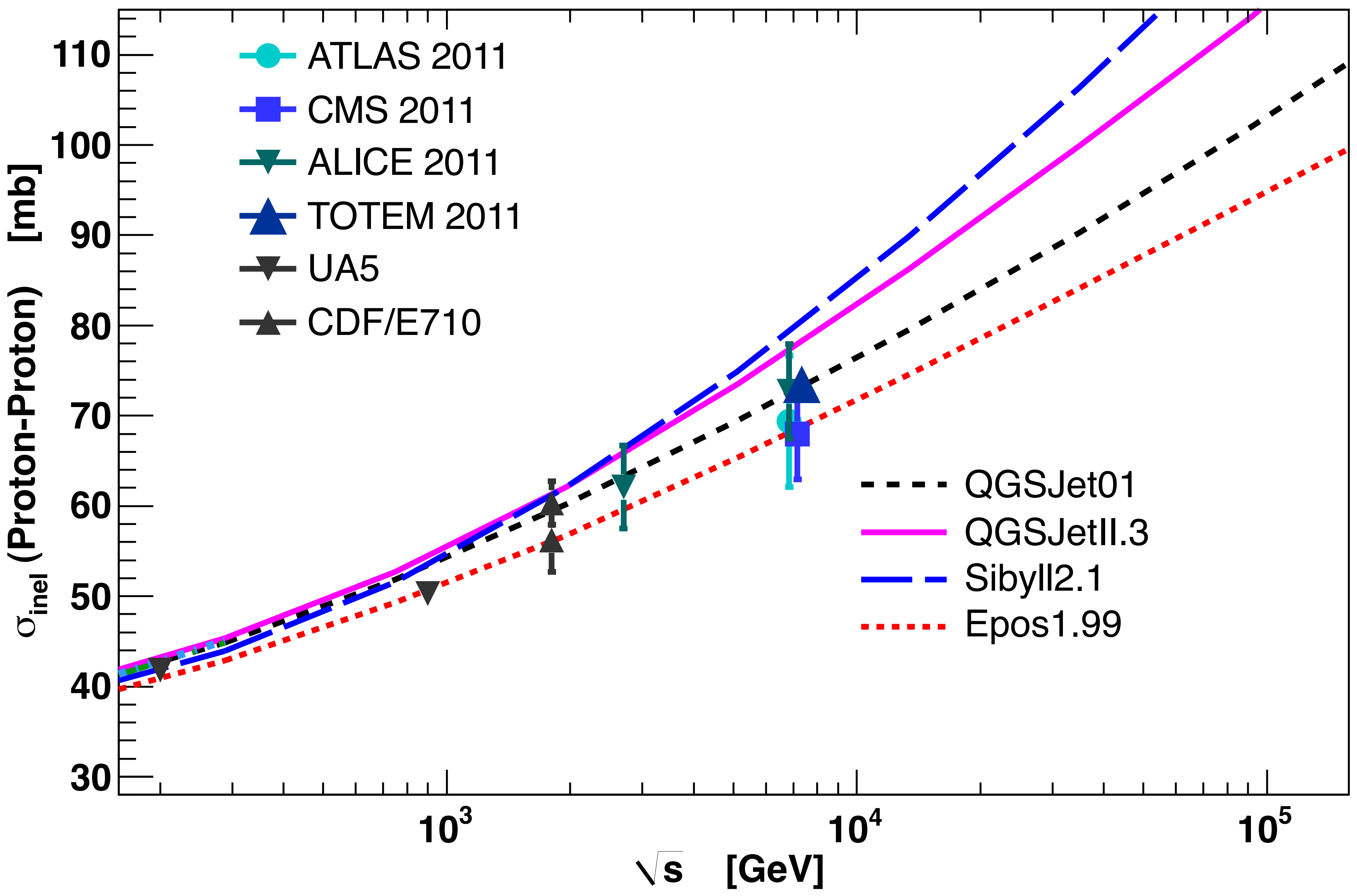


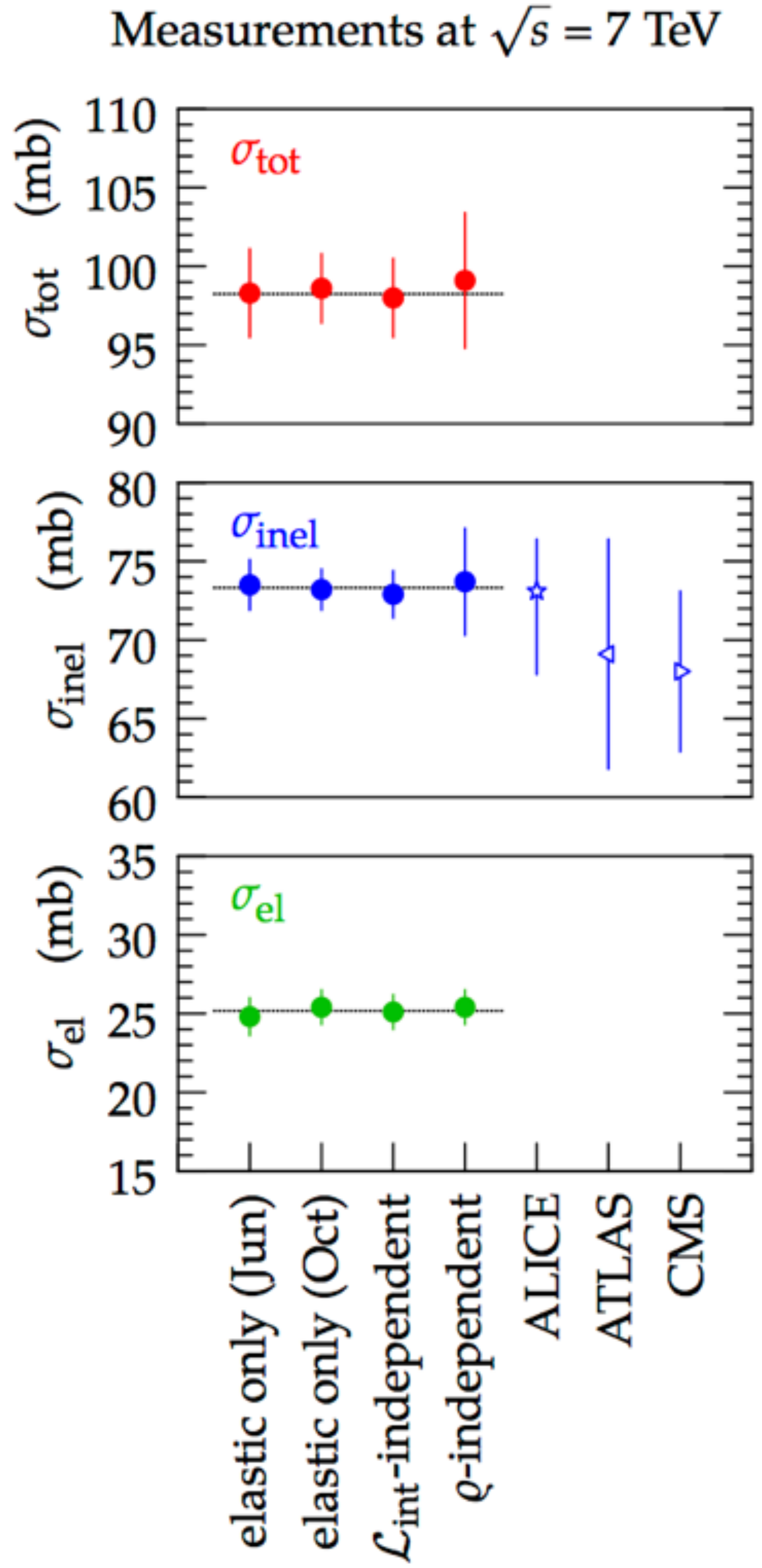
Models for air showers typically better in agreement with LHC data

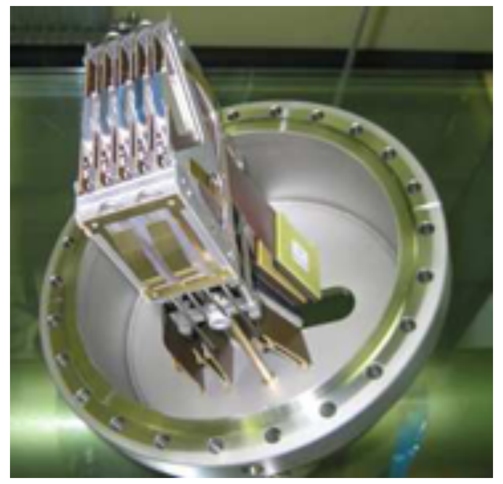
Cross section measurements at LHC

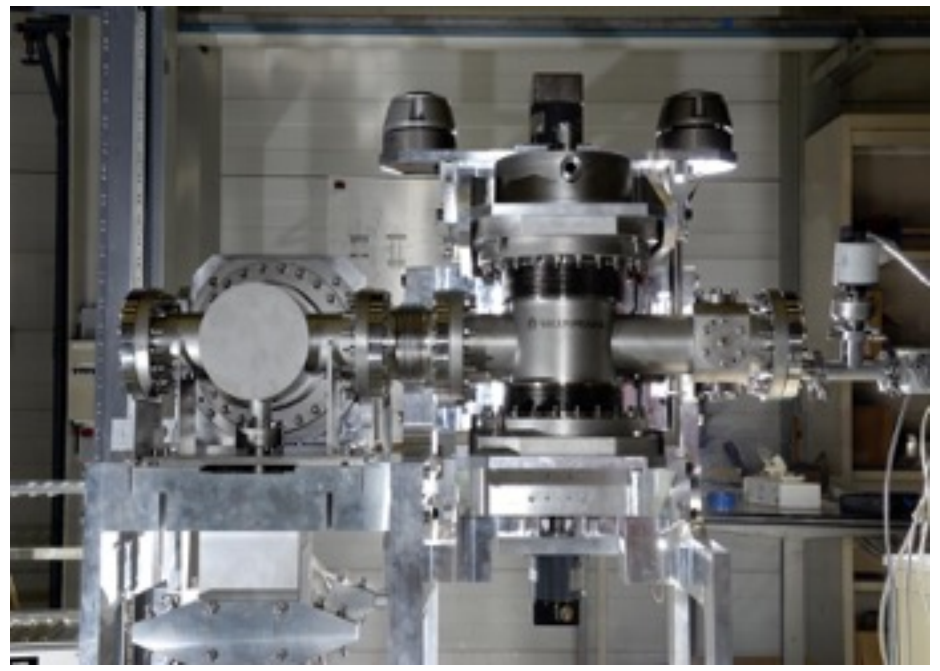
(Cafagna, ICRC 2015)



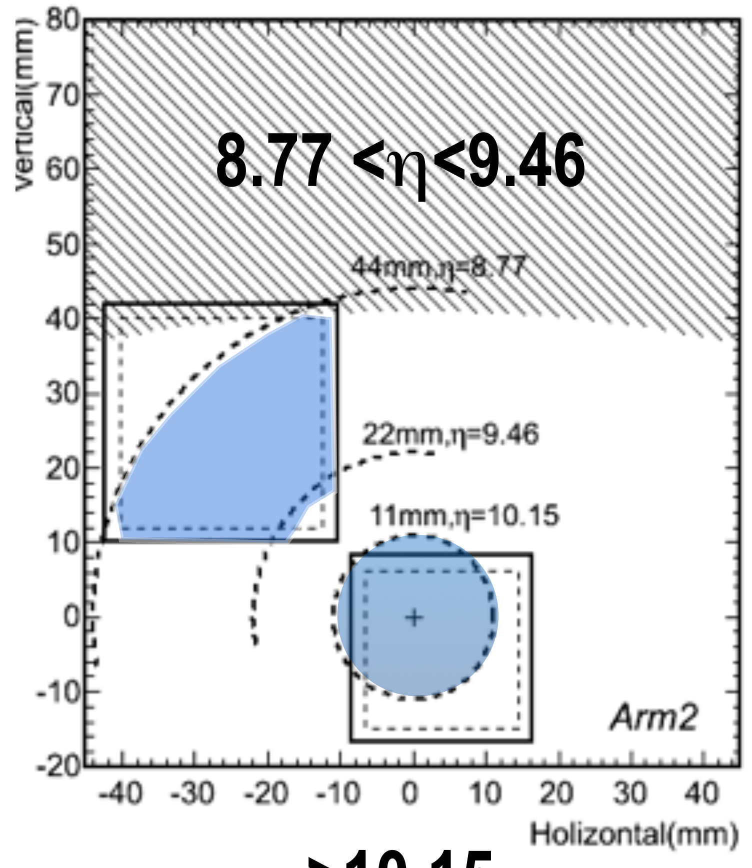


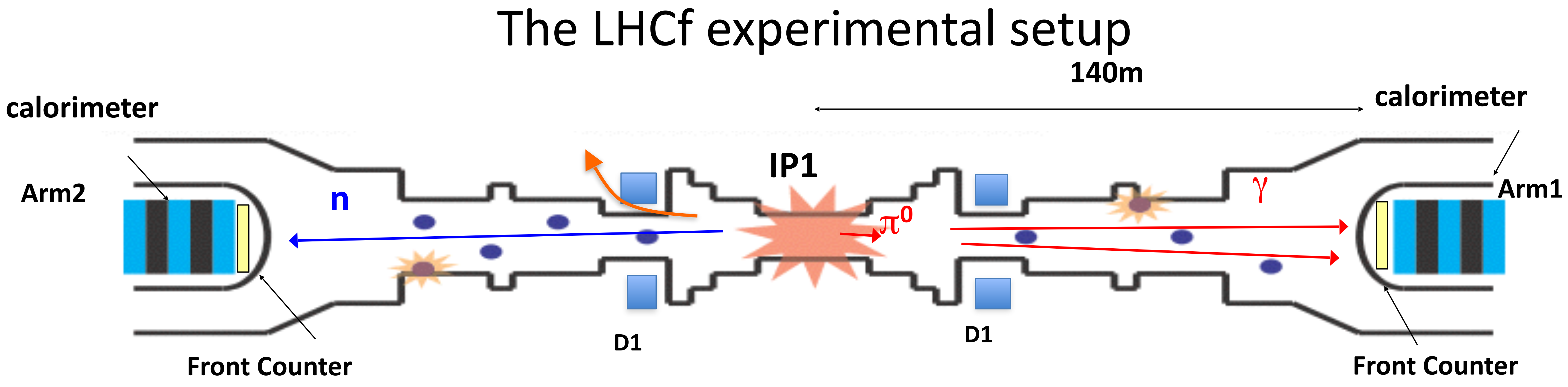


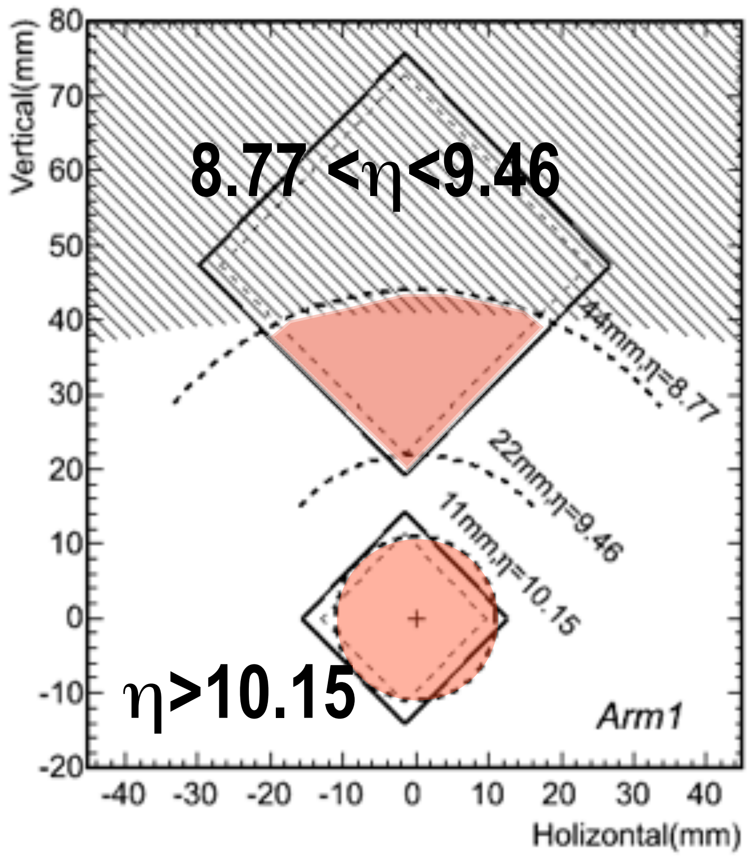




LHCf: very forward photon production at 7 TeV

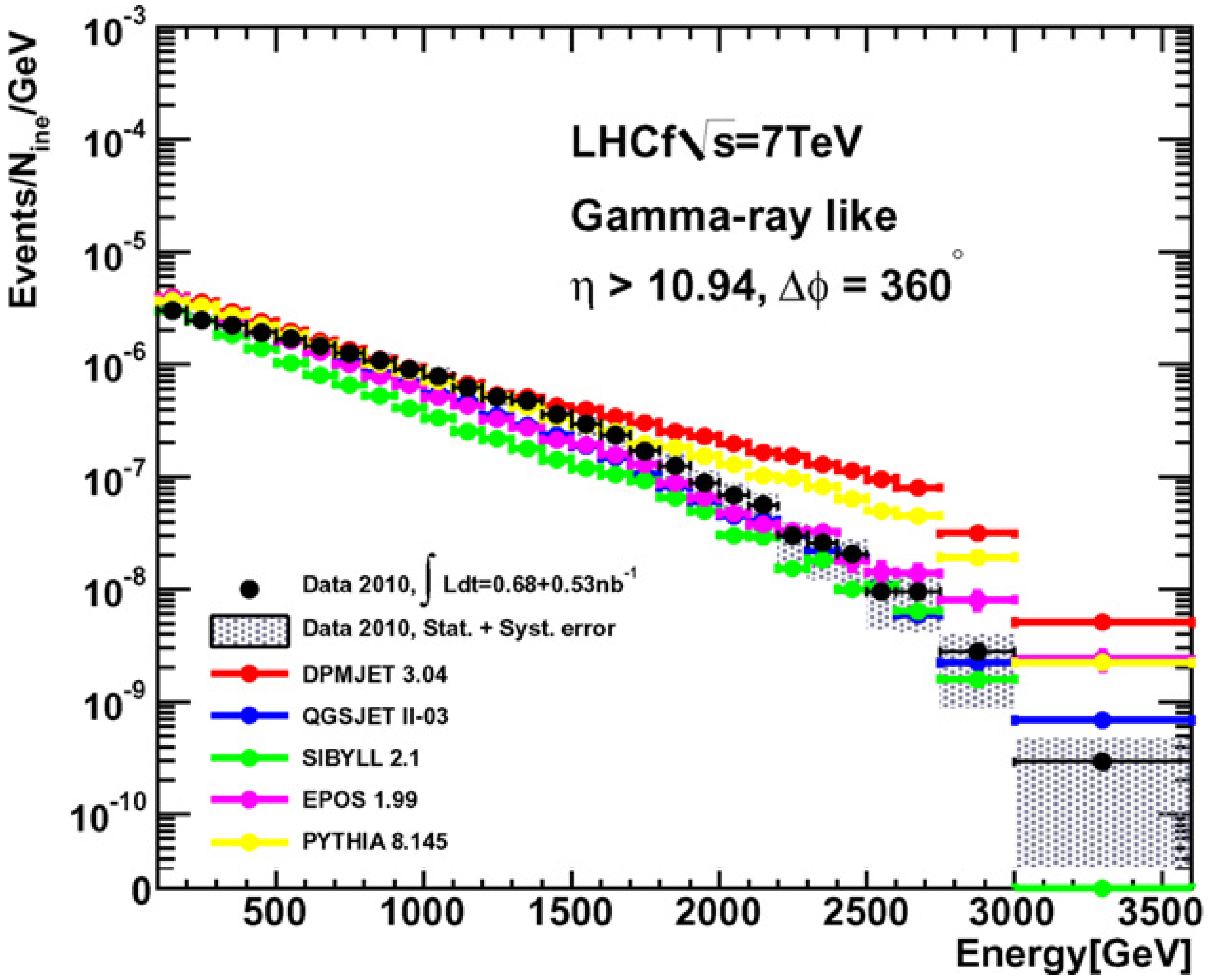


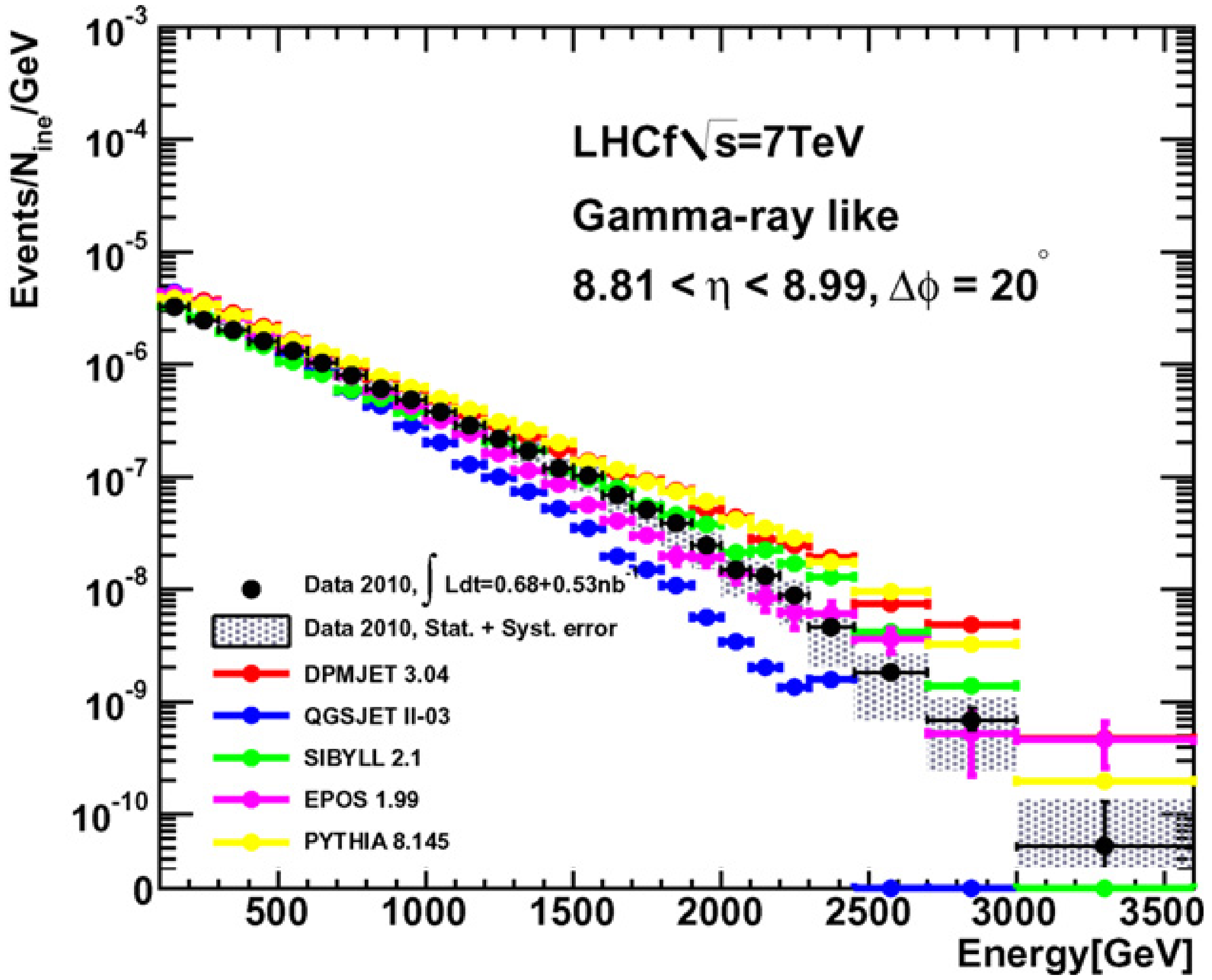


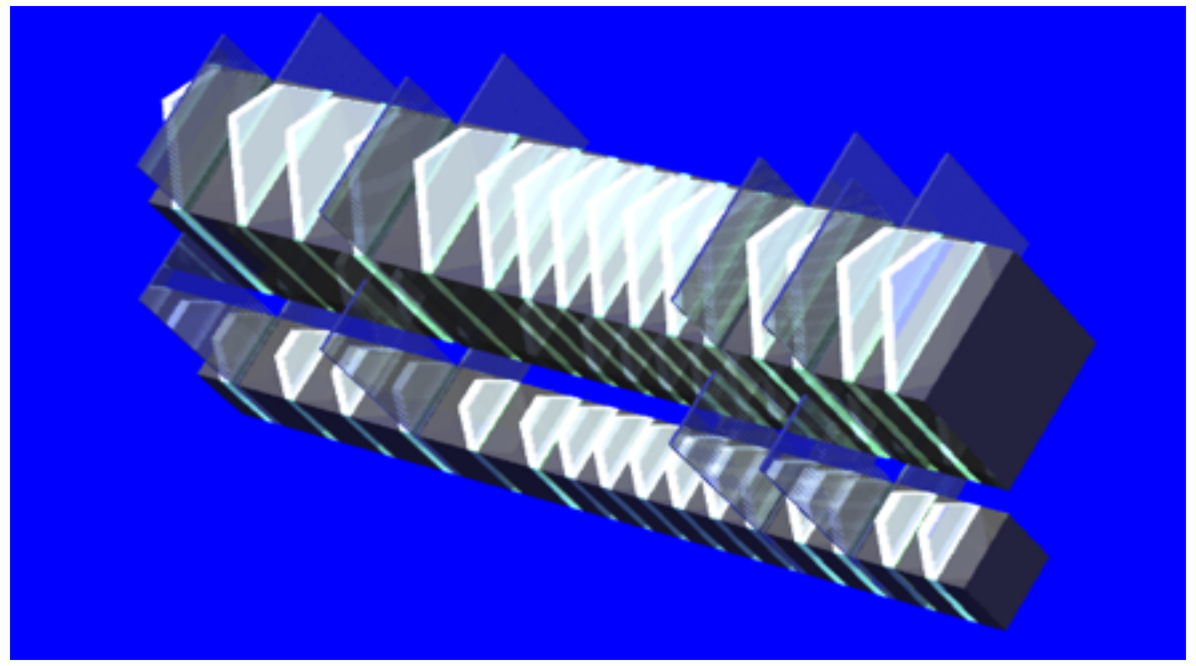


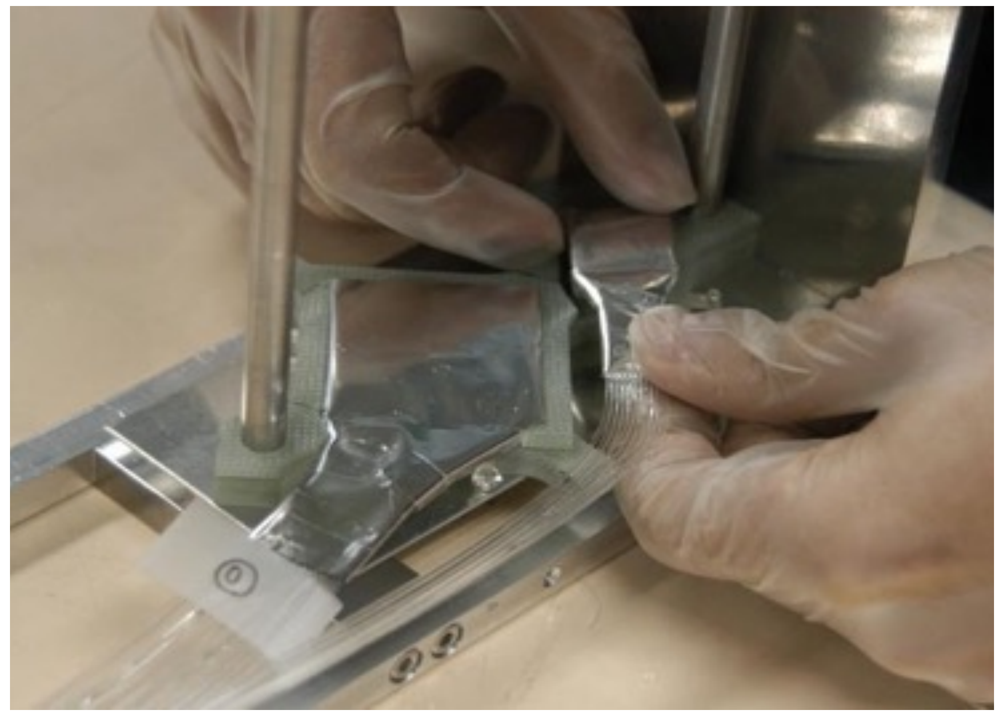
$$pp \to \gamma X$$

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



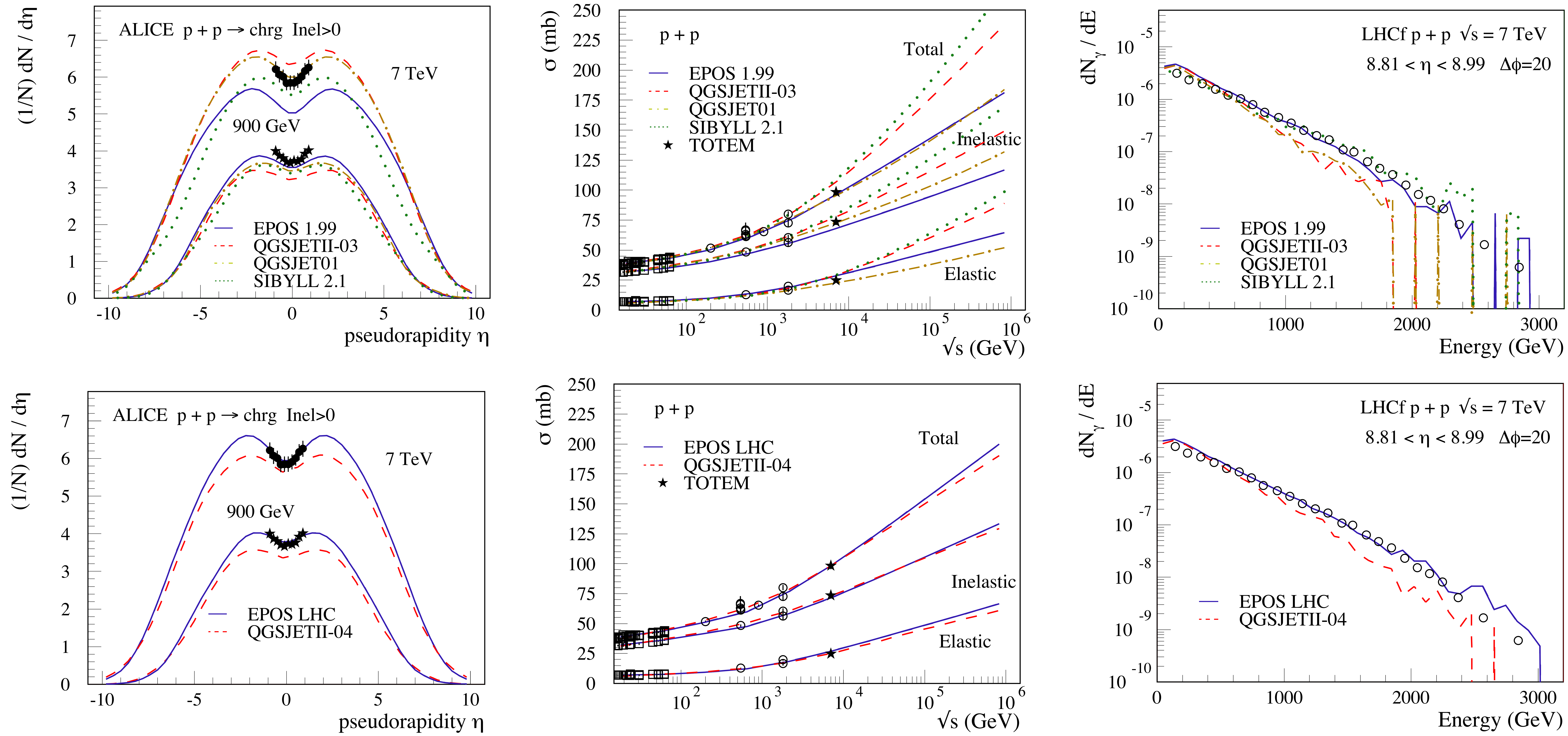






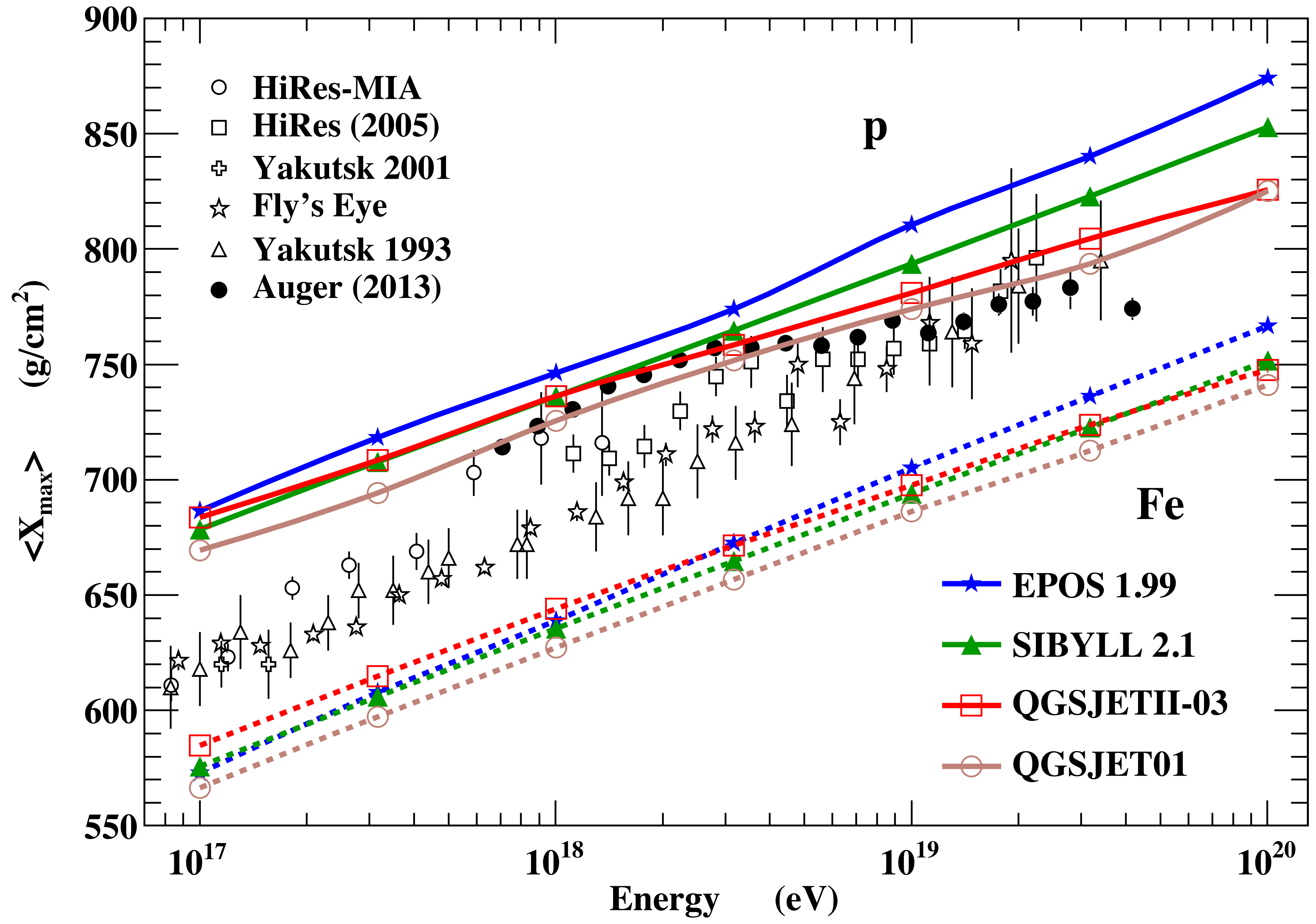
(Itow, ICRC 2015)

Examples of tuning interaction models to LHC data



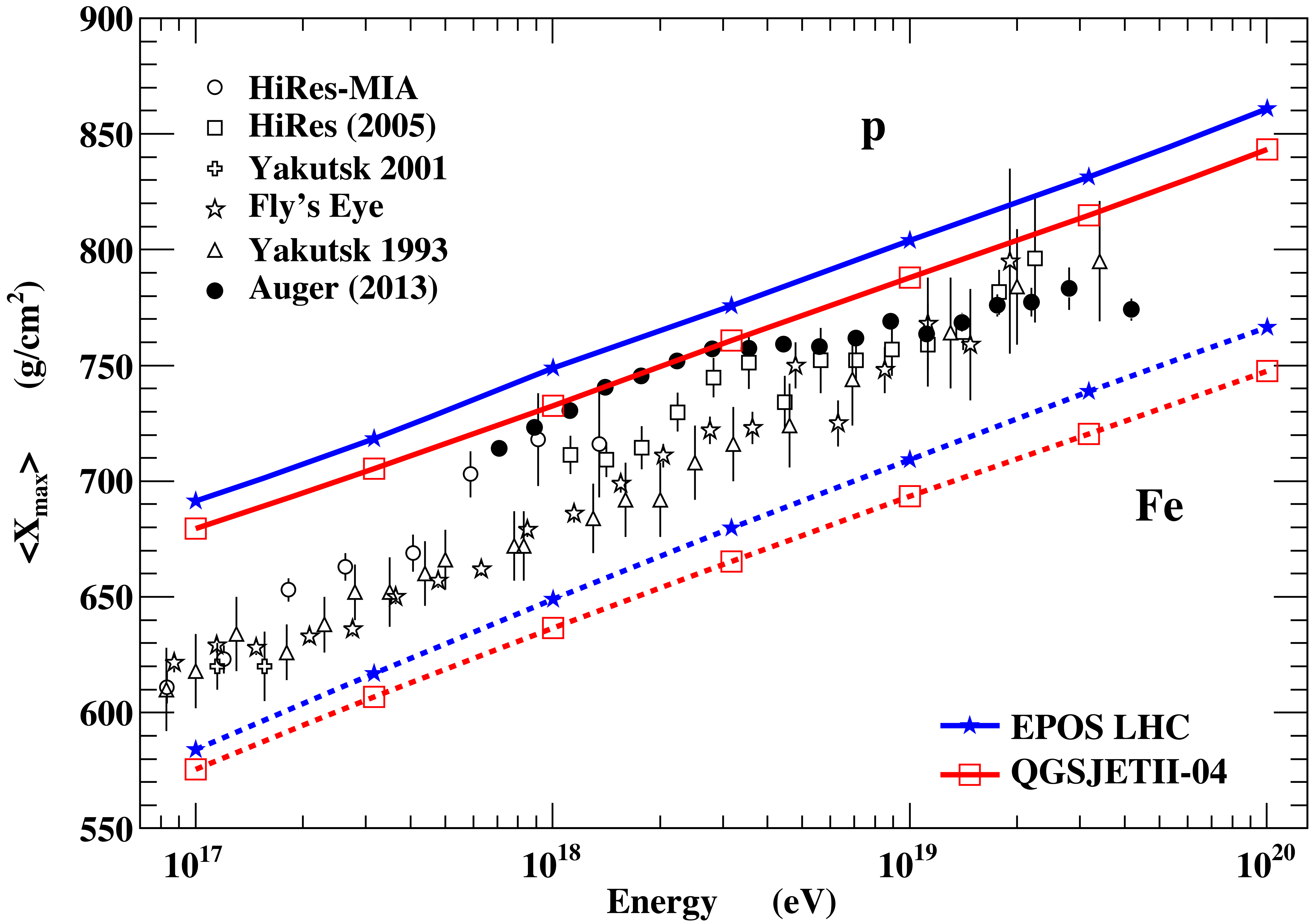
(Pierog 2013, 2014)

Predictions for depth of shower maximum



pre-LHC models

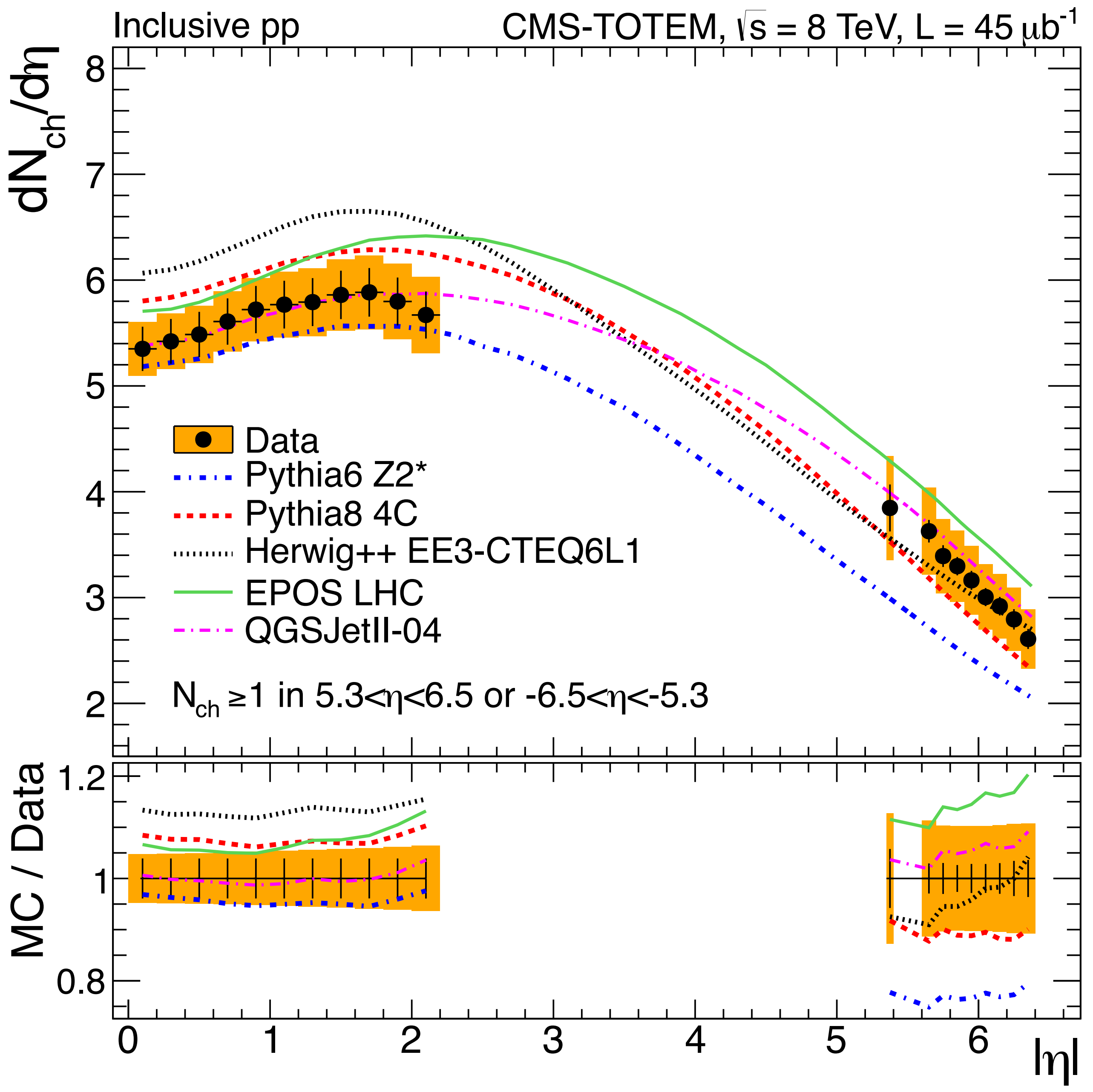
post-LHC models

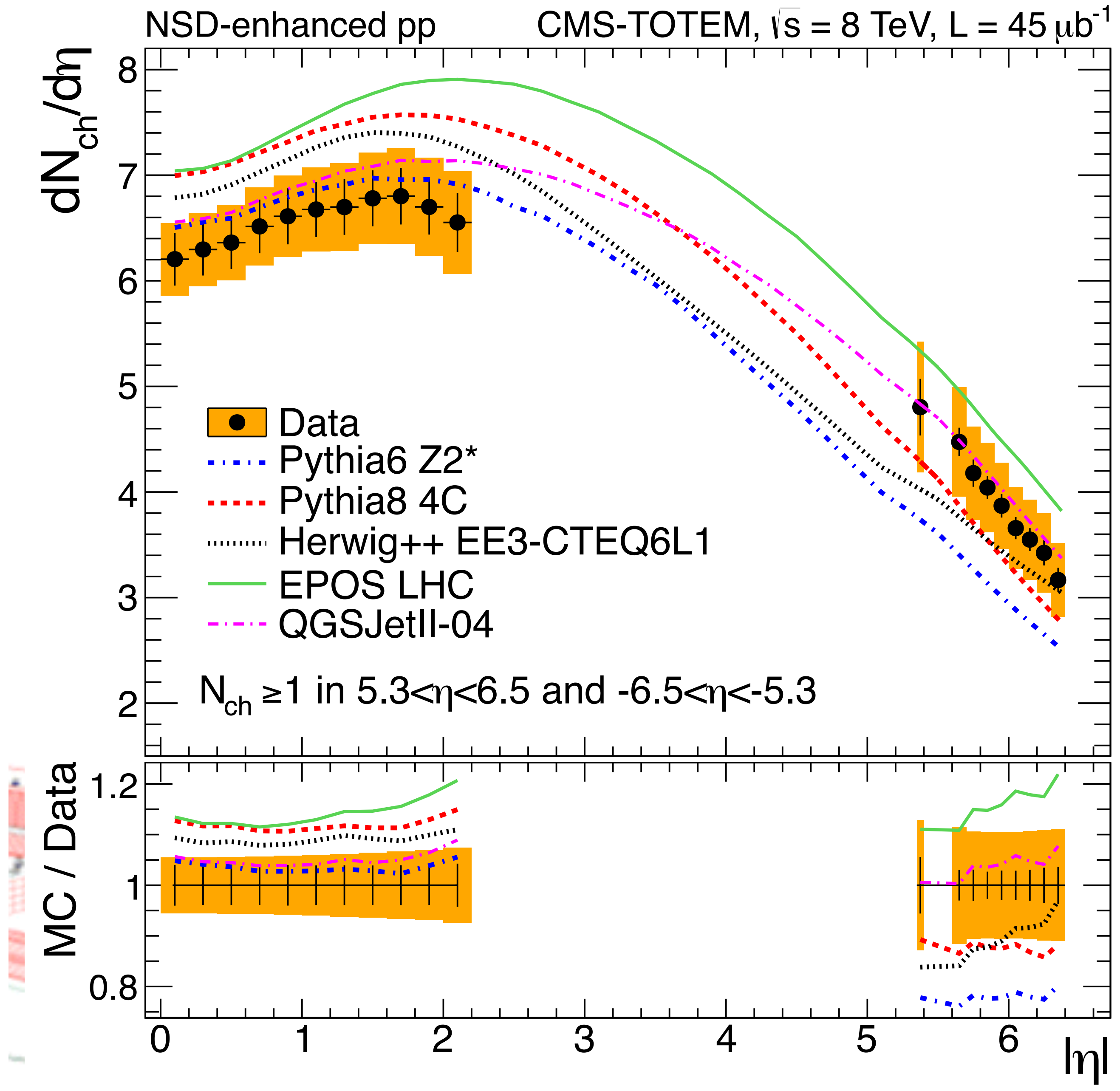


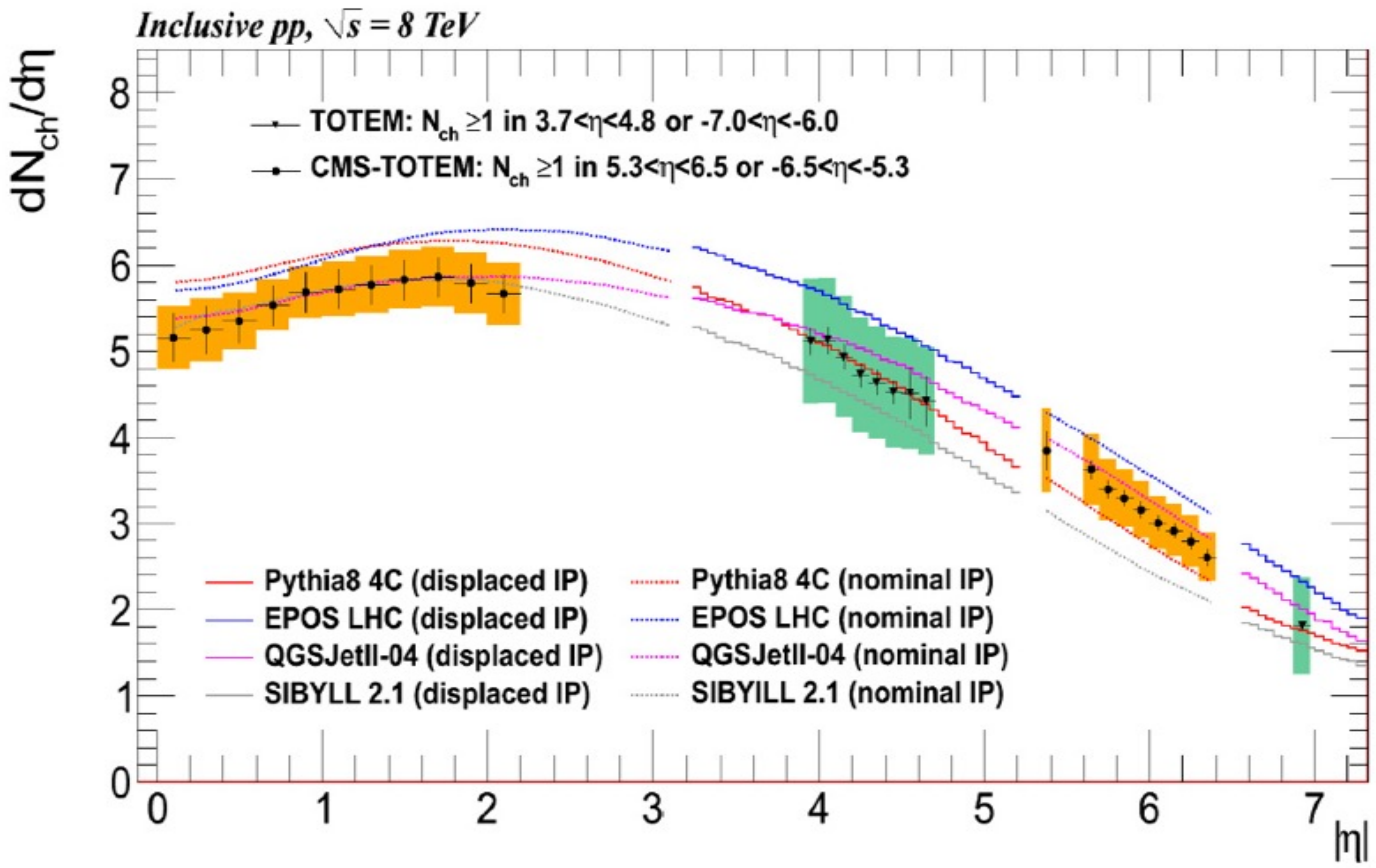
New models favour interpretation as heavier composition than before

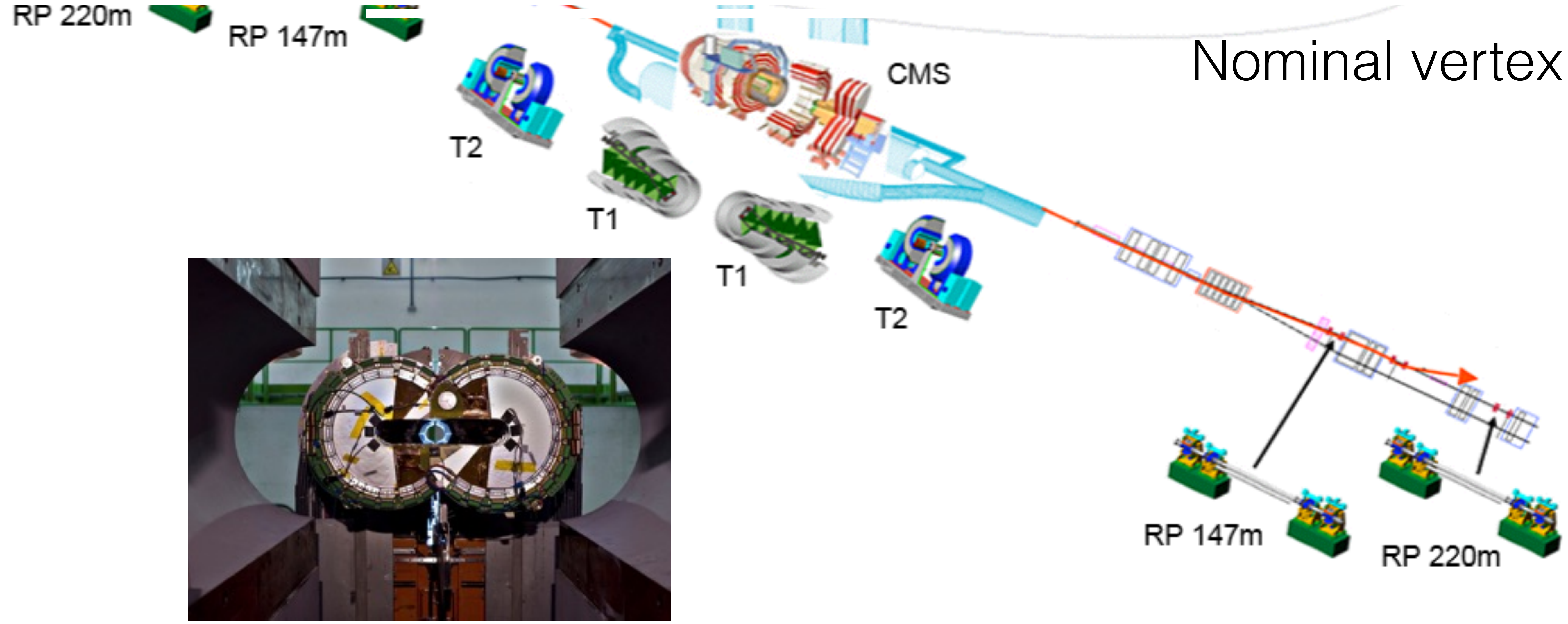
(Pierog 2013, 2014)

Combined CMS and TOTEM measurements



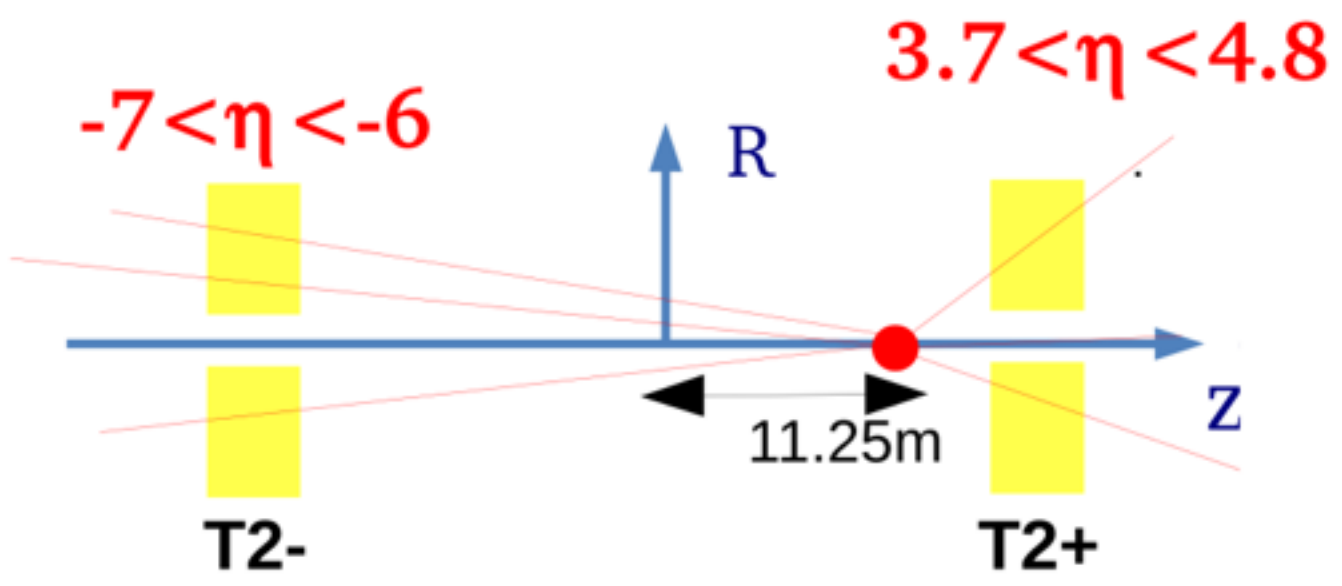




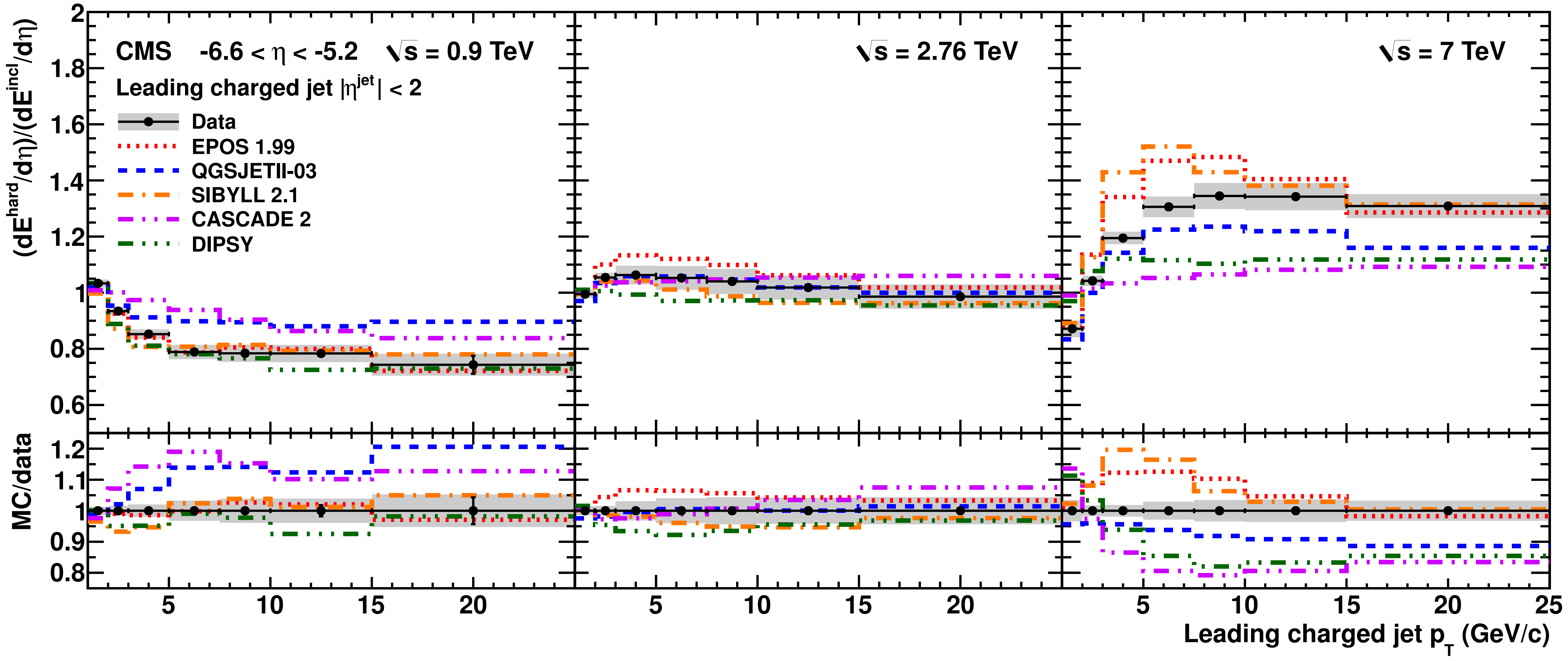


Nominal vertex

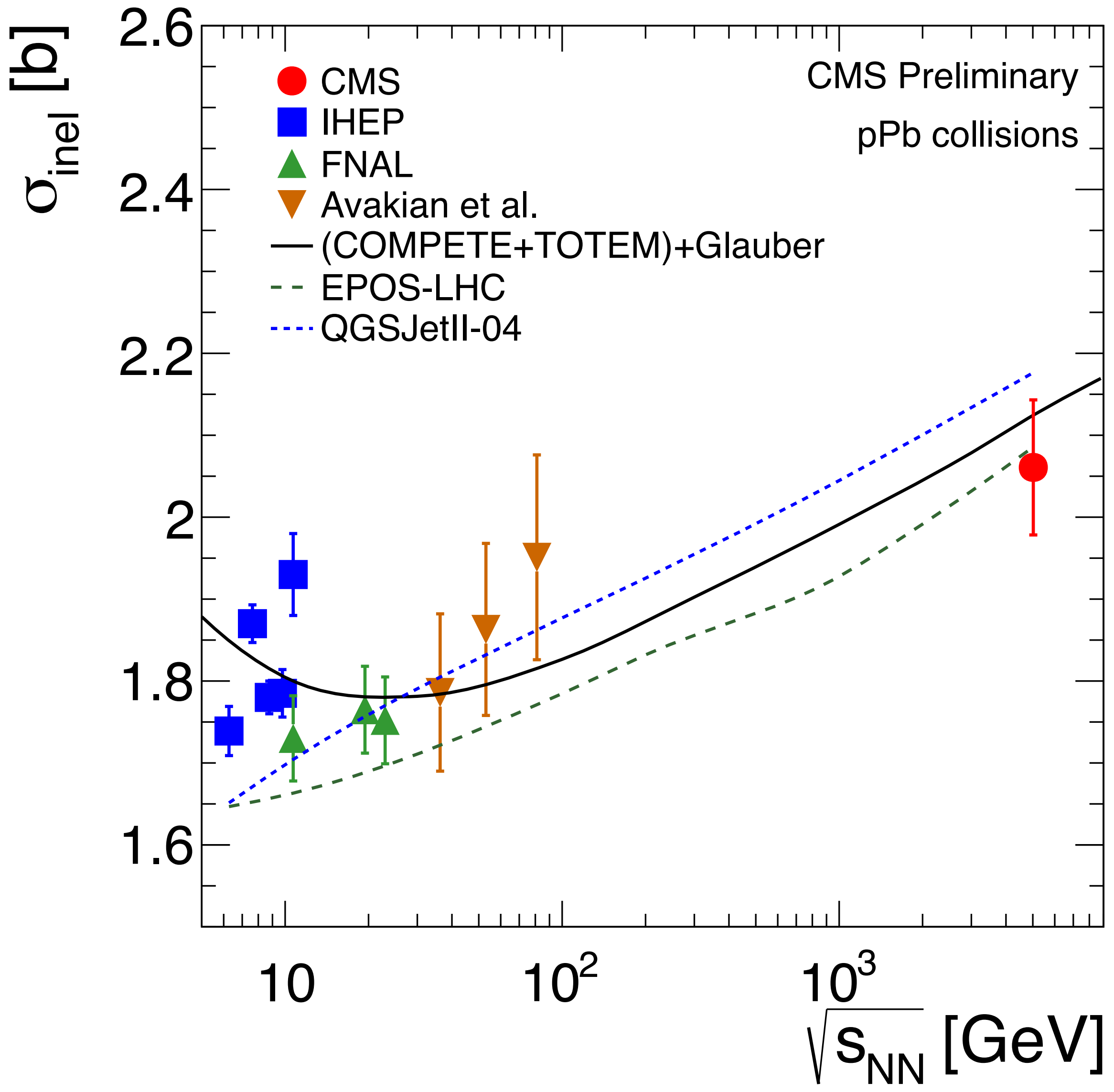
Shifted vertex



Multitude of new LHC measurements



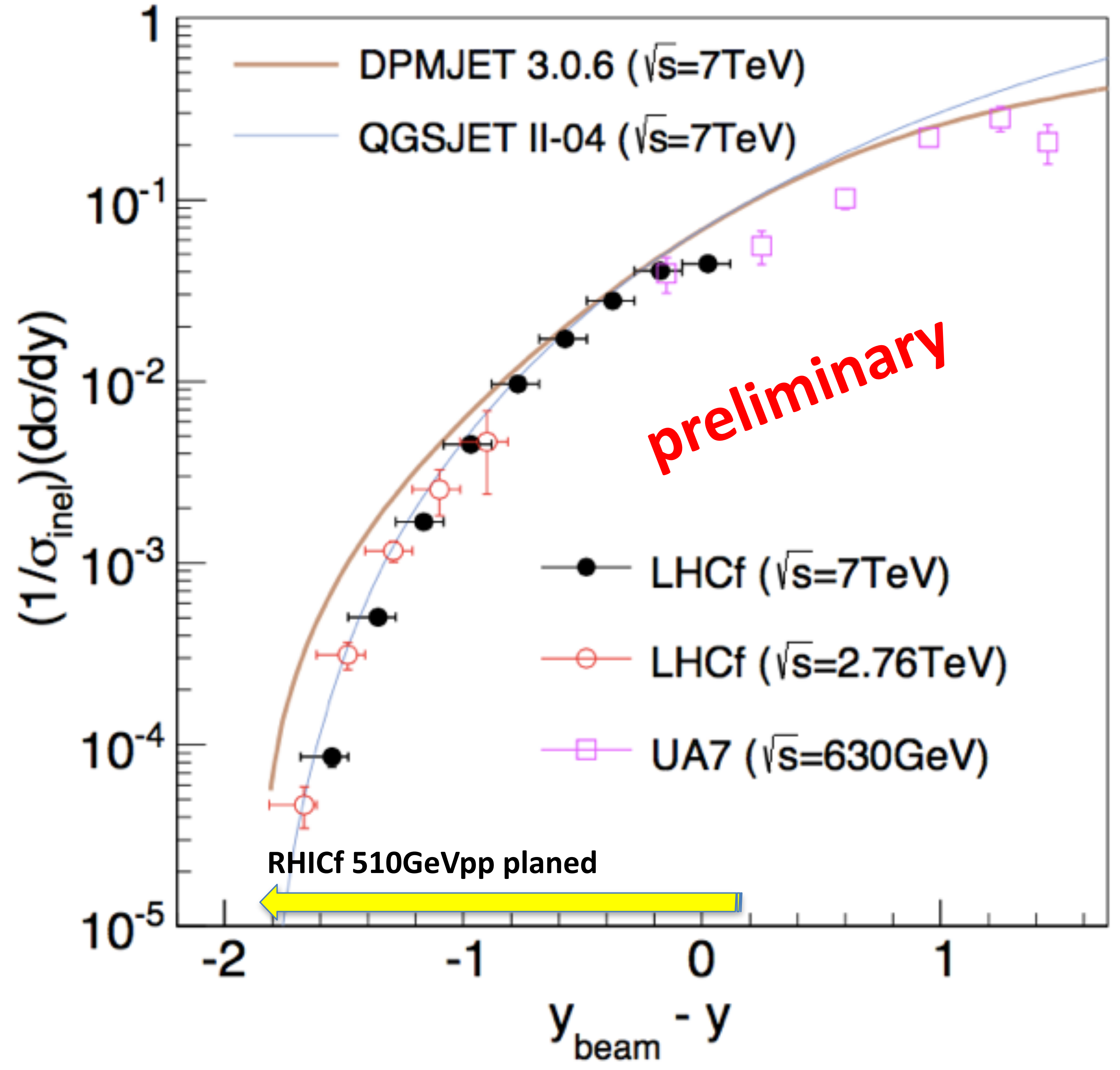
(CMS, JHEP04, 2013)



(CMS, Baus ICRC 2015)

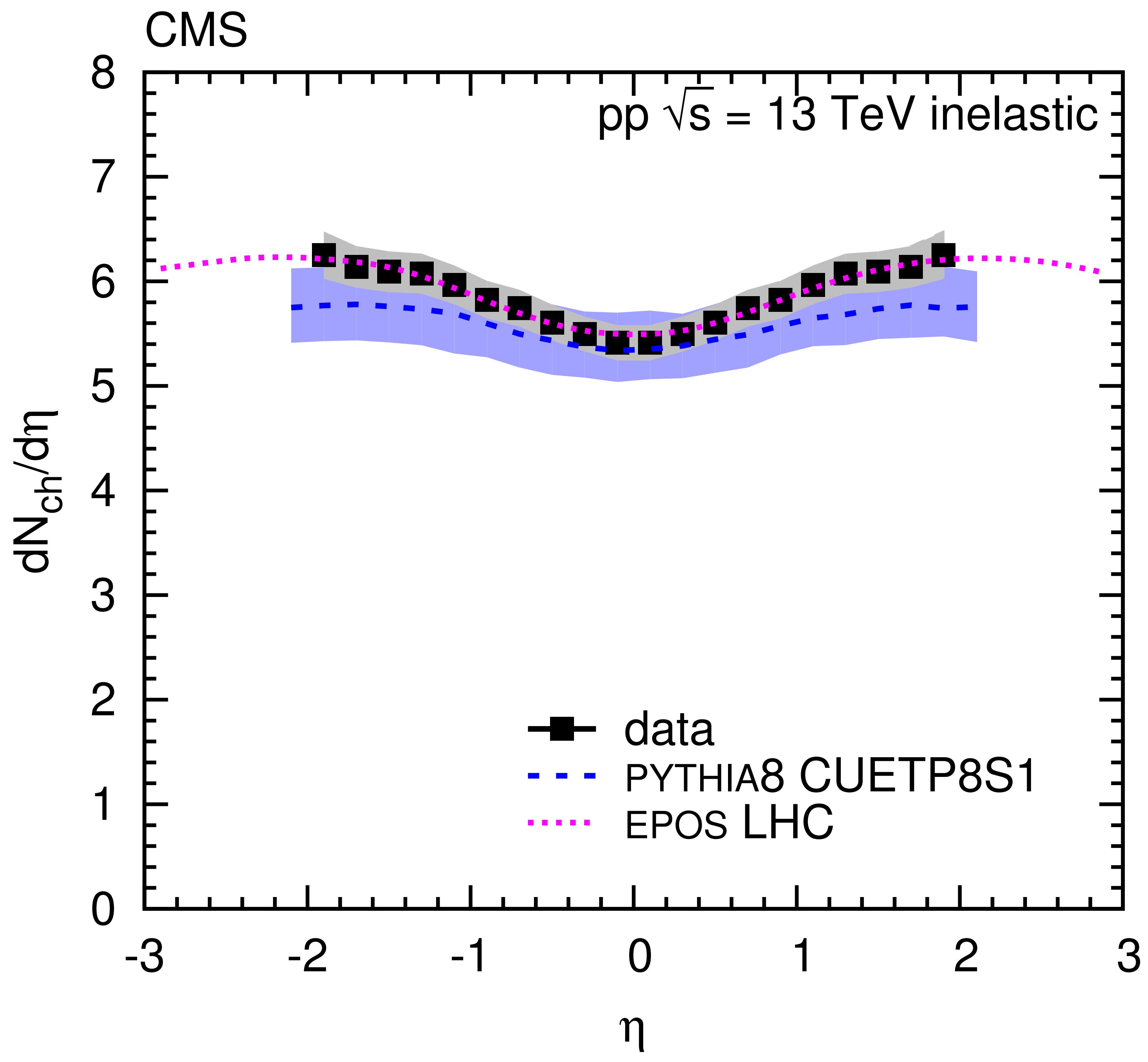
Increasing number of articles with direct comparison with cosmic ray models

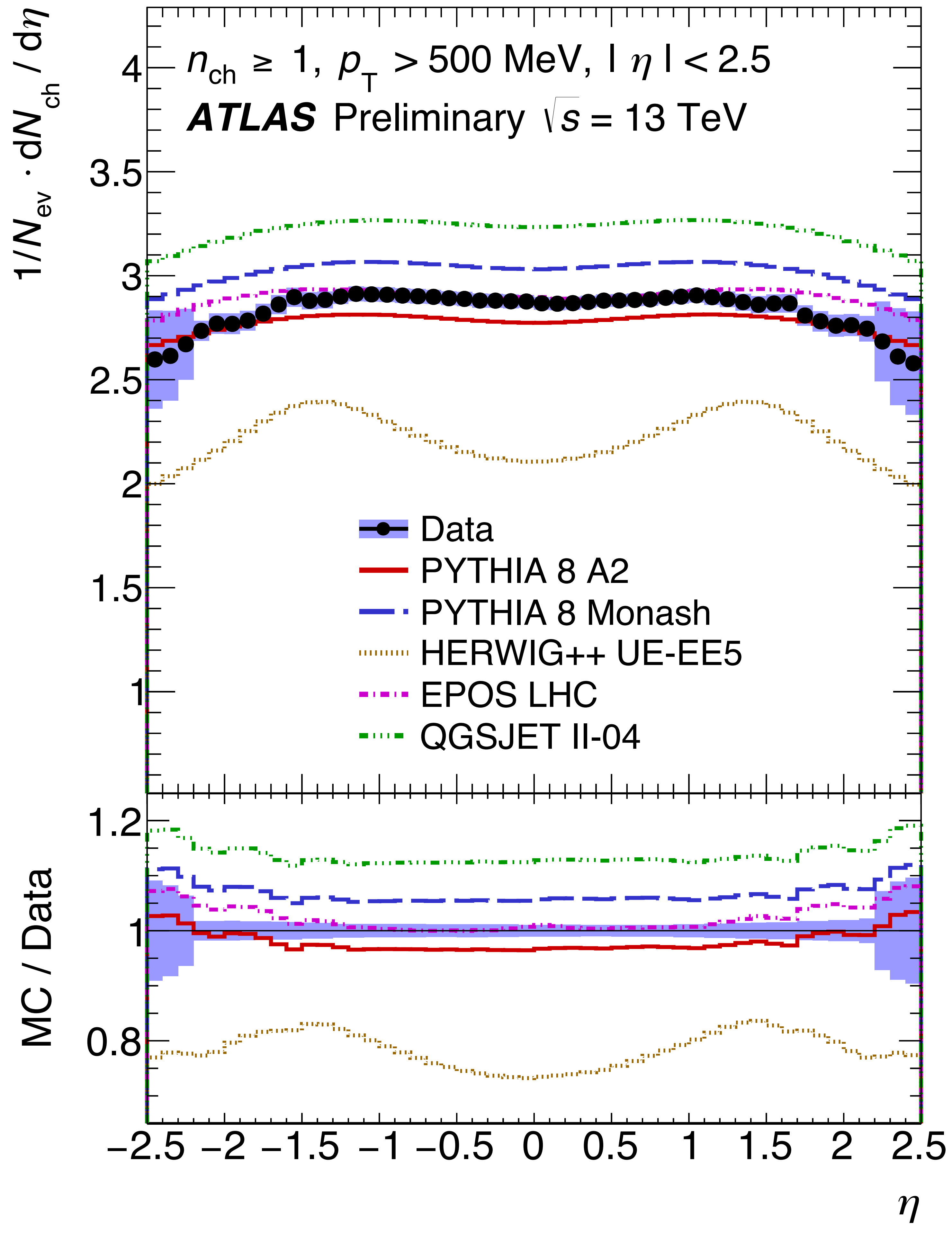
(LHCf, ICRC 2015)

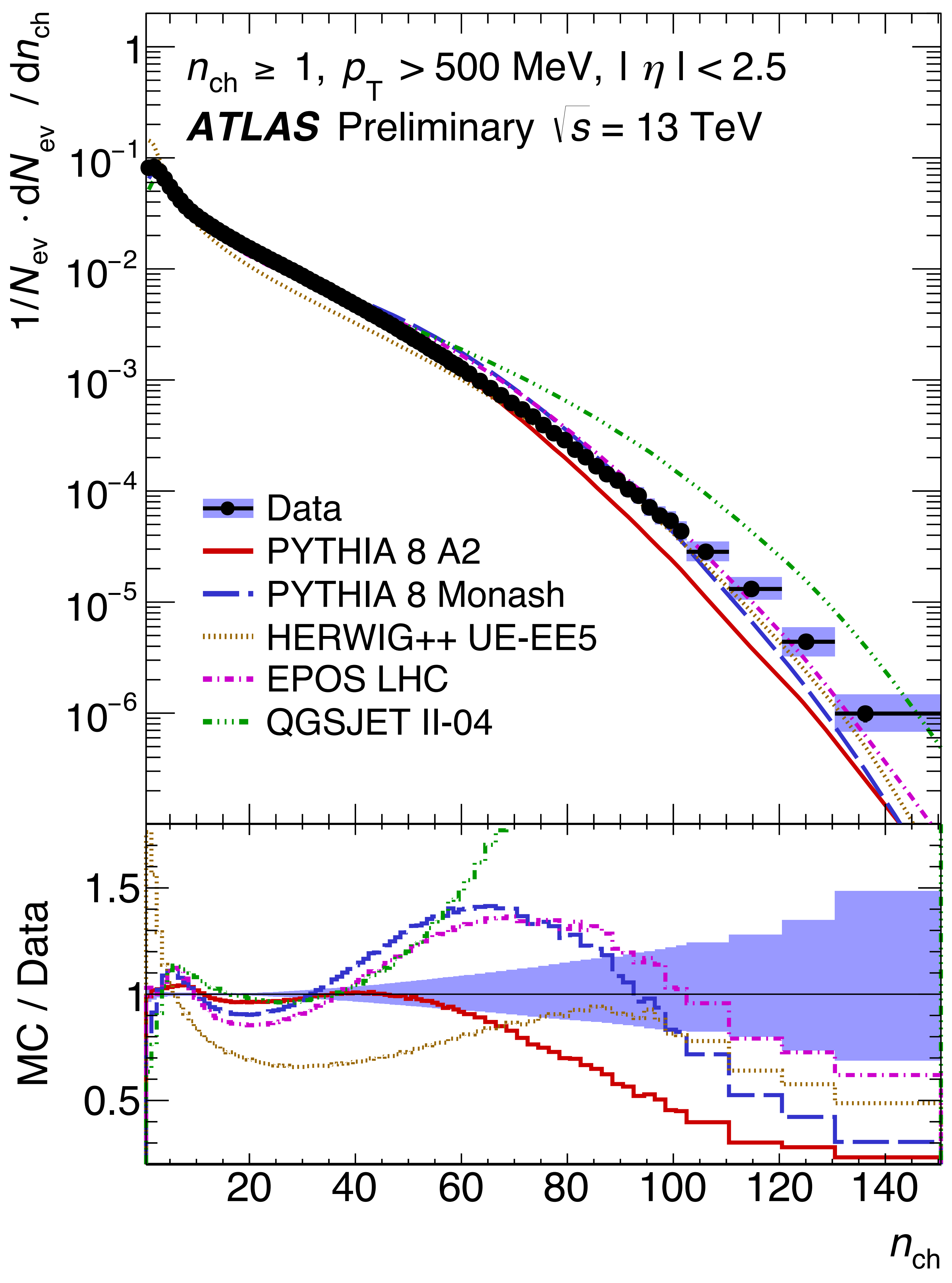


First LHC data at 13 TeV c.m. energy

(CMS, 1507.05915)







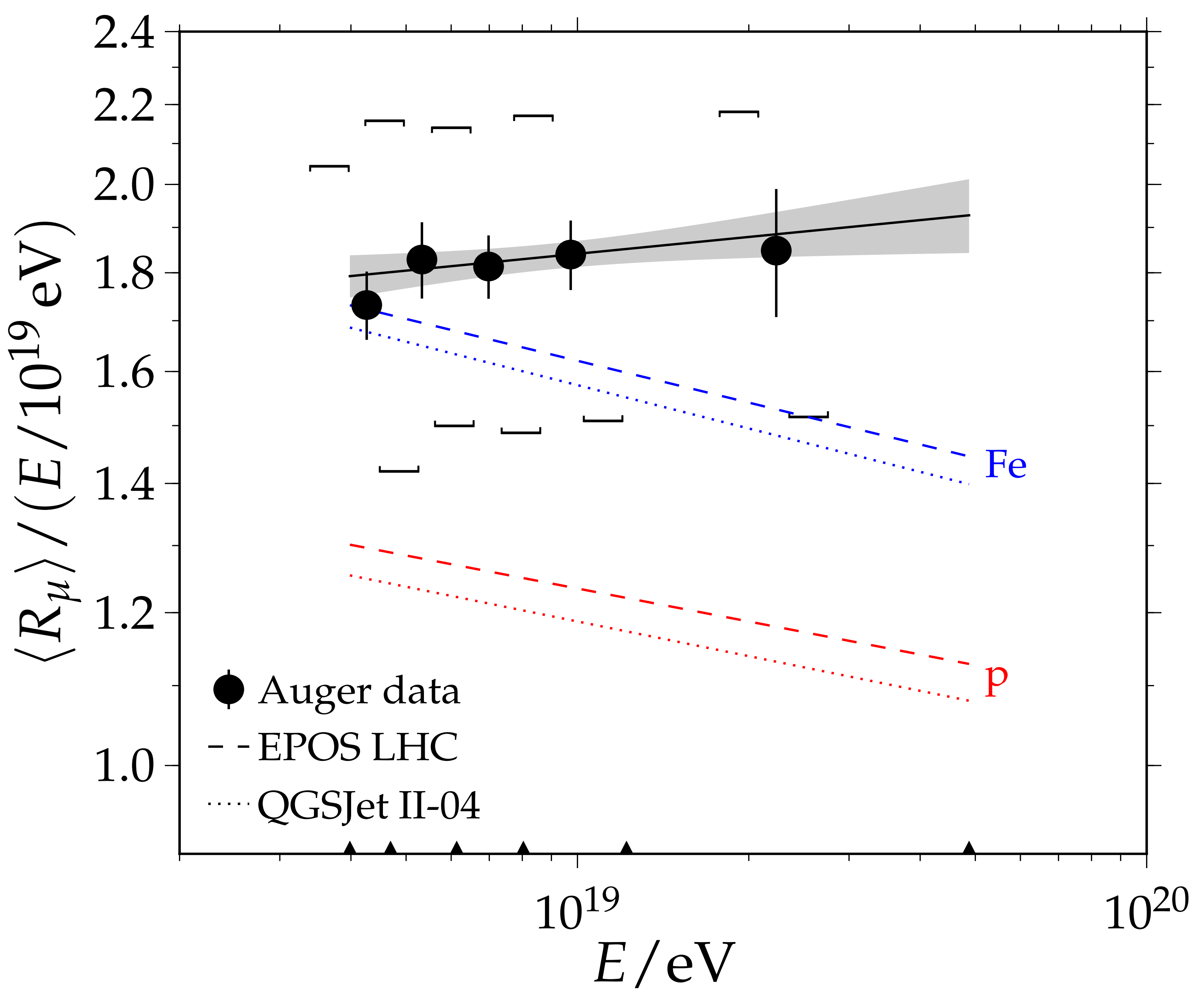
Good agreement with data !

(ATLAS, EPS Geneva 2015)

Indications for shortcomings of our current understanding

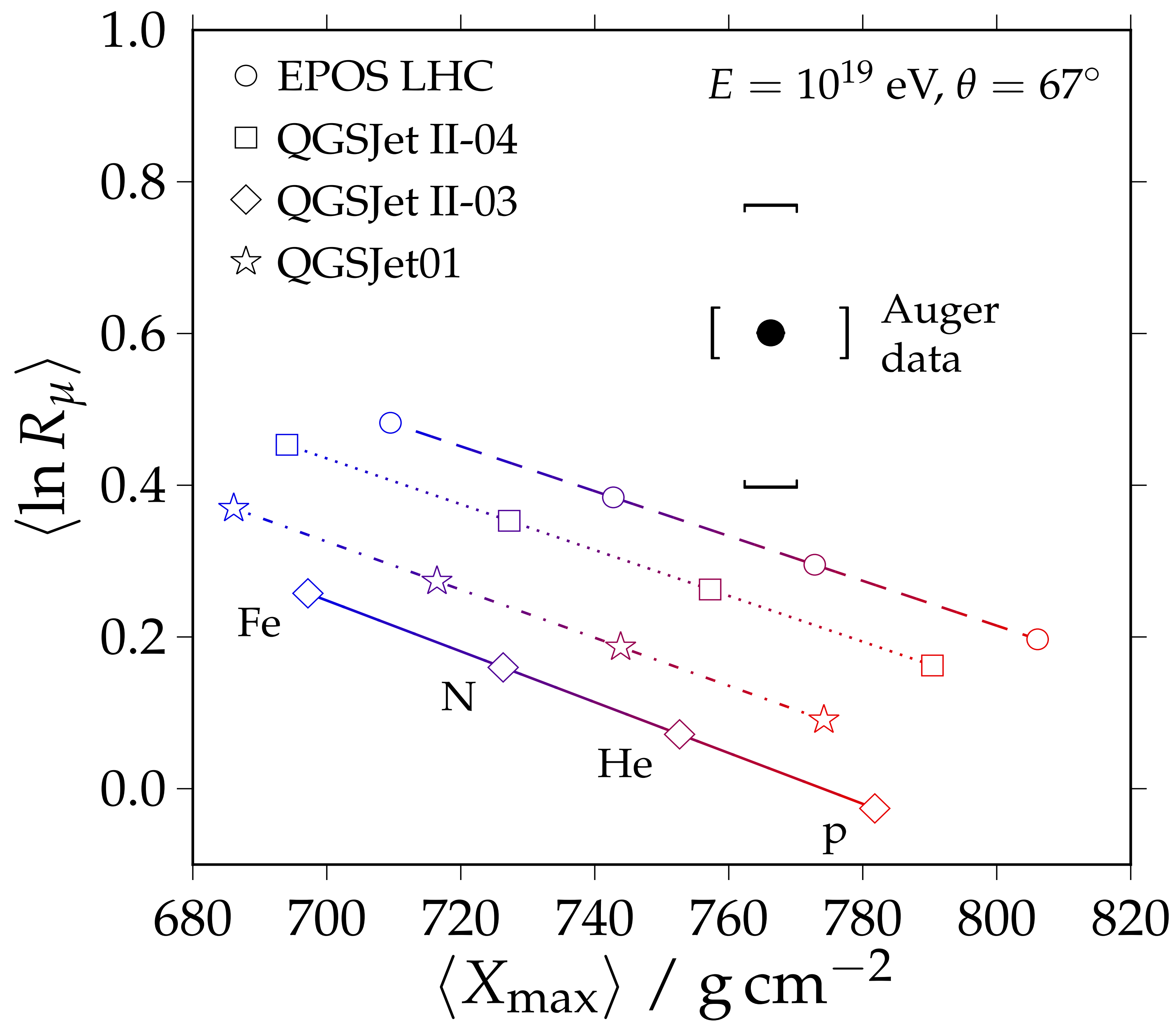
Muon number in inclined showers

Number of muons in showers with θ>60°



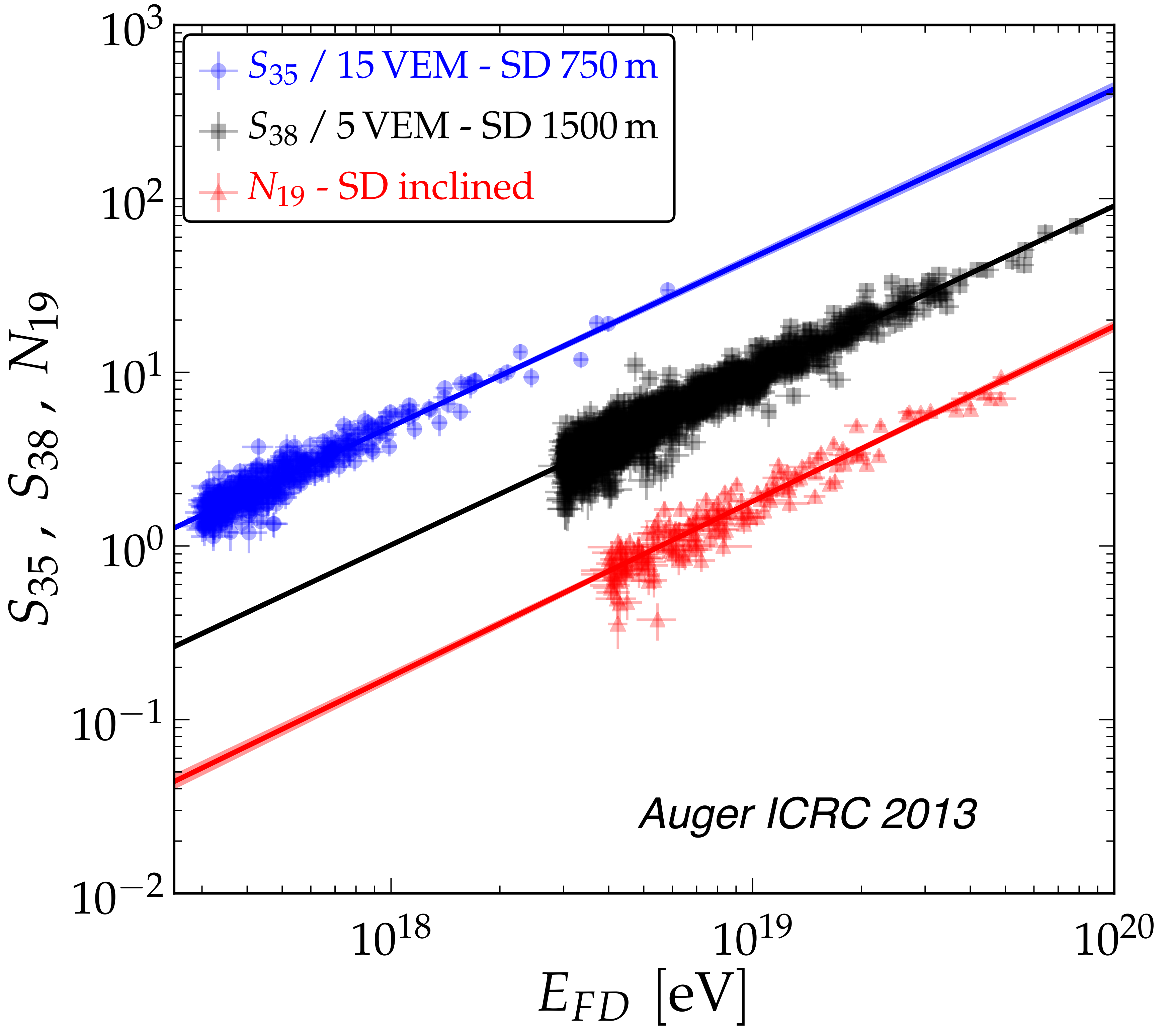
(Auger, PRD91, 2015)

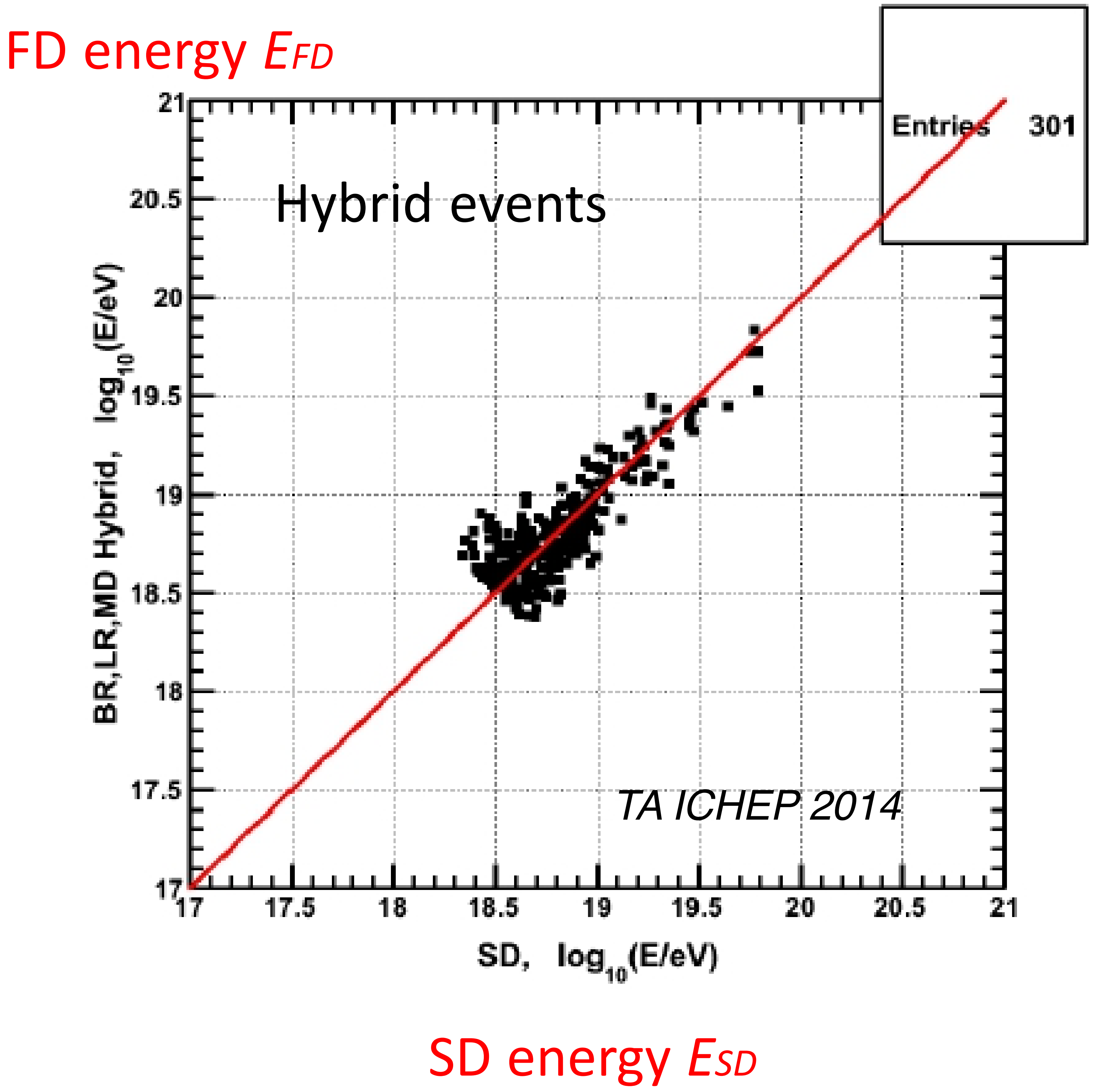
Combination of information on mean depth of shower maximum and muon number at ground



Several measurements: indications for muon discrepancy

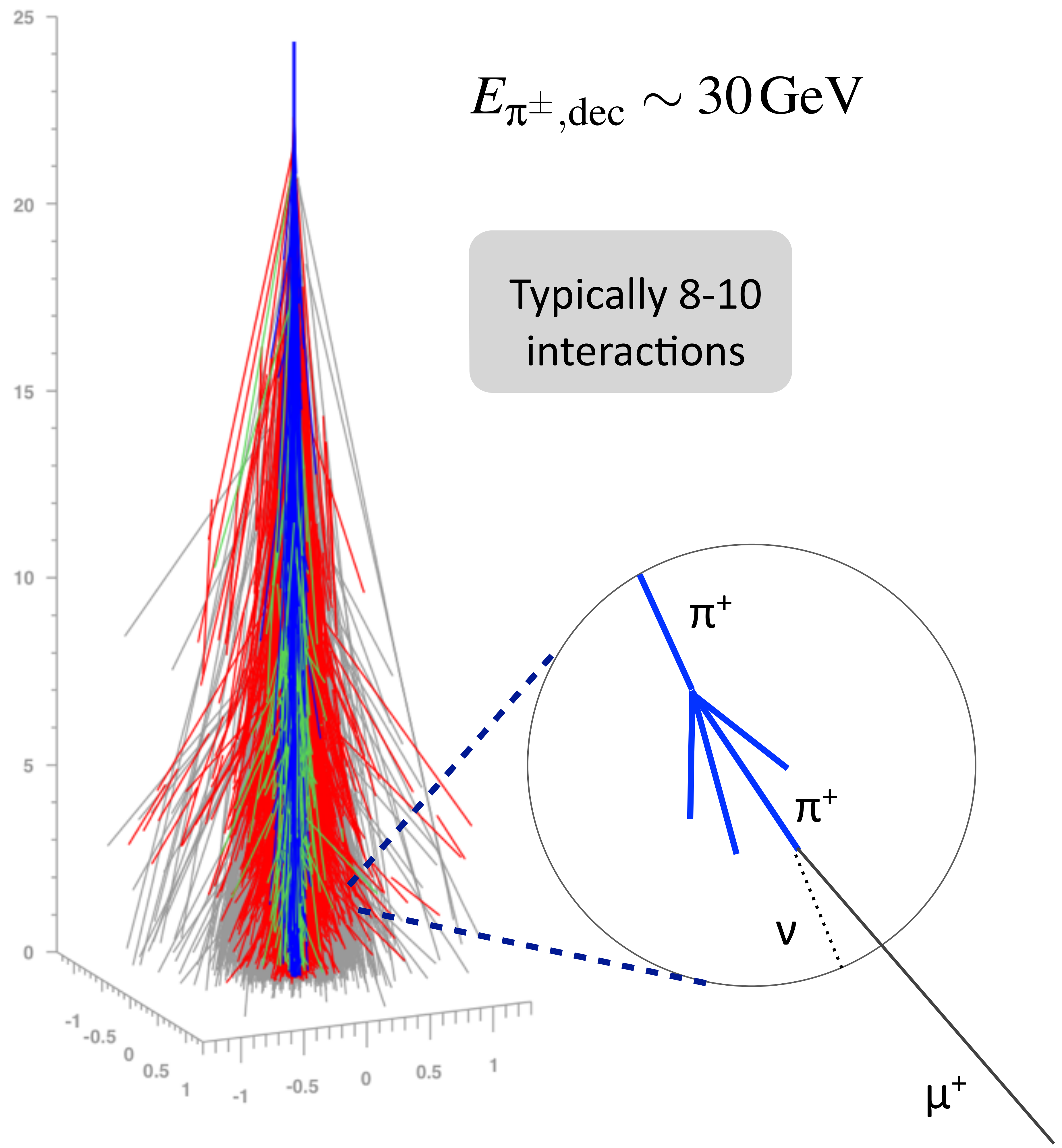
Difference in fluorescence and simulated array signal





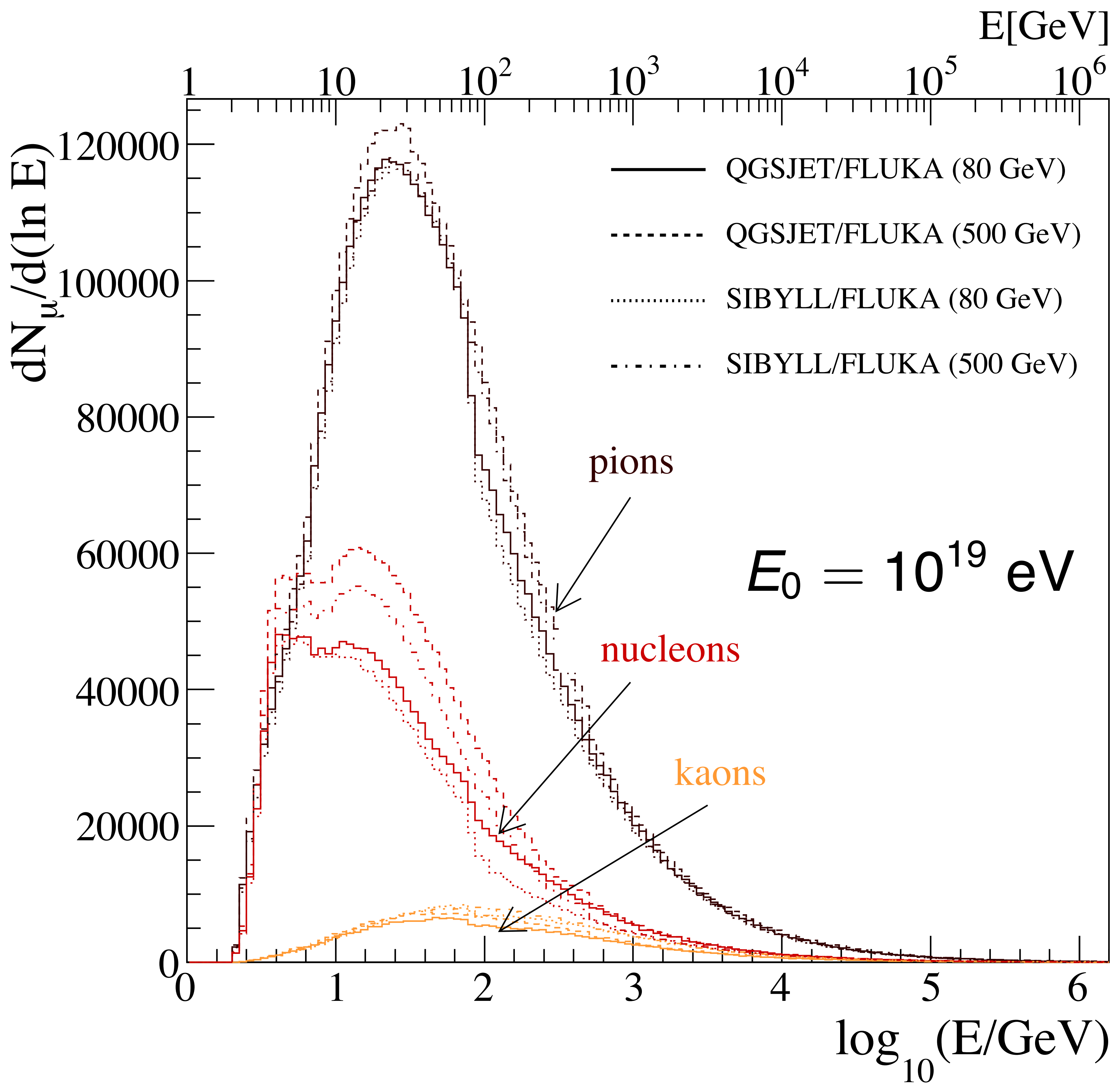
Auger: rescaling of 24% needed relative to 50/50 mix of p and Fe
TA: rescaling of 27% needed relative to protons (QGSJET II.03)

Muon production at large lateral distance



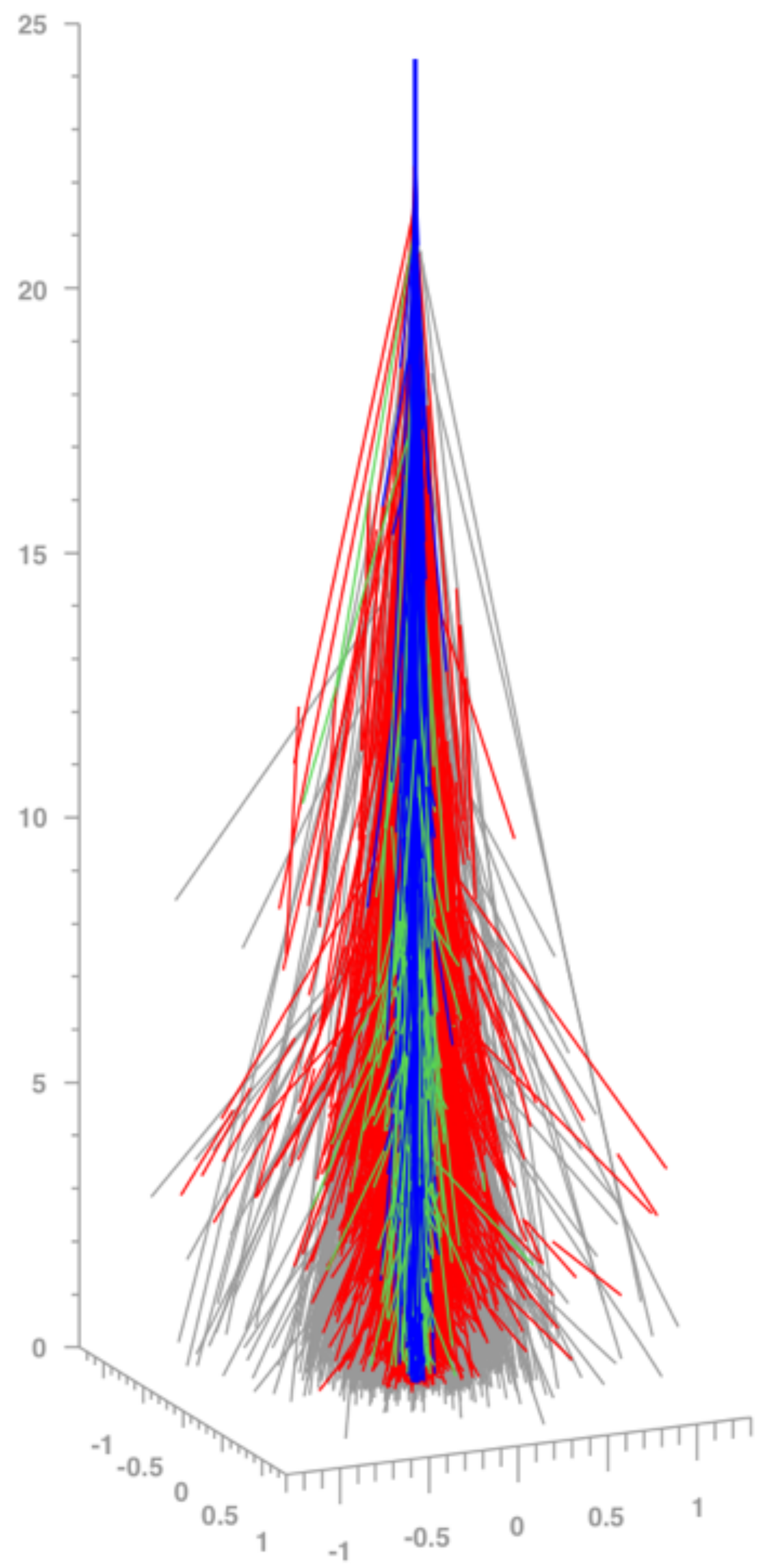
Muon observed at 1000 m from core

Energy distribution of last interaction that produced a detected muon

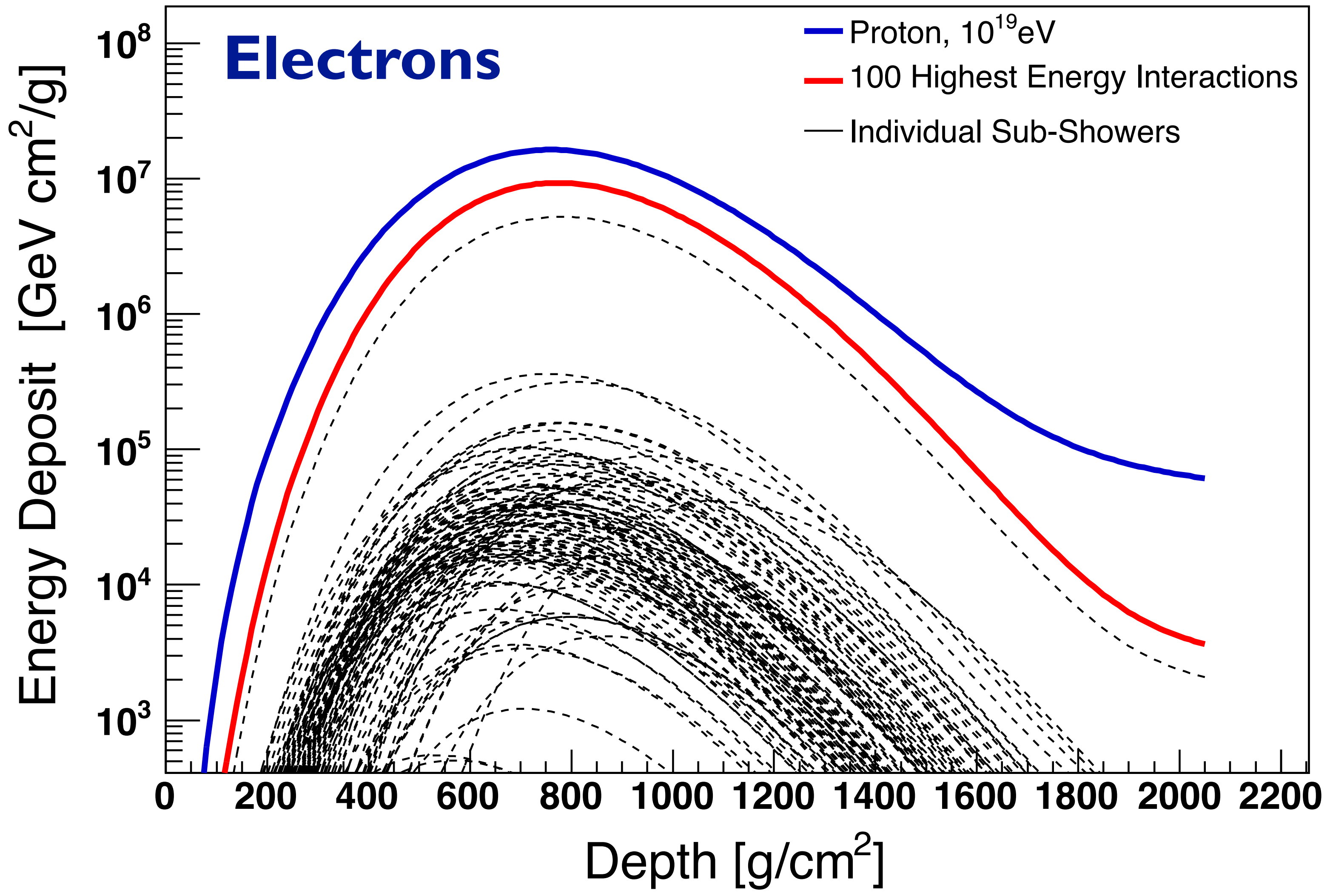


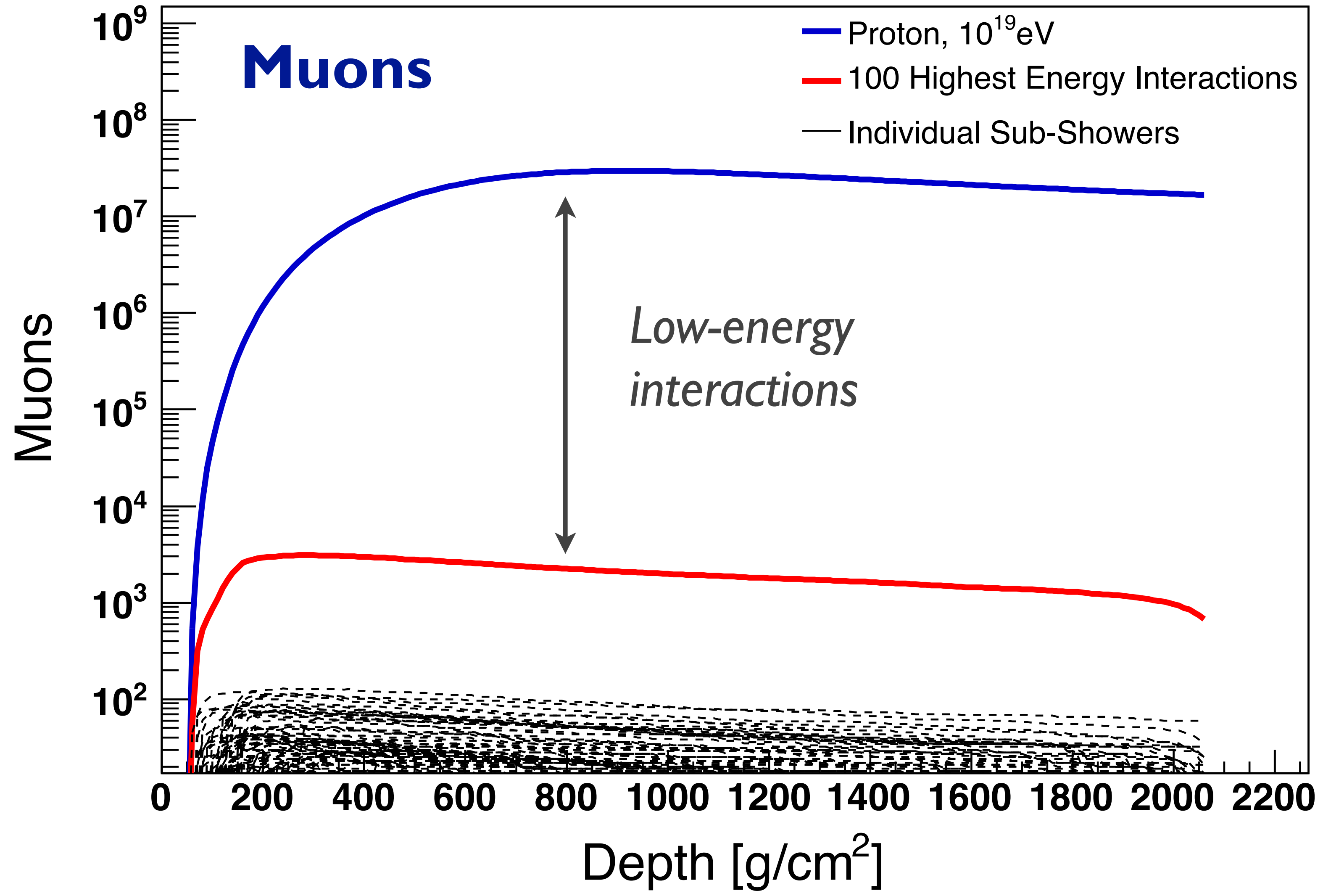
(Maris et al. ICRC 2009)

Importance of hadronic interactions



(Ulrich APS 2010)





Shower particles produced in 100 interactions of highest energy

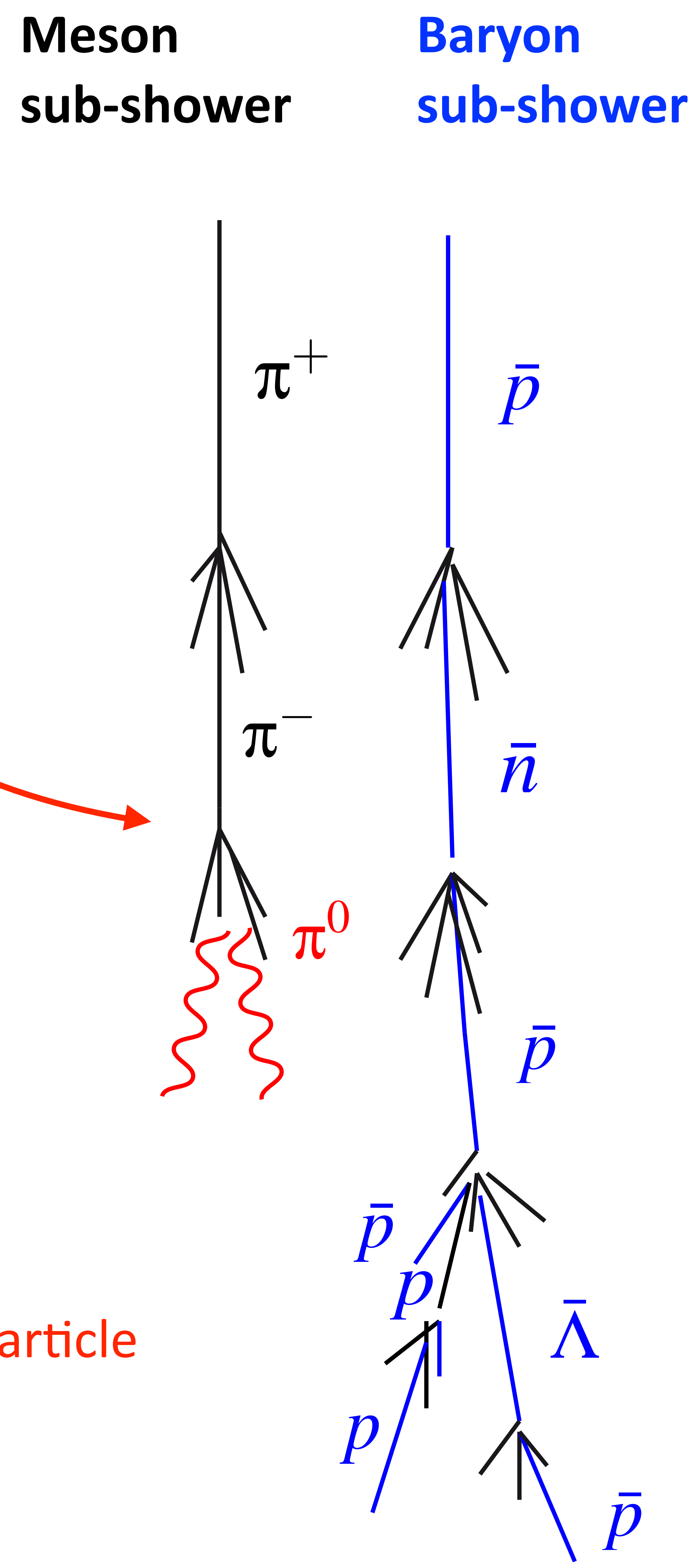
Electrons/photons: high-energy interactions

Muons/hadrons: low-energy interactions

Muons: majority produced in ~30 GeV interactions

Change of energy transferred to electromagnetic component

30% chance to have π^0 as leading particle



Decay of leading particle

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

- 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)

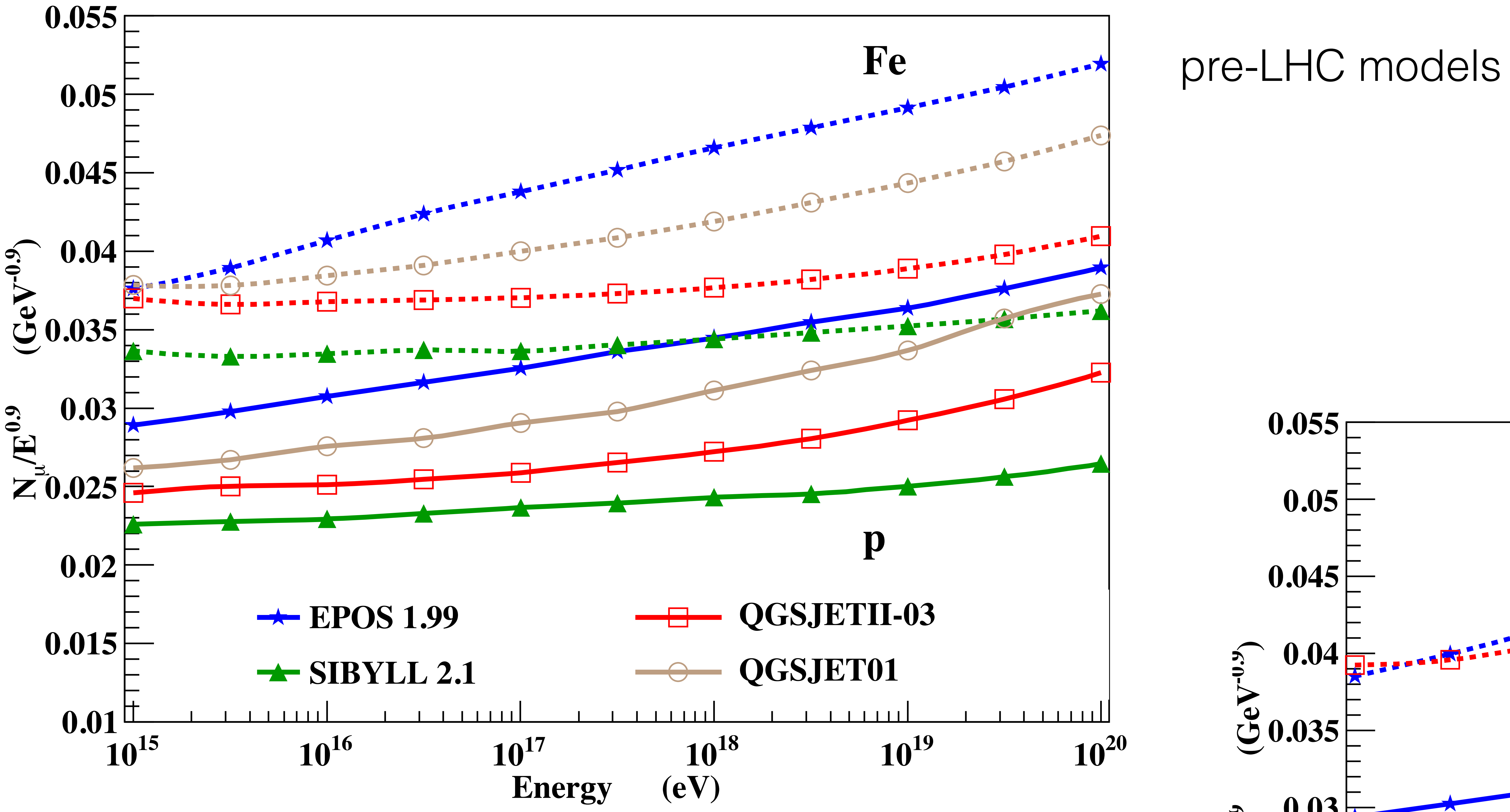
2 Leading particle effect for pions *(Drescher 2007, Ostapchenko)*

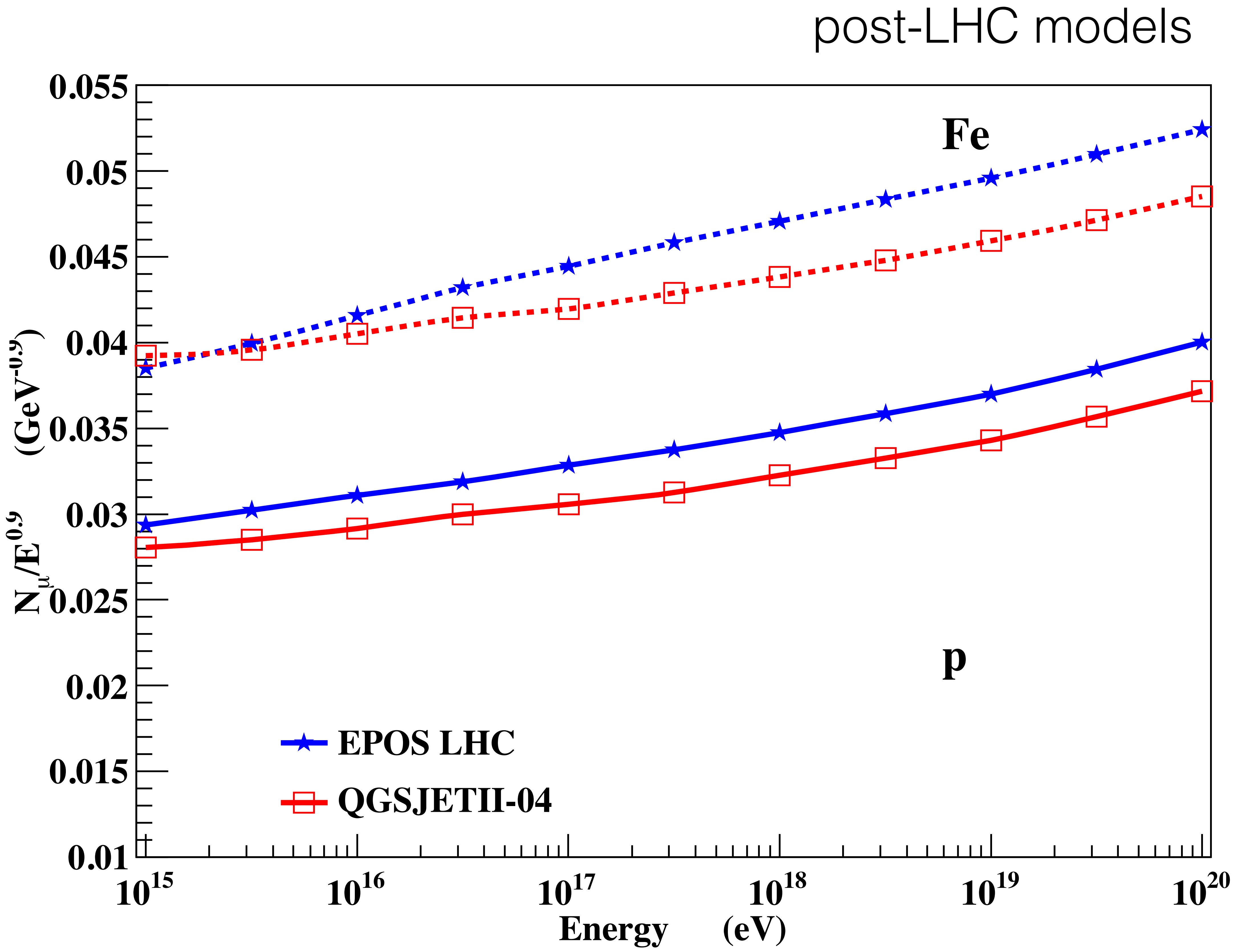
- Leading particle for a π could be ρ^0 and not π^0
- Decay of ρ^0 to 100% into two charged pions

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

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

Predictions for muon number at ground

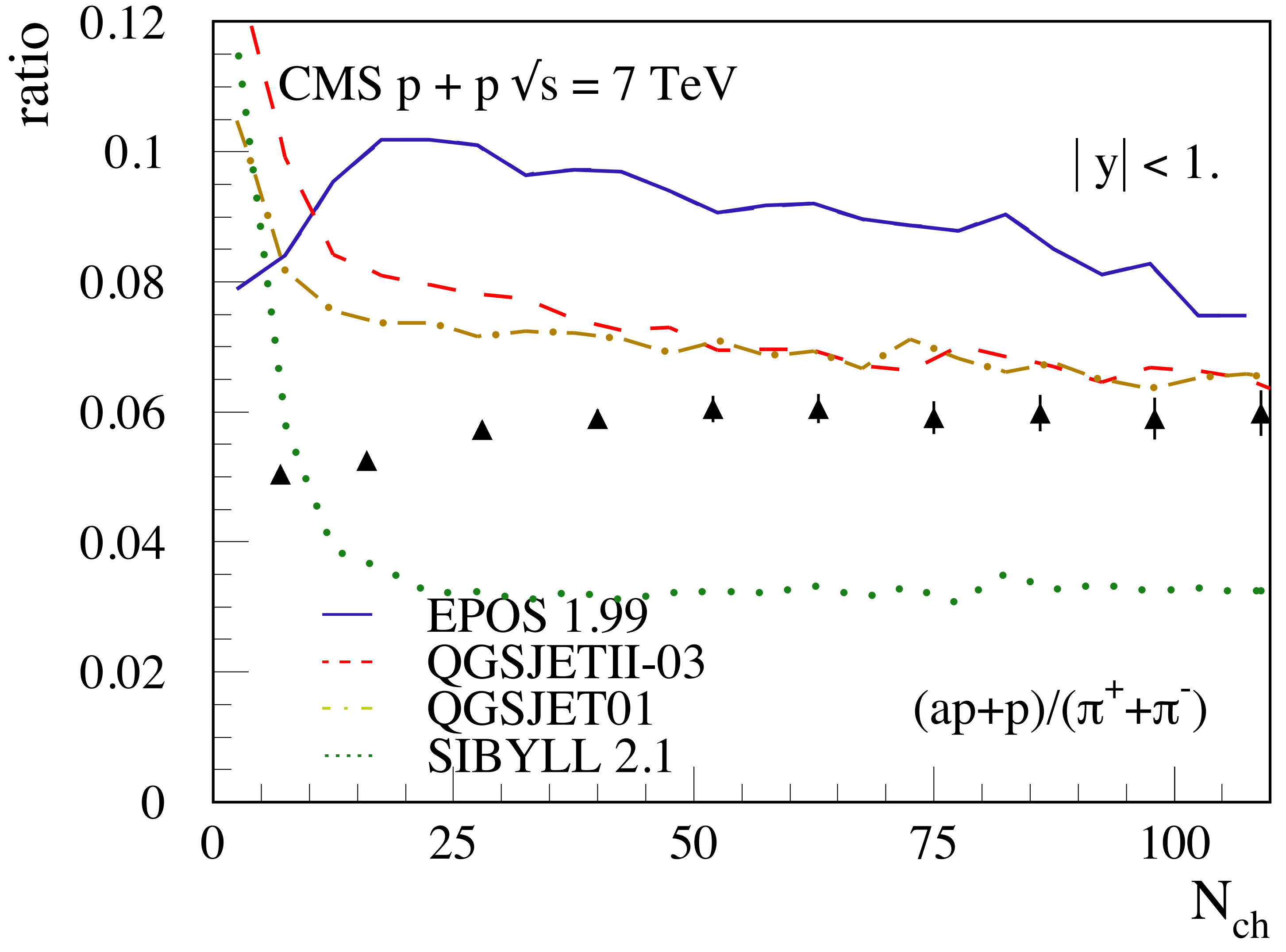


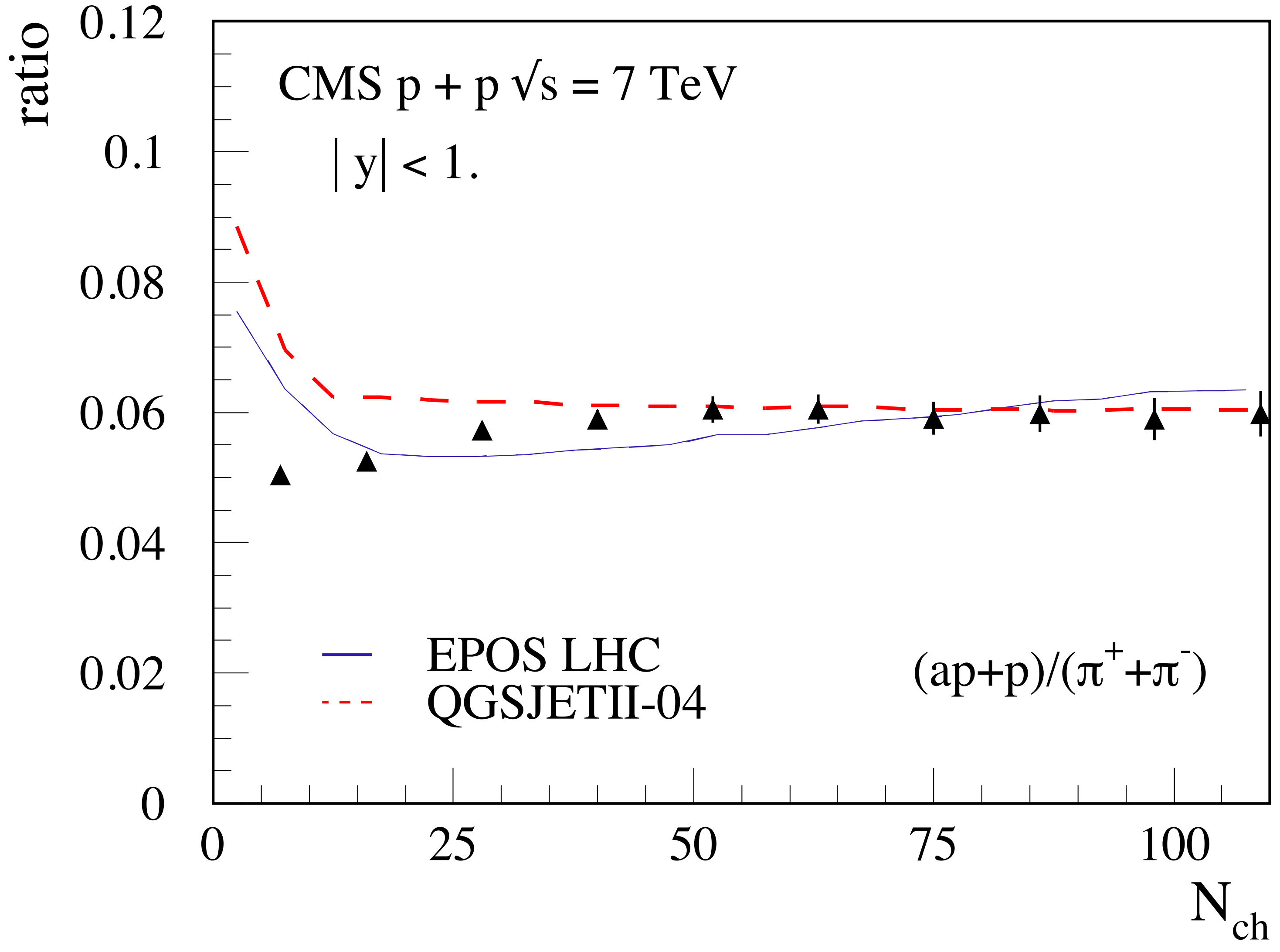


New models favour interpretation as lighter composition than before

(Pierog 2013, 2014)

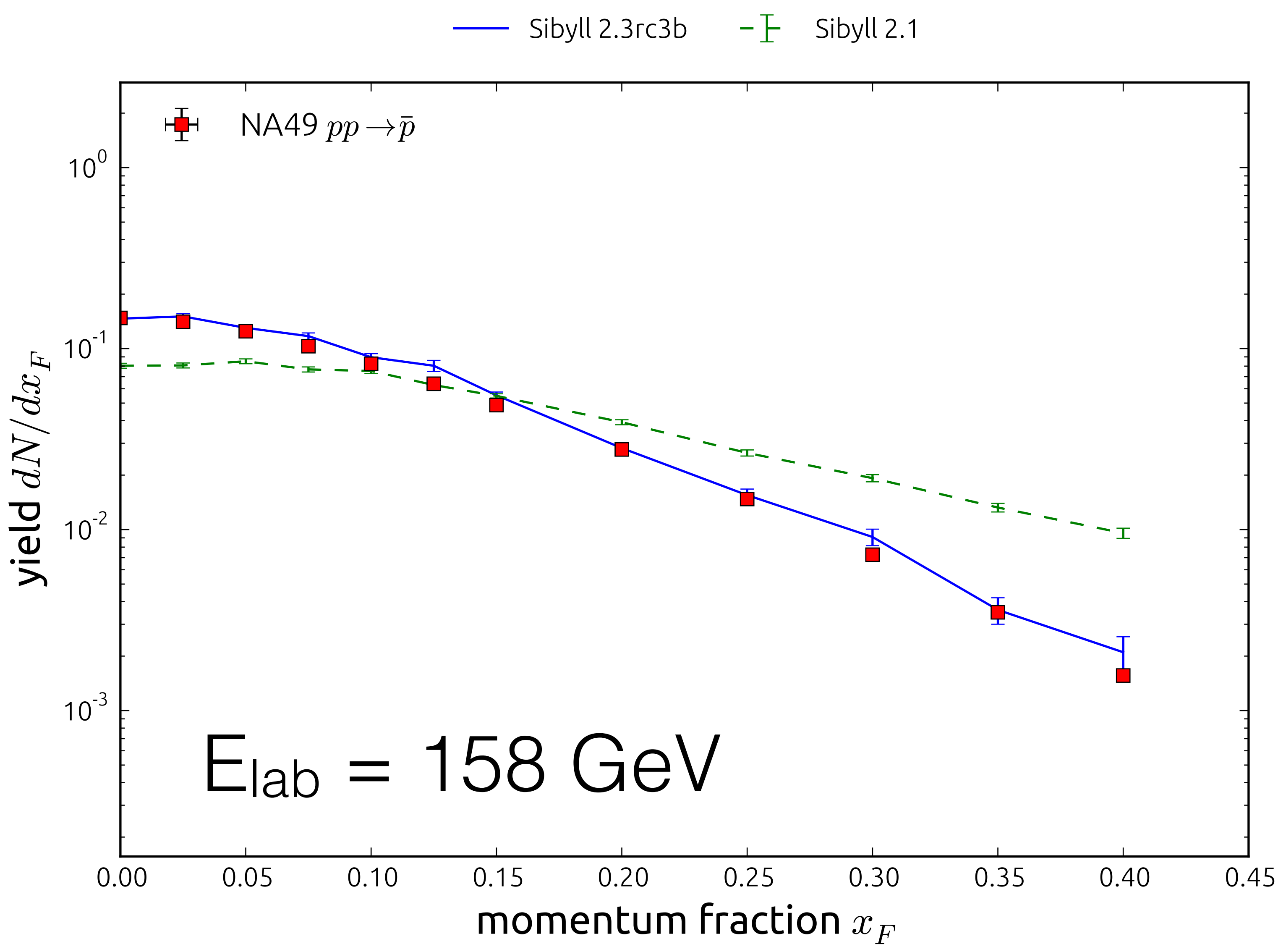
Tuning of baryon-antibaryon production

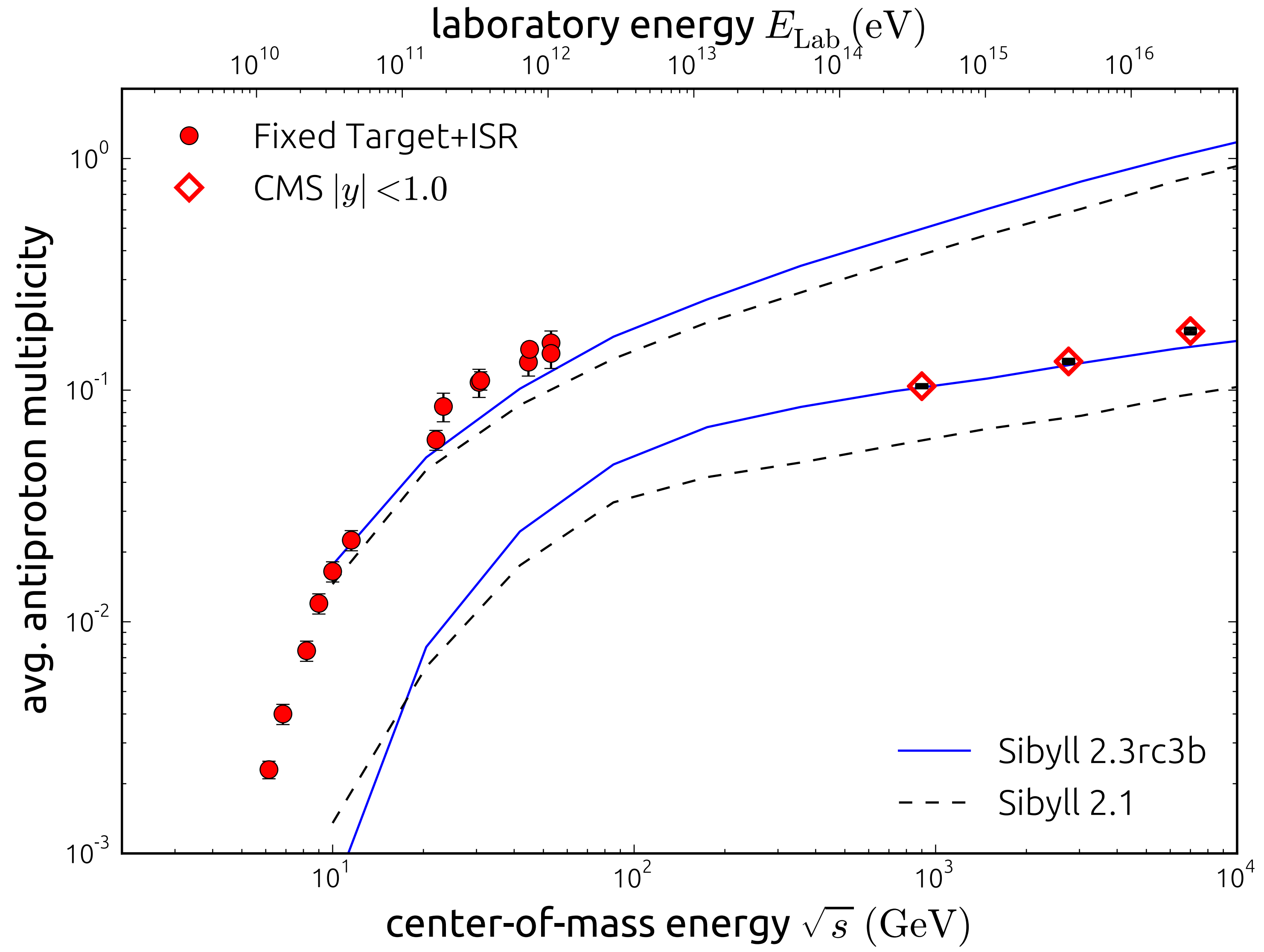




(Pierog 2013)

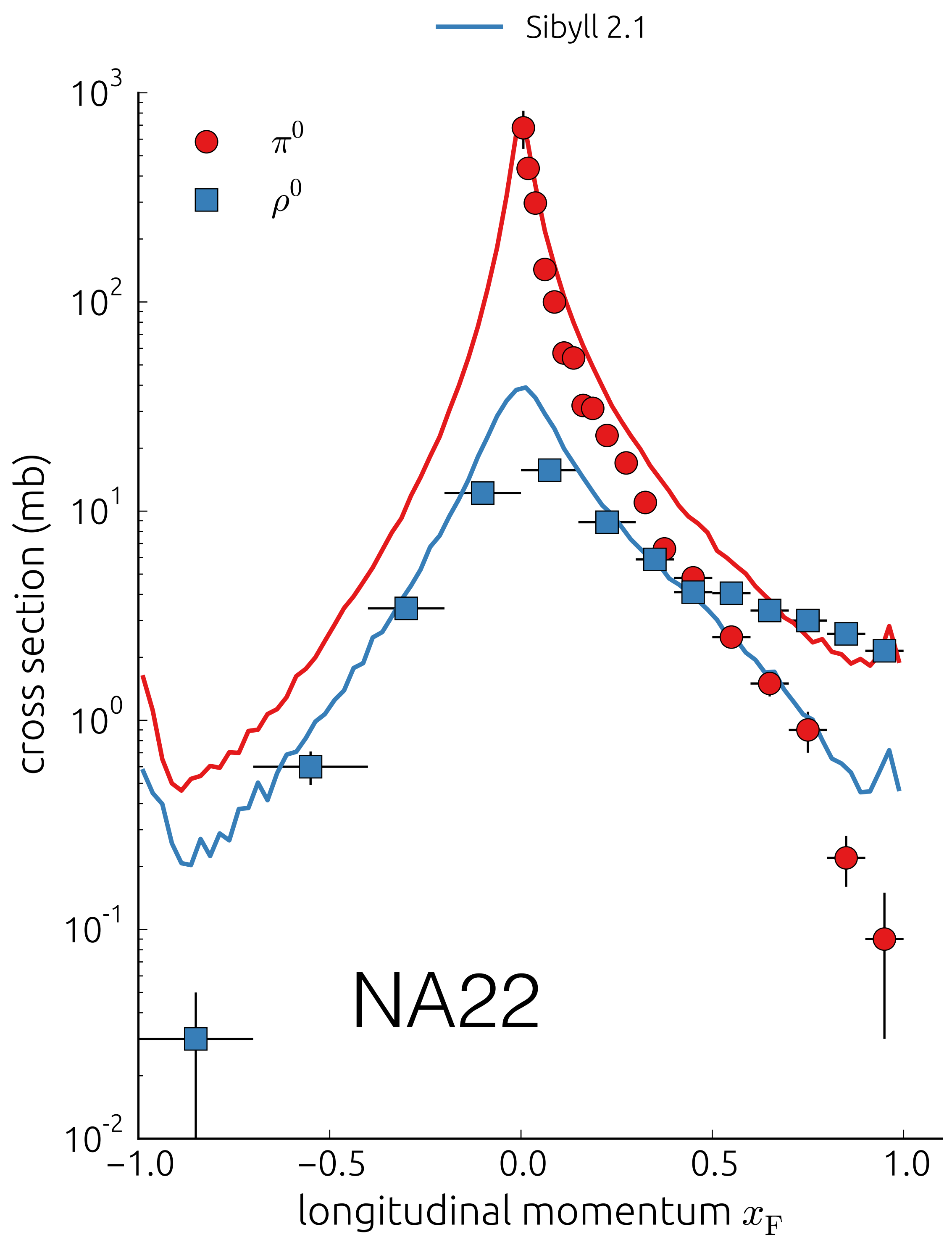
Sibyll 2.3
(release
candidate)

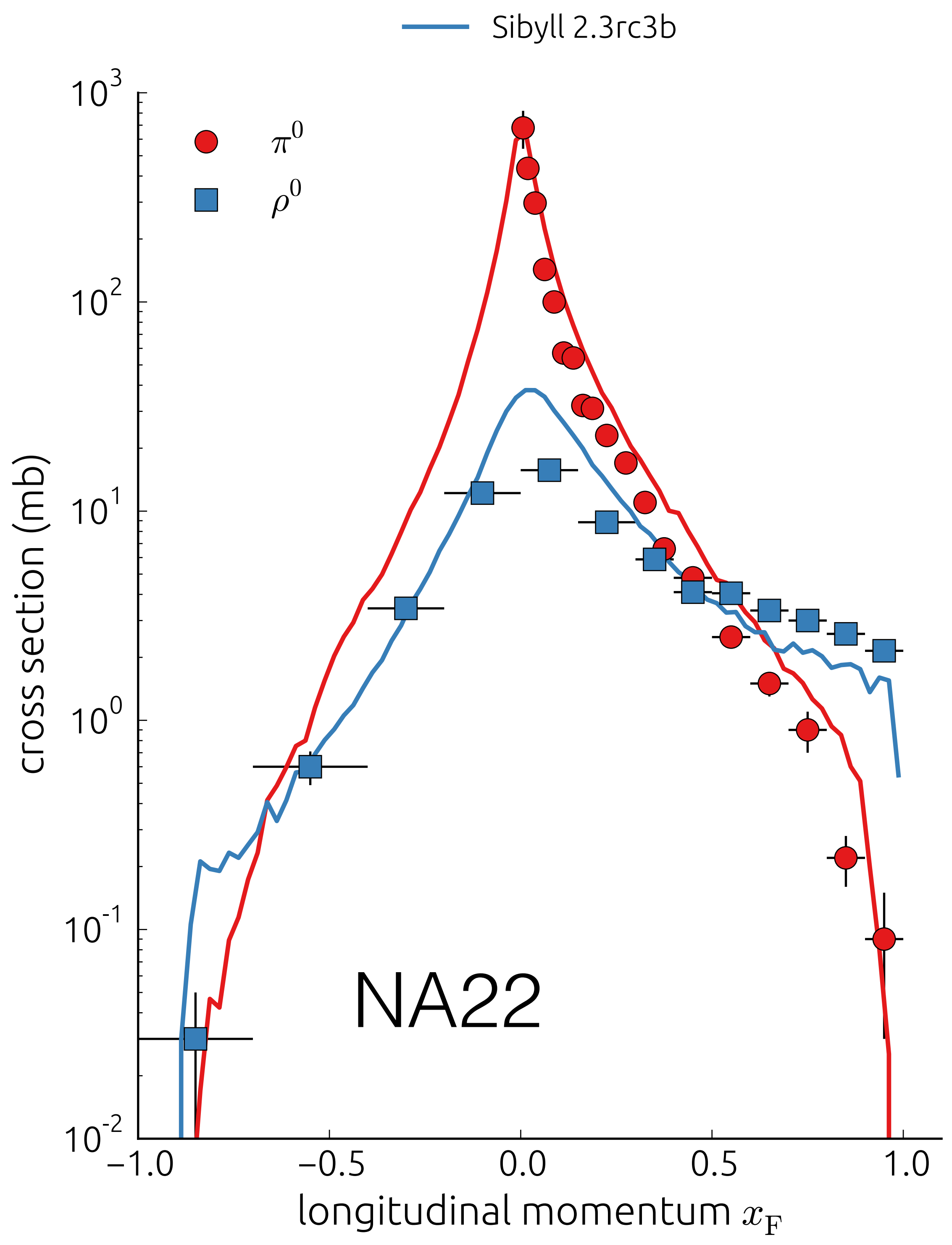


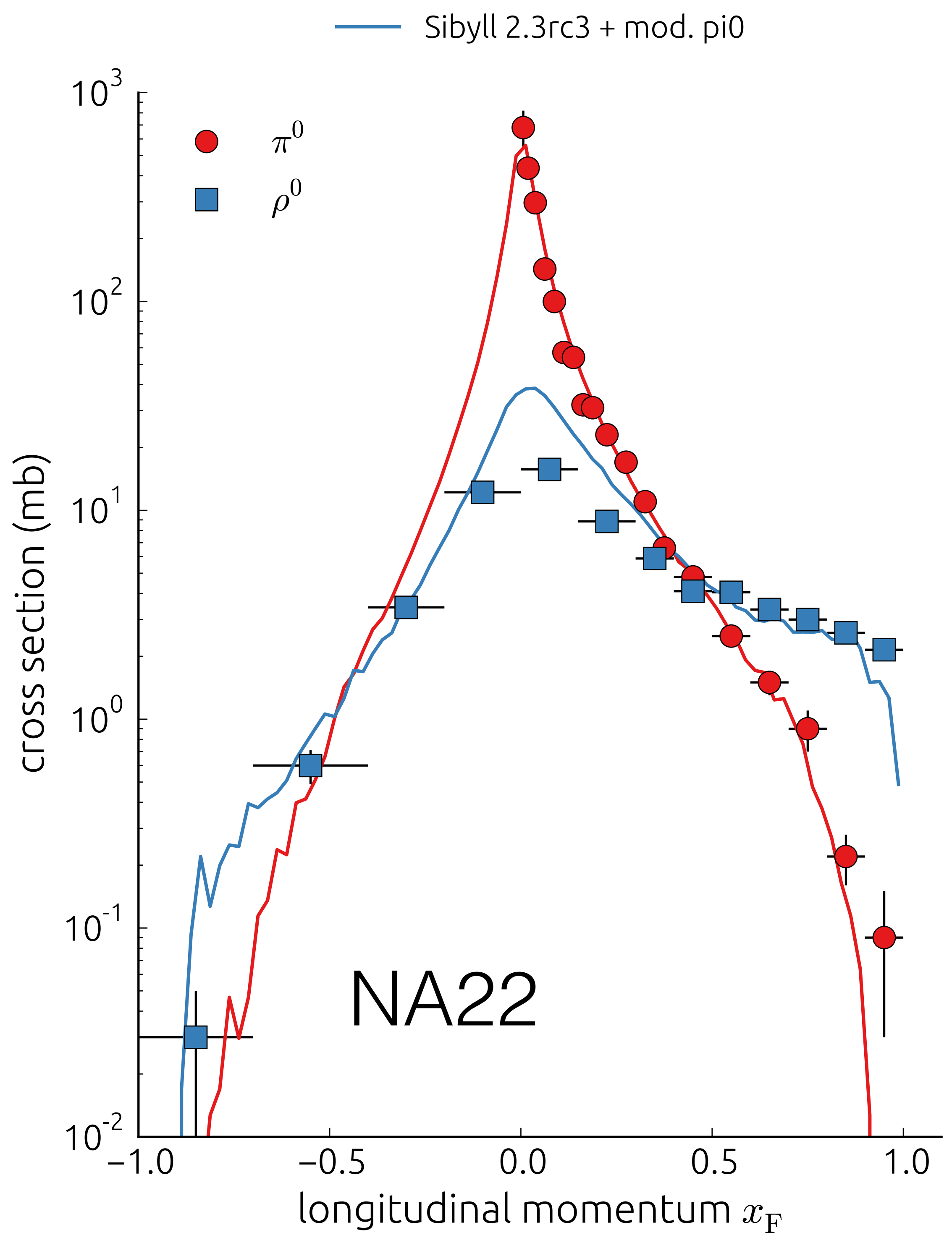


(Riehn 2015)

How important is forward π^0 and ρ^0 production ?







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

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

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

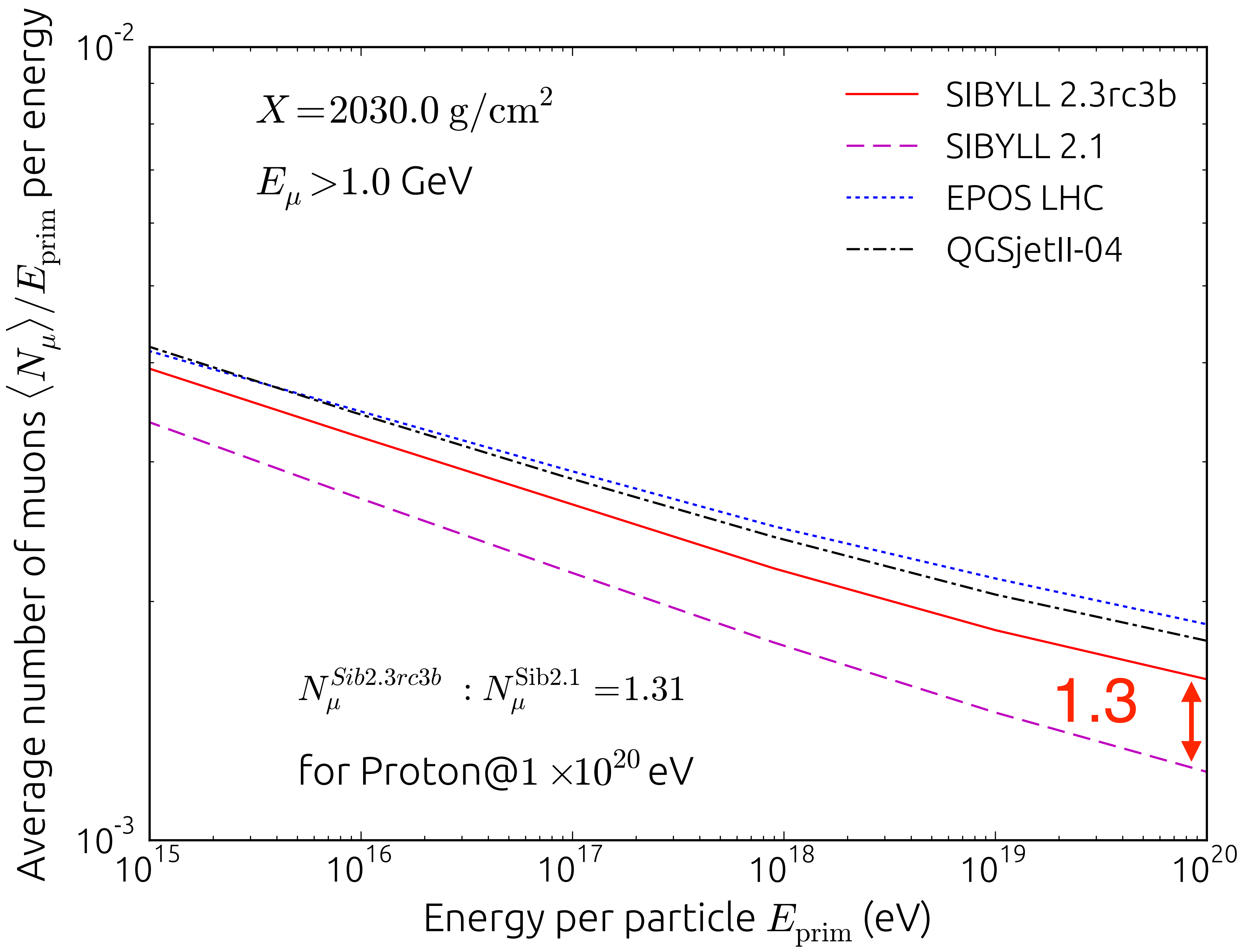
$E_{lab} = 250\,\mathrm{GeV}$

Sibyll 2.3
(release candidate)

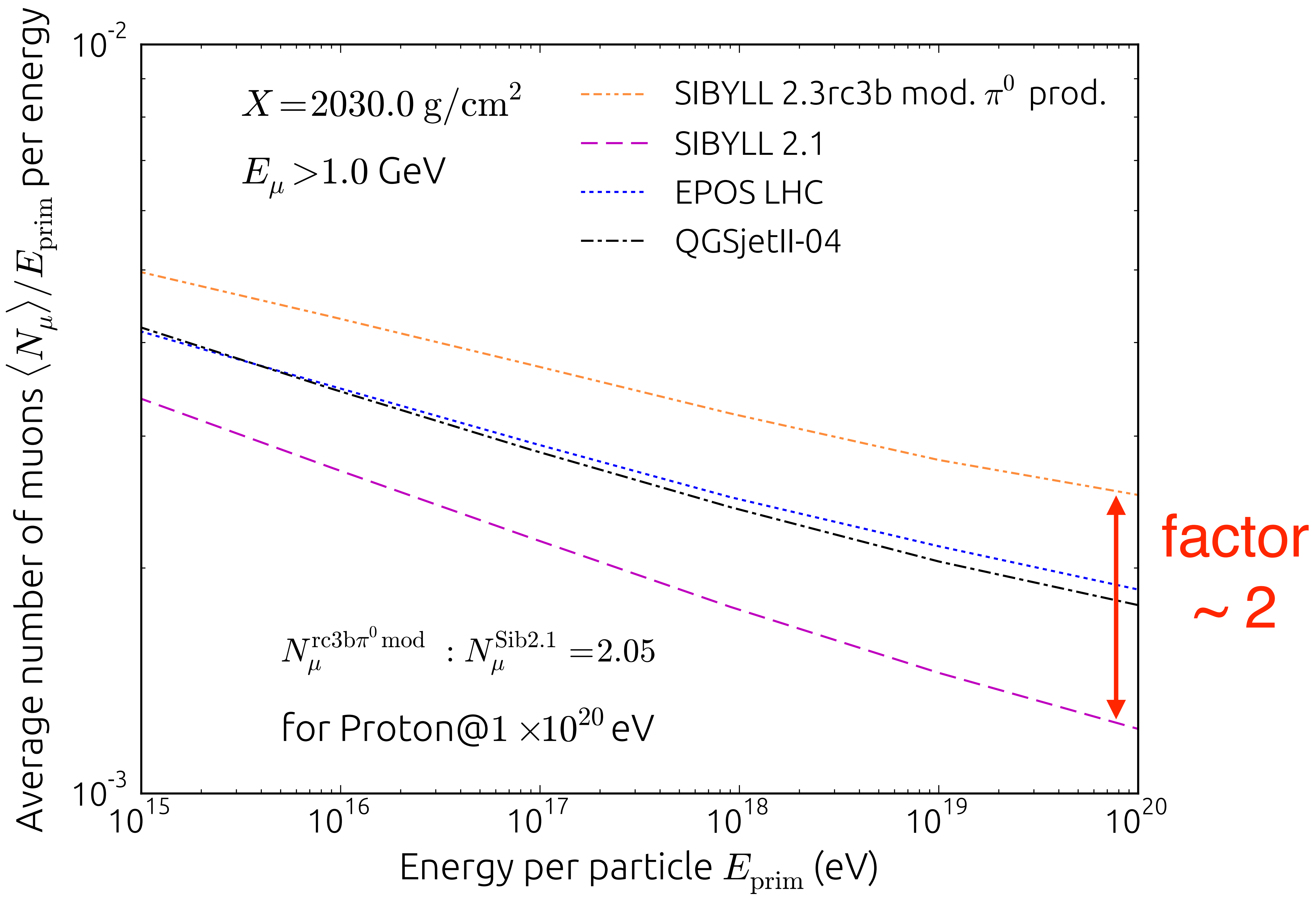
Sibyll 2.3
(mod. π^0)

(Riehn 2015)

How important is forward π^0 and ρ^0 production ?



Sibyll 2.3 (release candidate)

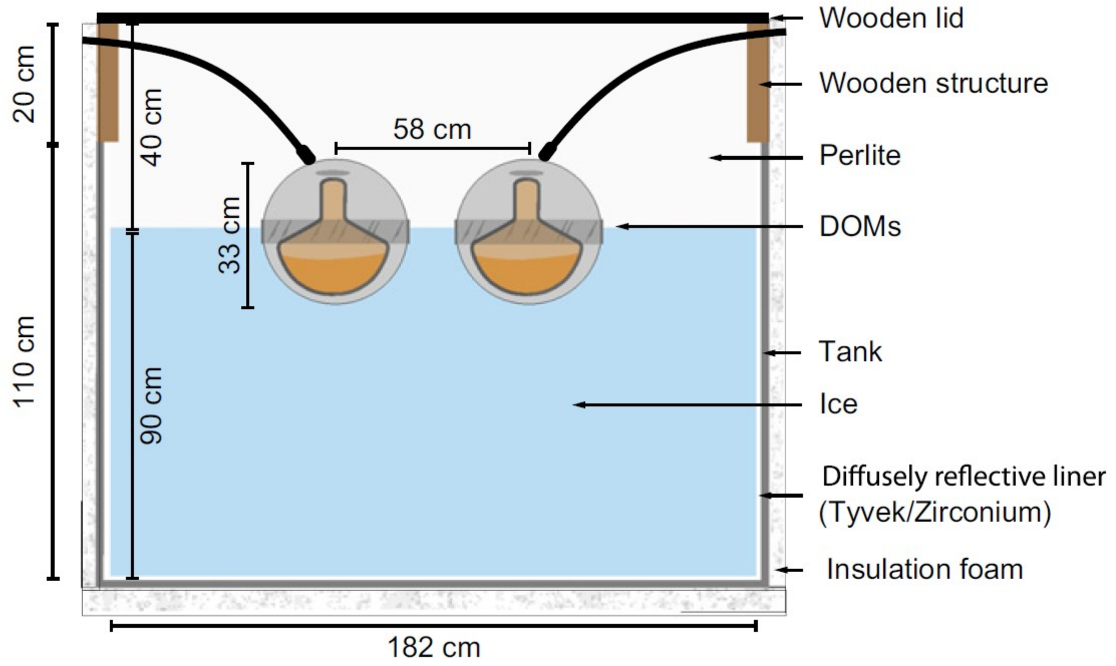


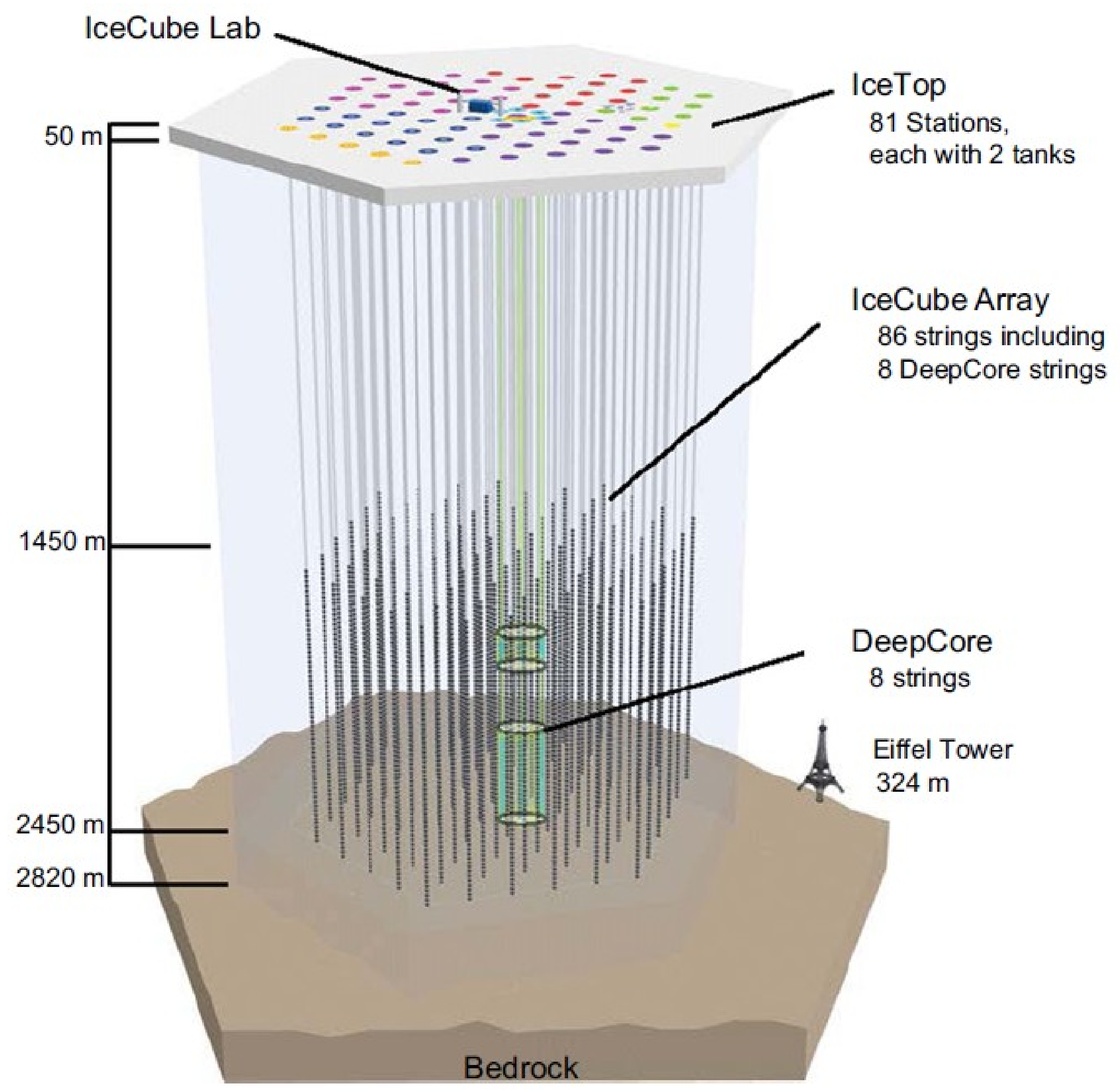
Sibyll 2.3 (mod. π^0)

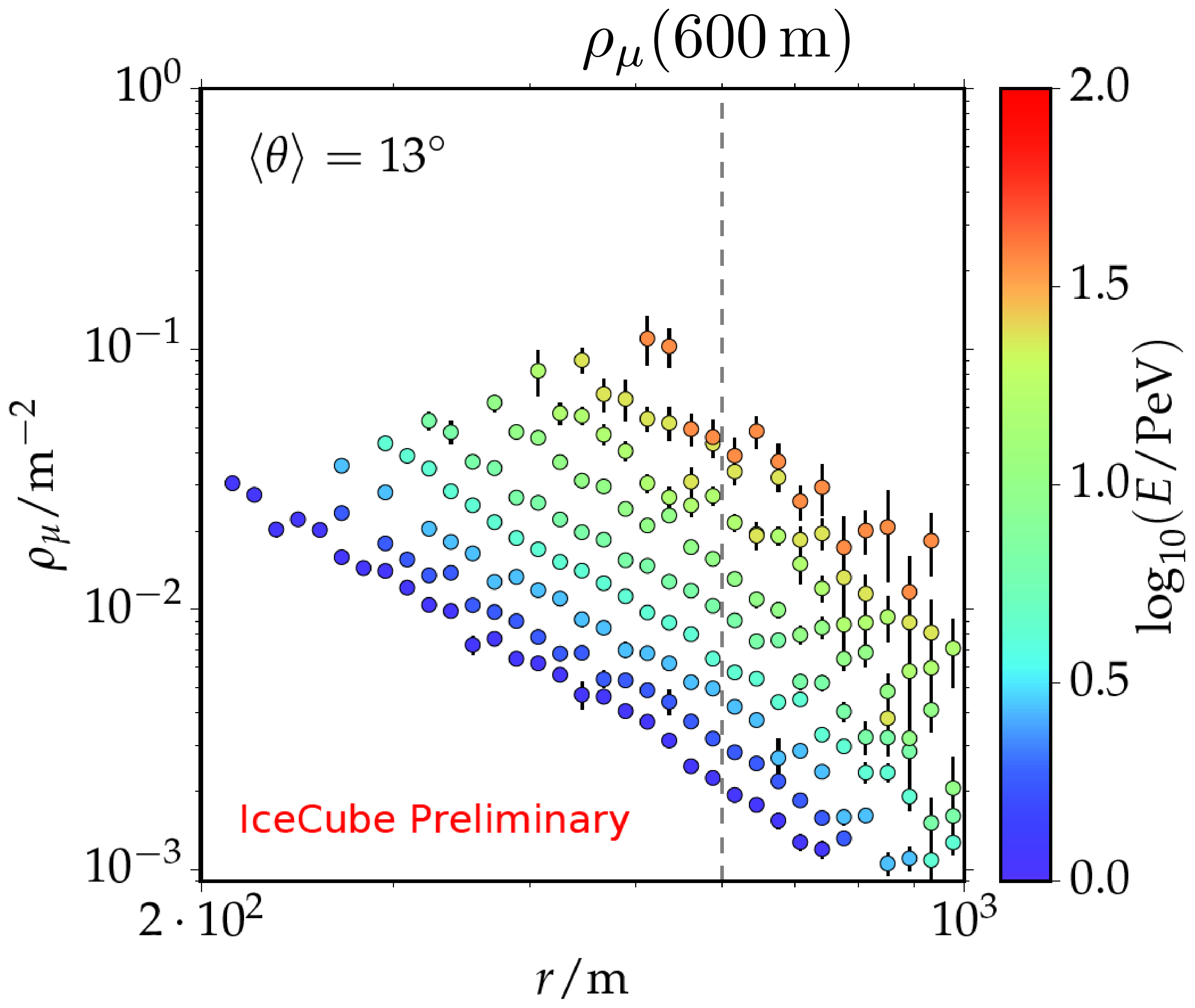
Note: change in Xmax due to enhanced ρ^0 production very small (negligible)

(Riehn 2015)

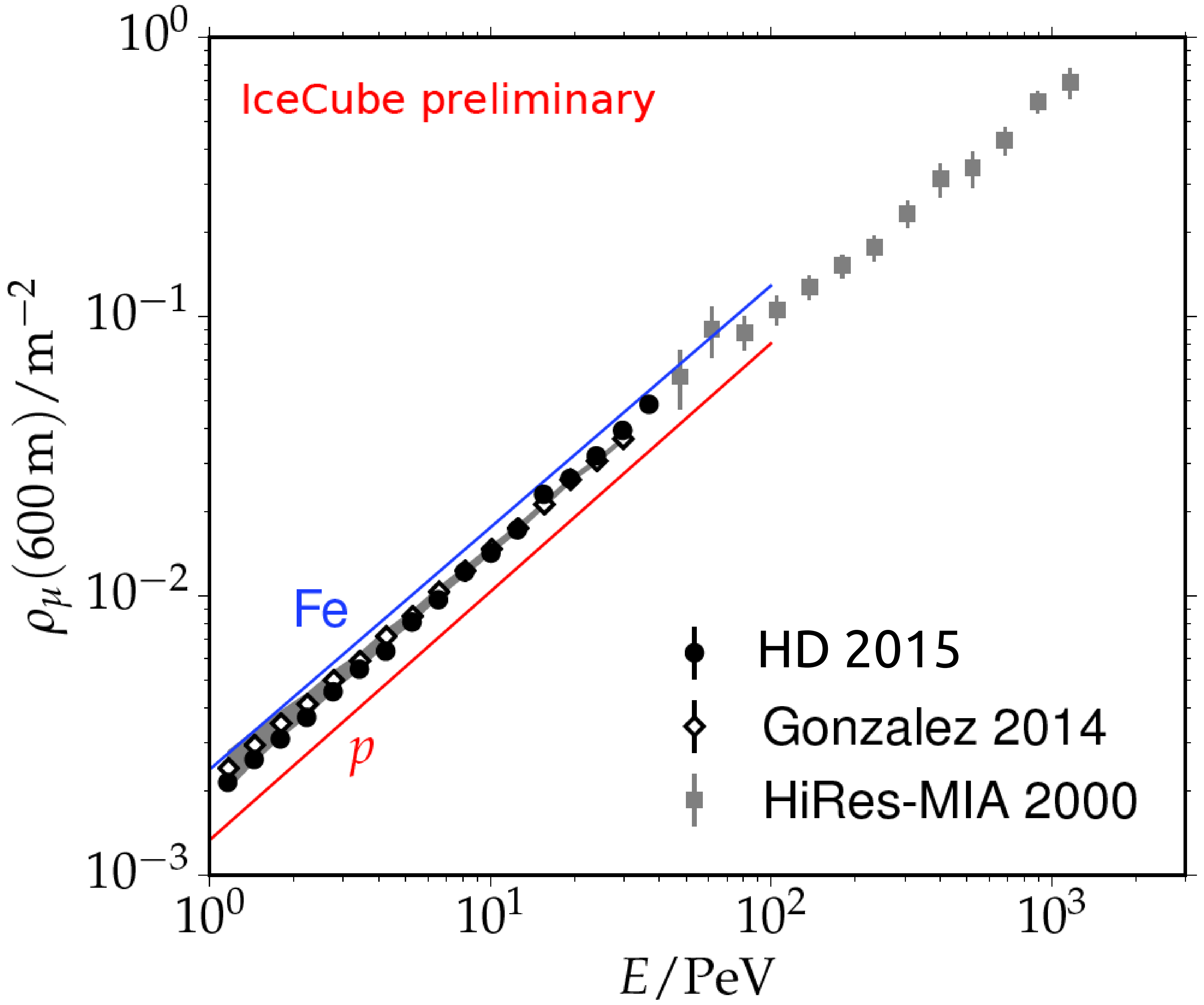
Compatible with data at lower energy – IceTop ?







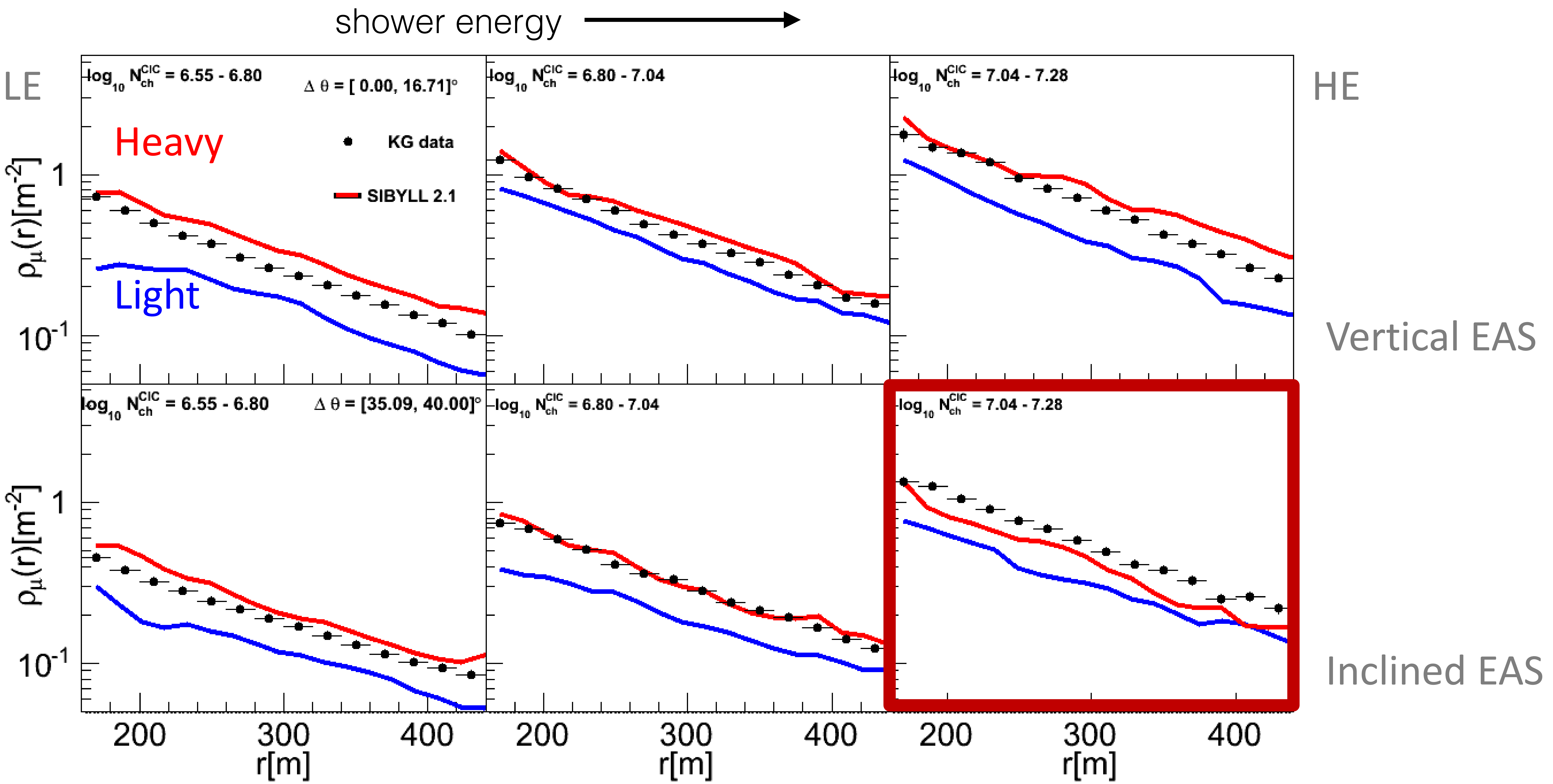
(IceCube, Dembinski & Gonzalez ICRC 2015)



Sibyll 2.1 predictions for p and Fe bracket data

Consistency with lower energy showers essential for confirmation

Compatible with data at lower energy – KASCADE-Grande ?

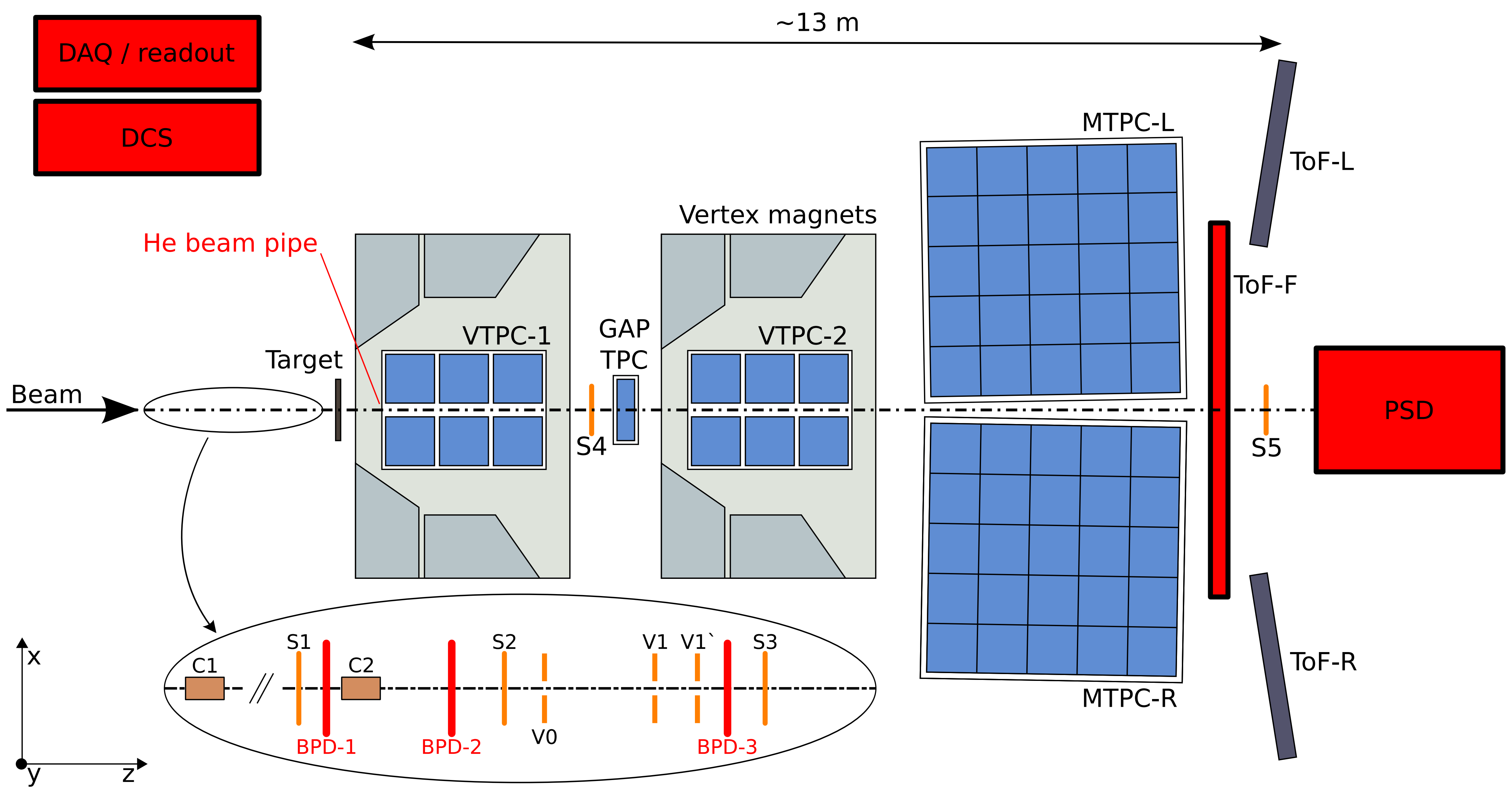


SIBYLL 2.1 predictions for Fe+Si/H+He are **smaller than the measured data** at HE for inclined EAS

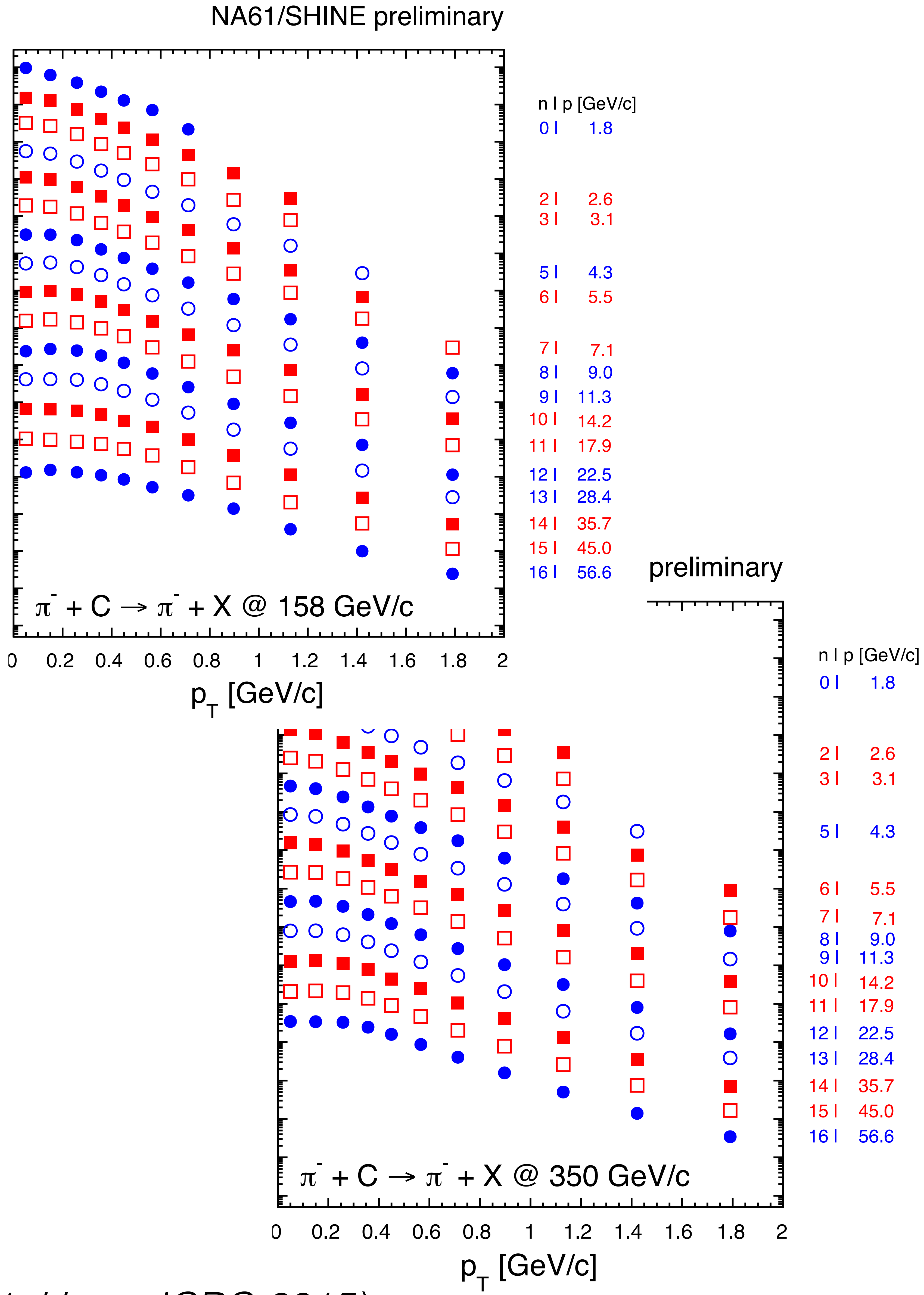
(Arteaga, KASCADE-Grande, ICRC 2015)

NA61 experiment at CERN SPS

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



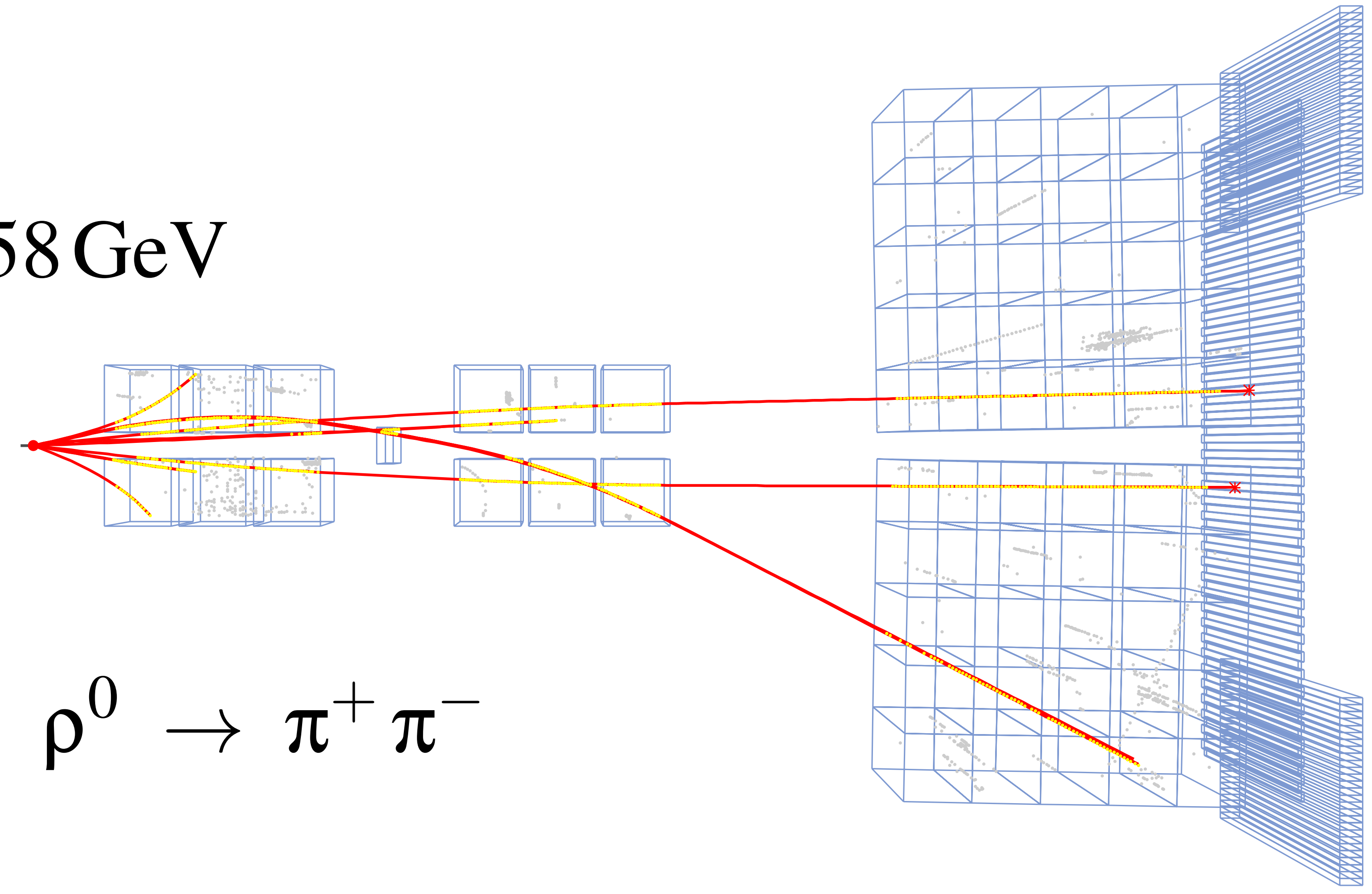
(former NA49 detector, extended)



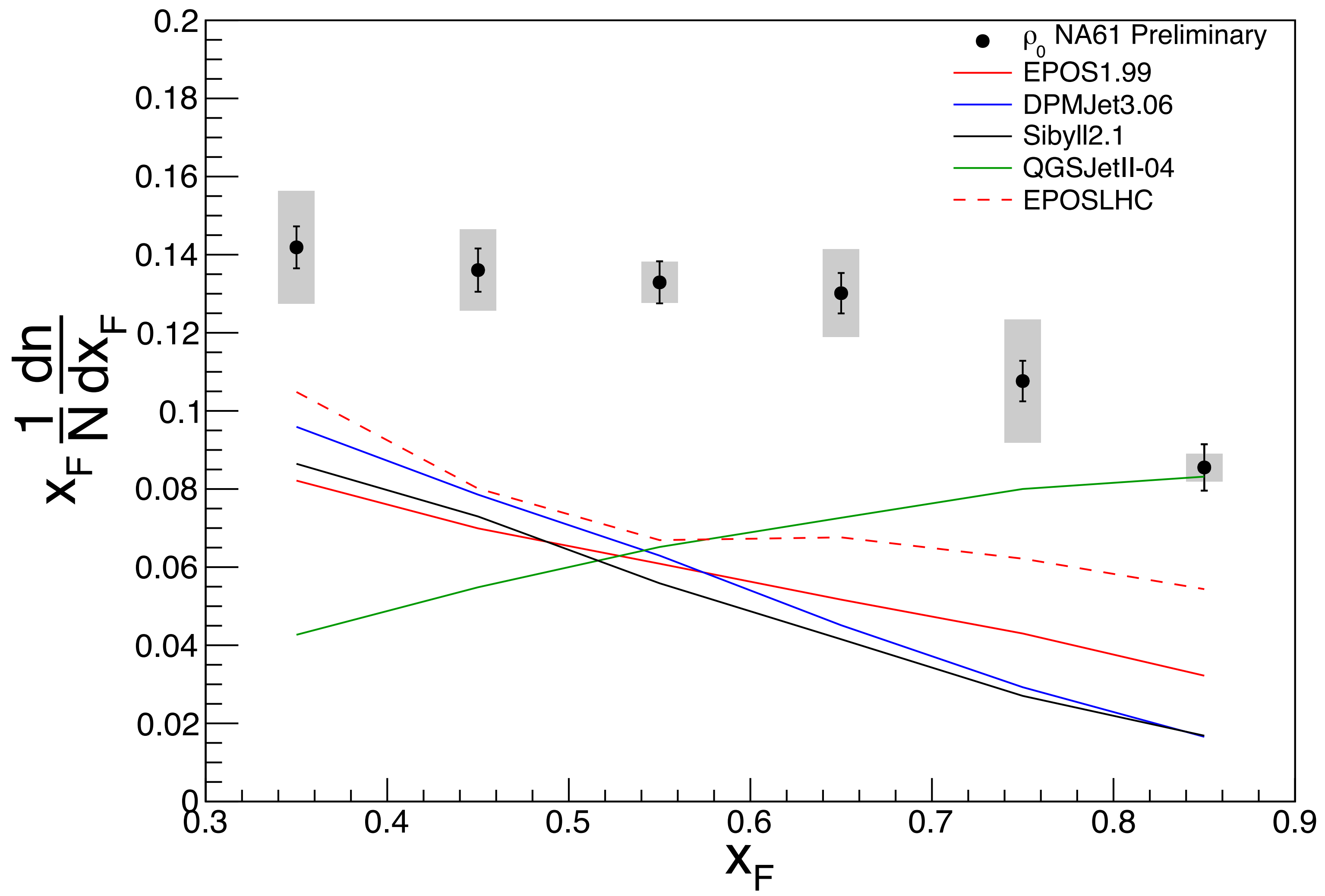
(NA61, Herve ICRC 2015)

New results from NA61: ρ^0 production

$$E_{\mathrm{lab}} = 158\,\mathrm{GeV}$$

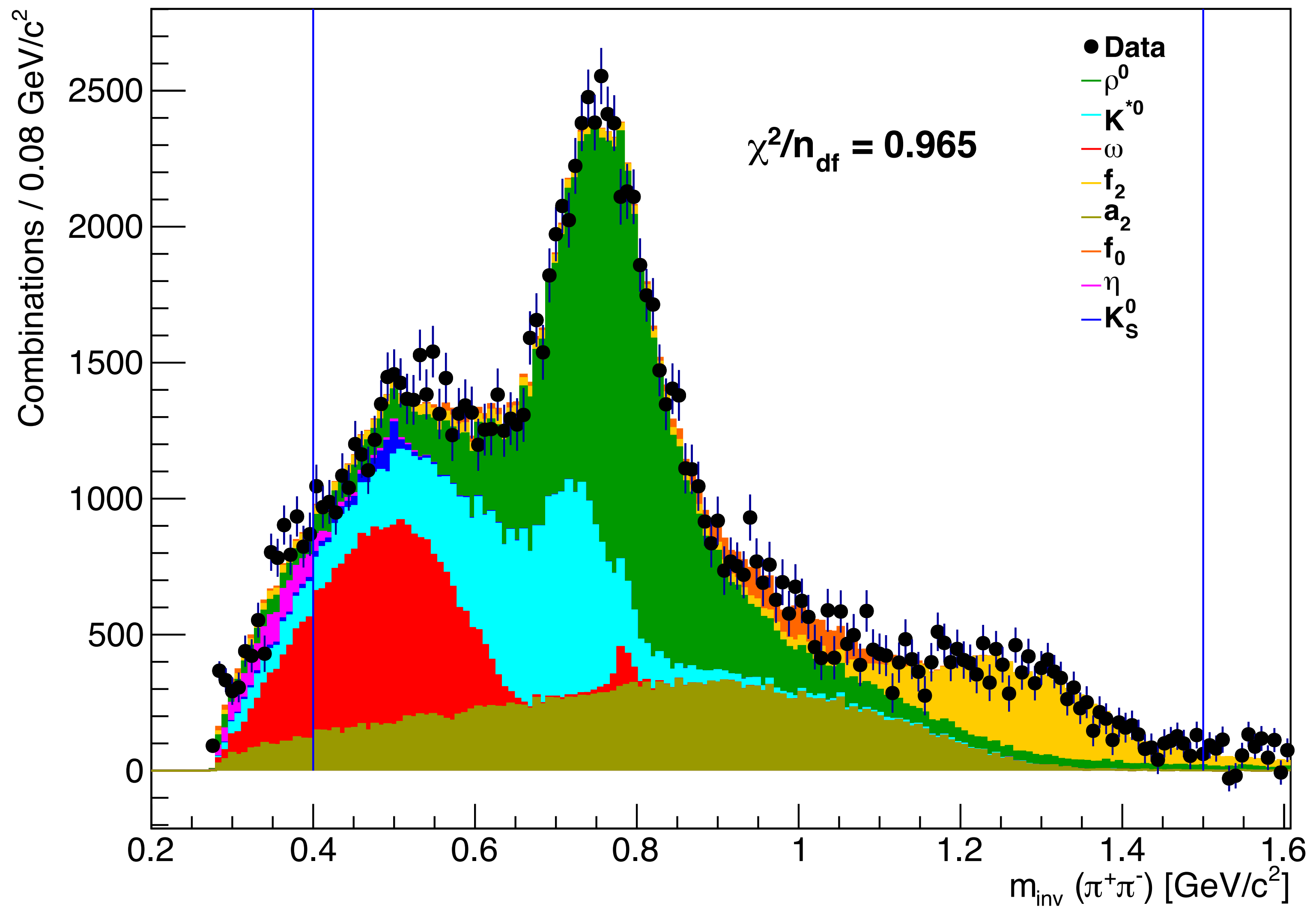


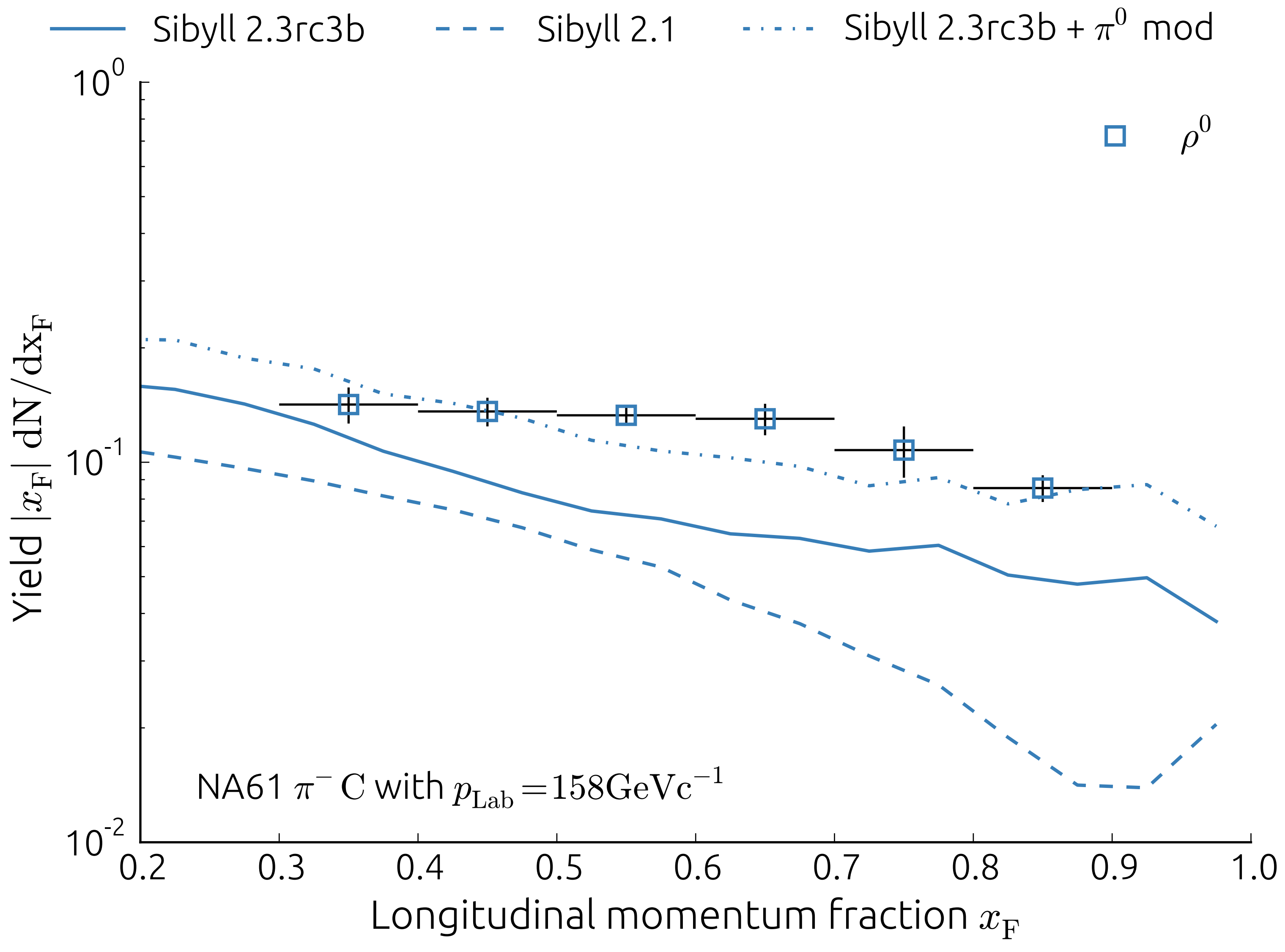
$$\pi^- C \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$$



(NA61, Herve, ICRC 2015)

Invariant mass of two charged tracks

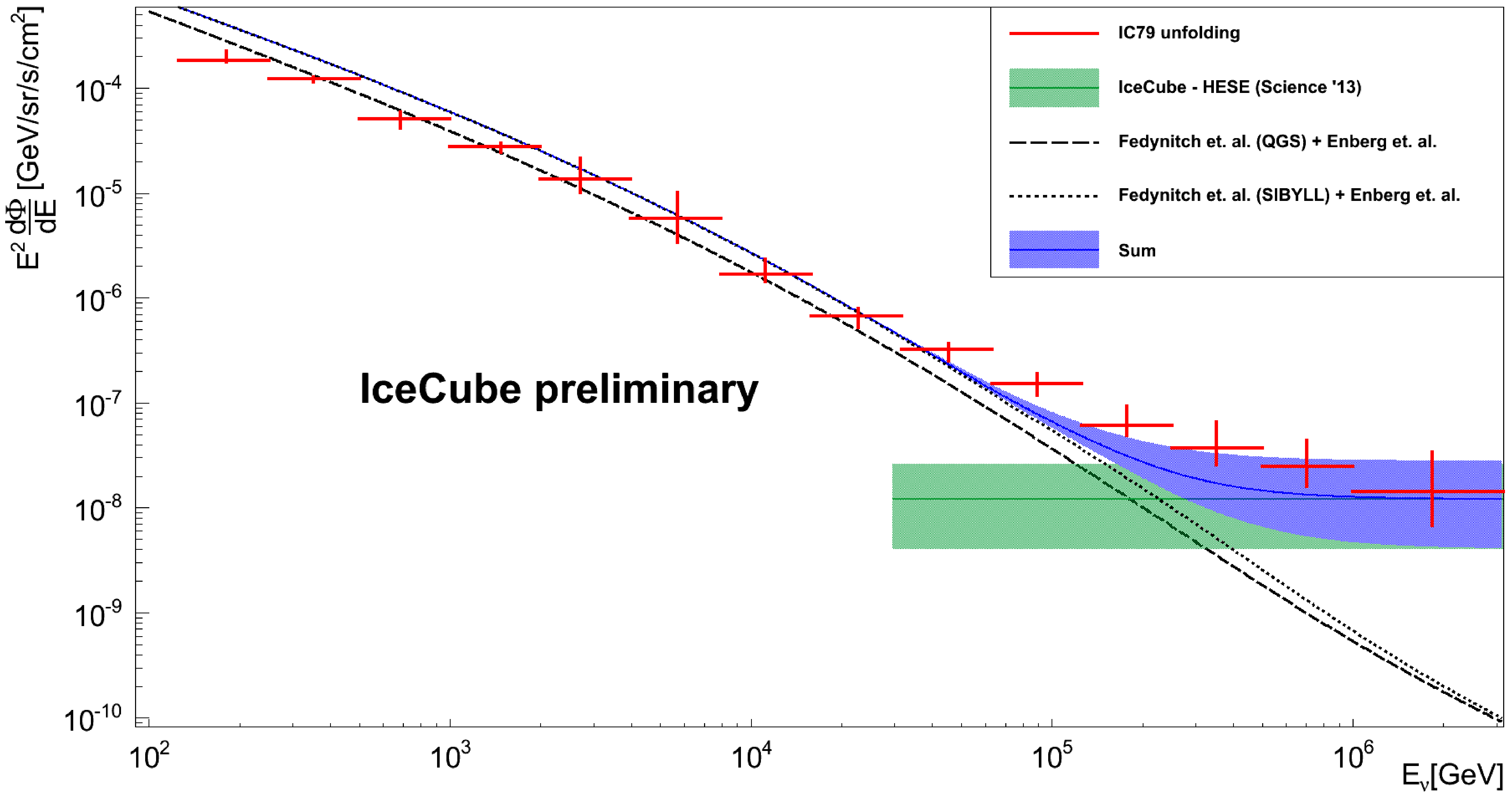




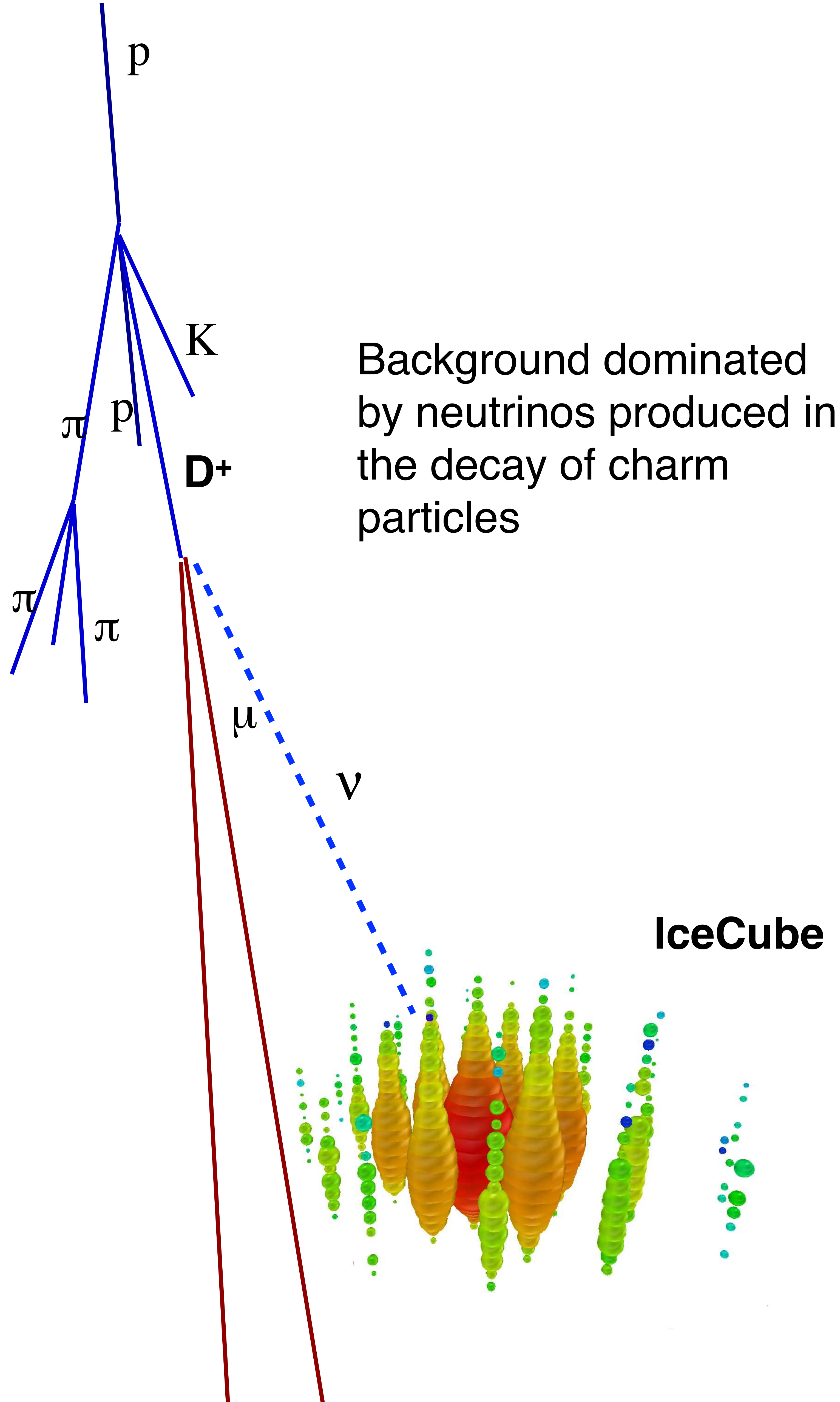
(Riehn 2015)

Atmospheric neutrinos

Atmospheric neutrinos as background to astrophysical signal



IceCube Analysis, ν–**induced muons**, TU Dortmund (Florian Scheriau, Martin Schmitz, Tim Ruhe, Wolfgang Rhode++), see their presentation @ Neutrino 2014



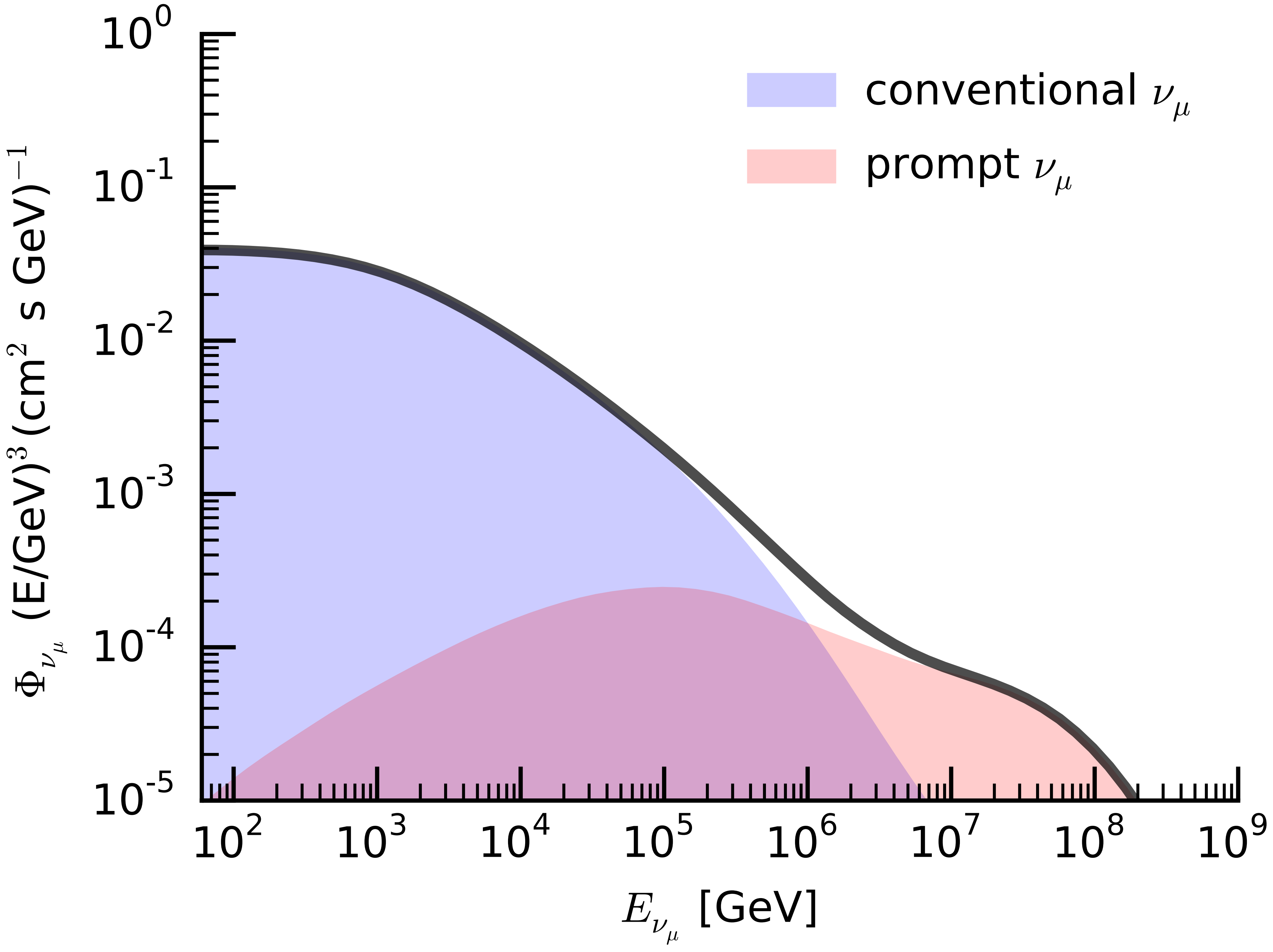
Background dominated by neutrinos produced in the decay of charm particles

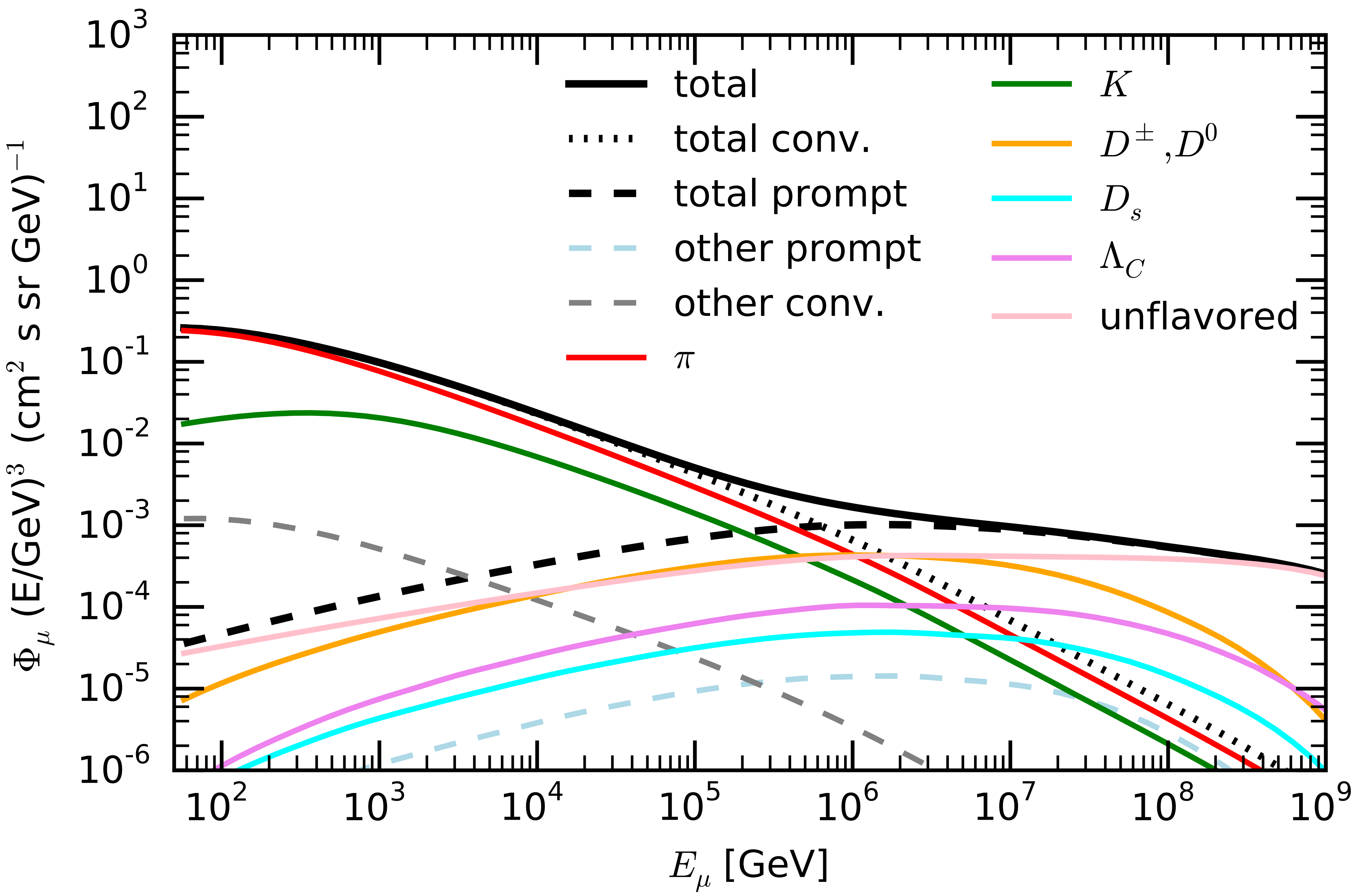
Atmospheric neutrinos: conventional & prompt components

$$\frac{dN_p}{dE_p} = A \times E_p^{-\gamma} = \Phi_p(E_p)$$

$$\frac{dN_\nu}{dE_\nu} \sim \Phi_p(E_\nu) \int_0^1 x^{\gamma-1} \frac{dN_{p\to\pi^\pm}}{dx} dx$$

$$(x = E_{\pi^\pm}/E_p)$$

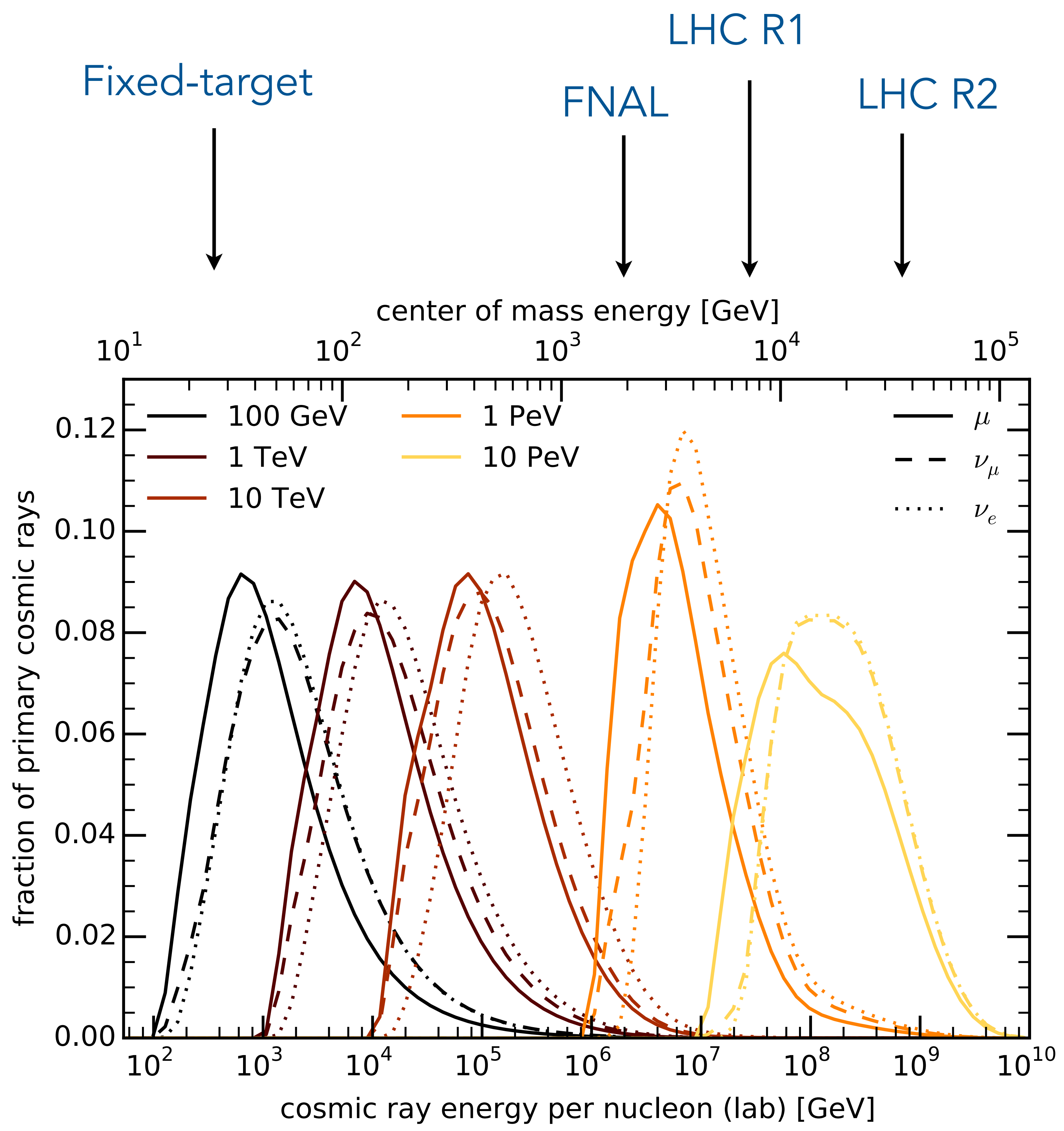


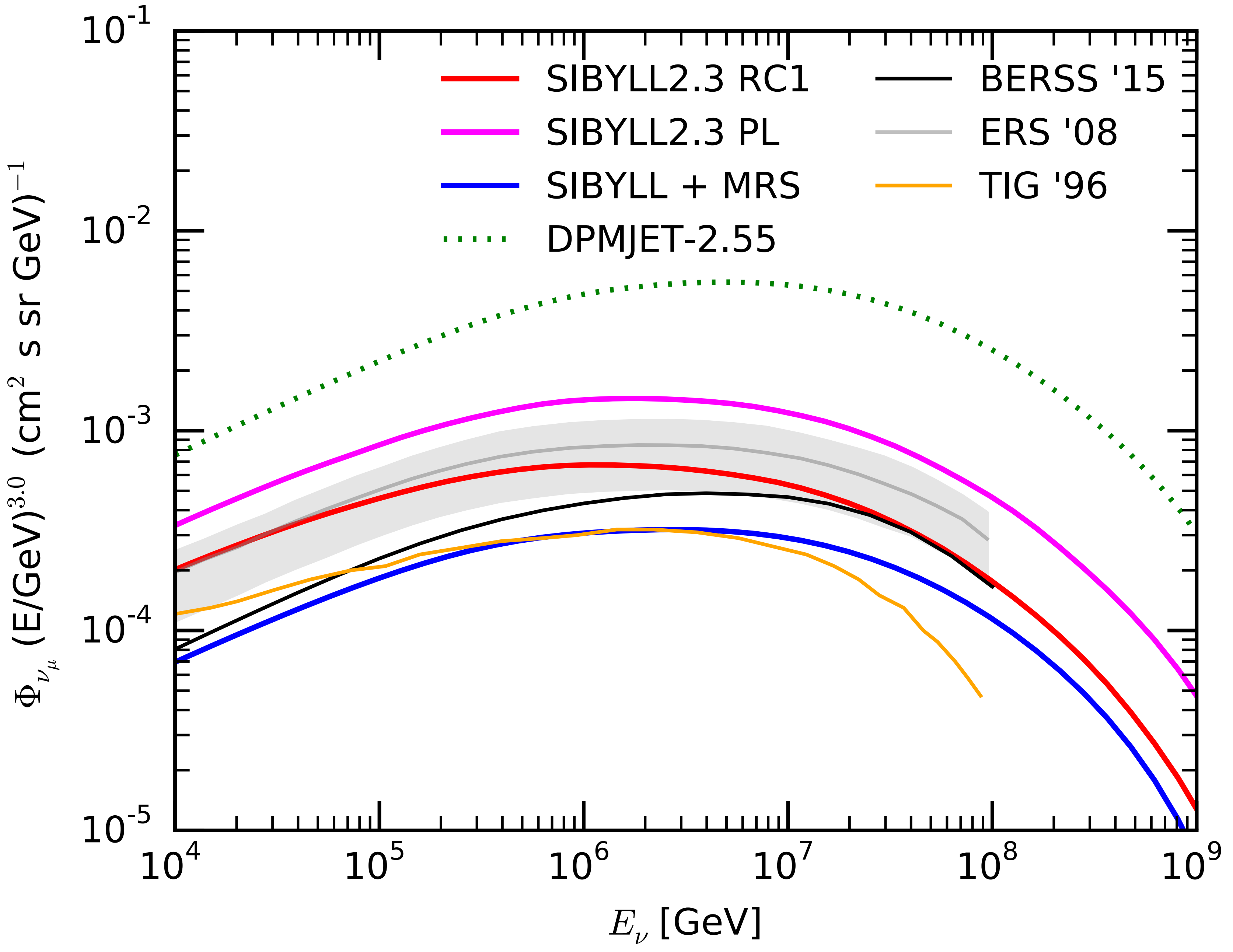


mostly **pion** decay | charm decay | charm interacts | unflavored decays

(Fedynitch 2015)

Energies of importance for lepton fluxes





A measurement of absolute normalization contains information

- non-perturbative effects
- intrinsic charm
- inclusive charm cross-section
- partonic saturation

BERSS: A. Bhattacharya, R. Enberg, M.H. Reno, I. Sarcevic and A. Stasto, arXiv:1502.01076

ERS: R. Enberg, M. H. Reno, and I. Sarcevic, Phys. Rev. D 78, 43005 (2008).

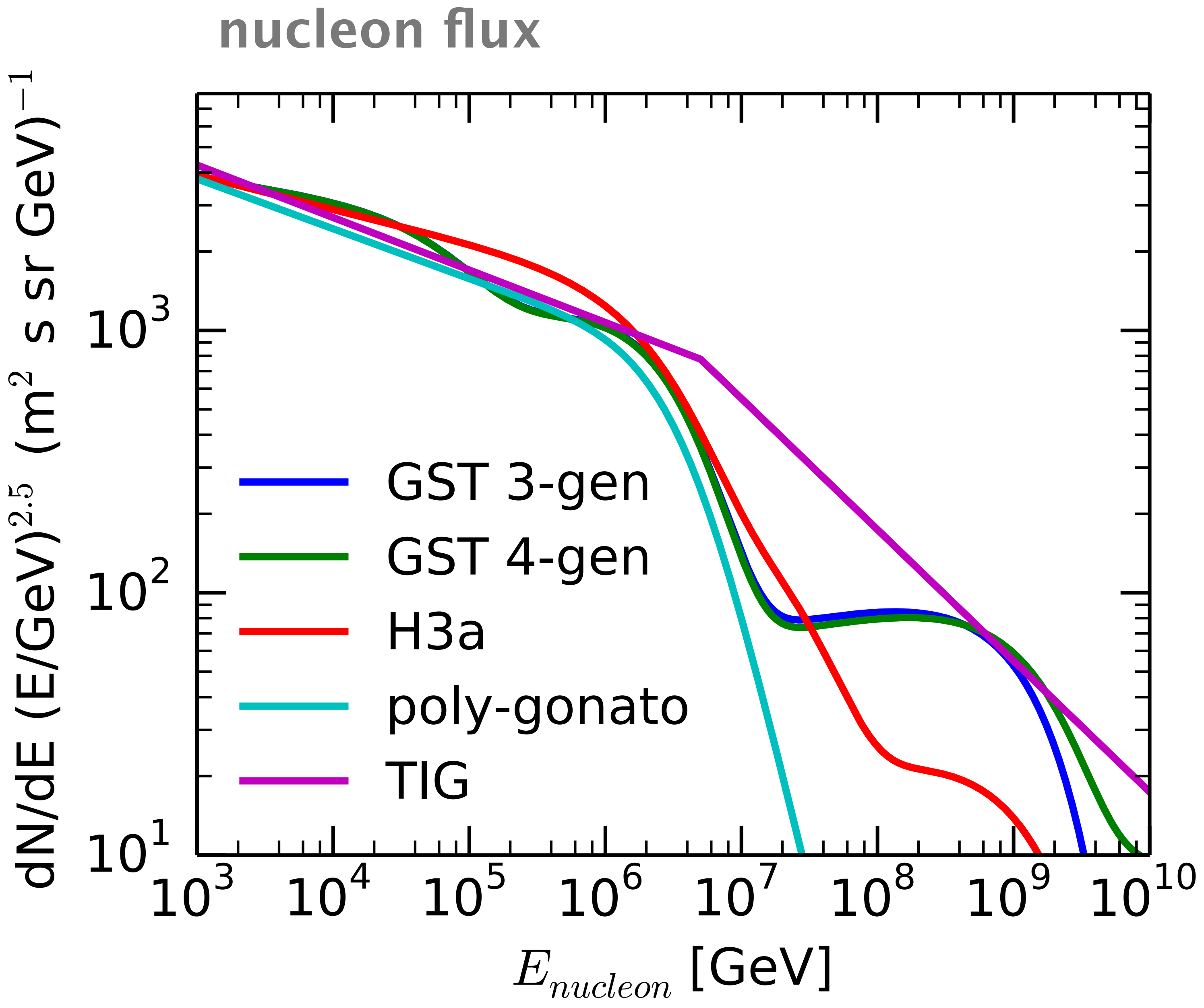
*MRS: A. D. Martin, M. G. Ryskin, and A. M. Stasto, Acta Physica Polonica B **34**, 3273 (2003).*

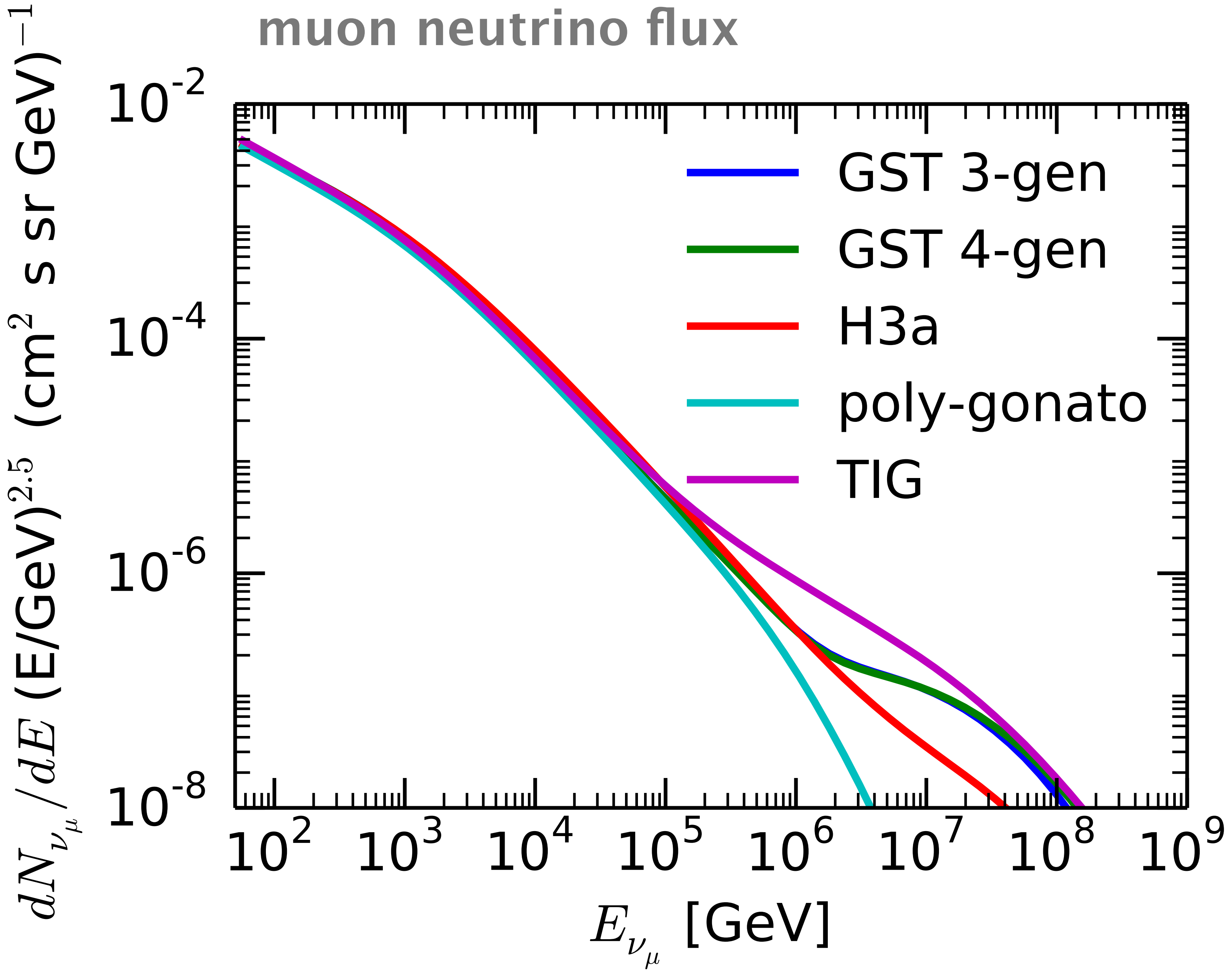
SIBYLL: arXiv:1503.00544 and arXiv:1502.06353

TIG: M. Thunman, G. Ingelman, and P. Gondolo, Astroparticle Physics 5, 309 (1996).

(Fedynitch 2015)

Additional complication: dependence on primary flux





Inclusive nucleon flux important for lepton flux

TIG - M. Thunman, G. Ingelman, and P. Gondolo, Astroparticle Physics 5, 309 (1996).

poly-gonato - [1] J. R. Hörandel, Astroparticle Physics 19, 2 (2003)

GST - T. K. Gaisser, T. Stanev, and S. Tilav, arXiv:1303.3565, (2013).

H3a - T. K. Gaisser, Astroparticle Physics 35, 801 (2012).

(Fedynitch 2015)

Summary

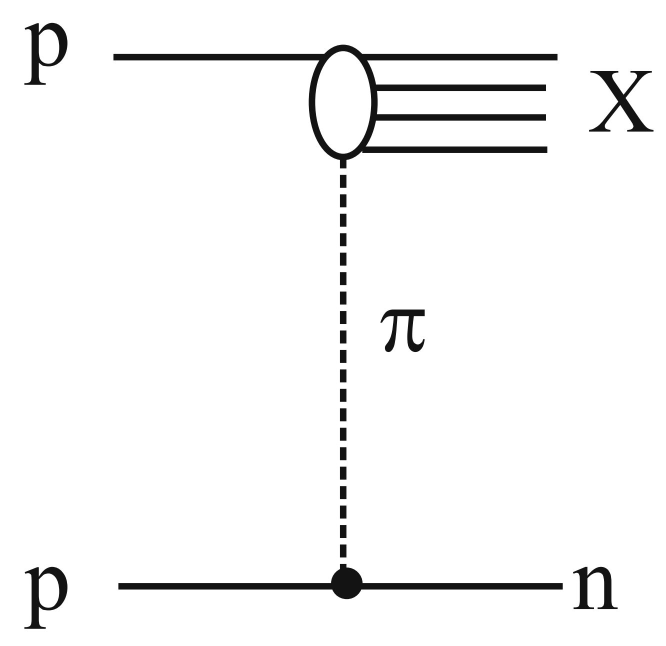
- Composition interpretation essential for understanding astrophysics
- LHC data of central importance for more reliable composition interpretation
- Very good collaboration between members of CR community and LHC/HEP
- Feedback from air shower observations, CR int. models very successful at LHC
- Cosmic ray data at $10^{19.5}$ eV most likely not protons (except exotic physics)
- Pion interactions as major uncertainty for muon discrepancy identified

  Need measurement of energy dependence of ρ^0 production

  Consistent description at lower energy, transition to direct measurements
- Forward charm production (theory and experiment) of increasing interest
- Primary flux composition also directly linked to inclusive lepton fluxes

Outlook: how to obtain data at higher energy ?

Measurement of pion exchange at LHC



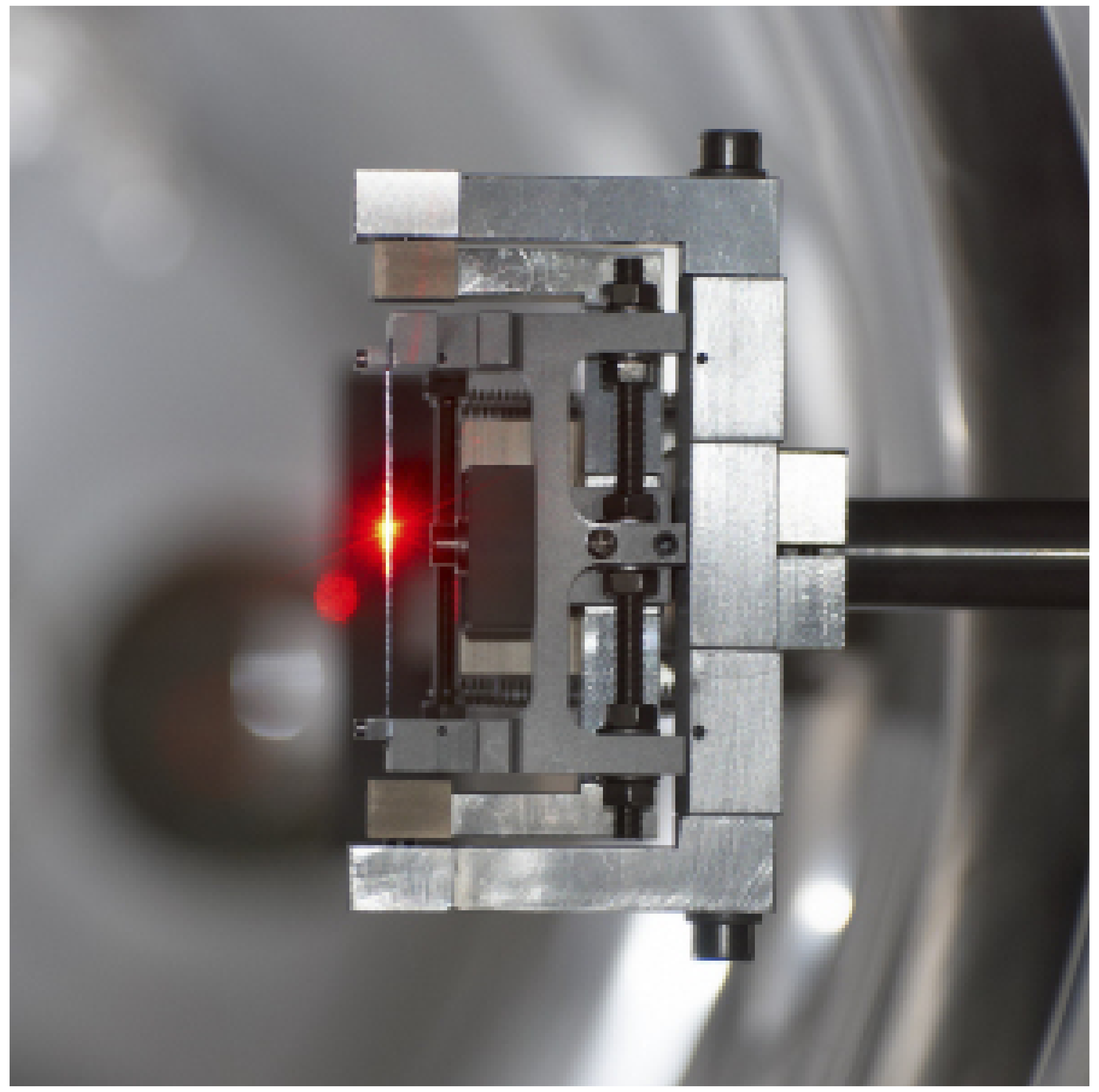
Pion fragmentation
region in ATLAS

Leading neutron in LHCf

Physics discussed in detail for HERA (H1 and ZEUS)
(see, for example, Khoze et al. Eur. Phys. J. C48 (2006), 797
Kopeliovich & Potashnikova et al.)

$$\frac{\mathrm{d}\sigma(\gamma p \to Xn)}{\mathrm{d}x_\mathrm{L}\,\mathrm{d}t} = S^2 \frac{G^2_{\pi^+ pn}}{16\pi^2} \frac{(-t)}{(t-m_\pi^2)^2} F^2(t) \times (1-x_\mathrm{L})^{1-2\alpha_\pi(t)} \sigma^{\mathrm{tot}}_{\gamma\pi}(M^2)$$

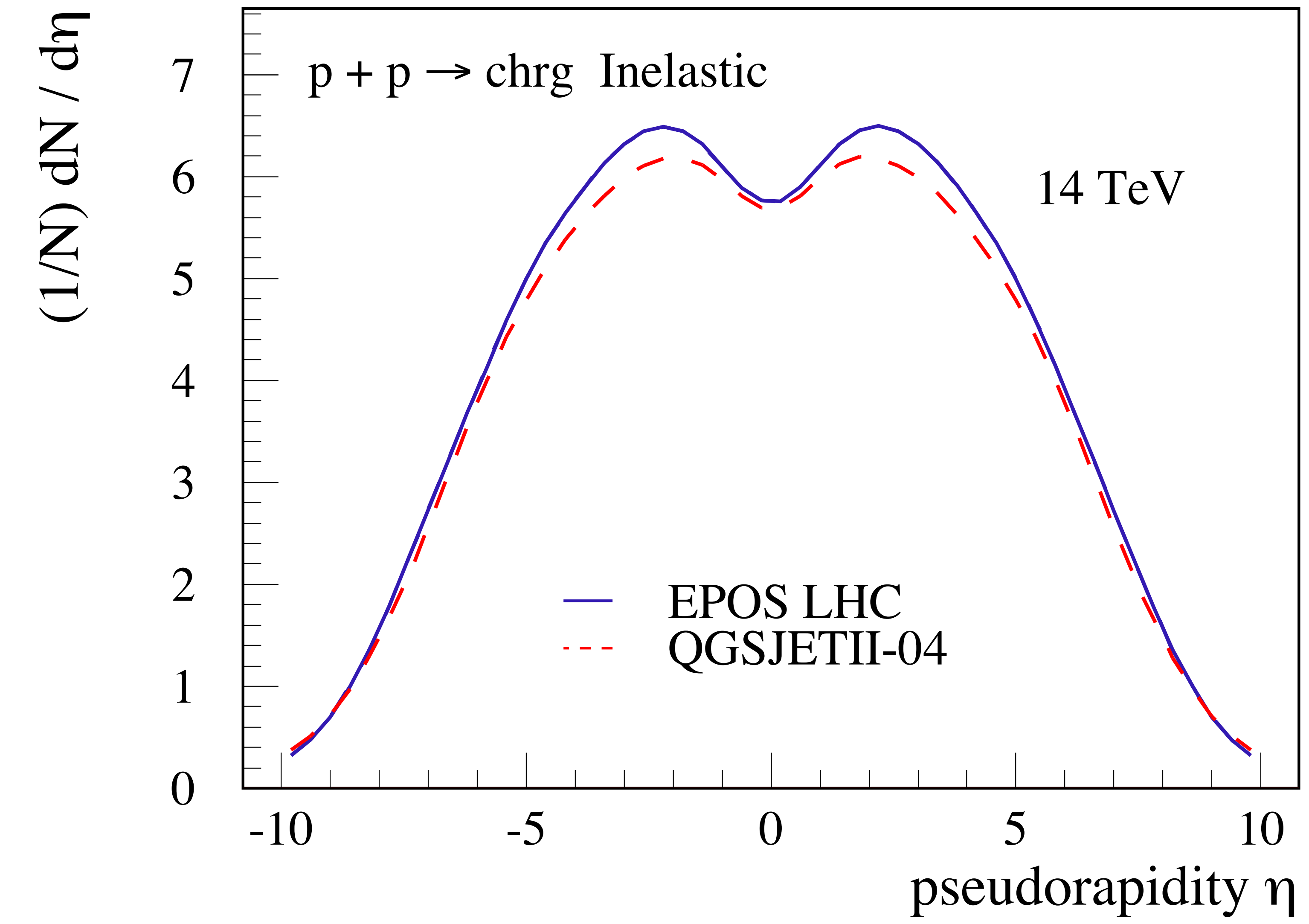
Fixed-target experiment at LHC

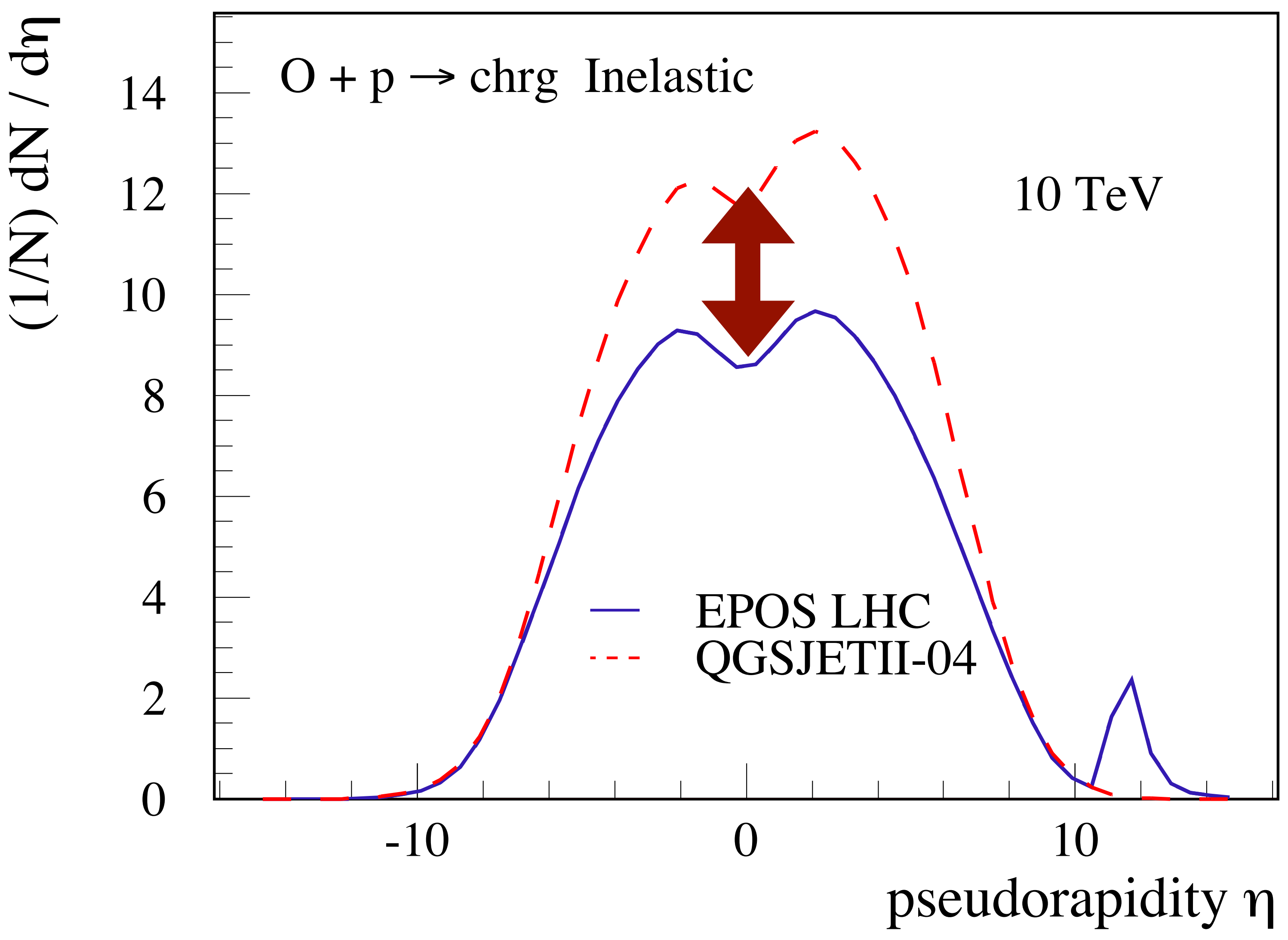


Deflection of protons
of beam halo by crystal

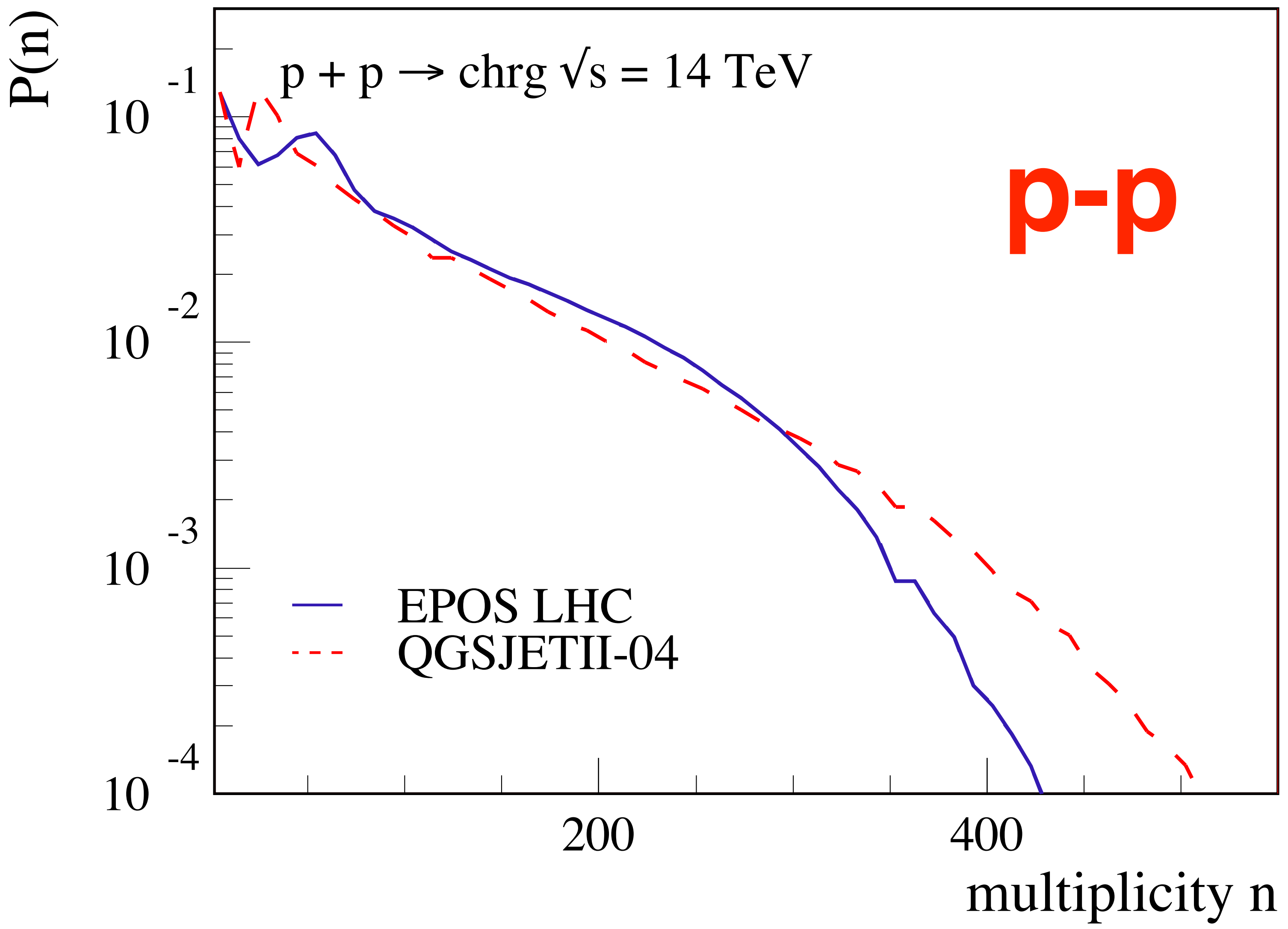
(Ulrich ICRC 2015)

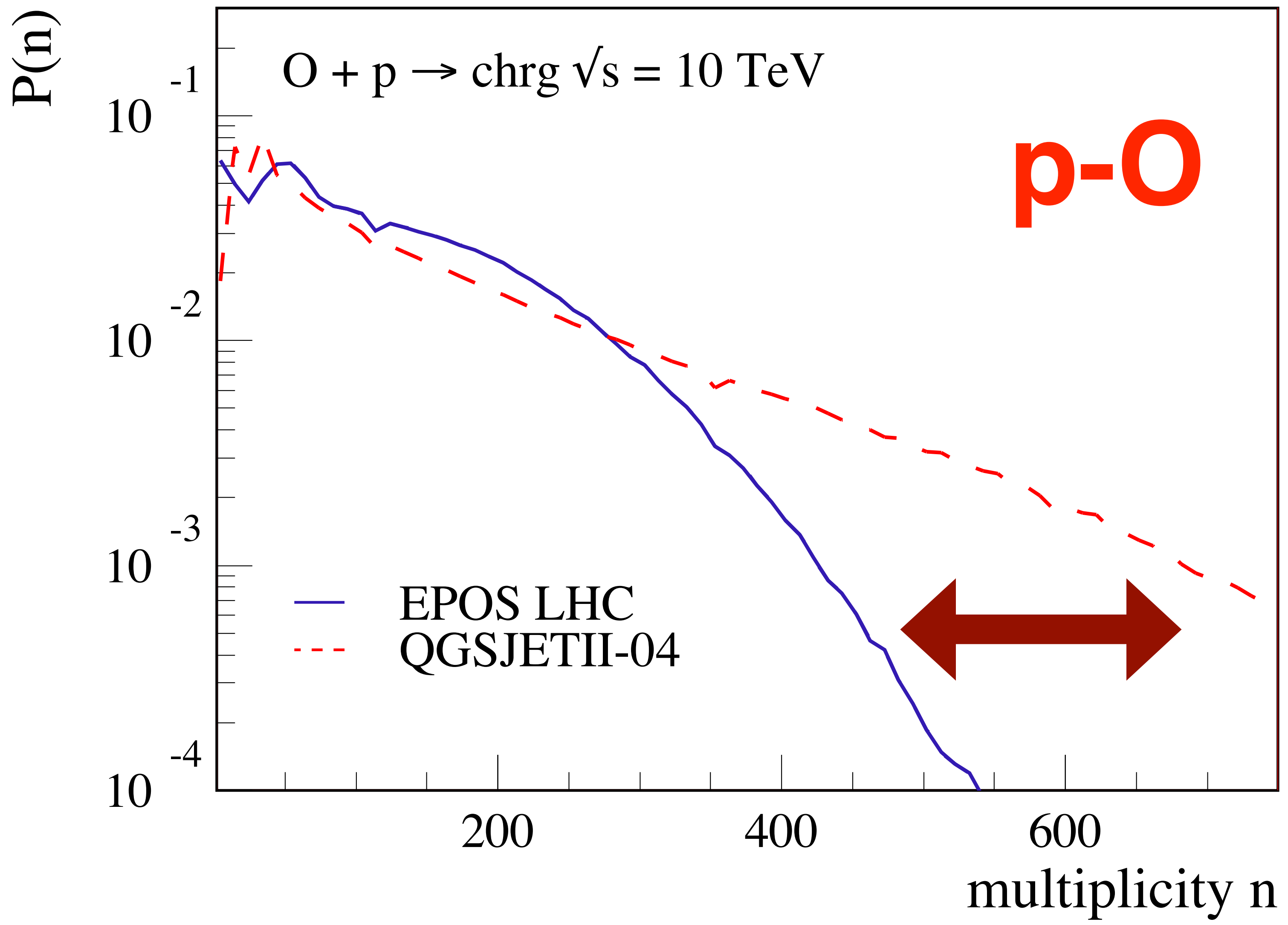
Outlook: further improvement due to p-O collisions at LHC





Currently predicted uncertainty in most optimistic case





p-O technically feasible (O used as ion for Pb)

Int. Symposium on Very High Energy Cosmic Ray Interactions 2016

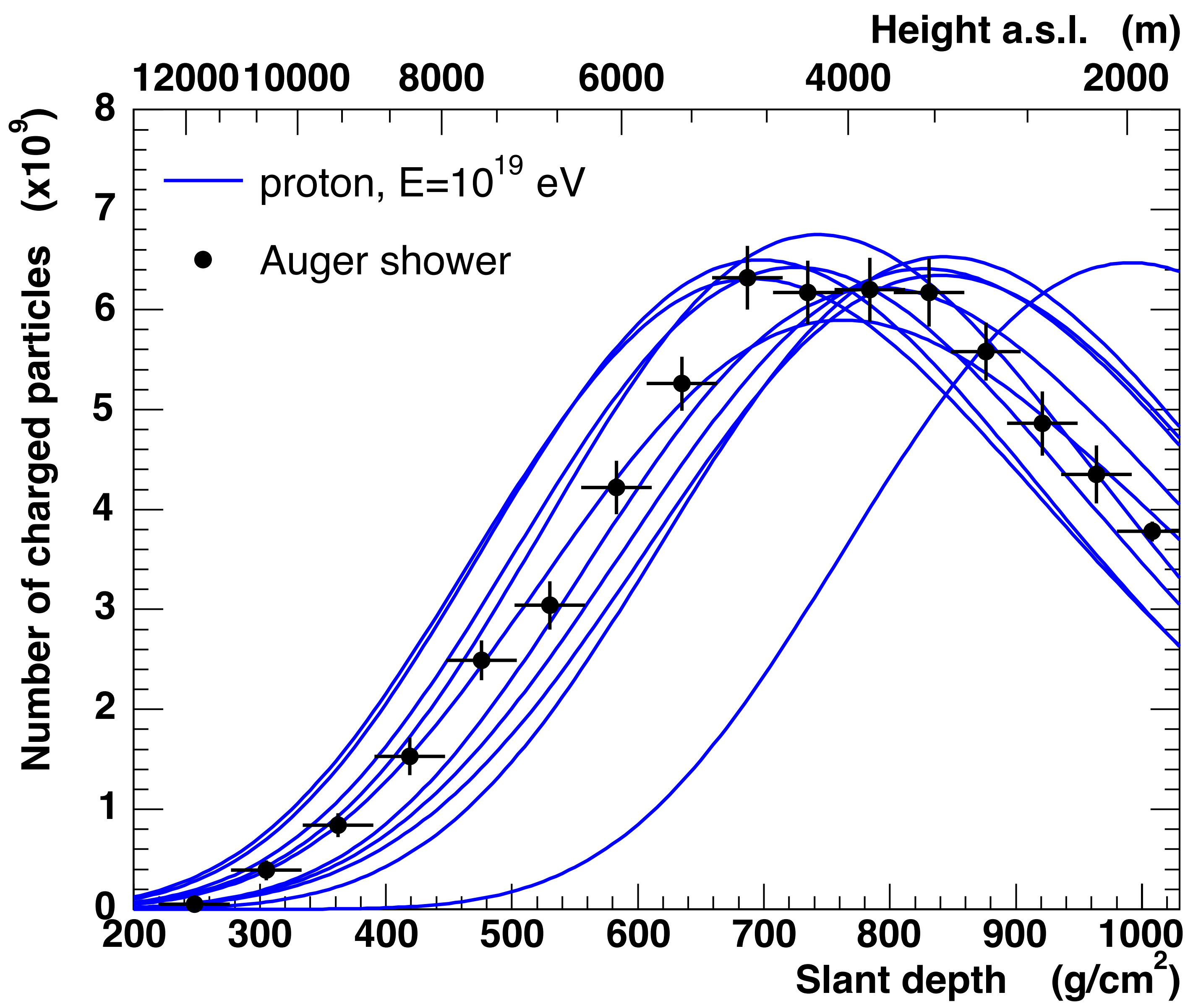
Moscow, 22-27th of August 2016

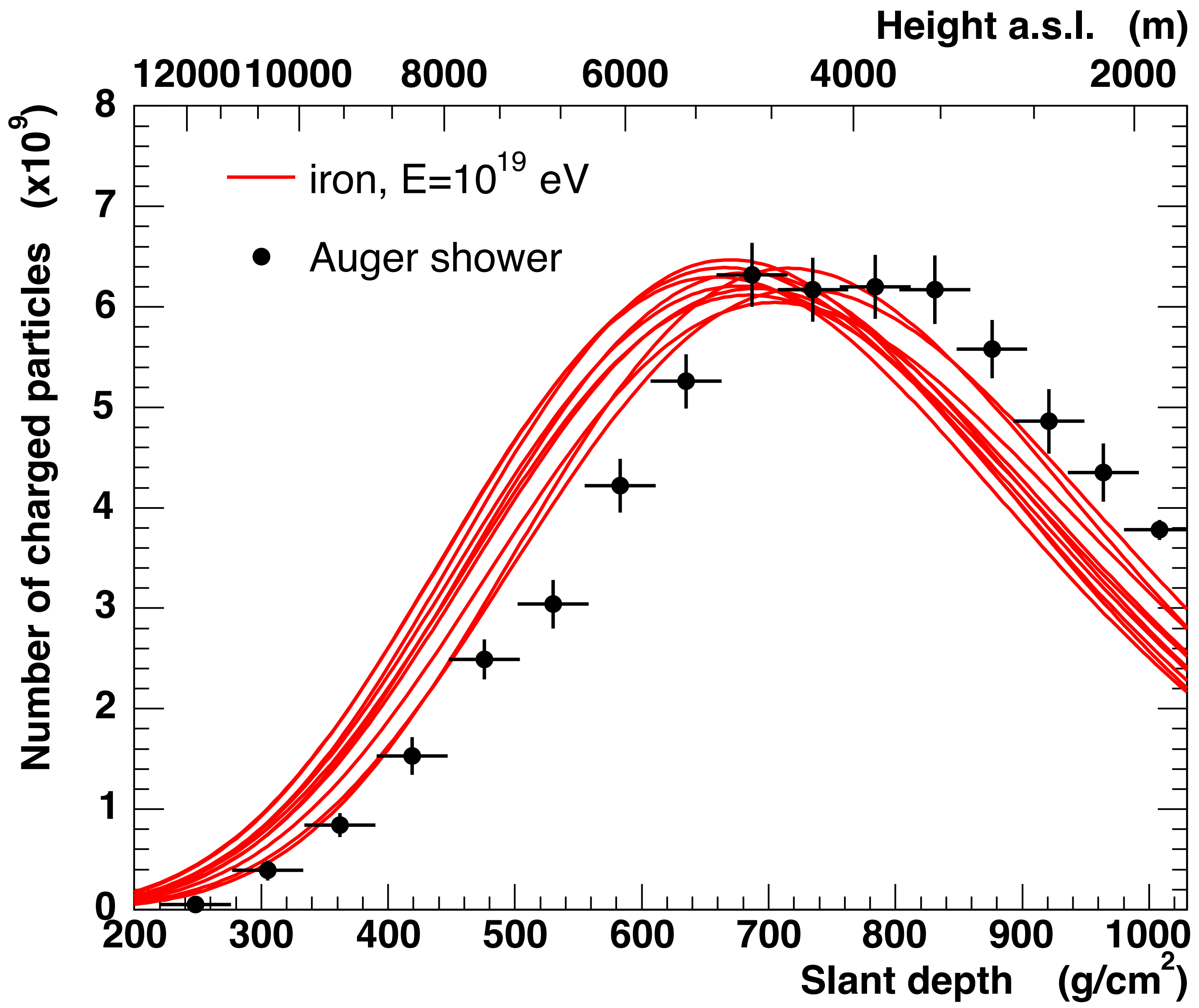
P.N.Lebedev Physical Institute of the Russian Academy of Sciences (FIAN)
National Research University 'Moscow Physical-Engineering Institute' (MEPhI)

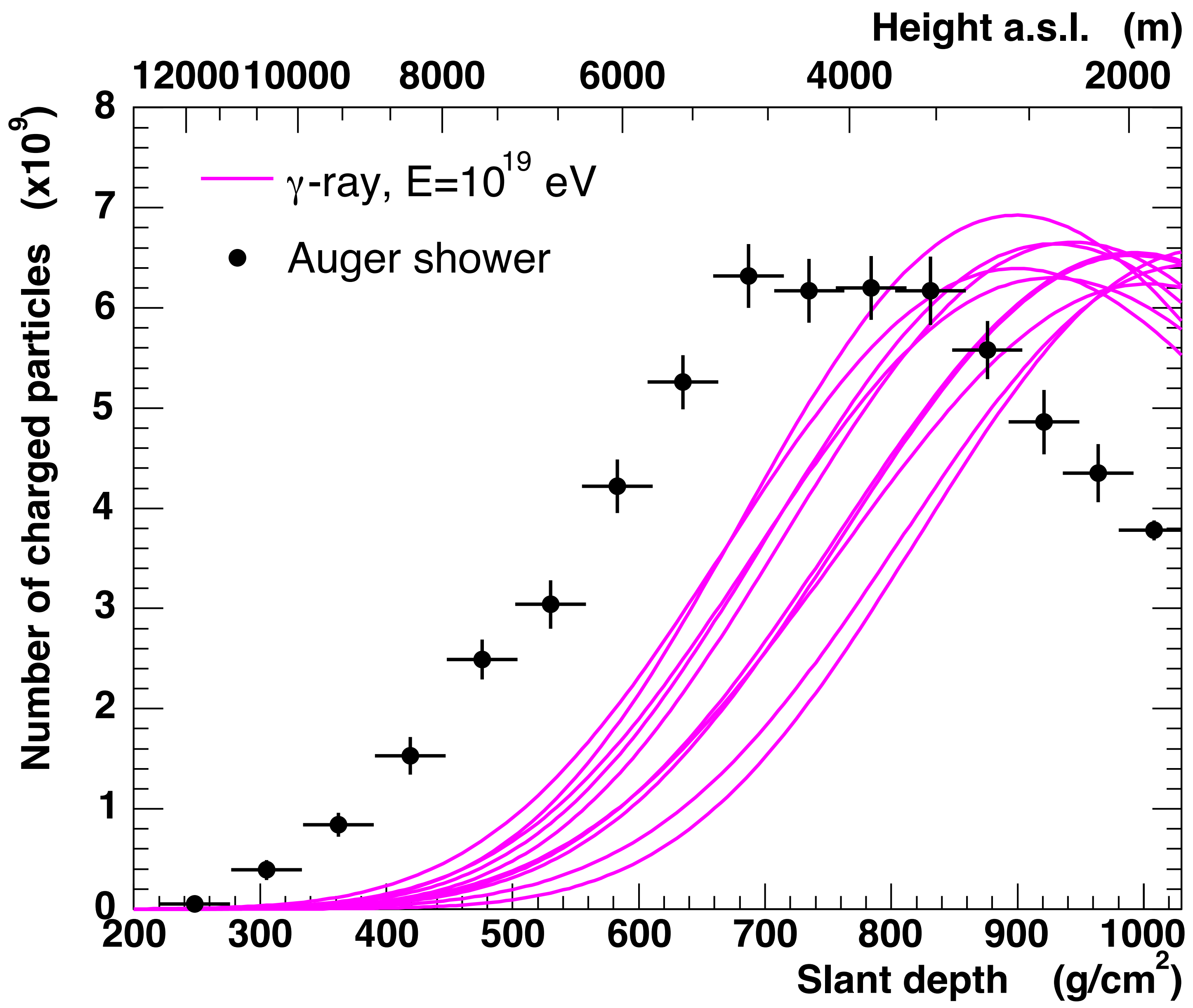
I. Nahodka, USSR; 1980
II. LaPaz, Bolivia & Rio de Janeiro, Brazil; 1982
III. Tokyo, Japan; 1984
IV. Beijing, China; 1986
V. Lodz, Poland; 1988
VI. Tarbes, France; 1990
VII. Ann Arbor, U.S.; 1992
VIII. Tokyo, Japan; 1994
IX. Karlsruhe, Germany; 1996
X. Assergi (Gran Sasso), Italy; 1998
XI. Campinas, Brazil & LaPaz, Bolivia; 2000
XII. Geneva (CERN), Switzerland; 2002
XIII. Pylos (NESTOR), Greece; 2004
XIV. Weihai, China; 2006
XV. Paris, France; 2008
XVI. Batavia (FNAL), USA; 2010
XVII. Berlin (DESY), Germany; 2012
XVIII. Geneva (CERN), Switzerland; 2014
XIX. Moscow (MEPhI/LPI), Russia; 2016

Backup slides

Longitudinal shower profile







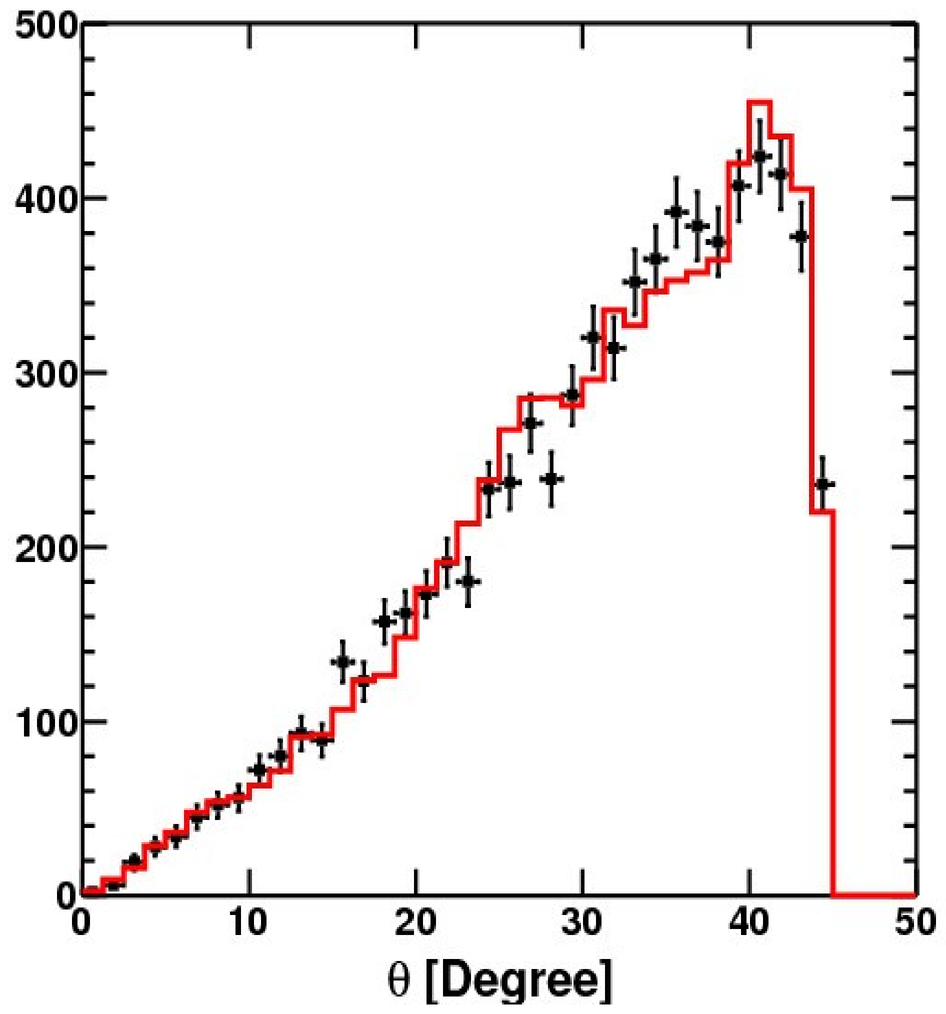
$$N_{\max} = E_0/E_c$$

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

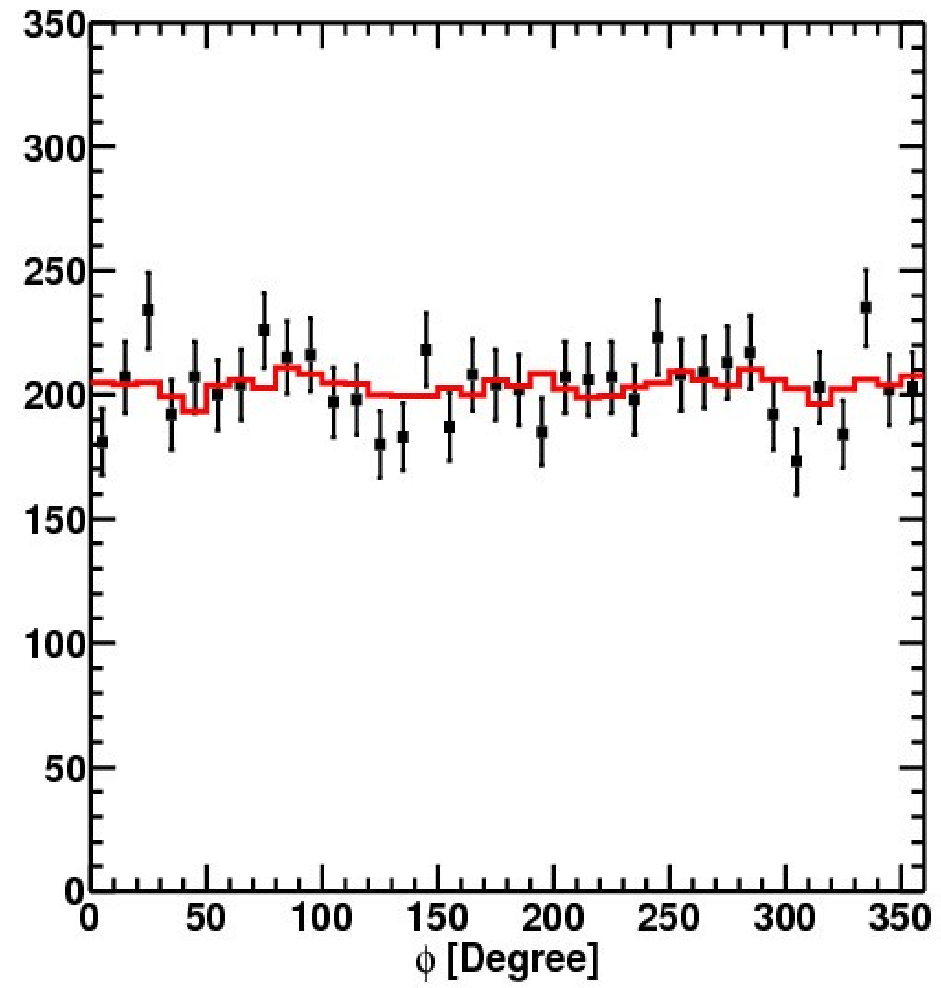
Superposition model:

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

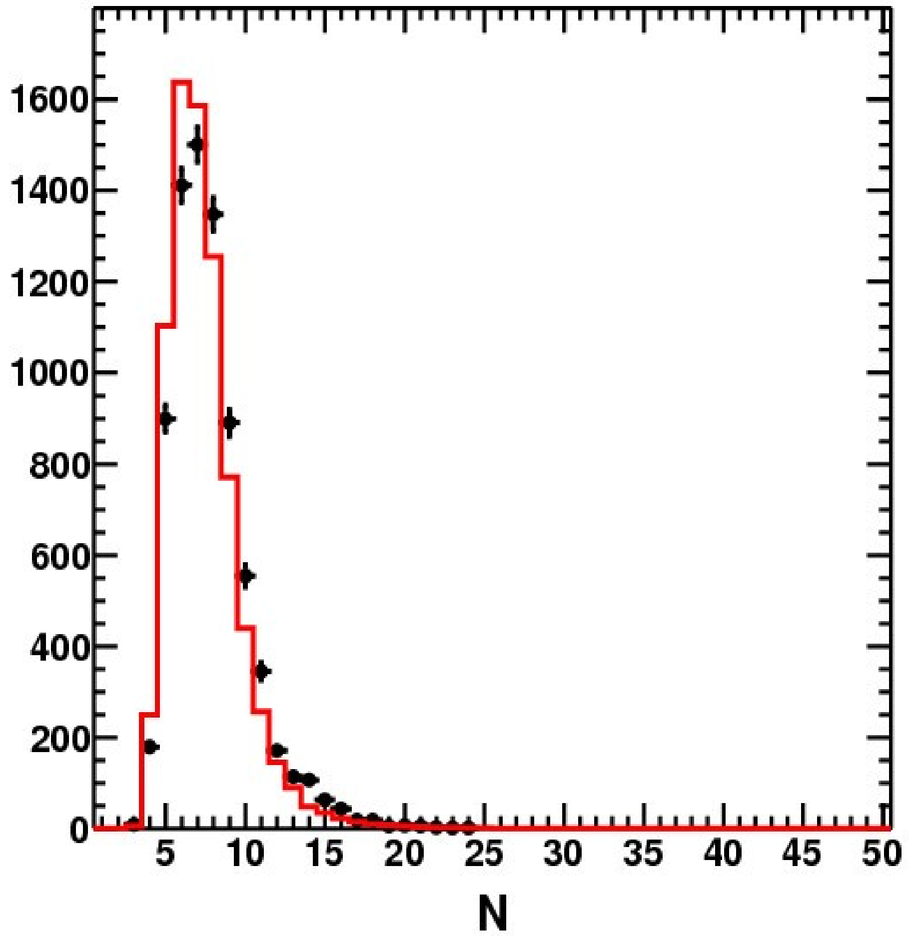
TA event simulation for surface array



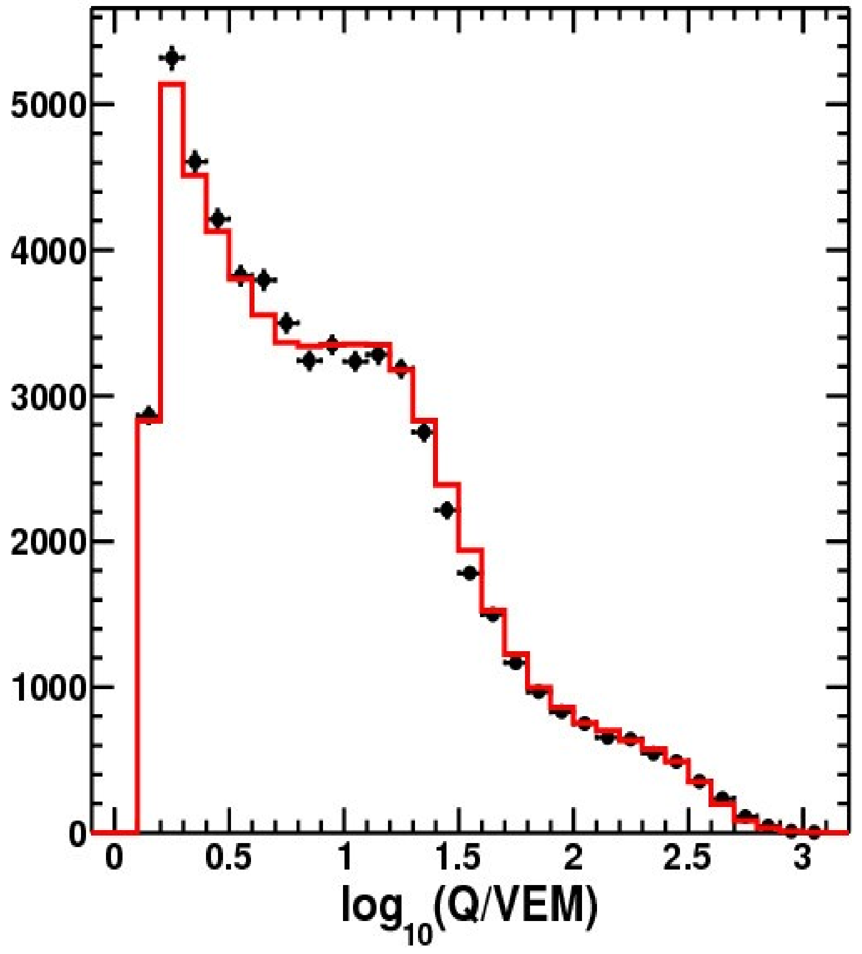
Zenith Angle



Azimuth Angle

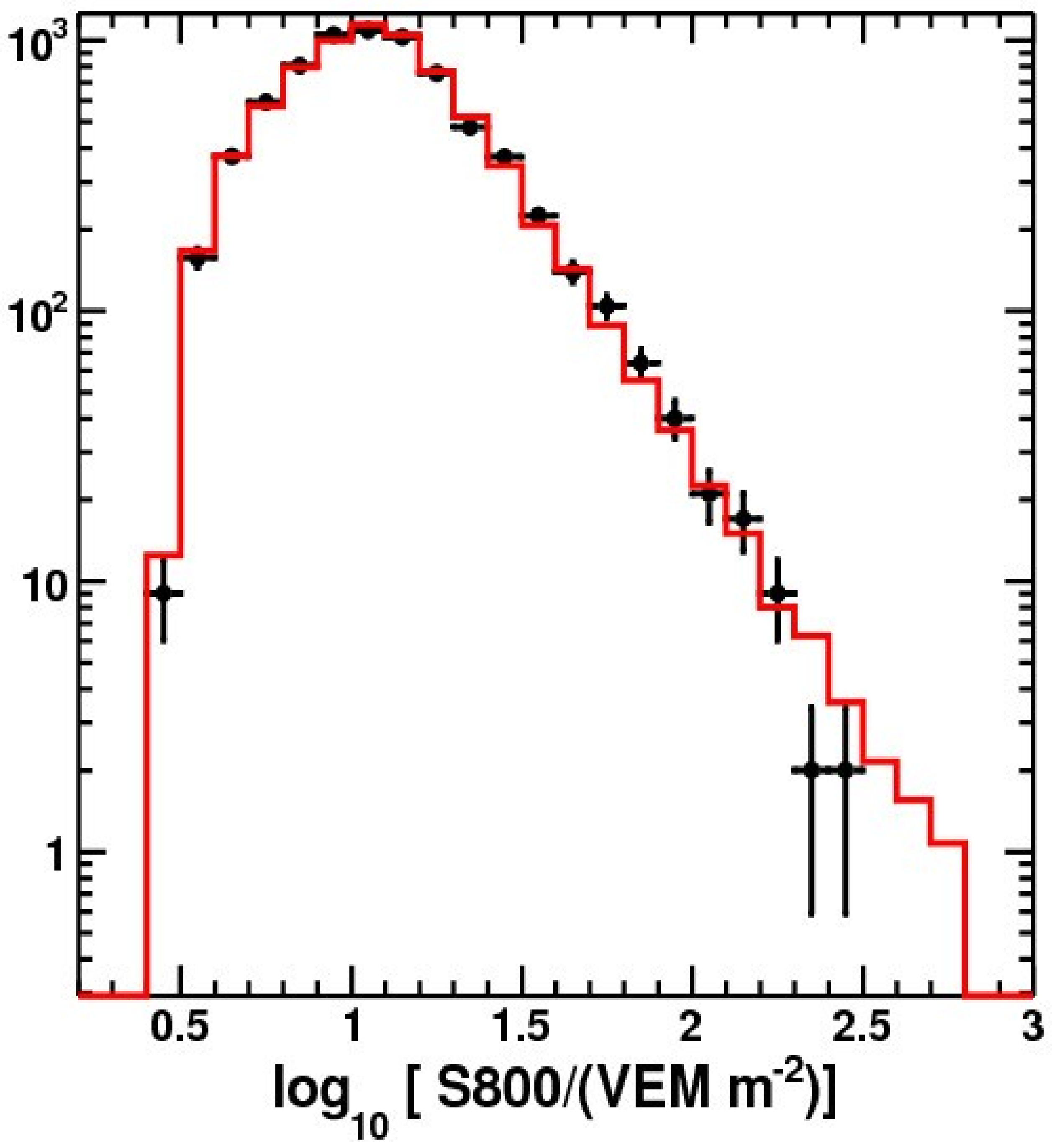


Number of Good Counters/Event



Charge/Counter/Event

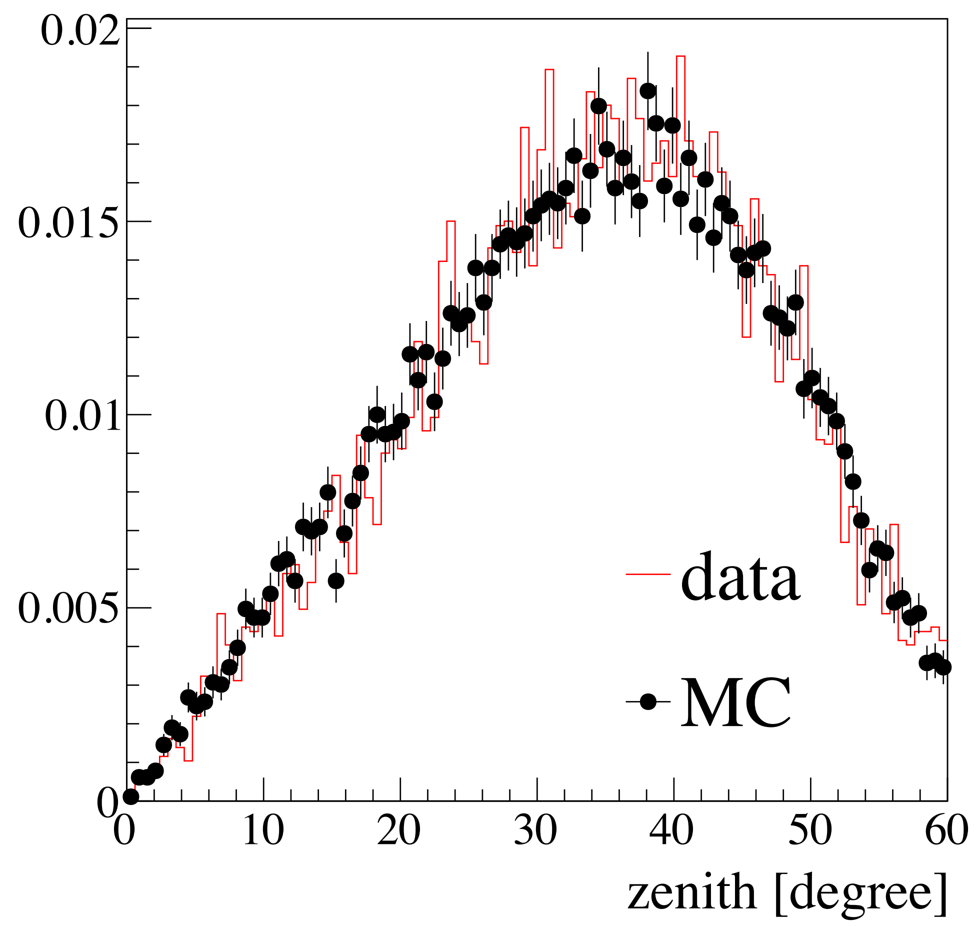
CORSIKA + full detector simulation (proton primaries)



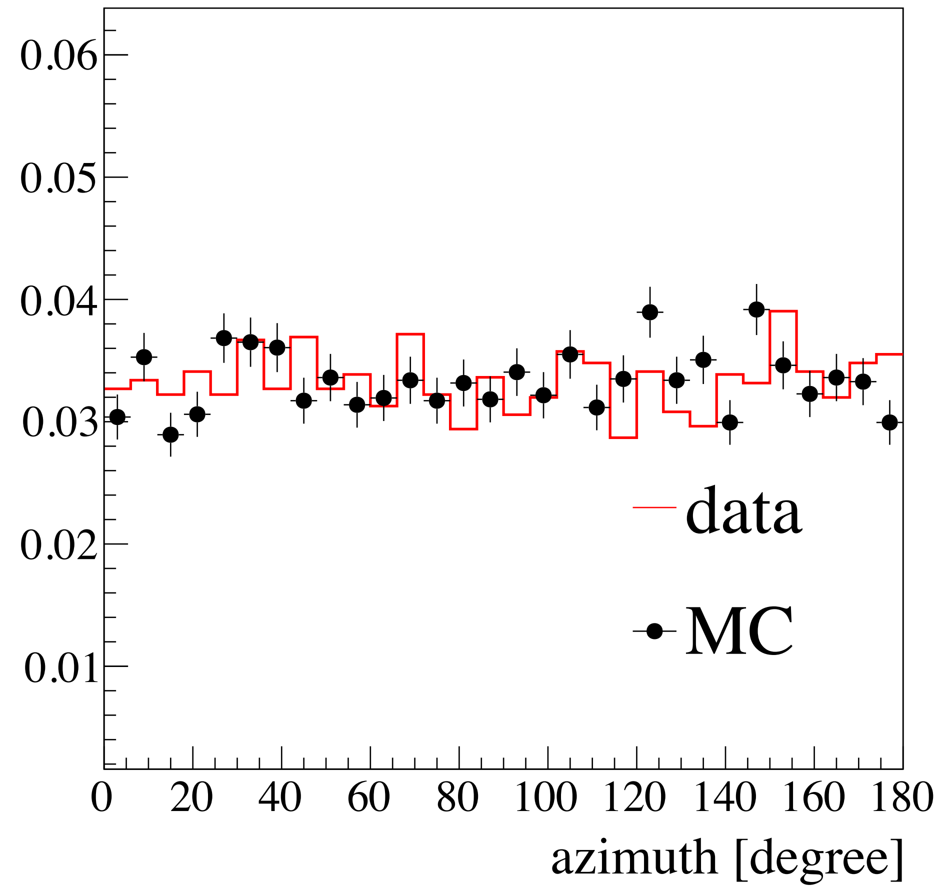
(UHECR 2012)

Very good agreement

Auger event simulation for surface array

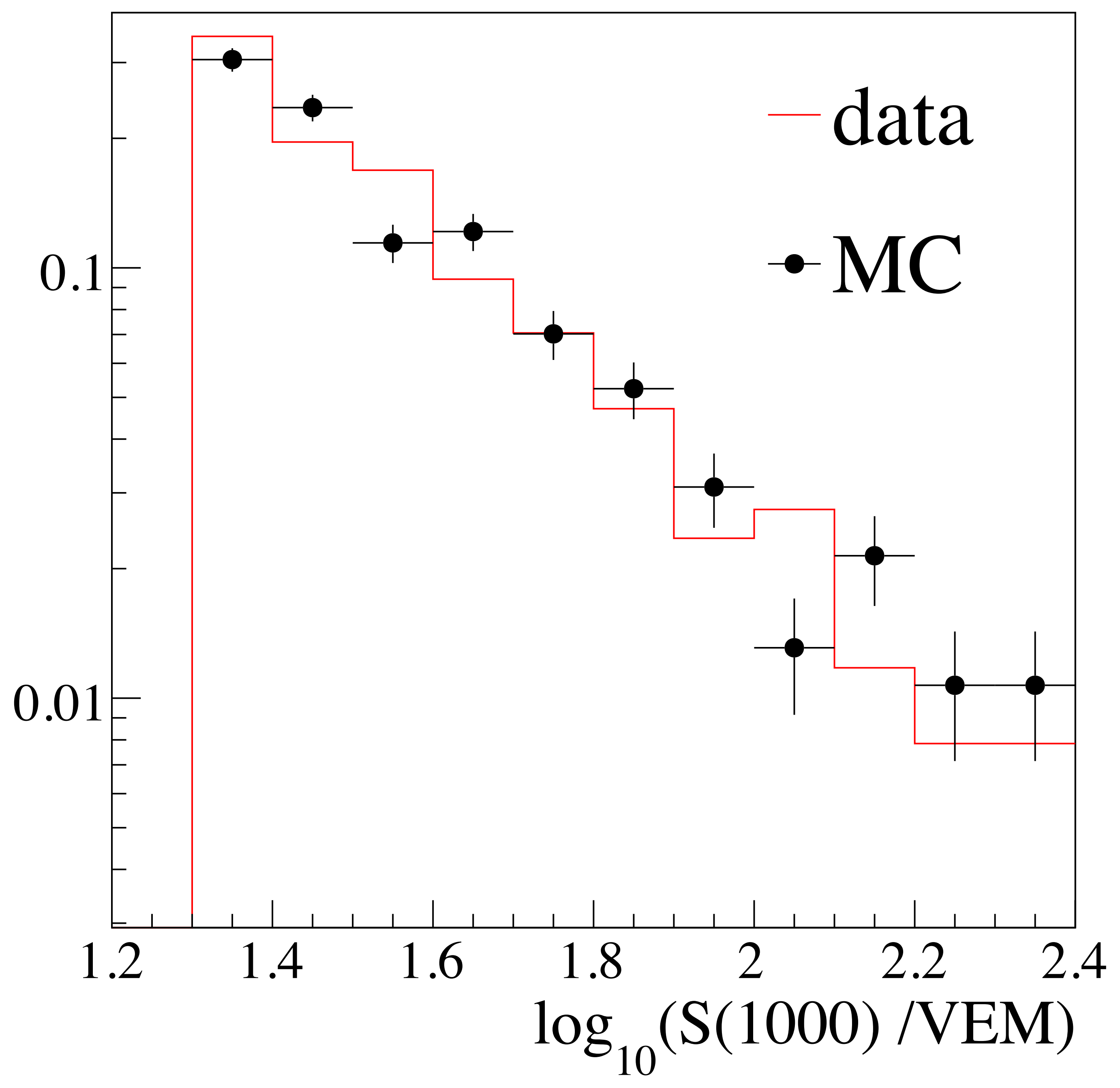


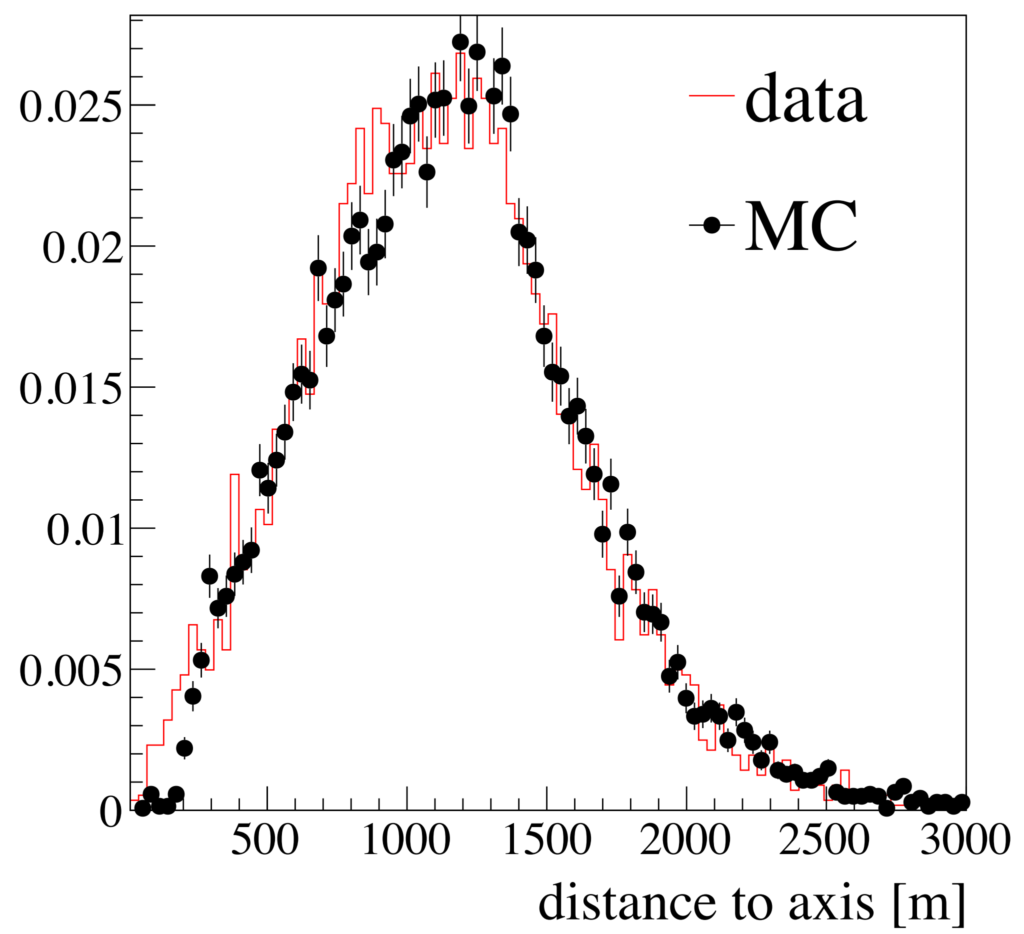
Zenith angle



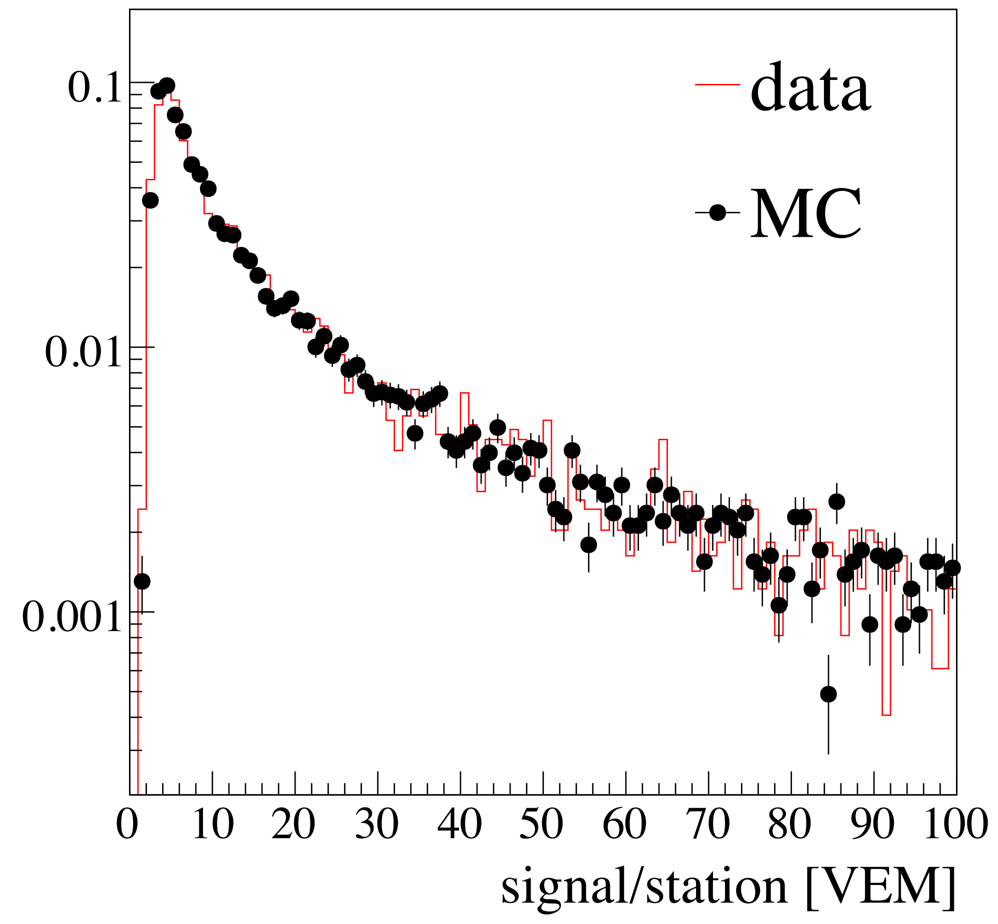
Azimuth angle

CORSIKA + full detector simulation
(50% p + 50% Fe)





Distance of triggered stations

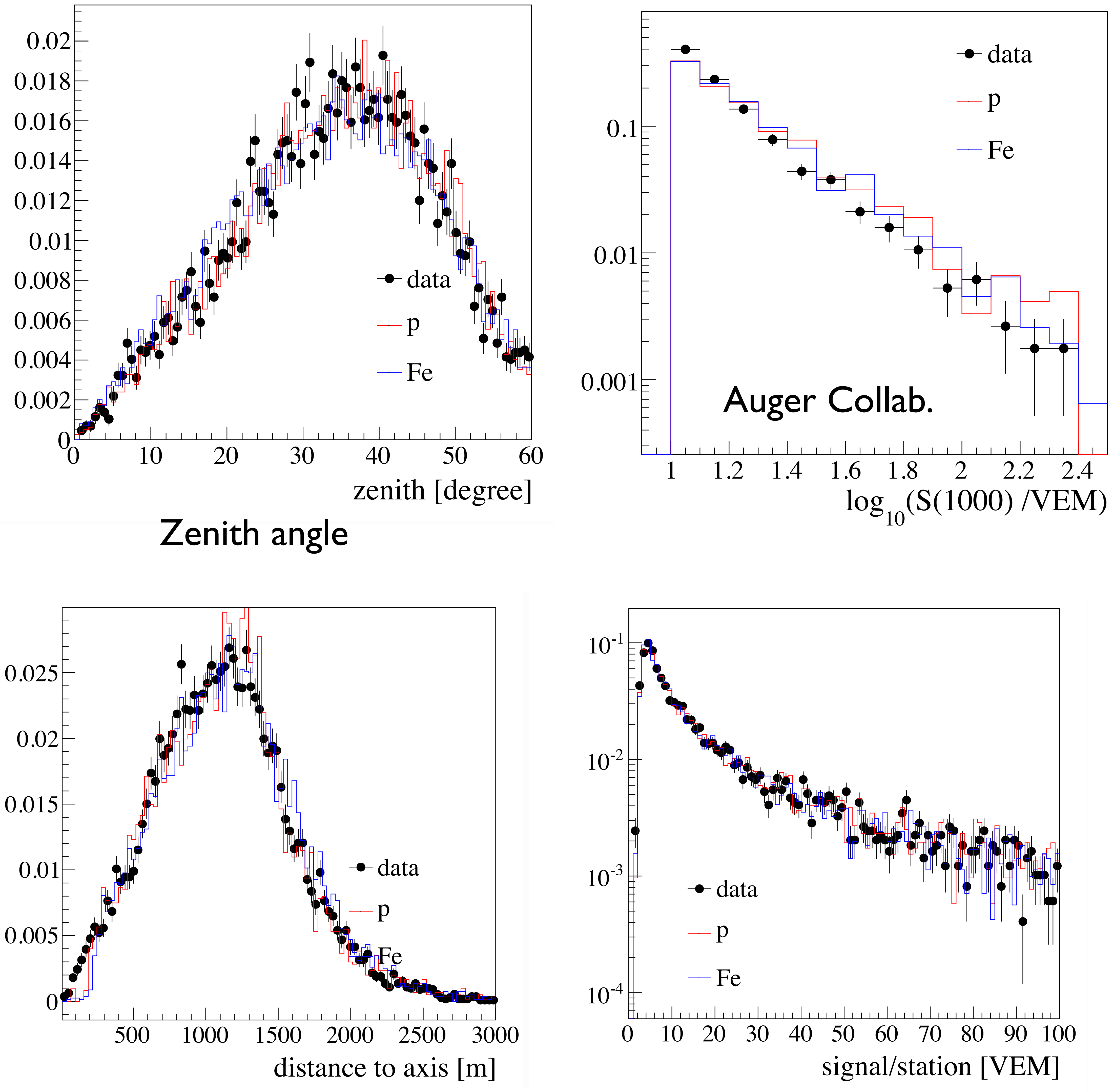


Signal per station

(UHECR 2012)

Very good agreement

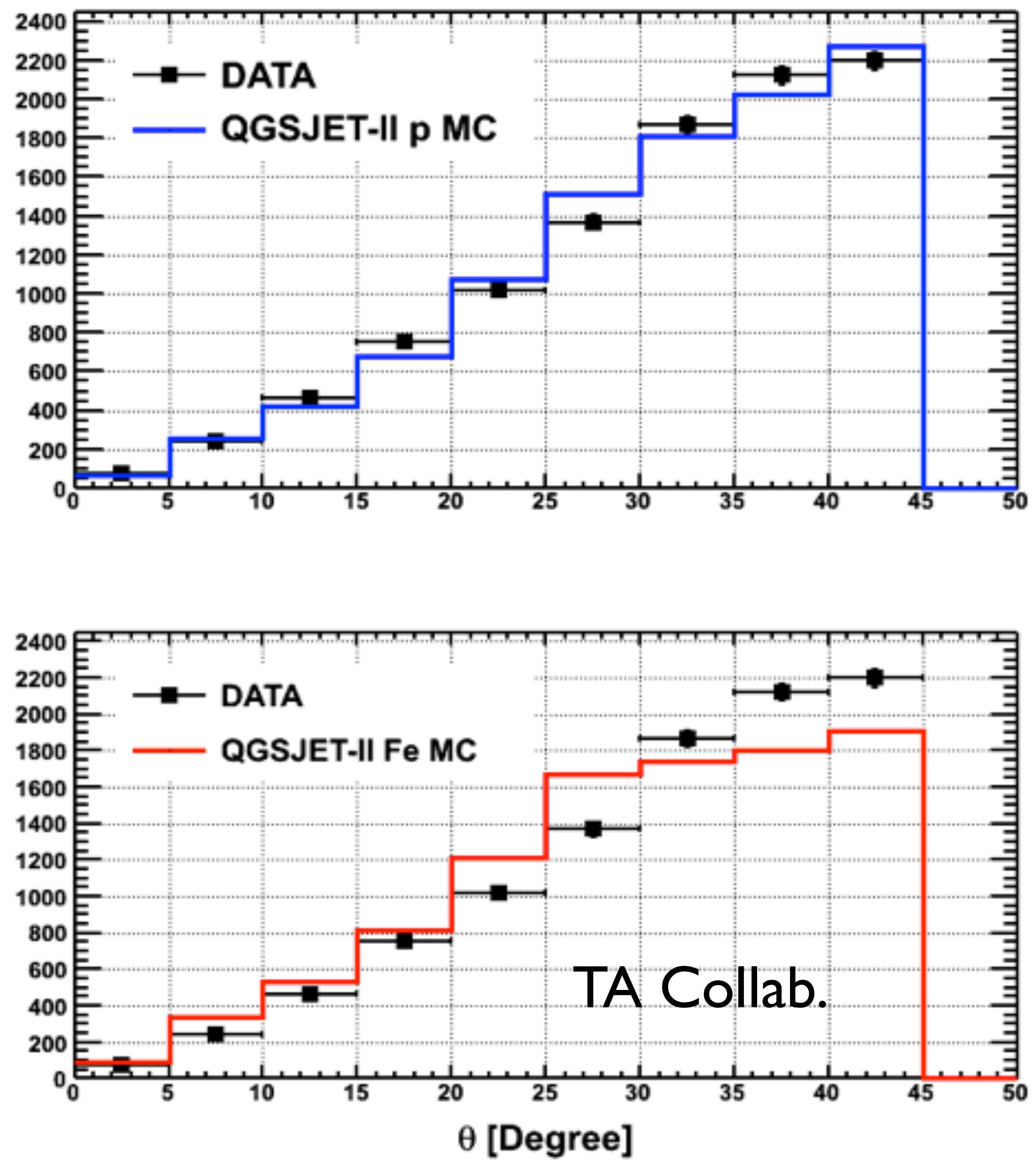
Composition and model sensitivity ?



Zenith angle

Distance of triggered stations

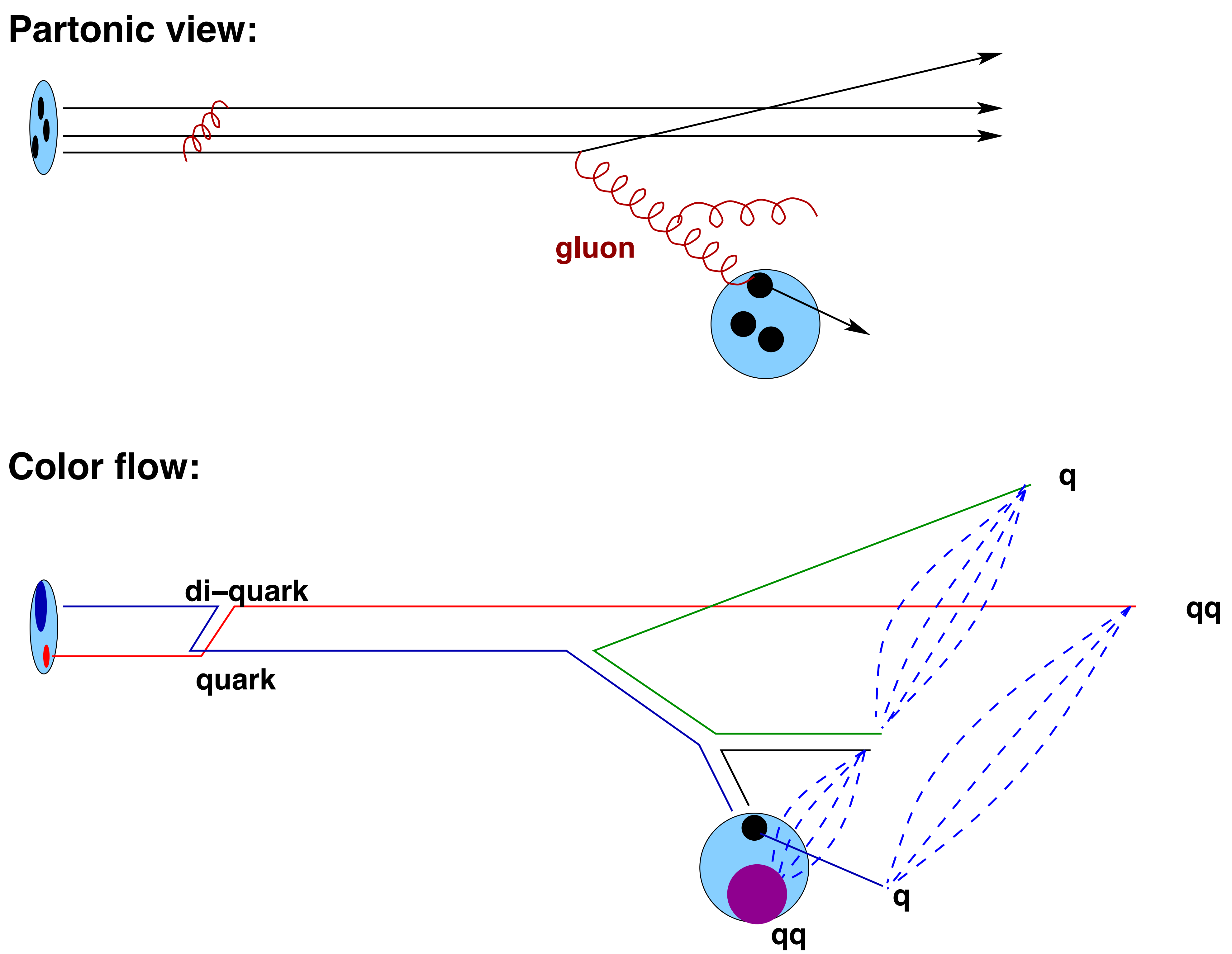
Signal per station



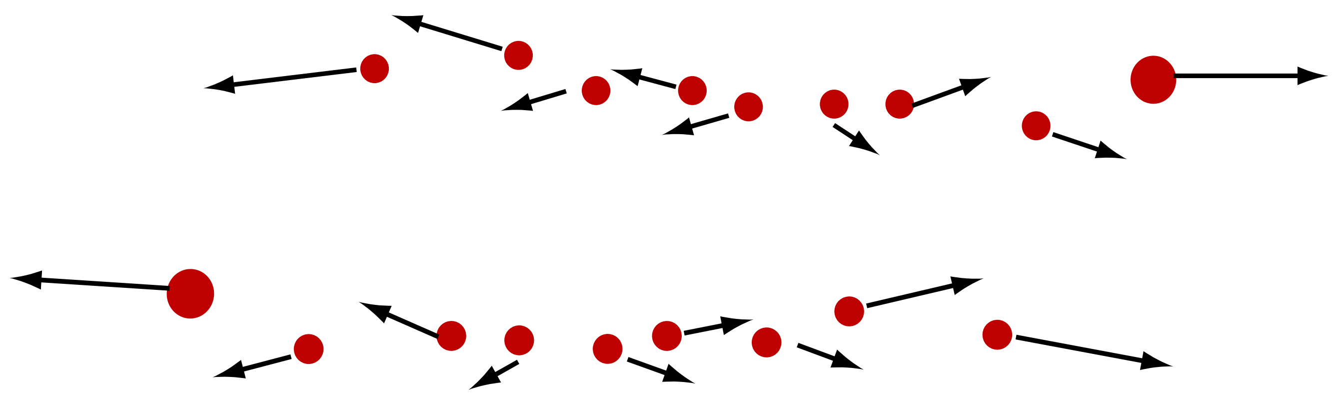
(UHECR 2012)

Most observables not very sensitive to details of shower simulation

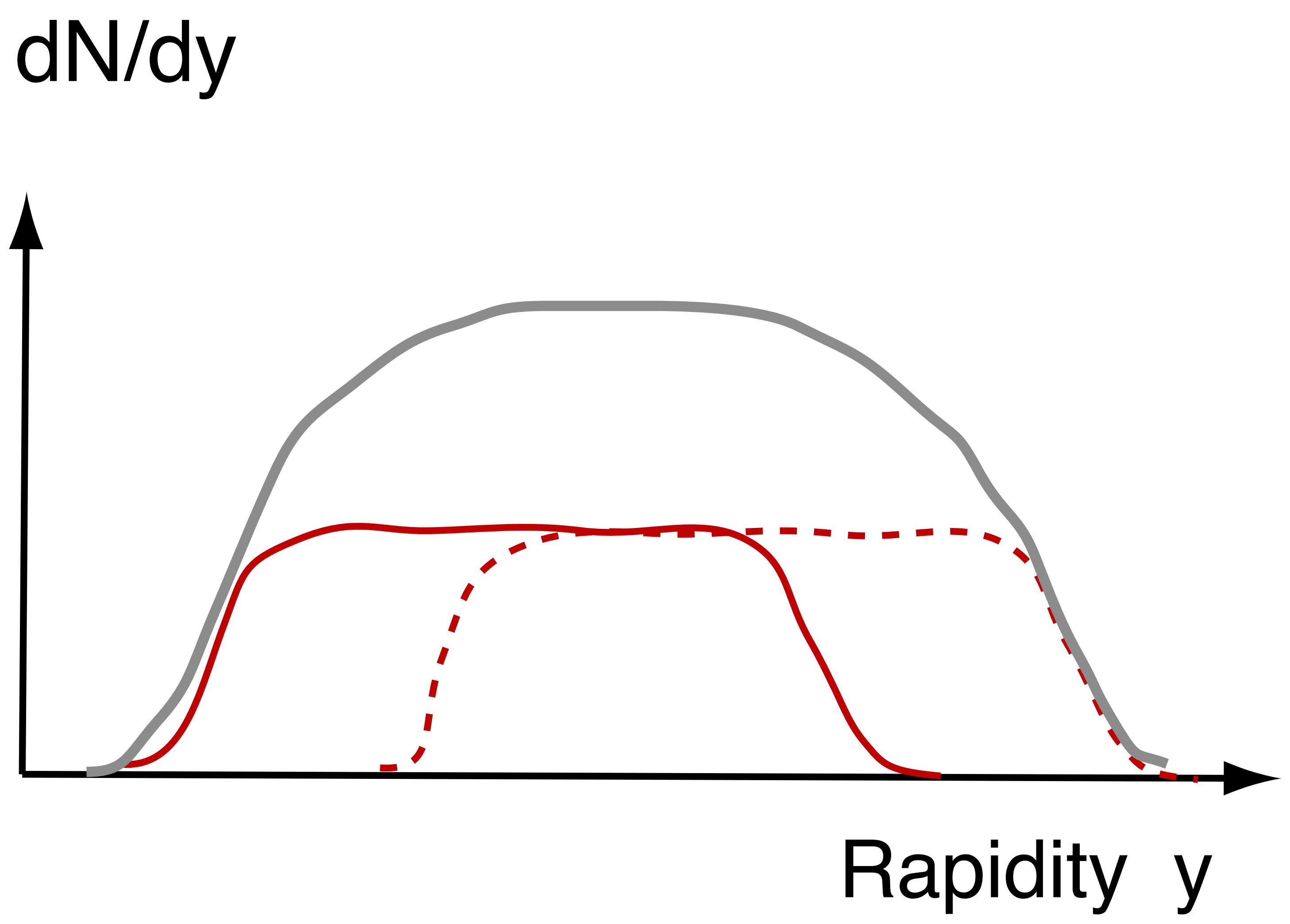
Color flow and final state particles



single-gluon exchange:
non-diffractive interaction

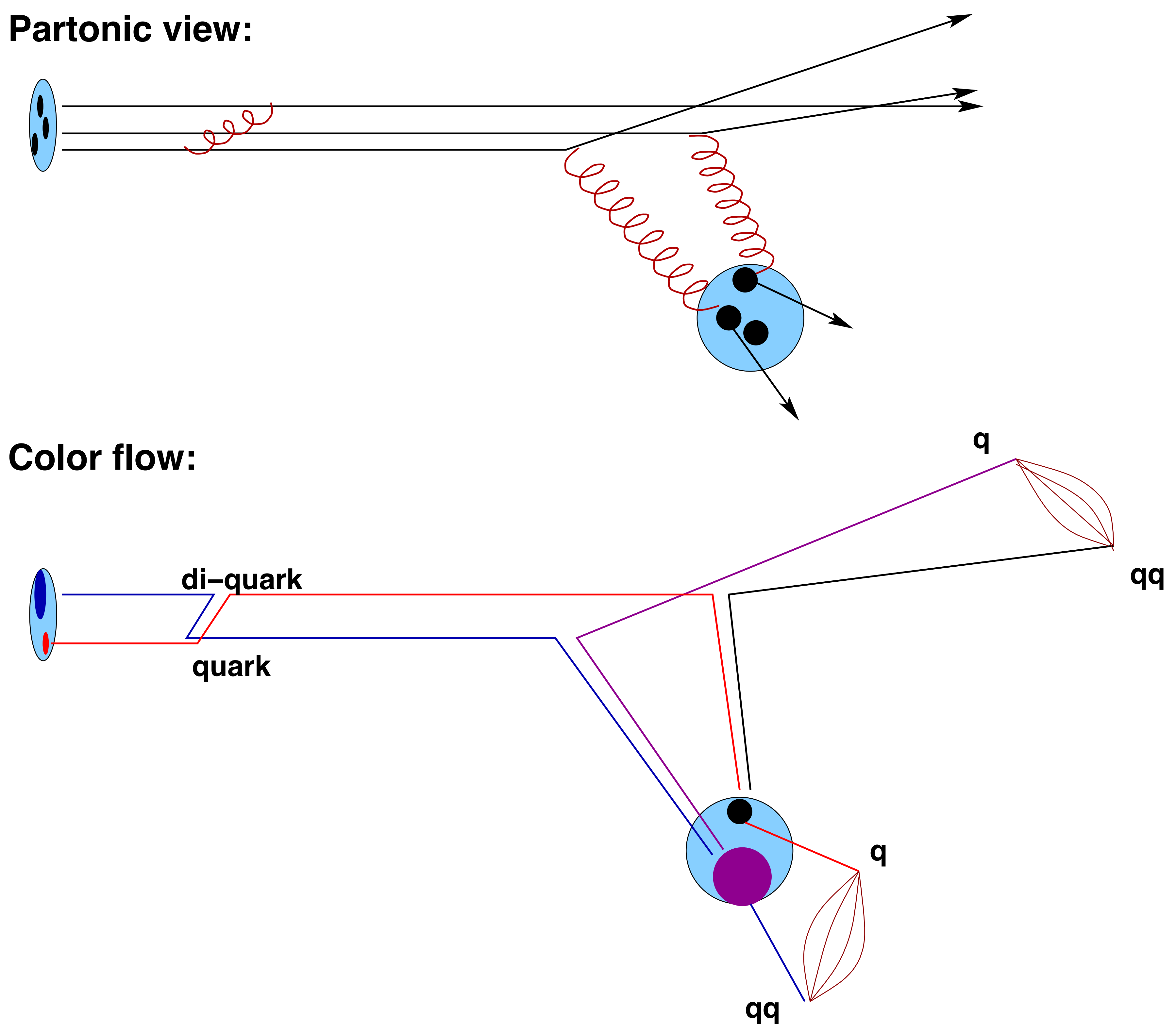


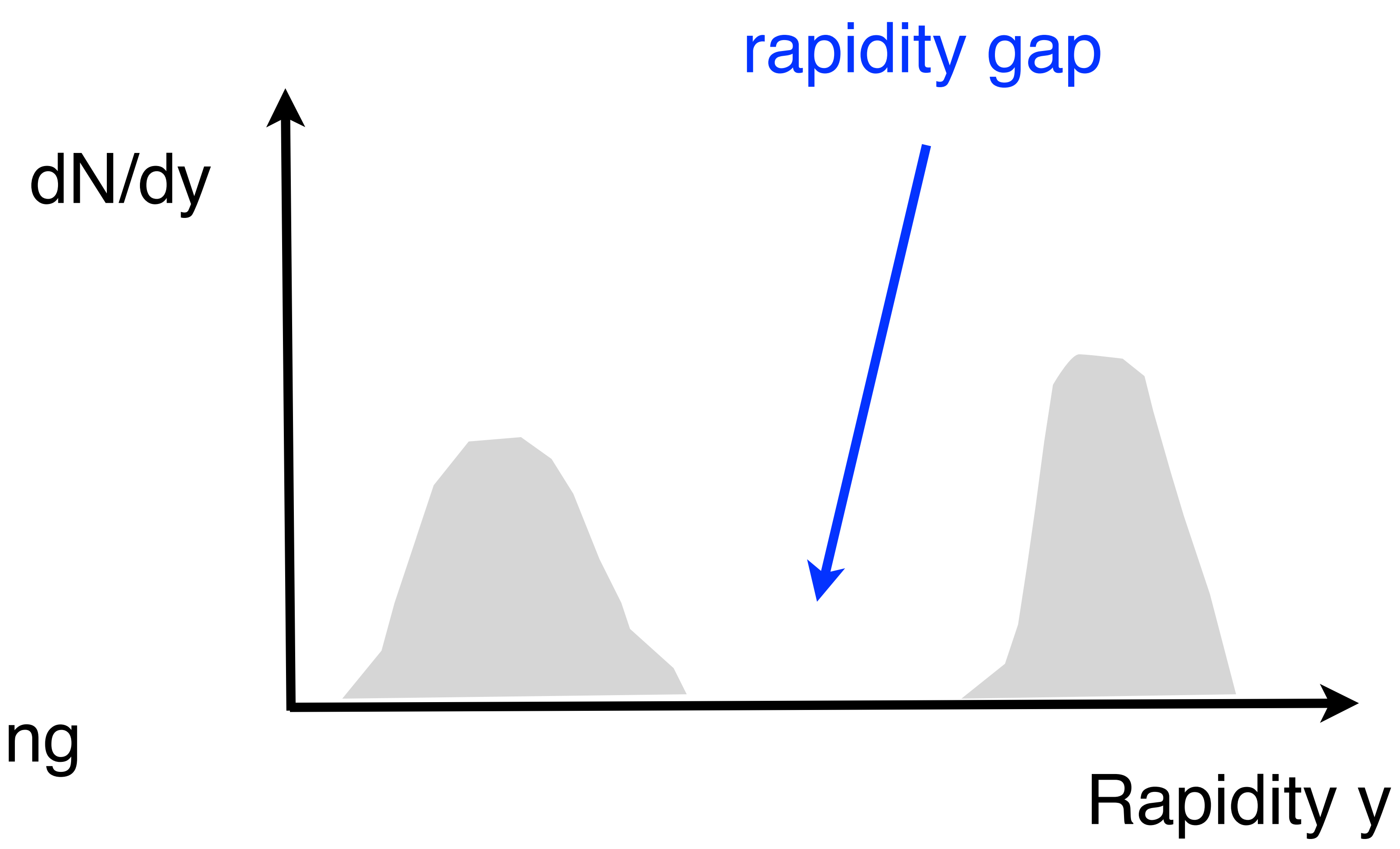
Initial and final state radiation
does not really change topology



$$f_{\rm nuc}^{\rm SIB}(x) \sim (x_q^2 + \mu^2/s)^{-1/4}(1 - x_q)^3$$

Other predicted color flow configurations

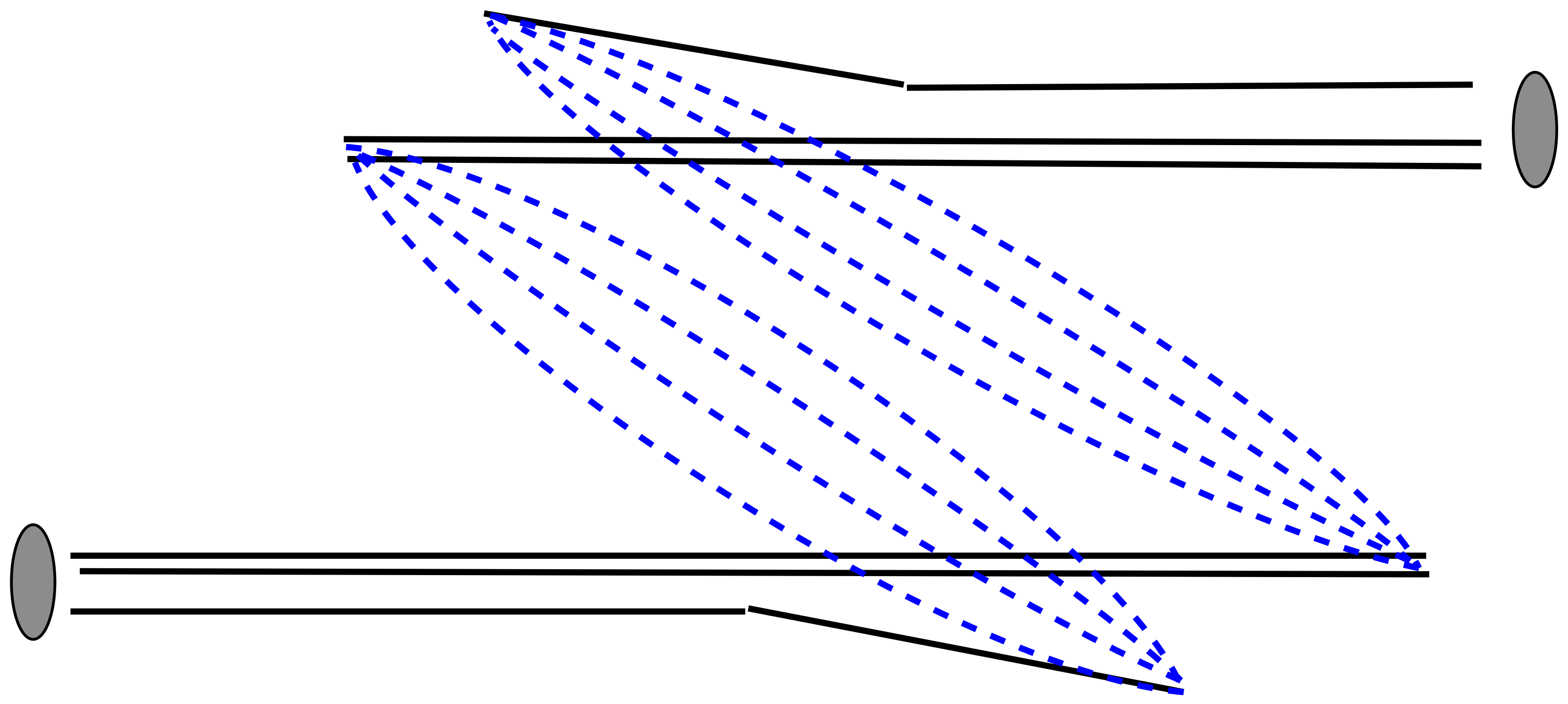




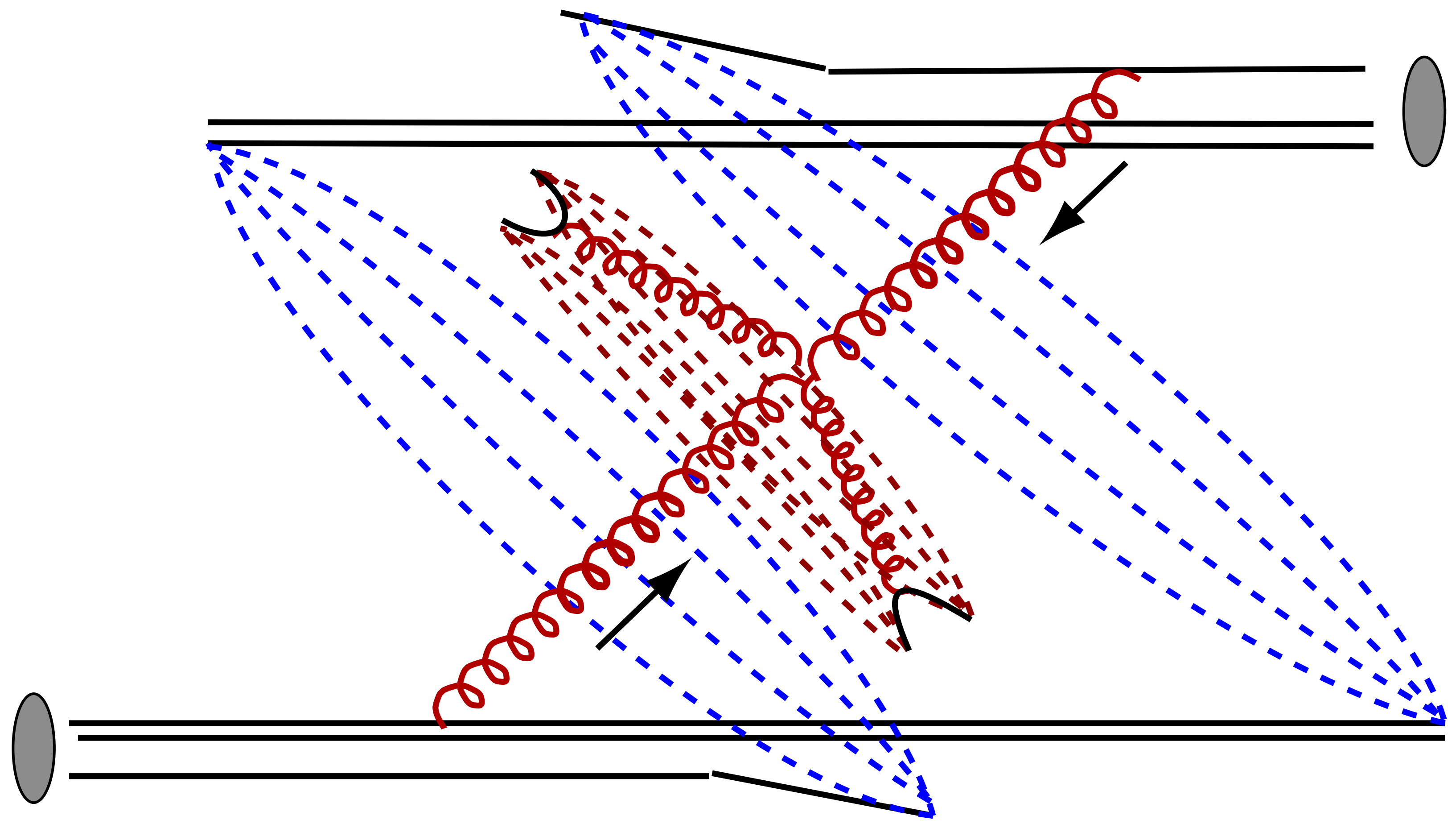
At very high energy (multi-gluon exchange):
Almost 50% of all events are elastic/diffractive scattering

Multiple soft and hard interactions

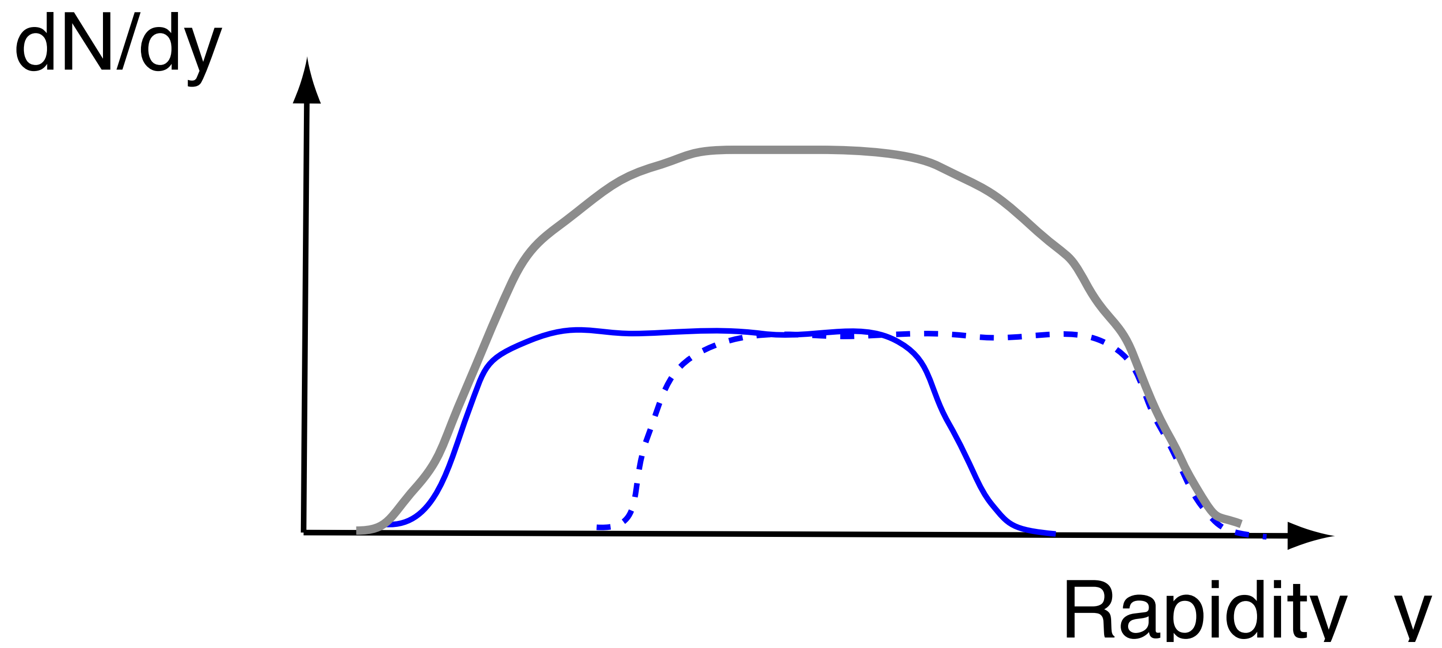
$$\sigma_{n_s,n_h} = \int d^2b \, \frac{[n_{\rm soft}(b,s)]^{n_s}}{n_s!} \, \frac{[n_{\rm hard}(b,s)]^{n_h}}{n_h!} \, e^{-n_{\rm hard}(b,s)-n_{\rm soft}(b,s)}$$

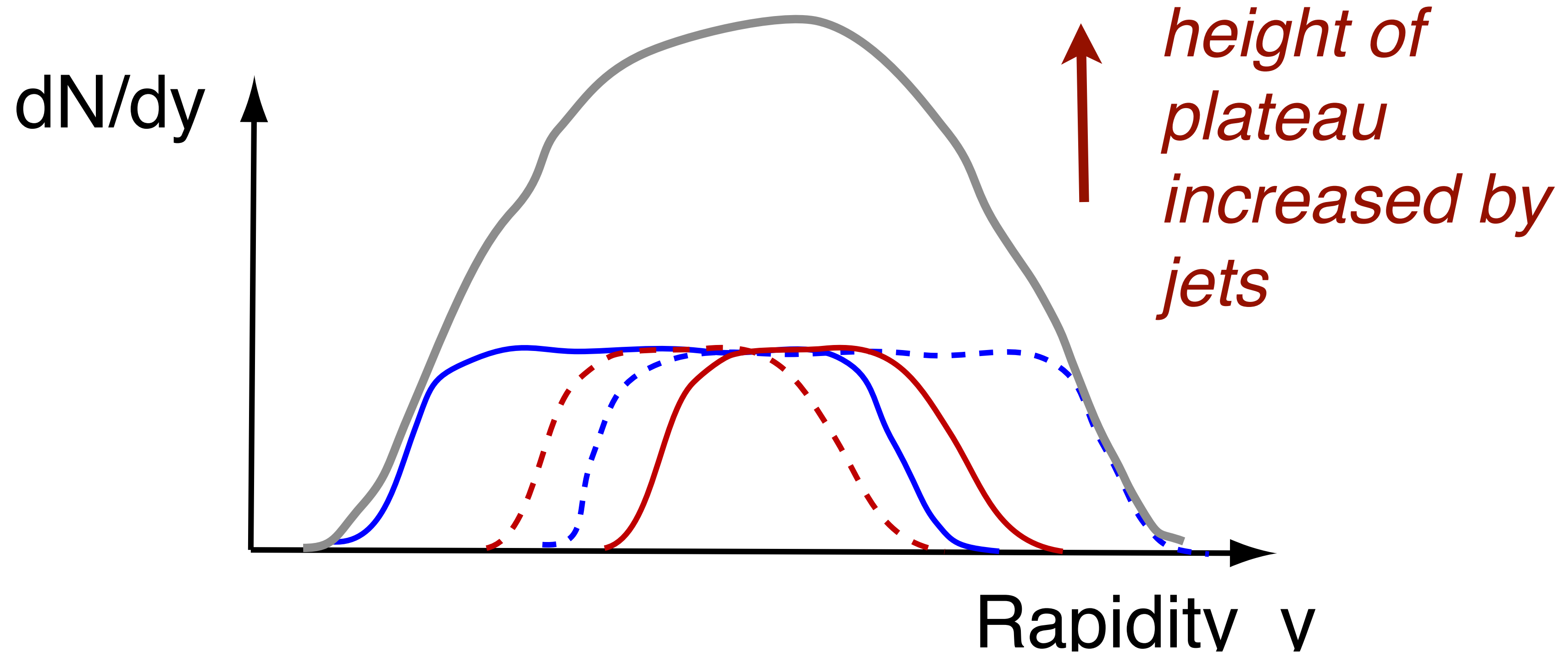


$n_s=1$, $n_h=0$



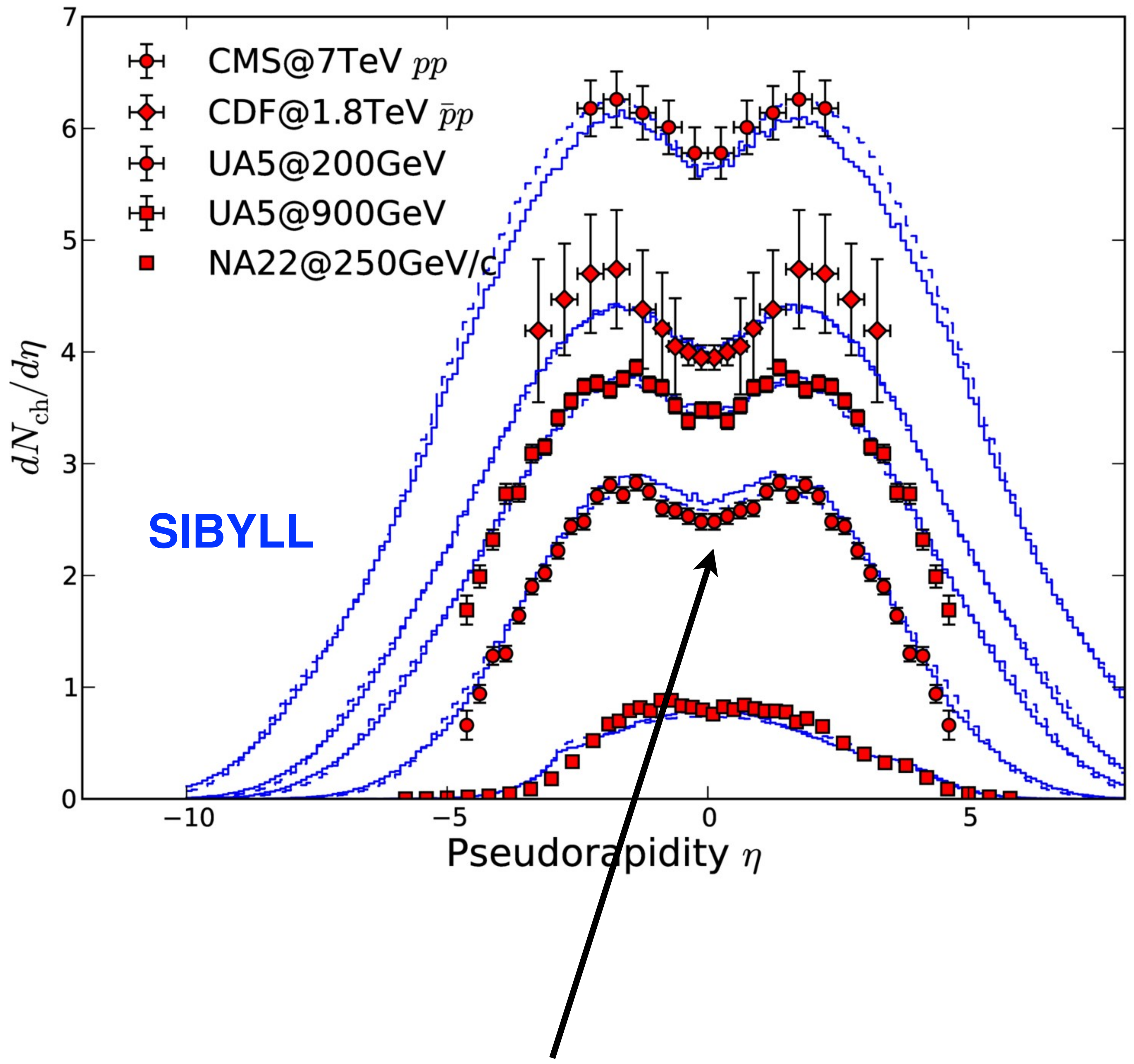
$n_s=1$, $n_h=1$





Rise of pseudorapidity plateau

(Riehn et al. 2014)



Feynman scaling violated for small $|x_F|$

Feynman scaling

$$x_F = \frac{p_\parallel}{p_{\rm max}} \approx \frac{2p_\parallel}{\sqrt{s}}$$

$$2E\frac{dN}{d^3p} = \frac{dN}{dy\, d^2p_\perp} \longrightarrow f(x_F, p_\perp)$$

With Feynman scaling:
distribution independent of energy

$$\frac{dN}{dx} \approx \tilde{f}(x) \qquad x = E/E_{\rm prim}$$