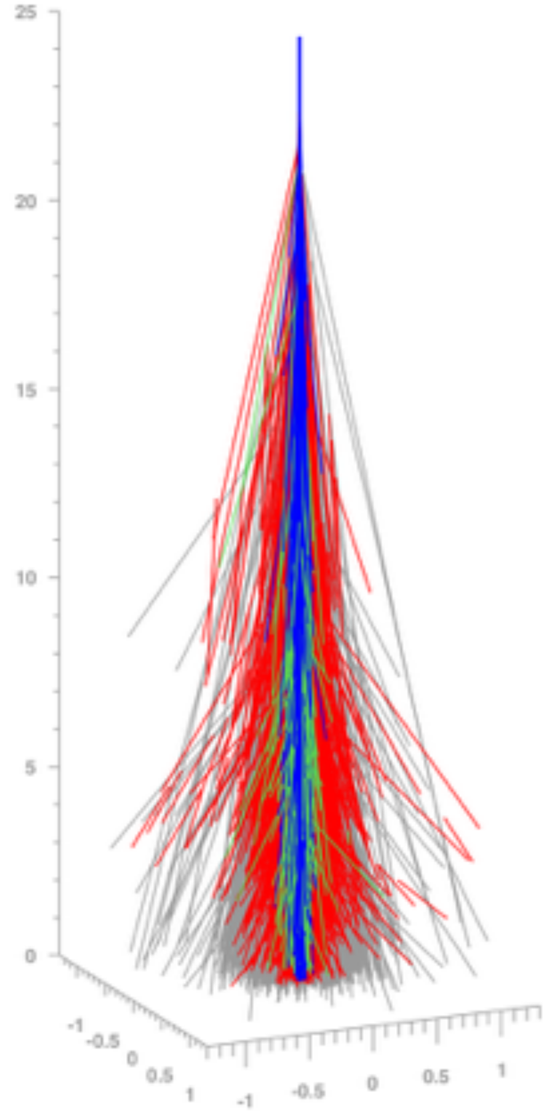
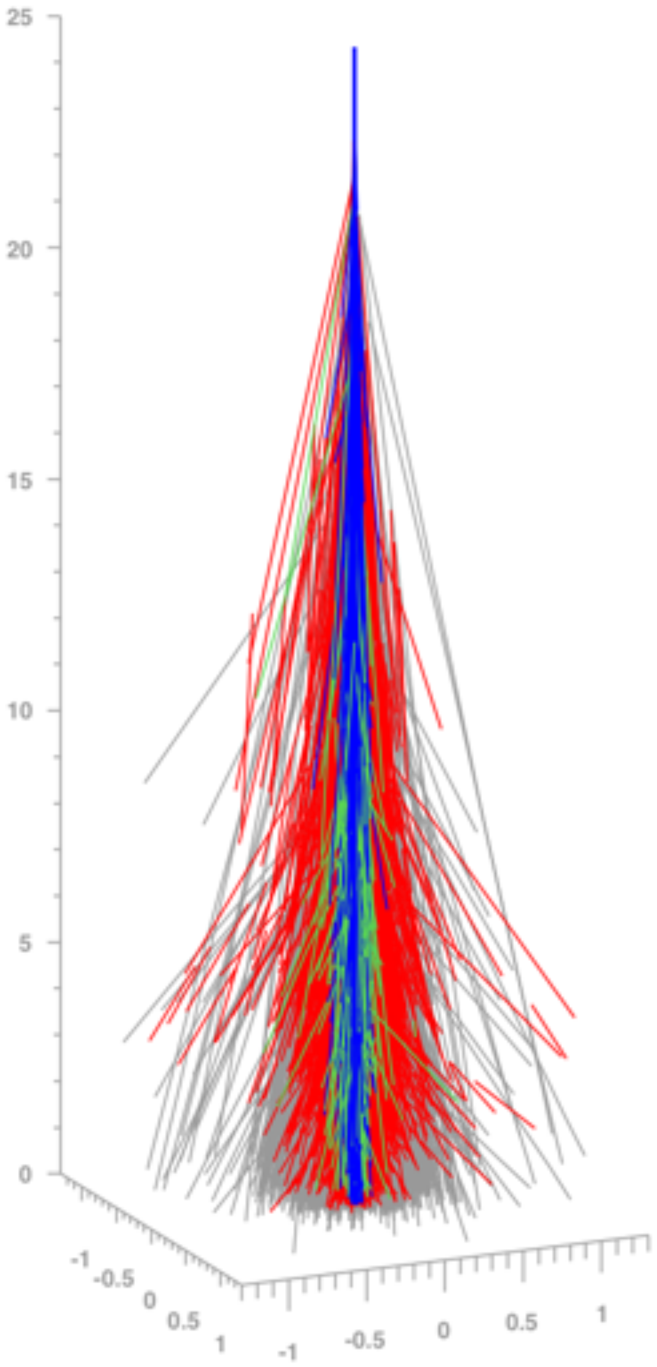
Hadronic Interactions and Shower Physics

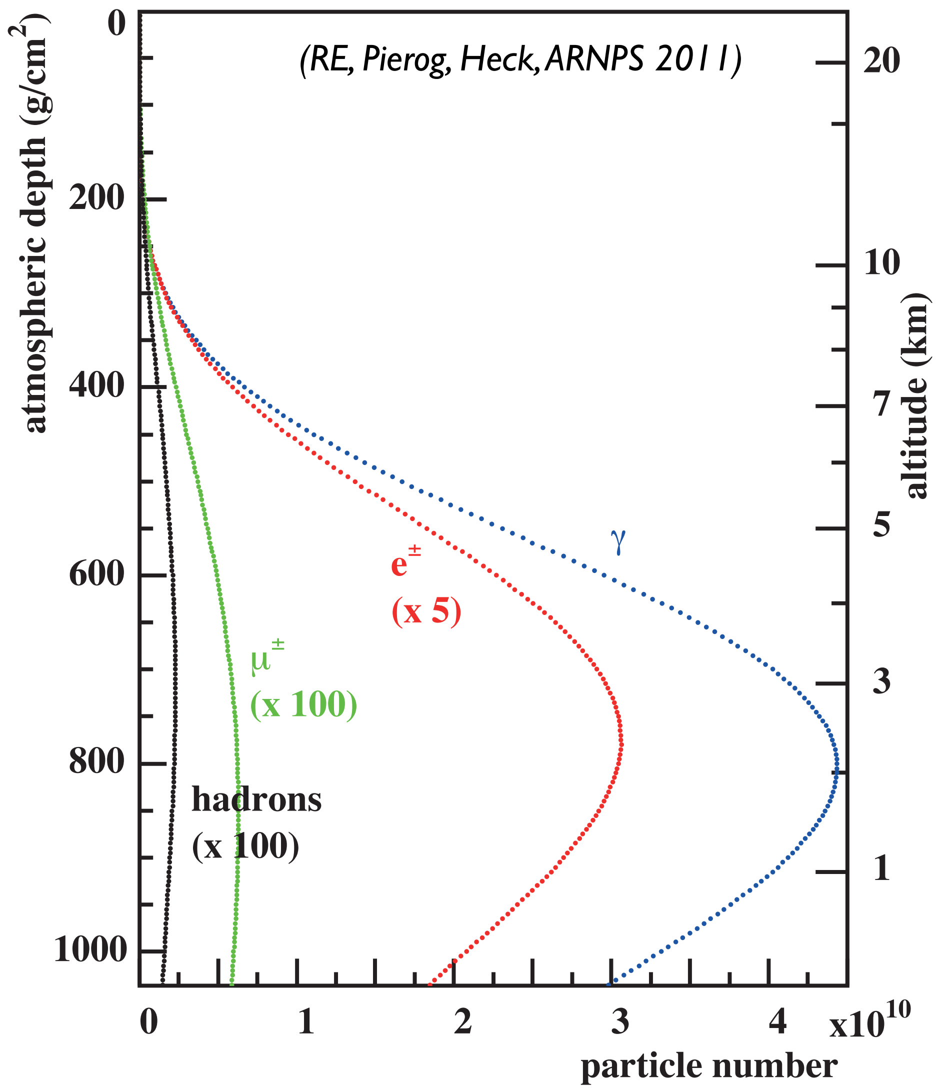


Ralph Engel

Karlsruhe Institute of Technology (KIT)

Measured components of air showers



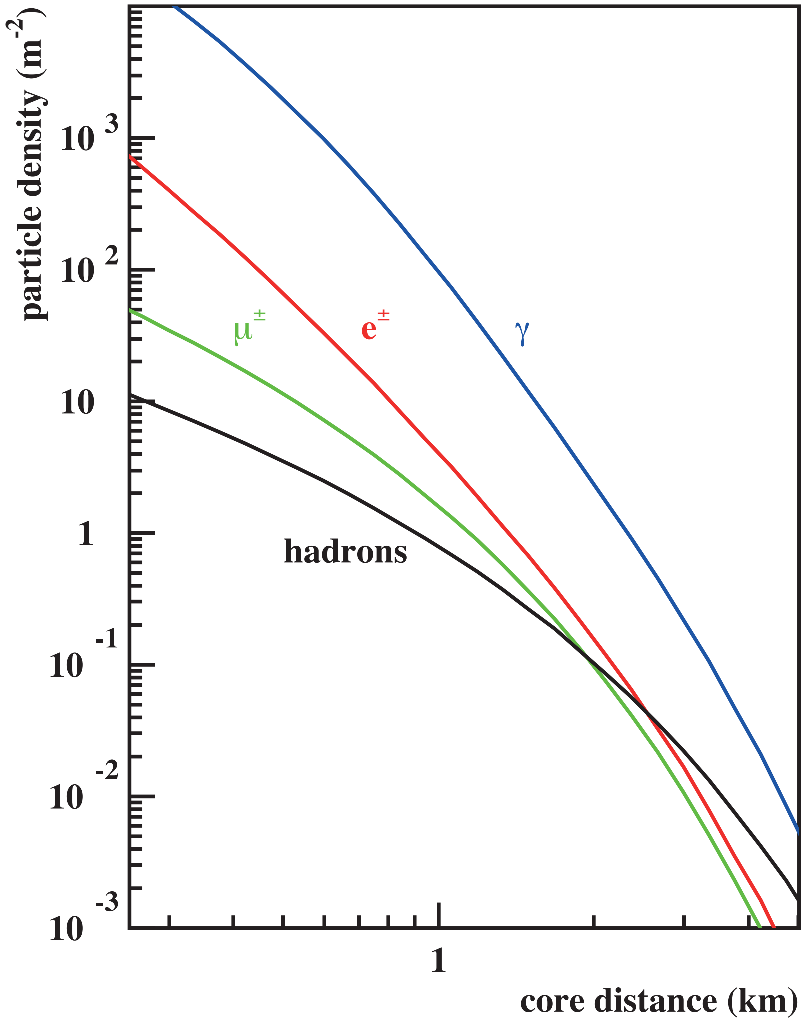


Longitudinal profile:

Cherenkov light
Fluorescence light
(bulk of particles measured)

Lateral profiles:

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



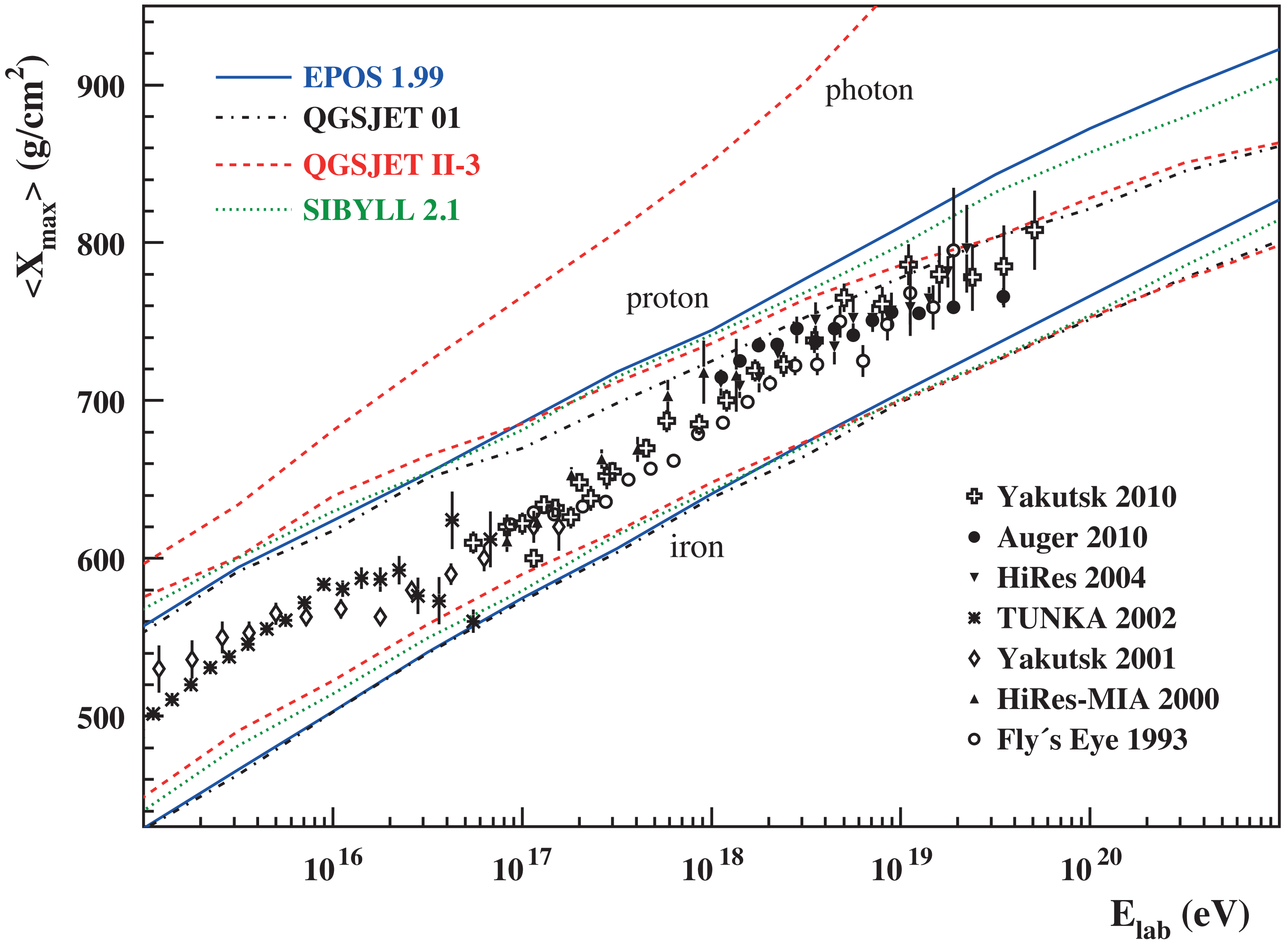
Types of energy and composition measurement

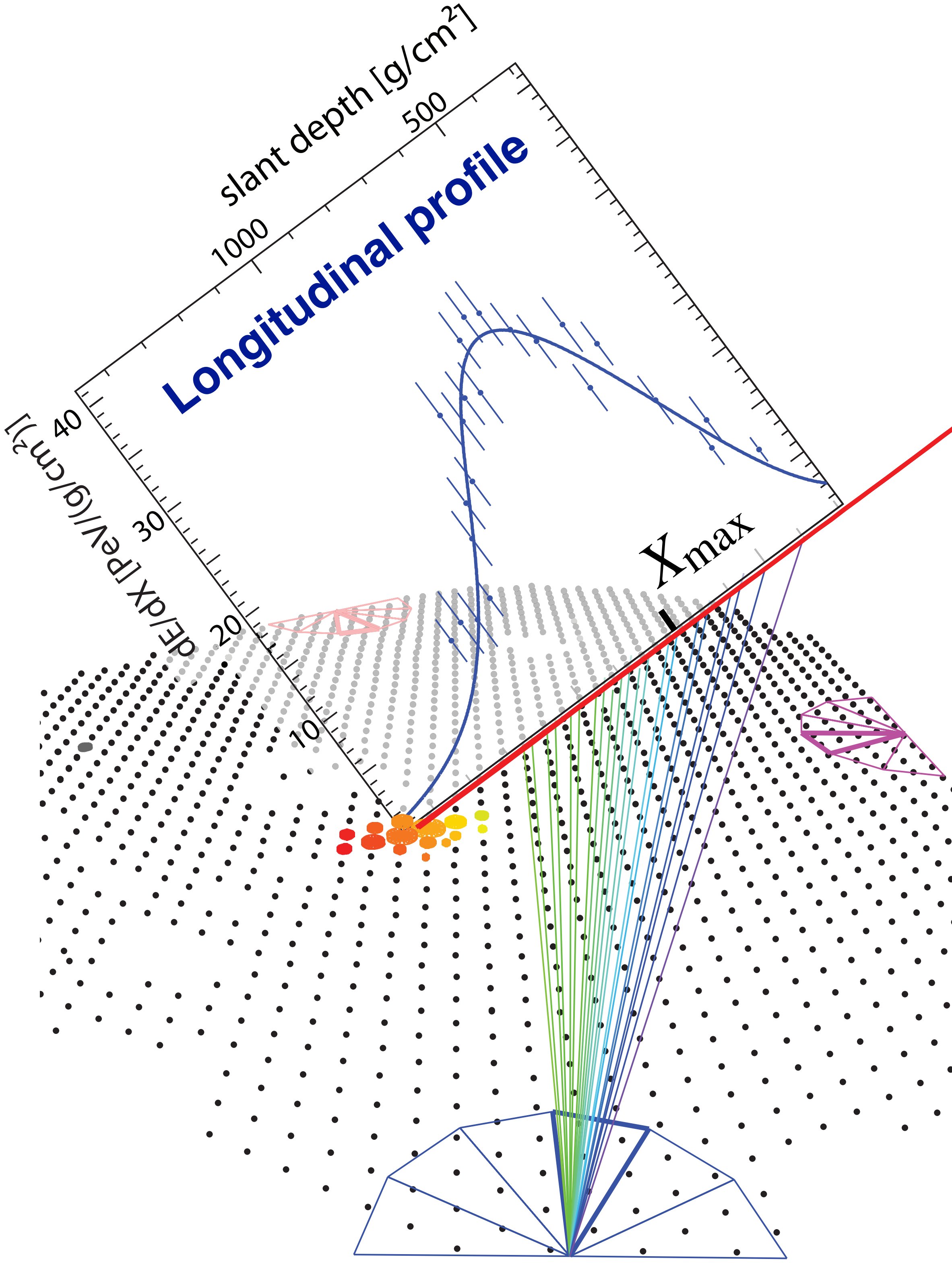
Fluorescence technique

Electrons:

$$E_{\mathrm{em}} = \int \left.\frac{\mathrm{d}E_{\mathrm{ion}}}{\mathrm{d}X}\right|_{\mathrm{meas.+extrap.}} \mathrm{d}X$$

$$E_{\mathrm{tot}} = (1 + f_{\mathrm{cor}})\, E_{\mathrm{em}}$$



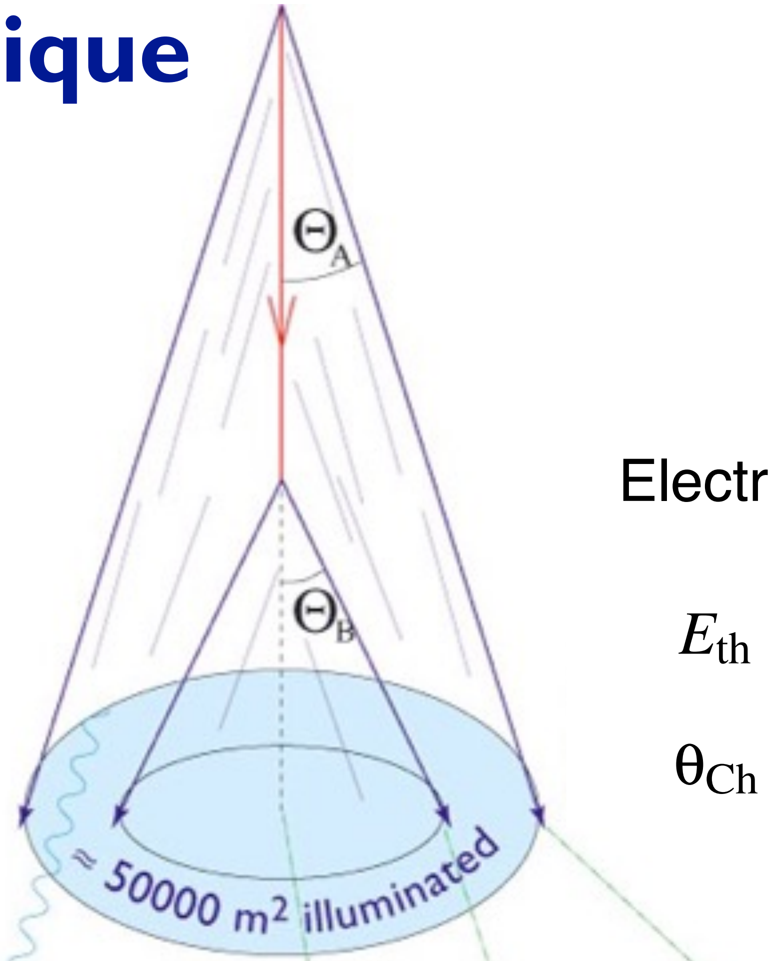


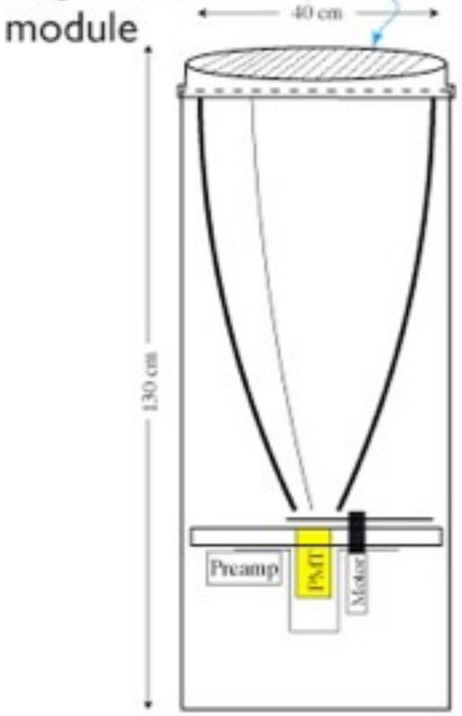
Example: event observed with Auger Observatory

(RE, Pierog, Heck, ARNPS 2011)

Non-imaging Cherenkov technique

Example: Tunka

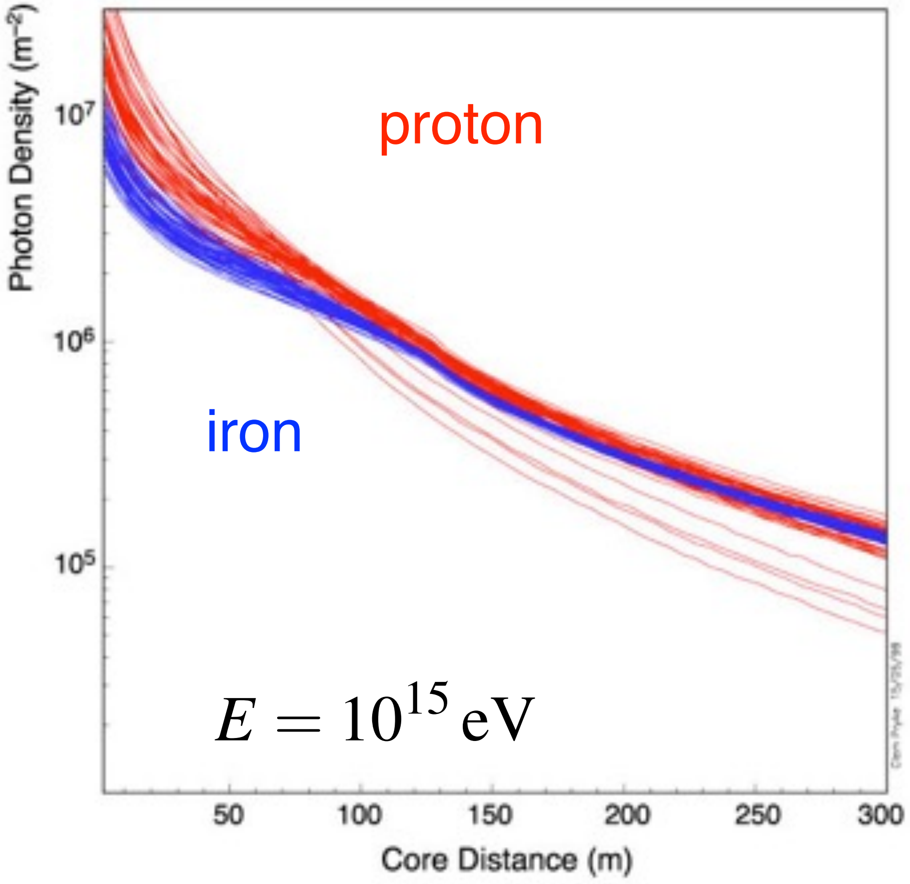




Electrons:

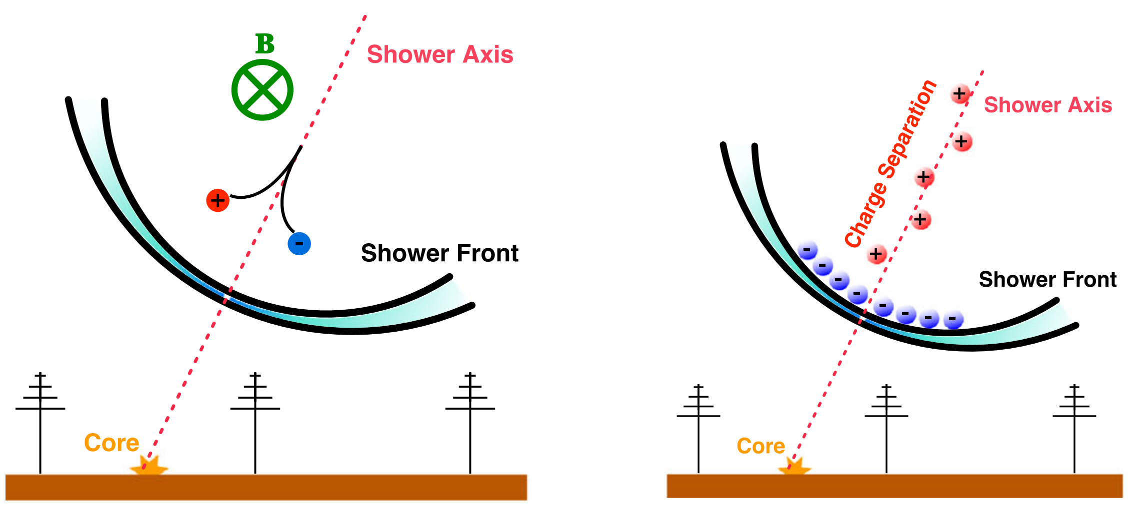
$$E_{\mathrm{th}} \approx 21\,\mathrm{MeV}$$

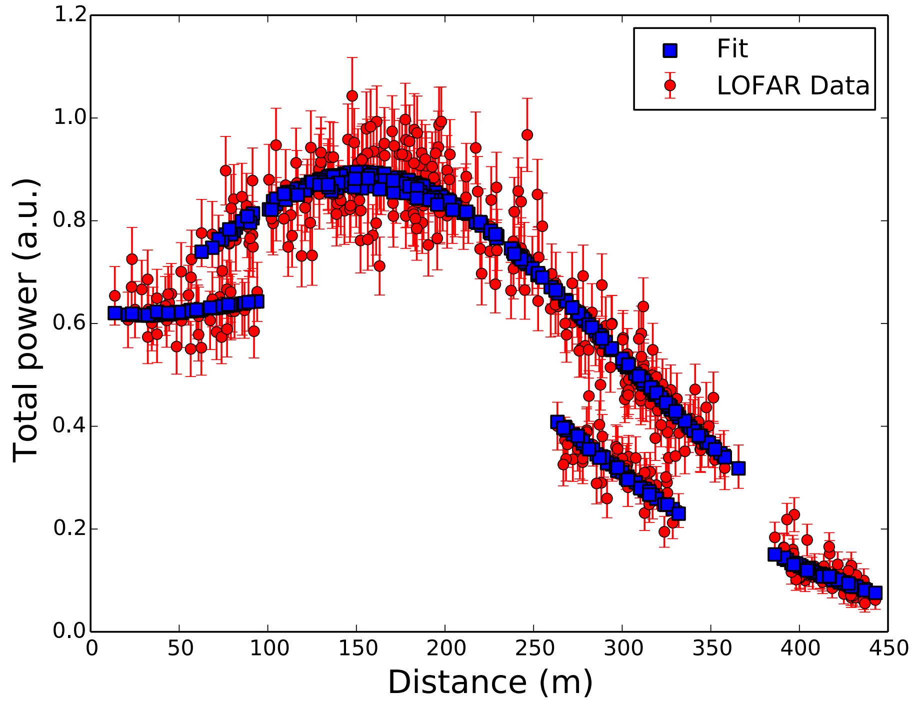
$$\theta_{\mathrm{Ch}} \approx 1.4^\circ$$



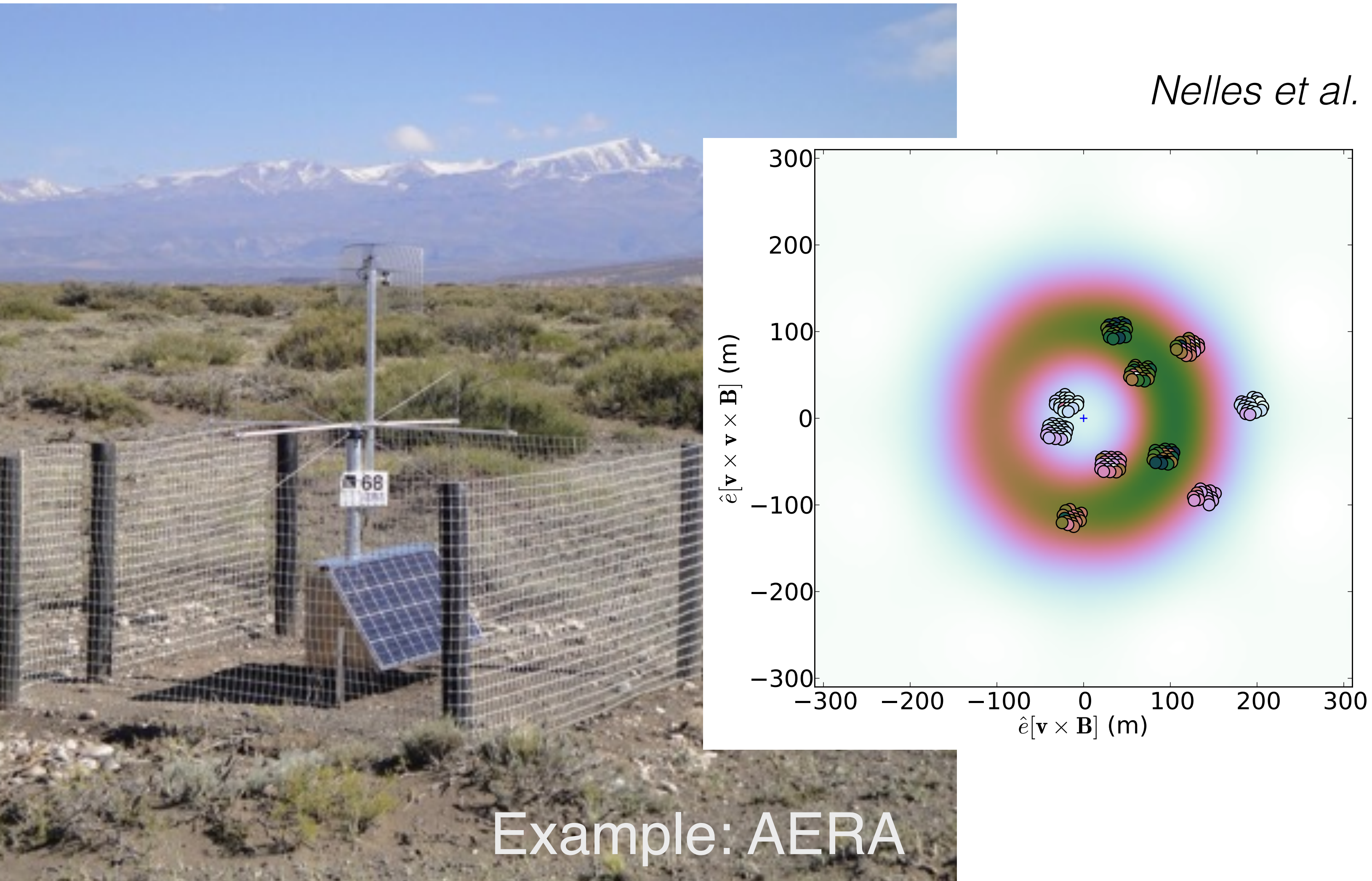
Radio signal measurement

Electrons/positrons

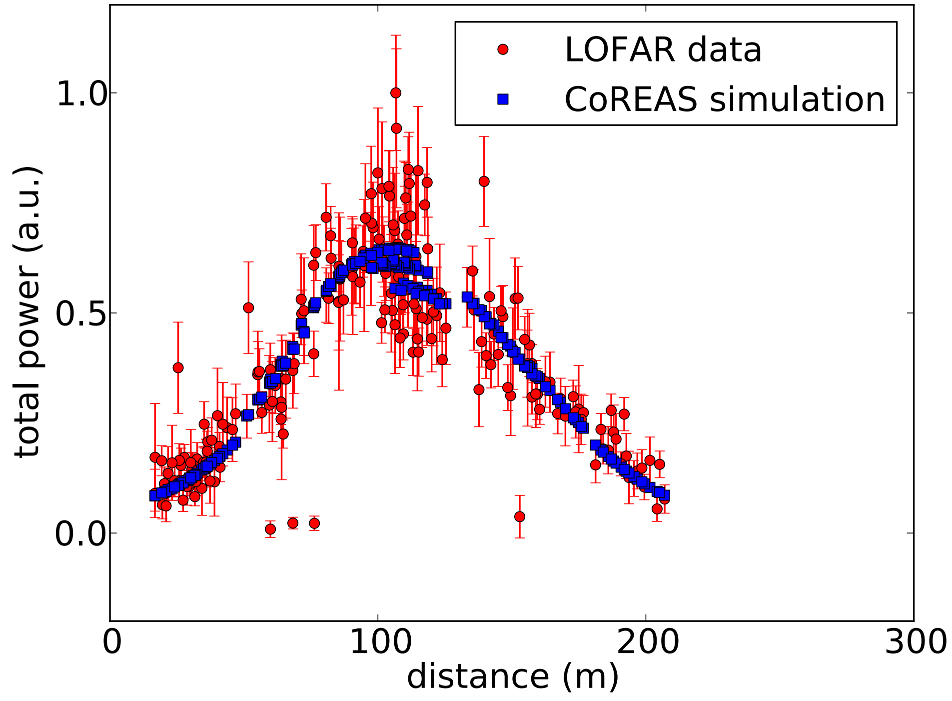




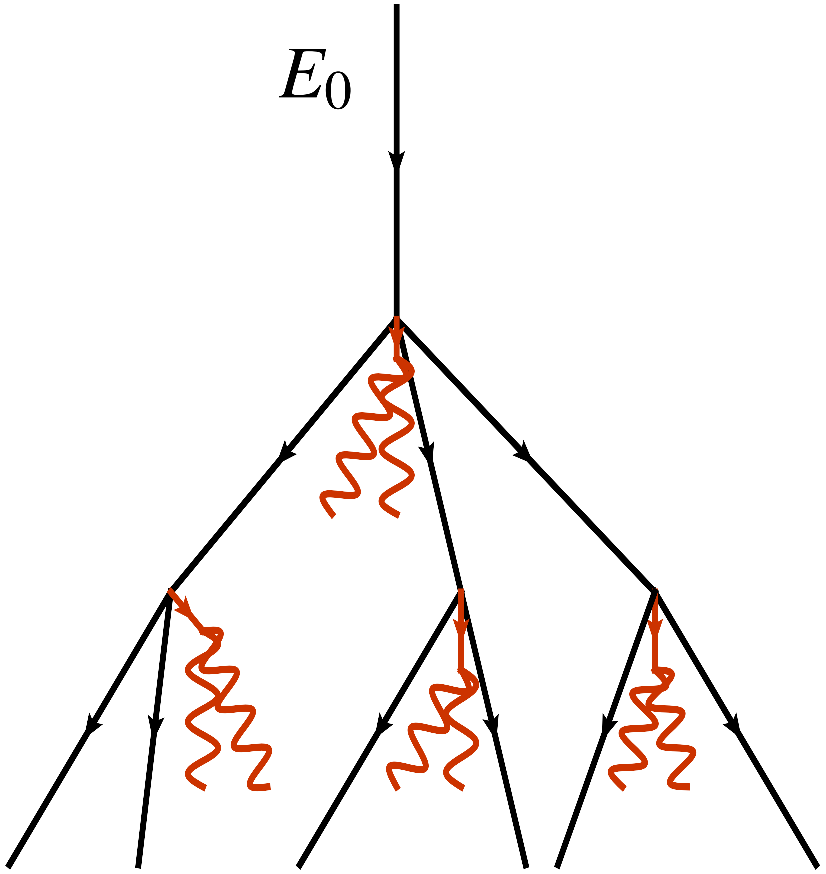
Nelles et al. (LOFAR), ECRS 2014



Example: AERA



Electromagnetic and hadronic energy budgets



Hadronic energy

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

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

o
o
o
o

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

Electromagnetic energy

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

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

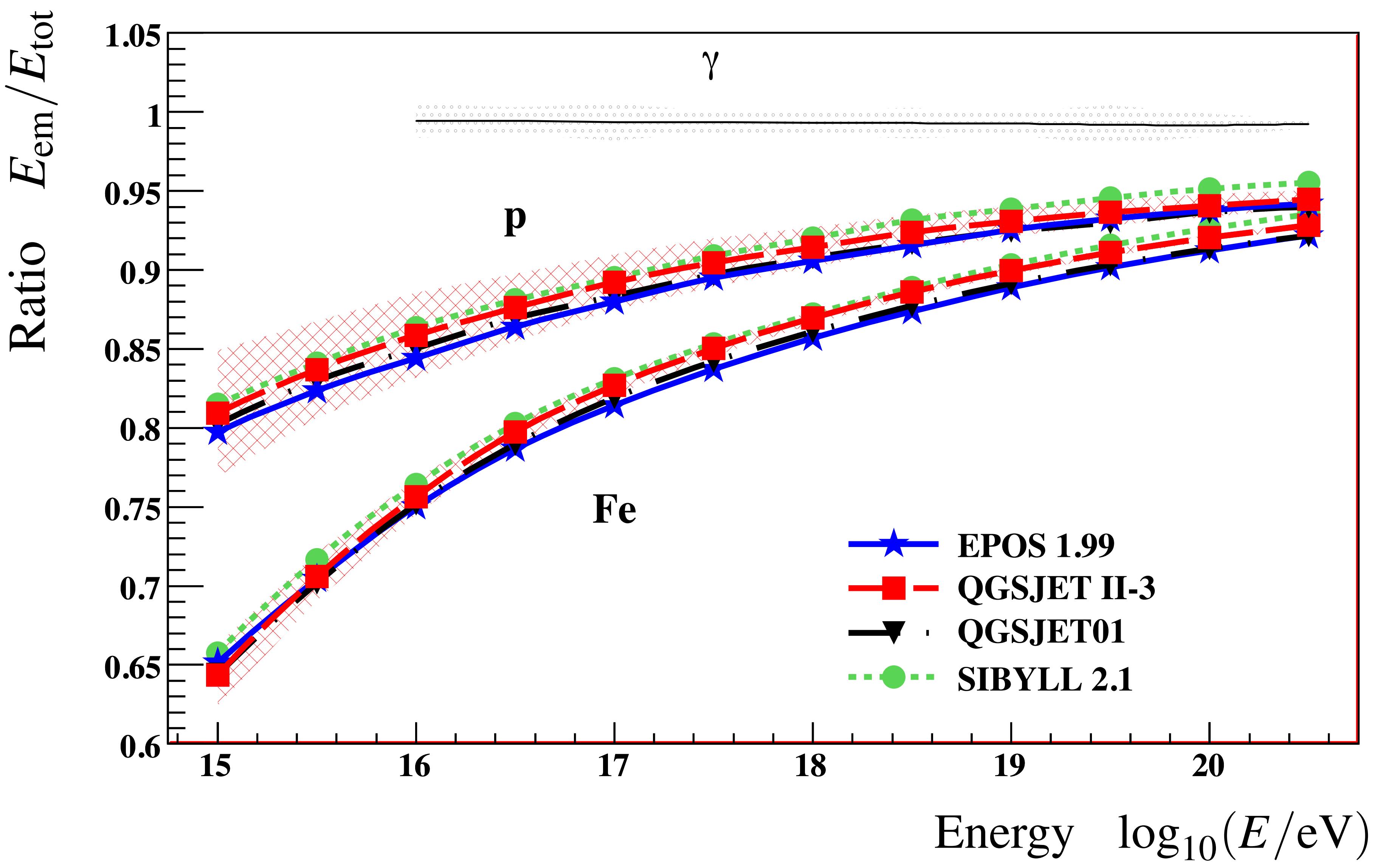
o
o
o
o

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

After n generations ...

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

Correction needed to obtain total energy



Ratio of em. to total shower energy

Detailed Monte Carlo simulation with CONEX

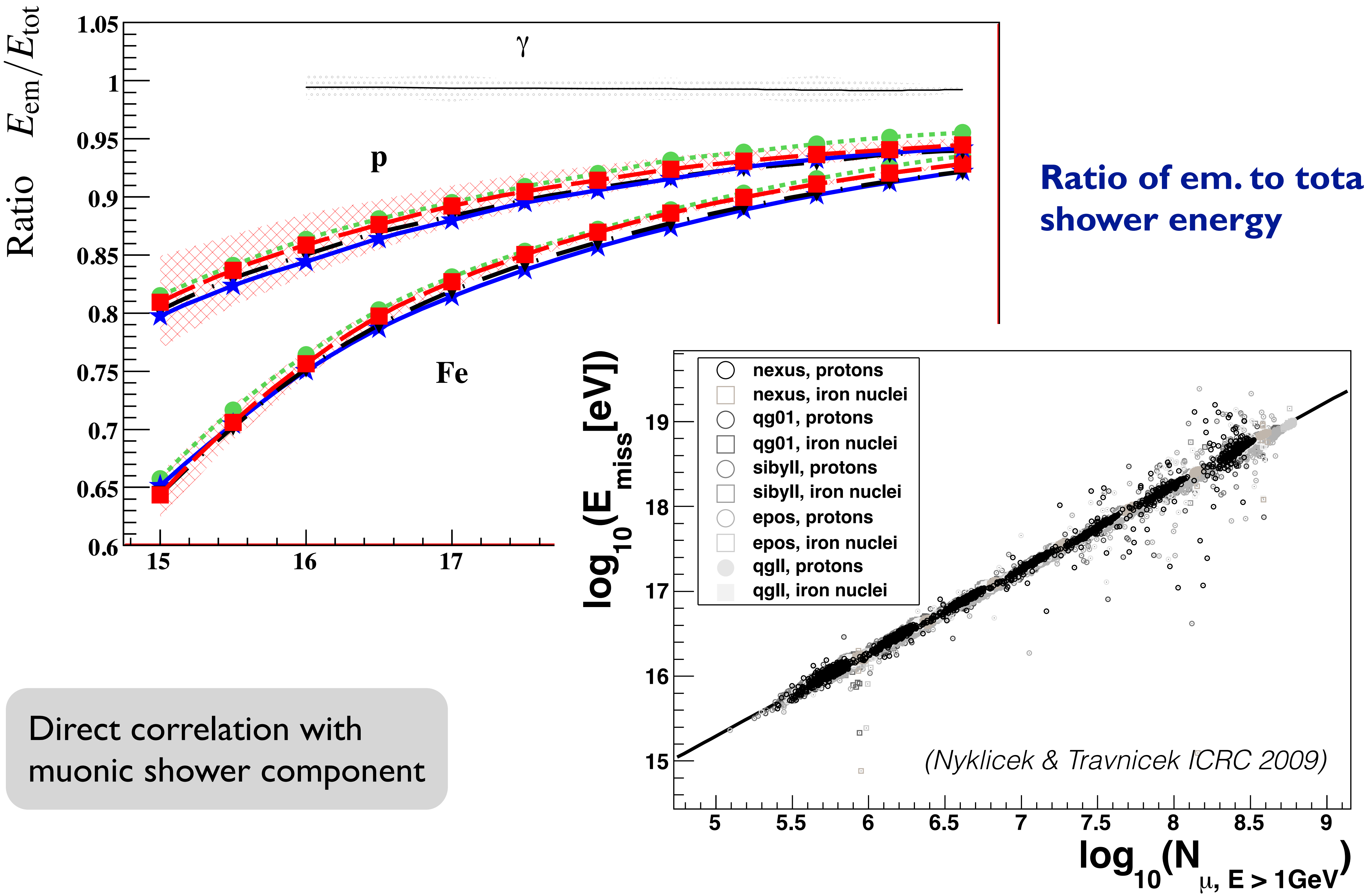
$(n_g = 5-6)$

$(n_g = 10-12)$

Large composition dependence at lower energies

(RE, Pierog, Heck, ARNPS 2011)

Correlation with number of muons

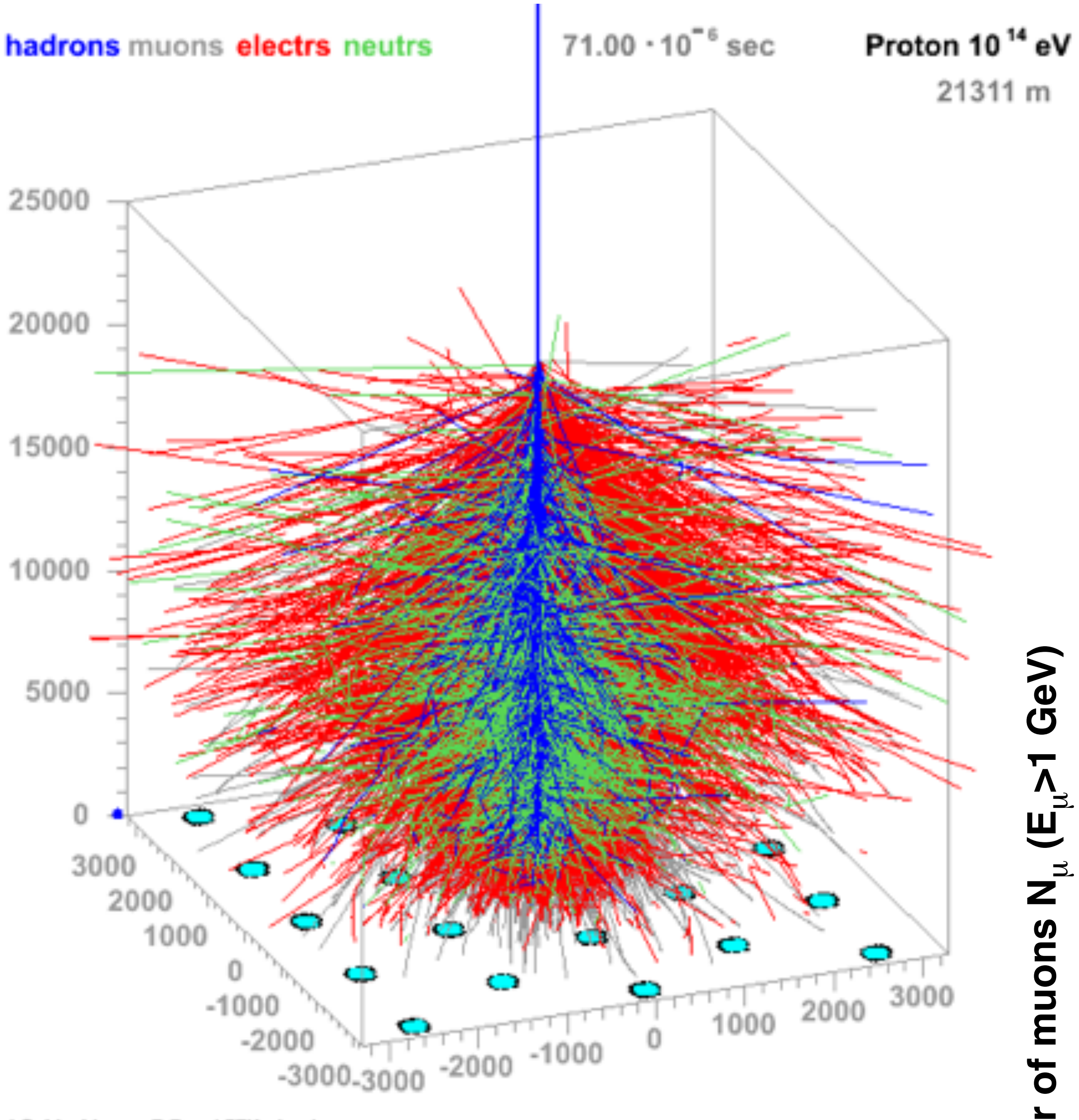


(Nyklicek & Travnicek ICRC 2009)

Ratio of em. to total shower energy

Direct correlation with muonic shower component

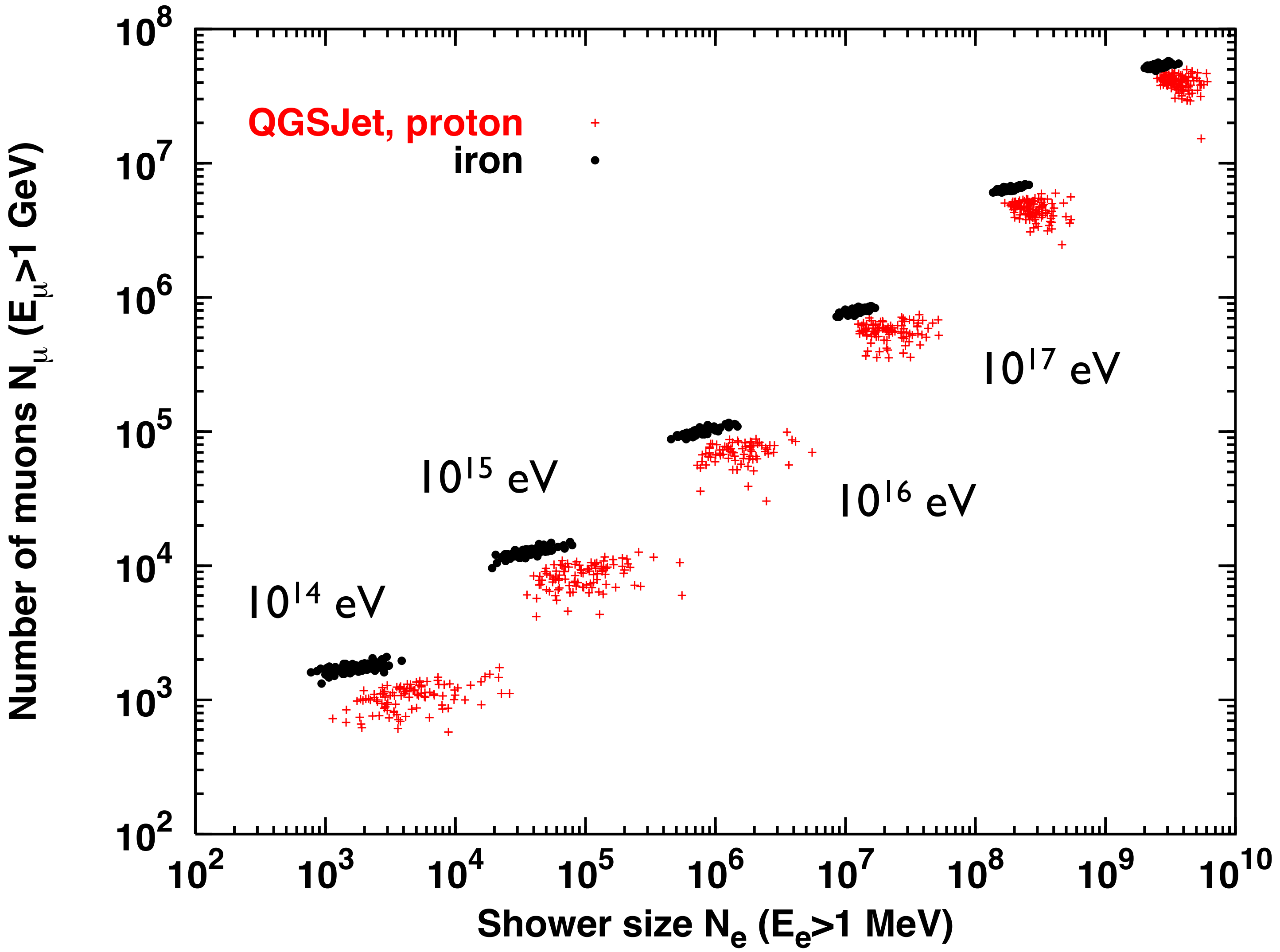
Electron-muon shower size correlation



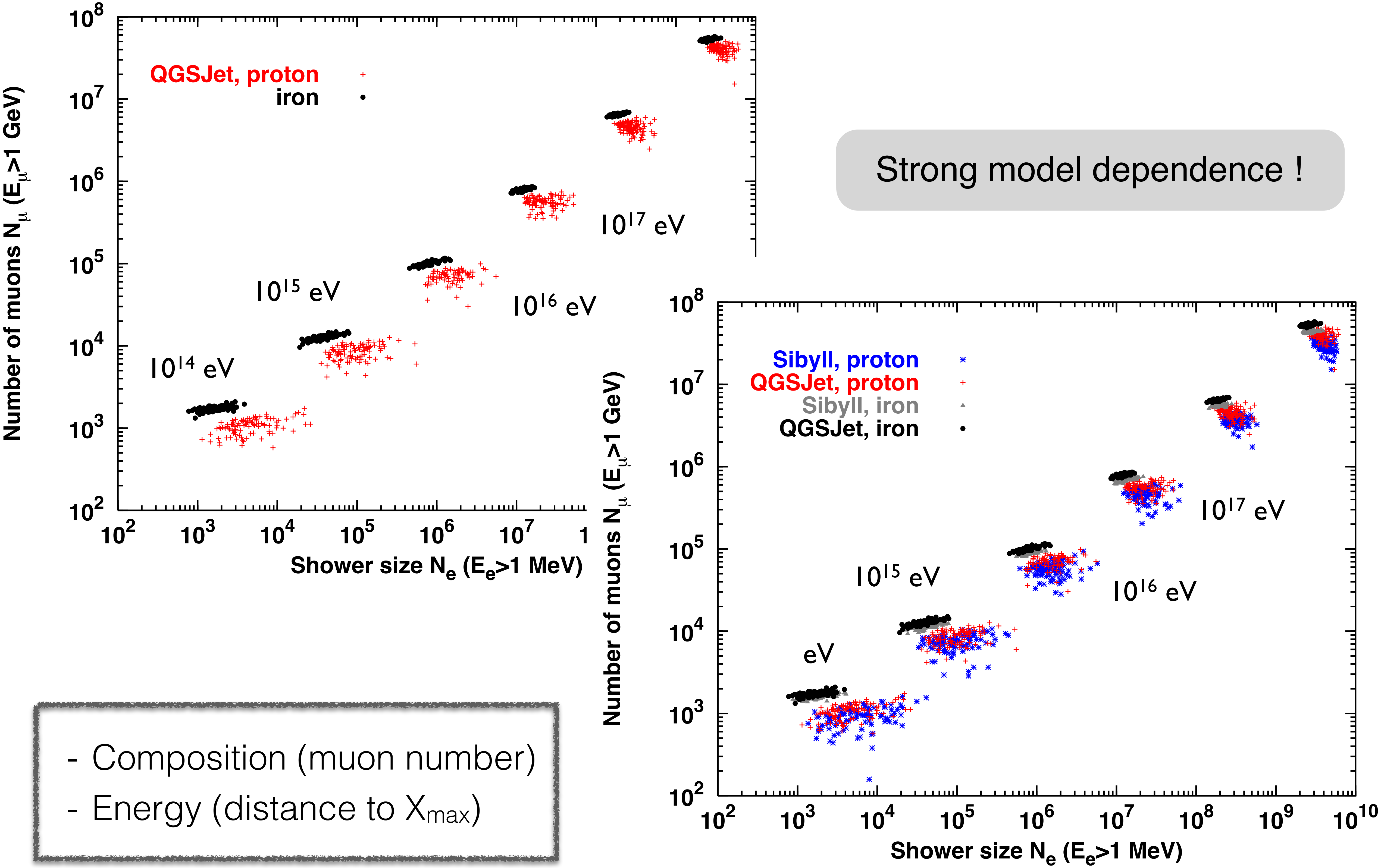
J.Oehlschlaeger,R.Engel,FZKarlsruhe

Example: KASCADE-Grande

Combined energy-composition analysis



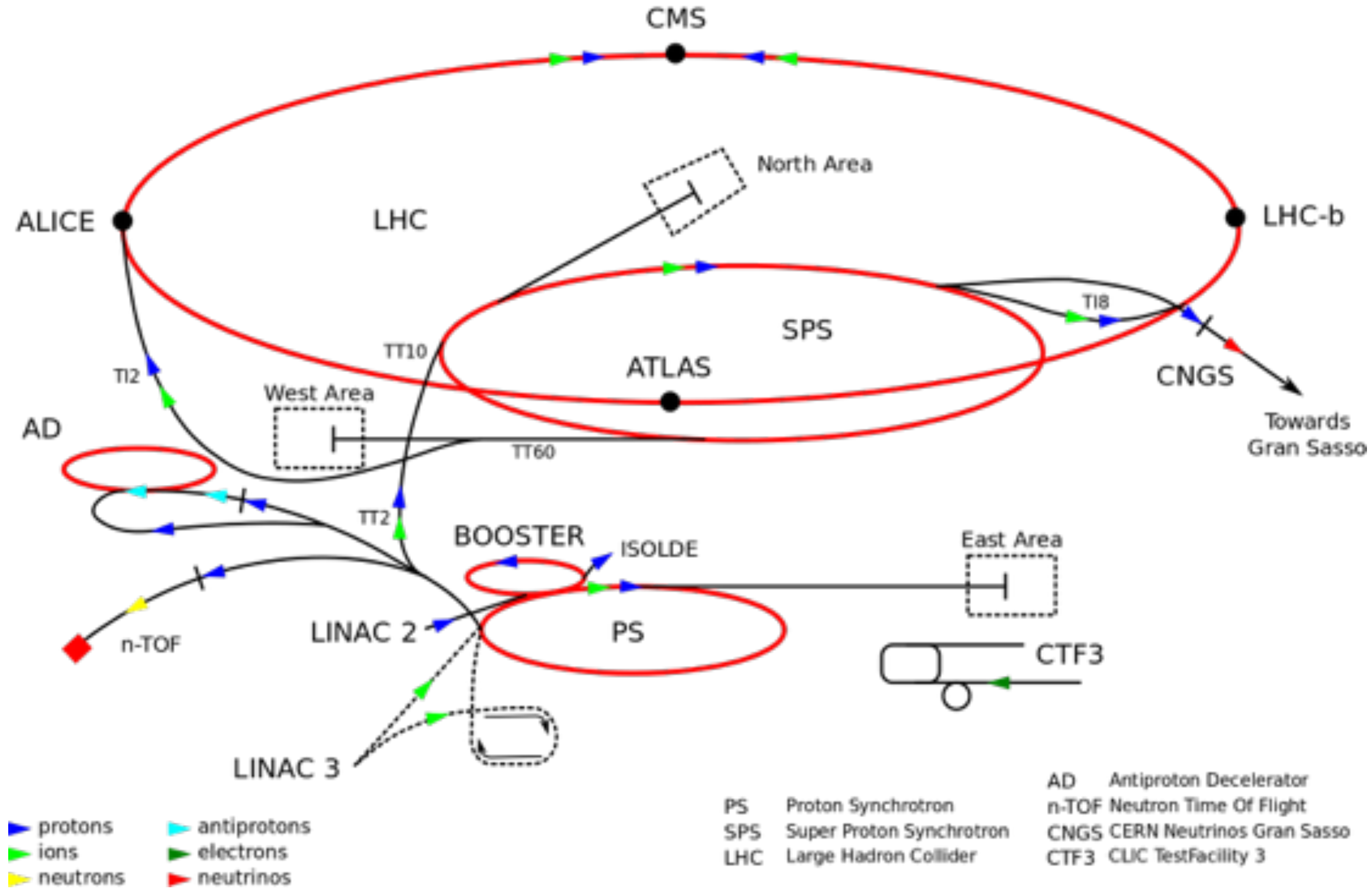
Model dependence of predictions



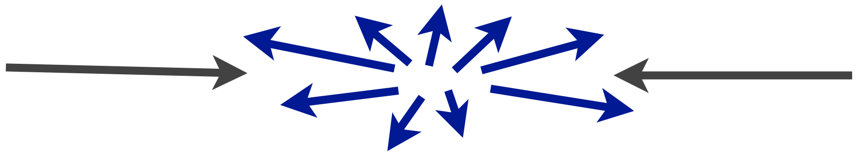
Strong model dependence !

- Composition (muon number)
- Energy (distance to X_{max})

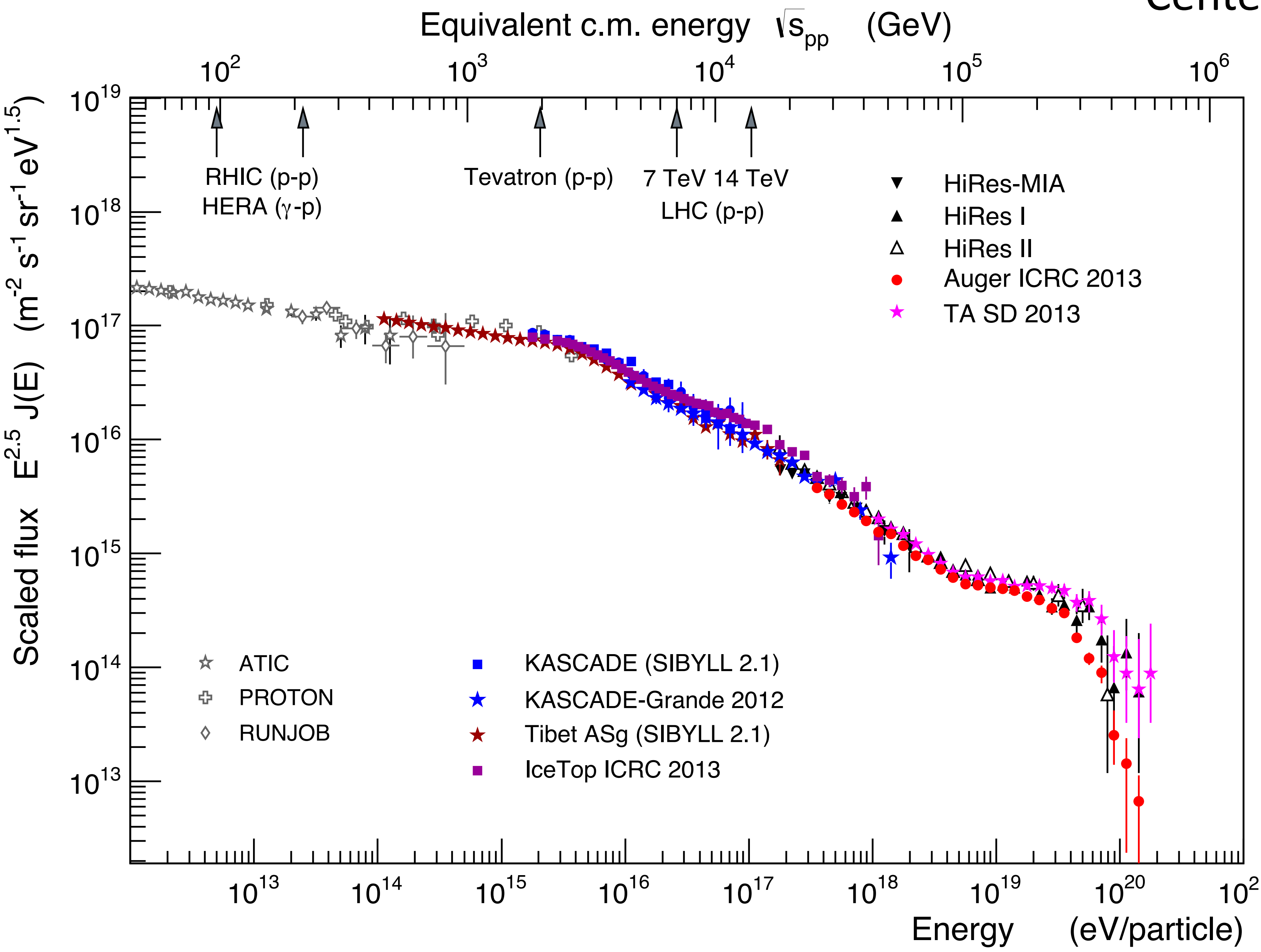
Accelerator data

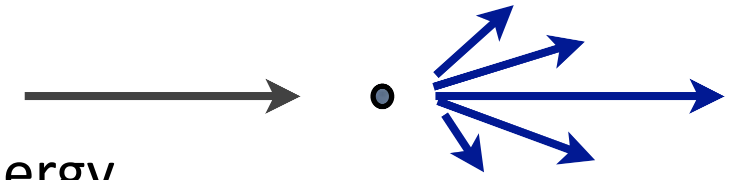


Cosmic ray flux and interaction energies



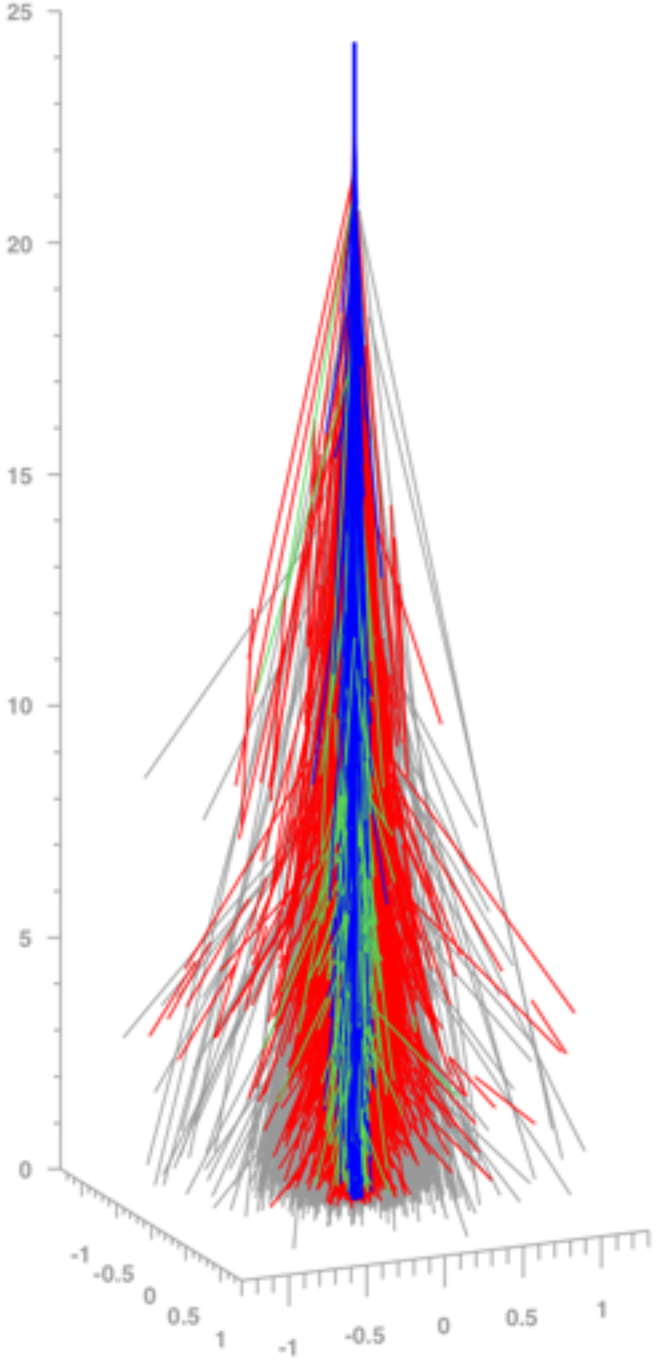
Center-of-mass energy



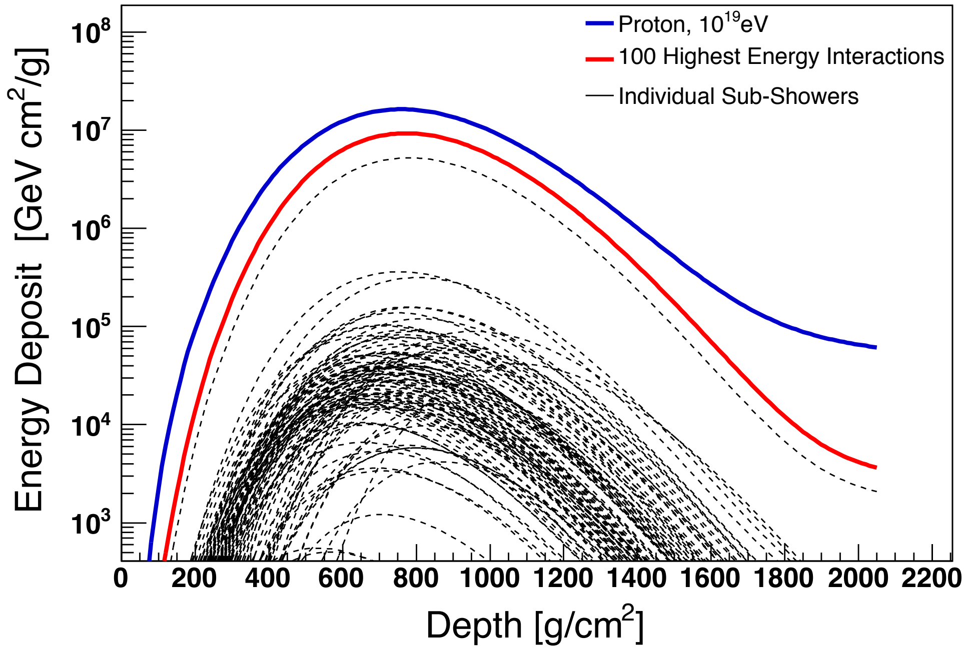


Laboratory energy

Importance of different interaction energies



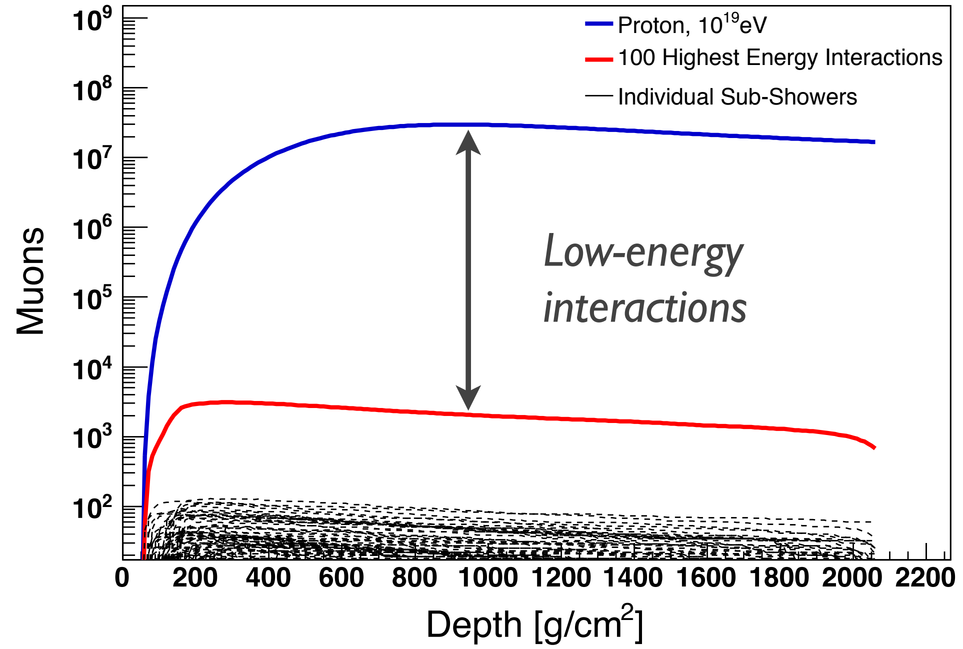
Electrons



Shower particles produced in 100 interactions of highest energy

Electrons/photons:
high-energy interactions

Muons



(Ulrich, APS 2012)

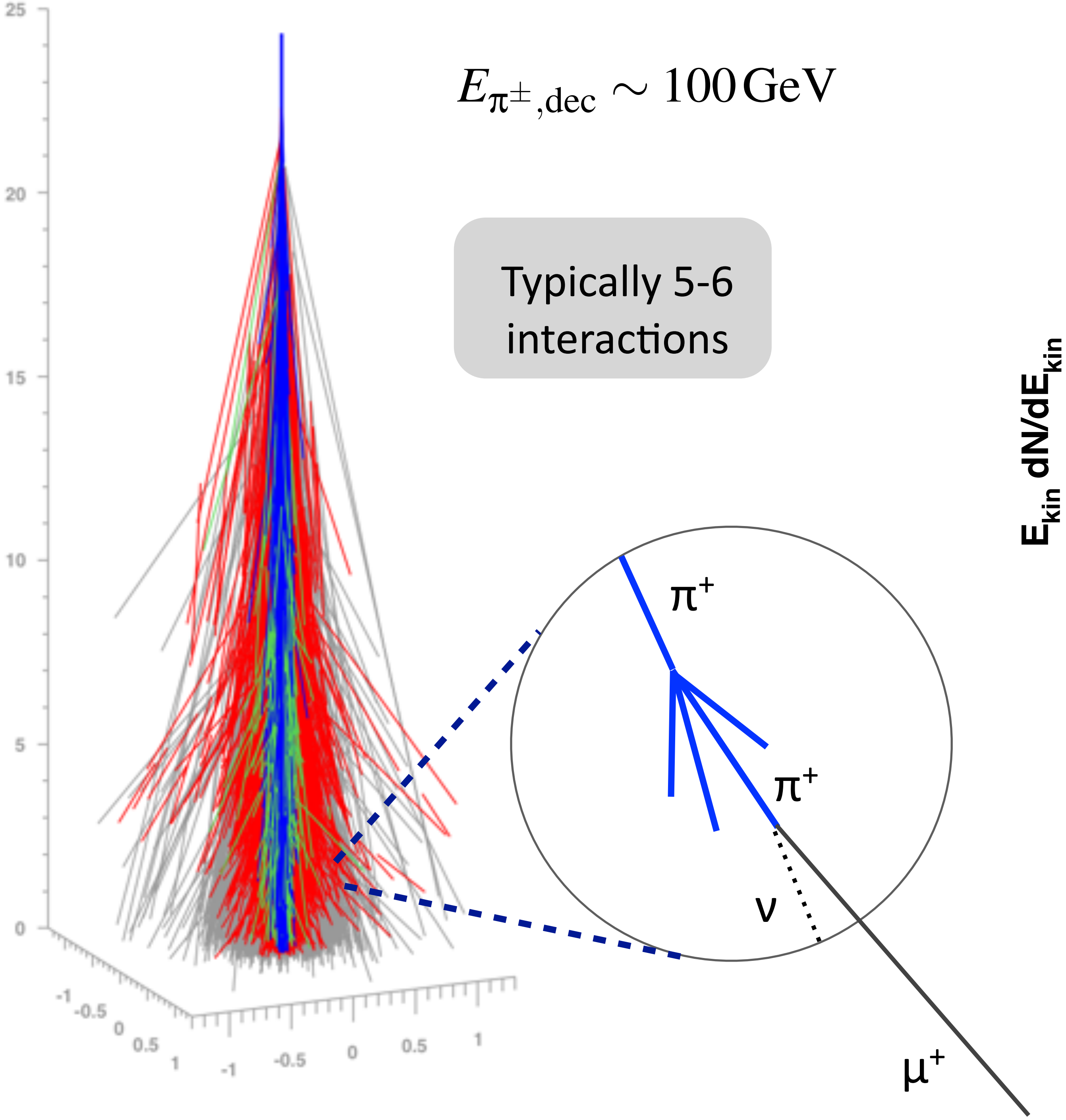
Muons/hadrons:
low-energy interactions

Muons: majority produced in low energy interactions (30-200 GeV lab.)

Muon production at large lateral distance

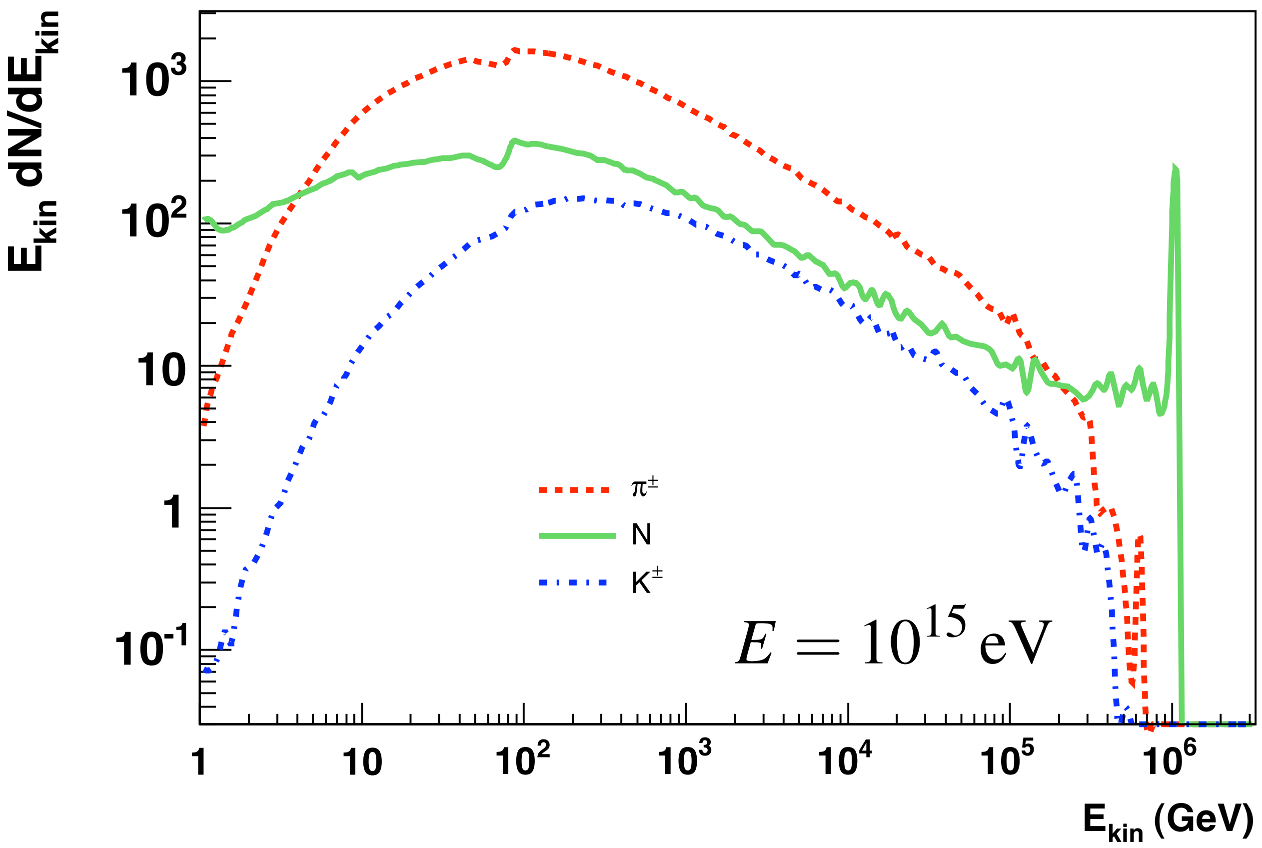
$E_{\pi^\pm,\mathrm{dec}} \sim 100\,\mathrm{GeV}$

Typically 5-6 interactions



Energy distribution of last interaction that produced a detected muon

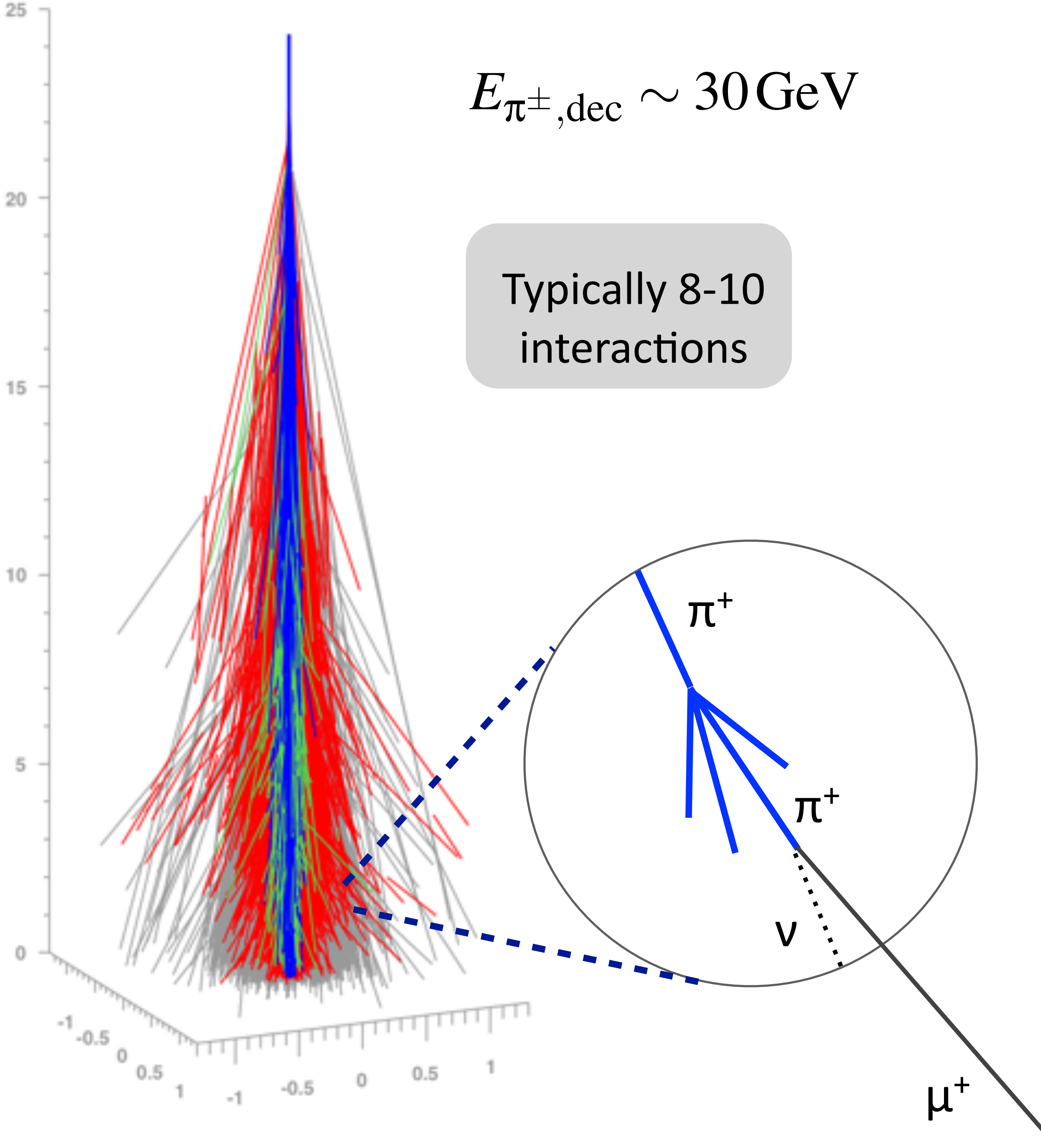
Example: KASCADE, proton shower



Muon observed 40 – 200 m from core

(Meurer et al. Czech. J. Phys. 2006)

Muon production at large lateral distance

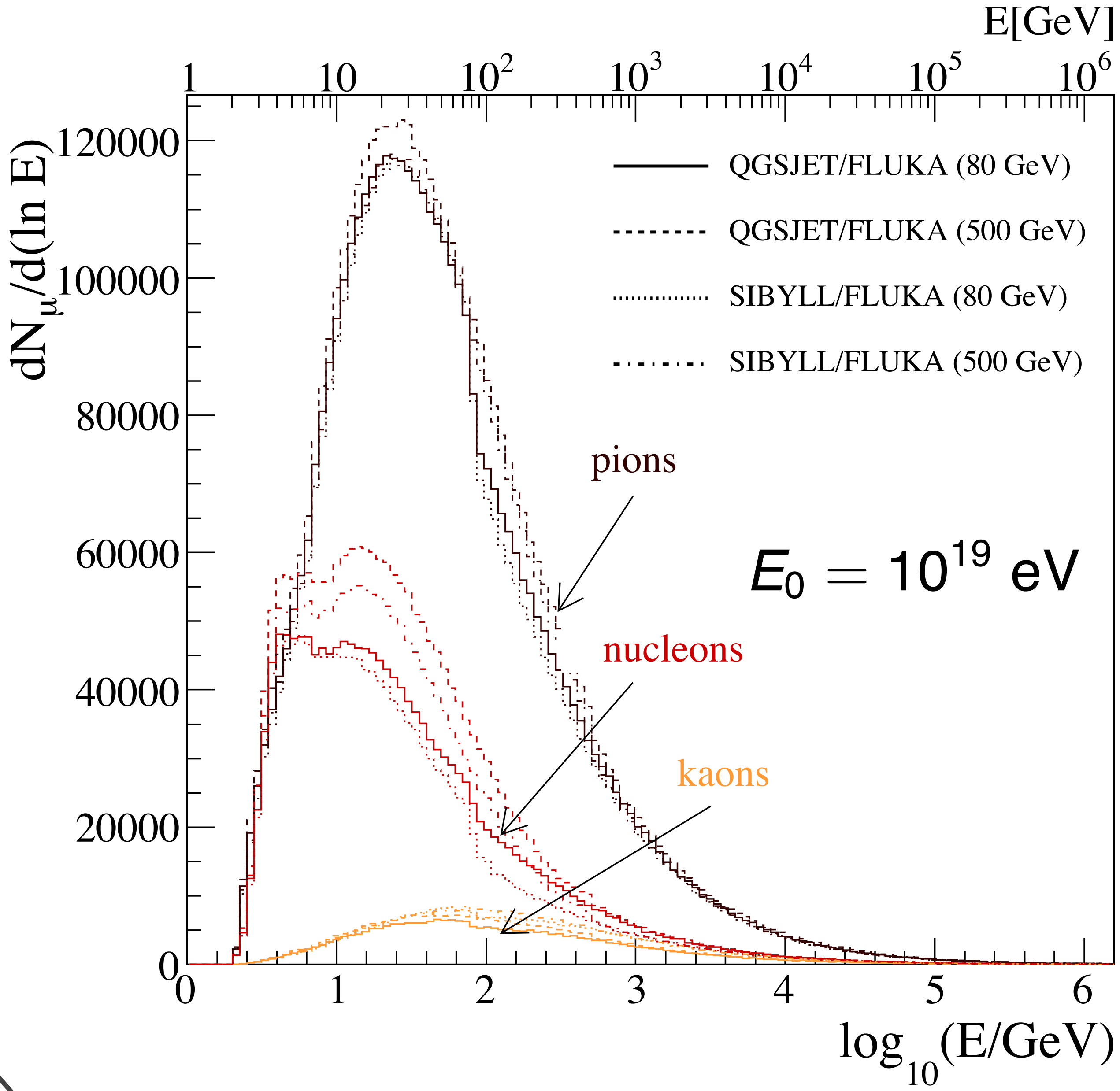


$$E_{\pi^\pm,\mathrm{dec}} \sim 30\,\mathrm{GeV}$$

Typically 8-10 interactions

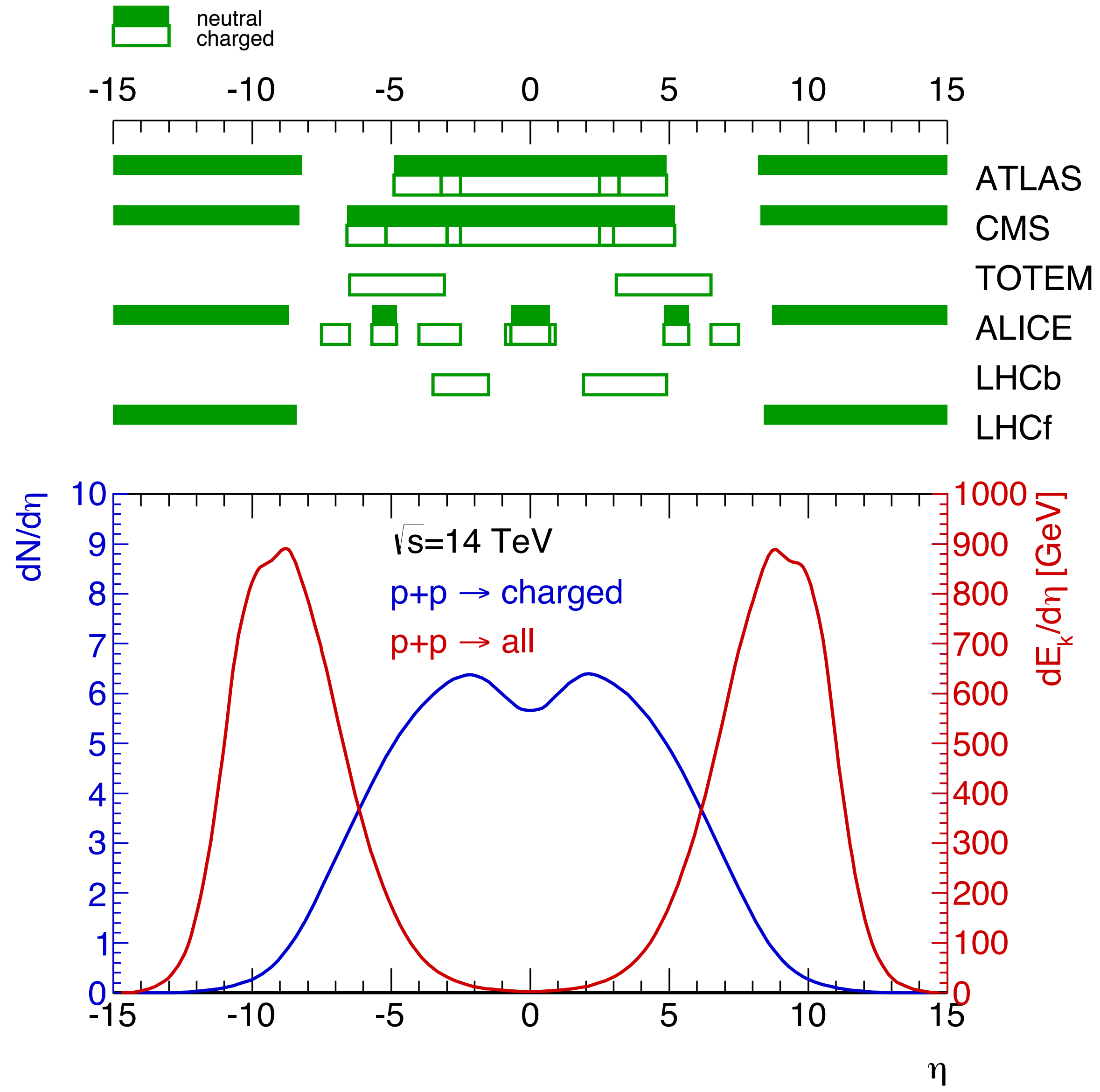
Muon observed at 1000 m from core

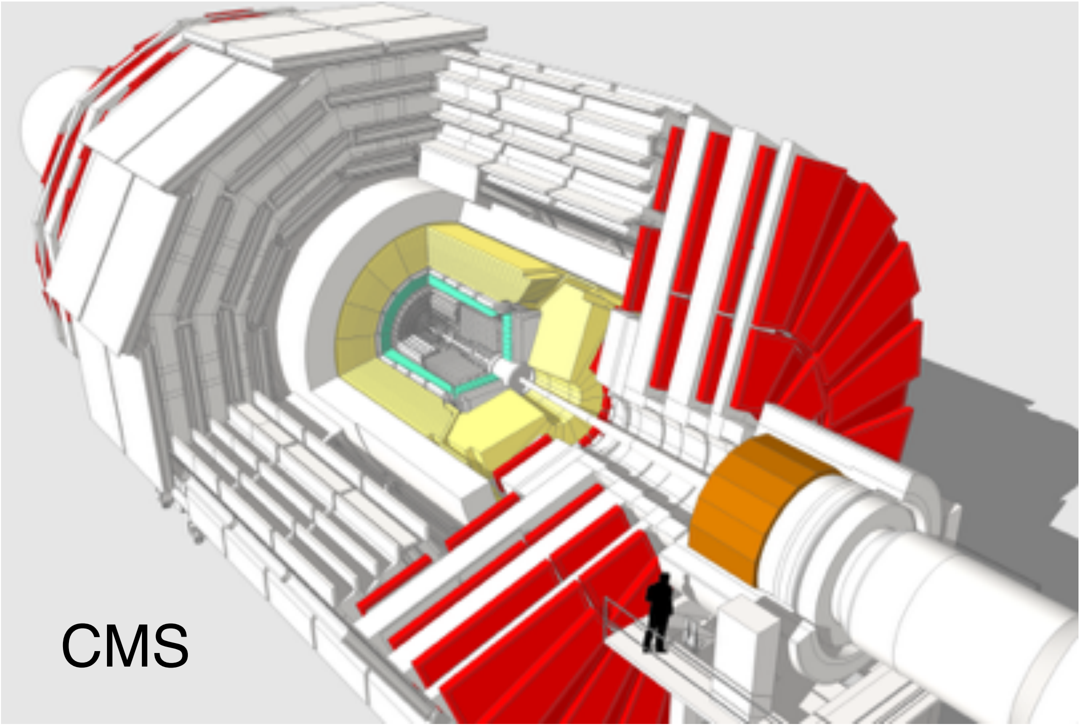
Energy distribution of last interaction that produced a detected muon

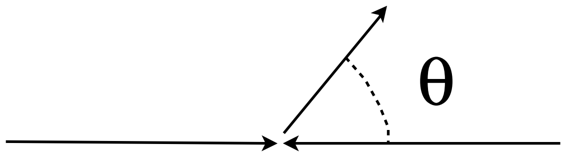


(Maris et al. ICRC 2009)

Phase space coverage at colliders







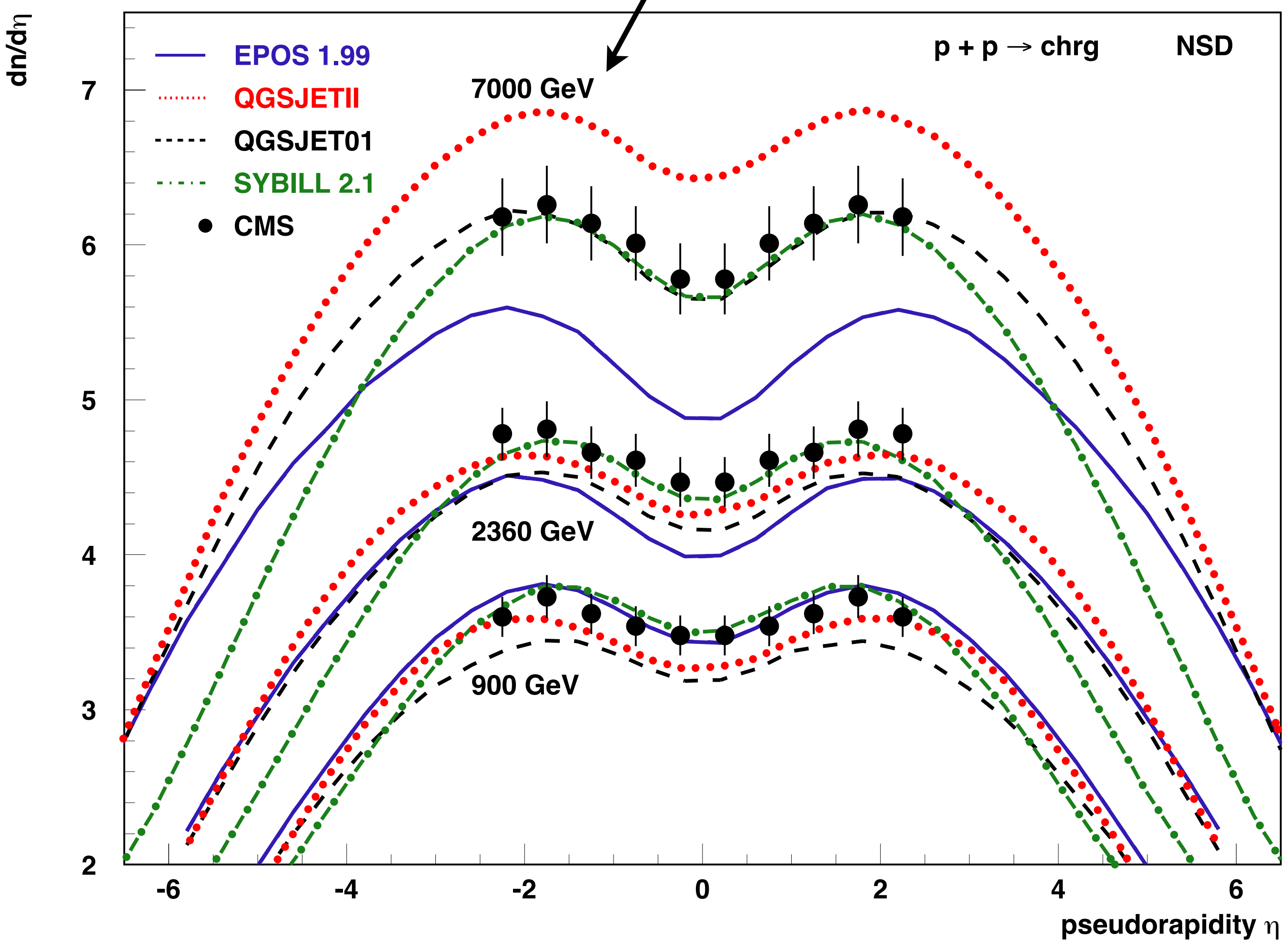
$$\eta = -\ln\tan\frac{\theta}{2}$$

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

(Salek et al., 2014)

Charged particle distribution in pseudorapidity

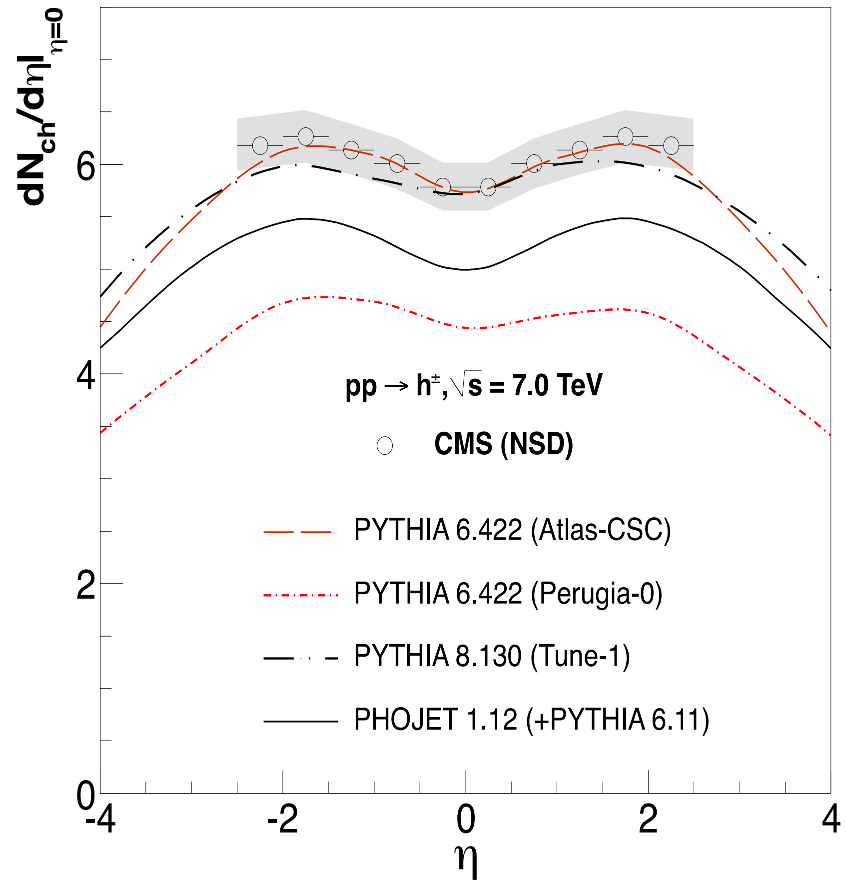
Protons: E_{lab} = 3 x 10^{16} eV



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

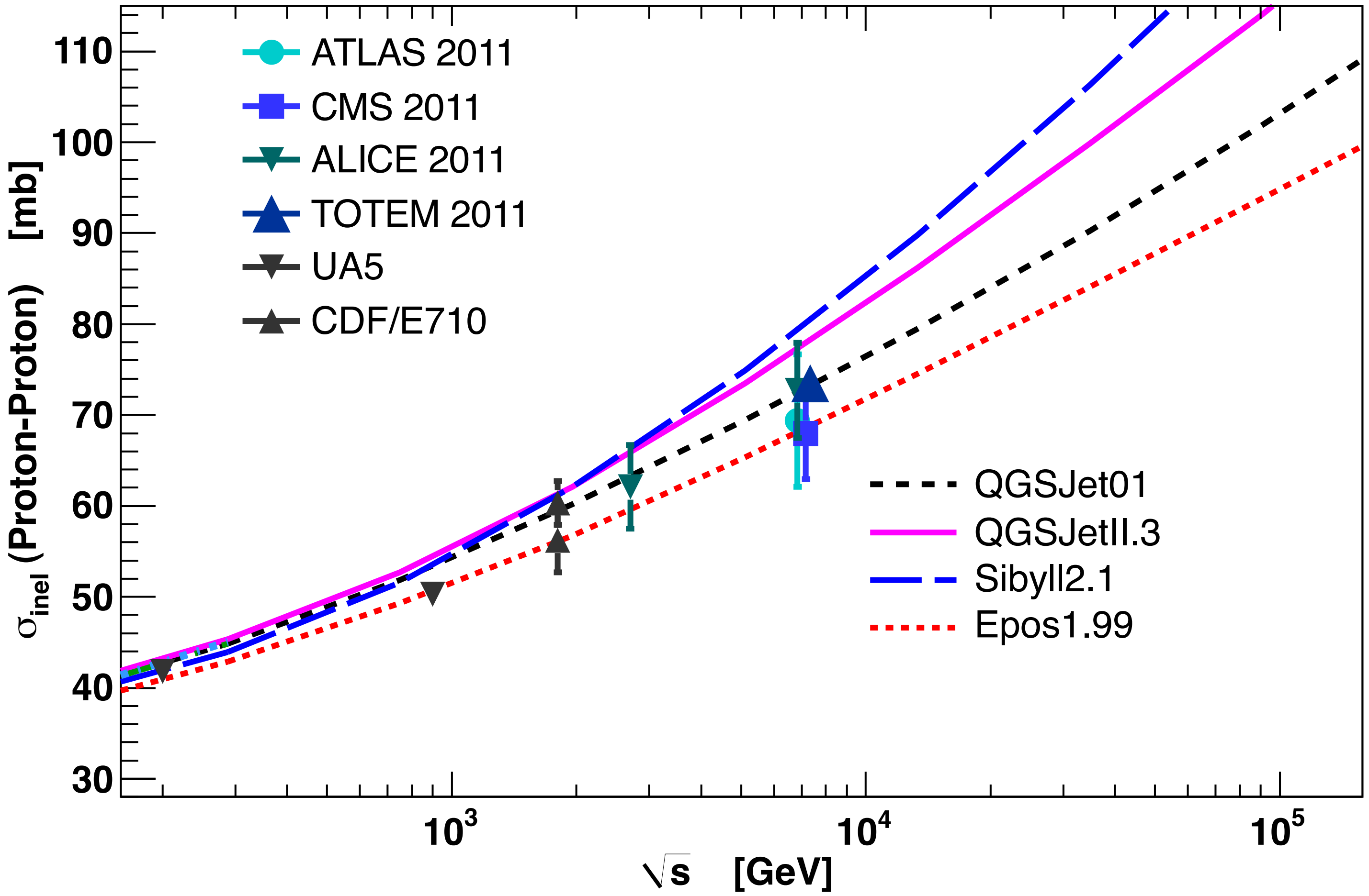
Detailed LHC comparison

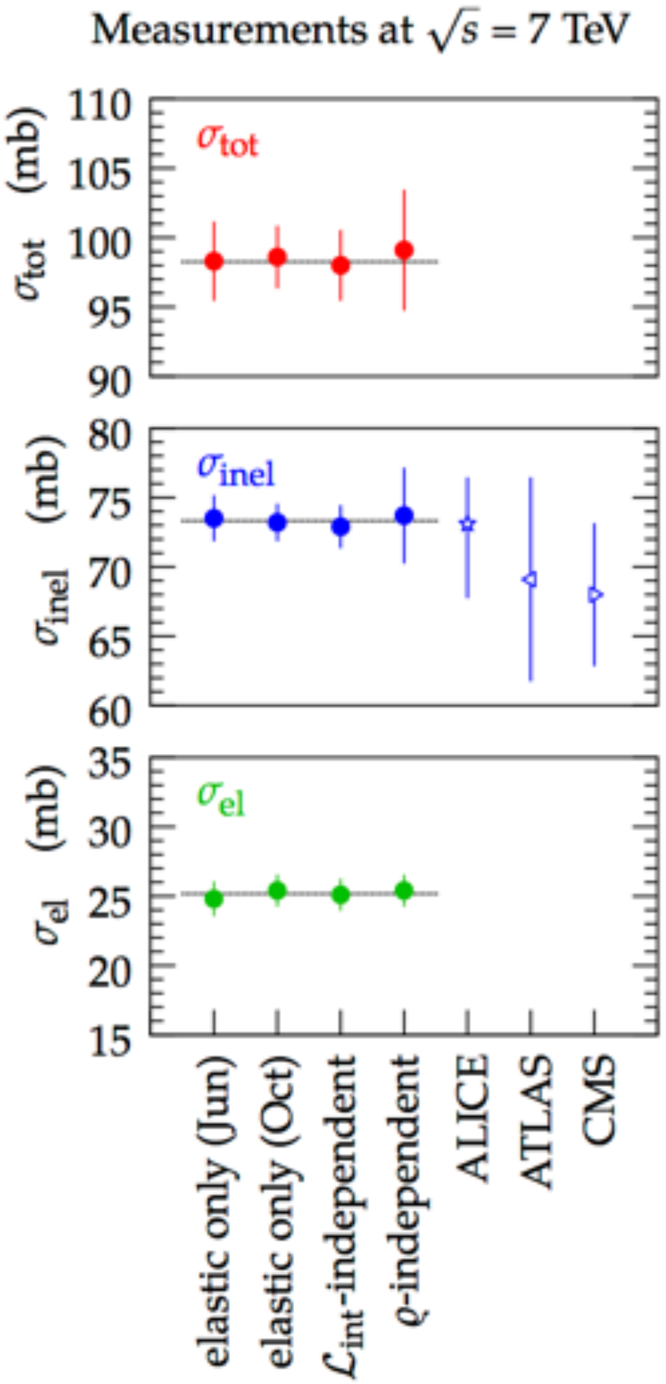
(D'Enterria et al., Astropart. Phys. 35, 2011)

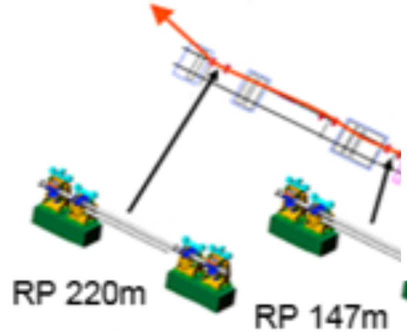


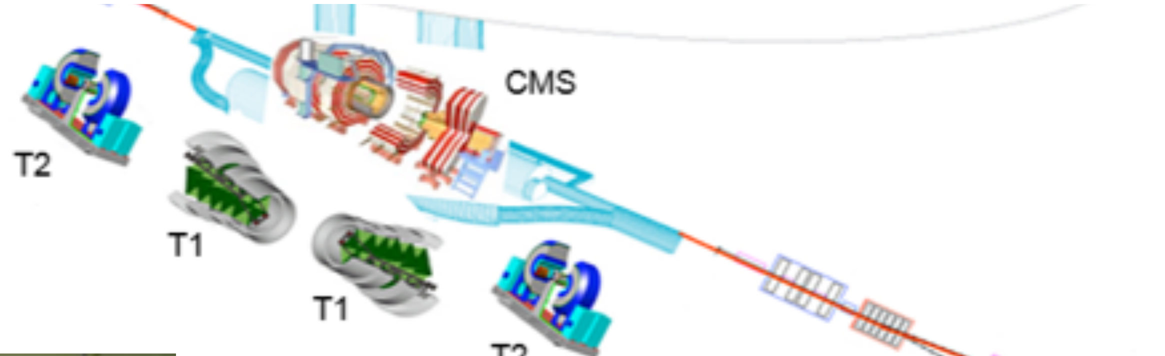
Models for air showers typically better in agreement with LHC data

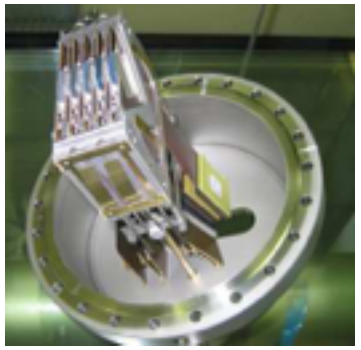
Proton-proton cross section

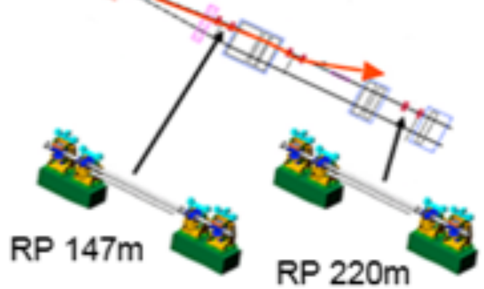






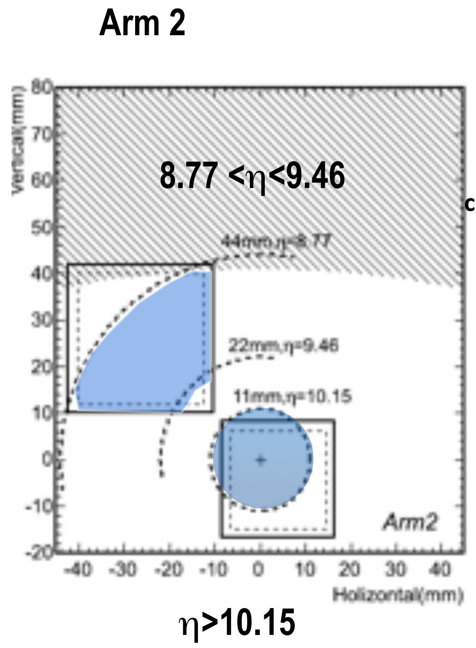


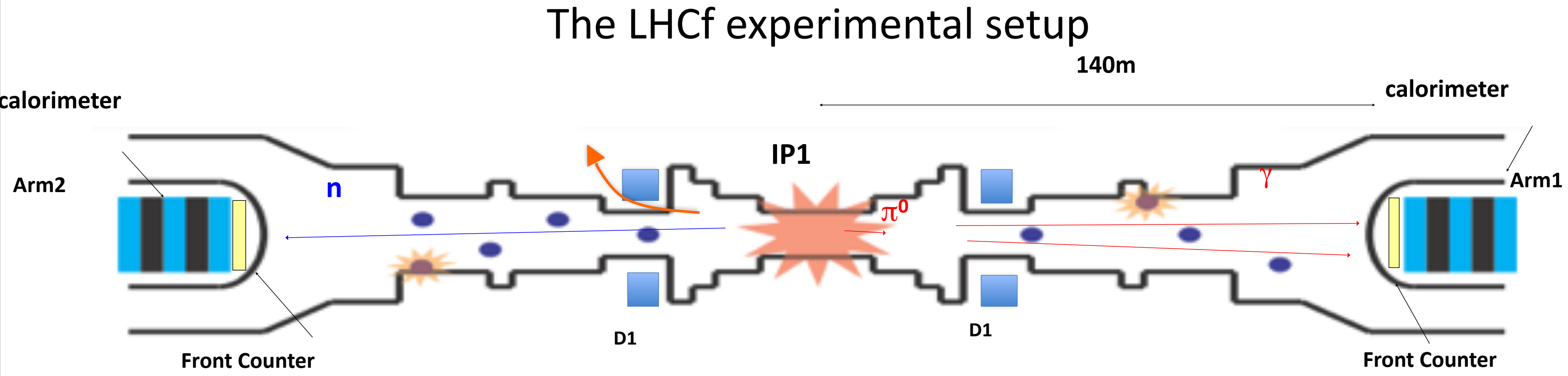


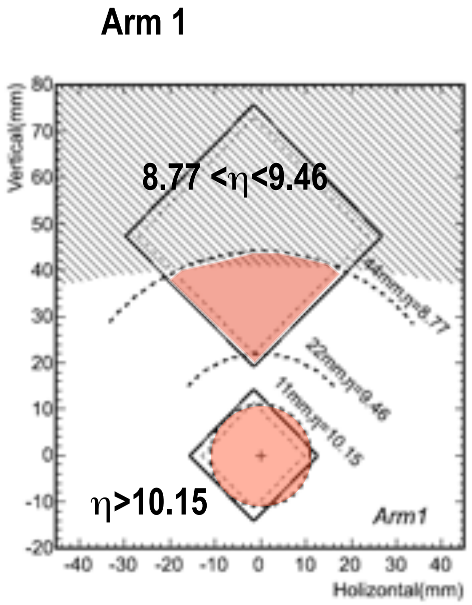


(Cafagna, ICRC 2015)

LHCf: very forward photon production

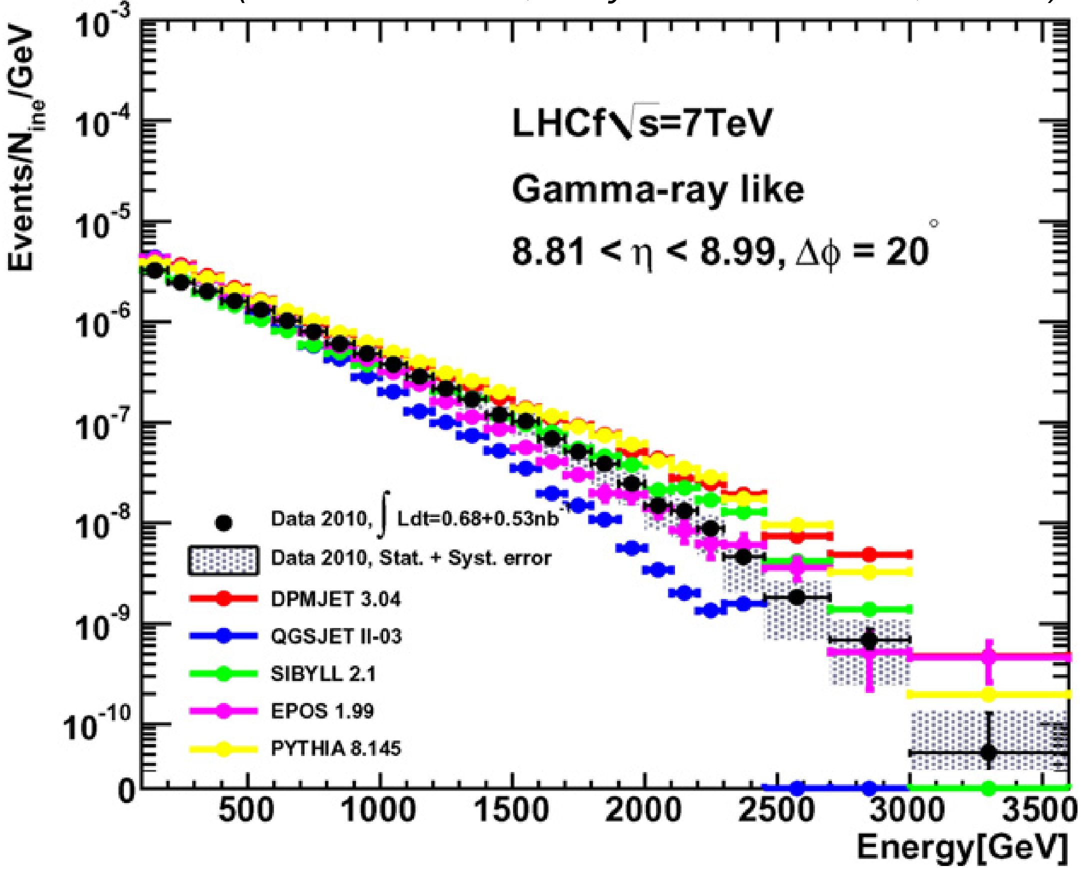




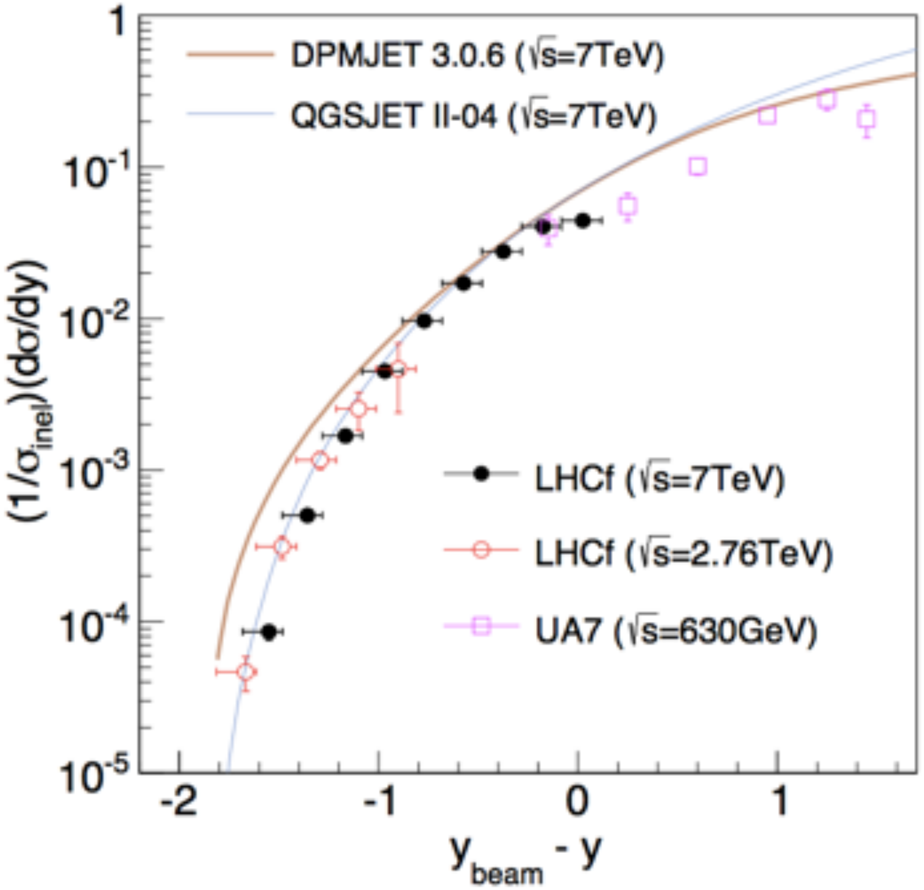


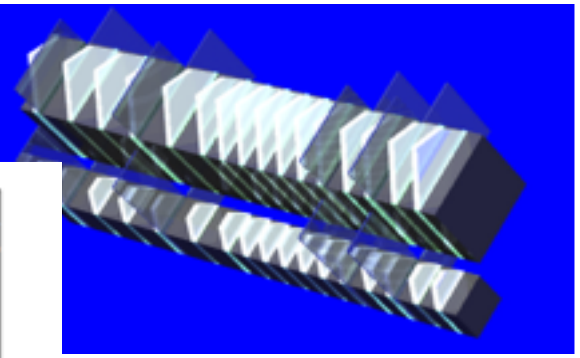
$$pp \rightarrow \gamma X$$

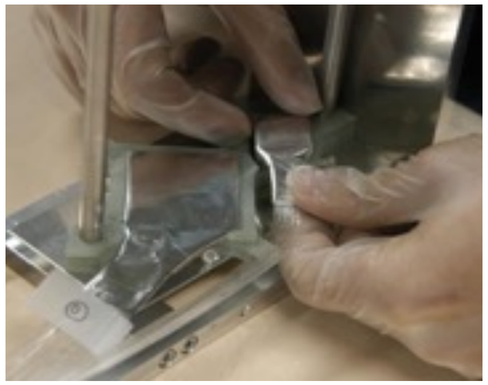
(LHCf Collab., Phys. Lett. B 703, 2011)



(LHCf, 1507.08764)

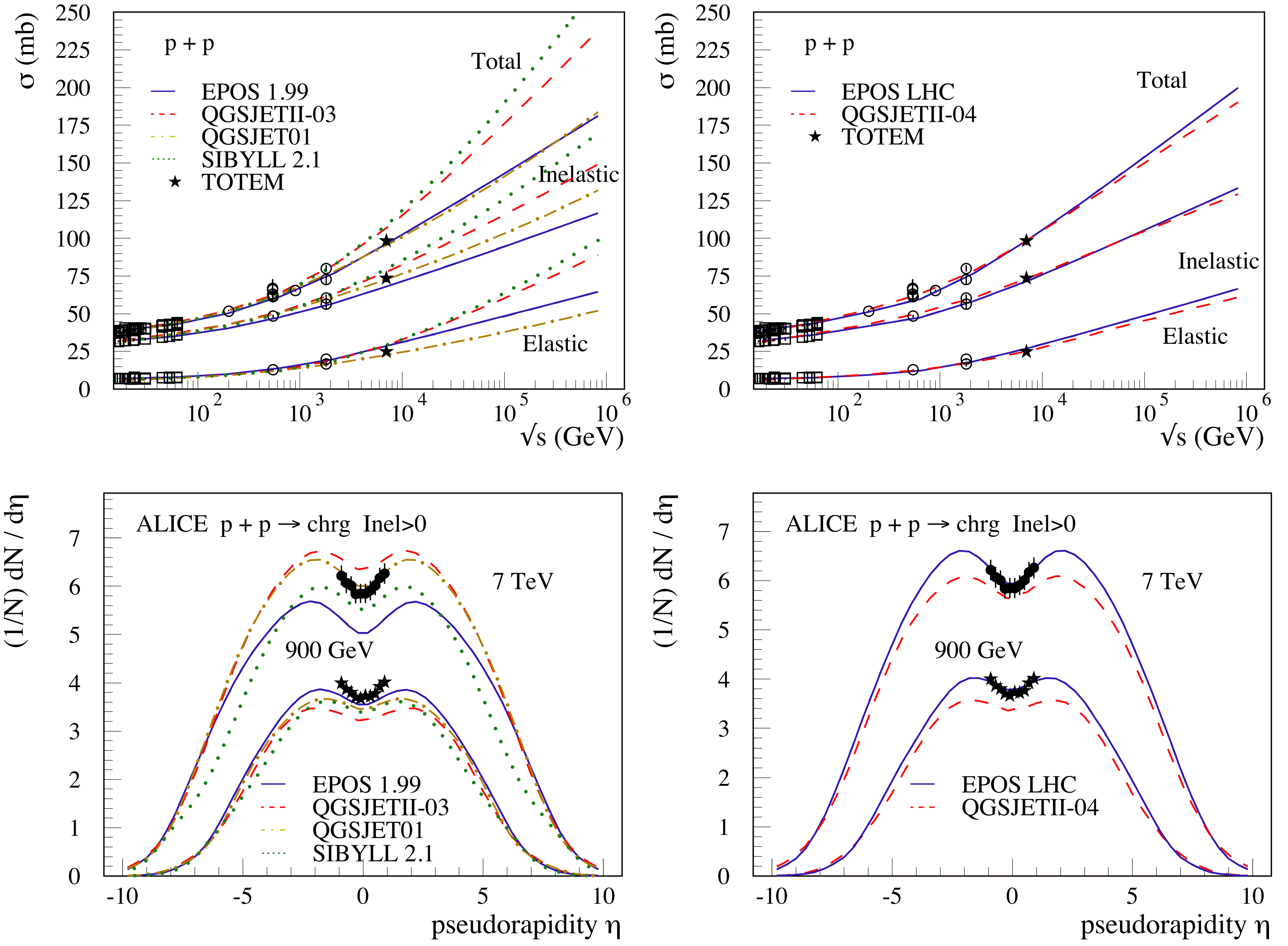






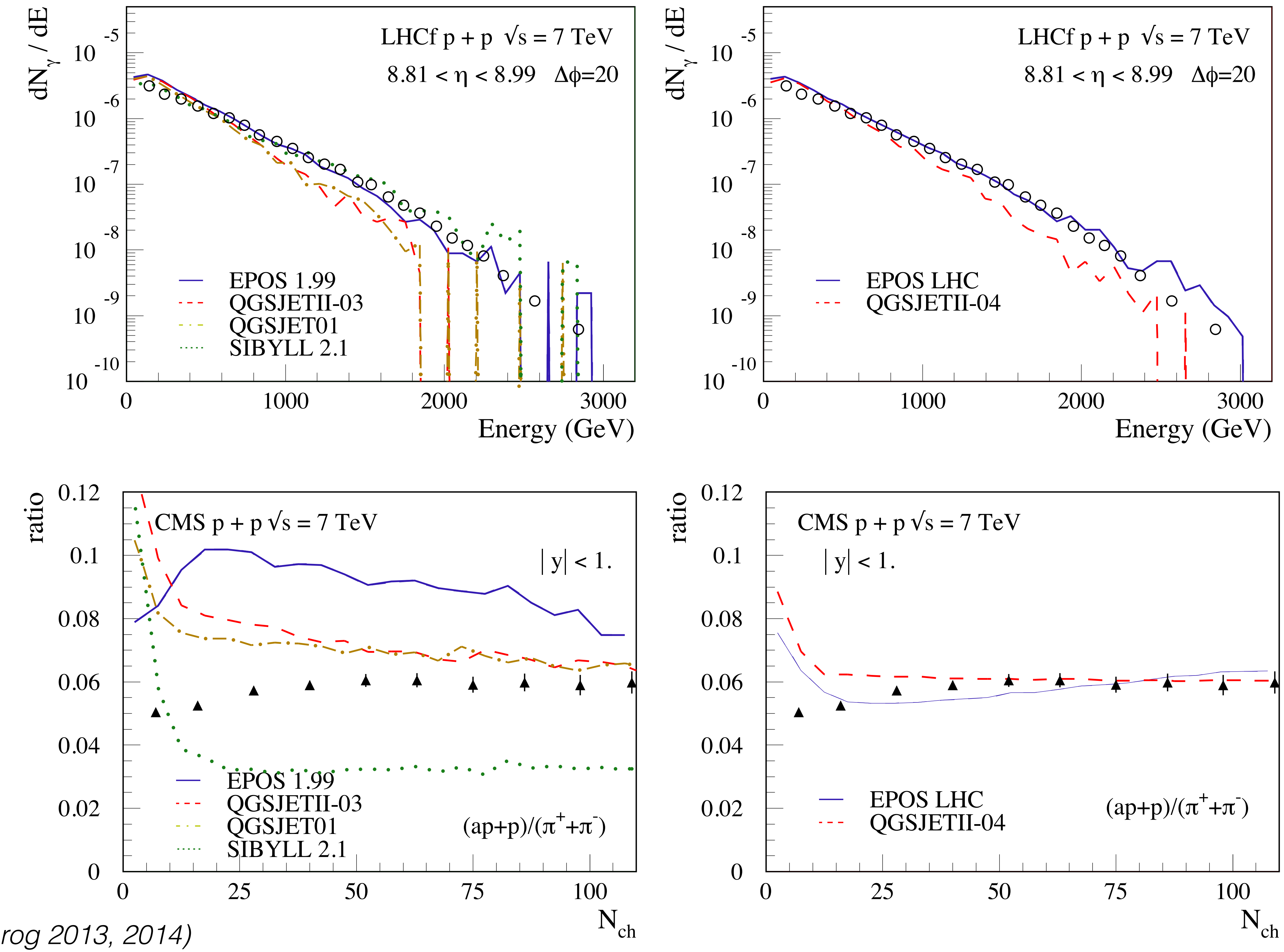
(Itow, ICRC 2015)

Tuning of interaction models to LHC data (i)



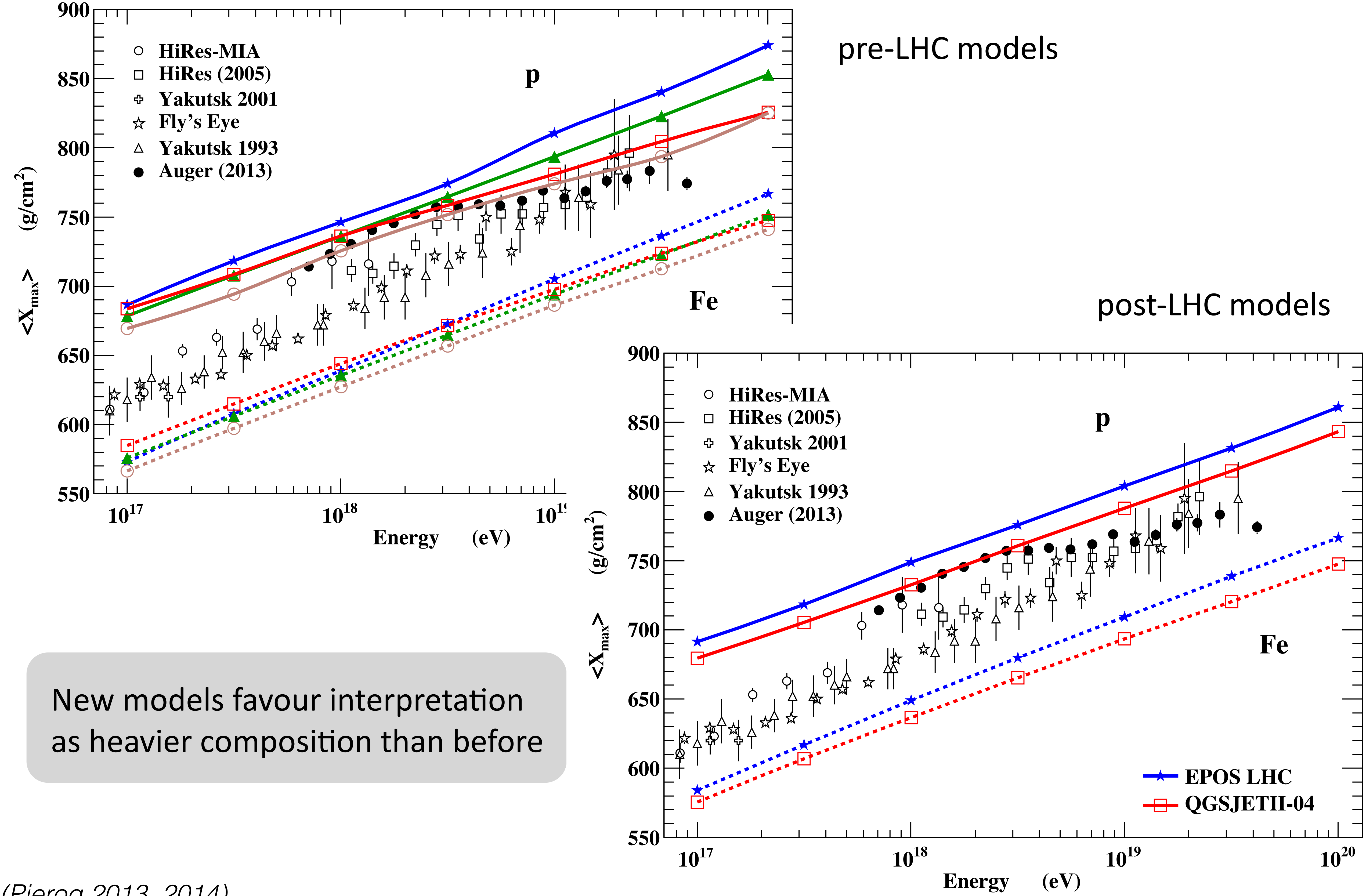
(Pierog 2013, 2014)

Tuning of interaction models to LHC data (ii)



(Pierog 2013, 2014)

Predictions for depth of shower maximum



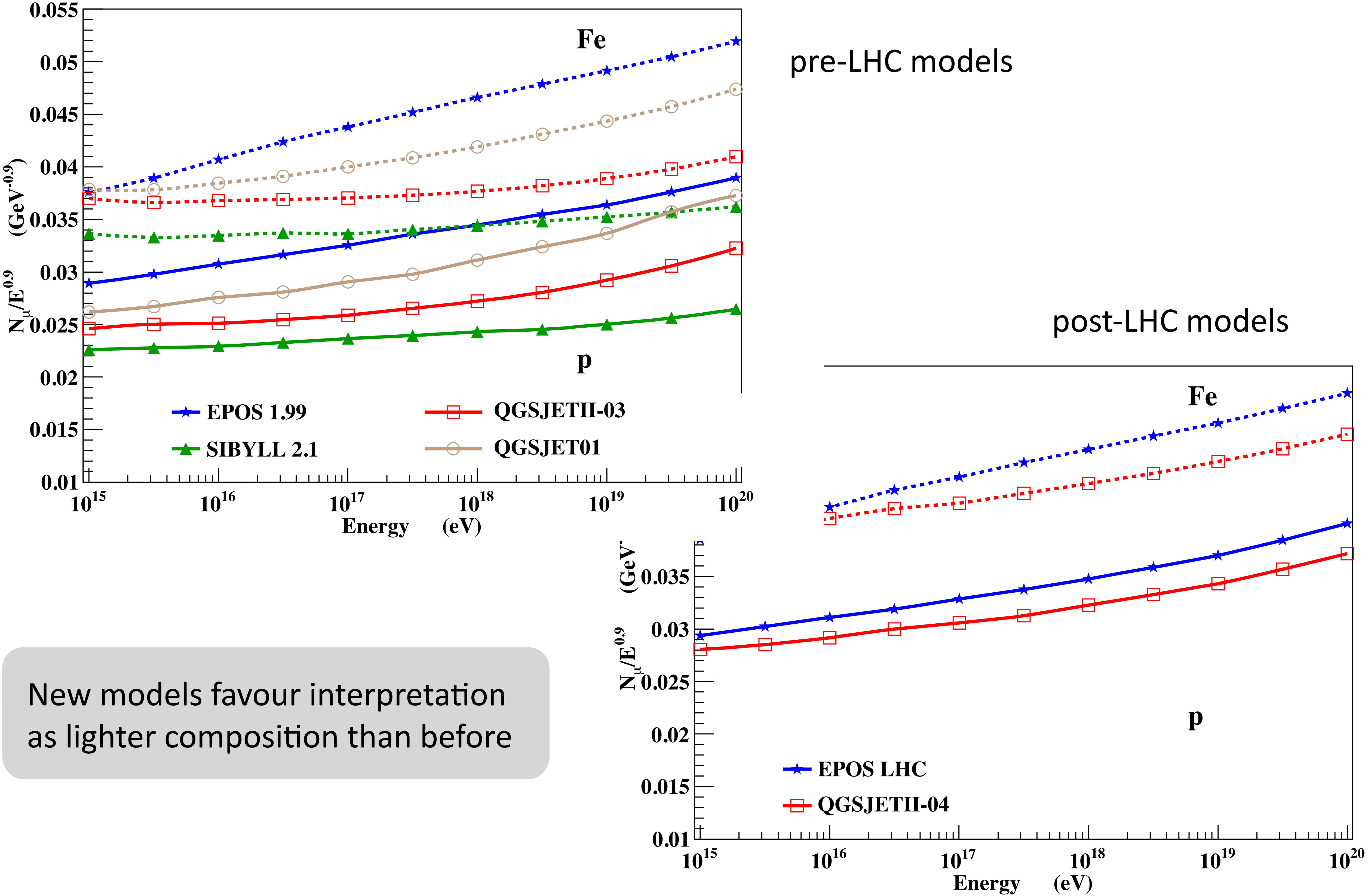
pre-LHC models

post-LHC models

New models favour interpretation as heavier composition than before

(Pierog 2013, 2014)

Predictions for muon number at ground



pre-LHC models

post-LHC models

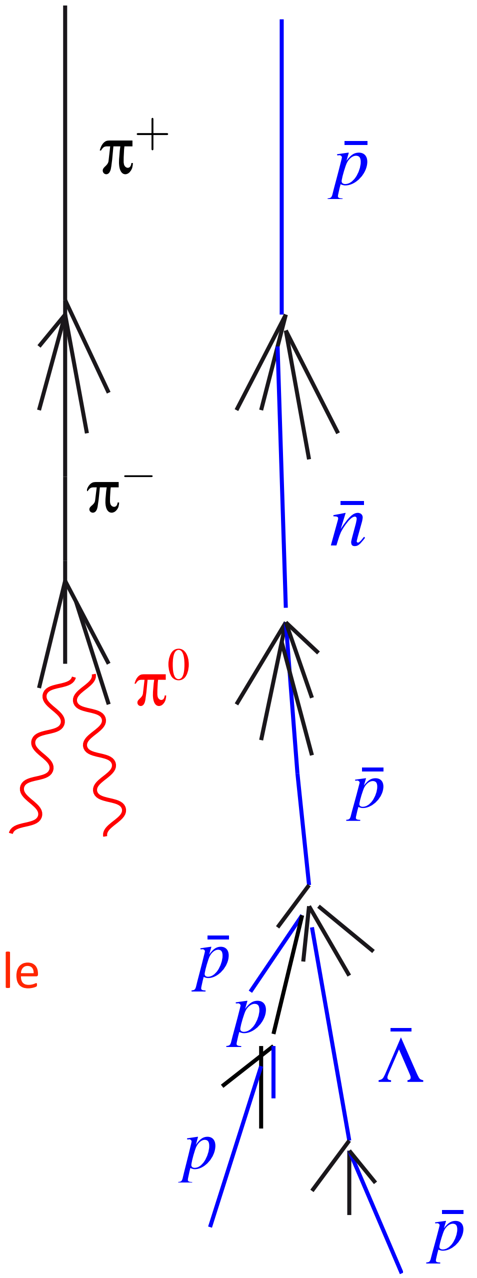
New models favour interpretation as lighter composition than before

(Pierog 2013, 2014)

Why did the muon number change so much ?

Meson sub-shower

Baryon sub-shower



Decay of
leading particle

$\pi^\pm$ ~30% chance to have
π^0 as leading particle

Not directly related to LHC data:

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

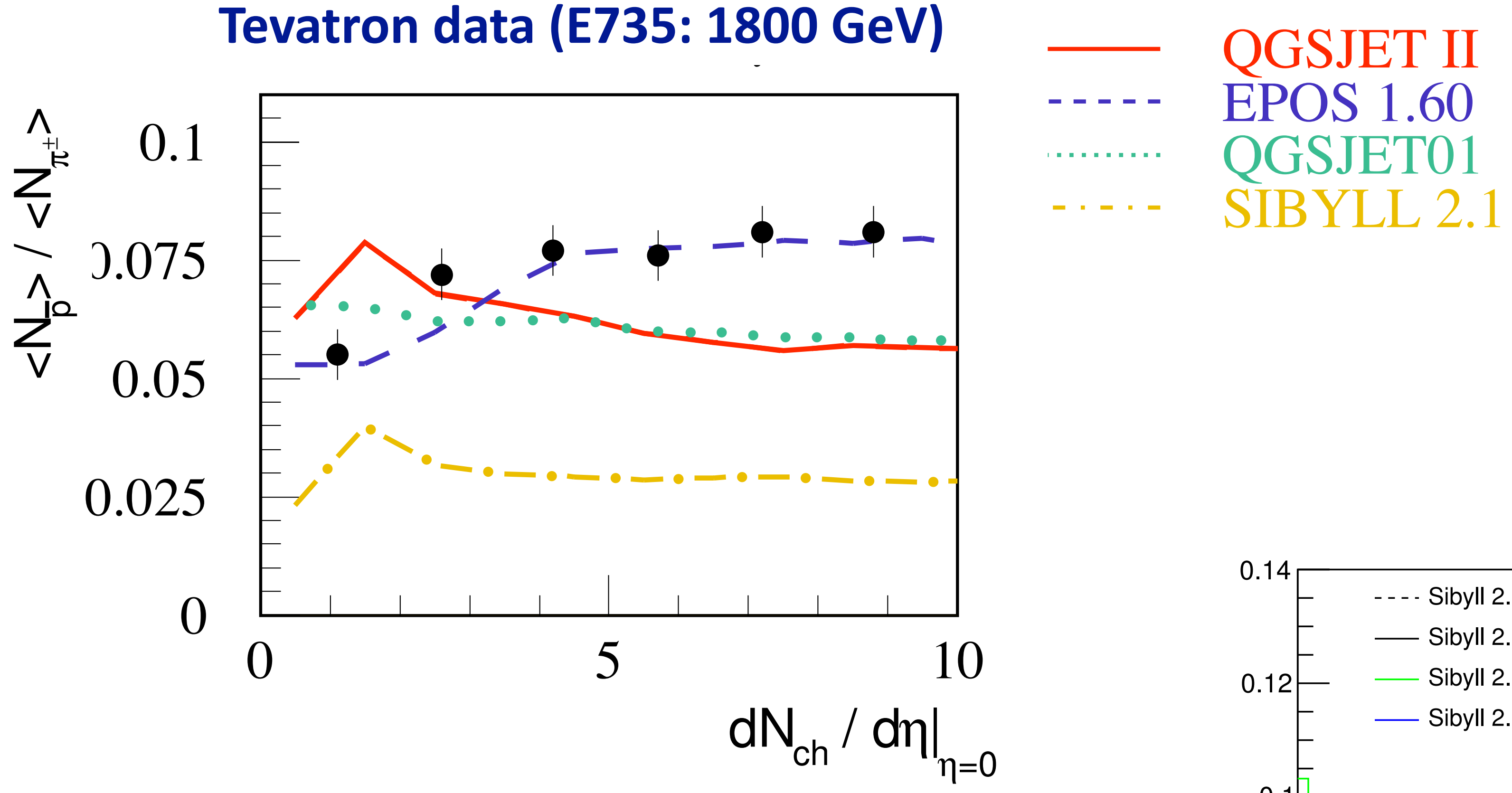
(Grieder ICRC 1973; Pierog, Werner PRL 101, 2008)

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 almost 100% into two charged pions

Baryon pair-production rate

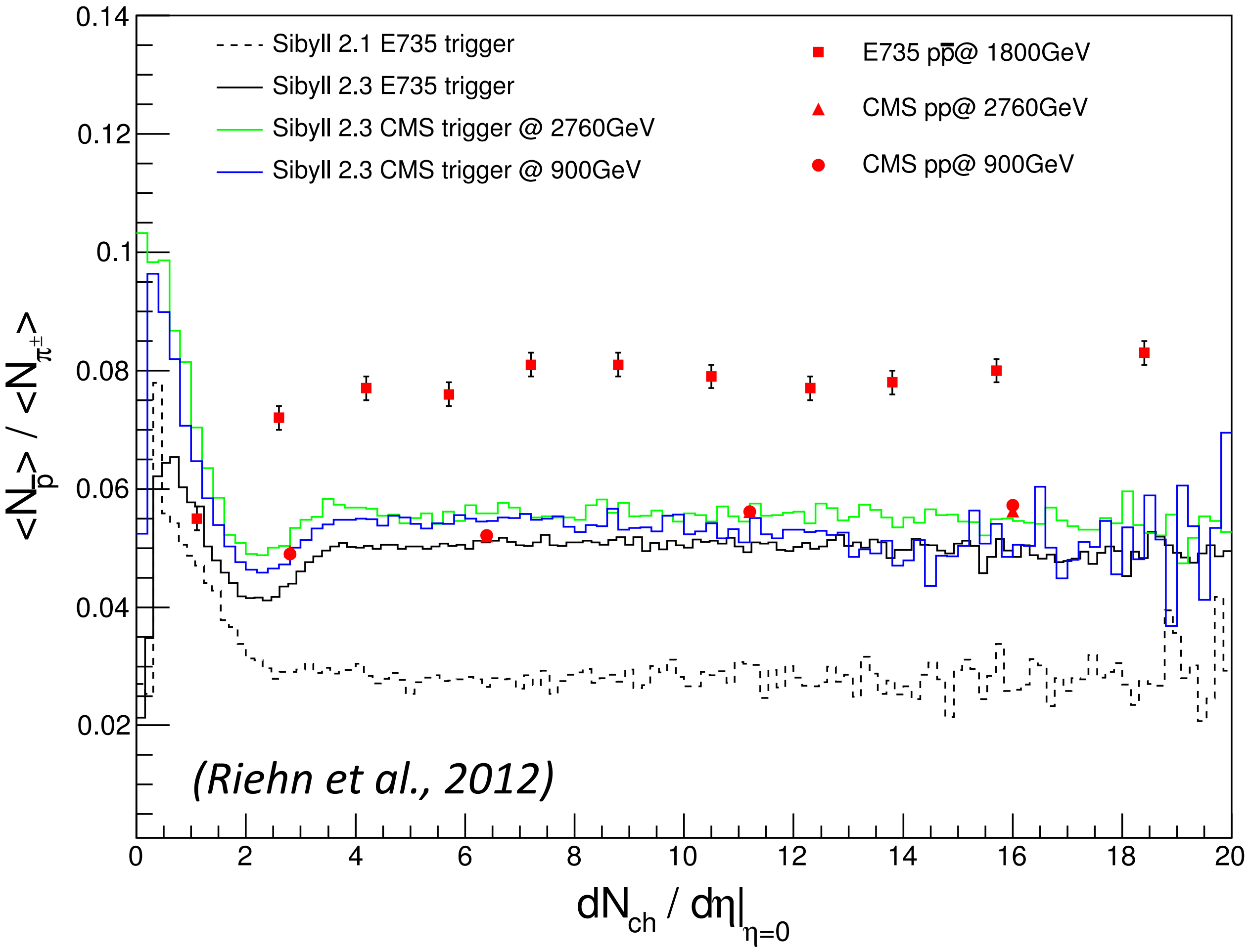
Tevatron data (E735: 1800 GeV)



(Pierog, Werner Phys. Rev. Lett. 101, 2008)

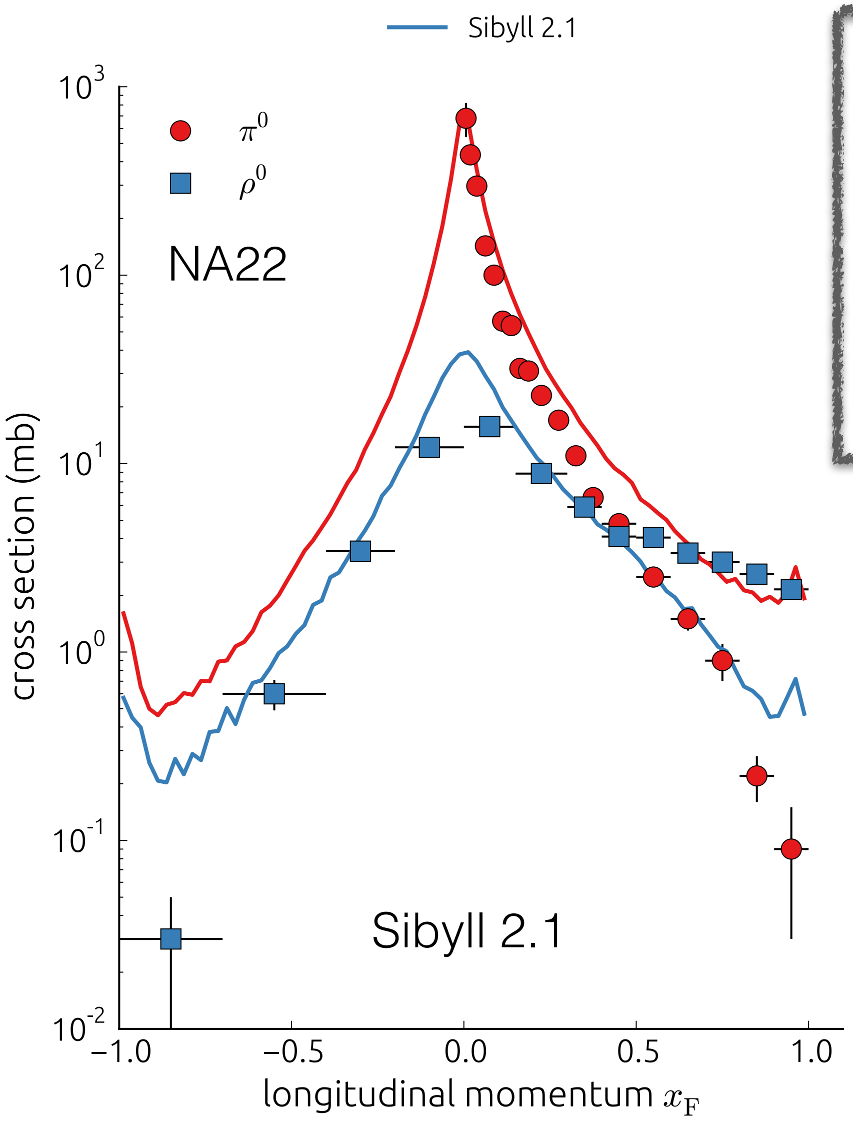
LHC measurements do not confirm Tevatron data (rapidity vs. pseudorap.?)

LHC data (CMS: 900 and 2760 GeV)



(Riehn et al., 2012)

Rho production in pion-proton interactions (i)

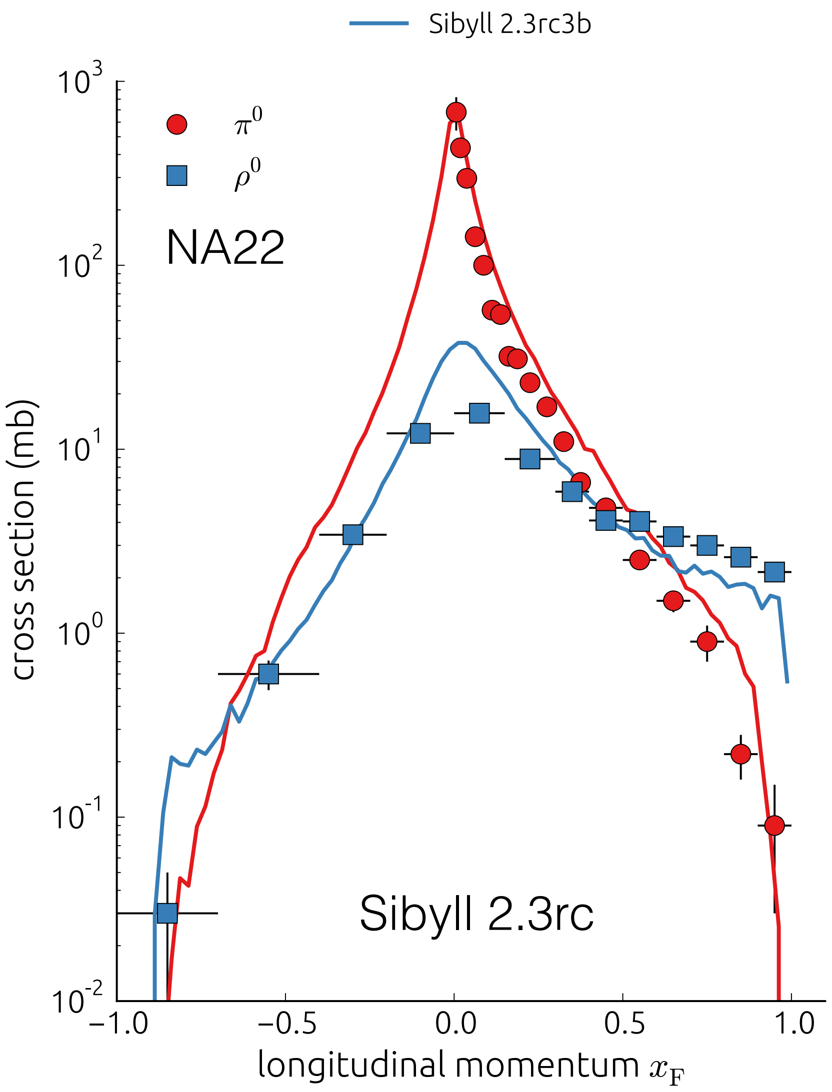


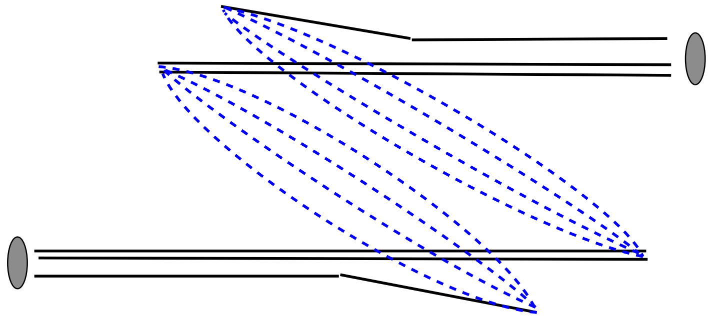
$$\pi^+ p \rightarrow \pi^0 \rightarrow 2\gamma$$

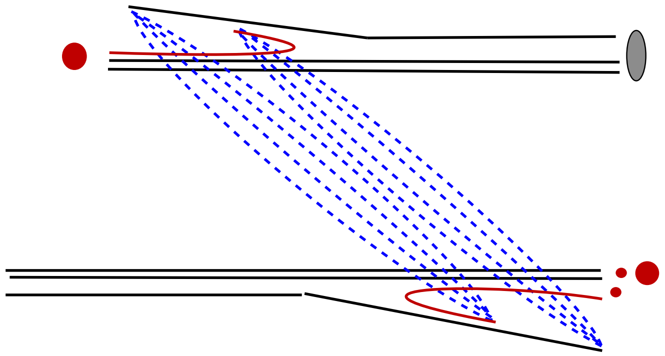
$$\pi^+ p \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$$

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

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

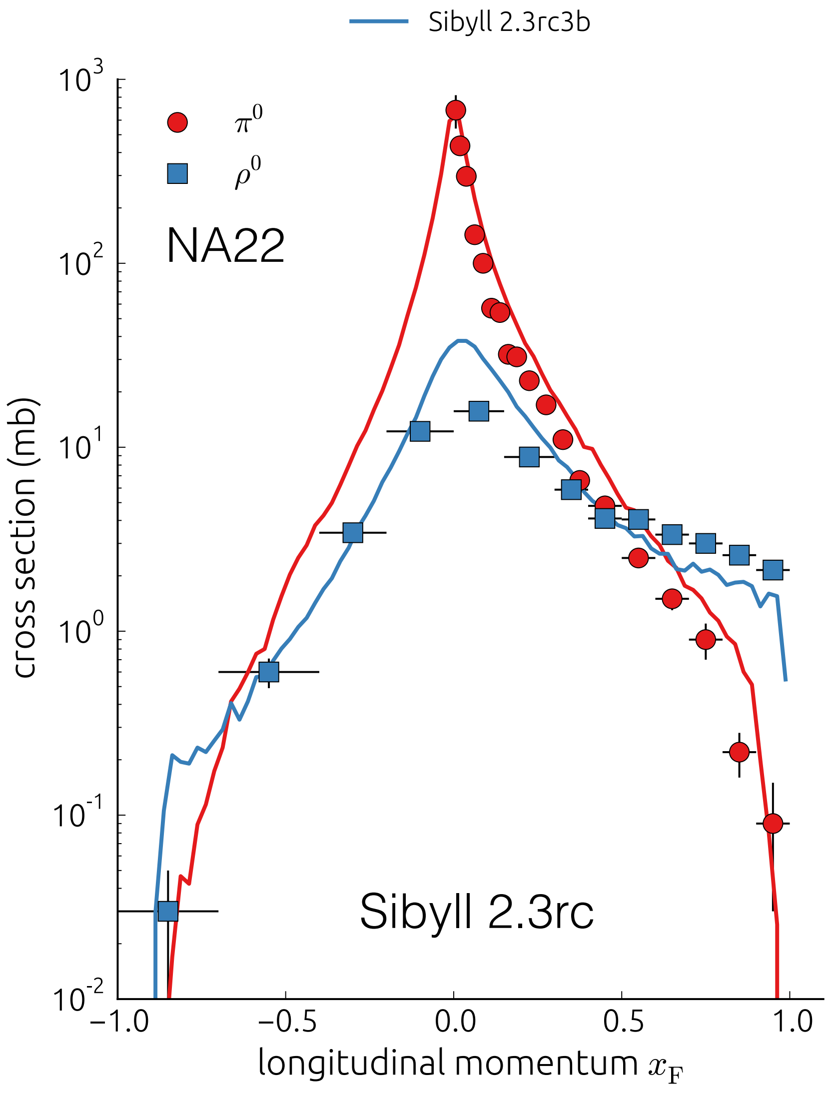




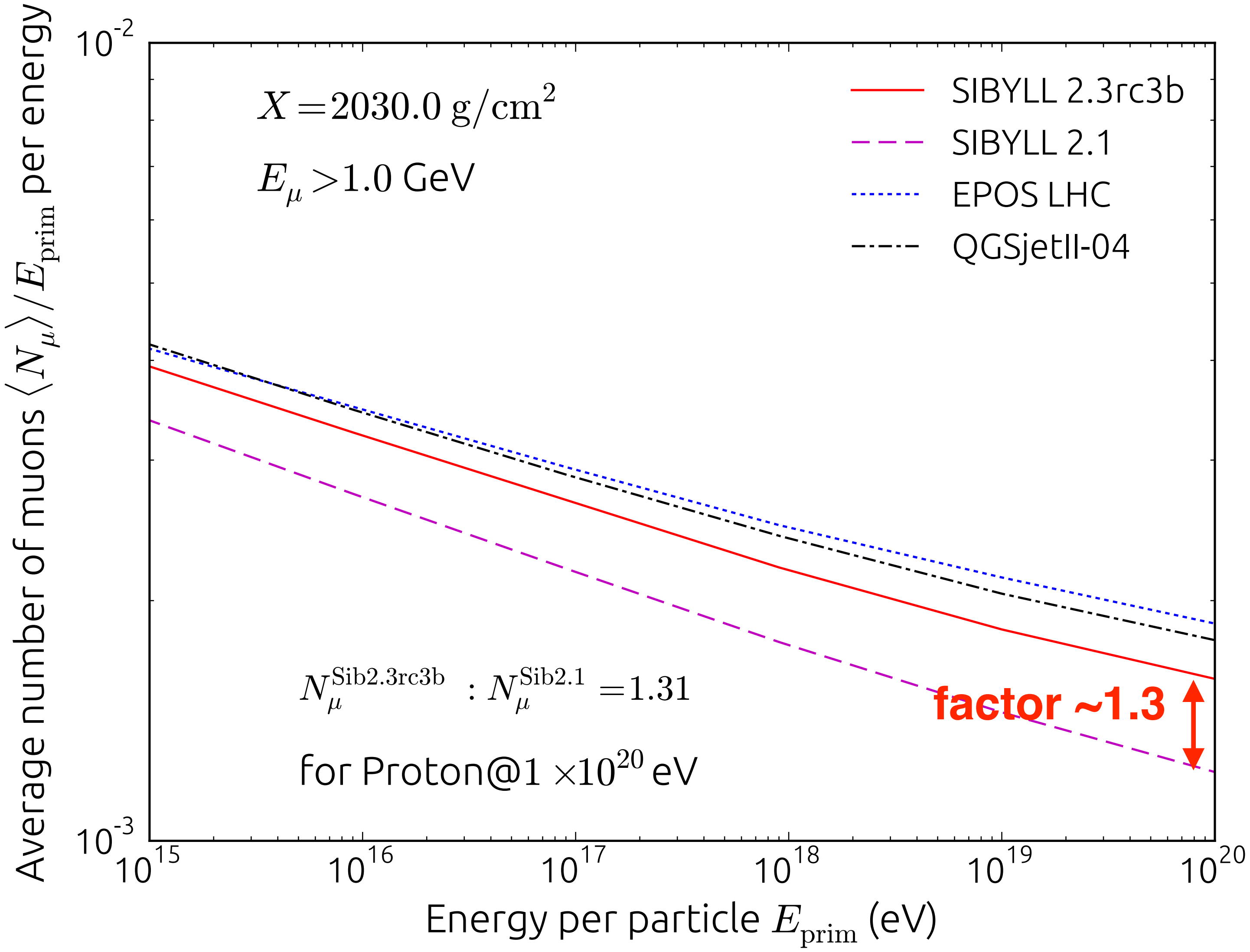


(Riehn et al., ICRC 2015)

Rho production in pion-proton interactions (ii)



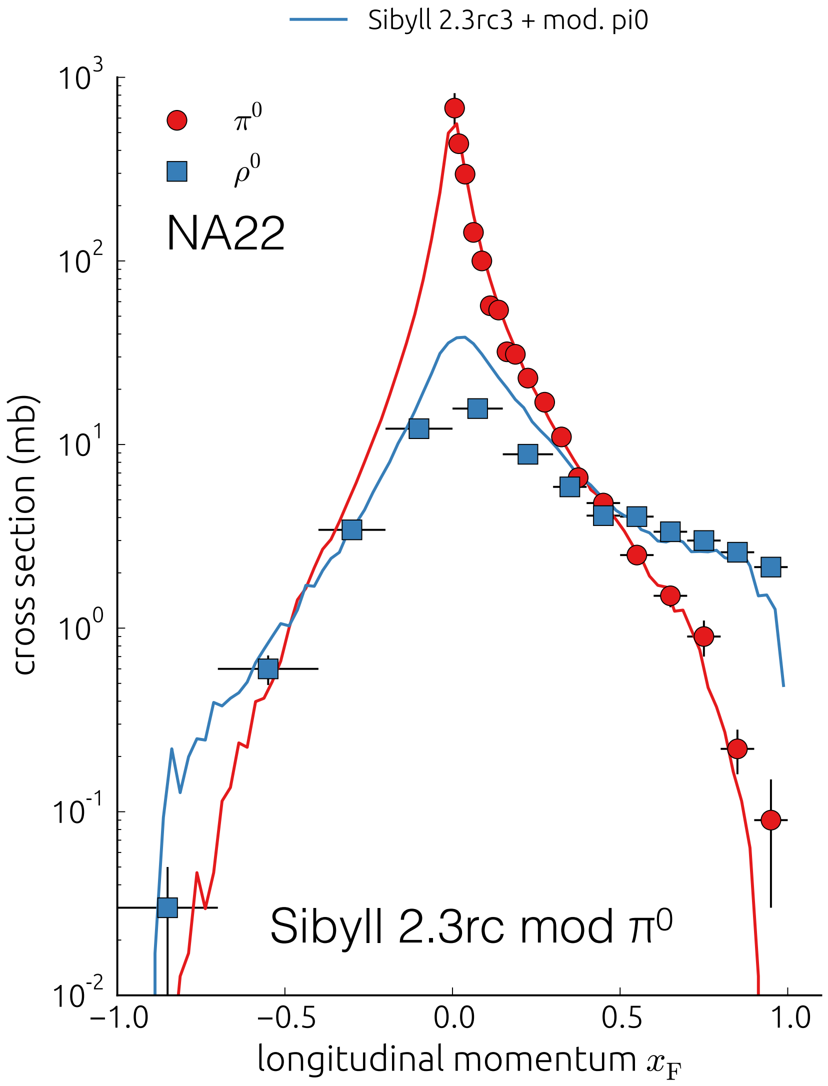
Description of data not optimal



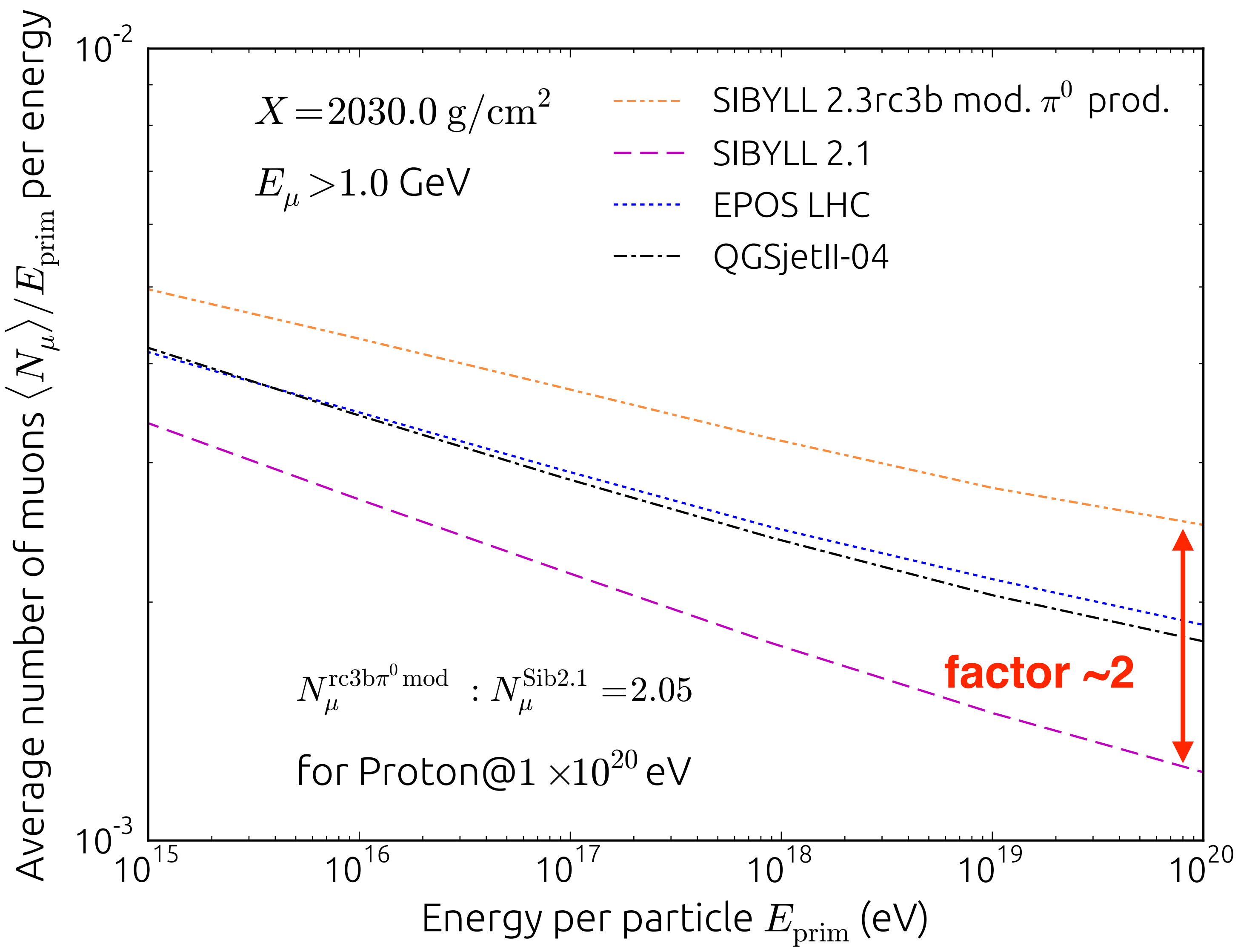
Sibyll 2.3 (release candidate)

(Riehn et al., ICRC 2015)

Rho production in pion-proton interactions (iii)



Sibyll 2.3rc mod π^0



$X = 2030.0\ {\rm g/cm^2}$

$E_\mu > 1.0$ GeV

factor ~2

$N_\mu^{{\rm rc3b}\pi^0\,{\rm mod}} : N_\mu^{\rm Sib2.1} = 2.05$

for Proton@1×10^{20} eV

Ad hoc modified ρ^0 and π^0 production

Sibyll 2.3rc mod π^0

(Riehn et al., ICRC 2015)

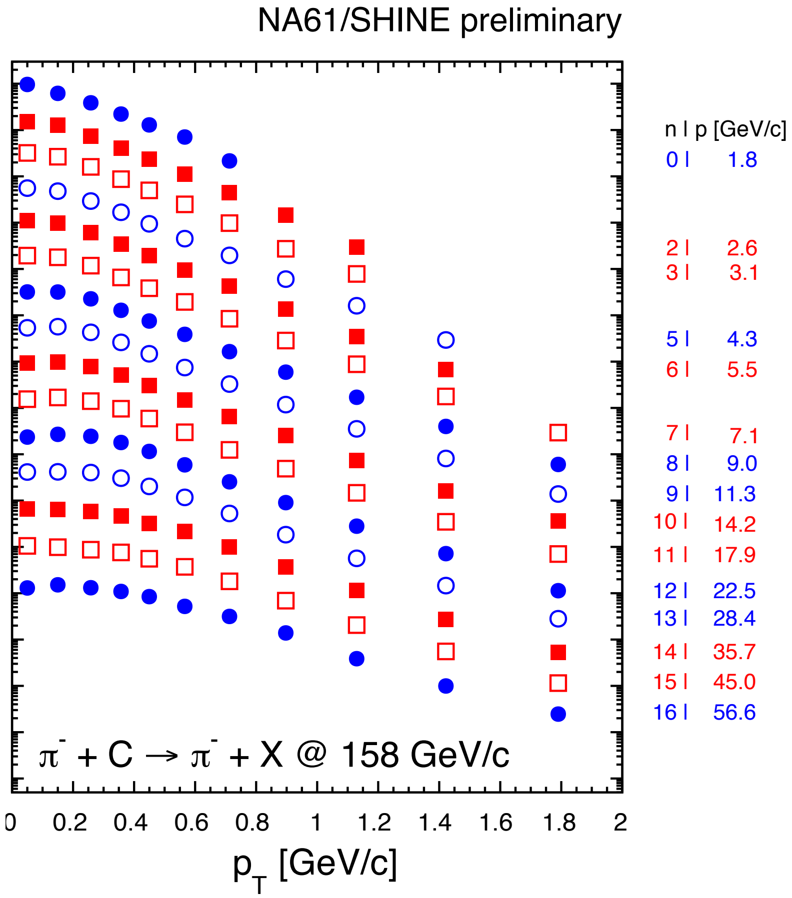
NA22 data only for pion-proton.

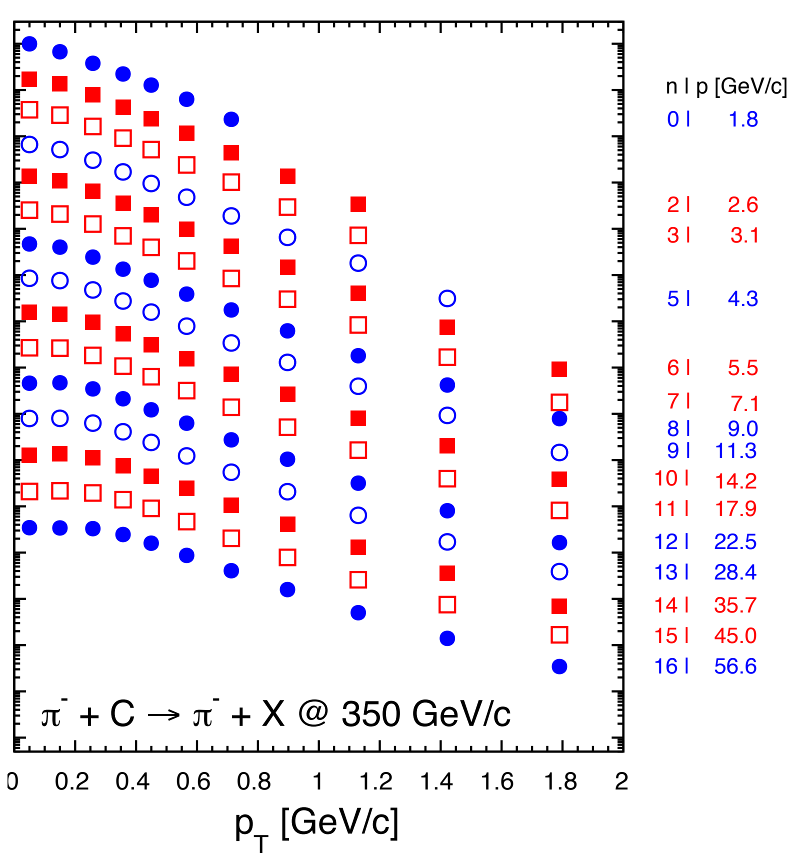
What about pion-nucleus interactions?

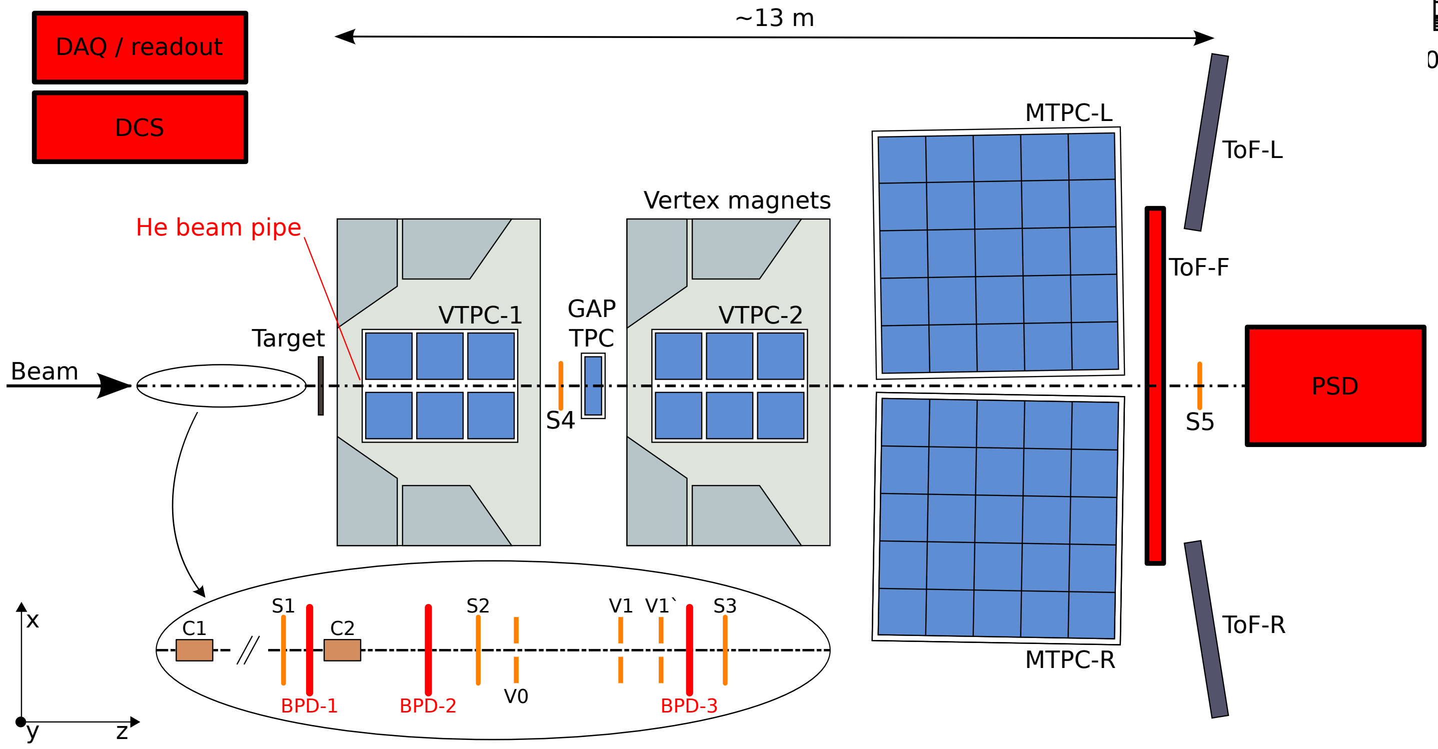
NA61 fixed-target experiment at CERN SPS

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

Analyzed by Auger members



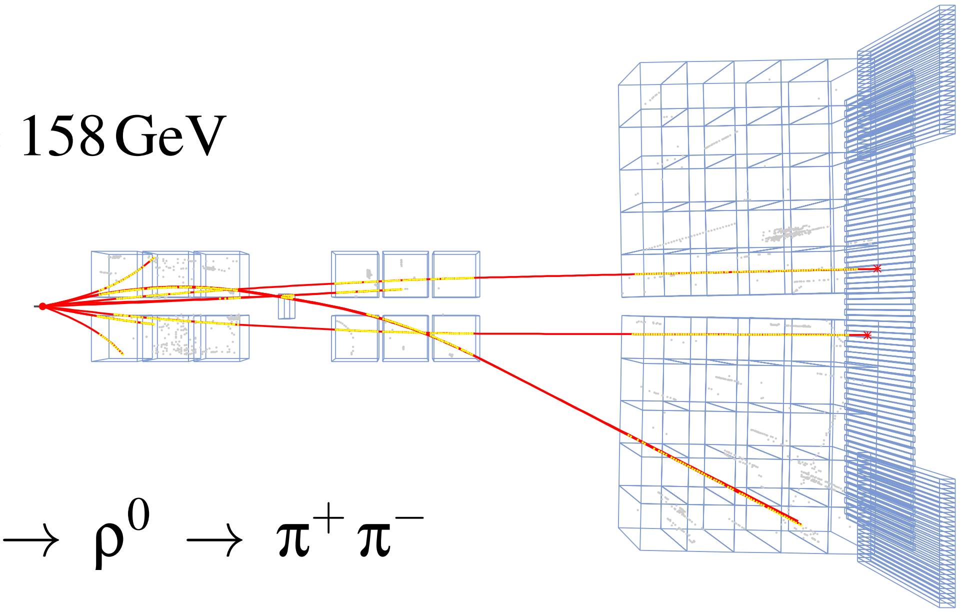




(NA61, Herve ICRC 2015, Unger CRIS 2015)

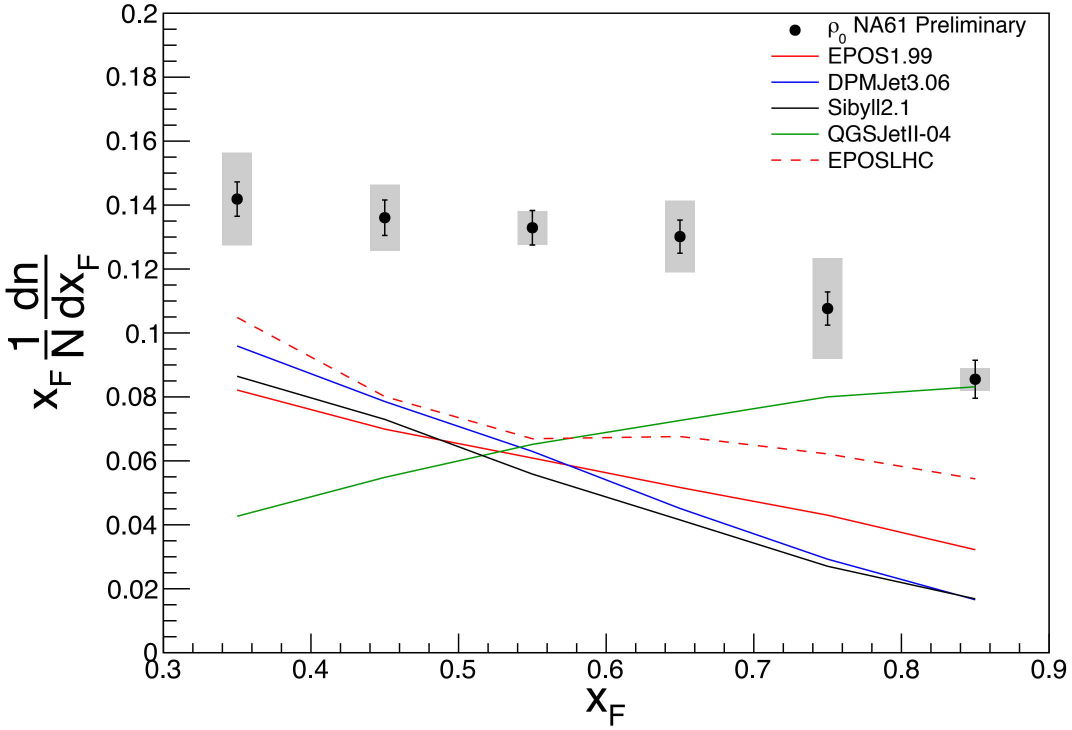
NA61 results on rho production on carbon

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

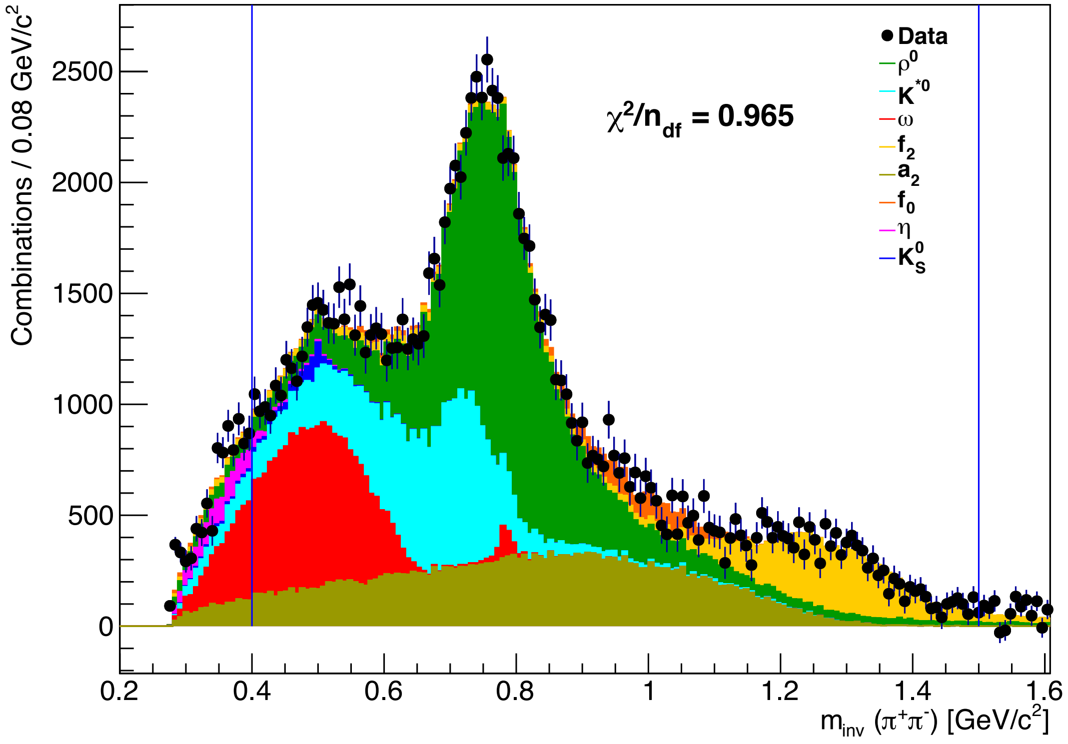


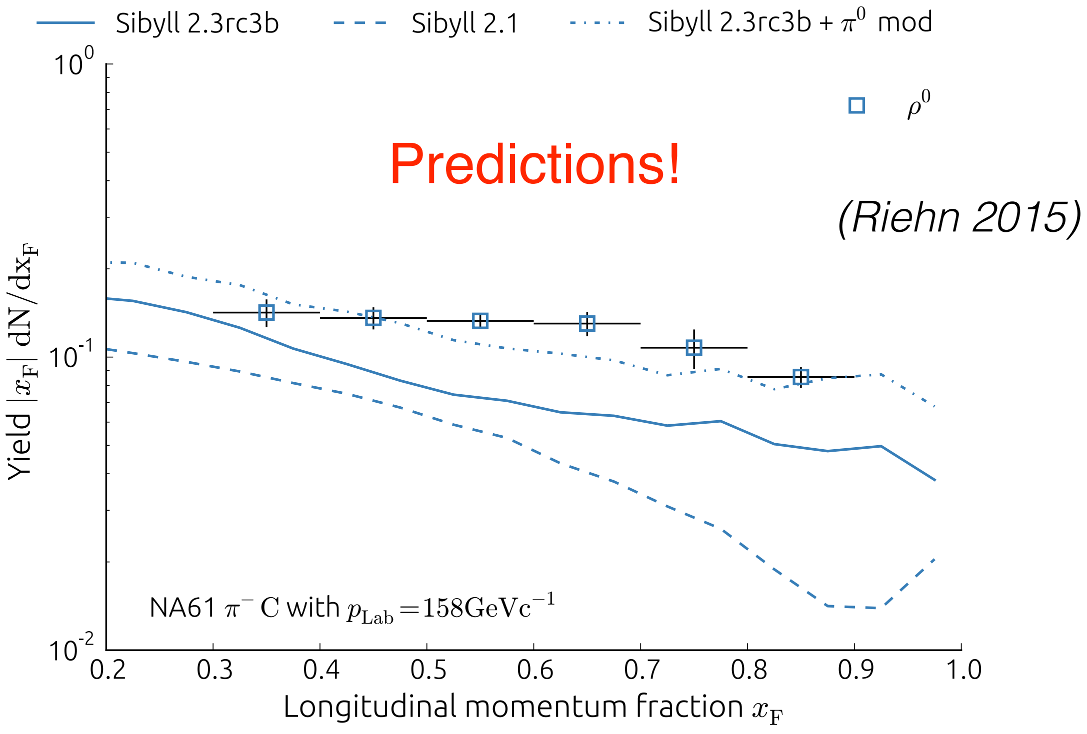
$\pi^- C \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$

(NA61, Herve, ICRC 2015)



Invariant mass of two charged tracks

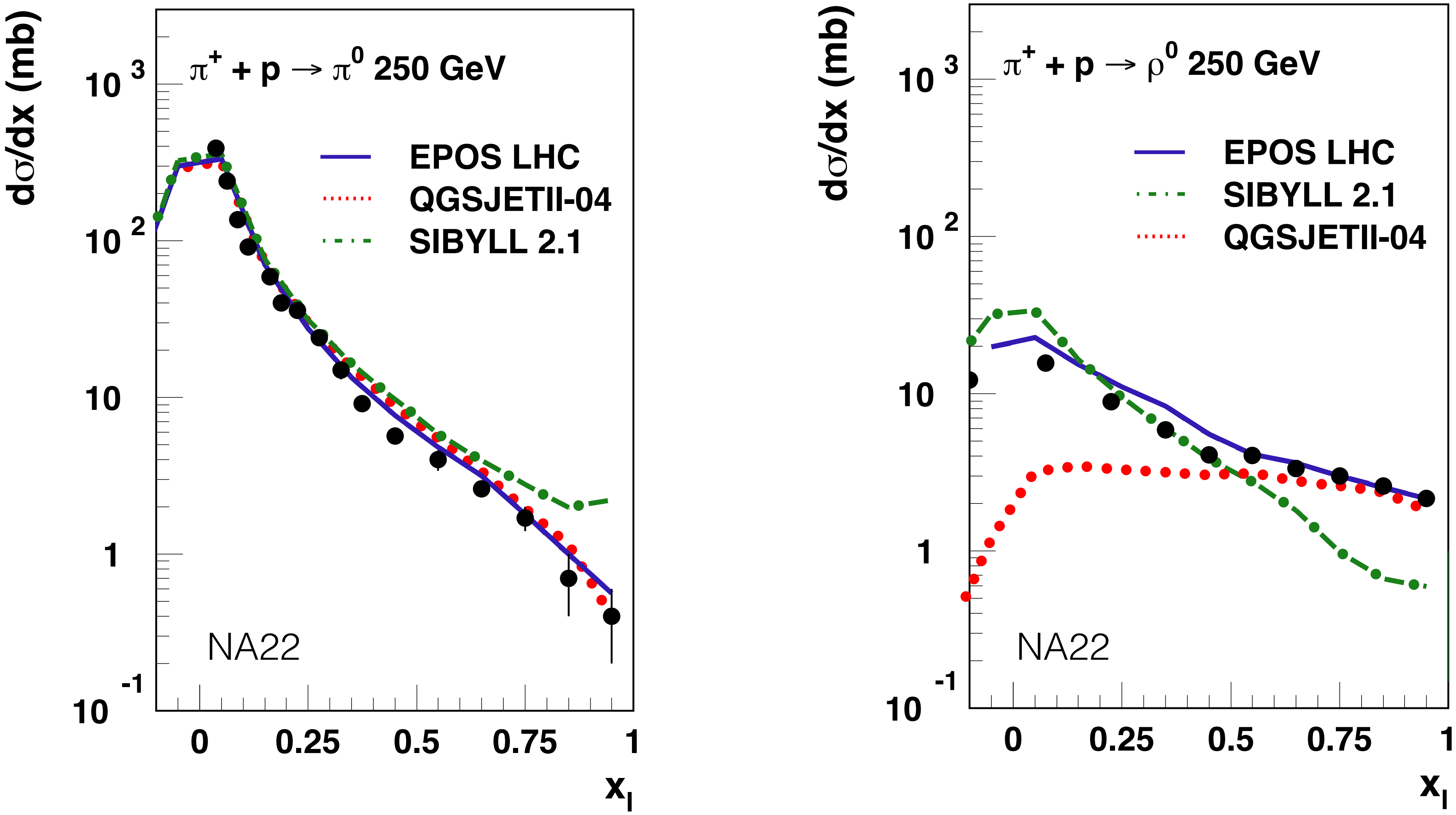




Predictions!

(Riehn 2015)

Open questions related to rho production

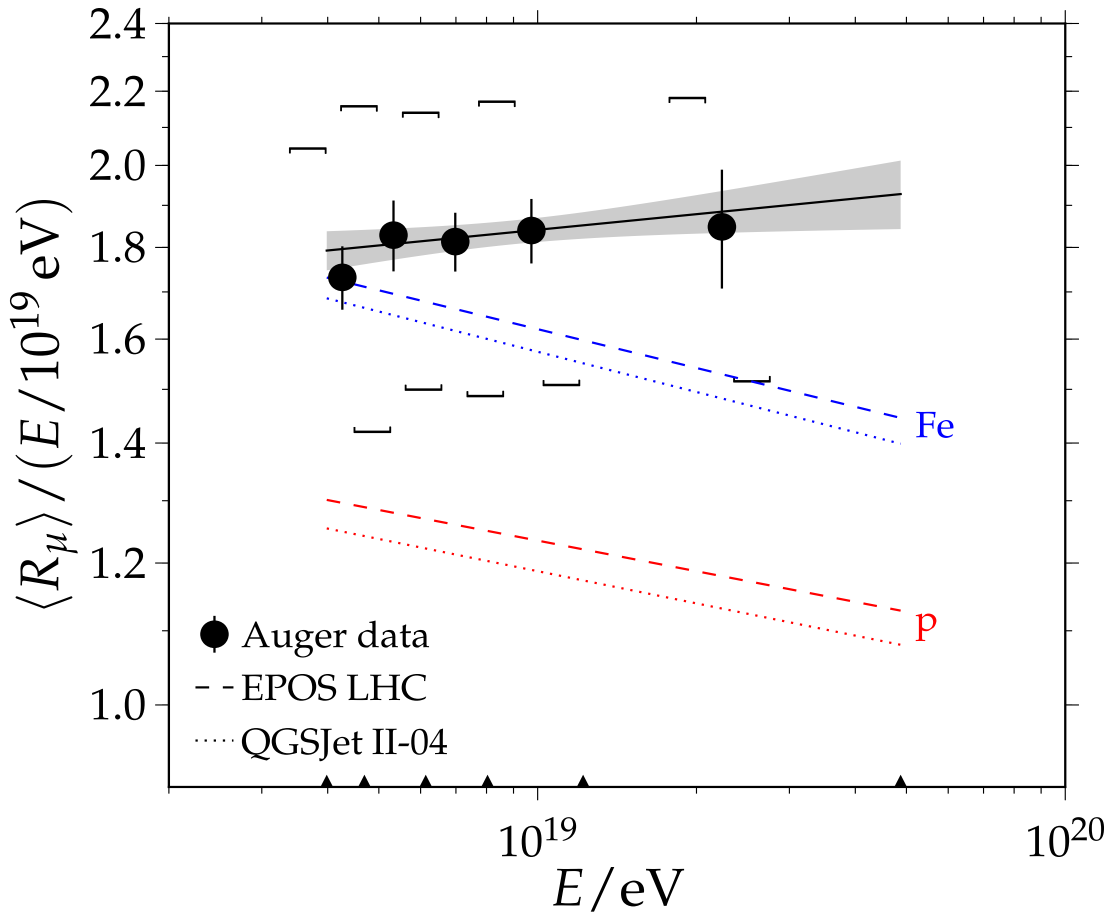


- EPOS and QGSJet tuned to reproduce π-p data
- Apparently origin of rho production not understood
- Suppression of π^0 production rather strong
- Energy dependence of these effects could be important

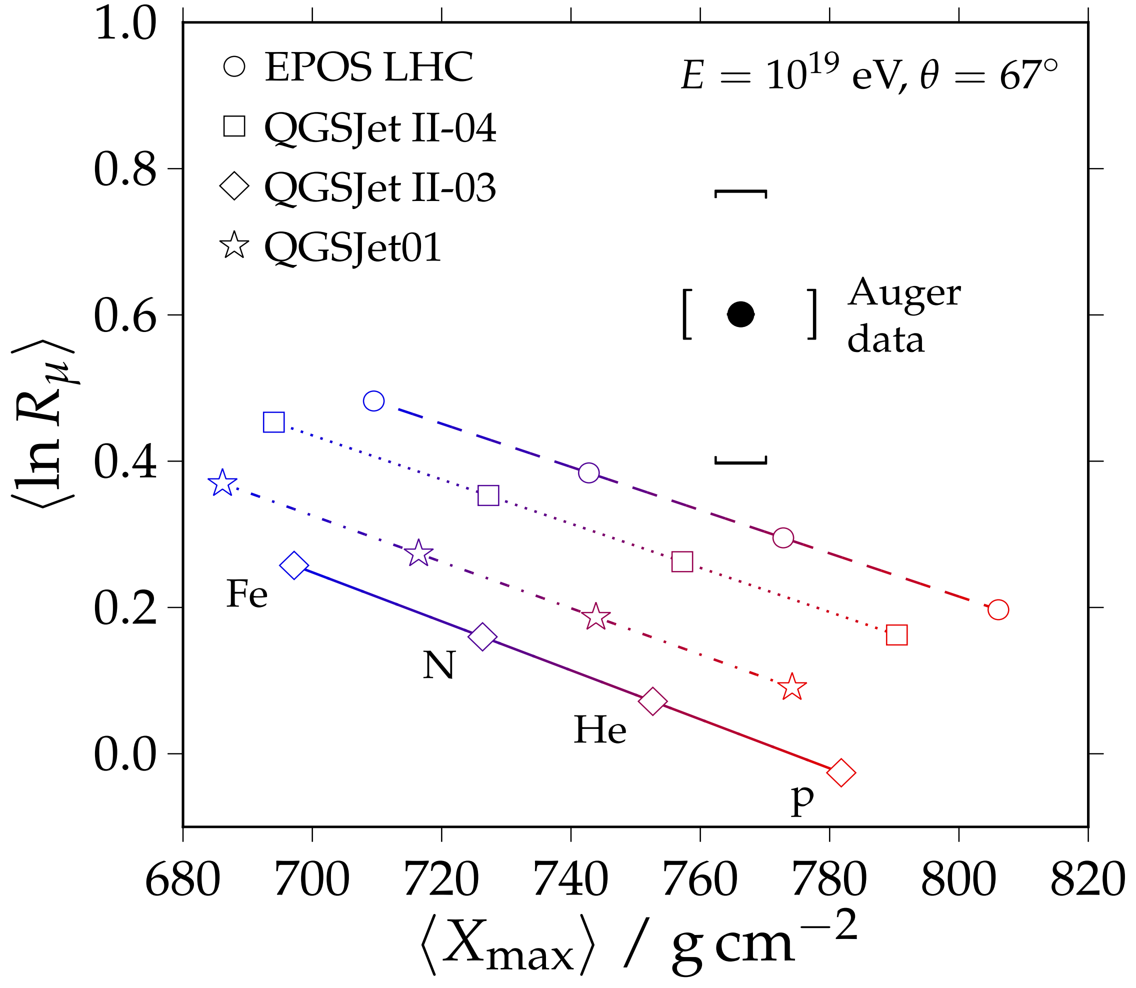
(Pierog 2015)

Muon number in inclined showers

Number of muons in showers with θ>60°



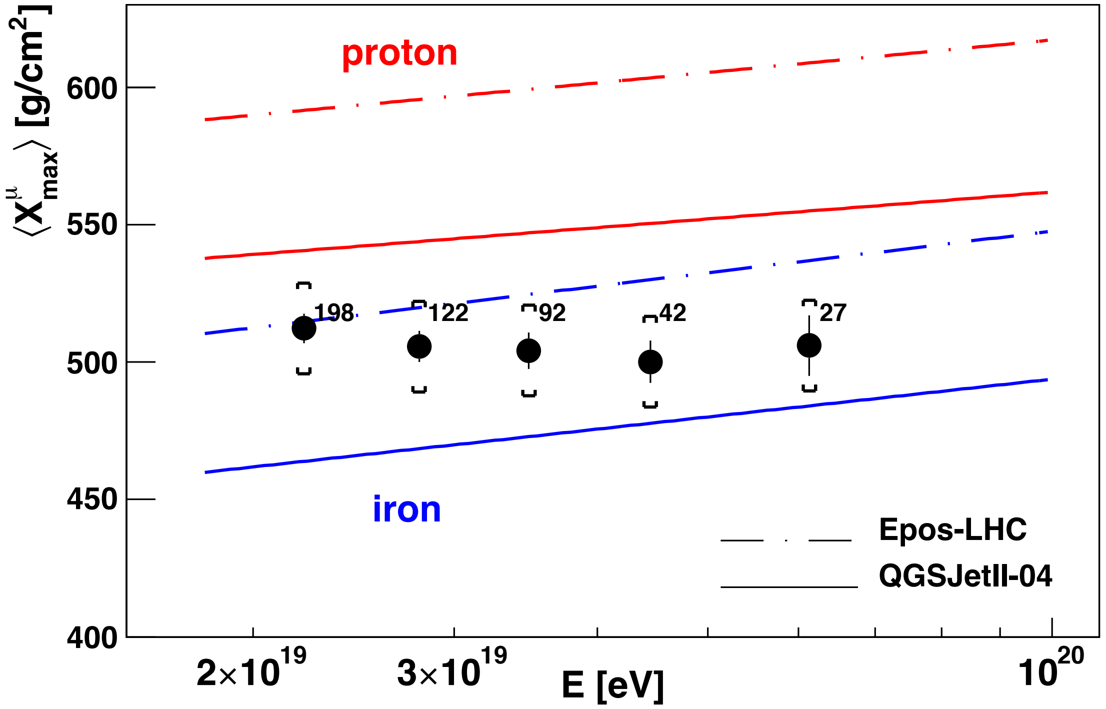
Combination of information on mean depth of shower maximum and muon number at ground



Muon discrepancy in Auger and KASCADE-Grande data

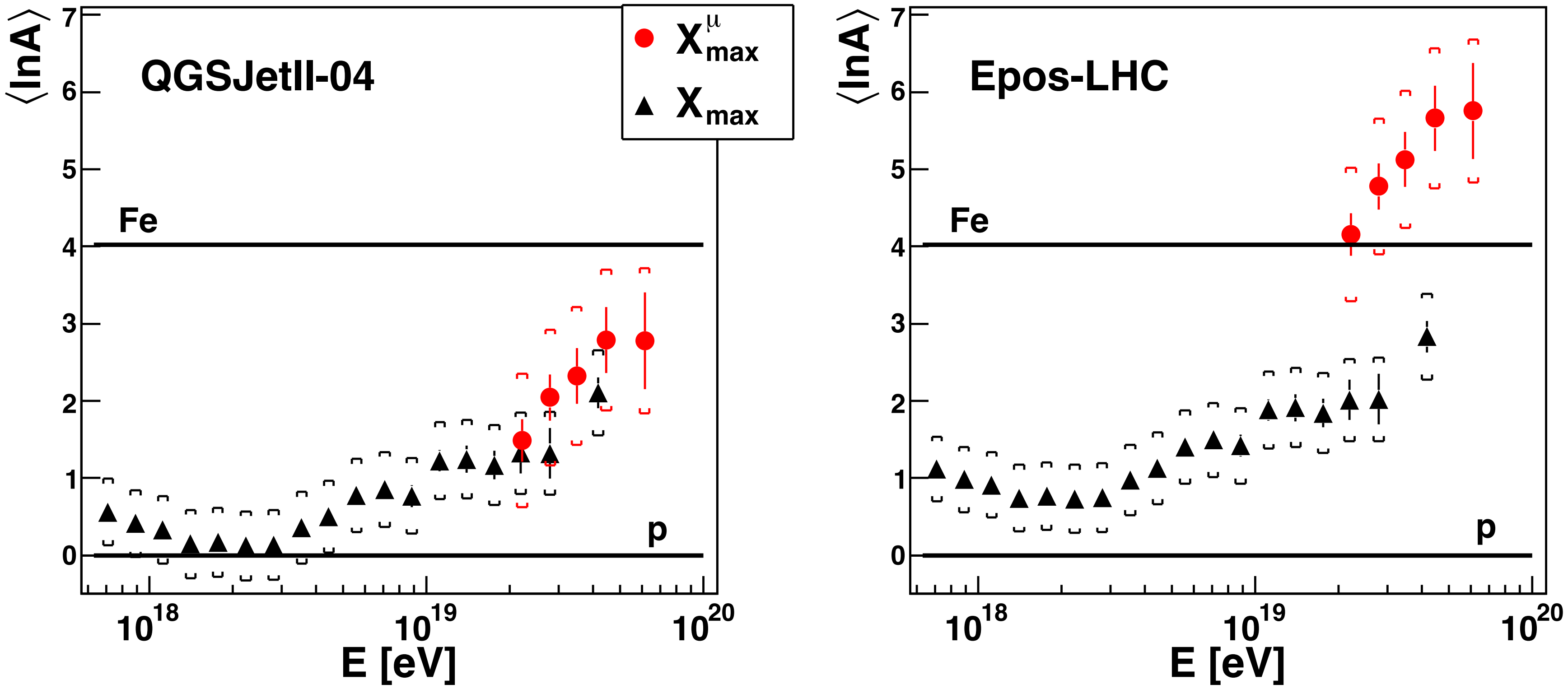
(Auger, arXiv:1408.1421)

Maximum of muon production depth distribution



X^{μ}_{max} complementary to X_{max}:

- X_{max} depends mainly on high-energy interactions
- X^{μ}_{max} depends on both high- and low-energy interactions
- X^{μ}_{max} data support change to heavier composition

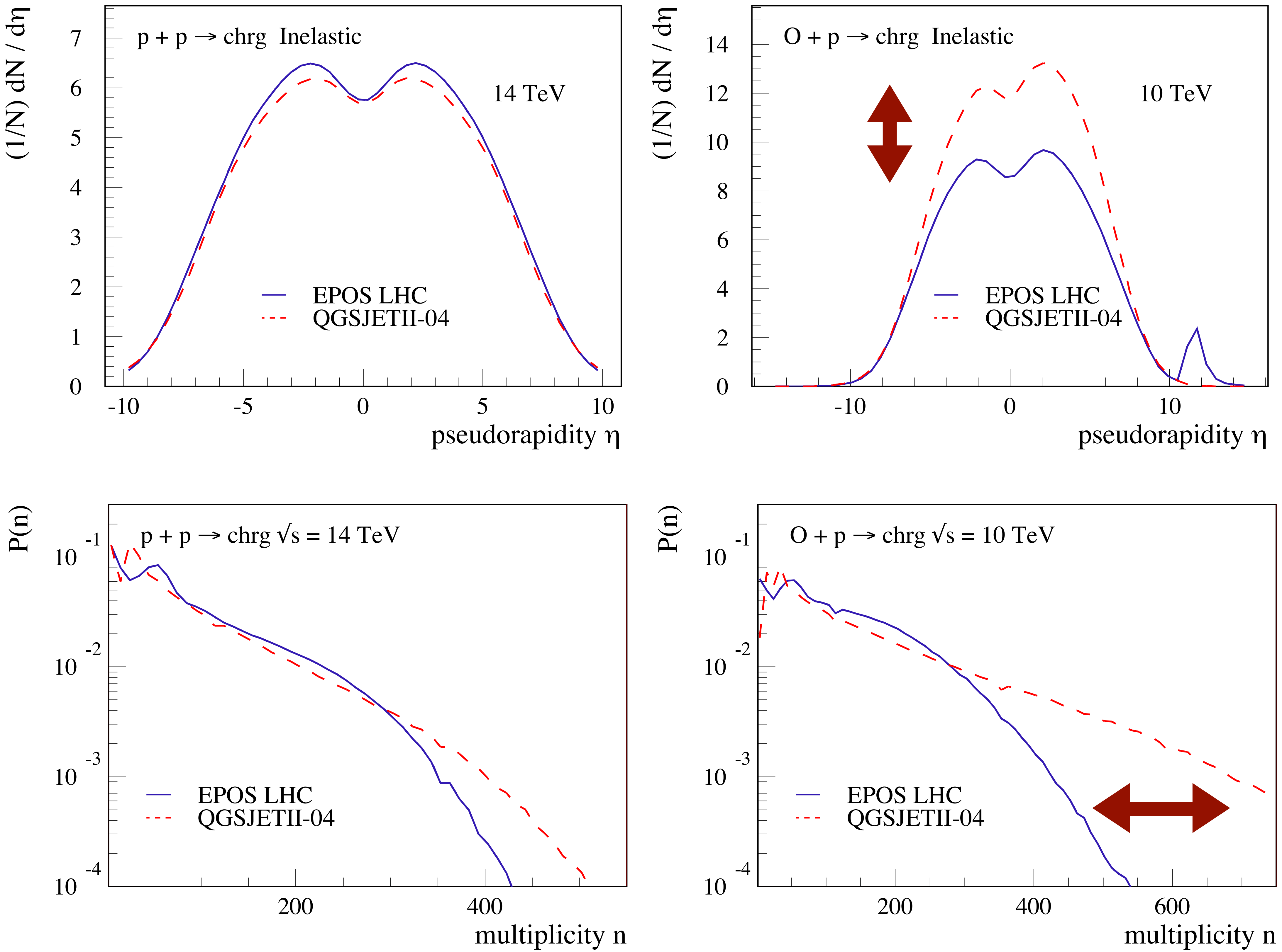


Large sensitivity to pion-air interactions

(Auger, Phys. Rev. D90 (2014) 012012)

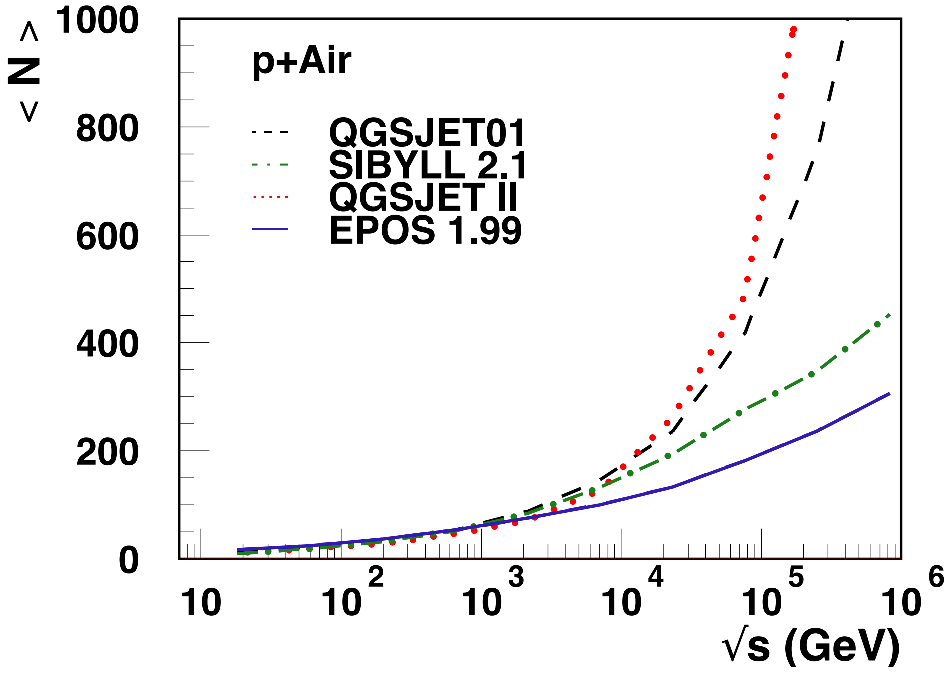
How to obtain more data to improve models?

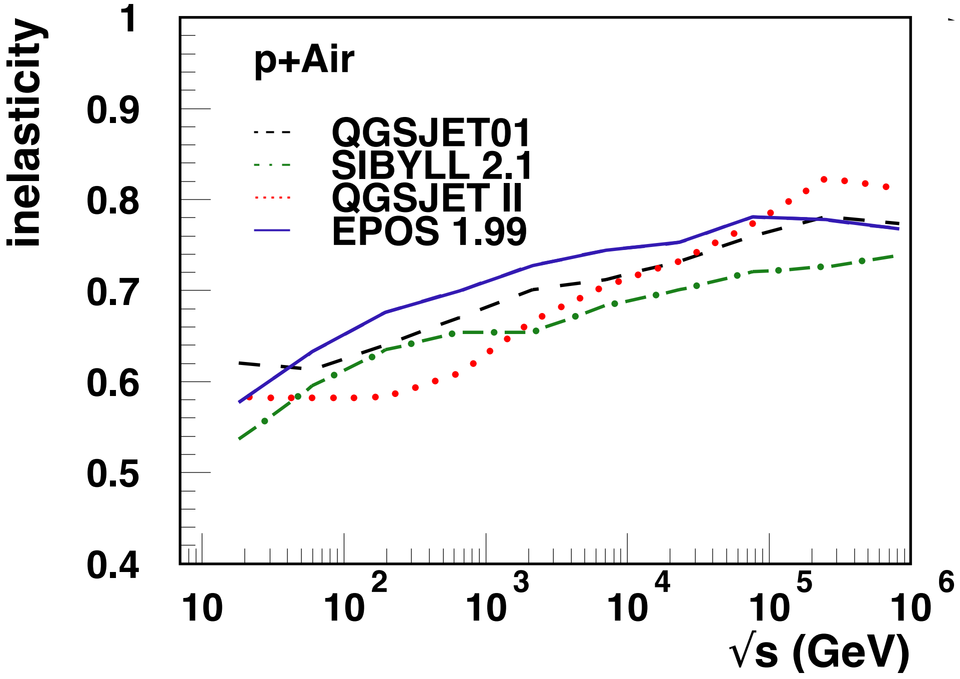
Further improvement: p-O collisions at LHC

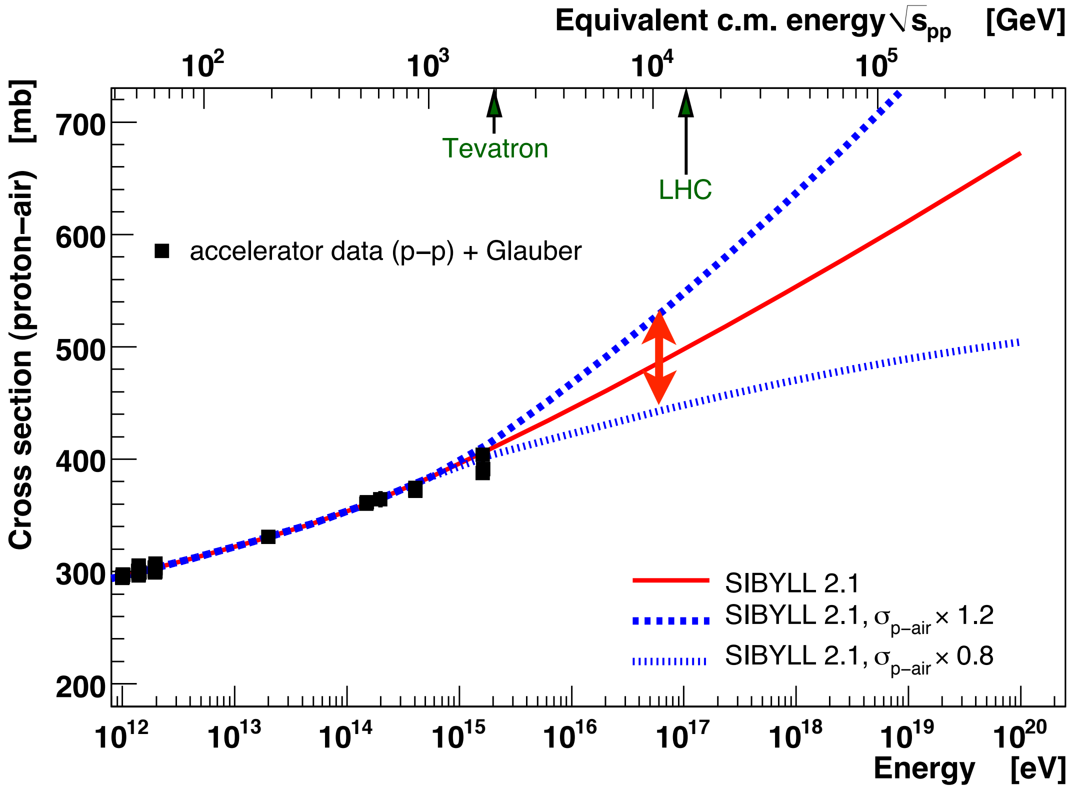


Currently predicted uncertainty in most optimistic case

Construction of phenomenological model







- LHC: p-O interactions with 10 TeV c.m.s. energy per nucleon
- Rescaling of specific features under study
- Extrapolation from 2 TeV c.m.s. energy linear in log(s)

(Berge et al., similar to Ulrich et al., Phys. Rev. D83, 2011)

Impact on predicted depth of shower maximum

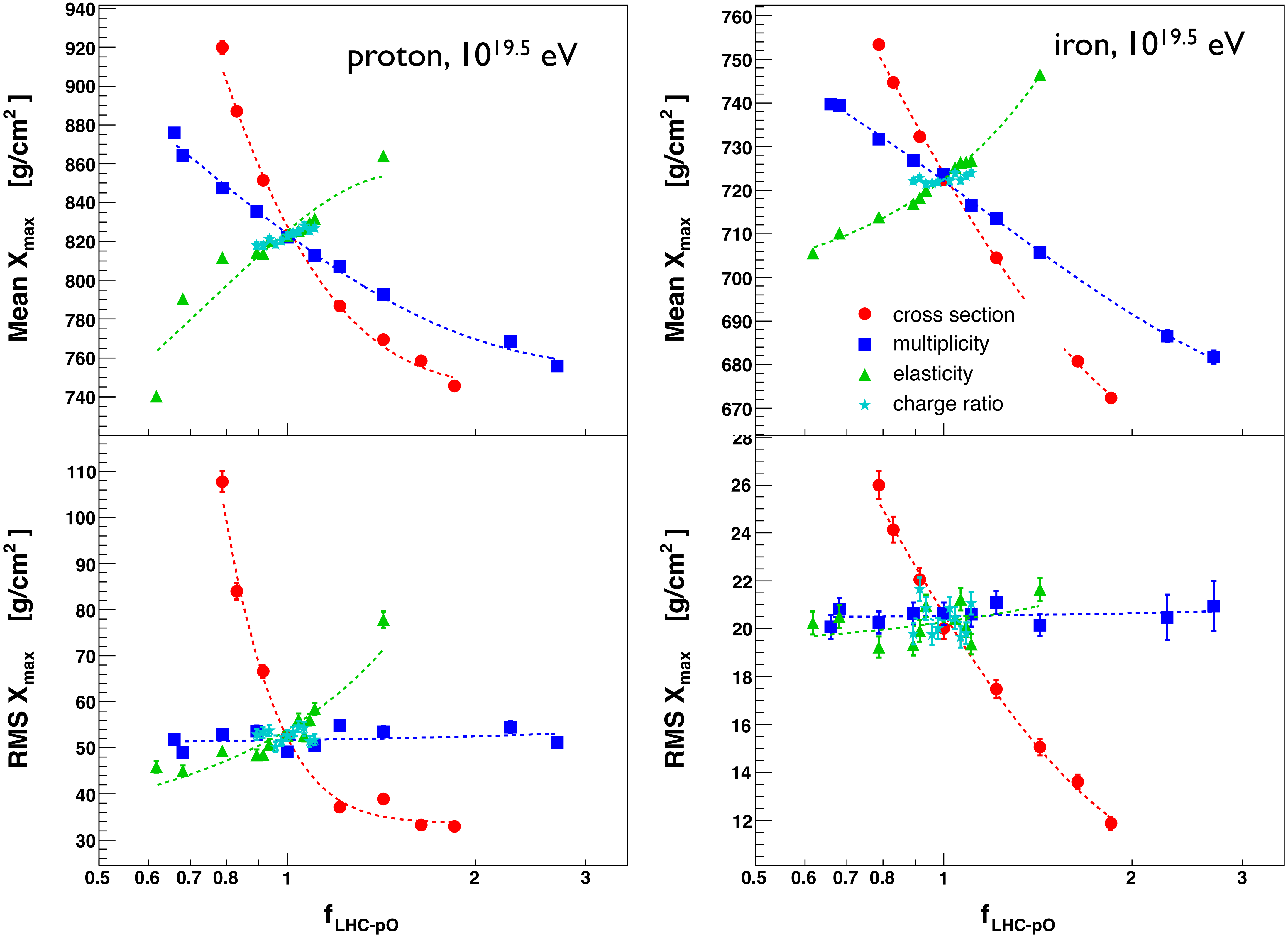
Fe

Si

CNO

He

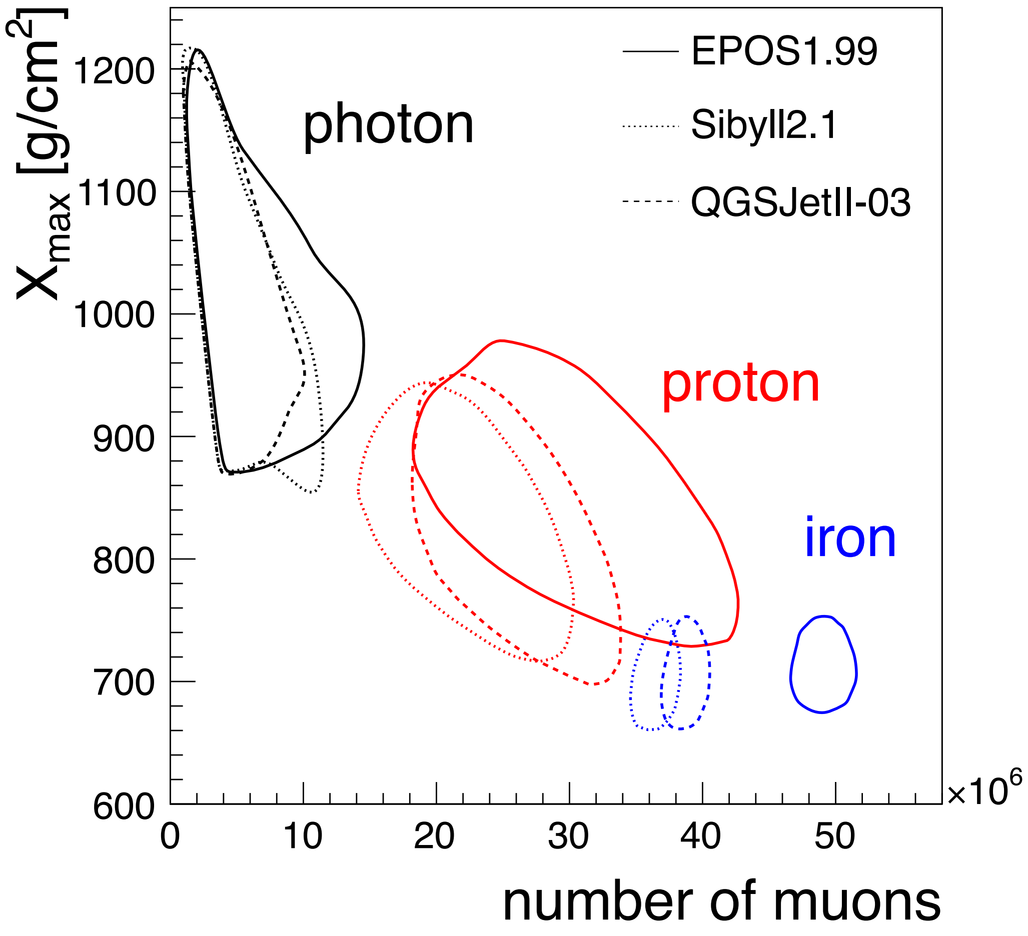
p



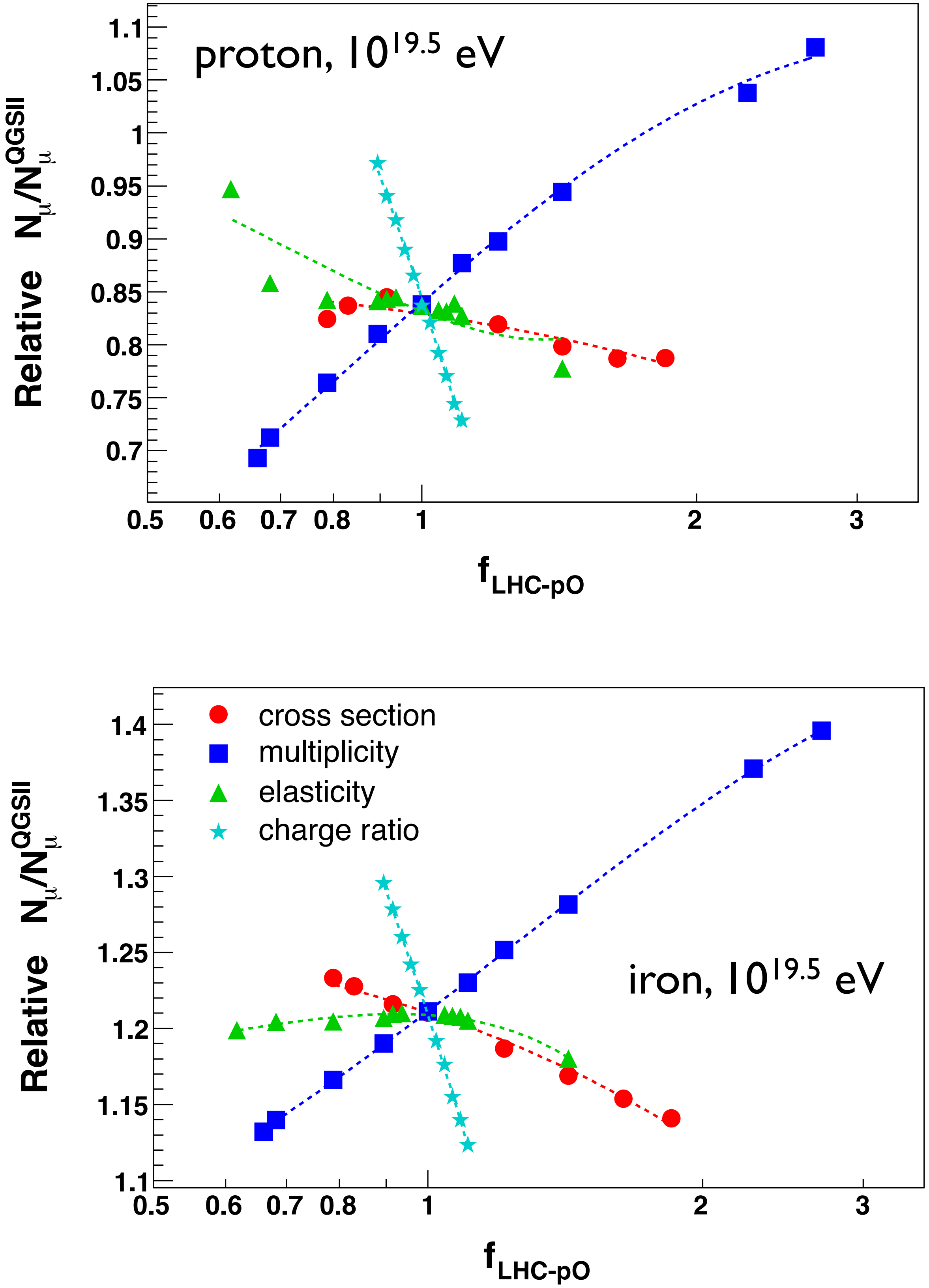
(Berge et al., 2014)

Impact on predicted muon number at ground

(Kampert & Unger, APP 35 (2012) 660)



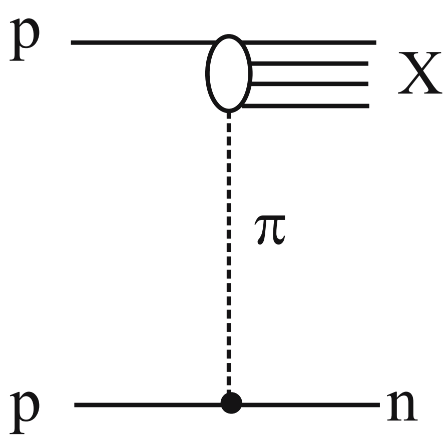
Changes of 10% important



(Berge et al., 2014)

Pion-proton and pion-nucleus interactions

Measurement of pion exchange at LHC



Pion fragmentation
region in ATLAS

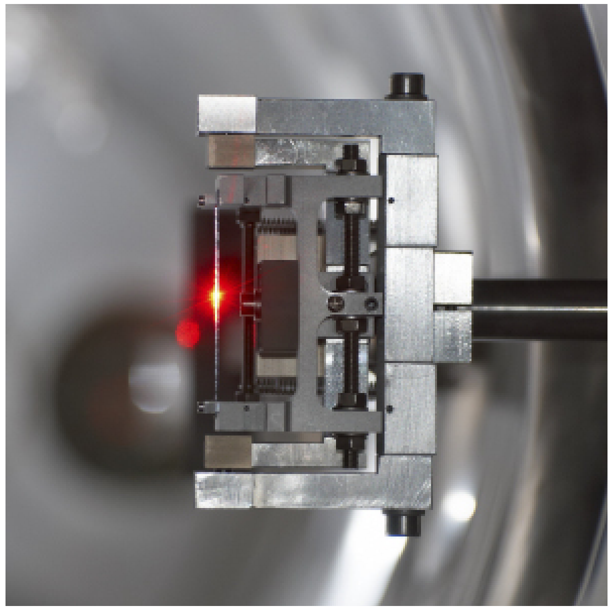
Leading neutron in LHCf

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

(Ulrich et al., ICRC 2015)



Deflection of protons
of beam halo by crystal

Summary & outlook

Overall reasonably good description of inclusive shower observables,
but some shortcomings in reproducing correlations (composition)

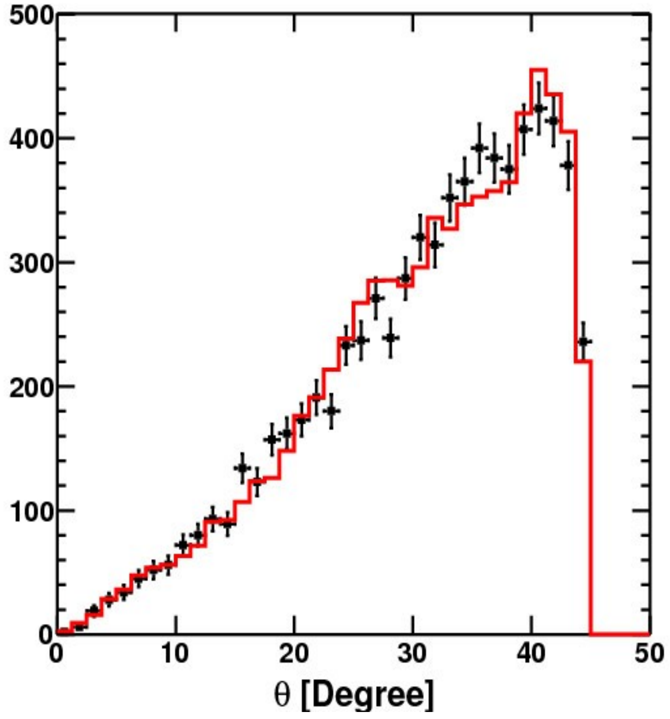
Accelerator data triggered new developments of hadronic interaction models

Muon production still rather uncertain, some sources of uncertainty identified

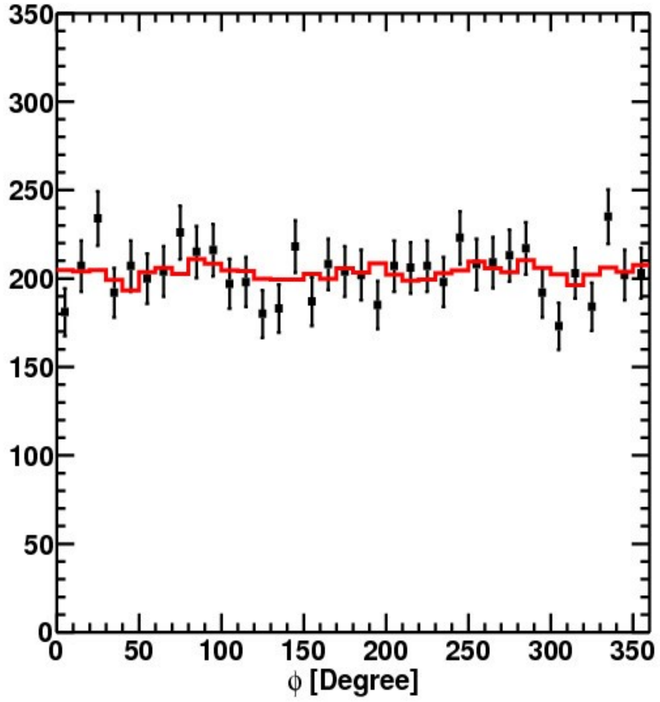
Uncertainty of X_{max} predictions not really understood

Dedicated accelerator measurements and data analyses possible
and needed to improve situation

TA event simulation for surface array

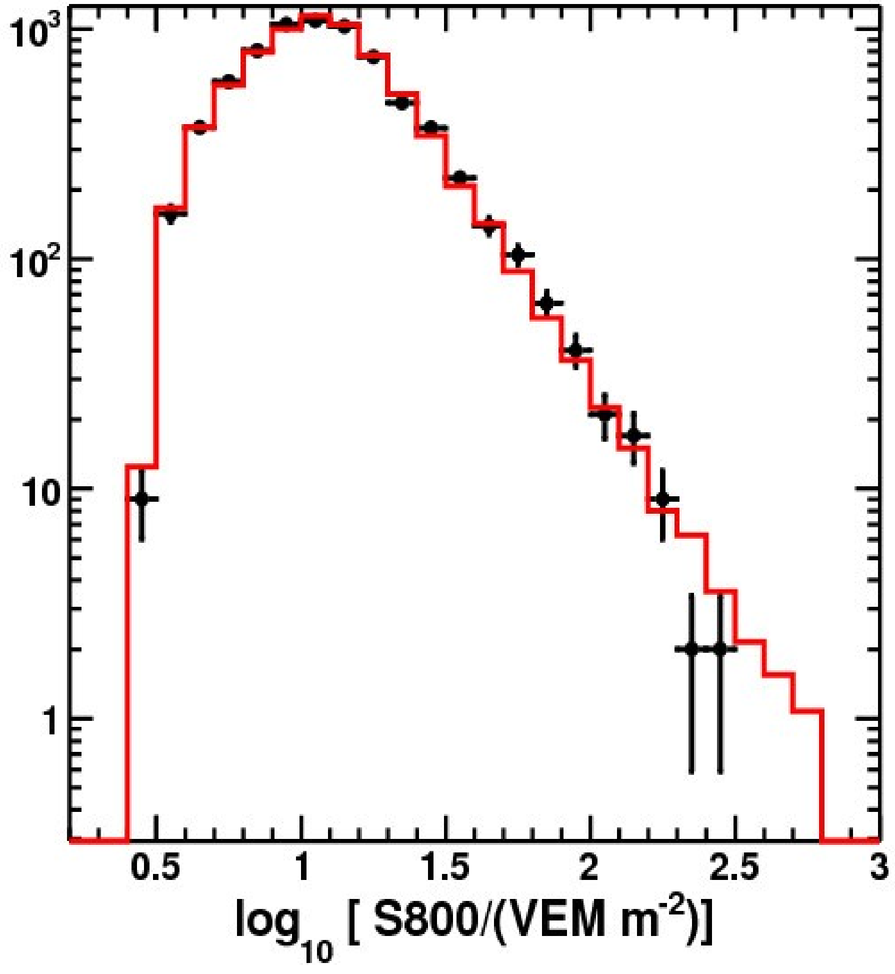


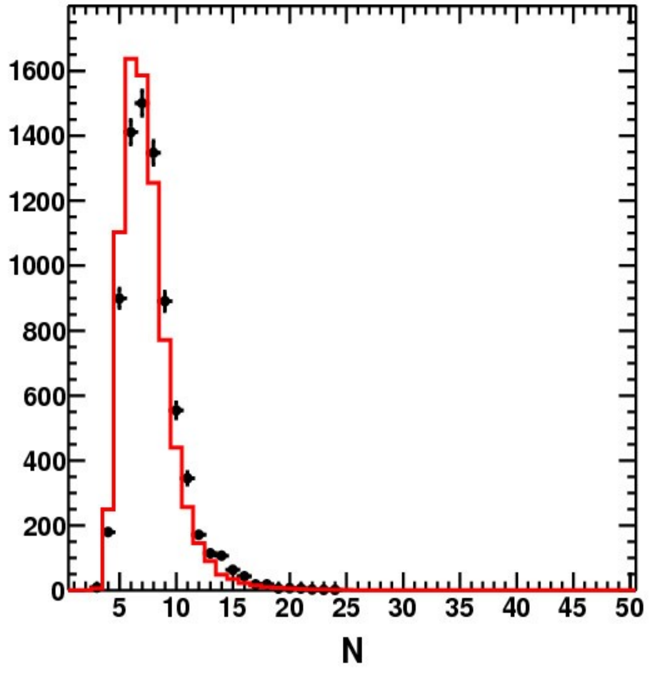
Zenith Angle



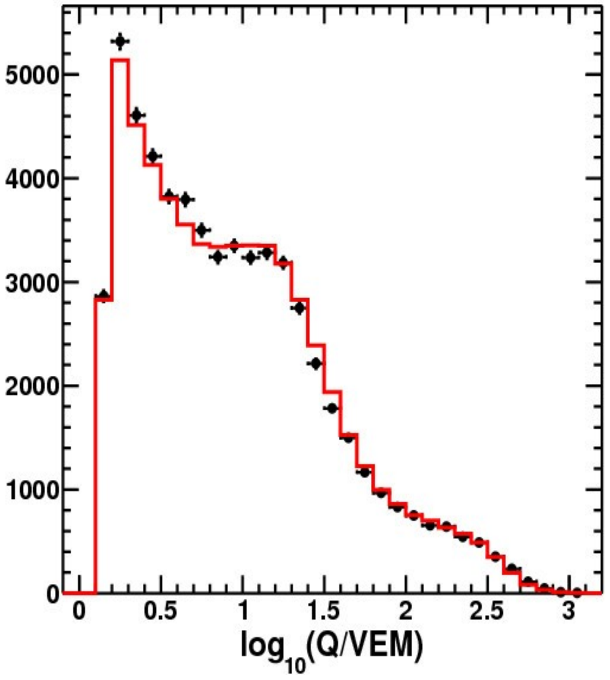
Azimuth Angle

CORSIKA + full detector simulation (proton primaries)





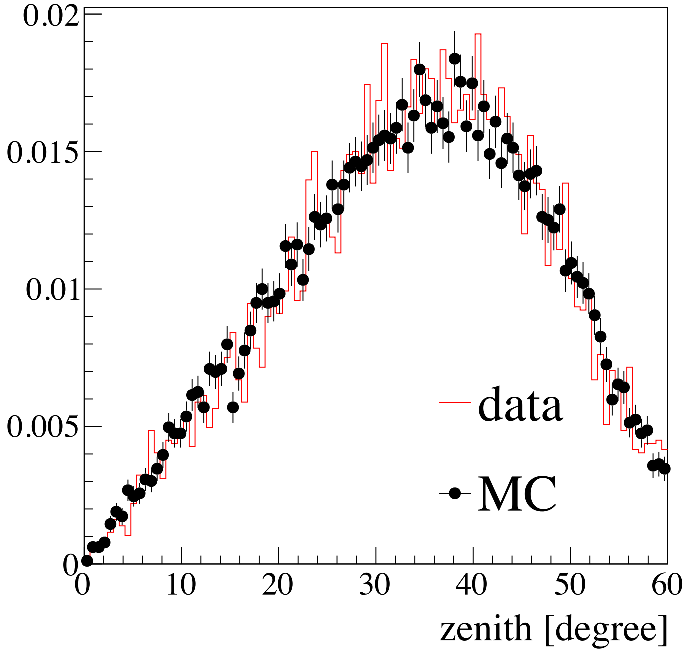
Number of Good Counters/Event



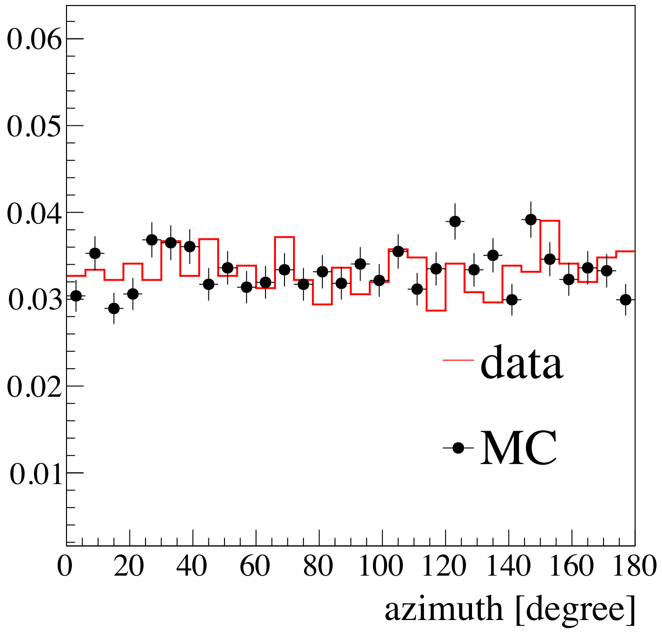
Charge/Counter/Event

Very good agreement

Auger event simulation for surface array

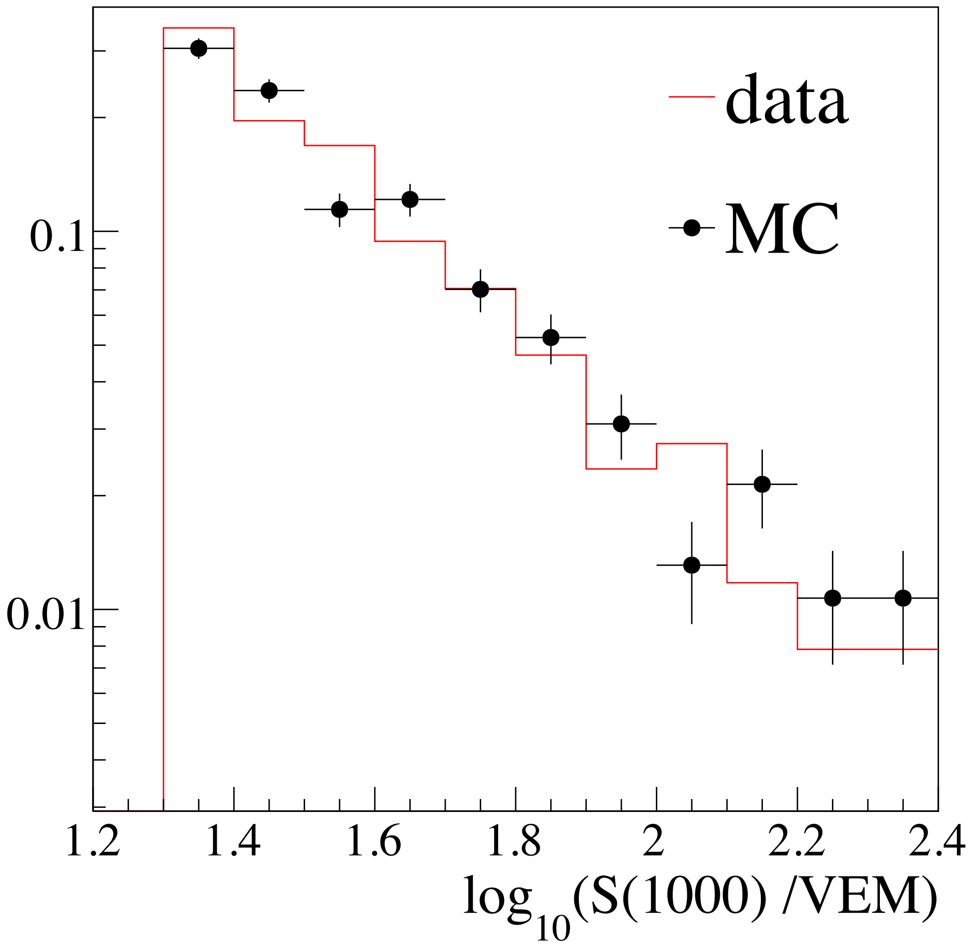


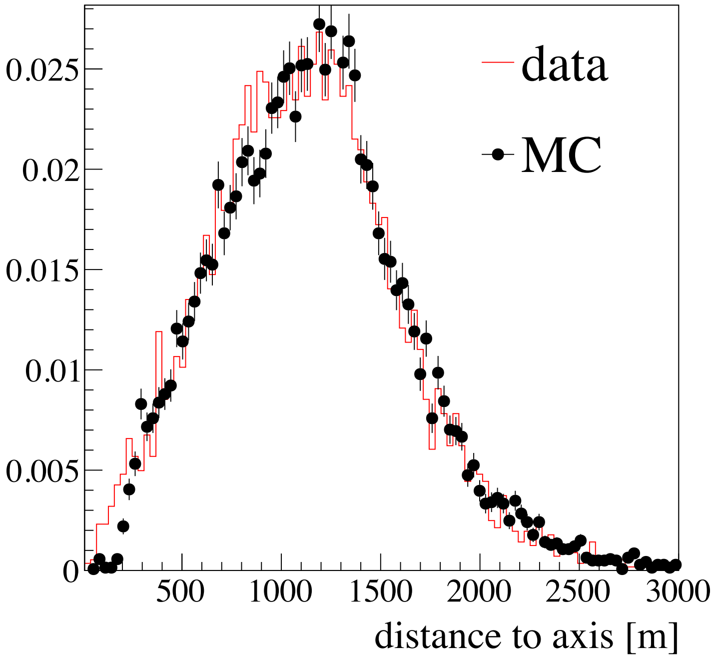
Zenith angle



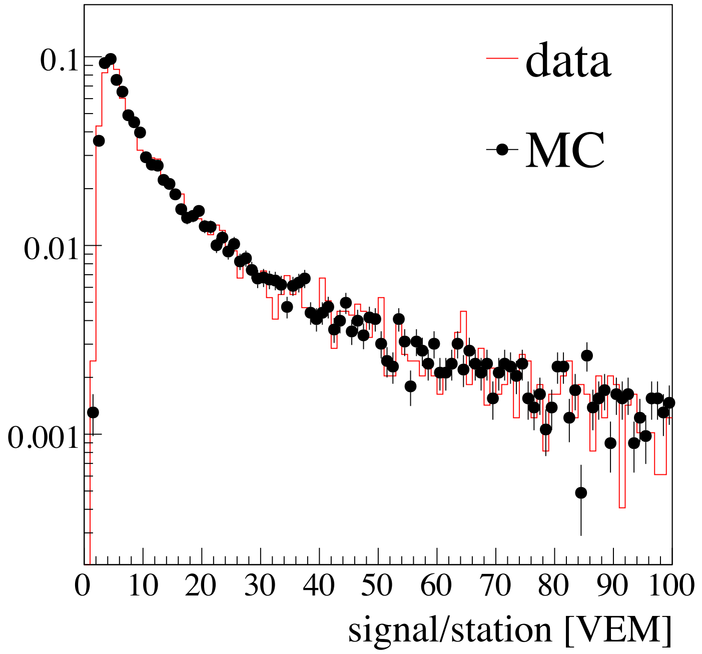
Azimuth angle

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





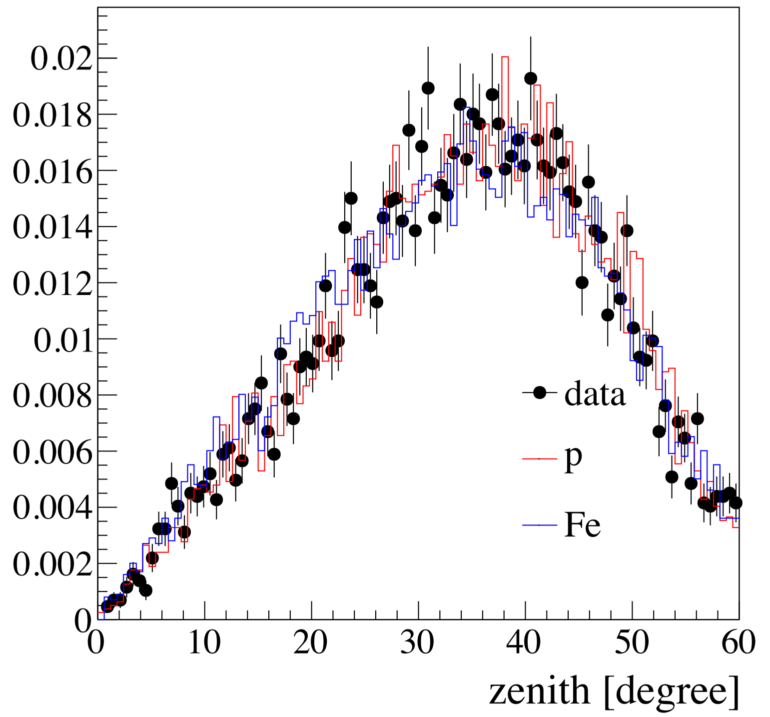
Distance of triggered stations



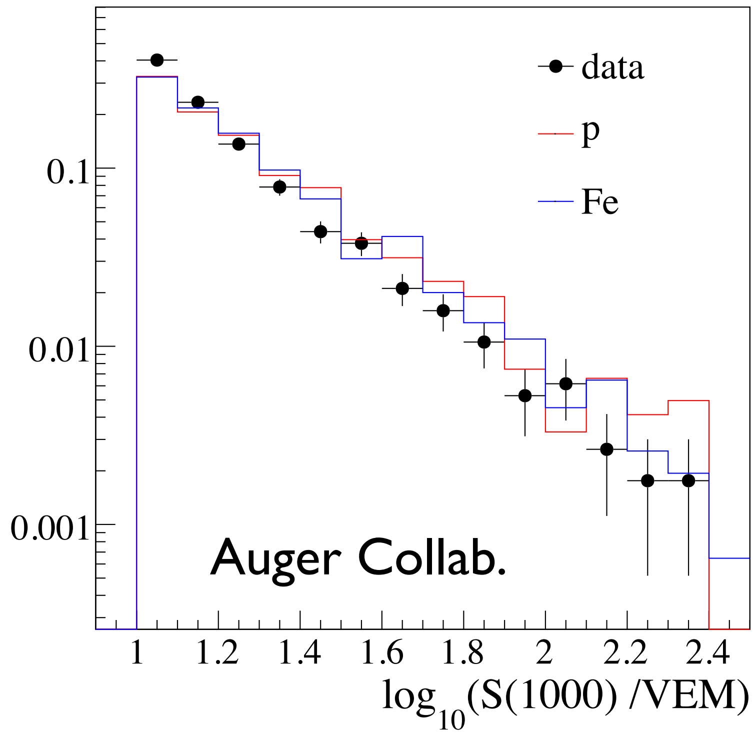
Signal per station

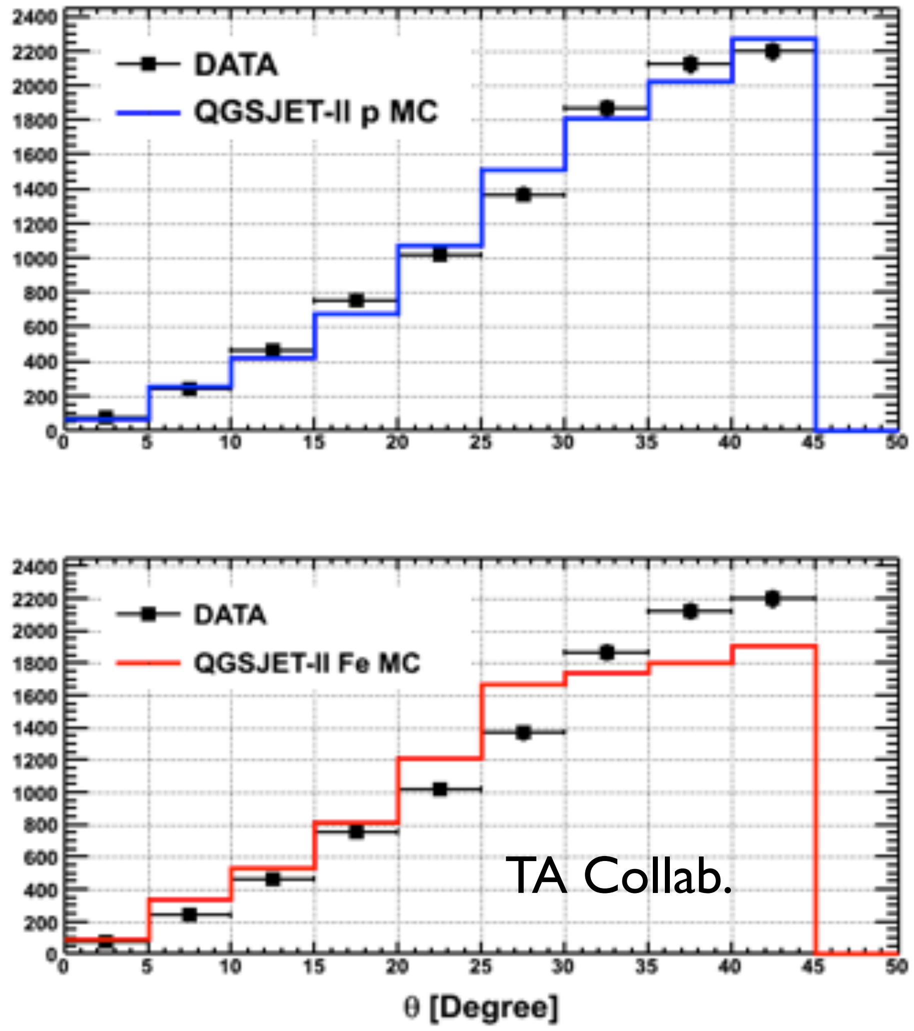
Very good agreement

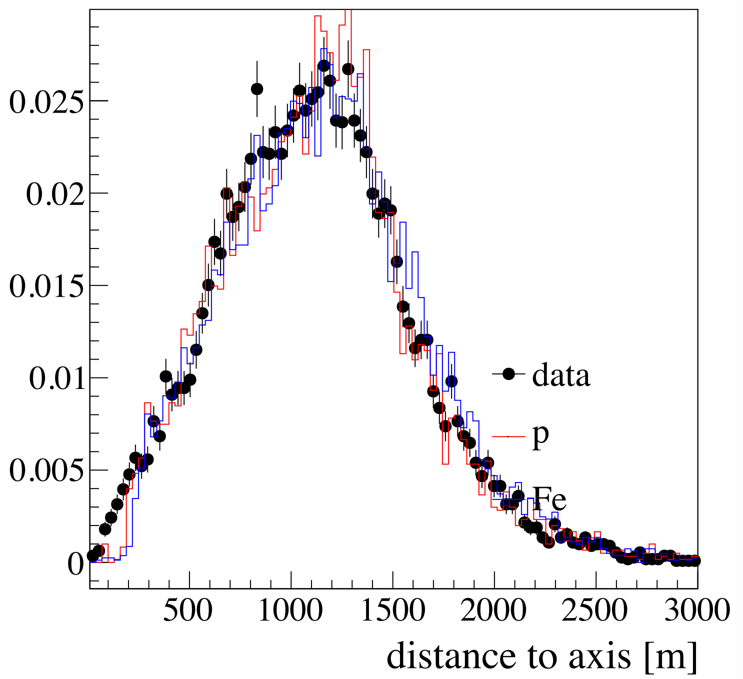
Composition and model sensitivity ?



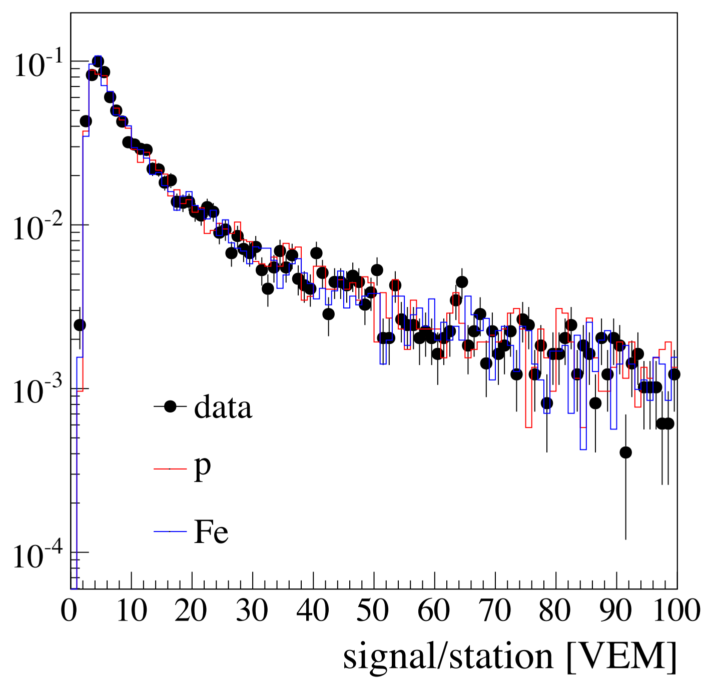
Zenith angle







Distance of triggered stations



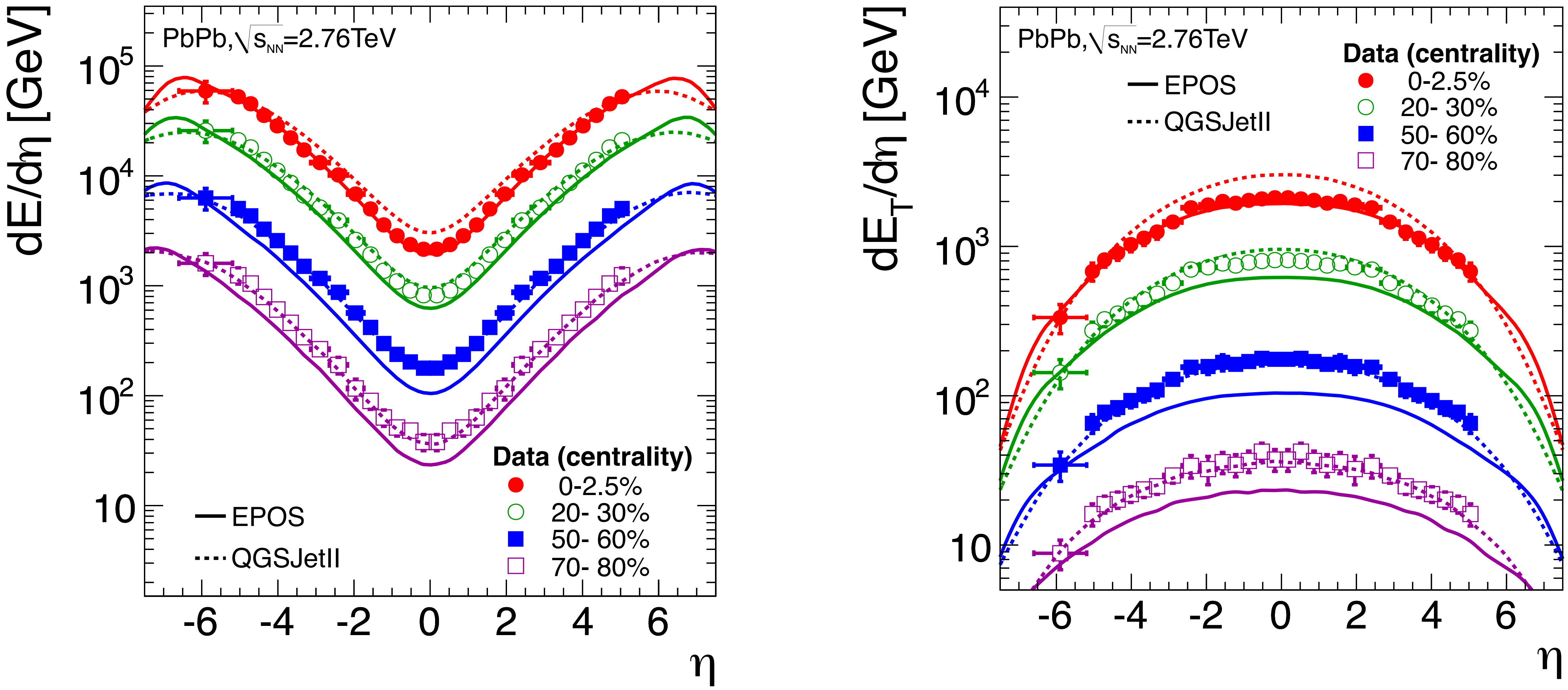
Signal per station

Most observables not very sensitive to details of shower simulation

Backup slides

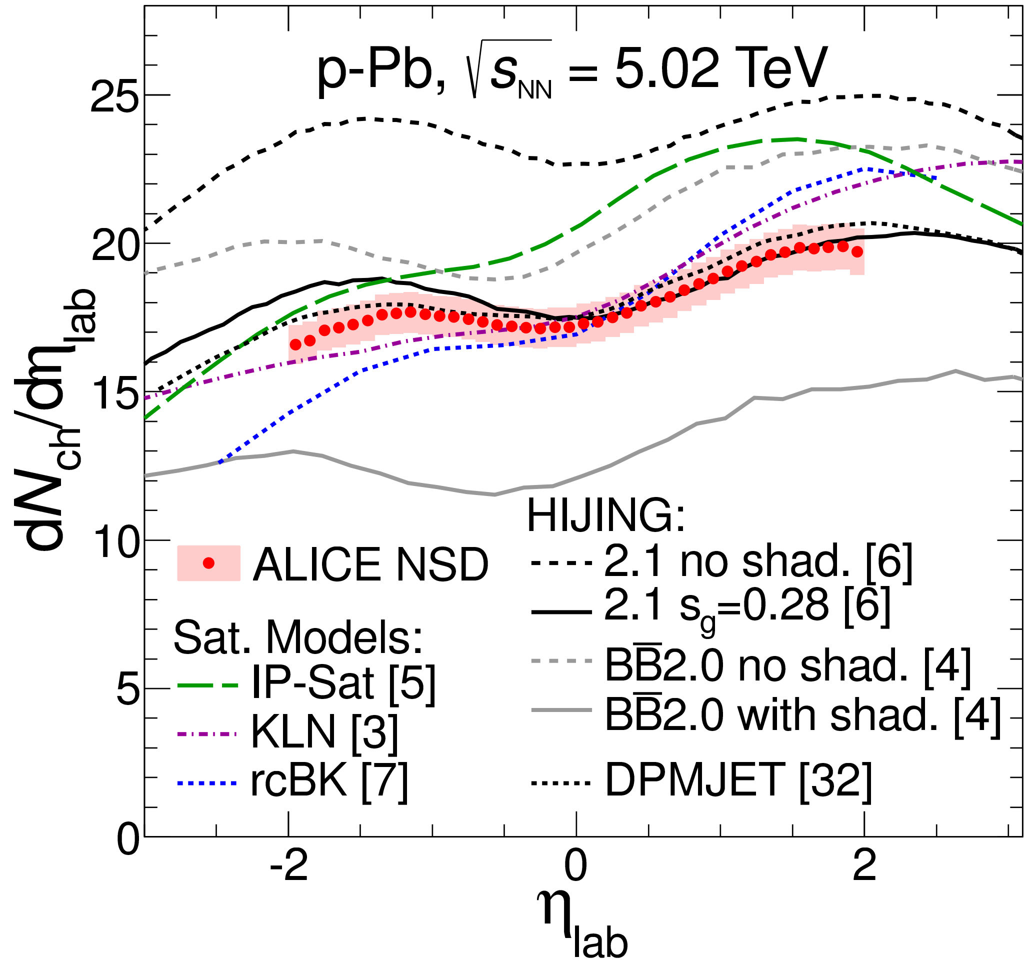
What can we learn from the Pb-Pb data ?

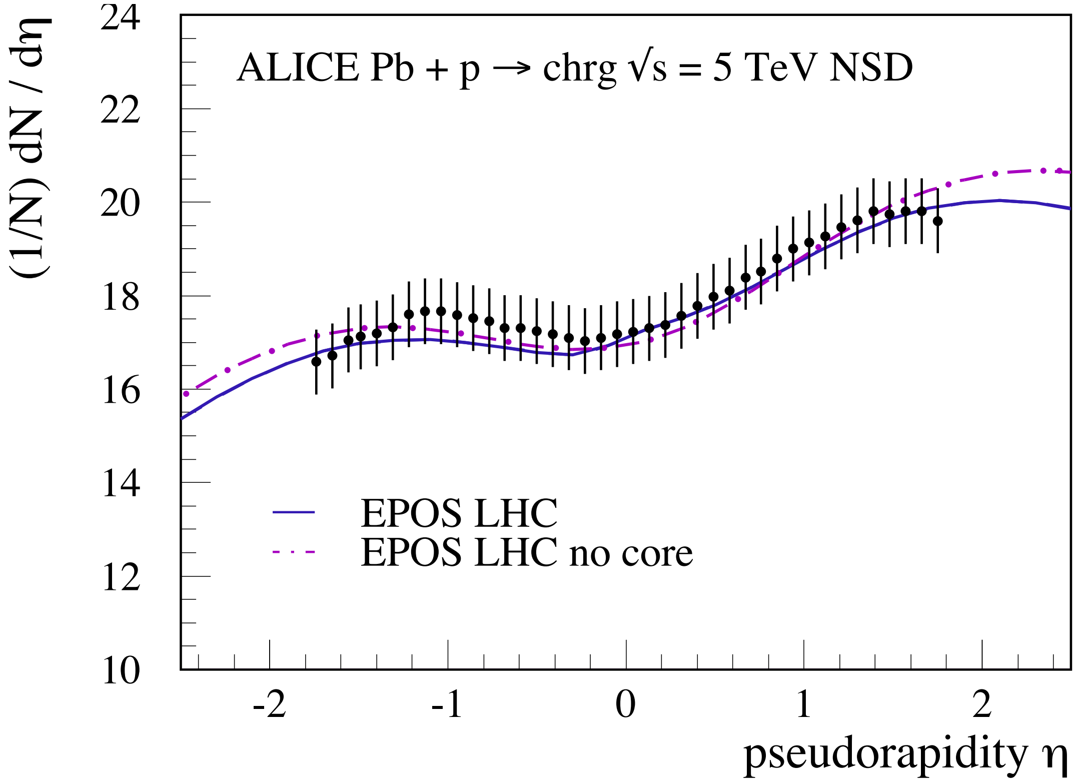
Example: lead-lead collisions (CMS results)

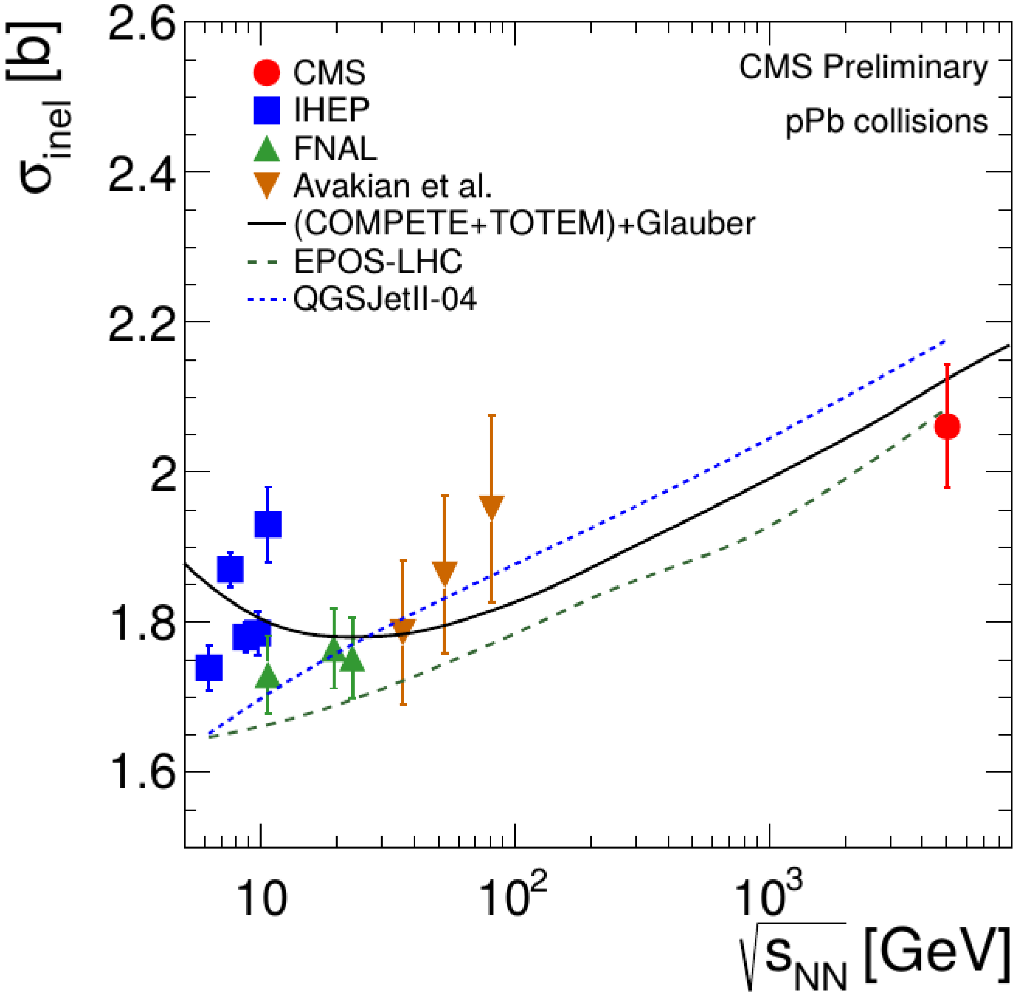


- Mixed results: EPOS better for central collisions, QGSJET better for peripheral ones ?
- Not all models can be run for heavy ions, no hydrodynamics implemented (except EPOS)
- Importance of high-density effects much higher in Pb-Pb than air showers

And what about p-Pb data ?





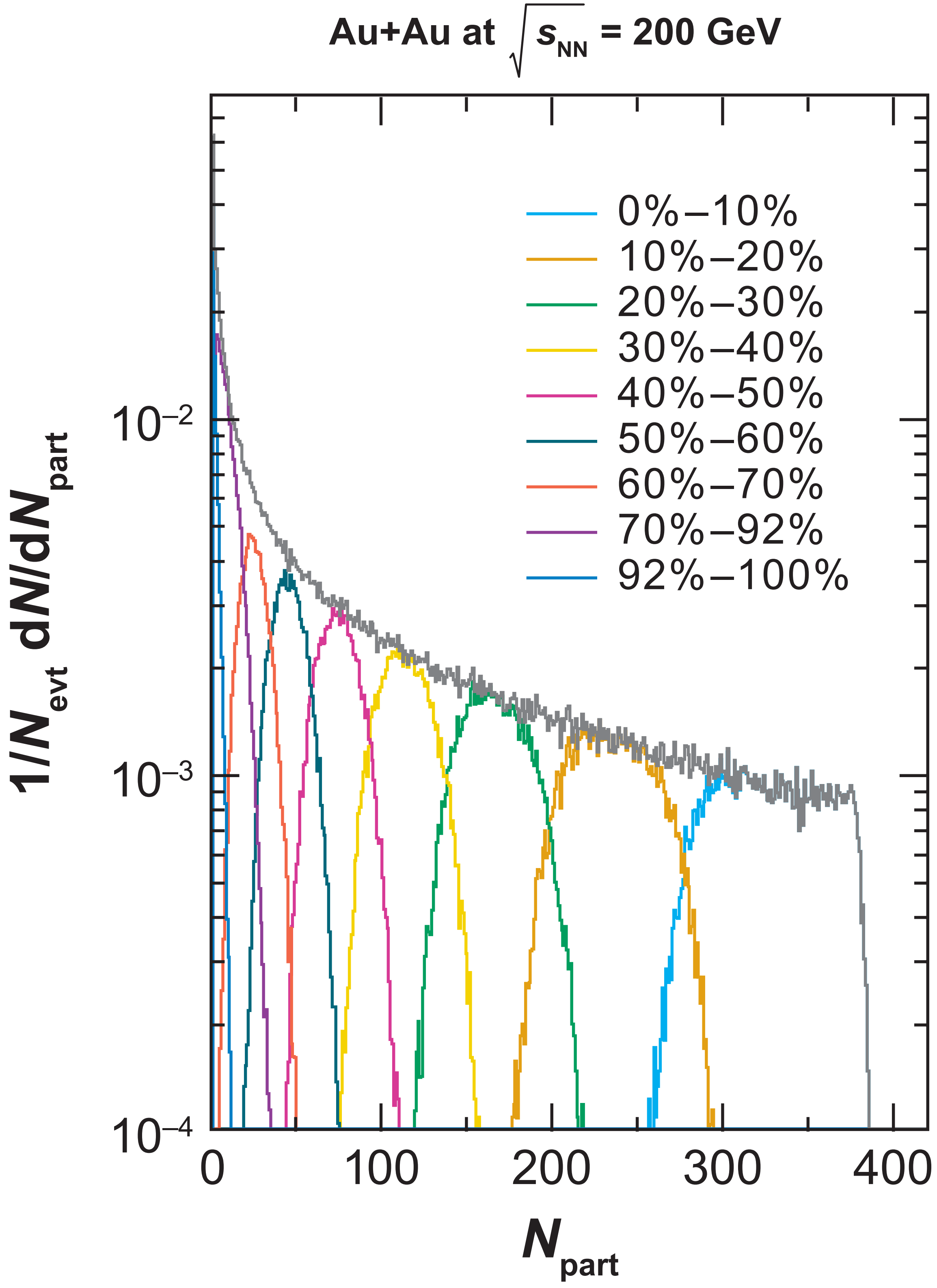


Problem: no theory or recipe for transition from high-density physics to peripheral collisions

How to select peripheral collisions ?

Selection using activity in
central region not suited,
as this should be an observable

Only practical possibility:
measurement of forward
spectator nucleons?

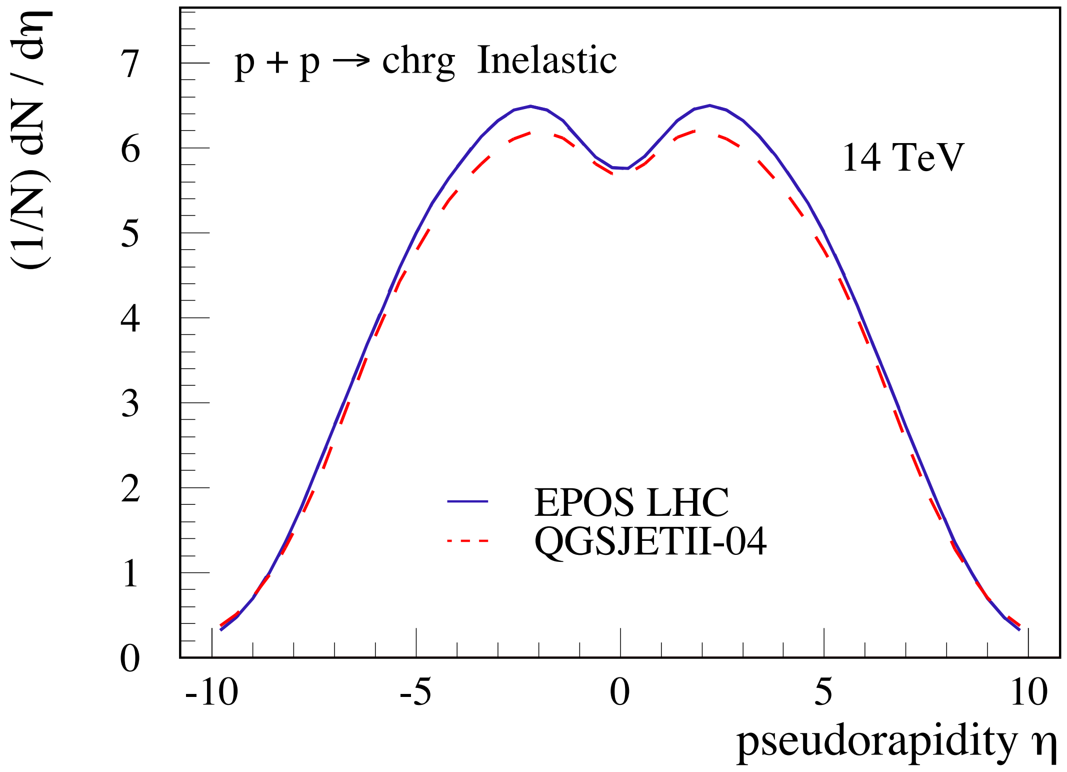


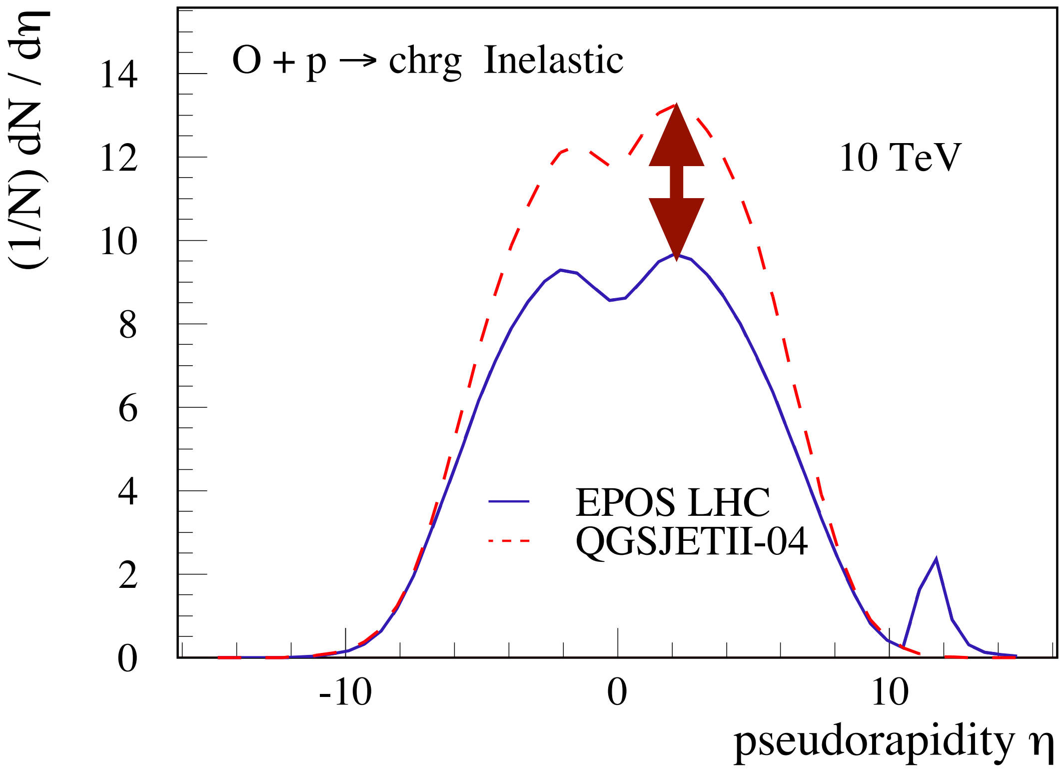
(Miller at al., Ann. Rev. Nucl. Part. Sci. 2007)

Need for measuring p-O collisions at LHC

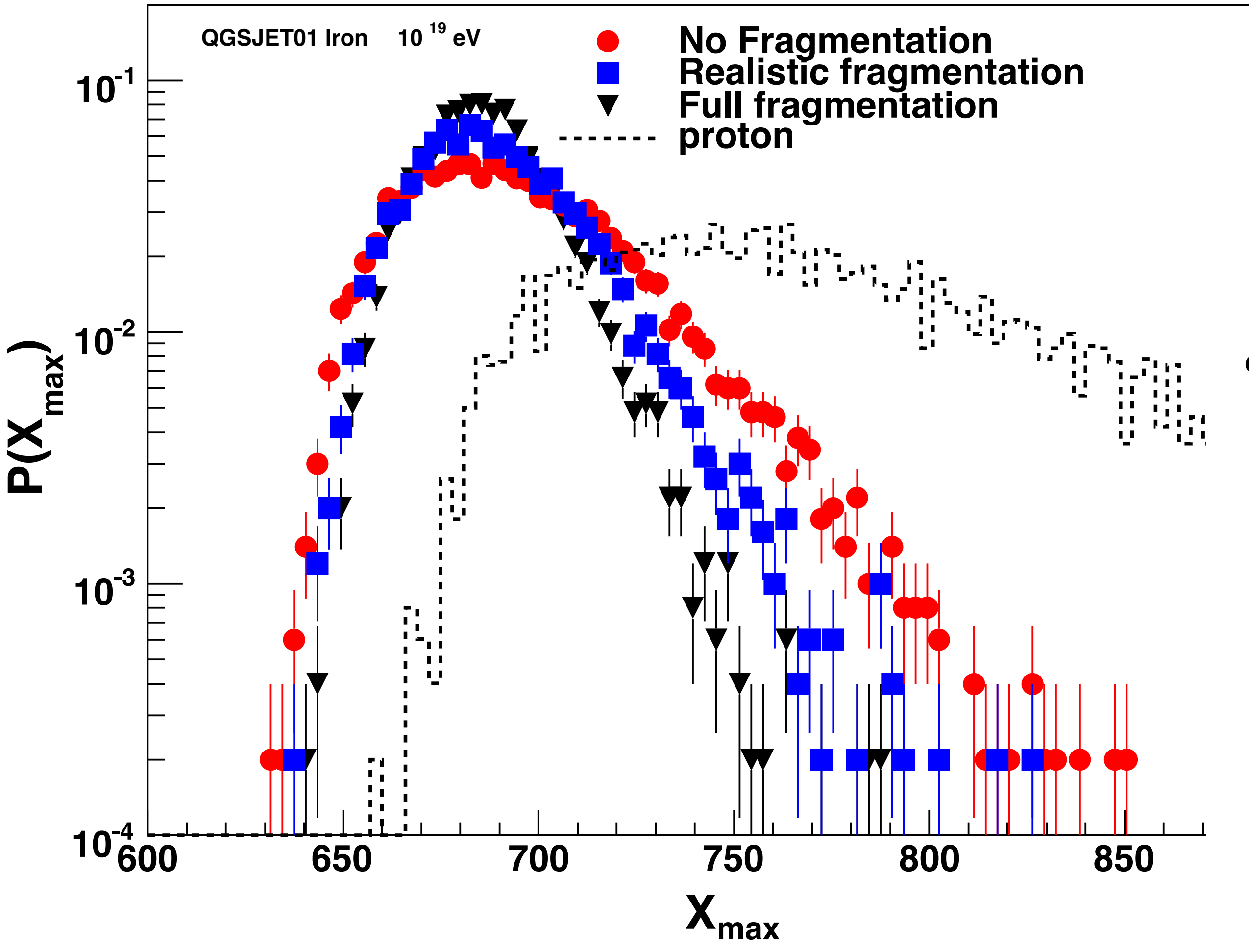
So far models only tuned for p-p interactions (and partially p-Pb, Pb-Pb)

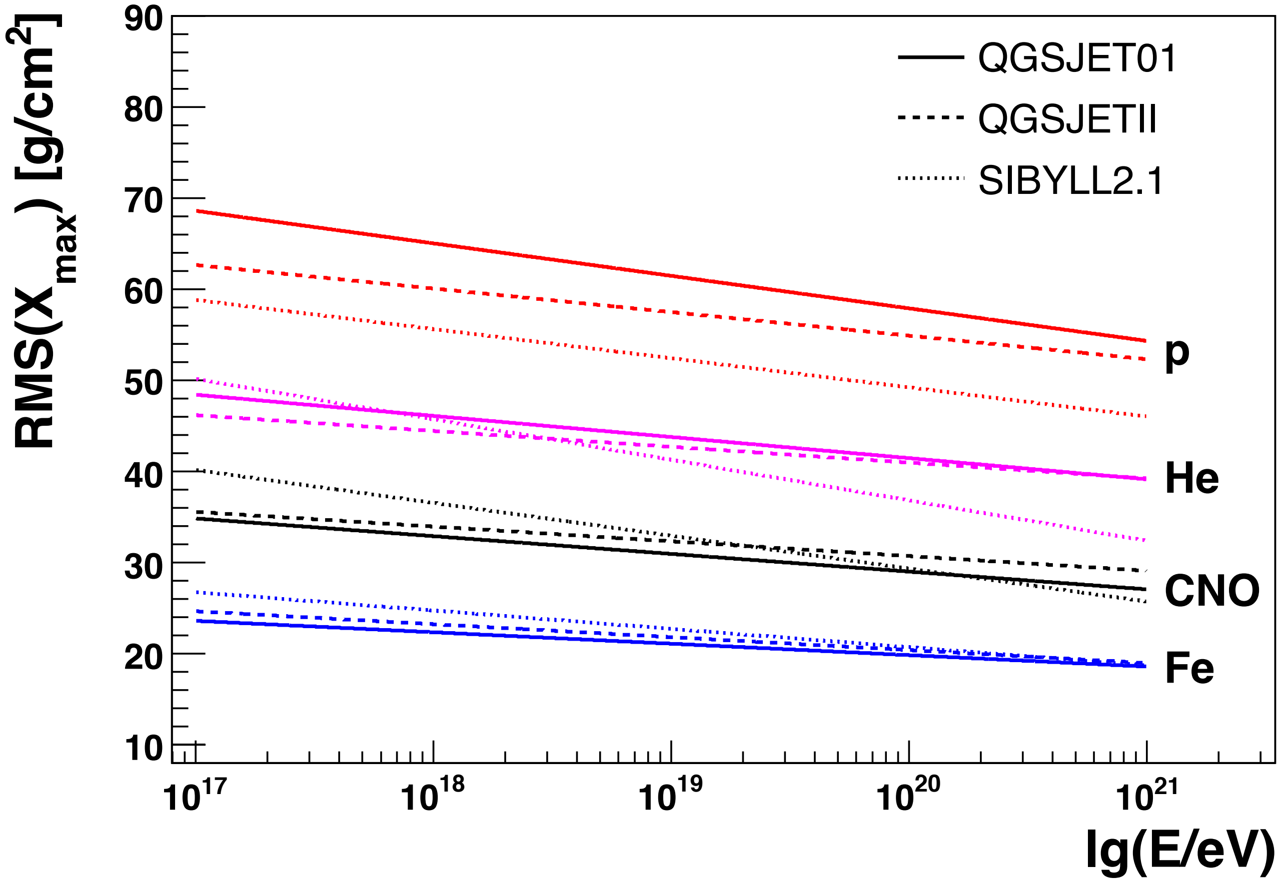
- Models with similar p-p predictions differ significantly for p-O
- Example: difference in multiplicity prediction of models corresponds to difference between p and He of cosmic ray particles (ΔXmax ~ 20 g/cm^2)
- Forward particle production in p-O essentially unknown
- Peripheral collisions in p-O much more important than in p-Pb
- Model predictions give only **lower limit to real uncertainty** due to similar assumptions, need data to estimate real uncertainty





Importance of correlations for fluctuations





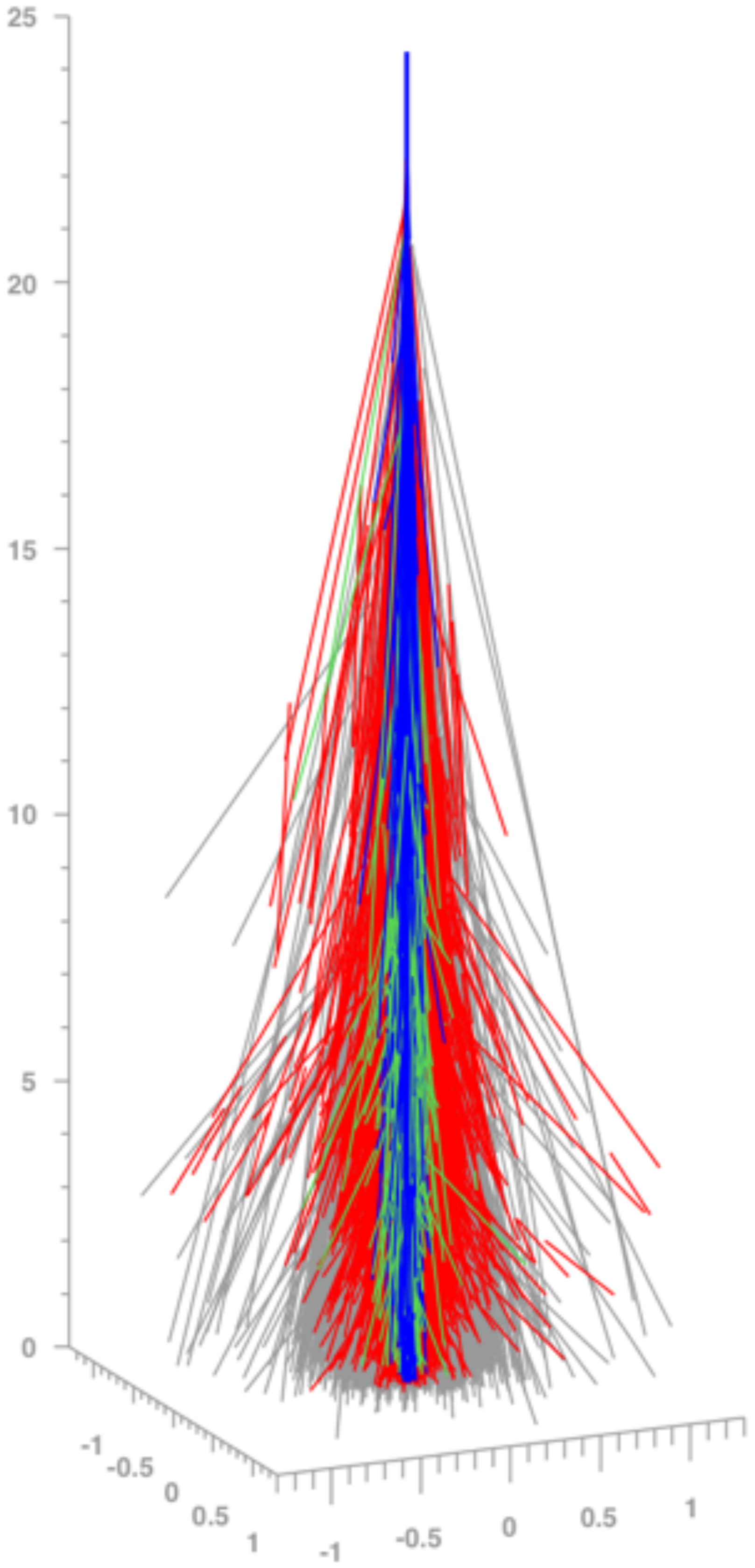
RMS(Xmax) = 29 g/cm^2

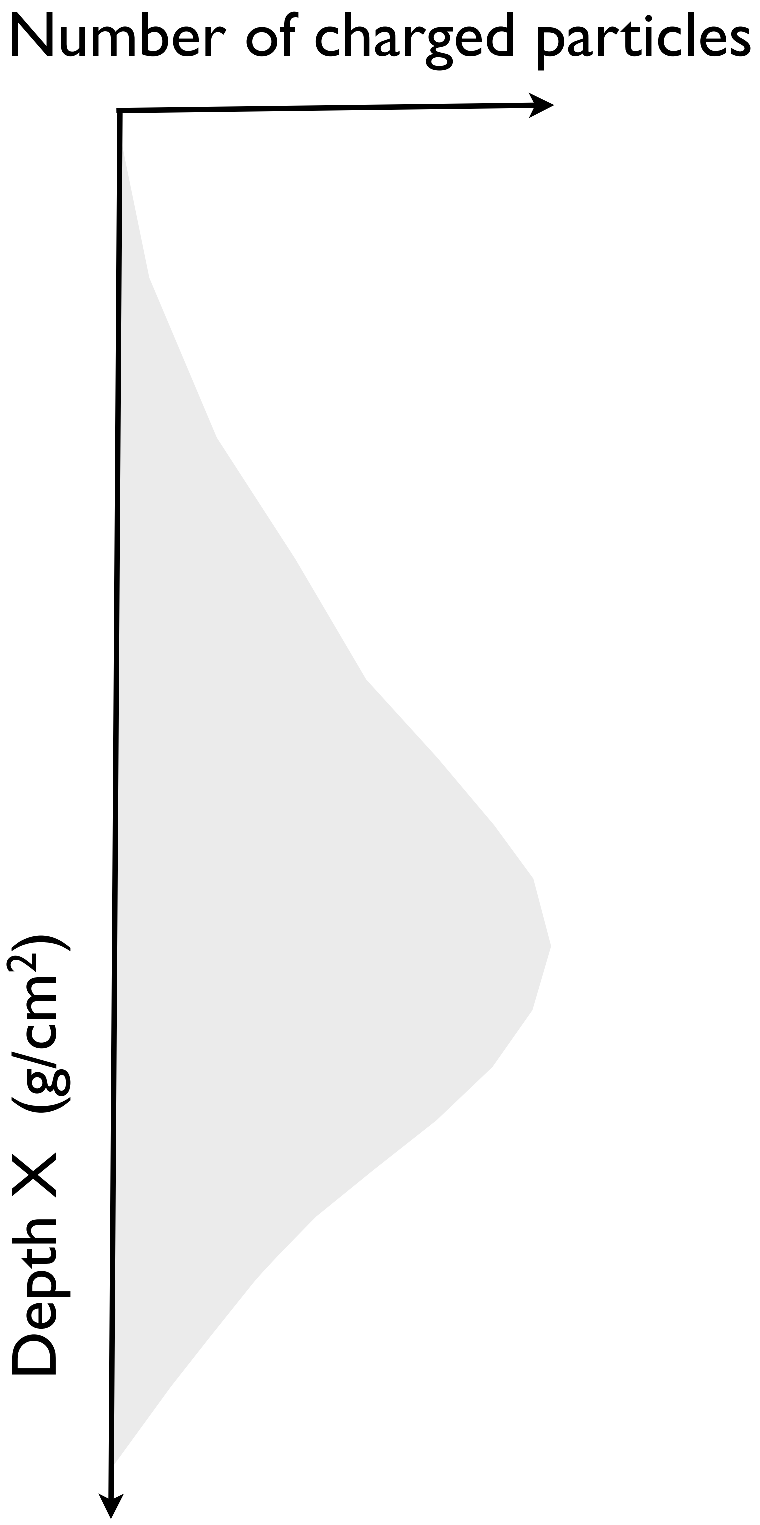
21 g/cm^2

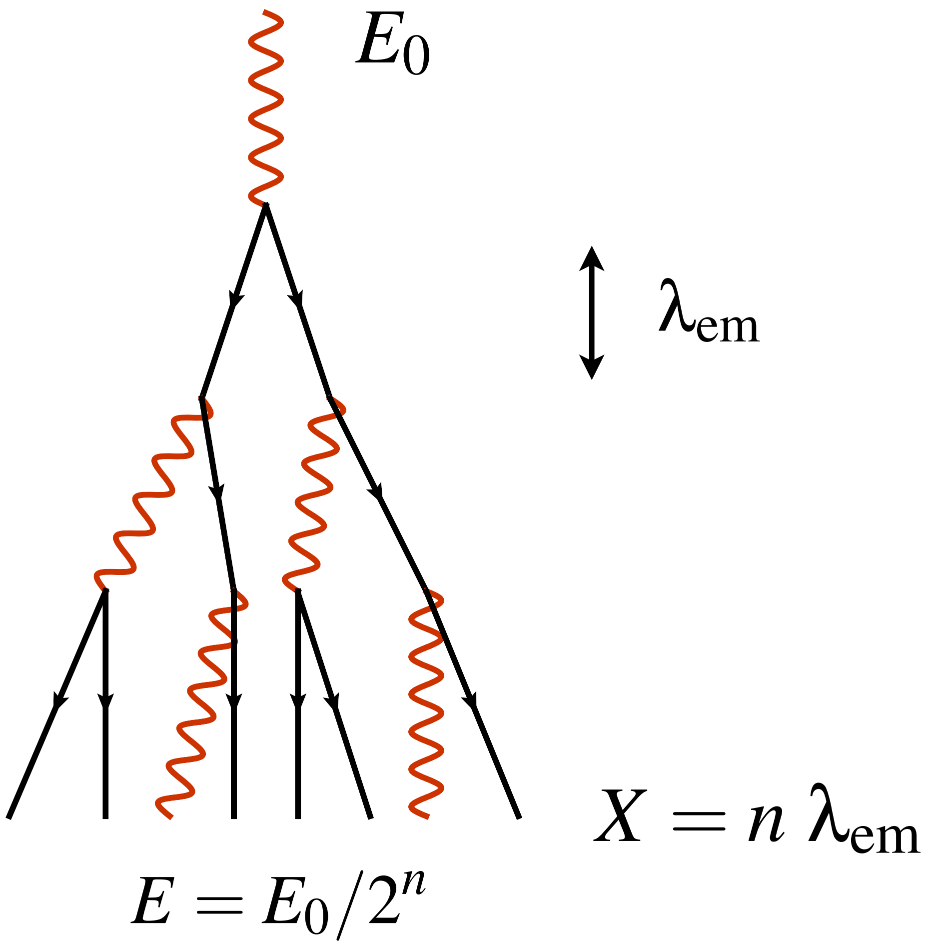
16 g/cm^2

Nuclear fragmentation is important for quantitative predictions

Electromagnetic showers: Heitler model







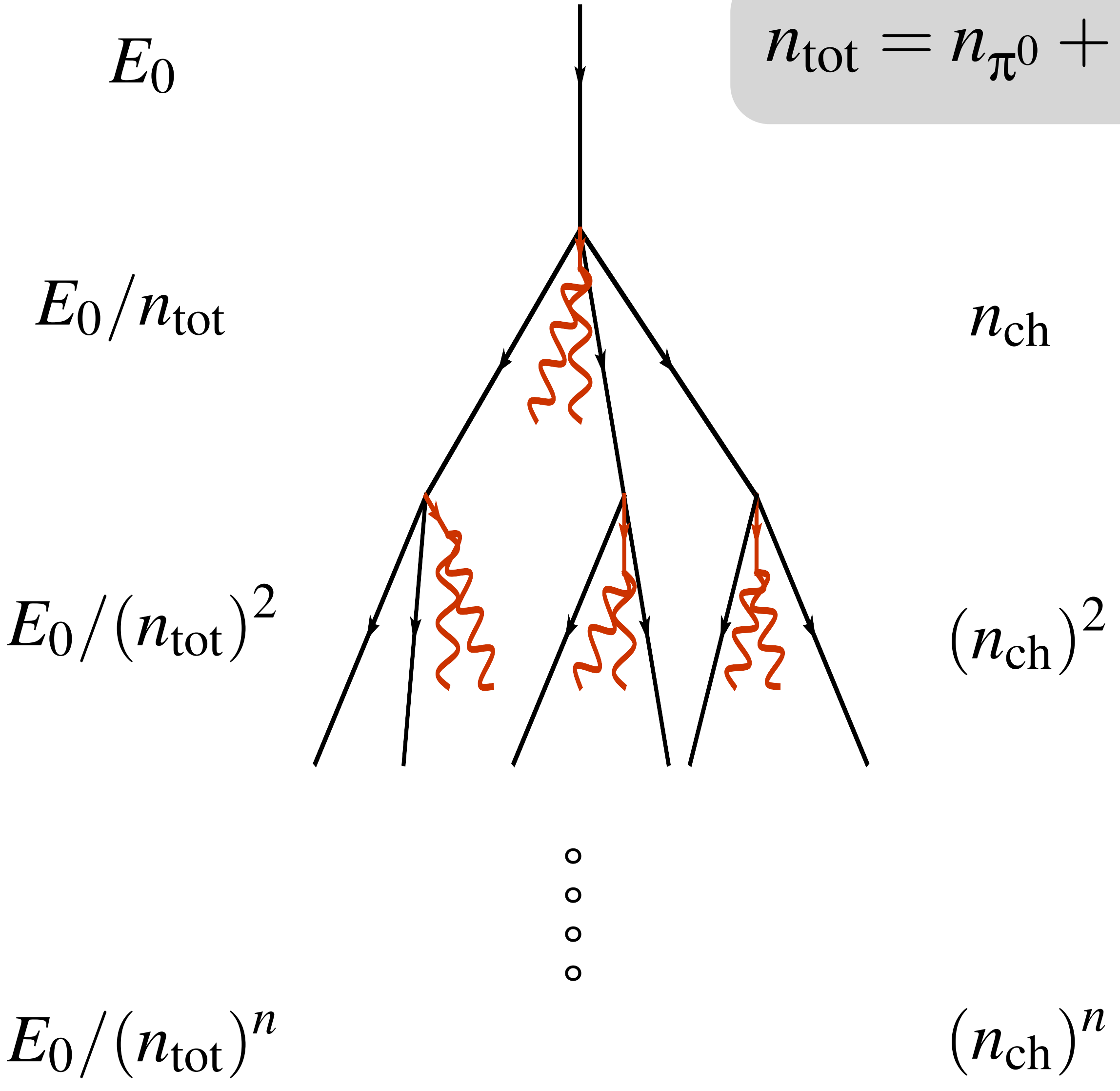
Shower maximum: $E = E_c$

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

$$X_{\max} \sim \lambda_{\rm em} \ln(E_0/E_c)$$

Muon production in hadronic showers

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



Primary particle proton

π^0 decay immediately

$\pi^\pm$ initiate new cascades

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

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

Assumptions:

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

(Matthews, Astropart.Phys. 22, 2005)

Superposition model

Proton-induced shower

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

$$X_{\max} \sim \lambda_{\mathrm{eff}} \ln(E_0)$$

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

$$\alpha \approx 0.9$$

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

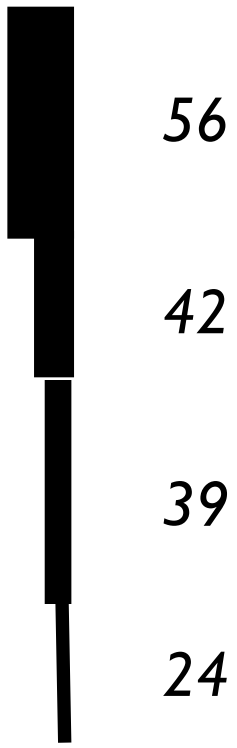
$$N_{\max}^A = A\left(\frac{E_0}{AE_c}\right) = N_{\max}$$

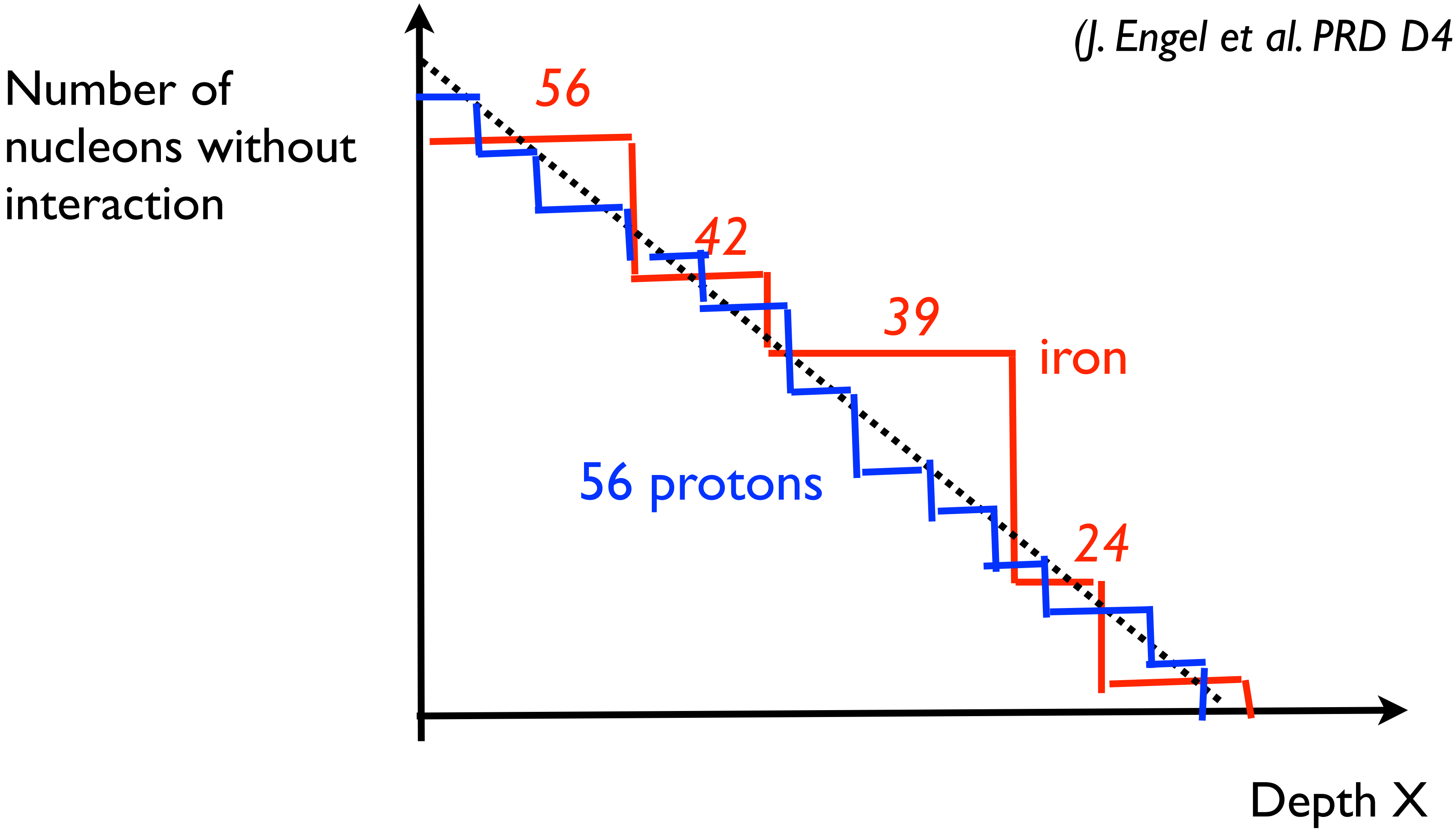
$$X_{\max}^A \sim \lambda_{\mathrm{eff}} \ln(E_0/A)$$

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

Superposition model: correct prediction of mean Xmax

iron nucleus





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

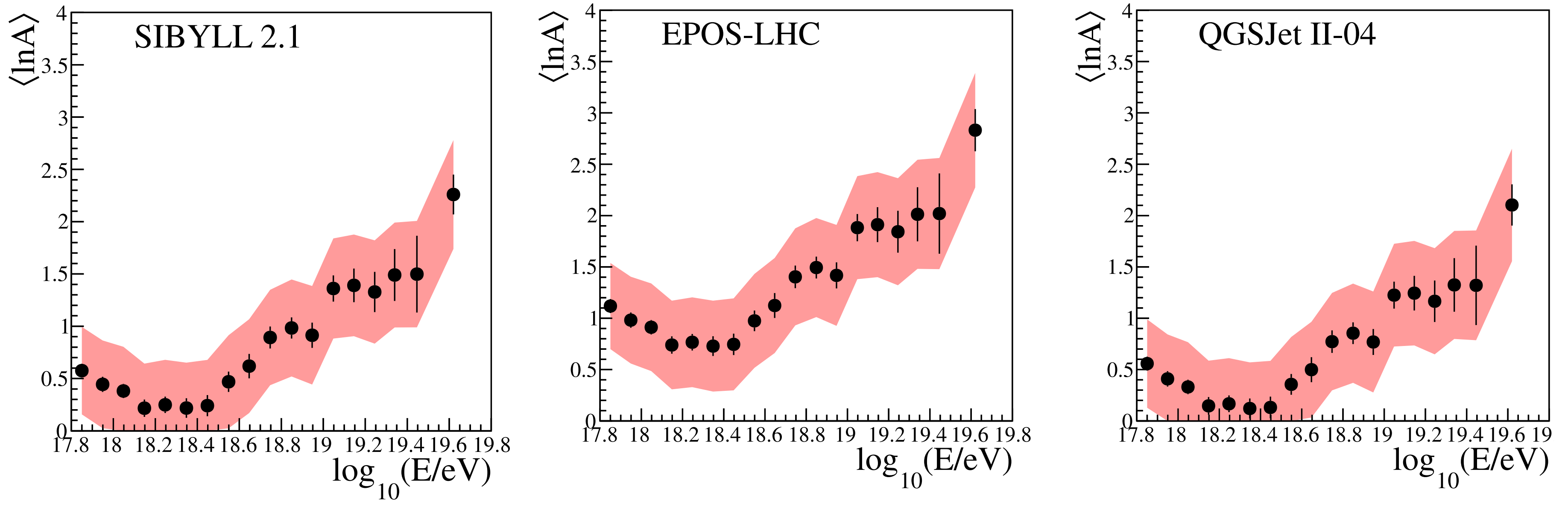
Glauber approximation (unitarity)

$$n_{\text{part}} = \frac{\sigma_{\text{Fe-air}}}{\sigma_{\text{p-air}}}$$

Superposition and semi-superposition models applicable to inclusive (averaged) observables

Consistent description of $X_{\max}$ data ?

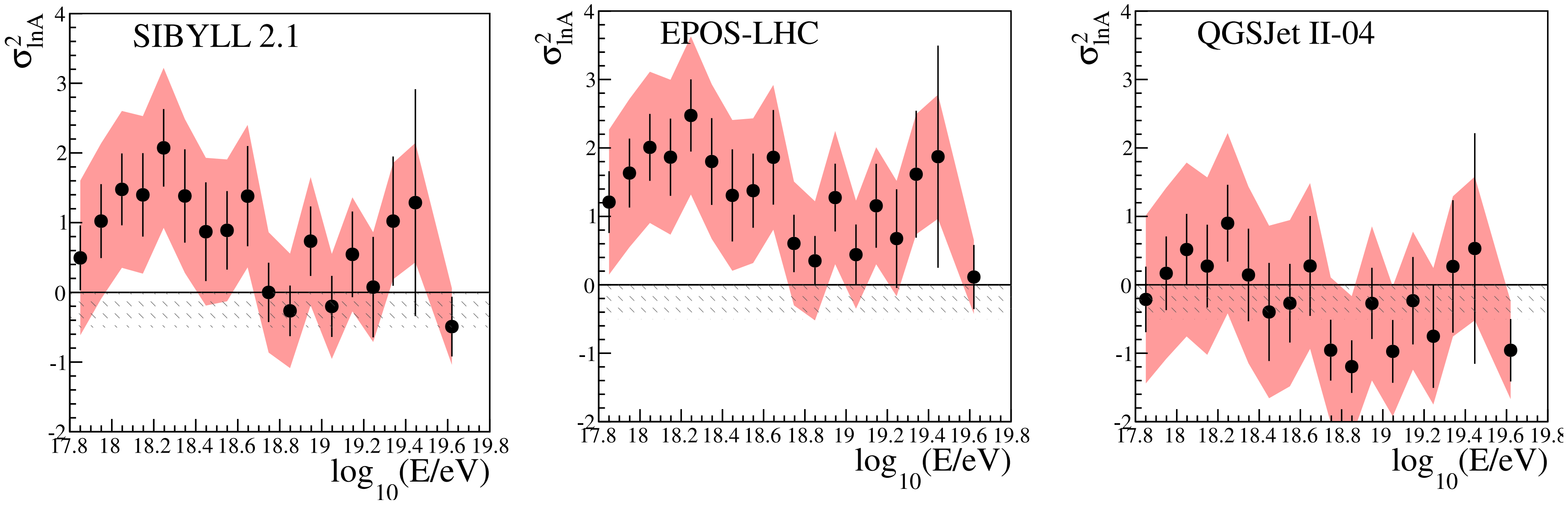
$$\langle X_{\max}\rangle \approx \langle X^{p}_{\max}\rangle - D_p\,\langle \ln A\rangle$$



← Fe

← p

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



← p/Fe 50:50

← mono-elemental

QGSJet II.04 disfavoured ?

(Auger, JCAP 02 (2013) 026)