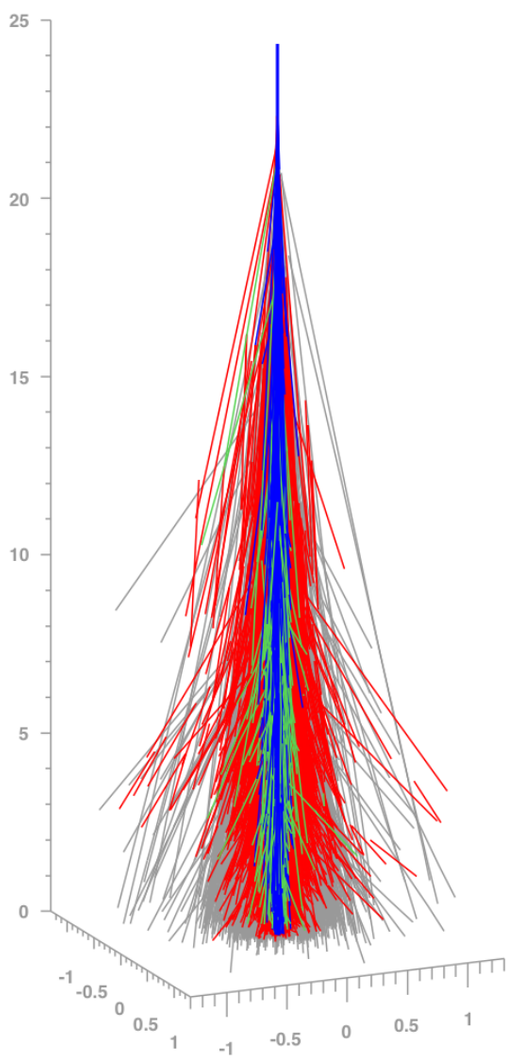
LHC Results and the Interpretation of Cosmic-Ray Data

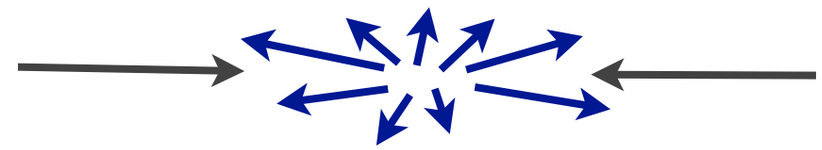


Ralph Engel, Tanguy Pierog, and Ralf Ulrich

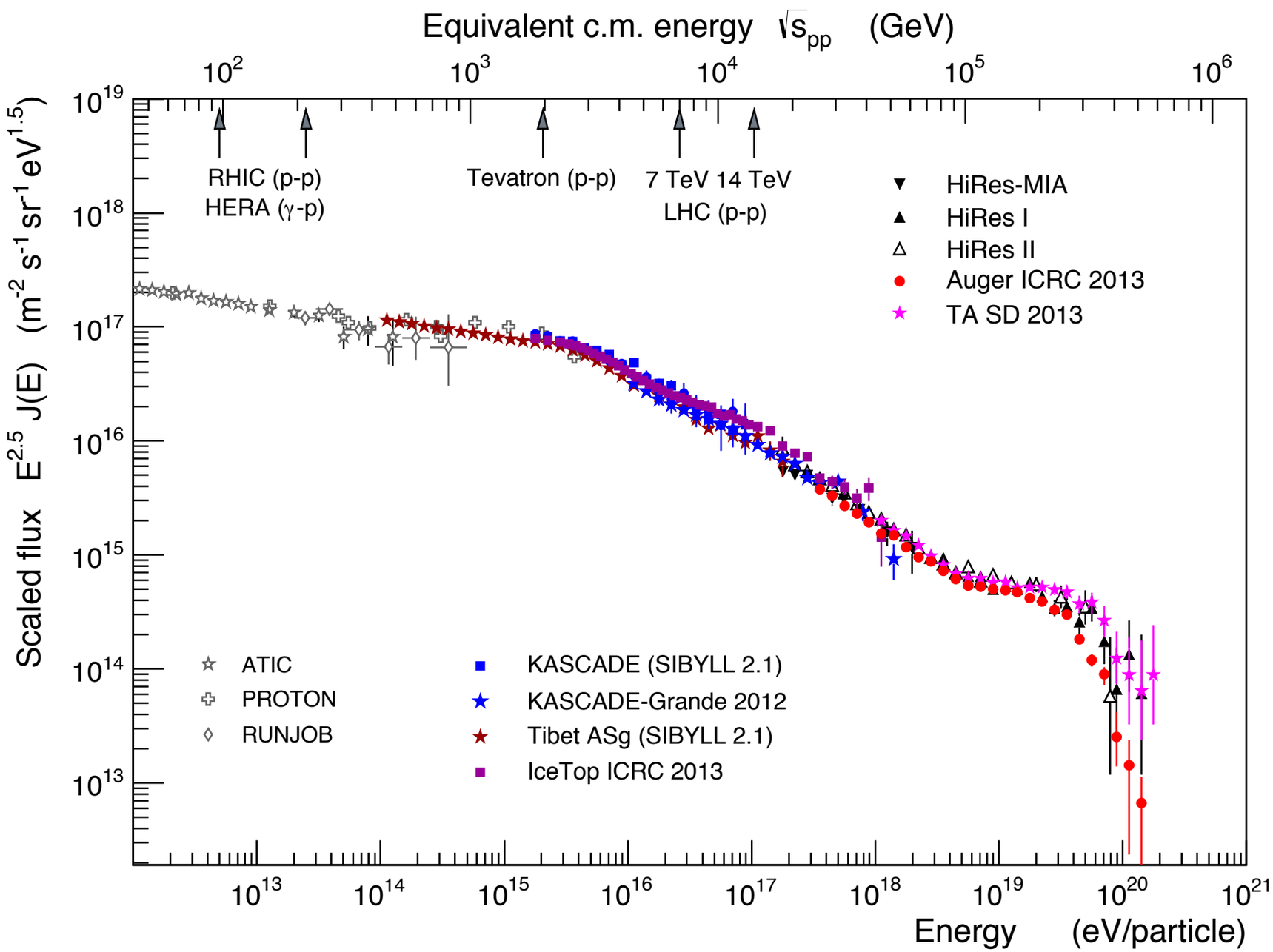
Karlsruhe Institute of Technology (KIT)

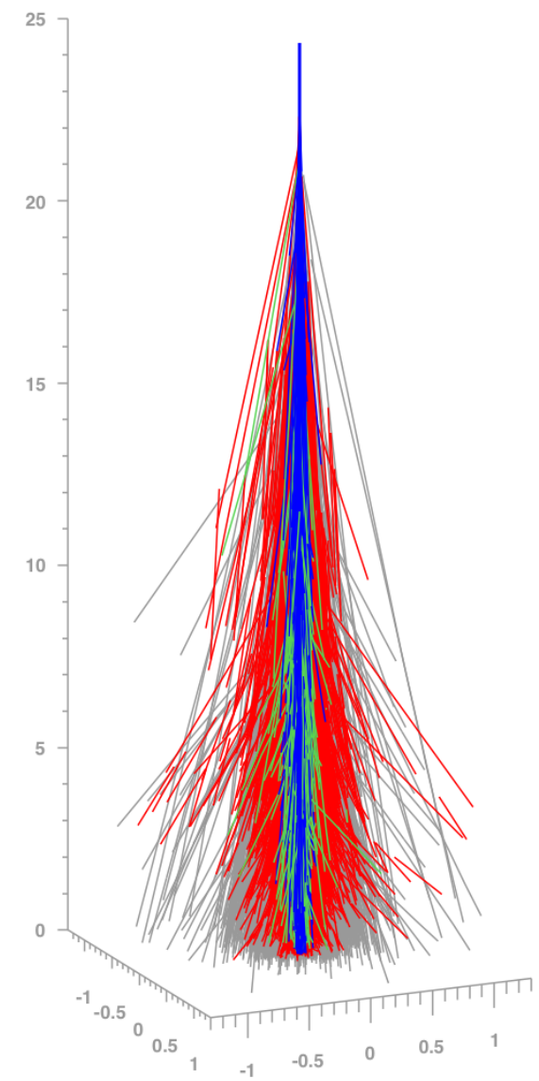
Karlsruhe Institute of Technology

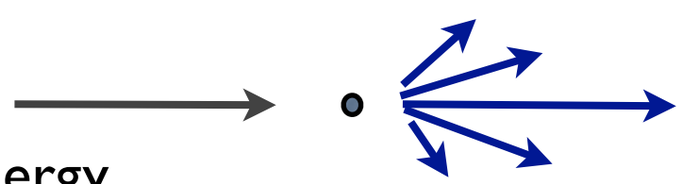
Cosmic ray flux and interaction energies



Center-of-mass energy

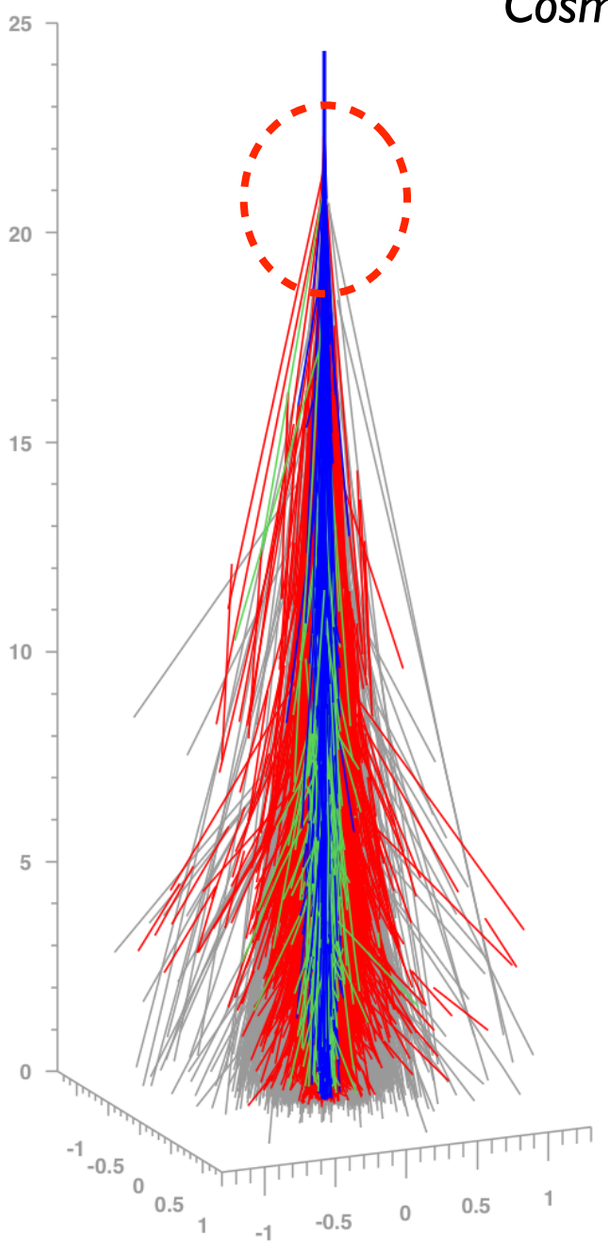


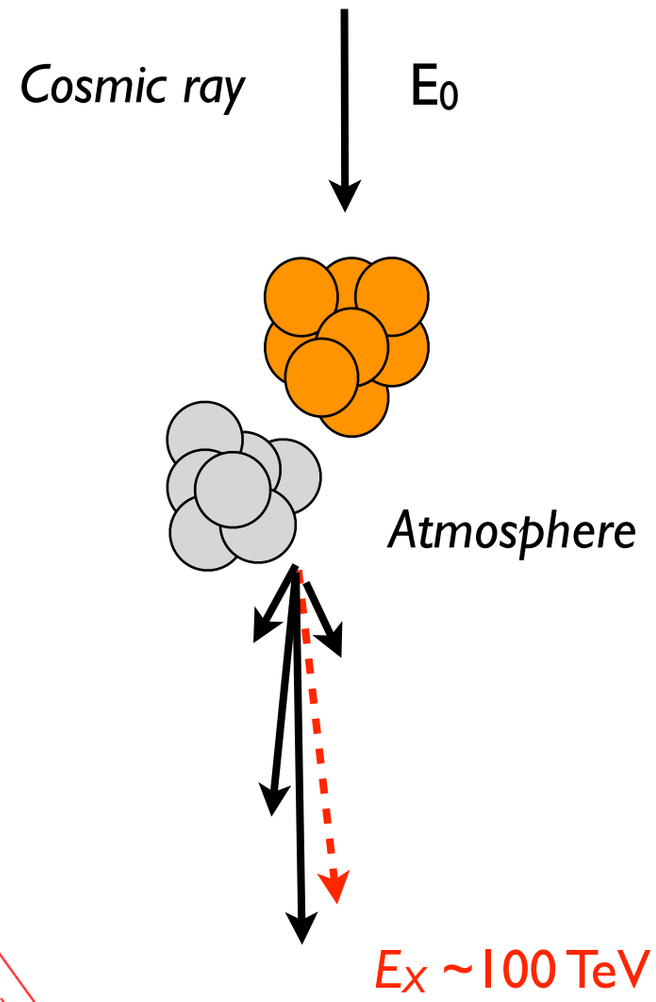




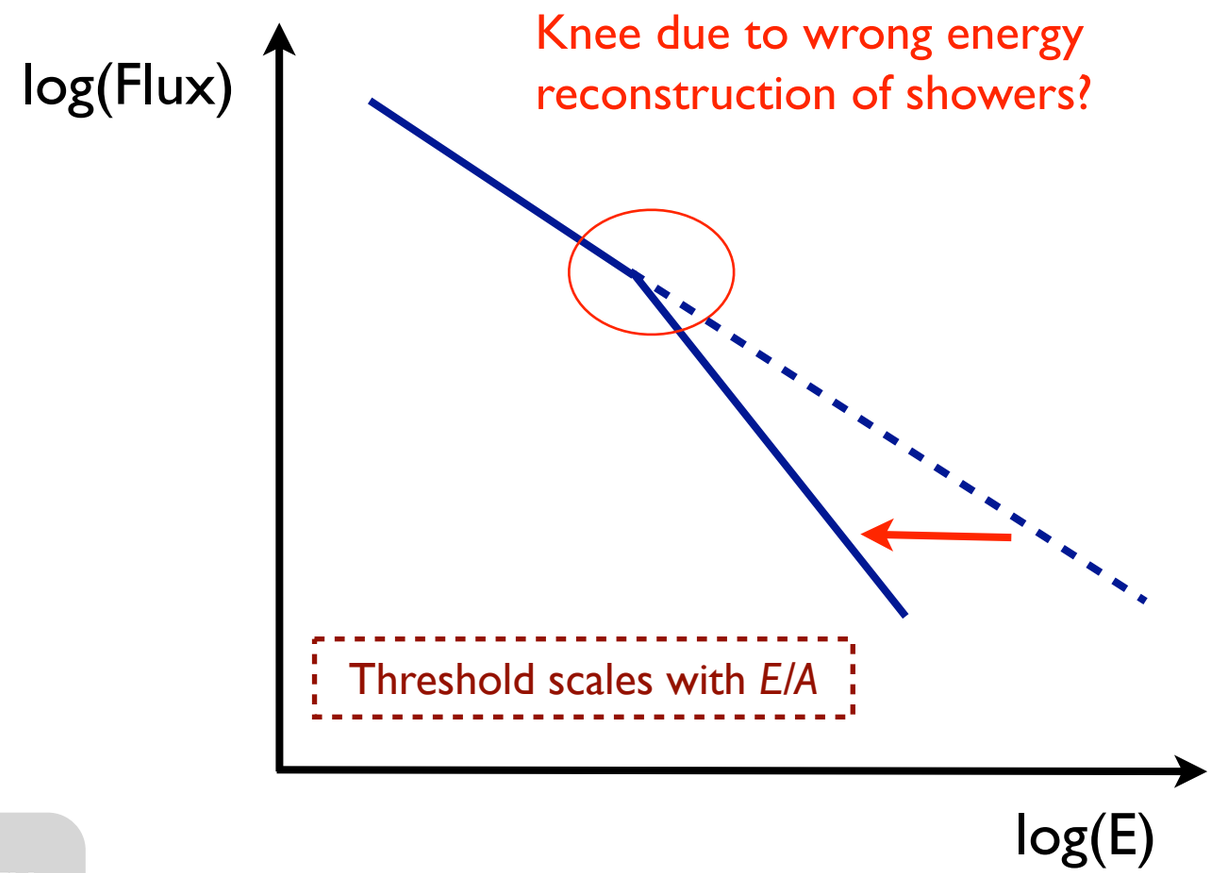
Laboratory energy

Exotic models for the knee



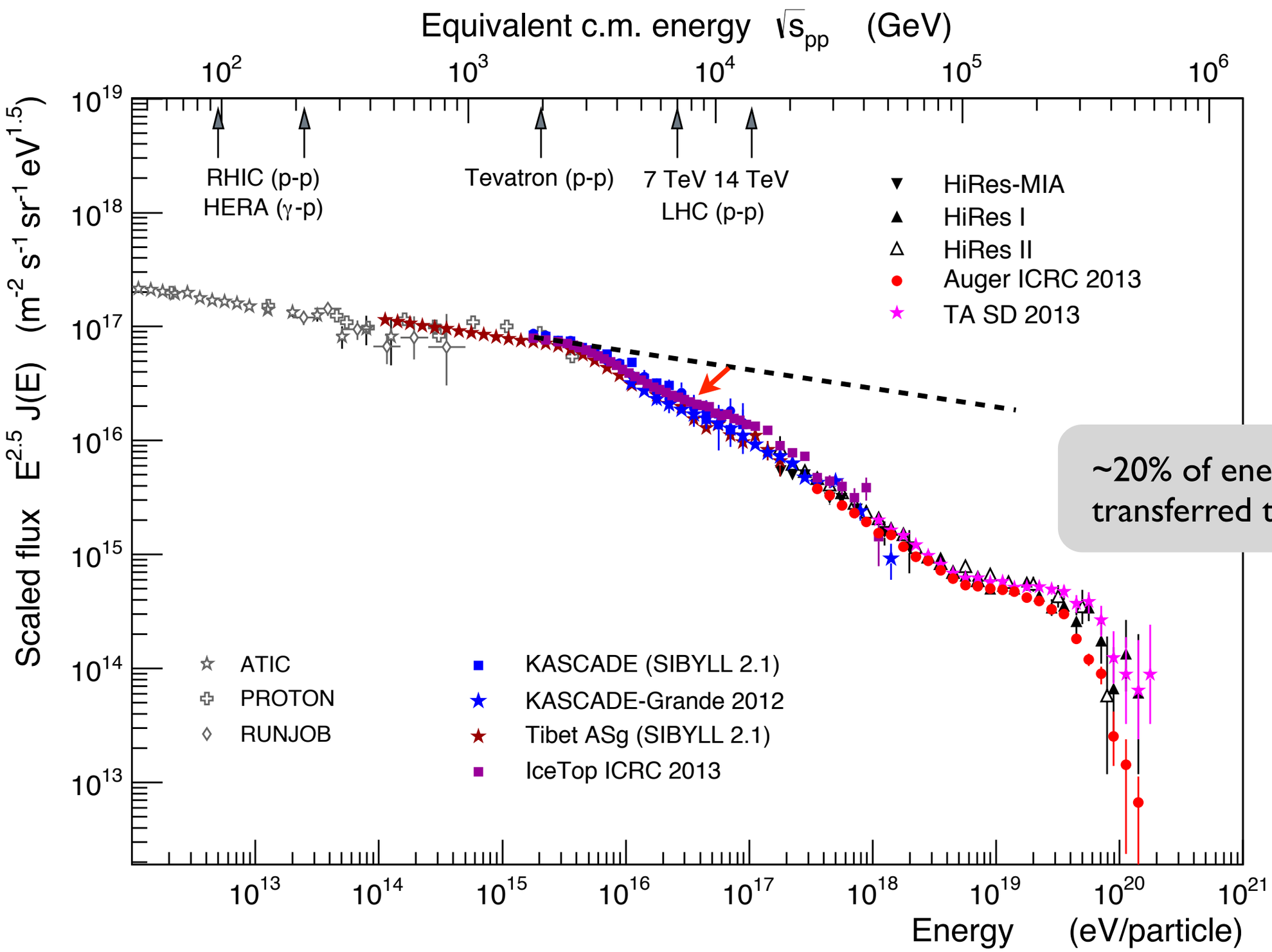


Petrukhin, NPB 151 (2006) 57
Barcelo at al. JACP 06 (2009) 027
Dixit et al. EPJC 68 (2010) 573
Petrukhin NPB 212 (2011) 235



New physics: scaling with nucleon-nucleon cms energy

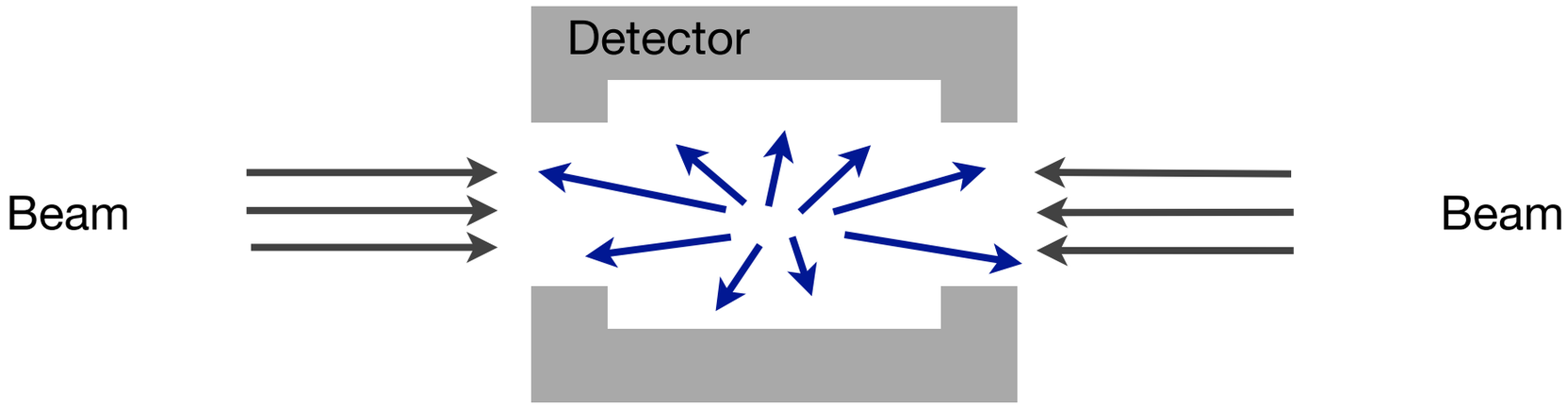
LHC data probe the region beyond the knee



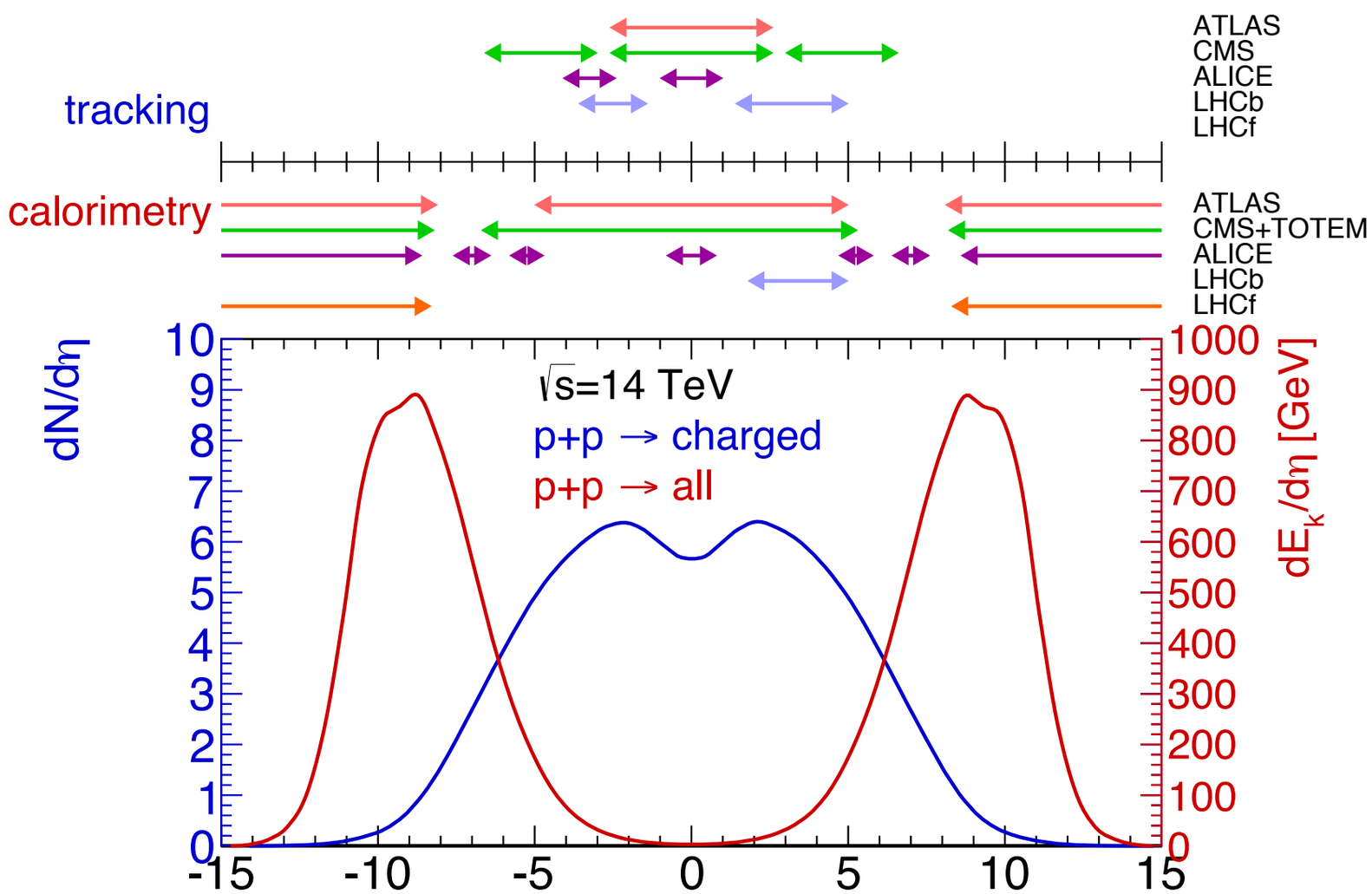
~20% of energy needs to be transferred to invisible channel

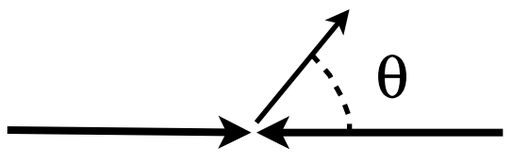
(d'Enterria et al., Astropart. Phys. 35, 2011)

Problem of limited phase space coverage



Collider setup





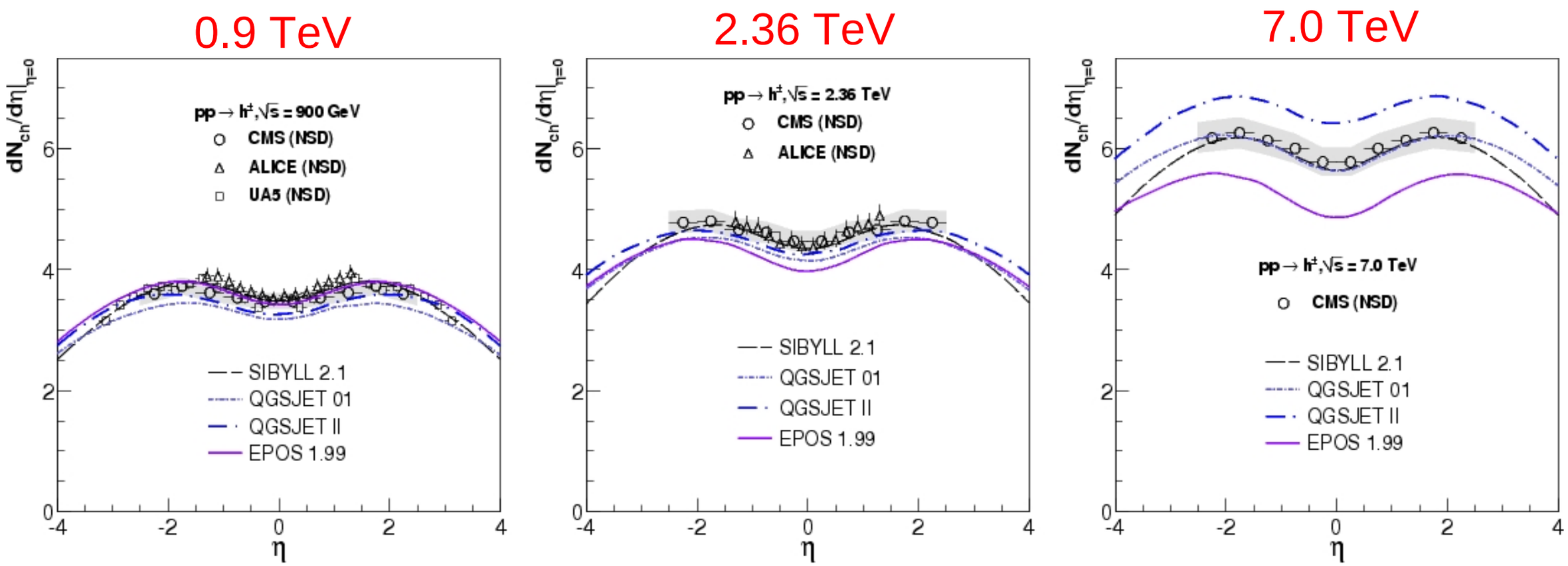
$$\eta = -\ln\tan\frac{\theta}{2}$$

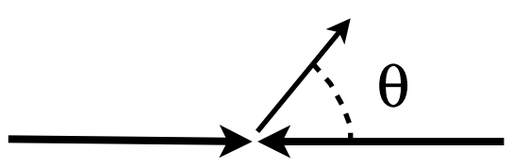
Air showers: Particles of highest energy most important

LHC data probe the region beyond the knee

Pseudorapidity distribution of charged particles

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





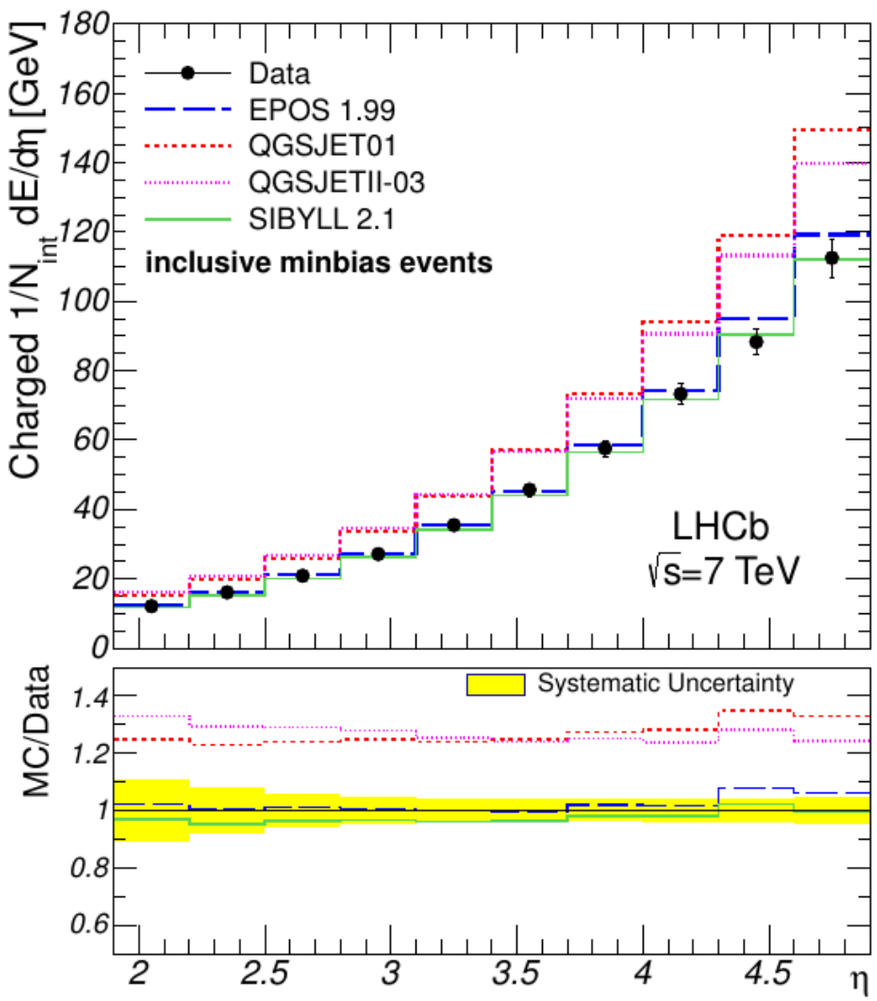
$$\eta = -\ln \tan \frac{\theta}{2}$$

LHC: Exotic scenarios for knee very unlikely, model predictions **bracket LHC data** on secondary particle multiplicity

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

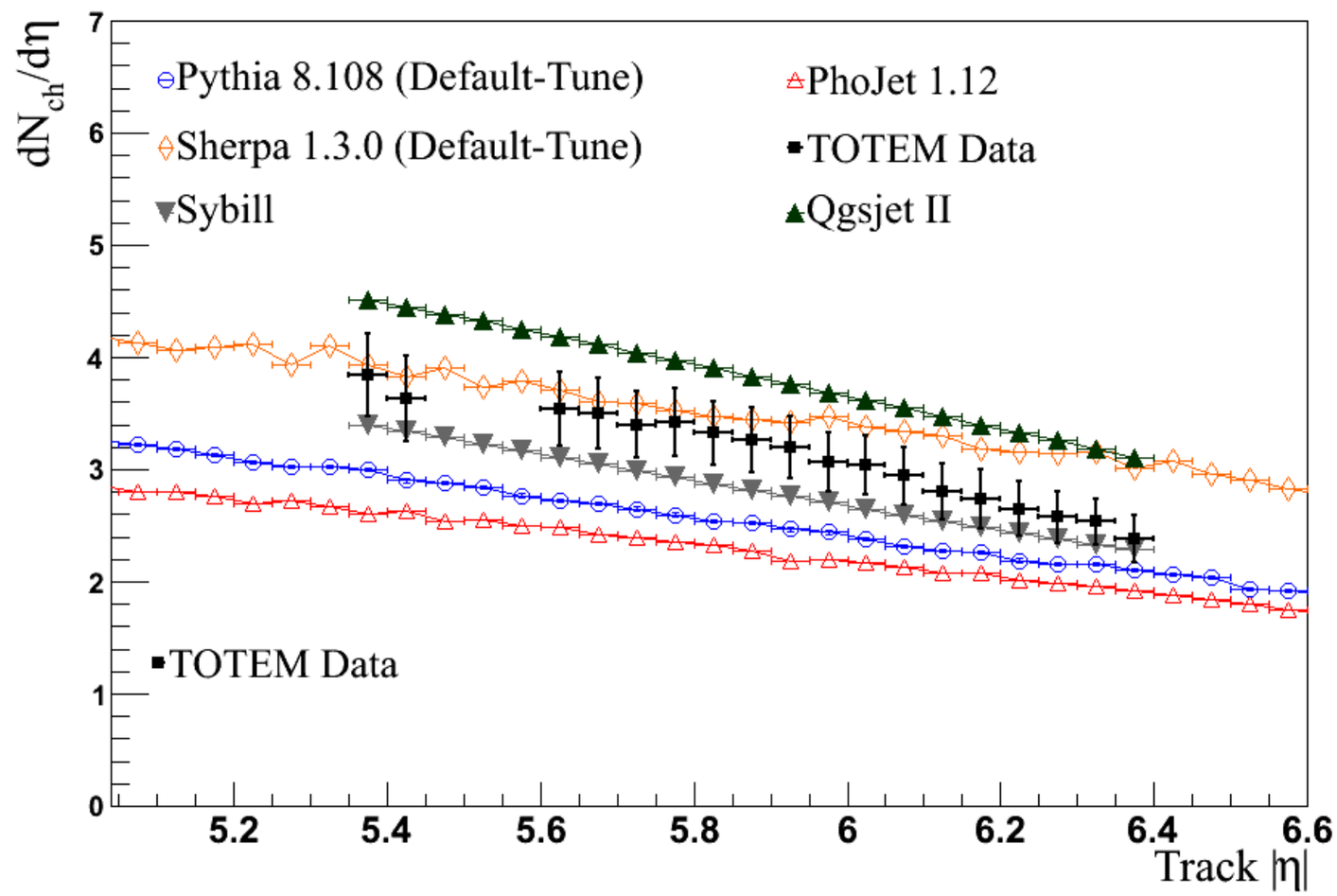
1.2 Interaction models for describing LHC data

Energy flow (CMS)



(Eur.Phys.J. C73 (2013) 2421)

Forward particle multiplicity (TOTEM)

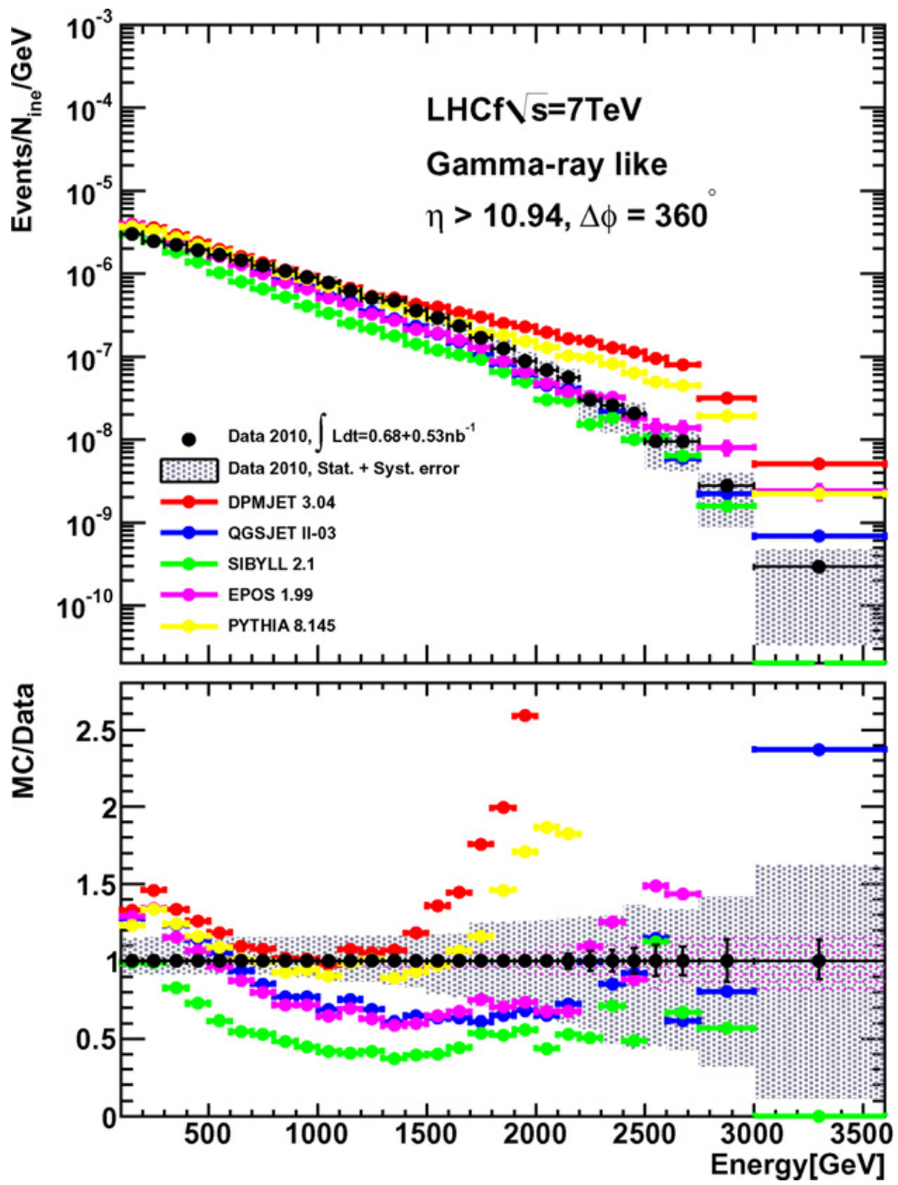


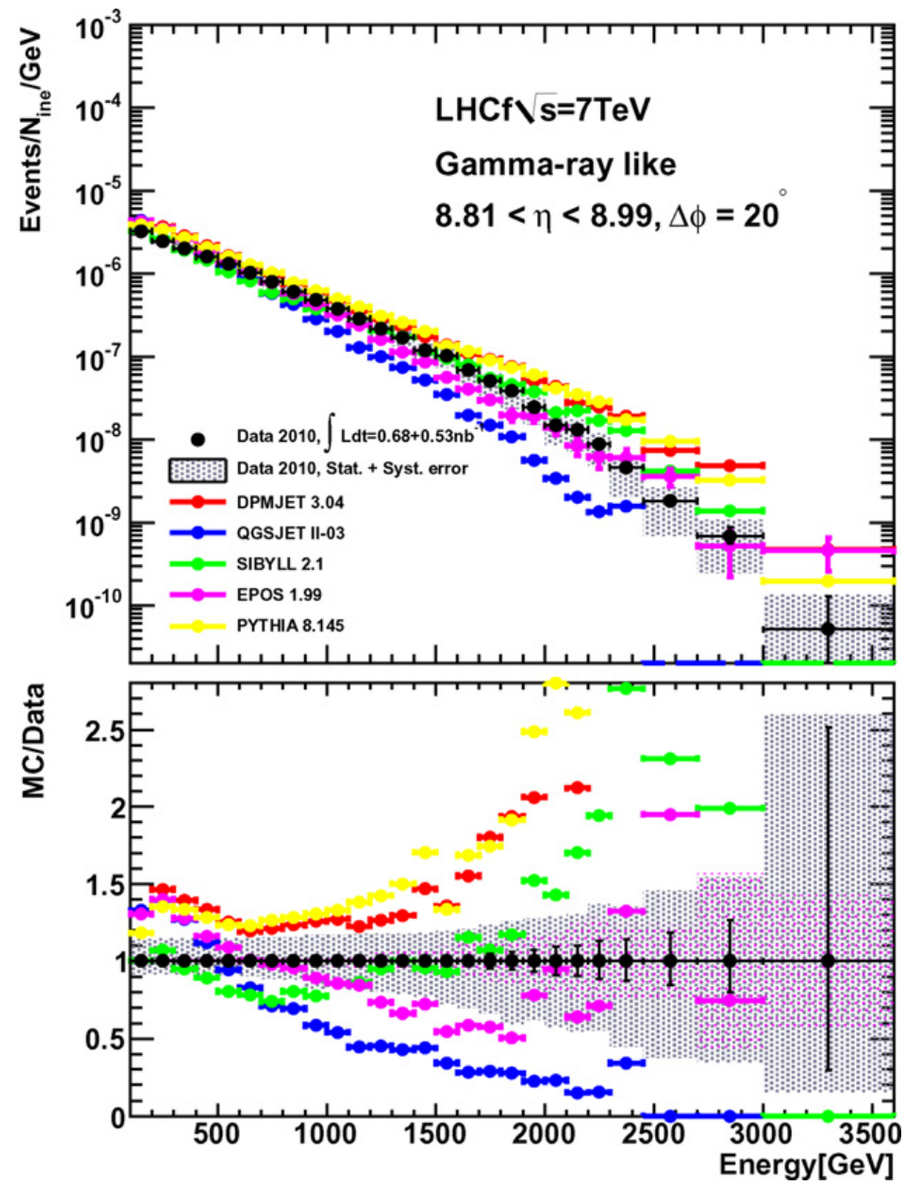
(Europhys.Lett. 98 (2012) 31002)

- Models used for p-p, p-Pb and Pb-Pb data
- Interface to cosmic ray event generators **CRMC** *(R. Ulrich et al.)*

LHCf: forward photon production at 7 TeV

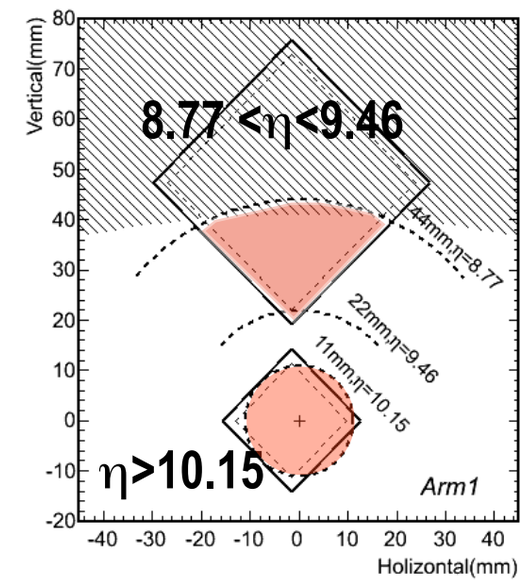
Forward production of gamma-rays with low pt $pp \to \gamma X$



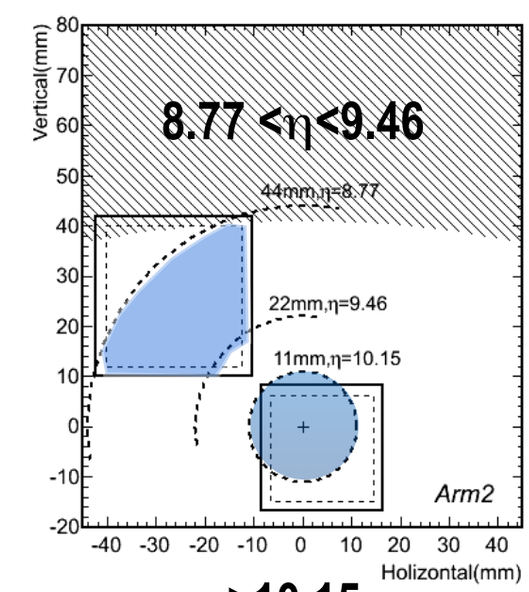


(LHCf Collab., Phys. Lett. B 703, 2011)

Arm 1



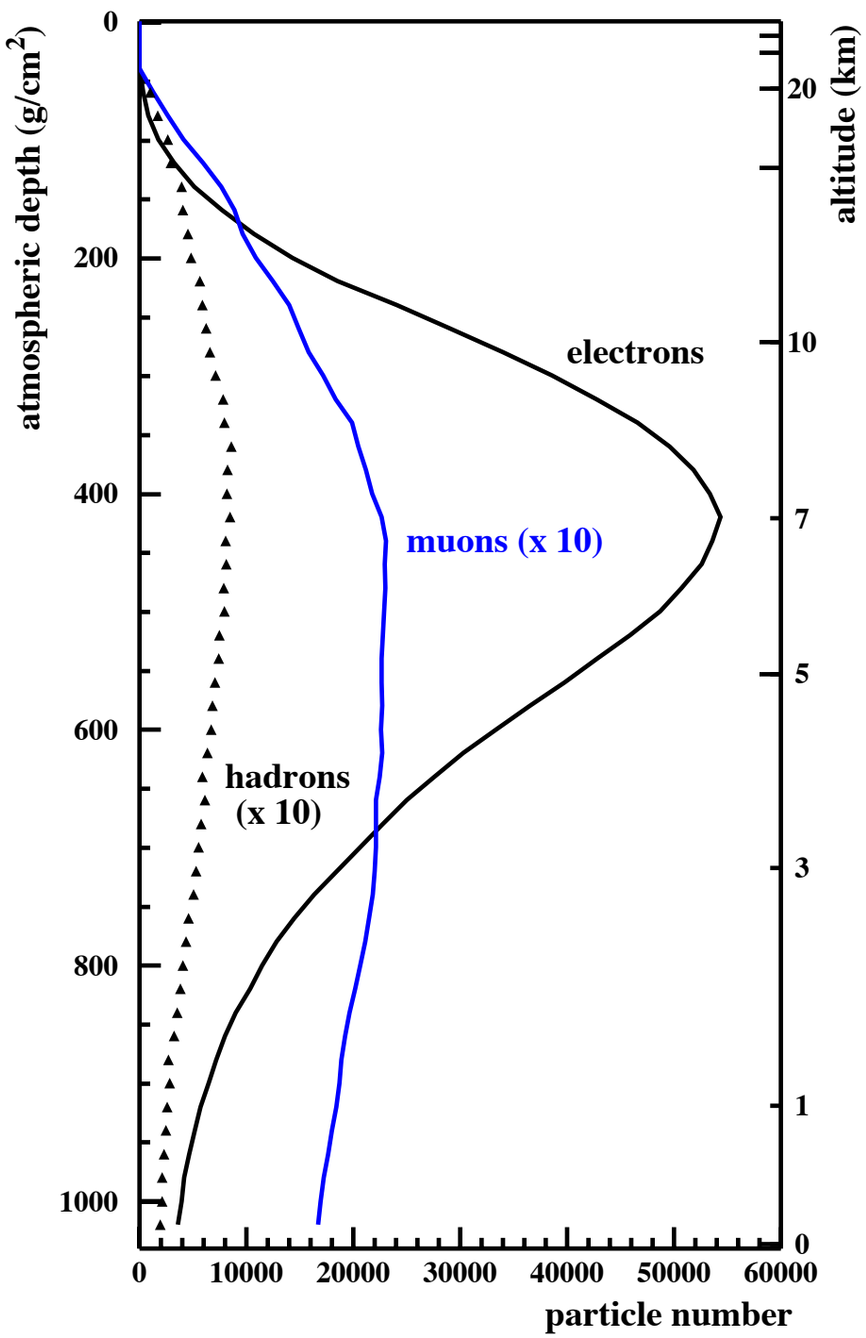
Arm 2

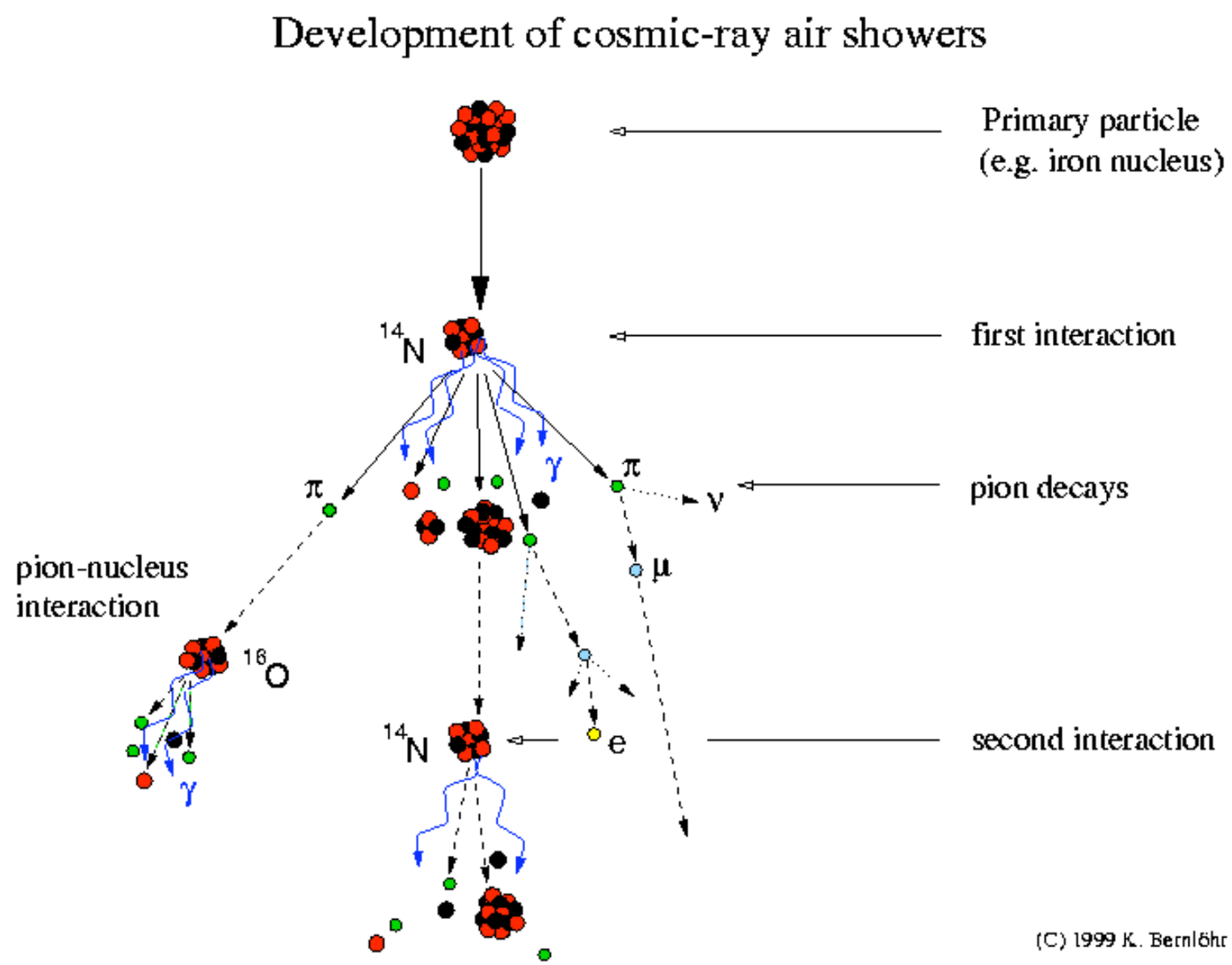


η>10.15

Re-tuning of models needed, size of effect still unclear, distributions for neutrons needed

Shower as cascade process: primary energy

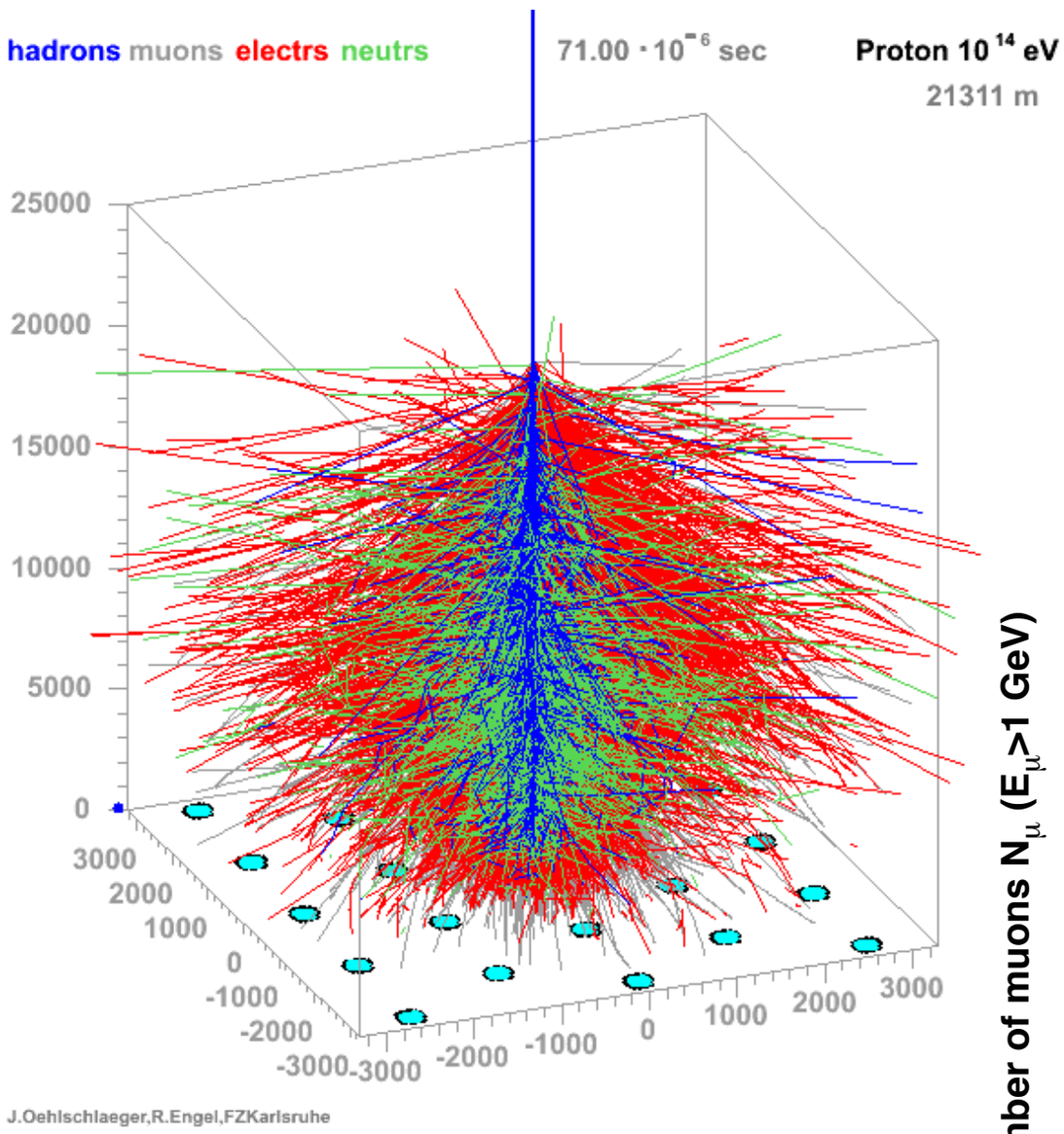




Decay of neutral pions feeds **em. shower component**

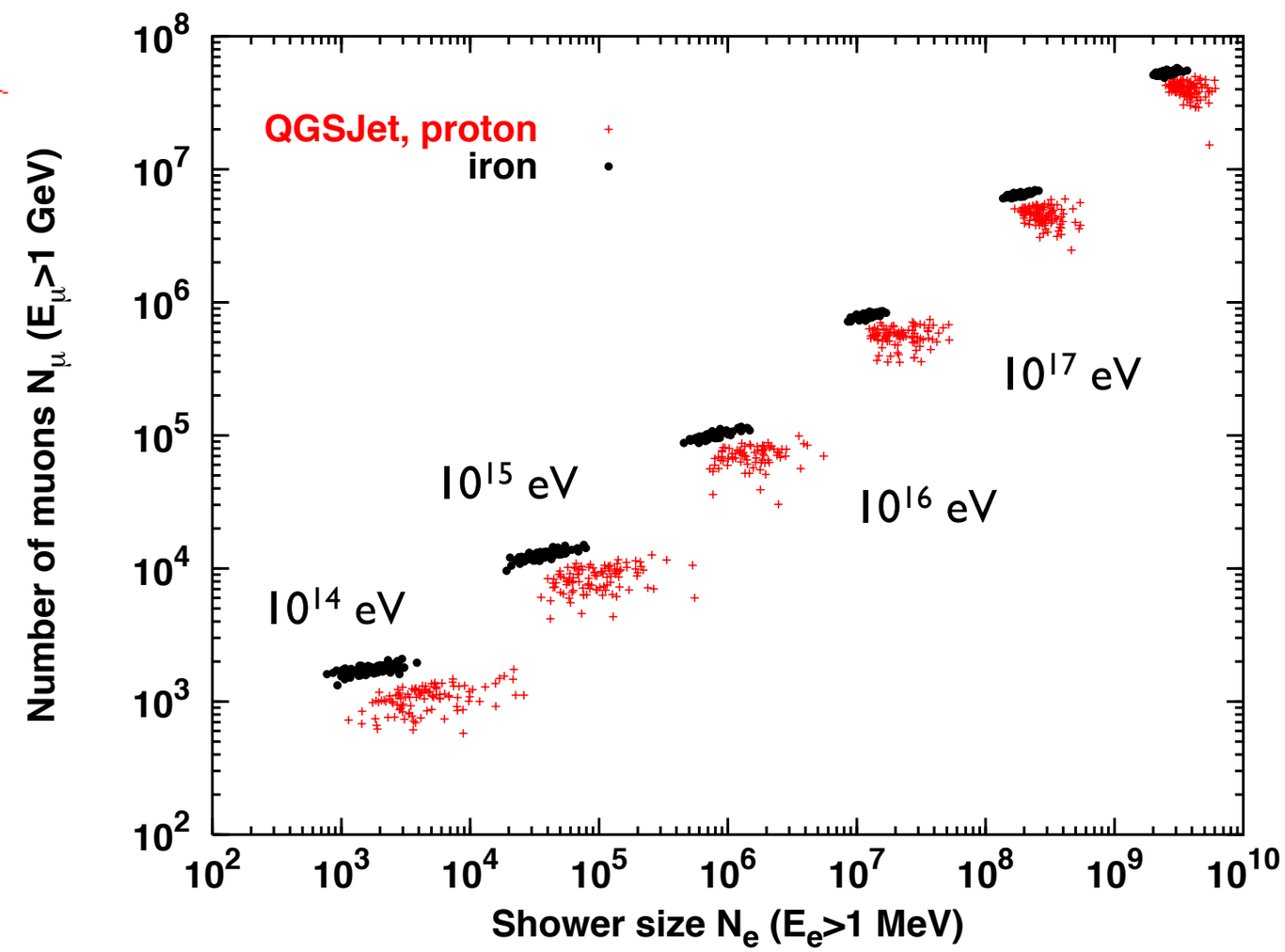
Decay of charged pions (~30 GeV) feeds **muonic component**

Air shower ground arrays: N_e and N_μ



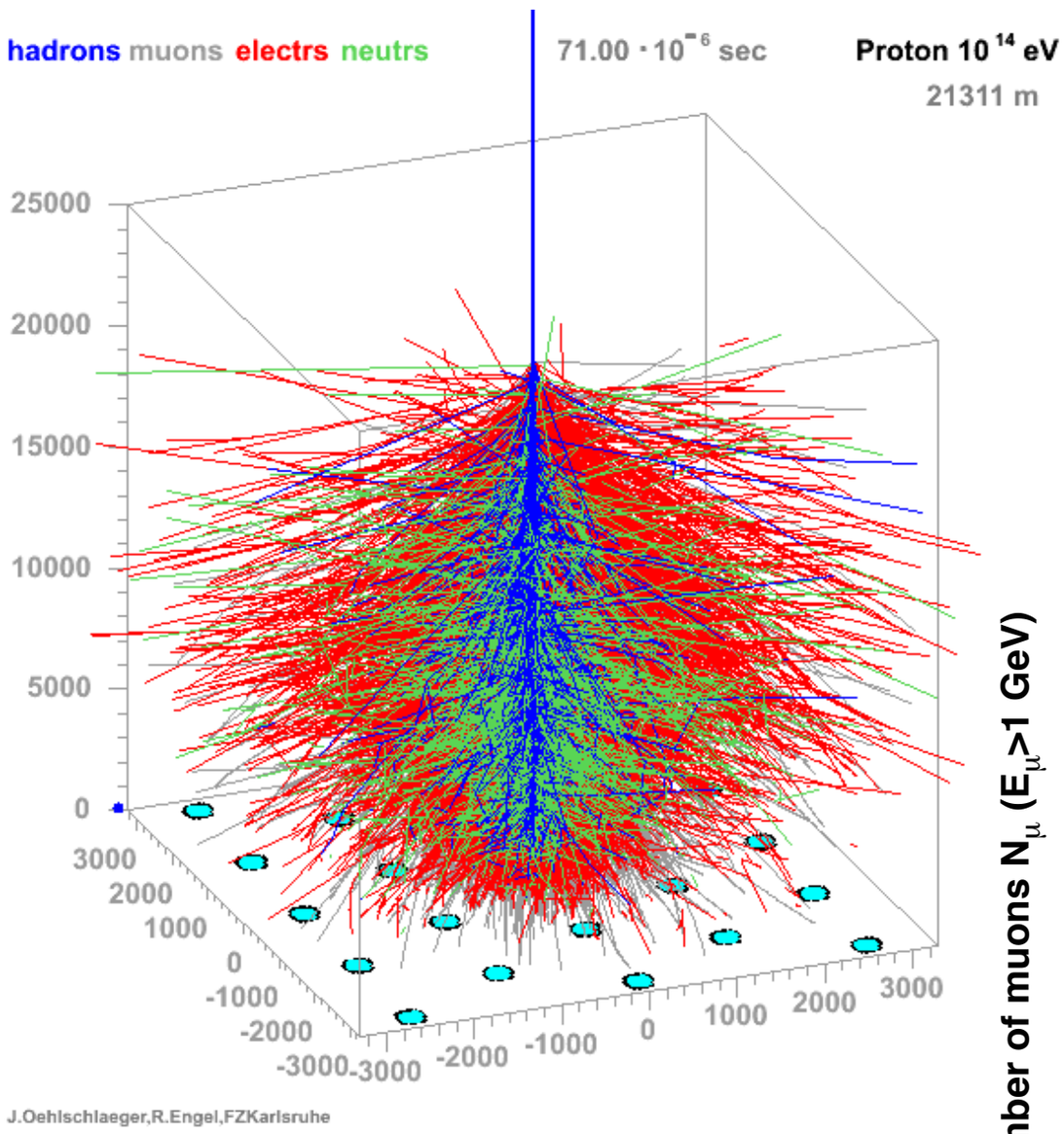
Energy conservation

$$\ln E = a \cdot \ln N_e + b \cdot \ln N_\mu$$



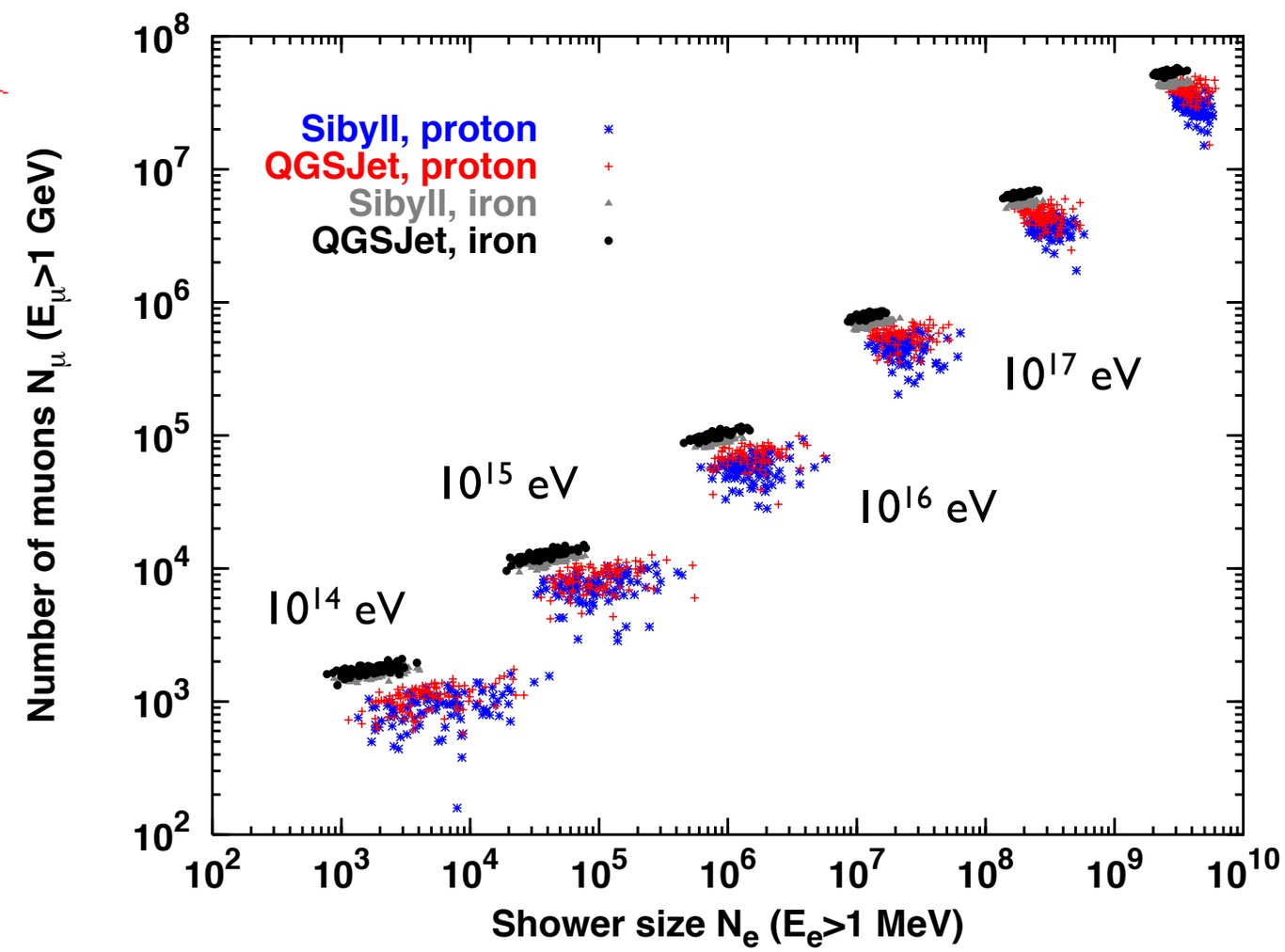
KASCADE and KASCADE-Grande

Air shower ground arrays: N_e and N_μ



Energy conservation

$$\ln E = a \cdot \ln N_e + b \cdot \ln N_\mu$$



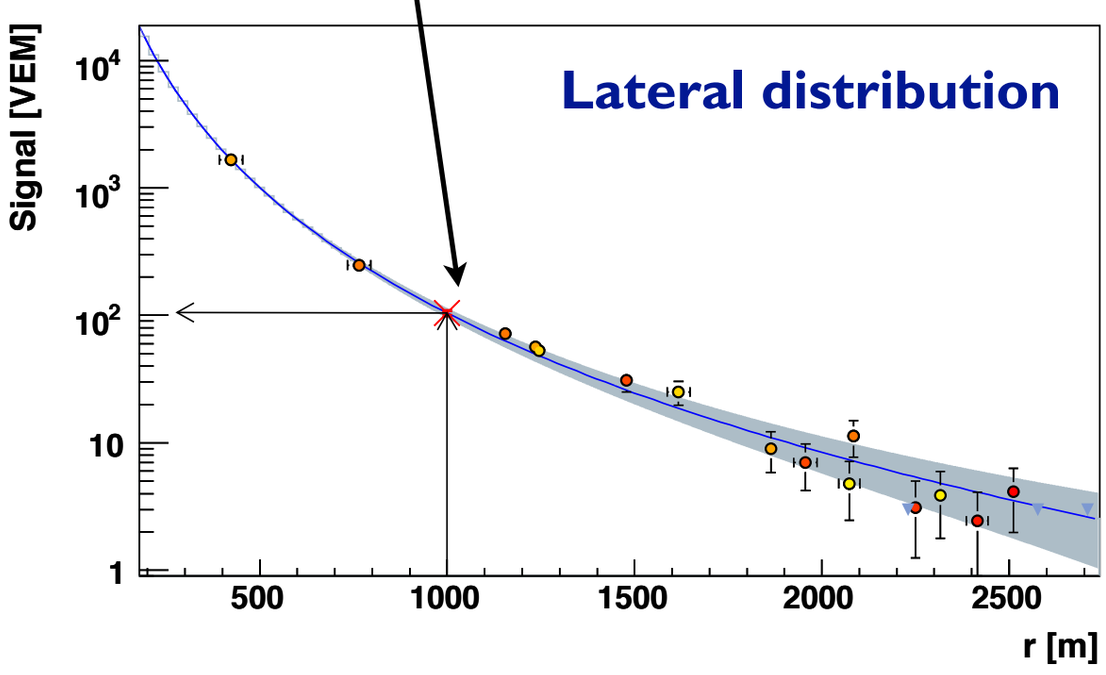
KASCADE and KASCADE-Grande

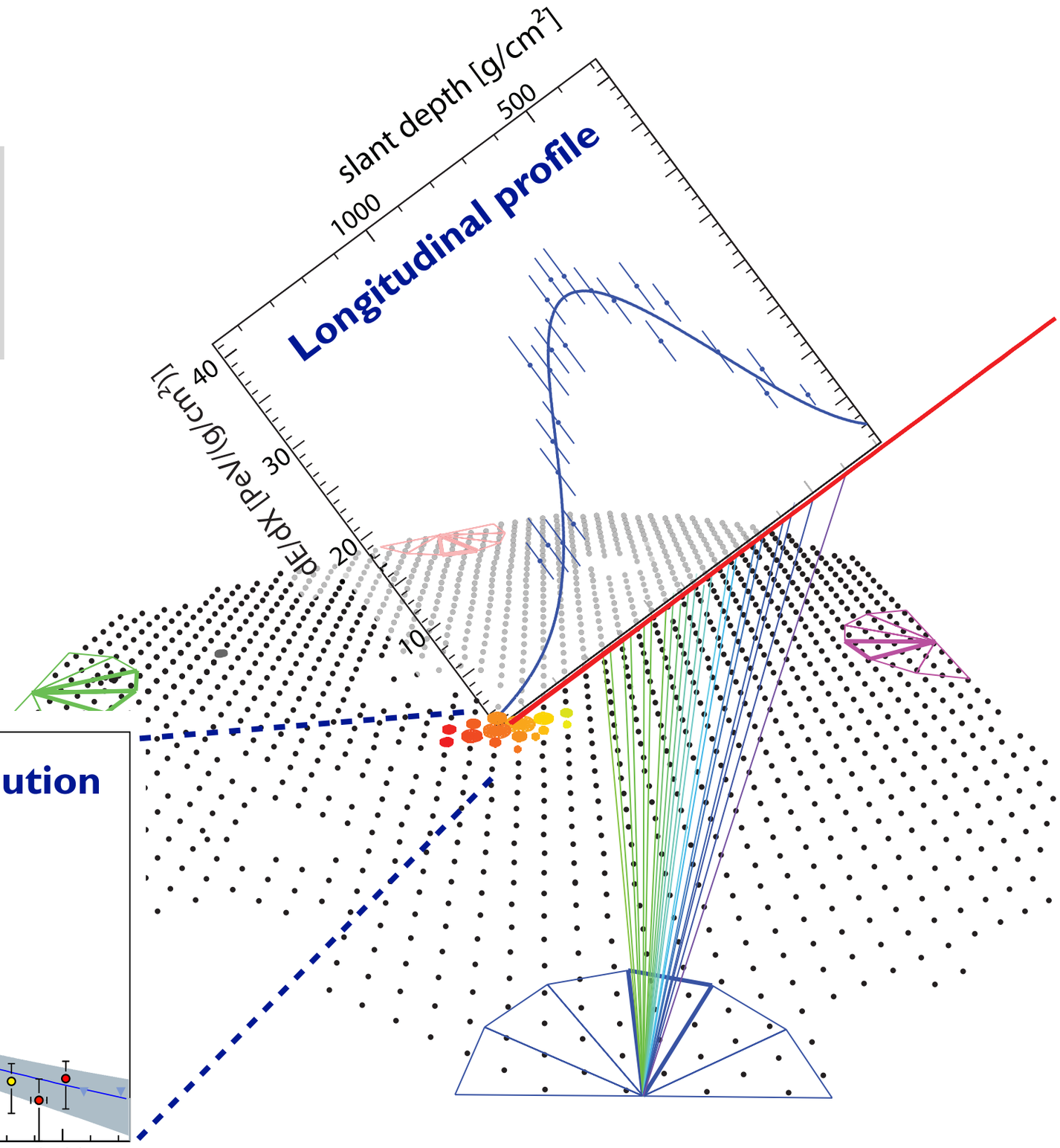
Calorimetric measurement at very high energy

$$E_{\mathrm{cal}} = \int \left(\frac{\mathrm{d}E_{\mathrm{ion}}}{\mathrm{d}X} \right)_{\mathrm{obs}} \mathrm{d}X$$

$$E = f_{\mathrm{corr}} \cdot E_{\mathrm{cal}}$$

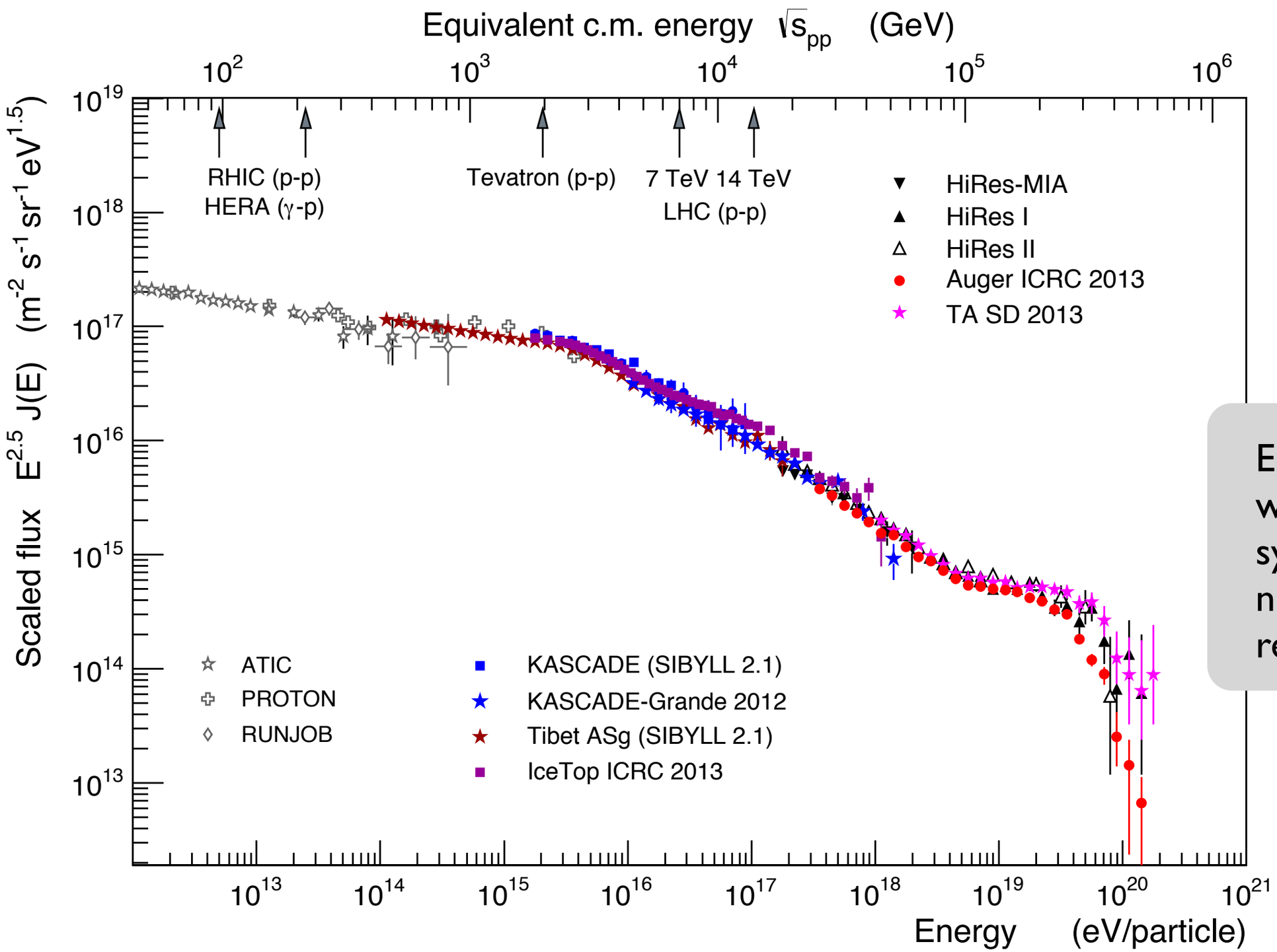
Cross-check:
Muons at ground





Example: event observed by Auger

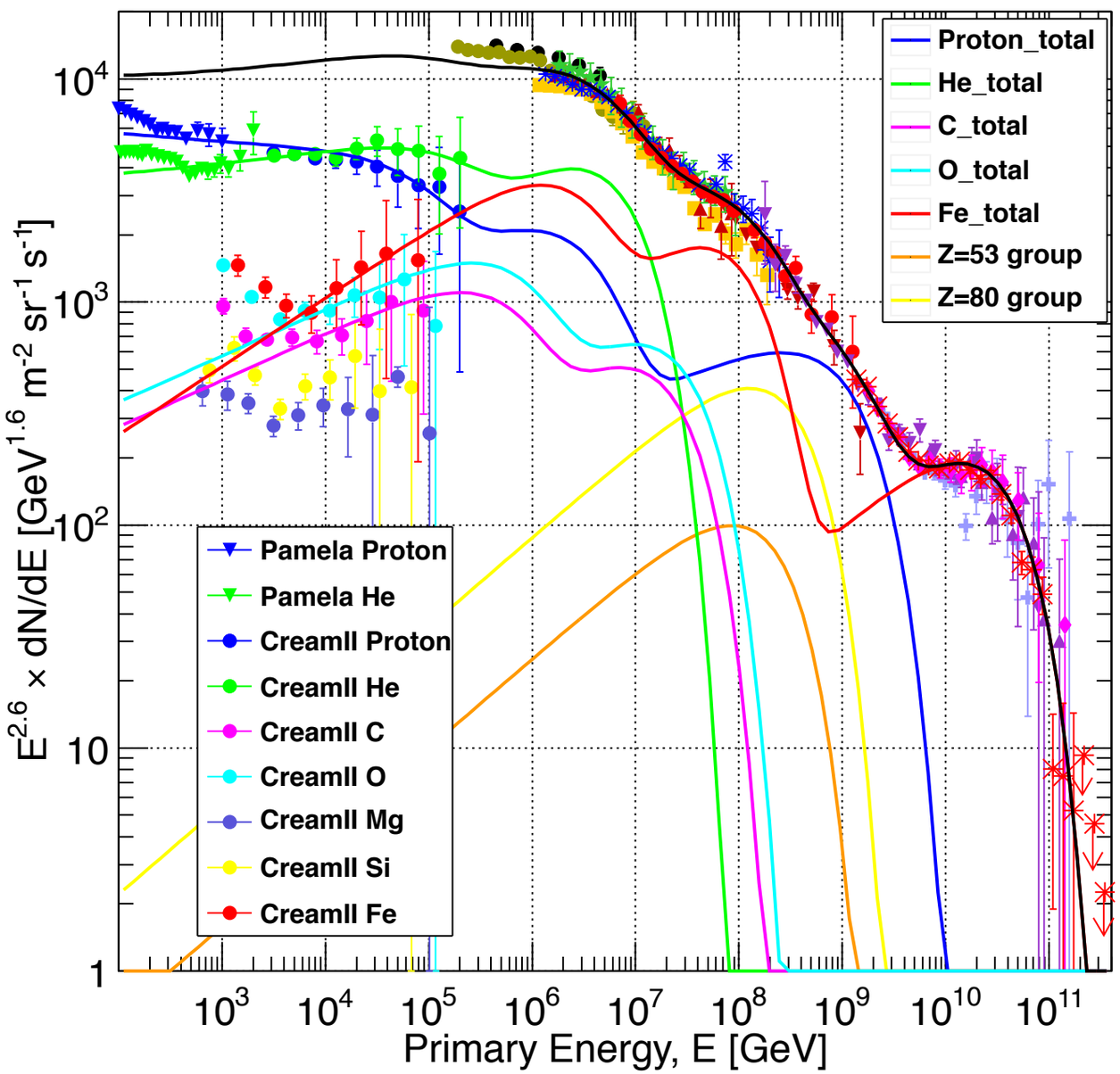
Energy spectrum of cosmic rays



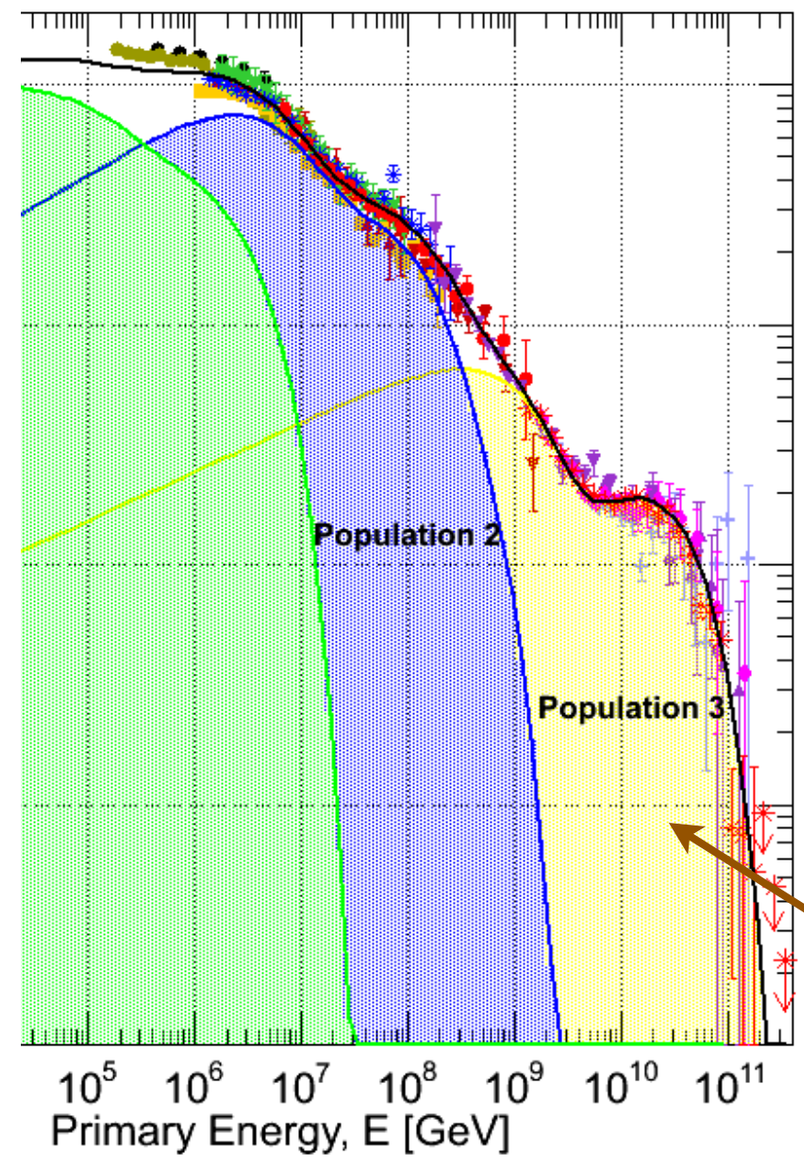
Energy spectrum well-measured, sys. uncertainties need to be reduced further

Key targets: mass composition and anisotropy

Composition not well-known at high energy, needed for astrophysical interpretation



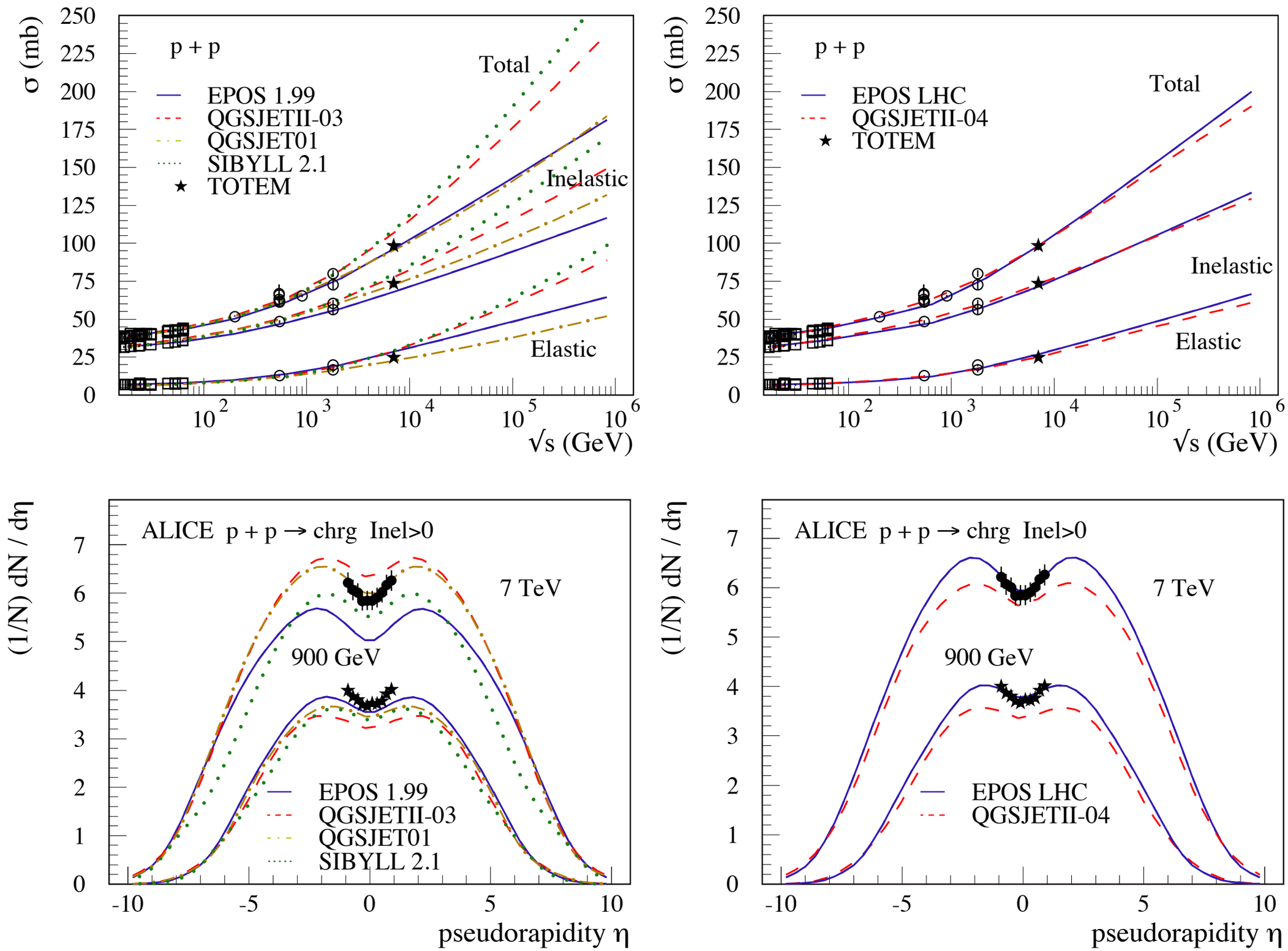
(Gaisser, Stanev, Tilav 1303.3565)



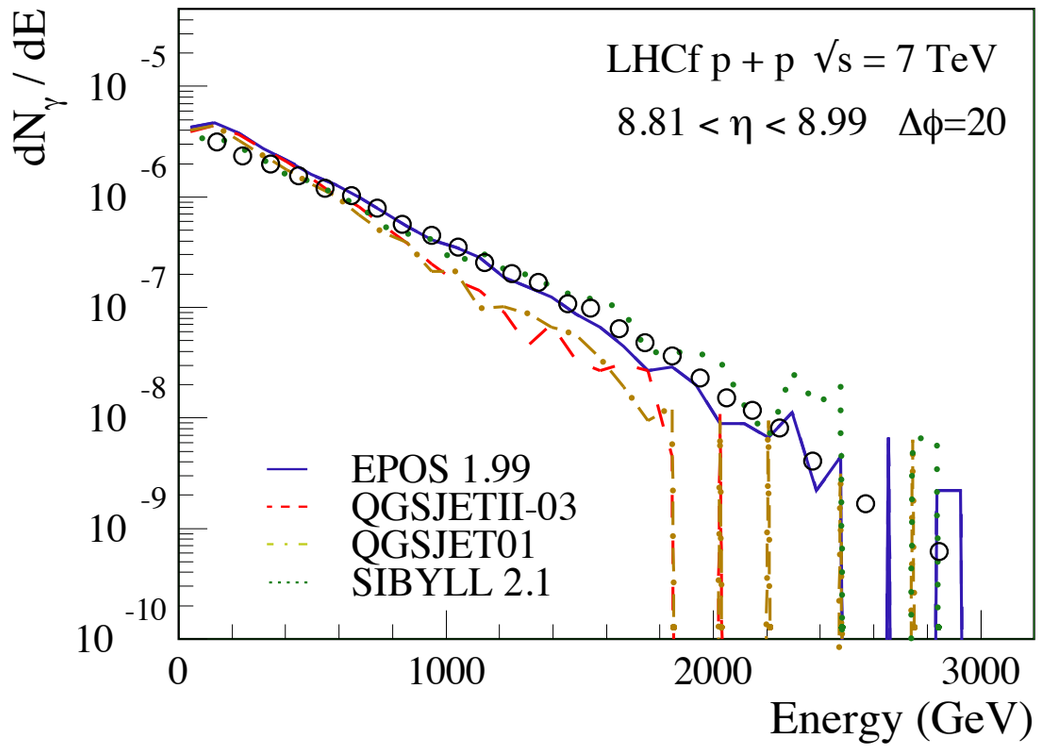
Extragalactic sources

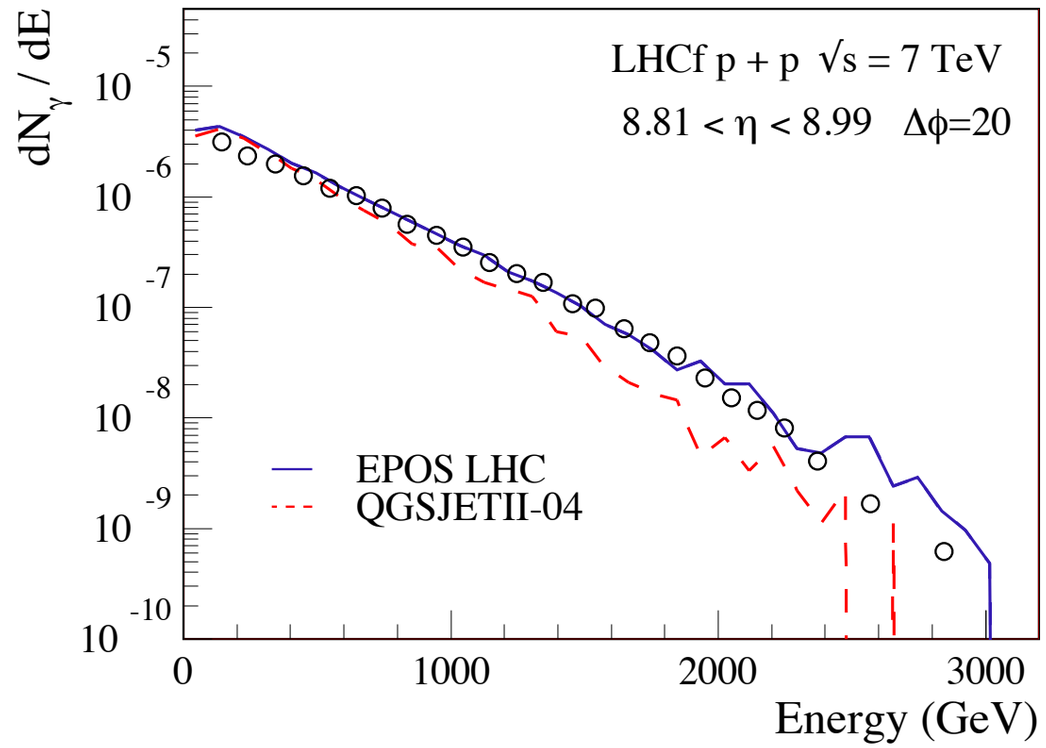
Example: three different source populations

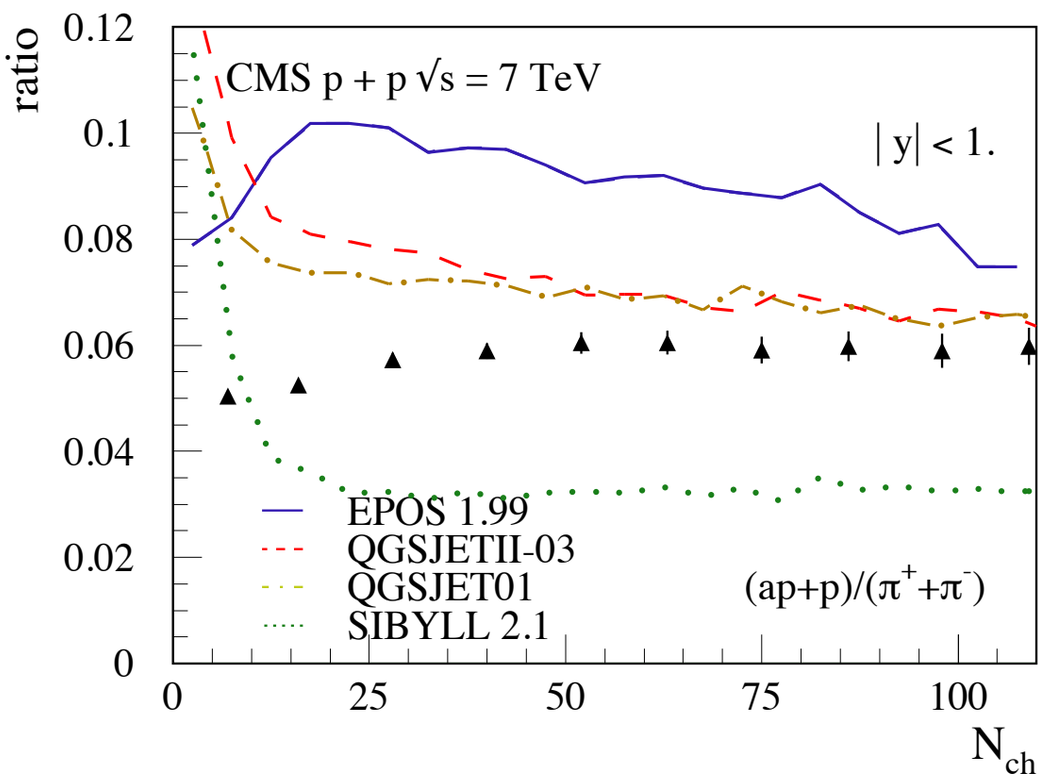
Tuning of interaction models to LHC data (i)

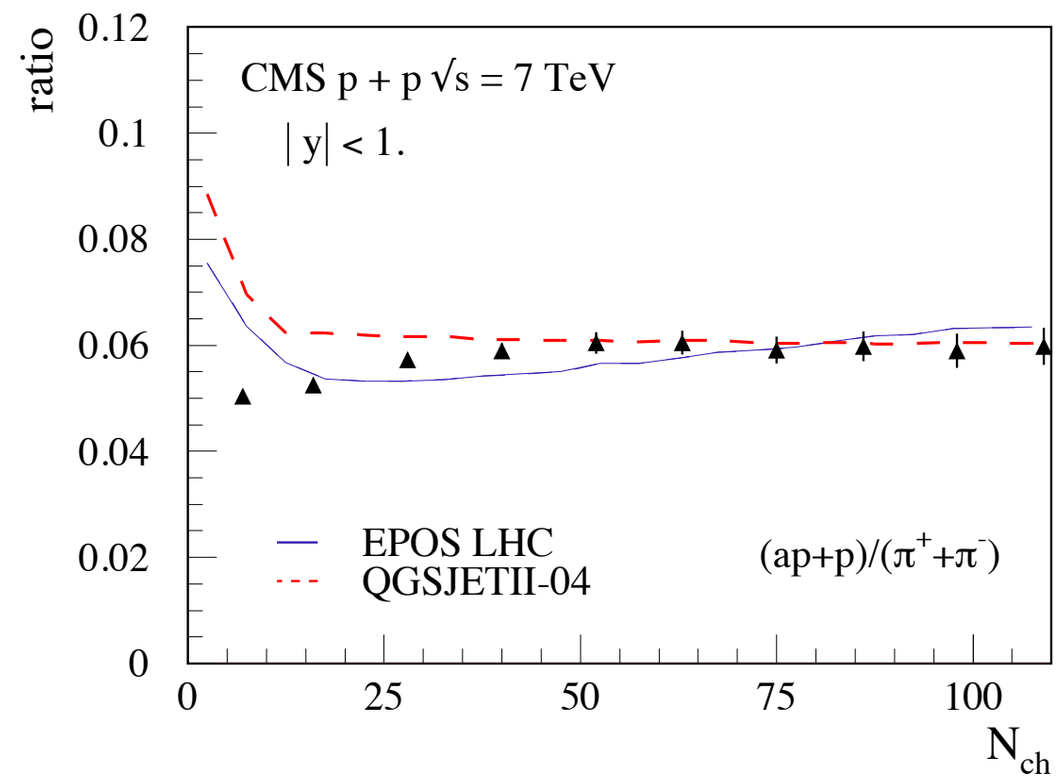


Tuning of interaction models to LHC data (ii)

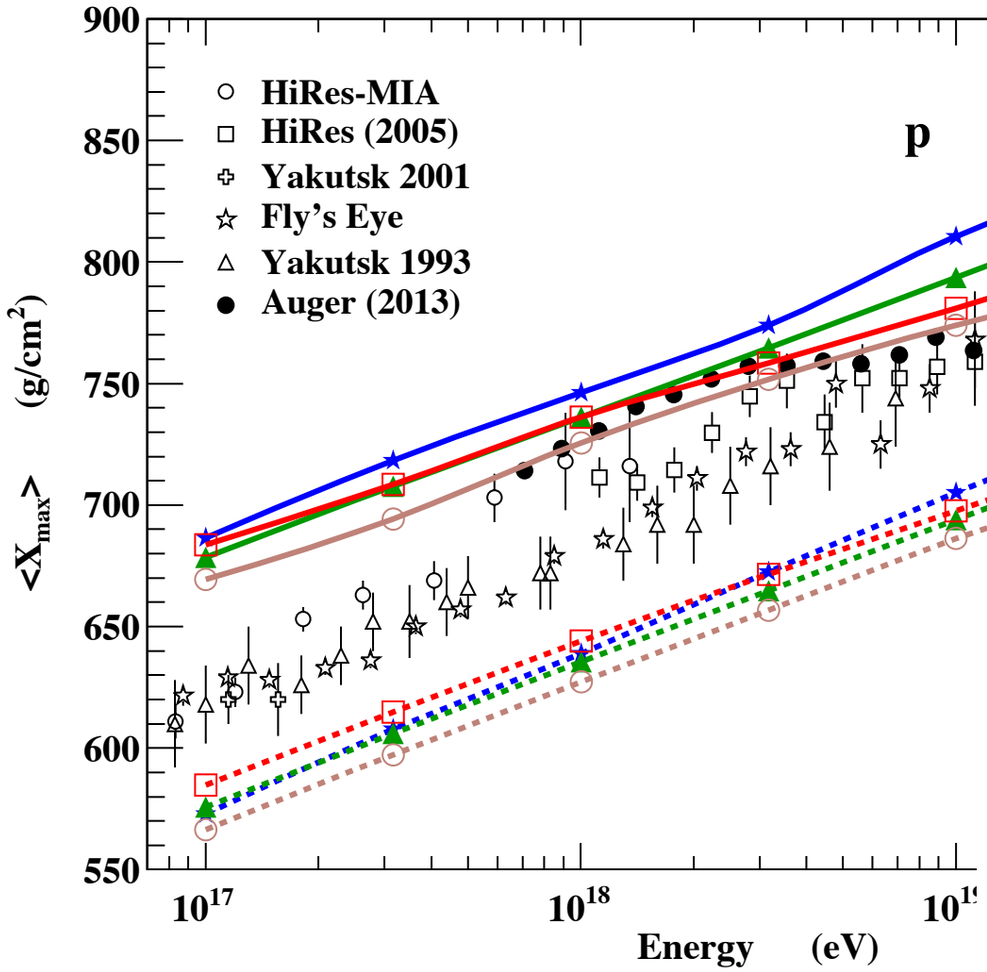






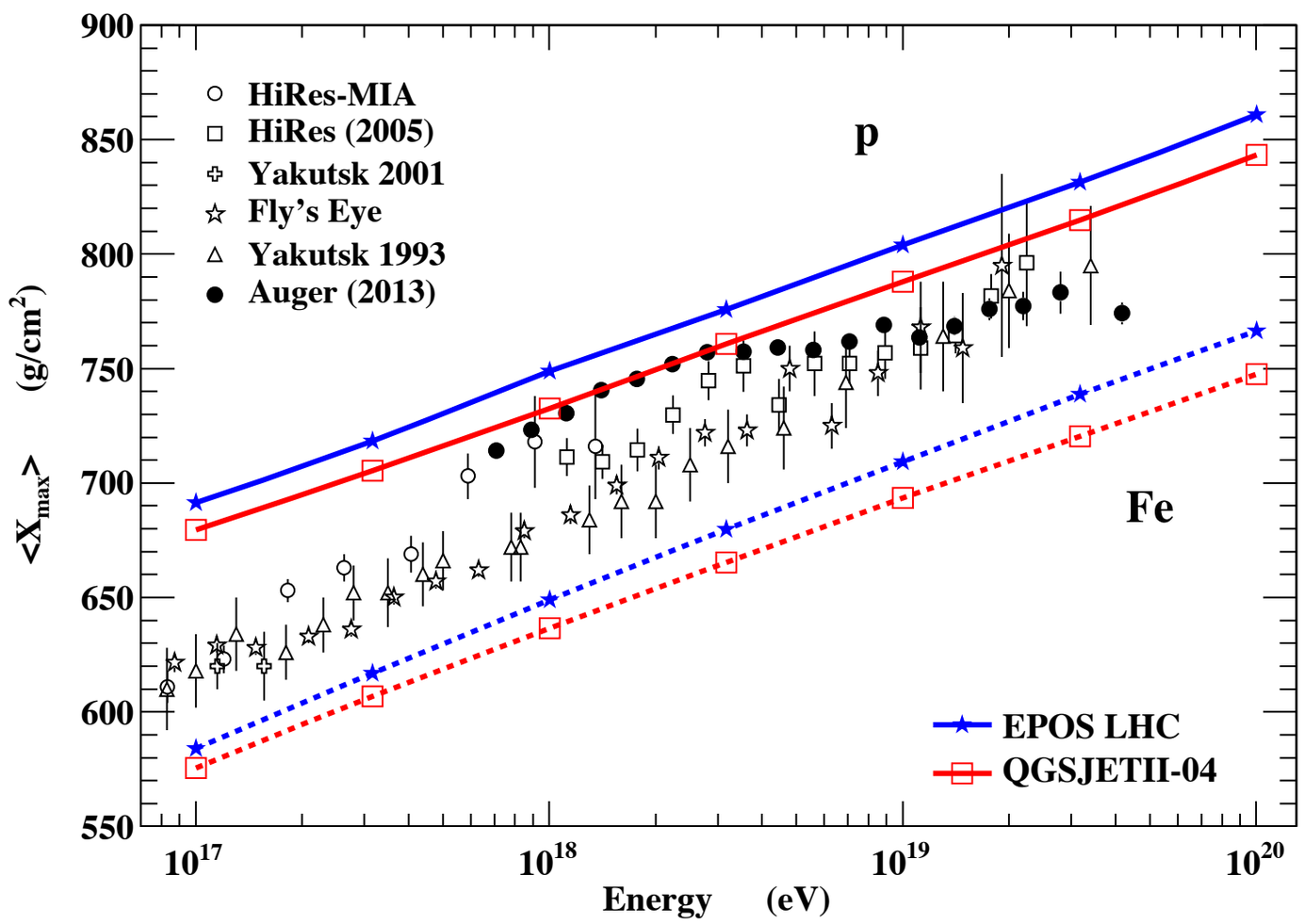


Predictions for depth of shower maximum



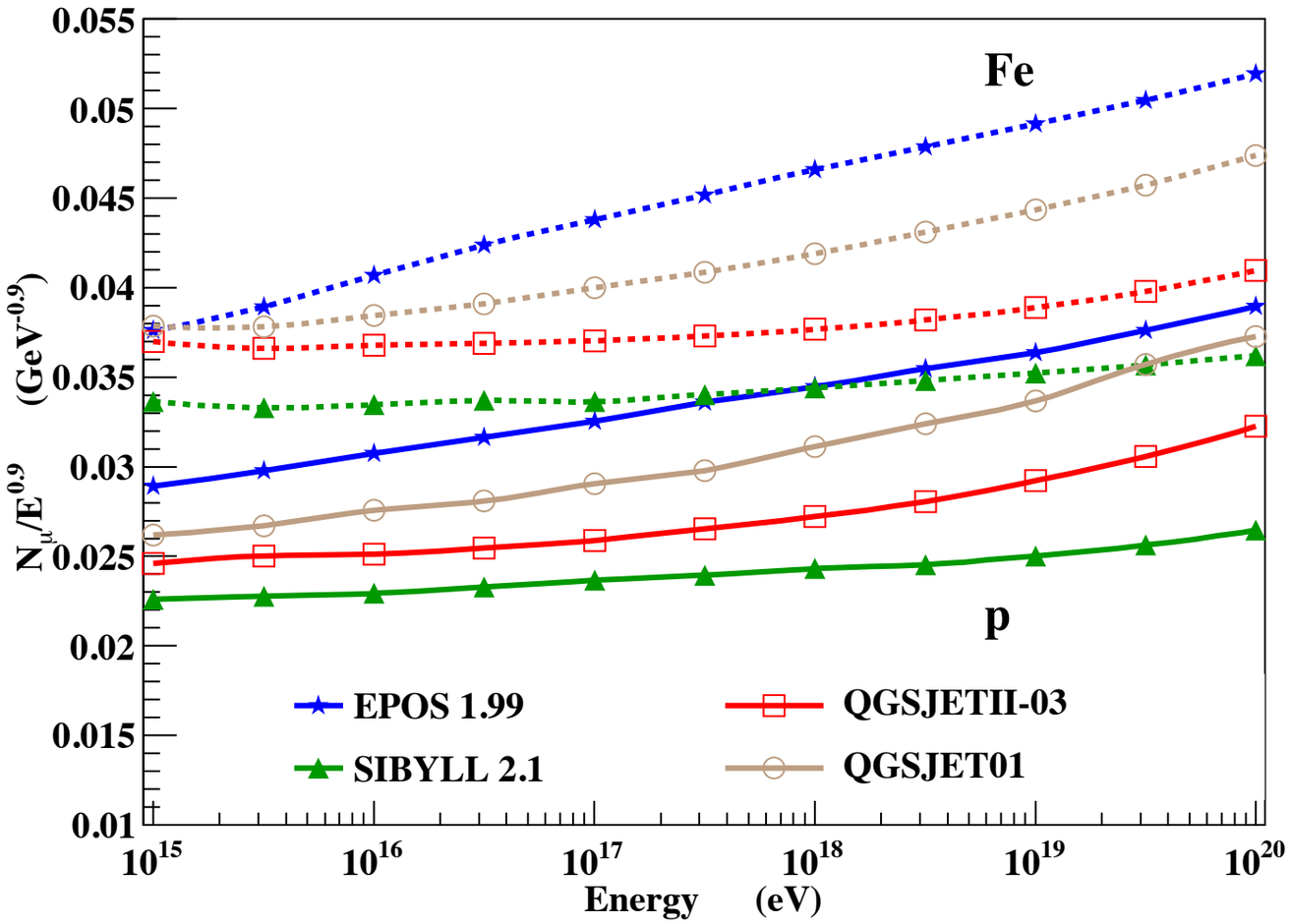
pre-LHC models

post-LHC models



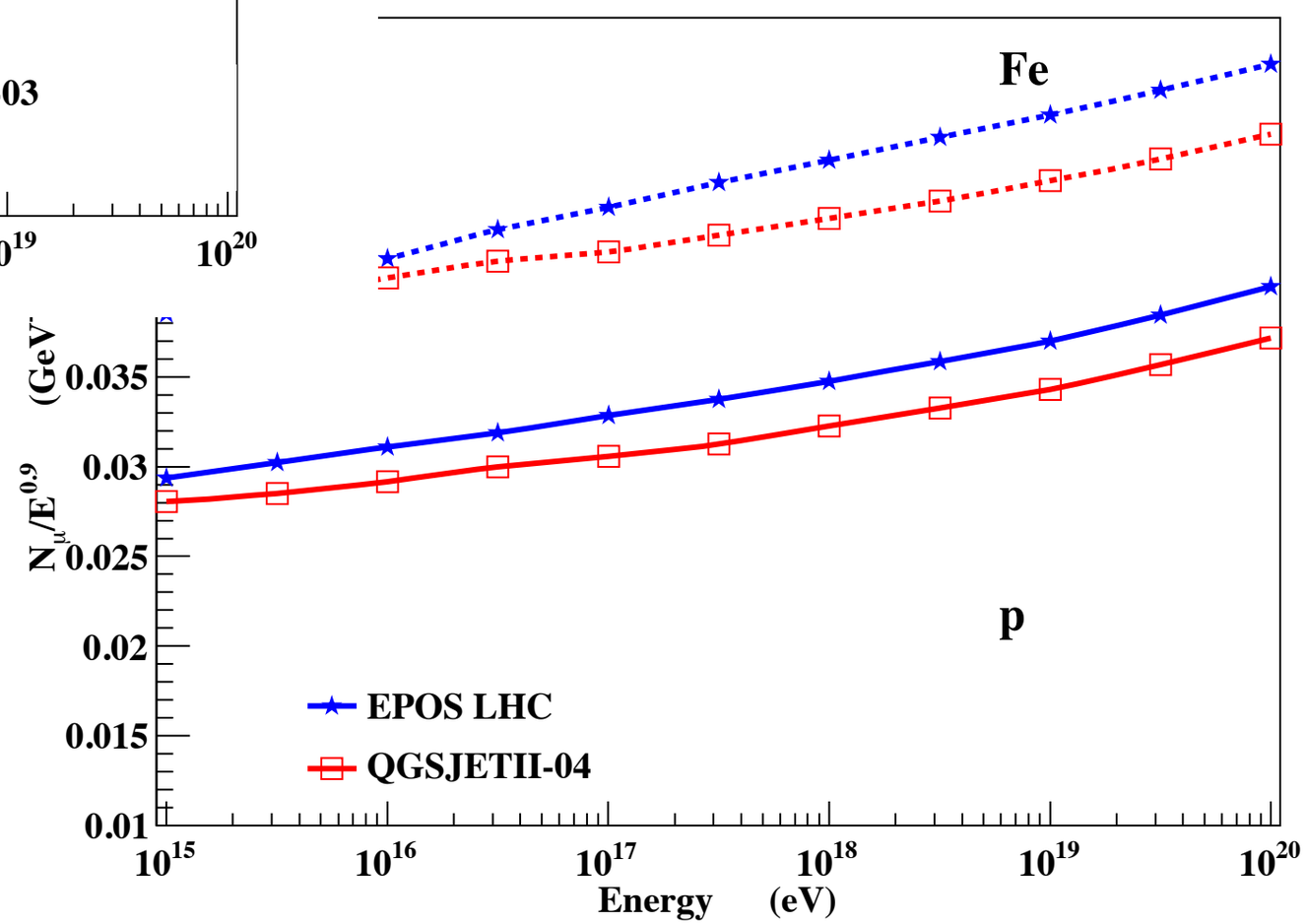
New models favour interpretation as heavier composition than before

Predictions for muon number at ground



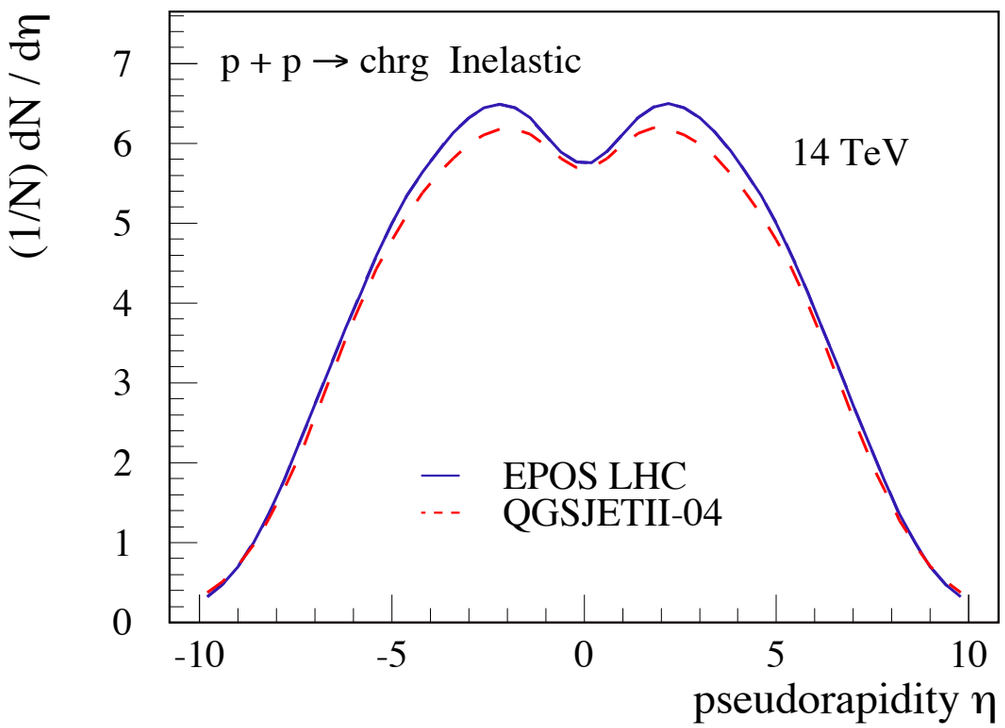
pre-LHC models

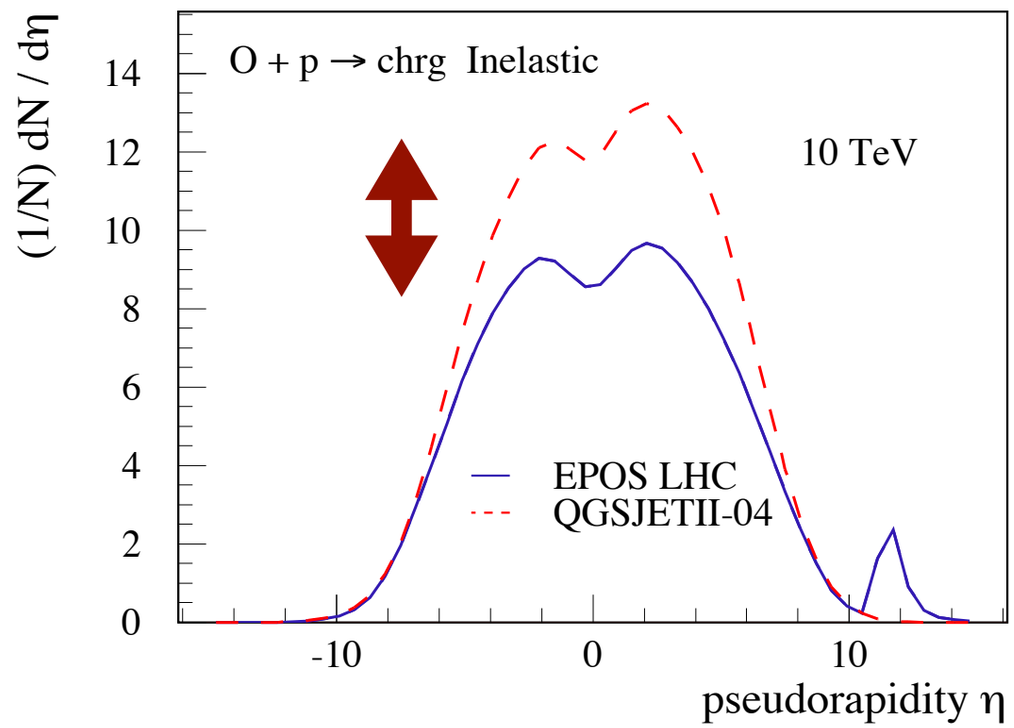
post-LHC models



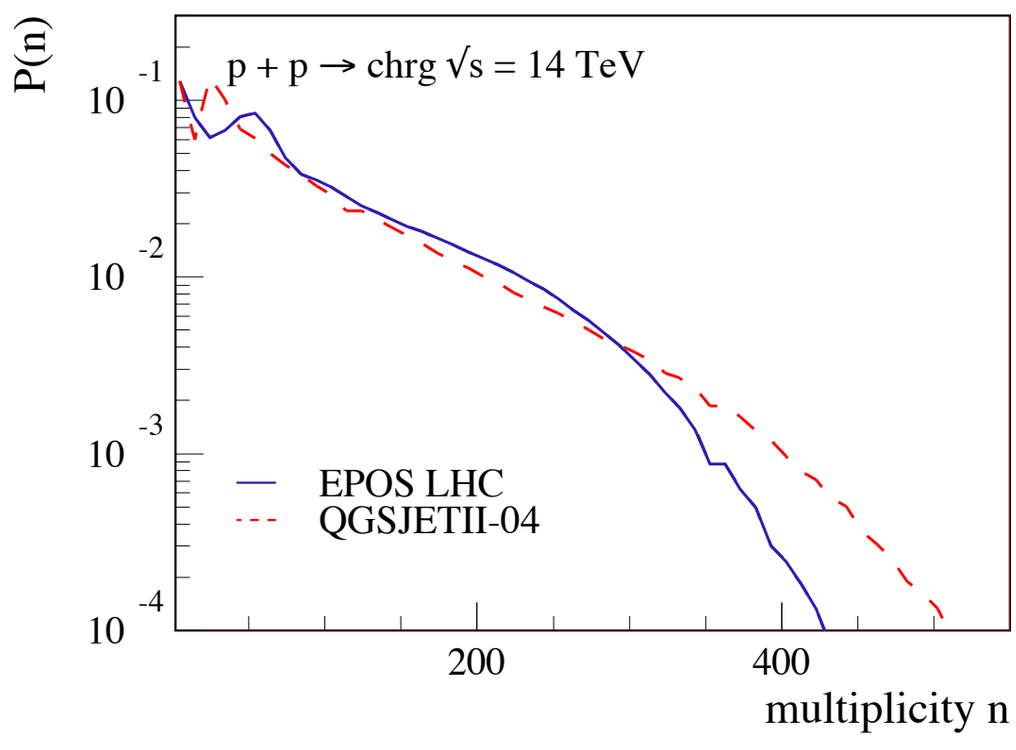
New models favour interpretation as lighter composition than before

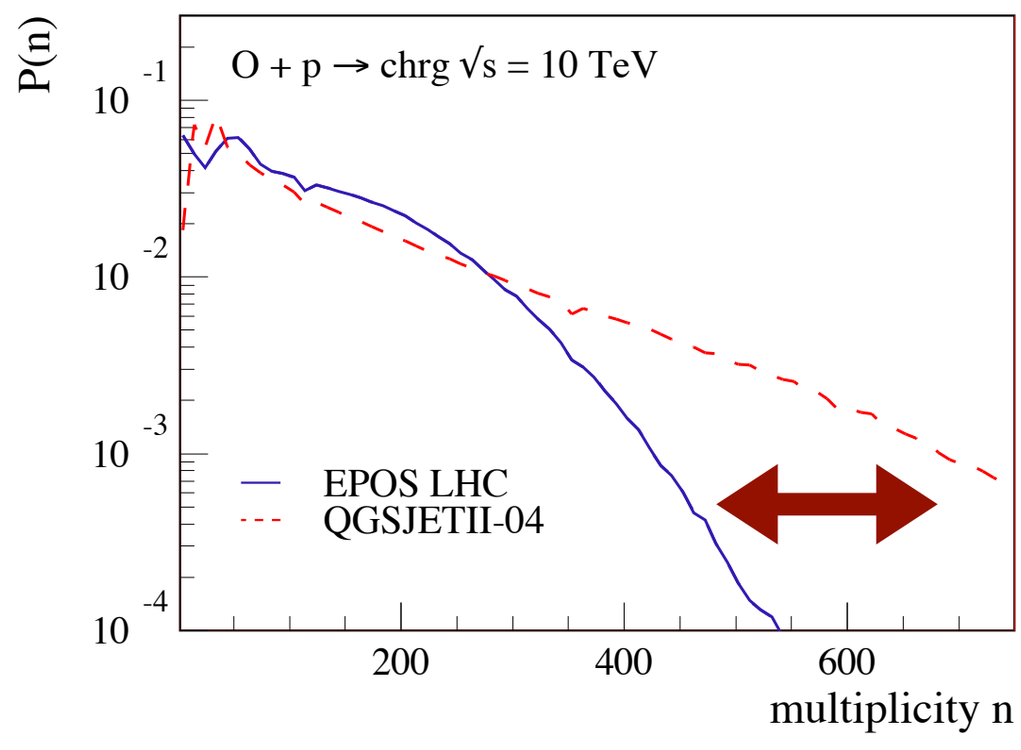
Further improvement: p-O collisions at LHC



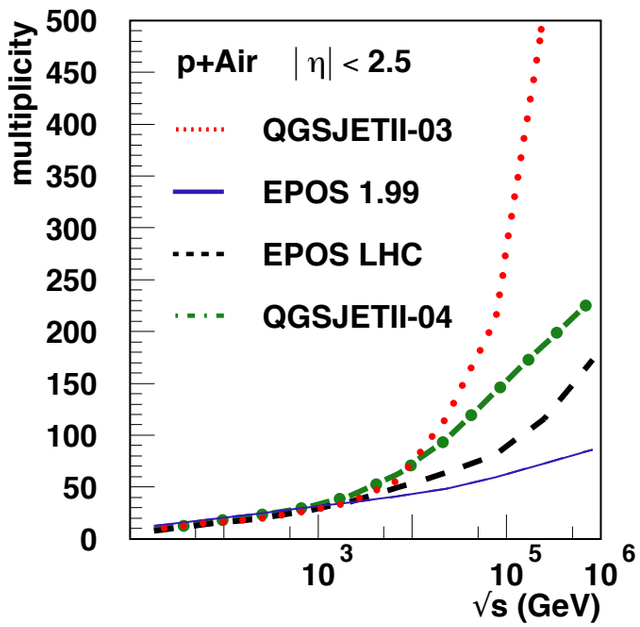


Currently predicted uncertainty in most optimistic case

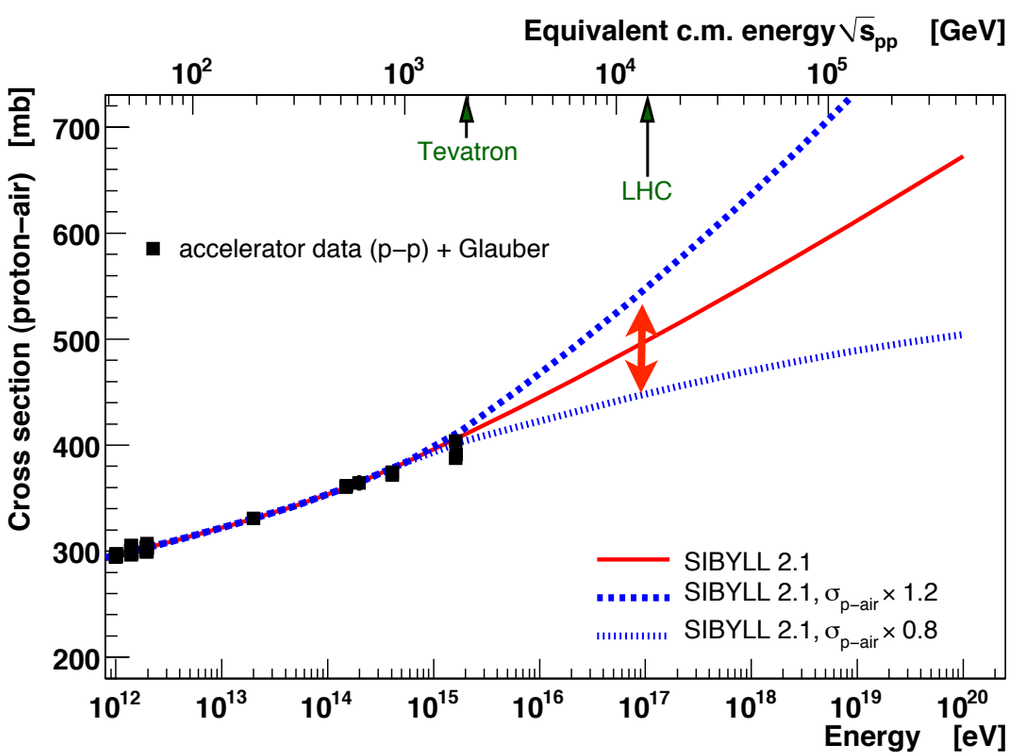


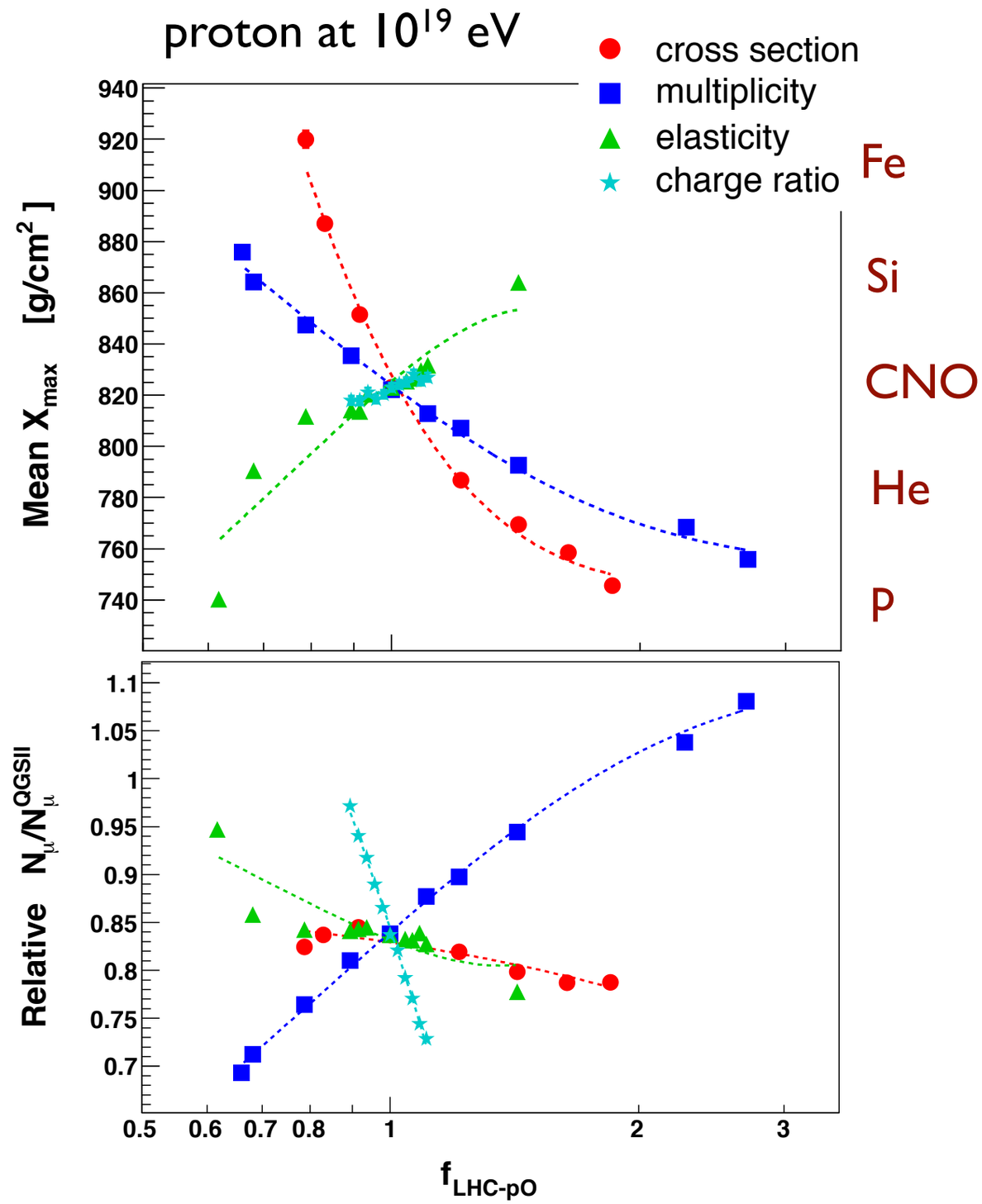


Expected sensitivity of shower observables



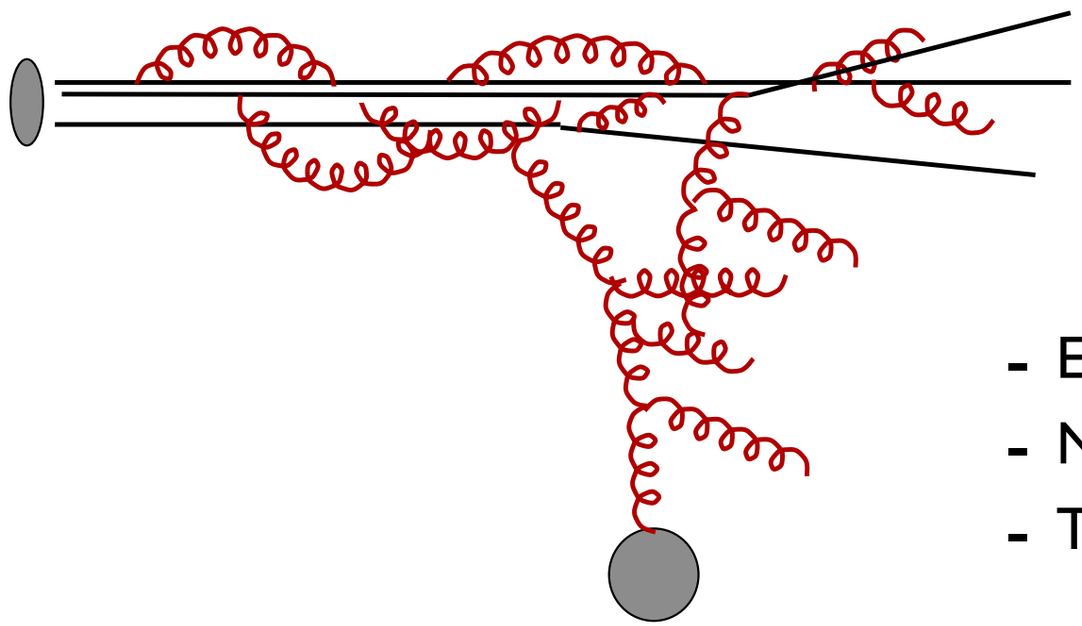
Ad hoc model modification



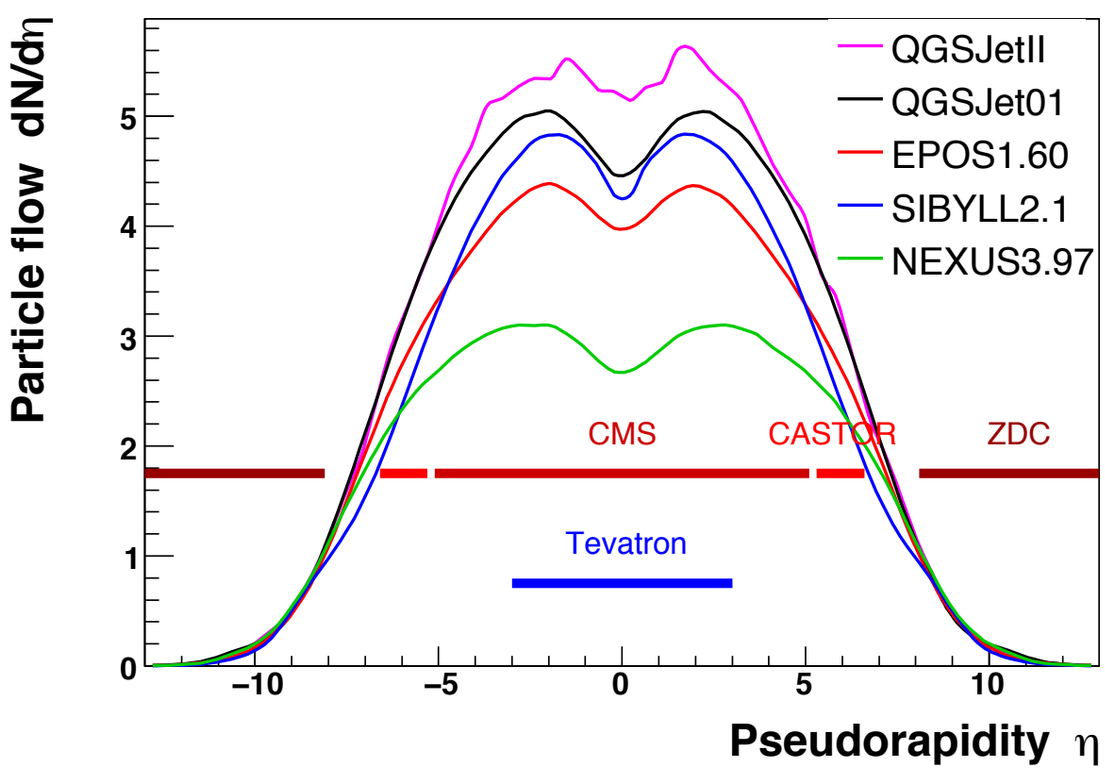


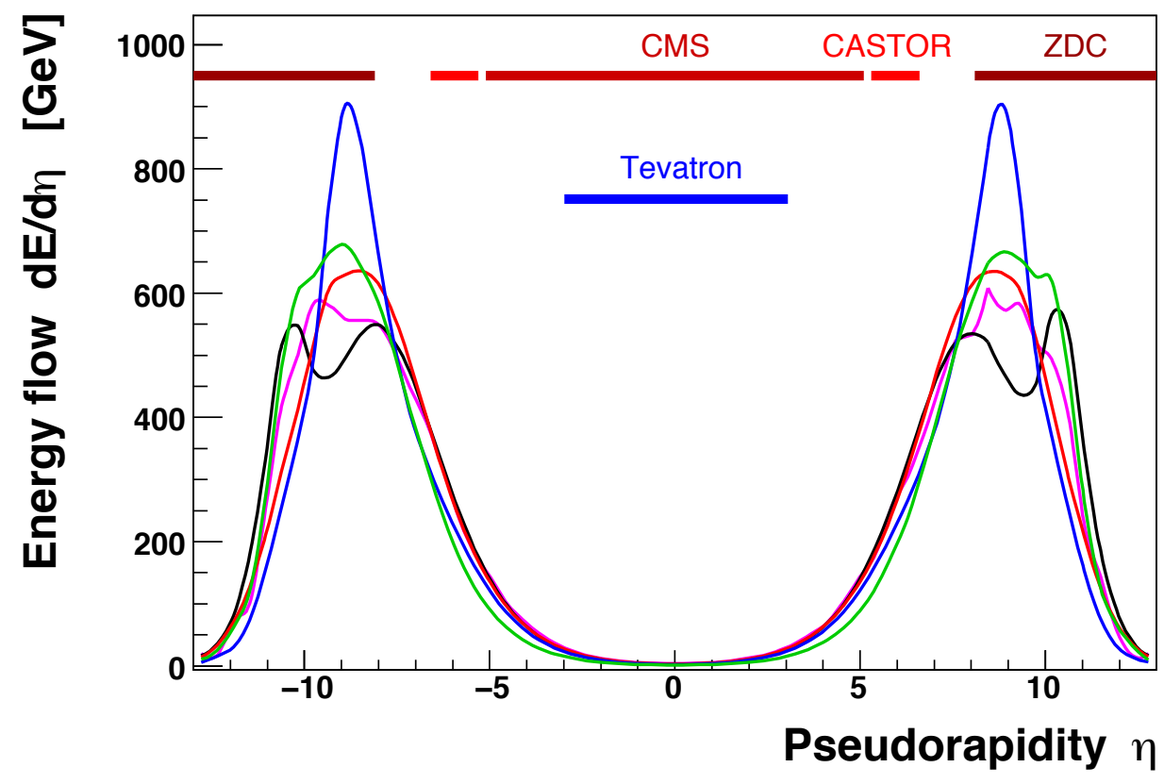
(Ulrich et al., Phys. Rev. D83, 2011)

How reliable are tuned model predictions ?

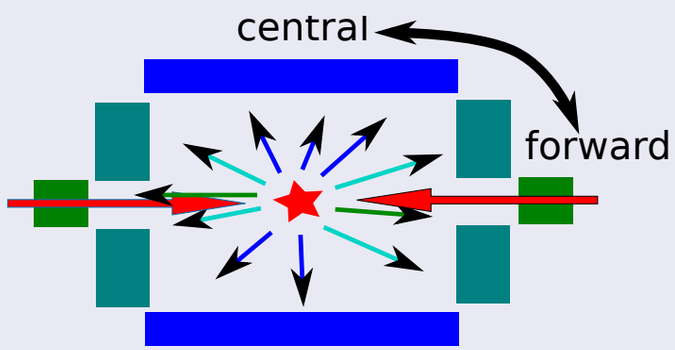


- Energy-momentum and charge/flavour conservation
- Non-trivial correlations: model dependent
- Tuning by adjusting internal model parameters

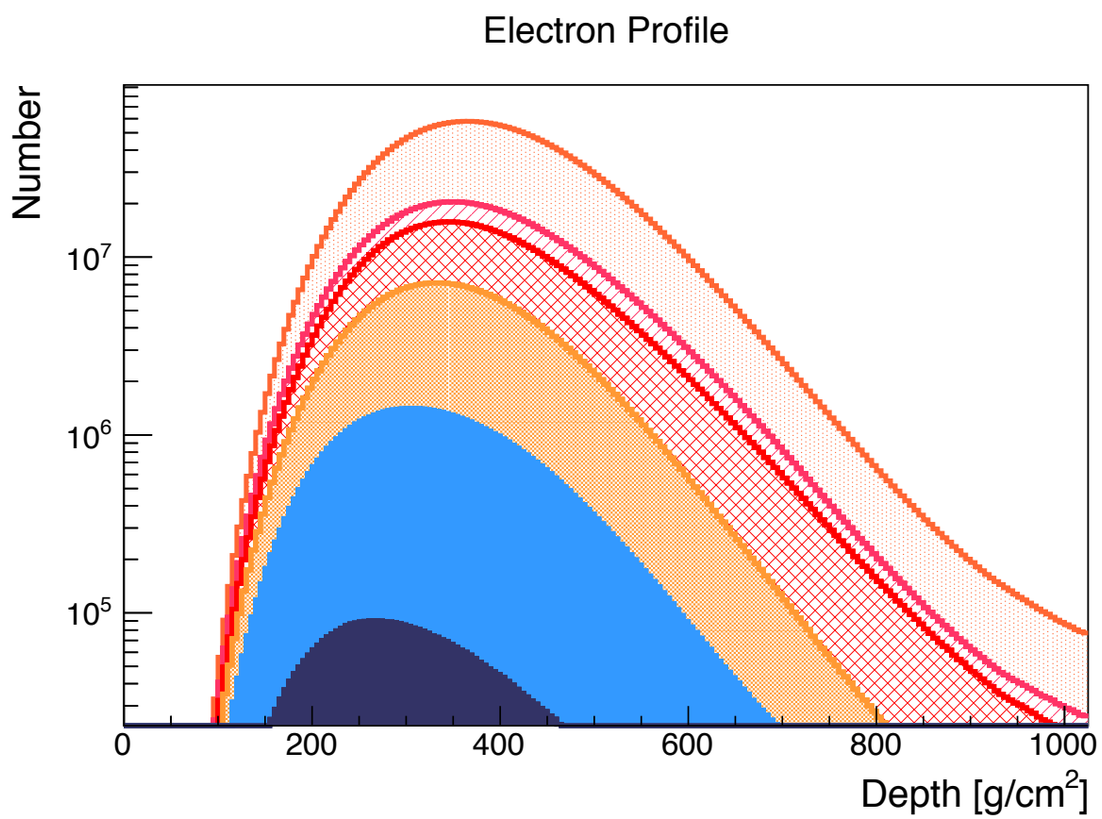


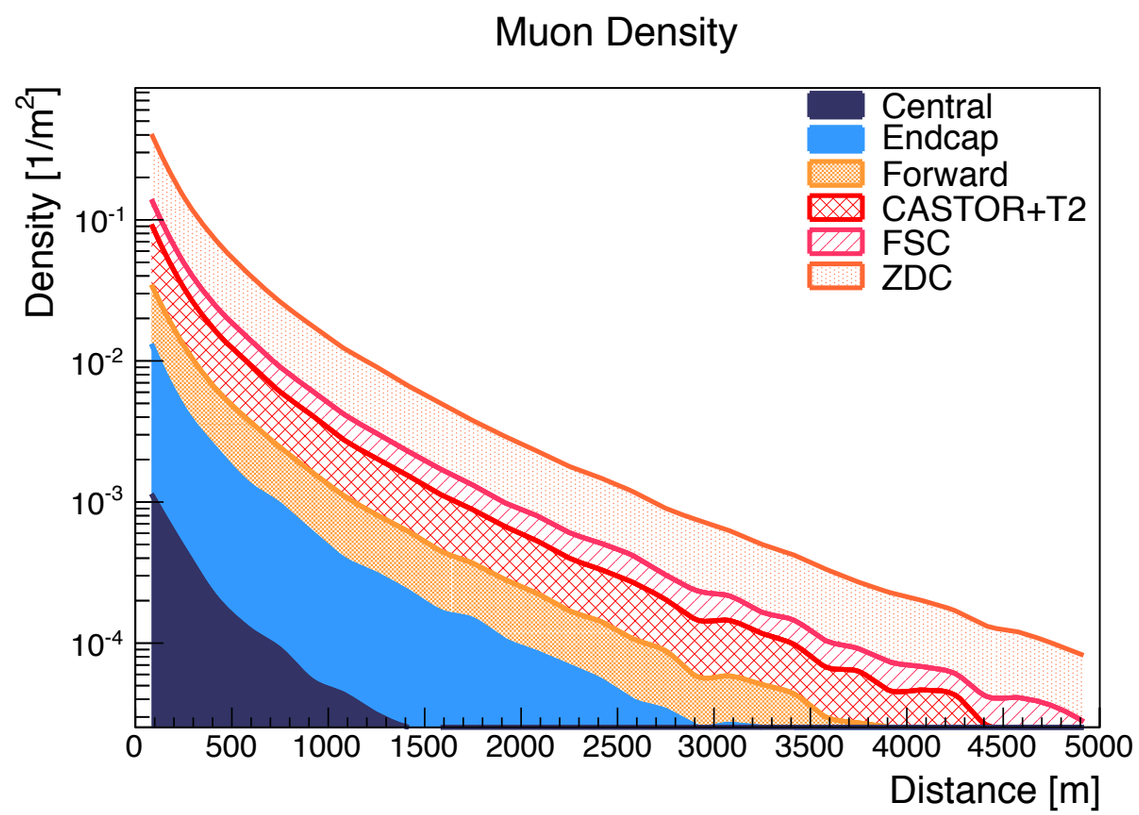


Example: generic LHC detector coverage



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





More than 50% of all measured secondaries from particles of η > 8

(Ulrich, DPG meeting 2014)

Summary and outlook

- Particle physics explanation of knee strongly disfavoured
- All-particle spectrum can be measured with small model uncertainty
- Composition measurements depend directly on interaction models
- Progress made thanks to LHC data (and also fixed-target data, NA61)

  Longitudinal shower profile: cosmic ray composition heavier than before

  Muon number at ground: cosmic ray composition lighter than before
- LHC run with p-O would be very helpful (low luminosity, forward detectors)
- Some uncertainty will remain due to limited phase space coverage