Cosmic Ray Interactions in the Atmosphere

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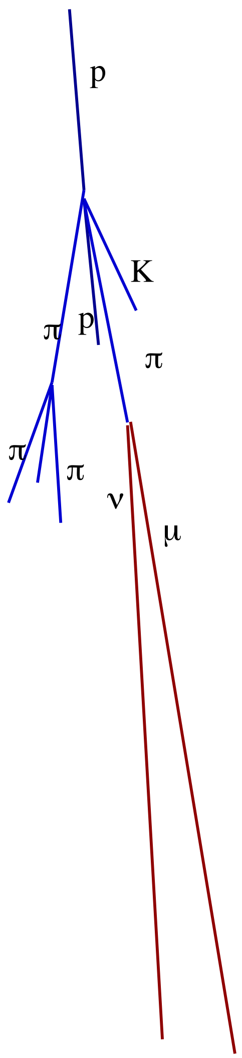
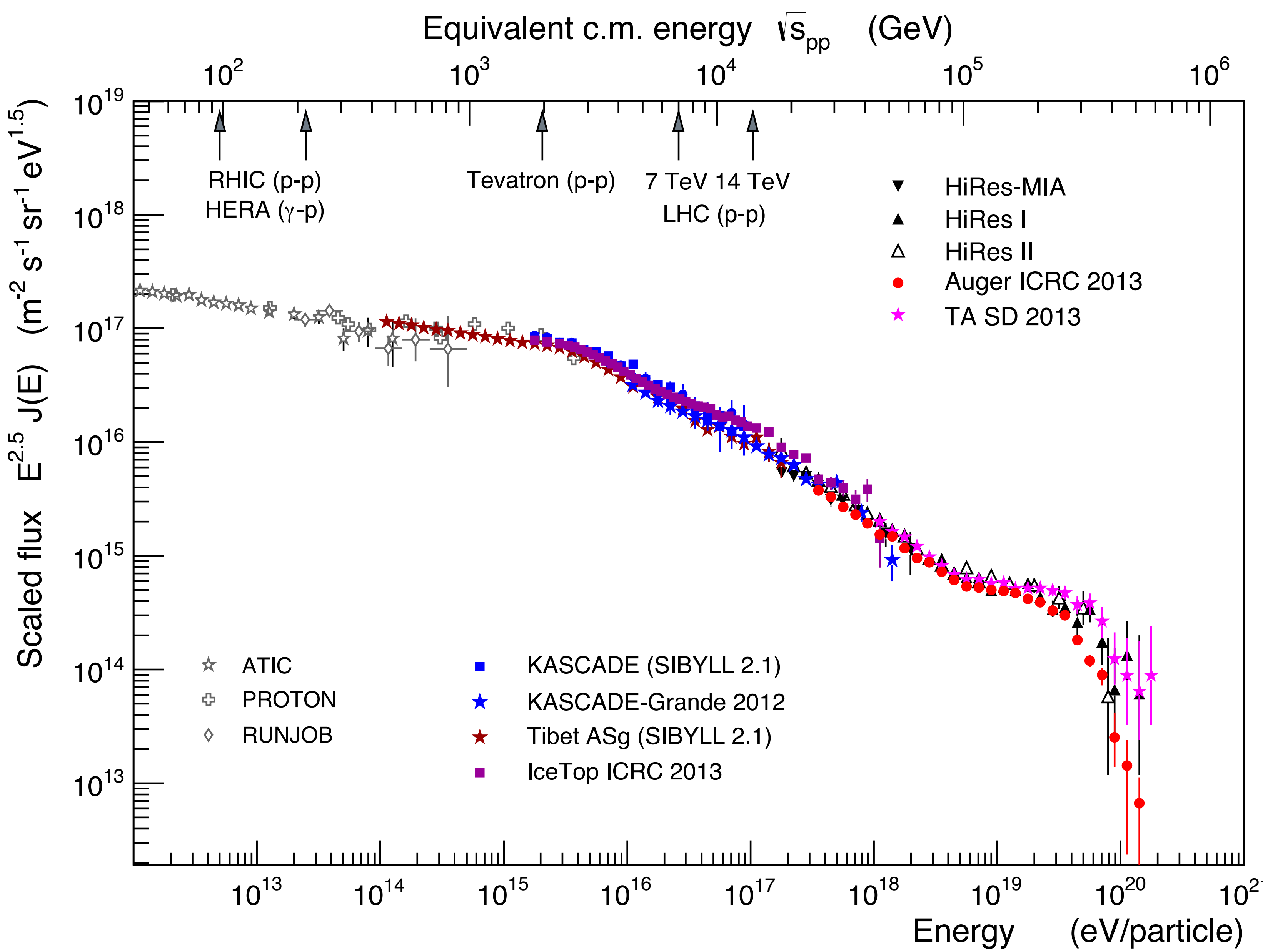
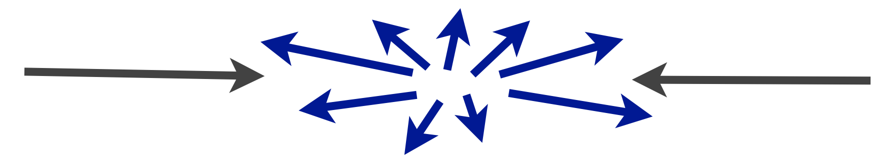
Acknowledgement (PhD theses in 2015):

Felix Riehn (Sibyll) & Anatoli Fedynitch (atm. lepton fluxes)

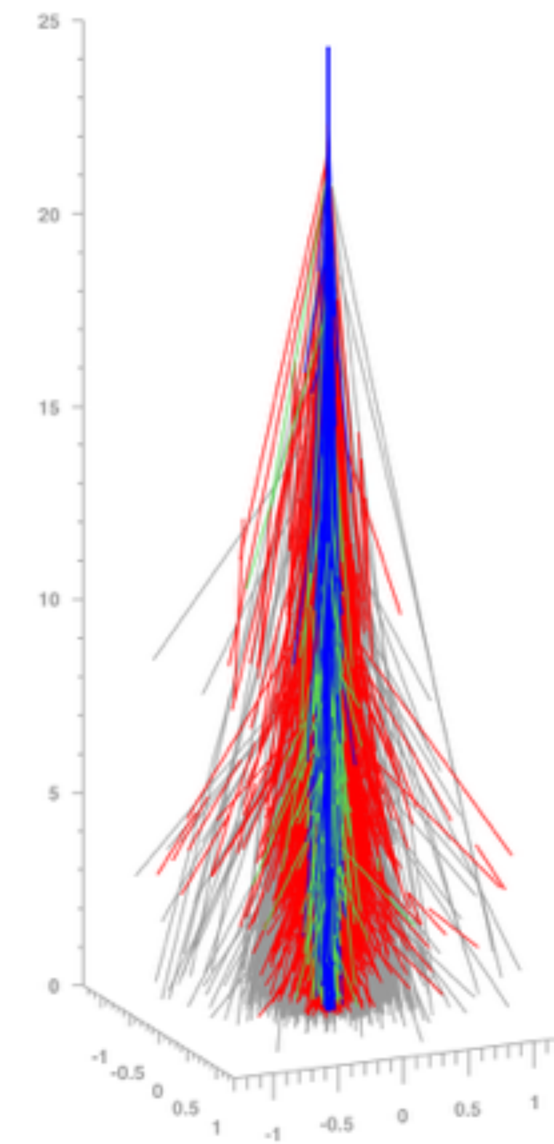
Cosmic ray flux and interaction energies

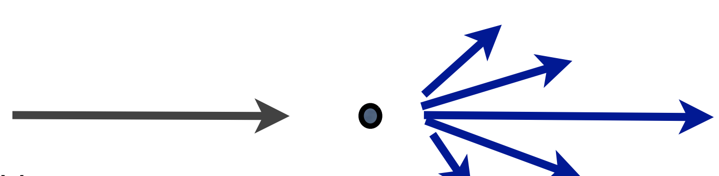






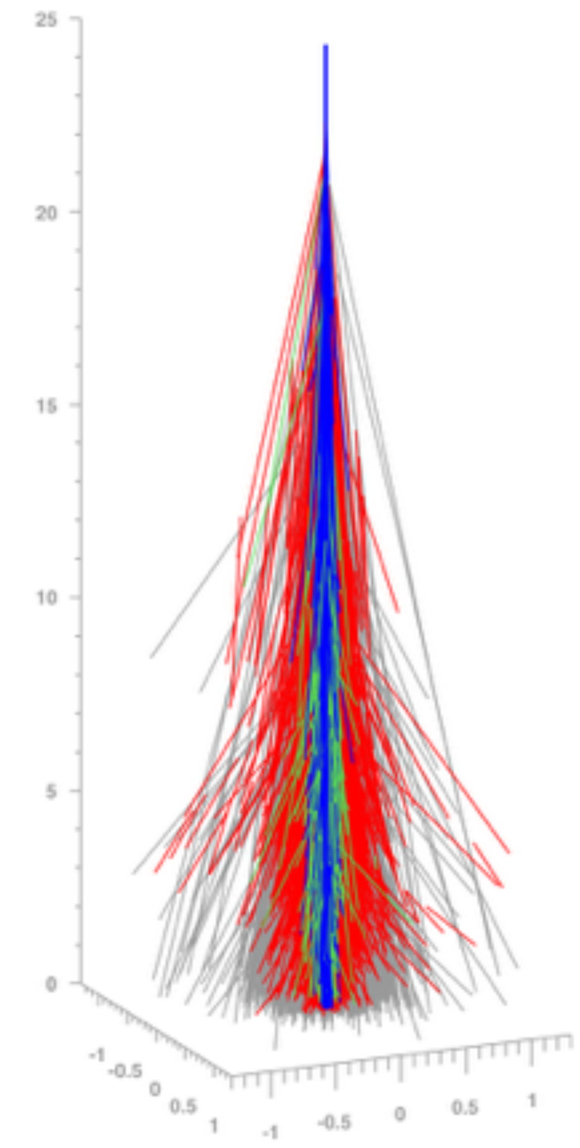
Center-of-mass energy



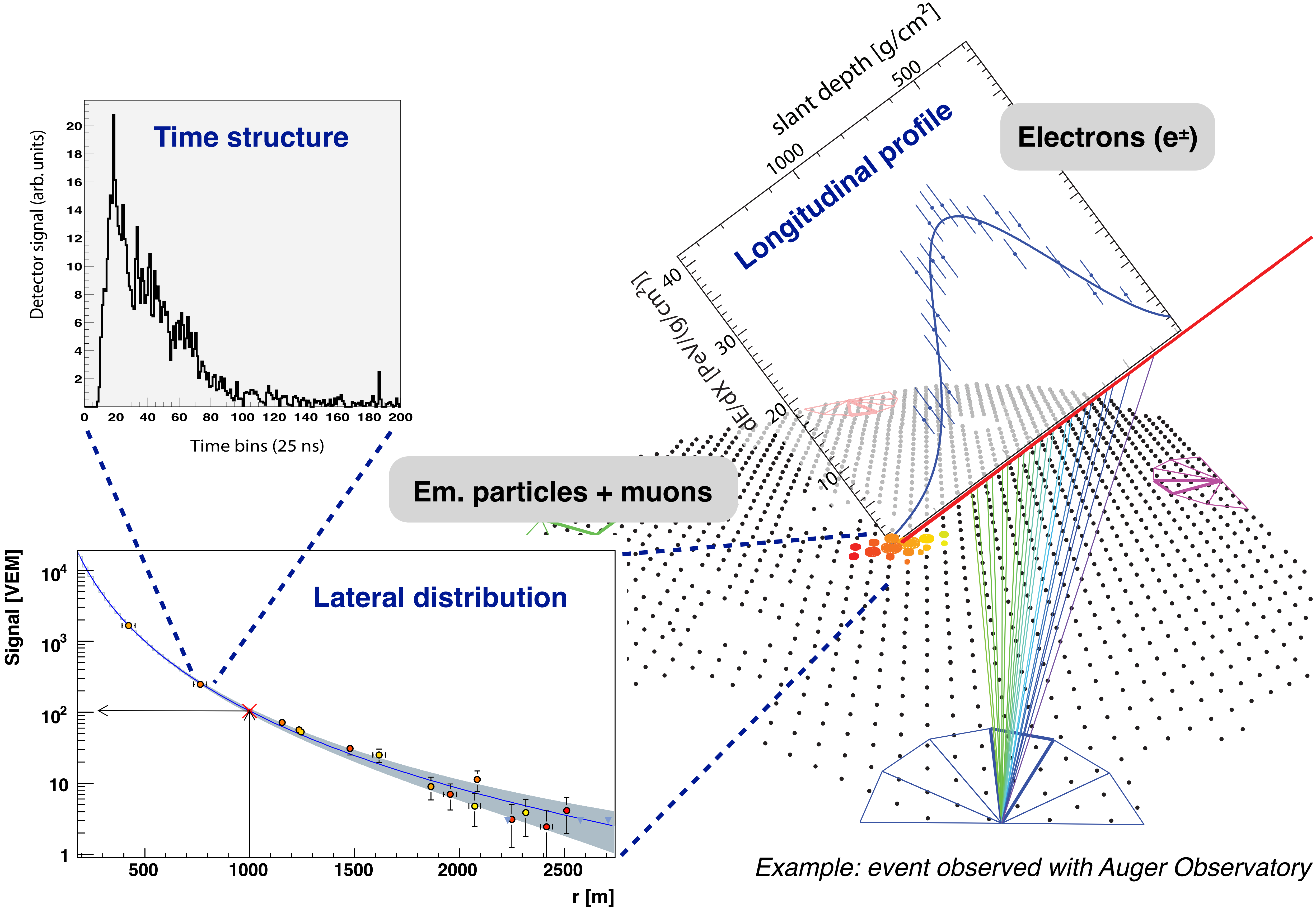


Laboratory energy

Part 1: Extensive Air Showers

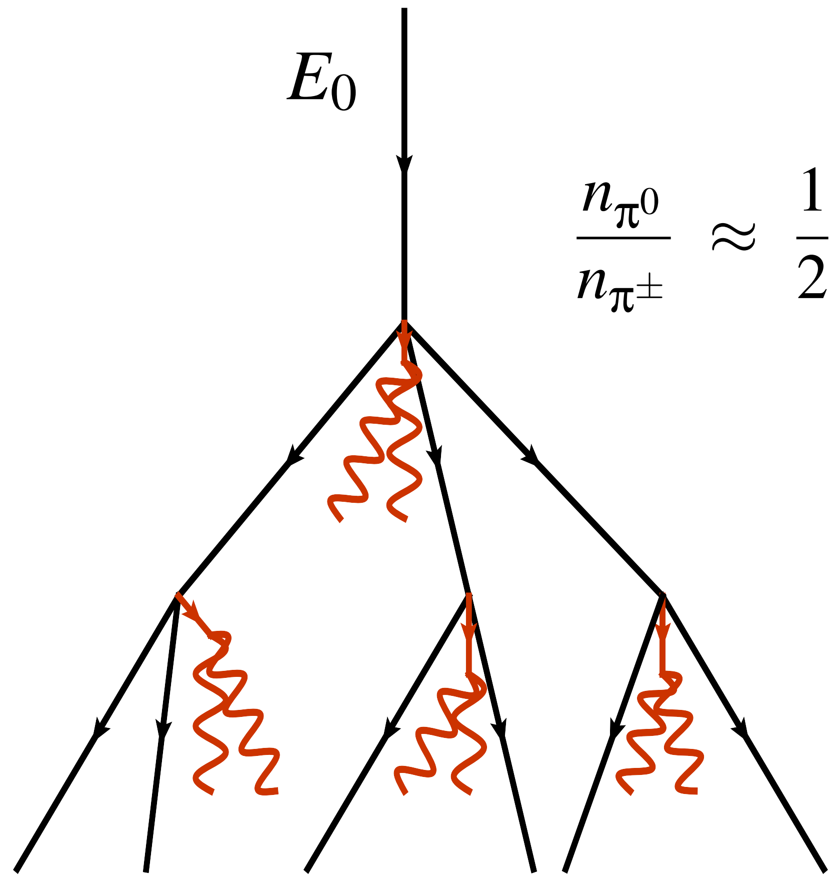


Measurement of different shower observables



Example: event observed with Auger Observatory

Shower physics: energy transfer



$$\frac{n_{\pi^0}}{n_{\pi^\pm}} \approx \frac{1}{2}$$

Hadronic energy

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

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

o
o
o
o

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

Decay after n generations

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

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

Electromagnetic energy

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

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

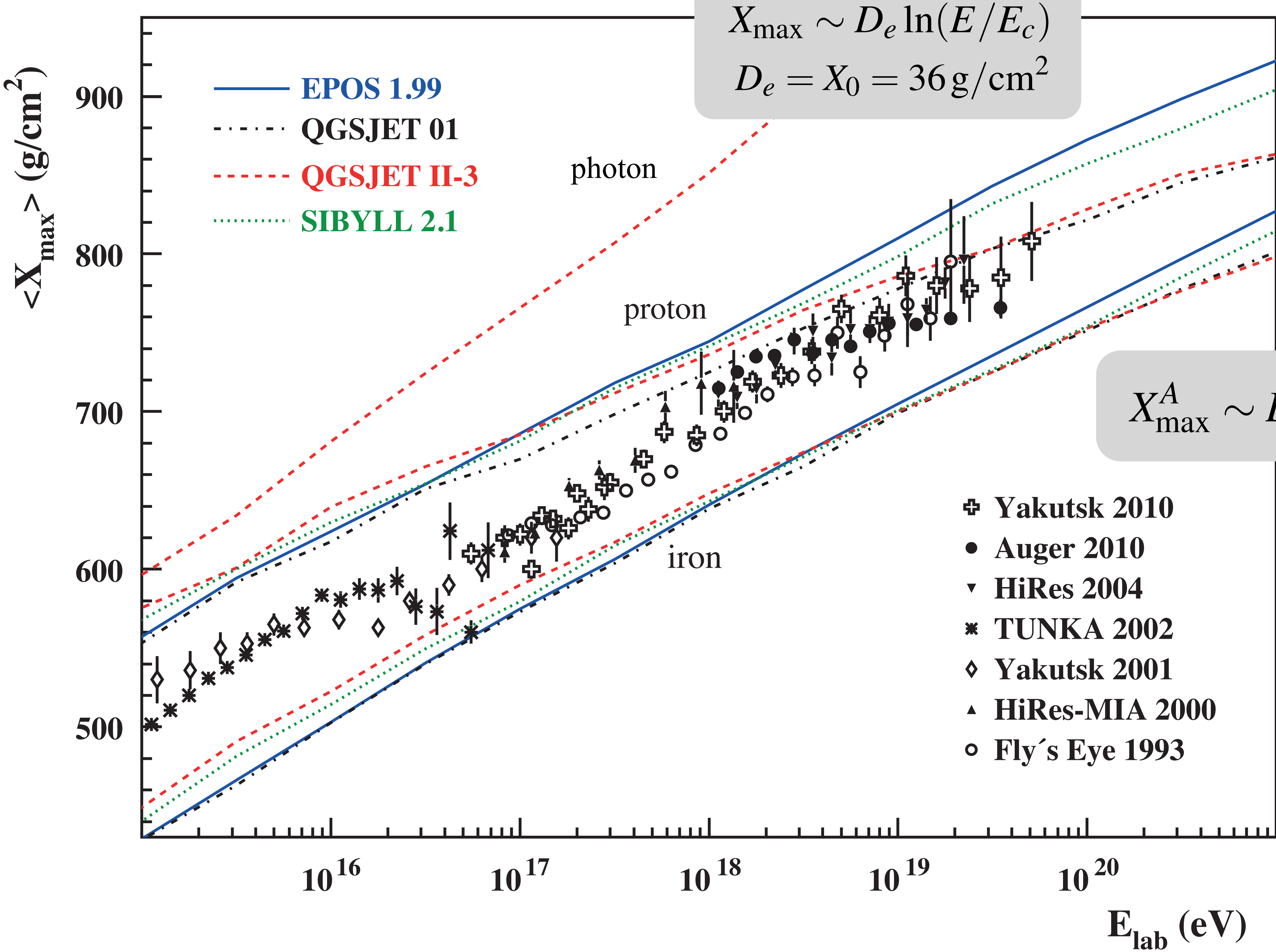
o
o
o
o

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

Depth of shower maximum:

High-energy interactions

Pre-LHC: mean depth of shower maximum



$$X_{\max} \sim D_e \ln(E/E_c)$$
$$D_e = X_0 = 36\,\mathrm{g/cm^2}$$

$$X_{\max}^A \sim D_e^{\mathrm{had}} \log(E_0/A)$$

(RE, Pierog, Heck, ARNPS 2011)

Elongation rate and model features

Elongation rate theorem

$$D_e^{\mathrm{had}} = X_0(1 - B_n - B_\lambda)$$

(Linsley, Watson PRL46, 1981)

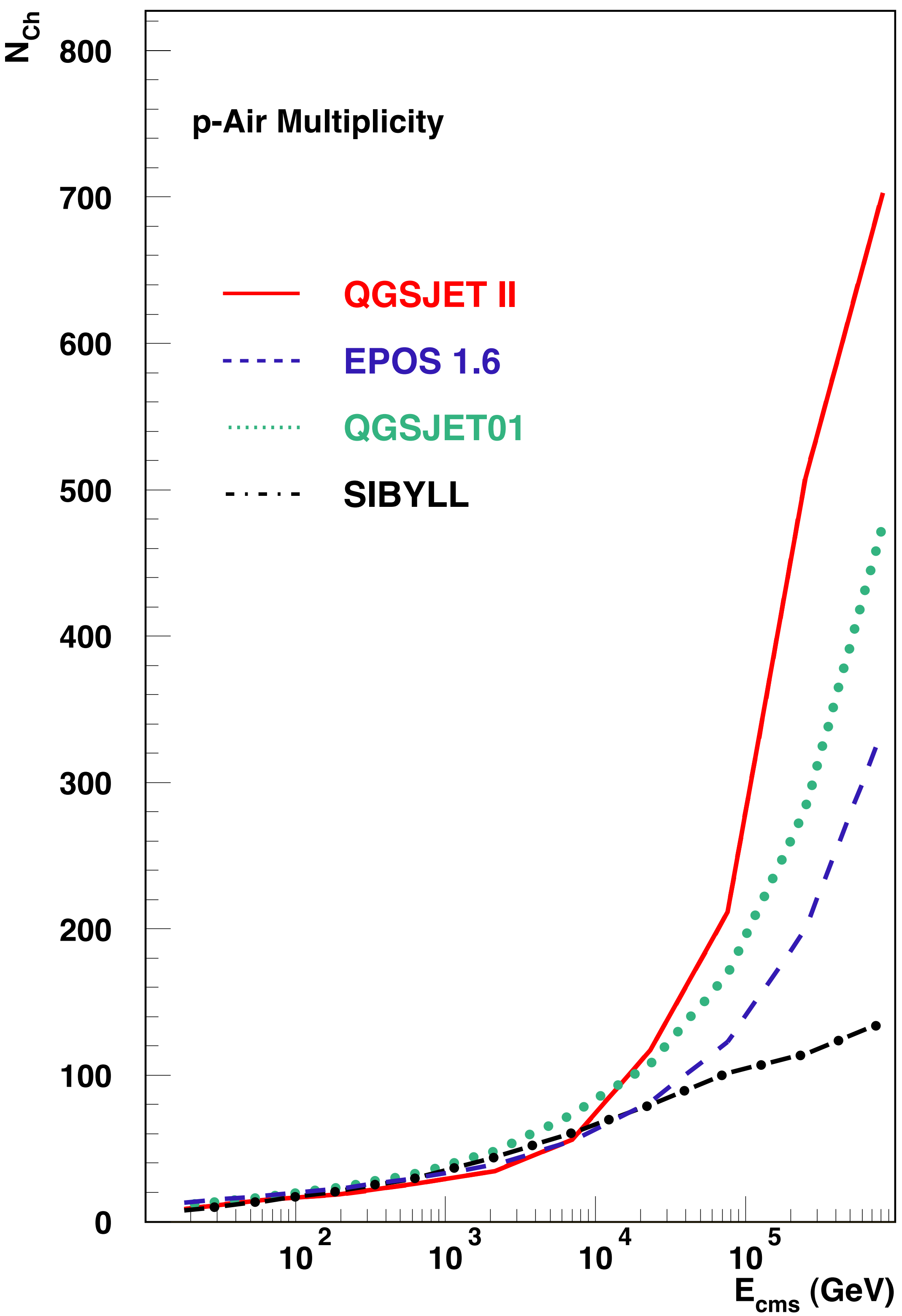
const. factor ~ 36 g/cm^2

$$B_n = \frac{\mathrm{d}\ln n_{\mathrm{tot}}}{\mathrm{d}\ln E}$$

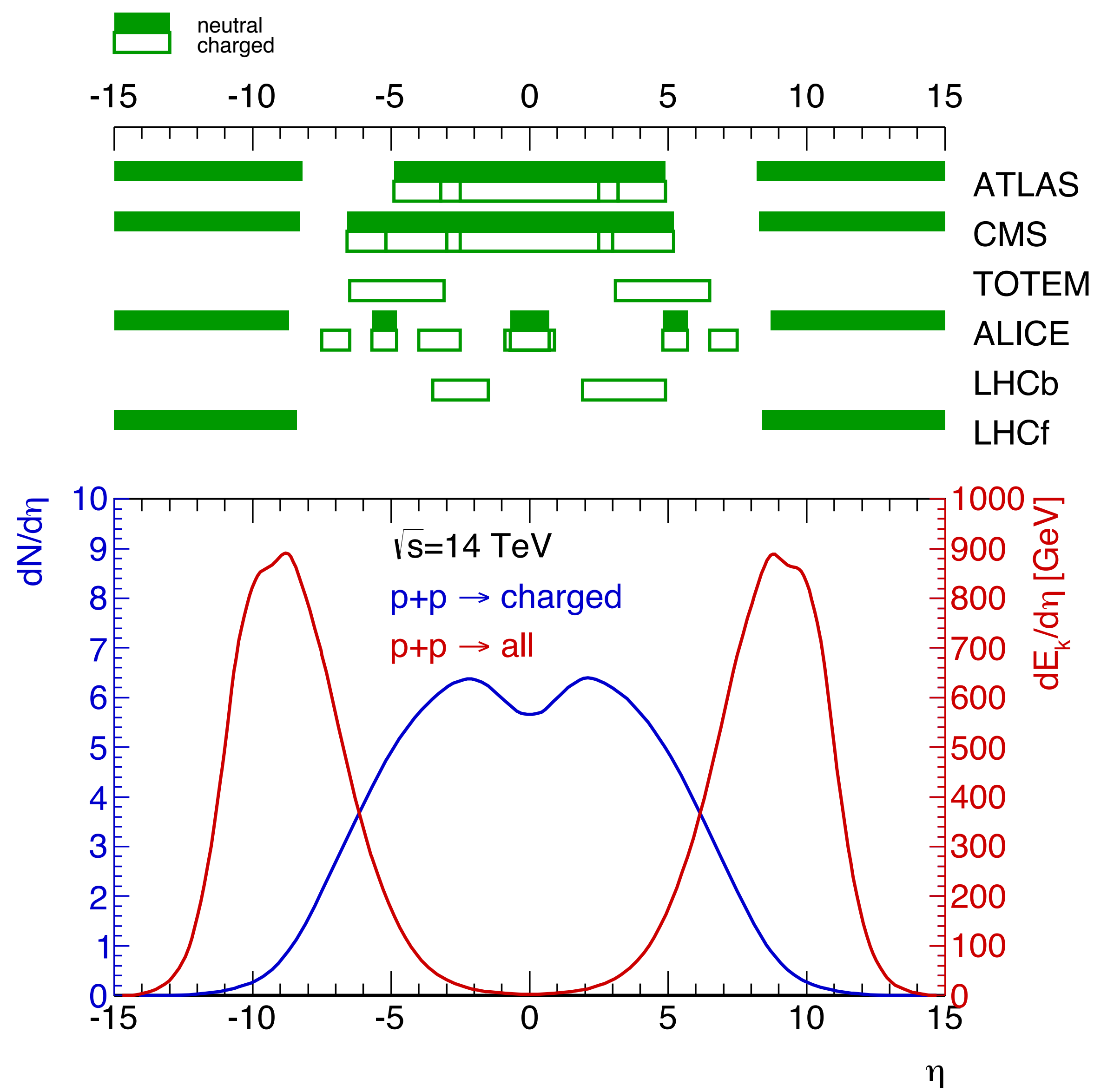
Large if multiplicity of high energy particles rises very fast, **zero in case of scaling**

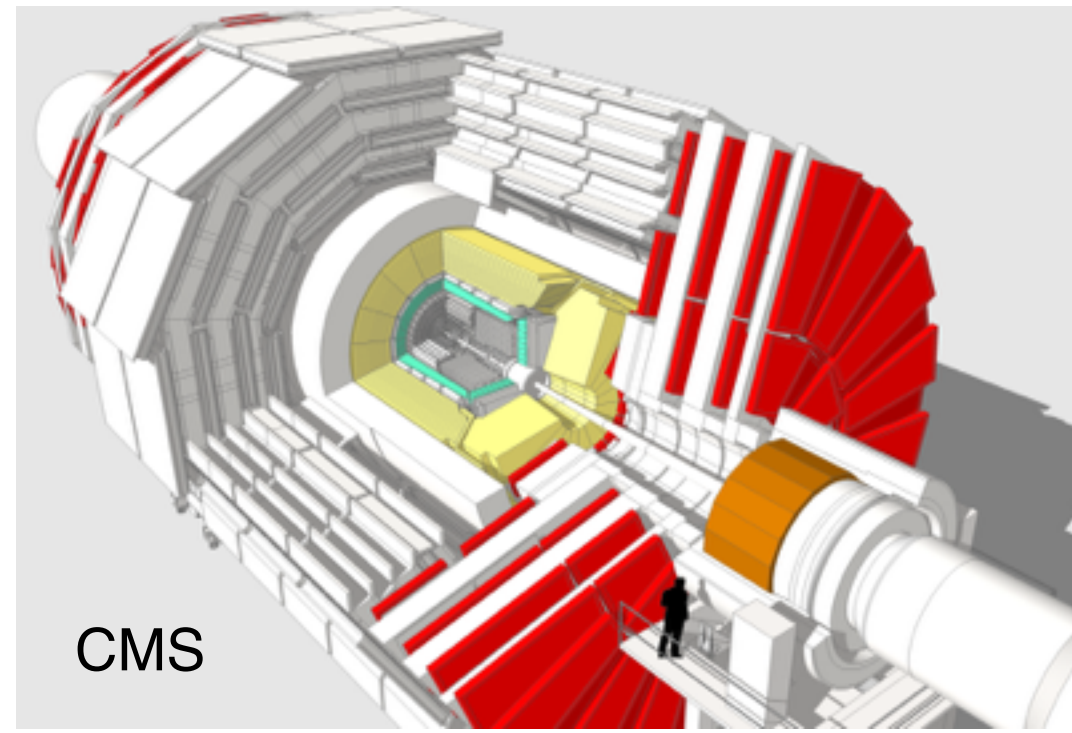
$$B_\lambda = -\frac{1}{X_0}\frac{\mathrm{d}\lambda_{\mathrm{int}}}{\mathrm{d}\ln E}$$

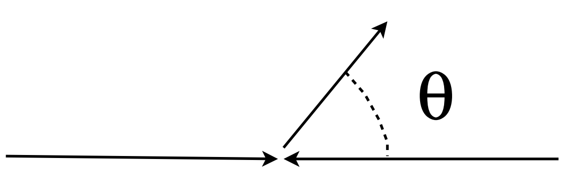
Large if cross section rises rapidly with energy



LHC experiments: phase space coverage





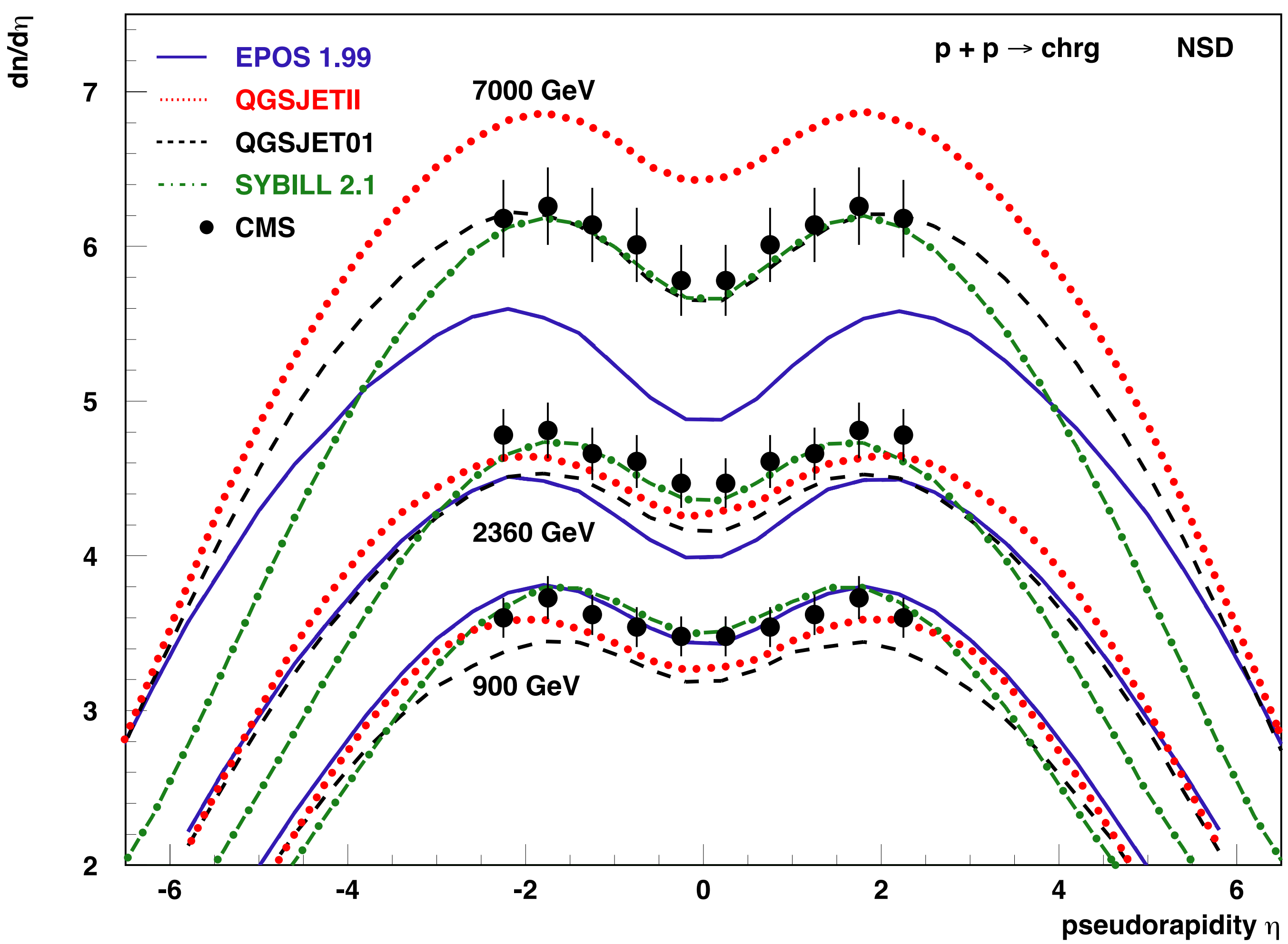


$$\eta = -\ln\tan\frac{\theta}{2}$$

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

(Salek et al., 2014)

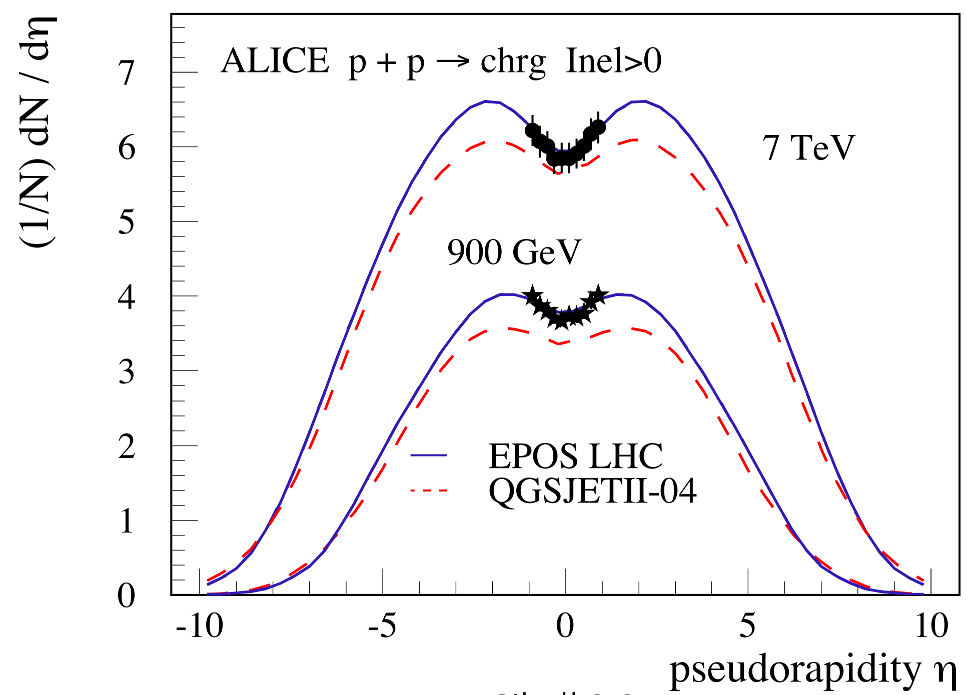
Charged particle distribution in pseudorapidity

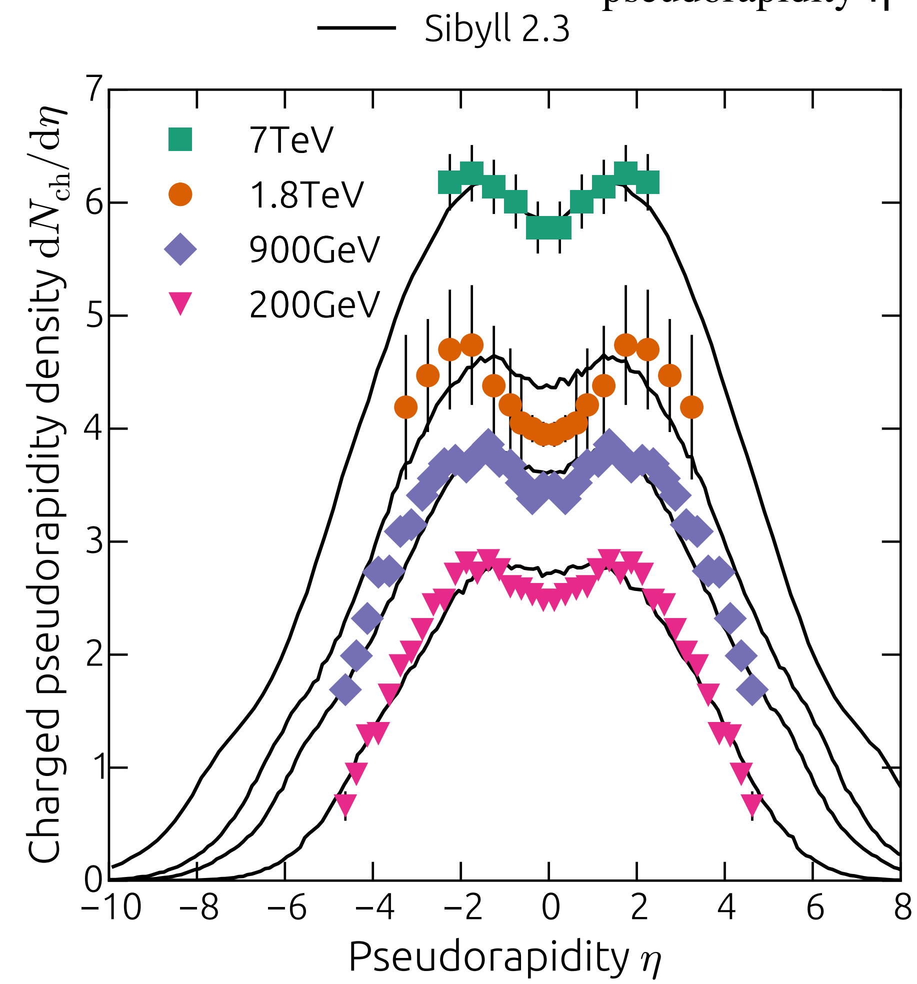


(data exist from all LHC experiments)

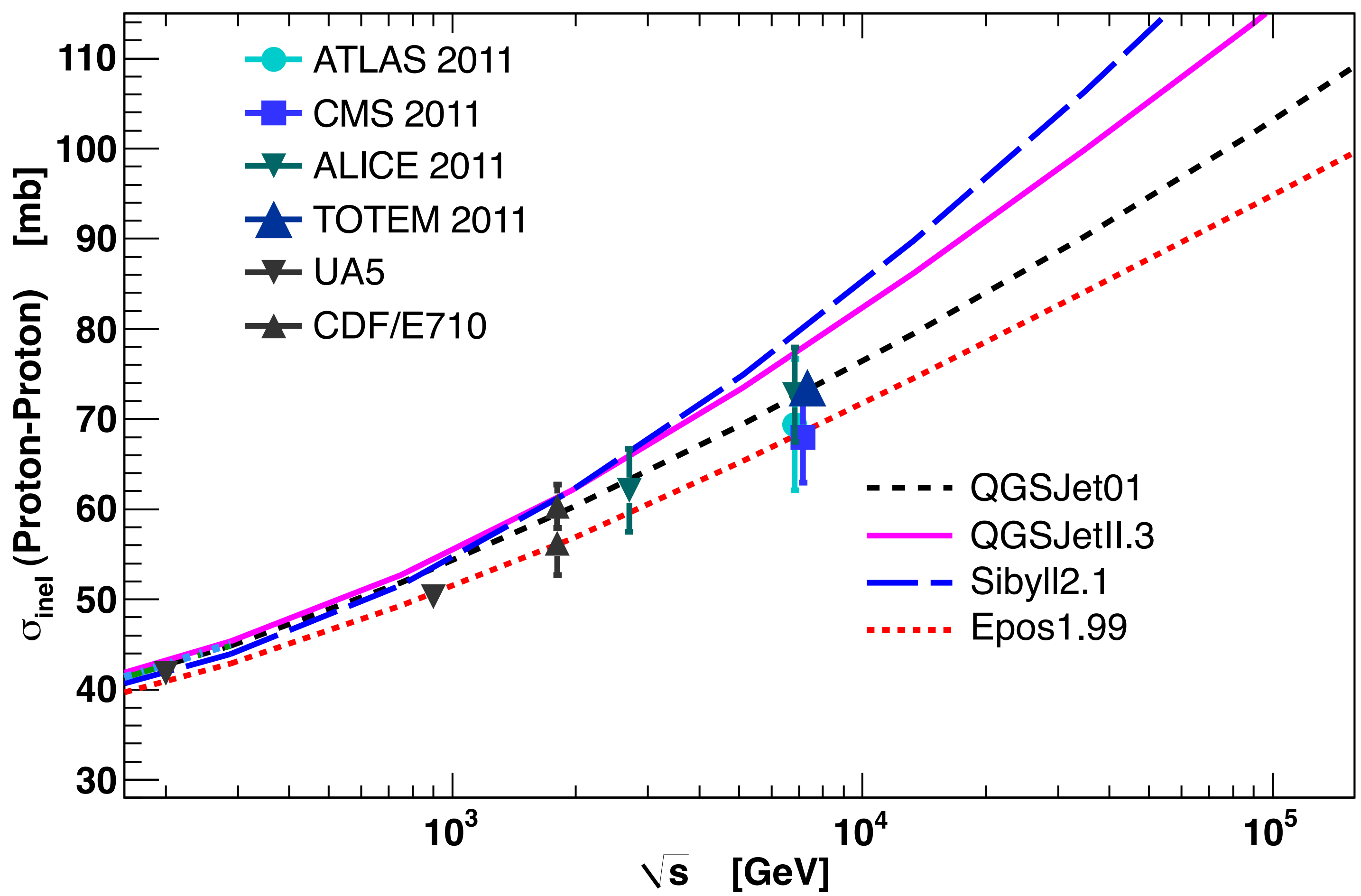
Moderate rise of particle multiplicity

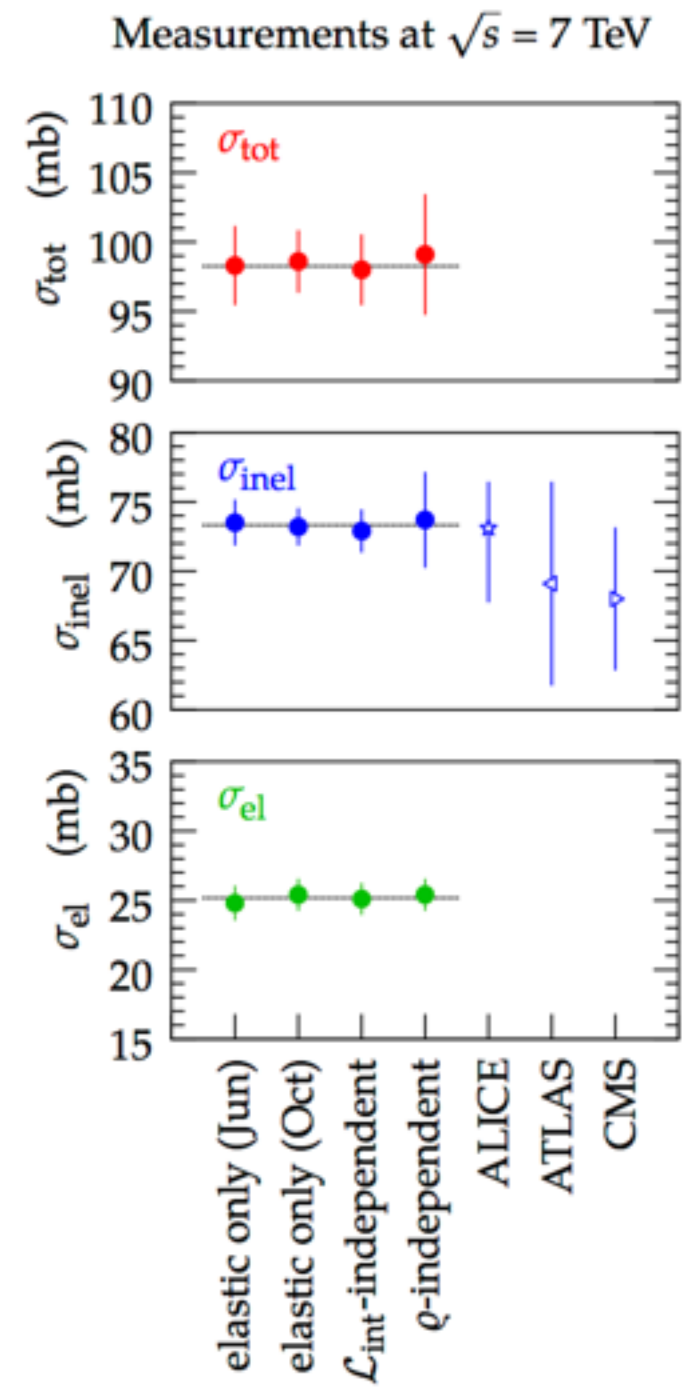
Feb. 2016: new version of Sibyll (v2.3)

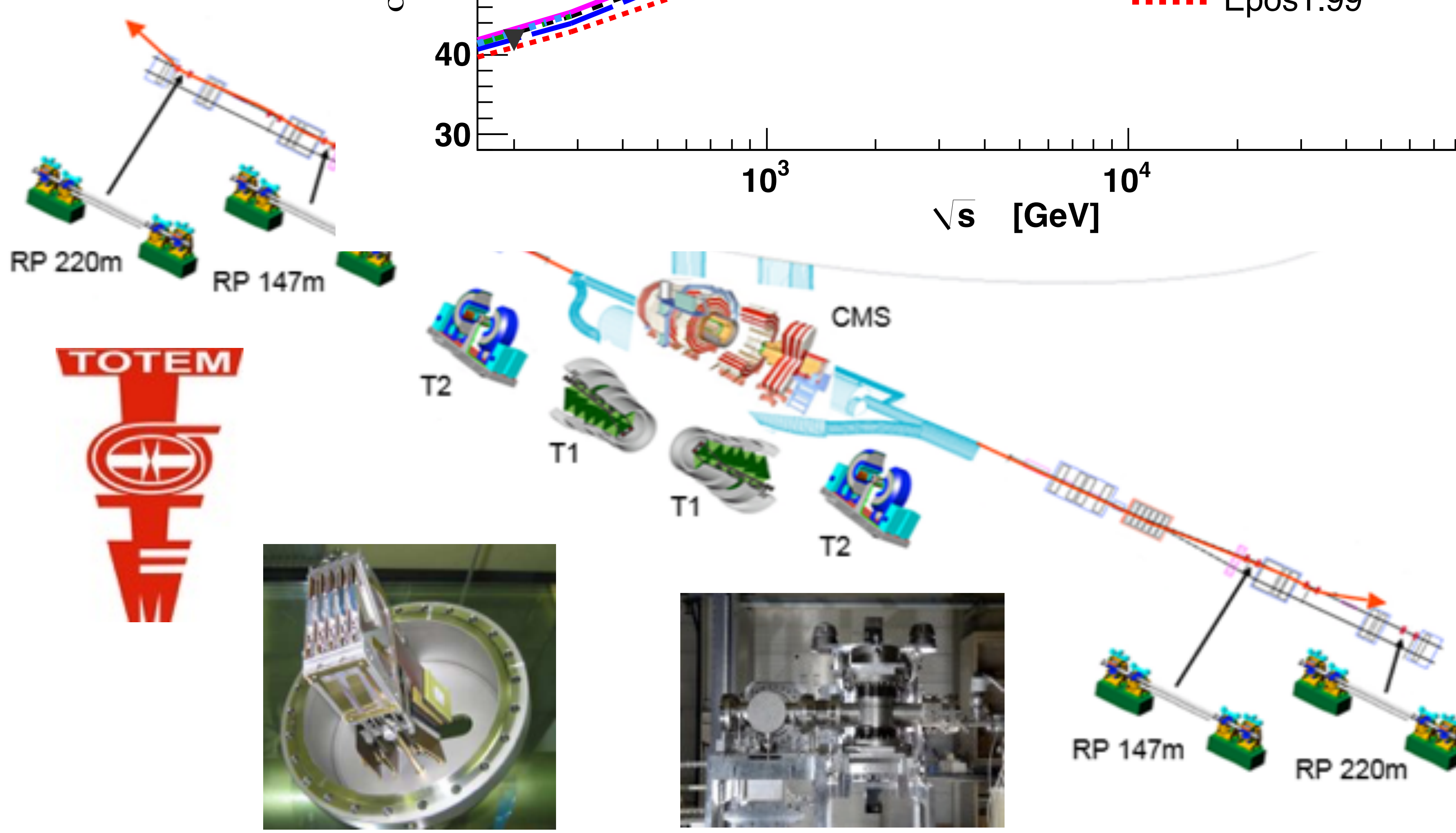




LHC: proton-proton cross section



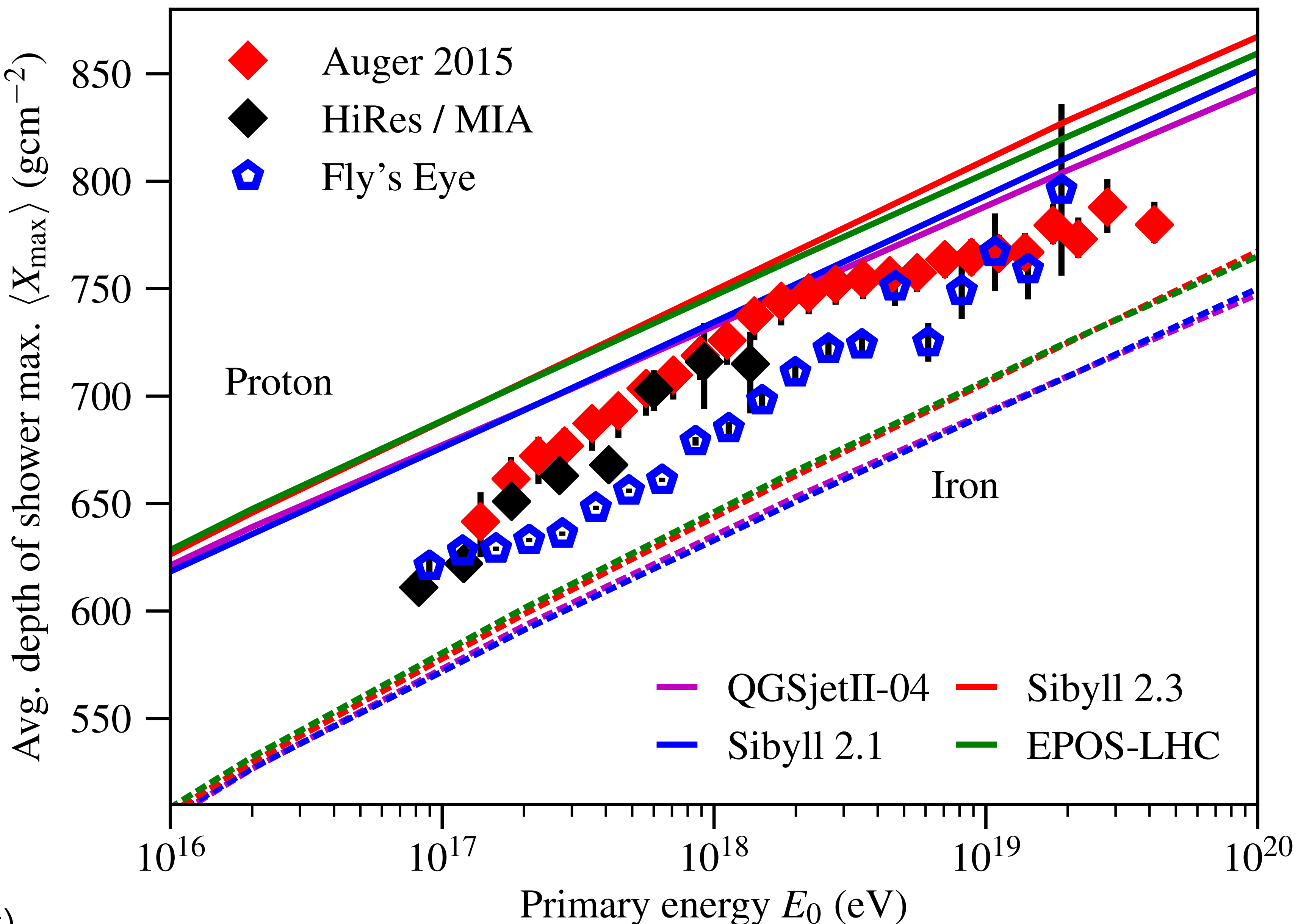




(Cafagna, ICRC 2015)

Current status: mean depth of shower maximum

(Riehn ICRC 2015, updated 2016)



(Data of TA not shown in this plot)

Change of model predictions well understood:
models predicting small elongation rates disfavored by LHC data

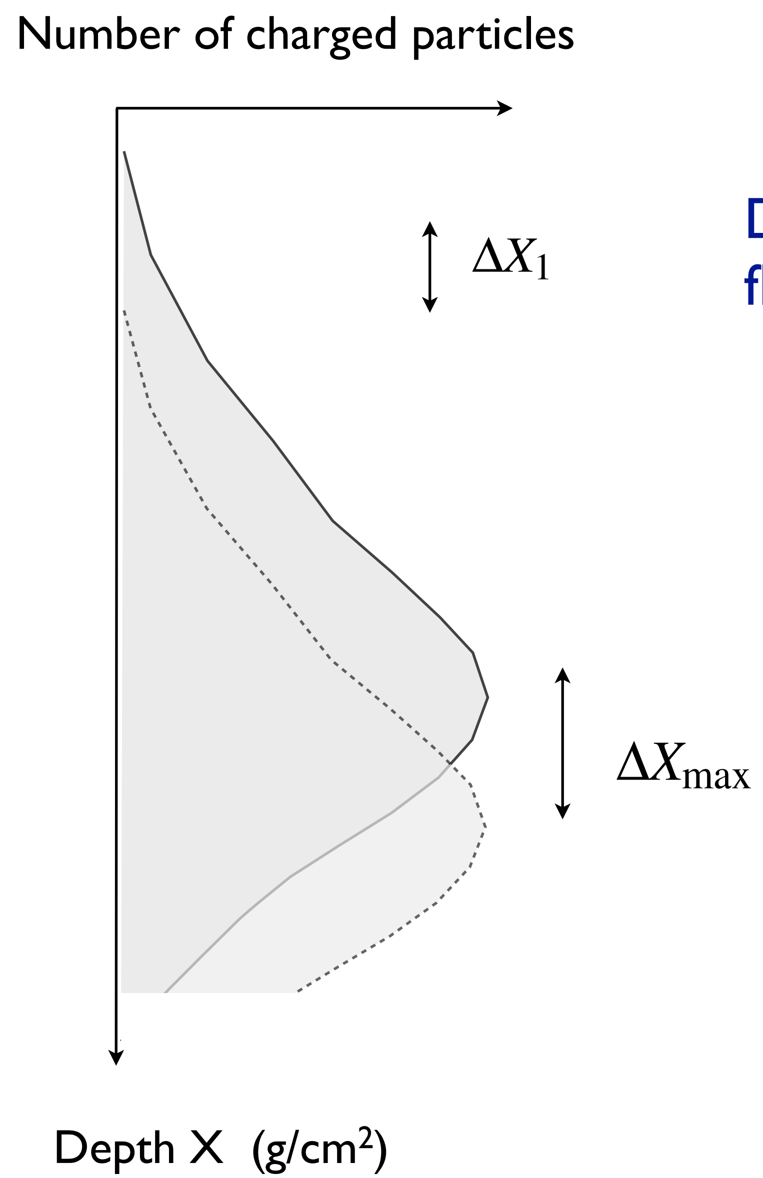
Change of composition or new particle physics?

Elongation rate theorem

$$D_e^{\mathrm{had}} = X_0(1 - B_n - B_\lambda)$$

(Linsley, Watson PRL46, 1981)

factor ~ 36 g/cm^2



Depth fluctuations

$$B_n = \frac{\mathrm{d}\ln n_{\mathrm{tot}}}{\mathrm{d}\ln E}$$

Large if multiplicity of high energy particles rises very fast, **zero in case of scaling**

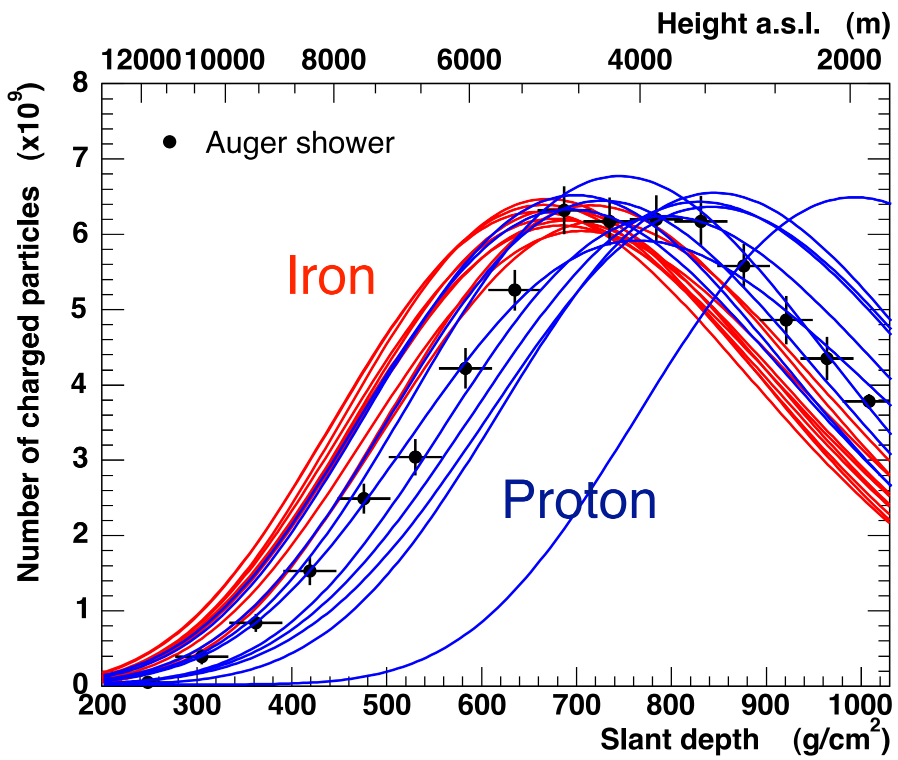
$$B_\lambda = -\frac{1}{X_0}\frac{\mathrm{d}\lambda_{\mathrm{int}}}{\mathrm{d}\ln E}$$

Large if cross section rises rapidly with energy

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

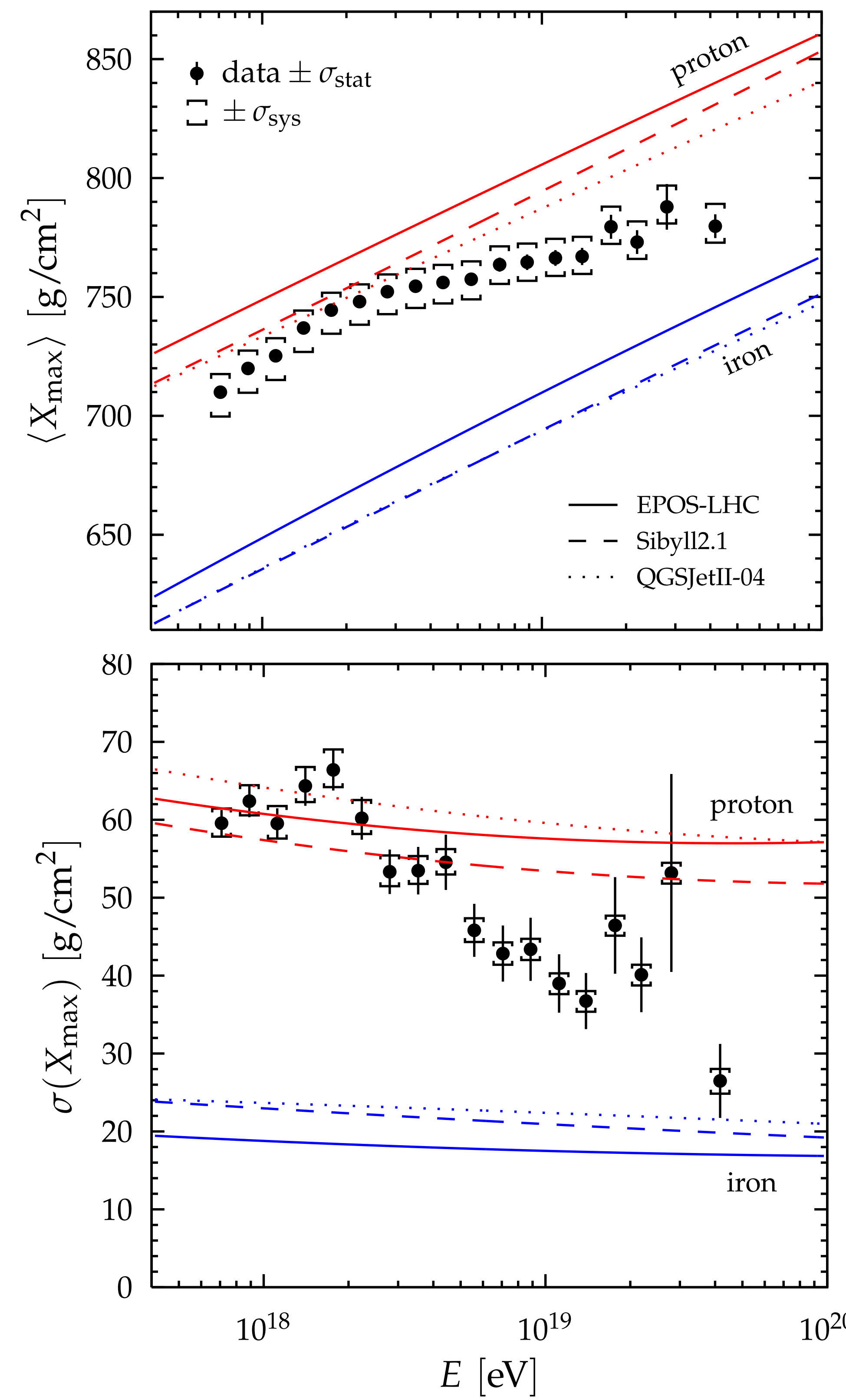
$$\sigma_{\mathrm{p-air}} = \frac{\langle m_{\mathrm{air}} \rangle}{\lambda_{\mathrm{int}}}$$

Change of composition or new particle physics?



Example: event measured by Auger Collab.

(Auger PRD90, 2014)



Protons: ~50% of X_{max} fluctuations due to depth of first interaction: large increase of cross section required (and further changes)

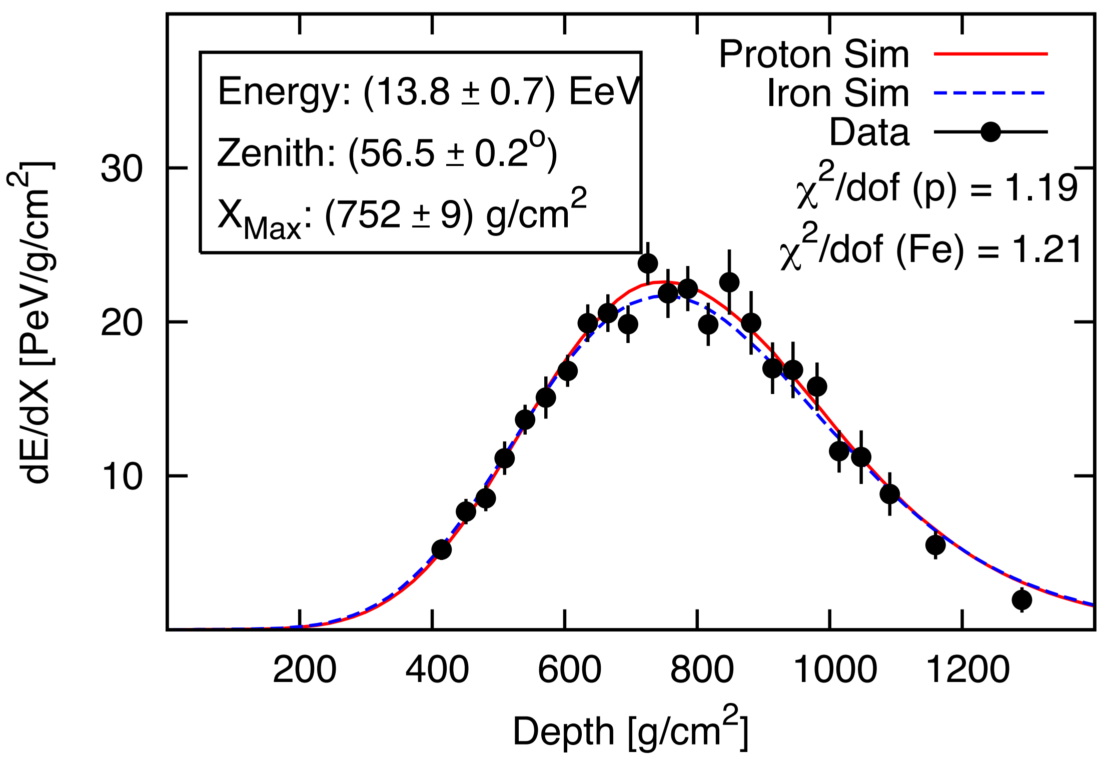
No deep showers at higher energies expected

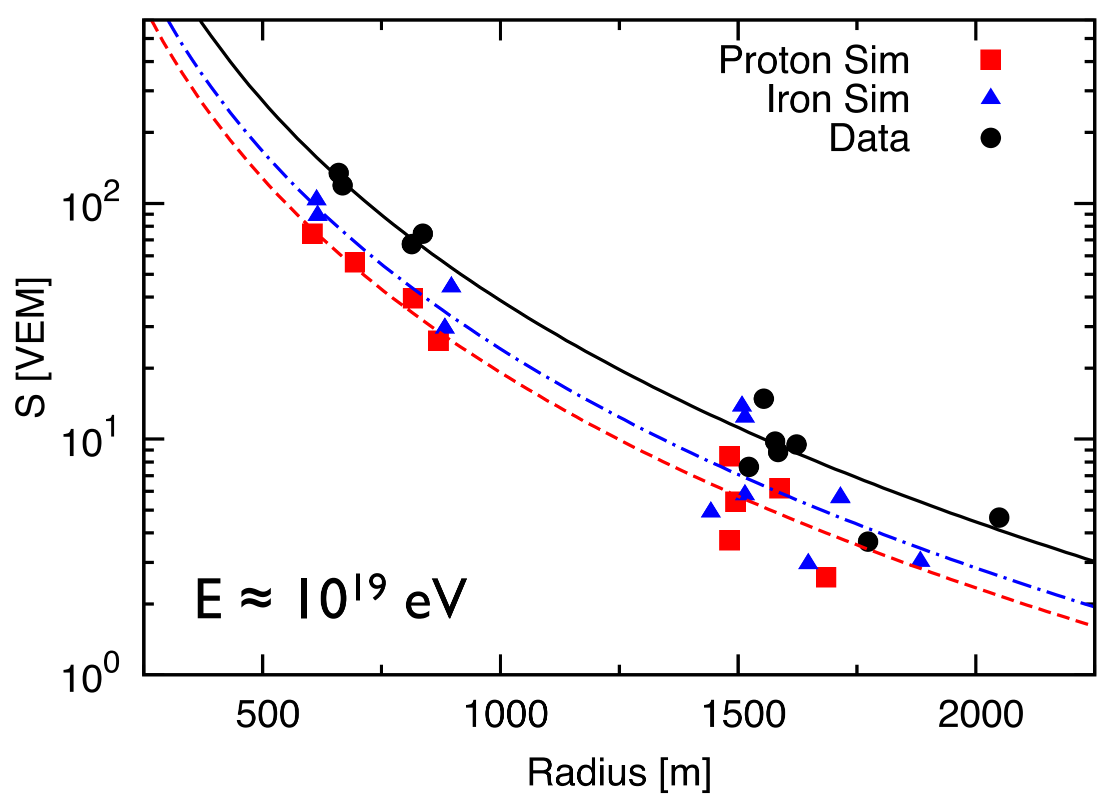
Multi-messenger constraints (GZK secondaries)

Muon number in air showers:

Low and intermediate energy interactions

Discrepancy: shower profile and particles at ground



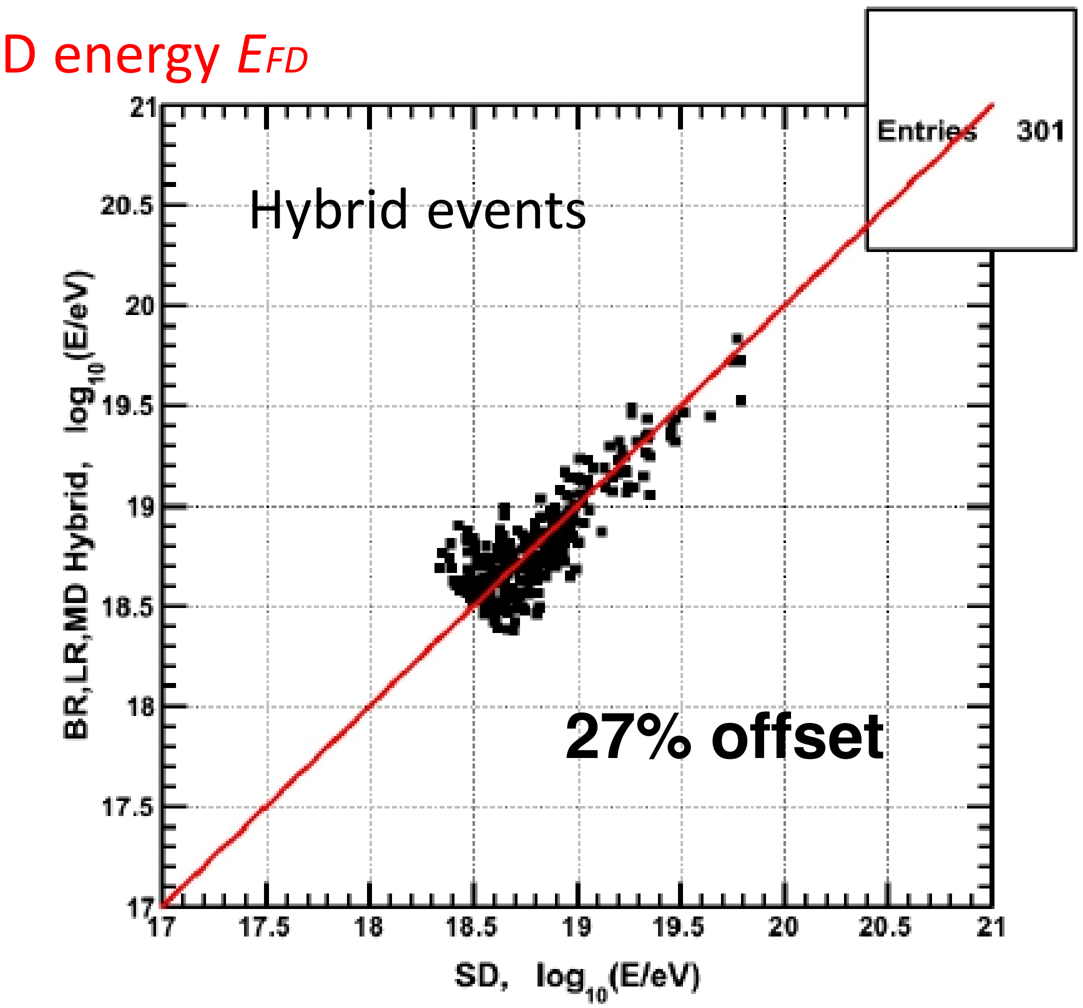


(Auger, to appear in PRL 2016)

Auger Observatory: angular dependence hints at lack of muons in simulation

Telescope Array

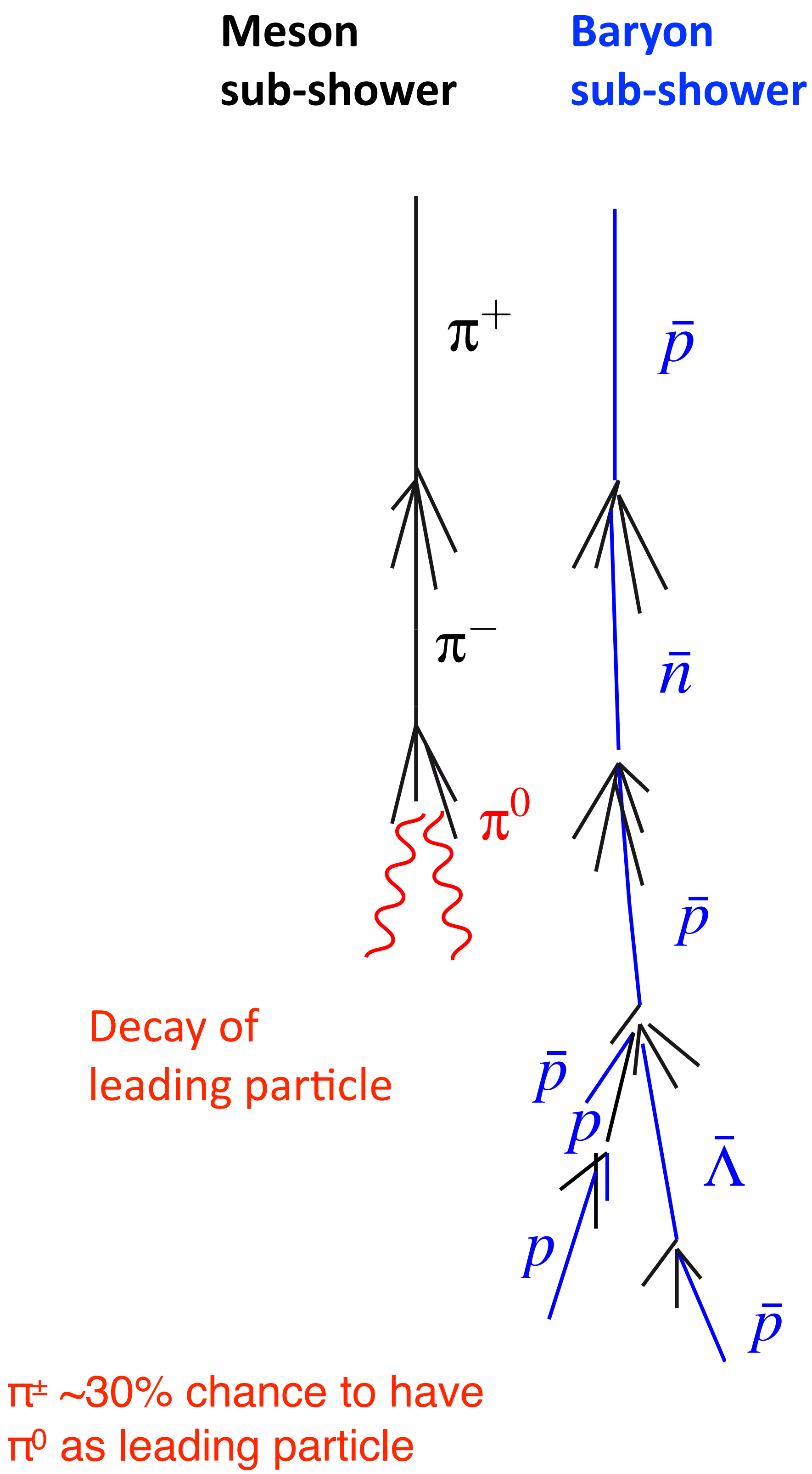
FD energy E_{FD}



SD energy E_{SD}

(TA RICAP 2016)

How to increase the number of muons?



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 2014)*

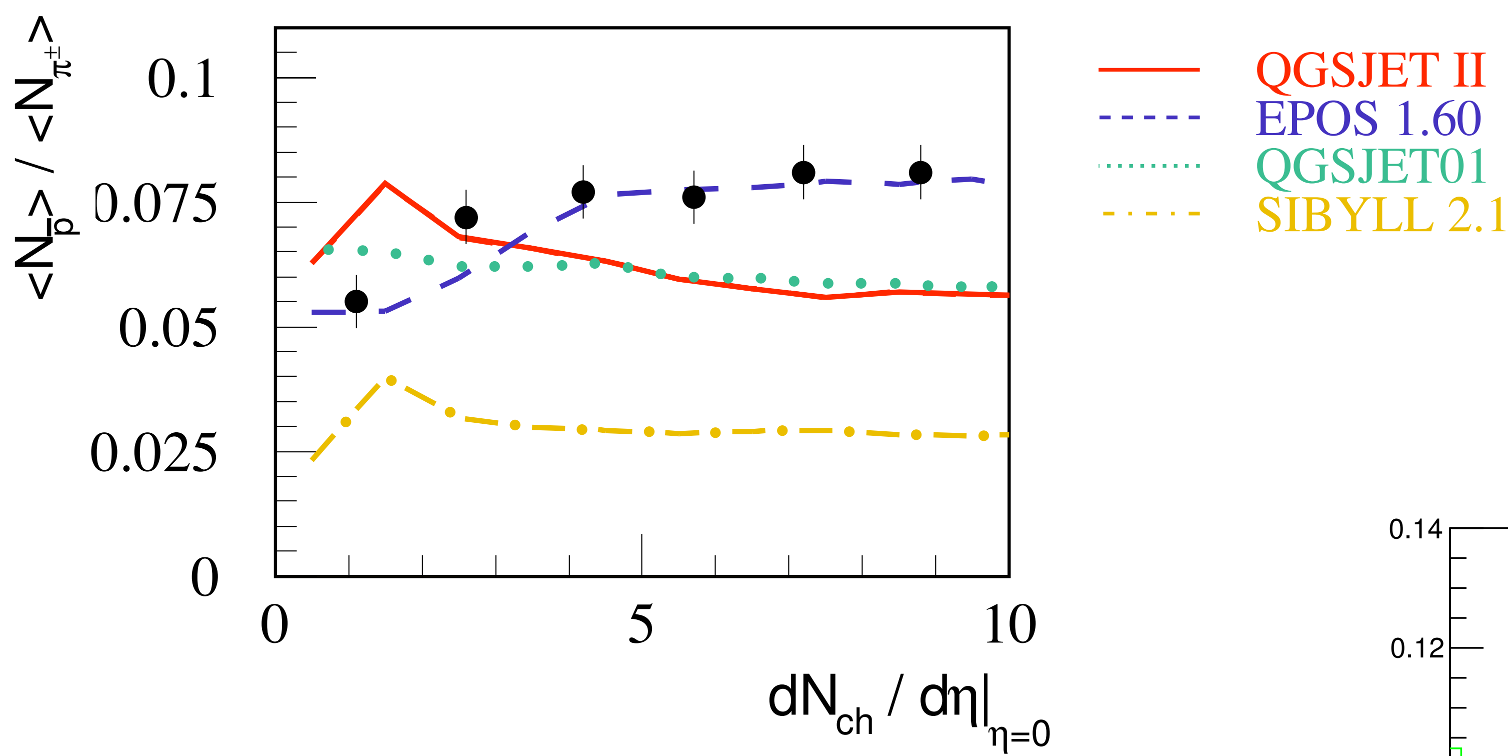
- Leading particle for a π could be ρ^0 and not π^0
- Decay of ρ^0 almost 100% into two charged pions

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

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

Baryon pair-production rate in p-p collisions

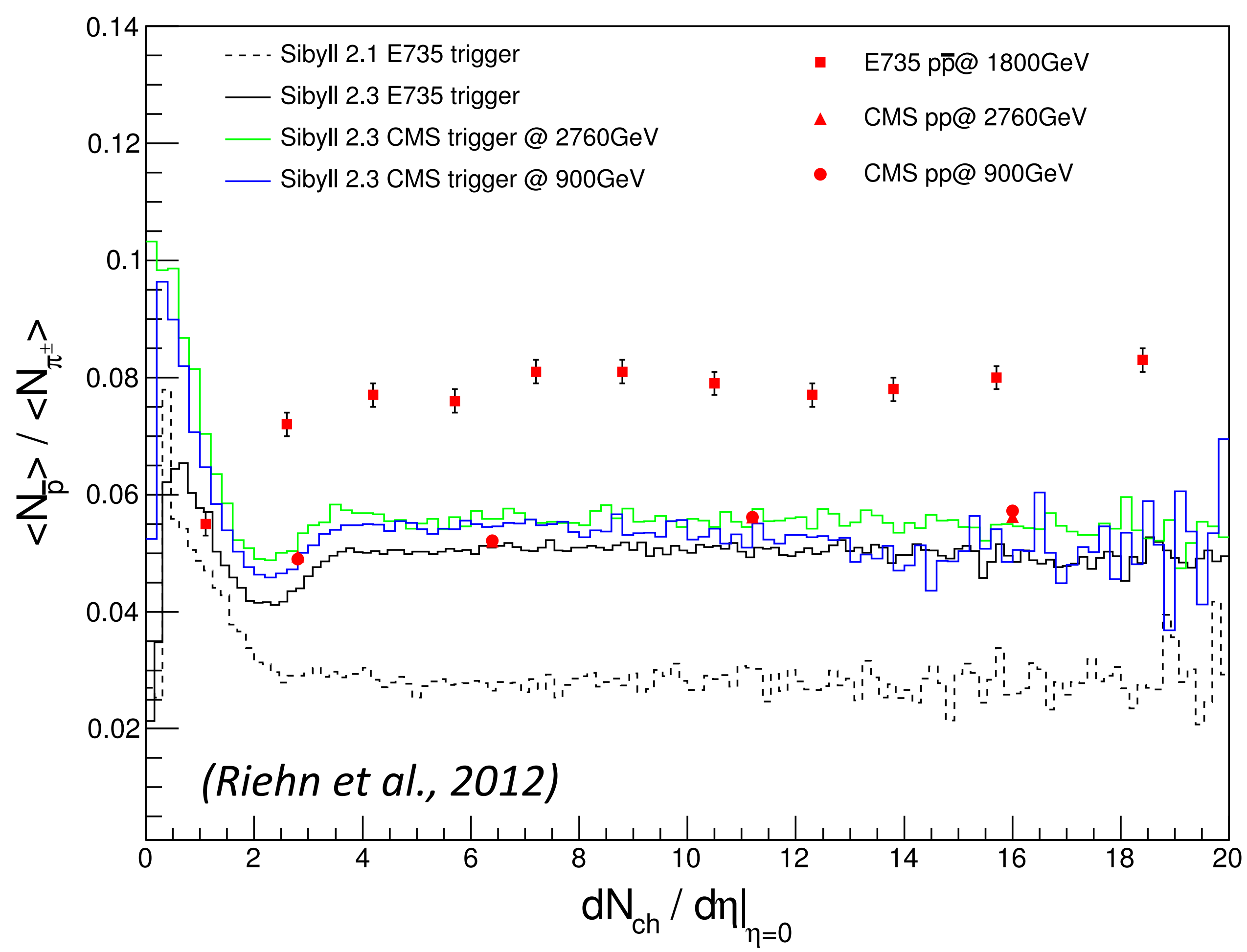
Tevatron data (E735: 1800 GeV)



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

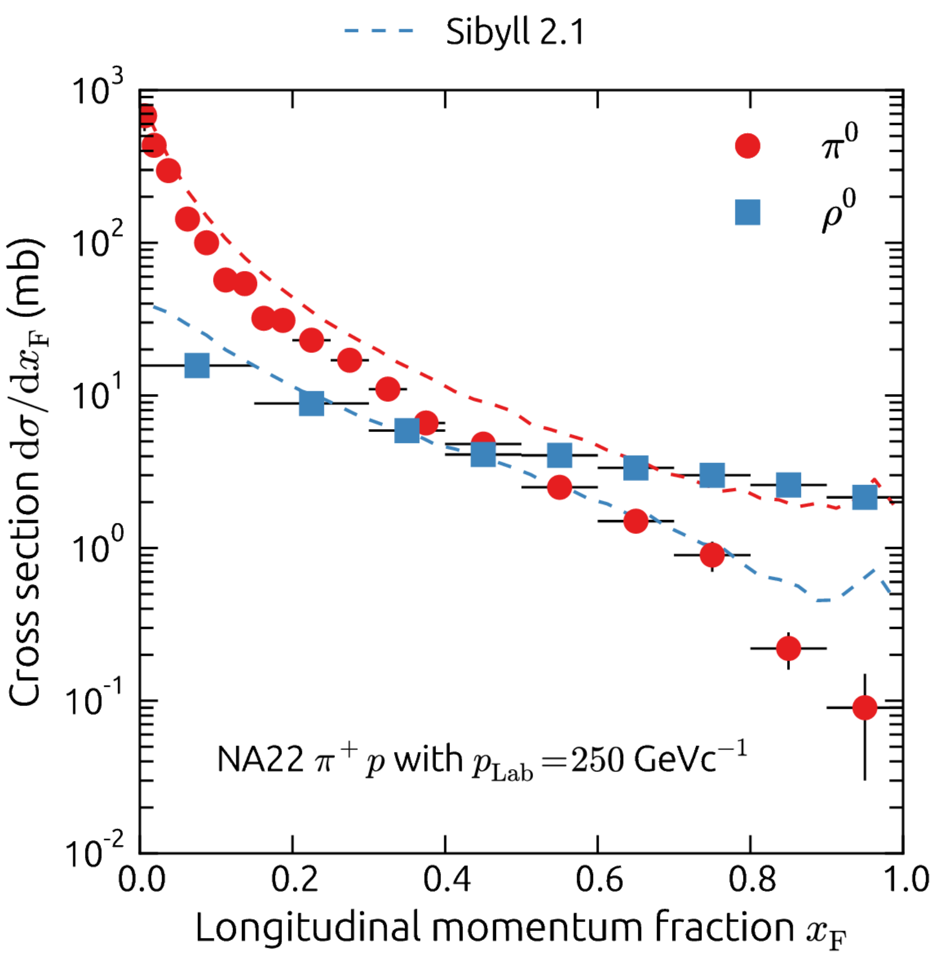
Ratio multiplicities of antiprotons to pions

LHC data (CMS: 900 and 2760 GeV)



LHC measurements do **not confirm** large antiproton production derived from Tevatron data (rapidity vs. pseudorap.?)

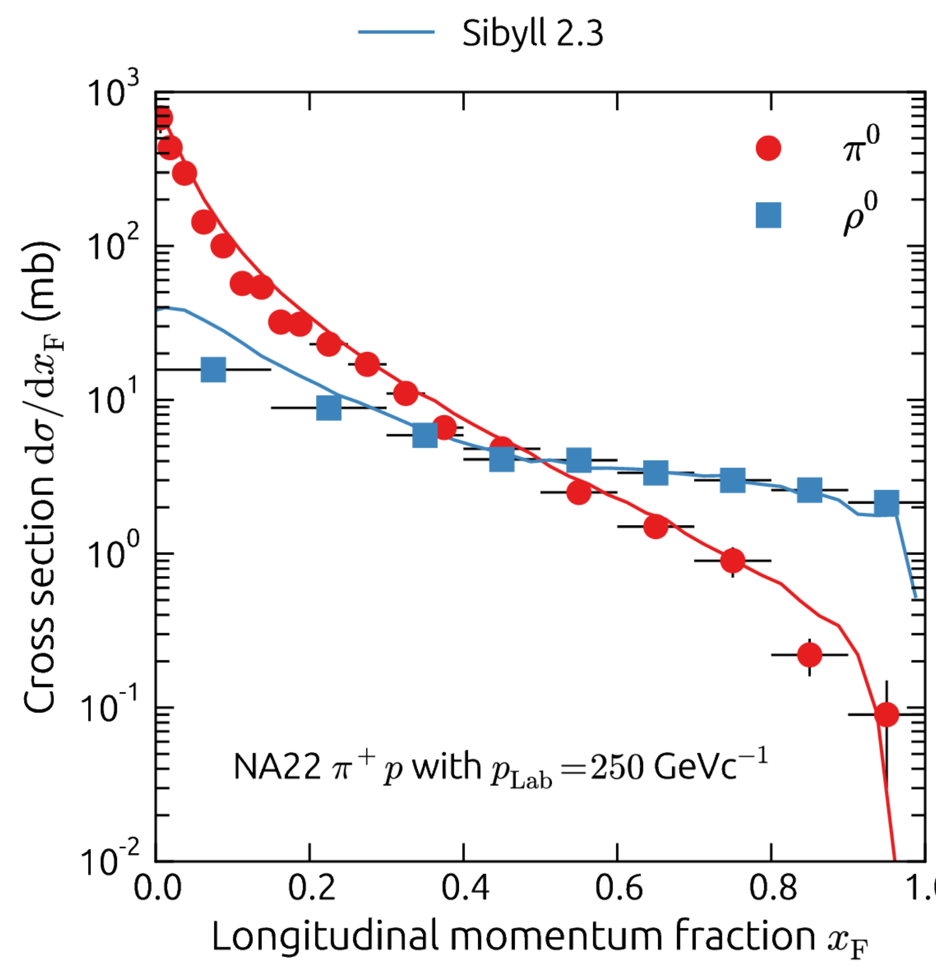
Rho production in pion-proton interactions (i)



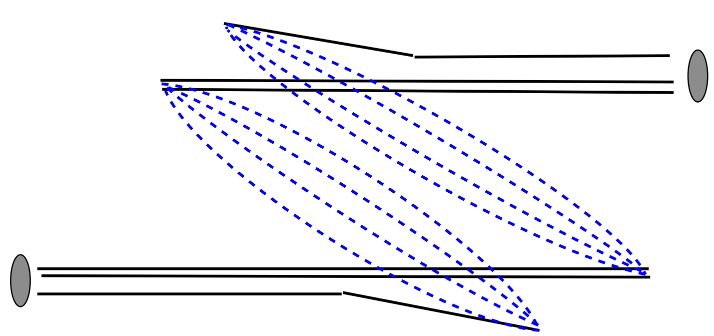
$$\pi^+ p \rightarrow \pi^0 \rightarrow 2\gamma$$

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

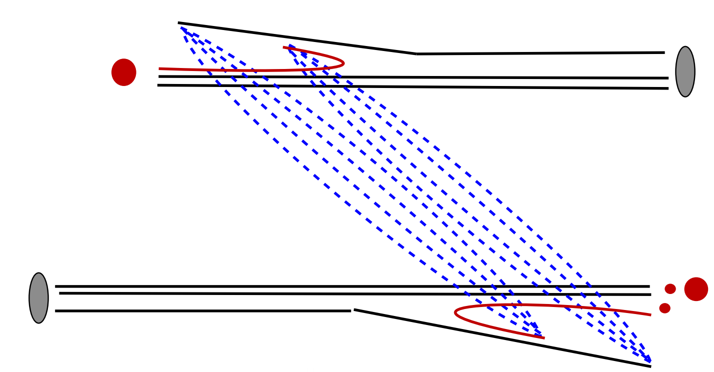
$$E_{lab} = 250\,\text{GeV}$$



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



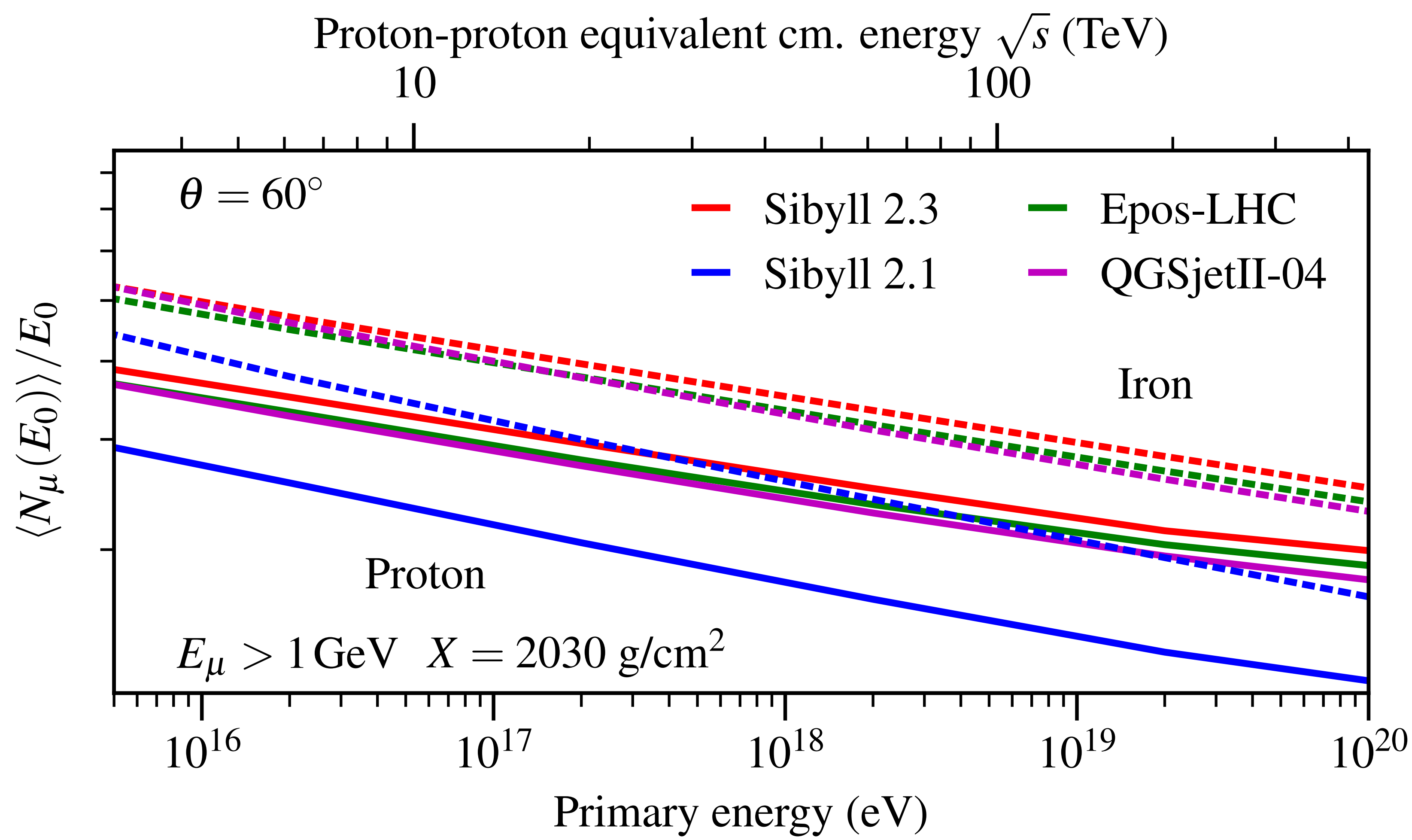
$$R_{\rho^0}/R_{\pi^0} = 0.3$$



$$R_{\rho^0}/R_{\pi^0} = f(x_F)$$

(Riehn et al., ICRC 2015, updated 2016)

Rho production in pion-proton interactions (ii)



After tuning rho production in Sibyll to π-p data

increase by factor ~1.6

Different muon "enhancement" processes:

- EPOS-LHC: mainly baryon production
- QGSjet II.04: very forward rho-0 production
- Sibyll 2.3: both processes (Sibyll 2.1 none)

Caution: convergence of predictions not reliable

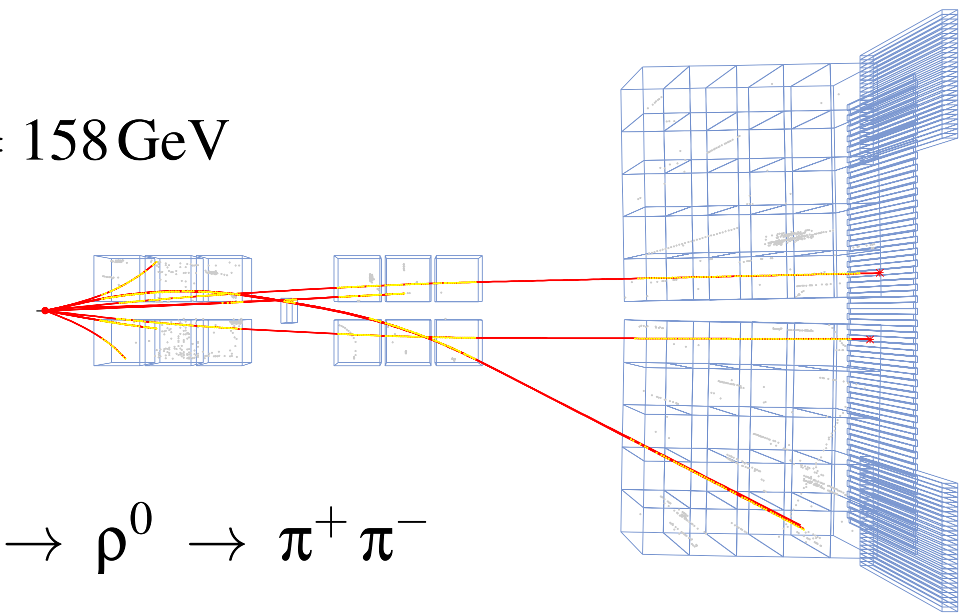
(Riehn et al., ICRC 2015, updated 2016)

NA61 at SPS: results on rho production on carbon

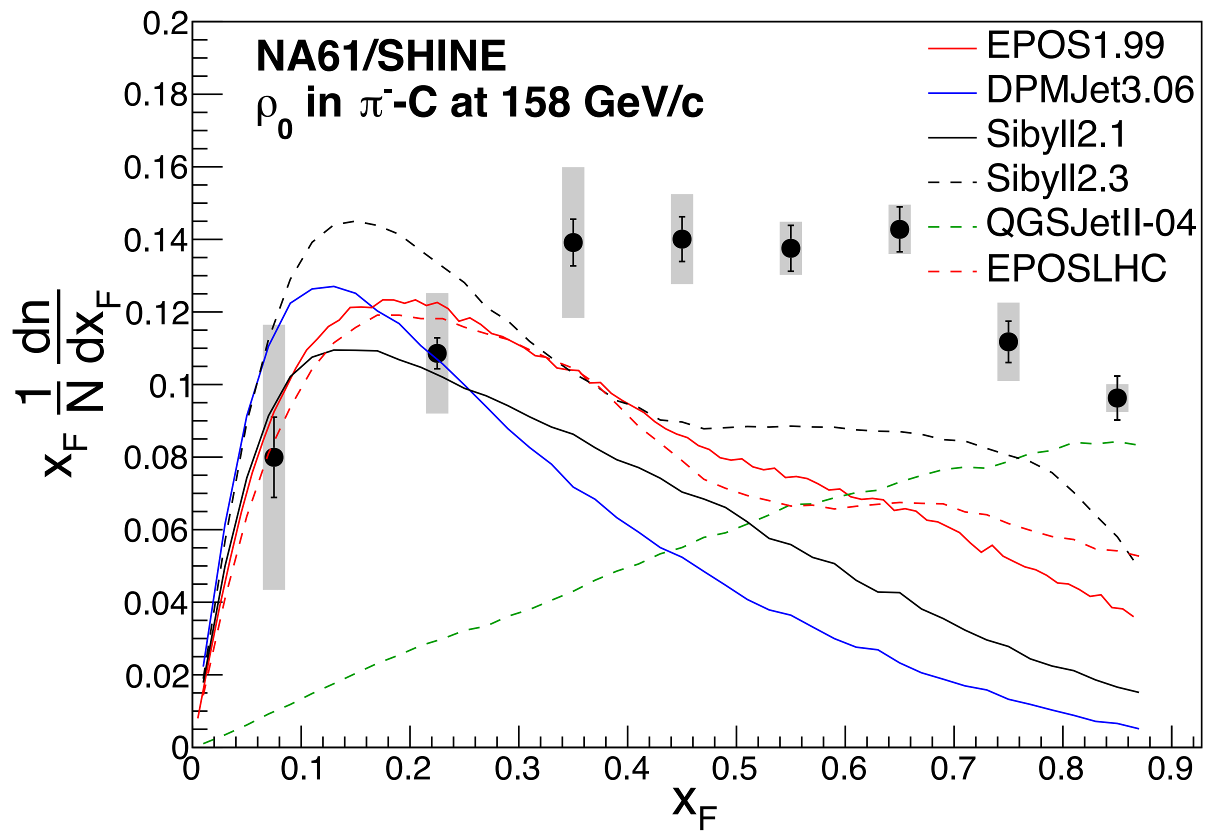
Dedicated cosmic ray runs
(π-C at 158 and 350 GeV)

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

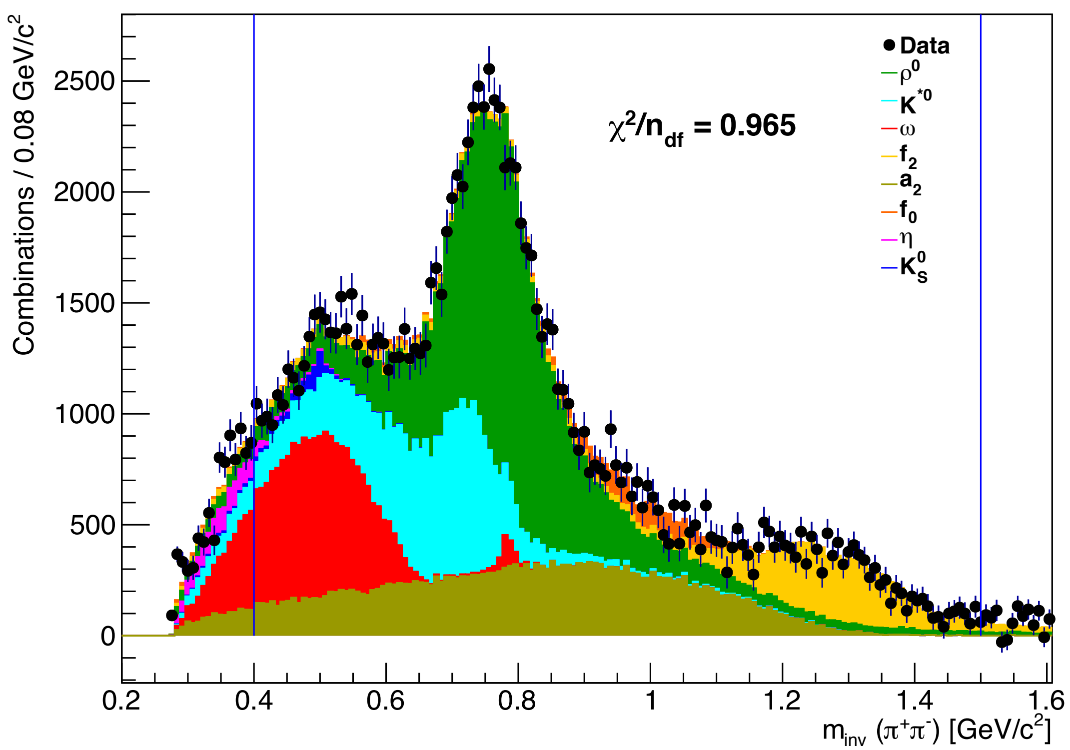
$\pi^- C \;\to\; \rho^0 \;\to\; \pi^+ \pi^-$



(NA61, Herve & Unger, ISVHECRI 2016)



Invariant mass of two charged tracks



Ad-hoc modification of Sibyll to fit NA61 data: additional ~25% increase of muon number

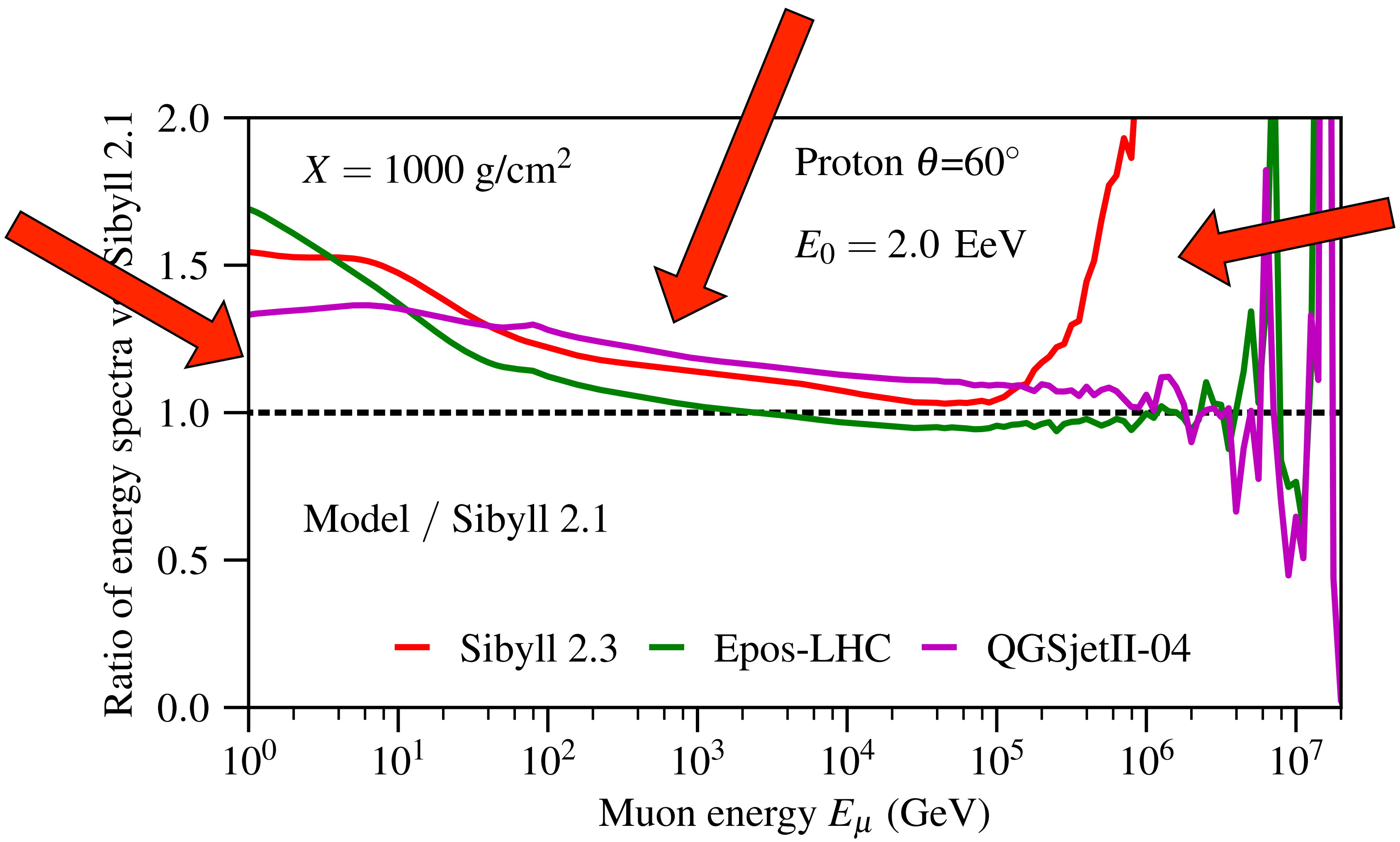
Energy spectrum of muons in EAS

Muon energy spectra relative to Sibyll 2.1

Rho-0 production

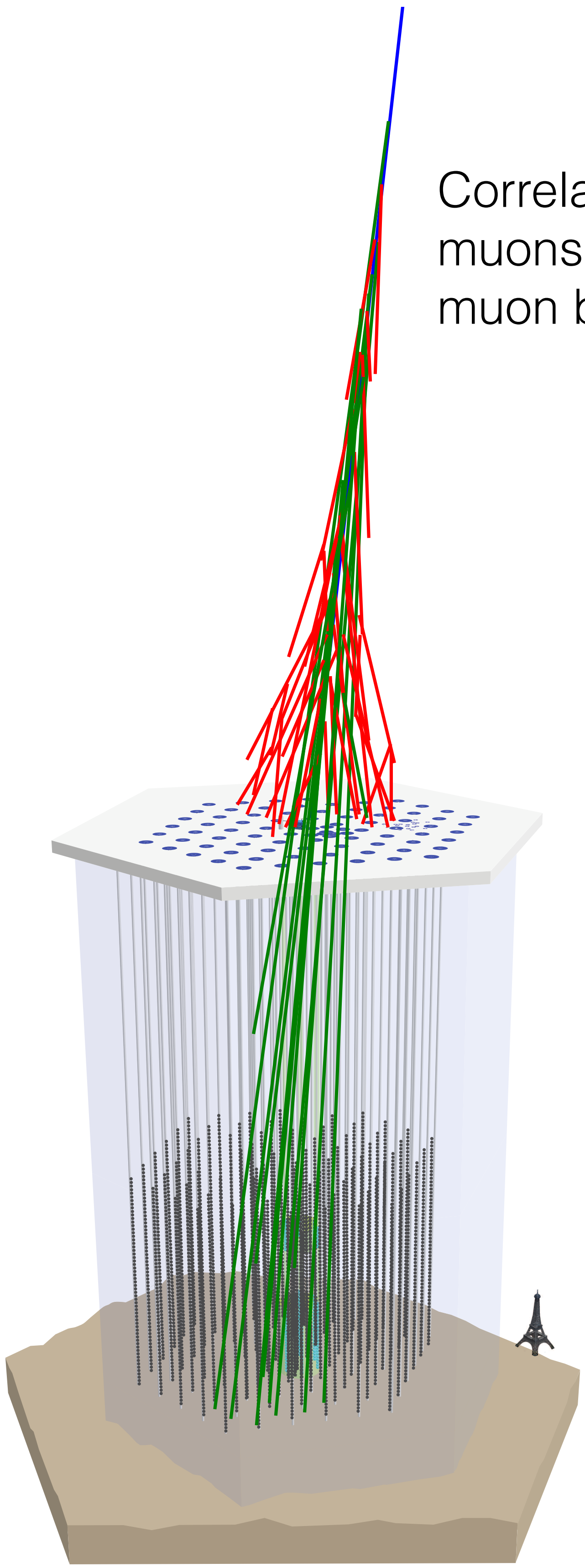
Low-energy
enhancement
due to baryon
pair production

Charm particles
(only Sibyll 2.3)



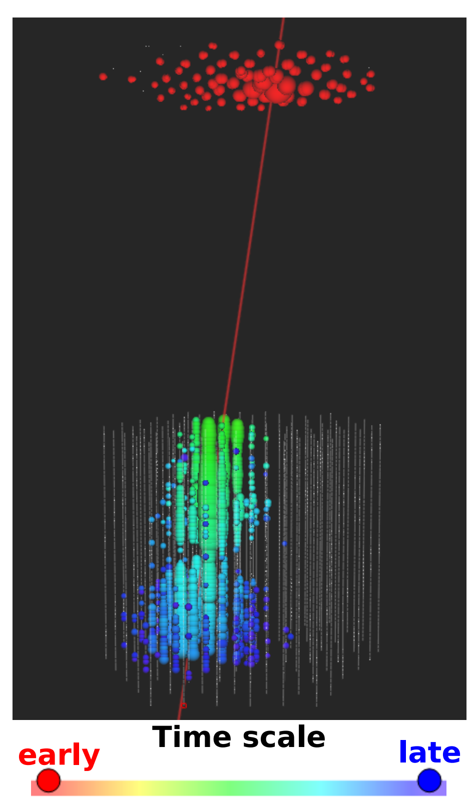
Discrimination by IceCube (surface array and in-ice muon data)?

IceCube: discrimination of scenarios?



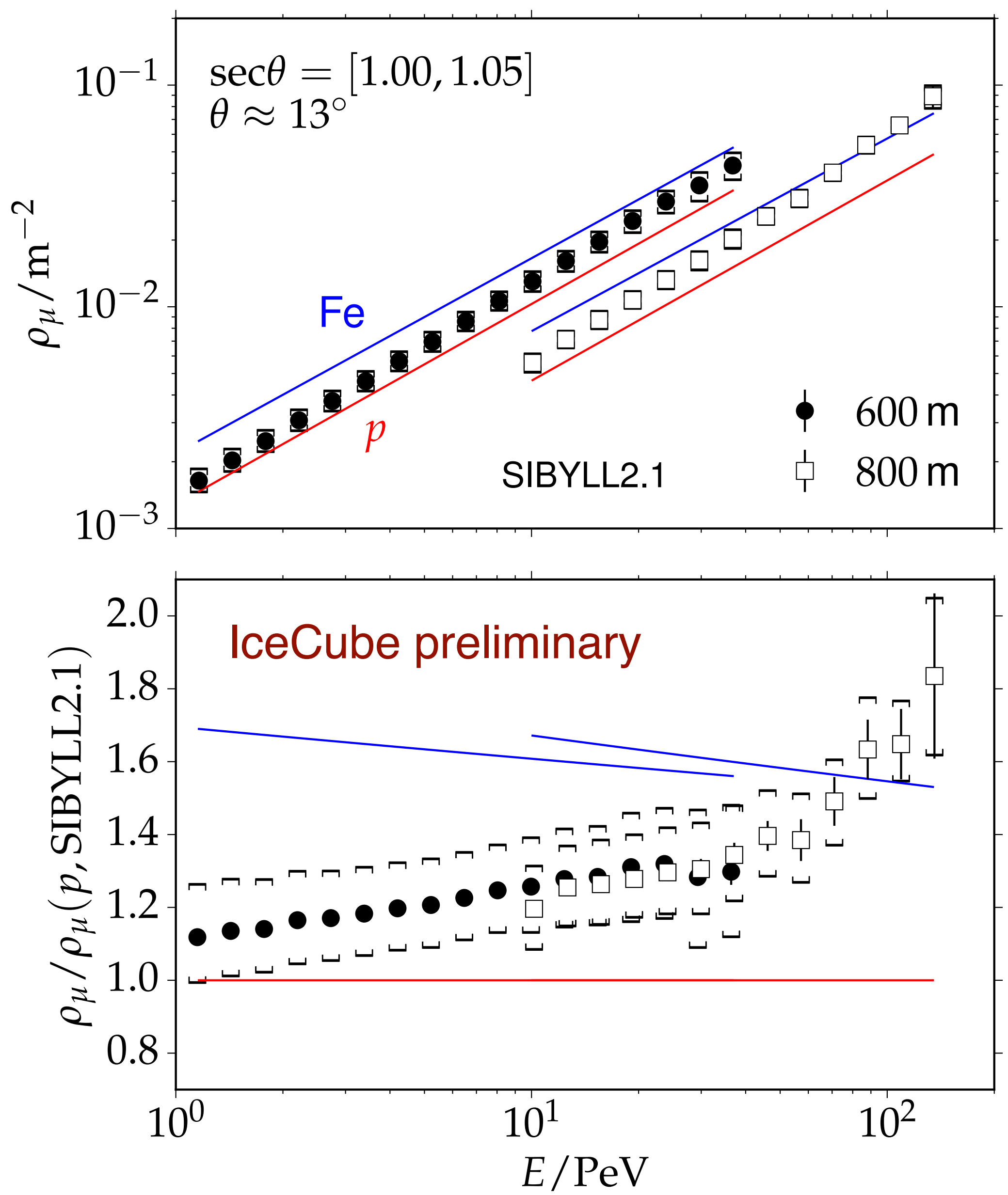
Correlation of low energy muons (surface) and in-ice muon bundles

IceTop: E_μ ~1 GeV

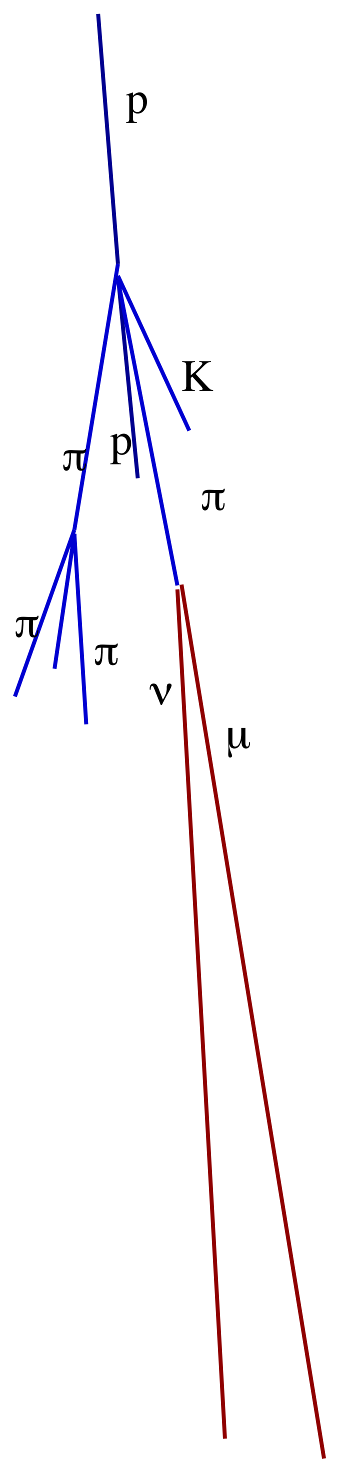


IceCube: E_μ >300 GeV

(IceCube, Gonzalez & Dembinski et al. 2016)

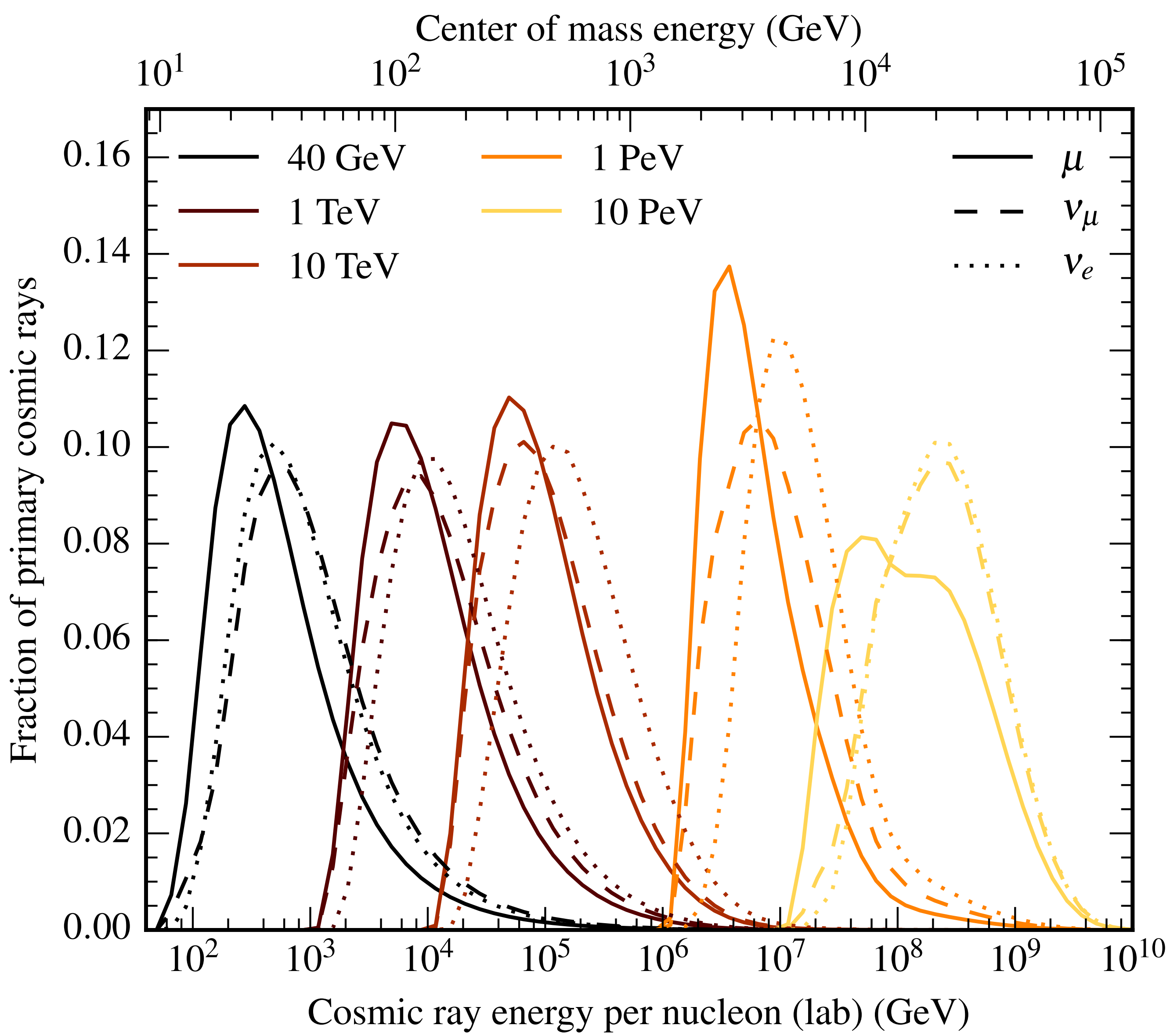


Part 2: Inclusive Lepton Fluxes

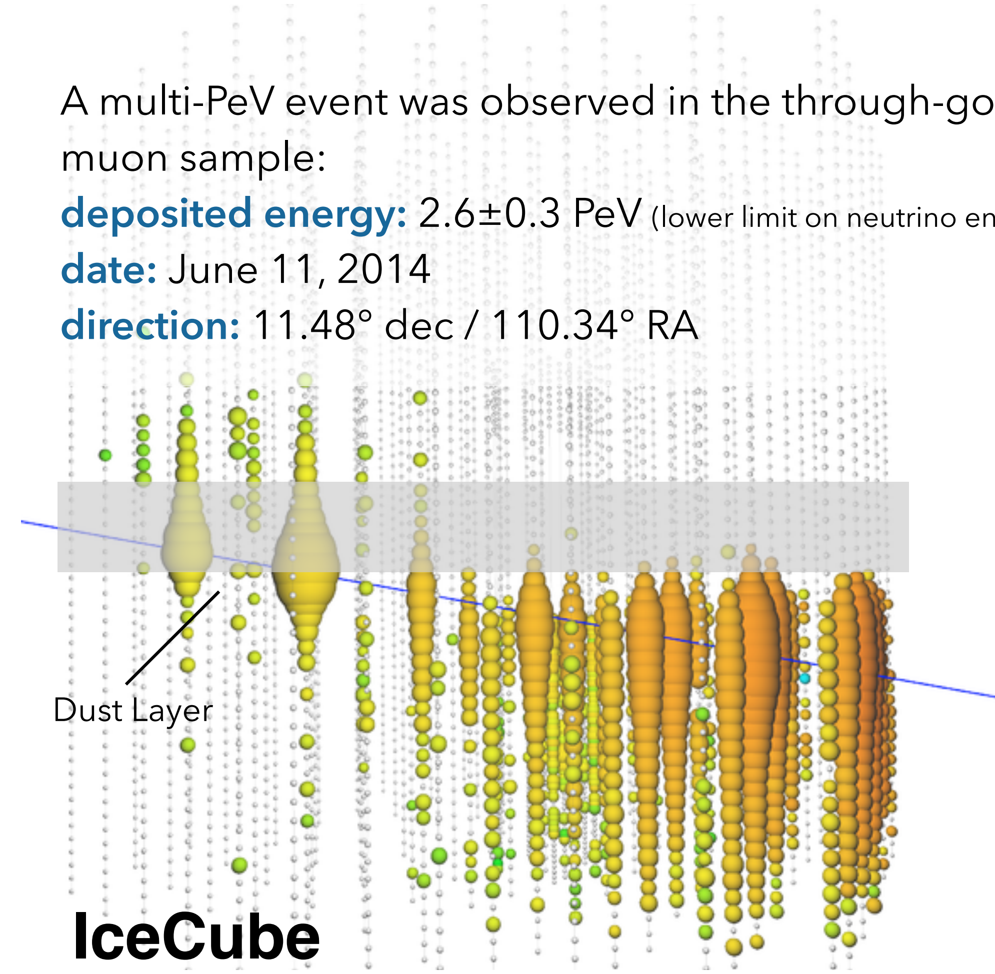


Typical interaction energies and generations

Energy distribution of primary nucleon



A multi-PeV event was observed in the through-going muon sample:
deposited energy: 2.6±0.3 PeV (lower limit on neutrino energy)
date: June 11, 2014
direction: 11.48° dec / 110.34° RA

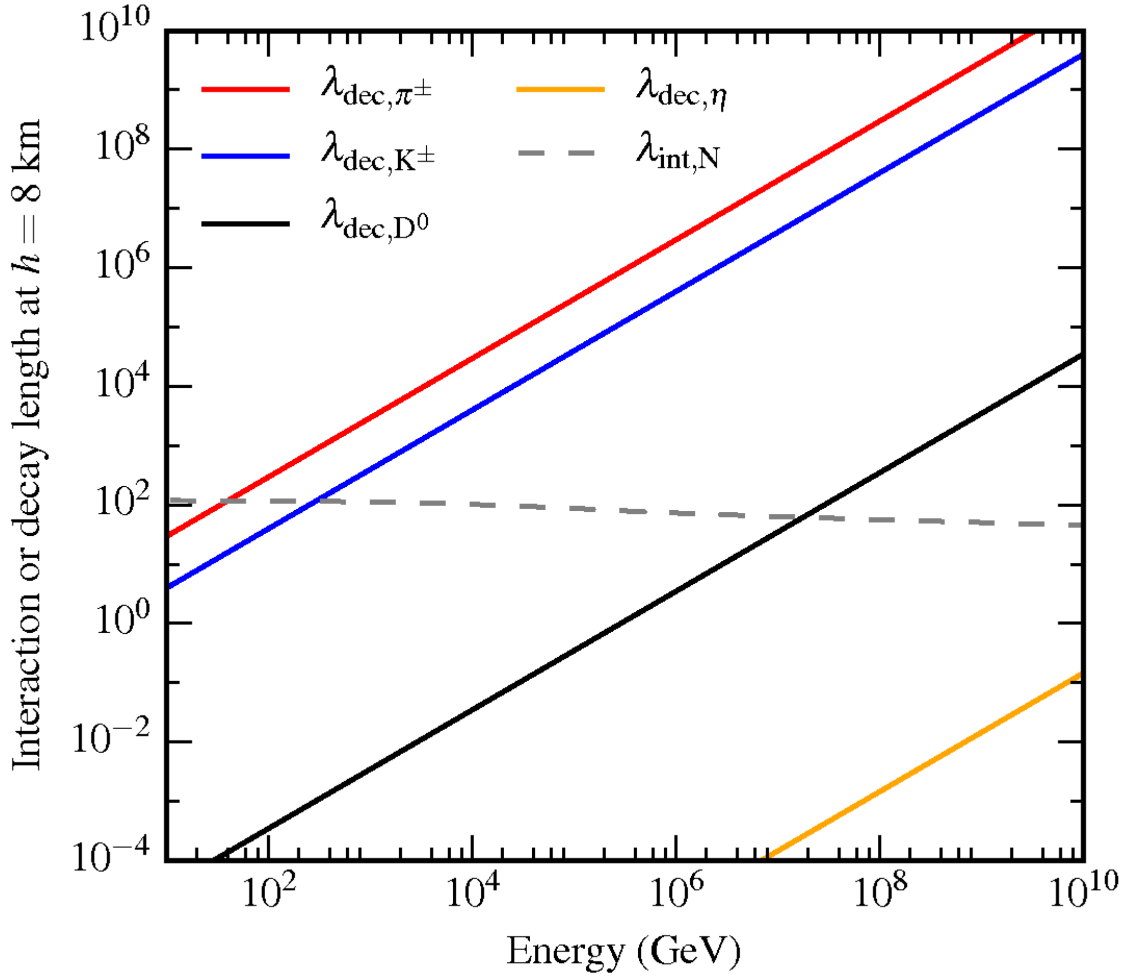


Multi-PeV events originate from interactions with LHC c.m. energy

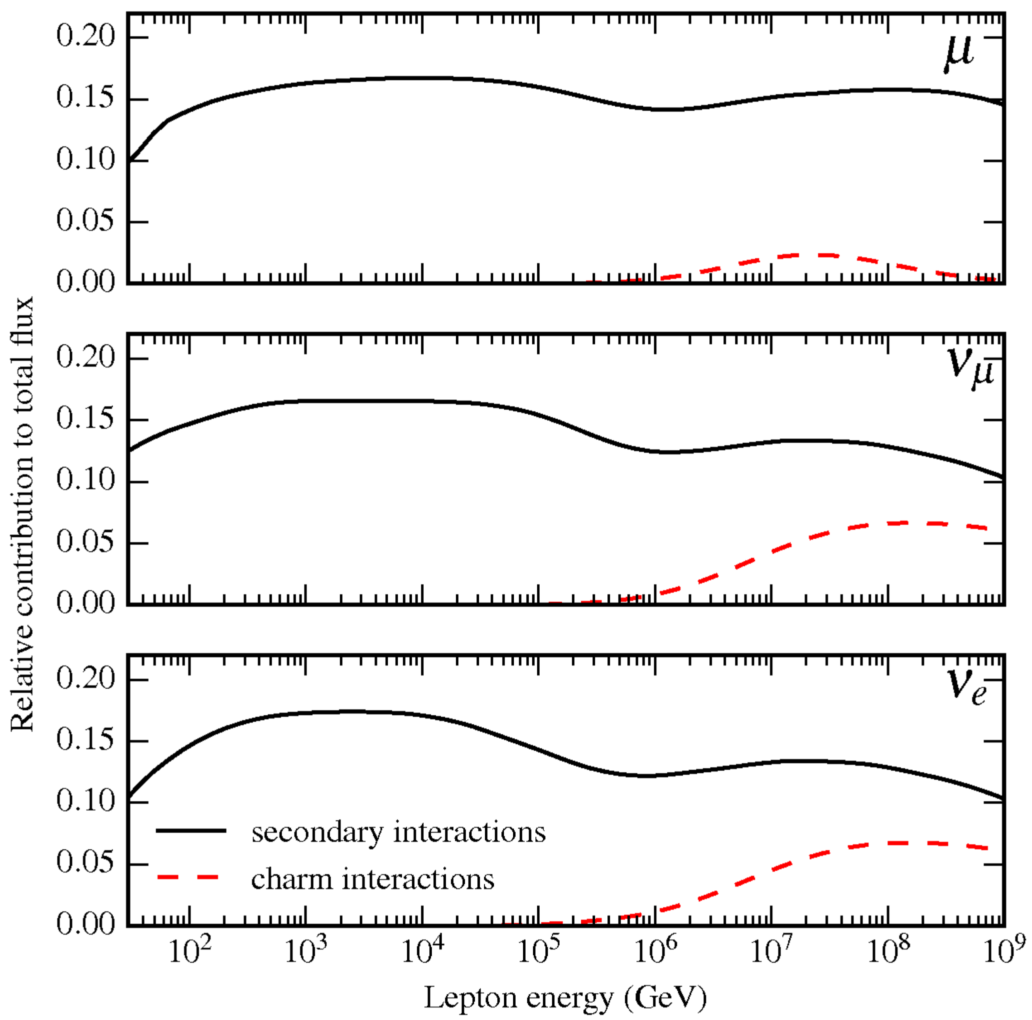
(Fedynitch, CRIS 2016)

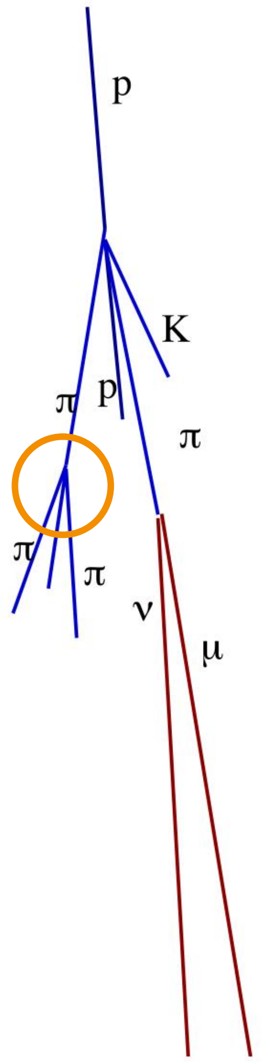
Interplay between CR spectrum and energy degradation

Comparison decay length
vs. typical interaction length



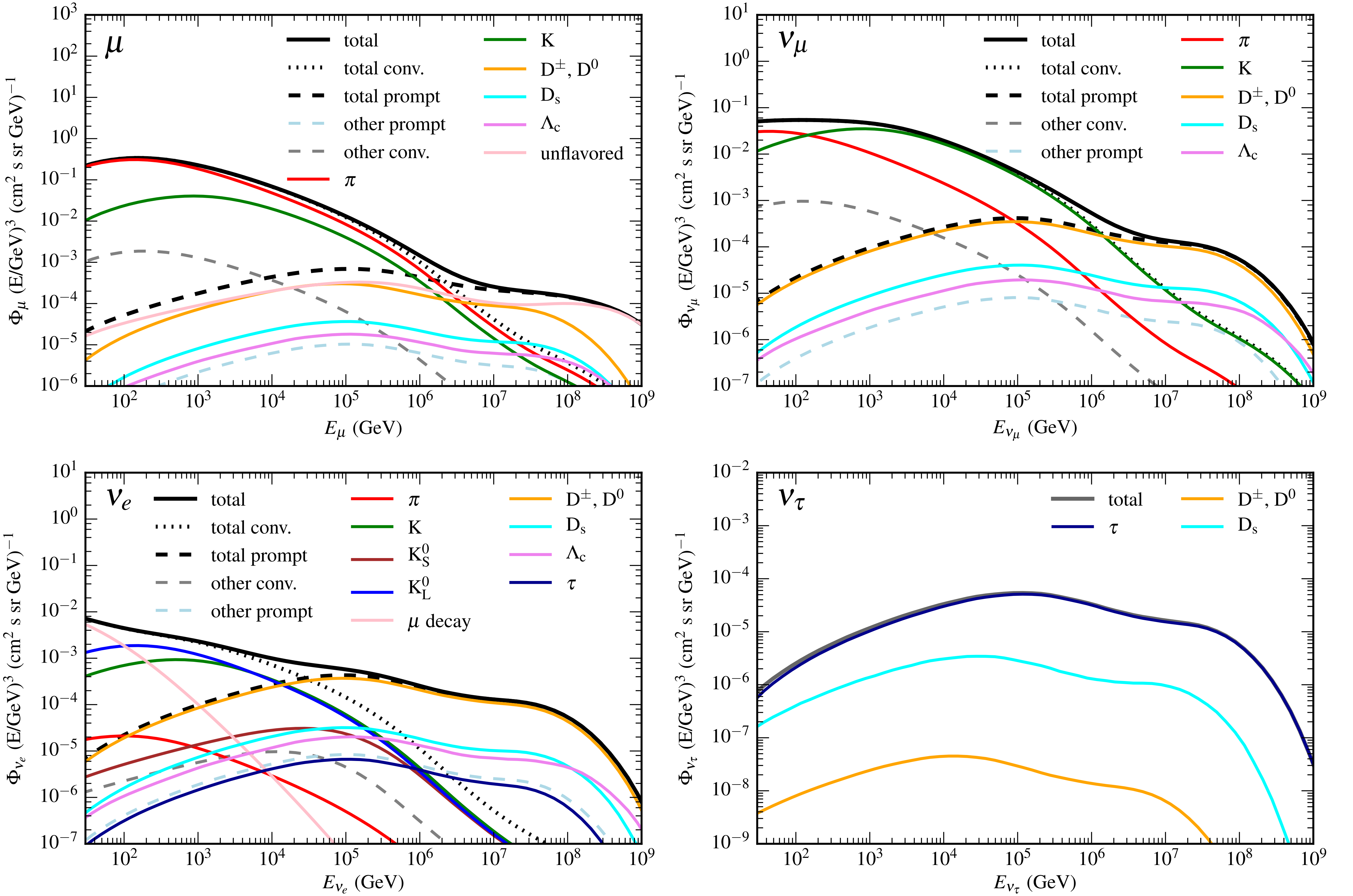
Contribution to lepton flux due to
secondary interactions of unstable particles





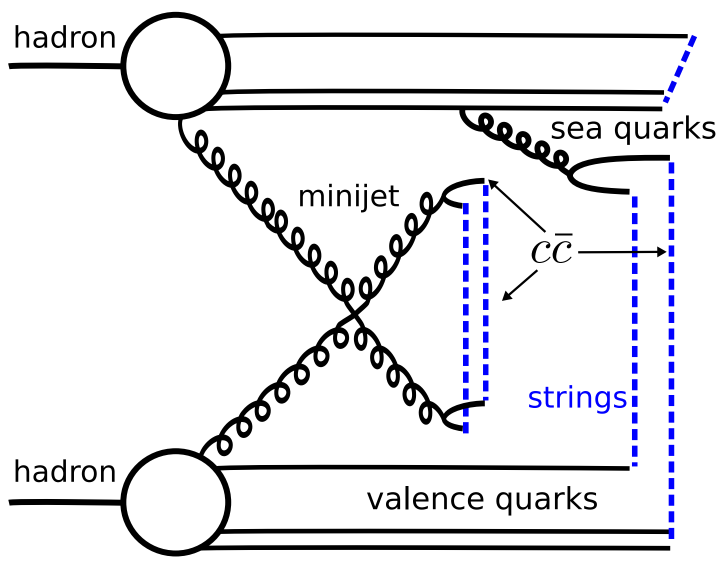
(Fedynitch, CRIS 2016)

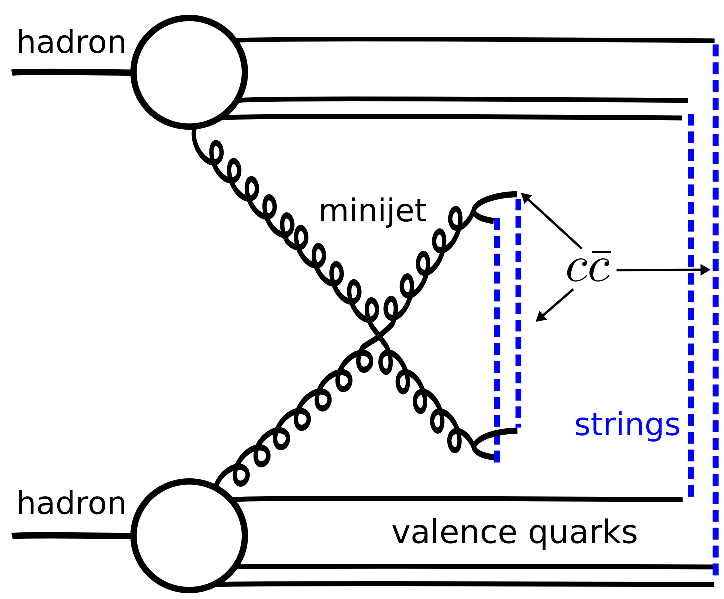
Example of lepton flux calculation



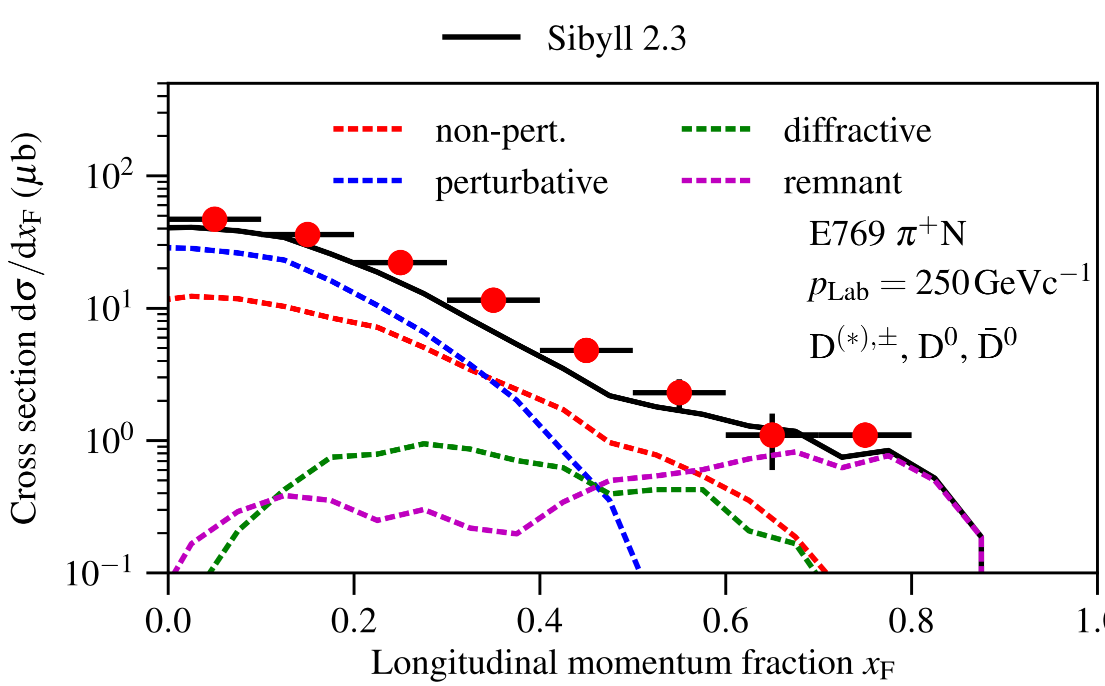
(Fedynitch et al., to be published 2016)

Phenomenological model of charm production in Sibyll

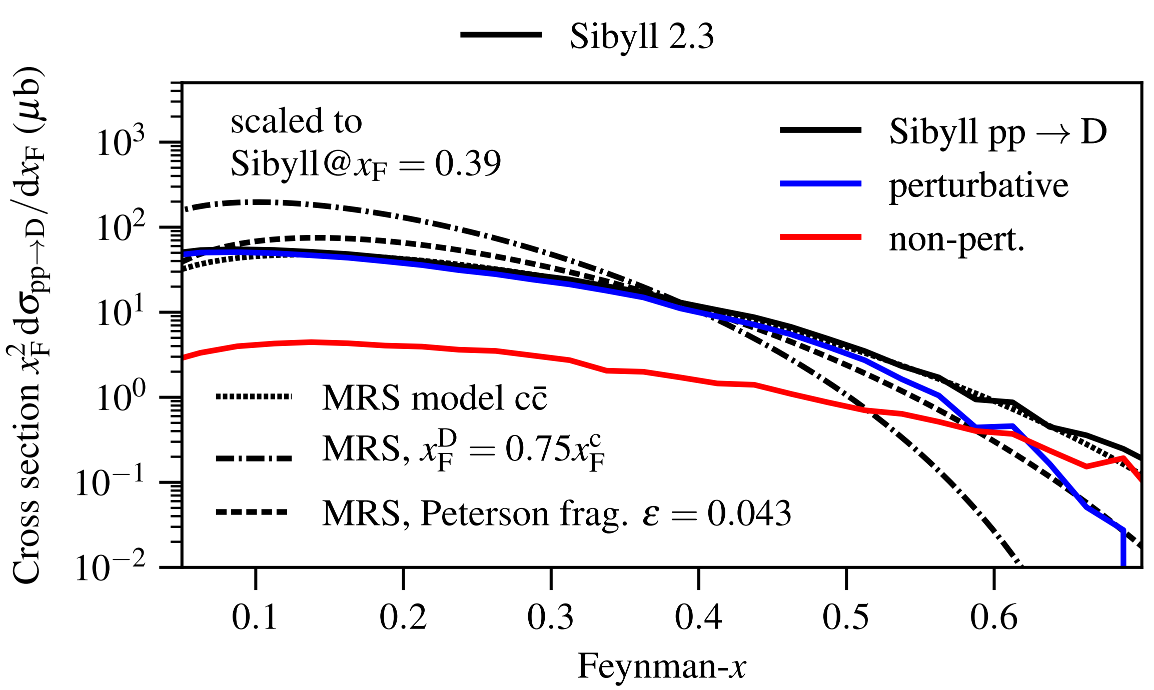




Perturbative and non-perturbative contributions (determined by fit to data)

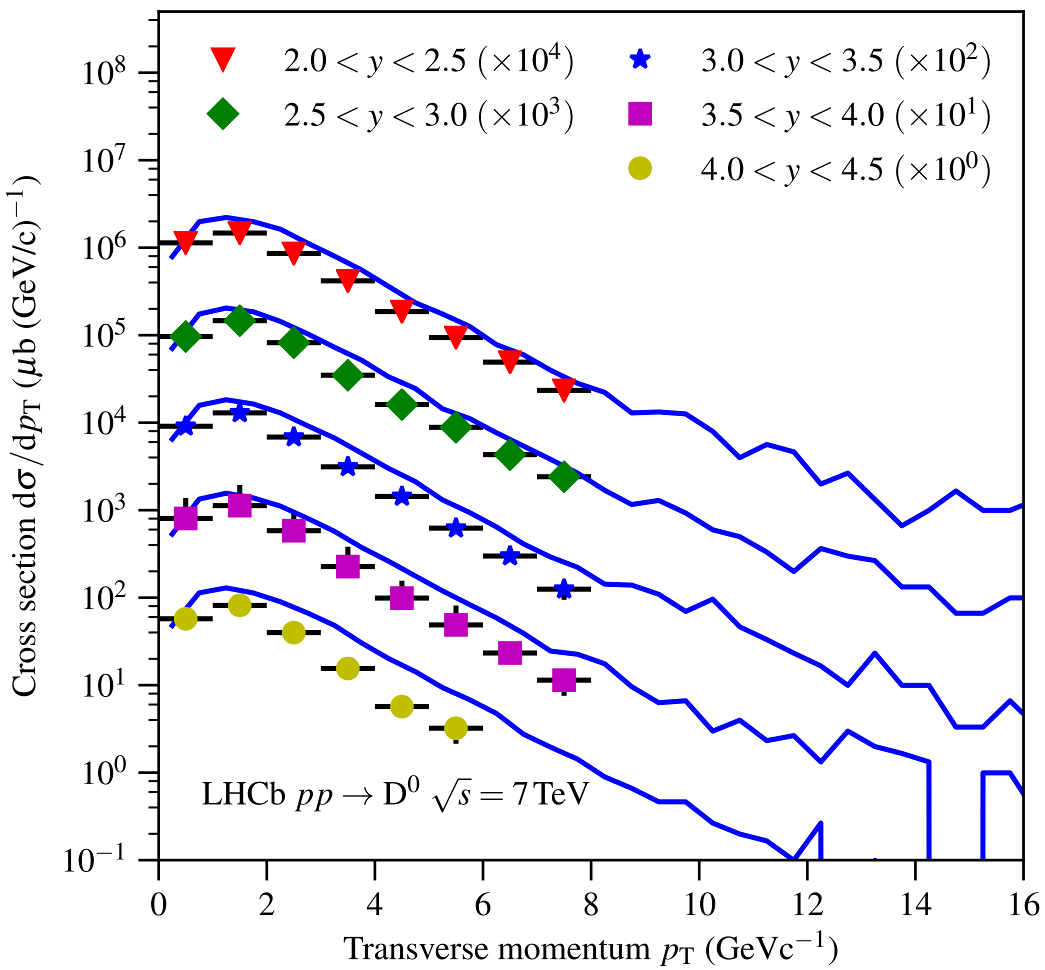


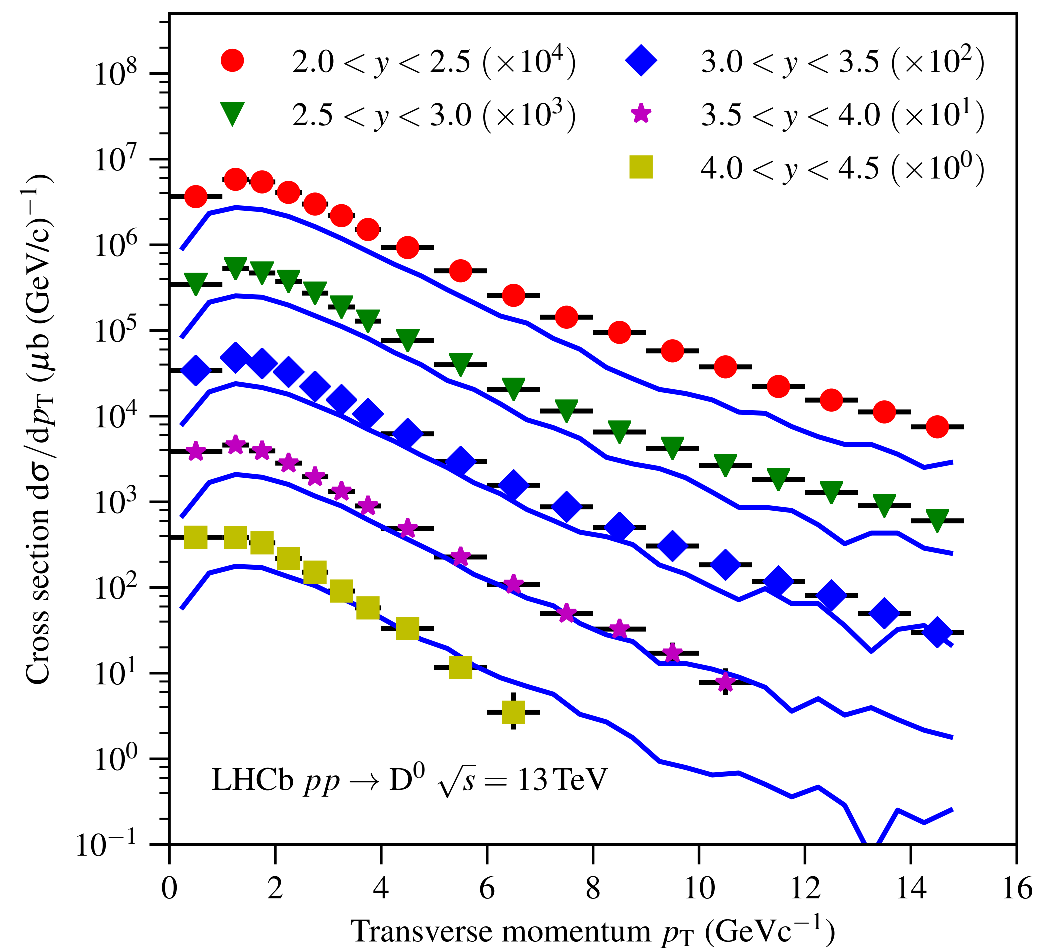
(Riehn et al., to be published 2016)



(Acta Phys.Polon. B34 (2003) 3273)

Comparison with LHC data (after tuning)

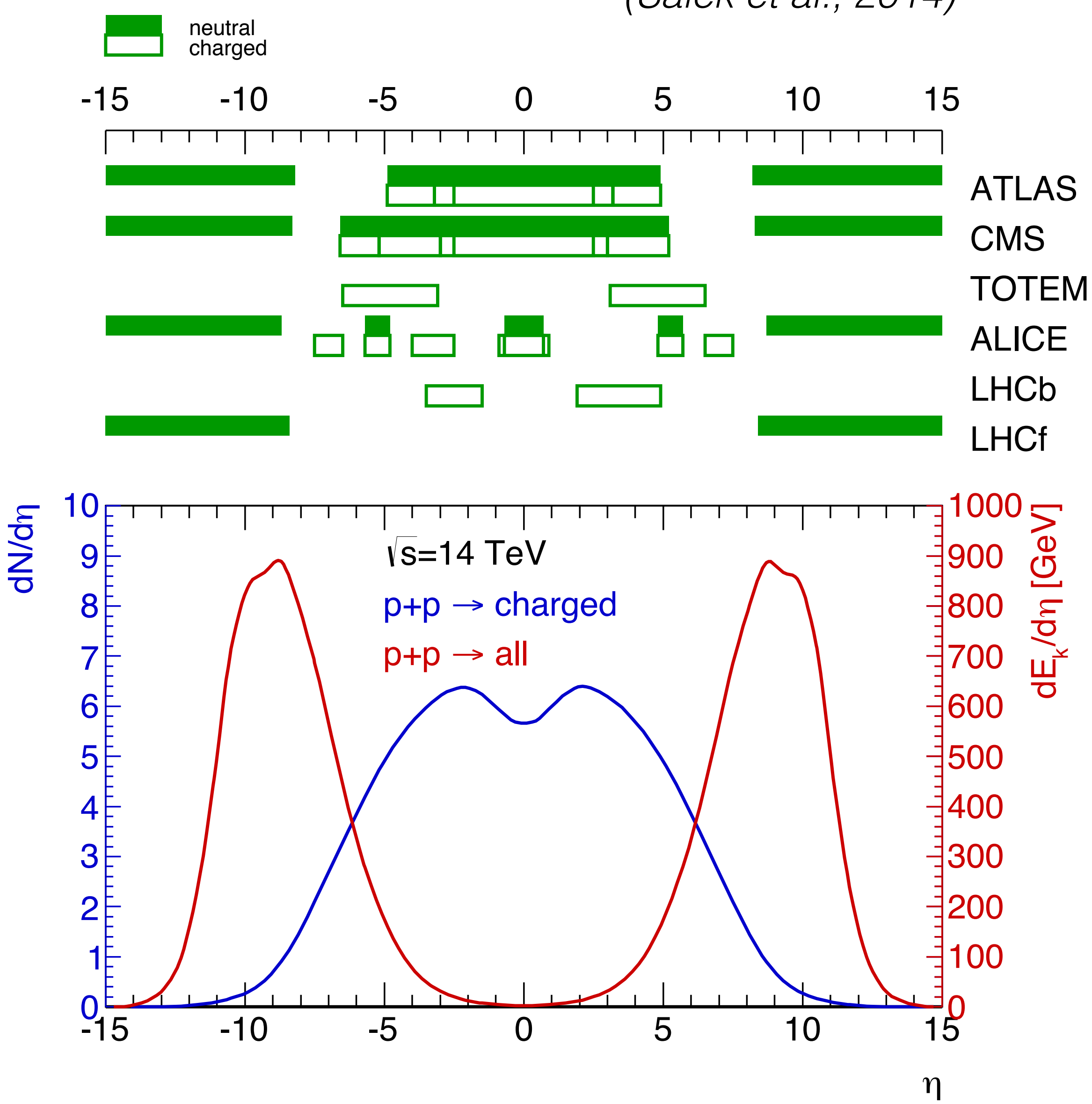




Difficult to describe 7 TeV and 13 TeV data of LHCb equally well, requires large perturbative component in model, leads to low non-perturbative component

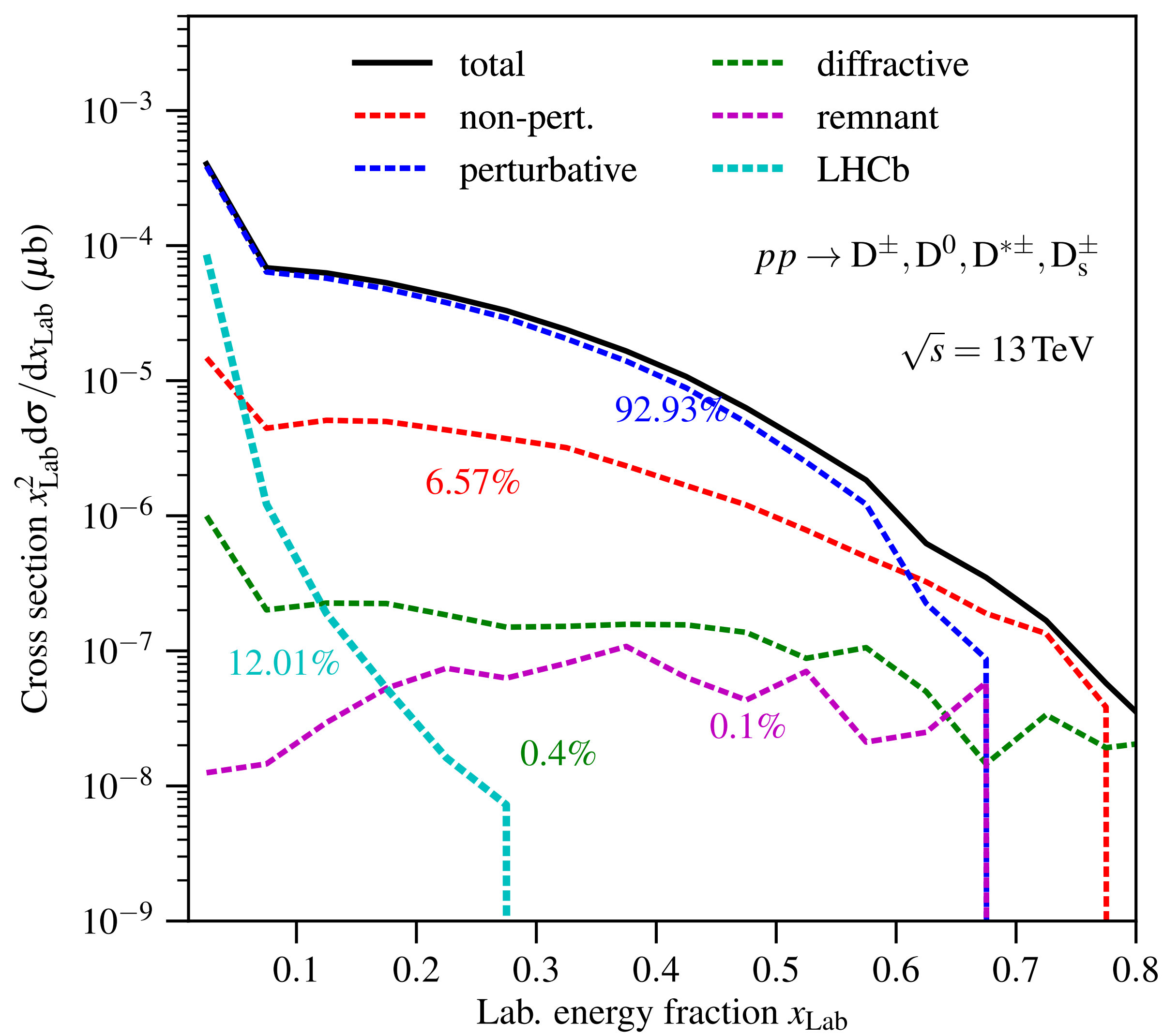
Phase space coverage of LHC for atm. lepton production

(Salek et al., 2014)



LHCb data (most detailed data sets)

(Riehn et al., to be published 2016)



No large non-perturbative component by LHC data required,
but only ~12% of relevant phase space for atm. leptons covered

Summary and outlook

- High-energy interactions in EAS: depth of shower maximum (X_{max}), low-energy interactions only important for muonic component

- Changes of X_{max} predictions understood, new predictions correspond to heavier primary CR composition, uncertainties still unclear

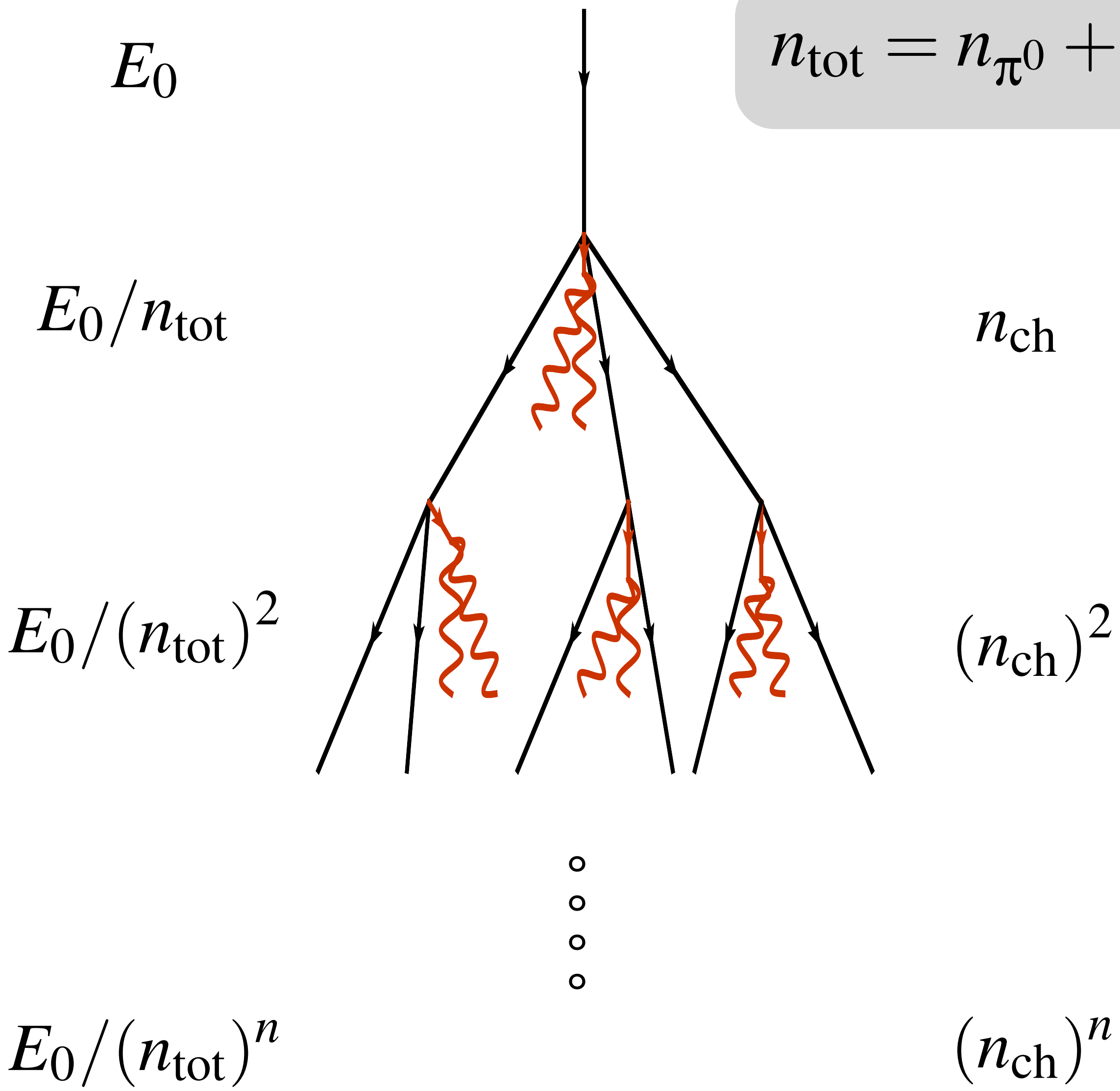
- Muon production still rather uncertain, some sources of uncertainty identified, could be used as handle for tuning to fit EAS data (very active field), IceCube data could be of decisive importance

- Atm. lepton fluxes: LHC data in optimal energy range for multi-PeV neutrinos, charm production very important for background estimates, only ~12% of phase space covered (data well described by pQCD calculations)

Backup slides

Shower physics: muon production

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



Primary particle proton

π^0 decay immediately

$\pi^\pm$ initiate new cascades

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

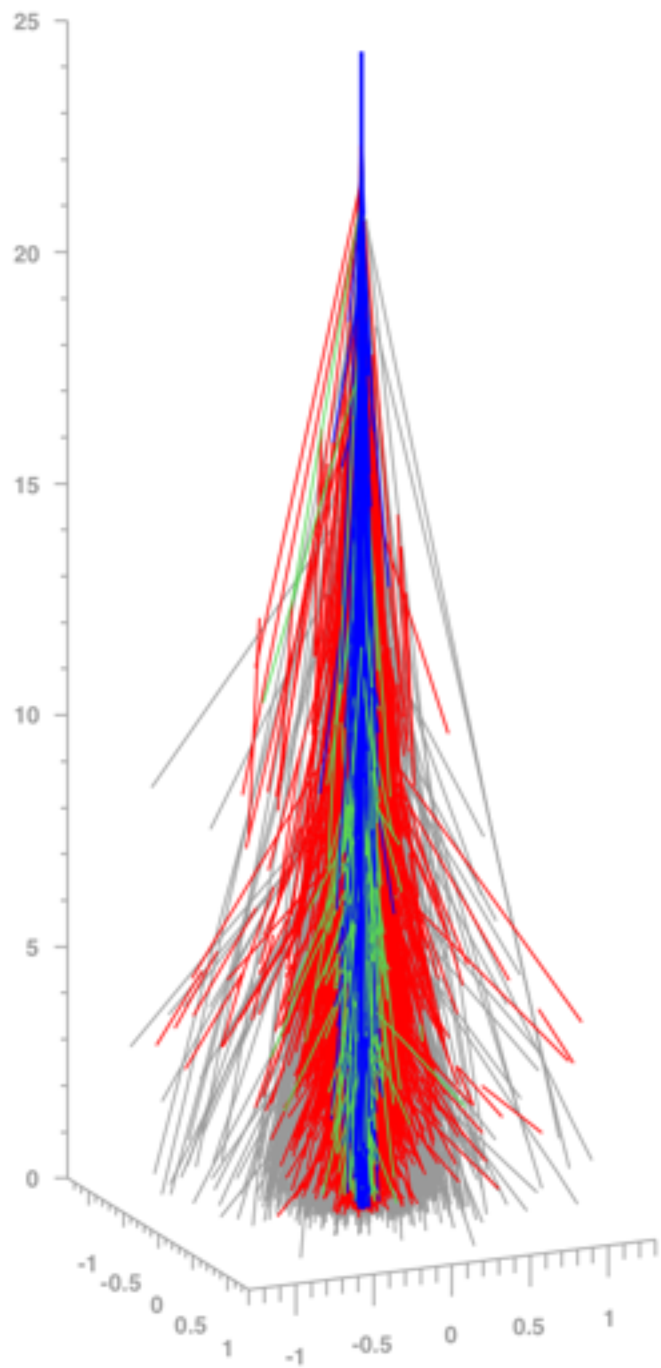
$$\alpha = \frac{\ln n_{ch}}{\ln n_{tot}} \approx 0.82 \ldots 0.9$$

Assumptions:

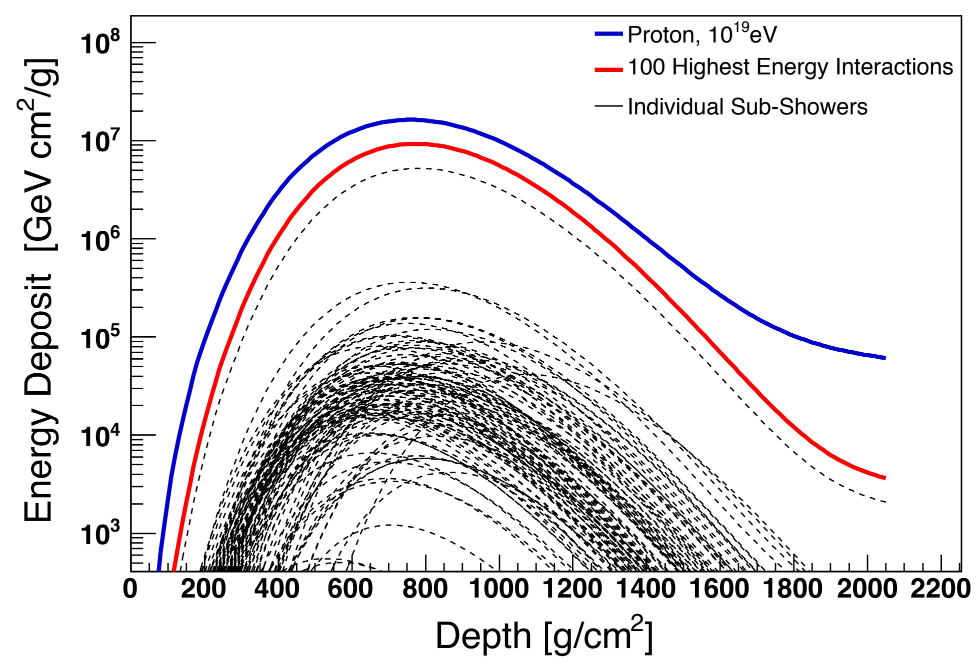
- cascade stops at $E_{part} = E_{dec}$
- each hadron produces one muon

(Matthews, Astropart.Phys. 22, 2005)

Importance of different interaction energies



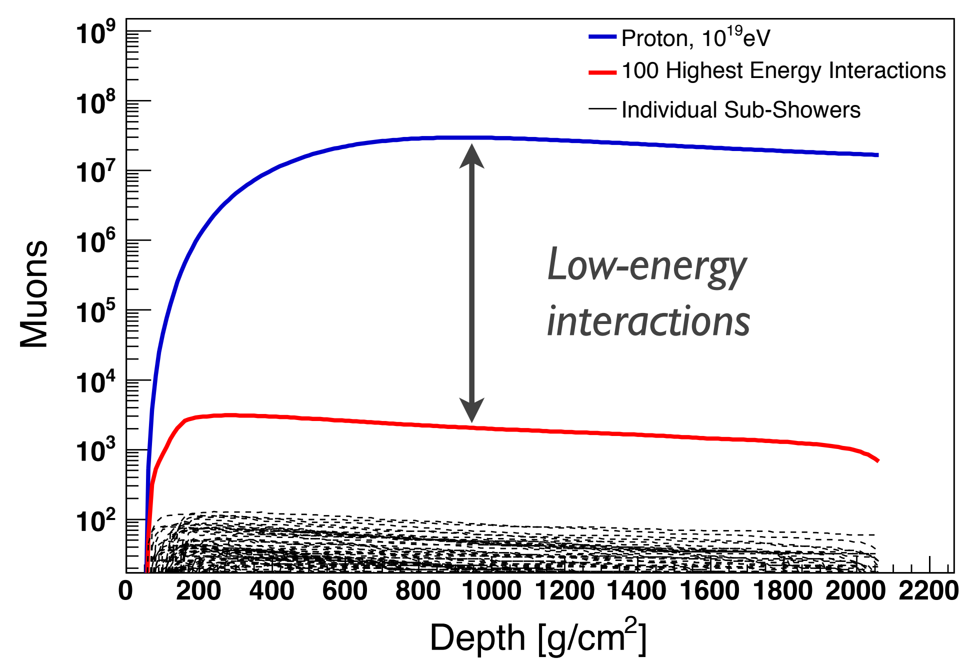
Electrons



Shower particles produced in 100 interactions of highest energy

Electrons/photons: high-energy interactions

Muons



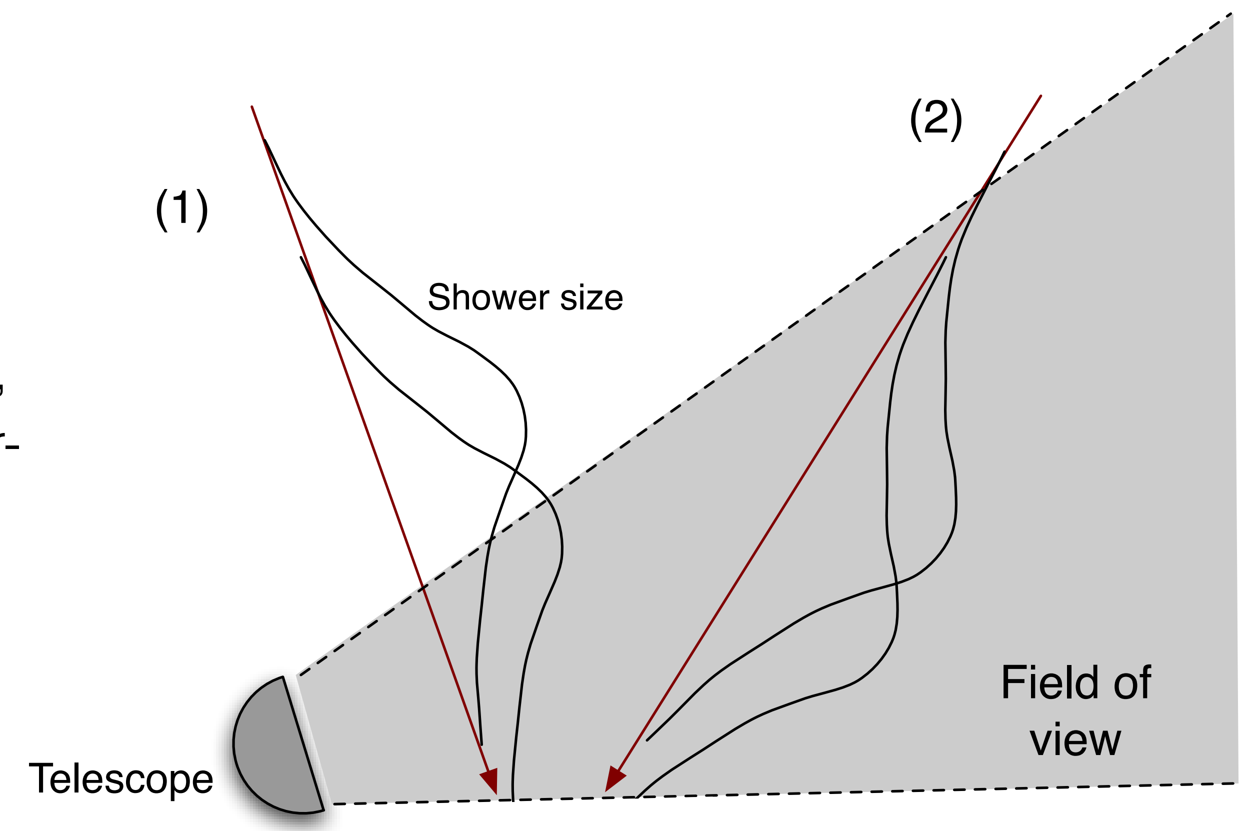
(Ulrich, APS 2012)

Muons/hadrons: low-energy interactions

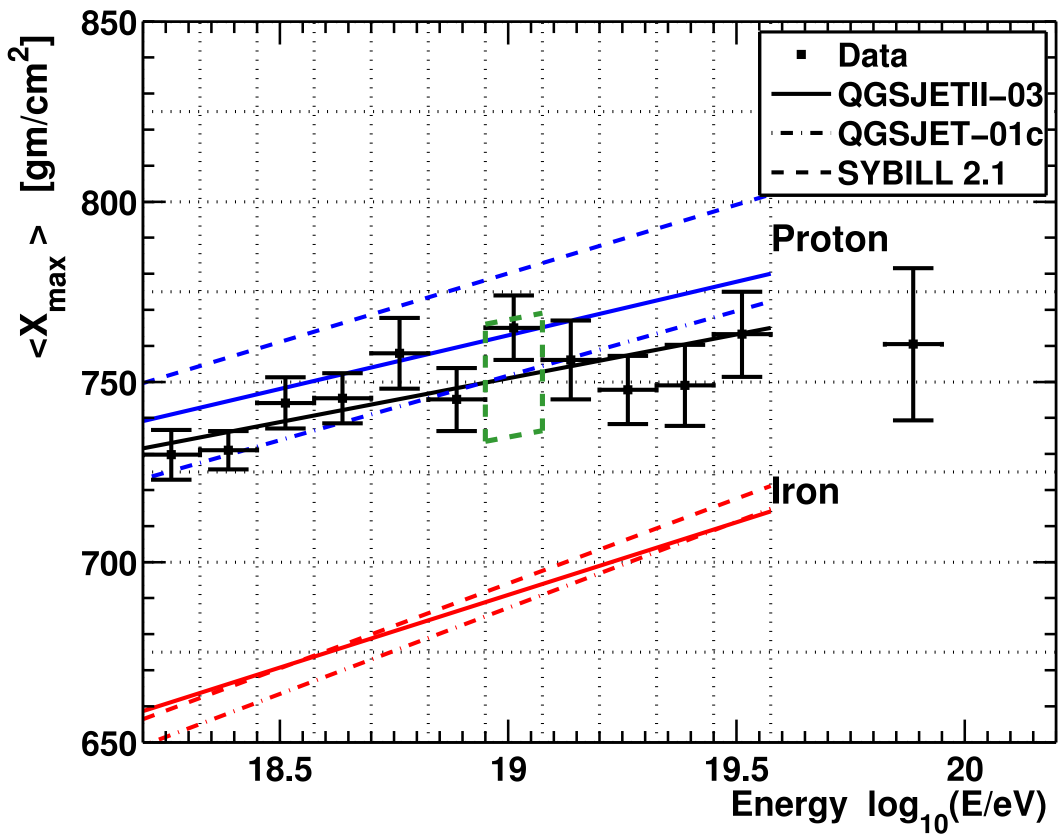
Muons: majority produced in low energy interactions (30-200 GeV lab.)

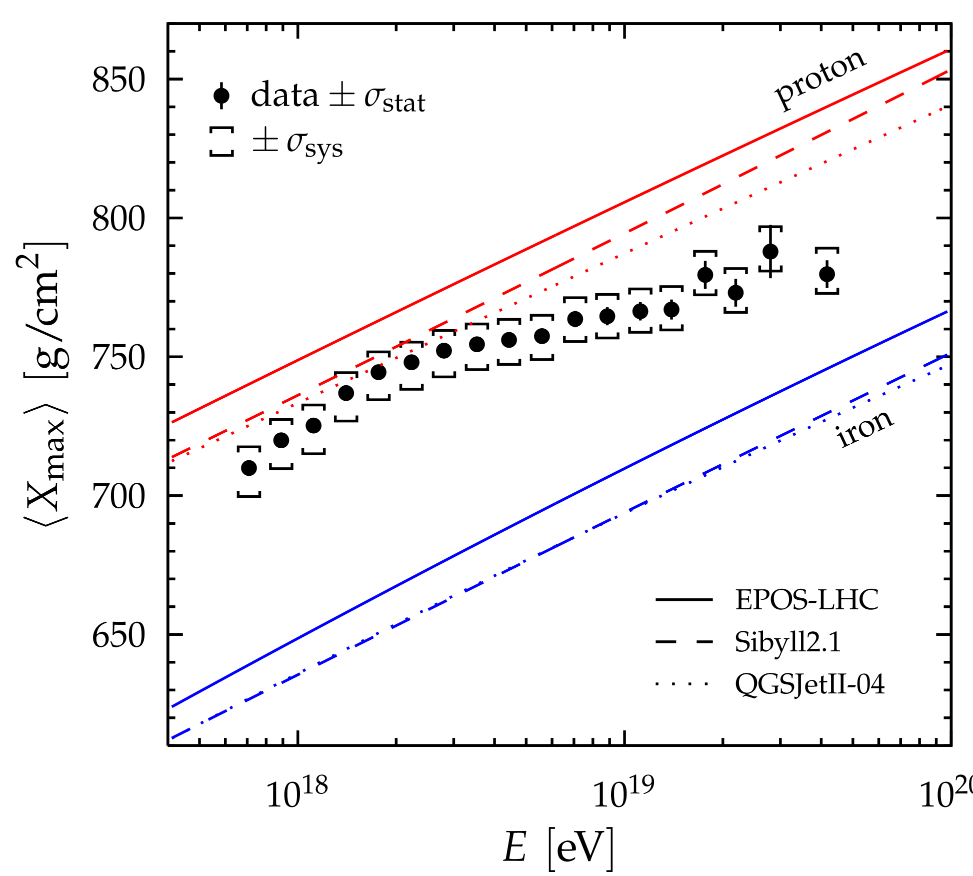
TA: protons, Auger: heavier elements

TA: all showers analyzed, comparison with detector-folded X_{max} distributions (biased by FoV)



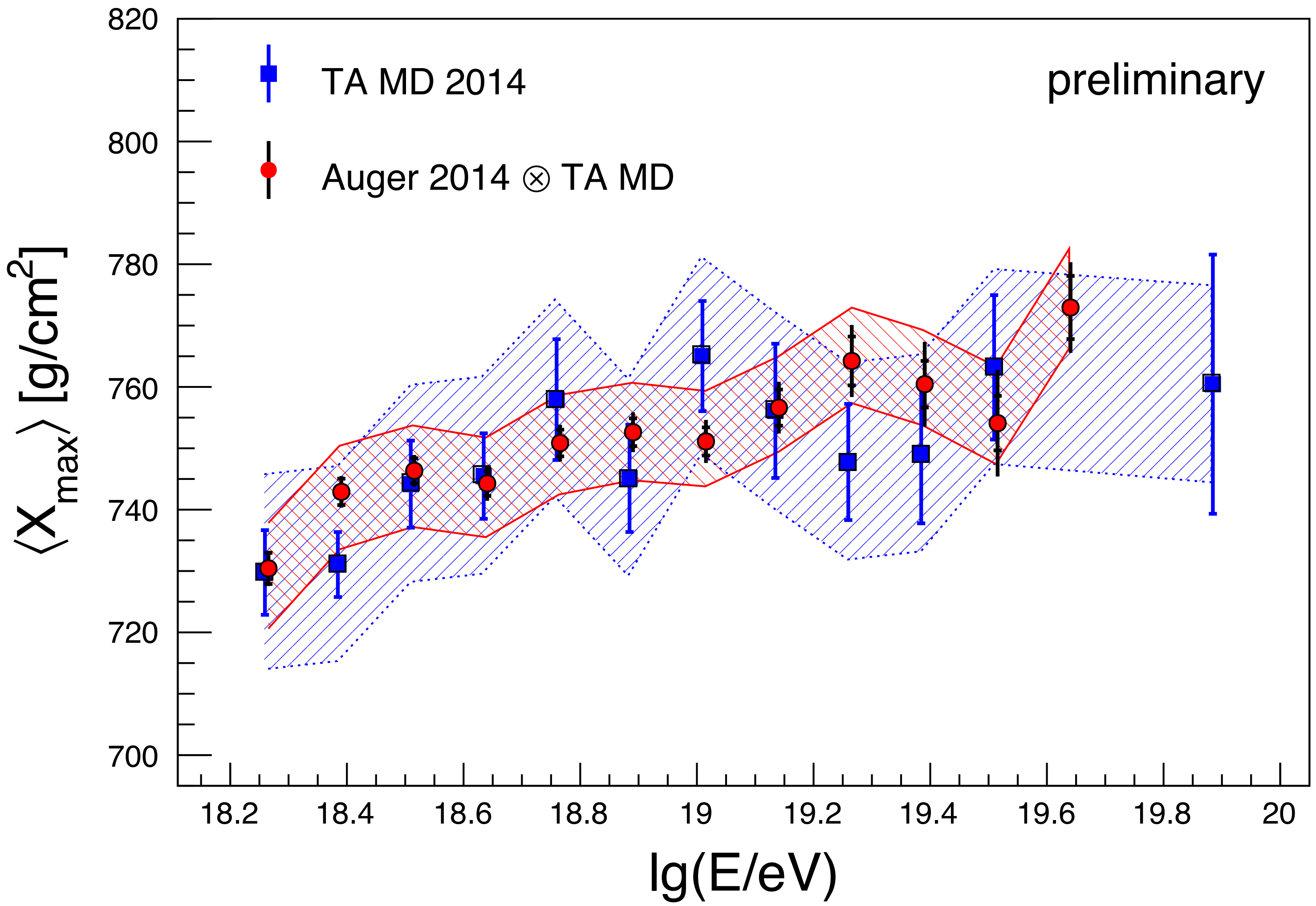
Auger: only analysis of showers for which all relevant X_{max} are observable, comparison with theoretical X_{max} distributions





Comparison of Auger and TA mean X_{max}

Auger-TA joint working group (ICRC 2015, 1511.02103)



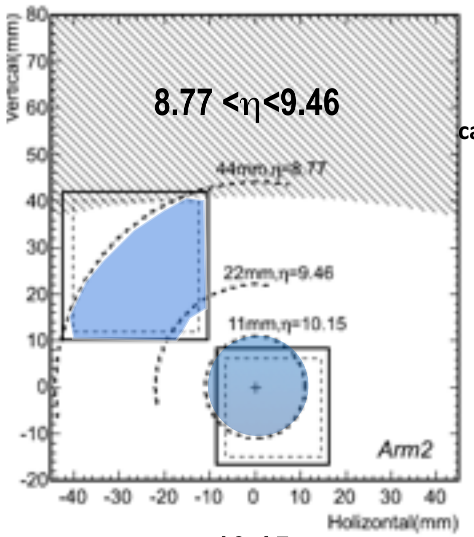
After accounting for TA detector acceptance both data sets are **fully compatible**

Still different interpretation because of reference models

- Auger: EPOS-LHC, QGSjet II.04, Sibyll 2.1
- TA: QGSjet II.03 (pre-LHC version)

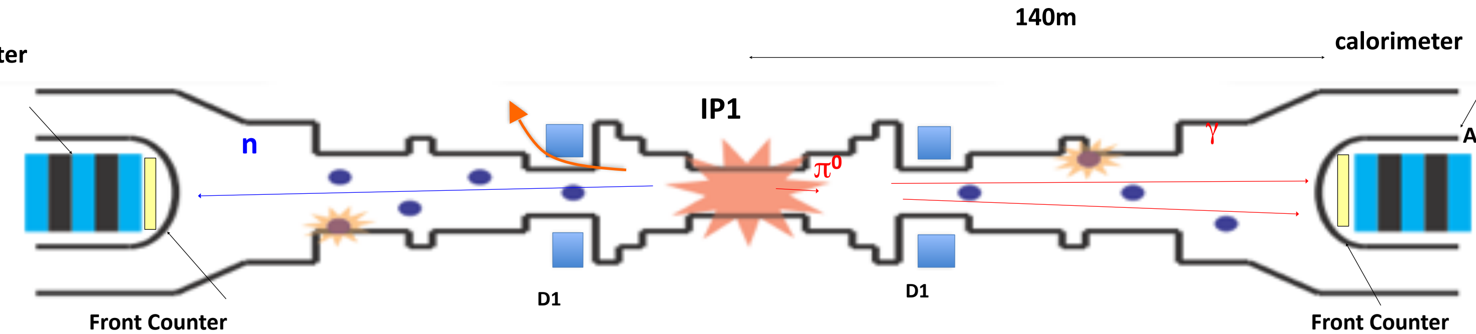
LHCf: very forward photon production

Arm 2

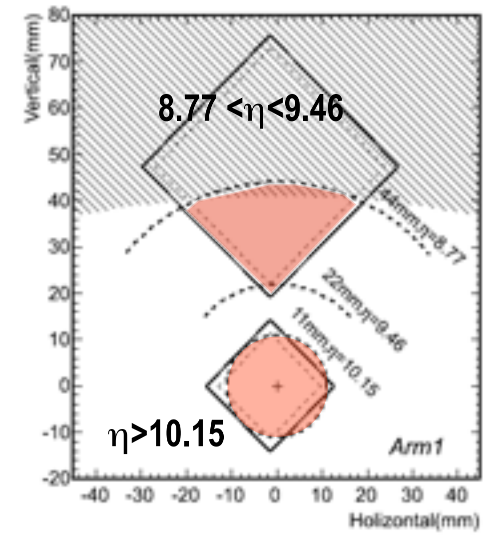


η>10.15

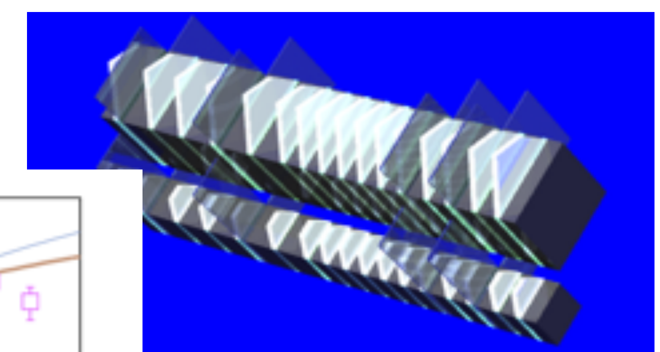
The LHCf experimental setup



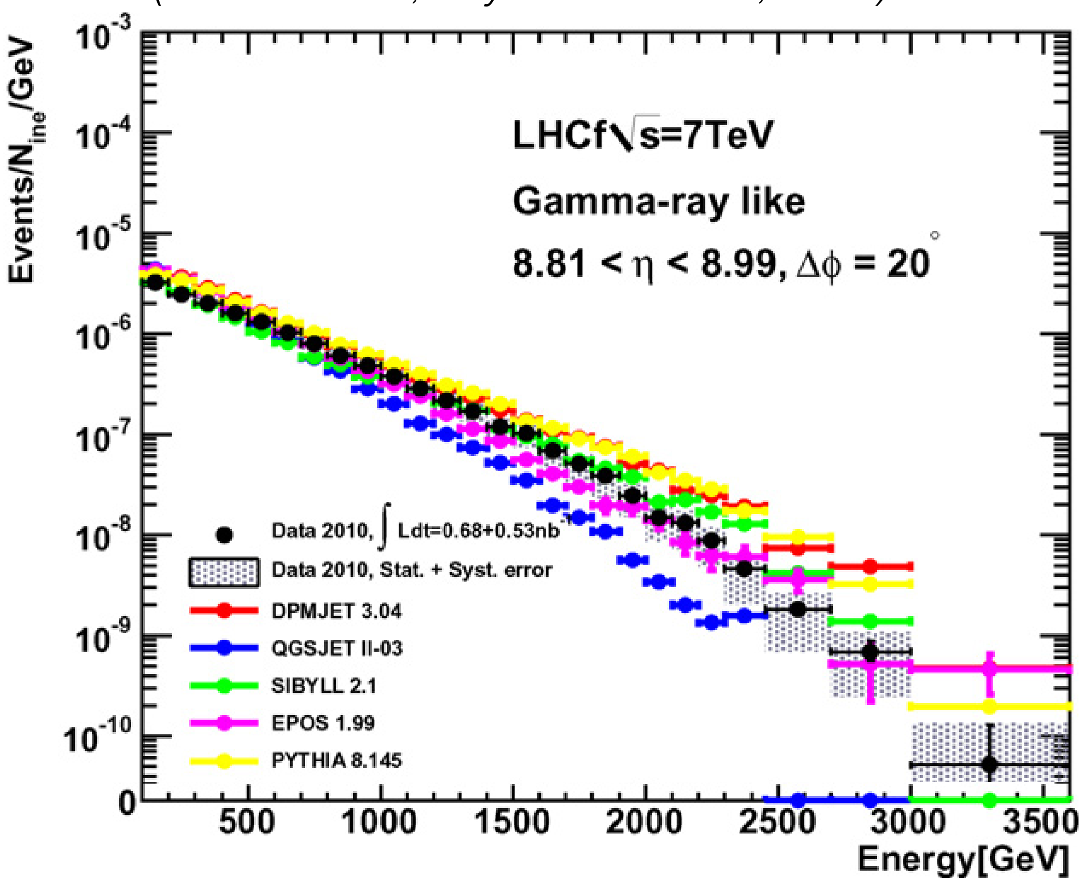
Arm 1



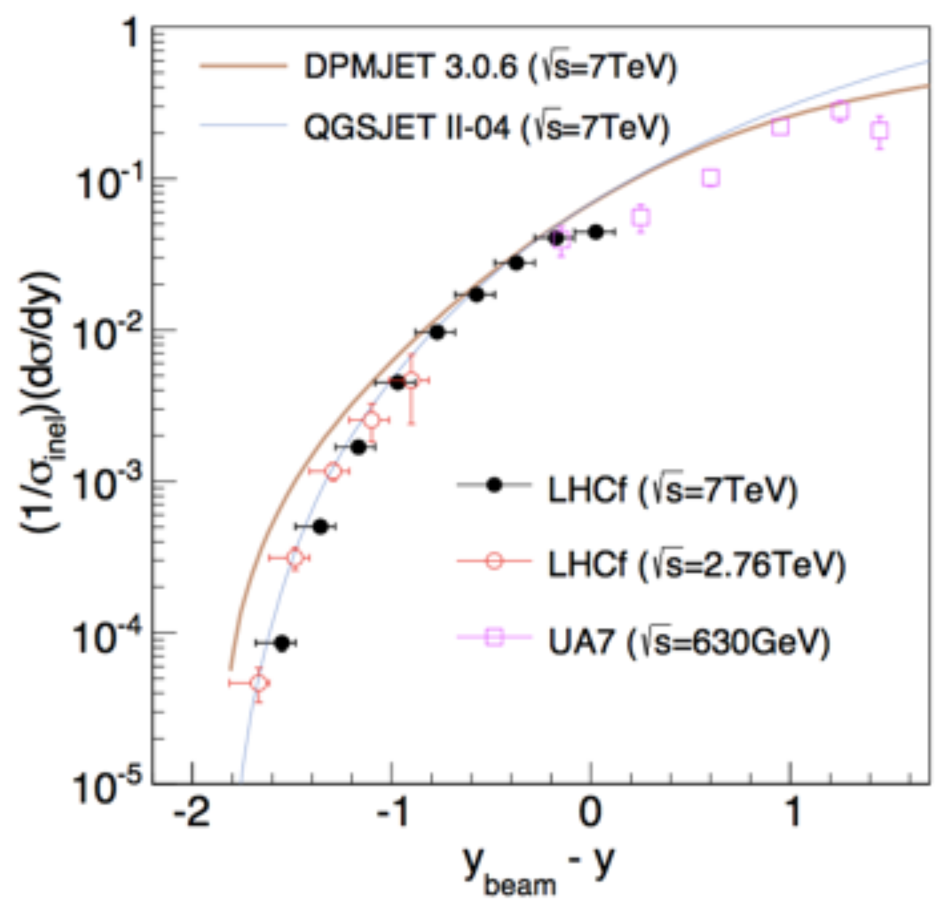
$$pp \rightarrow \gamma X$$



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

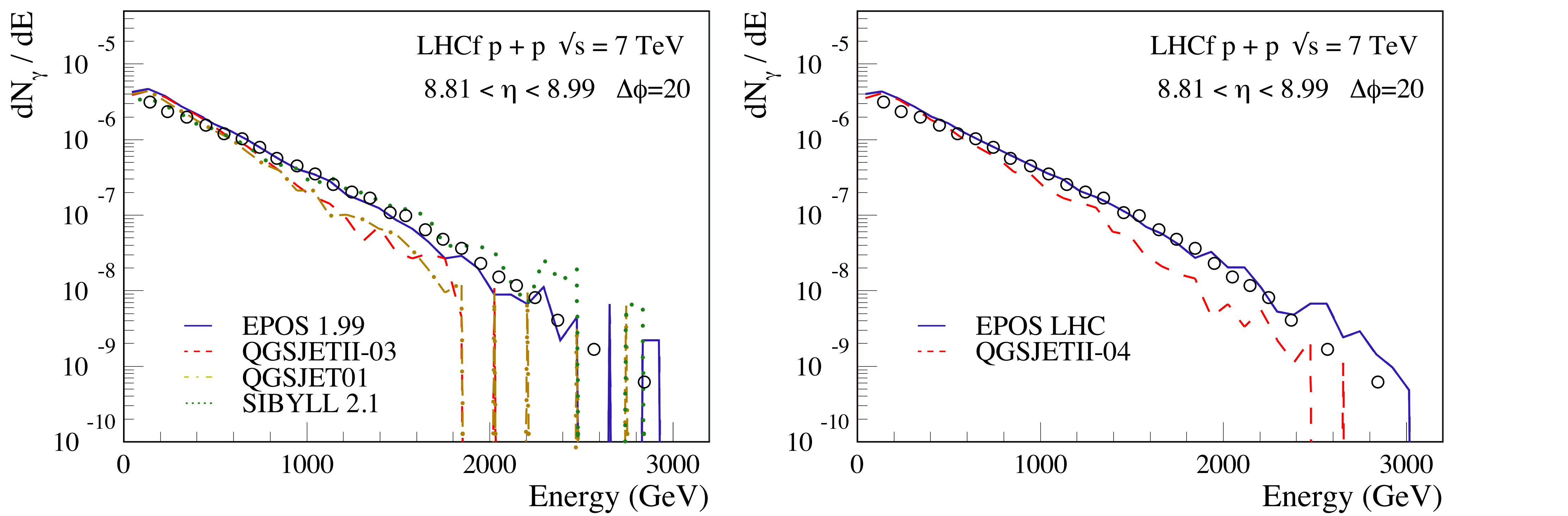


(LHCf, 1507.08764)

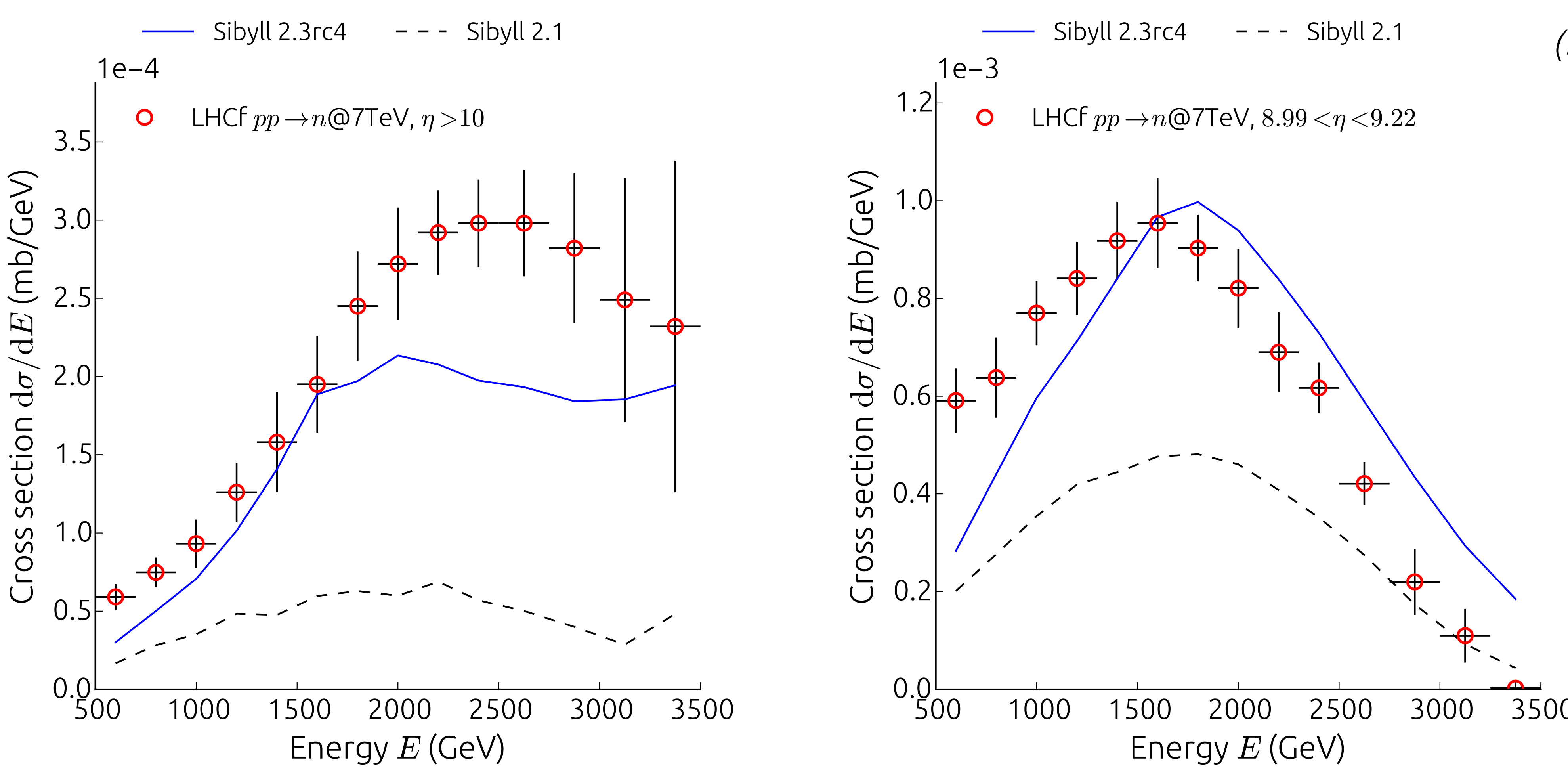


(Itow, ICRC 2015)

Tuning of interaction models to LHC data

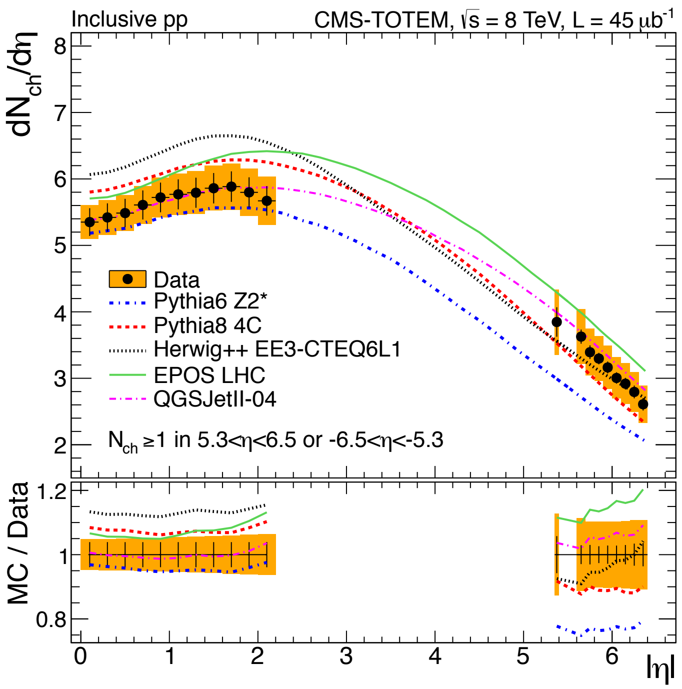


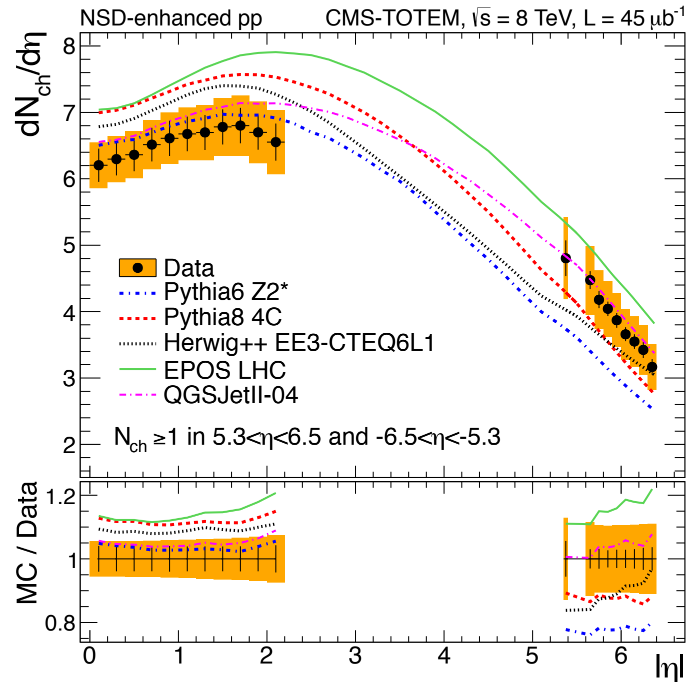
(Pierog 2014)



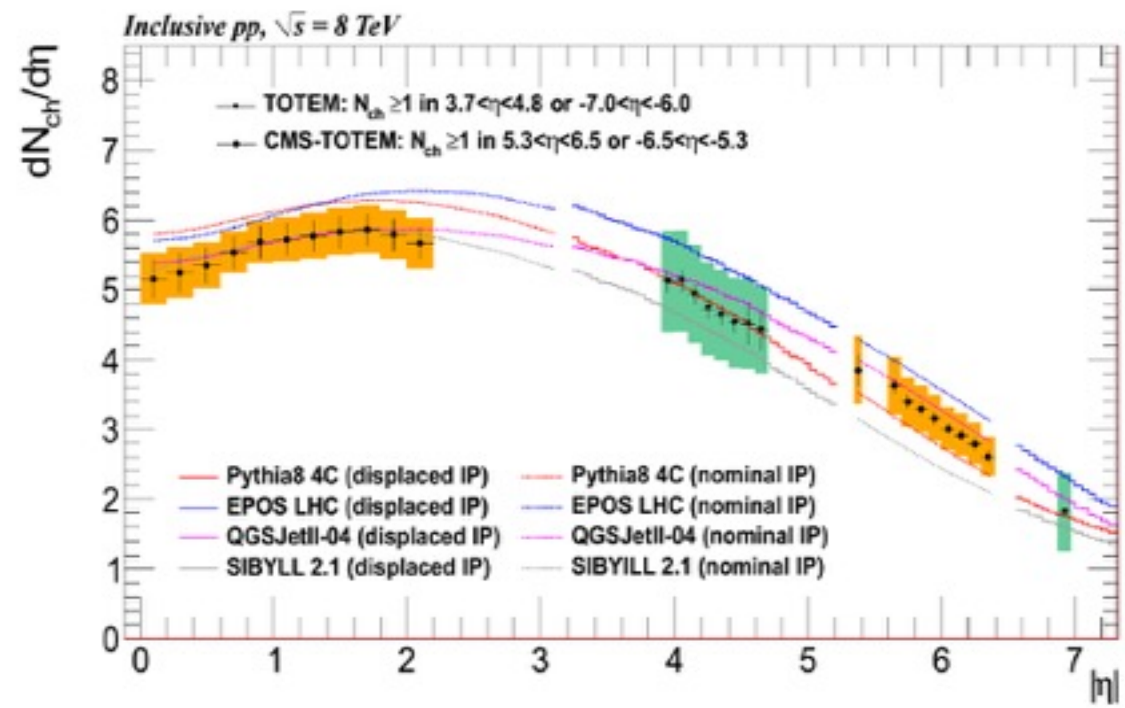
(Riehn 2015)

Combined CMS and TOTEM measurements

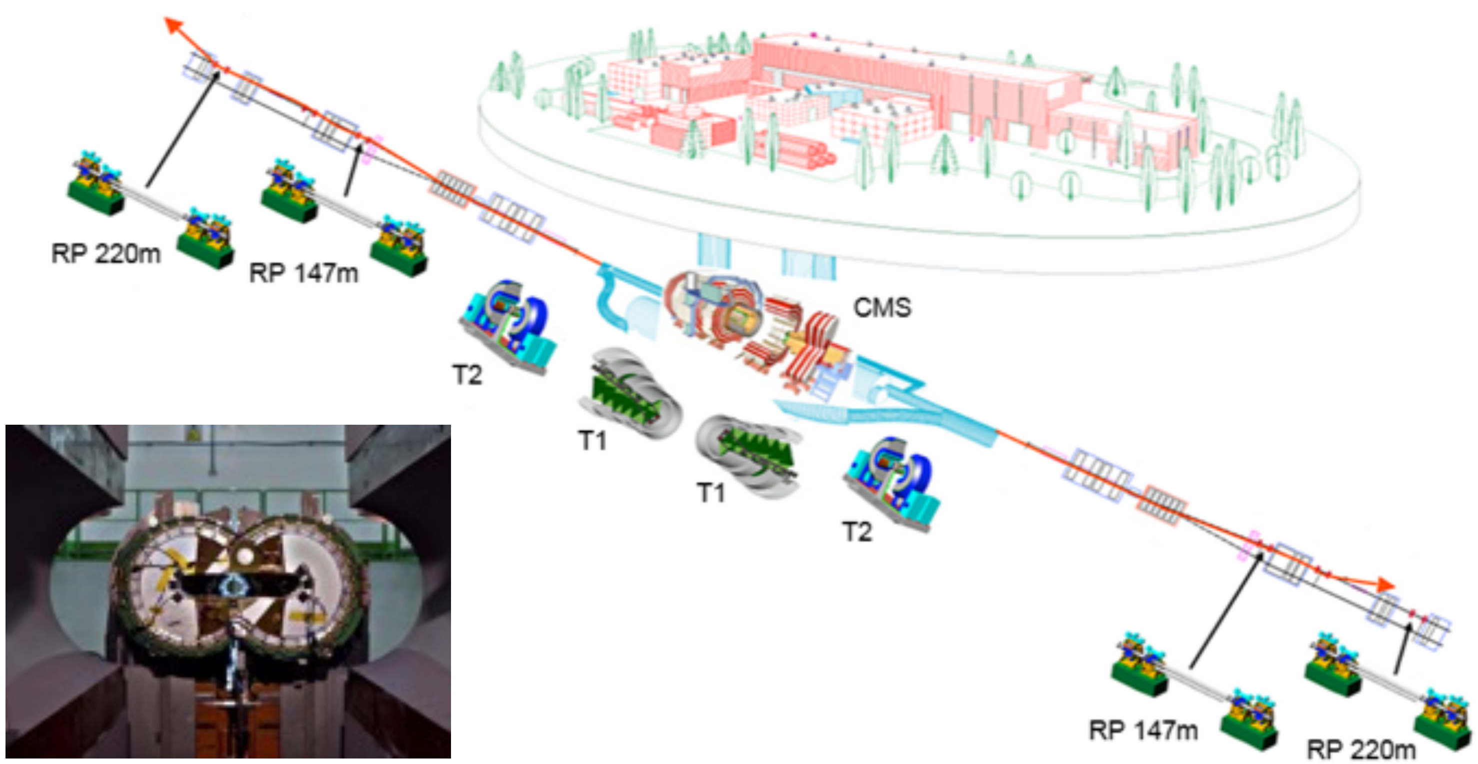


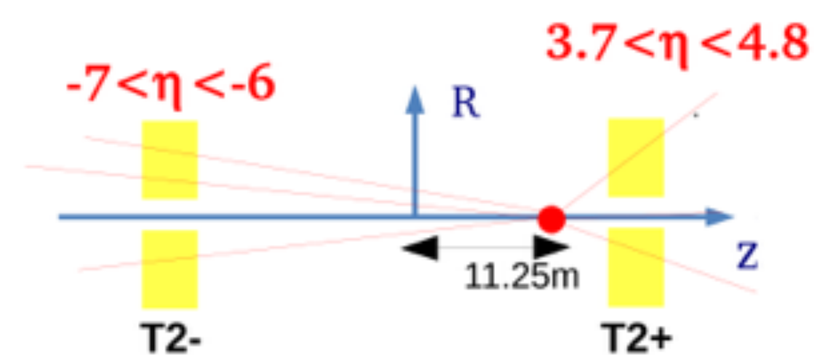


Nominal vertex



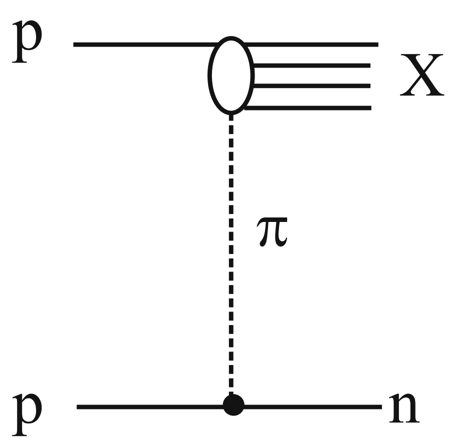
Shifted vertex





Pion-proton and pion-nucleus interactions at LHC

Measurement of pion exchange at LHC



Pion fragmentation region in ATLAS

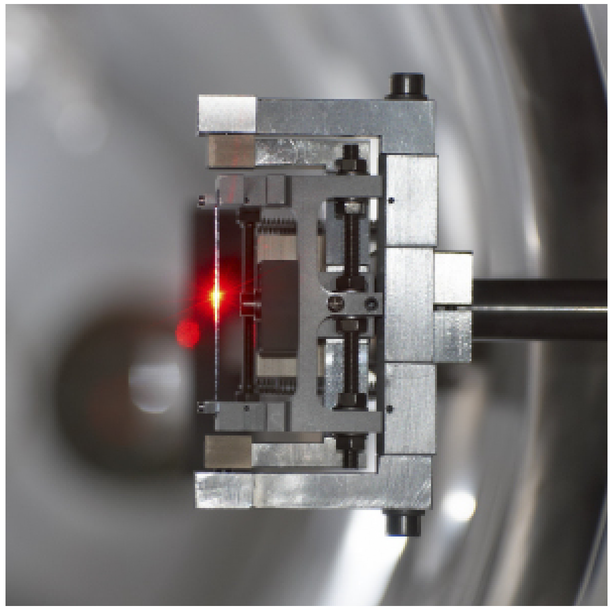
Leading neutron in LHCf

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

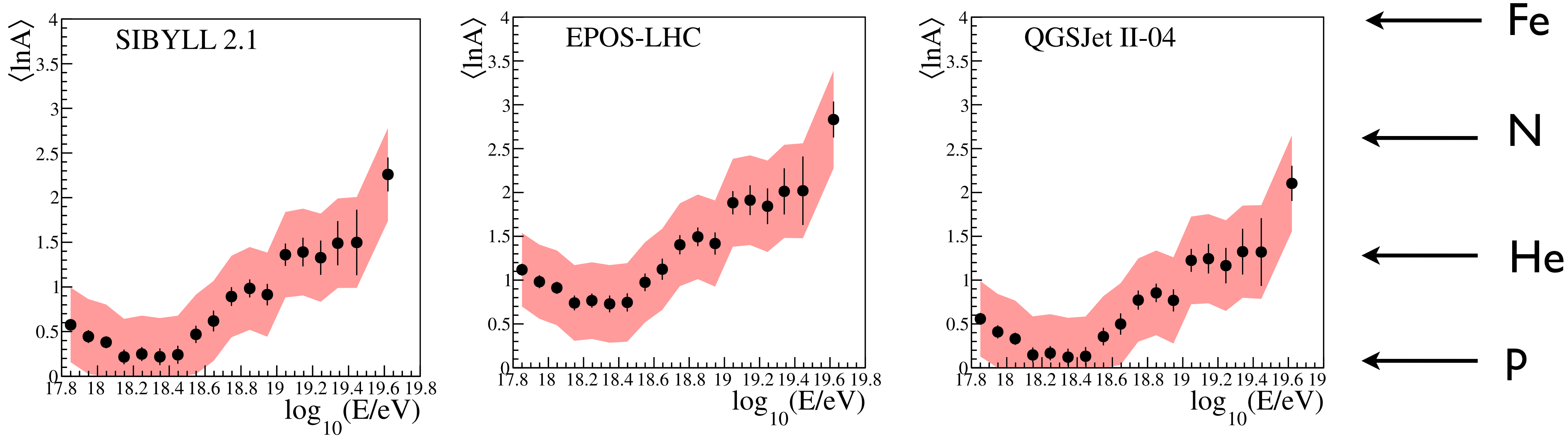
(Ulrich et al., ICRC 2015)



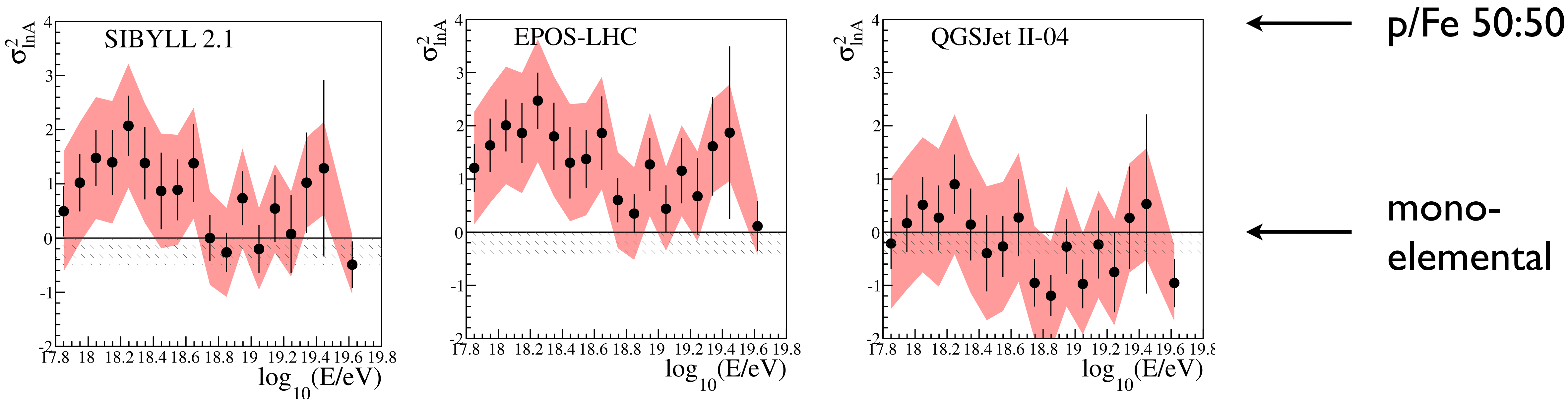
Deflection of protons of beam halo by crystal

Consistent description of X_{max} data ?

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



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

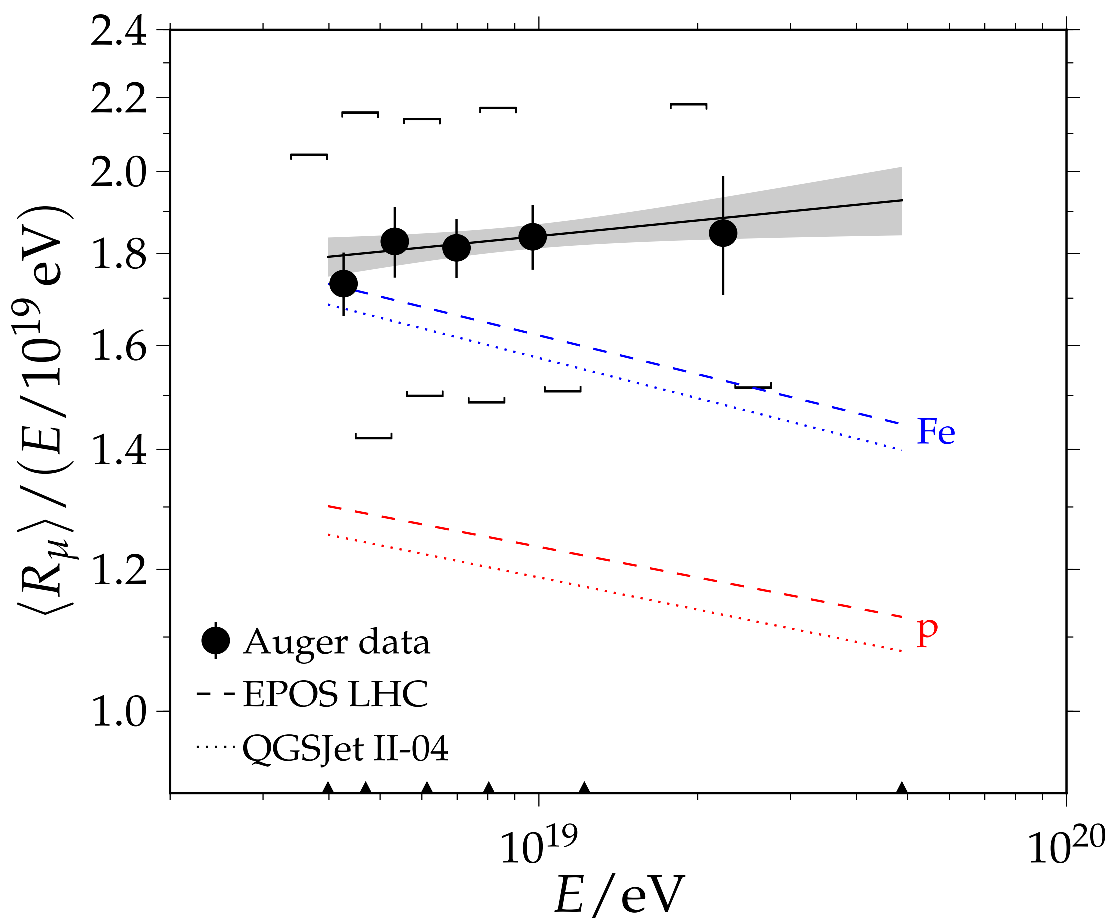


(Auger, JCAP 02 (2013) 026;
update: PRD 90 (2014) 122005)

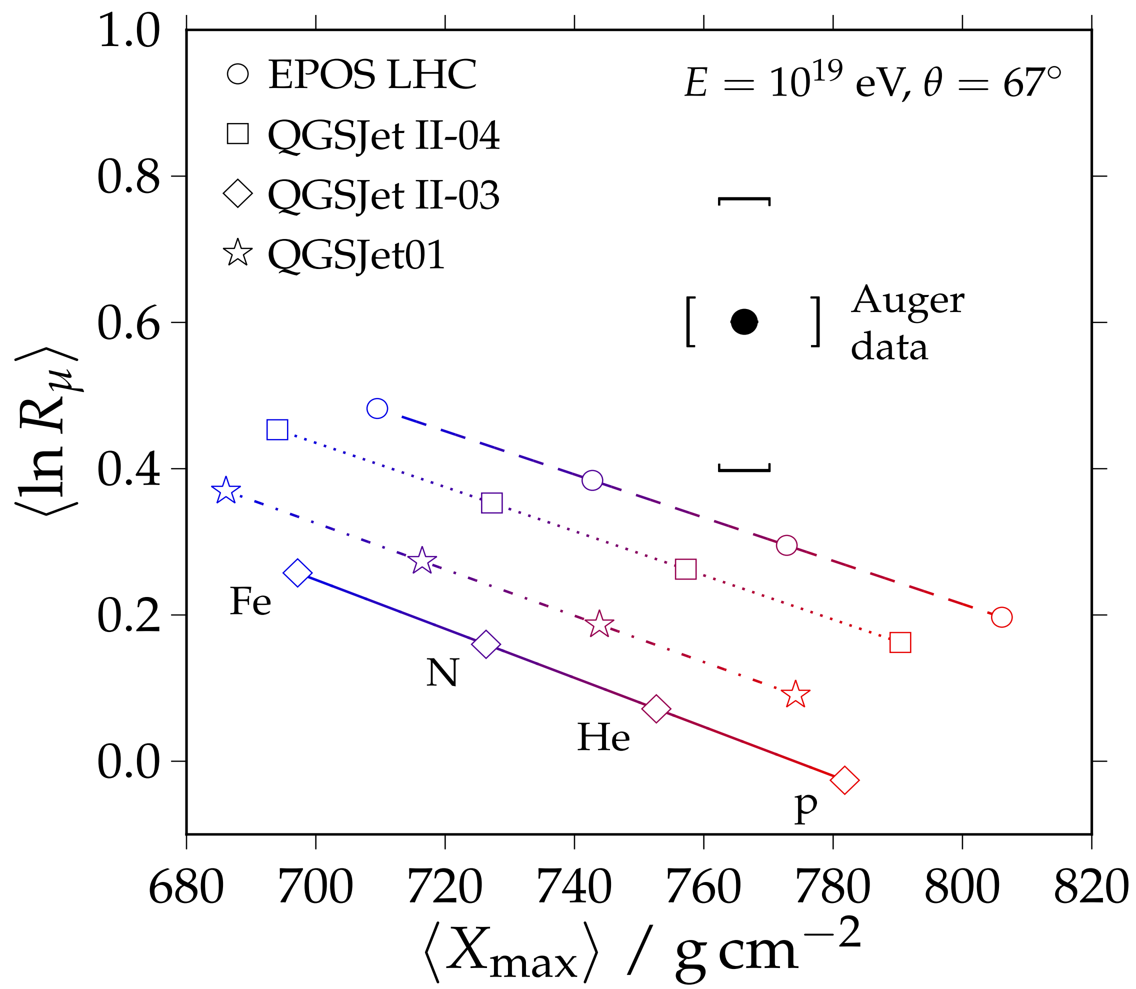
QGSJet II.04 disfavoured ?

Auger: 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



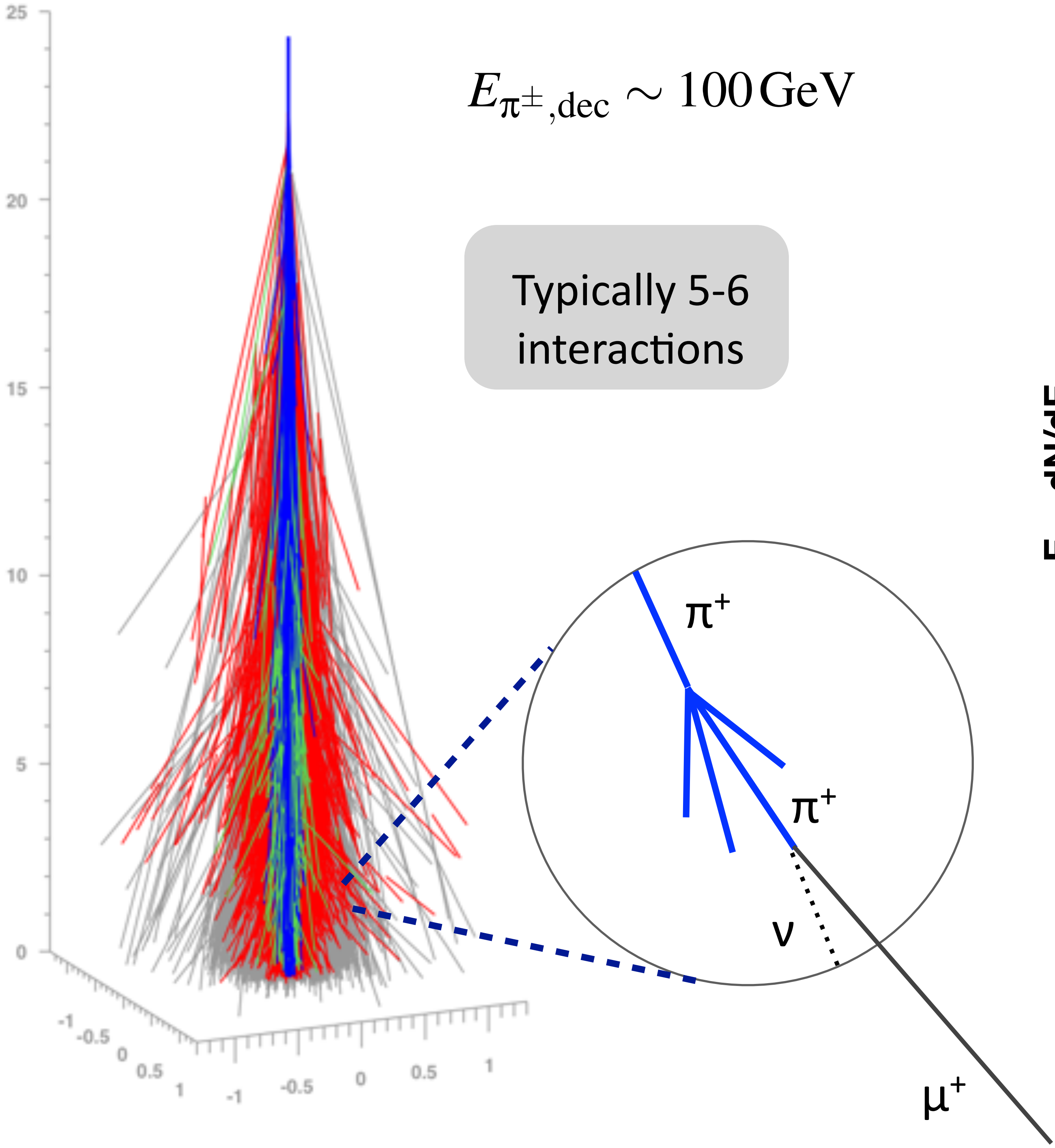
Muon discrepancy in Auger and KASCADE-Grande data

(Auger, arXiv:1408.1421)

Muon production at large lateral distance

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

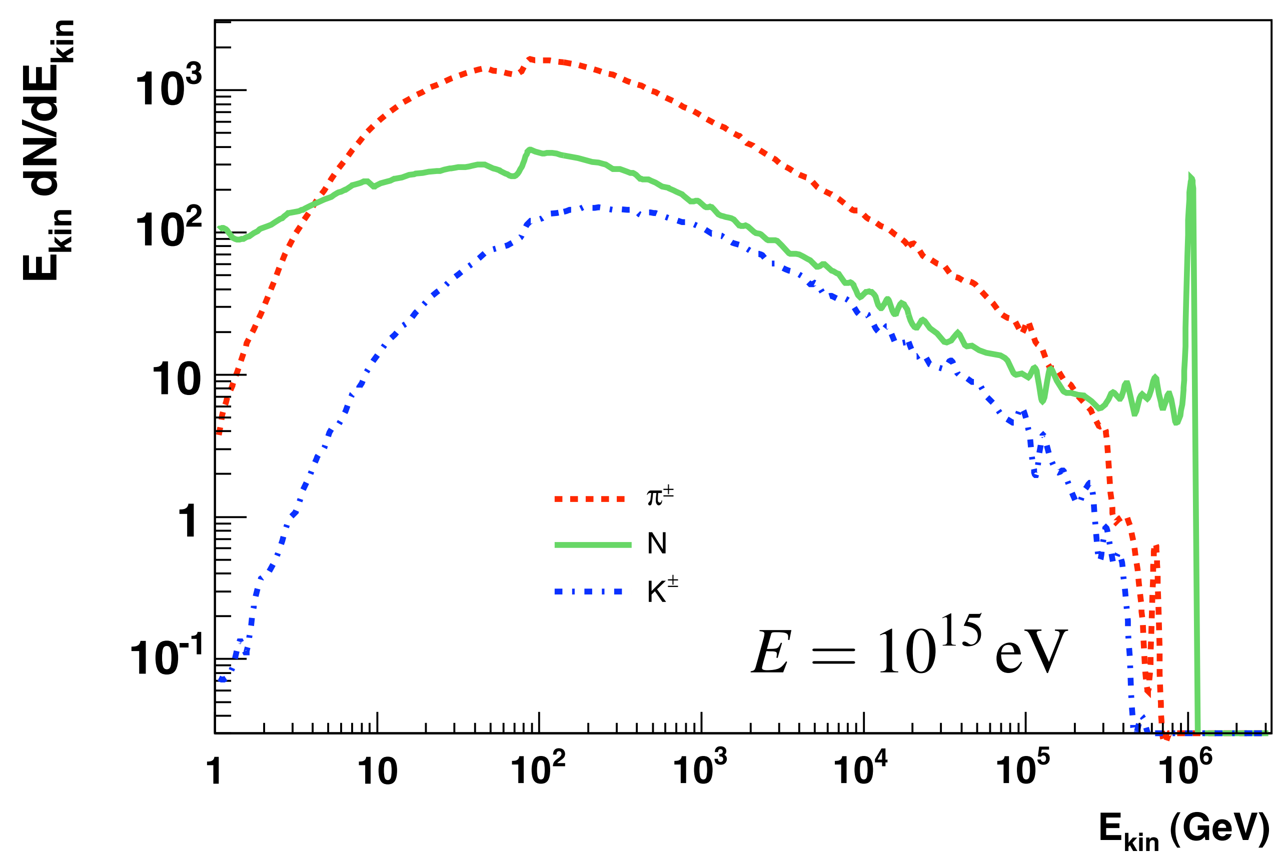
Typically 5-6 interactions



Muon observed 40 – 200 m from core

Energy distribution of last interaction that produced a detected muon

Example: KASCADE, proton shower

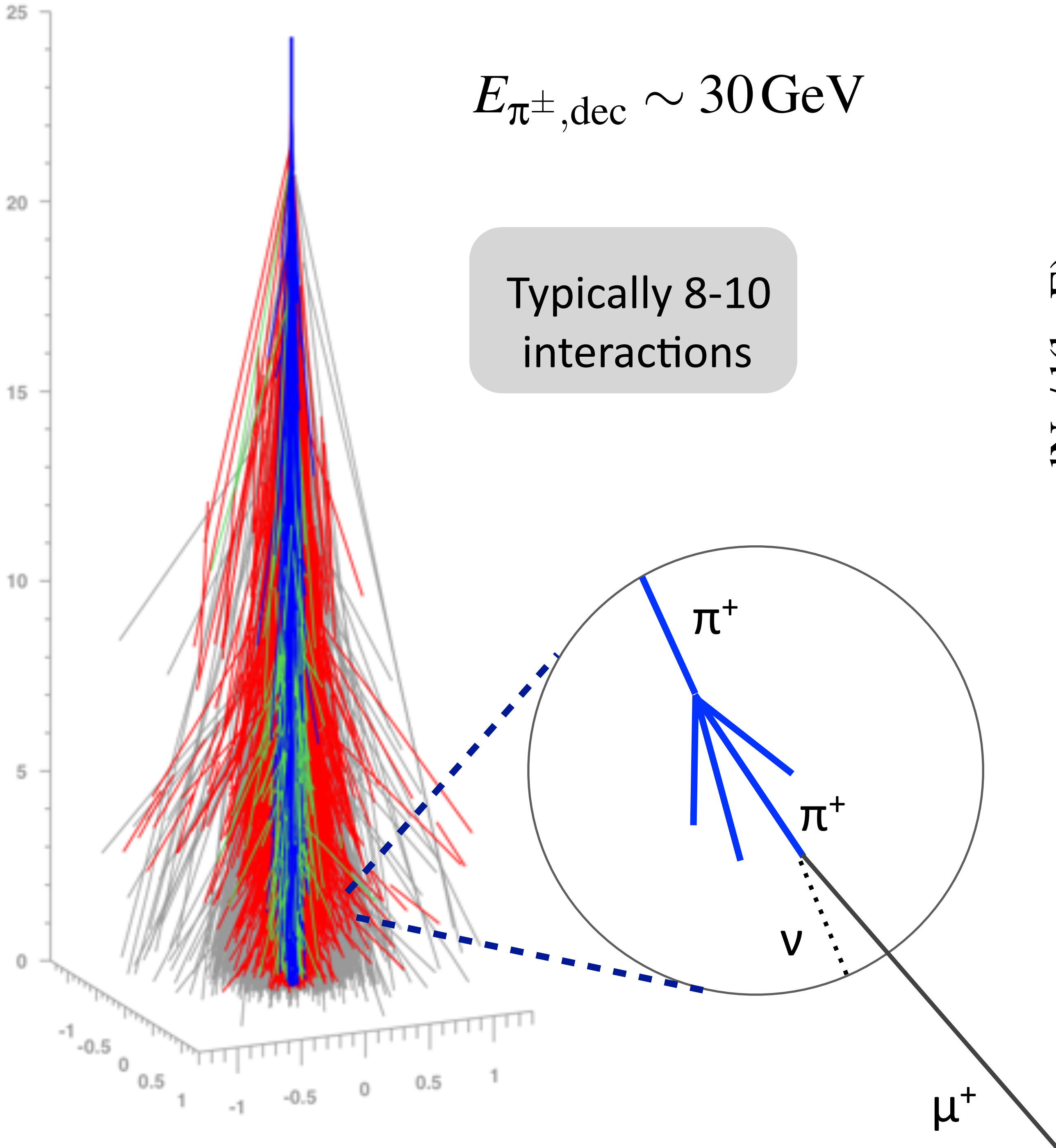


(Meurer et al. Czech. J. Phys. 2006)

Muon production at large lateral distance

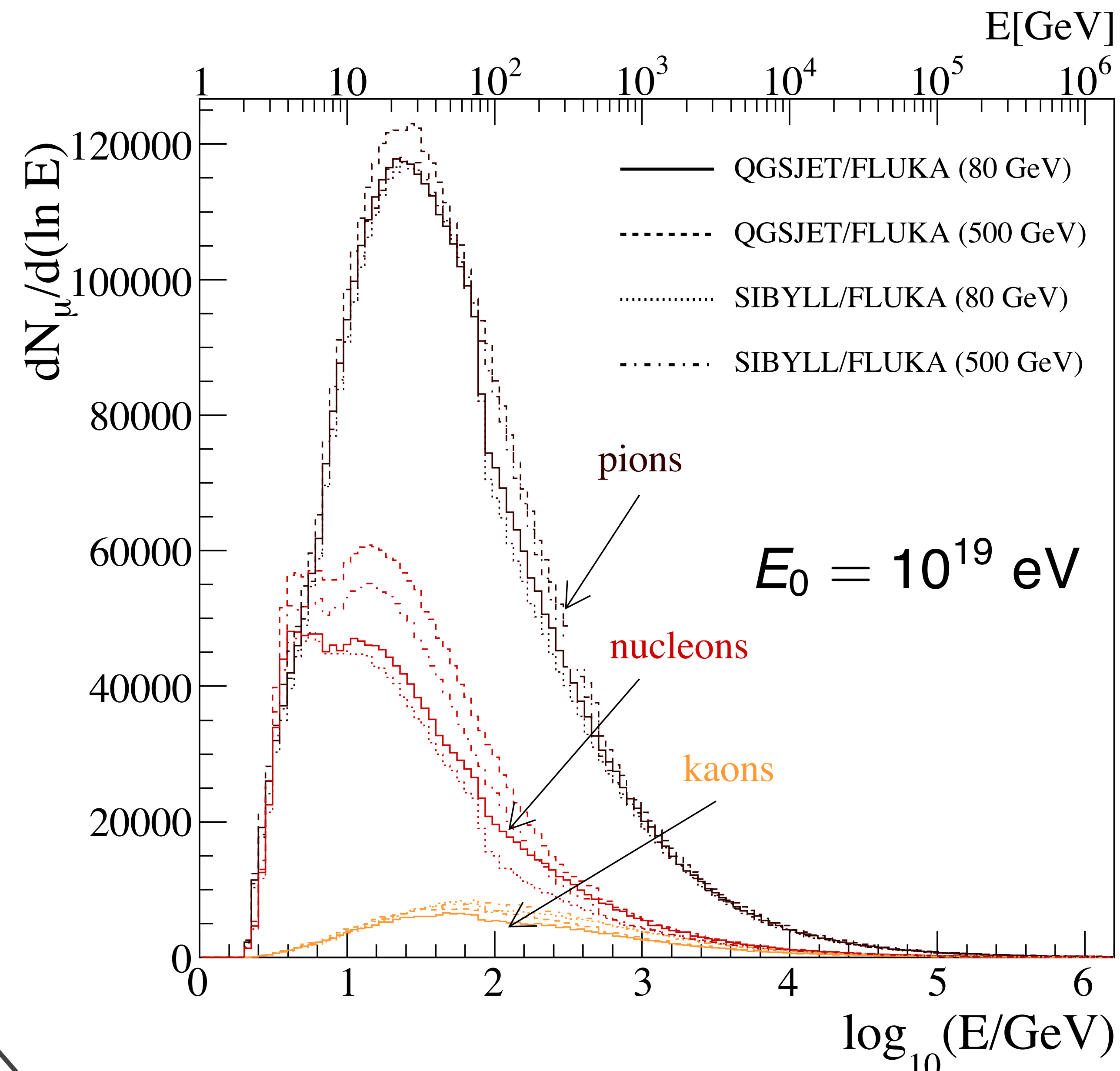
$E_{\pi^\pm,\mathrm{dec}} \sim 30\,\mathrm{GeV}$

Typically 8-10 interactions



Muon observed at 1000 m from core

Energy distribution of last interaction that produced a detected muon

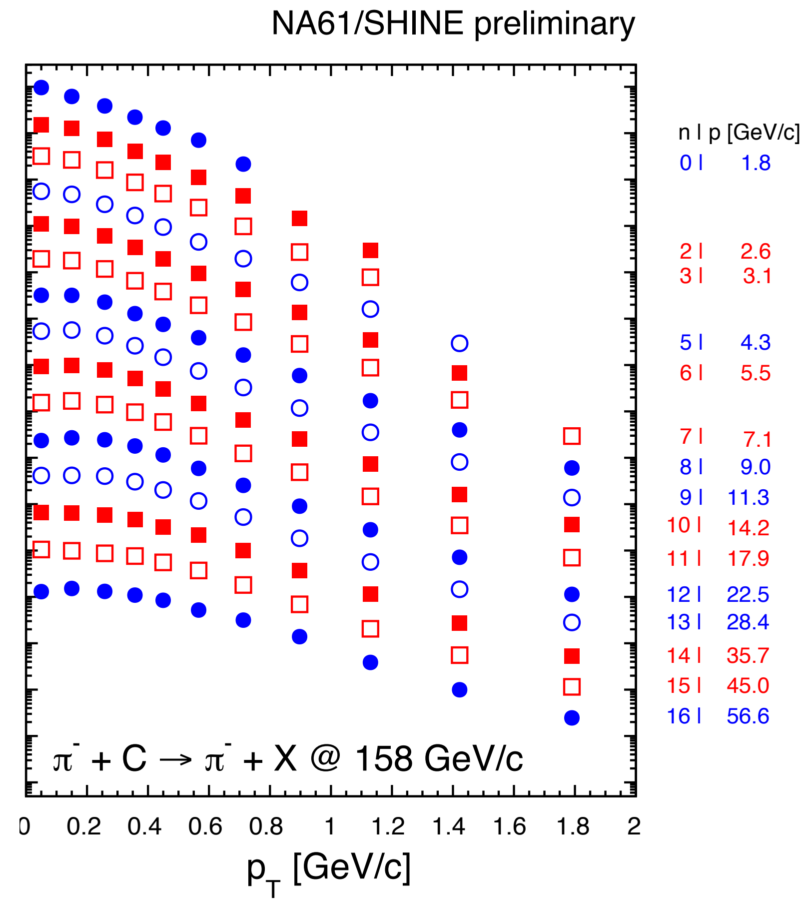


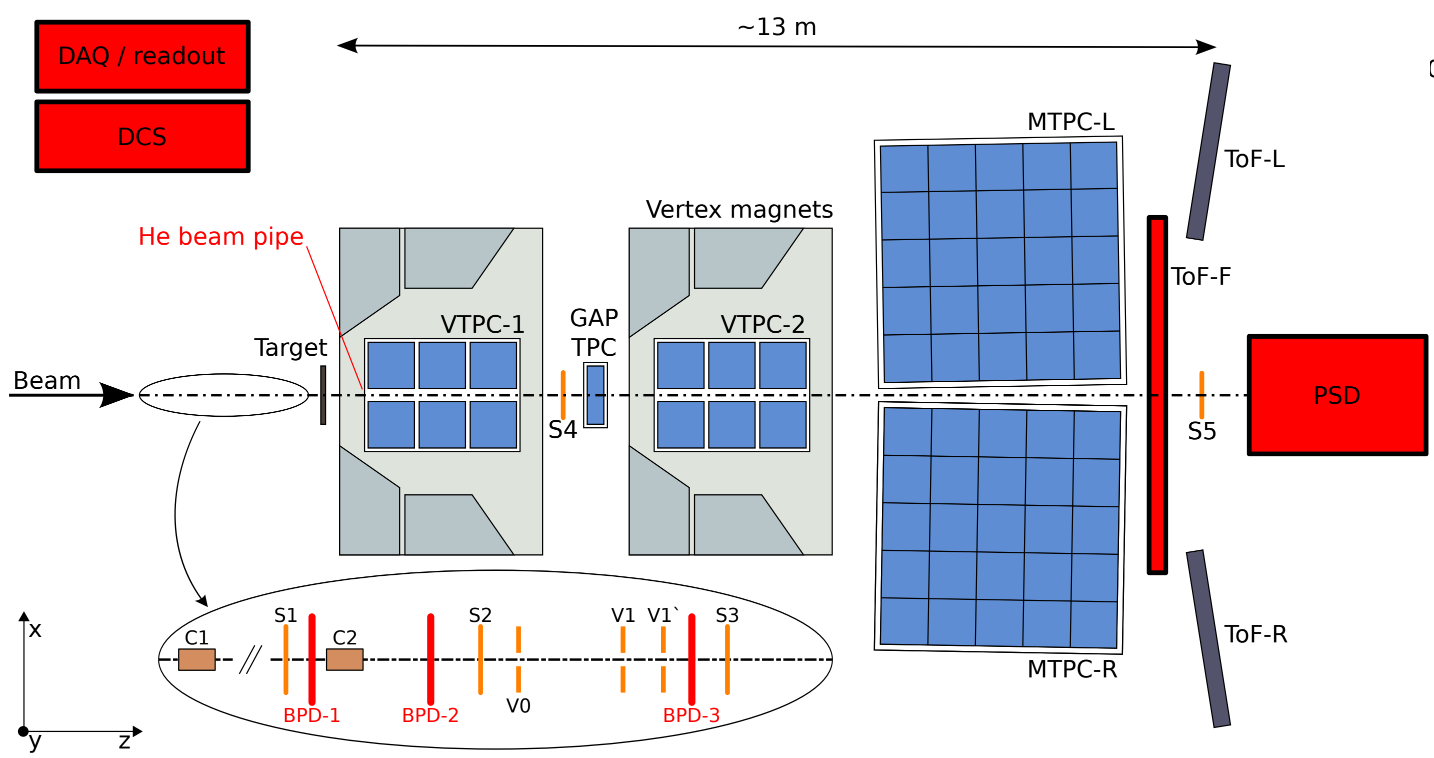
(Maris et al. ICRC 2009)

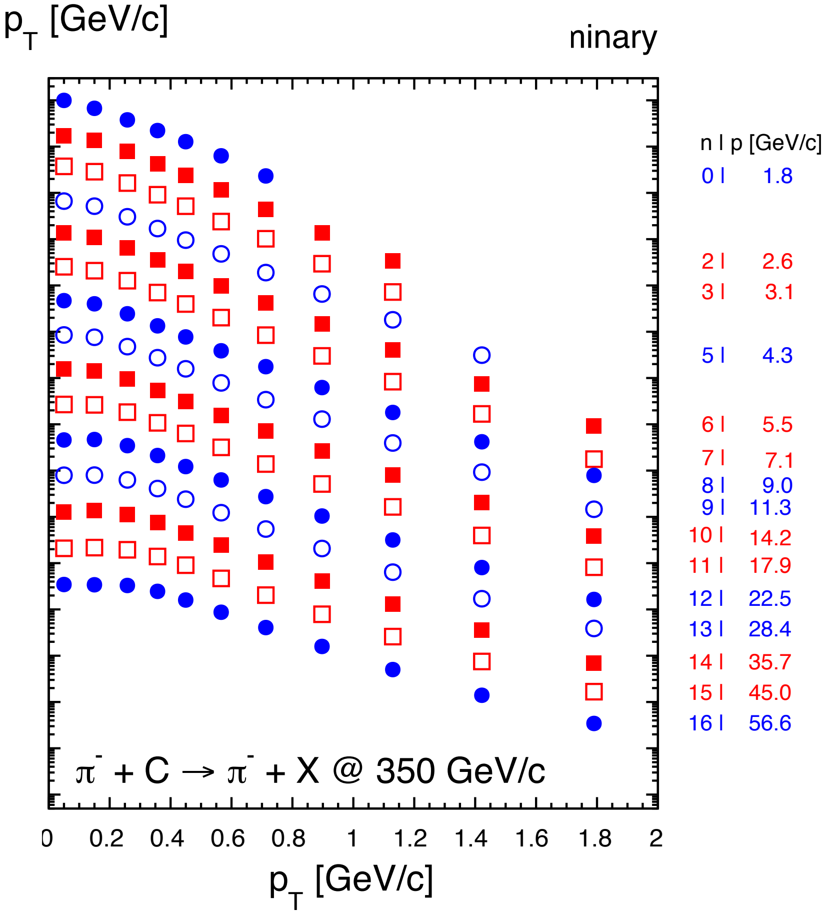
NA61 fixed-target experiment at CERN SPS

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

Analyzed by Auger members



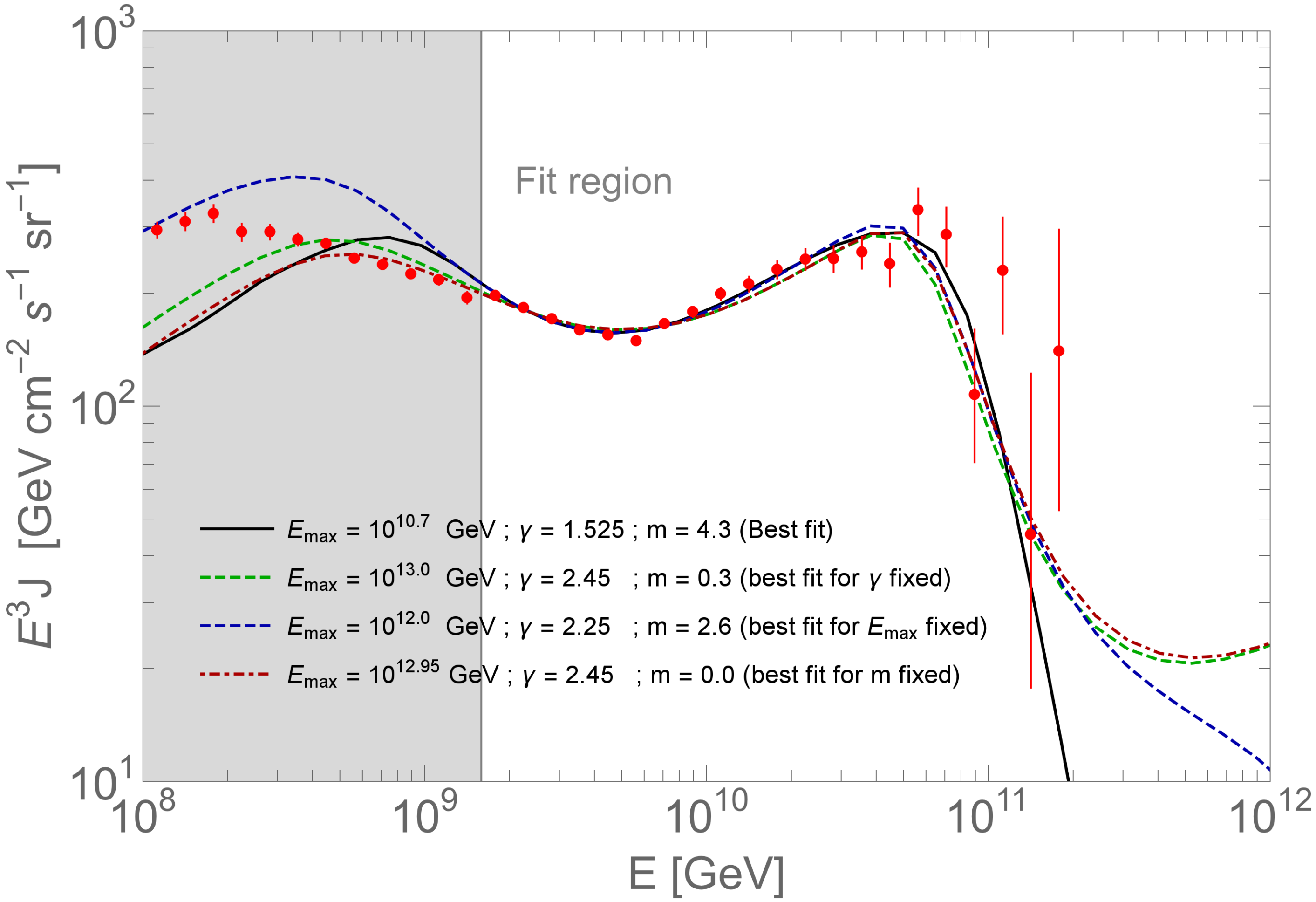




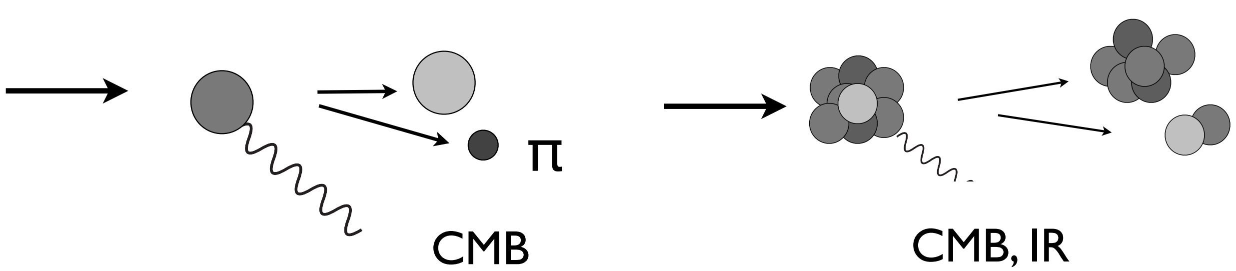
(NA61, Hervé ICRC 2015, Unger CRIS 2015)

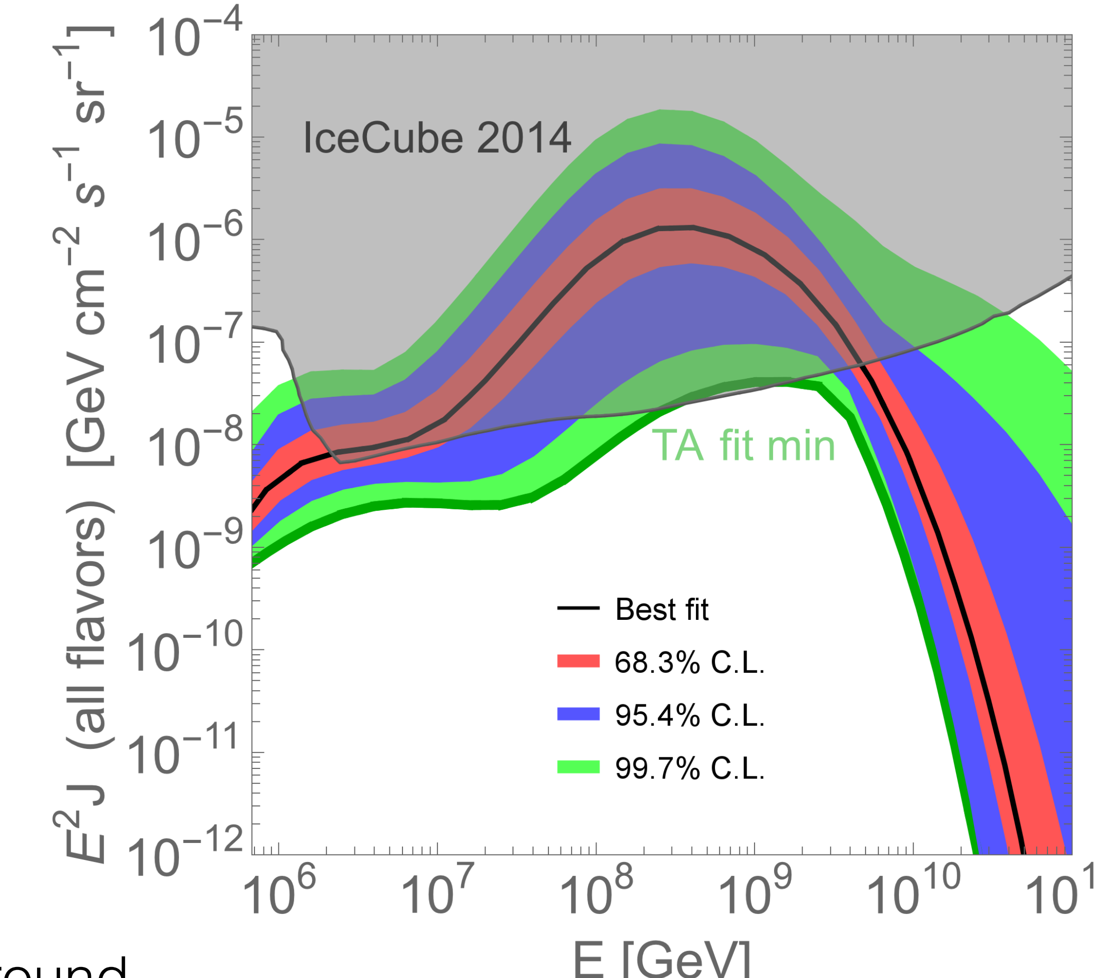
Example of emerging multi-messenger constraints

(Heinze et al. 1512.05988)



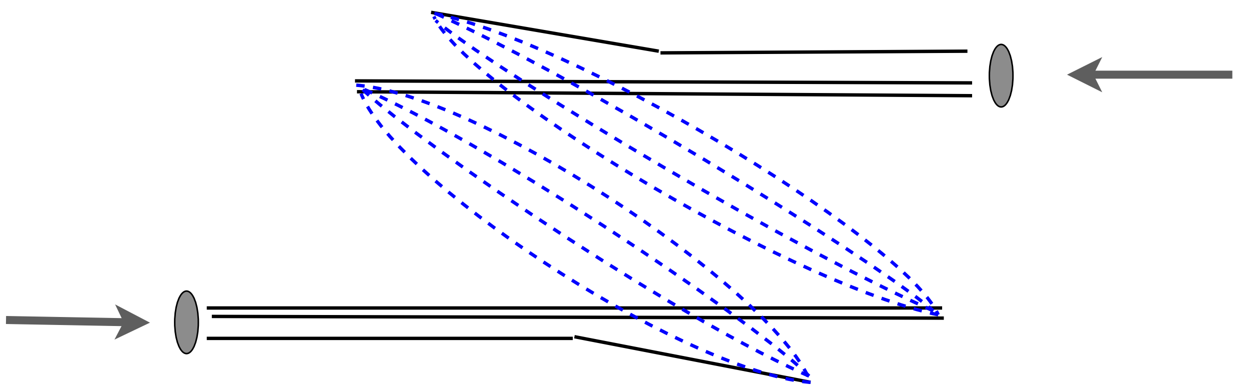
Hypothesis:
flux only protons,
fit to TA spectrum,
GZK neutrinos





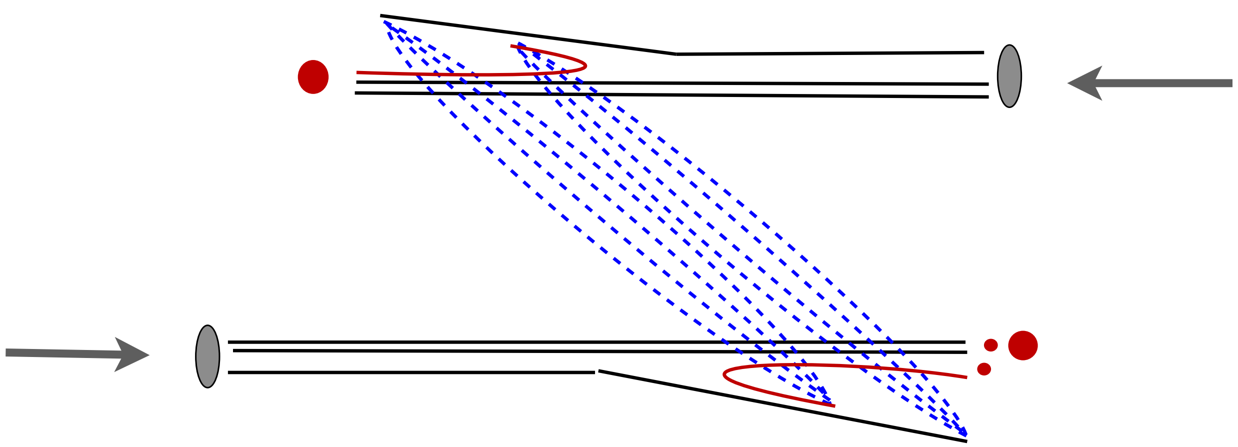
Similar considerations also for diffuse gamma ray background
(Ahlers et al., Taylor et al.)

Different implementations



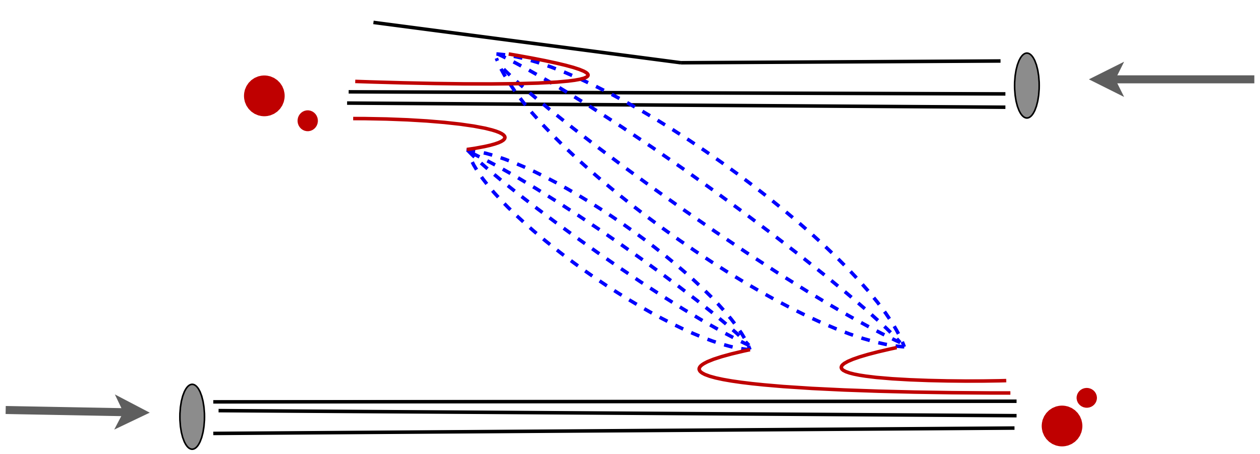
SIBYLL:

strings connected to valence quarks;
first fragmentation step with harder fragmentation function



QGSJET:

fixed probability of strings connected to valence quarks or sea quarks;
explicit construction of remnant hadron



EPOS:

strings always connected to sea quarks;
bags of sea and valence quarks fragmented statistically