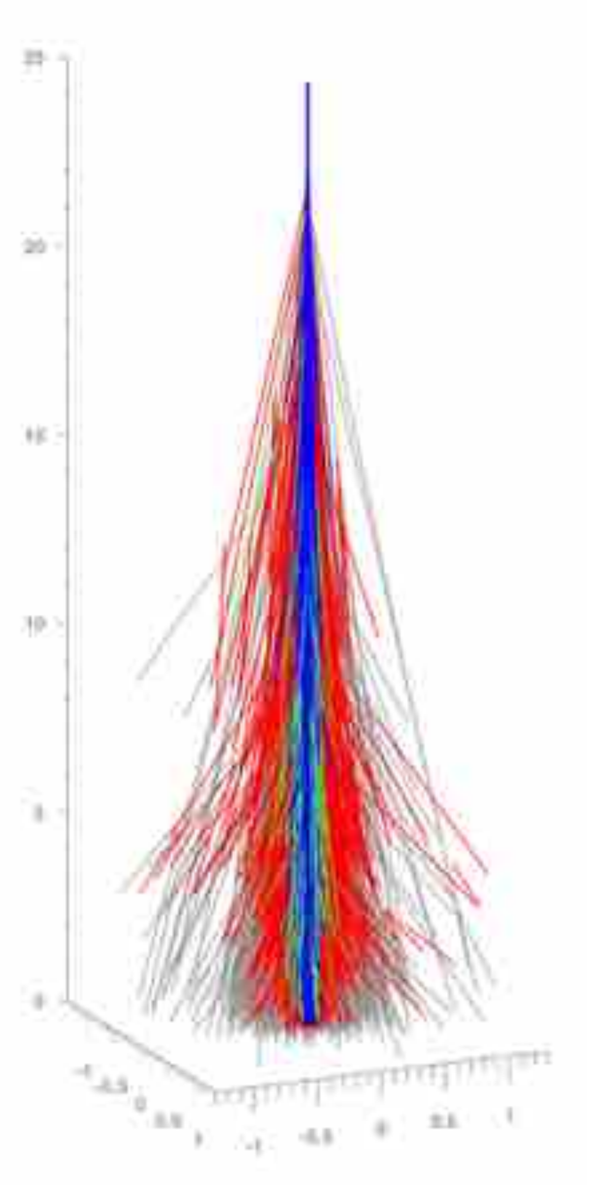
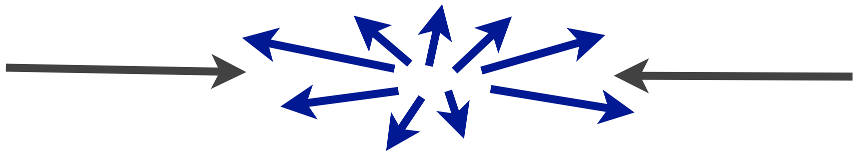
Hadronic Interactions and Cosmic Ray Physics



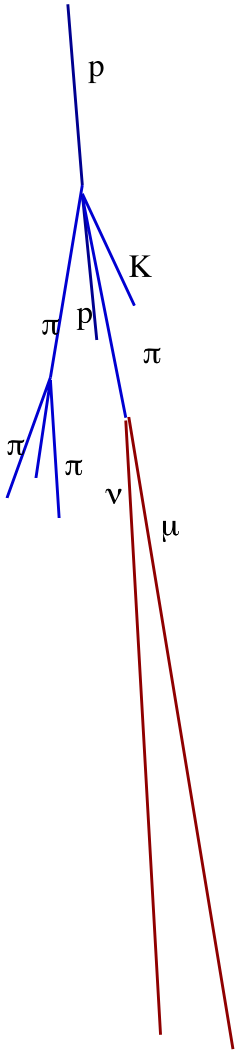
Ralph Engel

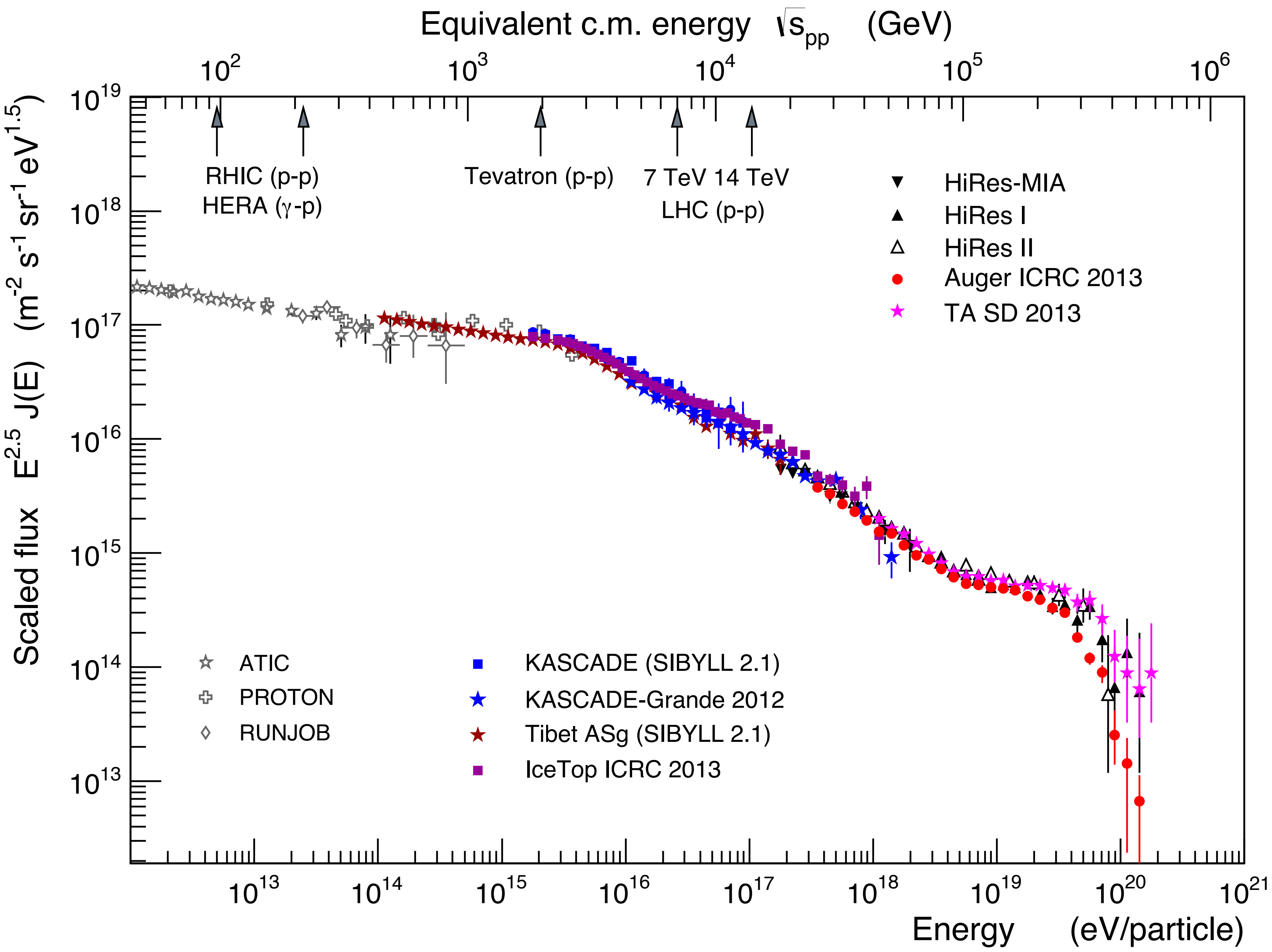
Karlsruhe Institute of Technology (KIT)

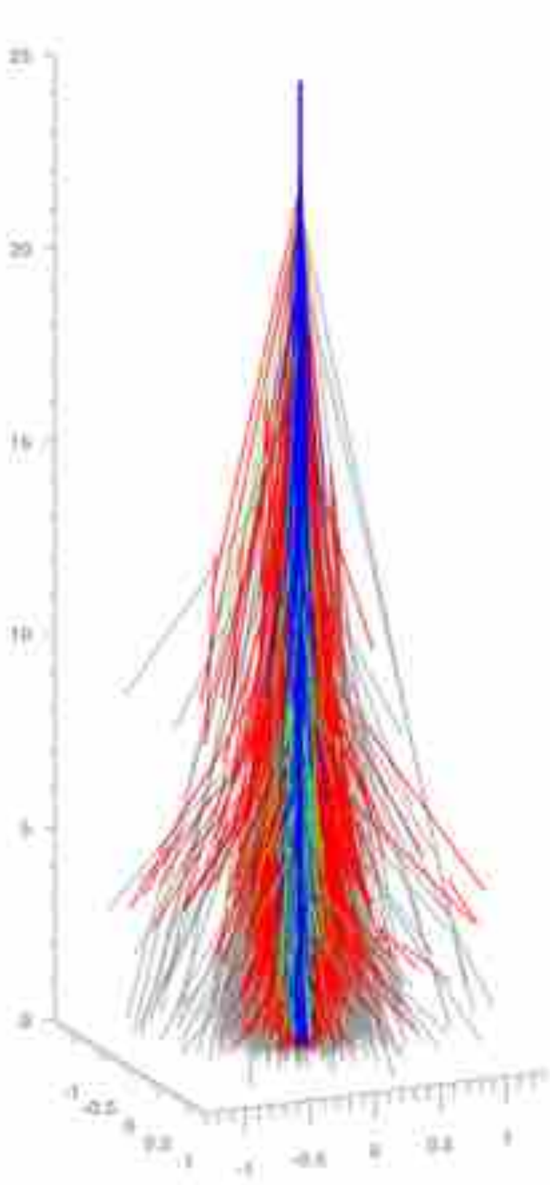
Cosmic ray flux and interaction energies

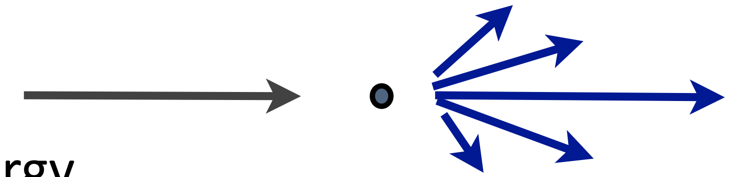


Center-of-mass energy





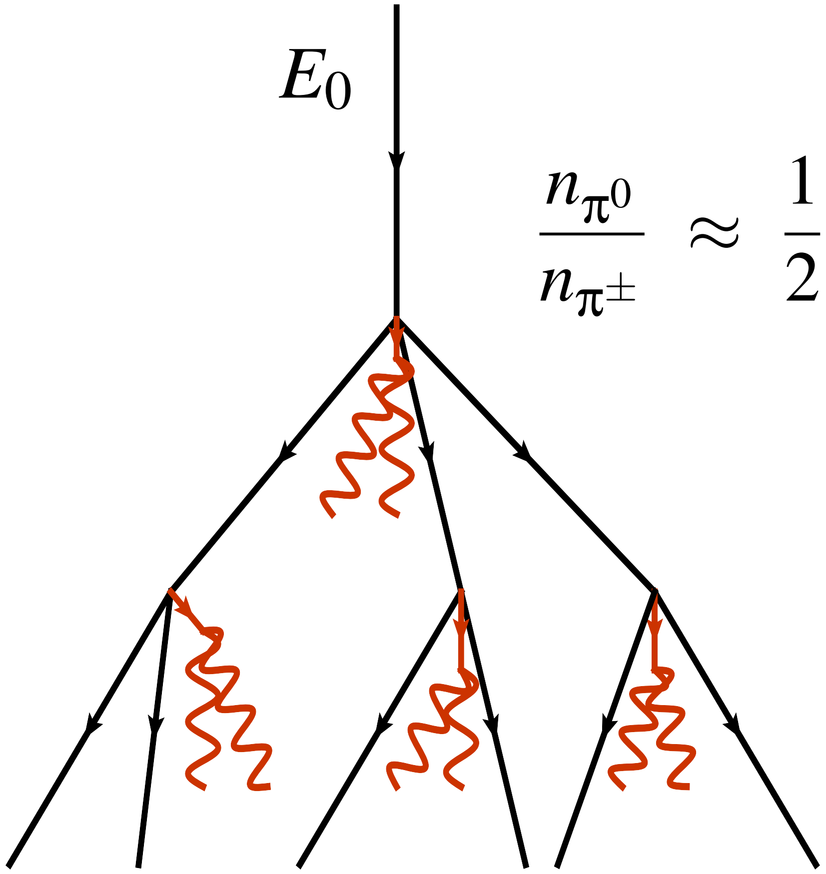




Laboratory energy

High-energy interactions

Shower physics: energy transfer



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

Hadronic energy

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

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

⋮

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

Decay after n generations

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

$$\boxed{\begin{aligned} n = 5,\ \ E_{\text{had}} &\sim 12\% \\ n = 6,\ \ E_{\text{had}} &\sim 8\% \end{aligned}}$$

Electromagnetic energy

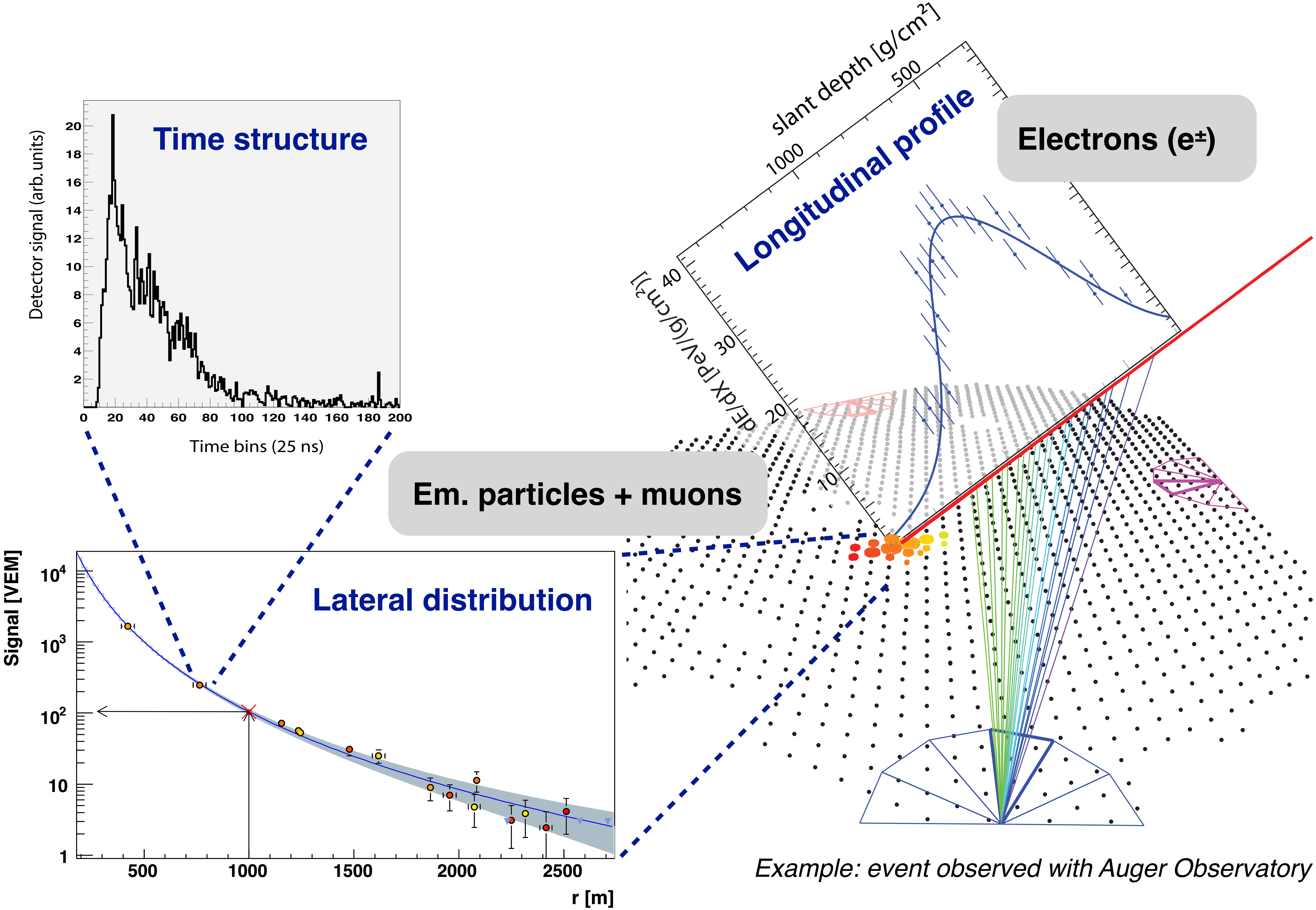
$$\frac{1}{3}E_0$$

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

⋮

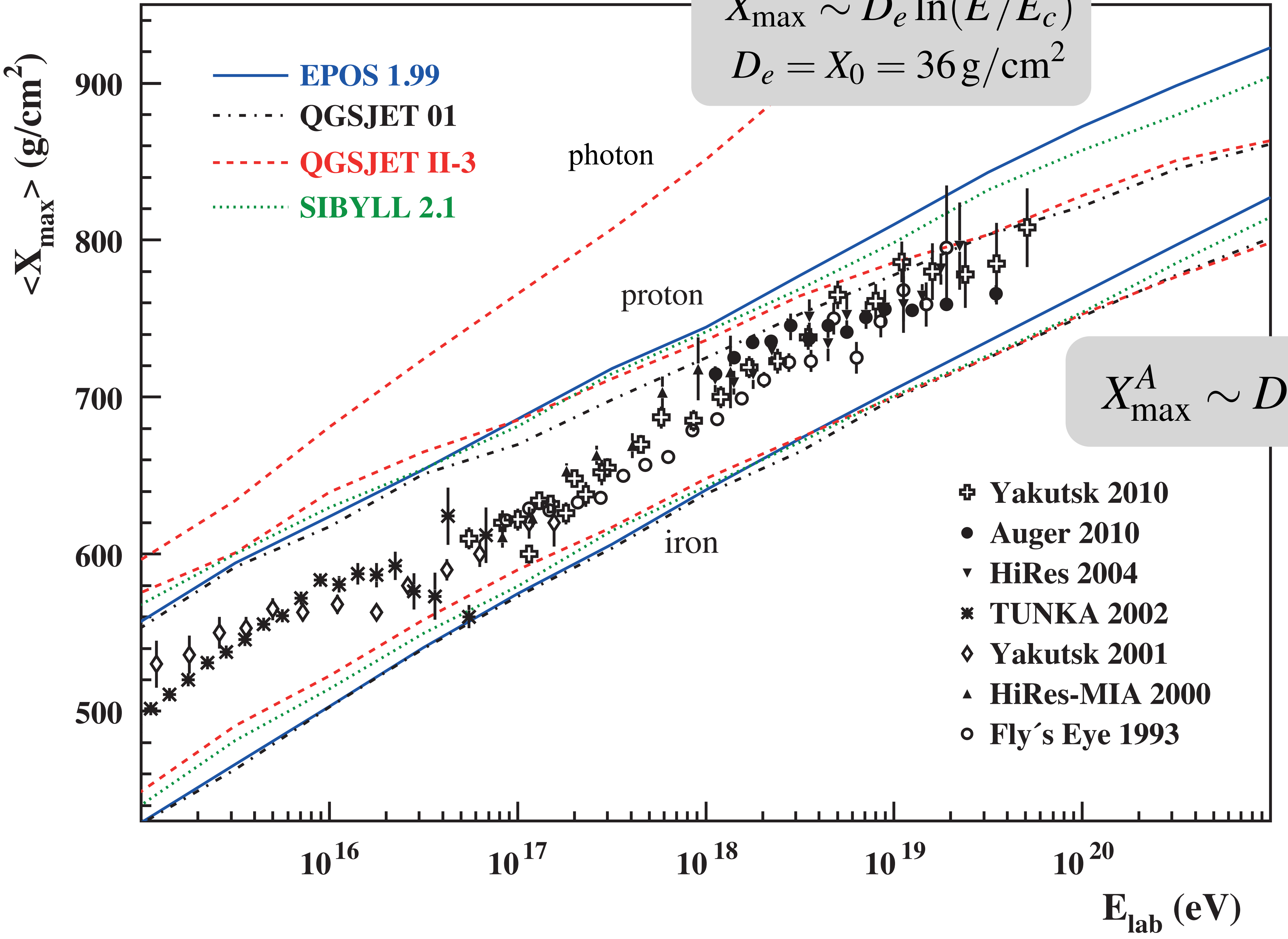
$$\boxed{E_{\text{em}} = \left[1 - \left(\frac{2}{3}\right)^n\right] E_0}$$

Measurement of different shower observables



Example: event observed with Auger Observatory

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 rates and model features

Elongation rate theorem

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

(Linsley, Watson PRL46, 1981)

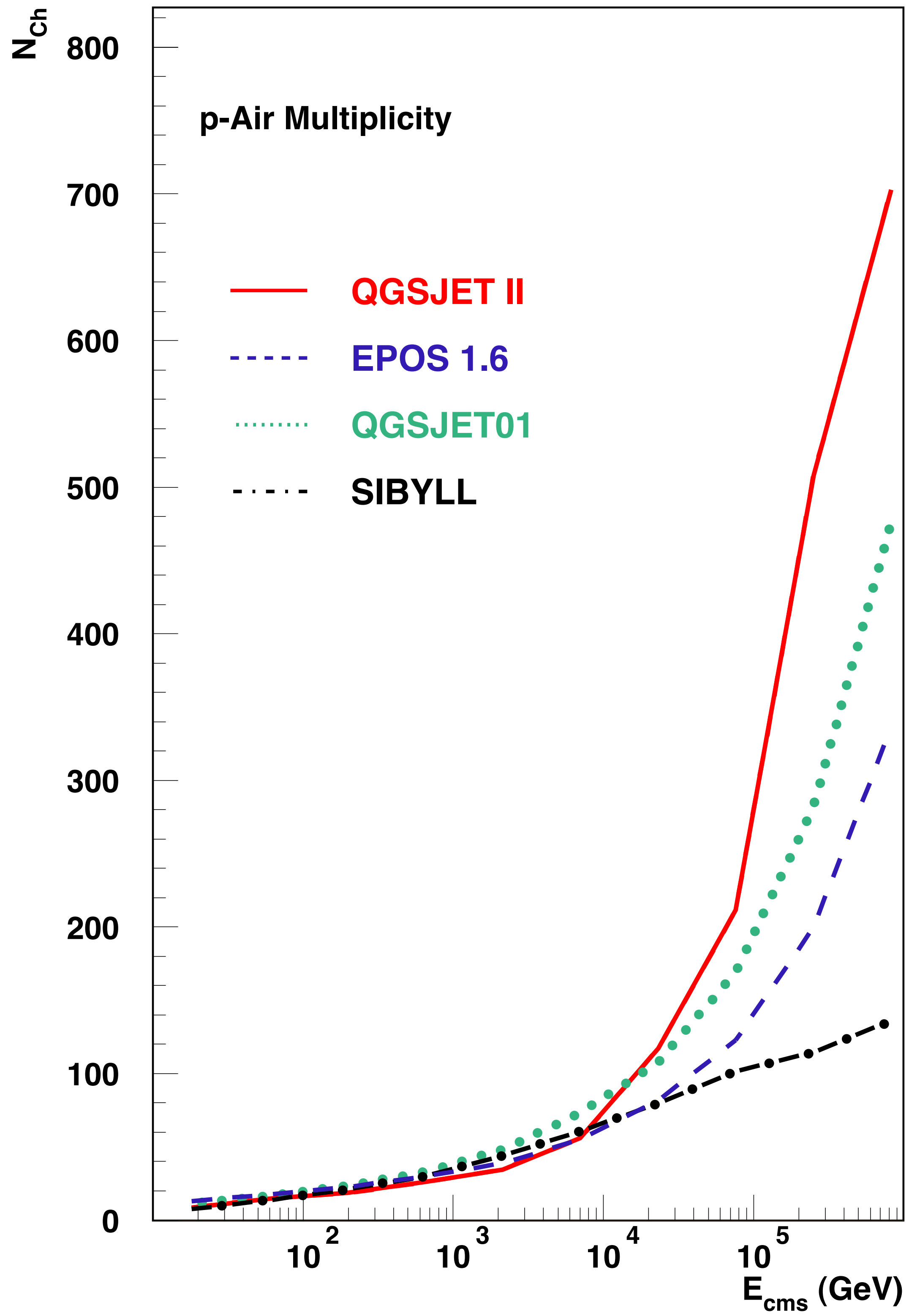
factor ~ 36 g/cm^2

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

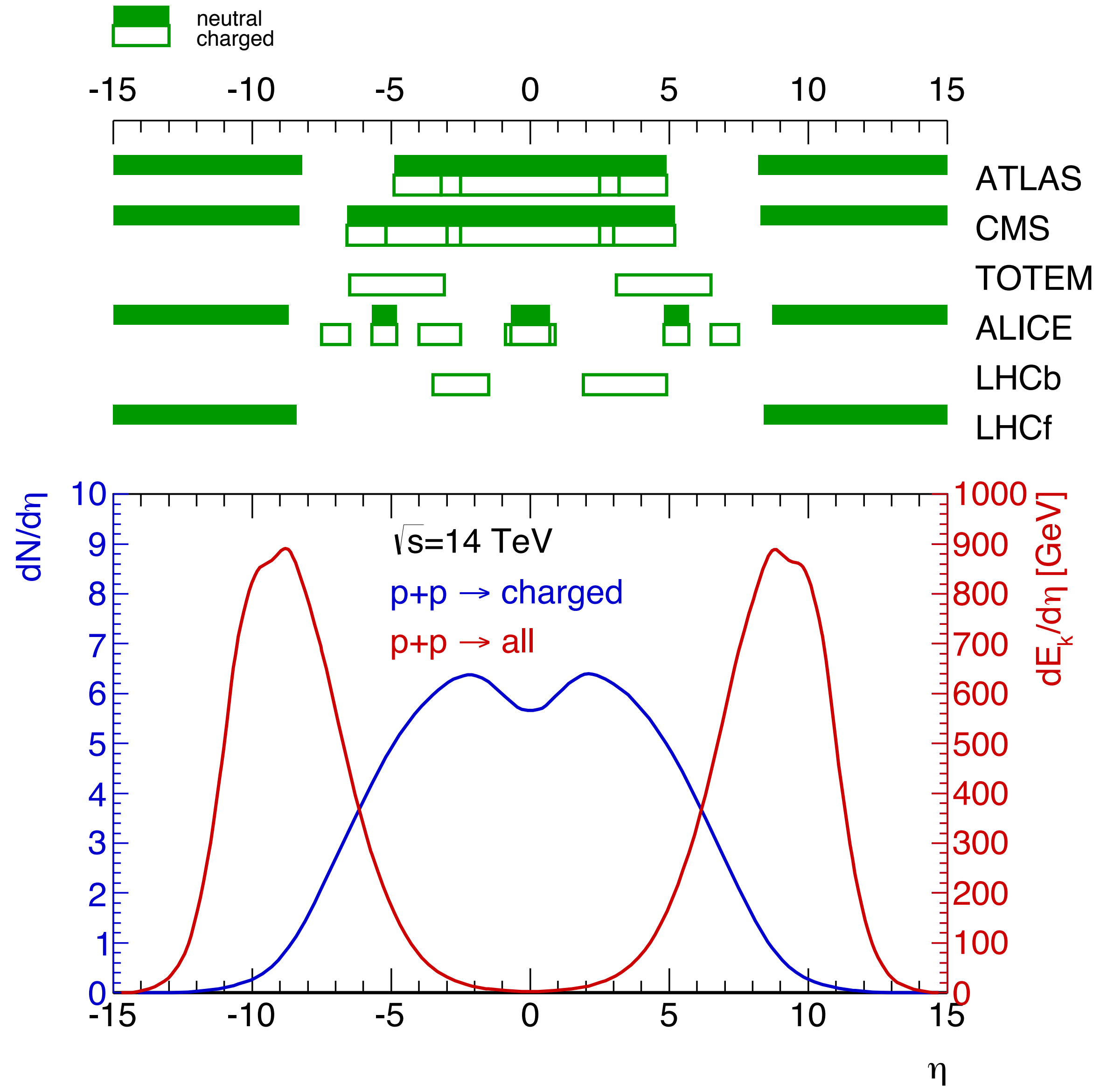
Large if multiplicity of high energy particles rises very fast, **zero in case of scaling**

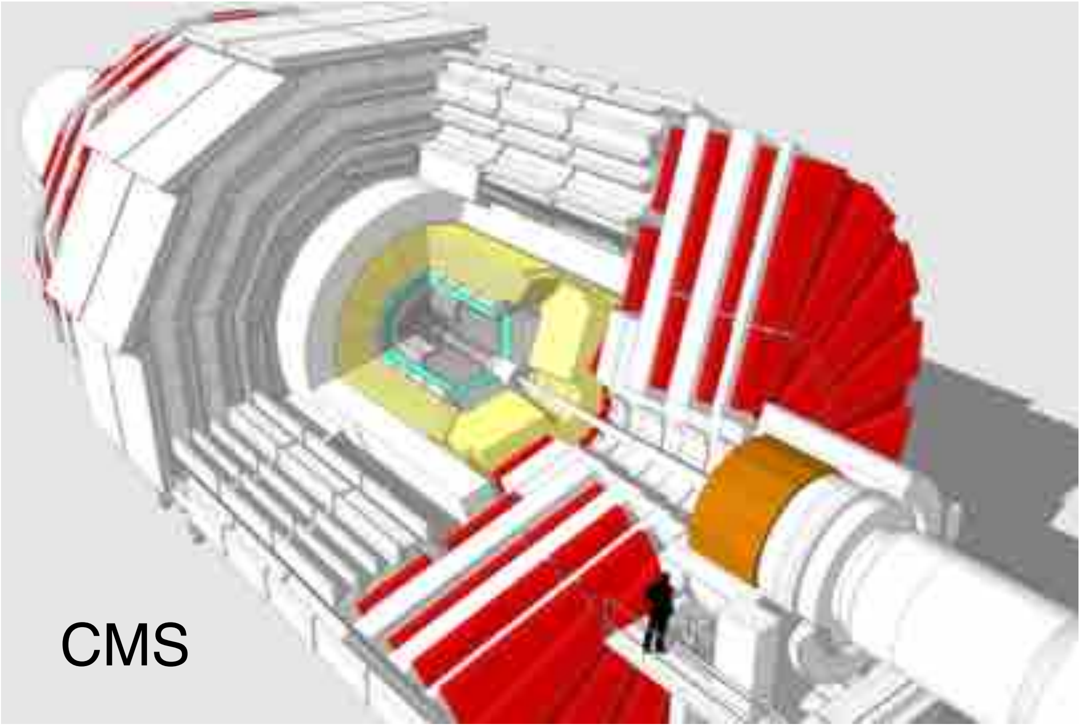
$$B_\lambda = -\frac{1}{X_0} \frac{d\lambda_{\mathrm{int}}}{d \ln E}$$

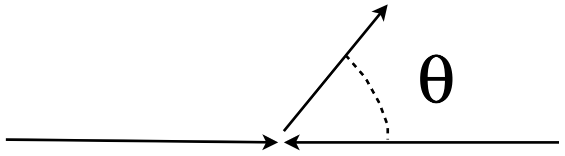
Large if cross section rises rapidly with energy



LHC experiments: phase space coverage





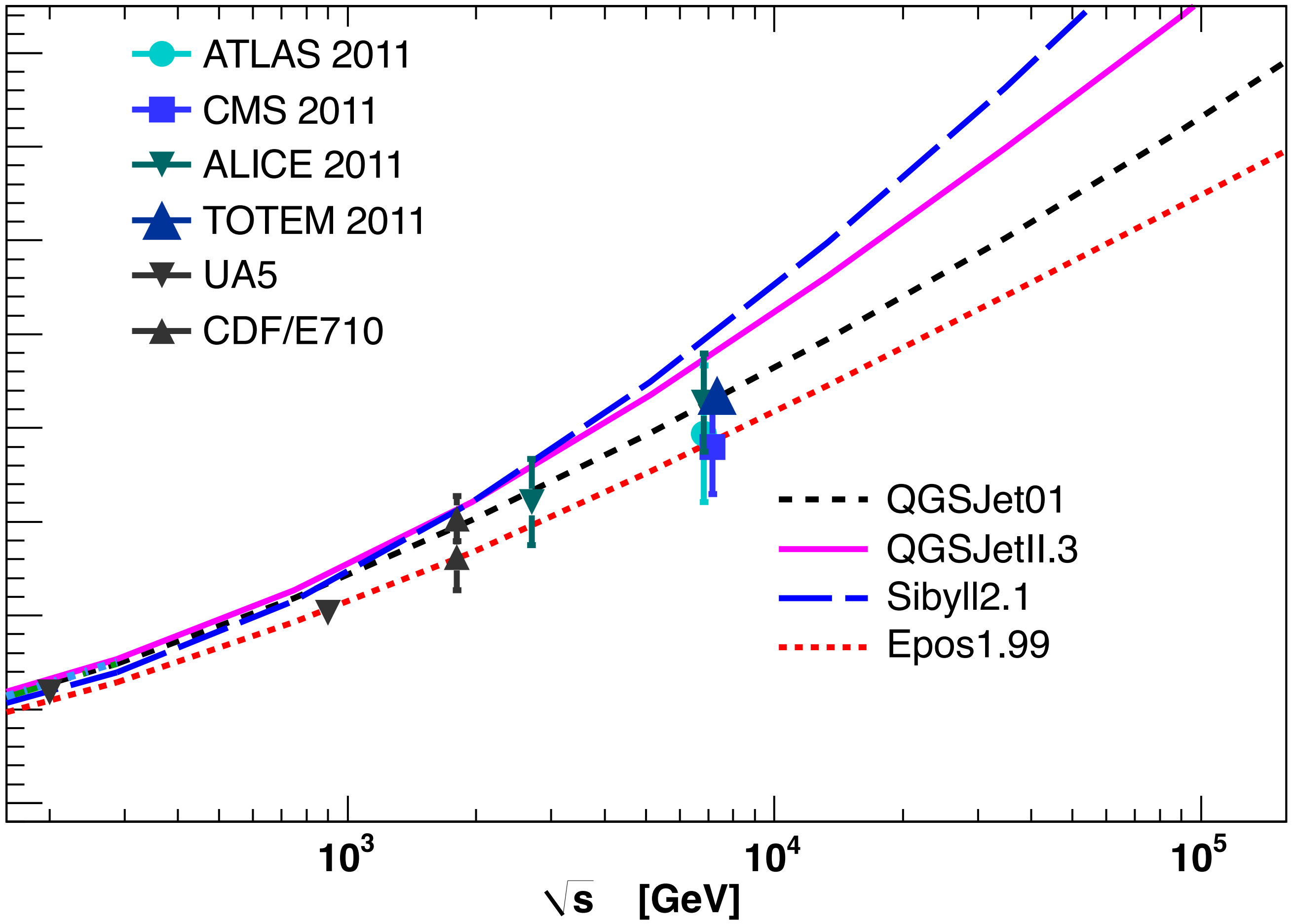


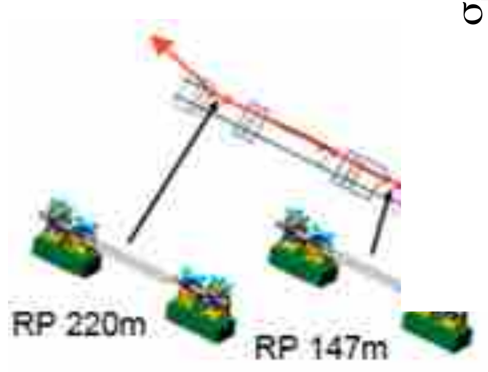
$$\eta = -\ln\tan\frac{\theta}{2}$$

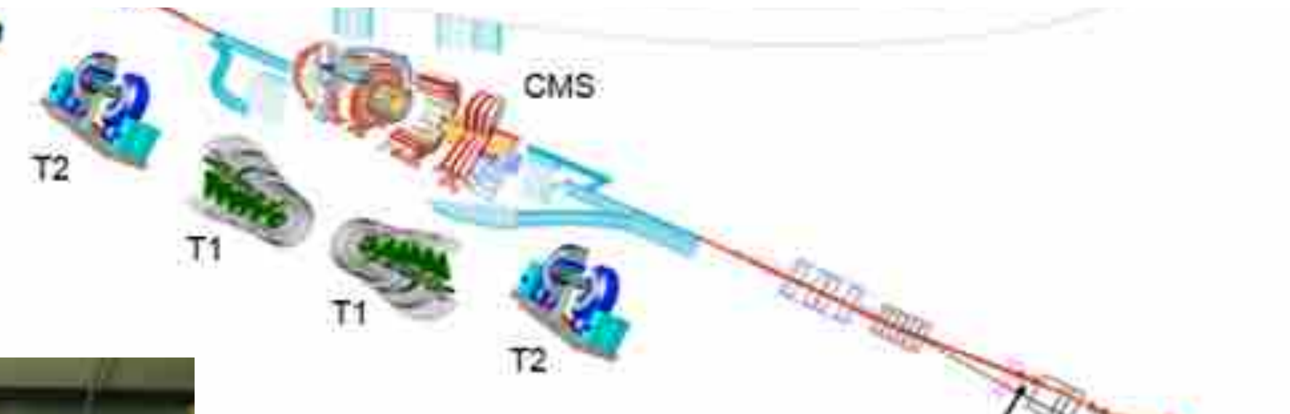
η	deg.	mrad.
3	5.7	97
5	0.77	10
8	0.04	0.7
10	0,005	0,009

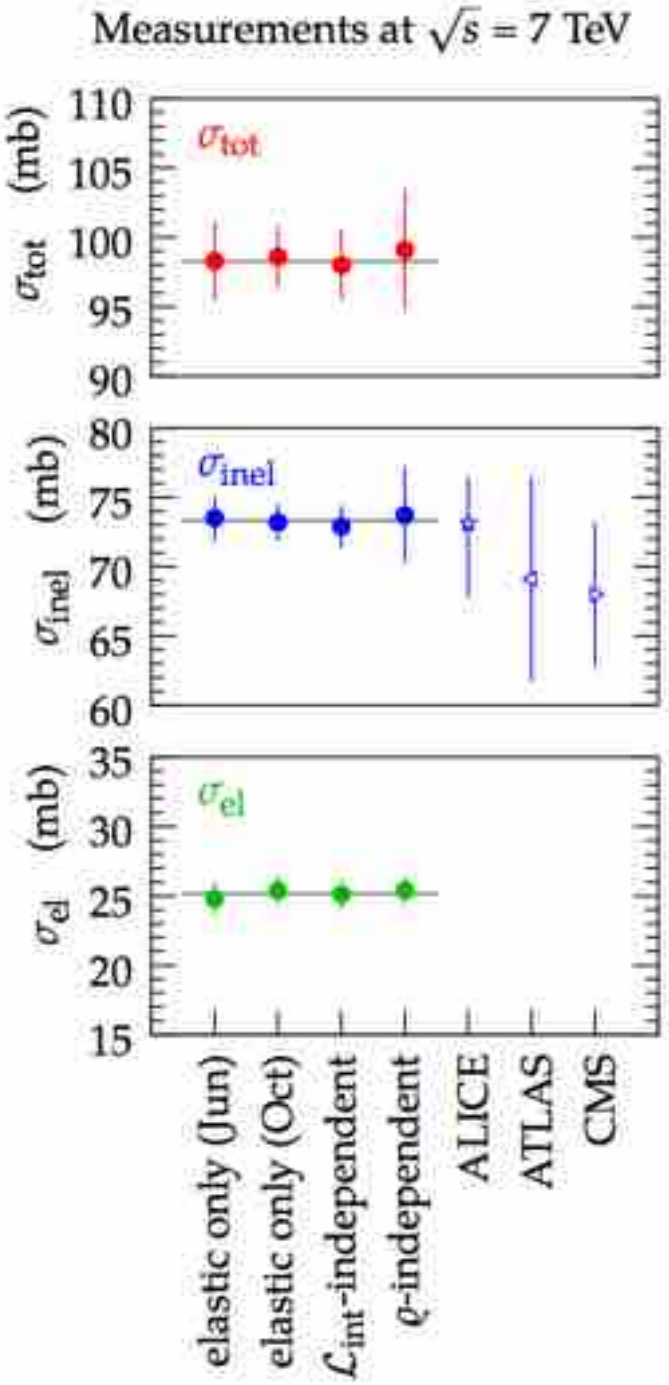
(Salek et al., 2014)

LHC: proton-proton cross section





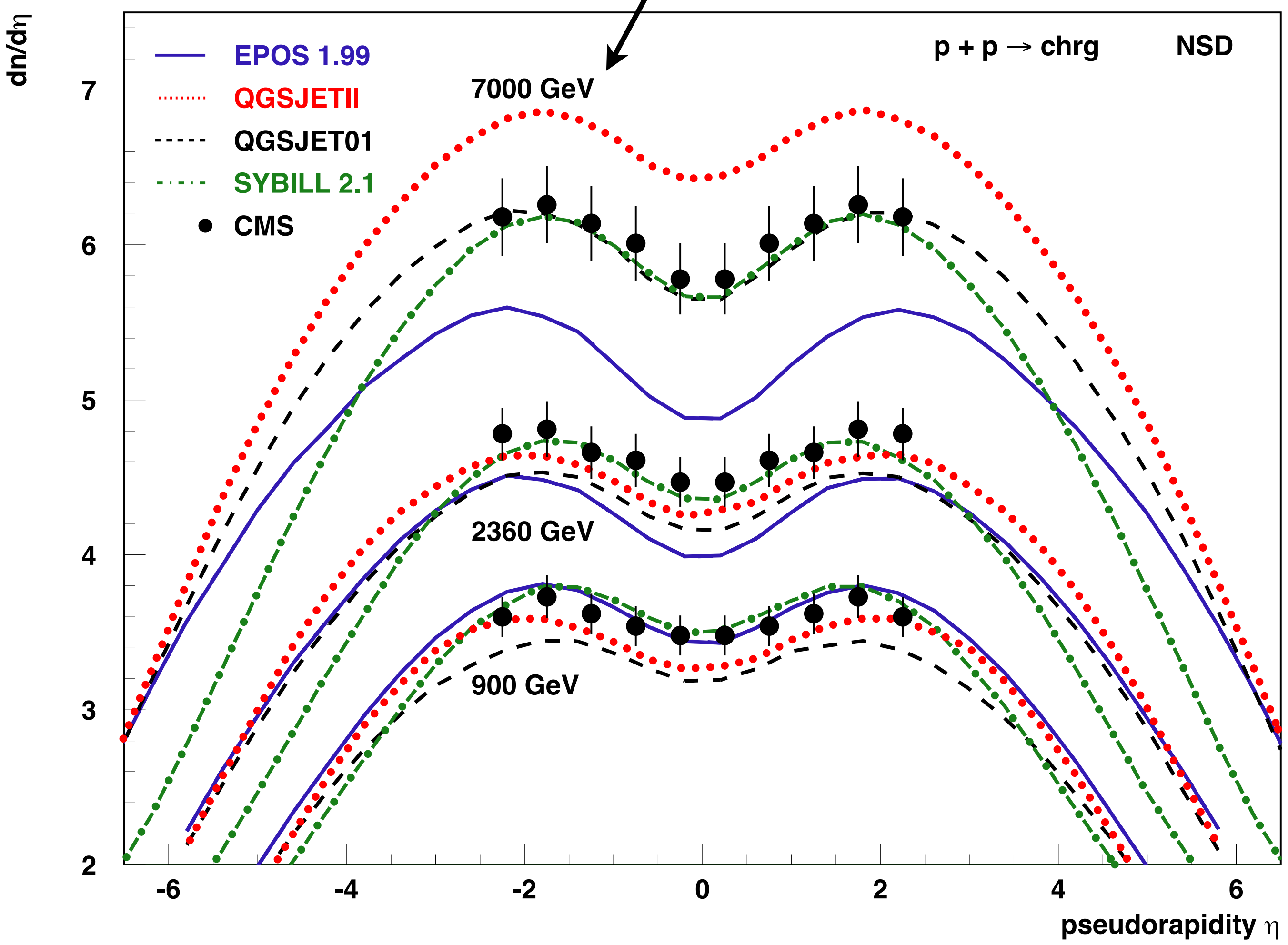




(Cafagna, ICRC 2015)

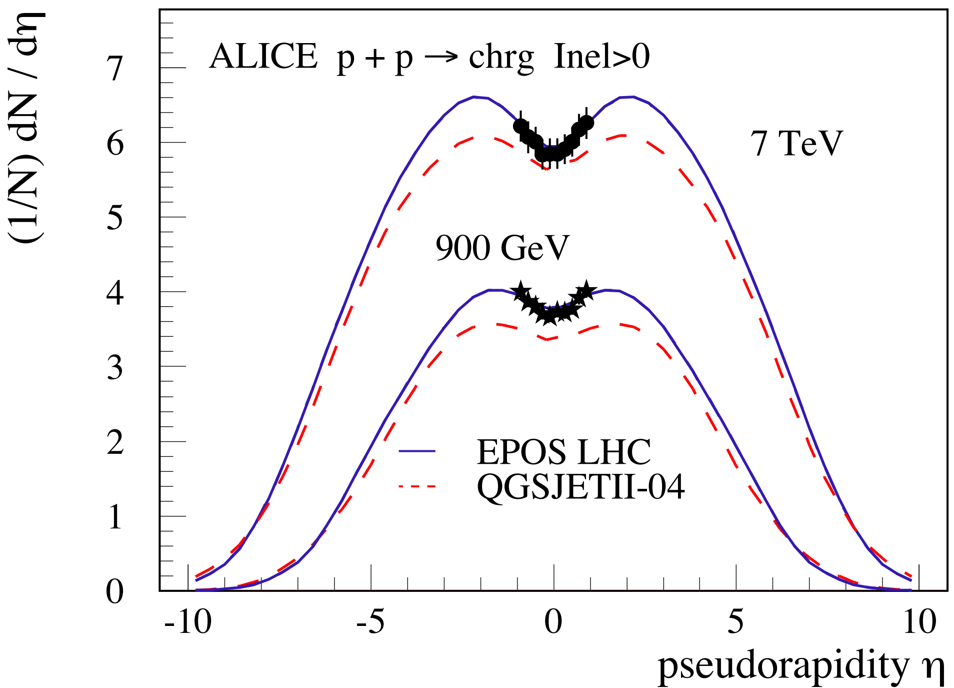
Charged particle distribution in pseudorapidity

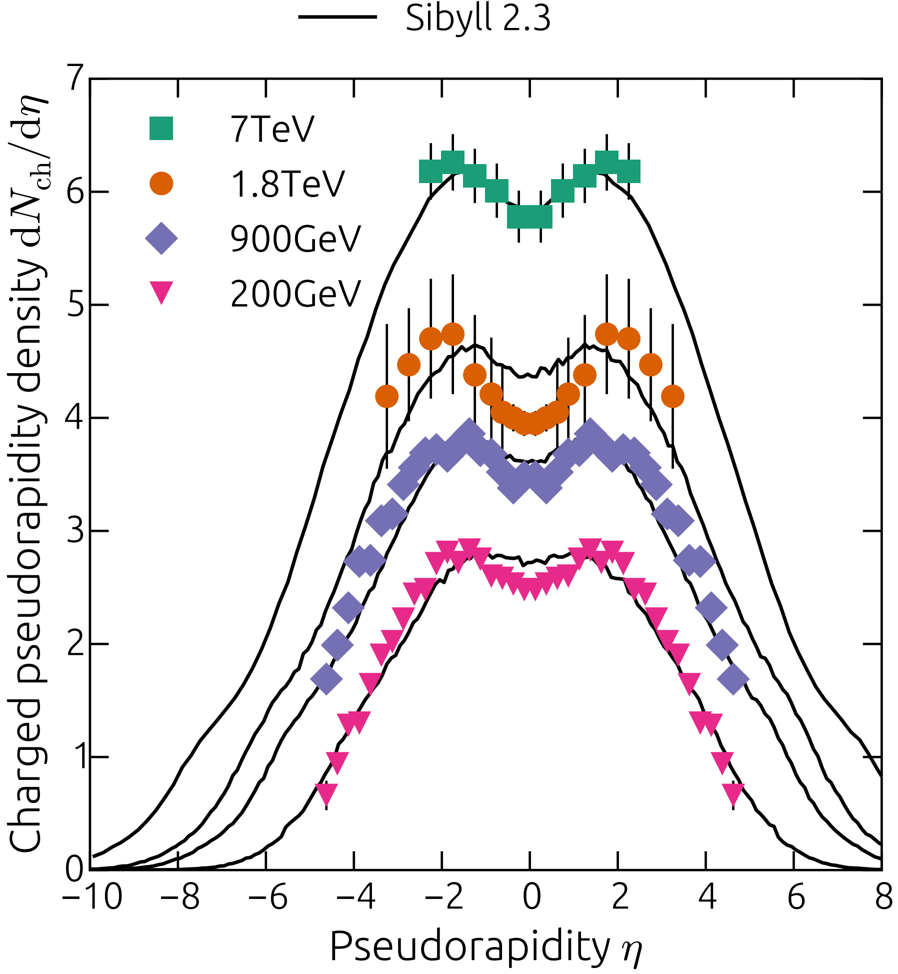
Protons: E_{lab} = 3 x 10^{16} eV



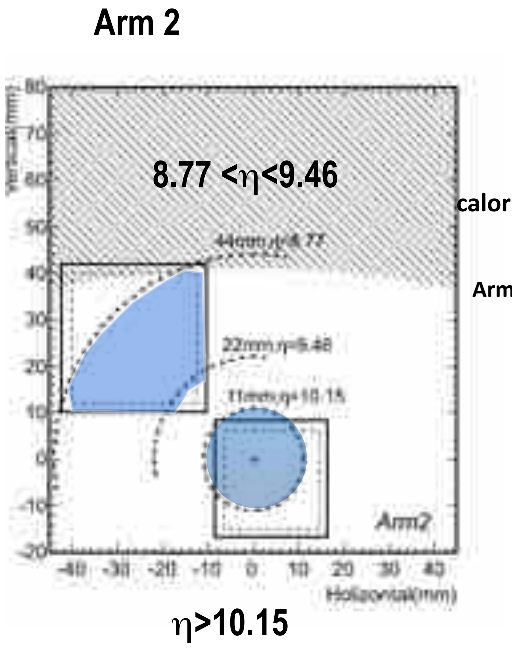
(data exist from all LHC experiments)

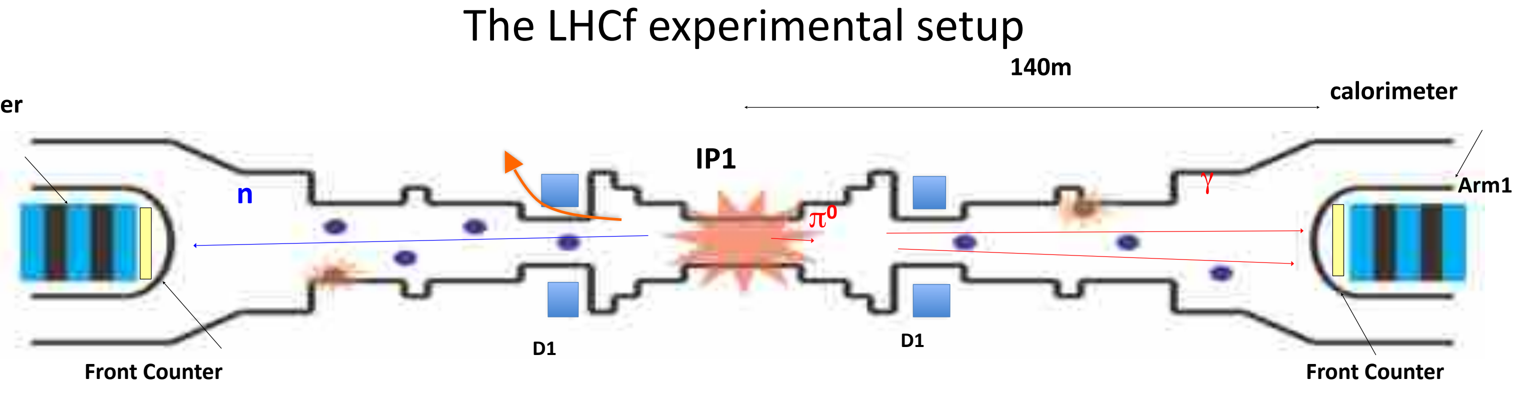
Feb. 2016: tuned version of Sibyll (v2.3)

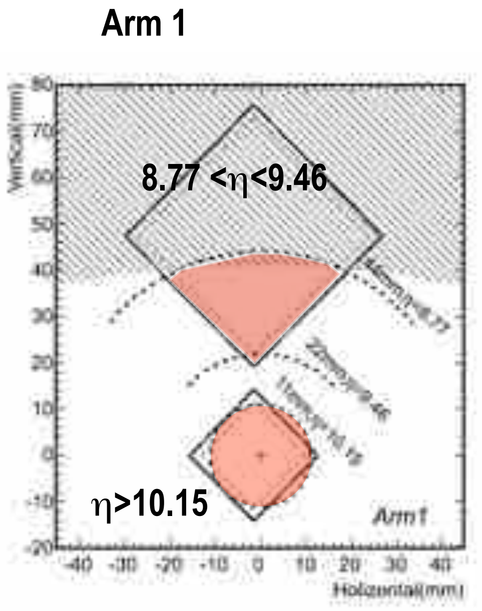




LHCf: very forward photon production

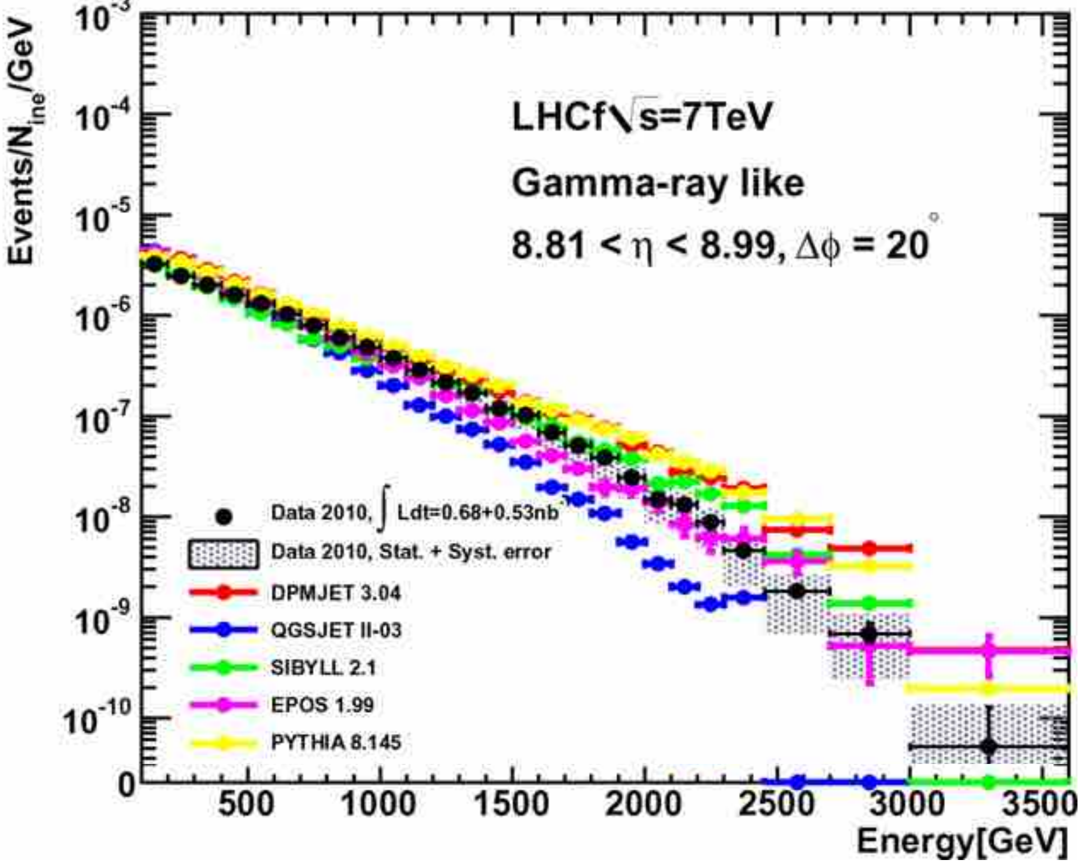



The LHCf experimental setup

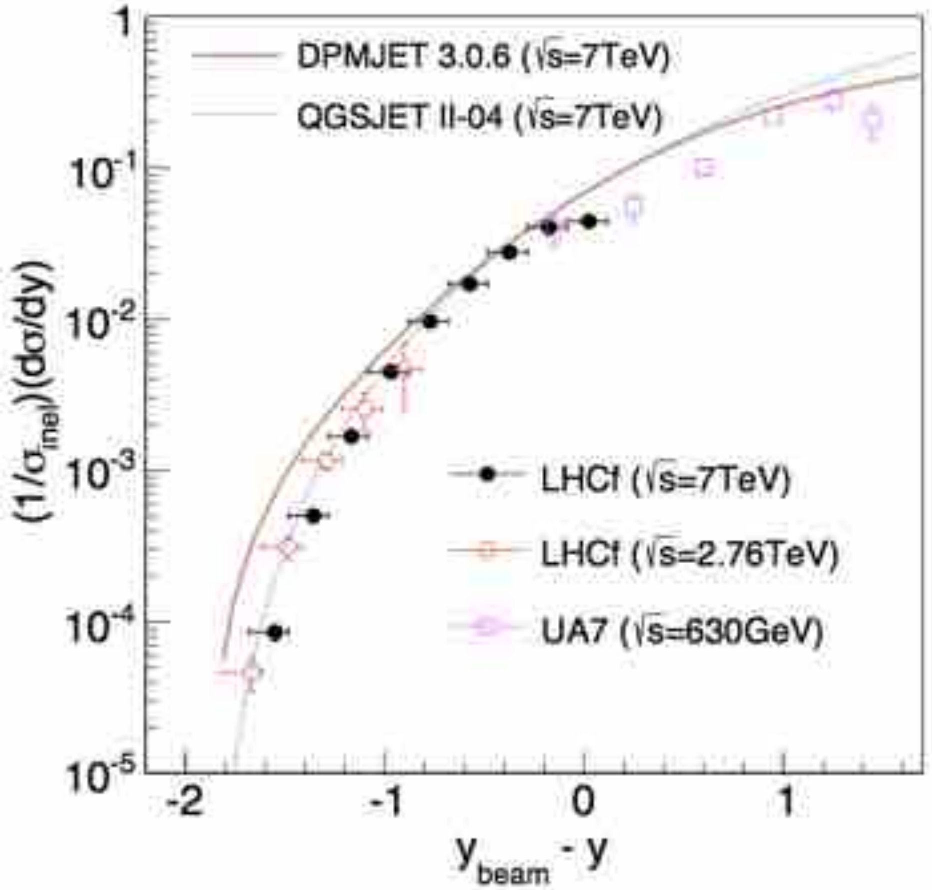


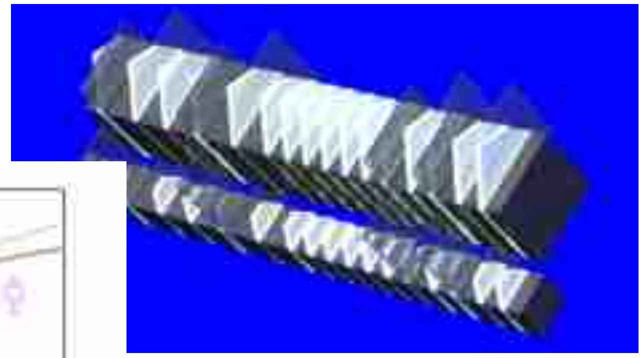
$$pp \to \gamma X$$

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



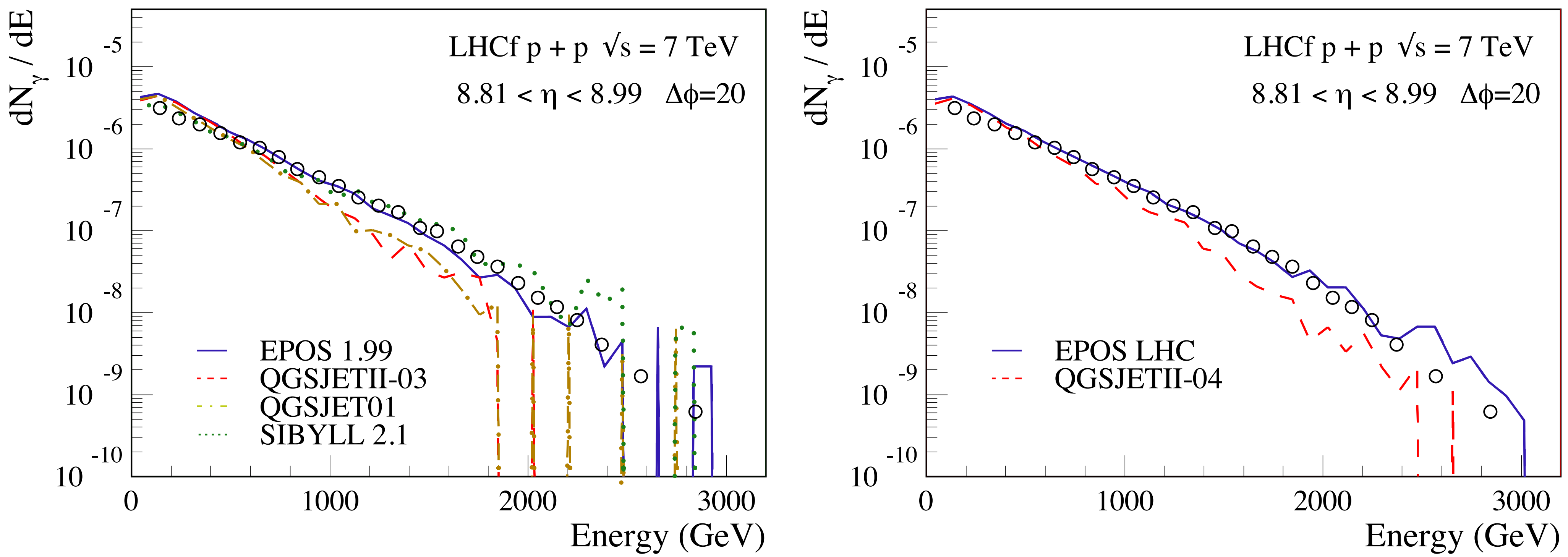
(LHCf, 1507.08764)



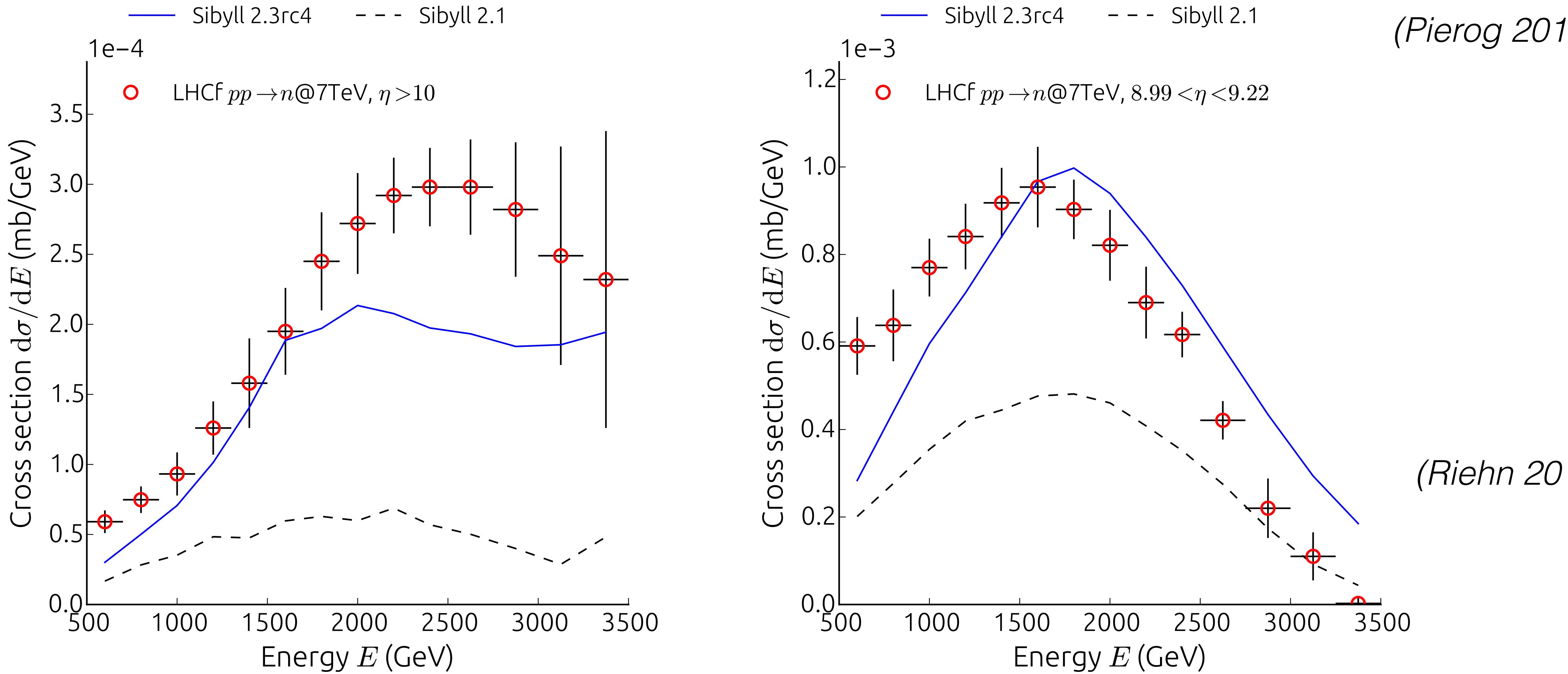


(Itow, ICRC 2015)

Tuning of interaction models to LHC data



(Pierog 2014)

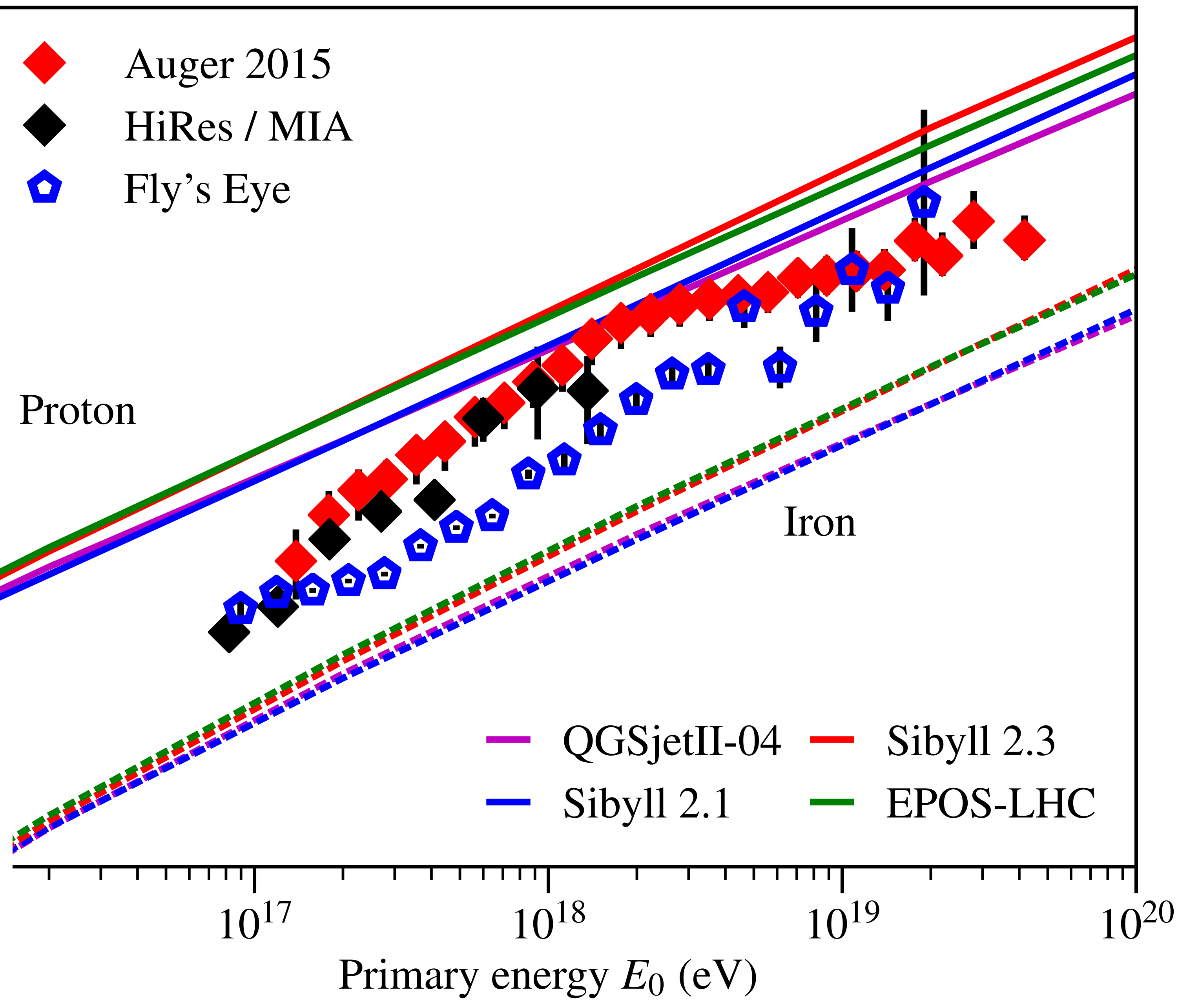


(Riehn 2015)

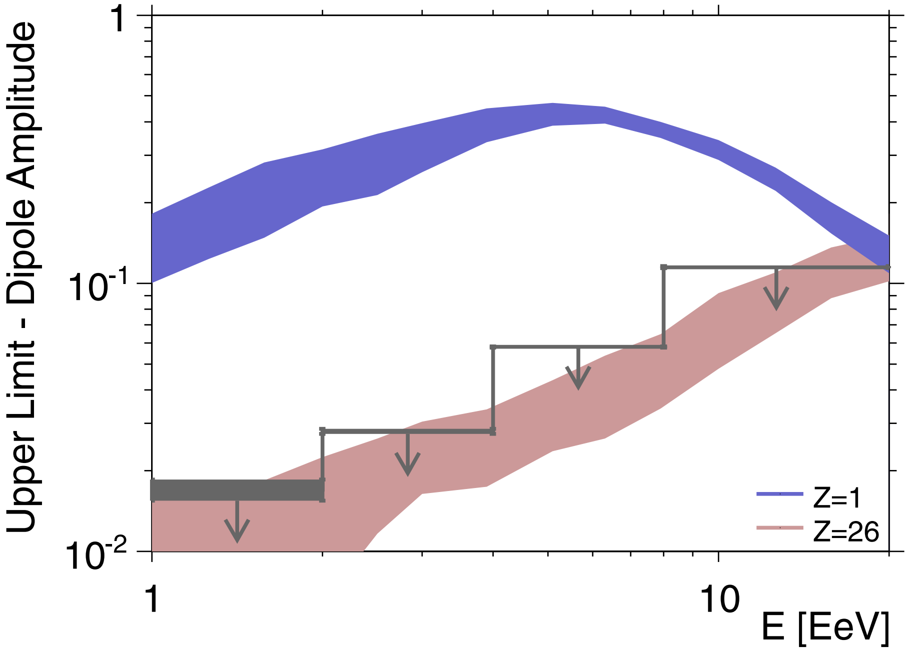
Current status: mean depth of shower maximum

(Data of TA not
shown in this plot)

(Riehn 2016)



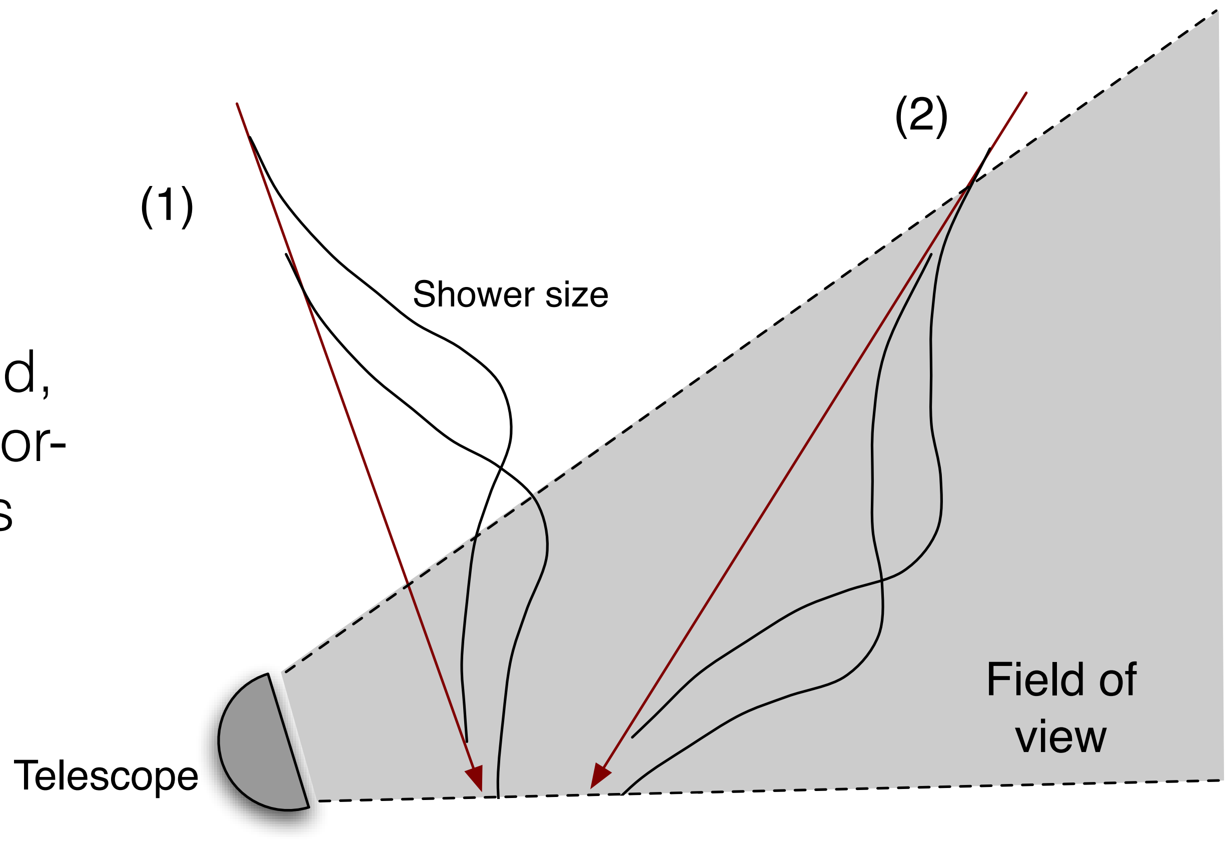
(Auger, ApJ 203, 2012)



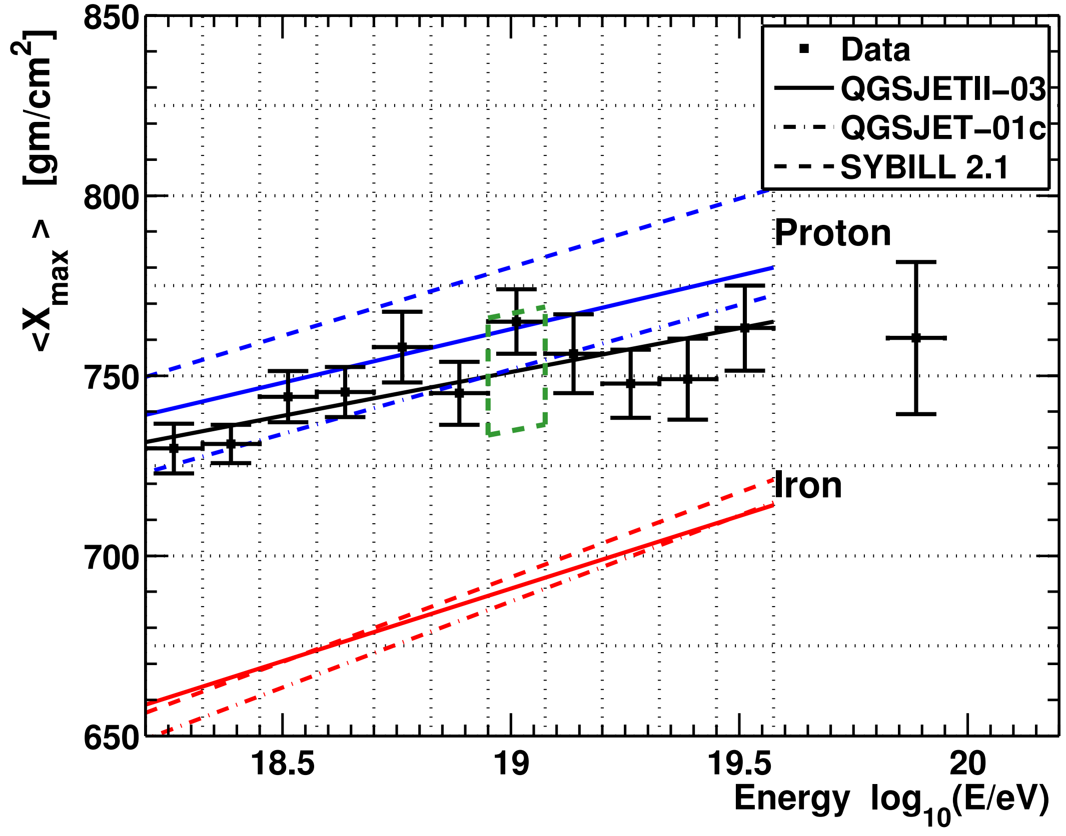
Change of model predictions well understood

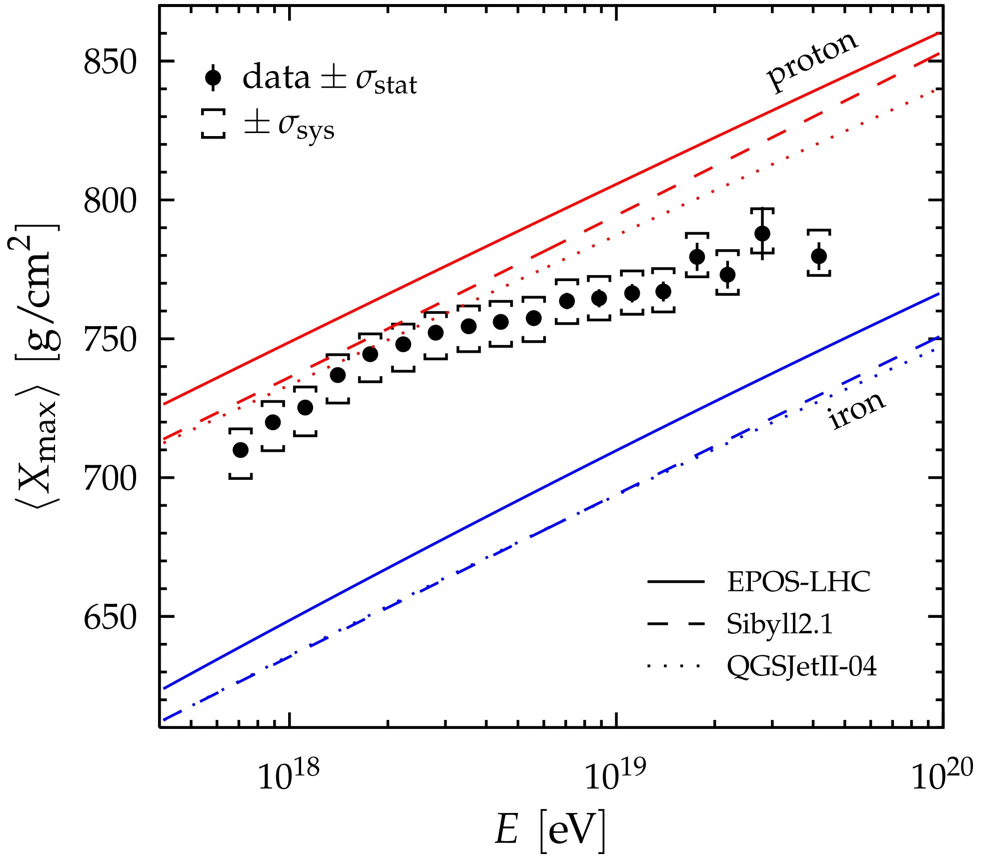
Auger and TA data cannot be shown in one plot

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



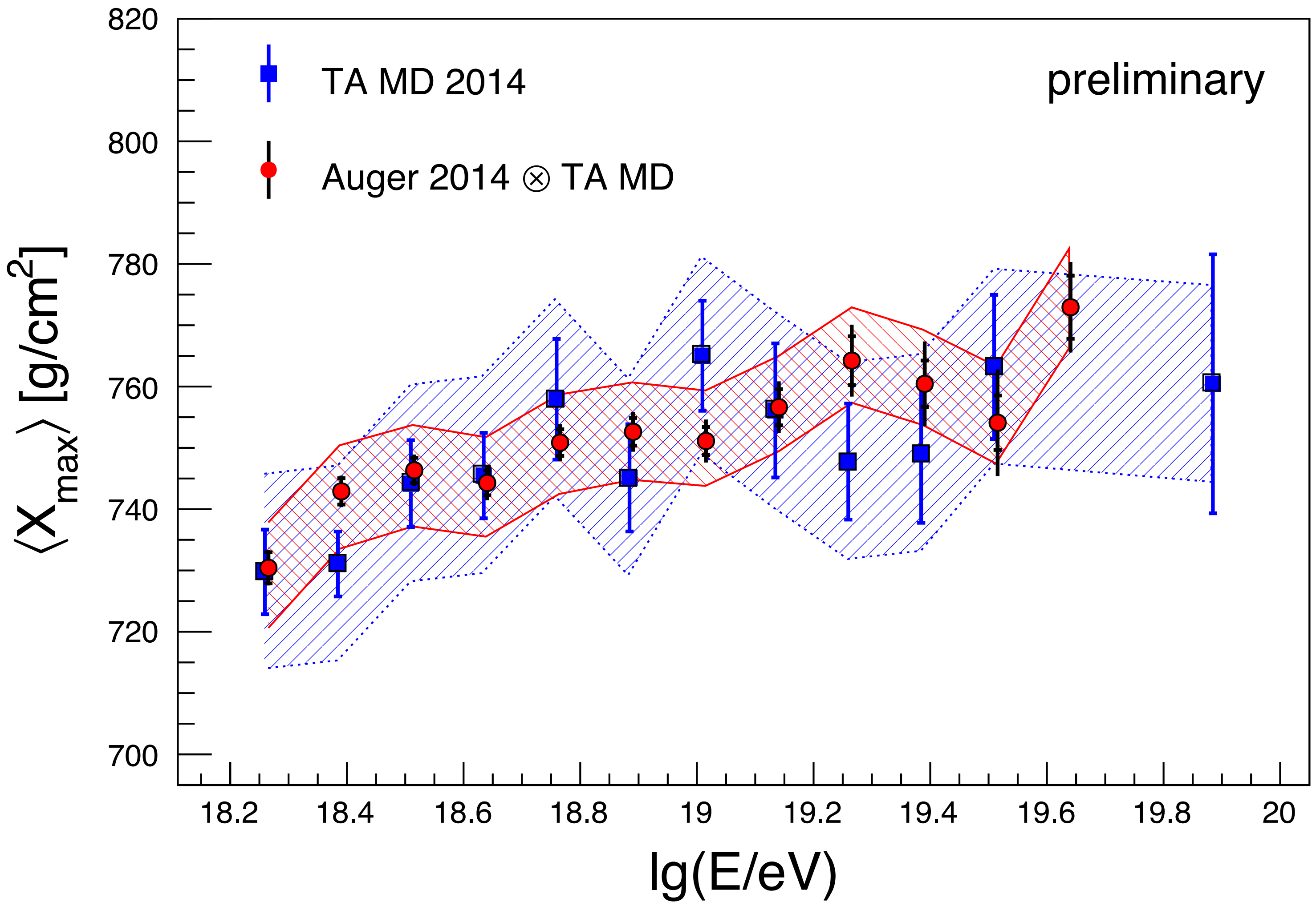
Auger: only analysis of showers for which all relevant X_{max} are observable, comparison with theoretical X_{max} distributions





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

Change of composition or new particle physics?

Elongation rate theorem

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

(Linsley, Watson PRL46, 1981)

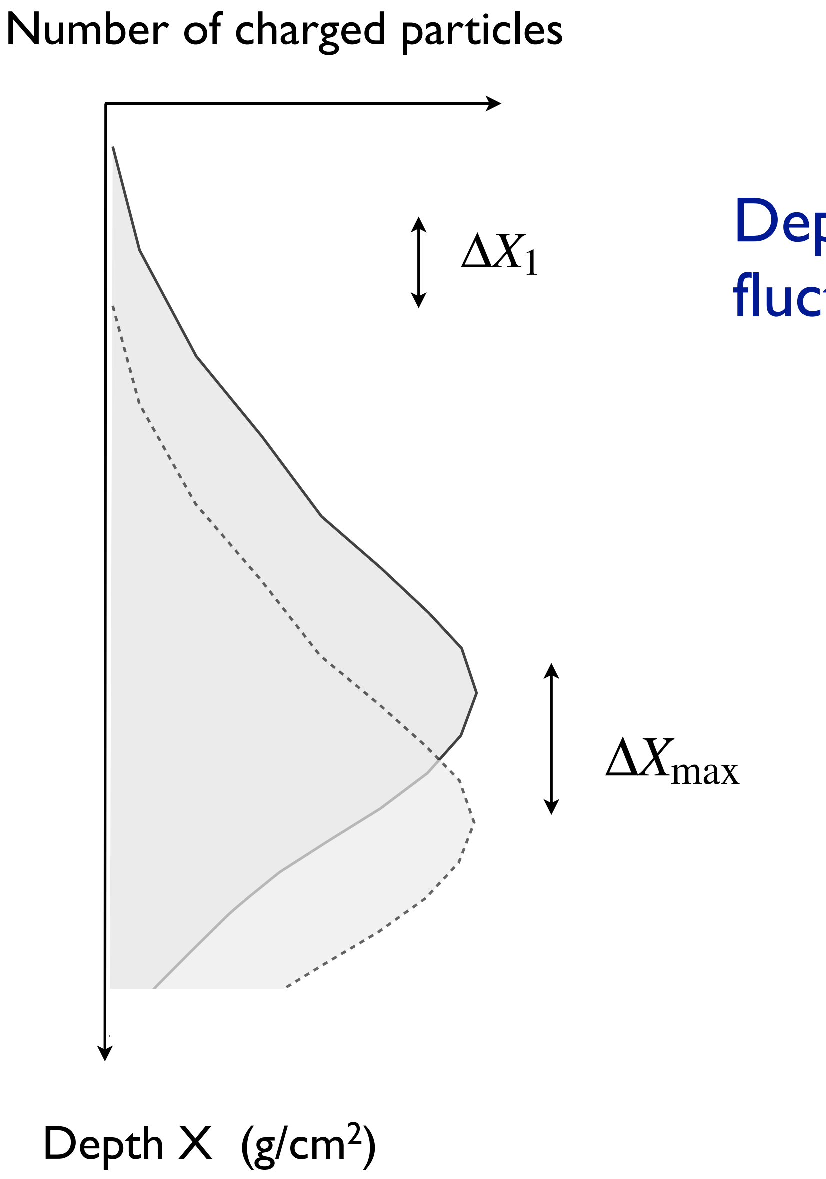
factor ~ 36 g/cm^2

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

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

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

Large if cross section rises rapidly with energy

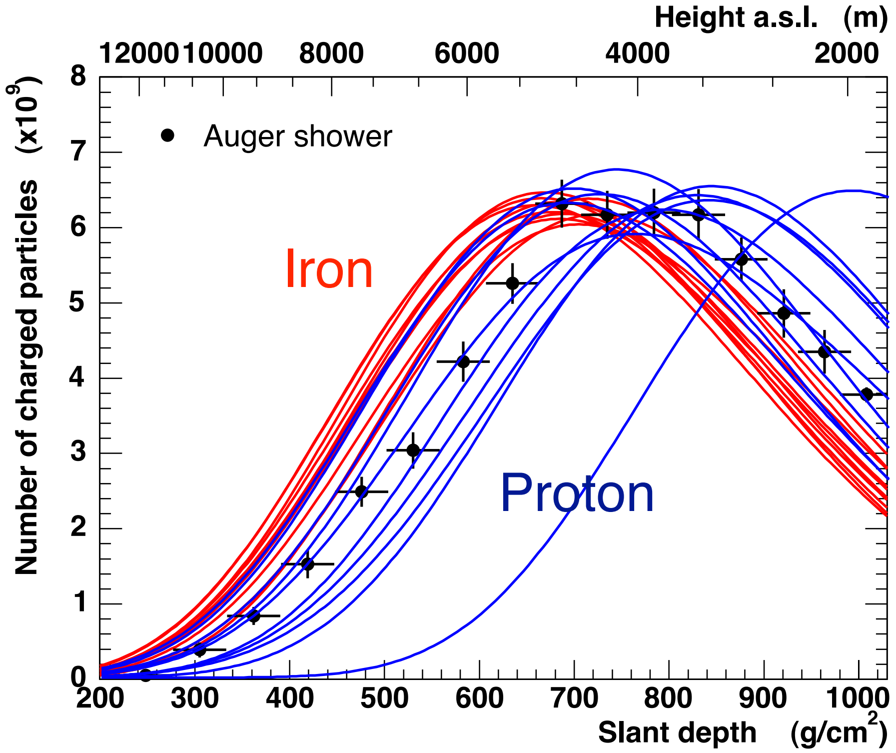


Depth fluctuations

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

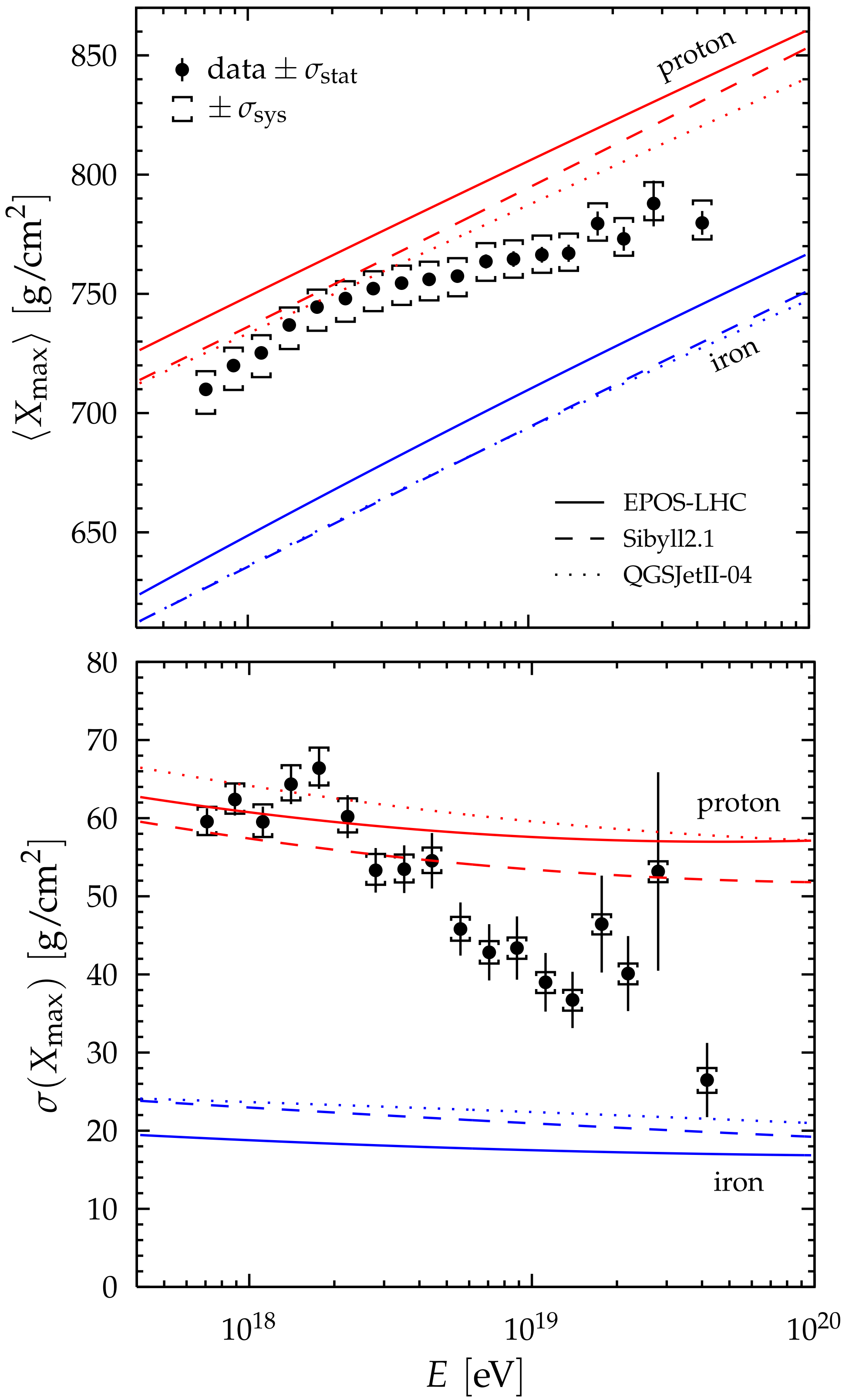
$$\sigma_{\text{p-air}} = \frac{\langle m_{\text{air}} \rangle}{\lambda_{\text{int}}}$$

Change of composition or new particle physics?



Example: event measured by Auger Collab.

(Auger PRD90, 2014)



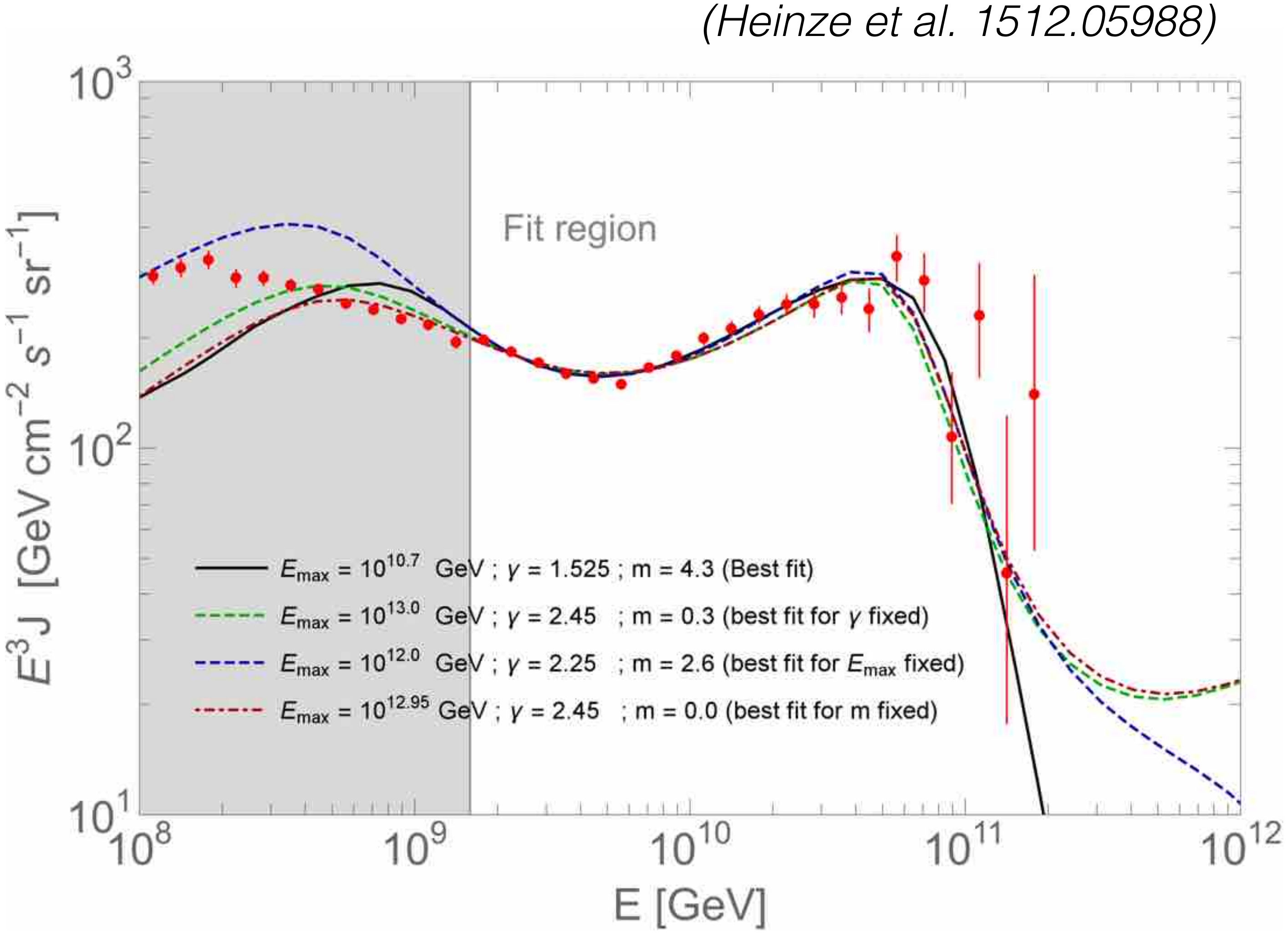
Protons: ~50% of X_{max} fluctuations due to depth of first interaction, large increase of cross section required (and further changes)

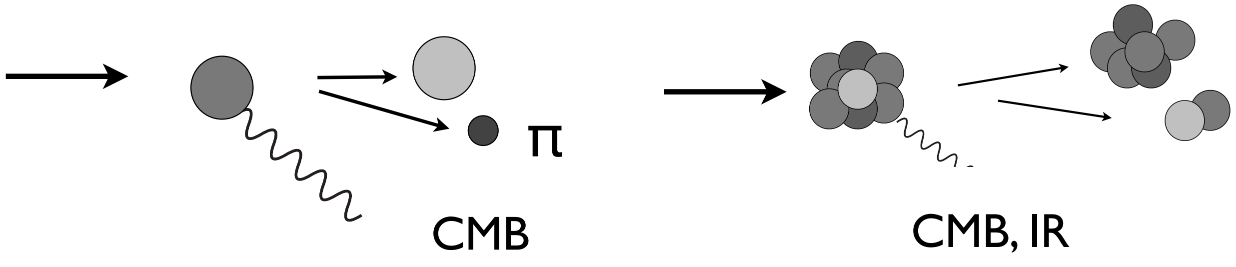
No deep showers at higher energies expected

Multi-messenger constraints (GZK secondaries)

Example of emerging multi-messenger constraints

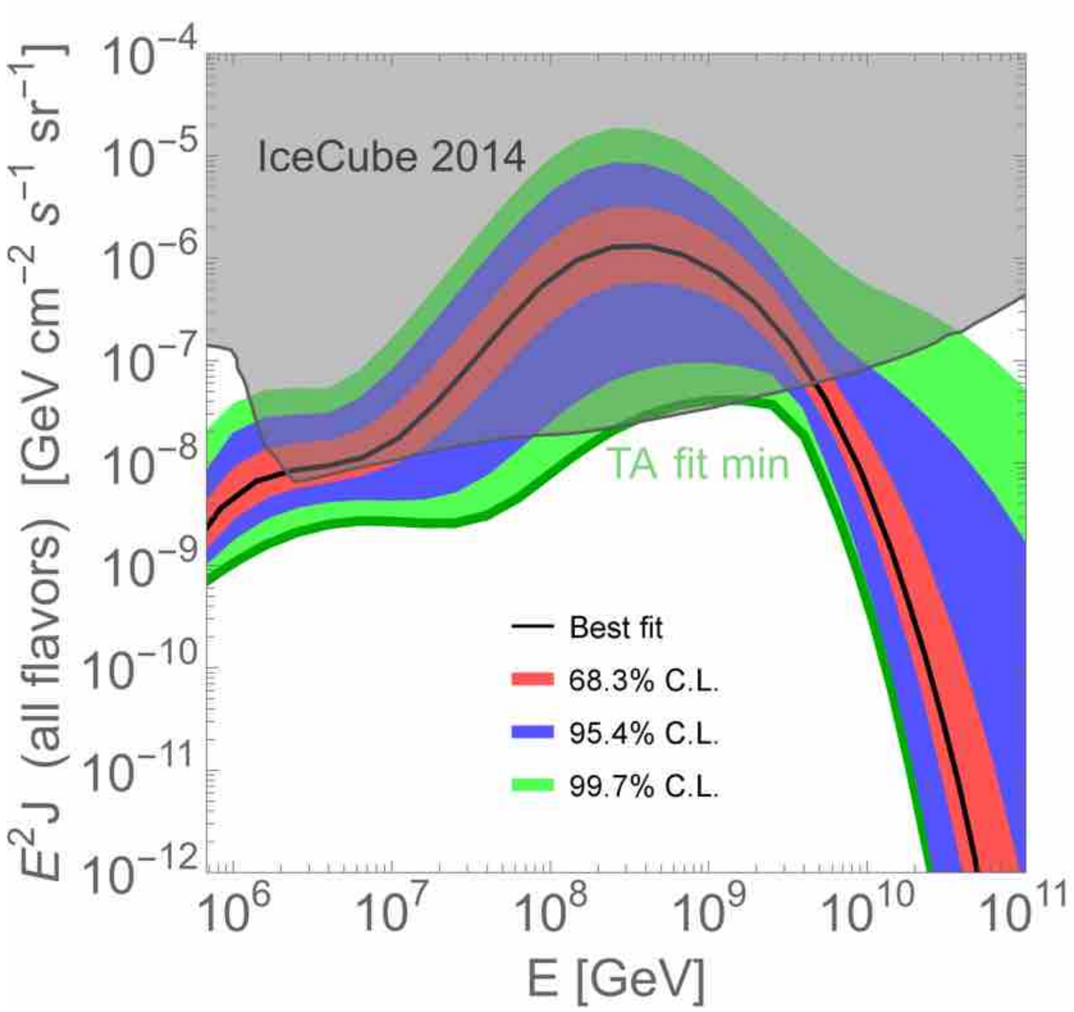
(Heinze et al. 1512.05988)





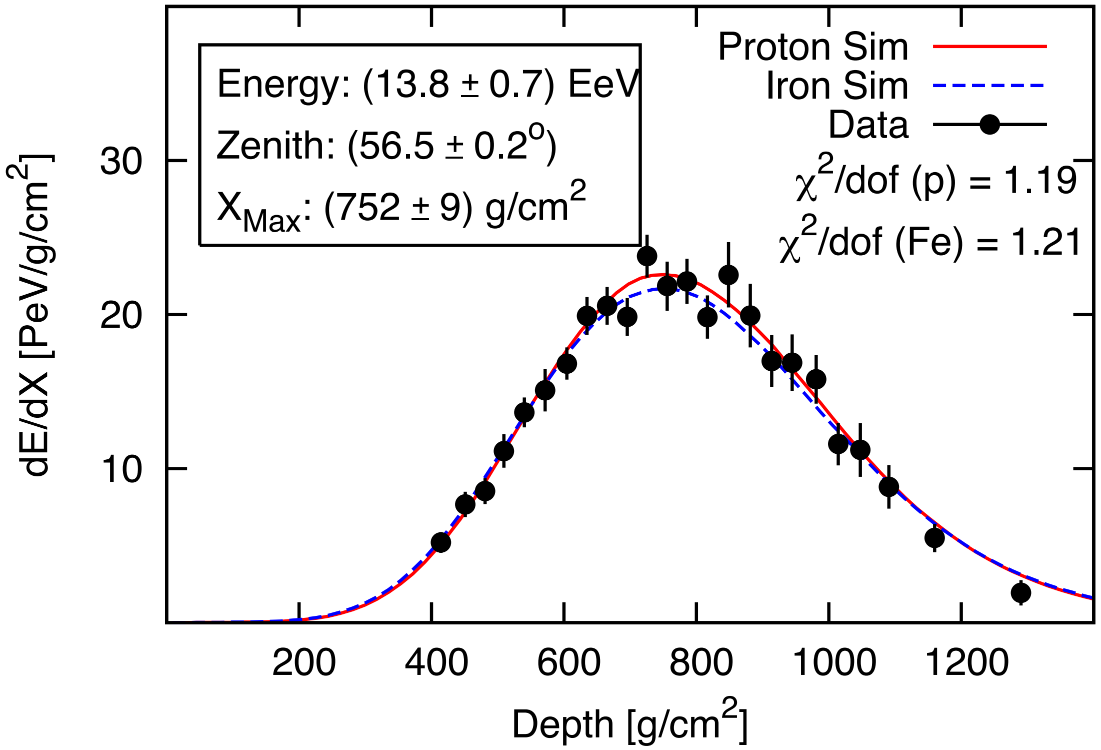
Similar considerations also for diffuse gamma ray background (Ahlers et al., Taylor et al.)

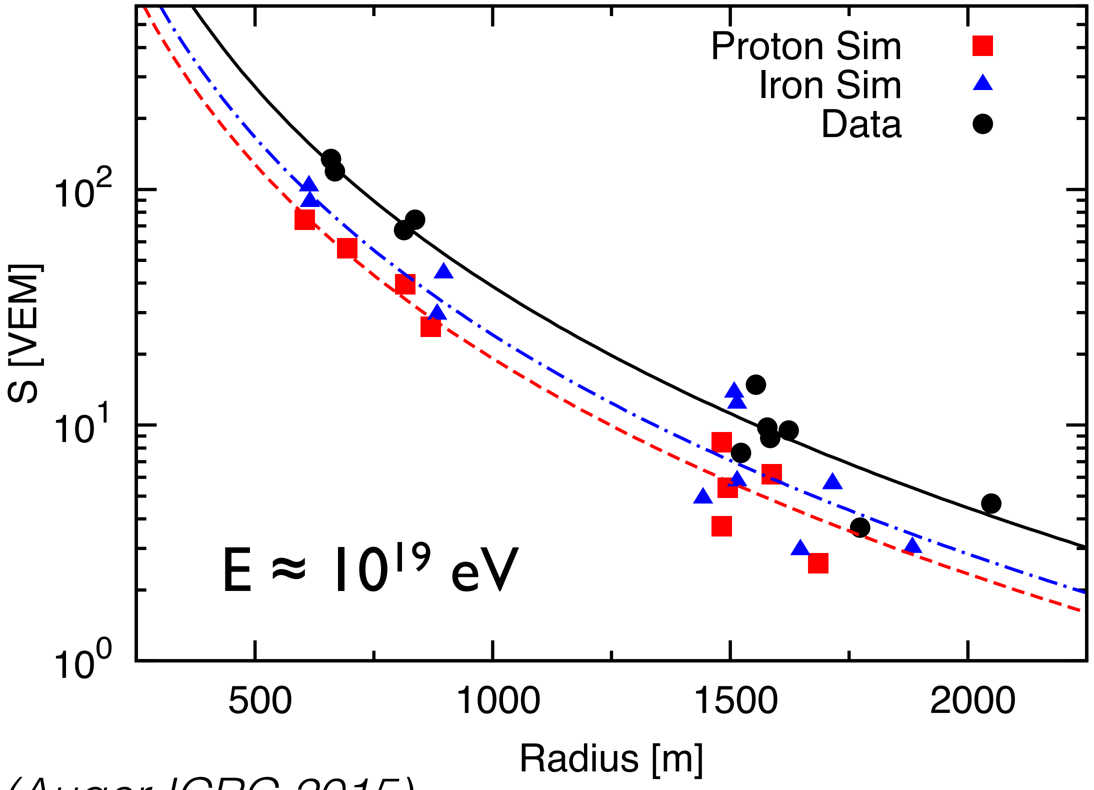
Hypothesis:
flux only protons,
fit to TA spectrum,
GZK neutrinos



Low and intermediate energy interactions

Discrepancy: shower profile and particles at ground



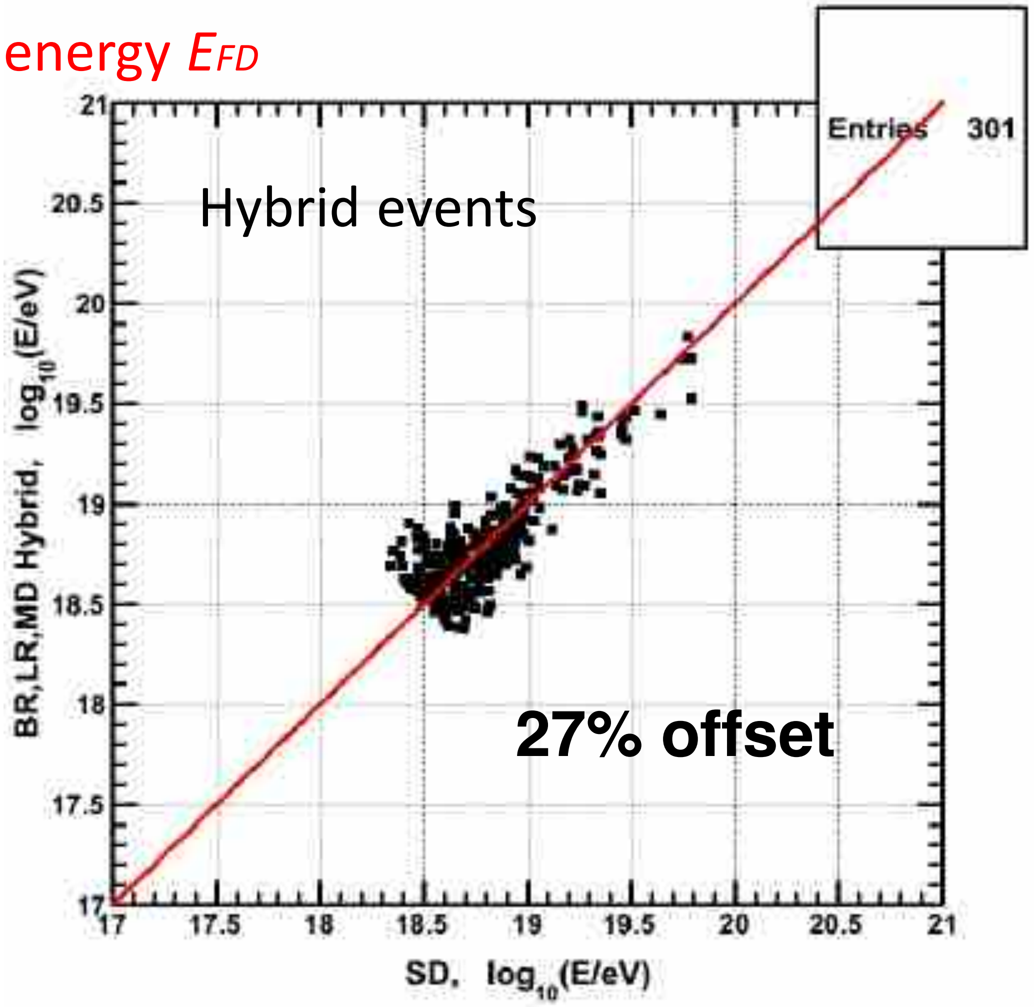


(Auger ICRC 2015)

Auger: angular dependence hints at lack of muons in simulation

Telescope Array

FD energy E_{FD}



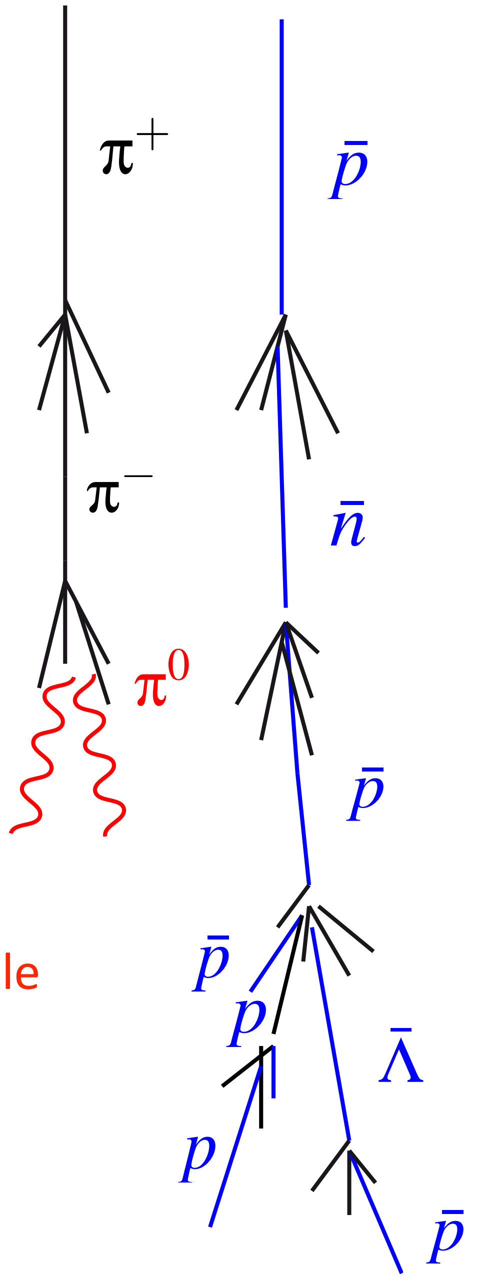
Hybrid events

27% offset

SD energy E_{SD}

(TA ICHEP 2014)

How to increase the number of muons?



Meson sub-shower

Baryon sub-shower

Decay of leading particle

$\pi^\pm$ ~30% chance to have π^0 as 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 2014)*

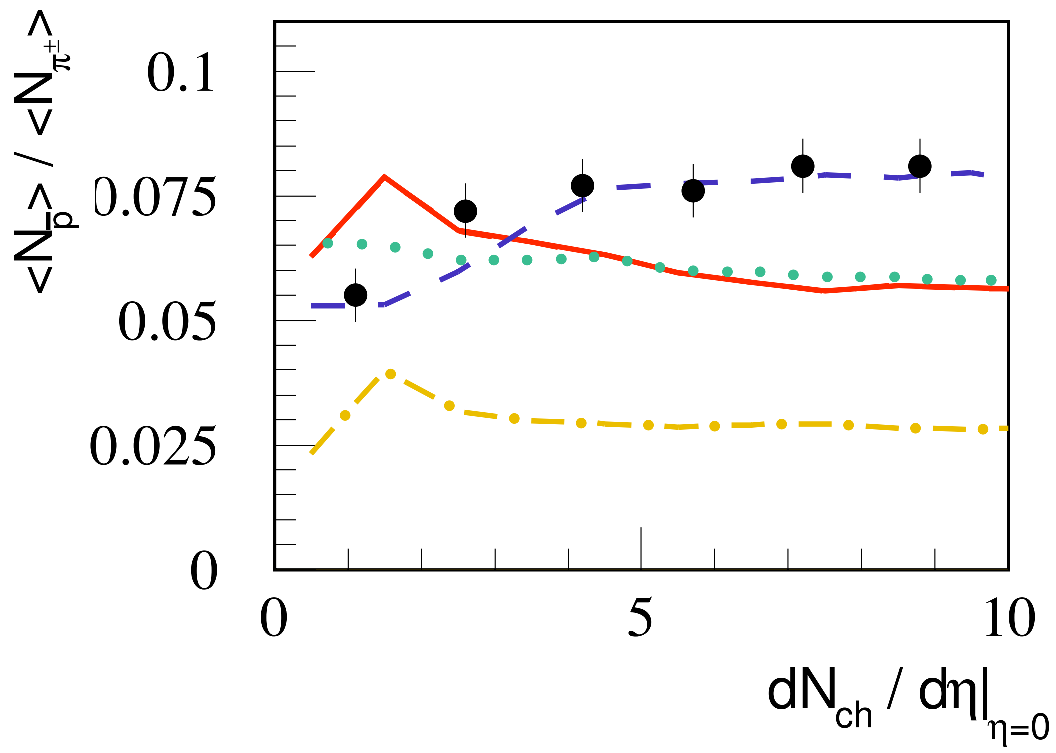
- Leading particle for a π could be ρ^0 and not π^0
- Decay of ρ^0 almost 100% into two charged pions

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)

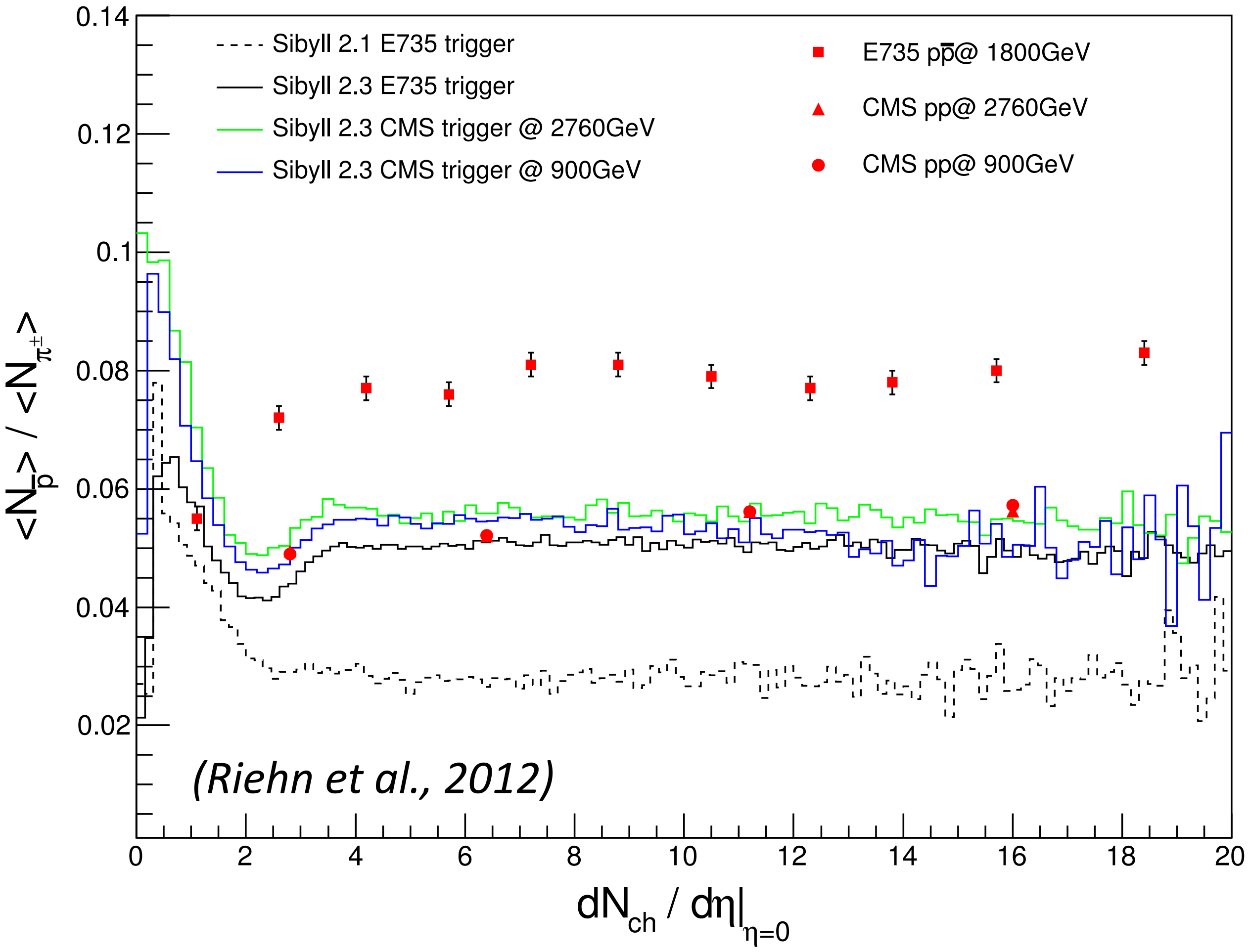


Ratio multiplicities of antiprotons to pions

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

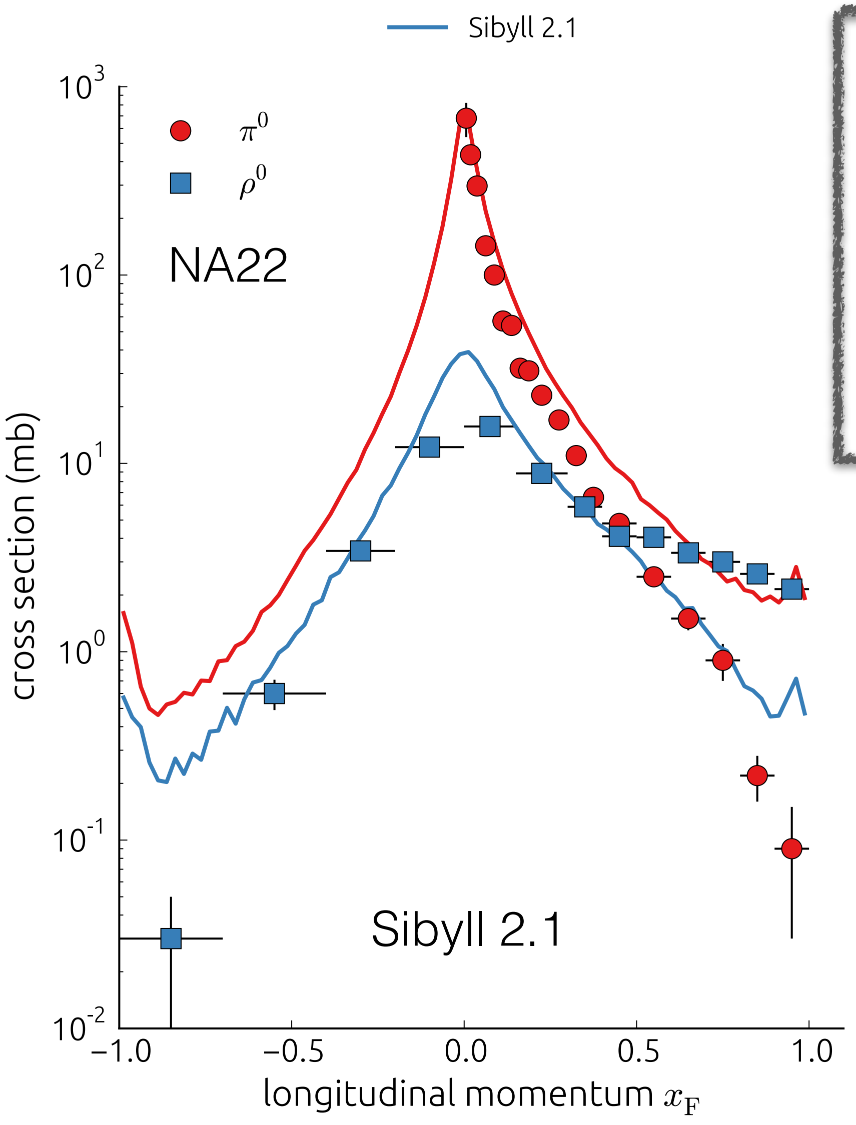
LHC measurements do not confirm large antiproton production derived from Tevatron data (rapidity vs. pseudorap.?)

LHC data (CMS: 900 and 2760 GeV)



(Riehn et al., 2012)

Rho production in pion-proton interactions (i)

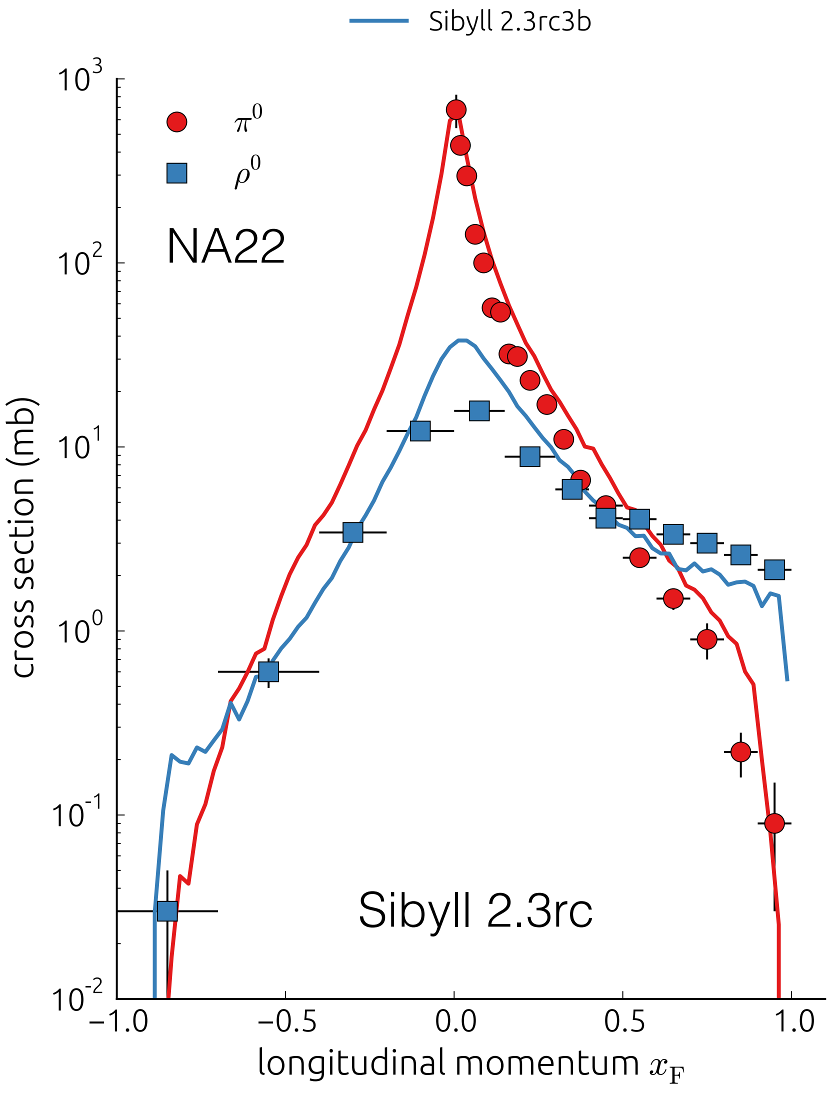


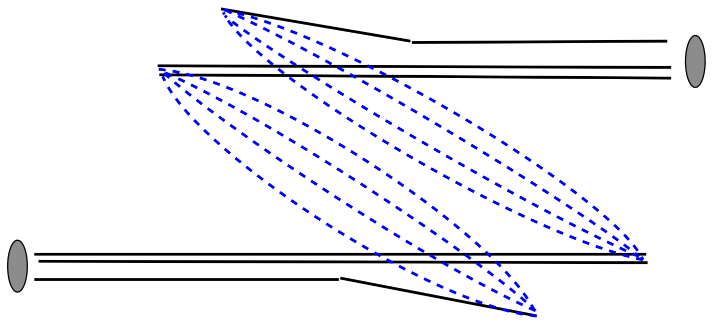
$$\pi^+ p \rightarrow \pi^0 \rightarrow 2\gamma$$

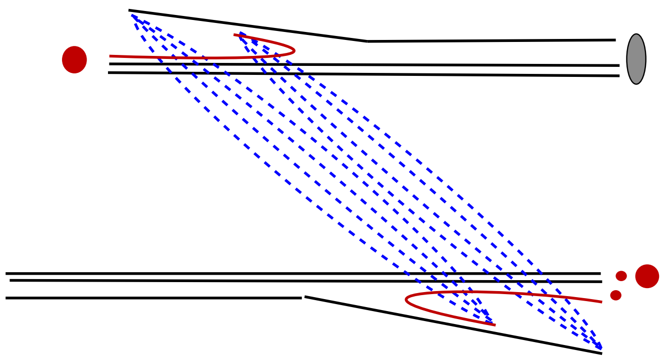
$$\pi^+ p \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$$

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

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

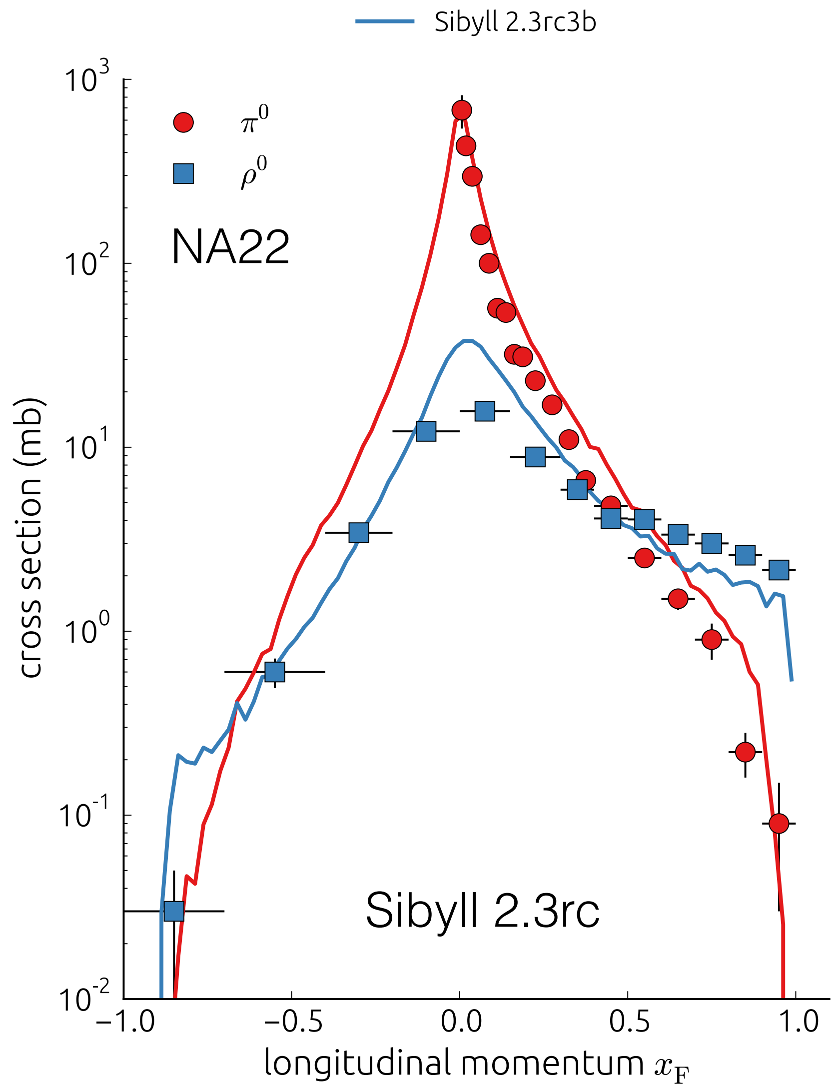




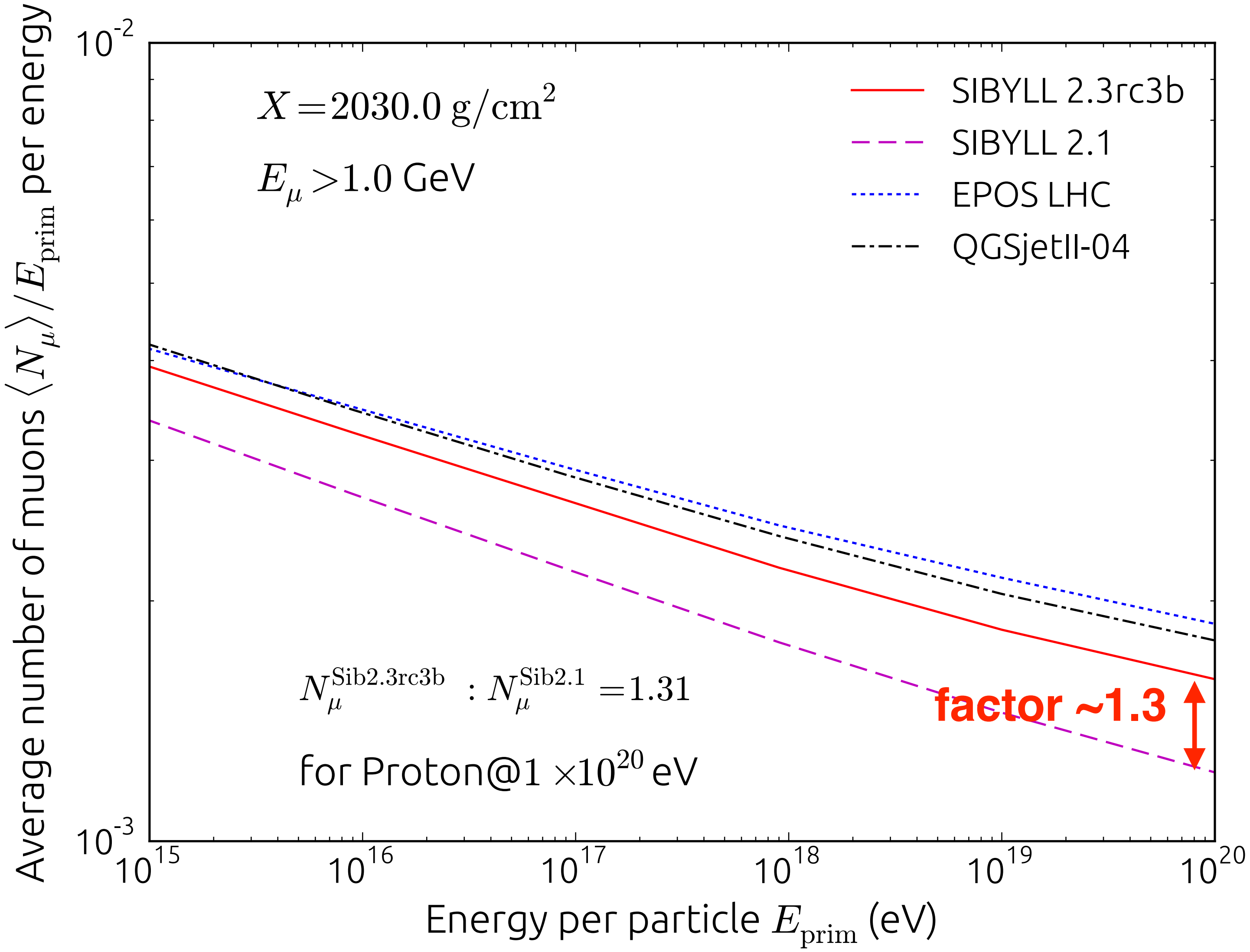


(Riehn et al., ICRC 2015)

Rho production in pion-proton interactions (ii)



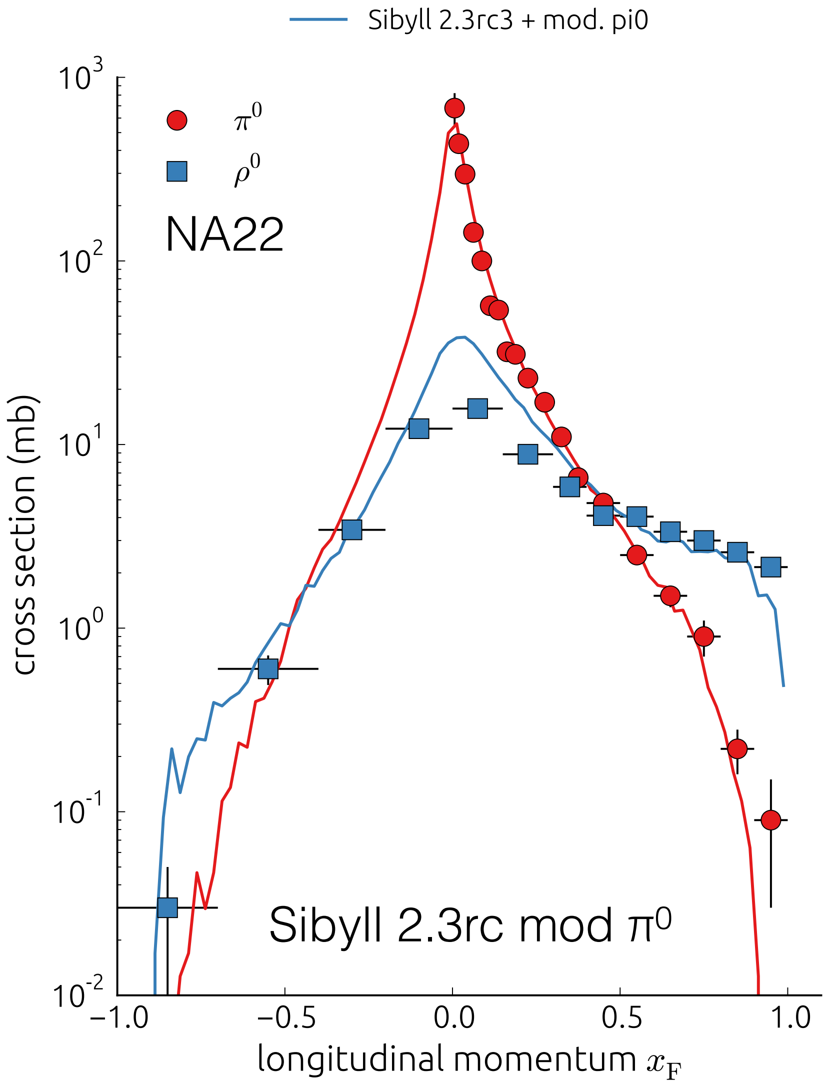
Description of data not optimal

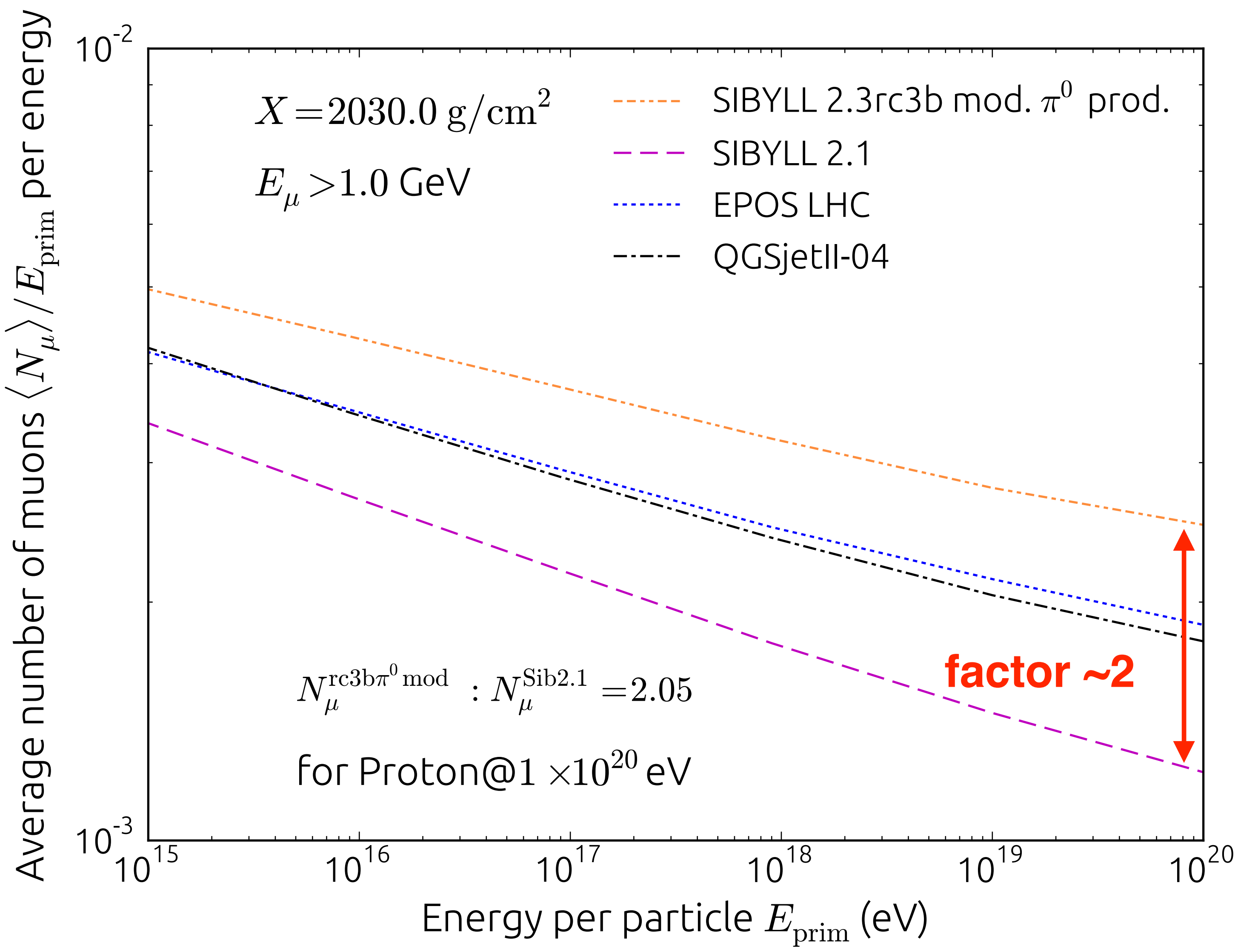


Sibyll 2.3

(Riehn et al., ICRC 2015)

Rho production in pion-proton interactions (iii)





Ad hoc modified ρ^0 and π^0 production

Sibyll 2.3rc mod π^0

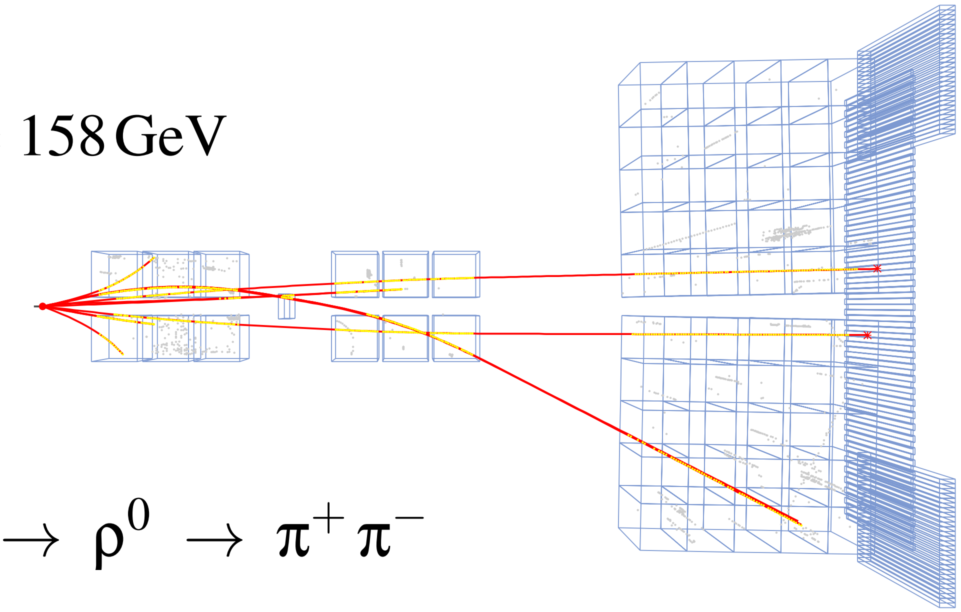
(Riehn et al., ICRC 2015)

NA61 at SPS: results on rho production on carbon

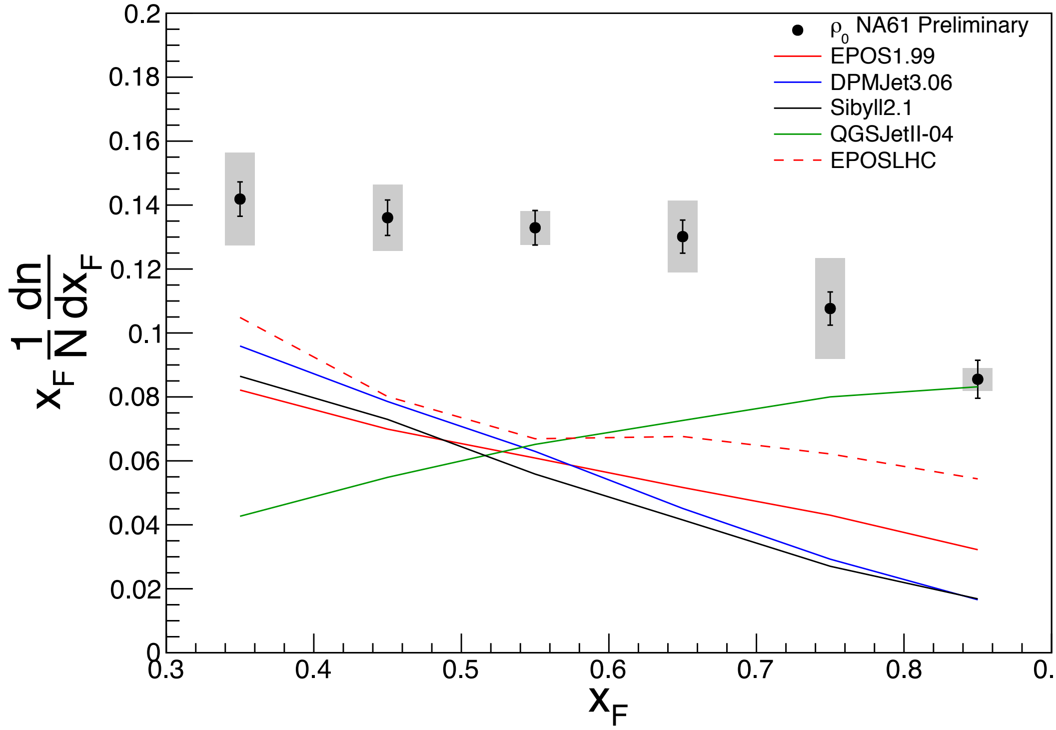
Dedicated cosmic ray runs
(π-C at 158 and 350 GeV)

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

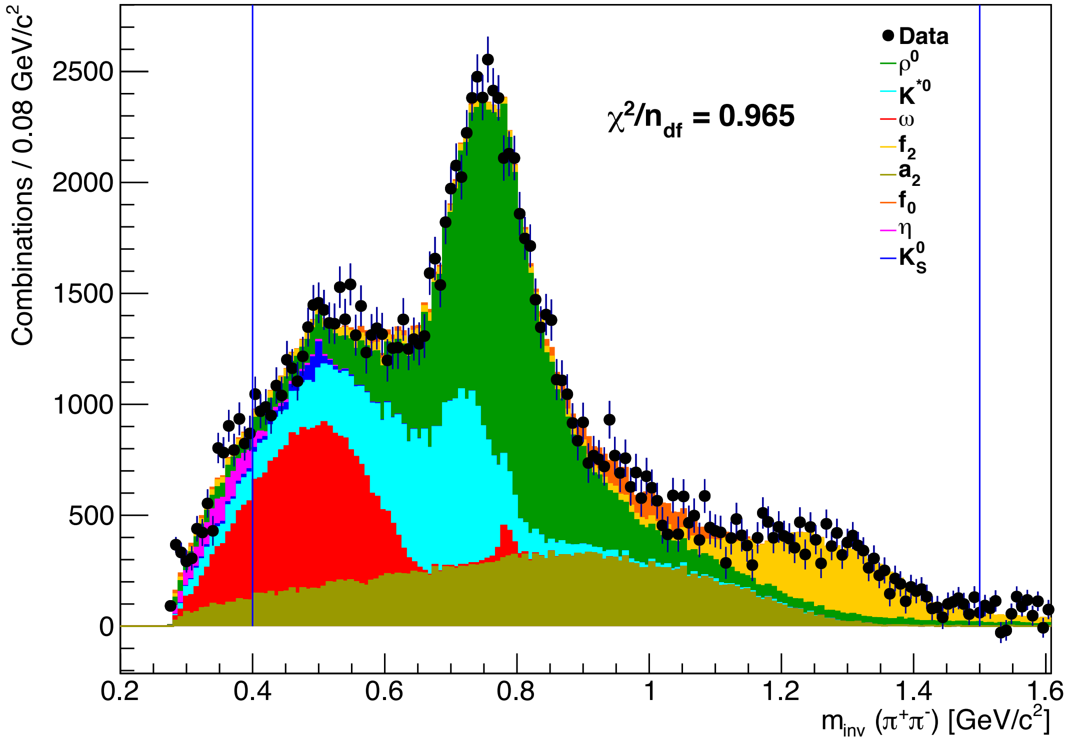
$$\pi^- C \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$$

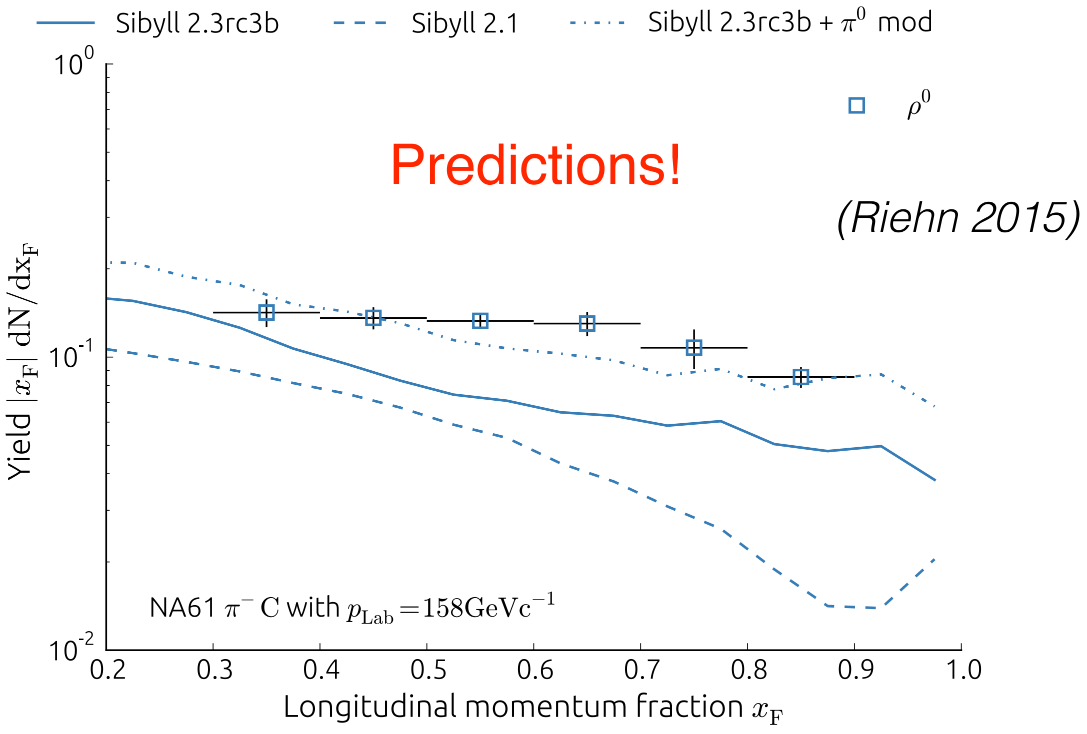


(NA61, Herve, ICRC 2015)



Invariant mass of two charged tracks



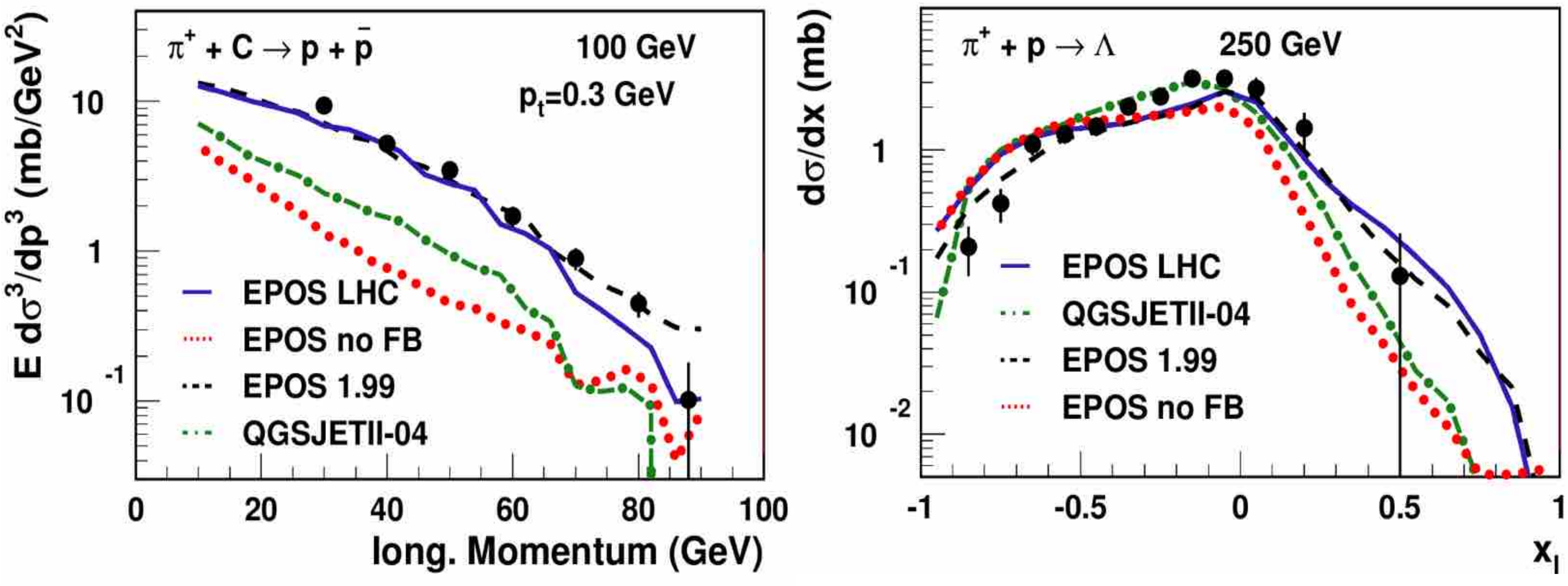


Predictions!

(Riehn 2015)

Baryon production in π-air interactions?

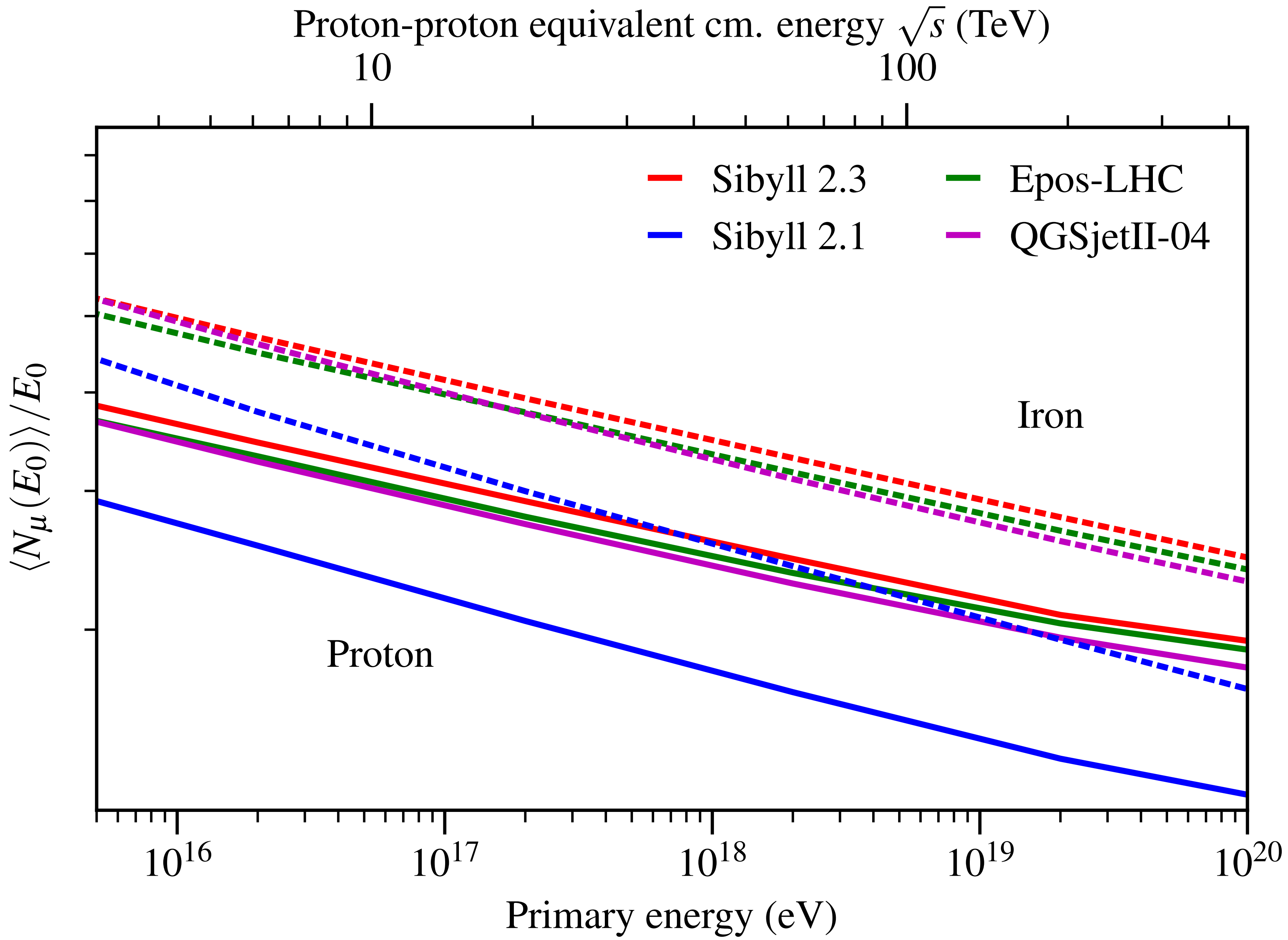
EPOS-LHC: lower rho-0 production rate than QGSjet II.04 but higher muon number



(Pierog, QCD at Cosmics, 2016)

Only one data set, indications for unexpectedly large baryon production rate,
Need NA61 data for confirmation (energy dependence?)

Current status of predicted muon numbers



(Riehn 2016)

Models differ in baryon and rho-0 production rate

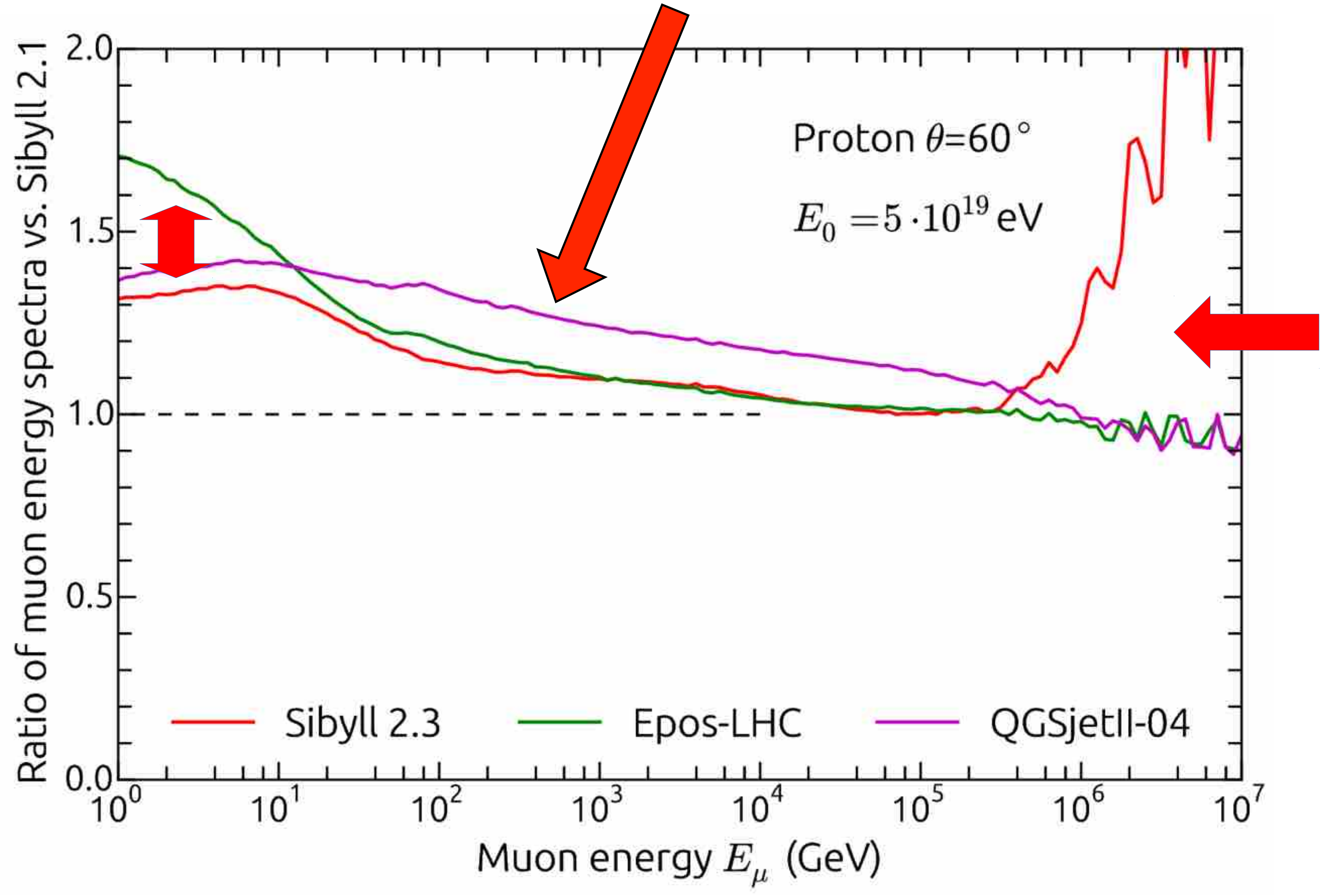
Convergence of predictions not reliable, further increase of muon number expected (due to increase of rho-0 production in interaction models)

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



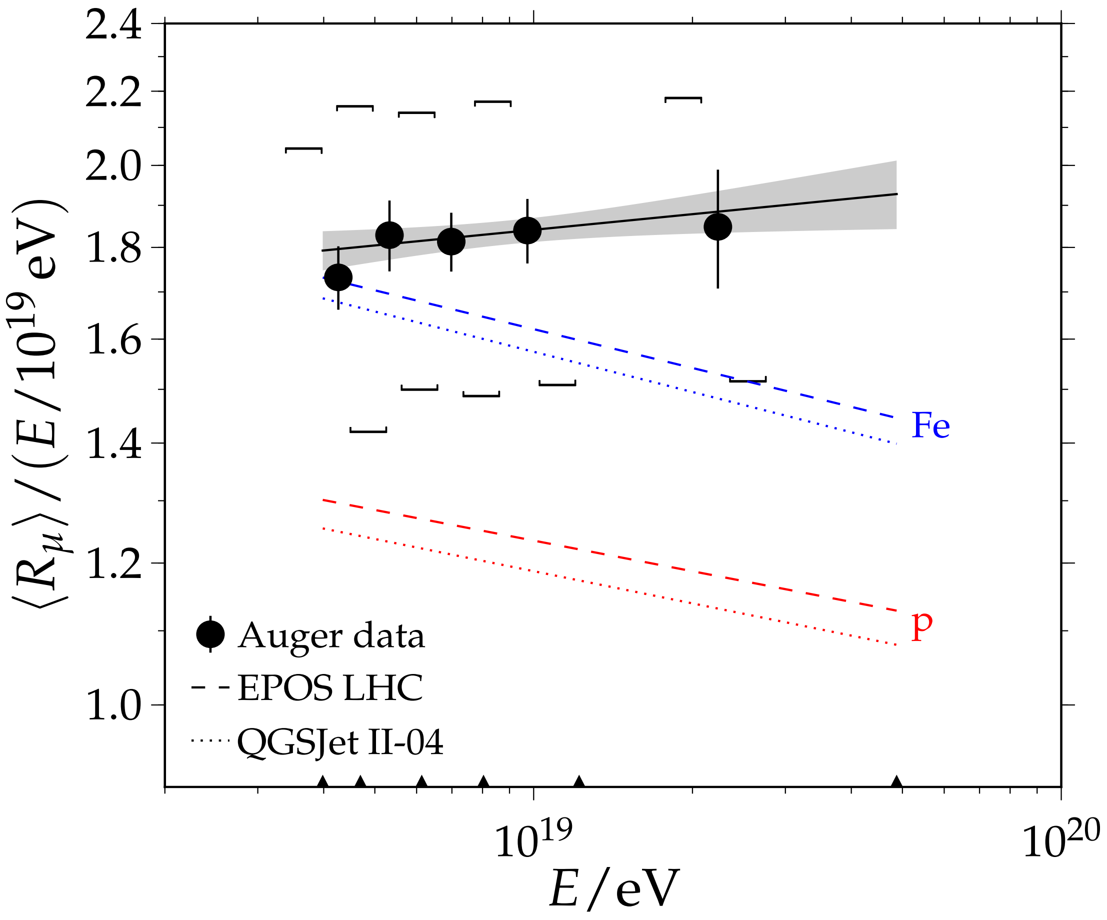
Charm particles (only Sibyll 2.3)

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

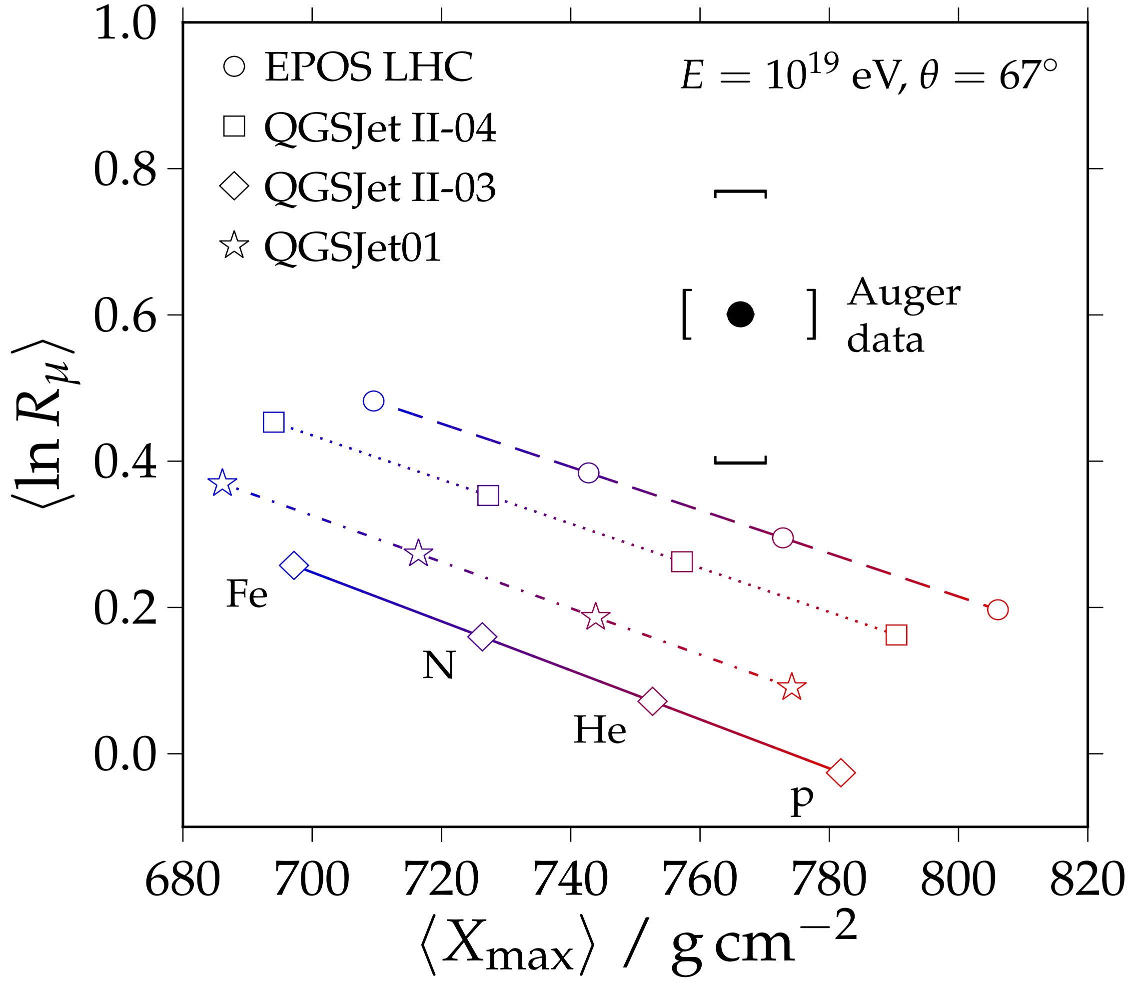
(Riehn et al 2016)

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

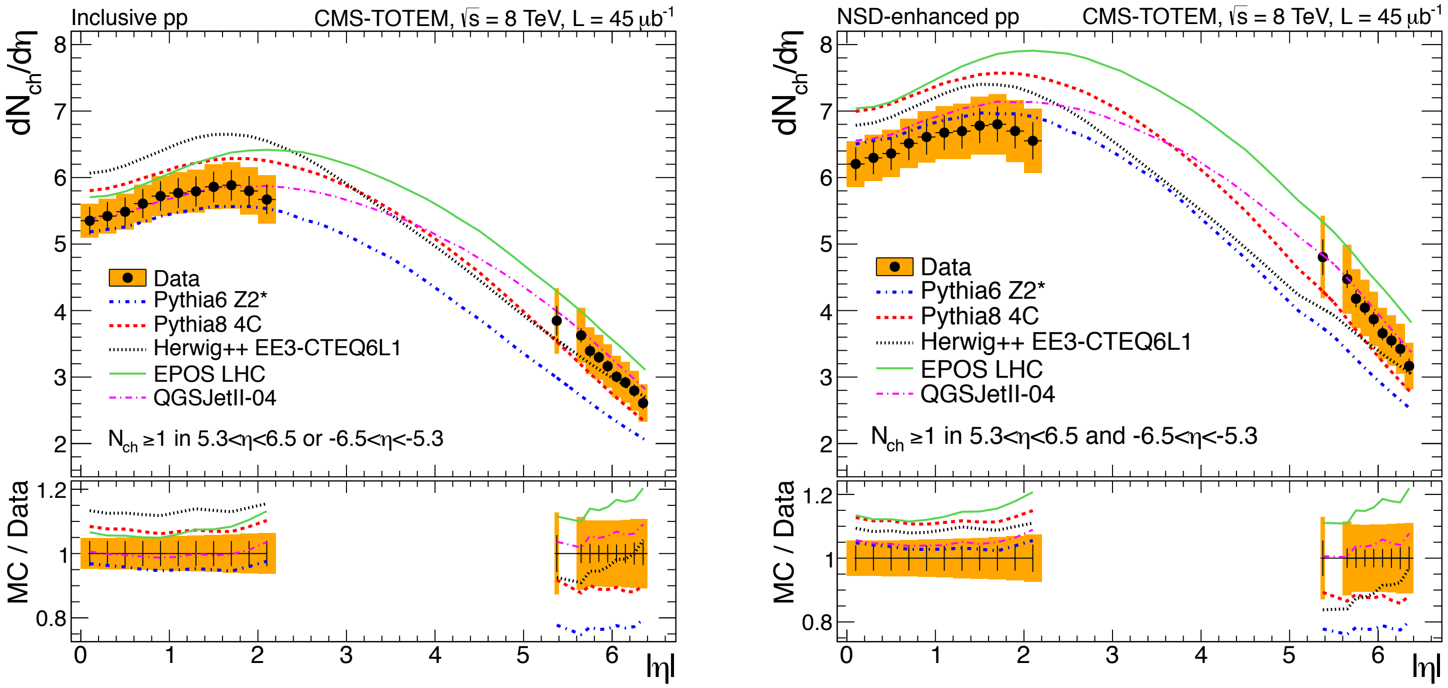
(Auger, arXiv:1408.1421)

Summary and outlook

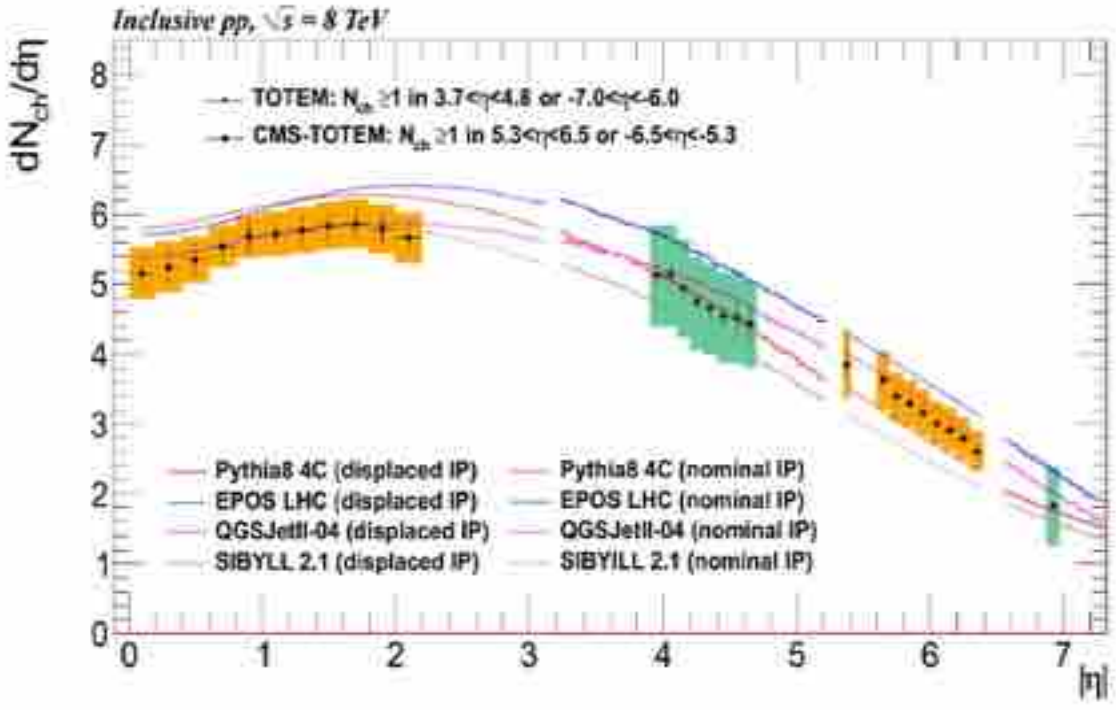
- Overall reasonably good description of inclusive shower observables, but shortcomings in reproducing correlations (composition)
- New accelerator data triggered development of tuned hadronic interaction models
- Changes of X_{max} predictions understood, new predictions correspond to heavier primary 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)
- Dedicated accelerator measurements and data analyses needed to improve situation, main source of uncertainty pion/kaon-nucleus interactions

Backup slides

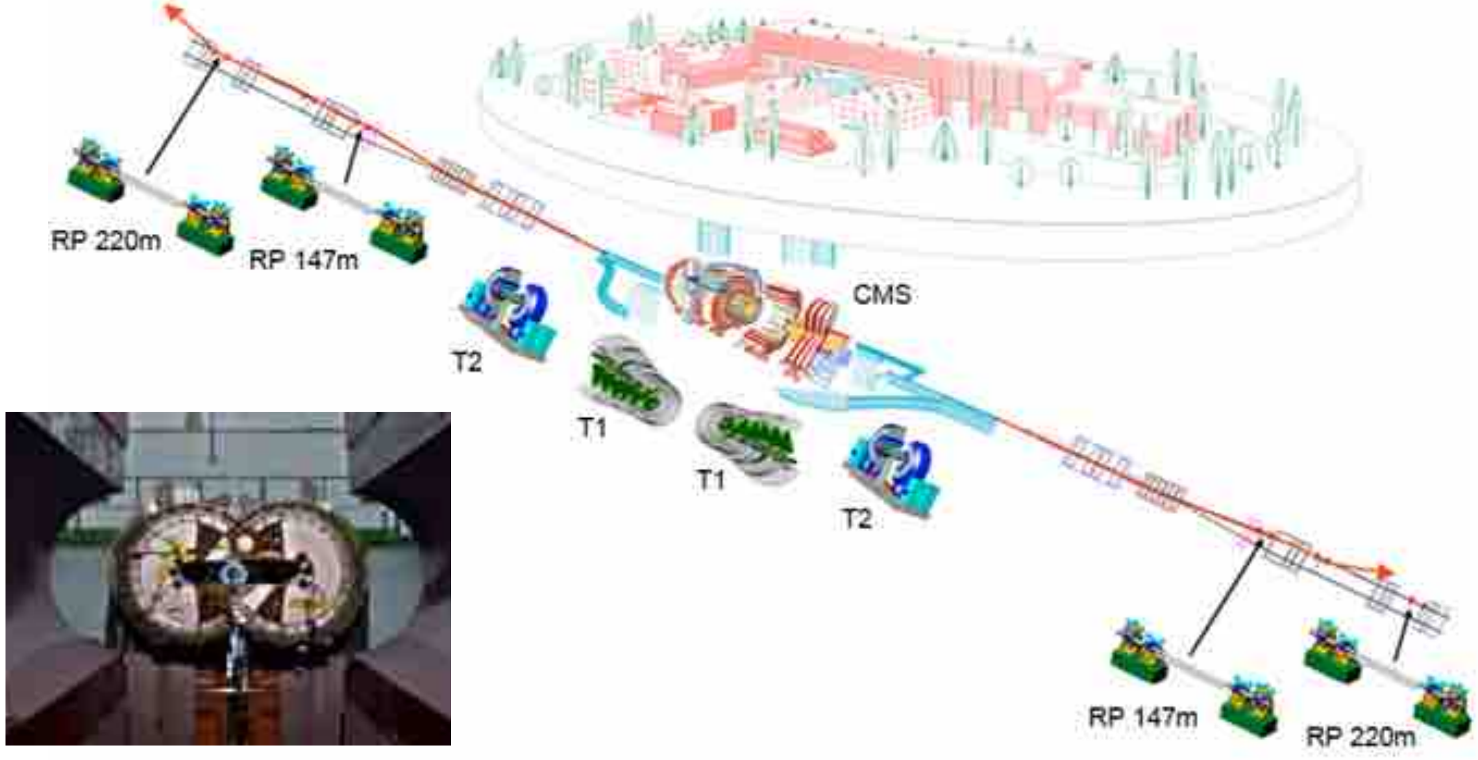
Combined CMS and TOTEM measurements

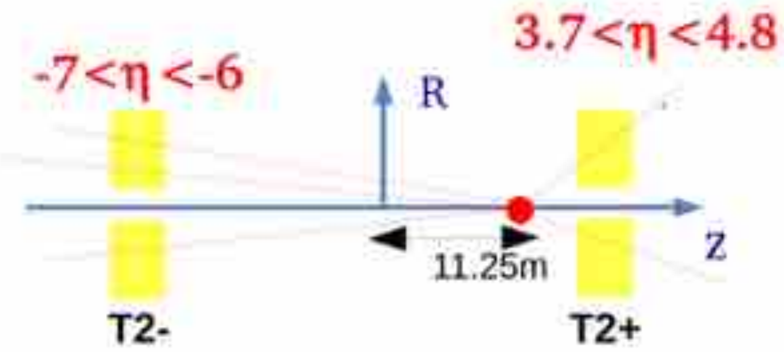


Nominal vertex



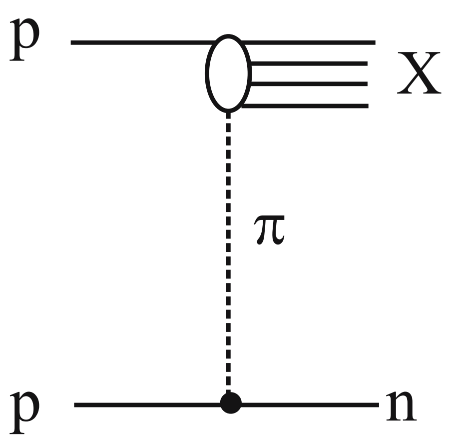
Shifted vertex





Pion-proton and pion-nucleus interactions at LHC

Measurement of pion exchange at LHC



Pion fragmentation region in ATLAS

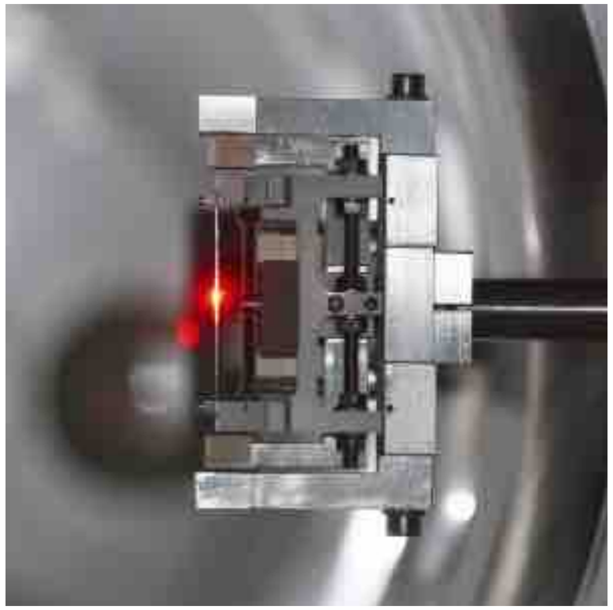
Leading neutron in LHCf

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

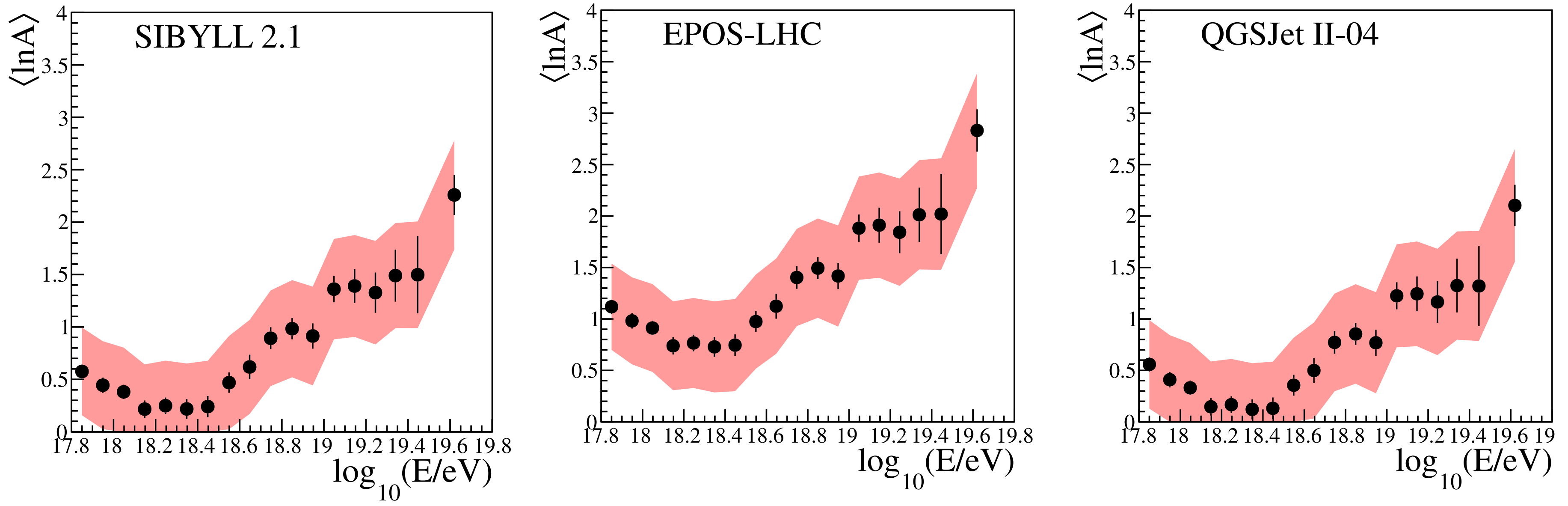
(Ulrich et al., ICRC 2015)



Deflection of protons
of beam halo by crystal

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

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



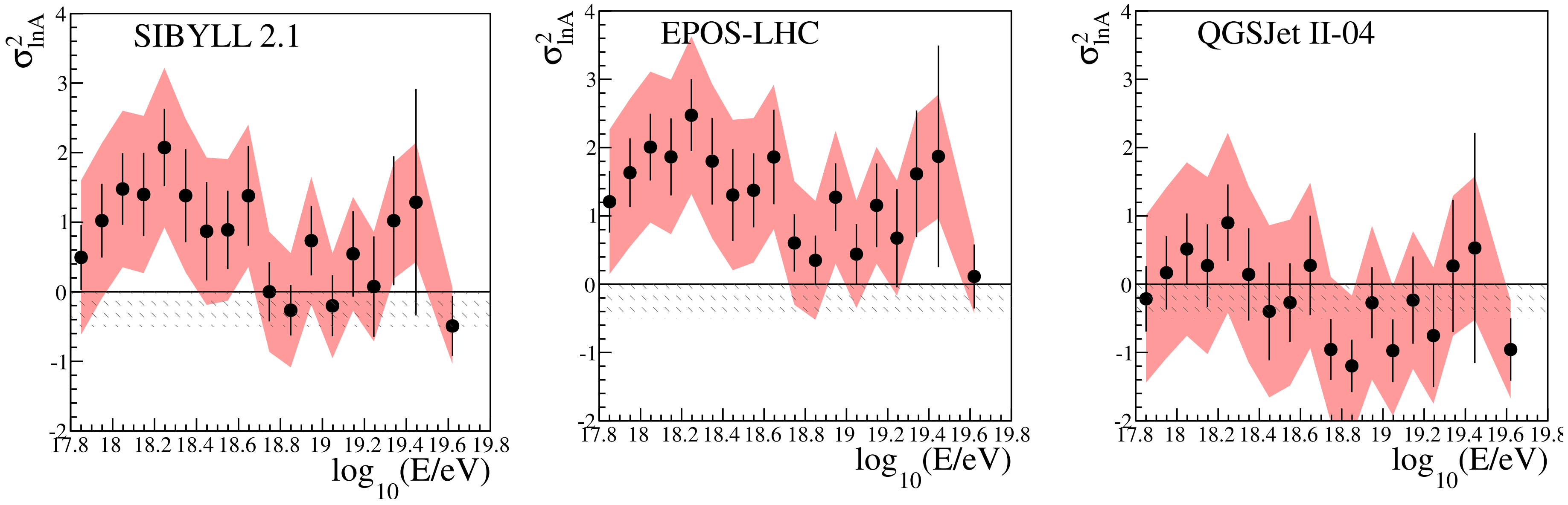
Fe

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

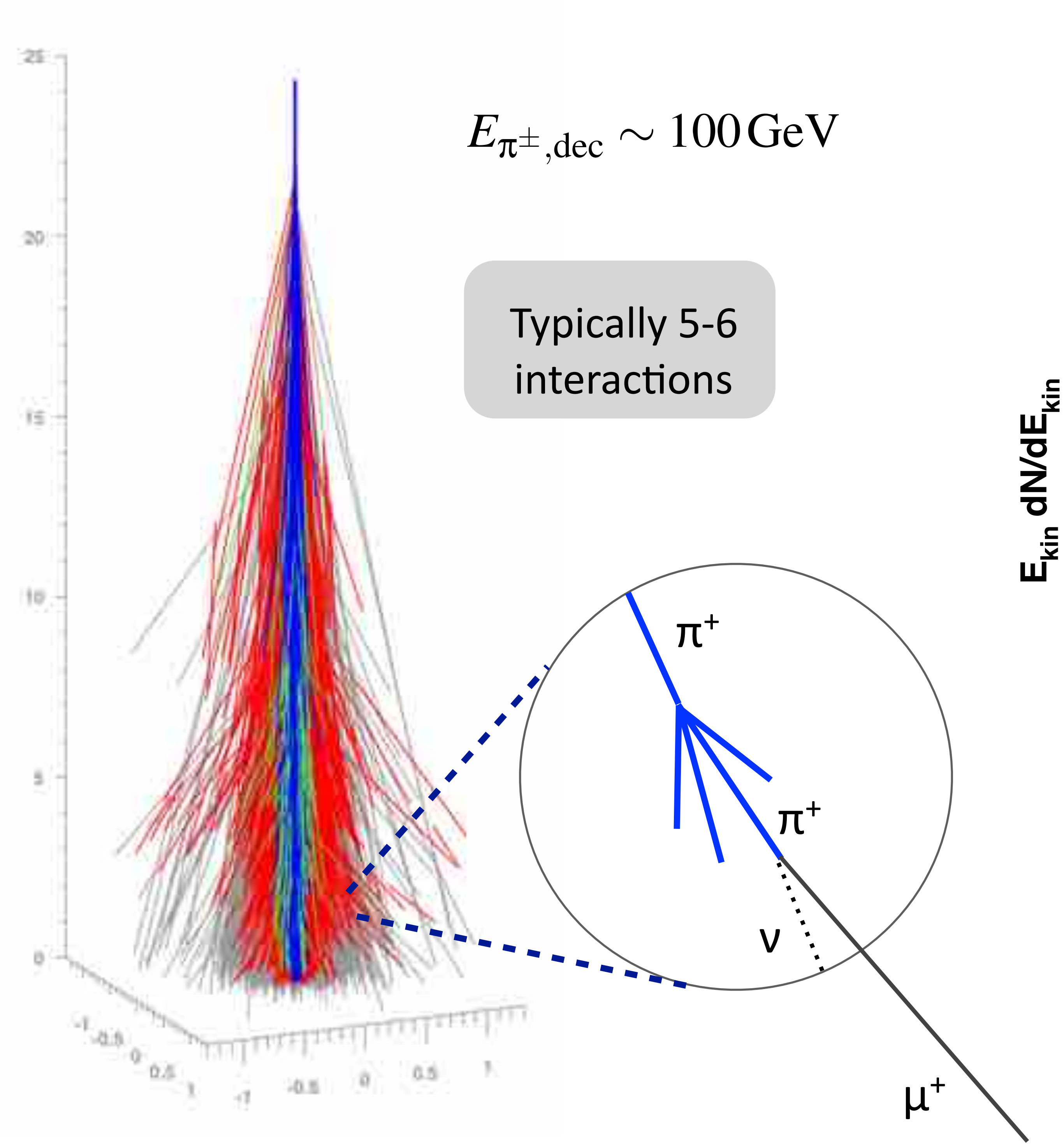
(Auger, JCAP 02 (2013) 026;
update: PRD 90 (2014) 122005)

QGSJet II.04 disfavoured ?

Muon production at large lateral distance

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

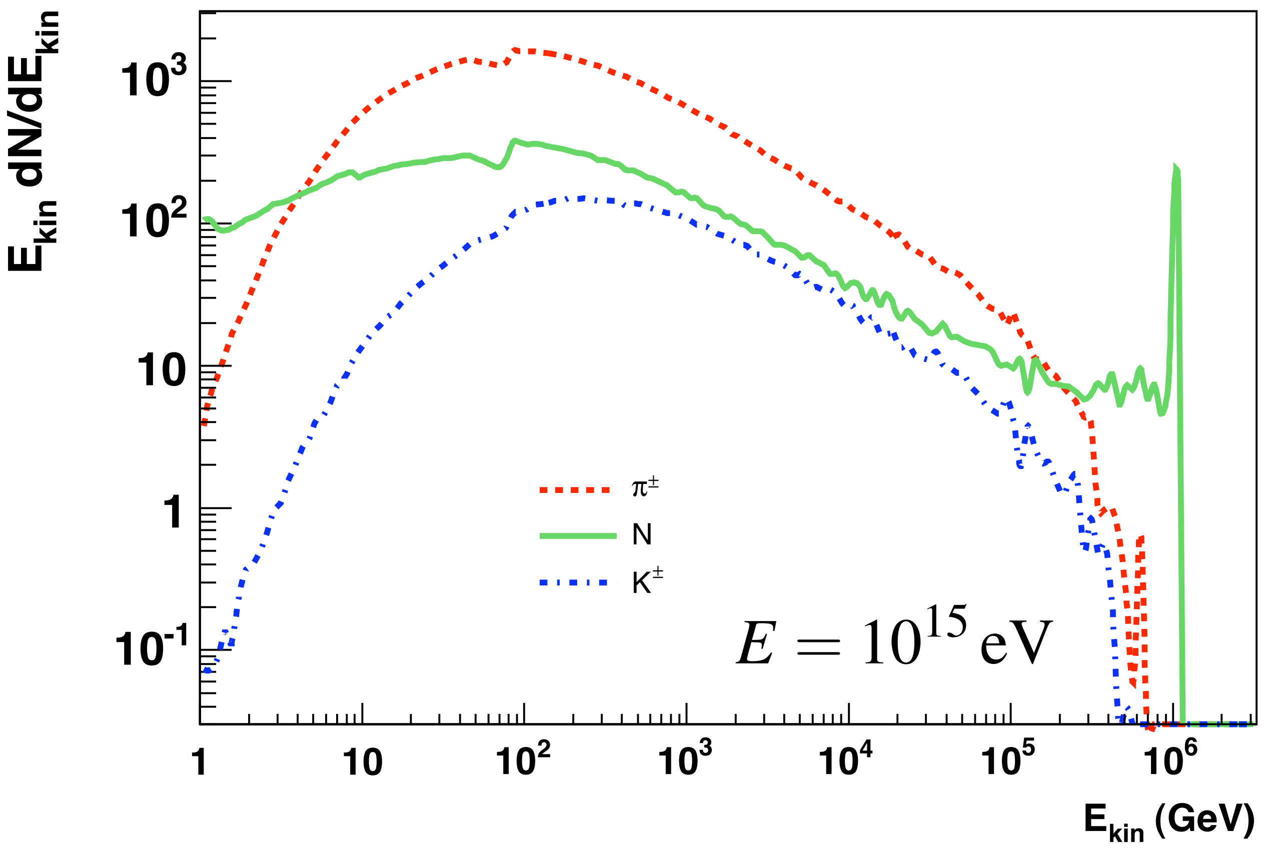
Typically 5-6 interactions



Muon observed 40 – 200 m from core

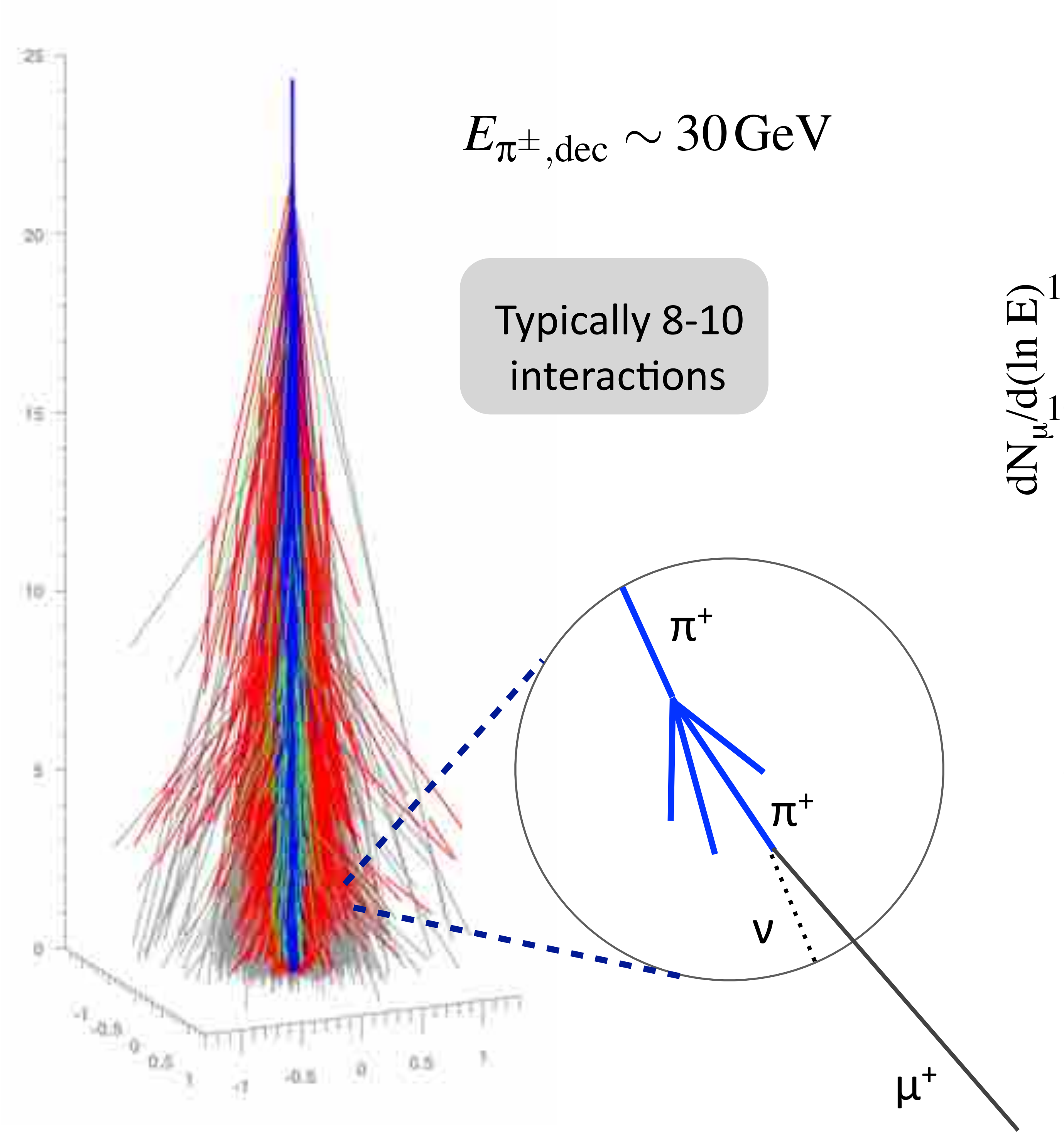
Energy distribution of last interaction that produced a detected muon

Example: KASCADE, proton shower



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

Muon production at large lateral distance

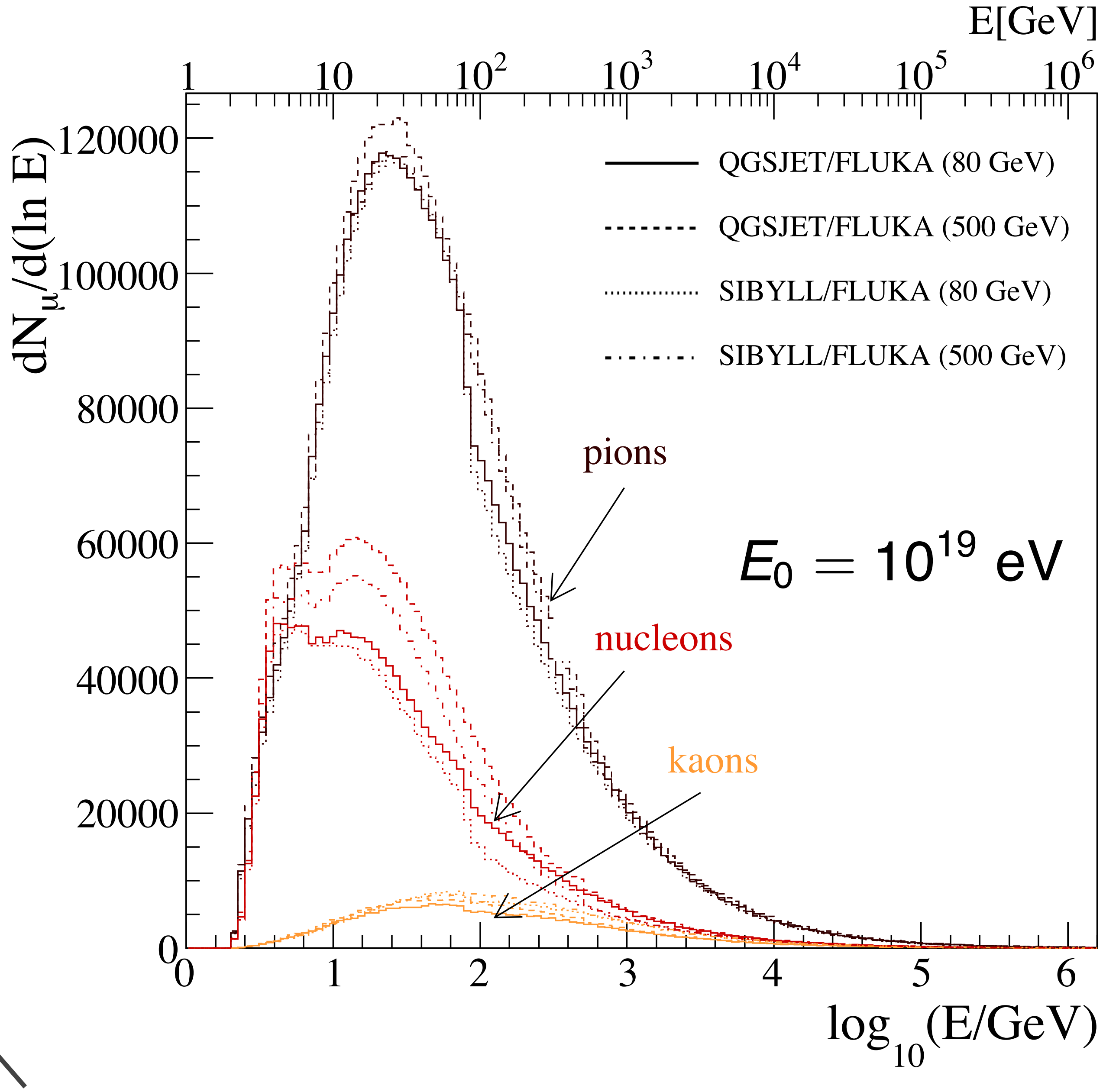


$E_{\pi^\pm,\mathrm{dec}} \sim 30\,\mathrm{GeV}$

Typically 8-10 interactions

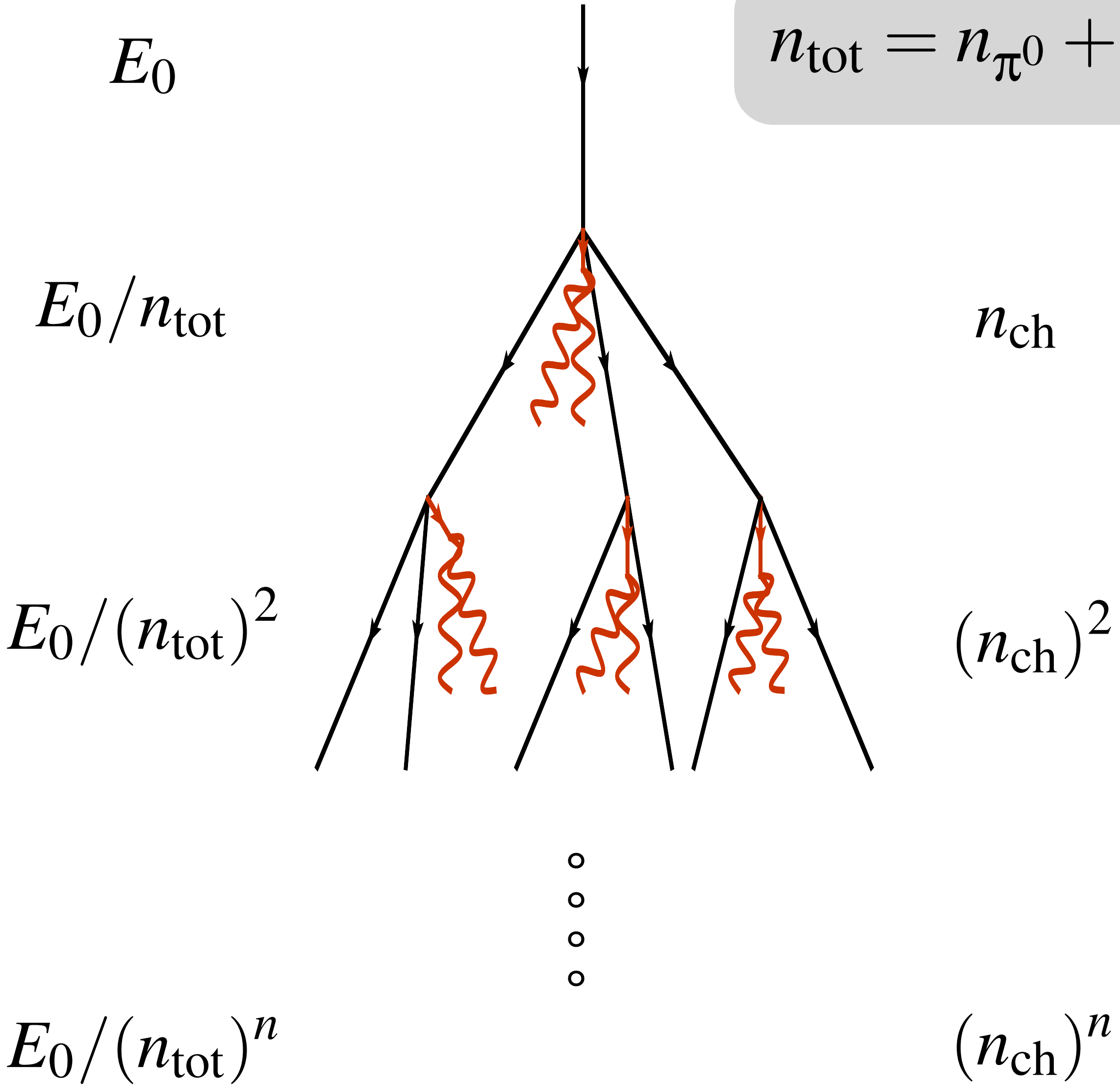
Muon observed at 1000 m from core

Energy distribution of last interaction that produced a detected muon



(Maris et al. ICRC 2009)

Shower physics: muon production



E_0

E_0/n_{tot} $\qquad n_{\mathrm{ch}}$

$E_0/(n_{\mathrm{tot}})^2$ $\qquad (n_{\mathrm{ch}})^2$

$E_0/(n_{\mathrm{tot}})^n$ $\qquad (n_{\mathrm{ch}})^n$

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

Primary particle proton

π^0 decay immediately

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

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

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

Assumptions:

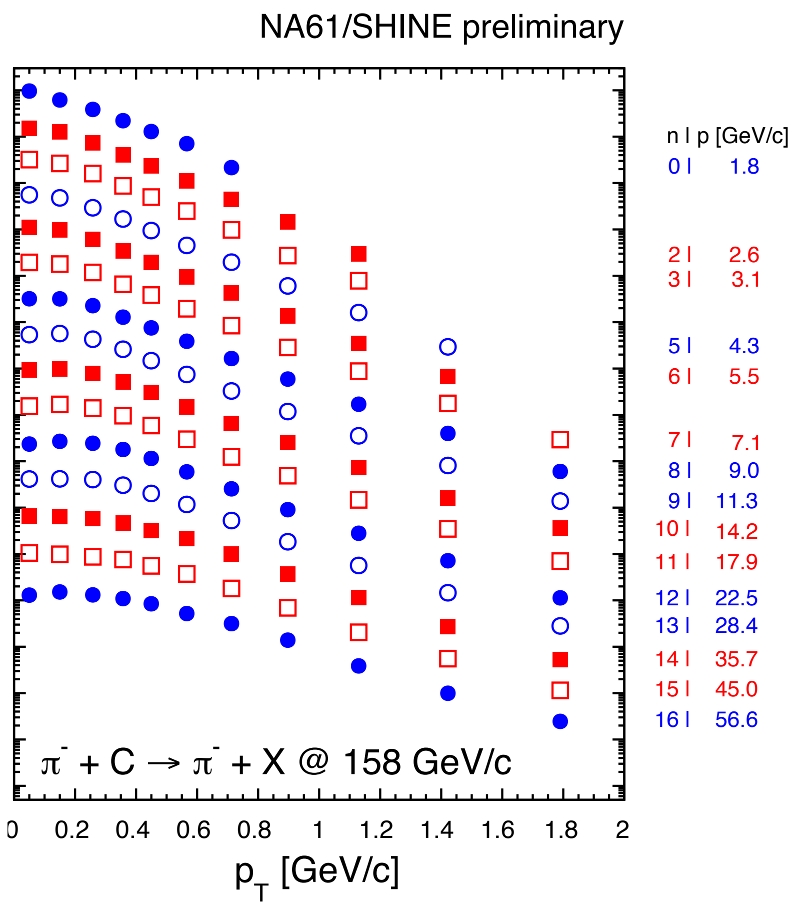
- cascade stops at $E_{\mathrm{part}} = E_{\mathrm{dec}}$
- each hadron produces one muon

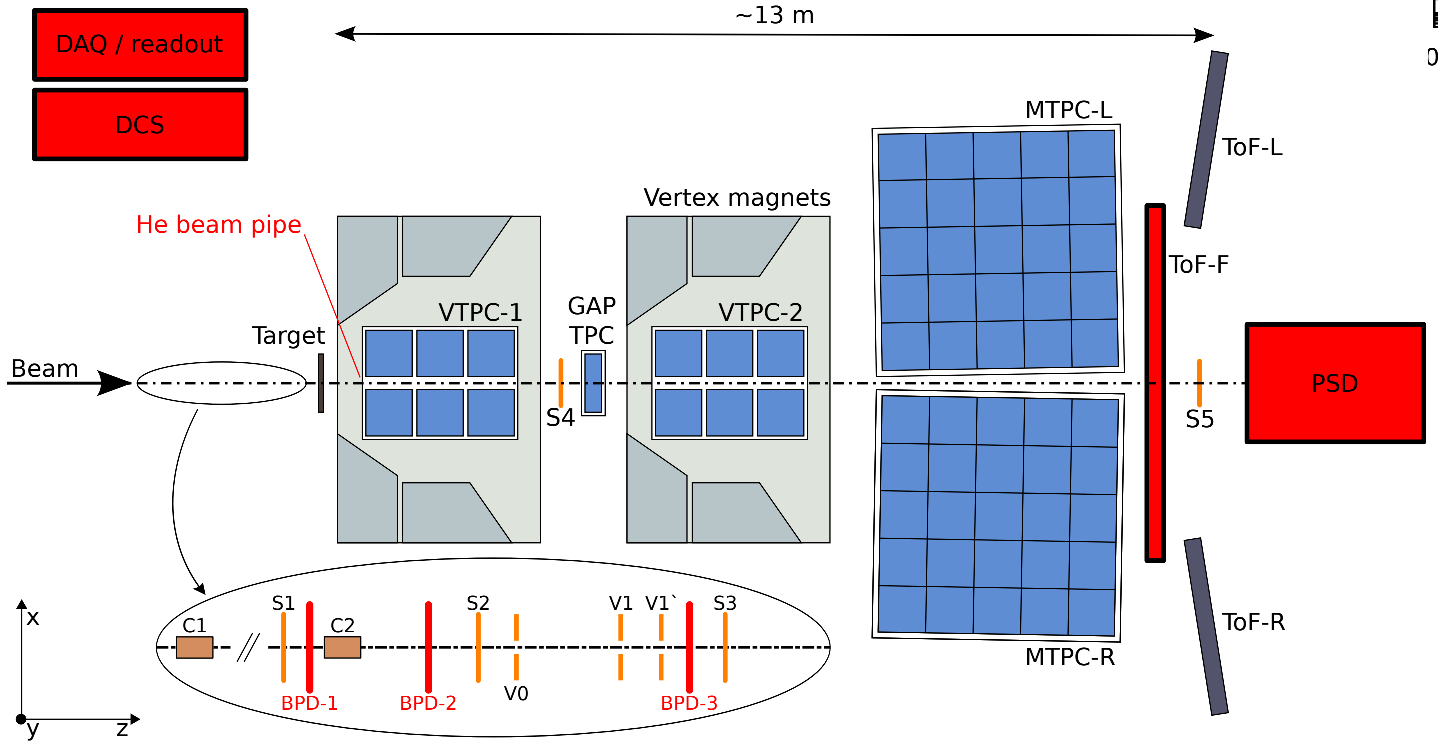
(Matthews, Astropart. Phys. 22, 2005)

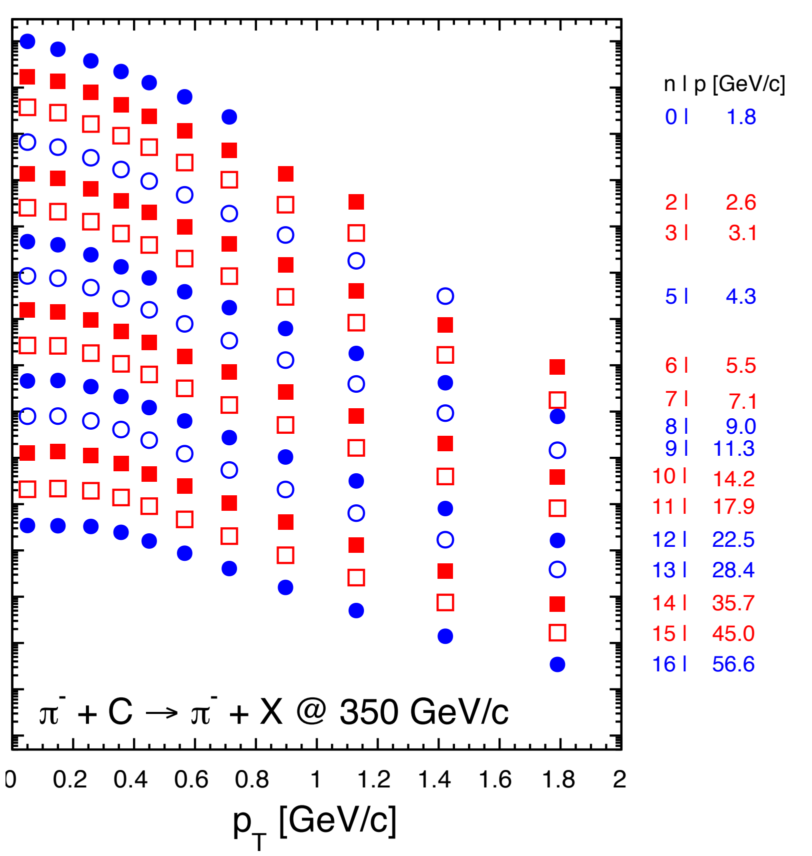
NA61 fixed-target experiment at CERN SPS

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

Analyzed by Auger members

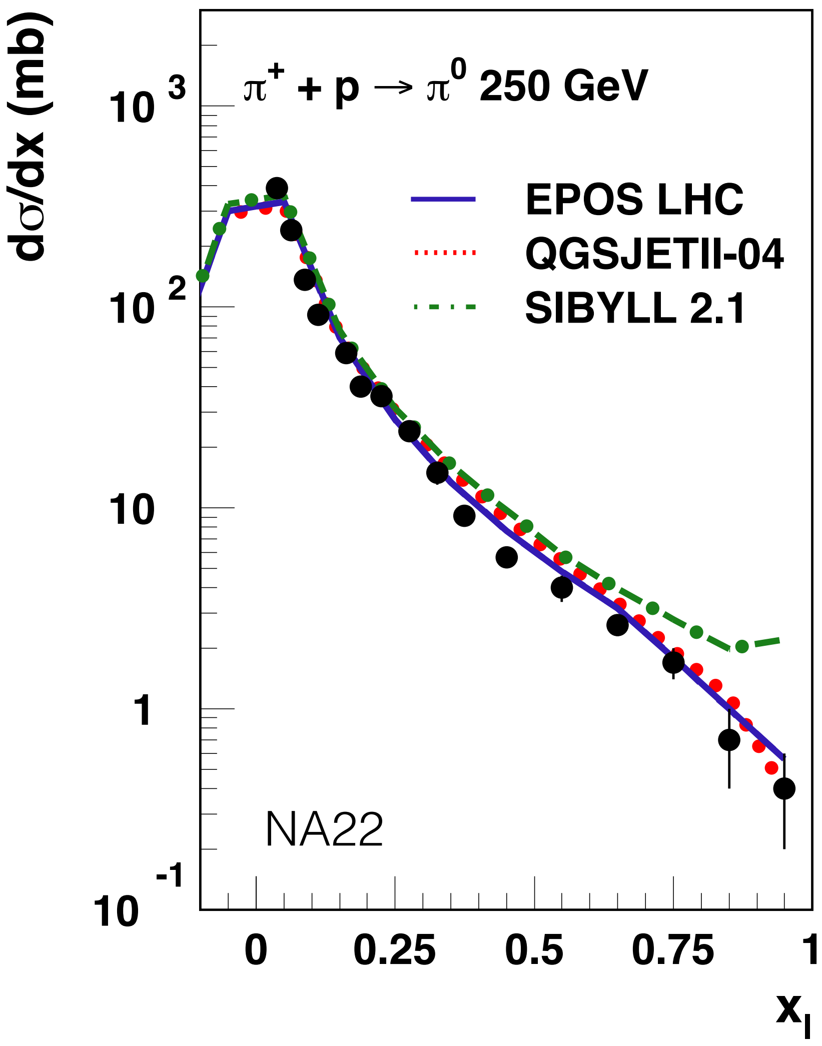


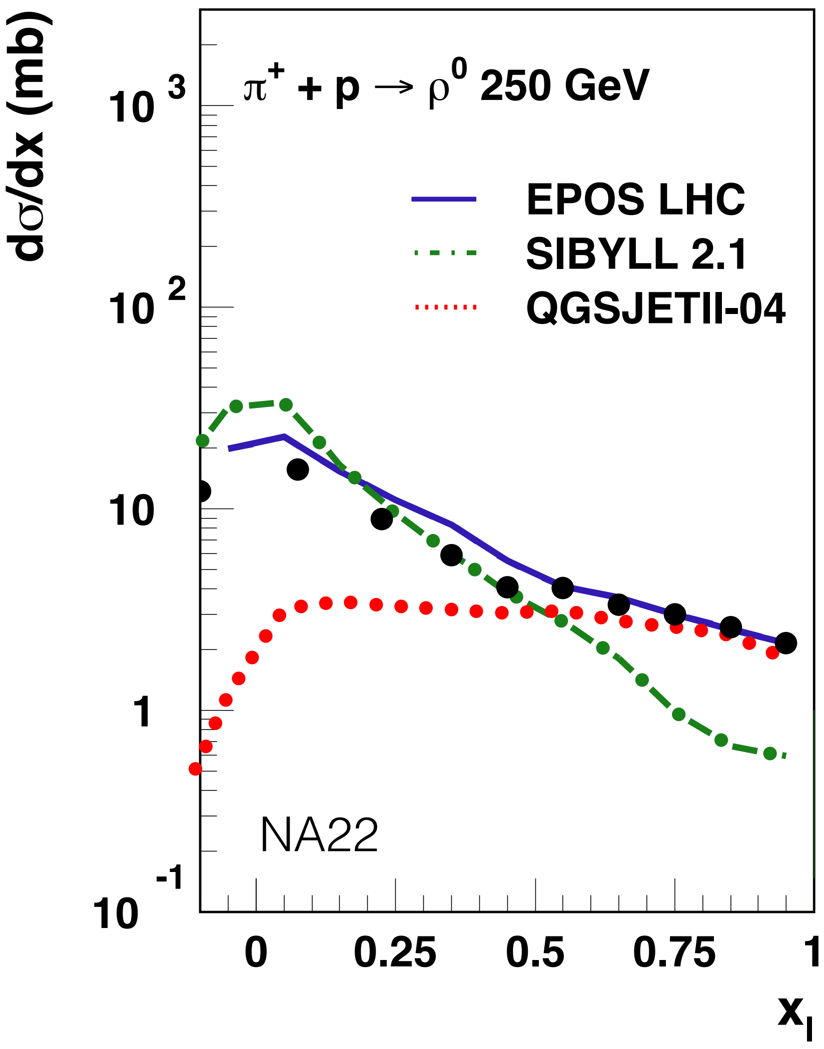




(NA61, Hervé ICRC 2015, Unger CRIS 2015)

Open questions related to rho production

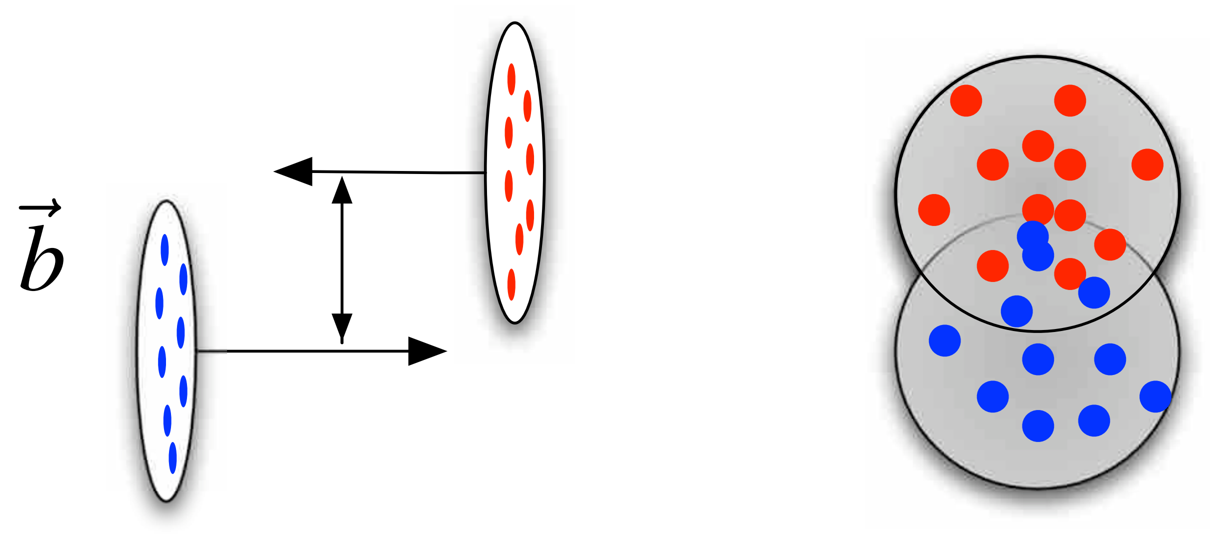




- EPOS and QGSJet tuned to reproduce π-p data
- Apparently origin of rho production not understood
- Suppression of π^0 production rather strong
- Energy dependence of these effects could be important

(Pierog 2015)

Multiple interaction model: underlying ideas



(effective field theory: Gribov-Regge theory)

Overlap function

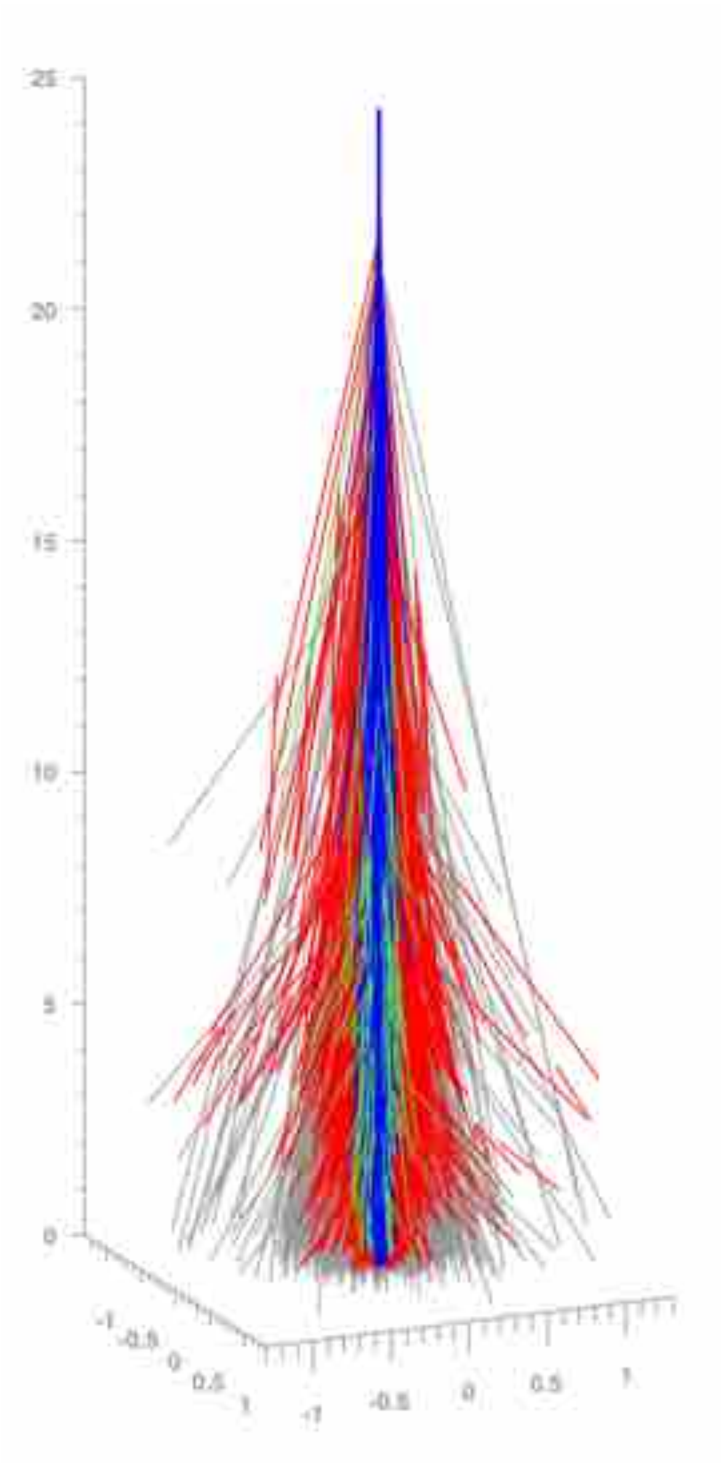
Independent hard interactions:
Poisson distribution

$$P_n = \frac{\langle n(\vec{b})\rangle^n}{n!} \exp\left(-\langle n(\vec{b})\rangle\right)$$

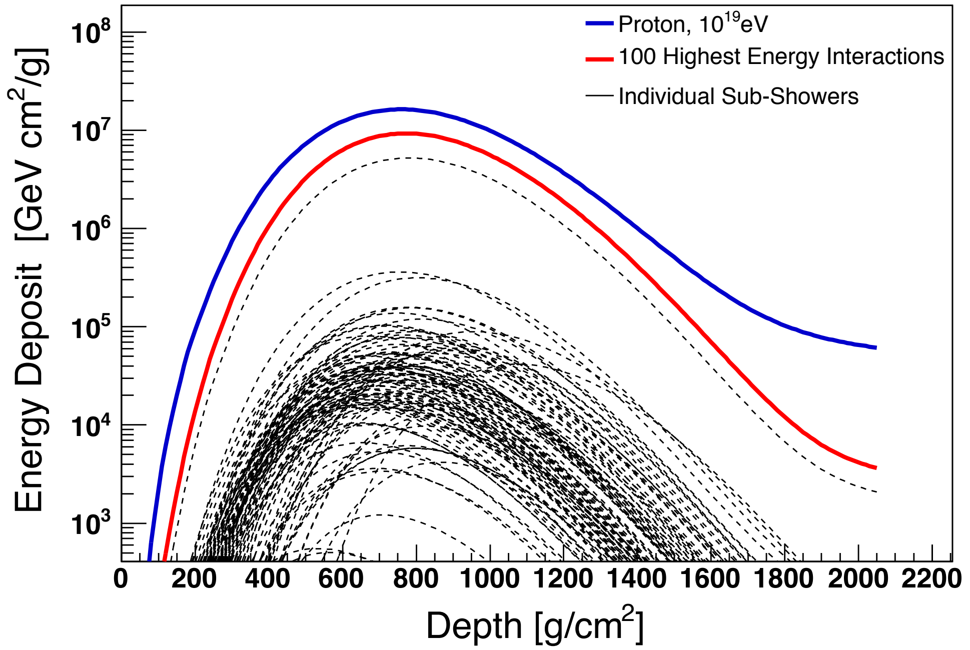
$$\langle n(\vec{b})\rangle = \sigma_{\mathrm{QCD}}\, A(s,\vec{b})$$

$$\sigma_{\mathrm{ine}} = \int d^2\vec{b} \sum_{n=1}^{\infty} P_n = \int d^2\vec{b} \left(1 - \exp\{-\sigma_{\mathrm{QCD}}\, A(s,\vec{b})\}\right)$$

Importance of different interaction energies



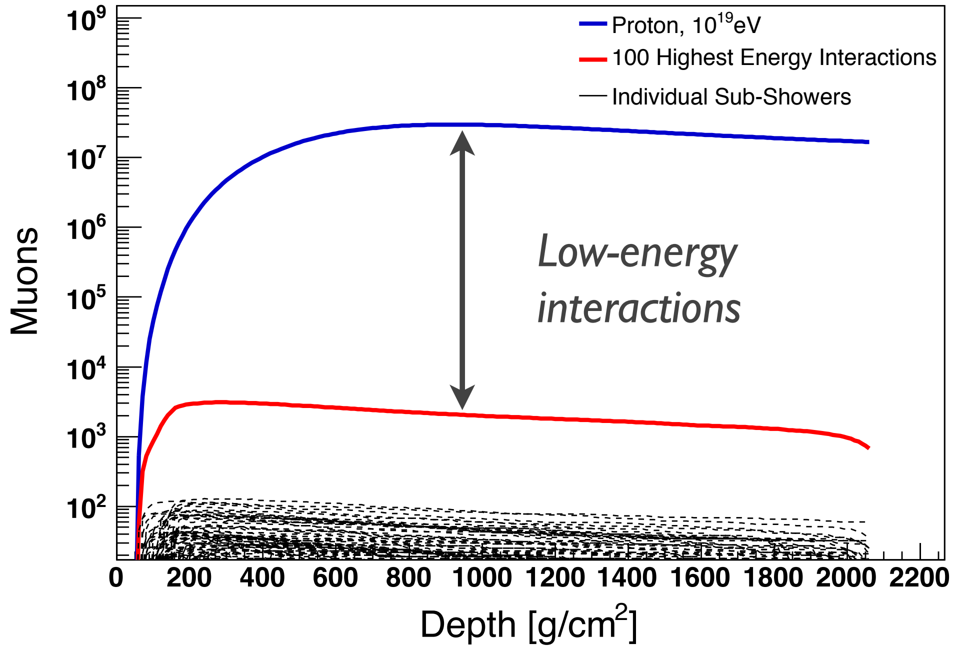
Electrons



Shower particles produced in 100 interactions of highest energy

Electrons/photons: high-energy interactions

Muons

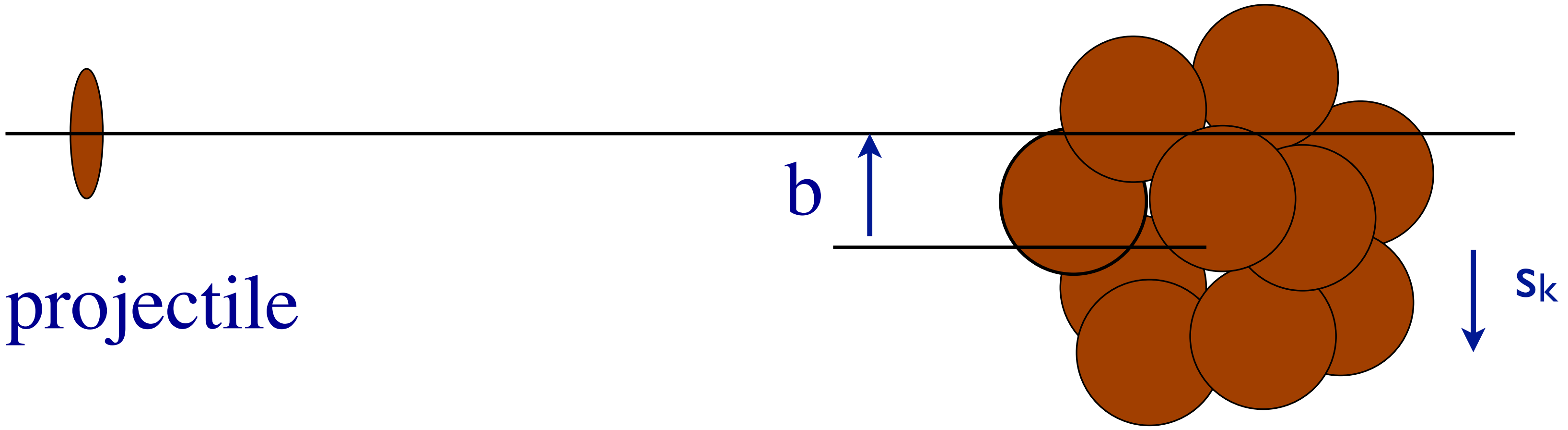


(Ulrich, APS 2012)

Muons/hadrons: low-energy interactions

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

Interaction of hadrons with nuclei



Glauber approximation:

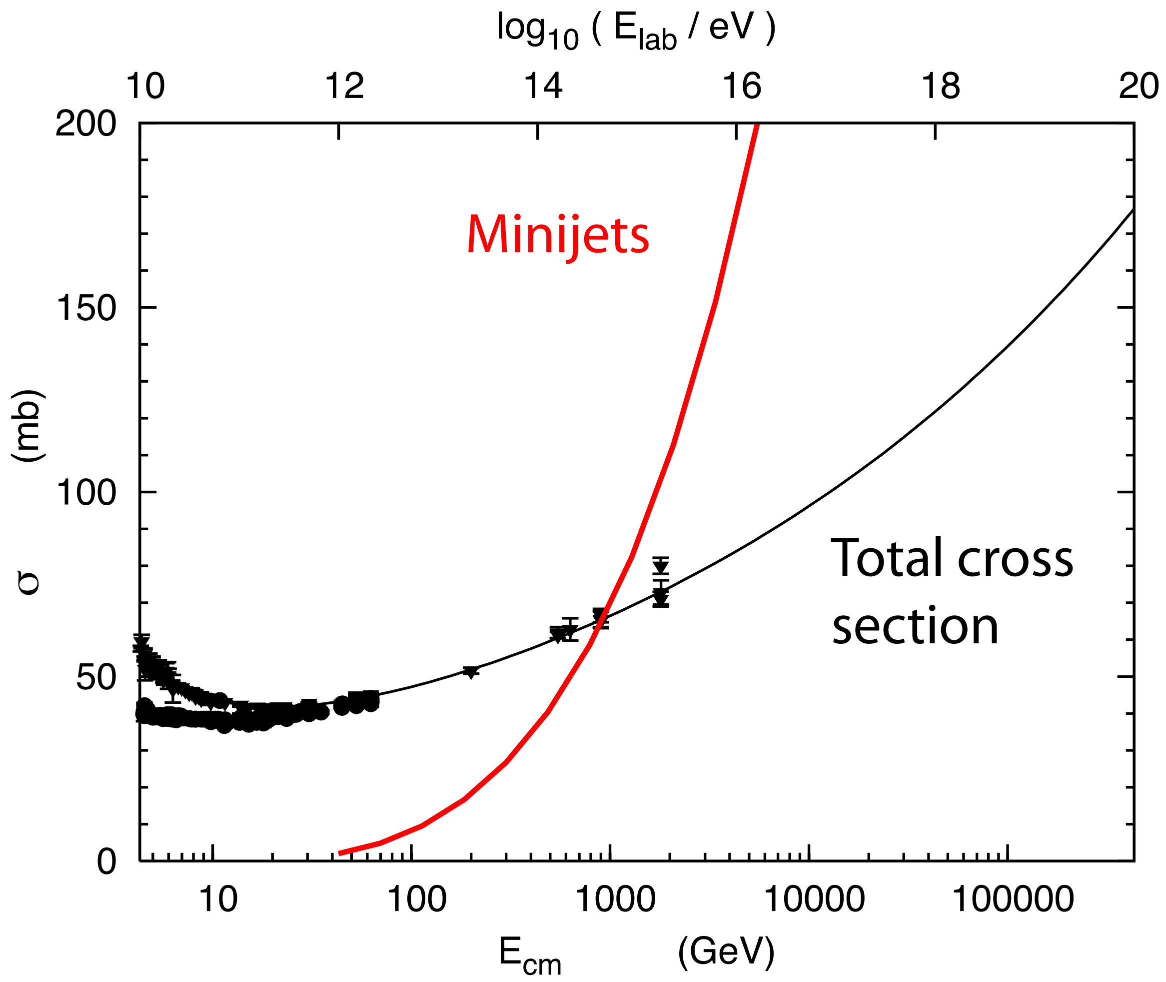
$$\sigma_{\mathrm{inel}} = \int d^2\vec{b} \left[1 - \prod_{k=1}^{A} \left(1 - \sigma_{\mathrm{tot}}^{NN} T_N(\vec{b} - \vec{s}_k)\right)\right] \approx \int d^2\vec{b} \left[1 - \exp\left\{-\sigma_{\mathrm{tot}}^{NN} T_A(\vec{b})\right\}\right]$$

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

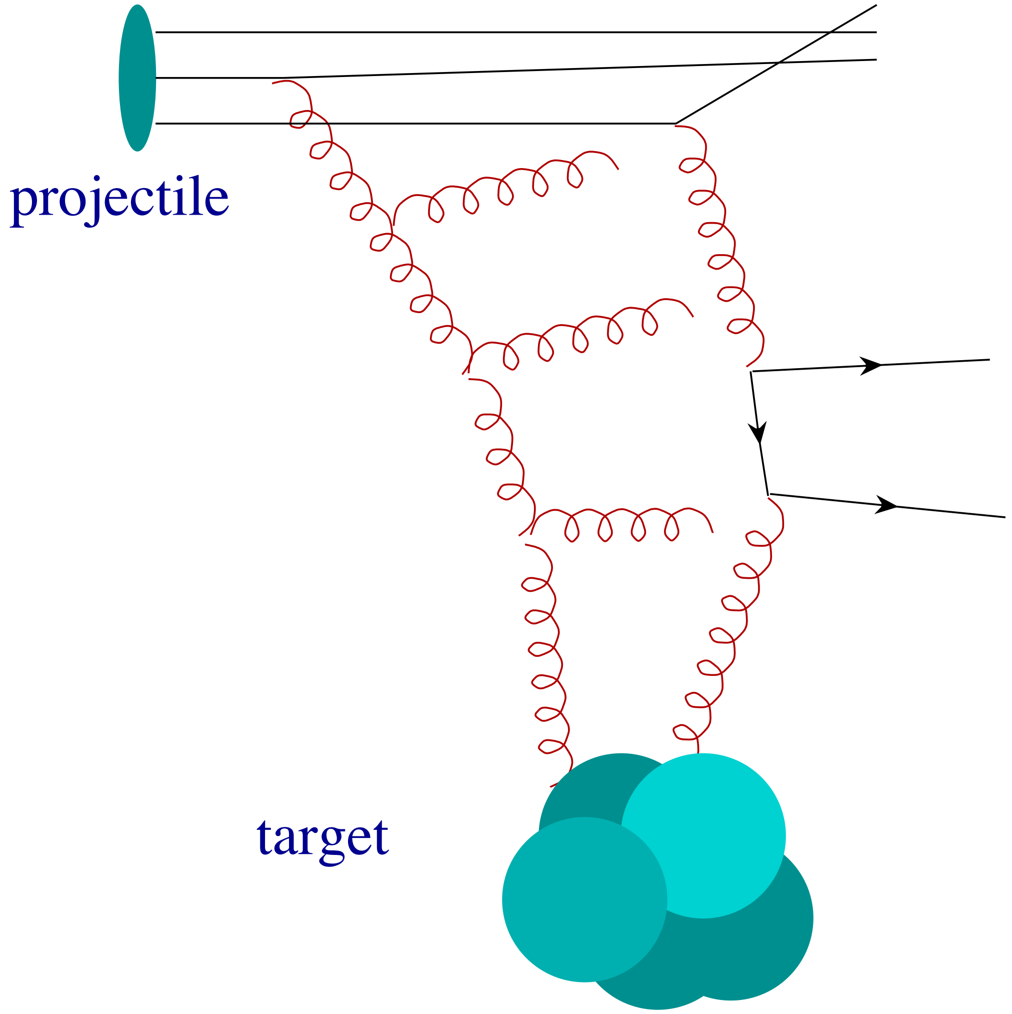
Coherent superposition of elementary nucleon-nucleon interactions

Solution: Multiple parton-parton interactions

Proton-proton cross section



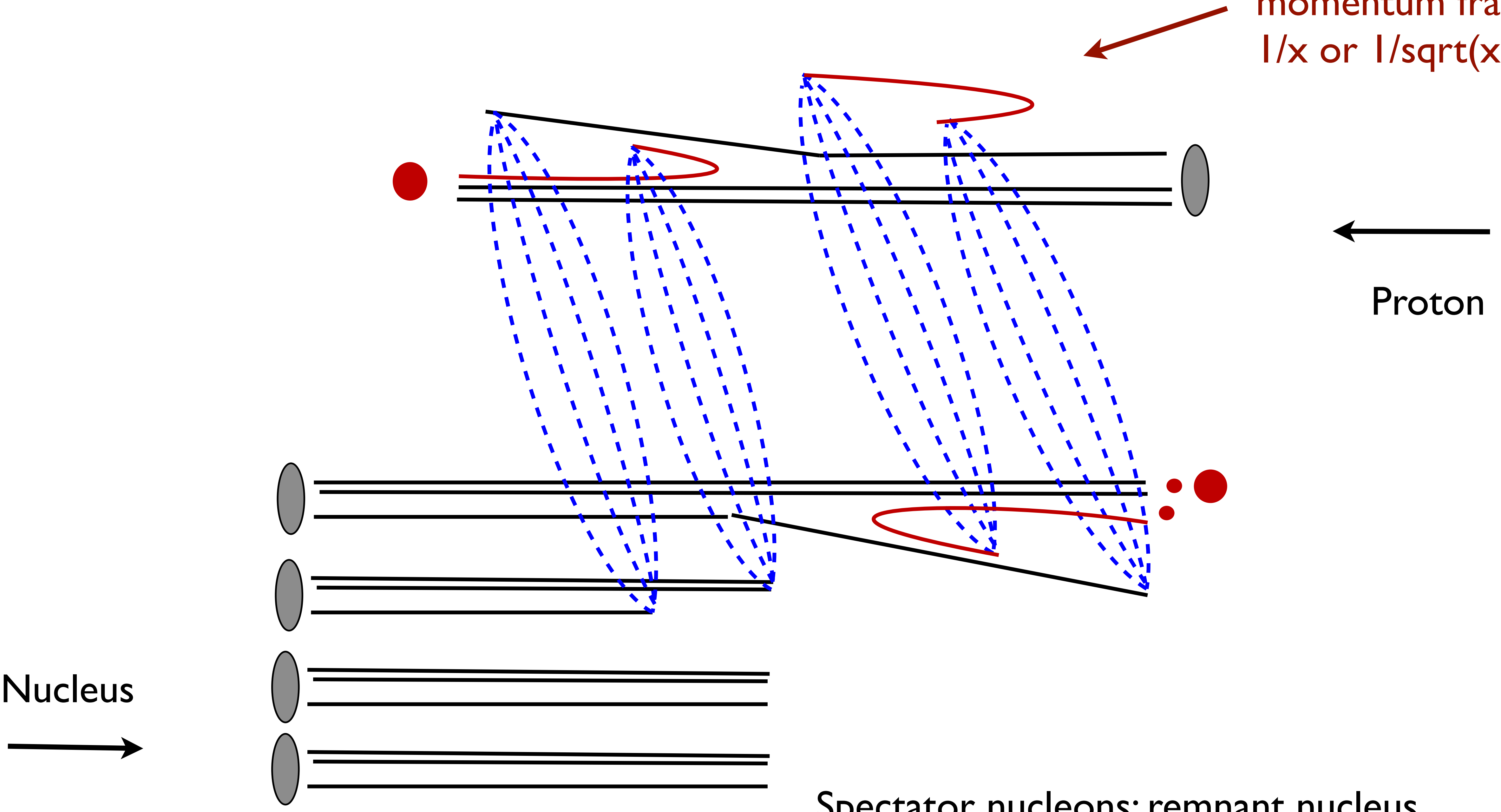
QCD prediction:
inclusive cross section



Average number of minijet pairs

$$\langle n_{\rm jet} \rangle = \frac{\sigma_{\rm QCD}}{\sigma_{\rm ine}}$$

String configuration for nucleus as target



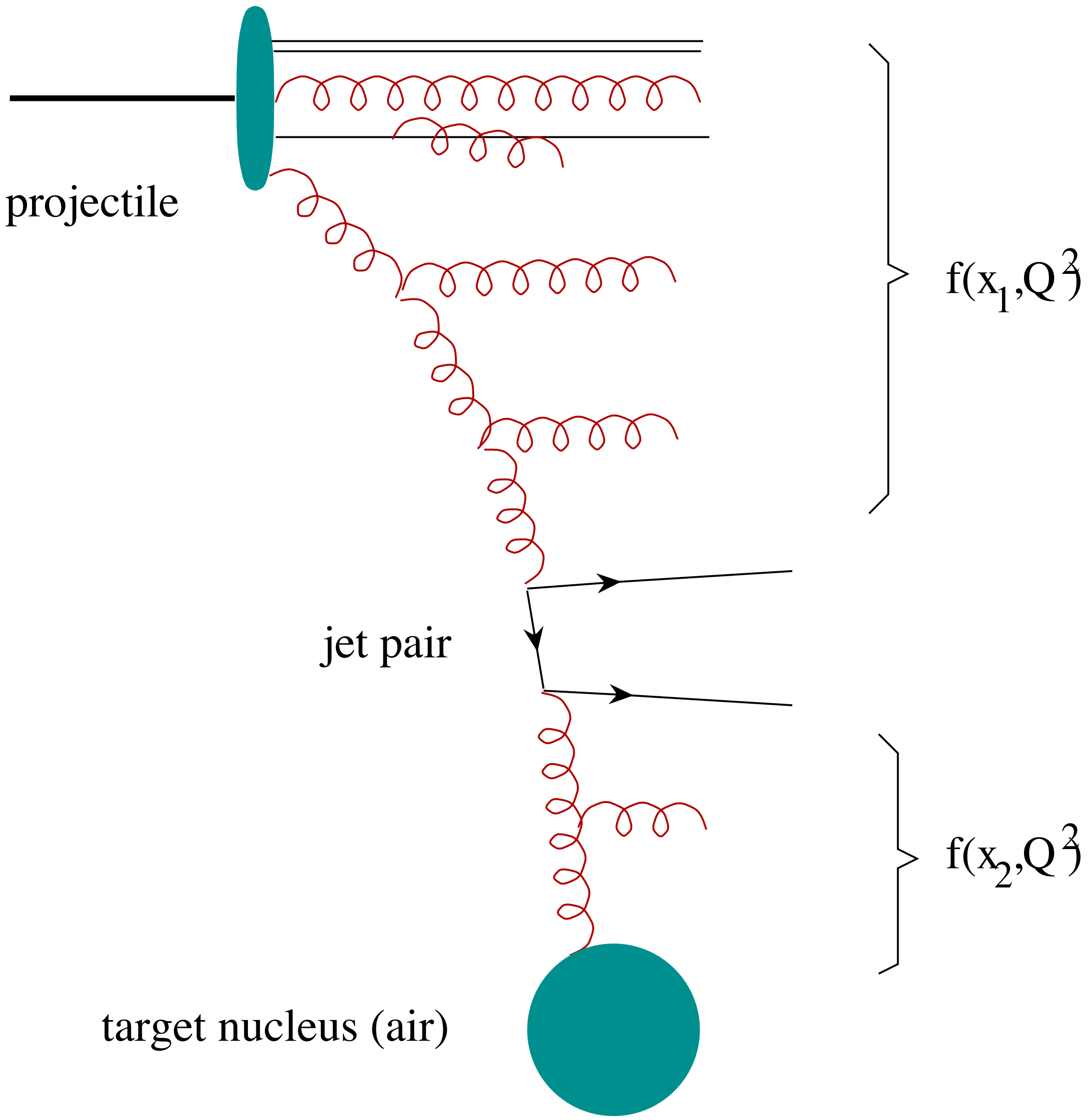
New quark pair with momentum fraction 1/x or 1/sqrt(x)

Proton

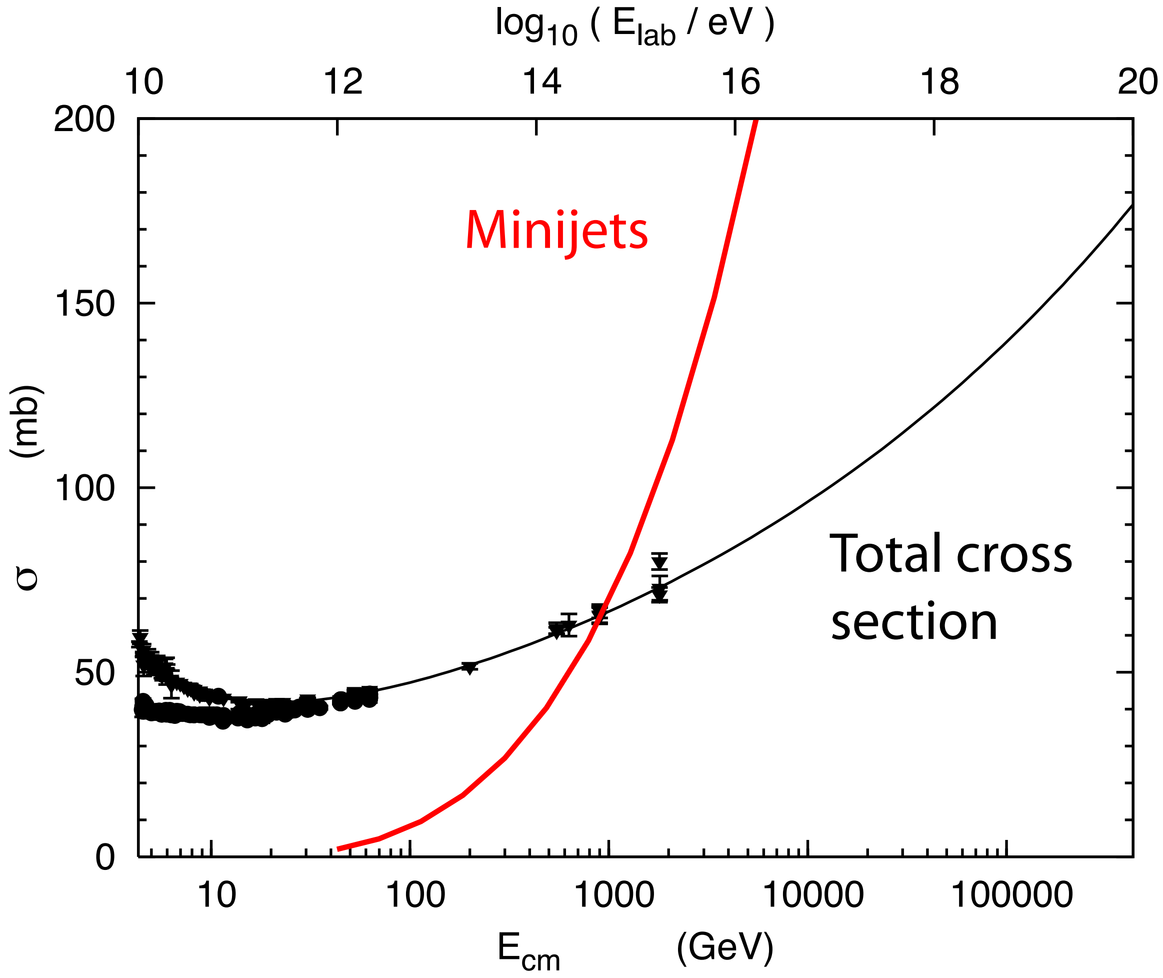
Nucleus

Spectator nucleons: remnant nucleus

QCD parton model: minijets

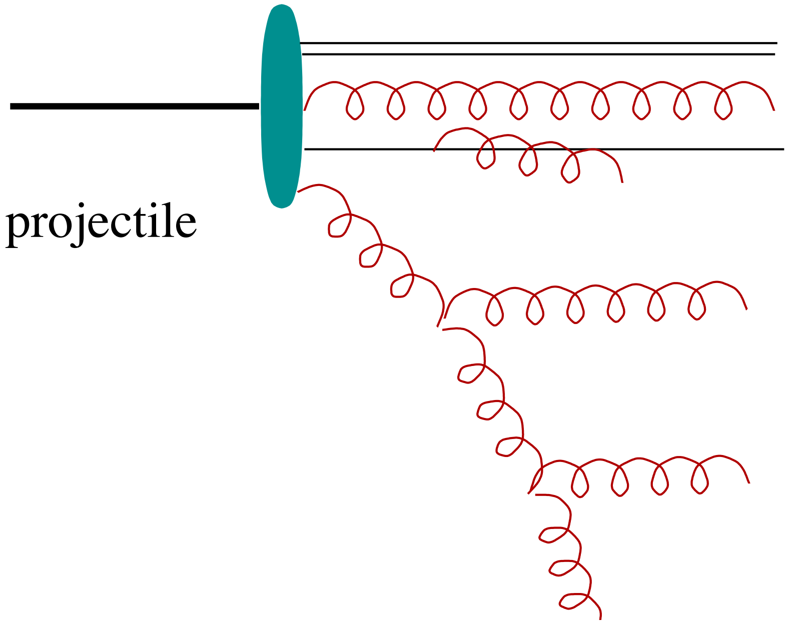


Proton-proton cross section



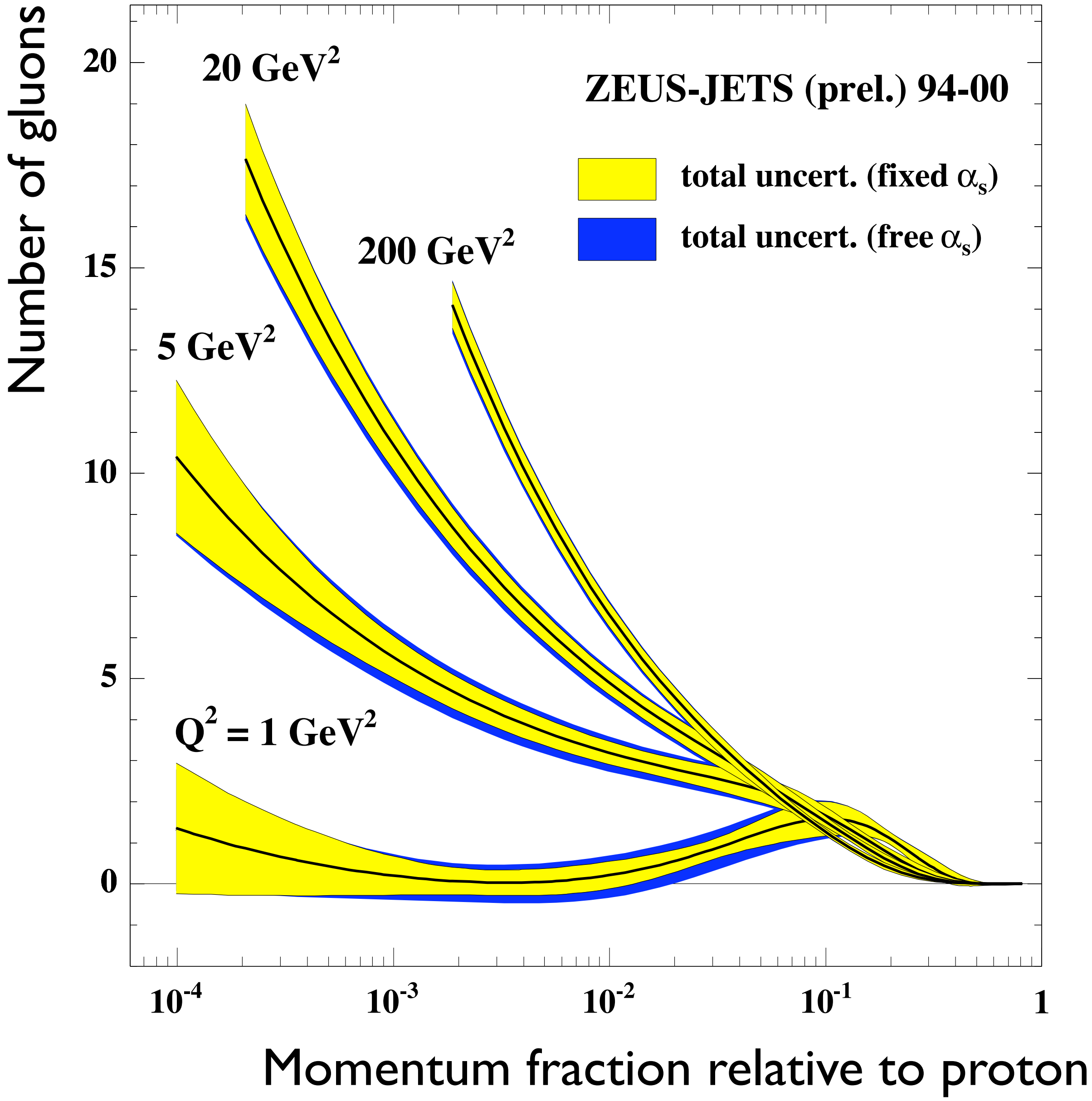
$$\sigma_{QCD} = \sum_{i,j,k,l} \frac{1}{1+\delta_{kl}} \int dx_1\, dx_2 \int_{p_\perp^{\mathrm{cutoff}}} dp_\perp^2\, f_i(x_1,Q^2)\, f_j(x_2,Q^2)\, \frac{d\sigma_{i,j\to k,l}}{dp_\perp}$$

Perturbative QCD predictions for parton densities



Evolution of parton number
given by DGLAP equation
(and non-linear versions of it)

HERA data

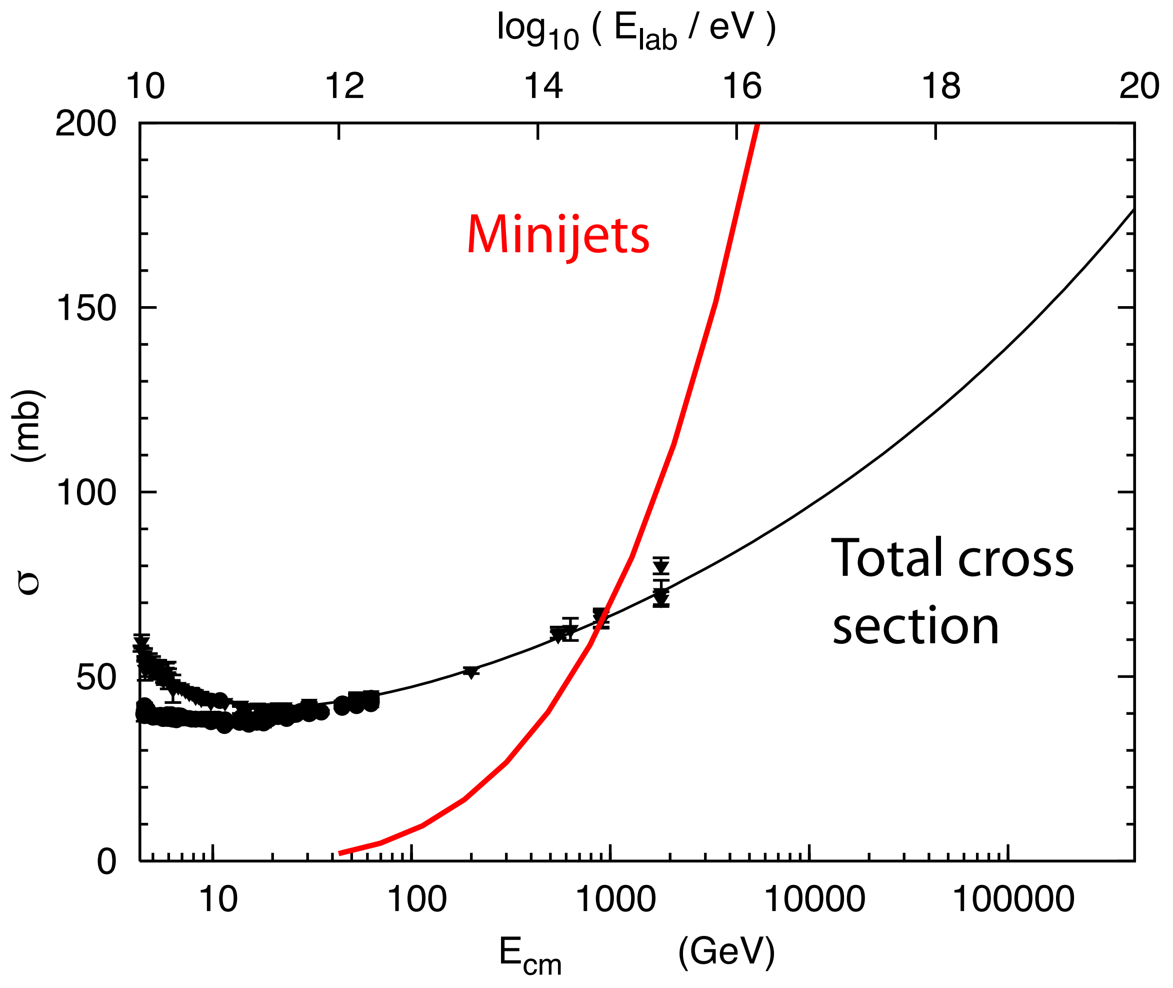


$$\frac{d f_i(x,Q^2)}{d\log Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dy}{y} \sum_j f_j(y,Q^2)\, P_{j\to i}\left(\frac{x}{y}\right)$$

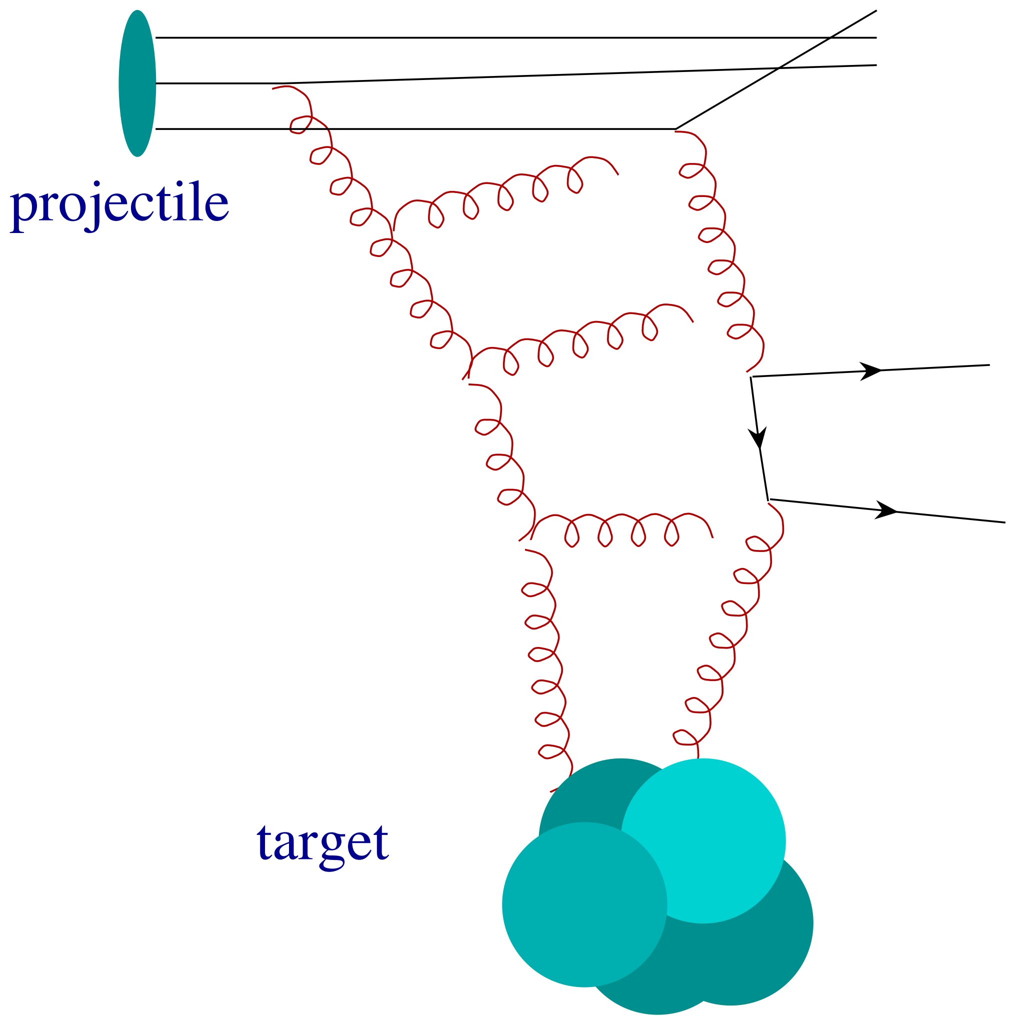
Prediction of
perturbative QCD

Solution: Multiple parton-parton interactions

Proton-proton cross section



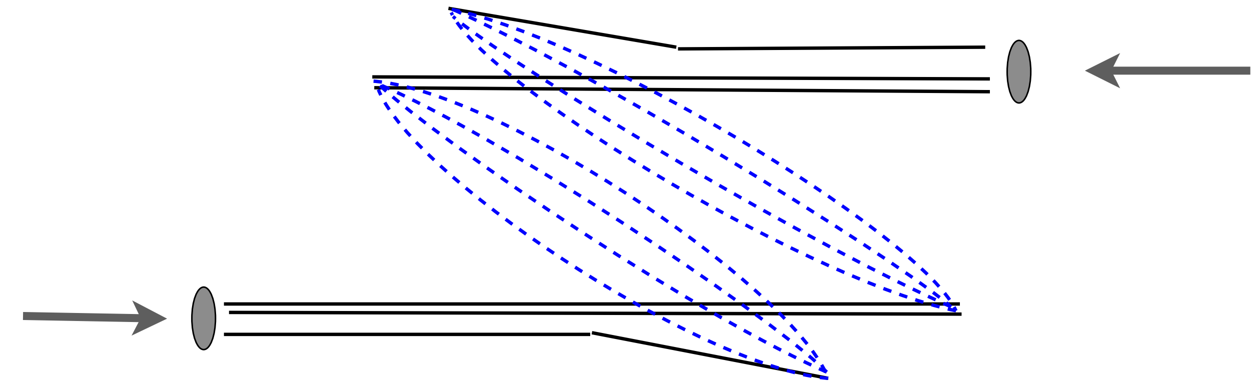
QCD prediction:
inclusive cross section



Average number of minijet pairs

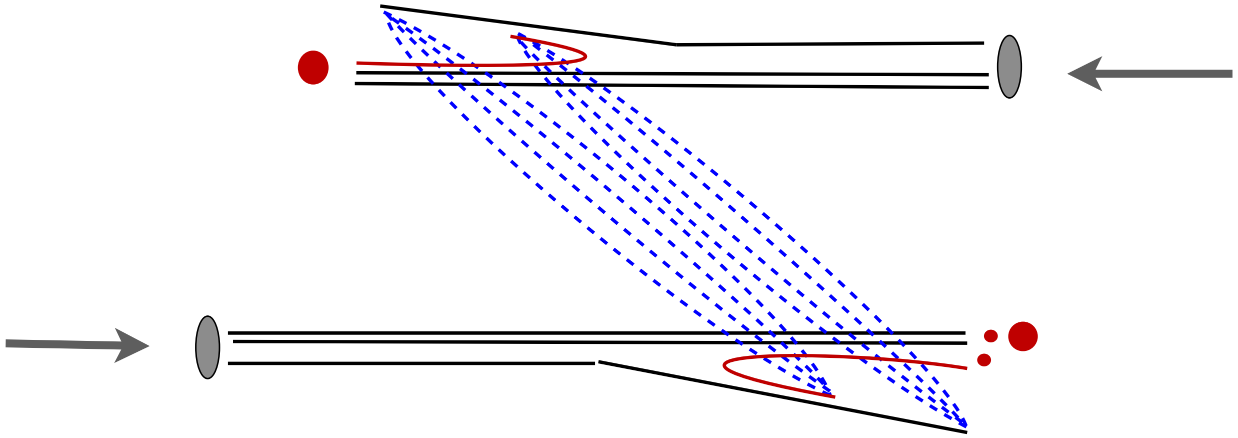
$$\langle n_{\text{jet}} \rangle = \frac{\sigma_{\text{QCD}}}{\sigma_{\text{ine}}}$$

Different implementations



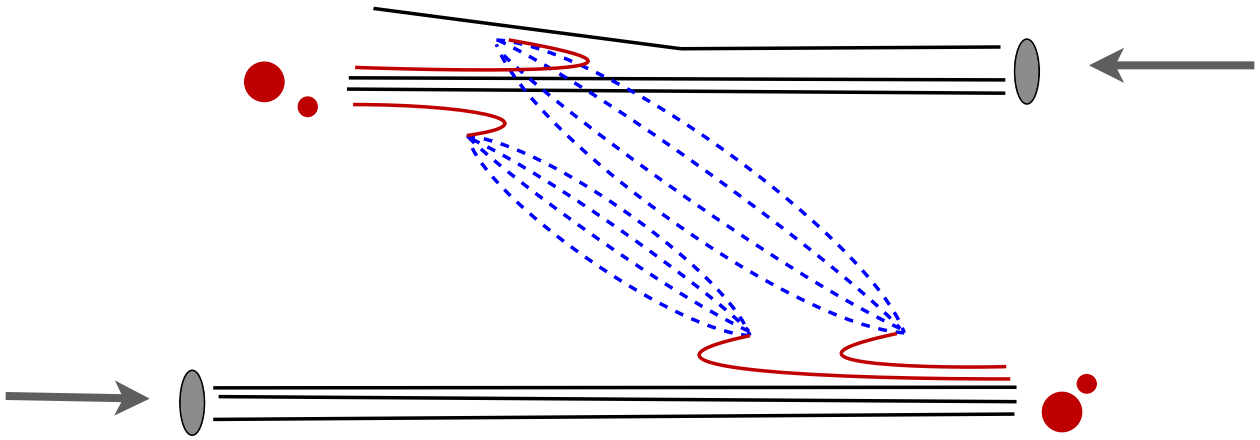
SIBYLL:

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