

High Energy Cosmic Ray Interactions

(Lecture 3: High energy interactions)

Ralph Engel

Karlsruhe Institute of Technology (KIT)

Outline

Lecture 1 – Basics, low-energy interactions

- Energies, projectile and target particles
- Cross sections
- Particle production threshold: resonances
- Hadronic interactions of gamma-rays

Lecture 2 – Intermediate energy physics

- Intermediate energy range: two-string models
- String fragmentation
- Rapidity, Feynman scaling
- Inclusive fluxes, spectrum weighted moments

Lecture 3 – Nuclei, highest energies, air shower phenomenology

- Extension to nuclei
- Minijets, multiple interactions, scaling violation
- Model predictions, uncertainties
- Outlook: accelerator measurements

Extension to nuclei

Interaction of photons with nuclei

Purely electromagnetic excitations:

- $E_\gamma \leq 20$ MeV: E and M transitions, Giant Dipole resonance, selection according to quantum numbers
- $50 \leq E_\gamma \leq 150$ MeV: mainly photon absorption by p and p-n pair
- evaporation: neutron, quasi-deuteron and alpha-particle emission

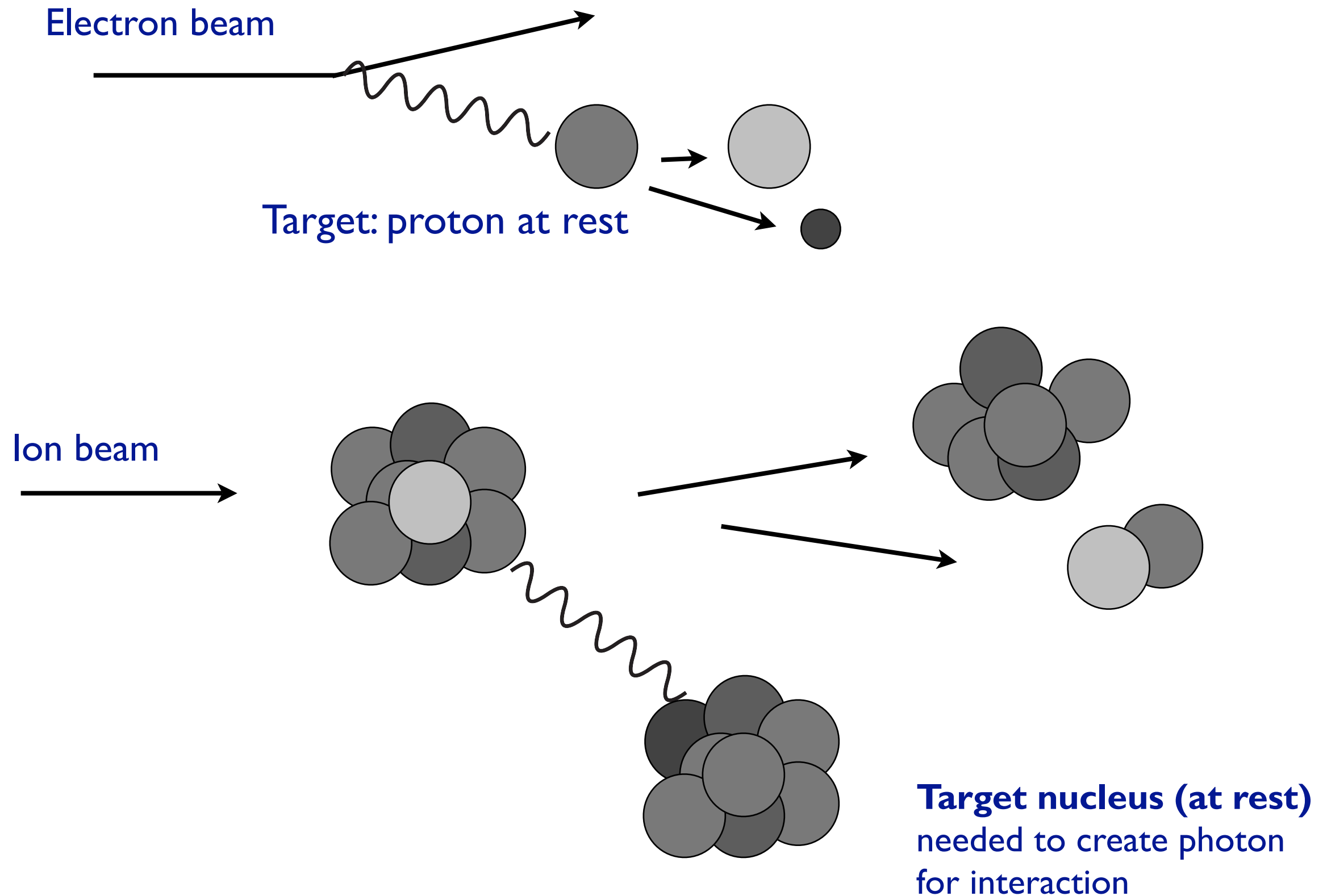
Hadronic interactions (particle production):

- $150 \leq E_\gamma \leq \text{few GeV}$: single nucleon absorption of photon
- intra-nuclear cascade of secondaries (formation time)
- evaporation, fission, multifragmentation

Available code packages

- RELDIS (RElativistic ELectromagnetic DISsociation) *I. Pshenichnov*
- FLUKA (FLUktuierende KAskade) *A. Ferrari et al. & G.I. Smirnov*

Measurement of nucleus disintegration

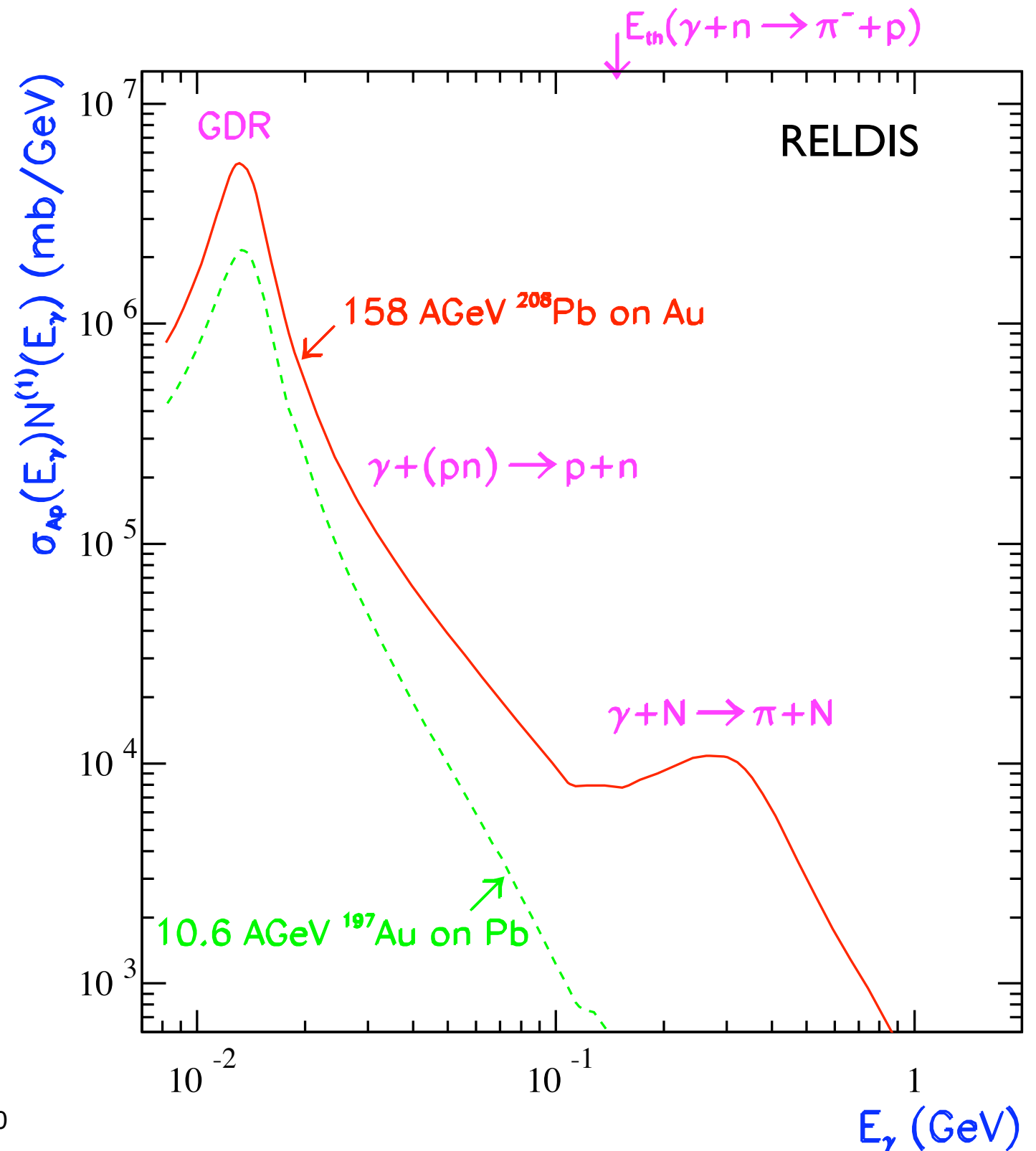
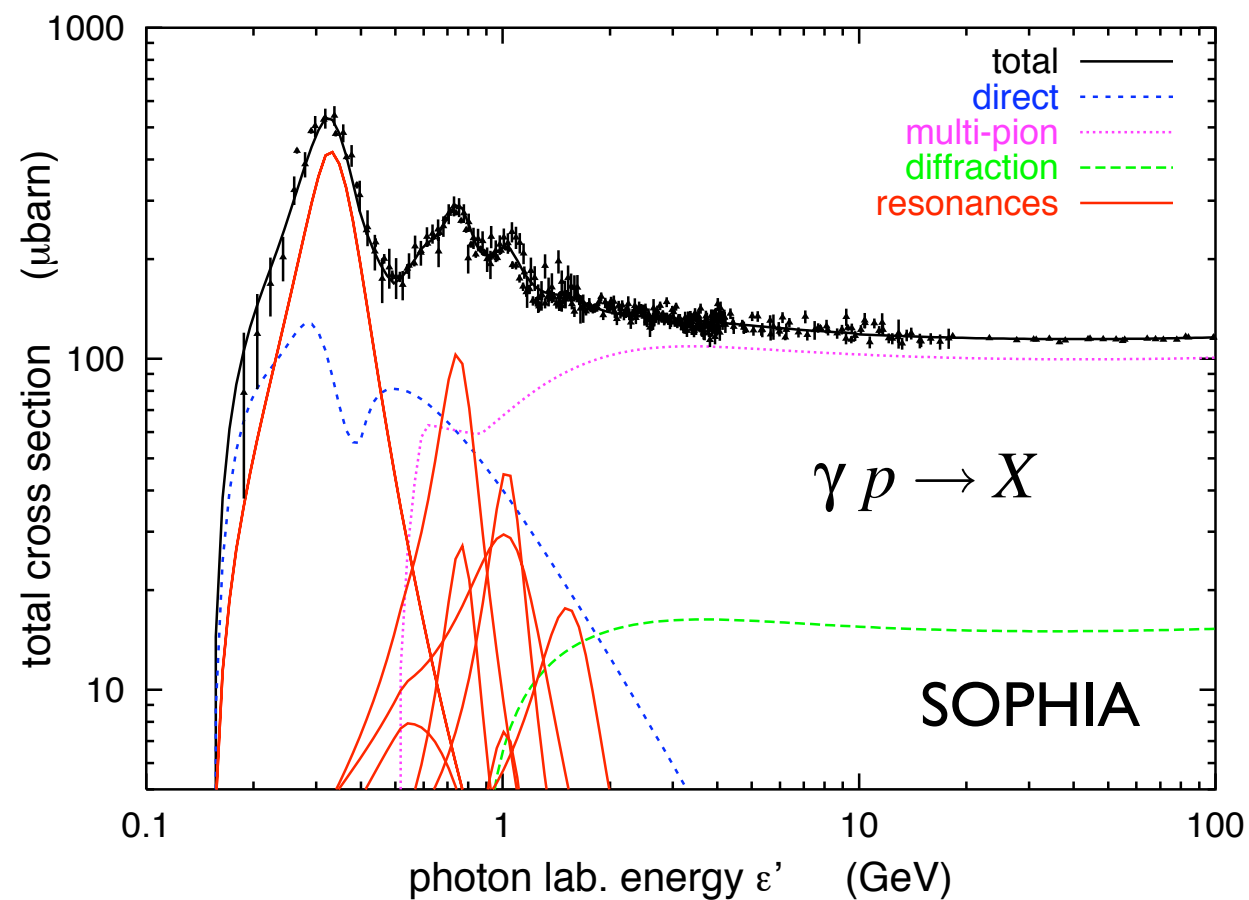


Effective em. dissociation cross section

Main contribution:
giant dipole resonance

Dominant emission processes:

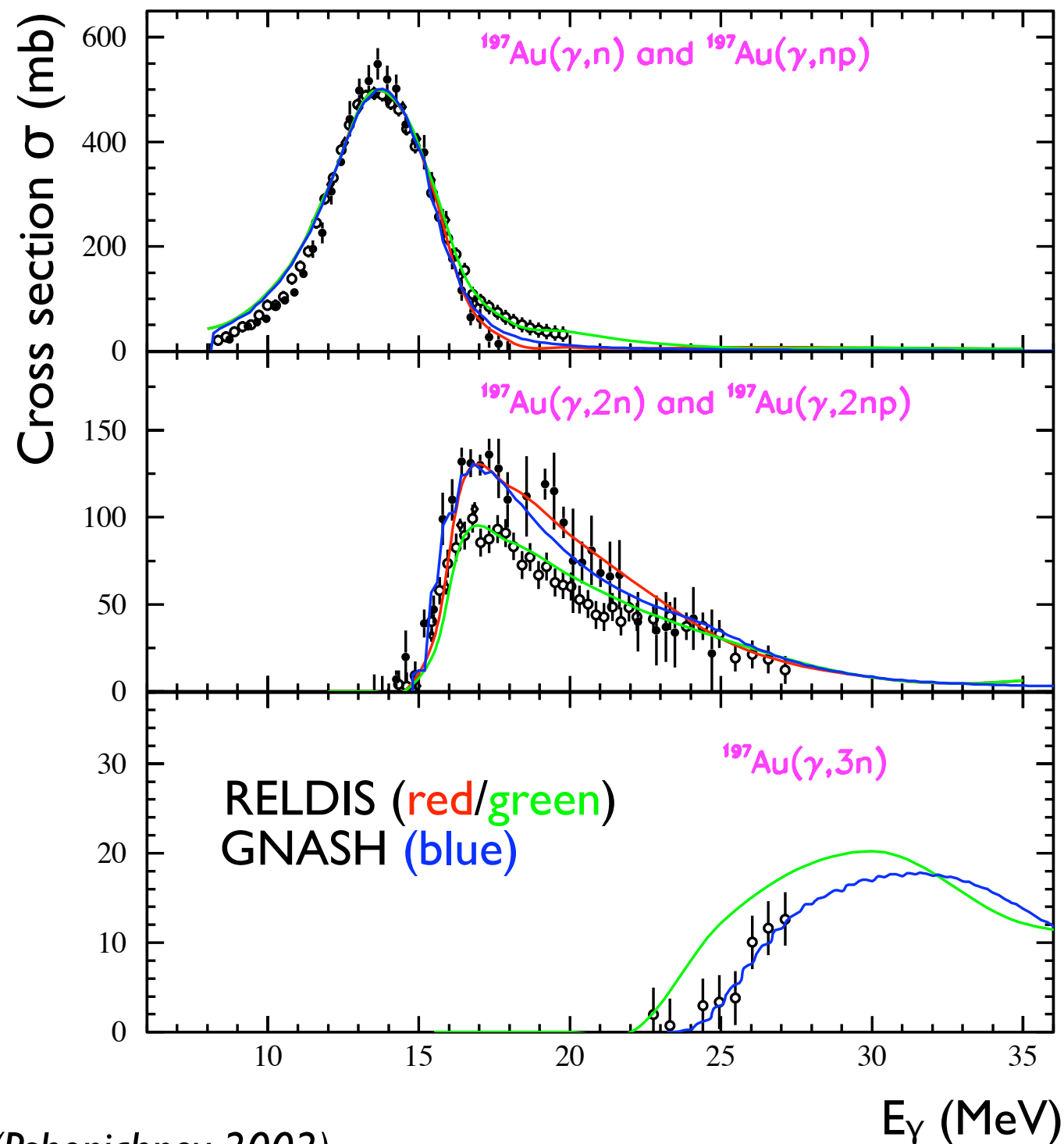
- single nucleon
- quasi-deuteron
- alpha particle



(Pshenichnov 2002)

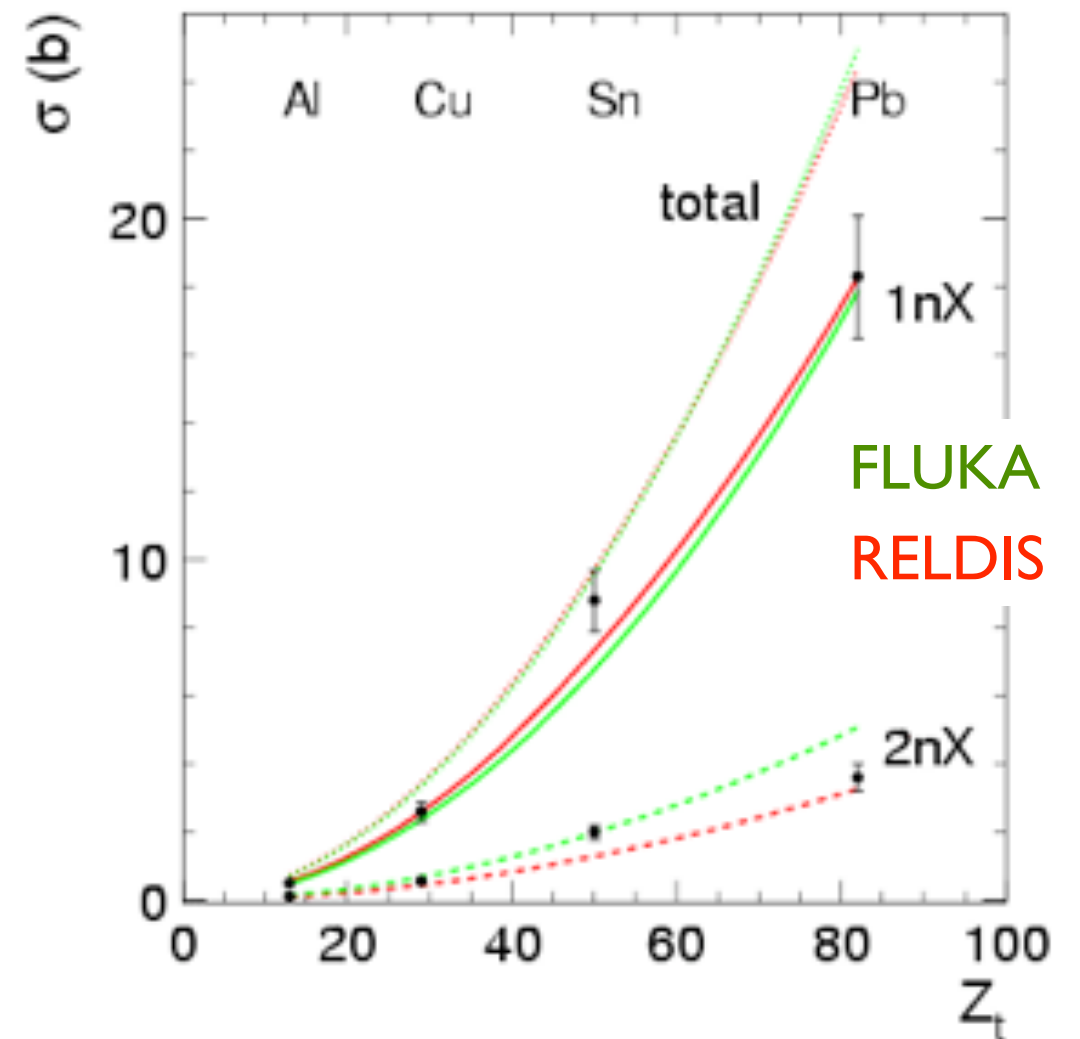
Example: photo-dissociation of nuclei

Saclay & Livermore data



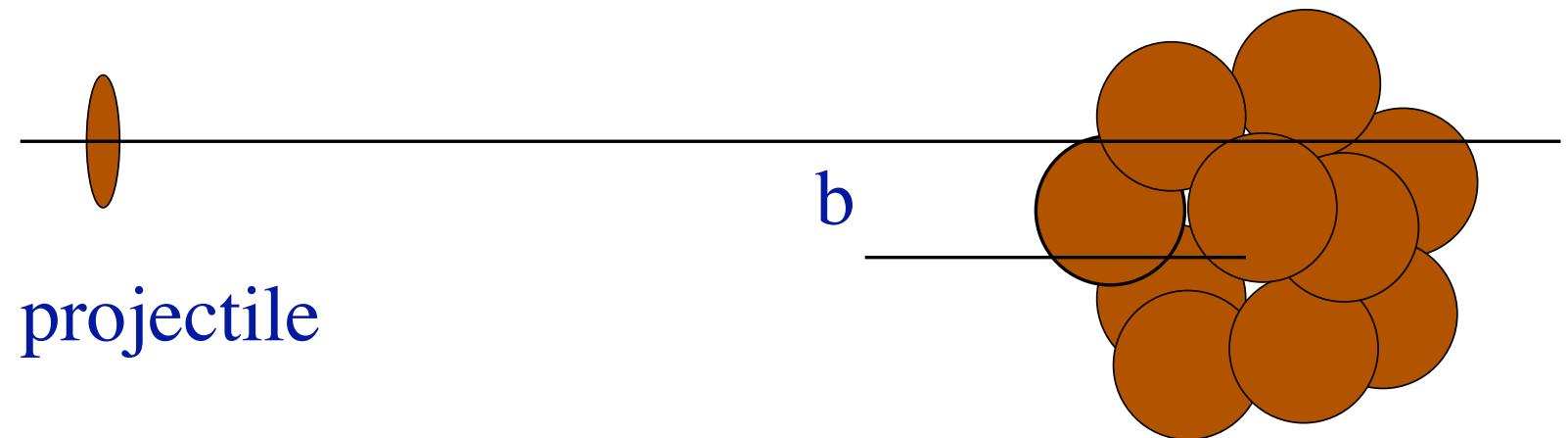
(Pshenichnov 2002)

Projectile: 30 AGeV Pb,
different targets



(Smirnov, 2005)

Interaction of hadrons with nuclei



Standard Glauber approximation:

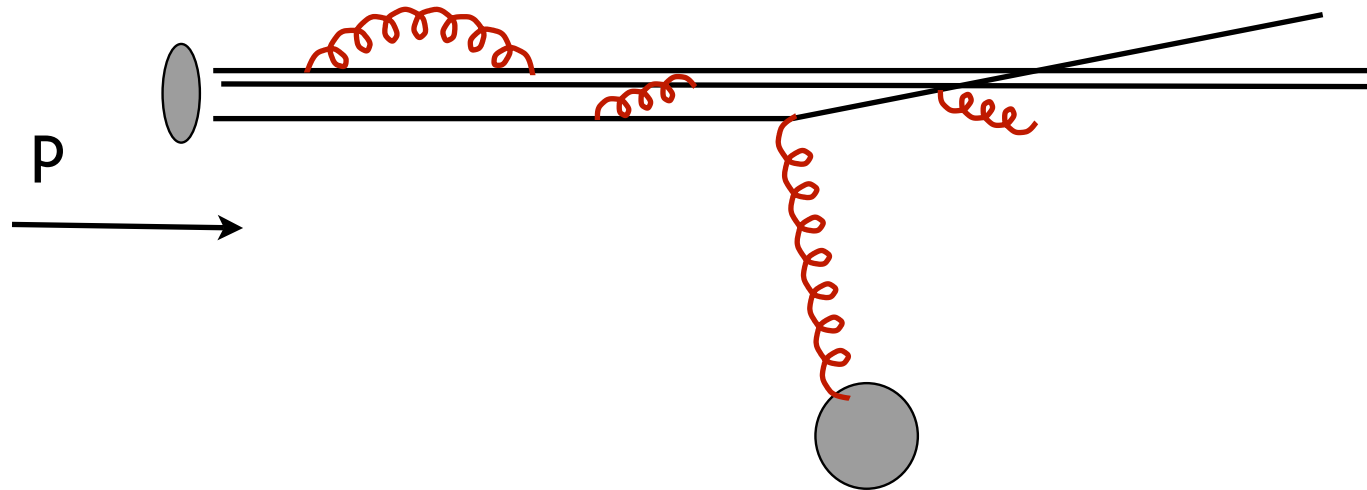
$$\sigma_{\text{inel}} = \int d^2\vec{b} \left[1 - \prod_{k=1}^A \left(1 - \sigma_{\text{tot}}^{NN} T_N(\vec{b} - \vec{s}_k) \right) \right] \approx \int d^2\vec{b} \left[1 - \exp \left\{ -\sigma_{\text{tot}}^{NN} T_A(\vec{b}) \right\} \right]$$

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

Coherent superposition
of elementary nucleon-
nucleon interactions

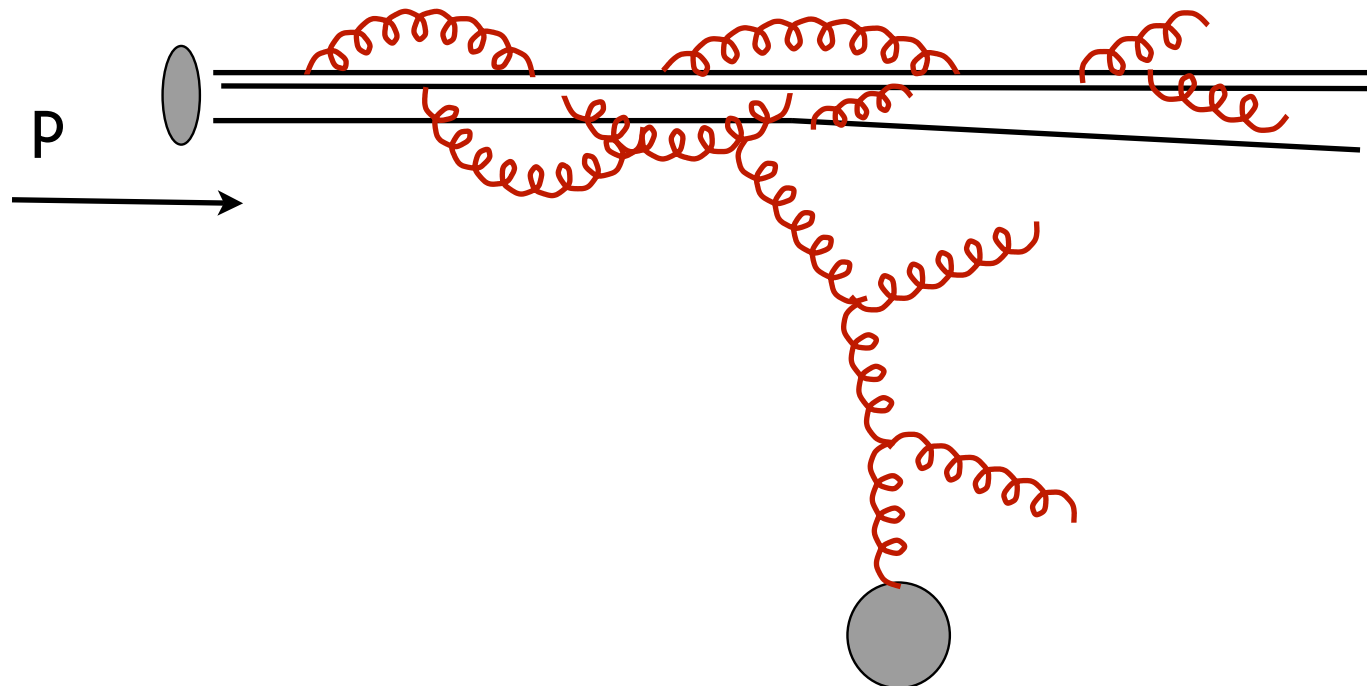
Interactions at high energy

Transition from intermediate to high energy



Intermediate energy:

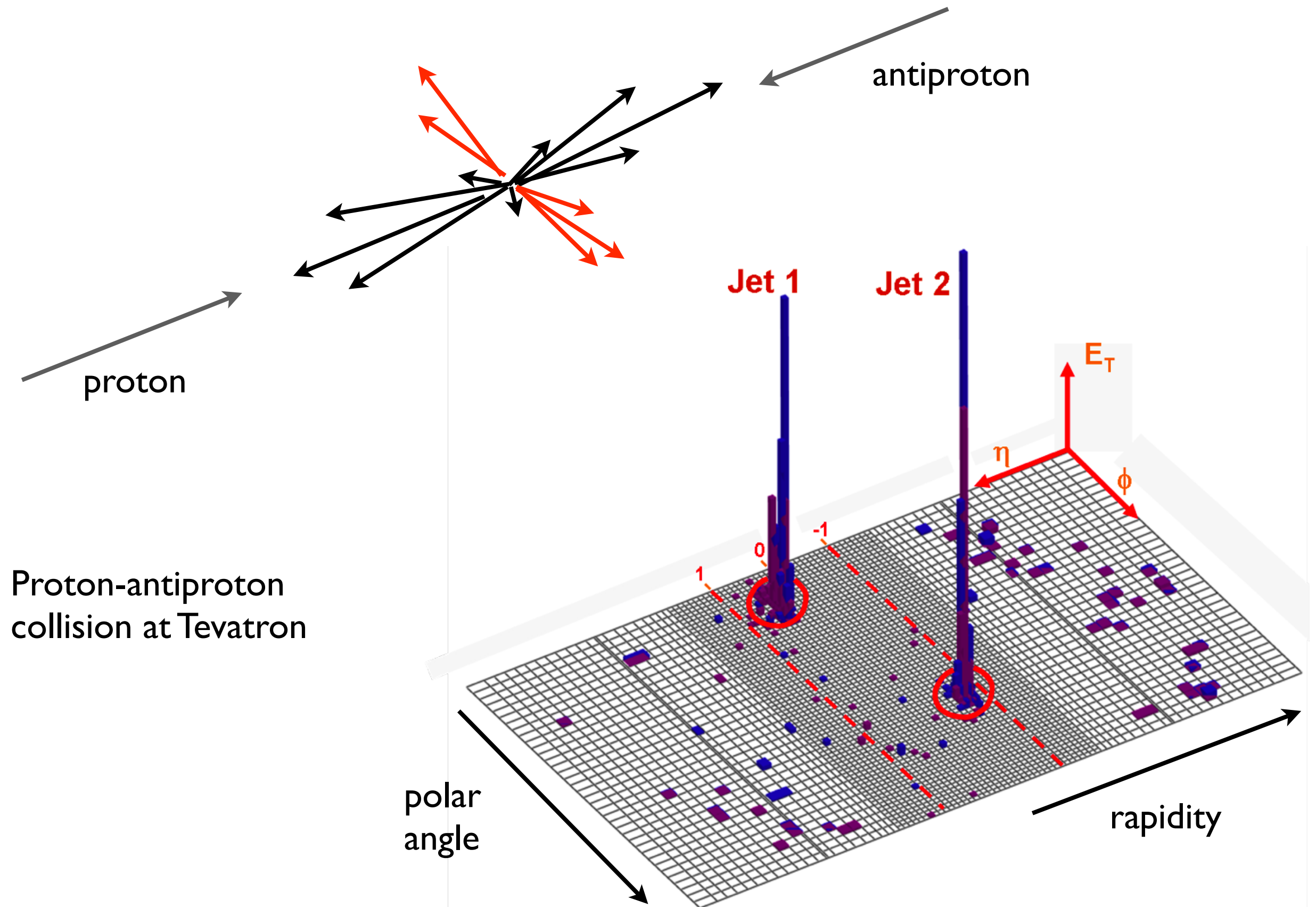
- $E_{\text{lab}} < 1,500 \text{ GeV}$
- $E_{\text{cm}} < 50 \text{ GeV}$
- dominated by valence quarks



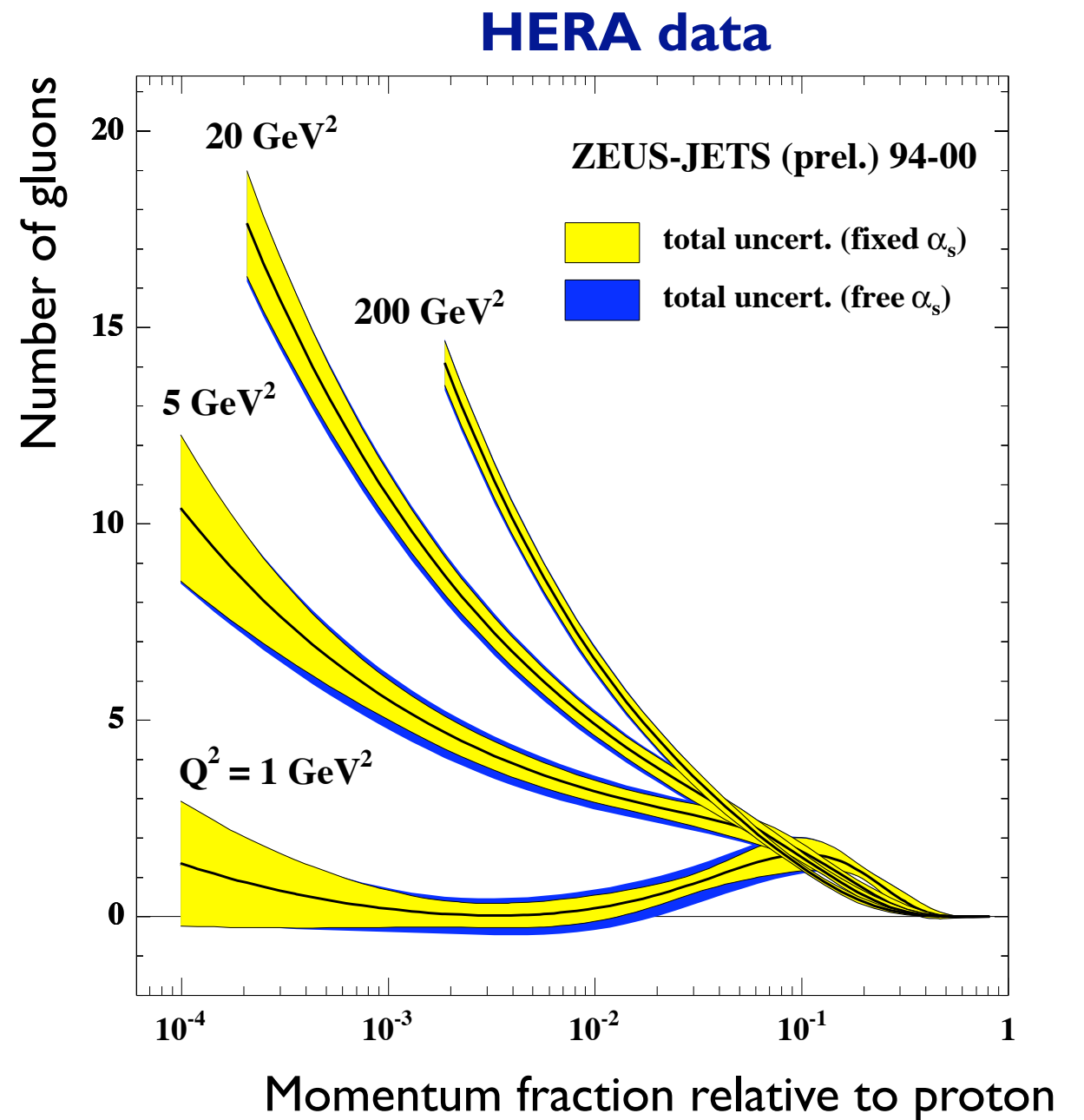
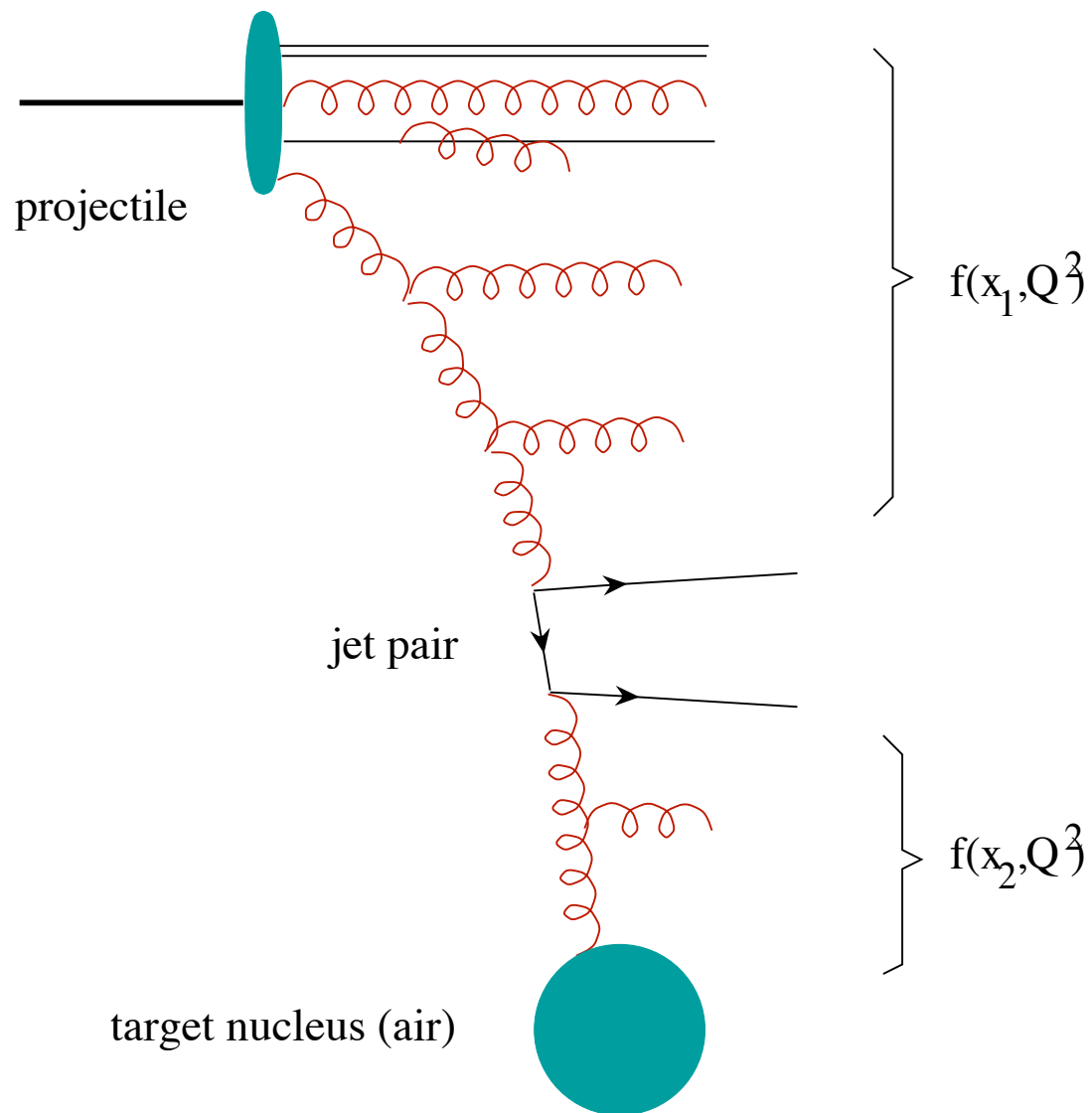
High energy regime:

- $E_{\text{lab}} > 21,000 \text{ GeV}$
- $E_{\text{cm}} > 200 \text{ GeV}$
- dominated by gluons and sea quarks

Scattering of quarks and gluons: jet production

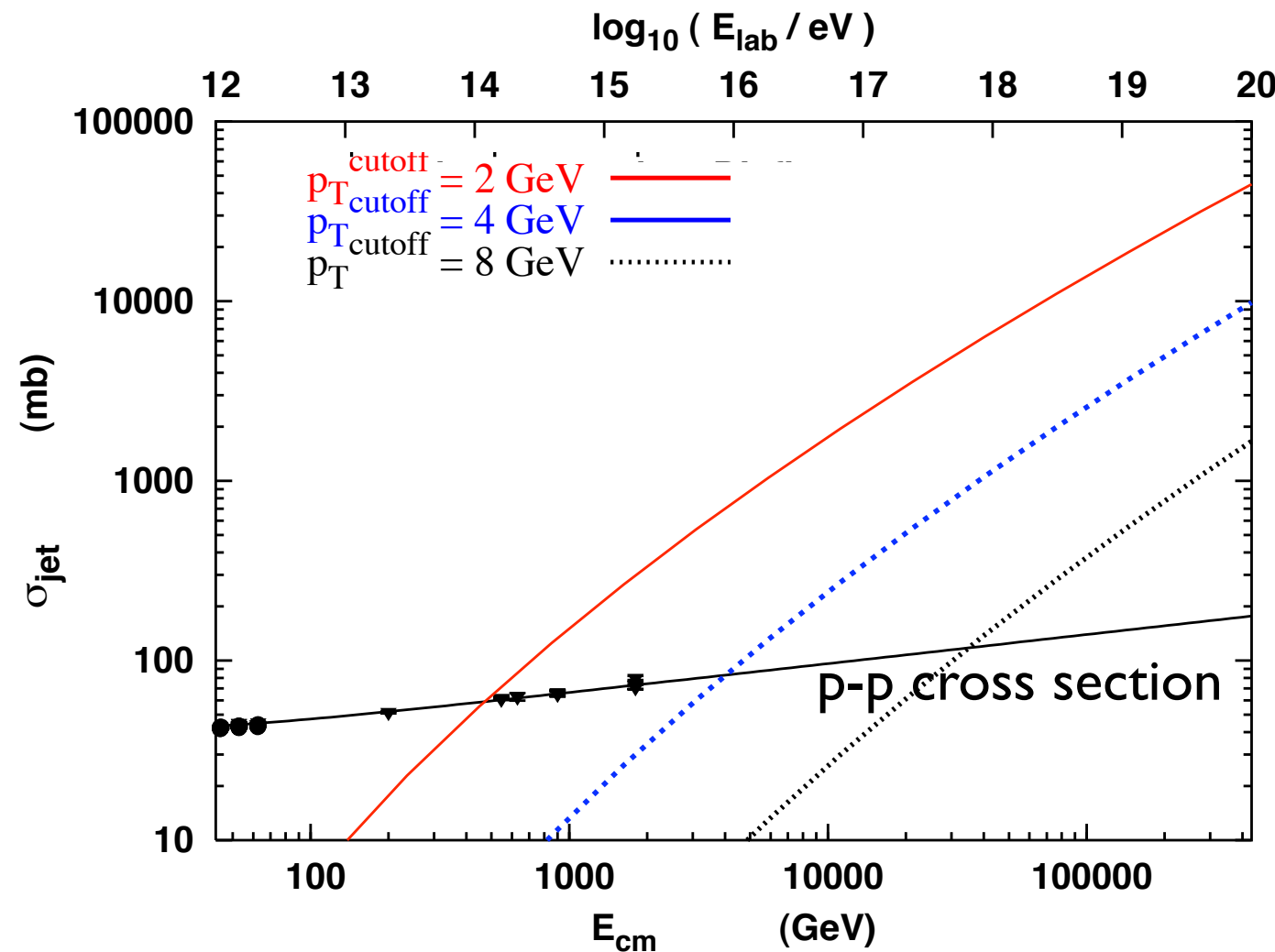


Perturbative QCD predictions for minijets



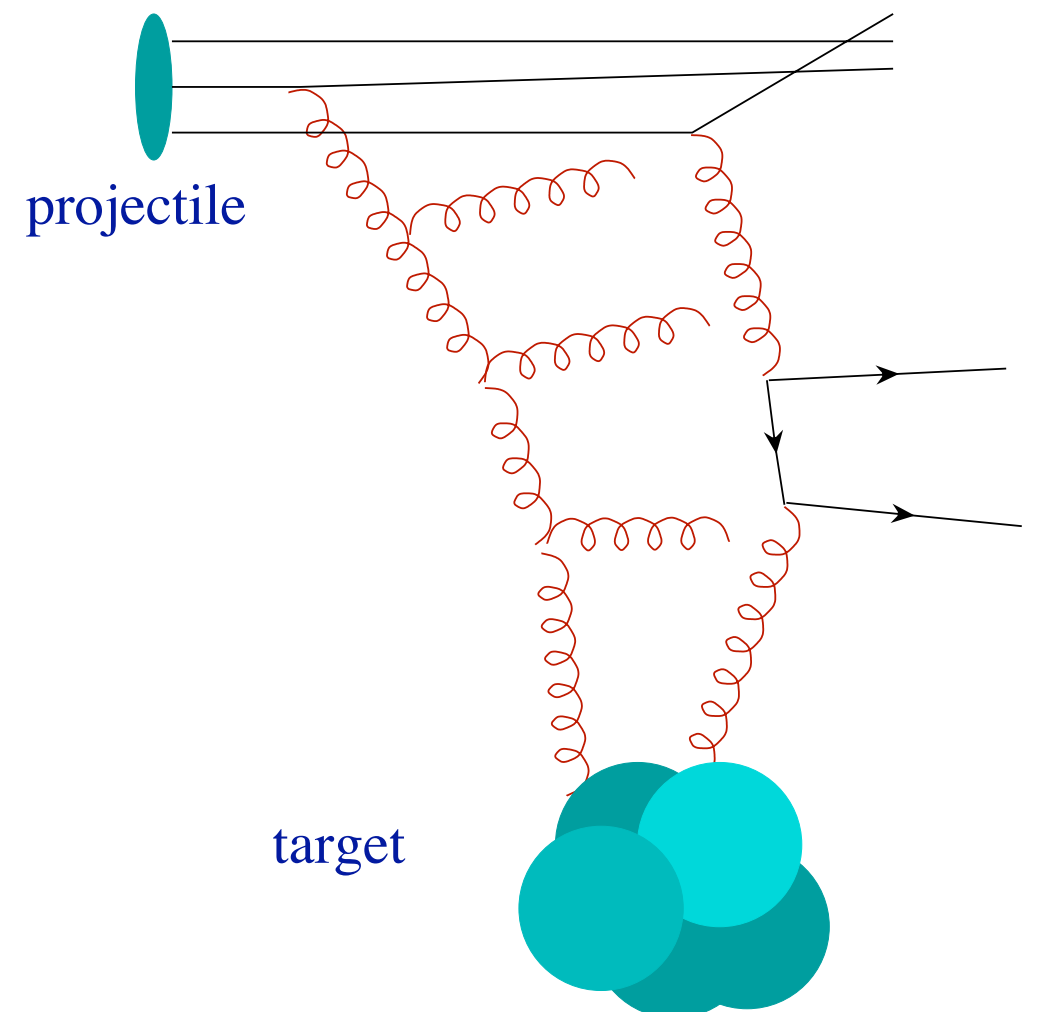
$$\sigma_{QCD} = \sum_{i,j,k,l} \frac{1}{1 + \delta_{kl}} \int dx_1 dx_2 \int_{p_{\perp}^{\text{cutoff}}} dp_{\perp}^2 f_i(x_1, Q^2) f_j(x_2, Q^2) \frac{d\sigma_{i,j \rightarrow k,l}}{dp_{\perp}}$$

Problem I: Dependence on cutoff parameter



Factor ~ 150

Multiple interactions

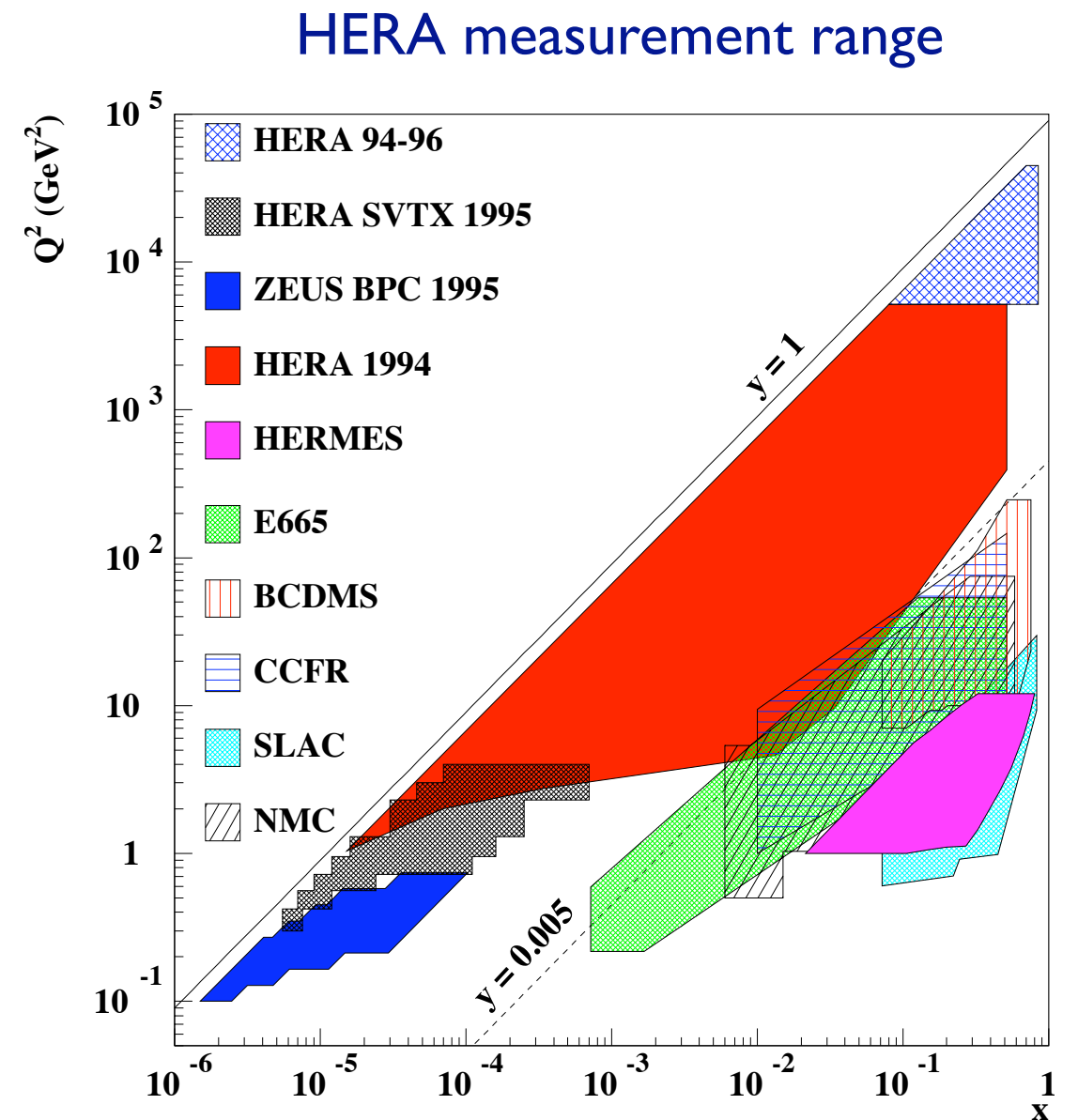
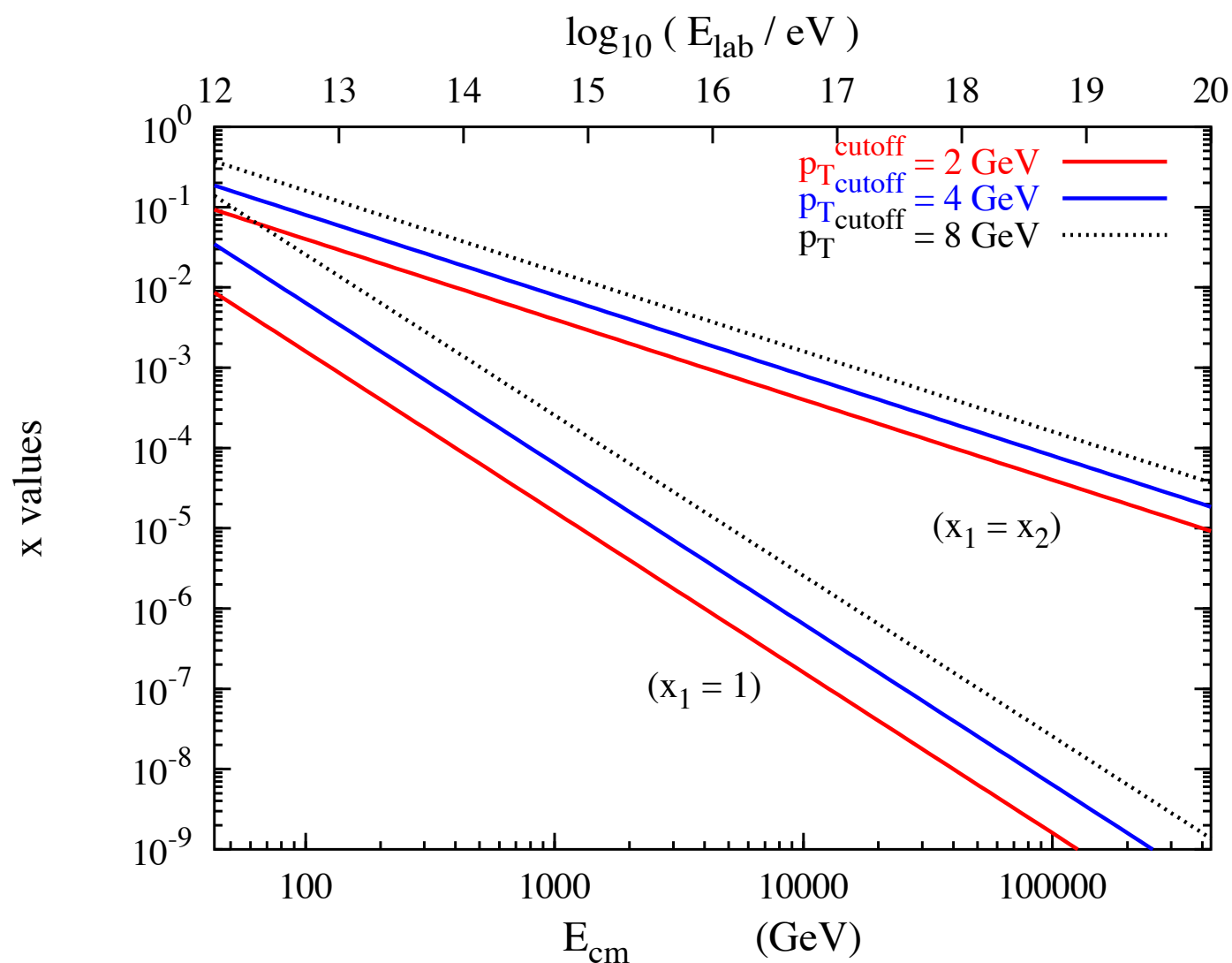


Average number
of minijet pairs

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

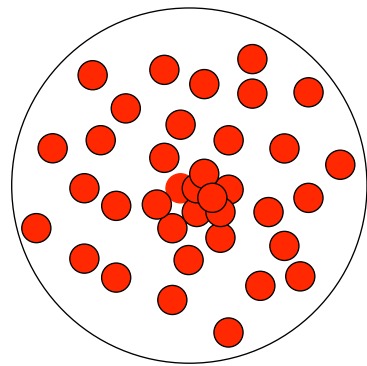
Problem 2: Parton densities not known at very low x

Range of x values (momentum fractions) needed in calculation

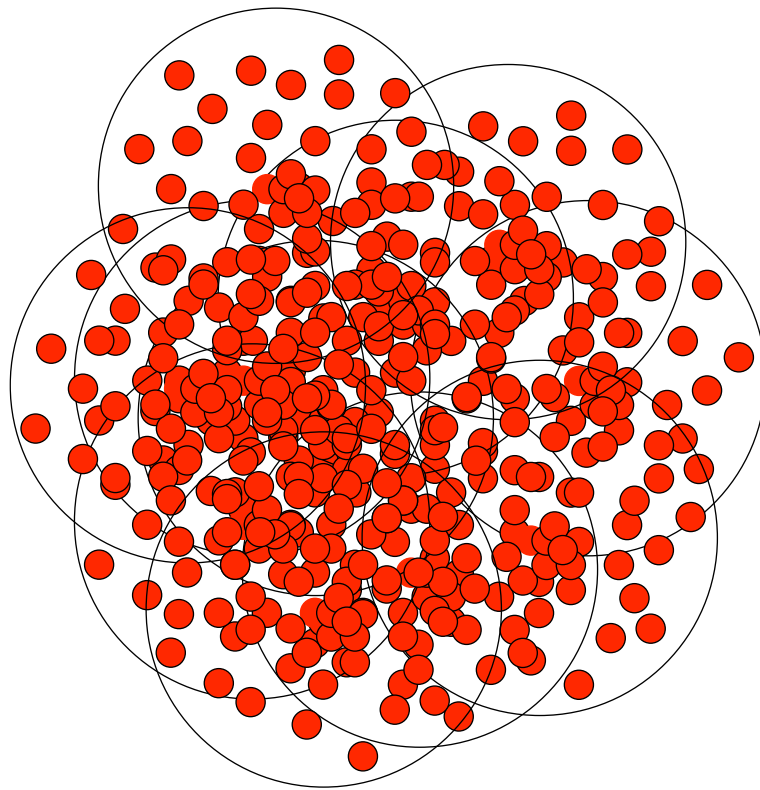


$$\hat{s} = x_1 x_2 s \geq 4p_{\perp}^2$$

Problem 3: Very high parton densities (saturation)



nucleon



nucleus

RHIC data very important

Saturation:

- parton wave functions overlap
- number of partons does not increase anymore at low x
- extrapolation to very high energy unclear

Simple geometric criterion

$$\pi R_0^2 \simeq \frac{\alpha_s(Q_s^2)}{Q_s^2} \cdot xg(x, Q_s^2)$$

size of proton

Size of
one gluon

number of
gluons

High energy interaction models

DPMJET II.5 and III

(Ranft / Roesler, RE, Ranft, Bopp)

- universal model
- saturation for hard partons via geometry criterion
- HERA parton densities

EPOS

(Pierog, Werner)

- universal model
- saturation by RHIC data parametrizations
- custom-developed parton densities

QGSJET 01

(Kalmykov, Ostapchenko)

- no saturation corrections
- old pre-HERA parton densities
- replaced by QGSJET II

QGSJET II.03

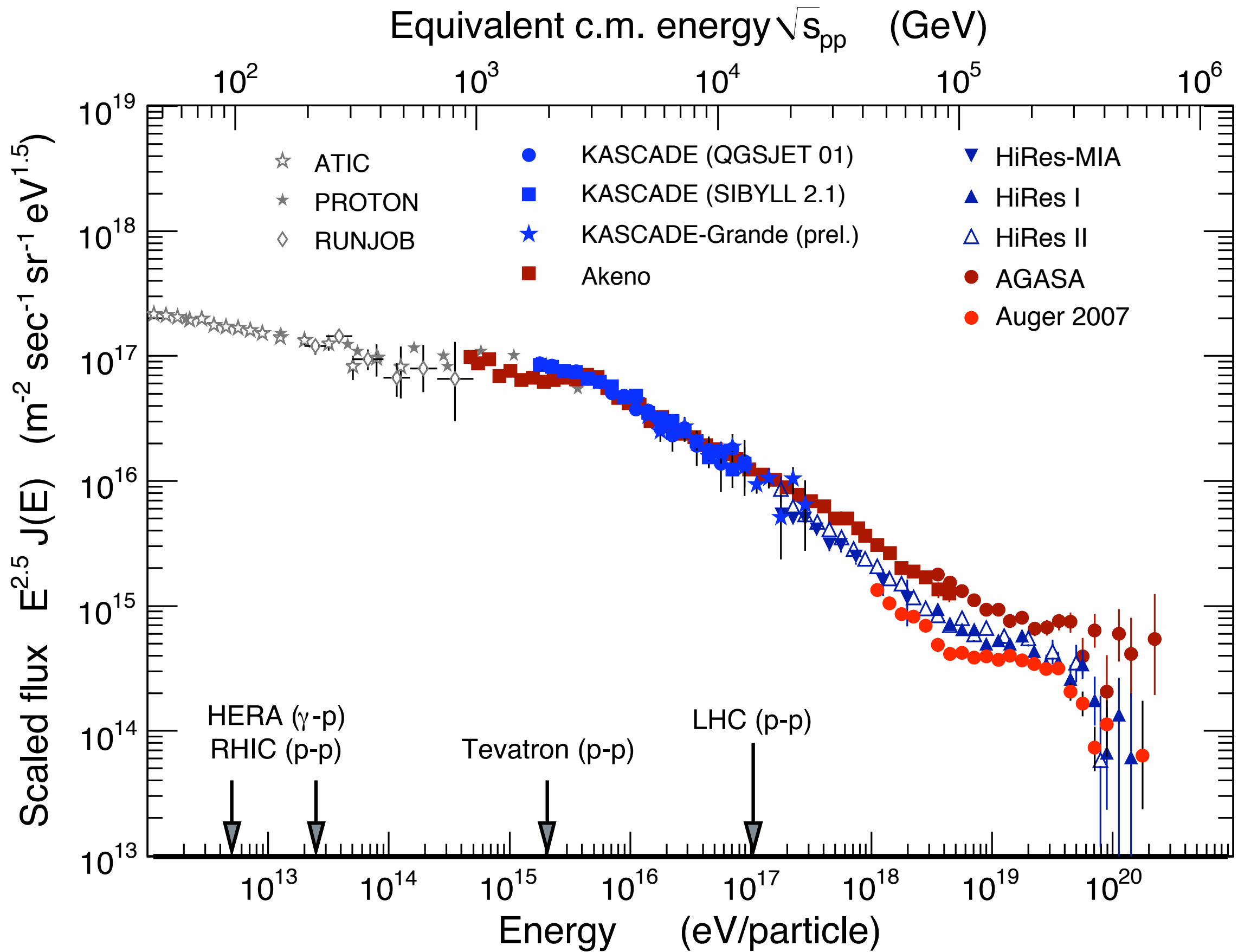
(Ostapchenko)

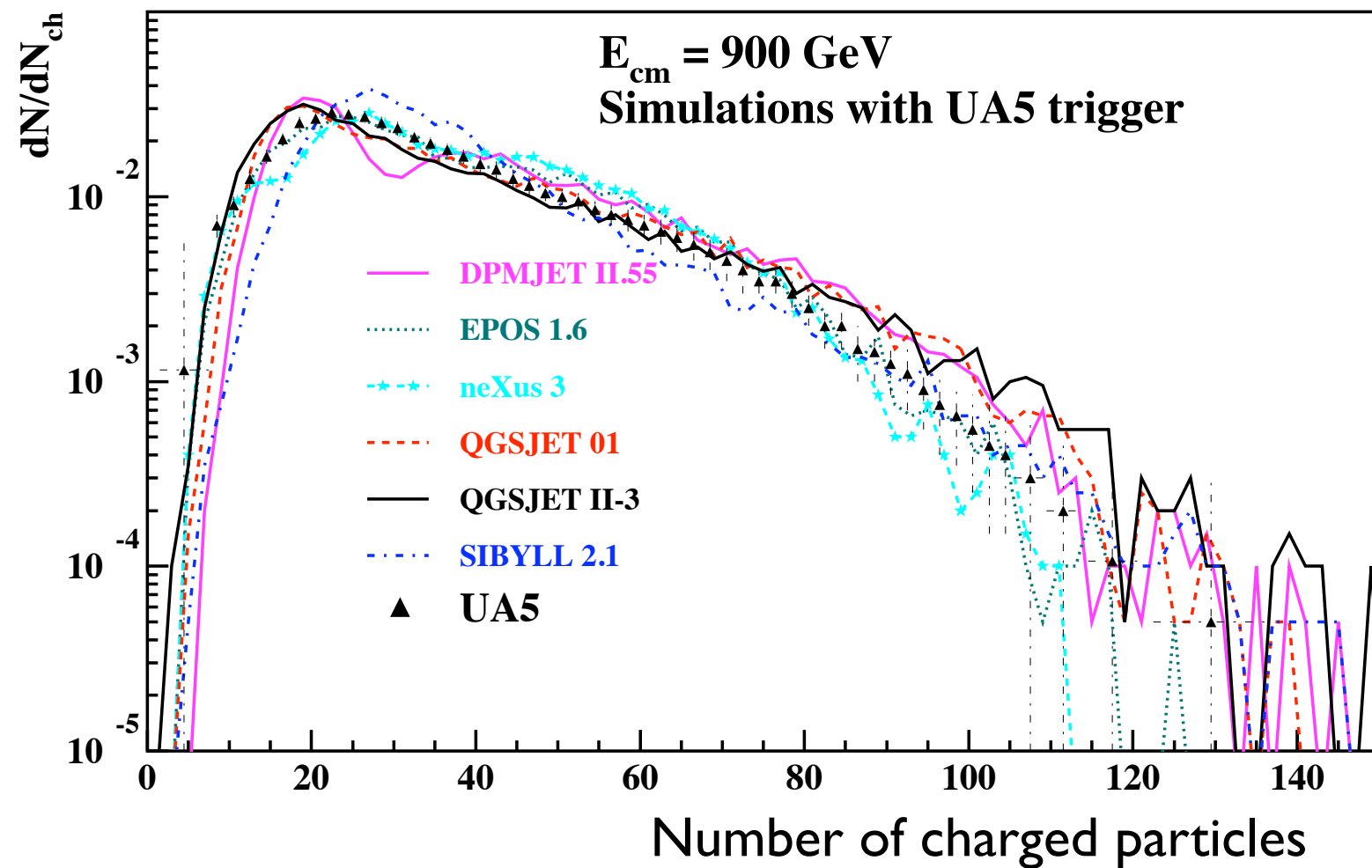
- saturation correction for soft partons via pomeron-resummation
- custom-developed parton densities

SIBYLL 2.1

(Engel, RE, Fletcher, Gaisser, Lipari, Stanev)

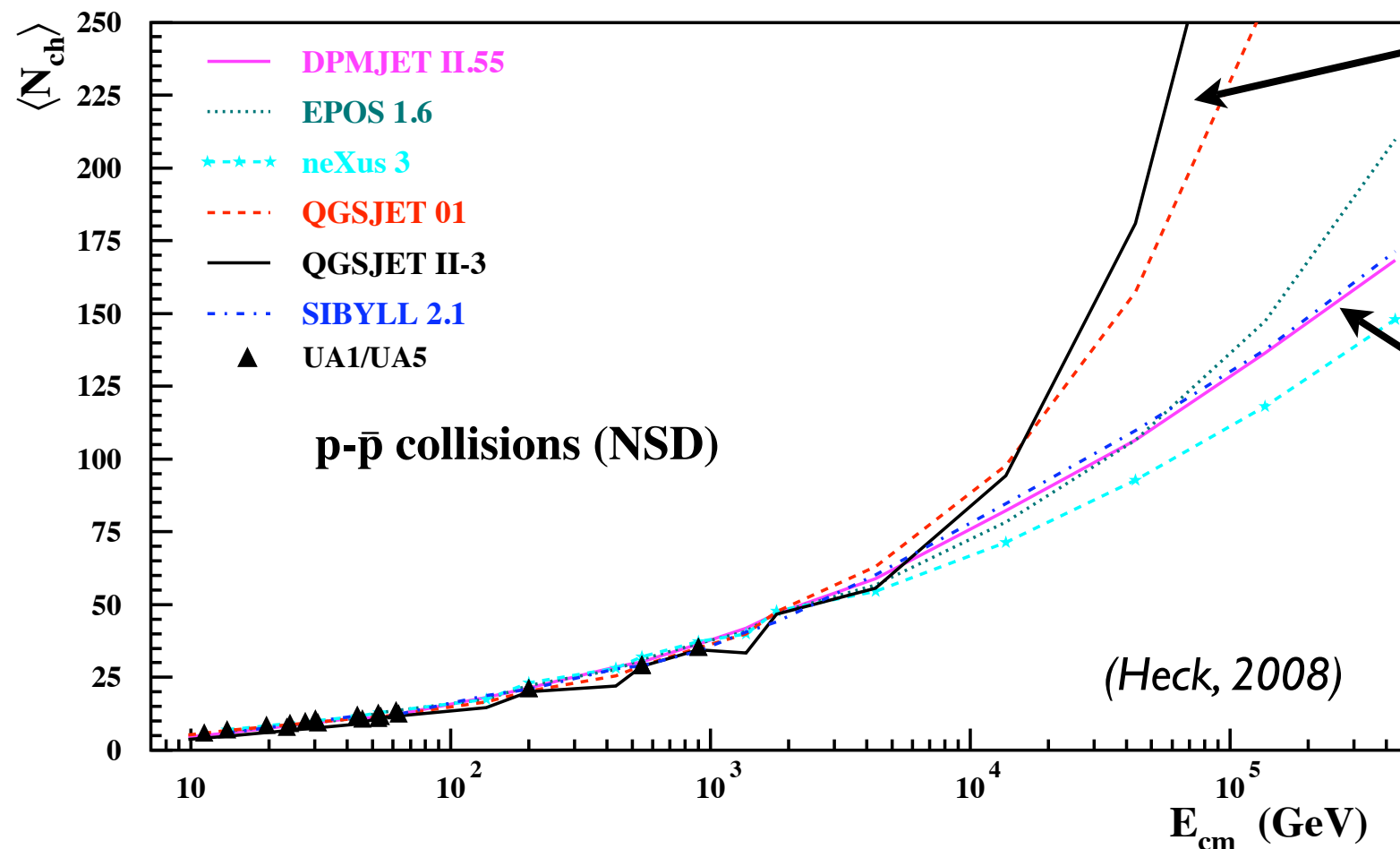
- saturation for hard partons via geometry criterion
- HERA parton densities





Comparison with
collider data (i)

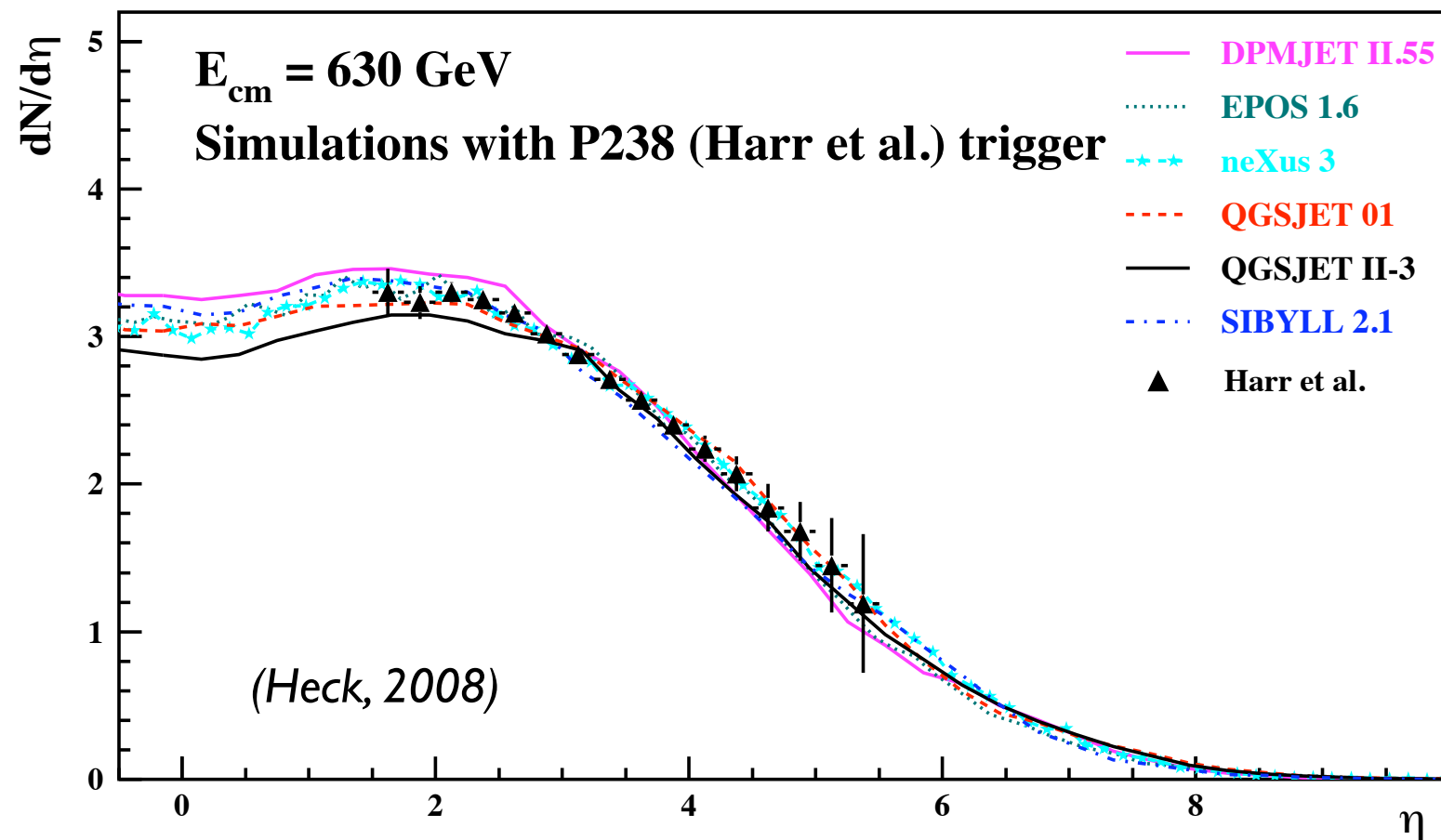
proton-antiproton collisions



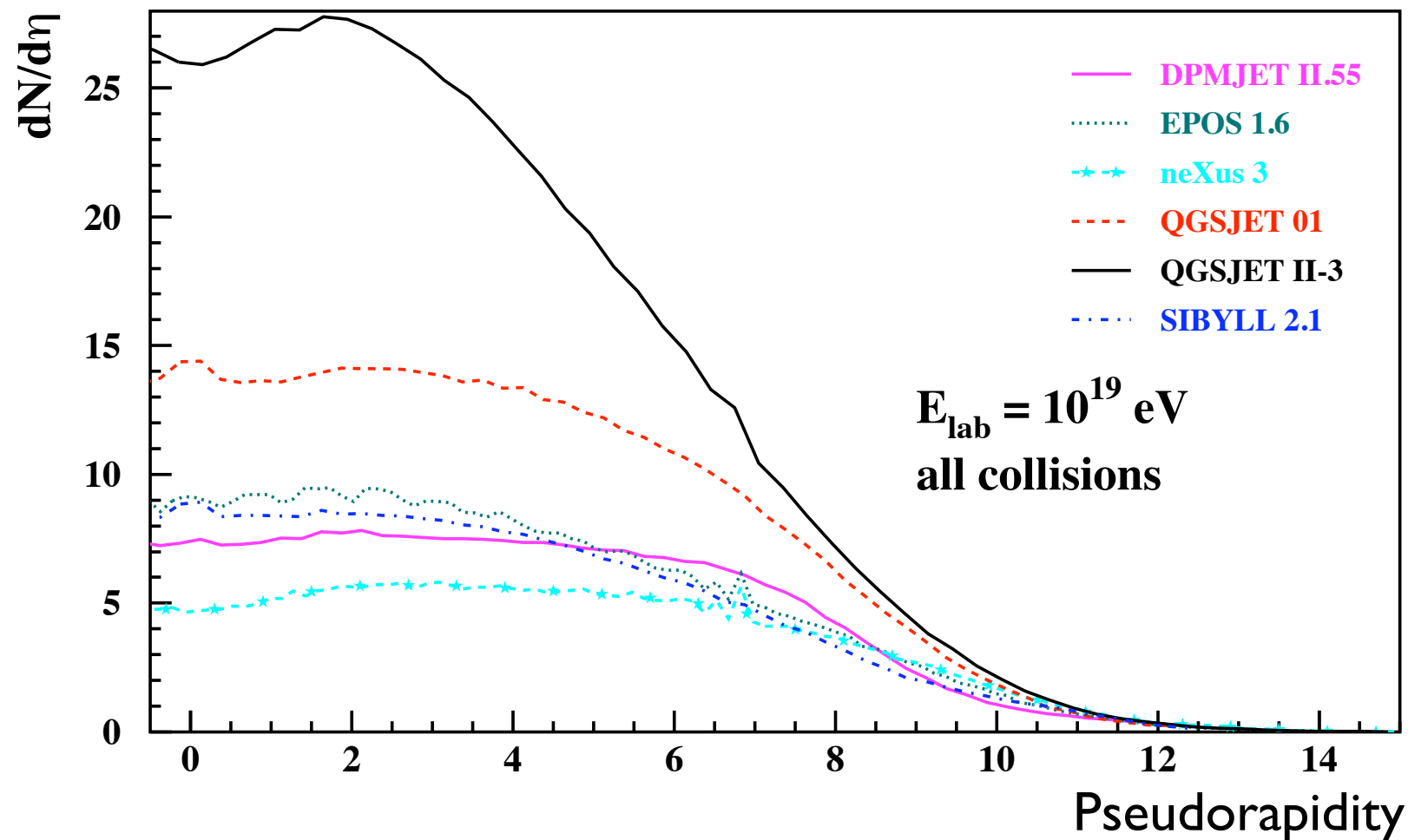
QGSJET: saturation effects
only for soft partons

Others: stronger saturation effects

Comparison with collider data (ii)



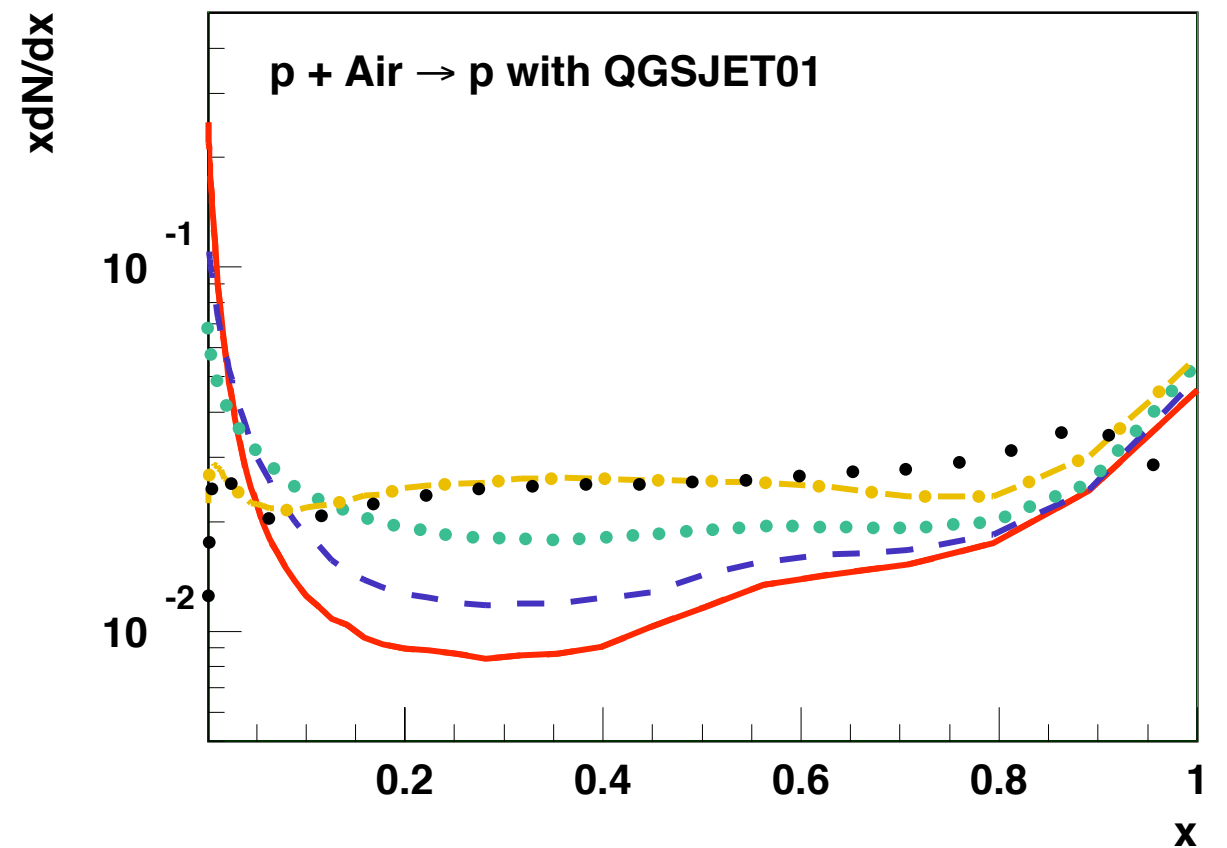
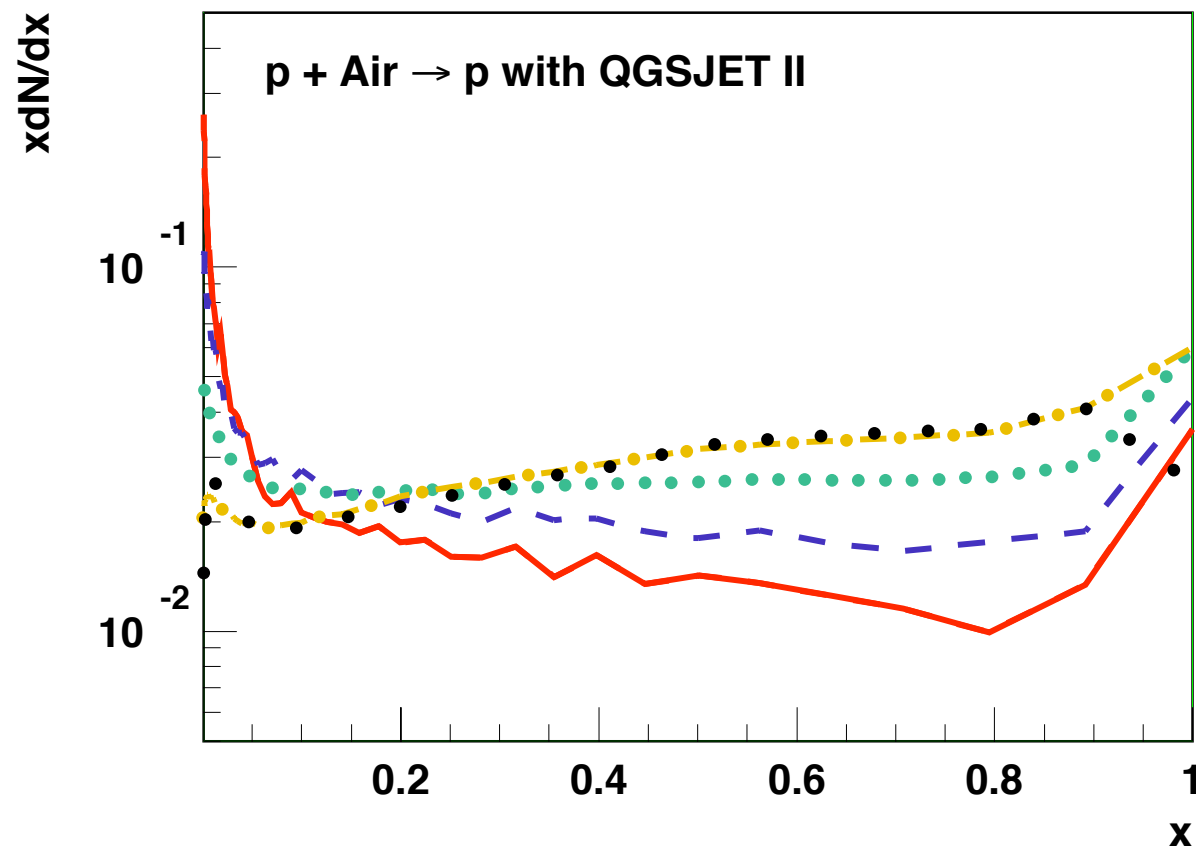
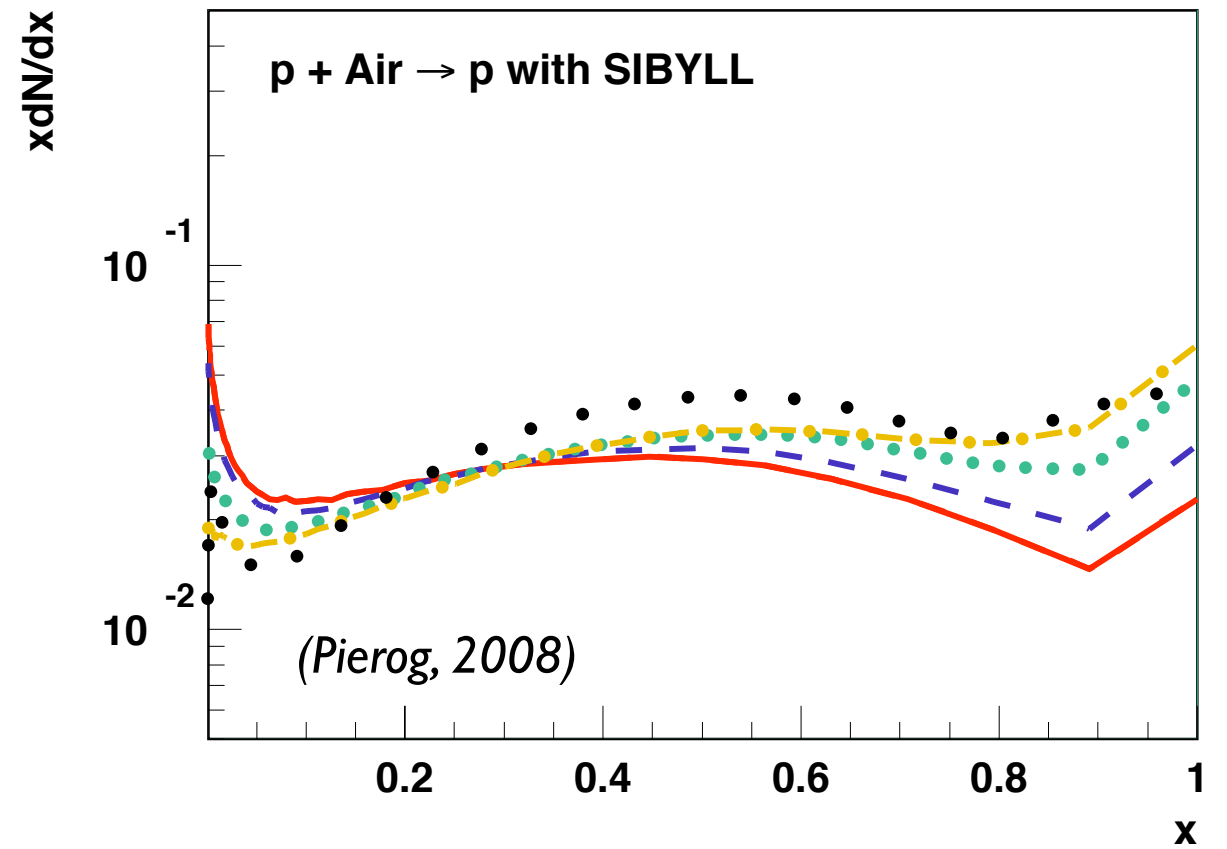
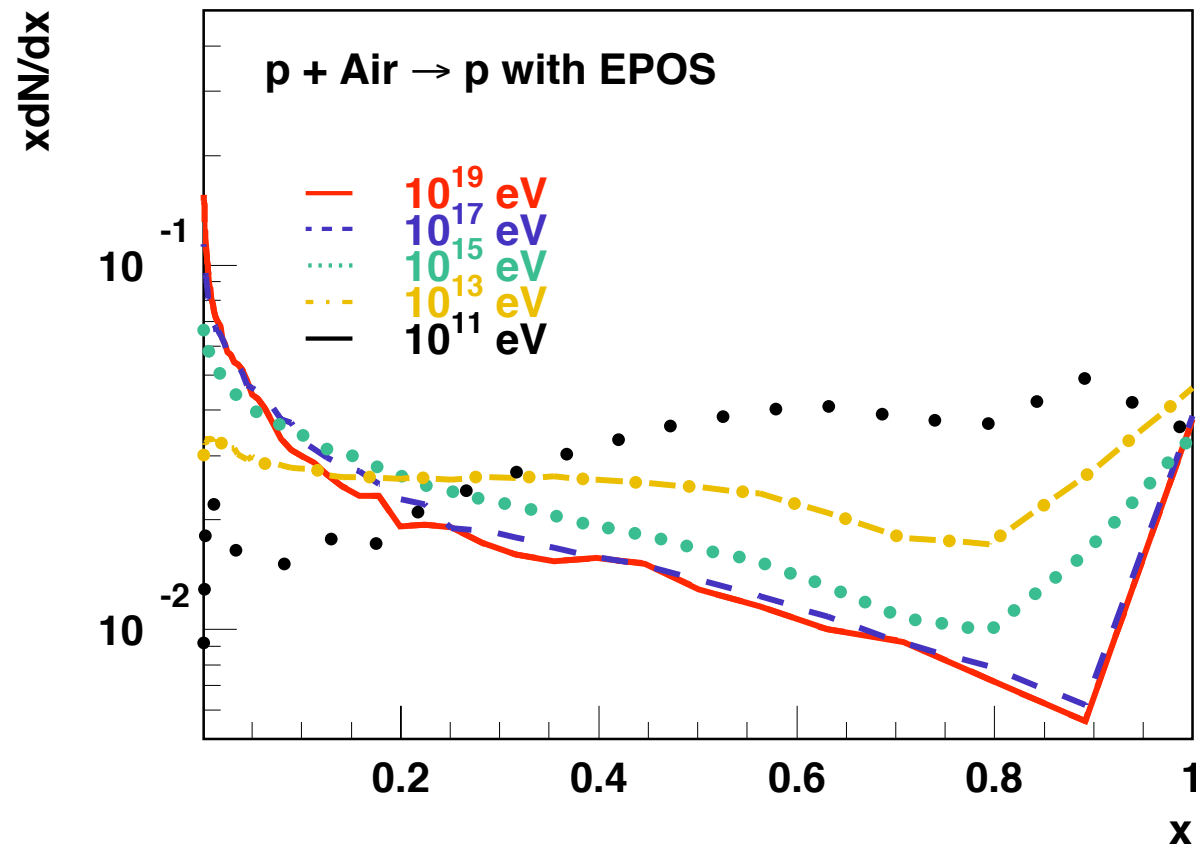
proton-antiproton collisions



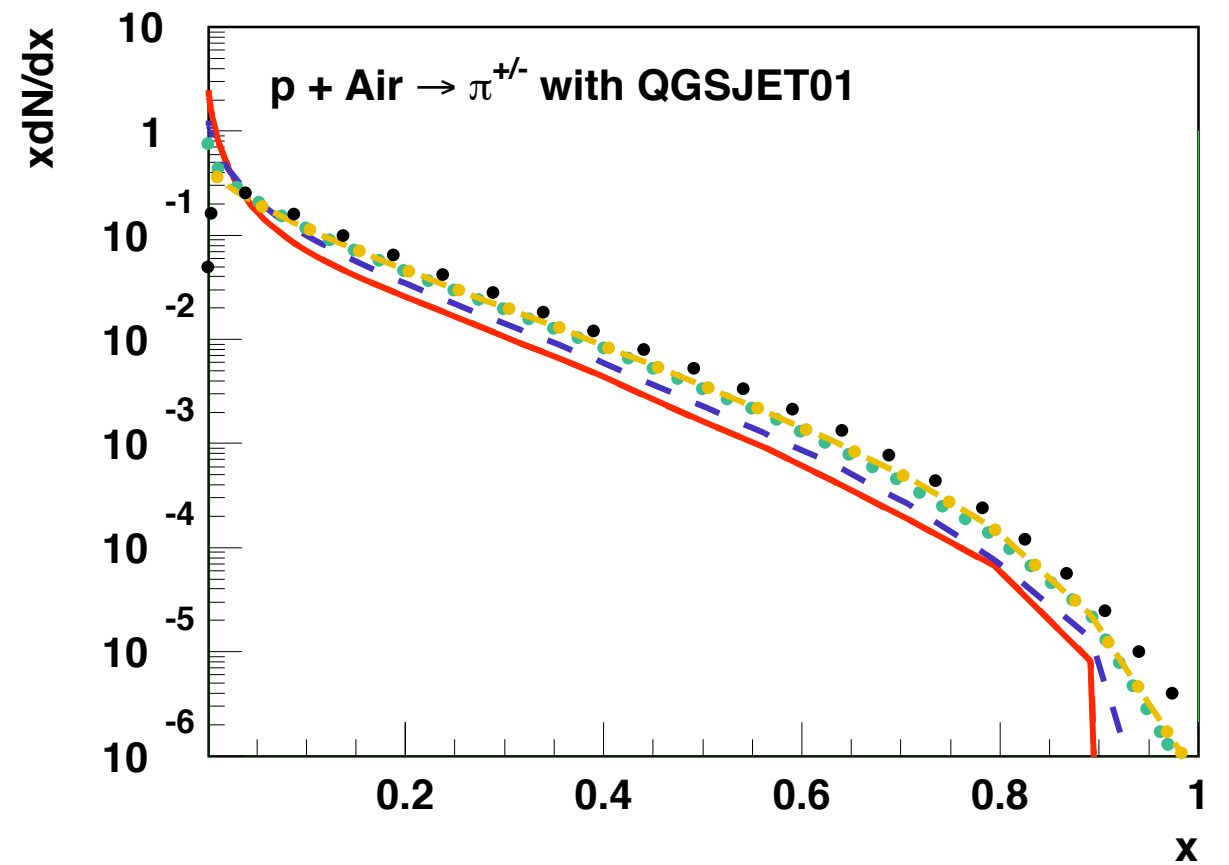
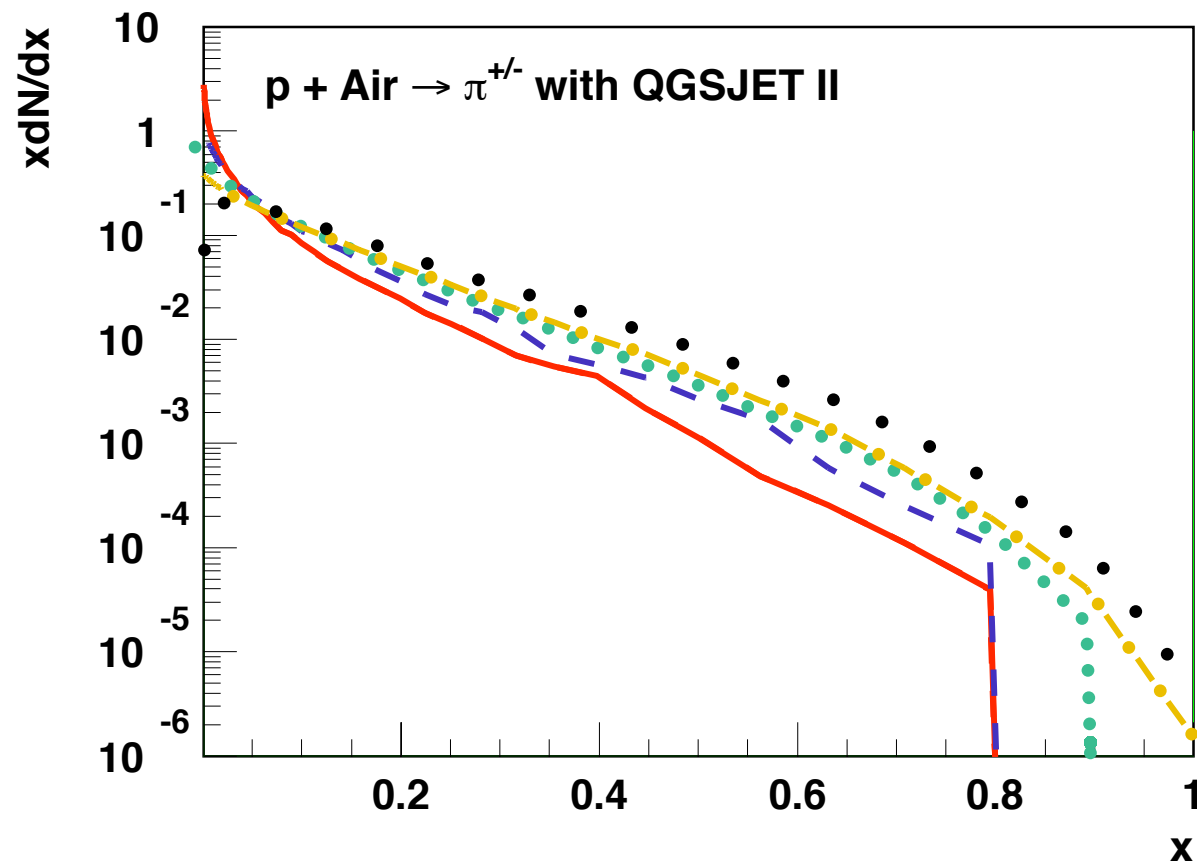
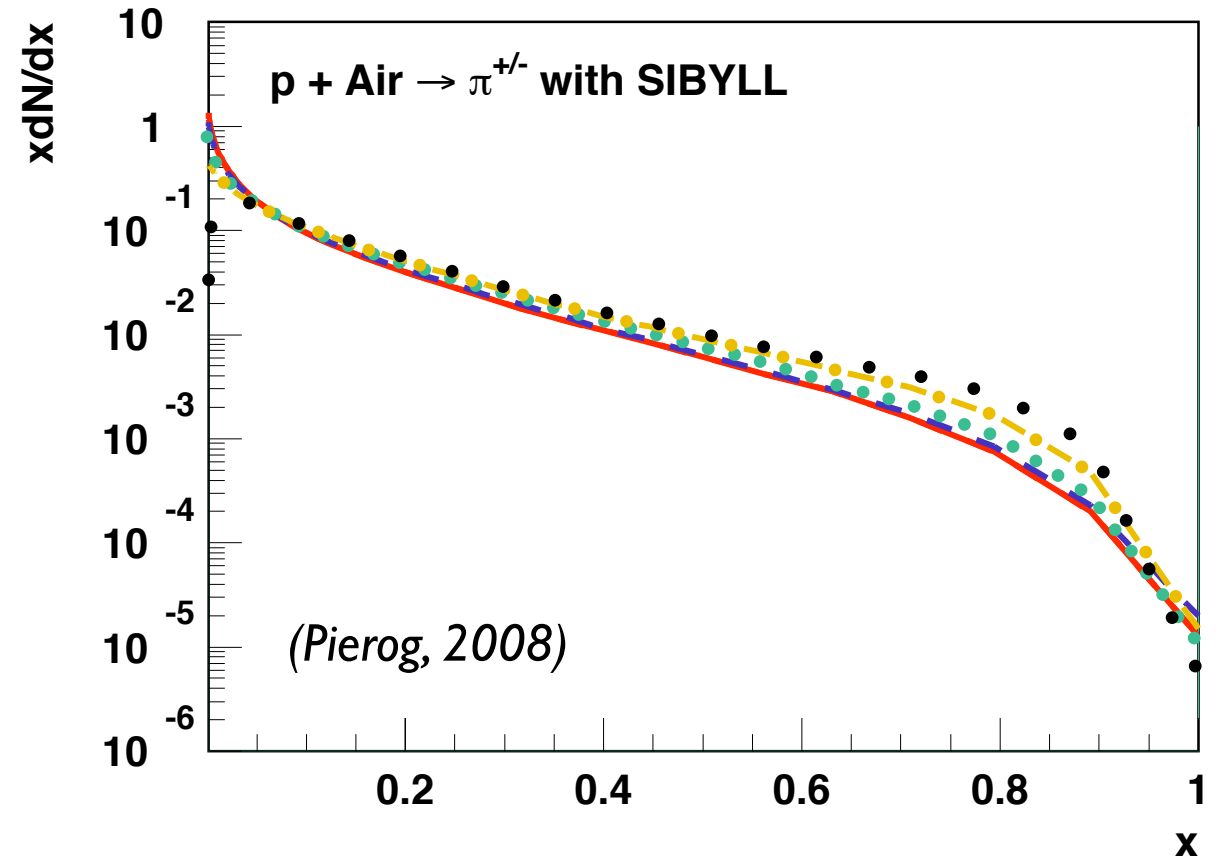
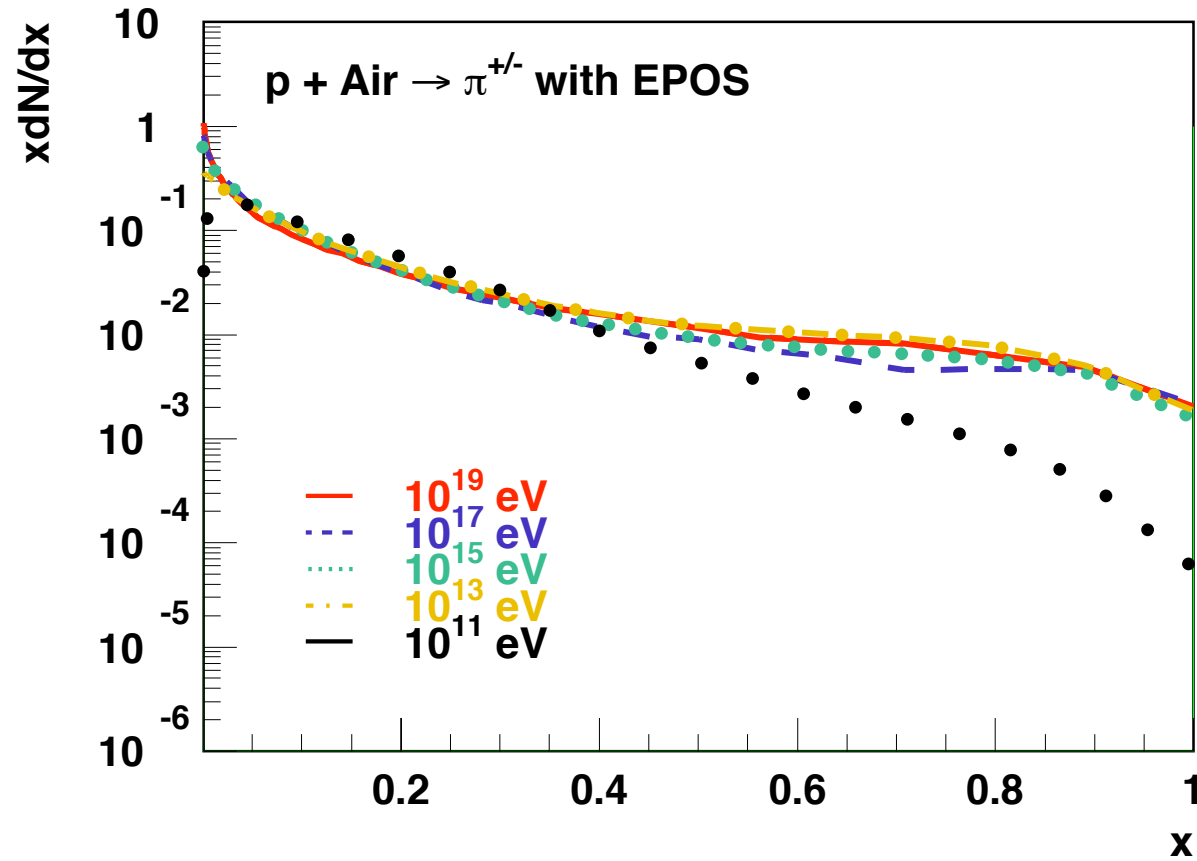
Extrapolation to

$$E_{\text{cm}} \approx 100,000 \text{ GeV}$$

Scaling: model predictions (i)

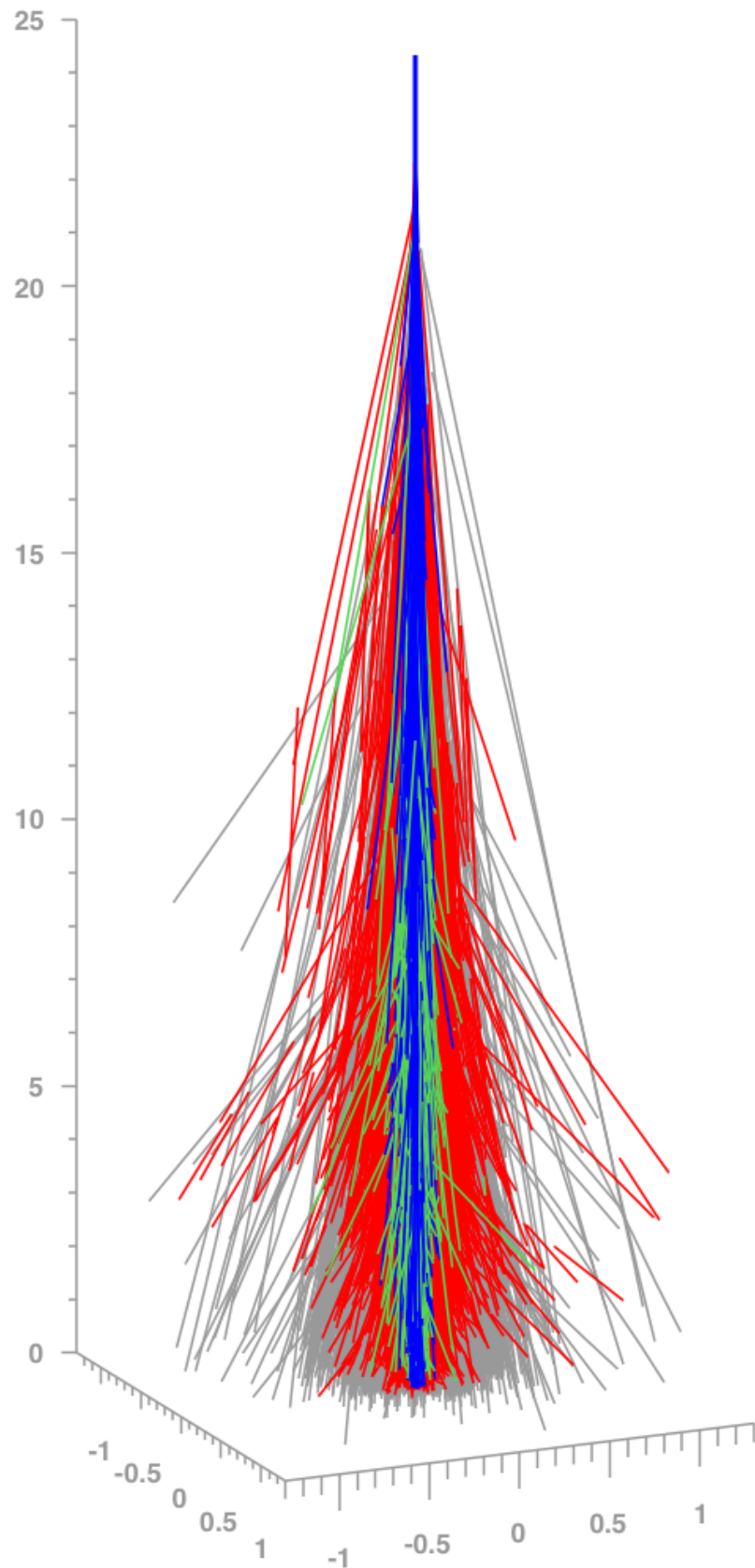


Scaling: model predictions (ii)

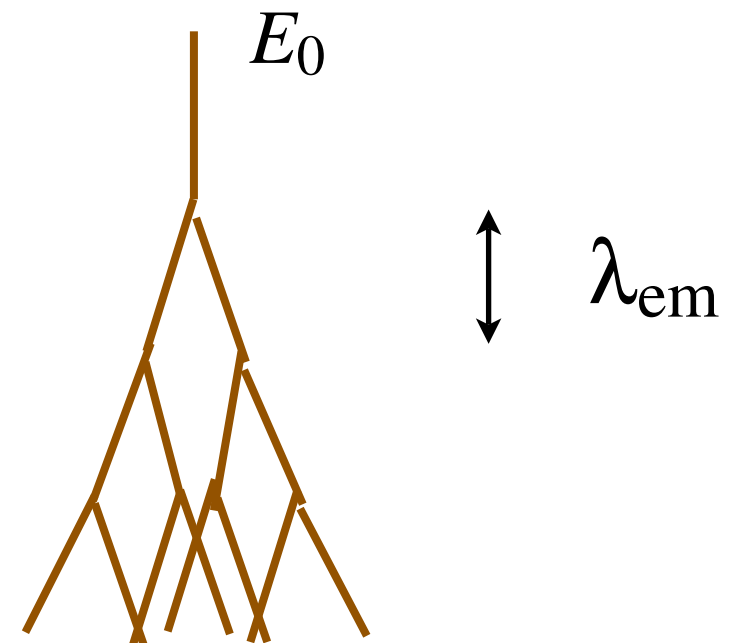
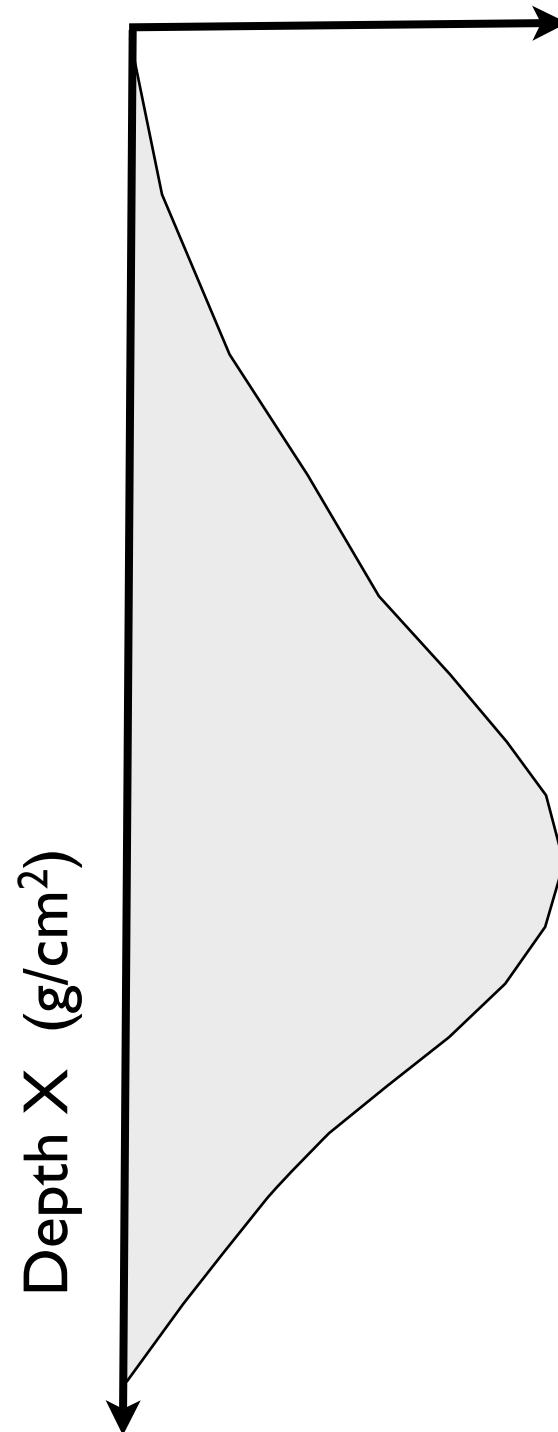


Air shower predictions

Heitler model of electromagnetic showers



Number of charged particles

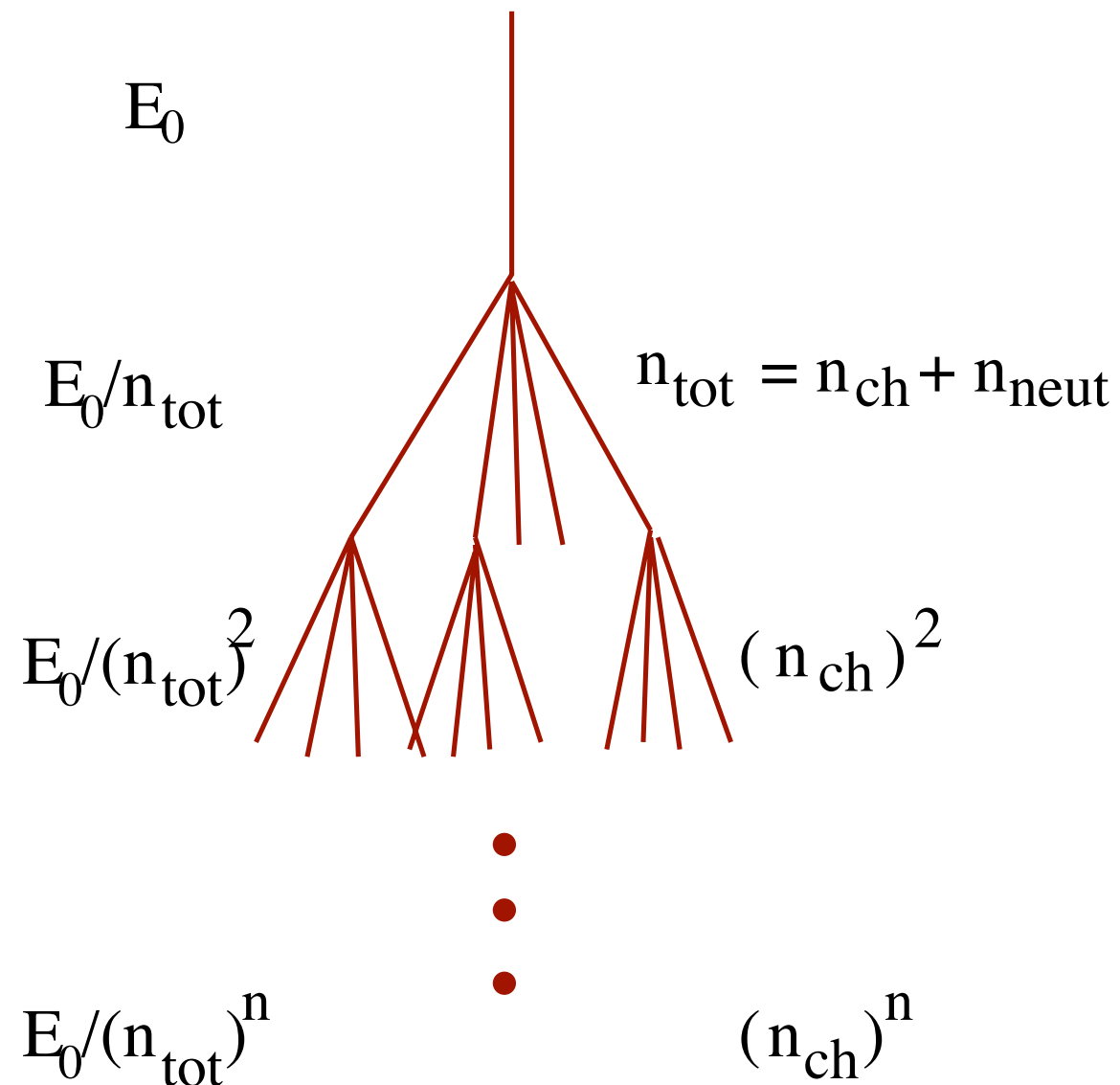


Shower maximum: $E = E_c$

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

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

Heitler-Matthews model: muon production



Assumptions:

- neutral pions decay immediately
- charged pions initiate secondary cascades
- cascades stop if $E = E_{\text{dec}}$

$$N_{\mu} = \left(\frac{E_0}{E_{\text{dec}}} \right)^{\alpha} \quad \alpha = \frac{\ln(n_{\text{ch}})}{\ln(n_{\text{tot}})} \approx 0.9$$

Superposition model

Proton-induced shower

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

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

$$N_{\mu} = \left(\frac{E_0}{E_{\text{dec}}} \right)^{\alpha} \quad \alpha \approx 0.9$$

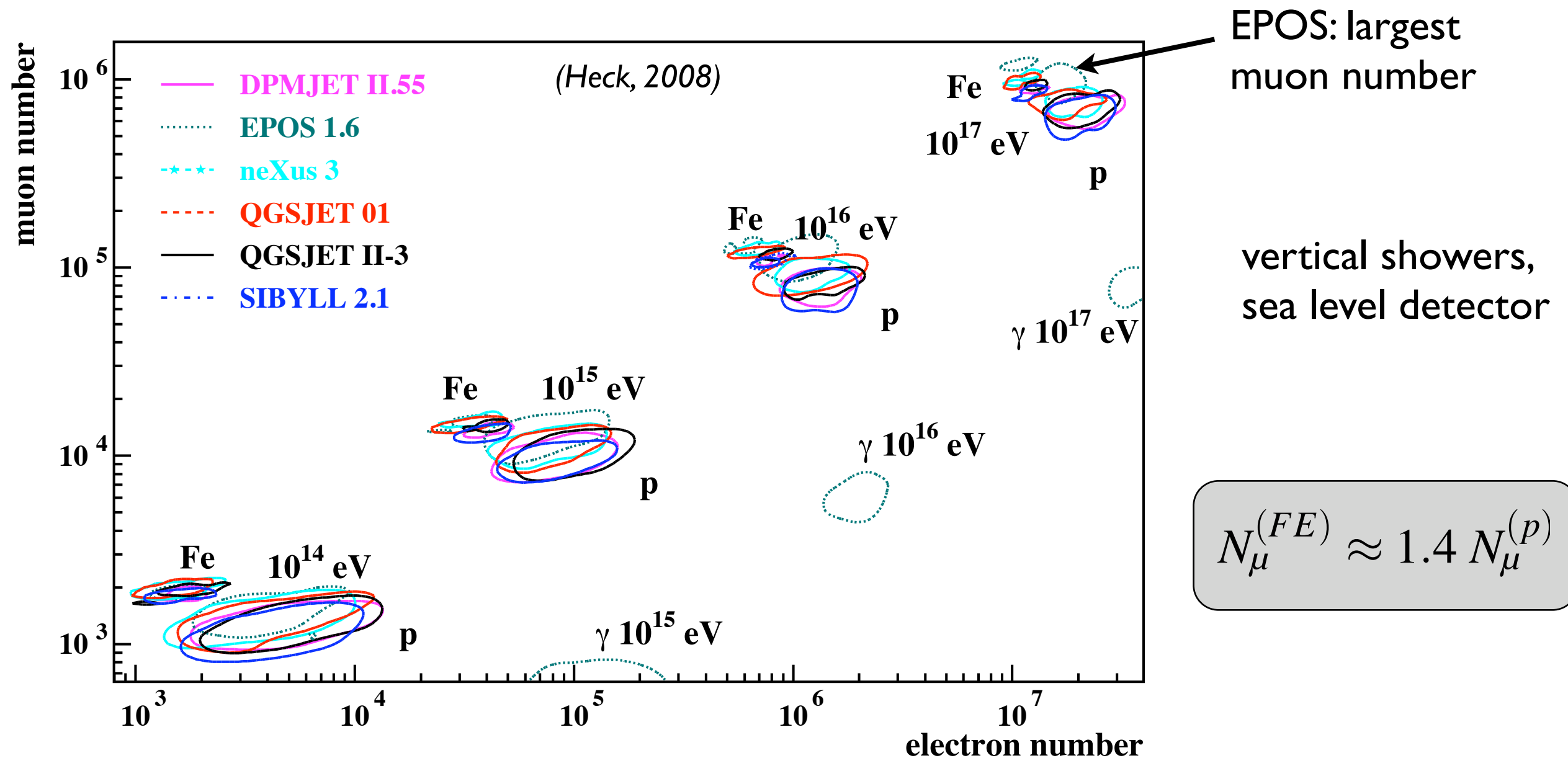
Assumption: nucleus of mass A and energy E_0 corresponds to A nucleons (protons) of energy $E_n = E_0/A$

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

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

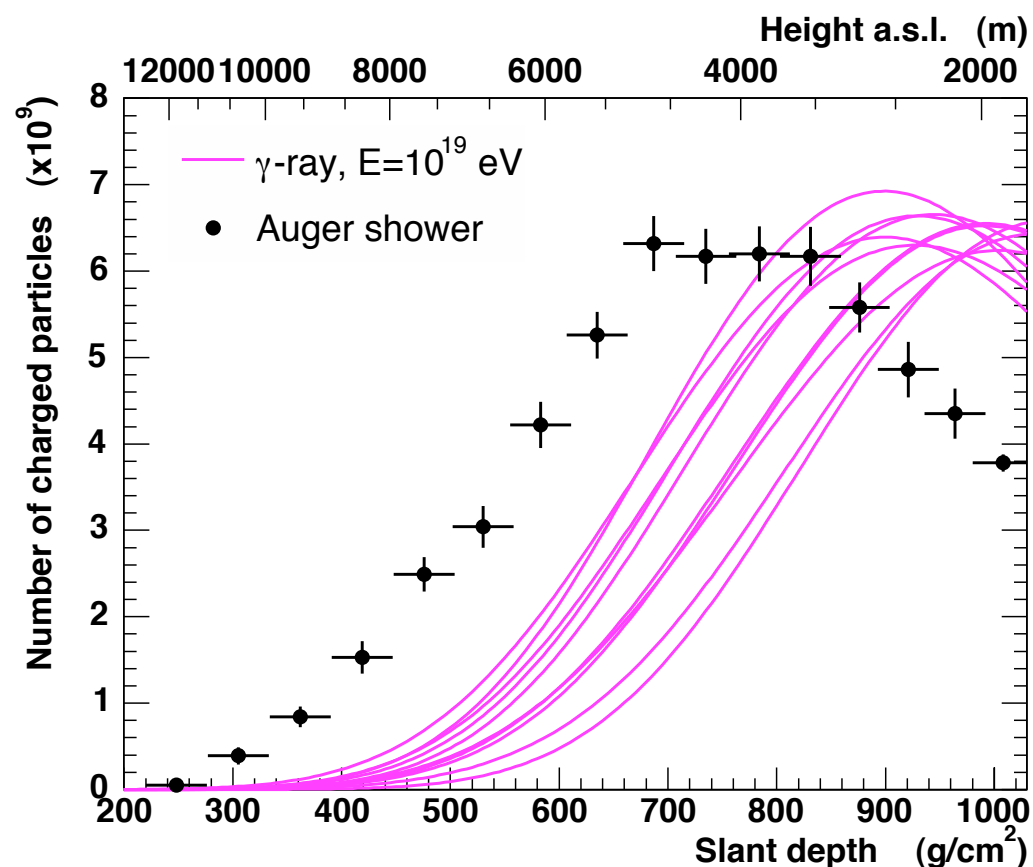
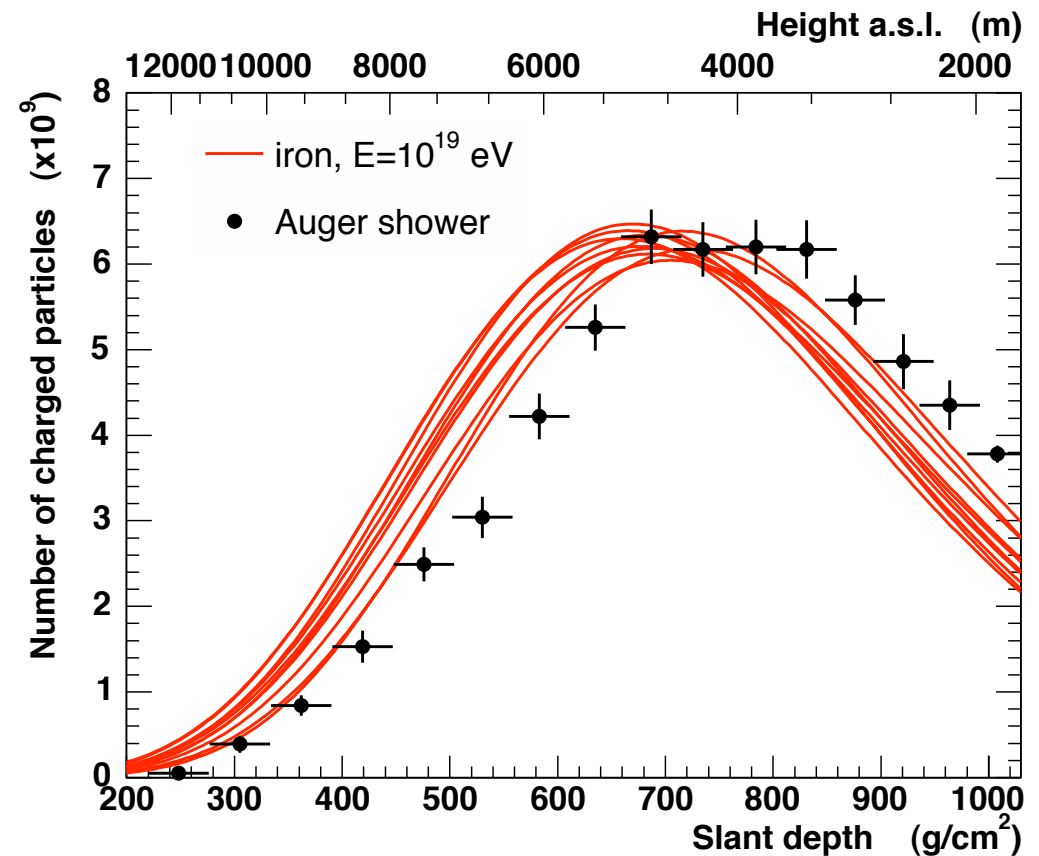
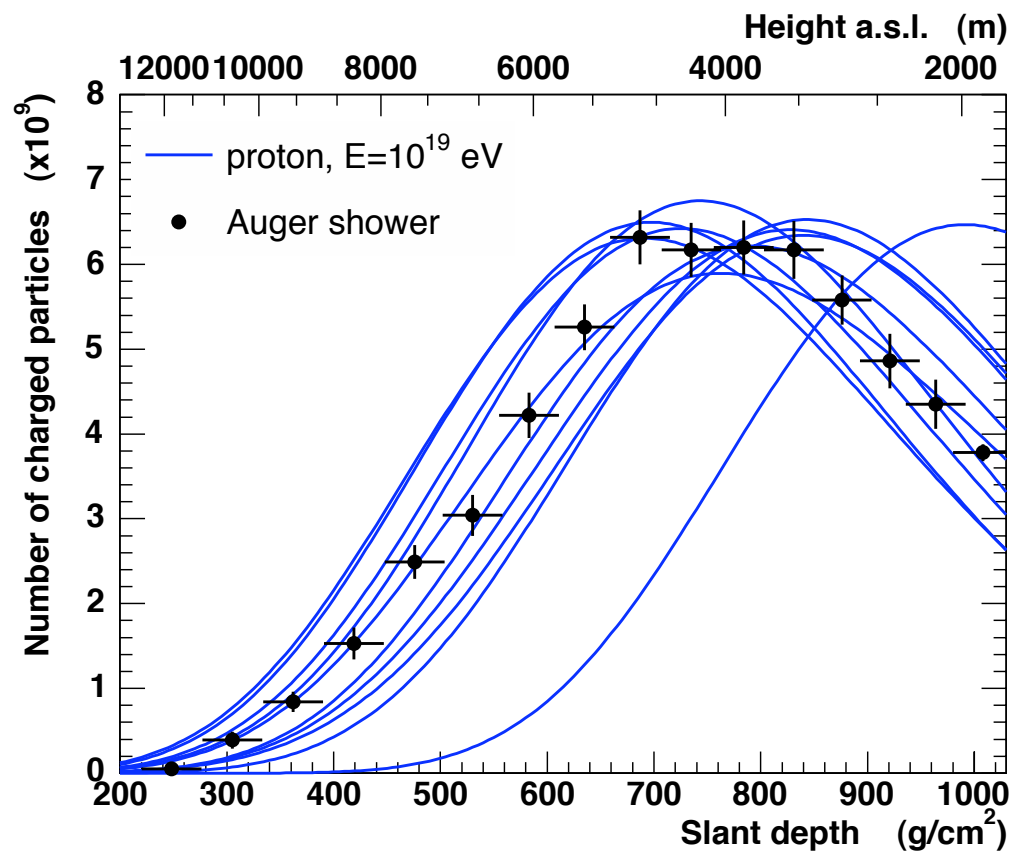
$$N_{\mu}^A = A \left(\frac{E_0}{AE_{\text{dec}}} \right)^{\alpha} = A^{1-\alpha} N_{\mu}$$

Energy-composition measurement using Ne-N_μ



Dominating uncertainty of composition and energy measurements due to hadronic interaction models

Longitudinal shower profile



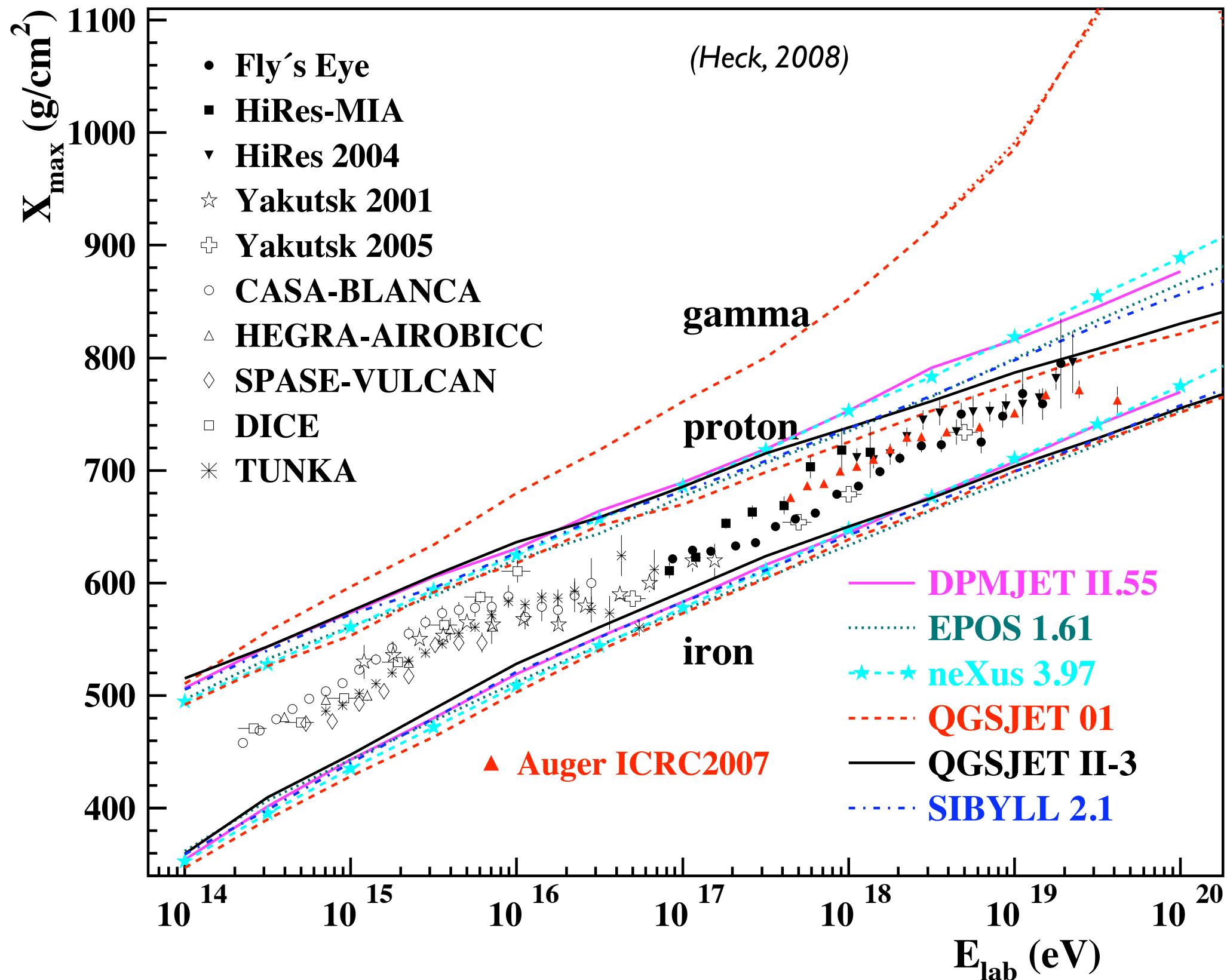
$$N_{\text{max}} = E_0 / E_c$$

$$X_{\text{max}} \sim D_e \ln(E_0 / E_c)$$

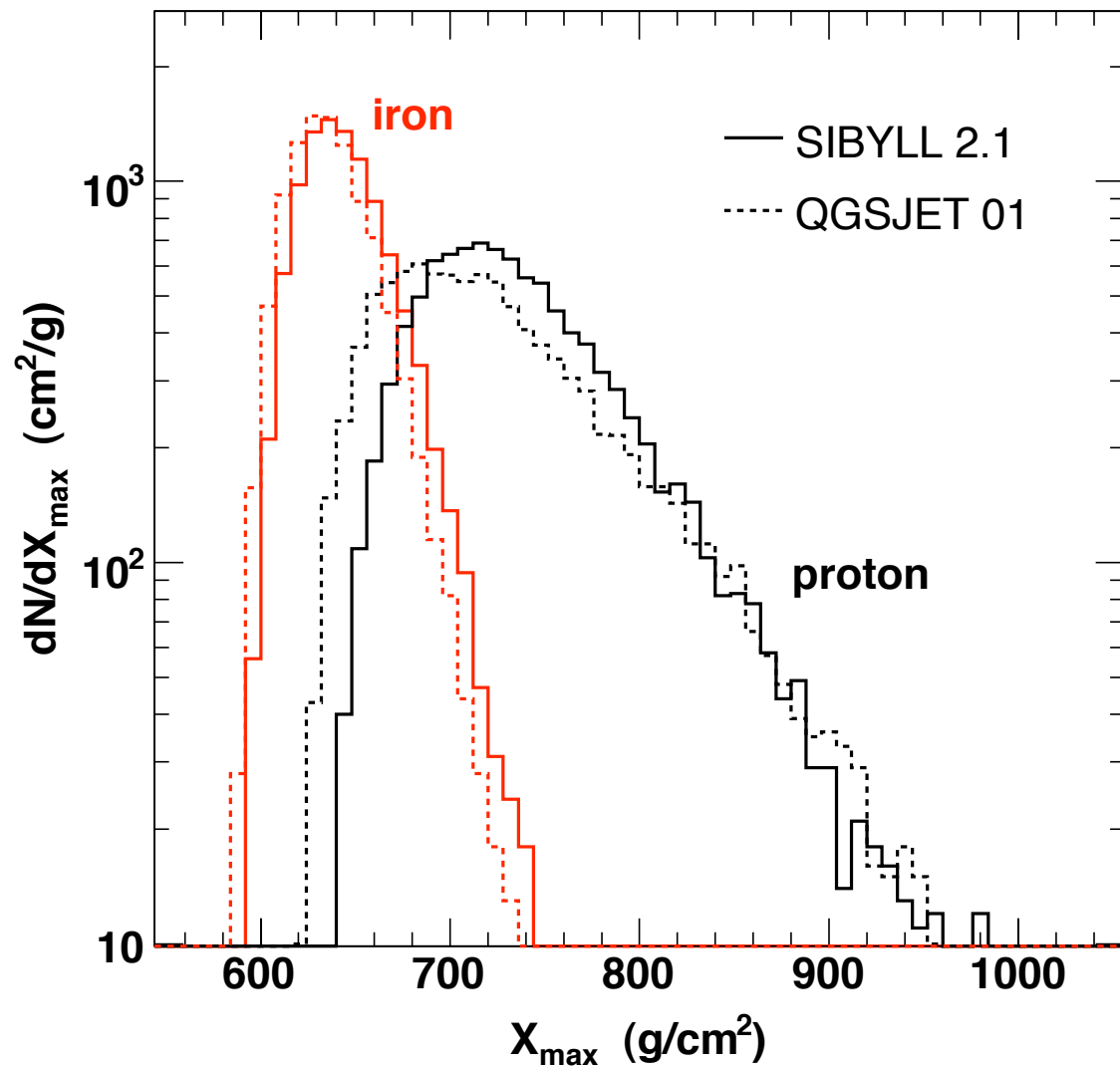
Elongation rate

$$X_{\text{max}}^A \sim D_e \ln(E_0 / A E_c)$$

Mean depth of shower maximum $\langle X_{\max} \rangle$

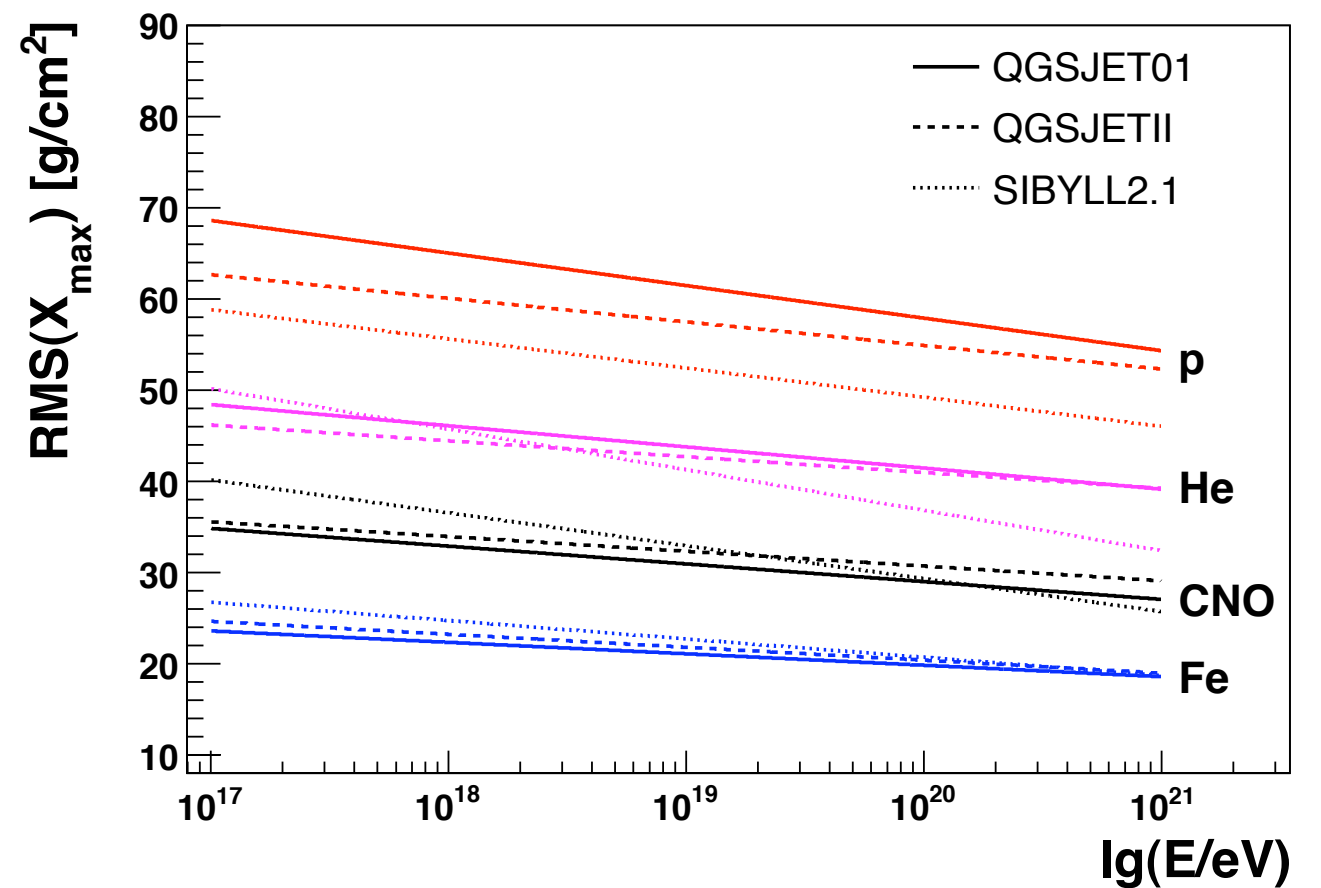


Fluctuations of $X_{\max}$ to discriminate?



$$E = 10^{19} \text{ eV}$$

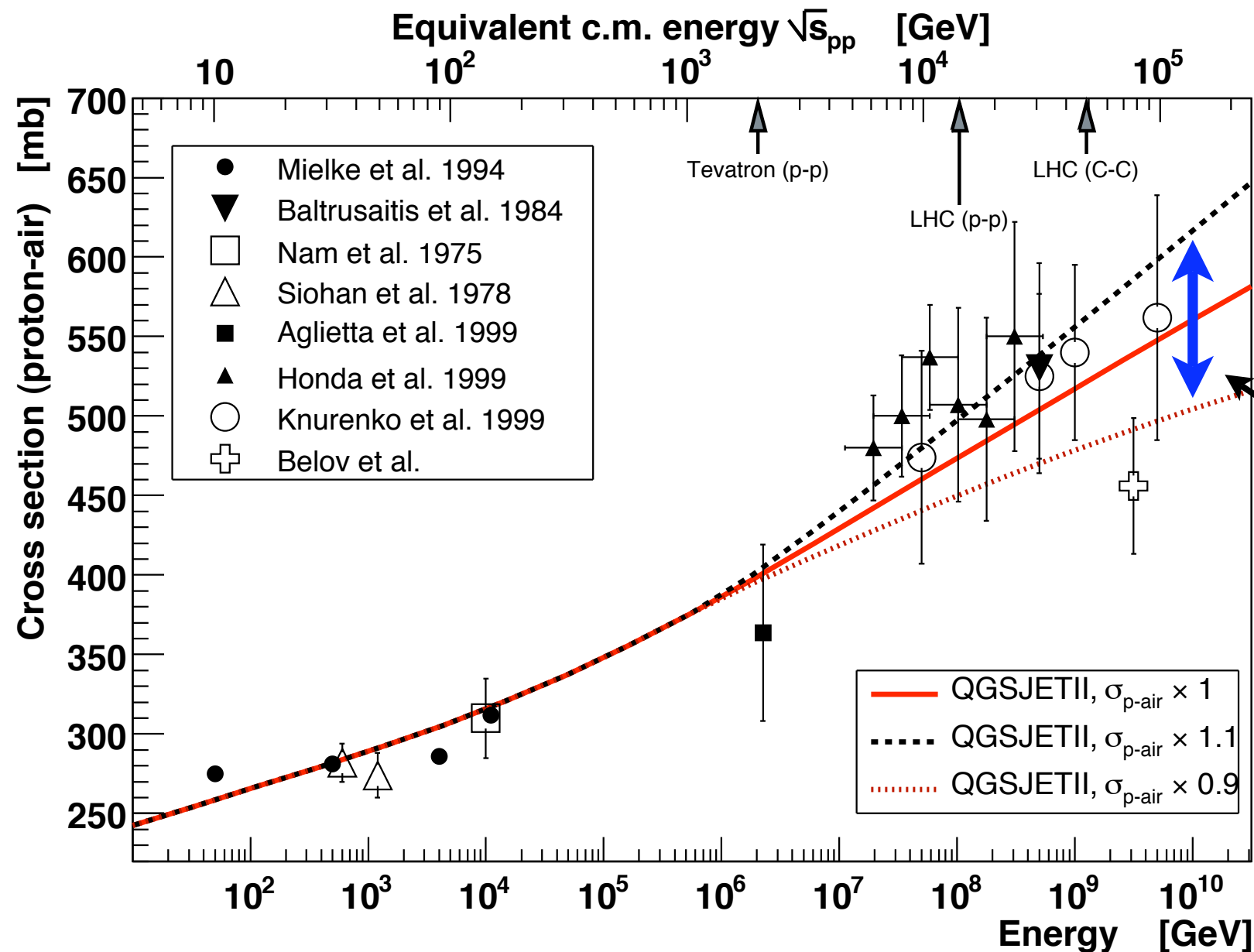
Doubled cross section:
Protons look like CNO



Measurement of $X_{\max}$
distribution needed

(Unger, 2007)

Study: modification of interaction models



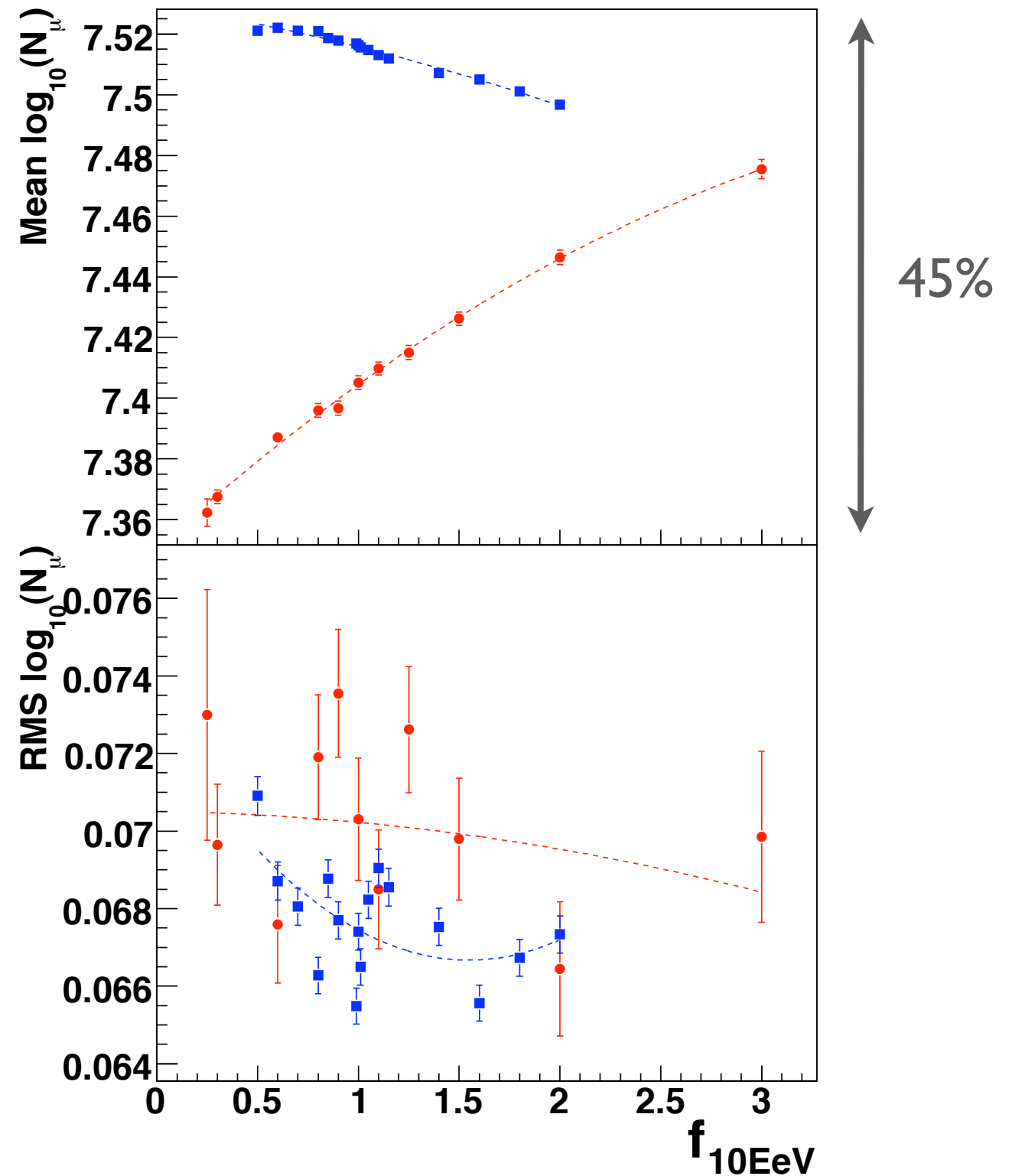
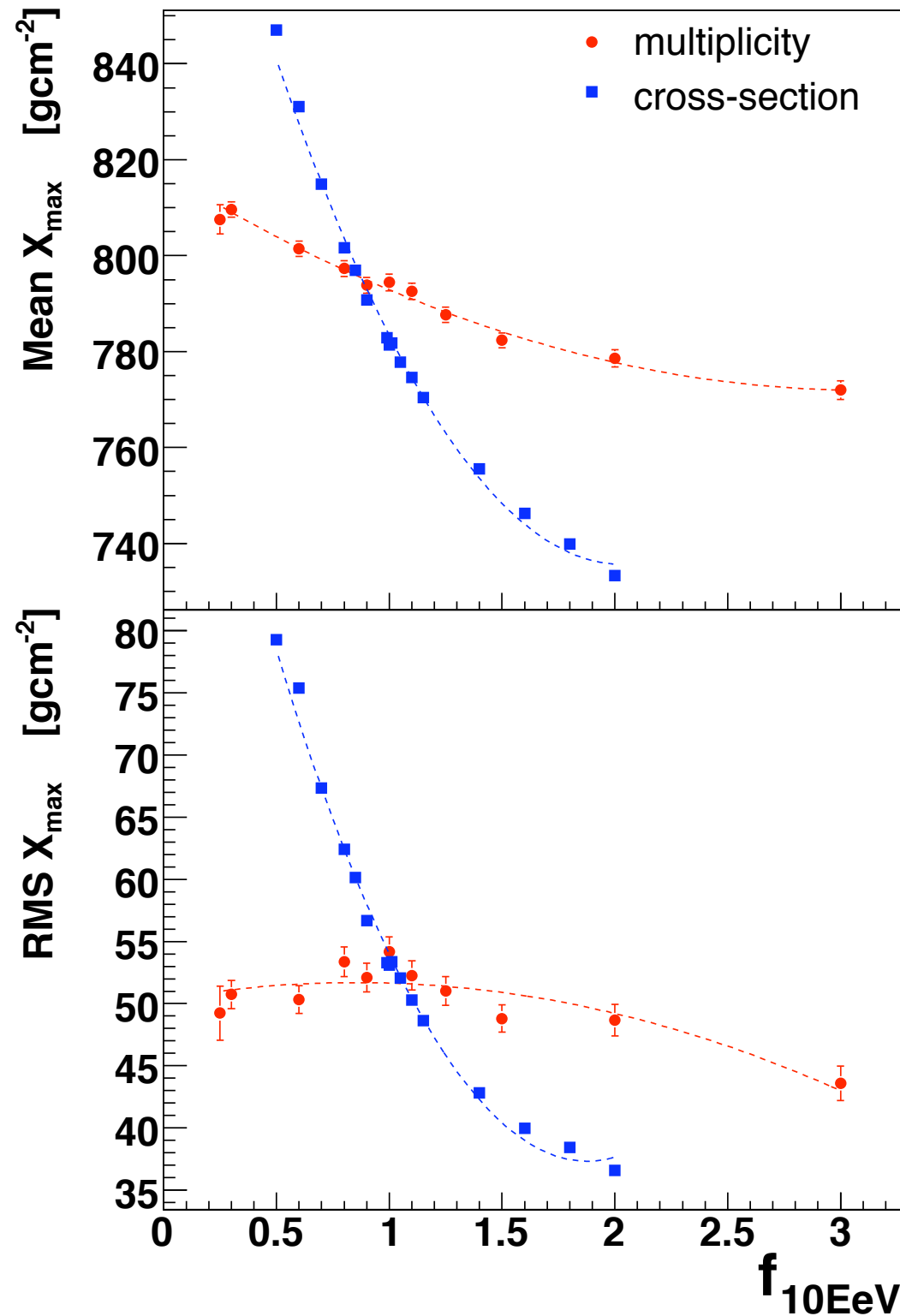
Example:
re-scaling of cross
section above
Tevatron energy

Scaling factor $f_{10\text{EeV}}$

Shower simulation with
modified models

(Ulrich et al., astro-ph/0709.1392)

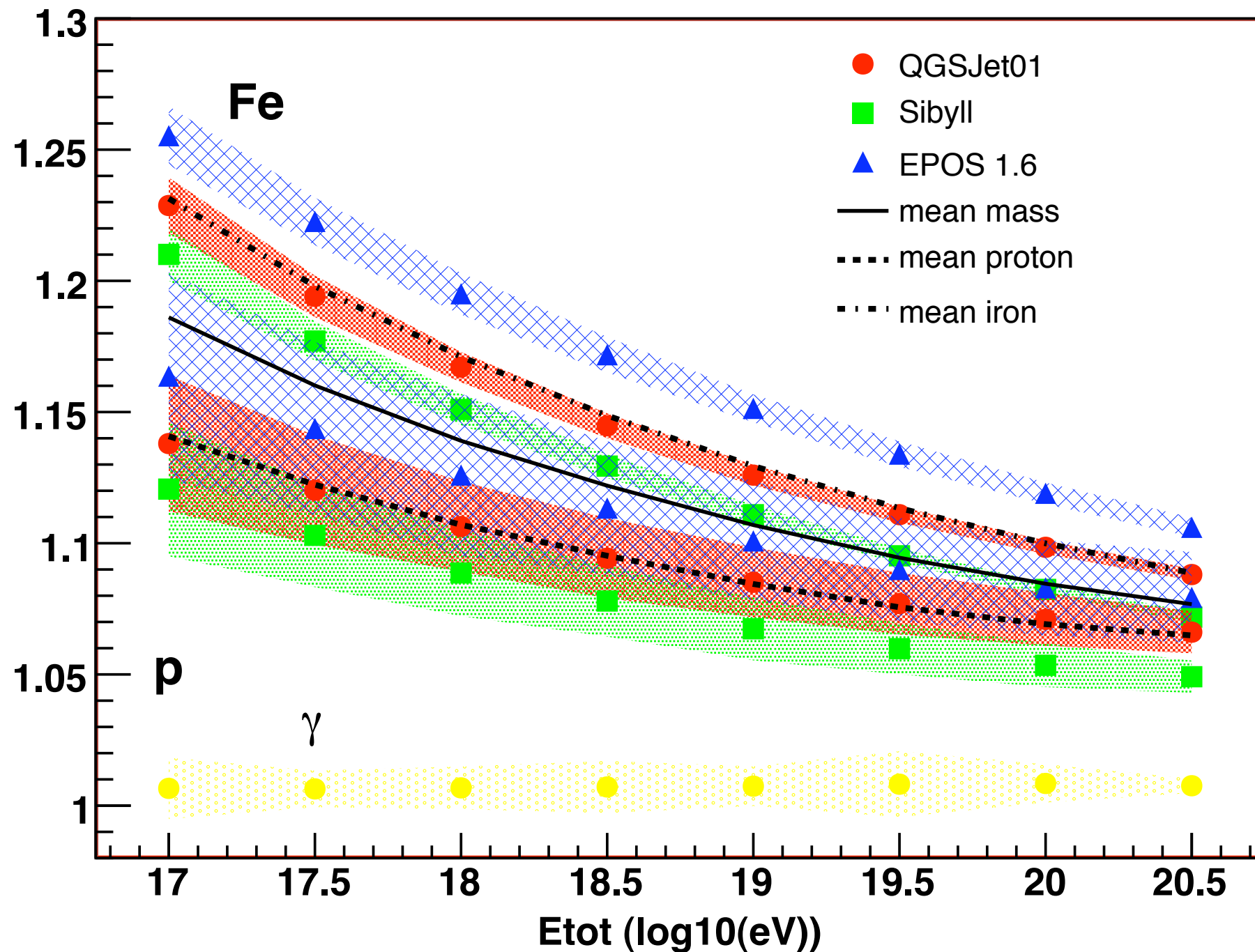
Sensitivity to cross section and multiplicity change



(Ulrich et al., astro-ph/0709.1392)

Energy correction for fluorescence detectors

$$f = E_{\text{tot}} / E_{\text{em}}$$



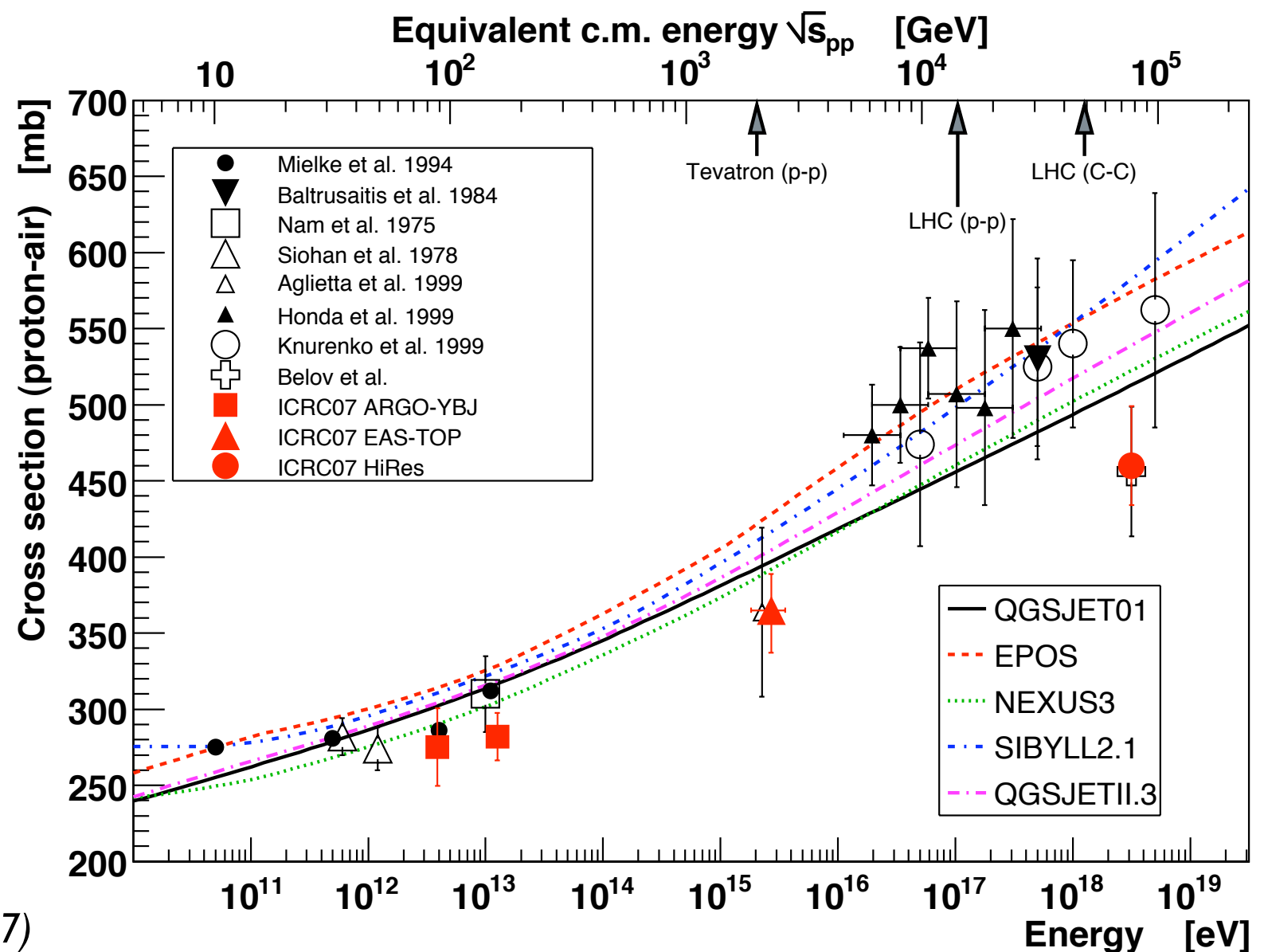
EPOS: Increased muon production directly linked to missing energy correction

Overall model dependence small

How to improve situation?

- Accelerator measurements (NA61, MIPP, HARP, ..., LHC experiments)
- Work on theory and phenomenology of hadronic interactions
- Validation of models using hybrid data (Auger, HiRes-MIA, KASCADE)
- Particle physics measurements with air showers

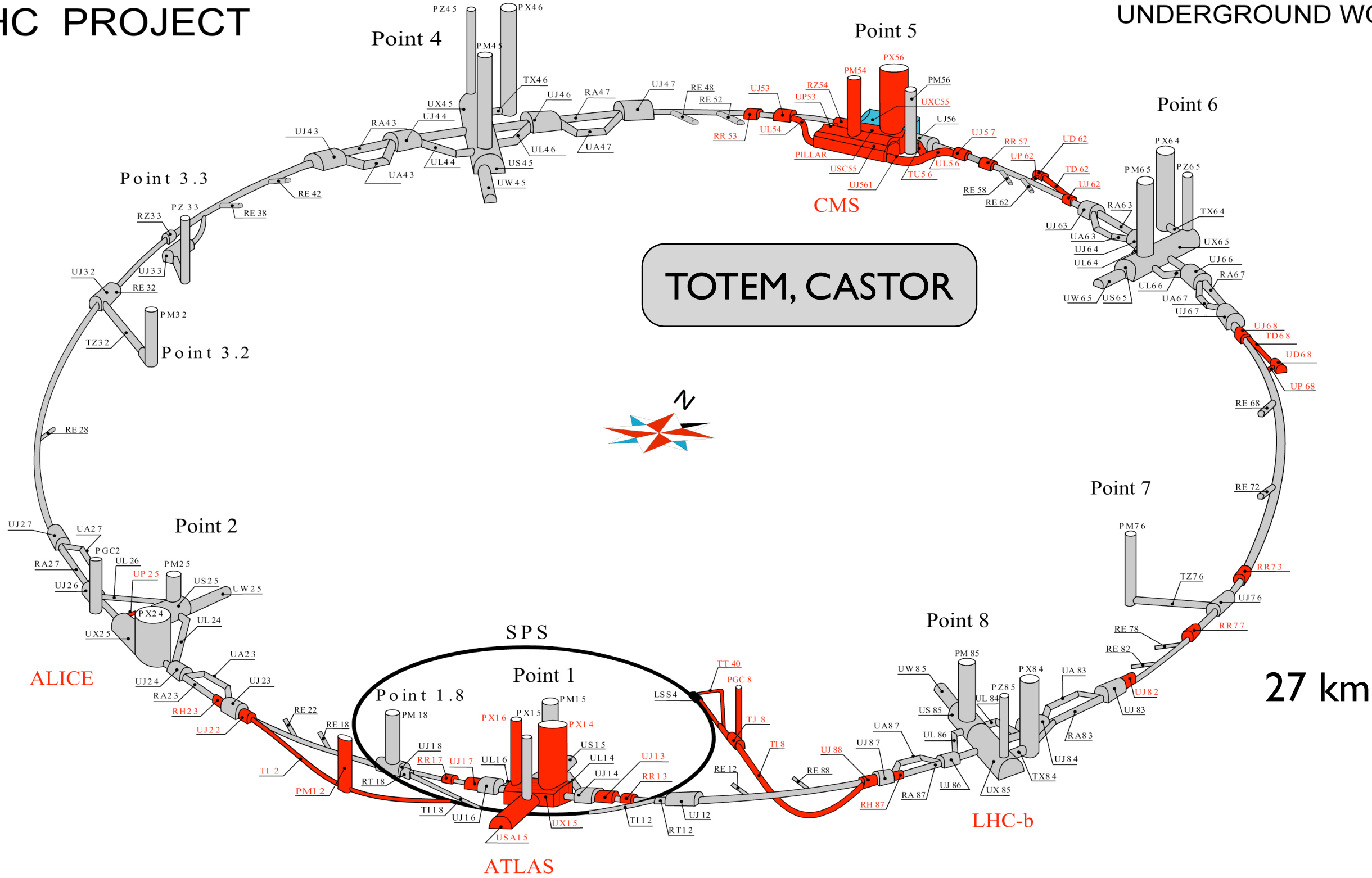
Proton-air cross section
measured with air showers



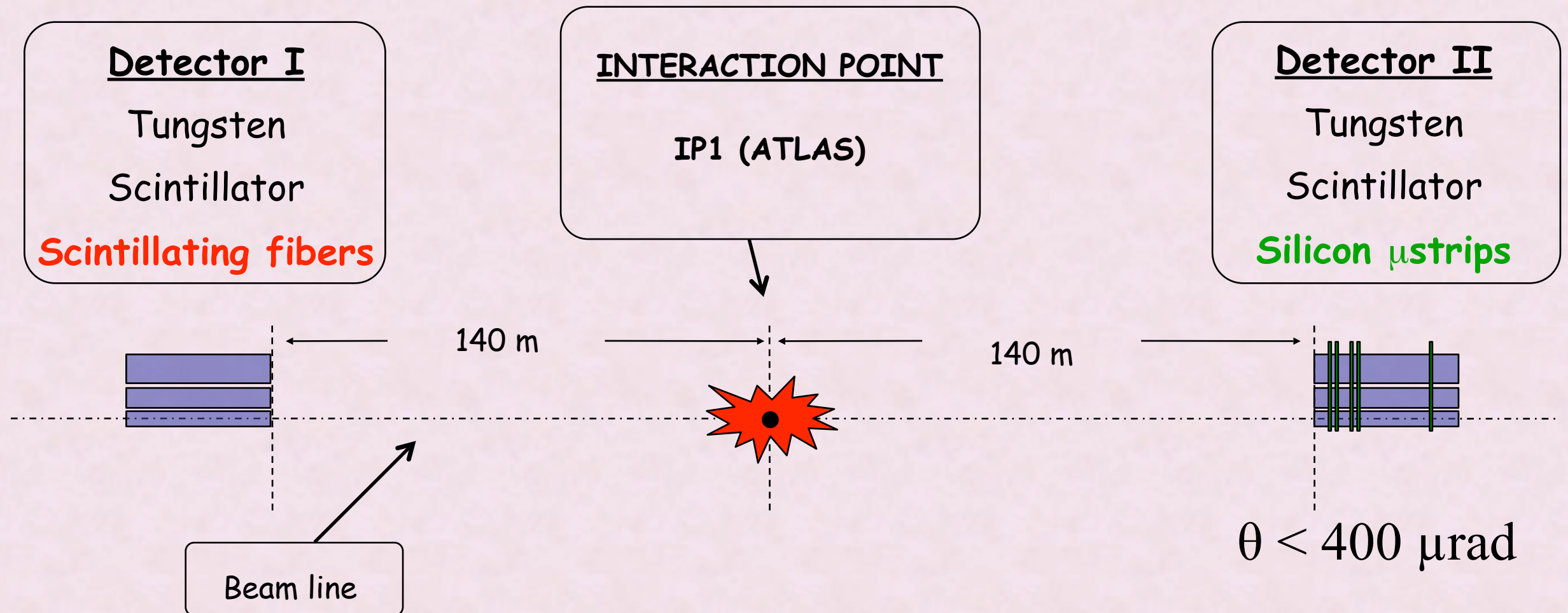
(Ulrich, 2007)

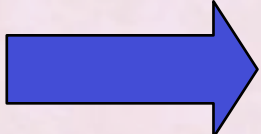
LHC PROJECT

UNDERGROUND WORKS

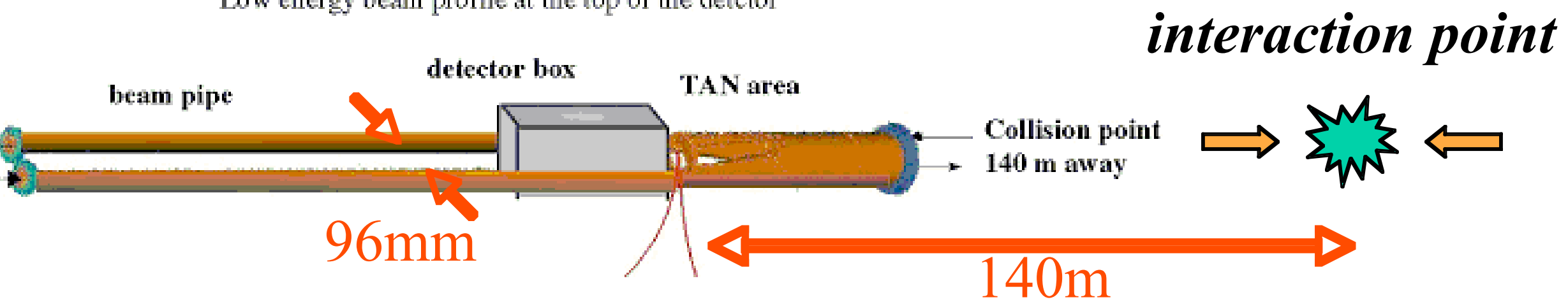


LHCf: detectors on both sides of IP1

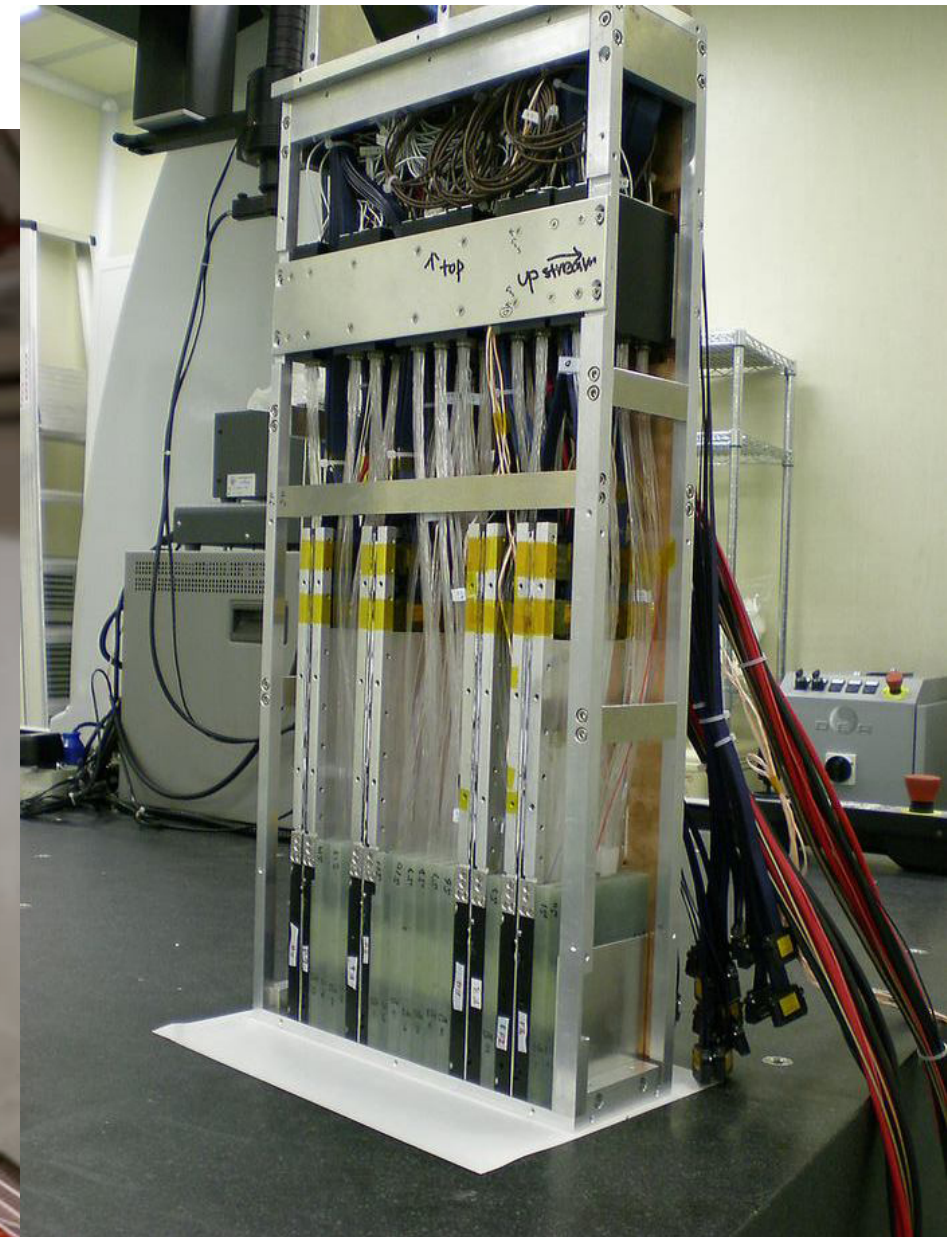


Detectors should measure energy and position of γ
from π^0 decays  e.m. calorimeters with
position sensitive layers

Low energy beam profile at the top of the detector



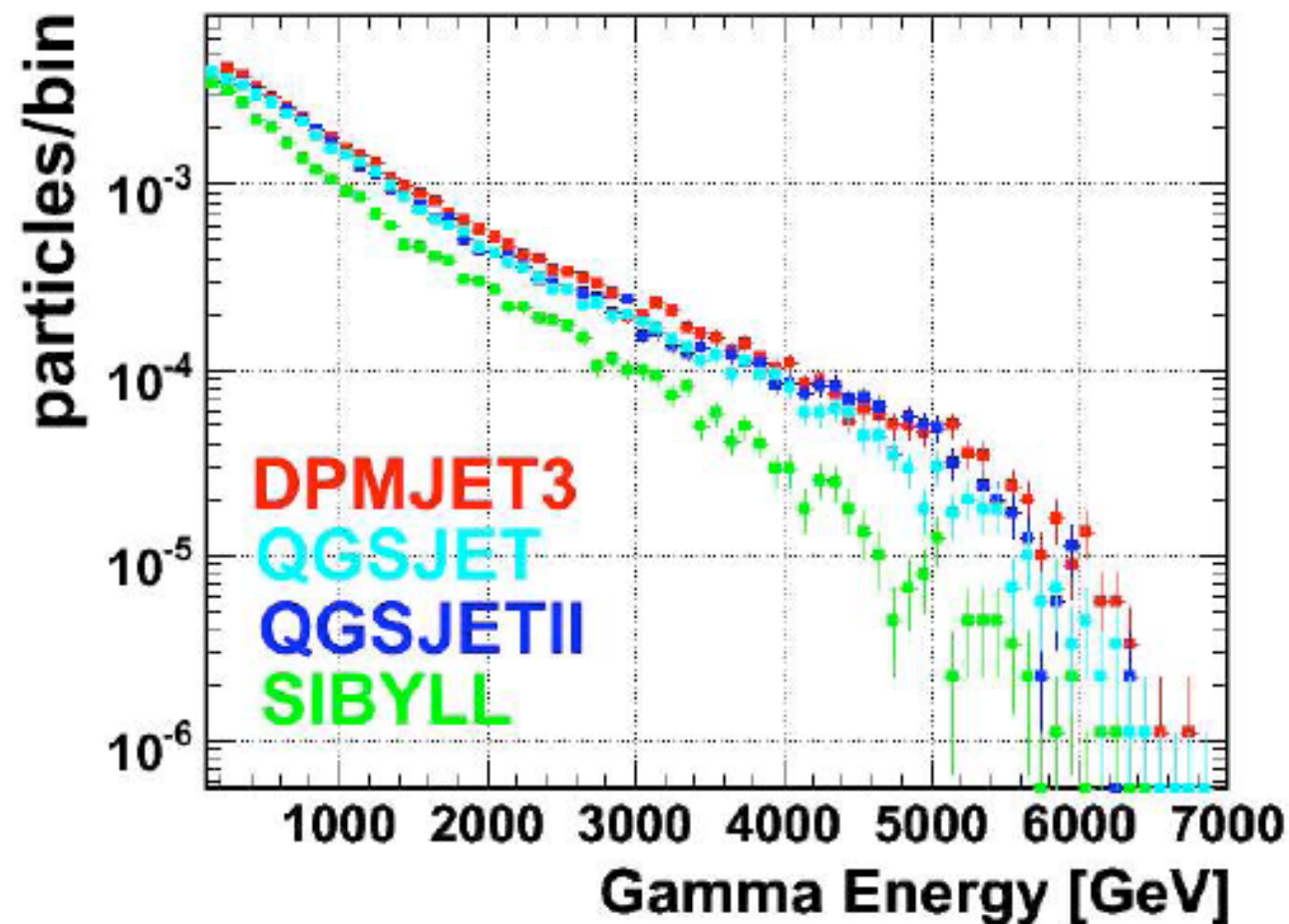
Arm I detector



Arm 2 detector

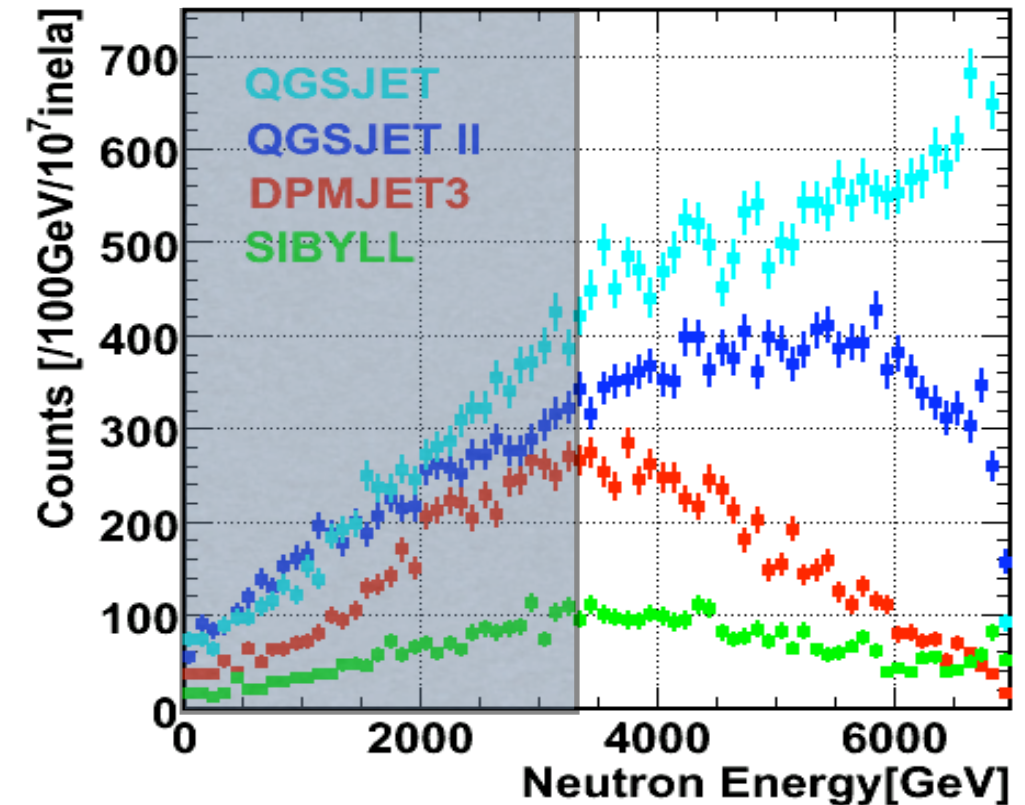
Expected signal and discrimination power

Gamma Energy Spectrum of 20mm square at Beam Center

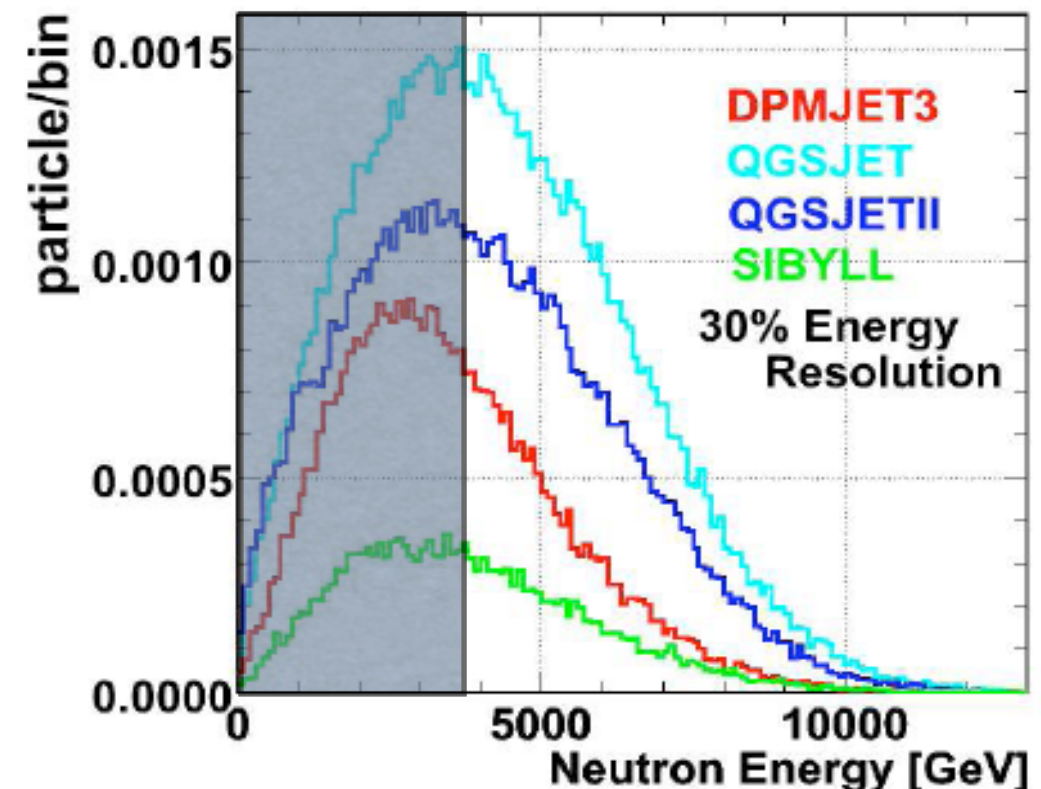


(Kasahara, ISVHECRI 2006)

Neutron Energy Distributions

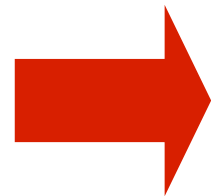


Neutron Energy Spectrum of 20mm Calorimeter at beam center

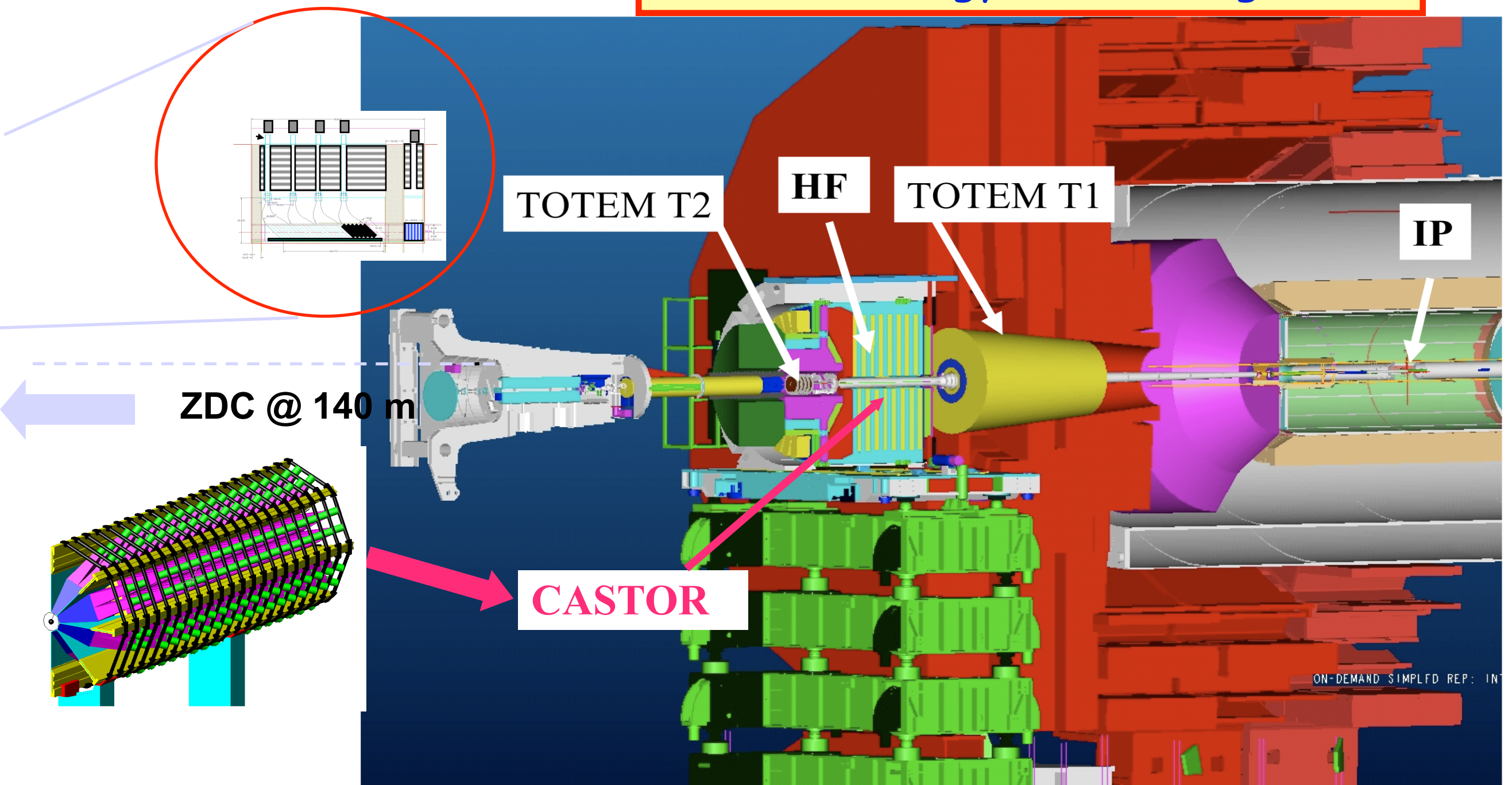


Forward Detectors in IP5: CMS/TOTEM

T1 $3.1 < \eta < 4.7$
T2 $5.3 < \eta < 6.7$
Castor $5.25 < \eta < 6.5$



Extend the reach in η from $|\eta| < 5$
to $|\eta| < 6.7$
+ neutral energy at zero degrees



Roman Pot

**BPM fixed to the structure :
precise position of the beam**

Horizontal Pot

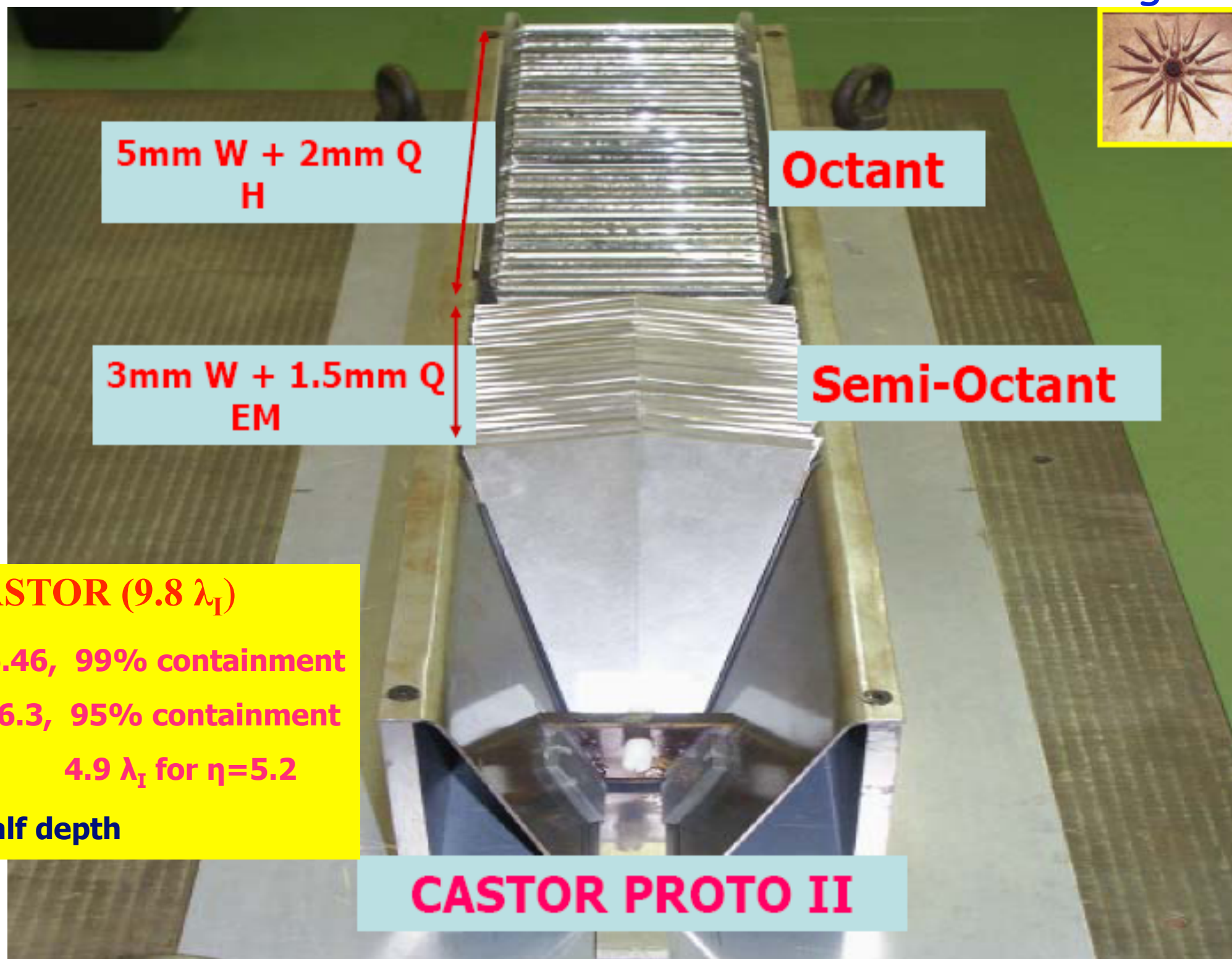
Vertical Pot

BPM

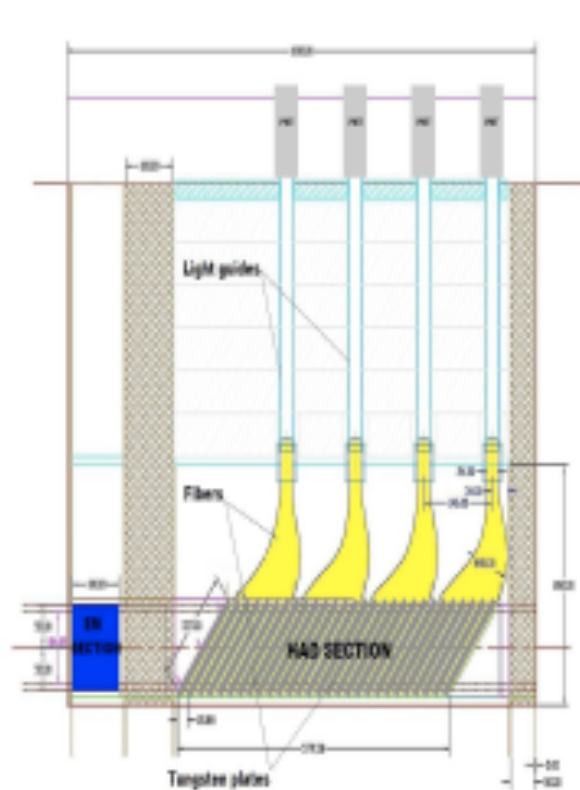
**RP station : 2 units, 4 m distance
Unit: 2 vertical / 1 horizontal insertions (Pot)**

Detector Progress: CASTOR

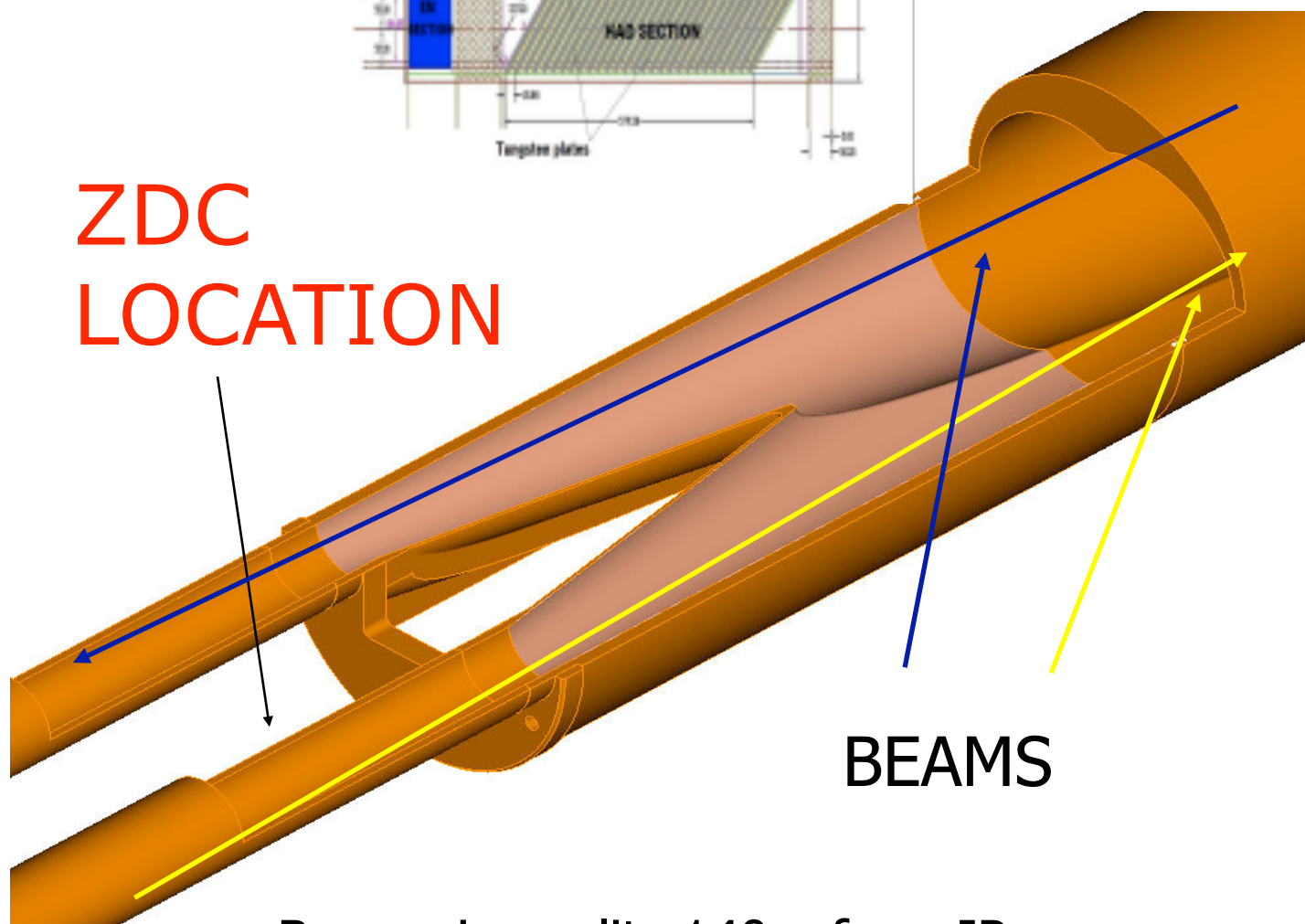
A. Panagiotou



ZDC: zero degree calorimeter (CMS)



ZDC
LOCATION



BEAMS

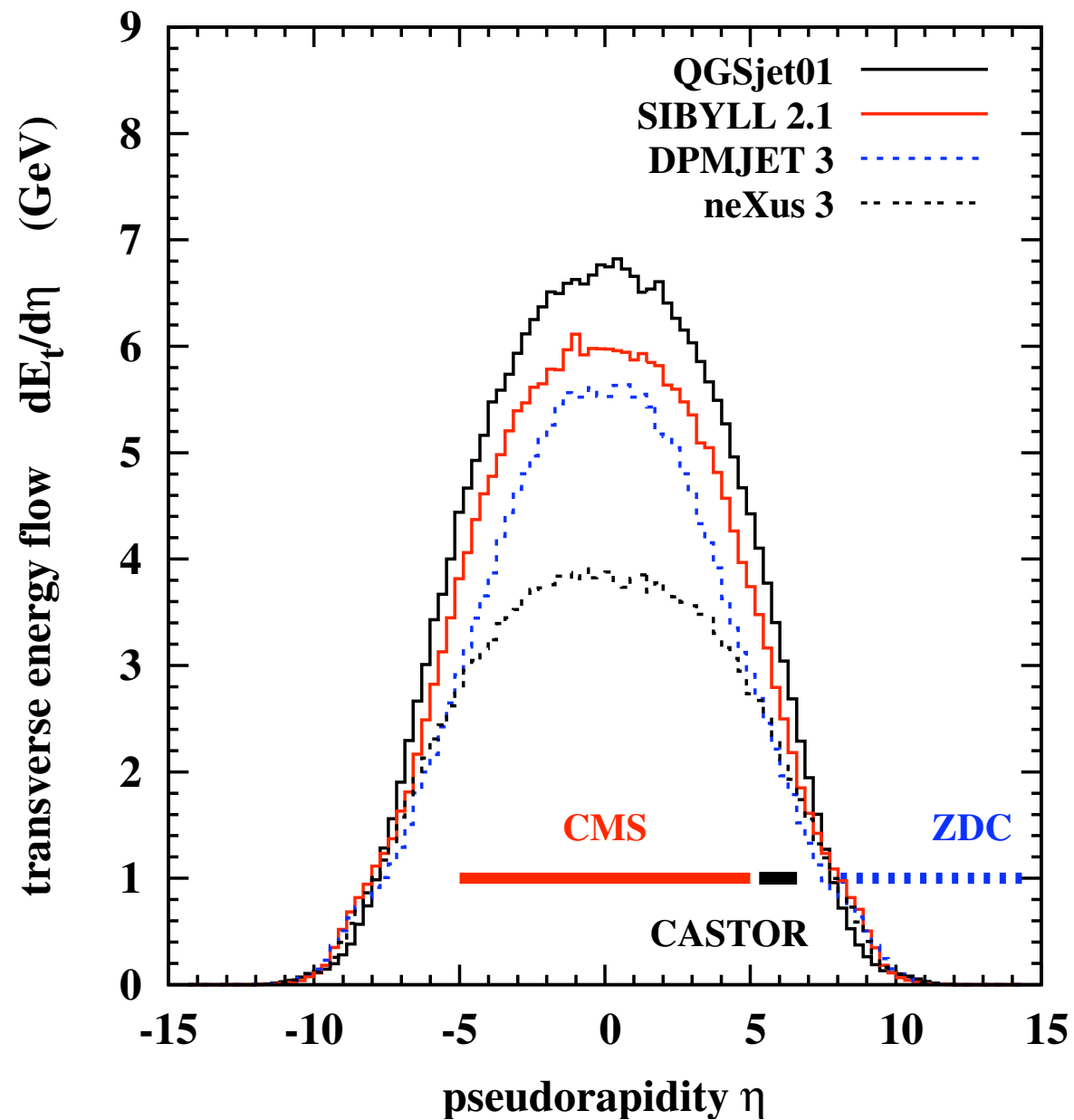
Beam pipe splits 140m from IR



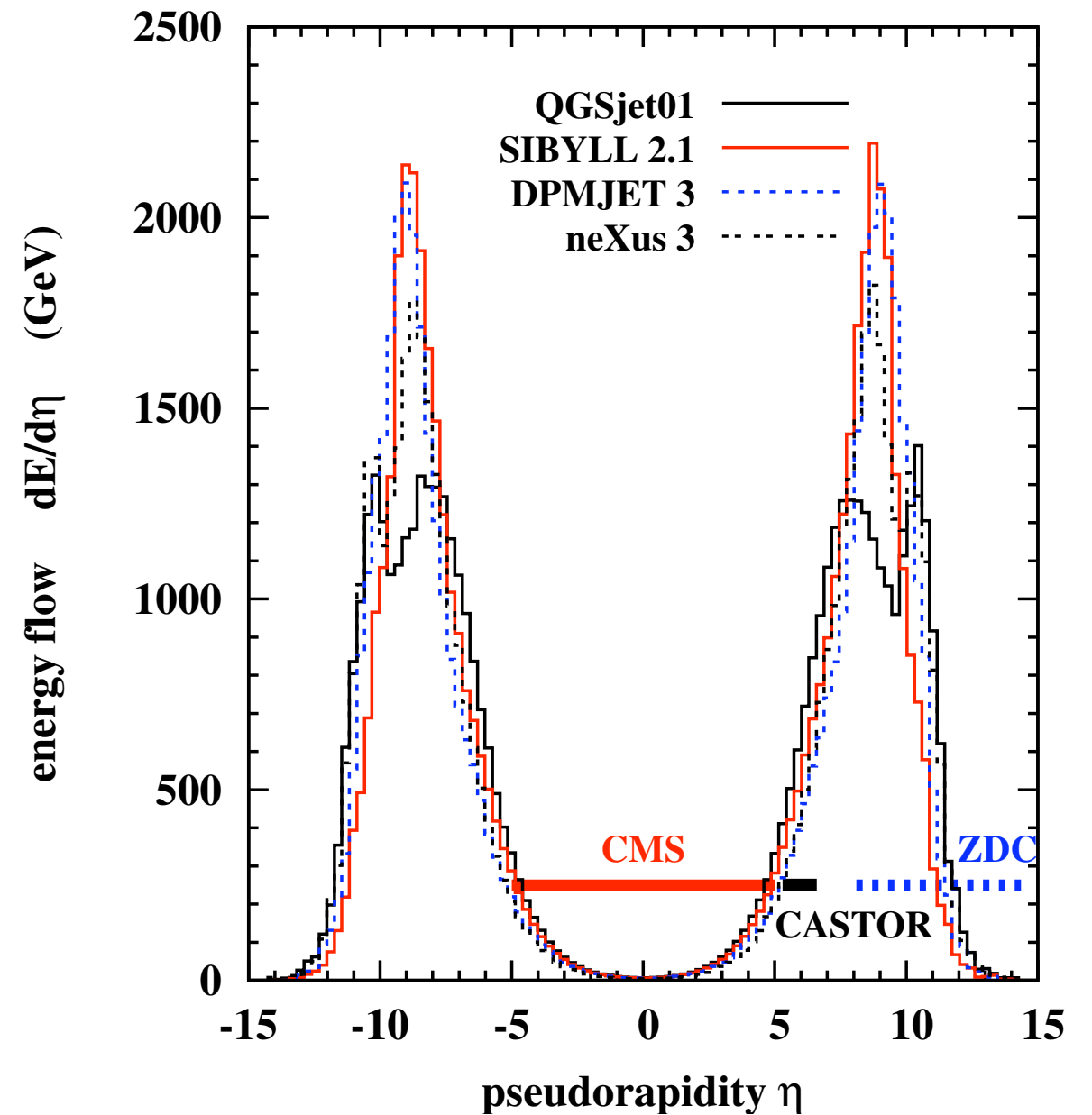
- Tungsten/ quartz fiber
- EM and HAD section
- Now in testbeam
- Installation of first detector next month, the 2nd next spring

Proton-proton at LHC (MC level)

Transverse energy

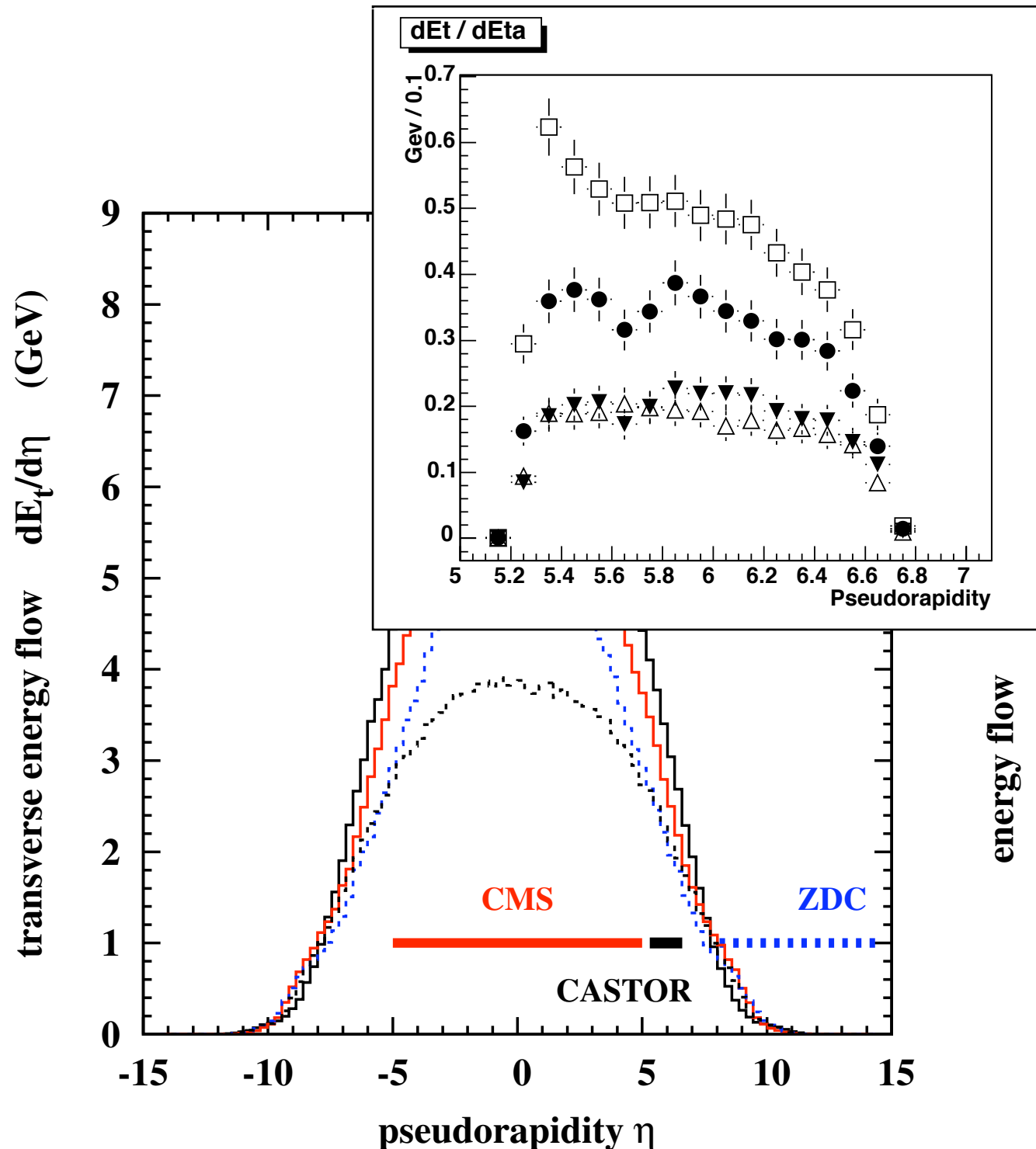


Total energy

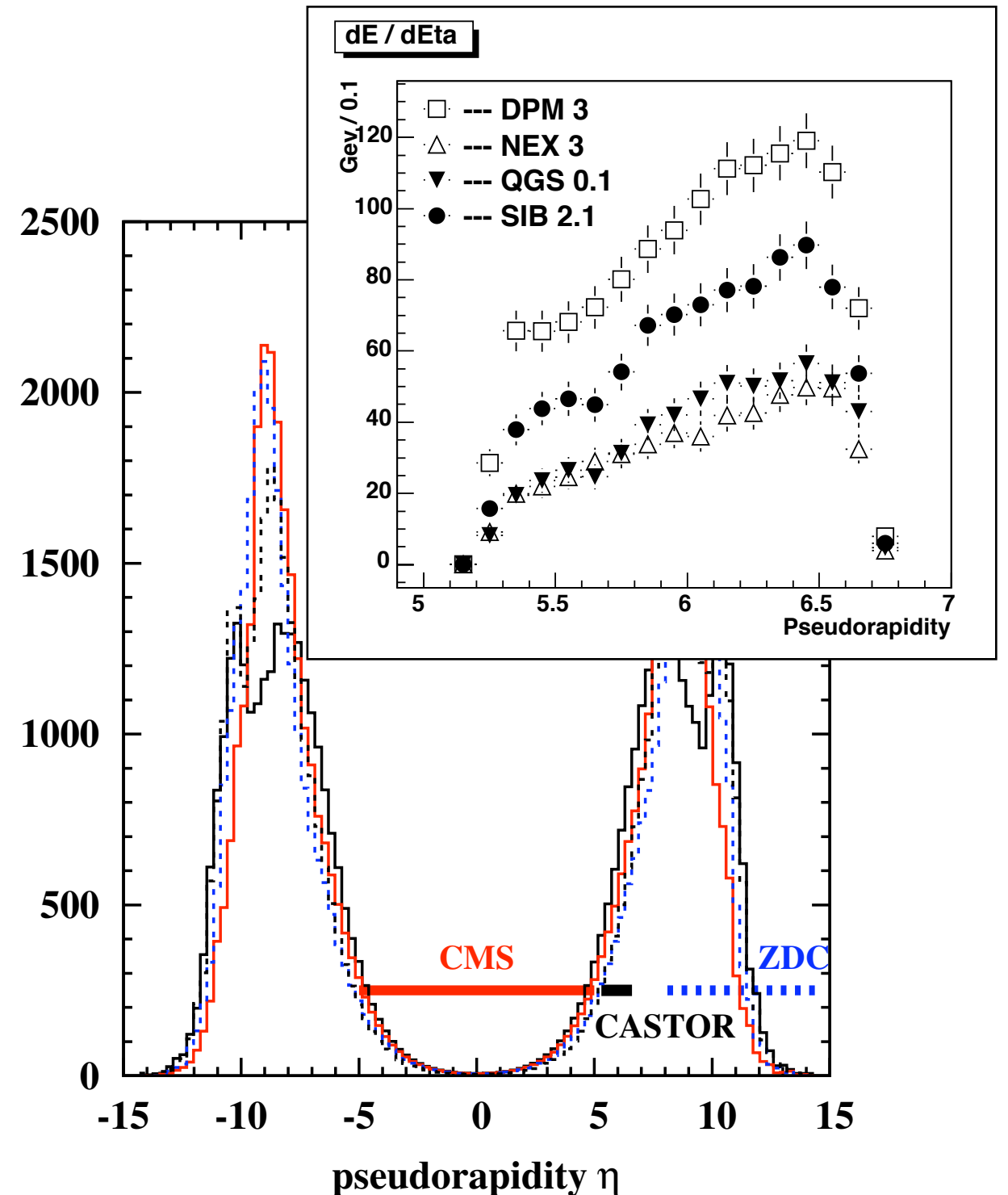


(Albrow et al., CERN/LHCC 2006-039/G-124)

Proton-proton at LHC (detector simulation)

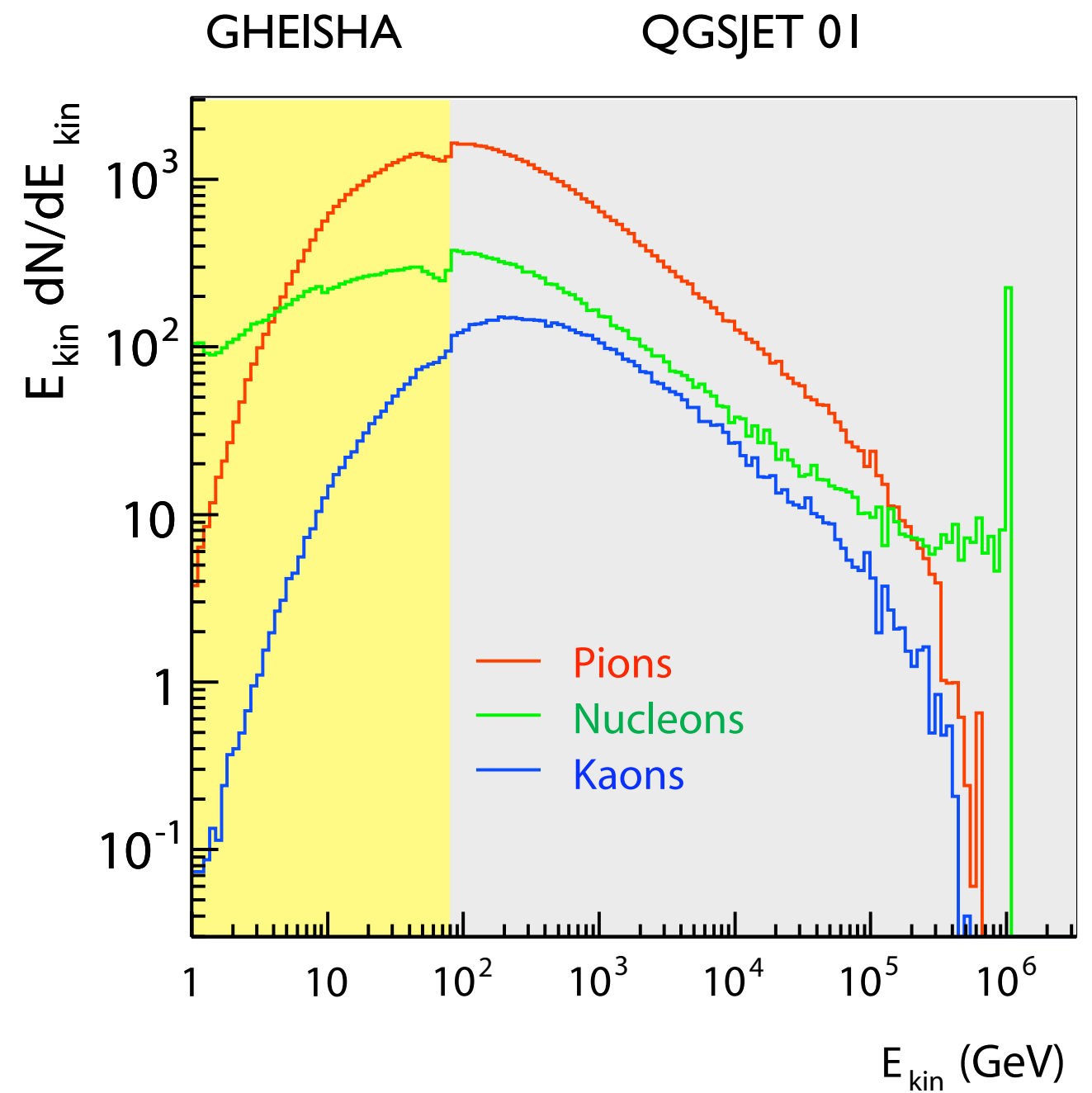
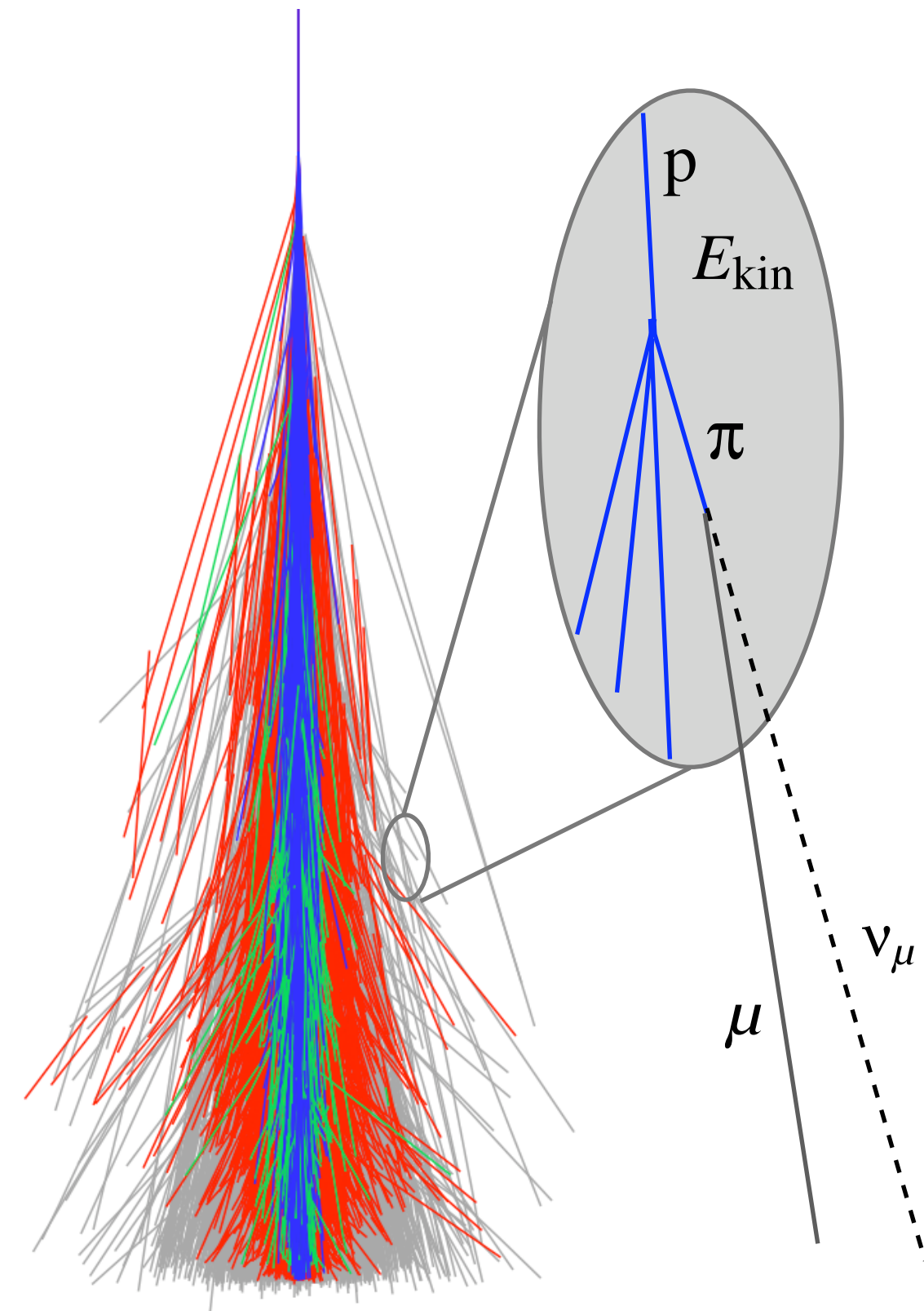


Transverse energy



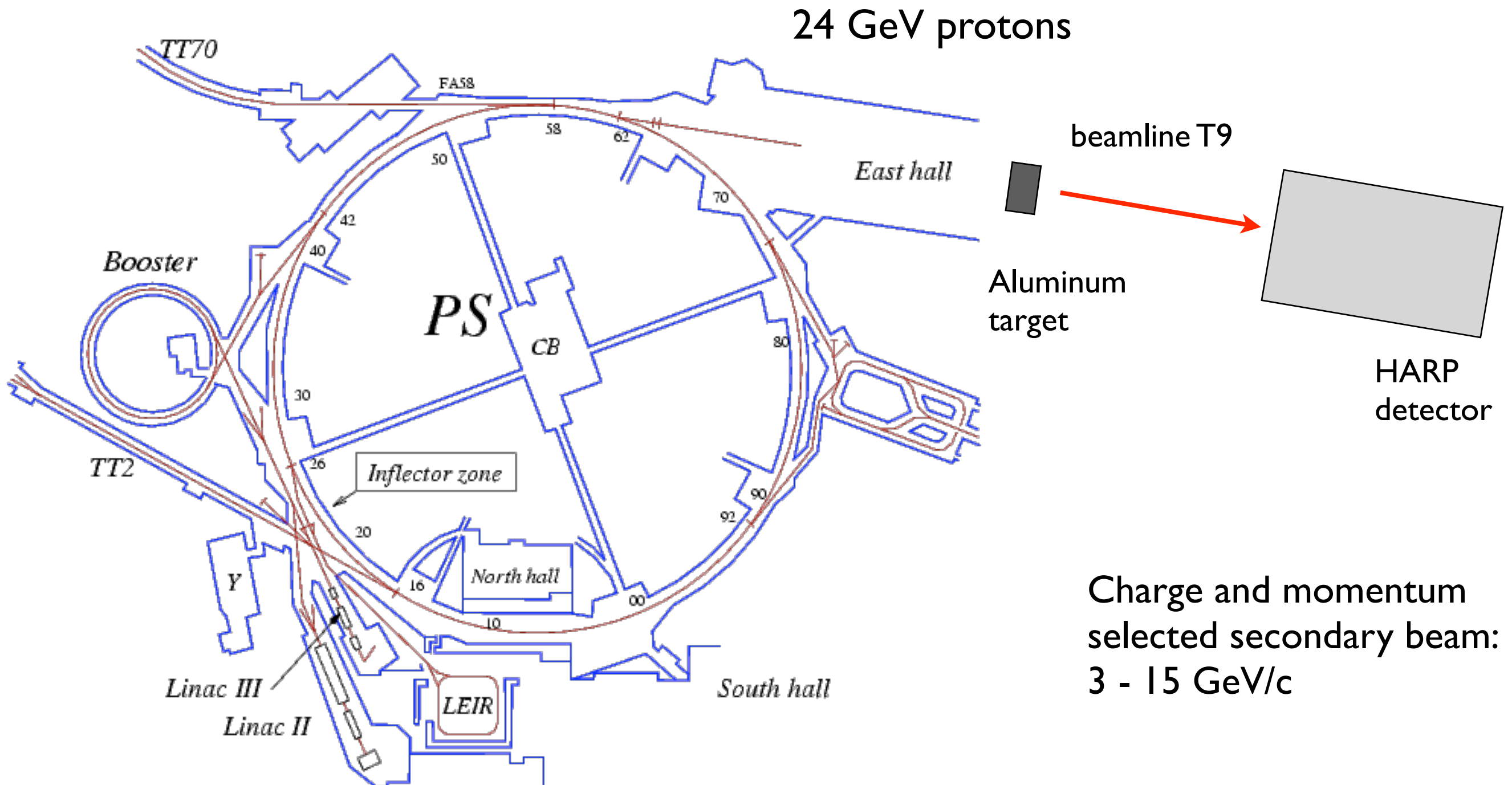
Total energy

Low-energy interactions in air showers

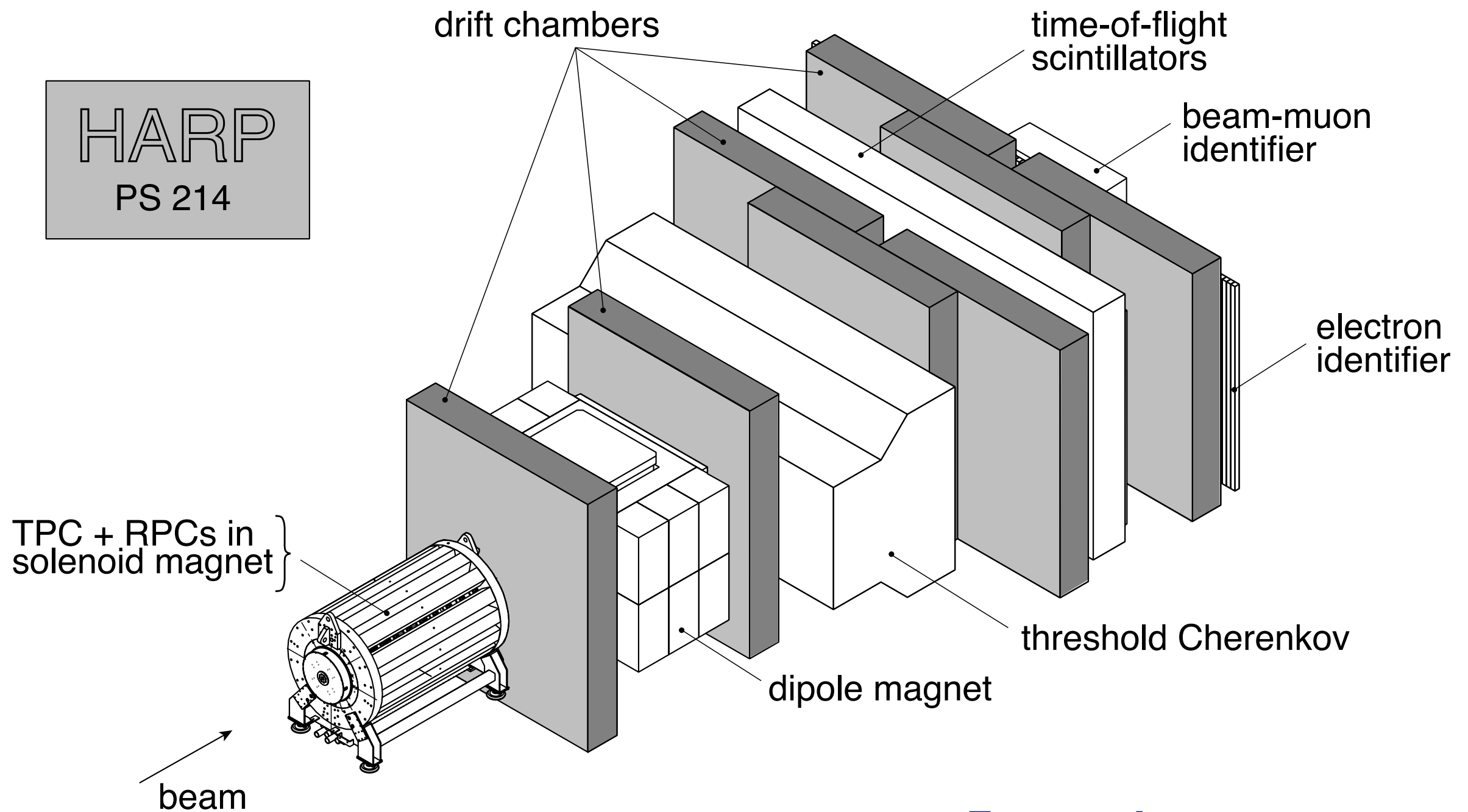


(C. Meurer et al., ICRC 2005, Pune, India)

HARP: Hadron Production Experiment at the PS



CERN Proton Synchrotron

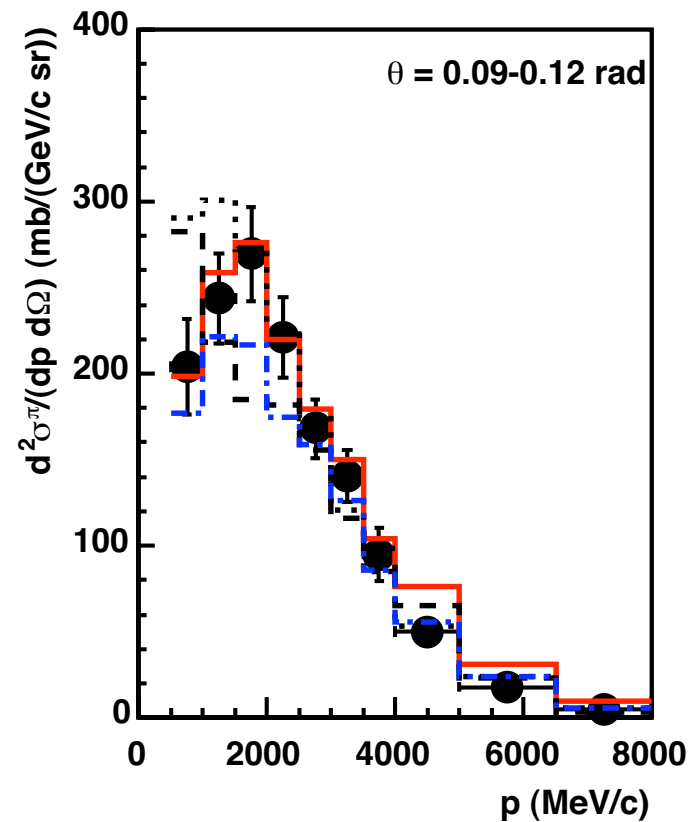
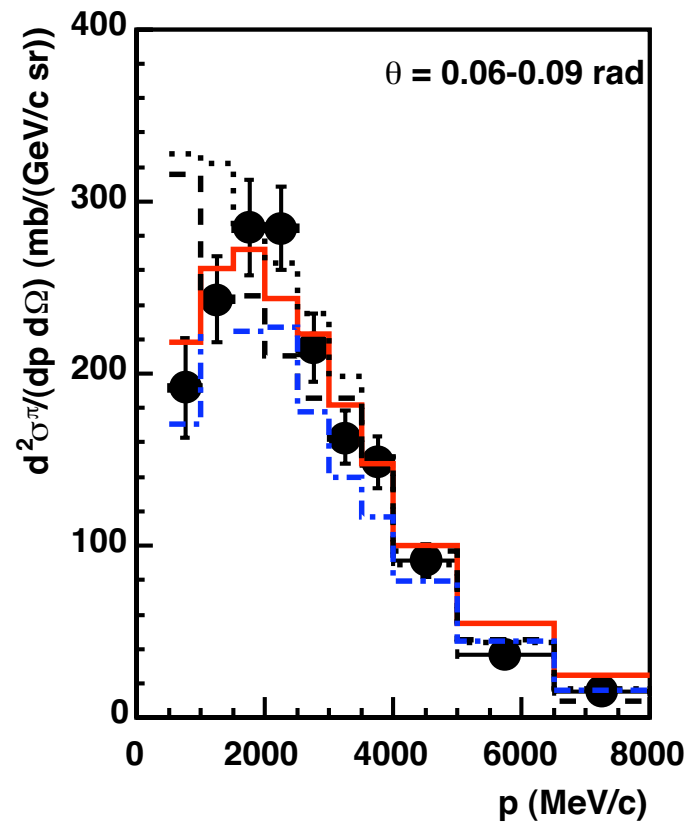


Large angle detector

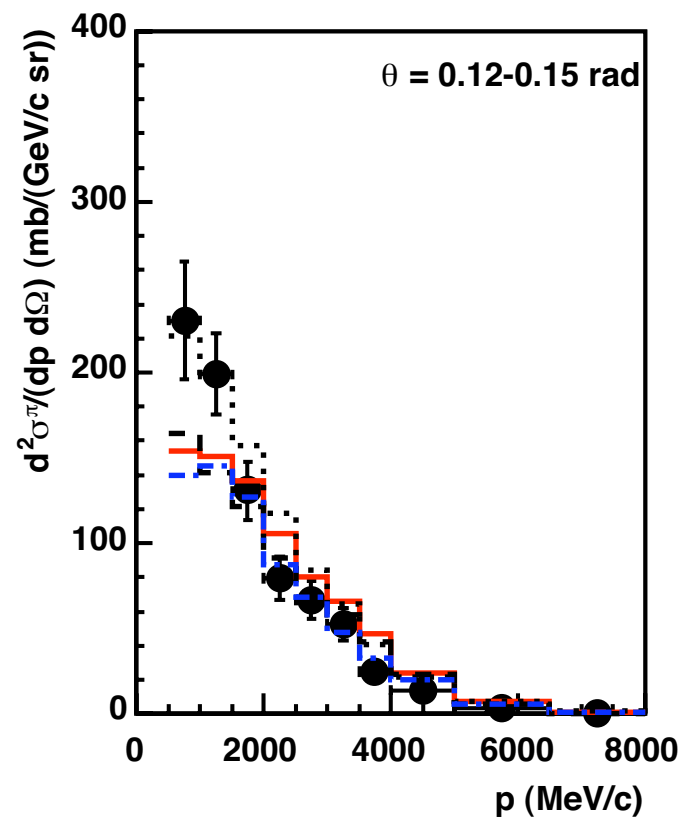
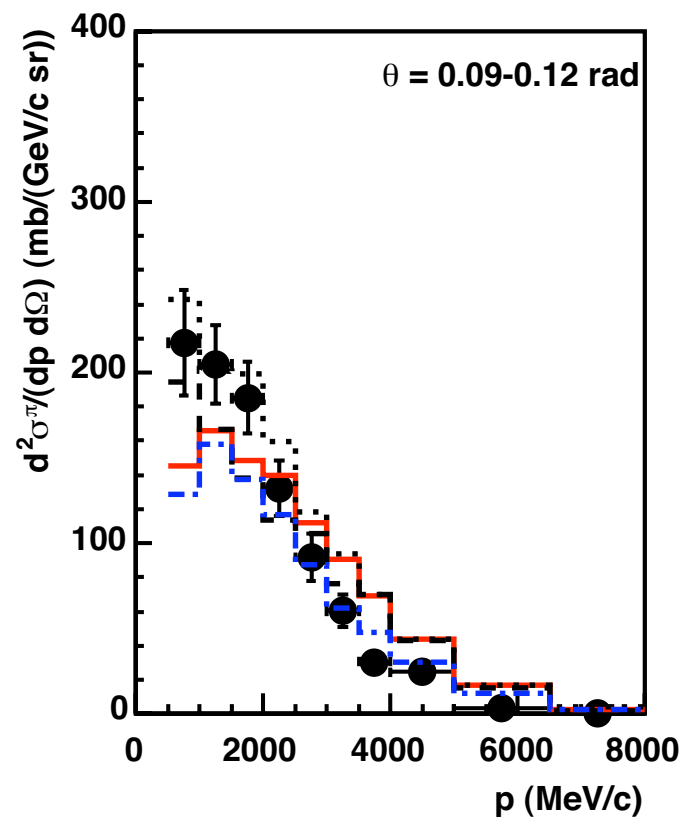
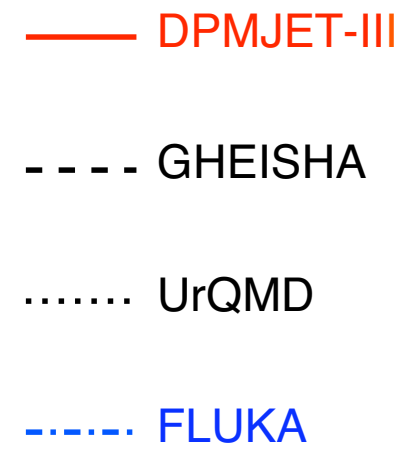
Forward spectrometer

(Catanesi et al., NIM A571, 2007)

HARP p-C data at 12 GeV



Positive pions



Negative pions

None of the models describes data consistently

Summary

Cosmic ray interaction and secondary particle production abundant

- inclusive fluxes of neutrinos, gamma-rays, neutrons, antiprotons
- extensive air showers
- energies: particle production threshold to highest energies in universe

Important information from interactions

- energy loss during propagation
- secondary particles

Models needed for description/simulation of interactions

- resonances, two-string model, minijet-model
- large uncertainties (composition measurements affected)
- accelerator measurements of central importance, collaboration with high energy physicists

**Many open questions at the interface between particle and
cosmic ray physics**

Elongation rate theorem

$$X_0 = 37 \text{ g/cm}^2$$



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

(Linsley, Watson PRL46, 1981)

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

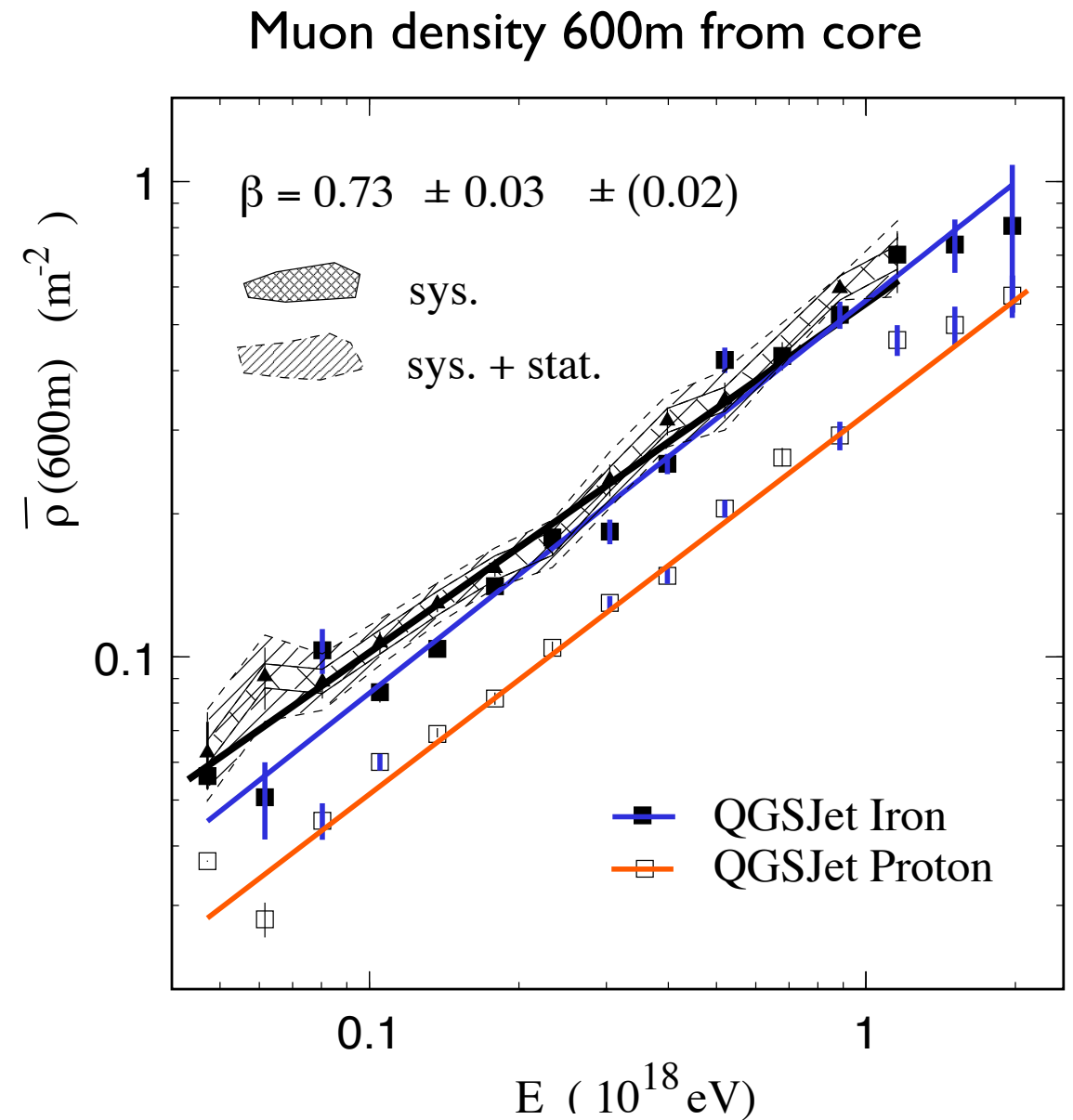
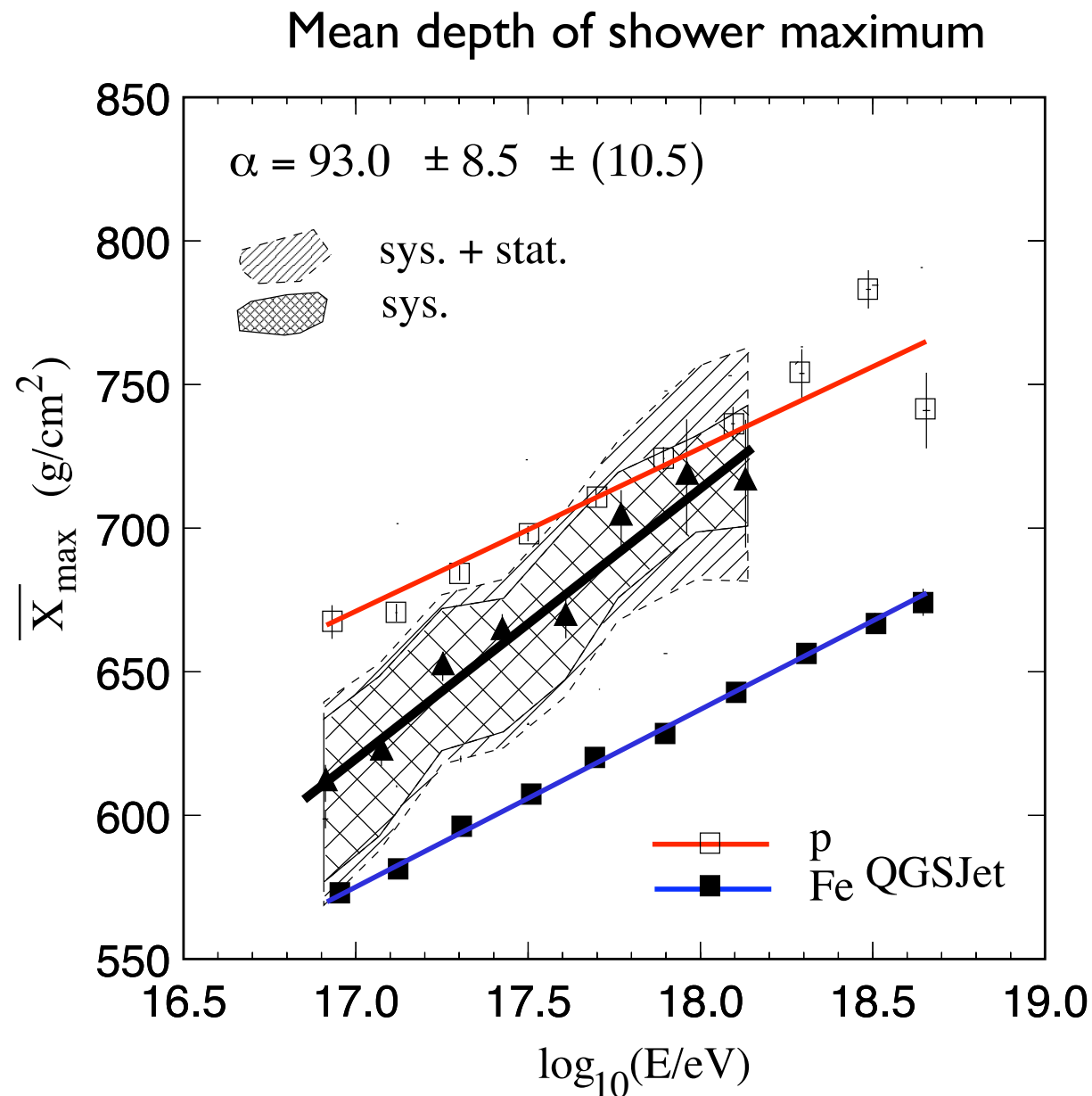
Large if multiplicity of high energy particles rises very fast, **zero in case of scaling**

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

Large if cross section rises rapidly with energy

Note: $D_{10} = \log(10) D_e$

Problem I: HiRes-MIA hybrid measurement



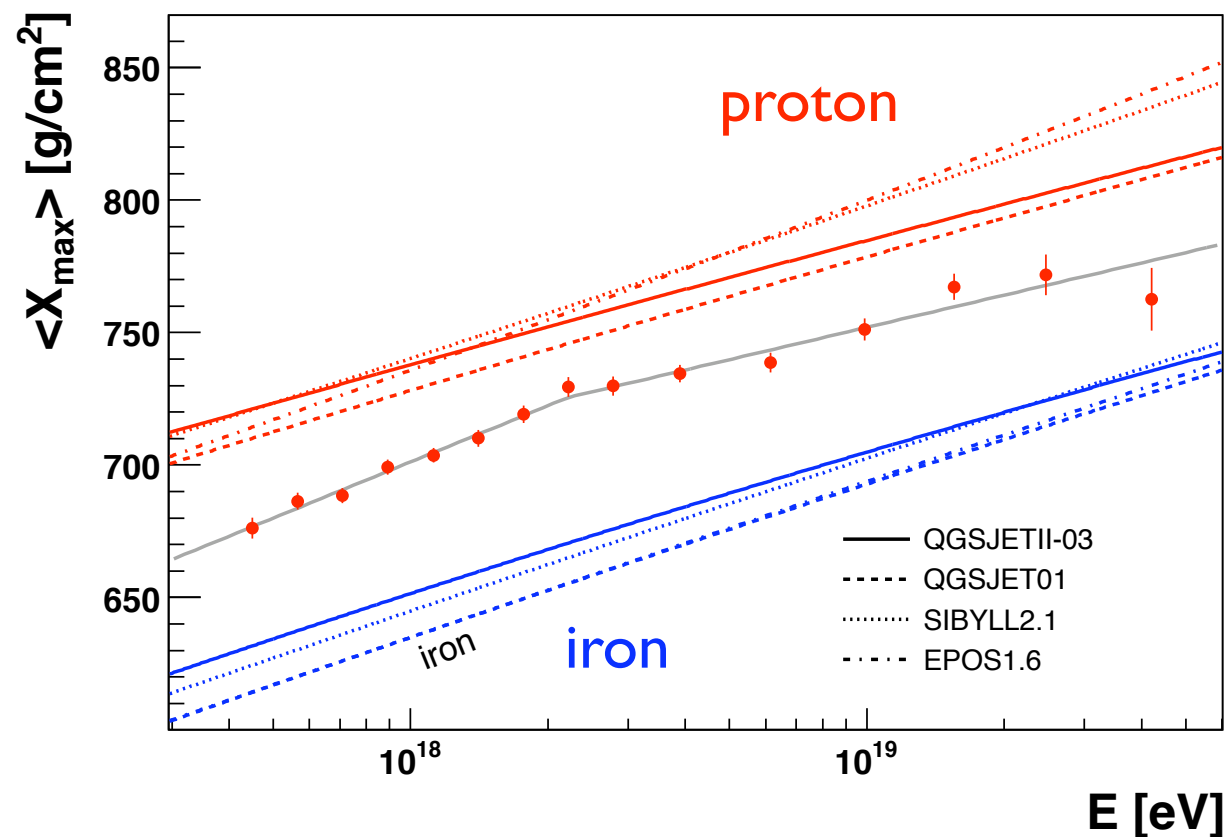
Analysis with QGSJET98 (very similar to QGSJET01)

Problem 2: Auger data analysis based on universality

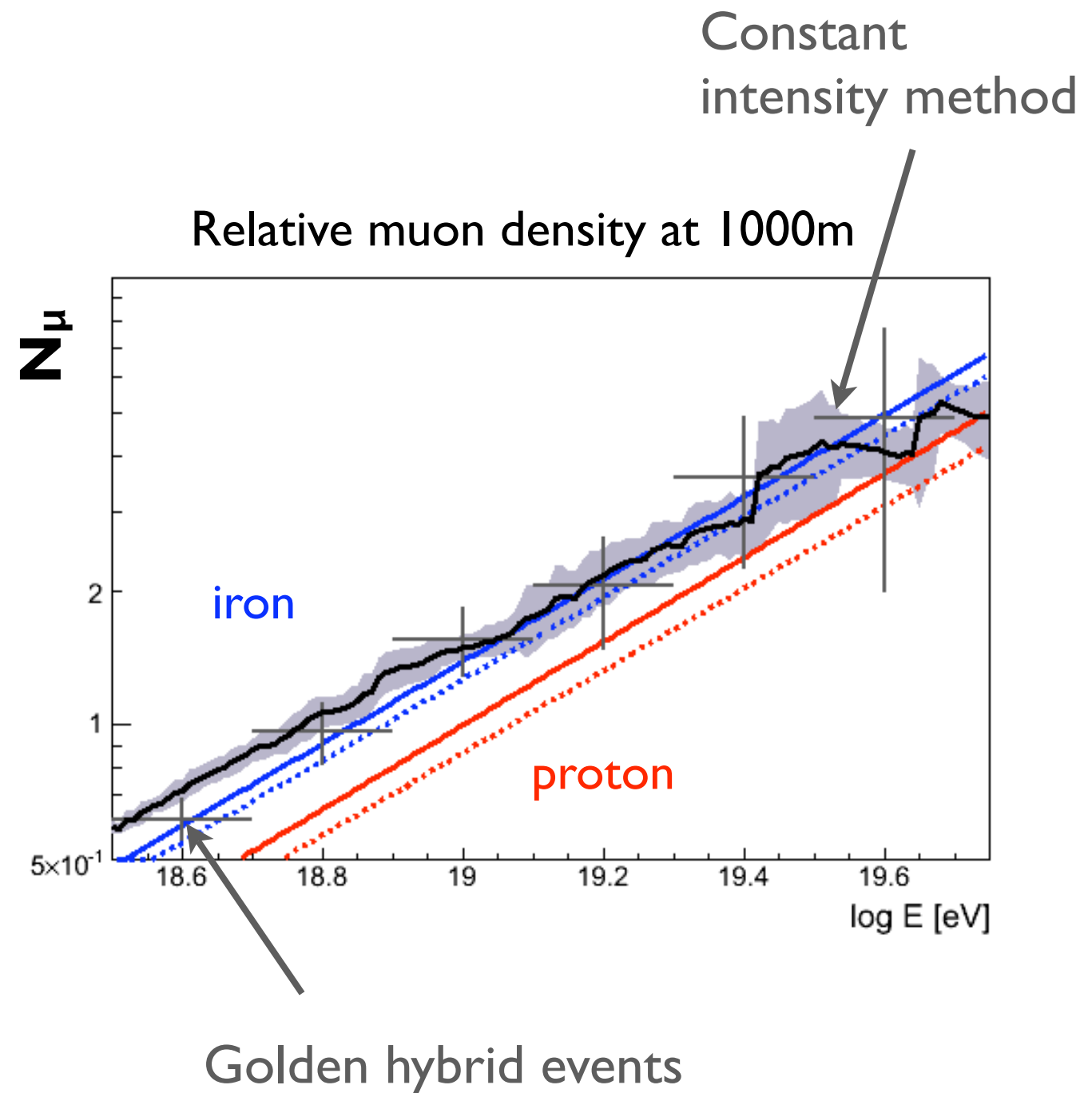
Universality of em. component of showers

(Schmidt et al., astro-ph/0712.3750)

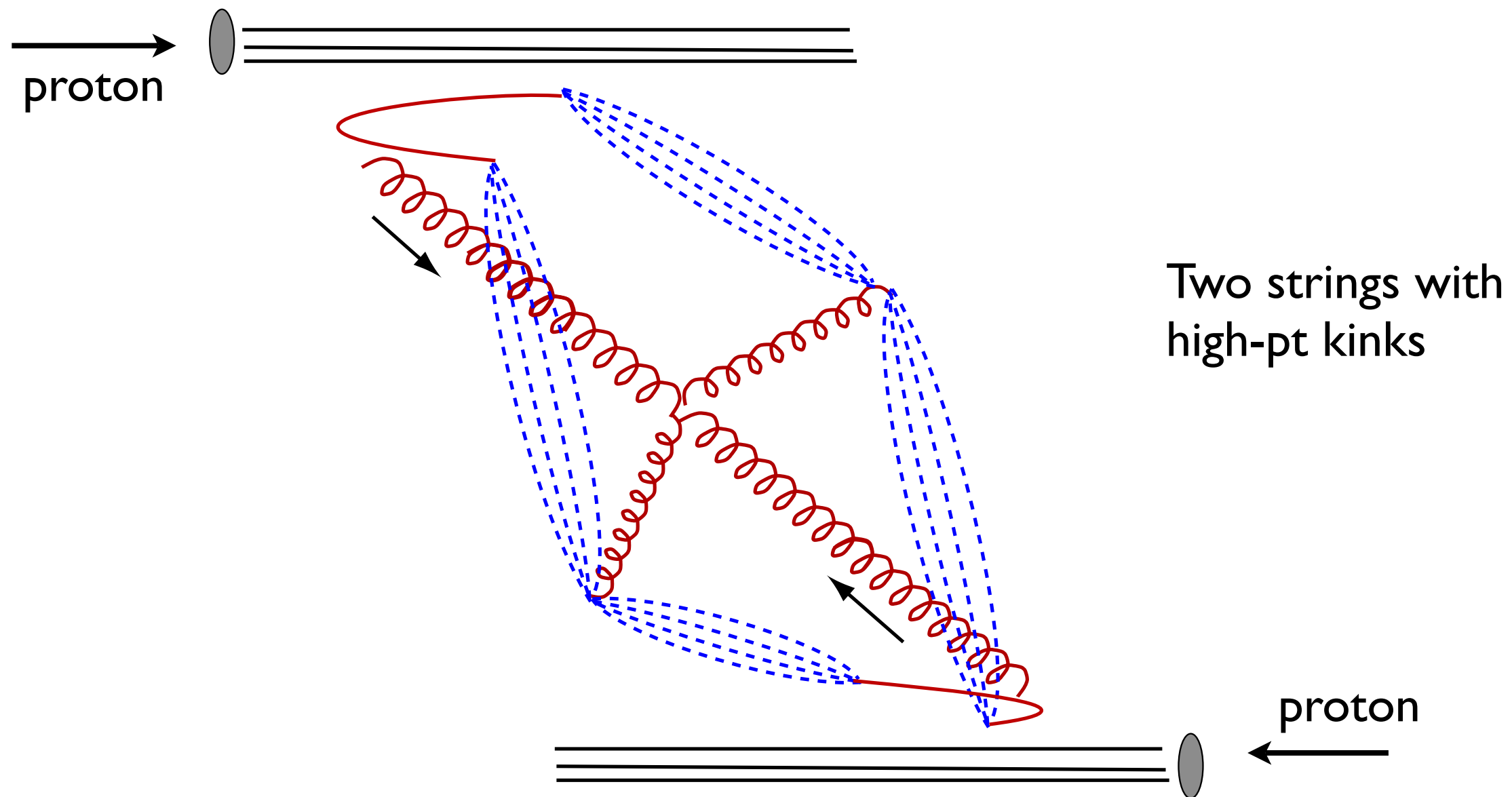
Mean depth of shower maximum



(Auger, ICRC 2007)



Two-gluon scattering: QGSJET



Sea quark pairs form end of strings, generated from model distribution

$$\frac{dP}{dx} \sim \frac{1}{\sqrt{x}}$$