Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

Karlsruhe Institute of Technology

Hadronic Interaction Models and Accelerator Data

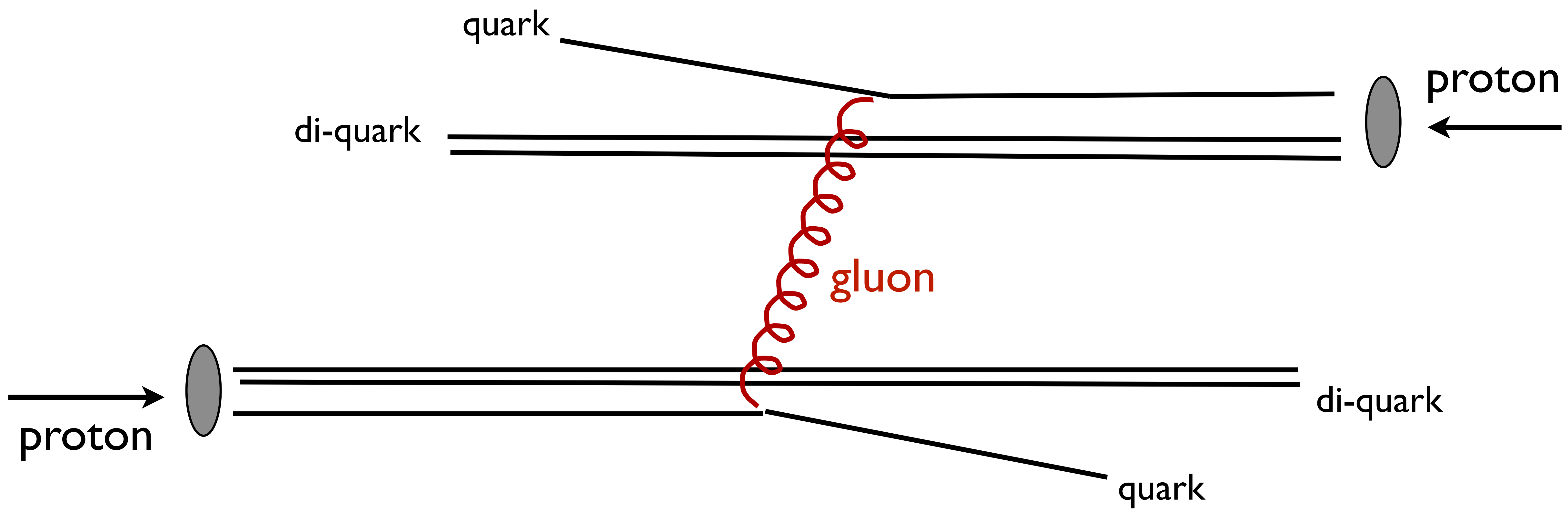
Ralph Engel, Dieter Heck, Sergey Ostapchenko,
Tanguy Pierog, and Klaus Werner

Outline

- **Introduction:** Color flow and strings
- **String fragmentation**
  - Baryon-antibaryon production
  - Popcorn effect
- **String configurations of different models**
  - Configurations and data
  - High-density effects
- **Model predictions and comparison with data**
  - Accelerator data
  - Air shower predictions

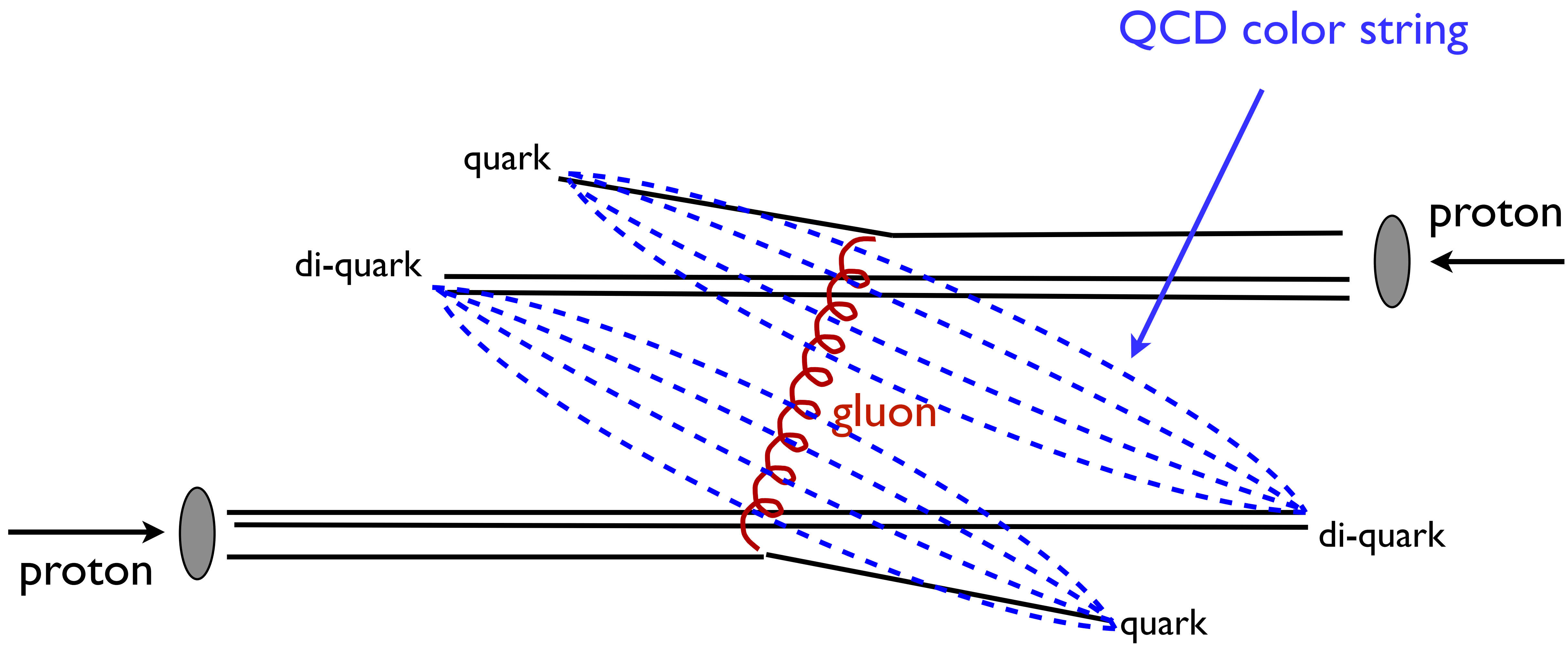
Color flow and strings (i)

Generic scattering diagram

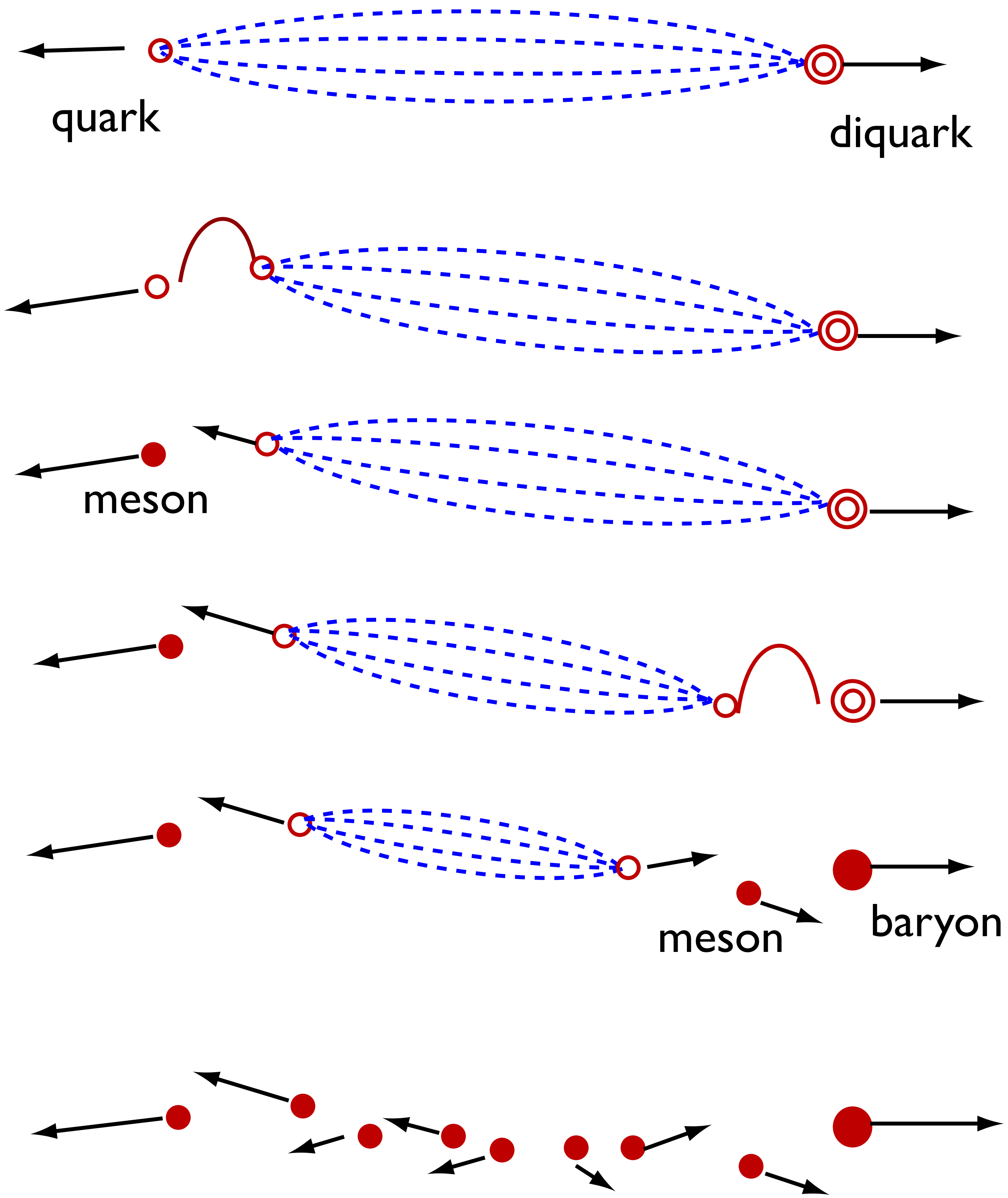


Color flow and strings (ii)

Generic scattering diagram



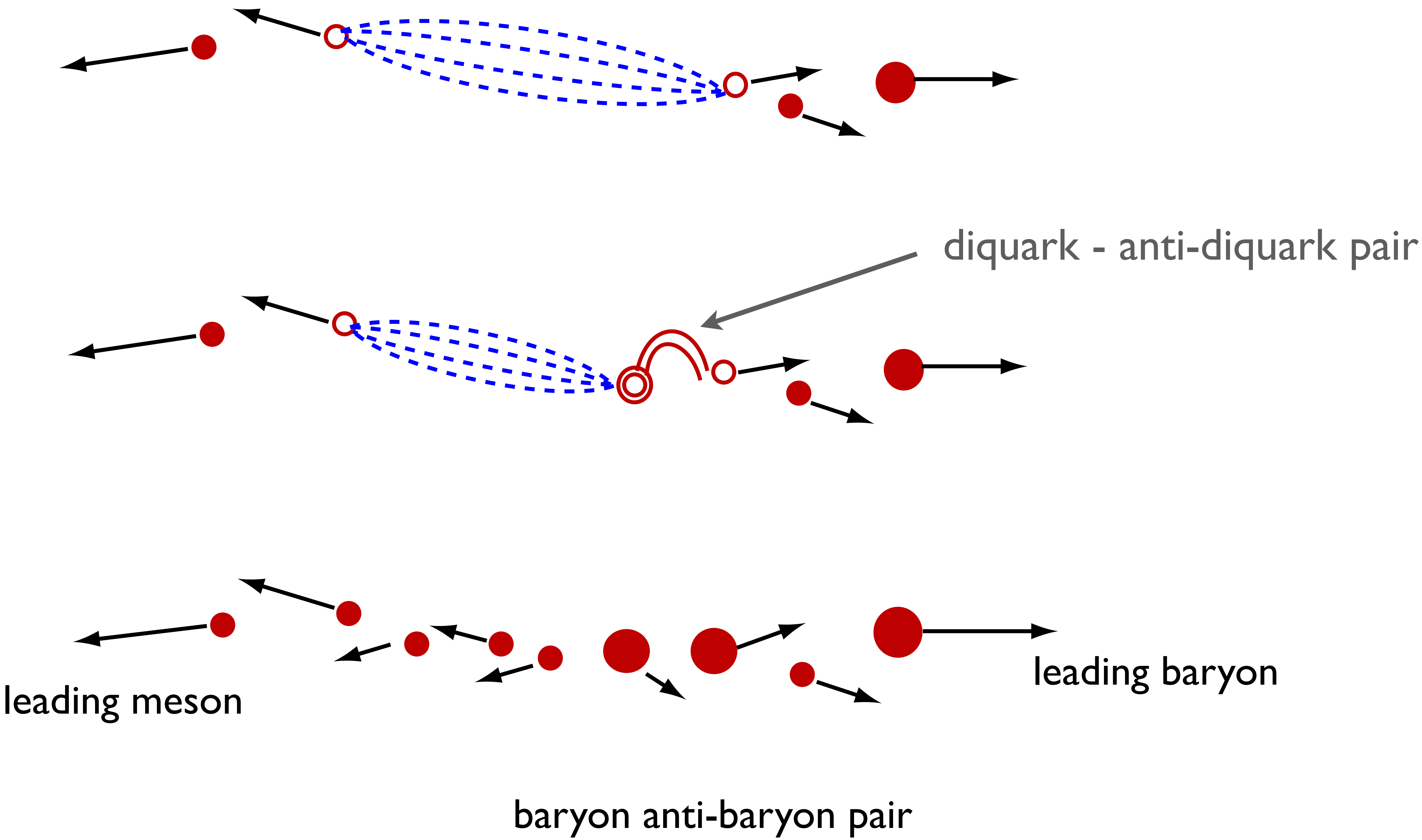
QCD string fragmentation



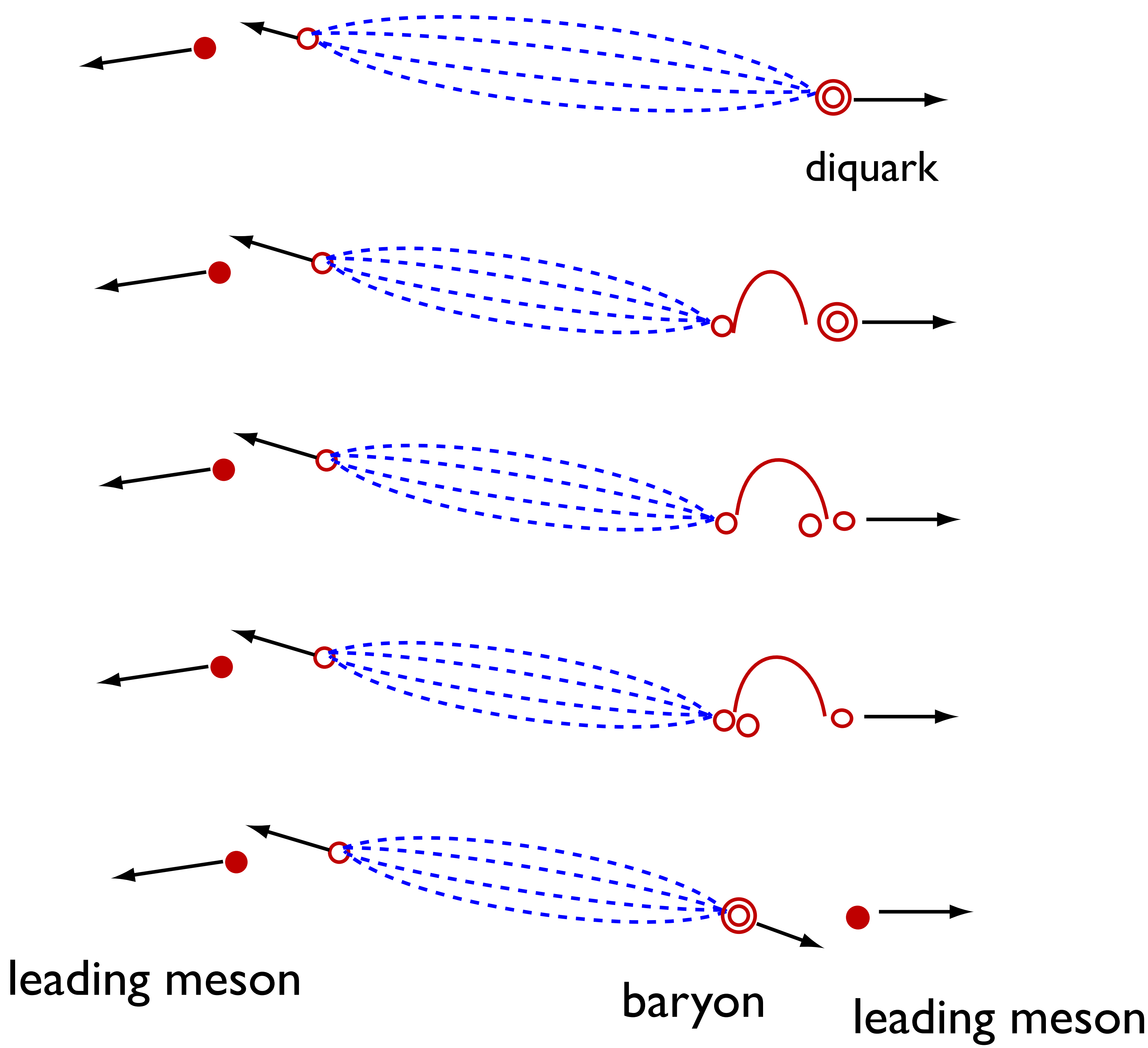
Chain of hadrons:

- large long. momenta near ends
- small trans. momenta

String fragmentation: baryon pairs

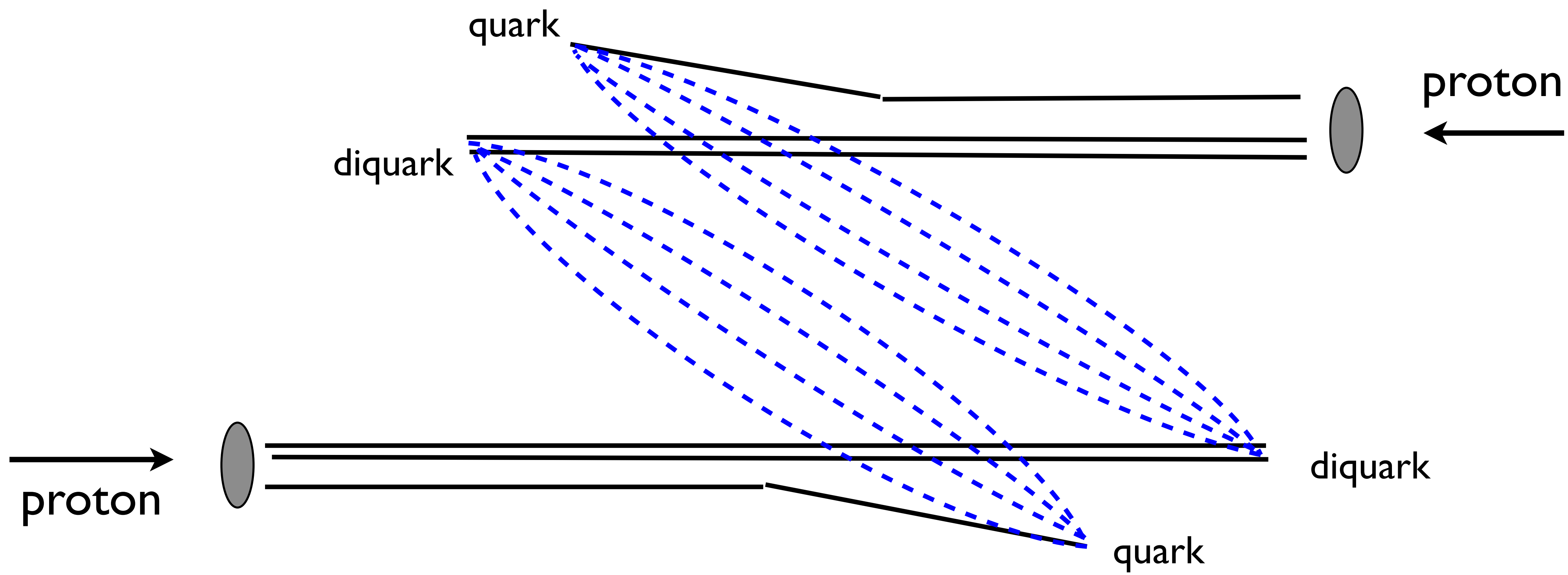


String fragmentation: popcorn effect



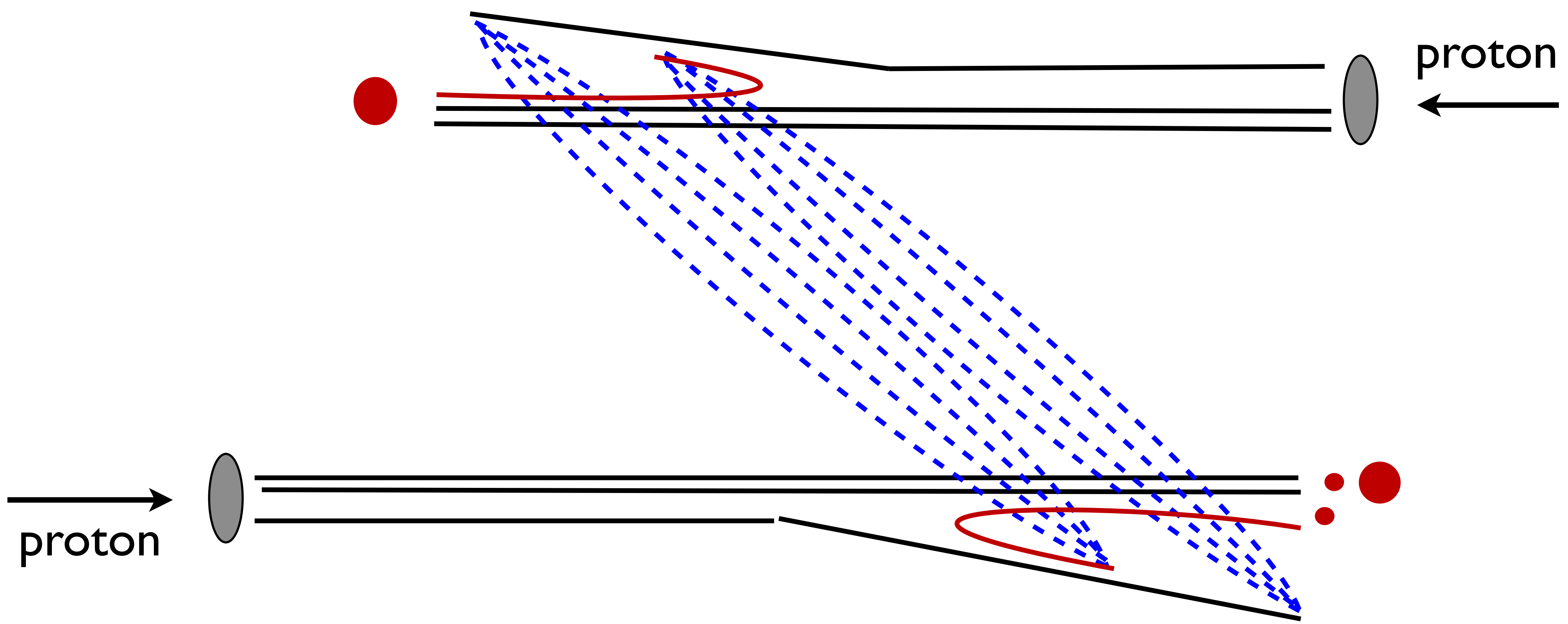
Diquark splitting: improved description of leading meson and baryon data

SIBYLL minimum string configuration



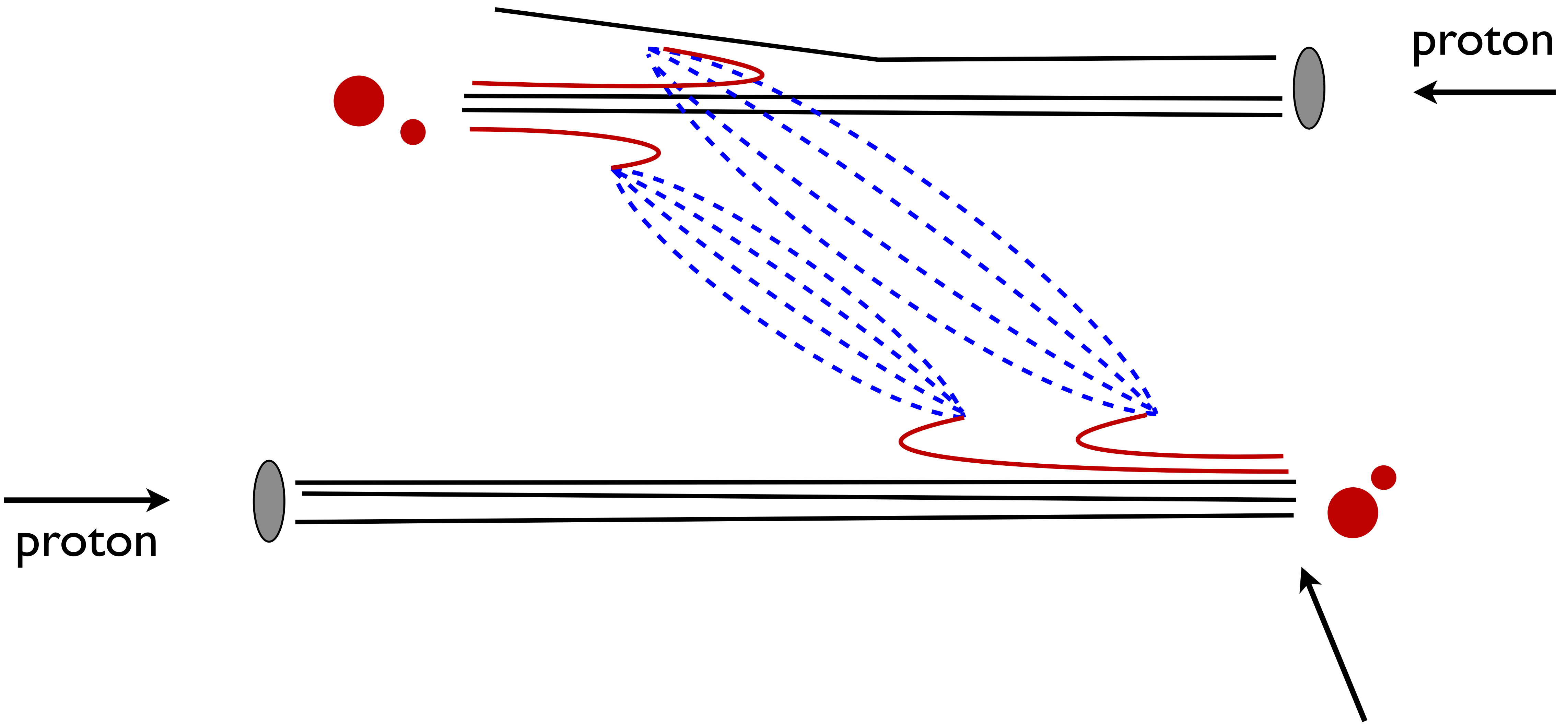
Special fragmentation function for leading diquarks needed for description of data

QGSJET minimum string configuration



Generation of sea quark anti-quark pair and leading/excited hadron

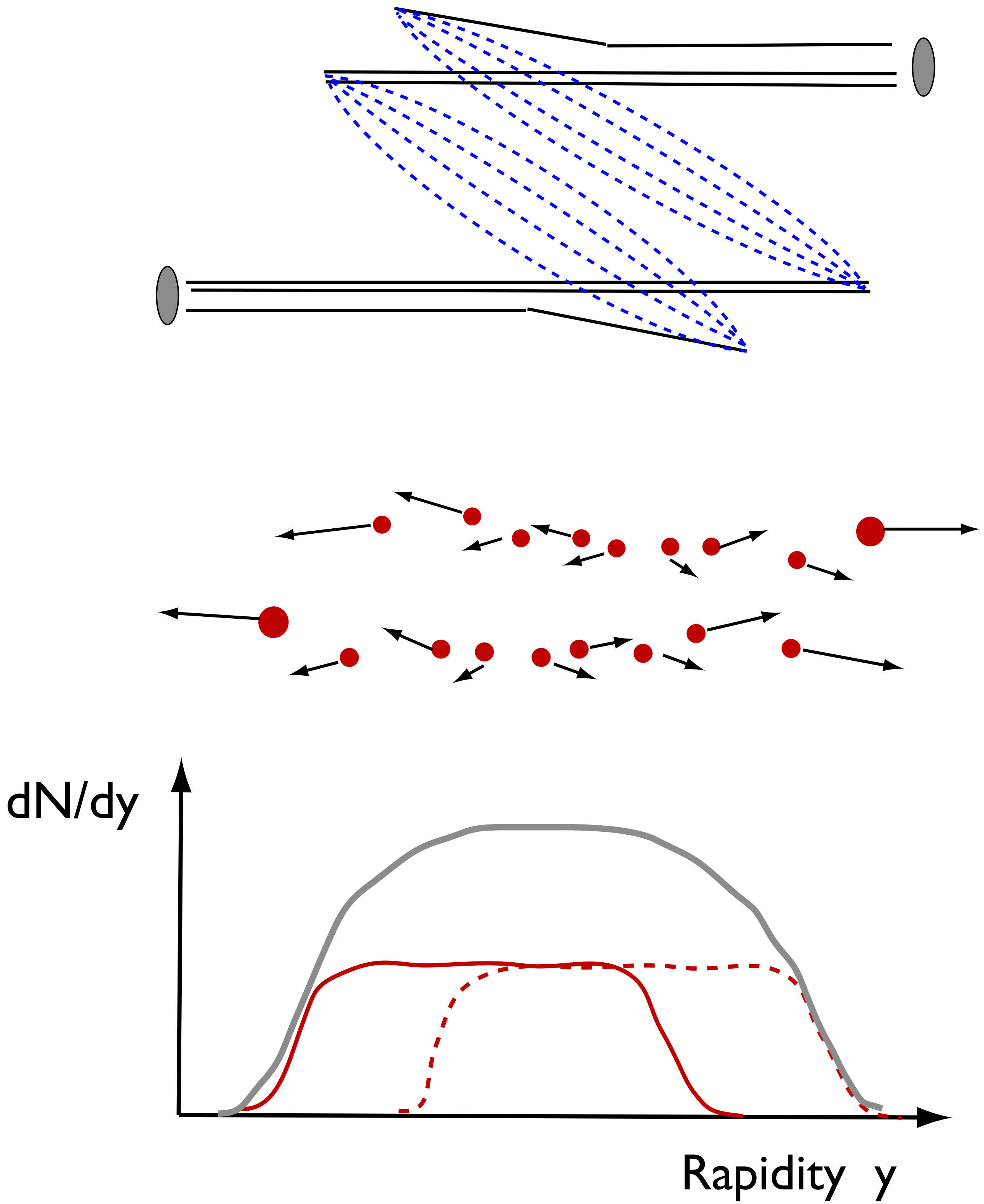
EPOS minimum string configuration



Generation of sea quark pair for each string

Micro-canonical decay of remnants to hadrons

Data and two-string models

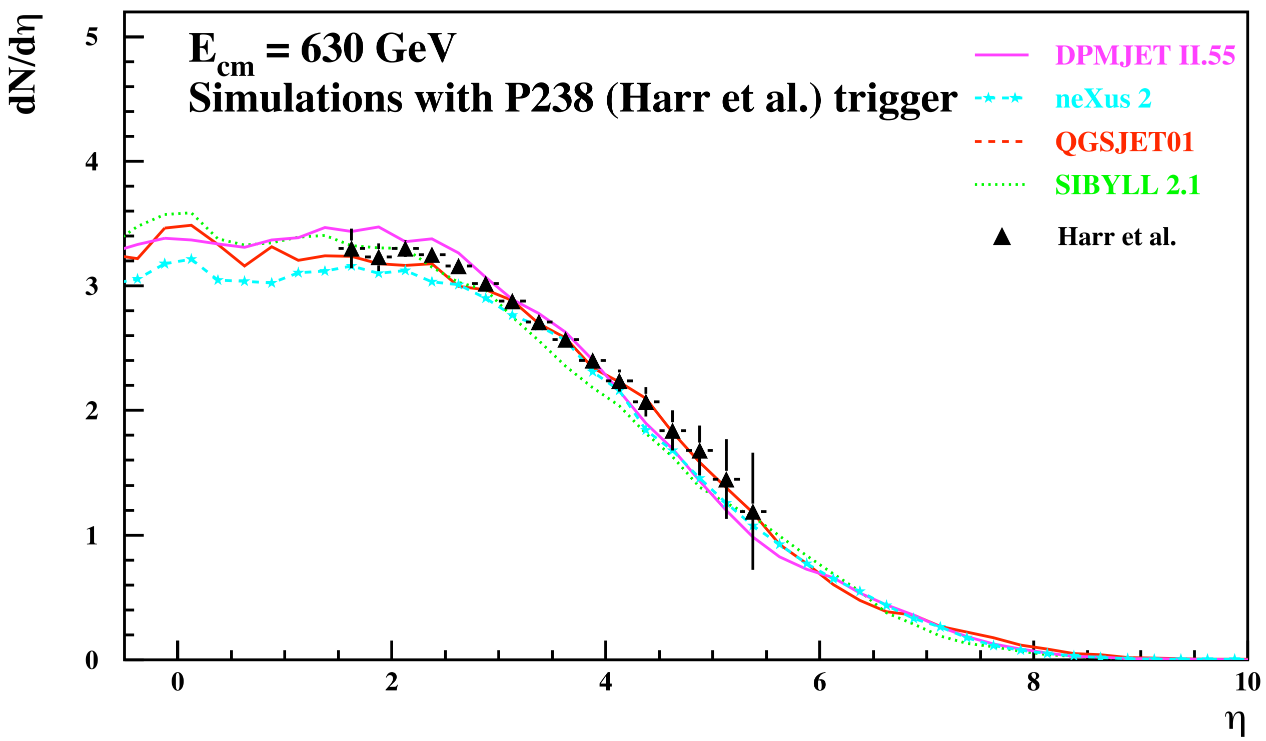


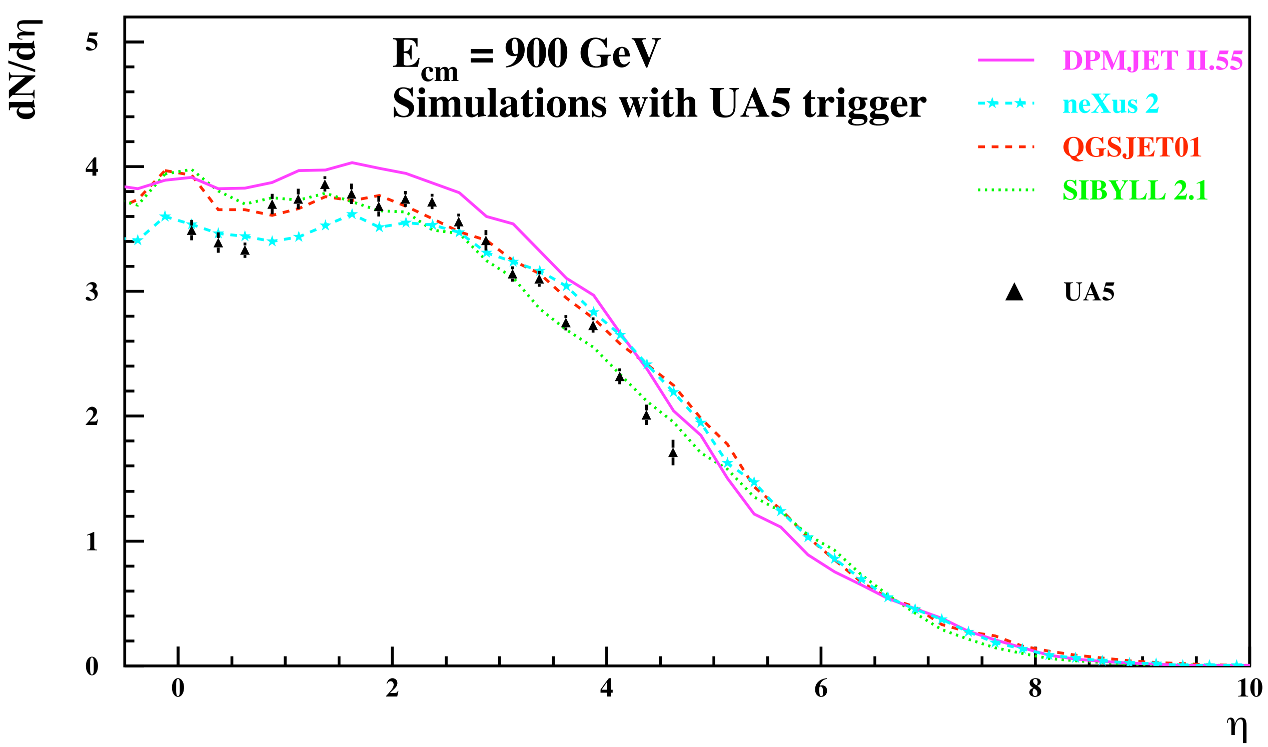
Two-string models:

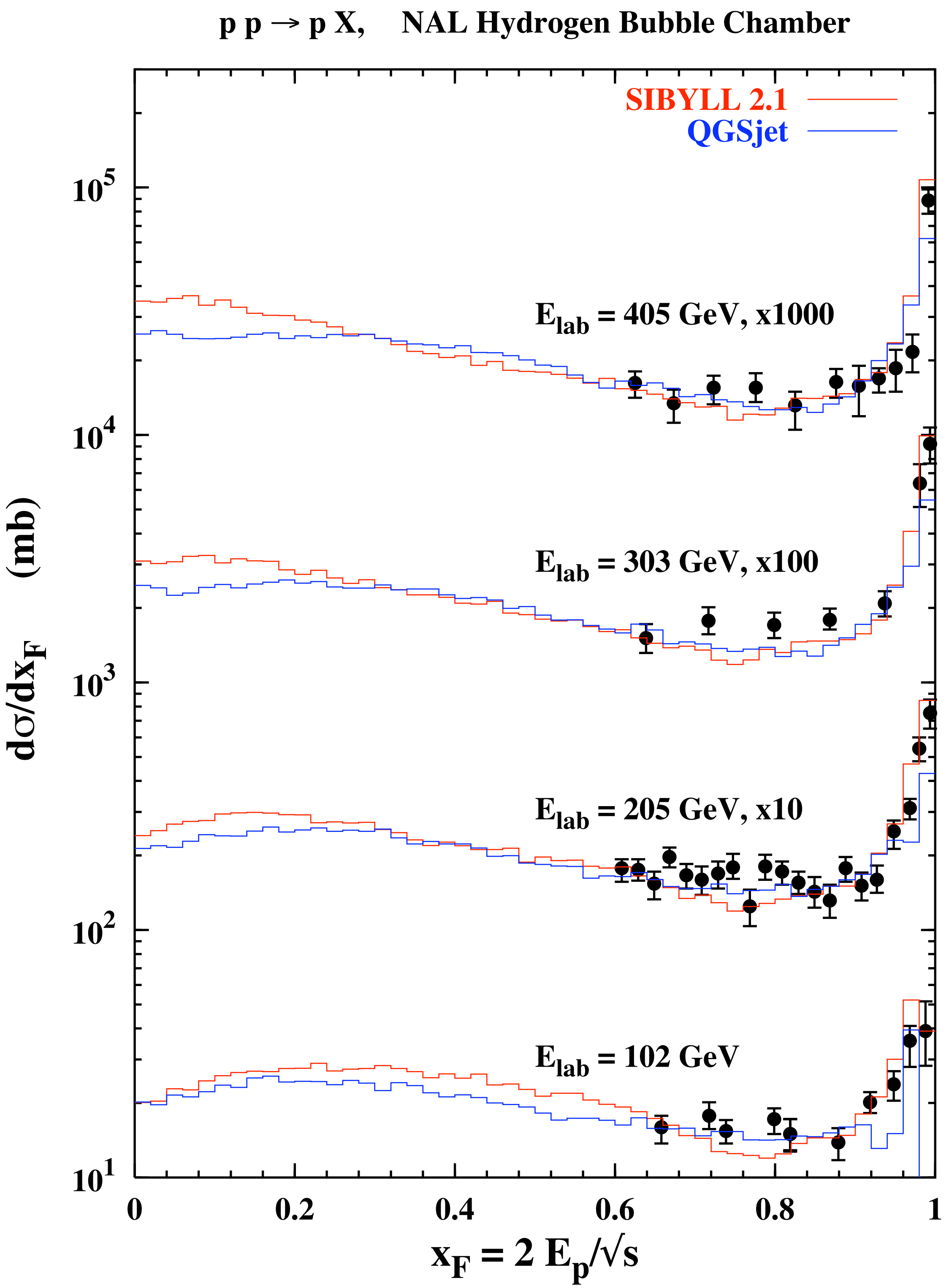
- very successful
- long-range correlations
- charge distribution
- delayed threshold for baryon pair production

(Capella et al., Physics Reports 1994)

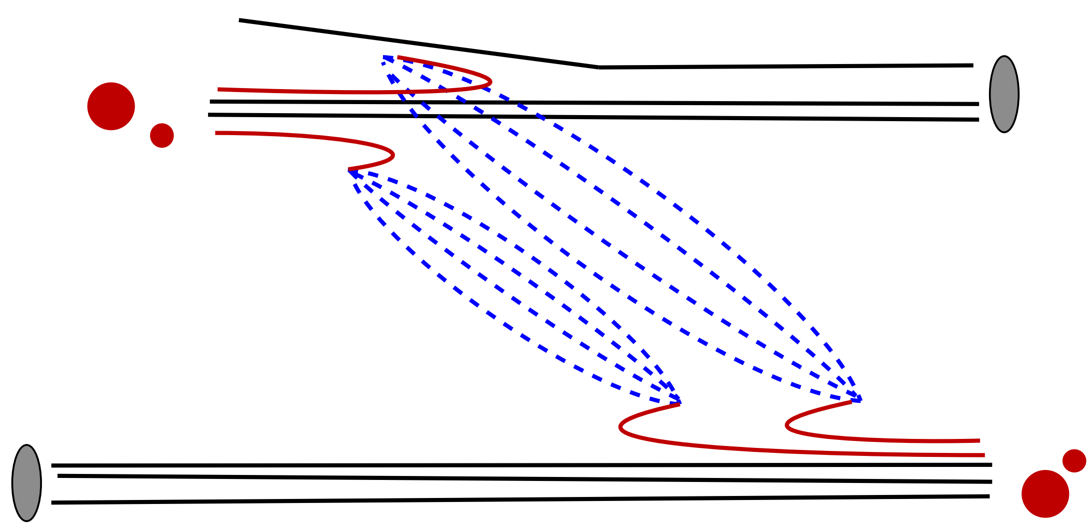
Examples of comparisons with data

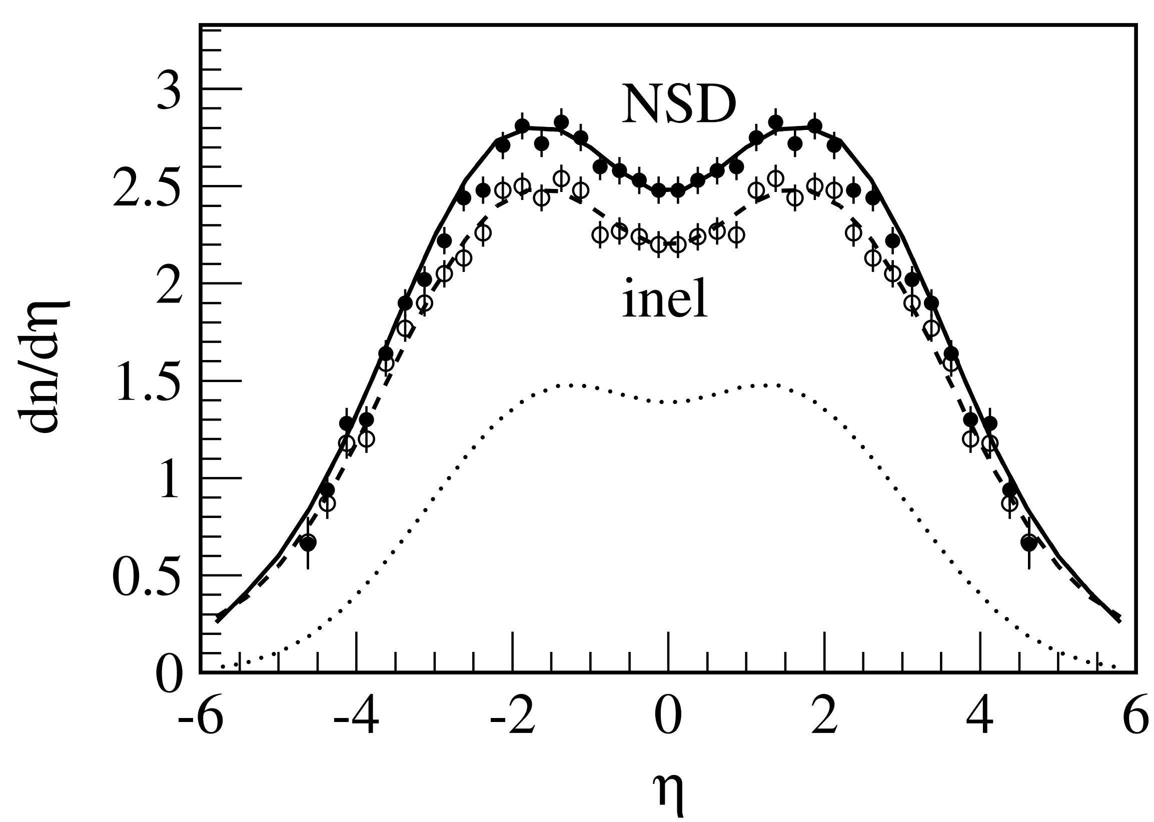


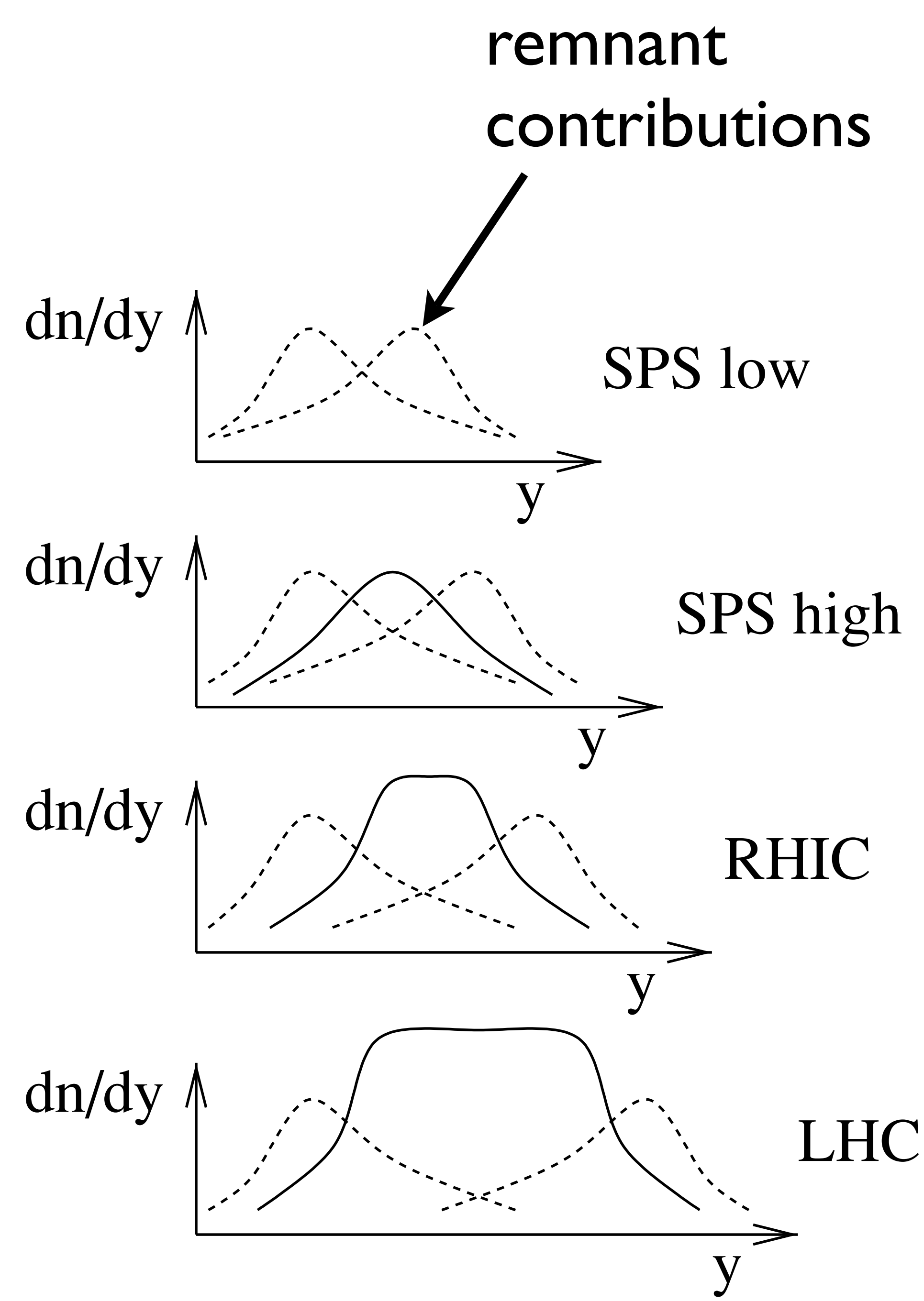




EPOS: string contributions

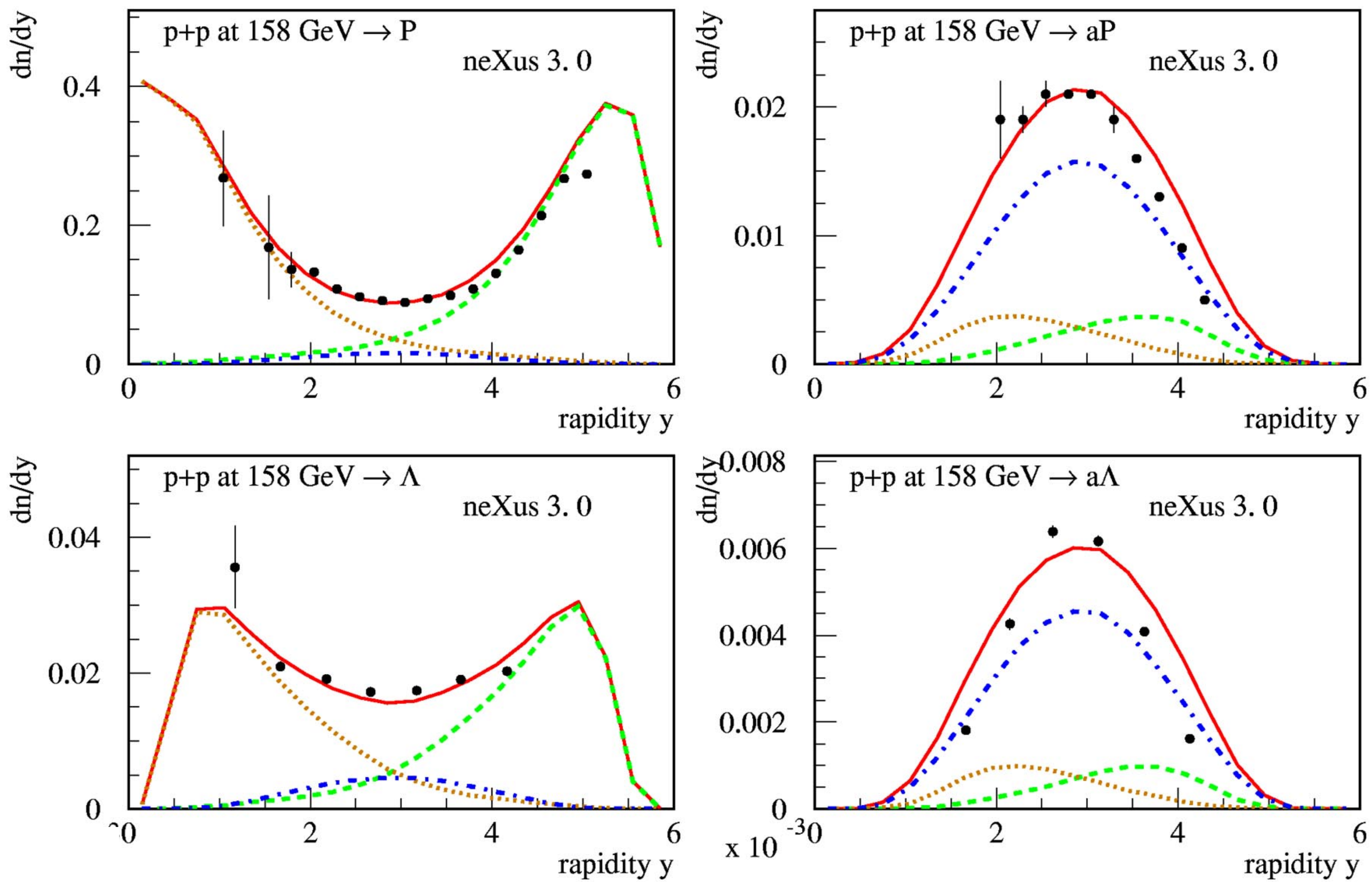






Only model for description of multi-strange baryon production (next slides)

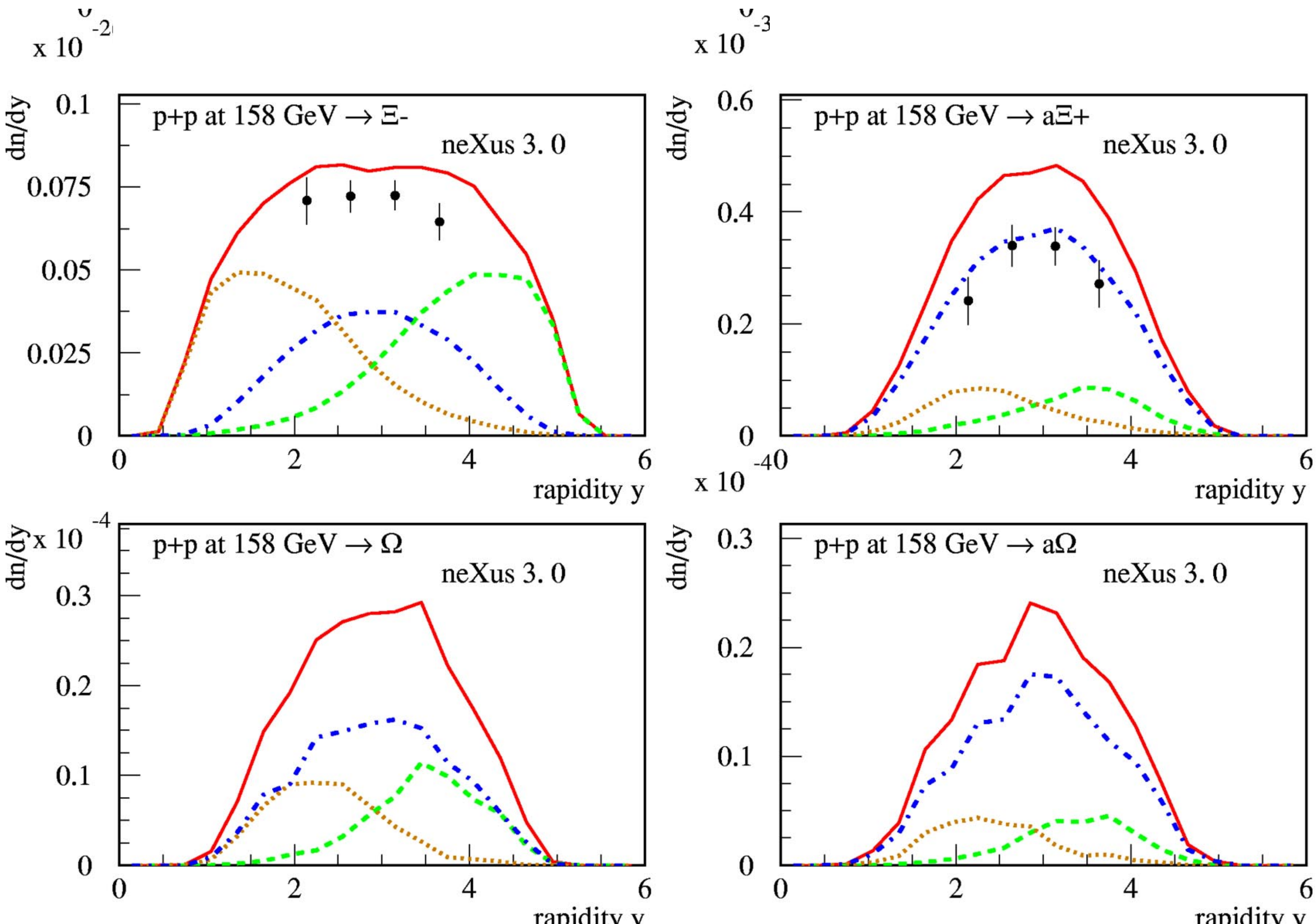
EPOS remnant model and data (i)



NA49 data

(Liu et al., PRD 2003)

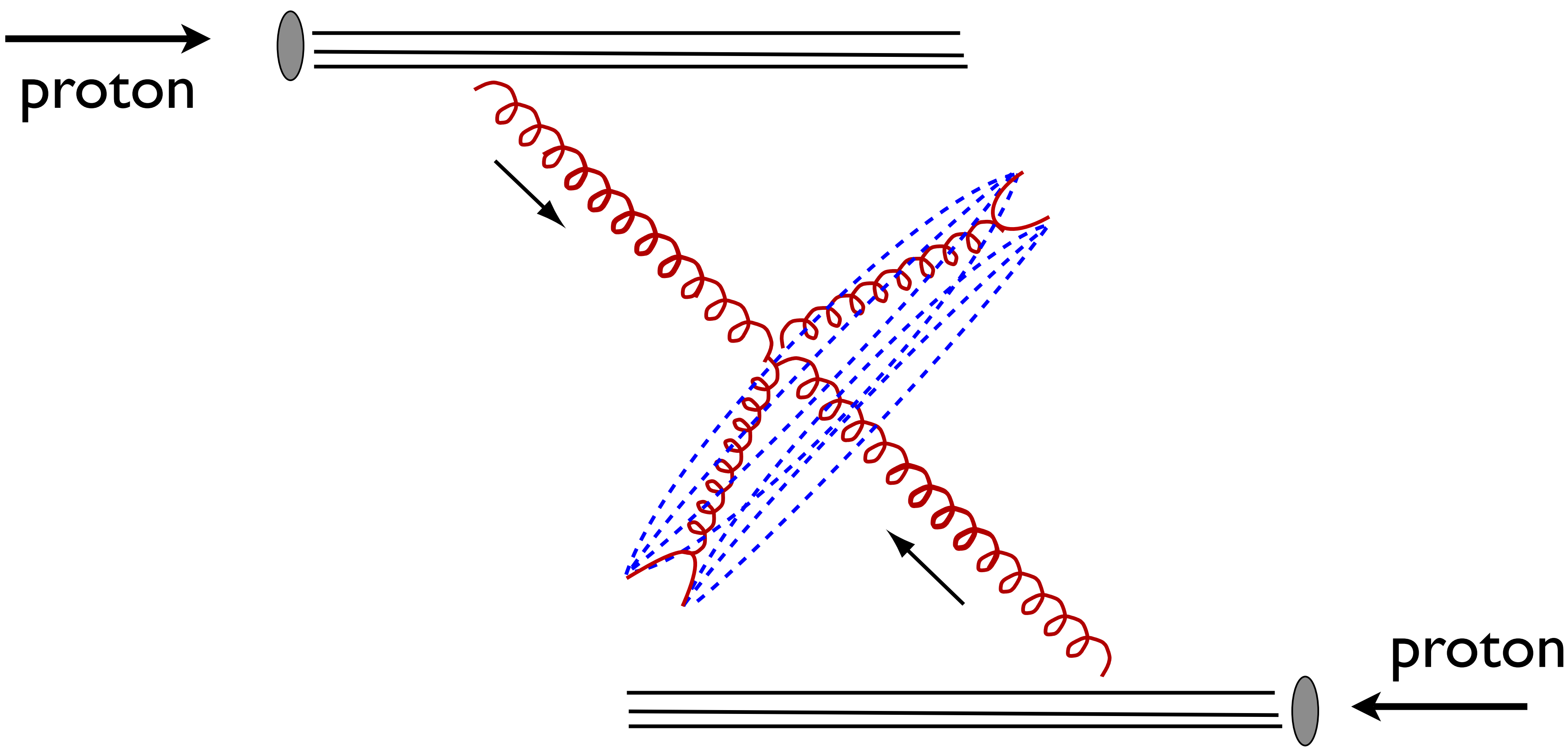
EPOS remnant model and data (ii)



NA49 data

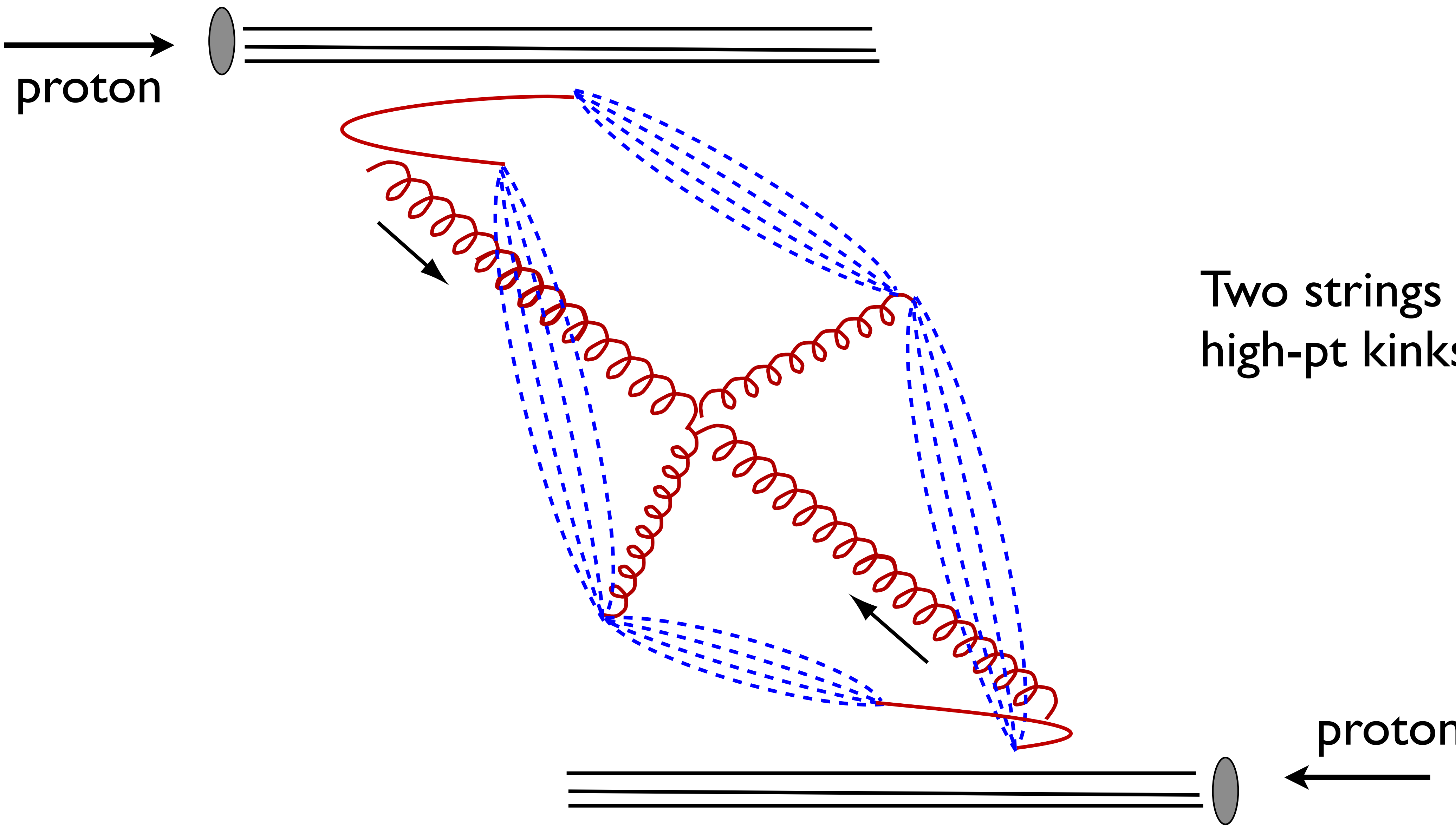
(Liu et al., PRD 2003)

Two-gluon scattering: SIBYLL



Kinematics etc. given by parton densities and perturbative QCD
Two strings stretched between quark pairs from gluon fragmentation

Two-gluon scattering: QGSJET

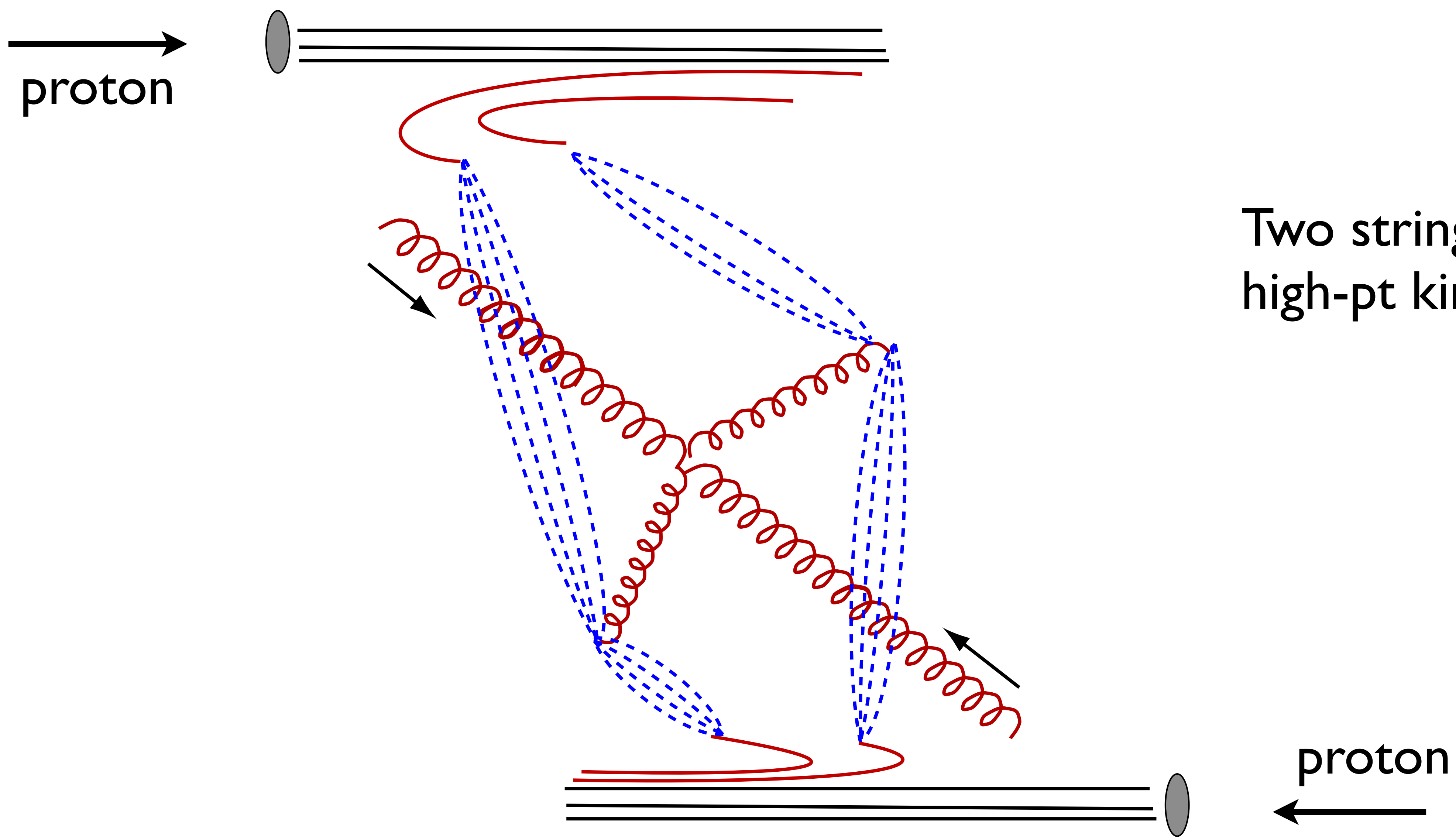


Two strings with high-pt kinks

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

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

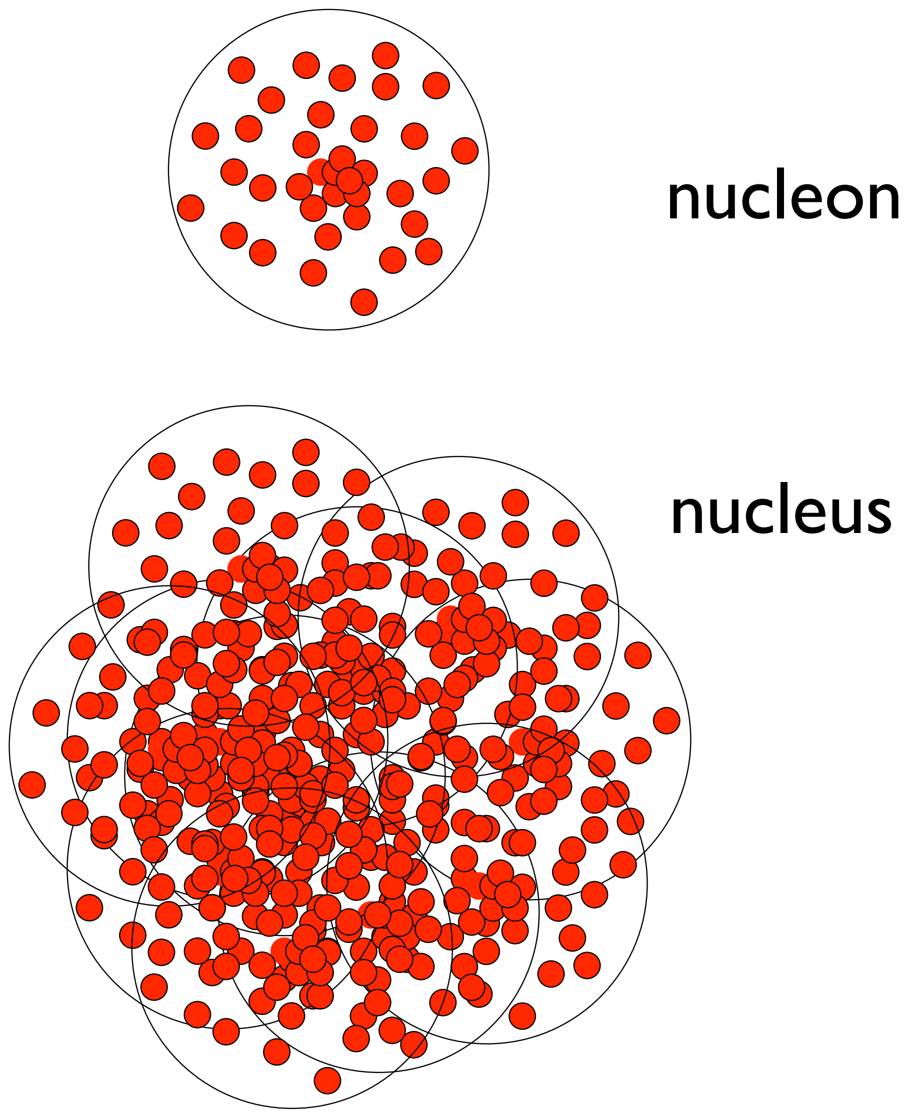
Two-gluon scattering: EPOS



Two strings with high-pt kinks

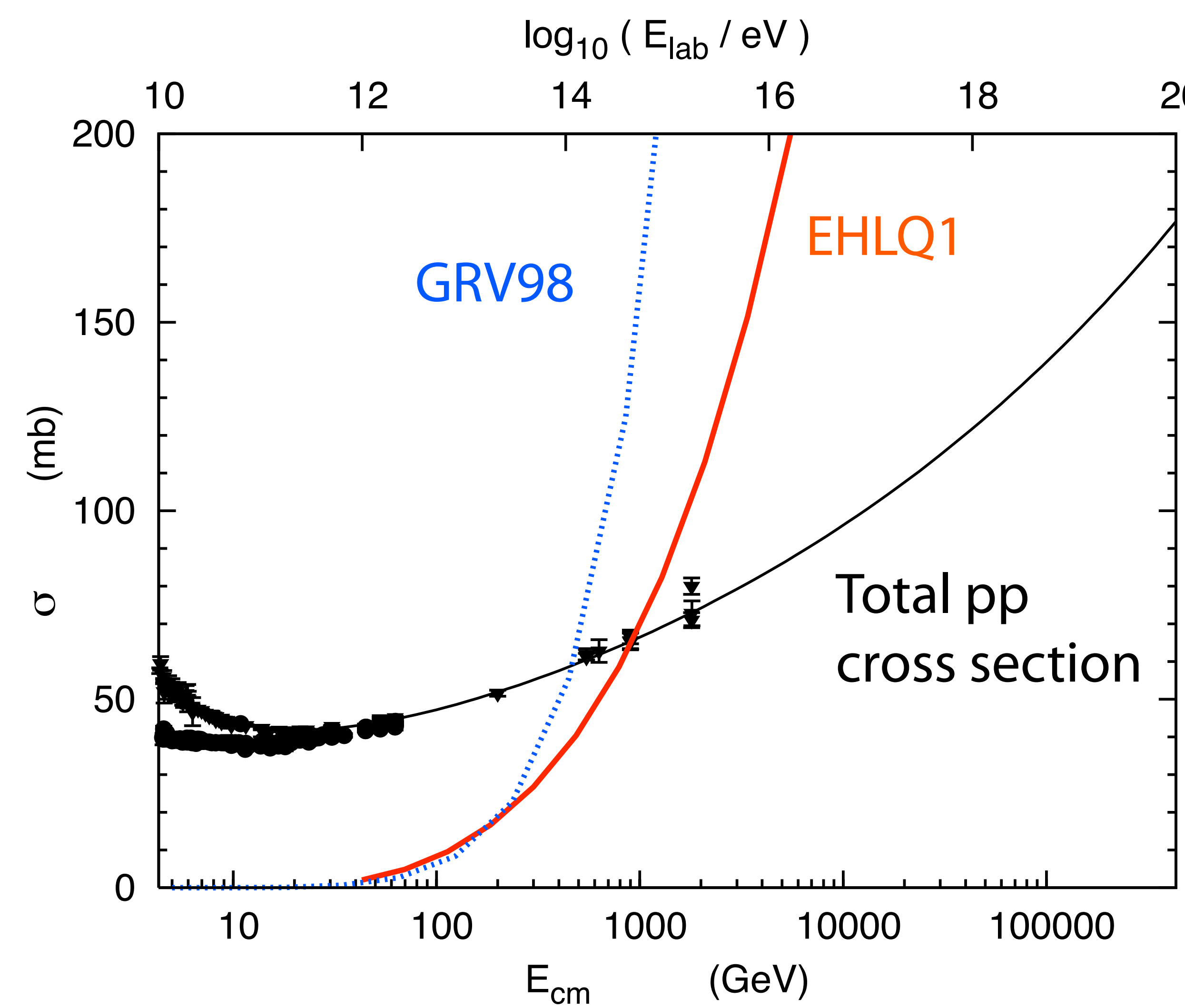
Independent sea quarks form string ends

SIBYLL: high parton density effects



SIBYLL: simple geometric criterion

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

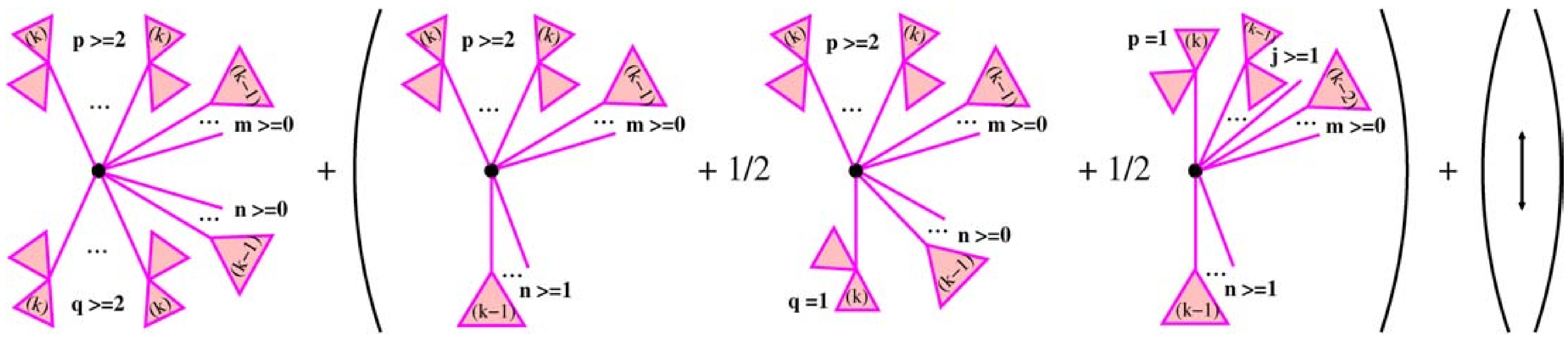


No dependence on impact parameter !

(R.E. et al., ICRC 1999)

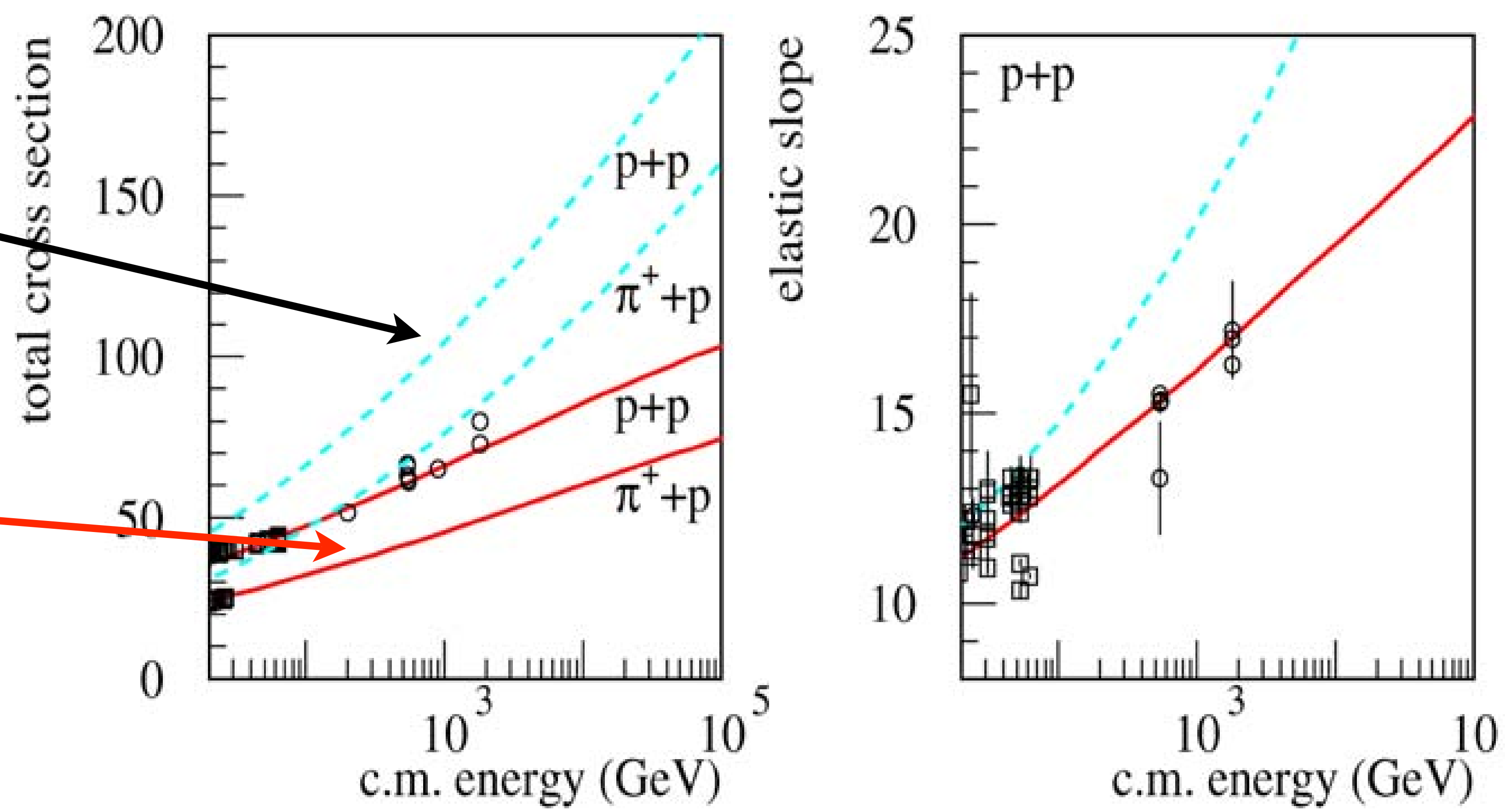
QGSJET: high parton density effects

Re-summation of enhanced pomeron graphs



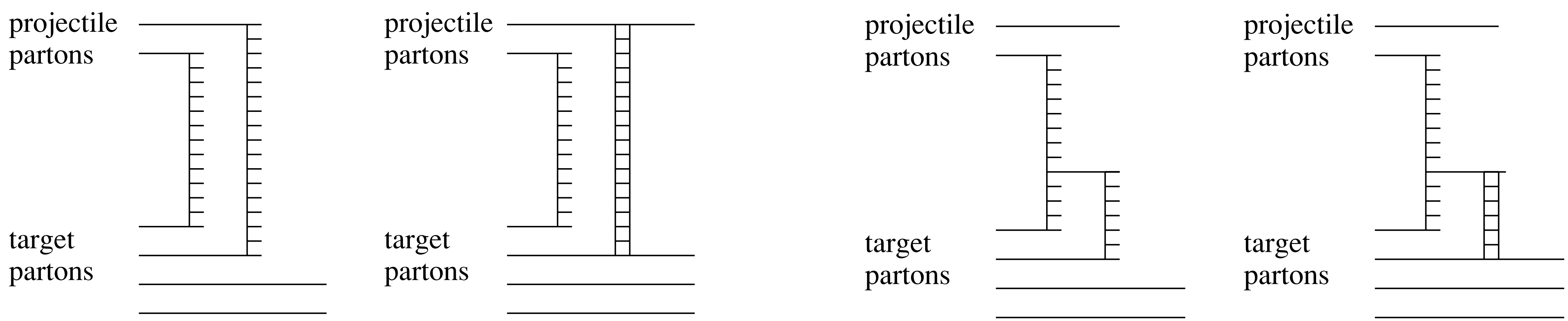
Without
enhanced graphs

With enhanced
graphs



(Ostapchenko, PLB 2006, PRD 2006)

EPOS: high parton density effects (i)

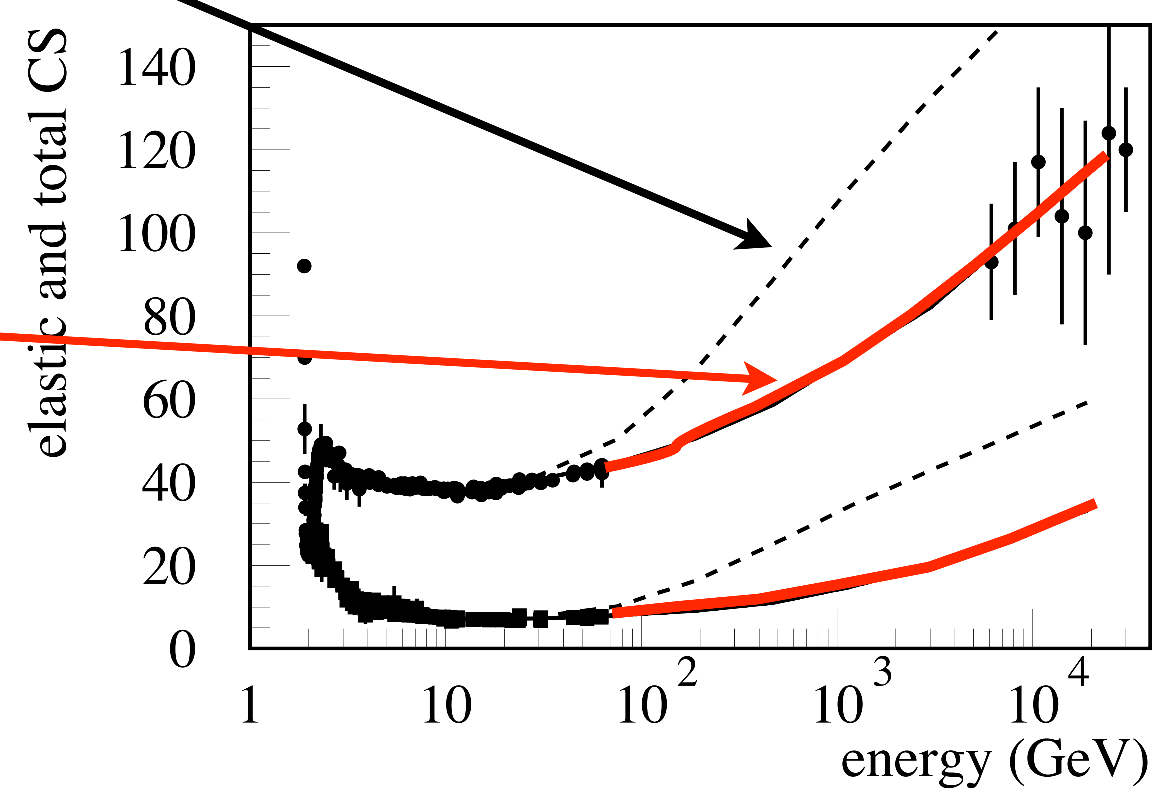


No effective coupling

$$A_{\text{pom}} \sim (x_1 x_2)^{\beta}$$

With effective coupling

$$A_{\text{pom}} \sim x_1^{\beta} x_2^{\beta-\varepsilon}$$

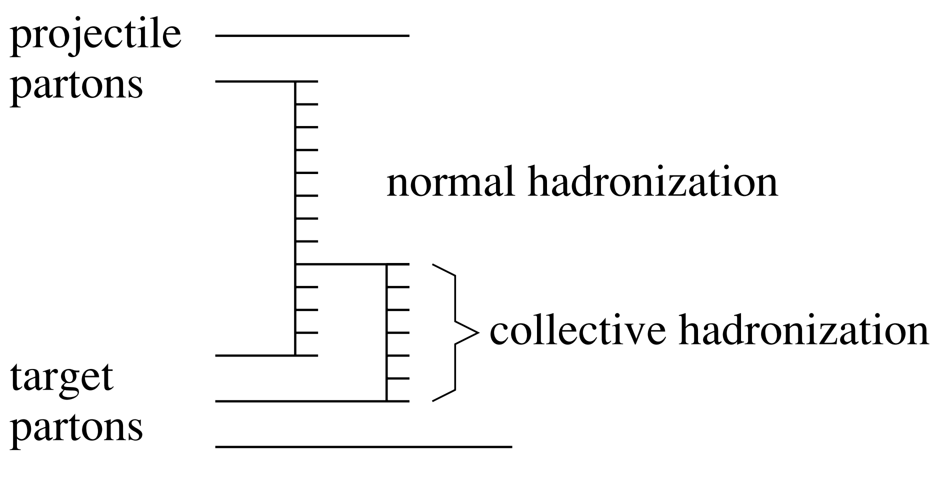


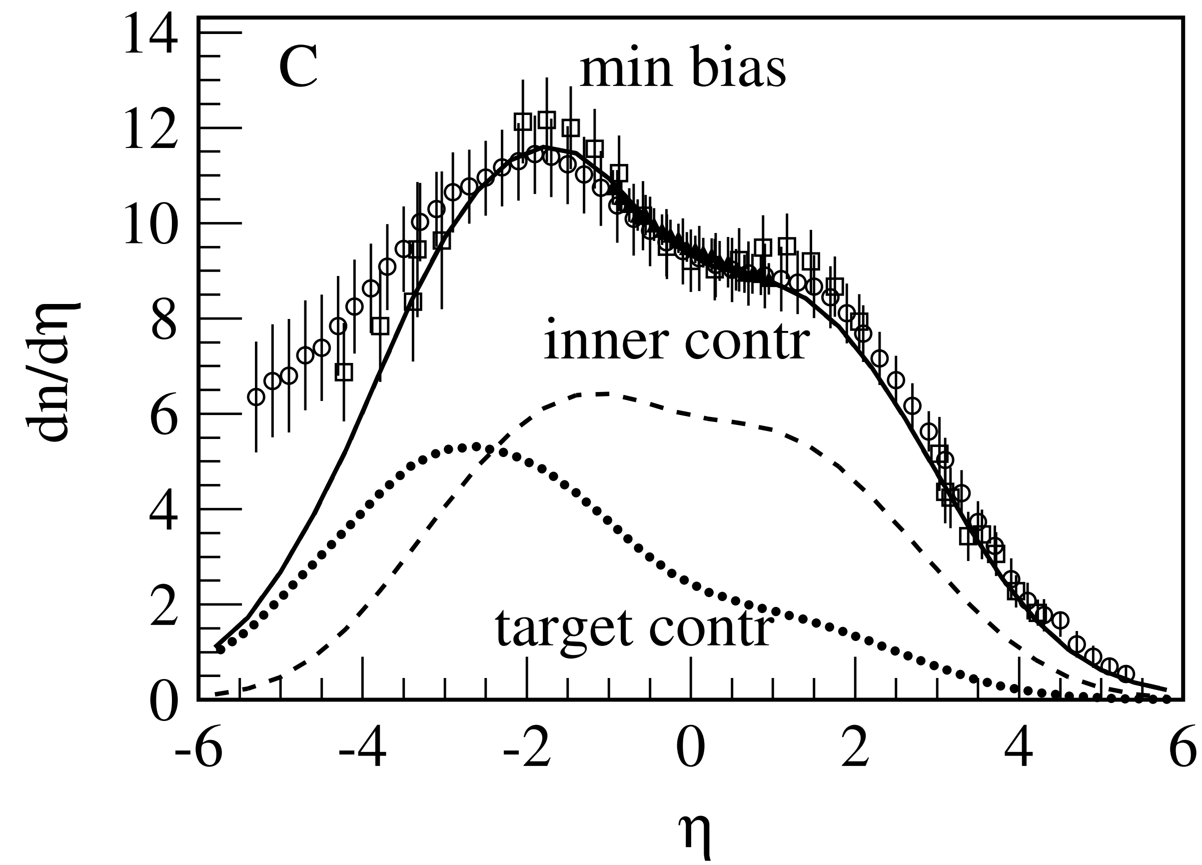
Parametrization

$$\varepsilon_S = a_S\, \beta_S Z,$$
$$\varepsilon_H = a_H\, \beta_H Z,$$

(Werner et al., PRC 2006)

EPOS: high parton density effects (ii)





Coefficient	Corresponding variable	Value
s_M	Minimum squared screening energy	$(25\text{ GeV})^2$
w_M	Defines minimum for z_0'	6.000
w_Z	Global Z coefficient	0.080
w_B	Impact parameter width coefficient	1.160
a_S	Soft screening exponent	2.000
a_H	Hard screening exponent	1.000
a_T	Transverse momentum transport	0.025
a_B	Break parameter	0.070
a_D	Diquark break probability	0.110
a_S	Strange break probability	0.140
a_P	Average break transverse momentum	0.150

$$Z_T(i,\, j) = z_0 \,\exp\big(-b_{ij}^2/2b_0^2\big) + \sum_{\substack{\text{target nucleons}\\ j'\neq j}} z_0' \,\exp\big(-b_{ij'}^2/2b_0^2\big),$$

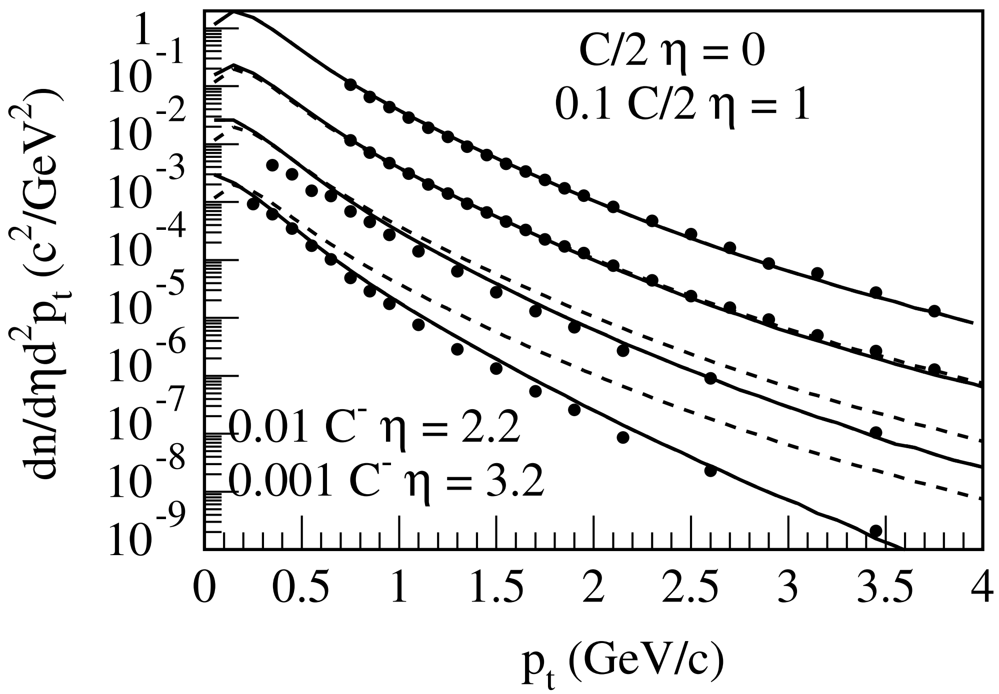
$$b_0 = w_B \sqrt{\sigma_{\mathrm{inel}\,pp}/\pi}$$

$$z_0 = w_Z \,\log s/s_M,$$

$$z_0' = w_Z \sqrt{(\log s/s_M)^2 + {w_M}^2},$$

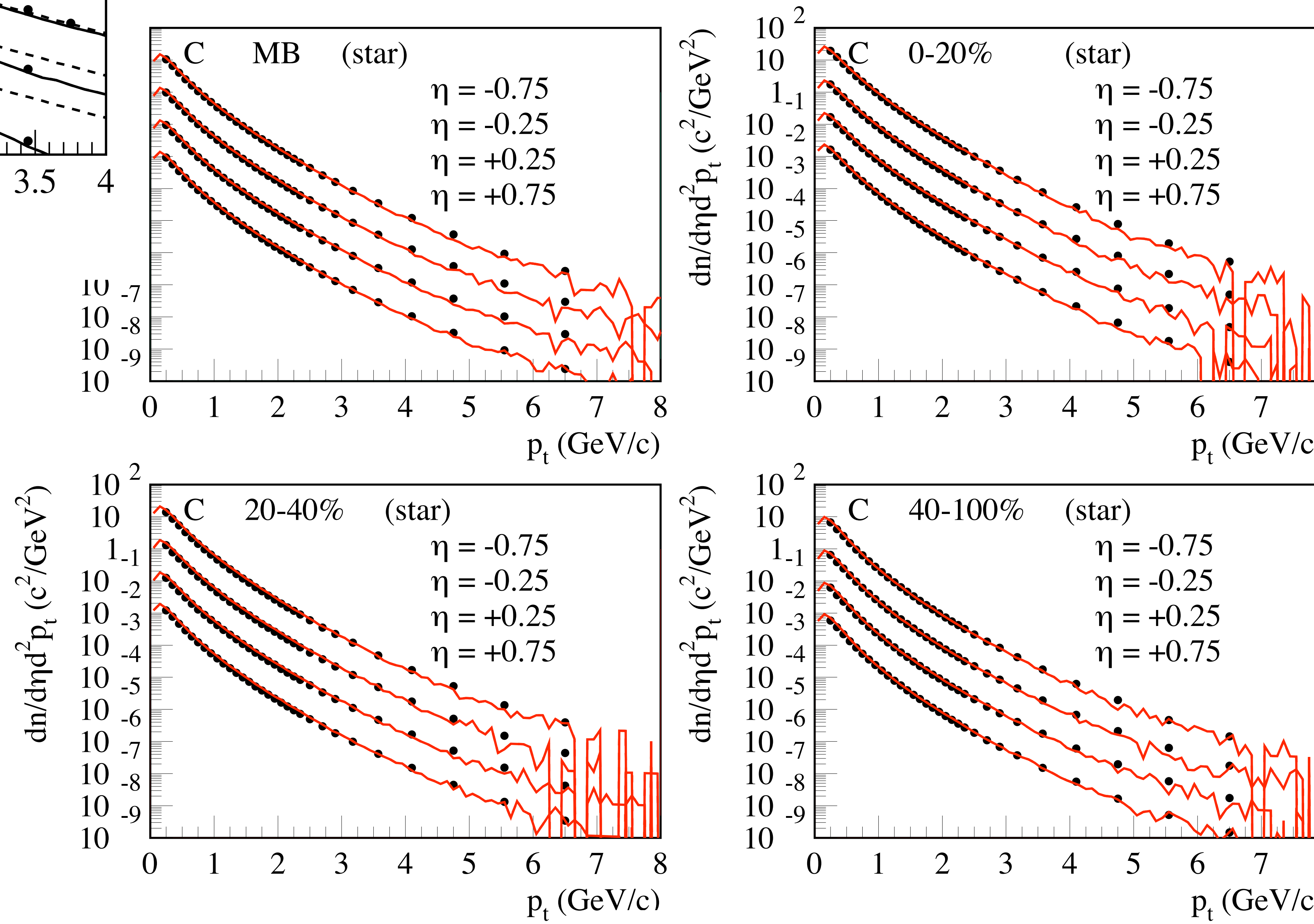
(Werner et al., PRC 2006)

Comparison with RHIC data



RHIC data: very good agreement,
(some measurements inconsistent)

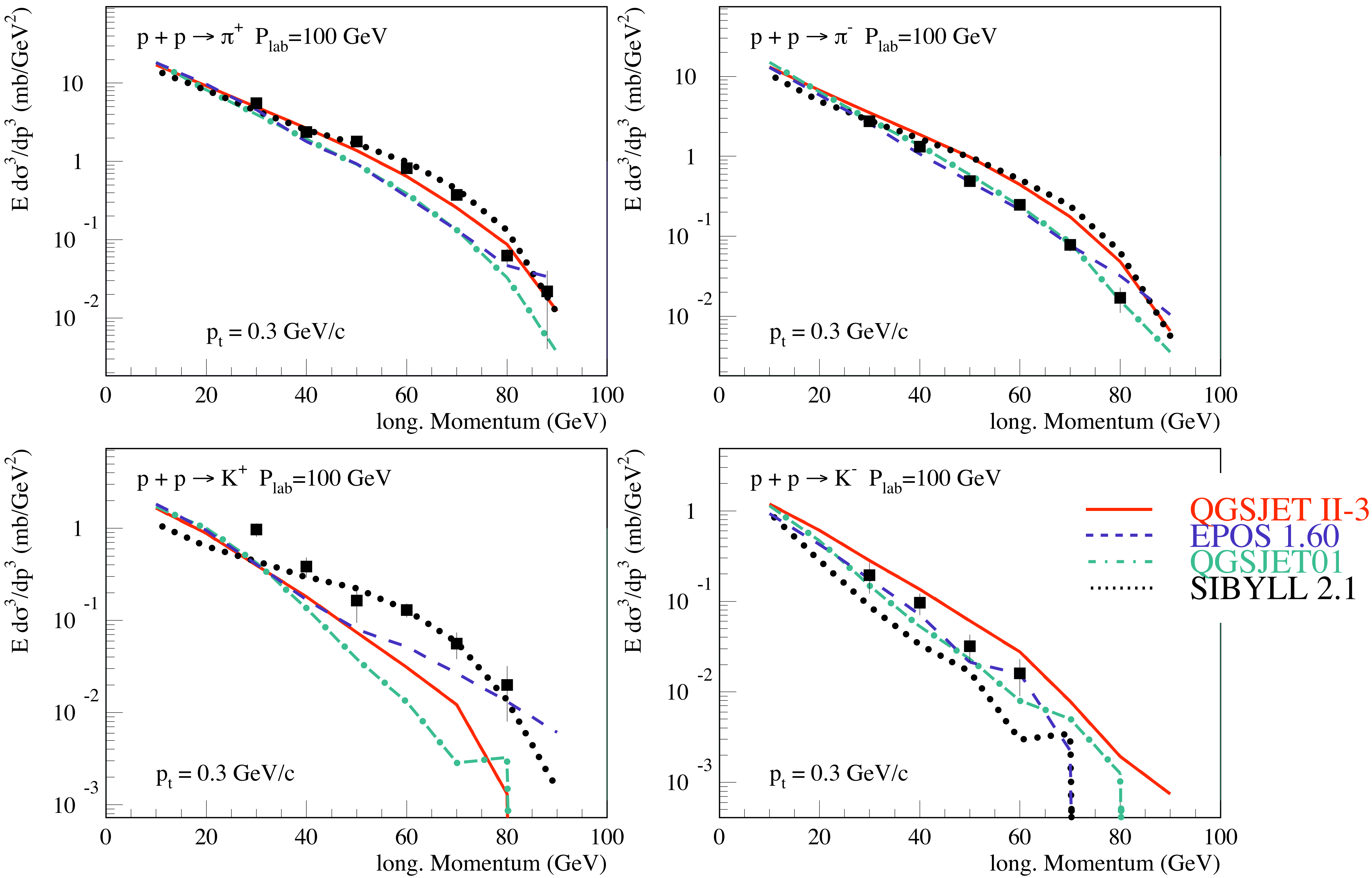
proton-proton
E_{cm} = 200 GeV



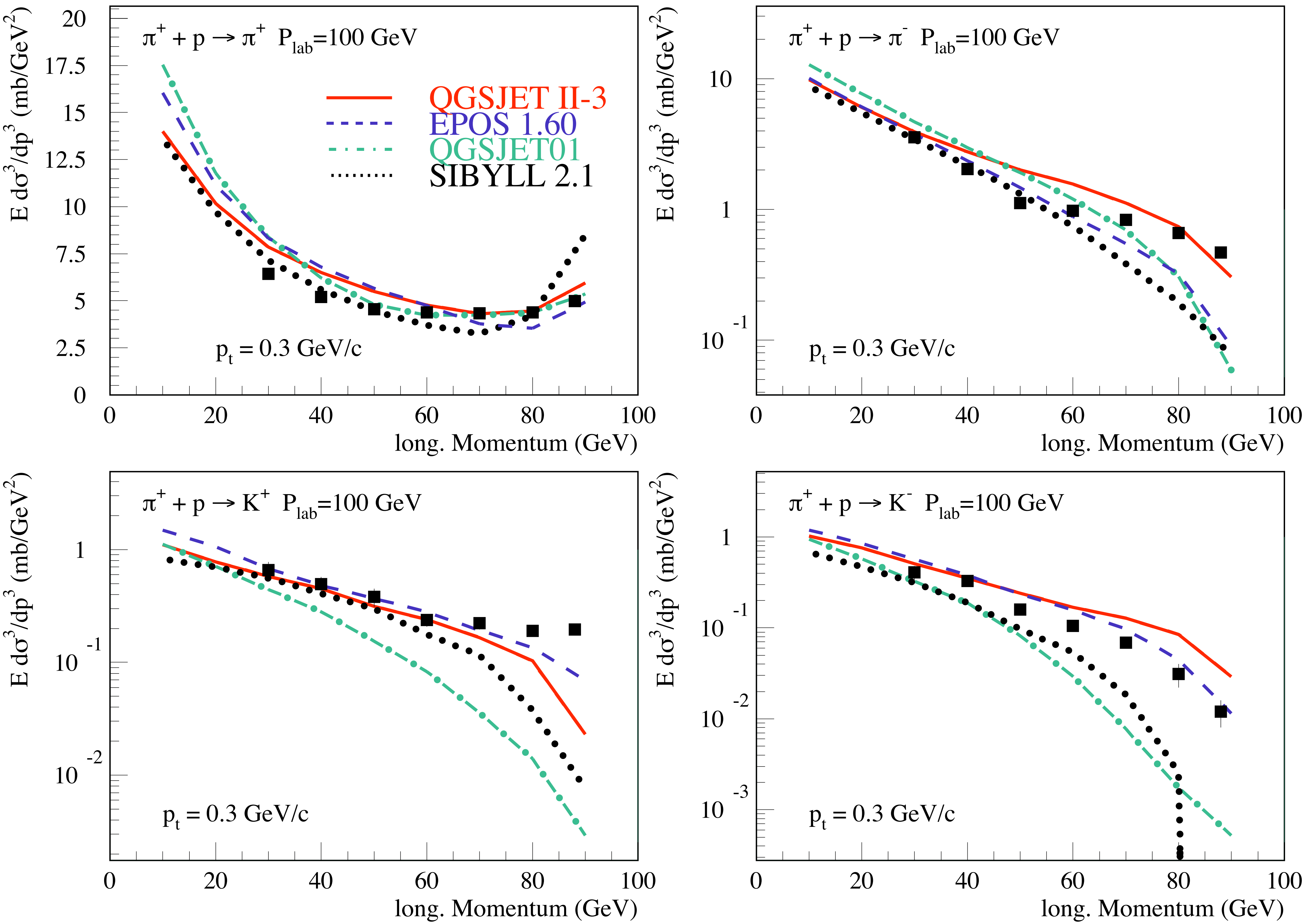
deuteron-gold
E_{cm} = 200 GeV

(Werner et al., PRC 2006)

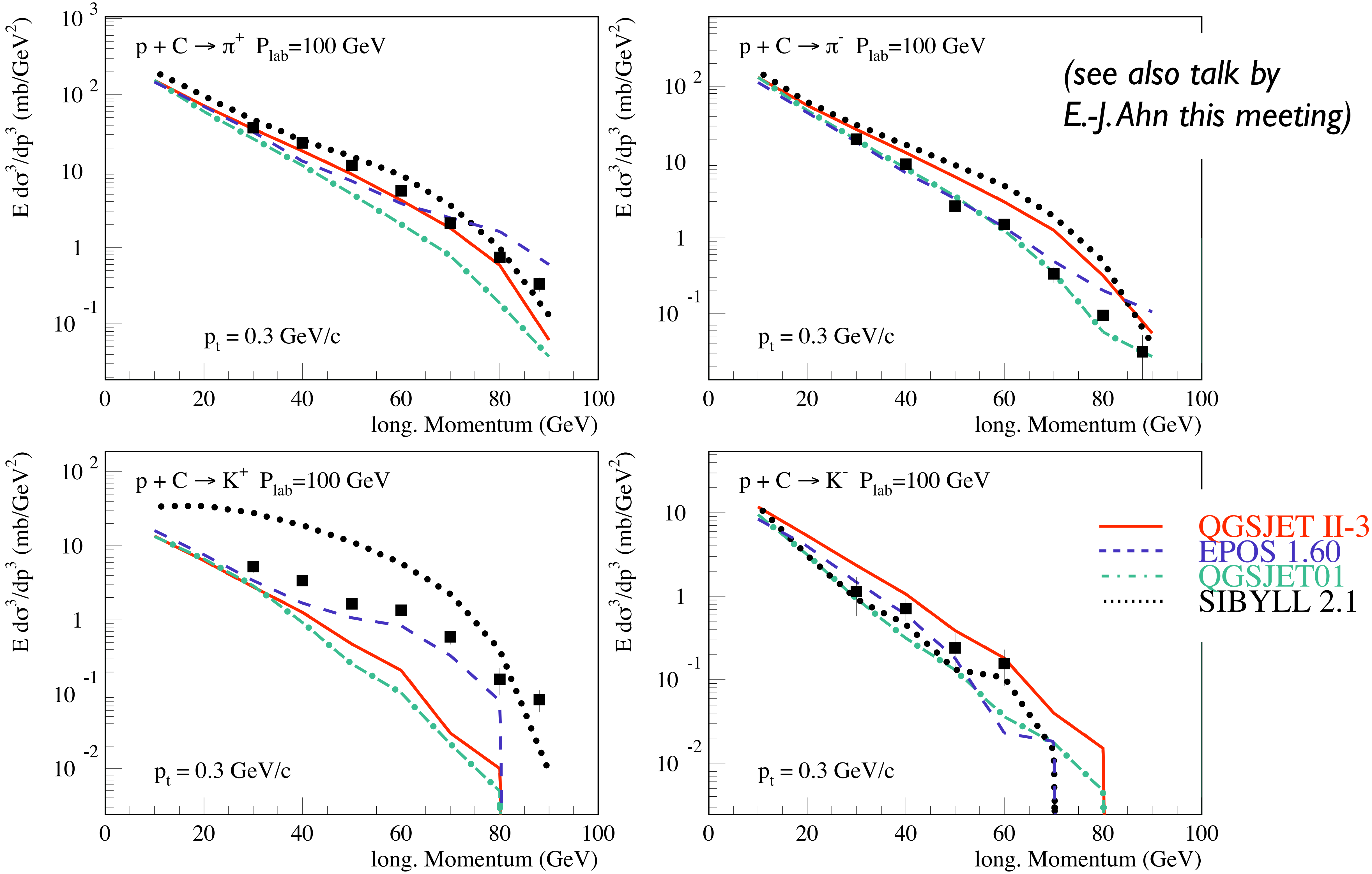
Model comparison: fixed target p-p data



Model comparison: fixed target π-p data



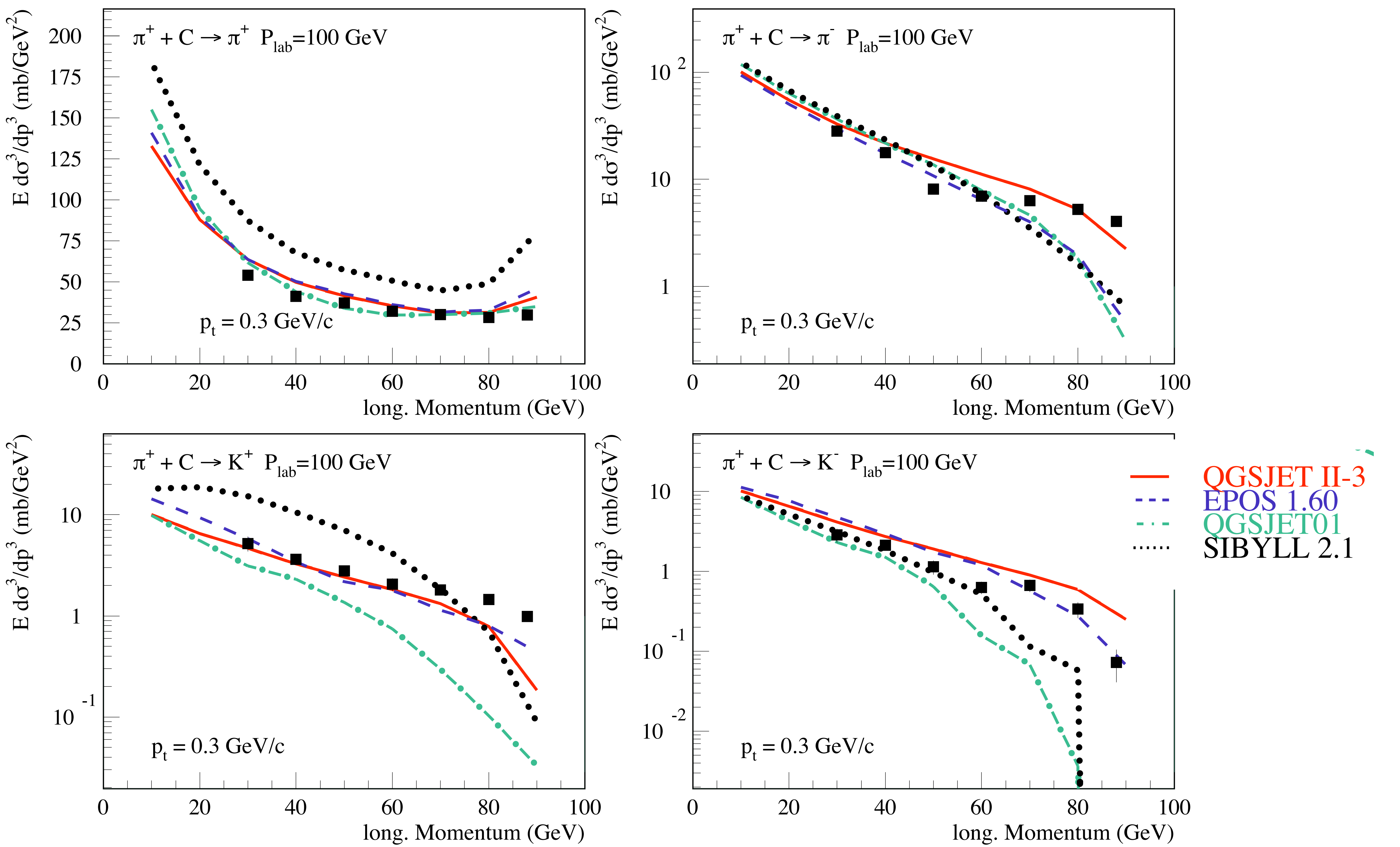
Model comparison: fixed target p-C data



(see also talk by E.-J. Ahn this meeting)

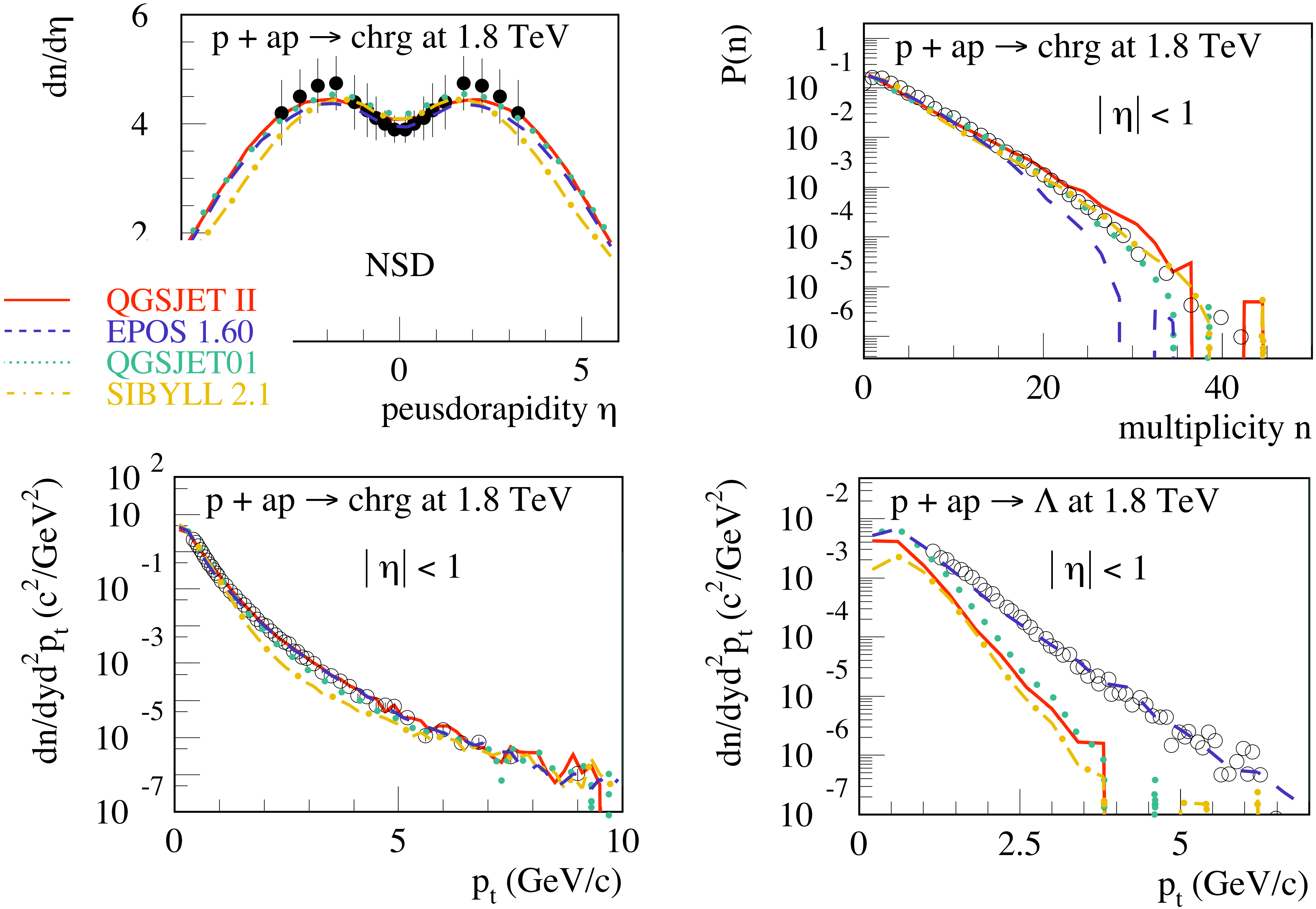
Note: SIBYLL plotting error, has to be scaled down by ~20%

Model comparison: fixed target π-C data

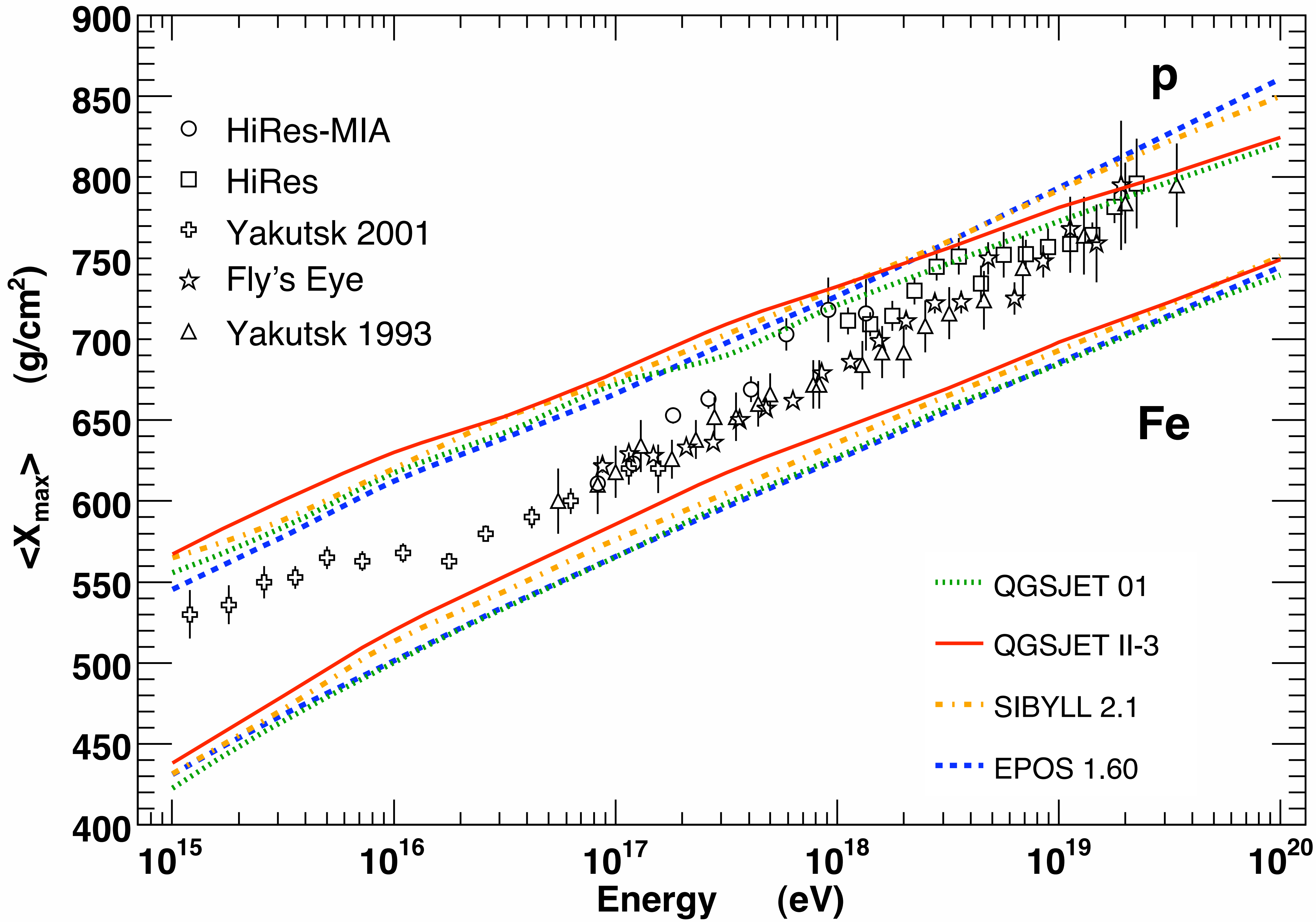


Note: SIBYLL plotting error, has to be scaled down by ~30%

Model comparison: Tevatron data

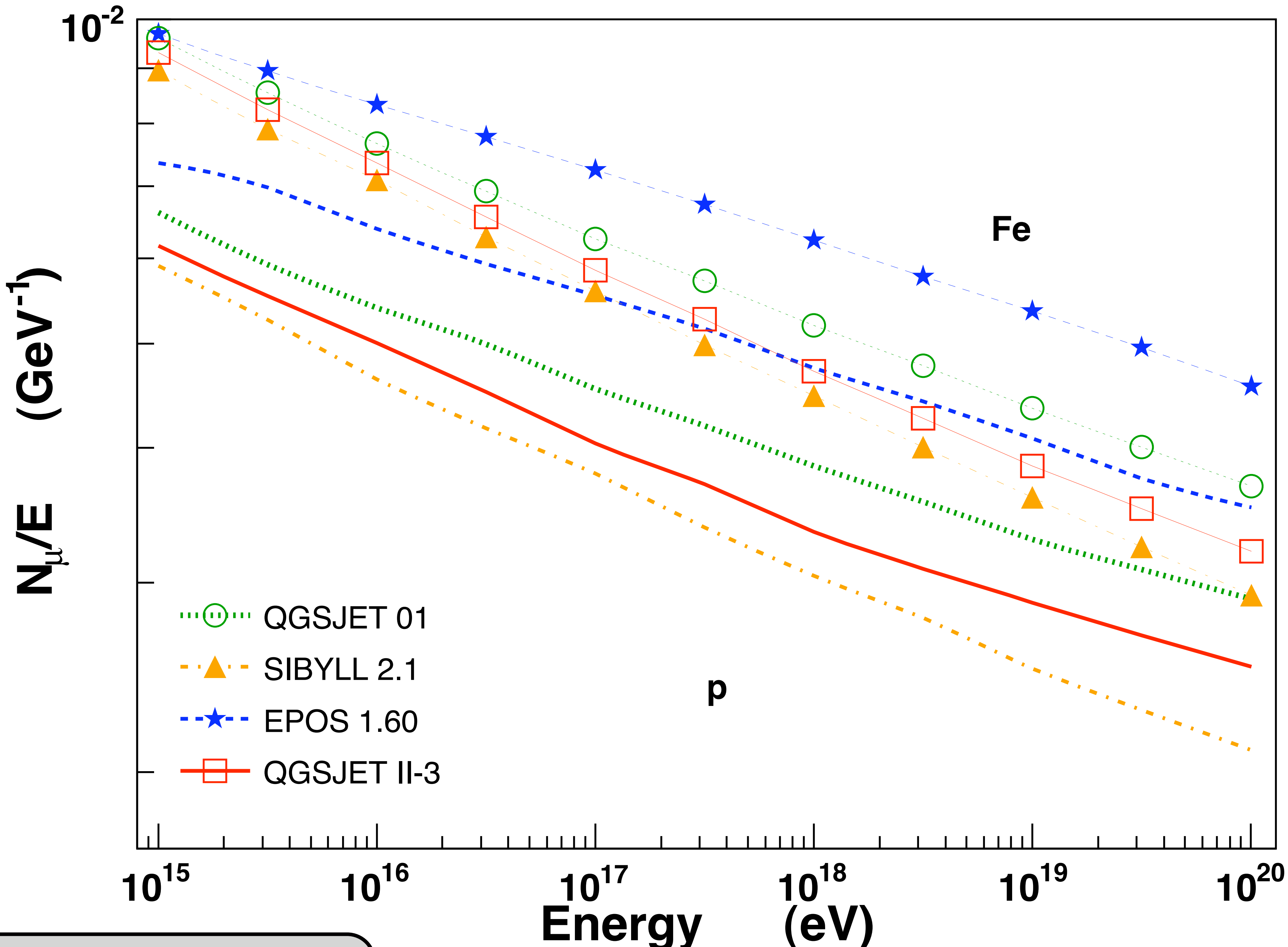


Mean depth of shower maximum



Mean number of muons at ground

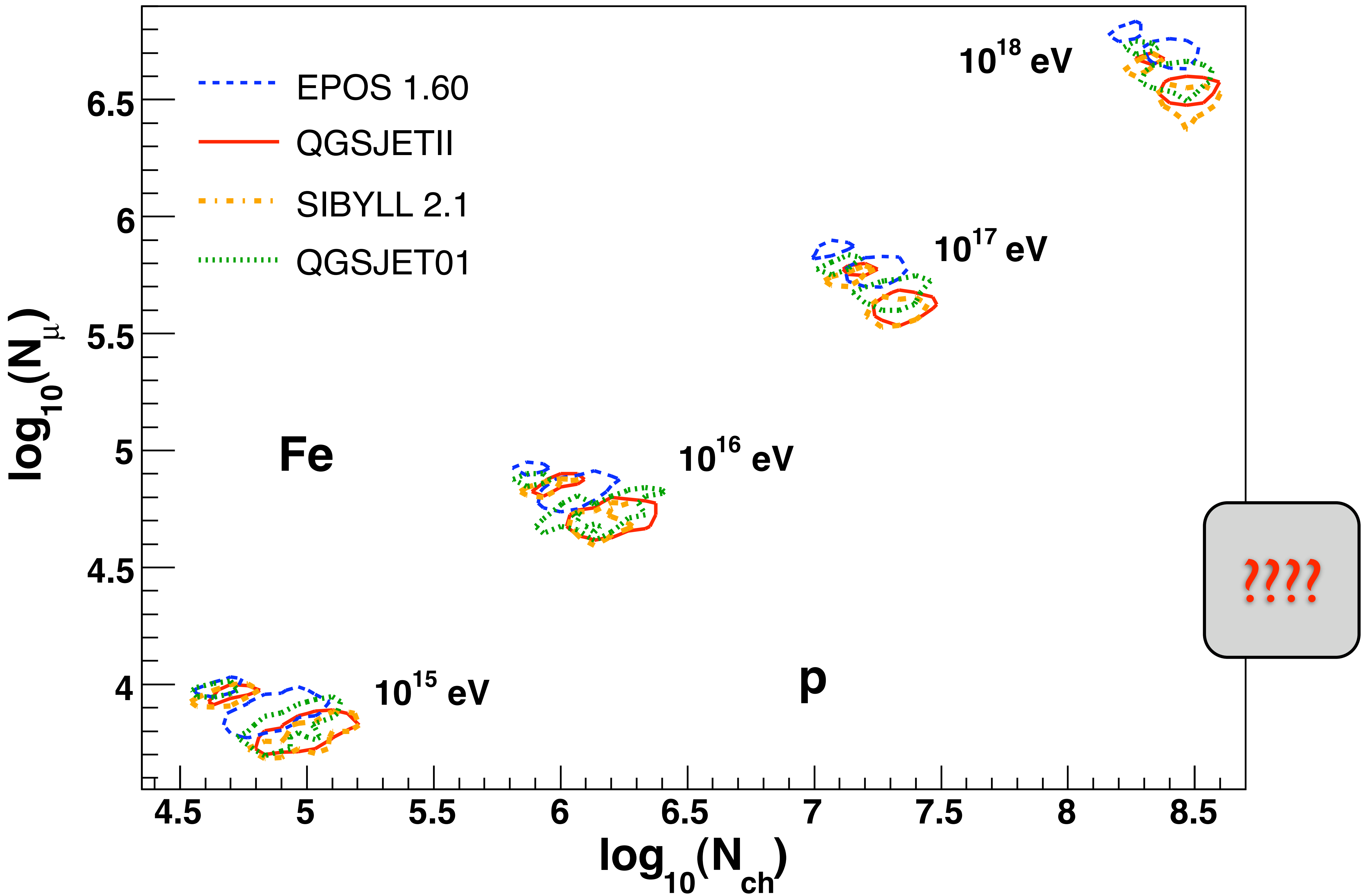
????



Iron (QGSJET) = proton (EPOS)

(at 10^{18} eV)

Electron-muon number correlation

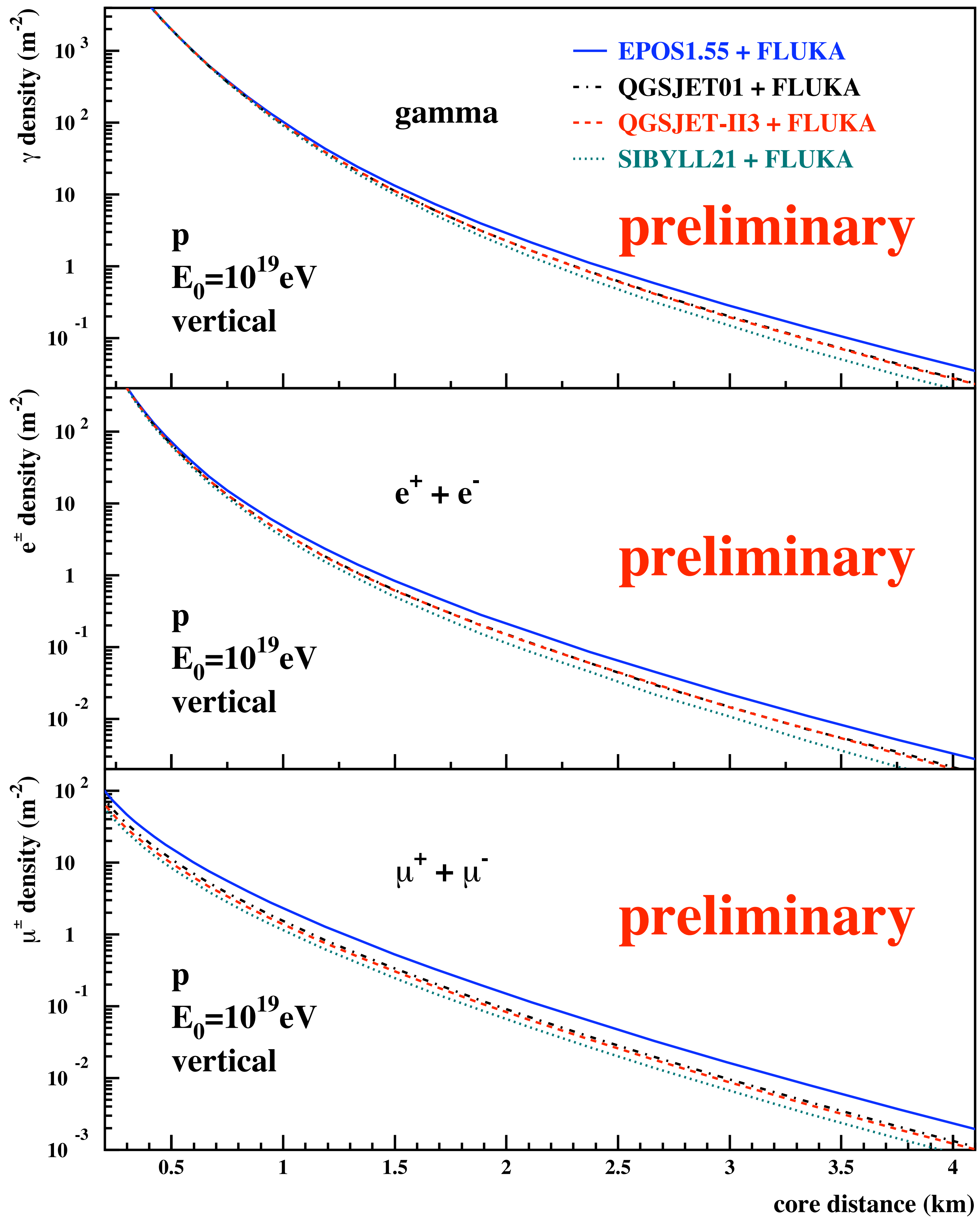


Lateral particle distribution

????

Note: Xmax similar for EPOS and SIBYLL 2.1

EPOS: much flatter lateral distribution for both muons and em. particles



Why is EPOS so much different ?

Possible sources of differences:

- baryon antibaryon pair production rate & spectra
- leading meson production (?)

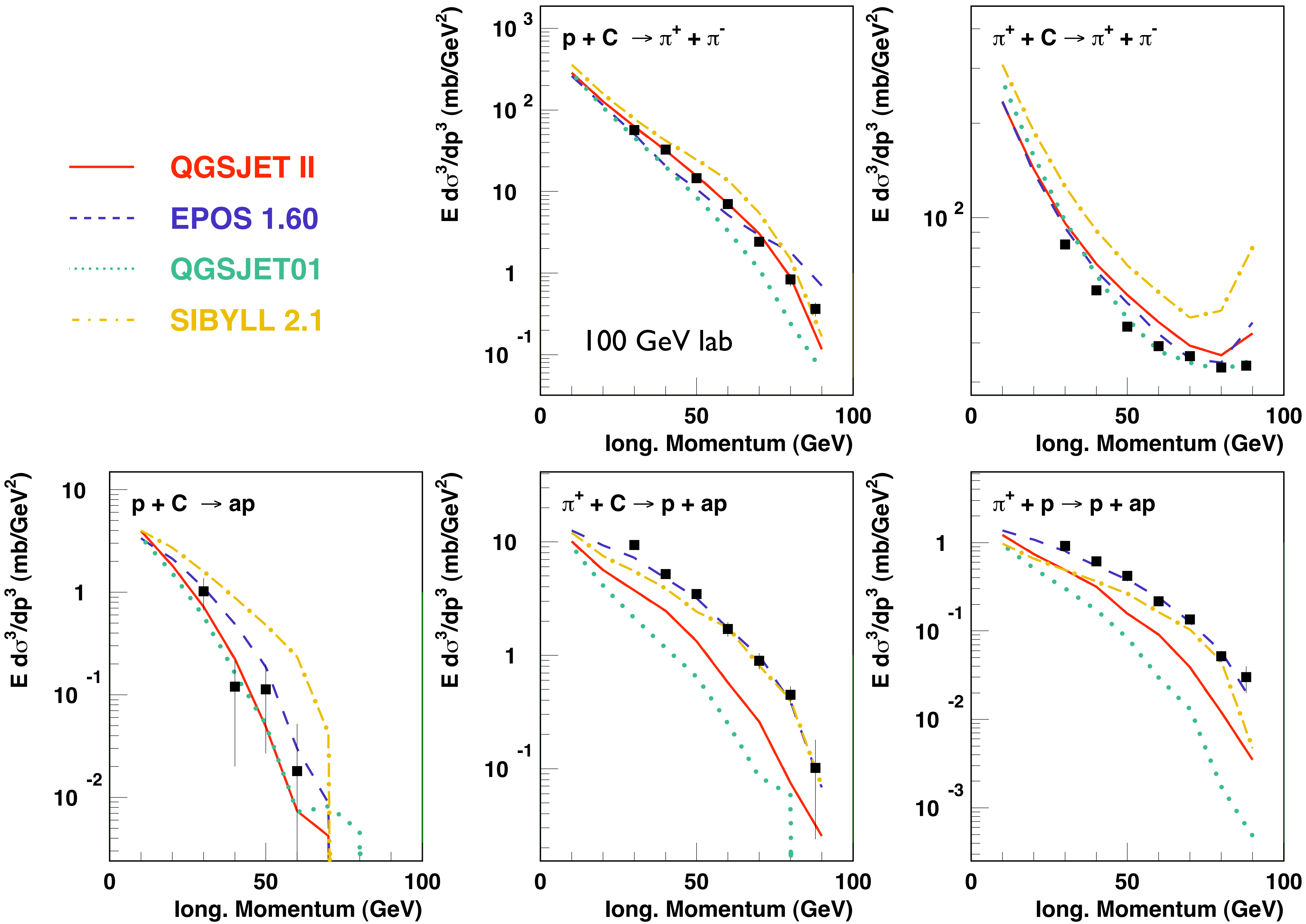
(Pierog & Werner, astro-ph/0611311)

EPOS predicts up to 5 times more baryons in hadronic shower core at high energy

Relevant effects (confirmed with modified version of SIBYLL):

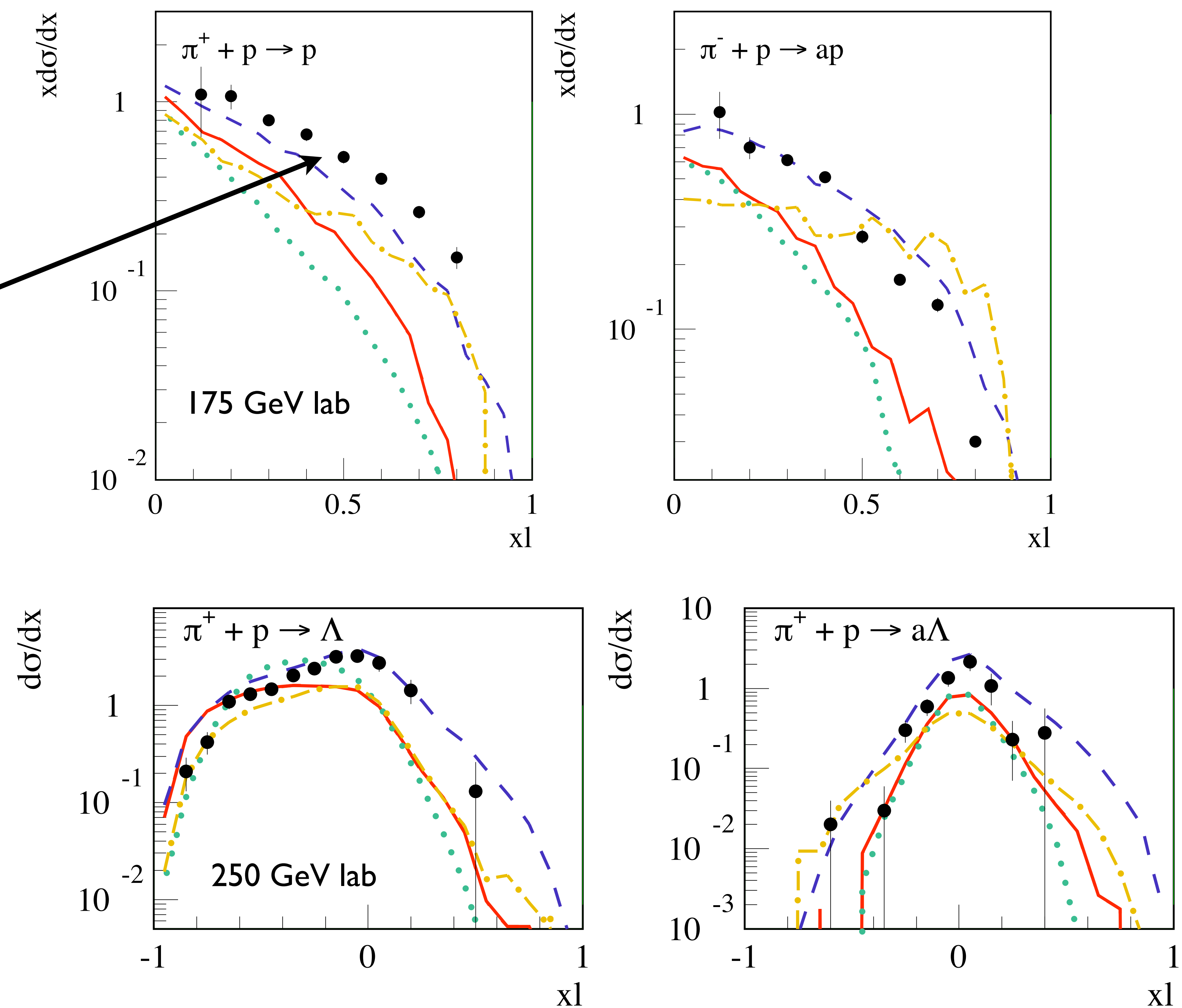
- baryon quantum number conservation
- transverse momentum distribution of baryons

Fixed target data on baryon production (i)



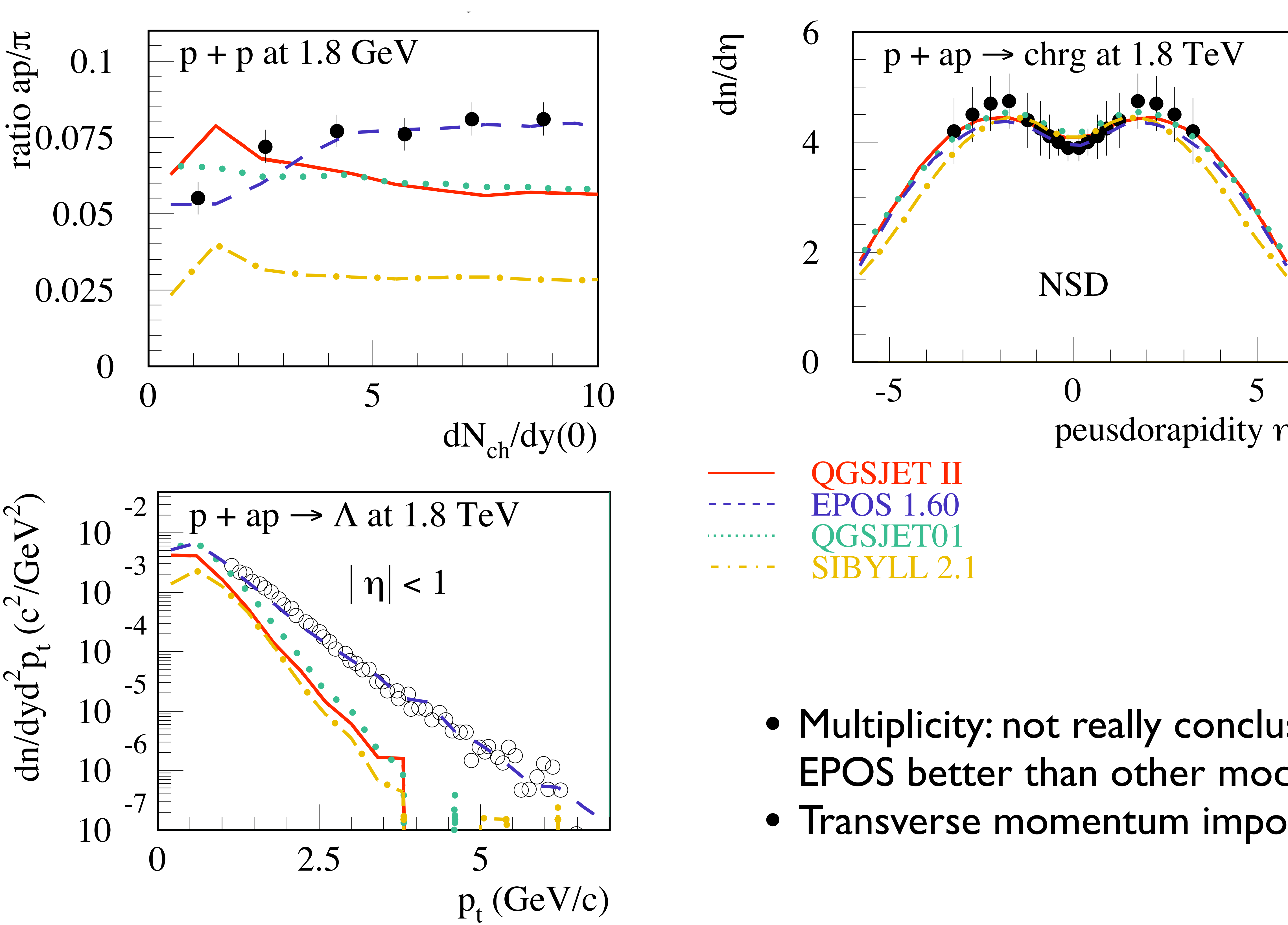
Fixed target data on baryon production (ii)

Data: possible misidentification of π+ and p ???



Need more data (MIPP, NA49)

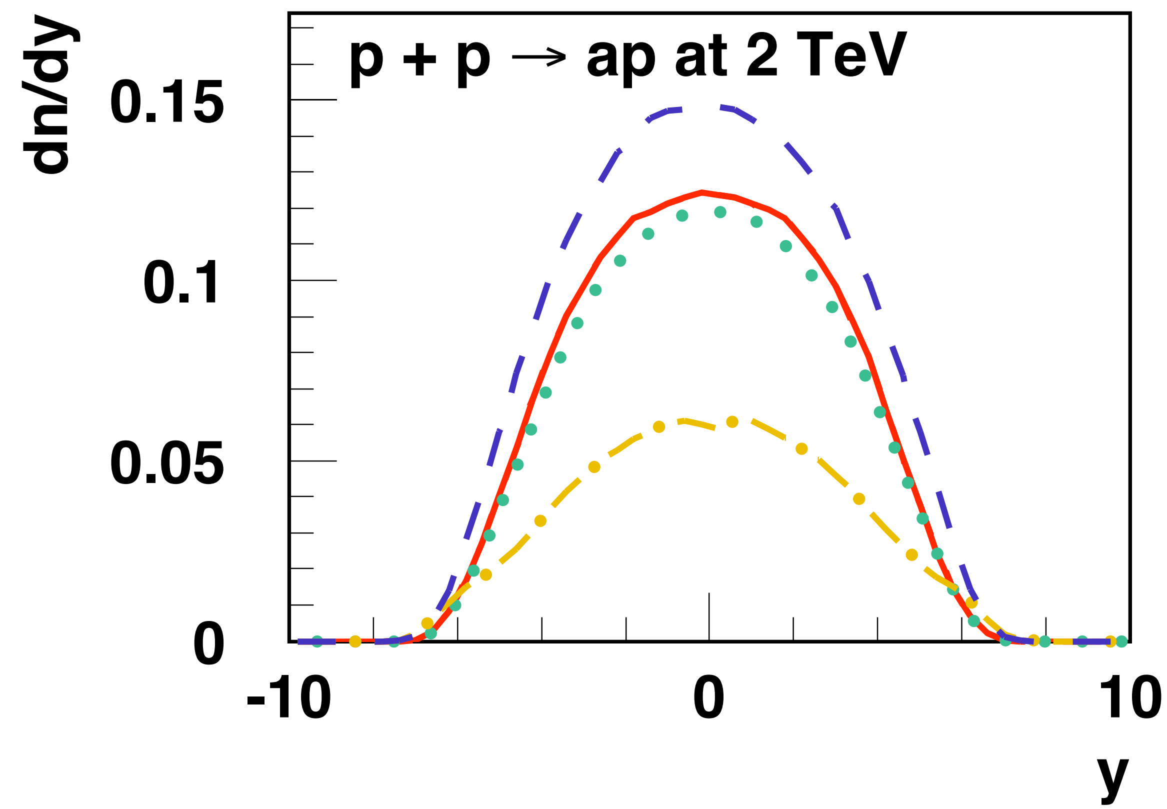
Tevatron data on baryon production

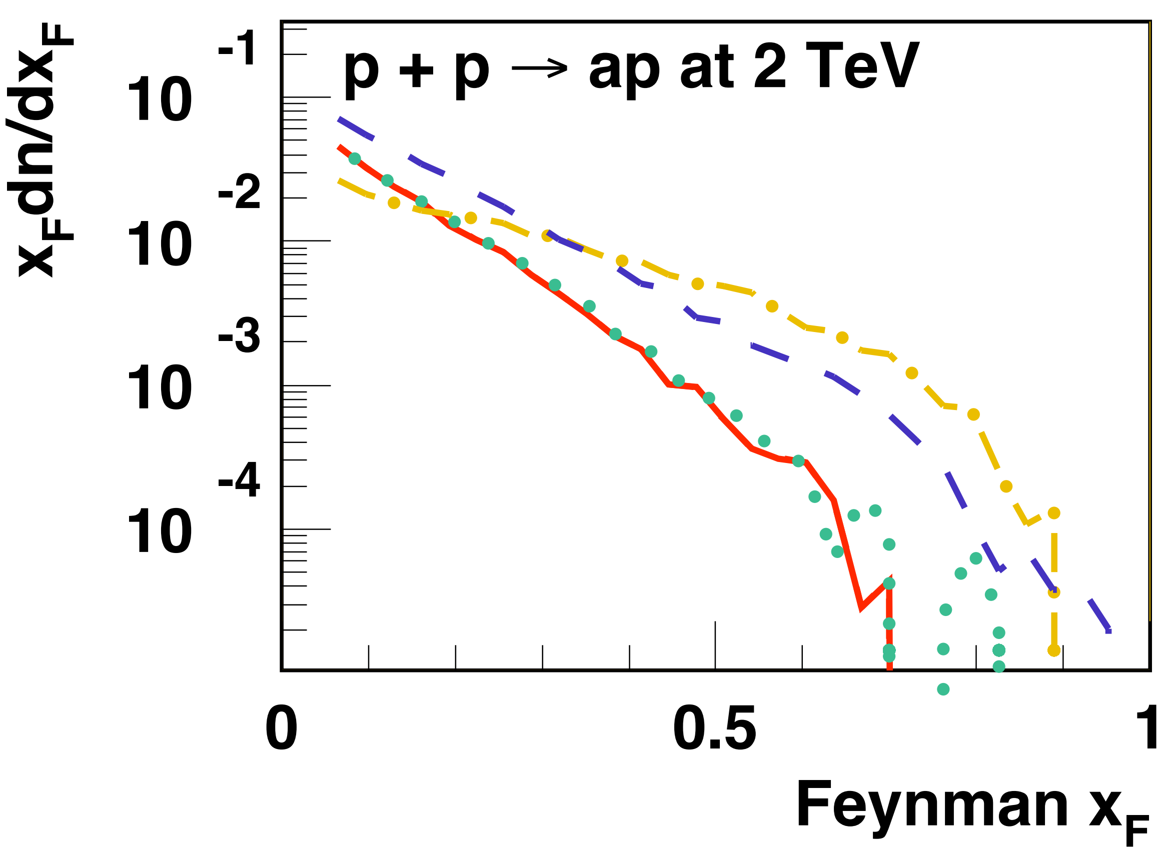


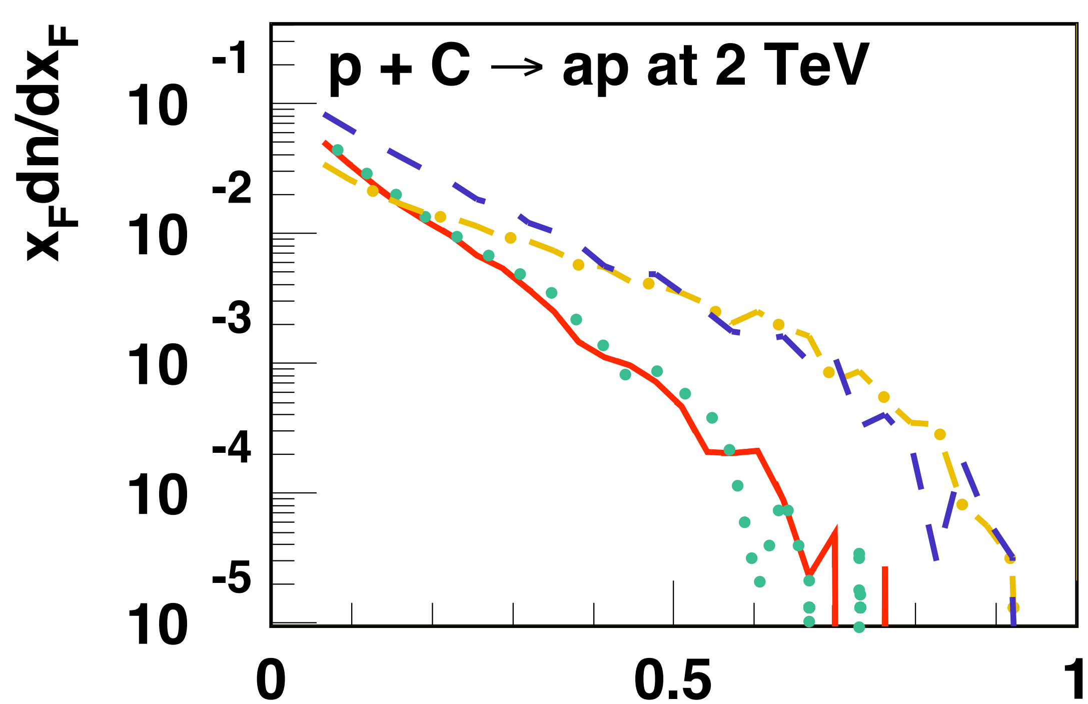
- Multiplicity: not really conclusive, EPOS better than other models
- Transverse momentum important

Model comparison: high energy

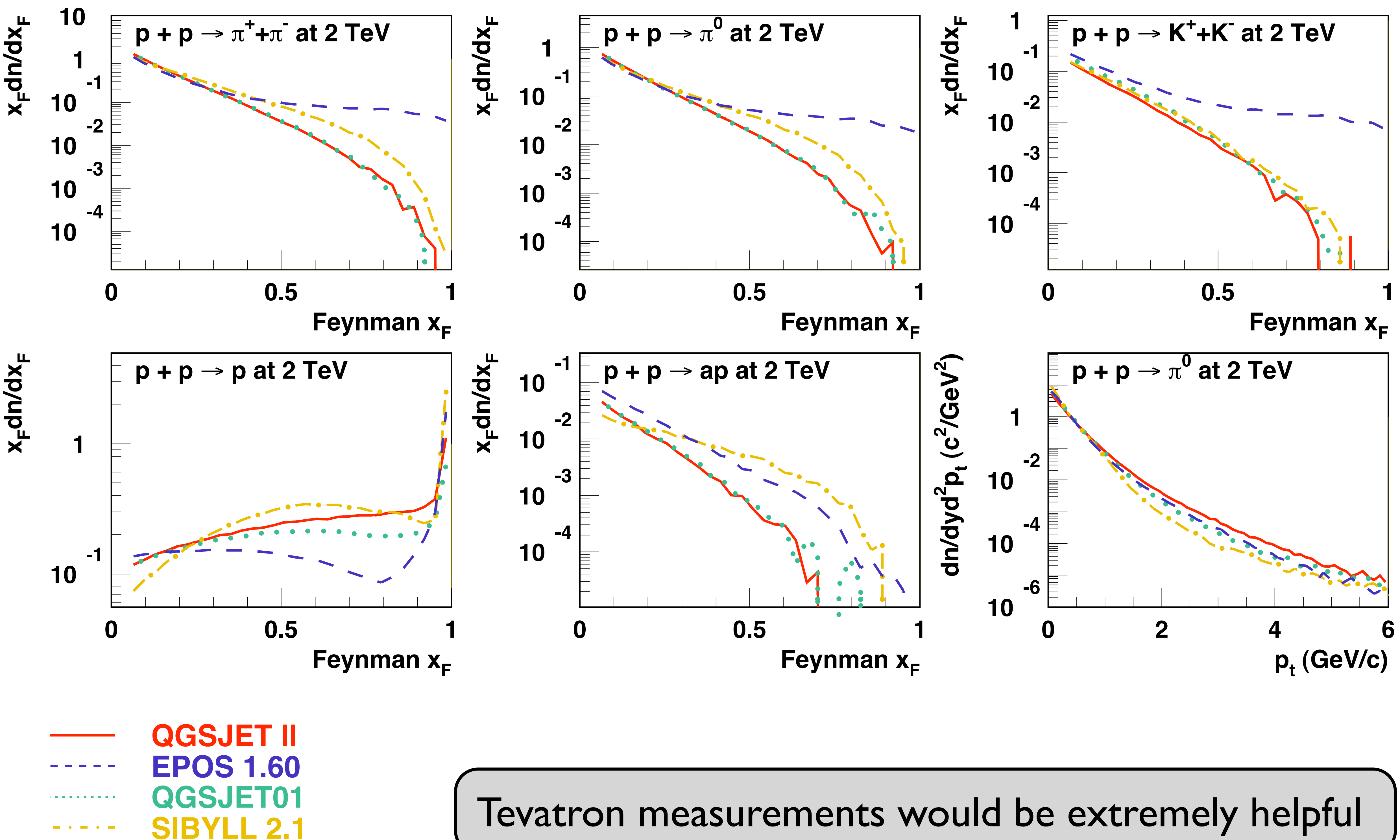
EPOS predicts up to
5 times more baryons
in hadronic shower core







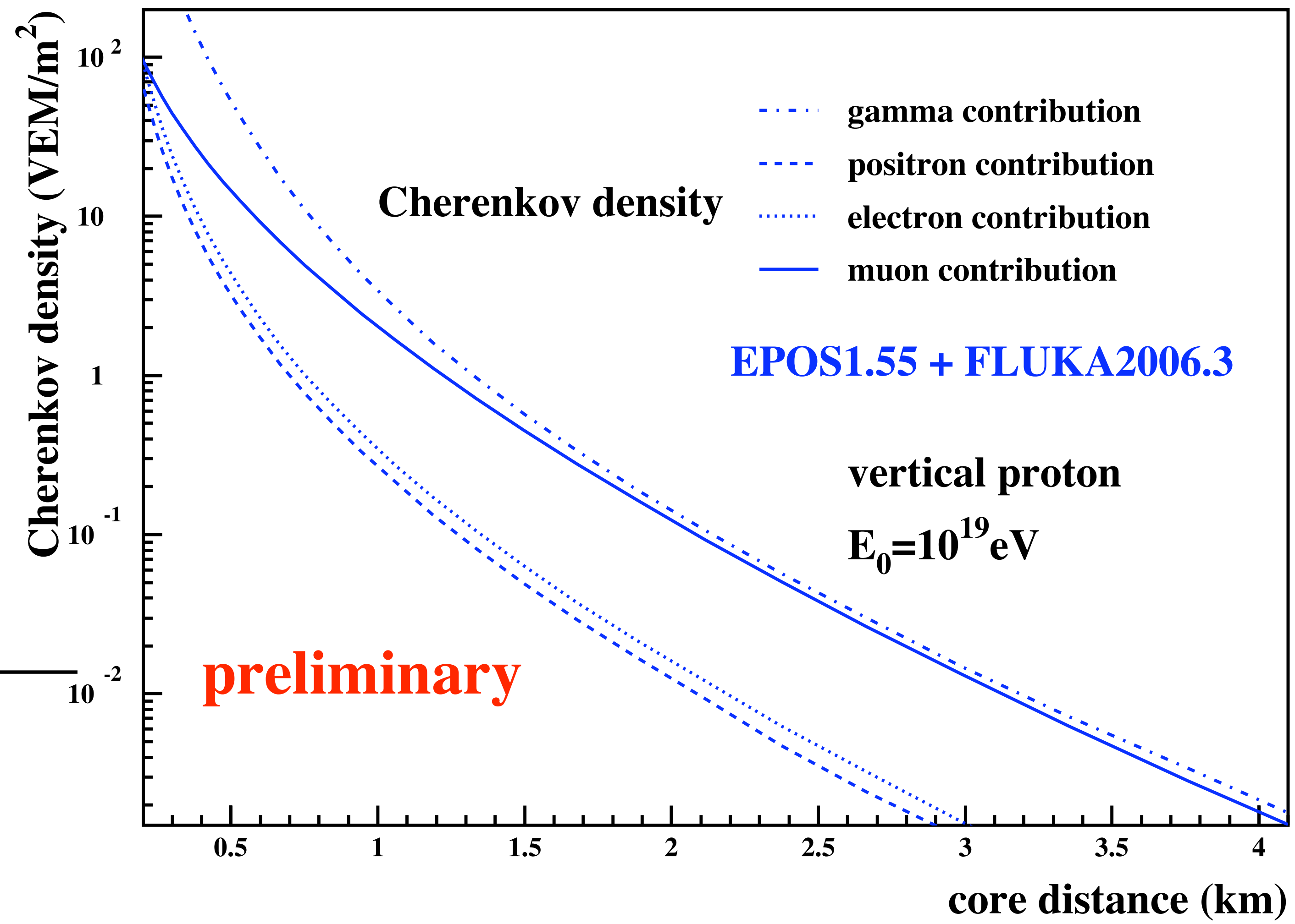
Popcorn effect: leading mesons

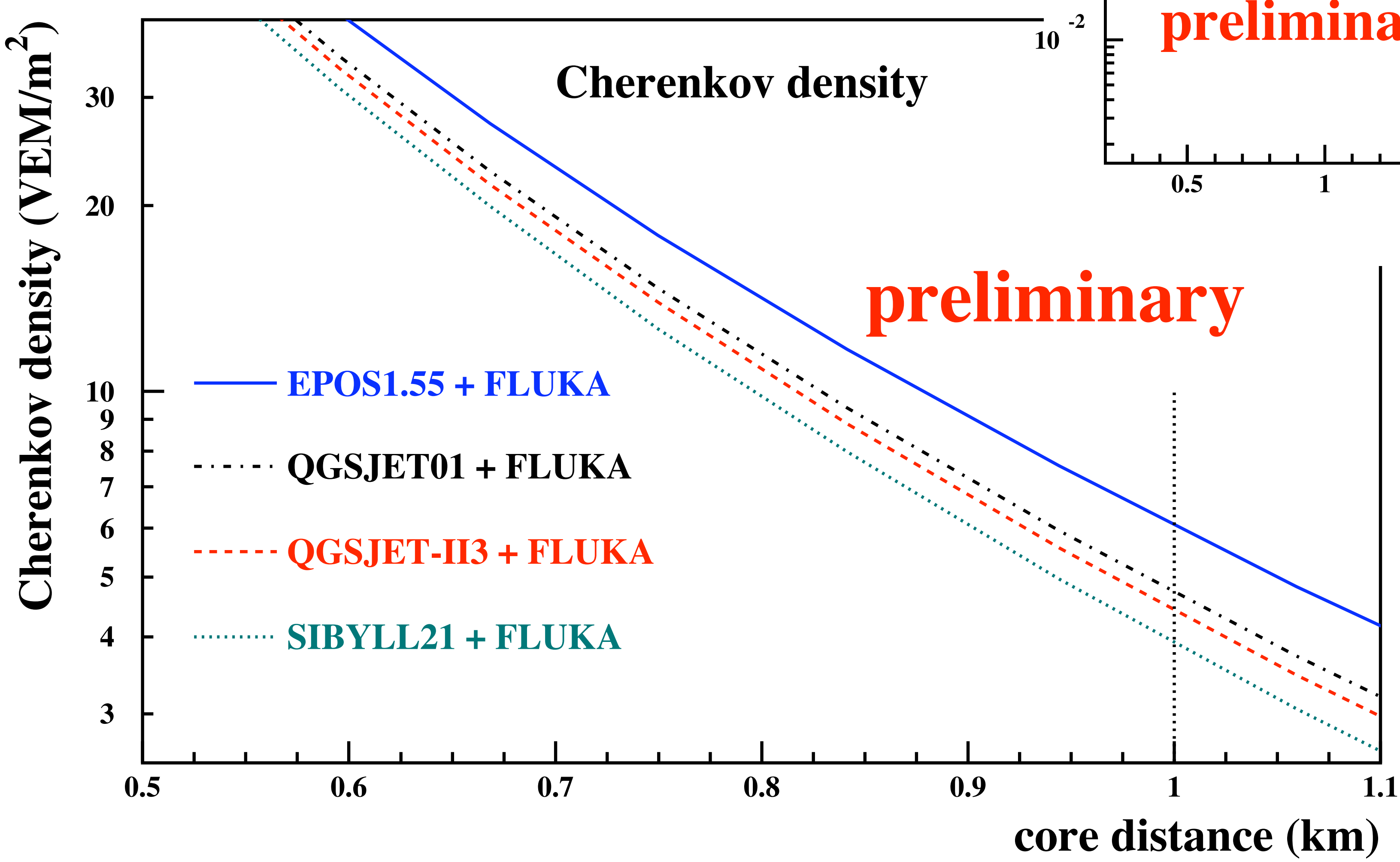


Tevatron measurements would be extremely helpful

Estimated signal for Auger tanks

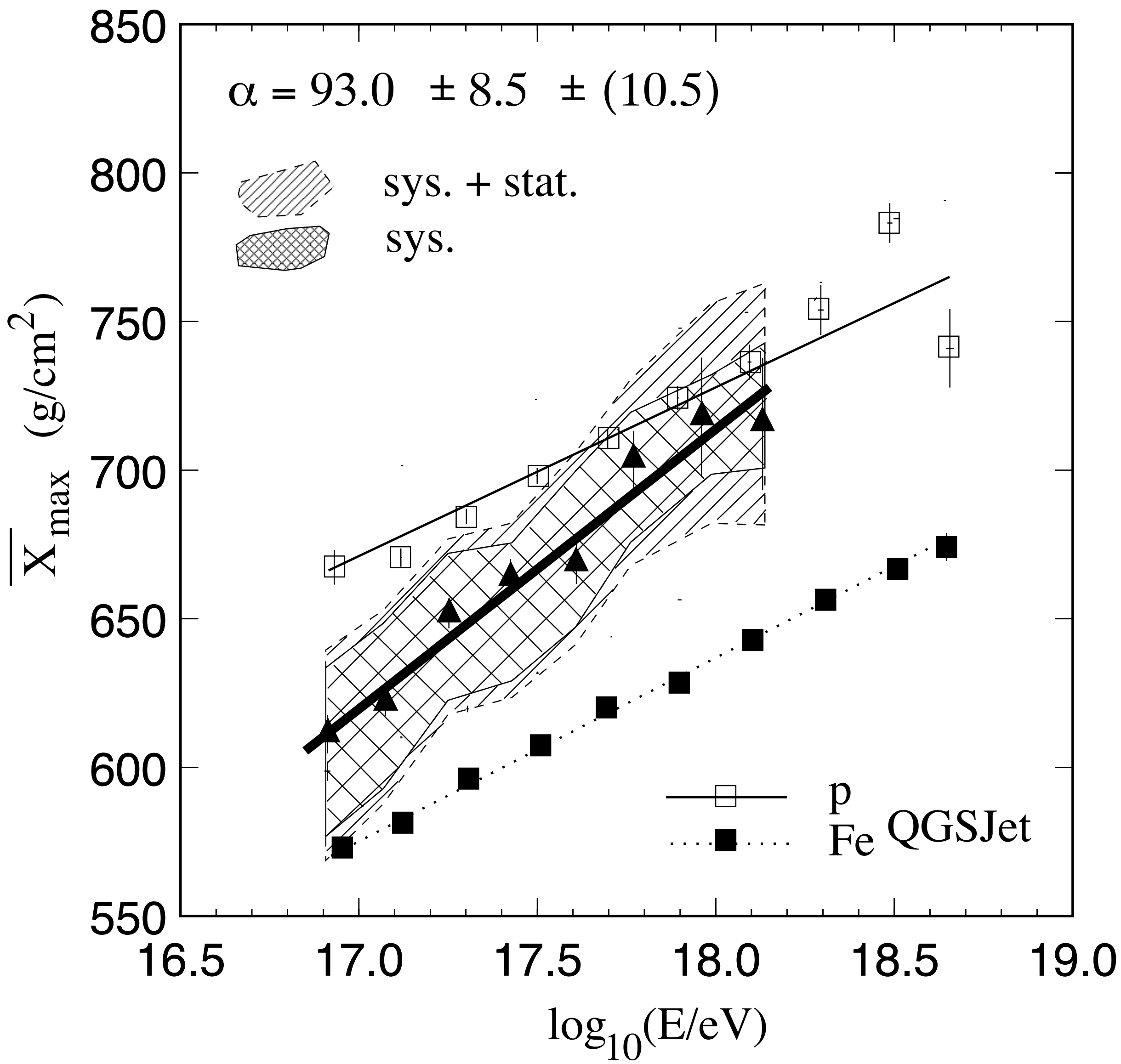
Prediction can be tested with Auger hybrid events



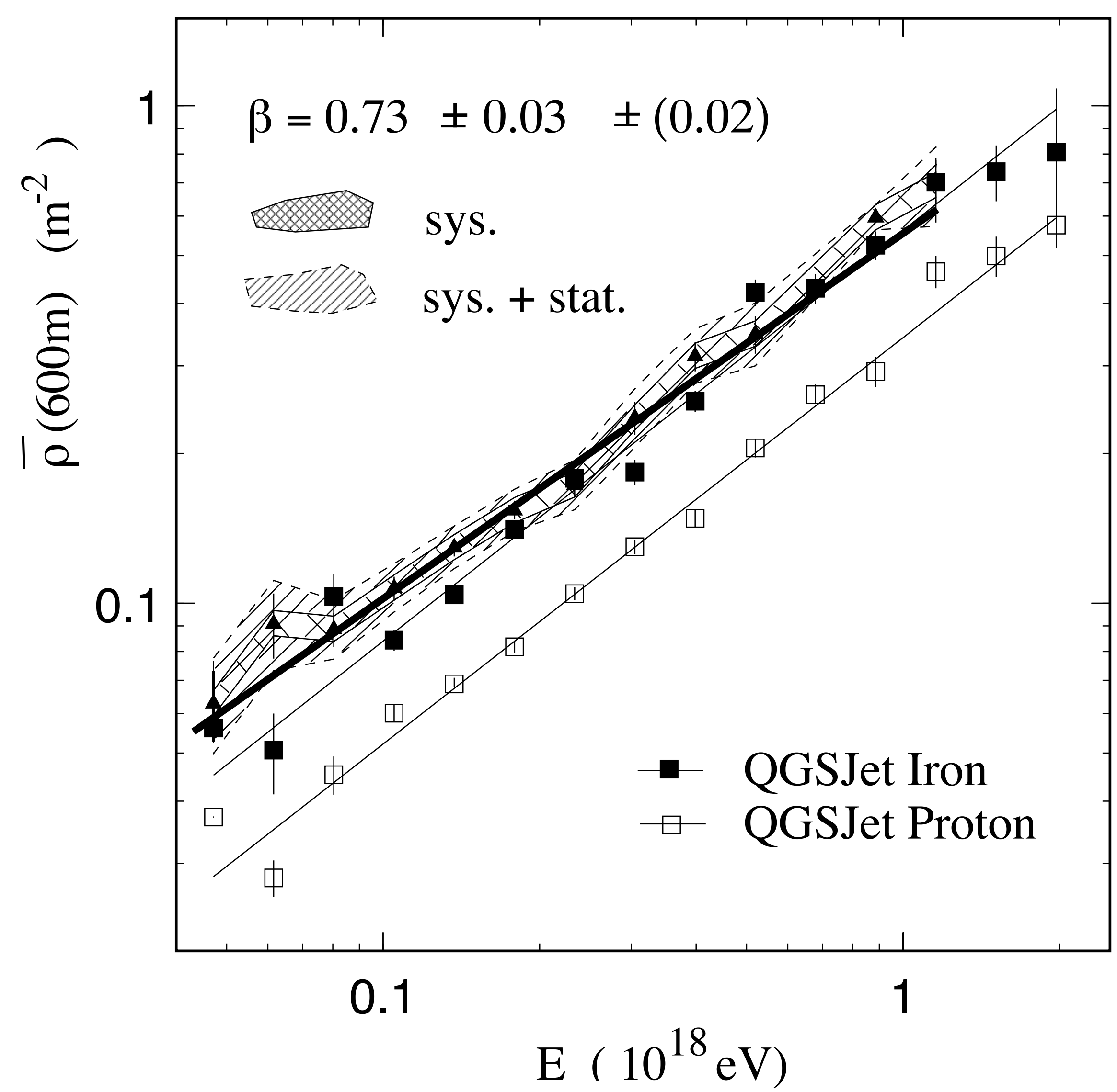


Hybrid measurement: HiRes-MIA

Mean depth of shower maximum



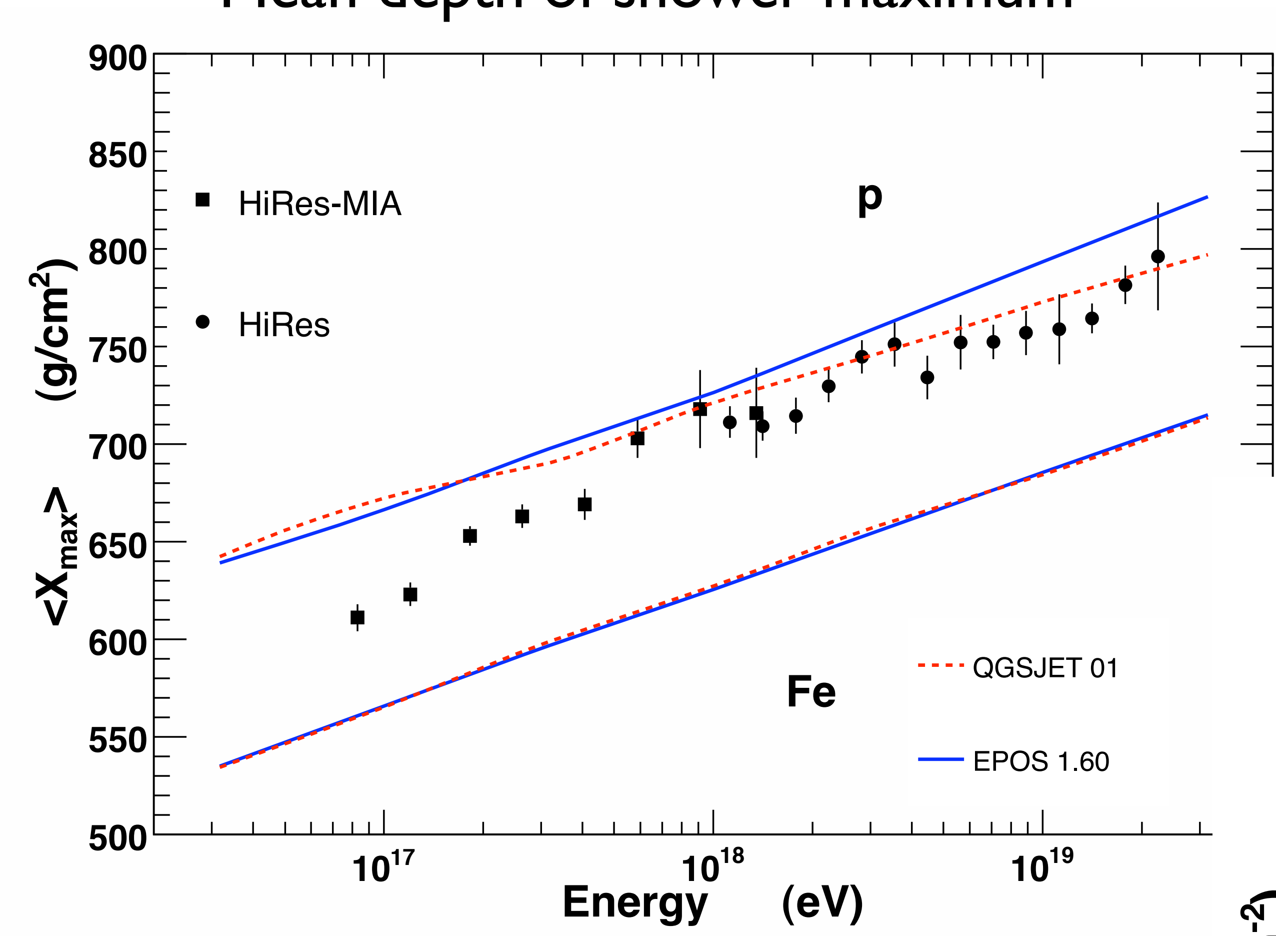
Muon density at 600 m



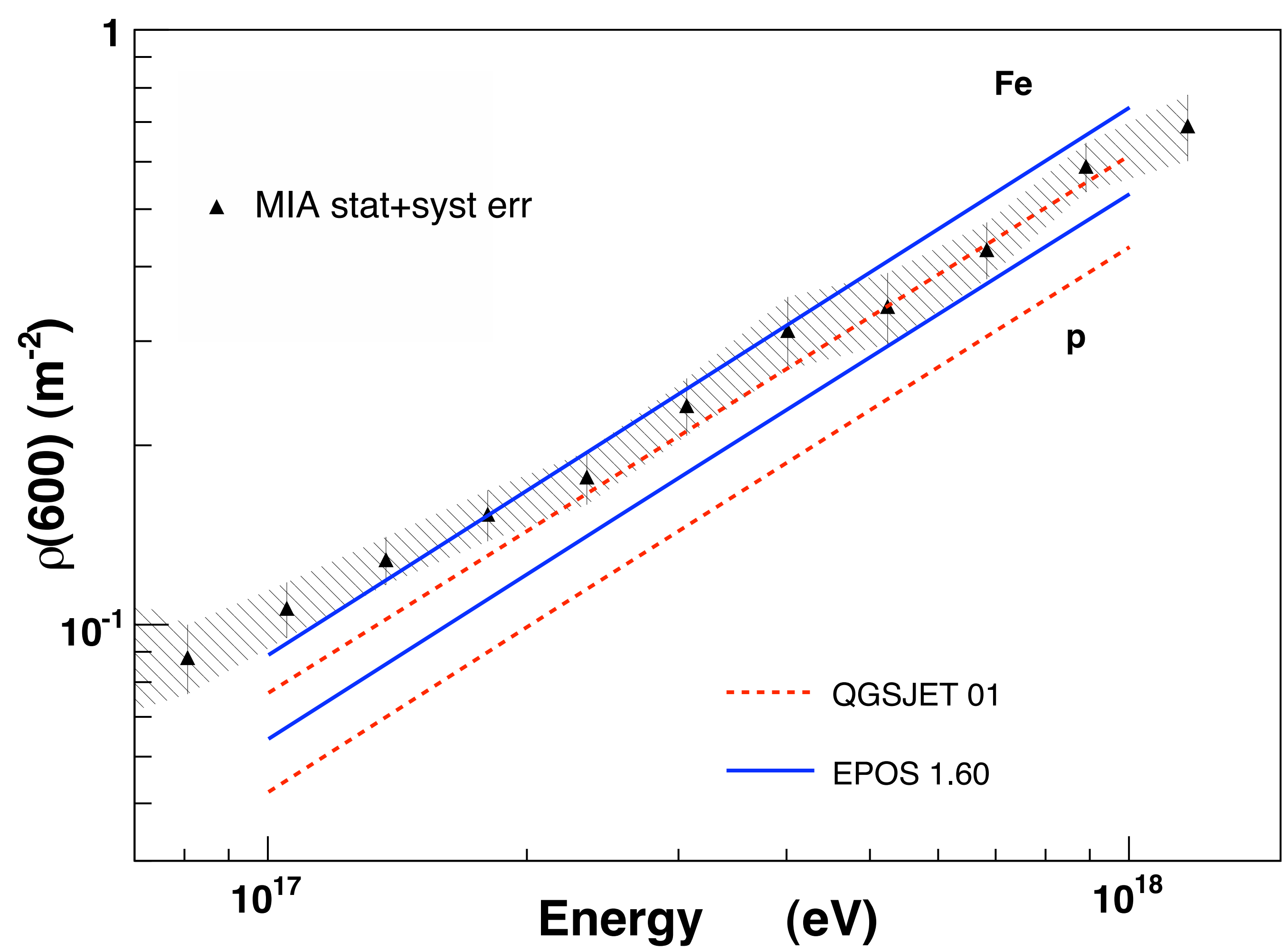
(HiRes-MIA, PRL 2000)

Simulation of HiRes-MIA data

Mean depth of shower maximum



Muon density at 600 m



Simulation done for QGSJET and EPOS

(Pierog & Werner, astro-ph/0611311)

Conclusions

- Different model concepts

- Models in reasonable agreement with pion production data
- Some discrepancies for K+ production
- Baryon antibaryon production underestimated

- EPOS gives very good description of data
- More fixed target measurements needed
- Tevatron and LHC measurements would help

- Cosmic ray data will help to discriminate between models (KASCADE: N_e-N_μ, hadrons; Auger hybrid events; inclusive muon flux measurements)

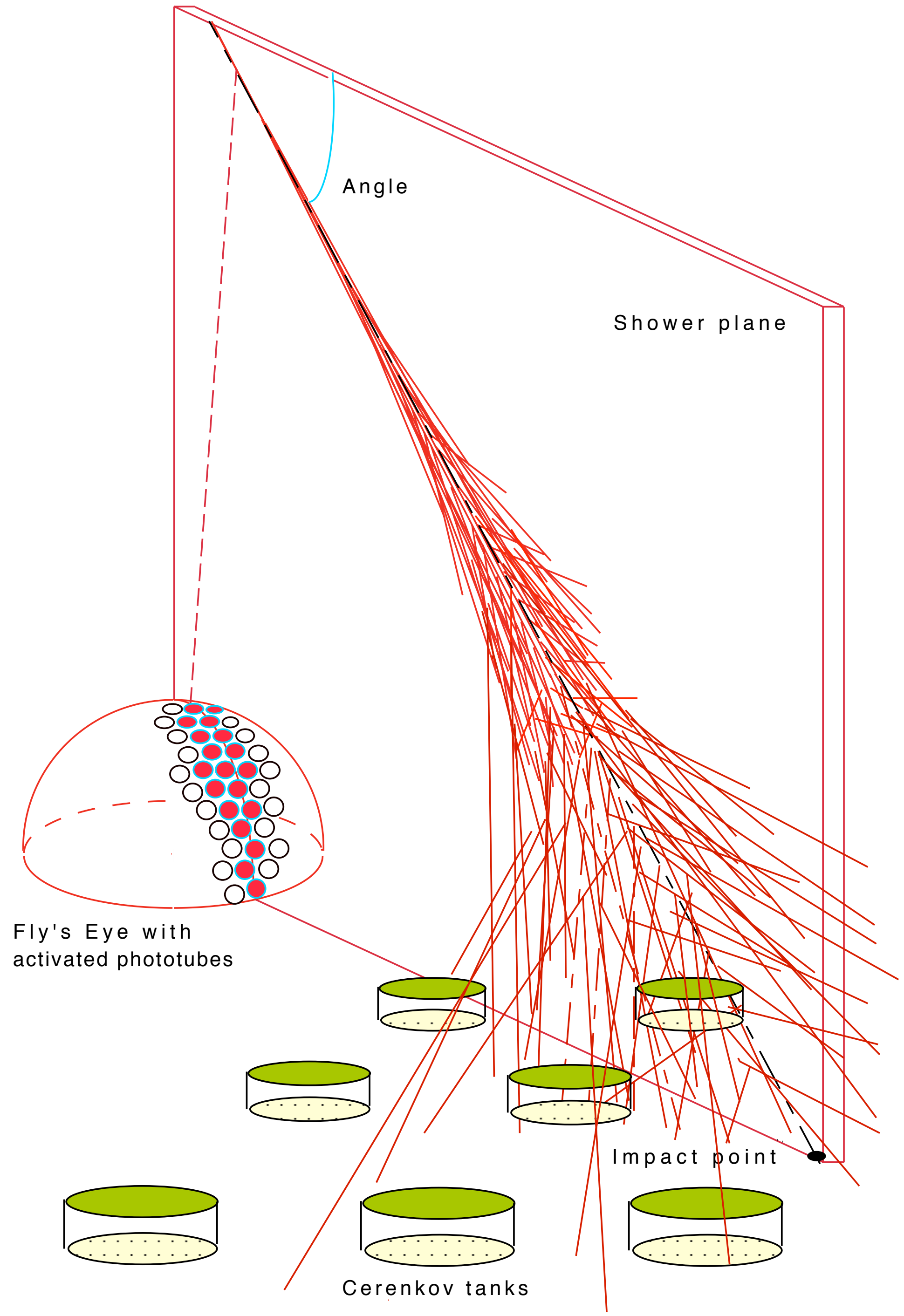
Hybrid measurement: Pierre Auger Observatory

29th International Cosmic Ray Conference Pune (2005) **00**, 101–106

First Estimate of the Primary Cosmic Ray Energy Spectrum above 3 EeV from the Pierre Auger Observatory

The Pierre Auger Collaboration
Presenter: P. Sommers (sommers@physics.utah.edu)

Measurements of air showers are accumulating at an increasing rate while construction proceeds at the Pierre Auger Observatory. Although the southern site is only half complete, the cumulative exposure is already similar to those achieved by the largest forerunner experiments. A measurement of the cosmic ray energy spectrum in the southern sky is reported here. The methods are simple and robust, exploiting the combination of fluorescence detector (FD) and surface detector (SD). The methods do not rely on detailed numerical simulation or any assumption about the chemical composition.



Simulation: particles at ground correspond to 25% higher shower energy than measured shower profile

Caution: within current systematic uncertainty

P. Sommers et al. astro-ph/0507150