Modeling of Hadronic Interactions

Lecture 2

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Outline

Lecture 1 – Low- and intermediate-energy interactions

- Particle production threshold: resonances
- Intermediate energies: two-string models
- Extension to nuclei and photons

Lecture 2 – Interactions at very high energy

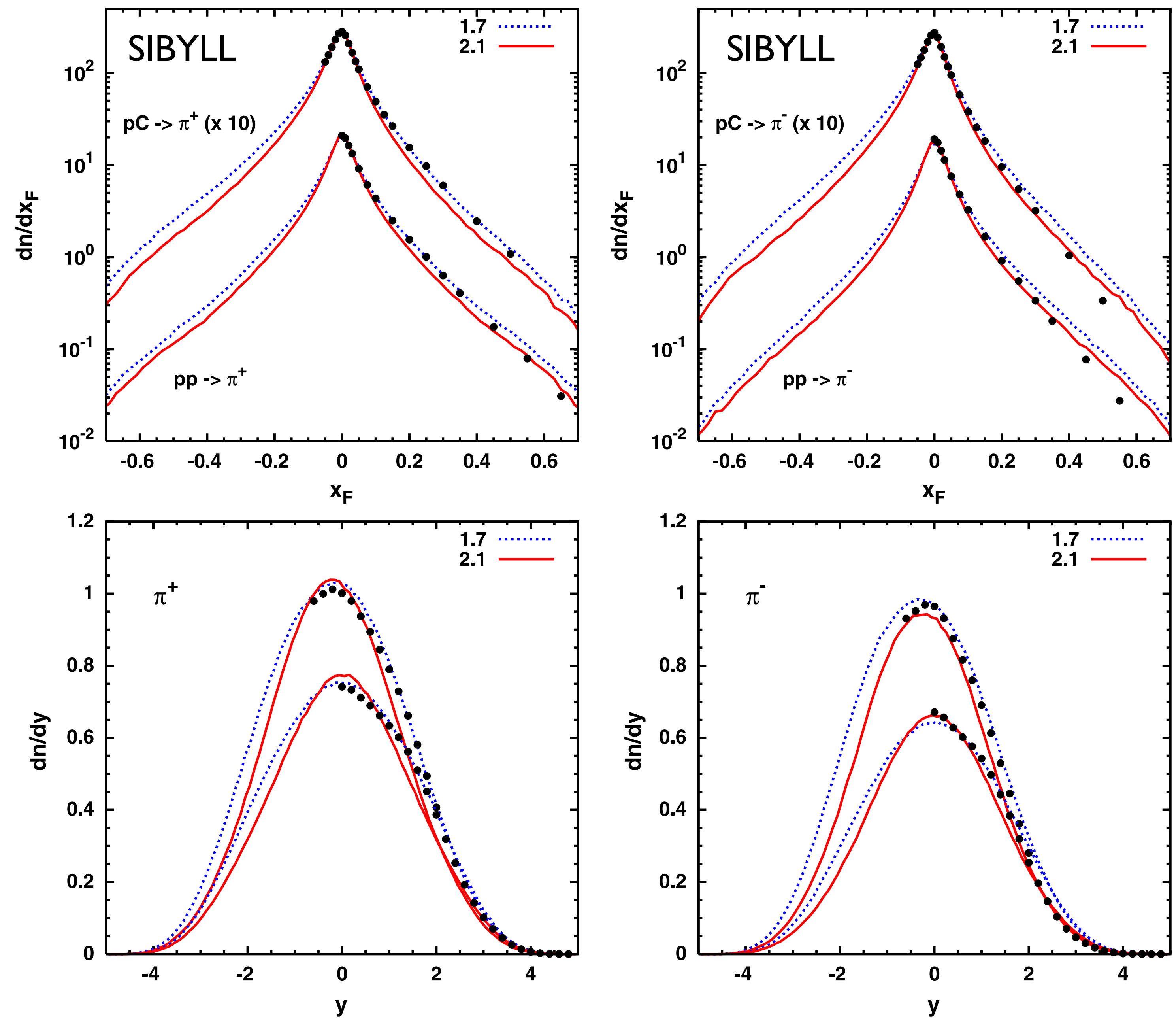
- Jets and minijets, multiple interactions
- Unitarization and saturation scenarios
- Comparison of models and uncertainties of extrapolations

Lecture 3 – Air shower phenomenology and accelerator data

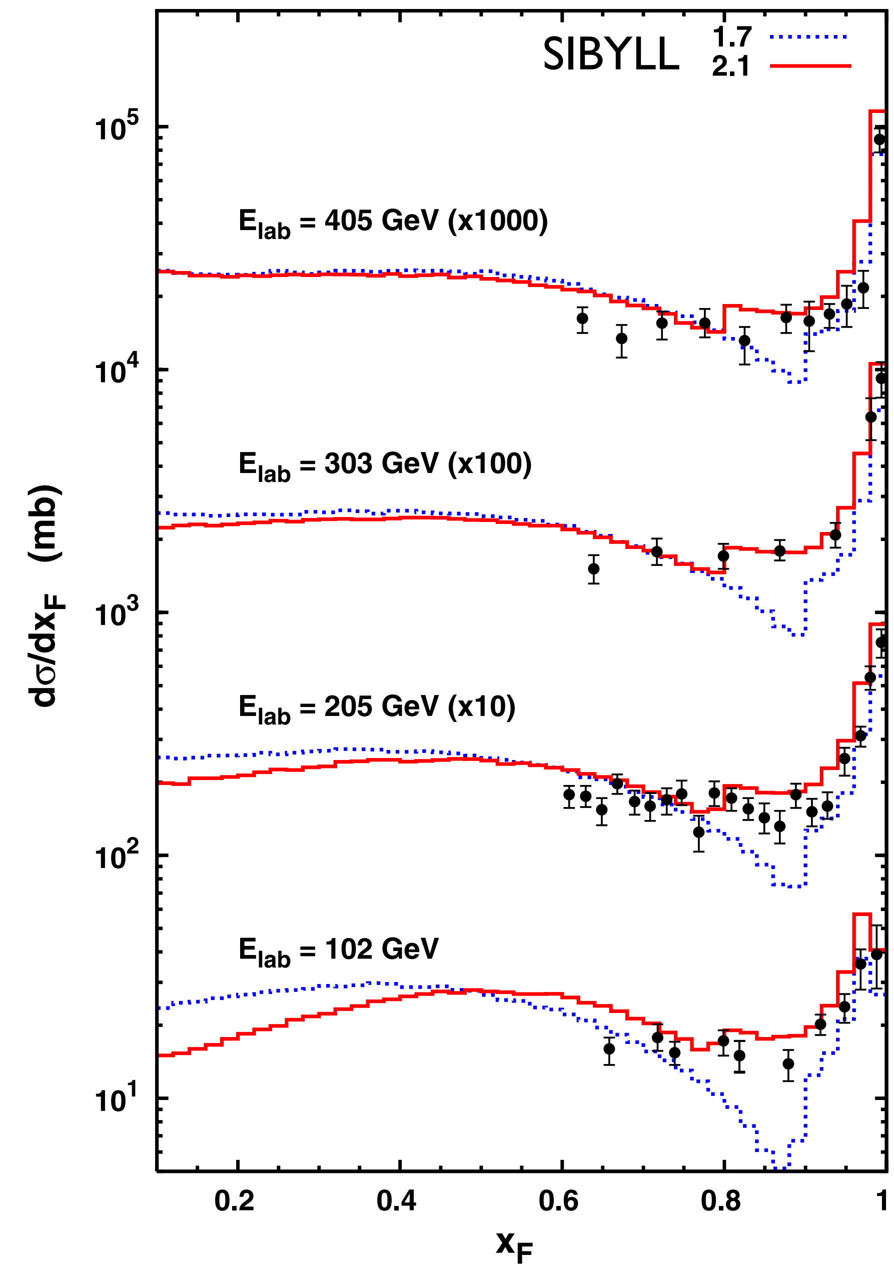
- Relation between hadronic interactions and air showers
- Accelerator experiments & discrimination potential of LHC
- Comparison of model predictions with accelerator data

SIBYLL: central & leading particle production

NA49 p-p and p-C at 158 GeV



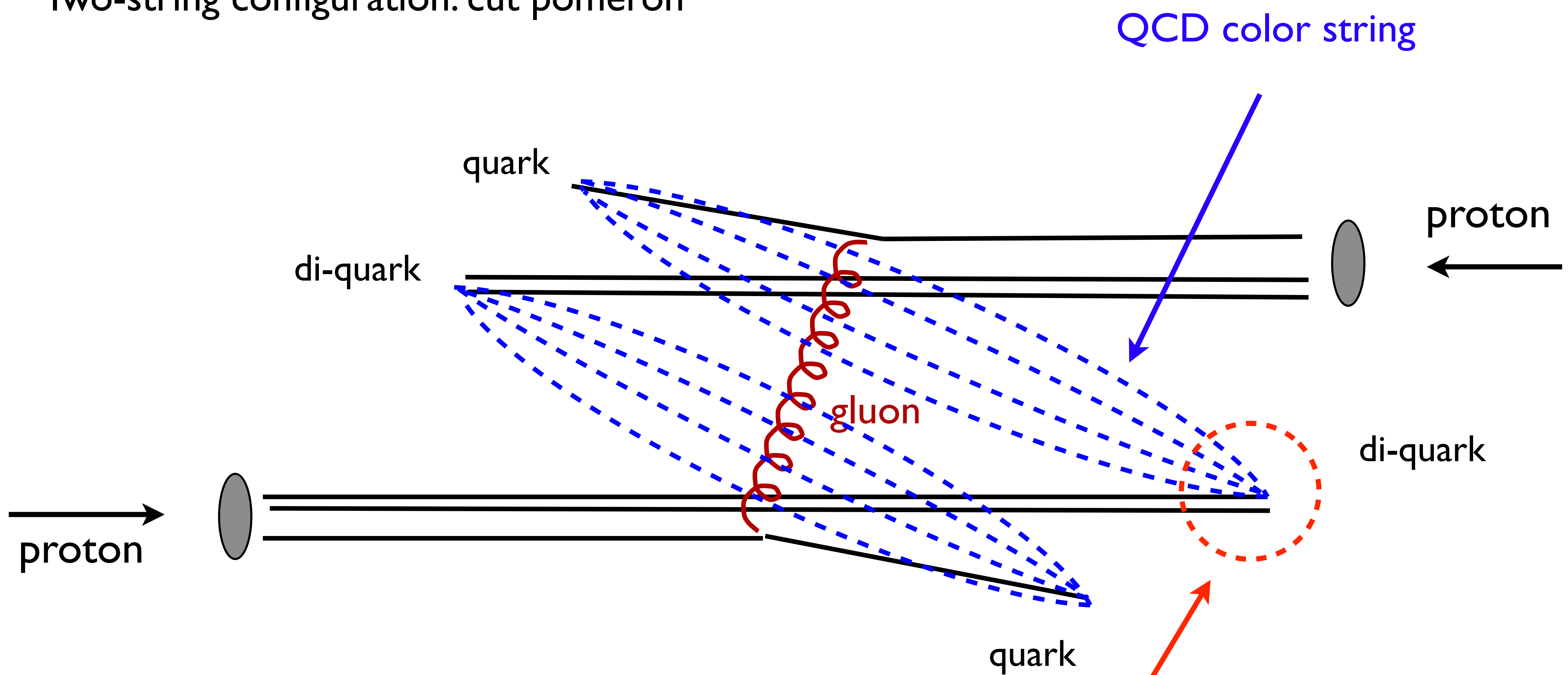
leading proton distributions



(Ahn et al., PRD80 (2009) 094003)

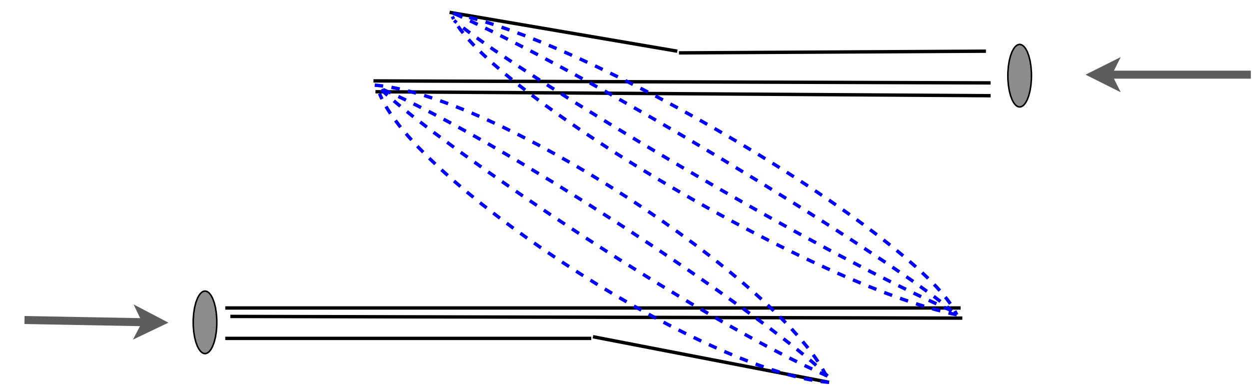
Simplest interaction scenario: single gluon exchange

Two-string configuration: cut pomeron

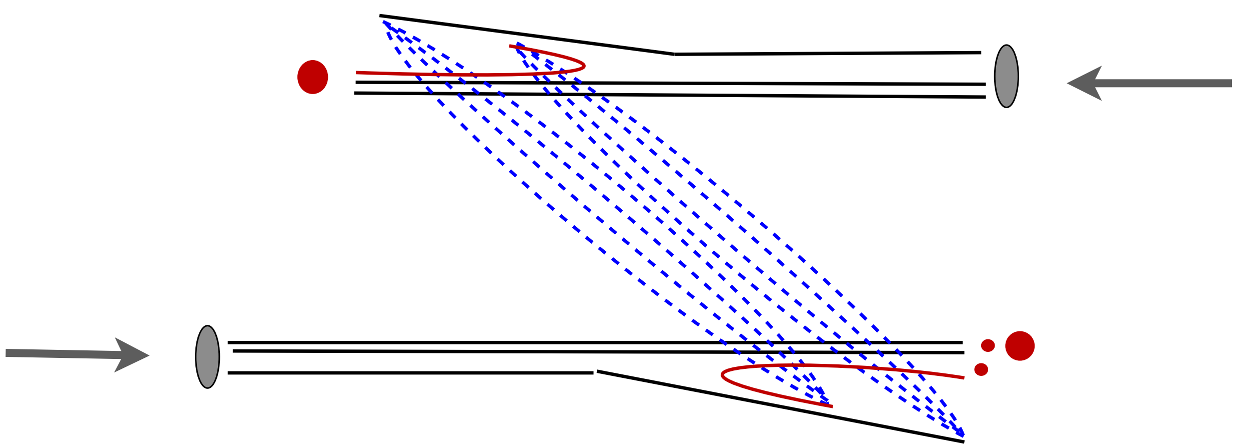


Leading particle production: first particle in string fragmentation contains quarks/diquarks from beam particle

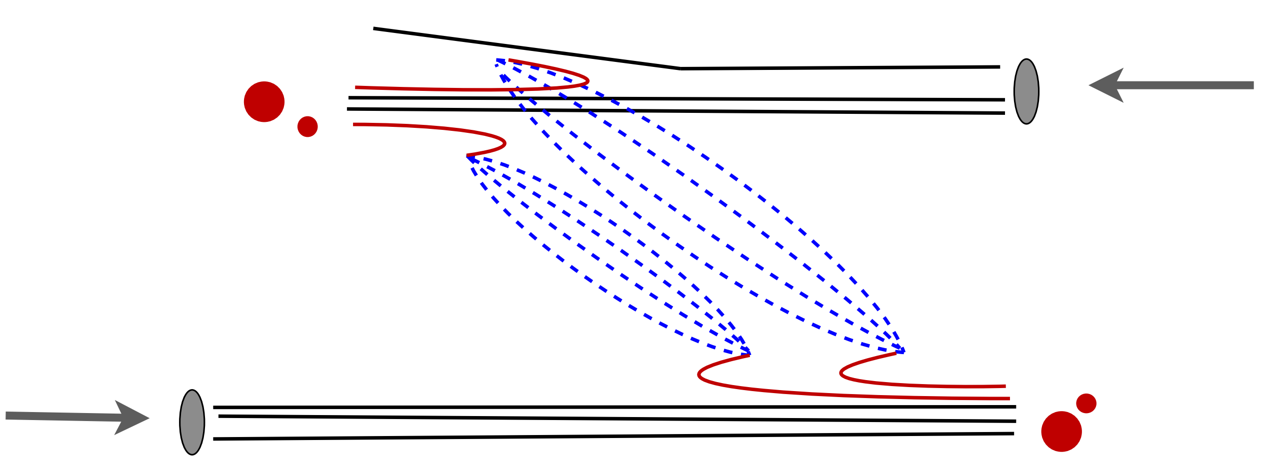
Different implementations



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

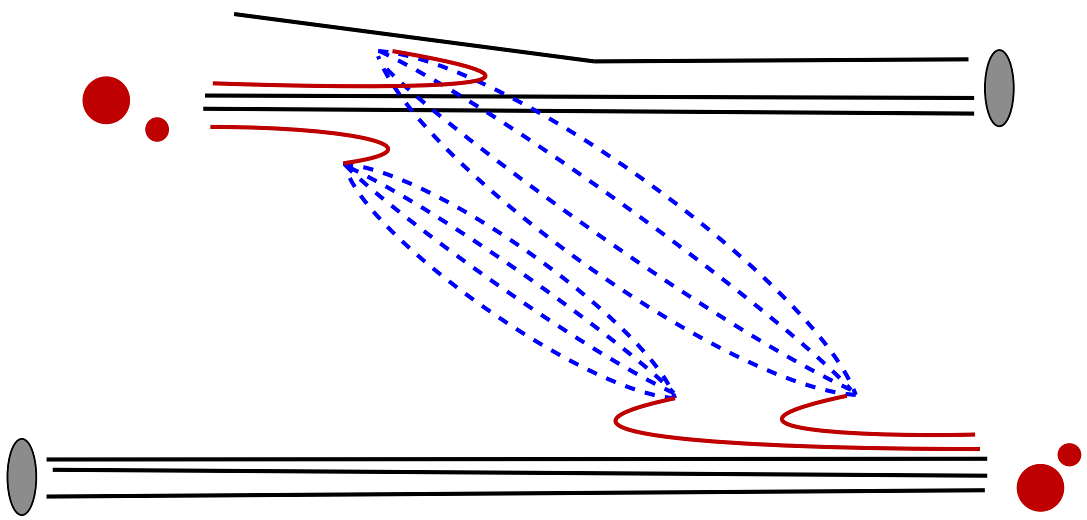


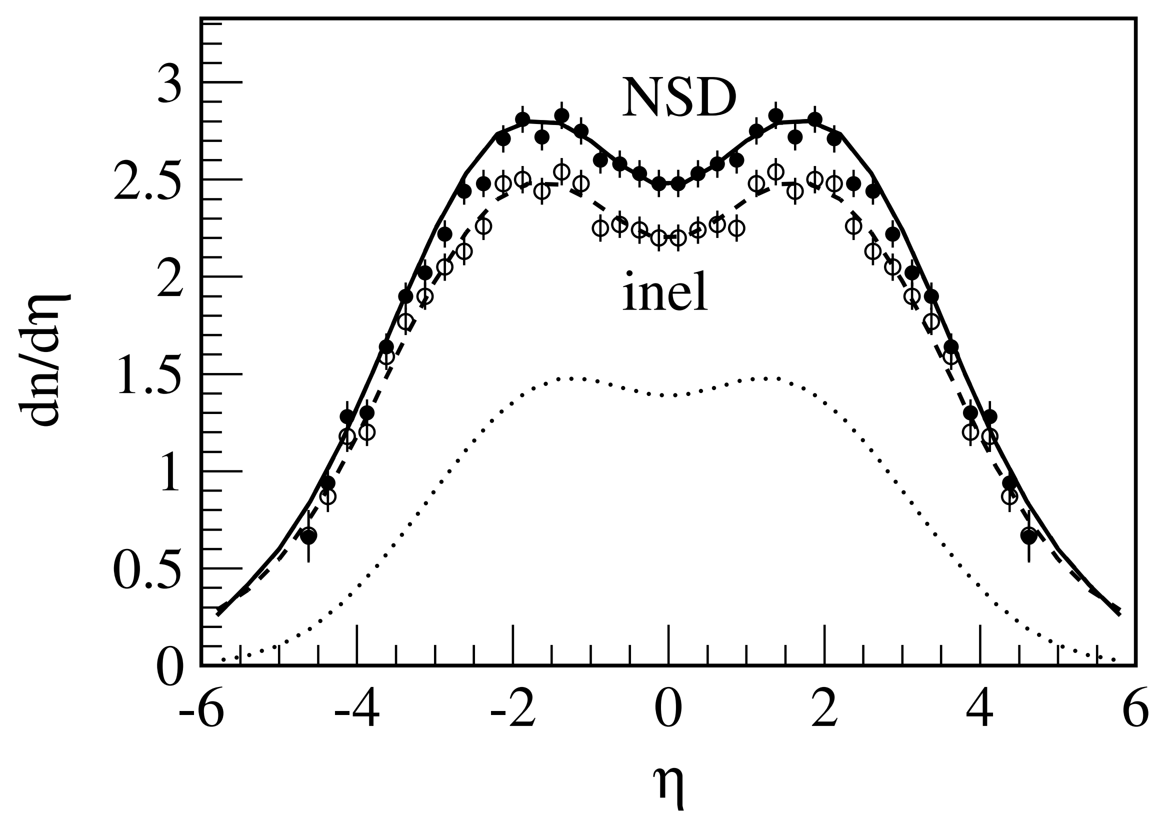
QGSJET:
fixed probability of strings connected to valence quarks or sea quarks;
explicit construction of remnant hadron

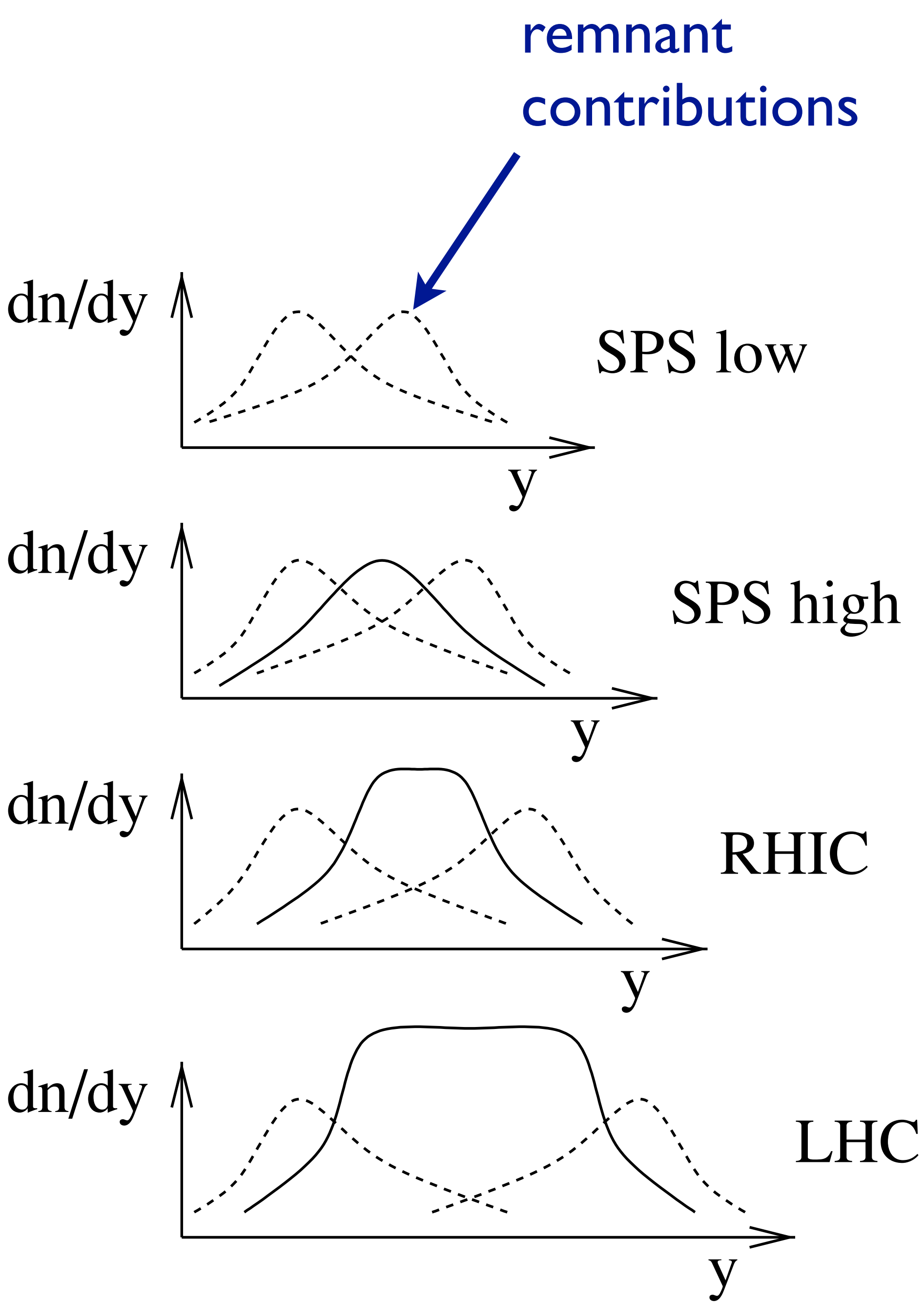


EPOS:
strings always connected to sea quarks;
bags of sea and valence quarks fragmented statistically

EPOS: remant vs. string contributions

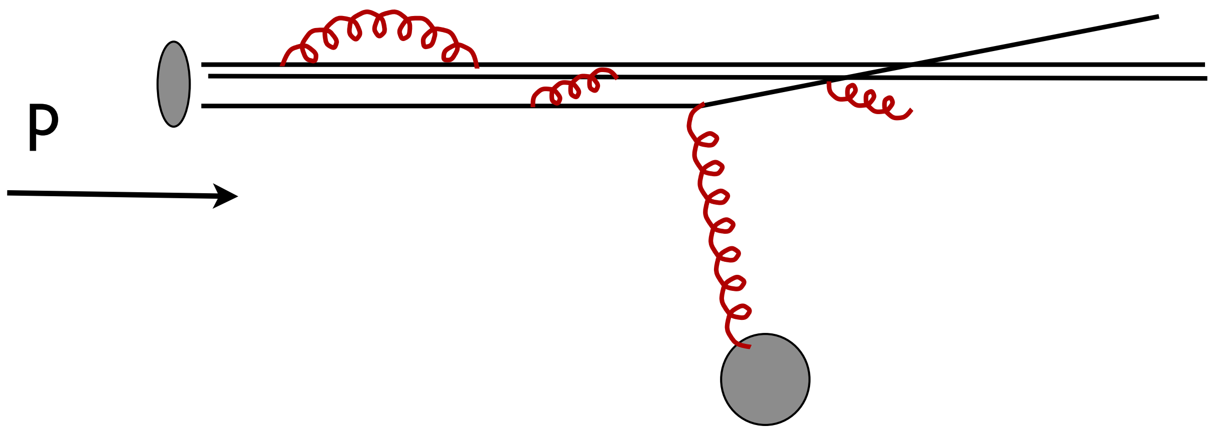






EPOS: change from remanant-dominated to string-dominated particle production

Transition from intermediate to high energy

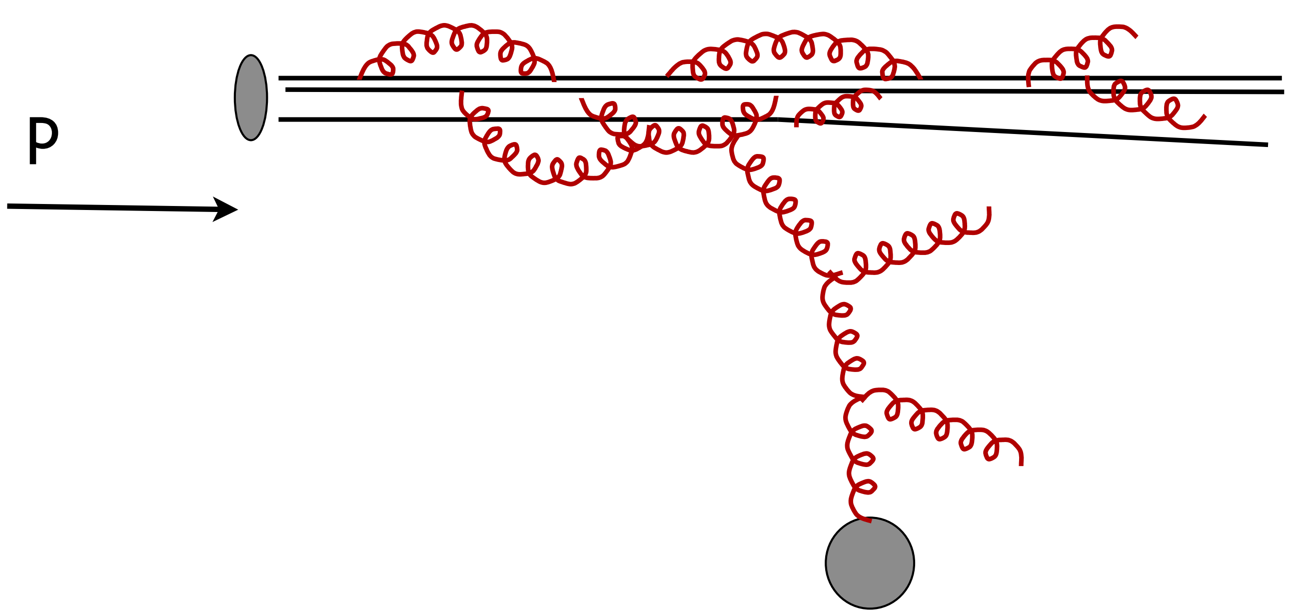


Intermediate energy:

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

Lifetime of fluctuations

$$\Delta t \approx \frac{1}{\Delta E} = \frac{1}{\sqrt{p^2+m^2}-p} = \frac{1}{p(\sqrt{1+m^2/p^2}-1)} \approx \frac{2p}{m^2}$$

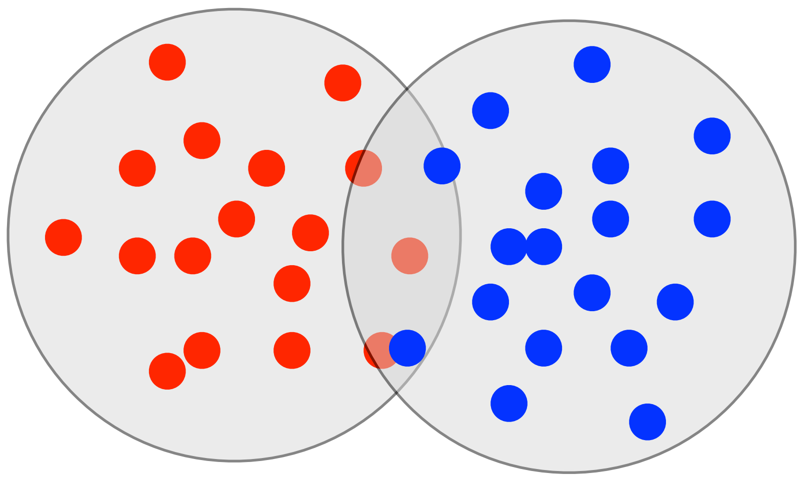


High energy regime:

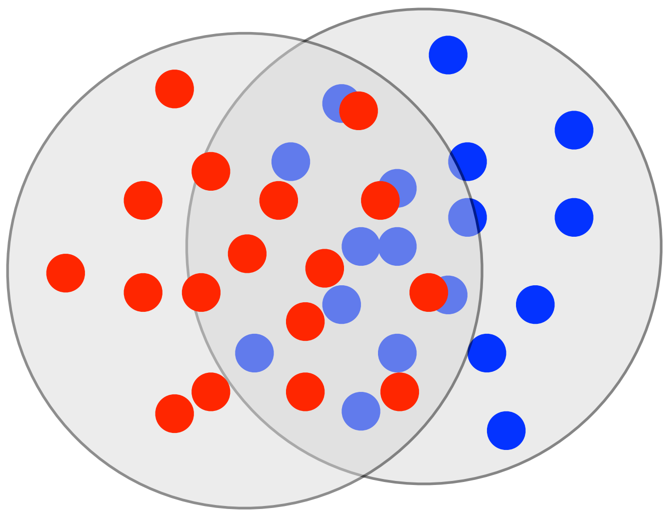
- E_{lab} > 21,000 GeV
- E_{cm} > 200 GeV
- dominated by gluons and sea quarks

Geometric interpretation of collision at high energy

Hadrons filled with partons from fluctuations
frozen in time (relative to time scale of interaction)

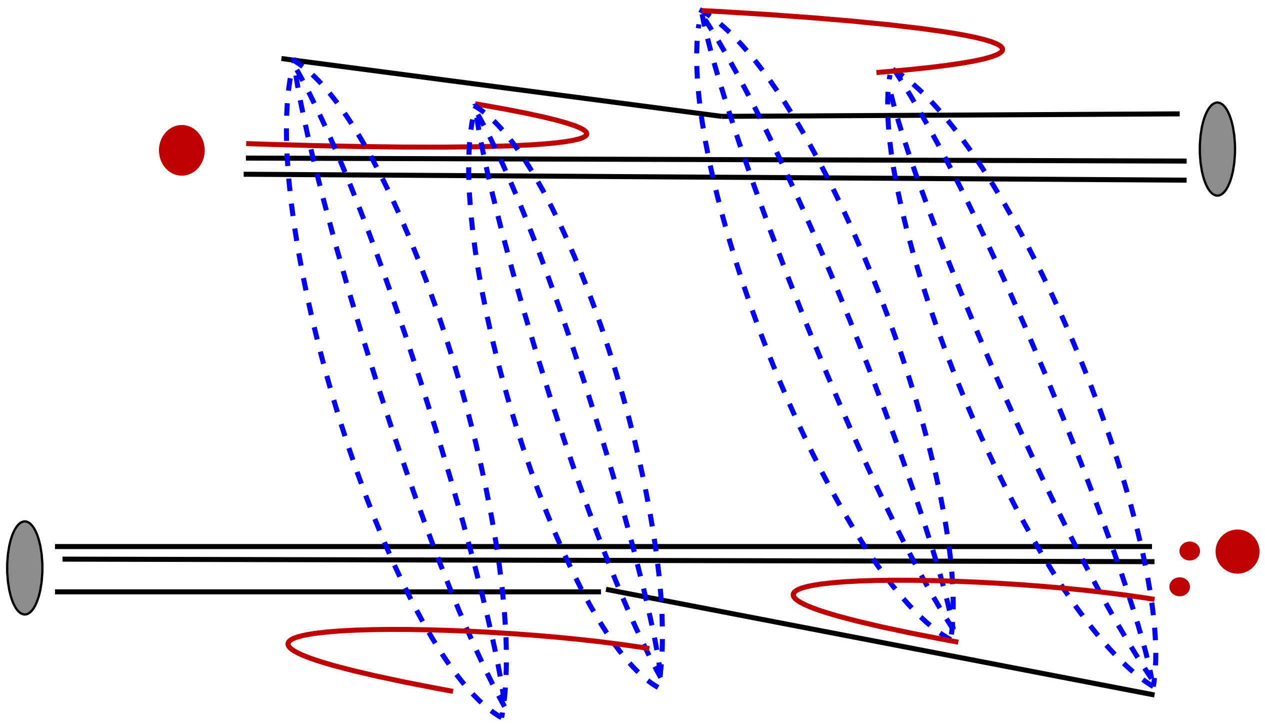


Peripheral collision:
only one parton-pair interacting



Central collision:
several parton-pairs interacting

Interaction of two parton pairs

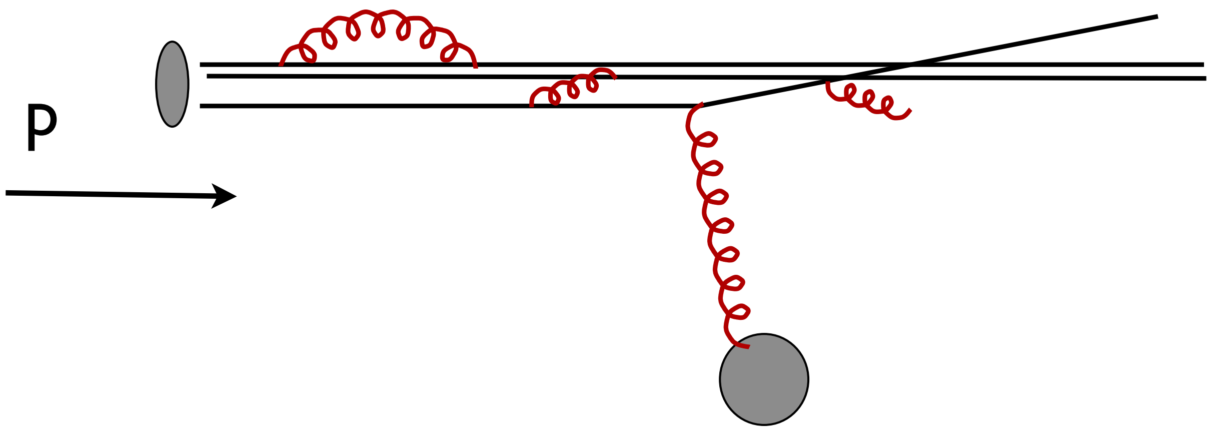


Two soft interactions

Generic diagram of interaction of two parton pairs

- gluon exchange between each pair produces two strings
- sea quarks needed for string ends (different combinations possible)
- other sea quark pairs possible but not explicitly simulated
- each string fragments into hadrons with small transverse momenta

Transition from intermediate to high energy

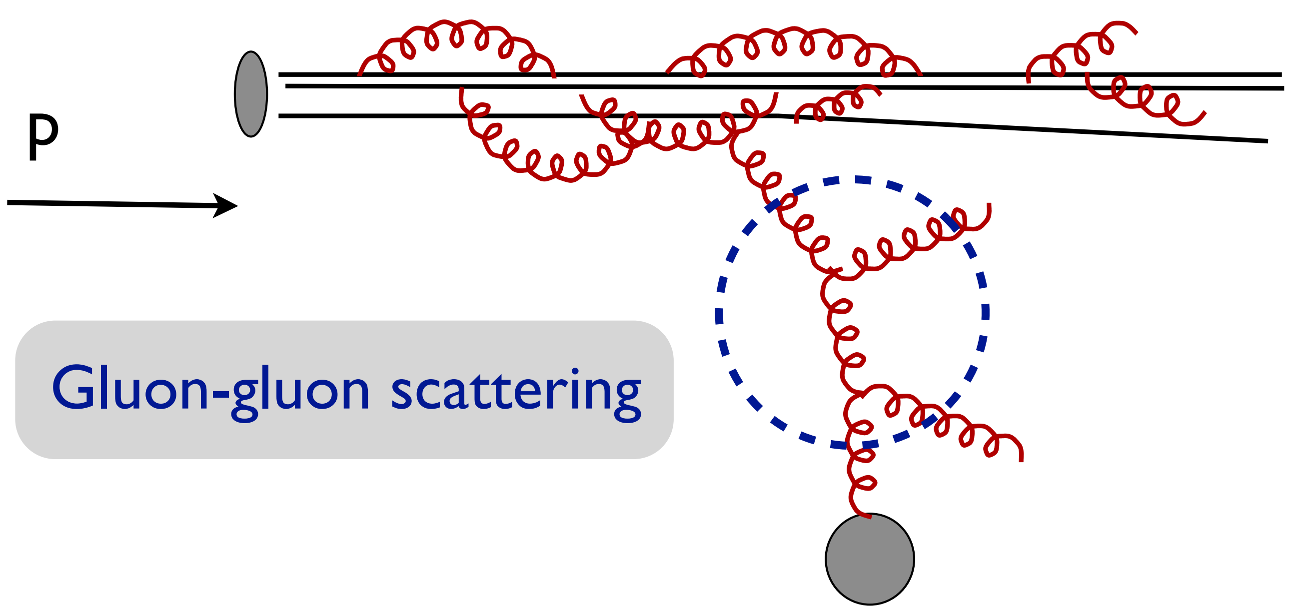


Intermediate energy:

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

Lifetime of fluctuations

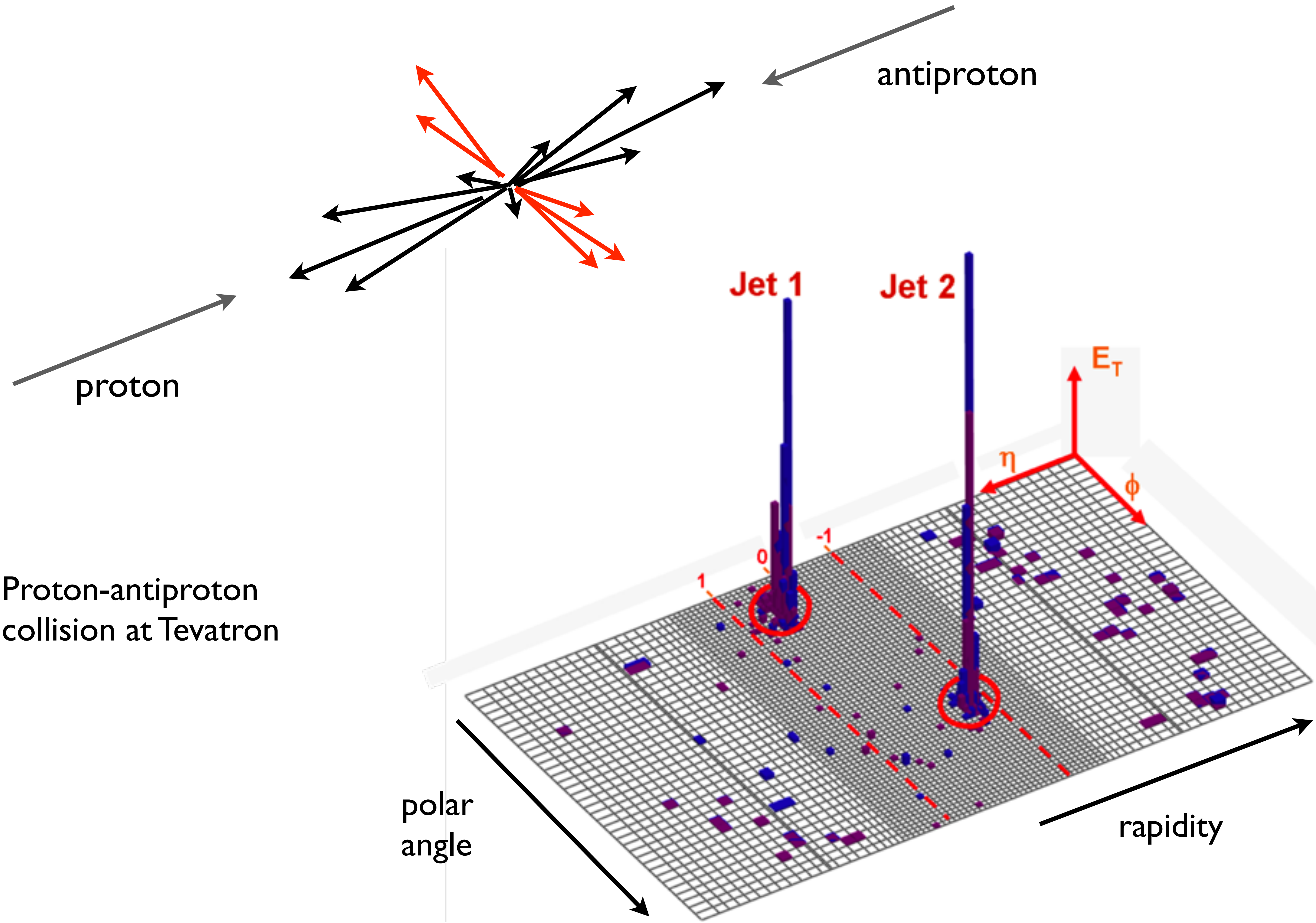
$$\Delta t \approx \frac{1}{\Delta E} = \frac{1}{\sqrt{p^2+m^2}-p} = \frac{1}{p(\sqrt{1+m^2/p^2}-1)} \approx \frac{2p}{m^2}$$



High energy regime:

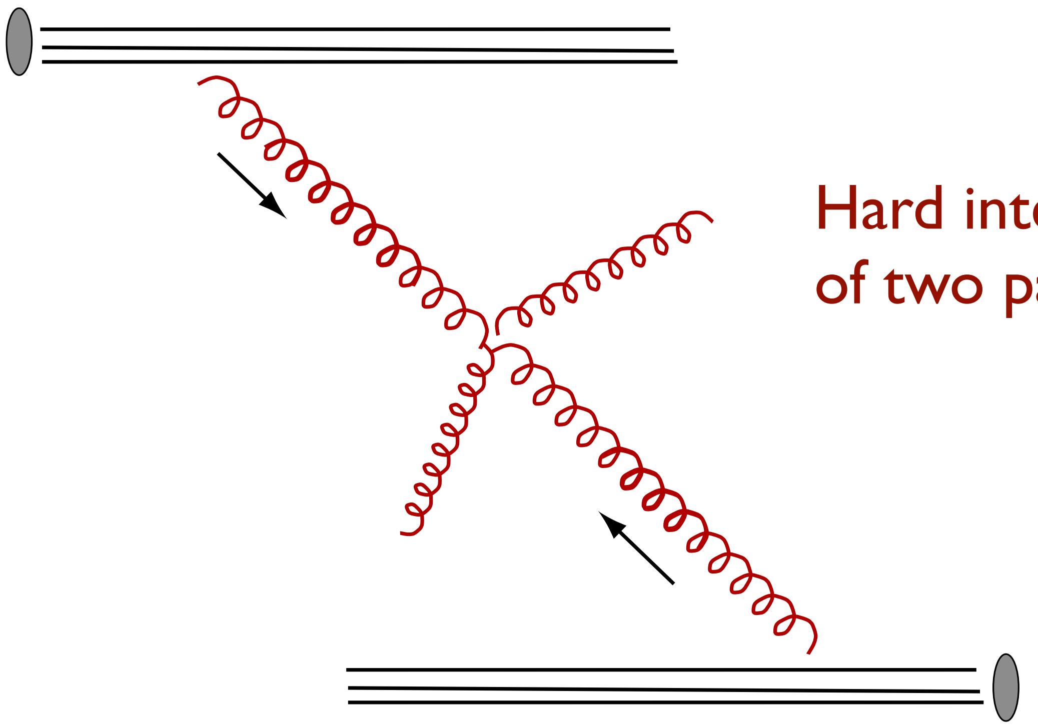
- $E_{\text{lab}} > 21{,}000$ GeV
- $E_{\text{cm}} > 200$ GeV
- dominated by gluons and sea quarks

Scattering of quarks and gluons: jet production

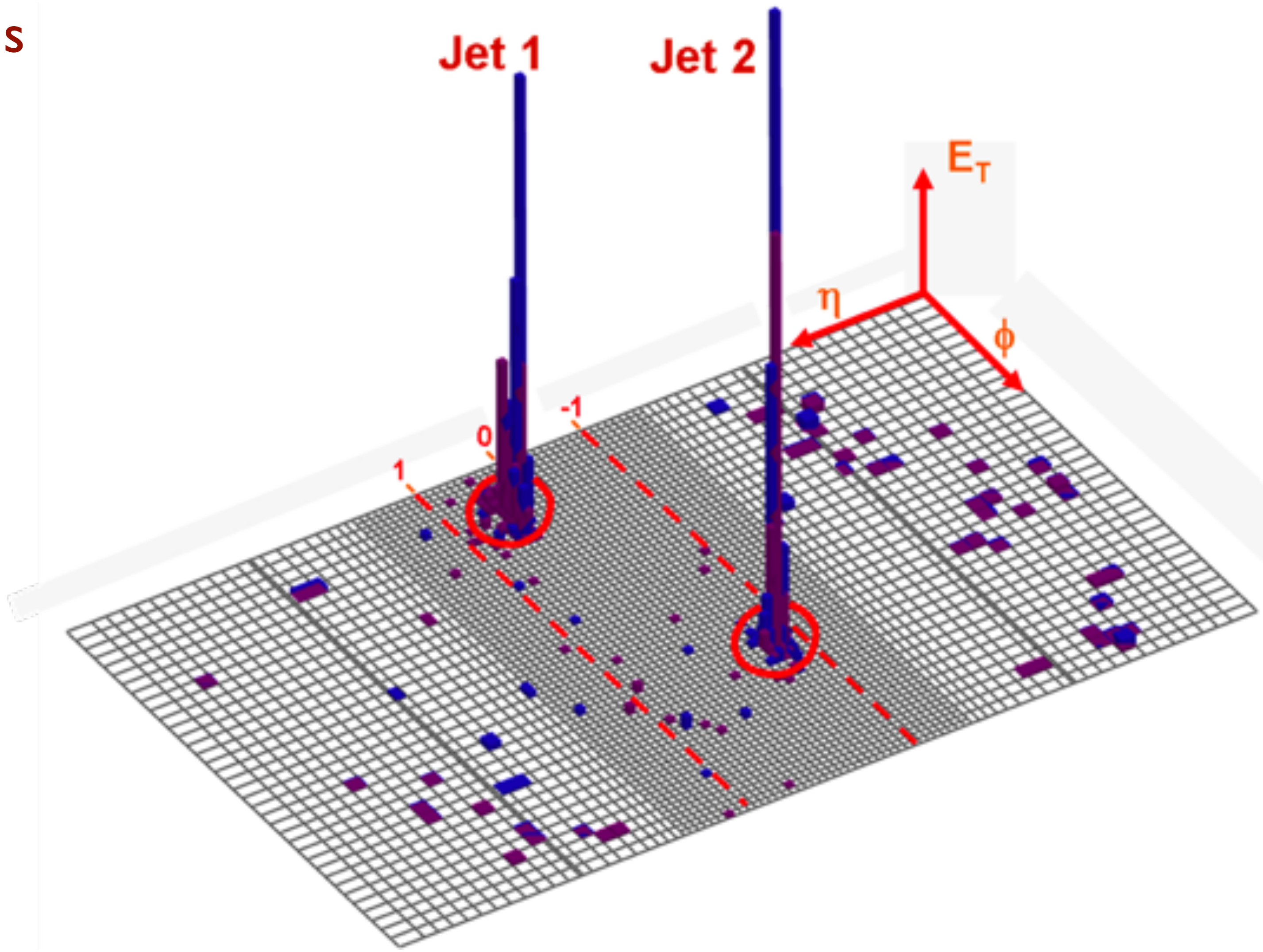


Proton-antiproton
collision at Tevatron

Interpretation within perturbative QCD



Hard interaction
of two partons

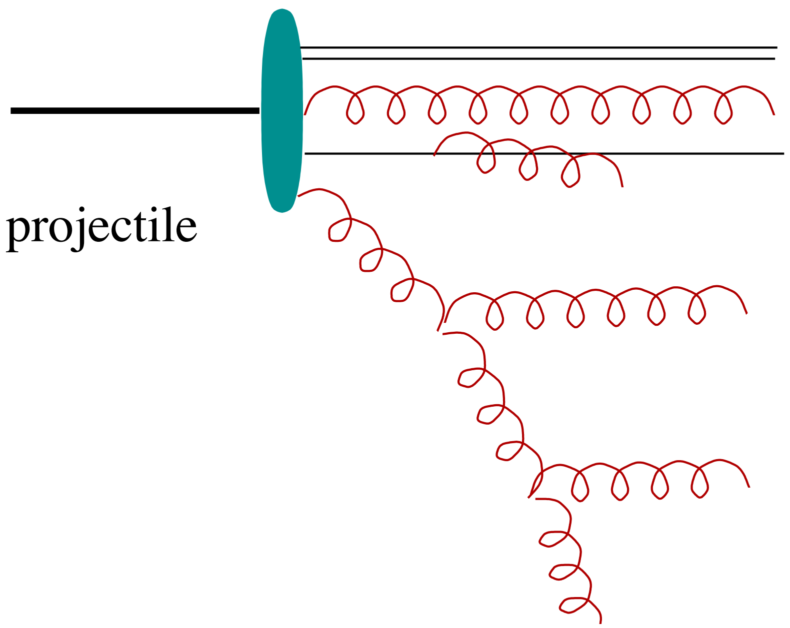


QCD predictions known
for parton-parton cross sections

Terminology

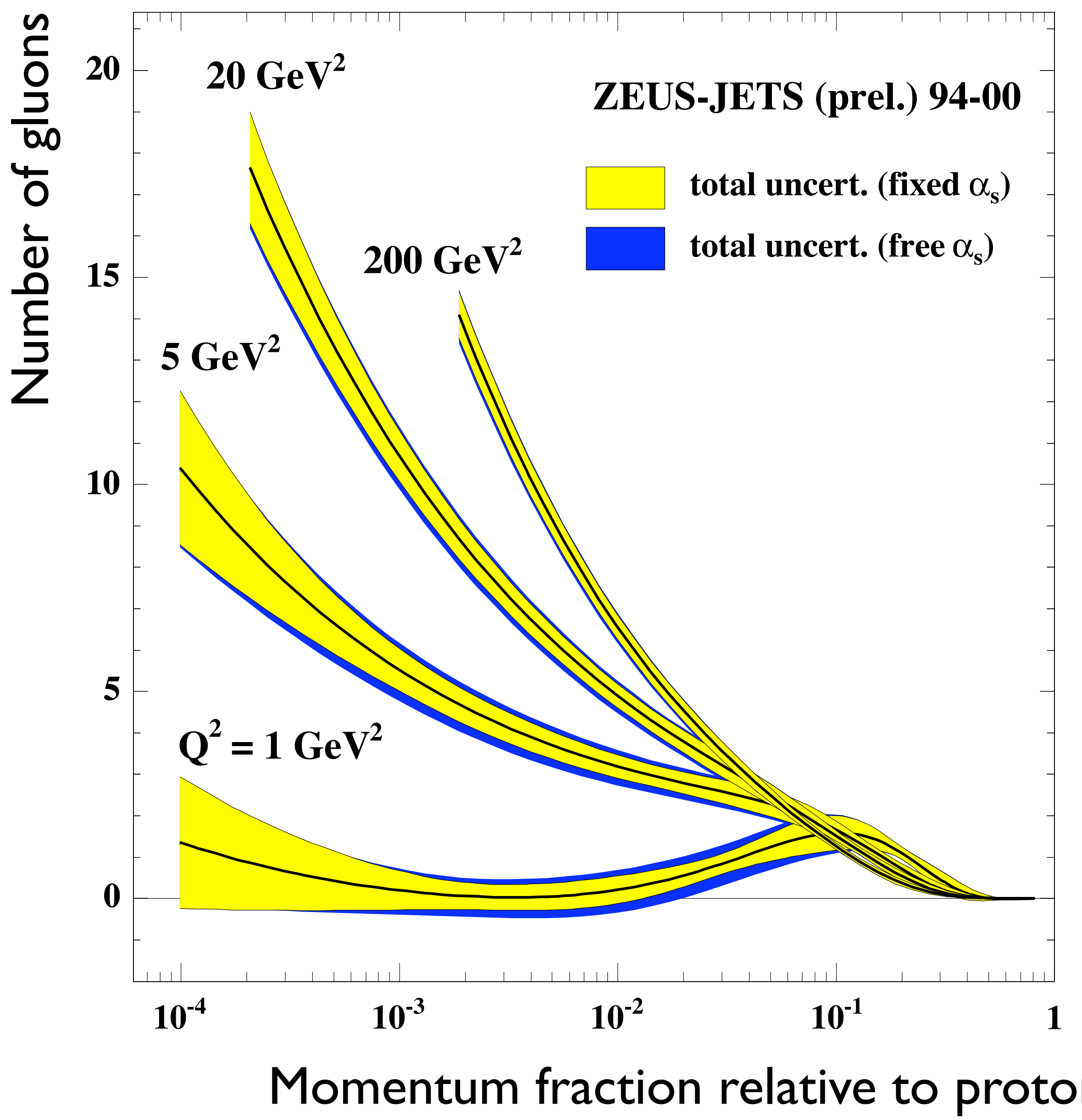
Soft interaction: no large momentum transfer
Hard interaction: large momentum transfer ($|t| > 2\ \mathrm{GeV}^2$)

Perturbative QCD predictions for parton densities



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

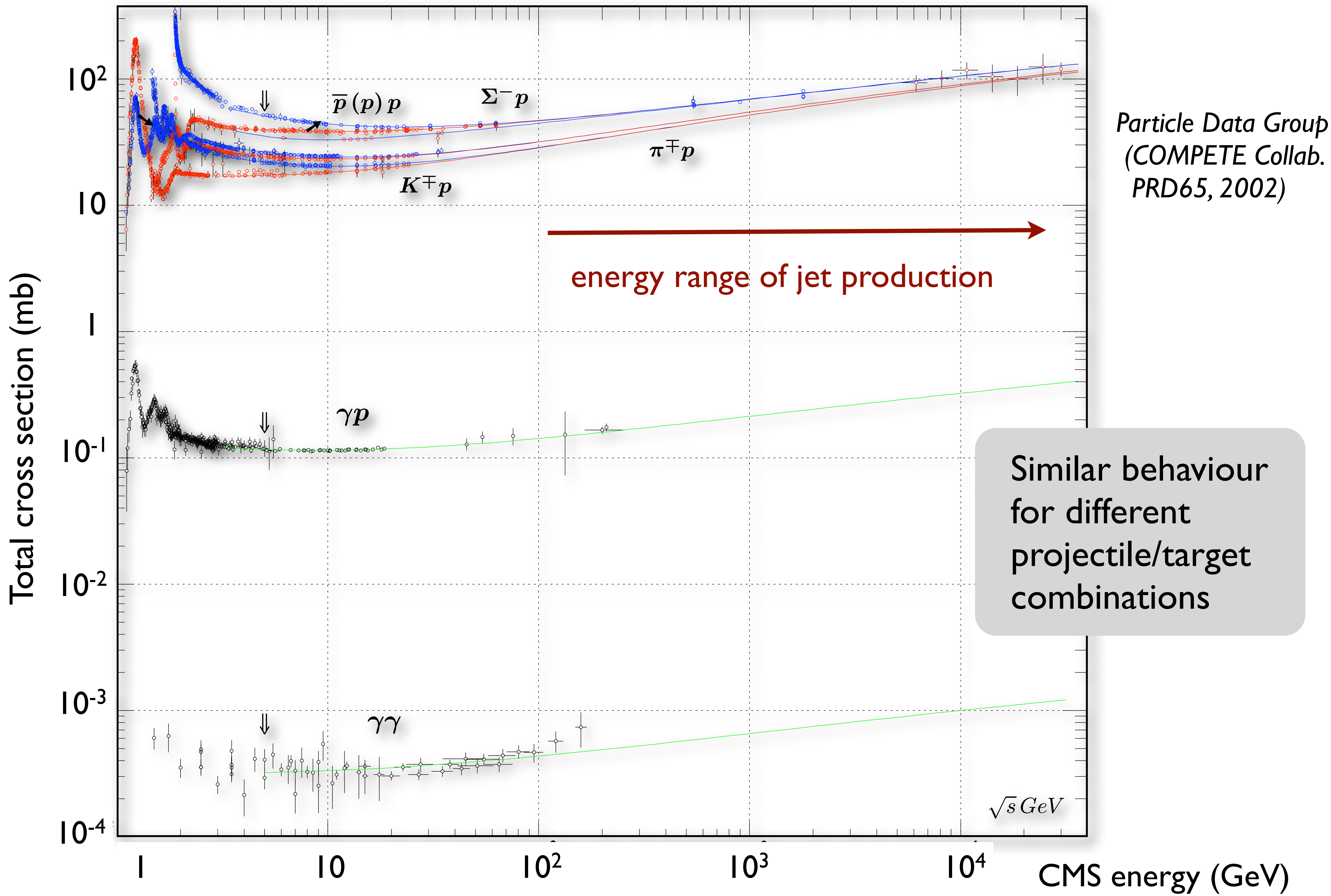
HERA data



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

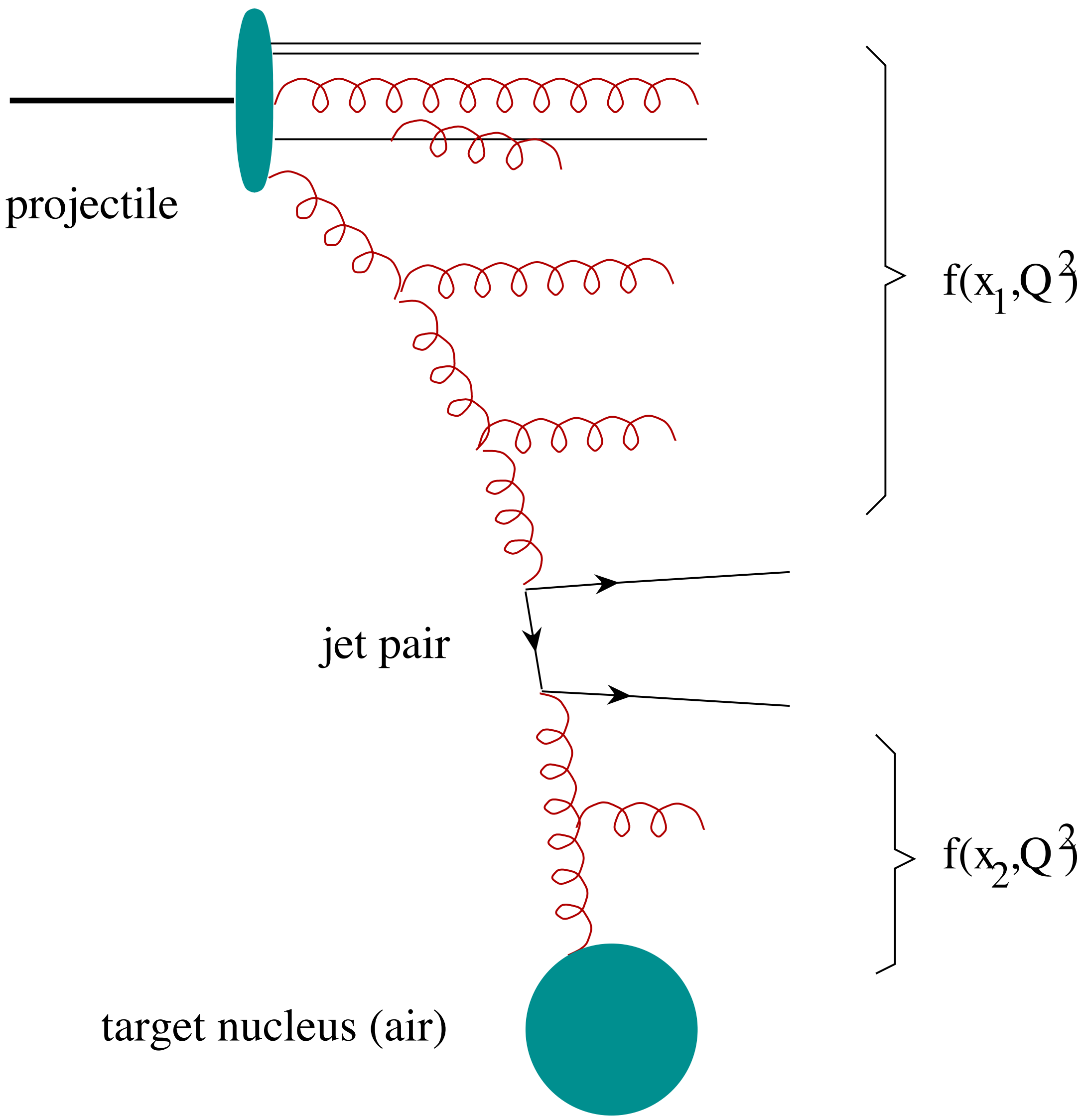
Prediction of perturbative QCD

Minijet model: rise of cross section due to jet production

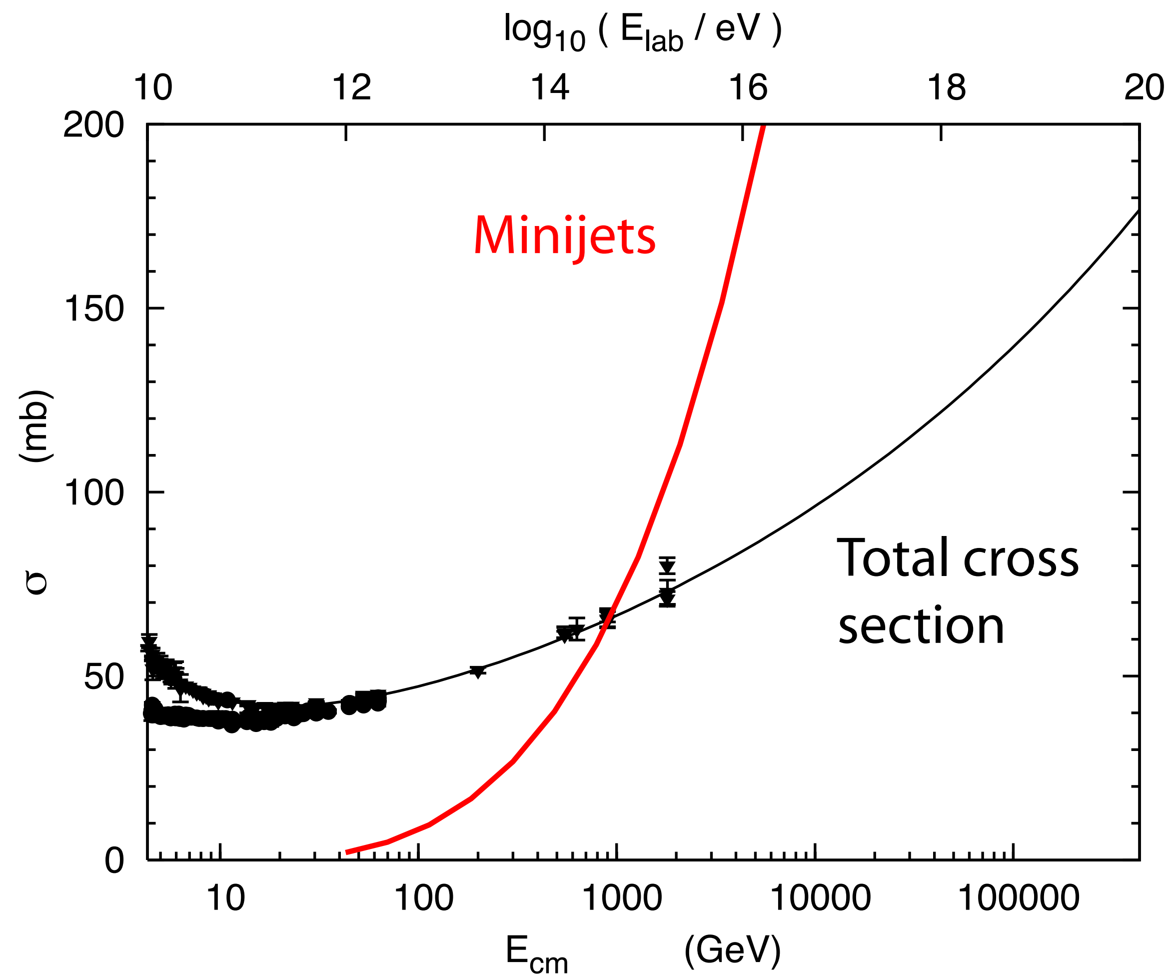


Similar behaviour for different projectile/target combinations

QCD parton model: minijets



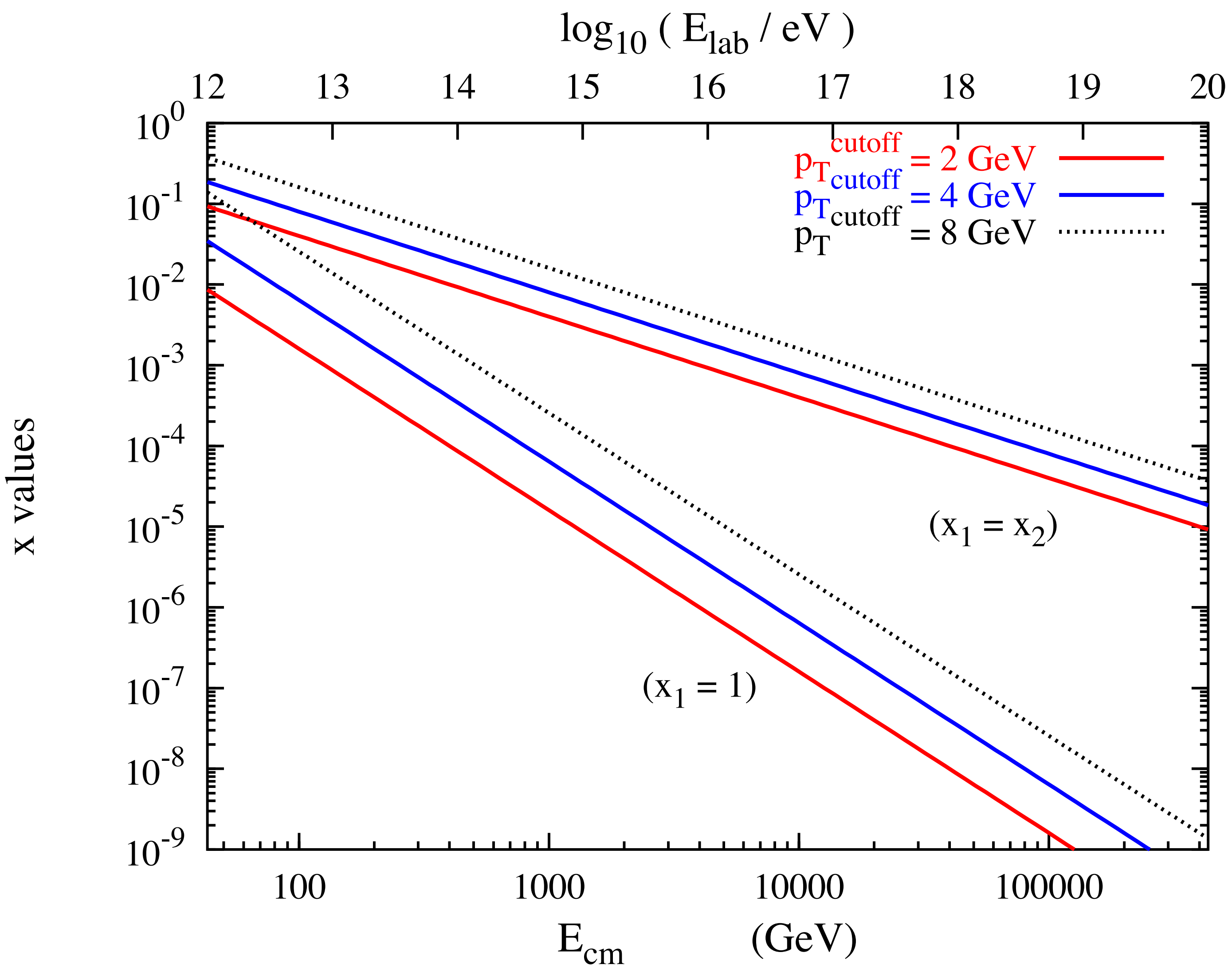
Proton-proton cross section



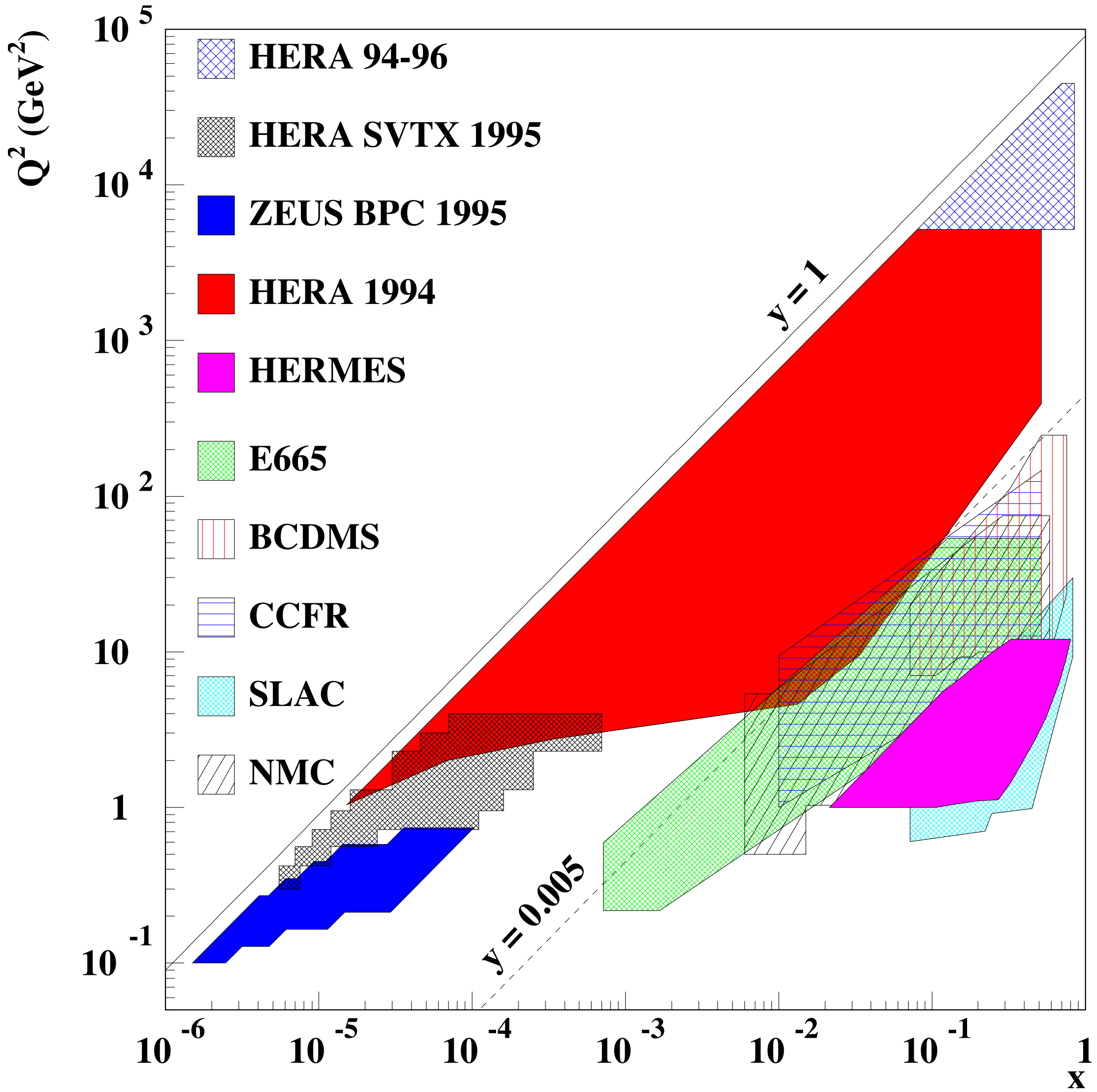
$$\sigma_{QCD} = \sum_{i,j,k,l} \frac{1}{1+\delta_{kl}} \int dx_1\, dx_2 \int_{p_\perp^{\mathrm{cutoff}}} dp_\perp^2\, f_i(x_1,Q^2)\, f_j(x_2,Q^2)\, \frac{d\sigma_{i,j\to k,l}}{dp_\perp}$$

Parton densities not known at very low x

Range of x values (momentum fractions) needed in calculation

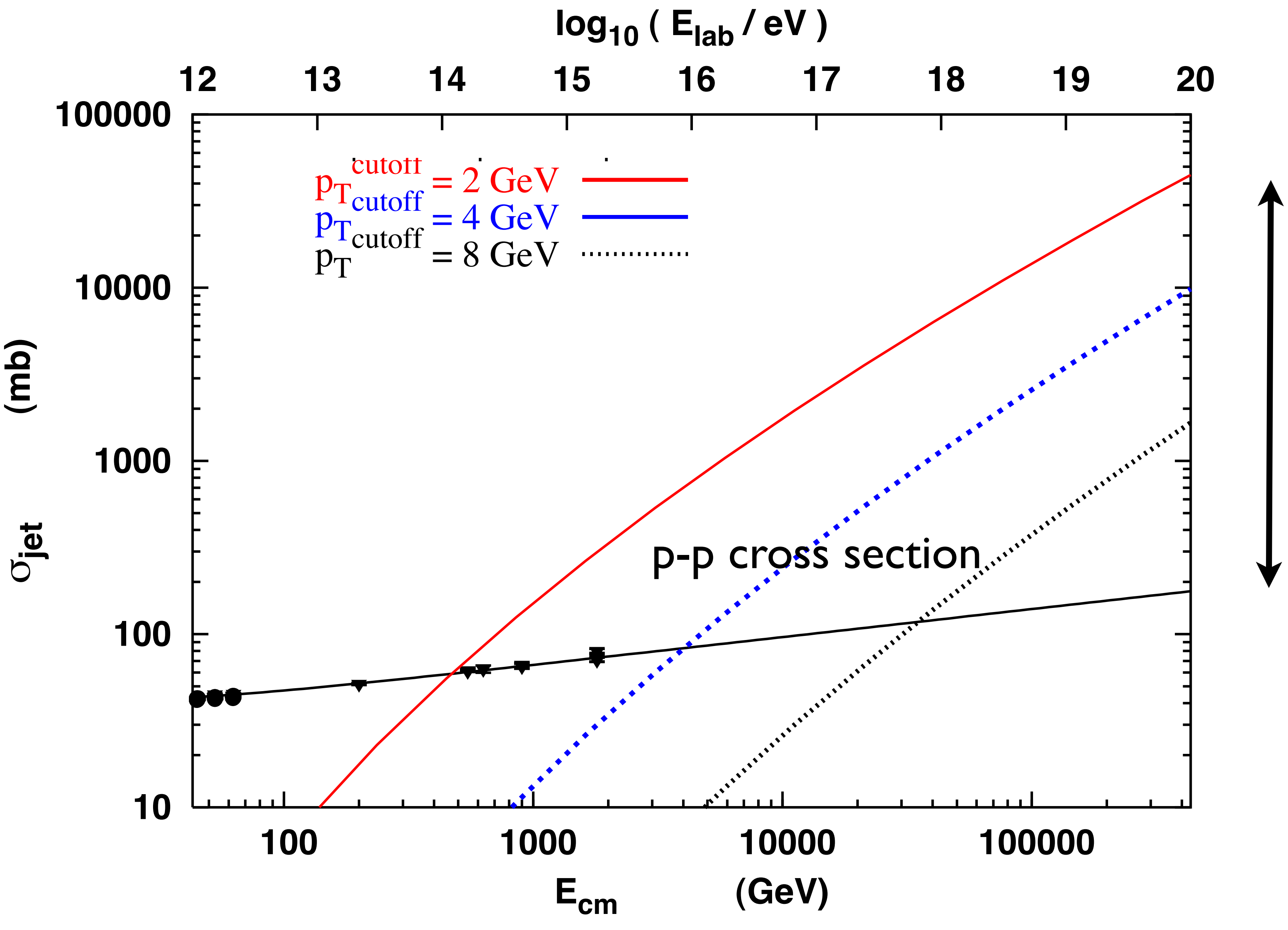


HERA measurement range



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

Dependence on transverse momentum cutoff



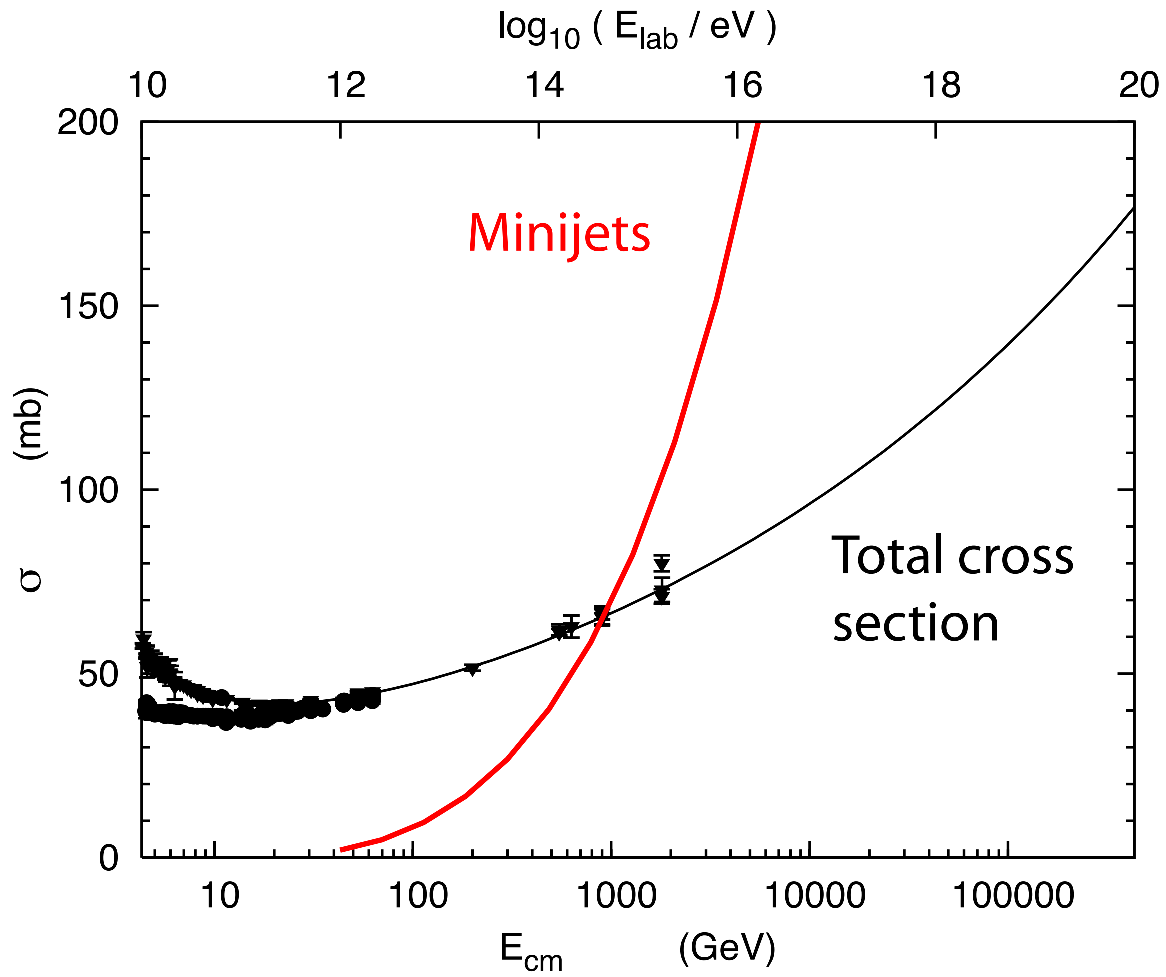
Factor ~ 150

Selecting different values for cutoff does not help

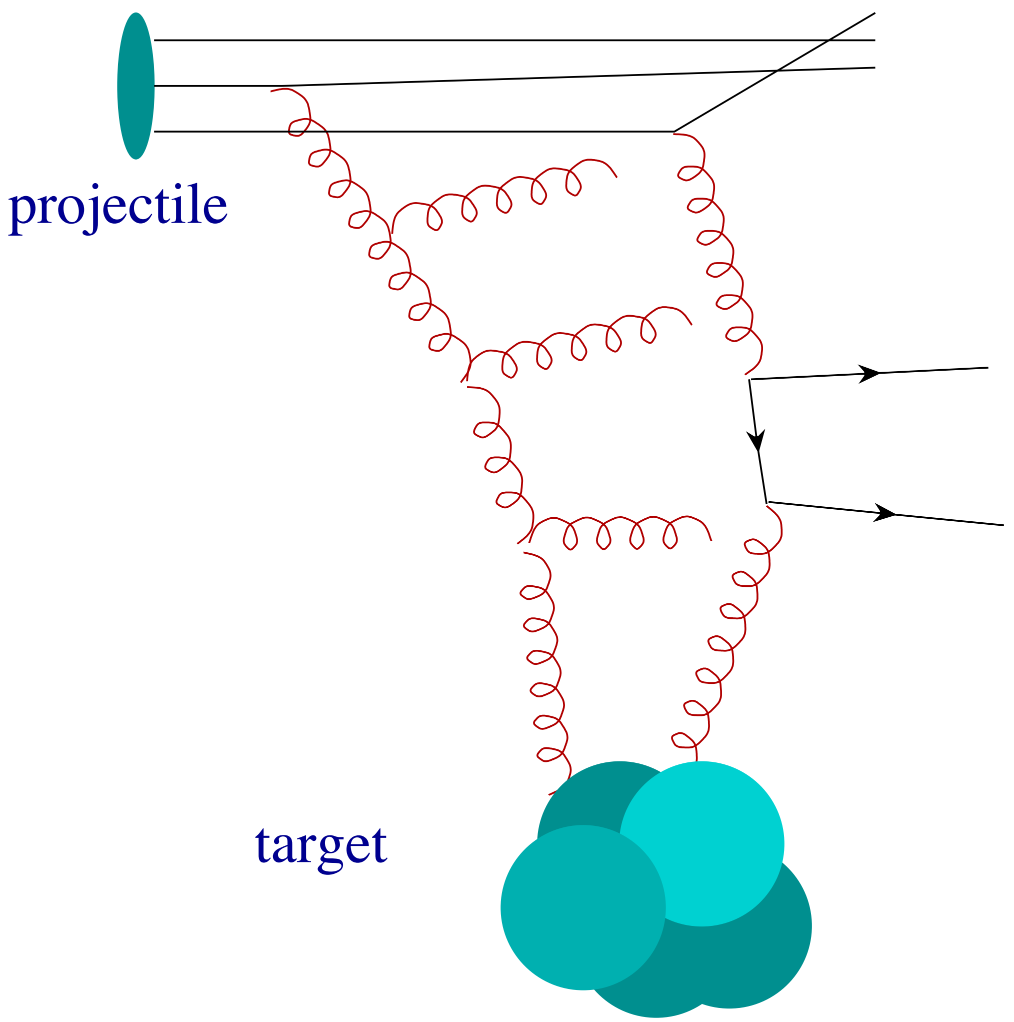
Cross section of new interaction process of minijet production cannot simply be added to cross section from soft interactions

Solution: Multiple parton-parton interactions

Proton-proton cross section



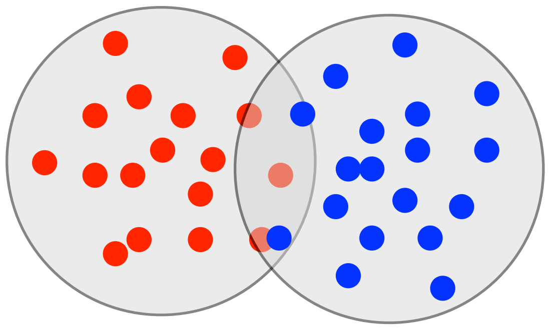
QCD prediction:
inclusive cross section



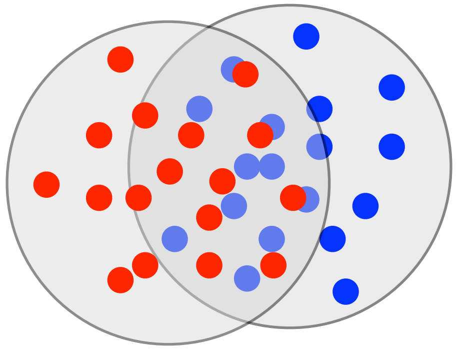
Average number of minijet pairs

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

Poissonian probability distribution



Peripheral collision:
only very few parton-pairs interacting



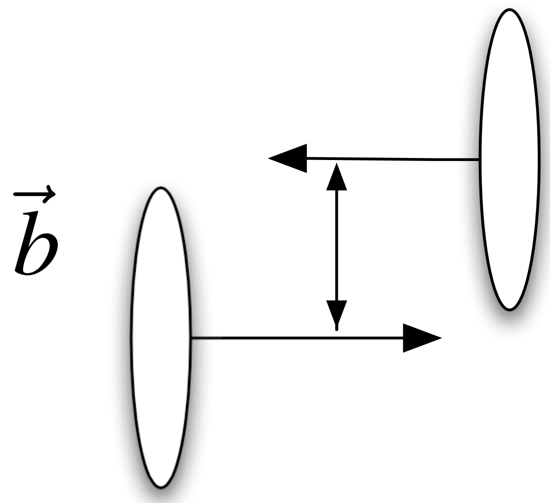
Central collision:
many parton-pairs interacting

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

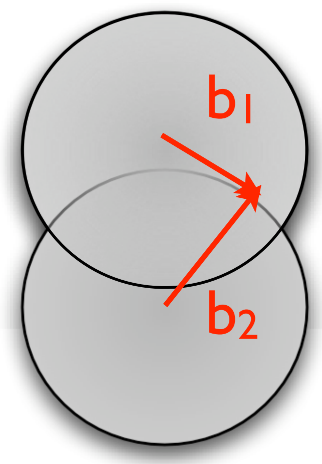
mean number of interactions for given impactparameter of collision

Need to know mean number of interactions as function of impact parameter

Minijet model: underlying ideas (unitarization)



(side view)



(view long beam axis)

Overlap function

$$A(s,\vec{b}) = \int d^2\vec{b}_1 \, d^2\vec{b}_2 \, A_p(s,\vec{b}_1)\, A_p(s,\vec{b}_2)\, \delta(\vec{b}-\vec{b}_1-\vec{b}_2)$$

Independent interactions:
Poisson distribution

$$\langle n_{\rm hard}(\vec{b})\rangle = \sigma_{\rm QCD}\, A(s,\vec{b})$$

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

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

Classic minijet model: free parameters

$$\sigma_{\rm ine} = \int d^2\vec{b} \left(1 - \exp\left\{-\sigma_{\rm soft} A_{\rm soft}(s,\vec{b}) - \sigma_{\rm QCD} A_{\rm hard}(s,\vec{b})\right\}\right)$$

- Soft cross section
- Transverse momentum cutoff for QCD cross section
- Soft and hard profile functions

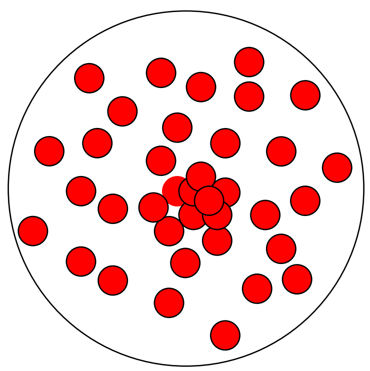
Classic Minijet Model (SIBYLL 1.7):

- Soft cross section const.
- Transverse momentum cutoff energy-independent
- Profile functions taken from form factor

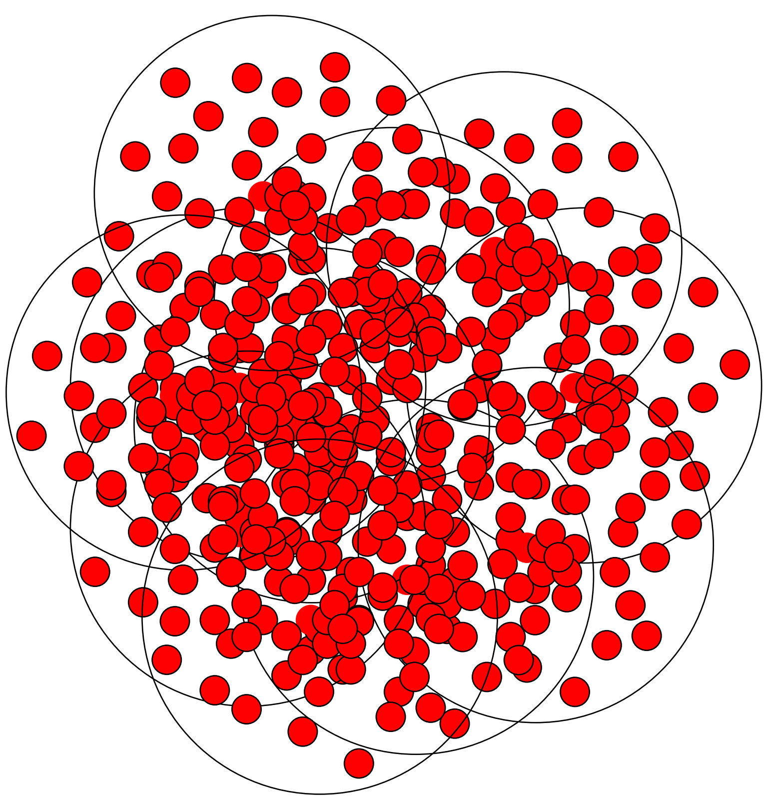
$$A_{pp}(\nu,\vec{B}) = \frac{\nu^2}{96\pi}(\nu|\vec{B}|)^3 K_3(\nu|\vec{B}|)$$

$$A_{\pi p}(\nu,\mu_\pi,\vec{B}) = \frac{1}{4\pi}\frac{\nu^2\mu_\pi^2}{\mu_\pi^2-\nu^2}\left((\nu|\vec{B}|)K_1(\nu|\vec{B}|) - \frac{2\nu^2}{\mu_\pi^2-\nu^2}\left[K_0(\nu|\vec{B}|) - K_0(\mu_\pi|\vec{B}|)\right]\right)$$

Problem: 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

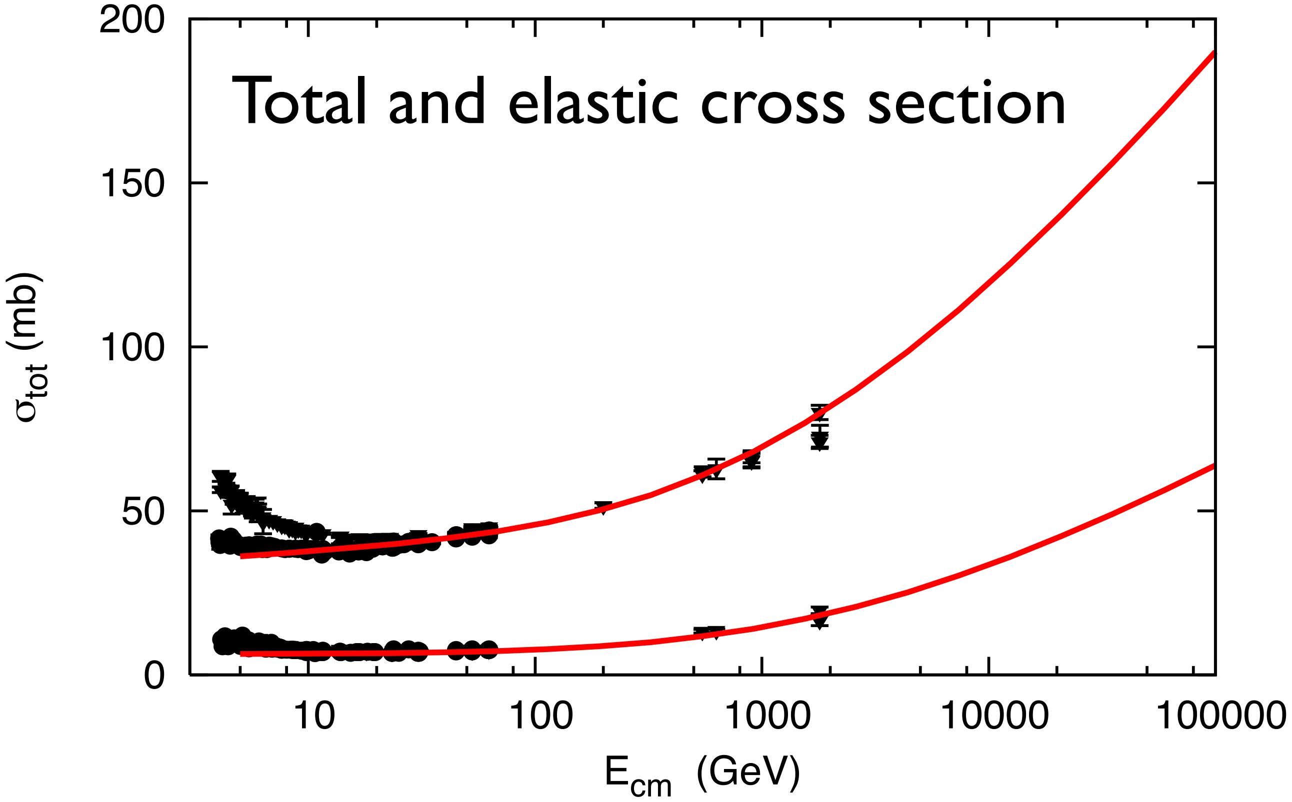
$$\pi R_0^2 \simeq \frac{\alpha_s(Q_s^2)}{Q_s^2} \cdot xg(x, Q_s^2)$$

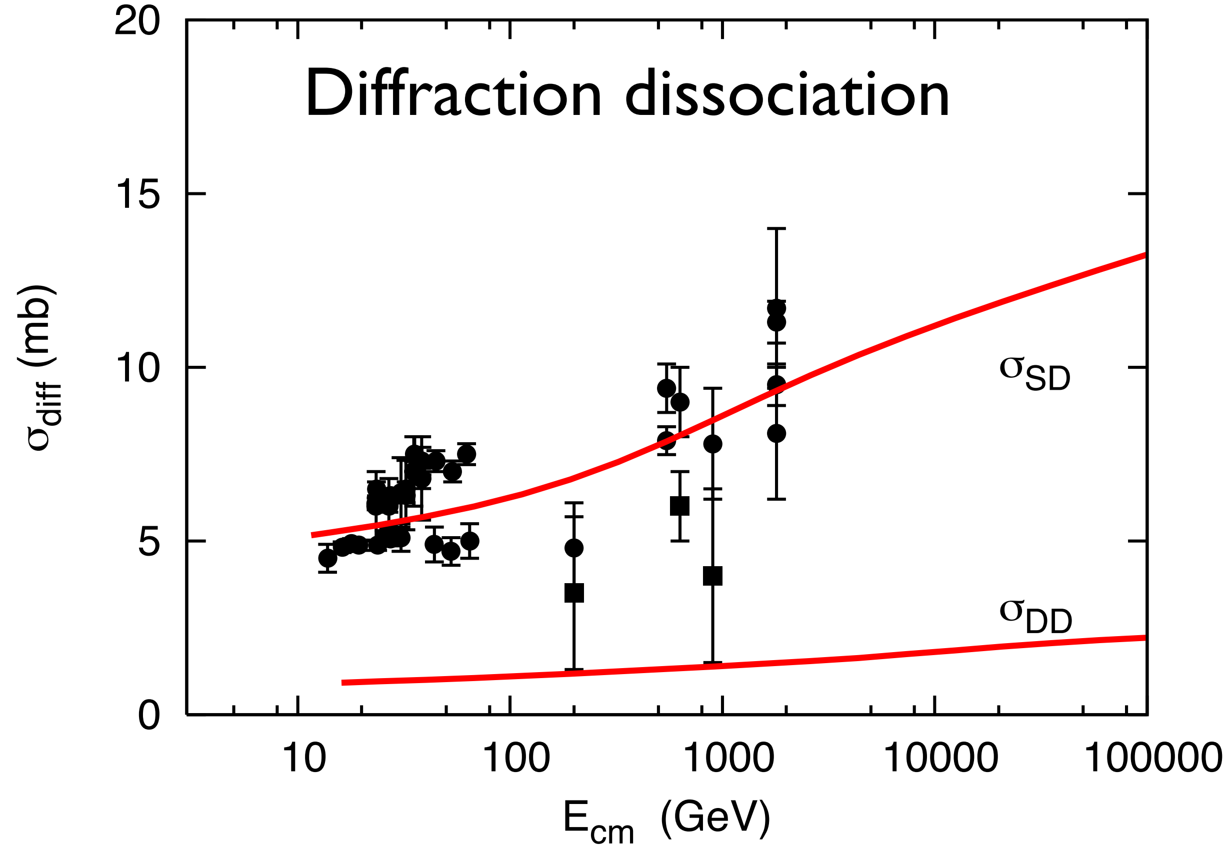
size of proton

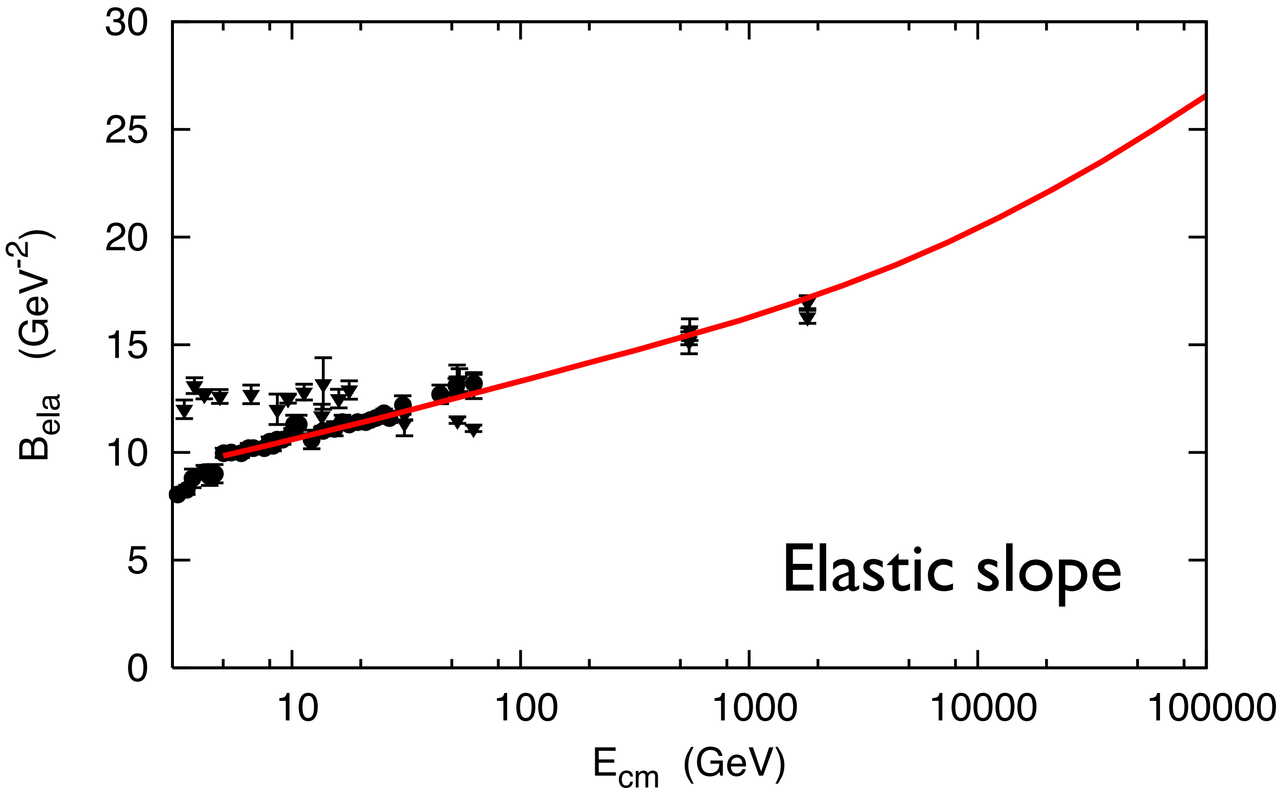
Size of one gluon

number of gluons

SIBYLL 2.1 cross section fits

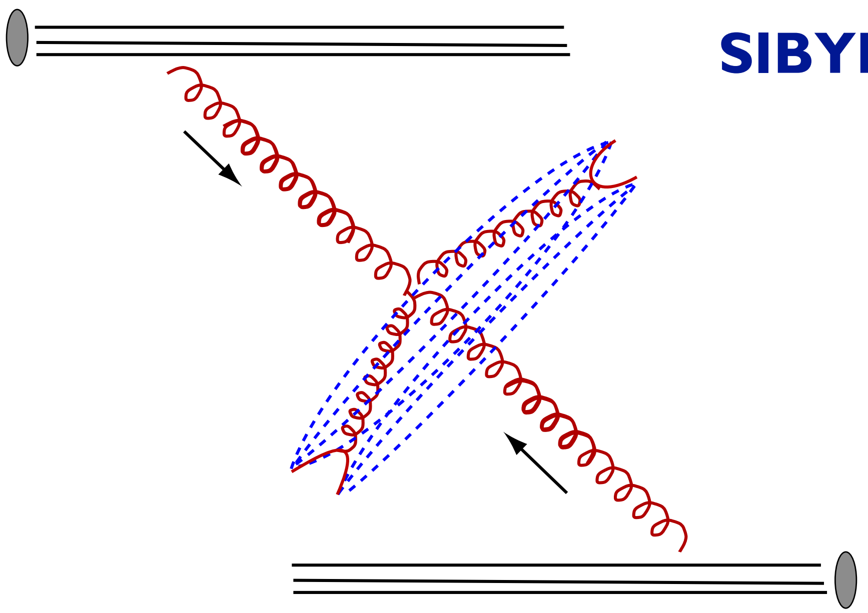






Low energy:
parametrizations
of data are used

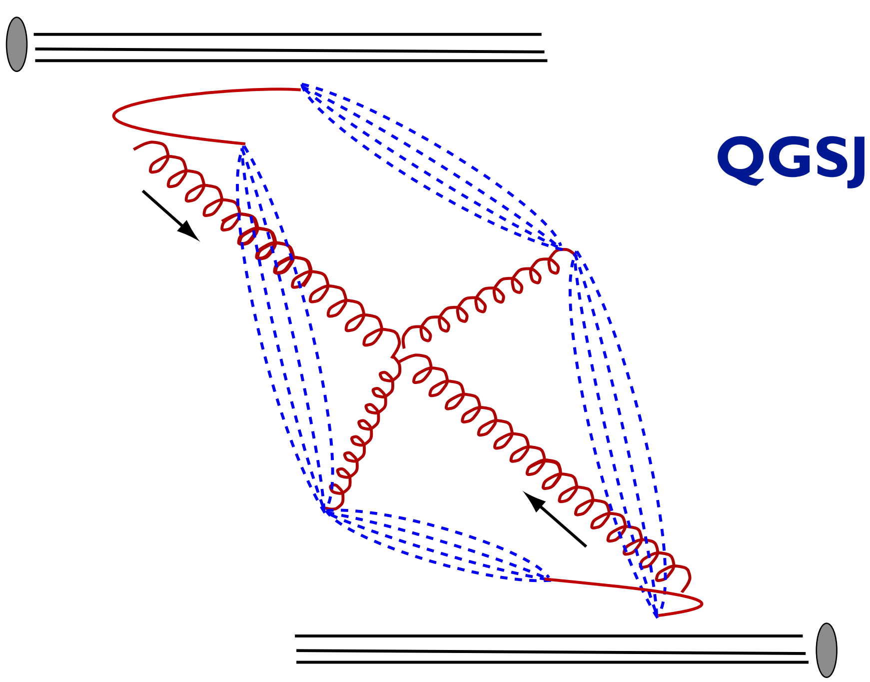
Different implementations of two-gluon scattering



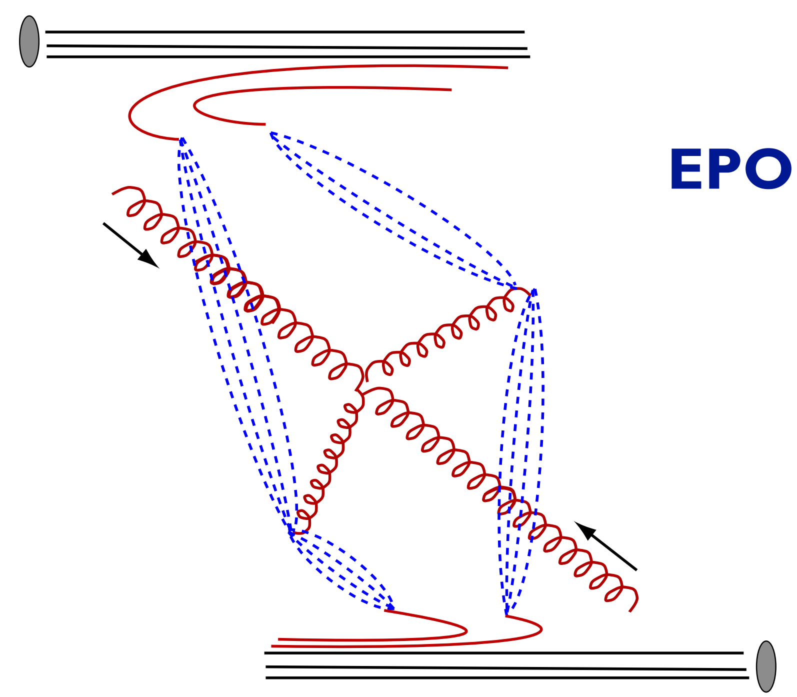
SIBYLL

Kinematics etc. given by parton densities and perturbative QCD

Two strings stretched between quark pairs from gluon fragmentation



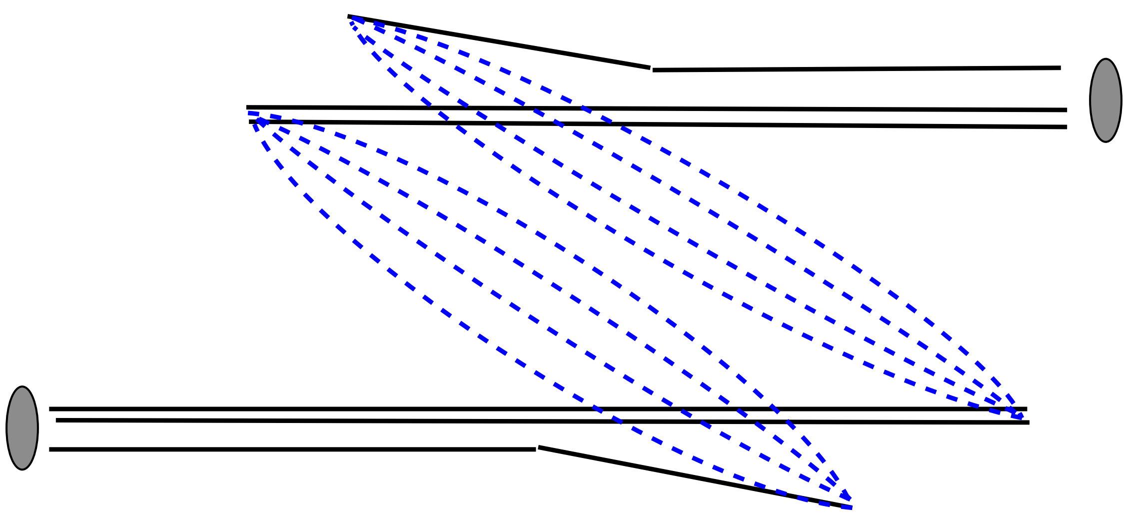
QGSJET



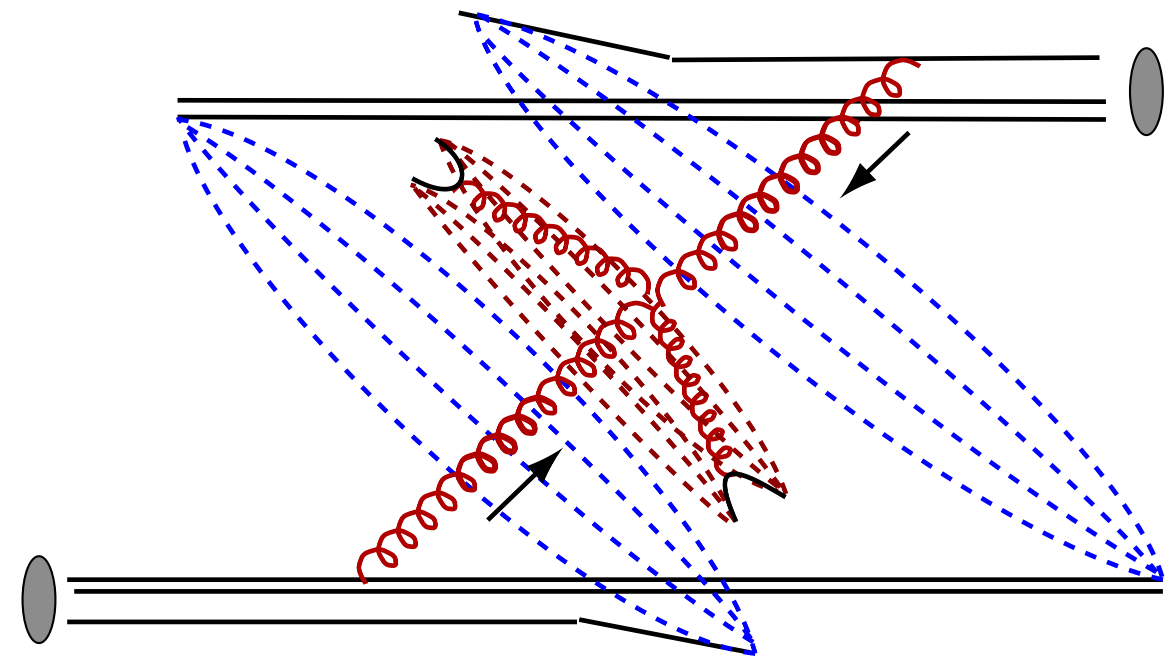
EPOS

Multiple soft and hard interactions

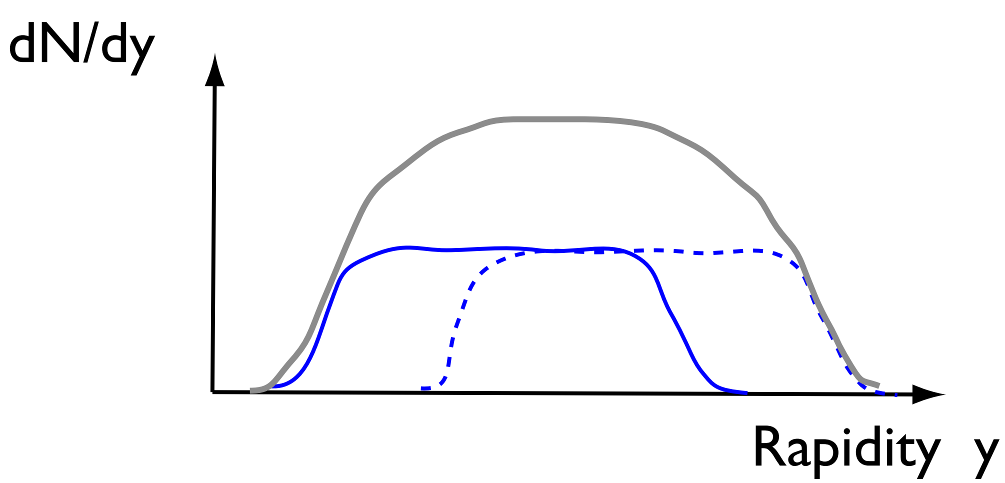
$$\sigma_{n_s,n_h} = \int d^2b \, \frac{[n_{\rm soft}(b,s)]^{n_s}}{n_s!} \, \frac{[n_{\rm hard}(b,s)]^{n_h}}{n_h!} \, e^{-n_{\rm hard}(b,s) - n_{\rm soft}(b,s)}$$

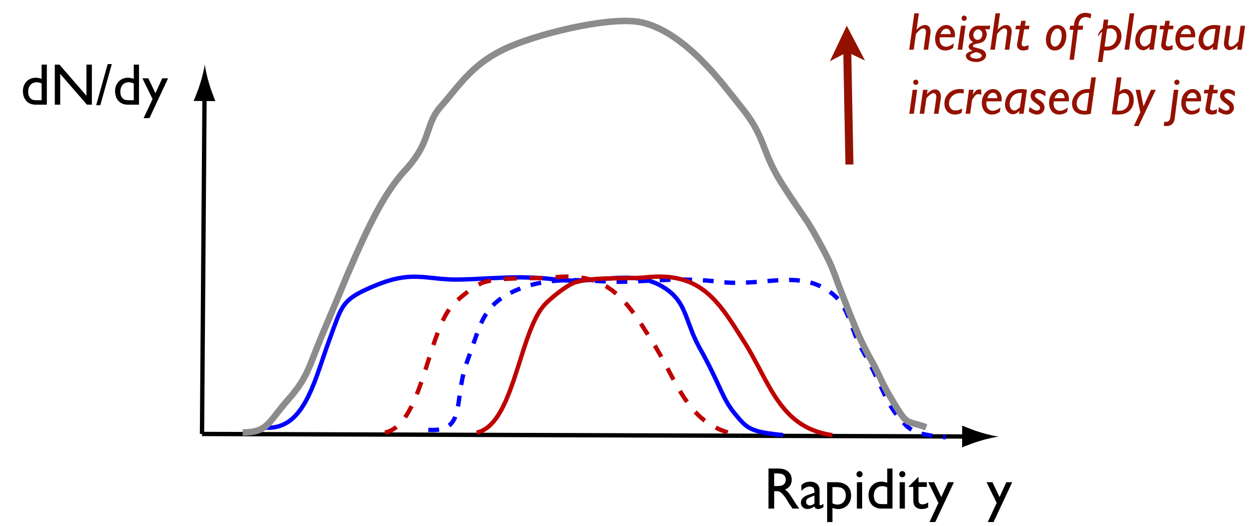


$n_s=1, n_h=0$



$n_s=1, n_h=1$

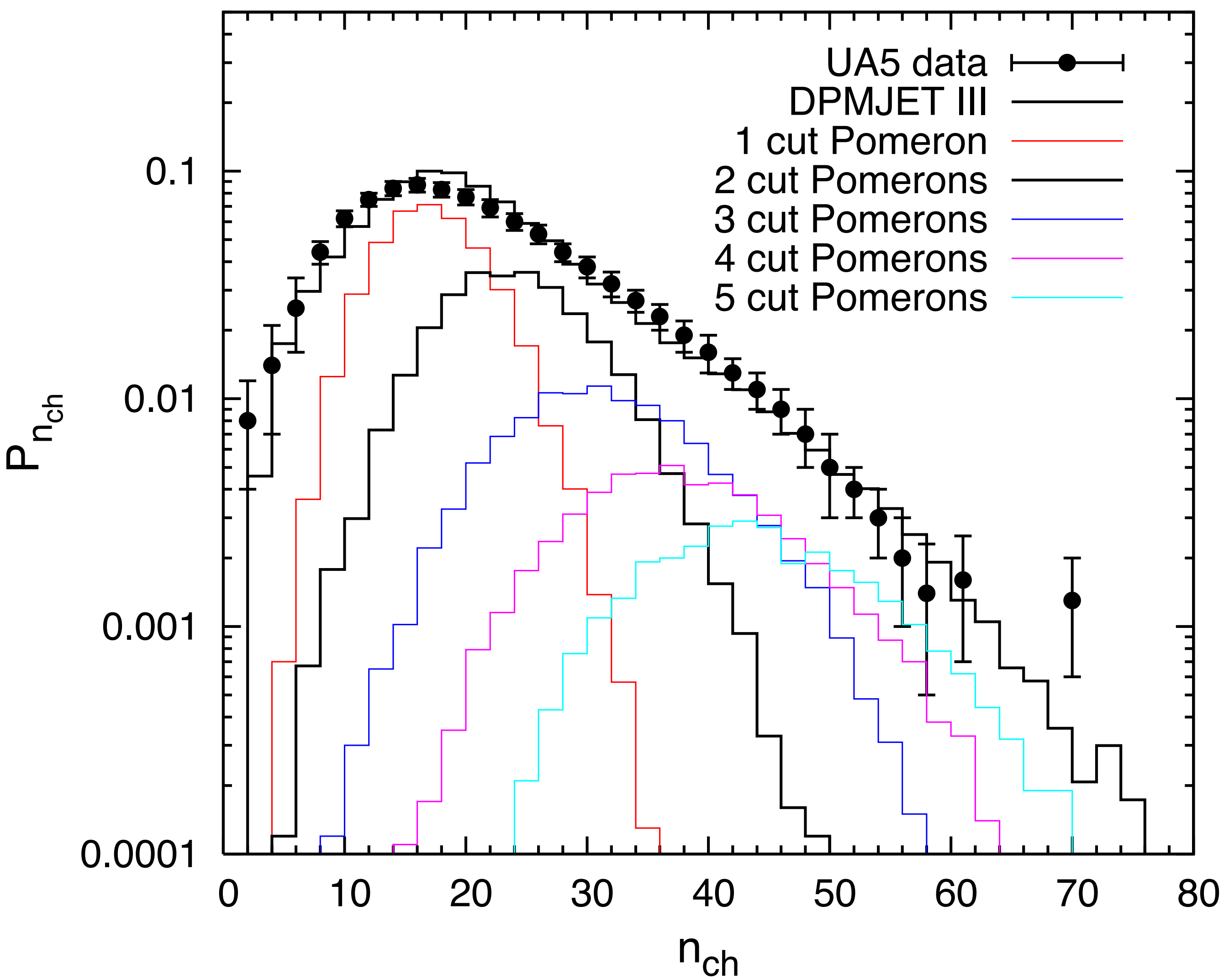


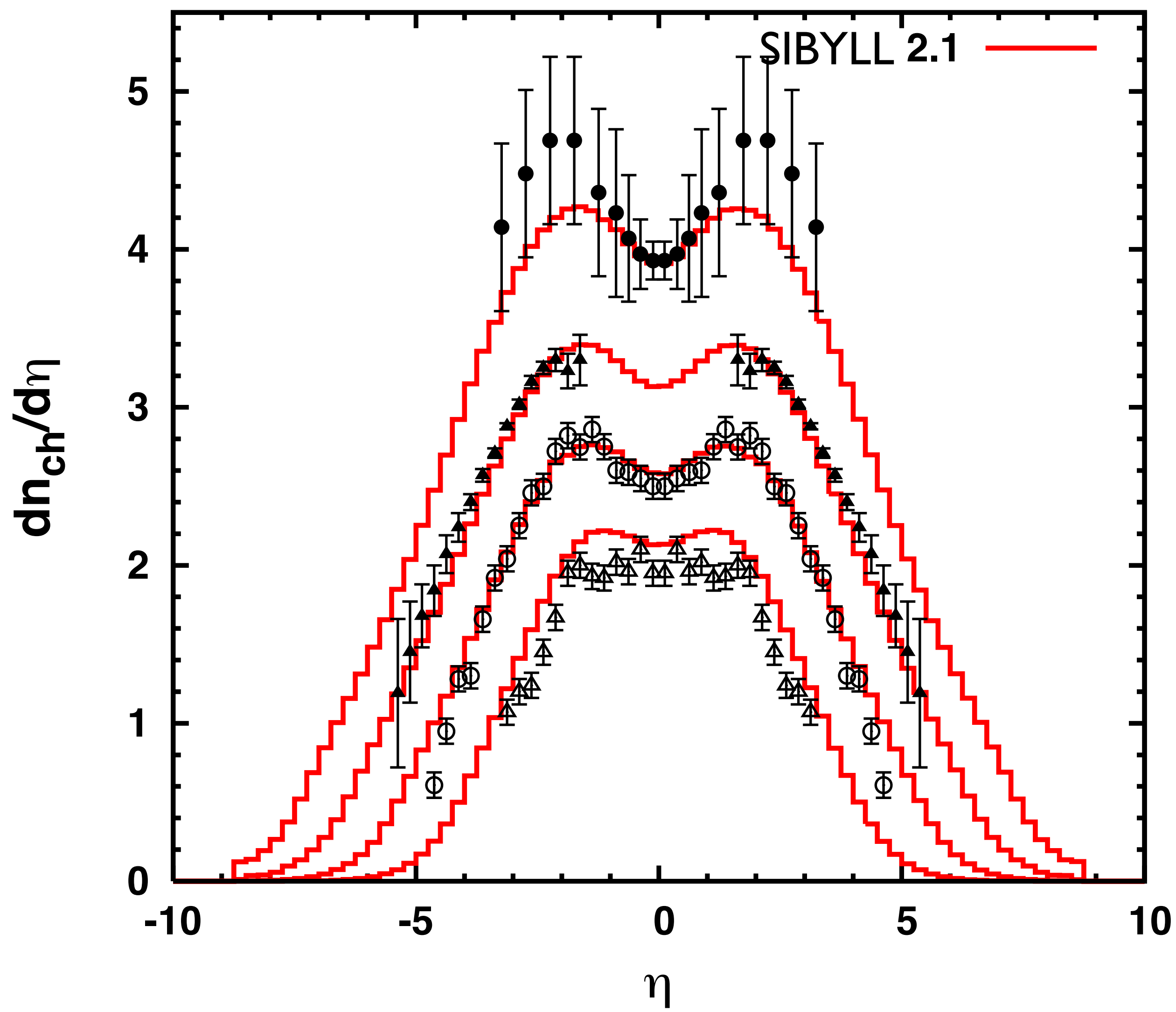


Comparison with collider data

Note: one cut pomeron means
one soft or hard interaction

Charged particle multiplicity
distribution at 200 GeV cms.



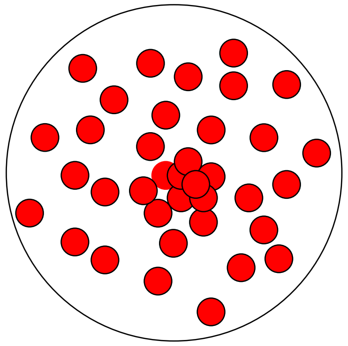


Charged particle
pseudorapidity distributions

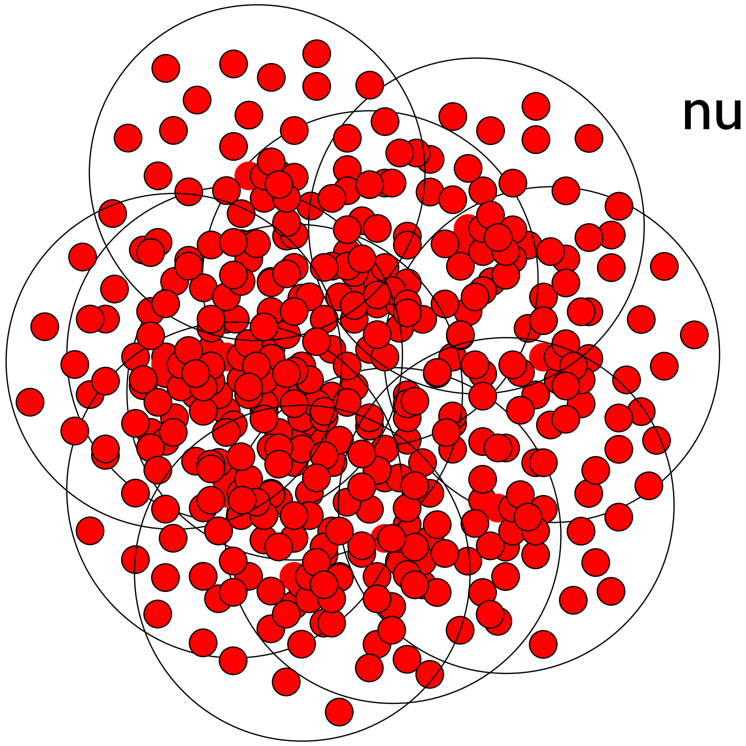
Comparison of high energy interaction models

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 parametriztions • 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

High parton densities: modification of minijet threshold



nucleon



nucleus

SIBYLL: simple geometric criterion

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

$$xg(x,Q^2) \sim \exp\left[\frac{48}{11-\frac{2}{3}n_f}\ln\frac{\ln\frac{Q^2}{\Lambda^2}}{\ln\frac{Q_0^2}{\Lambda^2}}\ln\frac{1}{x}\right]^{\frac{1}{2}}$$

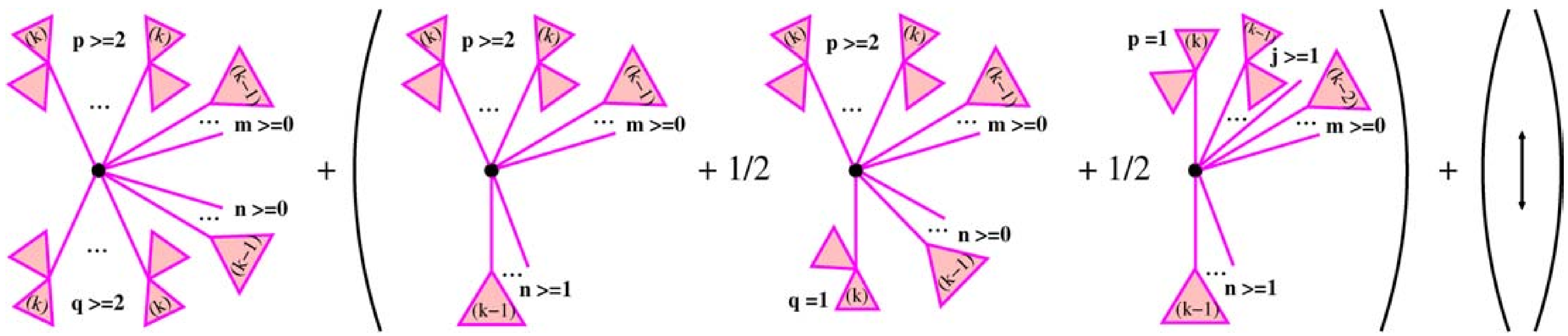
No dependence on impact parameter !

SIBYLL: $p_\perp(s) = p_\perp^0 + 0.065\text{GeV}\exp\left\{0.9\sqrt{\ln\, s}\right\}$

DPMJET: $p_\perp(s) = p_\perp^0 + 0.12\text{GeV}\left(\log_{10}\frac{\sqrt{s}}{50\text{GeV}}\right)^3$

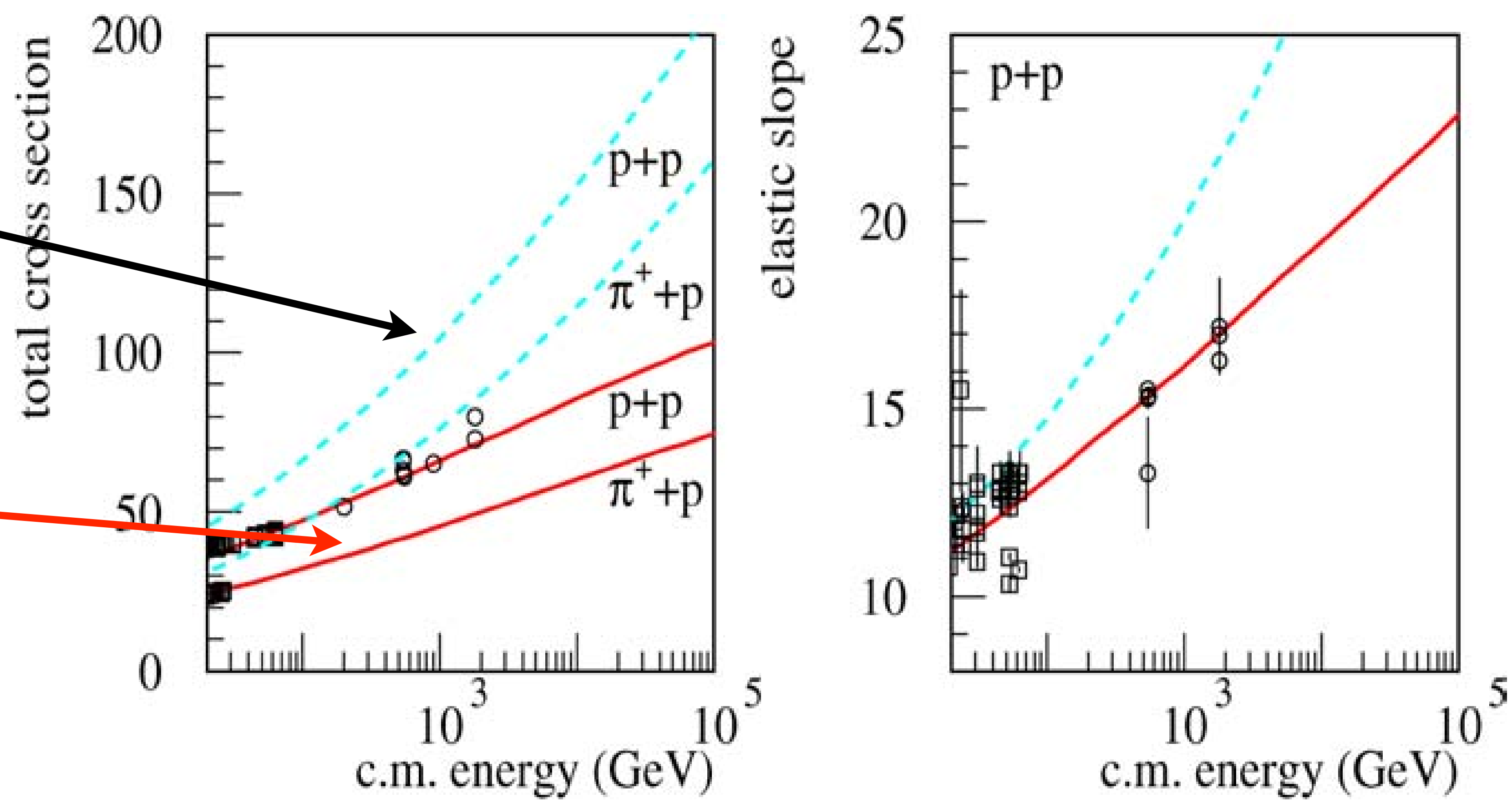
QGSJET II: high parton density effects

Re-summation of enhanced pomeron graphs



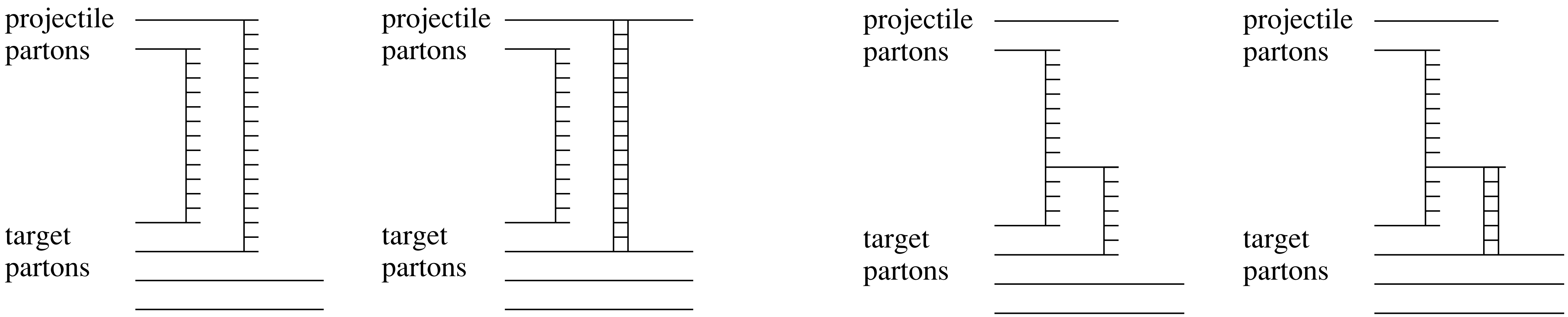
Without
enhanced graphs

With enhanced
graphs



(Ostapchenko, PLB 2006, PRD 2006)

EPOS 1.6x – high parton density effects (i)

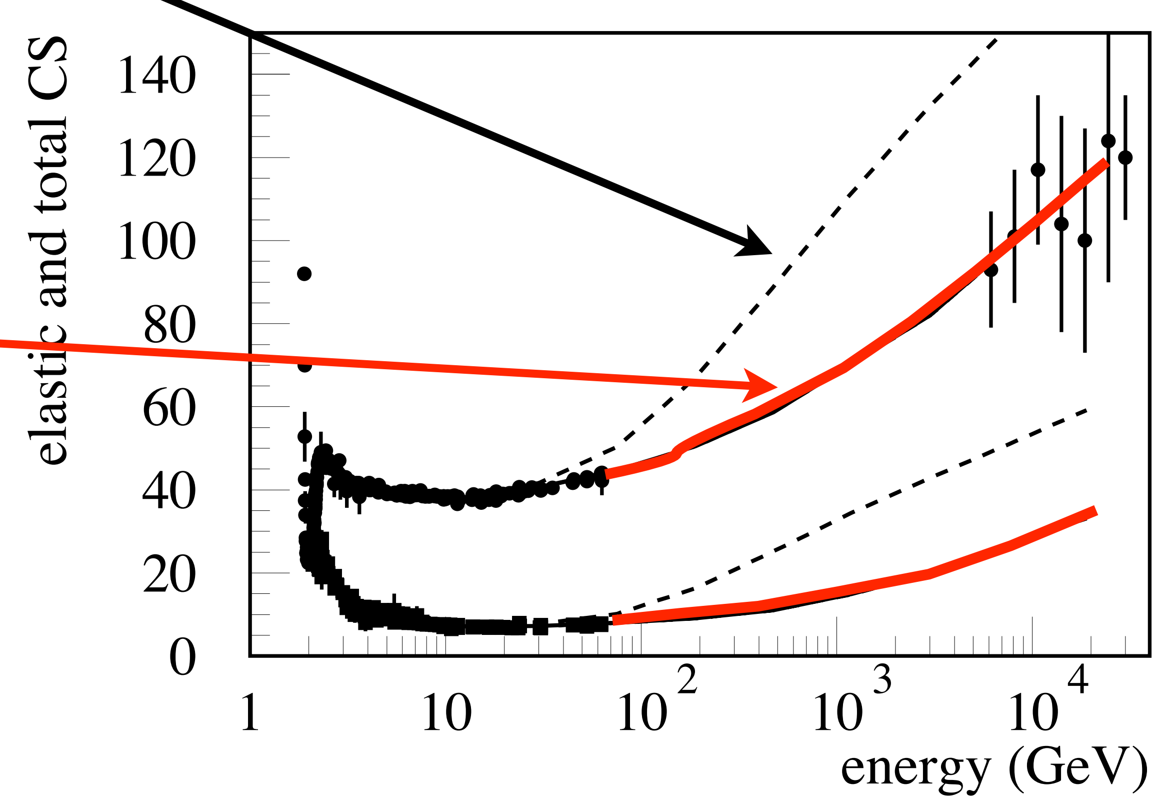


No effective coupling

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

With effective coupling

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



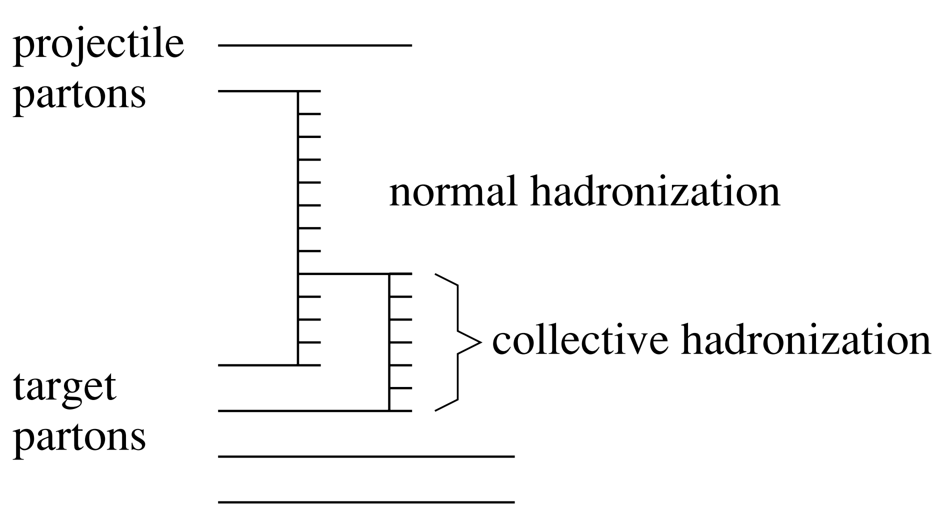
Parametrization

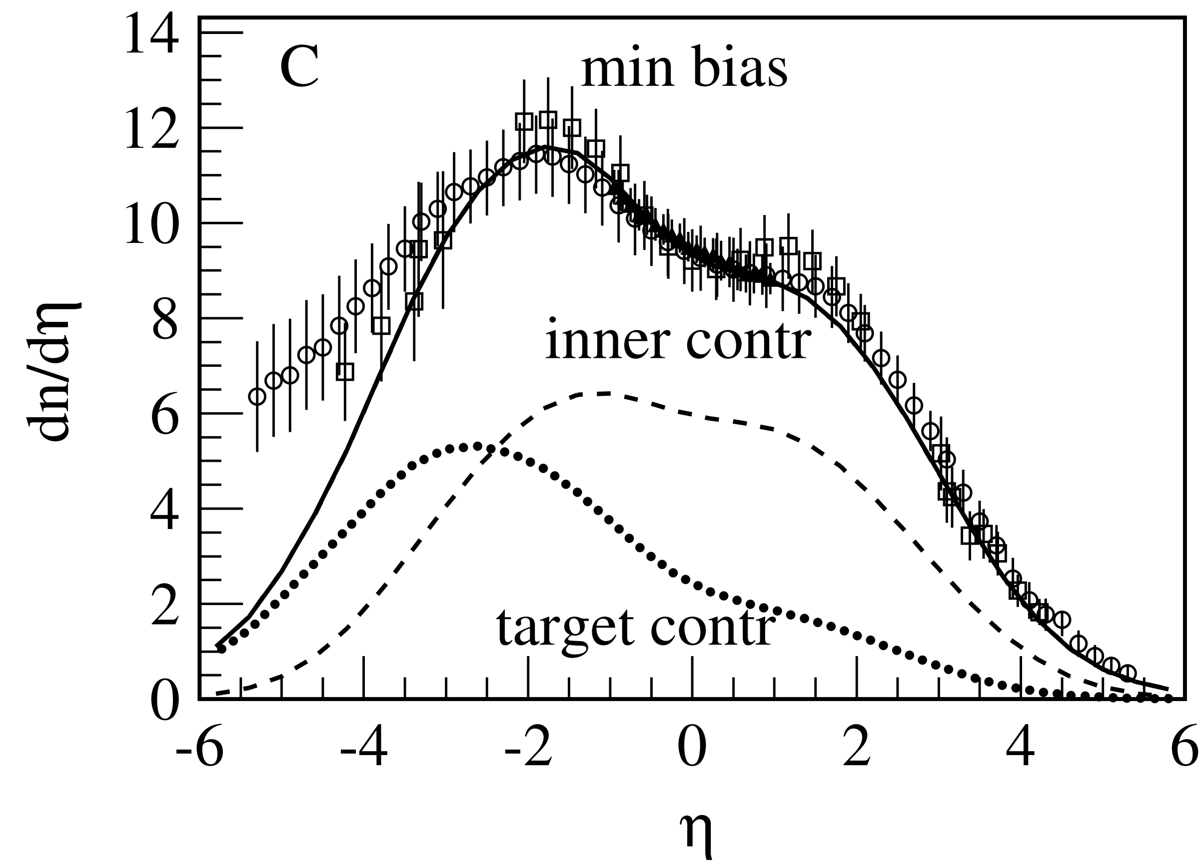
$$\varepsilon_S = a_S\,\beta_S Z,$$
$$\varepsilon_H = a_H\,\beta_H Z,$$

(Werner et al., PRC 2006)

EPOS 1.6x – high parton density effects (ii)

(Werner et al., PRC 2006)





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

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

EPOS 1.99: see Tanguy Pierog´s lecture

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

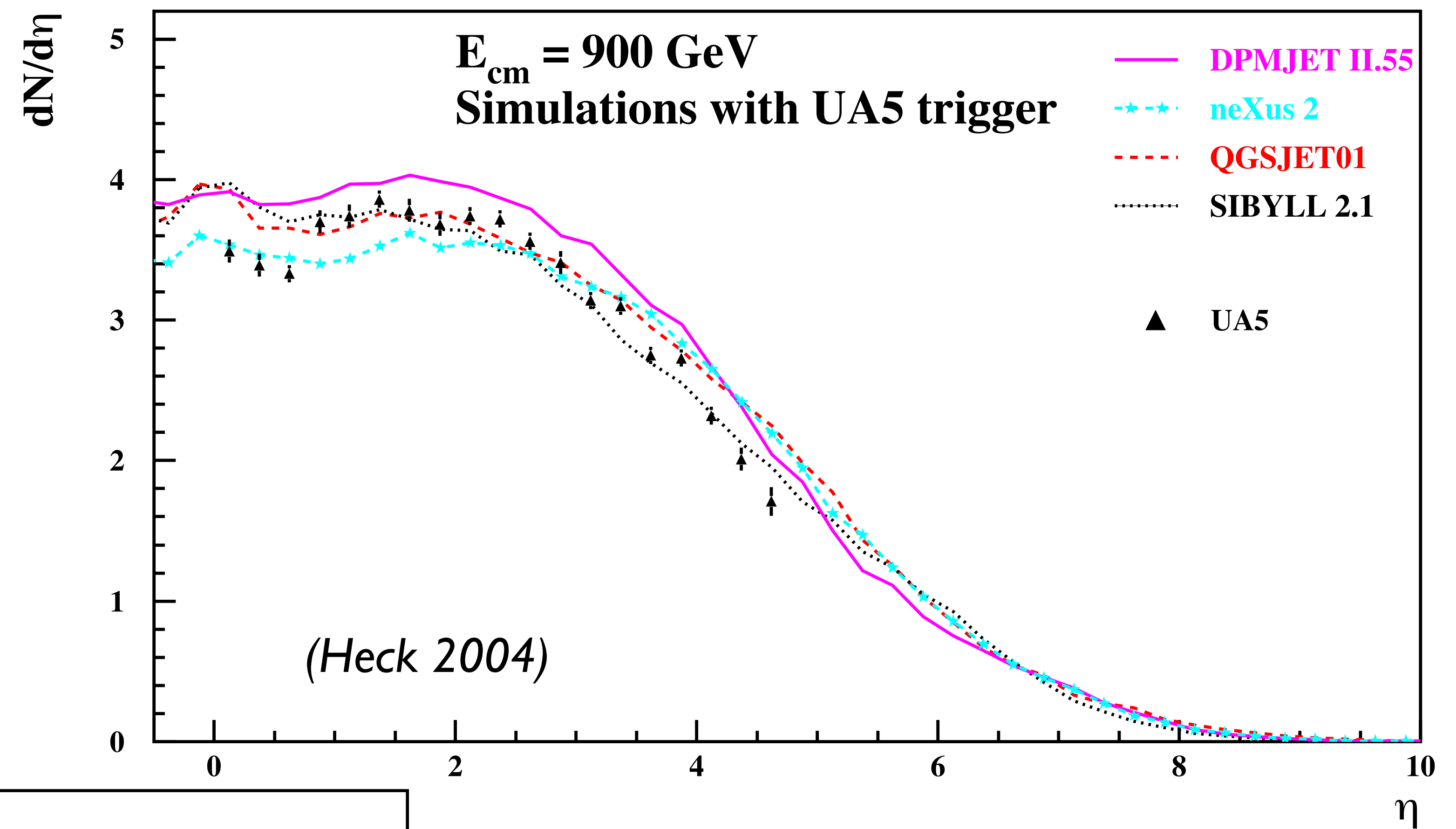
$$z_0 = w_Z\ \log s/s_M\,,$$

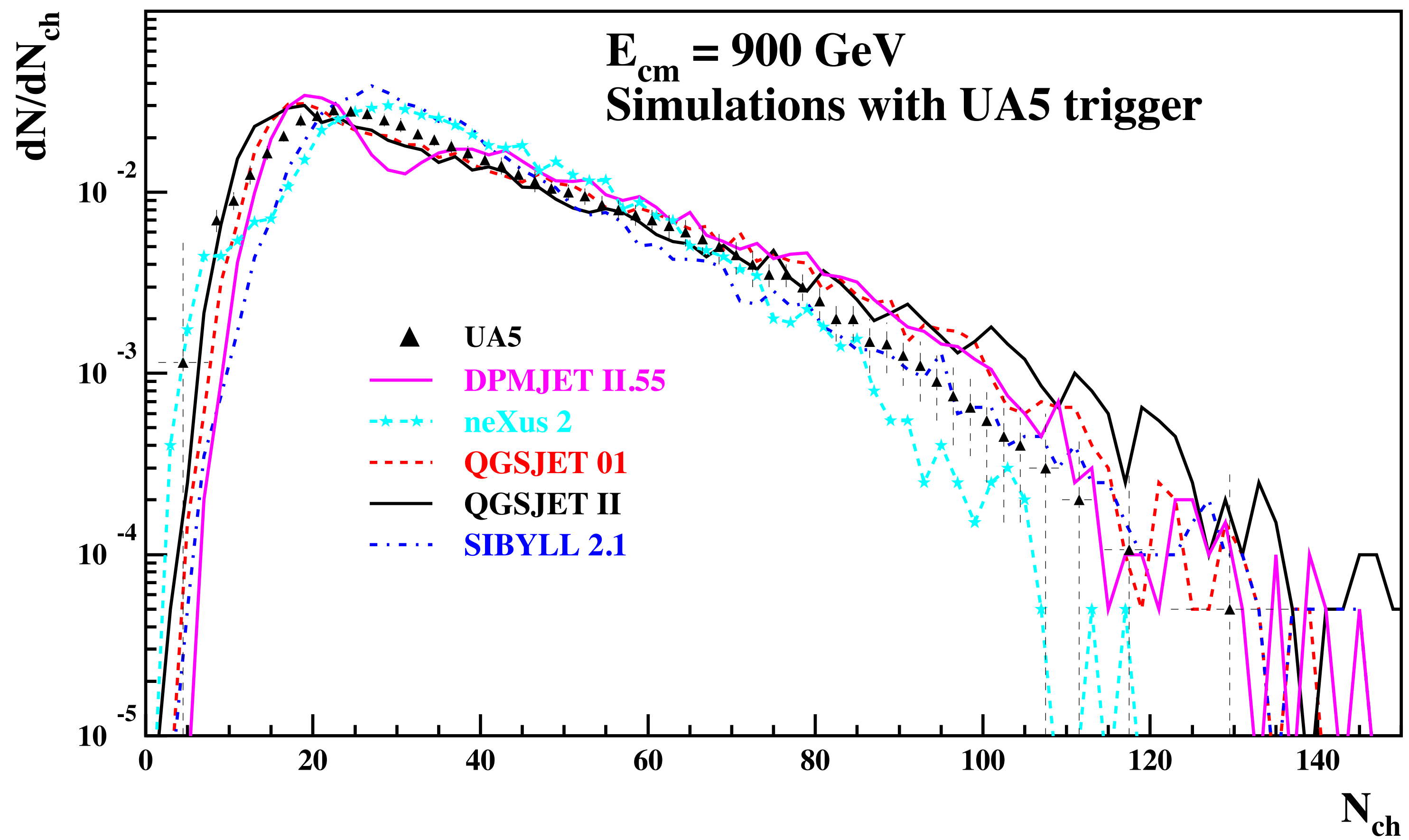
$$z_0' = w_Z\,\sqrt{(\log s/s_M)^2 + w_M{}^2},$$

Comparison of model predictions

Collider distributions: reasonable agreement

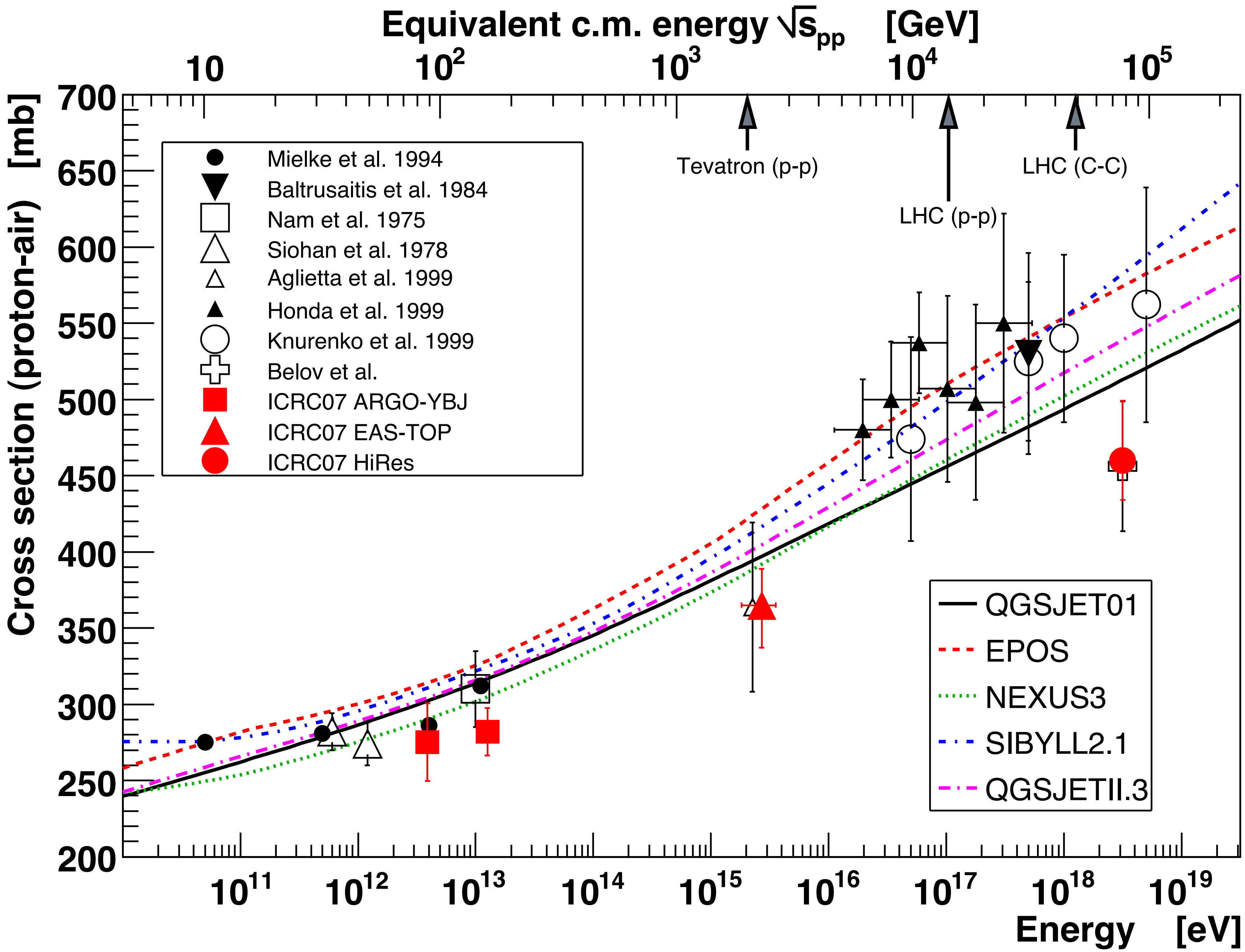
Many updated comparisons of models and data available, see talk by Tanguy Pierog





(Heck 2005)

Particle production cross section (p-air)

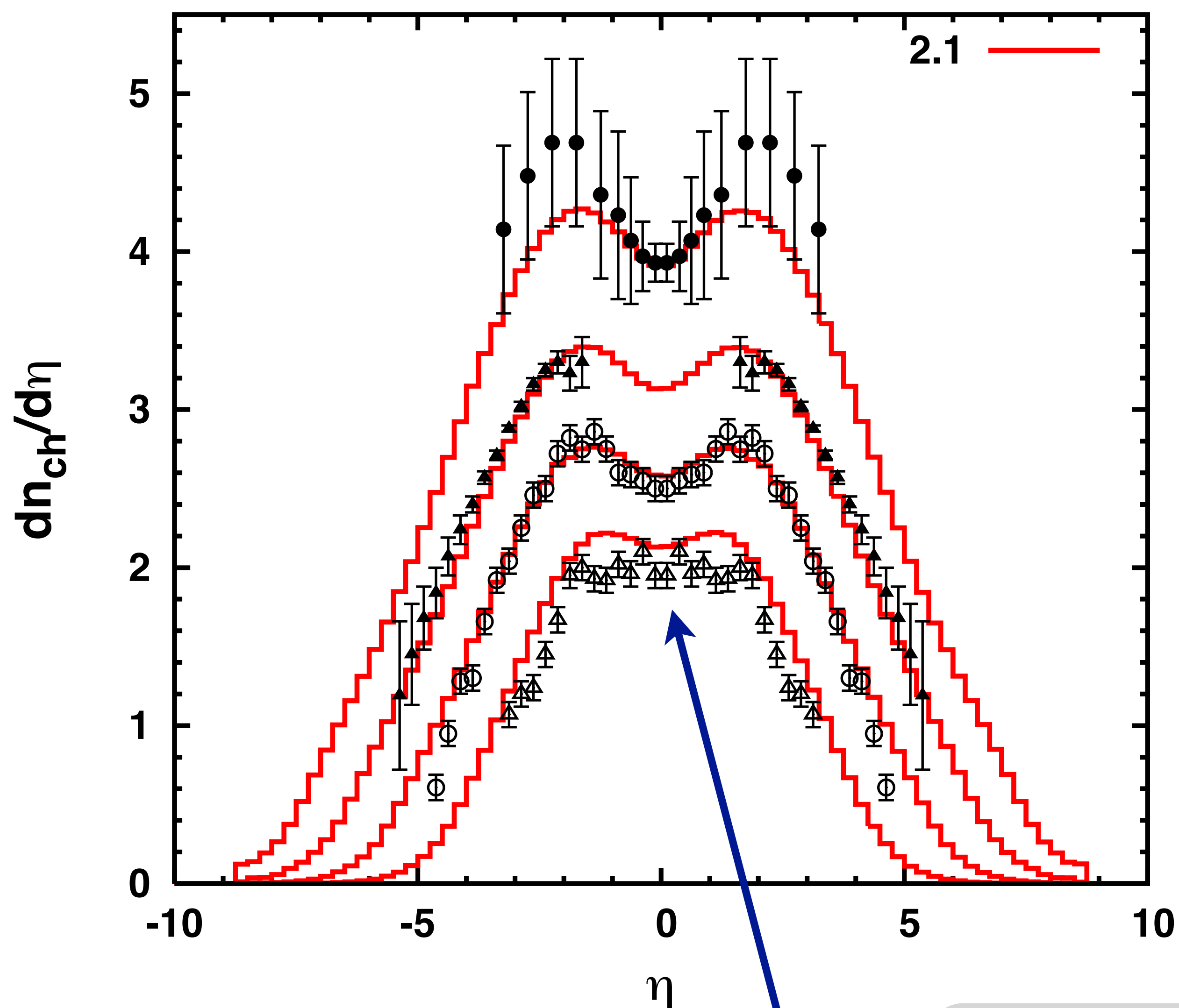


Differences stem from different effective profile functions and saturation models

Cross section extrapolations very similar

(R. Ulrich, 2007)

Violation of Feynman scaling



Feynman scaling

$$2E\frac{dN}{d^3p} = \frac{dN}{dy\,d^2p_\perp} \longrightarrow f(x_F, p_\perp)$$

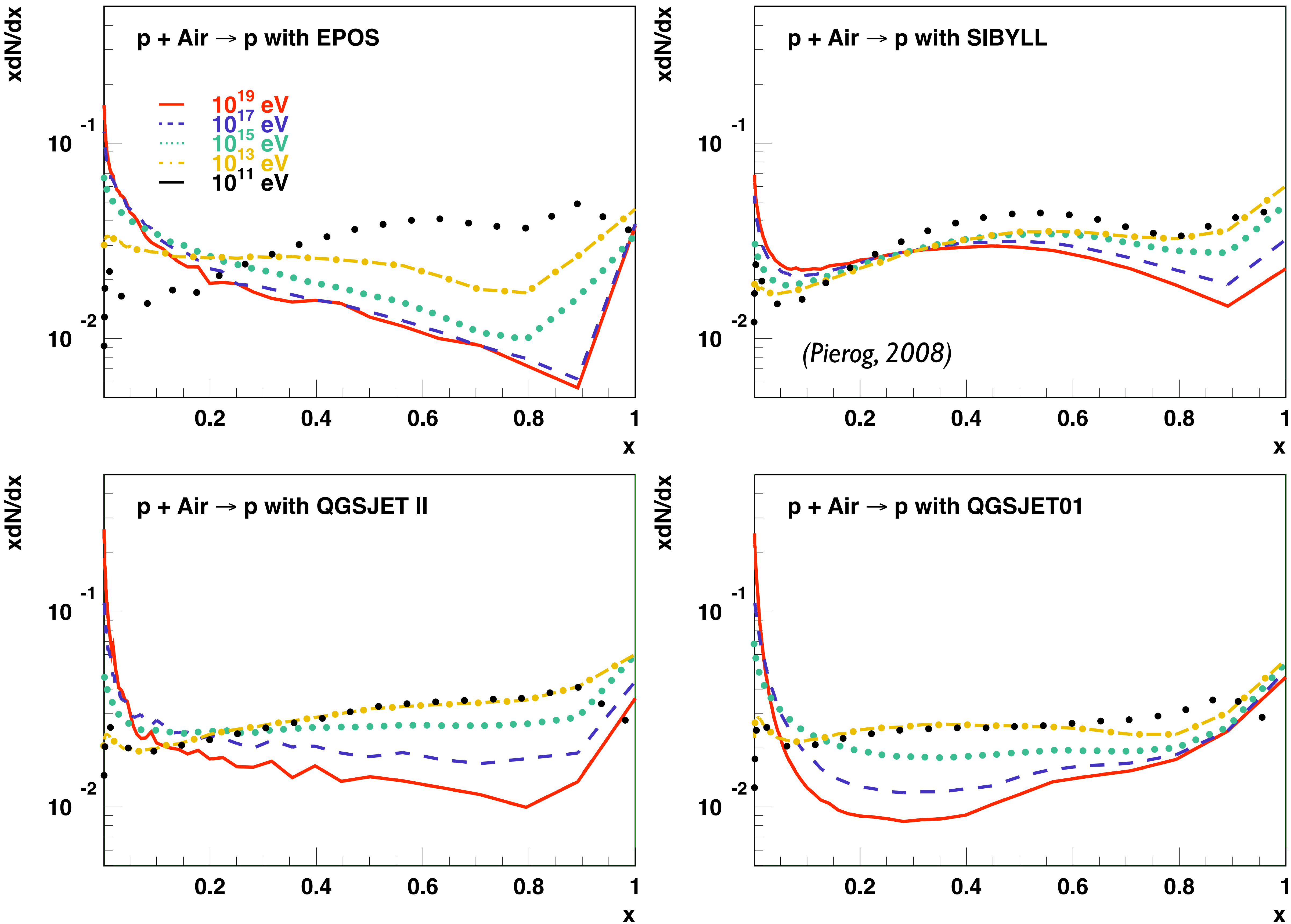
With Feynman scaling:
distribution independent of energy

$$\frac{dN}{dx} \approx \tilde{f}(x) \qquad x = E/E_{\rm prim}$$

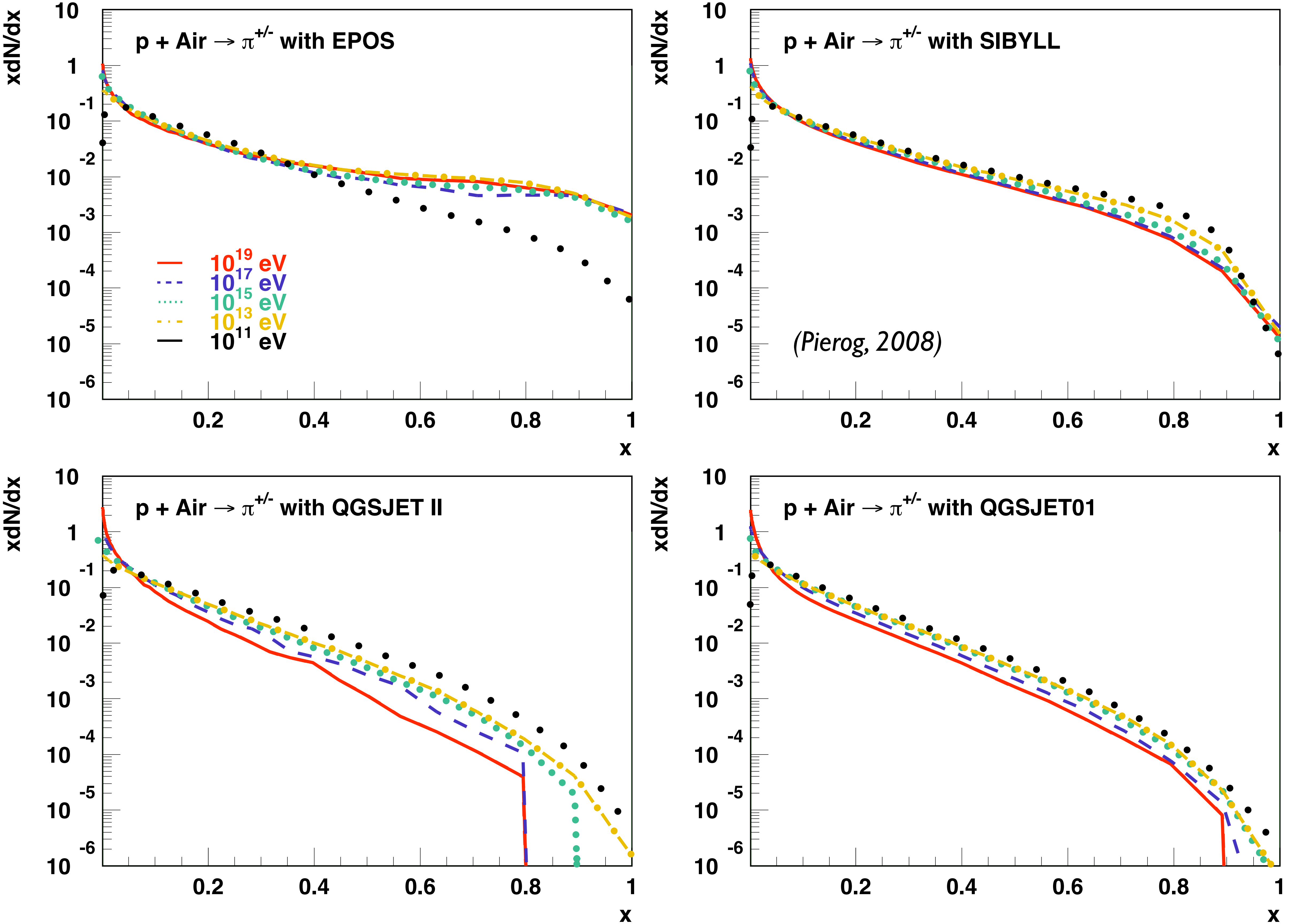
Feynman scaling violated for small $|x_F|$

$$\frac{dN}{dy\,d^2p_\perp} \approx \frac{dN}{dy}\,g(p_\perp^2)$$

Scaling: model predictions (i)

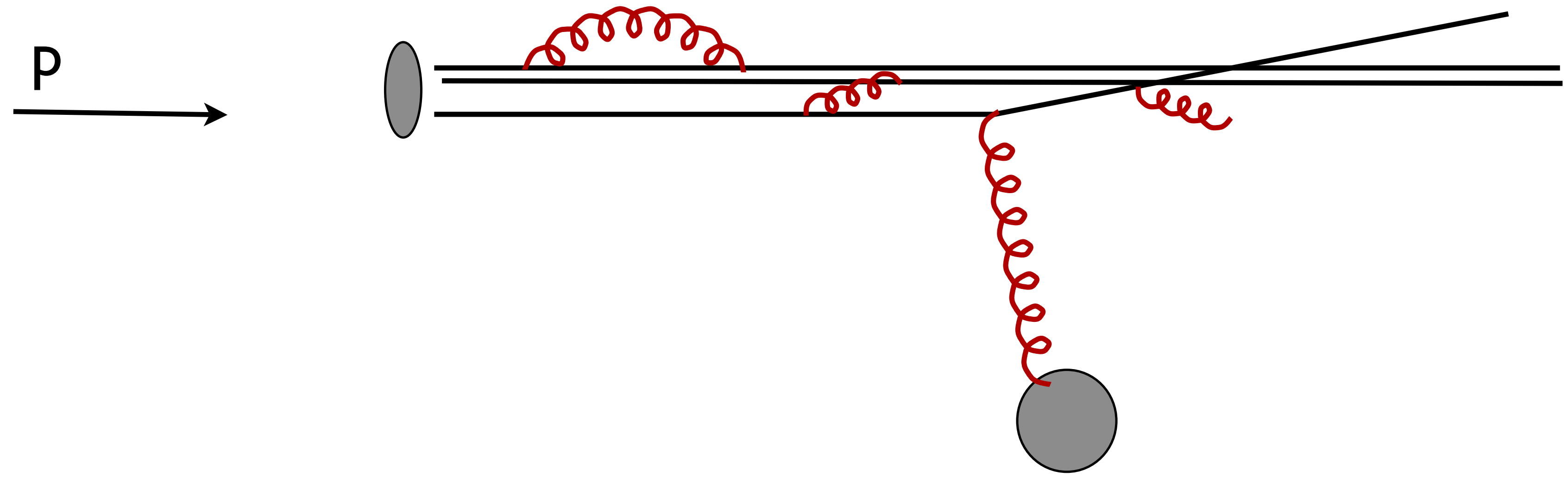


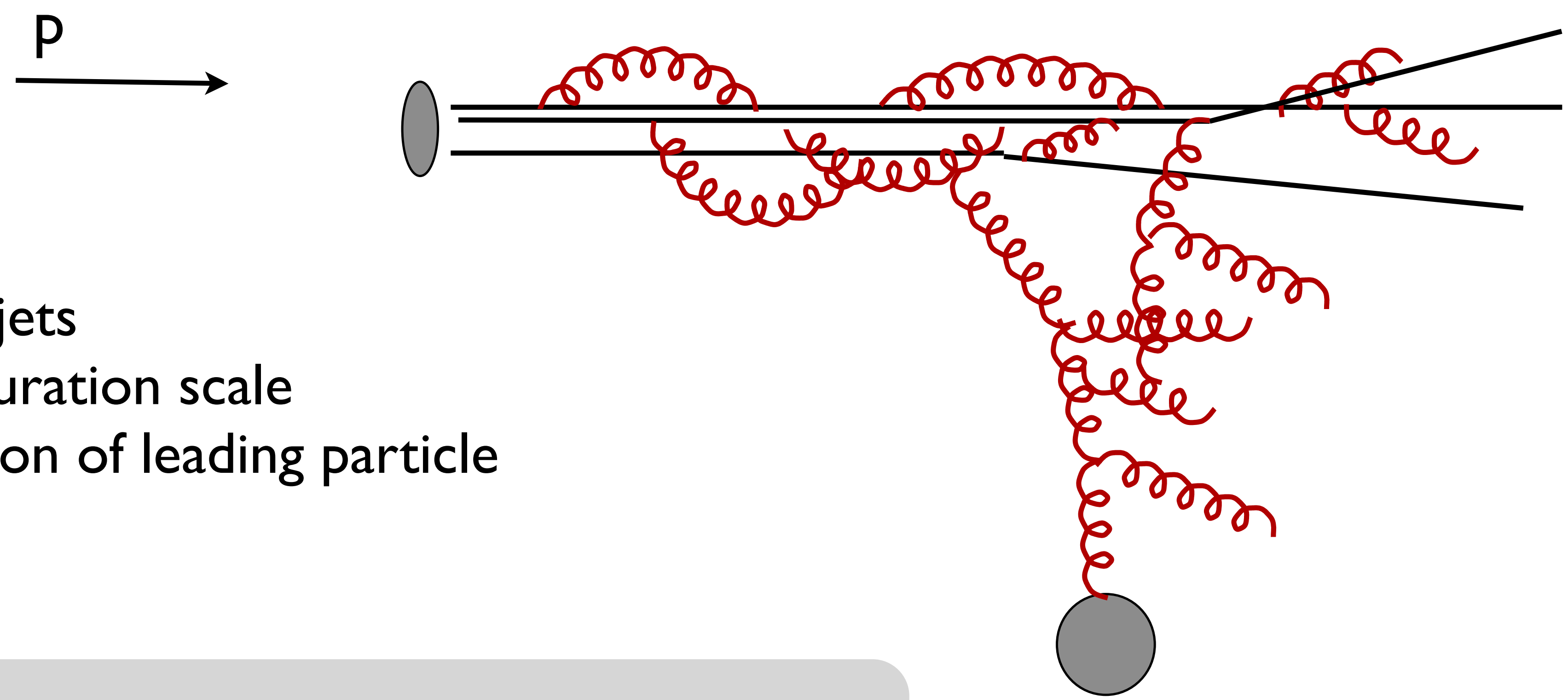
Scaling: model predictions (ii)



Black disk scenario of high energy scattering ?

High energy scattering





Black Disk Model

- large number of minijets
- high perturbative saturation scale
- complete disintegration of leading particle

Not implemeted as dominating process in current models

(Drescher et al. PRL 94, 2005)

Some conclusions

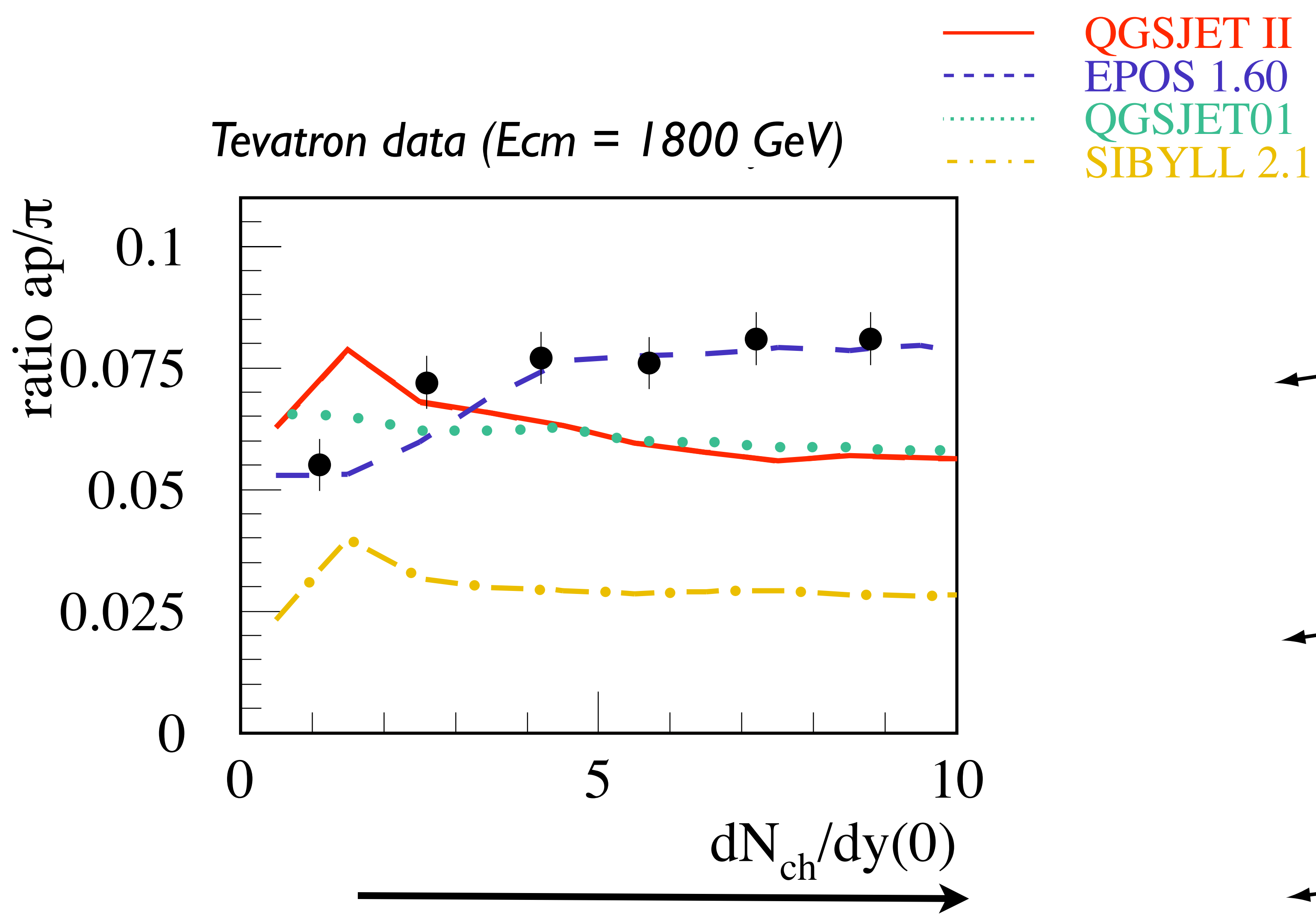
Minijet production changes characteristics of interactions

- Predicted within perturbative QCD
- Natural source of scaling violations
- Parameters for calculation very uncertain
- Saturation effects very important

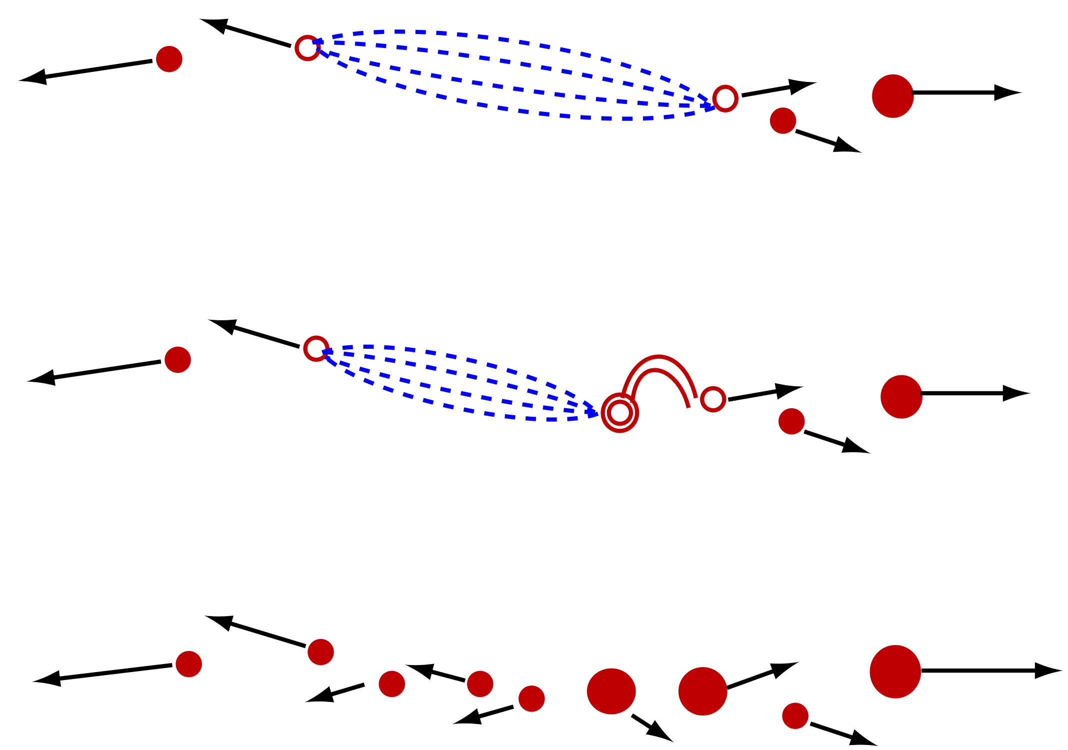
Models construction

- Construction elements very similar
- Model philosophies complementary
- Tuned to data from fixed target and collider experiments
- Differences in treatment of key questions for high-energy extrapolation
- Predicted particle production still very similar
- Models do not cover full range of uncertainty

Baryon pair-production not understood



String fragmentation and baryon pairs



Two strings of high mass

Many strings of low mass

EPOS: modification of fragmentation parameters as function of string density (RHIC data)

(K. Werner et al., Phys. Rev. C75, 2006)