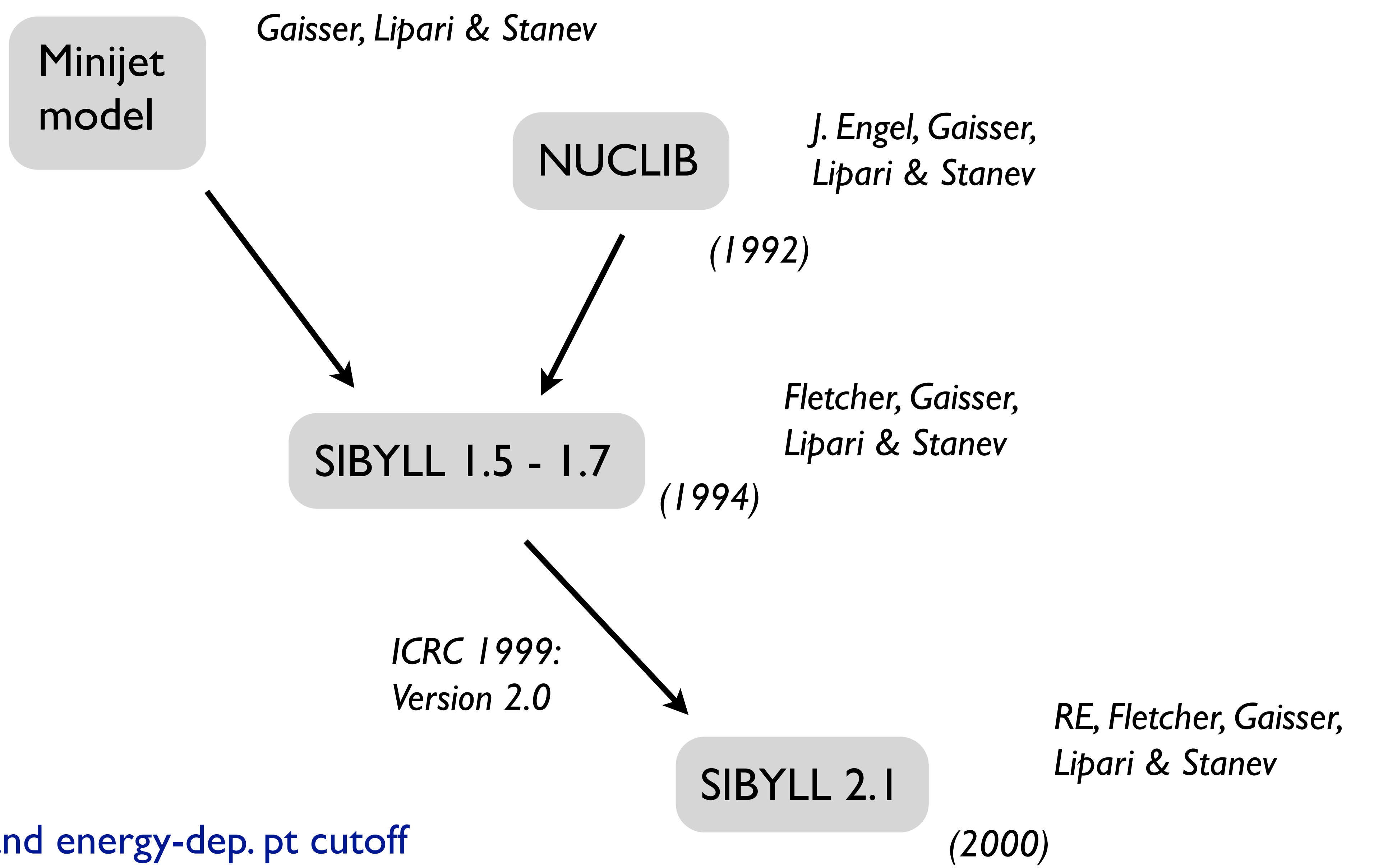
The event generator SIBYLL 2.1

Eun-Joo Ahn, Ralph Engel, Thomas K. Gaisser, Paolo Lipari, Todor Stanev

Karlsruhe Institute of Technology

History of SIBYLL

First QCD-inspired model for air shower simulations

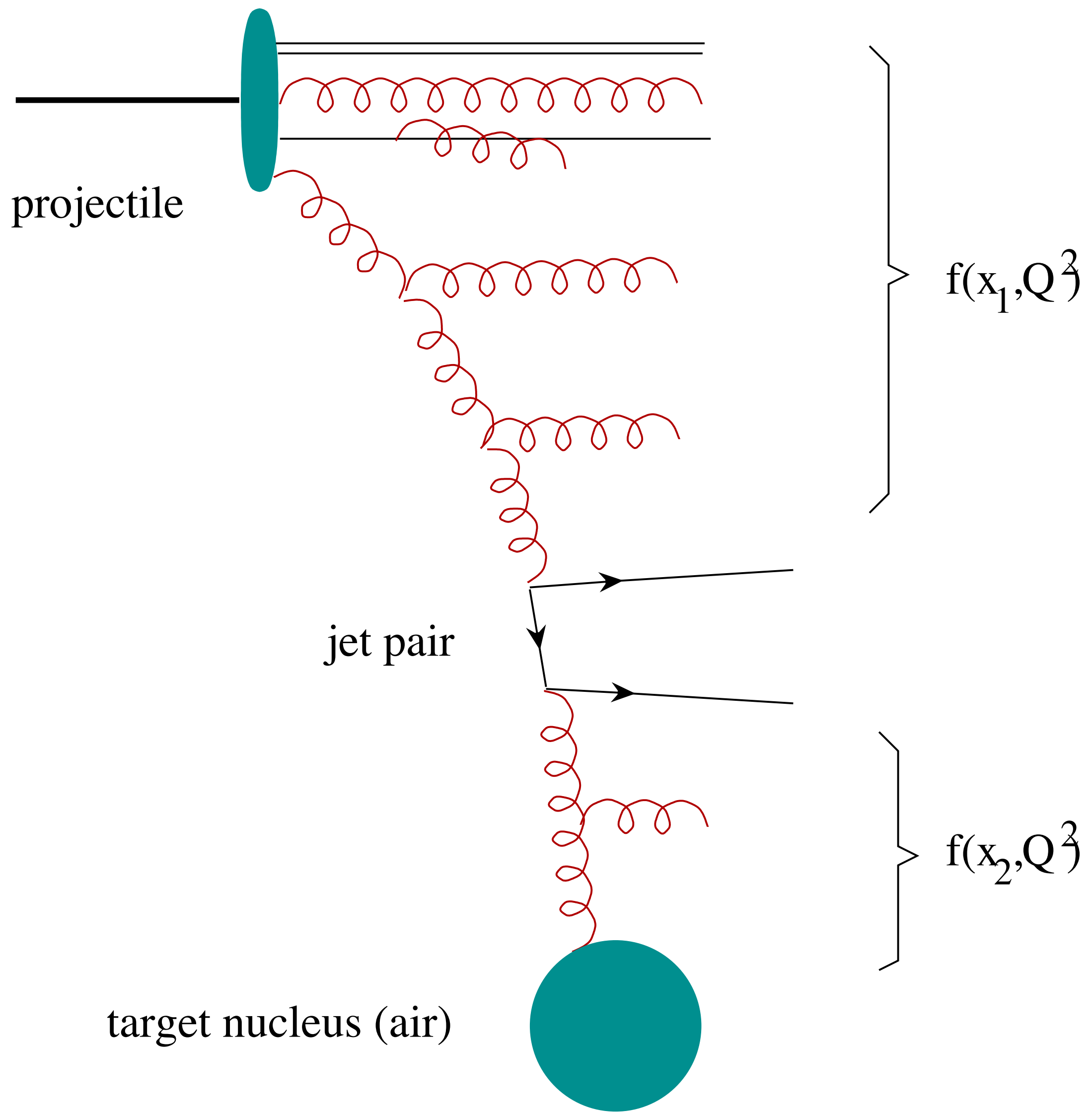


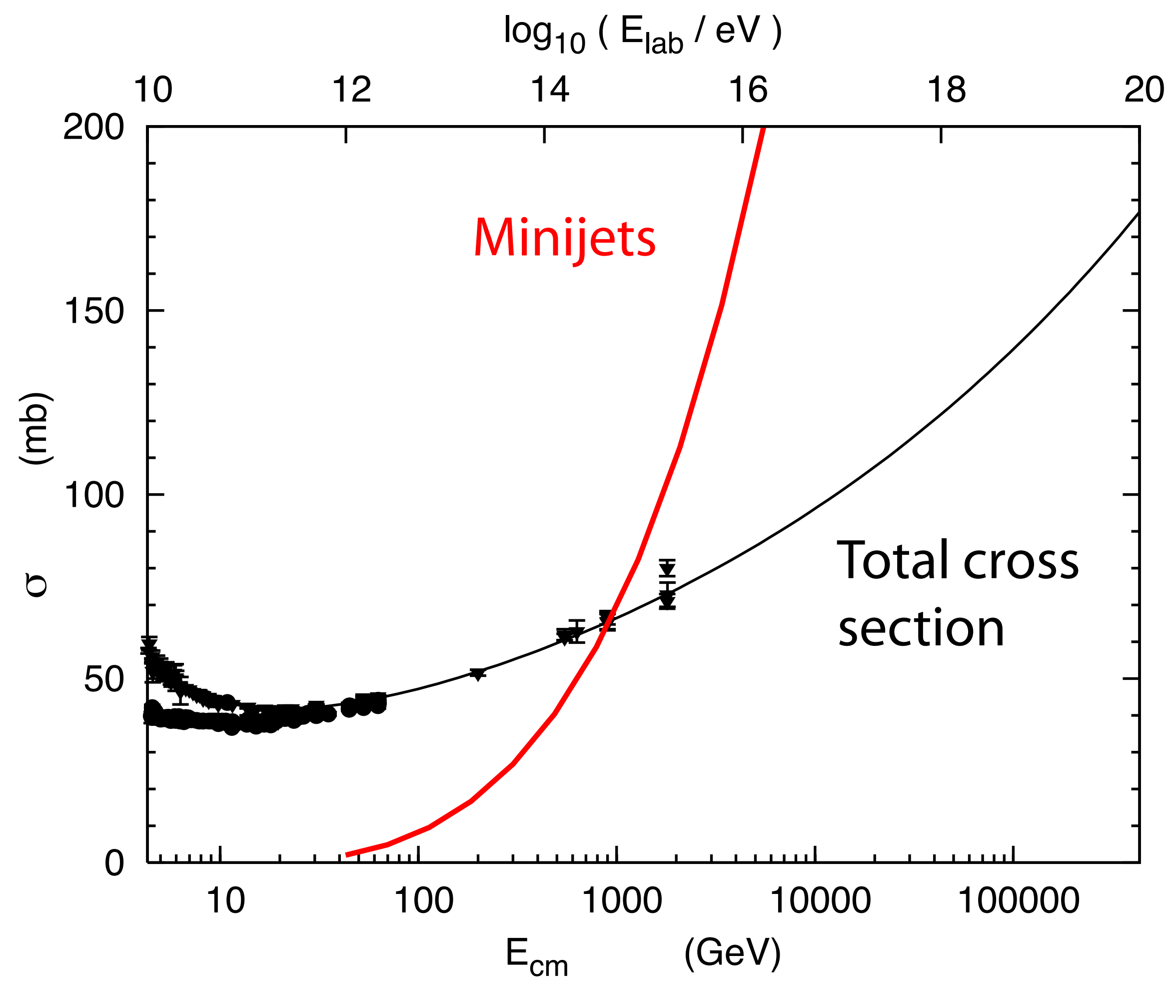
MOCCA
AIRES
CORSIKA

- HERA PDFs and energy-dep. pt cutoff
- multiple soft interactions
- two-channel model for diffraction

Plans for revised version *(Ahn et al.)*

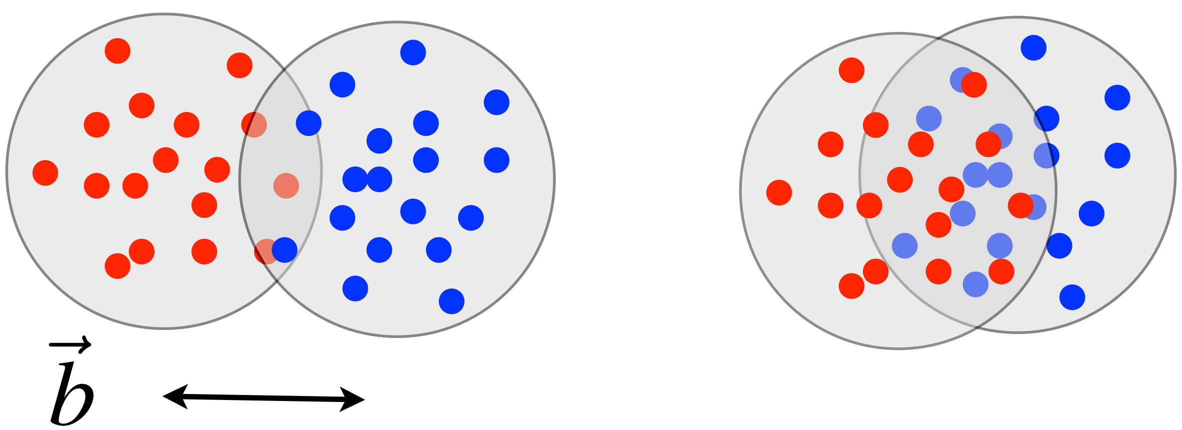
Minijet model: underlying ideas (i)





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

Minijet model: underlying ideas (ii)



Overlap function

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

Independent interactions:
Poisson distribution

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

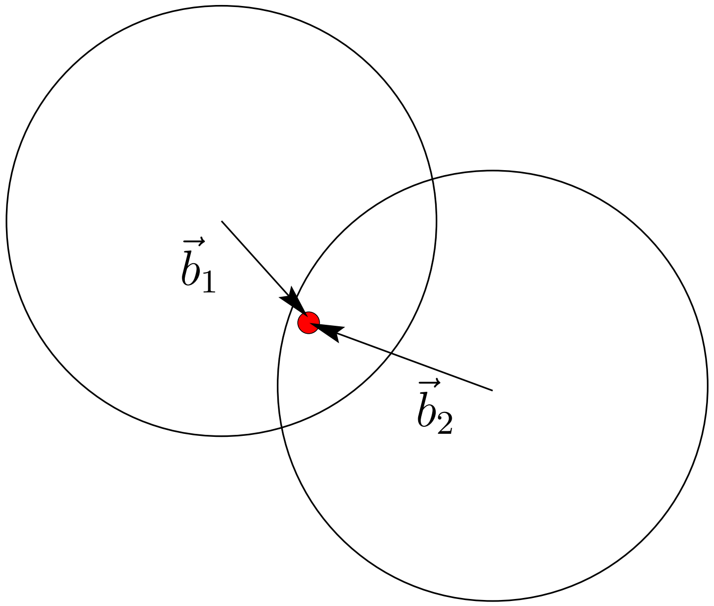
$$\sigma_{\rm ine} = \int d^2\vec{b} \sum_{n=1}^{\infty} P_n = \int d^2\vec{b} \left(1 - \exp\{-\sigma_{\rm QCD}\, A(s,\vec{b})\}\right)$$

Profile function for partons

Proton: dipole
$$A_p(\nu_p,\vec{b}) = \frac{1}{(2\pi)^2}\int d^2q \left(1+\frac{q^2}{\nu_p^2}\right)^{-2} e^{i\vec{q}\cdot\vec{b}} = \nu_p\,|\nu_p\vec{b}|\,K_1(|\nu_p\vec{b}|)$$

Meson: monopole
$$A_m(\nu_m,\vec{b}) = \frac{1}{(2\pi)^2}\int d^2q \left(1+\frac{q^2}{\nu_m^2}\right)^{-1} e^{i\vec{q}\cdot\vec{b}}$$

$$A_{pp}^{\text{hard}}(\nu_p,\vec{b}) = \int d^2\vec{b}'\,A_p(|\vec{b}-\vec{b}'|)\,A_p(|\vec{b}'|)$$



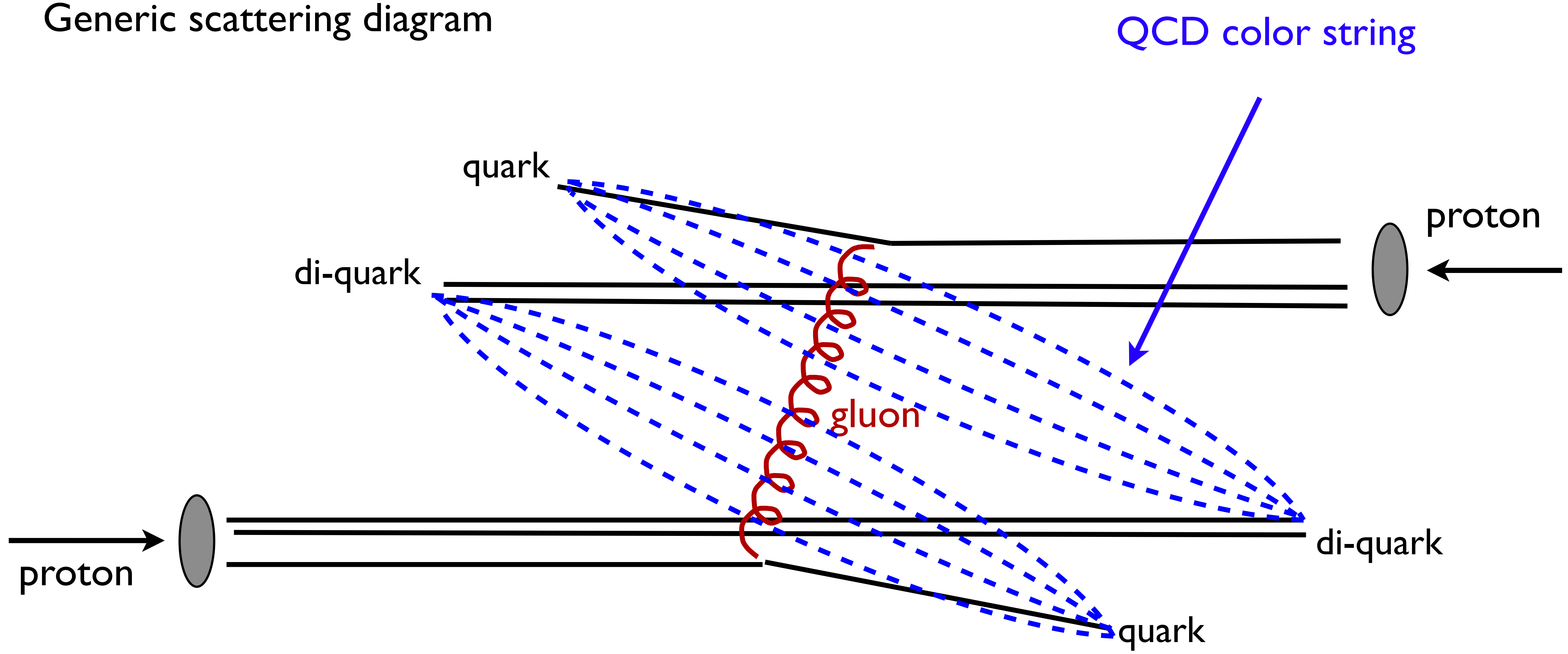
$$A_{pp}(\nu,\vec{b}) = \frac{\nu^2}{96\pi}(\nu|\vec{b}|)^3 K_3(\nu|\vec{b}|)$$

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

(Durand & Pi, PRD 1991)

Color flow and strings: valence quarks

Generic scattering diagram

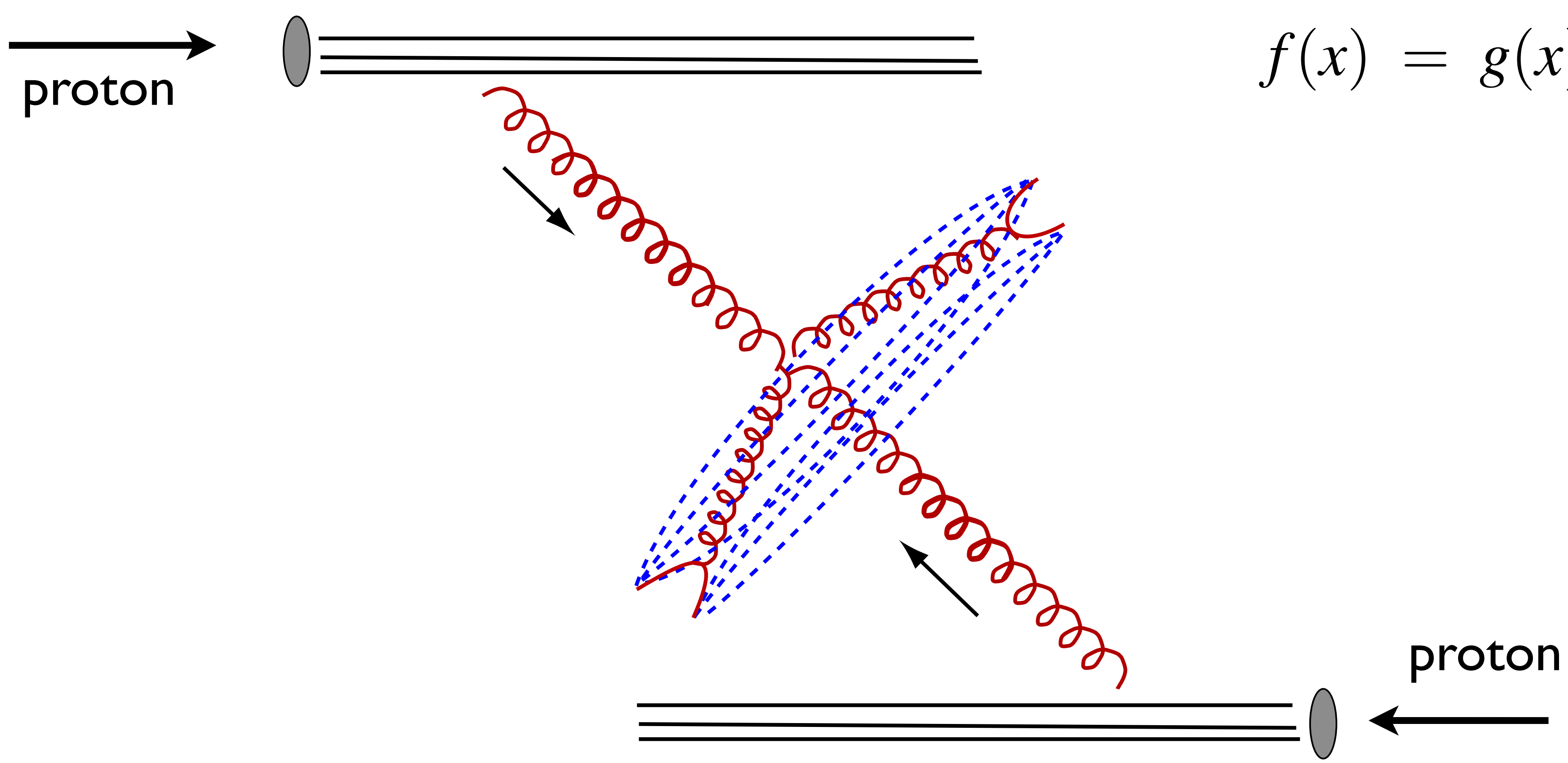


Momentum splitting $$f_q(x) = \frac{(1-x)^3}{(x^2 + \mu^2/s)^{1/4}}$$

Hard processes: two-gluon scattering

Only gluons considered, quarks included by effective parton density

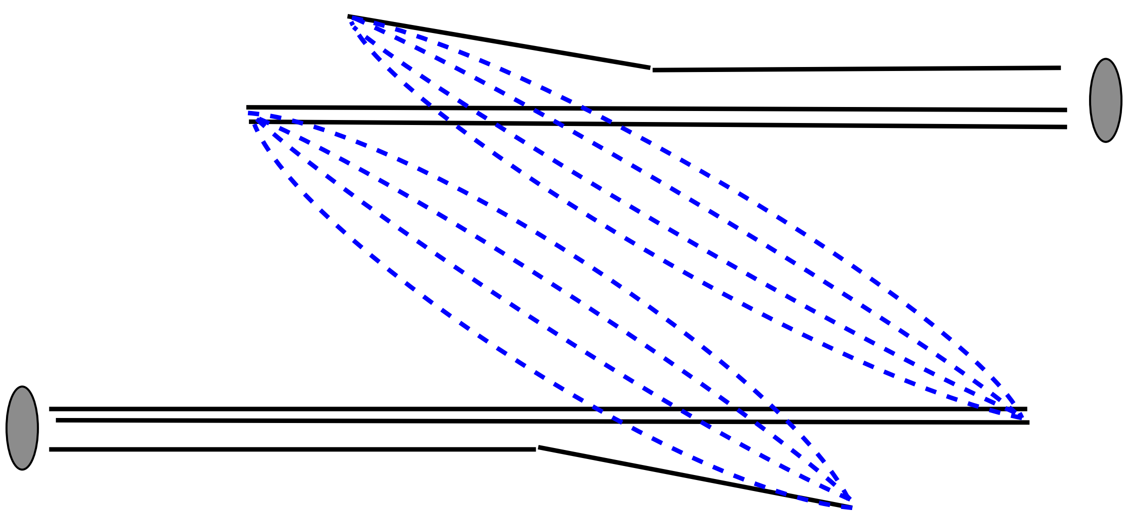
$$f(x) = g(x) + \frac{4}{9}\left[q(x) + \bar{q}(x)\right]$$

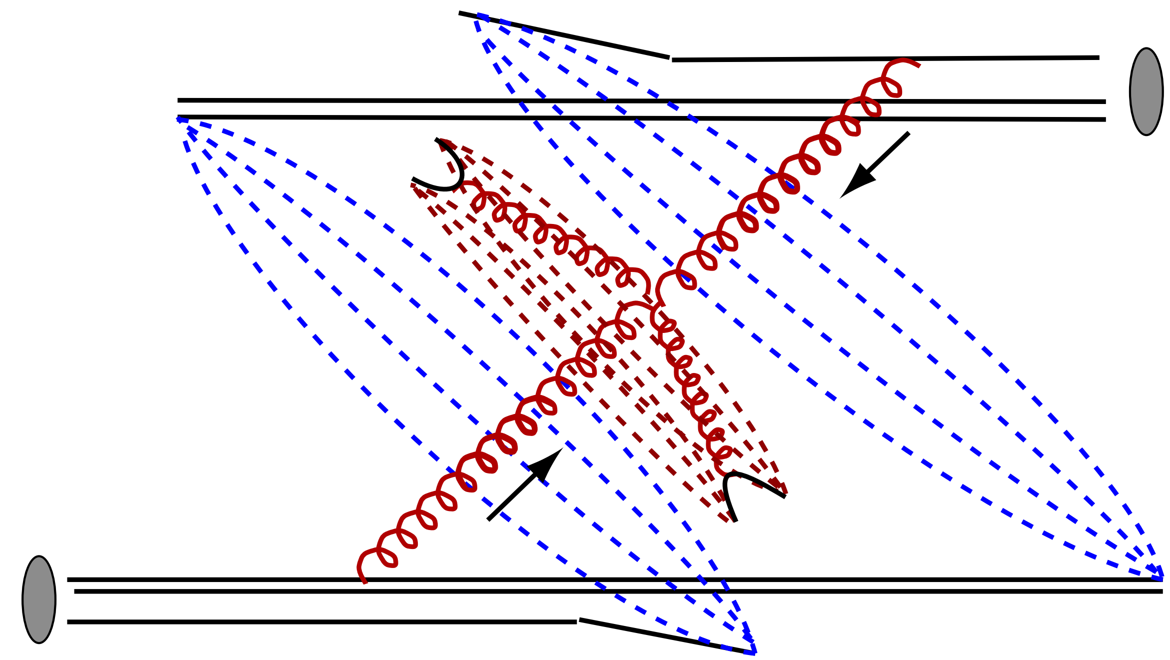


Kinematics etc. given by parton densities and perturbative QCD
Two strings stretched between quark pairs from gluon fragmentation

Multiple soft and hard interactions

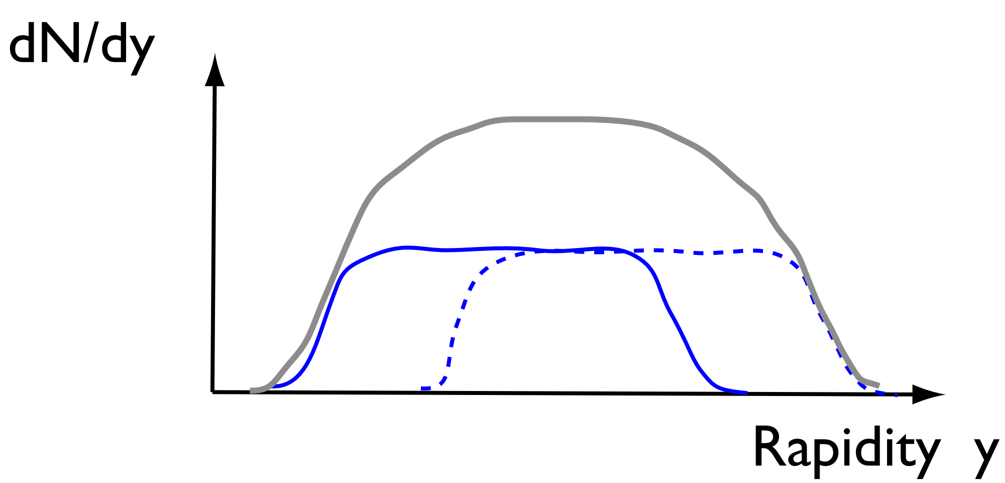
$$\sigma_{n_s,n_h} = \int d^2b \, \frac{[n_{\rm soft}(b,s)]^{n_s}}{n_s!} \, \frac{[n_{\rm hard}(b,s)]^{n_h}}{n_h!} \, e^{-n_{\rm hard}(b,s)-n_{\rm soft}(b,s)}$$

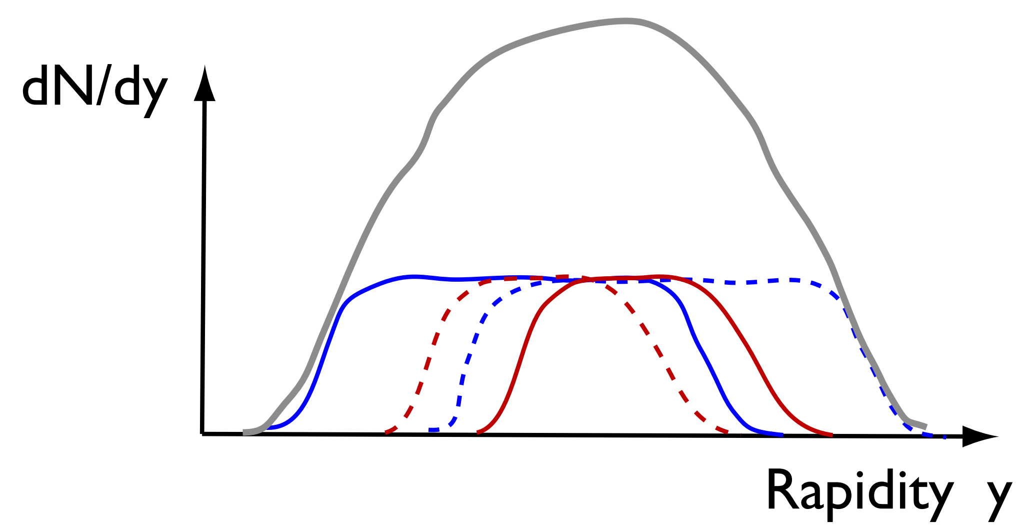




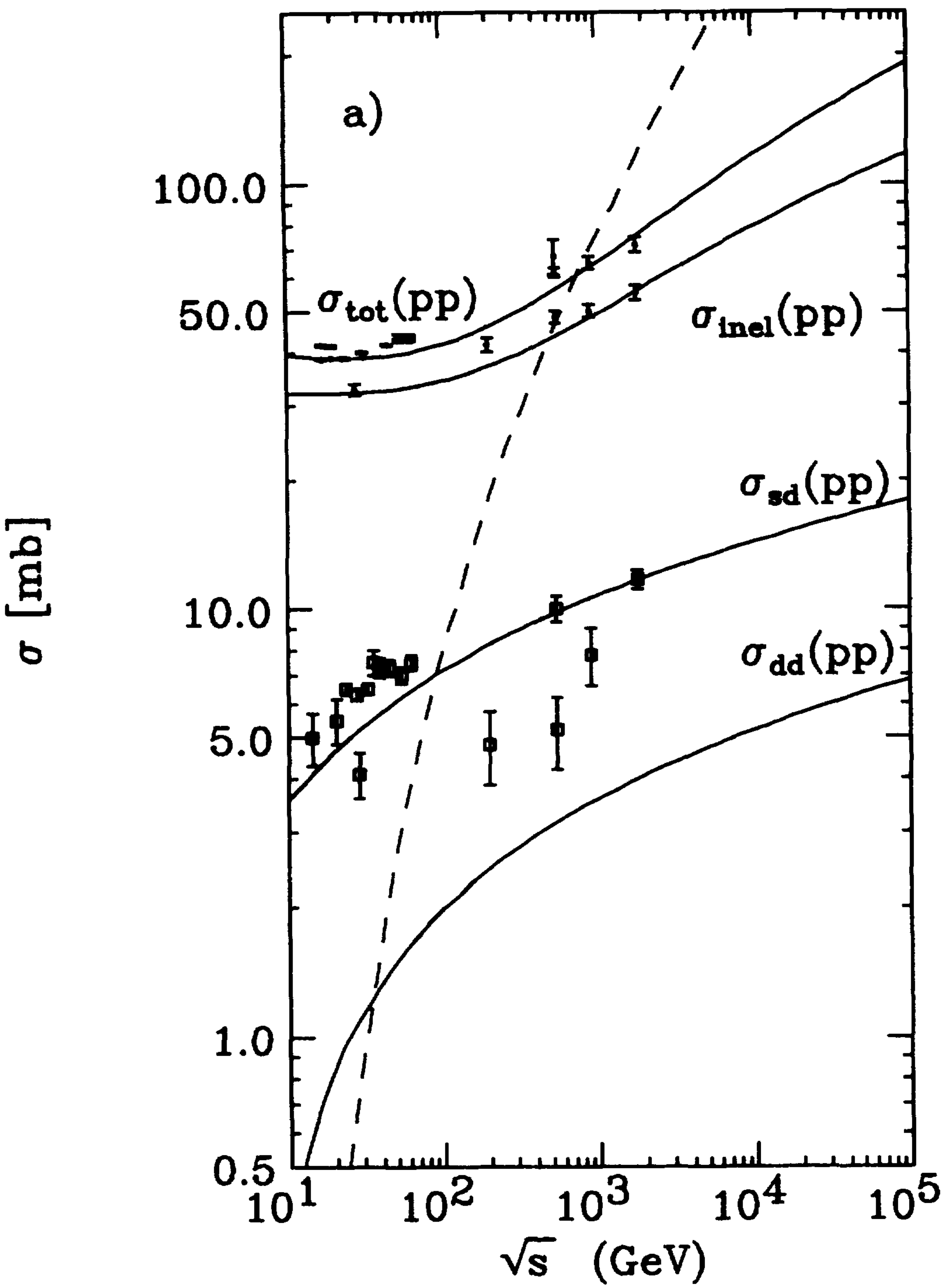
n_s=1, n_h=0

n_s=1, n_h=1





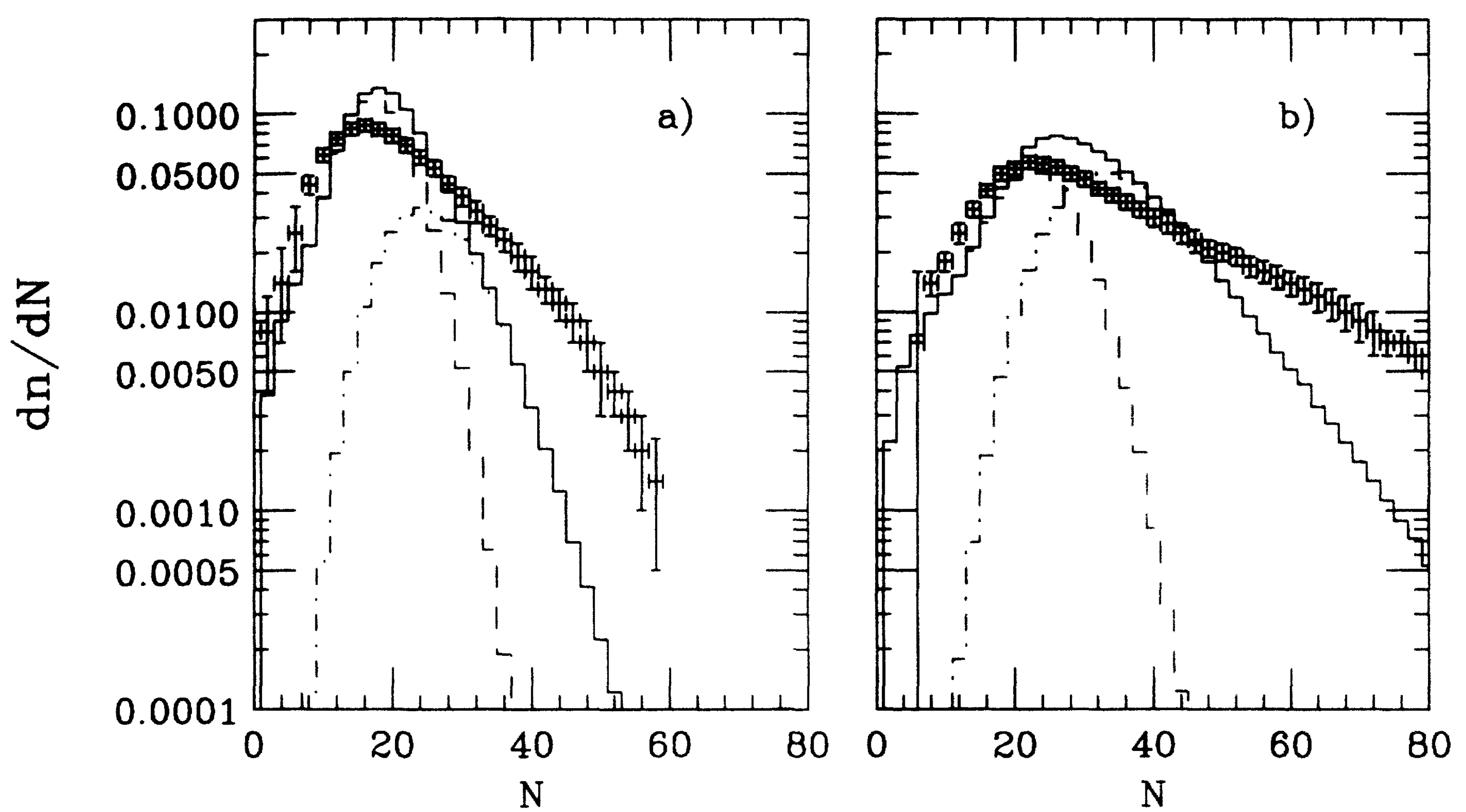
SIBYLL 1.7: shortcomings in describing data



(Fletcher et al., PRD 1994)

Problems at intermediate energies

UA5 Multiplicity distribution at 200 and 900 GeV c.m.s.

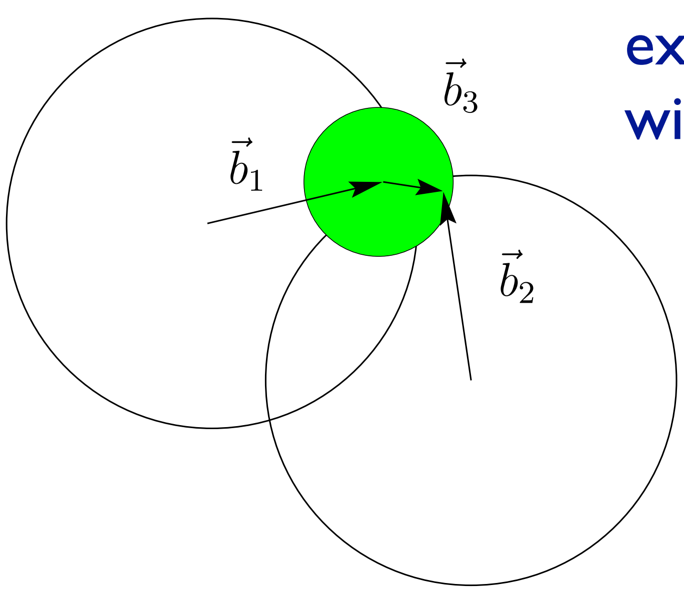


Extensions of model in SIBYLL 2.1

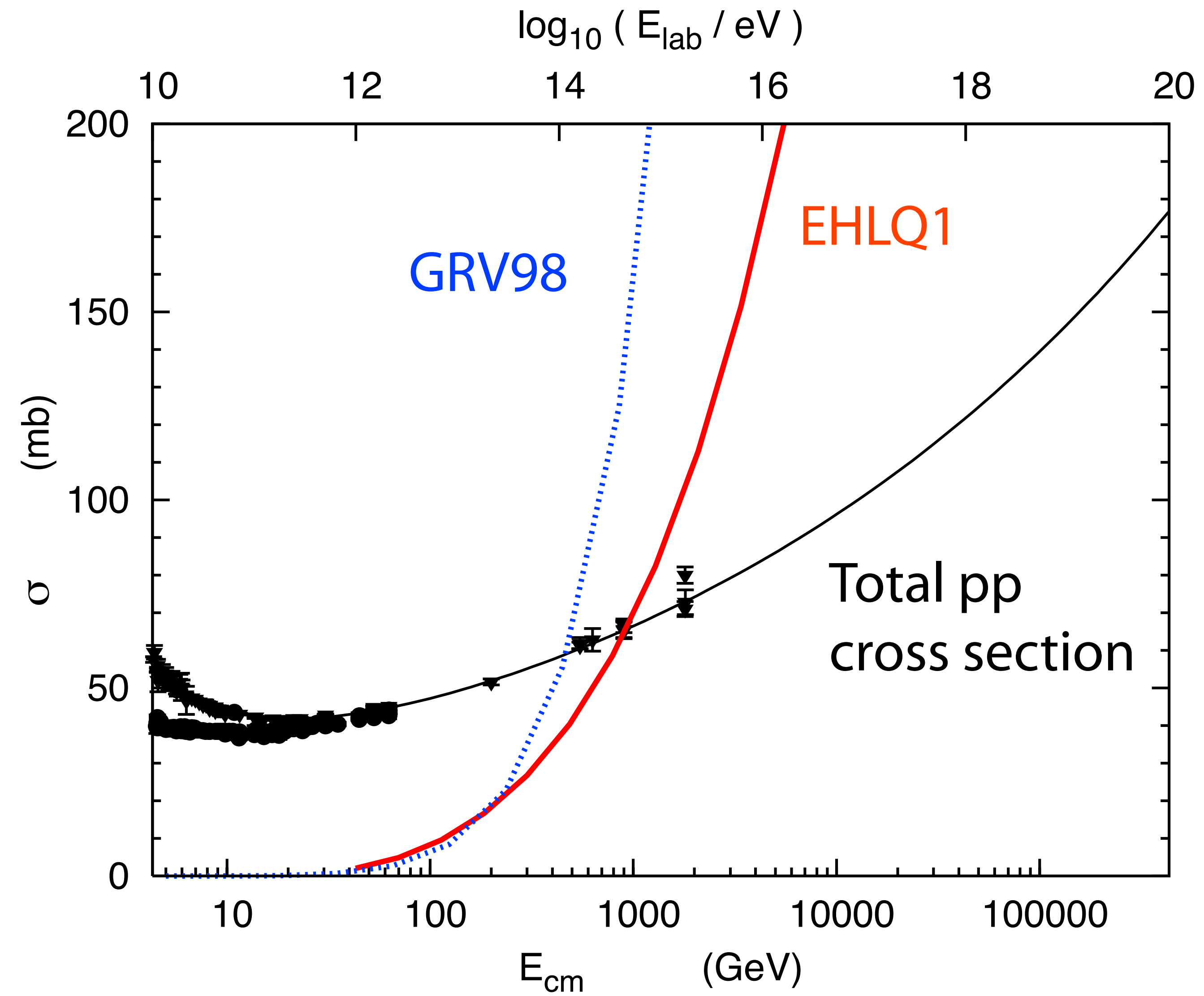
(Ahn et al., PRD80 (2009) 094003)

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

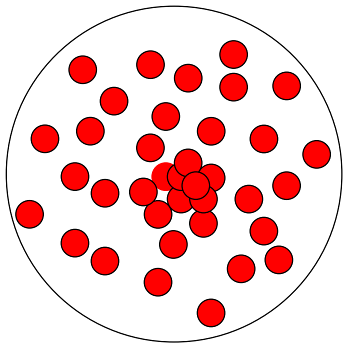
- Soft cross section energy dependent
- energy-dep. pt cutoff for QCD cross section
- soft and hard profile functions
- two-channel model for diffraction



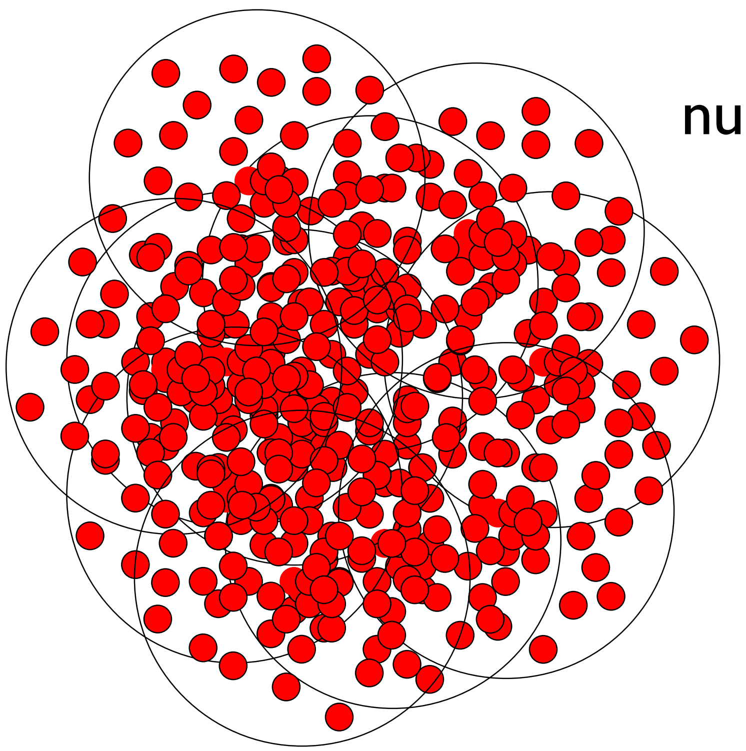
expanding
with energy



High parton densities



nucleon



nucleus

SIBYLL: simple geometric criterion

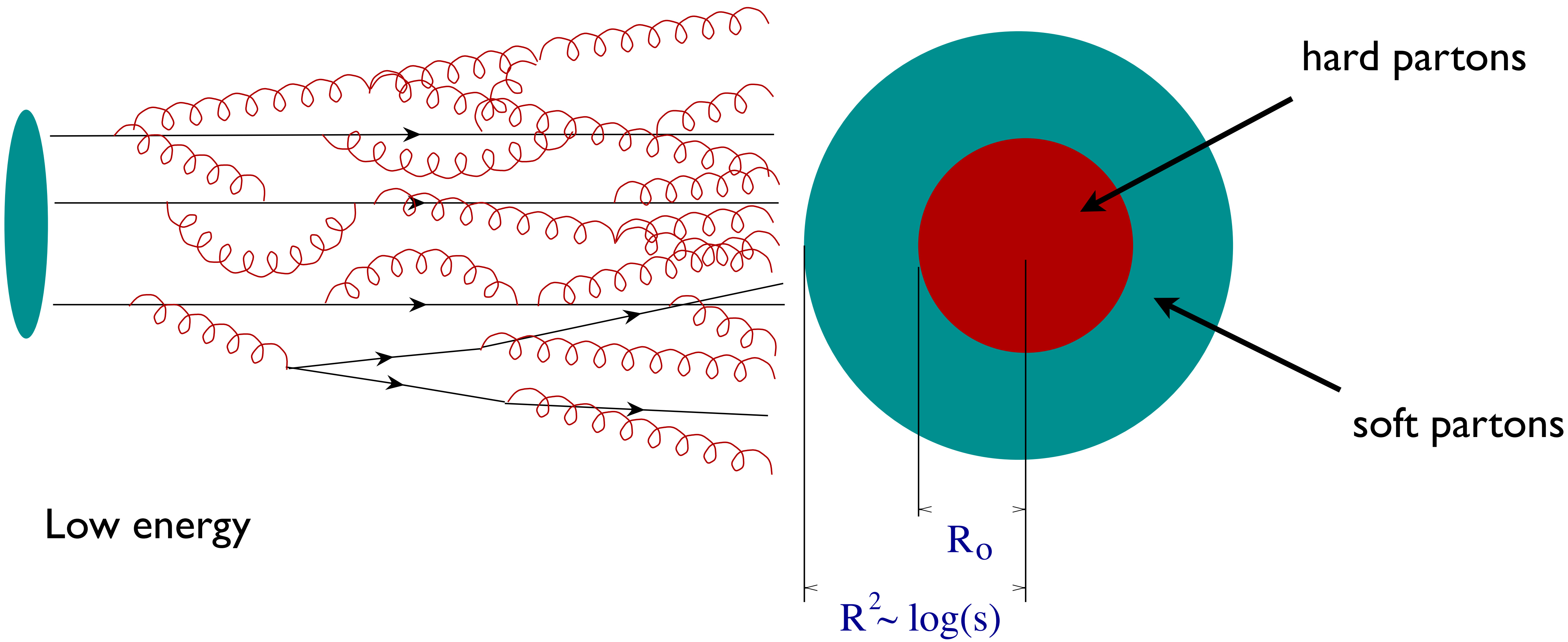
$$\pi R_0^2 \simeq \frac{\alpha_s(Q_s^2)}{Q_s^2} \cdot xg(x, Q_s^2)$$

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

No dependence on impact parameter !

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

Profile function of soft partons



$$\Delta\vec{b}\cdot\Delta\vec{p}_{\perp} \sim 1$$

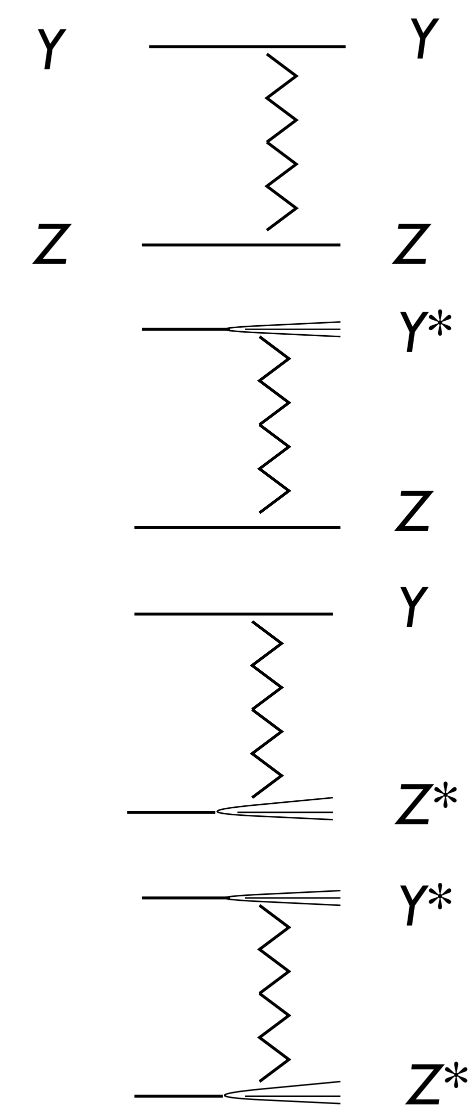
$$A_{\rm soft}(s,\vec{b}) = \frac{1}{4\pi R^2(s)} \exp\left\{-\frac{\vec{b}^2}{4R^2(s)}\right\}$$

$$R^2(s) = R_0^2 + \alpha' \ln s$$

Two-channel model for diffraction dissociation

(Kaidalov Phys Rep. 50 (1979) 157)

$$
\begin{aligned}
\langle YZ|\mathcal{M}^{\rm int}|YZ\rangle &= \mathcal{M}^{\rm Born}\\
\langle YZ|\mathcal{M}^{\rm int}|Y^\star Z\rangle &= \beta_Y\mathcal{M}^{\rm Born}\\
\langle YZ|\mathcal{M}^{\rm int}|YZ^\star\rangle &= \beta_Z\mathcal{M}^{\rm Born}\\
\langle YZ|\mathcal{M}^{\rm int}|Y^\star Z^\star\rangle &= \beta_Y\beta_Z\mathcal{M}^{\rm Born}\\
\langle Y^\star Z|\mathcal{M}^{\rm int}|Y^\star Z\rangle &= (1-2\alpha_Y)\mathcal{M}^{\rm Born}\\
\langle YZ^\star|\mathcal{M}^{\rm int}|YZ^\star\rangle &= (1-2\alpha_Z)\mathcal{M}^{\rm Born}\\
\langle Y^\star Z^\star|\mathcal{M}^{\rm int}|Y^\star Z^\star\rangle &= (1-2\alpha_Y)(1-2\alpha_Z)\mathcal{M}^{\rm Born}.
\end{aligned}
$$



$$
|Y,Z\rangle\sim\begin{pmatrix}1\\0\\0\\0\end{pmatrix},\qquad |Y^\star,Z\rangle\sim\begin{pmatrix}0\\1\\0\\0\end{pmatrix}\qquad |Y,Z^\star\rangle\sim\begin{pmatrix}0\\0\\1\\0\end{pmatrix},\qquad |Y^\star,Z^\star\rangle\sim\begin{pmatrix}0\\0\\0\\1\end{pmatrix}
$$

$$
\hat{\chi}(s,\mathbf{b}) = \begin{pmatrix}
1 & \beta_Y & \beta_Z & \beta_Y\beta_Z\\
\beta_Y & 1-2\alpha_Y & \beta_Y\beta_Z & \beta_Z(1-2\alpha_Y)\\
\beta_Z & \beta_Y\beta_Z & 1-2\alpha_Z & \beta_Y(1-2\alpha_Z)\\
\beta_Y\beta_Z & \beta_Z(1-2\alpha_Y) & \beta_Y(1-2\alpha_Z) & (1-2\alpha_Y)(1-2\alpha_Z)
\end{pmatrix}\chi(s,\mathbf{b})
$$

Multiple interactions within two-channel model

Diffraction changes probabilities for multiple interactions (hard and soft)

$$\sigma_{N_s,N_h} = \int d^2b \sum_{k=1}^{4} \Lambda_k \frac{[2\lambda_k \chi_{\mathrm{soft}}(s,\mathbf{b})]^{N_s}}{N_s!} \frac{[2\lambda_k \chi_{\mathrm{hard}}(s,\mathbf{b})]^{N_h}}{N_h!} \exp\{-2\lambda_k(\chi_{\mathrm{soft}}(s,\mathbf{b}) + \chi_{\mathrm{hard}}(s,\mathbf{b}))\}$$

Treatment equivalent to assumption of fluctuations in initial state of protons

(Blaettel et al. PRD 1993; Guzey et al. PLB 2006; Lipari & Lusignoli PRD 2009)

$$\gamma_j = \sqrt{\alpha_j^2 + \beta_j^2}$$

$$\Lambda_1 = \left(1 - \frac{\alpha_Y}{\gamma_Y}\right)\left(1 - \frac{\alpha_Z}{\gamma_Z}\right) \qquad \Lambda_2 = \left(1 - \frac{\alpha_Y}{\gamma_Y}\right)\left(1 + \frac{\alpha_Z}{\gamma_Z}\right)$$

$$\Lambda_3 = \left(1 + \frac{\alpha_Y}{\gamma_Y}\right)\left(1 - \frac{\alpha_Z}{\gamma_Z}\right) \qquad \Lambda_4 = \left(1 + \frac{\alpha_Y}{\gamma_Y}\right)\left(1 + \frac{\alpha_Z}{\gamma_Z}\right)$$

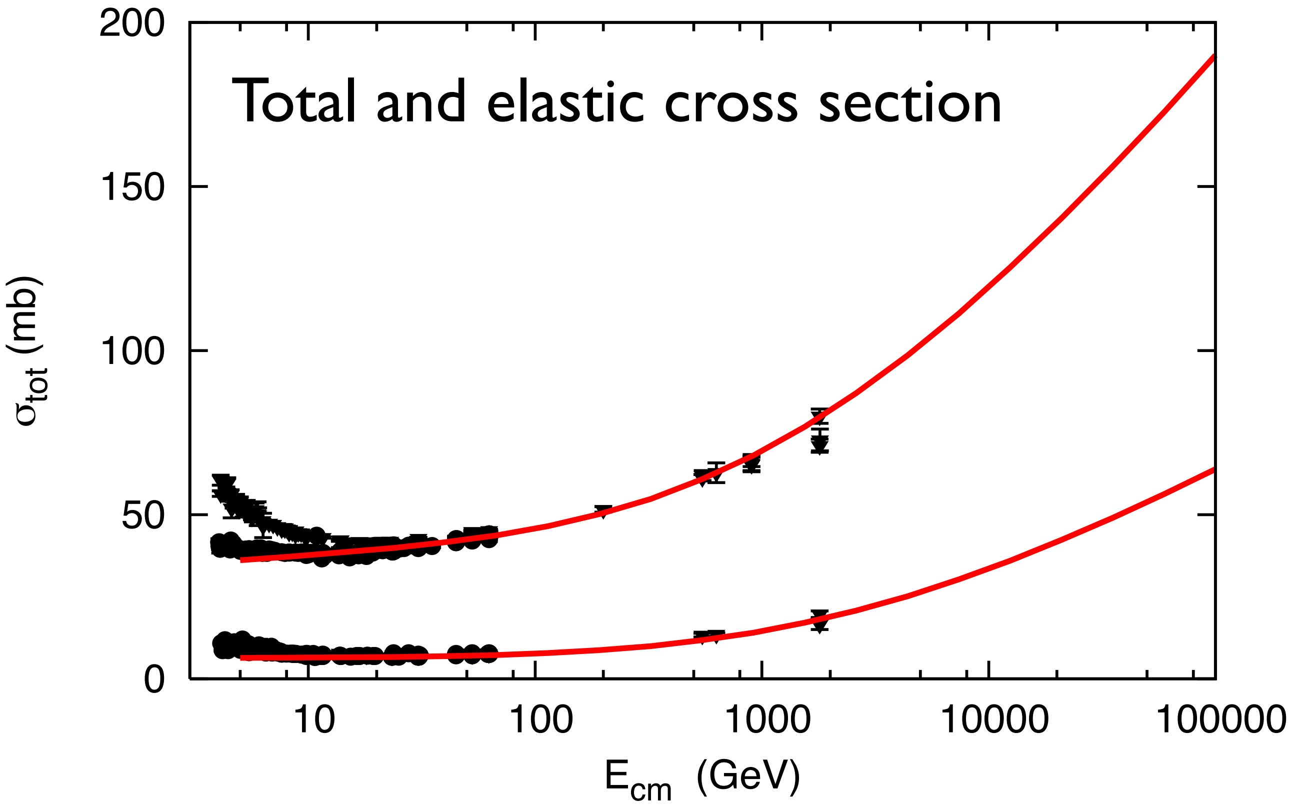
$$\lambda_1 = (1 - \alpha_Y - \gamma_Y)(1 - \alpha_Z - \gamma_Z)$$

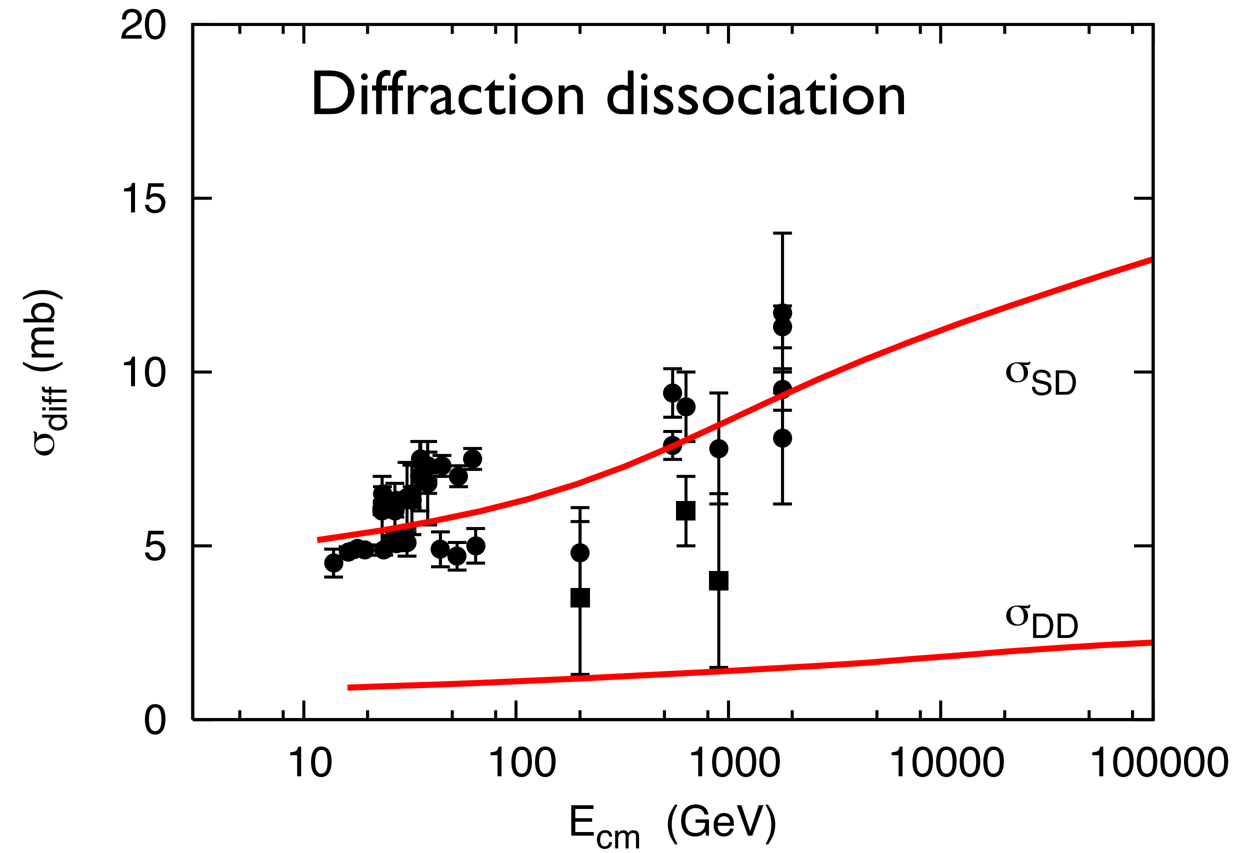
$$\lambda_2 = (1 - \alpha_Y - \gamma_Y)(1 - \alpha_Z + \gamma_Z)$$

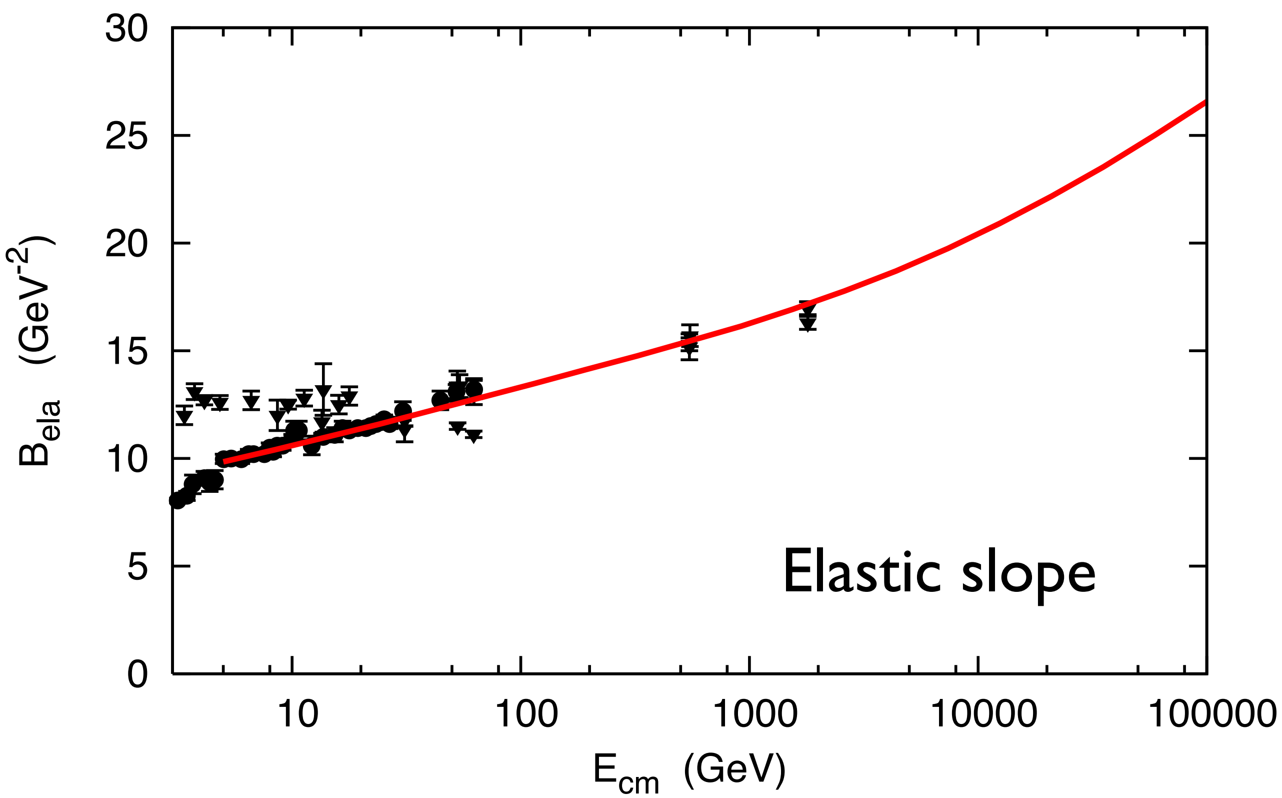
$$\lambda_3 = (1 - \alpha_Y + \gamma_Y)(1 - \alpha_Z - \gamma_Z)$$

$$\lambda_4 = (1 - \alpha_Y + \gamma_Y)(1 - \alpha_Z + \gamma_Z).$$

SIBYLL cross section fits



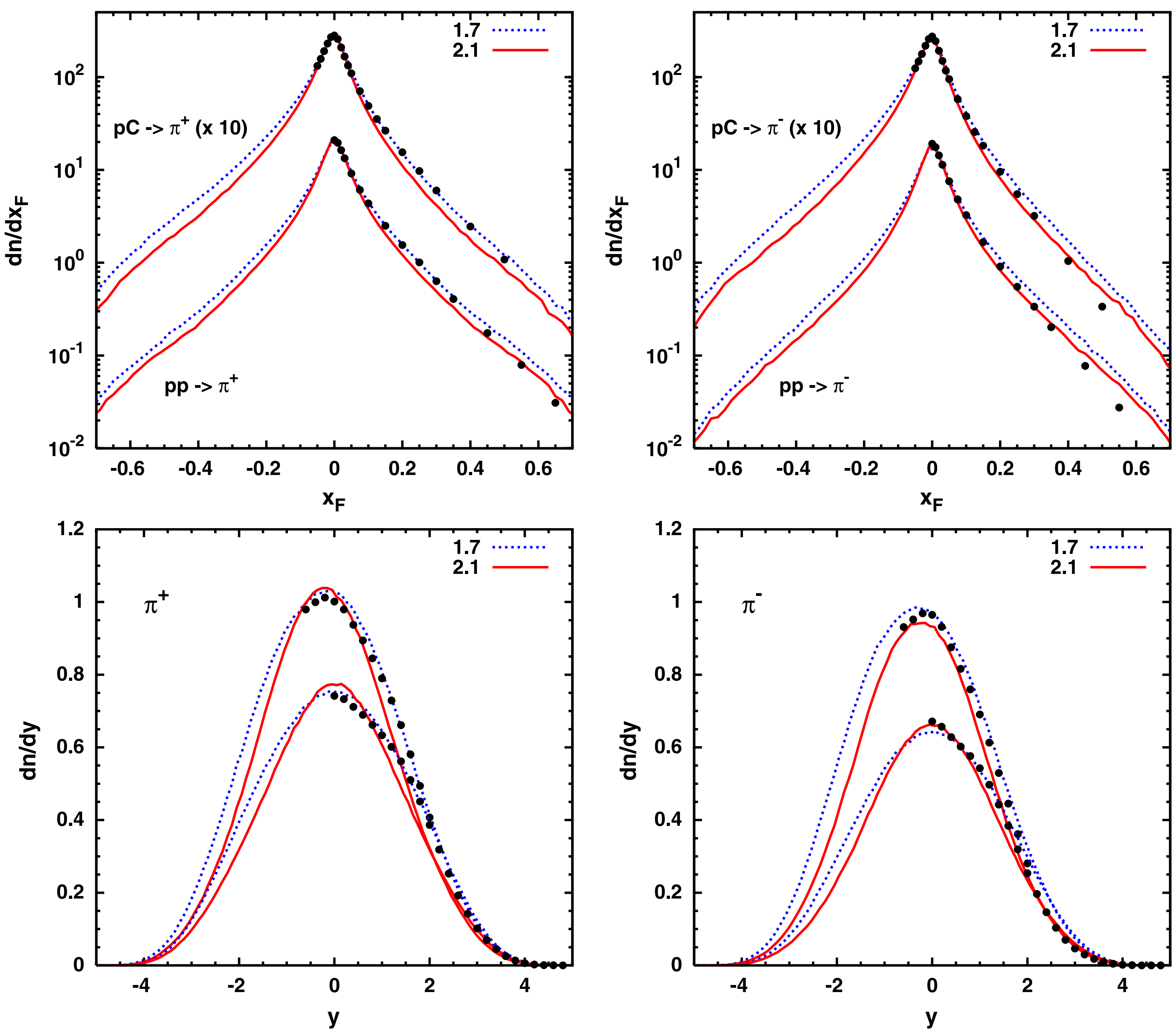




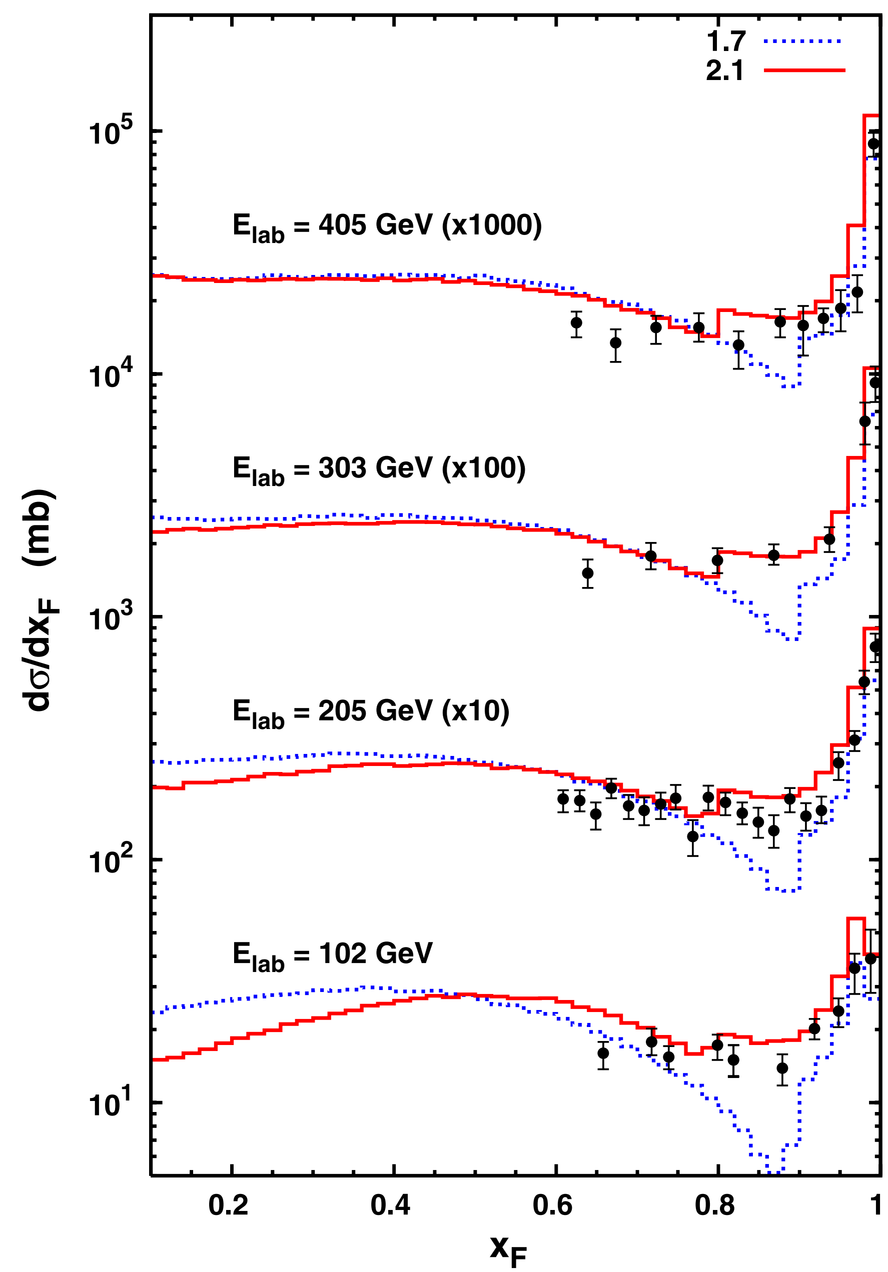
Low energy:
parametrizations of data are used

Comparison to fixed target data

NA49 p-p and p-C at 158 GeV

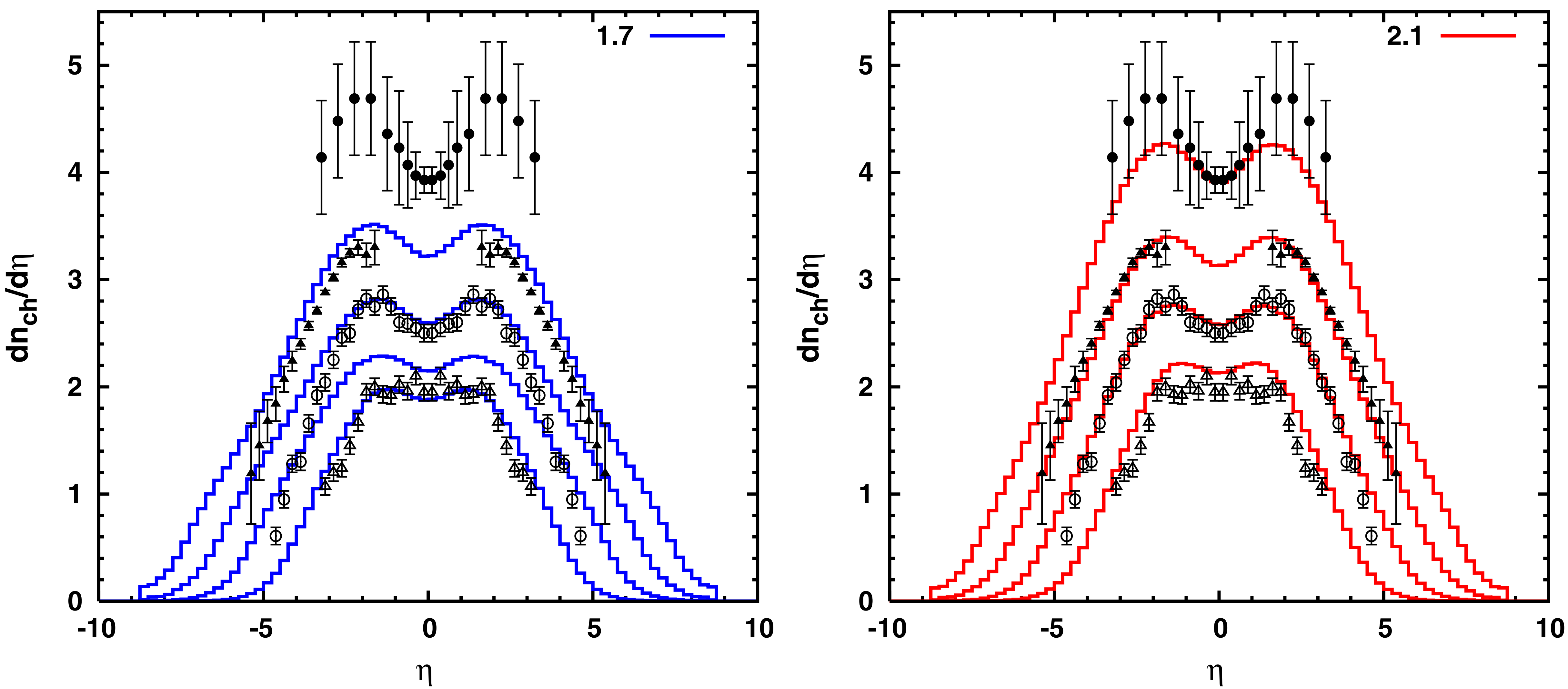


leading proton distributions



Comparison to collider data (i)

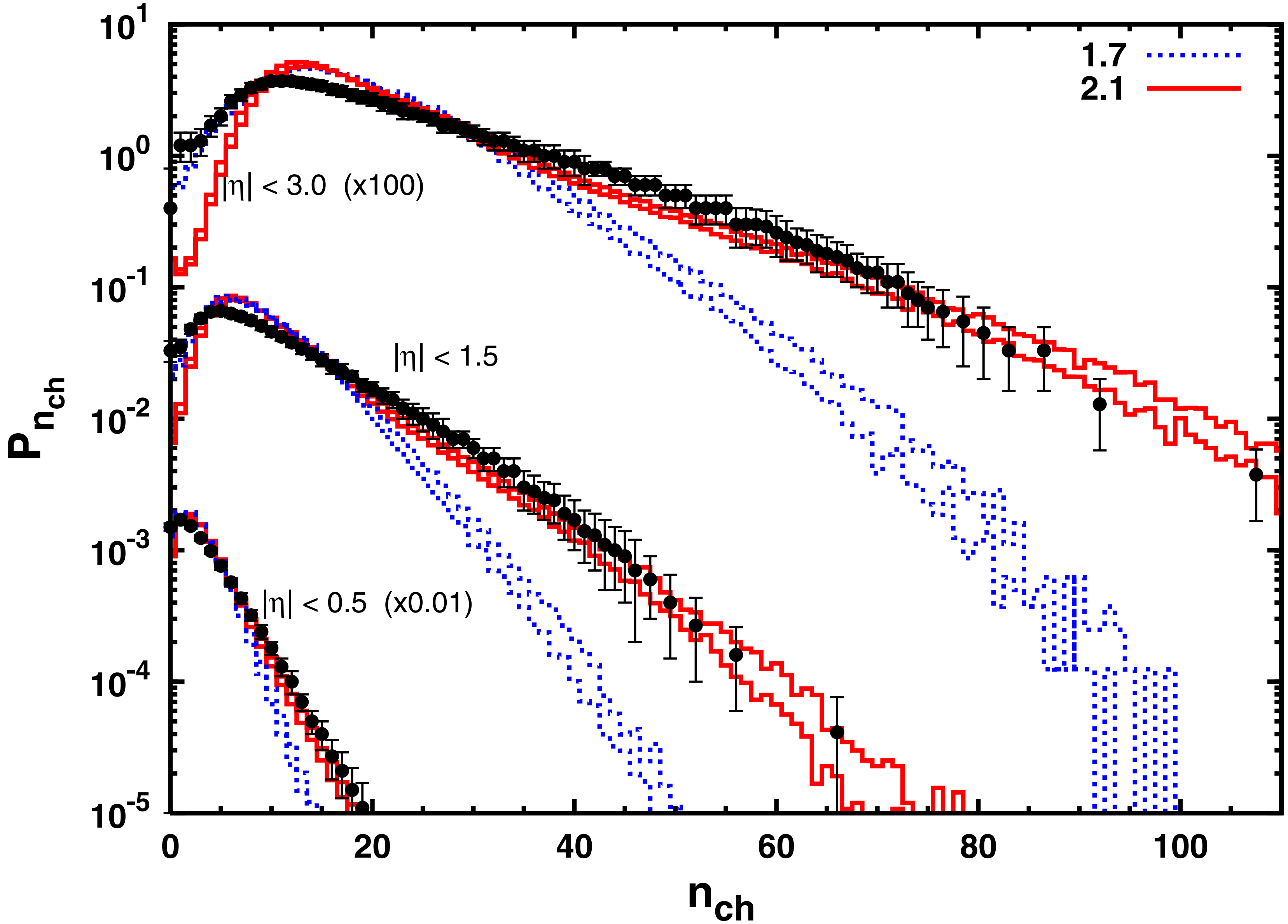
Pseudorapidity distribution of charged particles



Diffraction: part of cross section assigned to diffraction, increased number ofmultiple interactions in non-diffractive part of cross section

Comparison to collider data (ii)

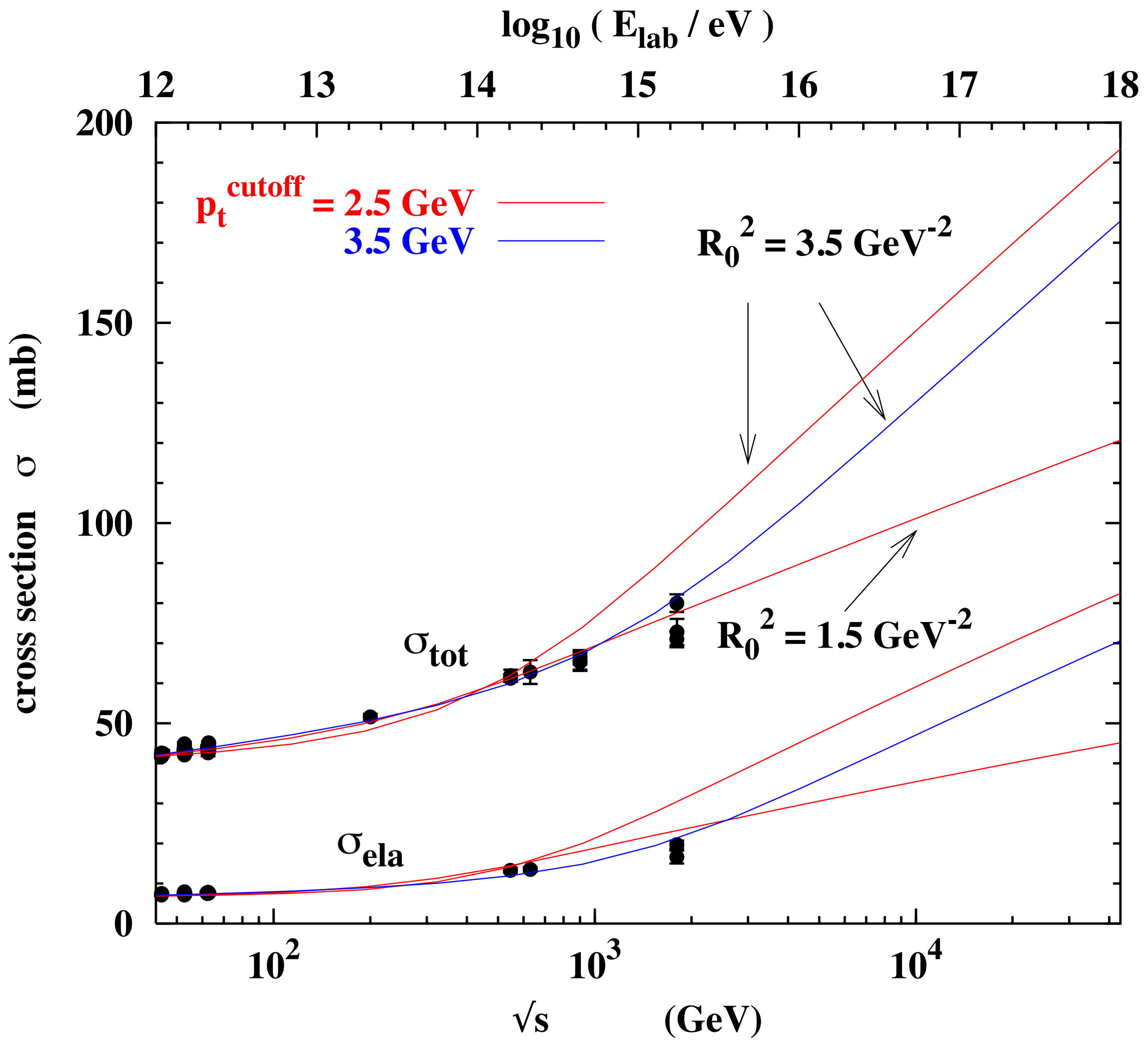
Charged multiplicity UA5, 900 GeV c.m.s.



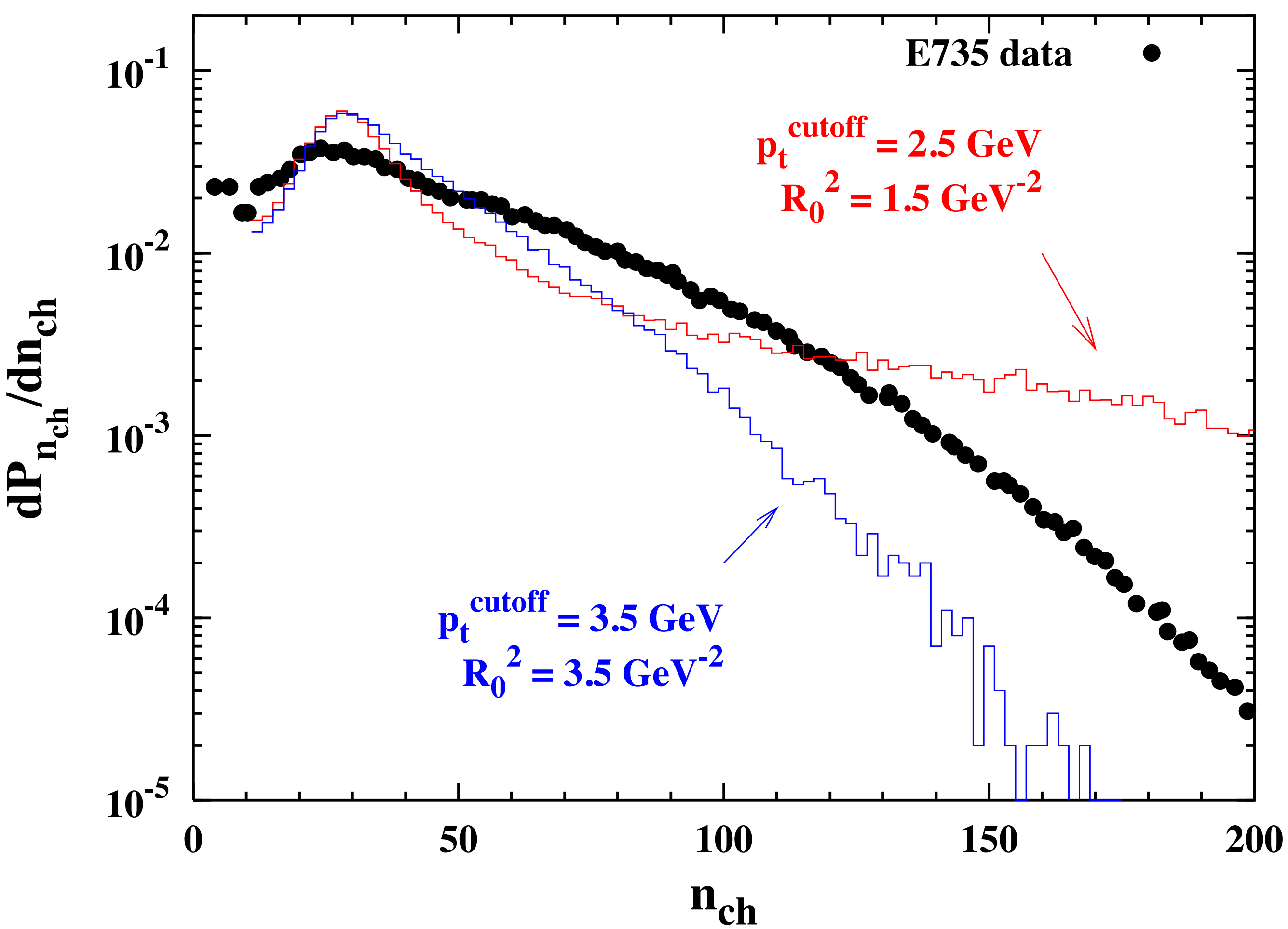
Wider distribution mainly related to inclusion of diffraction in eikonal formalism

Could also be achieved with different impact parameter profile, but then elastic scattering not correctly described

Impact of impact parameter profile

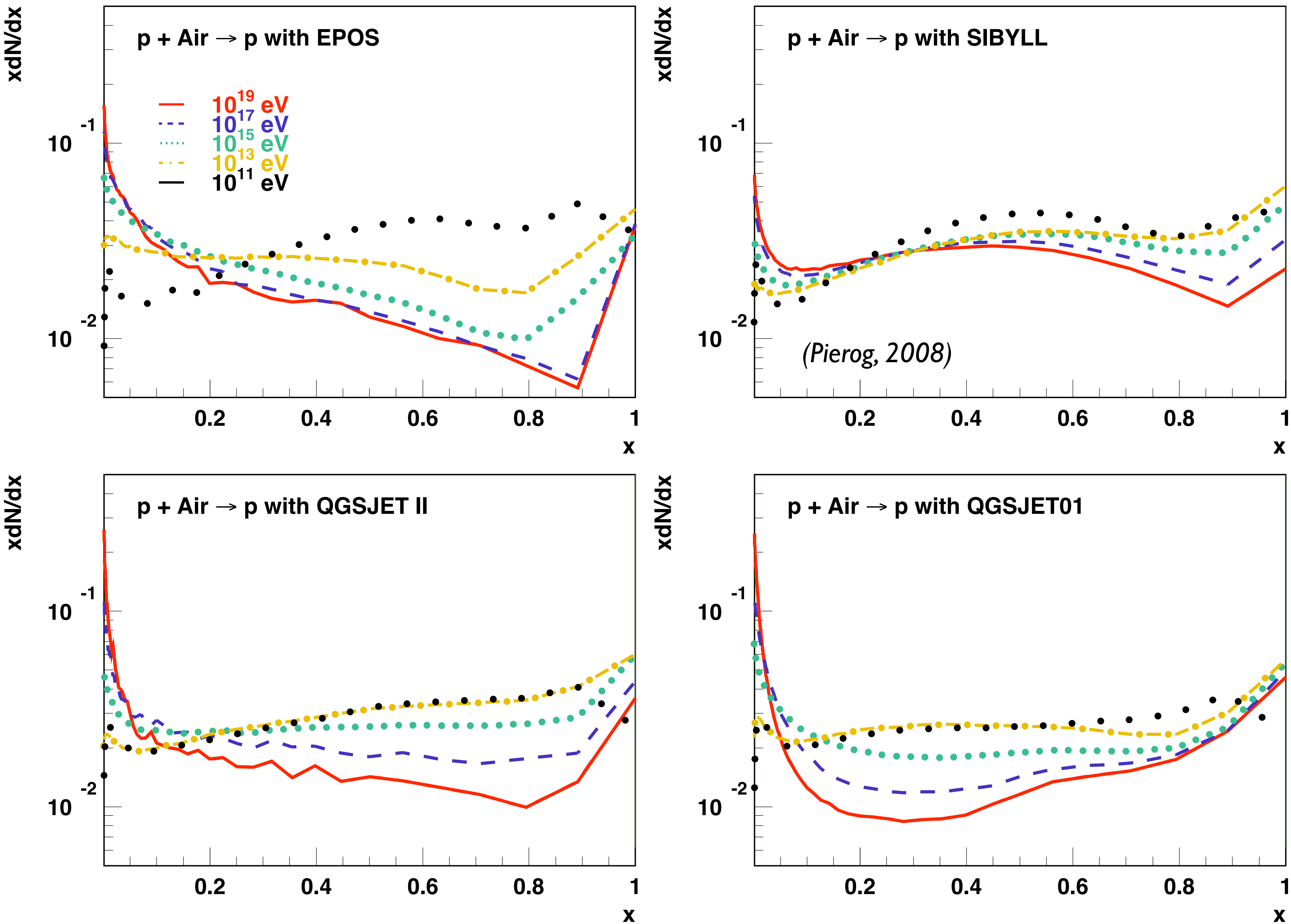


Change of transverse area populated with hard partons

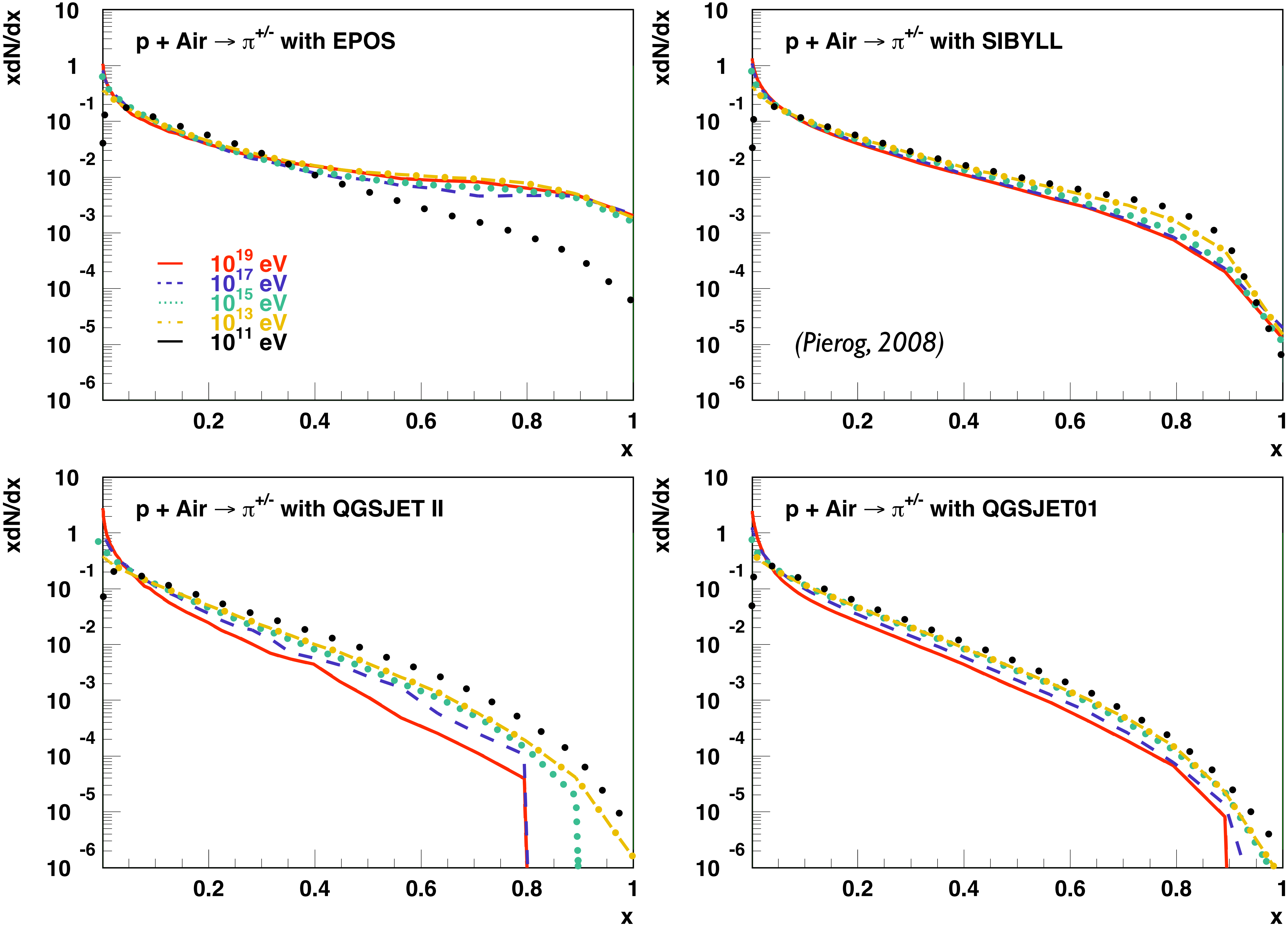


Direct correlation between cross section and distribution of multiple interactions

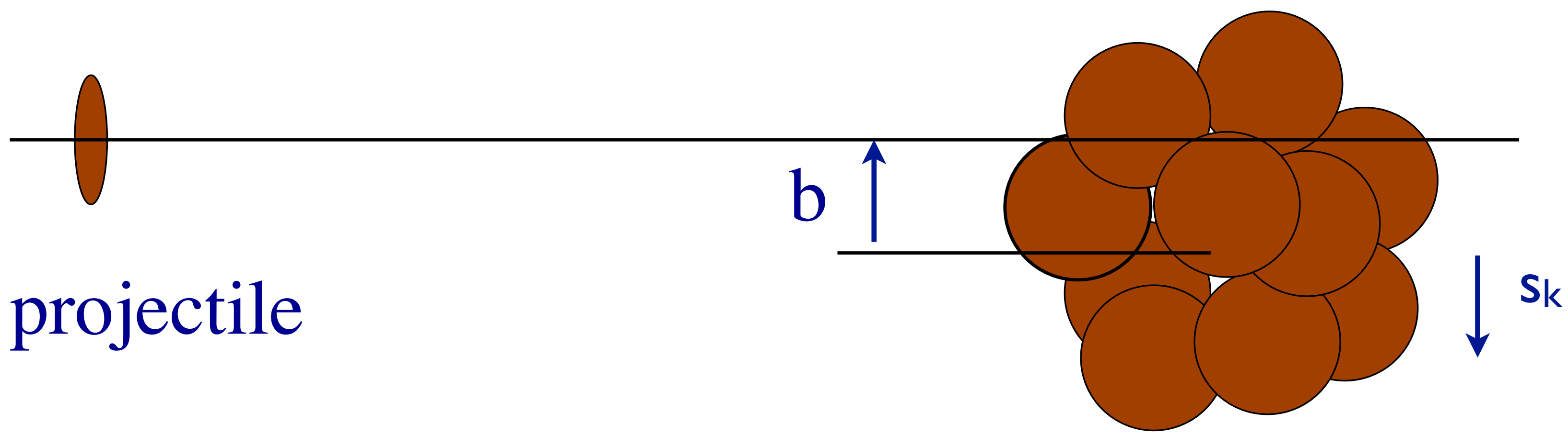
Scaling: model predictions (i)



Scaling: model predictions (ii)



Interaction of hadrons with nuclei



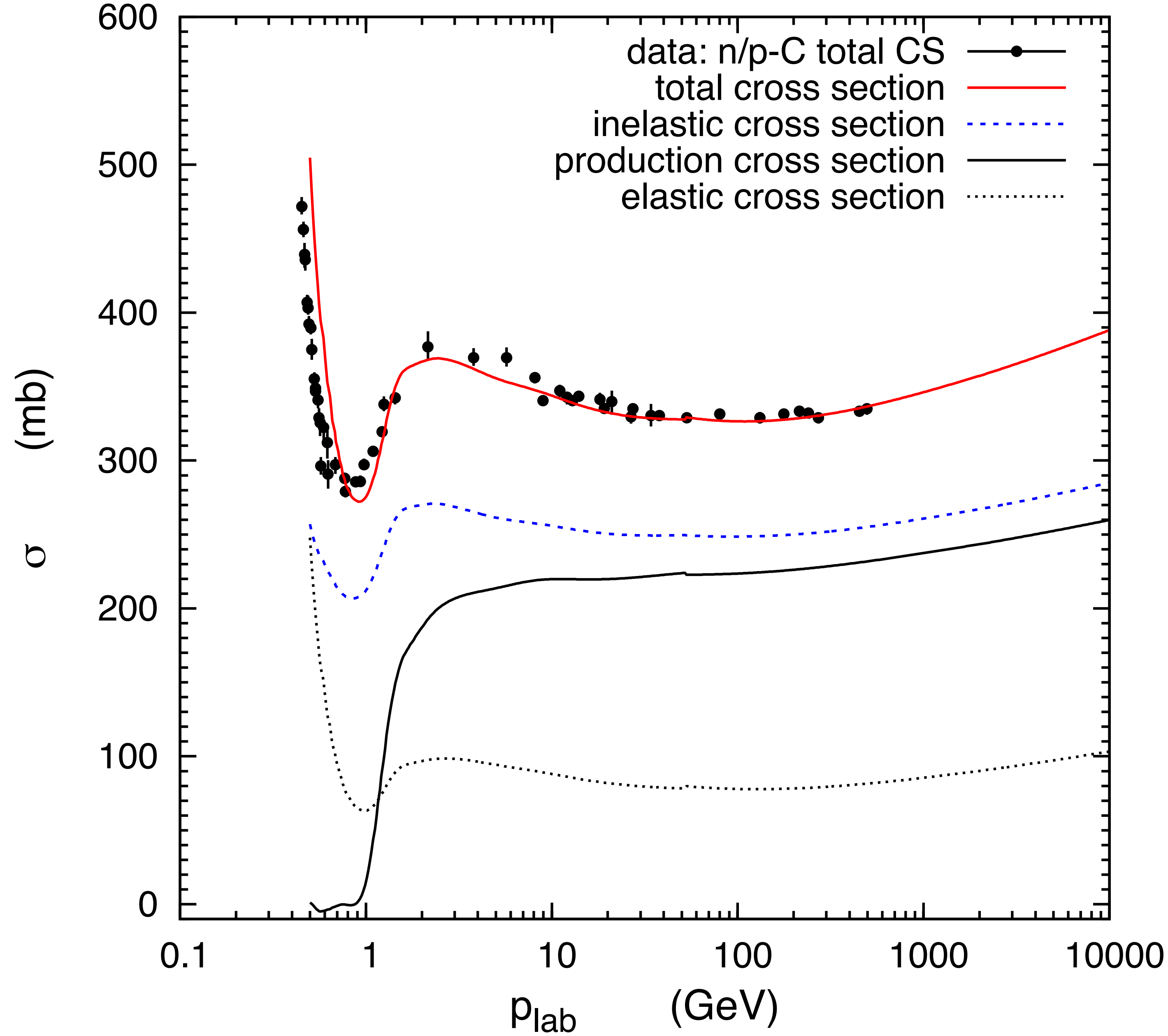
Standard Glauber approximation:

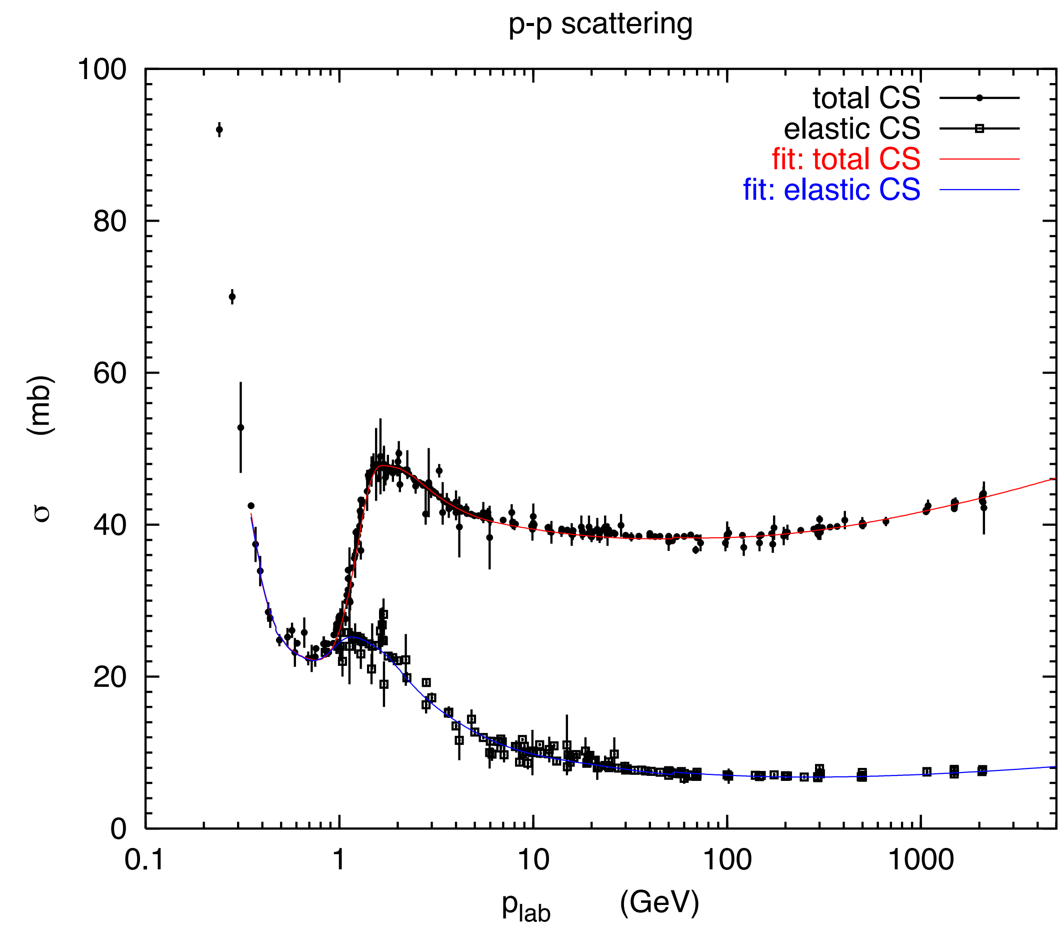
$$\sigma_{\text{inel}} = \int d^2\vec{b} \left[1 - \prod_{k=1}^{A} \left(1 - \sigma_{\text{tot}}^{NN} T_N(\vec{b} - \vec{s}_k) \right) \right] \approx \int d^2\vec{b} \left[1 - \exp\left\{ -\sigma_{\text{tot}}^{NN} T_A(\vec{b}) \right\} \right]$$

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

Coherent superposition of elementary nucleon-nucleon interactions

Example: proton-carbon cross section

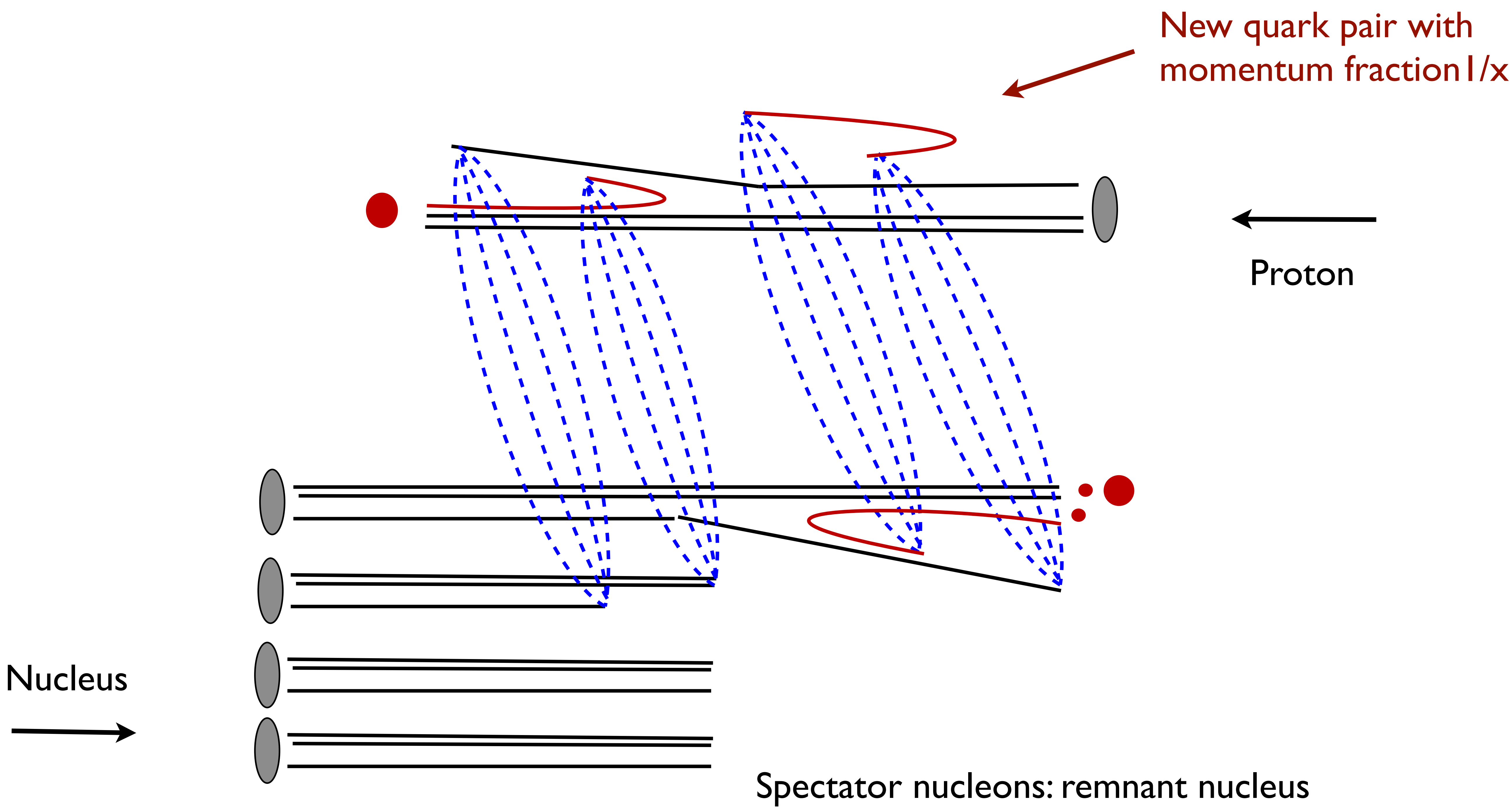




$$\sigma_{\text{prod}}^{\text{pC}} = \frac{A\sigma_{\text{ine}}^{\text{pp}}}{\langle n_{\text{part}} \rangle}$$

Number of participating target nucleons (1.8 at 100 GeV)

String configuration for nucleus as target



Outlook

New version with small updates:

(Ahn et al. ISVHECRI 2010)

- bug fixes and technical improvements
- increased baryon-antibaryon production
- charmed mesons and baryons