Hadronic Interactions and Extensive Air Shower Development

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"Better consistent and wrong than ... wrong and inconsistent!"

P. Sokolsky

"Avoid models as much as you can!"

"Important issues are INPUT OF REAL DATA ..."

A. Watson

Layout

- Hadronic interactions in air showers: key quantities
- 'Central' & peripheral collisions
- High energy interactions: qualitative picture
- 'Elementary' interaction
- Multiple scattering approach
- Diffraction dissociation
- Non-linear effects
- Hadronic cross sections: total inelastic or non-diffractive?
- Elongation rate & $X_{\rm max}$ distribution: model uncertainties?
- Outlook

Hadronic interactions in air showers

Extensive air shower (EAS) development $\Leftarrow$ high energy interactions

- backbone - hadron cascade
- guided by few interactions of initial (fastest secondary) particle
  $\Rightarrow$ main source of fluctuations

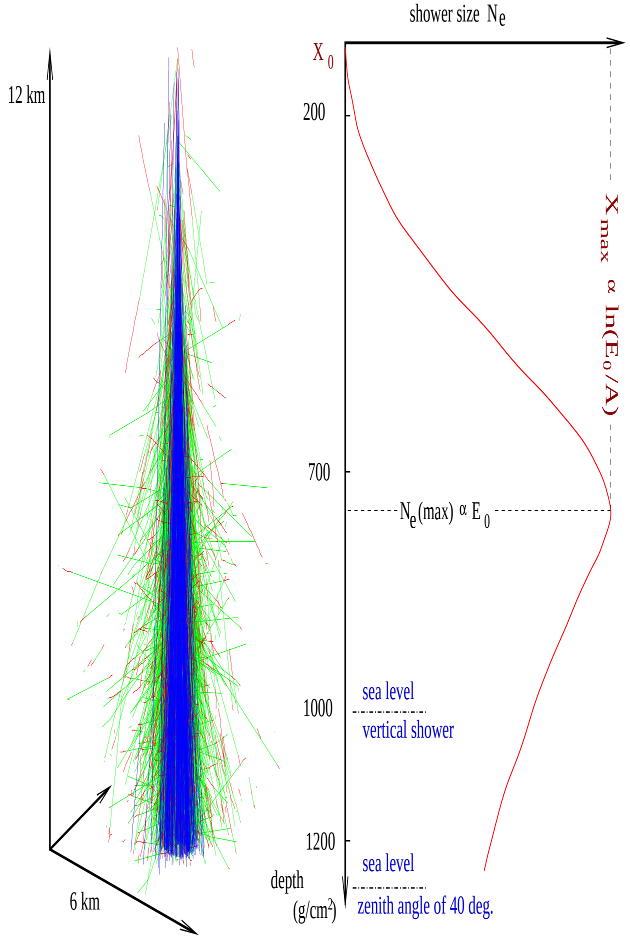
Basic quantities:

- shower maximum position $X_{\rm max}$
  - mainly sensitive to $\sigma^{\rm inel}_{p-{\rm air}}$ ($\sigma^{\rm non-diffr}_{p-{\rm air}}$), $K^{\rm inel}_{p-{\rm air}}$
- number of muons at ground N_μ
  - mainly depends on $N^{\rm ch}_{\pi-{\rm air}}$ (at energies $\sim \sqrt{E_0}$)

Fluorescence measurements:
- grossly depend on the primary particle interaction

Ground-based studies:

- very sensitive to pion-air interactions

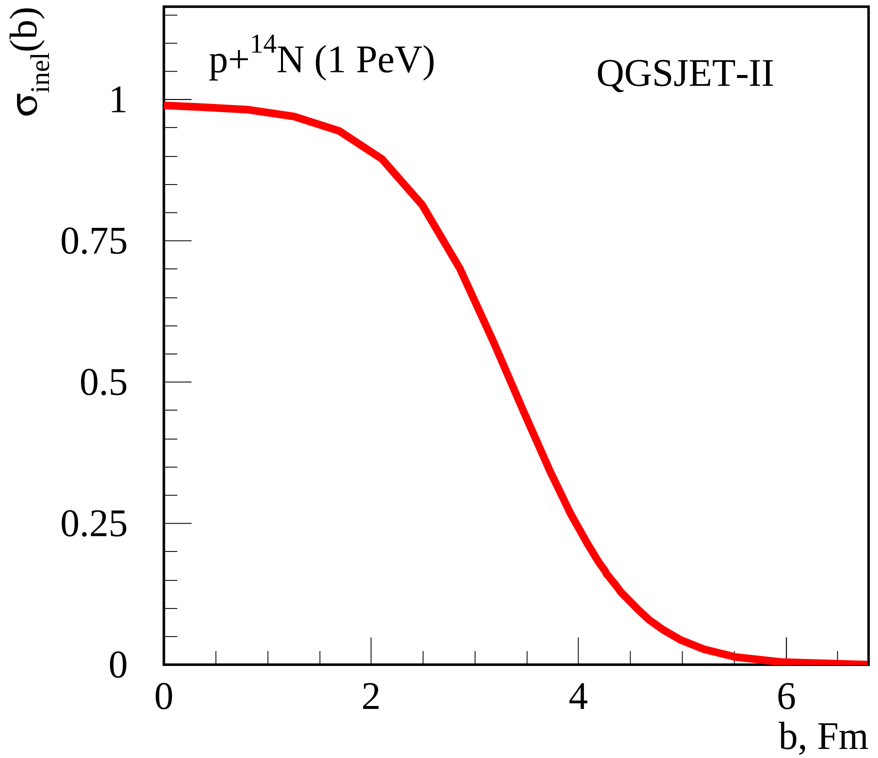


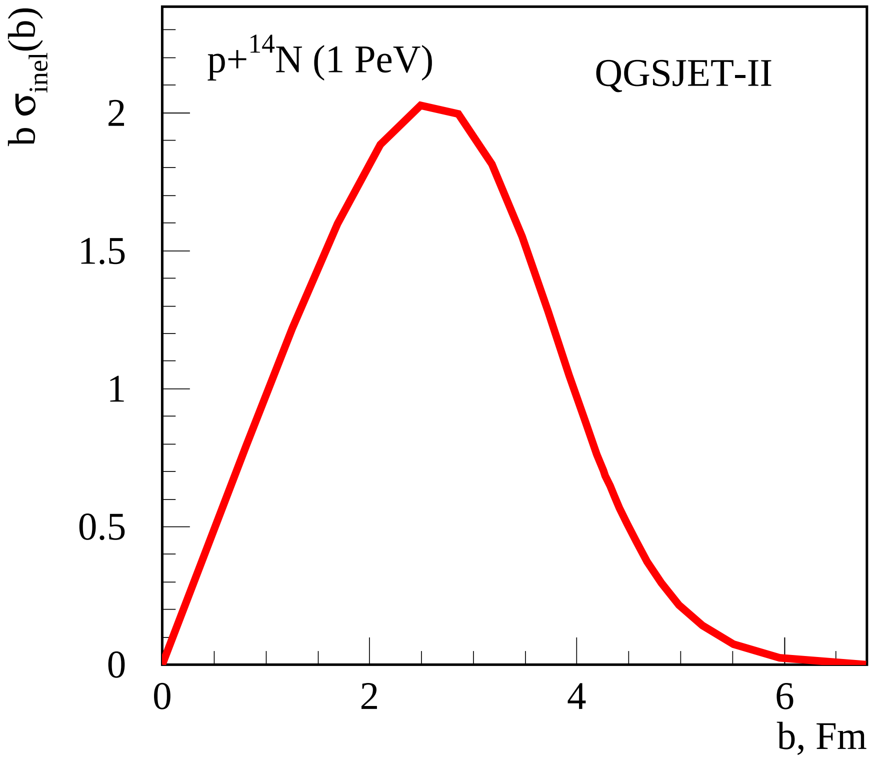
“Central” & peripheral collisions - relative importance?

What is “central”?

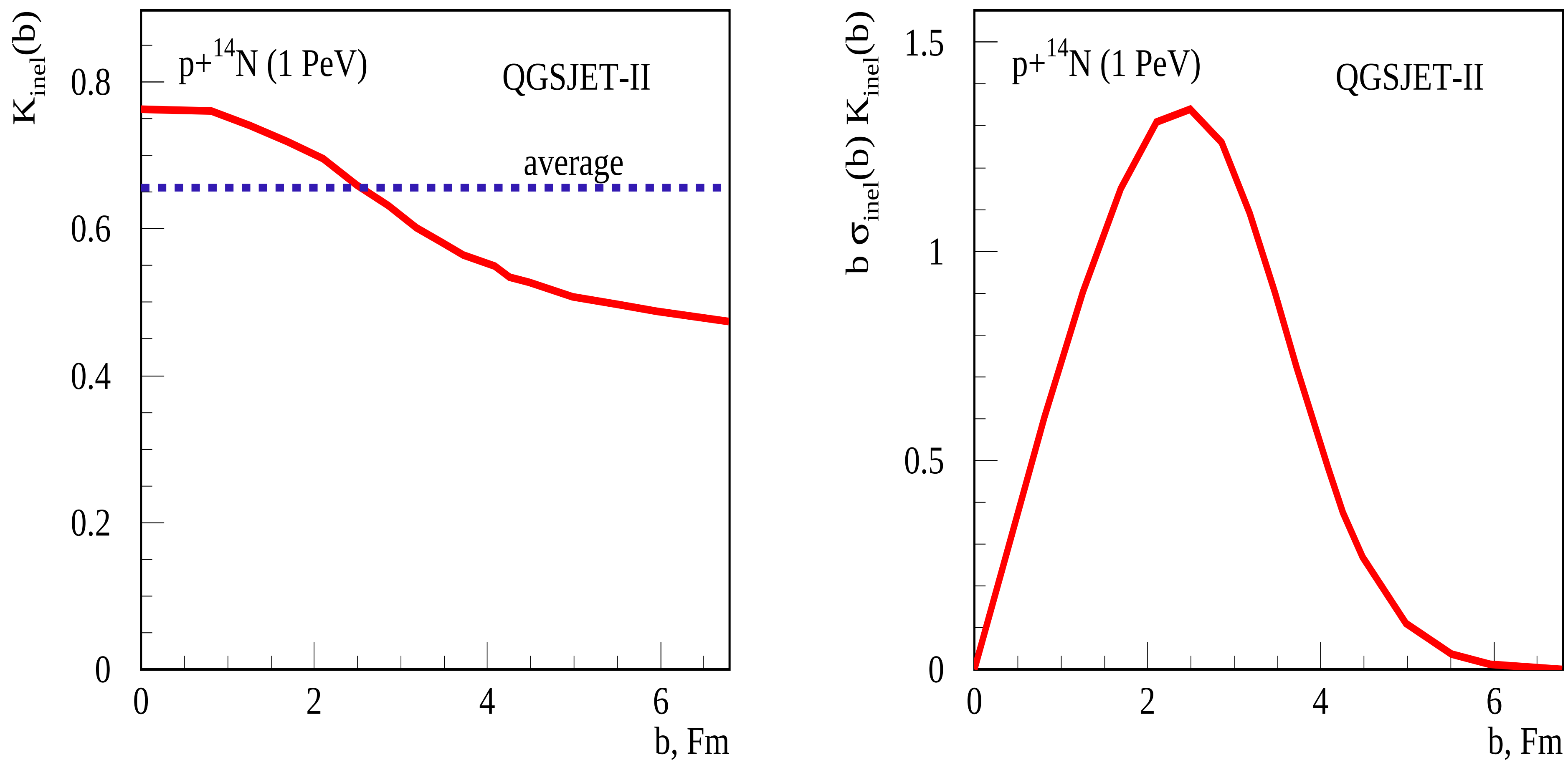
- “black disc” limit: $\sigma^{\rm inel}(b) \sim 1 \Rightarrow \sigma^{\rm el}/\sigma^{\rm tot} \simeq 1/2$
- experiment: $\sigma_{pp}^{\rm el}/\sigma_{pp}^{\rm tot} \simeq 1/4$ @ $\sqrt{s} = 1.8$ TeV

Interaction profile & b-contributions to $\sigma_{p-{\rm air}}^{\rm inel}$ @ $E_0 = 10^6$ GeV:



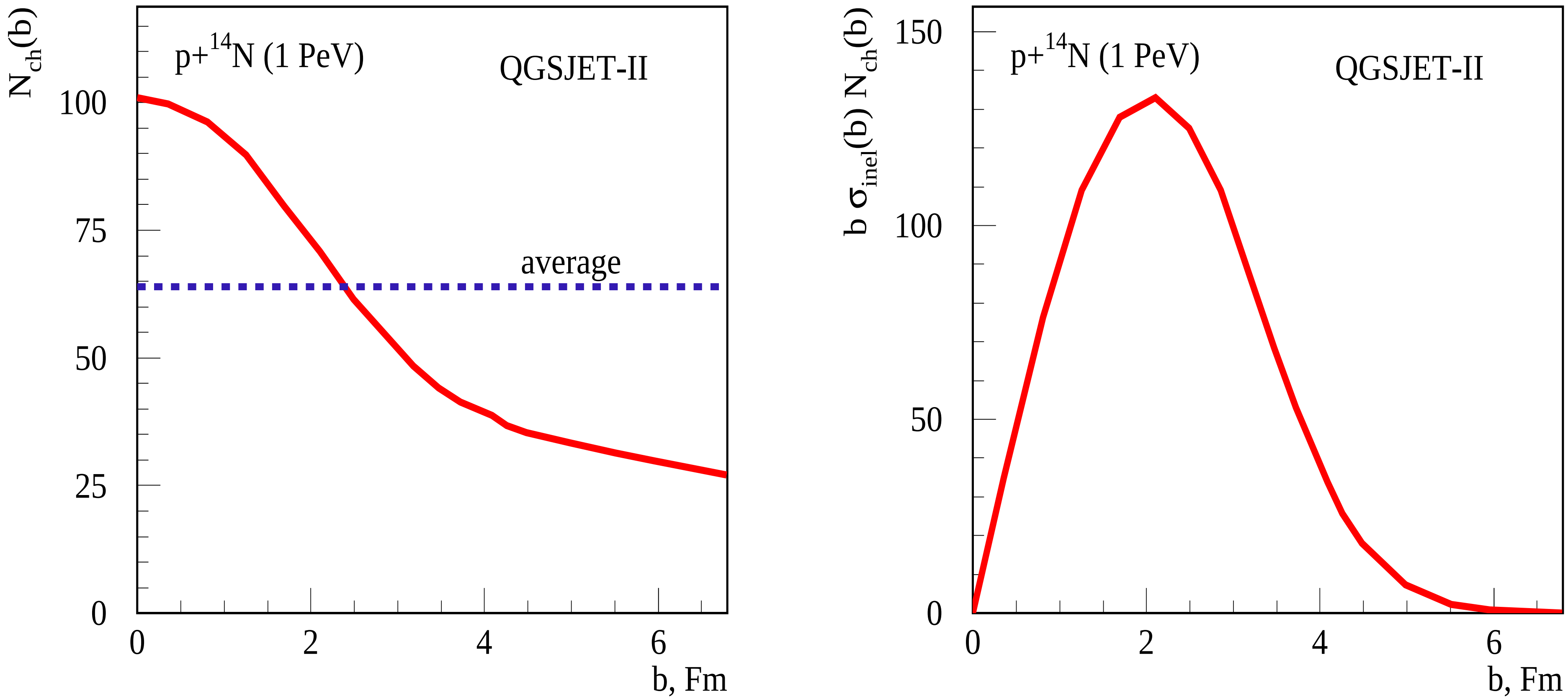


b-dependence & b-contributions to $K^{\rm inel}_{p-{\rm air}}$ @ $E_0 = 10^6$ GeV:



Model dependence - mainly due to the treatment of peripheral interactions

b-dependence & b-contributions to $N^{\rm ch}_{p-{\rm air}}$ @ $E_0 = 10^6$ GeV:



Knowledge of “central” physics - insufficient for EAS predictions

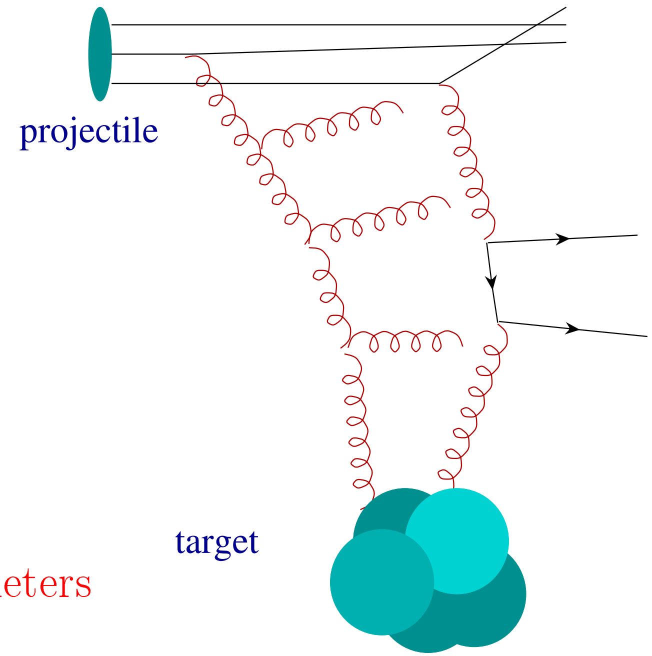
Peripheral contribution:

- decisive for cross sections & energy losses $\Rightarrow$ for $X_{\max}$
- still of high importance for $\langle N_{\rm ch}\rangle$ $\Rightarrow$ for N_μ

Qualitative picture of high energy interactions

Hadronic interactions - multiple scattering processes (parton cascades):

Single scattering:



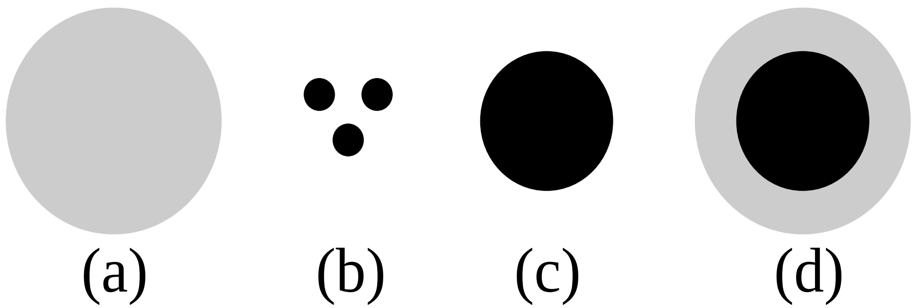
(picture from R. Engel)

- (a) "soft" (all $|q^2| \sim p_t^2 < Q_0^2,\ Q_0 \sim 1\,\mathrm{GeV}^2$) cascade
  - large effective area ($\Delta b^2 \sim 1/|q^2|$)
  - slow energy rise

  $\Rightarrow$ dominant at relatively low energies
- (b) cascade of "hard" partons (all $|q^2| \gg Q_0^2$)
  - small effective area
  - rapid energy rise

  $\Rightarrow$ important at very high energies and small impact parameters
- (c) "semi-hard" scattering (some $|q^2| > Q_0^2$)
  - large effective area
  - rapid energy rise

  $\Rightarrow$ dominates at high energies and over a wide b-range



'Elementary' interaction

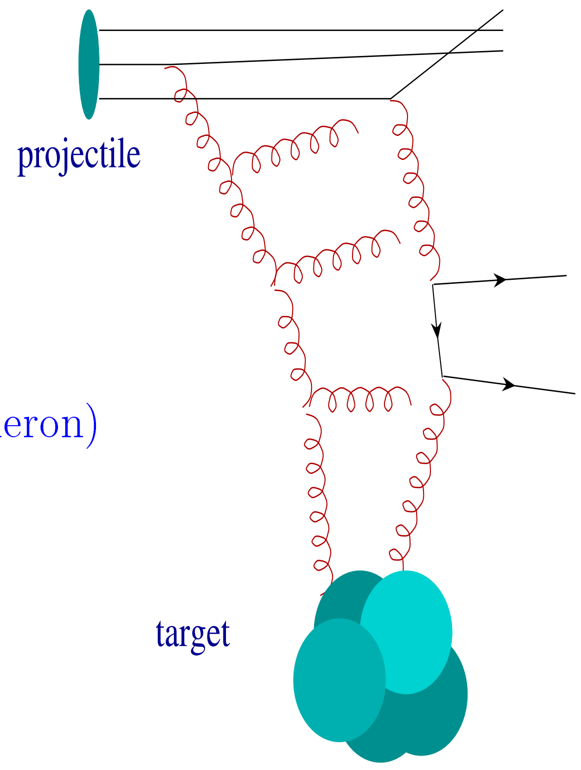
General model strategy:

- describe 'elementary' interactions (parton cascades)
  - scattering amplitude
  - hadronization procedure (conversion of partons into hadrons)
- apply Reggeon approach to treat multiple scattering processes
- describe particle production as a superposition of a number of 'elementary' processes

Parton cascades start at low virtualities

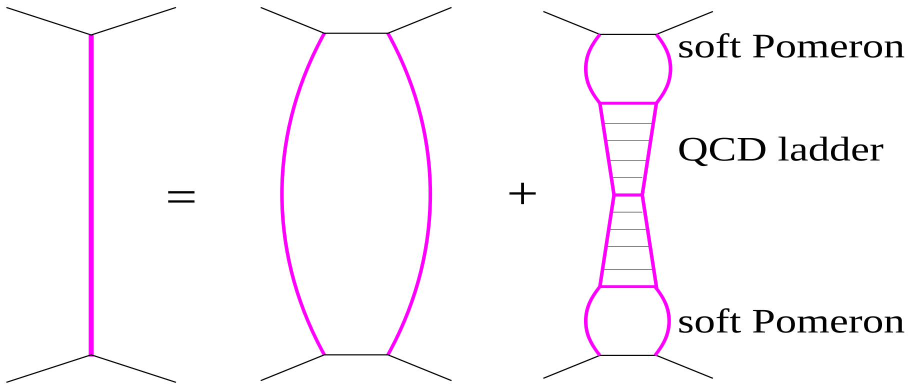
$\Rightarrow$ phenomenological scheme (QGSJET):

- Q_0^2 - cutoff between "soft" and perturbative physics
- "Soft" interactions (all $|q^2|$ - small $\Rightarrow \alpha_s(q^2) > 1$):
  - pQCD is inapplicable $\Rightarrow$ parameterized amplitude ('soft' Pomeron)
- "Semi-hard" processes ($|q^2| > Q_0^2 \Rightarrow \alpha_s(q^2) \ll 1$)
  - "soft" Pomeron for $\left|p_t^2\right| < Q_0^2$
  - QCD parton ladder for $\left|p_t^2\right| > Q_0^2$



General interaction $\Rightarrow$ "general Pomeron":

$$\chi_{ad}^{\mathbb{P}}(s,b) = \chi_{ad}^{\mathbb{P}_{\rm soft}}(s,b) + \chi_{ad}^{\mathbb{P}_{\rm sh}}(s,b)$$



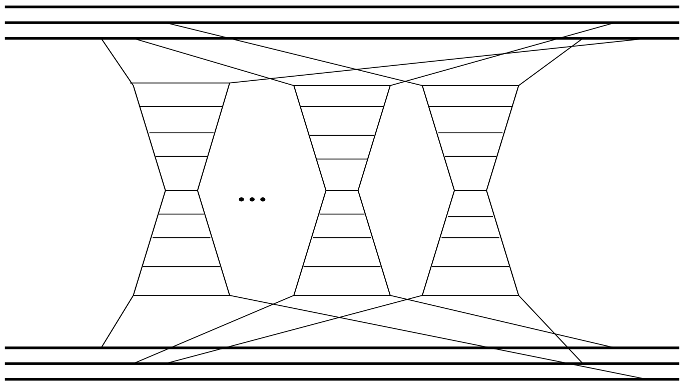
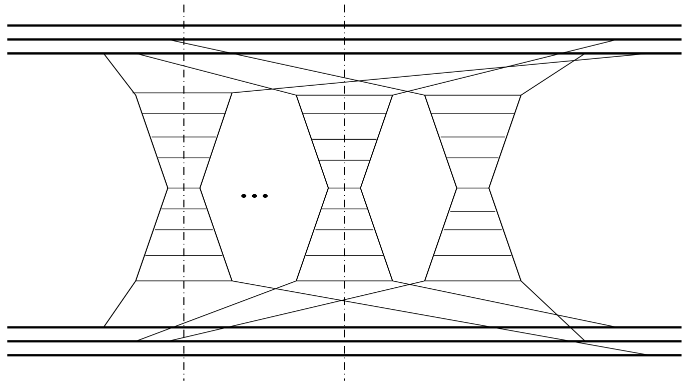
- particle production: perturbative (=calculable) parton cascade + string hadronization

Important: direct relation between the eikonal and inclusive jet cross section

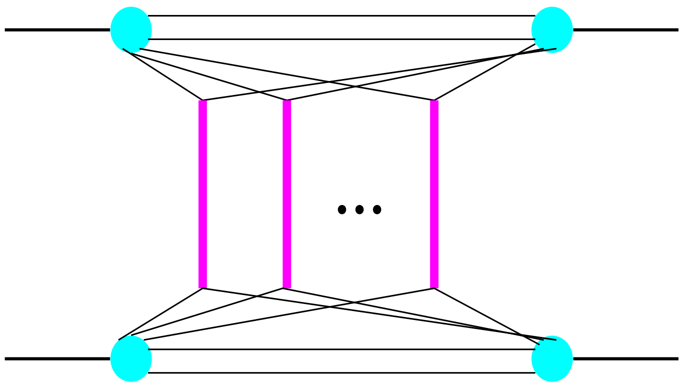
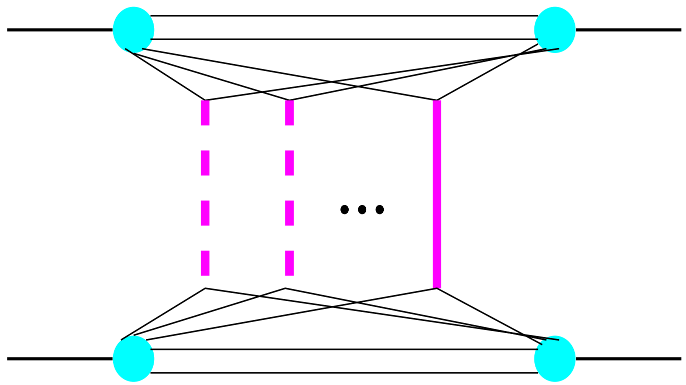
$$\int d^2b\ \chi_{ad}^{\mathbb{P}_{\rm sh}}(s,b) \ \equiv\ \sigma_{ad}^{\rm jet}(s,Q_0^2)$$

$$\sigma_{ad}^{\rm jet}(s,Q_0^2) \ = \ \sum_{I,J=q,\bar{q},g} \int_{p_t^2>Q_0^2} dp_t^2 \int dx^+ dx^- \ \frac{d\sigma_{IJ}^{2\to 2}(x^+x^-s,p_t^2)}{dp_t^2} \times \ f_{I/a}(x^+,M_F^2)\ f_{J/d}(x^-,M_F^2)$$

Multiple scattering approach

$\sigma_{ad}^{\text{tot}} = \quad \text{Im}$  $= \sum$ 

Or

$\sigma_{ad}^{\text{tot}} = \quad \text{Im}$  $= \sum$ 

Contribution with m inelastic and n elastic subprocesses:

$$\sigma_{ad}^{(m,n)}(s) \; = \; \int d^2b \, \frac{\left[2\chi_{ad}^{\mathbb{P}}(s,b)\right]^n}{n!} \, \frac{\left[-2\chi_{ad}^{\mathbb{P}}(s,b)\right]^n}{n!}$$

Physical quantity - 'topological' cross sections:

$$\sigma_{ad}^{(m)}(s) \;=\; \sum_{n=0}^{\infty} \sigma_{ad}^{(m,n)}(s) = \int d^2b \; \frac{\left[2\chi_{ad}^{\mathbb{P}}(s,b)\right]^n}{n!} \, e^{-2\chi_{ad}^{\mathbb{P}}(s,b)}$$

$\Rightarrow$ Inelastic cross section:

$$\sigma_{ad}^{\rm inel}(s) \;=\; \sum_{m=1}^{\infty} \sigma_{ad}^{(m,)}(s) = \int d^2b \; \left[1 - e^{-2\chi_{ad}^{\mathbb{P}}(s,b)}\right]$$

Hadron-nucleus (nucleus-nucleus) scattering - Glauber approach:

- phase additivity
- nucleons distributed according to the ground state wave function

$$\sigma_{aA}^{\rm inel}(s) \;=\; \int d^2b \; \left\{1 - \left[1 - \int d^2\zeta \; T_A(\zeta) \; \left(1 - e^{-2\chi_{ad}^{\mathbb{P}}(s,|\vec{b}-\vec{\zeta}|)}\right)\right]^A\right\}$$

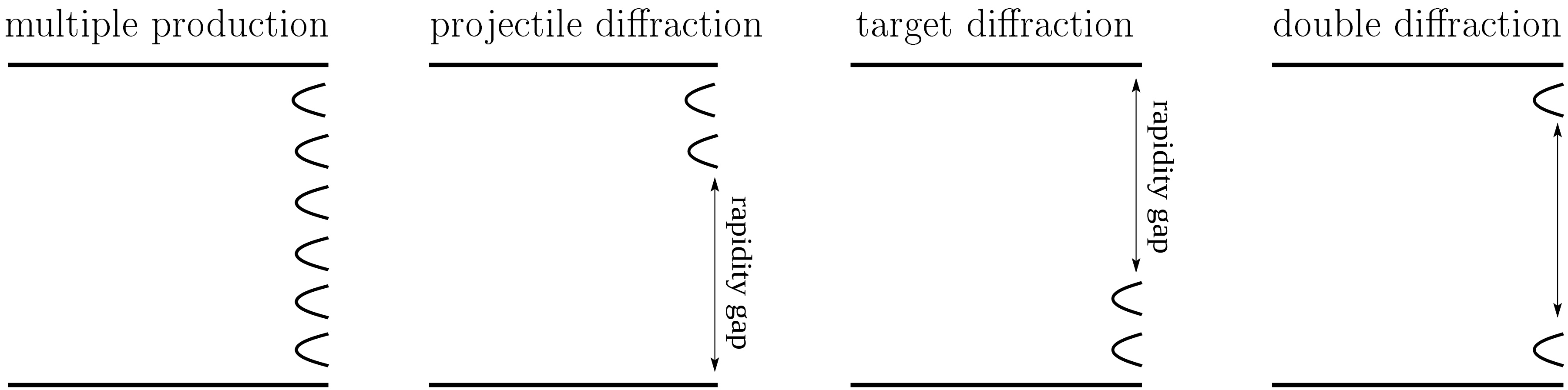
$T_A(\zeta) = \int dz \; \rho_A(\vec{\zeta}, z)$ - nuclear profile function

Often used:

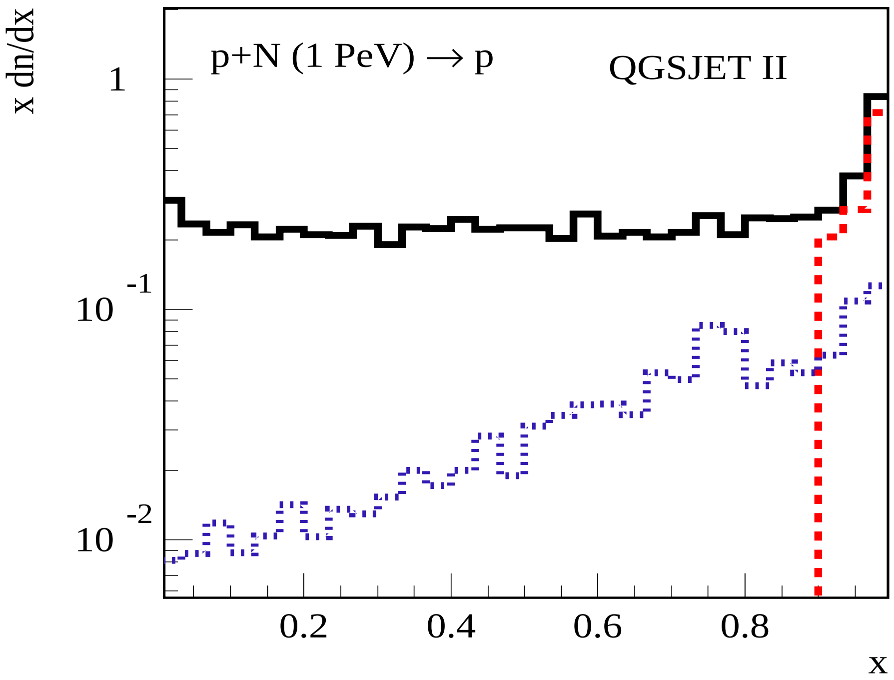
$$\sigma_{aA}^{\rm inel}(s) \;=\; \int d^2b \; \left\{1 - \left[1 - \sigma_{ap}^{\rm inel}(s) \; T_A(b)\right]^A\right\}$$

- incorrect (nucleon size neglected)

Diffraction dissociation



Leading proton spectrum & diffraction contributions



Good-Walker scheme for diffraction

Low mass diffraction - 2-component eikonal scheme: $|a\rangle = \frac{1}{\sqrt{2}}|1_a\rangle + \frac{1}{\sqrt{2}}|2_a\rangle$

$|k_a\rangle$ - diffractive eigenstates for hadron a;

couple to a Pomeron with different strength $\lambda_{k/a}$ $(\lambda_{k/a} + \lambda_{k/a} = 2)$

$$\sigma_{pp}^{\rm inel}(s) \; = \; \int d^2b \, \frac{1}{4} \sum_{i,j=1}^{2} \left[1 - e^{-2\lambda_{i/p}\,\lambda_{j/p}\,\chi_{pp}^{\mathbb{P}}(s,b)}\right]$$

$$\sigma_{pp}^{\rm s-diffr}(s) \; = \; 2\int d^2b \, \frac{1}{4} \sum_{j=1}^{2} \left[e^{-\lambda_{1/p}\,\lambda_{j/p}\,\chi_{pp}^{\mathbb{P}}(s,b)} - e^{-\lambda_{2/p}\,\lambda_{j/p}\,\chi_{pp}^{\mathbb{P}}(s,b)}\right]^2$$

$$\frac{1}{4} \sum_{i,j=1}^{2} \left[1 - e^{-2\lambda_{i/p}\,\lambda_{j/p}\,\chi_{pp}^{\mathbb{P}}(s,b)}\right] \; = \; \begin{cases} 1, & b \to 0 \\ 2\chi_{pp}^{\mathbb{P}}(s,b) - 2\,(2 - \lambda_{1/p}\,\lambda_{2/p})^2\,(\chi_{pp}^{\mathbb{P}}(s,b))^2 + \ldots, & b \to \infty \end{cases}$$

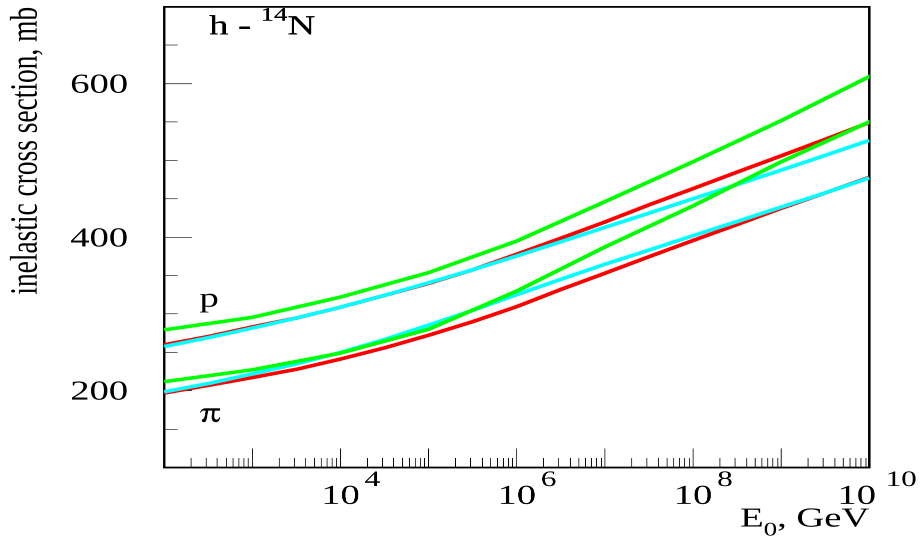
Higher diffraction $\Rightarrow$ cross sections reduced at high energies (inelastic screening)

Topological cross section (n inelastic sub-processes):

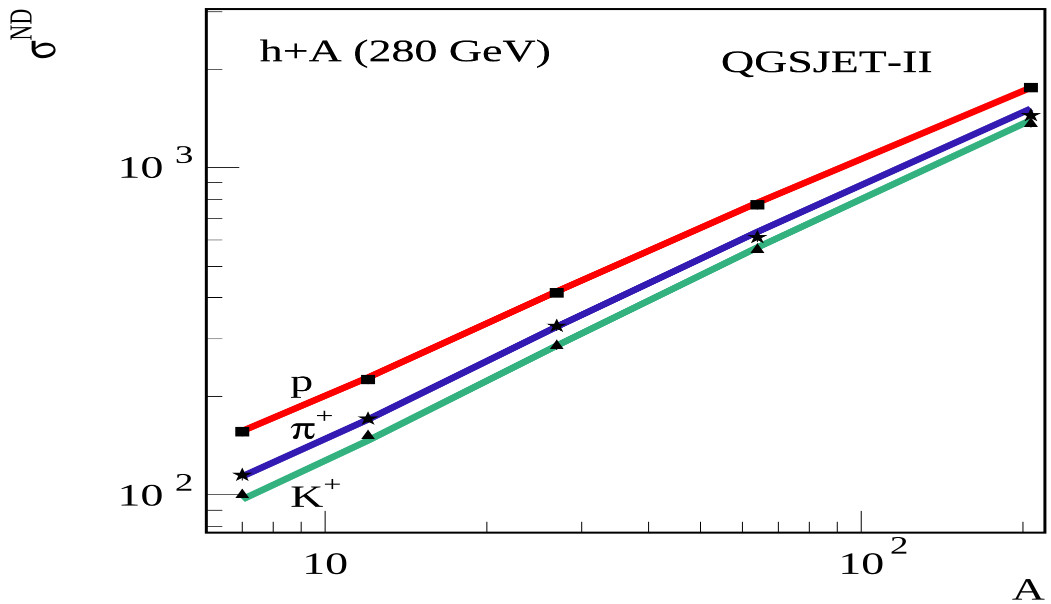
$$\sigma_{ad}^{(n)}(s) \; = \; \int d^2b \, \frac{1}{4} \sum_{i,j=1}^{2} \frac{\left[2\lambda_{i/a}\,\lambda_{j/d}\,\chi_{ad}(s,b)\right]^n}{n!} e^{-2\lambda_{i/a}\,\lambda_{j/d}\,\chi_{ad}(s,b)}$$

$\Rightarrow$ larger multiplicity fluctuations

Hadron-nucleus scattering - stronger inelastic screening (A-enhancement):
(probably) explains SIBYLL / QGSJET-II difference at low energies



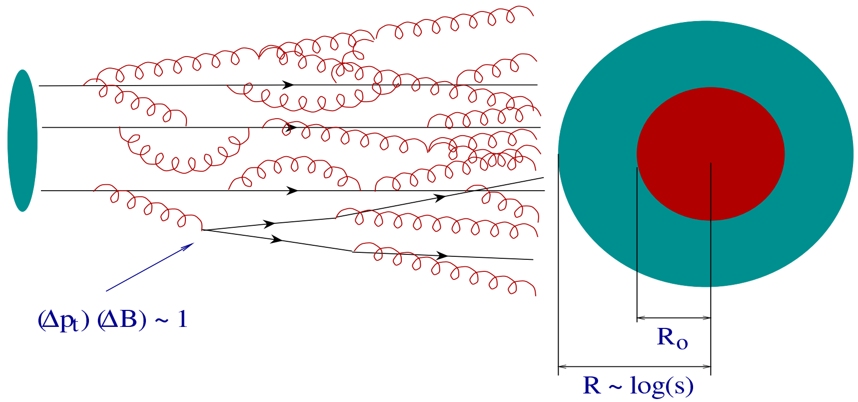
Non-diffractive hadron-nucleus cross section (QGSJET-II vrs. Carroll et al., 1979)



Non-linear effects (QGSJET II)

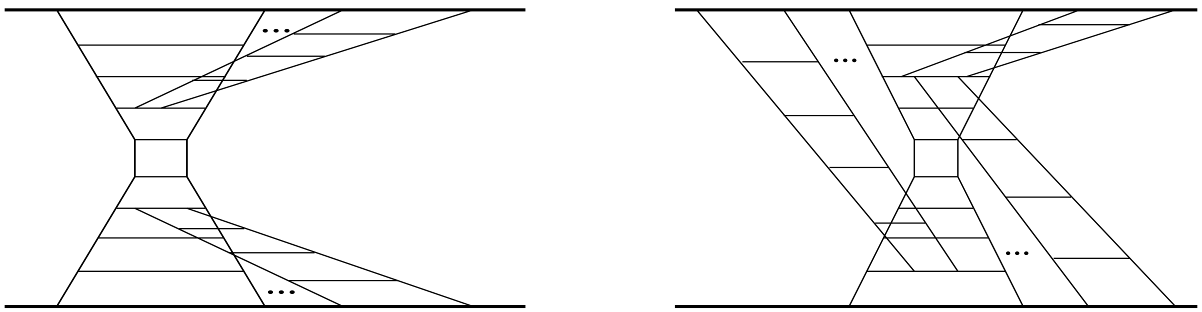
Large s, small b, large A:

- many partons closely packed
- $\Rightarrow$ parton cascades overlap and interact with each other
- $\Rightarrow$ parton shadowing (slower rise of parton density)
- saturation (maximal possible density reached)

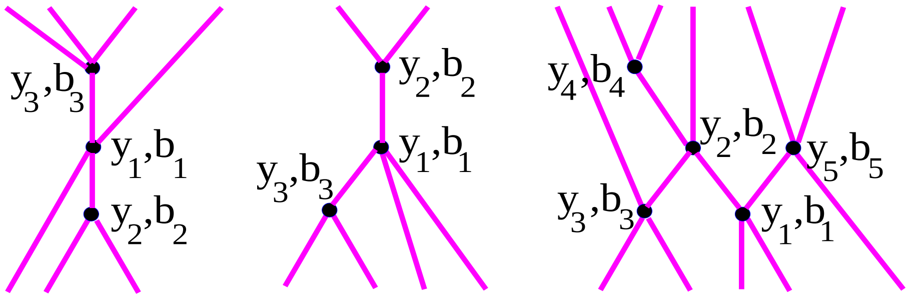


(picture from R. Engel)

Non-linear effects in QCD: interaction between parton ladders



Pomeron approach: non-linear effects $\equiv$ Pomeron-Pomeron interactions



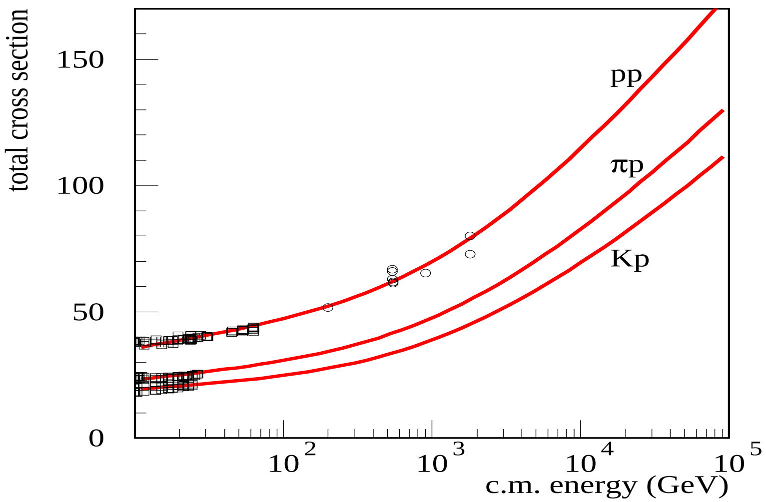
QGSJET II:

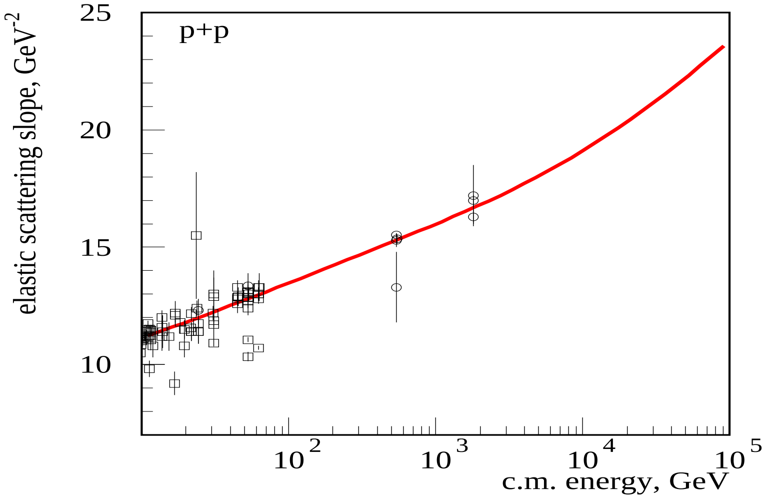
- all order re-summation of Pomeron "nets" (S.O., PLB 636 (2006) 40; PRD 74 (2006) 014026)
- non-linear screening corrections
- smooth transition to parton saturation at Q_0^2 scale
- A-enhancement of screening effects in hA (AA) collisions
- consistent treatment of cross sections & high mass diffraction
- preserves QCD factorization for inclusive jet cross section

$$\sigma_{ad}^{\rm jet}(s,Q_0^2) = \sum_{I,J=q,\bar{q},g} \int_{p_t^2>Q_0^2} dp_t^2 \int dx^+ dx^- \, \frac{d\sigma_{IJ}^{2\to 2}(x^+x^-s,p_t^2)}{dp_t^2} \times f_{I/a}^{\rm scr}(x^+,M_F^2)\, f_{J/d}^{\rm scr}(x^-,M_F^2)$$

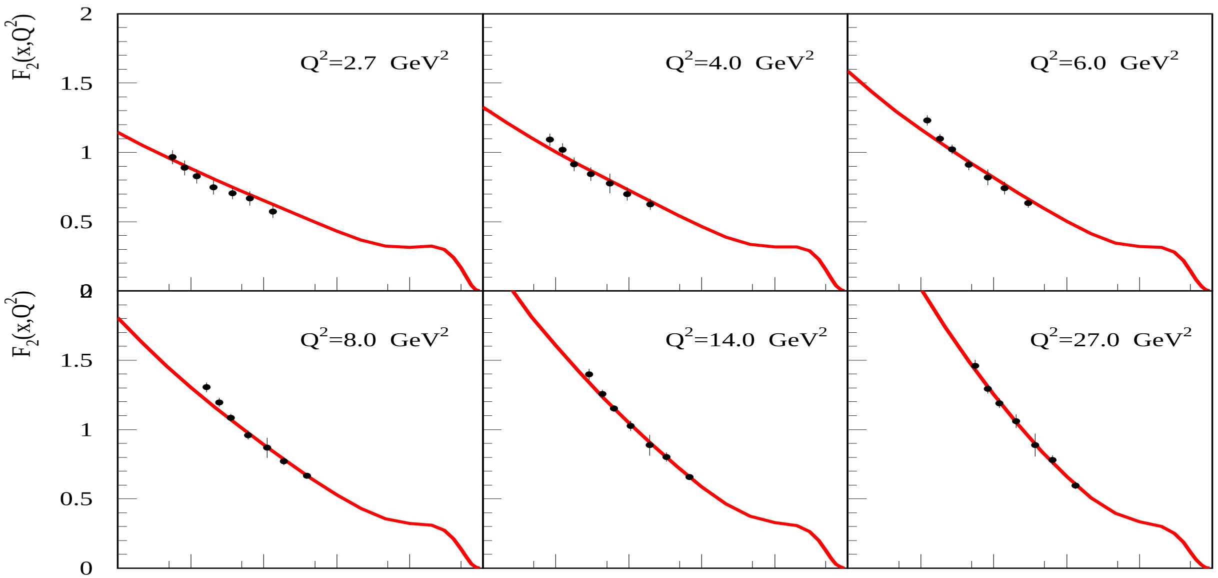
- but: $\int d^2b\, \chi_{ad}^{\mathbb{P}_{\rm sh}}(s,b) \neq \sigma_{ad}^{\rm jet}(s,Q_0^2)$ - due to non-factorizable contributions

Total hadron-proton cross sections & proton elastic slope



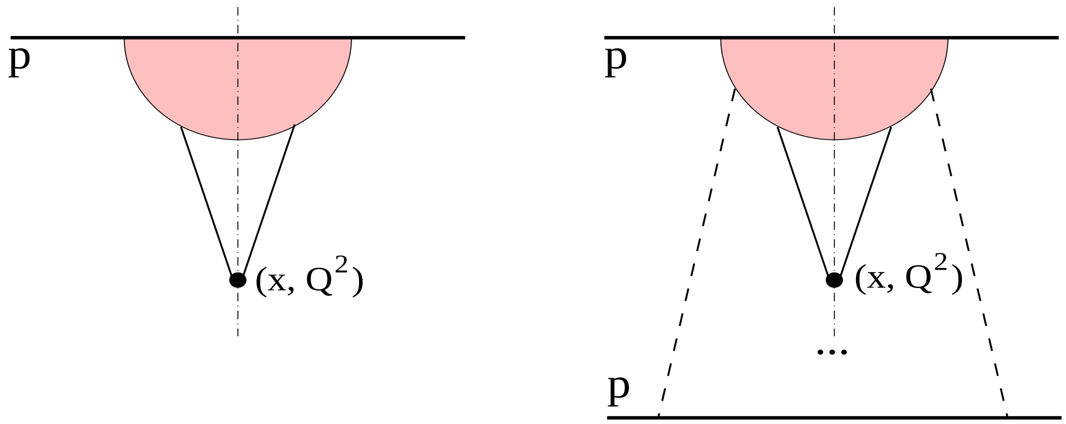


Structure function $F_{2/p}(x, Q^2)$ compared to ZEUS data:



Why?

- inclusive spectra - expressed via PDFs of free hadrons
- eikonal - expressed via “parton distributions” probed during interaction:



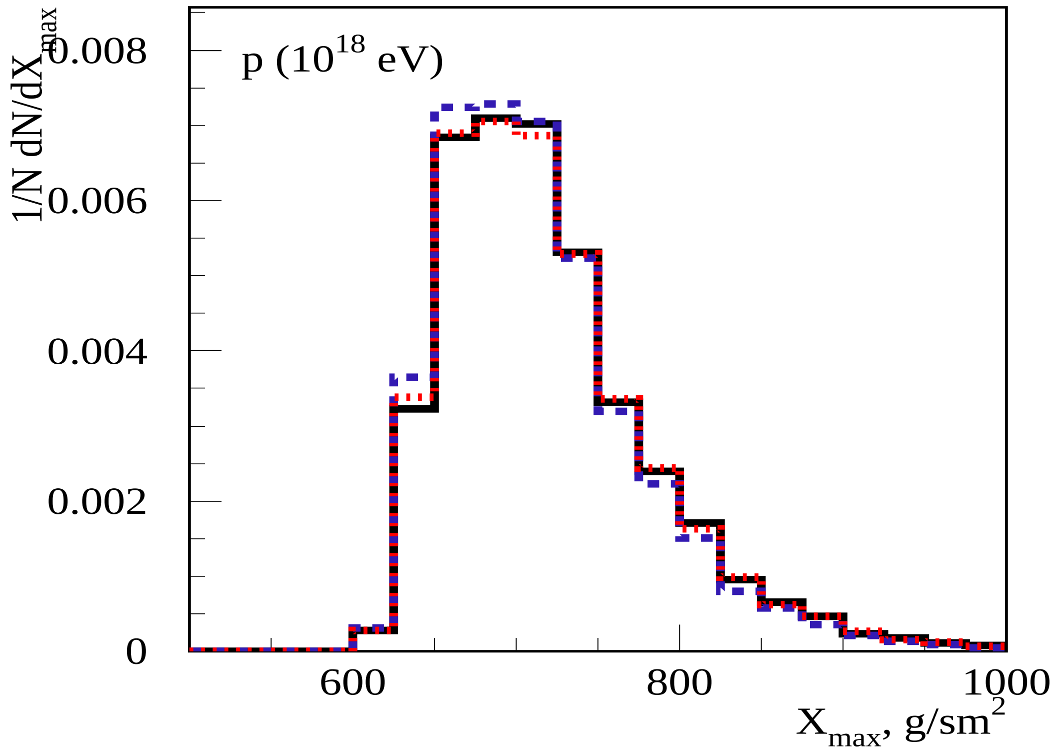
$\Rightarrow$ not easy to construct an ’effective’ linear model

Hadronic cross sections: total inelastic or non-diffractive?

EAS experiments - sensitive to non-diffractive interactions only

Example: $X_{\rm max}$ distribution @ $E_0 = 10^{18}$ eV

(default / diffraction ($K_{\rm inel} < 0.1$) switched off / no diffraction + $\sigma_{h-{\rm air}}^{\rm ND}$)



⇒ HIRES result (talk of K. Belov) - to be compared with $\sigma_{pp}^{\rm ND}$! (agrees with CDF: $\sigma_{pp}^{\rm tot} \simeq 80$ mb?)

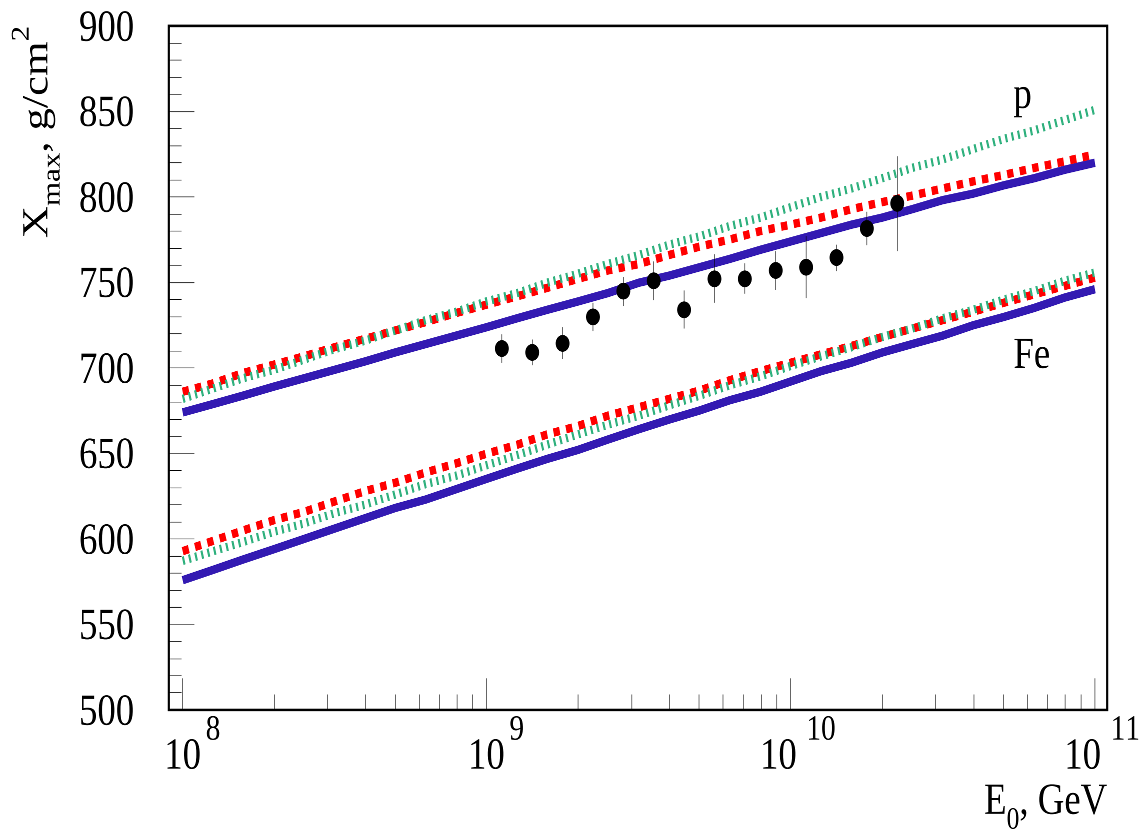
Elongation rate & $X_{\max}$ distributions: model uncertainties?

Model predictions for $\langle X_{\max} \rangle$ - ~ 20 g/cm^{2}uncertainty:

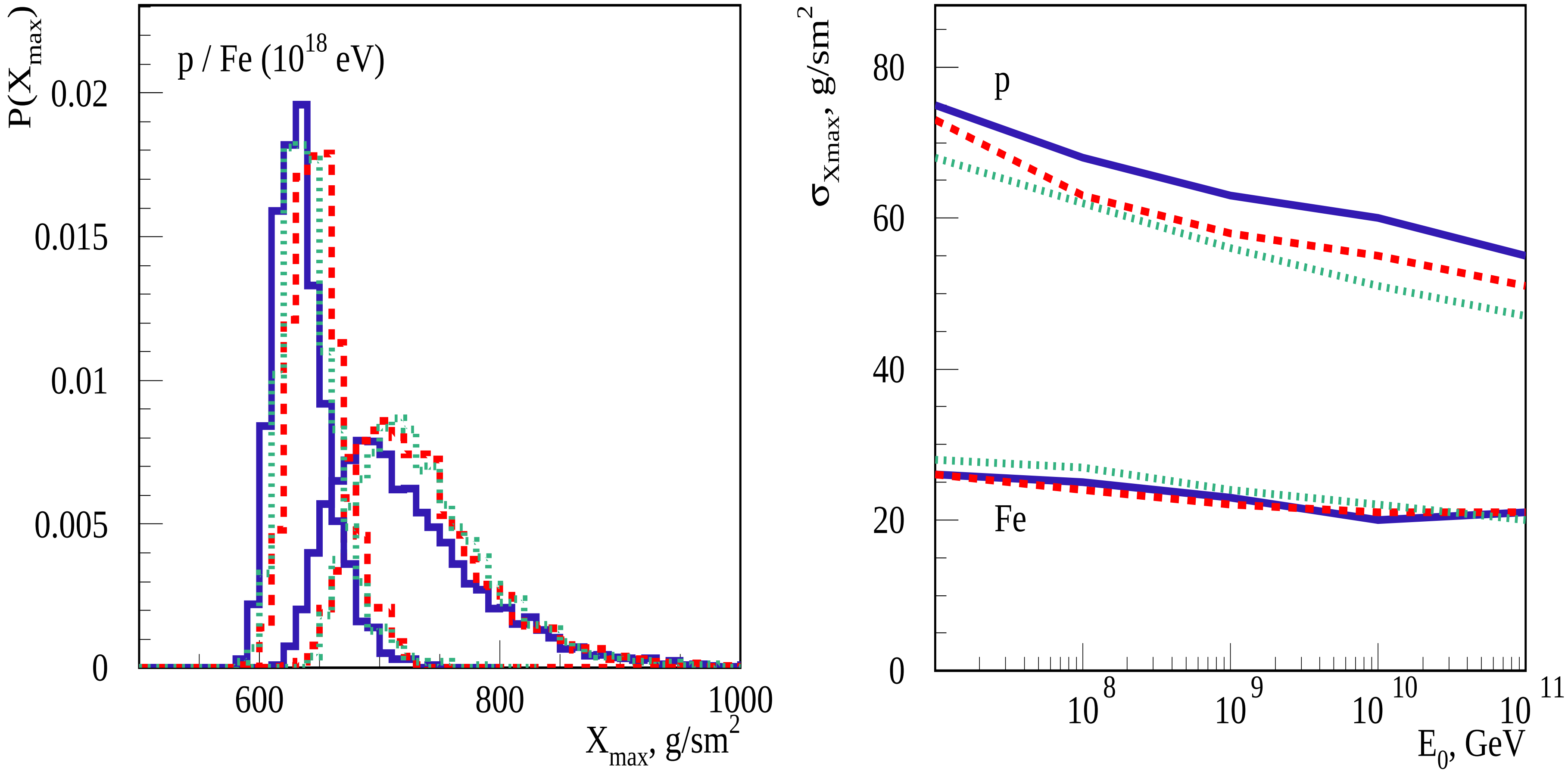
- inelastic cross section
- inelasticity & diffraction probability

Experiment: ~ 20 g/cm^2 systematic error

(QGSJET / QGSJET II / SIBYLL)



$X_{\rm max}$ distribution - more robust: width (practically) model independent



Outlook & future

Accurate treatment of peripheral collisions - of crucial importance for EAS simulation

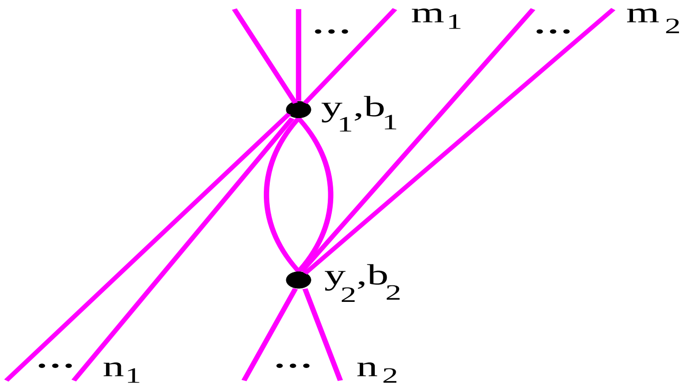
Model development: presently no alternative to the multiple scattering approach

QGSJET-II:

- microscopic treatment of nonlinear screening corrections
- consistent description of diffraction
- $\Rightarrow$ reference point for other models

Further development (presently in progress):

- Pomeron "loops":
  - small at low parton density ($\sim G^2$)
  - suppressed at high density:
  $\sim \sum_{n_1=0}^{\infty} \frac{(-\chi^{\mathbb{P}}_{d\mathbb{P}}(s_0 e^{y_1}, b_1))^{n_1}}{n_1!} = e^{-\chi^{\mathbb{P}}_{d\mathbb{P}}(s_0 e^{y_1}, b_1)}$

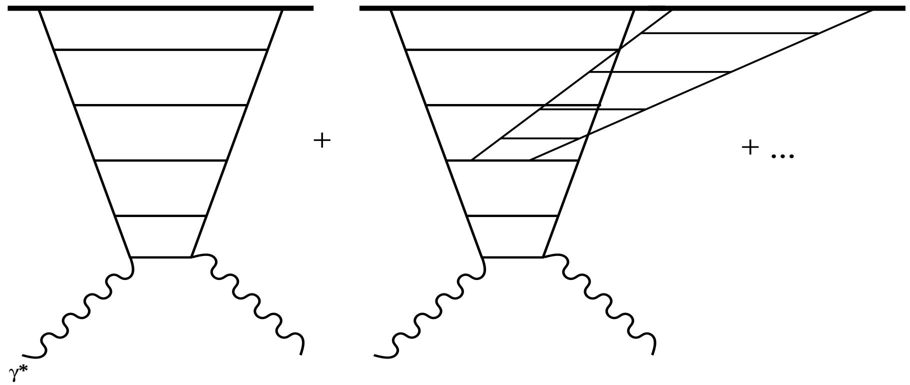


Still a finite correction at large b:

- of importance for $\sigma^{\rm tot}$, $\sigma^{\rm diffr}$
- will lead to smaller 3P-coupling
- $\Rightarrow$ smaller nuclear screening

Backup slides

Structure functions: perturbative ("fan") solution:



GLR approach (L. Gribov et al., 1983):

- $f_{g(q_s)}(x, Q^2)$ - increases at $x \to 0$
- $\Rightarrow \Delta f \sim f^2$ - increases faster
- $\Rightarrow$ leads to a saturation: $f(x, Q^2) \to f_{\rm sat}(Q^2)$ - saturation density

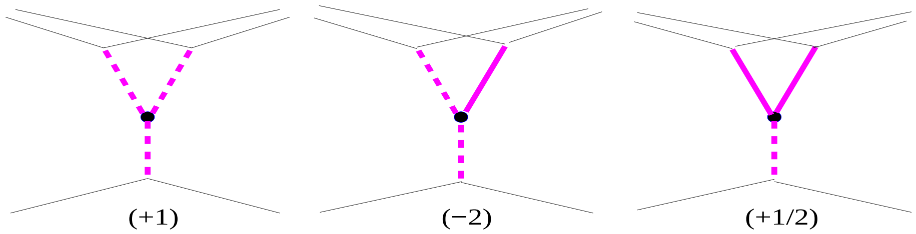
Any further increase damped by screening effects

Factorizable corrections can be absorbed in PDFs

But the scheme can not work without other contributions:
requires very high saturation scale to agree with $\sigma_{pp}^{\rm tot}$ $\Rightarrow$ contradiction with HERA

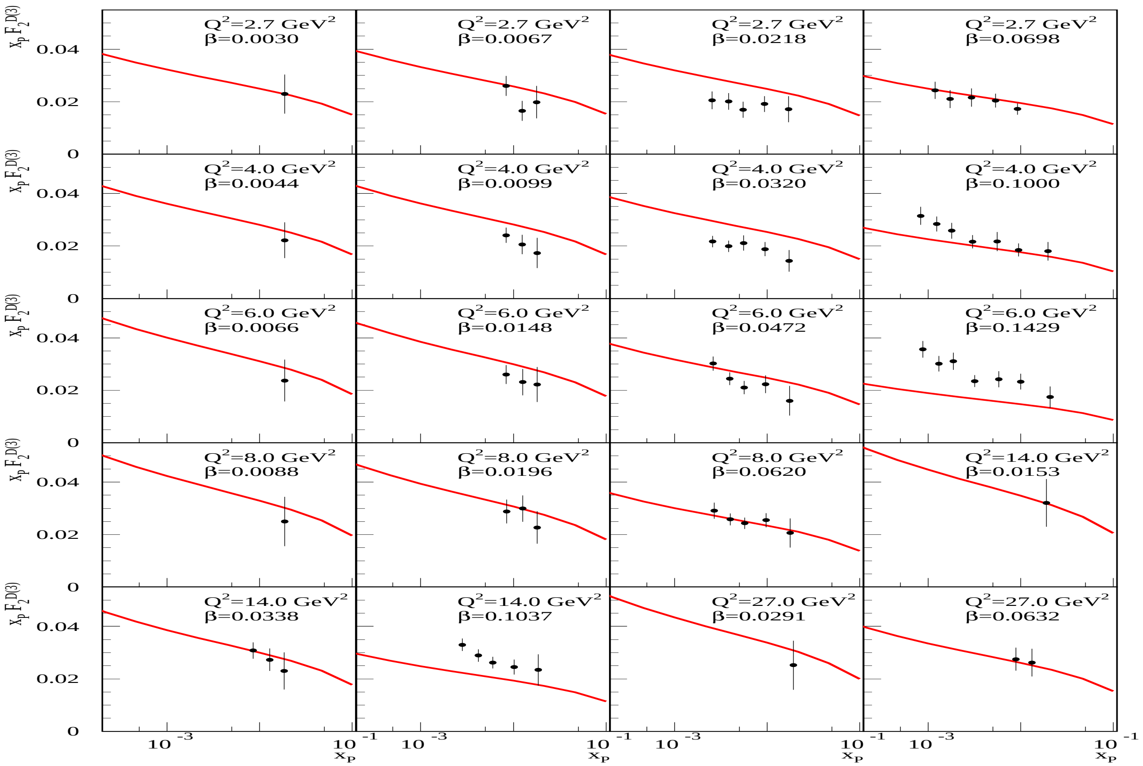
Optical theorem + AGK cutting rules: different inelastic final states can be related to certain unitarity cuts of elastic scattering diagrams

Example: applying AGK cutting rules to the triple-pomeron graph:

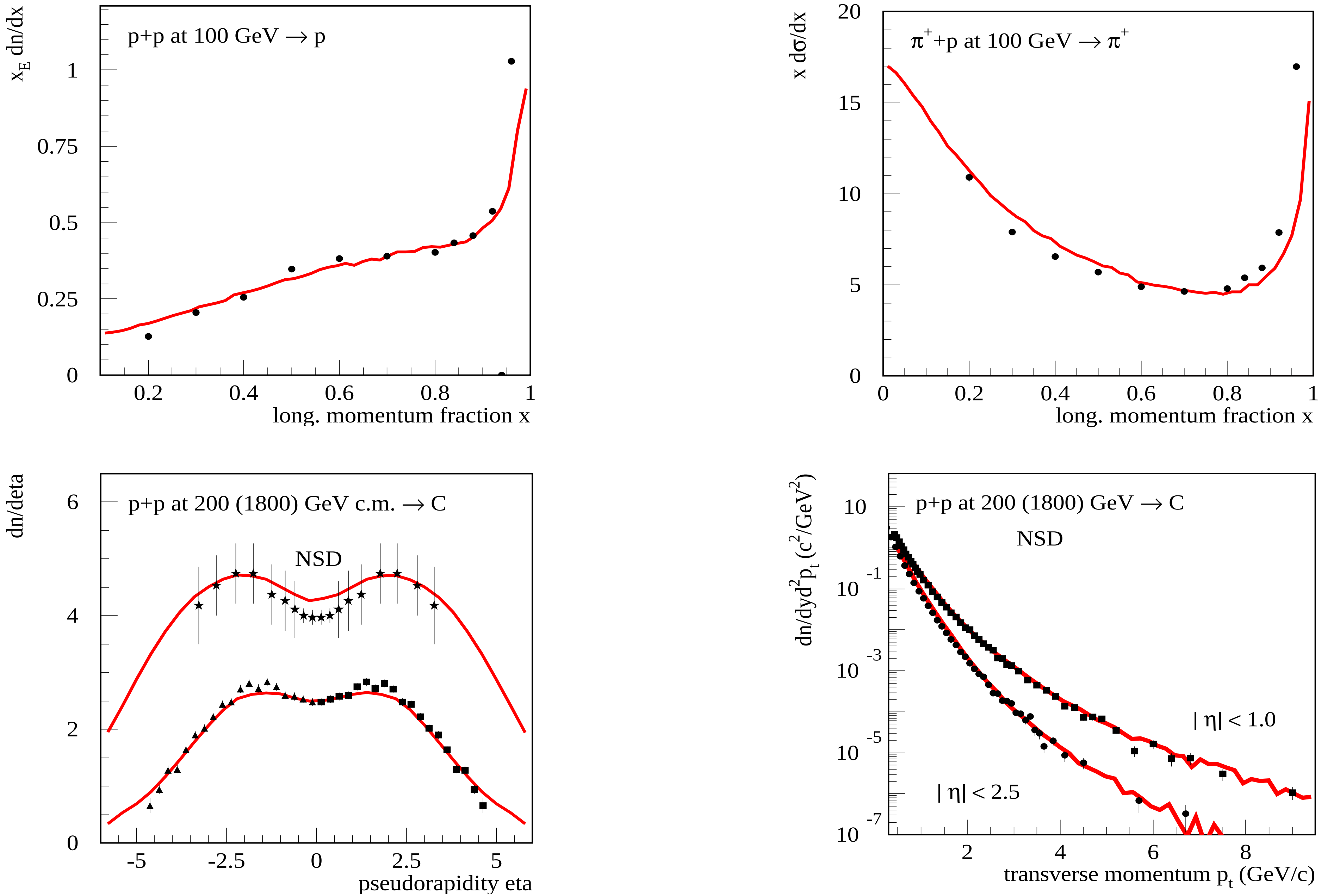


Triple-Pomeron coupling - can be fixed with "hard" diffraction data:

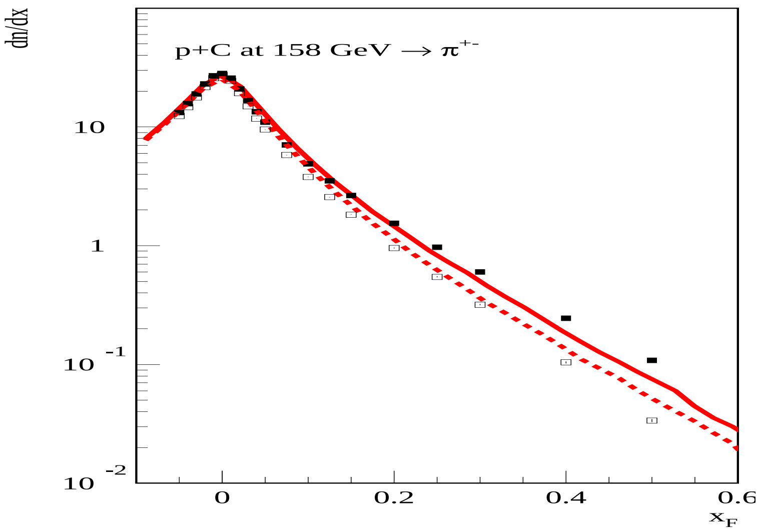
$F_2^{D(3)}(x, x_{\rm P}, \beta)$, $\beta \ll 1$ ($\beta = x/x_{\rm P}$, $x_{\rm P} = -\ln y_{\rm rap-gap}$)

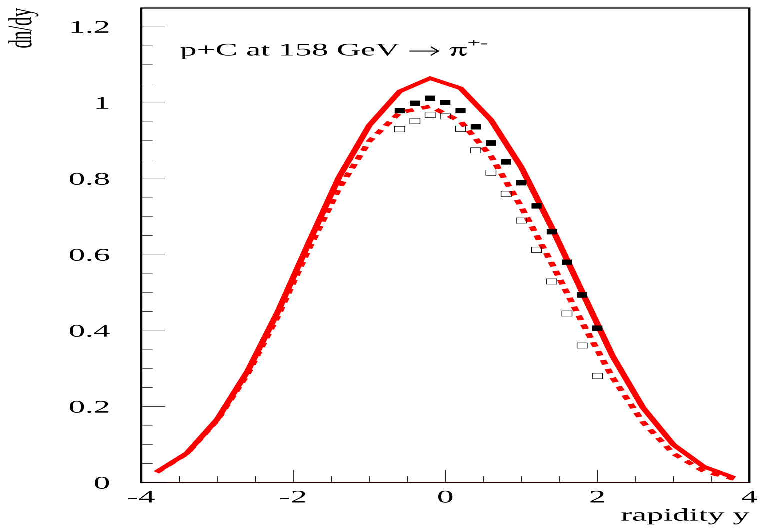


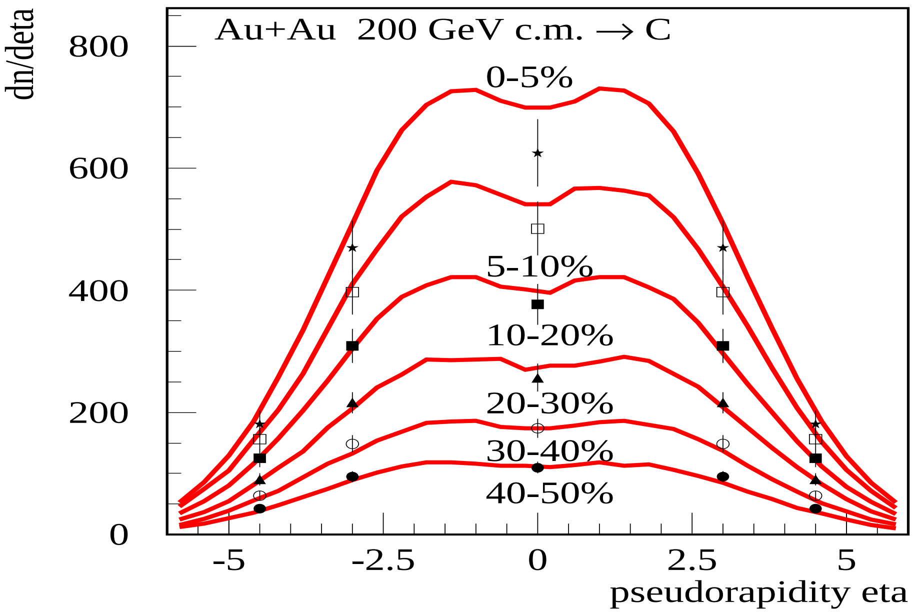
Particle production - calibrated with $h-p$



Comparison with NA49 data (hep-ex/0606028) & RHIC (Brahms Collab.)







QGSJET-II looks fine for $AA \Rightarrow$ "hard" screening seems to be small