Some comments on PHOJET

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Central elements of PHOJET

Two-component pomeron

only one pomeron with soft and hard contributions
topological identification of different terms (Dual Parton Model)
soft and hard partons differ in impact parameter distribution
application of existing parton density parametrizations
initial and final state radiation (leading-logQ^2 parton showers)

Attempt to treatment diffraction consistently

unitarization with two-channel eikonal model
enhanced pomeron graphs (only lowest order)
Abramovski-Gribov-Kancheli (AGK) cutting rules satisfied

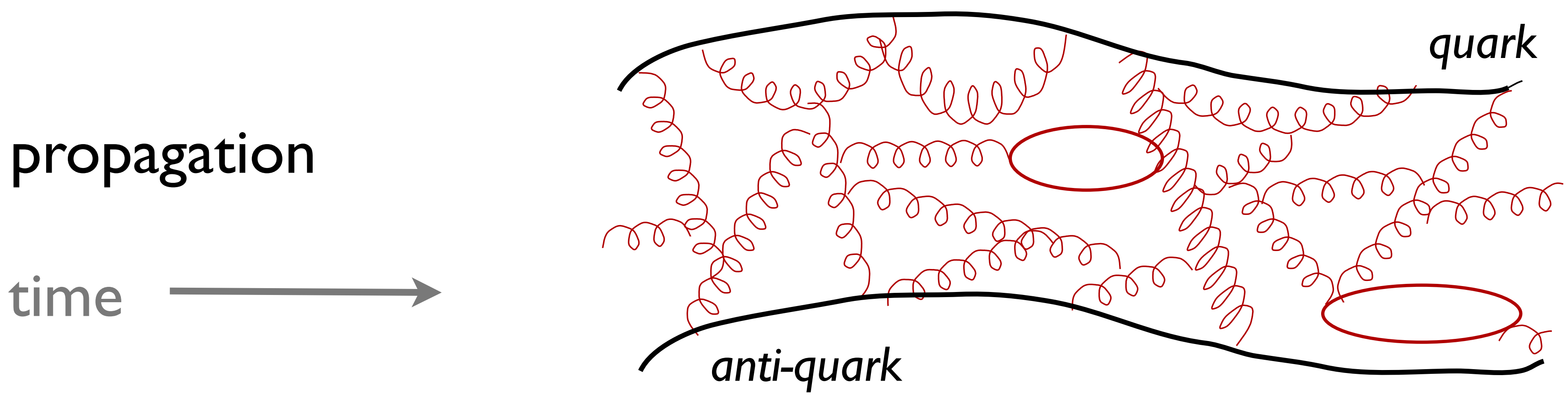
Can be considered as MC implementation of

Dual Parton Model (Capella et al.)
Quark-Gluon String Model (Kaidalov et al.)

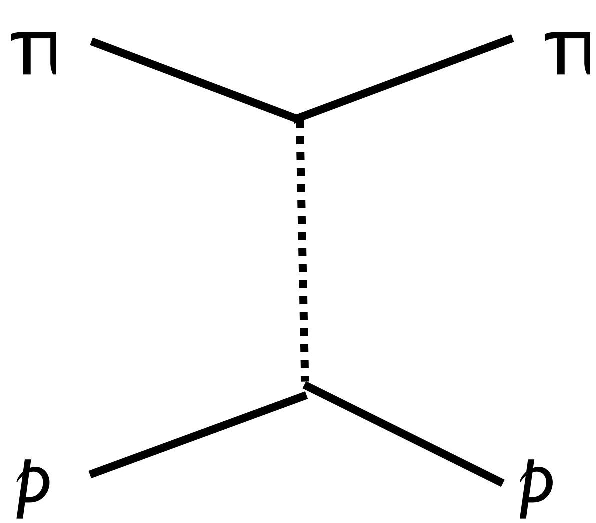
Soft interactions: color flow topologies (i)

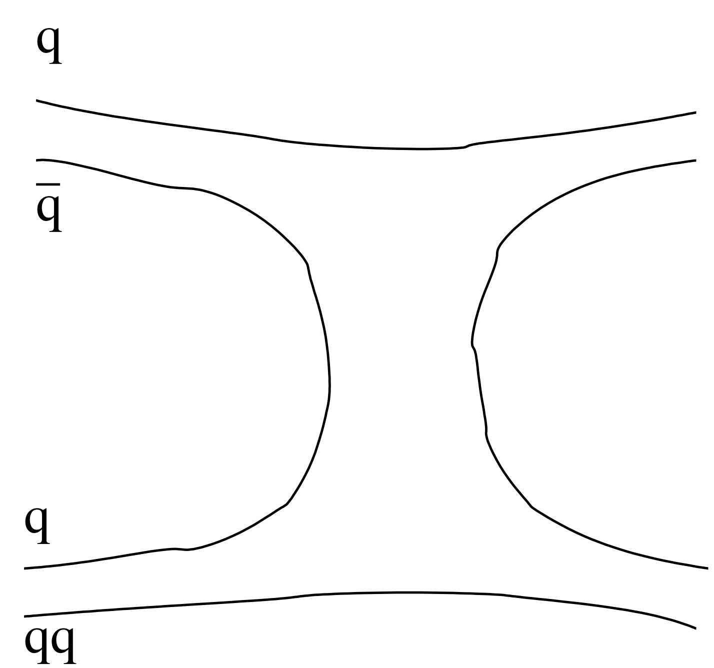
Partons only asymptotically free !

Example:
meson propagation



Scattering process:

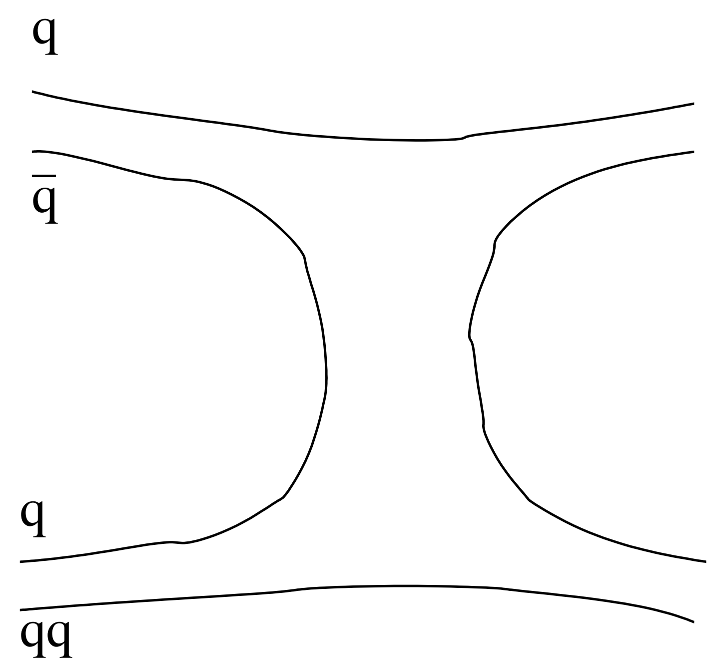




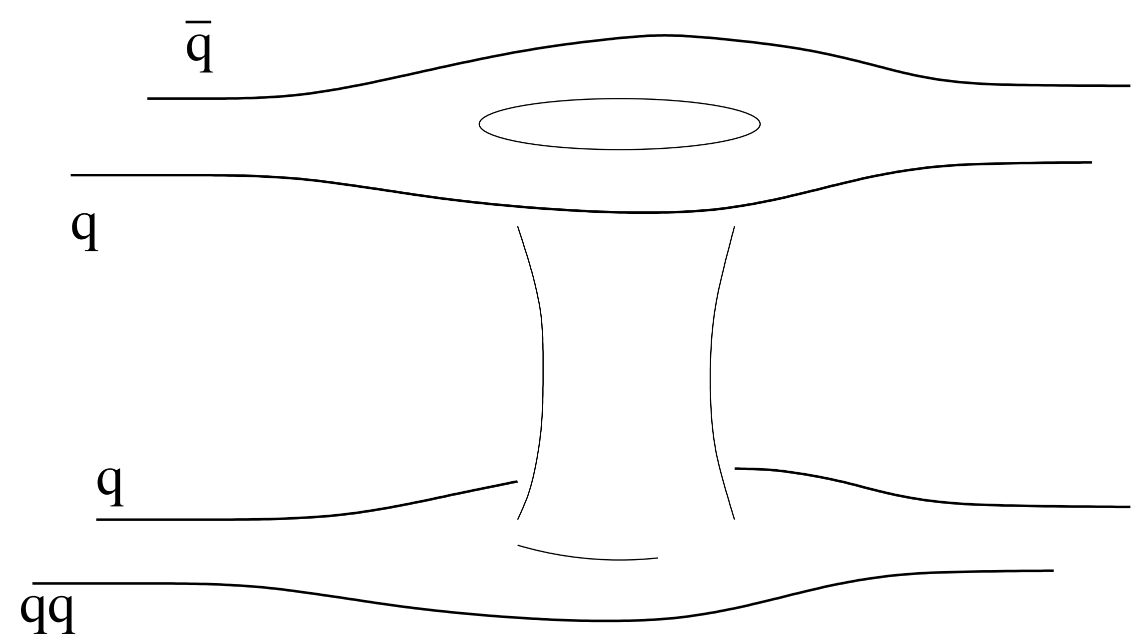
A. Fedynitch & R. Engel, Heraeus school on diffractive physics, Heidelberg 09/2013

Soft interactions: color flow topologies (ii)

Reggeon exchange
flat topology (dependence on valence quark combinatorics)

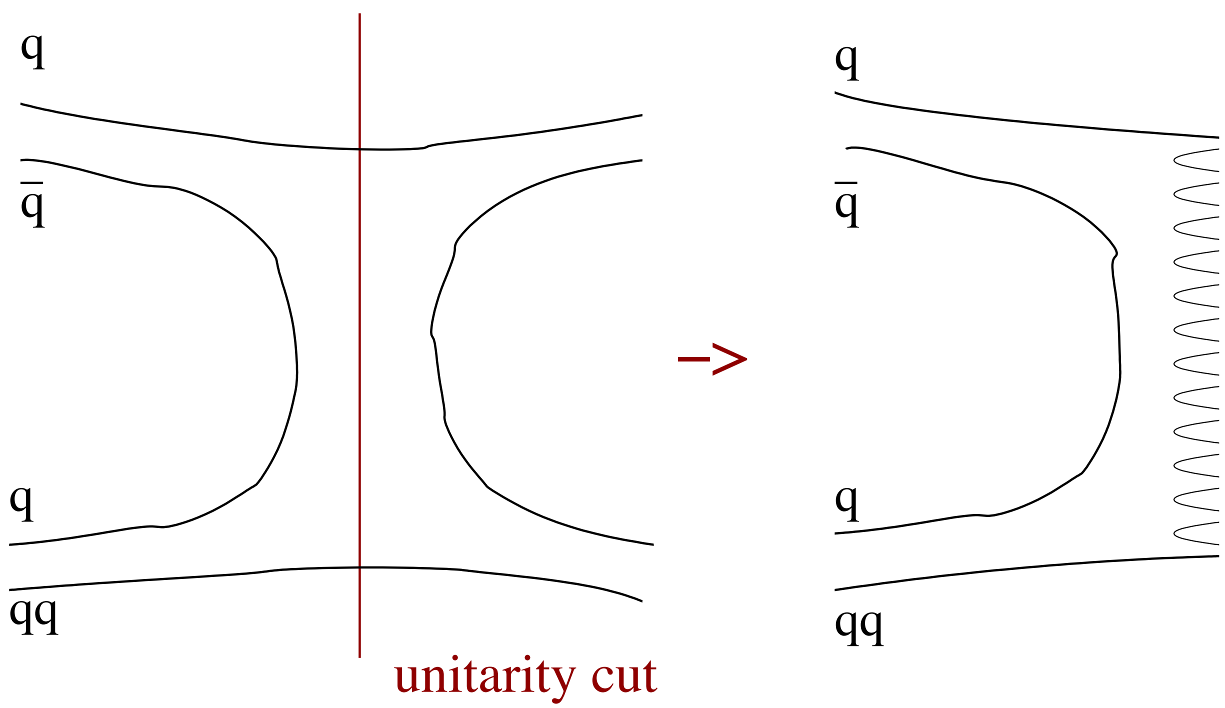


Pomeron exchange
cylinder topology (does not depend on flavour of scattering particles)

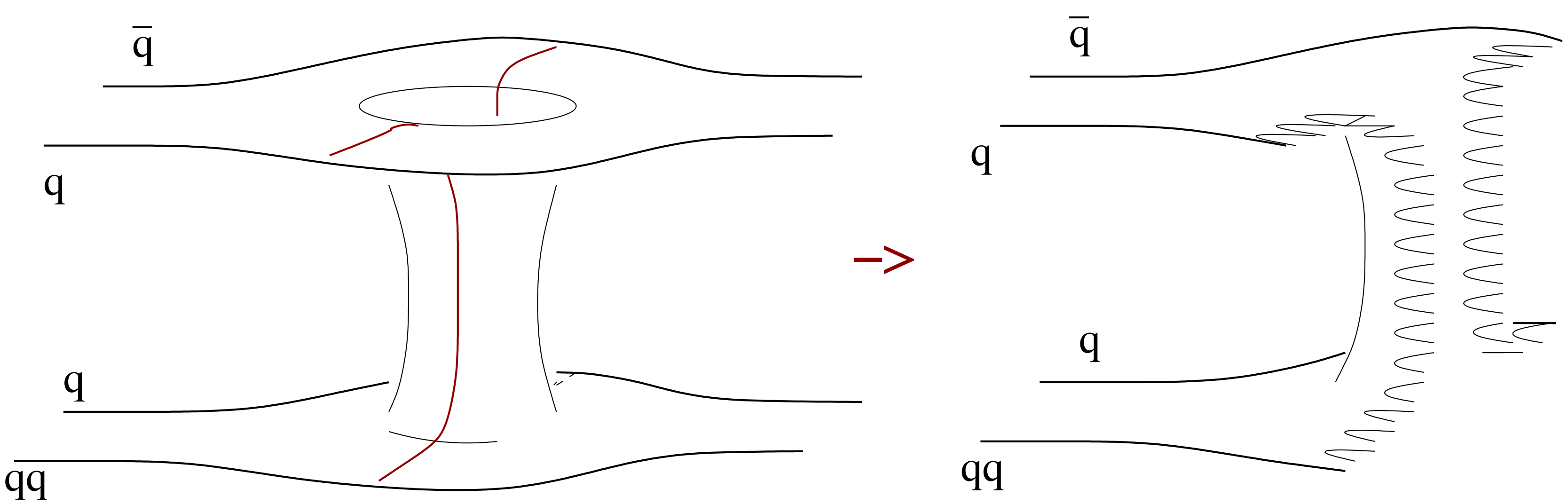


time →

Unitarity cuts (optical theorem)



Unitarity cut of Reggeon exchange: chain of hadrons



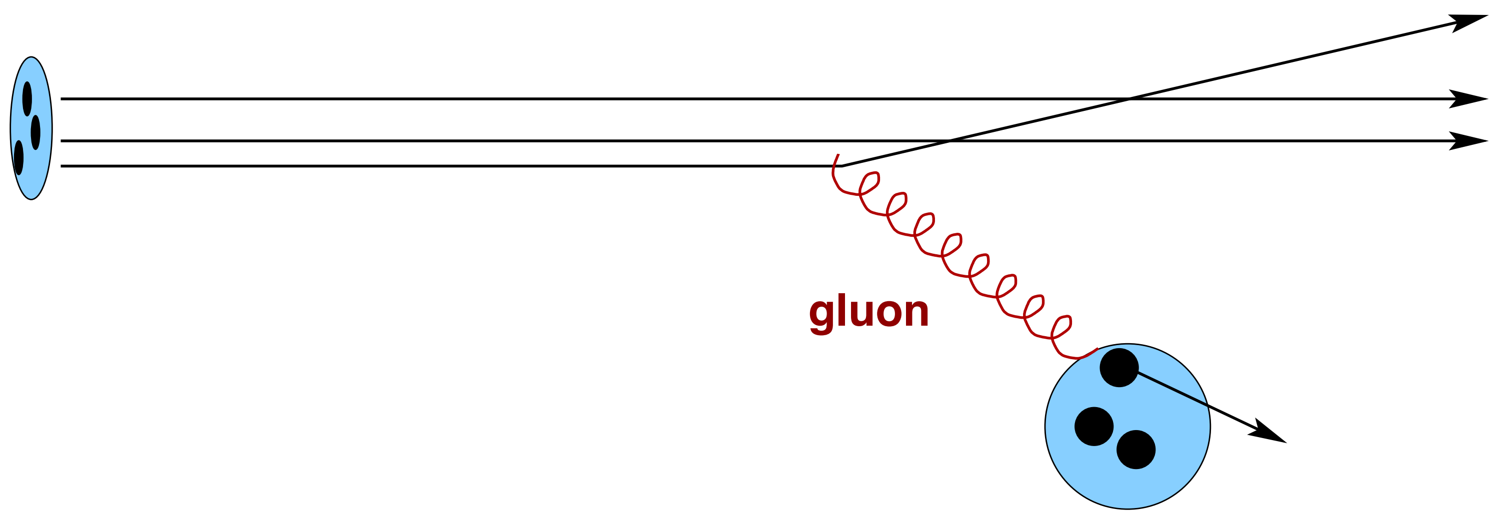
Pomeron exchange: two strings of hadrons

elastic scattering

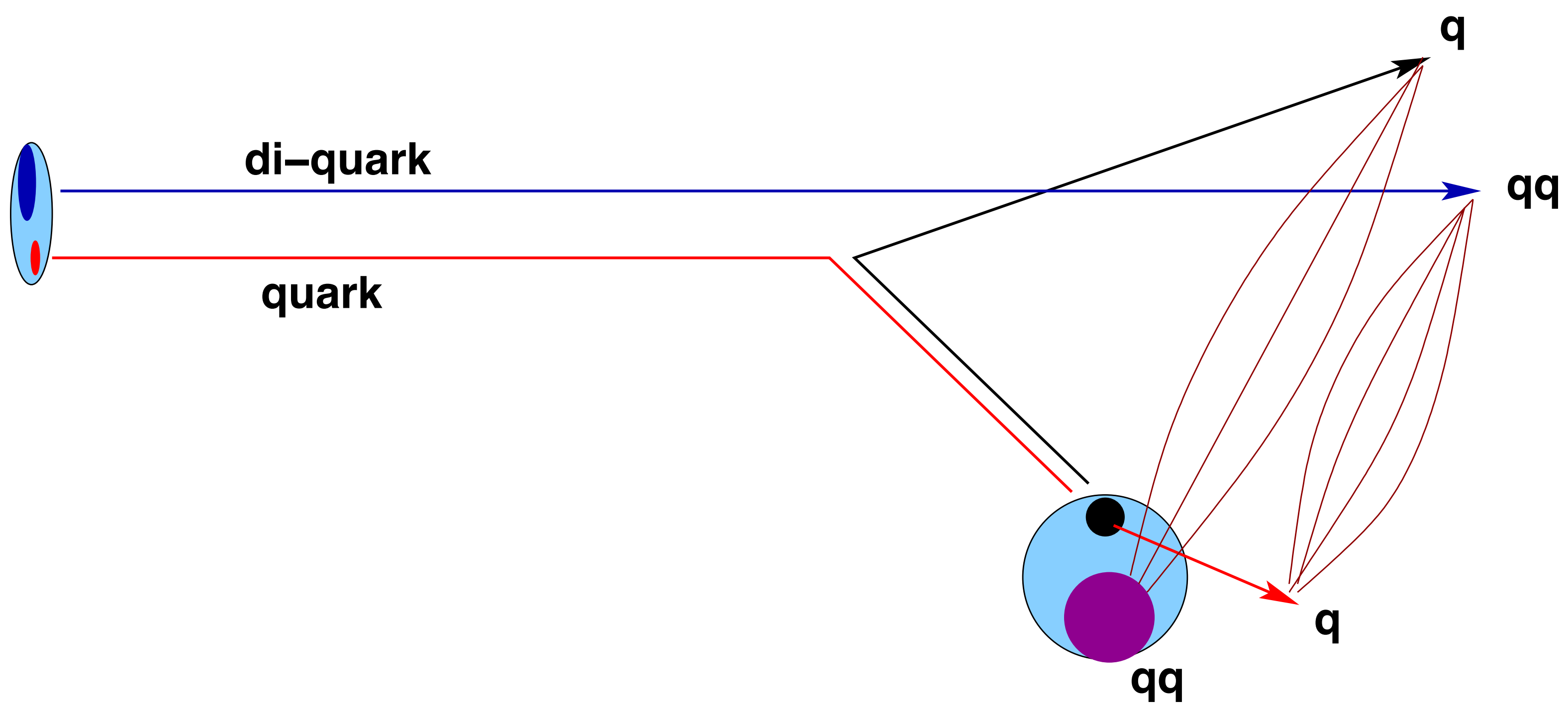
inelastic scattering

QCD color flow configurations (i)

Partonic view:

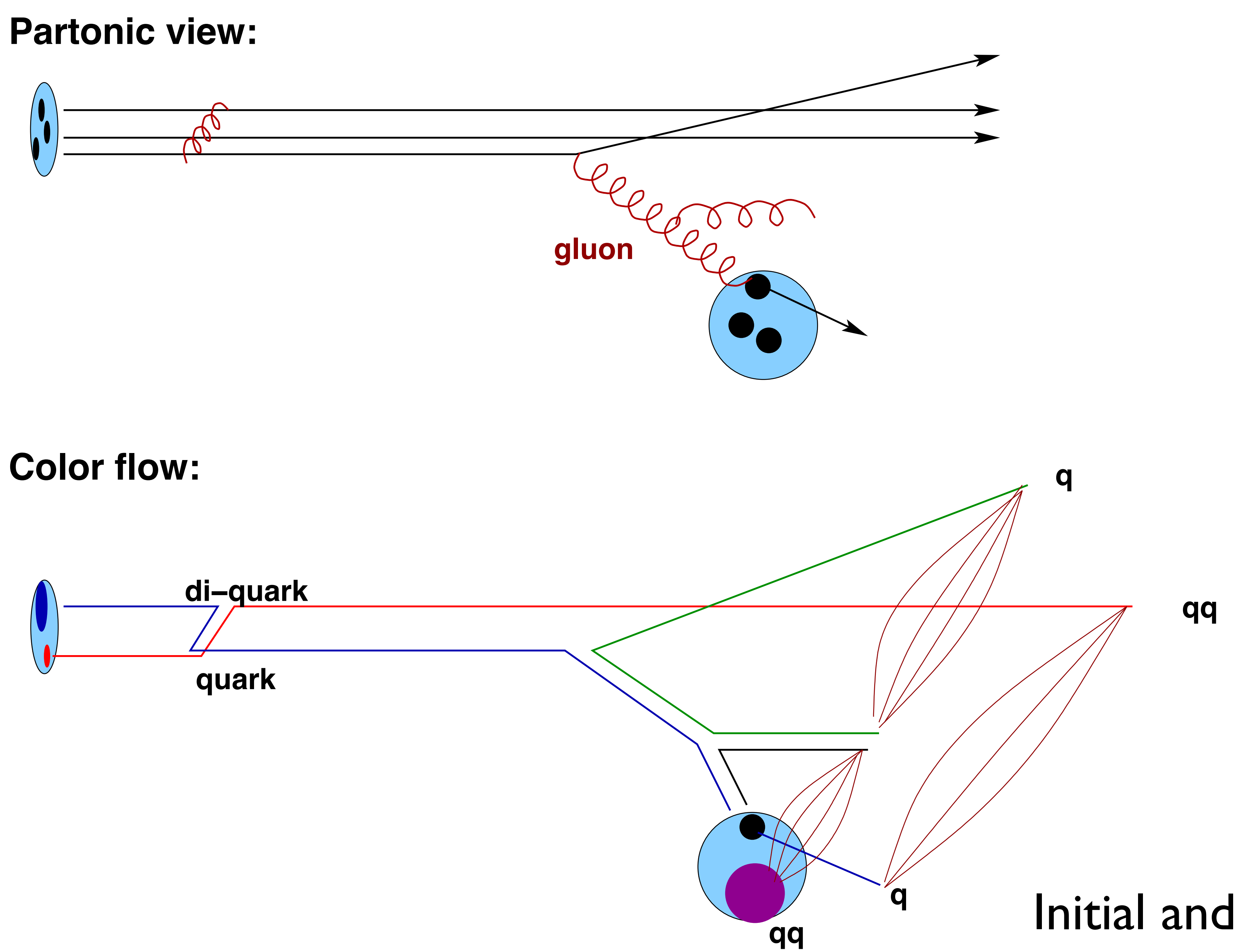


Color flow:



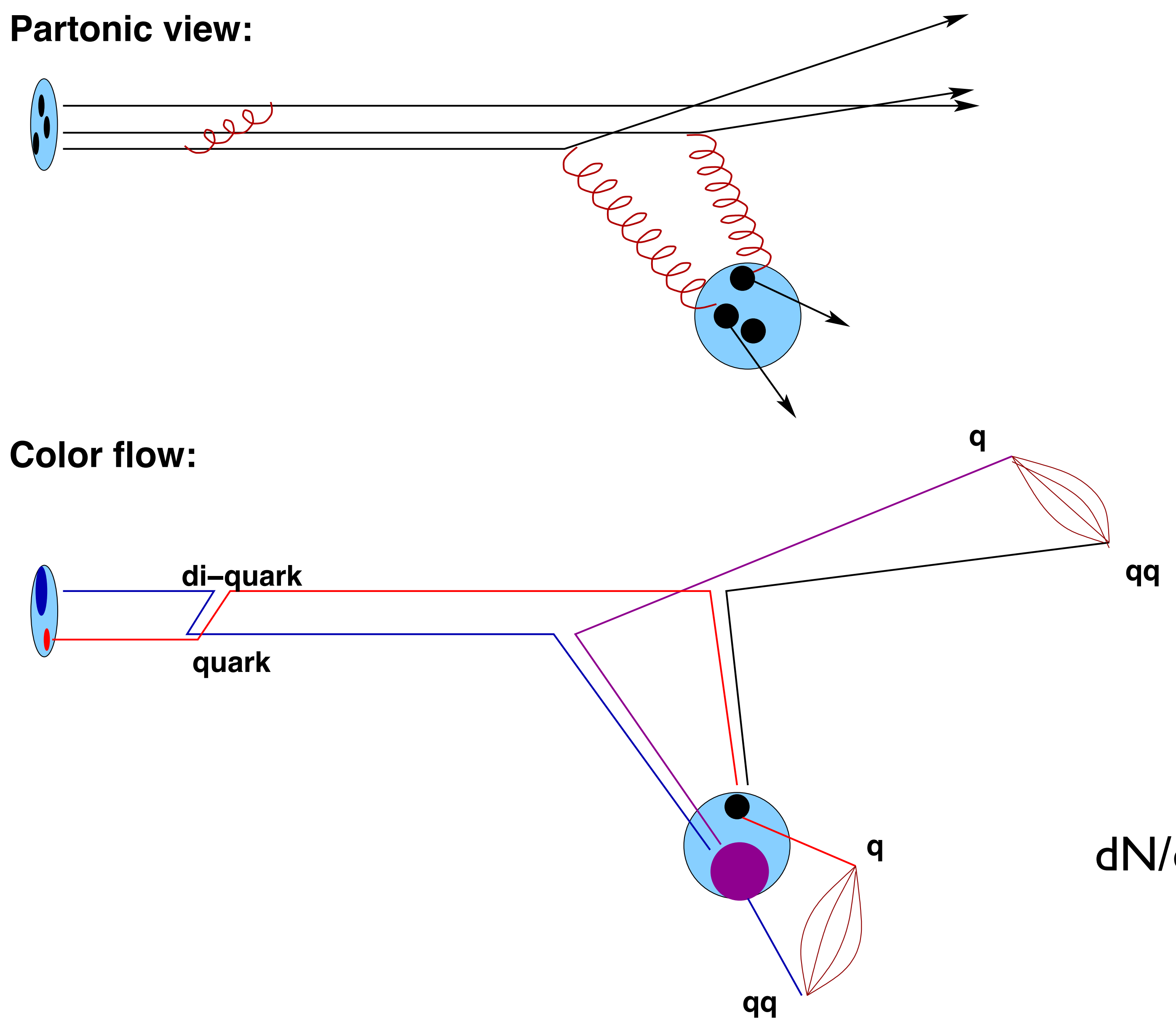
One-gluon exchange: two color fields (strings)

QCD color flow configurations (ii)

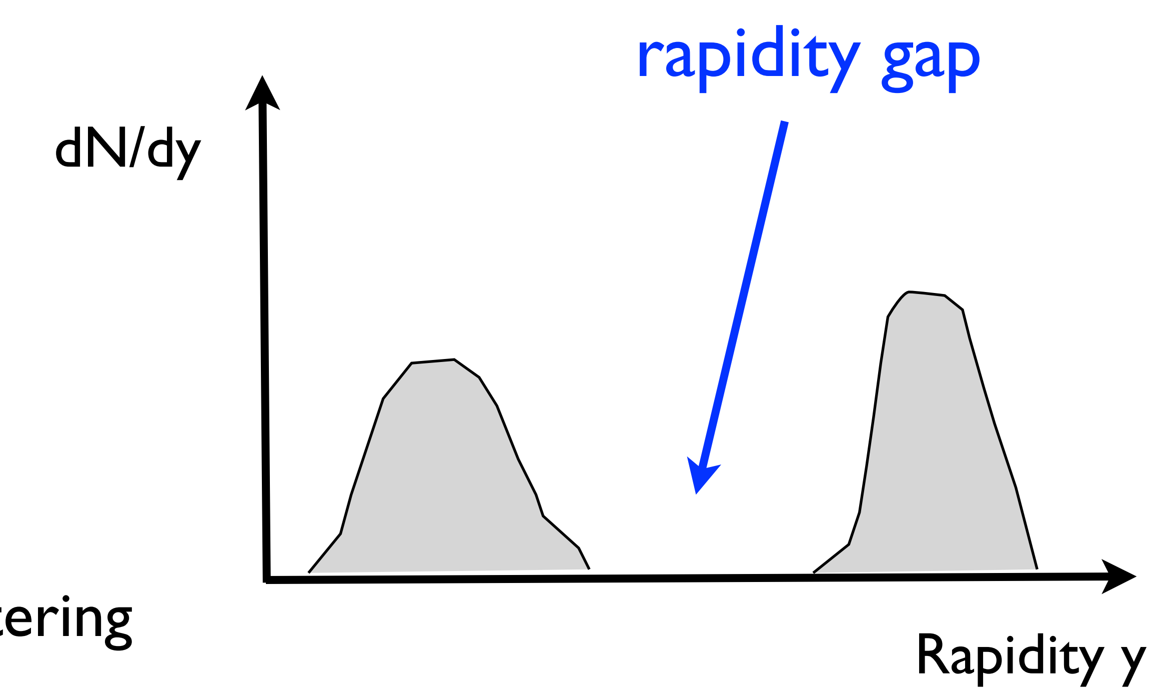


Initial and final state radiation does not change topology

Other predicted color flow configurations



Two-gluon exchange: diffraction dissociation

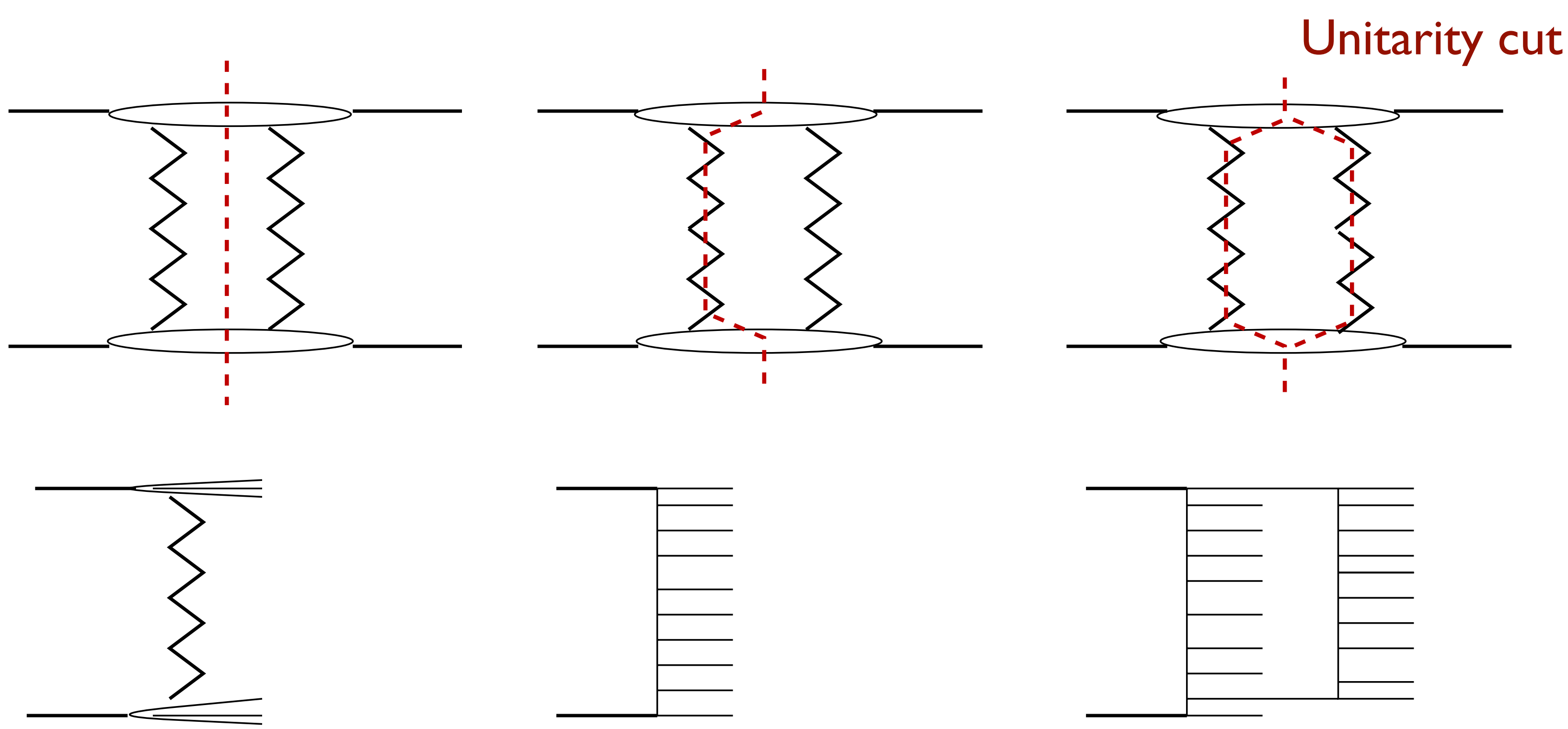


At very high energy (multi-gluon exchange):
Almost 50% of all events are elastic/diffractive scattering

Unitarization and AKG cutting rules

elastic scattering

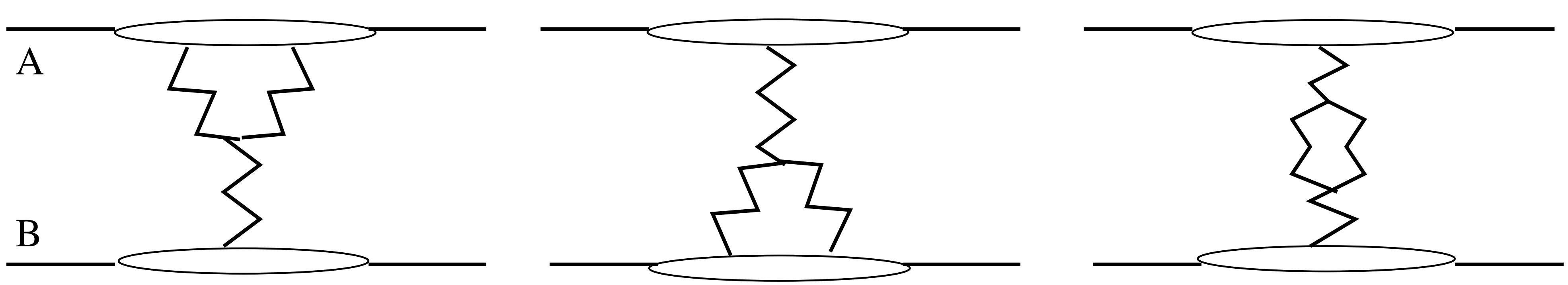
inelastic scattering



(Abramovskii, Gribov, Kancheli 1974)

Weights: (-1) (+4) (-2)

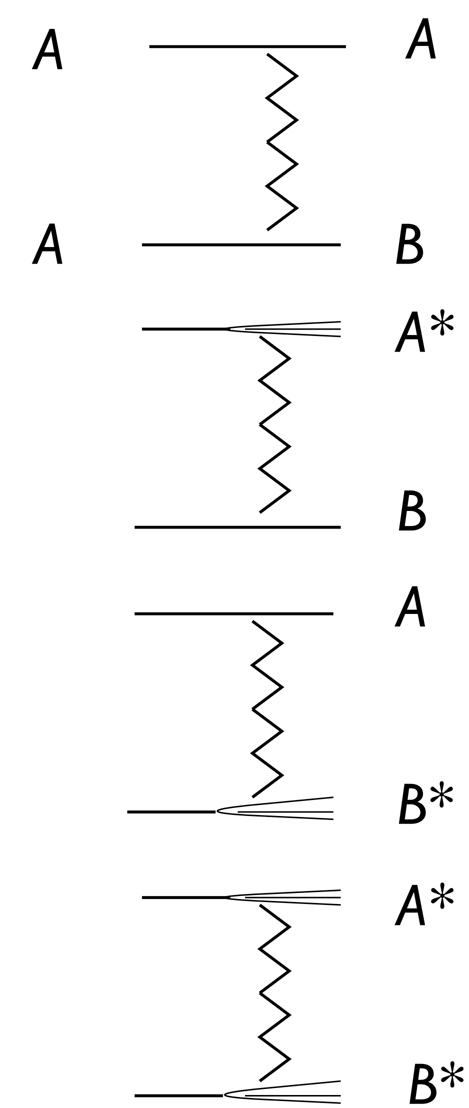
Other graphs explicitly calculated in PHOJET (and DPMEJT III)



Inclusion of low-mass diffraction dissociation

Two-channel model (Kaidalov Phys Rep. 50 (1979) 157)

$$
\begin{aligned}
\chi^{(A)} &= \chi(A,B \to A,B) &&= \chi(A^\star,B \to A^\star,B) \\
&= \chi(A,B^\star \to A,B^\star) &&= \chi(A^\star,B^\star \to A^\star,B^\star) \\
\chi^{(B)} &= \chi(A^\star,B \to A,B) &&= \chi(A,B \to A^\star,B) \\
&= \chi(A,B^\star \to A^\star,B^\star) &&= \chi(A^\star,B^\star \to A,B^\star) \\
\chi^{(C)} &= \chi(A,B^\star \to A,B) &&= \chi(A,B \to A,B^\star) \\
&= \chi(A^\star,B \to A^\star,B^\star) &&= \chi(A^\star,B^\star \to A^\star,B) \\
\chi^{(D)} &= \chi(A^\star,B^\star \to A,B) &&= \chi(A,B \to A^\star,B^\star) \\
&= \chi(A^\star,B \to A,B^\star) &&= \chi(A,B^\star \to A^\star,B)\ .
\end{aligned}
$$



PHOJET

matrix formalism to calculate cross section

not all low-mass states allow (quantum numbers)

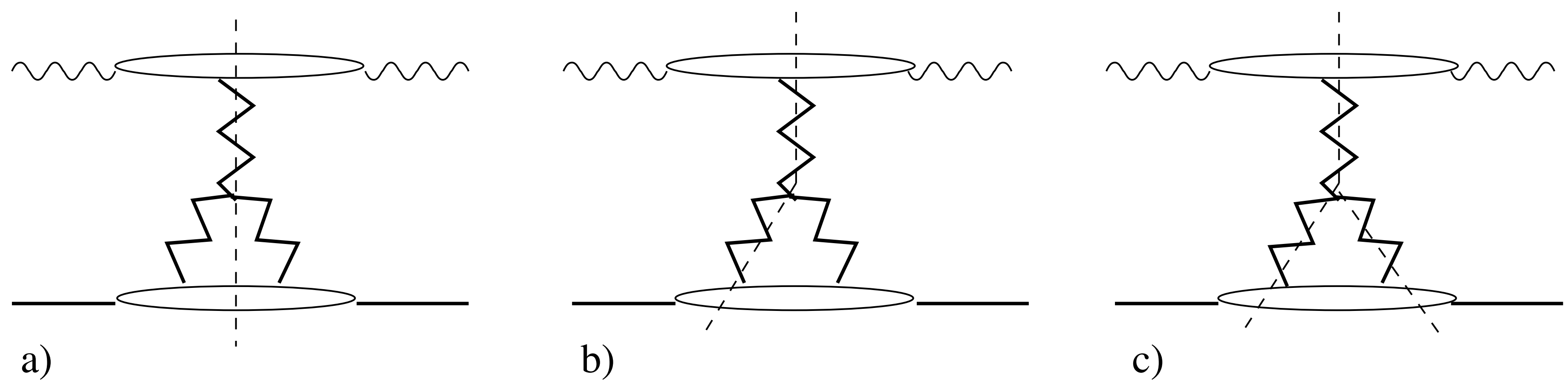
$$
|A,B\rangle \sim \begin{pmatrix}1\\0\\0\\0\end{pmatrix} \qquad |A^\star,B\rangle \sim \begin{pmatrix}0\\1\\0\\0\end{pmatrix} \qquad |A,B^\star\rangle \sim \begin{pmatrix}0\\0\\1\\0\end{pmatrix} \qquad |A^\star,B^\star\rangle \sim \begin{pmatrix}0\\0\\0\\1\end{pmatrix}
$$

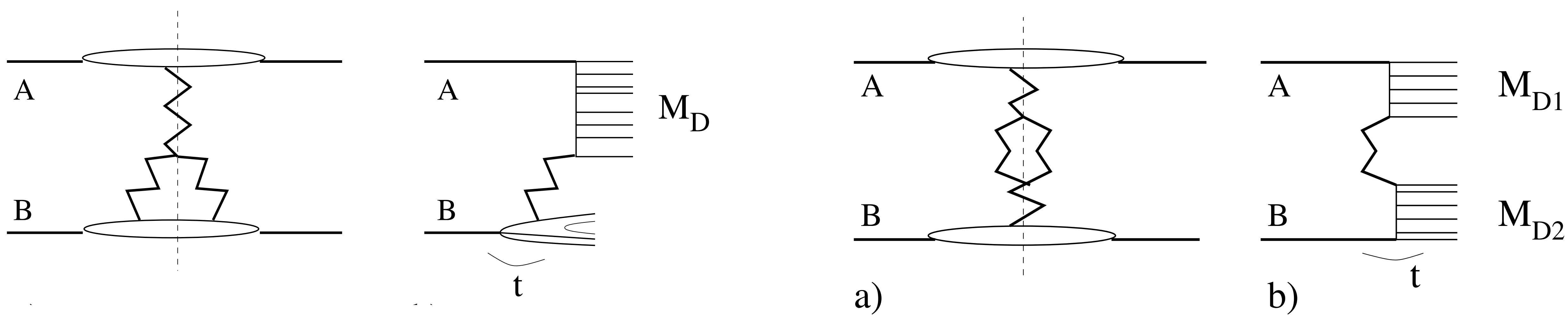
$$
\begin{aligned}
\chi^{(1)} &= \chi^{(A)} + \chi^{(B)} - \chi^{(C)} - \chi^{(D)} \\
\chi^{(2)} &= \chi^{(A)} - \chi^{(B)} + \chi^{(C)} - \chi^{(D)} \\
\chi^{(3)} &= \chi^{(A)} - \chi^{(B)} - \chi^{(C)} + \chi^{(D)} \\
\chi^{(4)} &= \chi^{(A)} + \chi^{(B)} + \chi^{(C)} + \chi^{(D)}
\end{aligned}
$$

Example: low-mass single diffraction dissociation

$$
\langle A^\star, B|\ a(s,\vec{B})\ |A,B\rangle = \frac{1}{4}\left\{-e^{-\chi^{(1)}} + e^{-\chi^{(2)}} + e^{-\chi^{(3)}} - e^{-\chi^{(4)}}\right\}
$$

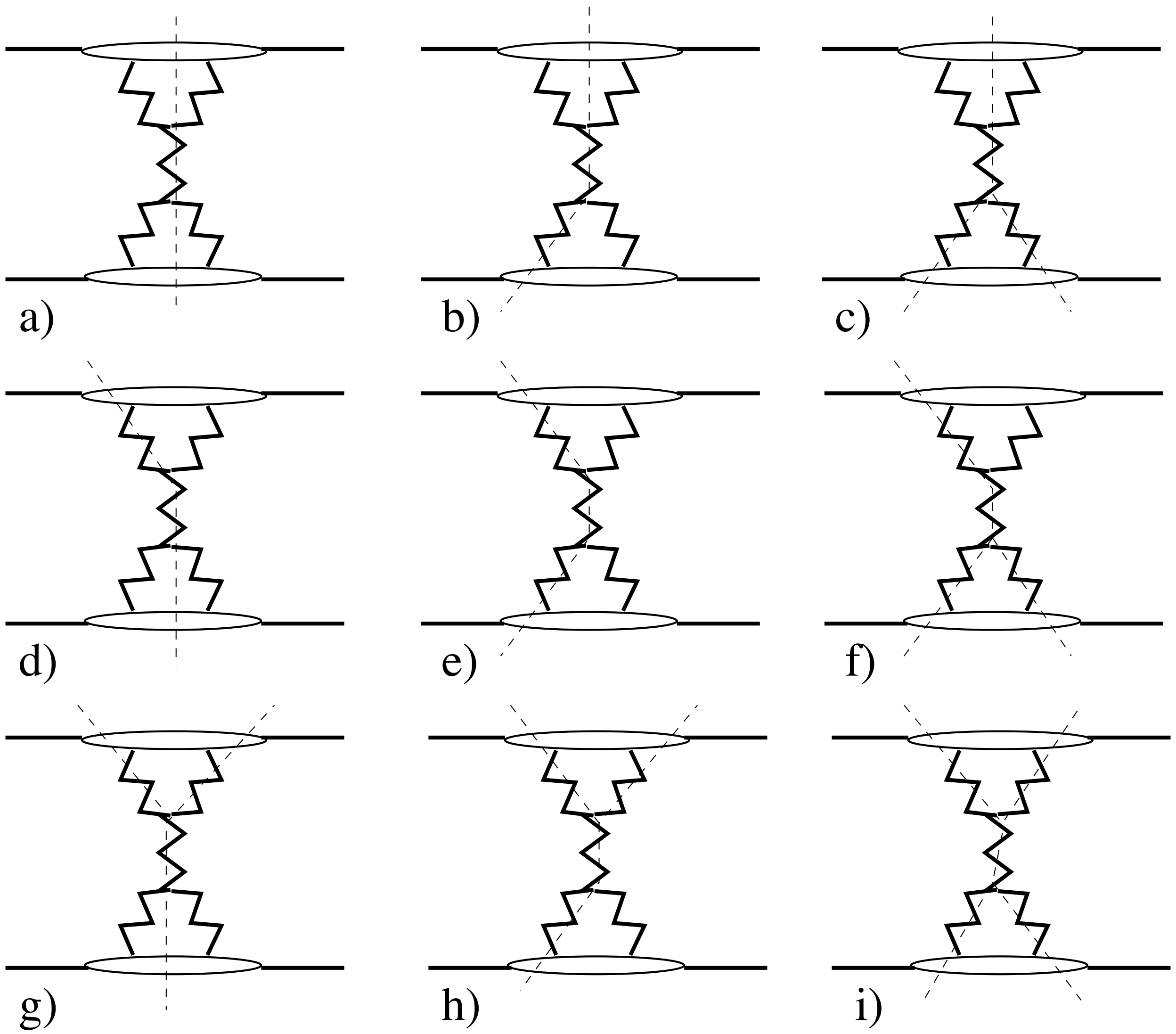
Single and double diffraction dissociation



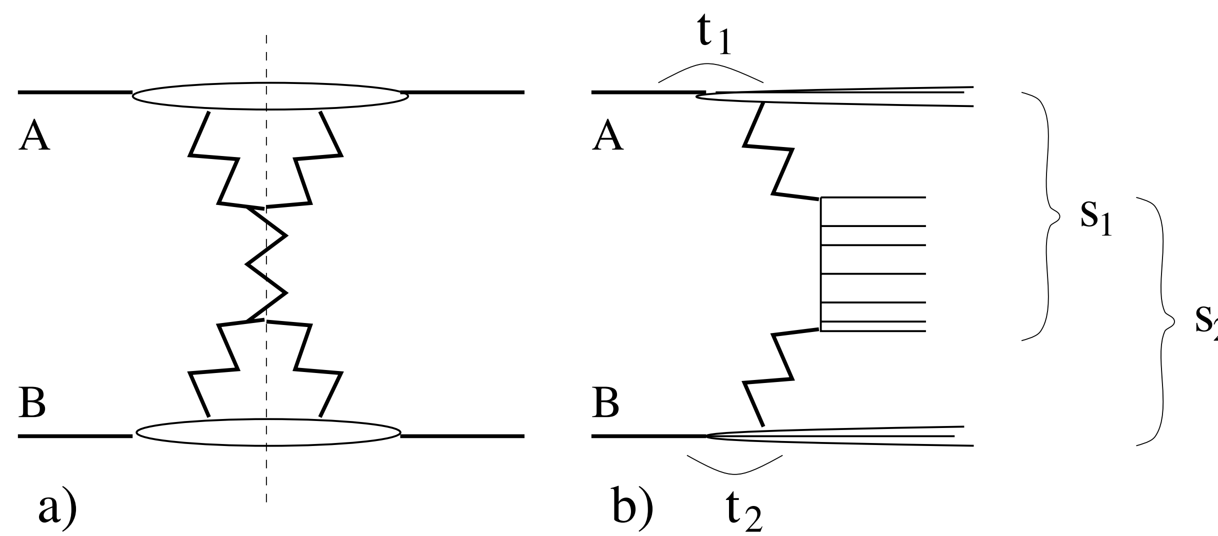


$$\frac{d^2\sigma_{AB}^{\mathrm{TP}}}{dt\,dM_D^2} = \frac{1}{16\pi}\left(g_{B\mathbb{P}}^0\right)^2 \; g_{3\mathbb{P}}^0 \; g_{A\mathbb{P}}^0 \left(\frac{s}{s_0}\right)^{2\Delta_{\tilde{\mathbb{P}}}} \left(\frac{s_0}{M_D^2}\right)^{\alpha_{\tilde{\mathbb{P}}}(0)} \exp\left(b_{AB}^{\mathrm{SD}} t\right)$$

Diagrams for pomeron-pomeron scattering



Central diffraction dissociation



$$\frac{d\sigma_{AB}^{\rm DP}}{dt_1 ds_1 dt_2 ds_2} = \frac{1}{256\pi^2}\frac{1}{s_0}\left(\frac{s}{s_0}\right)^{\Delta_{\tilde{I\!P}}}\left(\frac{s}{s_1}\right)^{\Delta_{\tilde{I\!P}}}\left(\frac{s}{s_2}\right)^{\Delta_{\tilde{I\!P}}}\left(g^0_{AI\!P}g^0_{3I\!P}g^0_{BI\!P}\right)^2$$
$$\times \frac{1}{s_1}\exp\left(b_A^{\rm CD}t_1\right)\frac{1}{s_2}\exp\left(b_B^{\rm CD}t_2\right).$$

Amplitude construction

Eikonal approximation

$$a^{(n)}(s,\vec{B}) = -\frac{i}{2}(i)^n \frac{1}{n!}\prod_{i=1}^{n}\left(2a^{(1)}(s,\vec{B})\right)$$

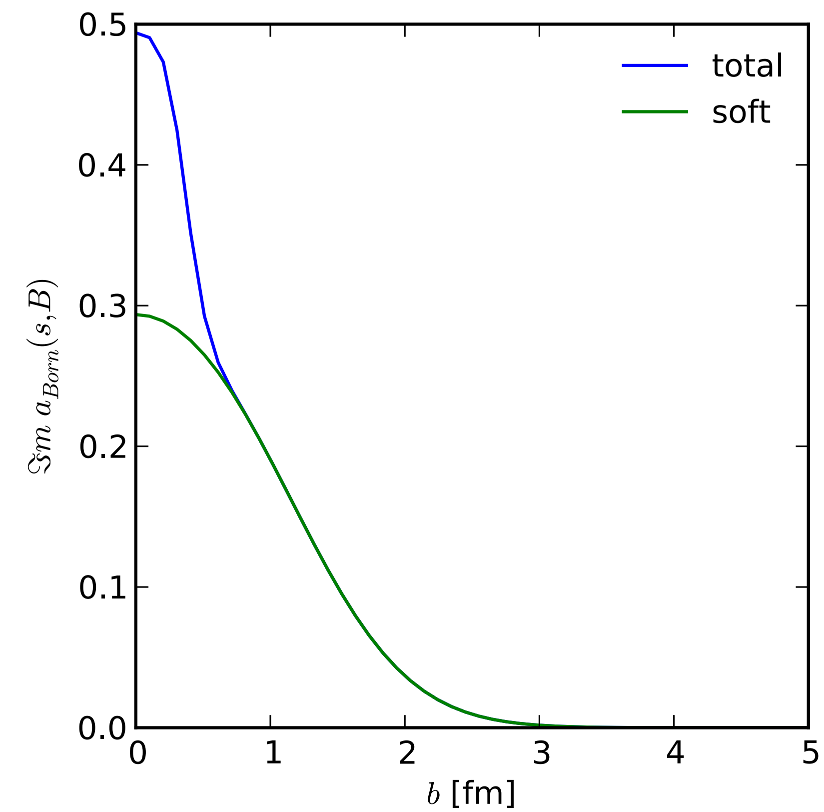
Interpretation as n independent one pomeron exchanges

$$\chi(s,\vec{B}) = -2ia^{(1)}(s,\vec{B}) \qquad P(n) = \int \mathrm{d}^2B\, \frac{(2\chi)^n}{n!}e^{-2\chi}$$

Eikonal vs. impact parameter aplitude

$$a(s,\vec{B}) = \sum_{n=1}^{\infty} a^{(n)}(s,\vec{B}) = \frac{i}{2}\left(1-\exp\left[-\chi(s,\vec{B})\right]\right)$$

Soft and hard part of the amplitude are separately defined in impact parameter space



'+' soft '+' hard '-' triple-pomeron

$$\chi(s,\vec{b}) = \chi(s,\vec{b})_{\mathrm{S}} + \chi(s,\vec{b})_{\mathrm{H}} + \chi(s,\vec{b})_{\mathrm{TP}}$$
$$+\chi(s,\vec{b})_{\mathrm{LP}} + \chi(s,\vec{b})_{\mathrm{DP}}$$

enhanced graphs

'-' loop-pomeron '+' double-pomeron scattering

Model parameters and Unitarization

PHOJET (SHERPA-SHRIMPS)

Unitarization via Eikonal

Fit to global total and elastic pp(-bar) cross section and elastic slope data using all included graphs and multiple interactions

Multiple soft, hard and diffractive interactions in one event possible

Multiple interactions in diffractive system

Not updated since 2001 = working at LHC energies means working with predictions

PYTHIA

Hard cross section is calculated first. The difference between hard and total cross section is split up between soft and diffractive

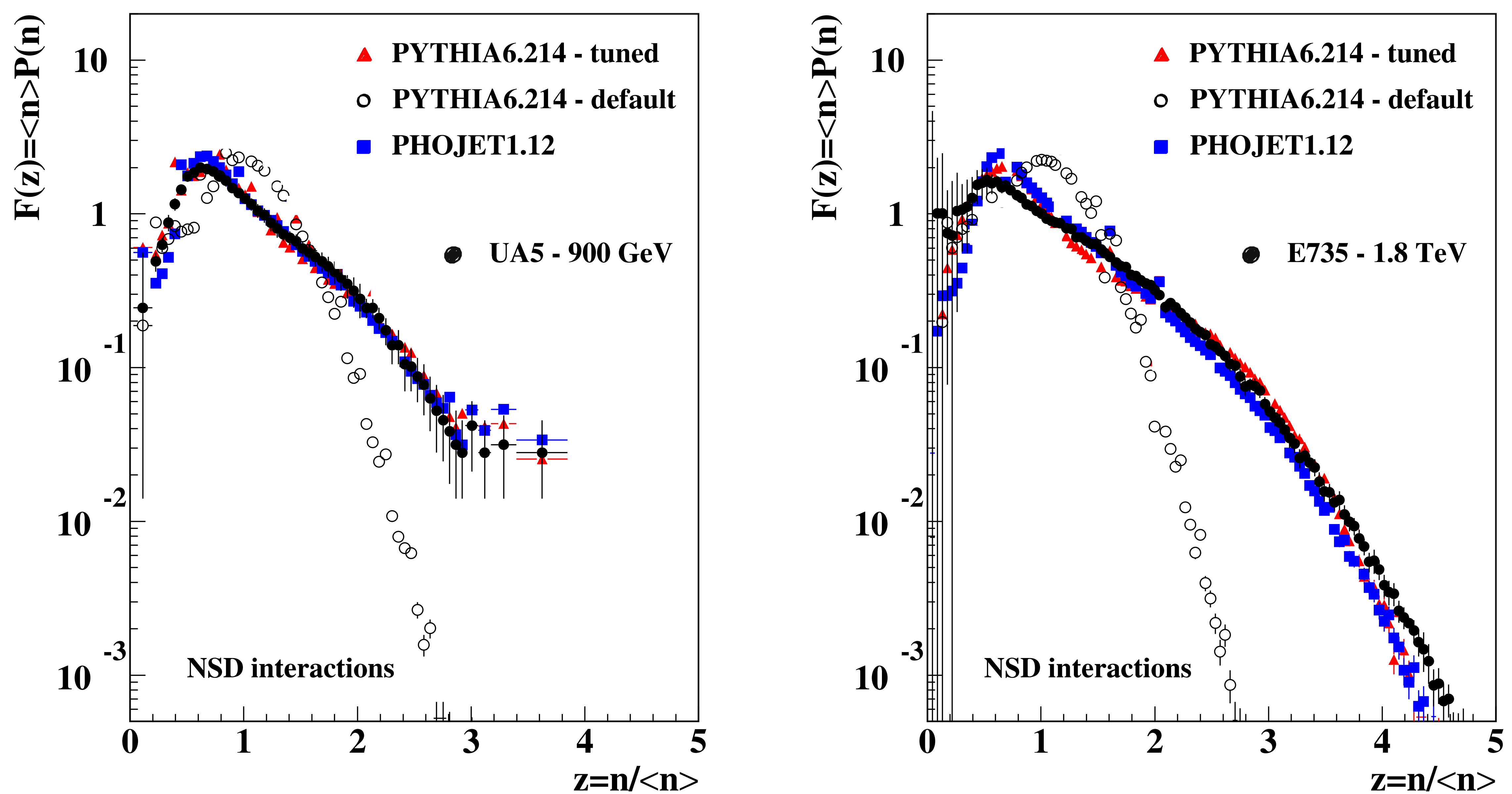
Multiple hard interactions

Soft color reconnection

Only one soft interaction per collision

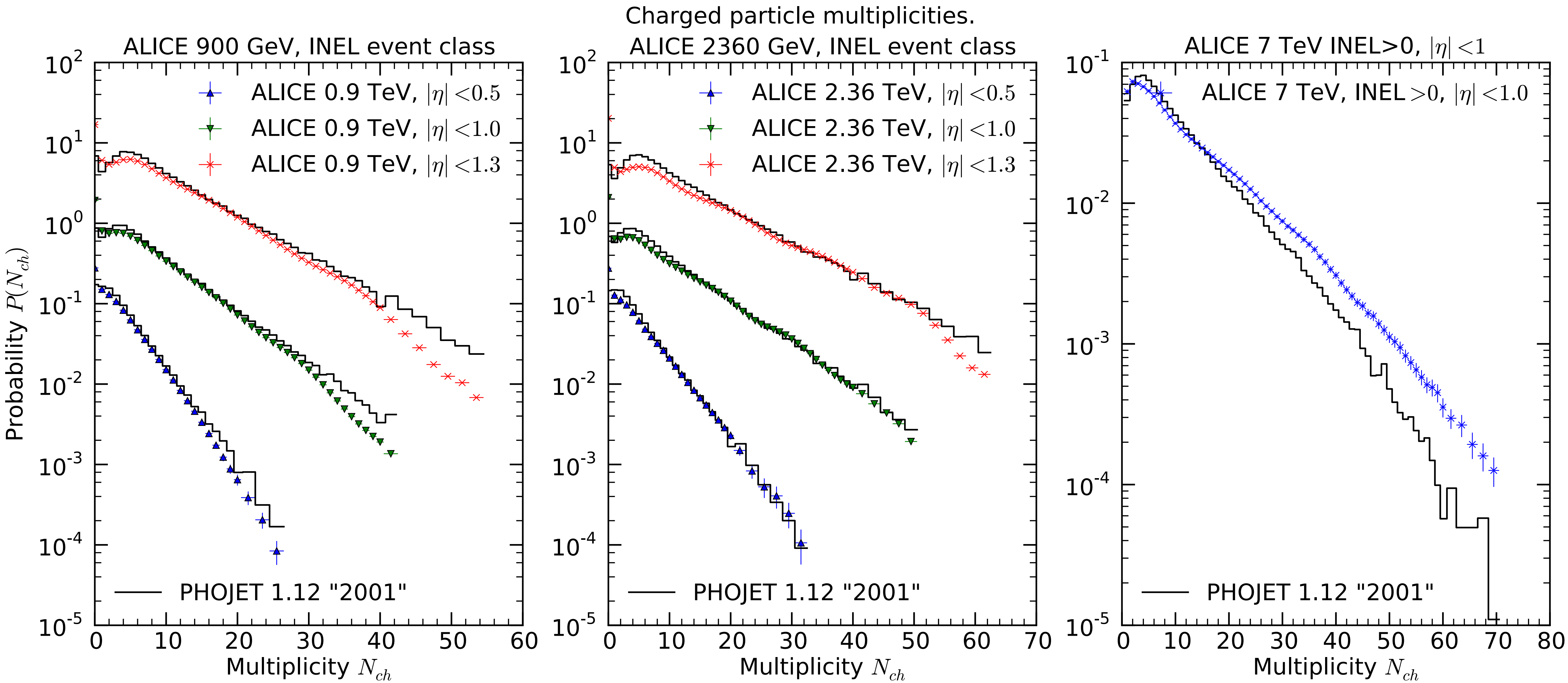
Different models for event building

Comparison with collider measurements

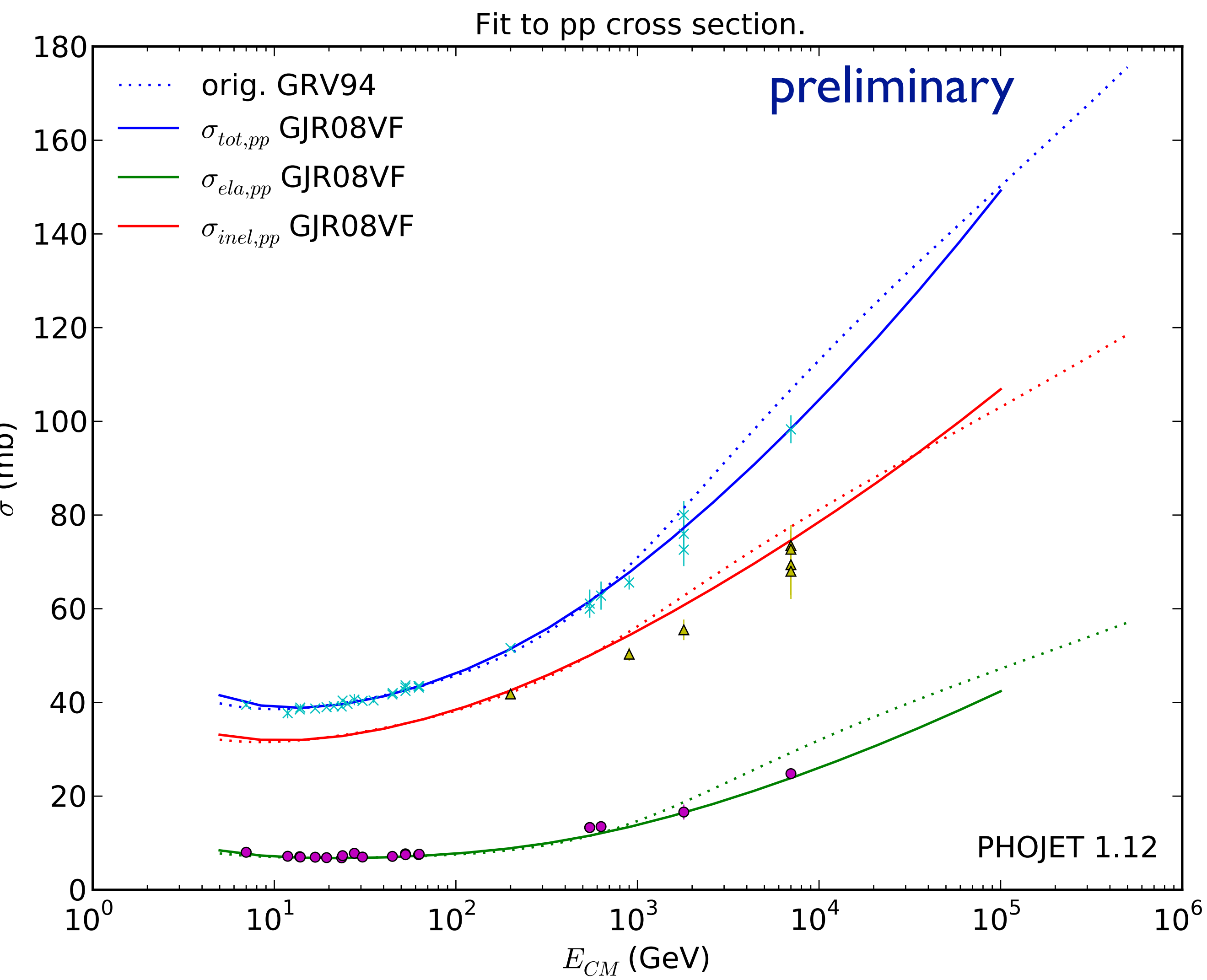


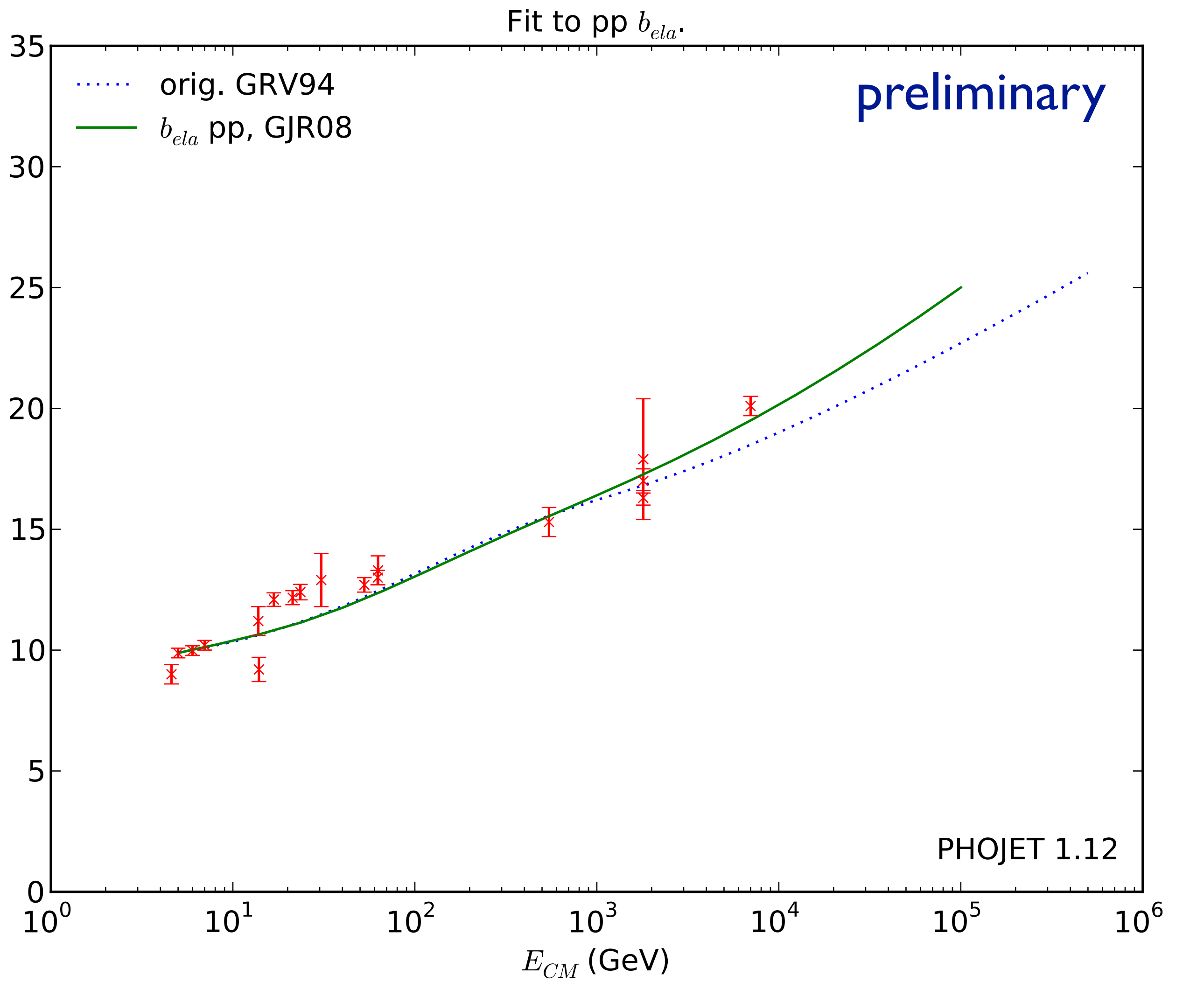
Moares, Buttar, Dawson: EPJC50 (2007) 435

Comparison with collider measurements



Cross section fits (GJR08 parton densities)





Difficult to fit total and elastic cross section and elastic slope at the same time

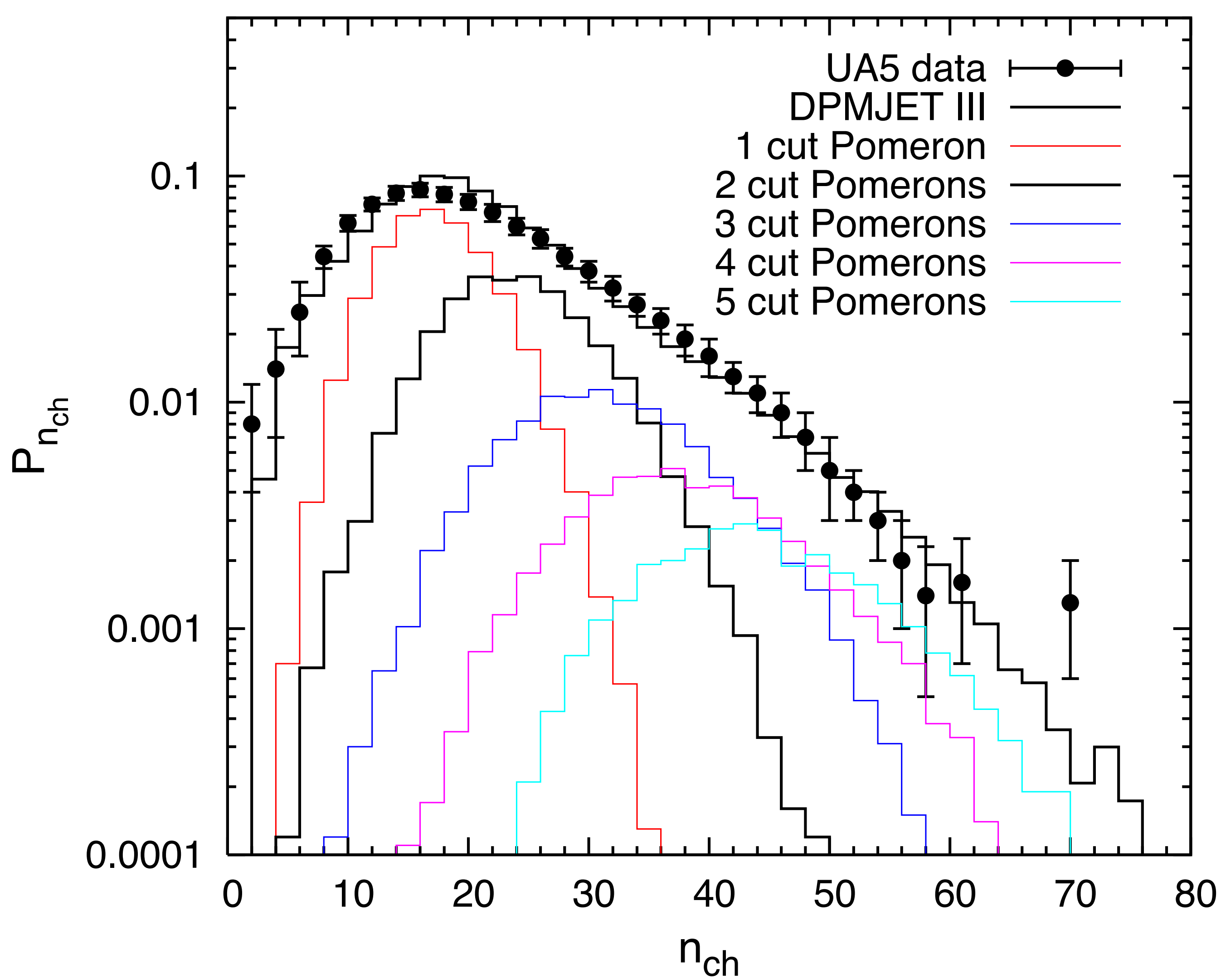
Inclusion of real part of the scattering amplitude should improve situation

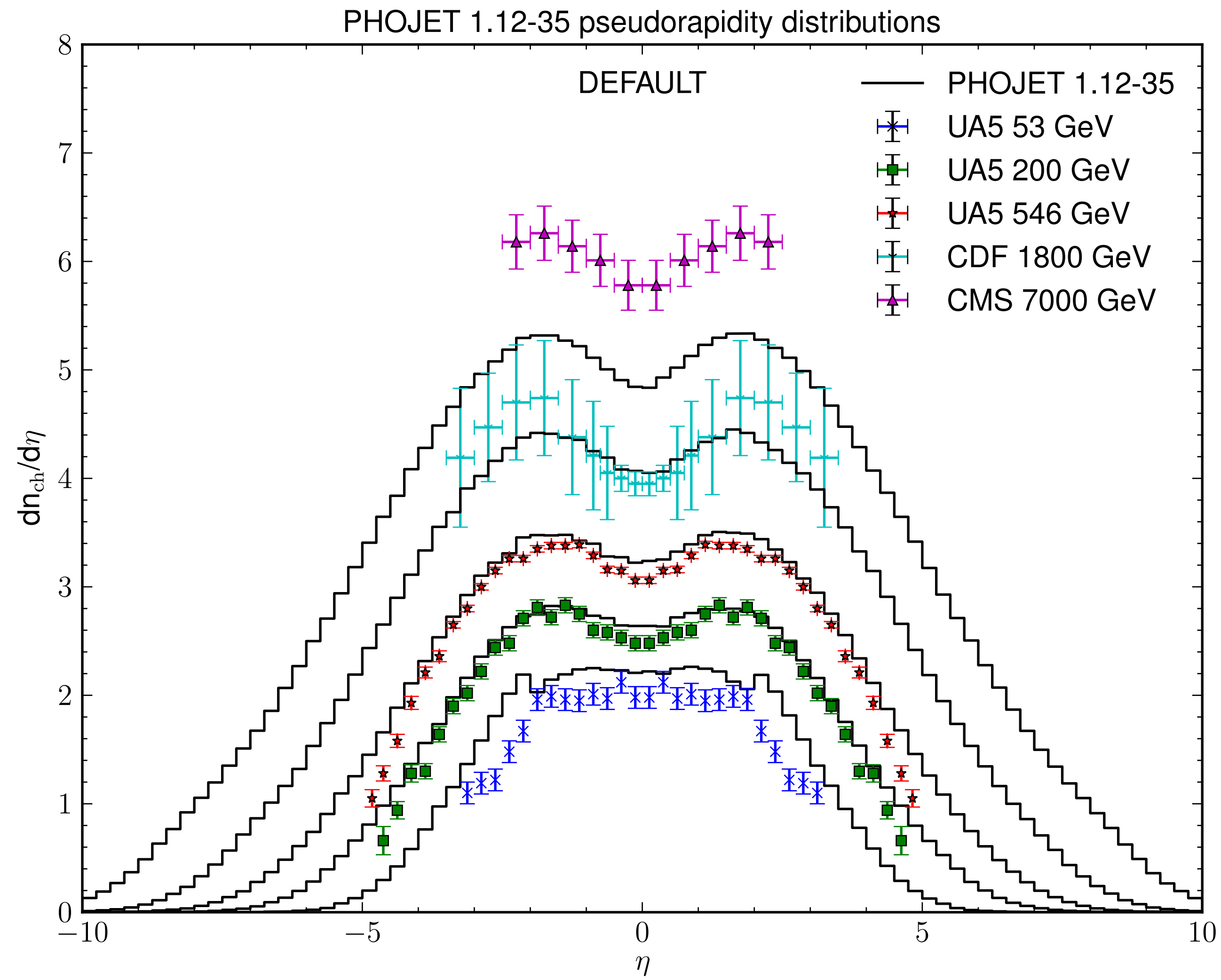
Model (fit) parameters

transverse distributions
soft part of pomeron (couplings, power law index)

Comparison with collider measurements

Charged particle multiplicity distribution at 200 GeV cms.



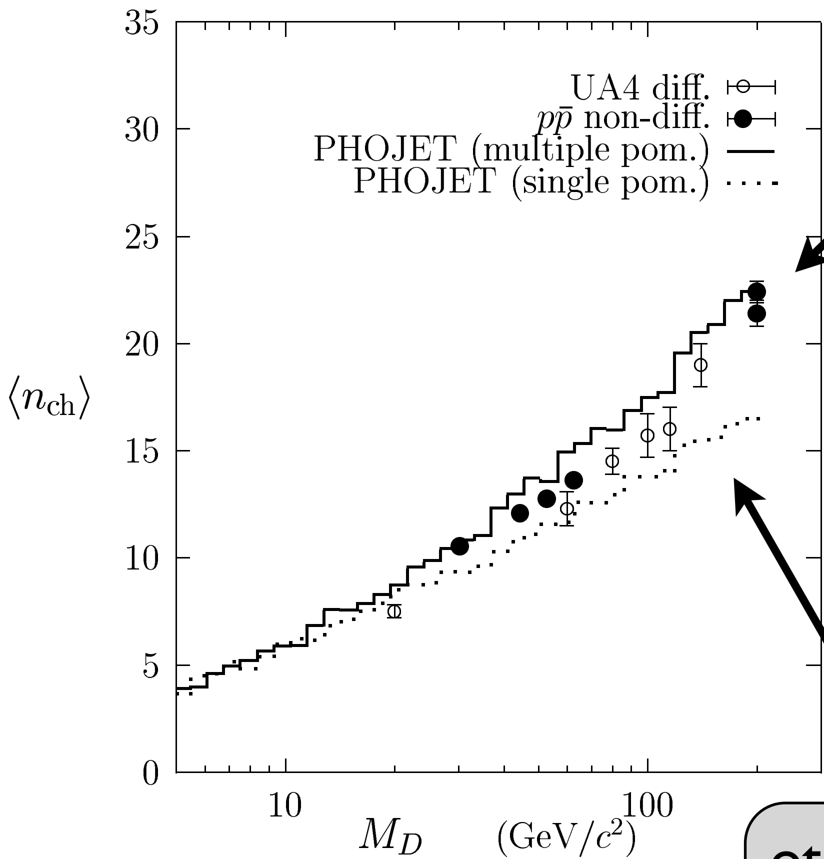


Charged particle pseudorapidity distributions

A. Fedynitch & R. Engel, Heraeus school on diffractive physics, Heidelberg 09/2013

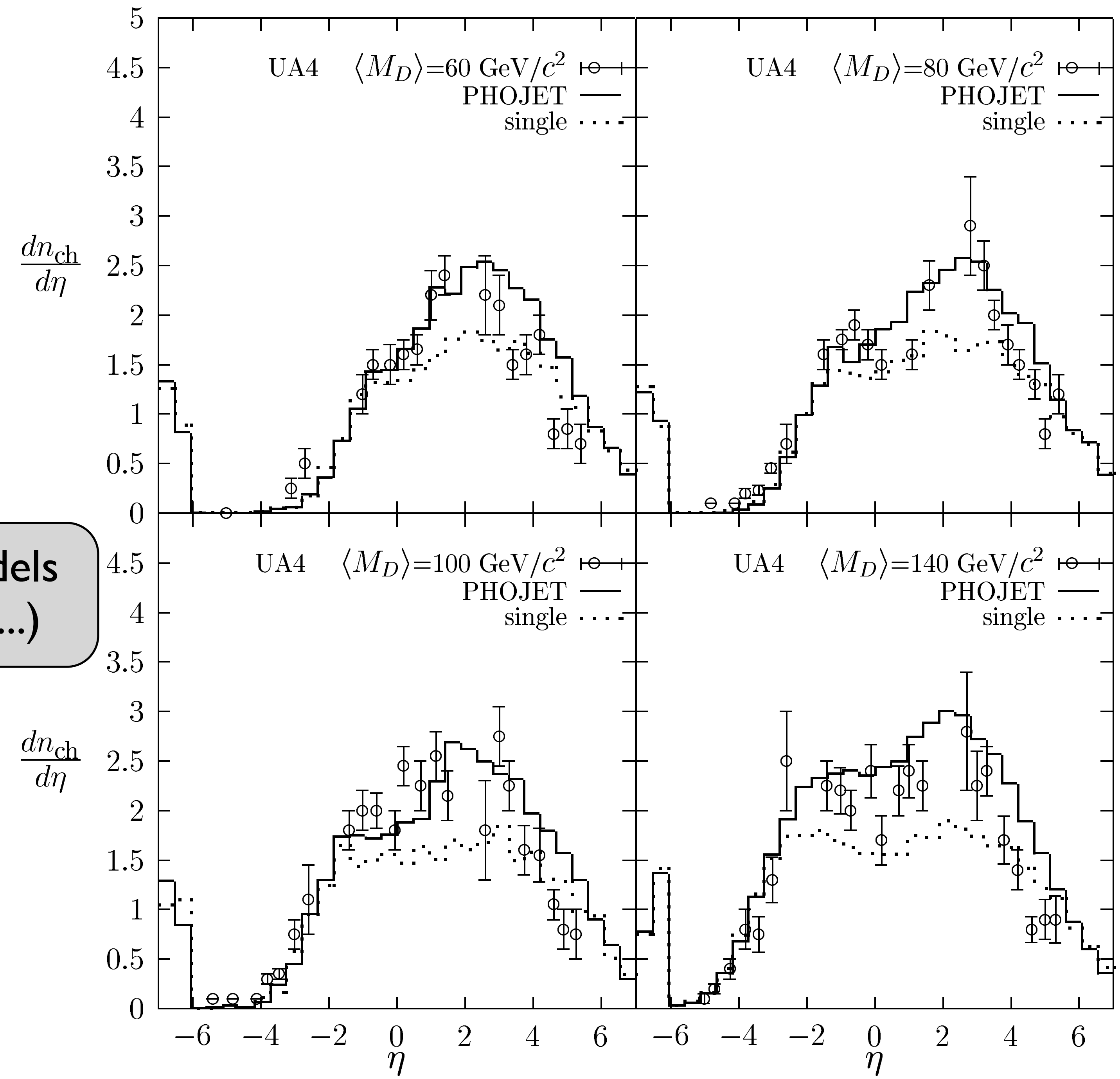
Comparison with collider measurements

PHOJET



other models (PYTHIA, ...)

UA4, Phys. Lett. B16 (1986) 459



Multiple interactions in "pomeron-hadron" or "pomeron-pomeron" scattering?

Limitations & Outlook

PHOJET (stable since ~2000)

- suited for minimum bias studies
- sensible default settings and predictions due to consistent unitarization
- sophisticated treatment of diffraction dissociation
- only leading order QCD processes (no W/Z etc.)
- no heavy quark production (massless production scheme)
- no dedicated high-pt physics options

New work on developing PHOJET recently started

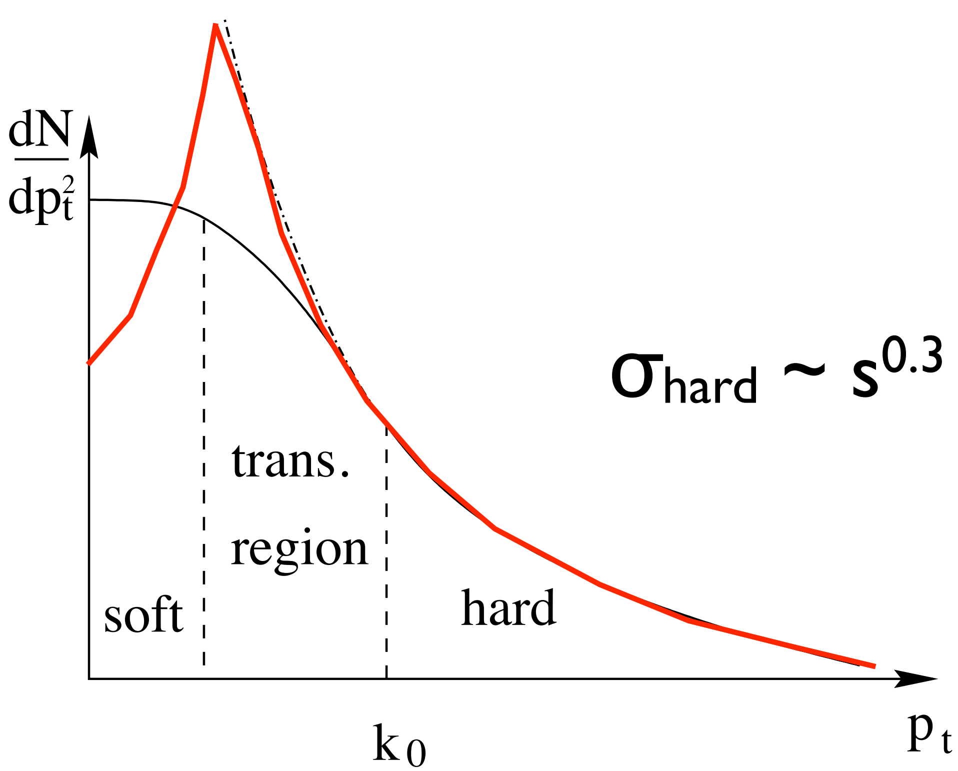
- implementation of new parton densities
- multiplicities at energies >= LHC
- real part of scattering amplitudes
- impact parameter dependent saturation

Backup

Conceptual problem: matching soft/hard

p_t distribution of partons due to one cut pomeron

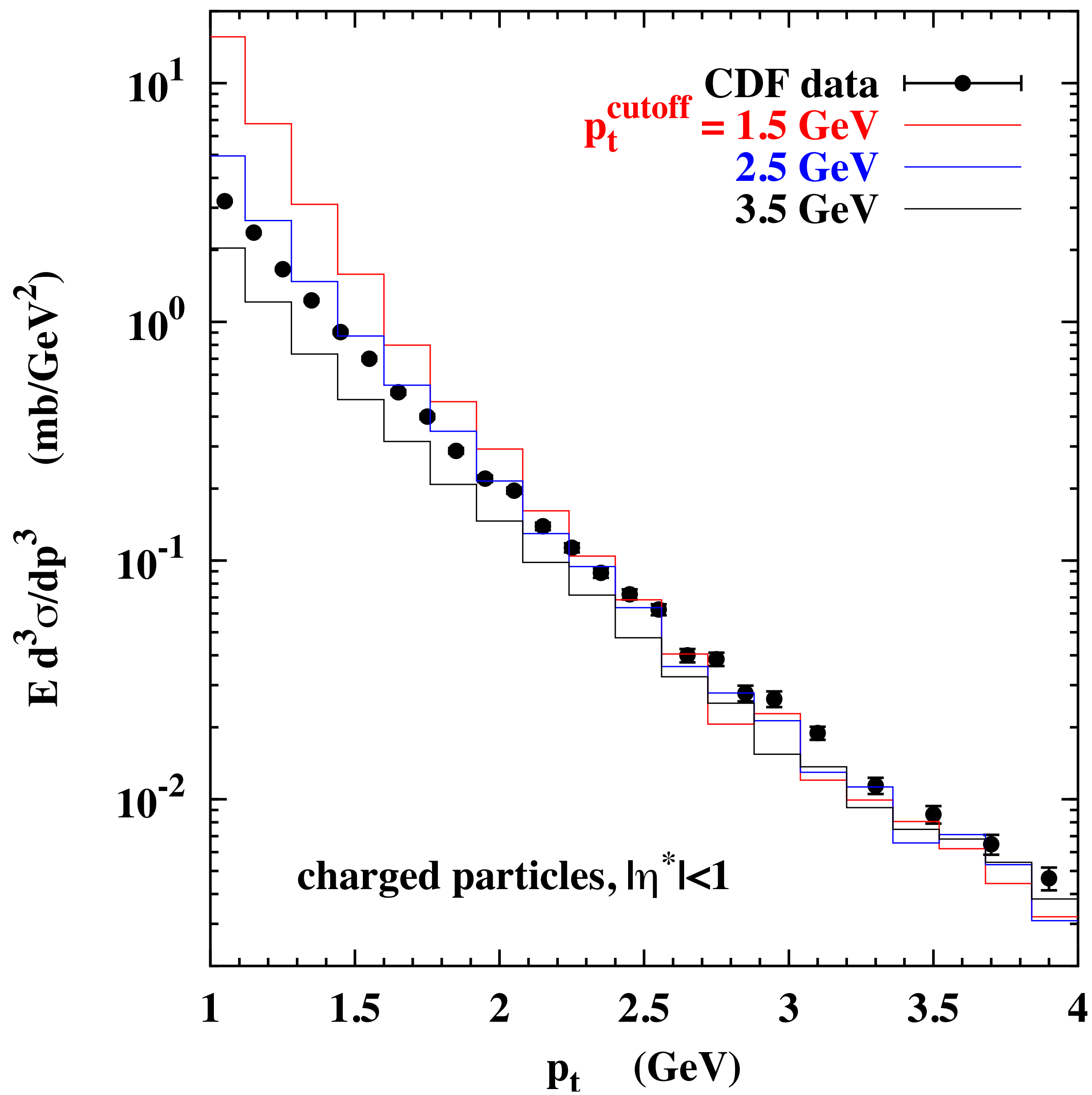
$\sigma_{soft} \sim s^{0.1}$



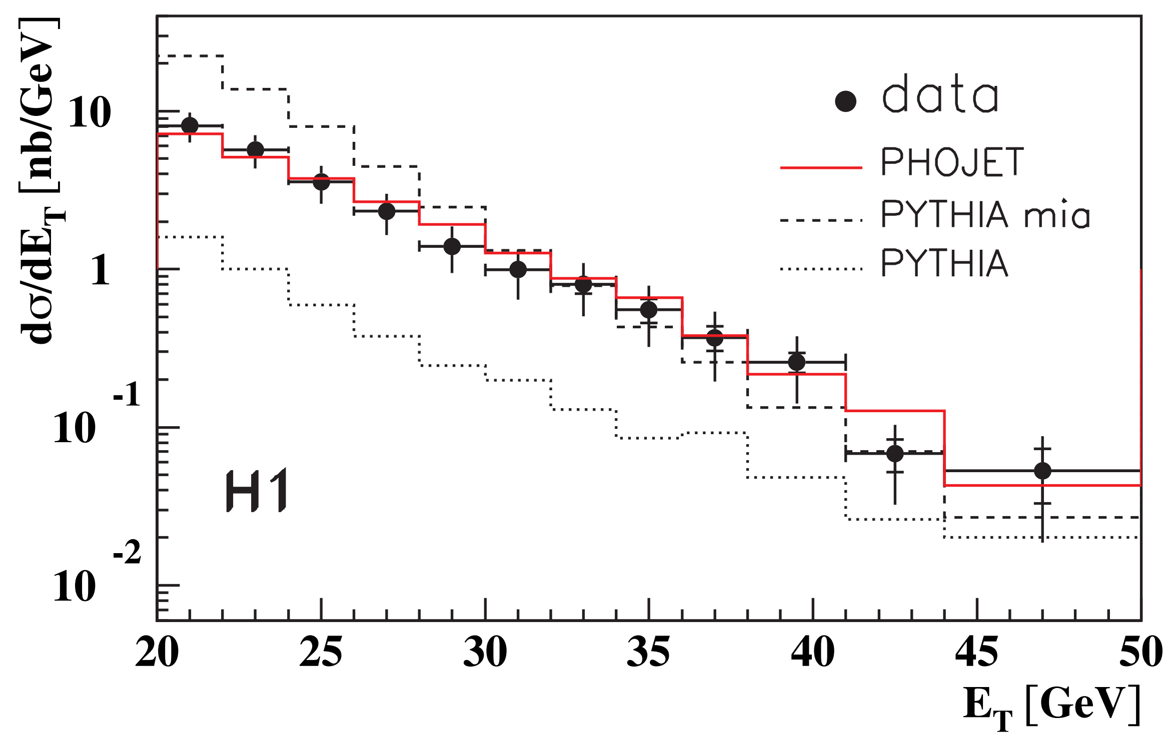
$\sigma_{hard} \sim s^{0.3}$

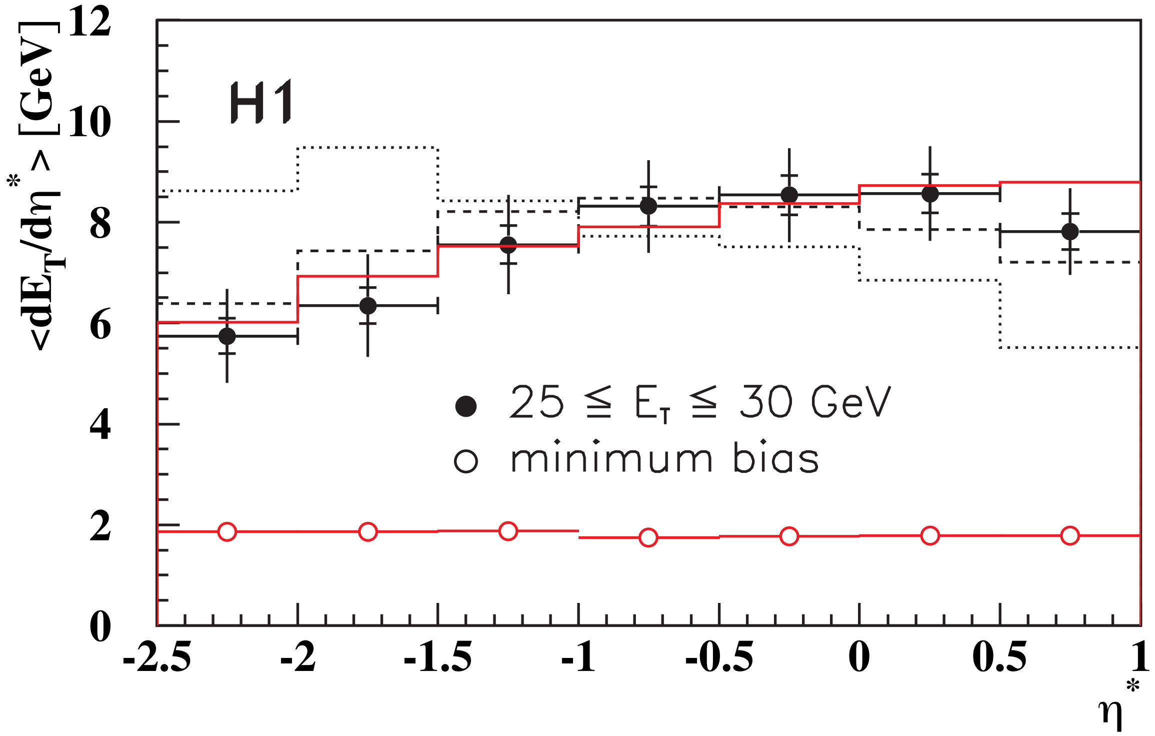
pt cutoff

CDF inclusive charged particle distribution

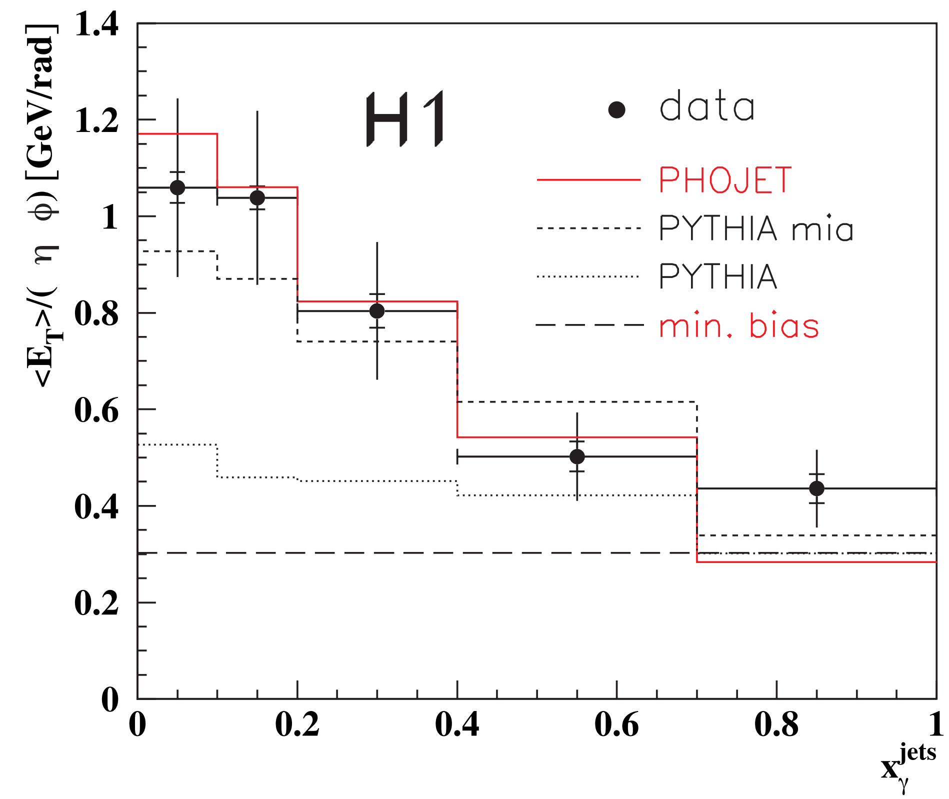


Photoproduction at HERA





Jet and multiple interaction study by H1

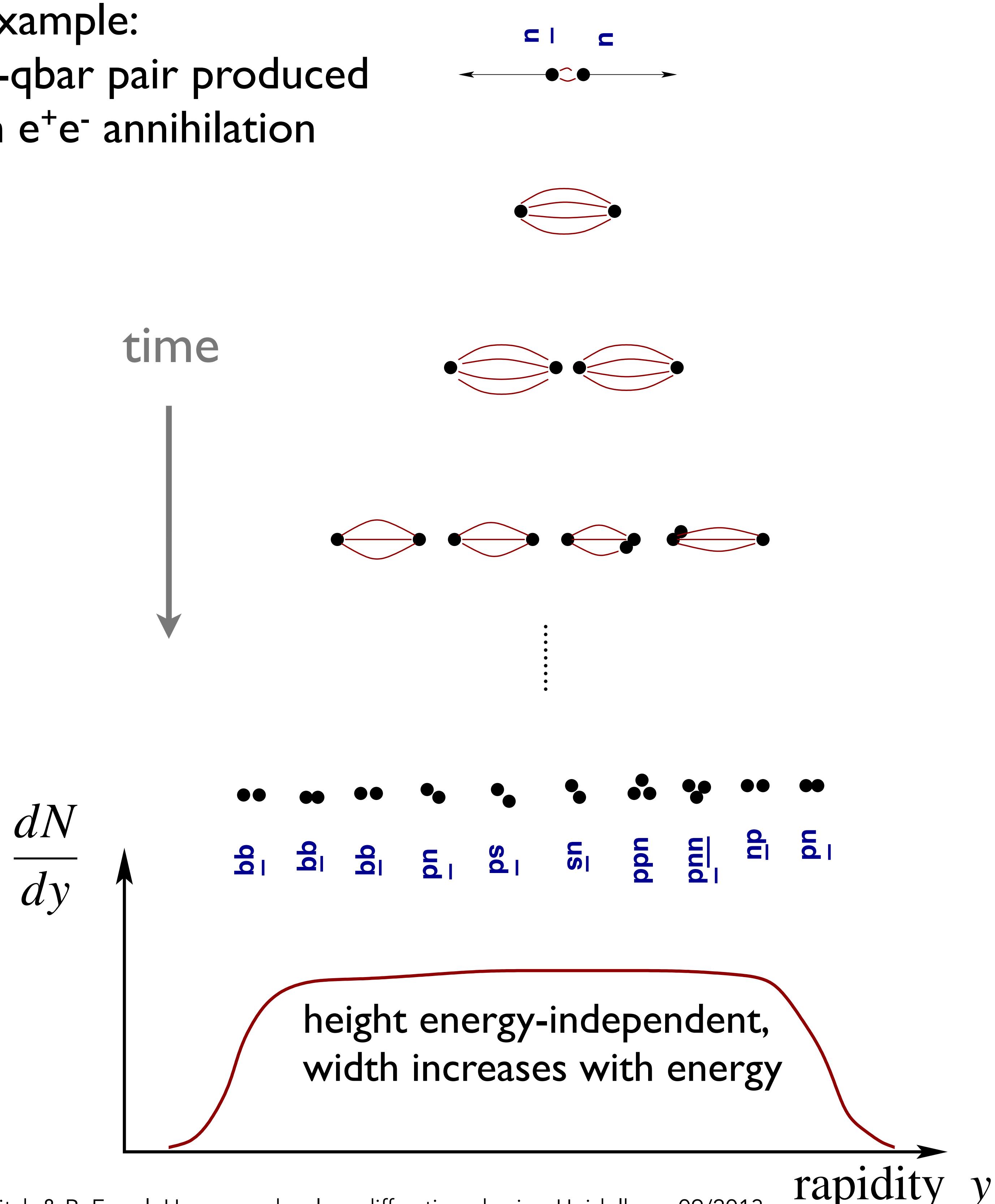


Energy density outside of jet cone, averaged over $-1 \leq \eta^* \leq 1$

(H1 Collab., ZPC 70, 1995)

String fragmentation and rapidity

Example:
q-qbar pair produced
in e^+e^- annihilation



Rapidity

$$y = \frac{1}{2} \ln \frac{E + p_{\|}}{E - P_{\|}}$$

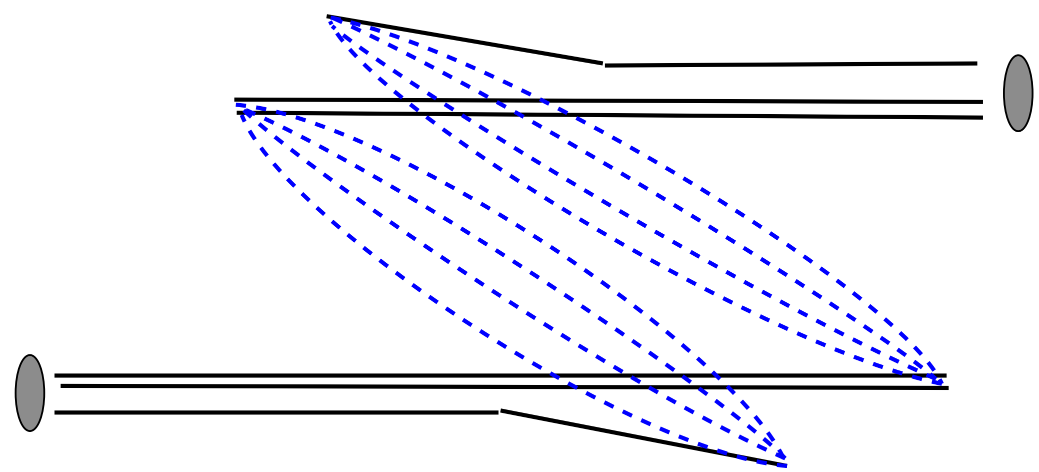
Rapidity of massless particles

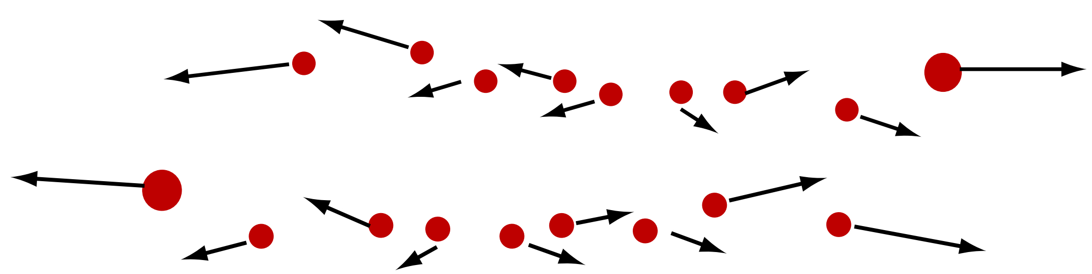
$$y = \frac{1}{2} \ln \frac{1 + \cos\theta}{1 - \cos\theta} = -\ln \tan \frac{\theta}{2}$$

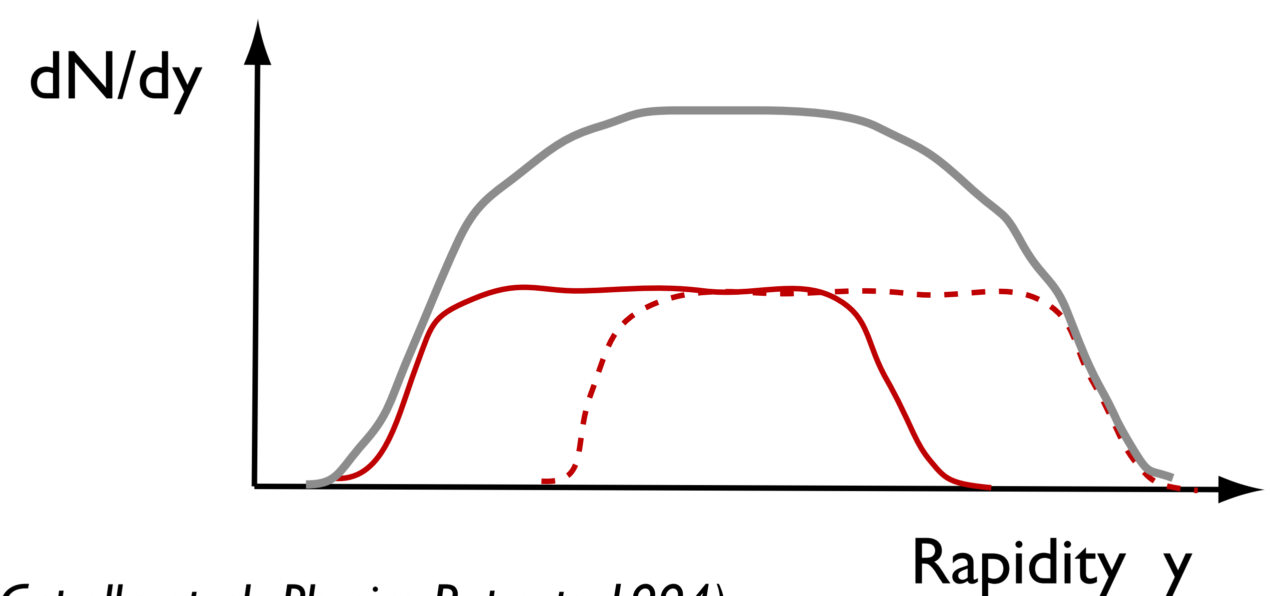
Pseudorapidity

$$\eta = -\ln \tan \frac{\theta}{2}$$

Predictions of two-string models







(*Capella et al., Physics Reports 1994*)

Two-string models:

- Feynman-scaling
- long-range correlations
- leading particle effect
- delayed threshold for baryon pair production

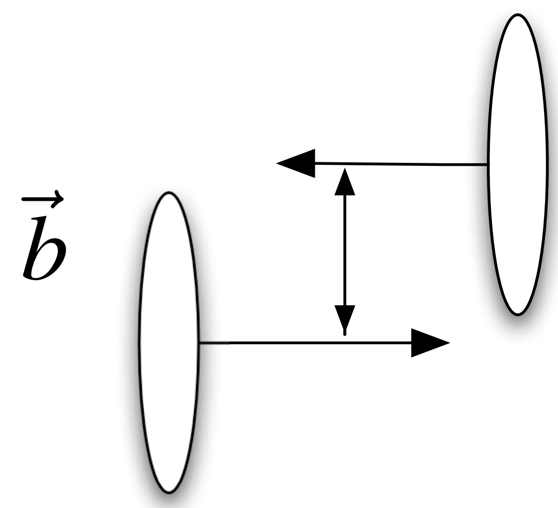
Feynman scaling

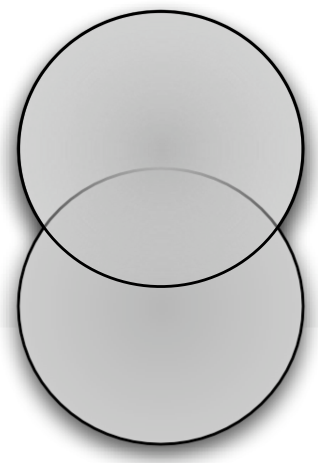
$$2E\frac{dN}{d^3p} = \frac{dN}{dy\, d^2p_\perp} \longrightarrow f(x_F, p_\perp)$$

Distribution independent of energy

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

Minijet model: underlying ideas





Overlap function

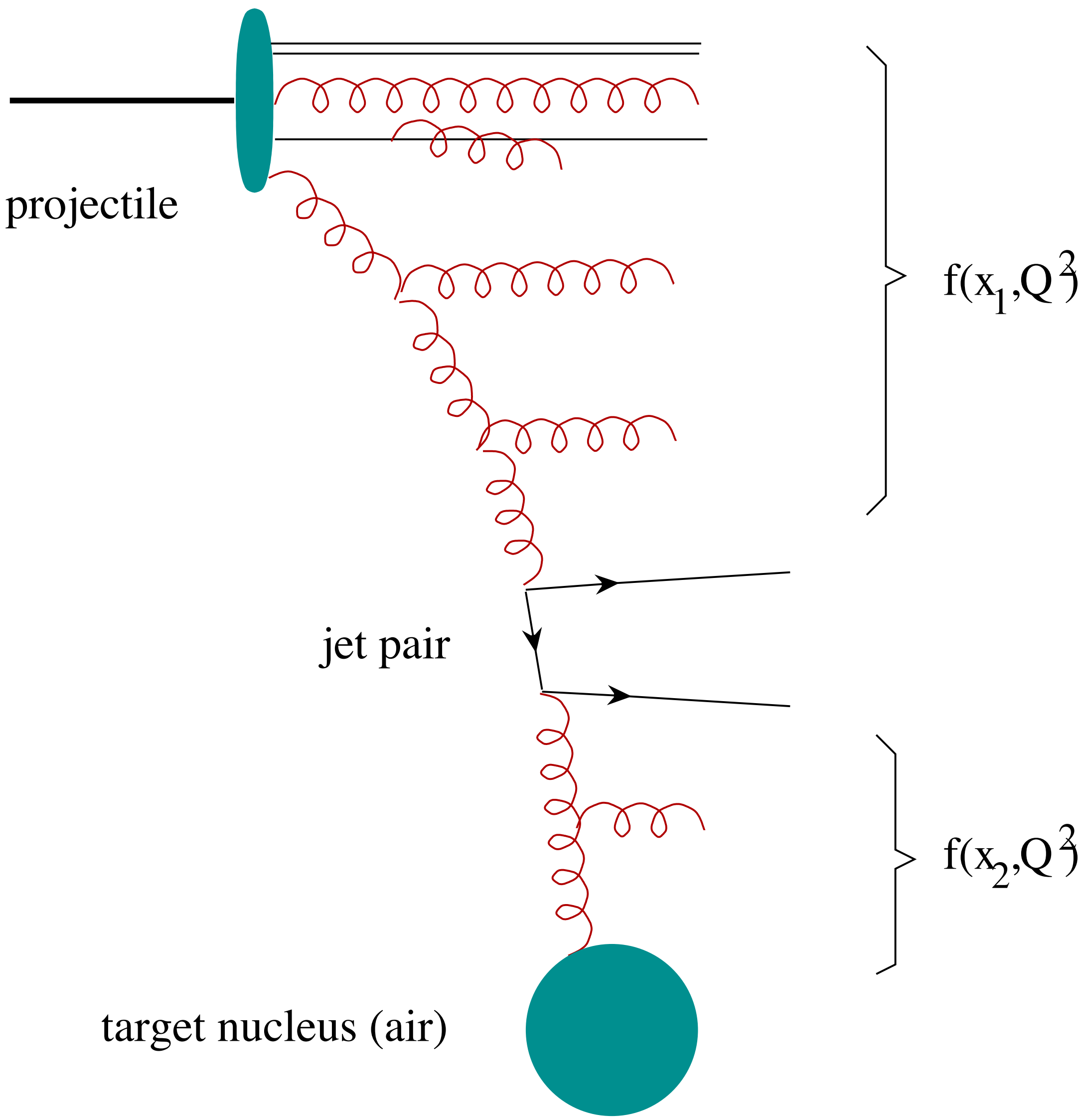
$$\langle n(\vec{b})\rangle = \sigma_{\rm QCD}\, A(s,\vec{b})$$

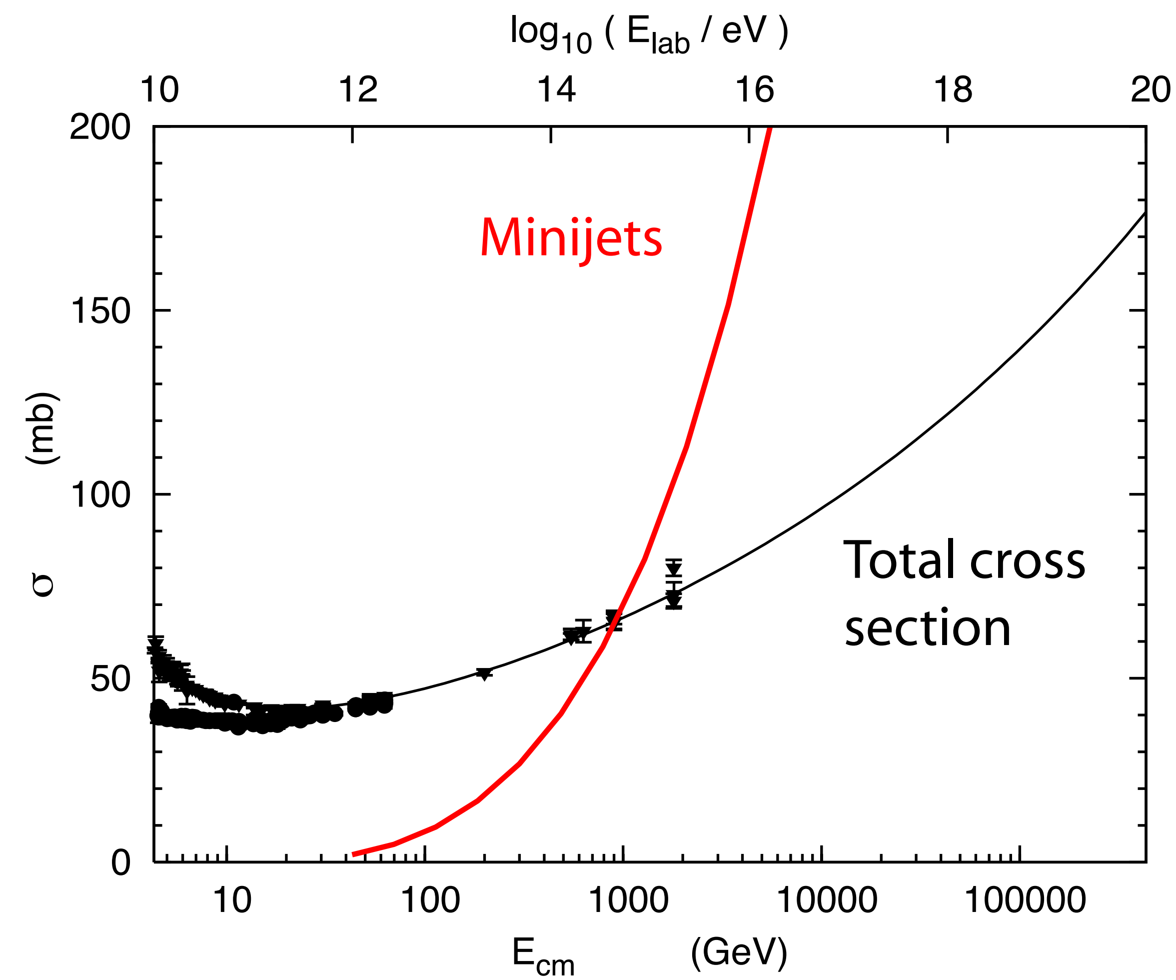
Independent interactions:
Poisson distribution

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

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

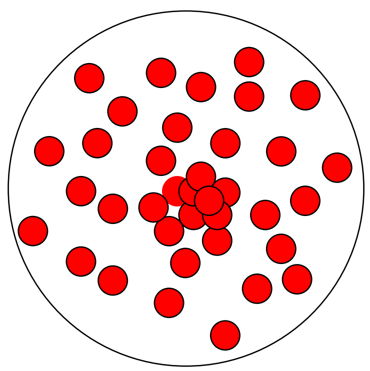
QCD parton model: minijets



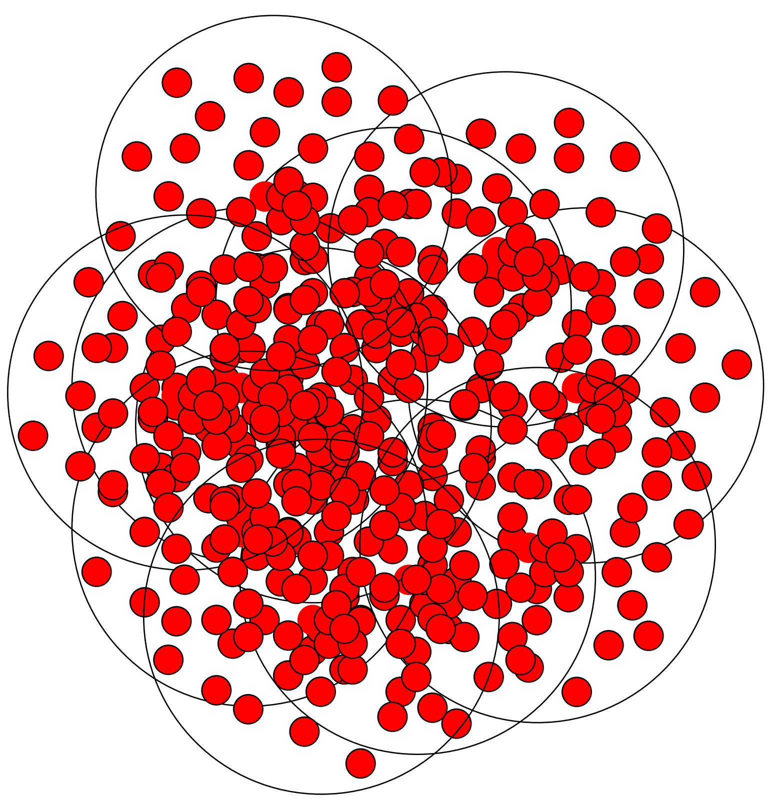


$$\sigma_{QCD} = \sum_{i,j,k,l} \frac{1}{1+\delta_{kl}} \int dx_1\, dx_2 \int_{p_\perp^{\text{cutoff}}} dp_\perp^2\, f_i(x_1, Q^2)\, f_j(x_2, Q^2)\, \frac{d\sigma_{i,j\to k,l}}{dp_\perp}$$

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

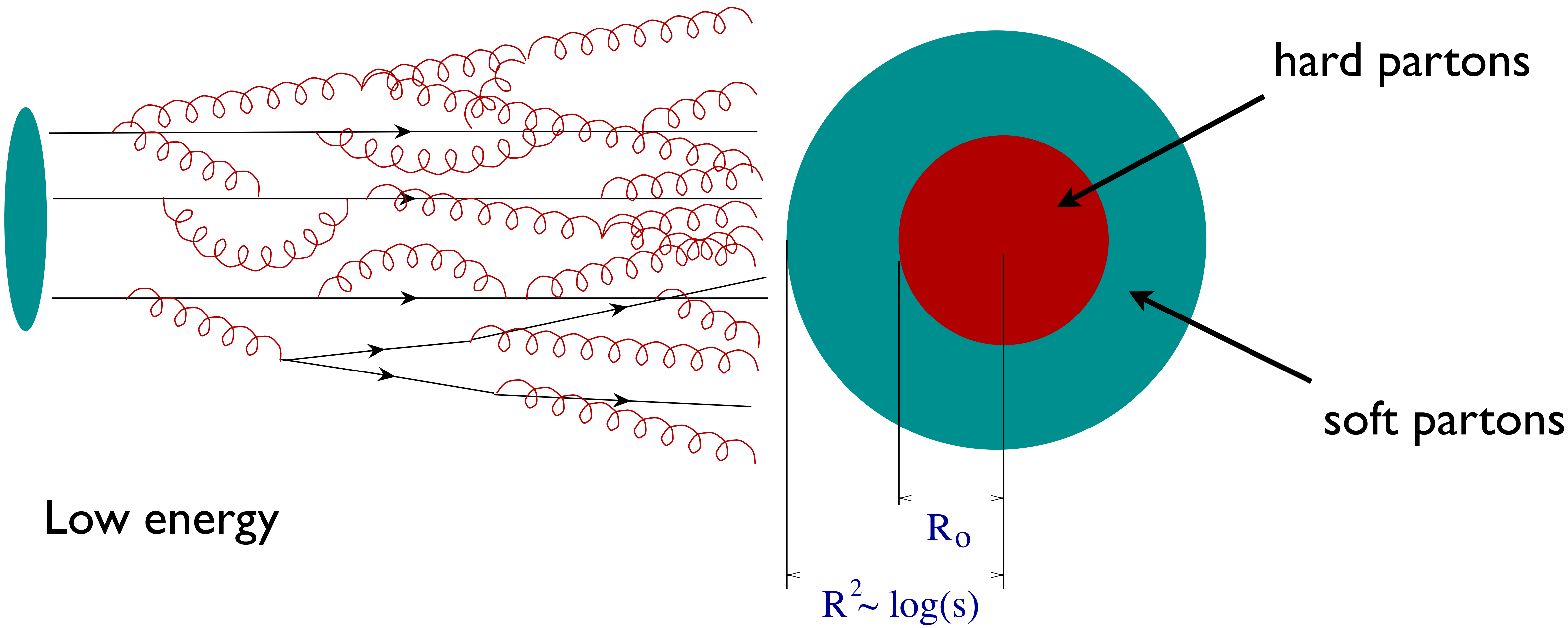
$$\pi R_0^2 \simeq \frac{\alpha_s(Q_s^2)}{Q_s^2} \cdot xg(x, Q_s^2)$$

size of proton

Size of one gluon

number of gluons

Profile functions



Low energy

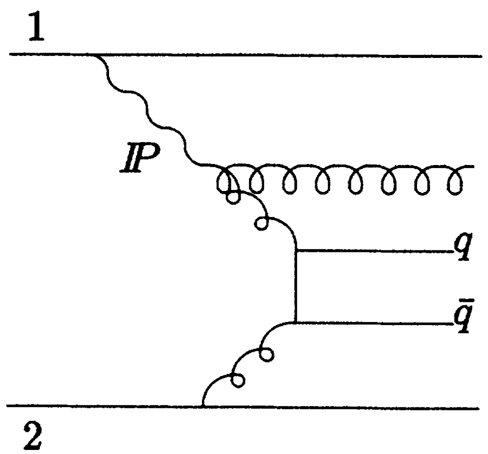
High energy

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

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

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

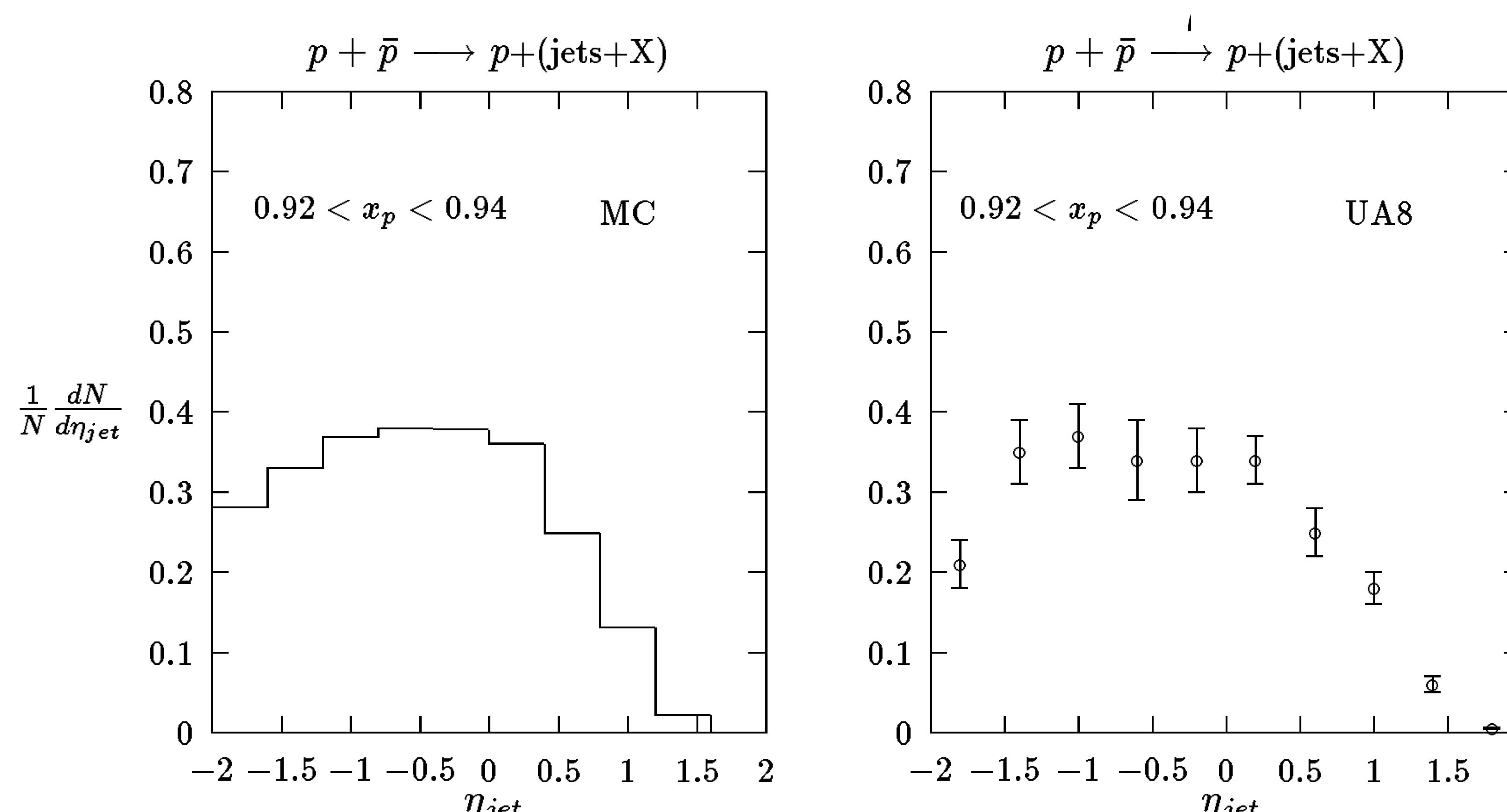
Hard diffraction



Hard interactions between diffractive mass and pomeron

$$\frac{d^2\sigma_{3I\!P}(s,t)}{dt\,dM^2} = \frac{1}{16\pi s^2}|g^{I\!P}_{11'}(t)|^2 g^{I\!P}_{22}(0)\Gamma^{3I\!P}(t,0)|\xi_{I\!P}(t)|^2\left(\frac{s}{M^2}\right)^{2\alpha_{I\!P}(t)}\left(\frac{M^2}{s_0}\right)^{\alpha_{I\!P}(0)}$$

Strong dependence on gluon distribution in pomeron PDF



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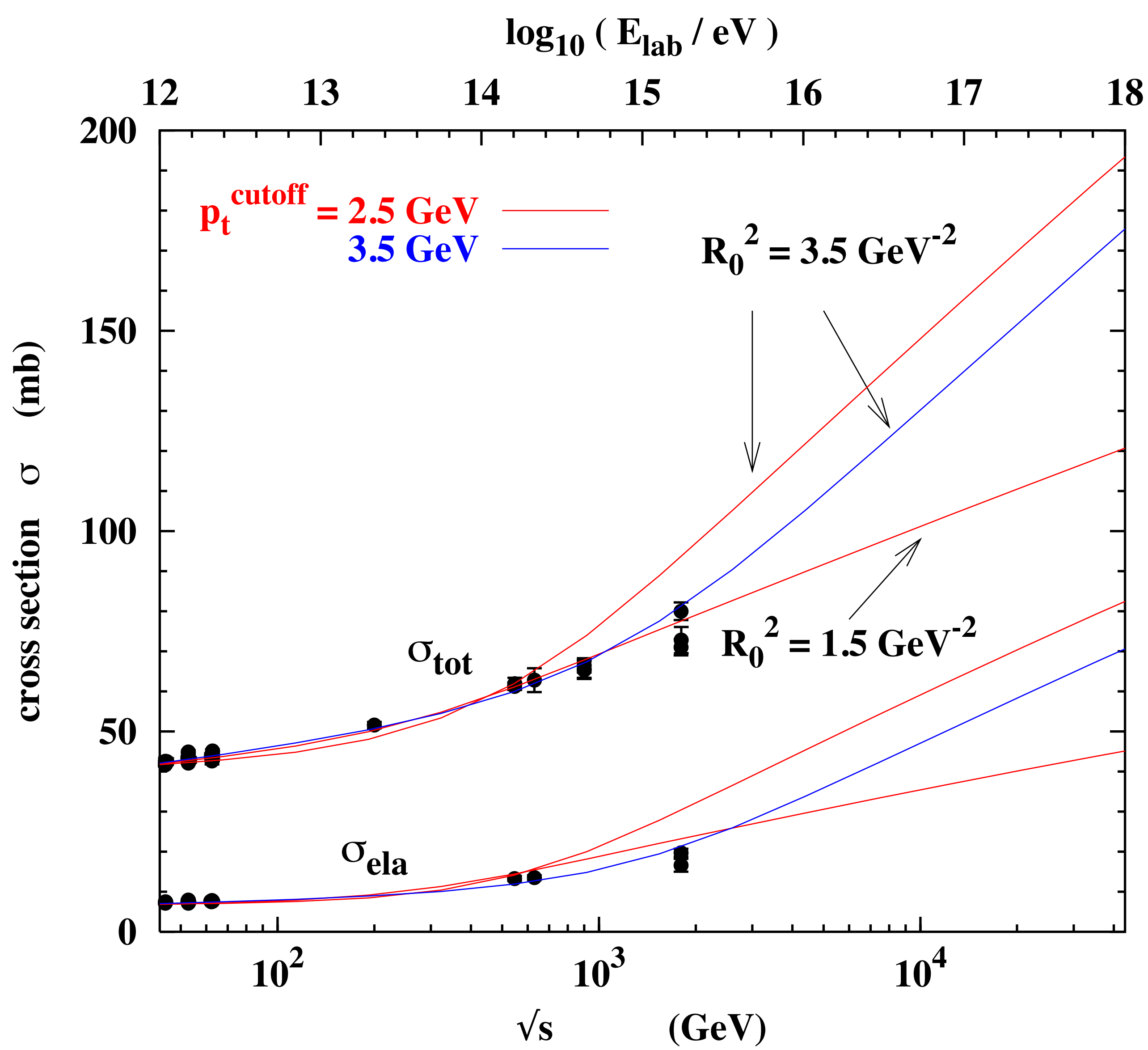
Correlation of hard cross section and impact parameter profile



Cross section fits with energy-independent Gaussian profiles for hard interaction

Charged particle multiplicity distribution