Soft colour screening effects in diffraction

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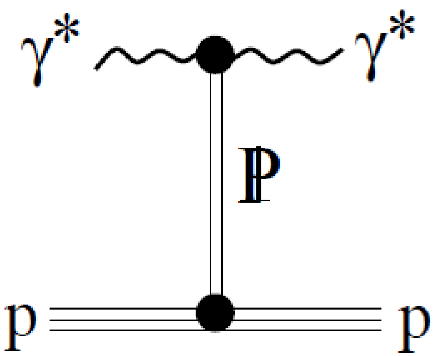
Soft QCD and diffraction

Soft processes are characterized by the soft hadronic scale: $R \sim 1\ \mathrm{fm}$

Hadronic diffraction ⟷ **predominantly soft phenomenon**

Regge theory approach

Perturbative QCD approach



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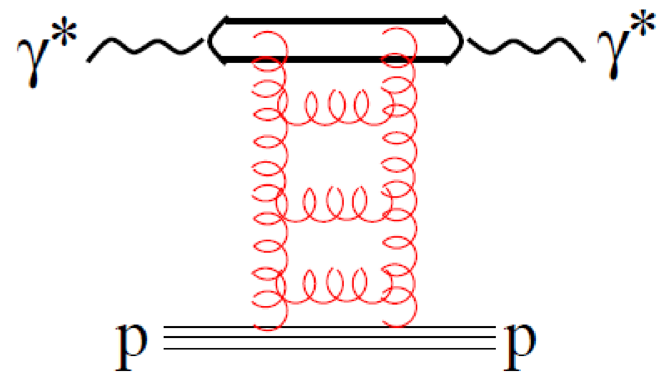


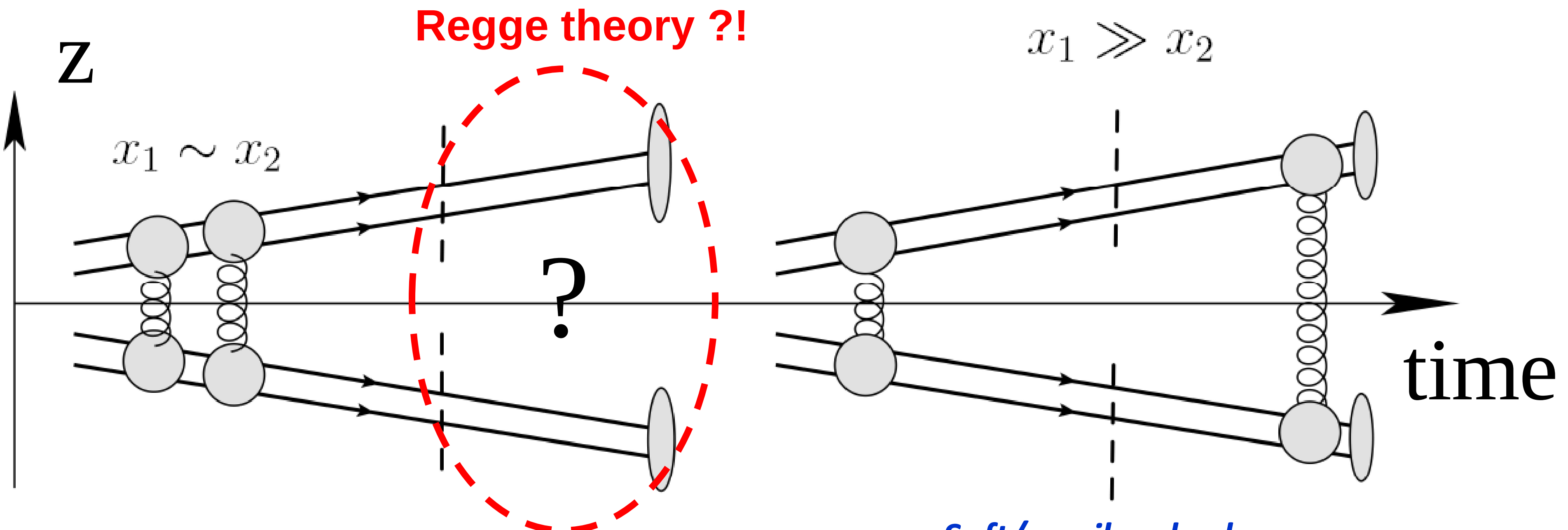
A. Donnachie, P.V. Landshoff, Nucl. Phys. **B231** (1984) 189.

Pomeron structure is still a mystery!

pQCD motivated models:

- Durham QCD mechanism
- Color Dipole Approach
- Soft Color Interactions model

Color screening



Perturbative color neutralization

Soft/semihard color neutralization

Lack of absorptive effects!

- *Both include unitarity corrections and color neutralisation*
- *Both diffractive – nondiffractive processes*

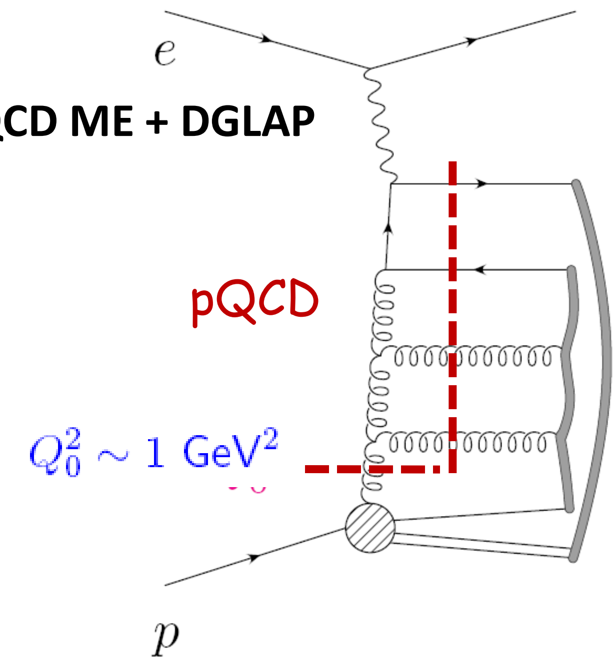
Diffractive Deep Inelastic Scattering: the NP color screening

G. Ingelman, A. Edin, J. Rathsman, Comput. Phys. Commun. **101**, 108-134 (1997).
A. Edin, G. Ingelman, J. Rathsman, Z. Phys. **C75**, 57-70 (1997).

✓ **The success of Soft Color Interaction (SCI) model**

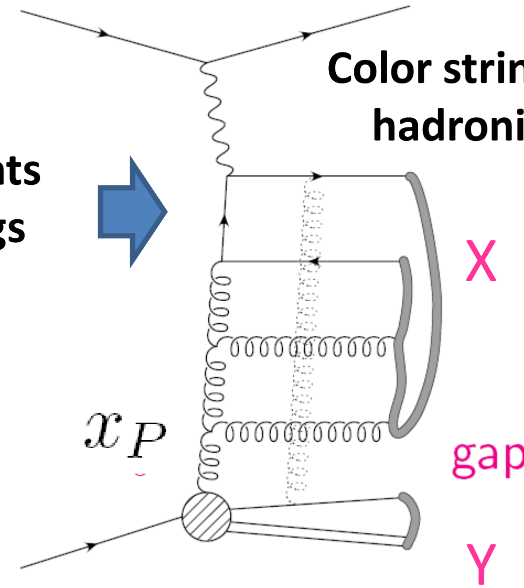
diffractive ↔ nondiffractive

pQCD ME + DGLAP



Color rearrangements modify colour strings topology

Color string (Lund) hadronisation



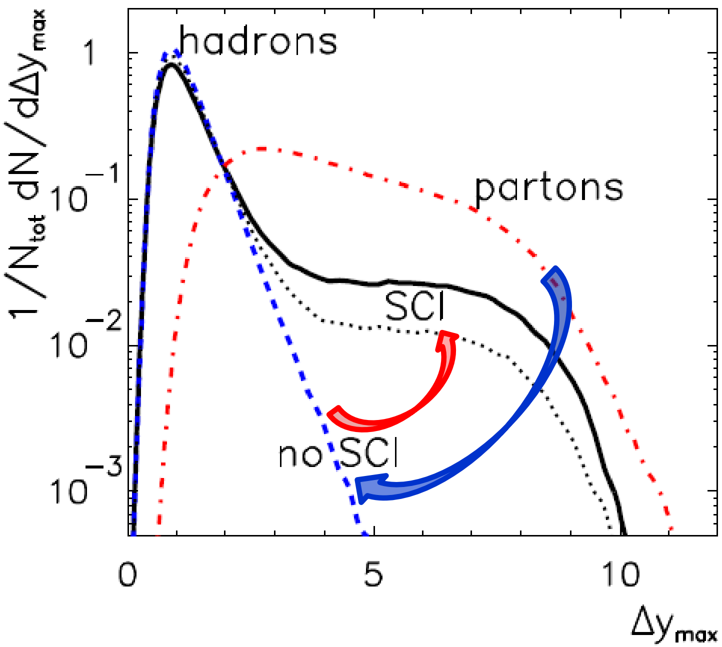
- ***Soft interactions among the final state partons and proton remnants (=> proton color field) at small momentum transfers < 1 GeV***
- ***Hard pQCD part (small distances) is not affected by soft interactions (large distances)***
- ***Single parameter - probability for soft colour-anticolour (gluon) exchange***
- ***Single model describing all final states: both diffractive and nondiffractive***

Soft Colour Interaction model (SCI)

Add-on to Lund Monte Carlo's LEPTO (ep) and PYTHIA ($p\bar{p}$)

ME + DGLAP PS $> Q_0^2$	$\rightarrow$	SCI model	$\rightarrow$	String hadronisation $\sim \Lambda$
colour ordered parton state		rearranged colour order		modified final state

Size Δy_{max} of largest gap in DIS events



SCI $\Rightarrow$ plateau in Δy_{max}
characteristic for diffraction

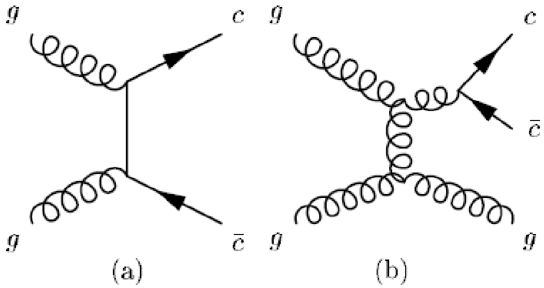
Small parameter sensitivity
— $P = 0.5$
$\cdots$ $P = 0.1$

Gap-size is infrared sensitive observable !

Large gaps at parton level
normally string across $\rightarrow$ hadrons fill up
SCI $\rightarrow$ new string topologies, some with gaps

Gap events not 'special', but
fluctuation in colour/hadronisation

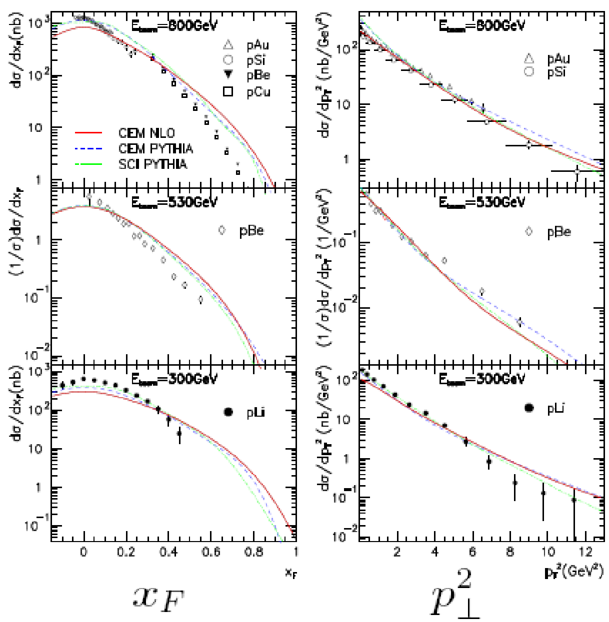
Soft Colour Interaction model → prompt charmonium



pert. QCD
↓
$c\bar{c}$ pair

Colour octet $c\bar{c}$ turned into singlet $c\bar{c}$

$m_{c\bar{c}} < 2m_D$ mapped on charmonium states
with spin statistics (+ soft smearing)

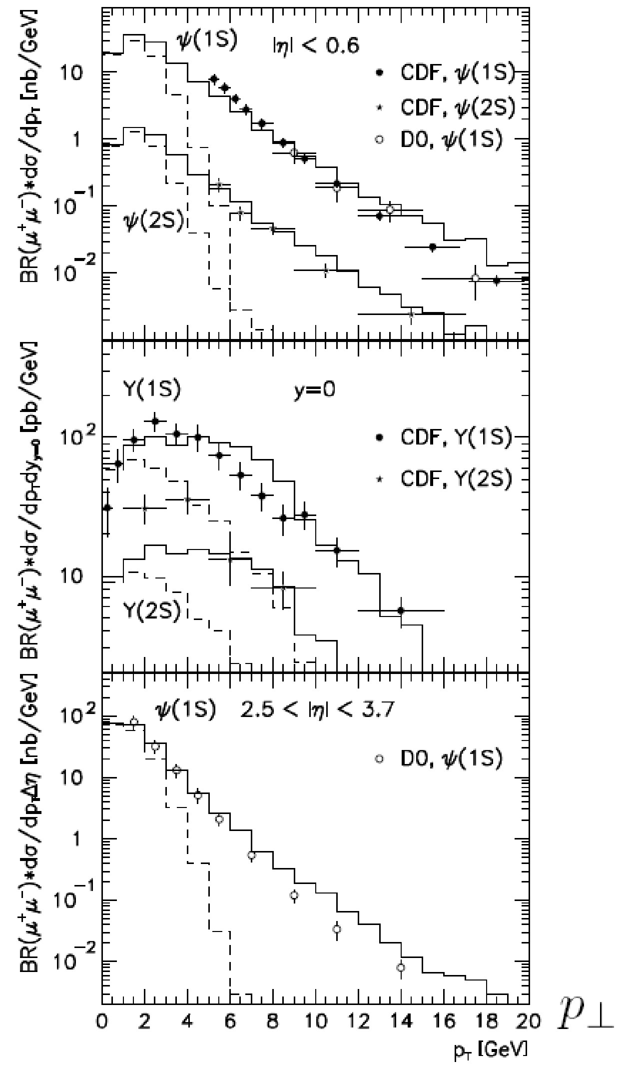


pA @

800 GeV

530 GeV

300 GeV



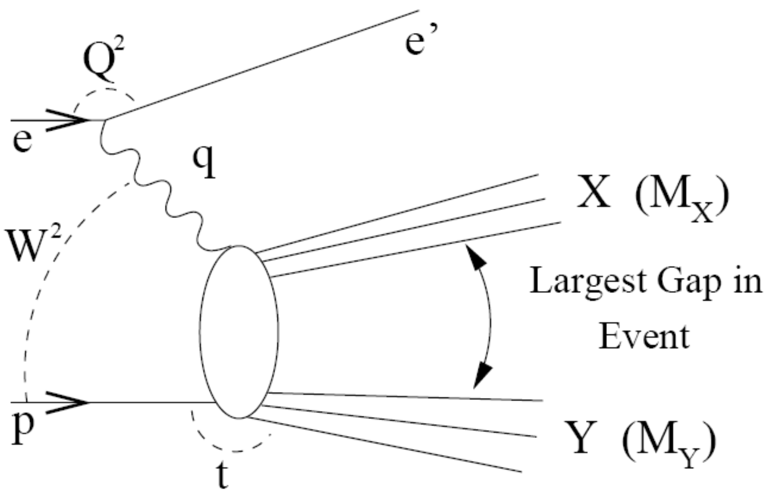
J/ψ, ψ' in fixed target πA, pA is OK   High-$p_\perp$ J/ψ, ψ', Υ at Tevatron is OK

A. Edin, G. Ingelman, J. Rathsman, Phys. Rev. **D56**, 7317-7320 (1997)

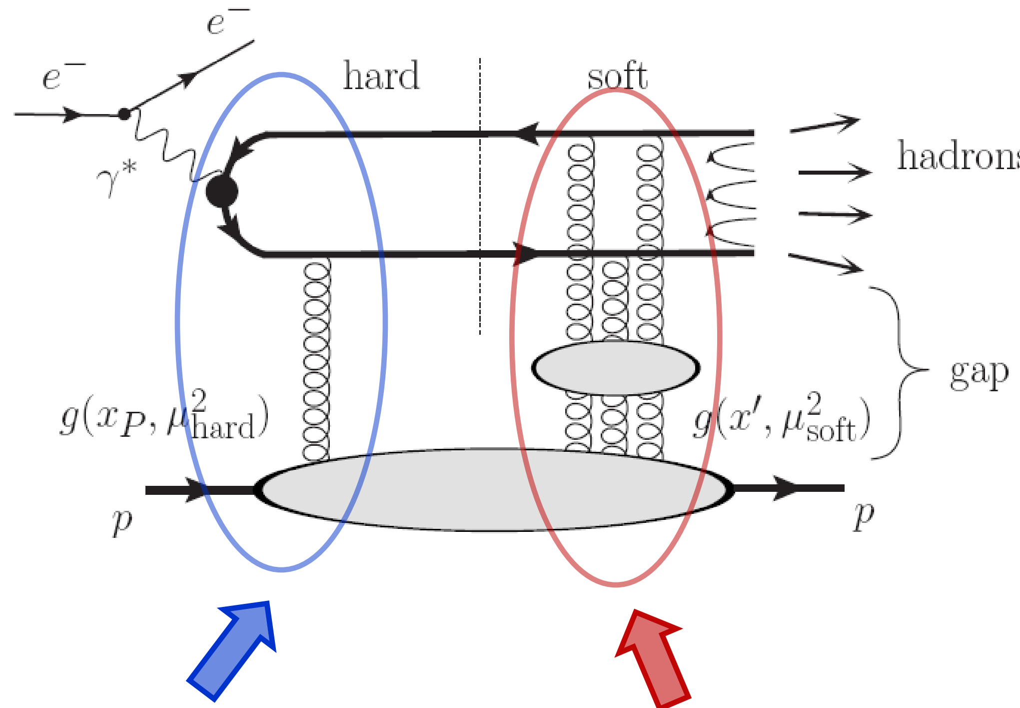
Pasechnik, Enberg, Ingelman, Phys.Rev. D82 (2010) 054036

QCD rescattering theory: the dipole model

Diffractive DIS at HERA



QCD rescattering model



Hard part
conventional
(small distance)

Soft part:
color-screening (octet)
multigluon exchange
(large distance)

Diffractive DIS at HERA: kinematics

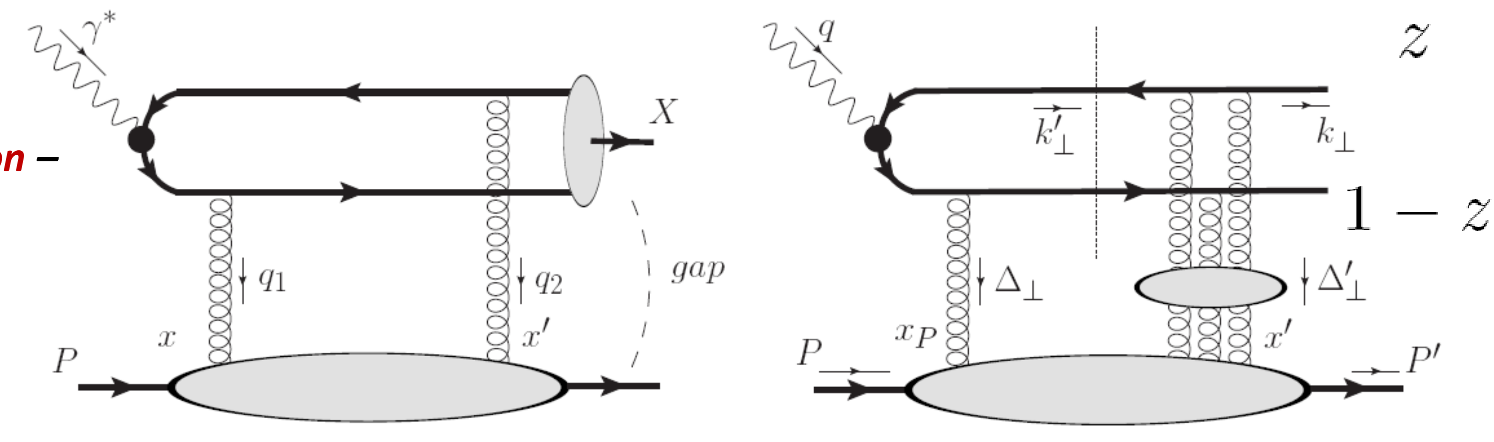
Basic variables:

$$x \equiv \frac{Q^2}{2Pq} = \frac{Q^2}{Q^2+W^2}, \quad \beta = \frac{Q^2}{Q^2+M_X^2}, \quad x_P = \frac{x}{\beta}, \quad t = (P'-P)^2$$

$$Q^2 = -q^2$$

***Leading contribution* – by quark dipole**

$$\beta = x/x_P \to 1$$



(a) (b)

$$x' \ll x_P$$

Invariant mass* of X system and *c.m.s energy

$$M_X^2 = \frac{1-\beta}{\beta} Q^2, \quad W^2 \simeq \frac{Q^2}{x_P \beta},$$

$$\varepsilon^2 = z(1-z)Q^2 + m_q^2, \quad k_\perp^2 = z(1-z)M_X^2 - m_q^2$$

Working domain of interest:

$$x_P \ll 1, \quad M_X \ll W$$

$$|t| \ll Q^2, \, M_X^2$$

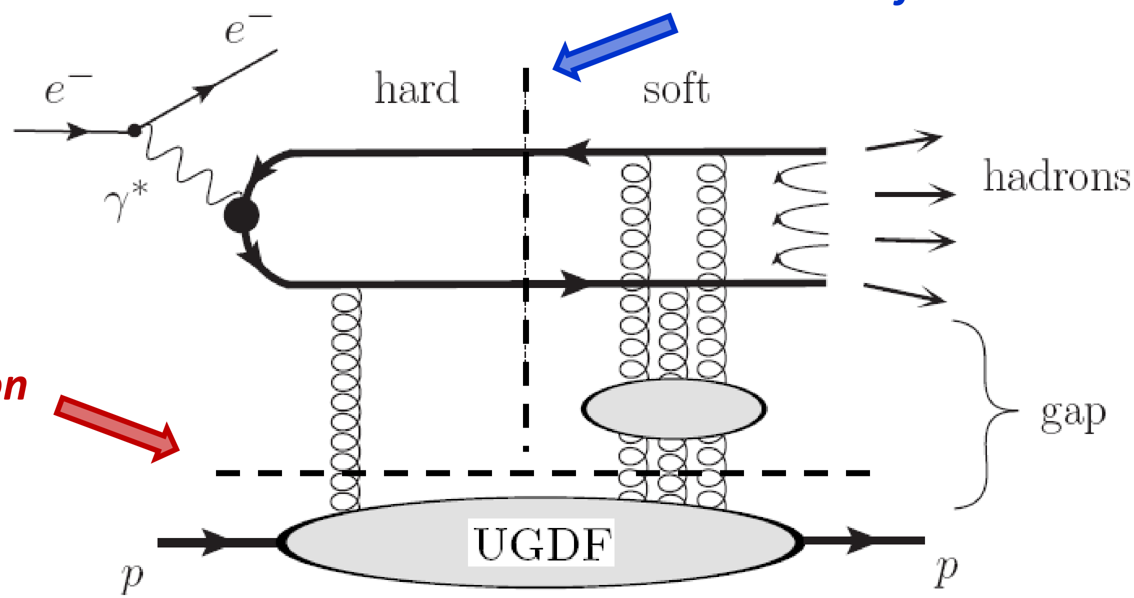
$$\boxed{\mu_F^2 = k_\perp^2 + \varepsilon^2 = z(1-z)\frac{Q^2}{\beta}}$$

***The hard QCD factorization scale* = quark virtuality!**

Hard-soft factorization scheme

s-channel factorisation

t-channel factorisation



loop integration + cutting rules

✓ **The total amplitude**

$$\delta \equiv \sqrt{-t} = |\boldsymbol{\Delta}_\perp + \boldsymbol{\Delta}'_\perp|$$

$$M(\delta) \sim \int \frac{d^2\Delta_\perp}{(2\pi)^2} \cdot M^{hard}(\boldsymbol{\Delta}_\perp) \cdot M^{soft}(\boldsymbol{\delta} - \boldsymbol{\Delta}_\perp)\ \mathcal{F}_g^{\rm off}$$

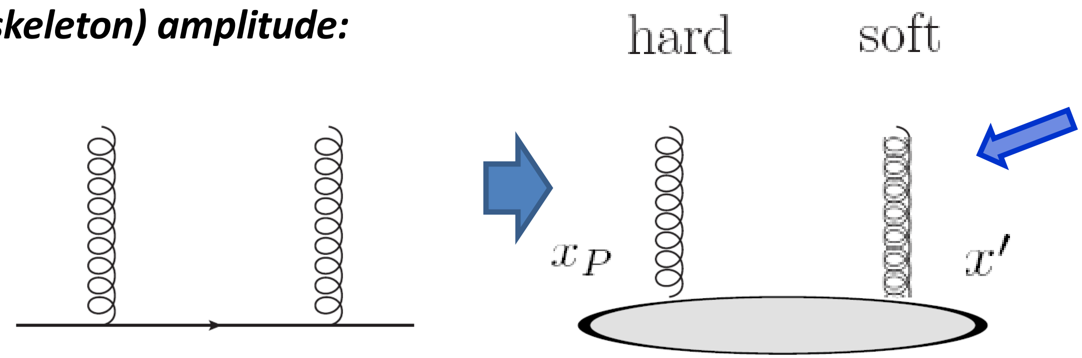
factorisation of the b-dependence

to the impact parameter representation →

$$\boxed{M(\delta, \mathbf{k}_\perp) \sim \int d^2r d^2b e^{-i\mathbf{k}_\perp \mathbf{r}} e^{-ik\mathbf{b}} \hat{M}^{\rm hard}(\mathbf{b}, \mathbf{r})\, \hat{M}^{\rm soft}(\mathbf{b}, \mathbf{r})\, \mathcal{V}(\mathbf{b}, \mathbf{r})}$$

Generalized (skewed) unintegrated gluon density

Partonic (skeleton) amplitude:



$C_F\alpha_s/\pi$ $\quad$ $f_g^{\rm off}(x_P, x', \Delta_\perp^2, \Delta_\perp'^2, \mu_F^2)$

"fat" soft gluon – effectively carries color octet charge in the limit of small $r \sim 1/k'_\perp$

Notion of "hardness" is different w.r.t. the standard one:

* ***"hard" gluon*** *in our case – the gluon which takes the largest* ***longitudinal*** *momentum, compensating the quark virtuality*

* ***"hard" scale*** *is related* ***with longitudinal momentum transfer*** *given by* x_P *(similarity with Durham model for CEP of Higgs)*

Off-diagonal UGDF currently unknown → different models are applied!

UGDF model and impact parameter representation

B. Pire, J. Soffer and O. Teryaev, Eur. Phys. J. C 8, 103 (1999)

The skewedness effect in UGDF using positivity constraints:

$$\mathcal{F}_g^{\rm off} \simeq \sqrt{\mathcal{F}_g(x_P, \Delta_\perp^2, \mu_F^2)\mathcal{F}_g(x', \Delta_\perp'^{\,2}, \mu_{\rm soft}^2)}\,,$$

Infrared behavior:

$$\frac{f_g(x, \Delta_\perp^2)}{\Delta_\perp^2} \equiv \mathcal{F}(x, \Delta_\perp^2) \to {\rm const}\,, \qquad \Delta_\perp^2 \to 0$$

Gluon at very small-*x'* unknown, fit

Gaussian Ansatz:

$$\sqrt{x_P}\mathcal{F}_g^{\rm off} \simeq \sqrt{x_P g(x_P, \mu_F^2)\boxed{x' g(x', \mu_{\rm soft}^2)}}\, f_G(\Delta_\perp^2),$$

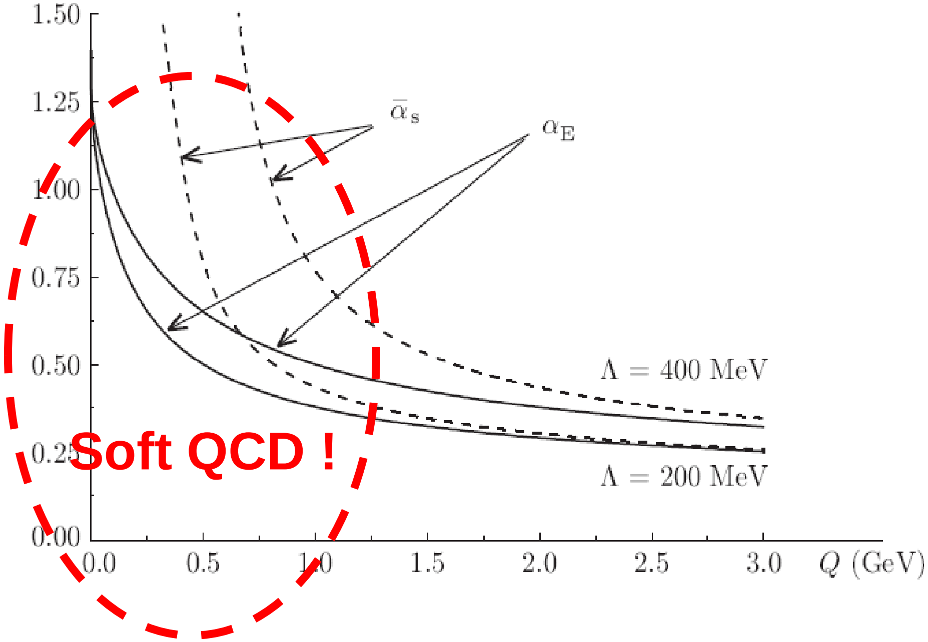
$$f_G(\Delta_\perp^2) = 1/(2\pi\rho_0^2)\,\exp\left(-\Delta_\perp^2/2\rho_0^2\right)\,,$$

Soft hardronic scale – transverse proton radius $\quad r_p \sim 1/\rho_0$

Diffractive slope (ZEUS) – given by a soft scale (proton radius)

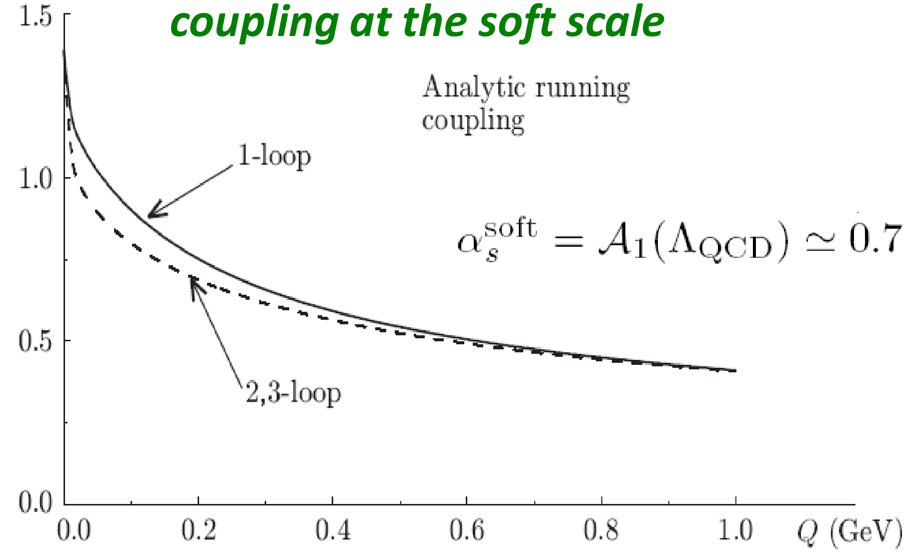
$$\sim \exp(B_D t) \qquad B_D = 1/\rho_0^2 \simeq 6.9 \pm 0.2 \ {\rm GeV}^2 \qquad \rho_0 \simeq 380 \ {\rm MeV}$$

QCD coupling at low scales



One-loop analytic coupling

Analytic (Shirkov-Solovtsev) coupling at the soft scale



$$\alpha_{\rm E}(Q^2) = \frac{1}{\pi}\int_0^\infty d\sigma\, \frac{\rho(\sigma)}{\sigma + Q^2},$$

$$\boxed{\alpha_{\rm E}^{(1)}(Q^2) = \frac{1}{\beta_0}\left[\frac{1}{\ln(Q^2/\Lambda^2)} + \frac{\Lambda^2}{\Lambda^2 - Q^2}\right].}$$

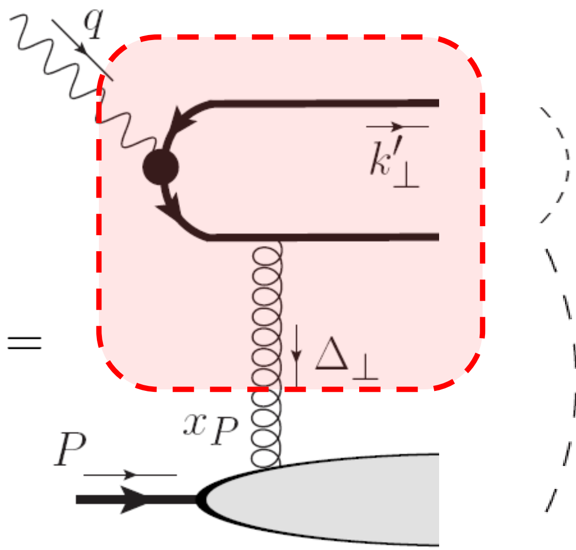
$$\rho_k(\sigma) = {\rm Im}\, \bar{\alpha}_{\rm s}^k(-\sigma - i\epsilon)$$

D.V. Shirkov, I.L. Solovtsov, JINR Rapid Comm. No.2 76-96 (1996) 5; Phys. Rev. Lett. 79 (1997) 1209, arXiv:hep-th/9704333;
K.A. Milton, I.L. Solovtsov, Phys. Rev. D 55 (1997) 5295, arXiv:hep-ph/9611438.

The hard scattering amplitude

✓ **Hard part**

$$M_{L,T}^{hard}(\Delta_\perp, k'_\perp) =$$



$$r \sim 1/k'_\perp$$

$$= \int d^2\mathbf{r} d^2\mathbf{b}\, \hat{M}_{L,T}^{hard}(\mathbf{b}, \mathbf{r}) e^{-i\mathbf{r}\mathbf{k}'_\perp} e^{-i\mathbf{b}\boldsymbol{\Delta}_\perp}$$

$$b \sim 1/\Delta_\perp$$

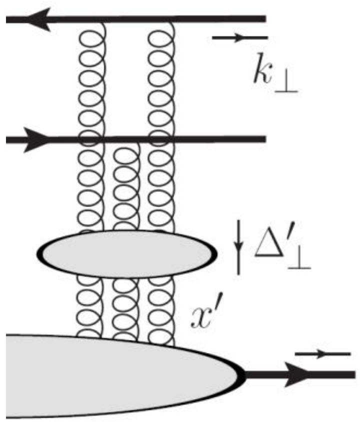
$$\hat{M}_L^{\rm hard} = i\mathcal{C}\, \alpha_s(\mu_F^2)\sqrt{\beta}\, W^3 z^{3/2}(1-z)^{3/2} K_0(\varepsilon r)$$

$$\hat{M}_{T,\pm}^{\rm hard} = i\mathcal{C}\alpha_s(\mu_F^2)\sqrt{\frac{2\beta}{1-\beta}}\, \frac{1}{\sqrt{x_P}} W^2 z^{1/2}(1-z)^{3/2}\, \varepsilon K_1(\varepsilon r)\frac{r_x \pm i r_y}{r}$$

Soft gluon scattering and "exponentiation"

✓ **Soft gluon exchanges generate only the phase shifts – to be resummed to all orders!**

$$M^{soft}(\Delta'_\perp, k_\perp) =$$



the large N_c limit – planar diagrams only!

$$e^{-i\mathbf{r}\mathbf{k}'_\perp} M_1^{soft} = \mathcal{A}\, e^{-i\mathbf{r}\mathbf{k}_\perp} \frac{1}{\Delta'^2_\perp} \left[e^{-i\mathbf{r}\boldsymbol{\Delta}'_\perp} - 1 \right],$$

$$e^{-i\mathbf{r}\mathbf{k}'_\perp} M_2^{soft} = \frac{\mathcal{A}^2}{2!} e^{-i\mathbf{r}\mathbf{k}_\perp} \times$$

$$\int \frac{d^2\Delta'_{2\perp}}{(2\pi)^2} \frac{1}{\Delta'^2_{1\perp}\Delta'^2_{2\perp}} \left[e^{-i\mathbf{r}\boldsymbol{\Delta}'_\perp} - e^{-i\mathbf{r}\boldsymbol{\Delta}'_{2\perp}} - e^{-i\mathbf{r}\boldsymbol{\Delta}'_{1\perp}} + 1 \right]$$

etc …

Fourier transform →

$$e^{-i\mathbf{r}\mathbf{k}'_\perp} \hat{M}_1^{soft} = e^{-i\mathbf{r}\mathbf{k}_\perp}\, \mathcal{A}\cdot\mathcal{W}(\mathbf{b},\mathbf{r}),$$

$$e^{-i\mathbf{r}\mathbf{k}'_\perp} \hat{M}_2^{soft} = e^{-i\mathbf{r}\mathbf{k}_\perp} \frac{\mathcal{A}^2\cdot\mathcal{W}(\mathbf{b},\mathbf{r})^2}{2!}, \quad \ldots$$

Summing series

↓

rescattering amplitude

Soft gluon rescattering amplitude →

$$e^{-i\mathbf{r}\mathbf{k}'_\perp} \hat{M}^{soft}(\mathbf{b},\mathbf{r}) = -e^{-i\mathbf{r}\mathbf{k}_\perp} \left(1 - e^{\mathcal{A}\cdot\mathcal{W}(\mathbf{b},\mathbf{r})}\right)$$

$$\mathcal{A} = i g_s^2 C_F/2 \qquad \mathcal{W}(\mathbf{b},\mathbf{r}) = \frac{1}{2\pi} \ln\frac{|\mathbf{b}-\mathbf{r}|}{|\mathbf{b}|}$$

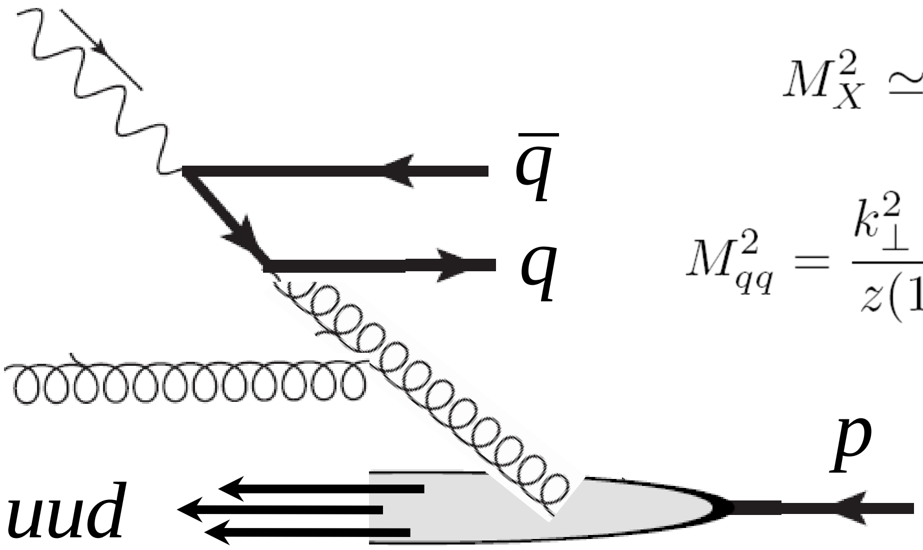
Analytic perturbation theory → coupling at soft scale

$$\alpha_s^{\rm soft} = \mathcal{A}_1(\Lambda_{\rm QCD}) \simeq 0.7$$

Inspired by Brodsky et al, PRD65, 114025 (2002)

Gluonic contribution @ large M_X

Gluon radiated from "hard" gluon is far away in *p*-space from $q\bar{q}$
$\rightarrow$ leading contribution to large M_X



$$M_X^2 \simeq M_{qq}^2 + \frac{p_\perp^2}{z'} \to \infty,$$

$$M_{qq}^2 = \frac{k_\perp^2 + m_q^2}{z(1-z)}, \quad z_g = \frac{z'}{x_P} + \beta\left(1 + \frac{M_{qq}^2}{Q^2}\right)$$

$$\boxed{z' \ll z \quad p_\perp \sim k_{1,\perp} \gg k_{2,\perp}}$$

$\rightarrow$ Altarelli-Parisi splitting $\otimes$ $q\bar{q}$-dipole $\otimes$ multiple gluon exchange

$$x_P F_{q\bar{q}g}^{D(4)} \simeq \frac{1}{N_c^2} \int \frac{dt_g dz_g}{t_g + m_g^2} P_{gg}(z_g) \frac{\alpha_s(t_g)}{2\pi} x_P F_{q\bar{q}}^{D(4)}$$

Diffractive DIS cross section

$$x_P \sigma_r^{D(3)} = x_P F_{q\bar{q},T}^{D(3)} + \frac{2-2y}{2-2y+y^2} x_P F_{q\bar{q},L}^{D(3)} + x_P F_{q\bar{q}g}^{D(3)} \qquad y = Q^2/(s x_B) \leq 1$$

$q\bar{q}$ dipole contribution:

$$x_P F_L^{D(4)} = \mathcal{S}\, Q^4 M_X^2 \int_{z_{min}}^{\frac{1}{2}} dz (1-2z)\, z^2 (1-z)^2 |J_L|^2$$

$$x_P F_T^{D(4)} = 2\mathcal{S}\, Q^4 \int_{z_{min}}^{\frac{1}{2}} dz (1-2z) \left\{(1-z)^2 + z^2\right\} |J_T|^2$$

with $\mathcal{S} = \sum_q e_q^2/(2\pi^2 N_c^3)$ and amplitudes:

$$J_L = i\alpha_s(\mu_F^2) \int d^2\mathbf{r} d^2\mathbf{b}\, e^{-i\boldsymbol{\delta}\mathbf{b}} e^{-i\mathbf{r}\mathbf{k}_\perp} K_0(\varepsilon r) \mathcal{V}(\mathbf{b},\mathbf{r}) \boxed{\left[1 - e^{\mathcal{A}\mathcal{W}}\right]}$$

$$J_T = i\alpha_s(\mu_F^2) \int d^2\mathbf{r} d^2\mathbf{b}\, e^{-i\boldsymbol{\delta}\mathbf{b}} e^{-i\mathbf{r}\mathbf{k}_\perp} \varepsilon K_1(\varepsilon r) \frac{r_x \pm i r_y}{r} \mathcal{V}(\mathbf{b},\mathbf{r}) \boxed{\left[1 - e^{\mathcal{A}\mathcal{W}}\right]}$$

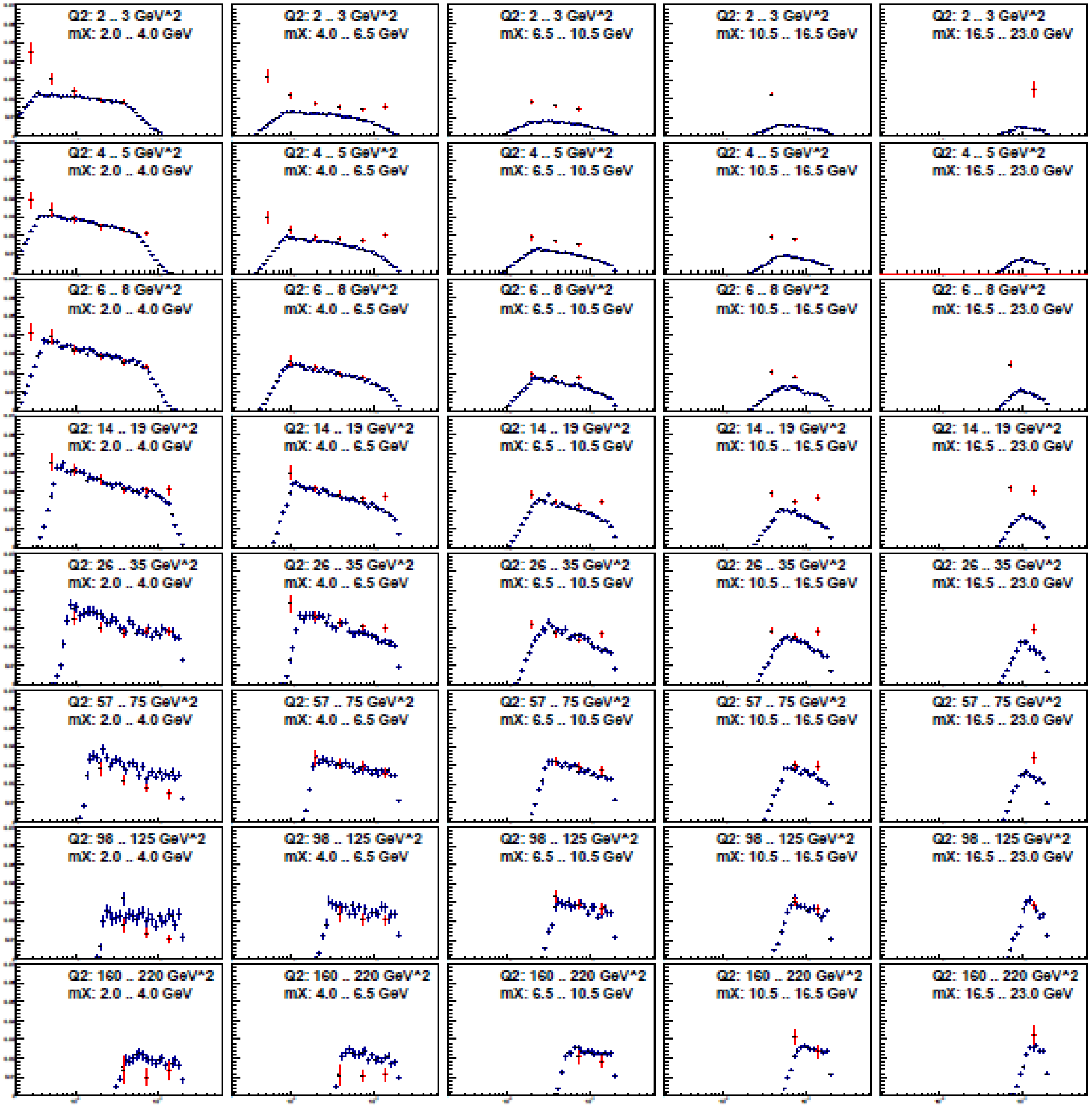
where
$$\mathcal{V}(\mathbf{b},\mathbf{r}) = \frac{1}{\alpha_s(\mu_{\rm soft}^2)} \frac{\bar{R}_g(x')}{(2\pi)^2} \sqrt{x_P g(x_P, \mu_F^2)} \left[e^{-\frac{\rho_0^2}{2}|\mathbf{b}-\mathbf{r}|^2} - e^{-\frac{\rho_0^2}{2}|\mathbf{b}+\mathbf{r}|^2}\right]$$

$$\boxed{\mathcal{A} = i g_s^2 C_F/2 \qquad \mathcal{W}(\mathbf{b},\mathbf{r}) = \frac{1}{2\pi} \ln \frac{|\mathbf{b}-\mathbf{r}|}{|\mathbf{b}|}}$$

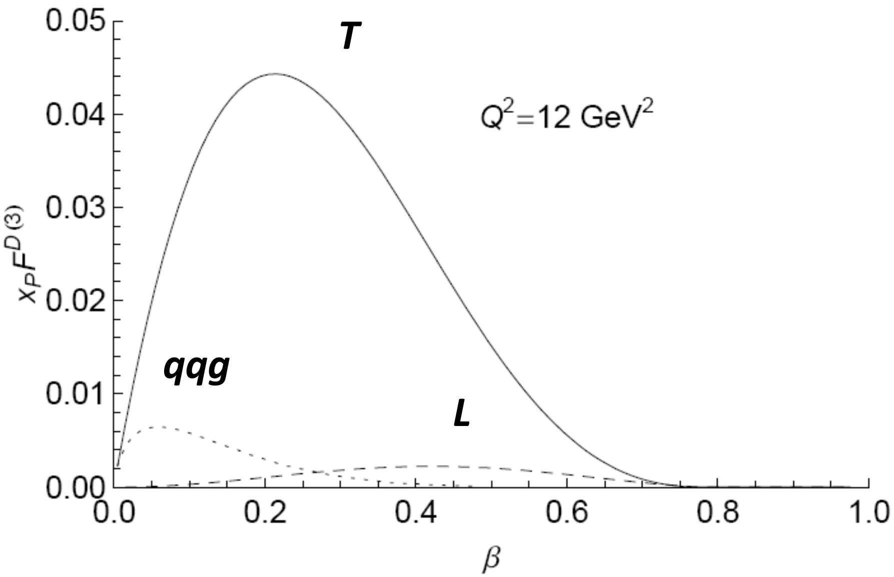
gluonic dipole contribution:

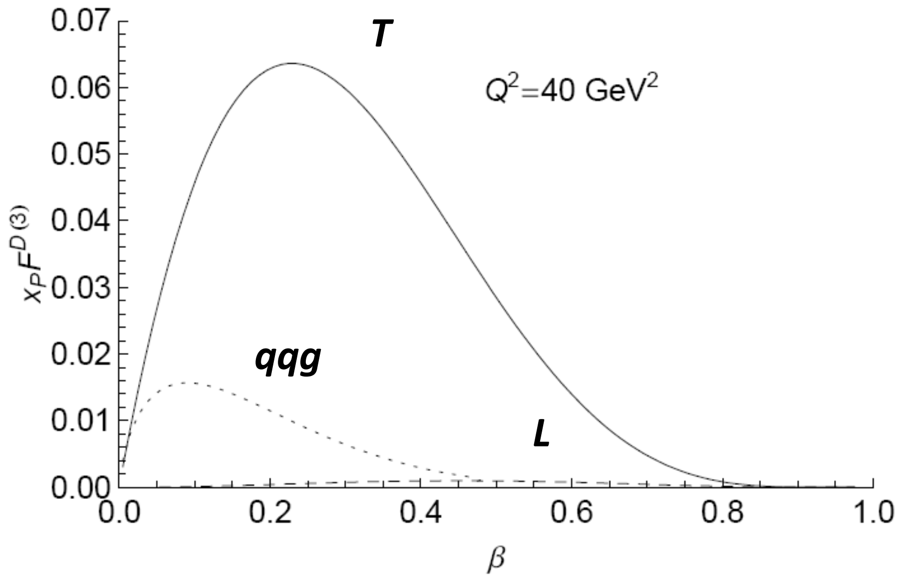
$$x_P F_{q\bar{q}g}^{D(4)} \simeq \frac{1}{N_c^2} \int \frac{dt_g dz_g}{t_g + m_g^2} P_{gg}(z_g) \frac{\alpha_s(t_g)}{2\pi} x_P F_{q\bar{q}}^{D(4)}$$

Comparison to HERA data: "Dynamical SCI" Monte-Carlo study



Photon polarization contributions and mass spectrum



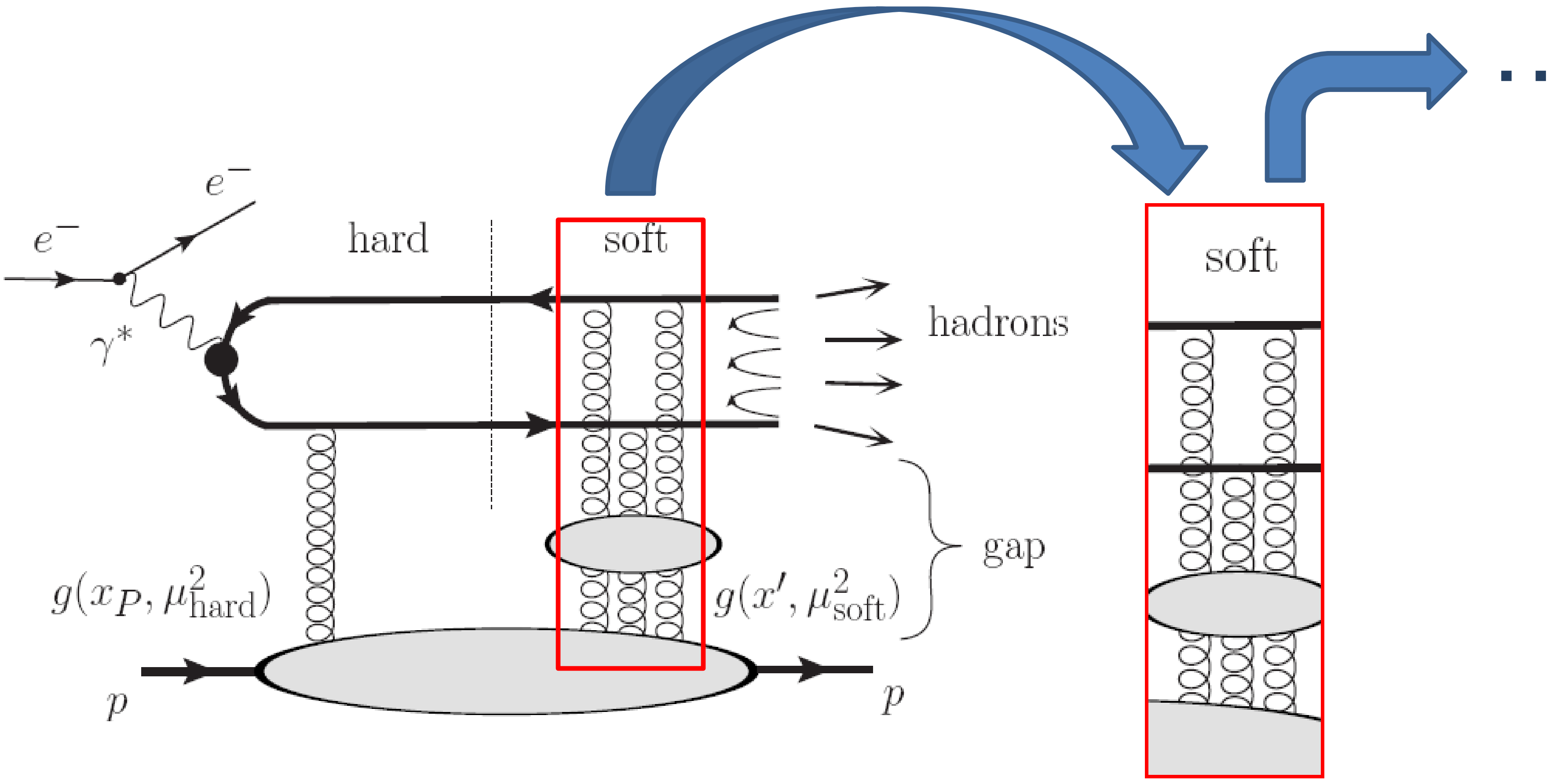


Gluonic contribution increases at high M_X and Q^2 !

Hard-soft factorization in impact space → universality !?

Use soft multigluon exchange amplitude from DIS

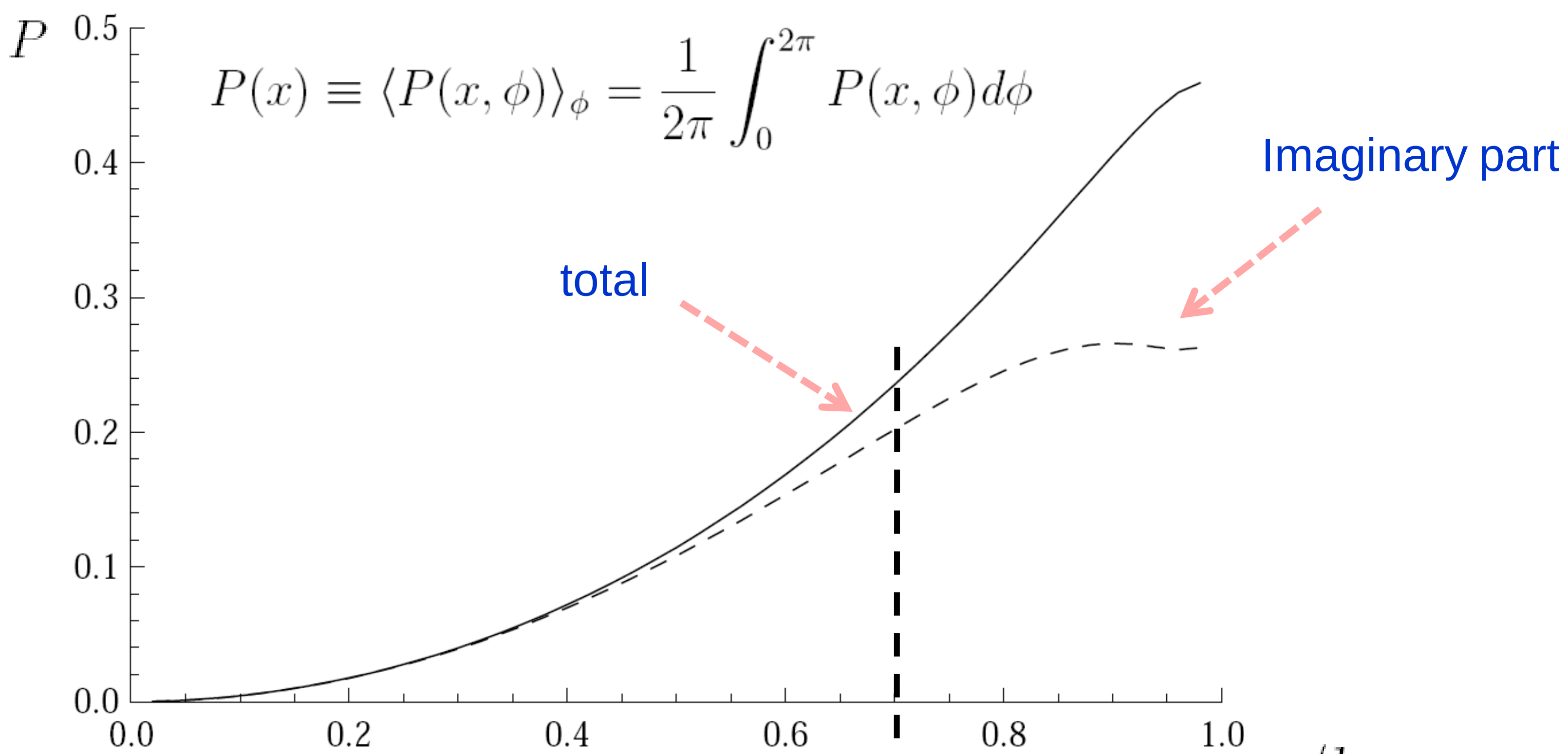
and insert in other scattering processes



Soft dipole-target rescattering probability

$$P(x,\phi) = \left|1 - \exp\left(\frac{i\mathcal{A}}{2\pi}\ln\sqrt{1+x^2-2x\cos\phi}\right)\right|^2, \qquad x = \frac{r}{b}$$

No dependence on the dipole orientation w.r.t. the colour background field:

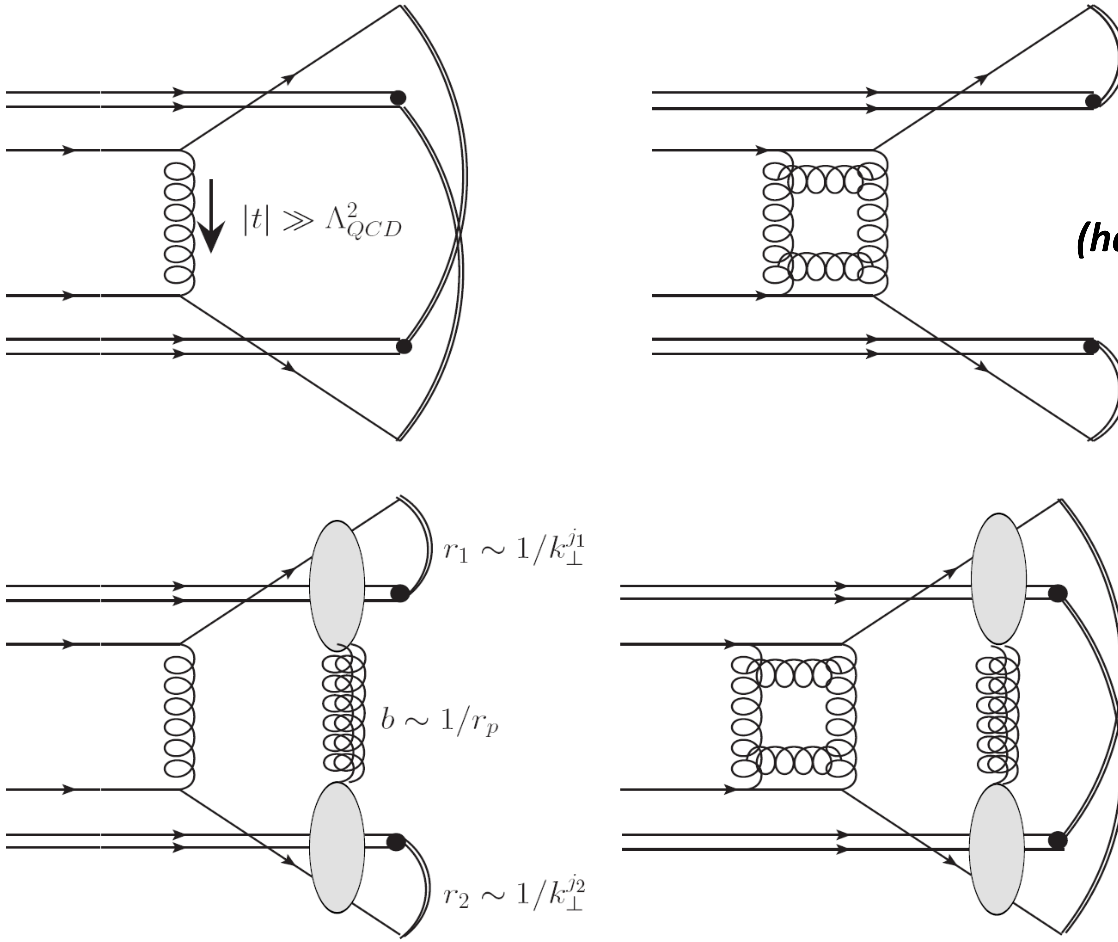


In diffractive limit the soft rescattering amplitude is dominated by its imaginary part!

Diffractive pp-scattering: gaps between jets

QCD contribution
(hard octet exchange)

BFKL contribution
(hard singlet exchange)



Soft dipole-dipole rescattering changes the string topology before hadronization!

R. Enberg, G. Ingelman, L. Motyka, Phys. Lett. **B524**, 273-282 (2002)

Summary

- ✓ Two different asymptotics for the color screening in diffractive processes has been investigated – the soft color screening in diffractive DIS and perturbative color screening in diffractive Drell-Yan

- ✓ The soft color screening model works basically well and leads to a good description of the HERA data on the diffractive structure function in most of the bins in photon virtuality and invariant mass of the final hadronic system without fitting parameters.

- ✓ Features of the soft gluon exchange / non-perturbative color interactions
  - soft gluons change colour string-field topology
  - new QCD framework for multiple gluon exchange in DIS
  - hard-soft factorization in impact parameter space
  - basis for phenomenological success of Soft Colour Interaction model
  - universality !? → applicability in many contexts/processes

- ✓ Extension of the dipole model to proton-proton diffractive scattering is considered. The model can be generalized to the central exclusive production.

- ✓ A new Monte-Carlo technique for soft dipole-target and dipole-dipole rescattering in diffractive ep and pp collisions is proposed.