Hard diffractive scattering from soft color screening effects

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Basics of Quantum ChromoDynamics – reminder

Group theory:

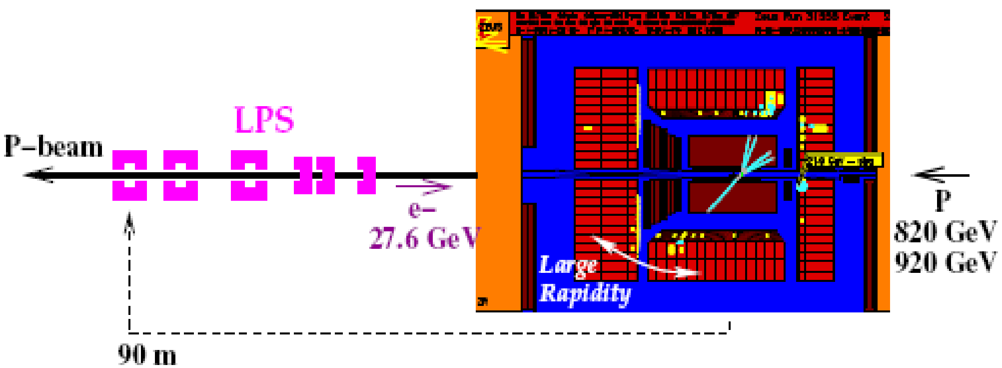
- Colour charge is the source of the field
- Gauge symmetry $\rightarrow$ group $SU(\mathbf{3})_C$
  representations **3, 8, 6, 10, 15** ...
- Fundamental representation:
  triplet $\mathbf{3} \rightarrow$ *red*, *green*, *blue* quarks
  antitriplet $\bar{\mathbf{3}} \rightarrow$ anti-quarks
- Local gauge symmetry $\Rightarrow$ interactions
  8 generators of $SU(\mathbf{3})_C$
  $\hookrightarrow$ octet $(\mathbf{8})$ representation
  8 gluons carrying colour–anticolour

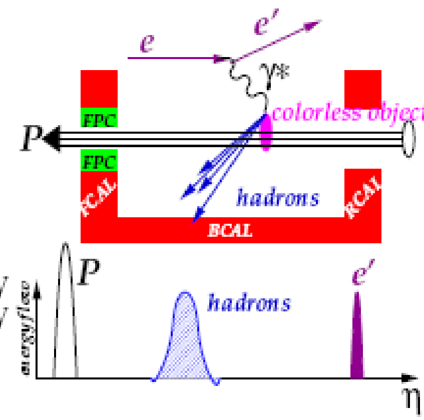
Dynamics:

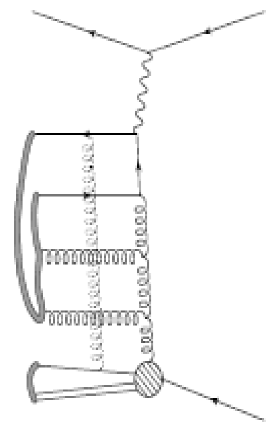
- Coupling $\alpha_s(Q^2) = \frac{12\pi}{(33-2n_f)\ln(Q^2/\Lambda^2)}$
  depends on momentum transfer Q^2
- QCD $\Lambda \sim 200$ MeV
- Hard QCD, $Q^2 \gg \Lambda^2$: small coupling
  $\Rightarrow$ perturbation theory
  Asymptotic Freedom
- Soft QCD, $Q^2 \sim \Lambda^2$: large coupling
  $\Rightarrow$ lattice theory or models
  Confinement
- QCD potential $V(r) = -\frac{\alpha_s}{r} + \kappa\, r$

Diffractive rapidity-gap events in ep at HERA

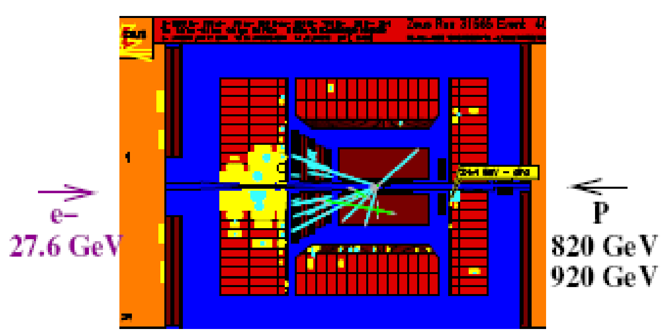
1. Diffractive scattering

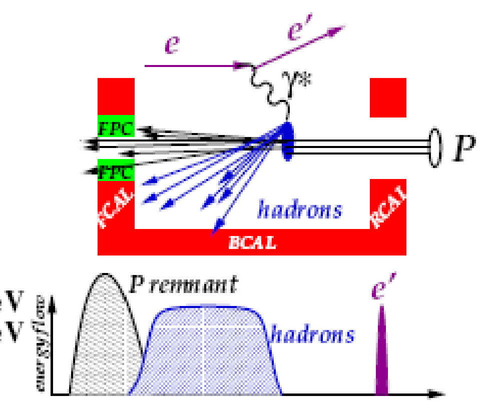


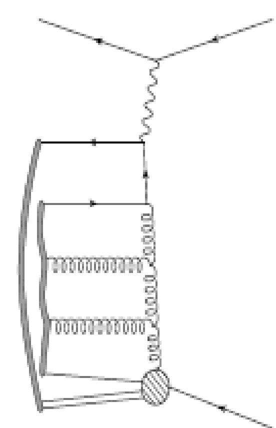




2. Non-diffractive scattering



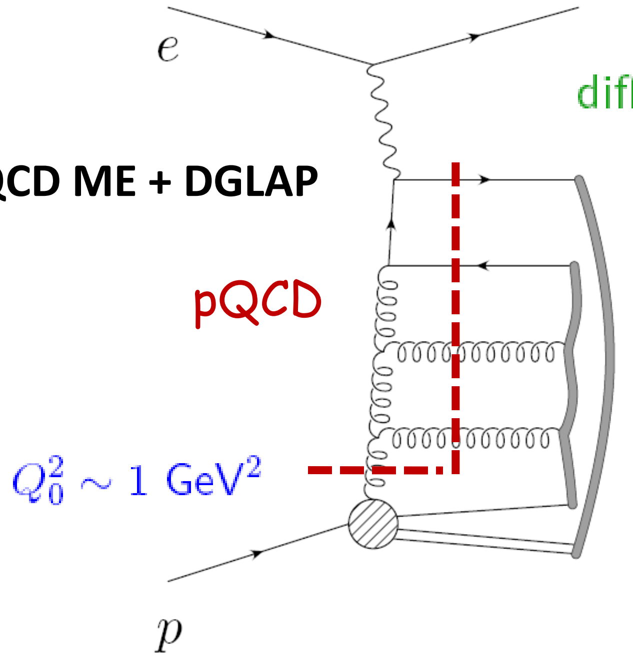




Diffractive Deep Inelastic Scattering: motivation

✓ The success of Soft Color Interaction (SCI) model (Edin, Ingelman, Rathsman'97)

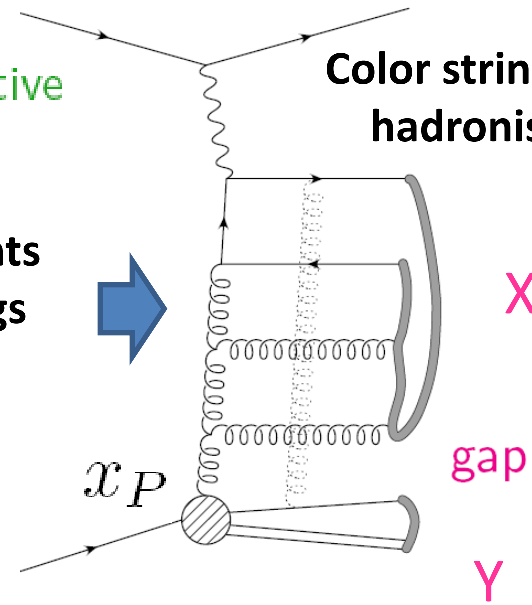
pQCD ME + DGLAP



diffractive ↔ nondiffractive

Color rearrangements modify colour strings topology

Color string (Lund) hadronisation



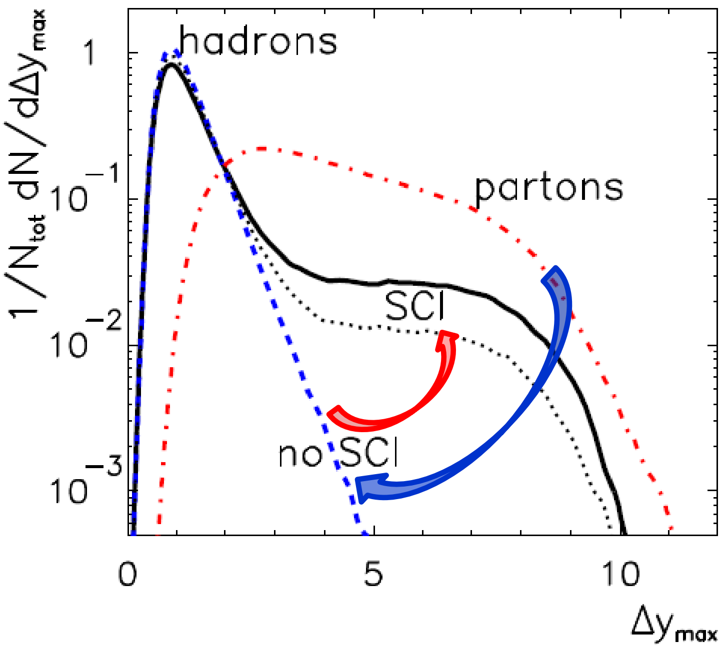
- *Soft interactions among the final state partons and proton remnants (=> proton color field) at small momentum transfers < 1 GeV*
- *Hard pQCD part (small distances) is not affected by soft interactions (large distances)*
- *Single parameter - probability for soft colour-anticolour (gluon) exchange*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

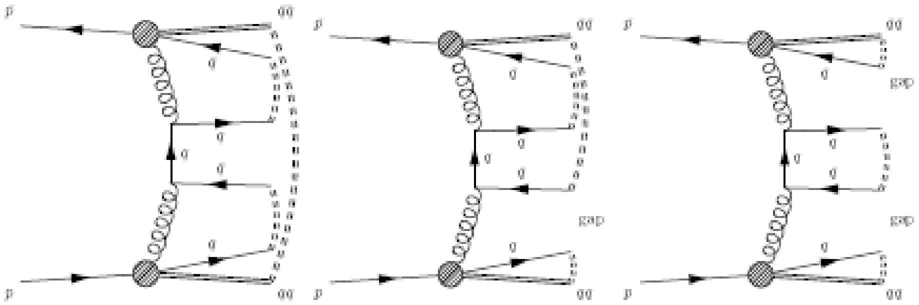
Jets, W, Z, $b\bar{b}$, J/ψ in diffractive gap events at the Tevatron

$$R_{\rm hard} = \frac{1}{\sigma_{\rm hard}^{\rm tot}} \int_{x_{F\rm min}}^{1} dx_F \, \frac{d\sigma_{\rm hard}}{dx_F}$$

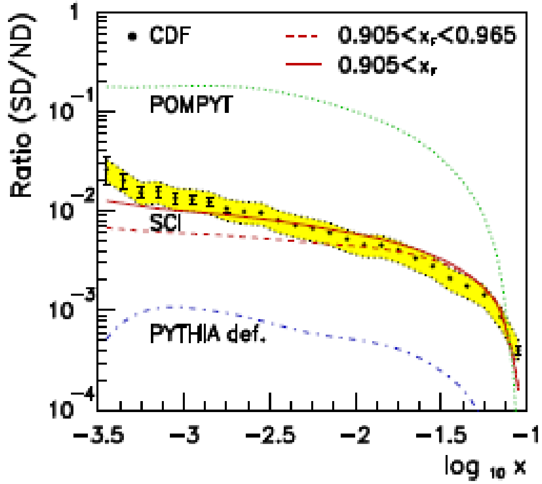
$R_{\rm hard}[\%]$	Exp.	observed	SCI
dijets	CDF	0.75 ± 0.10	0.7
W	CDF	1.15 ± 0.55	1.2
W	DØ	$1.08\,^{+0.21}_{-0.19}$	1.2
$b\bar{b}$	CDF	0.62 ± 0.25	0.7
Z	DØ	$1.44\,^{+0.62}_{-0.54}$	1.0
J/ψ	CDF	1.45 ± 0.25	1.4

$\uparrow$ predictions

SCI $\rightarrow$ gap & $c\bar{c}$ colour octet $\rightarrow$ singlet $\rightarrow$ J/ψ



$R_{\rm dijets}$ vs x of parton in $\bar{p}$



SCI model OK, also for two-gap (DPE) events

Pomeron model too high, PYTHIA too low

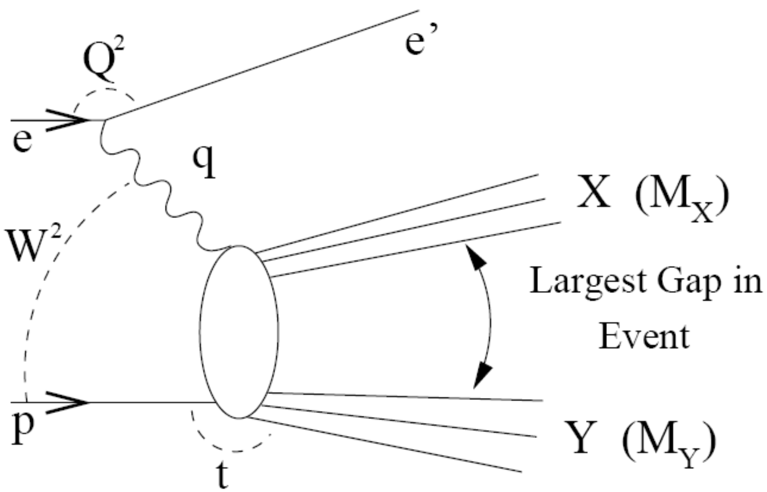
SCI model phenomenologically successful — Why ?

Captures most essential QCD dynamics $\Rightarrow$ theory emerging . . .

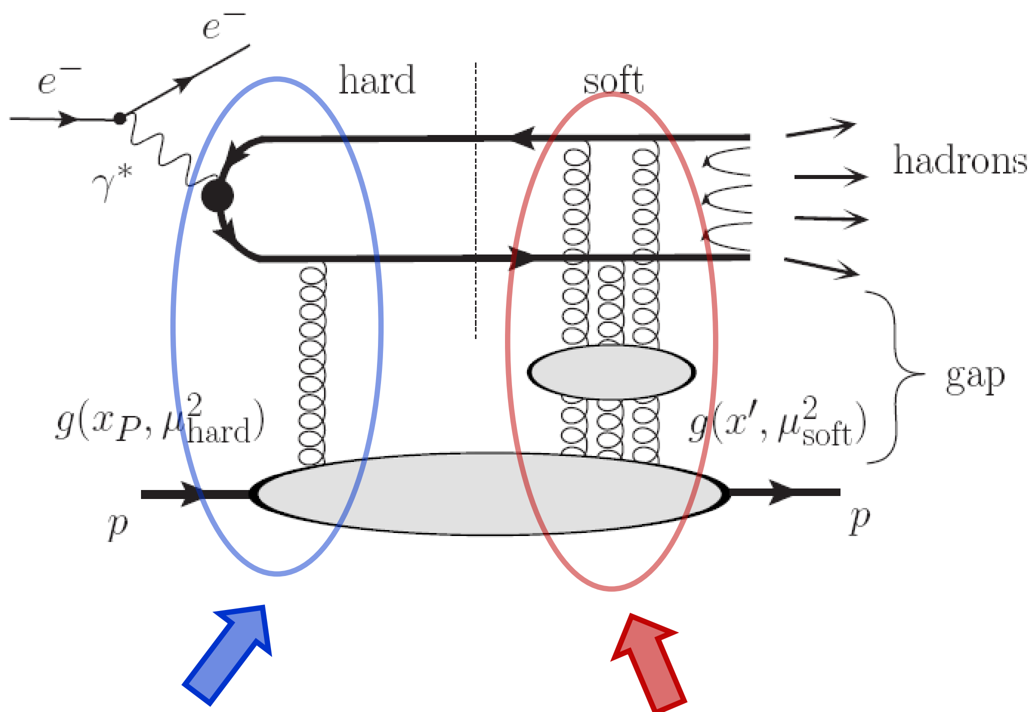
Pasechnik, Enberg, Ingelman, Phys.Rev. D82 (2010) 054036

QCD rescattering theory

Diffractive DIS at HERA



QCD rescattering model

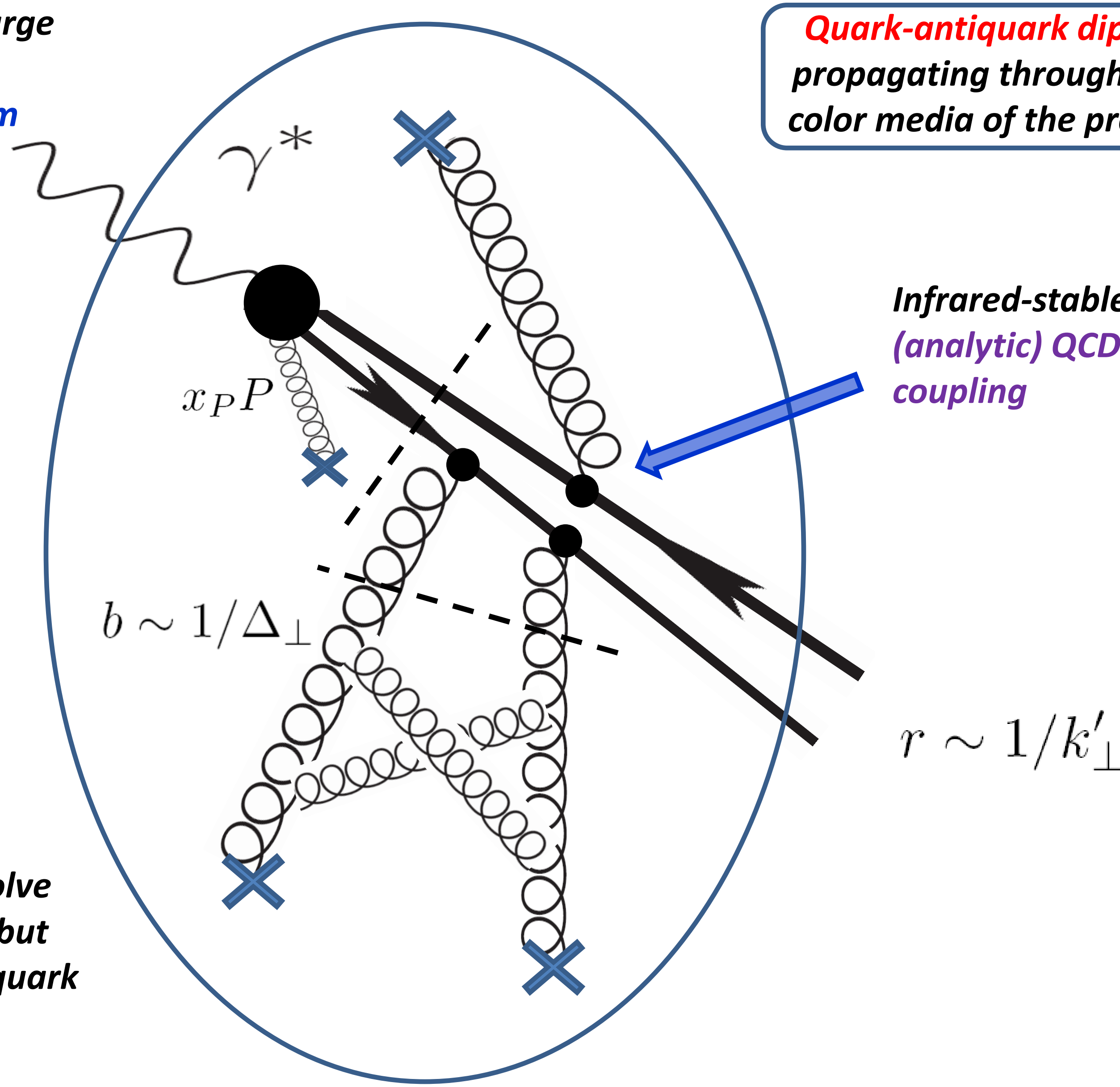


Hard part
conventional
(small distance)

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

Hard diffractive scattering in the dipole picture

Compensation of the large photon virtuality by longitudinal momentum transfer in the single hard interaction



Quark-antiquark dipole propagating through the color media of the proton

Infrared-stable (analytic) QCD coupling

t- and s-channel factorisation

Soft gluons cannot resolve quarks dynamically → but they always couple to quark current!

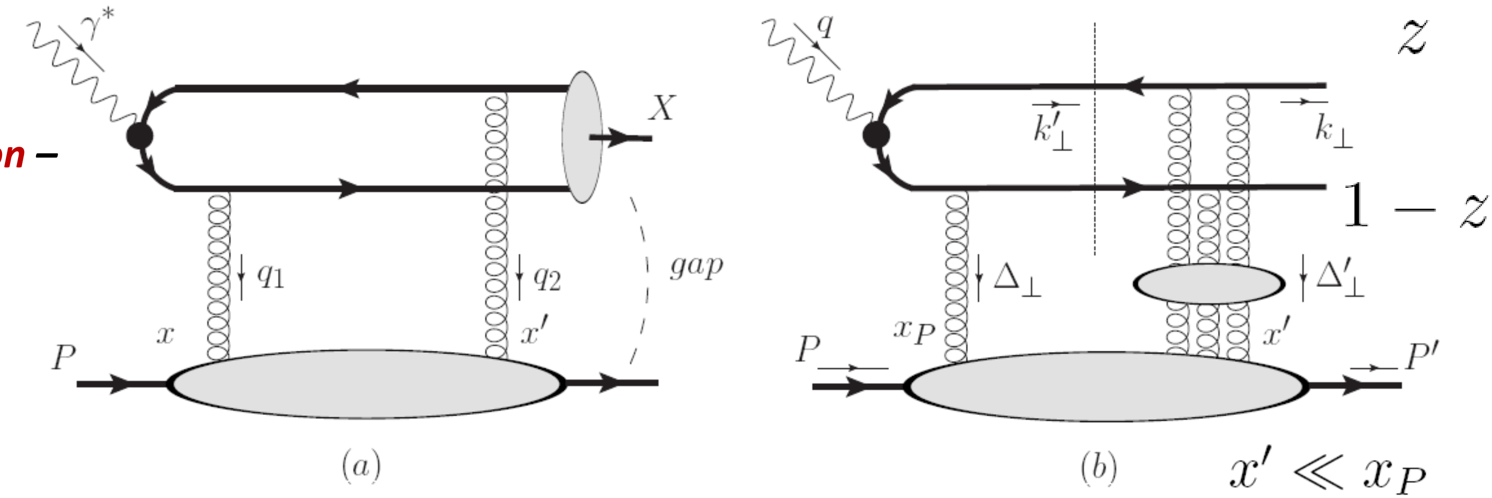
Diffractive DIS at HERA: kinematics

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**

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



$$x' \ll x_P$$

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

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

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

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

Working domain of interest:

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

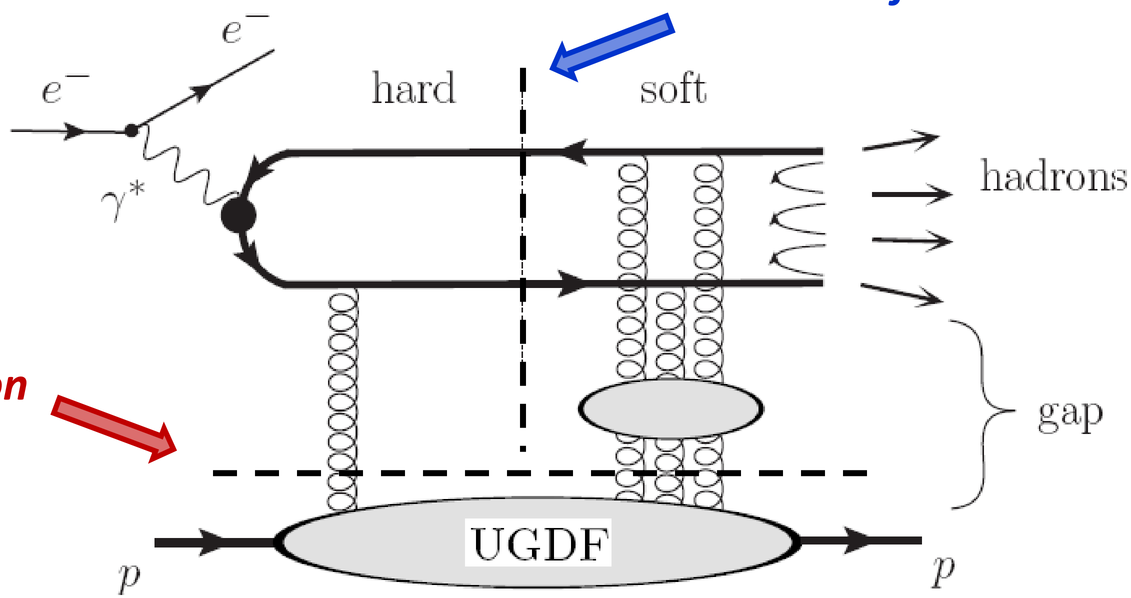
$$|t| \ll Q^2, \, M_X^2$$

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

Hard-soft factorization scheme

t-channel factorisation

s-channel factorisation



<u>*loop integration + cutting rules*</u>

✓ The total amplitude

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

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

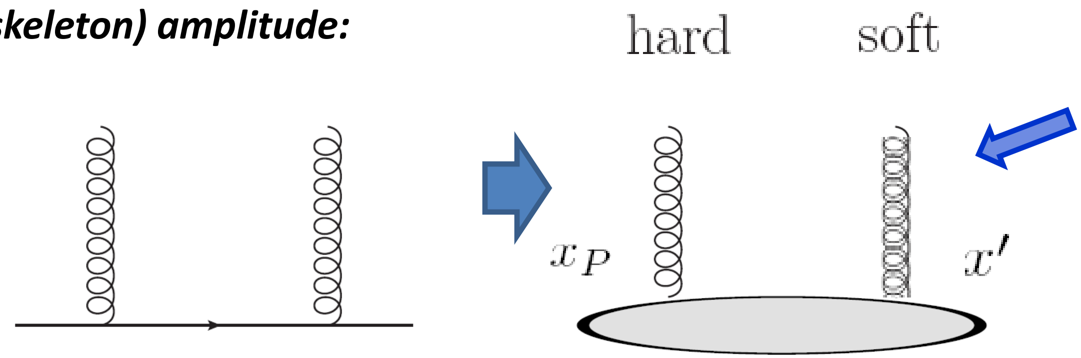
factorisation
of the b-dependence

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:



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

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

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

We model the skewedness effect using positivity constraints (Pire,Soffer,Teryaev'99) as

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

Infrared behavior:

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

Impact parameter representation:

$$\mathcal{V}(\mathbf{b}, \mathbf{r}) = \frac{1}{\alpha_s(\mu_{\rm soft}^2)} \int \frac{d^2\Delta_\perp}{(2\pi)^2} \sqrt{x_P}\, \mathcal{F}_g^{\rm off} \times \left\{e^{-i\mathbf{r}\mathbf{\Delta}_\perp} - e^{i\mathbf{r}\mathbf{\Delta}_\perp}\right\} e^{i\mathbf{b}\mathbf{\Delta}_\perp}.$$

Gaussian Ansatz:

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

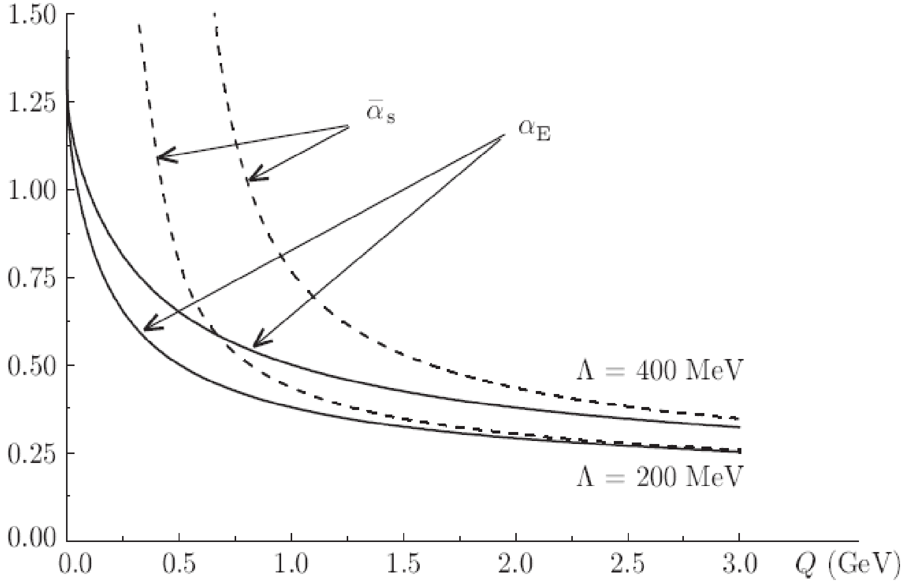
$$f_G(\Delta_\perp^2) = 1/(2\pi\rho_0^2)\, \exp\left(-\Delta_\perp^2/2\rho_0^2\right)\,,$$

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

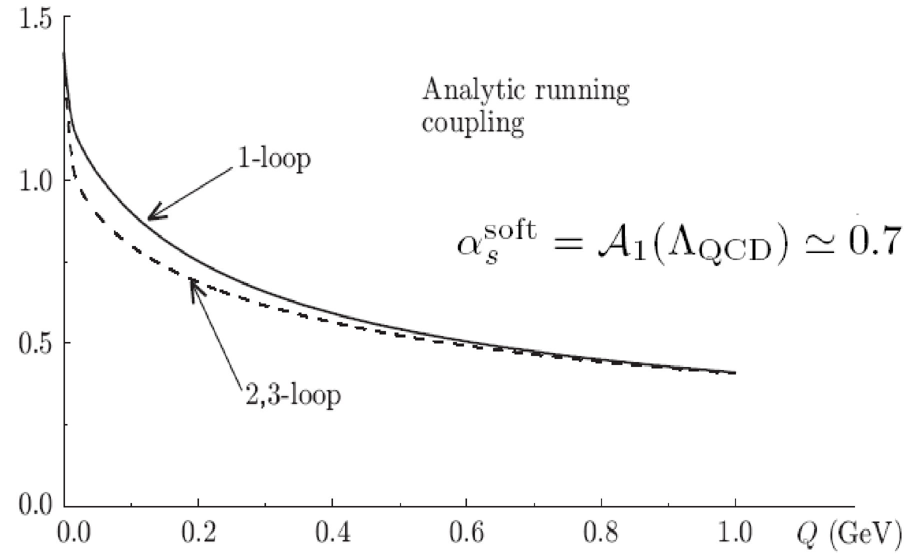
Diffractive slope (ZEUS)

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

QCD coupling at low scales



Analytic coupling at the soft scale



One-loop analytic coupling

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

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

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

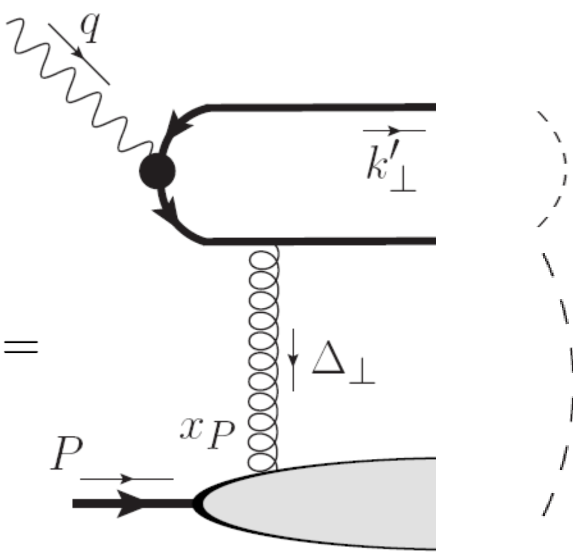
It can be important to parameterize PDFs using ghost-free analytic QCD approach…

The hard scattering amplitude

✓ **Hard part**

Factorization condition ***in the impact parameter space***

$$\Delta_\perp \sim \Delta'_\perp \ll k'_\perp \sim k_\perp \longrightarrow r \ll b$$



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

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

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

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

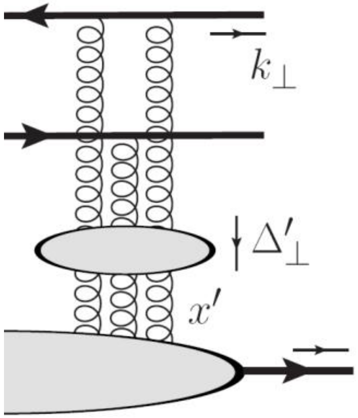
$$\hat{M}^{\rm hard}_{T,\pm} = i\mathcal{C}\alpha_s(\mu_F^2)\sqrt{\frac{2\beta}{1-\beta}}\,\frac{1}{\sqrt{x_P}} W^2 z^{1/2}(1-z)^{3/2}\,\varepsilon K_1(\varepsilon r)\frac{r_x \pm i r_y}{r}$$

Soft gluon scattering and "exponentiation"

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

the large N_c limit – planar diagrams only!

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



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

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

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

etc …

Fourier transform →

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

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

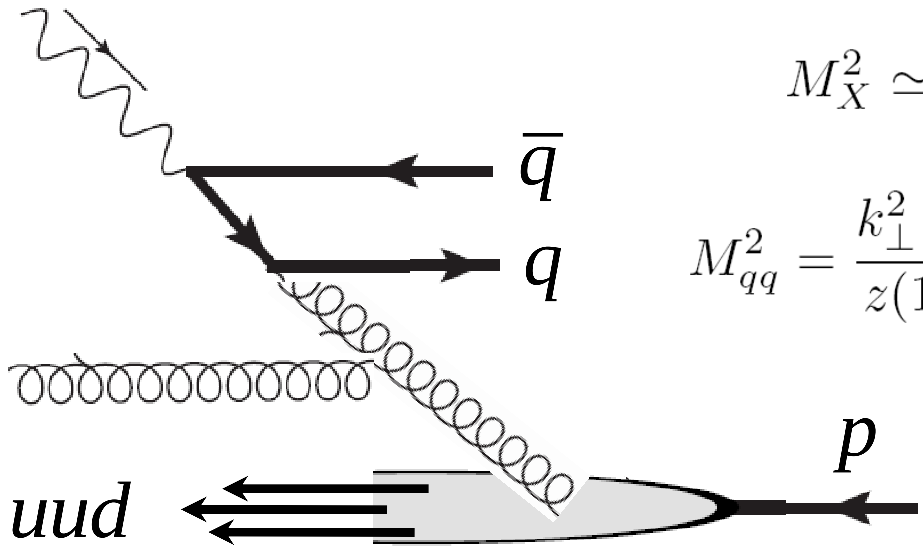
Soft gluon rescattering amplitude →

$$\boxed{\begin{gathered} e^{-i\mathbf{r}\mathbf{k}'_\perp} \hat{M}^{soft}(\mathbf{b},\mathbf{r}) = -e^{-i\mathbf{r}\mathbf{k}_\perp} \left(1 - e^{\mathcal{A}\cdot\mathcal{W}(\mathbf{b},\mathbf{r})}\right) \\ \mathcal{A} = i g_s^2 C_F/2 \qquad \mathcal{W}(\mathbf{b},\mathbf{r}) = \frac{1}{2\pi} \ln \frac{|\mathbf{b}-\mathbf{r}|}{|\mathbf{b}|} \end{gathered}}$$

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



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

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

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

$\rightarrow$ 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 structure function: results

Data are given in terms of the reduced cross section

$$\sqrt{s} = 318 \text{ GeV}$$

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

Quark dipole contribution:

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

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

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

Amplitudes:

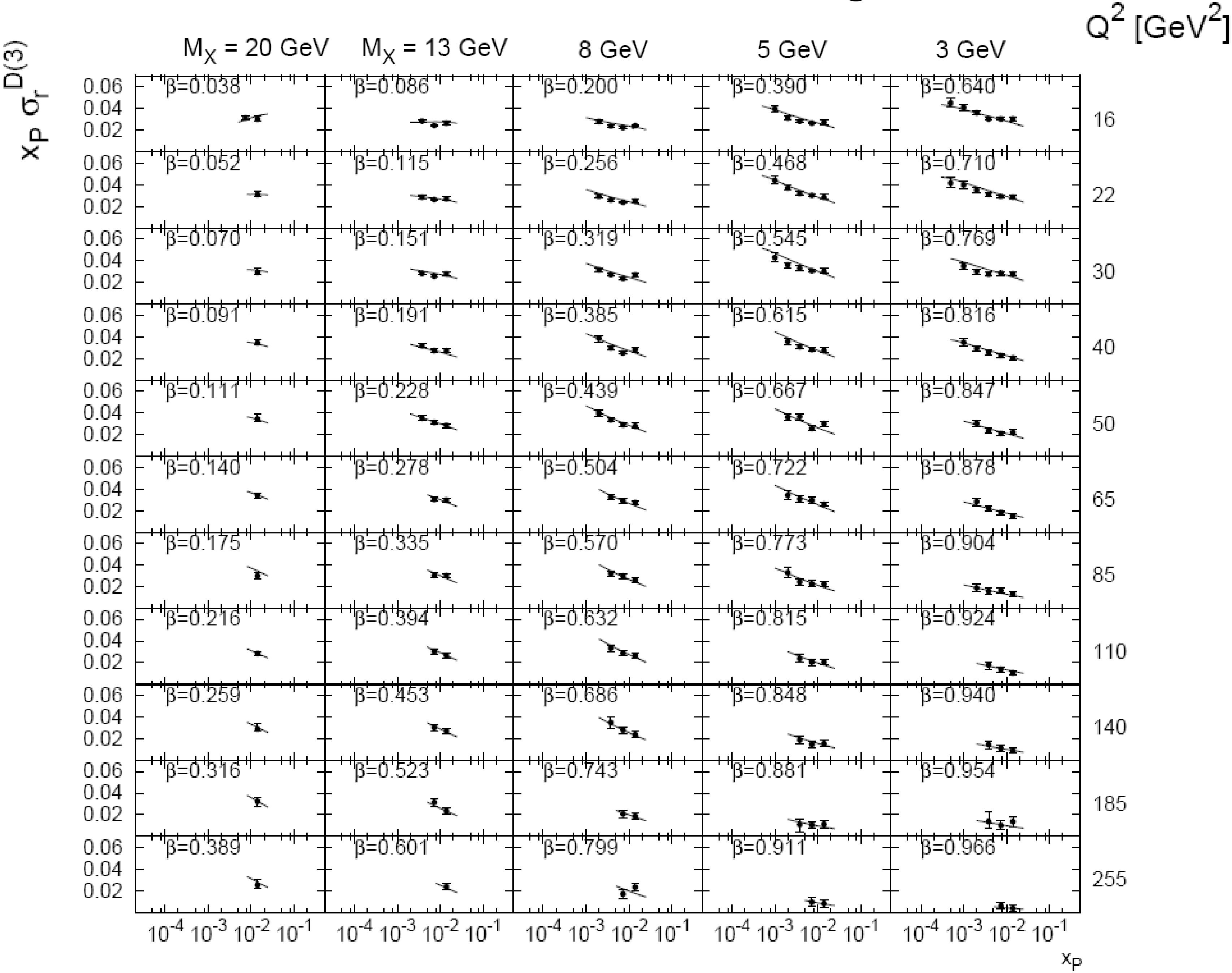
$$J_L = i\alpha_s(\mu_F^2) \int d^2\mathbf{r} d^2\mathbf{b}\, e^{-i\boldsymbol{\delta}\mathbf{b}} e^{-i\mathbf{r}\mathbf{k}_\perp} K_0(\varepsilon r) \times \mathcal{V}(\mathbf{b},\mathbf{r}) \left[1 - e^{\mathcal{A}\mathcal{W}}\right],$$

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

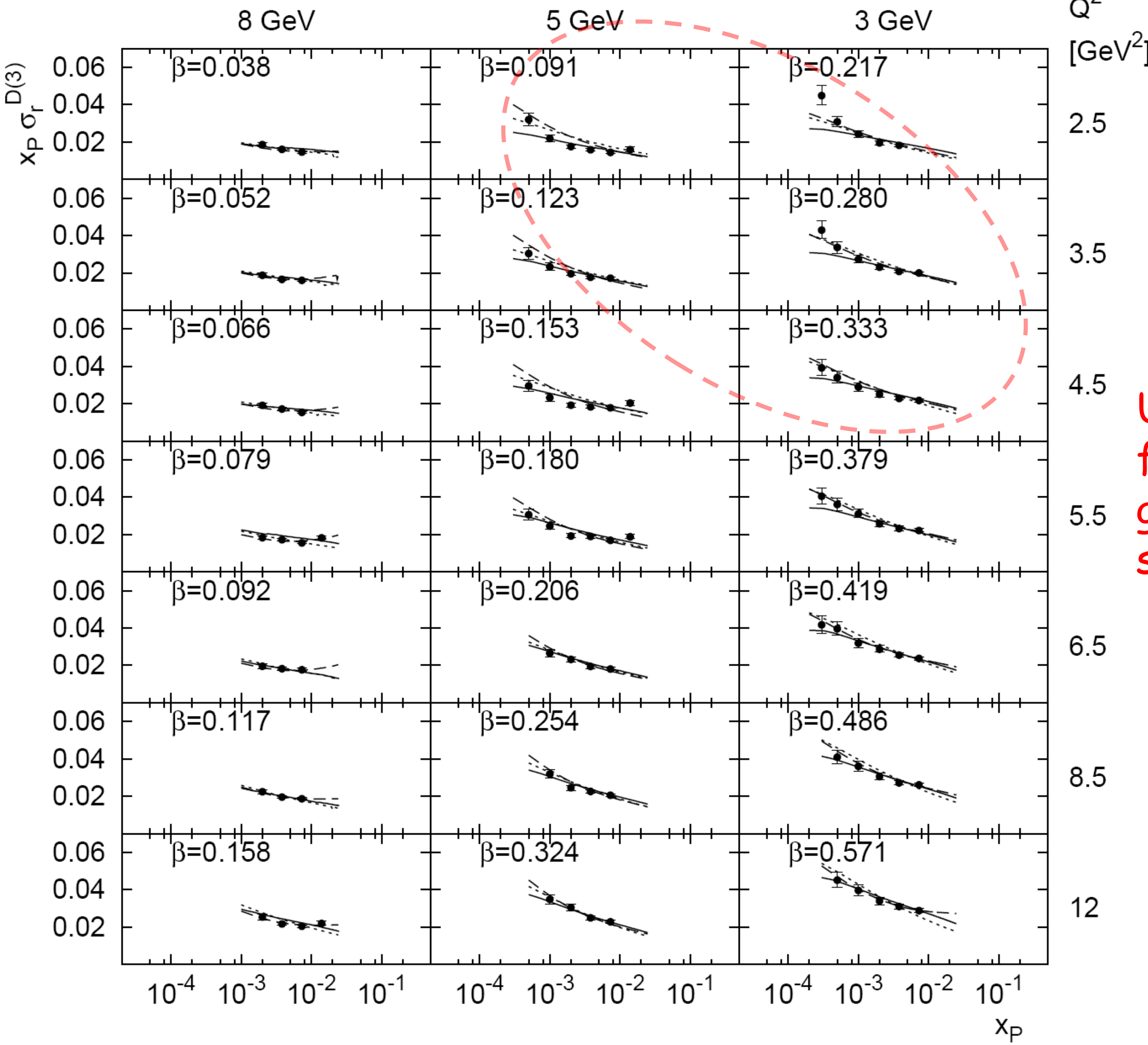
Gluonic dipole contribution:

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

Diffractive structure function: large Q^2



Comparison to HERA data: low Q^2

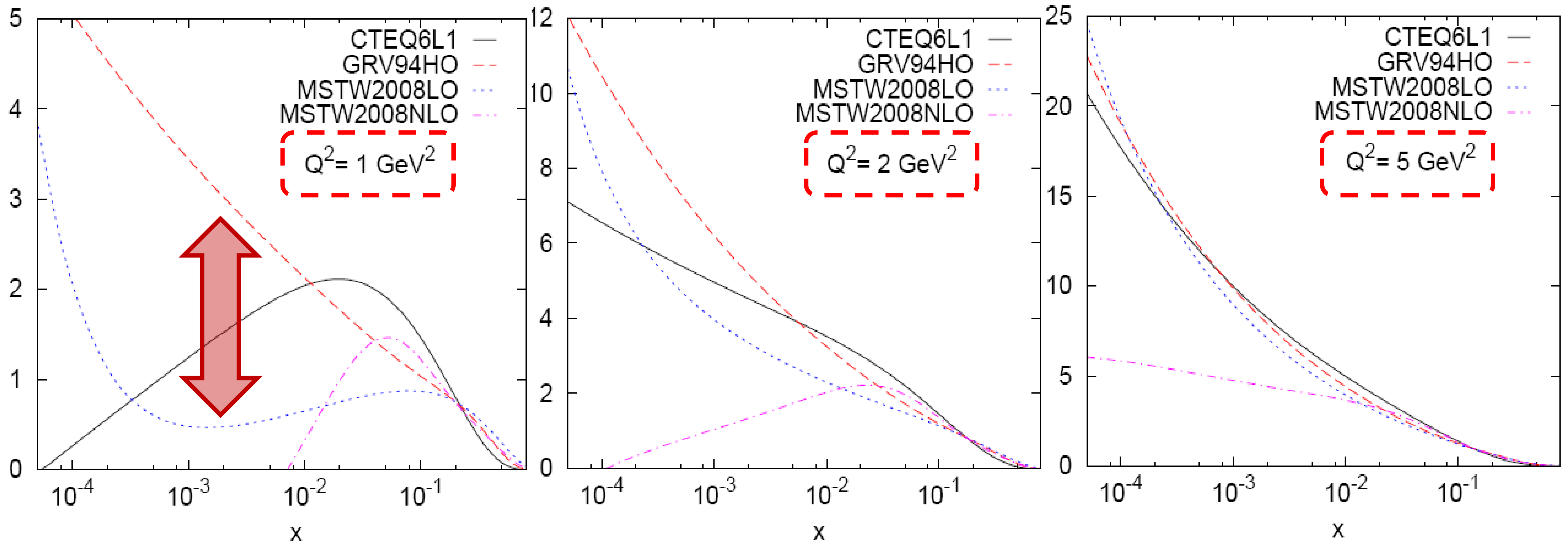


Curves for different $xg(x,\mu)$ parametrizations

Uncertainty from unknown gluon density at small x & scale

Possibility to extract $g(x,\mu_F)$ at $x \sim 10^{-4}$ μ_F < ~1 GeV

Gluon density parametrizations at low-x and low Q^2

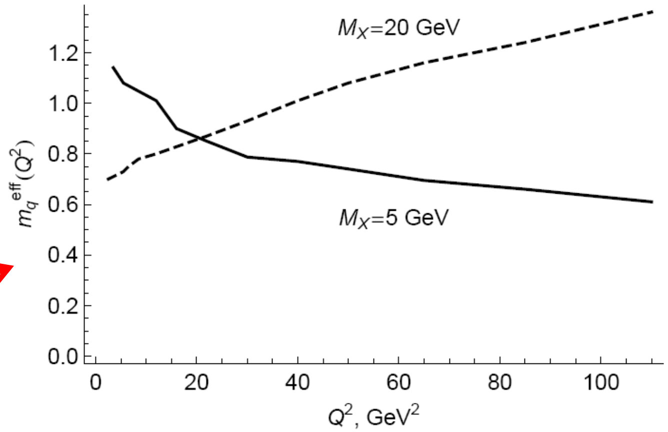


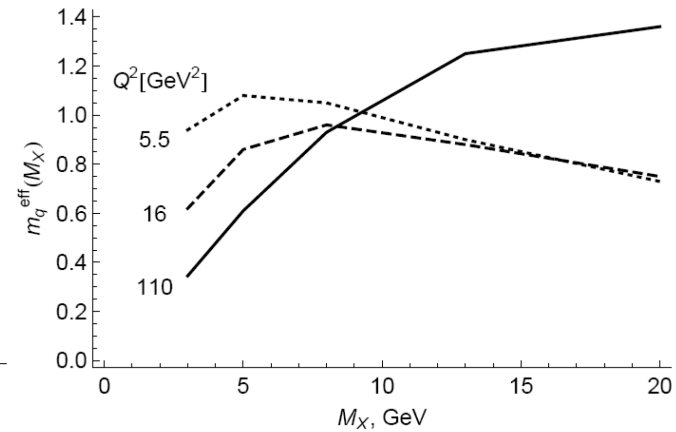
Large differences at $x<\sim10^{-2}$ and $Q^2<\sim2\ GeV^2$!!

$\rightarrow$ Unknown gluon density in this region !!!

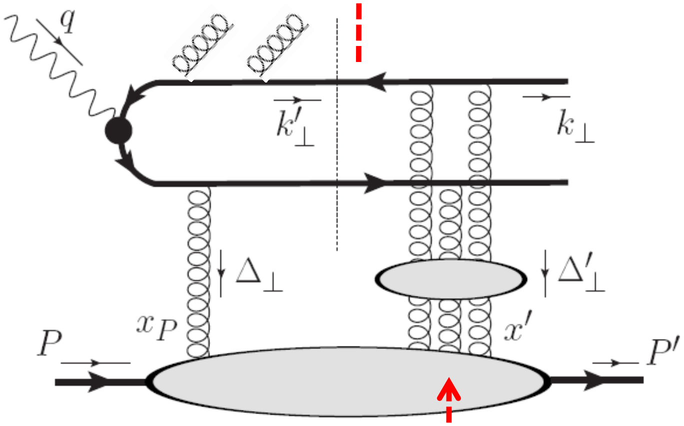
Model parameters

Effective mass m_{eff}
of 0.3—1.2 GeV
of quark in dipole
from dressing-up
with gluon radiation

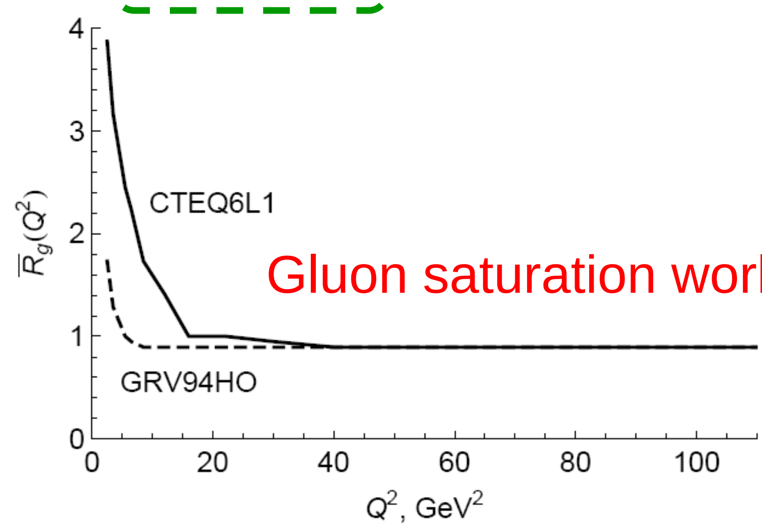




$$m_q \rightarrow m_{eff}$$



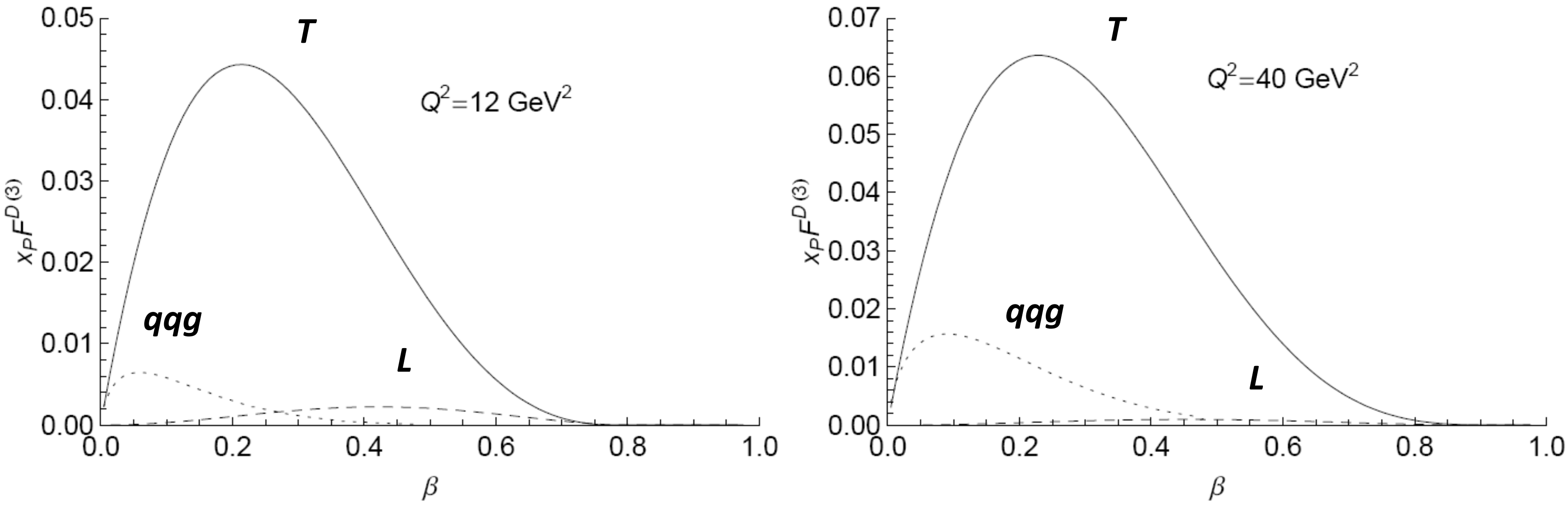
$$\sqrt{x_P}\mathcal{F}_g^{\mathrm{off}} \simeq \boxed{\bar{R}_g(x', \mu^2_{\mathrm{soft}})}\sqrt{x_P g(x_P, \mu_F^2)}\, f_G(\Delta_\perp^2)$$



Gluon saturation works!

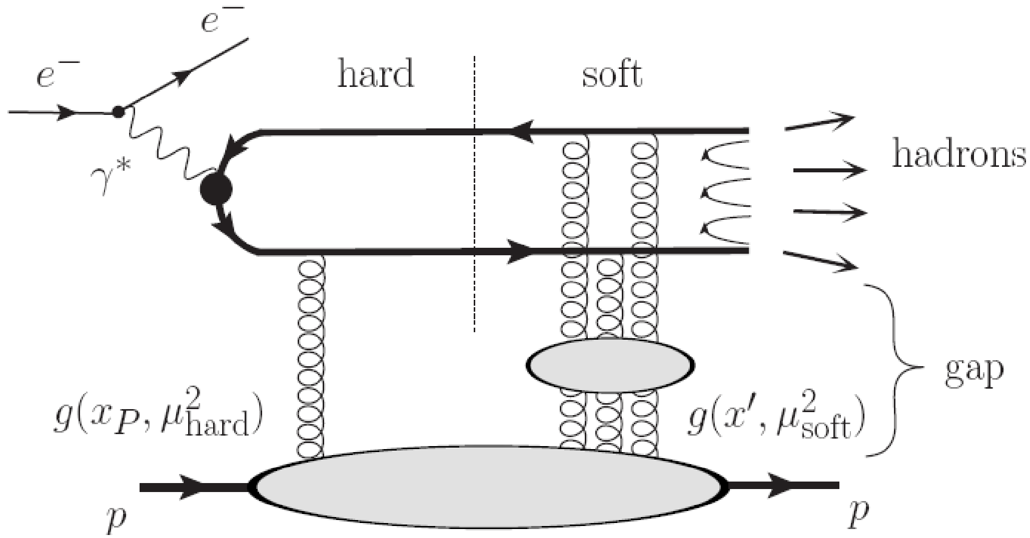
Soft gluon density function R_g
= constant ≈ 1, except at small Q^2

Photon polarization contributions and mass spectrum



Gluonic contribution increases at high M_X and Q^2 !!!

Proposal for “New” SCI Monte-Carlo technique



Probability for soft color exchanges:

1. ***…is actually dependent on dynamics of multiple gluon interactions and kinematics of emerging partons, and can be constrained from the first principles;***

2. ***…should be written in terms of infrared finite dipole-target or dipole-dipole rescattering;***

3. ***…can be written in terms of normalized sensitivity of the hard subprocess part to small fluctuations of transverse momenta of dipole constituents due to soft exchanges.***

Work in progress...

Summary

- ✓ We constructed the QCD based model for the soft gluon rescattering.

- ✓ The model works basically well and leads to a good description of the HERA data on the diffractive structure function in almost all bins in photon virtuality and invariant mass of the final hadronic system.

- ✓ At lower xP and Q^2 the uncertainties in conventional parton densities become significant, and some improvement of the data description is still needed.