Simultaneous QCD analysis of diffractive and inclusive DIS data

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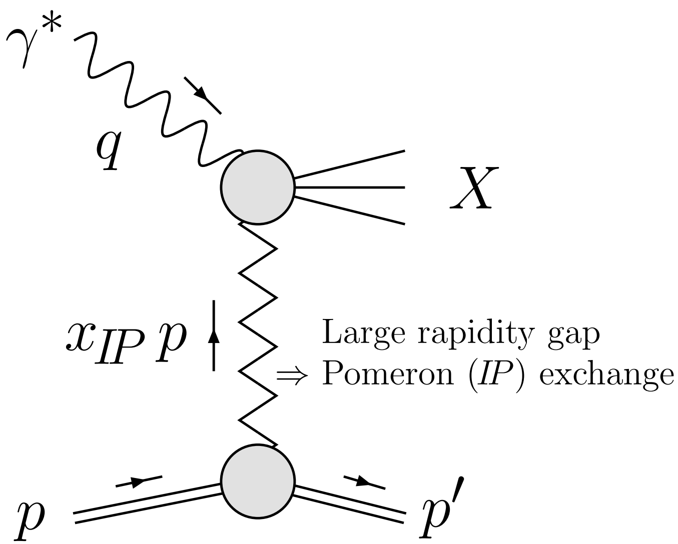
Diffractive DIS kinematics



- $q^2 \equiv -Q^2$
- $W^2 \equiv (q+p)^2 = -Q^2 + 2\,p \cdot q$

  $\Rightarrow \quad x_B \equiv \frac{Q^2}{2\,p\cdot q} = \frac{Q^2}{Q^2+W^2}$

  (fraction of proton's momentum carried by struck quark)
- $t \equiv (p-p')^2 \approx 0$, $(p-p') \approx x_{IP}\, p$
- $M_X^2 \equiv (q+p-p')^2 = -Q^2 + x_{IP}(Q^2+W^2)$

  $\Rightarrow \quad x_{IP} = \frac{Q^2+M_X^2}{Q^2+W^2}$

  (fraction of proton's momentum carried by Pomeron)
- $\beta \equiv \frac{x_B}{x_{IP}} = \frac{Q^2}{Q^2+M_X^2}$ (fraction of Pomeron's momentum carried by struck quark)

Diffractive structure function $F_2^{D(3)}$

- Diffractive cross section (integrated over t):

$$\frac{\mathrm{d}^3\sigma^D}{\mathrm{d}x_{I\!P}\,\mathrm{d}\beta\,\mathrm{d}Q^2} = \frac{2\pi\alpha_{\rm em}^2}{\beta\,Q^4}\,\left[1+(1-y)^2\right]\,\sigma_r^{D(3)}(x_{I\!P},\beta,Q^2),$$

where $y = Q^2/(x_{\scriptscriptstyle B}s)$, $s = 4E_eE_p$, and

$$\sigma_r^{D(3)} = F_2^{D(3)} - \frac{y^2}{1+(1-y)^2}\,F_L^{D(3)} \approx F_2^{D(3)}(x_{I\!P},\beta,Q^2),$$

for small y and/or small $F_L^{D(3)}/F_2^{D(3)}$

- Measurements of $F_2^{D(3)} \Rightarrow$ *diffractive* parton distribution functions (DPDFs)

$$a^D(x_{I\!P},\beta,Q^2) = \beta\Sigma^D(x_{I\!P},\beta,Q^2) \text{ or } \beta g^D(x_{I\!P},\beta,Q^2)$$

‘Traditional’ extraction of DPDFs

- Assume Regge factorisation [Ingelman-Schlein,1985]:

$$F_2^{D(3)}(x_{I\!P}, \beta, Q^2) = f_{I\!P}(x_{I\!P})\, F_2^{I\!P}(\beta, Q^2)$$

- Pomeron flux factor from Regge phenomenology:

$$f_{I\!P}(x_{I\!P}) = \int_{t_{\rm cut}}^{t_{\rm min}} {\rm d}t\, \frac{{\rm e}^{B_{I\!P}\, t}}{x_{I\!P}^{2\alpha_{I\!P}(t)-1}} \qquad (\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P}\, t)$$

  Fits to $F_2^{D(3)}$ data give $\alpha_{I\!P}(0) > 1.08$ (value from soft hadron data)
  $\Longrightarrow$ *effective* Pomeron intercept

- Evaluate Pomeron structure function $F_2^{I\!P}(\beta, Q^2)$ from quark singlet $\Sigma^{I\!P}(\beta, Q^2)$ and gluon $g^{I\!P}(\beta, Q^2)$ Pomeron PDFs DGLAP-evolved from arbitrary polynomial input at scale Q_0^2

New perturbative QCD approach

- Pomeron singularity not a *pole* but a *cut* [Lipatov,1986]
  $\Rightarrow$ continuous number of components of size $1/\mu$:

$$F_{2,\mathrm{P}}^{D(3)}(x_{I\!P},\beta,Q^2) = \int_{Q_0^2}^{Q^2} \mathrm{d}\mu^2\; f_{I\!P}(x_{I\!P};\mu^2)\; F_2^{I\!P}(\beta,Q^2;\mu^2)$$

- Perturbative Pomeron represented by two t-channel gluons in colour singlet:

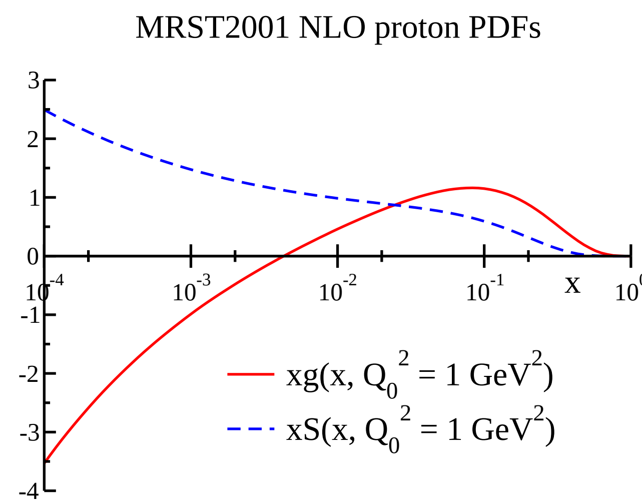
$$f_{I\!P=G}(x_{I\!P};\mu^2) = \frac{1}{x_{I\!P}}\left[\frac{\alpha_S(\mu^2)}{\mu^2}\, x_{I\!P}\, g(x_{I\!P},\mu^2)\right]^2$$

where $g(x_{I\!P},\mu^2)$ is the (integrated) gluon distribution of the proton

Problem: $x_{I\!P}\, g(x_{I\!P}, \mu^2)$ at low μ^2

- $f_{I\!P=G}(x_{I\!P}; \mu^2) \propto \left[x_{I\!P}\, g(x_{I\!P}, \mu^2)/\mu^2\right]^2$ $\Rightarrow$ dominant contribution from low scales $\mu \sim Q_0 \sim 1$ GeV
- $F_2^{D(3)}$ data need $x_{I\!P} g(x_{I\!P}, \mu^2) \sim x_{I\!P}^{-\lambda}$ with $\lambda \simeq 0.17$

- But ...



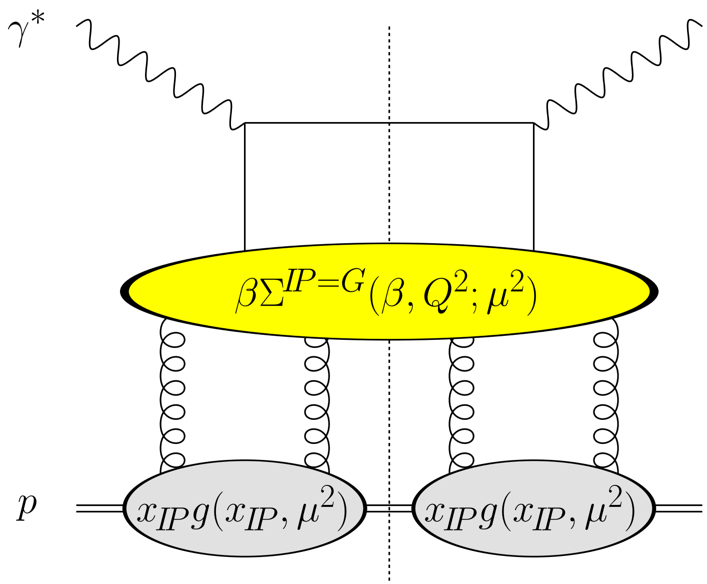
Solution:

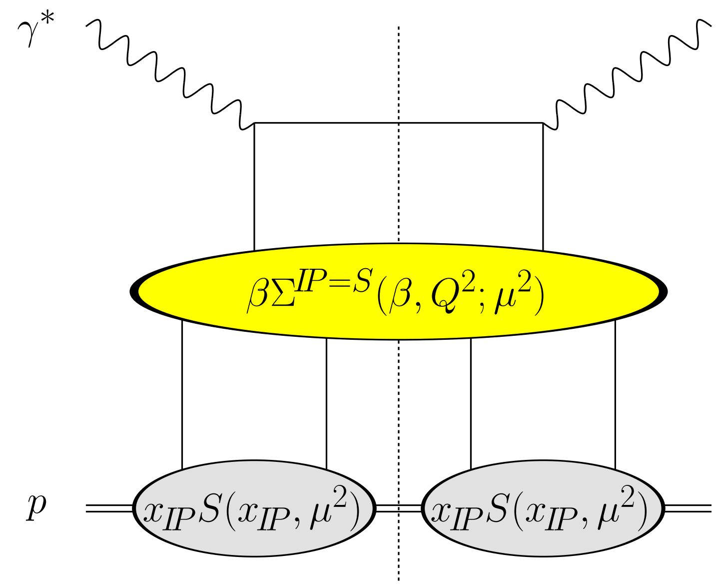
- Introduce Pomeron composed of two sea quarks in a colour singlet:

$$f_{I\!P=S}(x_{I\!P}; \mu^2) = \frac{1}{x_{I\!P}} \left[\frac{\alpha_S(\mu^2)}{\mu^2}\, x_{I\!P}\, S(x_{I\!P}, \mu^2) \right]^2$$

and interference term with two-gluon Pomeron ($I\!P = GS$)
(set $x_{I\!P} g(x_{I\!P}, \mu^2) = 0$ if $-$ve)

New perturbative QCD approach





- $F_2^{I\!P}(\beta, Q^2; \mu^2)$ calculated from quark singlet $\Sigma^{I\!P}(\beta, Q^2; \mu^2)$ and gluon $g^{I\!P}(\beta, Q^2; \mu^2)$ DGLAP-evolved from an input scale μ^2 up to Q^2
- Get input Pomeron PDFs $\Sigma^{I\!P}(\beta, \mu^2; \mu^2)$ and $g^{I\!P}(\beta, \mu^2; \mu^2)$ from lowest-order Feynman diagrams. Calculate using light-cone wave functions of the photon [Wüsthoff,1997]

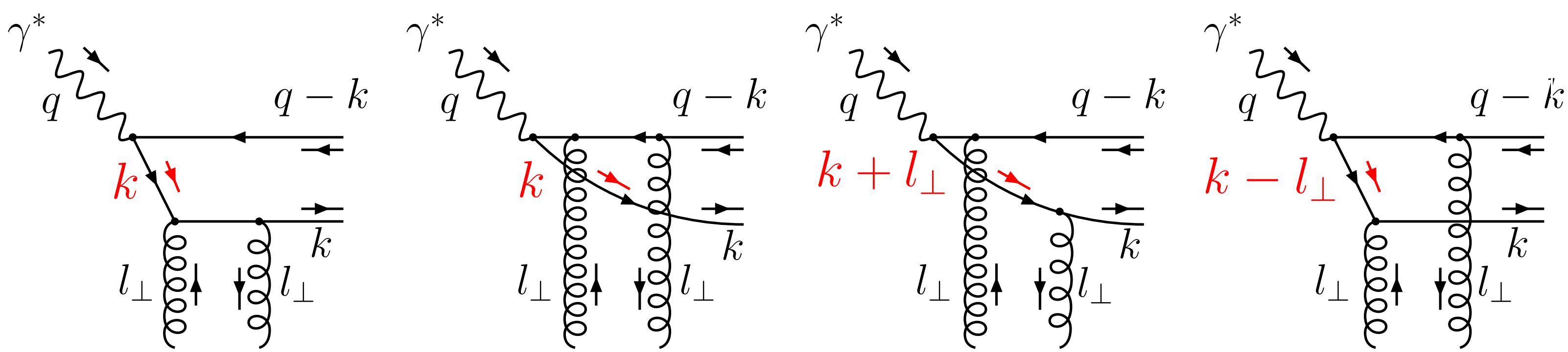
Example of dipole calculations

Two-gluon Pomeron, transversely-polarised photon, $\gamma^* \to q\bar{q}$:

$$\left.\frac{\mathrm{d}\sigma_{q\bar{q},T}^{\gamma^* p}}{\mathrm{d}t}\right|_{t=0} = \frac{N_C}{16\pi}\int_0^1 \mathrm{d}\alpha \int \frac{\mathrm{d}k_t^2}{2\pi} \sum_f e_f^2\, \alpha_{\mathrm{em}}\, \frac{1}{2} \sum_{\gamma=\pm 1} \sum_{h=\pm 1} \left| \int \frac{\mathrm{d}^2 \boldsymbol{l_t}}{\pi}\, D\Psi_h^\gamma\, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}l_t^2} \right|^2$$

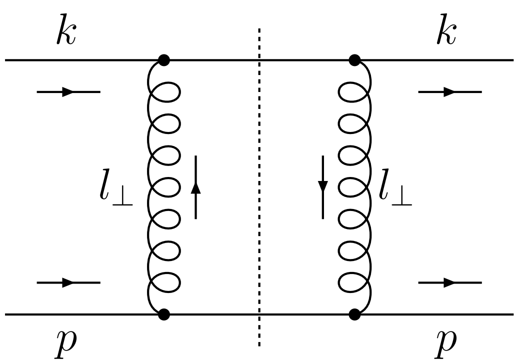
- Obtain four different permutations by simply shifting argument of wave functions:

$$D\Psi(\alpha, \boldsymbol{k_t}, \boldsymbol{l_t}) \equiv 2\Psi(\alpha, \boldsymbol{k_t}) - \Psi(\alpha, \boldsymbol{k_t} + \boldsymbol{l_t}) - \Psi(\alpha, \boldsymbol{k_t} - \boldsymbol{l_t})$$



Example of dipole calculations

- Obtain dipole cross section $\frac{d\hat{\sigma}}{dl_t^2}(qp \to qp)$ from $\frac{d\hat{\sigma}}{dl_t^2}(qq \to qq)$:



- Make replacement

$$\left.\frac{\alpha_S(l_t^2)}{2\pi} x_{I\!P} P_{gq}(x_{I\!P})\right|_{x_{I\!P} \ll 1} \to f_g(x_{I\!P}, l_t^2, \mu^2)$$

where $\mu^2 \equiv k_t^2/(1-\beta)$ and $f_g(x_{I\!P}, l_t^2, \mu^2)$ is the *unintegrated* gluon distribution

- Work in strongly-ordered limit ($l_t \ll k_t \ll Q$):

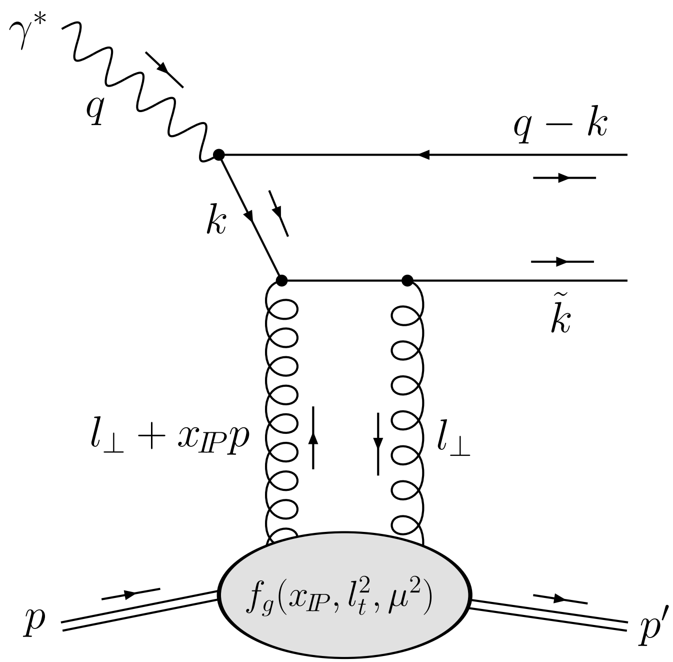
$$\int \frac{d^2\boldsymbol{l_t}}{\pi} D\Psi_h^\gamma \frac{d\hat{\sigma}}{dl_t^2} \sim \int_0^{\mu^2} dl_t^2\, l_t^2\, \frac{1}{l_t^4} f_g(x_{I\!P}, l_t^2, \mu^2) = x_{I\!P}\, g(x_{I\!P}, \mu^2)$$

$D\Psi_h^\gamma$ gives the β dependence of $\Sigma^{I\!P=G}(\beta, \mu^2; \mu^2)$

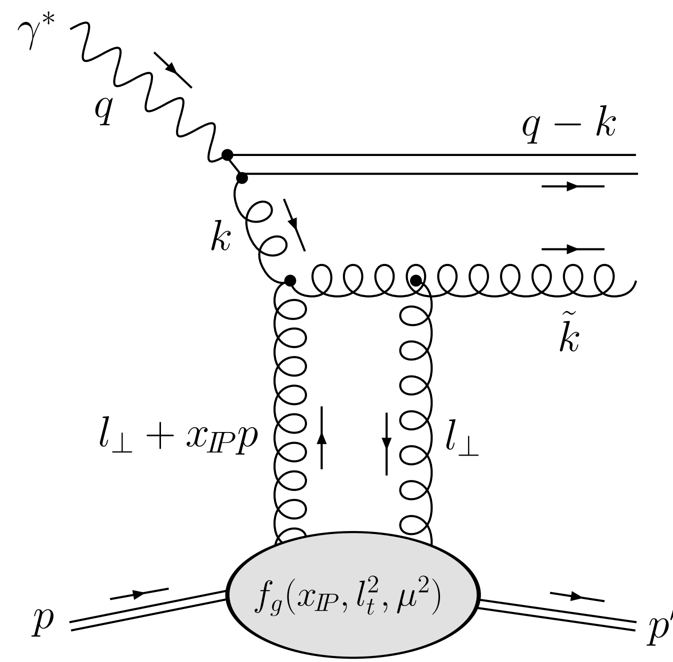
Two-gluon Pomeron

- Work in strongly-ordered limit: $l_t \ll k_t \ll Q$

Quark dipole



Effective gluon dipole



$$\beta\Sigma^{I\!P=G}(\beta,\mu^2;\mu^2) = c_{q/G}\,\beta^3\,(1-\beta)$$

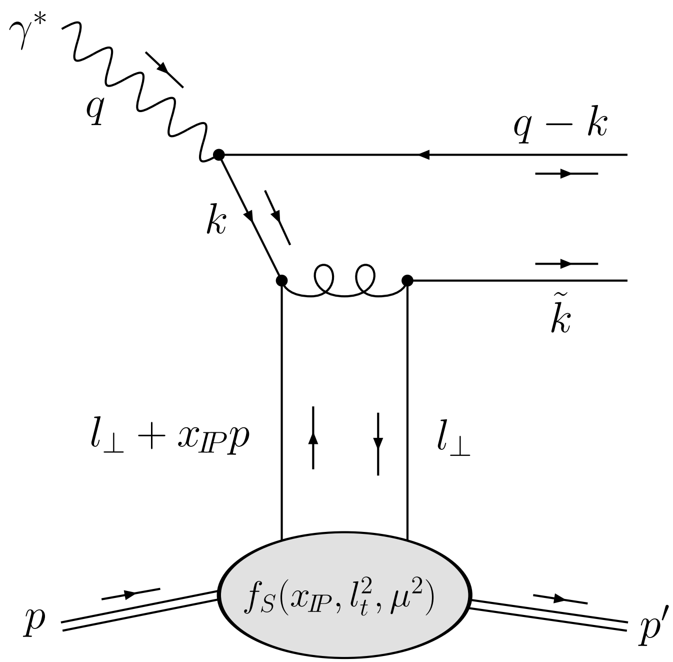
$$F_L^{I\!P=G}(\beta) = c_{L/G}\,\beta^3\,(2\beta-1)^2$$

$$\beta'\,g^{I\!P=G}(\beta',\mu^2;\mu^2) = c_{g/G}(1+2\beta')^2(1-\beta')^2$$

Two-quark Pomeron

- Work in strongly-ordered limit: $l_t \ll k_t \ll Q$

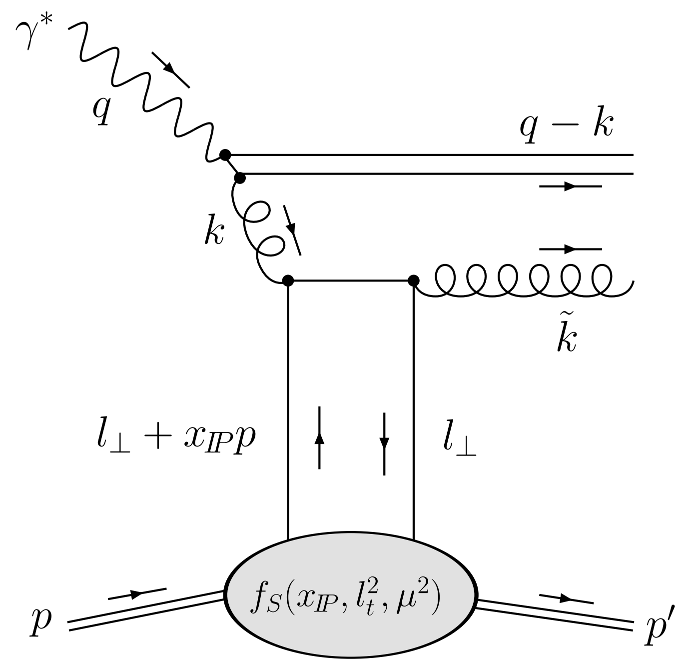
Quark dipole



$$\beta \Sigma^{I\!P=S}(\beta, \mu^2; \mu^2) = c_{q/S}\, \beta\, (1-\beta)$$

$$F_L^{I\!P=S}(\beta) = c_{L/S}\; \beta^3$$

Effective gluon dipole



$$\beta' g^{I\!P=S}(\beta', \mu^2; \mu^2) = c_{g/S}\, (1-\beta')^2$$

Other contributions to $F_2^{D(3)}$

$$F_2^{D(3)} = F_{2,\mathrm{P}}^{D(3)} + F_{2,\mathrm{NP}}^{D(3)} + F_{L,\mathrm{P}}^{D(3)} + F_{2,I\!\!R}^{D(3)}$$

- Non-perturbative contribution ($\mu < Q_0$, $\alpha_{I\!\!P}(0) = 1.08$):

$$F_{2,\mathrm{NP}}^{D(3)} = f_{I\!\!P=\mathrm{NP}}(x_{I\!\!P})\, F_2^{I\!\!P=\mathrm{NP}}(\beta, Q^2; Q_0^2)$$

$$\left[\beta\Sigma^{I\!\!P=\mathrm{NP}}(\beta, Q_0^2; Q_0^2) = c_{q/\mathrm{NP}}\,\beta\,(1-\beta), \quad \beta' g^{I\!\!P=\mathrm{NP}}(\beta', Q_0^2; Q_0^2) = 0\right]$$

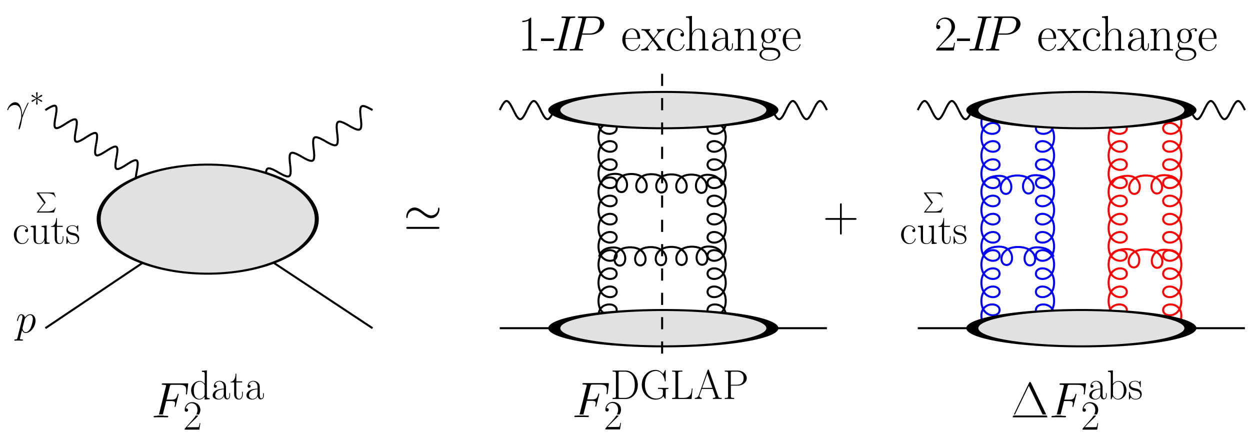
- Twist-four contribution:

$$F_{L,\mathrm{P}}^{D(3)} = \sum_{I\!\!P=G,S,GS} \left(\int_{Q_0^2}^{Q^2} \mathrm{d}\mu^2\, \frac{\mu^2}{Q^2}\, f_{I\!\!P}(x_{I\!\!P}; \mu^2) \right) F_L^{I\!\!P}(\beta)$$

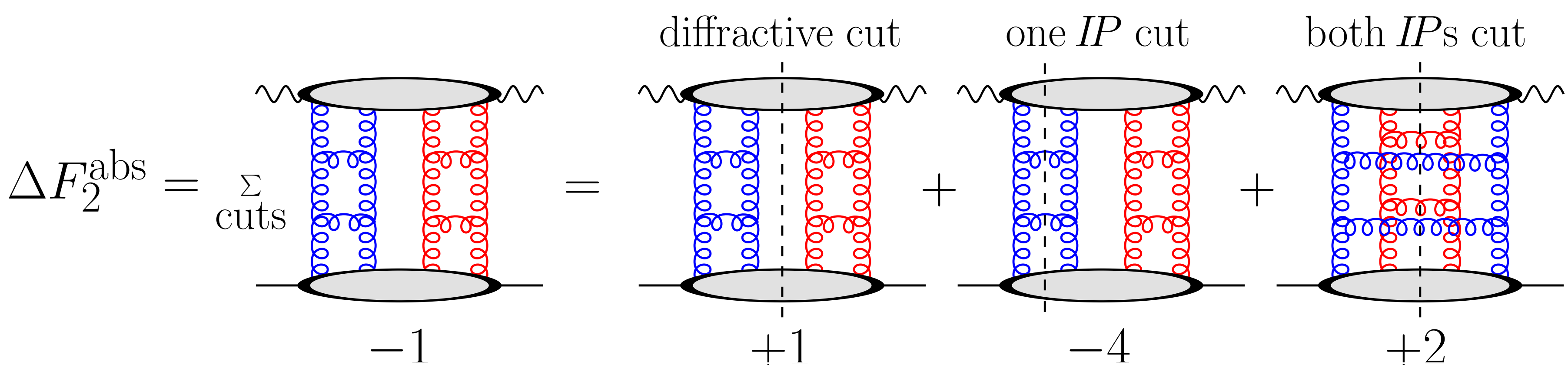
- Secondary Reggeon contribution ($\alpha_{I\!\!R}(0) = 0.50$):

$$F_{2,I\!\!R}^{D(3)} = c_{I\!\!R}\, f_{I\!\!R}(x_{I\!\!P})\, F_2^{\pi}(\beta, Q^2)$$

Absorptive corrections to F_2



- **AGK cutting rules** [a] $\Longrightarrow$ diffractive events are intimately related to absorptive corrections to the inclusive structure function F_2:



[a] **A**bramovsky-**G**ribov-**K**ancheli (1973) ⟶ QCD: Bartels-Ryskin (1997)

Absorptive corrections to F_2

$$F_2^{\rm data}(x_B,Q^2) = F_2^{\rm DGLAP}(x_B,Q^2) + \Delta F_2^{\rm abs}(x_B,Q^2)$$

$$\Delta F_2^{\rm abs}(x_B,Q^2) = -\int_{Q_0^2}^{Q^2} {\rm d}\mu^2 \; F_2^D(x_B,Q^2;\mu^2)$$

- $F_2^D(x_B,Q^2;\mu^2)$ is the contribution to $F_2^{D(3)}$ (integrated over x_{IP}) originating from a perturbative component of the Pomeron of size $1/\mu$. The $\mu < Q_0$ contributions to the absorptive corrections are already included in the input parameterisations to the F_2 fit
- To fit F_2 using the DGLAP equation, first need to 'correct' the data for absorptive effects: [a]

$$F_2^{\rm DGLAP} = F_2^{\rm data} - \Delta F_2^{\rm abs} = F_2^{\rm data} + \left|\Delta F_2^{\rm abs}\right|$$

[a] Aside: absorptive corrections $\sim$ non-linear effects, screening, shadowing, unitarity corrections, multiple scattering, multiple interactions, recombination, saturation effects, . . .

Simultaneous F_2 + $F_2^{D(3)}$ analysis

- Procedure:
  1. Start by fitting ZEUS + H1 F_2 data (279 points) [a] with no absorptive corrections $\sim$ MRST2001 NLO
  2. Fit ZEUS + H1 $F_2^{D(3)}$ data, using $g(x_{I\!P},\mu^2)$ and $S(x_{I\!P},\mu^2)$ from previous F_2 fit
  3. Fit $F_2^{\rm DGLAP} = F_2^{\rm data} + \left|\Delta F_2^{\rm abs}\right|$, with $\Delta F_2^{\rm abs}$ from previous $F_2^{D(3)}$ fit
  4. Go to 2.
- Only a few iterations needed for convergence

[a] Cuts: $x_B < 0.01$, $2 < Q^2 < 500$ GeV^2, $W^2 > 12.5$ GeV^2; match to MRST xg, xS at $x = 0.2$

Description of $F_2^{D(3)}$ data

- Fit three different data sets simultaneously, allowing for *different* relative normalisations due to *proton dissociation*:

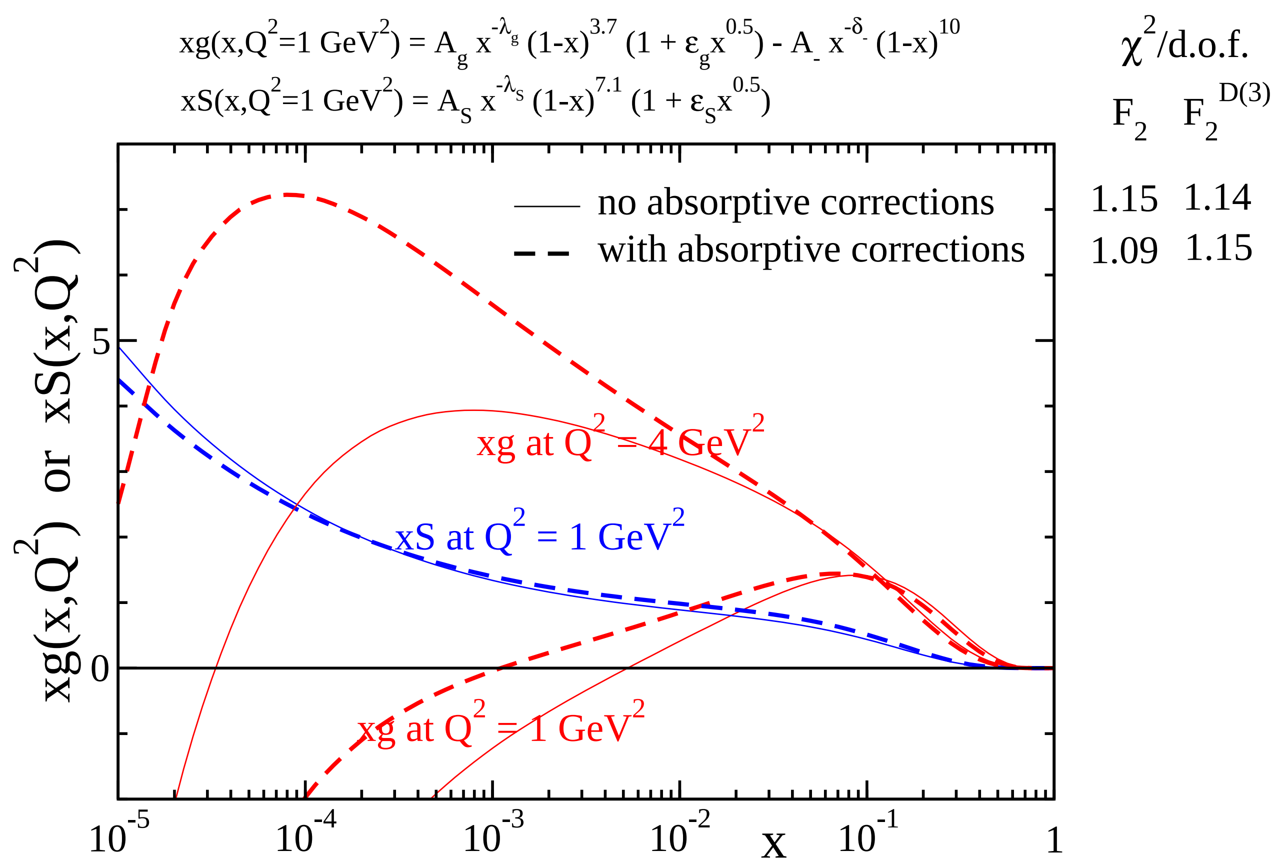
Data set	Points [a]	Proton dissociation	Normalisation
1997 ZEUS LPS (prel.)	69	none	1
1998/99 ZEUS (prel.)	121	$M_Y < 2.3$ GeV	≈ 1.5
1997 H1 (prel.)	214	$M_Y < 1.6$ GeV	≈ 1.2

- Only other free parameters are *normalisations* (effective K-factors) of the input Pomeron PDFs, the twist-four contributions and the secondary Reggeon contribution:

$c_{q/G}, c_{g/G}, c_{L/G}, c_{q/S}, c_{g/S}, c_{L/S}, c_{q/\mathrm{NP}}, c_{I\!R}$ $\quad$ ($Q_0 = 1$ GeV)
(Fix $c_{i/GS} = \sqrt{c_{i/G}\, c_{i/S}}$ for $i = q, g, L$)

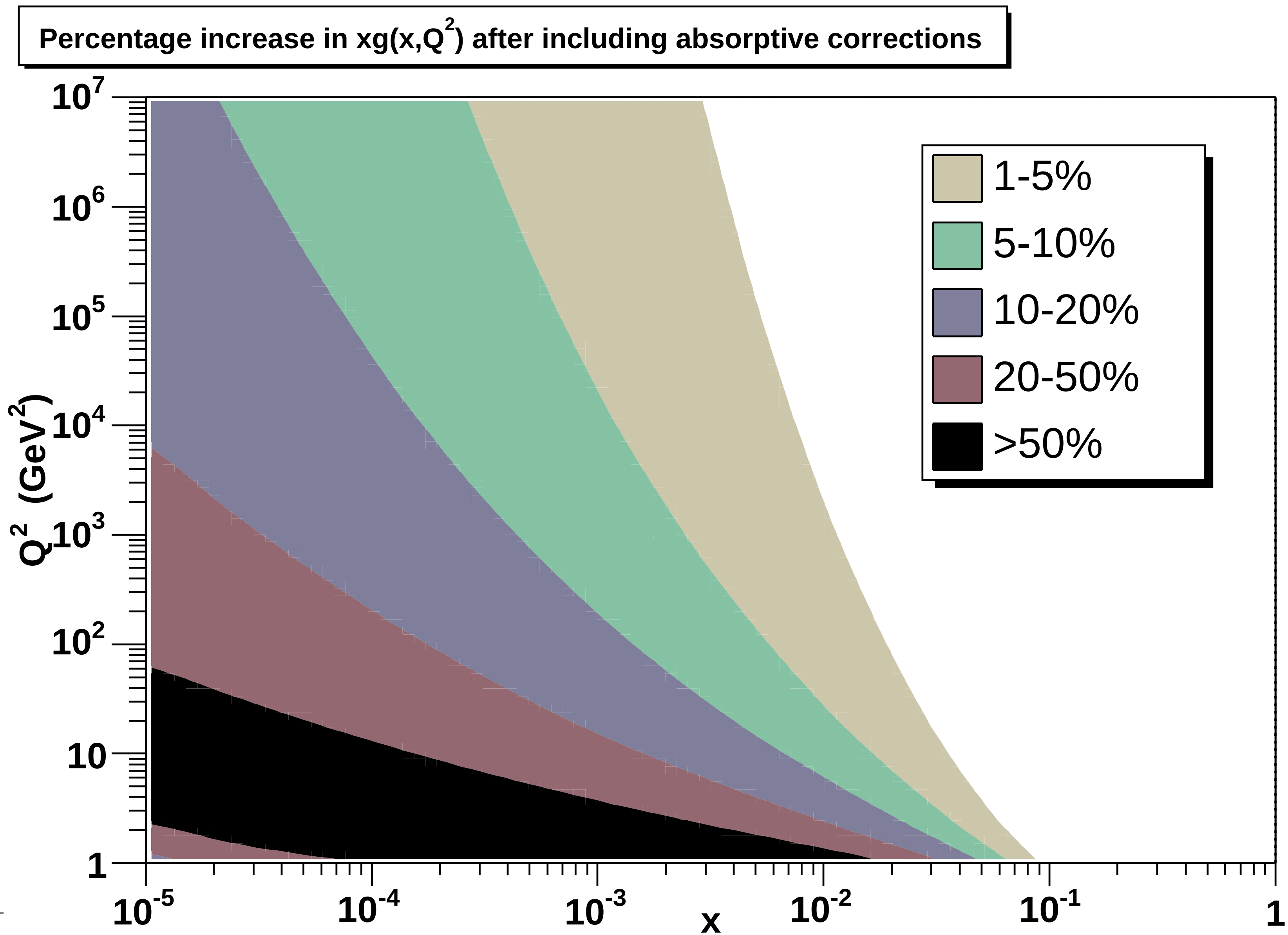
[a] Cuts: $M_X > 2$ GeV, $y < 0.45$

Gluon and sea quark PDFs

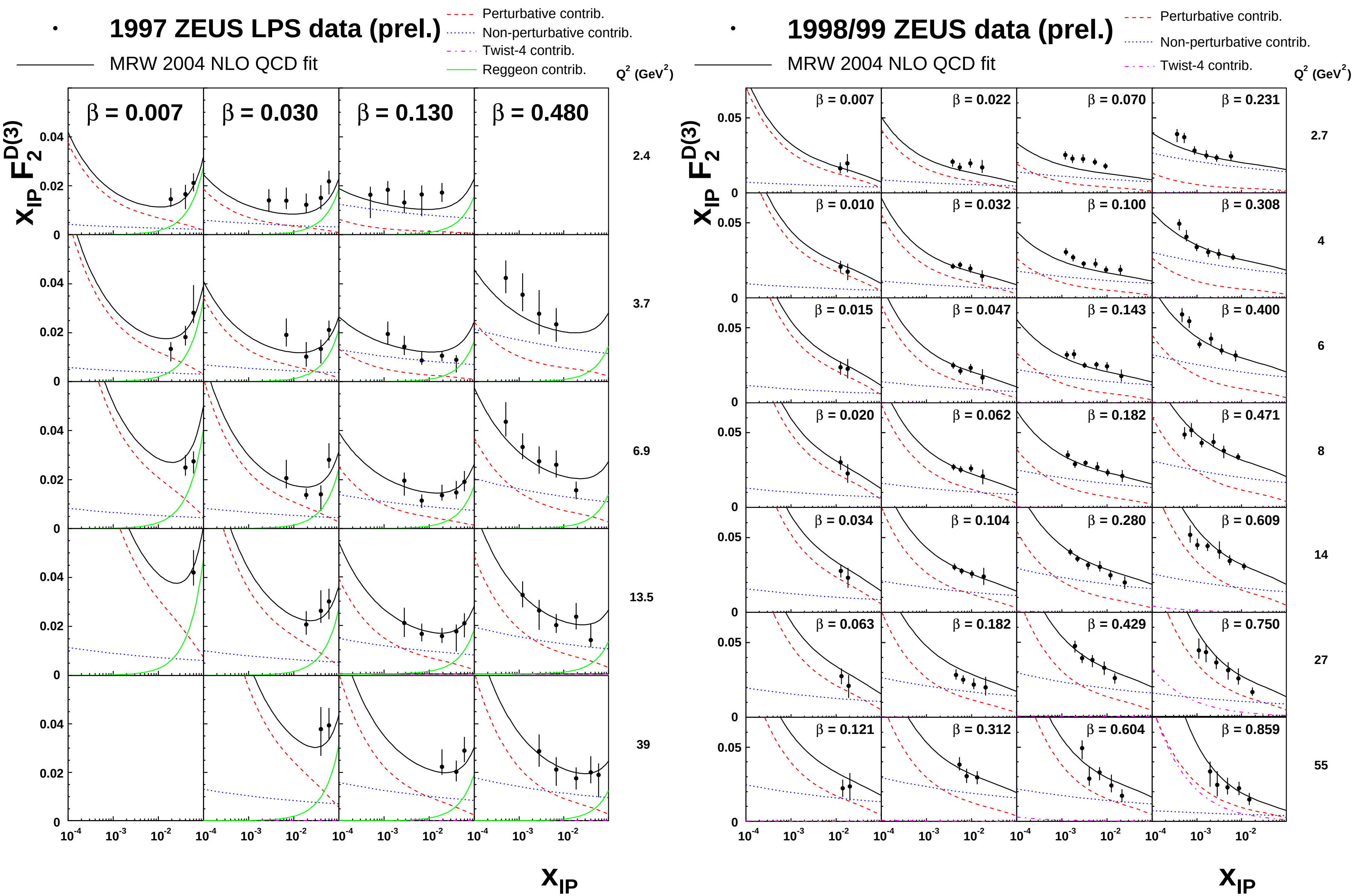


- Take +ve input gluon parameterisation ($A_- = 0$):
  - no absorptive corrections $\chi^2/\mathrm{d.o.f.} = 1.57$ for F_2, 1.17 for $F_2^{D(3)}$
  - with absorptive corrections $\chi^2/\mathrm{d.o.f.} = 1.11$ for F_2, 1.14 for $F_2^{D(3)}$

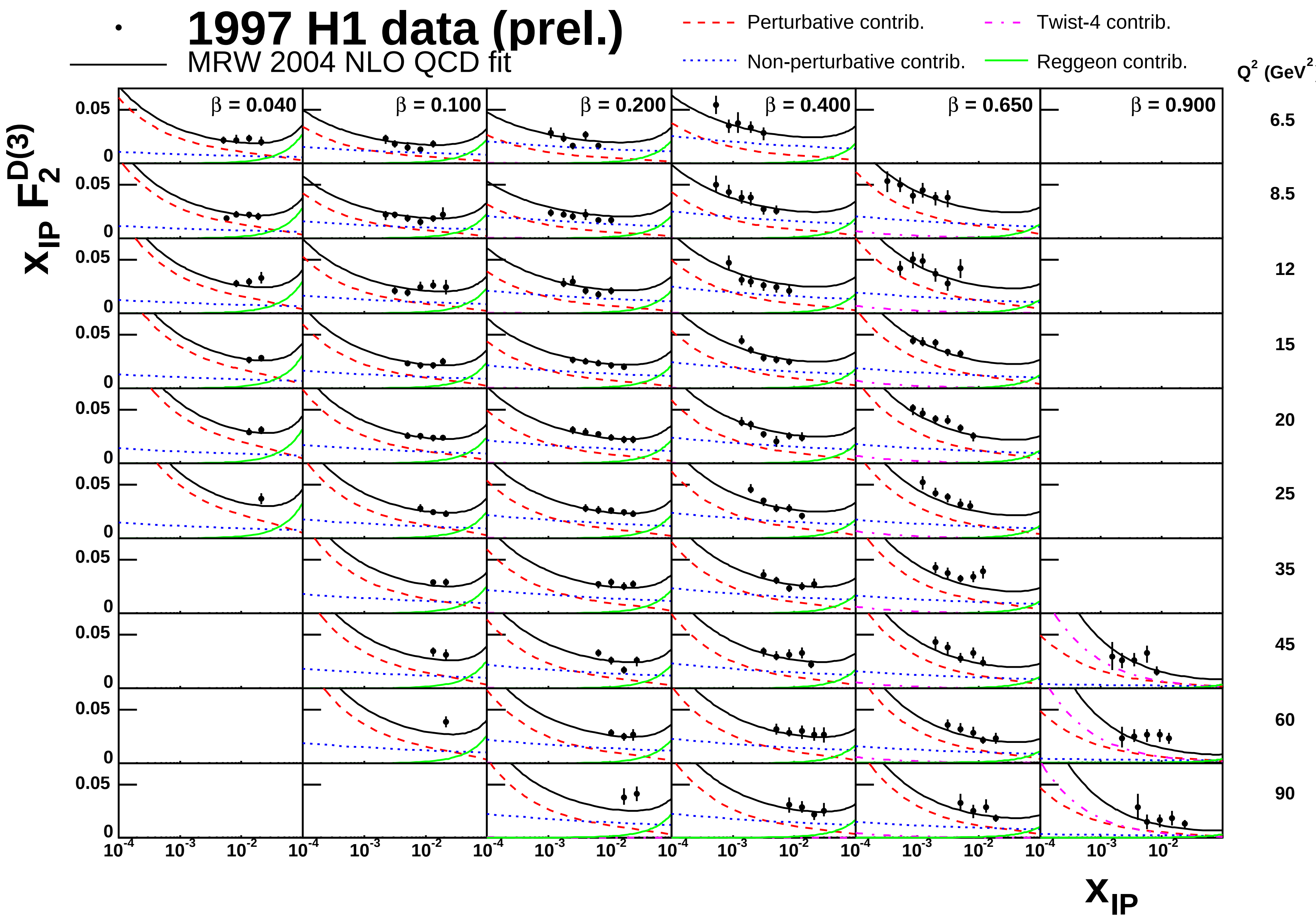
Percentage increase in gluon distribution



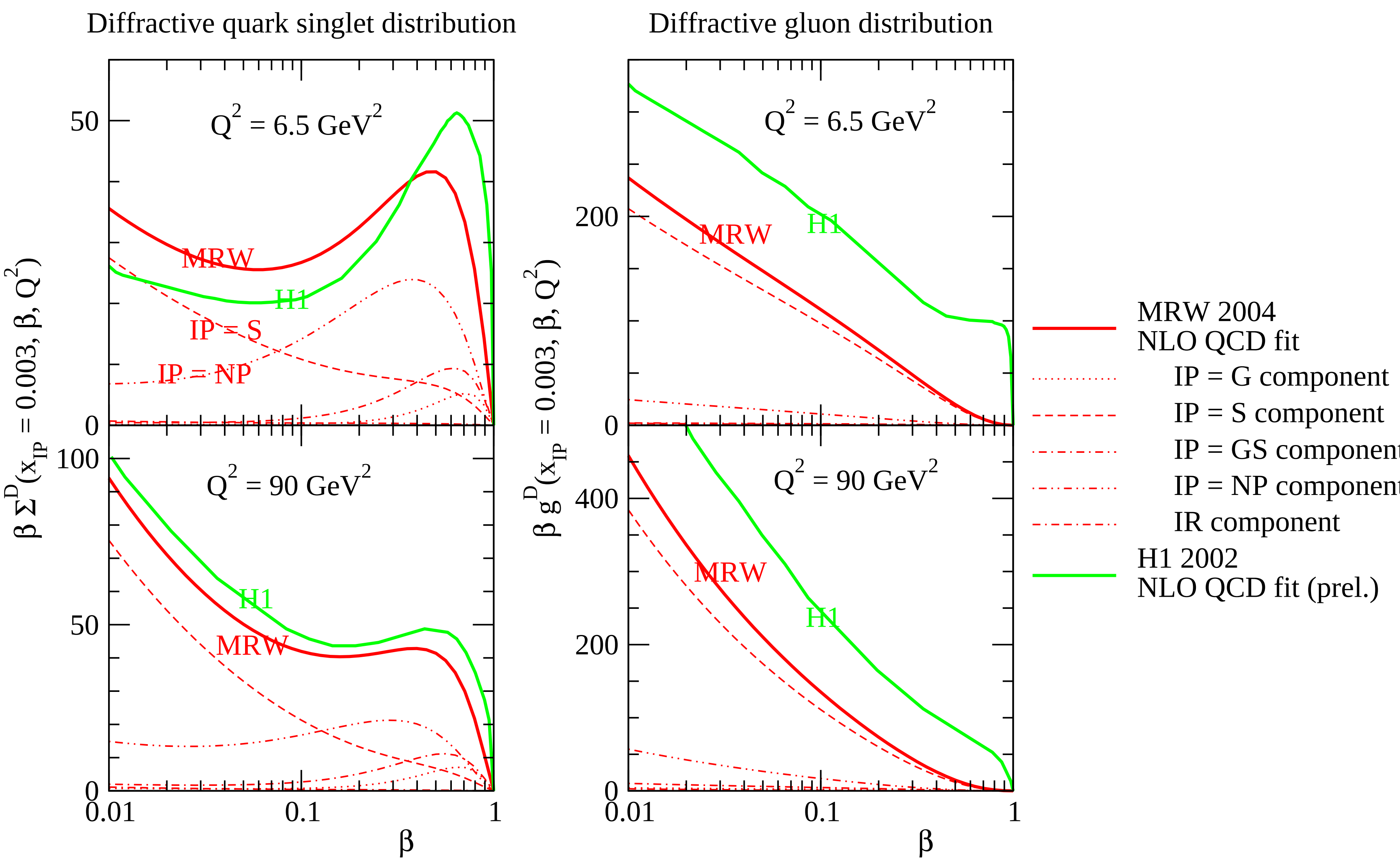
Fit to ZEUS + H1 $F_2^{D(3)}$



Fit to ZEUS + H1 $F_2^{D(3)}$



DPDFs compared to H1 fit

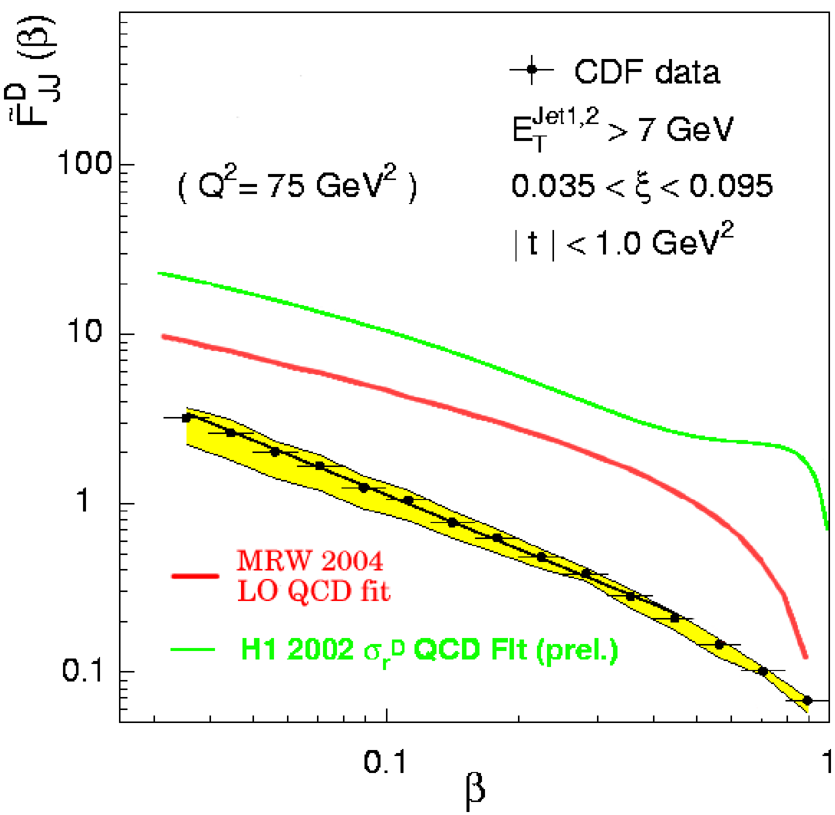


- H1 use a smaller α_S and have no twist-four contribution

CDF diffractive dijets

- Diffractive structure function of the antiproton:

$$\tilde{F}^D_{JJ}(\beta) = \frac{1}{\xi_{\max} - \xi_{\min}} \int_{\xi_{\min}}^{\xi_{\max}} \mathrm{d}\xi \left[\beta g^D(\xi, \beta, Q^2) + \frac{4}{9} \beta \Sigma^D(\xi, \beta, Q^2) \right]$$



- Results for "survival probability" of the rapidity gap do not contradict calculation by KKMR: [a]

$$S^2 \simeq 0.12\text{–}0.28$$

[a] Khoze-Martin-Ryskin, Eur. Phys. J. C **18** (2000) 167; Kaidalov-KMR, Eur. Phys. J. C **21** (2001) 521

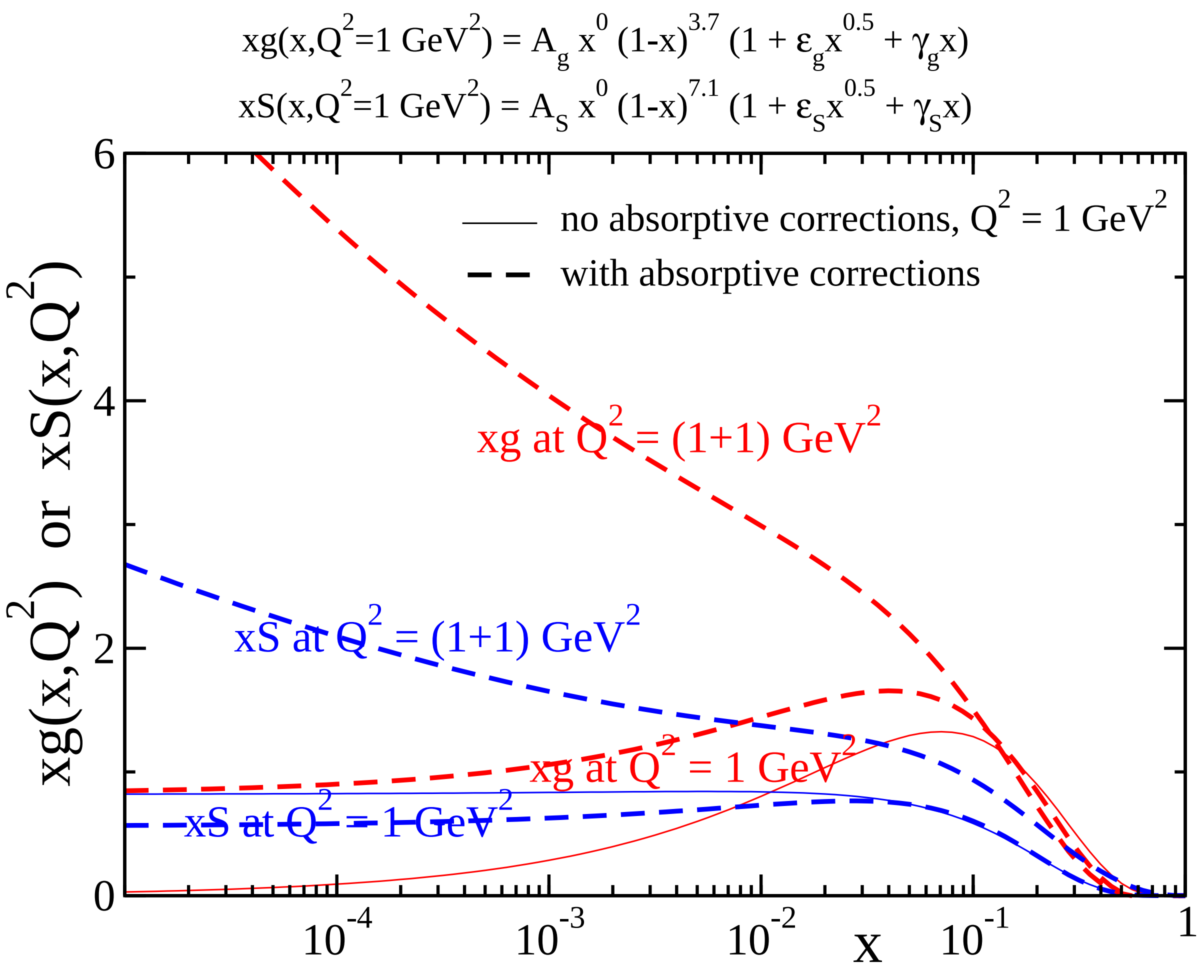
‘Pomeron-like’ xS but ‘valence-like’ xg ?

- Good news: Absorptive corrections remove the need for a negative input gluon distribution when fitting inclusive F_2 data
- Bad news: Still have ‘Pomeron-like’ sea quarks but ‘valence-like’ gluons at small x and low Q^2:

$$xg \sim x^{-\lambda_g}, xS \sim x^{-\lambda_S} \quad \text{with} \quad \lambda_g < 0 \text{ and } \lambda_S > 0$$

- Reminder:
  - Regge theory $\Longrightarrow \lambda_g = \lambda_S$
  - Resummed NLL BFKL $\Longrightarrow \lambda_g = \lambda_S \simeq 0.3$
  - Soft hadron data $\Longrightarrow \lambda \simeq 0.08$
- Must be some large non-perturbative effect causing the observed behaviour. One possibility: mimic unknown power corrections by shifting scale in F_2 and $F_2^{D(3)}$ fits by ≈ 1 GeV^2. Fix $\lambda_g = \lambda_S = 0$

Shift scale by 1 GeV^2 ?



χ^2/d.o.f.	
F_2	$F_2^{D(3)}$
1.45	1.30
1.15	1.29

- Satisfactory description of F_2 and $F_2^{D(3)}$ data with 'flat' asymptotic behaviour ($x \to 0$) of input xg, xS

Conclusions

- **New perturbative QCD description of $F_2^{D(3)}$**
  - Pomeron singularity not a *pole* but a *cut*
    $\Rightarrow$ Integral over Pomeron scale μ
  - Input Pomeron PDFs from lowest-order QCD diagrams
  - Two-quark Pomeron in addition to two-gluon Pomeron
- **Absorptive corrections to F_2 from AGK cutting rules**
  - Good news: remove need for negative gluon input
  - Dilemma: still have 'Pomeron-like' sea quarks but 'valence-like' gluons at small x and low Q^2
    1. Non-perturbative Pomeron doesn't couple to gluons, secondary Reggeon couples more to gluons than sea quarks ?
    2. Unknown non-perturbative power corrections slow down DGLAP evolution at low Q^2 ?