Diffractive parton distributions and absorptive corrections to F_2

Graeme Watt

Institute for Particle Physics Phenomenology

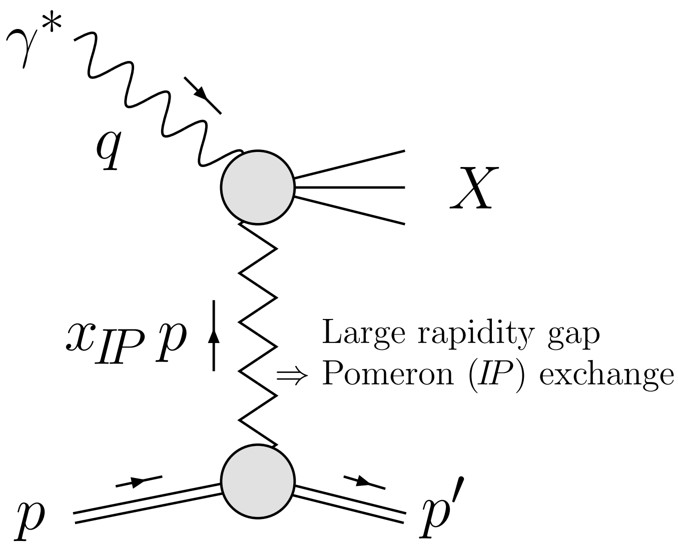
University of Durham, UK

Outline of talk

- Diffractive structure function ($F_2^{D(3)}$) at HERA
- 'Traditional' extraction of diffractive parton distributions from $F_2^{D(3)}$
- **New** improved perturbative QCD approach
- *Application:* absorptive corrections to inclusive F_2 from AGK cutting rules
- Simultaneous F_2 + $F_2^{D(3)}$ analysis

In collaboration with A.D. Martin and M.G. Ryskin

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)
- $t \equiv (p-p')^2 \approx 0$, $(p-p') \approx x_{I\!P}\, p$
- $M_X^2 \equiv (q+p-p')^2 = -Q^2 + x_{I\!P}(Q^2+W^2)$
  $\Rightarrow x_{I\!P} = \frac{Q^2+M_X^2}{Q^2+W^2}$ (fraction of proton's momentum carried by Pomeron)
- $\beta \equiv \frac{x_B}{x_{I\!P}} = \frac{Q^2}{Q^2+M_X^2}$ (fraction of Pomeron's momentum carried by struck quark)

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

- Diffractive cross section (integrated over t):

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

where $y = Q^2/(x_B s)$, $s = 4E_eE_p$, 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 distributions (DPDFs) $a^D(x_{I\!P},\beta,Q^2) = q^D$ or g^D

Collinear factorisation in DDIS

$$\frac{\mathrm{d}\sigma^{\gamma^* p}}{\mathrm{d}x_{I\!P}} = \sum_{a=q,g} \int_0^1 \mathrm{d}\beta' \, a^D(x_{I\!P}, \beta', Q^2) \, \hat{\sigma}^{\gamma^* a}$$

- $a^D(x_{I\!P}, \beta', Q^2)$ satisfy DGLAP evolution in Q^2
- $\hat{\sigma}^{\gamma^* a}$ **same** as in inclusive DIS
- Proven to hold for all diffractive DIS processes (Collins)
- Can extend to hadron-hadron collisions, but need rapidity gap 'survival probability' due to multi-Pomeron exchange (Kaidalov, Khoze, Martin, Ryskin)

‘Traditional’ extraction of DPDFs

- Assume Regge factorisation:

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

- Pomeron flux factor from Regge phenomenology:

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

  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)
  $\Rightarrow$ continuous number of components of size $1/\mu$:

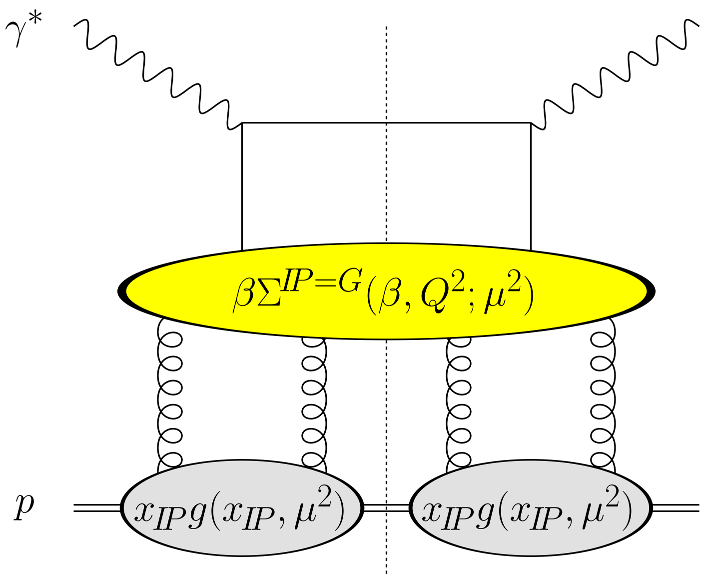
$$F_{2,P}^{D(3)}(x_{I\!P},\beta,Q^2) = \int_{Q_0^2}^{Q^2} \mathrm{d}\mu^2\; f_{I\!P}(x_{I\!P};\mu^2)\; F_2^{I\!P}(\beta,Q^2;\mu^2)$$

- 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

New perturbative QCD approach



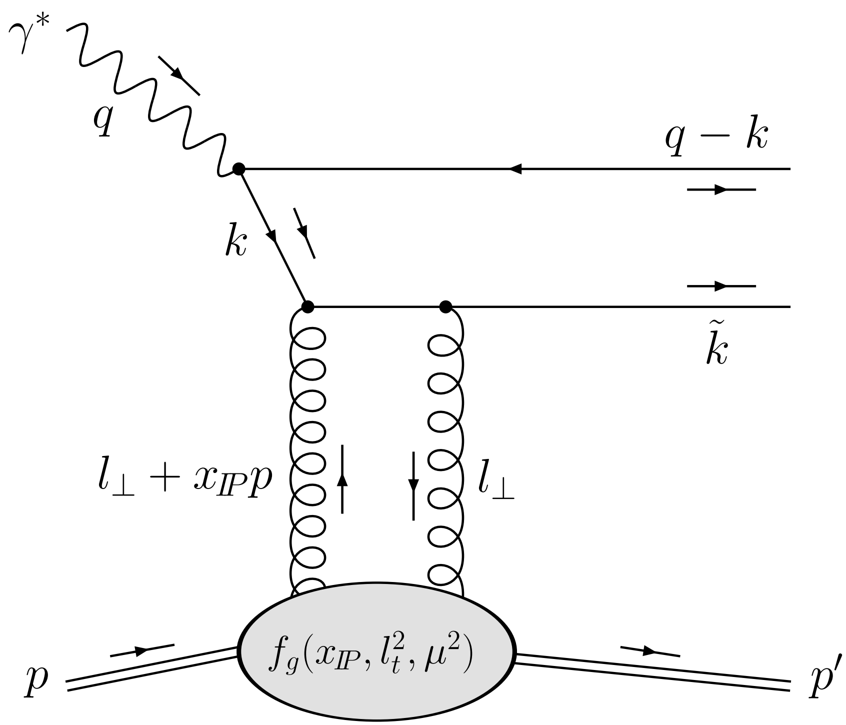
- $F_2^{I\!P}(\beta,Q^2;\mu^2)$ calculated from quark singlet $\Sigma^{I\!P}(\beta,Q^2;\mu^2)$ and gluon $g^{I\!P}(\beta,Q^2;\mu^2)$ DGLAP-evolved from an input scale μ^2 up to Q^2
- Get input Pomeron PDFs $\Sigma^{I\!P}(\beta,\mu^2;\mu^2)$ and $g^{I\!P}(\beta,\mu^2;\mu^2)$ from leading-order Feynman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

$$\sigma_{T,L}^{\gamma^* p} \sim \int \mathrm{d}\alpha \int \mathrm{d}^2\boldsymbol{k_t} \left|\Psi_{T,L}(\alpha,\boldsymbol{k_t})\right|^2 \; \hat{\sigma}^2$$

Two-gluon Pomeron

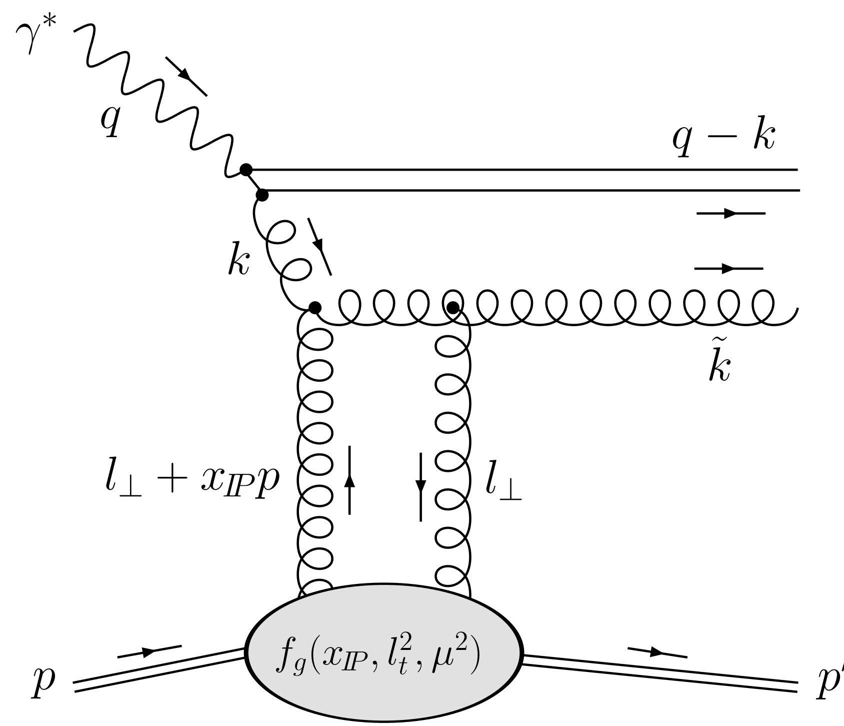
- Work in strongly-ordered limit: $l_t \ll k_t \ll Q$

Quark dipole



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

Effective gluon dipole



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

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

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

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

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

- Twist-four contribution:

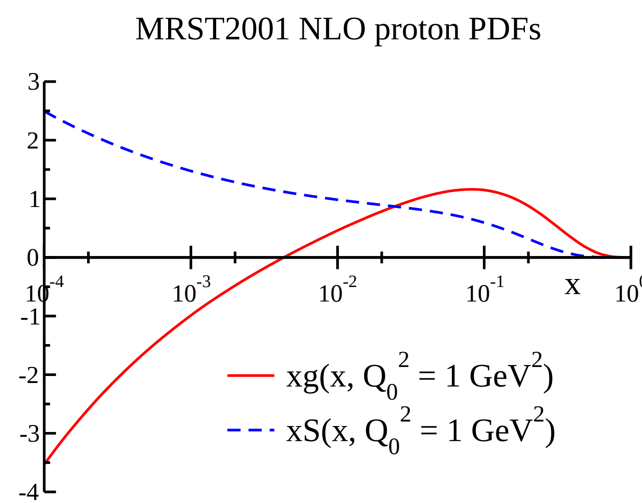
$$F_{L,P}^{D(3)} = \left(\int_{Q_0^2}^{Q^2} \mathrm{d}\mu^2\, \frac{\mu^2}{Q^2}\, f_{I\!P=G}(x_{I\!P}; \mu^2) \right)\, c_{L/G}\, \beta^3\, (2\beta - 1)^2$$

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

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

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 $x_{I\!P}\, g(x_{I\!P}, \mu^2) \sim x_{I\!P}^{1-\alpha_{I\!P}(0)}$
  with $\alpha_{I\!P}(0) > 1.08$
- But . . .



Solutions:

1. Parameterise with simplified form: $x_{I\!P}\, g(x_{I\!P}, \mu^2) \propto x_{I\!P}^{-\lambda}$
2. Introduce Pomeron composed of two sea quarks in a colour singlet:

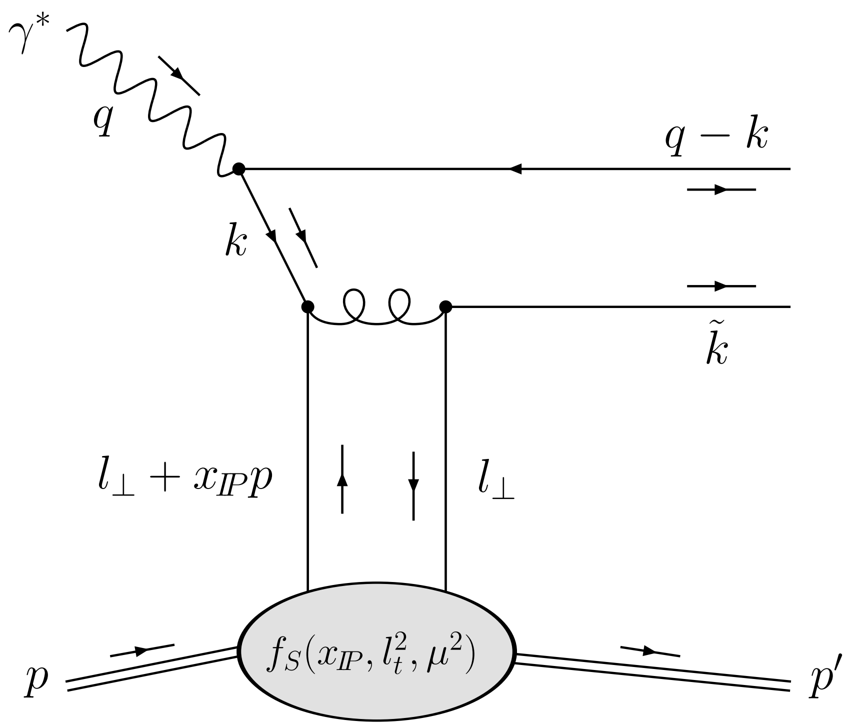
$$f_{I\!P=S}(x_{I\!P}; \mu^2) = \frac{1}{x_{I\!P}} \left[\frac{\alpha_S(\mu^2)}{\mu^2}\, x_{I\!P}\, S(x_{I\!P}, \mu^2) \right]^2$$

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

Two-quark Pomeron

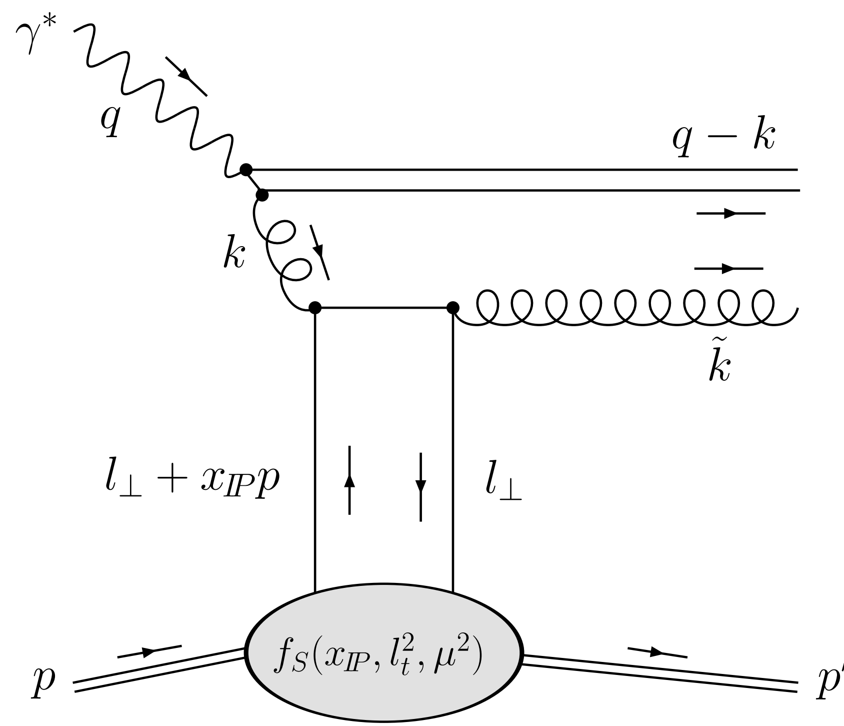
- Work in strongly-ordered limit: $l_t \ll k_t \ll Q$

Quark dipole



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

Effective gluon dipole



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

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

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

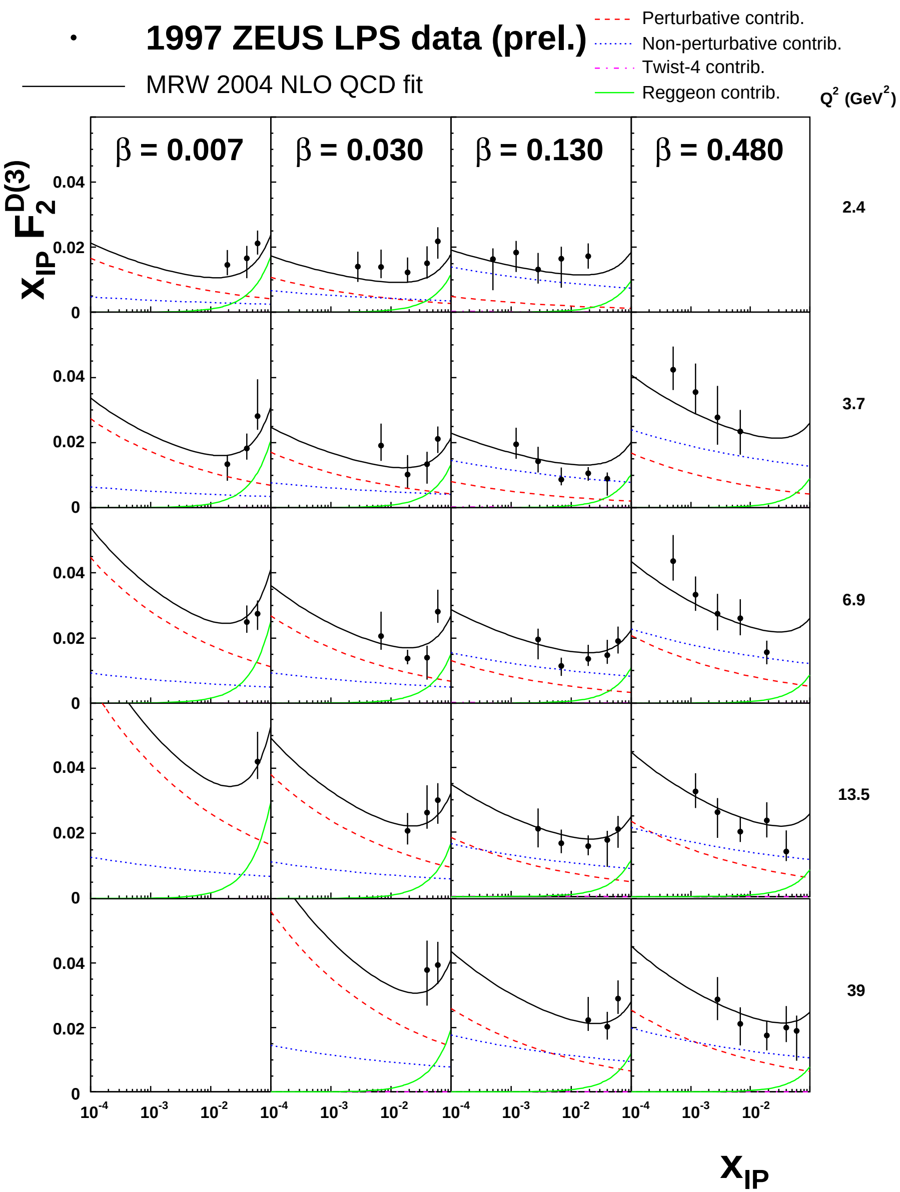
- Only free parameters are normalisation of each contribution to $F_2^{D(3)}$ (effective K-factors): ($Q_0 = 1$ GeV)

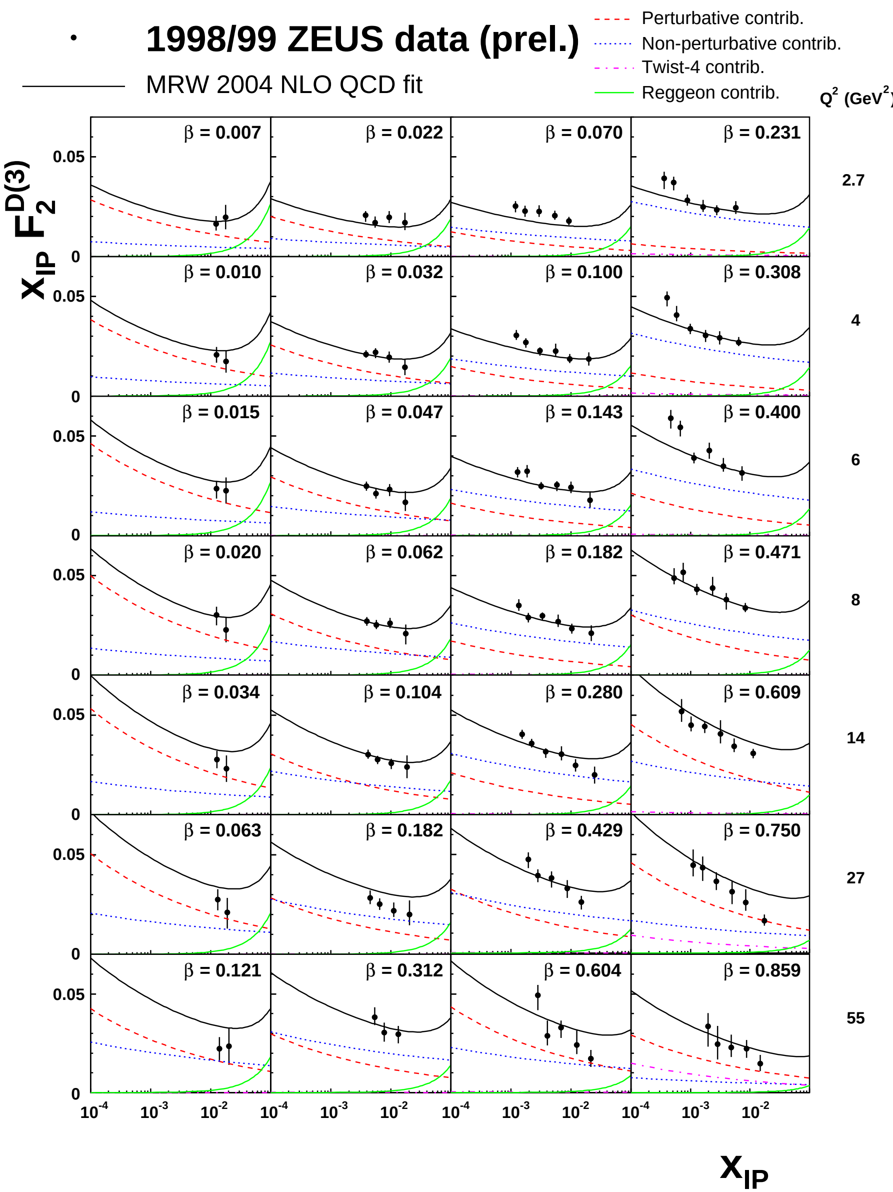
$$c_{q/G},\ c_{g/G},\ c_{L/G},\ (c_{q/S},\ c_{g/S},\ c_{L/S},)\ c_{q/NP},\ c_{I\!R}$$

	$x_{I\!P}\, g = x_{I\!P}^{-\lambda}$ $(x_{I\!P} S = 0)$		$x_{I\!P}\, g,\ x_{I\!P} S =$ MRST
Data sets fitted	λ	$\chi^2/\mathrm{d.o.f.}$	$\chi^2/\mathrm{d.o.f.}$
ZEUS	0.25	0.79	0.95
H1	0.13	1.08	0.71
ZEUS + H1	0.18	1.11	1.16

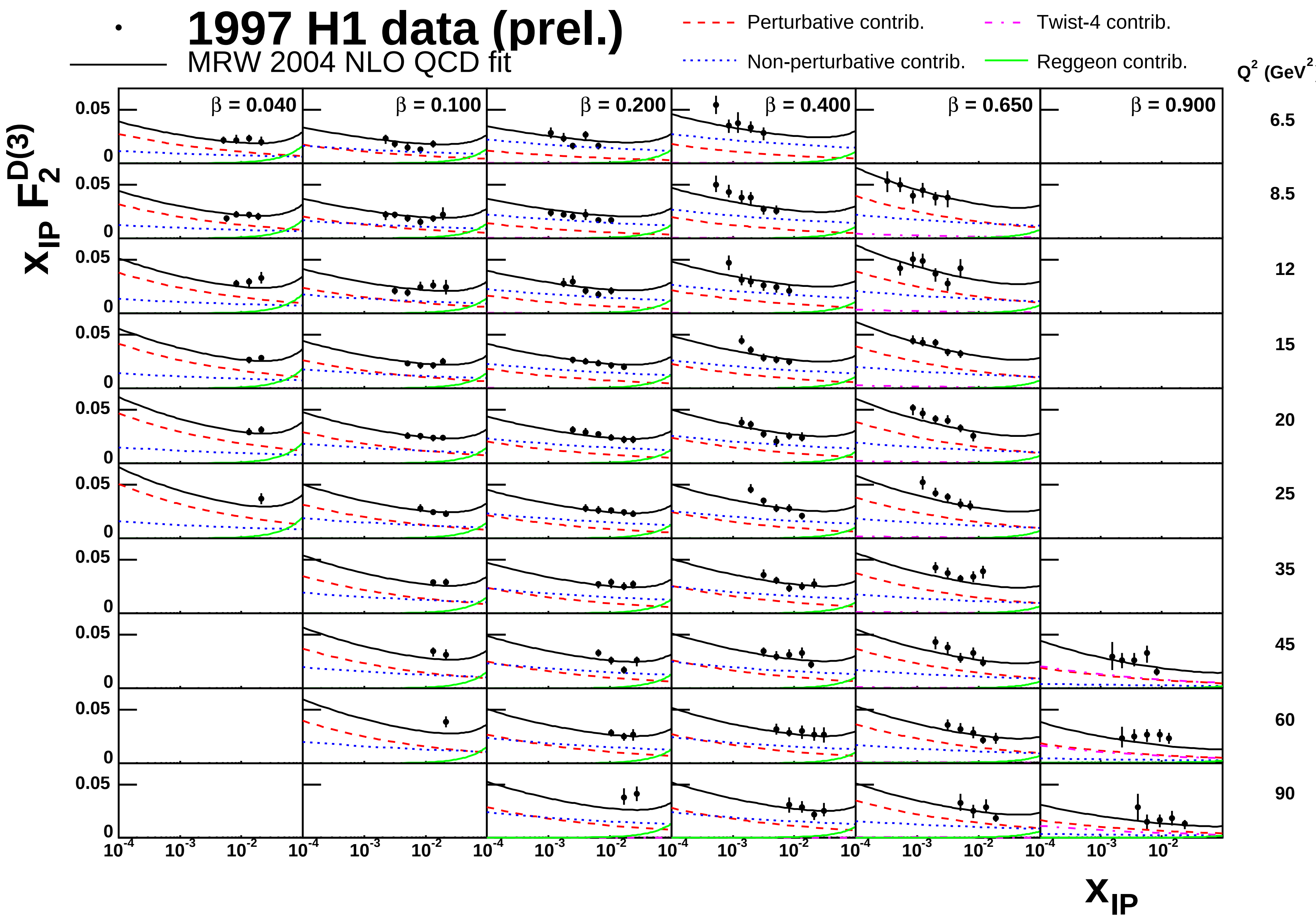
[a] Cuts: $M_X > 2$ GeV, $y < 0.45$

Fit to ZEUS+H1 with $x_{I\!P}g = x_{I\!P}^{-\lambda}$

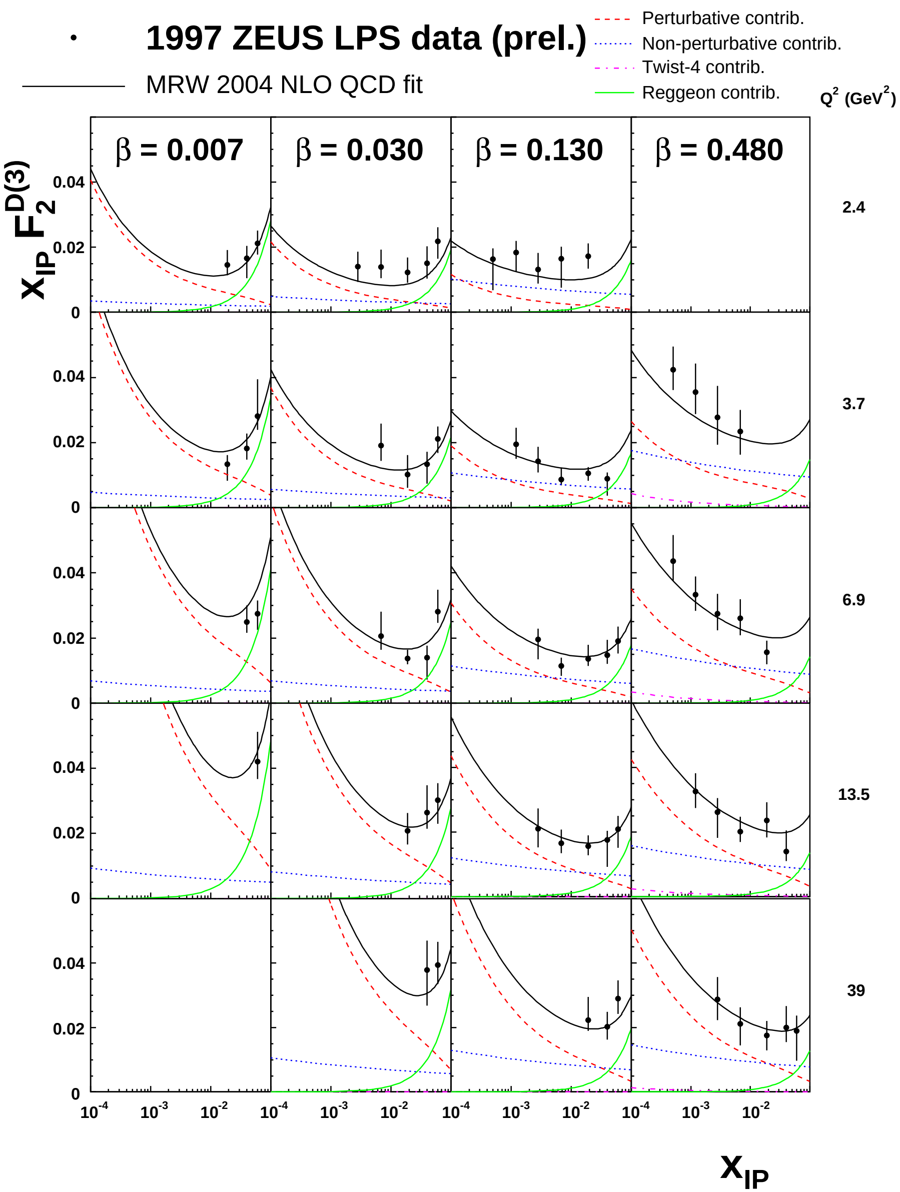


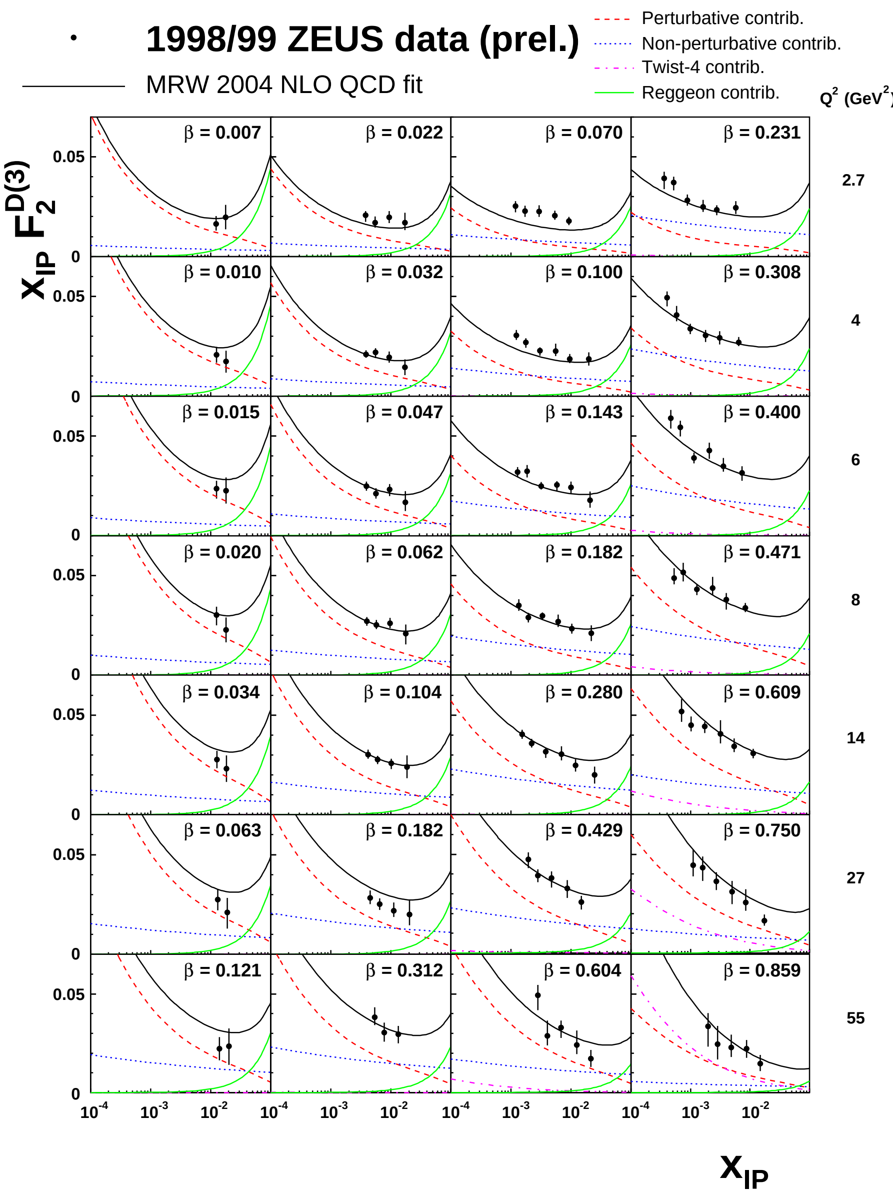


Fit to ZEUS+H1 with $x_{I\!P} g = x_{I\!P}^{-\lambda}$

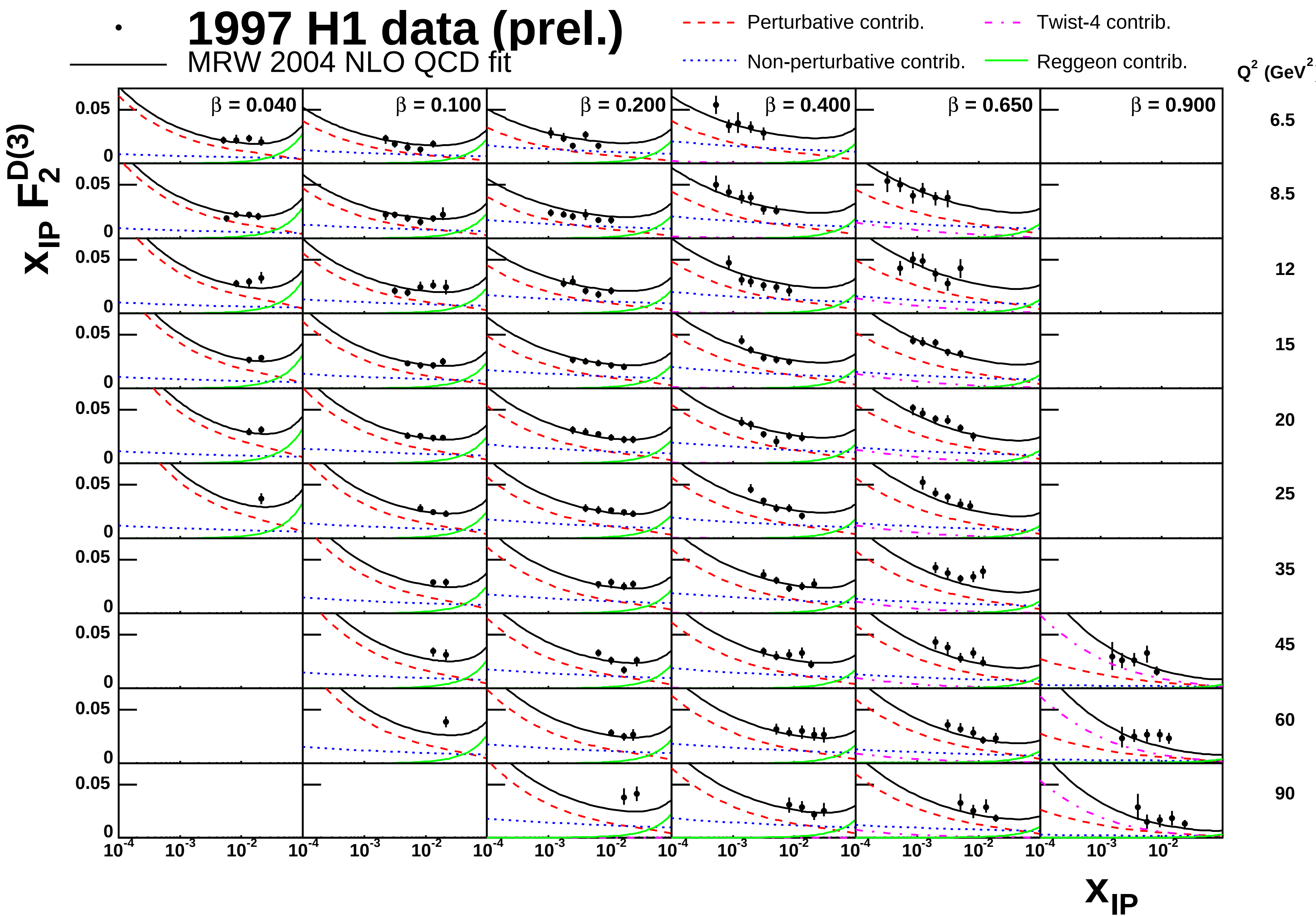


Fit to ZEUS+H1 with $x_{I\!P}g$, $x_{I\!P}S$ = MRST

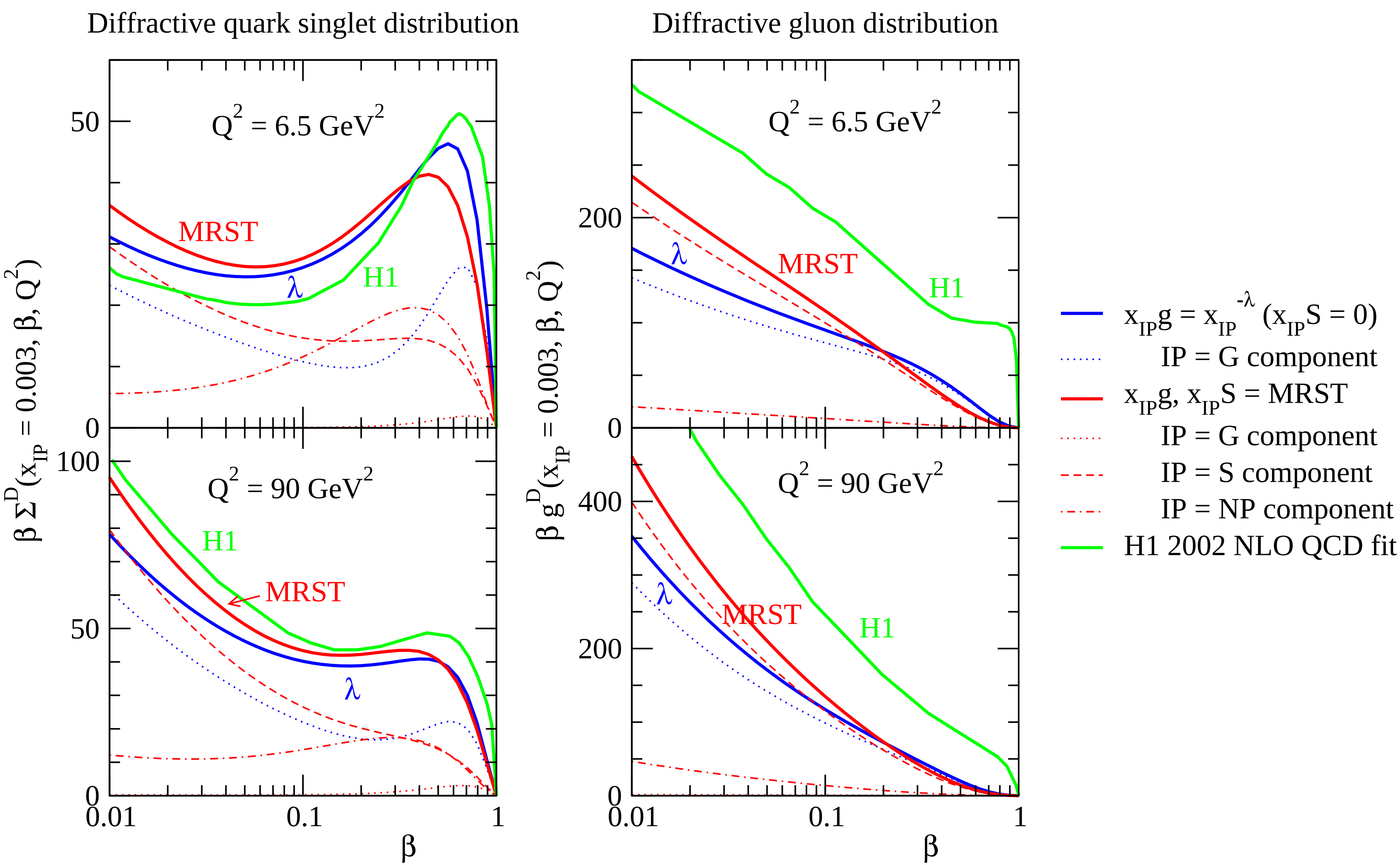




Fit to ZEUS+H1 with $x_{I\!P} g$, $x_{I\!P} S$ = MRST



DPDFs compared to H1 fit

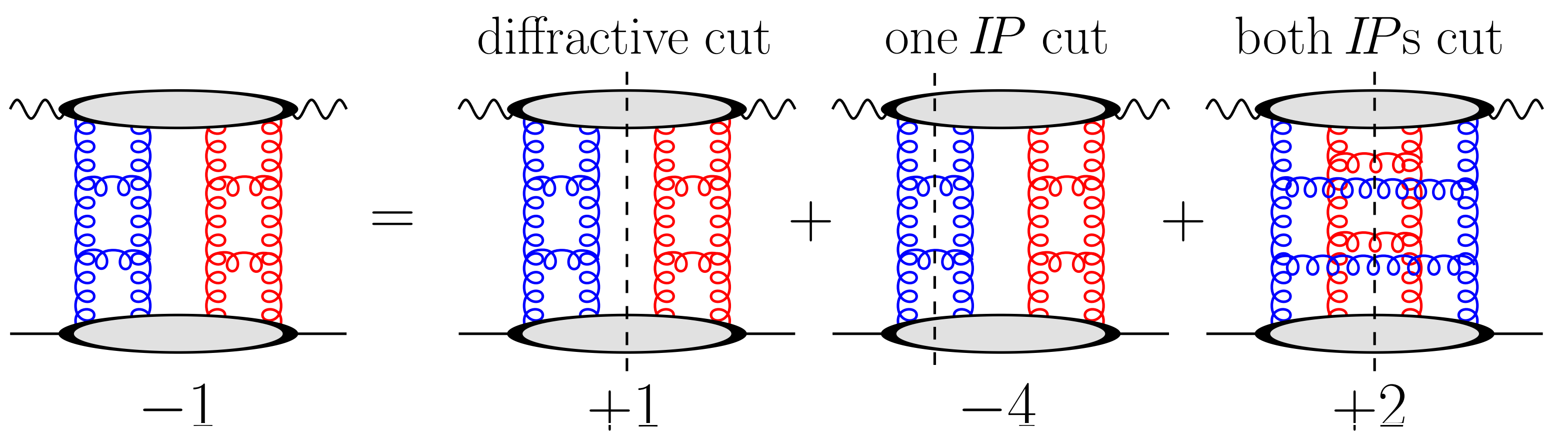


- H1 use a smaller α_S and have no twist-four contribution

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:

$\Delta F_2^{\mathrm{abs}} =$



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

[a] **A**bramovsky, **G**ribov, **K**ancheli ($\longrightarrow$ QCD: Bartels, Ryskin)

Absorptive corrections to F_2

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

$$\Delta F_2^{\rm abs}(x_B,Q^2) \simeq -\int_{x_B}^{0.1} {\rm d}x_{I\!P}\ \left[F_{2,P}^{D(3)}(x_{I\!P},\beta,Q^2) + F_{L,P}^{D(3)}(x_{I\!P},\beta,Q^2)\right]$$

- Only $\mu > Q_0$ contribution of $F_2^{D(3)}$ in $\Delta F_2^{\rm abs}$; $\mu < Q_0$ contribution already included in input parameterisations to F_2 fit
- Reminder: $F_{2,P}^{D(3)}$ = leading-twist, $F_{L,P}^{D(3)}$ = twist-four
- To fit F_2 using the DGLAP equation, first need to 'correct' the data for absorptive corrections:

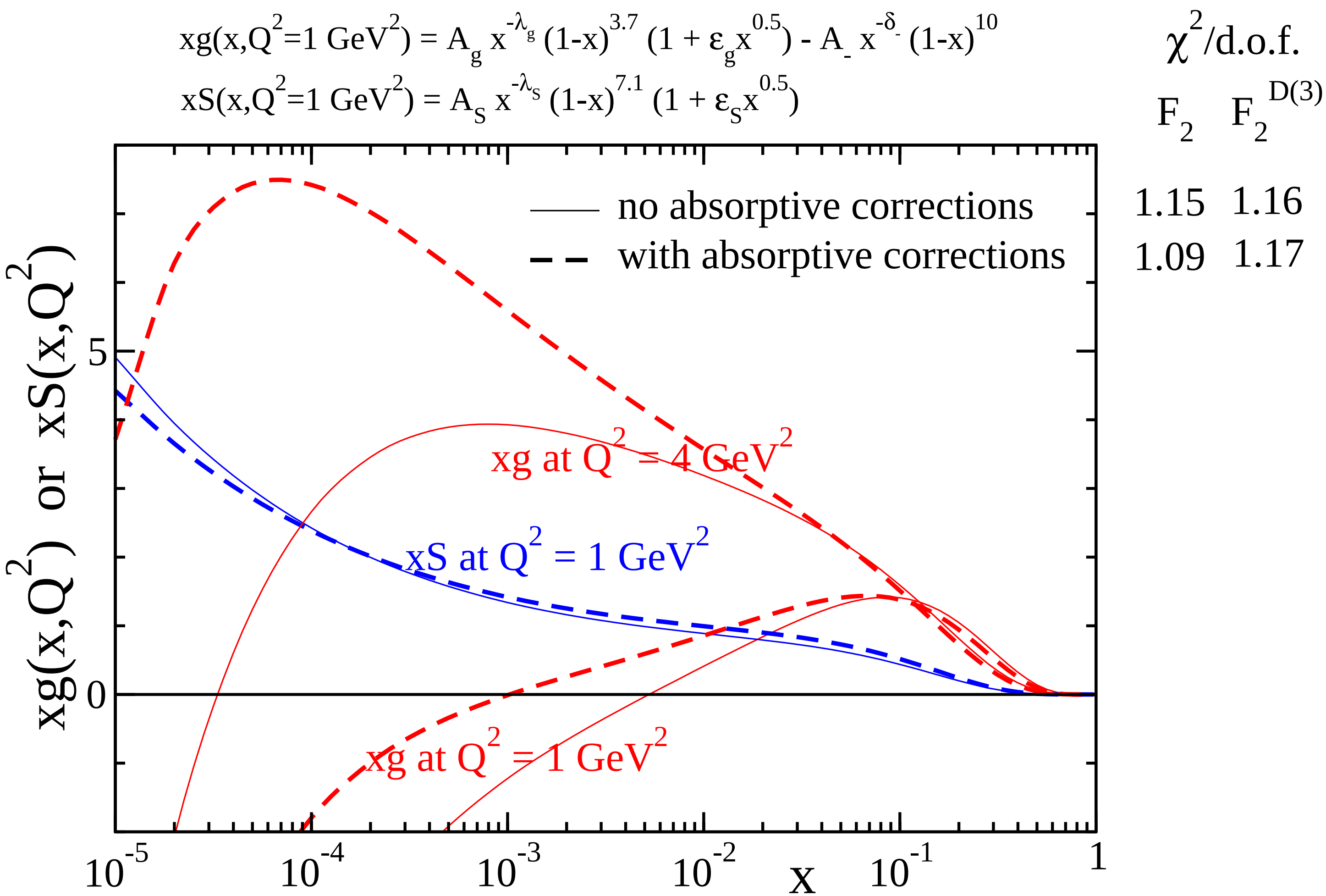
$$F_2^{\rm DGLAP} = F_2^{\rm data} - \Delta F_2^{\rm abs} = F_2^{\rm data} + \left|\Delta F_2^{\rm abs}\right|$$

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 $x_{I\!P}g$ and $x_{I\!P}S$ 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 (normalised to $2\times$ ZEUS LPS data: account for proton dissociation with $M_Y \lesssim 5$ GeV)
  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 $x = 0.2$

Gluon and sea quark PDFs



- Take +ve input gluon parameterisation ($A_- = 0$):
  - no absorptive corrections $\chi^2/\mathrm{d.o.f.} = 1.57$
  - with absorptive corrections $\chi^2/\mathrm{d.o.f.} = 1.10$

Multi-$I\!P$ exchange (approximately)

- s-channel unitarity relation:

$$2\,\mathrm{Im}\,T_{\mathrm{el}}(s,b_t) = |T_{\mathrm{el}}(s,b_t)|^2 + G_{\mathrm{inel}}(s,b_t)$$

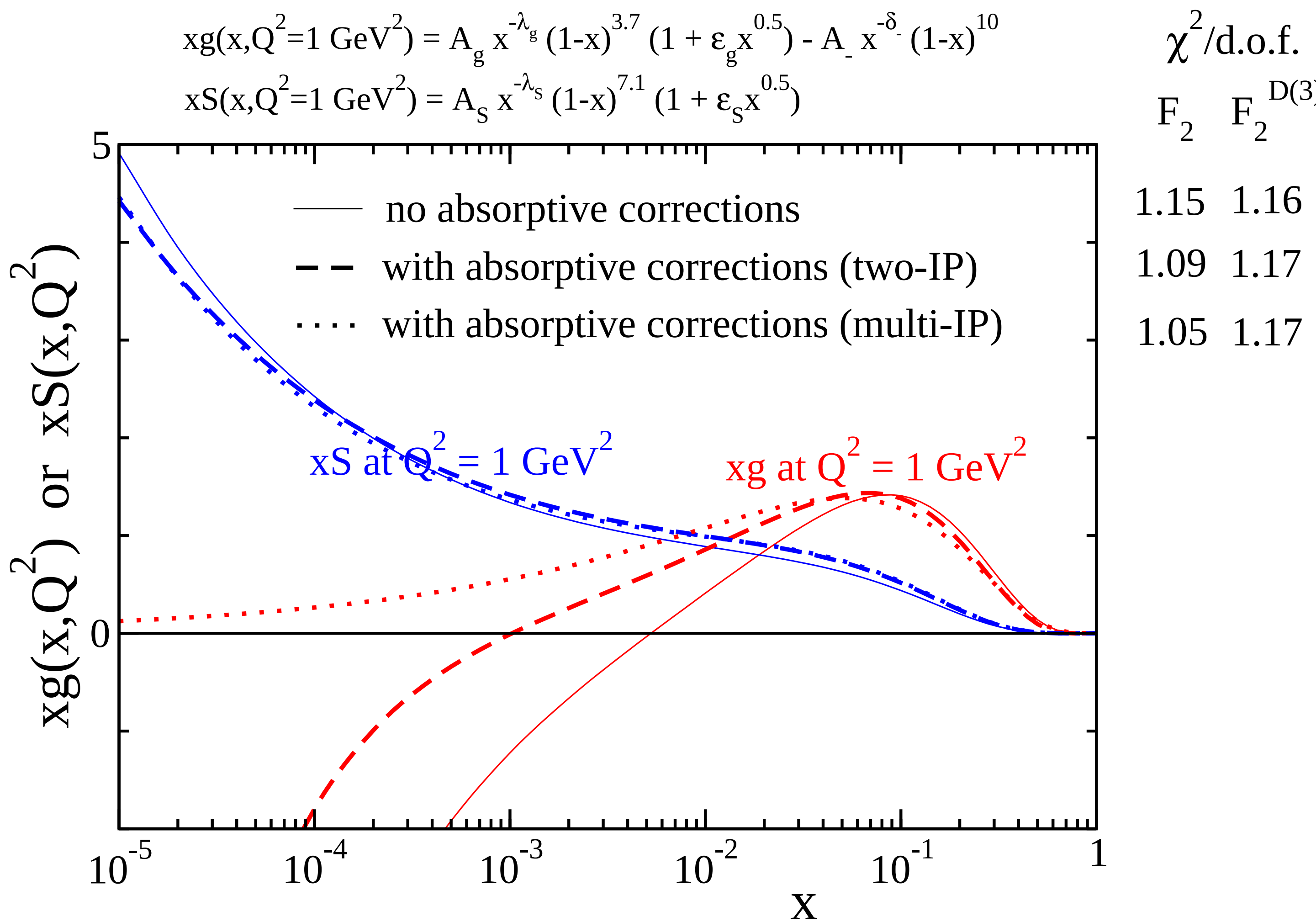
- Assume $\mathrm{Re}\,T_{\mathrm{el}} \ll \mathrm{Im}\,T_{\mathrm{el}}$, then $T_{\mathrm{el}} = i(1-\exp(-\Omega/2))$ where $\Omega(s,b_t)$ is the opacity (optical density) or eikonal
- Let $F_2^D \equiv \left|\Delta F_2^{\mathrm{abs}}\right|$ ($\mu > Q_0$), then, for some average b_t:

$$\boxed{\frac{F_2^D}{F_2^{\mathrm{data}}} = \frac{|T_{\mathrm{el}}|^2}{2\mathrm{Im}\,T_{\mathrm{el}}} = \frac{1}{2}(1-\exp(-\Omega/2))} \quad \Rightarrow \text{Solve for } \Omega/2$$

- To fit F_2 with DGLAP equation, need one-$I\!P$ exchange:

$$\boxed{F_2^{\mathrm{DGLAP}} = F_2^{\mathrm{data}}\,\frac{\Omega/2}{(1-\exp(-\Omega/2))}}$$

Gluon and sea quark PDFs



- Multi-Pomeron exchange $\Longrightarrow A_- \to 0$

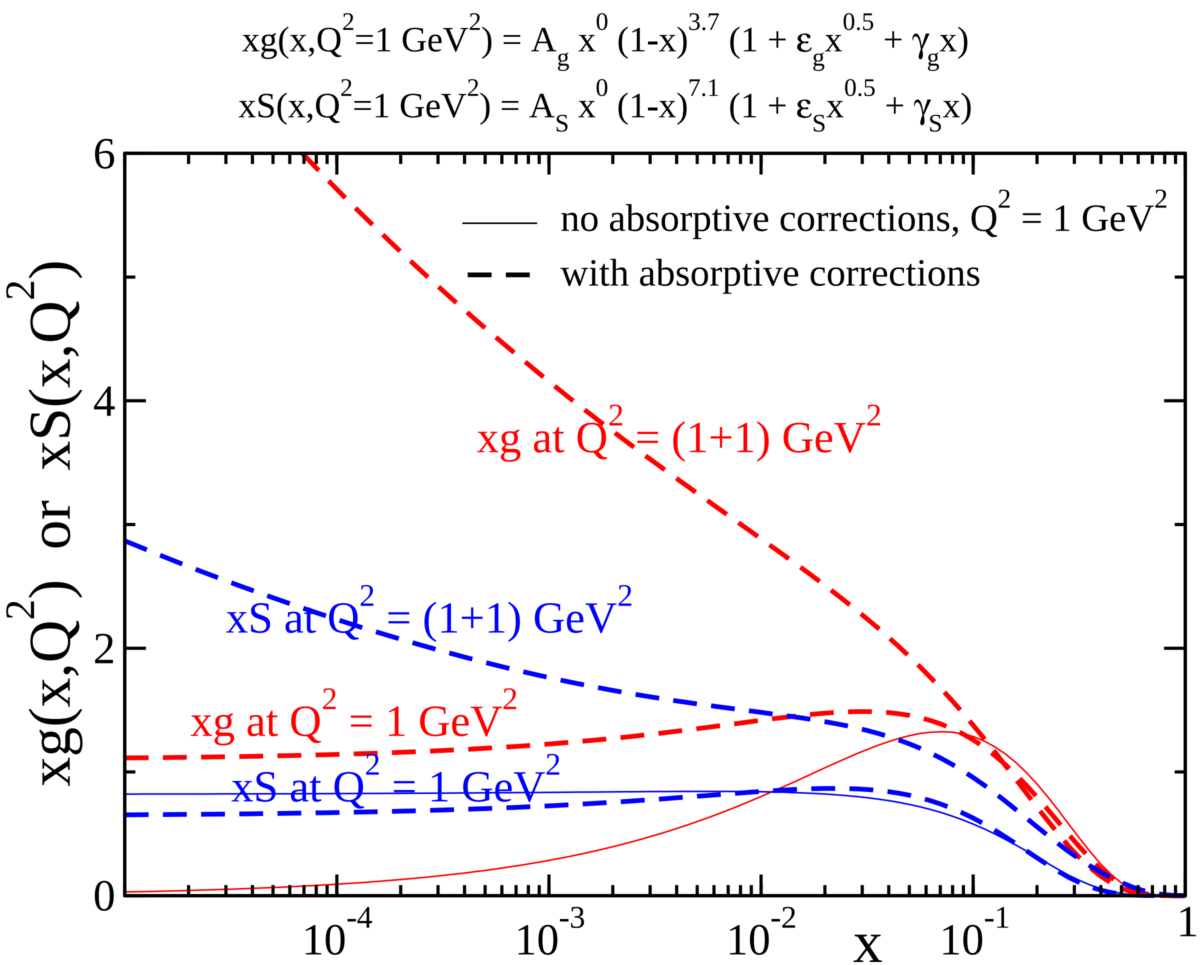
‘Pomeron-like’ xS but ‘valence-like’ xg ?

- Good news: Absorptive corrections remove the need for a negative input gluon distribution
- 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	1.12
1.22	1.11

- 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 leading-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 ?