Diffractive parton distributions: the demise of Regge factorisation

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Introduction

H1 extraction of Diffractive Parton Distribution Functions (DPDFs) from Diffractive Deep-Inelastic Scattering (DDIS) data uses **two** levels of factorisation:

Collinear factorisation is proven to hold asymptotically [Collins,1998]

- . . . But needs modification in the sub-asymptotic HERA regime

Regge factorisation is used in 'resolved Pomeron' model [Ingelman-Schlein,1985]

- . . . But should only be used for the 'soft Pomeron' contribution to DDIS, not to describe the **whole** diffractive structure function. Contribution from 'QCD Pomeron' is **calculable** using perturbative QCD

H1 2002 (prel.) QCD fit

Reminder of H1 2002 NLO DGLAP QCD Fit

QCD Fit Technique:

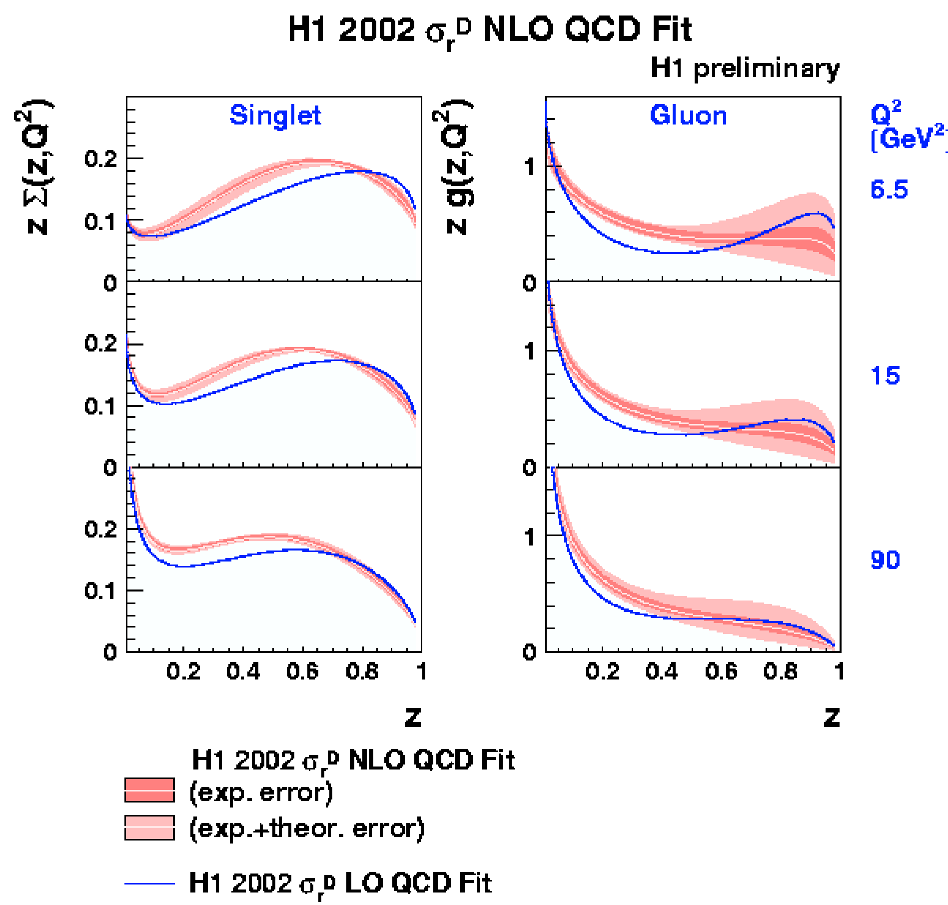
- factorize $f(x_{I\!P})f(z,Q^2)$
- Singlet Σ and gluon g parameterized at $Q_0^2 = 3\ \mathrm{GeV}^2$
- NLO DGLAP evolution
- Fit data for $Q^2 > 6.5\ \mathrm{GeV}^2$, $M_X > 2\ \mathrm{GeV}$

PDF's of diffractive exchange:

- Extending to large fractional momenta z
- Gluon dominated
- Σ well constrained

$$\chi^2/ndf = 308/306$$
$$\alpha_{I\!P}(0) = 1.173\ (\mathrm{Reggefit})$$

NB: $\Lambda_{QCD} = 200 \pm 30$ MeV variation included in outer error band



H1 α_S fixed by $\Lambda_{\rm QCD} = 200 \pm 30$ MeV

"The strong coupling constant α_S was fixed by setting $\Lambda_{\rm QCD} = 0.2$ GeV for 4 flavours, using the 1(2) loop expression for α_S at LO and NLO respectively" [H1prelim-03-015]

- **Tip:** always specify $\alpha_S(M_Z)$ instead of $\Lambda_{\rm QCD}$

  At NLO, relationship between α_S and $\Lambda_{\rm QCD}$ is not unique. QCDNUM, CTEQ, and MRST codes all use different definitions. Difference in α_S is tiny **if** same $\alpha_S(M_Z)$ is used [hep-ph/0502080, Appendix A]

- What $\alpha_S(M_Z)$ corresponds to $\Lambda_{\rm QCD} = 200$ MeV?

	$\alpha_S(M_Z)$
LO	0.1282
NLO (QCDNUM)	0.1085
NLO (CTEQ)	0.1091

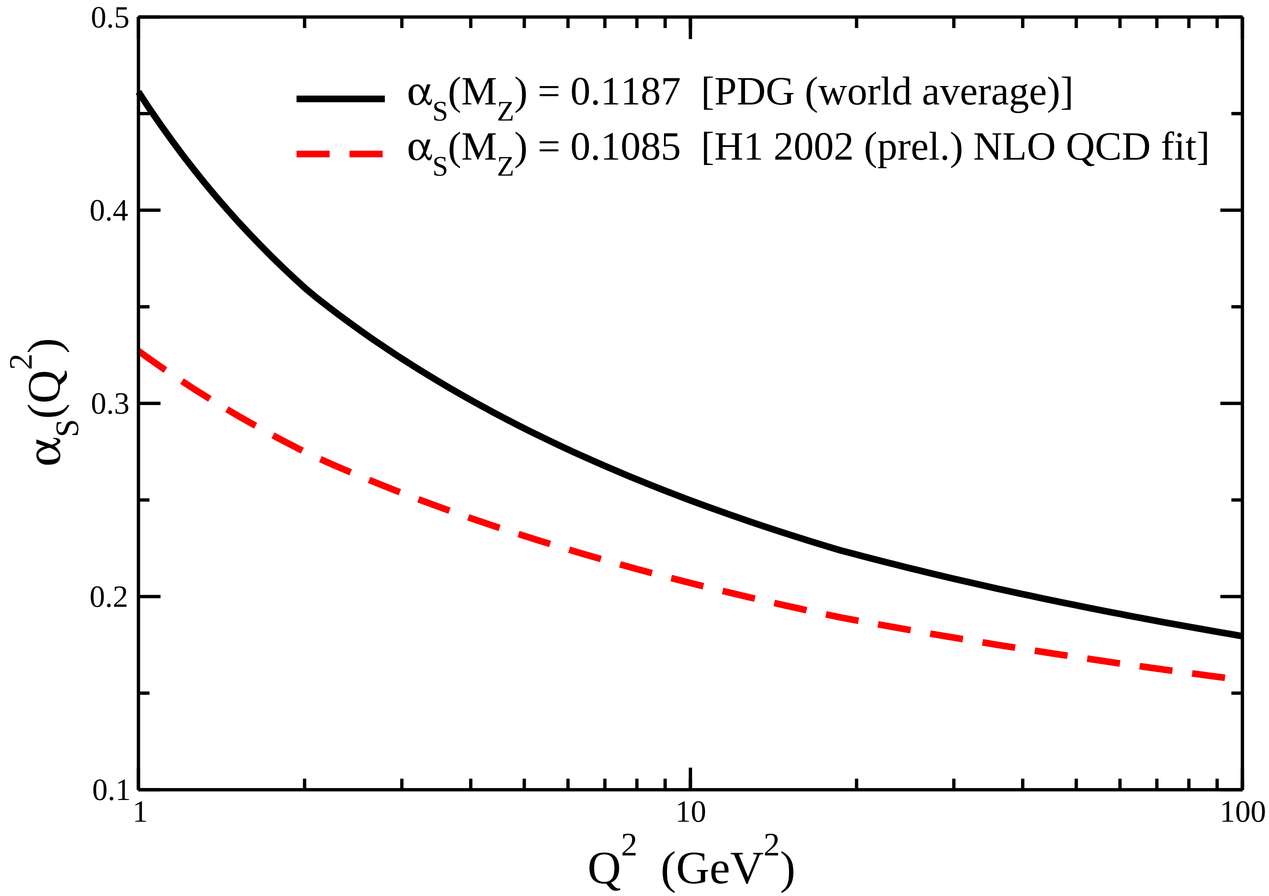
($m_c = 1.43$ GeV, $m_b = 4.3$ GeV)

- cf. world average [PDG] $\alpha_S(M_Z) = 0.1187 \pm 0.0020$

	$\Lambda_{\rm QCD}$
LO	125 MeV
NLO (QCDNUM)	351 MeV
NLO (CTEQ)	336 MeV

200 ± 30 MeV **underestimates error**

World average vs. H1 α_S at NLO

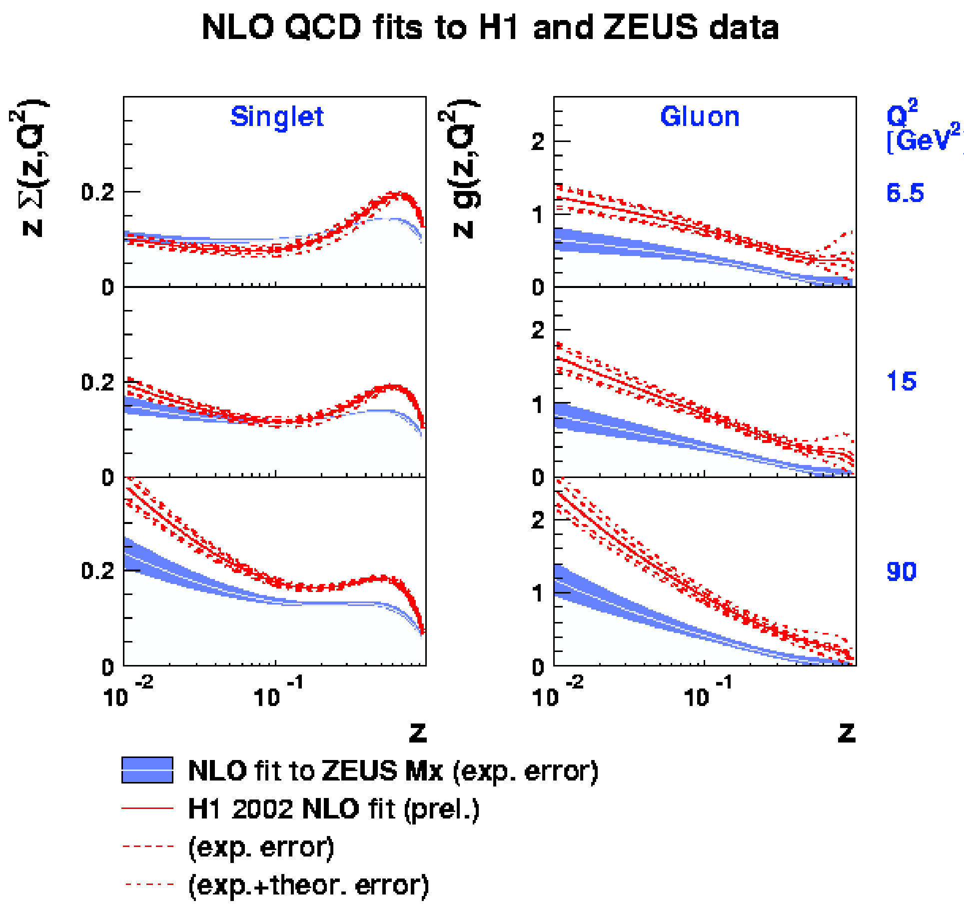


$$\partial F_2^{\mathrm{D}(3)}/\partial \ln Q^2 \sim \alpha_S \, g^{\mathrm{D}}$$

$\Longrightarrow$ low α_S means H1 2002 (prel.) NLO g^{D} is artificially large

ZEUS M_X data give smaller g^{D}

NLO fit to ZEUS Mx data



Observations:

- Singlet similar at low Q^2, evolving differenly to higher Q^2
- Gluon factor ~ 2 smaller than H1 gluon

Reminder that data comparisons revealed differences

- at low M_X (high β)
  Most of those points are not included in the fit
- in the Q^2 dependences
  Different Q^2 evolution means different gluon

$\longrightarrow$ Observed differences in the data explain the differences in the extracted pdfs

Experimental tests of factorisation

- Suppose that the ‘Regge factorisation’ approach **is** the correct way to analyse DDIS data [a]
- **Premature** to make claims about experimental tests of factorisation using final state observables if **only** the H1 2002 NLO (prel.) DPDFs are ever used:
  - World average α_S would give much smaller g^{D}
  - Fitting ZEUS M_X data instead of H1 data would give much smaller g^{D}
- In particular, H1 and ZEUS claim that both resolved and direct photoproduction are suppressed by a factor 0.5
- Are these conclusions changed if world average α_S is used, or DPDFs from fit to ZEUS M_X data?

[a] It’s not! (See later)

Collinear factorisation in DDIS

$$F_2^{\mathrm{D}(3)} = \sum_{a=q,g} C_{2,a} \otimes a^{\mathrm{D}} + \mathcal{O}(1/Q), \qquad (1)$$

where $C_{2,a}$ is the **same** as in inclusive DIS and where $a^{\mathrm{D}} = \beta\Sigma^{\mathrm{D}}$ or βg^{D} satisfy DGLAP evolution in Q^2:

$$\frac{\partial a^{\mathrm{D}}}{\partial \ln Q^2} = \frac{\alpha_S}{2\pi} \sum_{a'=q,g} P_{aa'} \otimes a'^{\mathrm{D}} \qquad (2)$$

> “The factorisation theorem applies when Q is made large while x_B, $x_{I\!P}$, and t are held fixed.” [Collins,1998]

Says **nothing** about the mechanism for diffraction: what **is** the colourless exchange (‘Pomeron’) which **causes** the large rapidity gap. Assuming a ‘QCD Pomeron’ we need to modify both (1) and (2)

H1 extraction of DPDFs

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

$$\boxed{a^{\mathrm{D}}(x_{I\!P}, \beta, Q^2) = f_{I\!P}(x_{I\!P})\, a^{I\!P}(\beta, Q^2)}$$

- Pomeron flux factor from Regge phenomenology:

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

"Regge factorisation relates the power of $x_{I\!P}$ measured in DDIS to the power of s measured in hadron-hadron elastic scattering." [Collins,1998]

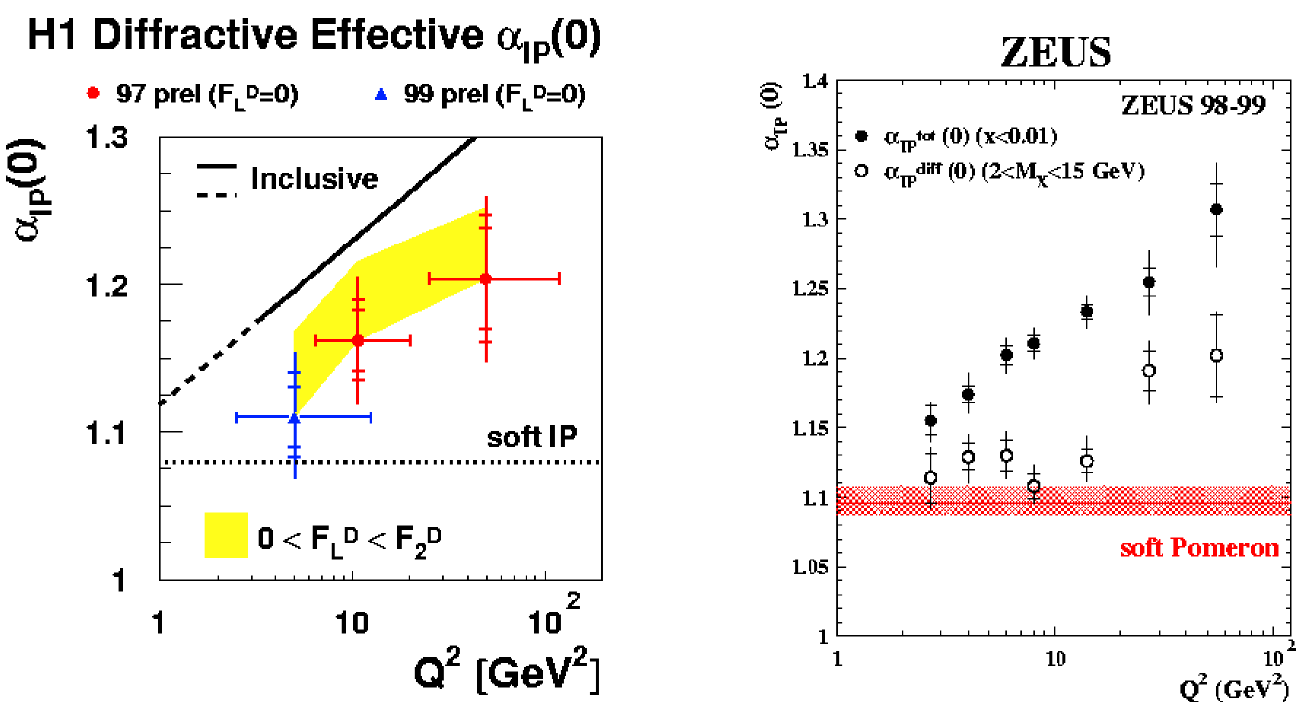
Fit to H1 $F_2^{\mathrm{D}(3)}$ data gives $\alpha_{I\!P}(0) = 1.17 > 1.08$ ('soft Pomeron' [Donnachie-Landshoff,1992]) $\Longrightarrow$ Regge factorisation **invalid**

- H1 and ZEUS definition of 'Regge factorisation' seems to be that the $x_{I\!P}$ dependence of $F_2^{\mathrm{D}(3)}$ factorises, with **any** $\alpha_{I\!P}(0)$, from the β and Q^2 dependence: also **invalid** $\rightarrow$

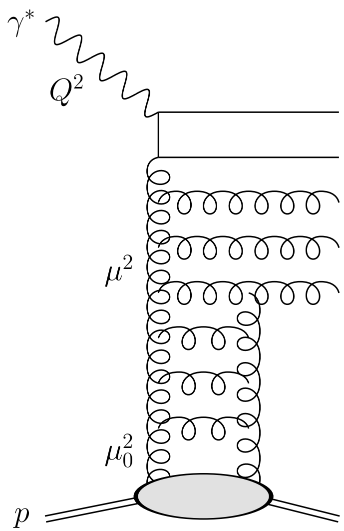
Diffractive $\alpha_{I\!P}(0)$ depends on Q^2

1.08 (soft Pomeron) $\lesssim \alpha_{I\!P}(0) \lesssim 1.3$ (QCD Pomeron)

H1 and ZEUS Pomeron Intercepts



The QCD Pomeron is a parton ladder

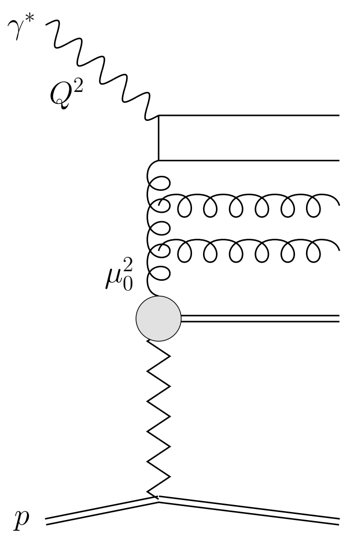


New feature: integral over scale μ^2 (starting scale for DGLAP evolution of Pomeron PDFs)

$$F_{2,\mathrm{pert.}}^{\mathrm{D}(3)} = \int_{\mu_0^2}^{Q^2} \frac{\mathrm{d}\mu^2}{\mu^2} \, f_{I\!P}(x_{I\!P};\mu^2)\, F_2^{I\!P}(\beta, Q^2; \mu^2)$$

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

(B_D from t-integration, R_g from skewedness)

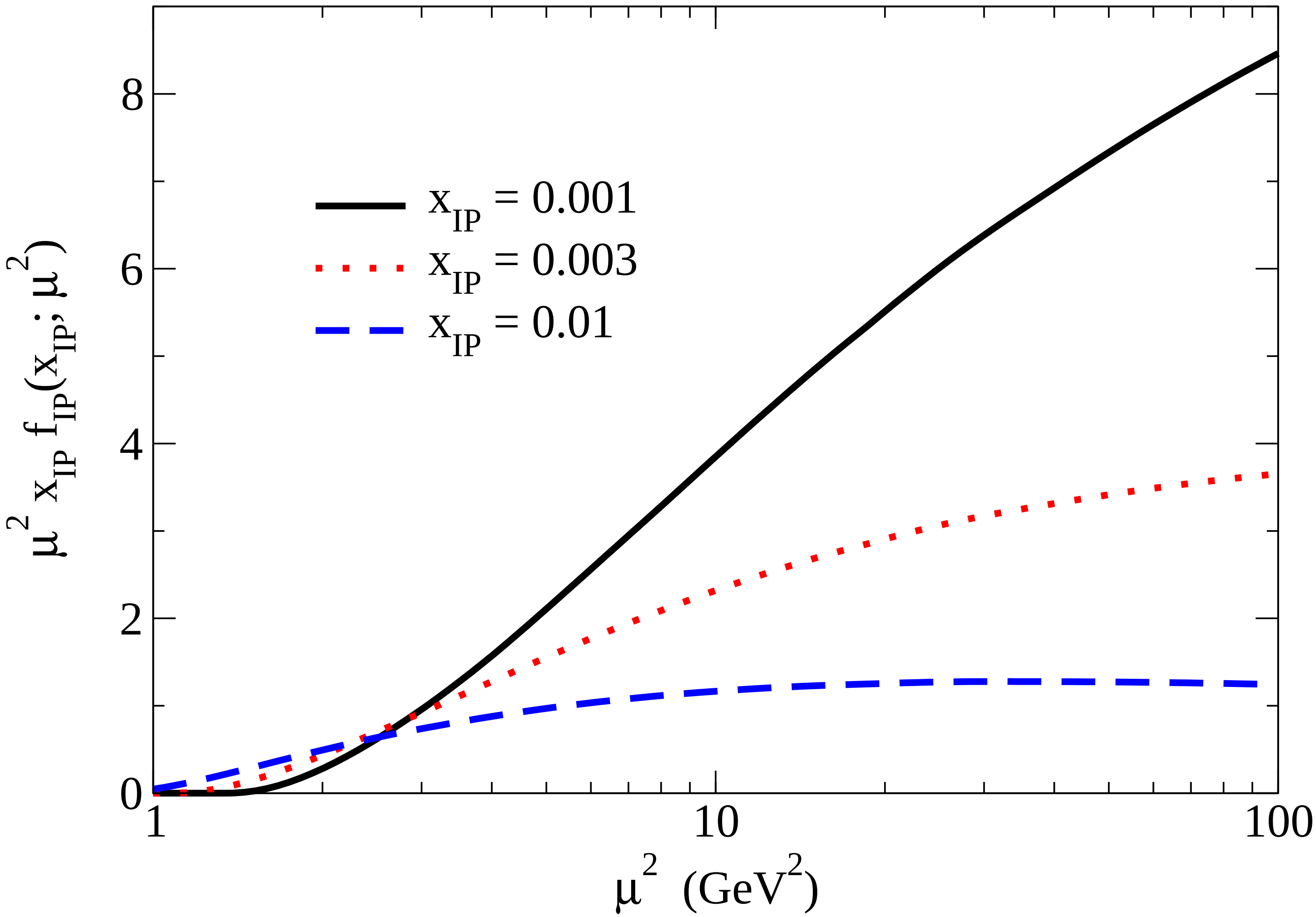


$$F_{2,\mathrm{non-pert.}}^{\mathrm{D}(3)} = f_{I\!P}(x_{I\!P})\, F_2^{I\!P}(\beta, Q^2; \mu_0^2)$$

$f_{I\!P}(x_{I\!P}) =$ same as in H1 fit, **but** with $\alpha_{I\!P}(0) = 1.08$

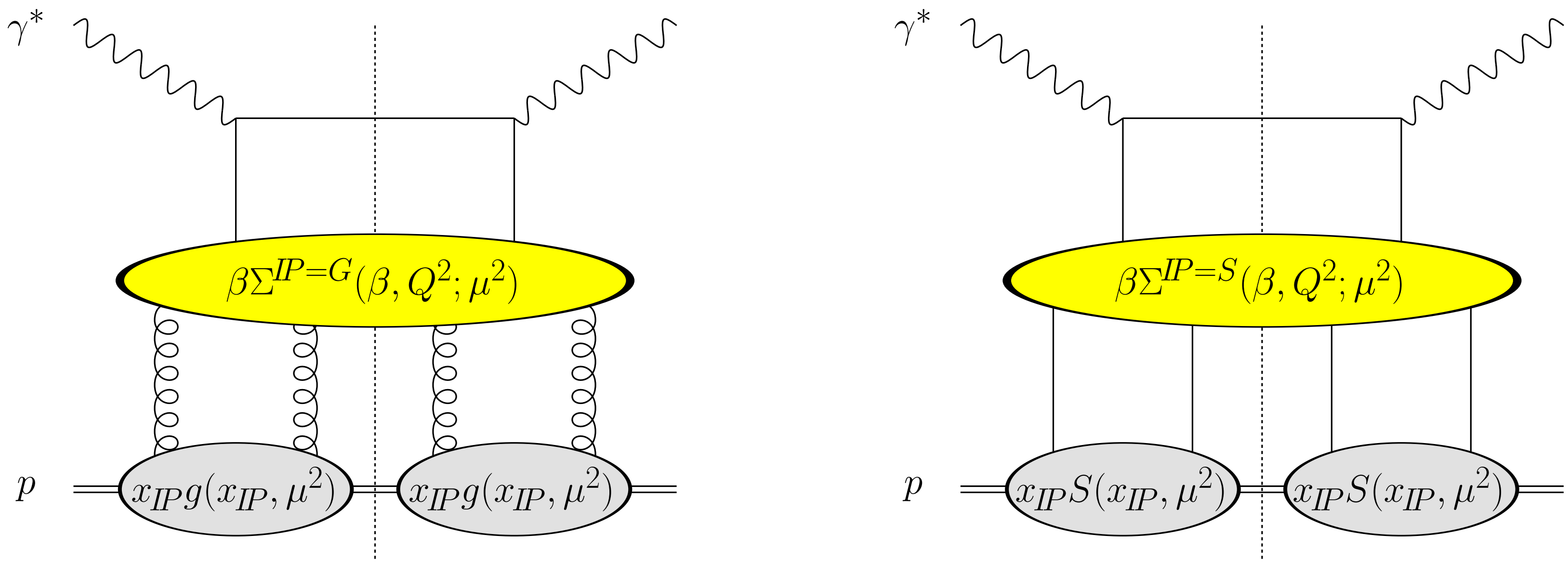
Separation between QCD Pomeron and soft Pomeron provided by scale $\mu_0 \sim 1$ GeV

$f_{I\!P}(x_{I\!P};\mu^2)$ does not behave as $1/\mu^2$



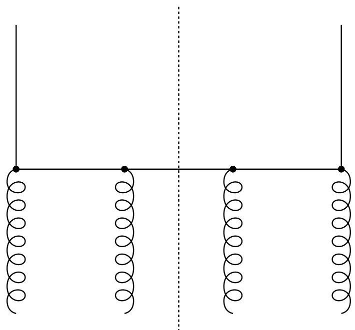
Using MRST2001 NLO gluon distribution (and temporarily setting $R_g^2/B_D = 1$ GeV^2)

Gluonic and sea-quark Pomeron



- Pomeron structure function $F_2^{IP}(\beta, Q^2; \mu^2)$ calculated from quark singlet $\Sigma^{IP}(\beta, Q^2; \mu^2)$ and gluon $g^{IP}(\beta, Q^2; \mu^2)$ DGLAP-evolved from an input scale μ^2 up to Q^2
- Input Pomeron PDFs $\Sigma^{IP}(\beta, \mu^2; \mu^2)$ and $g^{IP}(\beta, \mu^2; \mu^2)$ are Pomeron-to-parton splitting functions [e.g. Wüsthoff,1997]

Pomeron-to-parton splitting functions



- **Notation:** '$I\!P = G$' means gluonic Pomeron, '$I\!P = S$' means sea-quark Pomeron, '$I\!P = GS$' means interference between these
- $K_{a/I\!P}$ parameters account for higher-order corrections to the LO splitting functions. Allow these to go free in fit to data (typically, $K_{a/I\!P} \sim 1$)

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

$$\beta g^{I\!P=G}(\beta,\mu^2;\mu^2) = P_{g,I\!P=G}(\beta) = K_{g/G}\,\frac{9}{16}\,(1+2\beta)^2\,(1-\beta)^2,$$

$$\beta\Sigma^{I\!P=S}(\beta,\mu^2;\mu^2) = P_{q,I\!P=S}(\beta) = K_{q/S}\,\frac{4}{81}\,\beta\,(1-\beta),$$

$$\beta g^{I\!P=S}(\beta,\mu^2;\mu^2) = P_{g,I\!P=S}(\beta) = K_{g/S}\,\frac{1}{9}\,(1-\beta)^2,$$

$$\beta\Sigma^{I\!P=GS}(\beta,\mu^2;\mu^2) = P_{q,I\!P=GS}(\beta) = \sqrt{K_{q/G}K_{q/S}}\,\frac{2}{9}\,\beta^2\,(1-\beta),$$

$$\beta g^{I\!P=GS}(\beta,\mu^2;\mu^2) = P_{g,I\!P=GS}(\beta) = \sqrt{K_{g/G}K_{g/S}}\,\frac{1}{4}\,(1+2\beta)\,(1-\beta)^2$$

Evolve these input Pomeron PDFs from μ^2 up to Q^2 using NLO DGLAP evolution

Inhomogeneous evolution of DPDFs

$$a^{\mathrm{D}}_{\mathrm{pert.}}(x_{I\!P},\beta,Q^2) = \int_{\mu_0^2}^{Q^2} \frac{\mathrm{d}\mu^2}{\mu^2}\, f_{I\!P}(x_{I\!P};\mu^2)\; a^{I\!P}(\beta,Q^2;\mu^2).$$

Differentiate with respect to $\ln Q^2$:

$$\frac{\partial a^{\mathrm{D}}_{\mathrm{pert.}}}{\partial \ln Q^2} = \frac{\alpha_S}{2\pi} \sum_{a'=q,g} P_{aa'} \otimes a'^{\mathrm{D}}_{\mathrm{pert.}} \; + \; \underbrace{f_{I\!P}(x_{I\!P};Q^2)\, P_{aI\!P}(\beta)}_{\text{Extra inhomogeneous term}}$$

Analogous to inhomogeneous evolution of photon PDFs [Witten,1977]

Inhomogeneous evolution of DPDFs is **not a new idea**:

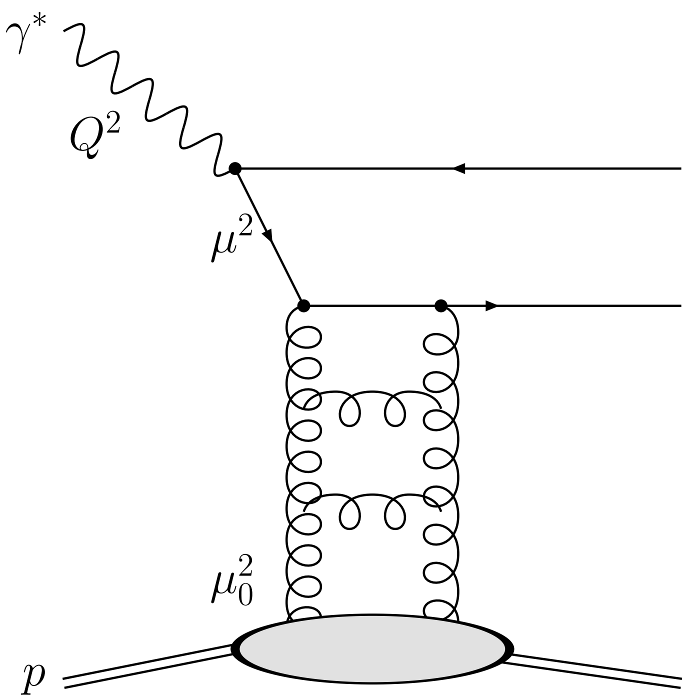
> "We introduce a diffractive dissociation structure function and show that it obeys the DGLAP evolution equation, **but**, with an additional inhomogeneous term." [Levin-Wüsthoff,1994]

Non-factorisable contributions

i.e. contributions to DDIS that **can't** be written as:

$$\sum_{a=q,g} C_{2,a} \otimes a^{\mathrm{D}}$$

QCD Pomeron couples **directly** to $q\bar{q}$ pair:



- Longitudinally polarised photon gives twist-four contribution important at large β: $F_{L,\mathrm{tw.4}}^{\mathrm{D(3)}}$ [e.g. Golec-Biernat–Wüsthoff,2001]
- In FFNS (no charm Pomeron PDF), need to add this 'direct' contribution for charm quarks for both T and L polarised photons: $F_{2,\mathrm{direct}}^{\mathrm{D(3)},c\bar{c}}$
- **Dijets:** also need to add this contribution (both T and L polarised photons)

What are the free parameters?

$$F_2^{\rm D(3)} = \underbrace{F_{2,\rm pert.}^{\rm D(3)} + F_{L,\rm tw.4}^{\rm D(3)} + F_{2,\rm direct}^{{\rm D(3)},c\bar{c}}}_{\text{QCD Pomeron}} + \underbrace{F_{2,\rm non-pert.}^{\rm D(3)}}_{\text{soft Pomeron}} + \underbrace{F_{2,I\!R}^{\rm D(3)}}_{\text{secondary Reggeon}}$$

$F_{2,\rm pert.}^{\rm D(3)}$: **4** parameters ('K-factors' for Pomeron-to-parton splitting functions)

$F_{L,\rm tw.4}^{\rm D(3)}$: **2** parameters (again, 'K-factors' to account for unknown higher-order corrections)

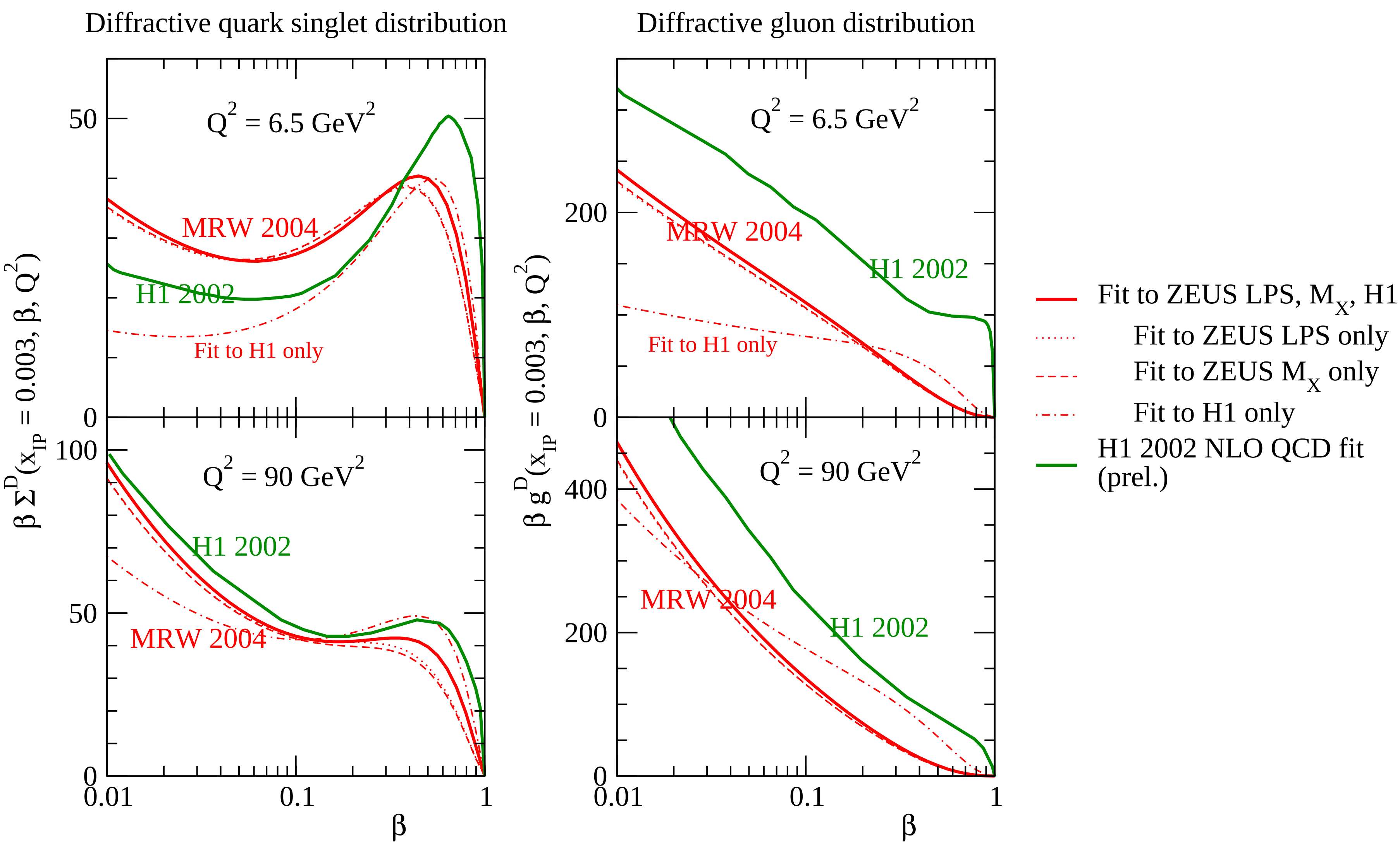
$F_{2,\rm non-pert.}^{\rm D(3)}$: **2** parameters. Input Pomeron PDFs unknown (as in H1 fit). Assume same β dependence as for sea-quark QCD Pomeron, with different normalisations

$F_{2,I\!R}^{\rm D(3)}$: **1** parameter (as in H1 fit). Use GRV pion PDFs

$\mu_0 \sim 1$ **GeV** : the scale separating the soft Pomeron and the QCD Pomeron. Take $\mu_0 = 1$ GeV. Larger μ_0 gives worse χ^2, don't know proton PDFs at smaller μ_0. **If** replace proton gluon distribution by power law (with zero sea quark distribution), and vary μ_0, best fit is obtained with $\mu_0^2 = 0.8$ GeV^2

Allow overall normalisation factors for ZEUS M_X and H1 data to account for proton dissoc.

DPDFs compared to H1 fit



- Fits published in EPJC **37** (2004) 285 (using MRST2001 NLO PDFs)

Why is MRW g^{D} smaller than H1 ?

$$F_{2,\mathrm{pert.}}^{\mathrm{D}(3)}(x_{I\!P},\beta,Q^2) = \int_{\mu_0^2}^{Q^2} \frac{\mathrm{d}\mu^2}{\mu^2}\; f_{I\!P}(x_{I\!P};\mu^2)\; F_2^{I\!P}(\beta,Q^2;\mu^2)$$

$$\frac{\partial F_{2,\mathrm{pert.}}^{\mathrm{D}(3)}}{\partial \ln Q^2} = \int_{\mu_0^2}^{Q^2} \frac{\mathrm{d}\mu^2}{\mu^2}\; f_{I\!P}(x_{I\!P};\mu^2)\frac{\partial F_2^{I\!P}(\beta,Q^2;\mu^2)}{\partial \ln Q^2} + f_{I\!P}(x_{I\!P};Q^2) F_2^{I\!P}(\beta,Q^2;Q^2)$$

$$\boxed{\frac{\partial F_2^{\mathrm{D}(3)}}{\partial \ln Q^2} \sim \alpha_S\, g^{\mathrm{D}} + \text{Extra inhomogeneous term}}$$

H1 2002 (prel.) NLO QCD fit uses a low α_S and neglects the inhomogeneous term

$\Longrightarrow$ H1 fit needs a larger g^{D} to reproduce the Q^2 slope of data

g^{D} from fits to H1 vs. ZEUS data

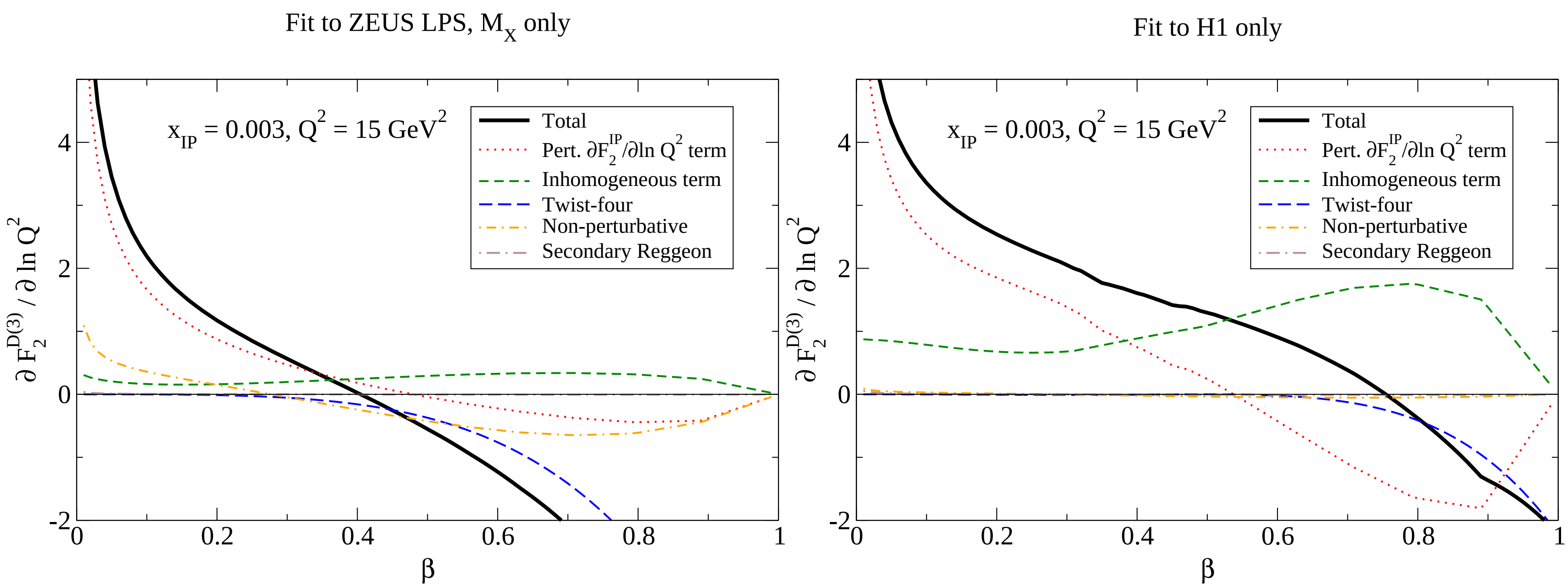
- Q. Why is MRW g^{D} from fit to only H1 data **smaller** (at low β) than g^{D} from fit to only ZEUS M_X data?

  ('Regge factorisation' fits find that the **opposite** is true, due to the larger scaling violations seen in the H1 data)

- A. Because of the **stronger** inhomogeneous term in the fit to only H1 data
  - Inhomogeneous term is **stronger** for gluonic Pomeron than sea-quark Pomeron (because gluon distribution increases more rapidly with scale than sea quarks)
  - Free parameters turn out very different for fits to only H1 data and only ZEUS data [EPJC **37** (2004) 285, Table 2]
  - Parameters for gluonic Pomeron ($I\!P = G$) consistent with zero for both ZEUS LPS and M_X data, but **not** for H1 data
  - Hence a **smaller** g^{D} is required for the fit to only H1 data, which has a **large** gluonic Pomeron component, even though the H1 data has larger scaling violations than the ZEUS data

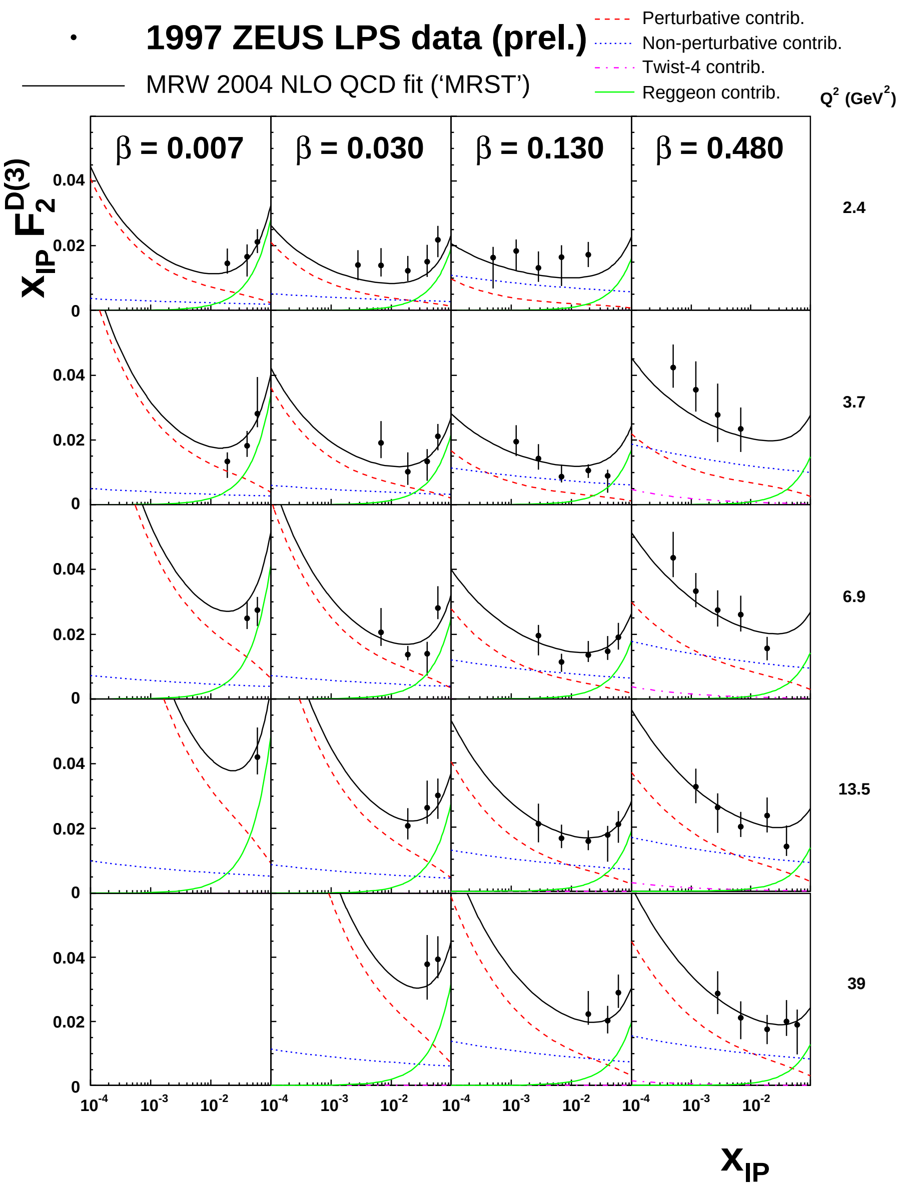
- Demonstrate by plotting contribution of inhomogeneous term to $\partial F_2^{\mathrm{D}(3)}/\partial \ln Q^2 \longrightarrow$

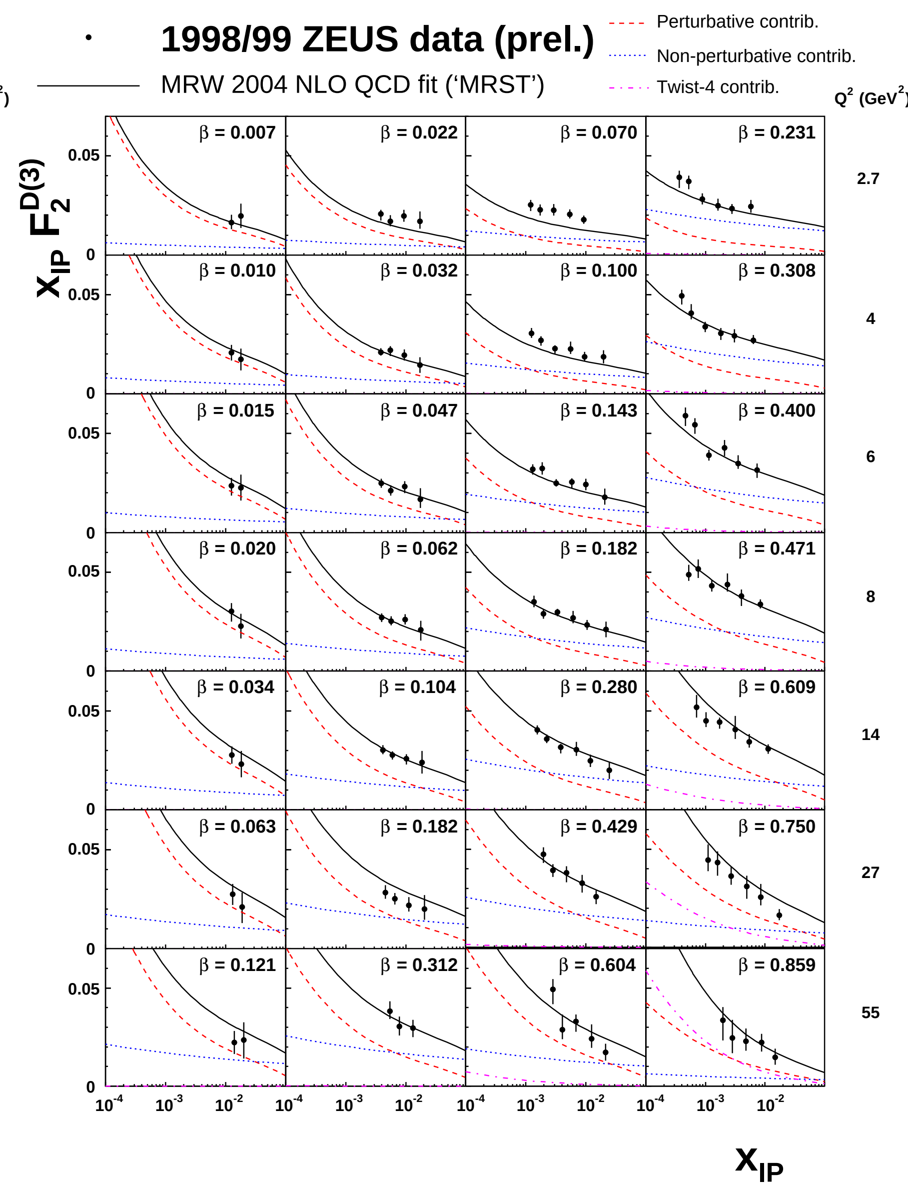
Q^2 slope of ZEUS vs. H1 data



- ZEUS (H1) data: positive scaling violations for $\beta \lesssim 0.4$ (0.75)
- Difference between ZEUS and H1 scaling violations is an experimental issue: needs further investigation
- Which data sets are 'correct'? Without this knowledge, should fit all sets together (philosophy of 'global' analysis) $\rightarrow$ get some 'average' result (?)

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





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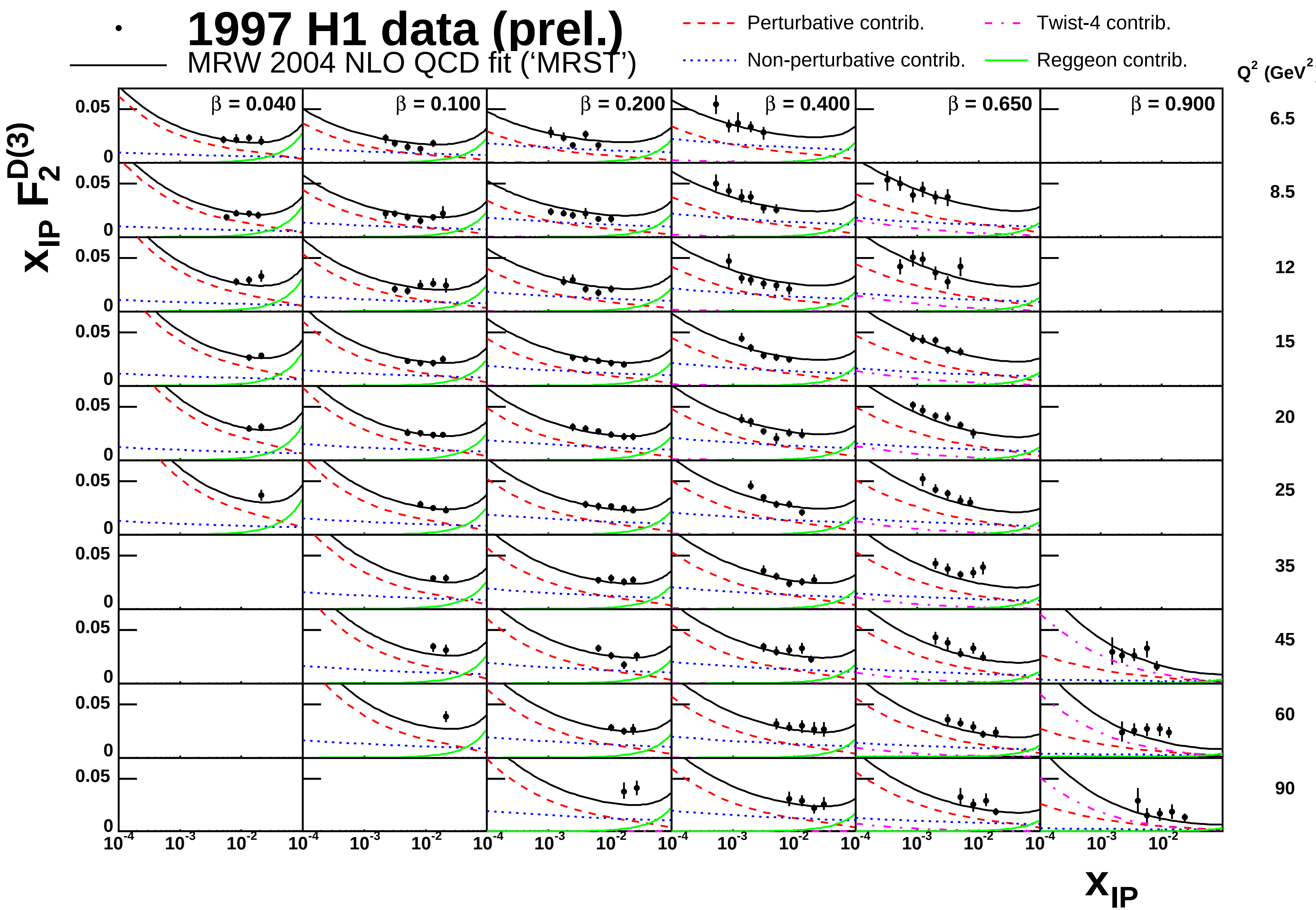

MRW 2004 DPDFs

- Available from `http://www.desy.de/~watt/mrw2004dpdfs.tar.gz`
- Fits are exactly those published in EPJC **37** (2004) 285
- Large 3-D grid for $a^{\mathrm{D}}(x_{I\!P}, \beta, Q^2)$ with Fortran code to interpolate (User doesn't need to perform inhomogeneous evolution themselves)
- **Can** be used for final state predictions in DDIS, e.g. dijet and D^* meson production cross sections, using standard NLO QCD codes
- . . . **But** need to add non-factorisable contributions separately
- Update in progress (MRW 2005):
  - Account for shadowing corrections in proton PDFs as in Phys. Rev. D **70** (2004) 091502 [`hep-ph/0406225`]
  - Include $F_{2,\mathrm{direct}}^{\mathrm{D(3)},c\bar{c}}$ (not in MRW 2004) and use more precise $F_{L,\mathrm{tw.4}}^{\mathrm{D(3)}}$
  - Fit H1 FPS and LRG (low and high Q^2) data when published

Conclusions

- Diffractive DIS is more complicated than inclusive DIS: **can't** blindly apply collinear factorisation with DGLAP-evolved DPDFs
- Regge factorisation should **only** be used for soft Pomeron
- Significant contribution to DDIS from QCD Pomeron
- QCD Pomeron modifies DDIS factorisation:
  - Inhomogeneous evolution of DPDFs
  - Need to add non-factorisable contributions separately
- This approach leads to quite different DPDFs than those obtained using naïve 'Regge factorisation' approach of H1
- ZEUS and H1 DDIS data give different DPDFs due to their different Q^2 dependence: should be investigated further