Hard Diffraction: from HERA to LHC

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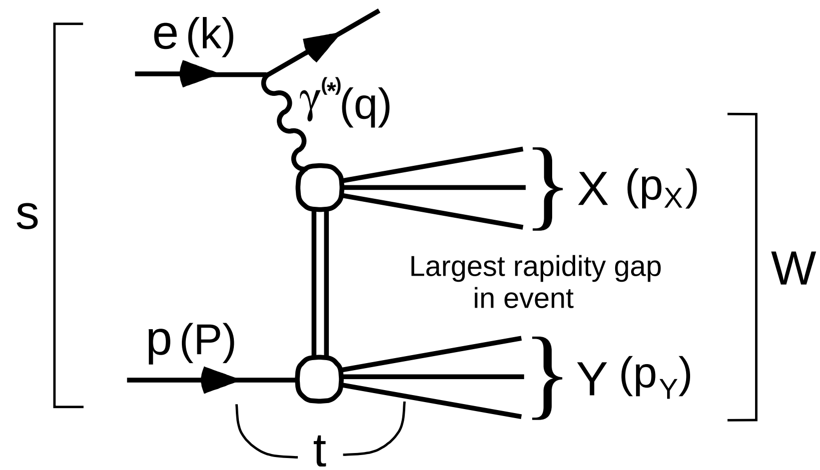
Outline

- Hard diffraction in DIS
- Theoretical framework: factorisation and evolution
- Factorisation tests at HERA
- Preliminar diffractive PDFs from combined HERA proton-tagged data
- Hard diffraction at hadron colliders

Hard diffraction in DIS

- Experiment
  - (hard) diffraction rebirth at HERA
  - $e(k) + p(P) \to e(k') + p(P') + X$
- kinematics
  - Target fragmentation region
  - $|t| \leq 1$ GeV^2
  - $x_{I\!P} \simeq 1 - E_{P'}/E_P < 0.1$
- diffractive selection:
  - large rapidity gap
  - M_X-method
  - proton tagging
- Key features
  - Leading twist: $\mathcal{O}(Q^{-4})$ (as iDIS)
  - scaling violations $\to$ parton dynamics



Theory setup in DDIS

- Hard-scattering factorisation:

$$F_k^{D(3)}(\beta, Q^2, x_{I\!P}) = \sum_i \int_\beta^1 \frac{d\xi}{\xi}\, M_i(\beta, \mu_F^2; x_{I\!P})\, C_{ki}\left(\frac{\beta}{\xi}, \frac{Q^2}{\mu_F^2}, \alpha_s(\mu_R^2)\right) + \mathcal{O}\left(\frac{1}{Q^2}\right)$$

Grazzini, Trentadue, Veneziano'98, Collins '98

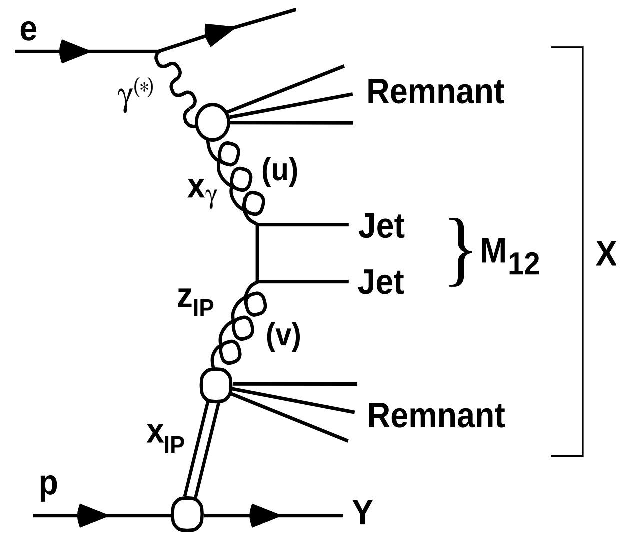
- C_{ki} $(k = 2, L)$ calculable as a power expansion α_s, same as in iDIS
- Diffractive parton distributions: $M_i(\beta, \mu_F^2, x_{I\!P})$
- Partonic structure of the colourless exchange
- DPDFs obey DGLAP evolution equations

$$Q^2 \frac{\partial M_i(\beta, Q^2, x_{I\!P})}{\partial Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_\beta^1 \frac{du}{u}\, P_{ji}(u)\, M_j\left(\frac{\beta}{u}, Q^2, x_{I\!P}\right)$$

- Phenomenological analyses of DPDFs via pQCD fits of DDIS data

Factorisation in hard diffraction: overview

- Diffractive PDFs have bees used to test hard-scattering factorisation in
  - dijet in DIS
  - dijet in PHP ($Q^2 \simeq 0$, $E_T \sim 5, 6$ GeV)
  - dijet or $W^{\pm}$ in $p\bar{p}$ collisions



- Results:
  - dijet in DIS: data/NLO $\simeq 1$
  - dijet in PHP: debated
    H1 reports violation: data/NLO $\simeq 0.5$
    ZEUS consistent with no violation: data/NLO $\simeq 1$
  - pp : Striking breakdown confirmed at Tevatron: data/NLO $\simeq 0.1$

- NB: Factorisation predicted to fail in Resolved PHP and hadronic collisions

Most recent factorisation tests at HERA

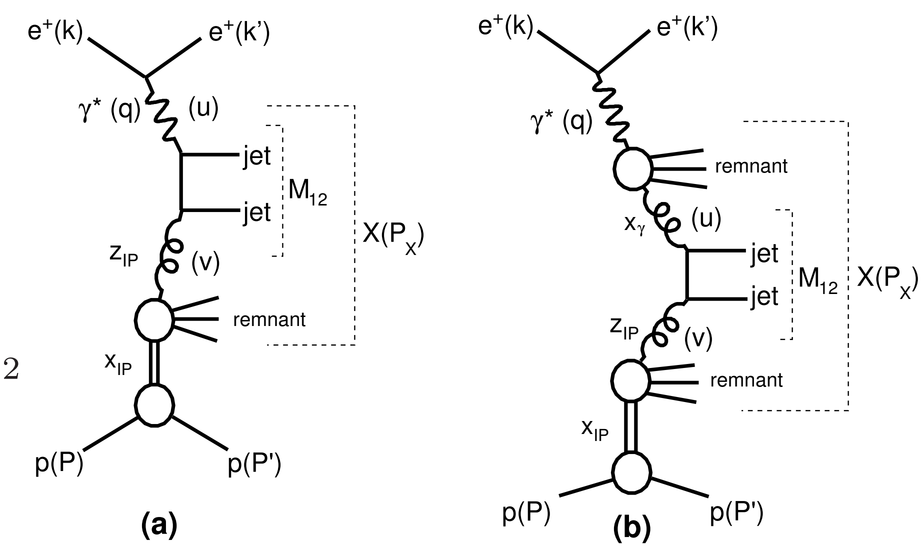
- Focus on the latest H1 results : DESY-14-242

1. Event phase space:
   PHP : $Q^2 < 2$ GeV^2
   DIS : 4 GeV$^2 < Q^2 < 80$ GeV^2
2. diffractive phase space:
   $0.010 < x_{I\!P} < 0.024$
3. jet phase space:
   $E_T^{*\mathrm{jet}1(2)} > 5.5(4.0)$ GeV

- Theory

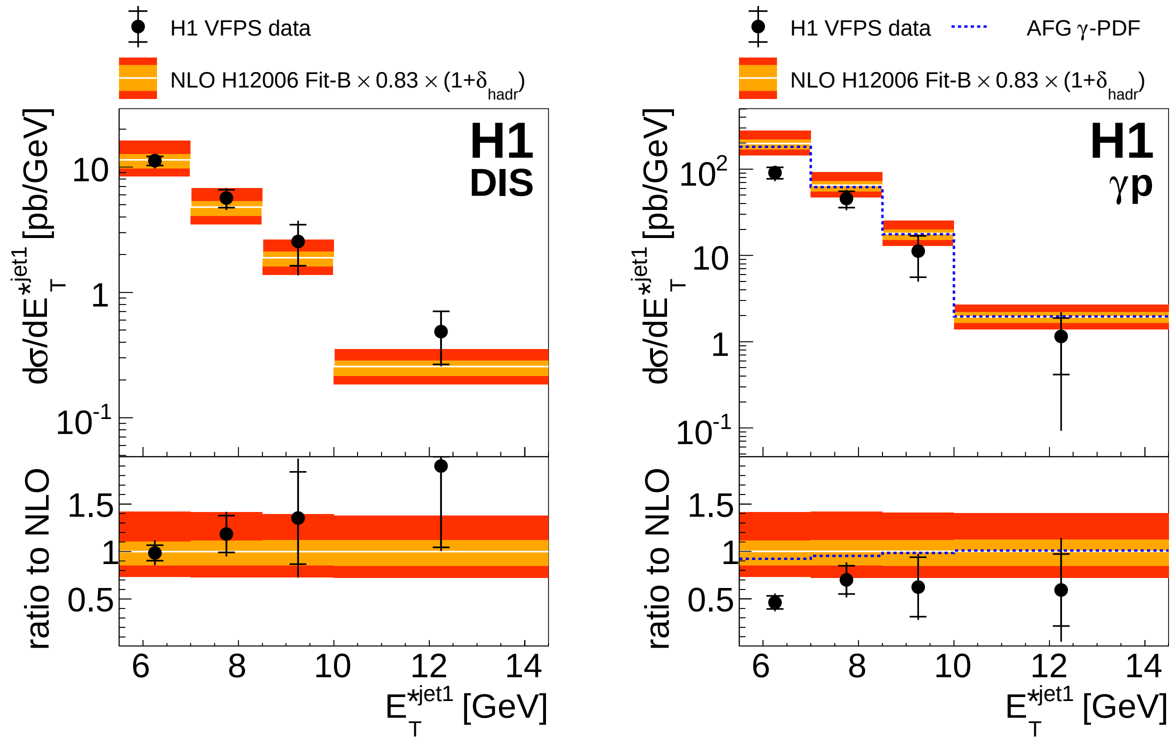
1. NLO accuracy
2. scale set to $\mu_R^2 = \mu_F^2 = \langle E_T^{*\mathrm{jet}} \rangle^2 + Q^2$
3. Theo uncertainty: $\mu \to 0.5\mu, 2.0\mu$
4. DPDFs from previous H1 '06 analysis

DIS PHP



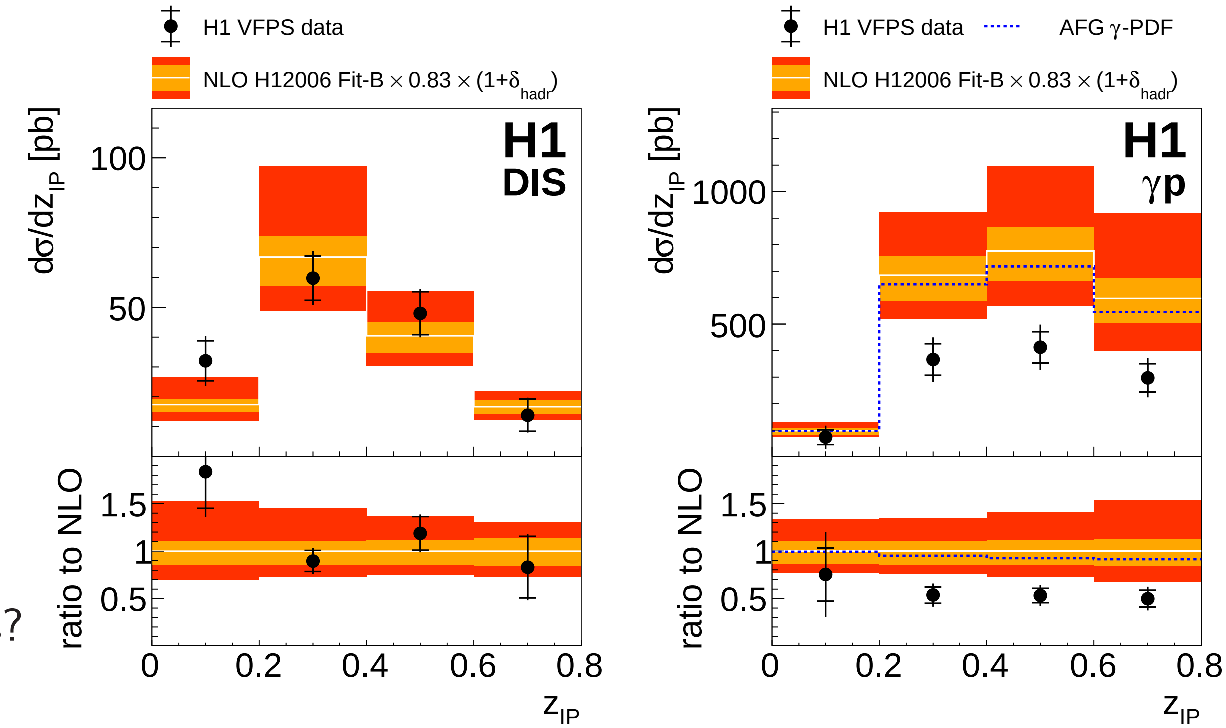
Results: $E_T^{*\mathrm{jet1}}$ distribution

- $E_T^{*\mathrm{jet1}}$:
  leading jet
  transverse energy
- distribution controlled
  by ME : E_T^{-4}
- large NLO corrections
- Theo hp:
  E_T-dependence
  of the suppression?
- Desiderata :
  same analysis
  at higher E_T with good statistics



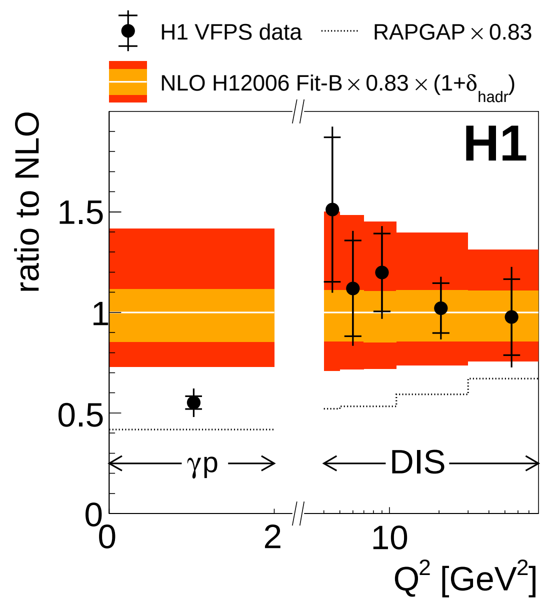
Results: $z_{I\!P}$ distribution

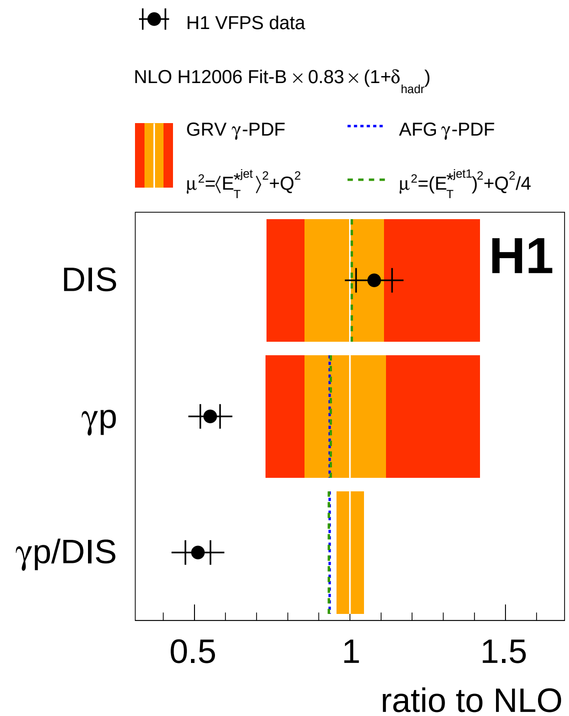
- $z_{I\!P}$ fractional momentum of the interacting parton
- determined by jets kinematics
- sensitive to DPDFs
- large NLO corrections
- shape ok
- "just" renorm DPDFs?



Results: ratios

- Ratio: get rid of large NLO corrections (or soft resummation?)
- H1 confirms an overall suppression factor ~ 0.5
- Critical variable: Q^2 not E_T
- factorisation broken for on-shell hadrons
- factorisation OK for pointlike probes virtual photon





Advances in DPDFs determination

- Knowledge on DPDFs can be further refined
  - Global fit? LRG+FPS+jets+charm diffracive data from both HERA collaboration
  - Latest fits:
    - H1 2006 (iDIS)
    - H1 2007 (iDIS+jets)
    - ZEUS 2010 (iDIS+jets)
  - gluon DPDF poorly constrained in DDIS: use diffractive dijet
- In this talk: alternative strategy
  - QCD analysis of combined proton tagged DDIS data from H1 and ZEUS (EPJ '12)
  - cross-calibration: improved precision of the cross section measurements
  - $2.5 < Q^2 < 200$ GeV^2
  - $0.00035 < x_{I\!P} < 0.09$
  - $0.09 < |t| < 0.55$ GeV^2

Fitting strategy

Imporant remark:

- hard-scattering factorisation holds at fixed values of $x_{I\!P}$ and t
- dependence on $x_{I\!P}$ and t fully contained in DPDFs
- these conditional parton distributions are uniquely fixed by the kinematics of the outgoing proton:
  they are, at least in principle, different for different values of $x_{I\!P}$ and t.

In practice:

- perform a series of QCD fits at fixed values of $x_{I\!P}$ with a common initial condition controlled by a set of parameters $\{p_i\}$.
- infere the approximate dependence of parameters $\{p_i\}$ on $x_{I\!P}$
- construct a generalised initial condition in the $(\beta, x_{I\!P})$-space to be used in a $x_{I\!P}$-combined QCD fit.

Fixed $x_{I\!P}$ fits

pQCD settings

- Evolution and convolution with `QCDNUM17` Botje '11
- ZM VFNS scheme to NLO
- $m_c = 1.4$ GeV, $m_b = 4.5$ GeV, $\alpha_s(M_Z^2) = 0.118$, $Q_0^2 = 1$ GeV^2
- $\mu_F^2 = \mu_R^2 = Q^2$

Momentum distributions at Q_0^2:

$$\begin{aligned} \beta\, M_\Sigma(\beta, Q_0^2) &= A_q\, \beta^{Bq}\, (1-\beta)^{Cq}\,, \\ \beta\, M_g(\beta, Q_0^2) &= A_g\, \beta^{Bg}\, (1-\beta)^{Cg} \end{aligned}$$

- M_Σ: flavour symmetric singlet distribution
- minimisation performed with `MINUIT`, stat $\oplus$ syst errors

Fixed $x_{\mathbb{P}}$ fits : Results

- No Q^2 or y cuts imposed. $M_X > 2$ GeV
- gluon constrained only by scaling violations:
  eigenvalue analysis suggests : $C_g = 0$ and $B_g = 0$
- initial condition contains 4 free parameters in each $x_{\mathbb{P}}$-bin
- mild dependence of χ^2 on Q_0^2

$x_{\mathbb{P}}$	χ^2	Fitted points
0.90E-03	3.52	8
0.25E-02	10.03	14
0.85E-02	15.95	23
0.16E-01	24.36	26
0.25E-01	26.96	25
0.35E-01	20.79	24
0.50E-01	28.48	27
0.75E-01	13.51	26
0.90E-01	6.36	10
Sum	149.9	183

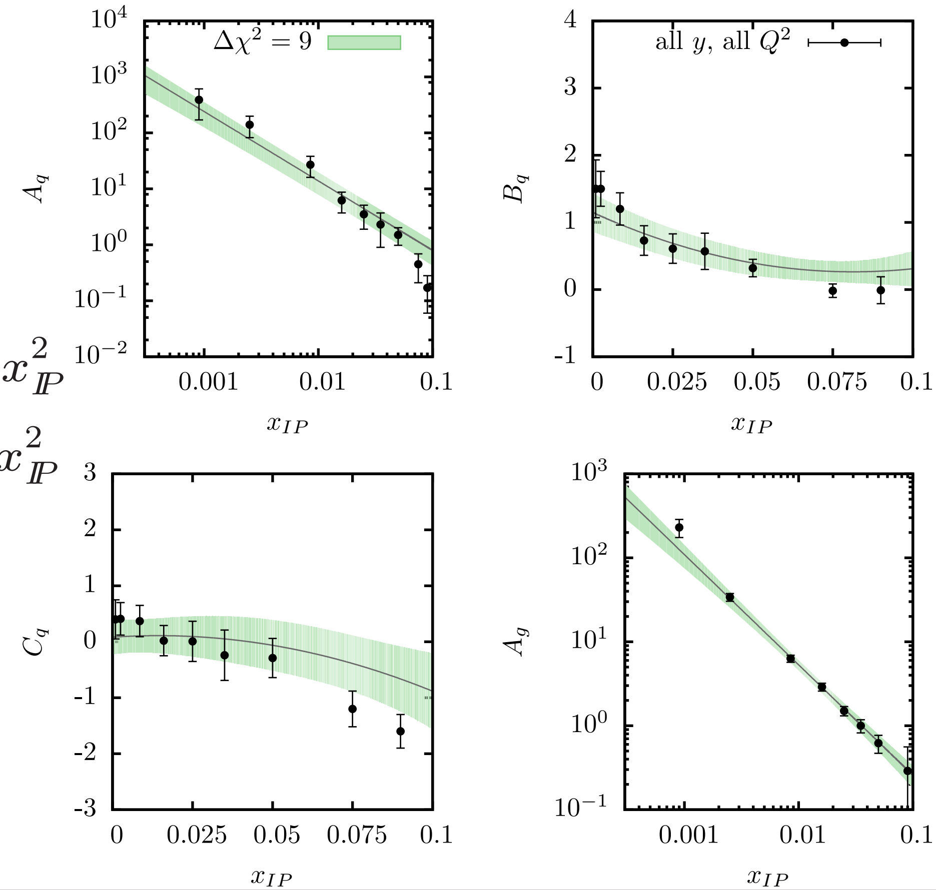
Generalised initial conditions

- Let depend the coefficients A_q,B_q,C_q and A_g on $x_{I\!P}$
- functional $x_{I\!P}$-dependence:

$$
\begin{aligned}
A_q(x_{I\!P}) &= A_{q0}\, x_{I\!P}^{A_{q,1}} \\
B_q(x_{I\!P}) &= B_{q0} + B_{q1}\, x_{I\!P} + B_{q,2} x_{I\!P}^2 \\
C_q(x_{I\!P}) &= C_{q0} + C_{q1}\, x_{I\!P} + C_{q,2} x_{I\!P}^2 \\
A_g(x_{I\!P}) &= A_{g0}\, x_{I\!P}^{A_{g,1}}
\end{aligned}
$$

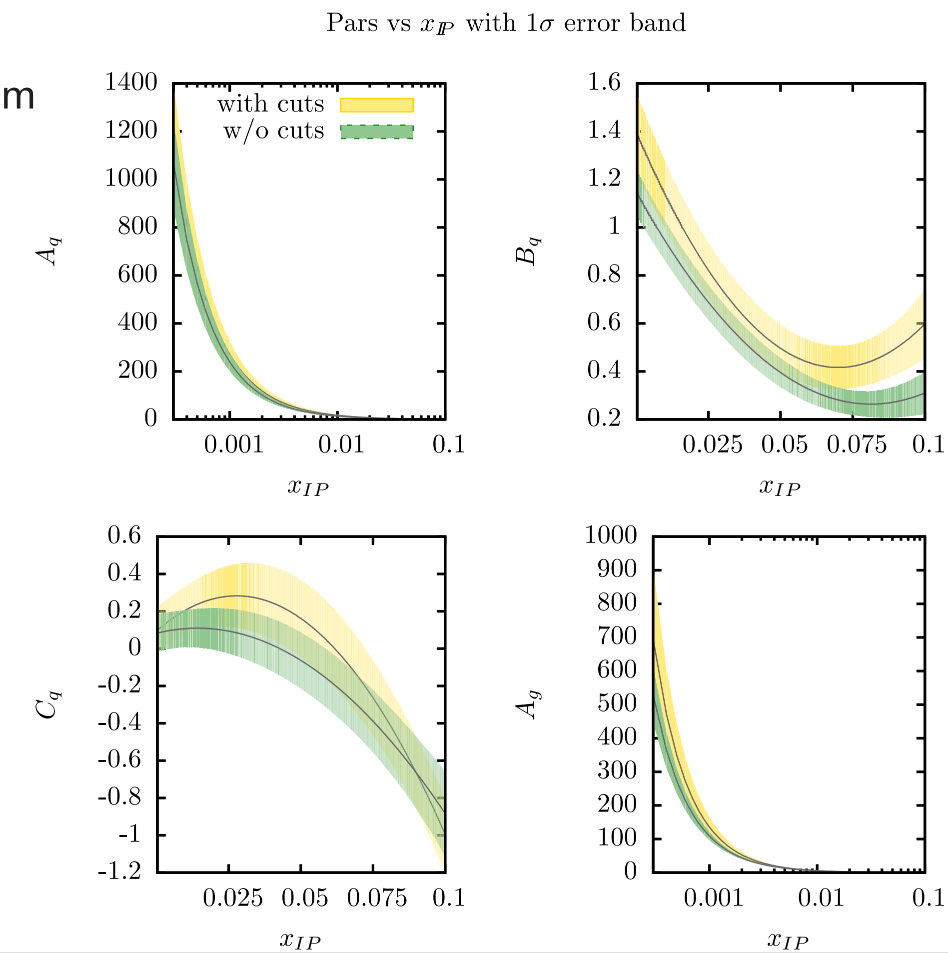
- 10 free pars

Pars vs $x_{I\!P}$ with error band



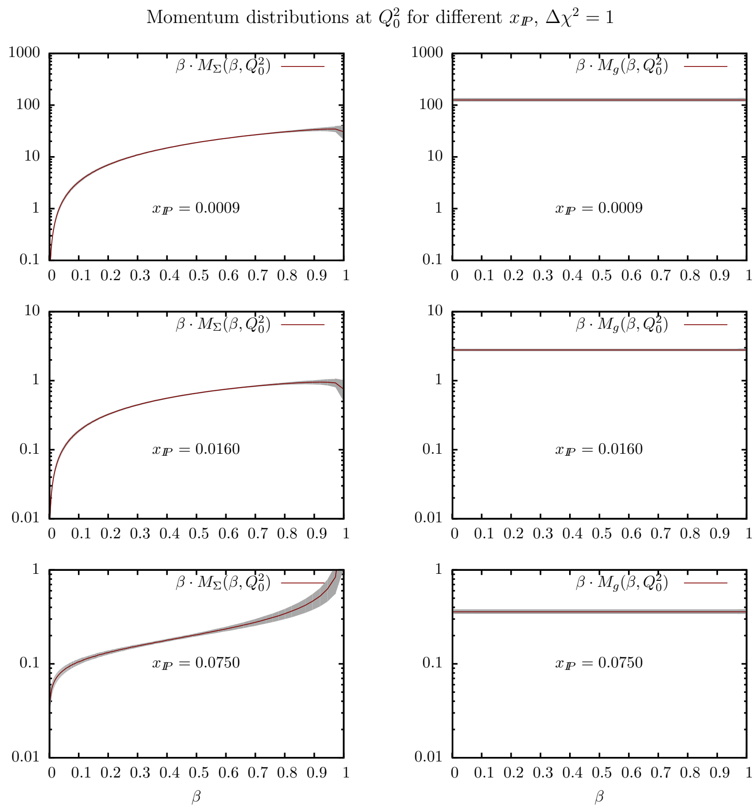
Fit result and stability

- χ^2 =193 for 192-10 degree of fredoom
- stability of the fit checked against variation of the cuts:
- $y < 0.5$, $Q^2 > 8$ GeV^2
- No cuts : default
- No dependence on Q^2_{min} (unlike H1 and ZEUS fits based on LRG data)
- some tension at large y ($y > 0.5$)
- combination price: ~ 40 χ^2 units: need improvements



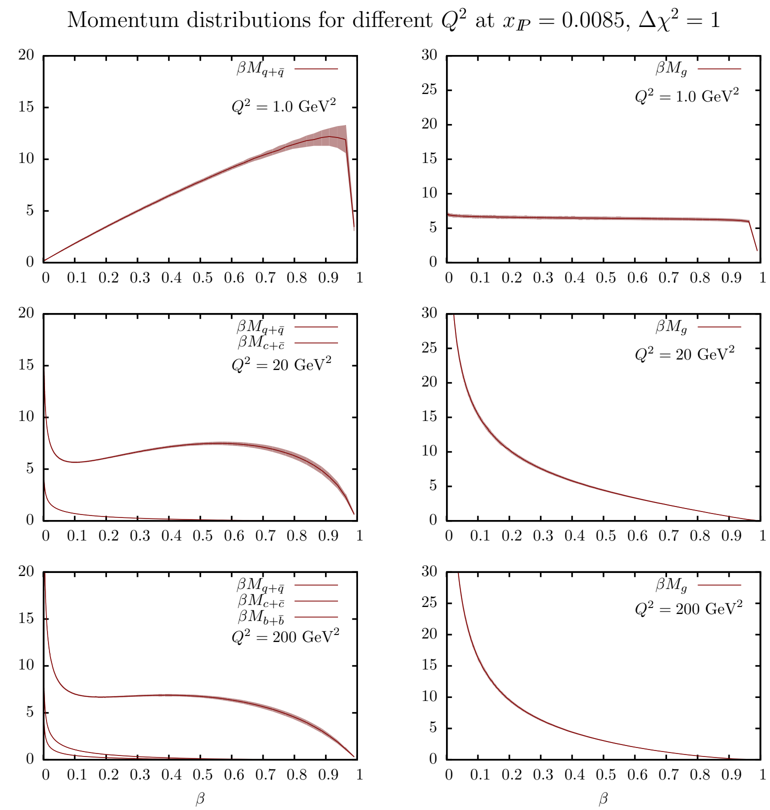
DPDFs at Q_0^2 at different $x_{I\!P}$

- initial condition at $Q_0^2 = 1$ GeV^2
- Light red band : $\Delta\chi^2 = 1$
- Slight shape deformation vs $x_{I\!P}$ at large β

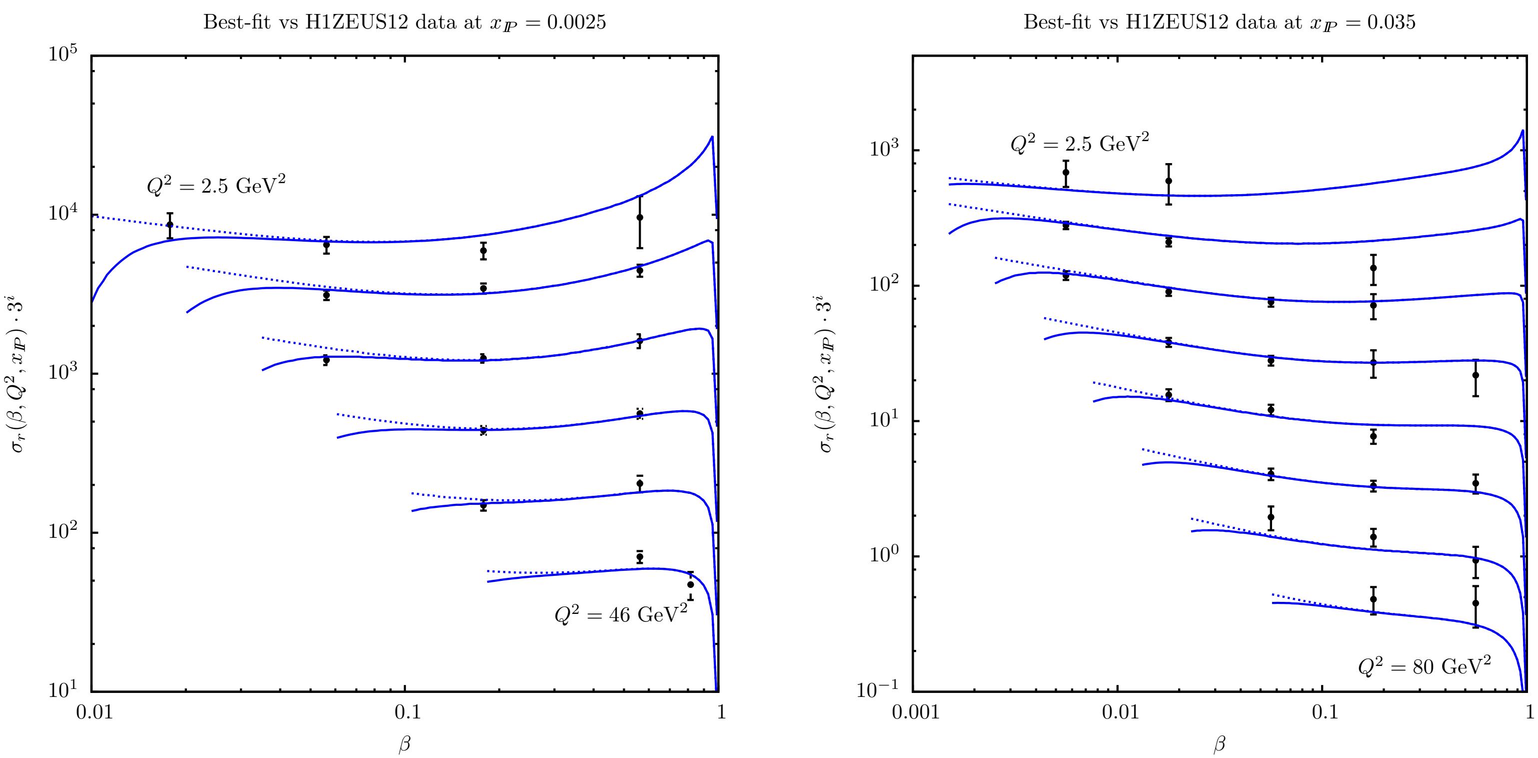


DPDFs evolution

- Singlet and gluon momentum distributions at $x_{I\!P} = 0.0085$
- Light red band: propagation experimental uncertainties with $\Delta\chi^2 = 1$ (eigenvector method)
- Singlet: valence-like at low Q^2
- Gluon: fast rise with raising Q^2 at low β
- Error shrinkage at high Q^2: effect of pQCD evolution

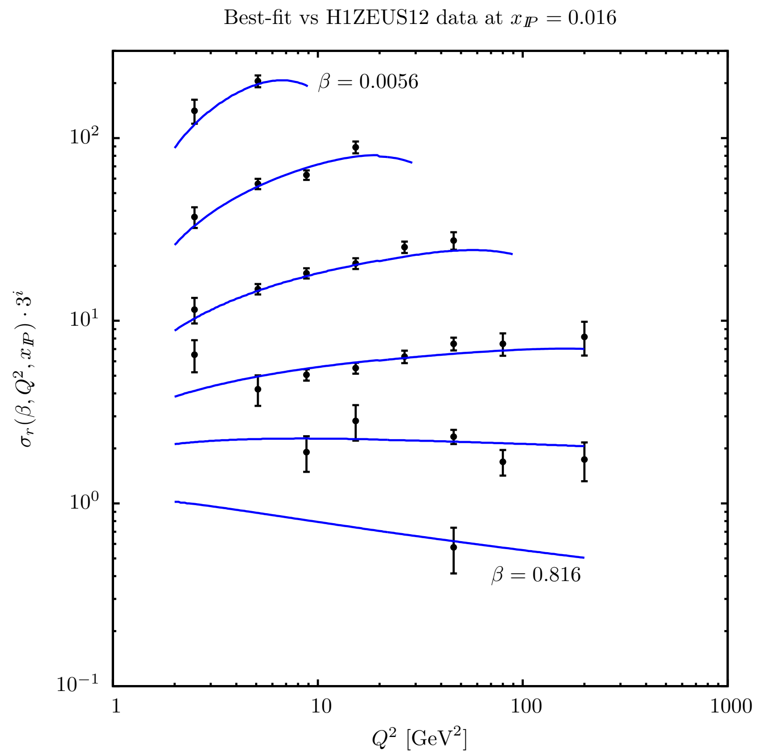


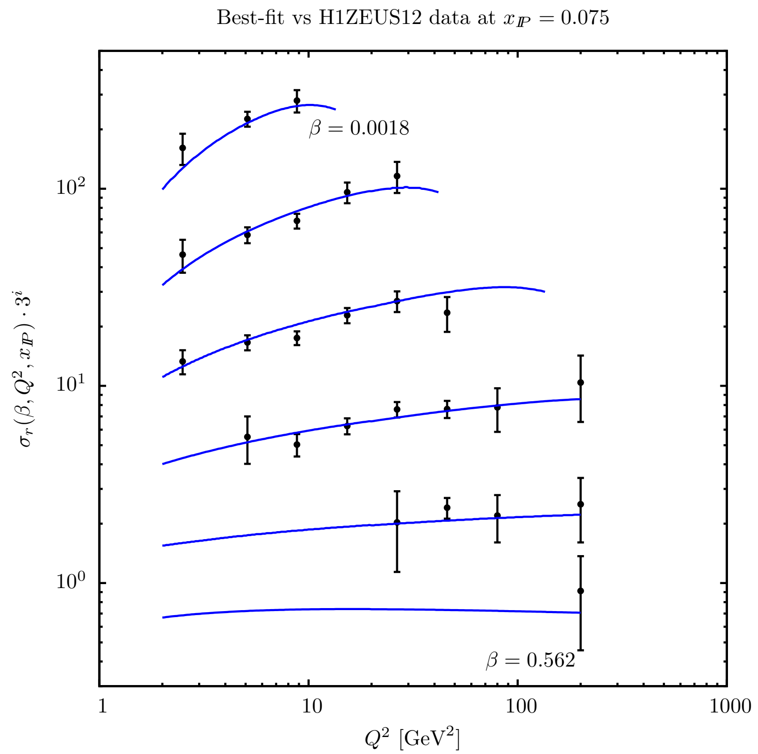
Best fit vs β at different Q^2



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

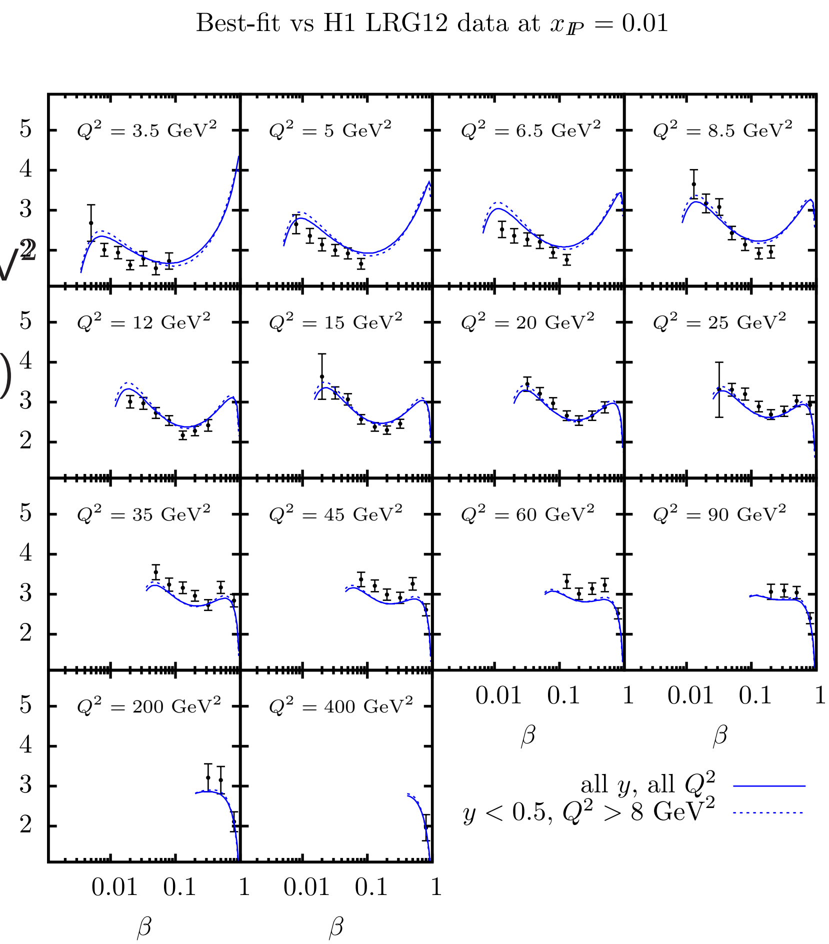
Best fit vs Q^2 at different β





Comparison with H1 LRG12 data at $x_{\mathbb{P}} = 0.01$

- LRG: $M_Y < 1.6$ GeV, $|t| < 1$ GeV^2
- FPS: $M_Y = m_p$, $0.09 < |t| < 0.55$ GeV^2
- Expected a constant rescaling factor ($\simeq 2$)
- BUT: rescaling does depend on Q^2
- same results for a fit with additional $y < 0.5$ and $Q^2 > 8$ GeV^2 cuts
- Open problem



Test: β-$x_{I\!P}$ factorised ansatz

- Accomodate all $x_{I\!P}$-dependence in a common flux factor for gluon and singlet

$$\mathcal{F}(x_{I\!P}) = x_{I\!P}^{f_0} \cdot (1 - x_{I\!P})^{f_1}$$

so that

$$\Sigma(\beta, Q_0^2, x_{I\!P}) = \mathcal{F}(x_{I\!P})\ s_0\ \beta^{s_1}\ (1-\beta)^{s_2}$$
$$g(\beta, Q_0^2, x_{I\!P}) = \mathcal{F}(x_{I\!P})\ g_0\ \beta^{g_1}\ (1-\beta)^{g_2}$$

◇ 8 free parameters fit, additional β and $x_{I\!P}$ dependence

○ Same pQCD settings and error treatment

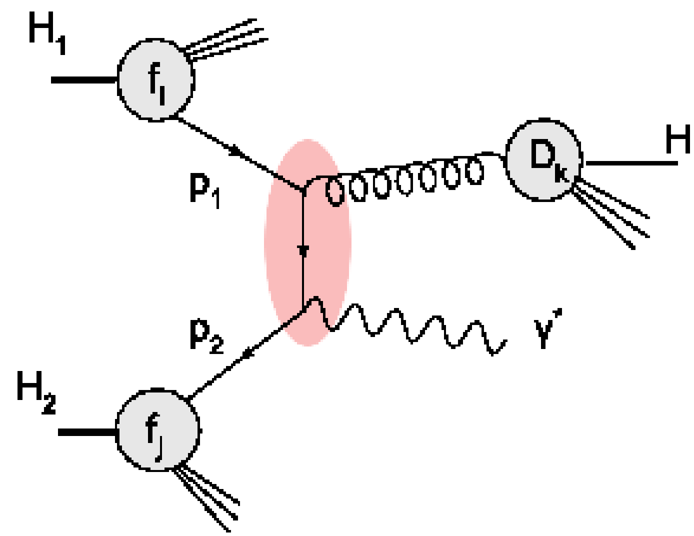
- The fit returns χ^2= 207 (vs 193) for 192-8 dregrees of freedom
- This implies an increase $\Delta\chi^2 = +14$
- Indication for a modulation in the β-shape of DPDFs depending on $x_{I\!P}$
- NB: with additional shaping, the factorised ansatz could still give a competitive fit

Near future plan

- Fit still preliminar but hopefully publicy available soon
- test of internal consistency with HERA LRG data
- input for predictions of hard diffraction at hadron collider

On hard-scattering factorisation

- Hard-scattering factorisation is at the basis of discovery and precision physics (especially) at hadron colliders.
- Consider $H_1 + H_2 \rightarrow H + \gamma^* + X$
- Assume hard scattering factorisation: $d\sigma \propto f_{H_1} \otimes f_{H_2} \otimes D_H \otimes d\hat{\sigma}$
- No factorisation theorem for generic QCD and/or BSM processes but we found it works well phenomenologically



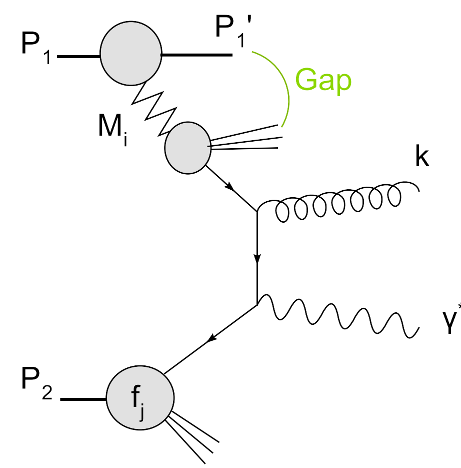
- Factorisation proven only for inclusive Drell-Yan (where it is easier to show that soft exchanges are power suppressed when one sums over final states).
- Use semi-inclusive DY to test factorisation: it will depend on the phase space region in which H is detected

→ Factorisation failure opens a window on NP (soft) physics:
NP physics is in the way it fails..

Hard Diffraction at LHC

- Numerous analyses on soft and hard diffraction are ongoing at LHC by all Collaborations.
- Method :
  - LRG with main detectors
  - forward proton tagger

▶ Strategy: Assume hard scattering factorization : use HERA DPDFs to predict (single) diffractive cross sections for
  - $W^{\pm}$,Z (clean, rare)
  - dijet (abundant, busy)
  - γ-jet
  - ...
- more processes, more knowledge



Drell-Yan : motivations

Drell-Yan process : $P_1 + P_2 \to \gamma^* + X$ Drell, Yan 1970

- Factorization of the process at "soft" level

Lindsay, Ross, Sachrajda, 1983
Collins, Soper, Sterman 1984
Bodwin, 1985

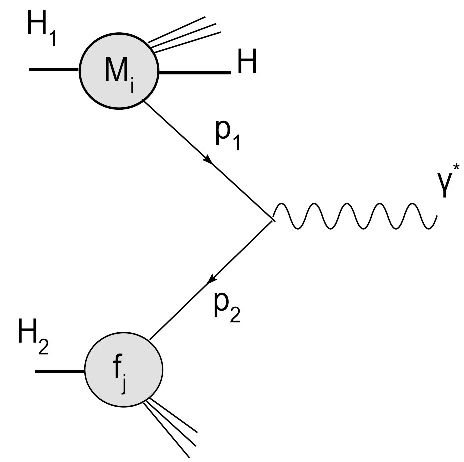
1. Perturbative trigger: the invariant mass Q^2 of the lepton pair can be accurately reconstructed;
2. The process is free of final state QCD corrections;
3. Higher order corrections known for $d\sigma/dQ^2$, $d\sigma/dy\, dQ^2$ and $d\sigma/dq_\perp^2 dQ^2$

$\oplus$ soft gluon resummations.

$\Downarrow$

Prototype process for factorisation studies in hadronic collisions.

Prototype process: diffractive DY



- consider: $H_1 + H_2 \to H_1 + \gamma^* + X$

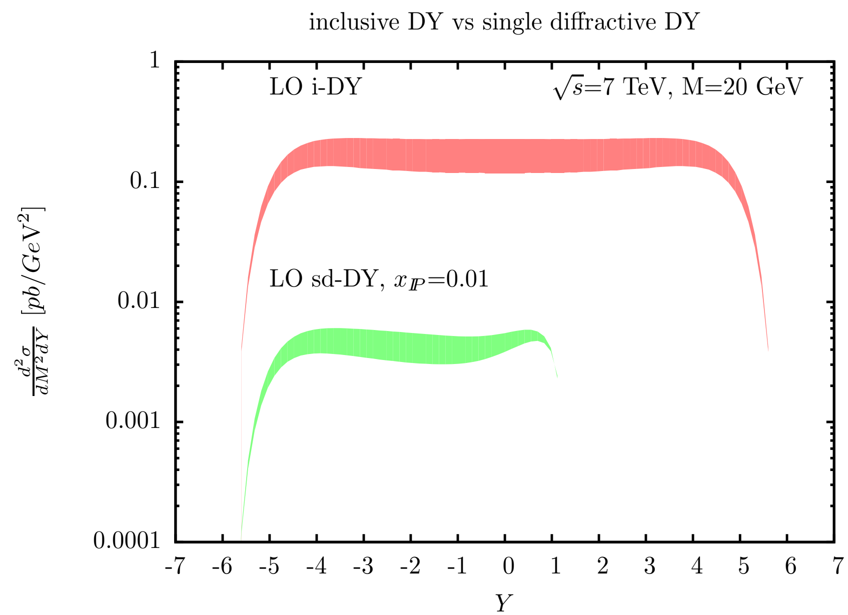
▶ Let us assume factorisation:

$$x_{I\!P} \frac{d\sigma^{DDY}}{dQ^2 dY dx_{I\!P}} = \sigma_0 \sum_q e_q^2 M^D_{q/I\!P}\left(\frac{\sqrt{\tau}e^Y}{x_{I\!P}}, Q^2, x_{I\!P}\right) f_{\bar{q}/P_2}(\sqrt{\tau}e^{-Y}, Q^2)$$

- Dependencies of the cross section:
  - DY mass: factorisation breaking vs Q^2 (not only around M_Z)
  - $x_{I\!P}$: possible different physics at different $x_{I\!P}$
  - DY rapidity: test the shape of HERA DPDFs vs measuraments
  - If possible, avoid extrapolation from HERA ranges: $0.001 < \beta < 1$, $0.001 < x_{I\!P} < 0.1$

Open questions

- Can we correct the factorisation formula by a factor S?
  $d\sigma \propto f^D \otimes f \otimes d\hat{\sigma} \otimes S(..)$
- which are the dependences of S?
- do we see the same partonic structure oberved at HERA?
- can be the cross section factorised at all?
- Compare Single and Double Diffraction
  $d\sigma \propto f^D \otimes f^D \otimes d\hat{\sigma} \otimes S'(..)$
- what are the relations between S and S'?
- What if one measures forward neutron instead of protons?



Hard diffraction : present and future

- Impressive knowledge on hard diffraction accumulated by HERA and Tevatron
- This knowledge is quantitative and predictive (dPDFs etc.)
  - New fit ready soon
- discovery-like program at hadron collider:
  - how factorisation is broken
  - to which extent the pomeron is universal?
  - if not, can we define modified DPDFs in hard diffraction in hadronic collisions?
  - Can we recover approximate predictivity?
- Single diffractive DY good candidate process for such studies