Predictions for single-diffractive Drell-Yan production at the LHC at 13 TeV

Federico Alberto Ceccopieri

IFPA, Université de Liège, Belgium

federico.alberto.ceccopieri@cern.ch

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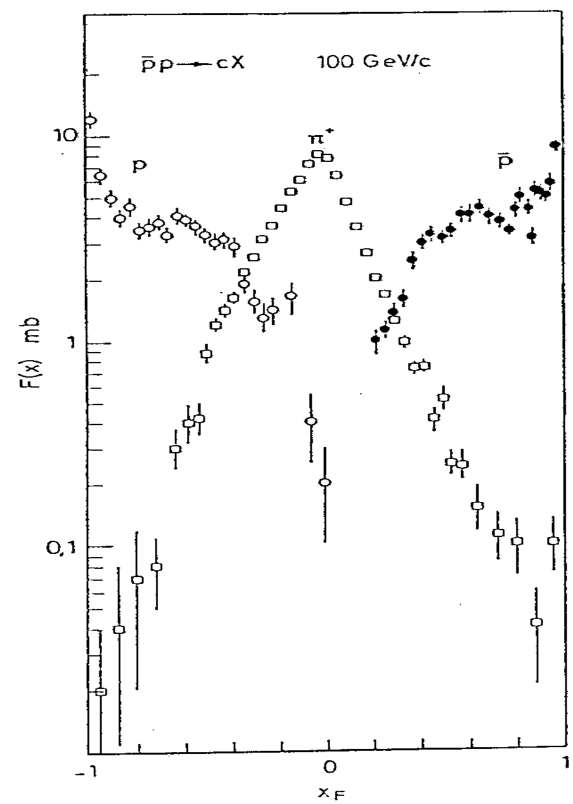
Outline

- Forward particle production in pp and ep collisions
- Hard diffraction in DIS : factorisation and evolution
- Factorisation tests at HERA
- Diffractive PDFs from combined HERA proton-tagged data
- Single-diffractive Drell-Yan pair production : a case study at hadron colliders
- Factorisation breaking effects vs Q^2, $\sqrt{s}$...

The leading particle effect in hadronic collisions

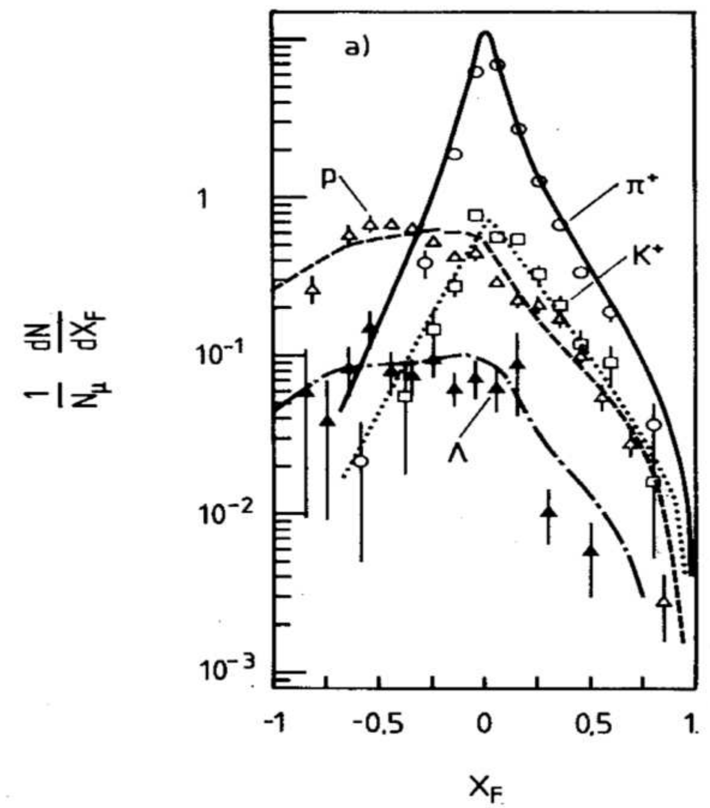
- particle production in hadronic collisions:
  $\bar{p}p \to c + X$
- $x_F = 2p_{||}/\sqrt{s}$ in hadronic centre of mass
- Leading particle effect : privileged quark-flavour quantum number flow from the initial state particle to the final state one
- the more the quark-flavour content is conserved from initial to final state hadron c, the more the latter carries a substantial fraction of the energy available in the reaction: $d\sigma \sim (1 - x_F)^n$
- Mesons don't show LPE
- However, no large momentum transfer $\to$ pQCD not applicable



Basile & al. '81

The leading particle effect in DIS

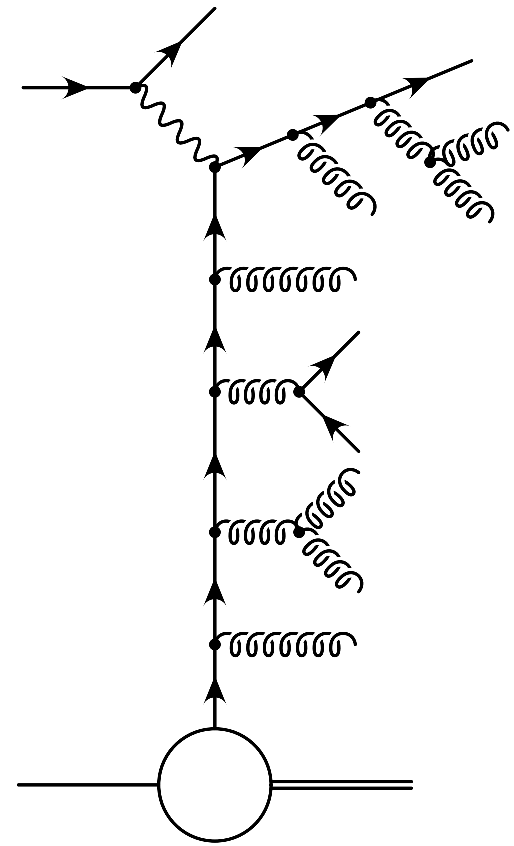
- Same effect observed in DIS
- $\mu p \rightarrow \mu + h + X$, DIS@280 GeV
- Same pattern as in hadronic collisions
- LPE for backward proton (uud) and Λ (uds)
- No LPE for $\bar{\Lambda}$ ($\bar{\text{u}}\bar{\text{d}}\bar{\text{s}}$), $\bar{p}$ ($\bar{\text{u}}\bar{\text{u}}\bar{\text{d}}$) and mesons
- But here an hard scale is present, $Q^2 \gg \Lambda^2_{QCD}$, pQCD analysis is possible:
  - Λ production : F.A.C. *EPJ* **C73** (2013) 2435
  - n production : F.A.C. *EPJ* **C74** (2014) 3029



EMC Coll. '81

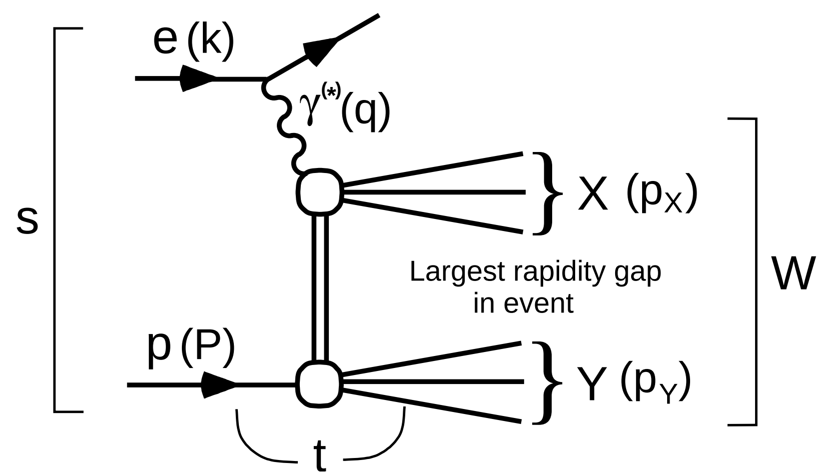
Fragmentation in SIDIS

- Deep Inelastic Scattering event in which a virtual photon interacts with a parton cascade in the nucleon
- Define $t = (P - p_h)^2$
- $t \sim Q^2$ current fragmentation : $d\sigma \propto f \otimes D$
- $0 \ll t \ll Q^2$ central region: higher order corrections, current/target separation depends on factorisation scale
- $t \sim 0$ target fragmentation : $d\sigma \propto M$, fracture functions (Trentadue, Venaziano '94)



Hard diffraction in DIS

- Experiment
  - (hard) diffraction rebirth at HERA
  - $e(k) + p(P) \to e(k') + p(P') + X$
- kinematics
  - proton 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 of diffractive structure functions $\to$ parton dynamics



Theory setup in DDIS

- Hard-scattering factorisation:

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

Grazzini, Trentadue, Veneziano'98, Collins '98

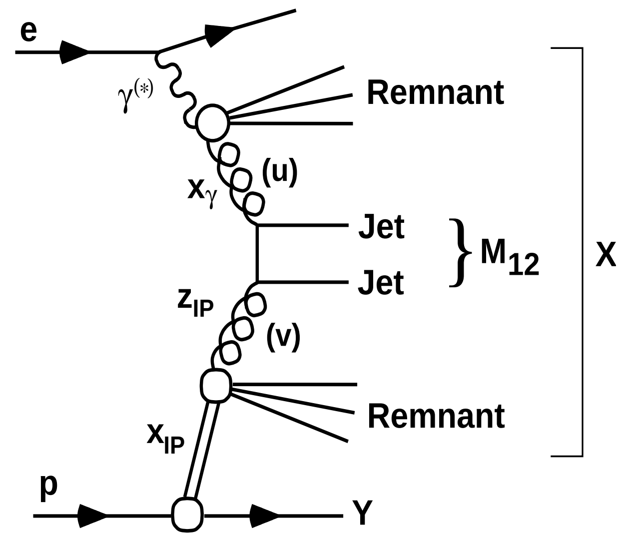
- C_{ki} $(k = 2, L)$ calculable as a power expansion α_s, same as in iDIS
- Diffractive parton distributions: $f_i^D(\beta, \mu_F^2, x_{\mathbb{P}})$
- Partonic structure of the colourless exchange
- DPDFs obey DGLAP evolution equations (for t integrated up to $t_{max} \ll Q^2$)

$$Q^2 \frac{\partial f_i^D(\beta, Q^2, x_{\mathbb{P}})}{\partial Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_\beta^1 \frac{du}{u}\, P_{ji}(u)\, f_j^D\left(\frac{\beta}{u}, Q^2, x_{\mathbb{P}}\right)$$

- 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 at HERA
  - dijet in PHP at HERA ($Q^2 \simeq 0$, $E_T \sim 5, 6$ GeV)
  - dijet and electroweak boson production in $p\bar{p}$ collisions at Tevatron



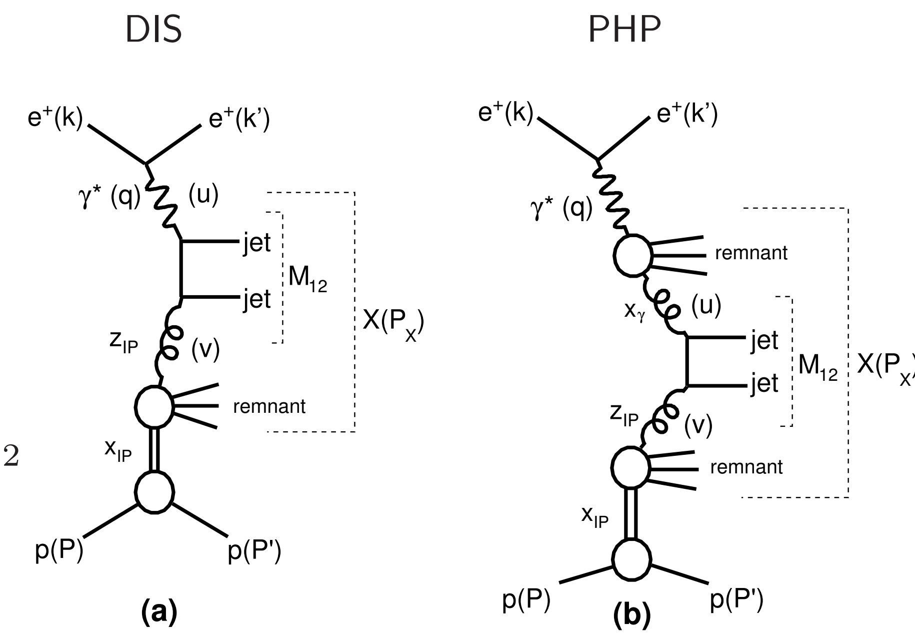
- Results:
  - dijet in DIS: data/NLO $\simeq 1$
  - dijet in PHP: debated
    H1 reports violation: data/NLO $\simeq 0.5$
    ZEUS consistent with no violation: data/NLO $\simeq 1$
  - $p\bar{p}$: Striking breakdown observed at Tevatron: data/NLO $\simeq 0.1$

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

Most recent factorisation tests at HERA

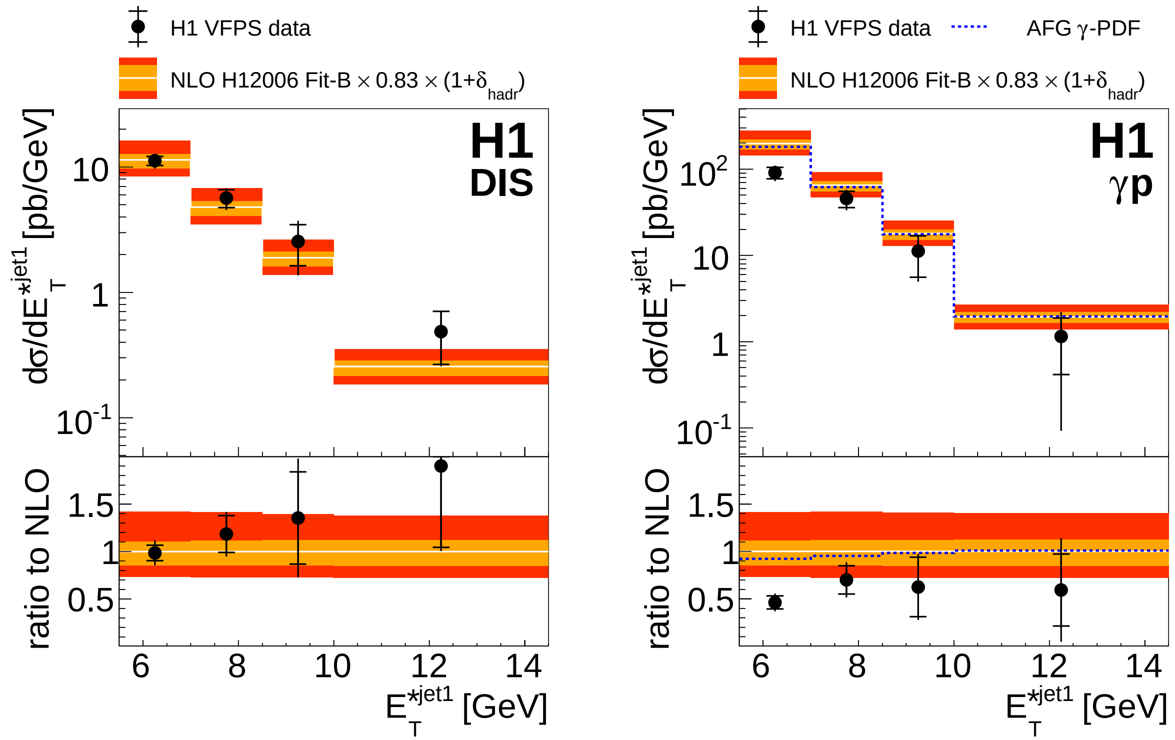
- Focus on the latest H1 results : JHEP 1505 (2015) 056
  1. Event phase space:
     PHP : $Q^2 < 2$ GeV^2
     DIS : 4 GeV$^2 < Q^2 < 80$ GeV^2
  2. diffractive phase space:
     $0.010 < x_{I\!P} < 0.024$
  3. jet phase space:
     $E_T^{*\text{jet1(2)}} > 5.5(4.0)$ GeV

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



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

- $E_T^{*\mathrm{jet1}}$: leading jet transverse energy
- distribution controlled by ME : E_T^{-4}
- large NLO corrections
- E_T-dependence of the suppression not confirmed



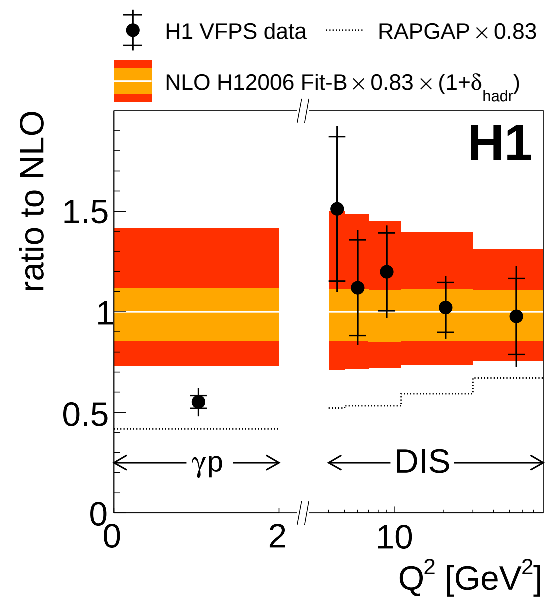
- Desiderata:
  – Diffractive PHP at higher E_T with good statistics

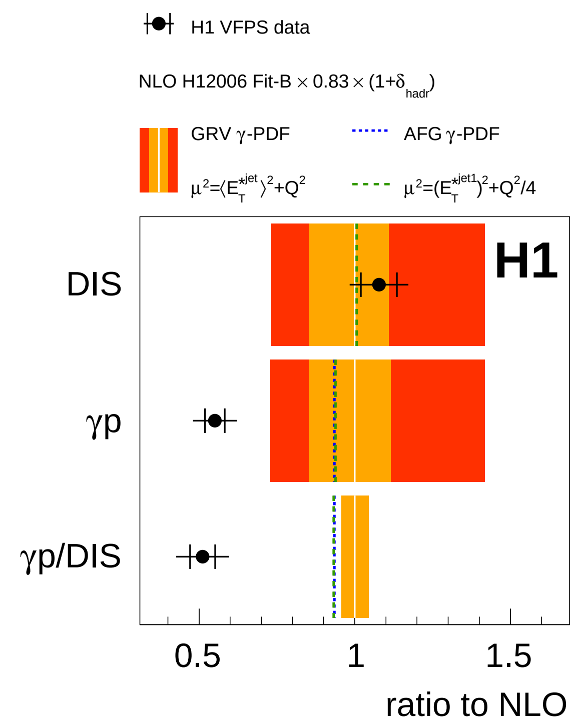
Results: double ratios

- large NLO corrections: jets produced nearly at threshold (soft gluon resum?)

$\hookrightarrow$ Consider ratios

- H1 confirms an overall suppression factor ~ 0.5
- Critical variable: Q^2 not E_T





Emerging picture:

$\Rightarrow$ factorisation broken for (spatially extended) hadrons

$\Rightarrow$ factorisation OK for pointlike probes as the virtual photon

diffractive PDFs pQCD fits : status

- 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: include in the fit diffractive dijet data
- In this talk:
  - QCD analysis of combined H1 and ZEUS proton tagged DDIS data (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 (restricted t-range to avoid extrapolations)
  - $10^{-3} < \beta < 1$

Fitting strategy

Remarks:

- 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: DPDFs are, in principle, different for different values of $x_{I\!P}$ and t.
- Approach exploited in F.A.C and L.Favart arXiv:1205.6356

H1ZEUS12 data:

- 192 points for $\sigma_r^{D(3)}(\beta, Q^2, x_{I\!P}) = F_2^{D(3)}(\beta, Q^2, x_{I\!P}) - \frac{y^2}{1+(1-y)^2} F_L^{D(3)}(\beta, Q^2, x_{I\!P})$
- 10 $x_{I\!P}$ bins, on average 20 points in each $x_{I\!P}$ bin
  $\Rightarrow$ too low sensibility to use this approach $\Rightarrow$ simpler approach

Initial condition and pQCD details

Fully factorised ansatz, momentum distributions at Q_0^2:

$$
\begin{aligned}
\mathcal{F}(x_{I\!P}) &= x_{I\!P}^{f_0}\,(1 + f_1 x_{I\!P}^{f_2})\,, \\
\beta\Sigma(\beta, Q_0^2, x_{I\!P}) &= \mathcal{F}(x_{I\!P})\; A_q\; \beta^{B_q}\;(1-\beta)^{C_q}(1 + D_q \beta^{E_q})\,, \\
\beta g(\beta, Q_0^2, x_{I\!P}) &= \mathcal{F}(x_{I\!P}) A_g\; \beta^{B_g}\;(1-\beta)^{C_g}\,.
\end{aligned}
$$

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

pQCD settings @LO

- Evolution and convolution with `QCDNUM17` Botje '11
- ZM VFNS scheme
- $m_c = 1.4$ GeV, $m_b = 4.5$ GeV, $\alpha_s(M_Z^2) = 0.130$, $Q_0^2 = 1.5$ GeV^2 (tuned)
- $\mu_F^2 = \mu_R^2 = Q^2$
- No Q^2 or y cuts imposed

Best-fit results and χ^2 breakdown

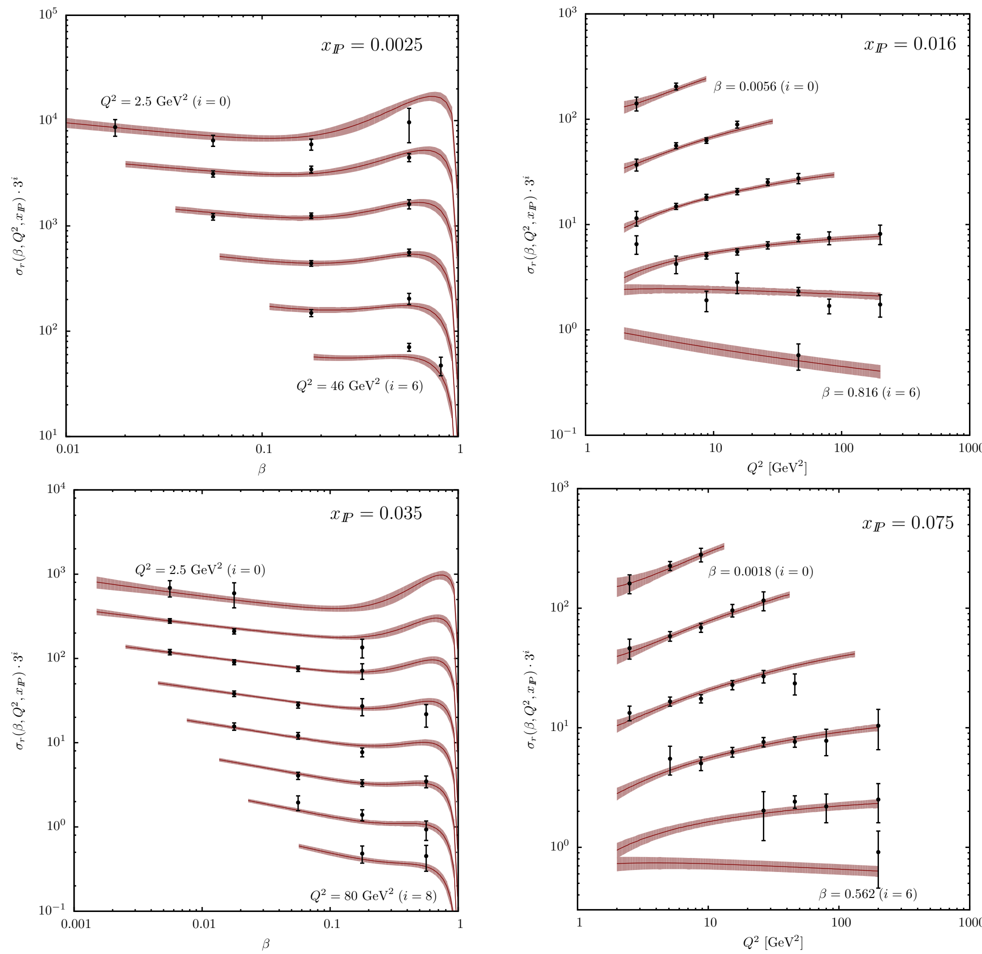
- C_q and C_g difficult to constrain : $C_q = C_g = 0.5$, large β controlled by D_q and E_q
- mild dependence of χ^2 on Q_0^2 (tuned)
- $\chi^2/d.o.f = 167/(192-9) = 0.91$
- parameters well constrained, no misrepresentation in any $x_{I\!P}$ bin

Parameter	$p_i \pm \delta p_i$
f_0	-1.208 $\pm$ 0.022
f_1	48.2 $\pm$ 11.9
f_2	1.42 $\pm$ 0.13
A_q	0.0039 $\pm$ 0.0007
B_q	-0.237 $\pm$ 0.026
C_q	0.5
D_q	22.6 $\pm$ 2.8
E_q	2.28 $\pm$ 0.20
A_g	0.057 $\pm$ 0.011
B_g	0.41 $\pm$ 0.13
C_g	0.5

$x_{I\!P}$	χ^2	Fitted points
0.00035	4.44	4
0.0009	6.78	10
0.0025	21.36	16
0.0085	20.34	24
0.0160	20.70	26
0.0250	27.24	25
0.0350	13.85	24
0.0500	28.69	27
0.0750	13.10	26
0.0900	10.51	10
Total	167.0	192

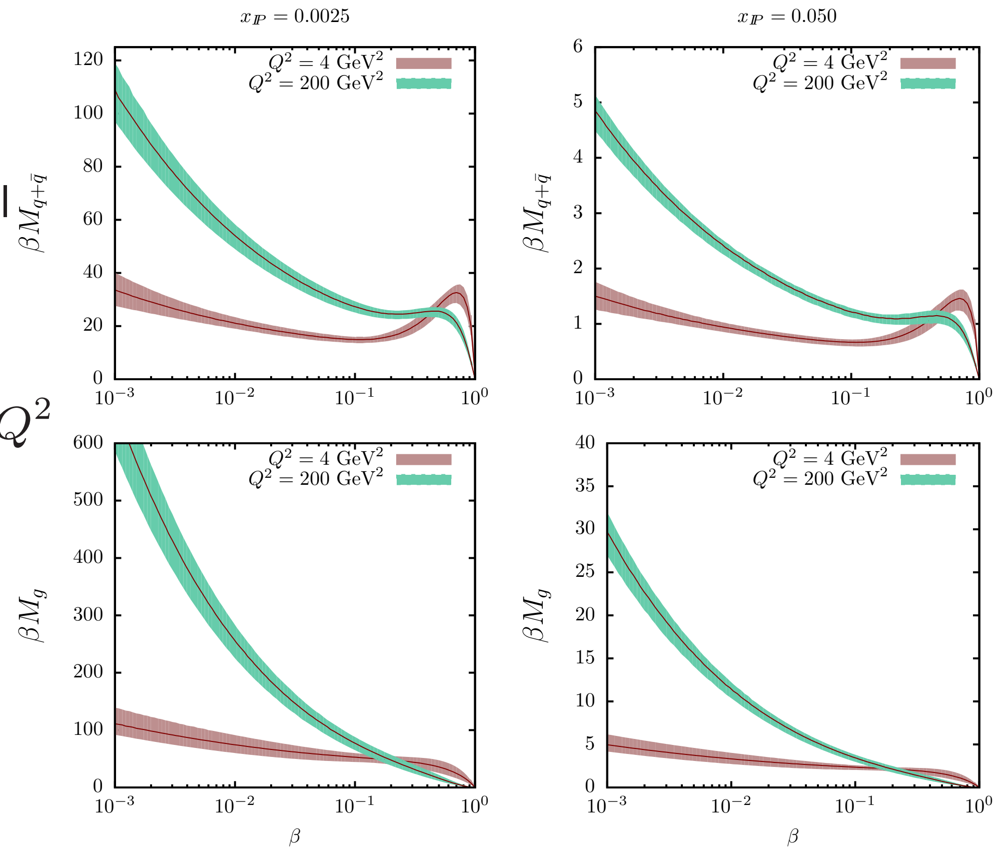
Best-fit vs combined H1ZEUS12 data

- σ_r vs β and Q^2
- the initial condition assumes same β-shape in all $x_{I\!P}$-bins
- this theo bias induces unnatural small error with the standard $\Delta^2_\chi = 1$ criterion.
- Allow for more flexibility: one χ^2-unit for $x_{I\!P}$ bin $\rightarrow \Delta^2_\chi = 10$



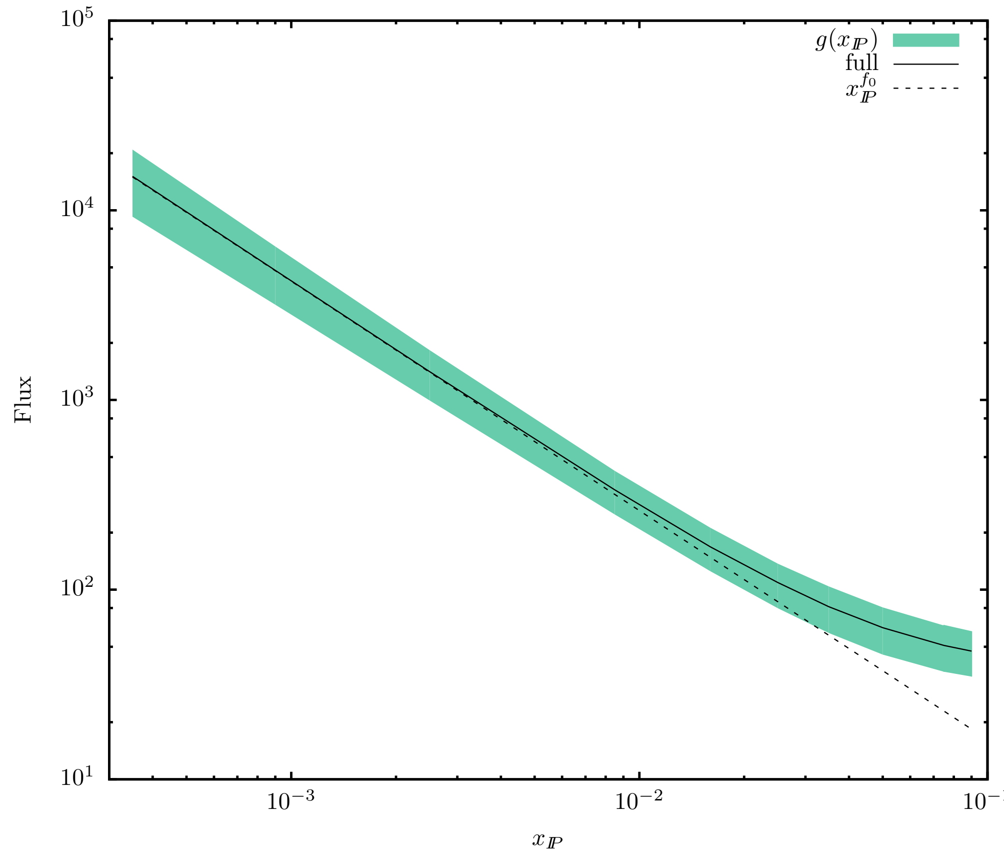
DPDFs evolution

- Singlet and gluon momentum distributions for two different $x_{I\!P}$ at different Q^2
- band: propagation of experimental uncertainties with $\Delta\chi^2 = 10$ (eigenvector method)
- Singlet (top): valence-like at low Q^2
- Gluon (bottom): fast rise with raising Q^2 at low β
- Error shrinkage at high Q^2: effect of pQCD evolution
- Evolution washes away the large-β bump



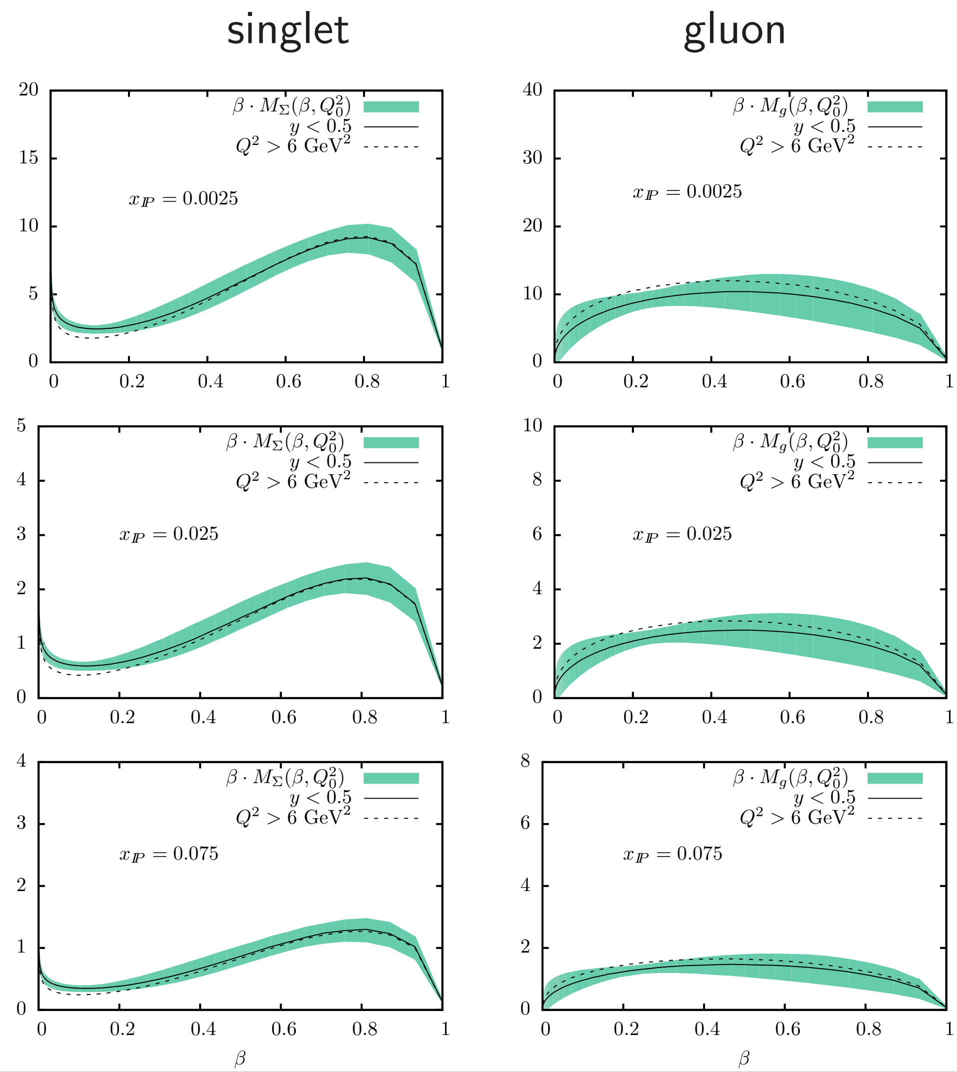
Flux factor

- flux factor with (solid) and without (dashed) the extra power term: $\mathcal{F}(x_{I\!P}) = x_{I\!P}^{f_0}\,(1 + f_1 x_{I\!P}^{f_2})$
- band = best fit + $\Delta\chi^2 = 10$



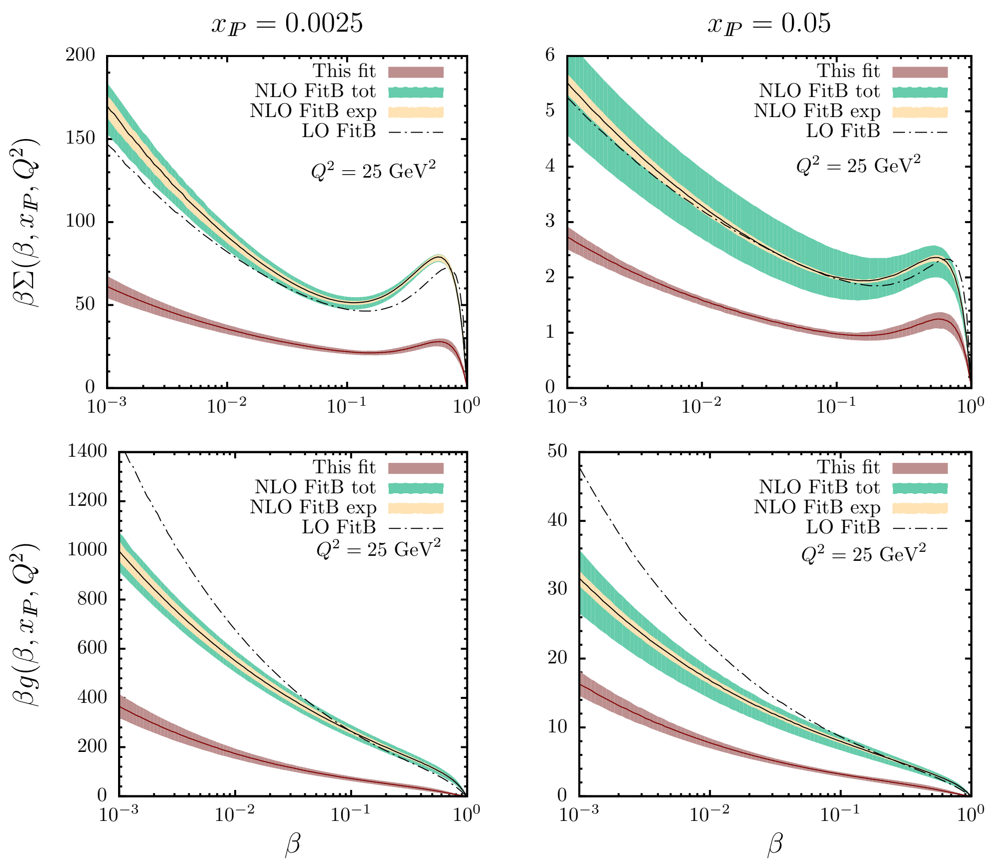
Fit results and stability

- $Q^2 = 1.5$ GeV^2
- Band $=$ best fit $\oplus \Delta\chi^2 = 10$
- stability of the fit checked against variation of the cuts:
- best-fit (band) vs
  fit with $y < 0.5$ (solid)
  fit with $Q^2 > 6$ GeV^2 (dashed)
- insensitive to variation of phase space boundary



Best-fit vs H1 parametrisations

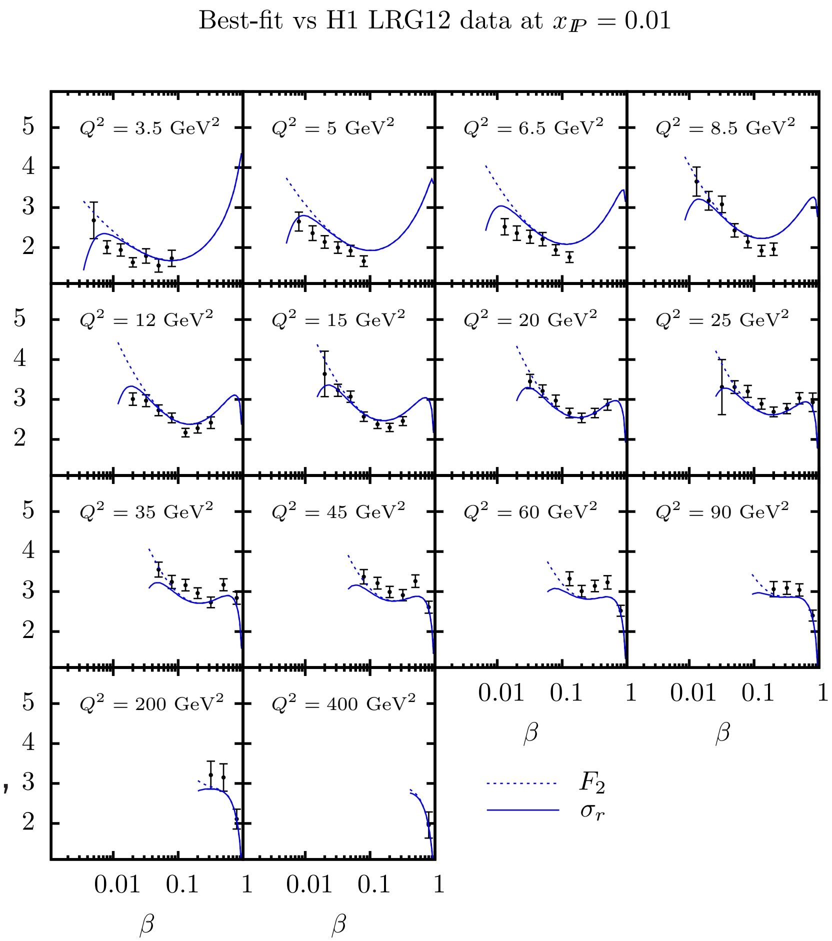
- Singlet (top) and gluon (bottom) momentum distribution at $Q^2 = 25$ GeV^2
- Comparison with FitB (based on LRG06 DDIS data) :
- similar hard valence at large β.
- no gluon structure at at large β
- Reduced errors at large $x_{I\!P}$, where FitB is dominated by systematics errors (for LRG06 : $x_{I\!P}^{max} < 0.03$)



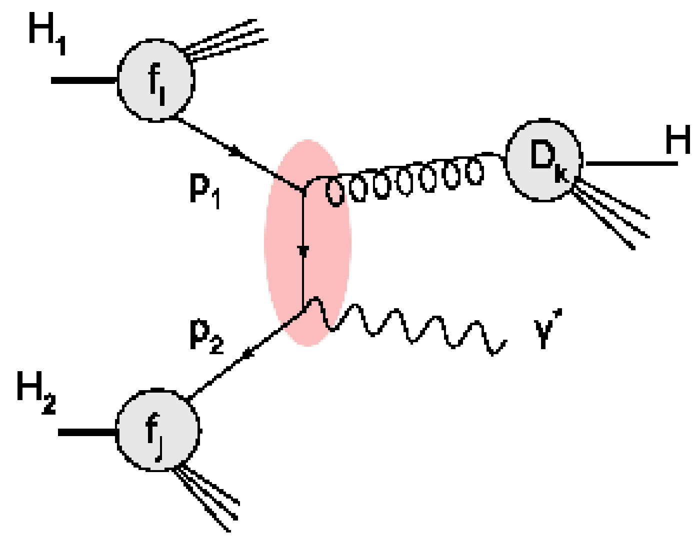
- Normalisations shift due to different t range and proton dissociation background

Preliminar NLO Best-fist vs H1 LRG 2012 data

- preliminar NLO fit ready
  (no error estimates yet)
- comparison with H1 LRG 2012
  inclusive DDIS data
  (H1 Coll. EPJ C72 (2012) 2014)
- $x_{I\!P} = 0.01$: overlap region of
  two data sets
- Best fit scaled up by a factor 2.3:
  - Extrapolation to $0 < |t| < 1$ GeV^2
  - proton dissociative background
- Acceptable description of H1 data in shape,
  BUT Q^2-dependent normalisation offset
- attempt combination?



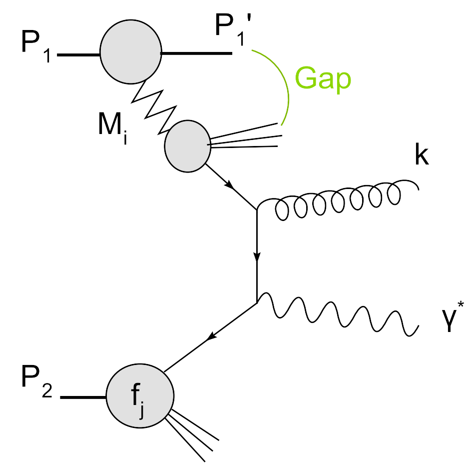
Hadronic collisions : on hard-scattering factorisation



- Hard-scattering factorisation is at the basis of discovery and precision physics at hadron colliders.
- Factorisation proven only for inclusive Drell-Yan (soft exchanges are power suppressed when one sums over final states).
- Generalise: $H_1 + H_2 \to H + \gamma^* + X$
- Assume hard scattering factorisation: $d\sigma \propto f_{H_1} \otimes f_{H_2} \otimes D_H \otimes d\hat{\sigma}$
  - $H = \pi^{\pm}$ at high p_t : factorisation should be ok
  - $H = \pi^{\pm}$ at low p_t : underlying event (beyond factorisation)
  - $H=$ forward p at at low p_t : single-diffractive DY, factorisation breaking

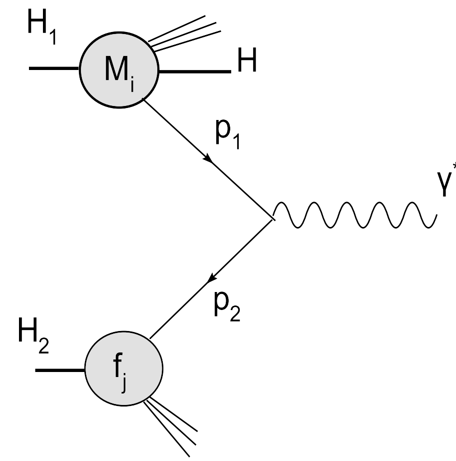
Hard Diffraction at LHC

- 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
  - ...
- Drell-Yan pairs provide easily tunable Q^2 (relevant scale)

Single Diffractive DRell-Yan: details



- SD-DY cross section written in terms of final state lepton rapidities y_3, y_4 and transverse momentum p_t

- $Y = \frac{1}{2}(y_3 + y_4)\,, \qquad \bar{y} = \frac{1}{2}(y_3 - y_4)$

- $\beta = \frac{x_1}{x_{I\!P}} = \frac{p_t}{x_{I\!P}\sqrt{s}}(e^{y_3} + e^{y_4}) \equiv \frac{M_{\mu\mu}}{x_{I\!P}\sqrt{s}} e^{Y}$

- $x_2 = \frac{p_t}{\sqrt{s}}(e^{-y_3} + e^{-y_4}) \equiv \frac{M_{\mu\mu}}{\sqrt{s}} e^{-Y}$

- Assume factorisation:

$$\frac{d\sigma^D}{dy_3 dy_4 dp_t dx_{I\!P}} = \sum_q e_q^2 \frac{f_q^D(\beta, x_{I\!P}, \mu_F^2)}{x_{I\!P}} f_{\bar{q}}(x_2, \mu_F^2) \frac{2p_t\hat{s}}{3s} \frac{2\pi\alpha_{em}^2}{\hat{s}^2} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2}$$

- factorisation scale : $\mu_F = M_{\mu\mu}$
- f_q^D from the fit, f_q CTEQ6@LO

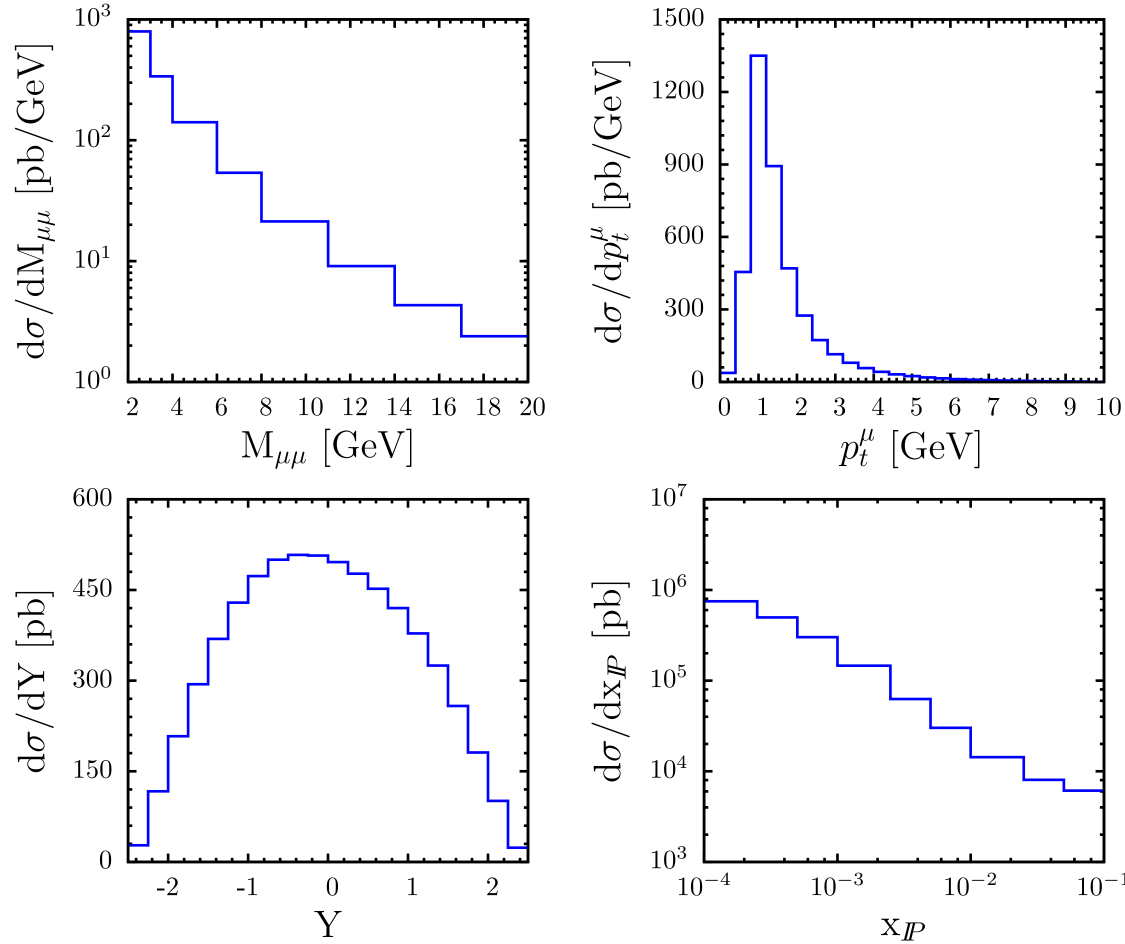
SD-DY fiducial cross sections

pp	$\sqrt{s}$=13 TeV
Muon pair kinematics	$\lvert y^{\mu}\rvert < 2.45$ $2 <$ M$_{\mu\mu} < 20$ GeV No cuts on muon p_t or $\boldsymbol{p}$
Proton kinematics	$0.09 < \lvert t\rvert < 0.55$ GeV^2 $10^{-4} < x_{I\!P} < 10^{-1}$
$\sigma^{SD,DY}$	1635 $\pm$ 60 (exp) $^{+650}_{-460}$ (scale) pb

- single-side result (x2 double side)
- the result does not include SGR
- integrated over the t-range of the out of which dPDFs are estracted.
- dominated by theo errors associated with higher order corrections
- if $\mathcal{L}^{-1} = 0.4$pb^{-1}, $N = 1635$pb $\cdot\, 2 \cdot 0.1 \cdot 0.4$pb^{-1} $= 130$ events

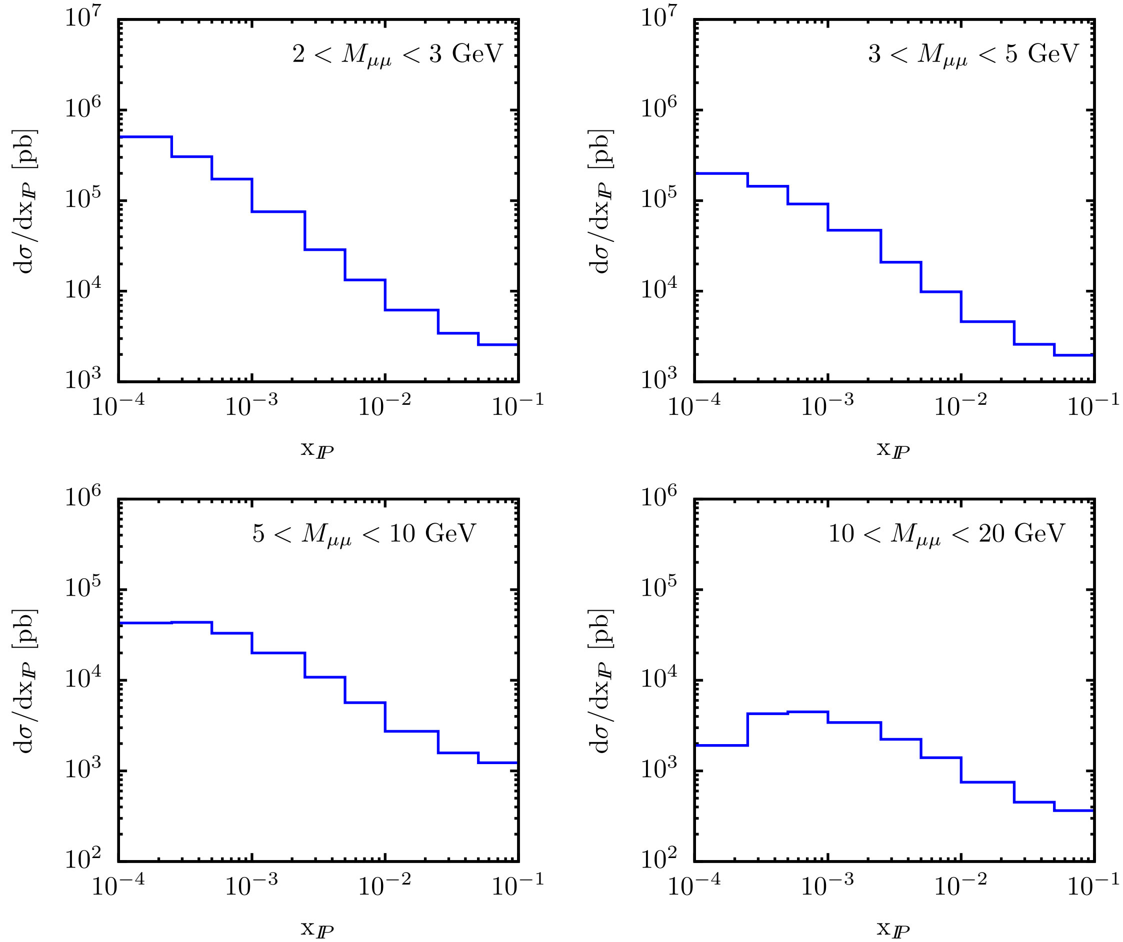
SD-DY cross sections, first glance

- p_t distribution as a maximum at $M_{\mu\mu}^{min}$
- jacobian peak
- Scattered proton at positive $Y \sim 9$
- DY pair has a rather symmetric Y distribution



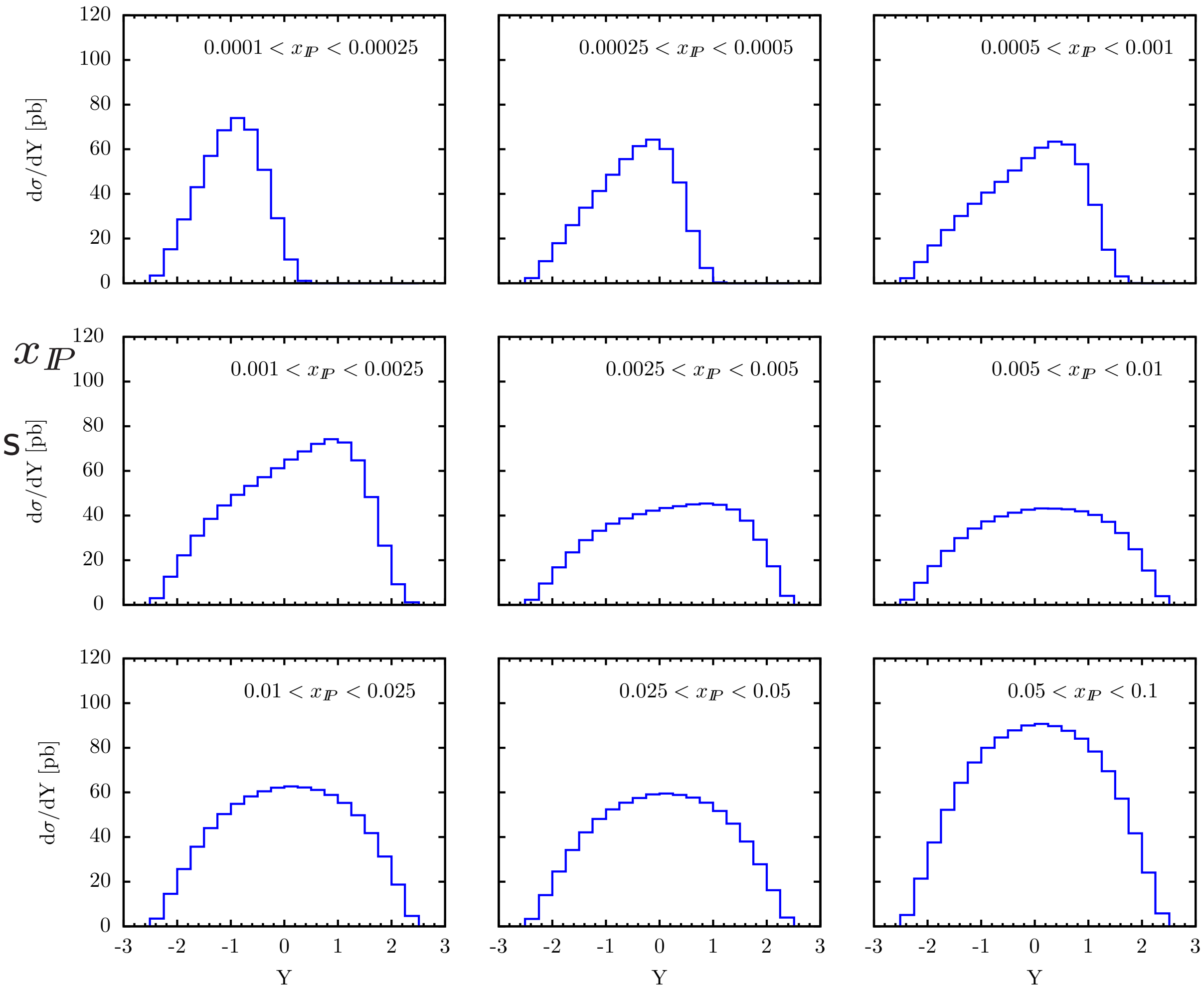
$x_{I\!P}$-dependence

- at low $M_{\mu\mu}$ behaves as inverse power of $x_{I\!P}$
- at higher masses, the pomeron has not enough energy to produce the pair: $\Rightarrow$ $x_{I\!P}$ distributions flattens at low $x_{I\!P}$



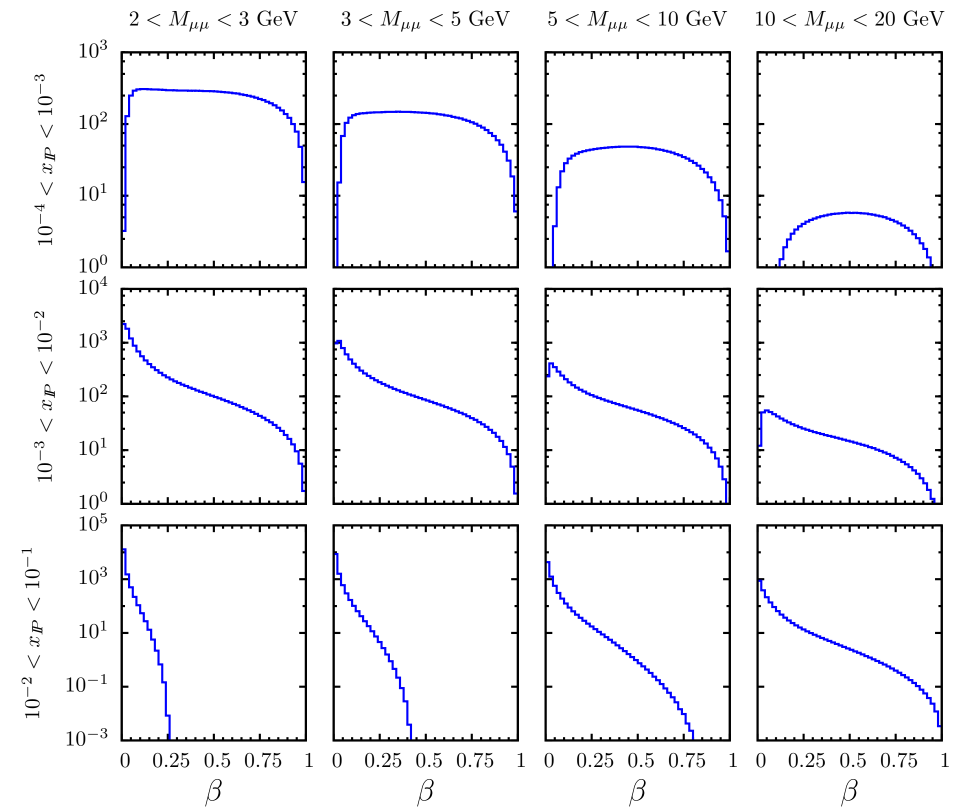
$x_{\mathbb{P}}$-Y correlations

- cross section integrated over masses $2 < M_{\mu\mu} < 20$ GeV
- rapidity of the pair Y strongly correlated with $x_{\mathbb{P}}$
- at large $x_{\mathbb{P}}$ distributions get rather symmetric
- $Y < 0$ dissociated proton direction



Universality and diffractive PDFs

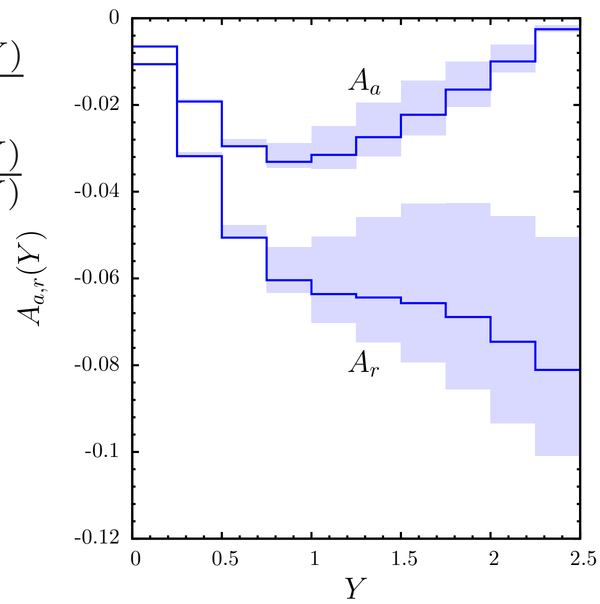
- Sensitivity of the measurement to diffractive PDFs
- β is fractional momentum with respect to the pomeron
- recall : $M_{\mu\mu}^2 = \beta x_{I\!P} x_1 s$
- Up to normalisation effects, is dPDFs β-dependence in hadronic collisions compatible with the one observed at HERA? (pomeron universality)

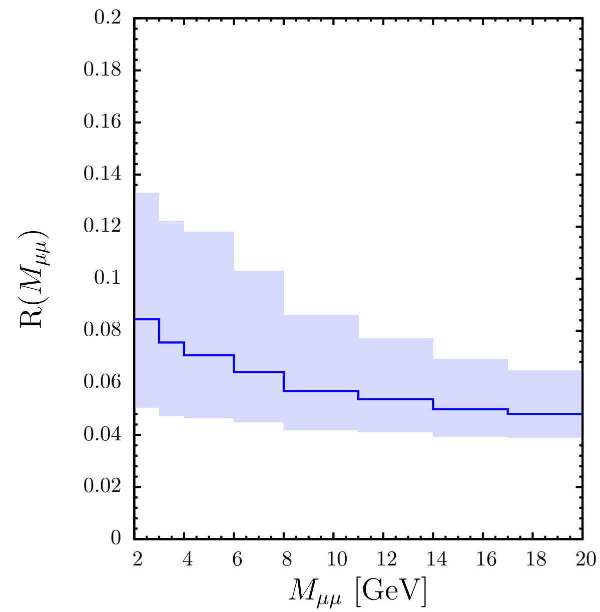


SD-DY: asymmetries and ratio

Control theoretical error $\Rightarrow$ consider ratios

- $A_a(Y) = \frac{d\sigma(Y) - d\sigma(-Y)}{\sigma^{SD,DY}}$
- $A_r(Y) = \frac{d\sigma(Y) - d\sigma(-Y)}{d\sigma(Y) + d\sigma(-Y)}$
- NB: inclusive DY does not show such an asymmetry





- $R = \frac{\sigma(pp \to pXY)}{\sigma(pp \to XY)}$
  - peculiar $M_{\mu\mu}$ dependence of the ratio
  - slowly decreasing from 9% to 5% (no SGR included)

Some phenomenological speculation

	DIS	PHP	hadronic collisions
MPI	no	?	yes
factorisation in diffraction	yes	?	no

- DIS : $|b| \sim 1/Q$ (c.f.r. dipole model, Nikolaev and Zakharov '91)
- hadronic collision : $|b| \sim 1/\Lambda_{QCD}$

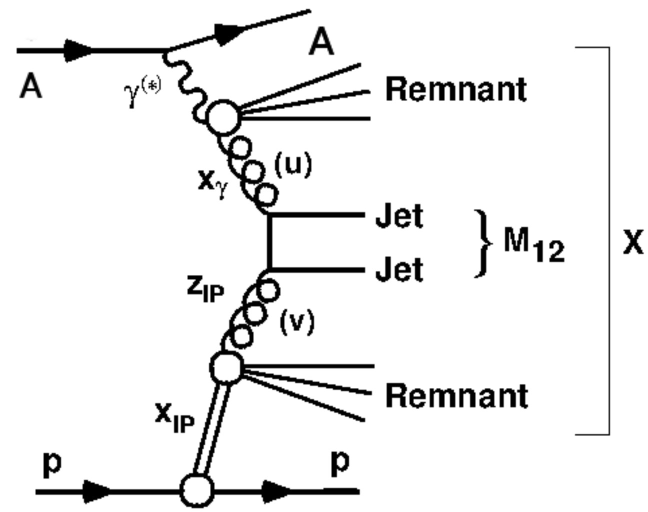
$\Rightarrow$ Critical is then the transverse profile $T(\boldsymbol{b})$ of the probe:
$\boldsymbol{b}$ relative distance of interacting partons (from double parton scattering)

rethink diffraction:

$$\sigma^{SD} \propto \int d^2\boldsymbol{b}\; T_{a=\gamma^*,\gamma,p}(\boldsymbol{b})\; T_{b=p}(\boldsymbol{b})$$

LHC as a γp machine

PHP regime crucial for studying factorisation breaking and the transition from large to small b (interparton transverse distance) of the probe:
Can we use pA collisions at LHC to exploits the large quasi-real photon flux from A to measure diffractive dijets in γp?



- Hard scale in the final state :
  like in PHP in ep they guarantee the applicability of pQCD techniques.
- Factorisation breaking related to jets E_T or to size $b \sim 1/Q$ of the quasi-real photon?

Conclusions and Perspectives

- Impressive knowledge on hard diffraction accumulated by HERA and Tevatron
- This knowledge is quantitative and predictive (dPDFs etc.)
- Hard diffraction program at hadron collider:
  - Prediction: with $0.4\text{pb}^{-1} \sim 130$ SD-DY events
  - SD-DY is ideal place to study details of factorisation breaking vs Q^2, $\sqrt{s}$
  - Explore the feasibility to use LHC pA runs in γp mode to settle the diffrative PHP factorisation issue raised at HERA
- Plans (in stand-by):
  - NLO fit $\rightarrow$ can be used to predict cross section in other SD channel: dijet,prompt photon,W
  - Impact of higher order corrections : SD-DY @ NLO