

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

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QCD at LHC: forward physics and UPC collisions of heavy ions,
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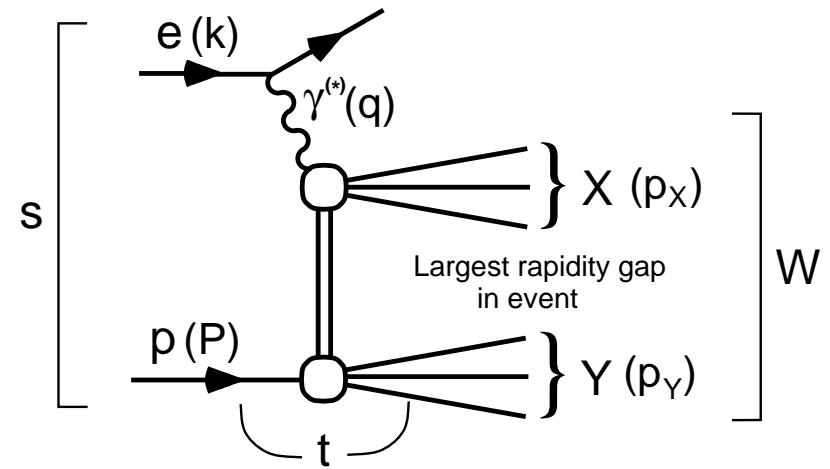
F.A.Ceccopieri, e-Print: arXiv:1606.06134, to appear in EPJC

Outline

- 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
- Investigate factorisation breaking effects vs Q^2 , \sqrt{s} ...

Hard diffraction in DIS

- Experiment
 - (hard) diffraction rebirth at HERA
 - $e(k) + p(P) \rightarrow e(k') + p(P') + X$
- kinematics
 - proton fragmentation region
 - $|t| \leq 1 \text{ GeV}^2$
 - $x_{IP} \simeq 1 - E_{P'}/E_P < 0.1$
- 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 \rightarrow parton dynamics



Theory setup in DDIS

- Hard-scattering factorisation:

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

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: $f_i^D(\beta, \mu_F^2, x_{IP})$
- Partonic structure of the colourless exchange
- DPDFs obey DGLAP evolution equations (for t integrated up to $t_{max} \ll Q^2$)

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

- Phenomenological analyses of DPDFs via pQCD fits of DDIS data

Factorisation in hard diffraction: overview

- Diffractive PDFs have been used to test hard-scattering factorisation in

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

- Results:

- dijet in DIS: data/NLO $\simeq 1$

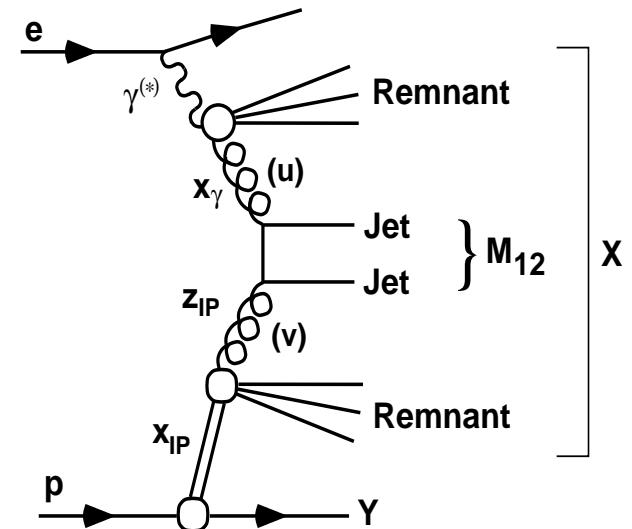
- dijet in PHP: **debated**

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**

- Event phase space:

$$\text{PHP} : Q^2 < 2 \text{ GeV}^2$$

$$\text{DIS} : 4 \text{ GeV}^2 < Q^2 < 80 \text{ GeV}^2$$

- diffractive phase space:

$$0.010 < x_{IP} < 0.024$$

- jet phase space:

$$E_T^{*\text{jet}1(2)} > 5.5(4.0) \text{ GeV}$$

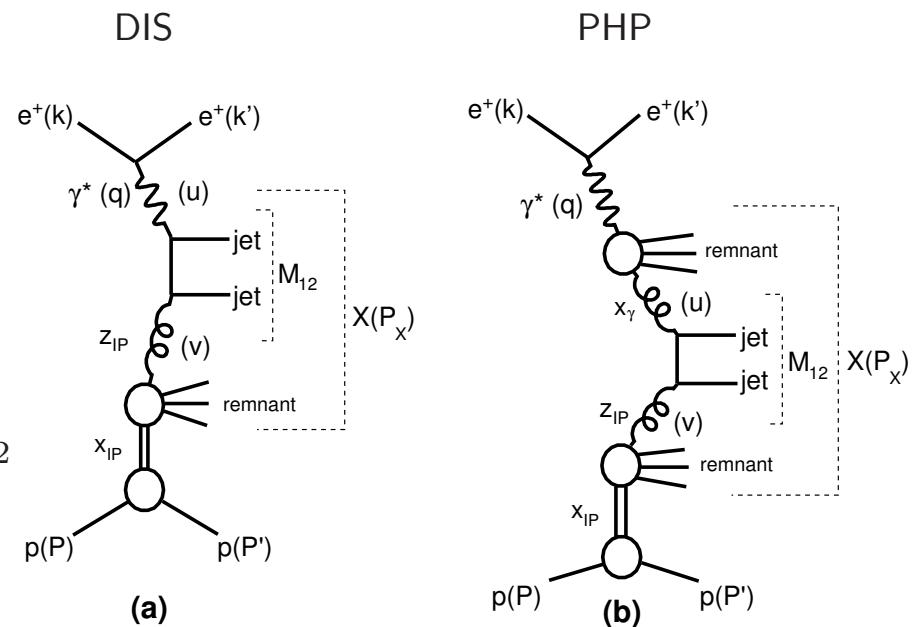
- Theory**

- NLO accuracy

$$2. \text{ scale set to } \mu_R^2 = \mu_F^2 = \langle E_T^{*\text{jet}} \rangle^2 + Q^2$$

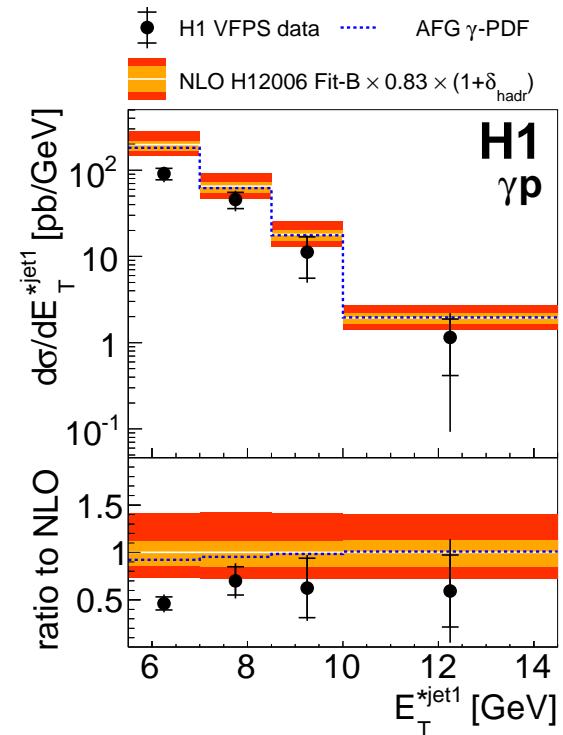
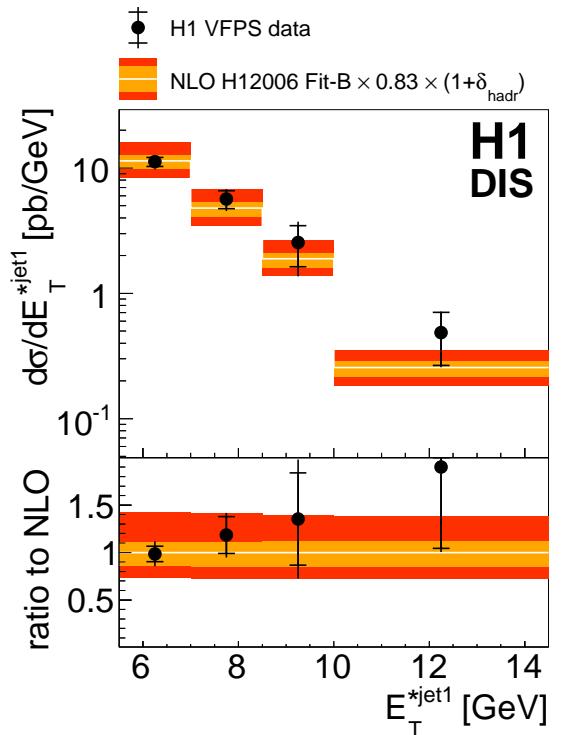
- Theo uncertainty: $\mu \rightarrow 0.5\mu, 2.0\mu$

- DPDFs from previous H1 '06 analysis



Results: $E_T^{*\text{jet}1}$ distribution

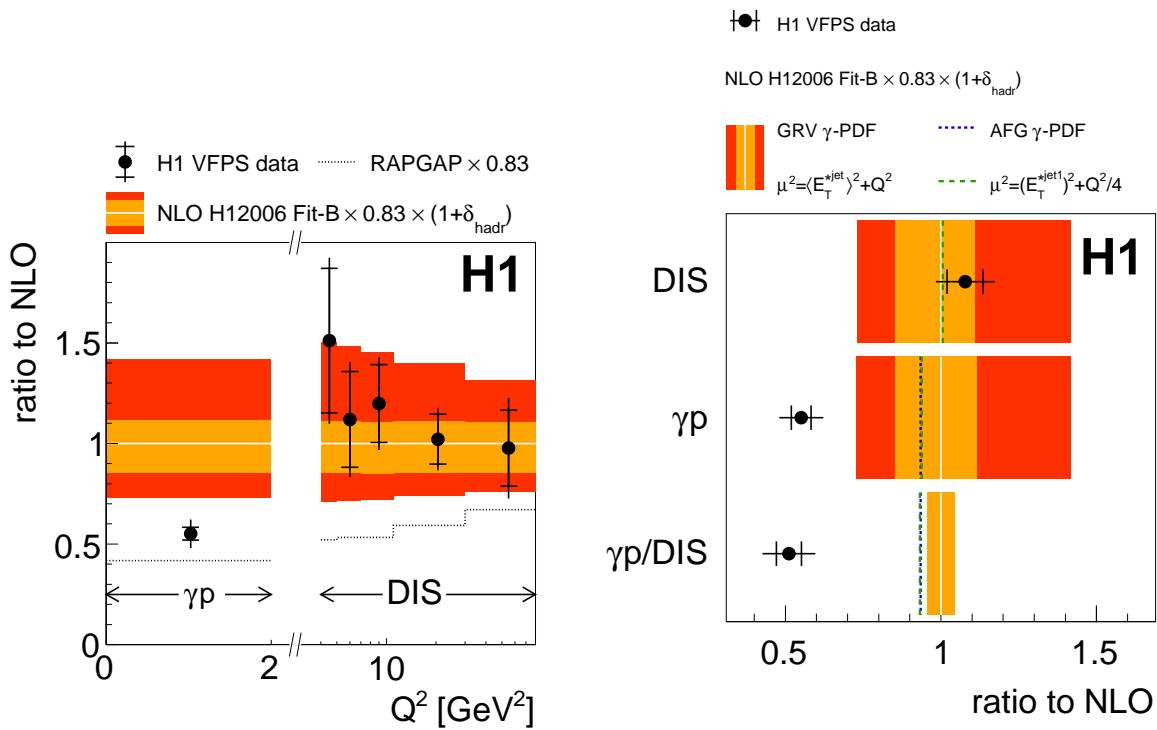
- $E_T^{*\text{jet}1}$:
leading jet
transverse energy
- distribution controlled by ME : E_T^{-4}
- large NLO corrections
- E_T -dependence of the suppression not confirmed
- Desiderata:
– Diffractive PHP at higher E_T with good statistics



Results: double ratios

- large NLO corrections:
jets produced nearly
at threshold (soft
gluon resum?)
- ↪ Consider ratios
- H1 confirms an
overall suppression
factor ~ 0.5
- Critical variable: Q^2
not E_T

Emerging picture:



- ⇒ factorisation **broken** for (spatially extended) hadrons
 ⇒ 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 diffractive 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
 - $2.5 < Q^2 < 200 \text{ GeV}^2$
 - $0.00035 < x_{IP} < 0.09$
 - $0.09 < |t| < 0.55 \text{ GeV}^2$ (**restricted t -range to avoid extrapolations**)
 - $10^{-3} < \beta < 1$

Fitting strategy

Remarks:

- hard-scattering factorisation holds at fixed values of x_{IP} and t
- dependence on x_{IP} 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_{IP} and t .
- Approach exploited in F.A.C and L.Favart arXiv:1205.6356

H1ZEUS12 data:

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

Initial condition and pQCD details

Fully factorised ansatz, momentum distributions at Q_0^2 :

$$\begin{aligned}\mathcal{F}(x_{IP}) &= x_{IP}^{f_0} (1 + f_1 x_{IP}^{f_2}), \\ \beta \Sigma(\beta, Q_0^2, x_{IP}) &= \mathcal{F}(x_{IP}) A_q \beta^{Bq} (1 - \beta)^{Cq} (1 + D_q \beta^{E_q}), \\ \beta g(\beta, Q_0^2, x_{IP}) &= \mathcal{F}(x_{IP}) A_g \beta^{Bg} (1 - \beta)^{Cg}.\end{aligned}$$

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

pQCD settings @LO

- Evolution and convolution with QCDCNUM17 Botje '11
- ZM VFNS scheme
- $m_c = 1.4 \text{ GeV}$, $m_b = 4.5 \text{ GeV}$, $\alpha_s(M_Z^2) = 0.130$, $Q_0^2 = 1.5 \text{ GeV}^2$ (tuned)
- $\mu_F^2 = \mu_R^2 = Q^2$
- No Q^2 or y cuts imposed

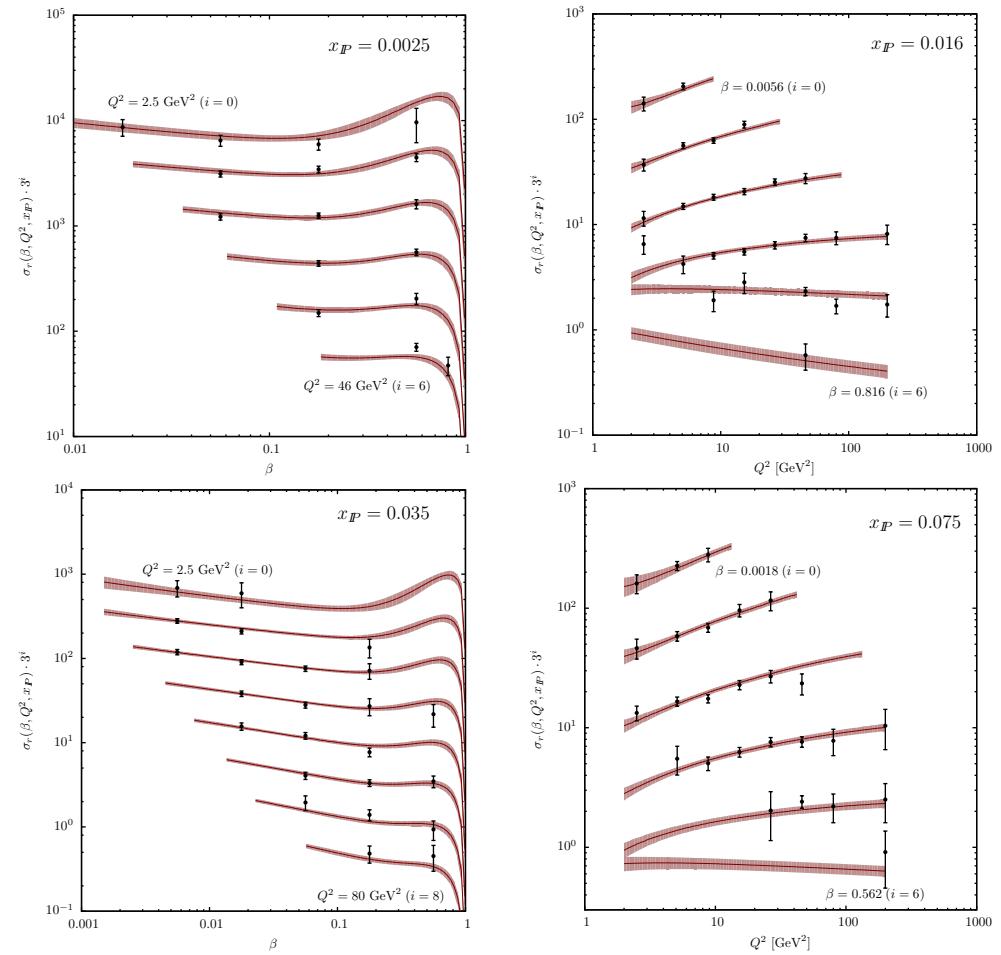
Best-fit results and χ^2 breakdown

- 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)
- $\chi^2/d.o.f = 167/(192 - 9)$
- parameters well constrained, no misrepresentation in any x_{IP} bin

Parameter	$p_i \pm \delta p_i$	x_{IP}	χ^2	Fitted points
f_0	-1.208 ± 0.022	0.00035	4.44	4
f_1	48.2 ± 11.9	0.0009	6.78	10
f_2	1.42 ± 0.13	0.0025	21.36	16
A_q	0.0039 ± 0.0007	0.0085	20.34	24
B_q	-0.237 ± 0.026	0.0160	20.70	26
C_q	0.5	0.0250	27.24	25
D_q	22.6 ± 2.8	0.0350	13.85	24
E_q	2.28 ± 0.20	0.0500	28.69	27
A_g	0.057 ± 0.011	0.0750	13.10	26
B_g	0.41 ± 0.13	0.0900	10.51	10
C_g	0.5	Total	167.0	192

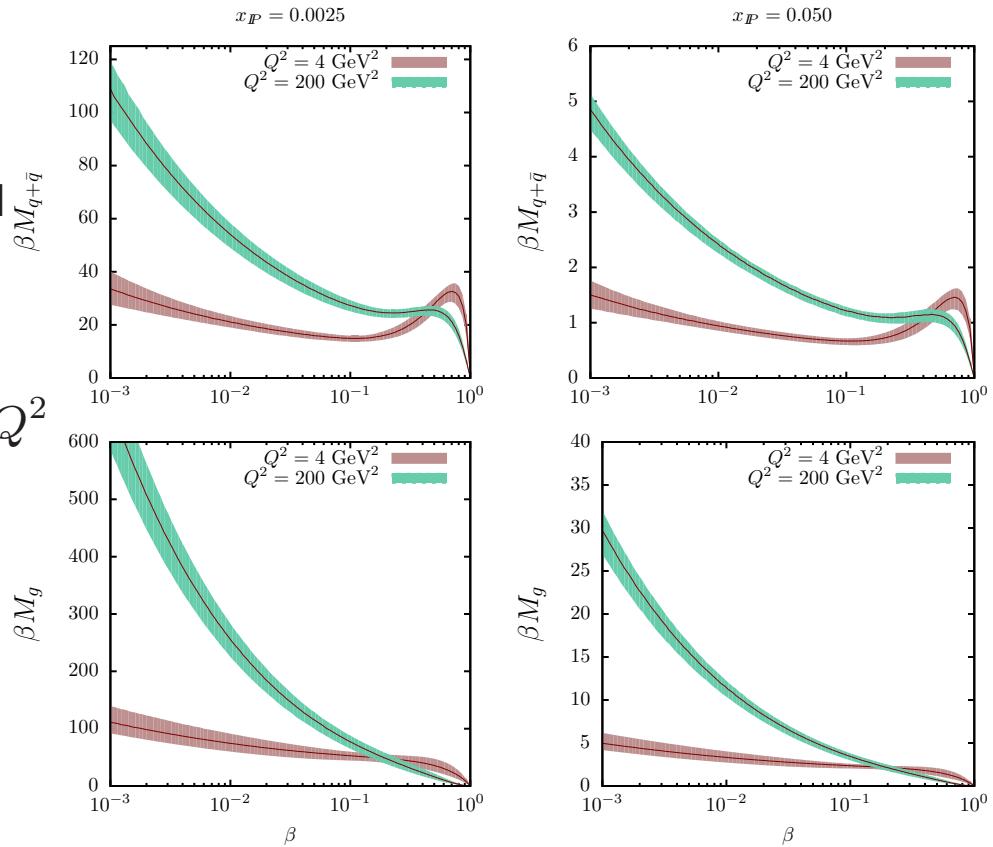
Best-fit vs combined H1ZEUS12 data

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



DPDFs evolution

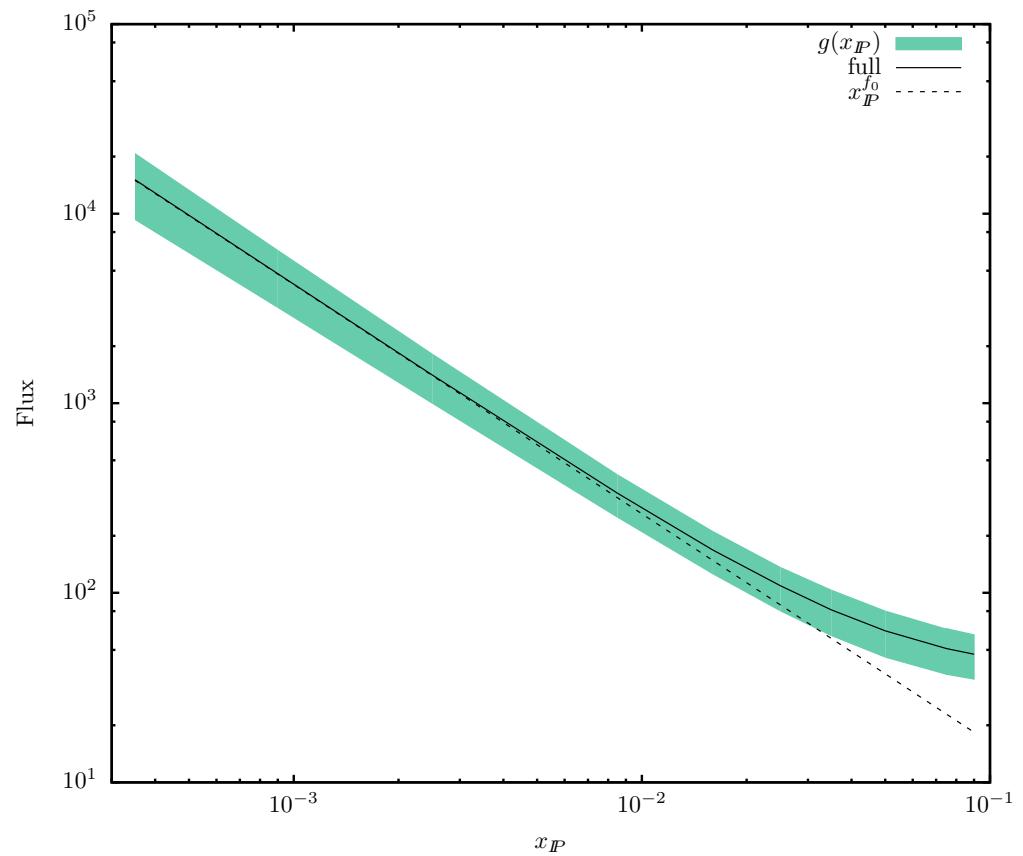
- Singlet and gluon momentum distributions for two different x_{IP} at different Q^2
- band: propagation of experimental uncertainties with $\Delta\chi^2 = 10$ (eigenvector method)
- **Singlet (top)**: valence-like at low Q^2
- **Gluon (bottom)**: fast rise with raising Q^2 at low β
- Error shrinkage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



Flux factor

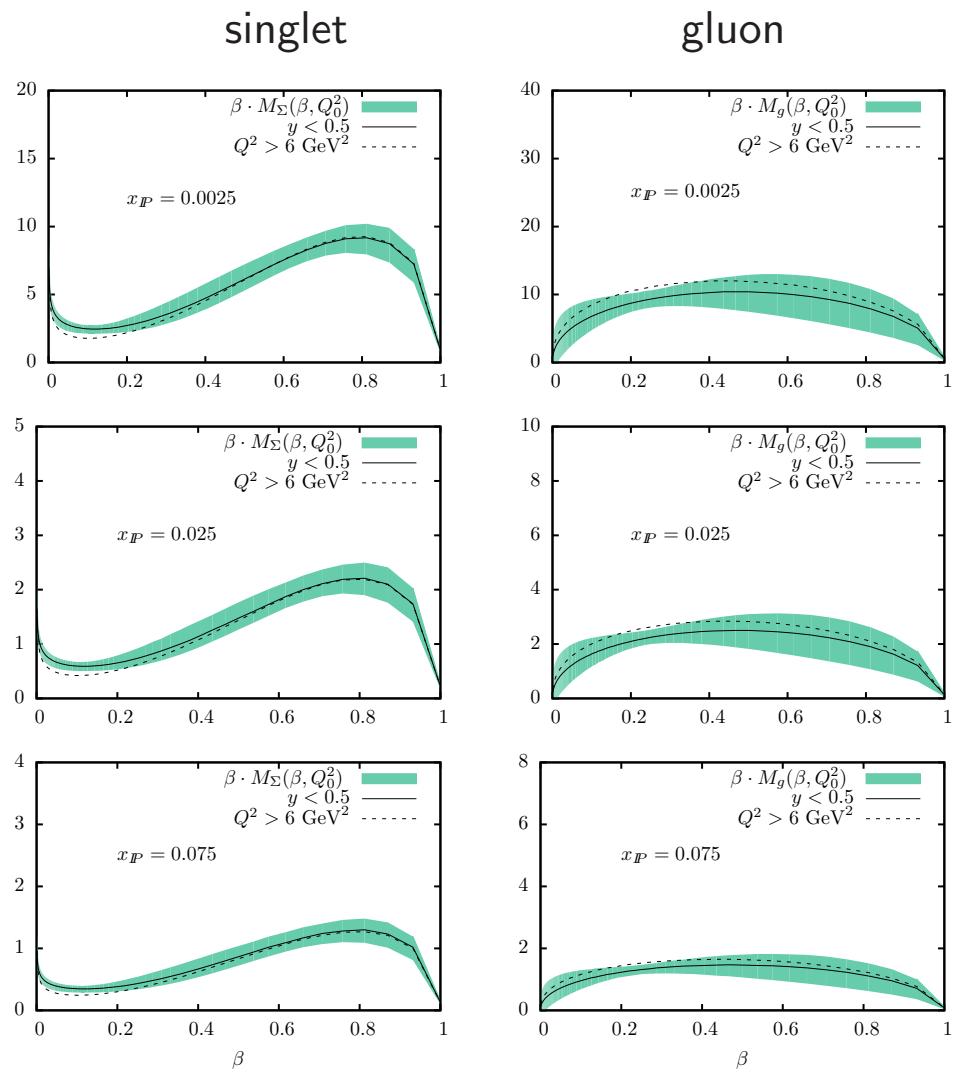
- flux factor with (solid) and without (dashed) the **extra power term**:

$$\mathcal{F}(x_{IP}) = x_{IP}^{f_0} (1 + f_1 x_{IP}^{f_2})$$
- band = best fit + $\Delta\chi^2 = 10$



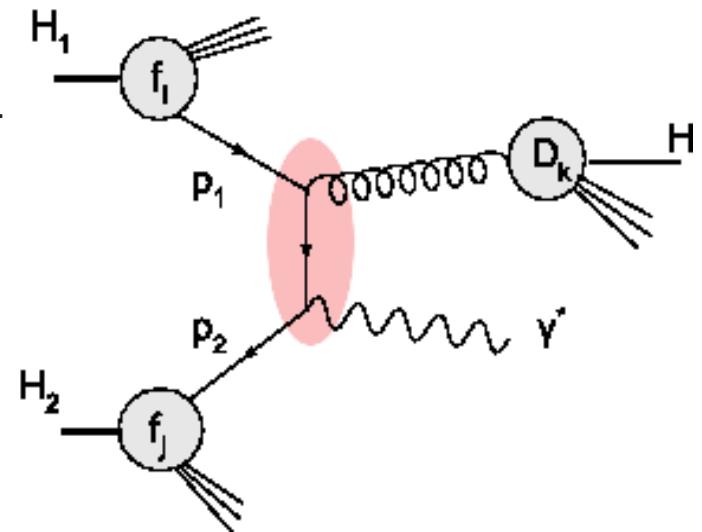
Fit result and stability

- $Q^2 = 1.5 \text{ GeV}^2$
- 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 $Q^2 > 6 \text{ GeV}^2$ (dashed)
- **insensitive** to variation of phase space boundary



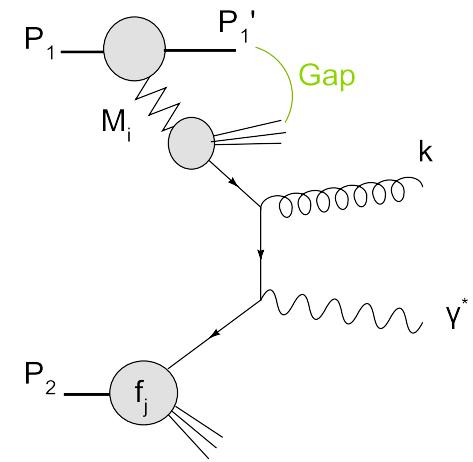
On hard-scattering factorisation

- 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: $H_1 + H_2 \rightarrow H + \gamma^* + X$
- Assume hard scattering factorisation:
 $d\sigma \propto f_{H_1} \otimes f_{H_2} \otimes D_H \otimes d\hat{\sigma}$
 - $H = \pi^\pm$ at high p_t : factorisation should be ok
 - $H = \pi^\pm$ at low p_t : underlying event (beyond factorisation)
 - $H =$ forward p at 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
 - ...
- DY provides easily tunable Q^2 (relevant scale)



SD-DY: cross section details

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

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

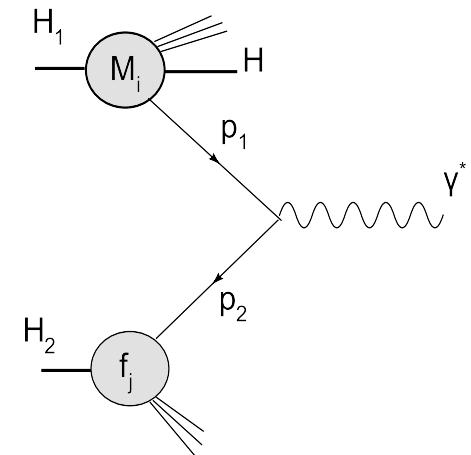
- $\beta = \frac{x_1}{x_{IP}} = \frac{p_t}{x_{IP}\sqrt{s}}(e^{y_3} + e^{y_4}) \equiv \frac{M_{\mu\mu}}{x_{IP}\sqrt{s}}e^Y$

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

- Assume factorisation:

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

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



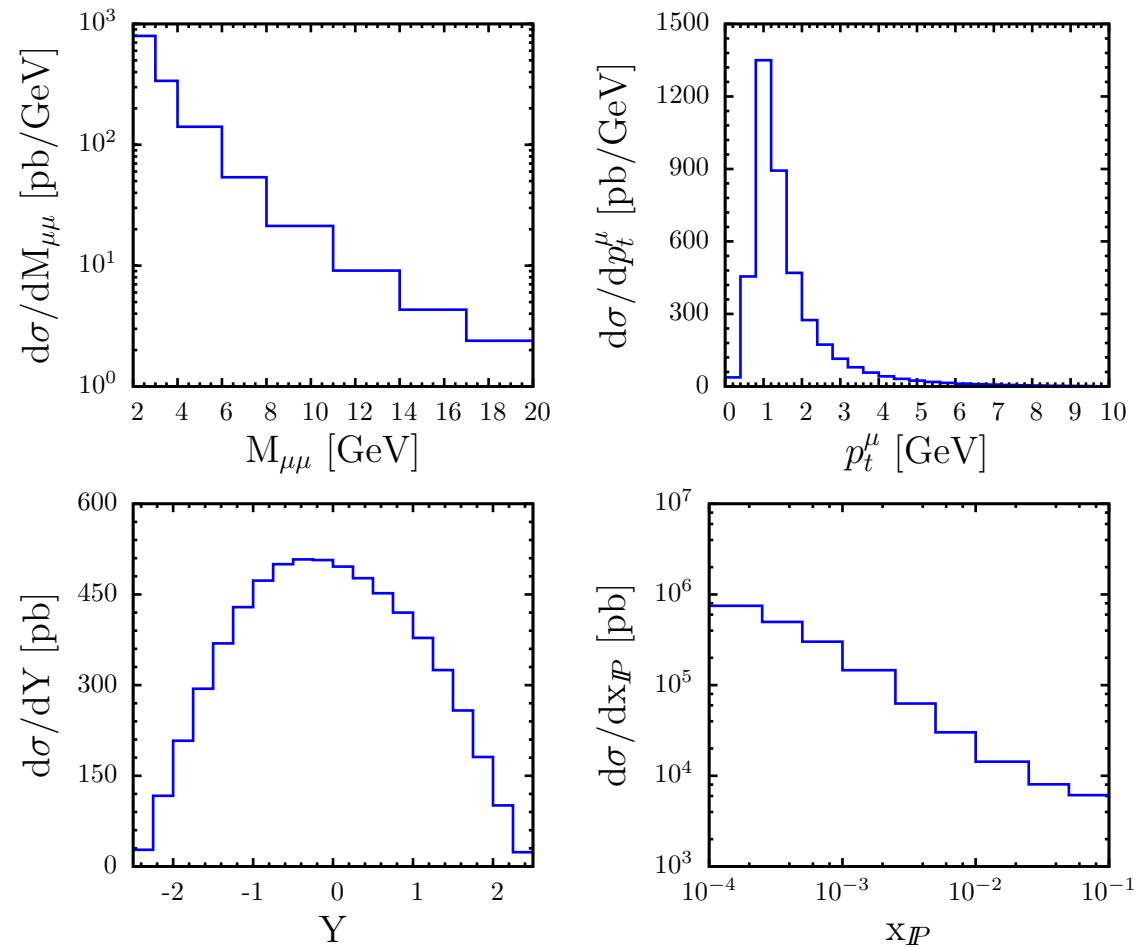
SD-DY fiducial cross sections

pp	$\sqrt{s}=13 \text{ TeV}$
Muon pair kinematics	$ y^\mu < 2.45$ $2 < M_{\mu\mu} < 20 \text{ GeV}$ No cuts on muon p_t or \mathbf{p}
Proton kinematics	$0.09 < t < 0.55 \text{ GeV}^2$ $10^{-4} < x_{IP} < 10^{-1}$
$\sigma^{SD,DY}$	$1635 \pm 60 \text{ (exp)} \begin{array}{l} +650 \\ -460 \end{array} \text{ (scale) pb}$

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

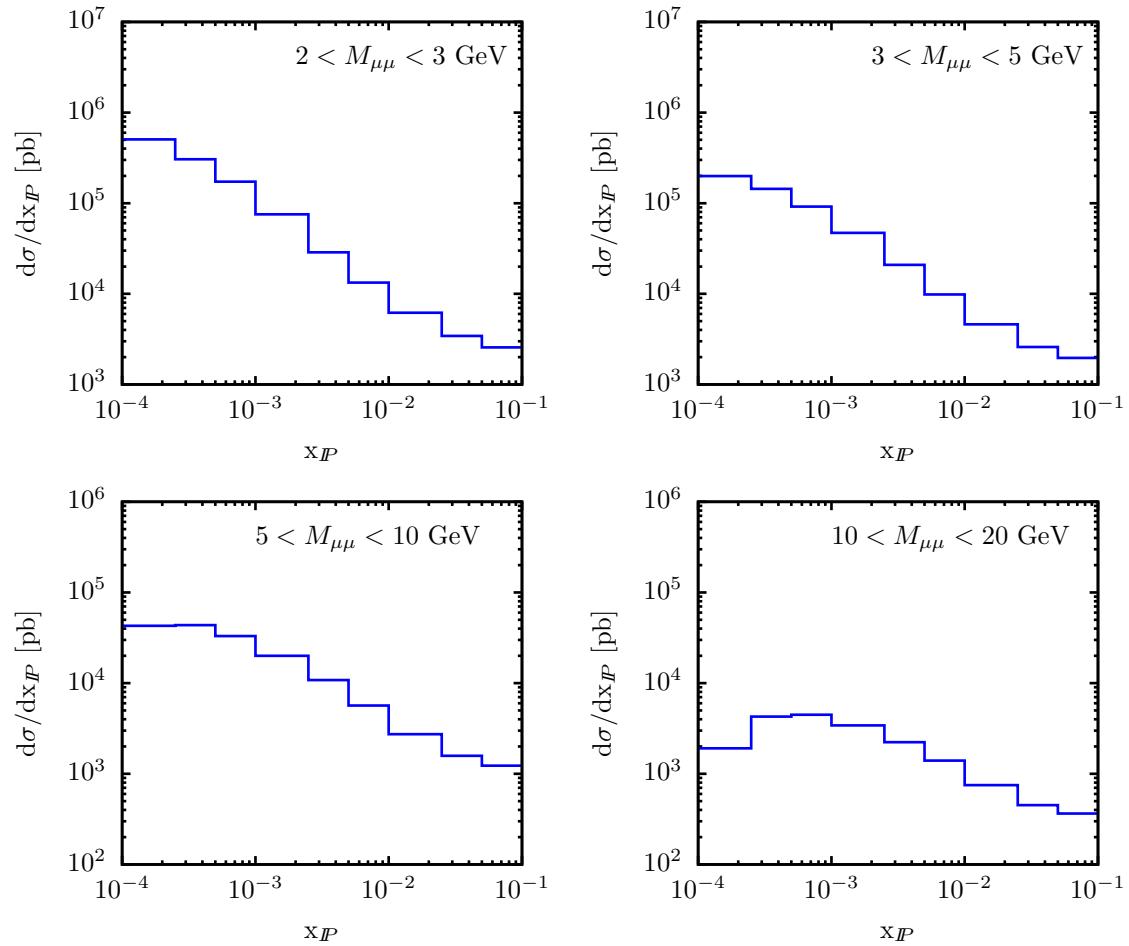
SD-DY cross sections, first glance

- 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



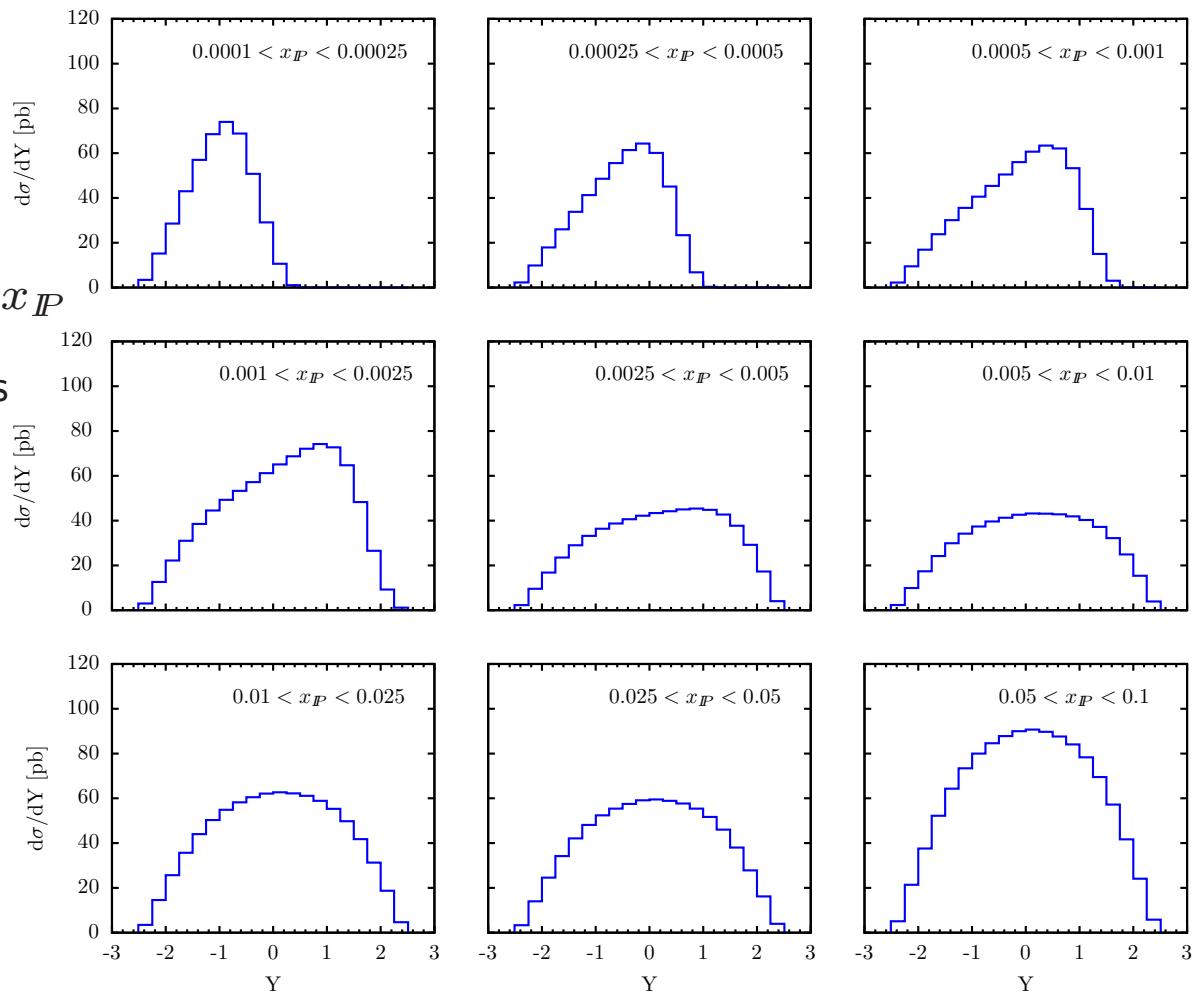
x_{IP} -dependence

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



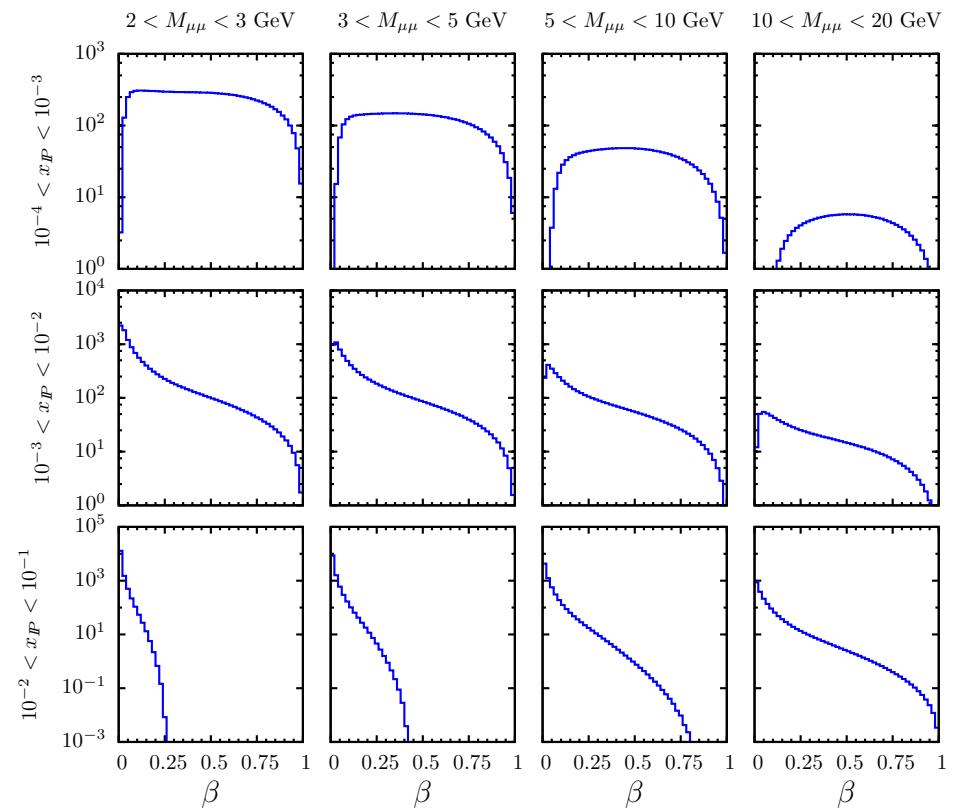
x_{IP} -Y correlations

- cross section integrated over masses
- rapidity of the pair Y strongly correlated with x_{IP}
- at large x_{IP} 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 : $M_{\mu\mu}^2 = \beta x_P x_1 s$



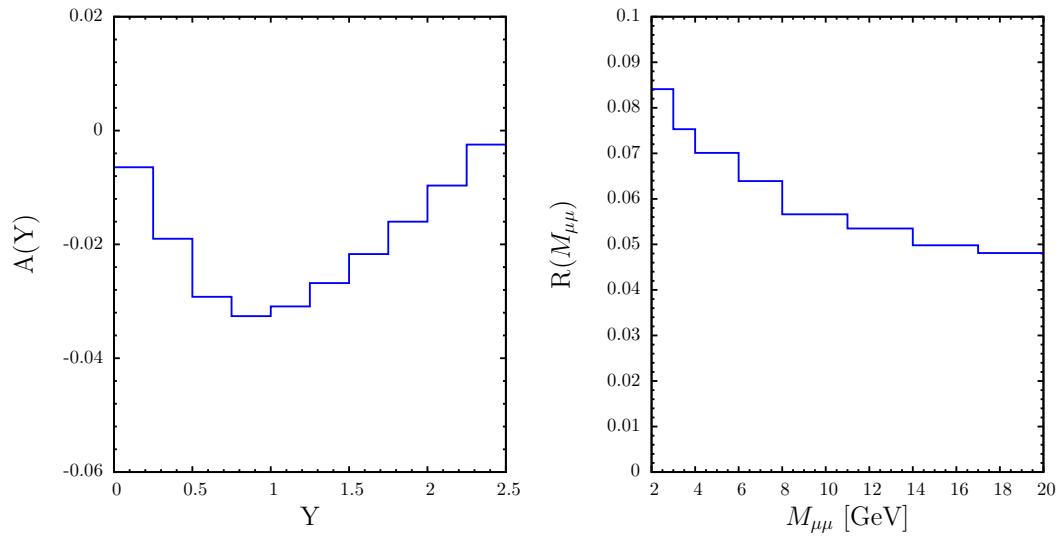
SD-DY: asymmetries and ratio

Control theoretical error:

⇒ consider ratios

- $A(Y) = \frac{d\sigma(Y) - d\sigma(-Y)}{d\sigma(Y) + d\sigma(-Y)}$
- asymmetry observable?
it depends on integrated lumi

- $R = \frac{\sigma(pp \rightarrow pXY)}{\sigma(pp \rightarrow XY)}$
- 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 : $|b| \sim 1/\Lambda_{QCD}$

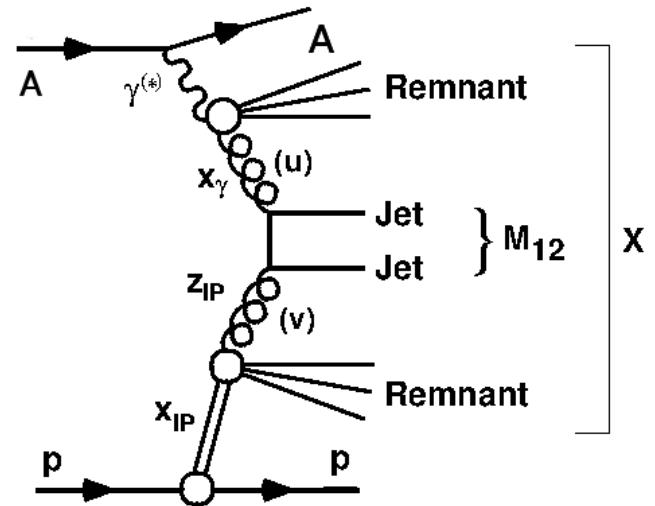
⇒ Critical is then the **transverse profile $T(\mathbf{b})$** of the probe:
 \mathbf{b} relative distance of interacting partons (from double parton scattering)

rethink diffraction:

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

LHC as a γp machine

PHP regime crucial for studying factorisation breaking and the transition from large to small b 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 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}
 - Opportunity to use LHC as a γp machine in pA runs to settle the PHP issue
- near future plan
 - publicly available NLO fit + diffractive W predictions