QCD analysis of diffractive processes

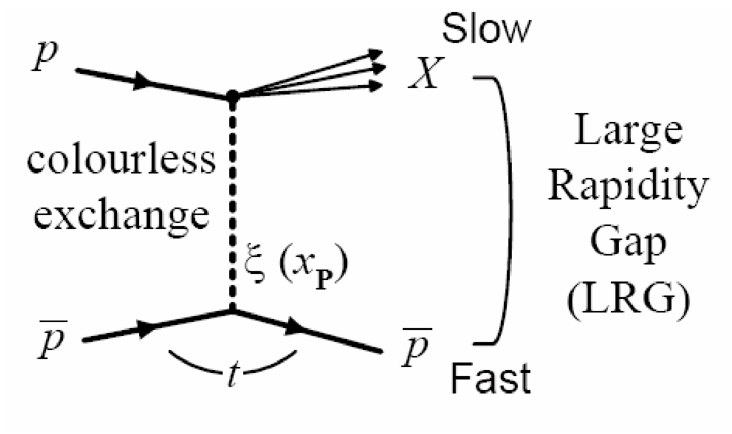
Laurent Schoeffel
CEA Saclay

Panorama of « diffraction » in high energy phyisics :
From the basics (no previous knowledge needed) till the latest developments

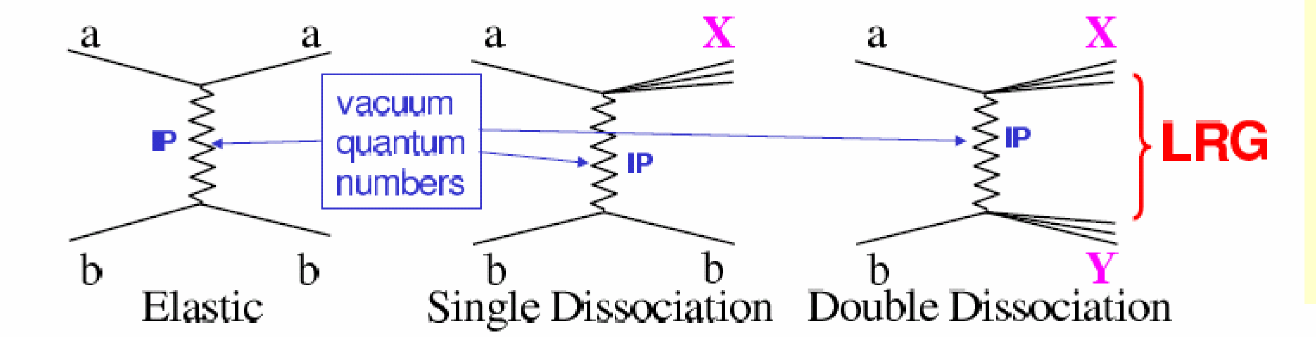
We will talk of 3D picture of the nucleon, GPDs, Higgs searches etc.

Definition of hadronic diffraction

Diffraction in particle physics @ large Energy (s >> t)



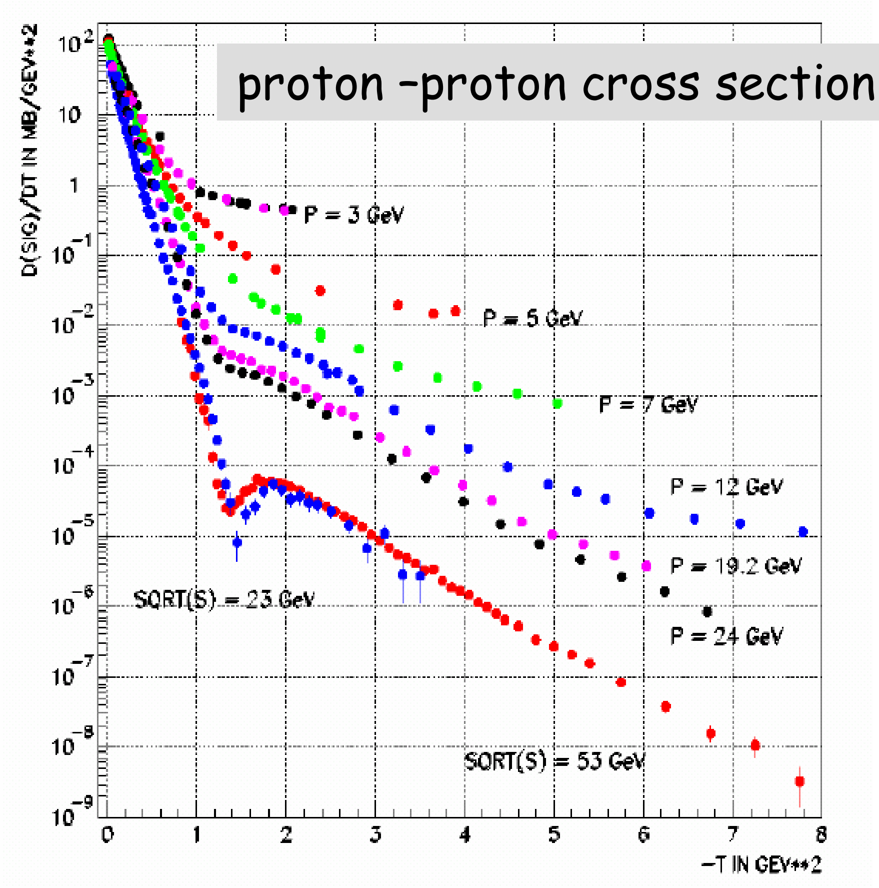
- The proton is left intact or quasi-intact
- Large Rapidity Gap (LRG)
- Vacuum Quantum Number exchange [no colour flow] == Pomeron (IP)



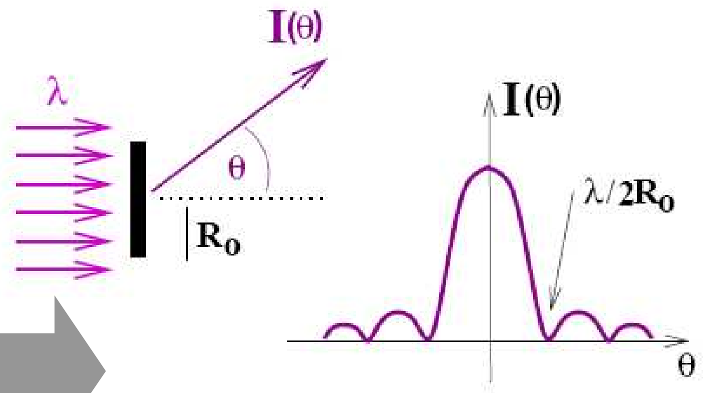
Diffraction : *generalisation* of elastic Scattering

Why « diffraction » ?

proton –proton cross section measurements



Diffraction in optics



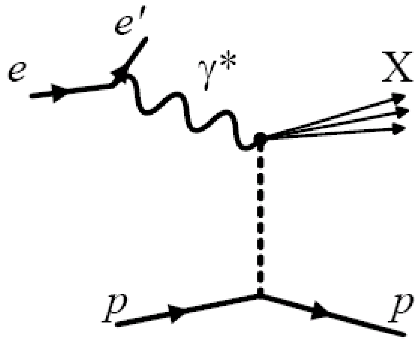
$$\frac{I(\theta)}{I(\theta=0)} = \frac{[2J_1(x)]^2}{x^2} \simeq 1 - \frac{R_0^2}{4}(k\theta)^2$$

$$\frac{\frac{d\sigma}{dt}(t)}{\frac{d\sigma}{dt}(t=0)} \simeq e^{-b|t|} \simeq 1 - b\,(P\theta)^2$$

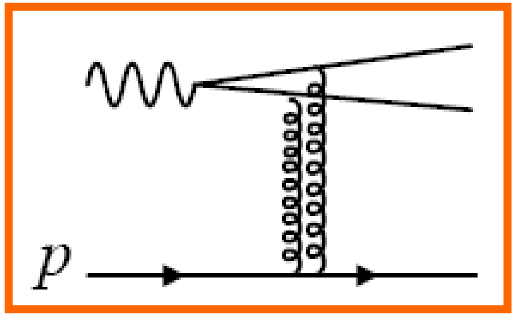
Also, σ_{diff} ~ 30% of the total cross section in p-p @ large s

Diffraction @ HERA

HARD diffraction @ HERA (i.e. in the presence of a hard sacle)



<u>Ideal channel to analyse :</u>
Diffractive exchange @ HERA with the hard scale provided by Q^2 (the virtuality of the photon)
Observed since 1994 @ HERA



Then, the challenge is to understand these processes in terms of pQCD

- Partonic structure for diffractive processes // standard DIS ?
- Colorless exchange can be realised by an exchange of 2 gluons exchange
  => Generic mechanism of diffraction ?

Why studying diffraction ? (headlines)

-hadron-hadron cross section @ large energy

- longstanding pb of the IP structure (specific PDFs)

-Modeling DIFF => saturation effects in the nucleon

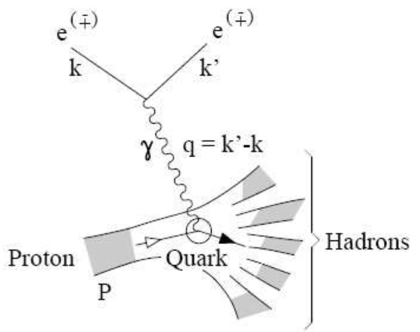
-Structure of the proton in 3D

-Higgs @ LHC

DIS vs DIFF events @ HERA

"Ordinary" Deep-Inelastic

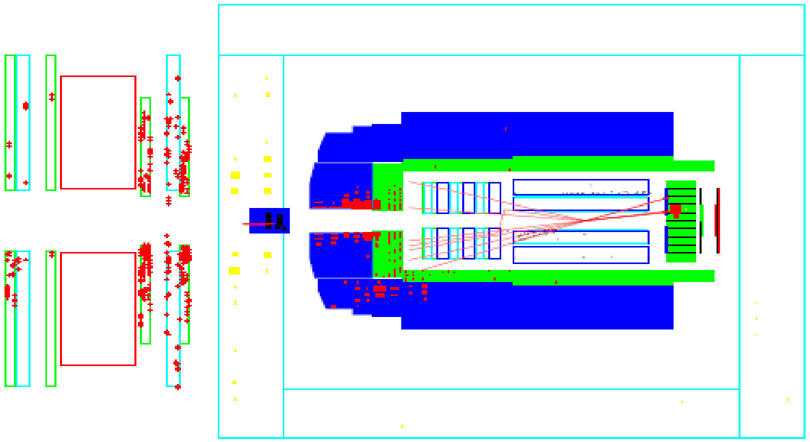
PDFs

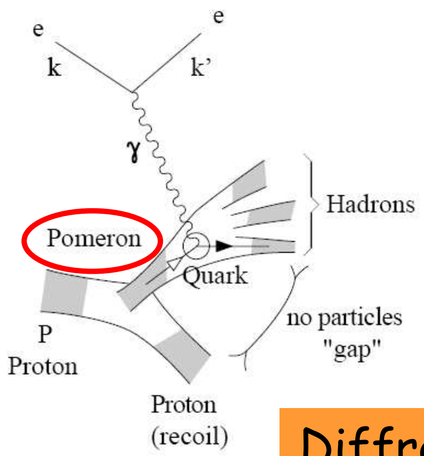


= quark momentum XP

= interaction volume : $Q^{-1} = (-q^2)^{-1/2}$

= final quark momentum (x P + q)

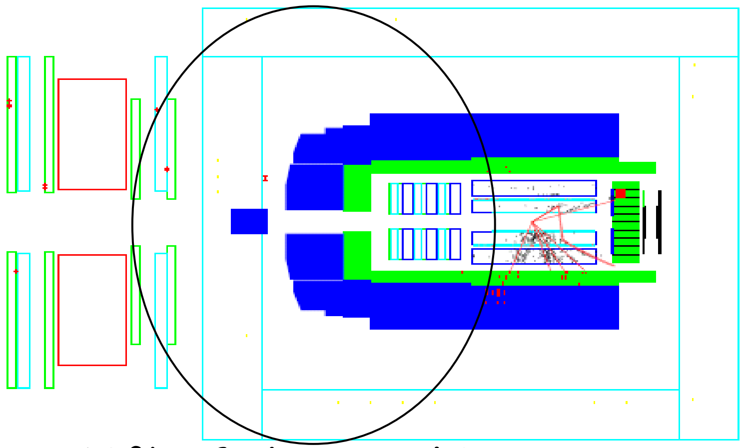




Diffractive PDFs

"Diffractive" Deep-Inelastic

The Pomeron as a composite object



~ 10% of the total DIS events

QCD factorisation for diffractive events

Can we study diffractive events in pQCD ?

=> Factorisation ?

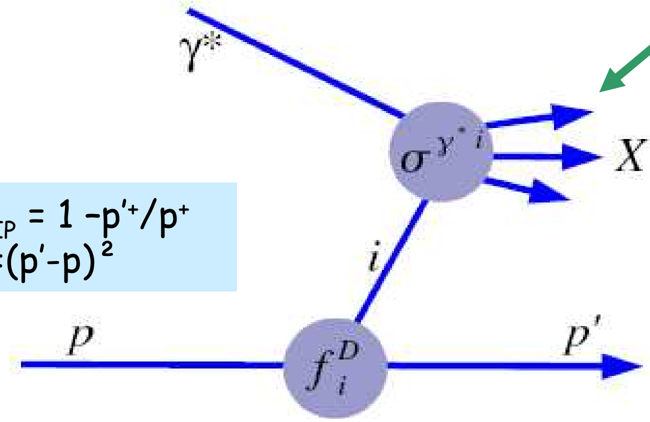
PHYSICAL REVIEW D VOLUME 57, NUMBER 5 1 MARCH 1998

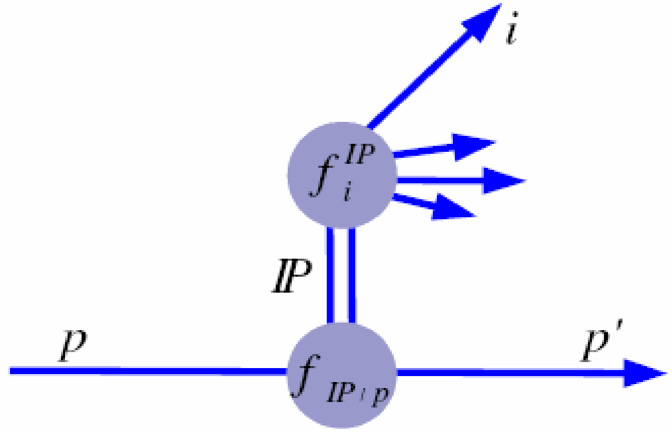
Proof of factorization for diffractive hard scattering

John C. Collins*
Penn State University, 104 Davey Lab, University Park, Pennsylvania 16802
(Received 14 October 1997; published 6 February 1998)

A proof is given that hard-scattering factorization is valid for deep-inelastic processes which are diffractive or which have some other condition imposed on the final state in the target fragmentation region.
[S0556-2821(98)00507-4]
PACS number(s): 13.85.Ni, 12.38.Aw, 13.60.−r

$x_{IP} = 1 - p'^{+}/p^{+}$
$t = (p'-p)^2$





$$f_{IP}(x_{IP}) = \int_{t_{cut}}^{t_{min}} e^{B_{IP} t} / (x_{IP}^{2\alpha_{IP}(t)-1})\, dt$$

QCD (Collins) factorisation at fixed x_{IP} & t

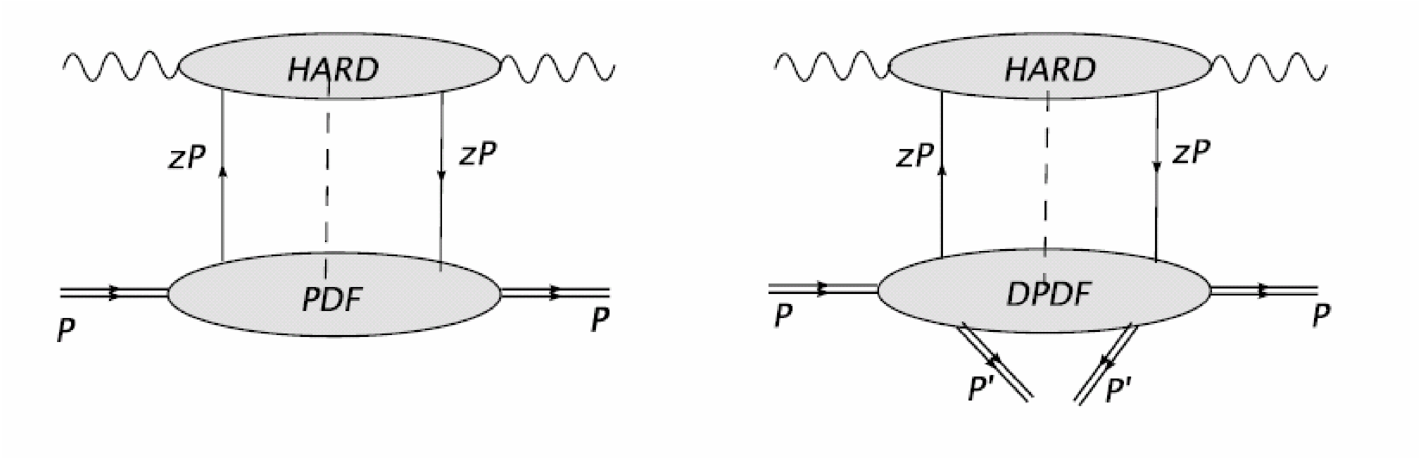
$$d\sigma_{\text{parton } i}(ep \to eXY) = f_i^D(x, Q^2, x_{IP}, t) \otimes d\hat{\sigma}^{ei}(x, Q^2)$$

Proton vertex factorisation of the x_{IP} dependence (hypothesis not rooted in QCD)

$$f_i^D(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \cdot f_i^{IP}$$

dPDFs

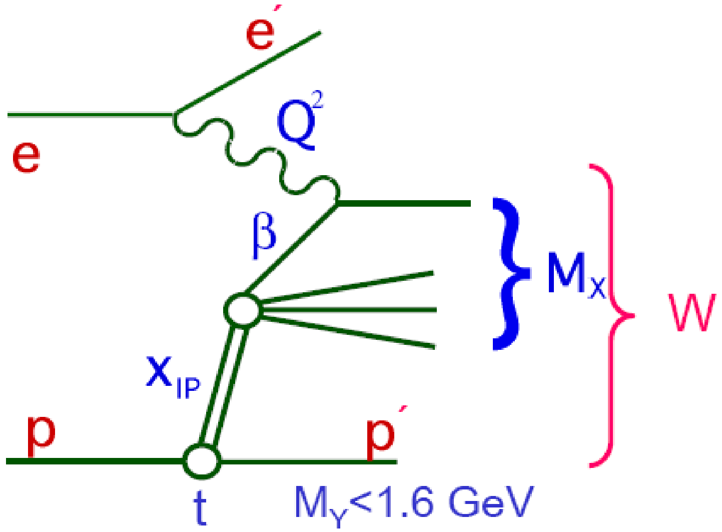
QCD factorisation DIS vs DIFF



$$f_a^D(z,\mu^2,x_{I\!P},t) = \sum_X \int dy_- \, e^{-izP^+y^-} \langle P\,|\overline{\psi_a}(y_-)\gamma^+ \underbrace{|P'X\rangle\langle P'X|}\psi_a(0)|\,P\rangle$$

dPDFs (β,Q^2) follow the DGLAP QCD evolution eq. // standard PDFs

Kinematics & diffractive S.F.



Standard DIS kinematic variables : Q^2, x, W

$x_{IP} = 1 - p'^+/p^+$: fraction of the longitudinal momentum lost by the proton (below a few%)

$\beta = x/x_{IP}$: *fraction of the IP momentum carried by the struck quark in the diffractive exch.*

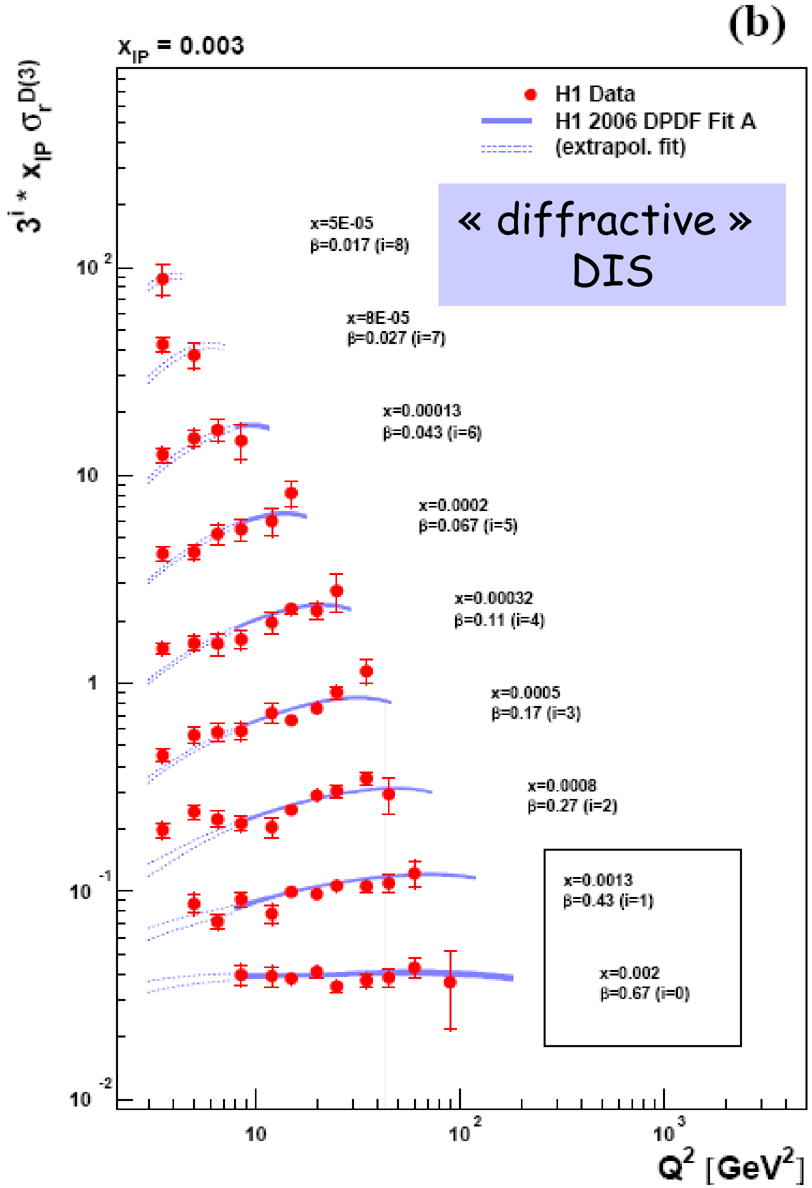
Important formula : $\beta \approx Q^2 / (Q^2 + M_X^2)$

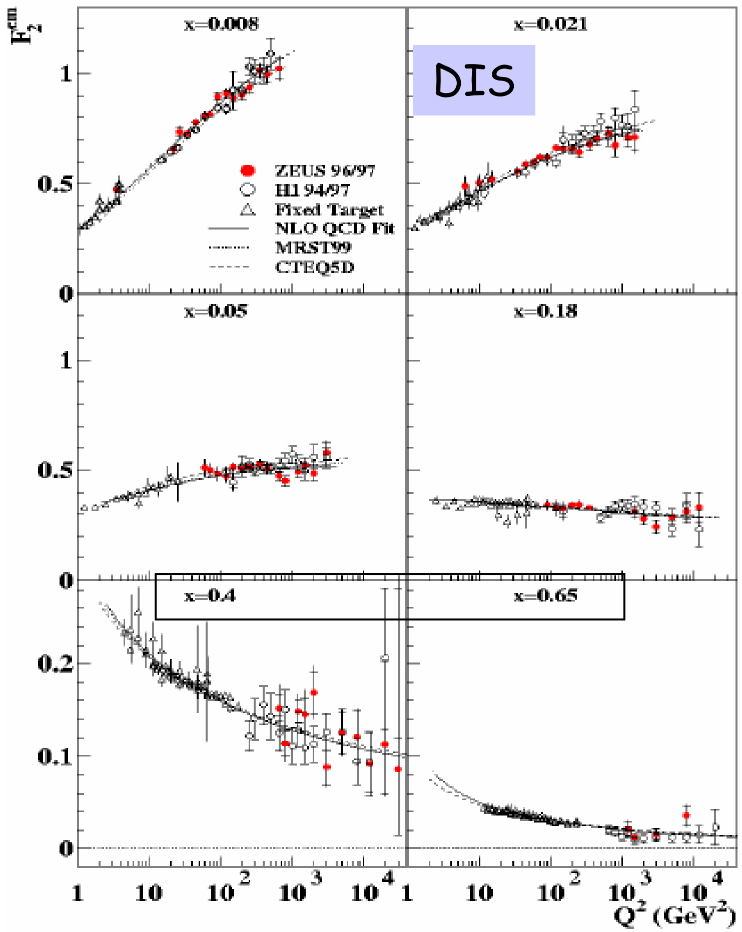
$$\frac{d^3\sigma}{d\beta dQ^2 dx_{IP}} = \frac{4\pi\alpha^2}{\beta Q^4}\left(1 - y + \frac{y^2}{2}\right)\sigma_r^{D(3)}(\beta, Q^2, x_{IP})$$

$$\sigma_r^{D(3)} = F_2^{D(3)} - \frac{y^2}{2(1 - y + y^2/2)} F_L^{D(3)}$$

We measure the diffractive cross section, then we get F_2^D

Diffractive S.F.

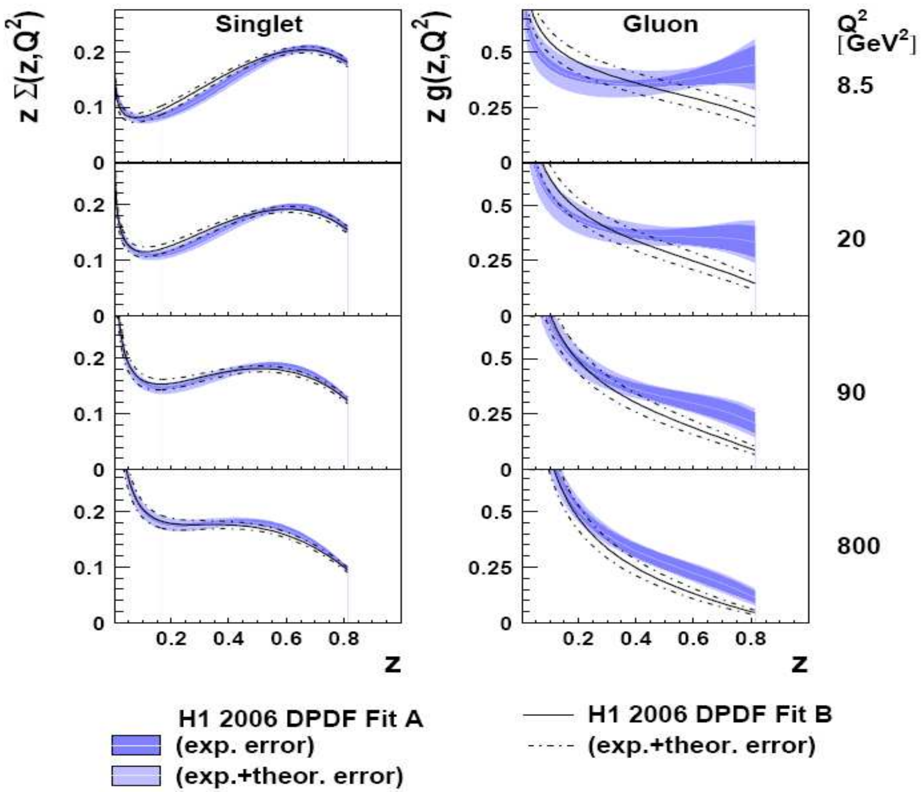


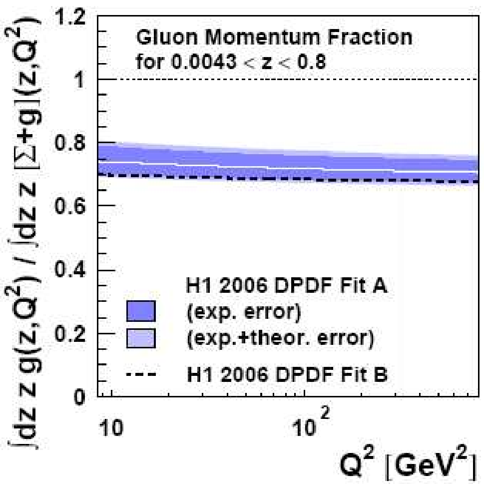


At large β values : scaling violations still >0 for diffraction, *<0 for standard DIS*

=> Large gluon content expected for DIFF

Diffractive PDFs





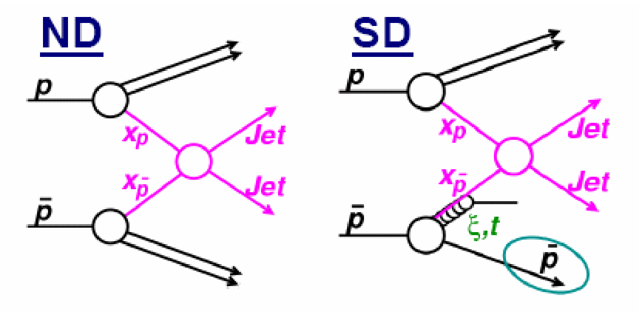
Large gluon content (in the IP)
carrying the main part of the momentum

Large uncertainty @ large β

The factorisation theorem (+resolved IP model+dPDFs)
gives a good description of the F2D data

The limit of factorisation @ Tevatron

Universality of dPDFs extracted from HERA data ?



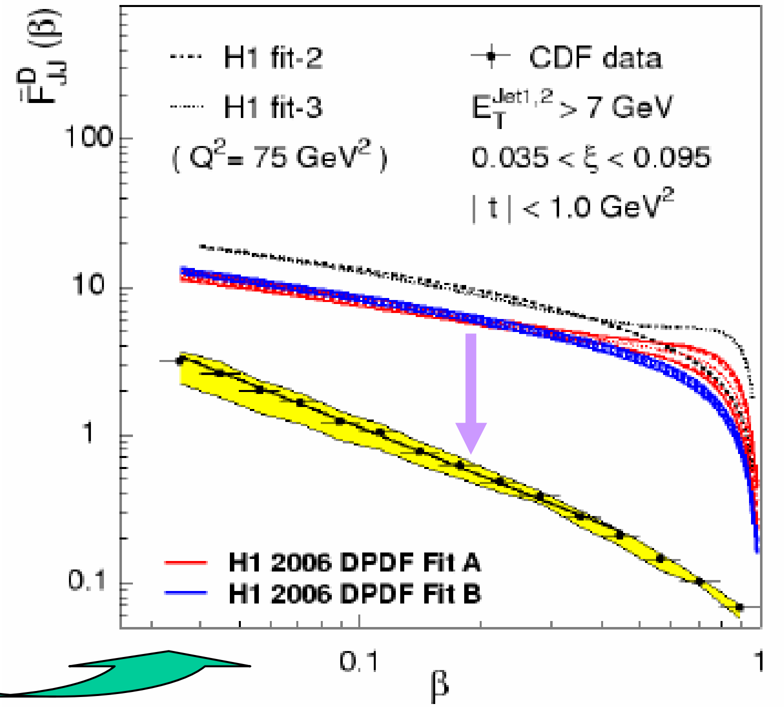
Diff. Structure Function Measurement:

$$R_{\frac{SD}{ND}}(x_{\bar{p}},\xi_p) \approx \frac{F_{jj}^D(x_{\bar{p}},\xi_p)}{F_{jj}(x_{\bar{p}})} \quad \text{(LO QCD)}$$

to be measured — global fit

=> F_{jj}^D can be derived and compare to expectations from HERA dPDFs

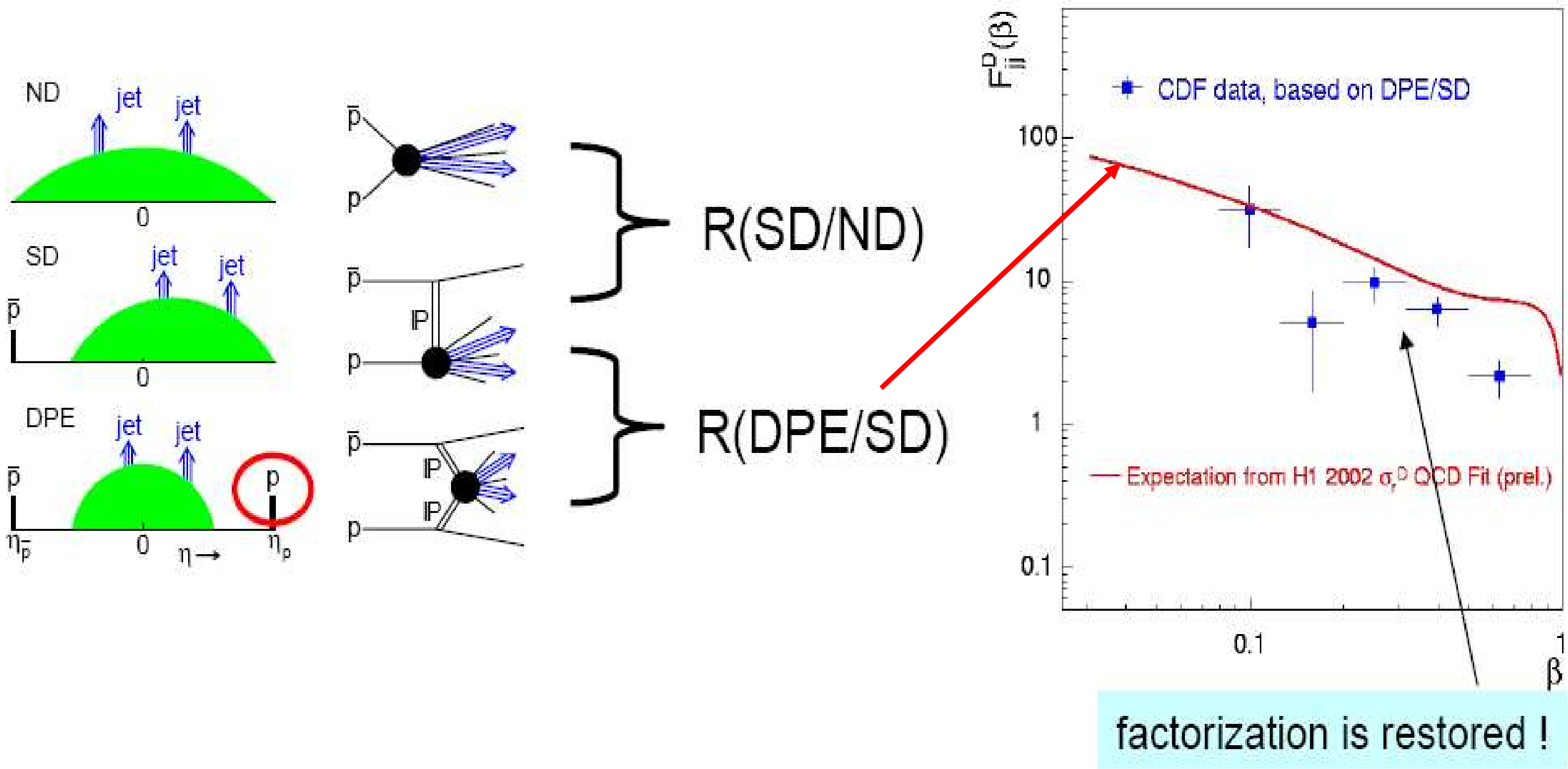
$$\tilde{F}_{JJ}^D(\beta) = \frac{1}{\xi_{\max}-\xi_{\min}}\int_{\xi_{\min}}^{\xi_{\max}} d\xi \left[\beta g^D(\xi,\beta,Q^2) + \frac{4}{9}\beta\Sigma^D(\xi,\beta,Q^2)\right]$$



Mismatch of a factor~10 => factorisation does not hold !

As expected for p-p collisions : underlying interaction that spoils the gap in rapidity (« survival » gap probability of a few %)

« Restoring » factorisation @ Tevatron

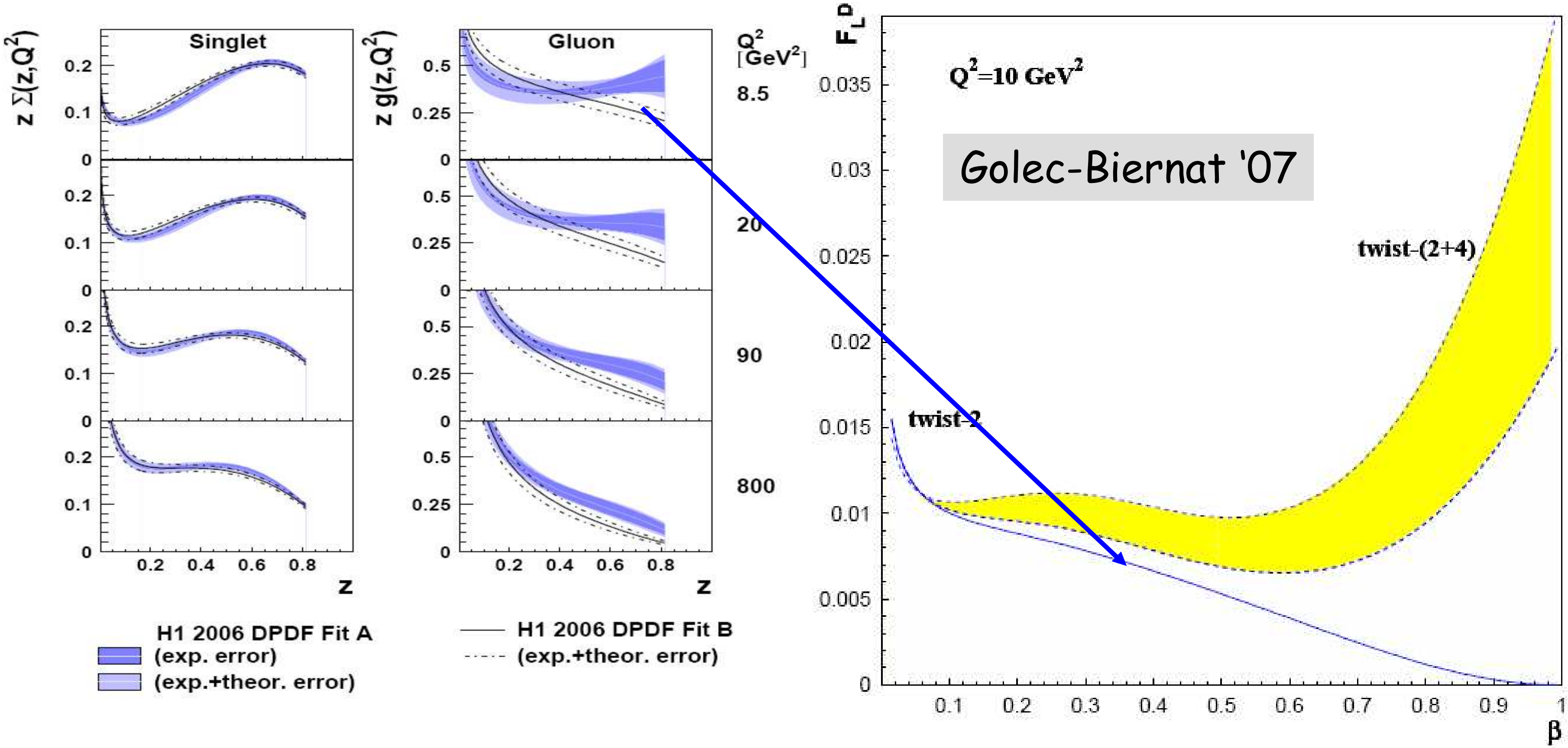


The diffractive S.F. measured on the proton side in events with a leading anti-proton is not suppressed :

The price for producing a gap (survival probability) is paid only once!

This confirms that the survival Gap probability may be just an underlying interaction between spectator partons in the protons…

Conclusion on diffractive PDFs



Diffractive PDFs : only « twist-2 » functions (by definition)

=> Essential measurement of FLD needed to conclude if this hypothesis is correct or not [& dPDF(gluon) usable beside F2D]!

Why studying diffraction ? (headlines)

-hadron-hadron cross section @ large energy

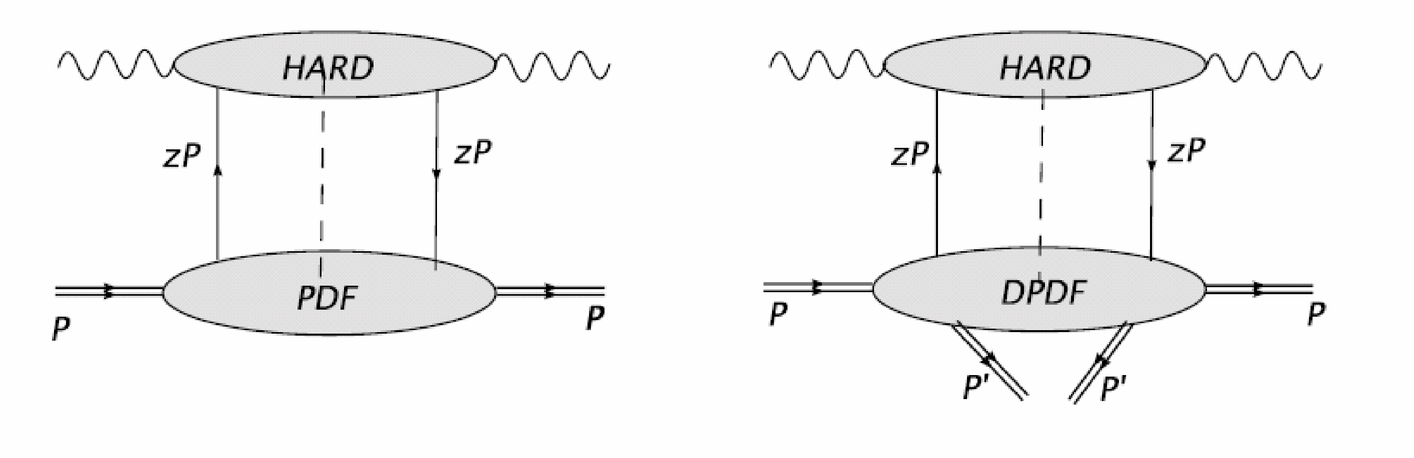
- longstanding pb of the IP structure (specific PDFs)

-Modeling DIFF => saturation effects in the nucleon

-Structure of the proton in 3D

-Higgs @ LHC

Weakness of dPDFs

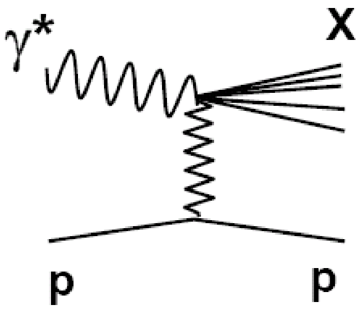


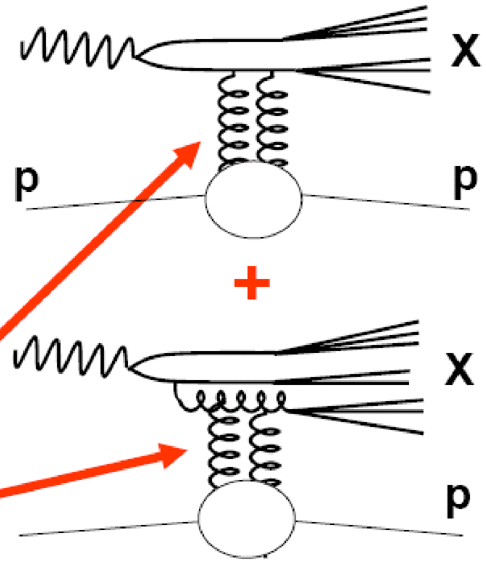
$$f_a^D(z,\mu^2,x_{I\!P},t) = \sum_X \int dy_-\, e^{-i\,zP^+y^-} \langle P\, |\overline{\psi_a}(y_-)\gamma^+ \underbrace{|P'X\rangle\langle P'X|}\psi_a(0)|\, P\rangle$$

Not a universal description of DIS and DIFF :
We need 2 completly different sets of PDFs!

Can we find a model for DIFF following directly DIS ?

Beyond the dPDFs : modeling the diffractive exchange





2-gluon exchange:
LO realisation of vacuum
quantum numbers in QCD

Universal description DIFF/DIS

Then $\sigma_{diff} \sim$ Coef $\otimes [xG(x,Q^2)]^2$

with $\sigma_{DIS} \sim$ Coef' $\otimes [xG(x,Q^2)]$

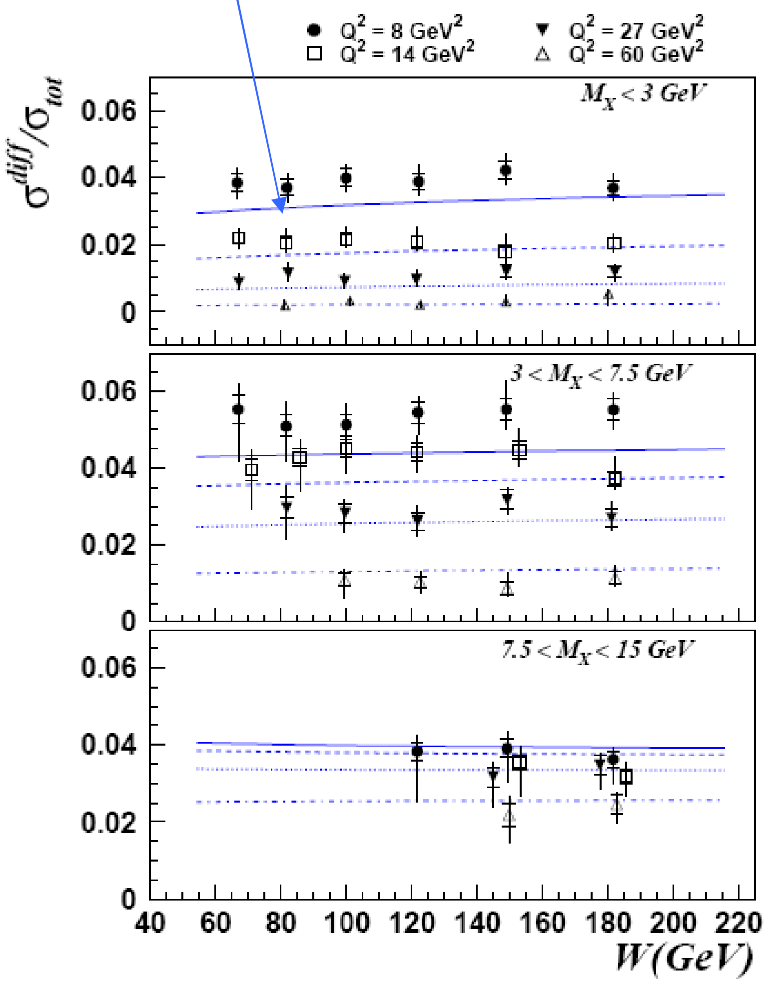
CONSEQUENCE :

@ low x : σ_{DIS} (F2) ~ W^a (a~0.8) => $\sigma_{diff} \sim W^{2a}$ => $\sigma_{diff}/\sigma_{DIS} \sim W^a$

we expect a strong W dependence for the ratio ?!

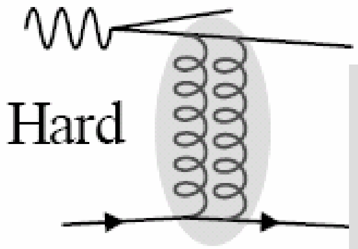
Modeling the diffractive exchange

Prediction of the 2-gluon exchange model + saturation



$\sigma_{diff}/\sigma_{DIS}$ ~ constant [W] !

=> Inclusive diffraction : softer than a pure 2-(hard) gluons exchange



Effects of saturation that screen the increase of the « dipole » cross section

What next ?

Modeling the DIFF exchange in **exclusive diffractive processes** (cleaner events / inclusive case)

Why studying diffraction ? (headlines)

-hadron-hadron cross section @ large energy

- longstanding pb of the IP structure (specific PDFs)

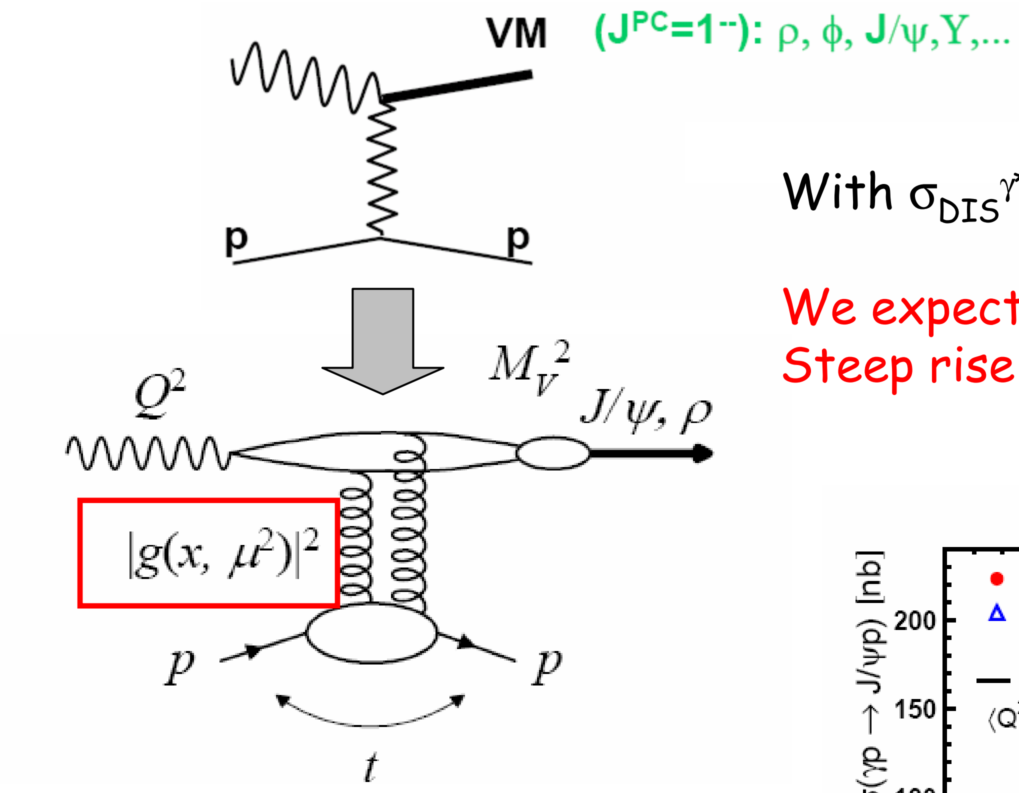
-Modeling DIFF => saturation effects in the nucleon

-Structure of the proton in 3D

-Higgs @ LHC

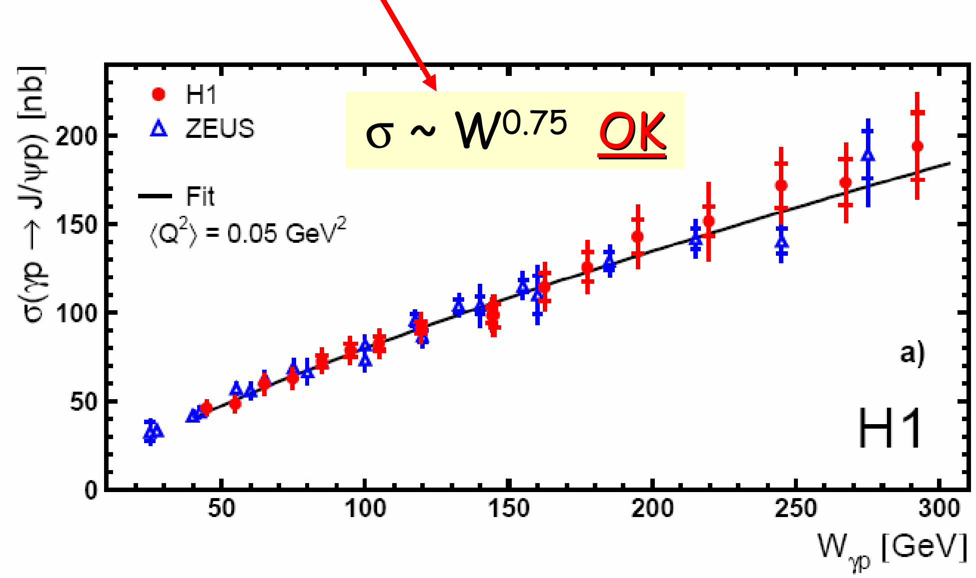
Exclusive processes @ HERA

For exclusive processes : <u>can we apply the same concept of 2g exchange ?</u>



With $\sigma_{DIS}^{\gamma^* p}$ ($= 4\pi^2\alpha / Q^2 \,.\, F_2$) ~ $W^{2\lambda}$ ~ $W^{0.3/0.4}$

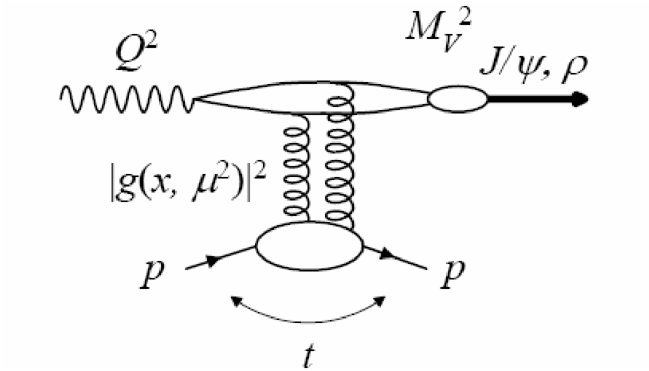
We expect : σ(J/ψ) ~ $W^{0.6/0.8}$
Steep rise of the xs => the concept (2-g) works!



A 2-gluons exchange is the LO realisation of a vacuum Q.N. exchange

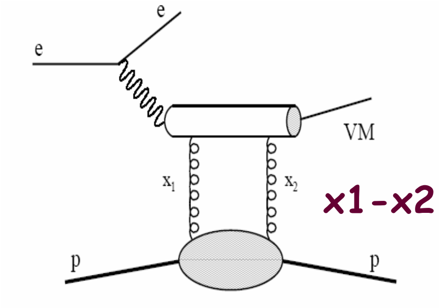
Exclusive processes & QCD

$d\sigma_{VM}/dt \sim \alpha_S \,/\, \langle Q\rangle^8 \,.\, |xG(x,\langle Q\rangle^2)|^2 \;(1+Q^2/M^2)$ $\quad \langle Q\rangle^2=(Q^2+M^2)/4 \;;\; x= 4\langle Q\rangle^2/W^2$



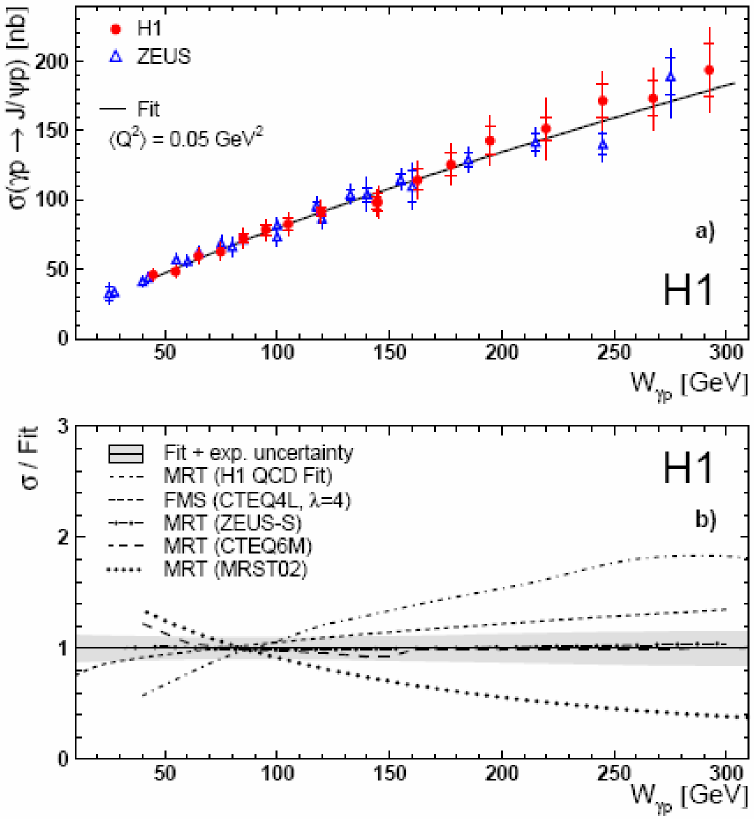
The comple formula includes :

- Unintegrated PDFs
- Skewing effects



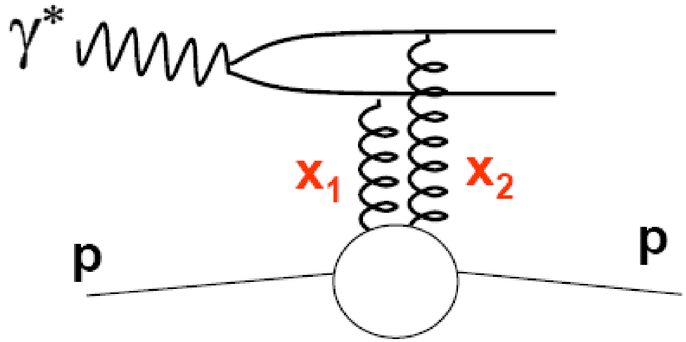
$x1-x2 \sim [Q^2+M^2] / W^2$

PDFs(x_{bj}) GPDs(x_1,x_2)
large effects on xs!



Good description of the data
=> The 2-gluons exchange is a correct generic hard process (hard Pomeron in pQCD)

First comments on skewing



In general, $x_1 \neq x_2$:

$$\sigma \propto [x\, g(x)]^2$$

↓

$$\boxed{\sigma \propto [H(x_1, x_2)]^2}$$

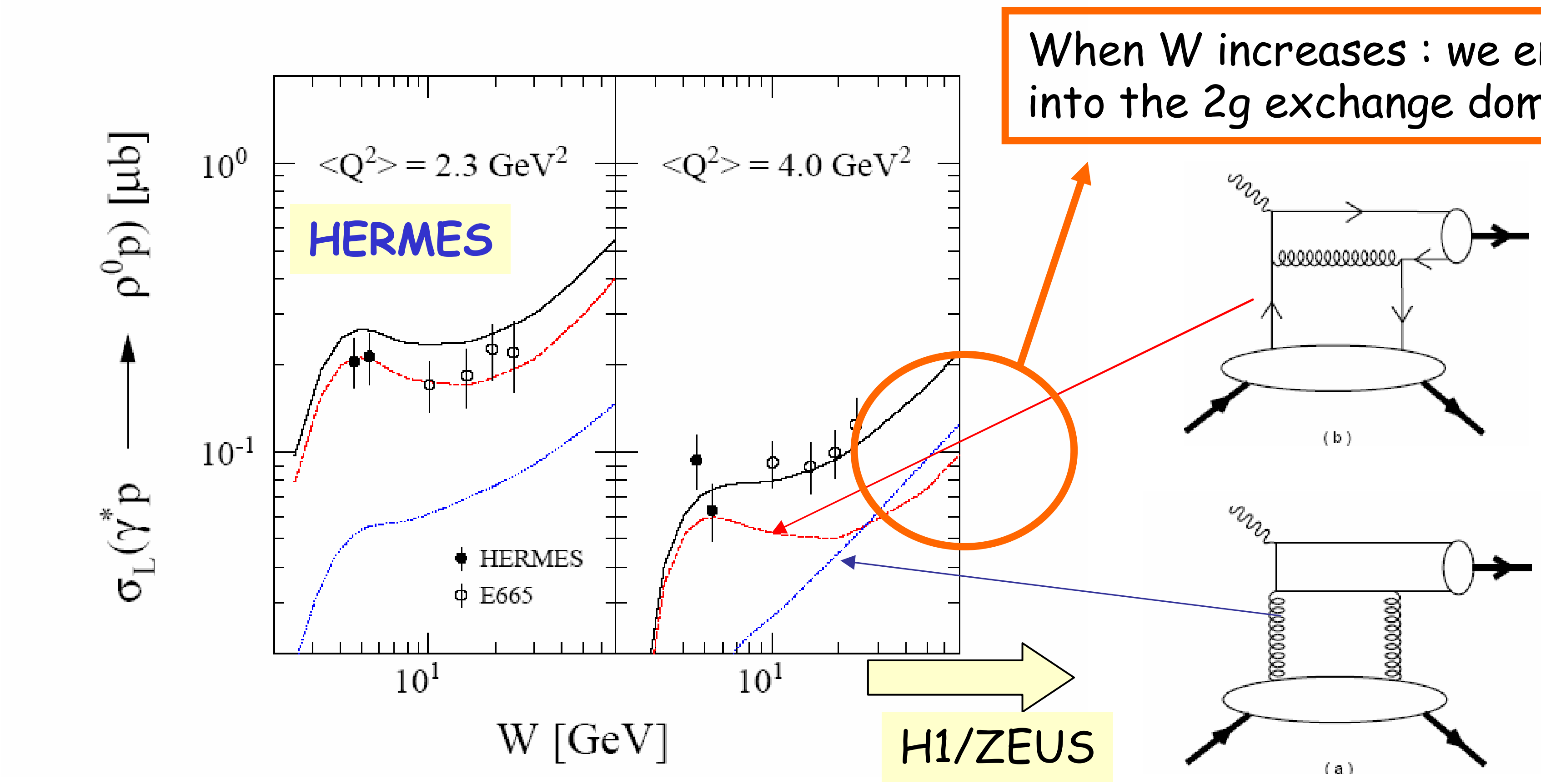
Generalised parton distribution functions (GPD)

GPDs modifies the prediction by ~ 30% for J/ψ prod. (vs no skewing)

It can be a factor 4 on cross section for exclusive γ production

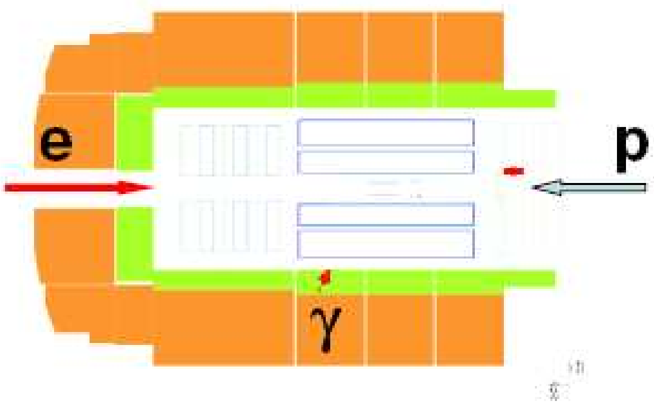
Exclusive processes & QCD

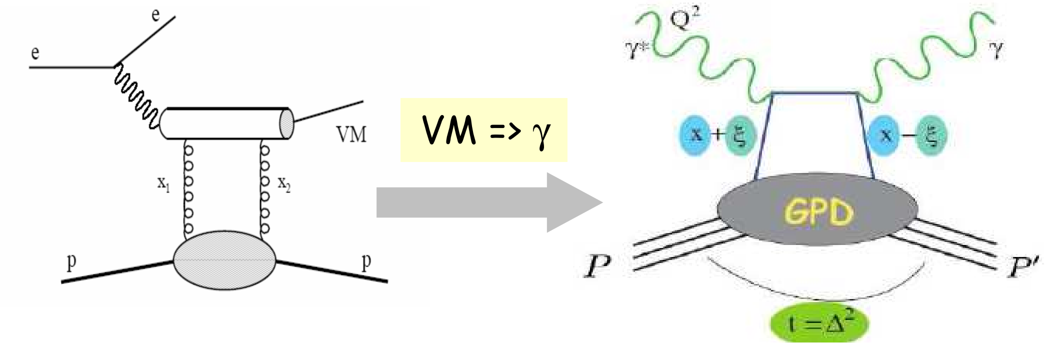
@ lower W (larger x) : the qq exchange contributes with a xs > 2g exchange
the pQCD calculations predict these two terms with the correct amplitude taking into account the GPDs formalism (skewing effects)



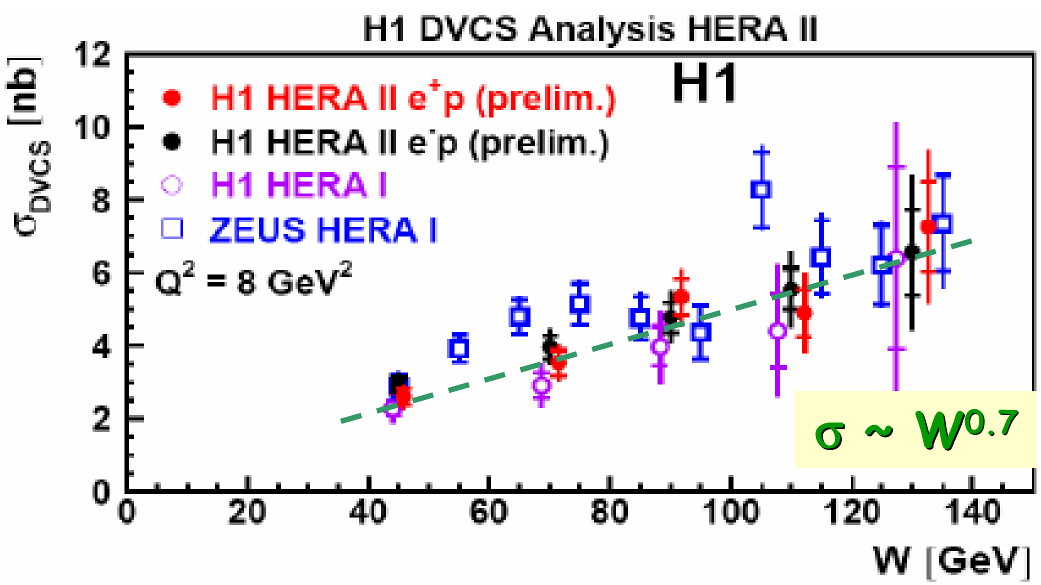
The *simplest* process : e p →e γ p

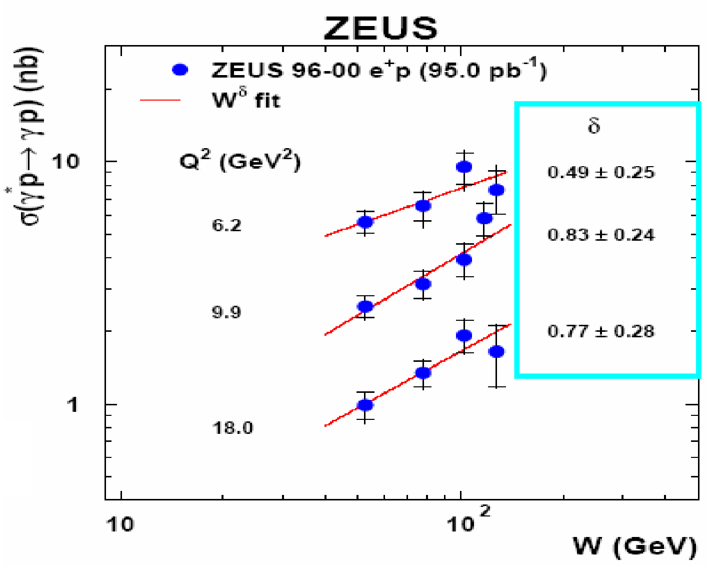
Deeply Virtual Compton Scattering (DVCS)



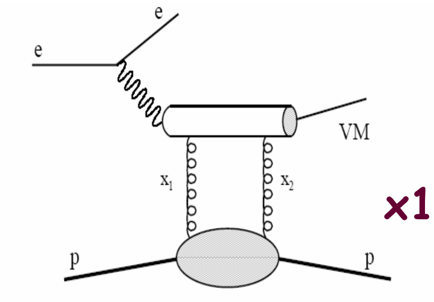


x1-x2 ~ [Q²+M²] / W²=> $\xi \sim x_{bj}/2$





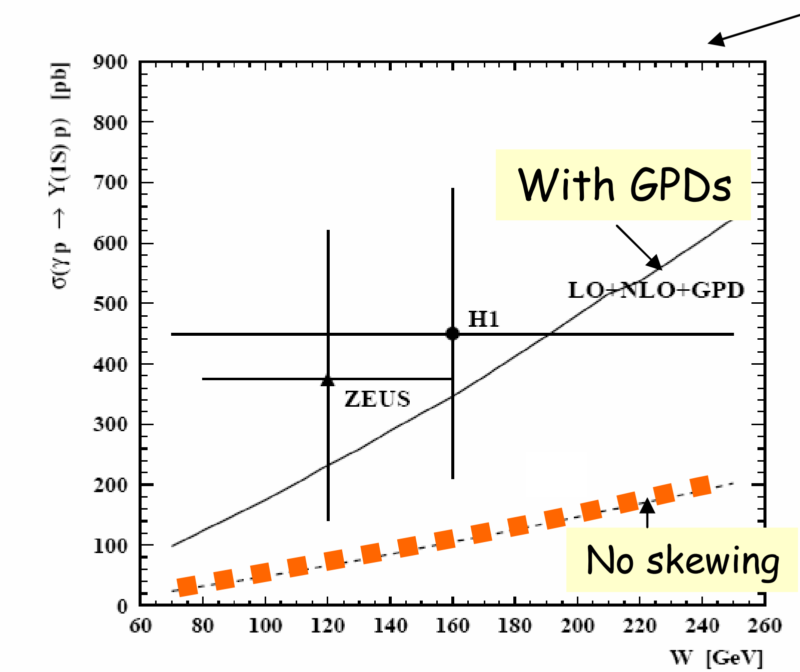
On the importance of skewing



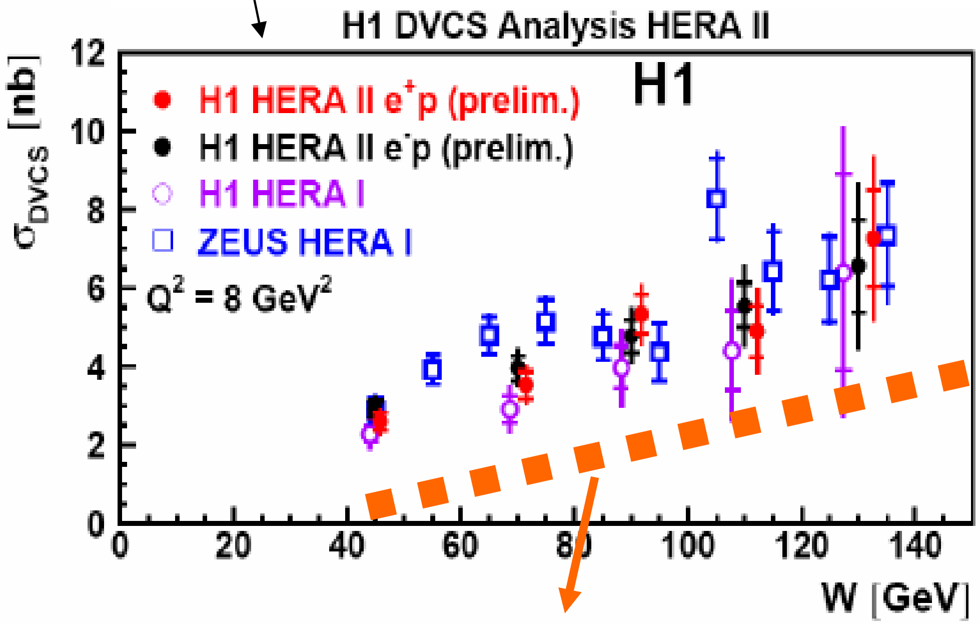
$x1 - x2 \sim [Q^2+M^2] / W^2$

The DVCS xs calculations include terms in $|GPD(x1,x2)|^2$ (skeewing)

If we forget these effects, we replace GPD by PDF in calulations but it fails!

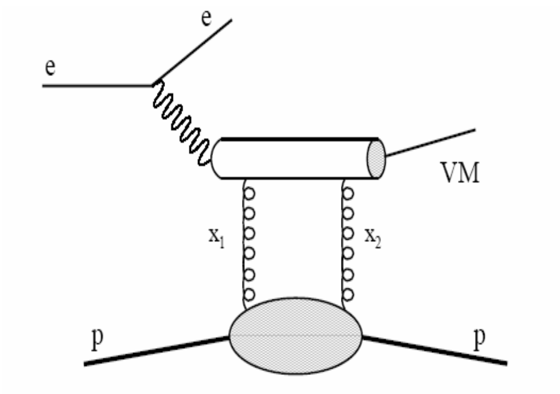


The first observation of skeewing (GPDs) impact



Prediction without skewing
(i.e. forgetting about GPDs) :
a factor~4 below the data

QCD and diffraction (exclusive)



The 2 gluons exchange mechanism works well in the presence of a hard scale : large M, large Q^2

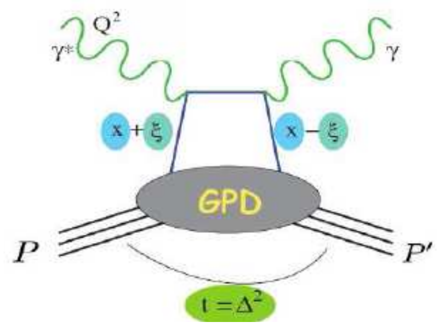
+ some refinements due to skewing effects : $x1-x2 \sim [Q^2+M^2] / W^2$

For VMs, predictions are still uncertain due to the unknown in the VM wave function!

=> Interest of DVCS (γ) : *pure* QCD prediction avaible @ NLO (& even NNLO recently)

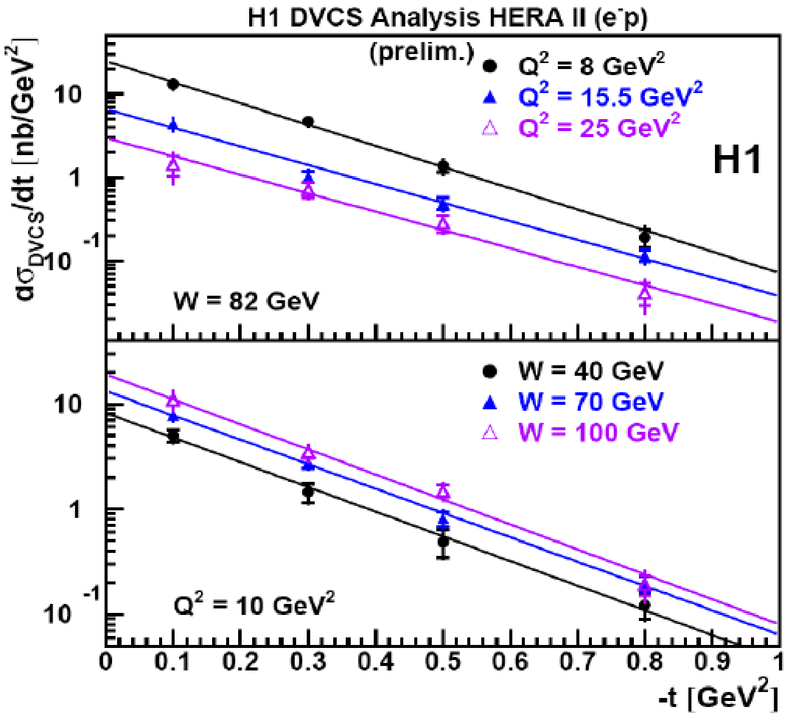
QCD predictions on DVCS

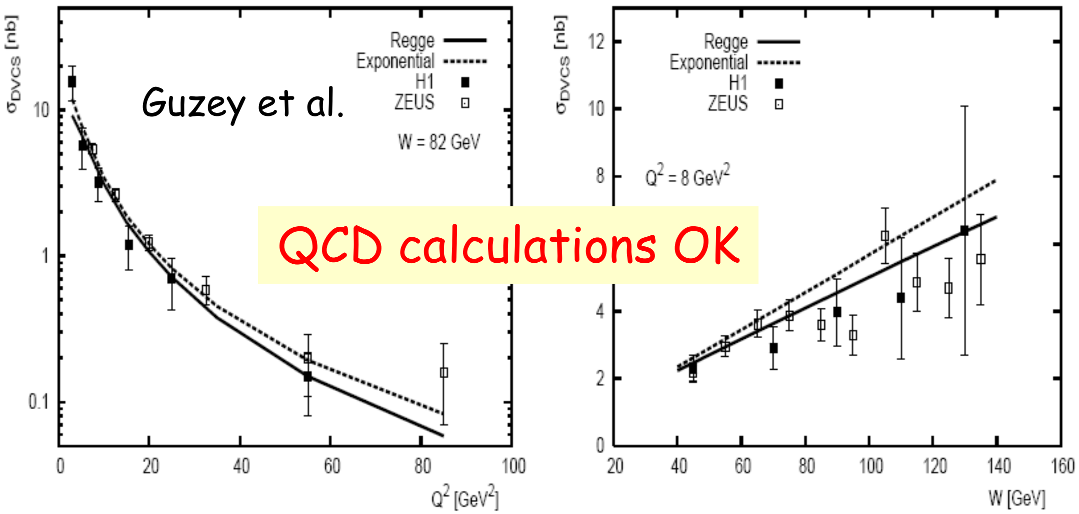
Essential measurement of the t dependence



If $d\sigma_{dvcs}/dt \sim |f(x_1,x_2,\langle Q\rangle^2)|^2\ \exp(bt)$
=> $\sigma_{dvcs} \sim \mathbf{1/b}\ |f(x_1,x_2,\langle Q\rangle^2)|^2$

With the measured t-dependence =>
a QCD prediction becomes possible :

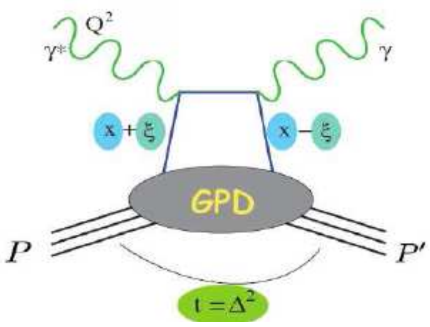




Guzey et al.

QCD calculations OK

Nucleon tomography (3D) : a new issue

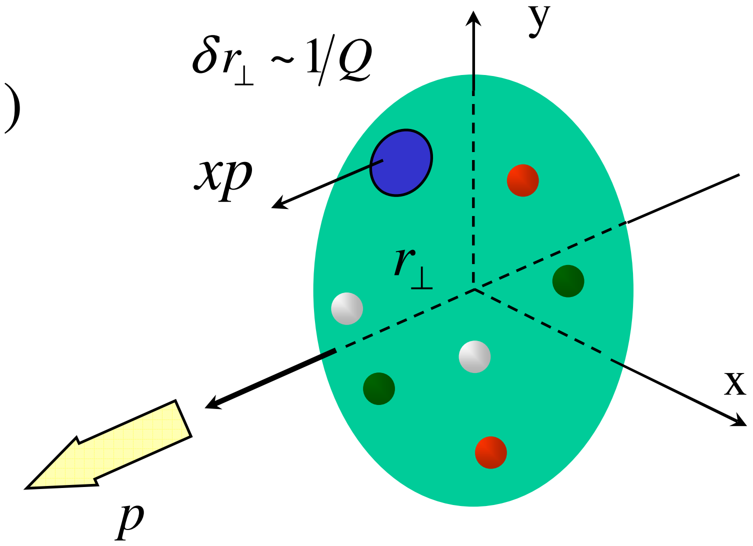


With DVCS, we measure/extract a GPD(x_1,x_2,t)

- We have seen that the t-dependence is essential in normalisation of QCD predictions
- **A more fundamental point : it gives access to a completly new issue in nucleon physics : the TRANSVERSE SIZE!**

PDF (transverse plane) ≡ F.T. { GPD[$\Delta_\perp$] }

$$q(x,\mathbf{r}_\perp,Q^2) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-i\mathbf{r}_\perp\cdot\Delta_\perp} \, GPD_q(x,Q^2,t=-\Delta_\perp^2)$$

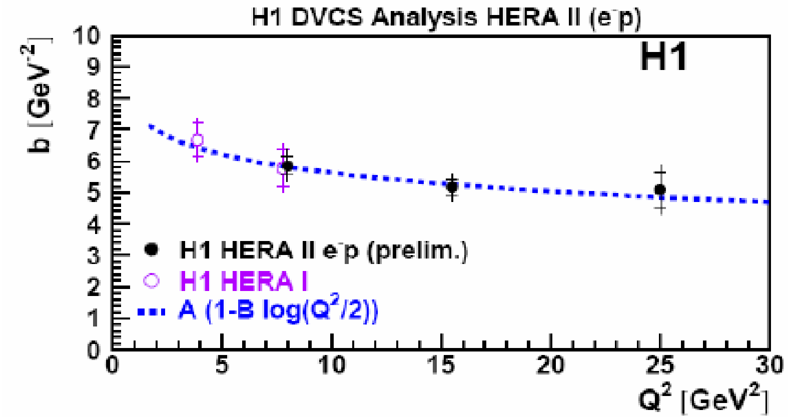


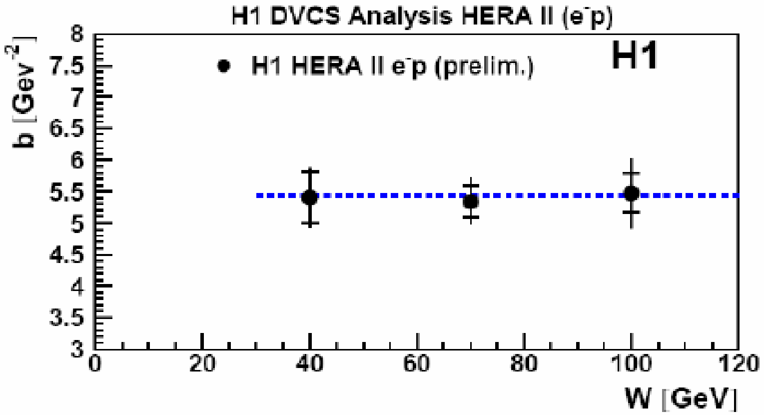
$r_\perp$ & $\Delta_\perp$ are conjugate variables :

$\langle r_T^2 \rangle$ =4 d/dt[GPD(x,t)]/GPD(x,0)

H1 : measurement of dσ/dt[DVCS]
=> spatial distribution of sea and glue

Nucleon tomography (3D) : measurement



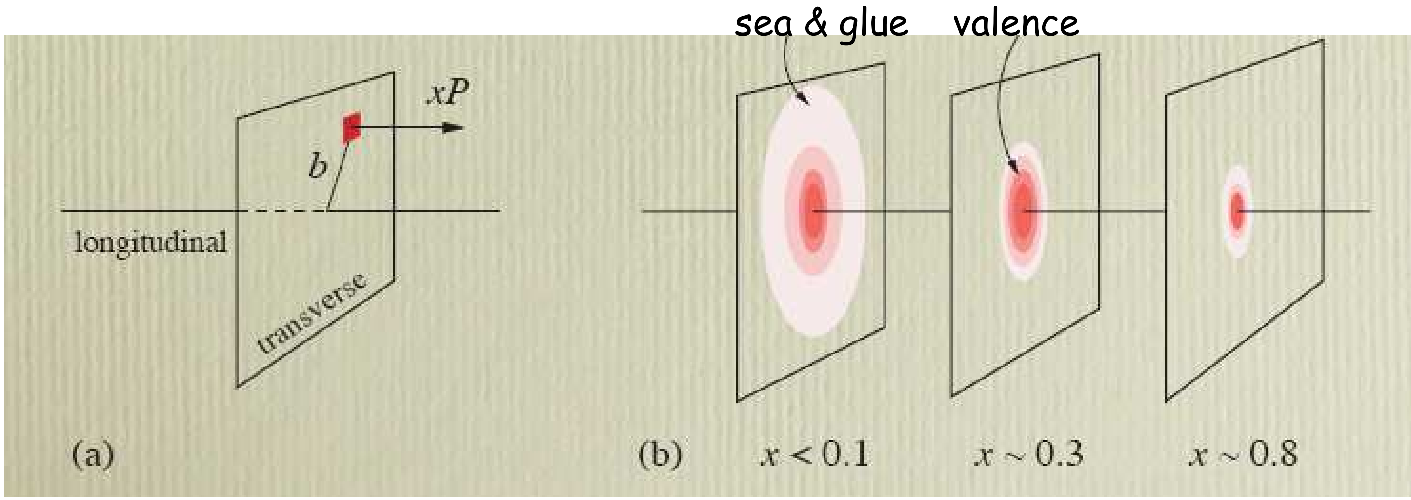


$$b = 5.45 \pm 0.19 \pm 0.34 \text{ GeV}^{-2}$$

=> $\sqrt{\langle r_T^2 \rangle}$=0.65 fm

\>\> valence quarks value

b() measurements @ H1 (low x) : dominated by glue and sea quarks // exclusive production of light states (ρ,ϕ)



Nucleon tomography (3D) : summary

$$b = 5.45 \pm 0.19 \pm 0.34 \text{ GeV}^{-2}$$

=> $\sqrt{\langle r_T^2 \rangle} = 0.65$ fm

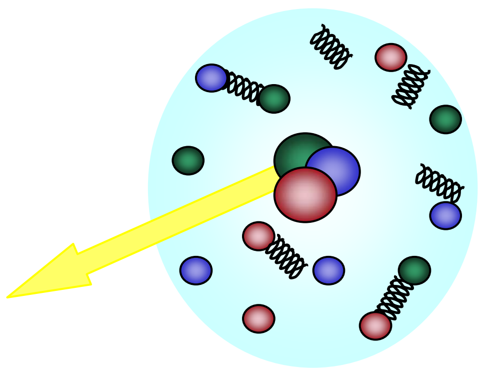
>> valence quarks value

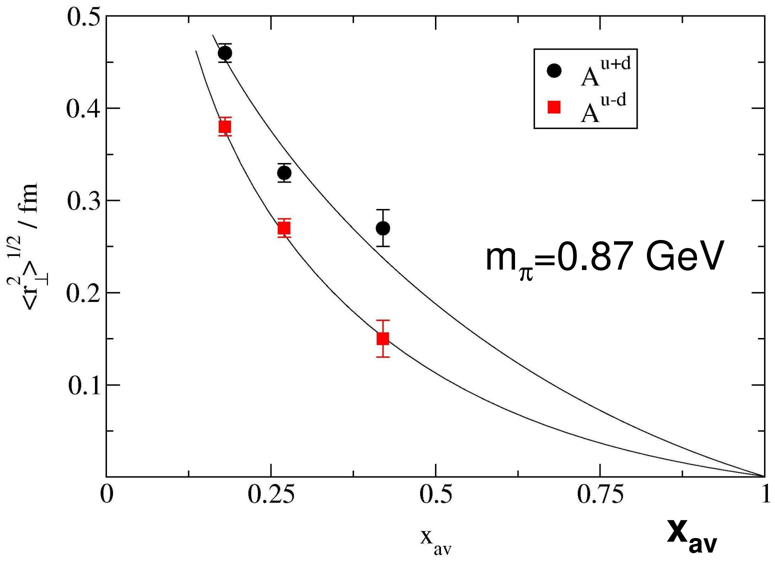
Important measurement in the context of the fast improving lattice calculations!

Lattice calculation (unquenched QCD):

Negele *et al.*, NP B128 (2004) 170
Göckeler *et al.*, NP B140 (2005) 399

- **fast parton close to the N center**
  - ≡ **small valence quark core**
- **slow parton far from the N center**
  - ≡ **widely spread sea q and gluons**





The x dependence of GPDs

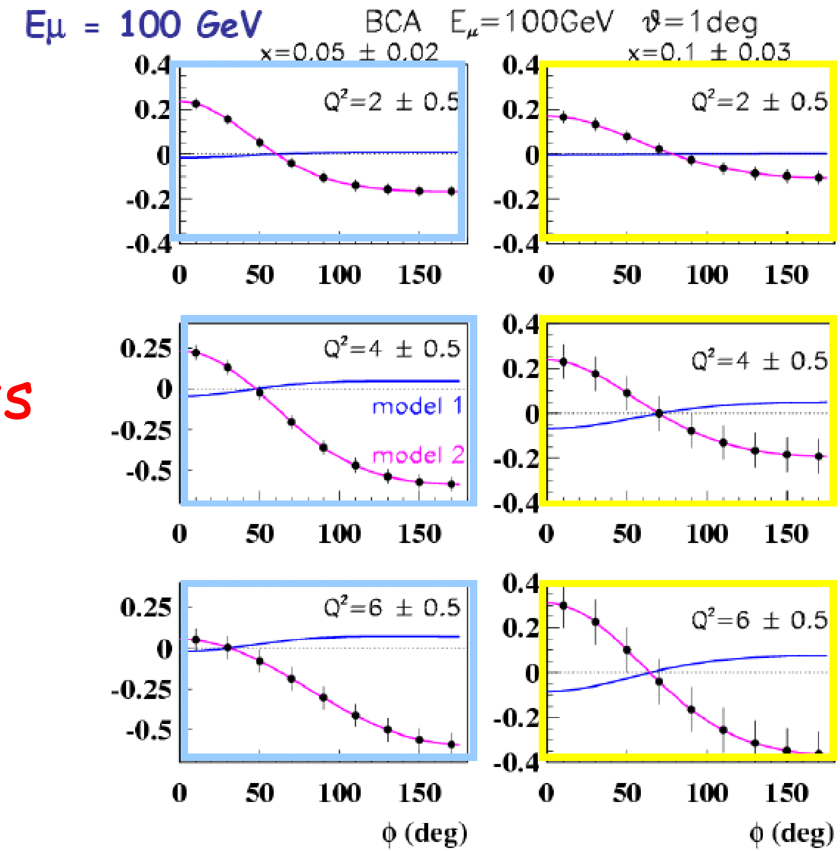
Measure the DVCS cross section with lepton(+) and lepton(-) beams
Determine the beam charge asymmetry : $(\sigma+ - \sigma-)/(\sigma+ + \sigma-)$
BCA(ϕ) ~ P.V.[∫GPD(x,ξ,t)/(x- ξ) + c.t.] . cos(ϕ) + terms in cos((n>1)ϕ)

We can 'access' GPDs!

First results @ HERMES/H1

Future precision measurements @ COMPASS

large discrimination
vs
models of GPDs



DVCS and the nucleon orbital momentum

A longstanding difficult problem that can be addressed by DVCS/GPDs

Contribution to the nucleon spin knowledge

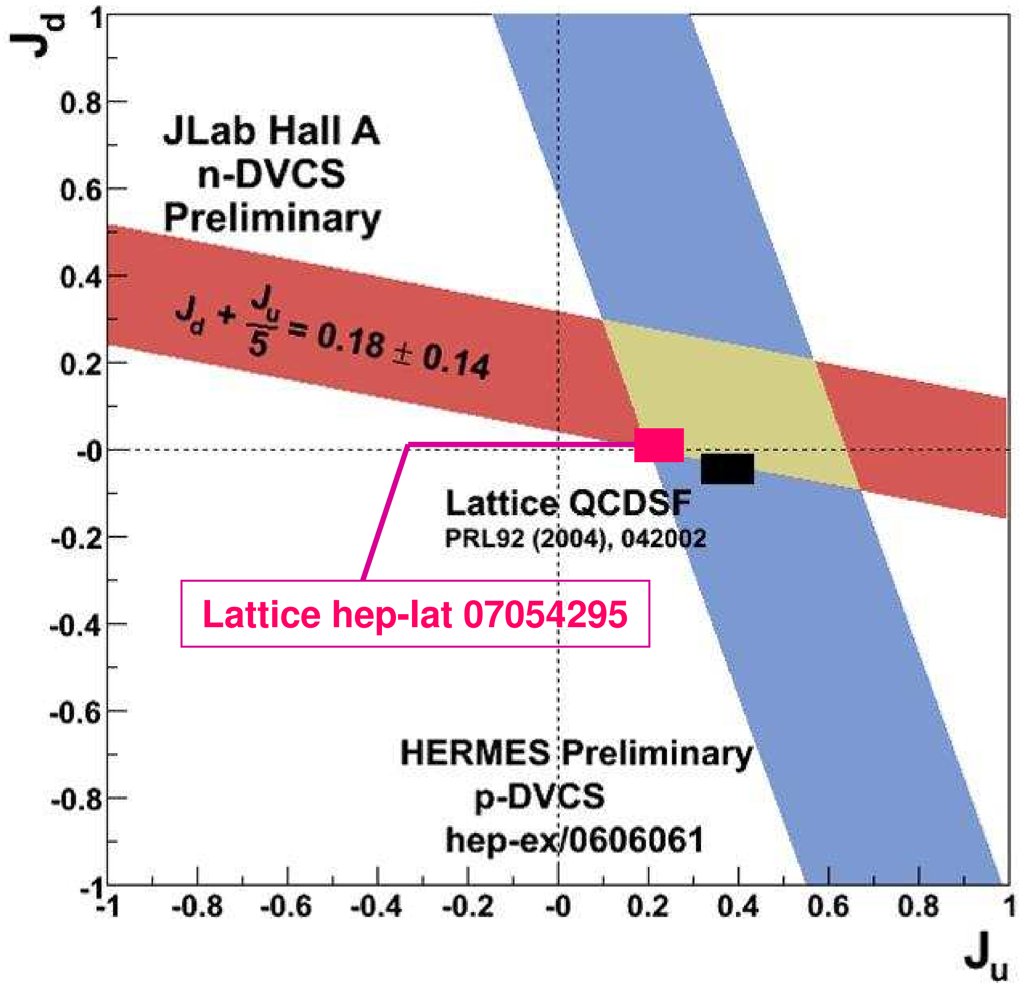
$$\frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + \Delta G + \langle L_z^q \rangle + \langle L_z^g \rangle$$

$$2J_q = \int x\,(H^q(x,\xi,0) + E^q(x,\xi,0))\,dx$$

=> J can be accessed with GPDs

$\Delta\Sigma + \Delta G$ determined from EMC/SLAC/COMPASS results *(on going work)*

=> ORBITAL MOMENTUM



Why studying diffraction ? (headlines)

-hadron-hadron cross section @ large energy

- longstanding pb of the IP structure (specific PDFs)

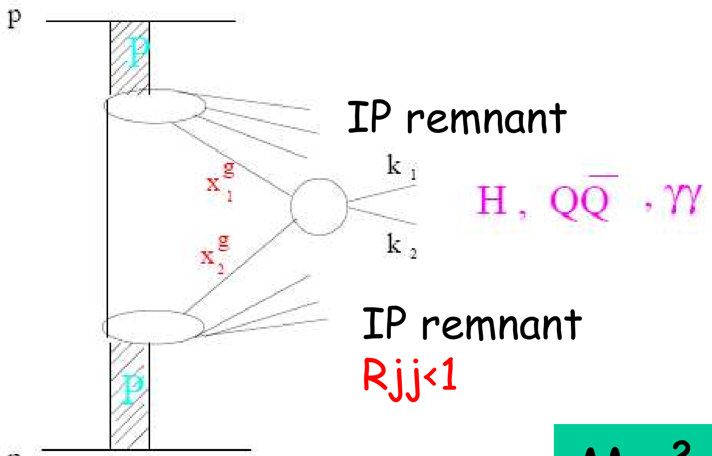
-Modeling DIFF => saturation effects in the nucleon

-Structure of the proton in 3D

-Higgs @ LHC

Double Pomeron Exchange in pp collisions

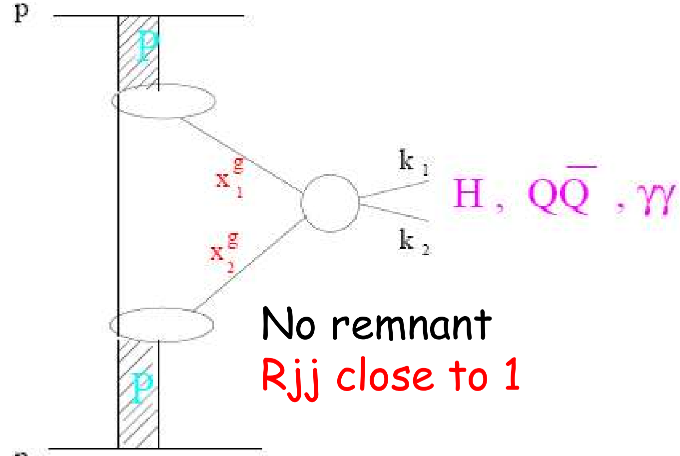
2 protons tagged on both sides (double diffractive event)
+ measurement of their energy loss $\xi_{1,2}$



IP remnant

IP remnant
Rjj<1

"Inclusive"



No remnant
Rjj close to 1

"Exclusive "

$$M_X^2 = s\,\xi_1\xi_2$$

- Pb : Does Double Pomeron Exchange (DPE) exists in the exclusive mode ?
  If yes, why not Higgs boson ? (in a clean environment)

- **First, we have to check if excl. evts exist @ TeV ?!**

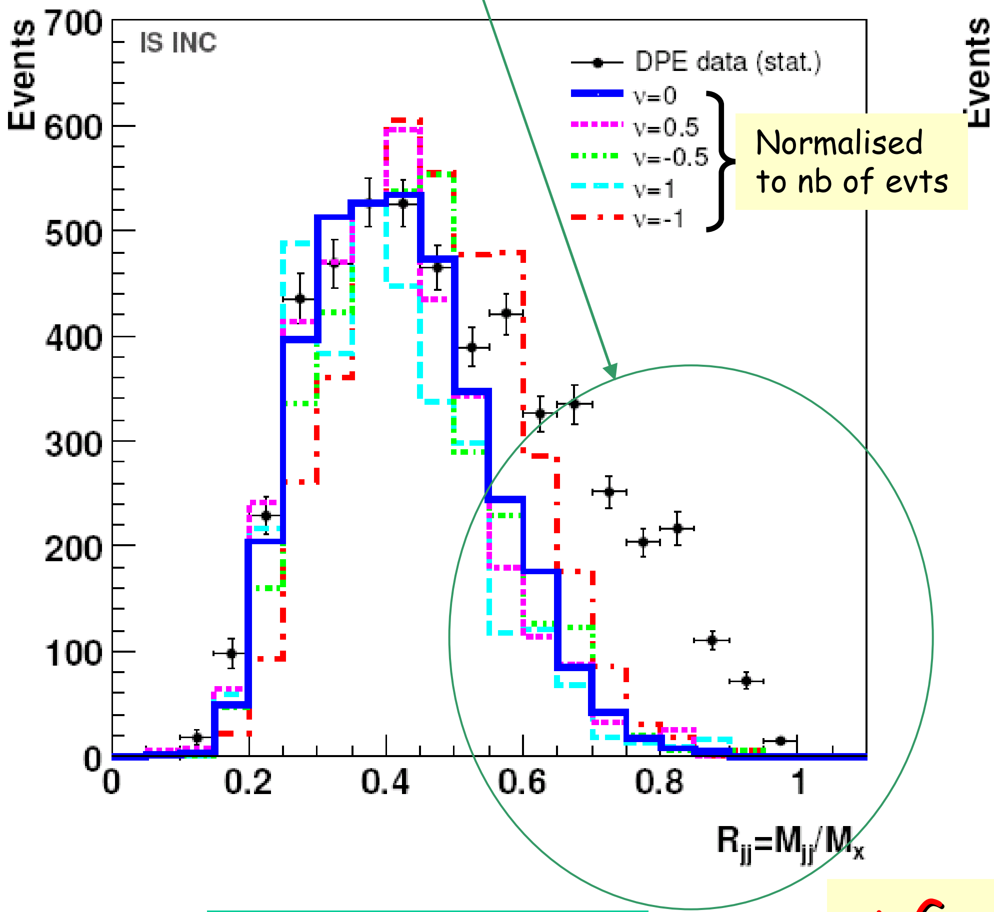
Measurement of the Dijet Mass Fraction @ TeV

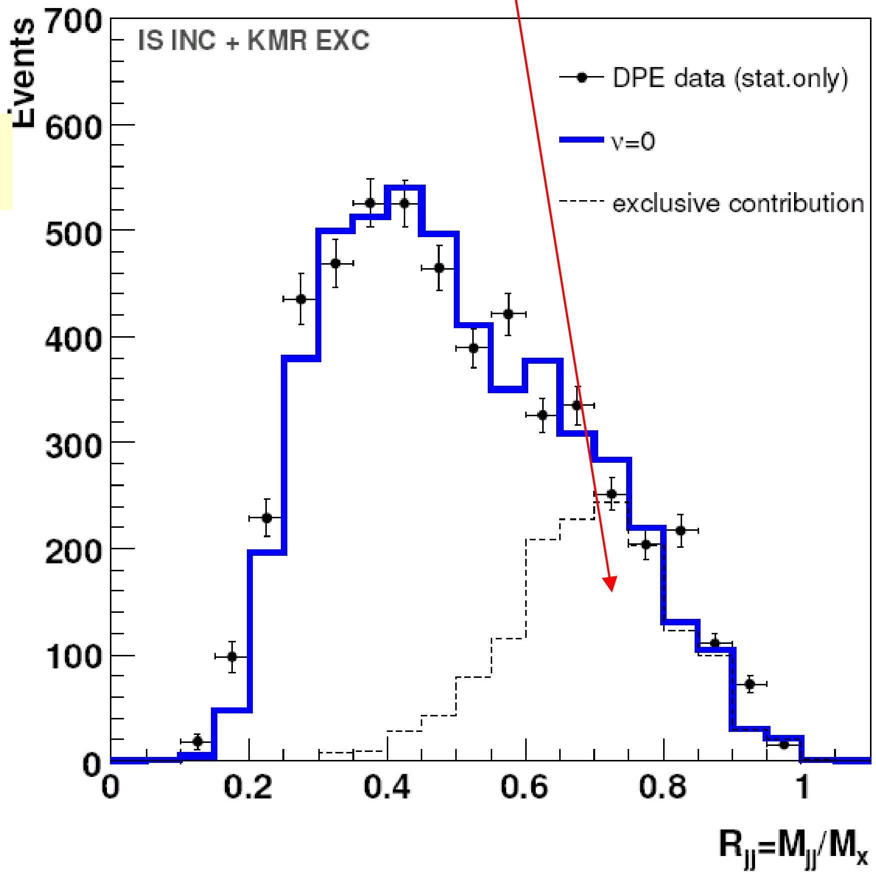
$$R_{jj} = \frac{M_{jj}}{M_X}$$

Dijet mass fraction @ TeV : measurement & predictions

Effect of the gluon uncertainty :
multiply zG by $(1-z)^{\nu}$
It does not cover the large R!

predictions with exclusive production





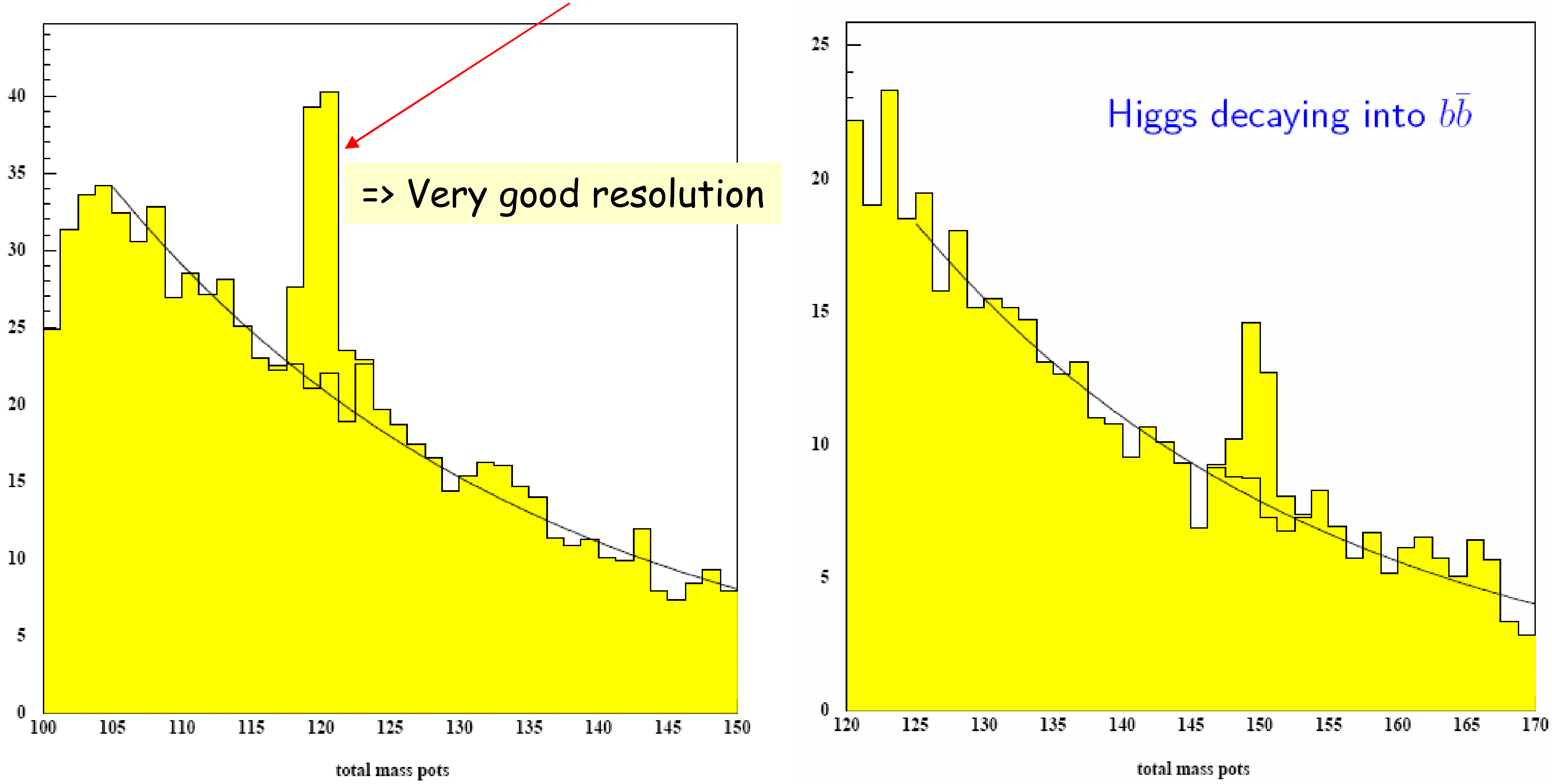
pT (jets) > 10 GeV

=> Good hint that exclusive events exist

Exclusive Higgs production @ LHC

After the hints from the TeV, let's come back on the Higgs exclusive production @ LHC : **simul for a 120 & 150 GeV mass Higgs!**

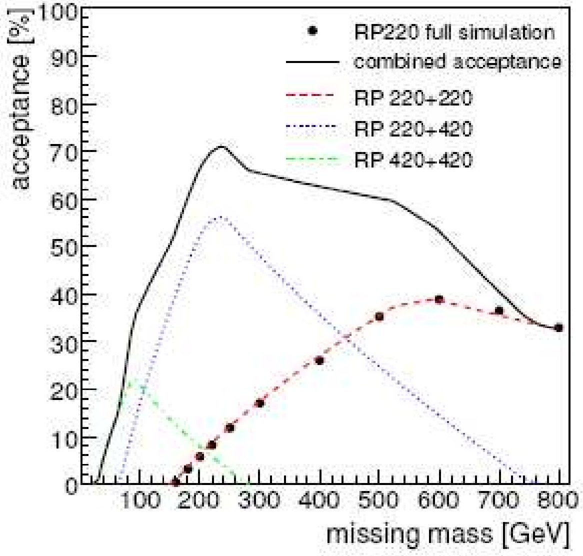
Measurement of the mass from : $M_X^2 = s\,\xi_1\xi_2$

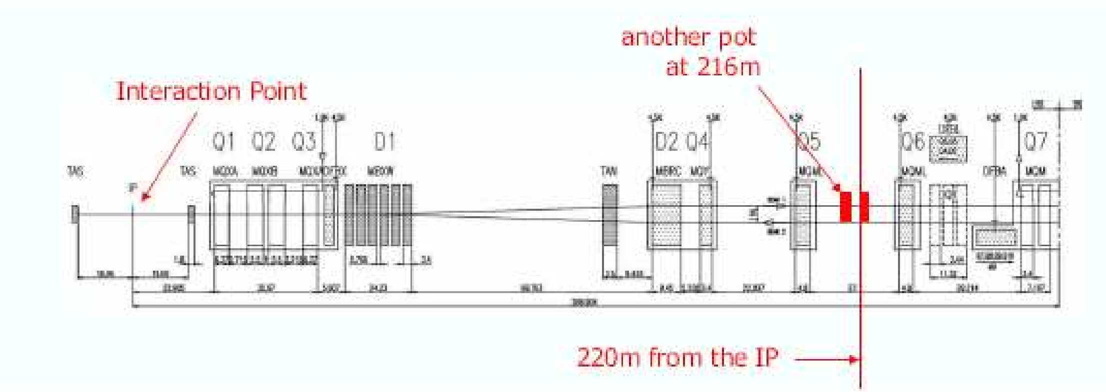


Signal and background for different Higgs masses for 100 fb^{-1}

Experimental aspects @ LHC

- FP420: Project of installing roman pot detectors at 420 m both in ATLAS, CMS; collaboration being built
- Roman pot detectors at 220 m in ATLAS:
  - Natural follow-up of the ATLAS luminosity project at 240 m to measure total cross section
  - Complete nicely the FP420 m project
  - Collaboration between Saclay. Prague, Cracow and Stony Brook (so far) being pursued
  - Collaboration with the FP420 m project concerning detectors, triggers, simulation...





Summary & Conclusion

-hadron-hadron cross section @ large energy

- longstanding pb of the IP structure (specific PDFs)

-Modeling DIFF => saturation effects in the nucleon

-Structure of the proton in 3D

-Higgs @ LHC

=> New windows opened on the proton structure
driving the theory on the low x dynamics, lattice calculations etc.