Diffraction and its QCD interpretation HERA/Tevatron and LHC

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On behalf of H1 and ZEUS collaborations

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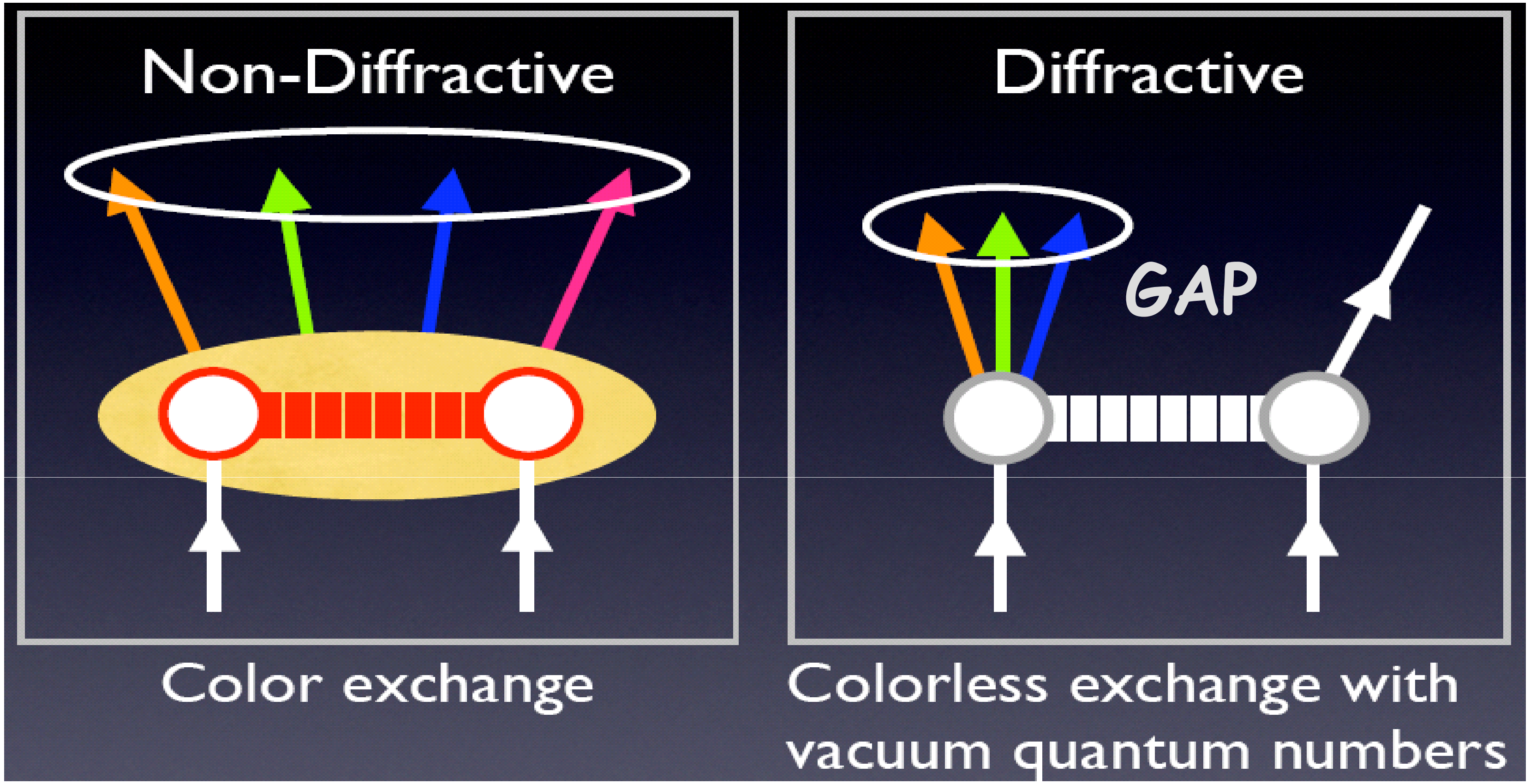
Definition of hadronic diffraction in ep & pp

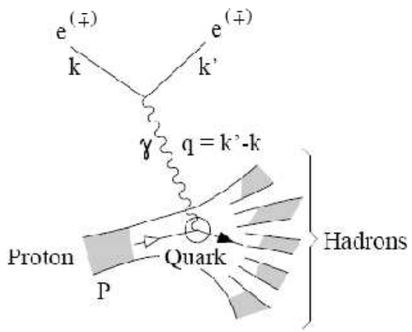


-The proton is left intact or
quasi-intact : **Large Rapidity Gap (LRG)**

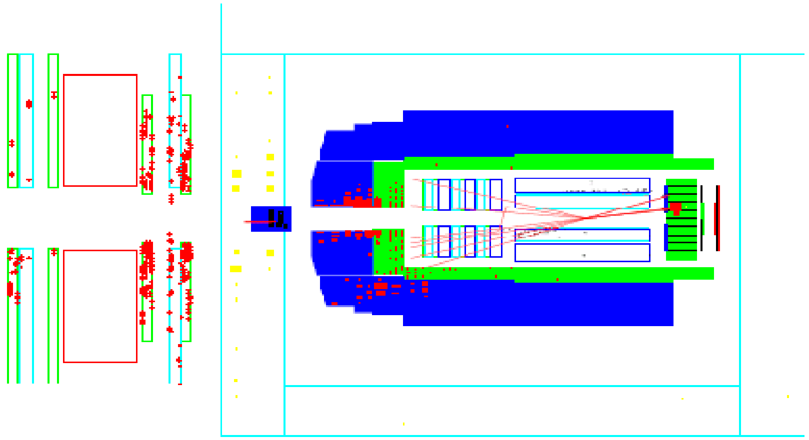
- Vacuum Quantum Number exchange
== Pomeron (IP)

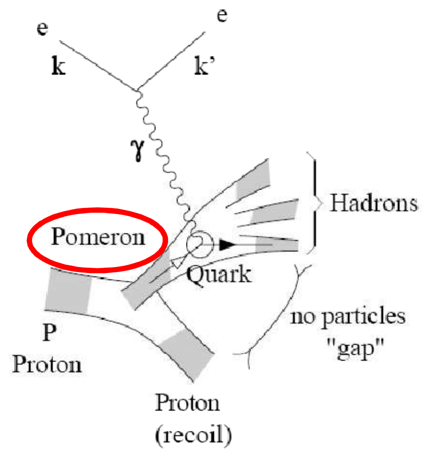
DIS vs diffractive events @ HERA

"Ordinary" Deep-Inelastic

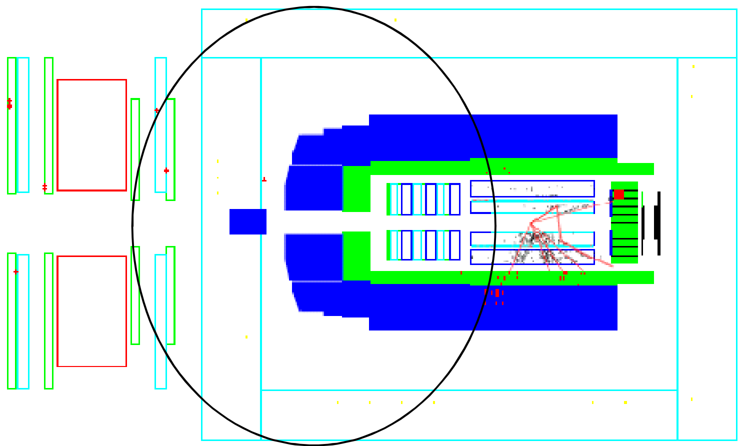


—>— = quark momentum XP
○ = interaction volume : $Q^{-1} = (-q^2)^{-1/2}$
—▶— = final quark momentum (x P + q)





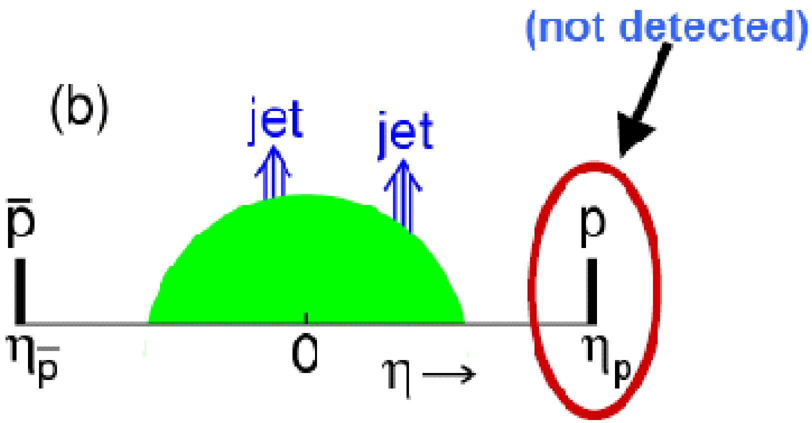
"Diffractive" Deep-Inelastic
The Pomeron as a composite object

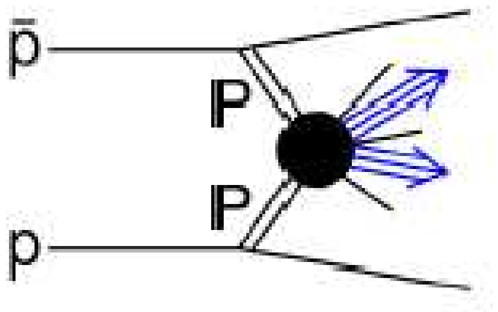


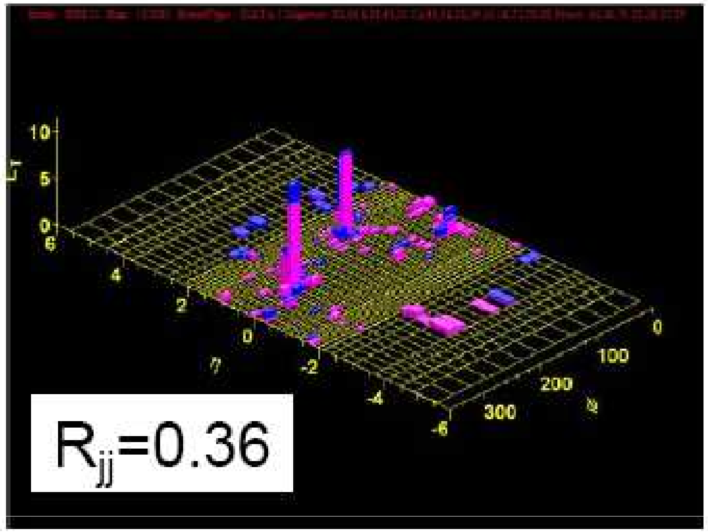
~ 10% of the total DIS events

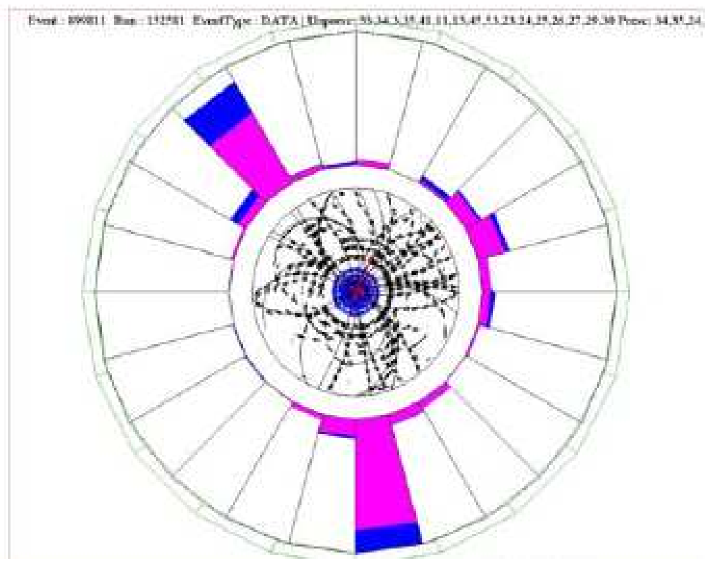
Diffractive event @ Tevatron

Hard diffraction with
2 central jets & 2 gaps



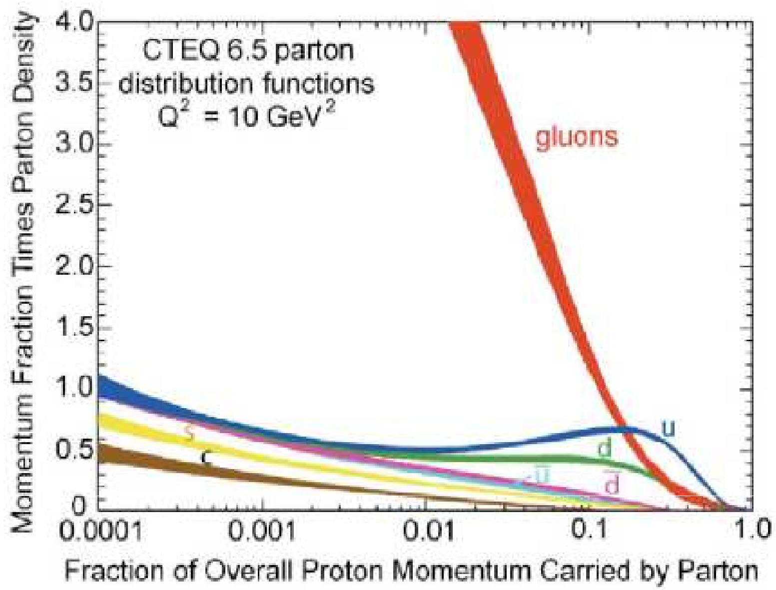




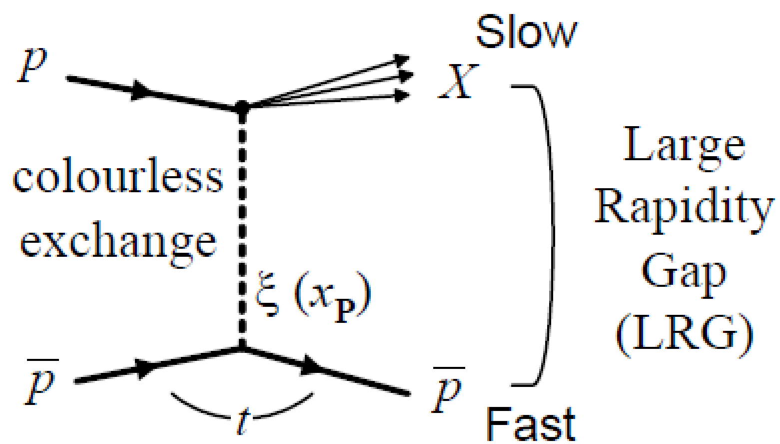


Why studying hadronic diffraction?

Very high gluon density in the proton @ low x is associated to the large fraction of diffractive events… (this talk)
=> Sensitivity to low x physics like saturation effects… (this talk)



Measure f(t) dependence
=> Essential to access the internal structure of the probed particle (a first ex. => next slide) this talk for recent results



An example from the past

ELASTIC AND INELASTIC SCATTERING OF 1.37 GeV α-PARTICLES FROM ^{40,42,44,48}Ca

G. D. ALKHAZOV [†], T. BAUER [††], R. BERTINI [†††], L. BIMBOT [‡], O. BING [†††], A. BOUDARD, G. BRUGE, H. CATZ, A. CHAUMEAUX, P. COUVERT, J. M. FONTAINE [‡‡], F. HIBOU [†††], G. J. IGO [‡‡‡], J. C. LUGOL and M. MATOBA [*]

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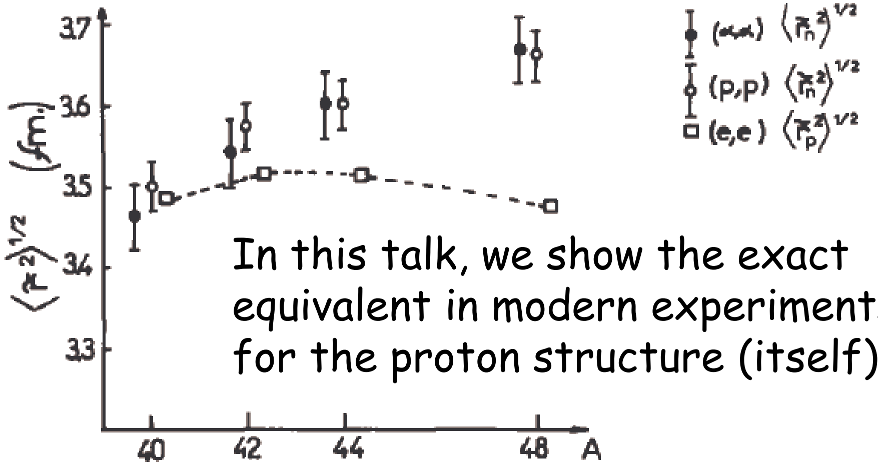
CEN Saclay, BP 2, 91190 Gif-sur-Yvette, France

Received 6 October 1976
(Revised 9 December 1976)

ϑ (or $|t|^{1/2}$) dependence presents the standard diffractive pattern (optics)

Extract the structure in neutron (and proton) for the Calcium!



In this talk, we show the exact equivalent in modern experiments for the proton structure (itself)…

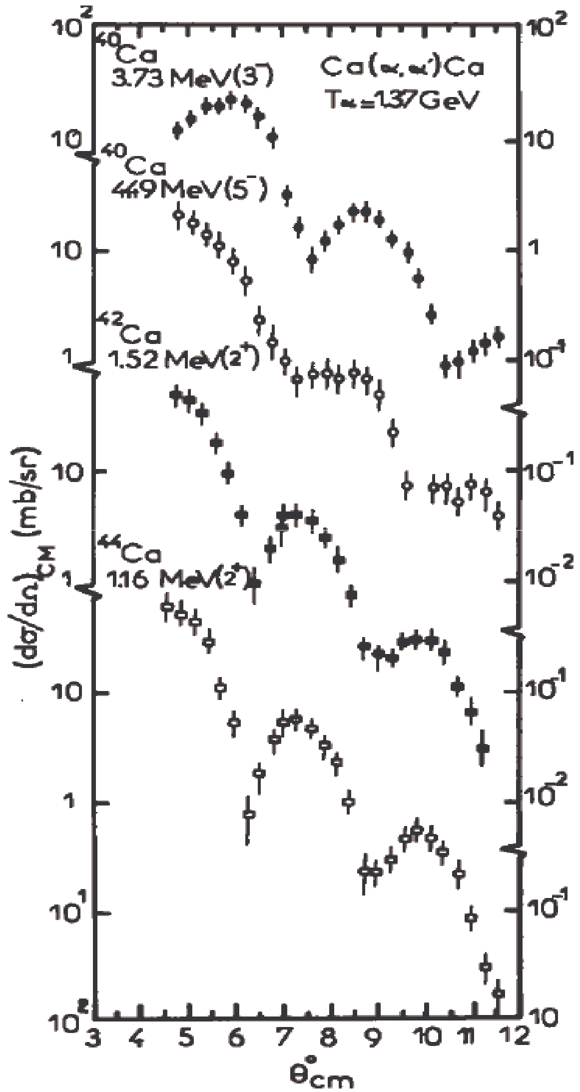


Fig. 3. Differential cross sections of inelastic scattering of 1.37 GeV α-particles from the 3_1^- and 5_1^- states in ^{40}Ca and the 2_1^+ states in ^{42}Ca and ^{44}Ca.

Diffractive Kinematics at HERA

Standard DIS variables …

x = momentum fraction q/p
Q^2 = $|\gamma^*$ 4-momentum squared$|$

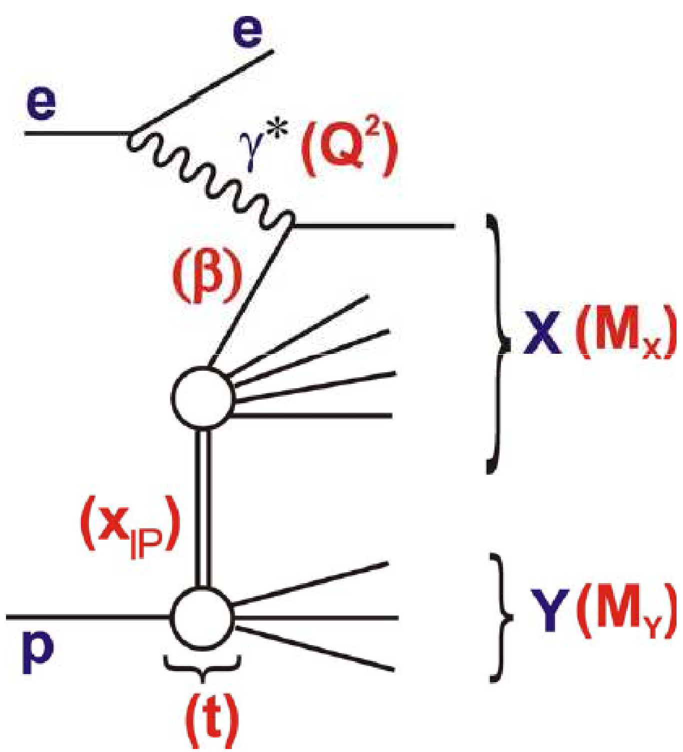
Additional variables for diffraction …

t = squared 4-momentum transfer at proton vertex

x_{IP} = fractional momentum loss of proton (momentum fraction IP/p)

$\beta = x / x_{IP}$ (momentum fraction q / IP)

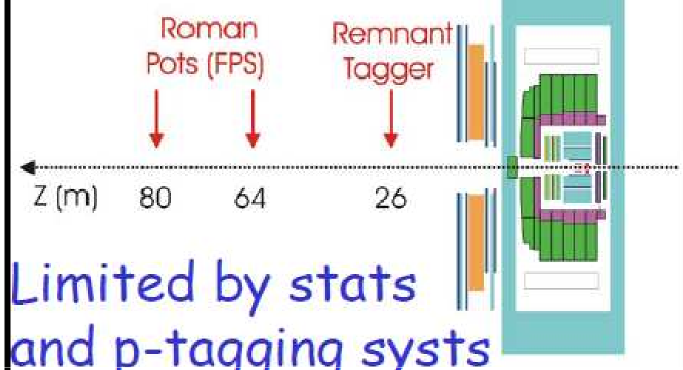
Most generally ep→eXY …



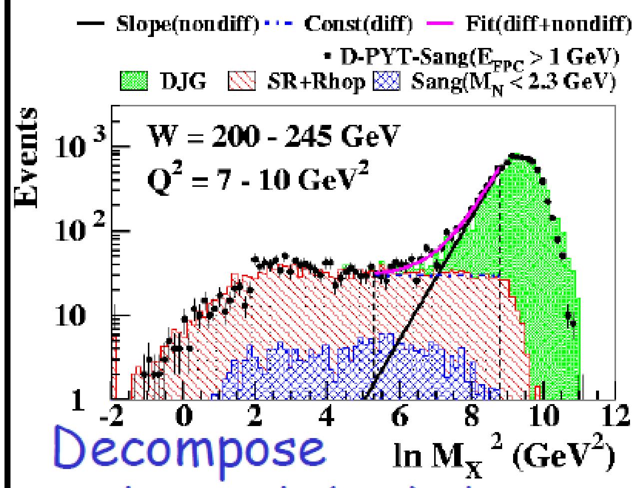
In most cases here, Y=p, (small admixture of low mass excitations)

Measurements at HERA

Scattered proton in ZEUS LPS or H1 FPS



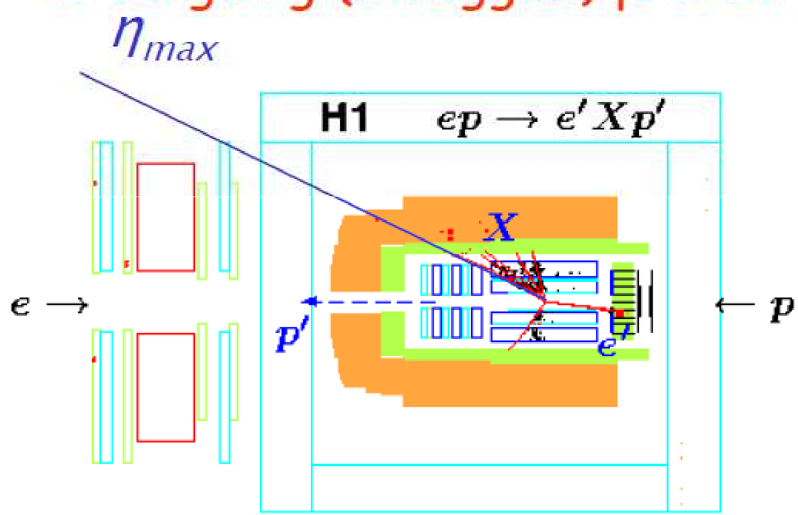
Limited by stats and p-tagging systs



Decompose inclusive $\ln(M_x)$ distn

Signatures and Selection Methods

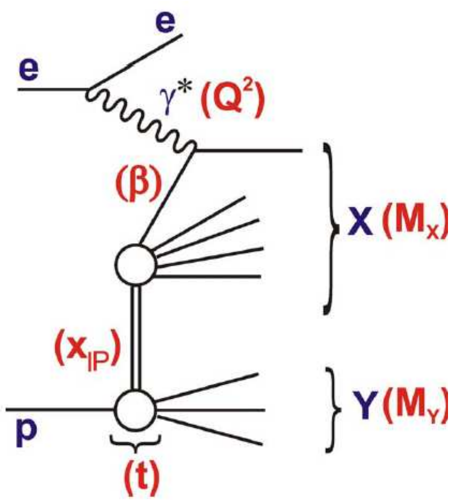
'Large Rapidity Gap' adjacent to outgoing (untagged) proton



Limited by p-diss systs

<u>The methods have very different systematics!</u>

Cross sections (definitions)



Evaluate the number of events per bin
Correct from acceptances

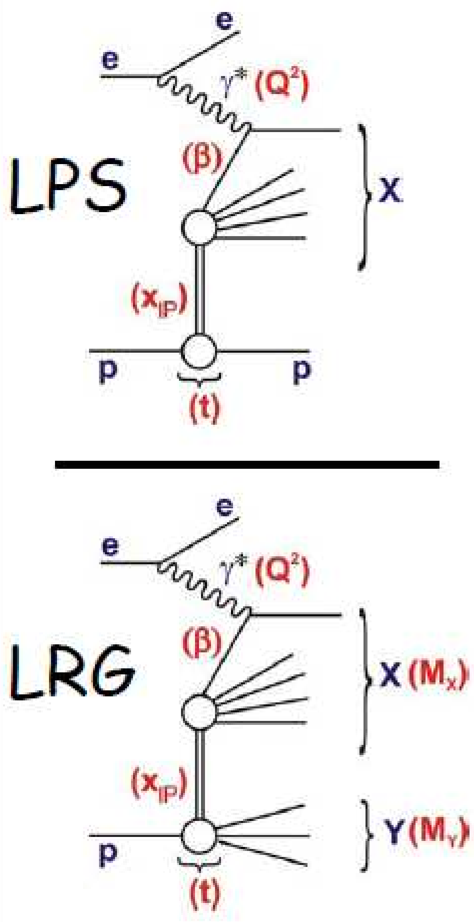
Derive cross sections (// F2)

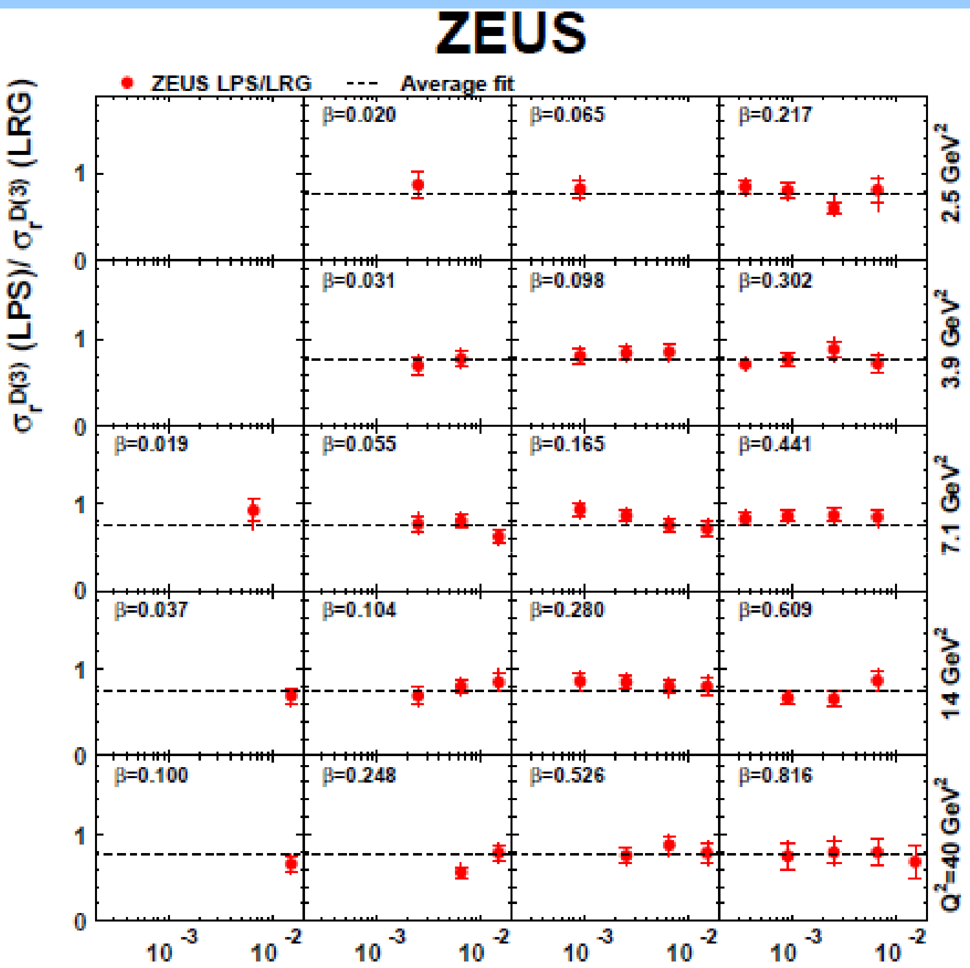
$$\frac{d^3\sigma}{d\beta dQ^2 dx_{IP}} = \frac{4\pi\alpha^2}{\beta Q^4}(1-y+\frac{y^2}{2})\sigma_r^{D(3)}(\beta,Q^2,x_{IP})$$

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

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

Proton tag versus LRG measurements

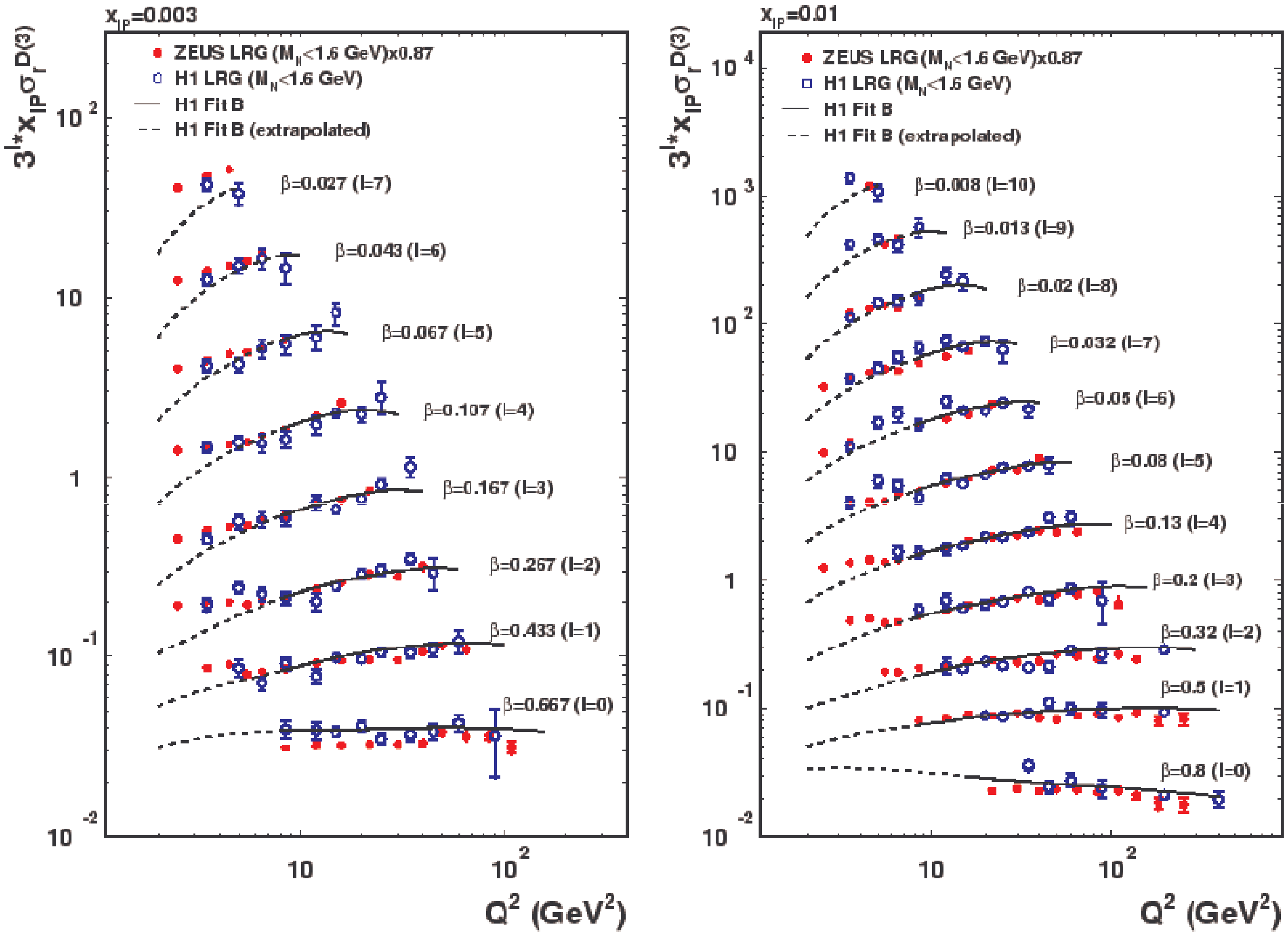




- LRG selections contain typically 20% p diss
- No significant dependence on any variable
- Similar compatibility with Mx method

… **well controlled, precise measurements**

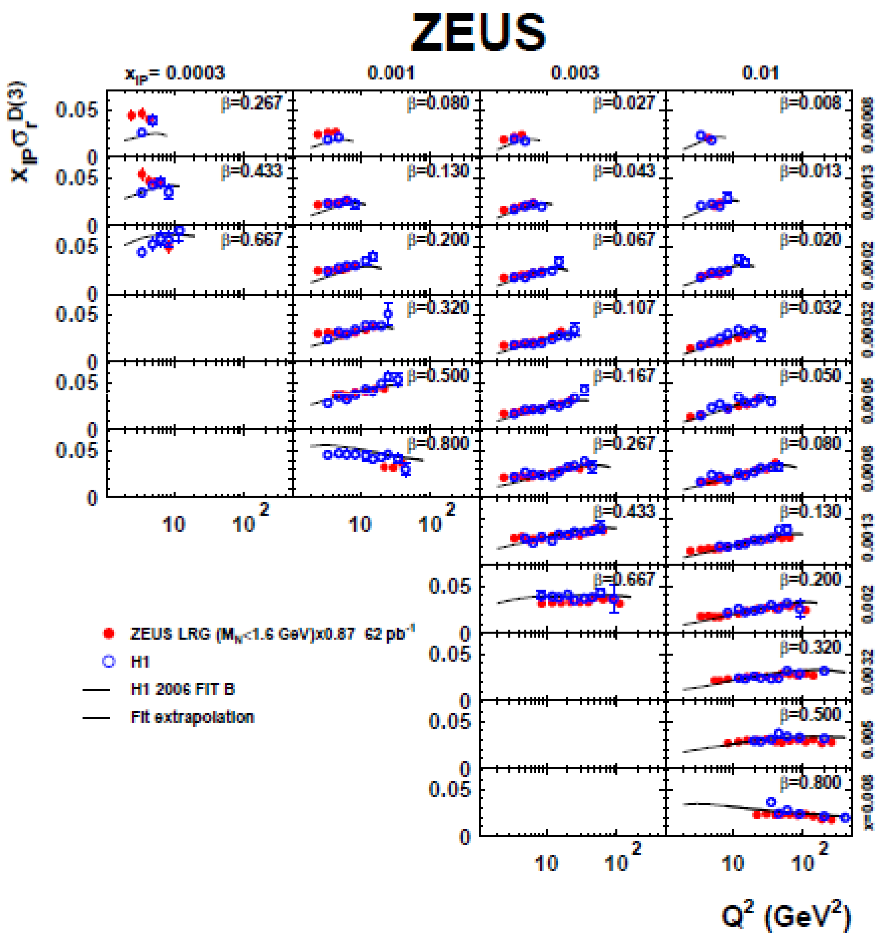
LRG comparison H1/ZEUS

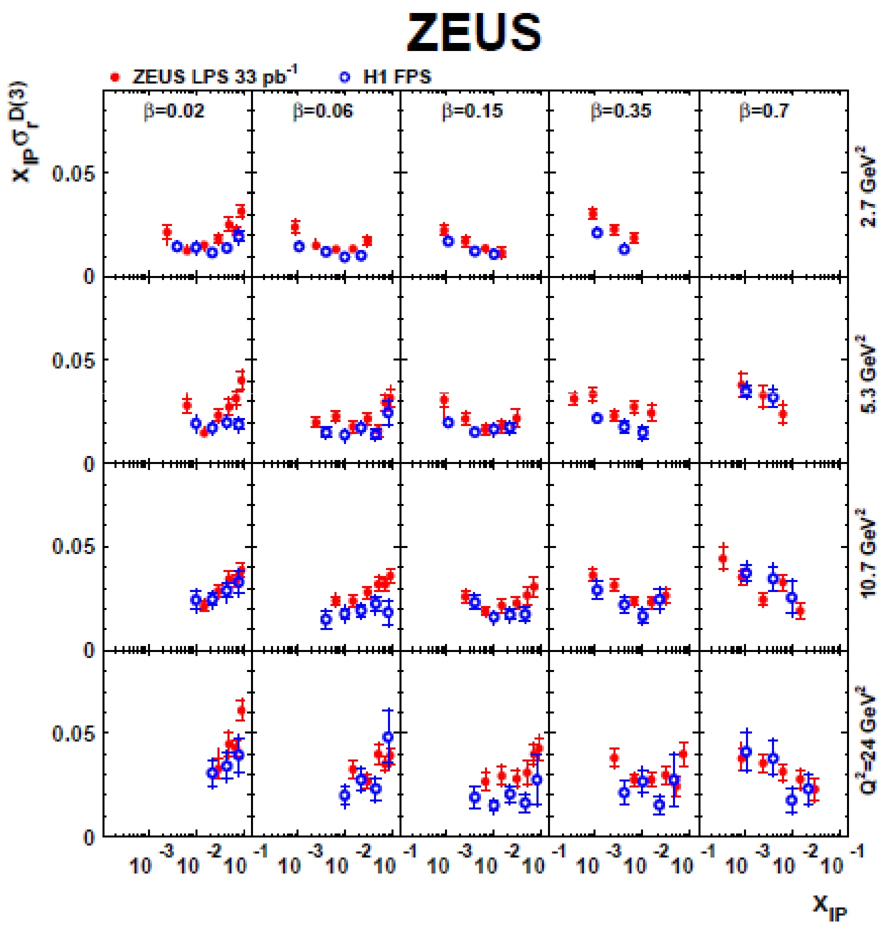


Final ZEUS LRG data ($62\ pb^{-1}$) reach new level of statistical precision

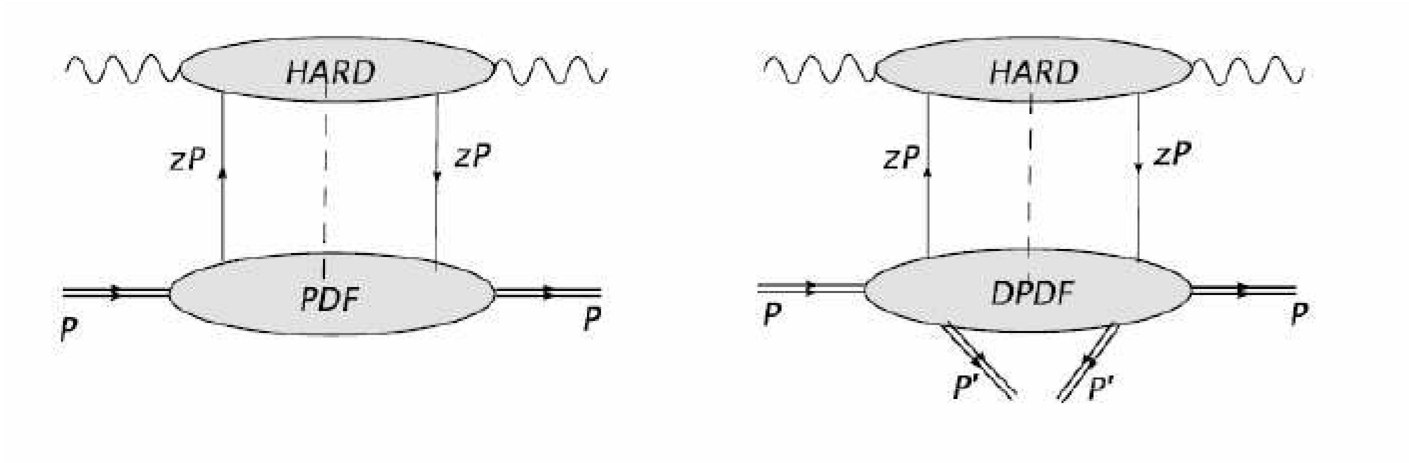
Overall 13% H1-ZEUS difference within normalis^n errors
Good shape agreement in most of phase space (high, low β?)

Global view LRG & Proton tag





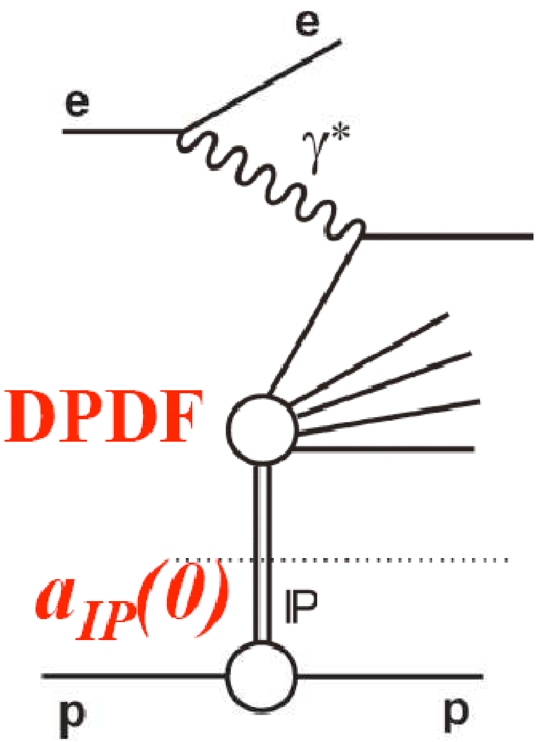
QCD and diffraction



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

=> Diffractive PDFs

QCD and diffraction (con't)



2 steps process…

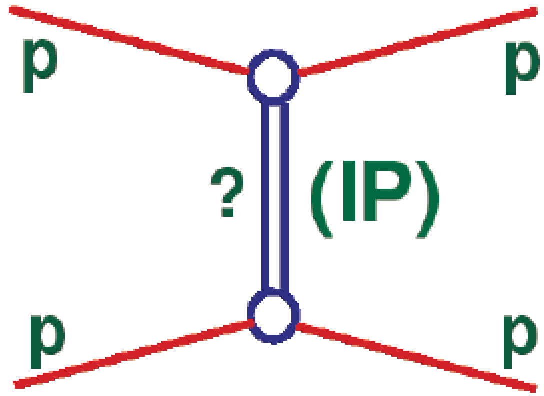
(i) parametrise the IP flux (x_{IP},t) & factorise it (hypothesis)

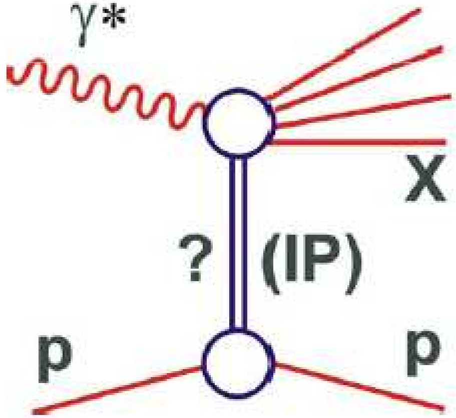
(ii) Then, fit diff PDFs(β,Q²)

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

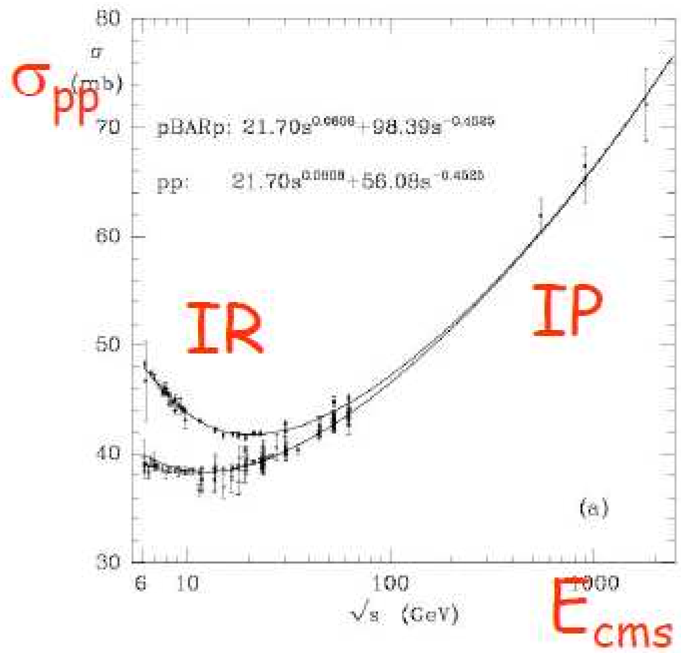
1^{st} step: $f(x_{IP},t)$ dependences

- Diffractive DIS reminiscent of (soft) diffractive hadronic scattering
- **Vacuum exchange `pomeron' (IP)** introduced in Regge theory context



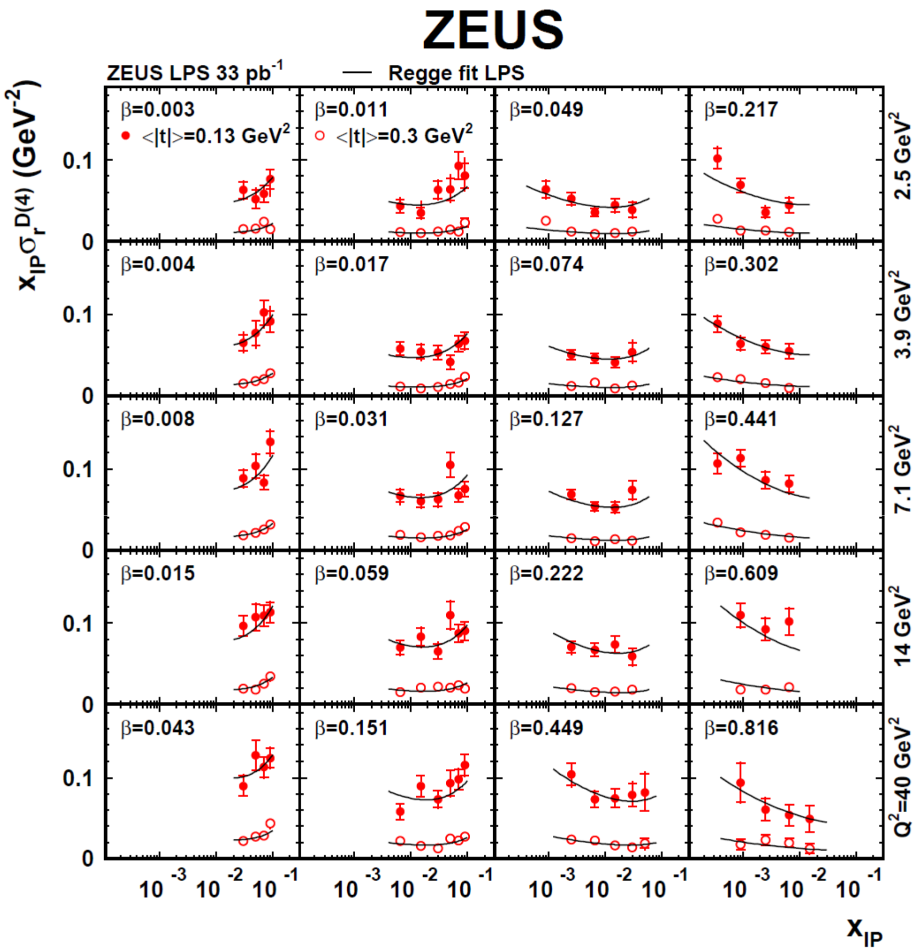


looks similar to soft IP



extract effective IP trajectory: $\alpha_{IP}(0)+\alpha'_{IP}t$

1^{st} step: $f(x_{IP})$ from data



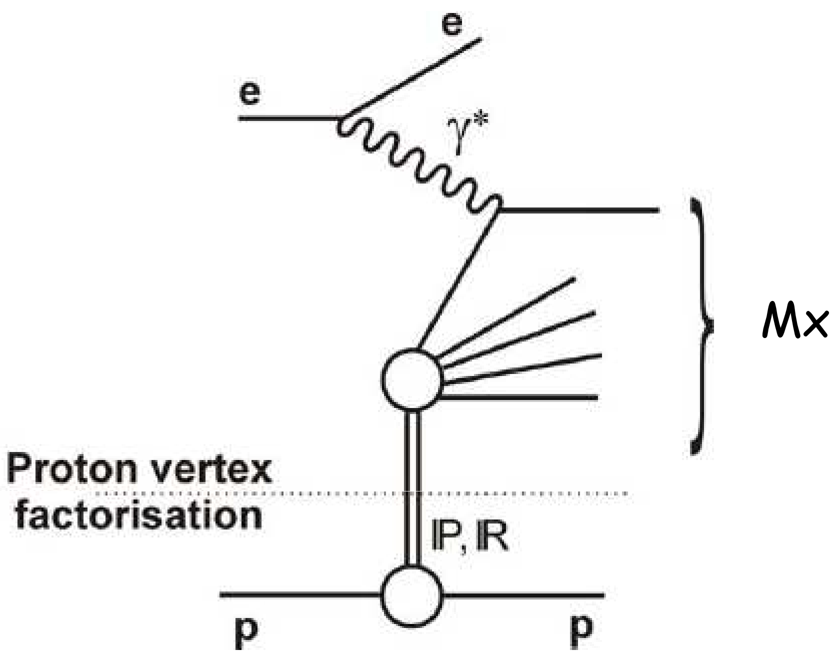
- 1^{st} diffractive structure function measurement at multiple t values
- Low x_{IP} / high β … falling (IP-like) behaviour
- High x_{IP} / low β … rising (IR-like) behaviour

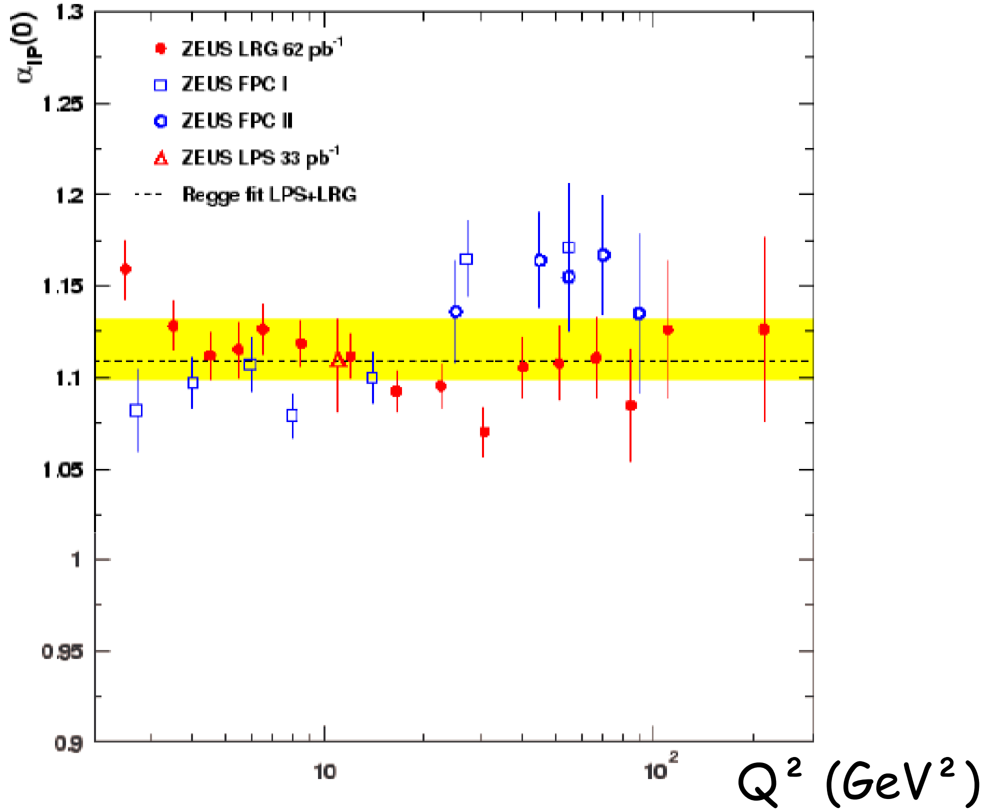
ZEUS $\alpha_{IP}(0) = 1.11 \pm 0.02(\text{stat.}) \pm 0.02(\text{syst.}) \pm 0.02(\text{model})$

c.f. H1 $\alpha_{IP}(0) = 1.12 \pm 0.01(\text{exp.}) \pm 0.02(\text{model})$

Consistent with soft IP intercept

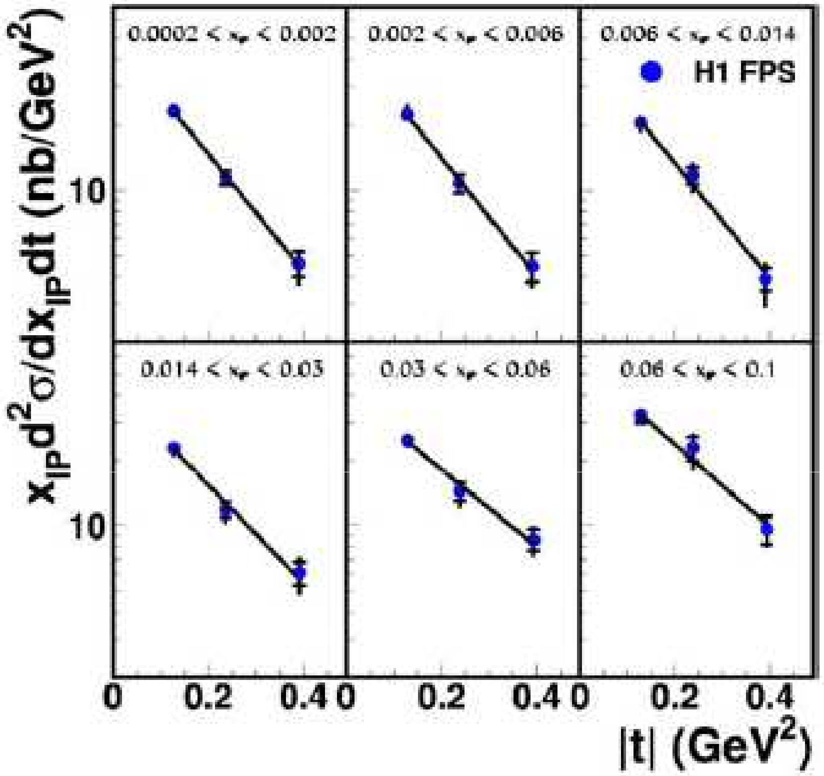
1st step: $f(x_{IP})$ from data

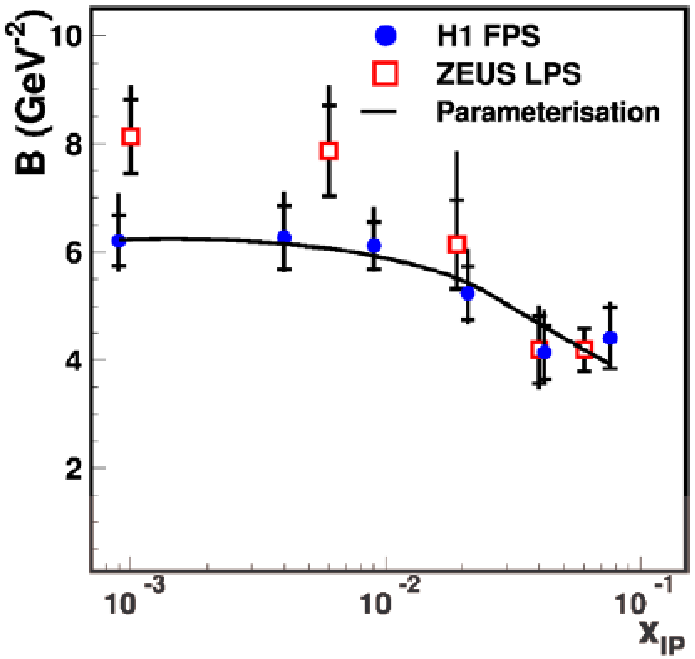




$f(x_{IP},t)$ factorises from (β,Q^2) dependence

1^{st} step: f(t) from data





Fitting to e^{bt} yields
b=6-7 GeV^{-2},
independently of β, Q^2

ZEUS LPS:

$$\alpha'_{IP} = -0.01 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})$$

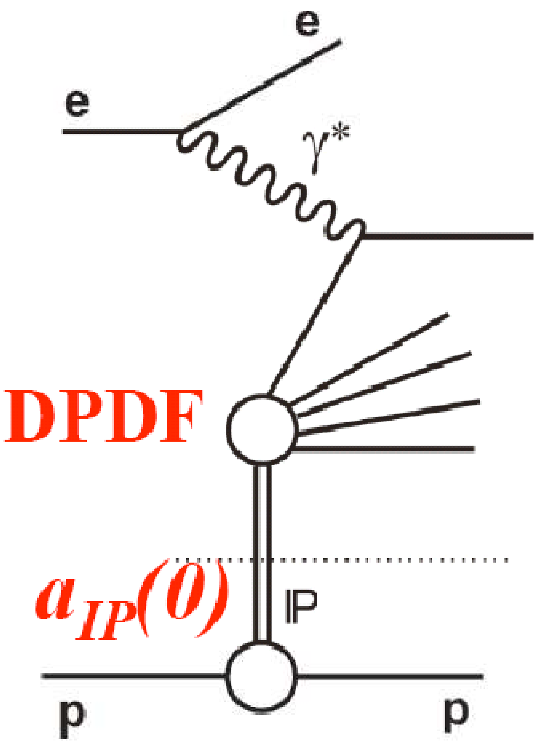
c.f. H1: $\alpha'_{IP} = 0.06 \pm 0.13$

Not consistent with soft IP intercept… more complex effects…

2^{nd} step: Diffractive PDFs $f(\beta,Q^2)$

(ii) Then, fit diff PDFs(β,Q^2)

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



The process (//QCD fits of F2):

…parametrise quark and gluon densities(z) at initial scale Q_0^2

…Evolution in Q^2 (DGLAP equations)

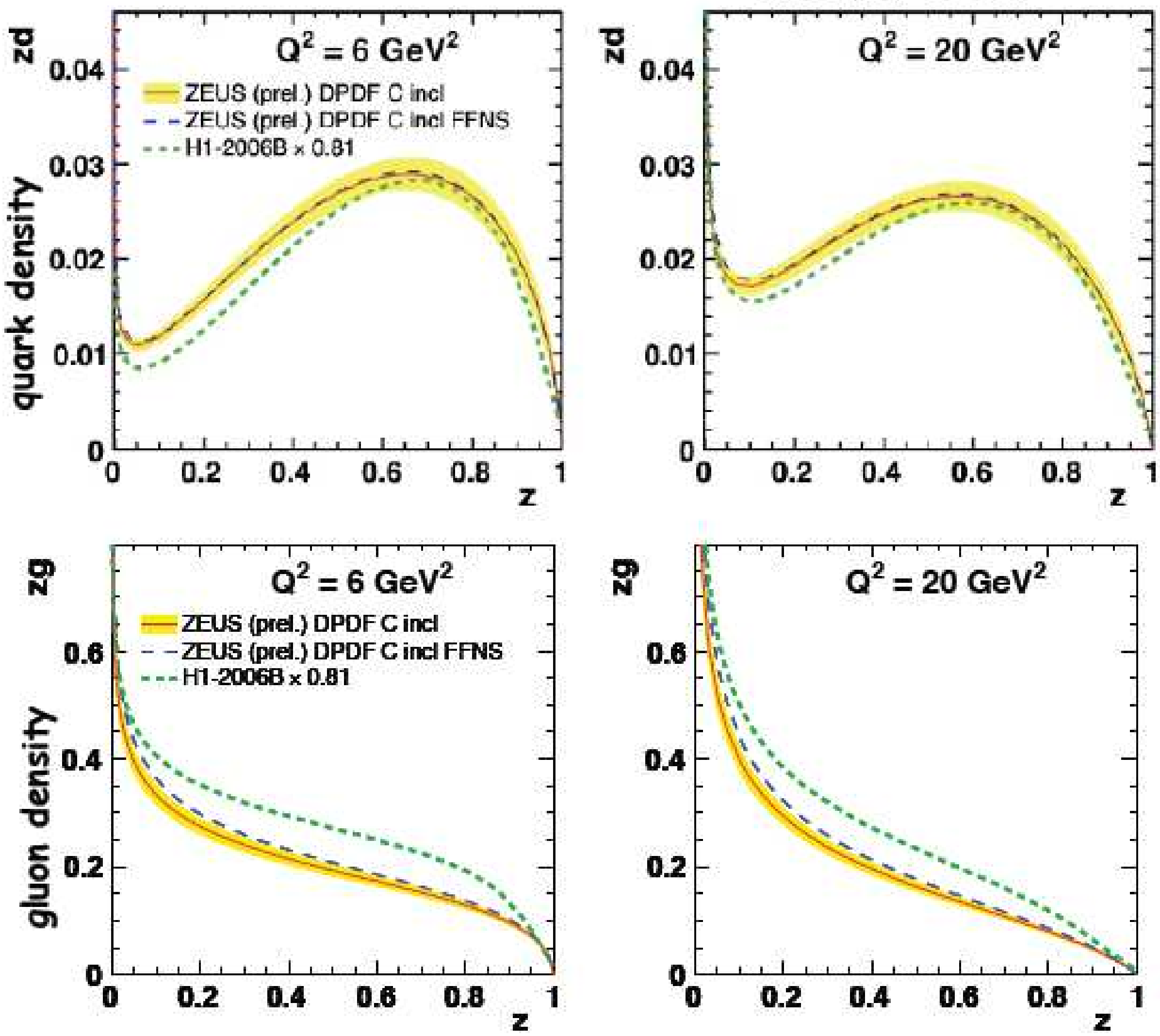
…Fit to F2D data

$$z\Sigma(z,Q_0^2) = A_q z^{B_q}(1-z)^{C_q}$$

$$zg(z,Q_0^2) = A_g(1-z)^{C_g}$$

2nd step: Diffractive PDFs f(β,Q²)

ZEUS-prel-09-004



- z = incoming momentum fraction of parton (= β for quarks, > β for gluons)

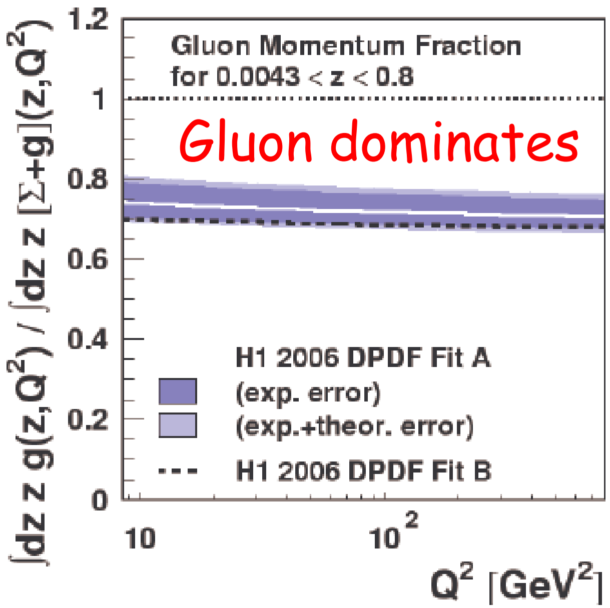
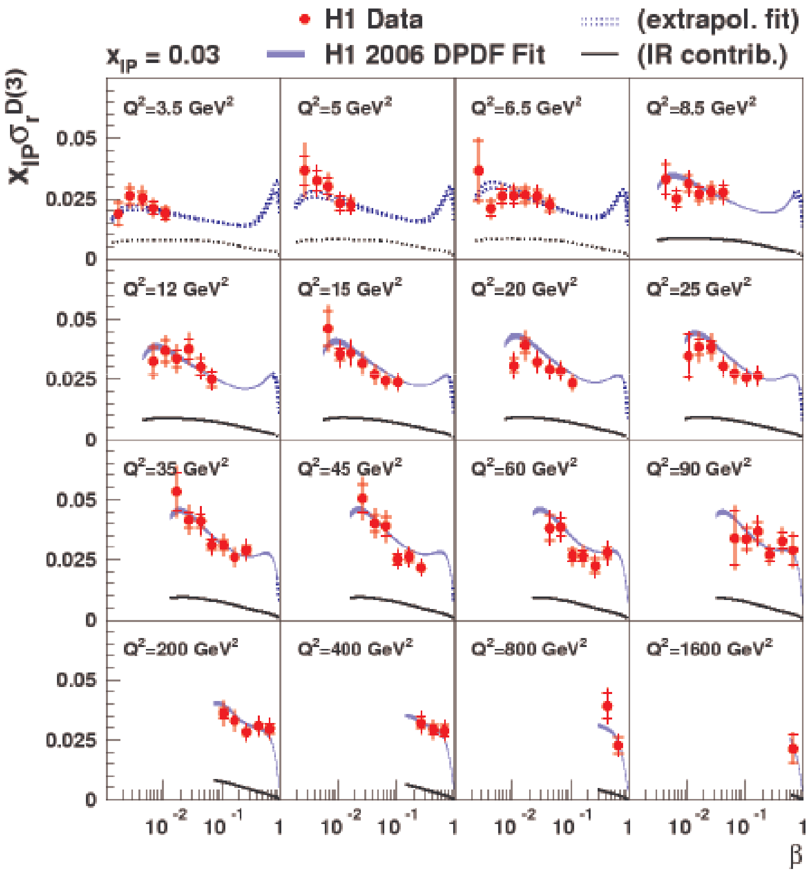


Illustration of the (β,Q²) dependences

F2D data + QCD fit prediction



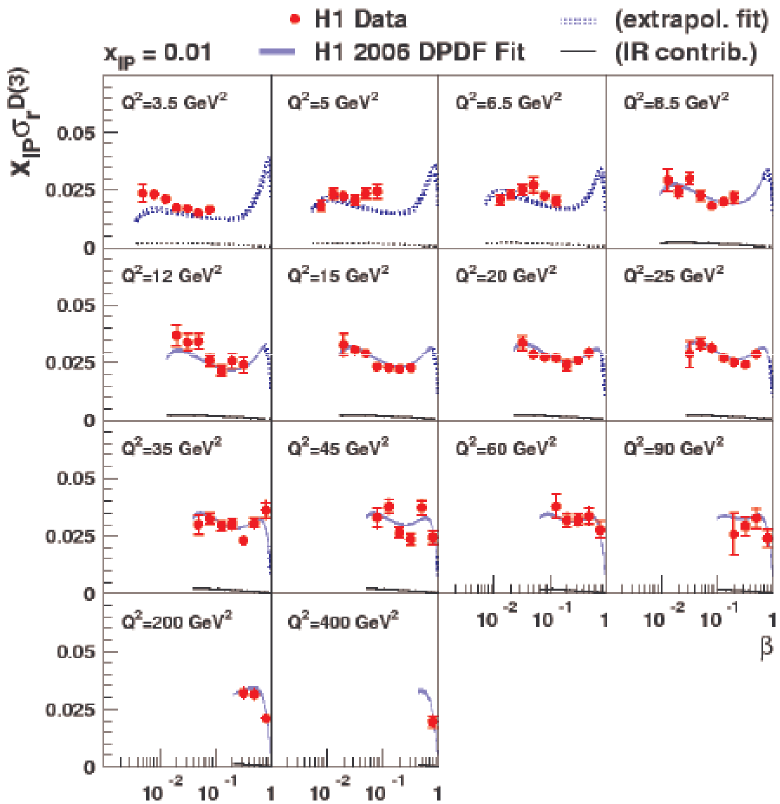
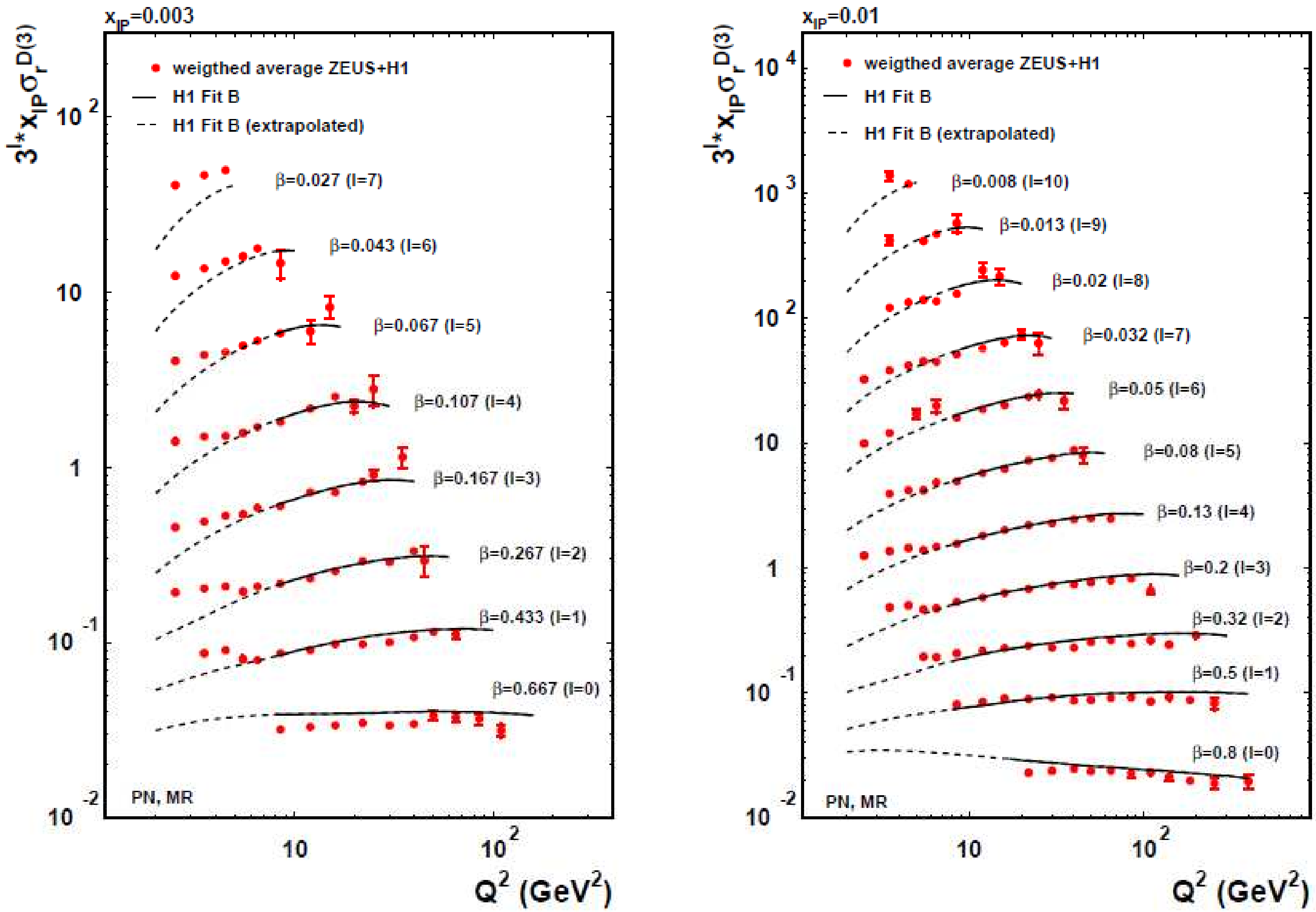
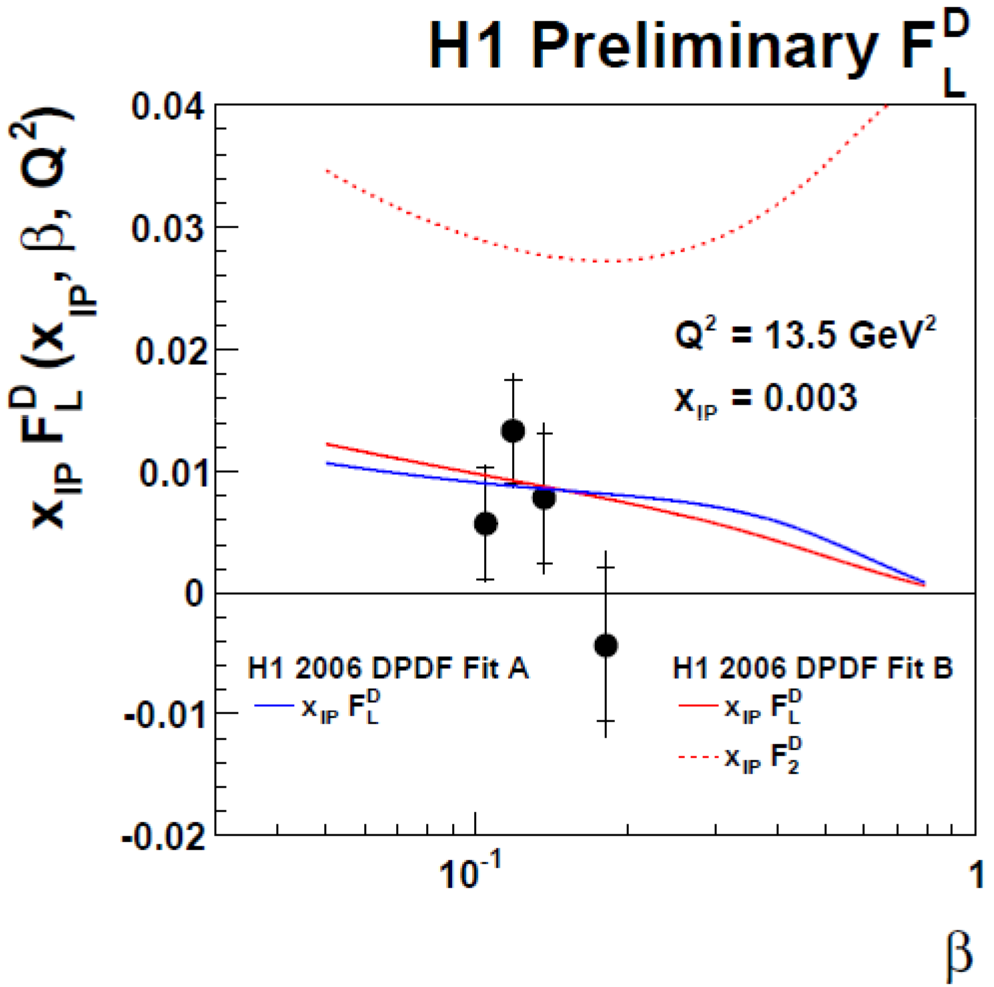


Illustration of the (β,Q²) dependences

Scaling violations: H1 & ZEUS data combined + QCD Fit



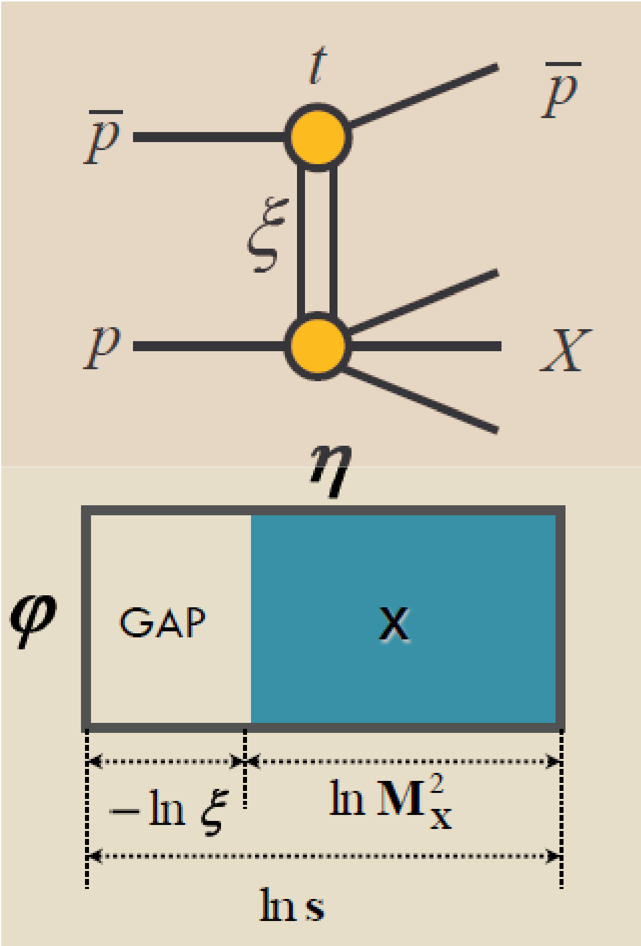
dPDFs can describe recent FLD measurement

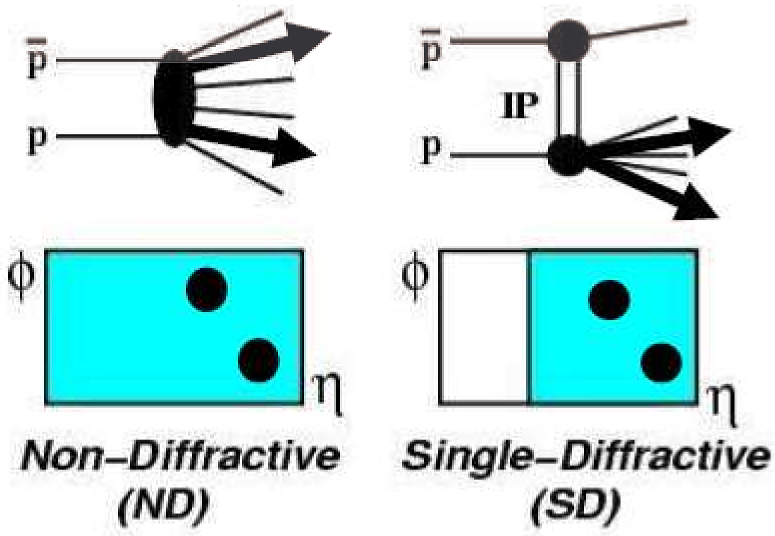


The limit of factorisation @ Tevatron

Introduction

Consider dijet production

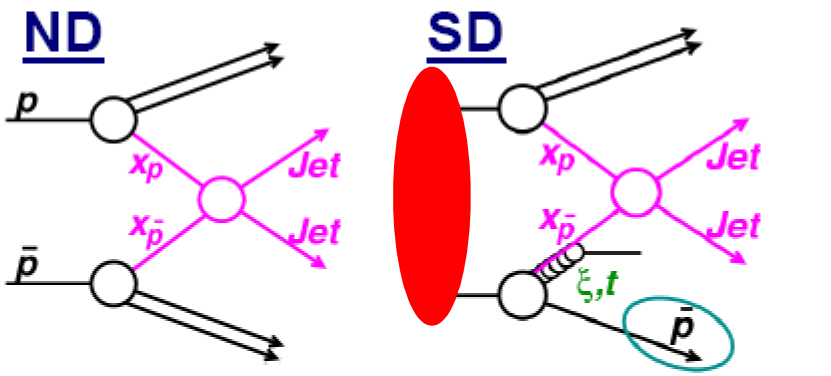




$$R(x_{Bj}) \equiv \frac{\mathrm{Rate}_{jj}^{SD}(x_{Bj})}{\mathrm{Rate}_{jj}^{ND}(x_{Bj})}$$

$$\Rightarrow \frac{F_{jj}^{SD}(x_{Bj})}{F_{jj}^{ND}(x_{Bj})}$$

The limit of factorisation @ Tevatron

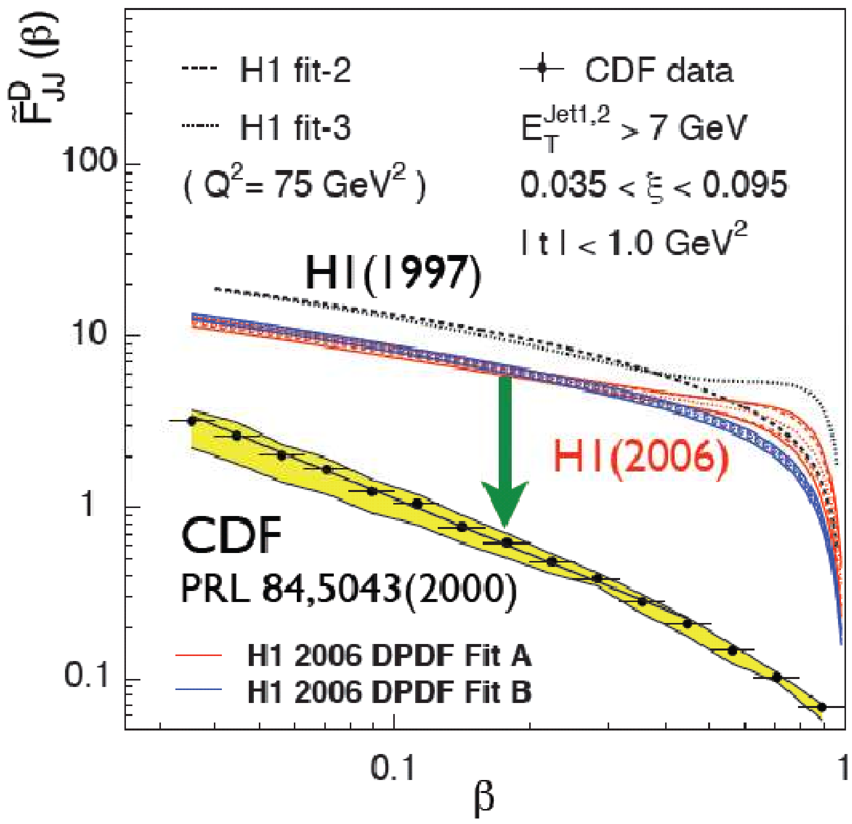


Diff. Structure Function Measurement:

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

to be measured — global fit

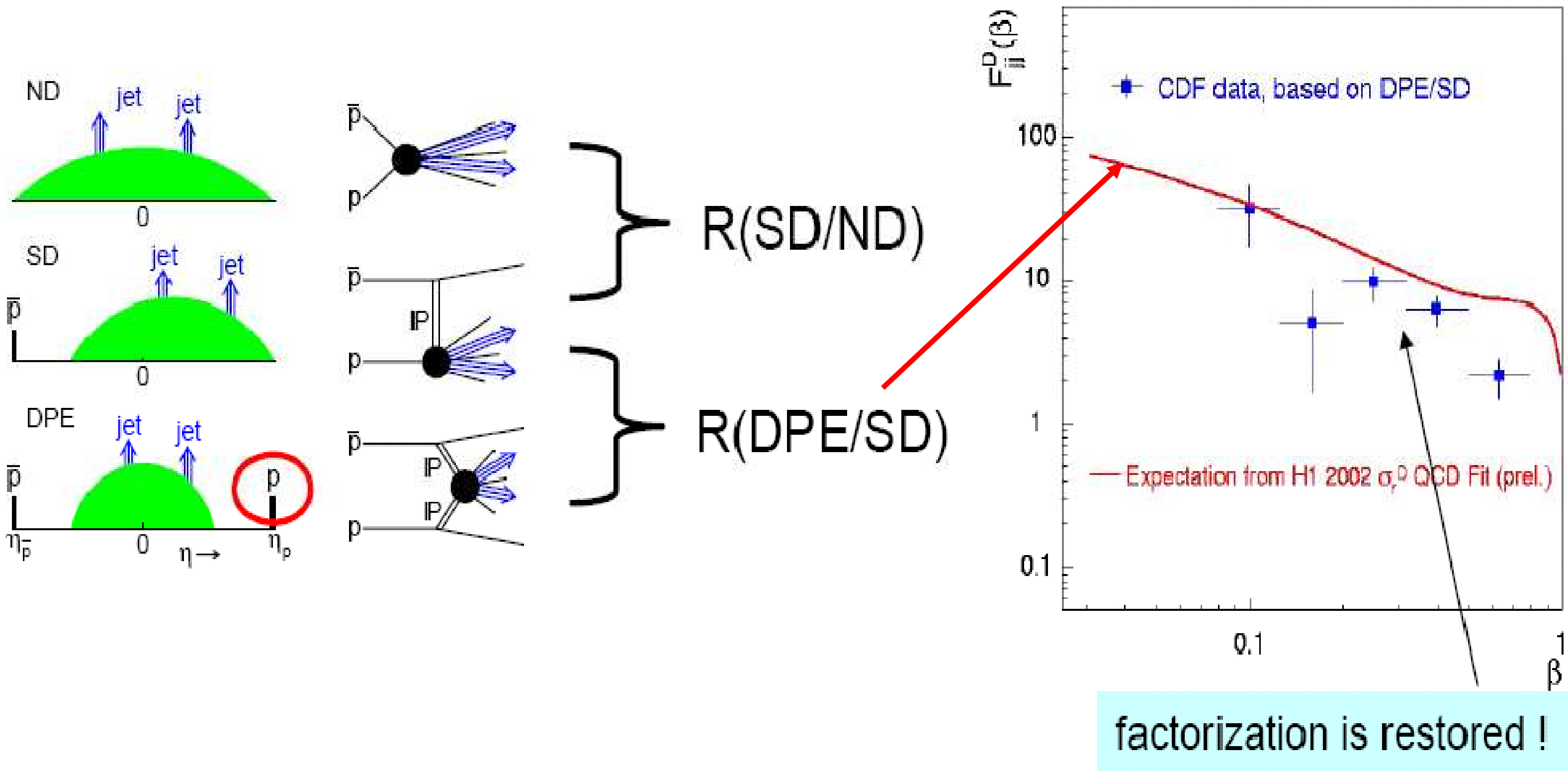
=> F_{jj}^{D} can be derived and compare to expectations from HERA dPDFs



Mismatch of a factor~5 to 10 => factorisation does not hold !

=> « survival » gap probability of a few % ?

Double Pomeron Exchange @ Tevatron



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

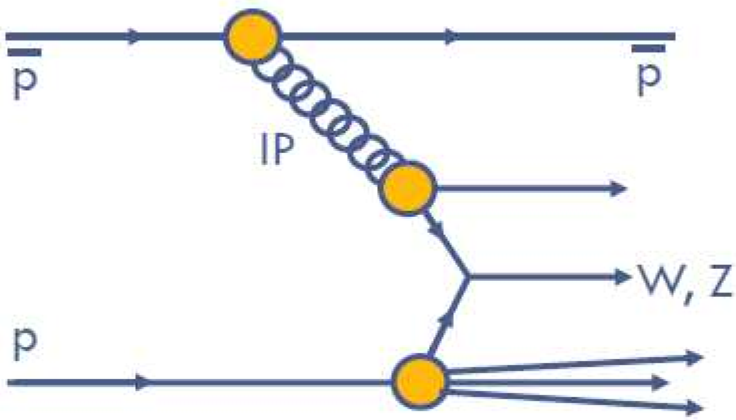
The price for producing a gap (survival probability) is paid only once!

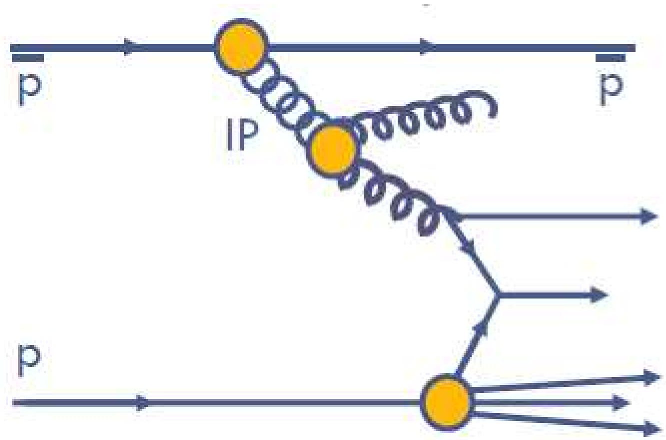
This confirms that the survival Gap probability may be just an underlying interaction between spectator partons in the protons…

Diffraction at the Tevatron: W/Z

Diffractive production of W and Z

…probes the quark content in the Pomeron
…contributions from gluons are suppressed by a factor α_S





Diffraction at the Tevatron: W/Z

Run I results: using rapidity gap selection for diffractive events

Fraction of W events due to Single IP exchange

CDF: **1.15** $\pm 0.51 \pm 0.20$ %

D0 : **0.89** $\pm 0.19 \pm 0.17$ %

Fraction of Z events

D0 : **1.44** $\pm 0.61 \pm 0.52$ %

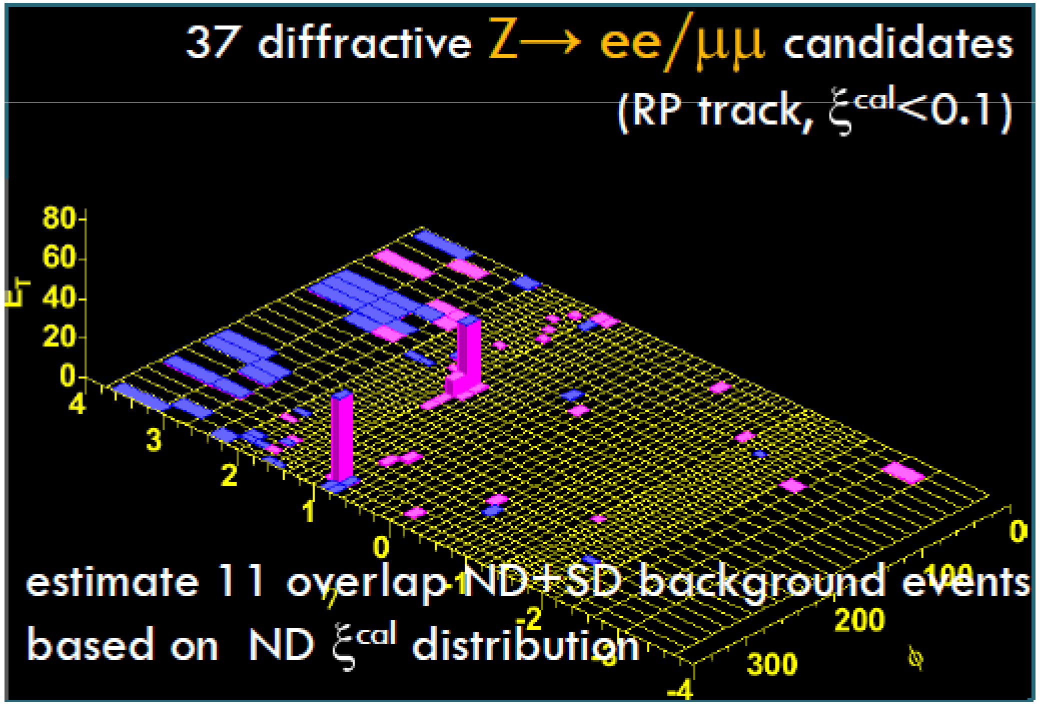
Run II using Roman pots

Fraction of W events

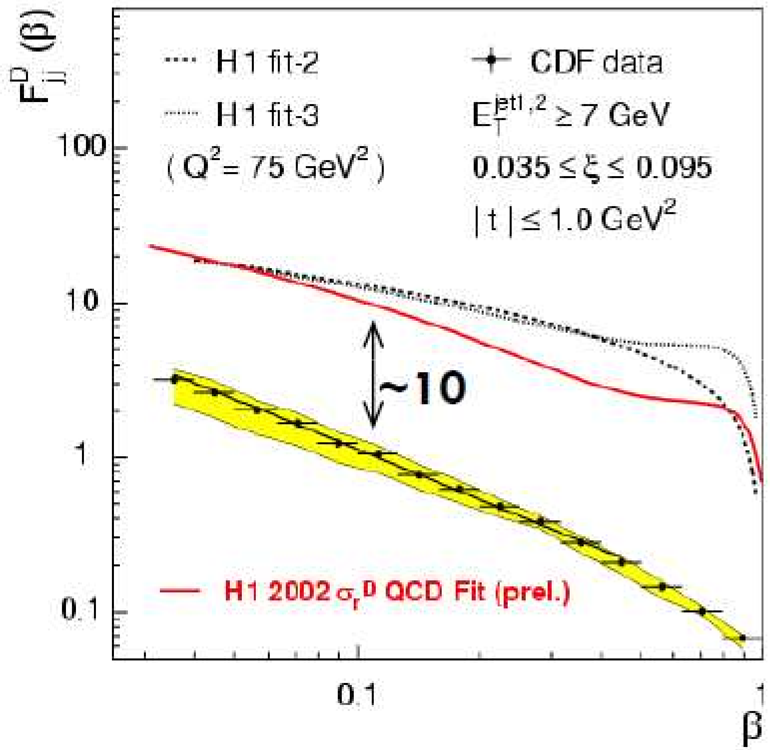
CDF: **0.97** $\pm 0.05 \pm 0.11$ %

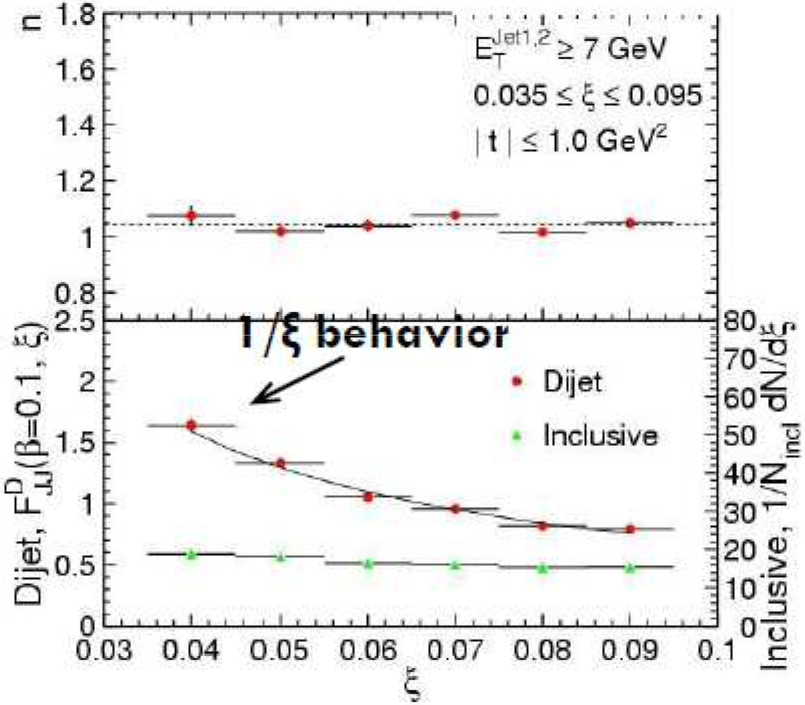
Fraction of Z events

CDF: **0.85** $\pm 0.20 \pm 0.11$ %



Diffractive PDFs at the Tevatron





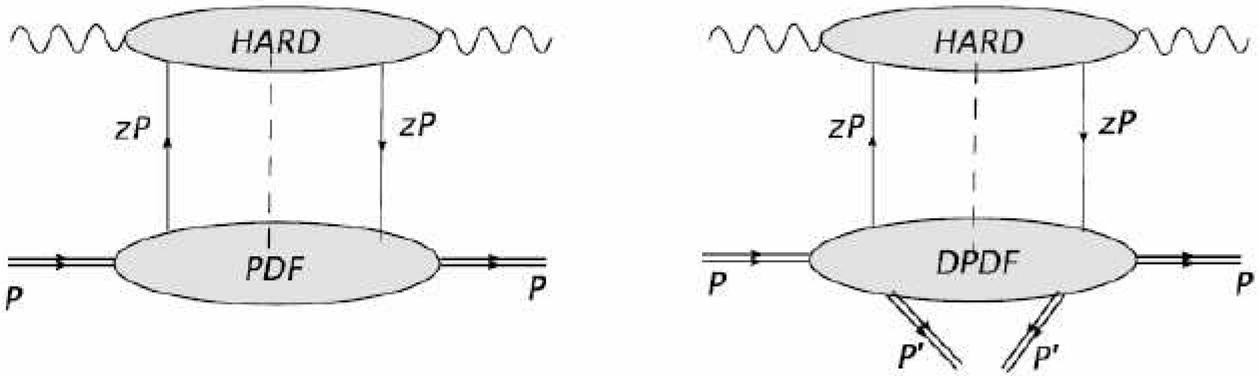
QCD Factorisation breaking
(see previous slides)

$$F^D_{jj} = C\beta^{-n}\xi^{-m}$$

for $\beta < 0.5$
$n = 1.0 \pm 0.1$
$m = 0.9 \pm 0.1$

=> f(ξ:=x_{IP},t) . f(β)
Regge factorisation holds

Coming back on diffractive PDFs

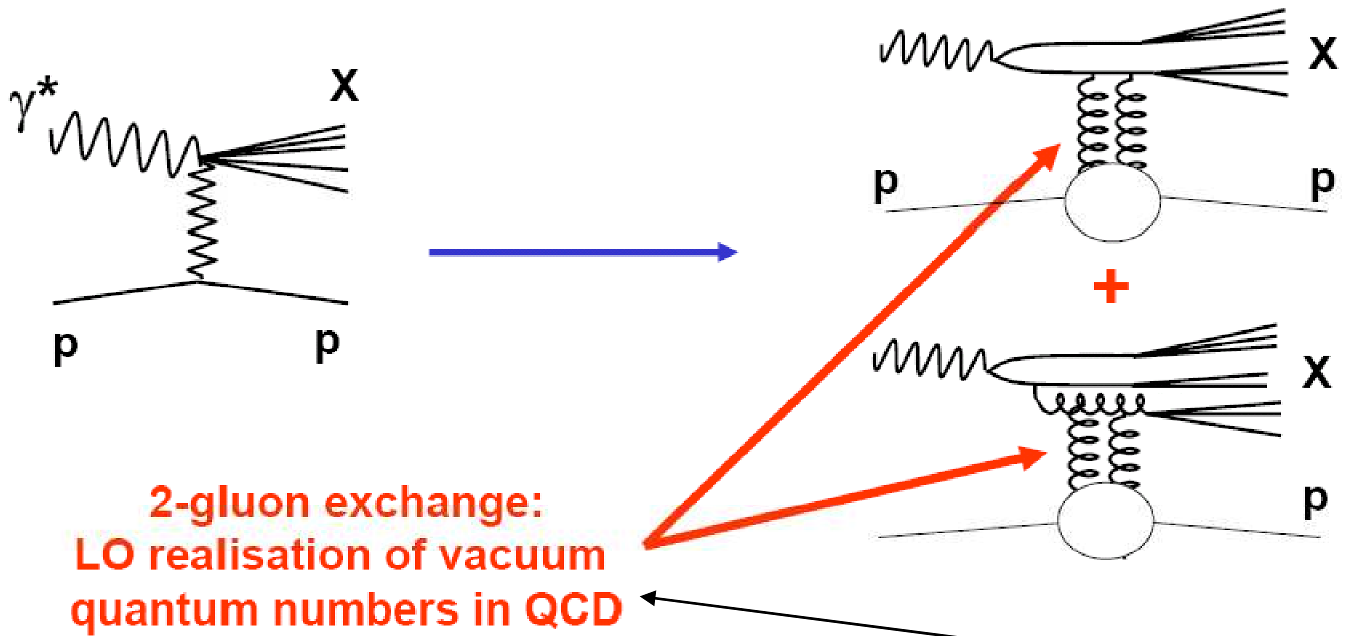


$$f_a^D(z,\mu^2,x_{IP},t) = \sum_X \int dy_- \, e^{-izP^+y^-} \langle P\,|\overline{\psi_a}(y_-)\gamma^+ \underbrace{|P'X\rangle\langle P'X|}\psi_a(0)|\,P\rangle$$

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 ?

Can we find a common model for DIFF & DIS ?

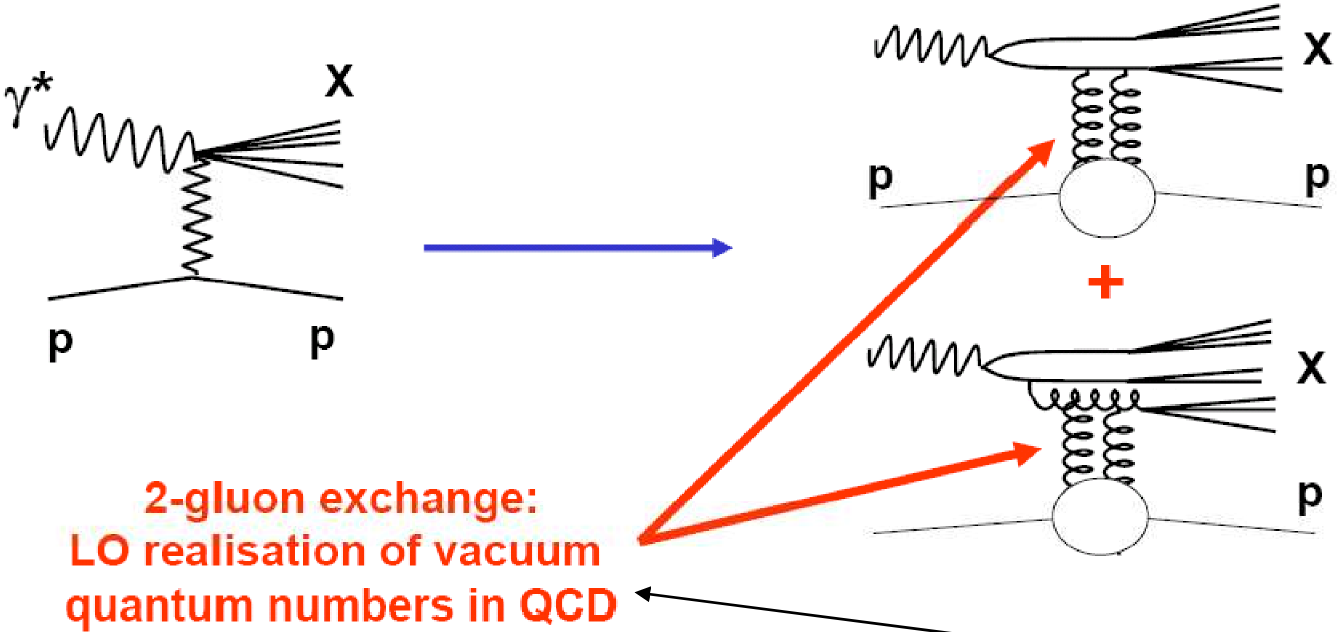


Universal description DIFF/DIS

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

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

Can we find a common model for DIFF & DIS ?



Universal description DIFF/DIS

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

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

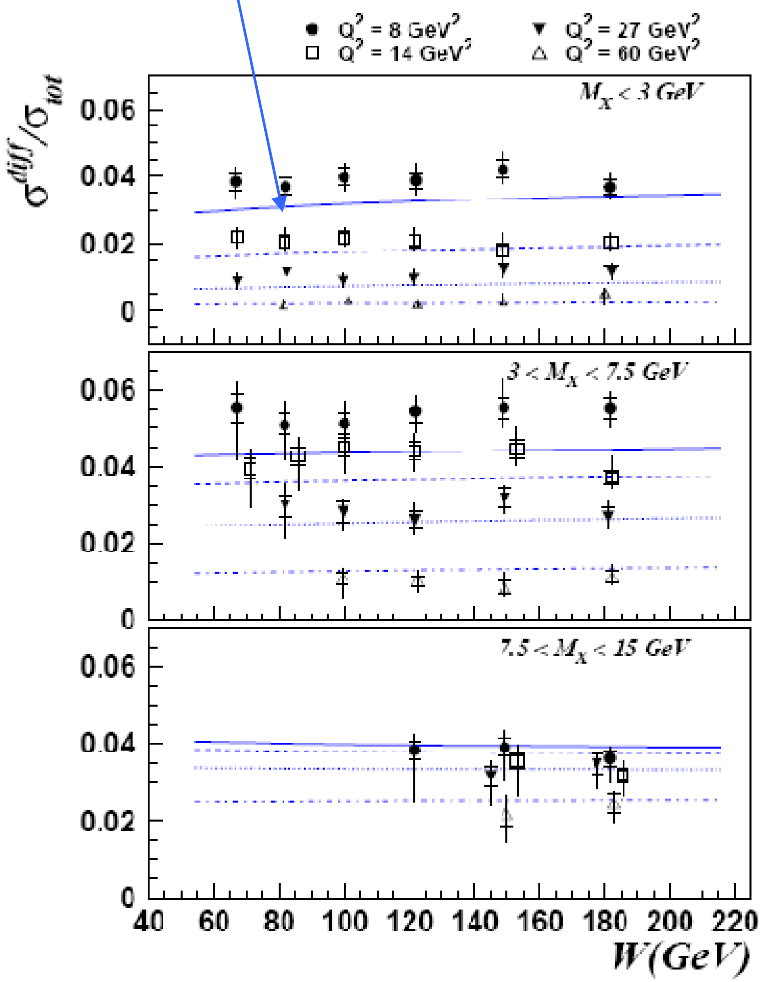
CONSEQUENCE :

@ 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

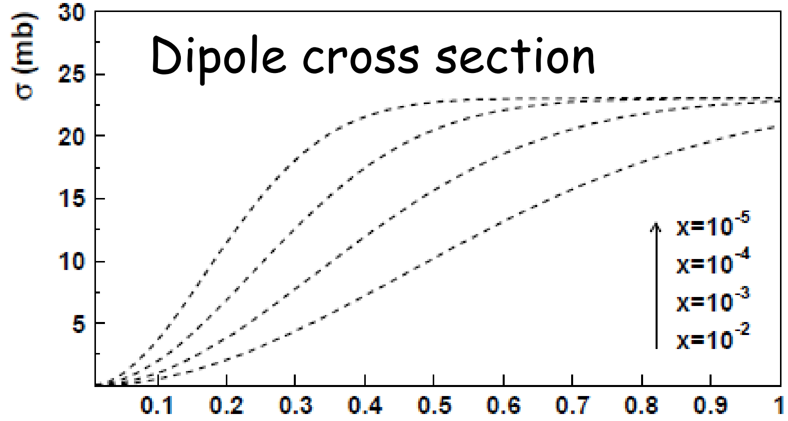


$\sigma_{diff}/\sigma_{DIS}$ ~ constant [W] !

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

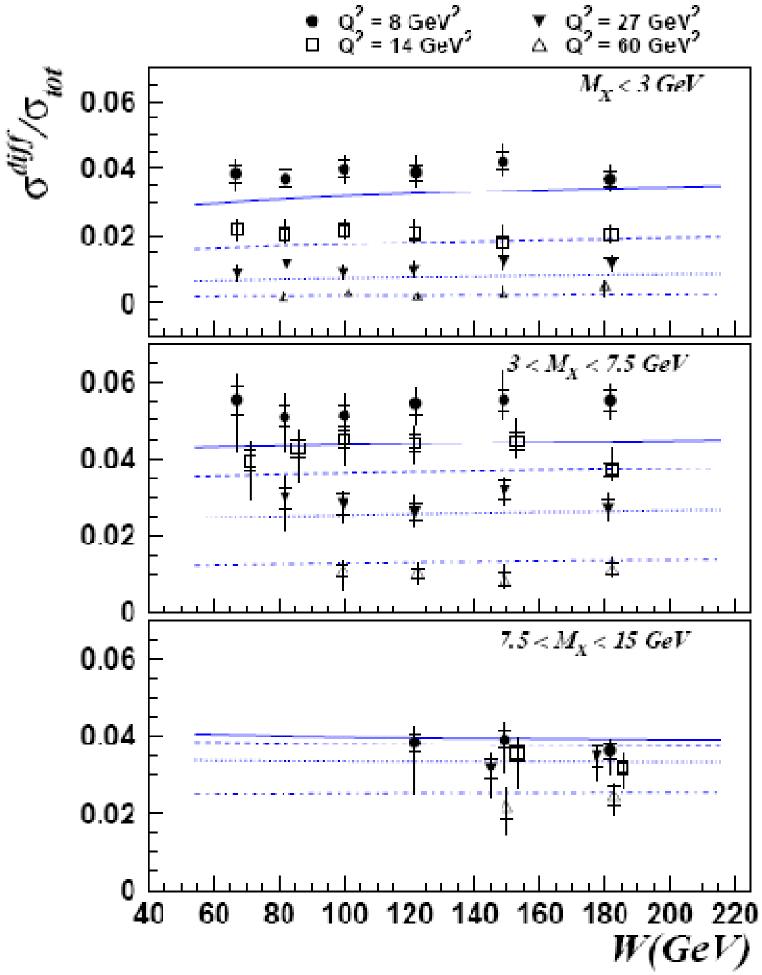
$\sigma_{diff} \neq$ Coef $\otimes$ $[xG(x,Q^2)]^2$
=> DIFF sensitive to saturation (large W)

$$\hat{\sigma}_{q\bar{q}} = \sigma_0 \left\{ 1 - \exp\left(-\frac{r^2}{4R_0^2(x)} \right) \right\}$$



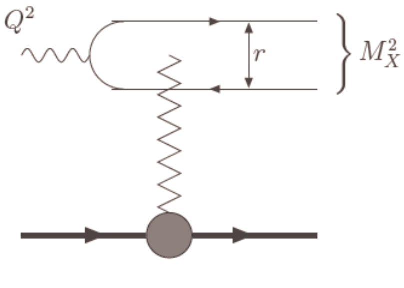
r : dipole size

Modeling the diffractive exchange



$$\hat{\sigma}_{q\bar{q}} = \sigma_0 \left\{ 1 - \exp\left(-\frac{r^2}{4R_0^2(x)} \right) \right\}$$

r : dipole size
Qs:=1/R_0



$$\frac{d\sigma_{dif}}{dt}_{|t=0} = \frac{1}{16\pi} \int_{r,z} |\Psi(r,z,Q)|^2 \, \hat{\sigma}^2_{q\bar{q}}(x_{I\!P}, r)$$

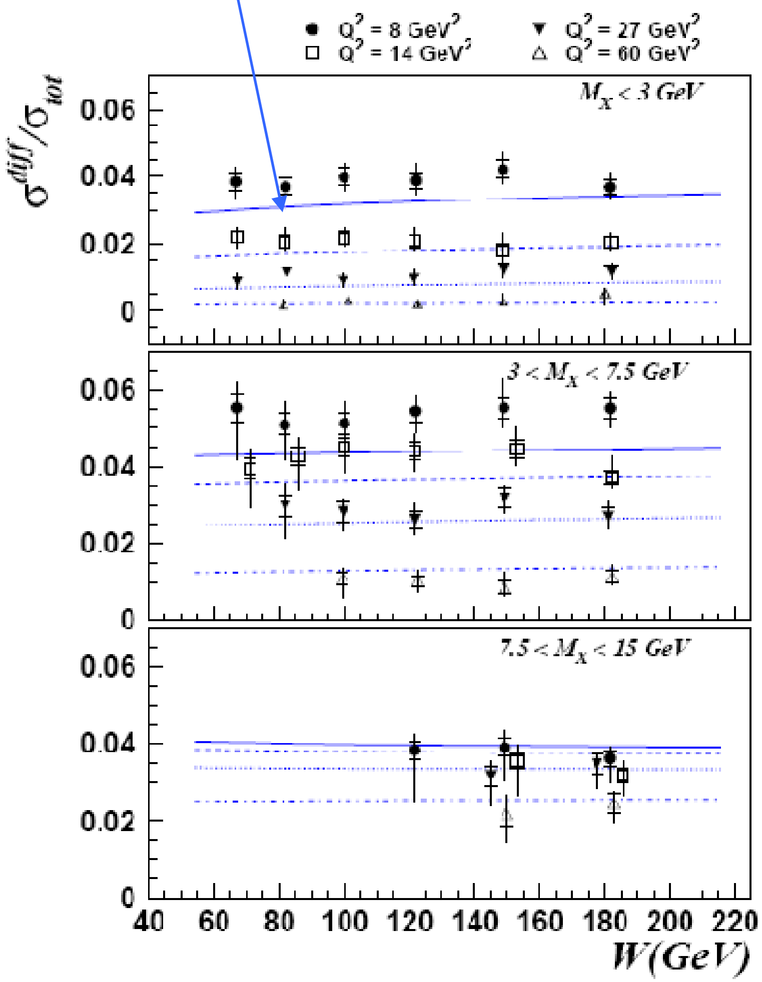
$$\sim \frac{1}{Q^2} \int_{1/Q^2}^{1/Q_s^2} \frac{dr^2}{r^4} \left(r^2 Q_s^2(x) \right)^2 \sim \frac{Q_s^2(x)}{Q^2} \propto x^{-\lambda}$$

At sufficiently high energy, gluon saturation cuts off the large dipoles already on the 'semi–hard' scale $1/Q_s$!

$\sigma_{diff}/\sigma_{tot}$ ~ constant [W or x] @ fixed Q^2

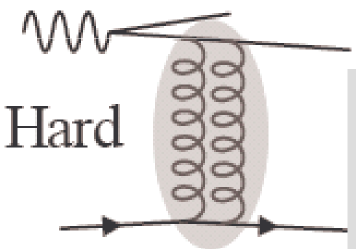
Modeling the diffractive exchange

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 ?

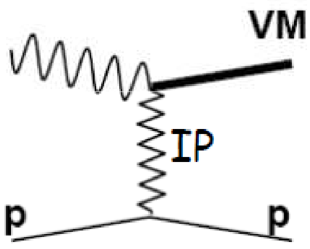
...Modeling the DIFF exchange in exclusive diffractive processes

Exclusive processes @ HERA

Why exclusive events?

(a) Decisive to study the soft-hard transition(scale)

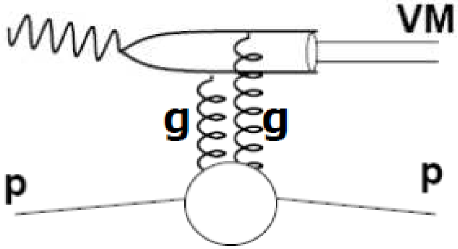
(b) Trigger the generic mechanism of diffraction(scale)
Better sensitivity to saturation effects…



'soft'

$$\sigma(W) \propto W^{\delta}$$

$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$



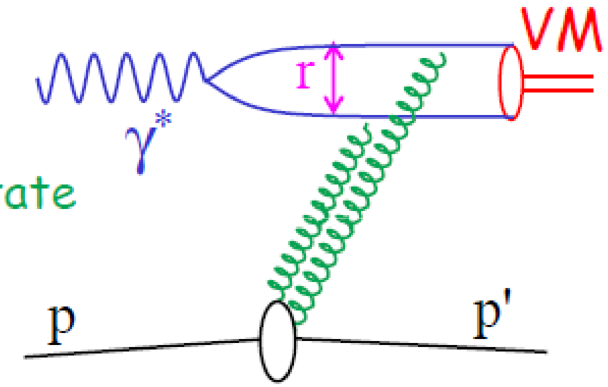
'hard'

- Expect δ to increase from soft (~0.2, from 'soft Pomeron' value) to hard (~0.8, from $xg(x,Q^2)^2$)
- Expect b to decrease from soft (~10 GeV^{-2}) to hard (~4-5 GeV^{-2})

Exclusive processes and QCD (reminder)

In the presence of a **hard scale** ⇒ perturbative QCD applicable
<u>In the target frame</u>, VM production is a 3-step process:

1. $\gamma^* \rightarrow q\bar{q}$ oscillation
2. $q\bar{q}$ scatters off the proton by two-gluon exchange (at lowest order) in colour singlet state
3. VM is formed after the interaction

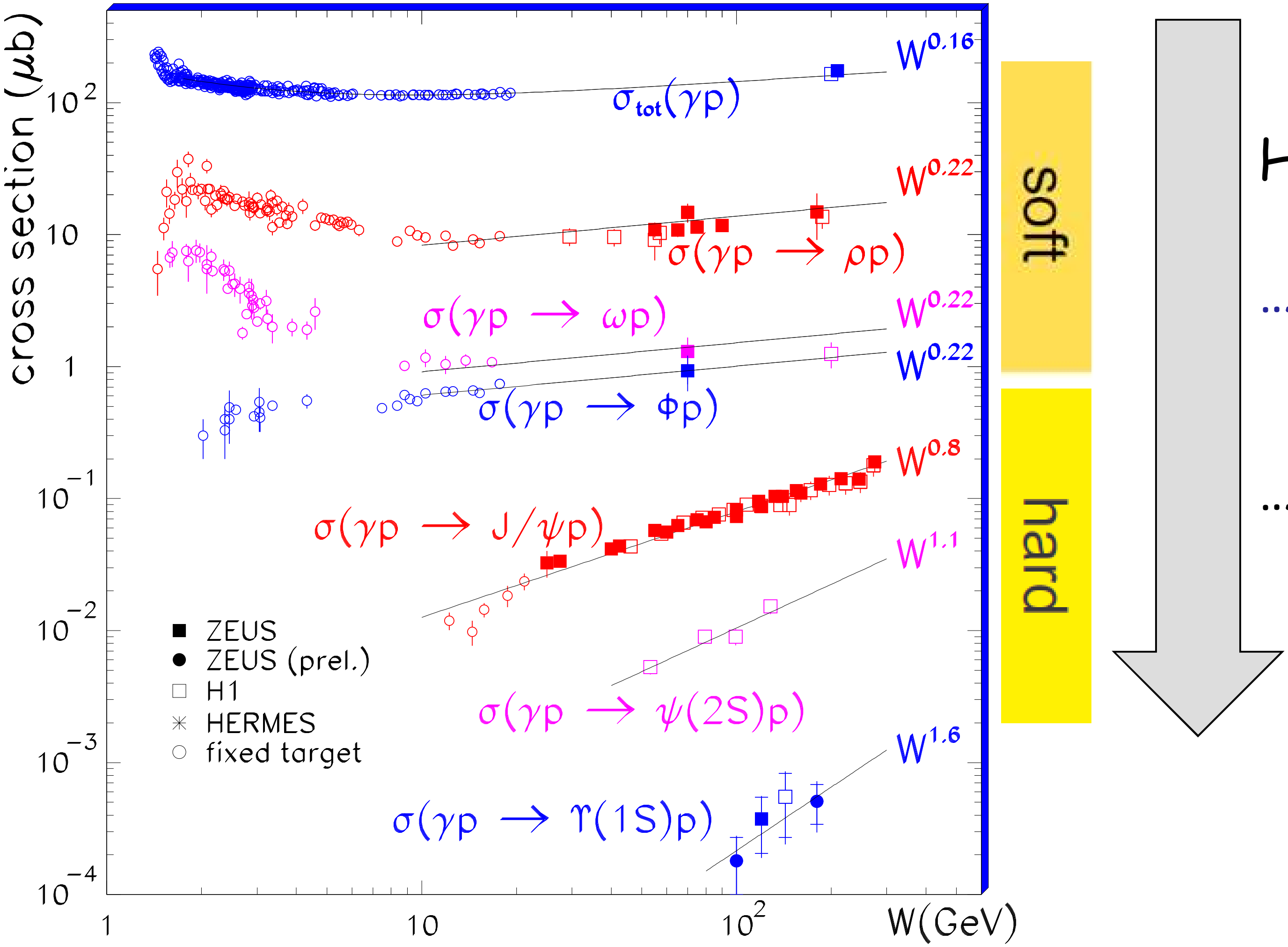


If **dipole size** $r = 1/[z(1-z)Q^2 + m_q^2]^{\frac{1}{2}}$ is **small**
(large m_q or γ^*_L at high Q^2) ⇒ **$q\bar{q}$ pair resolves gluons**

…Immediate complementarity with inclusive diffraction

Exclusive processes: W dependence

Scale = mass of the VM



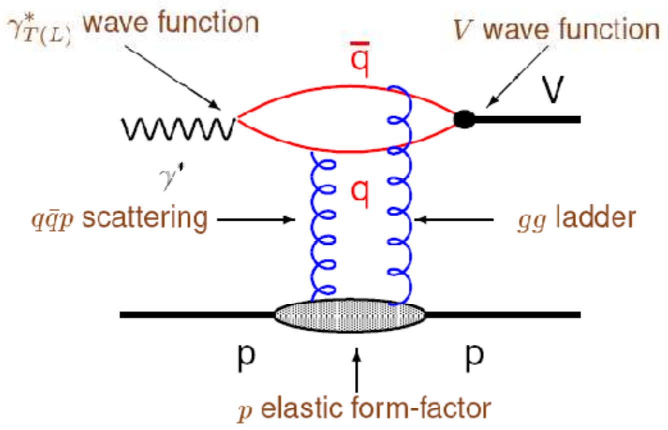
Higher mass VM

…select small qqbar config

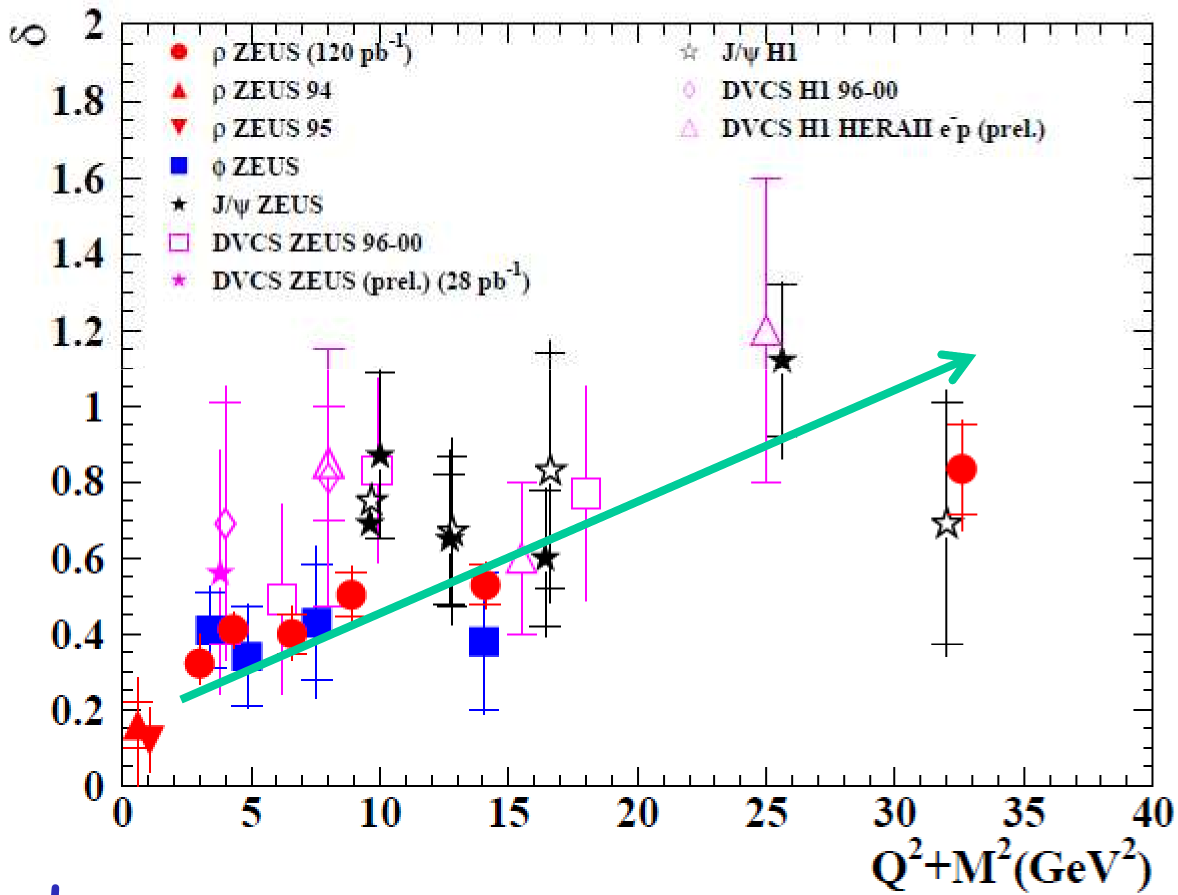
…harder (pQCD) process

Exclusive processes: W dependence

Scale = Q^2+M^2

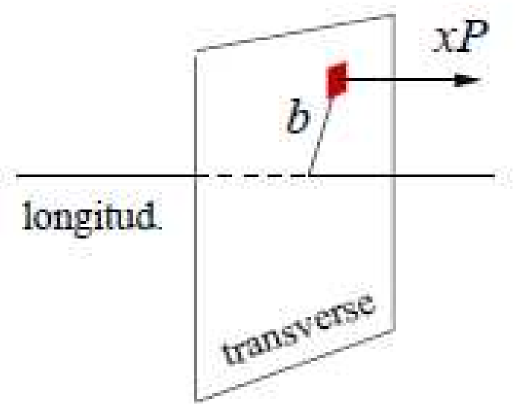


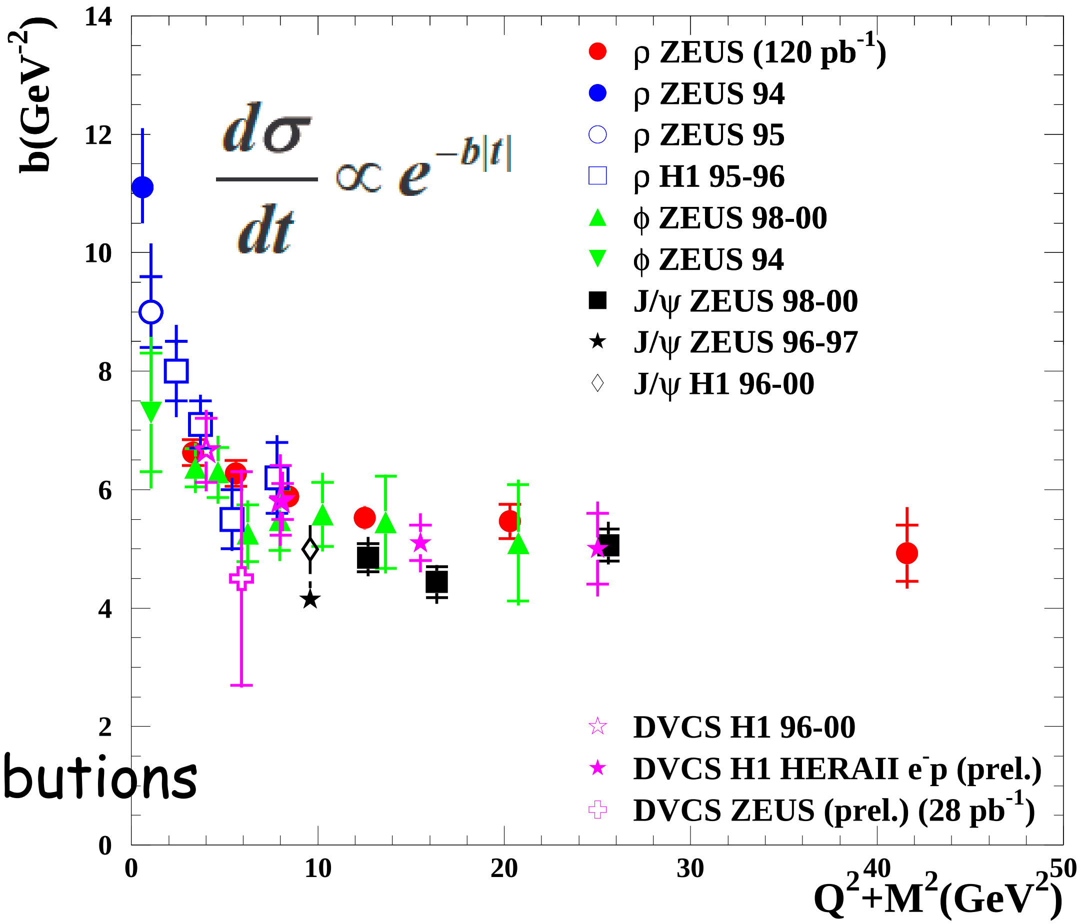
$$\sigma(W) \propto W^{\delta}$$



Larger Q^2+M^2 => harder process

Exclusive processes: t dependence





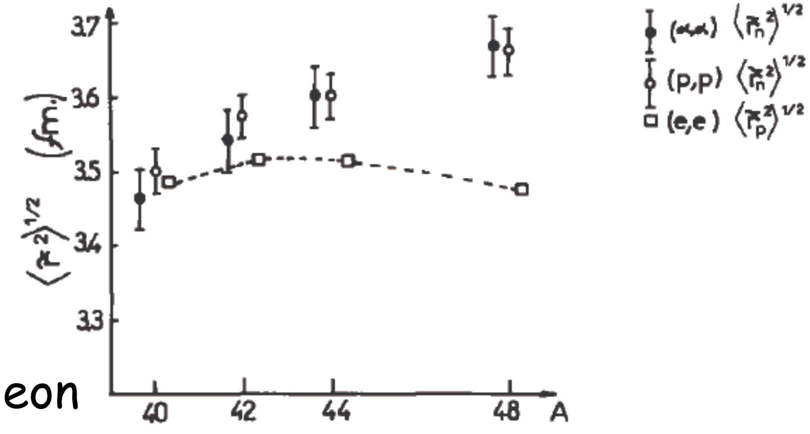
t-slopes [f(t)]

…universality of slopes @ large Q^2 := point like configuration dominates

…impact parameter distributions of partons

F(t) dependence

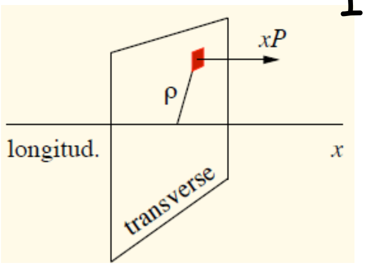
Reminder:
Diffraction on Calcium gives
the internal structure of the Calcium…

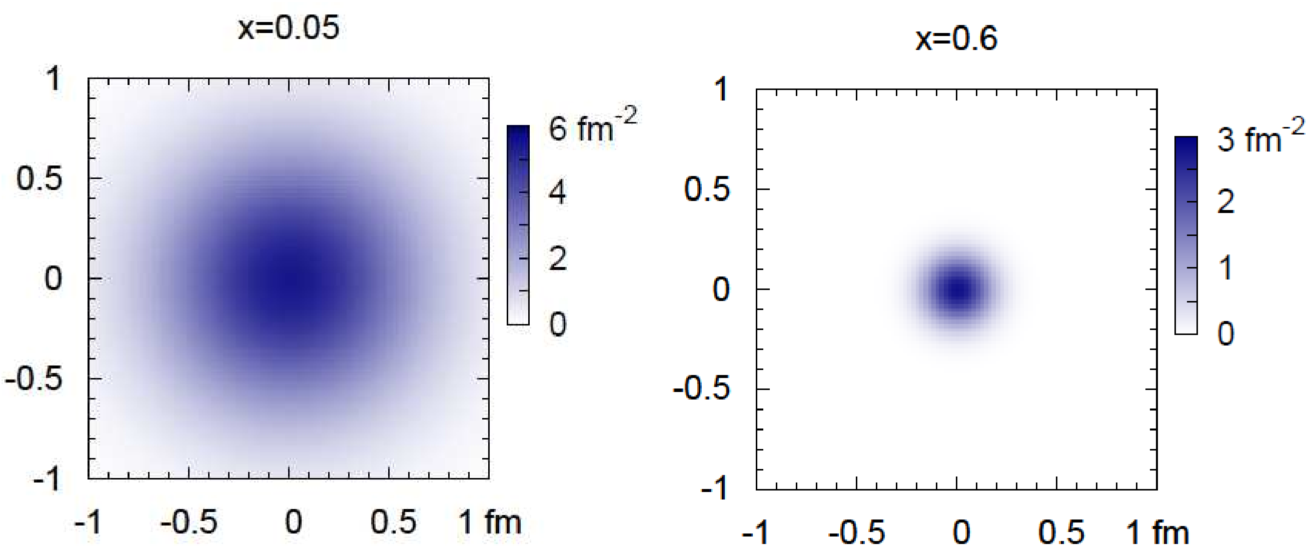


Similarly for exclusive processes
f(t) => impact parameter distributions
Resolve the spatial structure of the nucleon

$$F_g(x,t) = \int d^2\rho \, e^{-i\vec{\Delta}_\perp \cdot \vec{\rho}} F_g(x,\rho)$$

Illustration of $u_{valence}$ quark images (impact parameter in the proton)

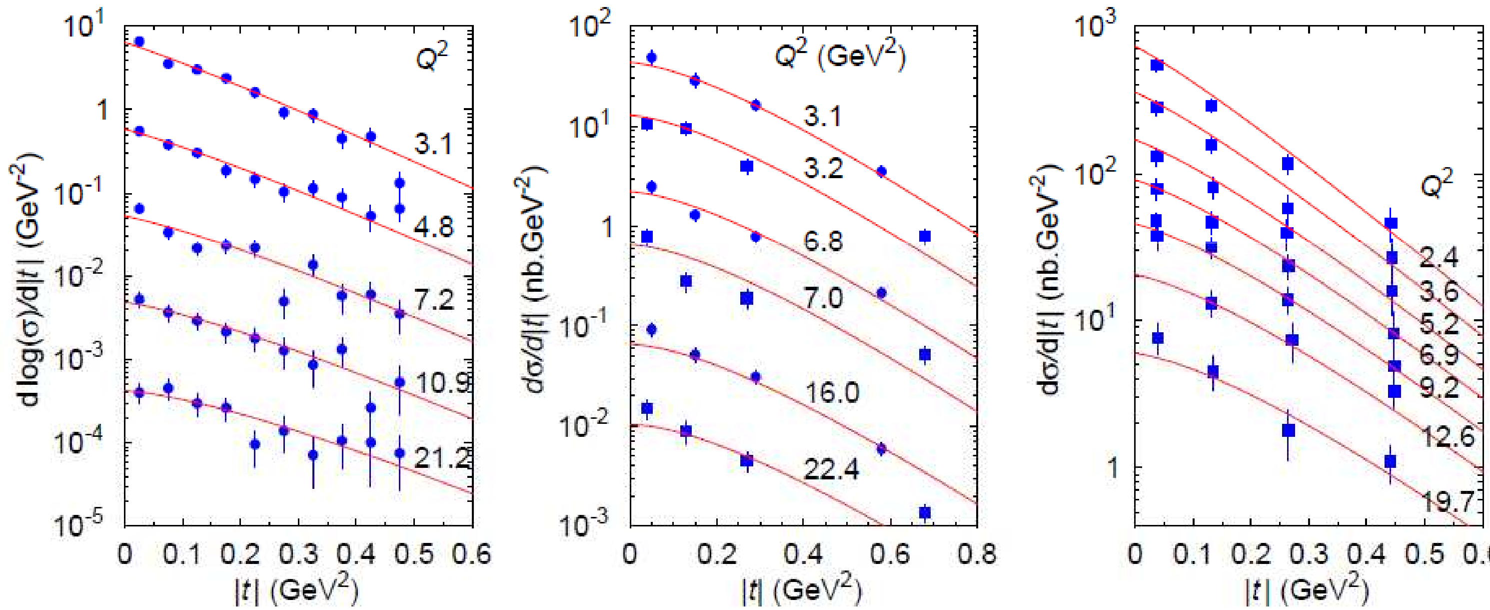




Exclusive processes and QCD (saturation effects)

Prediction of the dipole model (2-gluon exchange) + saturation works well also for all exclusive processes… (in the pQCD regime)

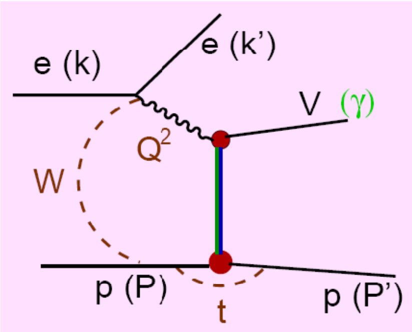
Full calculations once the VM w.f. is modeled



(a) ρ meson at $W = 75$ (b) J/Ψ meson at $W = 90$ (c) ϕ meson at $W = 75$

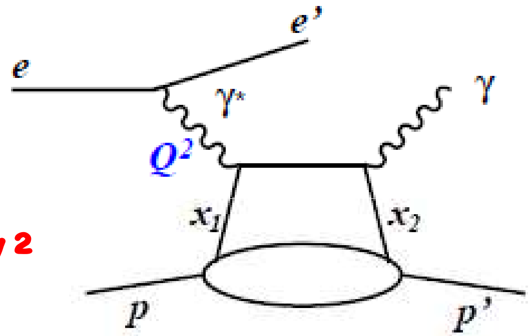
VMs also directly sensitive the the saturation scale R_0=1/Qs
// inclusive diffractive processes…

Case study: DVCS

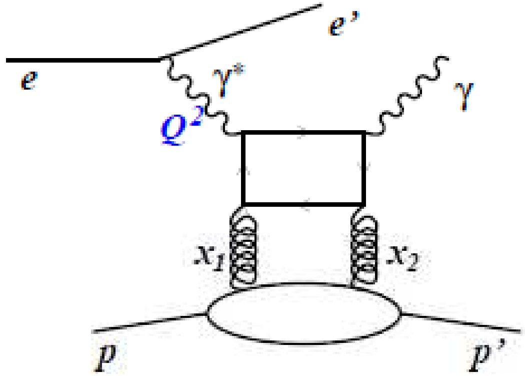


When a real γ is emitted
Simplest process to calculate in pQCD

Handbag diagram, $x_1 \neq x_2$



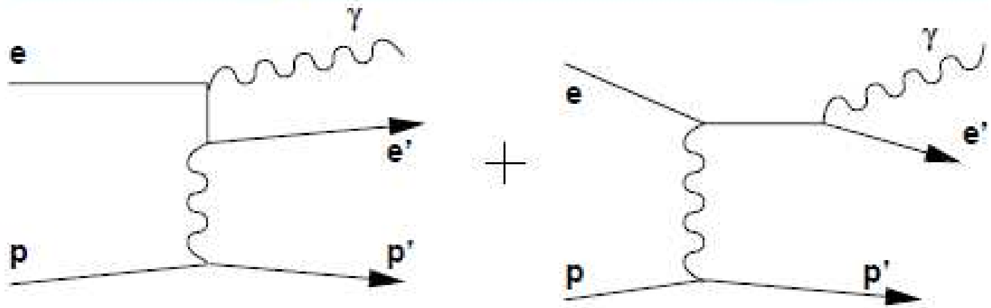
Dominant contribution at low-x



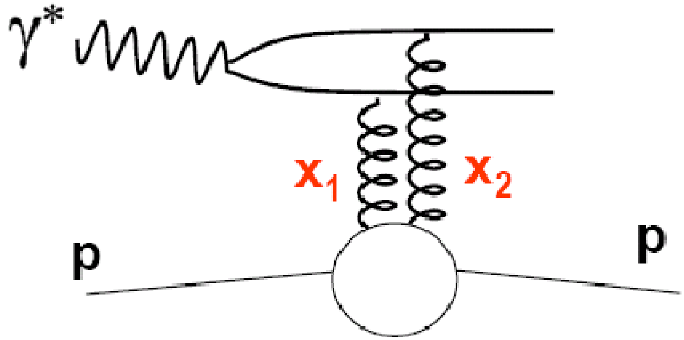
Note:
x1-x2 ~ [Q²] / W²
Skewing: x1≠x2…

DVCS competes with
BH (pure QED)
=> interference

Competing: QED Bethe-Heitler process



Comment on skewing



In general, $x_1 \neq x_2$:

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

↓

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

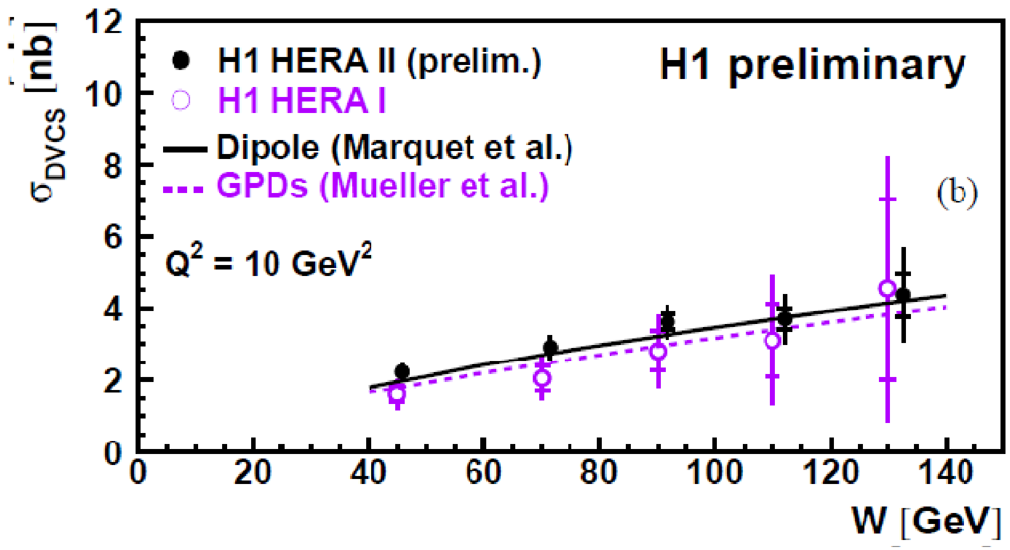
Generalised parton distribution functions (GPD)

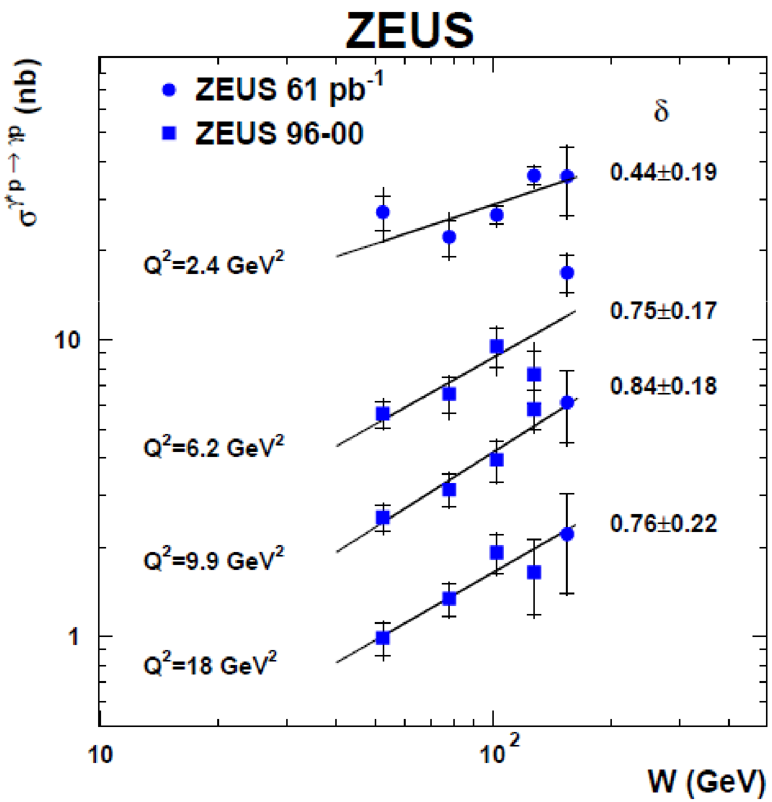
GPDs modifies the prediction by ~ 30% for J/ψ prod. (vs no skewing)
It can be a factor 4 on cross section for exclusive γ production (DVCS)
Essential process to learn more about GPDs…
Extend the concepts of PDFs to
**Correlations of longitudinal momenta of partons
**t-dependence and localisation of partons in the proton

DVCS: W dependence and QCD

Very good description by pQCD models // VMs

Primary observation that GPDs models give a good description of data…



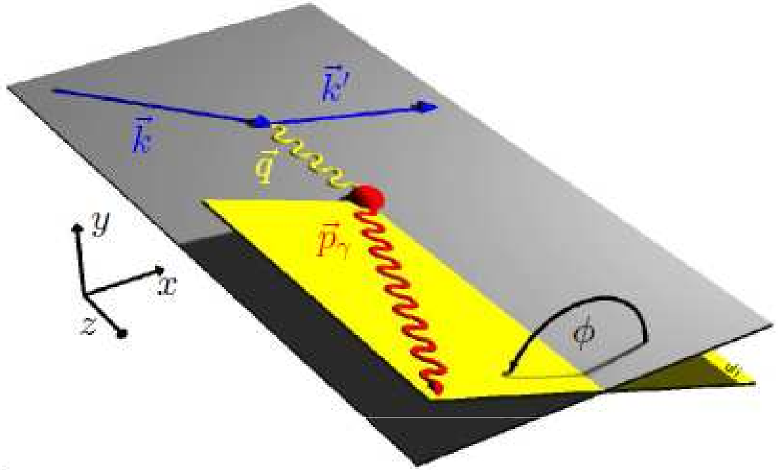


DVCS/BH interference

Principles

Idea: learn more about GPDs… from DVCS/BH interference

Fourier expansion in ϕ for
- beam polarization P_B
- beam charge C_B
- unpolarized target:



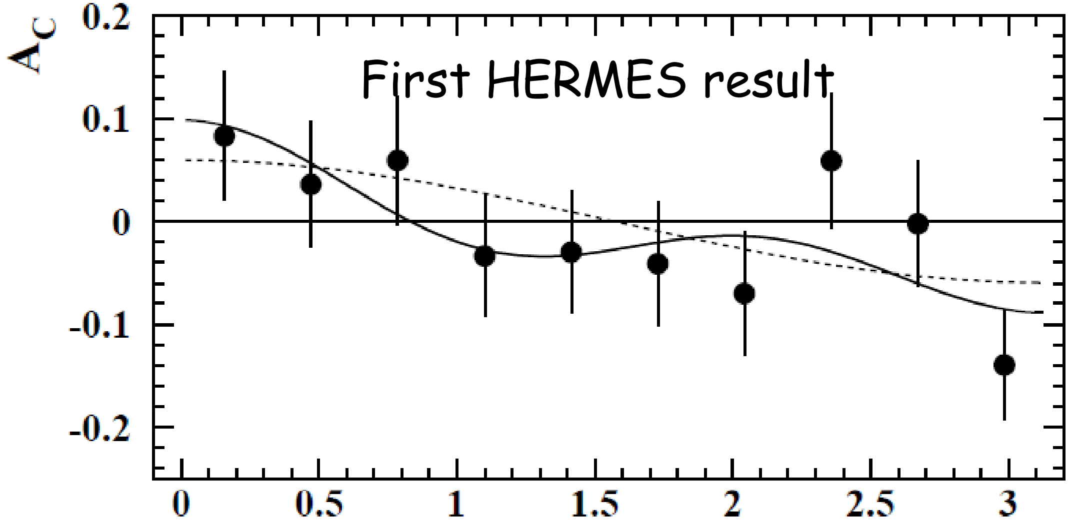
$$|\mathcal{T}_{\rm BH}|^2 = \frac{K_{\rm BH}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\rm BH} \cos(n\phi)$$

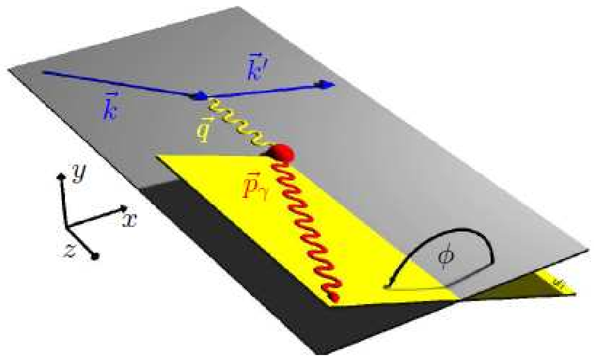
$$|\mathcal{T}_{\rm DVCS}|^2 = K_{\rm DVCS} \left[\sum_{n=0}^{2} c_n^{\rm DVCS} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{\rm DVCS} \sin(n\phi) \right]$$

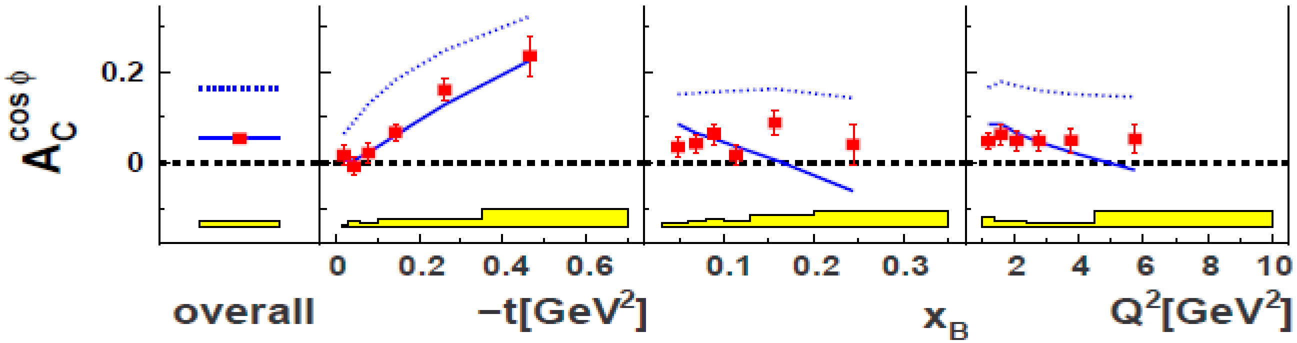
$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

We discuss only the beam charge asymmetry in this talk…

DVCS/BH interference







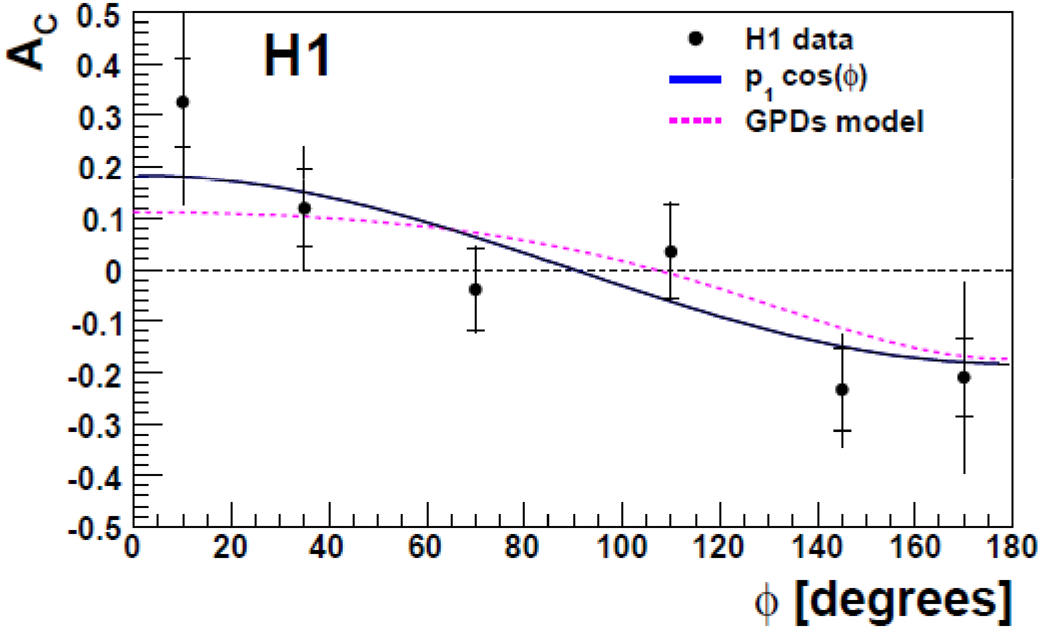
Last HERMES result (x_{Bj}~0.1) directly on the cos(Φ) term

BCA ~ p1 cos(Φ)

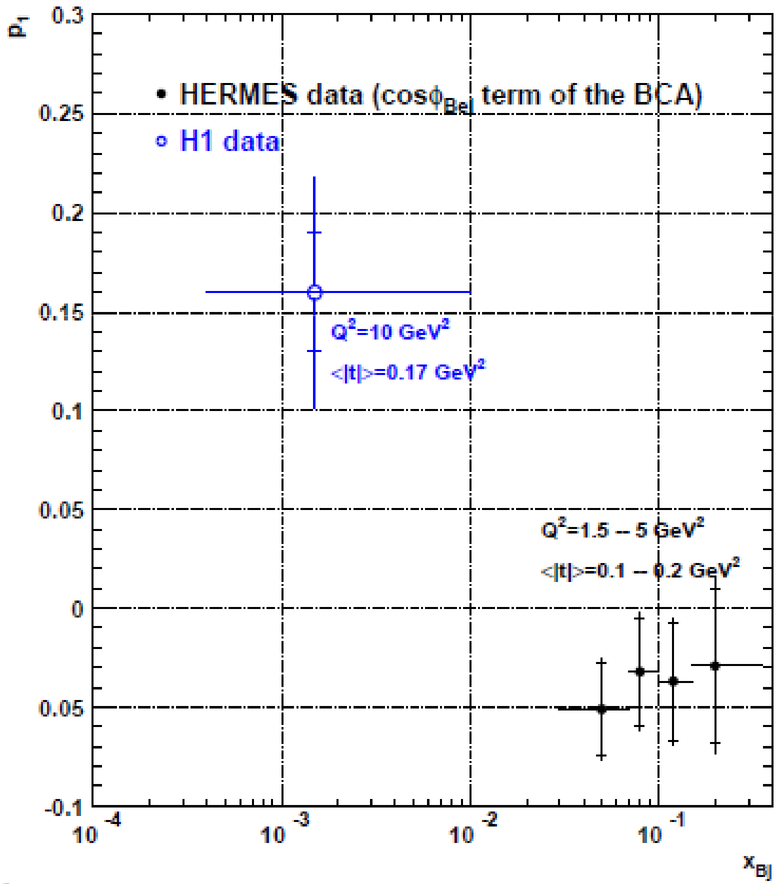
DVCS/BH interference

Recent result from H1 (x_{Bj}~10^{-3})

BCA ~ p1 cos(Φ) ~ 0.16 cos(Φ)



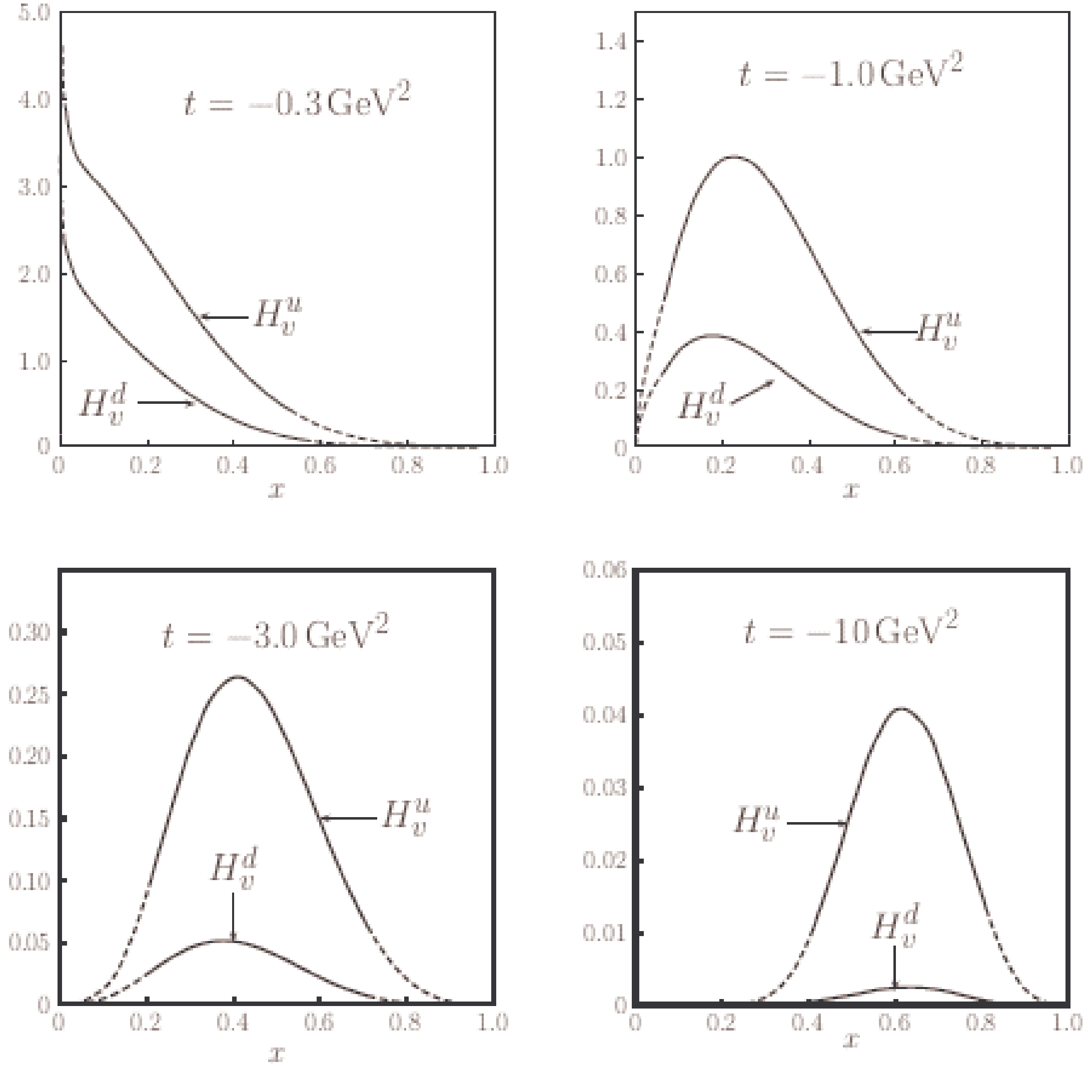
Compilation HERMES & H1 for p1 [BCA~p1 cos(Φ)]



Without details: GPDs provide already a good description of data… work in progress…

What GPDs(x,t) look like?

From Diehl et al.



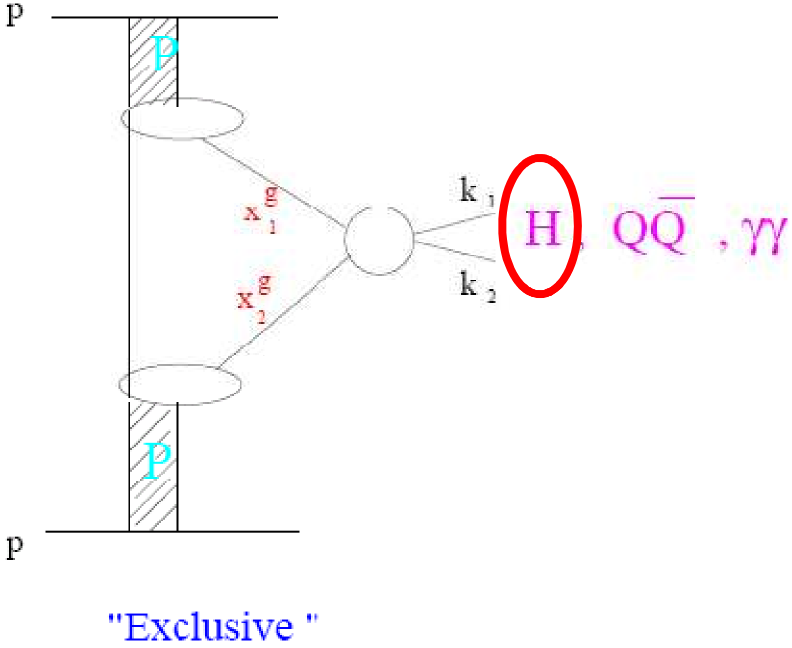
Small t: close to PDFs

As |t| is increasing

(i) Presence of a maximum
(ii) Shift of the maximum
to higher x!
=> high |t| means high x
for the struck parton
// Feynman mechanism…

In the future, the aim is to improve this knowledge and also the general (**x1**,**x2**,t) dependence…

Prospects for diffraction at the LHC



Exclusive production of heavy objects in double pomeron exchange (DPE) :

Tag protons on both sides
=> mass of the central system with a high resolution :

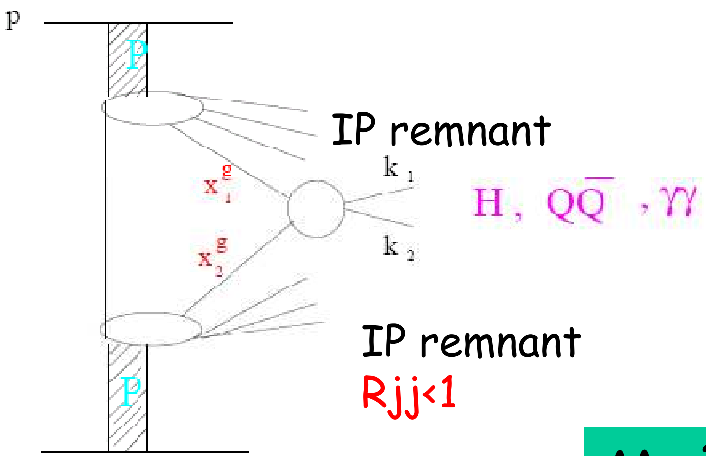
$$M_X^2 = s\ \xi_1 \xi_2$$

Exclusive models:

- KMR model
  - perturbative calc., direct coupling of two gluons to the protons
- Bialas-Landshoff exclusive model
  - non-perturbative, soft pomeron

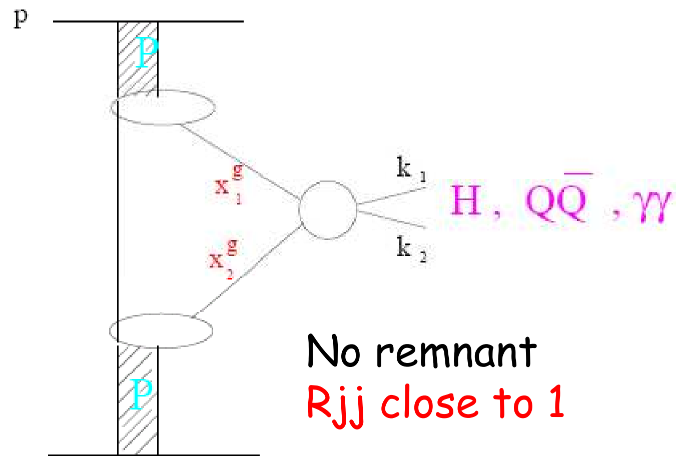
First Checks possible @ Tevatron

Double Pomeron Exchange in pp collisions



"Inclusive"

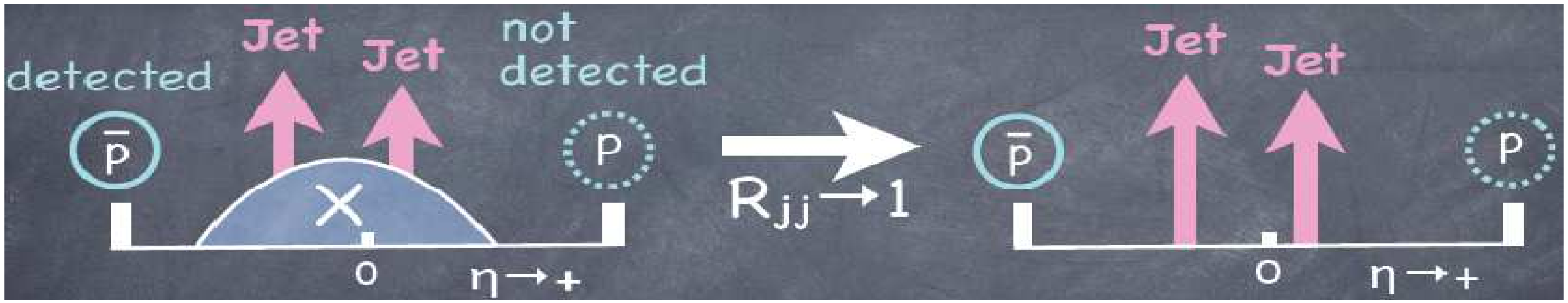
$$M_X^{\ 2} = s\ \xi_1\xi_2$$



"Exclusive "

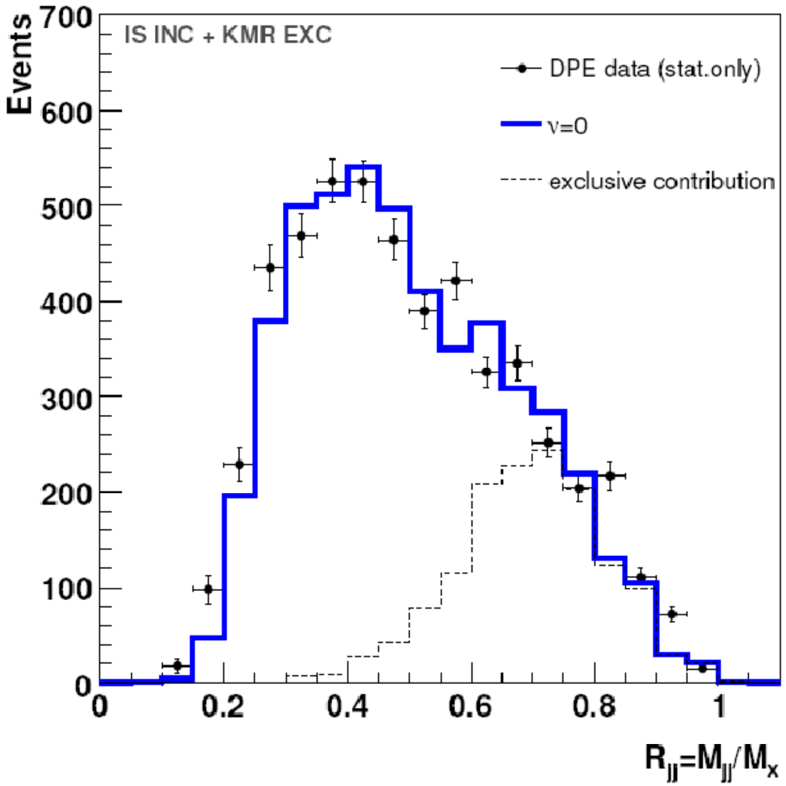
Measurement of the Dijet Mass Fraction @ TeV

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



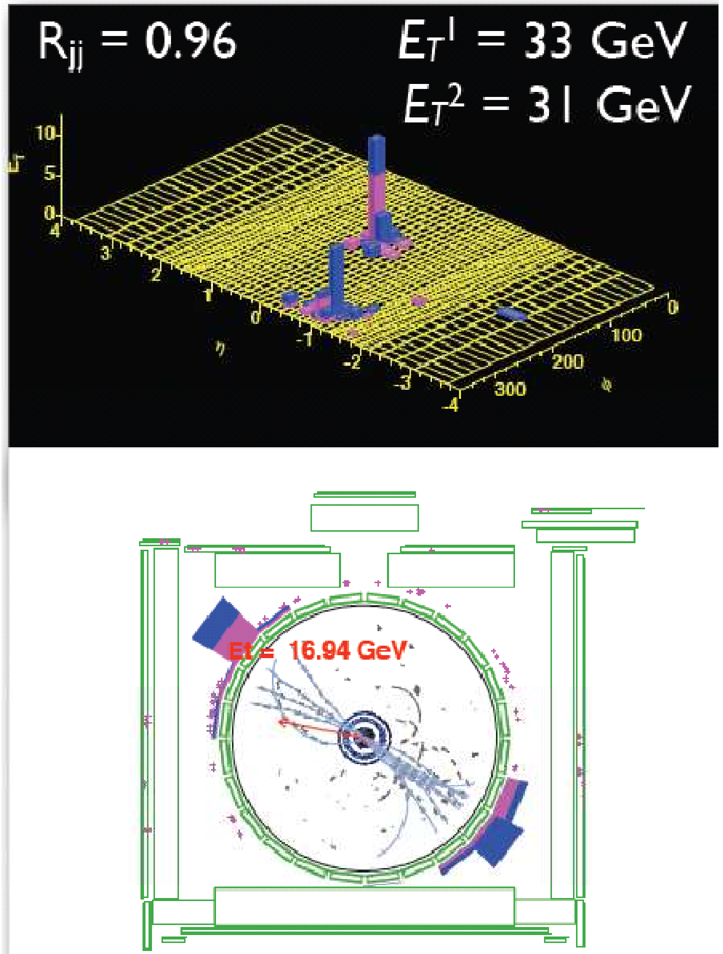
Dijet mass fraction @ TeV : measurement & predictions

Prediction using dPDFs ⊗ survival gap probability
+ exclusive production (no-remnant)



Exclusive events observed ?!

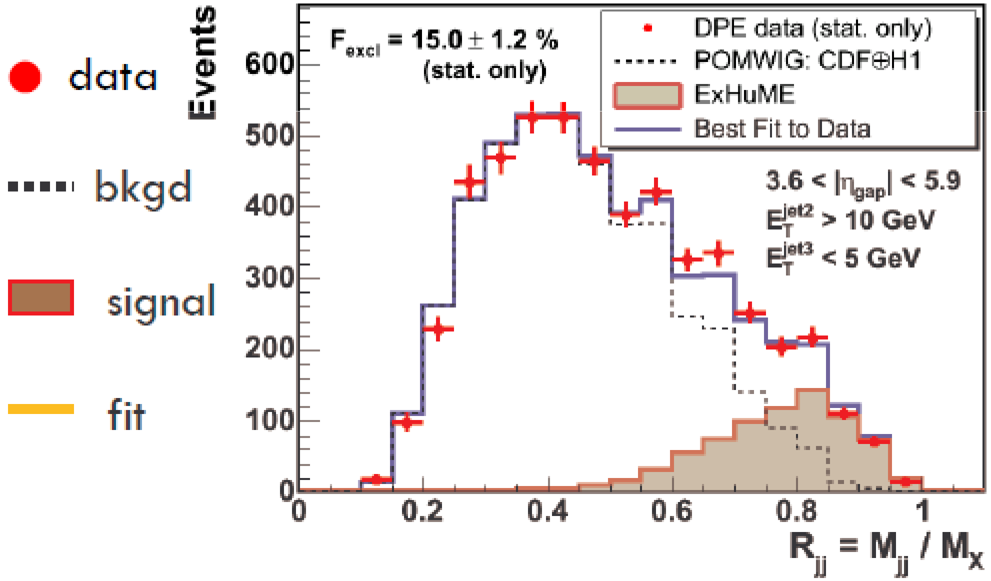
CDF Run II Preliminary



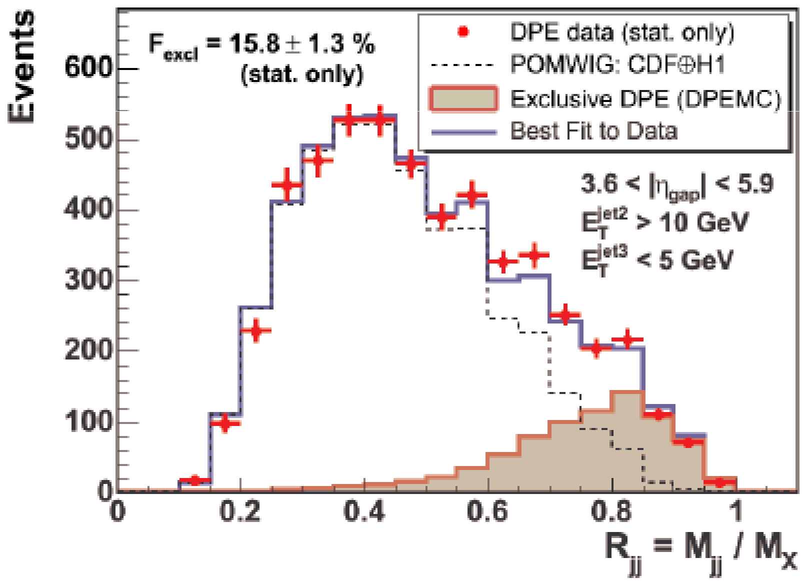
Searching for exclusive events at the Tevatron

Confirmed by different MC (models) for the no-remnant contribution

Signal MC ExHuME *CPC 175,232 (2006)*



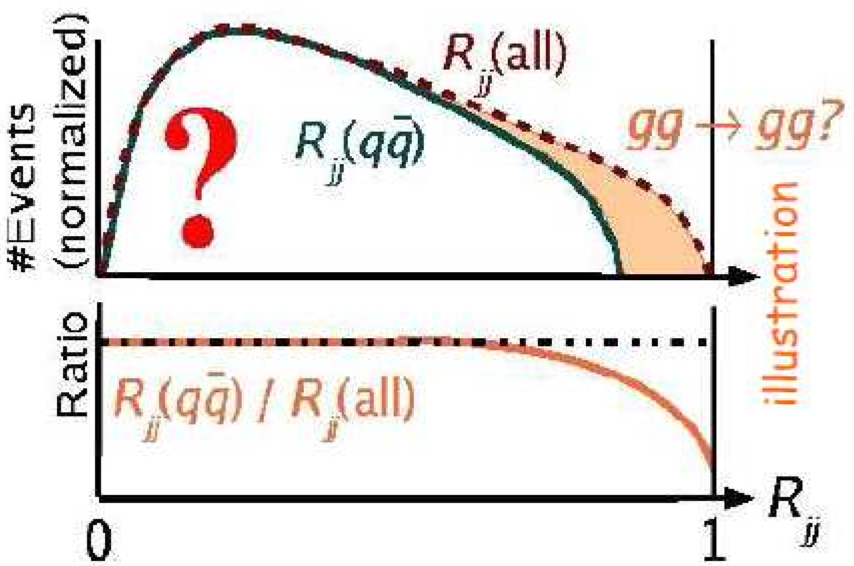
Exclusive DPE as input to DPEMC *CPC 167,217 (2005)*



Another idea to search for exclusive events @ Tevatron

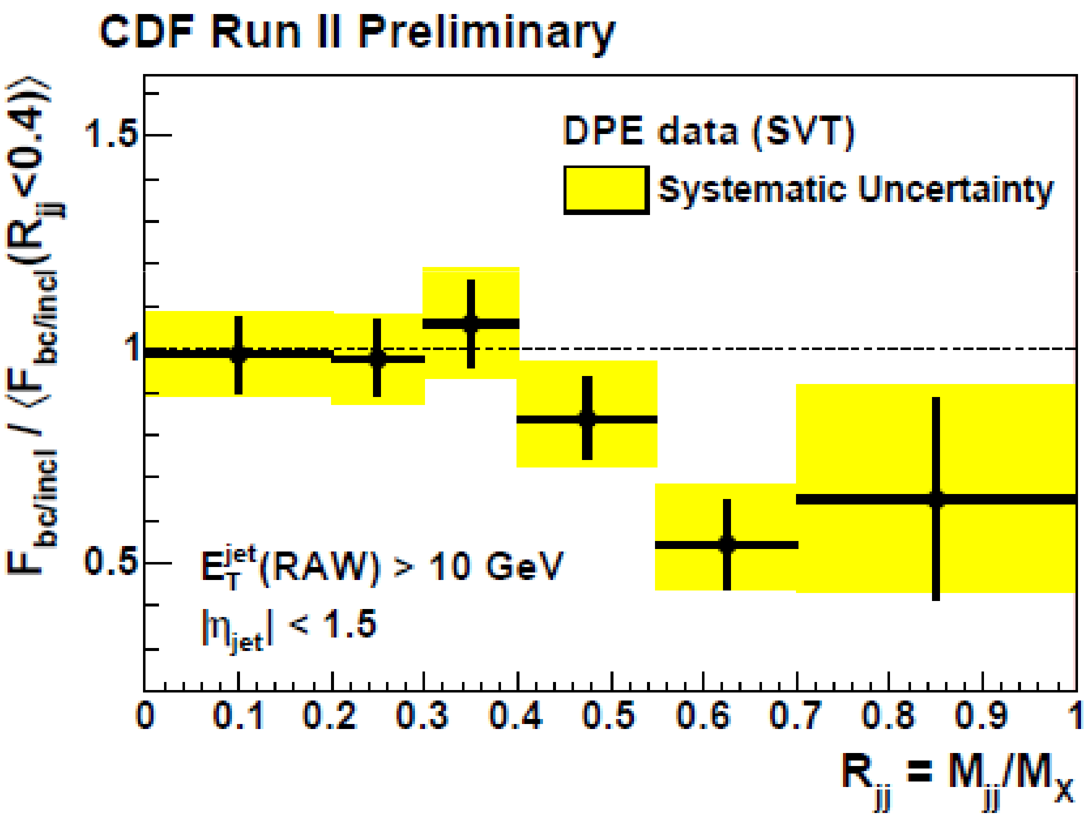
(i) Look for exclusive events in bbar

(ii) If exclusive events exist, the ratio R(bbar)/R(all) should be smaller at high dijet mass fraction as exclusive b jet prod is suppressed



Another idea to search for exclusive events @ Tevatron

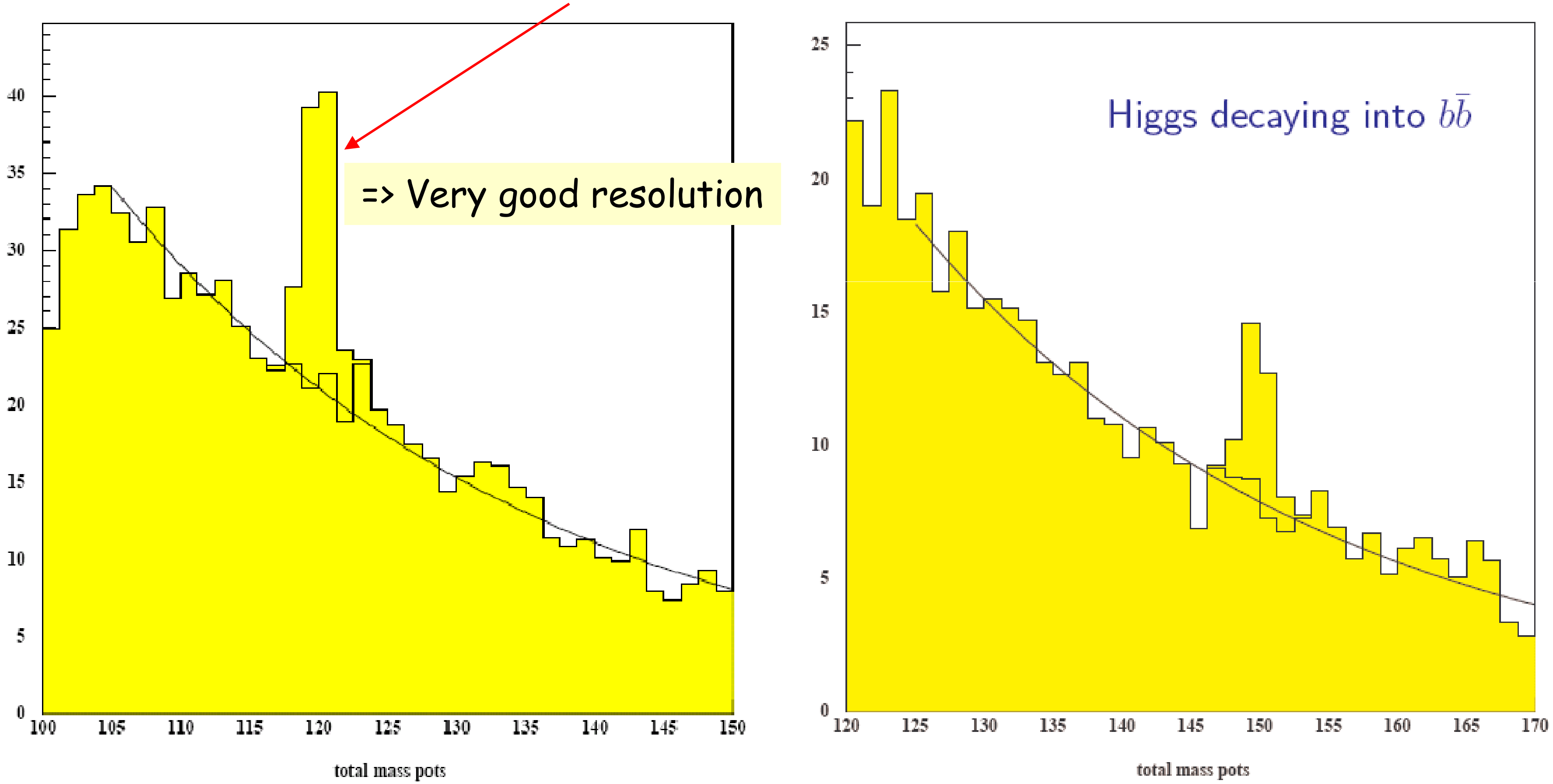
Observation: ok but need more data…



Coming back on excl 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 : $M_X^2 = s\ \xi_1 \xi_2$

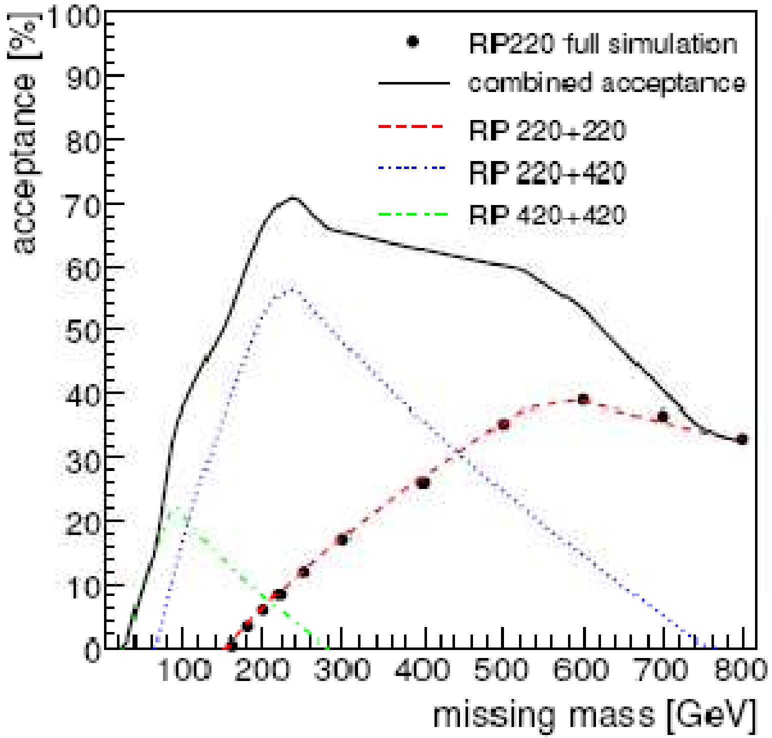


Signal and background for different Higgs masses for 100 fb^{-1}

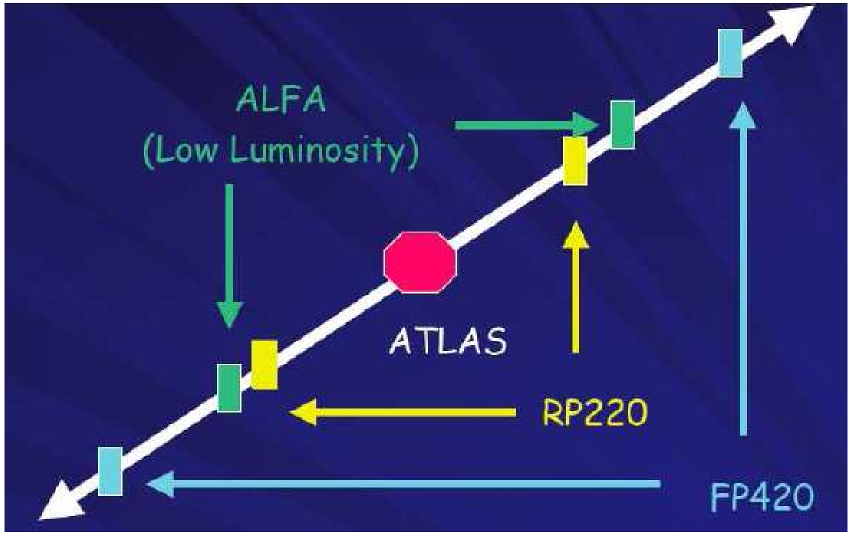
Experimental aspects @ LHC

Project: Install roman pots @ the LHC at 220m and 420m
Projects on going in ATLAS and CMS

Acceptance as a fonction of Mx =>



Need both locations 220m & 420m to get the best coverage in acceptance…



Outlook for the next year(s)

Still a large wealth of data on F2D in the analysis process @ DESY => diffractive PDFs will improve also with H1/ZEUS working together

Exclusive VMs processes or DVCS:
…essential triggers of the diffractive mechanism…
…a way to map out the GPDs in the future => Lq of partons?!
confirmation of 'Lattice' calculations?!

More refined results from Tevtatron =>
… it provides the direct link with LHC: dijets with no-remnants is a promising process