Diffraction at HERA

On behalf of H1 and ZEUS collaboations

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Paris 2011

1st part:
Inclusive diffraction at HERA and the dynamical structure of the proton at low x…

2nd part:
The spatial structure of the nucleon from exclusive processes

Perspectives and Summary

Diffraction on nuclear waves

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

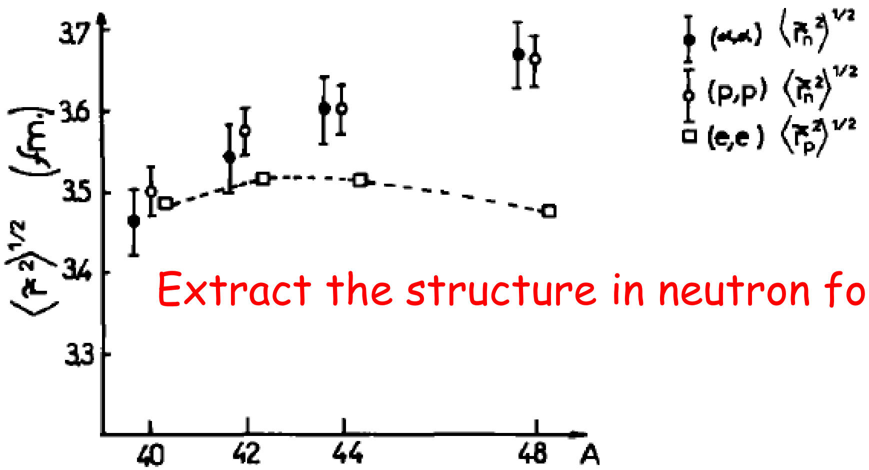
G. D. ALKHAZOV [†], T. BAUER [††], R. BERTINI [†††], L. BIMBOT [‡], O. BING [†††], A. BOUDARD, G. BRUGE, H. CATZ, A. CHAUMEAUX, P. COUVERT, J. M. FONTAINE [‡‡], F. HIBOU [†††], G. J. IGO [‡‡‡], J. C. LUGOL and M. MATOBA [*]

Service de Physique Nucléaire à Moyenne Energie
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)

Amplitude(**q**,k) ~ $ik/2\pi \int d\mathbf{b}\, e^{i\mathbf{b}\mathbf{q}} D(\mathbf{b},k)$



Extract the structure in neutron for Calcium

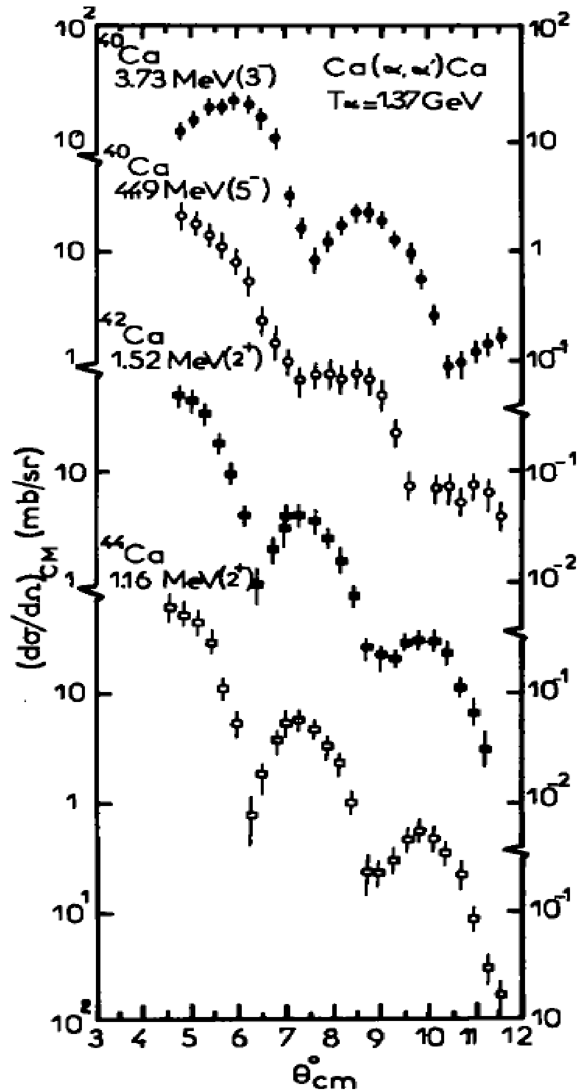
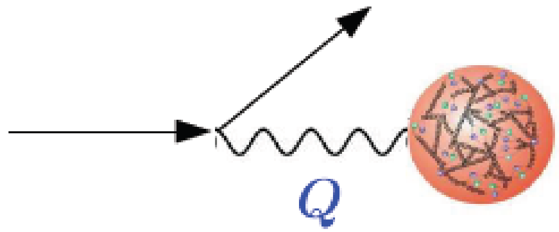


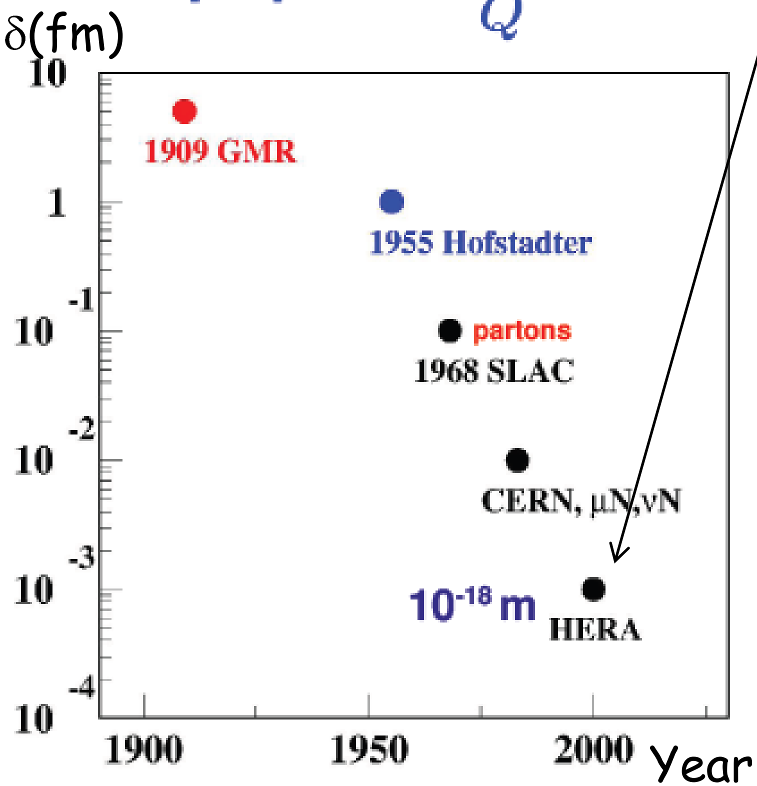
Fig. 3. Differential cross sections of inelastic scattering of 1.37 GeV α-particles from the 3_1^- and 5_1^- states in ^{40}Ca and the 2_1^+ states in ^{42}Ca and ^{44}Ca.

Subnuclear waves



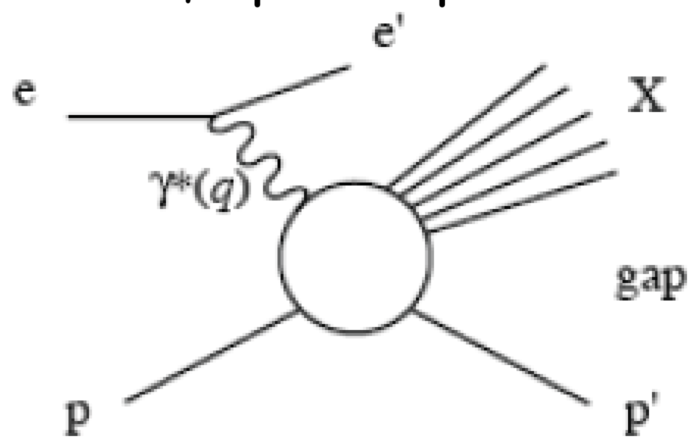
Probe the proton with a lepton beam
=> Virtual photon (γ^*) of resolution ~1/Q

$$\delta\ [\mathrm{fm}] \simeq \frac{200\ \mathrm{MeV}}{Q}$$



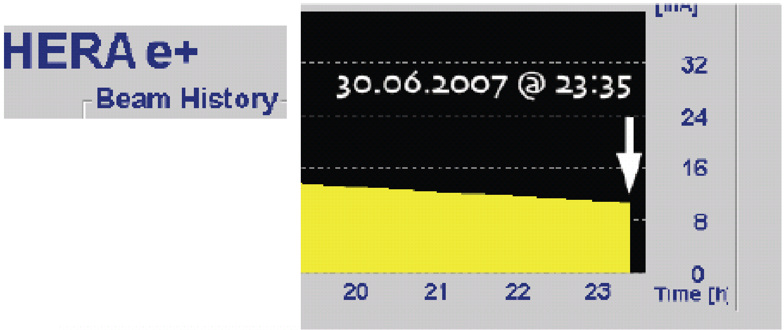
Diffraction of subnuclear waves
at HERA [E_{cm}=320 GeV]

$$\gamma^* p \rightarrow X p$$



The proton is left intact (or quasi-intact)
** Color singlet exchange
** Presence of a GAP in rapidity
(between X and p')

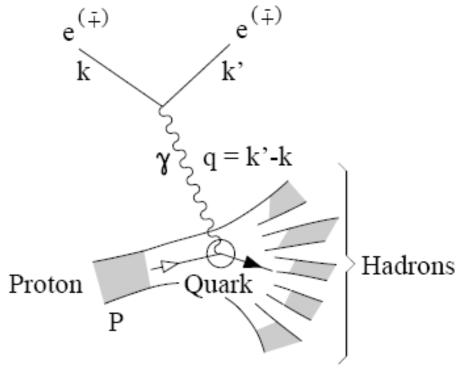
HERA-DESY: 1992-2007



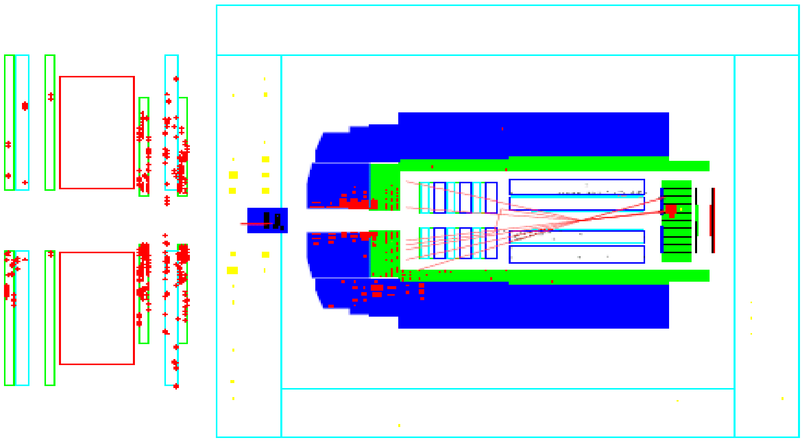
Total luminosity=1 fb^{-1} for H1+ZEUS

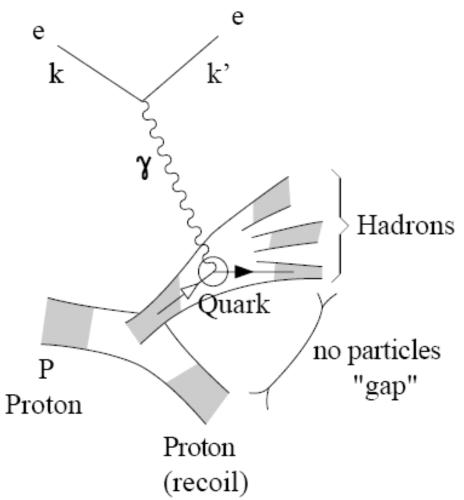
350 collaborators per experiment (H1+ZEUS)
+HERMES

Diffractive events are observed

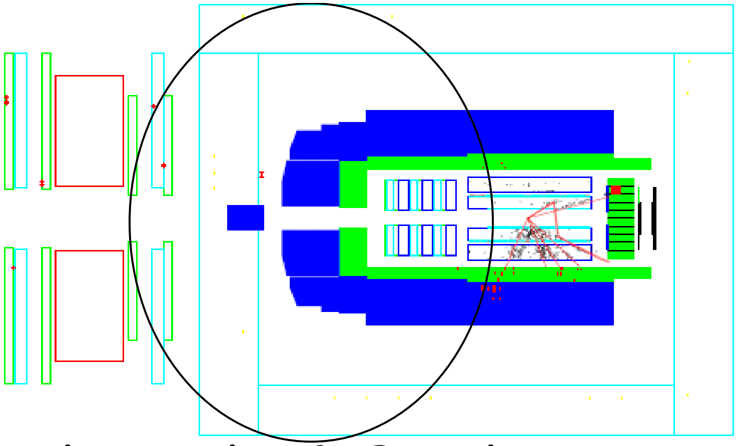


Deep Inelastic Scattering (DIS) => F_2





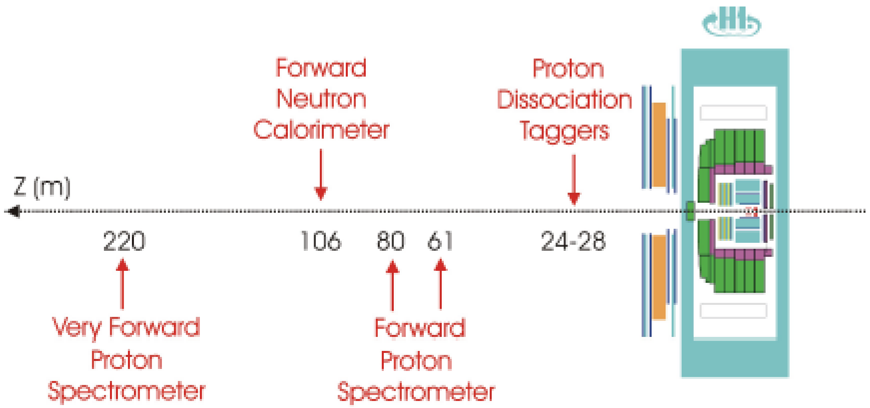
Diffractive Deep Inelastic Scattering (DDIS) => F_2^D



This is the GAP with no particle

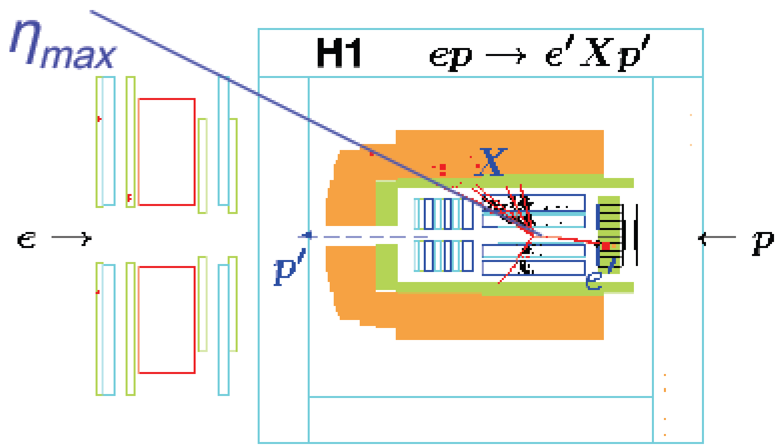
Experimental selection methods

Scattered proton in Leading Proton Spectrometers **(LPS)**



Limited by statistics and p-tagging systematics

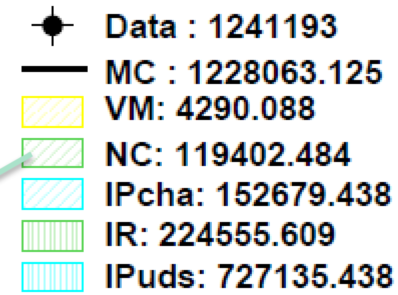
`Large Rapidity Gap' **(LRG)** adjacent to outgoing (untagged) proton

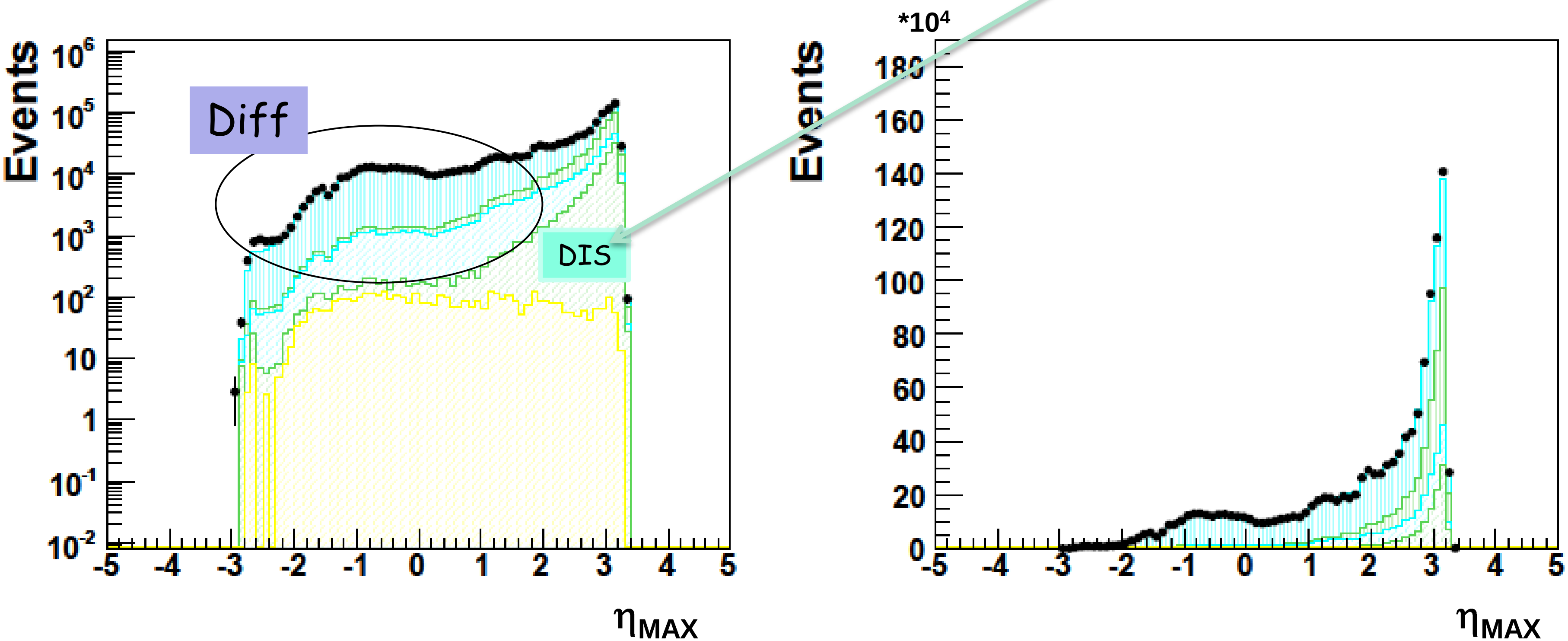


Limited by p-diss systematics

Diff events are produced with a quite large rate

Lower η_{MAX} means that the <u>GAP with no particle</u> is large
…illustration on all HERAII data (Lumi=330 pb^{-1})

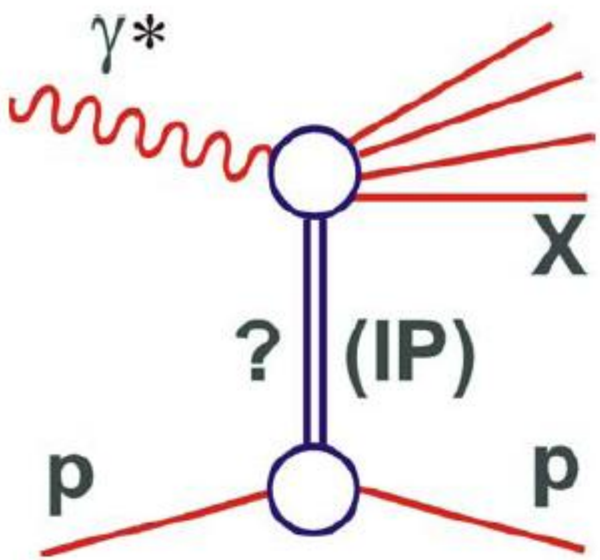




Why DIFF rate is large @ HERA (low x)?

...certain (Fock) states of the virtual photon $|\psi_K\rangle$ do not feel the the strong interaction, while others are strongly affected...

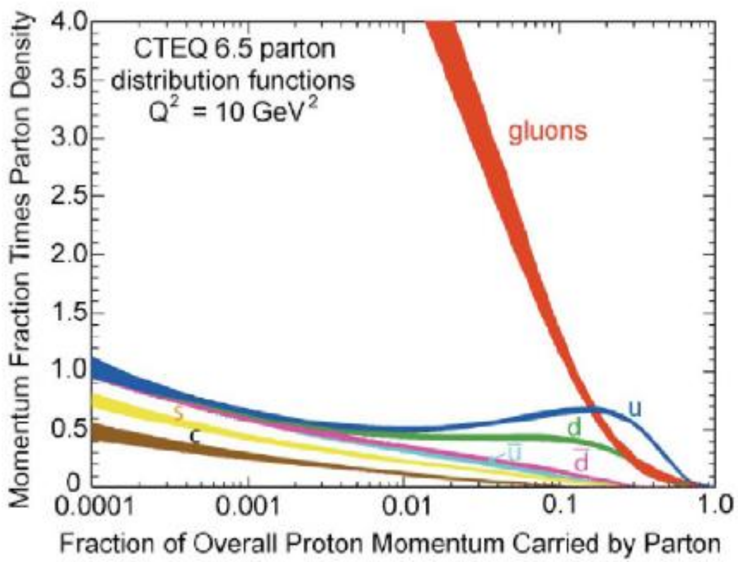
=> Large fluctuations in the absorbption coefficients of these states...



This is (obviously) linked to the dominance of the gluon density at small x.

It finds a natural extension in the dipole approach:

$T(b) \sim \alpha_S r^2 \; xG(x,1/r^2)/(\pi R^2) \; * \exp(-b^2/b_0^2)$



Kinematics and notations

Standard DIS variables …

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

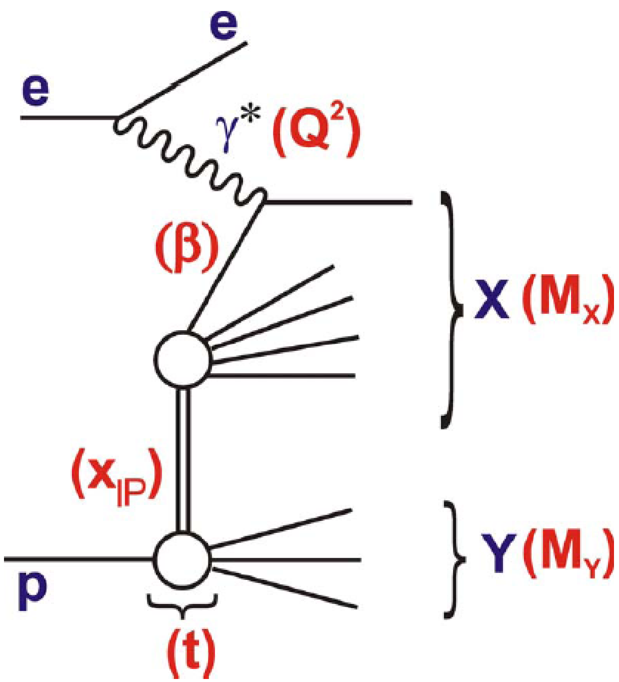
Additional variables
for diffraction …

$\mathbf{t}$ = squared 4-momentum
transfer at proton vertex

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

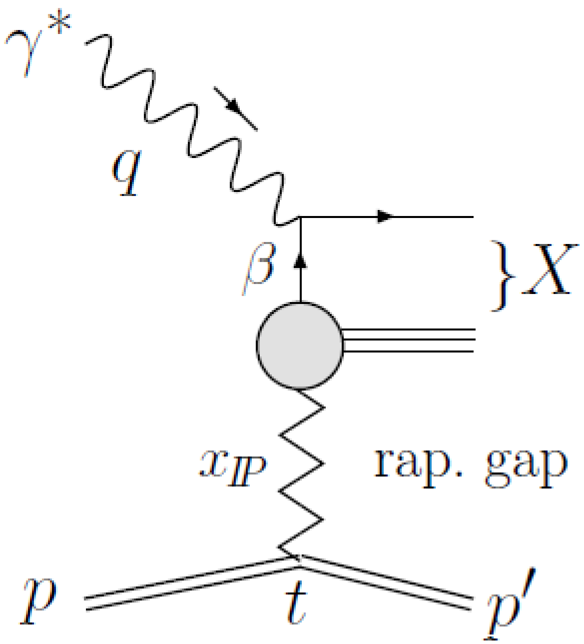
$\beta = x / x_{IP}$
(momentum fraction q / IP)

Most generally ep→eXY …



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

Diffractive cross sections (definition)

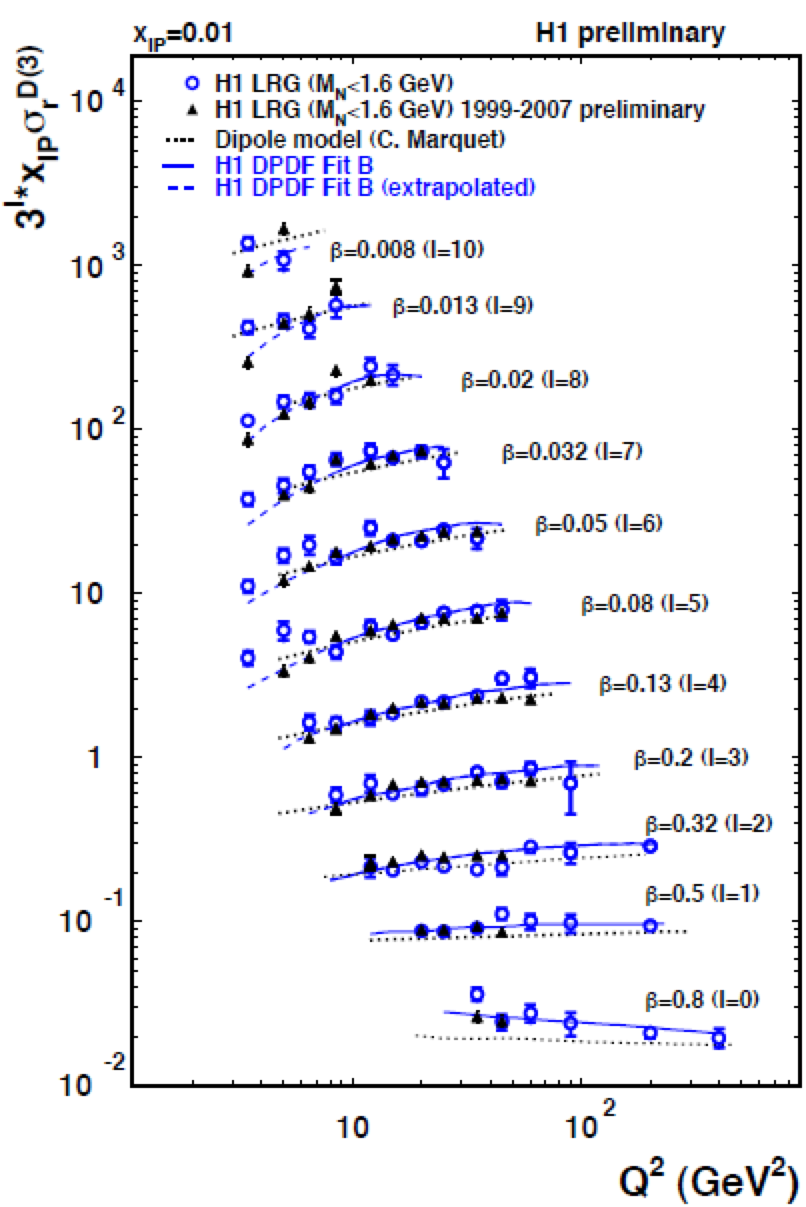


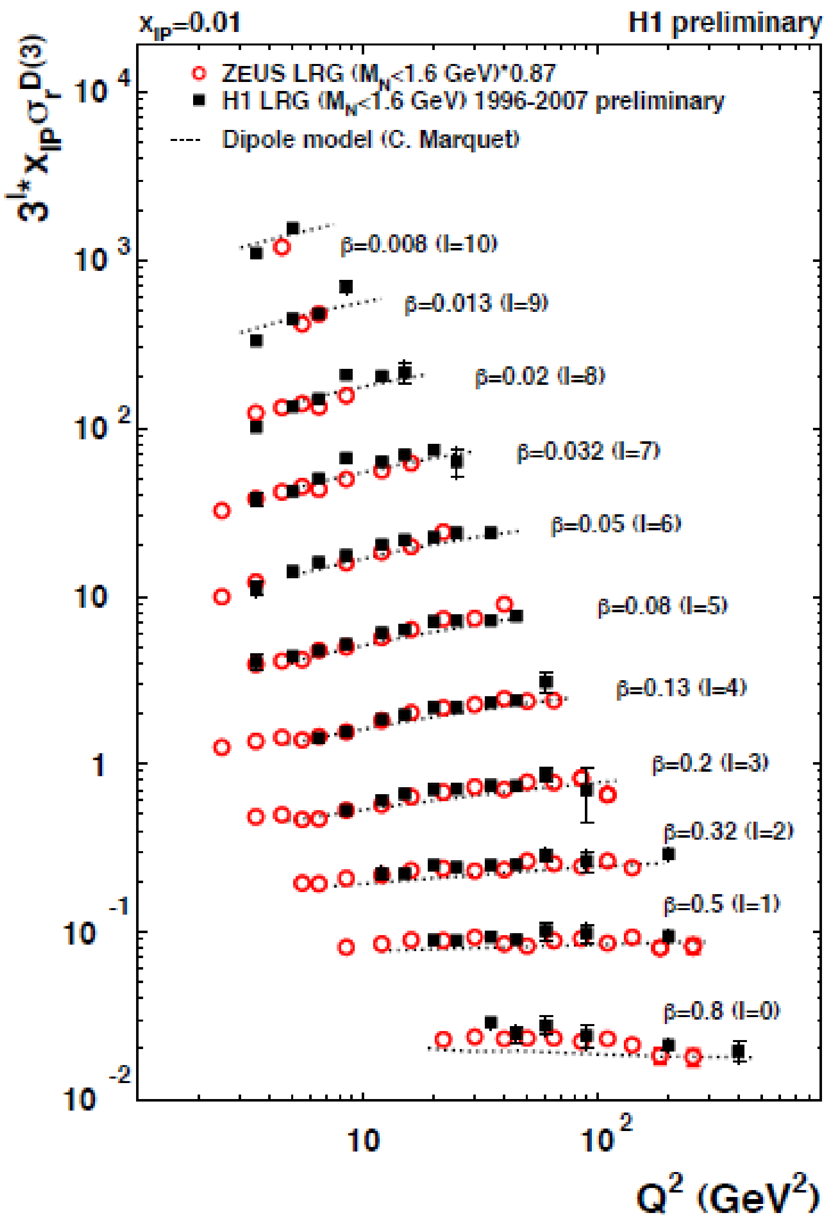
Select diffractive events
Correct for detector effects
Derive cross sections (// F2)

$$\frac{d^3\sigma^D}{dx_{\mathbb{P}}\,d\beta\,dQ^2} = \frac{2\pi\alpha_{em}^2}{\beta\,Q^4}\left[1+(1-y)^2\right]\sigma_r^{D(3)}(x_{\mathbb{P}},\beta,Q^2)$$

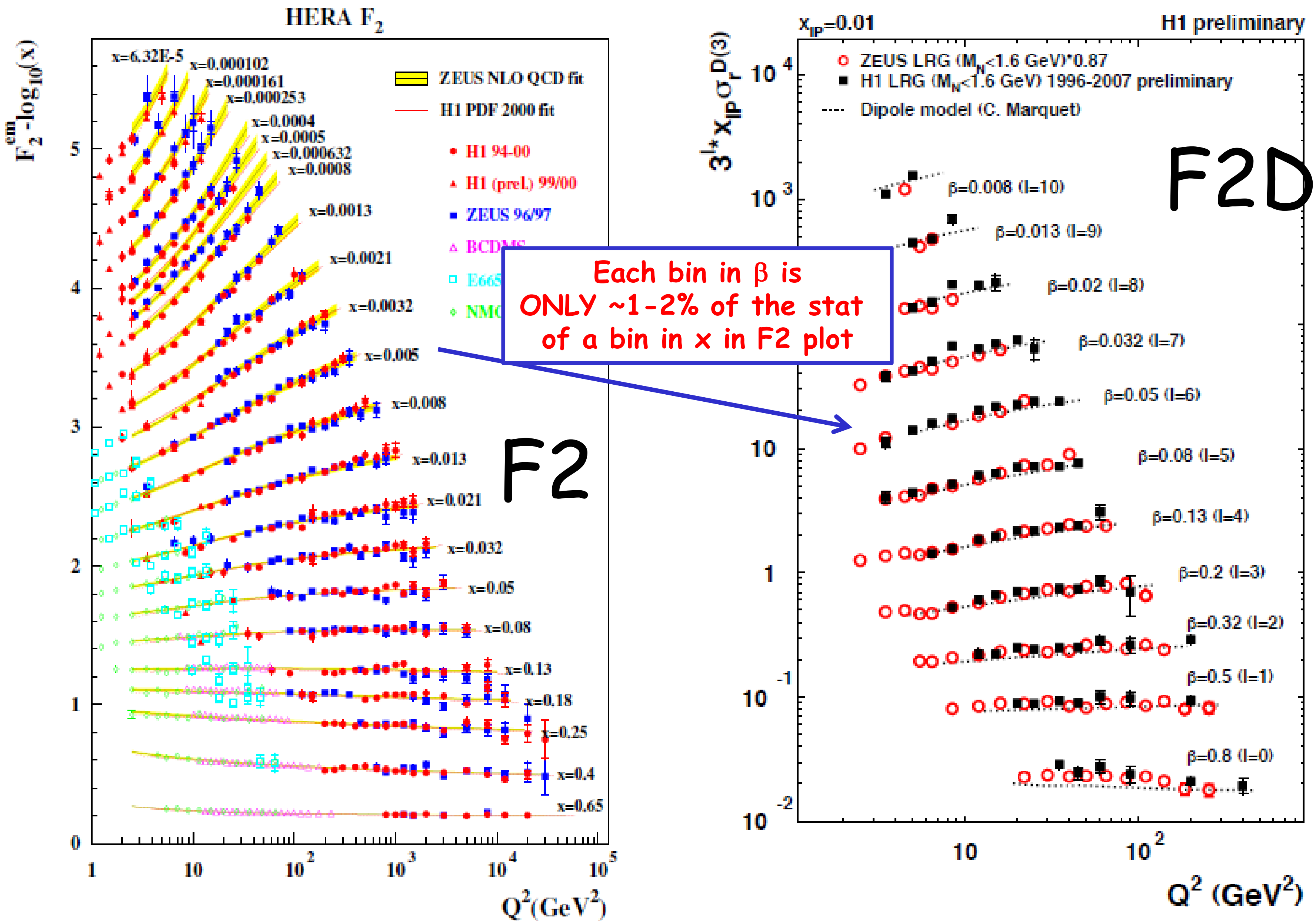
$$\sigma_r^{D(3)} = F_2^{D(3)} - \frac{y^2}{1+(1-y)^2}F_L^{D(3)} \approx F_2^{D(3)}(x_{\mathbb{P}},\beta,Q^2)$$

Results ($x_{IP} F_2^D$)[Q^2]: LRG selection

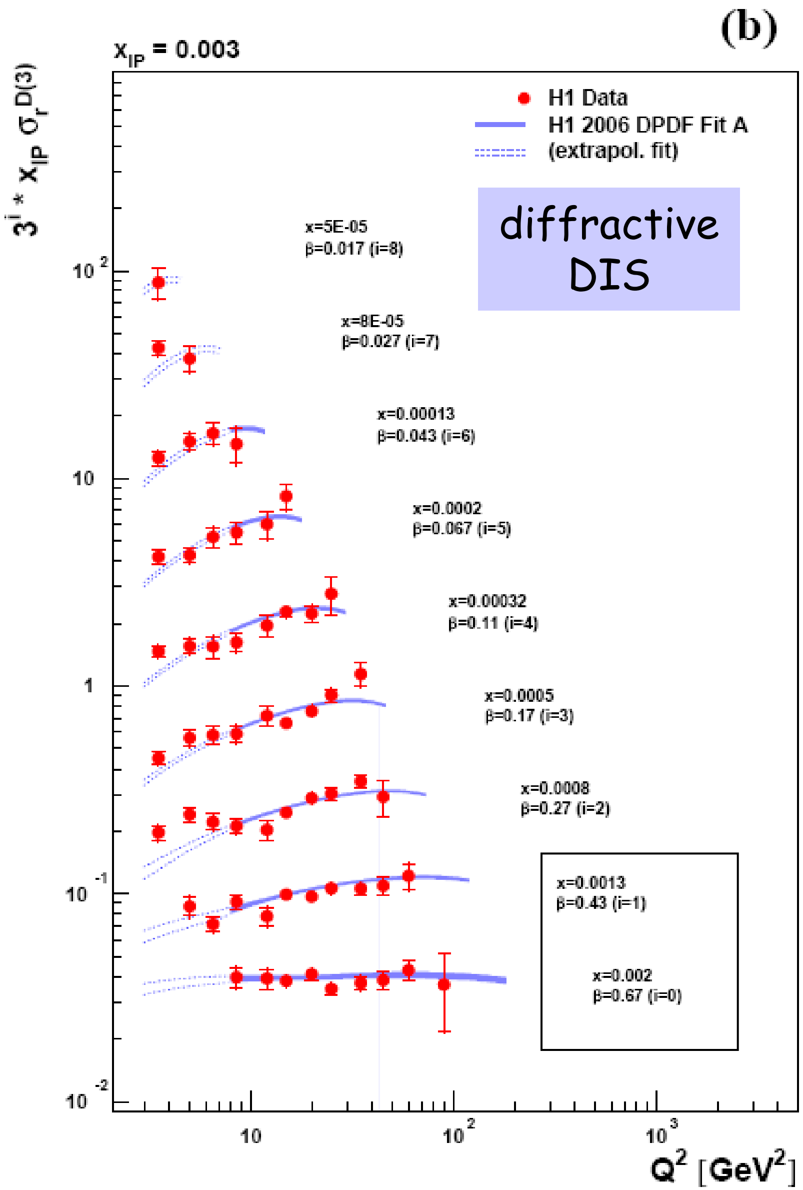


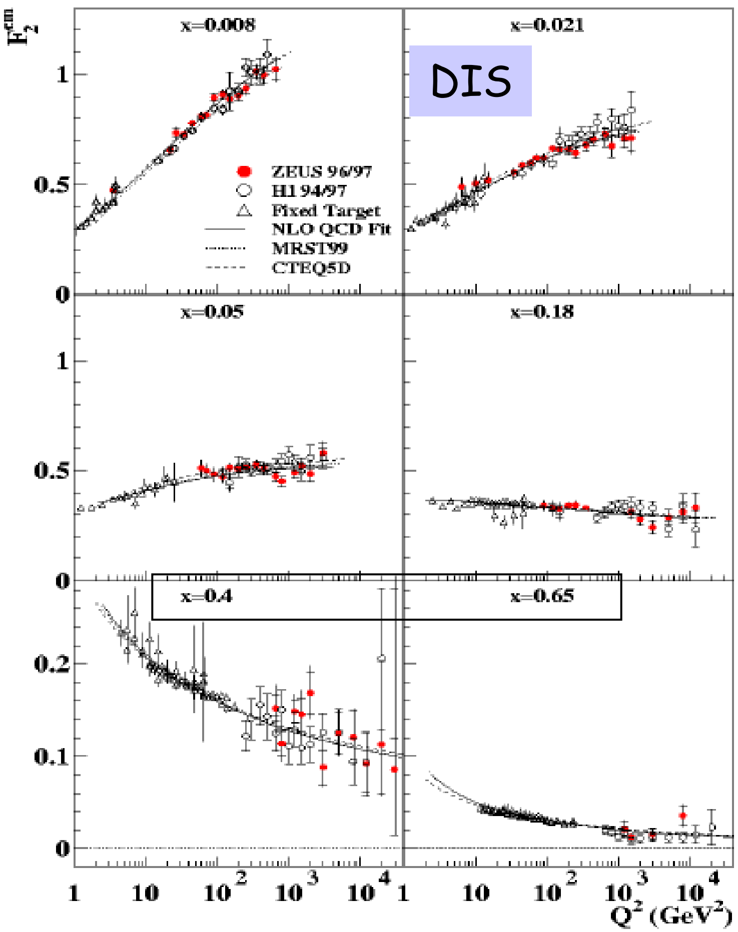


F2 versus F_2^D



Scaling(Q^2) of DIFF versus DIS



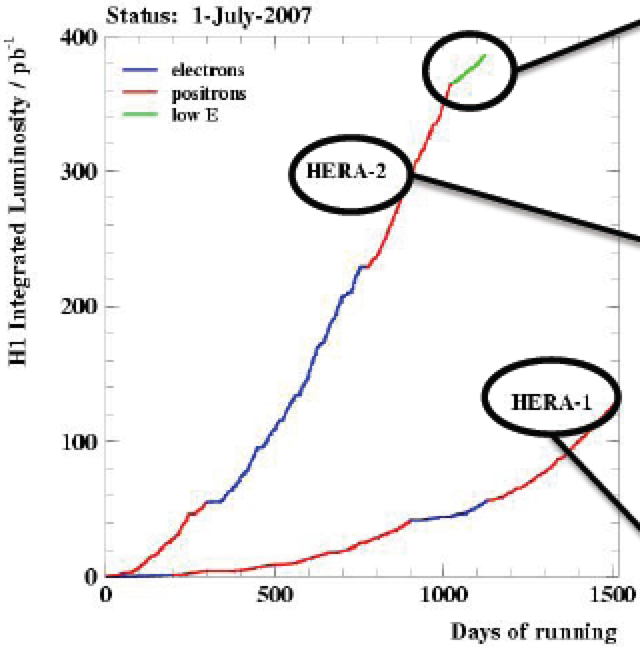


At large β values : scaling violations still >0 for diffraction, *<0 for standard DIS*

=> Large gluon content expected for DIFF

Diffraction at HERA is still a very active field:

Below the bastracts for new results submitted to ICHEP 2010



419) The Longitudinal Diffractive Structure Function, F_L^D [H1]

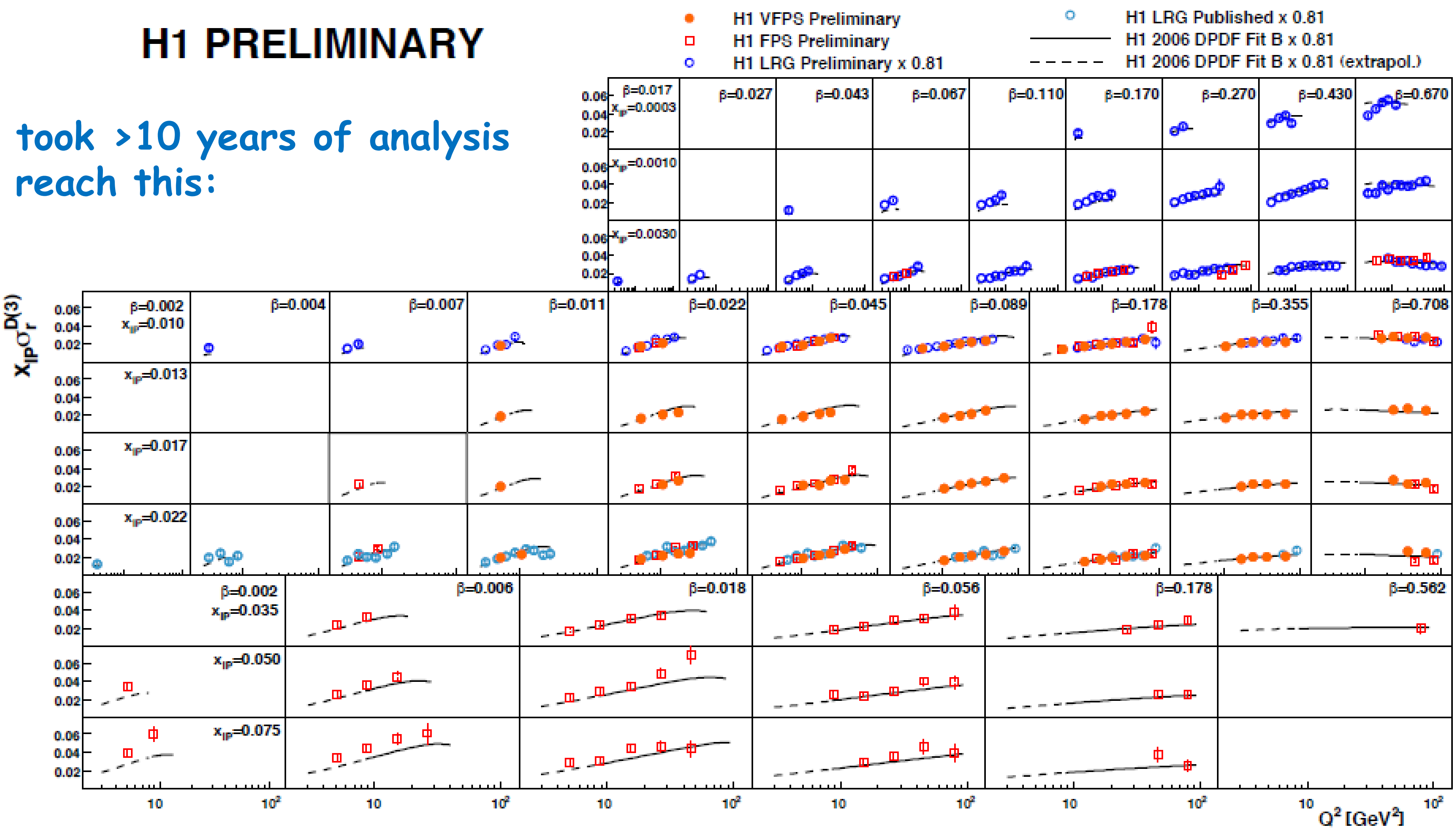
762) DIS with Leading Protons or Large Rapidity Gaps [ZEUS]
764) A QCD Analysis of ZEUS Diffractive Data [ZEUS]
421) Inclusive Measurement of Diffractive DIS [H1]
423) Measuring F_2^D with a Very Forward Proton Spectrometer [H1]
418) Diffractive DIS Cross Sections with a Leading Proton [H1]
414) Leading Neutron Production in DIS [H1]
425) Diffractive Jet Production in DIS with a Leading Proton [H1]

416) Diffractive Dijet Photoproduction in ep Collisions [H1]
771) Leading Proton Production in DIS [ZEUS]
773) Dijet Photoproduction for Leading Neutron Events [ZEUS]

F_2^D

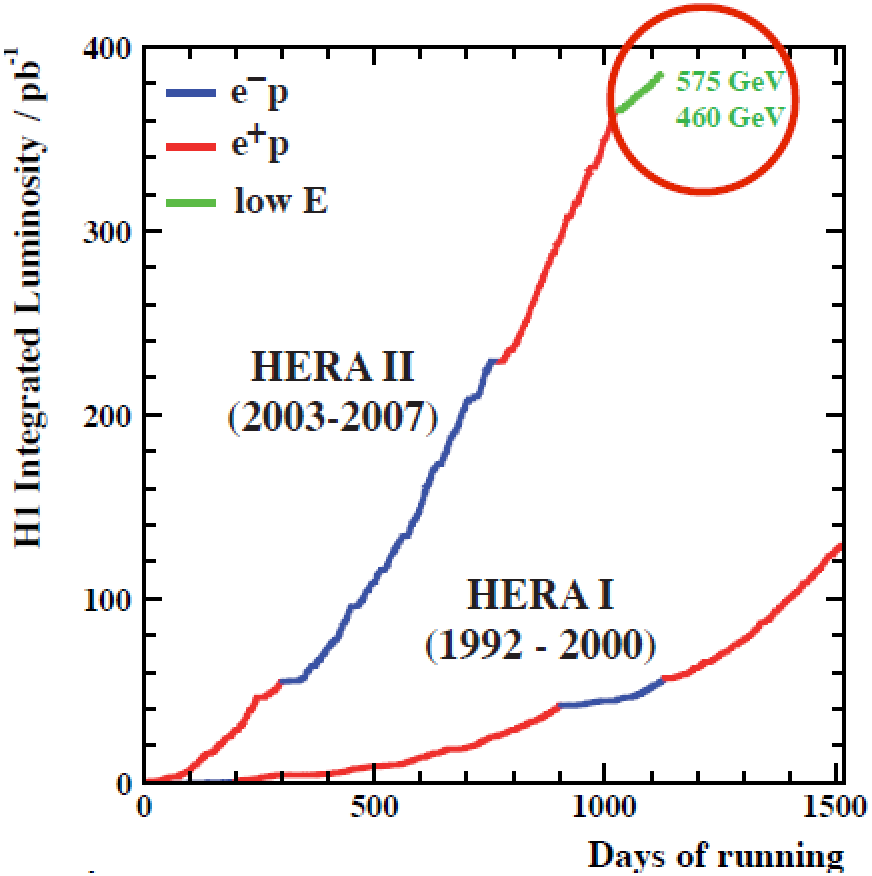
H1 PRELIMINARY

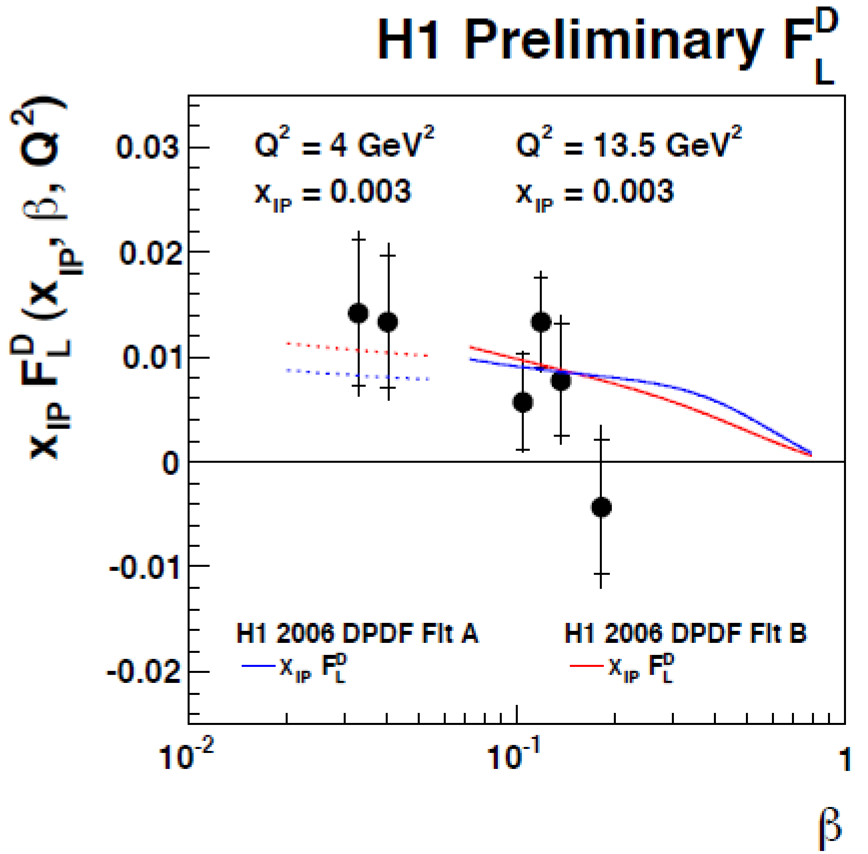
It took >10 years of analysis to reach this:



Sideway pb: time scale for these difficult analysis VS time scale of the the appreciation of a research work...

Results (x_{IP} F_L^D)

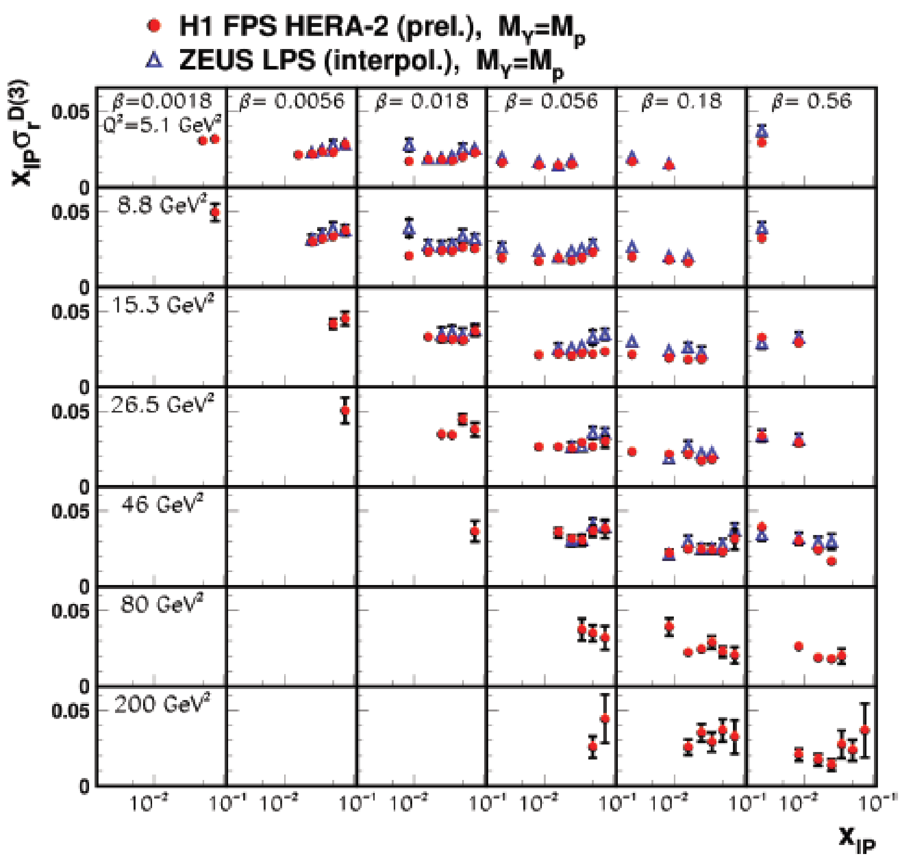




Results (x_{IP} F_2^D): Proton Tag selection

Quadruple-differential cross sections! $\sigma_r^{D(4)}(\beta, Q^2, x_{IP}, t)$

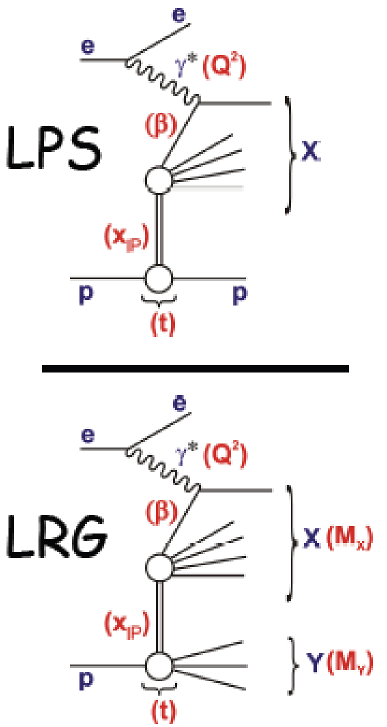
Integrated over t in this example H1-ZEUS comparison

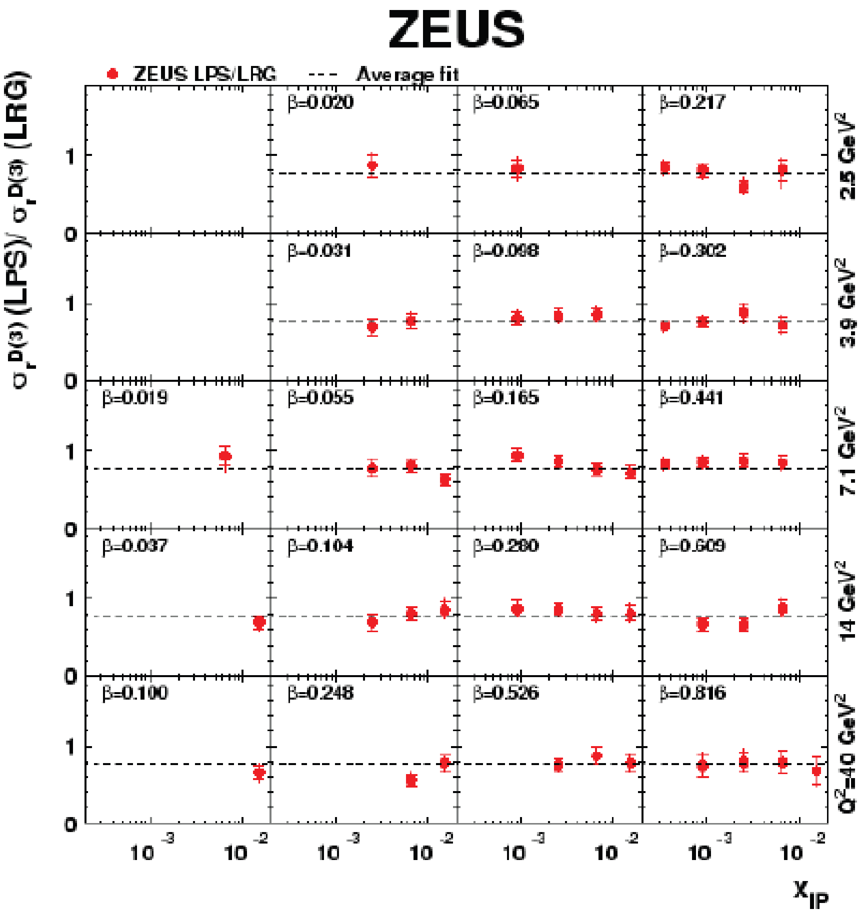


- All available data used by both collaborations
  → x_{IP} ~ 0.1
- H1 HERA-II (157 pb^{-1}) yields higher Q^2 data
- Good H1-ZEUS agreement on kinematic dependences
- 15% difference in overall normalisation compatible with uncertainties

Comparison between F2D measurement methods

Proton Tag / LRG





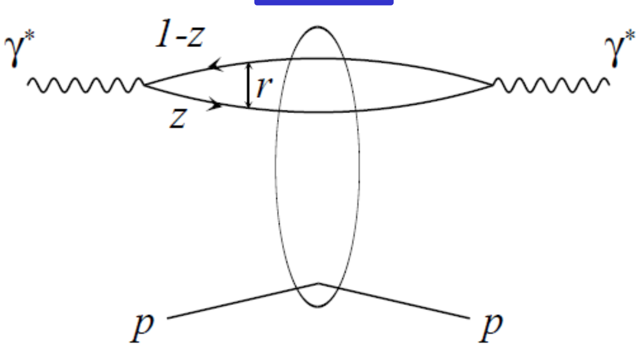
- LRG selections contain typically 20% p diss
- No significant dependence on any variable
- **... well controlled, precise measurements**

One major interest of F2D measurements

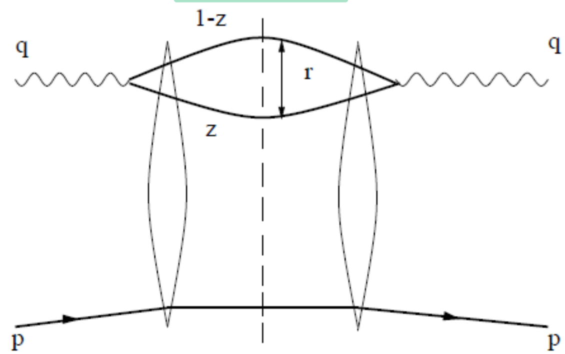
As already mentioned, inelastic inclusive diffraction is intimately linked to the structure of the proton @ small x…
with an better sensitivity to the gluon density (at small x) than standard F2

And at first order (in the development of dipole states) it can be written:

DIS



DDIS



$\sigma_{incl} \sim \int d^2\mathbf{r}dz\ |\Psi(r,z,Q)|^2\ T(x,r)$

$d\sigma_{diff}/dt \sim 1/16\pi \int d^2\mathbf{r}dz\ |\Psi(r,z,Q)|^2\ T^2(x_{IP},r)$

$x \approx Q^2/W^2 \ll 1$

$x_{IP} \approx (Q^2+Mx^2)/W^2 \ll 1$

One major interest of F2D measurements

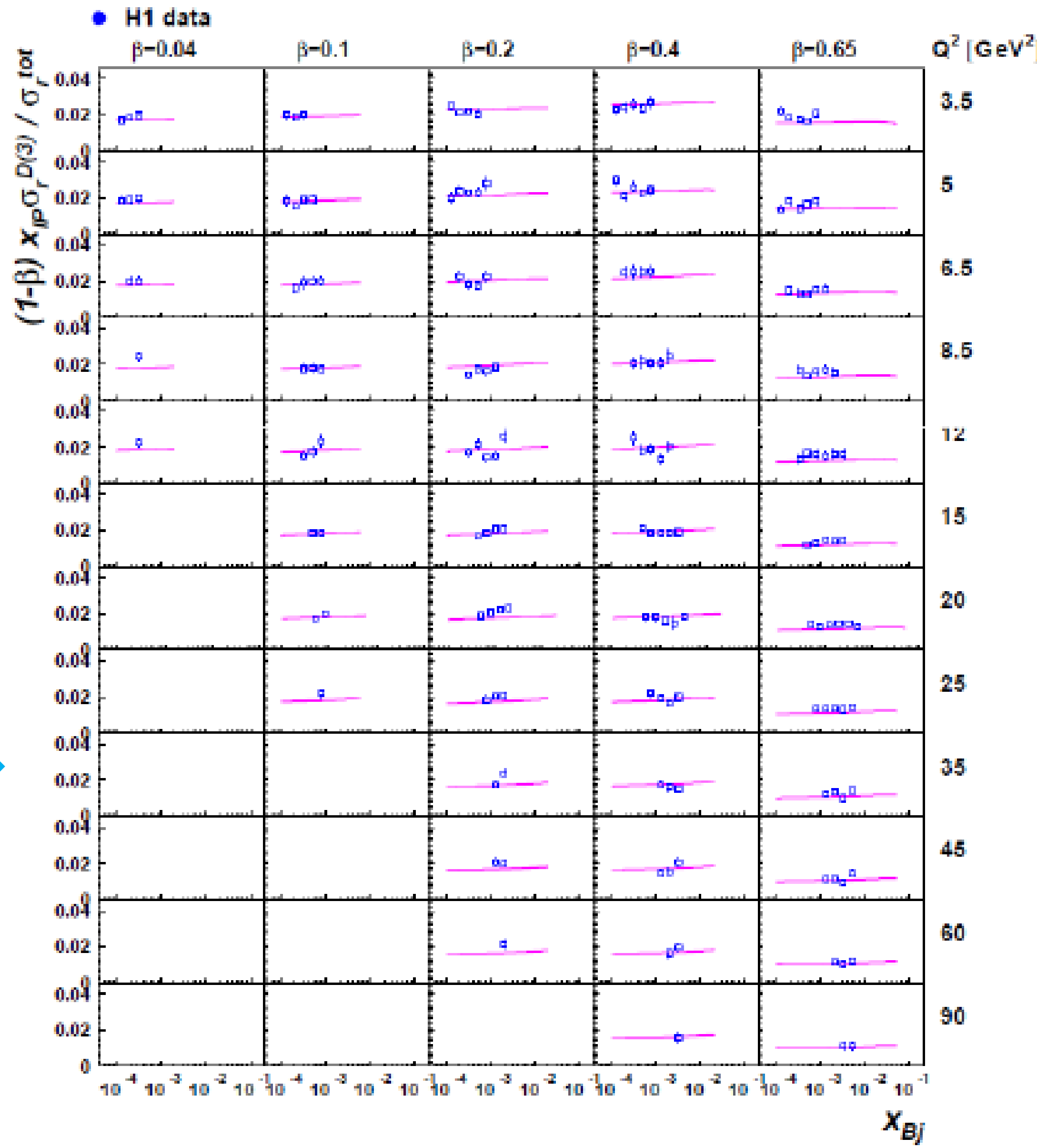
This provides a direct sensitivity
to possible saturation effects
of the gluon density
at small x in the proton

More precisely,

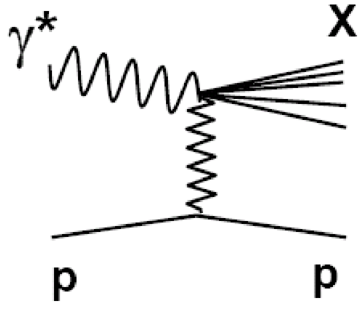
(a)
diffractive scattering
is dominated
by dipoles of size ~1/Qs

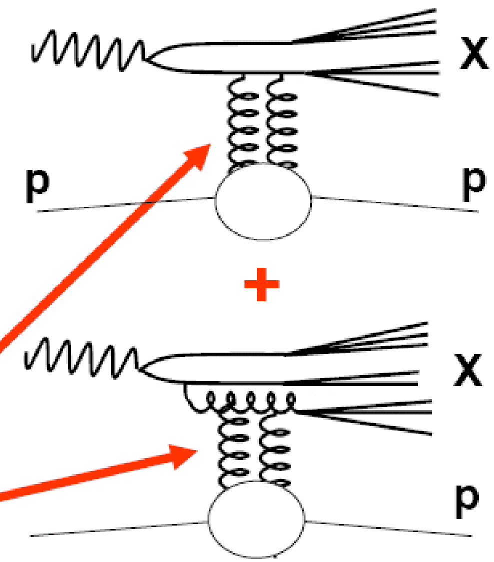
which gives at
the experimental level

(b)
$\sigma_{diff}/\sigma_{incl}$ **~ constant(x)**
at fixed Q^2 and β
(up to log[Q^2/Q_0^2] terms)



With no saturation effects (first approx)





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

As mentioned previously [with T ~ xG]

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

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

@ low x : σ_{DIS} (F2) ~ $1/x^{\lambda}$ (λ~0.3) => $\sigma_{diff} \sim 1/x^{2\lambda}$

And $\sigma_{diff}/\sigma_{DIS}$ ~ $1/x^{\lambda}$ **function of x**!

What happens (at first approx)

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

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

At sufficiently high scale @ high energy, gluon saturation cuts off the large dipole sizes at the semi-hard scale 1/Qs!

(see E.Iancu and many others)

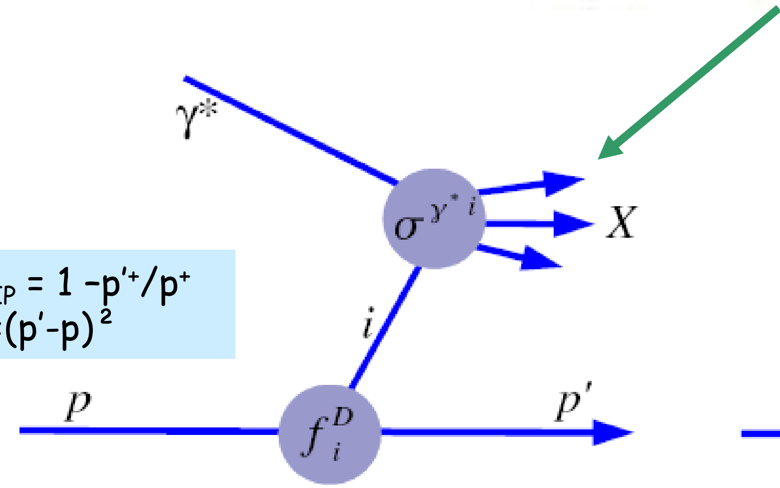
Another view: QCD factorisation for diffractive events

PHYSICAL REVIEW D VOLUME 57, NUMBER 5 1 MARCH 1998

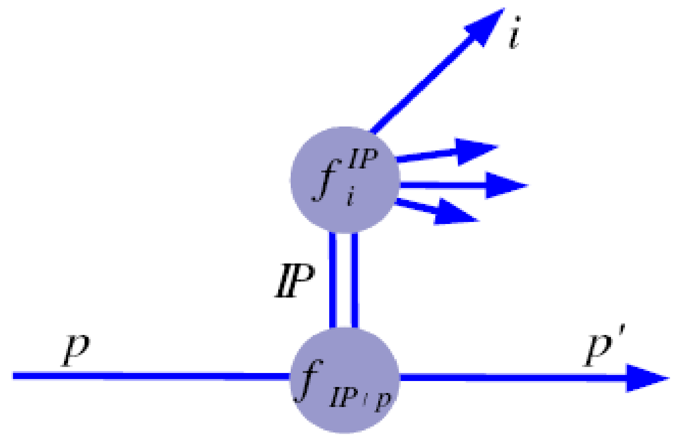
Proof of factorization for diffractive hard scattering

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**)

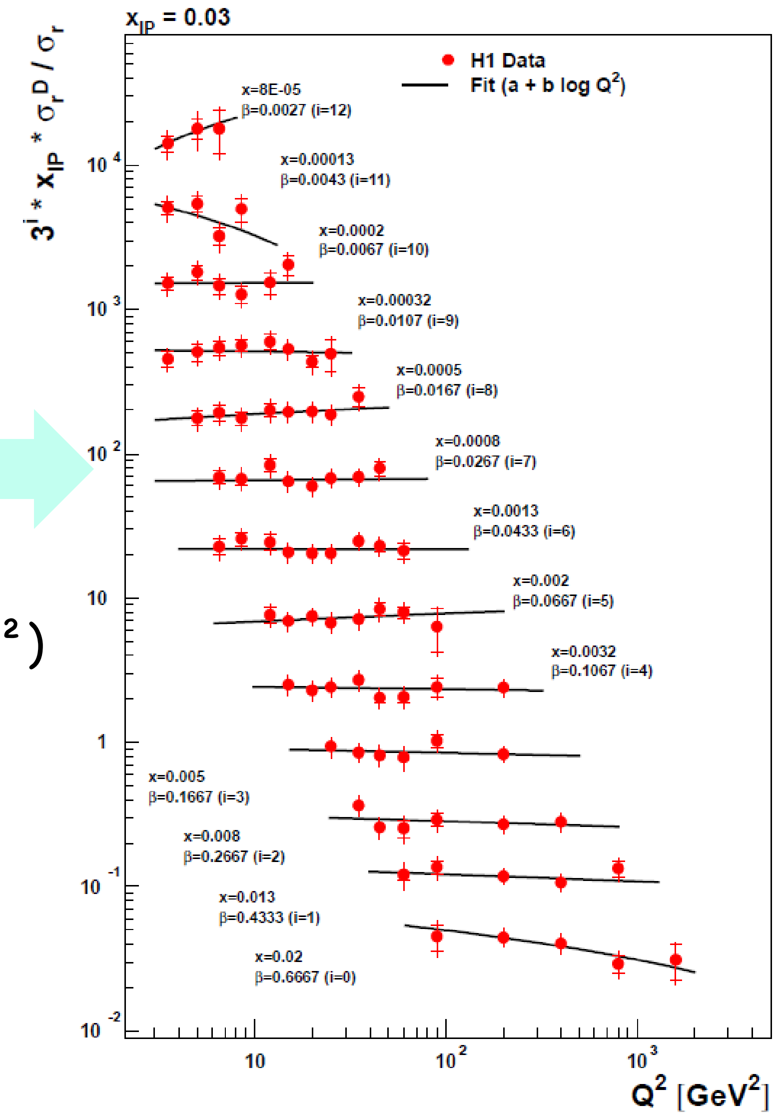
$$f_i^D(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \cdot f_i^{IP}$$

dPDFs

Before quants: experimental support of the Collins factorisation

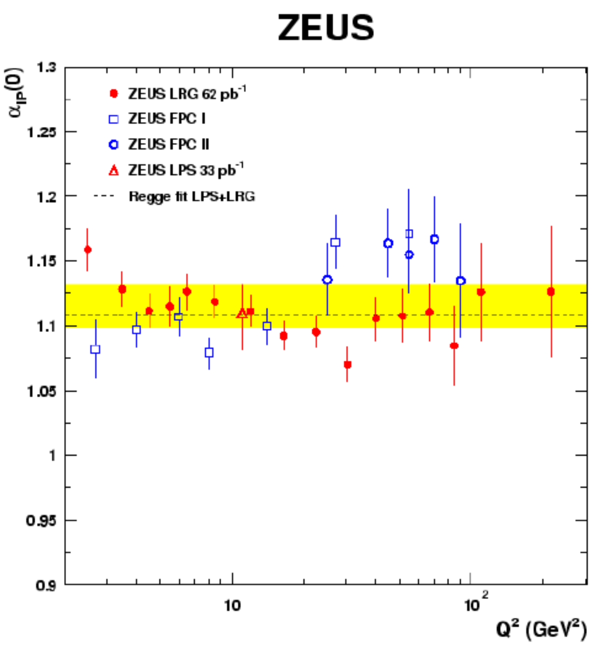
Look at the ratio of the diffractive to inclusive cross section

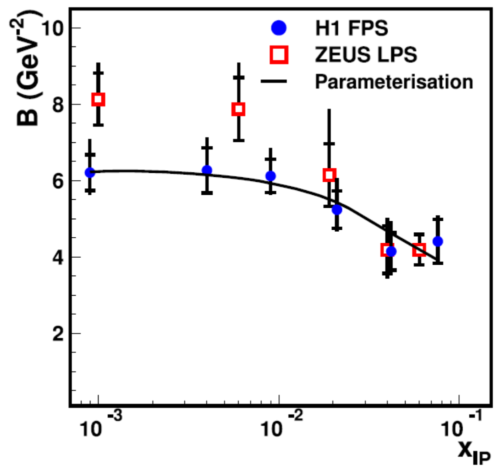
Observation: Q^2 dependence approximately similar for diff and incl…

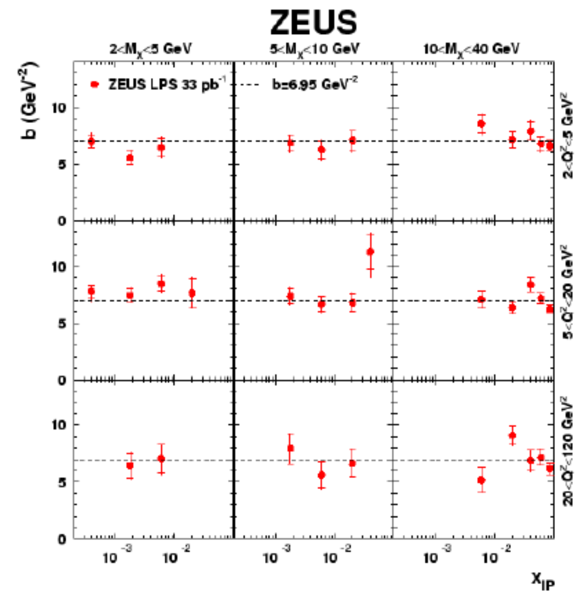


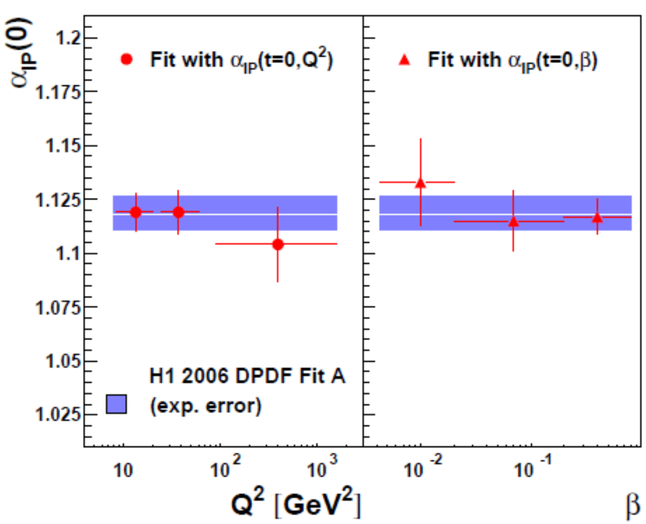
Support the fact that evolution equations(Q^2) can be applied for diff…
(// standard inclusive F2)

α_{IP} and t-slope determinations









IP flux parameter: $\alpha_{IP}(t)= \alpha_{IP}(0)+\alpha' t$

$\alpha_{IP}(0)=1.11\pm0.02\pm0.02$

// « soft Pomeron »

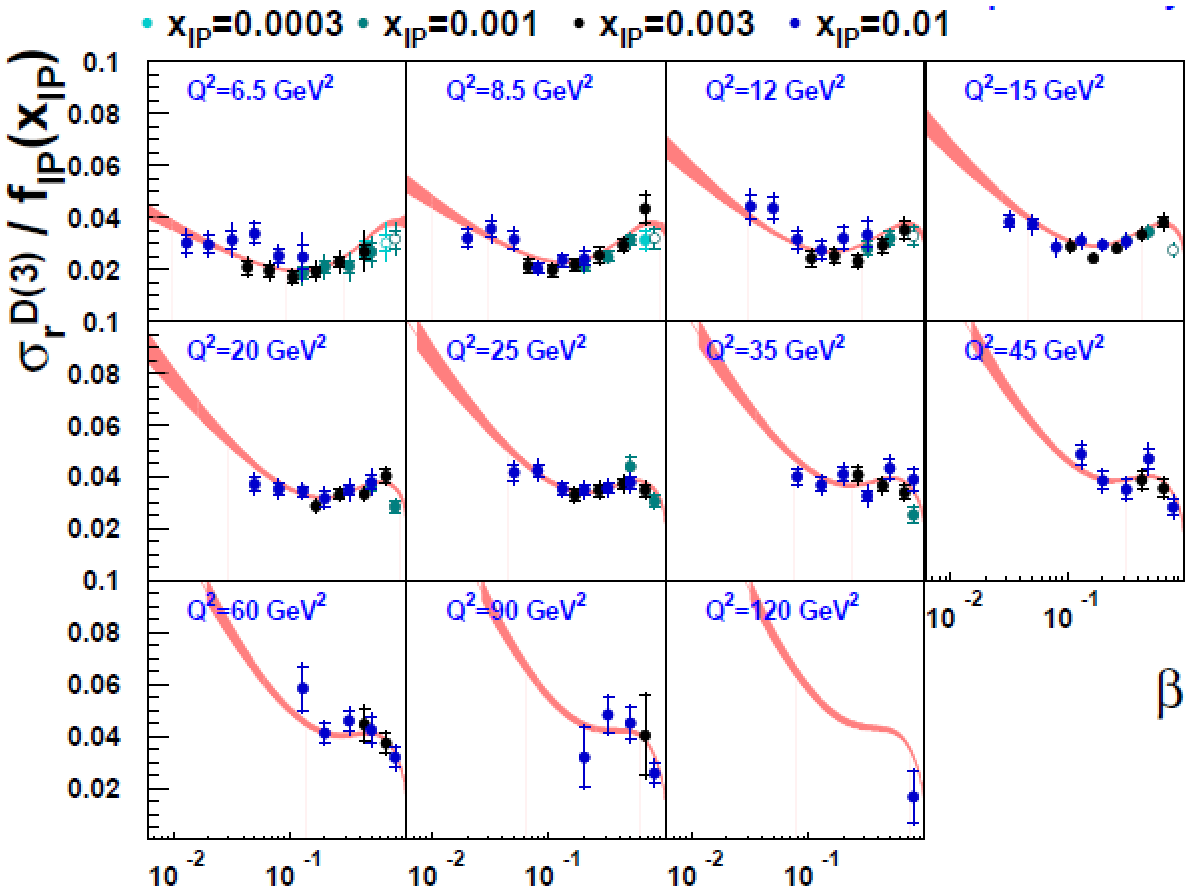
(consistent between H1/ZEUS)

B (low x_{IP})~6-7 GeV^{-2} for H1 and ZEUS

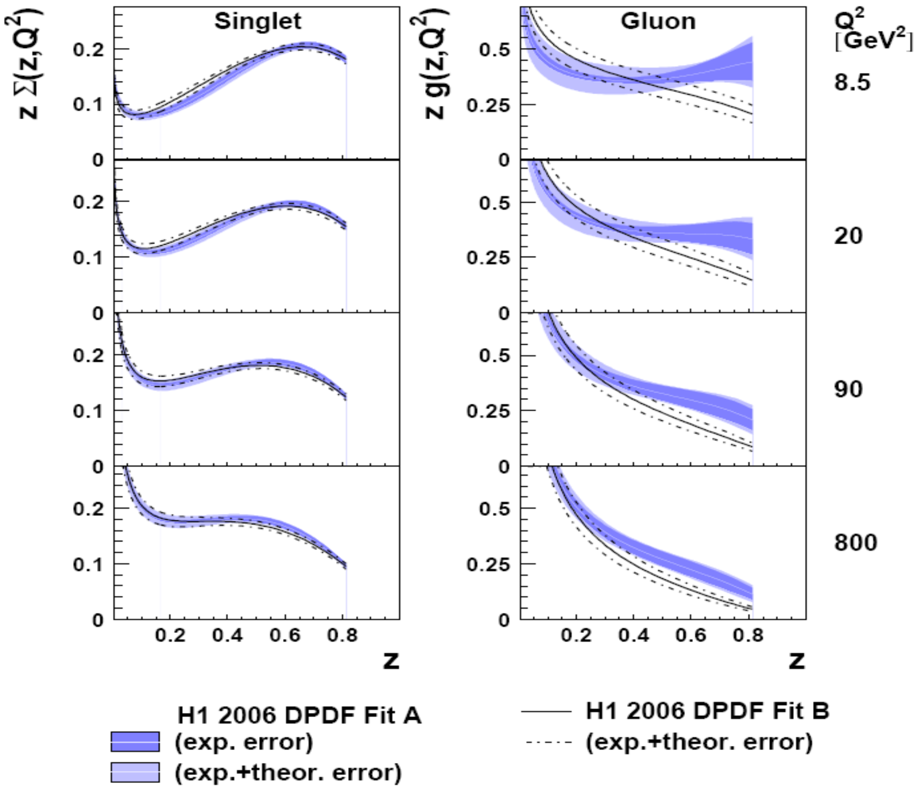
Why the « Regge » factorisation is reasonable?

$$a^D(x_{\mathbb{P}}, z, Q^2) = f_{\mathbb{P}}(x_{\mathbb{P}})\, a^{\mathbb{P}}(z, Q^2)$$

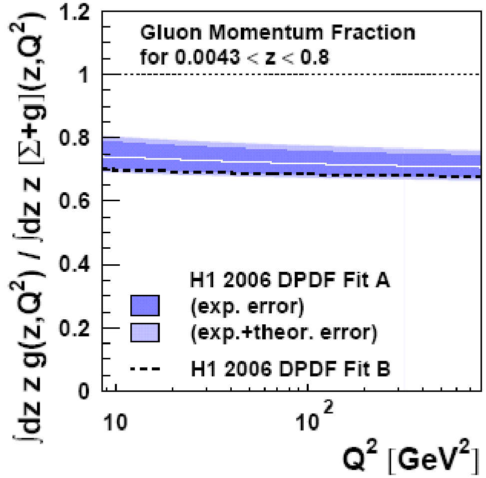
This means that if we divide F_2^D by $f_{IP}(x_{IP})$ the dependence in ($z=\beta, Q^2$) must be the same for all x_{IP} values (small $x_{IP}<10^{-2}$)…



Diffractive PDFs



Again (with another view)
=> Enhanced sensitivity to
'saturation effects' of the gluon
density at small x in the proton



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

As anticipated with the
>0 scaling violations till
large β

Large uncertainty @ large β

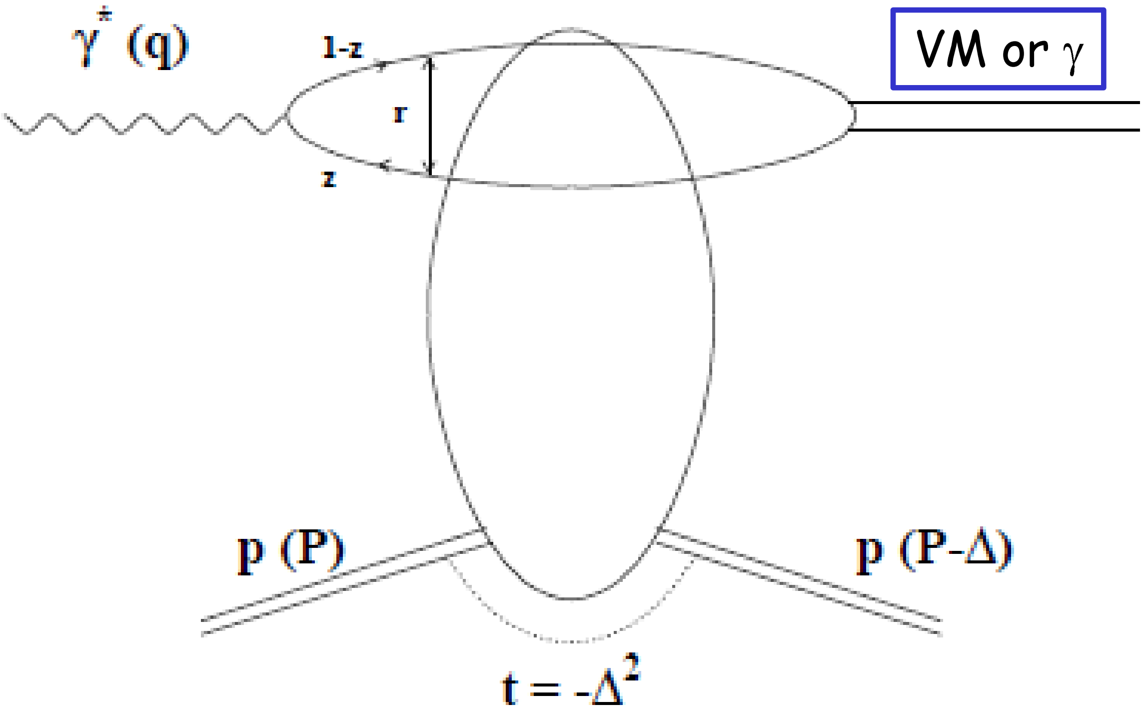
1st part:
Inclusive diffraction at HERA and the dynamical structure of the proton at low x… Few words on Tevatron

2nd part:
The spatial structure of the nucleon from exclusive processes

Summary

Processes under study

Exclusive production of Vector Mesons or real photon (DVCS)
DVCS:= Deeply Virtual Compton Scattering

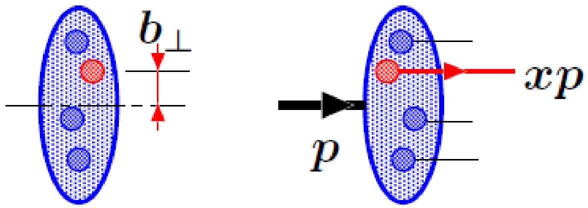


t is the momentum exchange (squared) at the proton vertex

Nucleon structure from the Basic principe

The Fourier transform of the square root of the cross section (VM)
is directly related to the S matrix

$$S(x, r_Q, b) = 1 - \frac{1}{2\pi^{3/2} N(Q)} \int d^2\Delta e^{-i\Delta b} \sqrt{\frac{d\sigma}{dt}}$$



b (:=$b_\perp$) is the impact parameter in the proton
N(Q) is a flux factor (coming from the overlap of γ^* and VM wave function)

S tells us how how dense the nucleon looks like!
S=0 means blackness (unitarity limit)
and $1\text{-}S^2$ is the interaction probability of the γ^* (or dipole) that hits the nucleon at impact parameter b

Program: Measure $d\sigma/dt$, extract S and then conclude on the proton structure

Result from ρ meson from HERA[Q^2]

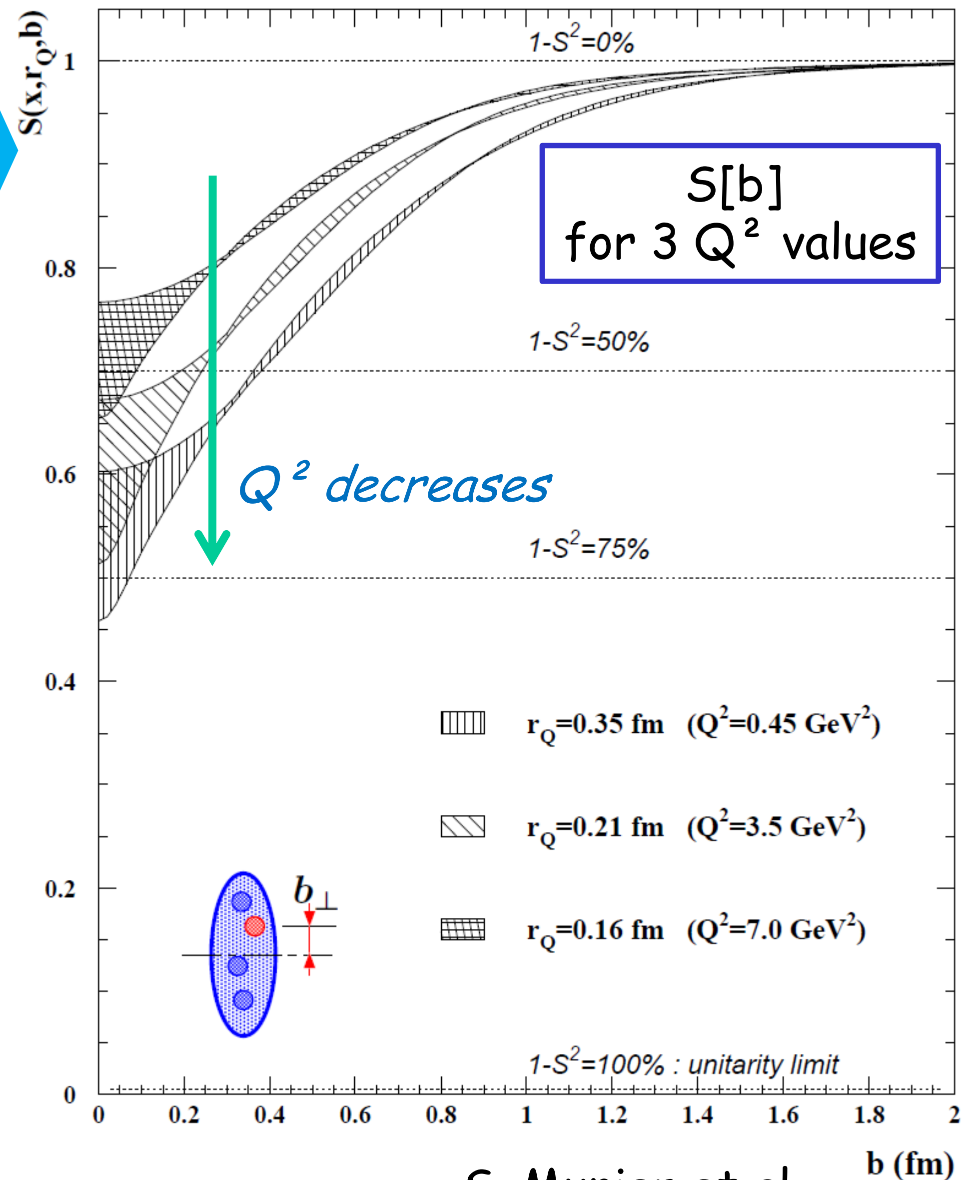
Analysis done for $x<10^{-2}$
with HERA data on ρ exclusive production

Large error at small b due to the lack of data for $|t|>0.6$ GeV^2

Interaction probability>50%(75%)
in the center of the proton
b<0.3 fm (« black disk »)

And then, proton is more transparent when b is increasing ('grey area')
(more transparent also at larger Q^2
-smaller dipole (probe) size-
similar to optics)

Similar results for J/ψ



S. Munier et al.

Imaging the quark/gluon structure of the proton

Historical measurement:

In 1955, R. Hosftadter measures the elastic cross section ep->ep

$d\sigma/dt \sim |F.F.[-\Delta^2]|^2$ (F.F.:=Form Factor) $\Delta = \boldsymbol{p}' - \boldsymbol{p}$

Then $\rho(\mathbf{r}) = \int d^3\Delta/(2\pi)^3 \exp(i\Delta\mathbf{r})\, F.F.(-\Delta^2)$

=> Charge Radius of the proton~0.8 fm

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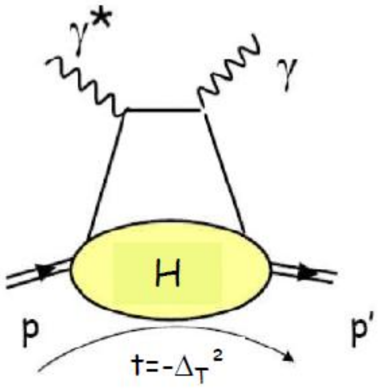
DVCS (Deeply Virtual Compton Scattering): $\gamma^* p \rightarrow \gamma p$
is extending this seminal work:

$d\sigma/dt \sim |H(x,-\Delta_T^2)|^2$ with $x \sim x_{Bjorken}$
where H(x,t) generalises the concept of FF for given x



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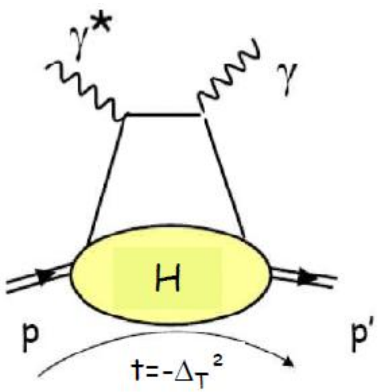


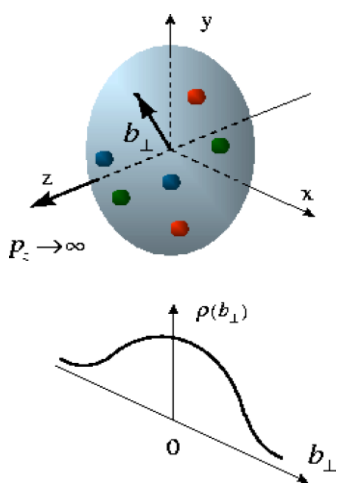
$q(x,\mathbf{r}_T) = \int d^2\Delta_T/(2\pi)^2 \exp(i\Delta_T \mathbf{r}_T)\, H(x,-\Delta_T^2)$ H is called a GPD Generalised PDF

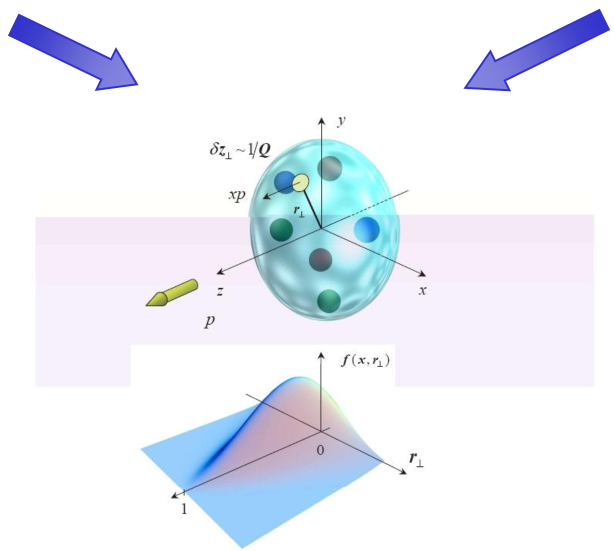
With DVCS, we probe the spatial extend (Tansverse) of parton[x] in the nucleon

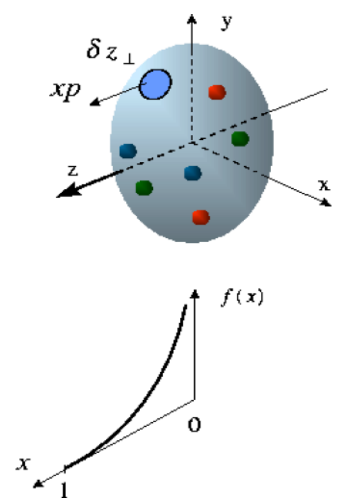
GPD as a generalisation of PDFs and F.F.

form factors
location of partons in nucleon

parton distributions
longitudinal momentum fraction x





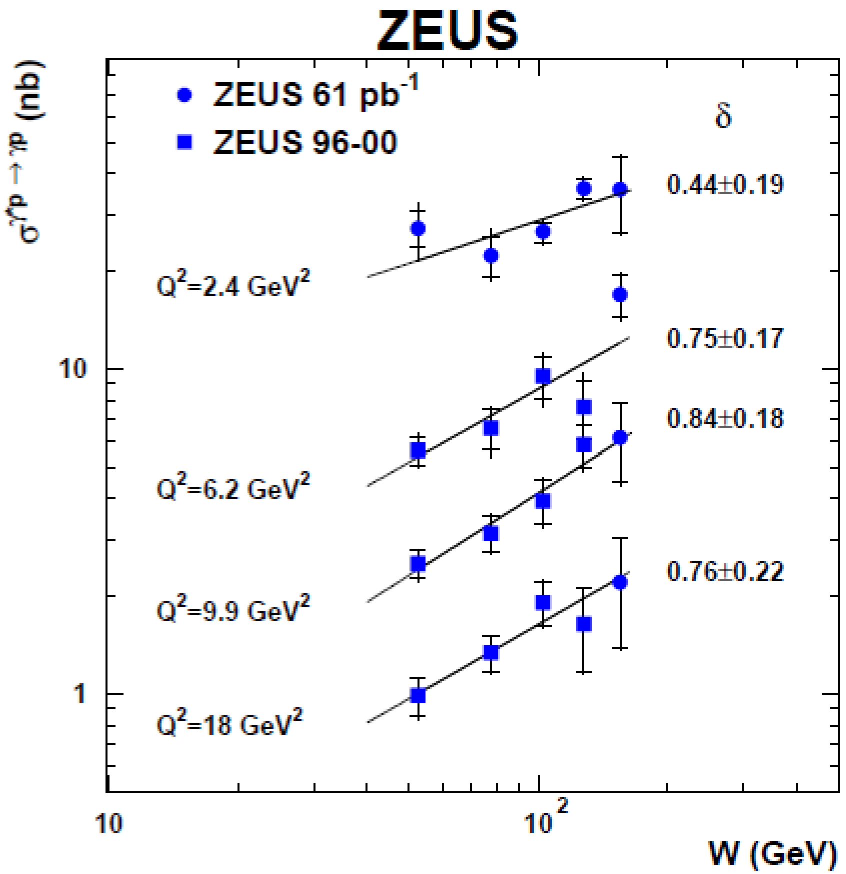


generalised parton distributions (GPDs)
longitudinal momentum fraction x at transverse location $b_\perp$

only known framework to gain information on 3D picture of hadrons

DVCS and the Bjorken limit (at low $x \sim 10^{-3}$)

First, we need to prove experimentally that DVCS measured (at HERA) is a hard process: $\mathbf{e\ p \rightarrow e\ \gamma\ p}$



In average:
$\sigma_{DVCS} \sim W^{\delta}$ with $\delta \sim 0.6$

**** Hard (QCD) process**

** Factorisation makes sense
Note: $\delta \sim 0.2$-0.3 for soft reactions

Experimental results

Very efficient parameterisation of the t dependence at low x~10^{-3}

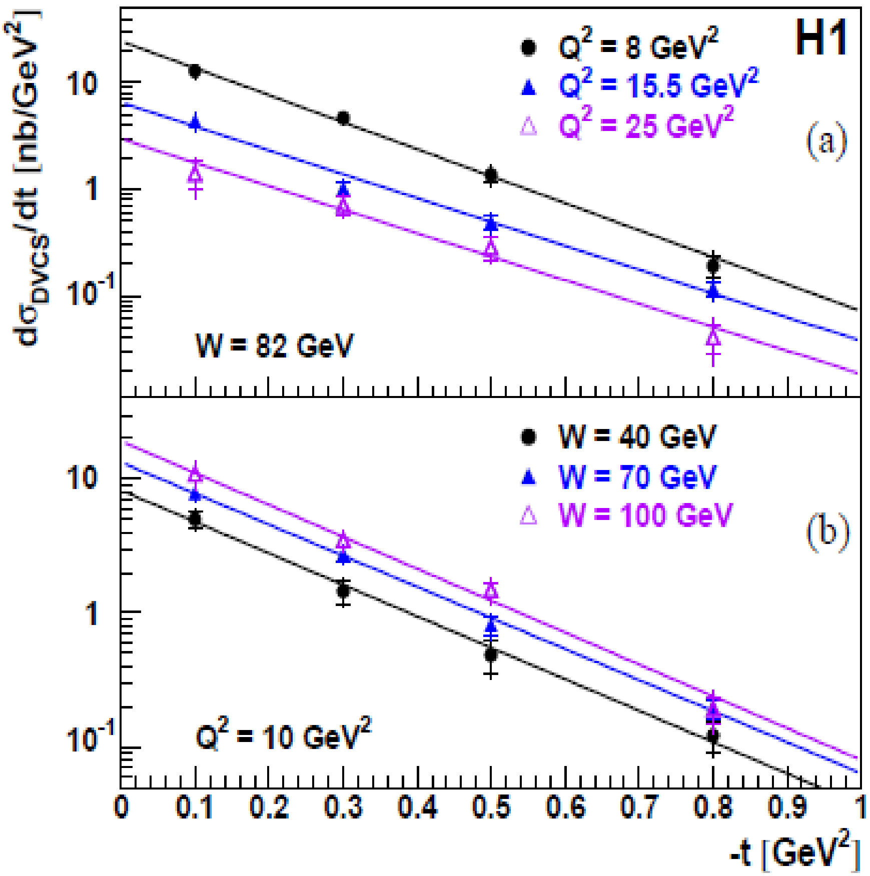
$d\sigma_{DVCS}/dt \sim \exp(bt)$

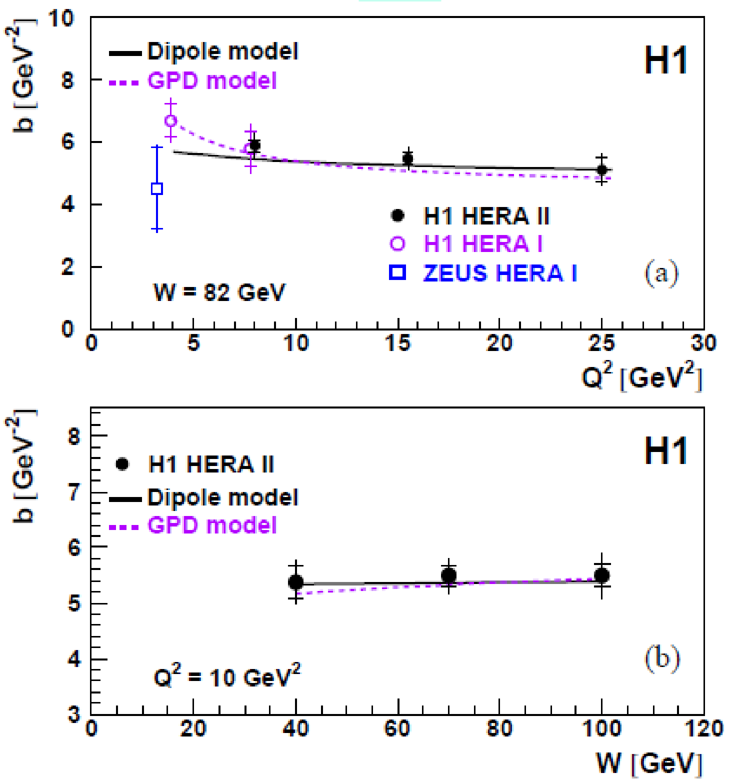
In average $Q^2 > 5$ GeV^2

b=5.41 ±0.14 ±0.31 GeV^{-2}

which gives =>

$[\langle r_T^2 \rangle]^{1/2} = 0.64 \pm 0.02$ fm





Comments on b and $[\langle r_T^2 \rangle]^{1/2}$

For $\langle Q^2 \rangle$ = 10 GeV^2 and $\langle x \rangle$=1.2 10^{-3}

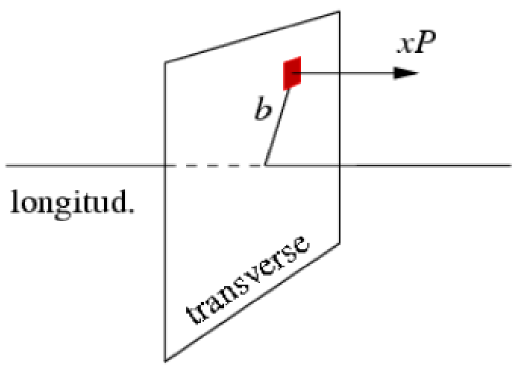
b=5.41 ±0.14 ±0.31 GeV^{-2} → The statistical limit is reached

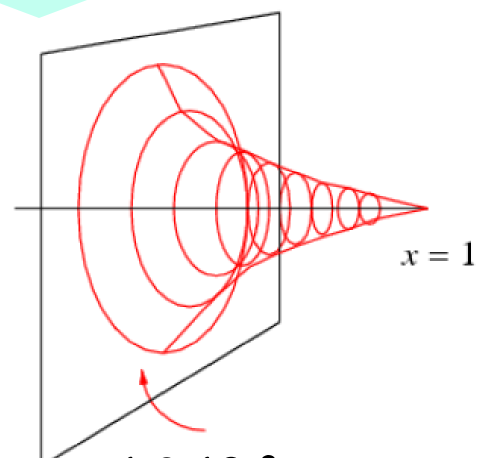
$[\langle r_T^2 \rangle]^{1/2}$ = 0.64 ± 0.02 fm

Transverse width of the parton distribution (probed in the reaction)

The spatial structure of the proton (in slices of x):

cloud of slow (low x) gluons/sea-quarks and a core of fast (large x) quarks…



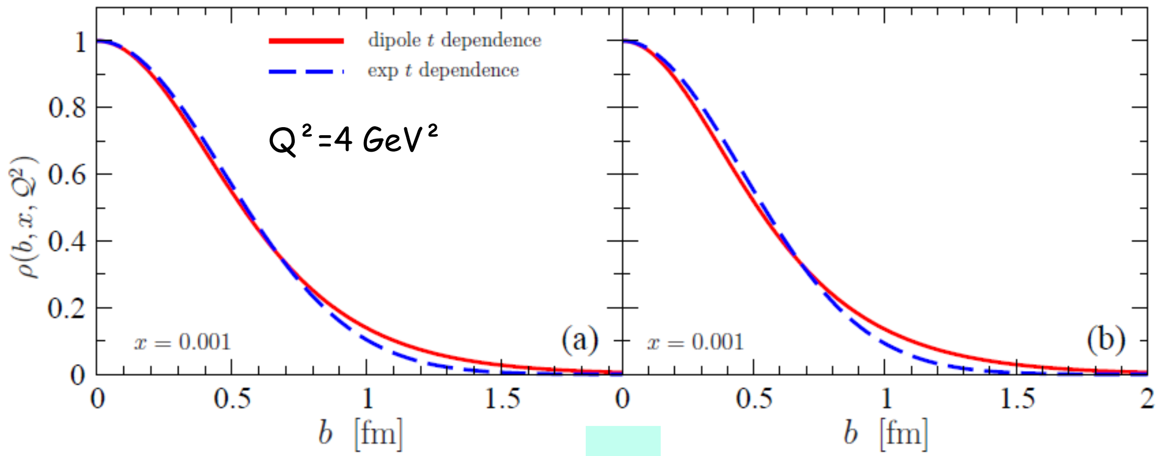


$\langle x \rangle$=1.2 10^{-3}

Sea quarks and gluons

More refined theoretical analysis of $[\langle r_T^2 \rangle]^{1/2}$

From Mueller et al. ('09), global fits of low x DVCS data (H1/ZEUS)+F2
With different hypothesis on t dependences (and initial param of H)…



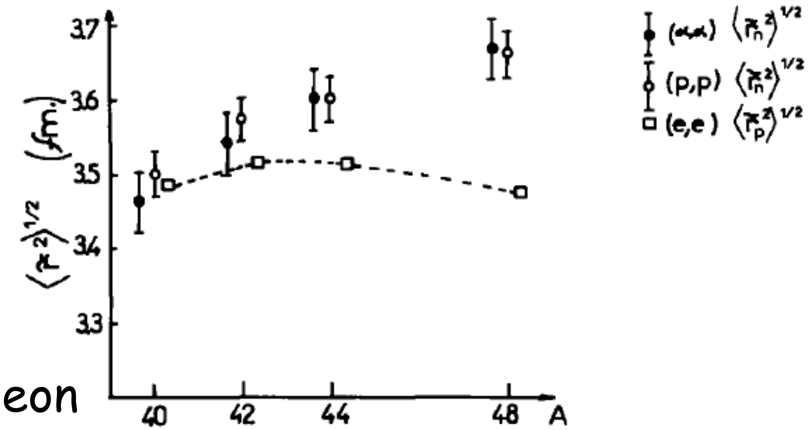
Profile distributions
for sea-quarks and gluons
in the proton
@ $x=10^{-3}$

$[\langle r_T^2 \rangle_{q\ or\ g}]^{1/2} \sim 0.64$ fm : **OK**

Similar results can be
extracted from VMs data

In pictures

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

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

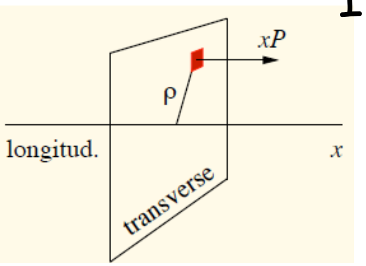
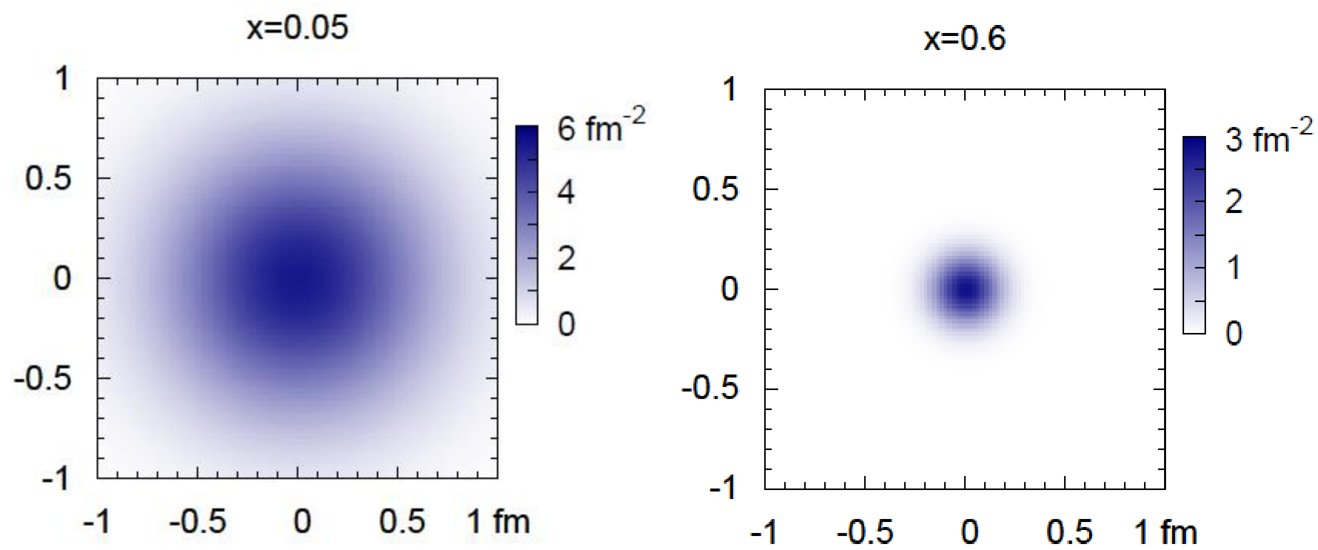


Illustration of $u_{valence}$ quark images (impact parameter in the proton)

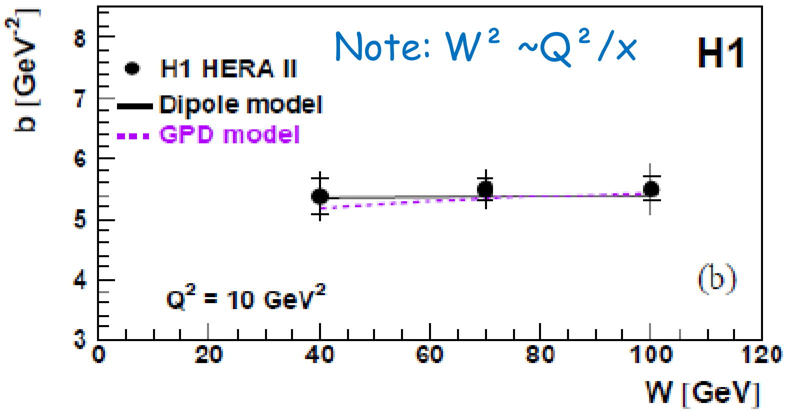


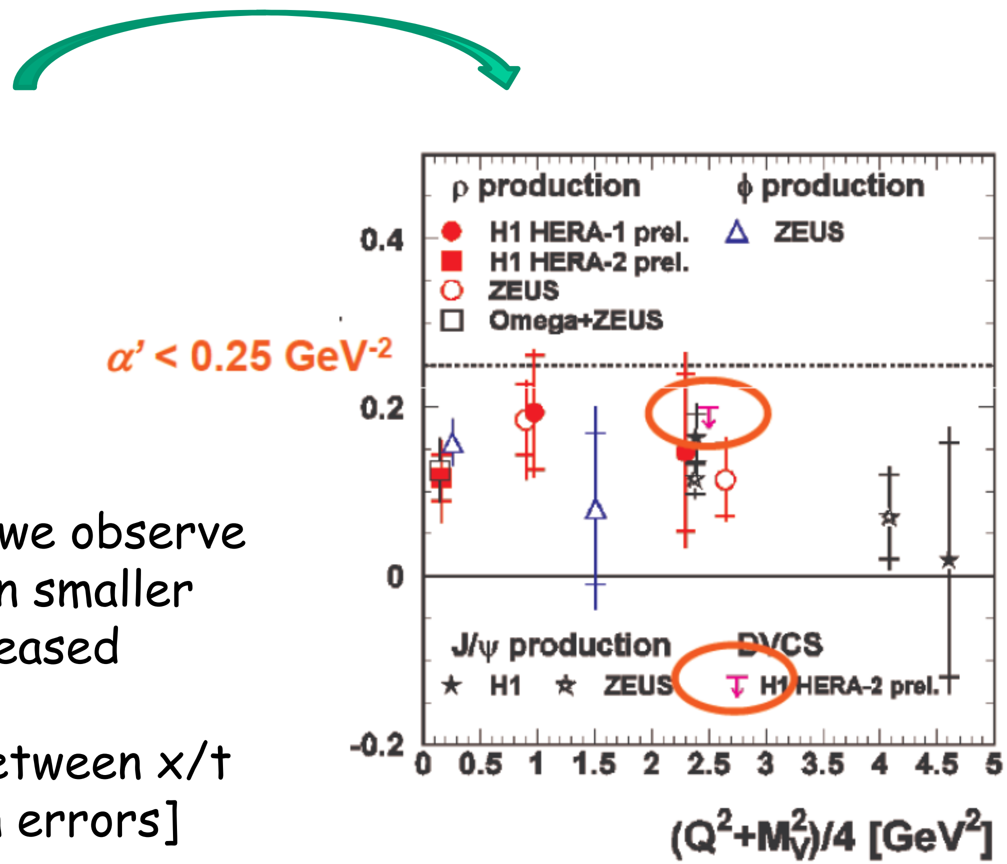
Remark 1: The interplay between x and t

We can examine the dependence of B(x)

Let's write $B(x) = B_0 + \alpha' \, Log(1/x)$

From previous slide, we know that α' is small





For all VM + DVCS at HERA we observe a small value of α' and even smaller values when Q^2 is increased

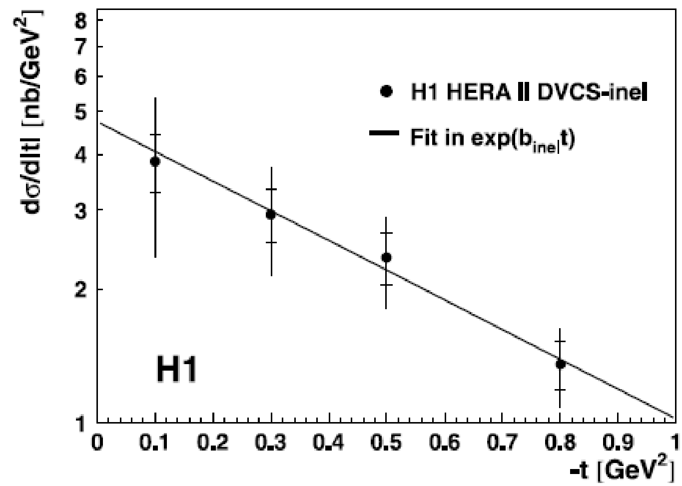
Then, *negligible* interplay between x/t at small x (x<0.01) [within errors]

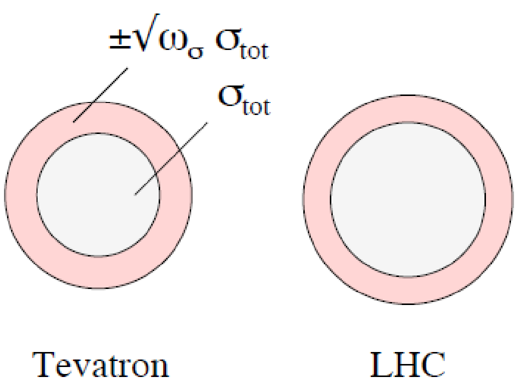
Essential measure for GPD parameterization!

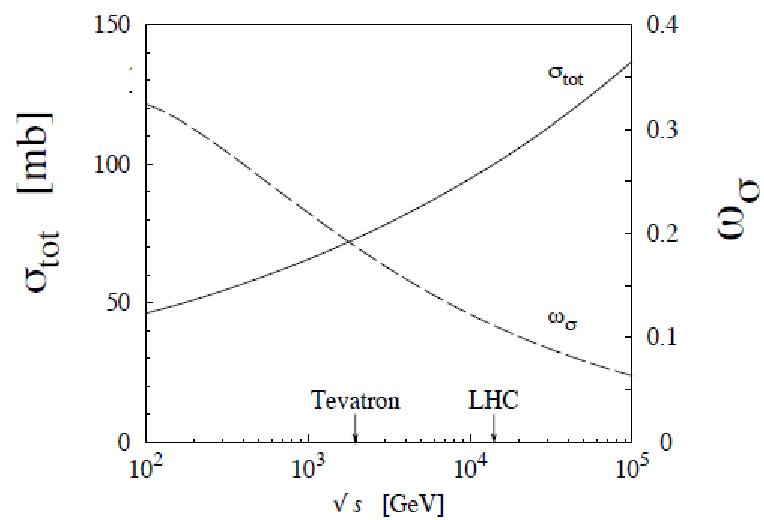
Remark 2: Another result from t-slopes measurements

We can measure inelastic DVCS: $ep \to eY\gamma$ (for My>1.4 GeV)

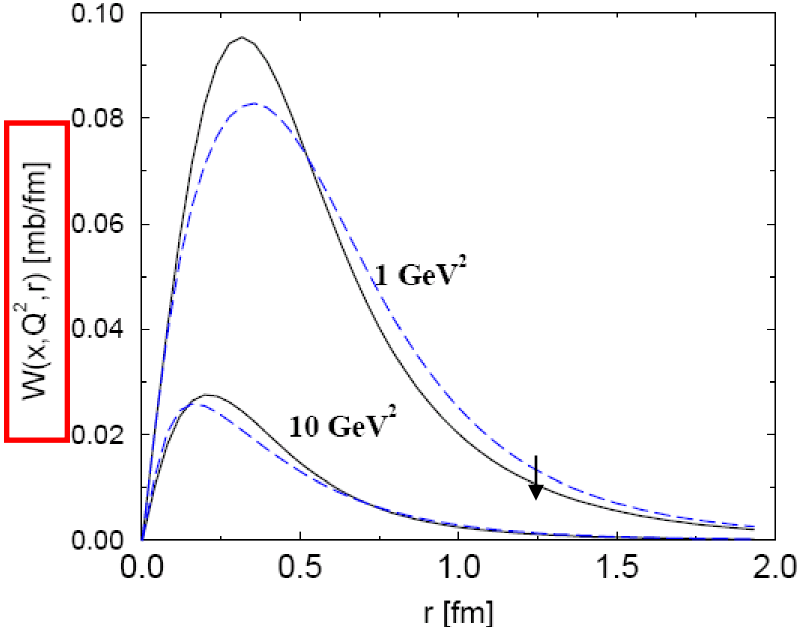
Which gives =>
$\omega := [d\sigma_{inel}/dt \;/\; d\sigma_{el}/dt]|_{t=0} \sim 0.25$
This ratio is quite universal among Vector Meson production *and independent of* Q^2!
Clearly realated to fluctuations of the Gluon field in the proton
$\omega \sim \langle G^2\rangle - \langle G\rangle^2 \;/\; \langle G\rangle^2$
Must be measured at different energies and compare with predictions
=> Important result for pp scattering







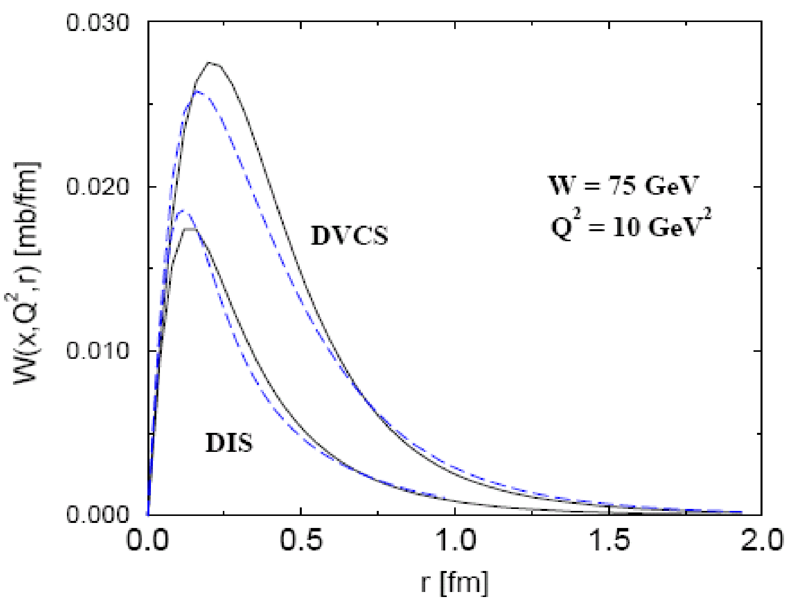
Remark 3: Dipole sizes DIS versus DVCS



W() is the profile function
=> σ(DVCS) = $\int d^2r$ W()

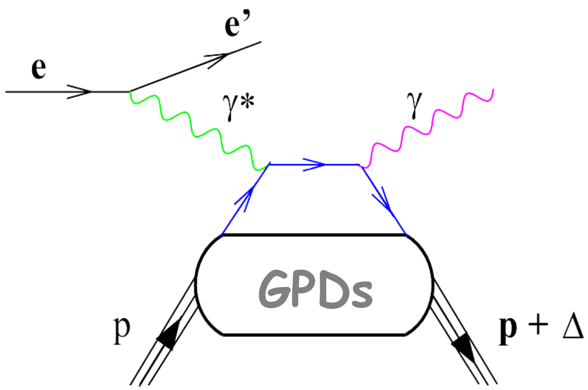
Where r is the size of the dipoles contributing to the DVCS process (size of the γ^* := q-qbar pair)

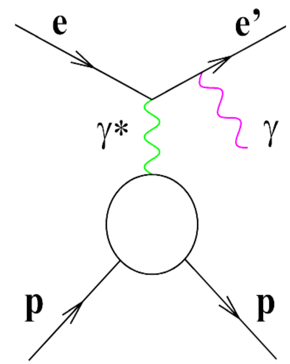
With increasing Q^2, the contribution of large size configurations decreases rapidely… (QCD)



If we compare the profile function for DVCS & DIS @ same kinematics
=> The contributions of large size configs is larger in DVCS!
(// diffractive reactions:
DIS dominated by dipoles of b~1/Q
and DIFF by b~1/Qs)

Sensitivity to GPD H: Beam Charge Asymmetry (BCA)
Interference between QCD & QED at HERA



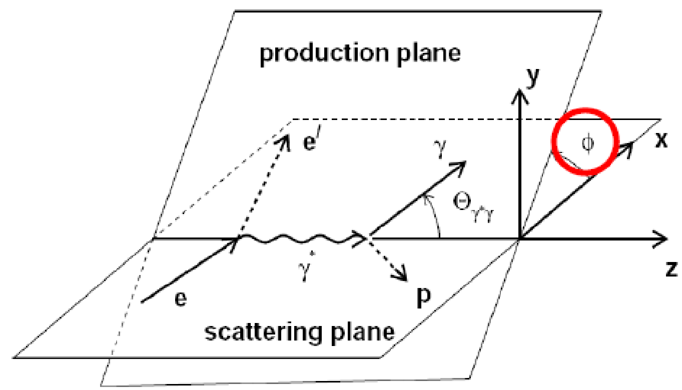


Principles:

DVCS and Bethe-Heitler (QED graphs) have the same final state
Both processes interfere
The BCA is sensitive to this interference
At HERA II, we have almost 150pb^{-1} for each set e^+p and e^-p
with ~0 average polarisation per set…

We measure:
$A_C(\varphi) = [d\sigma^+/d\varphi - d\sigma^-/d\varphi] / [d\sigma^+/d\varphi + d\sigma^-/d\varphi]$

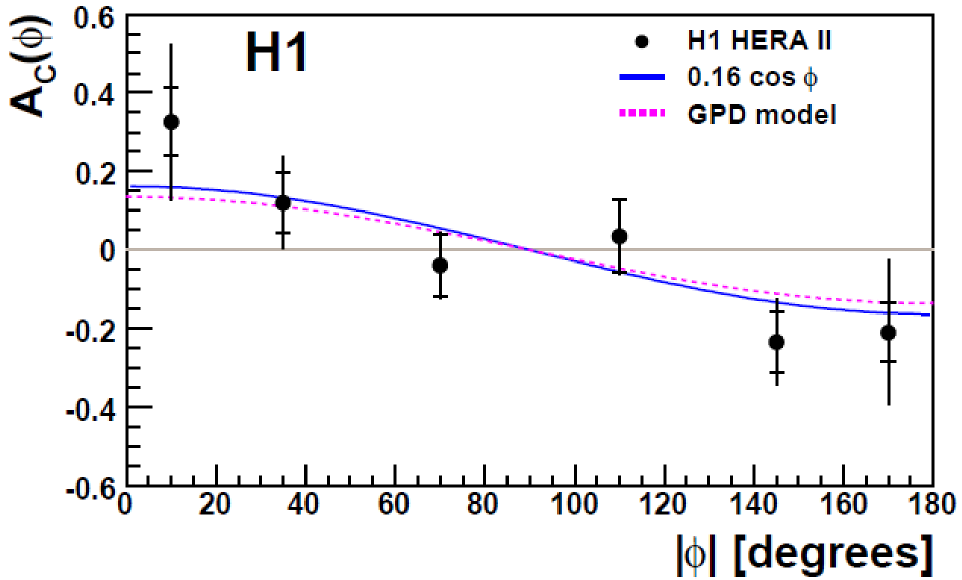
$$A_C(\phi) = p_1 \cos\phi = 2A_{BH} \frac{\boxed{\mathrm{Re}A_{DVCS}}}{|A_{DVCS}|^2 + |A_{BH}|^2} \cos\phi$$



Proportional to a GPD (modulo a convolution with a known function)

Beam Charge Asymmetry (BCA)

Kin bin (H1):
x=1.2 10-3
Q^2=10 GeV^2
=>
Extract one value
for $A_c(\cos\varphi)$
for this bin…



We obtain $A_C(\varphi) = (0.16\pm0.04\pm0.06)\cos(|\varphi|)$
which gives:
$ReA_{DVCS}/ImA_{DVCS} = 0.2\pm0.05\pm0.08$

+ test of the dispersion relations

Then, ReA_{DVCS} is an essential variable to constraint GPDs
Good description obtained by present GPD models

Beam Charge Asymmetry (BCA): another look

- From BCA & DVCS cross section, we can determine a key observable: η**=Re(a$_{DVCS}$)/Im(a$_{DVCS}$)**

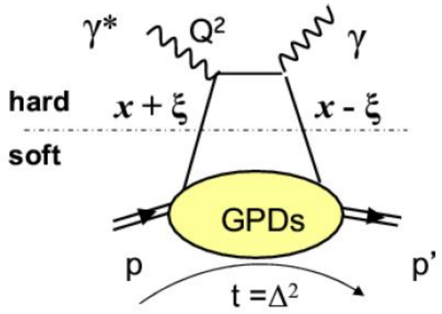
  => η = 0.23 +/- 0.10 (1)

- We have another way to extract this ratio from dispersion relations:
  η**=Re(a$_{DVCS}$)/Im(a$_{DVCS}$) == tan(π/2 δ/4)**
  @ low x with σ_{DVCS}**~W**$^{\delta}$ with δ~0.75 (similar value for H1 & ZEUS)

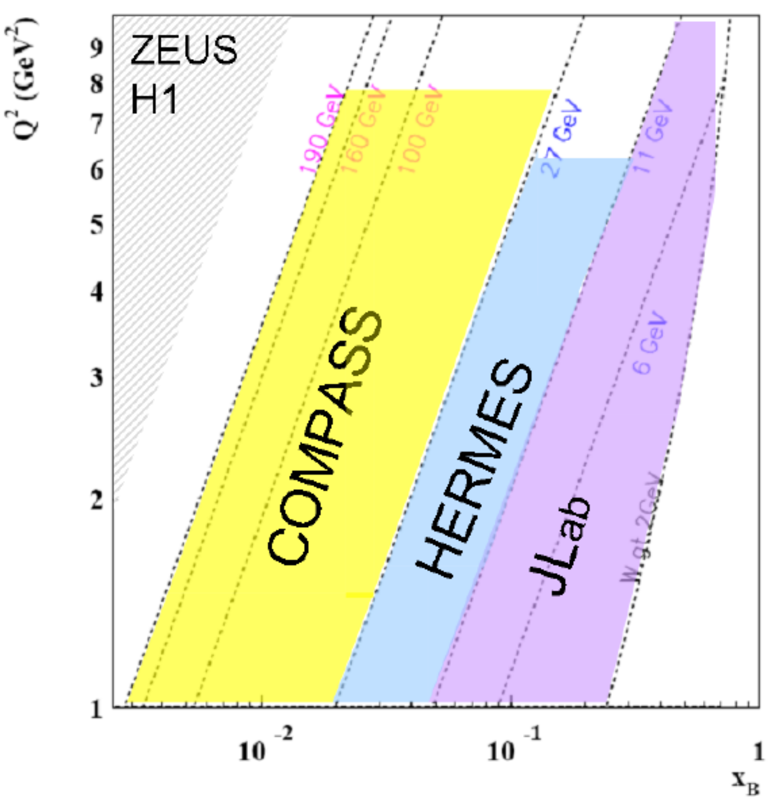
  => η = 0.28 +/-0.07 (2)

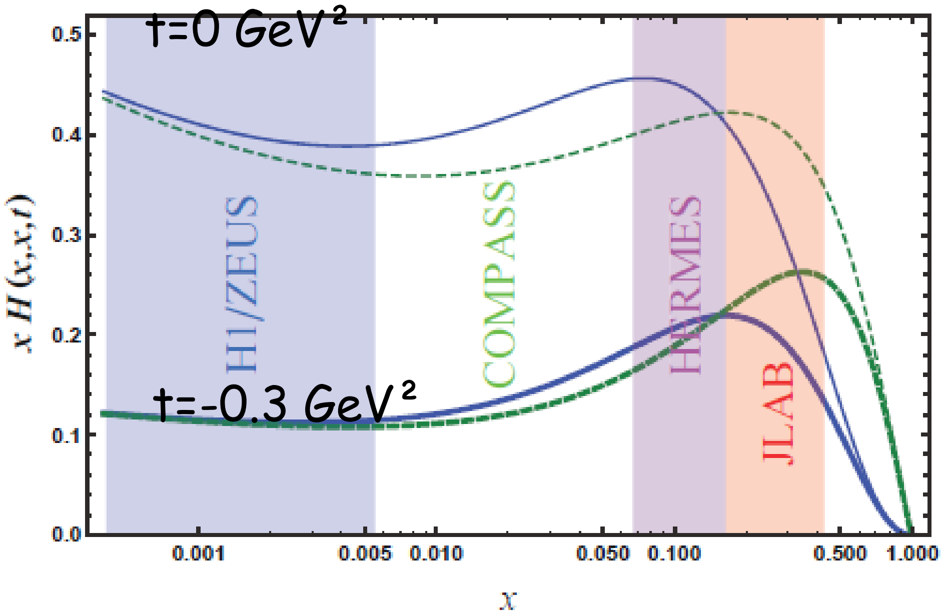
- Both values (1) & (2) are in good agreement => Good confidence in the difficult BCA measurement…

The GPD experimental perspective



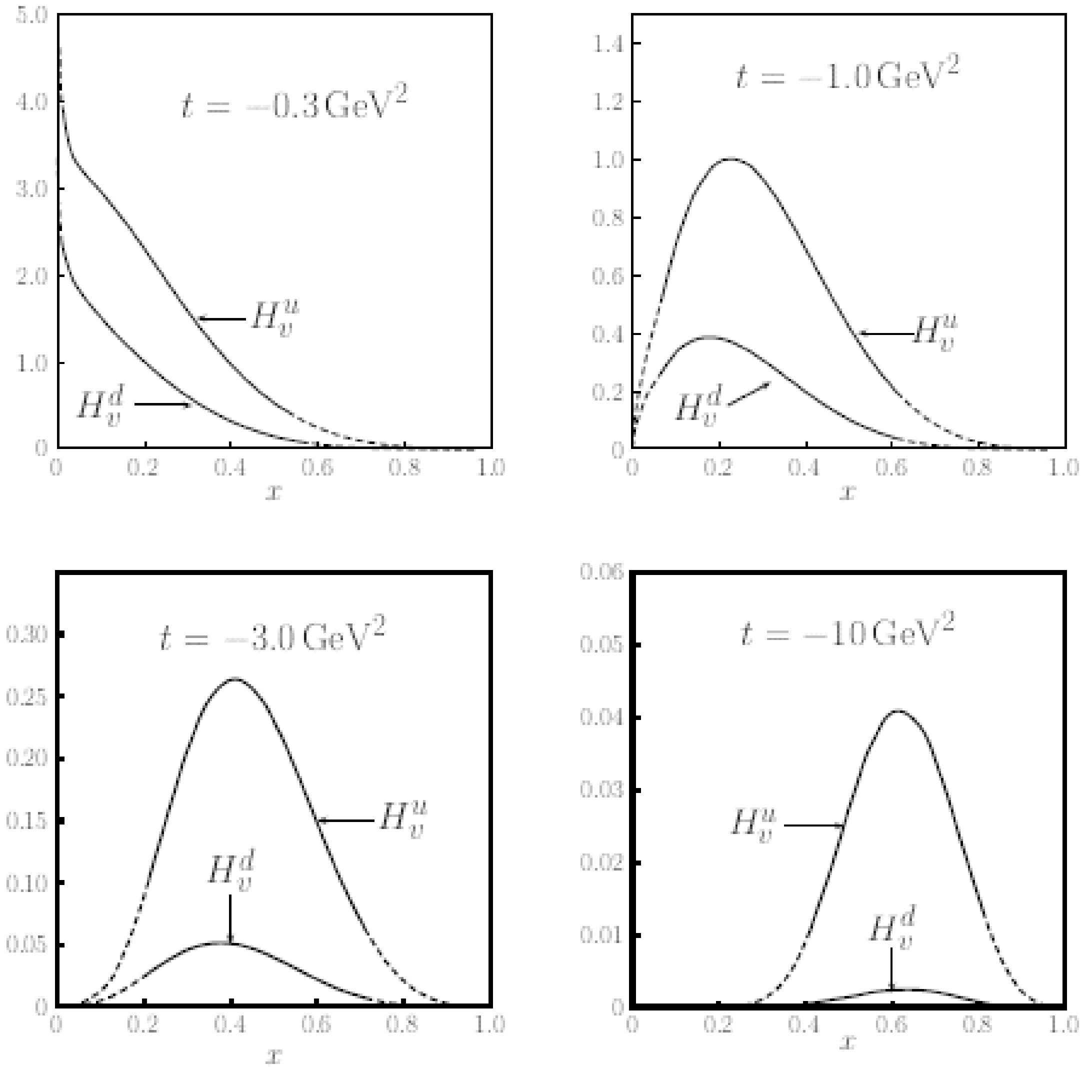
All experiments are useful in determination (fits) of GPDs:
with the goal of a better understanding of how the proton is built up by partons





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…

Summary (on F2D)

As an experimentalist, I want to remind that it took 10Y to get all the points on this plot of F2D! … consequences on saturation effects in QCD are still under study…