What can diffraction at HERA offer to LHC ? Part II

1a) Exclusive vector meson production
1b) Deeply Virtual Compton Scattering

} Sensitivity to gluons in p
Generalised PDFs

2) High-|t| processes → BFKL

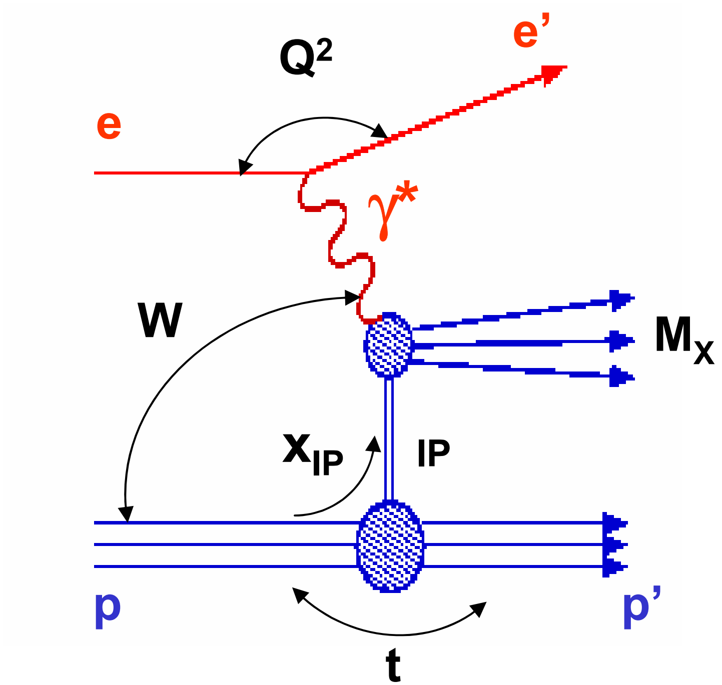
3) Saturation

4) Leading baryon production

M. Arneodo
University of Eastern Piedmont, Novara, and INFN Torino, Italy

HERA-LHC Workshop, CERN, March 26th 2004

Diffractive DIS



Q^2 = virtuality of photon =
= (4-momentum exchanged at e vertex)^2

t = (4-momentum exchanged at p vertex)^2
typically: $|t|<1$ GeV^2

W = invariant mass of photon-proton system

M_X= invariant mass of photon-Pomeron system

x_{IP} = fraction of proton's momentum taken by Pomeron
= ξ in Fermilab jargon

β = Bjorken's variable for the Pomeron
= fraction of Pomeron's momentum carried by struck quark
= x/x_{IP}

Previous talk: Diffractive Deep Inelastic Scattering probes the diffractive PDFs of the proton, relevant when the vacuum quantum numbers are exchanged

N.B. will drop e, e' from the diagrams in the rest of the talk

Part I:
The colour dipole approach

- The picture discussed in the previous talk emerges in a frame in which the proton is fast (the Breit frame)

- Can learn more about the structure of the proton by studying diffraction in a frame in which the virtual photon is faster than the proton. Find out that in exclusive processes

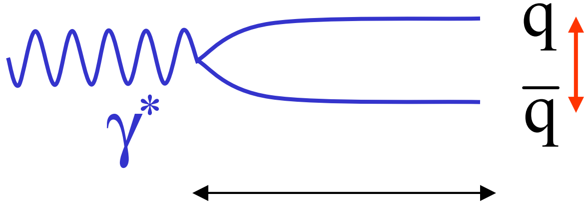
  $\sigma^{diffr} \propto$ [gluon density in proton]^2

  Example: exclusive vector meson production
  Calculable in QCD !

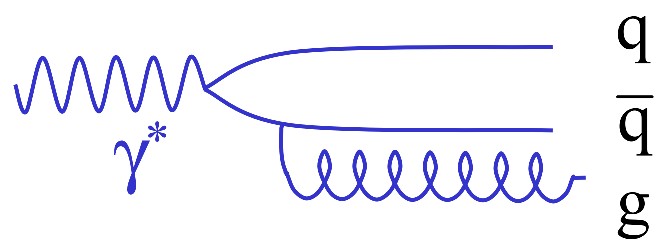
- Correlations in the proton: Generalised Parton Distributions (GPDs)

The colour dipole picture

Virtual photon fluctuates to $q\bar{q}$, $q\bar{q}g$ states (colour dipoles)



$$\propto \frac{1}{\sqrt{Q^2 + M_{q\bar{q}}^2}}$$

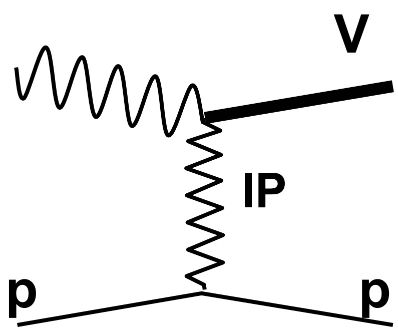


$$\propto E_\gamma \sim W^2 \sim 1/x$$

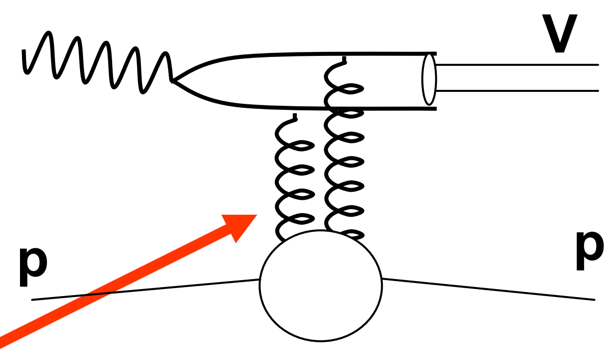
- **Lifetime of dipoles very long because of large γ boost ($E_\gamma \approx$ 50TeV!)**
  $\rightarrow$ it is the dipole that interacts with the proton
- **Transverse size proportional to $1/\sqrt{(Q^2 + M_{q\bar{q}}^2)}$**
  (for *longitudinally* polarised photons)
- **This is why can do diffraction in ep collisions !**

Transverse size of incoming hadron beam can be reduced at will. Can be so small that strong interaction with proton becomes perturbative (colour transparency) !

Example: Vector Meson production



($J^{PC}=1^{--}$): $\rho, \phi, J/\psi, \Upsilon, \ldots$



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

Gluon density in the proton

Cross section proportional to probability of finding 2 gluons in the proton

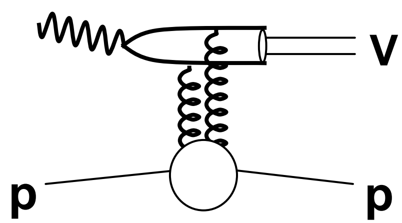
$$\begin{cases} \sigma \propto [x\, g(x, \mu^2)]^2 \\ x = \mu^2 / W^2 \\ \mu^2 \propto (Q^2 + M_V^2) \end{cases}$$

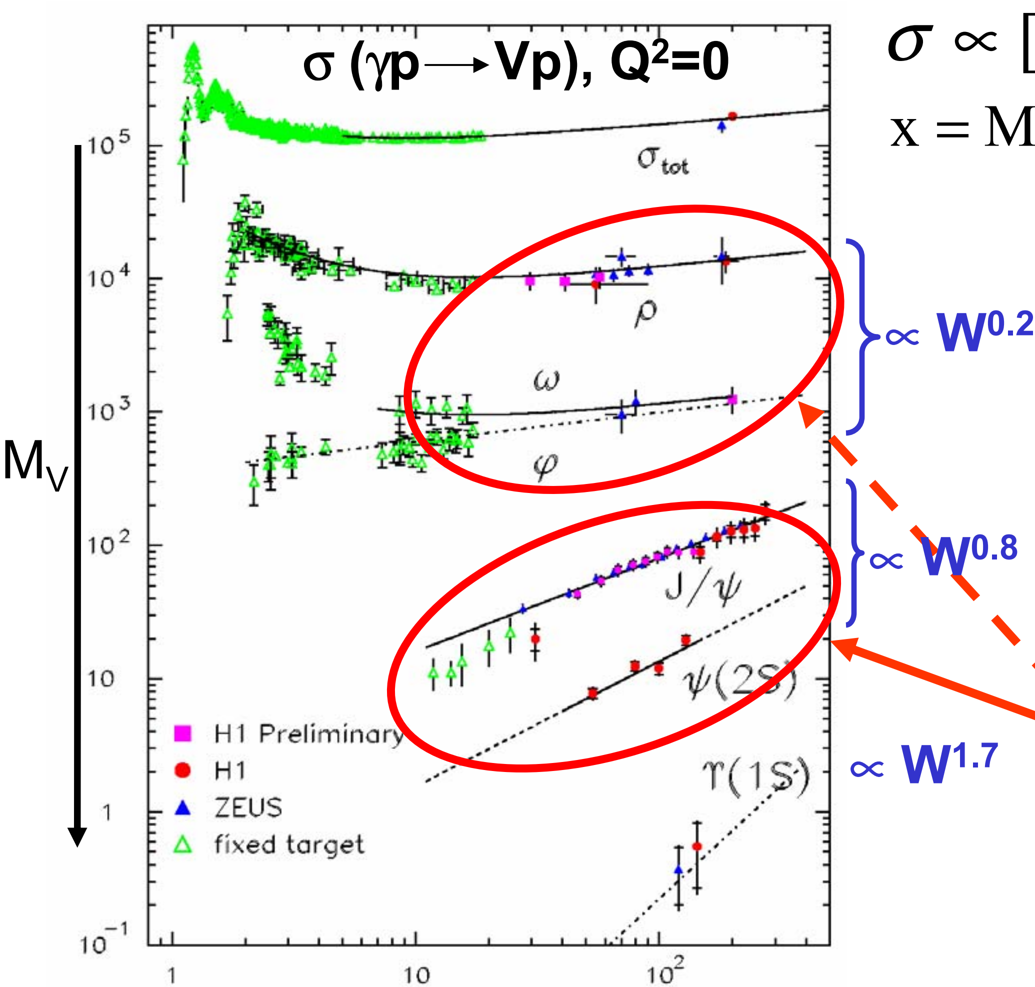
!

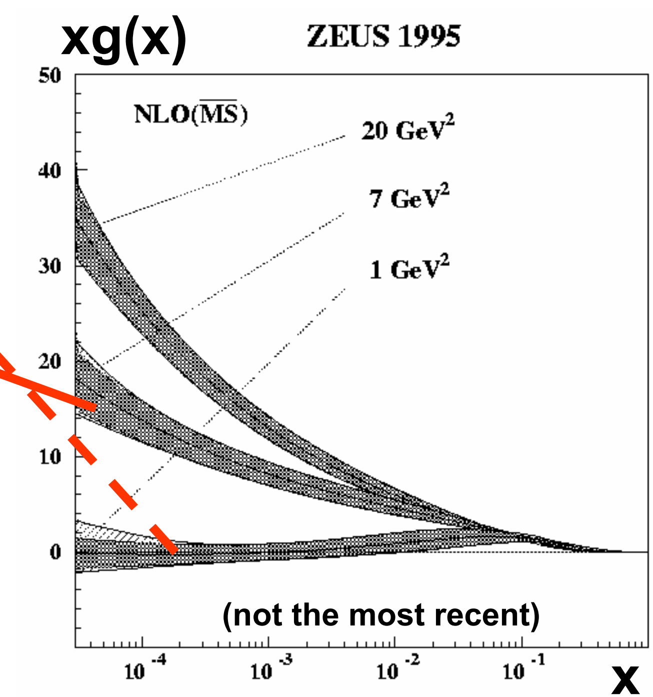
Ryskin (1993), Nikolaev et al (1994), Brodsky et al (1994),...

VM: sensitivity to gluons in proton

$$\sigma \propto [x\, g(x, M_V^2)]^2$$
$$x = M_V^2 / W^2$$







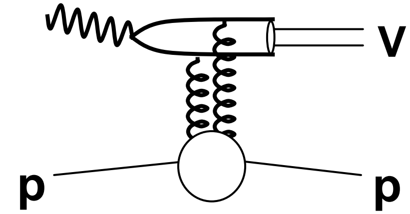
$W \propto 1/\sqrt{x}$

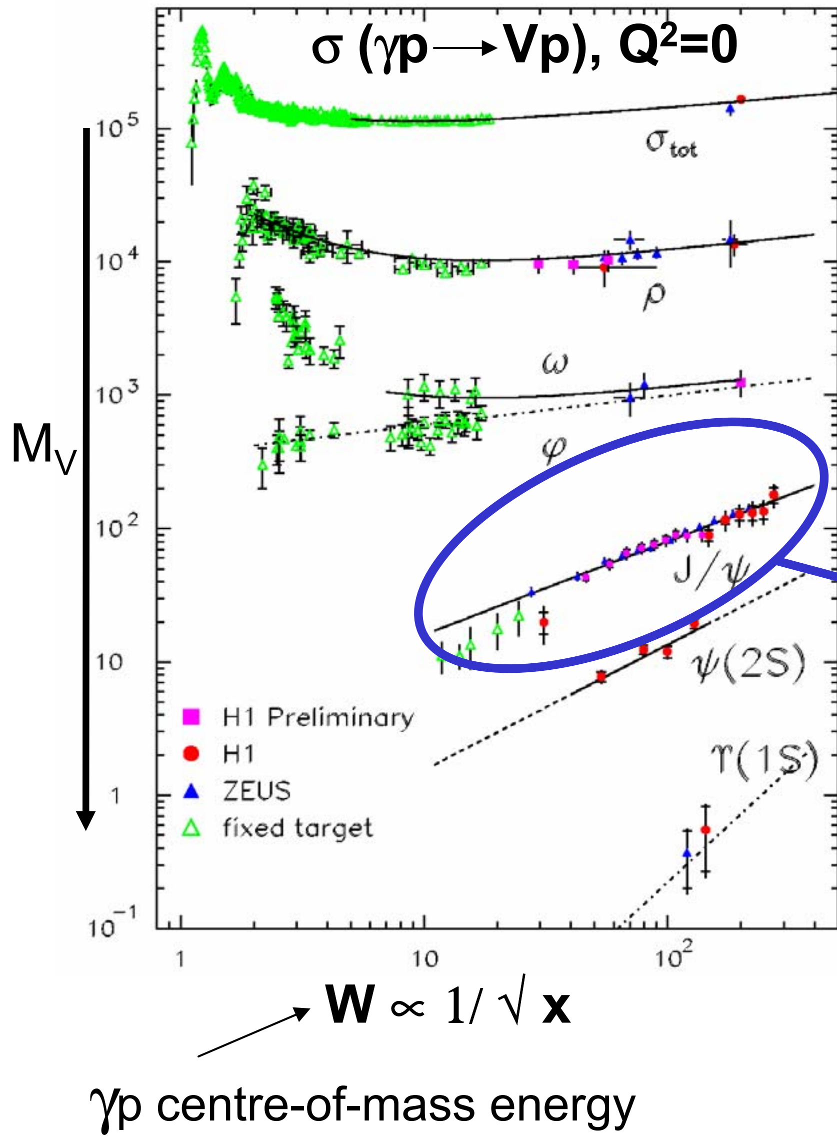
γp centre-of-mass energy

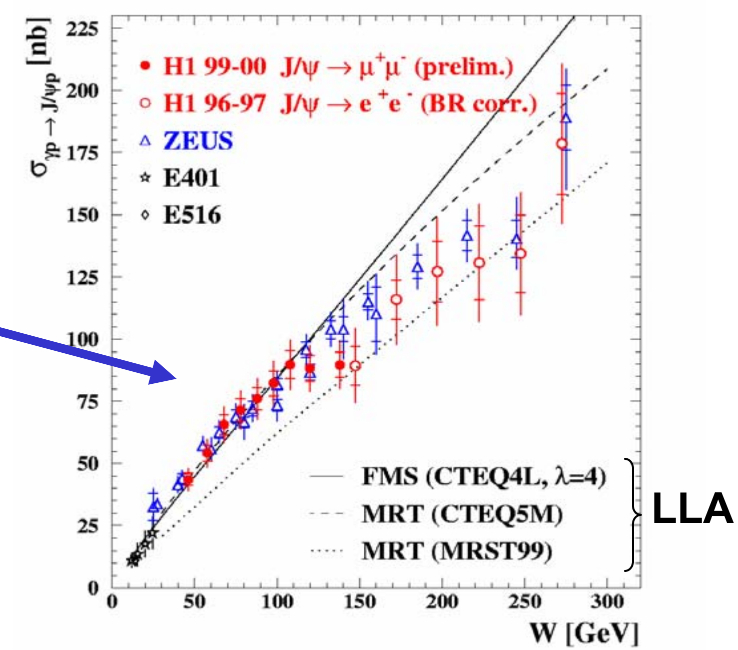
VM: sensitivity to gluons in proton

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

$$x = M_V^2 / W^2$$

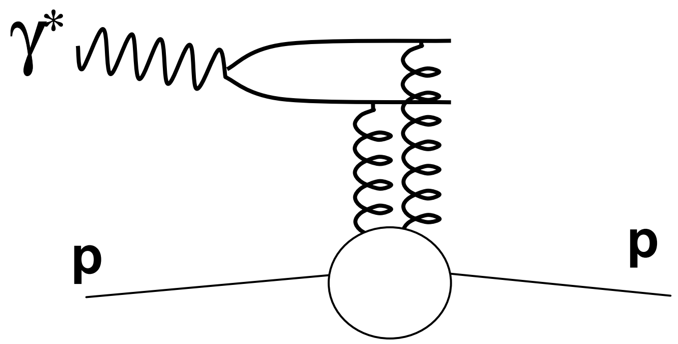






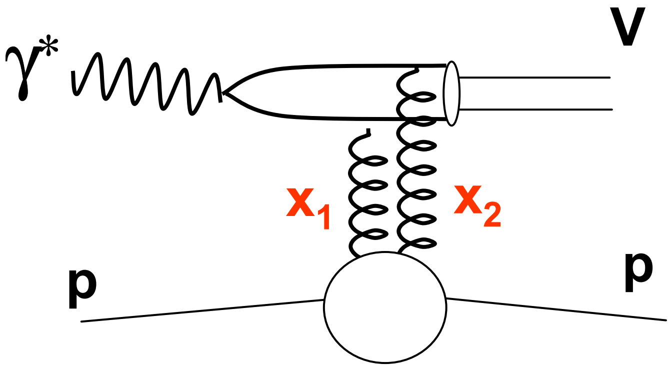
At large M_V, data well reproduced by pQCD

Take a closer look at:



Discover sensitivity to parton-parton correlations in the proton

Generalised PDFs (GPDs)



In general, $x_1 \neq x_2$:

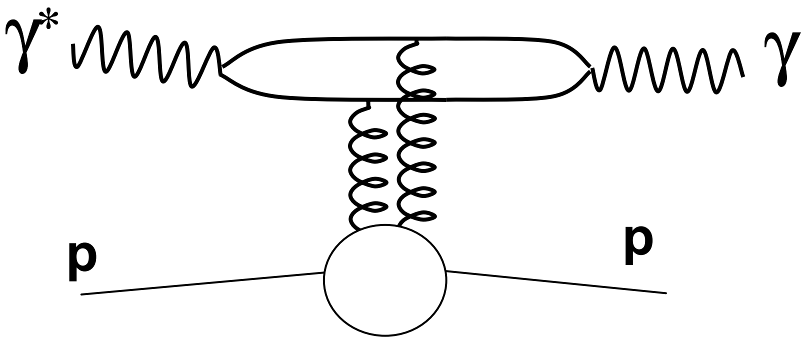
$$\sigma \propto [x\, g(x, \mu^2)]^2$$

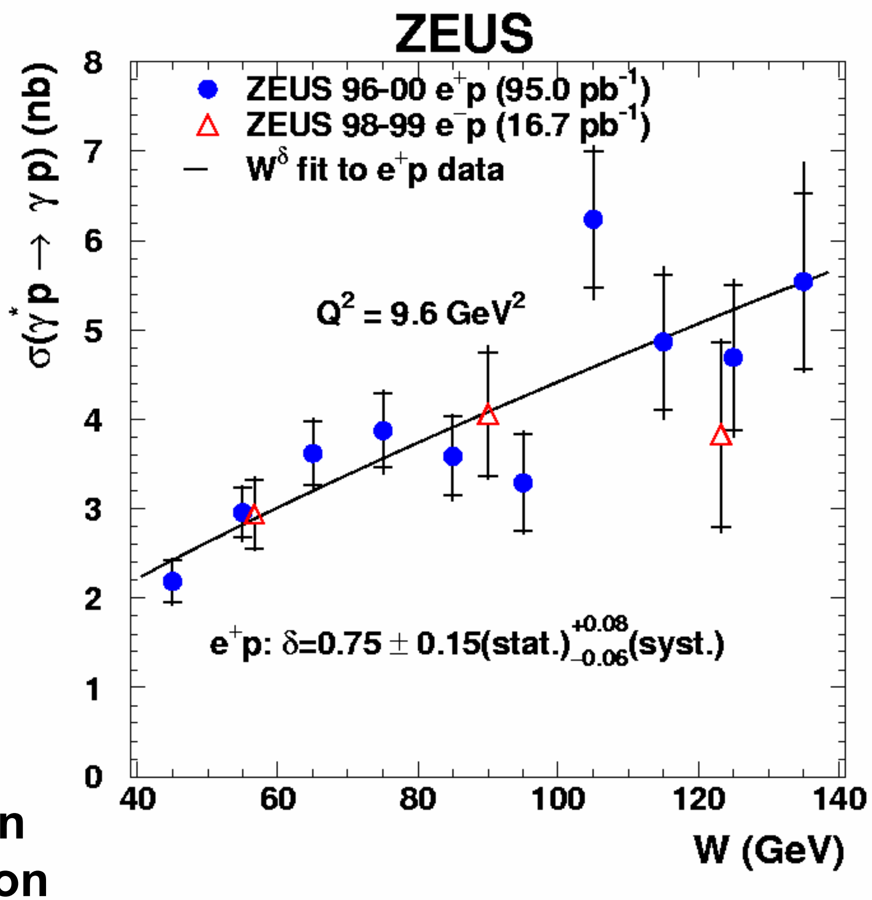
$$\sigma \propto [H(x_1, x_2, t, \mu^2)]^2$$

- <u>Generalised PDFs</u> (also non-diagonal, skewed PDF): sensitive to parton-parton correlations in the proton
- Related to probability of finding parton 2 with momentum x_2, conditional to having found parton 1 with momentum x_1
- t-dependence gives distribution of gluons in transverse plane (via Fourier transform) $\rightarrow$ correlate longitudinal and transverse degrees of freedom

Effect large for heavy vector mesons: factor ≈ 3 for Υ

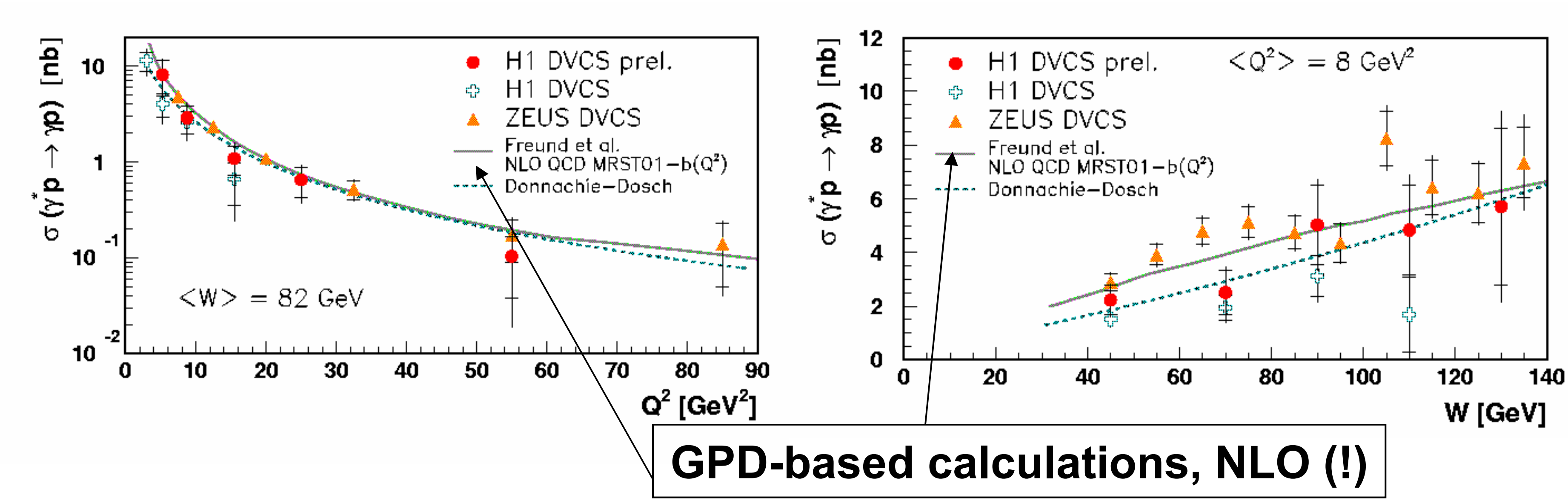
Deeply Virtual Compton Scattering





- Similar to elastic VM production, but γ instead of VM in final state
- No VM wavefunction involved
- Again rapid increase of cross section with W – a reflection of the large gluon density at low x

DVCS vs GPDs



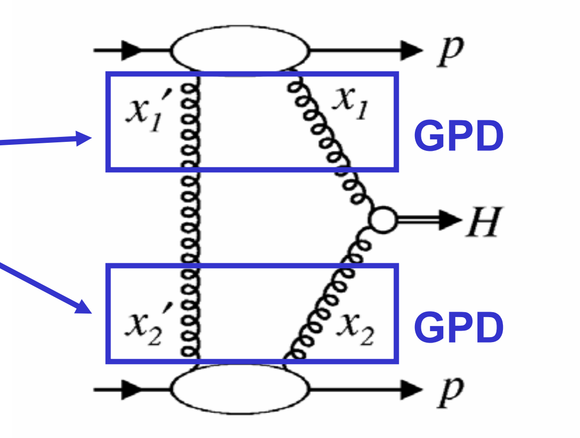
- **Sensitivity to GPDs (so far) in DVCS (large Q^2) and Υ production**
- **Effect is significant – factor 3 for Υ production**
- **A field in its infancy. Holds the promise of mapping parton-parton correlations and transverse distribution of partons in the proton**
- **Important to find how to extract GPDs from data**

Summary I

- **Hard diffraction sensitive to proton structure and calculable in QCD**

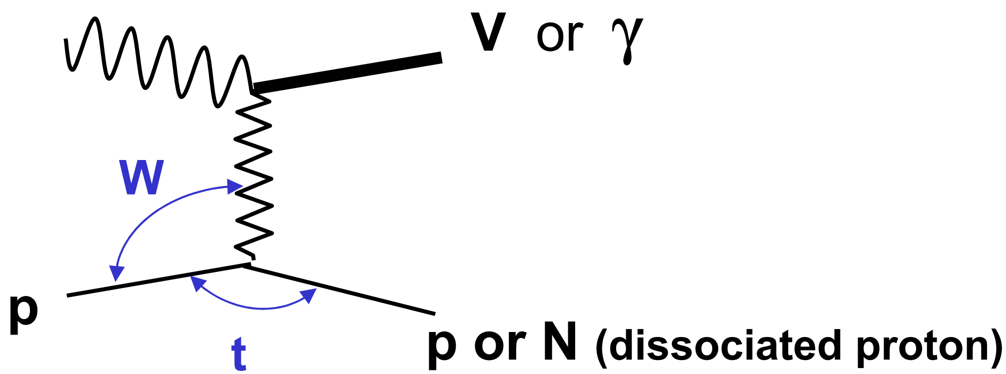
- **Hard diffraction sensitive to parton correlations and transverse distribution of partons in proton via GPDs**

- **Ingredient for estimating diffractive cross sections at LHC**

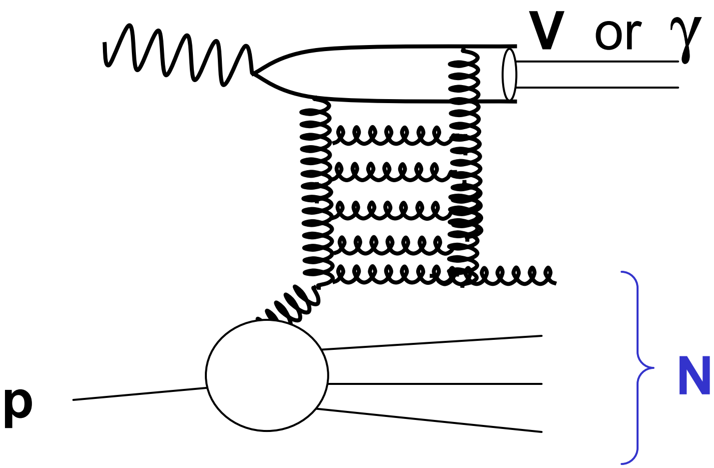


- **In this workshop: how do we extract GPDs from data ? How can HERA results be fed into LHC calculations ?**

Part II:
BFKL in high-t vector mesons and photons



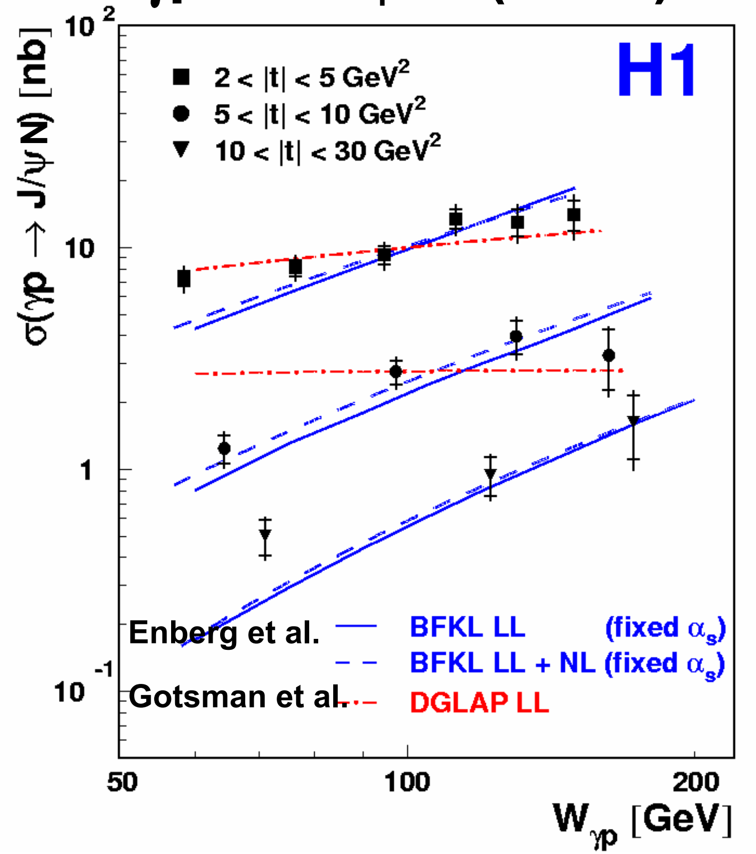
Large |t|



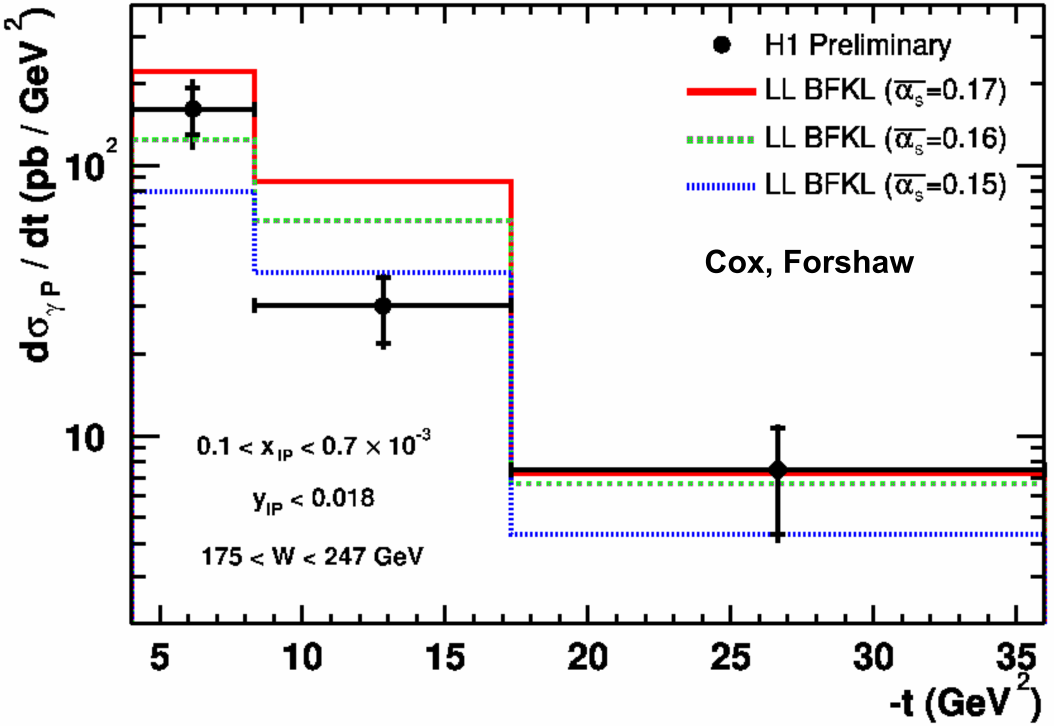
- At large |t| (but |t|<< W^2), this is testing ground for BFKL
  [resum powers of type $\alpha_s^n \ln^n(W^2/|t|)$]
- cf gaps between jets
- Since |t| large, proton mostly dissociates

BFKL in high-|t| vector mesons and photons

$\gamma p \rightarrow J/\psi \; N \; (Q^2=0)$



$\gamma p \rightarrow \gamma N \; (Q^2=0)$

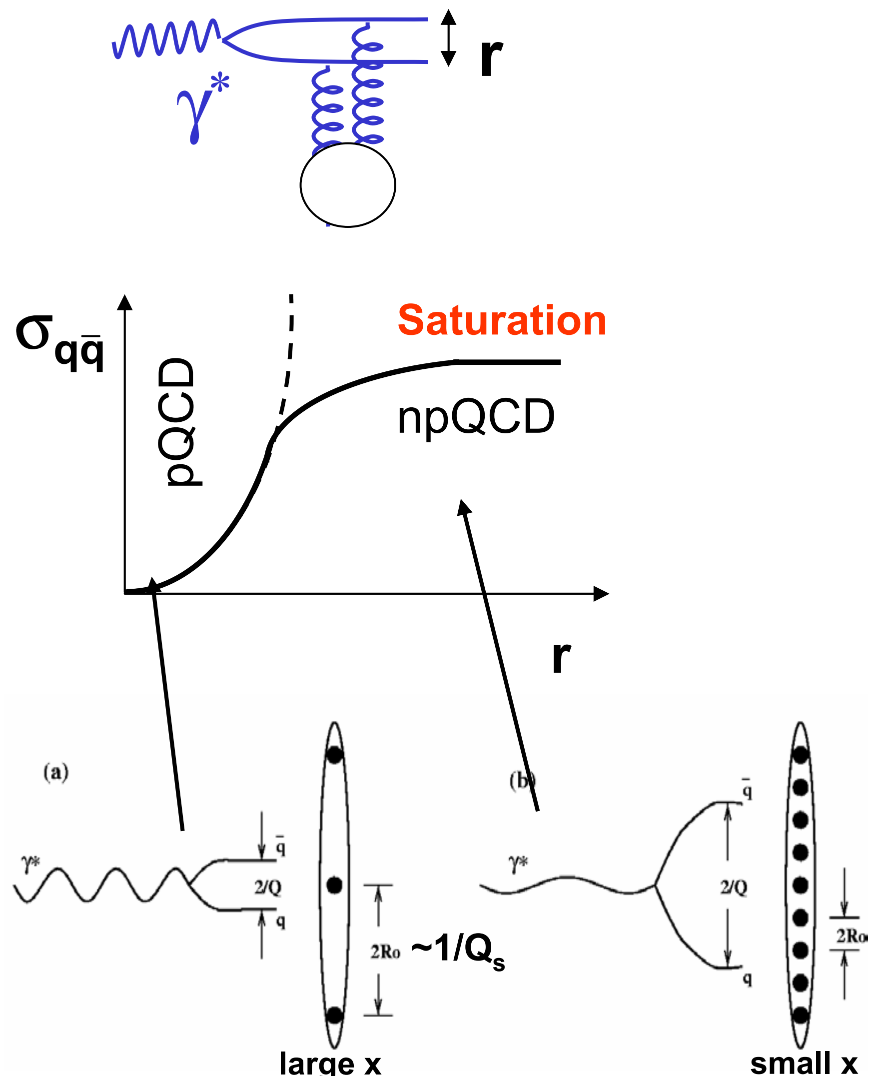


- BFKL-based models reproduce the trend of the data – but NLO missing
- cf also light vector meson production at high-|t| (but more of a challenge)
- cf also gaps between jets
- Relevant for understanding low-x structure of proton !

Part III: saturation

(how dense is the proton at low x ???)

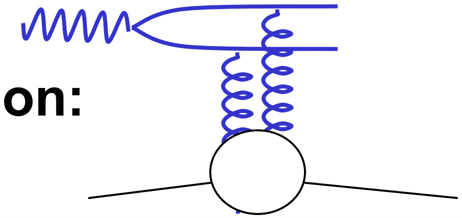
- pQCD: $\sigma_{q\bar{q}} \propto r^2 \propto 1/Q^2$
  (colour transparency)
- As $Q^2 \rightarrow 0$, $\sigma_{q\bar{q}} \rightarrow \infty$
  violation of unitarity
- Growth tamed by $\sigma_{q\bar{q}}$ saturating
  at $\sigma_{q\bar{q}} \approx \sigma(\rho p)$
- Saturation occurs at
  "saturation scale"
  $Q_s^2(x) \propto [xg(x)] \propto (x_0/x)^\lambda$
  with $x_0 \approx 10^{-4}$, $\lambda \approx 0.3$
  (proton denser at small x)
- Connection to high-density QCD,
  saturation of parton densities,
  Colour Glass Condensate,
  geometric scaling, physics of RHIC



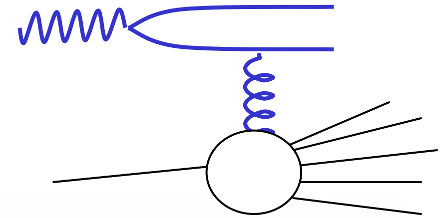
cf talks by S. Munier, D. Kharzeev, C. Marquet

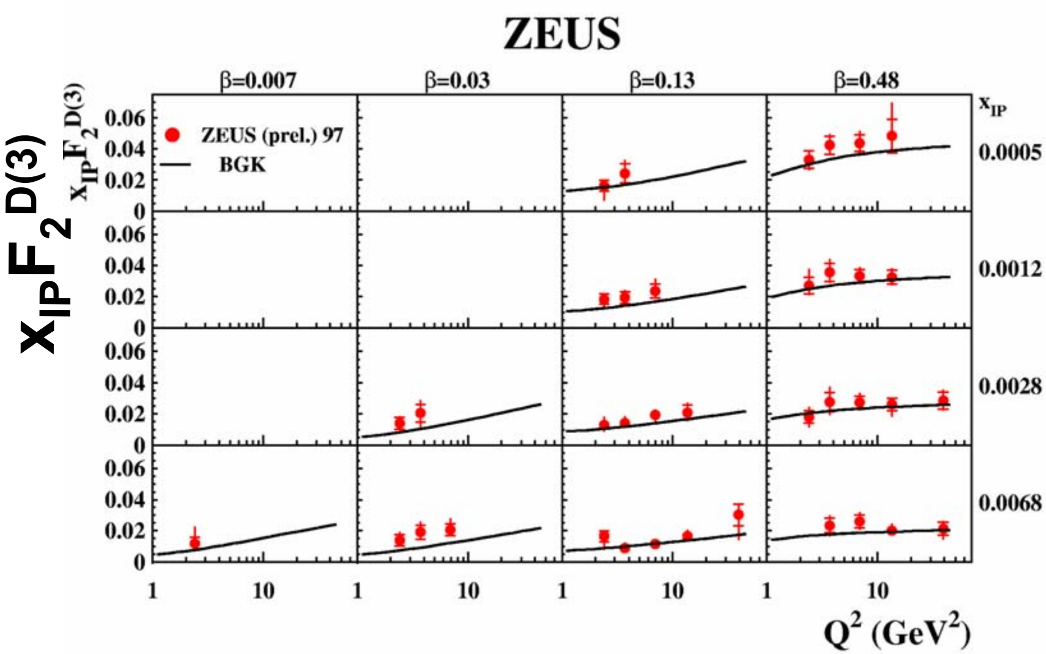
Saturation vs data

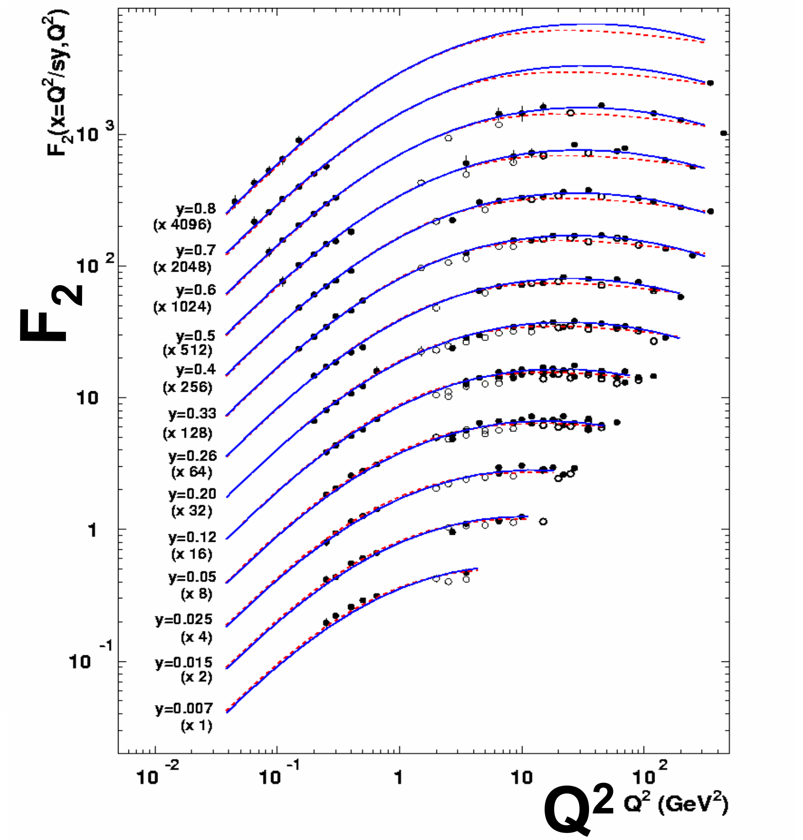
Inclusive diffraction:



Inclusive DIS:







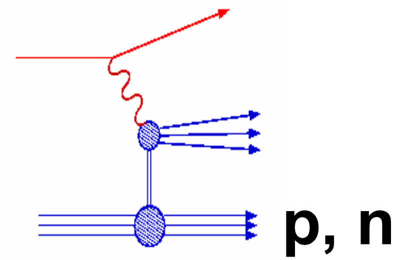
Diffraction more sensitive to saturation than inclusive: mainly probe intermediate dipole sizes, close to saturation

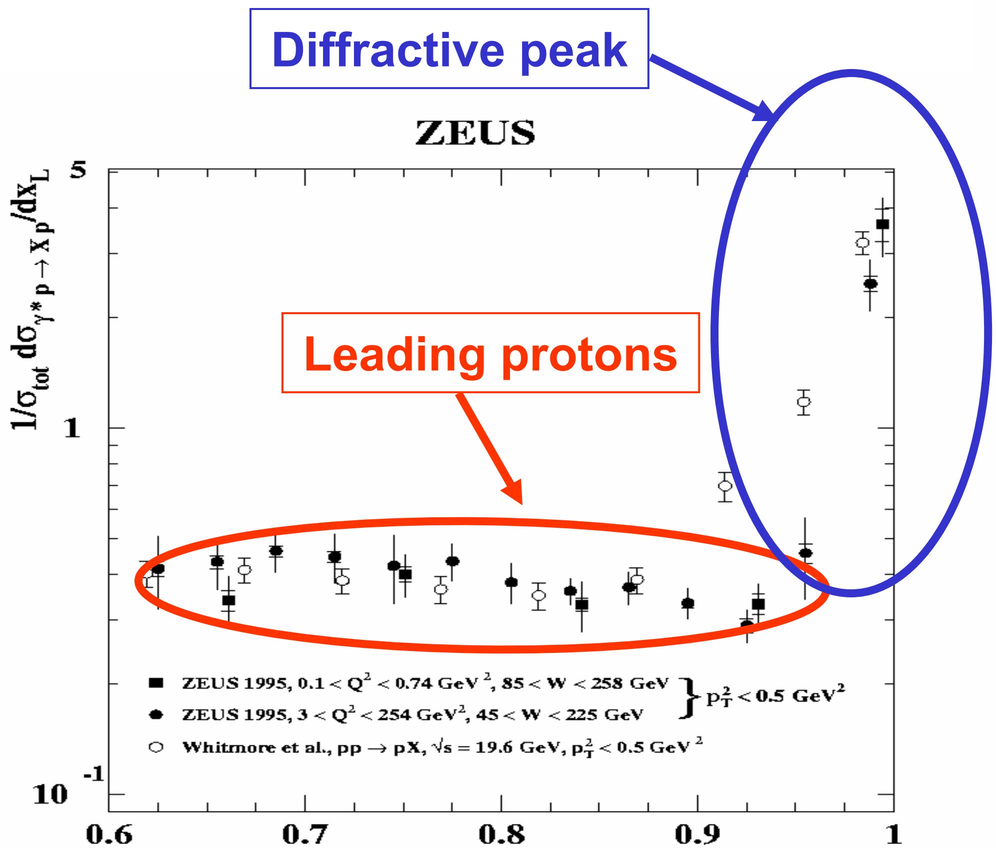
Also good description of VM, DVCS...

Golec-Biernat,Wuesthoff,
Bartels, Golec-Biernat, Kowalski

Part IV: Leading Baryons

Events with a fast proton (outside the diffractive peak) or a fast neutron





$x_L = P'/P_{beam}$

- Longitudinal and transverse momentum spectra measured
- Not described by 'standard' hadronisation packages, eg Jetset (Lund)
- How to extrapolate to LHC ?

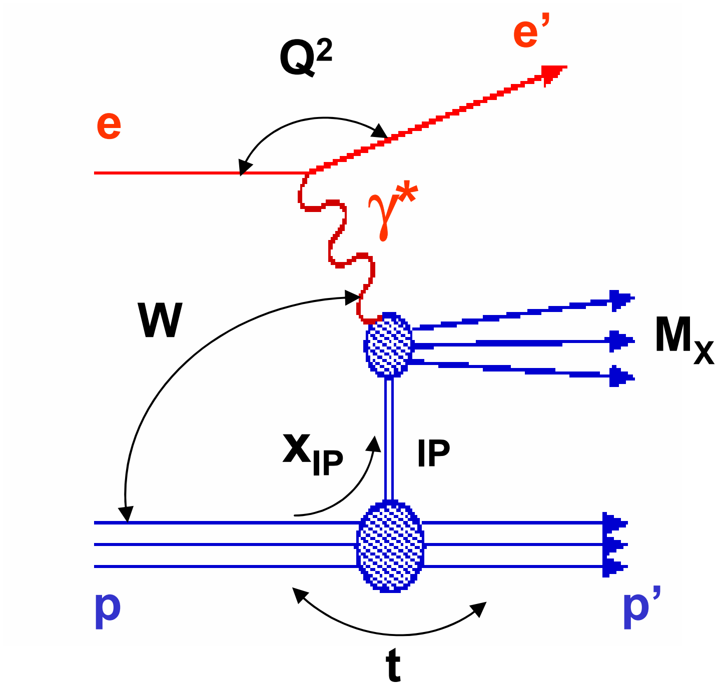
talk by G. Iacobucci
in MC session

Grand summary

- Diffraction is due to the exchange of partons *from the proton* carrying the vacuum quantum numbers
  $\rightarrow$ probe diffractive PDFs of the proton (mainly gluons)
- Hard scattering factorisation works in diffractive DIS events (but rescattering corrections to go from ep to pp, $p\bar{p}$)
- Diffraction with a hard scale calculable in QCD
- Sensitivity to gluon density, correlations in proton (GPDs)
- Sensitivity to BFKL evolution
- Saturation: a window on high-density QCD
- Leading proton and neutron data available for LHC simulations
- All above based on <100 pb^{-1} – expect $\approx$ factor 10 more data at HERAII (+long. e polarisation)
- This workshop: how can these data be turned into input for LHC ?

RESERVE

Diffractive PDFs



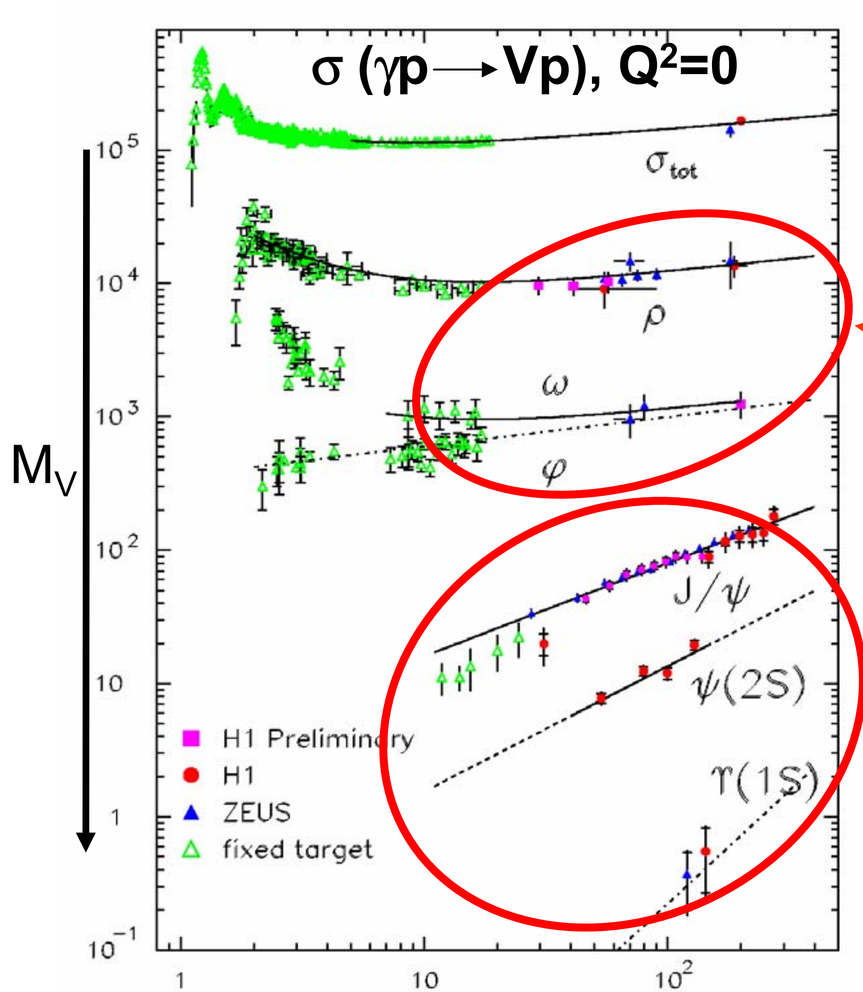
Rather than IP exchange: probe diffractive PDFs of proton

A new type of PDFs, with same dignity as standard PDFs. Applies when vacuum quantum numbers are exchanged

***$f_{i/p}^{D}(z,Q^2,x_{IP},t)$*: probability to find, with probe of resolution Q^2, in a proton, parton *i* with momentum fraction *z*, under the condition that proton remains intact, and emerges with small energy loss, x_{IP}, and momentum transfer *t* – diffractive PDFs are a feature of the proton**

cf. F.-P. Schilling's talk

VM: sensitivity to gluons in proton

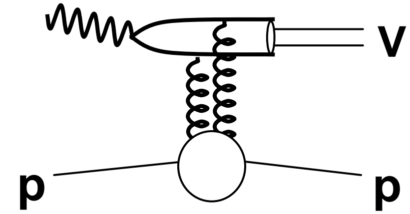


$\mathbf{W} \propto 1/\sqrt{\mathbf{x}}$

γp centre-of-mass energy

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

$$x = M_V^2 / W^2$$

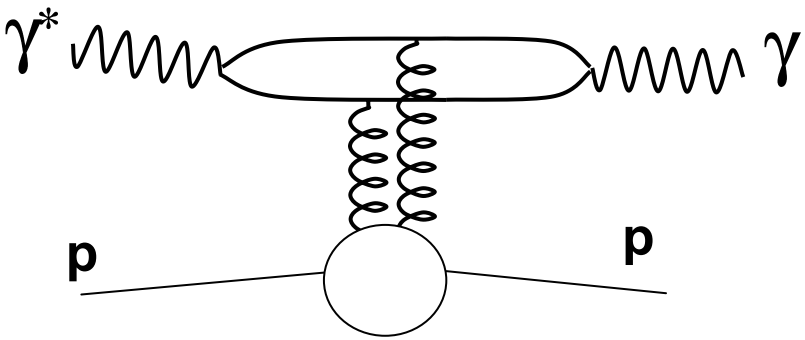


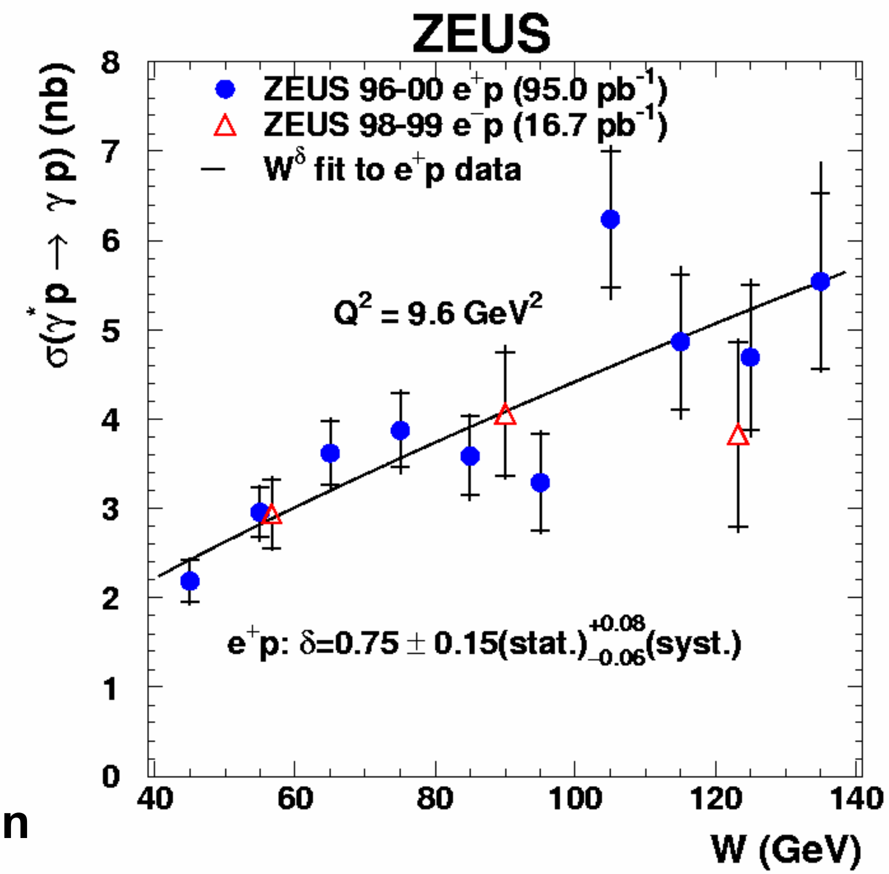
•At small M_V ($M_V^2 \approx 1$ GeV²):
Incoming dipole behaves like a normal-size hadron: the two exchanged gluons are soft – cf $\sigma_{tot}(\gamma p)$

Flat σ vs W reflects flat "gluon distribution" for $Q^2 \to 0$ (better: flat F_2)

•At large M_V :
Fast growth of σ with W reflects growth of gluon distribution with decreasing x

Deeply Virtual Compton Scattering



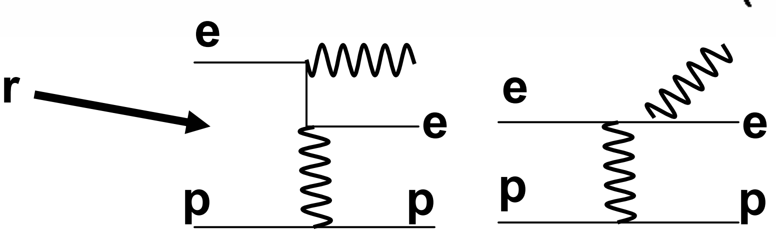


- Similar to elastic VM production, but γ instead of VM in final state

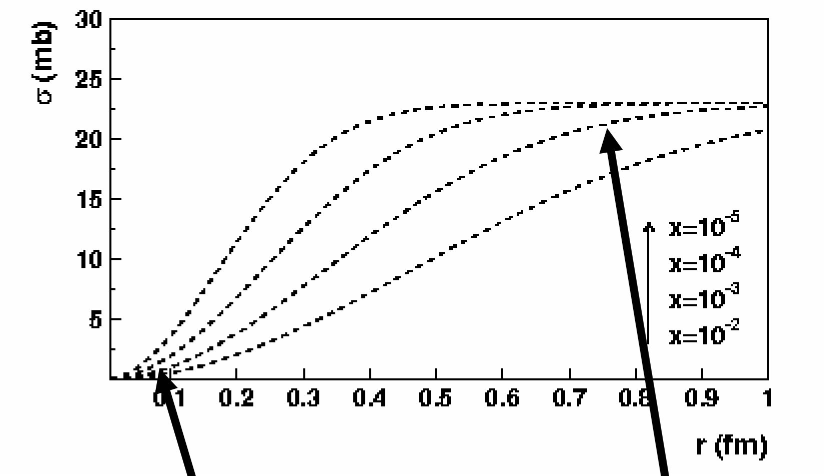
- No VM wavefunction involved

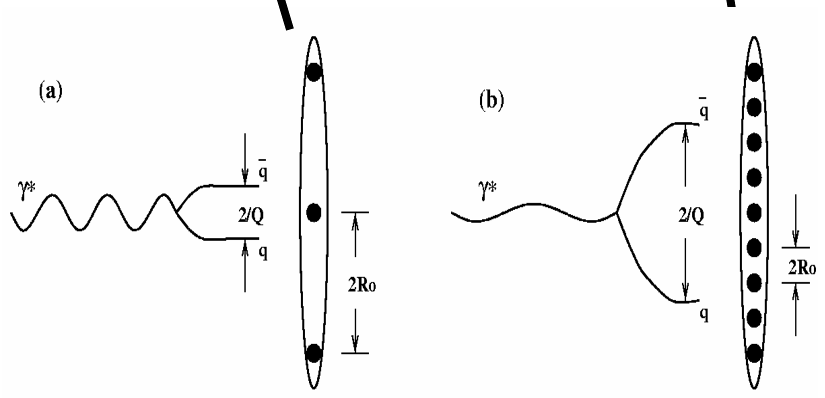
- Again rapid increase of cross section with W

- Same final state as QED Bethe-Heitler
$\rightarrow$ interference
$\rightarrow$ access to real part of amplitude



Saturation in the proton (II)





$$\sigma^{Diff} \propto \int d^2r dz \left|\Psi_\gamma(r,z)\right|^2 [\sigma_{q\bar{q}}(r,z)]^2$$

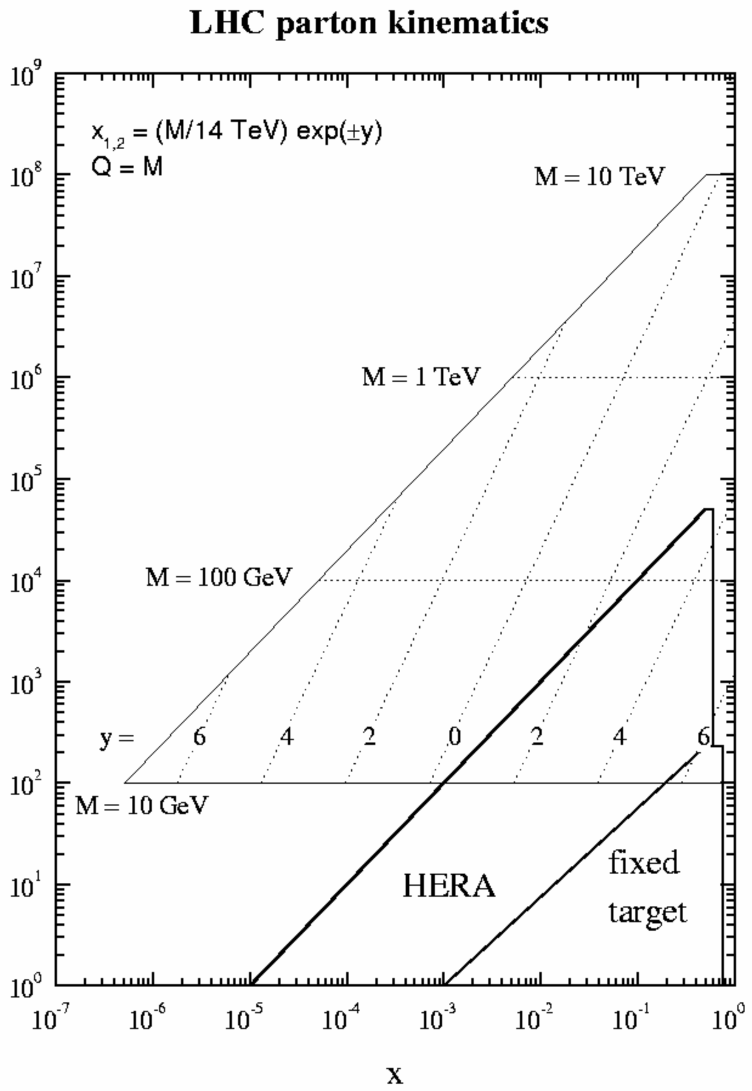
Photon wave-function

$$\sigma^{tot} \propto \int d^2r dz \left|\Psi_\gamma(r,z)\right|^2 \sigma_{q\bar{q}}(r,z)$$

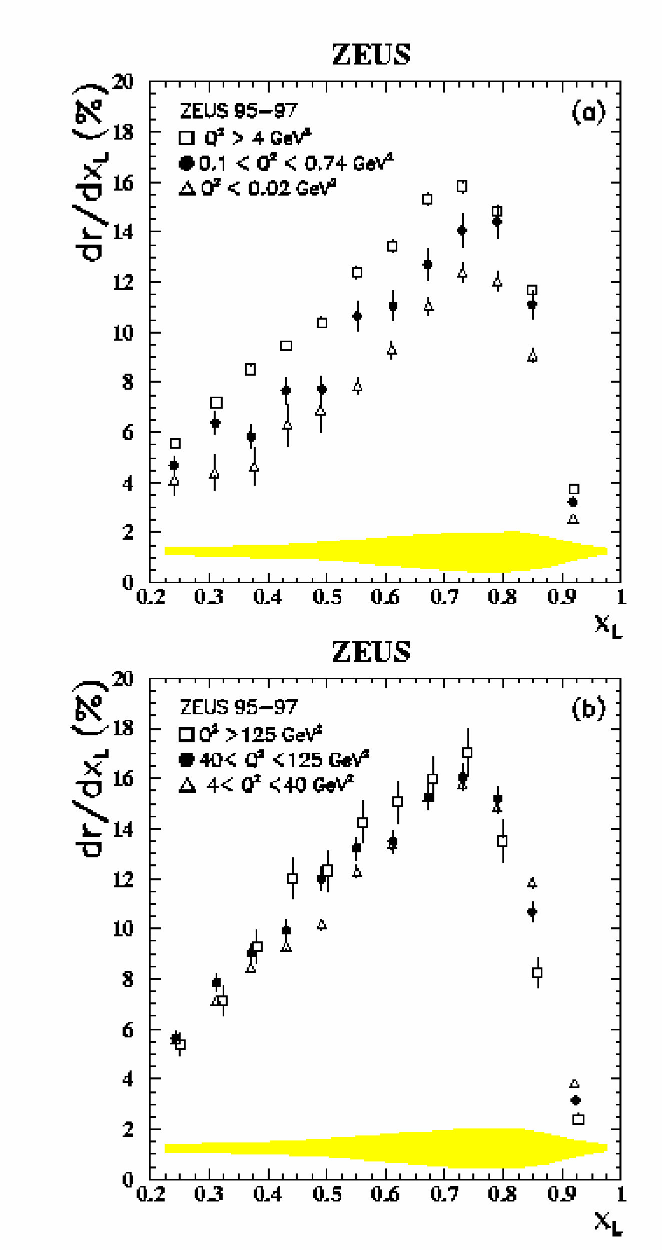
NB: σ^{Diff} more sensitive to saturation than σ^{tot}:

σ^{Diff} mainly probes intermediate dipole sizes, close to saturation region, r>Q/2, with r<Q/2 suppressed by extra power of Q^2

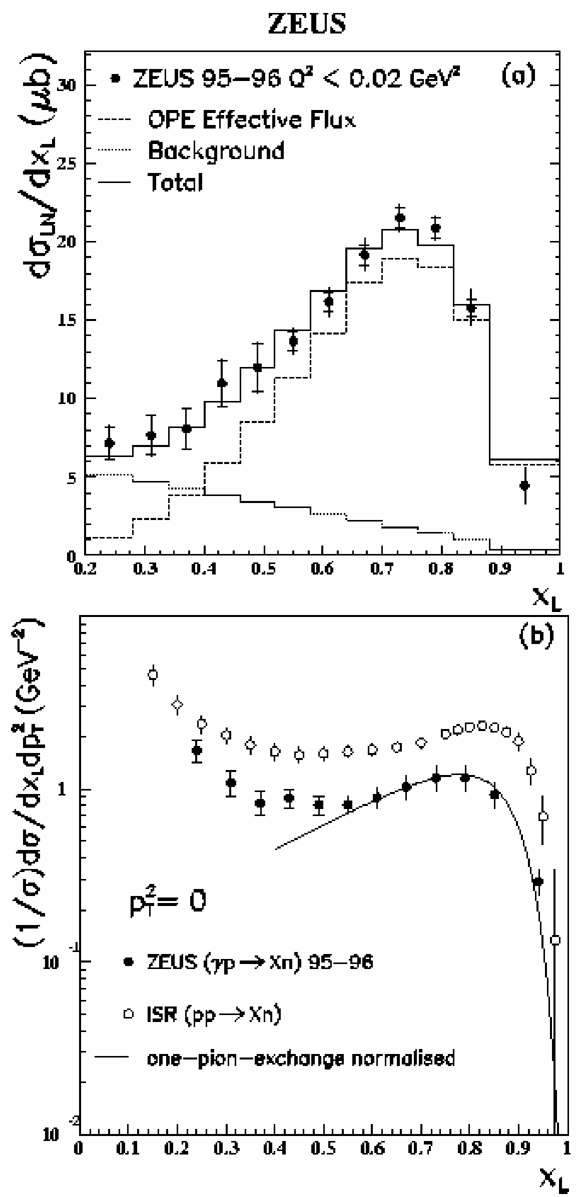
Diffractive Higgs production at LHC



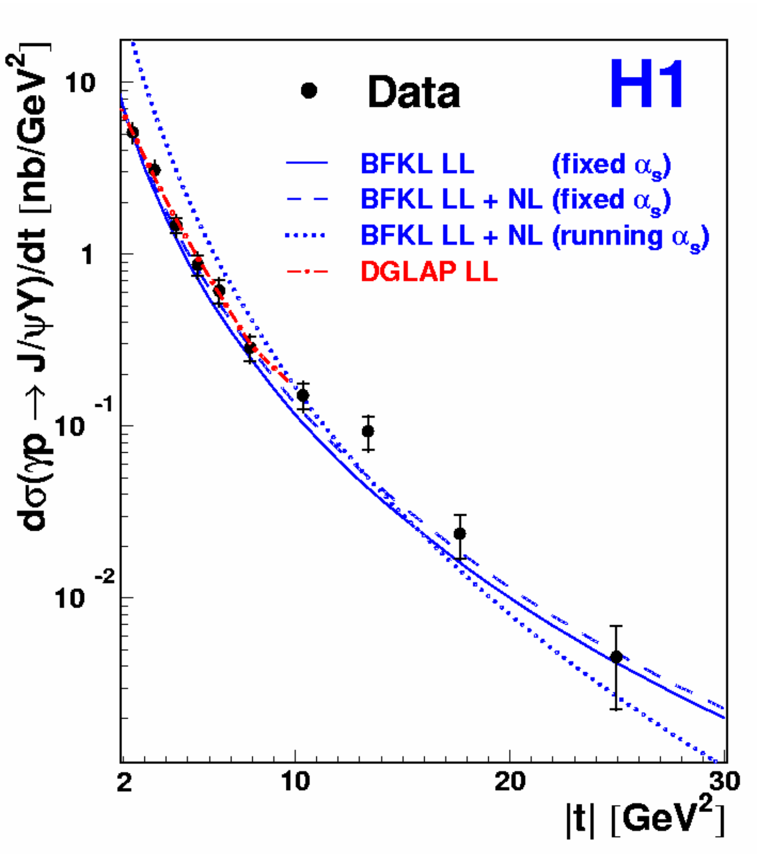
Leading neutrons

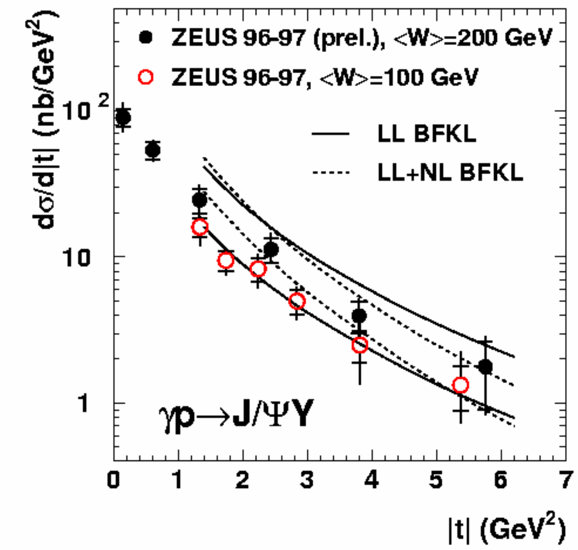


Leading neutrons



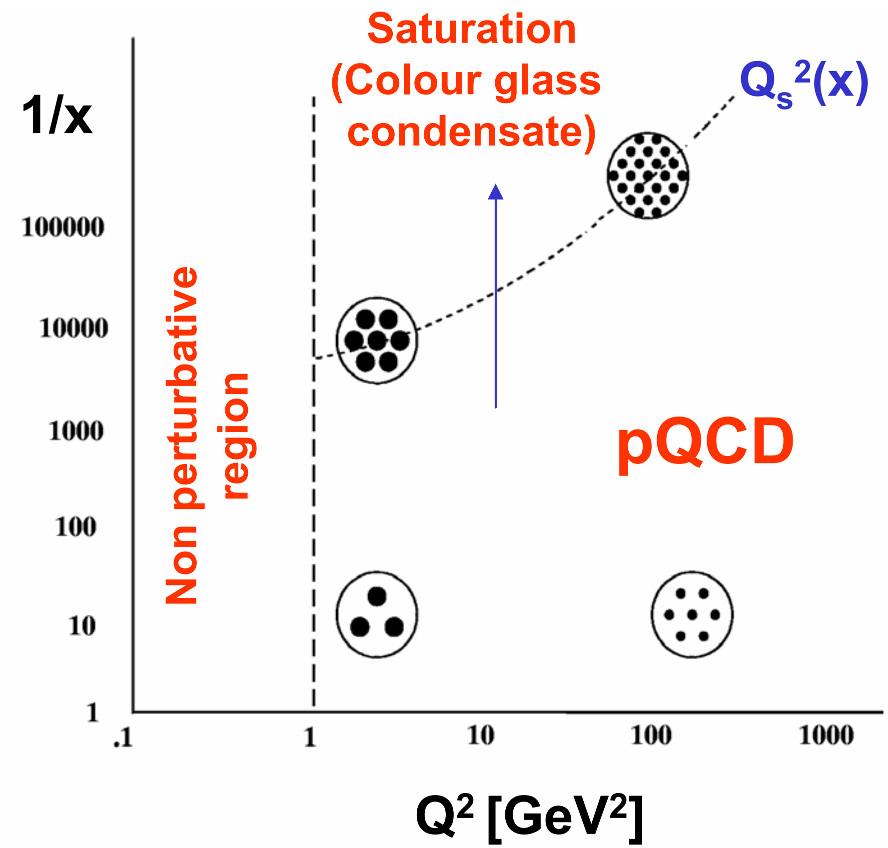
High-|t| VM and DVCS vs BFKL





Part III: Transition pQCD↔npQCD: *saturation*

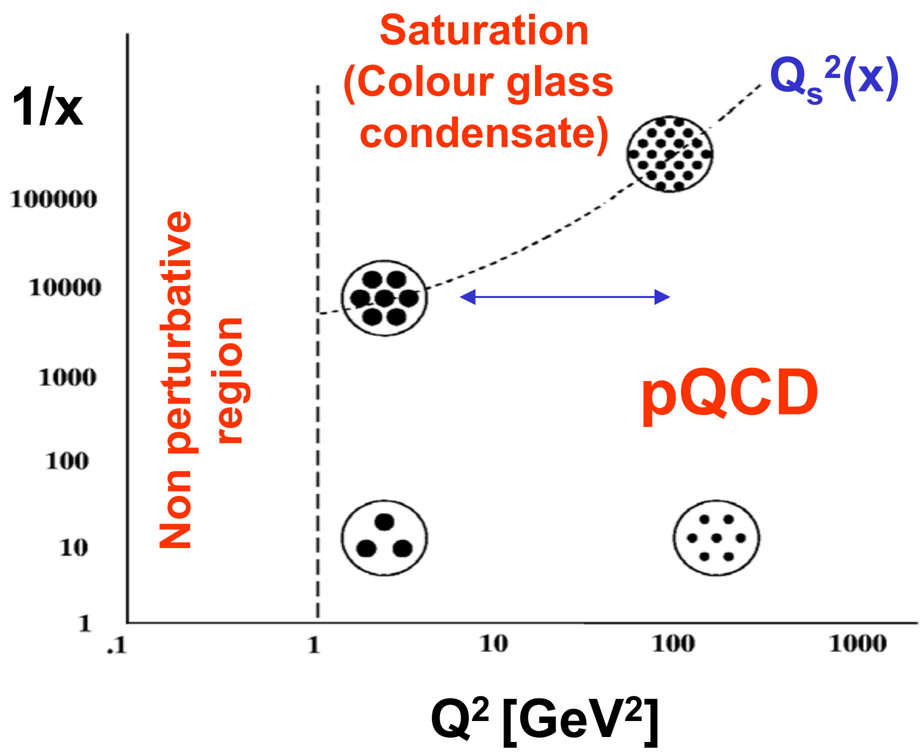
- When $x \rightarrow 0$ at Q^2 > a few GeV^2 DGLAP predicts steep rise of parton densities
- At small enough x, this violates unitarity [Gribov, Levin, Ryskin, 1983, Mueller, Qiu, 1986, …]
- Growth is tamed by gluon fusion $\rightarrow$ *saturation* of parton densities a $Q^2=Q_s^2(x)$
- Gluon fusion $\propto [xg(x,Q^2)]^2 \propto F_2^D$!!



- Test transition to high-density QCD (cf RHIC, EIC, LHC…)
- So far, no compelling evidence in the proton (seen in nuclei ??)

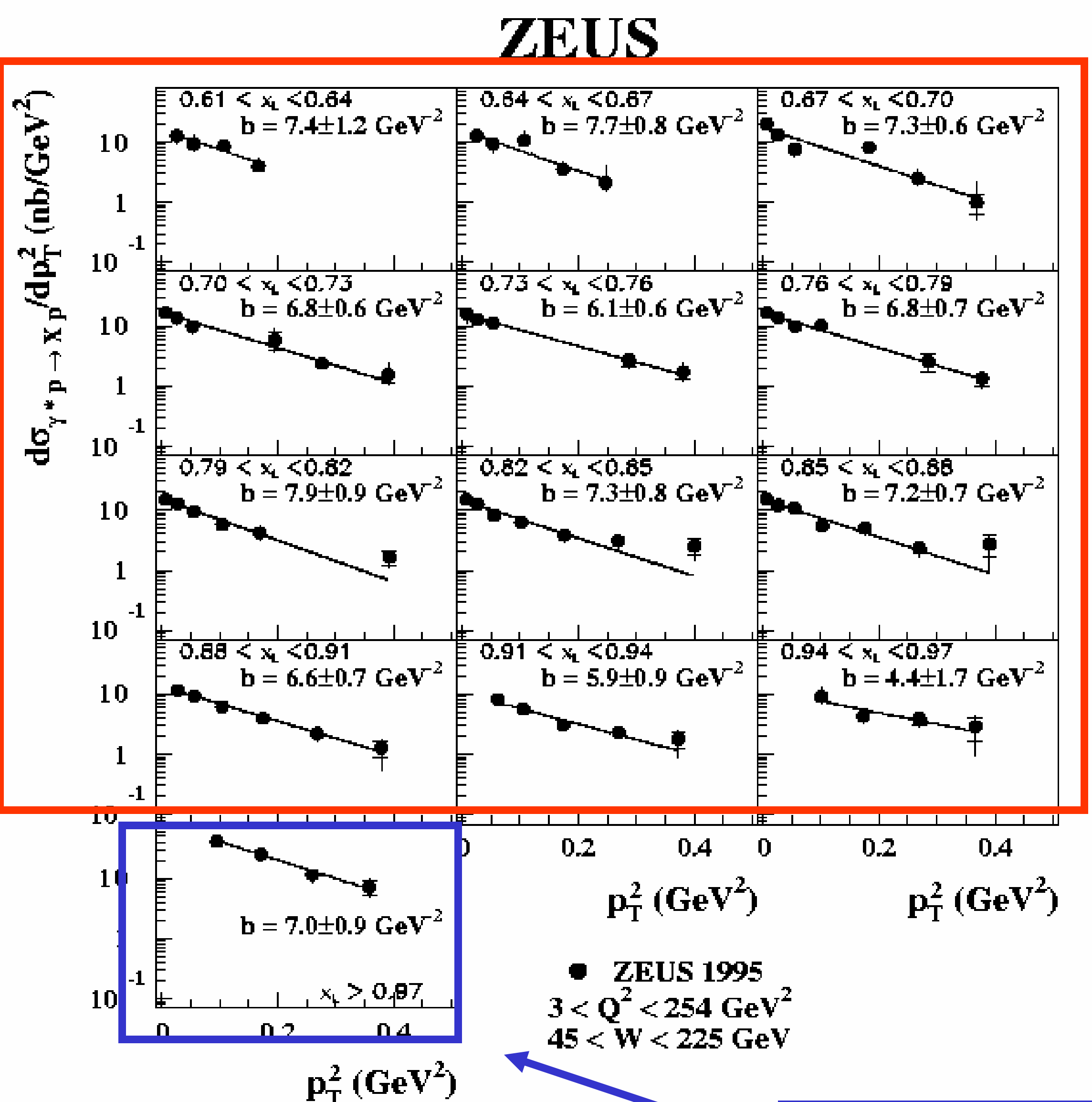
Summary III

- Saturation: a glimpse of the transition pQCD↔ npQCD; connection to high-density QCD, colour glass condensate, physics of RHIC



- How can this be turned into useful input for LHC ?

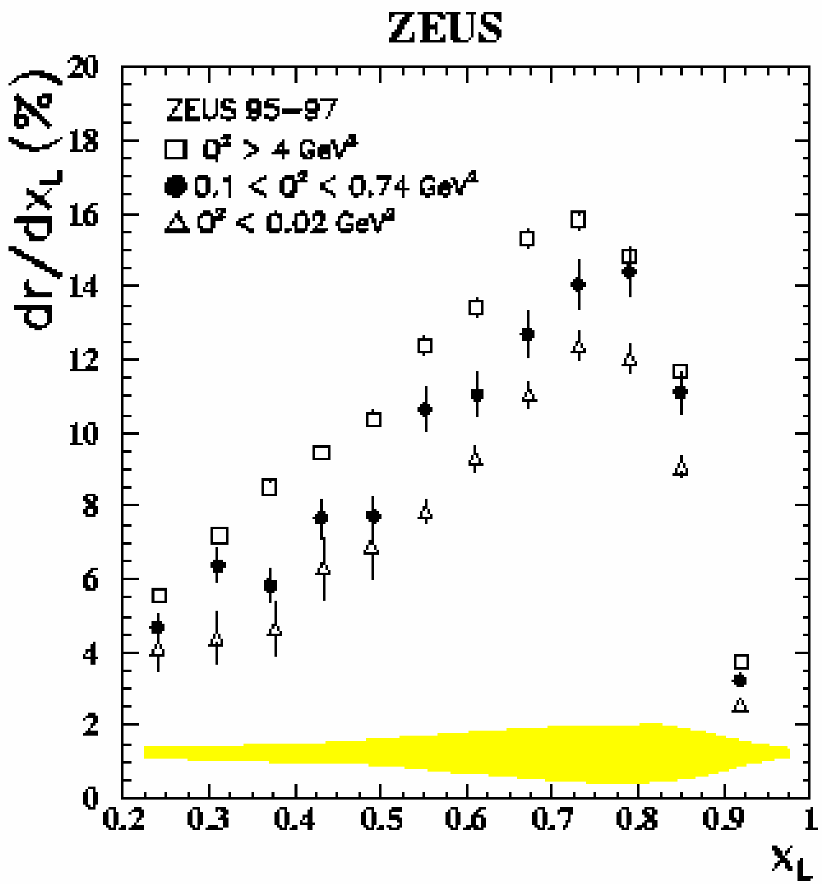
Leading protons

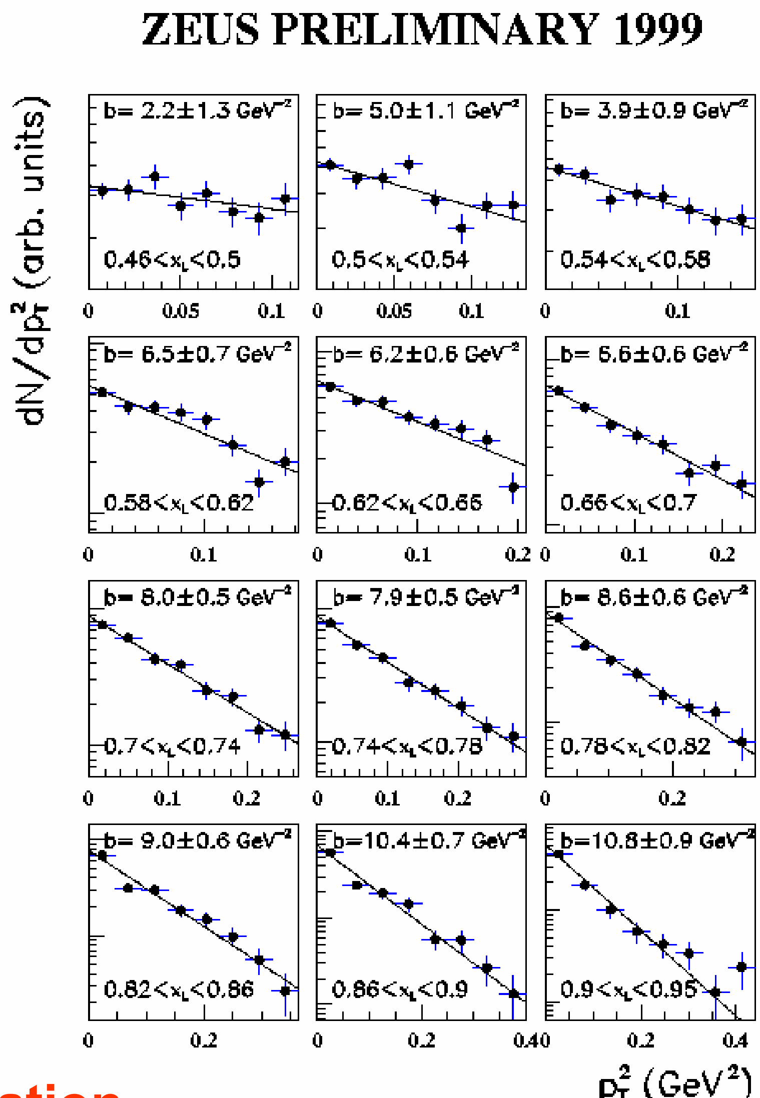


Diffractive peak

- Leading proton transverse momentum spectra measured
- Leading proton transverse momentum spectrum also not described by 'standard' hadronisation packages
- Specific models ok (eg Regge based)
- How to extrapolate to LHC ?

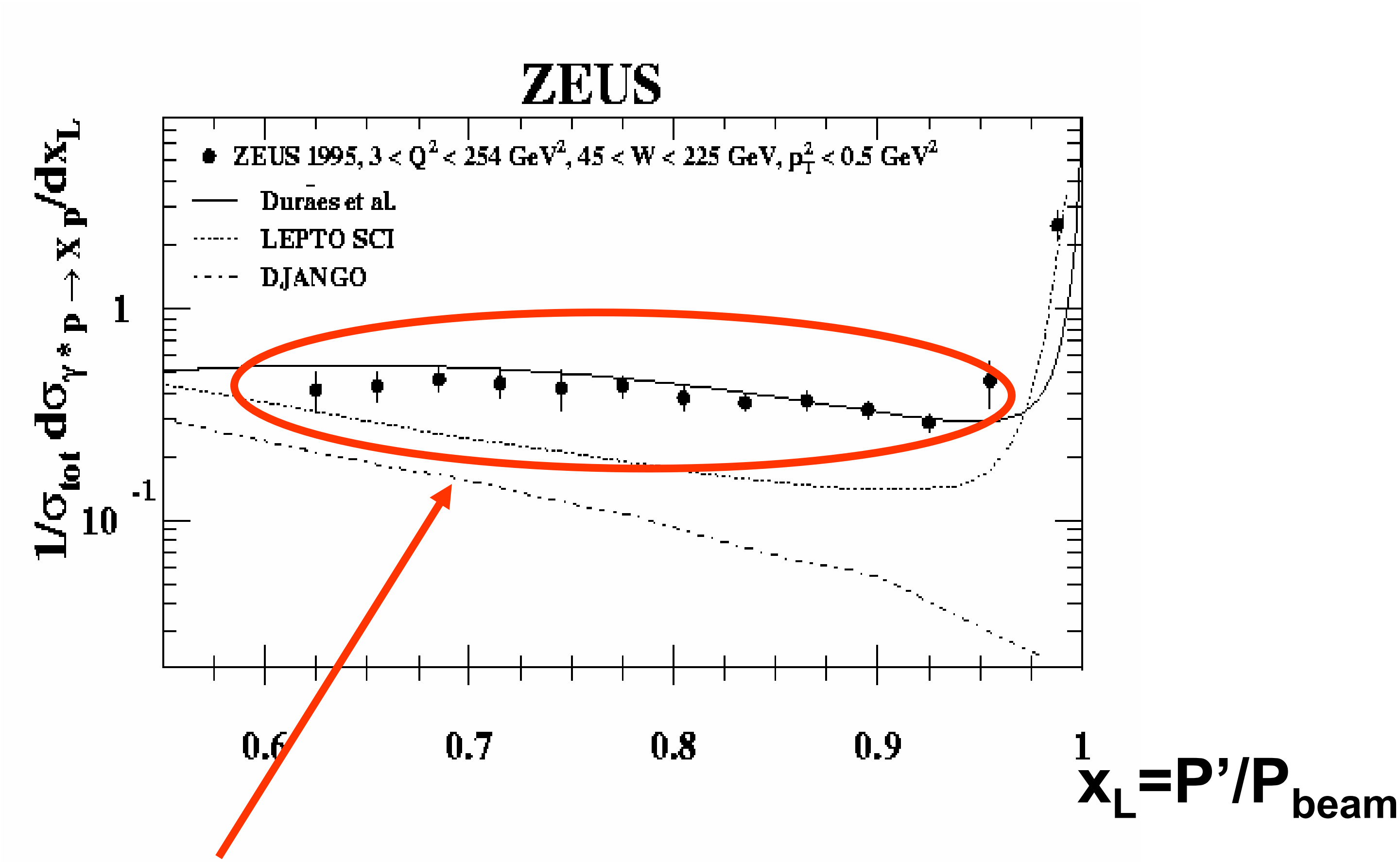
Leading neutrons





- **Leading neutron spectra measured at HERA**
- **Not described by ‘standard’ hadronisation packages**

Leading protons



- Leading proton longitudinal momentum measured at HERA
- Spectrum not described by 'standard' hadronisation packages, eg Jetset (Lund)
- Specific models ok (eg Regge based)
- How to extrapolate to LHC ?

DVCS

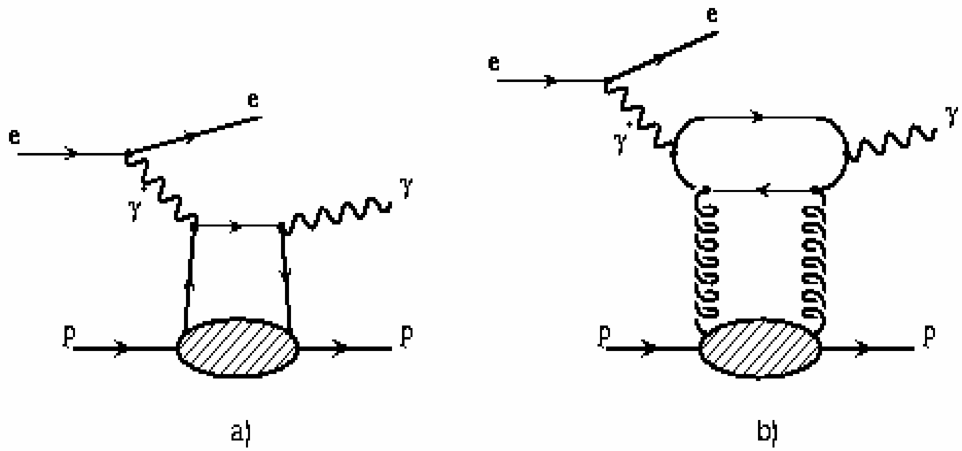


Figure 2: *The two leading DVCS diagrams in a QCD picture.*

DVCS

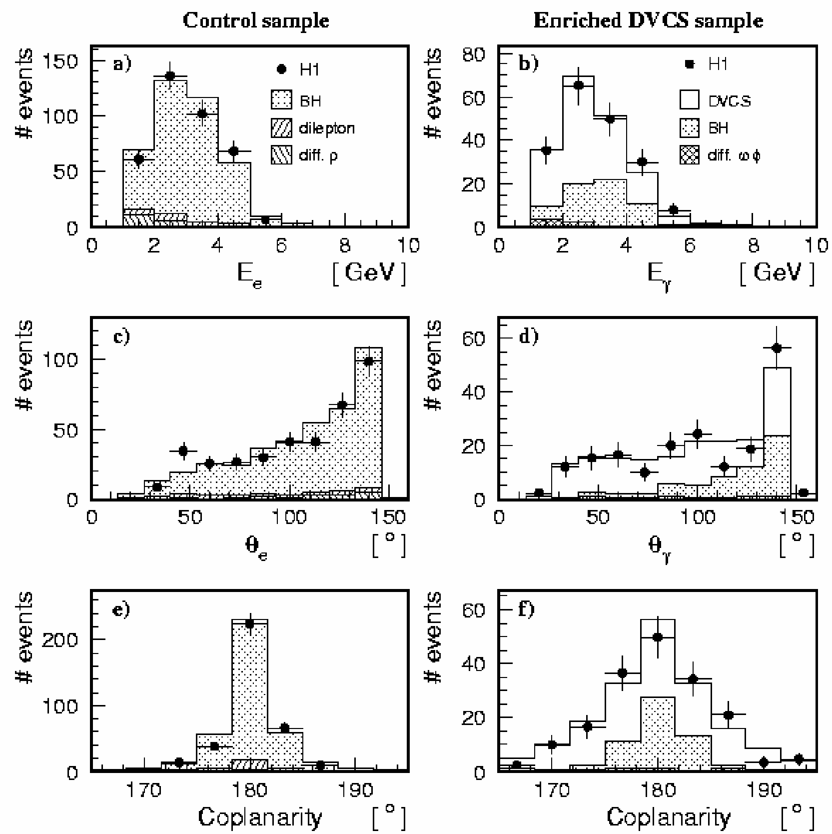


Figure 3: *Event distributions of the control sample (left) and of the enriched DVCS sample (right). a-b) energy of the cluster in the LAr calorimeter, c-d) polar angle of the cluster in the LAr calorimeter, e-f) coplanarity, i.e. difference of the azimuthal angle of the positron and photon candidates. The error bars on data points are statistical. Control sample: the cluster in the LAr calorimeter corresponds to the positron candidate. The data are compared to the sum of the predictions for the Bethe-Heitler process, elastic dilepton production and diffractive ρ production. All predictions are normalised to luminosity. Enriched DVCS sample: the cluster in the LAr calorimeter corresponds to the photon candidate. The data are compared to the sum of the predictions for the $e^+p \to e^+\gamma p$ reaction according to FFS, added to ω and ϕ diffractive backgrounds. The backgrounds and the BH contribution (shown on top of the backgrounds) are normalised to luminosity whereas the DVCS prediction is normalised in such a way that the sum of all contributions is equal to the total number of events.*

DVCS

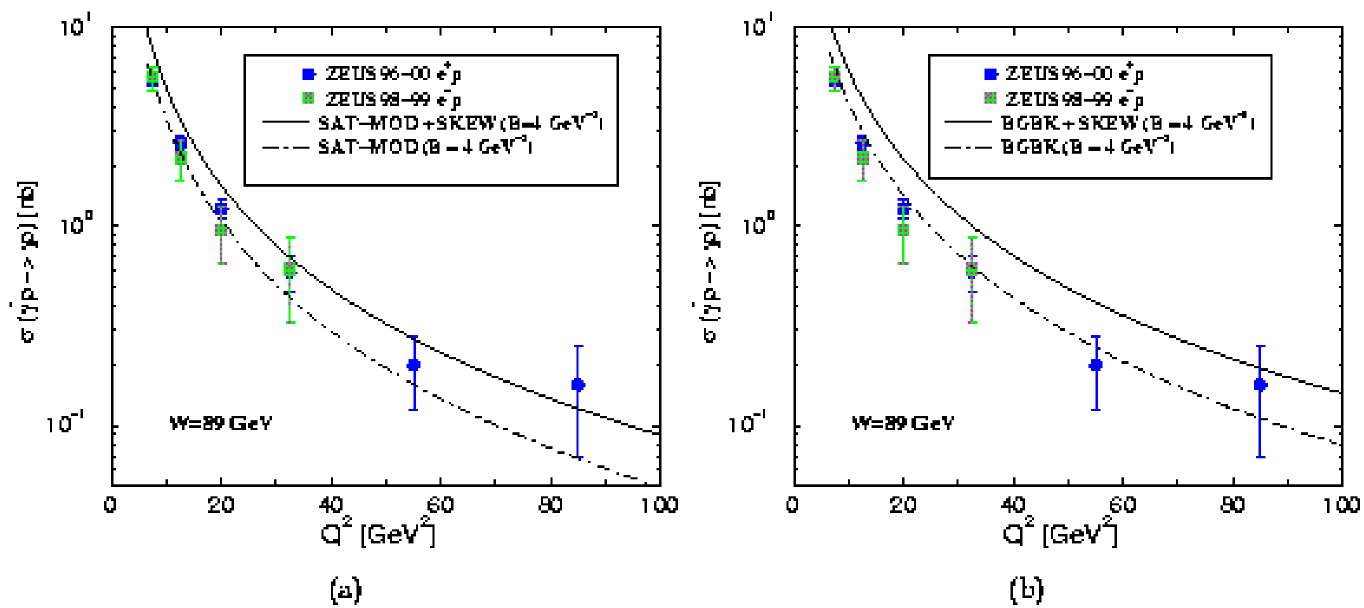


FIG. 3: The results for the (a) saturation model with (full) and without (dot-dashed) skewedness effect and (b) BGBK model, with (dot-dashed) and without (full) skewedness effect for a fixed $B = 4$ GeV^{-2}.