Exclusive results at HERA

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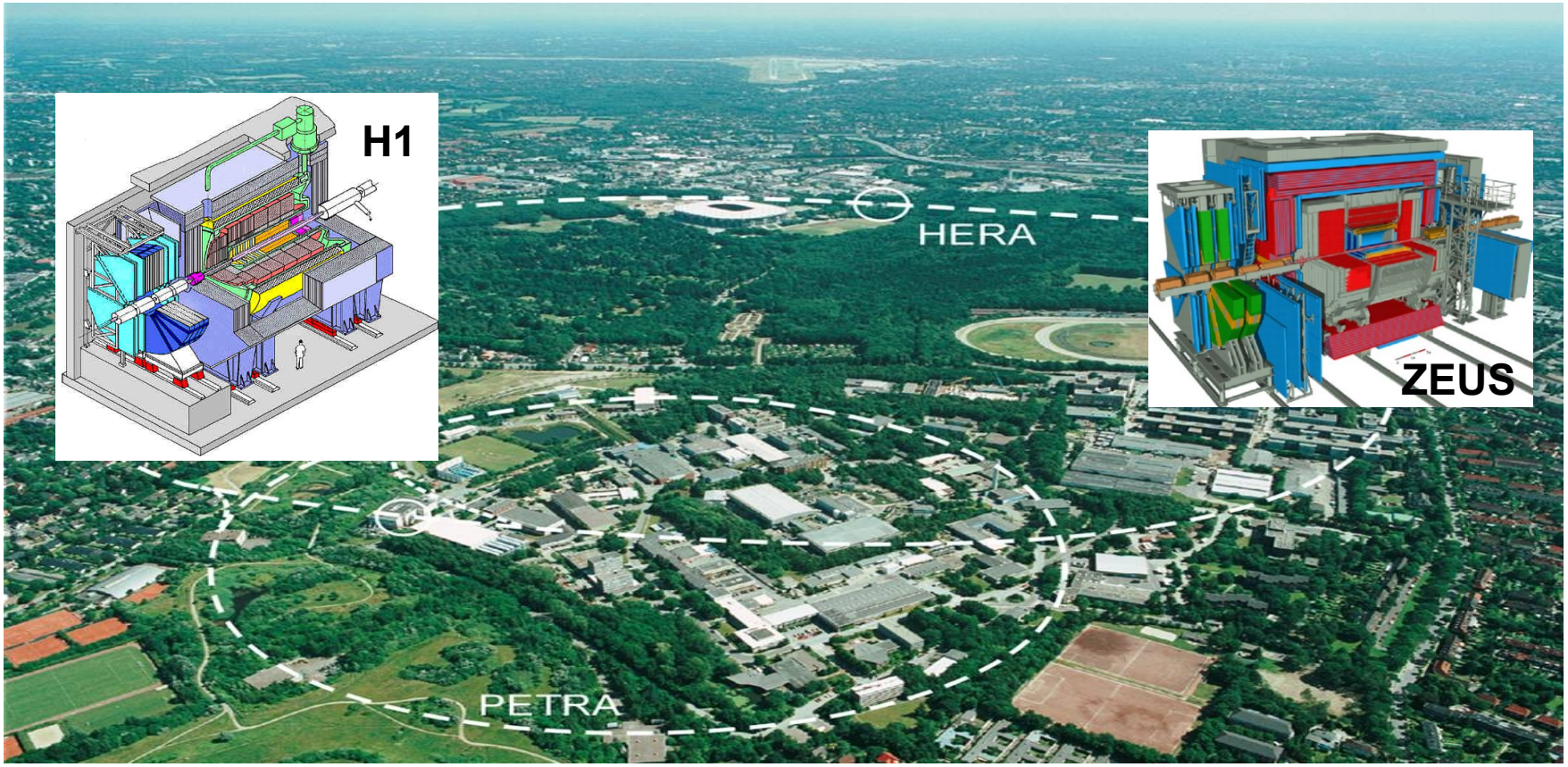
- on behalf of H1 and ZEUS Collaborations

HESZ, Nagoya, 9-12 September 2015

HERA ep collider 1992 – 2007, DESY, Hamburg

- **The world's only electron/positron-proton** collider
- **Ee = 27.6 GeV, Ep = 920 GeV** (820, 460, 575 GeV)
- **total luminosity ~ 0.5 fb^{-1} per experiment**

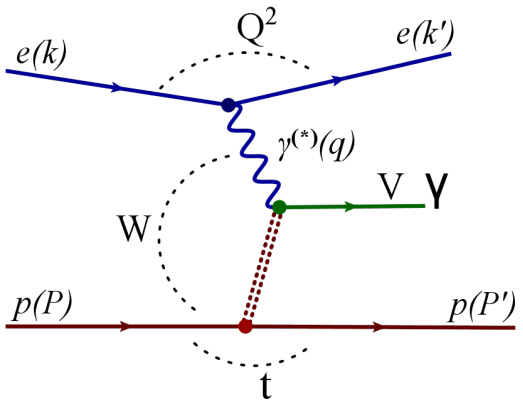


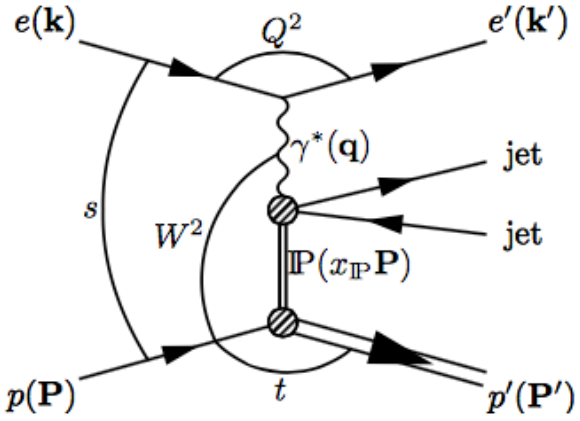
Overview

At HERA exclusive production of VMs, photons (Deeply Virtual Compton Scattering, DVCS) and dijets has been investigated

- A quick revue
- Recent results from H1 and ZEUS:
  - ψ' / J/ψ ratio [ZEUS prel-14-003 and prel-15-003]
  - ρ^0 photoproduction with a leading neutrons [H1 DESY-15-120]
  - Exclusive dijet production [ZEUS, arXiv:1505.05783v1]

Exclusive processes – kinematic variables





Exclusive production of Vector mesons 1^{--} ($\rho,\omega,\Phi,J/\psi,\psi',\Upsilon$), photons, or jets:

Q^2 photon virtuality, [0-100 GeV^2]

W photon-proton centre-of-mass energy [20-300 GeV]

$t=(p-p')^2$ – four momentum transfer squared at proton vertex [$-t<30$GeV^2]

x–Bjorken – fraction of proton's momentum carried by struck quark, $x=Q^2/(Q^2+W^2)$ [10^{-2}-10^{-4}]

For jets

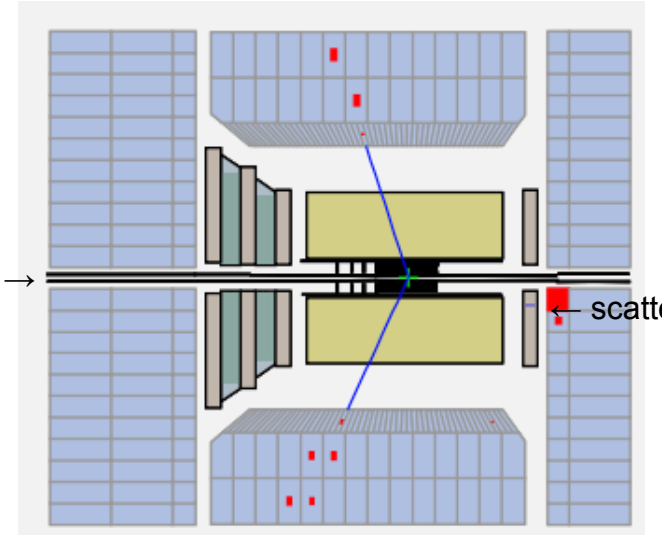
$x_{\mathbb{P}}$ – fraction of proton's momentum carried by exchanged colour singlet

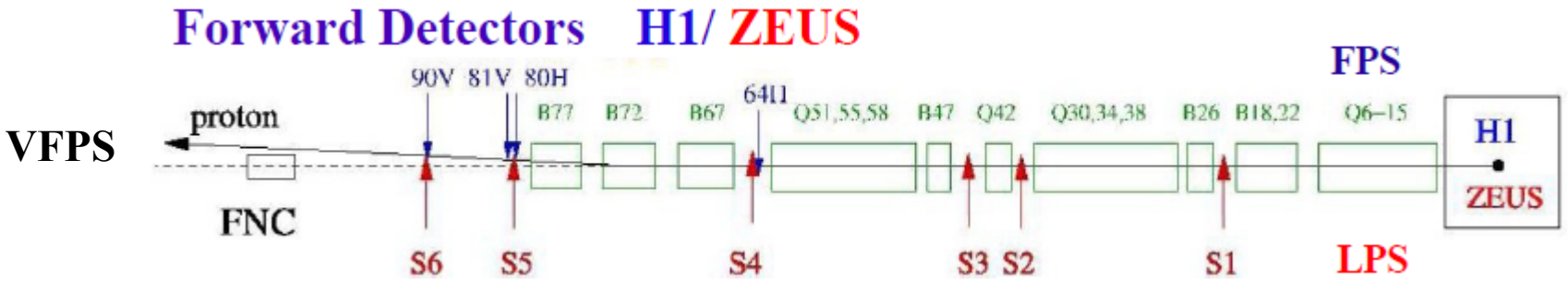
Exclusive processes - experimental methods

Exclusive processes are very clean experimentally

Kinematic variable fully reconstructed, usually measuring scattered electron (in DIS) and vector meson decay products or f nal photons or jets.

Scattered p detected with lower acceptance



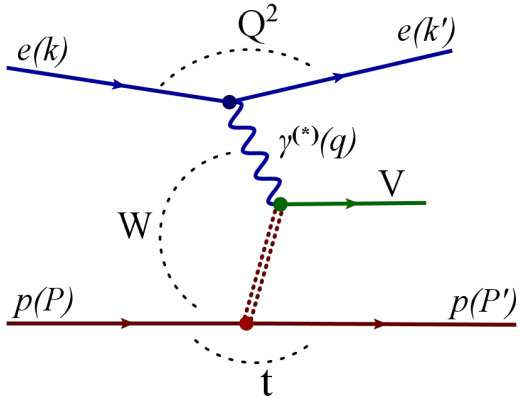


DVCS and Vector Meson production - models

- Soft physics:

  Vector Dominance Model,

  Regge theory



- Same energy dependence of $\sigma_{\gamma p}$

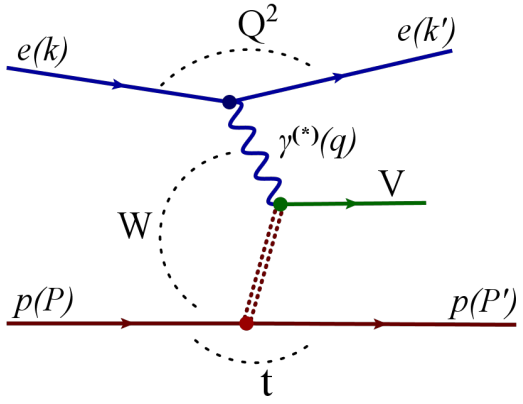
- At the start of HERA, it looked not very promising …

DVCS and Vector Meson production - models

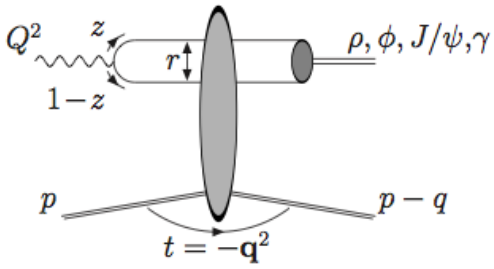
- Soft physics:

  Vector Dominance Model,

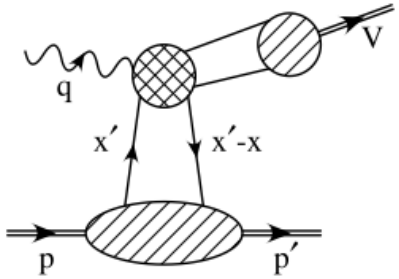
  Regge theory



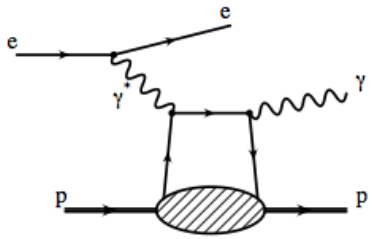
In presence of a hard scale (M_{VM}, Q^2, t) calculations in pQCD are possible...



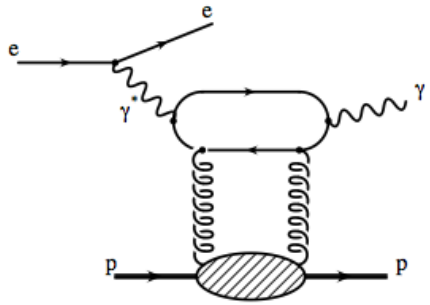
Dipole approach



GPDs



LO

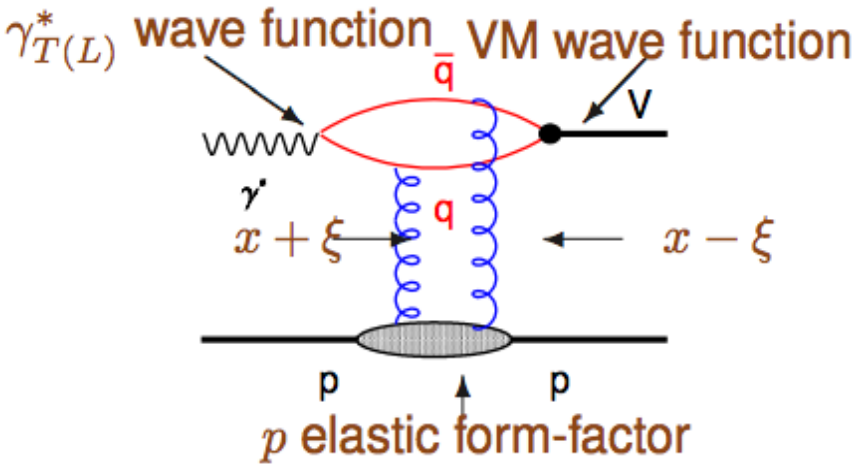


NLO

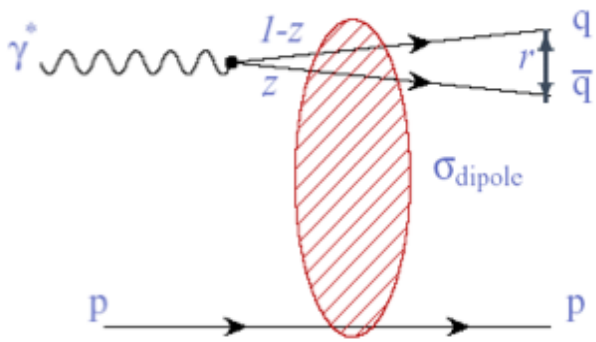
Study of exclusive final states has been very prolific and very successful, these papers are between the most cited at HERA

DVCS and Vector Meson production – QCD factorization

QCD - Breit frame



Colour dipole - target frame



NLO calculation available for DVCS, Υ, J/ψ (γp, DIS), ρ (DIS)

$\sigma_L \simeq \frac{\alpha_S^2}{Q^6}|xG(x,Q^2)|^2 \Rightarrow$

$\sigma_L \propto \frac{\alpha_S^2}{Q^6}|H(x_1,x_2,t,Q^2)|^2$

Generalised PDFs build from PDFs with skewing effect and t-dependence

- γ^* fluctuates in $q\bar{q}$ + $q\bar{q}g$ + ..
- Lifetime of dipole very long because of large γ boost
- Transverse size $\propto 1/(Q^2 + M^2_{q\bar{q}})$

$\sigma_{\gamma^* p}(x,Q^2) =$

$\int dr^2 dz \psi^{in}(r,z,Q^2)\sigma^2_{dipole}(x,r)\psi^{out}(r,z,Q^2)$

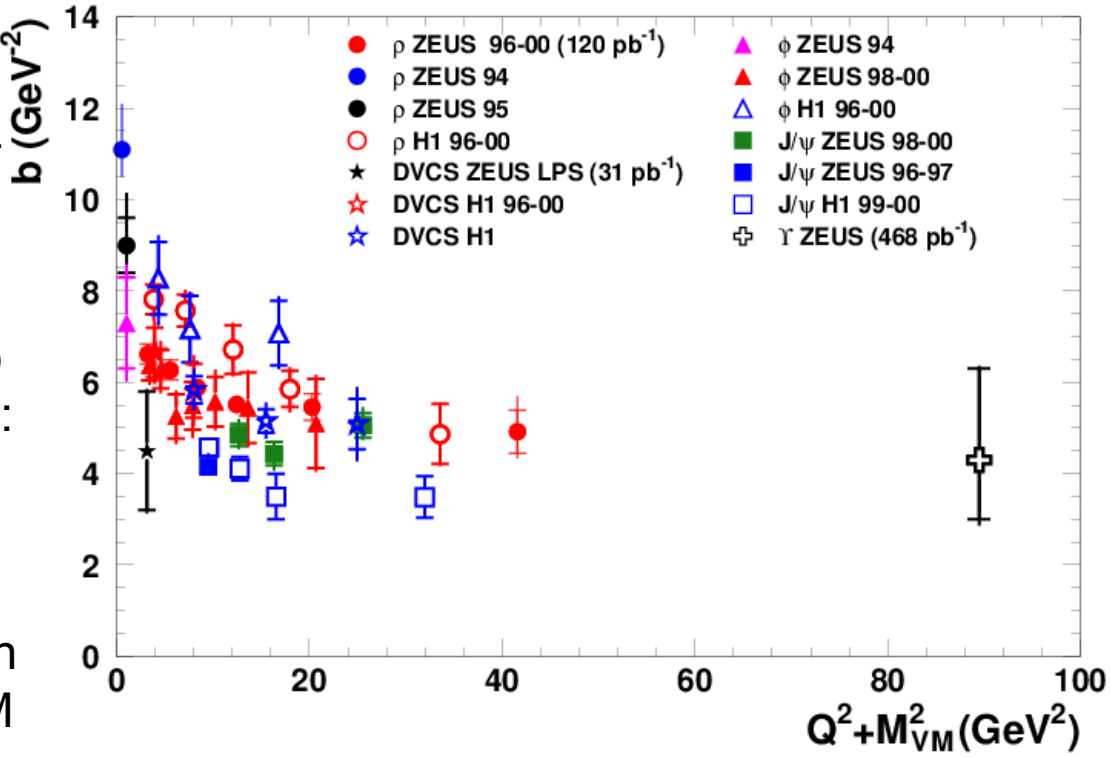
- σ_{dipole} from models (2-gluons, ..)

VM production and DVCS: t-dependence, $b(Q^2+M^2_{VM})$

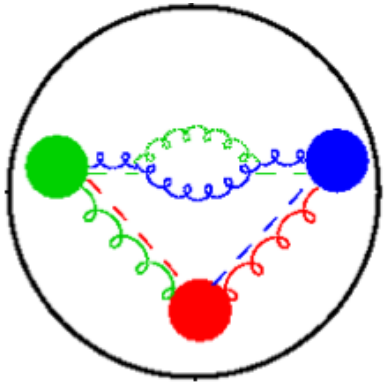
- $d\sigma/dt \sim e^{-b|t|}$
- Data show b decreasing vs $Q^2 + M^2_{VM}$ up to an asymptotic value
- In optical model approach, via Fourier transform, b is related to the size of the interaction region:

  $b \sim (R^2_p + R^2_{VM})/4$

- For b~4.5 GeV^{-2} → radius of interaction ~ 0.6 fm, smaller than the radius of proton tested in EM interactions to be 0.8 fm

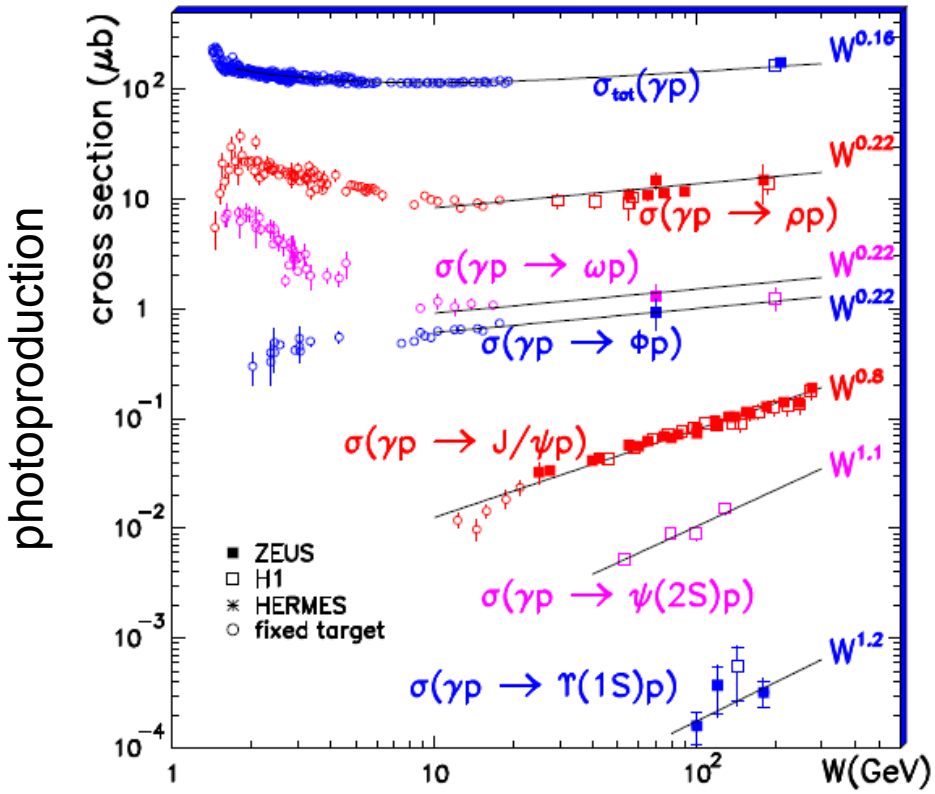


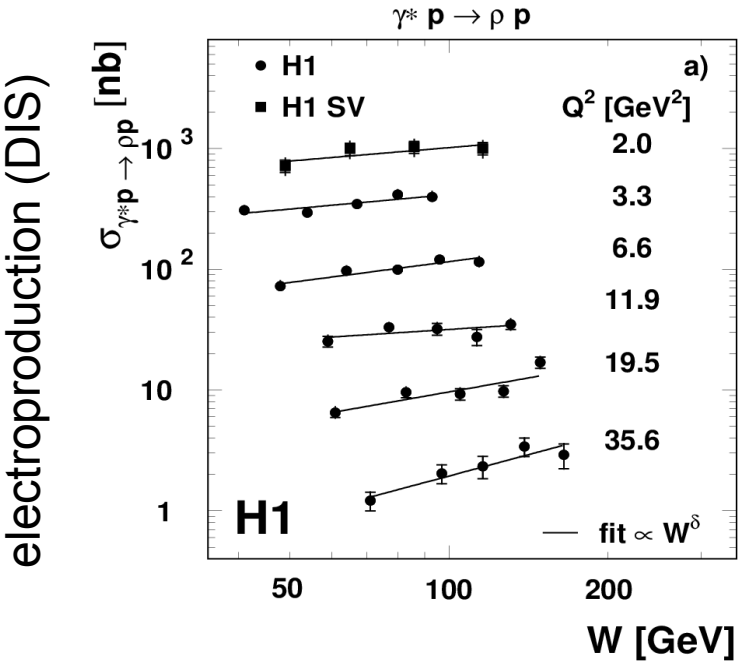
size of interacting gluons within the protons is smaller than the size of the quarks in the proton and is getting smaller with $Q^2 + M^2_{VM}$



Vector Meson production: W-dependence, $\sigma \sim W^{\delta}$

- The cross section dependence on W can be parameterised as $\sigma \sim W_{\gamma p}^{\delta}$

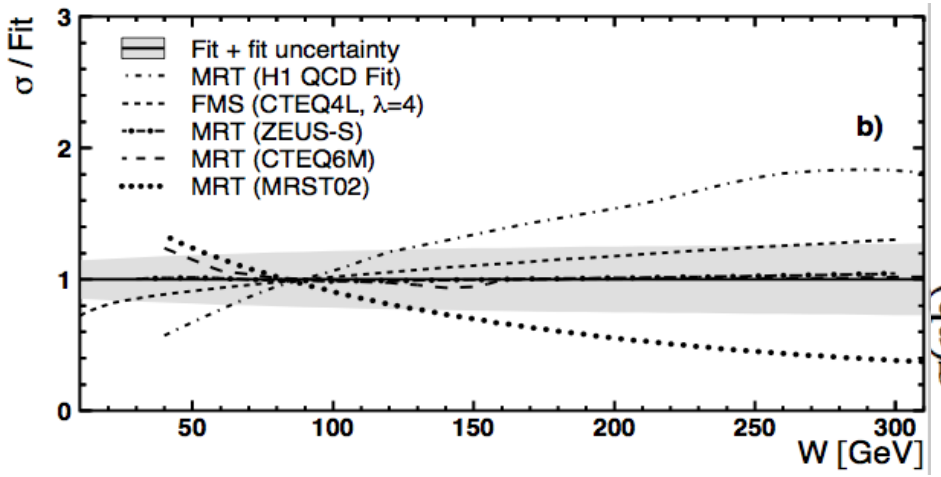




- Decrease of σ with decreasing interaction size
- Decrease partially compensated by rise of cross section with $W_{\gamma p}$, related to the increasing gluon density at low values of x-Bjorken $x \sim 1/W^2_{\gamma p}$

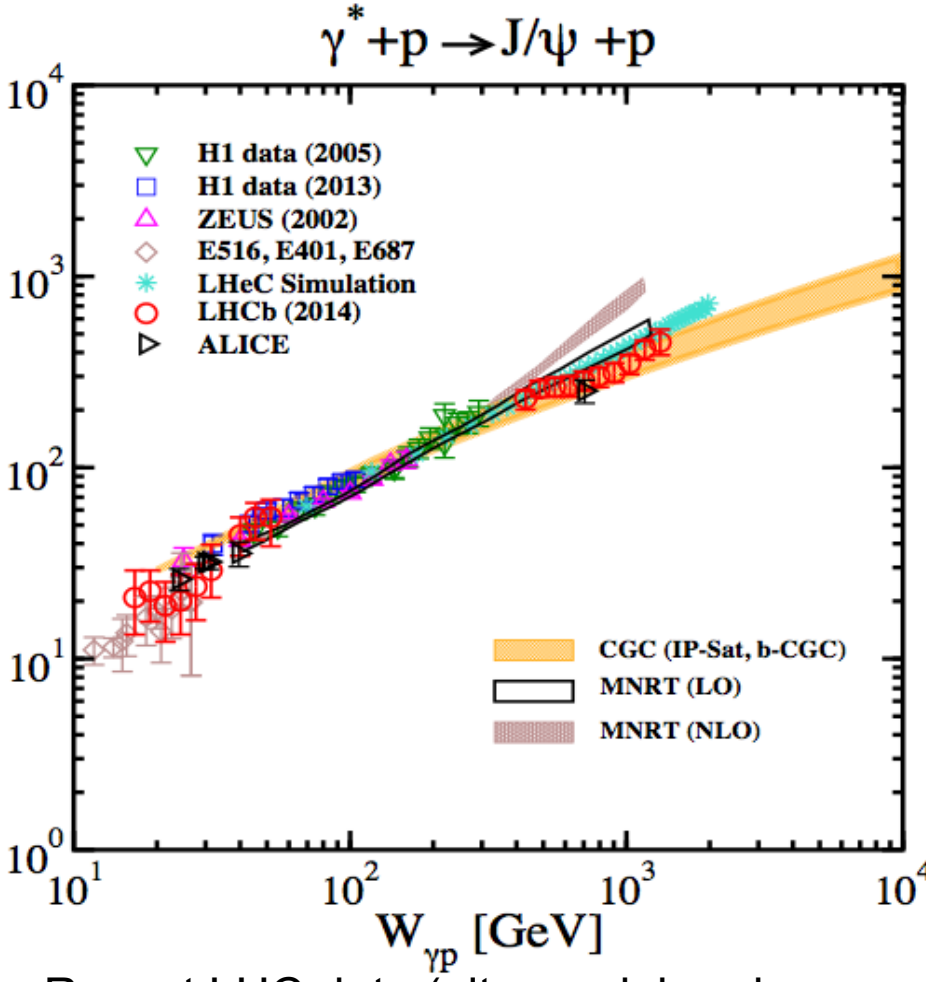
VM at NLO and gluon distributions at low x

2002



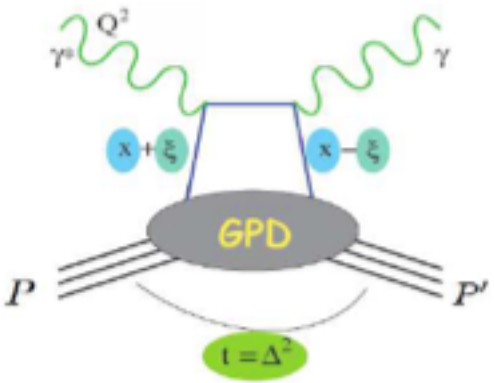
Strong sensitivity to generalised gluon distribution, tested up $x \sim 10^{-4}$

2015: *"data for pp → pYp can now be included in the global PDF fits to determine the gluon in the low x regime"* 1507.06942 Jones, Martin, Ryskin, Teubner



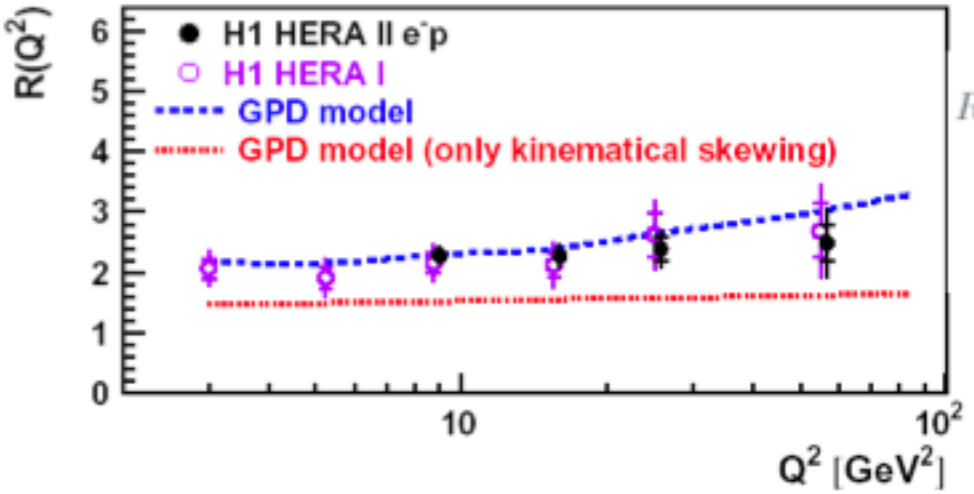
Recent LHC data (ultra-peripheral collisions) favours saturation at small x

Deeply Virtual Compton Scattering: ep → e p γ



GPDs: $G(x,Q^2) \Rightarrow H(x_1,x_2,t,Q^2)$

Distribution of gluons described vs x and t → access to the 3-dimensional picture of the proton

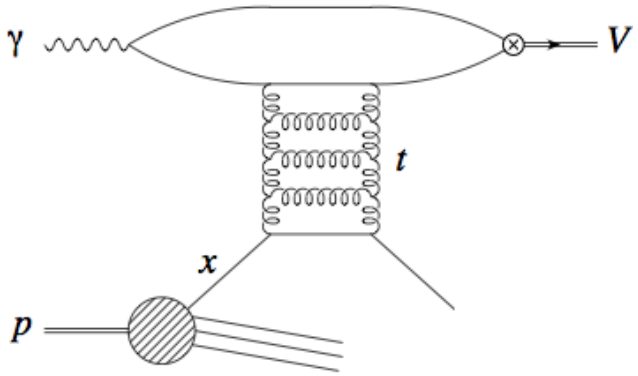


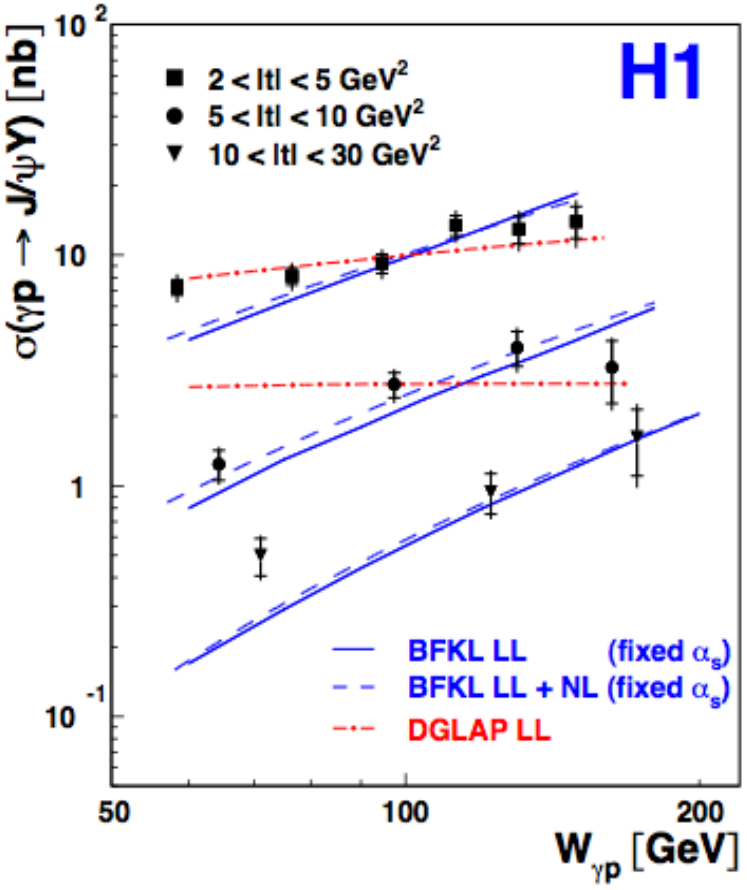
$$R = \frac{\mathcal{I}m\ A(\gamma^* p \to \gamma p)}{\mathcal{I}m\ A(\gamma^* p \to \gamma^* p)} = \frac{4\sqrt{\pi\ \sigma_{DVCS}\ b(Q^2)}}{\sigma_T(\gamma^* p \to X)\sqrt{(1+\rho^2)}}$$

ratio R of the imaginary parts of the DVCS and DIS amplitudes

DVCS data used in global fit to extract Generalised Parton Distributions

VM at high t – non DGLAP evolution





At high t, p mostly dissociates

DGLAP dynamics driven by term $\ln(M_{J/psi}^2/(Q_0^2-t))$, not valid at high t

BFKL evolution ~$\alpha_s^n \ln^n(W^2/t)$

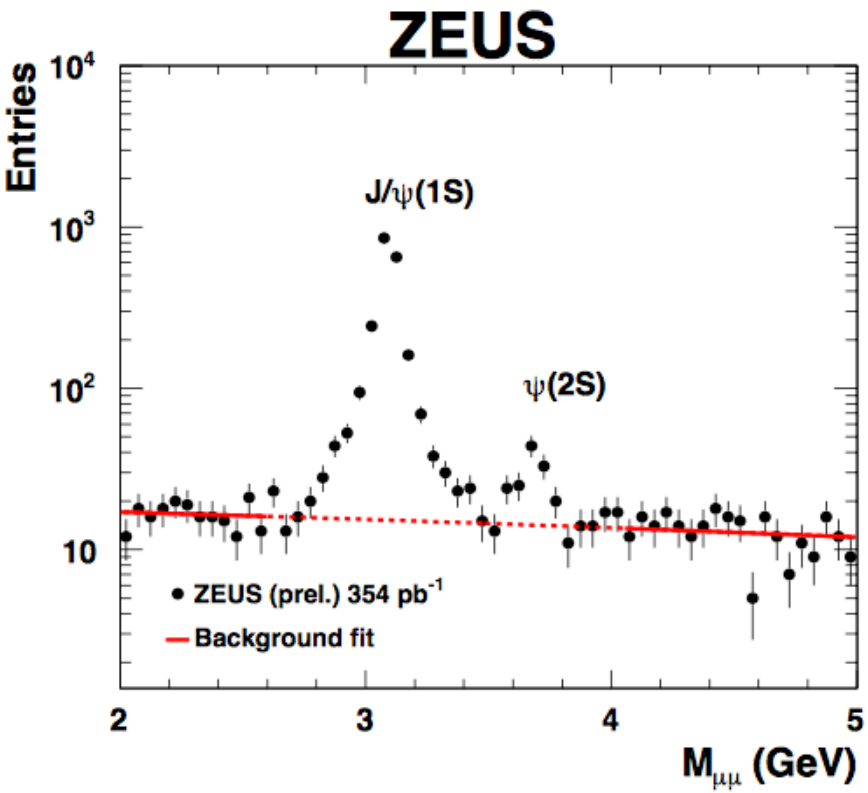
Data show increase with gluon density also at hight t,
better described by models with BFKL evolution or assuming saturation

Measurement of the cross section ratio $\sigma_{\psi(2s)}/\sigma_{J/\psi}$ in deep inelastic exclusive ep scattering at HERA I+II and comparison with various theory predictions

ZEUS-prelim-15-003

ψ(2s) and J/ψ(1S) production in DIS

$R = \sigma\gamma p \to \psi(2S)p \,/\, \sigma\gamma p \to J/\psi p$

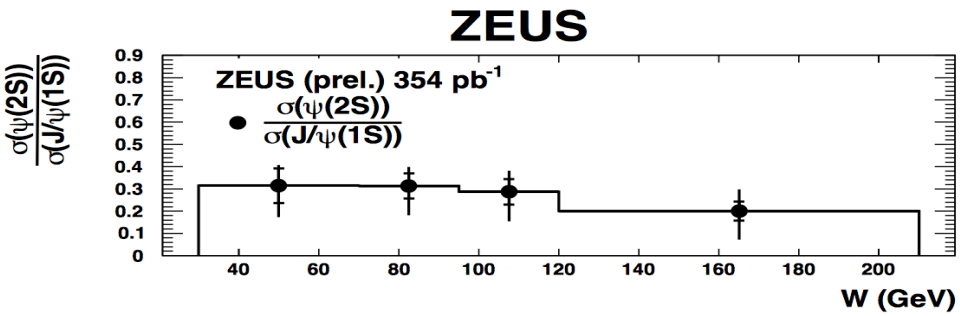


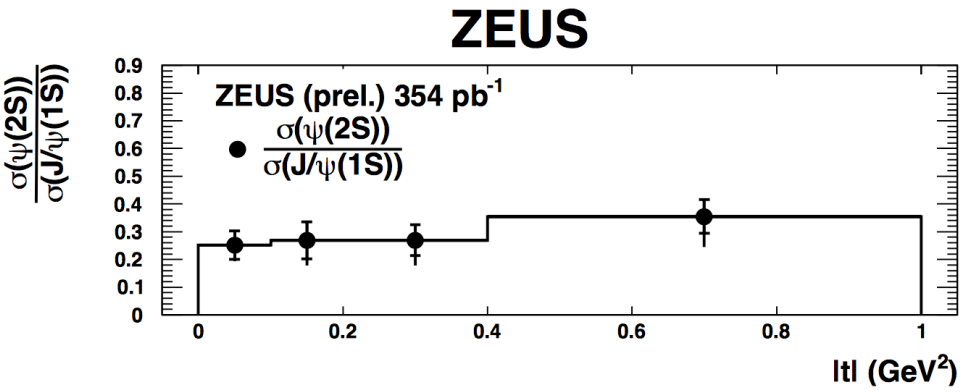
Decays: $J/\psi \to \mu\mu$

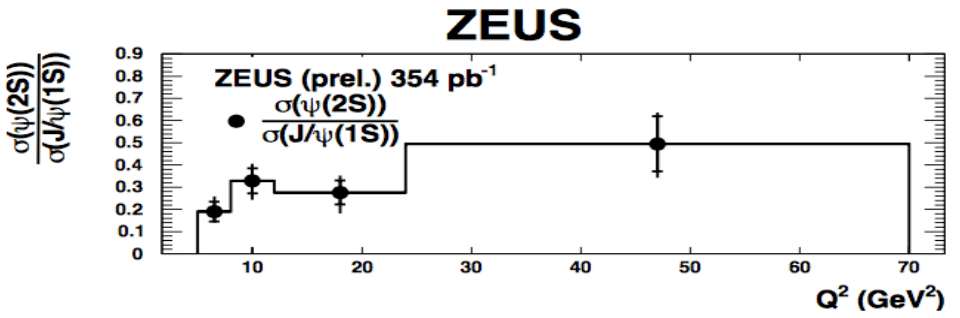
$\Psi \to \mu\mu$, $\Psi \to J/\psi\pi\pi$

- Measurement sensitive to charmonium wave function
- Different rate of ψ(2s) and J/ψ(1s) expected due to different wave function, ratio estimated in QCD models to be R~0.17, rising with Q^2
- Kinematic range: $5<Q^2<70$ GeV^2, $30<W<210$ GeV, $|t|<1$ GeV^2

ψ(2s) / J/ψ(1S) ratio vs W, t, Q^2





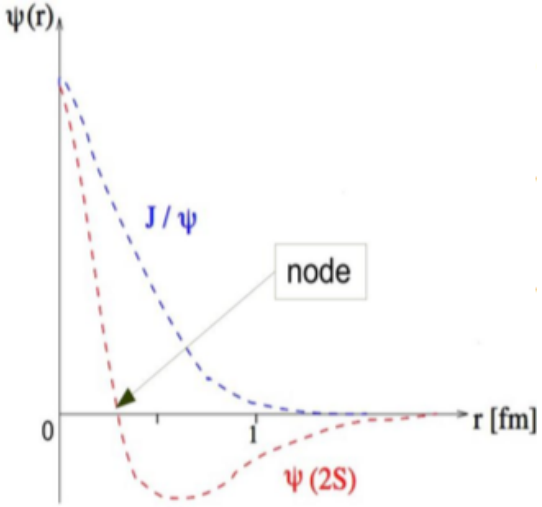


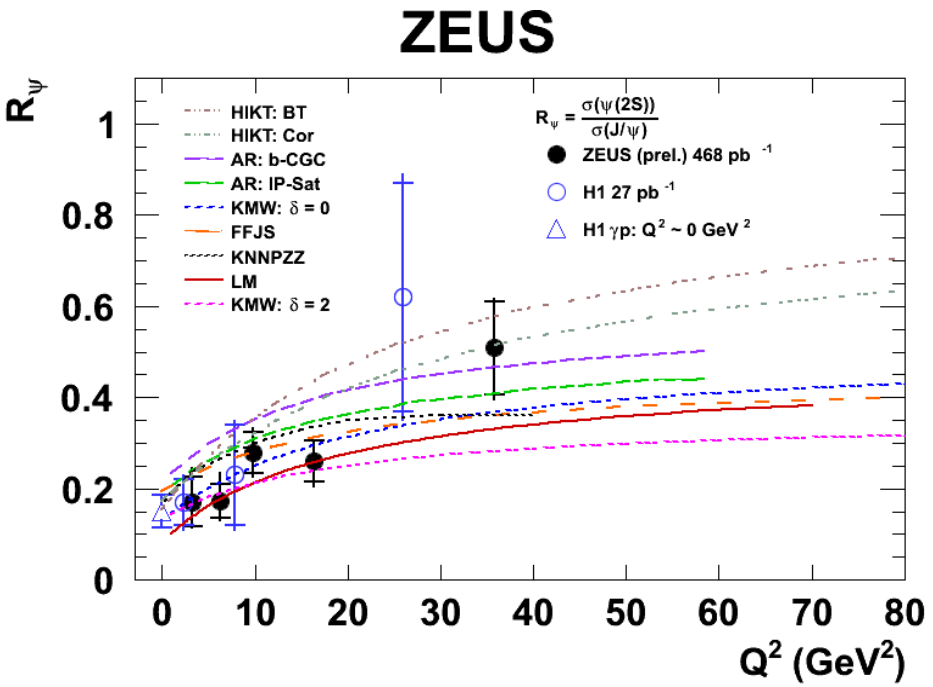
Ratio:

- Independent of W
- Independent of t
- Increase with Q^2

ψ(2s) / J/ψ(1S) vs Q^2, comparison with models

Same quark content and similar mass, but different wave function





pQCD model calculations predict R~0.17 in PHP rising with Q^2 reaching plateau at $Q^2 >> M^2\psi$

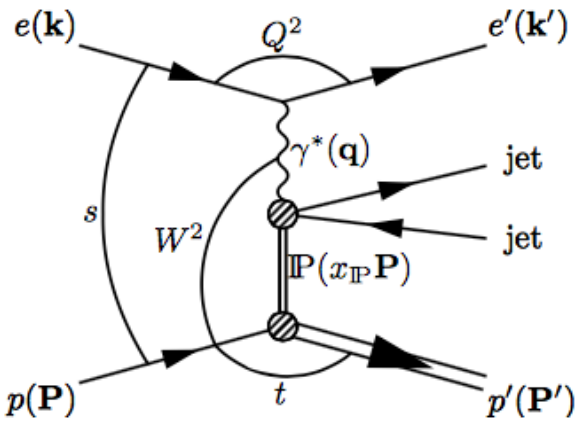
HIKT, Hufner et al.: dipole model, dipole-proton constrained by inclusive DIS data
AR, Armesto and Rezaeian: impact parameter dependent CGC and IP-Sat model
KMW,Kowalski Motyka Watt: QCD description and universality of quarkonia production
FFJS, Fazio et al.: two component Pomeron model
KNNPZZ, Nemchik et al.: color-dipole cross section derived from BFKL generalised eq. LM, Lappi and Mäntysaari: dipole picture in IP-Sat model

Production of exclusive dijets in diffractive DIS at HERA

ZEUS
DESY-15-070, arXiv:1505.05783

Exclusive dijets production in diffractive DIS, arXiv:1505.05783

$e + p \rightarrow e + jet1 + jet2 + p$



Data 2003-2007, 372 pb^{-1}

Only dijet, scattered electron and proton in the final state

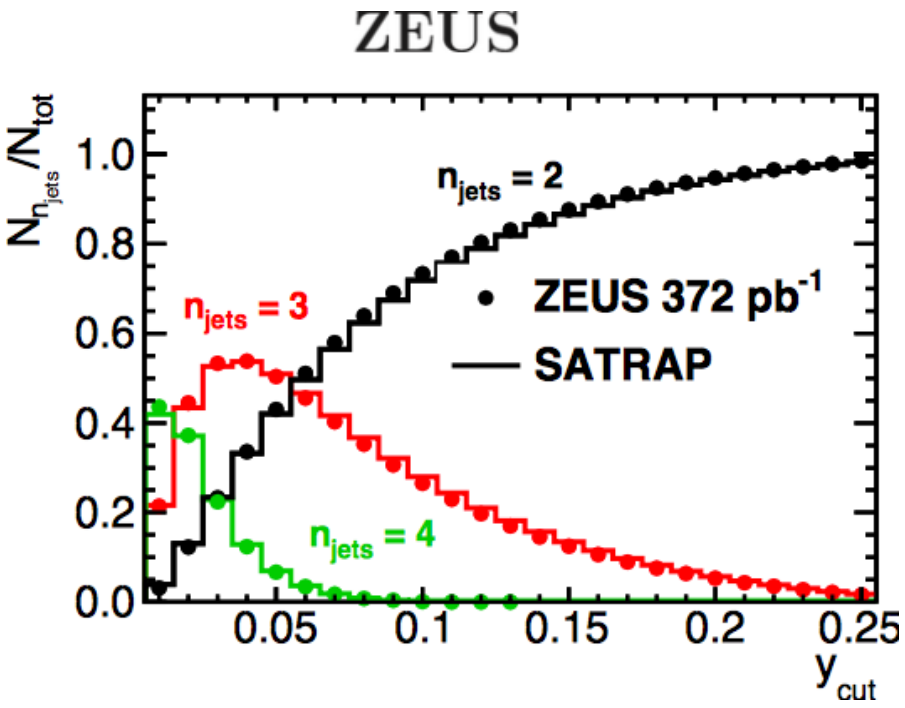
$Q^2 > 25\ GeV^2$

$90 < W > 250\ GeV$

$x_{IP} < 0.01$ – fraction of proton's momentum carried by exchanged color singlet

Large Rapidity Gap

Exclusive dijet production in diffractive DIS



SATRAP MC model

(Golec-Biernat, Wustoff, 1999):

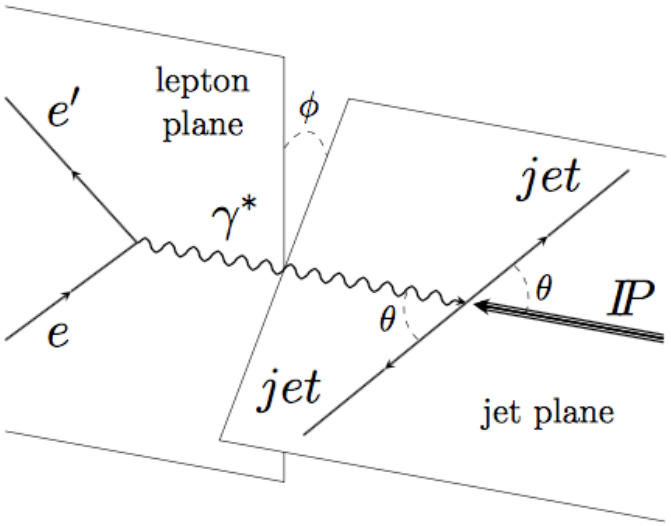
- color dipole model with saturation
- $\mathbf{q\bar{q}}$ and $\mathbf{q\bar{q}g}$ in a final state
- good agreement with data, used for detector level

Exclusive dijet may originate from two, three, many parton states

Jets were found in γ*-IP rest frame

- using Durham kT jet algorithm in exclusive mode: all objects are merged in jets
- with resolution parameter y_{cut} = 0.15 optimizes efficiency versus purity of jet sample
- $p_T$jet > 2 GeV selects hard jets
- $\eta_{jet} < 2$ select diffractive events with LRG

Exclusive dijets production in diffractive DIS



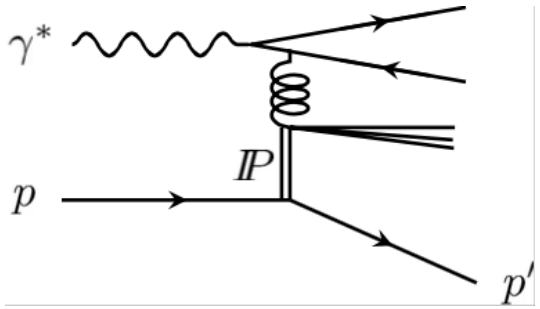
Test the nature of the object in diffractive interaction by reconstructing the azimuthal angle between lepton and jet plane

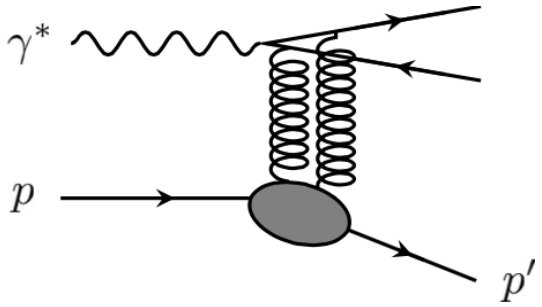
$d\sigma/d\Phi \sim 1 + A(p_T jet)\cos(2\Phi)$

J.Bartels et al, PLB386 (1996) 389:

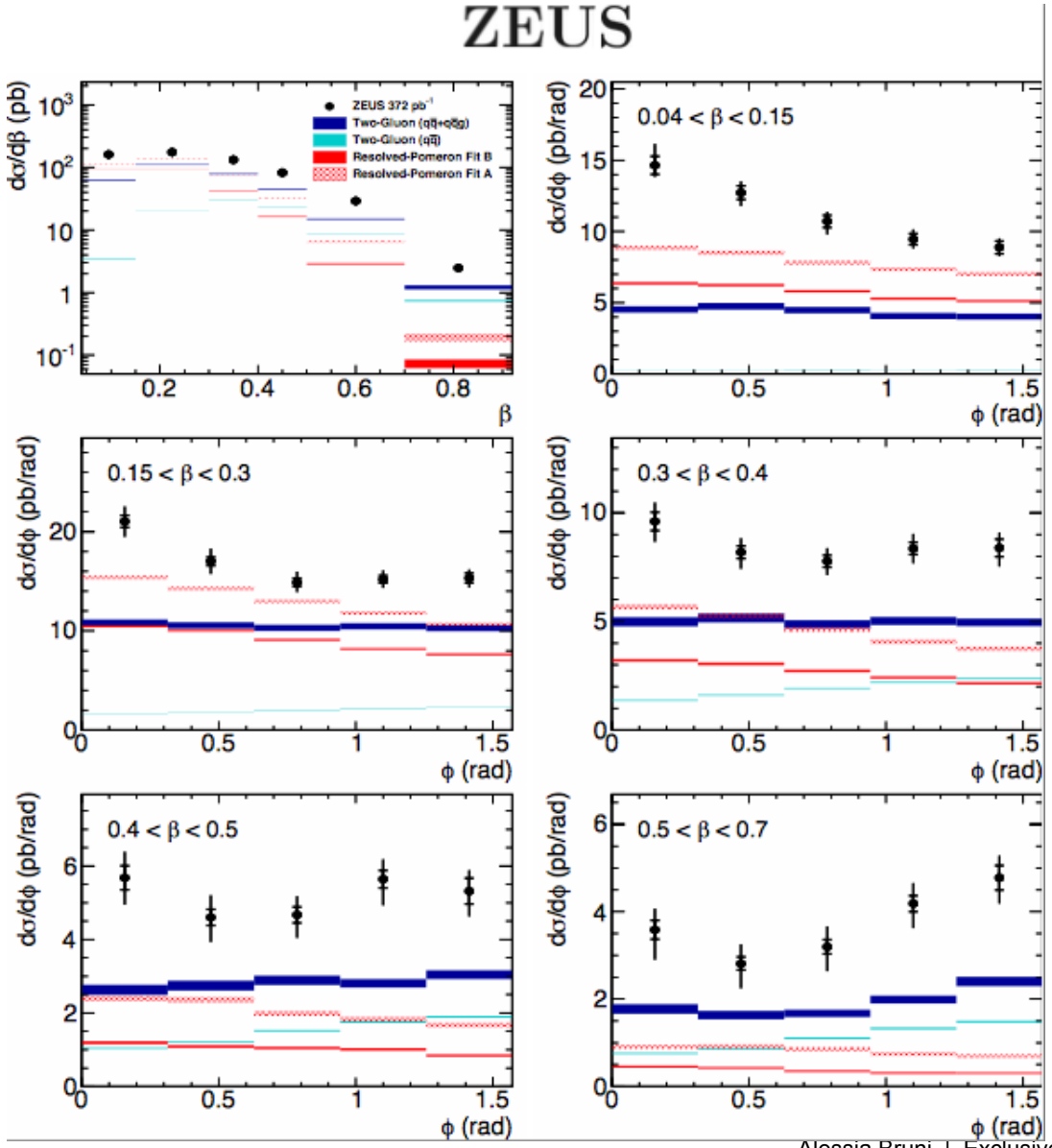
A<0 for two gluons exchange

A>0 for $\mathbf{q\bar{q}}$ produced from single gluon





Exclusive dijet production in diffr. DIS, angle between jets



dσ/dΦ fitted for different β bins,

$\beta = x / x_{IP}$ – fraction of Pomeron momentum 'seen' by photon

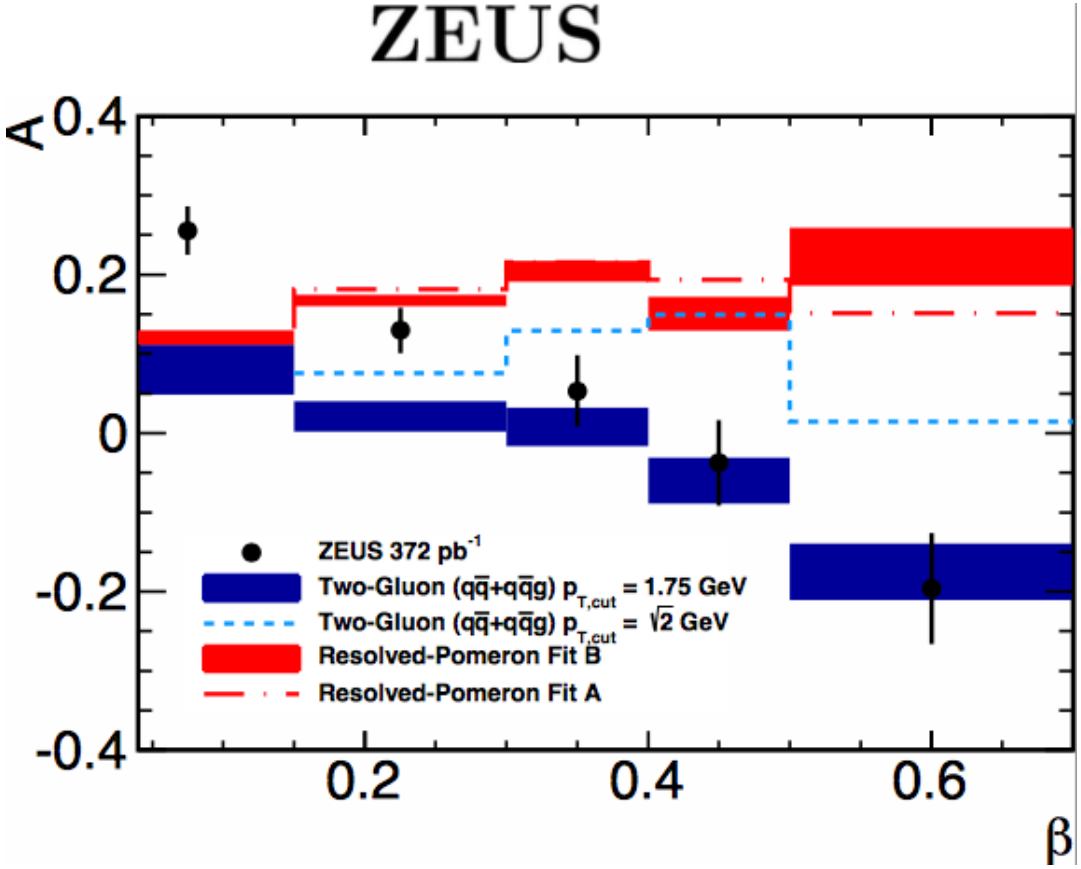
Normalisation discrepancy of factor two (NLO corr. large?)

The slope of the angular distribution changes sign around β = 0.4

Exclusive dijet production in diffractive DIS

$d\sigma/d\Phi \sim 1 + A(p_T jet)\cos(2\Phi)$

A vs β, comparison with model predictions



In resolved Pomeron model, the parameter A positive and constant in the whole β range

$\beta = x / x_{IP}$ – fraction of Pomeron momentum 'seen' by photon

In two-Gluon-Exchange model value of A varies from positive to negative; it agrees quantitatively with the data in the range $0.3 < \beta < 0.7$

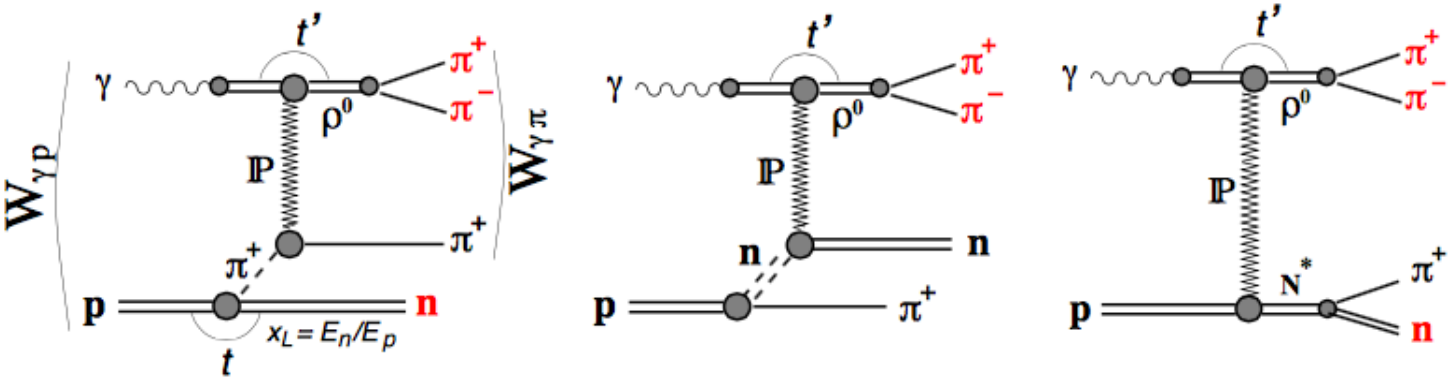
Data favour the Two-Gluon-Exchange model prediction

Exclusive ρ^0 meson photoproduction with a leading neutron at HERA

H1 DESY 15-120, submitted to Eur. Phys. JC

Exclusive PHP of rho mesons with forward neutron

- $\gamma p \rightarrow \rho^0 \pi + n$, $\rho^0 \rightarrow \pi^+\pi^-$



One Pion Exchange additional contributions

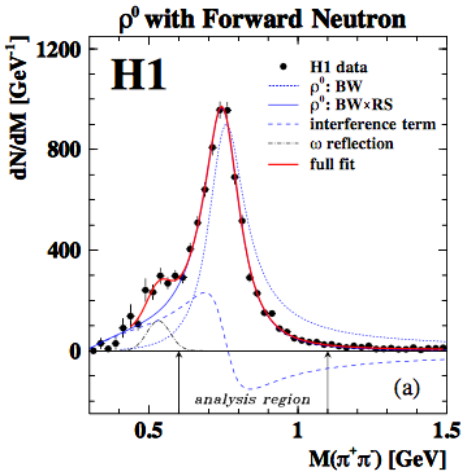
theoretical model : exchange of two Regge trajectories in a double-peripheral scattering process DPP

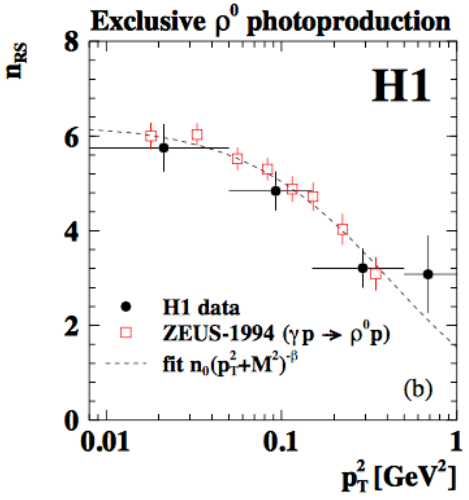
Key observables :

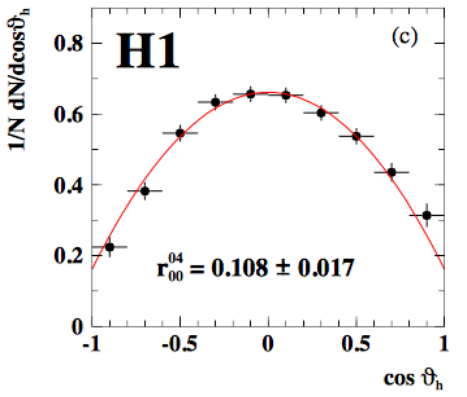
- $x_L = E_n / E_p$ (or $x_\pi = 1 - x_L$)
- W dependence : ~ W^δ - nature of exchange objects
- t-slope of ρ^0 (b ~ R^2 in geometric picture)

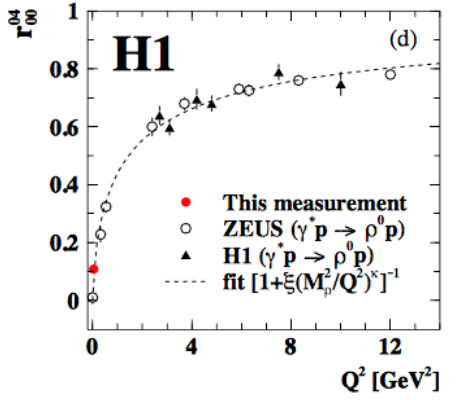
In One Pion Exchange assumption, factorization of the proton vertex (valid at small t) → $\sigma_{\gamma p} \sim f_\pi / p\,(x_L) \sigma_{\gamma \pi}$

Exclusive ρ photoproduction with forward n









Kinematic range:
$Q^2 < 2$ GeV^2
$|t| < 1$ GeV^{-2}
$0.3 < m_{\pi\pi\pi} < 1.5$ GeV
$20 < W_{\gamma\pi} < 100$ GeV

No hard scale

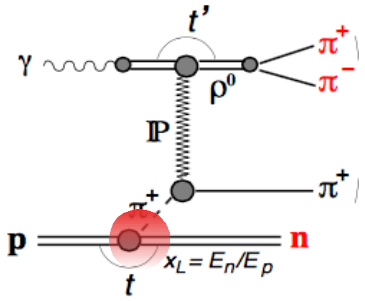
The BW shape is distorted due to interference with non-resonant ππ production amplitude

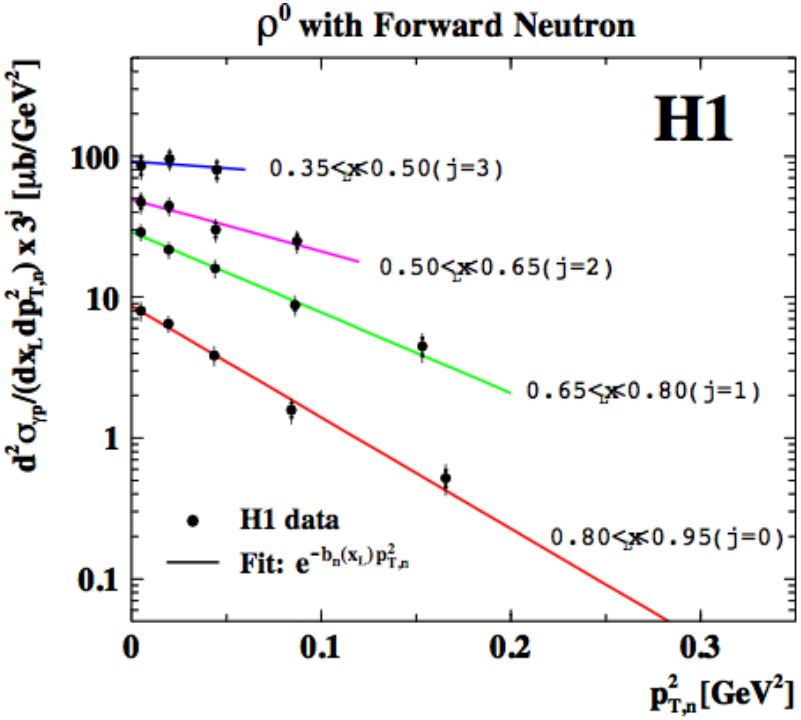
The strength of the distortion is p_t dependent and characterised by the skewing parameter n_{RS} (Ross,Stodolsky 1966)

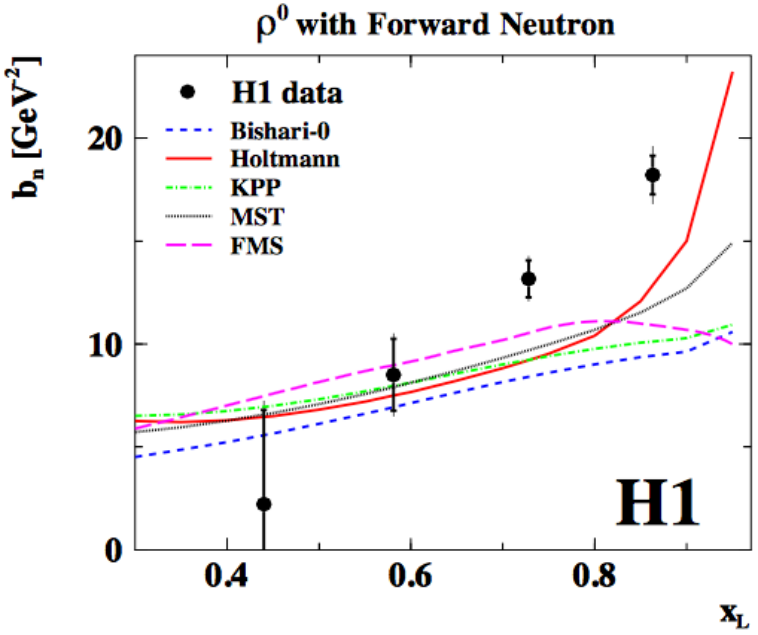
Property of two-pion system compatible with previous measurements

Exclusive ρ photoproduction with forward n – slope at n vertex

Slope of momentum transfer at p-n vertex vs $x_L = E_n/E_p$



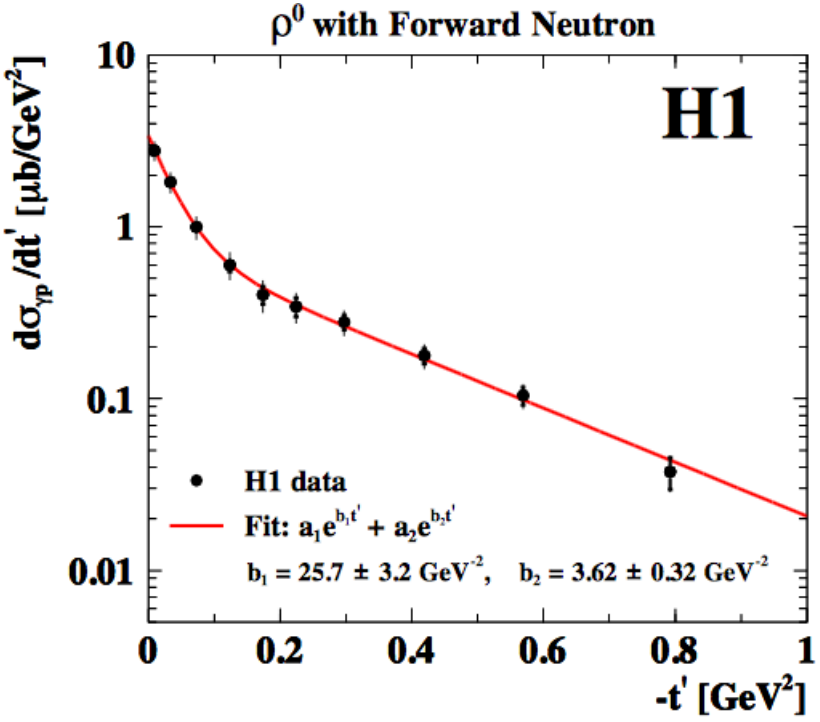




Steep rise with increasing x_L expected from models, but rise is stronger than predicted by various pion-flux parametrisations

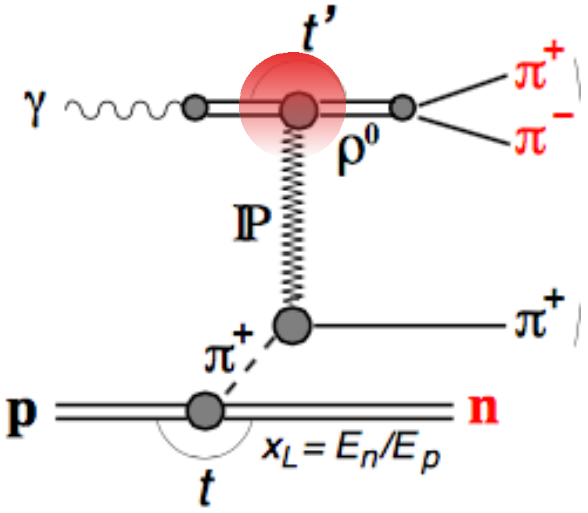
Exclusive ρ photoproduction with forward n – slope at γp vertex

$d\sigma_{\gamma p} / dp_{t,\rho}$ vs t', 4-momentum transfer of rho meson



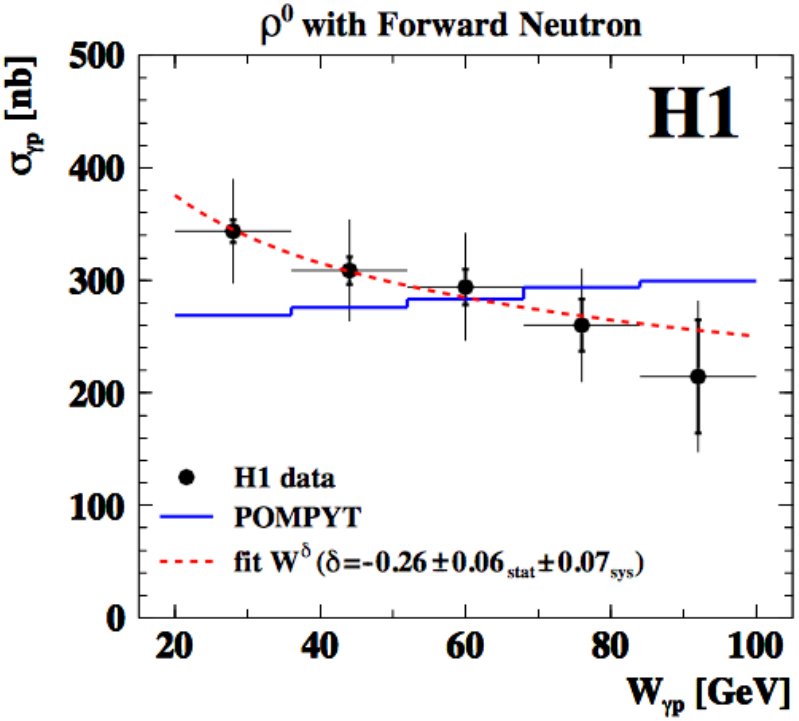
t' - dependence has two components, (two b parameters)

In Double Peripheral Process, this is due to double exchange, IP and π

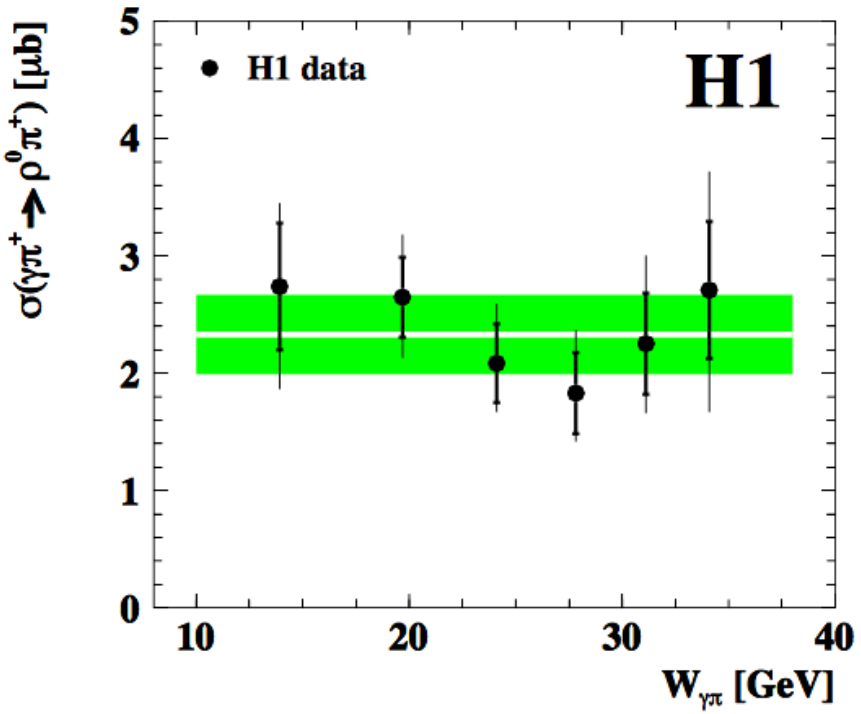


Exclusive ρ photoproduction with forward n, σ vs W

cross section γp→ρ^0 π+ n



cross section γπ→ρ^0 π+ n



γp: Regge motivated power low fit W^{δ} yields $\delta < 0$

Using pion-flux parametrisations, the gamma-pion cross section γπ can be measured

γπ: cross section independent from W within uncertainties

Ratio σγπ/σγp ~ 0.25, small, indicating rescattering or large absorption corr.

Summary

Studies of VM, DVCS and exclusive state production performed at HERA very inspiring to the theory and LHC experiments

- The cross section ratio $\sigma\psi(2S)/\sigma J/\psi(1S)$ in exclusive DIS has been measured with improved precision, in agreement with QCD models

- First measurement in ep of diffractive production of exclusive dijets in DIS. Production consistent with two gluon exchange.

- Photoproduction of exclusive ρ^0 associated with leading neutron measured for the first time at HERA.
- Differential cross sections for the reaction $\gamma p \rightarrow \rho^0 n \pi+$ exhibit features typical for exclusive double peripheral process.
- Process used to extract the elastic photon-pion cross section $\sigma(\gamma\pi \rightarrow \rho^0\pi+)$ in the OPE approximation.
  The cross section ratio $\sigma (\gamma\pi) / \sigma (\gamma p)$ suggests large absorption corrections suppressing $\sigma (\gamma p)$

Conclusions

Exclusive production sensitive to the gluon distribution, $[xG(x,Q^2)]^2$

- also at low x → check for saturation

By measuring the squared momentum transfer t, they give access

- to the transverse spatial distribution of the gluons in the proton, that cannot be probed in inclusive DIS, i.e Generalised Parton Distributions
- to BFKL dynamics

- **Studies of VM, DVCS and exclusive state production performed at HERA still very inspiring for QCD theory and LHC experiments**