Diffractive Physics at the HERA Collider

… a review illustrated by recent results

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Workshop on Forward Physics and High Energy Scattering at Zero Degrees

Nagoya, Japan
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Last Time I was in Japan (DIS'06, Tsukuba)

Diffractive Cross Sections and Parton Densities from Rapidity Gap and Leading Proton Measurements

P.Newman (Birmingham) for the H1 Collaboration

Measurement and QCD Analysis of the Diffractive Deep-Inelastic Scattering Cross Section at HERA

H1 Collaboration

Abstract

A detailed analysis is presented of the diffractive deep-inelastic scattering process $ep \to eXY$, where Y is a proton or a low mass proton excitation carrying a fraction $1 - x_{I\!P} > 0.95$ of the incident proton longitudinal momentum and the squared four-momentum transfer at the proton vertex satisfies $|t| < 1\ \mathrm{GeV}^2$. Using data taken by the H1 experiment, the cross section is measured for photon virtualities in the range $3.5 \leq Q^2 \leq 1600\ \mathrm{GeV}^2$, triple differentially in $x_{I\!P}$, Q^2 and $\beta = x/x_{I\!P}$, where x is the Bjorken scaling variable. At low $x_{I\!P}$, the data are consistent with a factorisable $x_{I\!P}$ dependence, which can be described by the exchange of an effective pomeron trajectory with intercept $\alpha_{I\!P}(0) = 1.118 \pm 0.008\ (\mathrm{exp.})\ ^{+0.029}_{-0.010}\ (\mathrm{theory})$. Diffractive parton distribution functions and their uncertainties are determined from a next-to-leading order DGLAP QCD analysis of the Q^2 and β dependences of the cross section. The resulting gluon distribution carries an integrated fraction of around 70% of the exchanged momentum in the Q^2 range studied. Total and differential cross sections are also measured for the diffractive charged current process $e^+p \to \bar{\nu}_e XY$ and are found to be well described by predictions based on the diffractive parton distributions. The dynamics of the ratio of the diffractive to the inclusive neutral current ep cross sections are studied. Over most of the kinematic range studied, this ratio shows no significant dependence on Q^2 at fixed $x_{I\!P}$ and x or on x at fixed Q^2 and β fixed.

Diffractive Deep-Inelastic Scattering with a Leading Proton at HERA

H1 Collaboration

Abstract

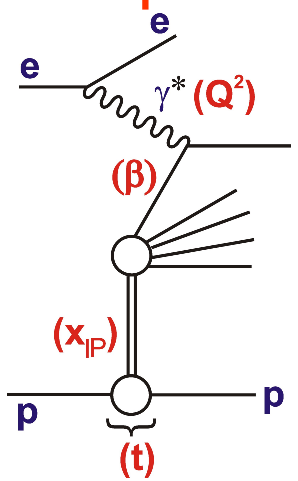
The cross section for the diffractive deep-inelastic scattering process $ep \to eXp$ is measured, with the leading final state proton detected in the H1 Forward Proton Spectrometer. The data analysed cover the range $x_{I\!P} < 0.1$ in fractional proton longitudinal momentum loss, $0.08 < |t| < 0.5\ \mathrm{GeV}^{-2}$ in squared four-momentum transfer at the proton vertex, $2 < Q^2 < 50\ \mathrm{GeV}^2$ in photon virtuality and $0.004 < \beta = x/x_{I\!P} < 1$, where x is the Bjorken scaling variable. For $x_{I\!P} \lesssim 10^{-2}$, the differential cross section has a dependence of approximately $d\sigma/dt \propto e^{6t}$, independently of $x_{I\!P}$, β and Q^2 within uncertainties. The cross section is also measured triple differentially in $x_{I\!P}$, β and Q^2. The $x_{I\!P}$ dependence is interpreted in terms of an effective pomeron trajectory with intercept $\alpha_{I\!P}(0) = 1.110 \pm 0.018\ (\mathrm{stat.}) \pm 0.012\ (\mathrm{syst.})\ ^{+0.040}_{-0.030}\ (\mathrm{model})$ and a sub-leading exchange. The data are in good agreement with an H1 measurement for which the event selection is based on a large gap in the rapidity distribution of the final state hadrons, after accounting for proton dissociation contributions in the latter. Within uncertainties, the dependence of the cross section on x and Q^2 can thus be factorised from the dependences on all studied variables which characterise the proton vertex, for both the pomeron and the sub-leading exchange.

Final results, new for this conference. Everything shown is taken from these two closely related papers.

→ H1 2006 Fit B Diffractive PDFs

The HERA Collider

ep collisions
at √s ~ 300 GeV
1992-2007
~ 0.5 fb^{-1} per expt.

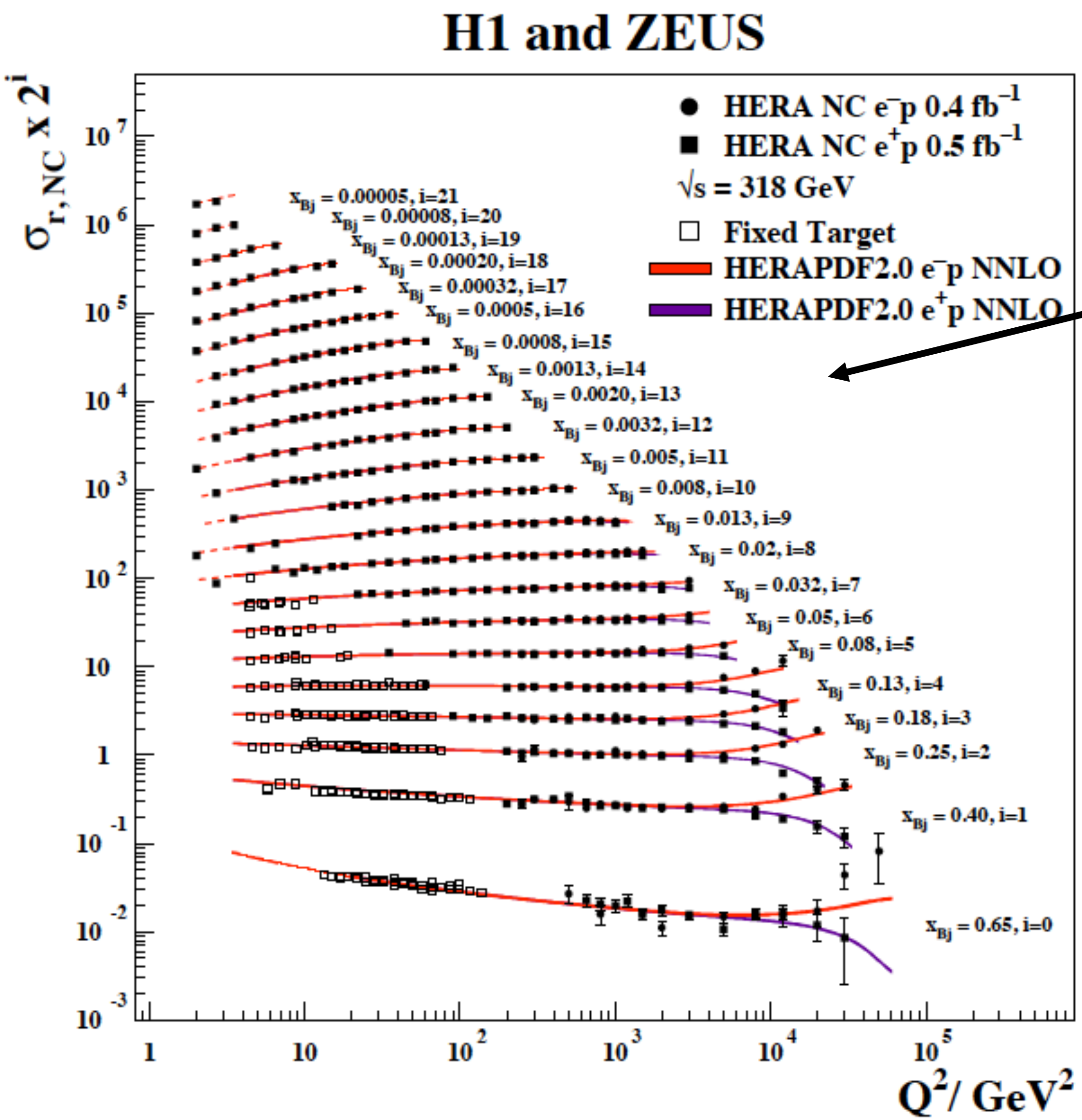


e.g. H1 publications on diffraction (similar numbers in ZEUS):

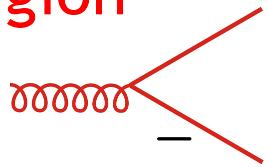
- Diffractive cross sections:	15 papers
- Diffractive final states:	18 papers
- Quasi-elastic cross sections:	22 papers
- Total cross sections / decomposition:	2 papers

Low x Physics: A Frontier of Standard Model

Gluon density knowledge entirely from inclusive NC HERA data …



- NC Q^2 dependence in perturbative region driven by …

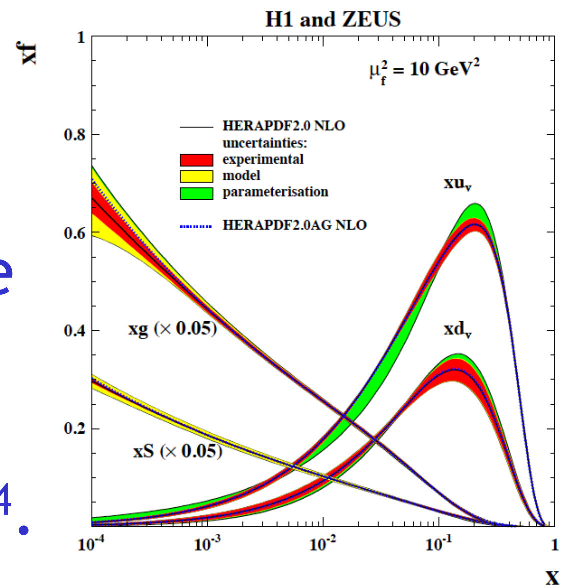


$$g \to q\bar{q}$$

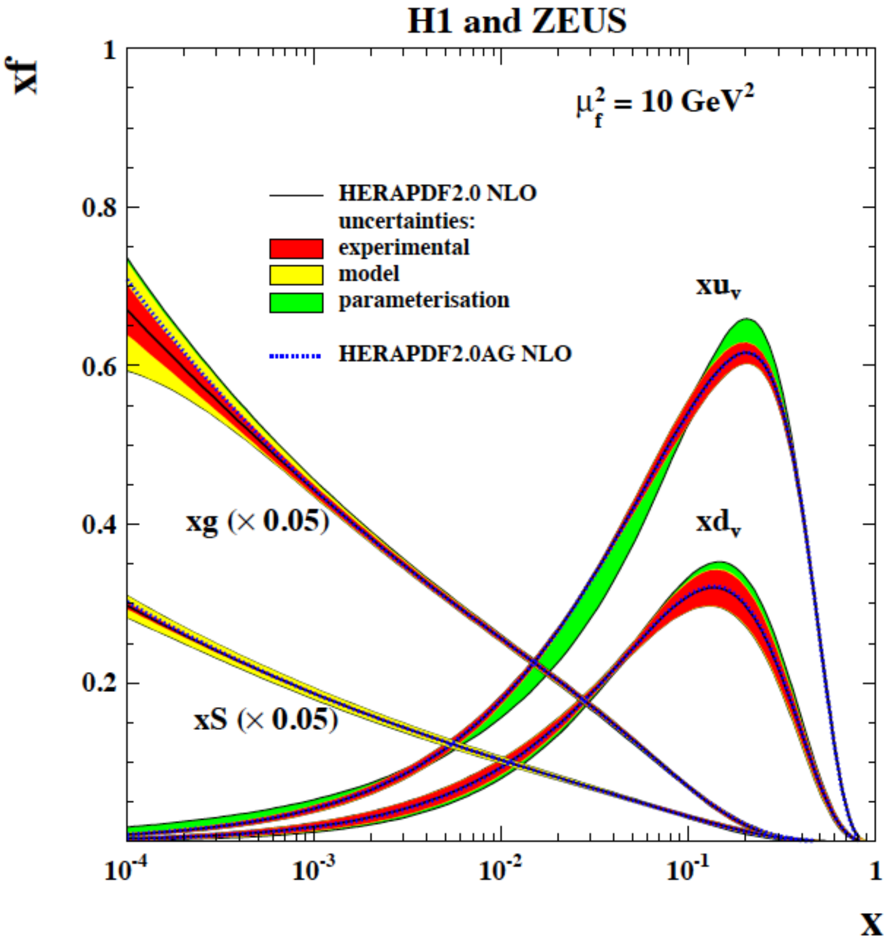
- e.g. Prytz approx:

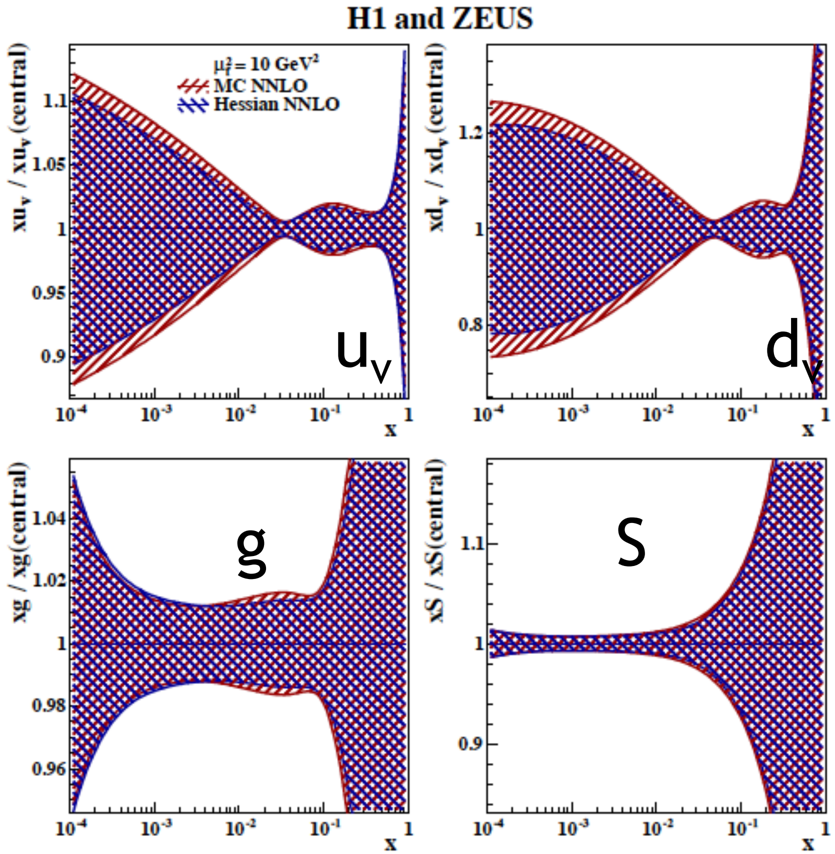
$$\frac{dF_2(x,Q^2)}{d\ln Q^2} \sim G(2x)$$

- needs lever-arm in Q^2 … reasonable precision only to $x \sim 10^{-3}/10^{-4}$.



Final HERA Picture of Proton (HERAPDF2.0)



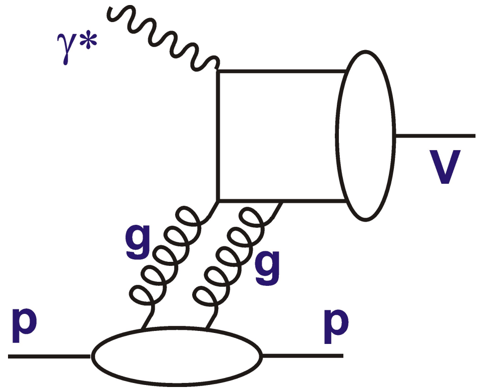


- ~2% precision on gluon over a wide range of x
- Gluon rises in a non-sustainable way

→ emergent phenomena at high parton density & strong coupling (including diffraction, non-linear evolution, confinement, mass …)

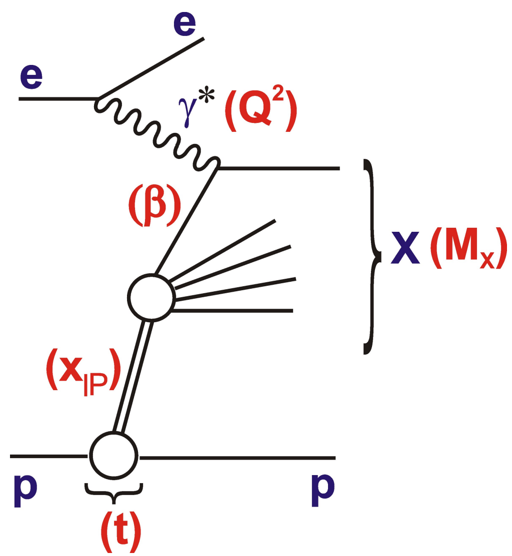
Exclusive / Diffractive Channels

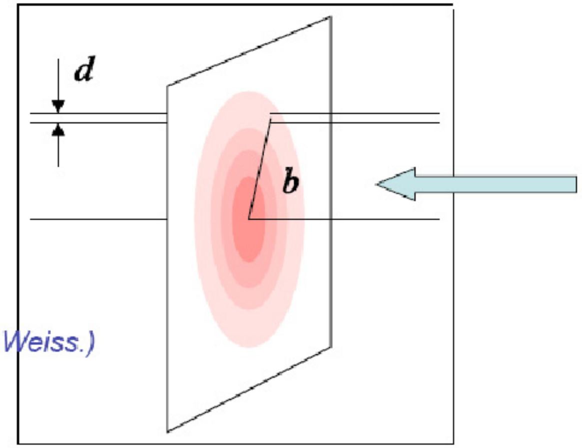
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon (at least for exclusives)



2) Additional variable t gives access to impact parameter (b) dependent amplitudes

→ Large t (small b) probes densest packed part of proton?

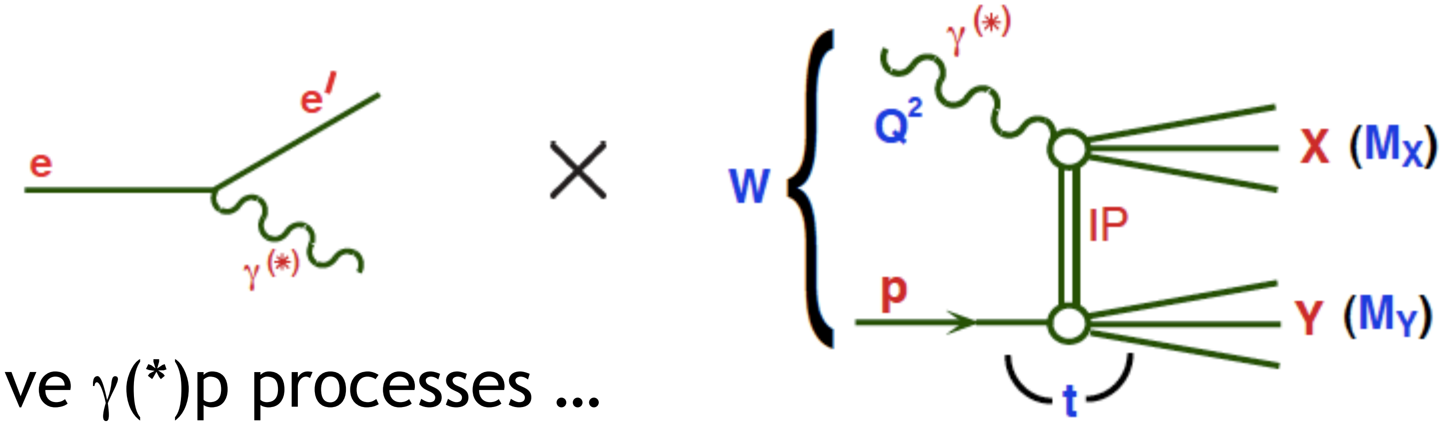




(figure from C. Weiss.)

Central black region growing with decrease of x.

Colour singlet exchange processes at HERA



Diffractive γ(*)p processes …

All 5 of the kinematic variables shown can be measured.

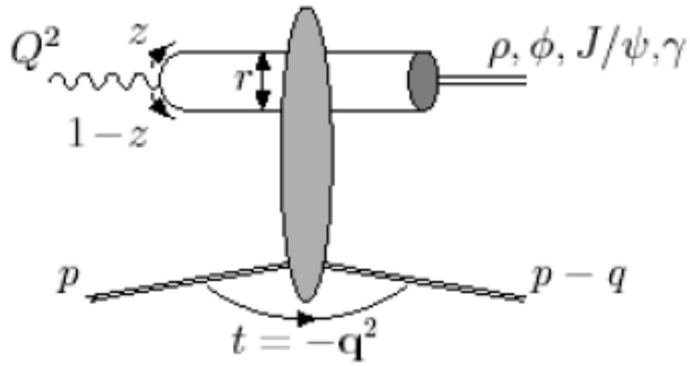
Favourable kinematics to study X system (photon dissociation)

By varying Q^2, the process can be smoothly changed
- from a soft process (real photon, $Q^2 \rightarrow 0$)
- to a deep inelastic process (highly virtual photon, large Q^2, resolving partons and probing QCD structure of diffraction)

Exclusive Vector Meson Production

Describing Vector Mesons in terms of Partons

Factorisation theorem



Dipole Models

step 1. γ fluctuation into $q\bar{q}$ dipole

step 2. dipole – proton interaction $A = \int dr^2\, dz\, \Psi_\gamma\, \sigma(dip-p)\, \Psi_V$

step 3. pair recombination into VM

1. γ wave function

well known : $\Psi(z, k_t)$

however : large $|t|$ studies -> chiral odd contributions

- Basically known

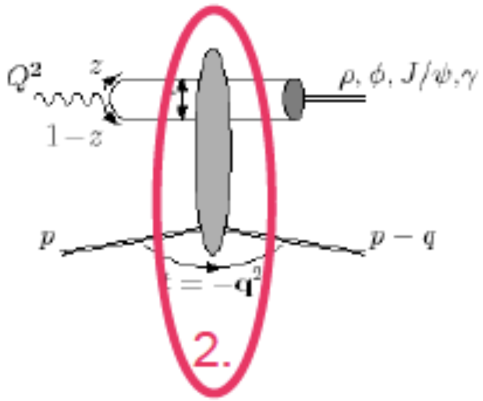
3. pair recombination into VM

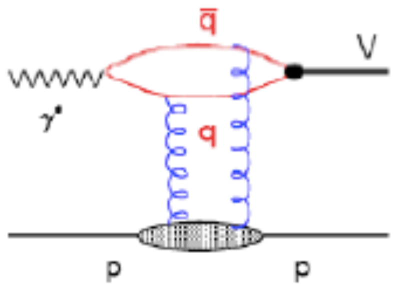
- VM wave function description ?
- role on σ_L / σ_T and helicity amplitudes

- Limits theoretical precision

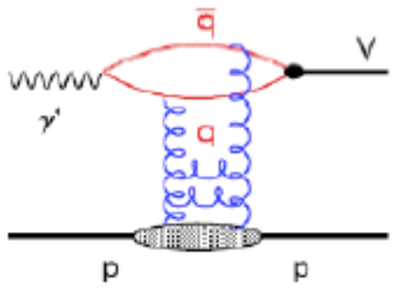
The Dipole-Proton Interaction

2. dipole – proton interaction - The interesting physics





LO 2 gluons



LL1/x ladder

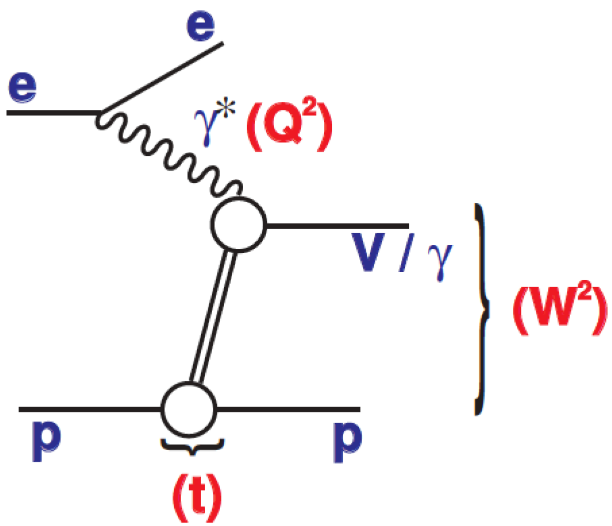
In principle, VM production is a promising candidate to learn about the gluon distribution in the proton

Many models on the details of $\sigma(r)$!

What is the relevant scale?... r depends on Q^2 and M_V^2

$$Q^2_{eff} = z\,(1-z)\,(Q^2+M_V^2) \sim (Q^2+M_V^2)\,/\,4$$

Vector Mesons & the Soft → Hard Transition



Behaviour usually parameterised in Regge-theory motivated form

$$\frac{d\sigma_{el}}{dt} \sim \left(\frac{W^2}{W_0^2}\right)^{2\alpha(t)-2} e^{bt}$$

– $\alpha(t)=\alpha(0)+\alpha' t$ is the effective pomeron trajectory
eg $\alpha(t) \sim 1.08 + 0.25t$ for soft pomeron

- e^{bt} empirically motivated – Fourier transform of spatial distribution of interaction
$b = b_{dipole} + b_{proton} \rightarrow b_{proton}$ as dipole size → 0

- Signatures for 'hard' behaviour include increase in $\alpha(0)$, decrease in b and (maybe) decrease in α'

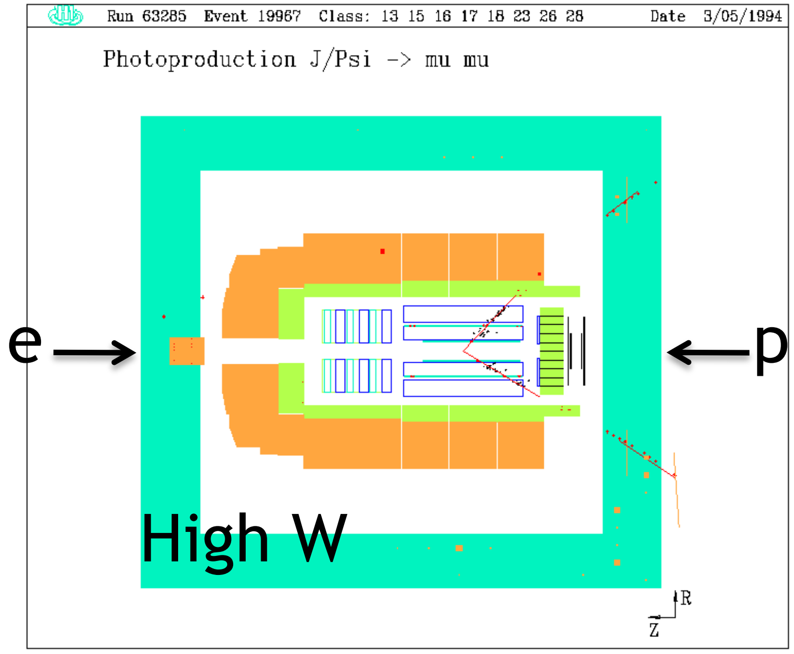
Experimental Selection

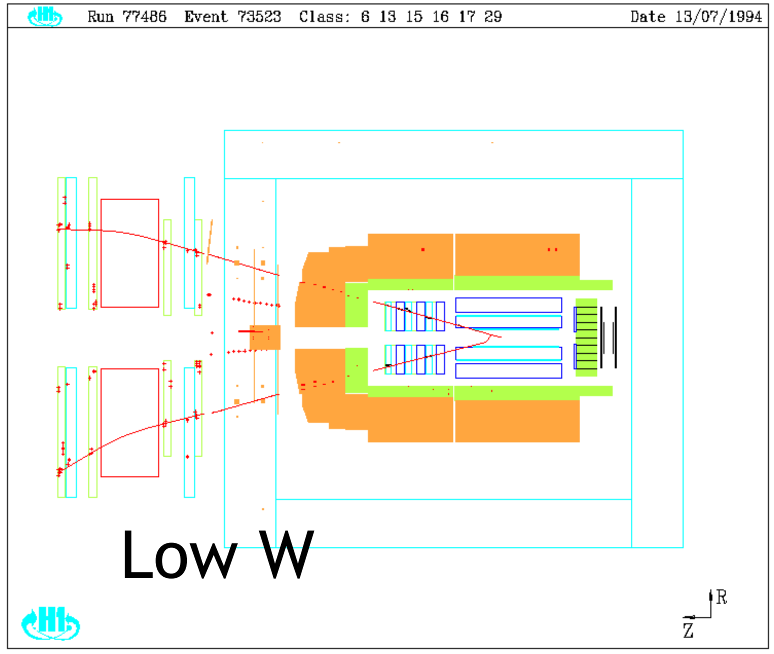
2-prong decays give beautifully clean events.

→ Select by requiring otherwise empty detector

→ Decay muon direction is determined by $W = \sqrt{s_{\gamma p}}$

e.g. Elastic J/Ψ → μμ





Photoproduction of Light v Heavy VM

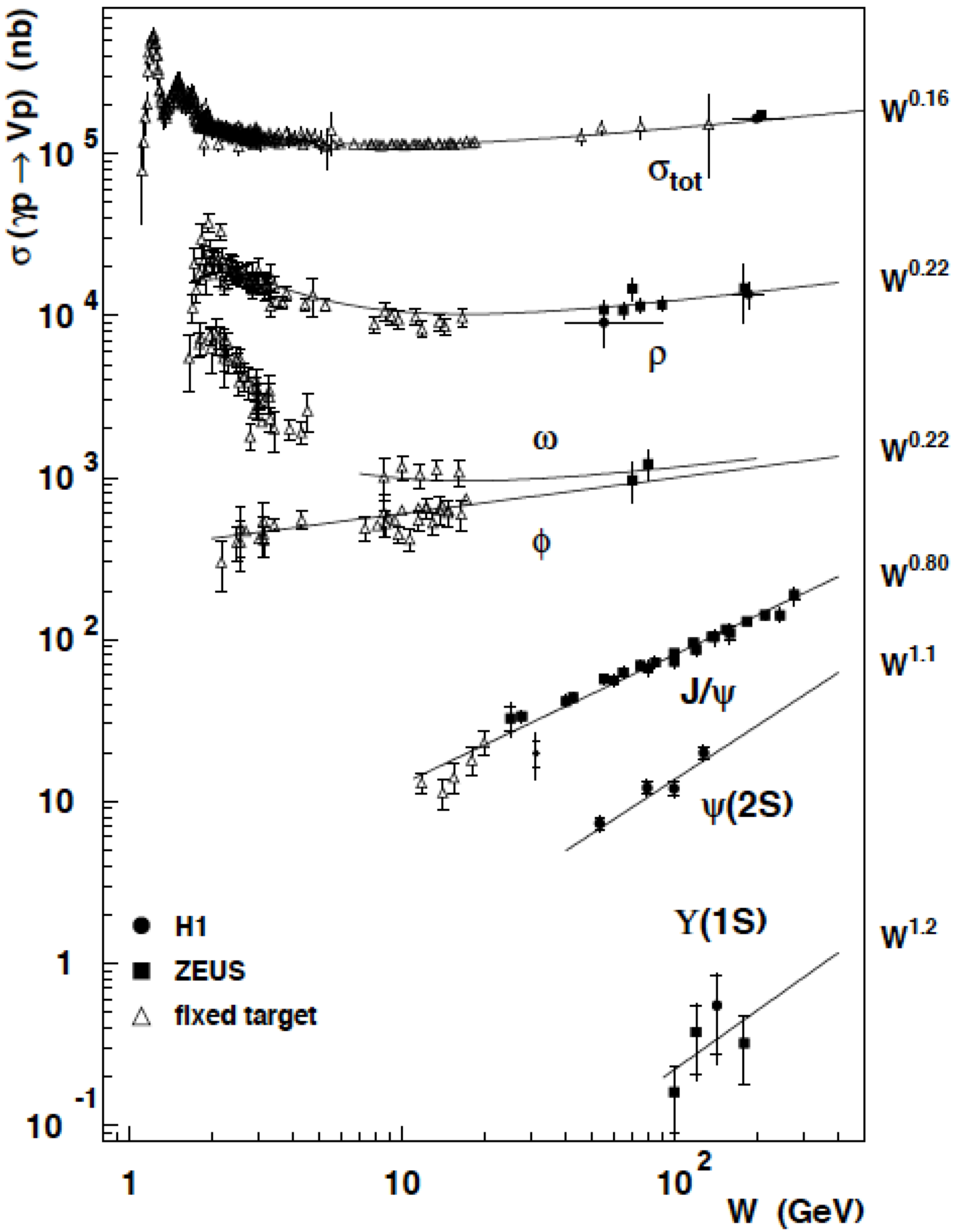
Increasing M_V leads to harder energy dependences

$\sigma \propto W^{\delta}$ with $\delta=4\alpha(<t>)-4$

- Consistent with soft pomeron for light vector mesons

- For J/Ψ, effective $\alpha(t) \sim 1.20 + 0.13t$

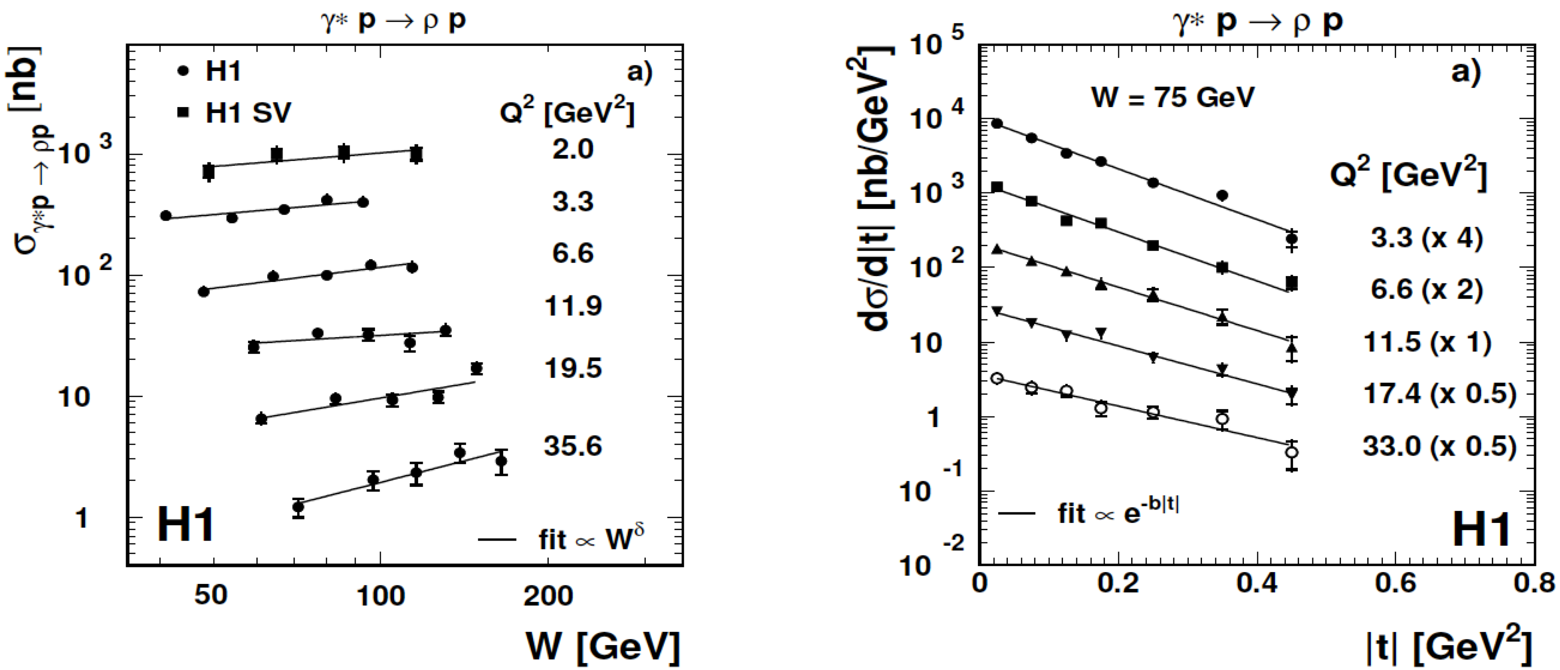
… c, b mass implies pQCD already valid for J/Ψ, Υ at $Q^2 = 0$



Turning the Q^2 Handle

-J/Ψ: W & t dependences ~ unchanged - already hard @ Q^2=0

- Light vector meson behaviour evolves from soft to hard



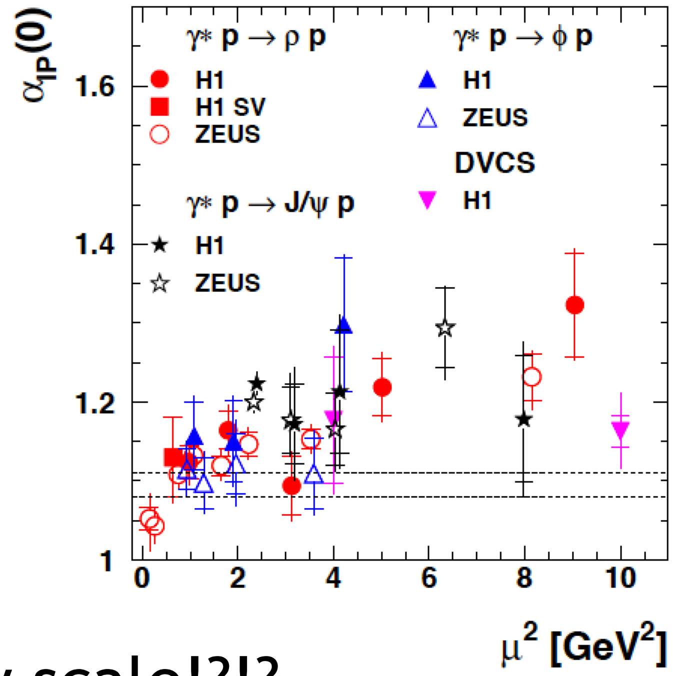
- Vector mesons produced from longitudinal and transverse polarised photons behave slightly differently
- Fast reduction in cross section illustrates higher twist nature of process: $\sigma_L \sim 1/(Q^2+M_V^2)^{2.1}$, $\sigma_T \sim 1/(Q^2+M_V^2)^{2.9}$
… reasonably well described by dipole (2 gluon) models

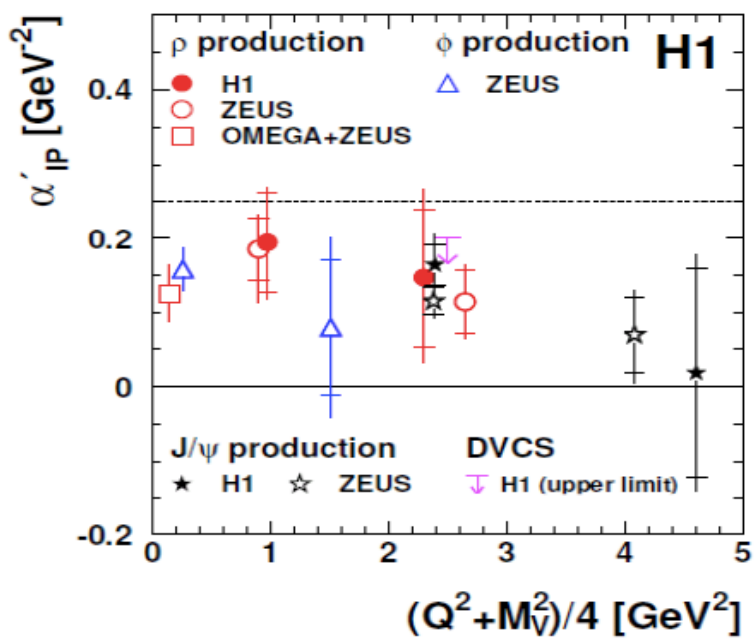
VM Characterisation Summary

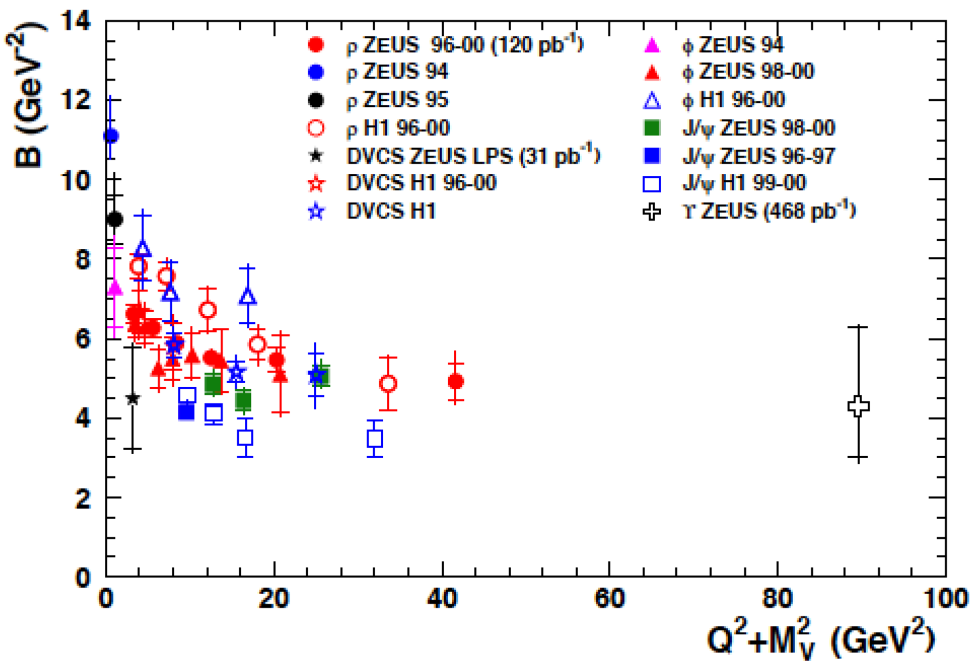
- Approximate scaling between different meson species in $(Q^2 + M_V^2)/4$

-t-slope approaches B~ 4-5 GeV^{-2} ~ 0.6fm … slightly smaller than EM size of proton?

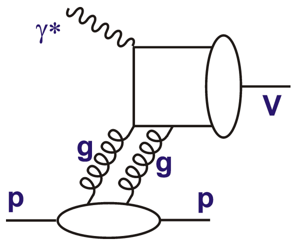
– α' shows no significant variation with any scale!?!?

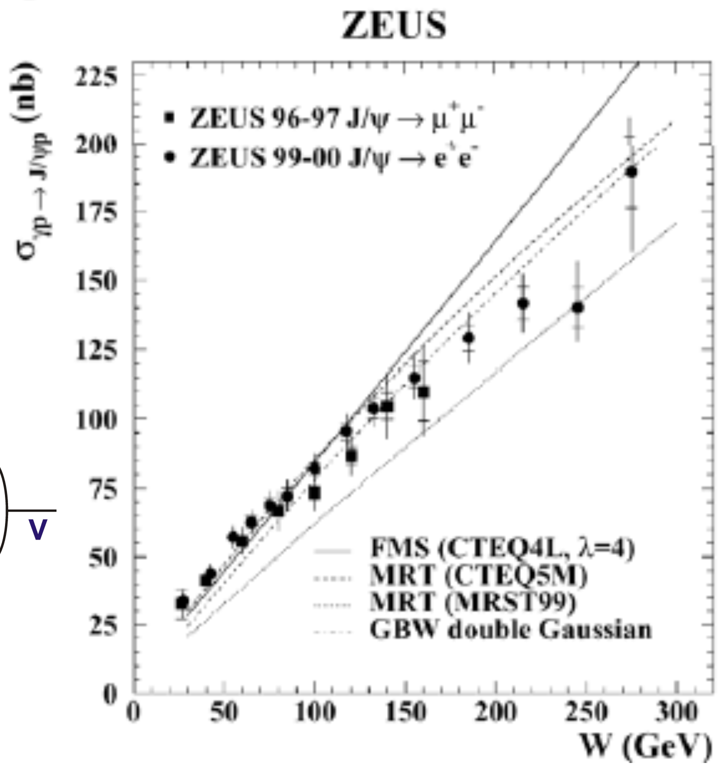


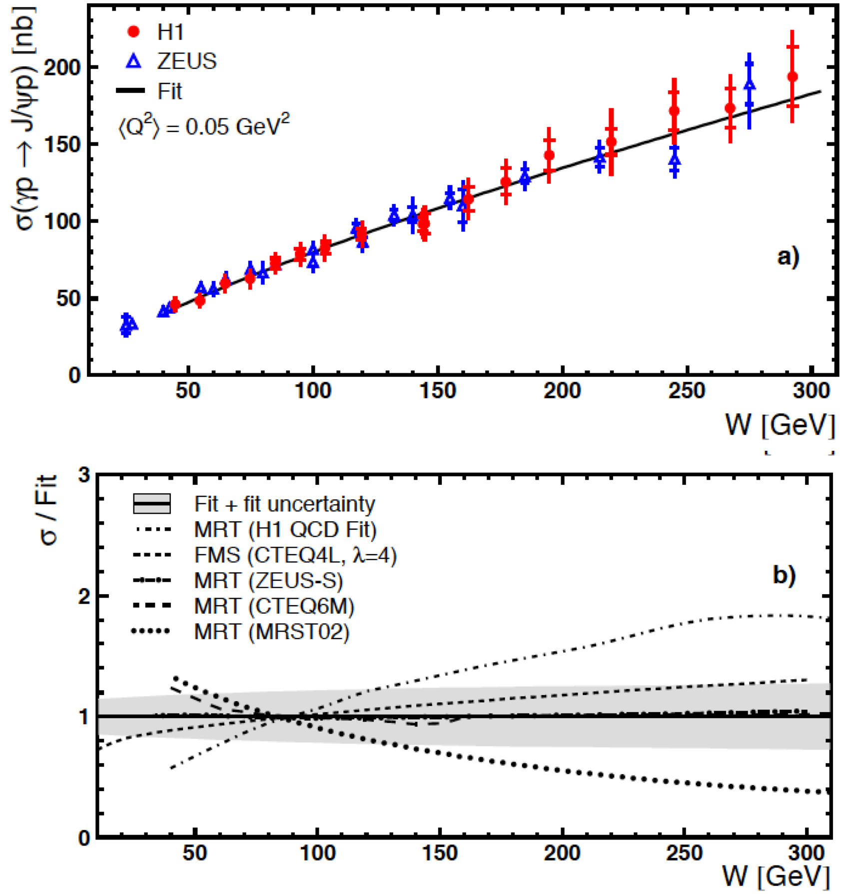


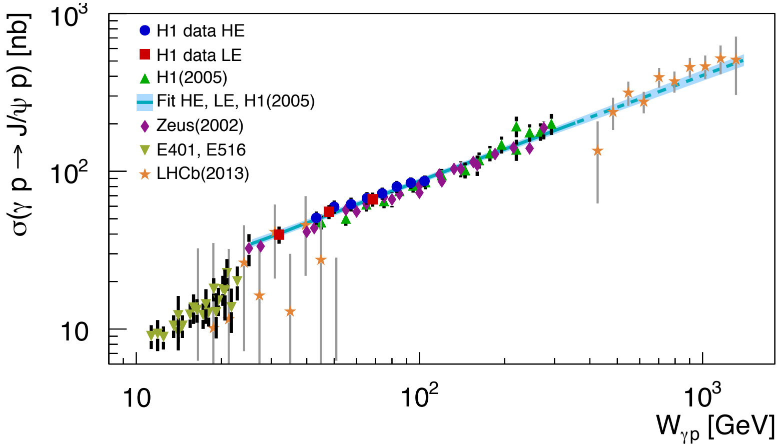


Photoproduction of J/Ψ and the Gluon Density



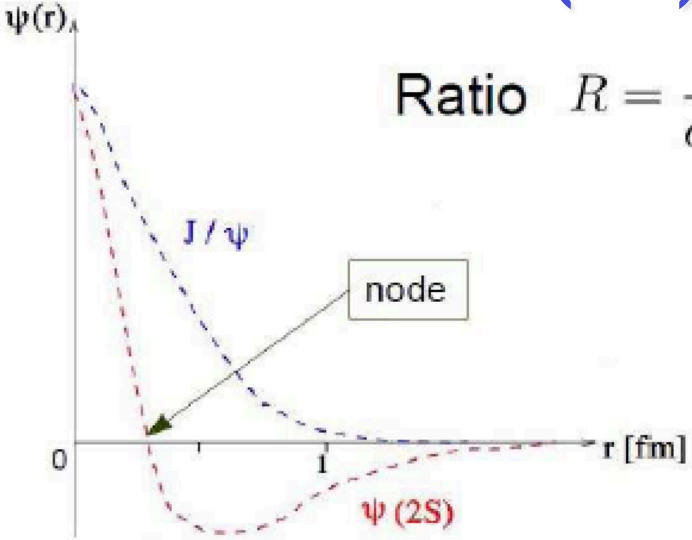






- QCD models based on 2-gluon exchange describe data well & show power to discriminate between PDFs
- Sensitivity limited by theory uncert’s (wavefunctions, scales …)
- Now studied in Ultra-peripheral collisions at the LHC

Testing Understanding of the Wavefunction: $\Psi(2S)$ / $J/\Psi(1S)$ ratio



Ratio $R = \frac{\sigma_{\gamma p \to \psi(2S) p}}{\sigma_{\gamma p \to J/\psi p}}$ gives information about the dynamics of hard process

sensitive to radial wave function of charmonium

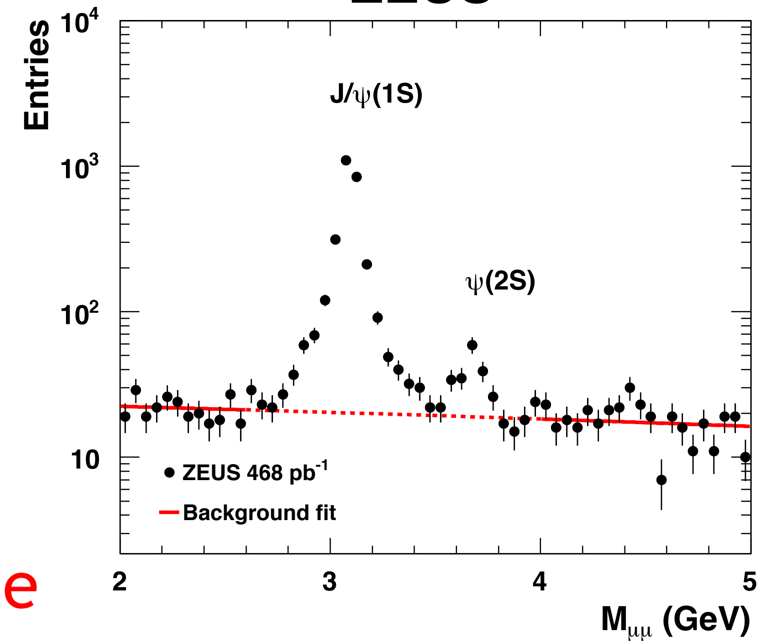
$\psi(2S)$ wave function different from J/ψ wave function:

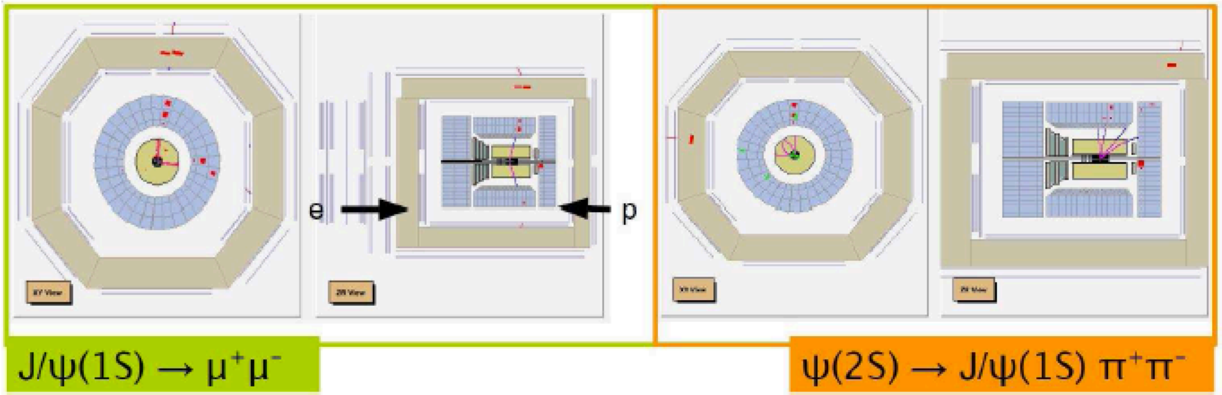
- Has a node at $\approx$ 0.35 fm
- $\langle r^2_{\psi(2S)} \rangle \approx 2 \langle r^2_{J/\psi(1S)} \rangle$

(-ish)

→ pQCD predicts ratio ~0.17 at Q^2=0, rising as Q^2 increases and <r> probed decreases

→ZEUS measurement with 468pb^{-1} sample



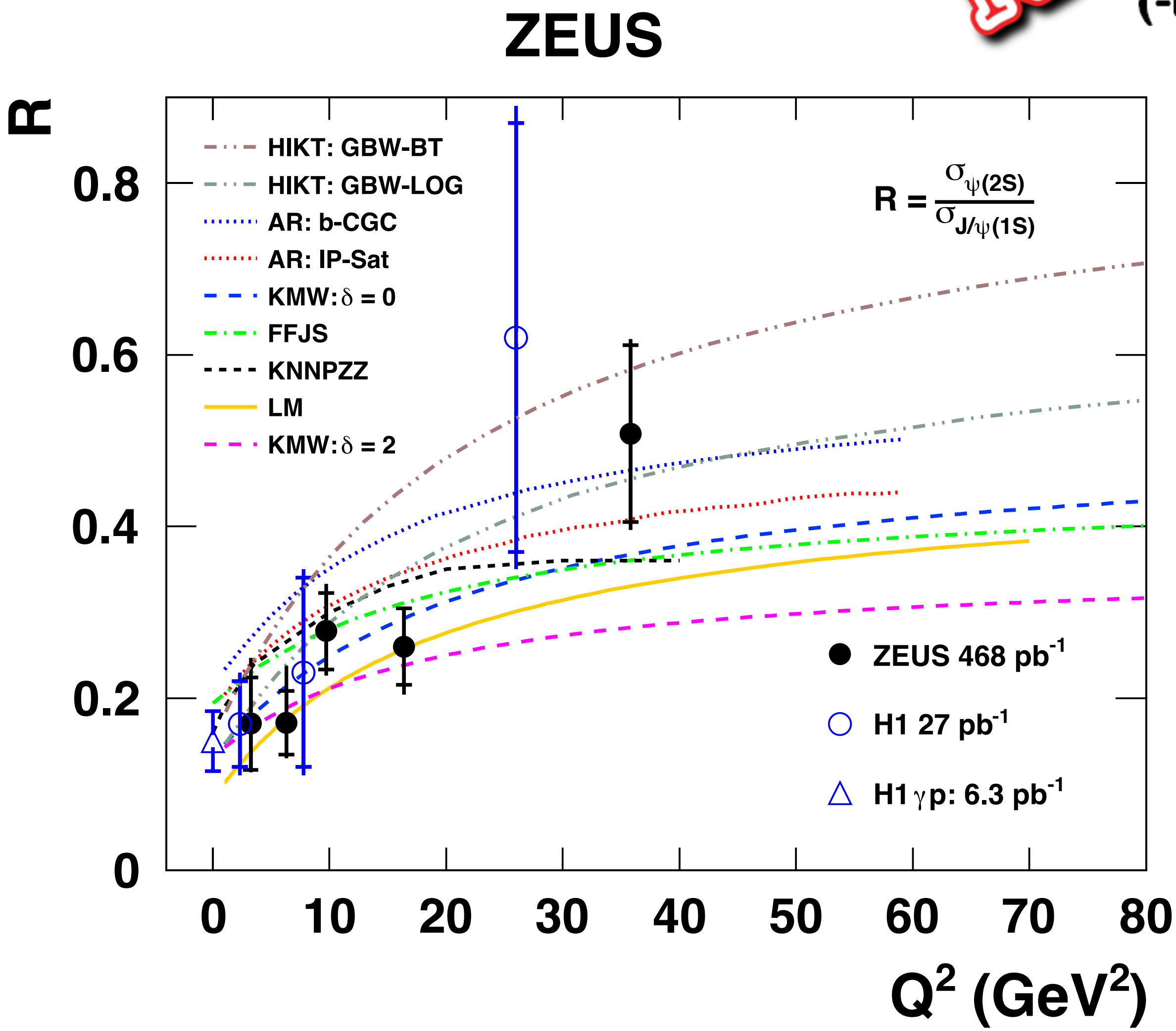


Ψ(2S) / J/Ψ(1S) ratio

NEW! (-ish)

- Data in qualitative agreement with pQCD models

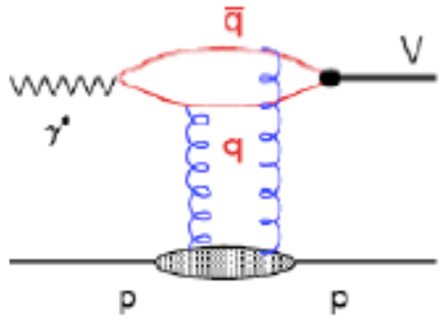
-Some distinguishing power, though statistically limited at large Q^2



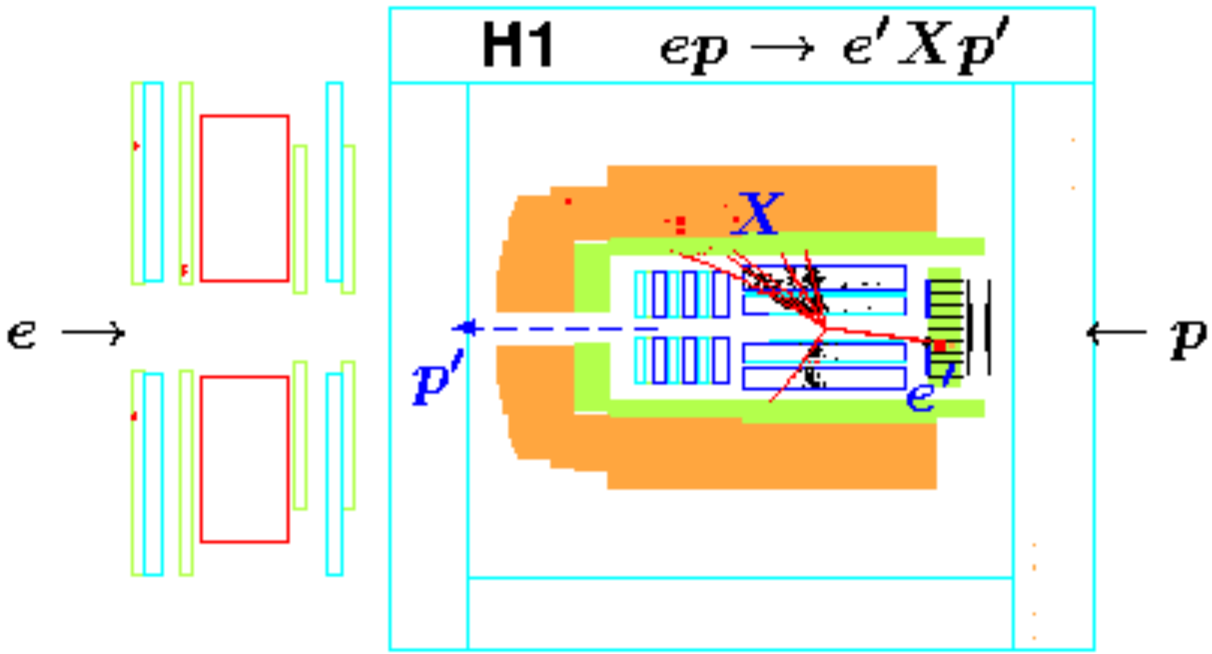
Inclusive Diffraction in Deep Inelastic Scattering

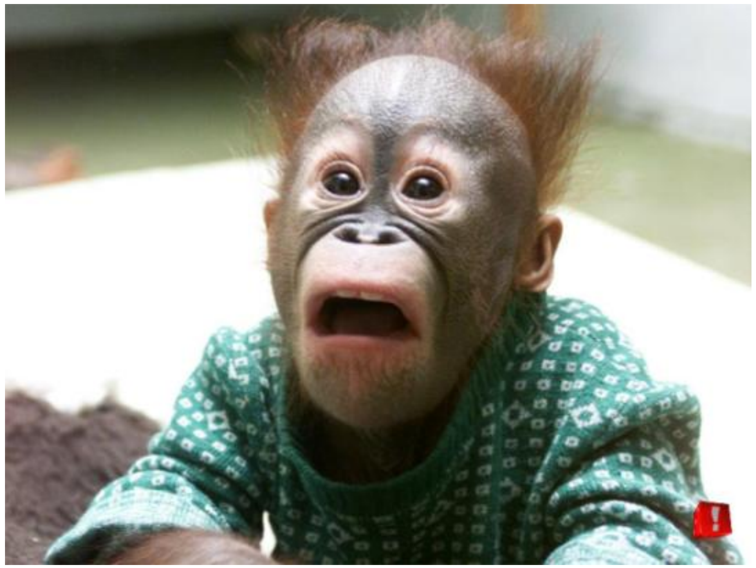
Diffractive DIS

Vector meson production is a 'higher twist' (Q^2 suppressed) process



There are 'leading twist' diffractive processes with same Q^2 dependence as the bulk DIS cross section …

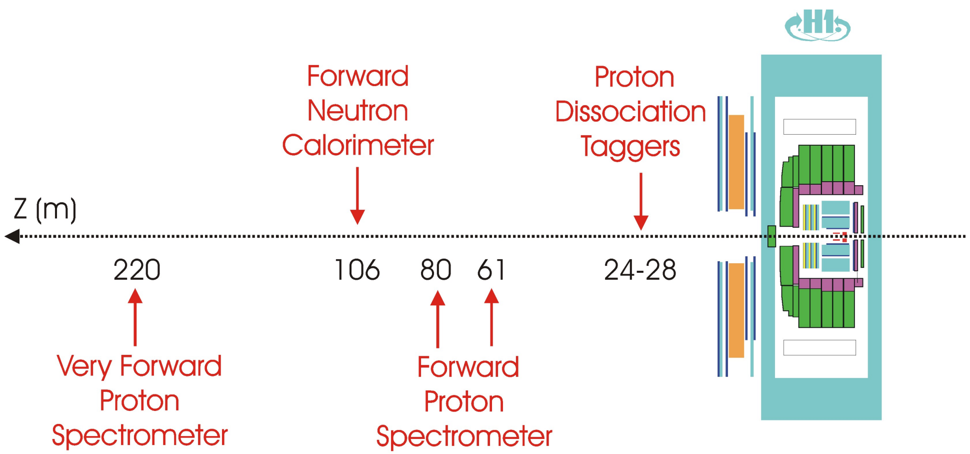




~10% of DIS events have no forward energy flow

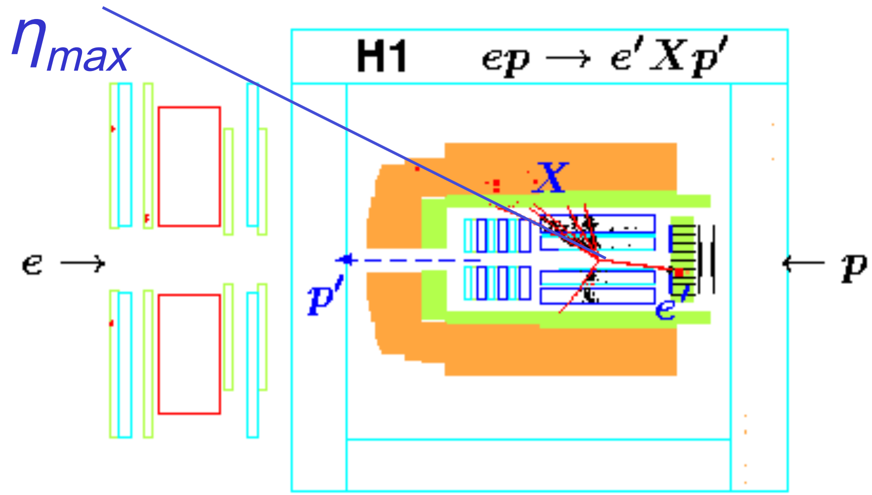
Signatures and Selection Methods

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



Limited by statistics and p-tagging systematics

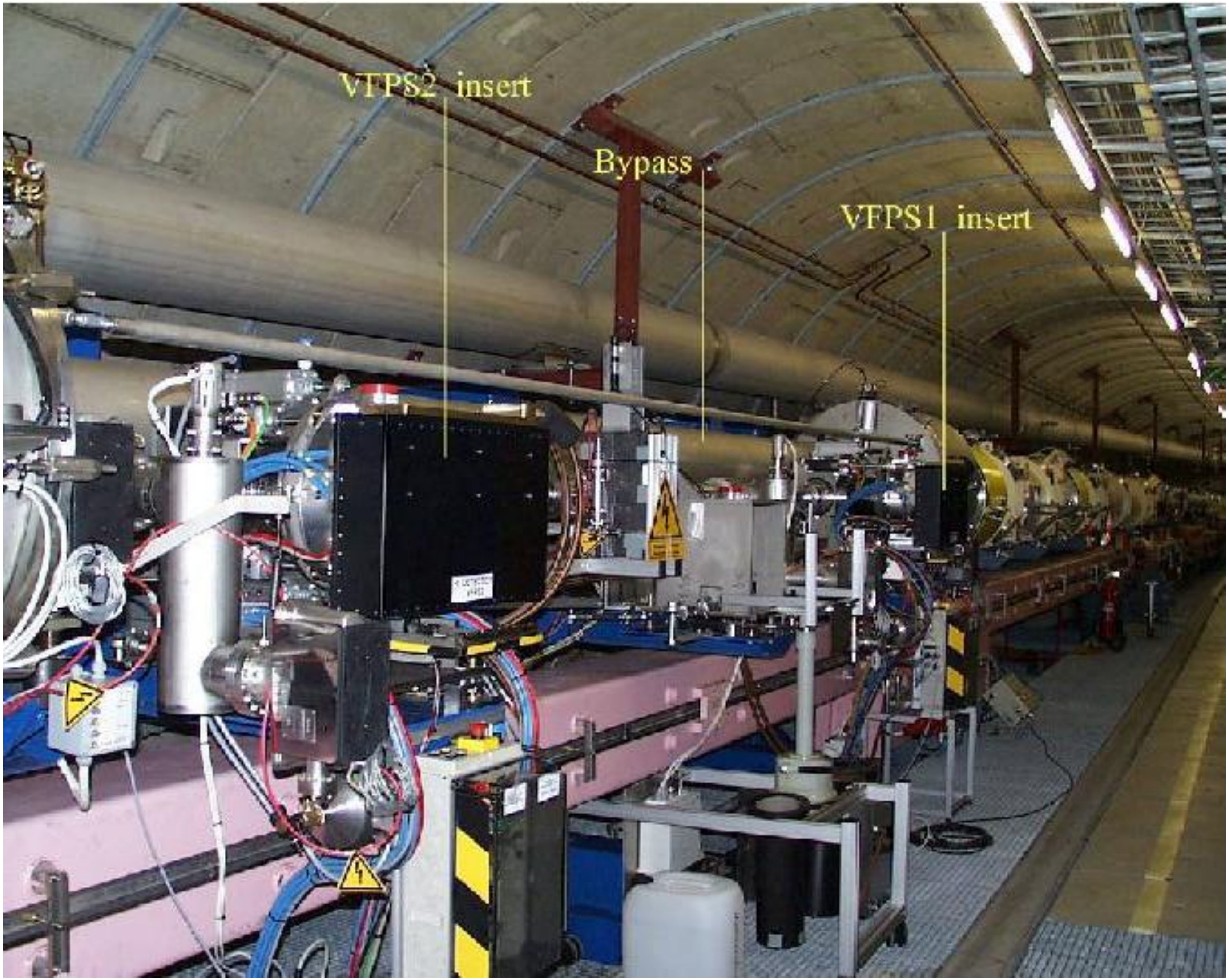
`Large Rapidity Gap' **(LRG)** adjacent to outgoing (untagged) proton



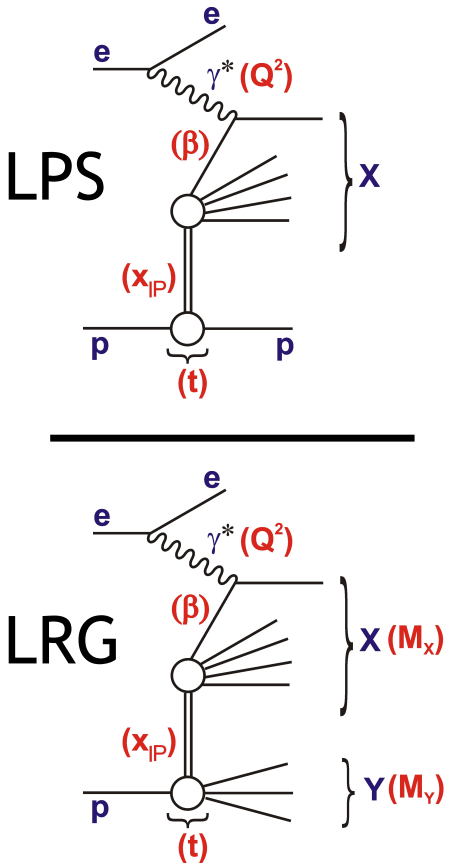
Limited by p-diss systematics

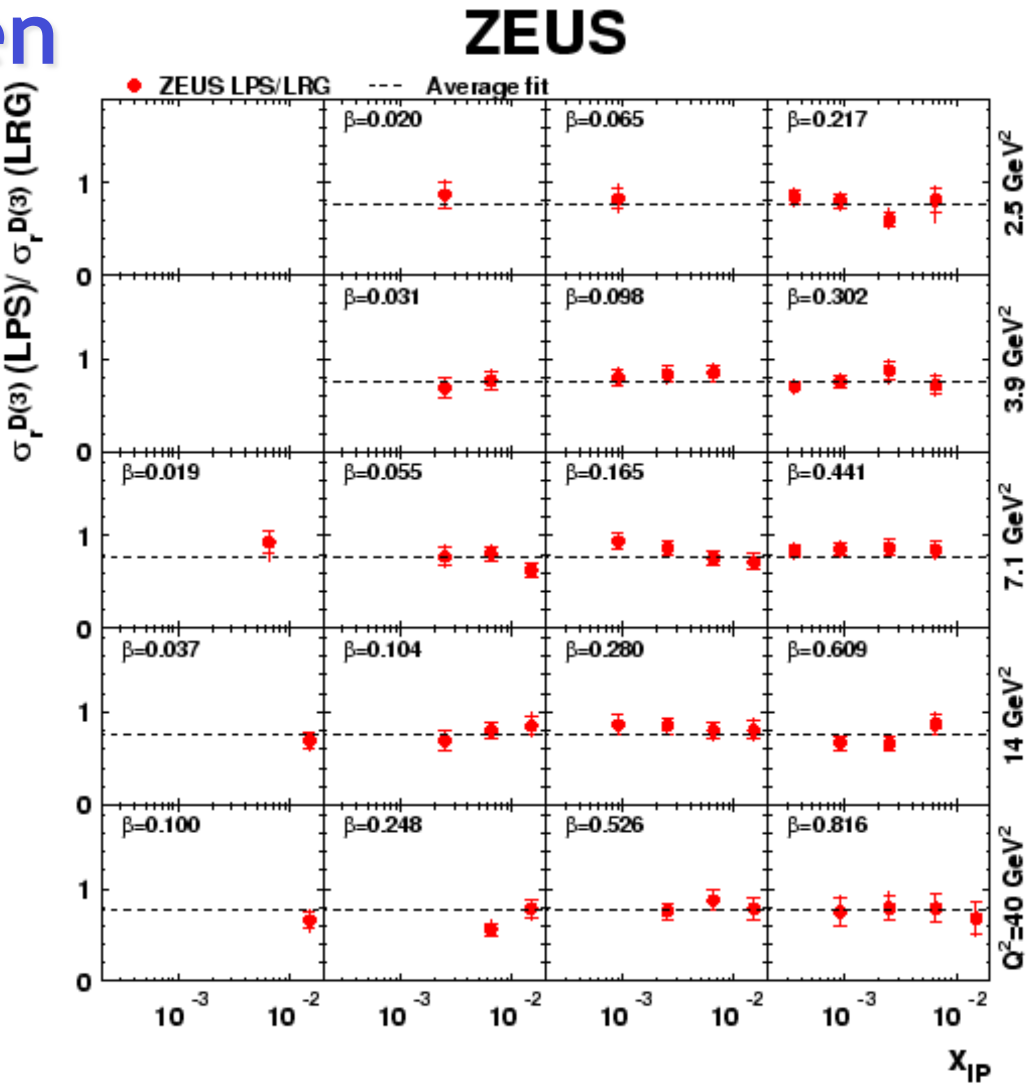
• The 2 methods have very different systematics

Example Roman Pots (H1 VFPS)



Comparisons between Methods





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

Measurements and Observables

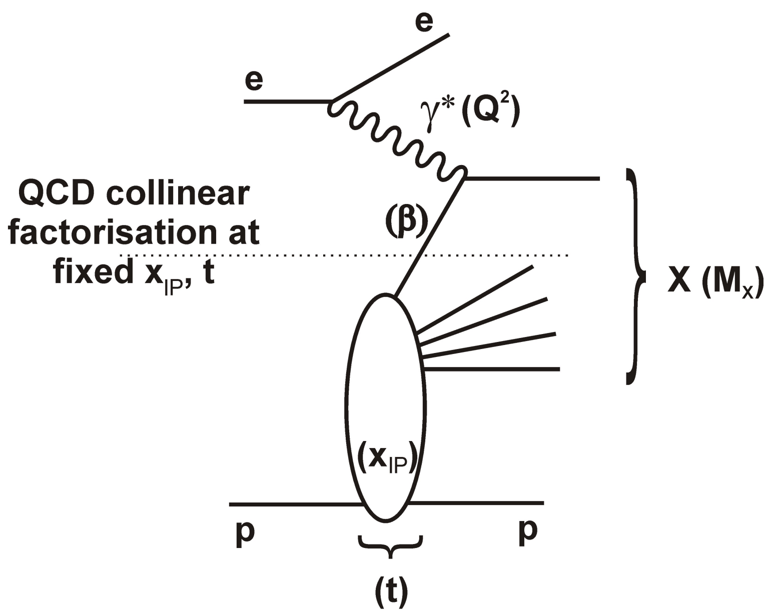
Main observable is the Diffractive `reduced cross section' …

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

… cross section (or structure fn.) dependent on 3 variables

… 4 if you also include t → $\sigma_r^{D(4)}(\beta, Q^2, x_{IP}, t)$

… can only realistically study 1 (maybe 2) variables at a time!



"Semi-inclusive QCD Factorisation"

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

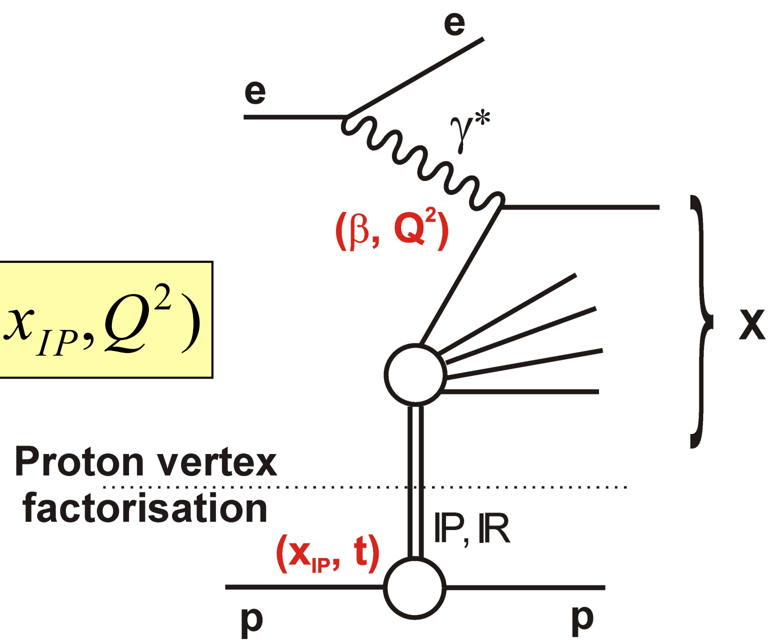
-i.e. can define

diffractive PDFs (DPDFs), f_i^D…

- At fixed (x_{IP}, t), DPDF Q^2 evolution is same as inclusive PDFs!

A deeper factorisation?

'Proton vertex' factorisation
… completely separate (x_{IP}, t) from (β, Q^2) dependences.



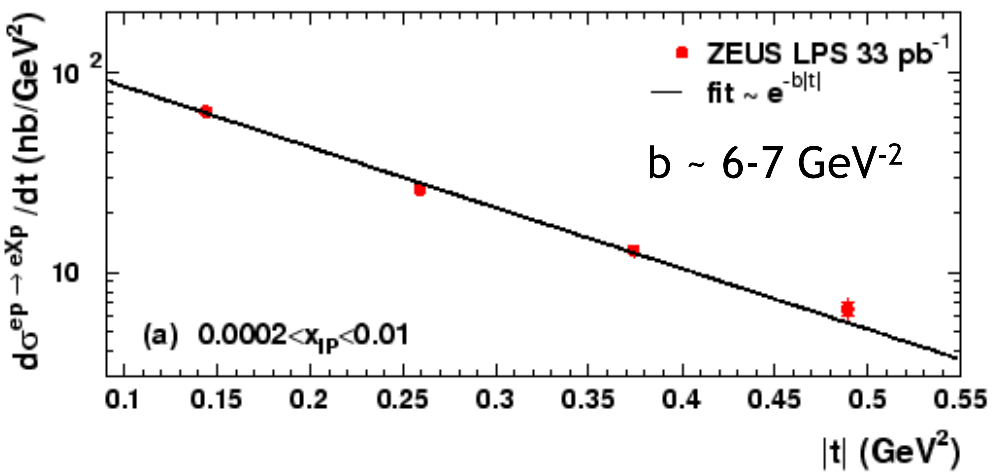
$$f_i^D(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \cdot f_i^{IP}(\beta = x / x_{IP}, Q^2)$$

No firm QCD basis, but consistent with all experimental data

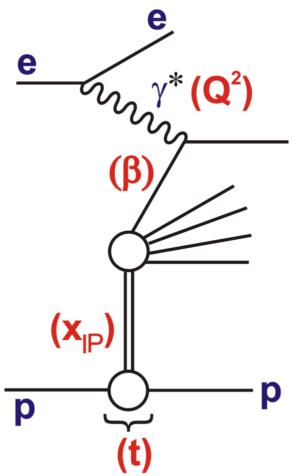
… Regge-based parameterisation works well → Ingelman-Schlein

$$f_{IP/p}(x_{IP}, t) = \frac{e^{B_{IP} t}}{x_{IP}^{2\alpha_{IP}(t)-1}}$$

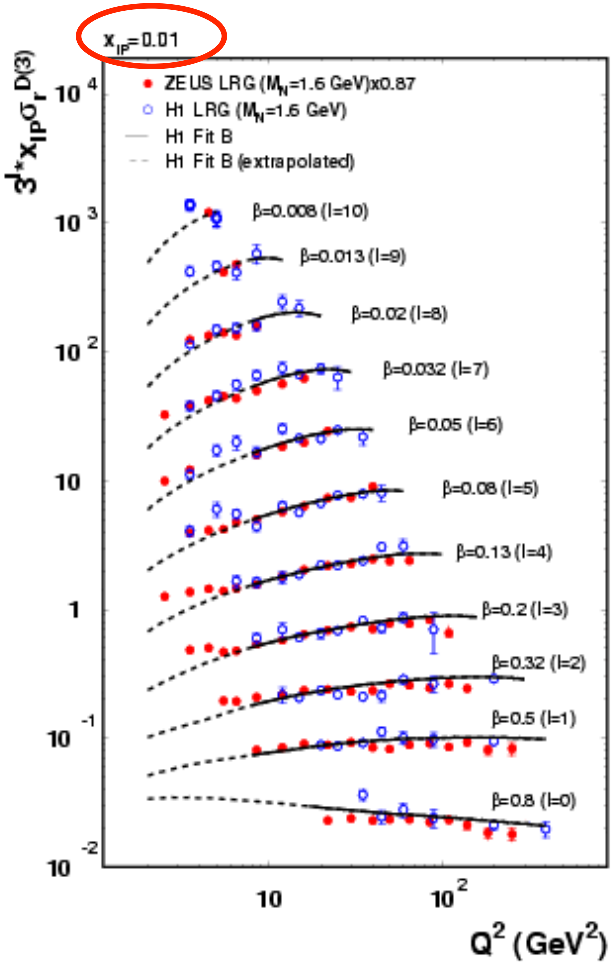
DPDFs f_i^{IP} then measure partonic structure of the exchanged system (IP)

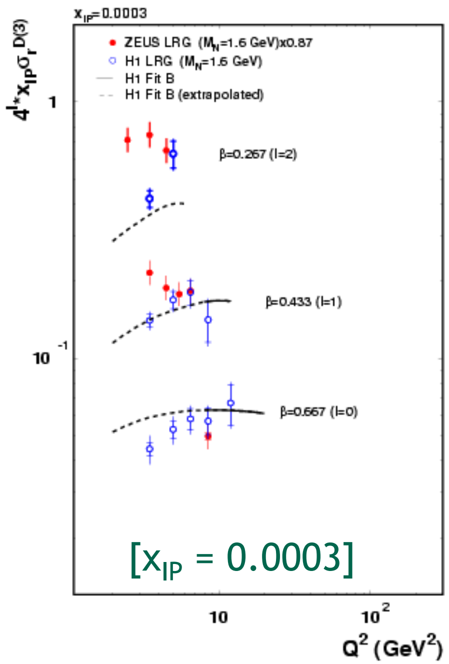


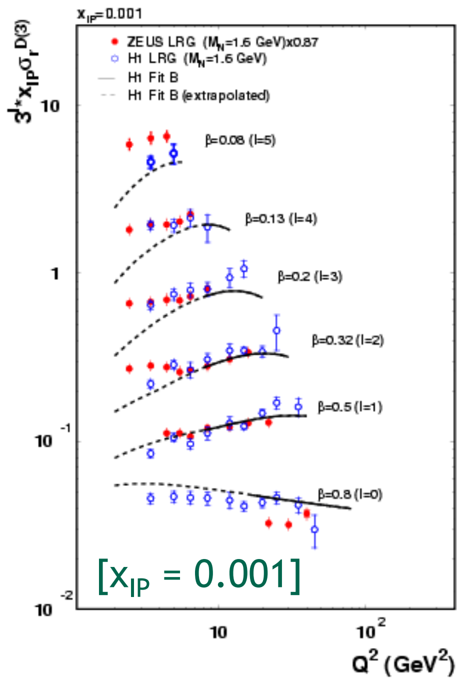
(Some) Inclusive Diffraction Data

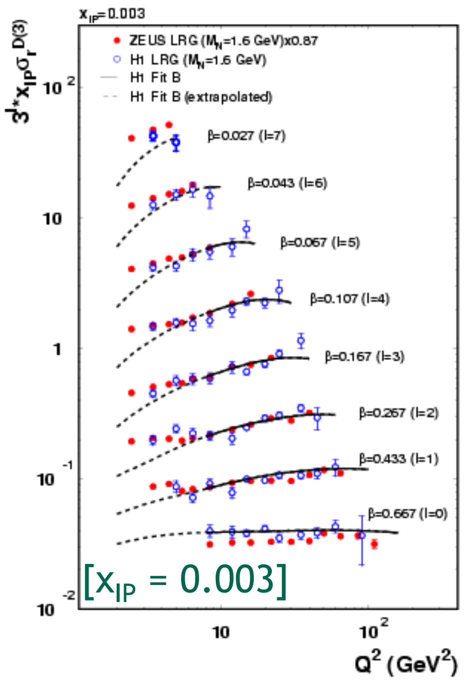


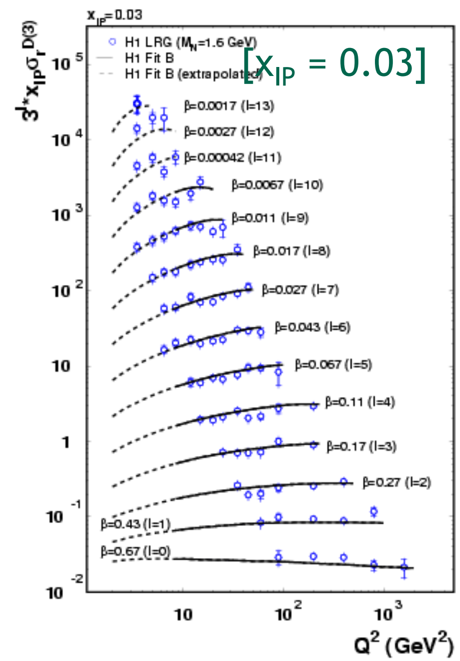
Huge topic
with
rich outputs



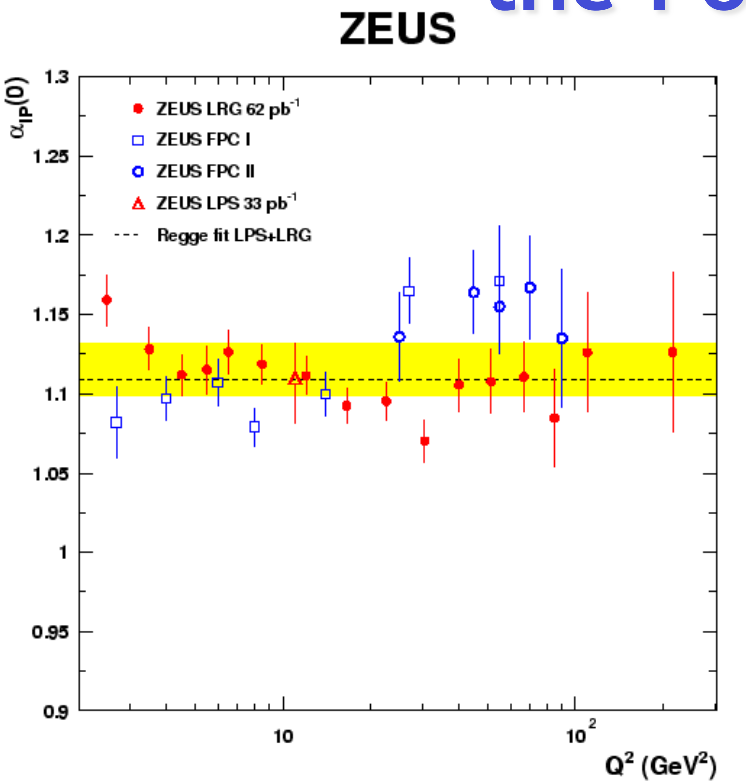


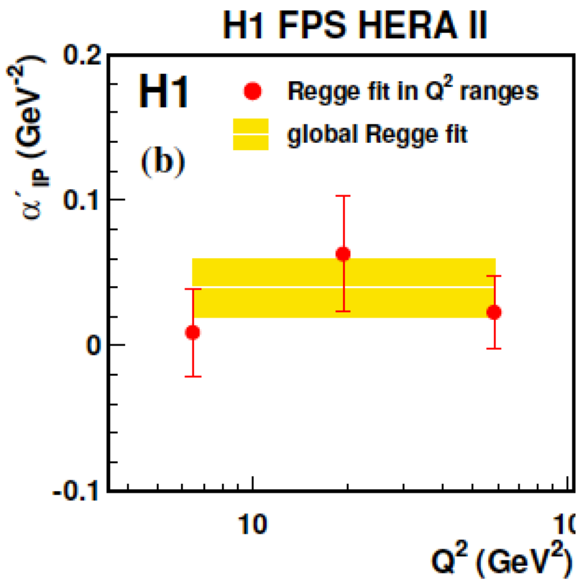


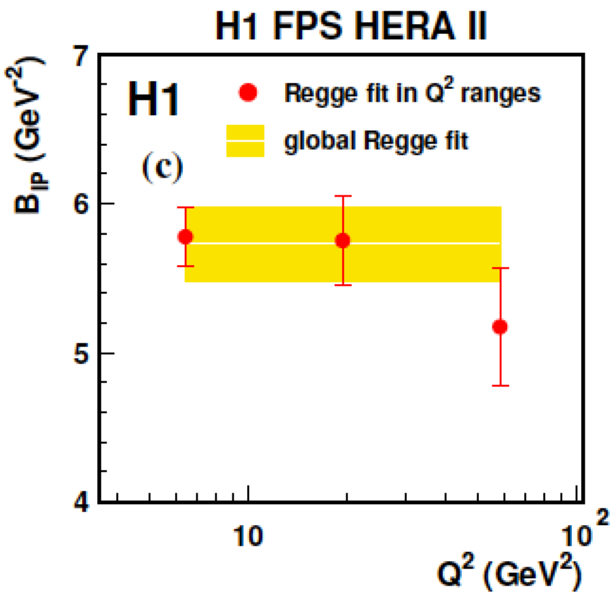




Evidence for Proton Vertex Factorisation & the Pomeron Flux Factor







Excellent consistency between experiments and methods.

e.g. From H1 FPS data:

$$\alpha_{IP}(0) = 1.10 \pm 0.02\ (\text{exp.}) \pm 0.03\ (\text{model})$$

$$\alpha'_{IP} = 0.04 \pm 0.02\ (\text{exp.}) \pm 0.07\ (\text{model})\ \text{GeV}^{-2}$$

$$B_{IP} = 5.7 \pm 0.3\ (\text{exp.}) \pm 0.9\ (\text{model})\ \text{GeV}^{-2}$$

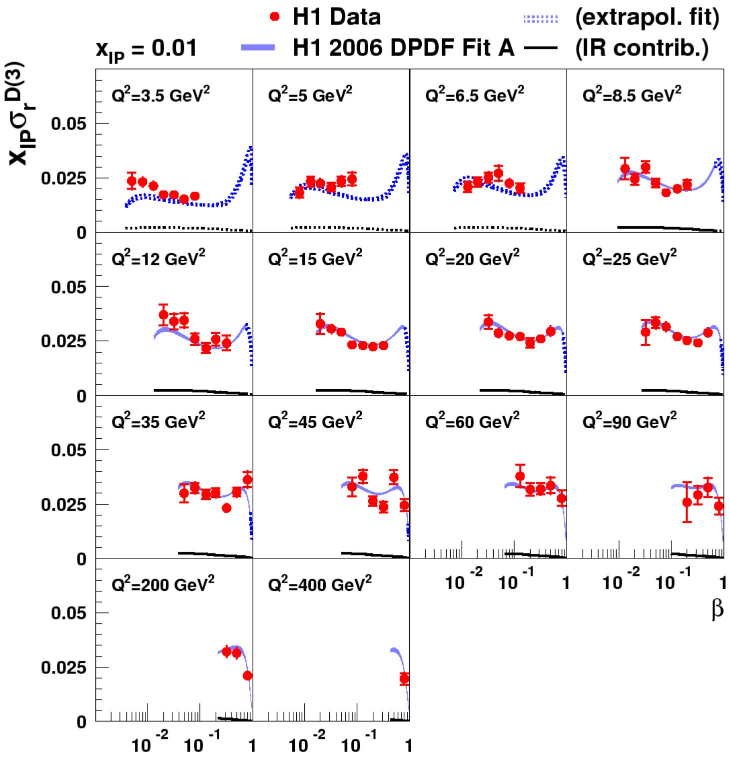
$\alpha_{IP}(0)$ consistent with soft IP → Dominantly soft exchange

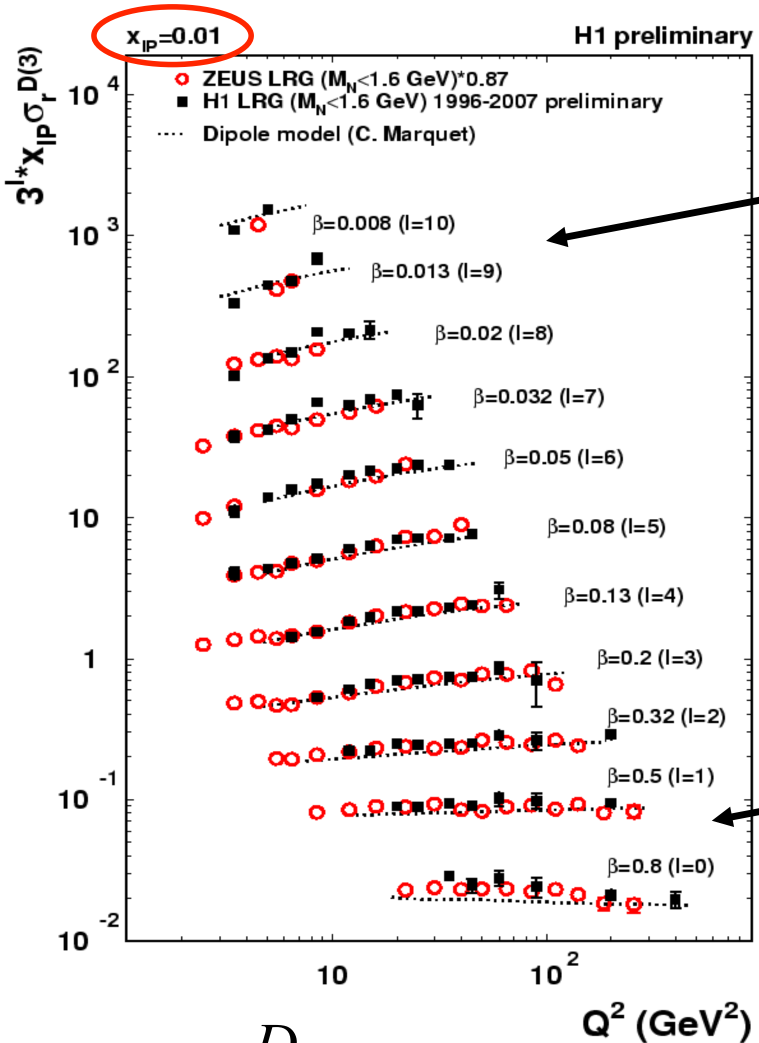
α_{IP}' smaller than soft IP → Absorptive effects?...

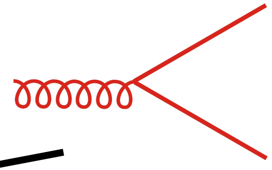
Diffractive Parton Densities and Final States

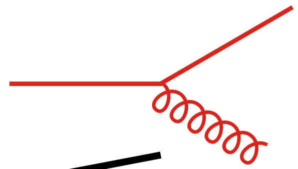
Sensitivity to Diffractive Quarks & Gluons

Similarly to Inclusive DIS …









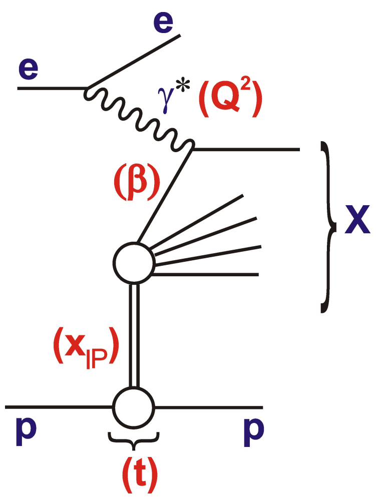
Q^2 dependence tells us gluon density via DGLAP eqns

Diffractive cross section measures quark density

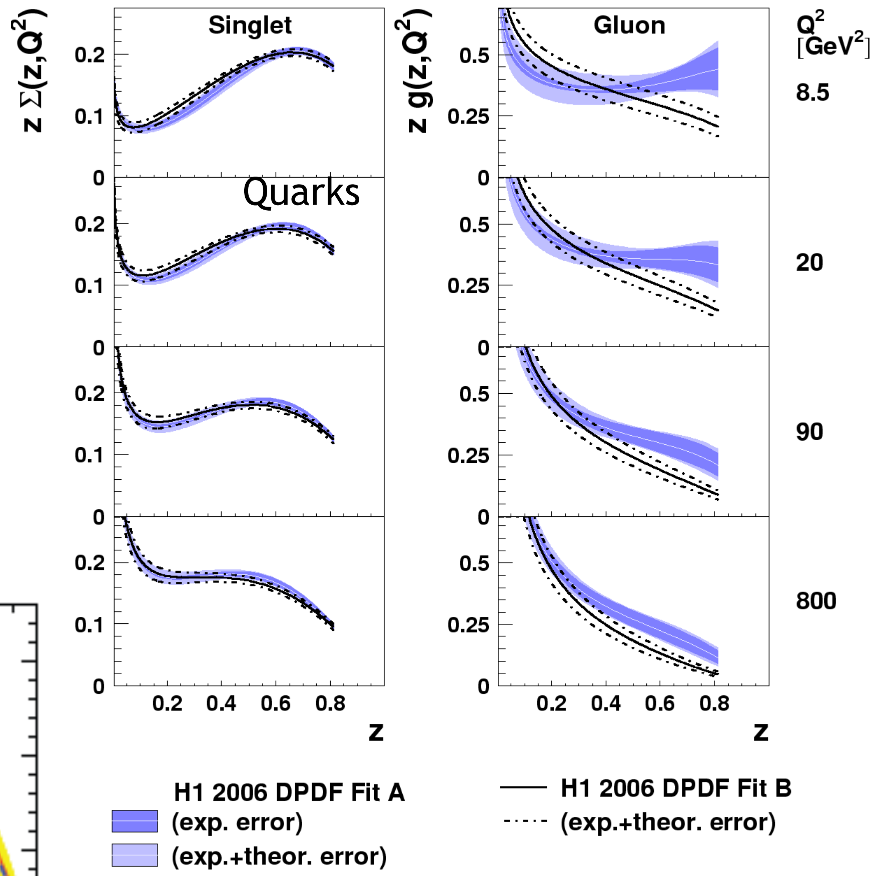
$$F_2^D = \sum_q e_q^2 \, \beta \, (q + \bar{q})$$

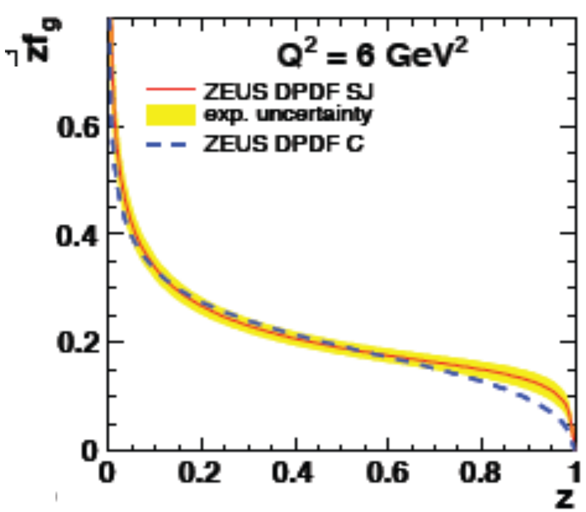
$$\frac{d\sigma_r^D}{d\ln Q^2} \sim \frac{\alpha_s}{2\pi}\left[P_{qg} \otimes g \;+\; P_{qq} \otimes q\right]$$

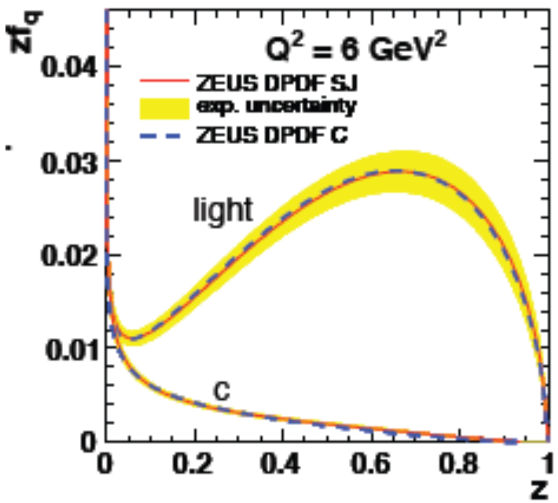
Diffractive Parton Densities (DPDFs)



DPDFs extracted through fits to inclusive (& jet) data, assuming NLO DGLAP evolution, similar to inclusive DIS



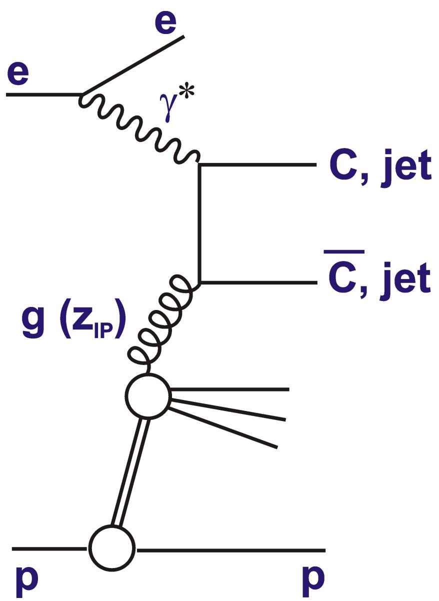




… dominated by gluon density extending to large mom fractions, z

- NLO DGLAP QCD fits describe data over most of phase space
- Failure of diffractive PDF fits to describe data at lowest Q^2 …

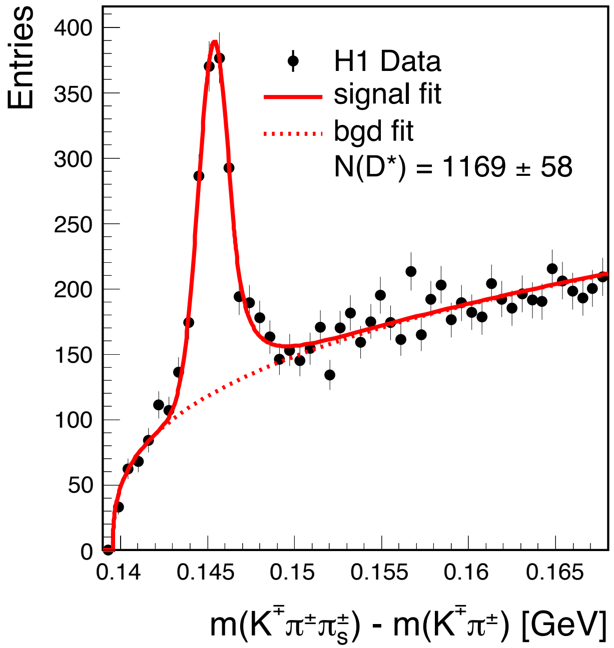
Testing Factorisⁿ and the Gluon with Charm



- Charm production up to 30% of total diffractive cross section

- Directly sensitive to gluon density

- Recent example:
H1, Eur Phys J C77 (2017) 340



- Sample of ~1170 D* mesons in $287pb^{-1}$

$$D^{*+} \rightarrow D^0 \pi^+_{slow} \rightarrow (K^- \pi^+) \pi^+_{slow} + C.C.$$

- Differential cross sections compared with NLO QCD (HVQDIS in FFNS, H1 DPDF 2006, m_c=1.5GeV, $\mu_R^2=\mu_F^2=4Q^2+m_c^2$, charm frag function from H1 non-diff analysis

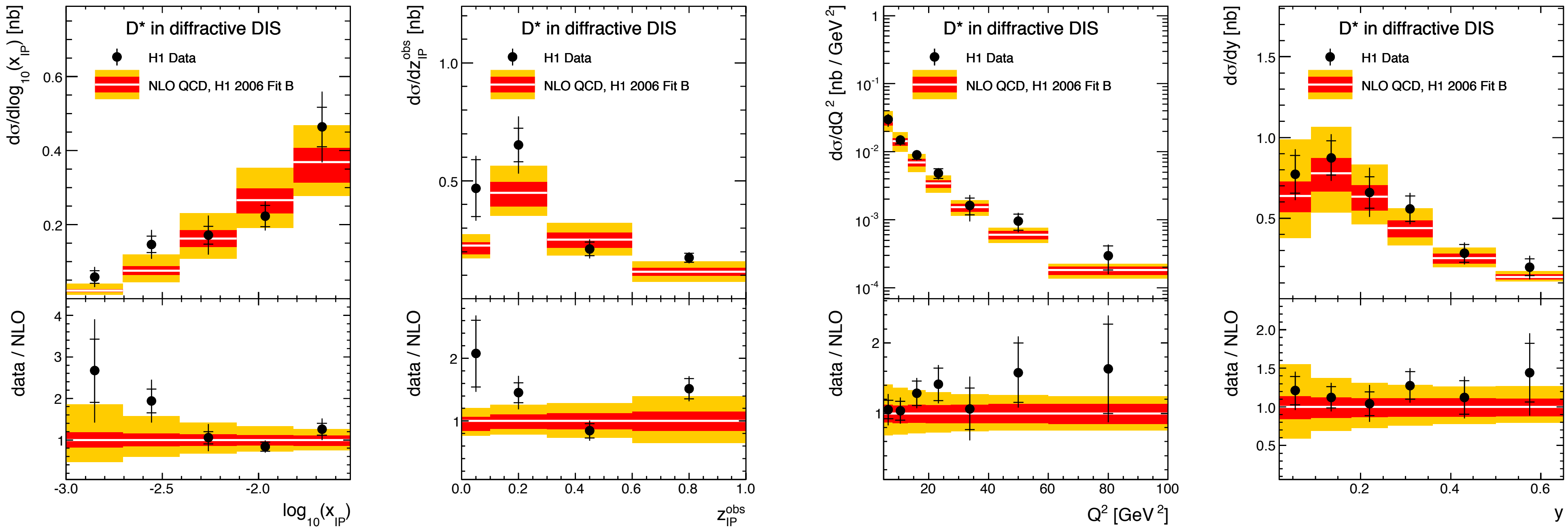
DIS phase space
$5 < Q^2 < 100$ GeV^2 $0.02 < y < 0.65$
D^* kinematics
$p_{t,D^*} > 1.5$ GeV $-1.5 < \eta_{D^*} < 1.5$
Diffractive phase space
$x_{I\!P} < 0.03$ $M_Y < 1.6$ GeV $\|t\| < 1$ GeV^2

Differential D* Cross Sections

Integrated over all phase space:

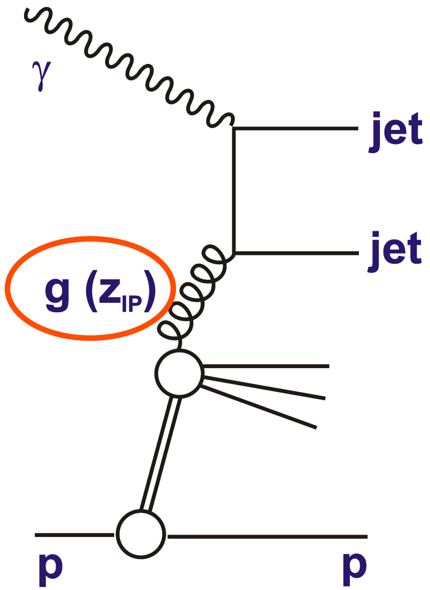
$$\sigma_{ep \to eYX(D^*)} = 314 \pm 23 \text{ (stat.)} \pm 35 \text{ (syst.) pb.}$$

$$\sigma^{\text{theory}}_{ep \to eYX(D^*)} = 265 \,^{+54}_{-40} \text{ (scale)} \,^{+68}_{-54} \,(m_c)\, ^{+7.0}_{-8.2} \text{ (frag.)} \,^{+31}_{-35} \text{ (DPDF) pb.}$$



Remarkable agreement over wide kinematic range

Testing Factorisation / Gluon with Jets

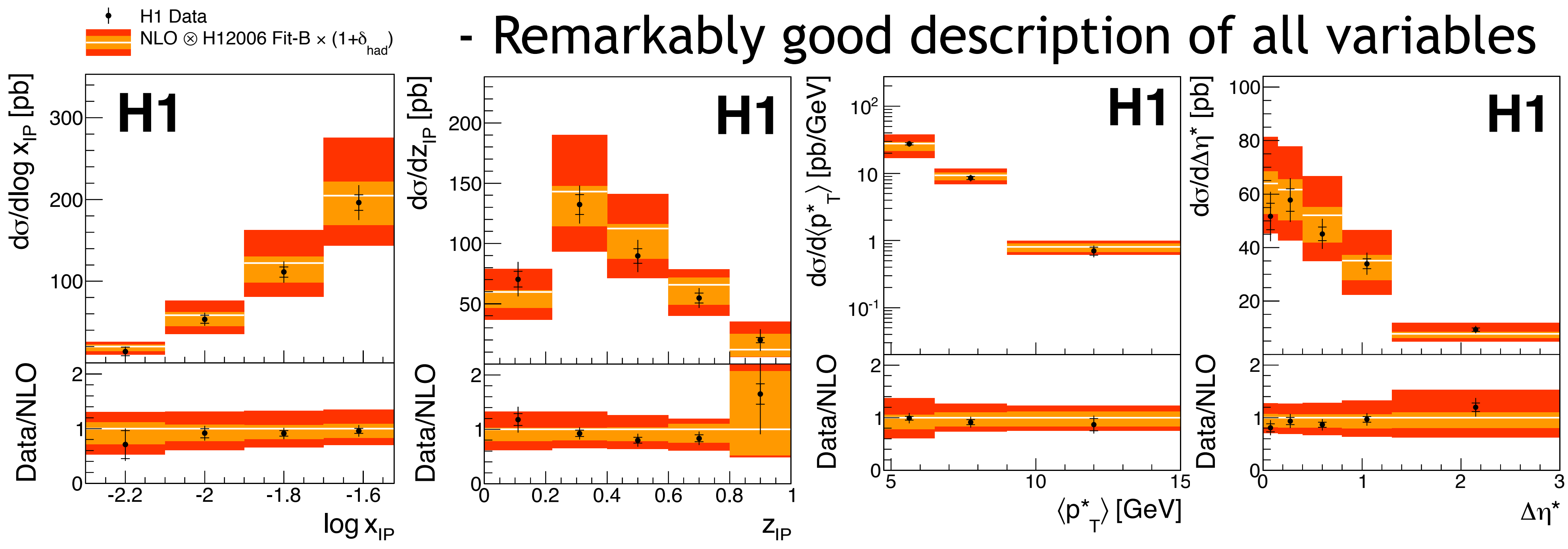


- Most recent measurement H1 (2015) using rapidity gaps and $E_T^{jet1,2}$ > 5.5 GeV, 4GeV

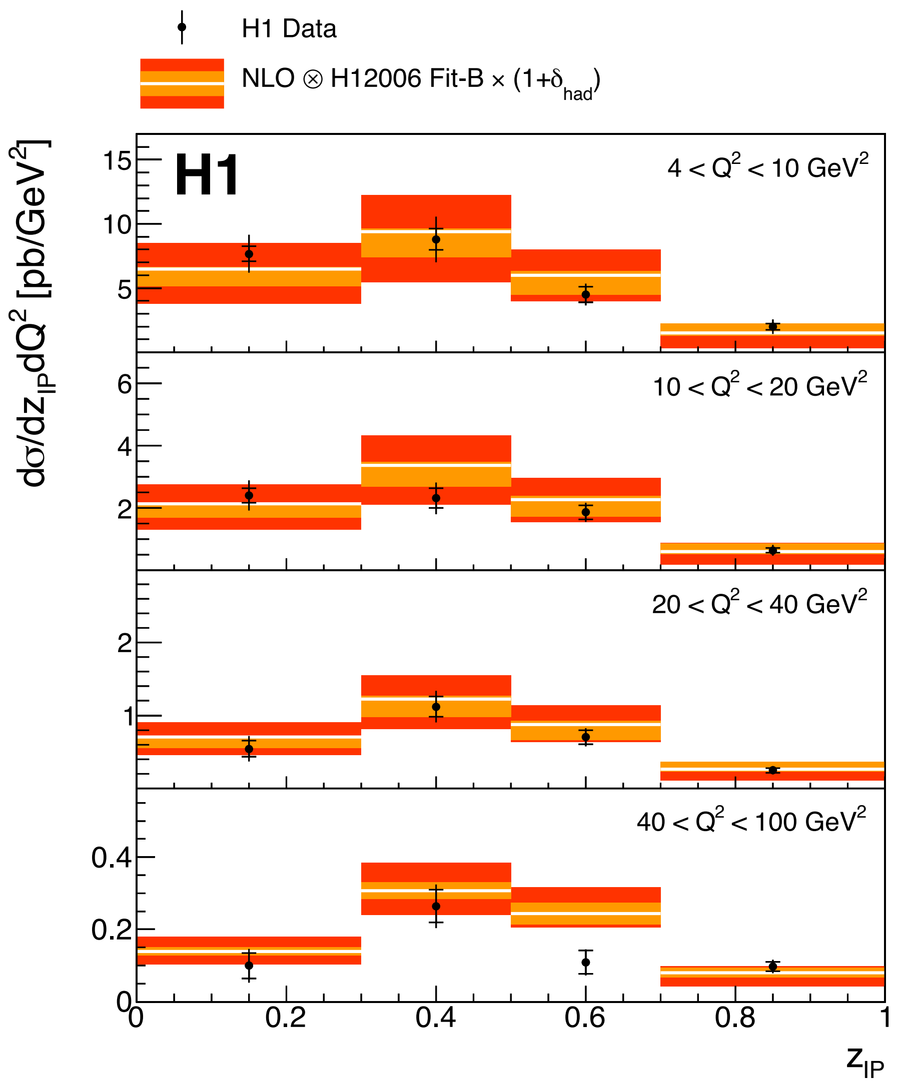
NEW! (-ish)

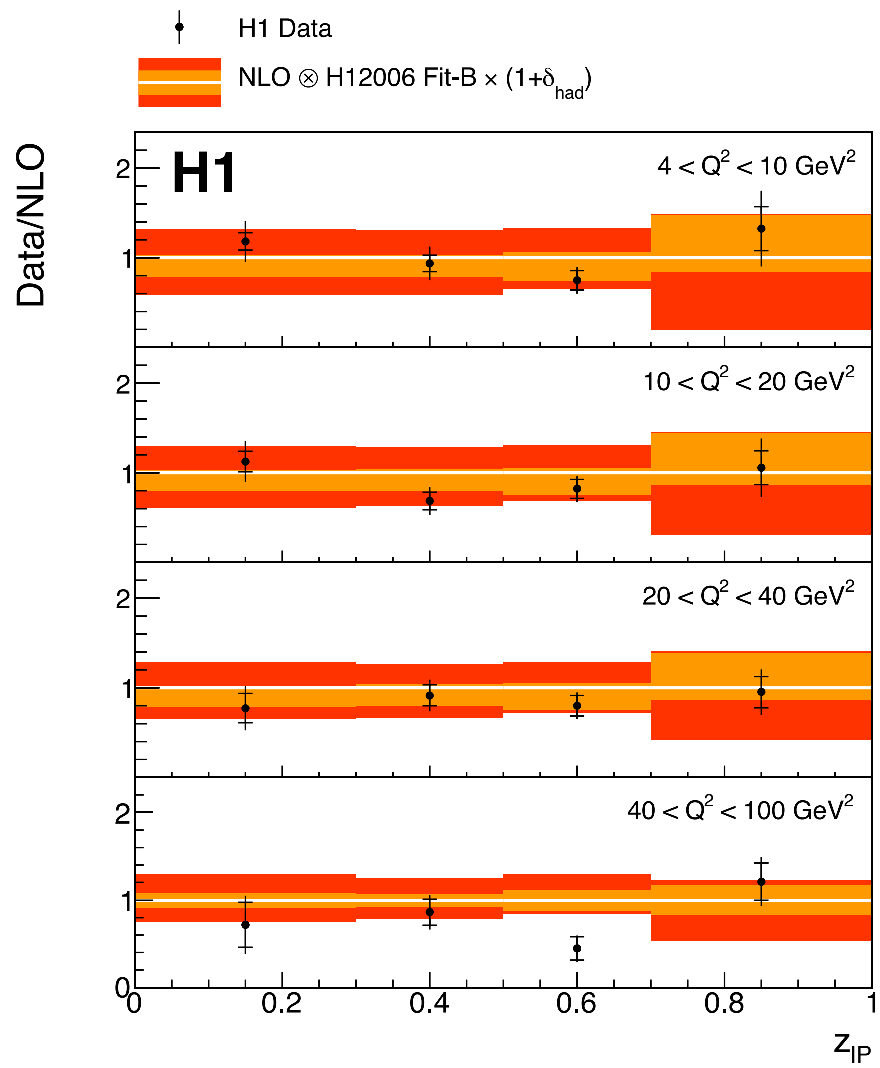
- 50pb-1 compared with NLO QCD calculations → H1 2006 Fit B DPDFs, NLOJET++, $\mu_R^2=\mu_F^2=Q^2+\langle E_T^{*2}\rangle$

- Remarkably good description of all variables



Double Differential Jet Cross Sections





- Description remains excellent for all z_{IP}, Q^2

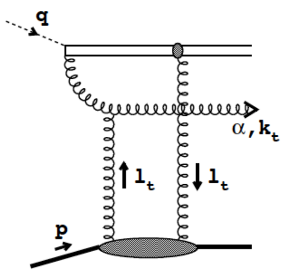
-Many more observables tested (CC, F_L^D, flow and spectra …)

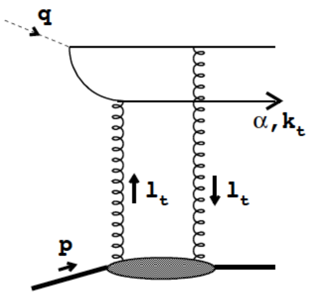
…Factorisation works in diffractive DIS at current precision

Diffractive DIS & Dipole Models

– χ^2 / ndf increases systematically in H1 DPDF fits when data of Q^2 < 8.5 GeV^2 are included (slightly lower in ZEUS)
… low Q^2 breakdown of pure Leading Twist DGLAP approach

- Dipole models also applied, but need qqbar-g terms (and perhaps higher Fock states)

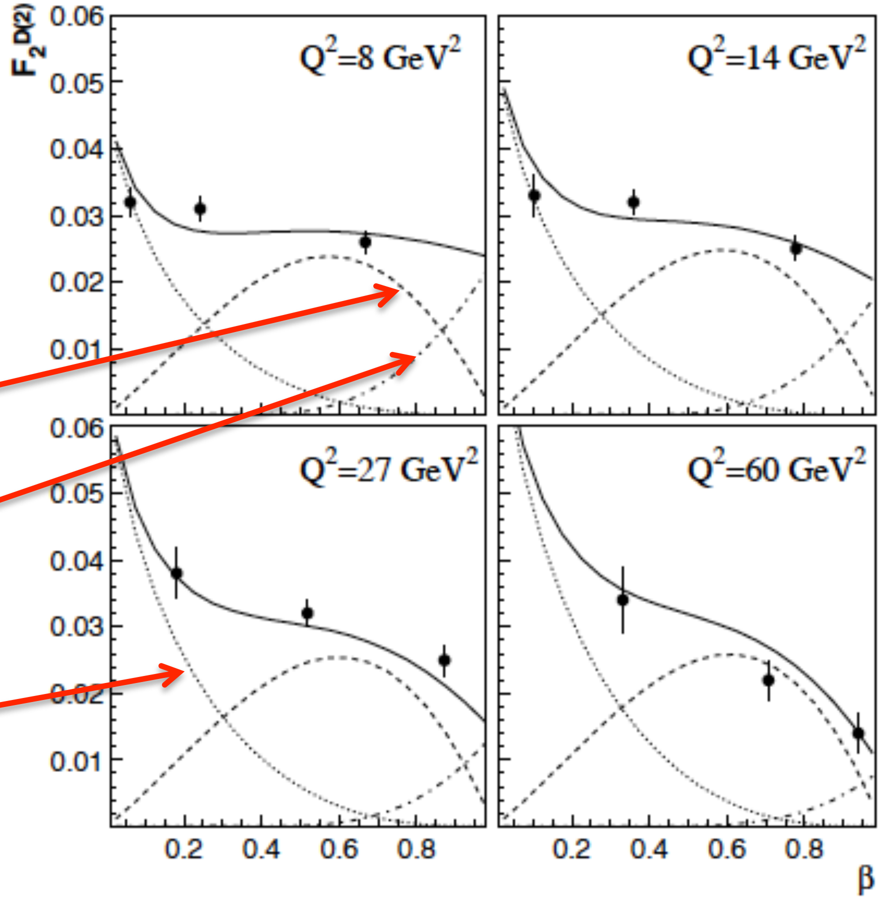




qq_T (Leading Twist)

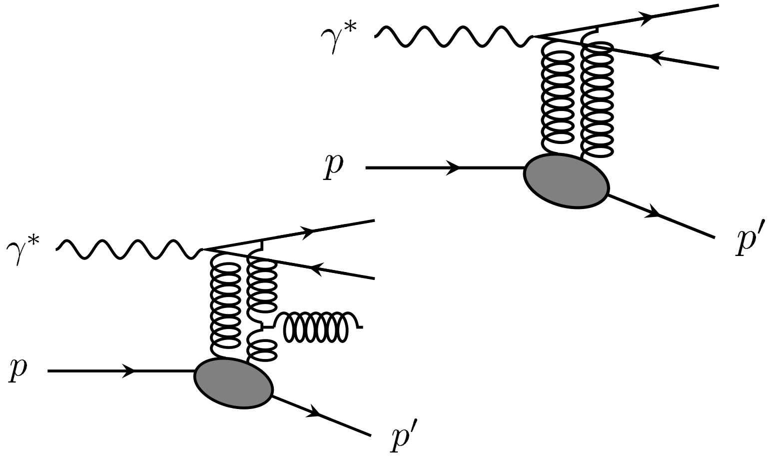
qq_L (Higher Twist)

qqg_T (Leading Twist)

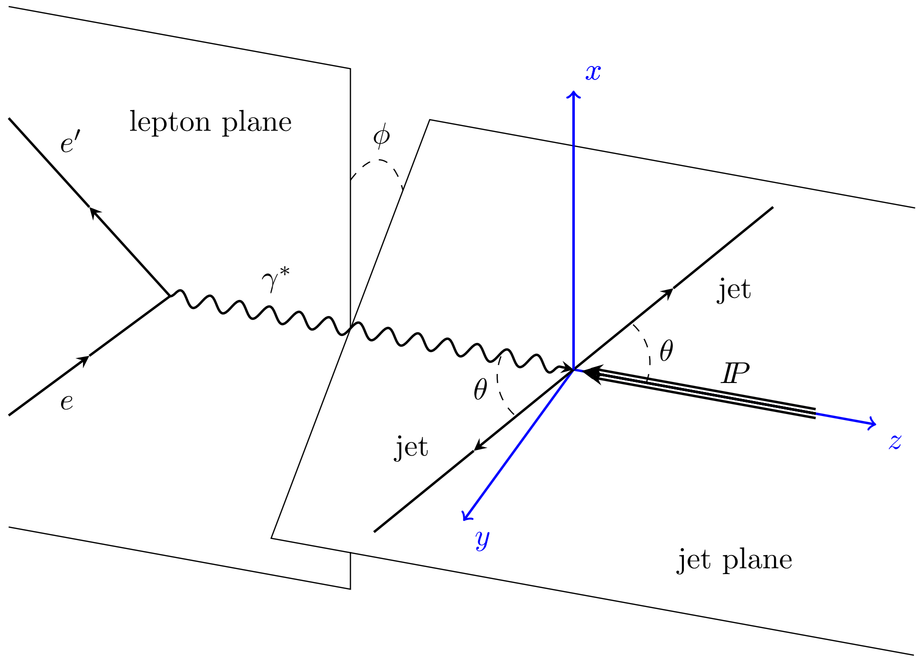


- Not yet describing fine detail
- Unravelling this rich phenomonology can yield big rewards!

Is a 'Direct' Component to the Pomeron present in Diffractive Dijets?



- Perturbative '2 gluon exchange' process leads naturally to exclusive dijet Production ($z_{IP} \rightarrow 1$)



- Leads to a different shape of the dijet azimuthal angle distribution from 'resolved' pomeron (boson-gluon fusion)

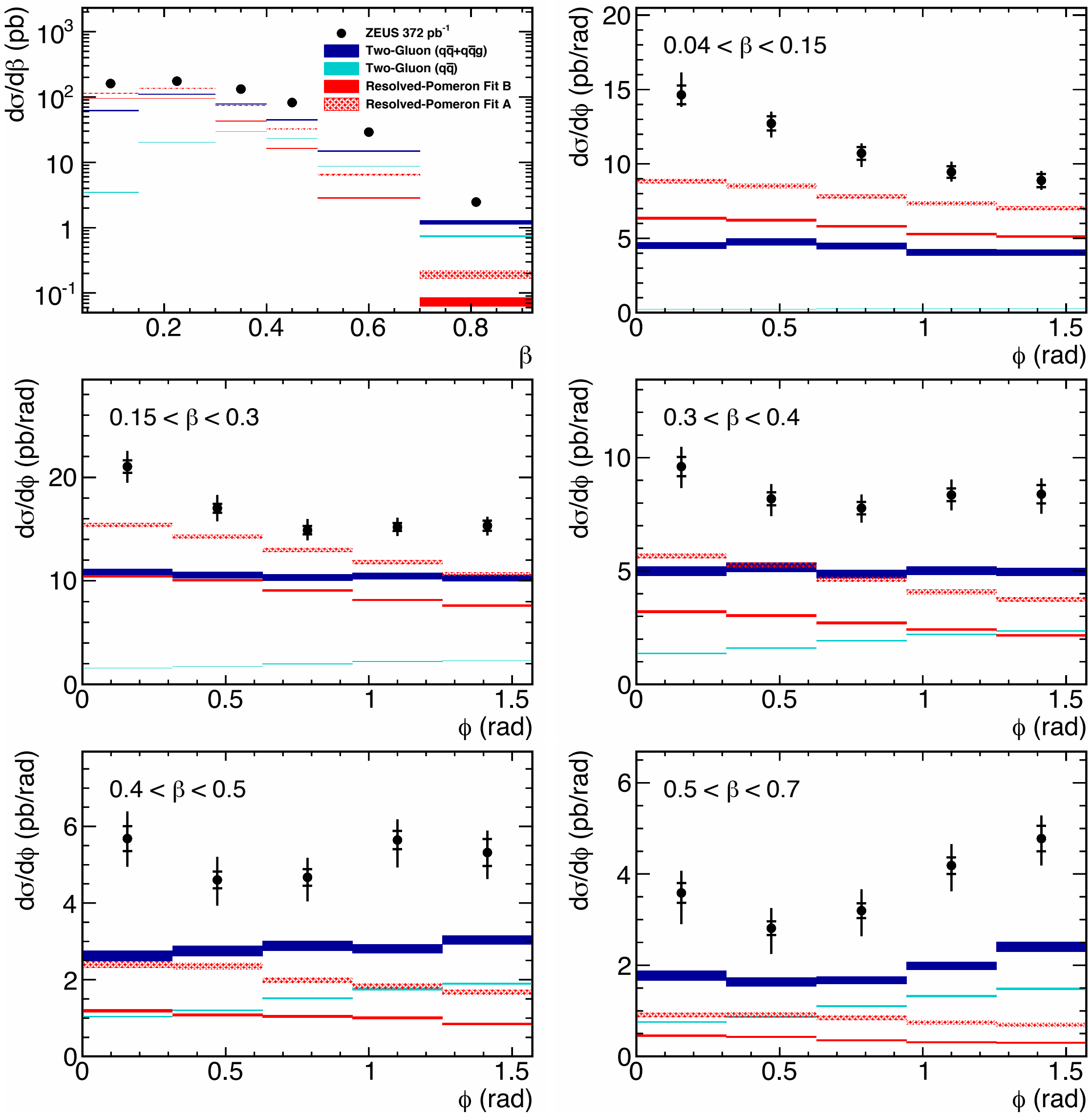
$$d\sigma/d\phi \propto 1 + A\cos(2\phi)$$

- A is +ve if 1 gluon enters hard interaction, -ve for 2 gluons

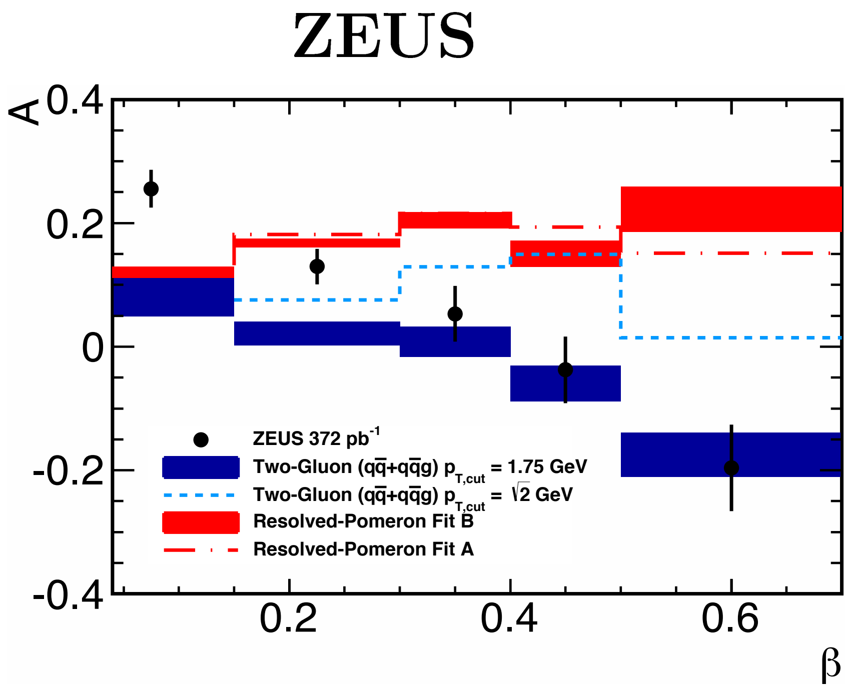
Evidence for Exclusive Dijet Production

NEW! (-ish)

ZEUS study with 372pb-1 (2015)

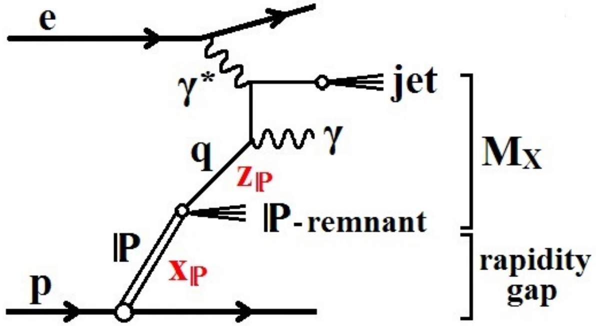


Shape of ϕ distribution changes with β in a way that is well described by 2 gluon model (Bartels et al)

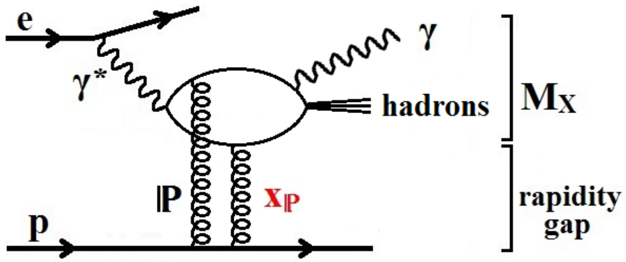


$$d\sigma/d\phi \propto 1 + A\cos(2\phi)$$

Diffractive Prompt Photon Production

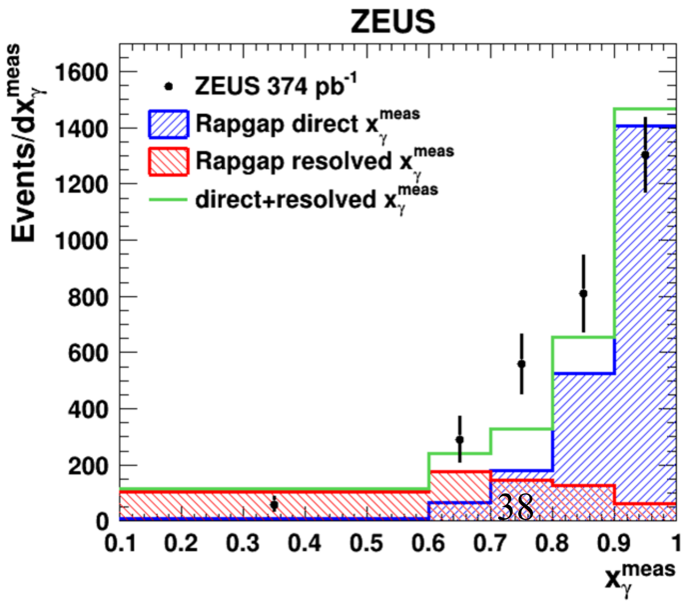


- Sensitive to *quark* component of DPDFs in standard resolved pomeron model

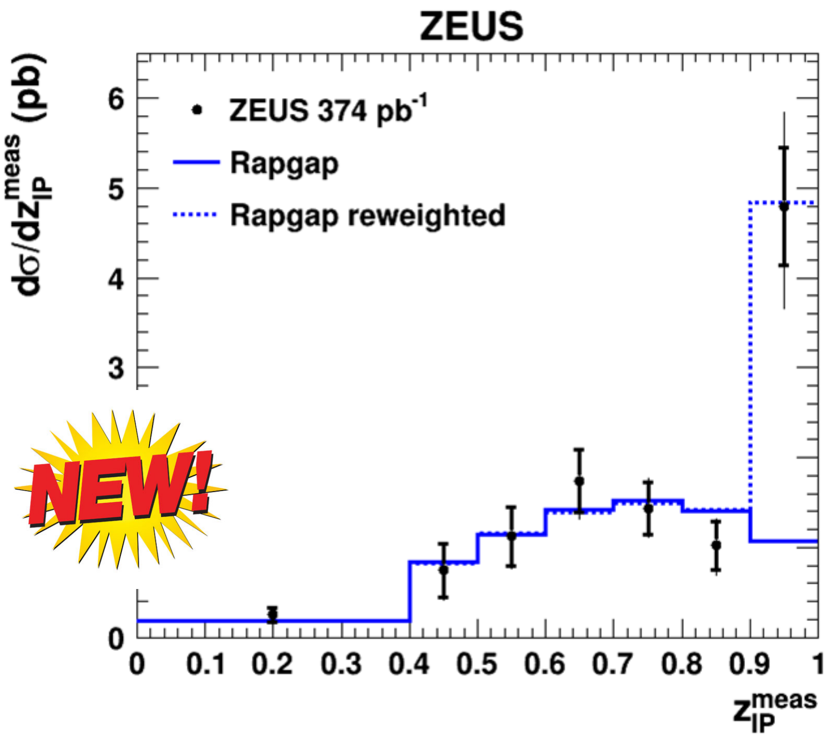


- Potential direct pomeron / 2-gluon contribution if cross section large

- ZEUS analysis of 456pb-1 of LRG data
- Inclusive isolated photons (E_T^{γ}>5 GeV) and (photon+jet) topology
- Sample dominated by direct photons ($x_\gamma \rightarrow 1$)
- Data compared with (normalised) LO RAPGAP model – H1 2006 Fit B DPDFs



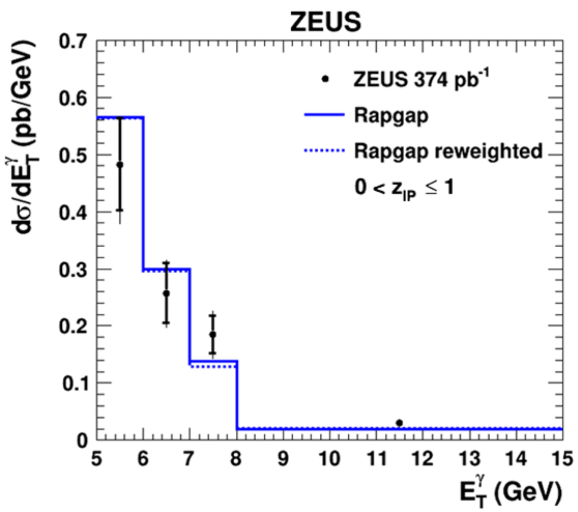
Evidence for Direct Pomeron Contribution in Diffractive Prompt Photon Production

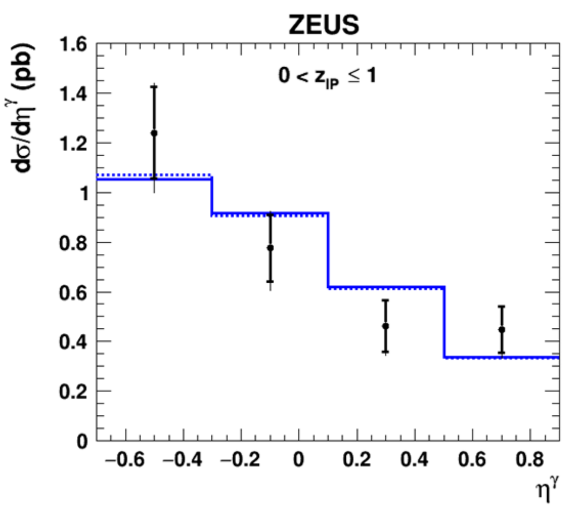


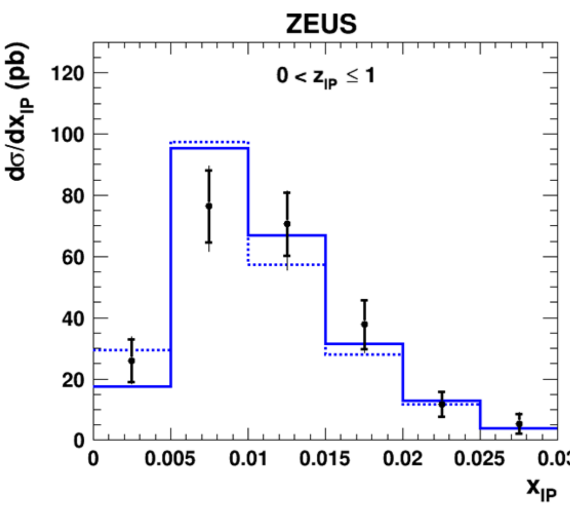
- Shape of z_{IP} distribution can't be described by 'resolved pomeron' model with standard DPDFs

- Excess at large z_{IP} → evidence for 2-gluon exchange contribution

- All other important distributions well described

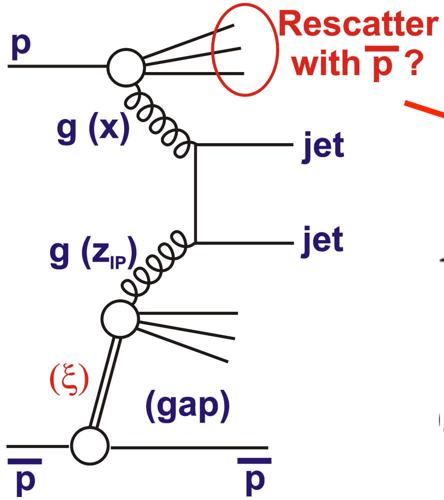


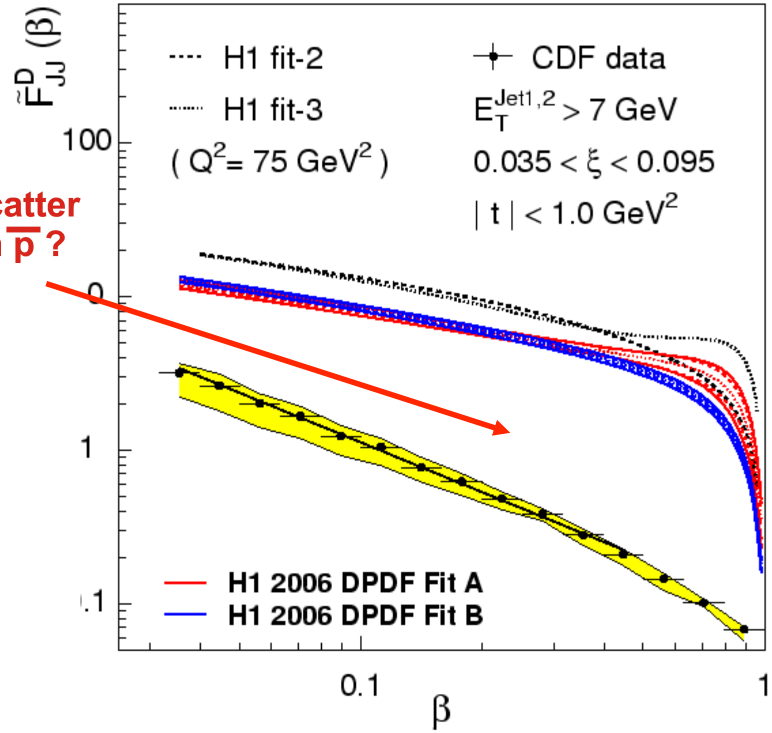




.. meanwhile in pp(bar) ...

Strong evidence for absorptive effects in comparing Tevatron diffractive dijets with HERA DPDFs …
\`rapidity gap survival probability' $S^2 \sim 0.1$

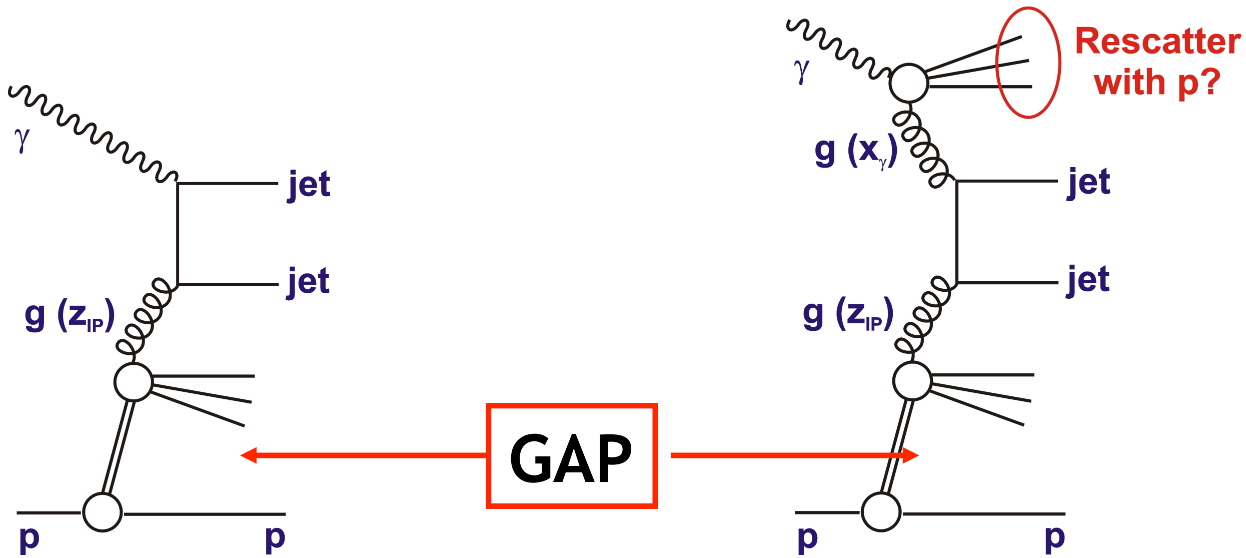




… photoproduction jets as the perfect control experiment?…

"Direct" photon
($x_\gamma \to 1$)

"$S^2 = 1$"



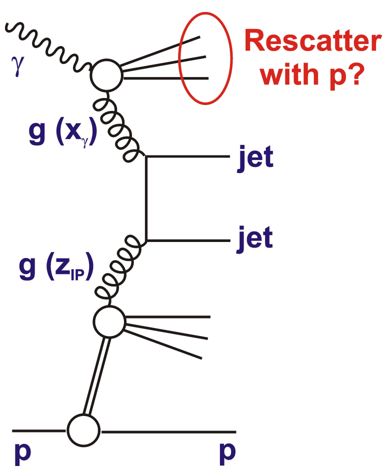
"Resolved" photon
($x_\gamma < 1$)

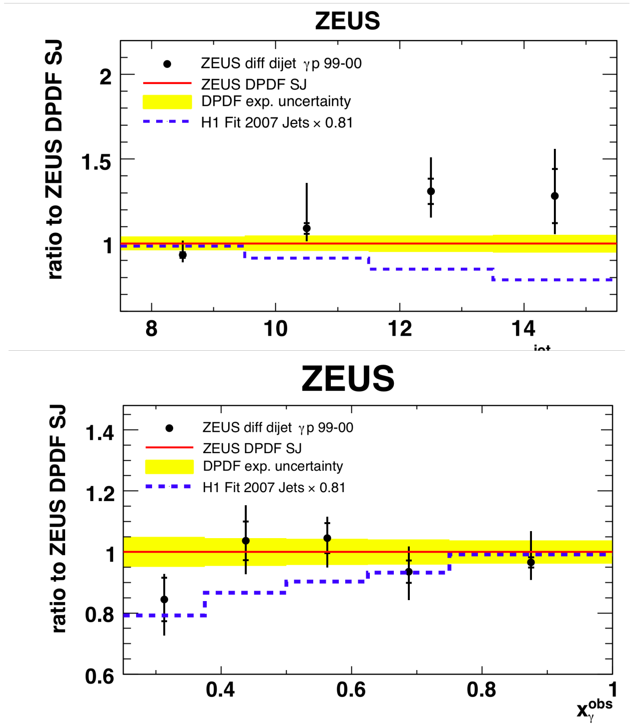
S^2 ?

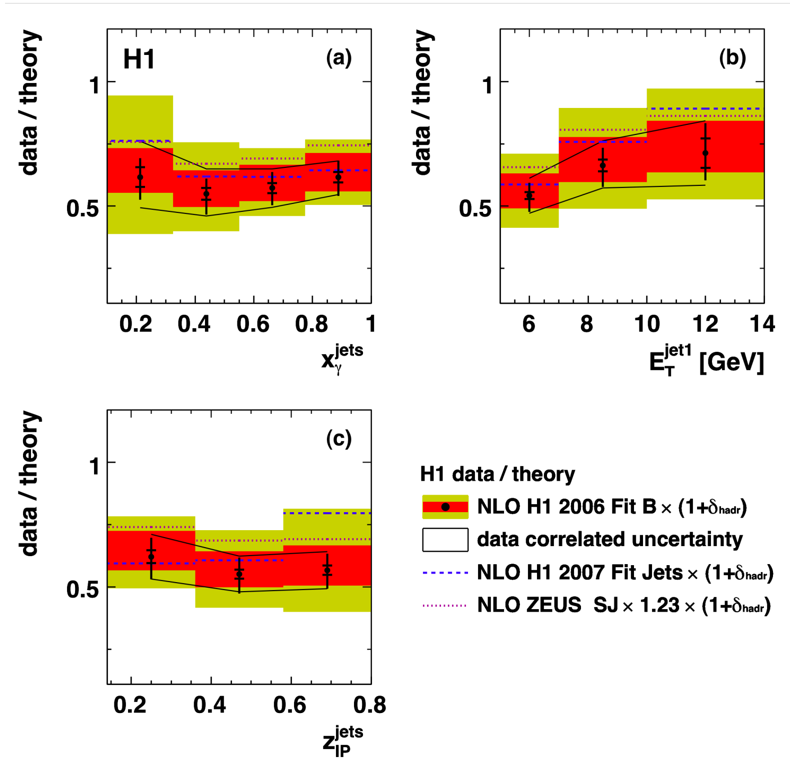
Rapidity Gap Survival Probability in Diffractive Dijet Photoproduction: Old Data

ZEUS [$E_T^1 > 7.5$ GeV]… No evidence for any gap destruction
H1 [$E_T^1 > 5$ GeV]… Survival probability < 1 at 2σ significance

$$\sigma(\text{H1 data}) / \sigma(\text{NLO}) = 0.58 \pm 0.12\ (\text{exp.}) \pm 0.14\ (\text{scale}) \pm 0.09\ (\text{DPDF})$$



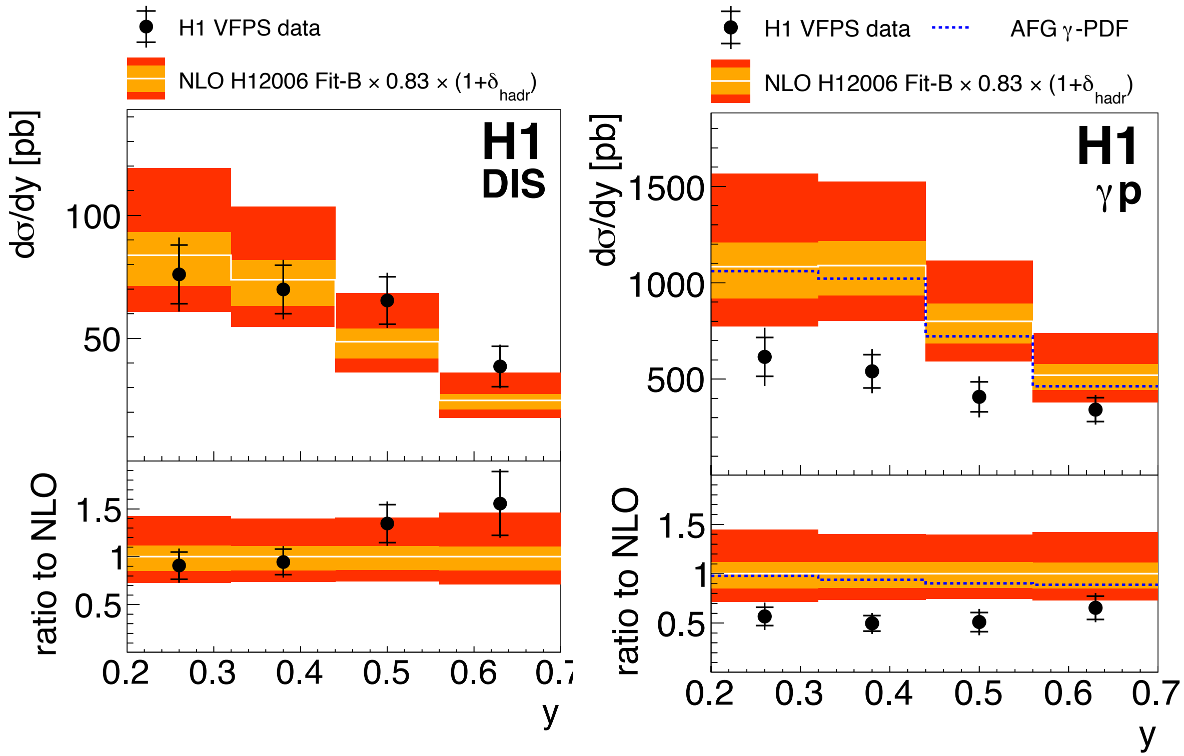




- Gap survival unexpectedly has little dependence on x_γ
- Hint of a dependence on jet E_T?

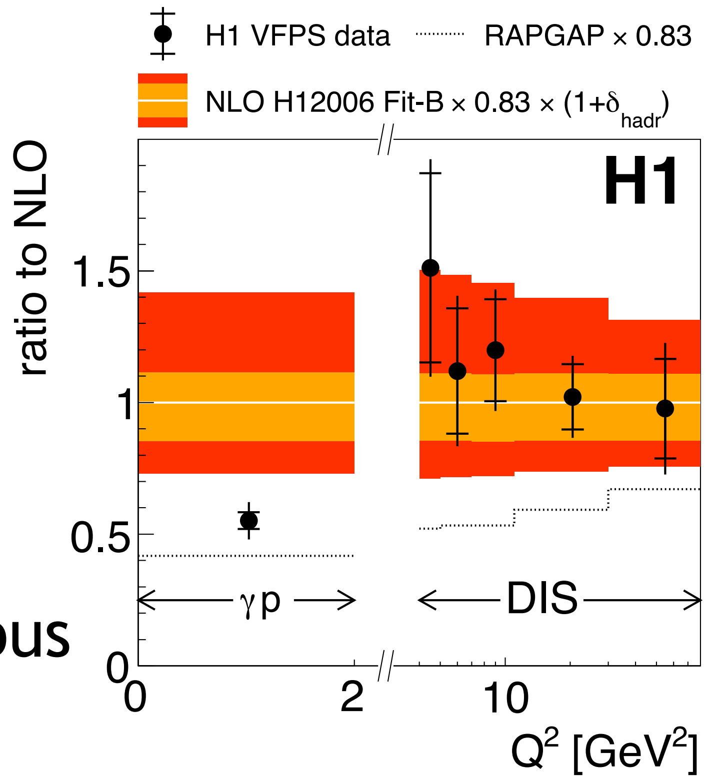
Latest Data, Tagged Protons (VFPS)

NEW! (-ish)



Data v NLO QCD with H1 2006 Fit B DPDFs

$E_T^{jet1,2}$ > 5.5 GeV, 4GeV



From double ratio:

(data/theory) (γp / DIS) = 0.51 ± 0.09

- Effect persists at similar level to previous

… will remain a mystery for now …

Summary: Diffraction & the HERA revolution

- Extensive studies of diffraction at HERA have led to a revolution in our understanding in QCD

→ **Inclusive process** is leading twist … original Ingelman-Schlein model works well with only slight modification to factorisable 'soft pomeron' properties

→ Evidence for non-factorising '2 gluon exchange' contribution from exclusive jj and γj final states

→ **Vector meson production** is an Inherently exclusive process

→ Turn-on of hard scales mapped for multiple meson species, $(Q^2 + M_V^2)/4$ is often a good choice of scale for comparisons

→ Hard vector meson production sensitive to proton gluon density / saturation and showed the way for UPC at LHC