Diffraction at HERA

P.Newman
University of Birmingham
H1, ATLAS and LHeC Collaborations

Summer School on Diffractive & Electromagnetic Phenomena, Acquafredda, 10 September 2010

Thanks to IPPP Durham for additional support

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… with additional material from Pierre Marage

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… with additional material from Pierre Marage

… and occasional commentary from George W Bush

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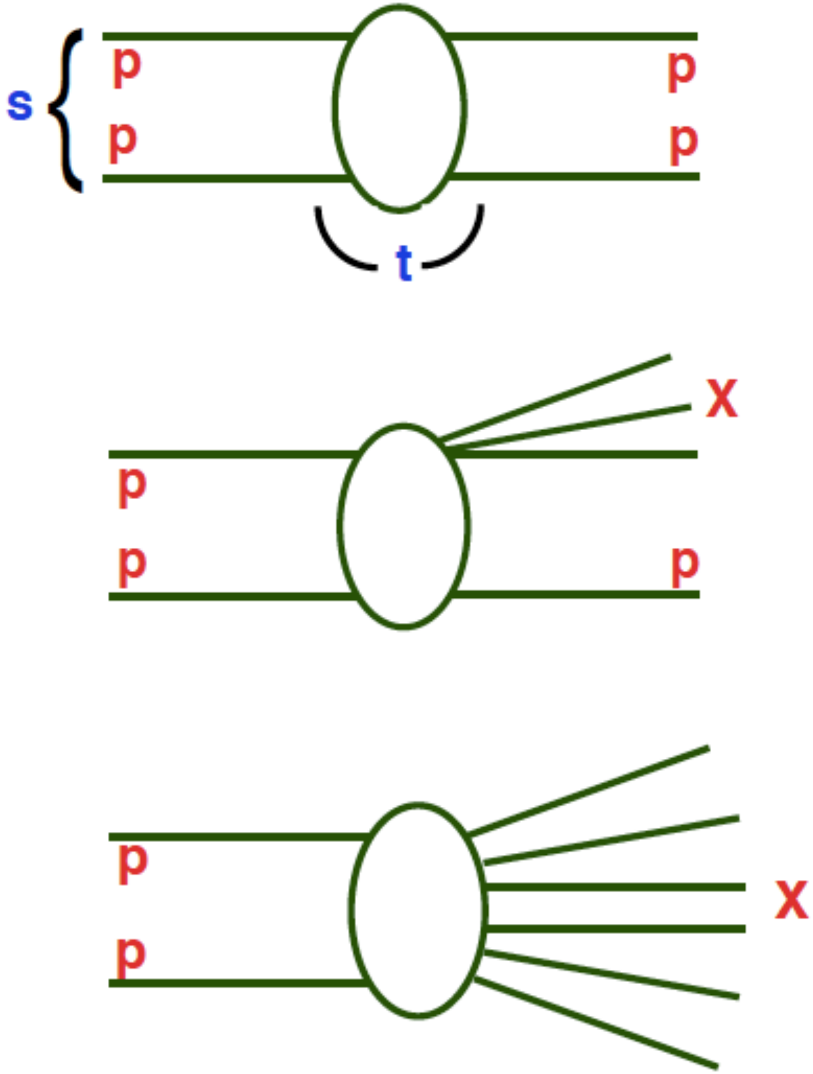
Contents

- A bit of revision
- HERA and electron-proton scattering
- Exclusive vector meson production
- Diffractive Deep Inelastic Scattering
- Diffractive Parton Densities
- Factorisation Breaking and Rapidity Gap Survival
- [Sub-leading colour singlet exchanges]

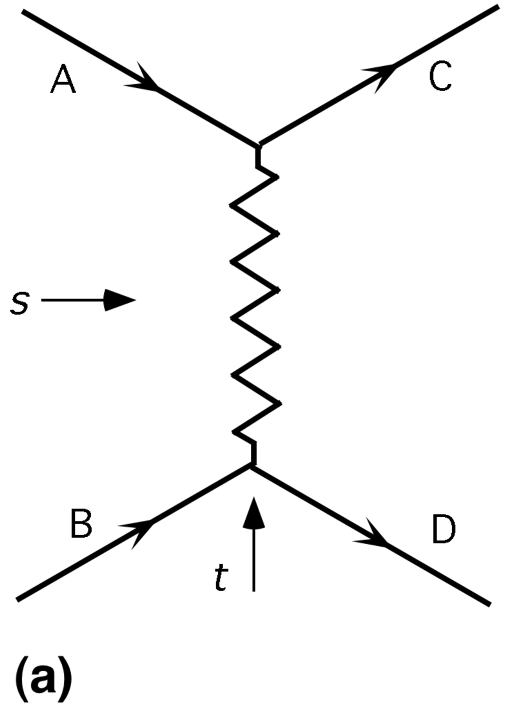
A Quick Bit of Revision

(= Ancient History)

A Bit of Quick Revision (Ancient History)



Colour singlet exchange processes in pp physics often described in terms of t channel exchanges.



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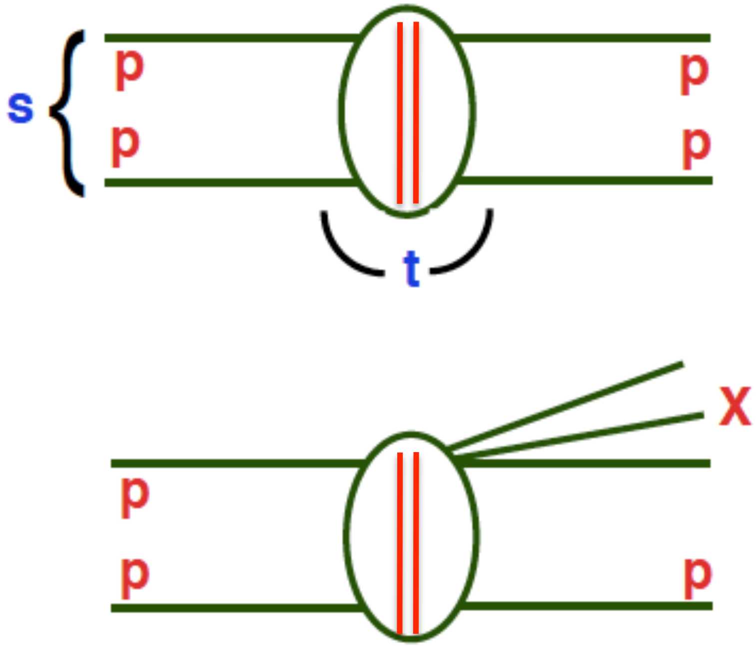

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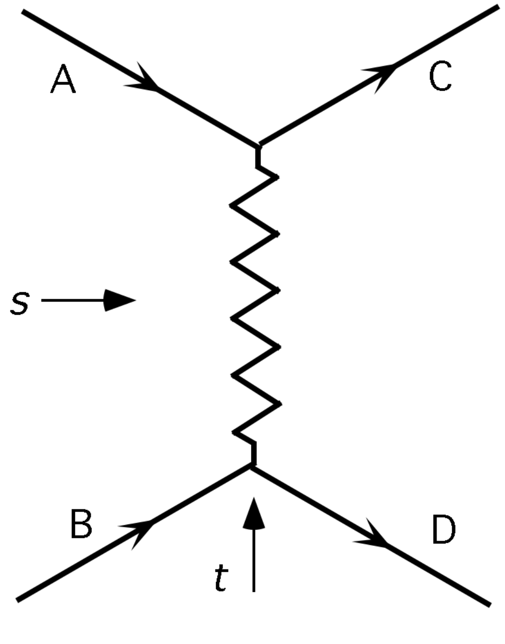
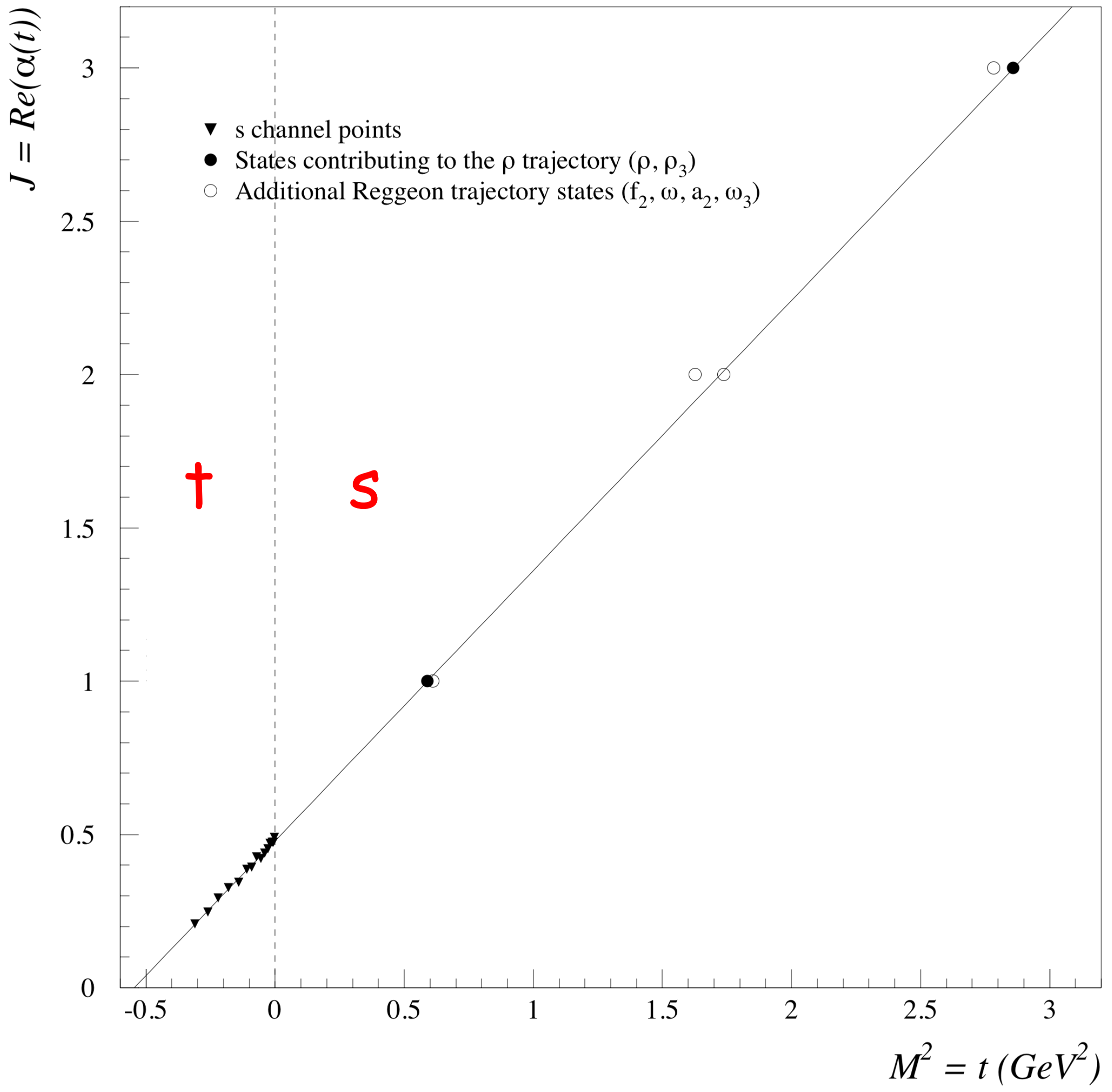


(a)

… but what is exchanged in the t channel?

A Bit of Quick Revision (Ancient History)



… meson exchange …

… Chew-Frautschi plots of M^2 (or t) v Spin show linearity and s ←→ t channel continuity.

$\alpha(t) = \alpha(0) + \alpha' t$

e.g.

ρ,ω,f,a: $a(t) \sim 0.5 + t$

π: $a(t) \sim 0 + t$

Just the One Slide on Regge Theory

Fundamental equation of Regge theory:

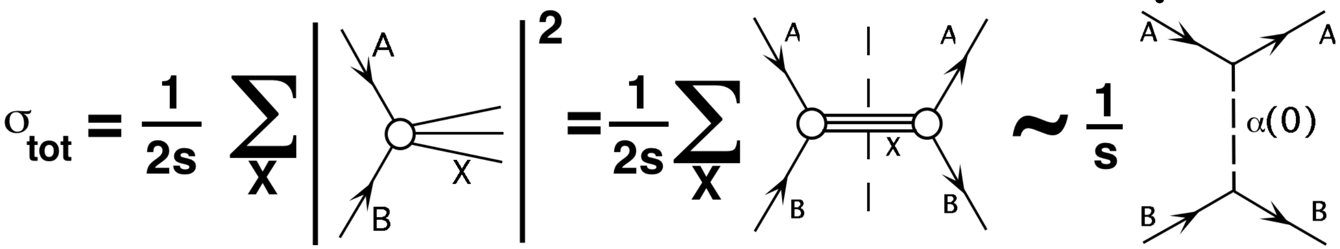
At fixed t, with s >>t …

Amplitude for a process governed by the exchange of a trajectory α(t) is $T(s,t) \sim \left(s/s_0\right)^{\alpha(t)}$

… note that t dependence not predicted …

Leads to **elastic** cross section: $\dfrac{d\sigma_{el}}{dt} \sim s^{2\alpha(t)-2}$

… and **total** cross section via the **optical theorem:**

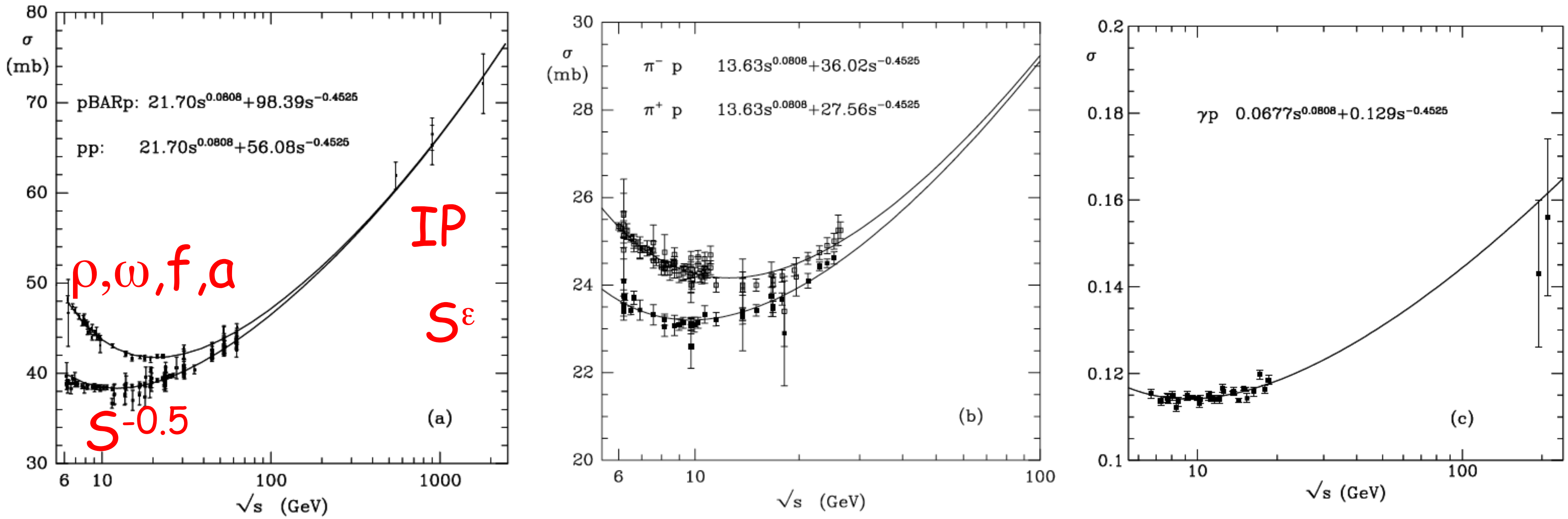


$$\sigma_{tot} = \frac{1}{s}\,\mathrm{Im}\left\{T_{el}\right\}_{t=0}$$

$$\sigma_{tot} \sim s^{\alpha(0)-1}$$

See also Mueller's generalised optical theorem & triple Regge phenomenology … not used in anything I show here.

Some Total Cross Section Data



Many measurements in pp in particular →
A pomeron exchange trajectory … $\alpha(t) \sim 1.10 + 0.25\,t$

If this pomeron is universal and factorisable, it can also be applied to total, elastic, diffractive dissociation cross sections in e.g. γp collisions

End of Historical Introduction!

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You shouldn't believe all the wisdom you read in history books

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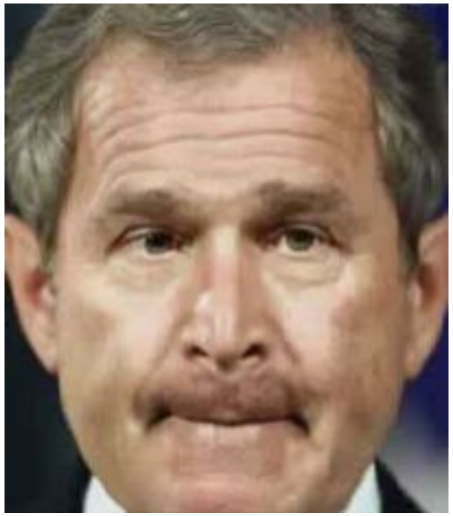
The preceding Regge theory / pomeron discussion is a convenient language in which to describe what we see at HERA

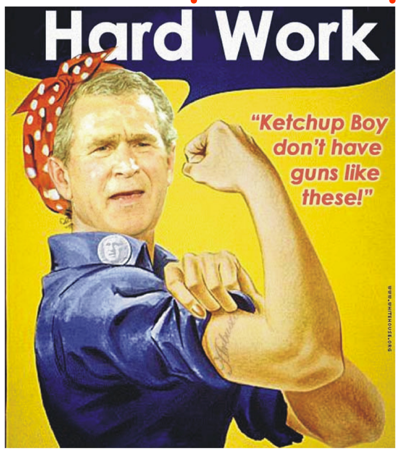
… though it doesn't really work ☹



Electron-Proton Scattering and the HERA Collider

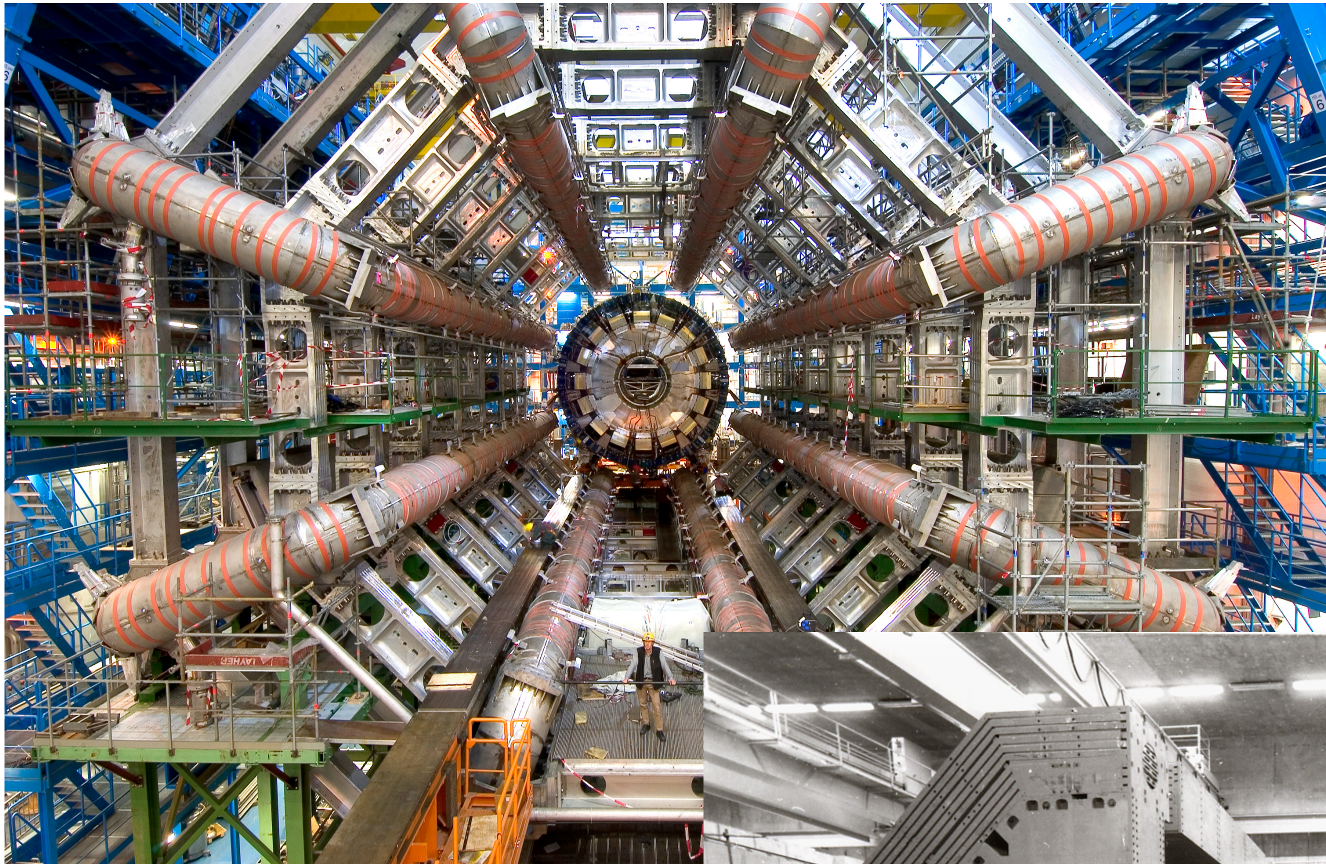
The HERA Collider

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

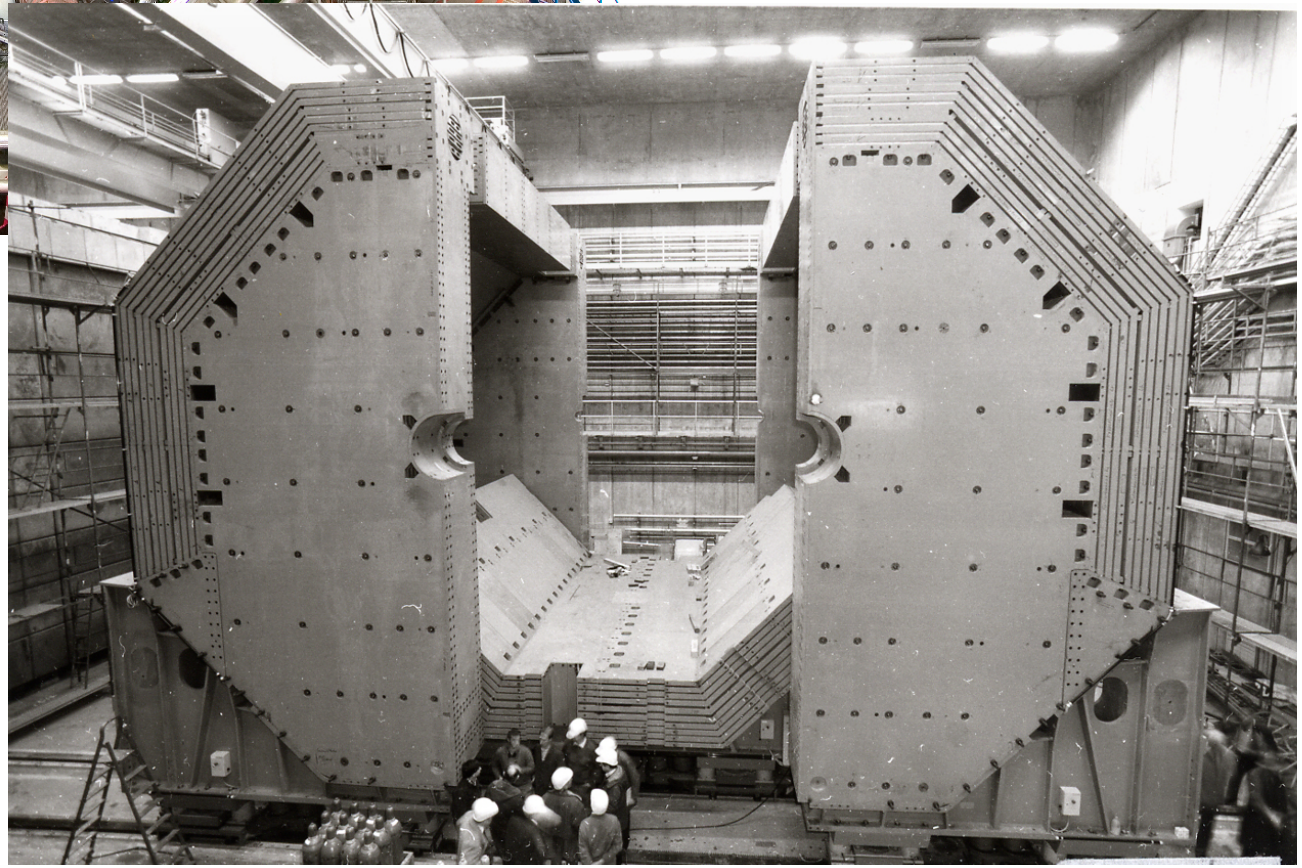


e.g. H1 publications on diffraction (similar numbers in ZEUS):

- Diffractive cross sections (SD,DD): 11 papers
- Diffractive final states: 14 papers
- Quasi-elastic cross sections: 20 papers
- Total cross sections / decomposition: 2 papers



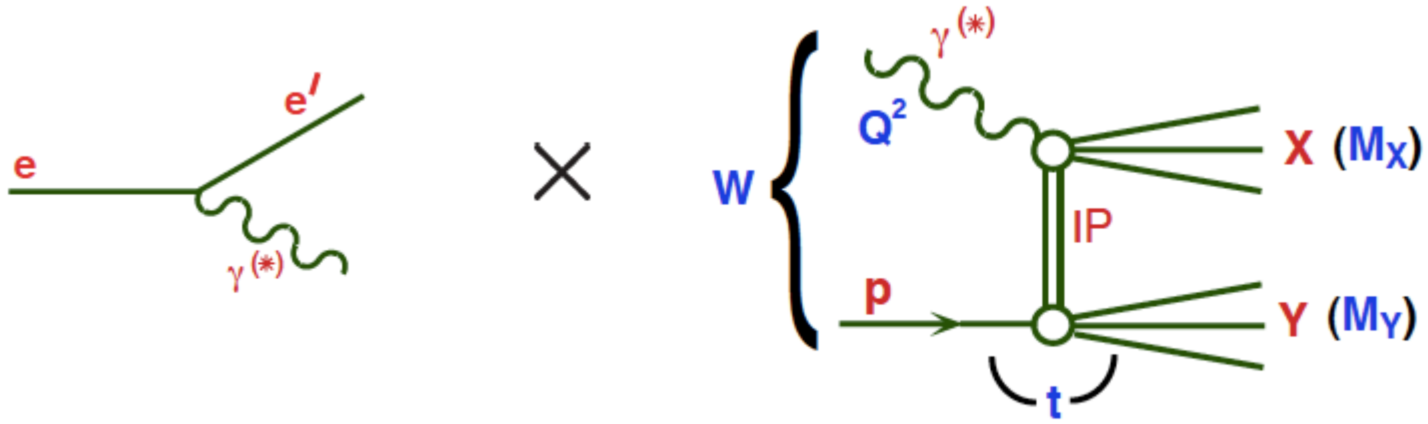
Scale:
H1 v
ATLAS



... yet x range of PDF sensitivity at HERA is very well matched to LHC requirements!

Colour singlet exchange processes at HERA

At the HERA ep collider, diffractive $\gamma^{(\star)}p$ interactions can be studied.



All 5 of the kinematic variables shown can be measured.

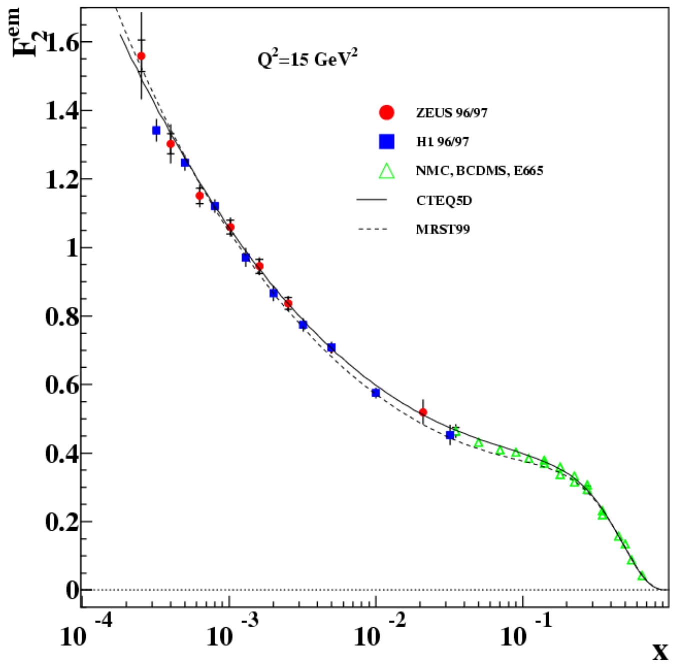
By varying Q^2, the process can be smoothly changed
- from a soft process (real photon, $Q^2 \rightarrow 0$)
- to a deep inelastic process (highly virtual photon, large Q^2, resolving partons and probing QCD structure of diffraction)
- I will concentrate on cases where t is small

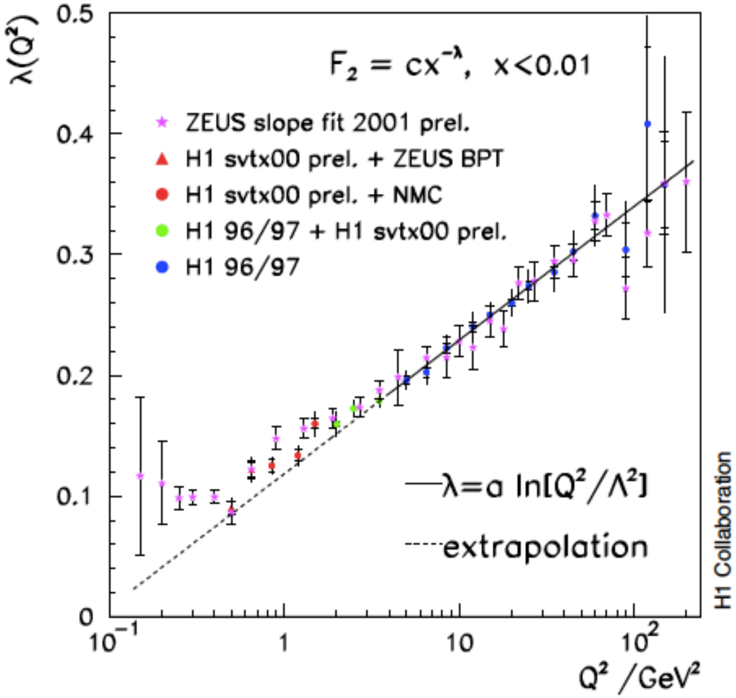
Total γ*p Cross Sections at HERA

Low x Kinematics … $W^2 = Q^2 / x$

The rise of F_2 with decreasing x is equivalent to the rise of the total cross section with increasing W at fixed Q^2

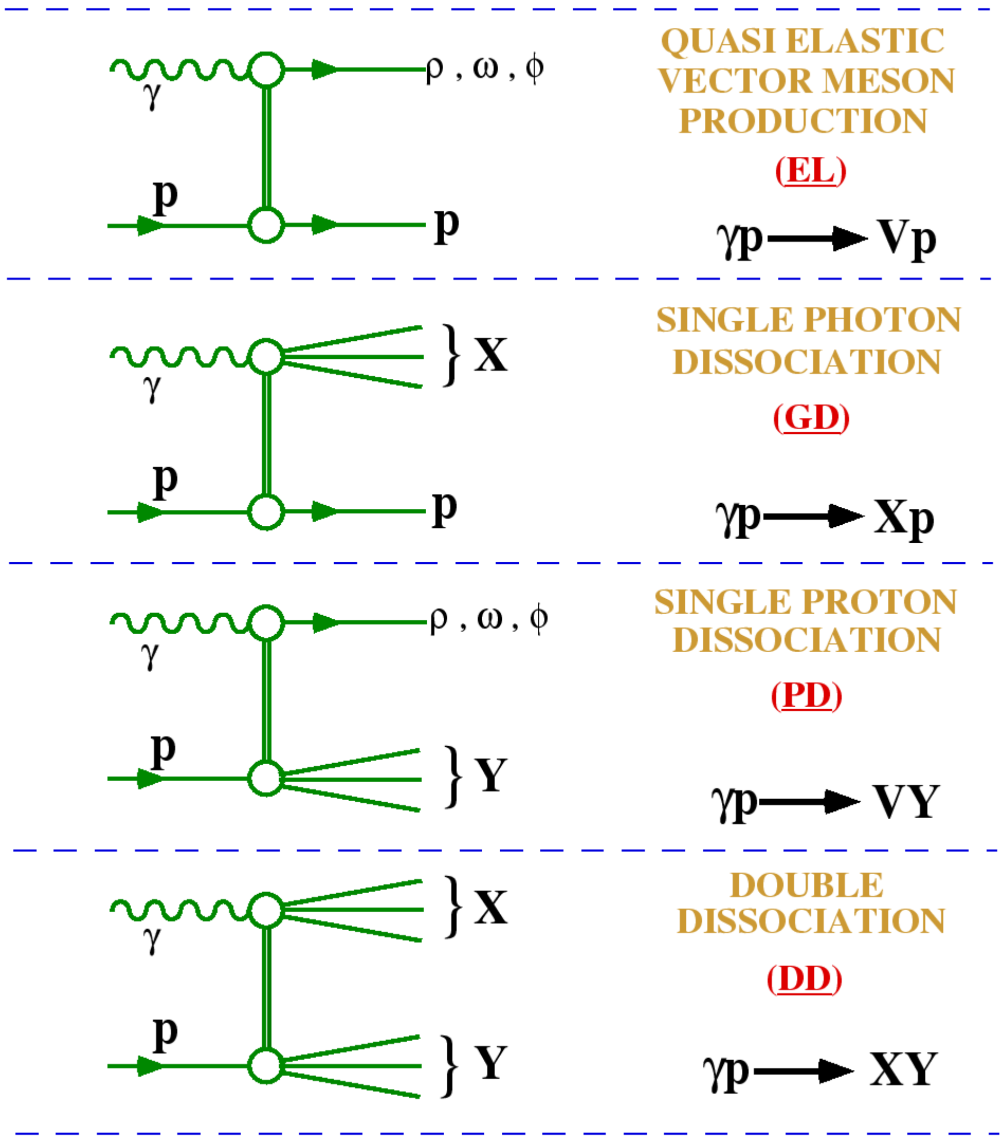
$F_2 \sim x^{-\lambda}$ ←→ $\sigma_{tot} \sim s^{\alpha(0)-1}$ …… $\lambda = \alpha(0) - 1$





- The idea of a universal pomeron dead from the outset at HERA!… harder scales give stronger energy dependences

Colour singlet exchange processes at HERA



LHC analogue is pp→pp

LHC analogue is pp→Xp

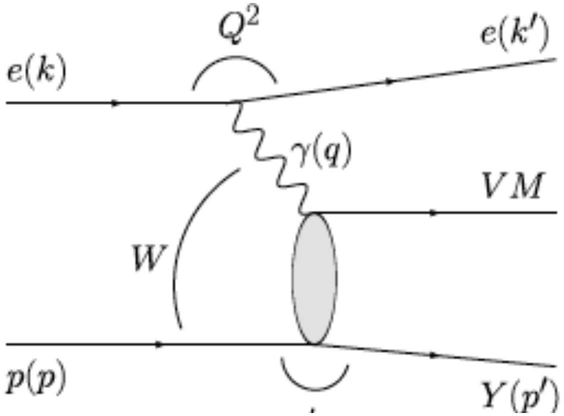
LHC analogue is pp→pX

LHC analogue is pp→XY

Favourable kinematics to study X system (photon dissociation)

Exclusive Vector Meson Production

Vector Mesons & the Soft → Hard Transition



γ ρ ω ϕ J/ψ ψ(2s) Υ

p p. diss. (M_Y)

Phenomenological parameterisation in Regge theory:

$$\frac{d\sigma}{dt} \propto \left(\frac{W^2}{W_0^2}\right)^{2\alpha_{\mathbb{P}}(t)-2} e^{b_0 t} \quad ; \quad b_0 \sim R_p^2 + R_{\gamma^{(*)}\to V}^2$$

For soft processes, expect $\alpha_{\mathbb{P}}(t) \sim 1.08 + 0.25t$.

[e^{bt} empirically motivated … Fourier transform of spatial distribution of Interaction]

Signatures of hard processes:

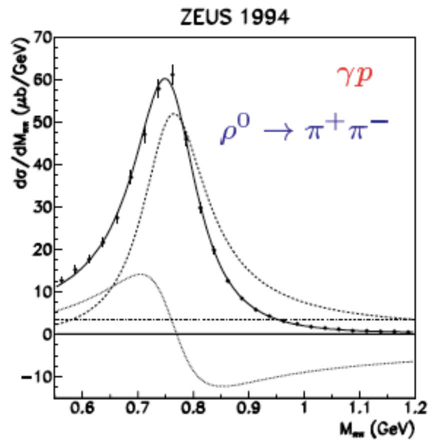
- Increase in effective $\alpha_{\mathbb{P}}(0)$.
- Decrease in $\alpha'_{\mathbb{P}}$.
- $R^2_{\gamma^{(*)}\to V} \to 0 \quad ; \quad b_0 \to R_p^2$

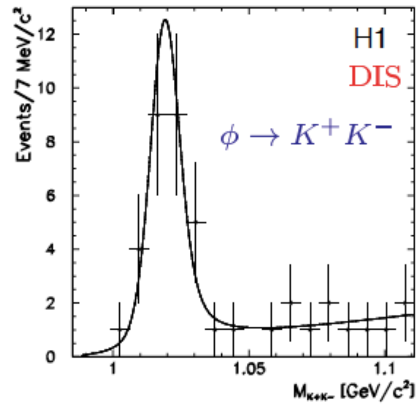
Possible quantitative QCD description where hard scales availiable:

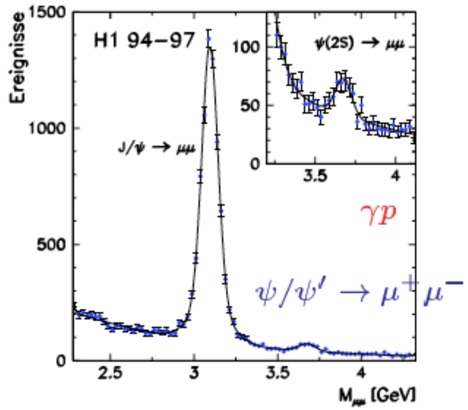
Selection and Some Early Signals

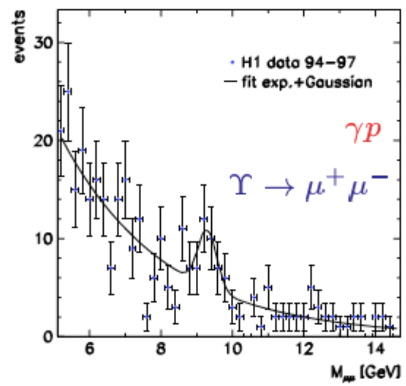
Study VMs in 2-prong decay channels.

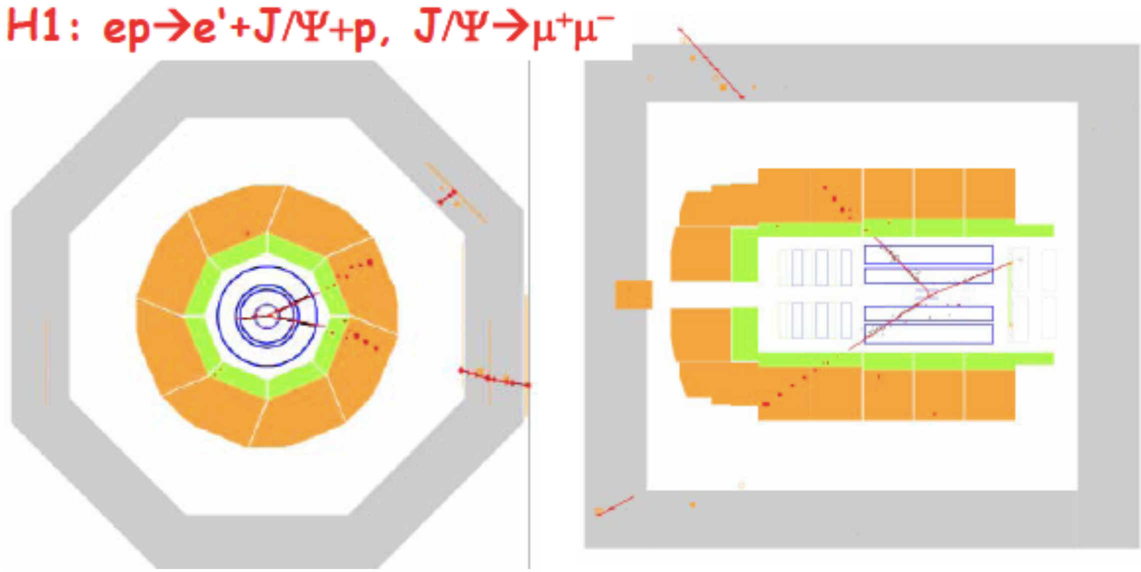
… Select events where detector is 'empty' apart from VM decay products and maybe scattered lepton





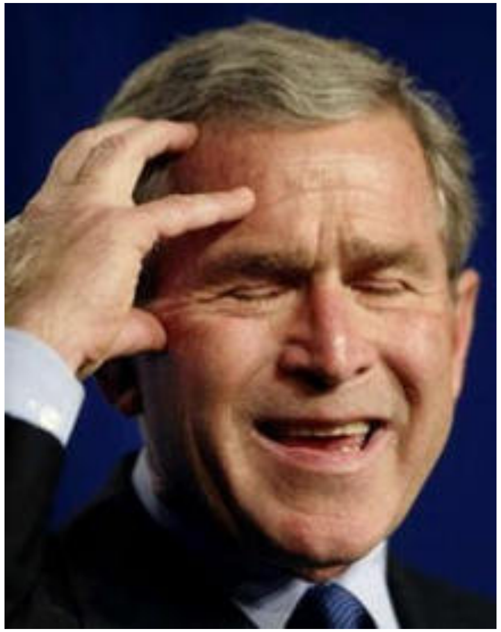




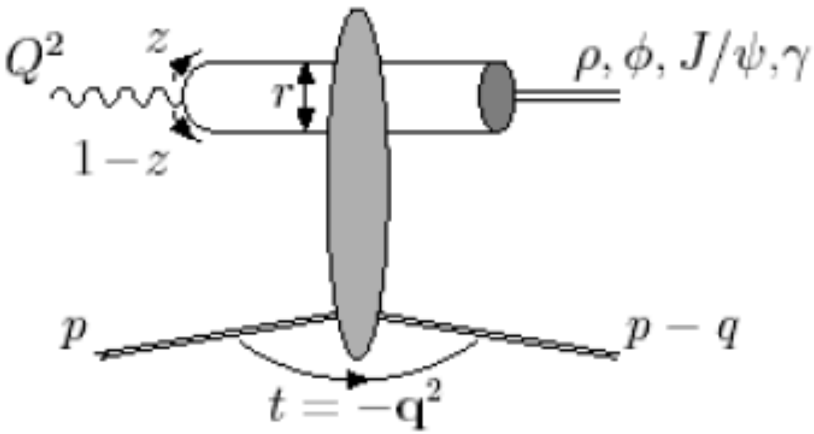


Scattered proton disappears into forward beampipe (low t …)

Describing Vector Mesons in terms of Partons



Factorisation theorem

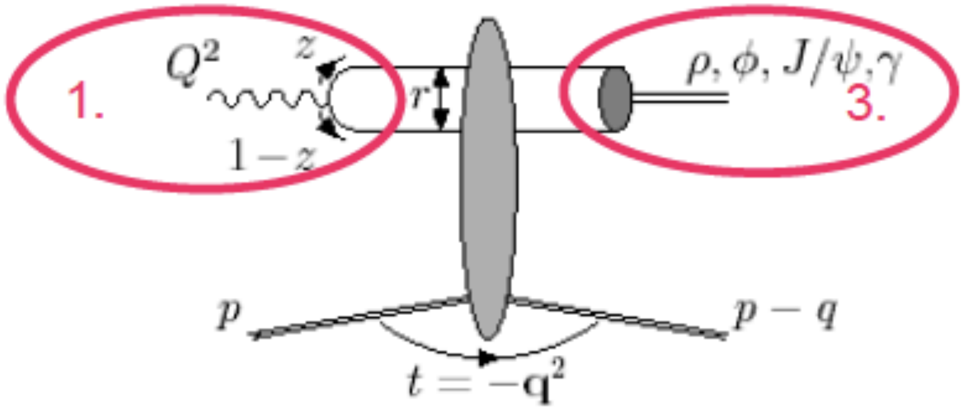


step 1. γ fluctuation into $q\bar{q}$ dipole

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

step 3. pair recombination into VM

The Wavefunctions



1. γ wave function

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

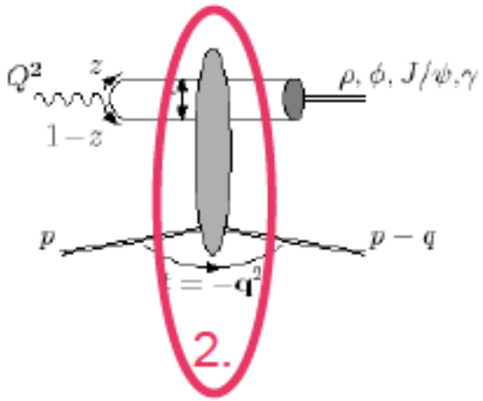
however : large |*t*| studies -> chiral odd contributions

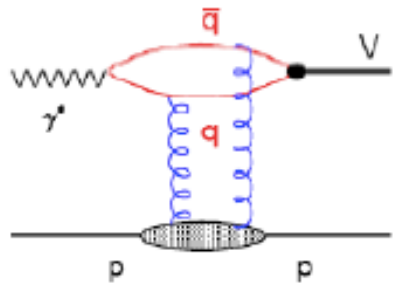
3. pair recombination into VM

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

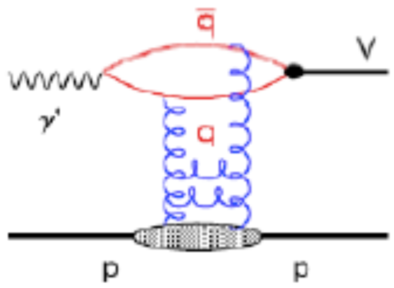
The Dipole-Proton Interaction

2. dipole – proton interaction





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 $M_V{}^2$

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

Whistlestop VM Theory

Regge parameterisation at fixed t:

$$\frac{d\sigma_{el}}{dt} \sim s^{2\alpha(t)-2}$$

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

→ W is the $\gamma^{(*)}p$ CMS energy

→ Kinematics … $W^2 = Q^2 / x$

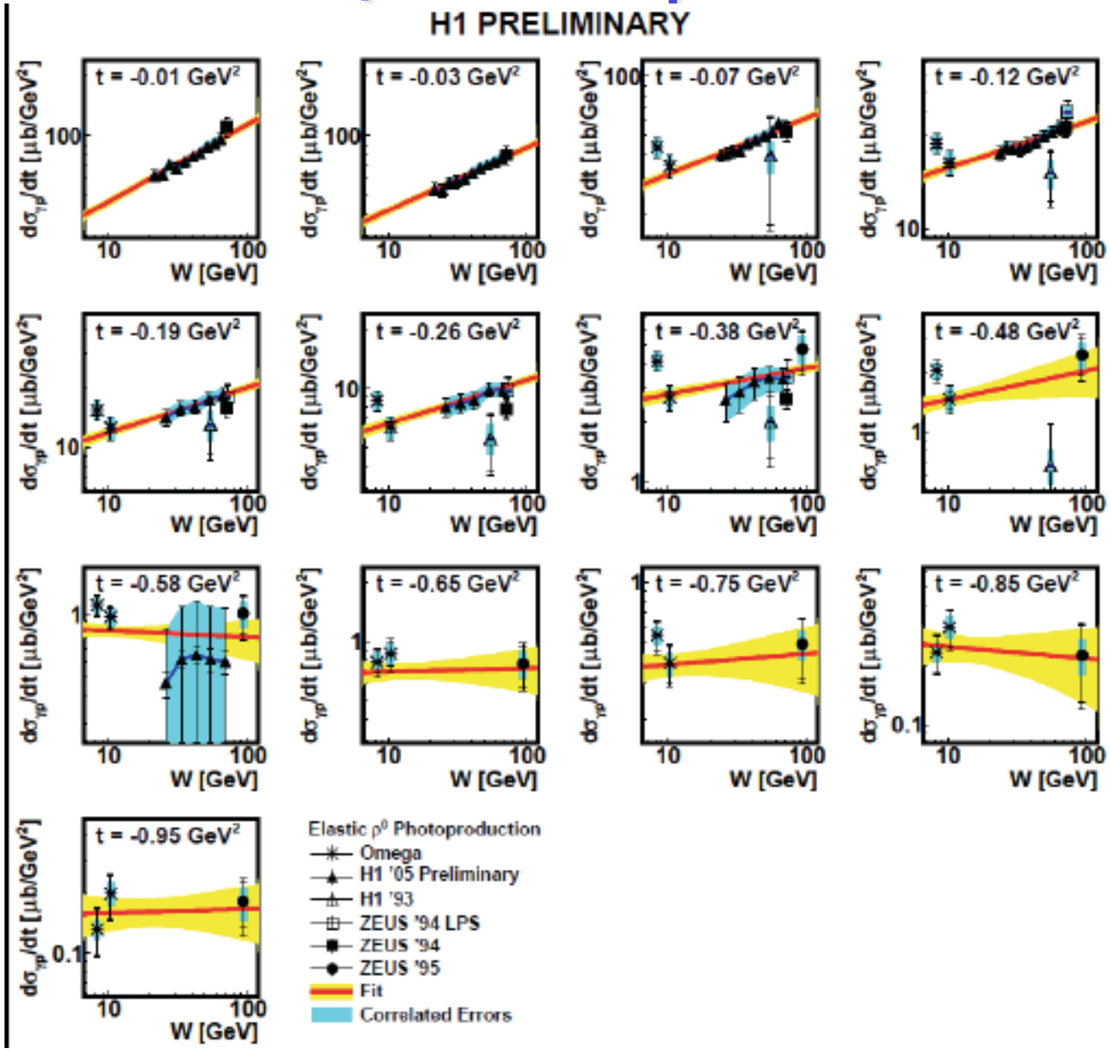
→ Crudely, 2 gluon model … $\sigma_{el} \sim \left| x\, g(x, Q^2_{eff}) \right|^2$

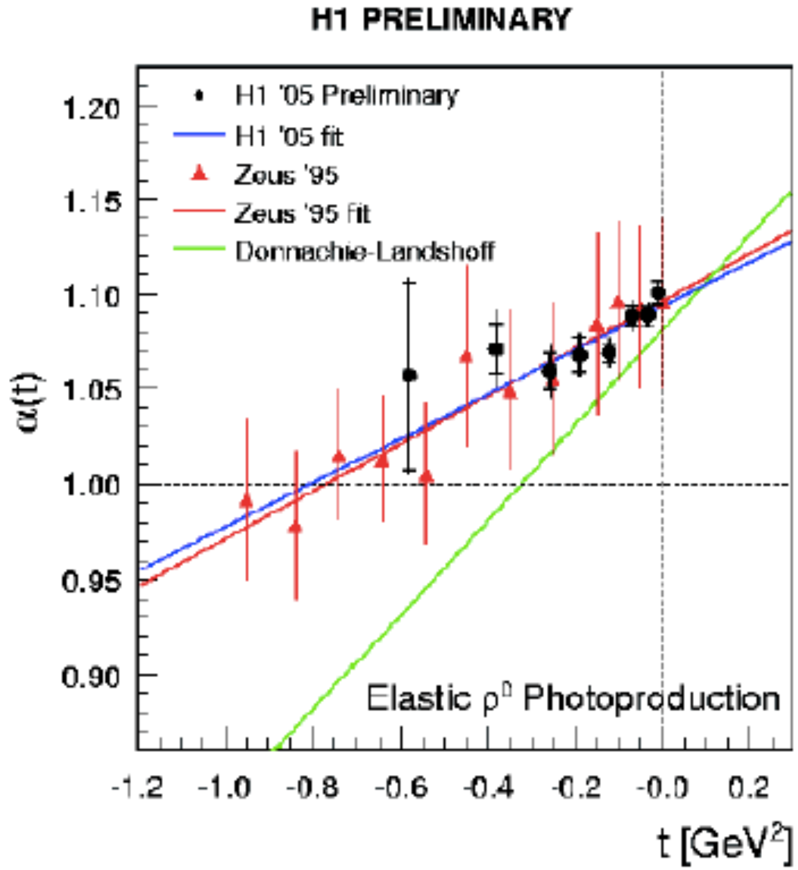
→ e^{bt} term is empirical … Fourier transform of spatial distribution of the interaction

$b = b_{dipole} + b_{proton}$ → b_{proton} as dipole size → 0

Soft ρ Photoproduction

$$\frac{d\sigma_{\gamma p}(W)}{dt} \propto \left(\frac{W}{W_0}\right)^{4(\alpha_{IP}(t)-1)}$$





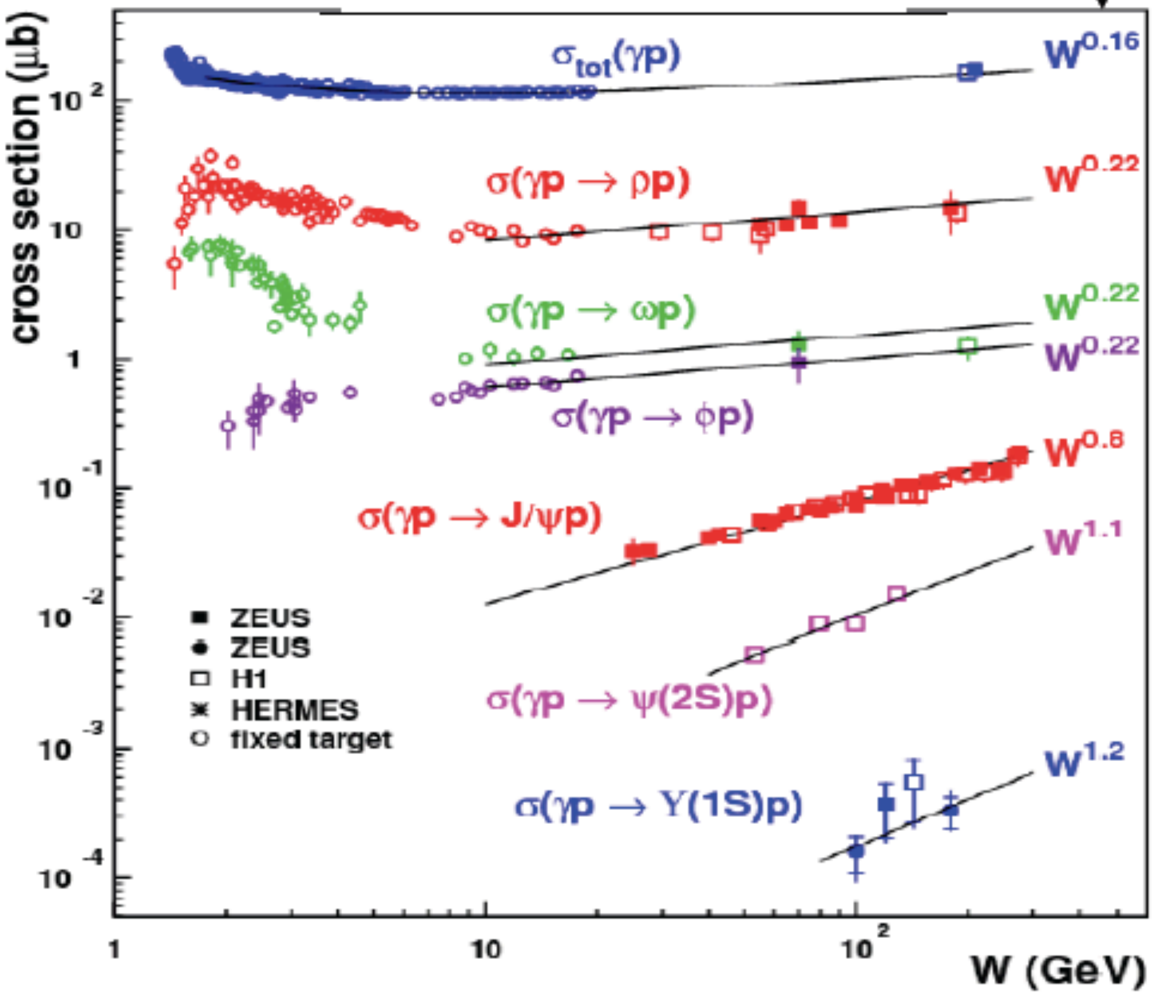
$\alpha_{IP}(0)=1.0871 \pm 0.0026(stat) \pm 0.0030\ (sys)$ ~ soft IP in pp

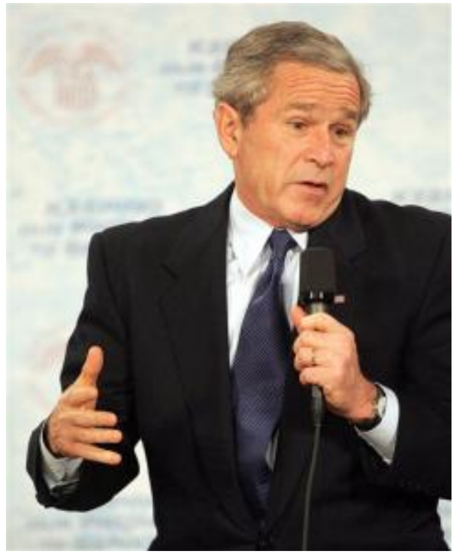
$\alpha_{IP}' = 0.126 \pm 0.013(stat) \pm 0.012(sys)\ GeV^{-2}$ Smaller than soft pp

Similar results from ZEUS … not even the soft IP is universal!

Photoproduction of Light v Heavy VM

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

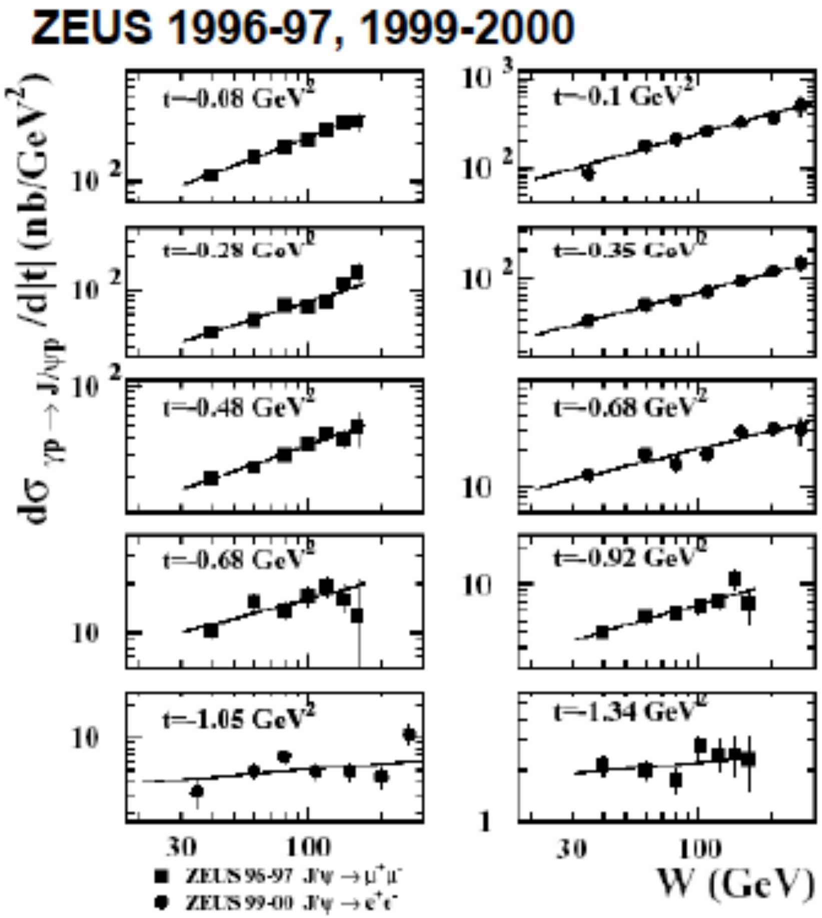


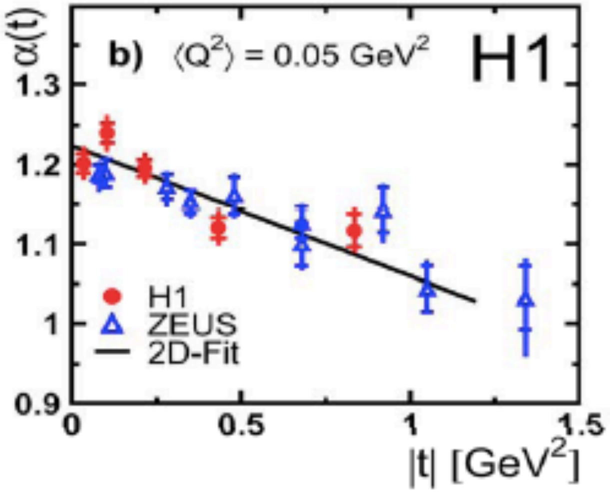


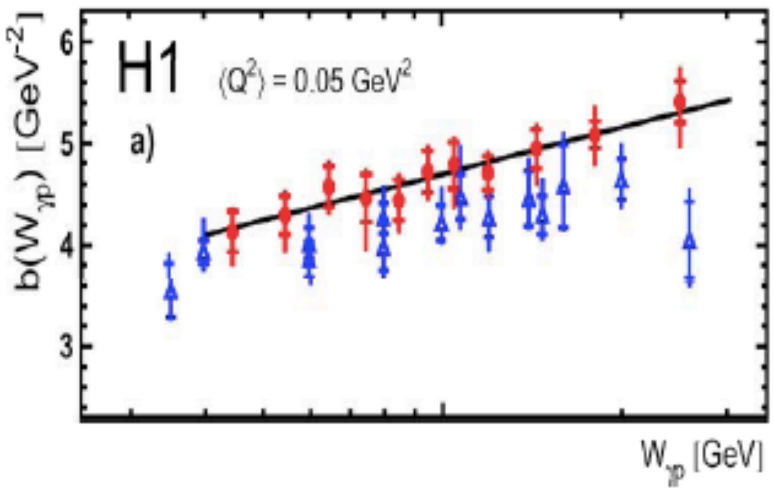
Increasing M_V leads to harder energy dependences

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

Effective Trajectory for J/Ψ Photoproduction







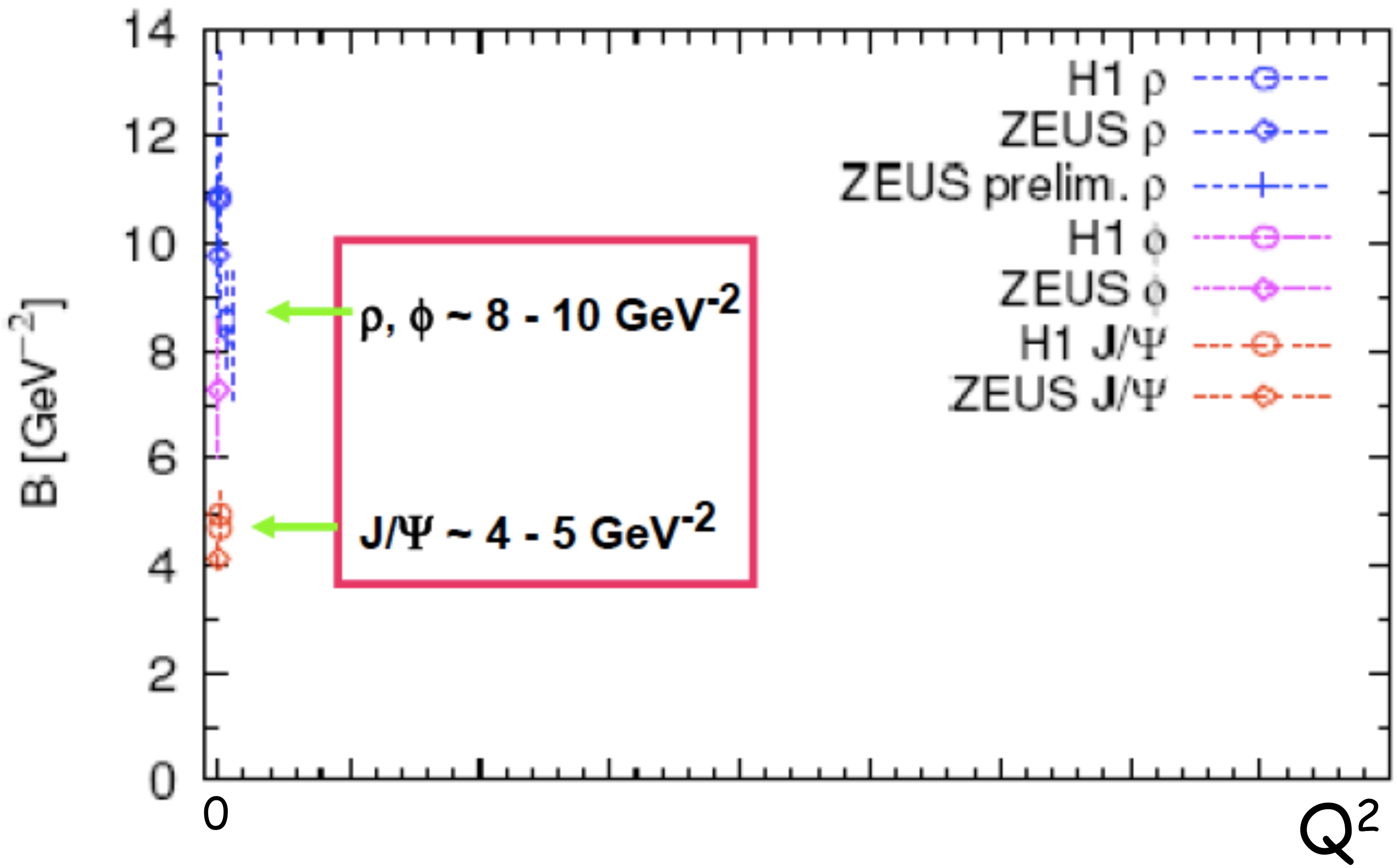
hard intercept $\alpha(0) \sim 1.20$

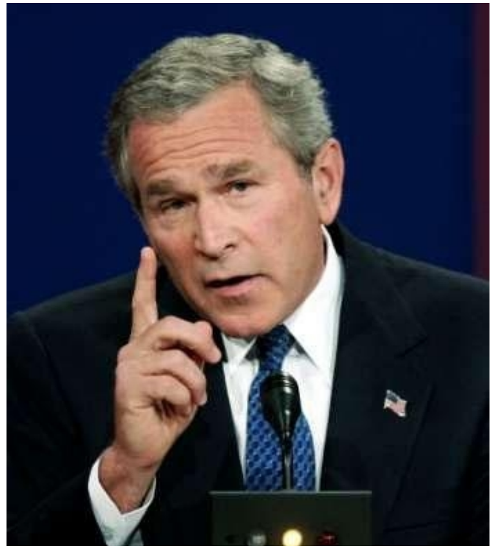
lower (?) slope $\alpha' \sim 0.12$ - 0.16 GeV^{-2}

ZEUS
$$\alpha_{I\!P}(0) = 1.200 \pm 0.009^{+0.004}_{-0.010}$$
$$\alpha'_{I\!P} = 0.115 \pm 0.018^{+0.008}_{-0.015}\ \mathrm{GeV}^{-2}$$

	α_0	α' [GeV^{-2}]
H1	$1.224 \pm 0.010 \pm 0.012$	$0.164 \pm 0.028 \pm 0.030$

Photoproduction t Slopes





B ~ 4 GeV^{-2} corresponds to the size of the proton

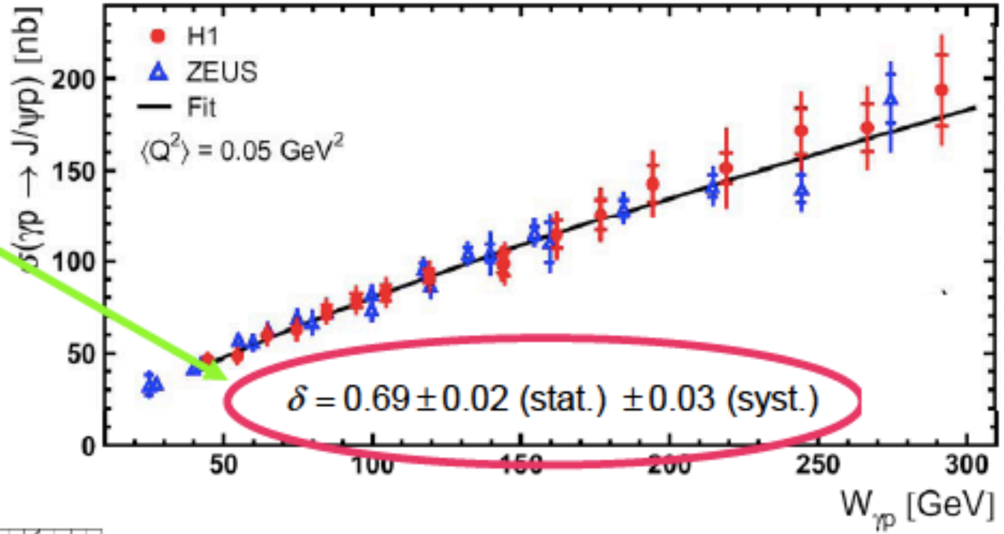
… ~ nothing added to size of interaction region by dipole
… J/Ψ photoproduction is a short distance, hard process

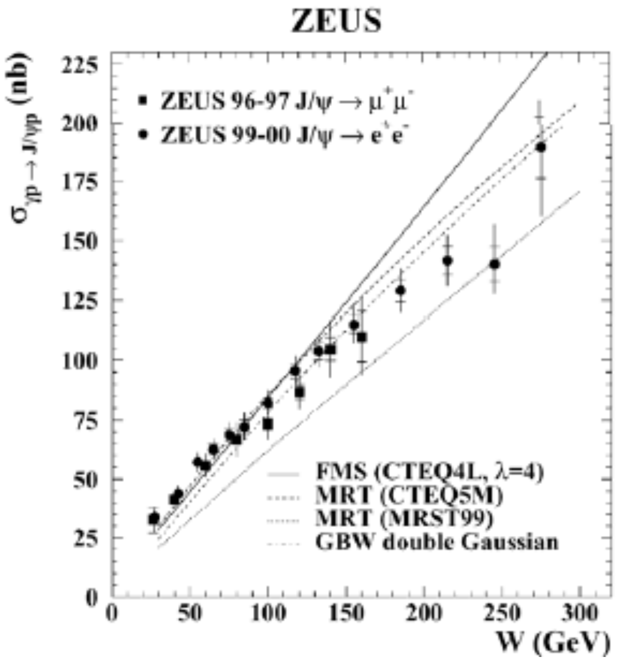
Photoproduction of J/Ψ

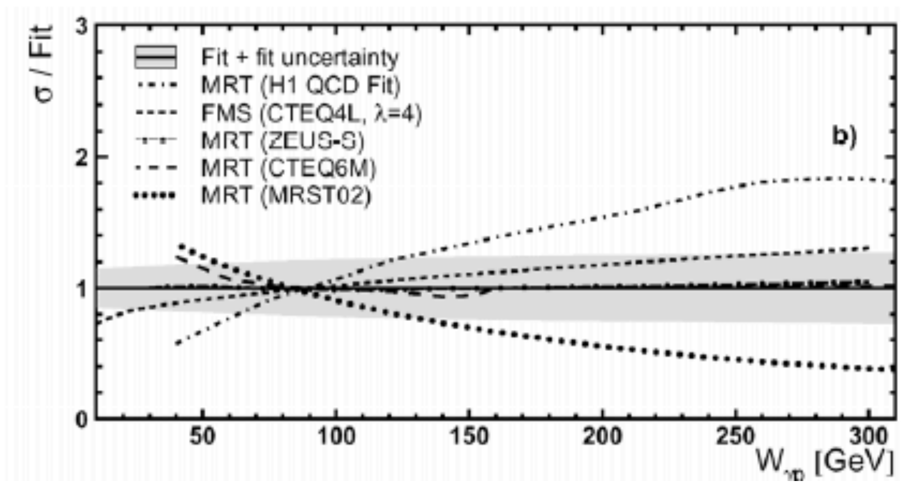
ZEUS, H1 1999-2000

hard slope

mass = hard scale
=> comparisons with theory
tests of pdf's



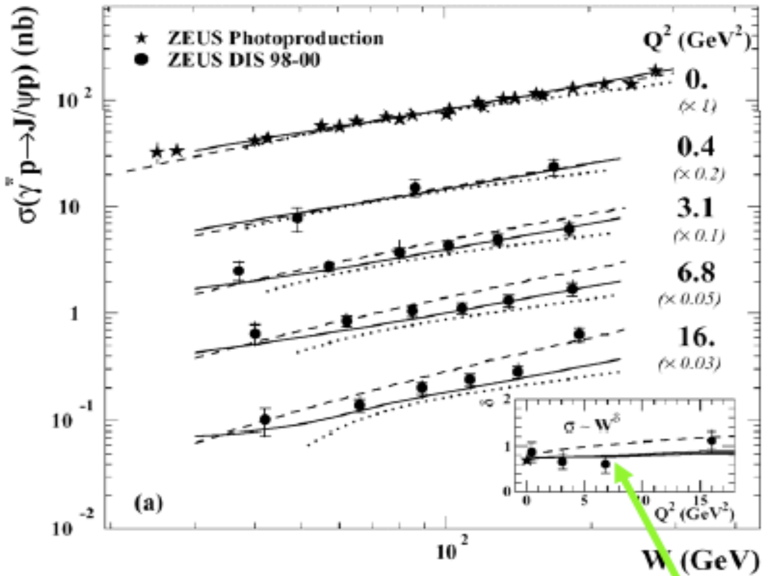


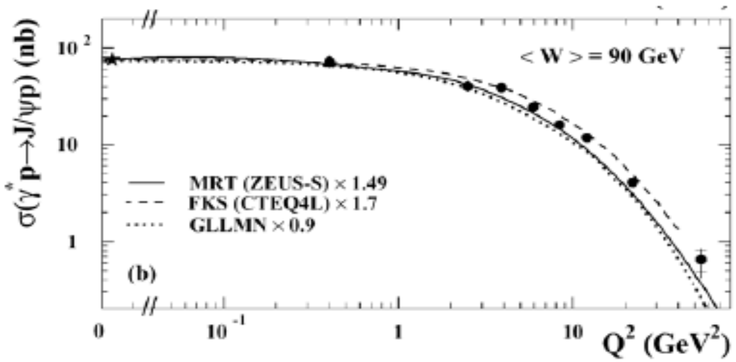


Sensitivity to gluon density … but is theory well enough understood to distinguish PDF fits (wavefunctions, scales …)?

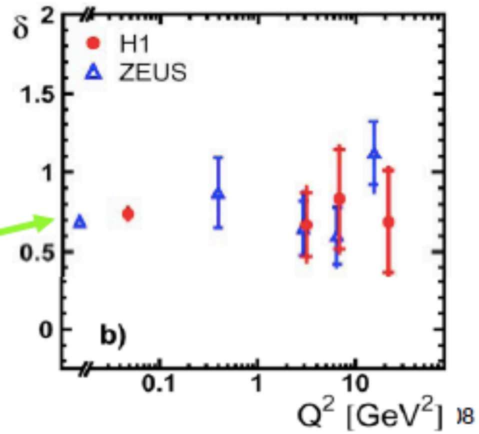
Turning the Q^2 Handle for J/Ψ

J/Ψ hard in photoproduction
With Q^2, second hard scale
-> predictions of $d\sigma/dQ^2$, W dep.



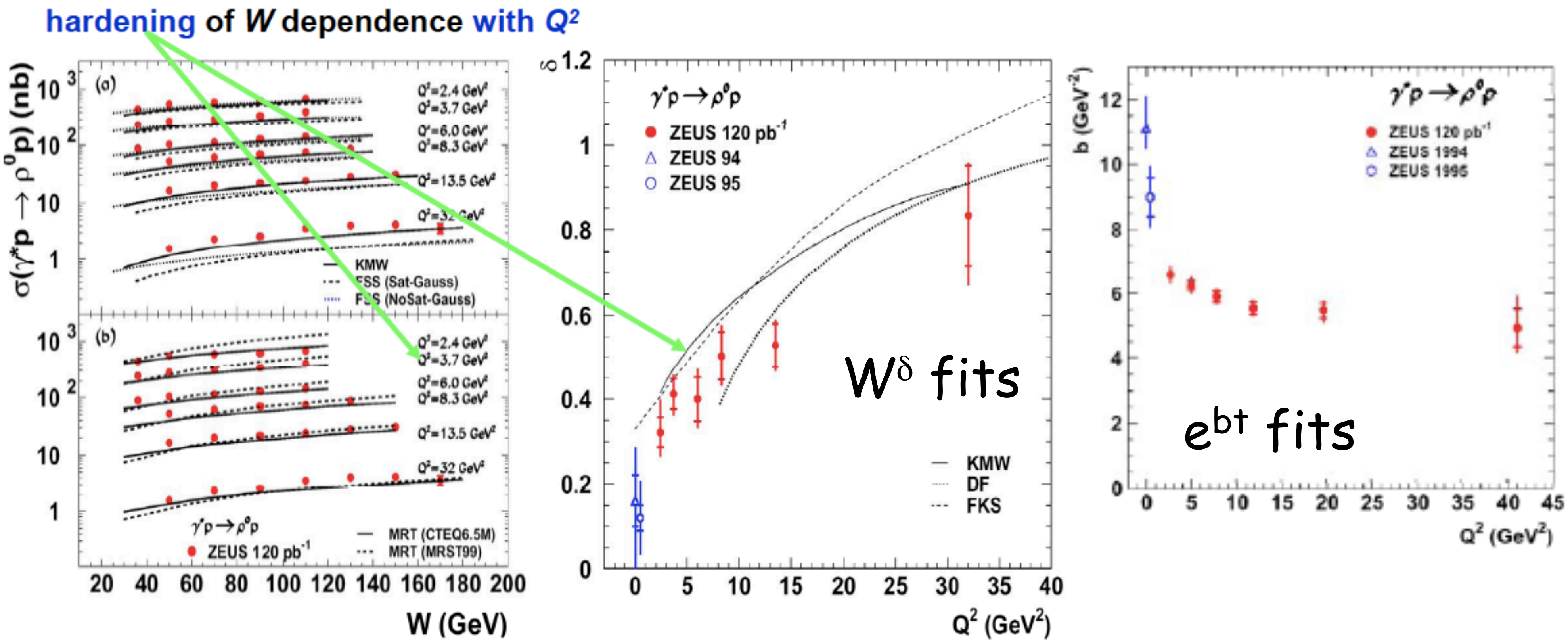


hard ($\alpha(0) = 1.20$), indep. of Q^2



- Fast reduction in cross section (>~ $1/Q^6$), reasonably described by 2 gluon models
- W dependence, t slope ~ unchanged (already hard @ $Q^2 = 0$)

Turning the Q^2 Handle for ρ



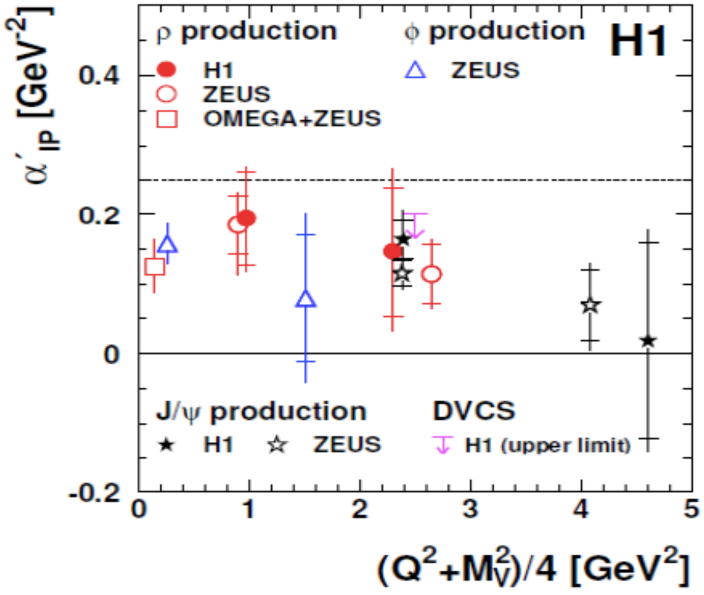
W and t dependences show transition from soft to hard process as Q^2 grows

Wealth of data available … interpretation in terms of 2 gluon exchange more problematic than J/Ψ due to ρ wavefunction

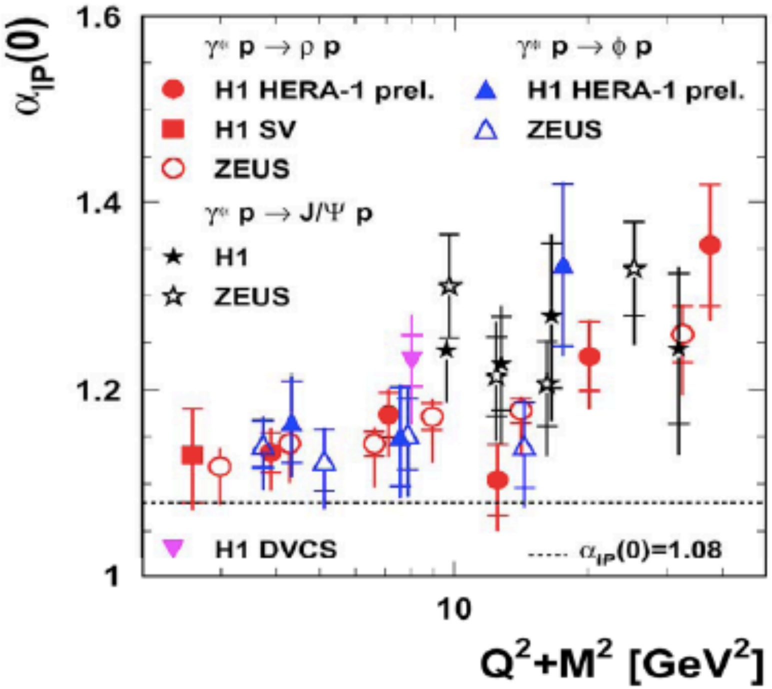
VM Summary

- Directly observing the transition From soft (hadronic) to hard (partonic) dynamics

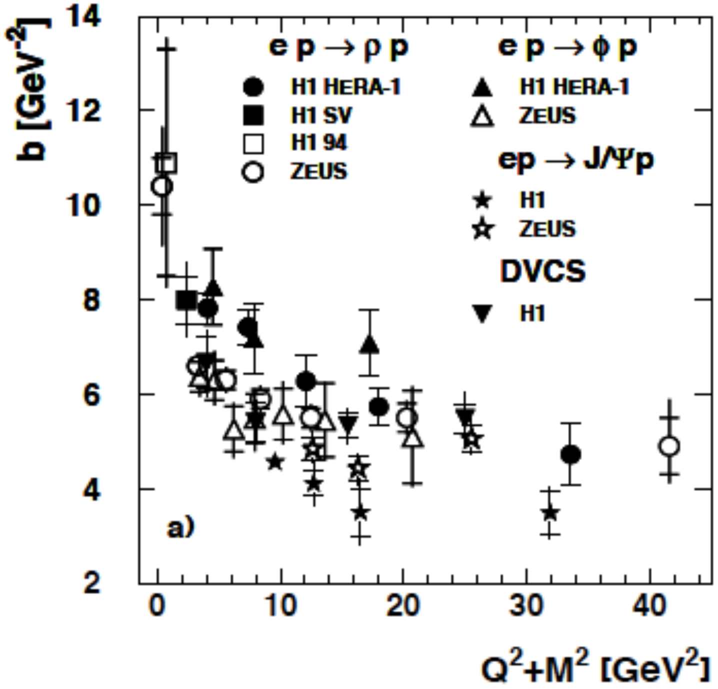
- Approximate scaling in $Q^2 + M_V^2$
– α' shows no significant variation with any scale!?!?



hard energy dependences



hard *t* slopes

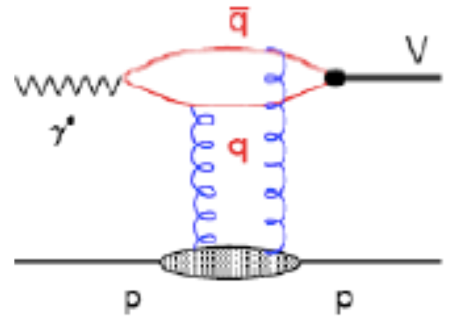


Inclusive Diffraction in Deep Inelastic Scattering

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 …



Diffractive DIS

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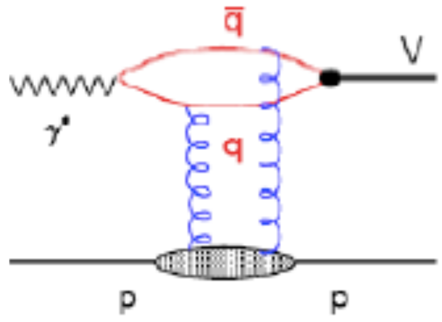
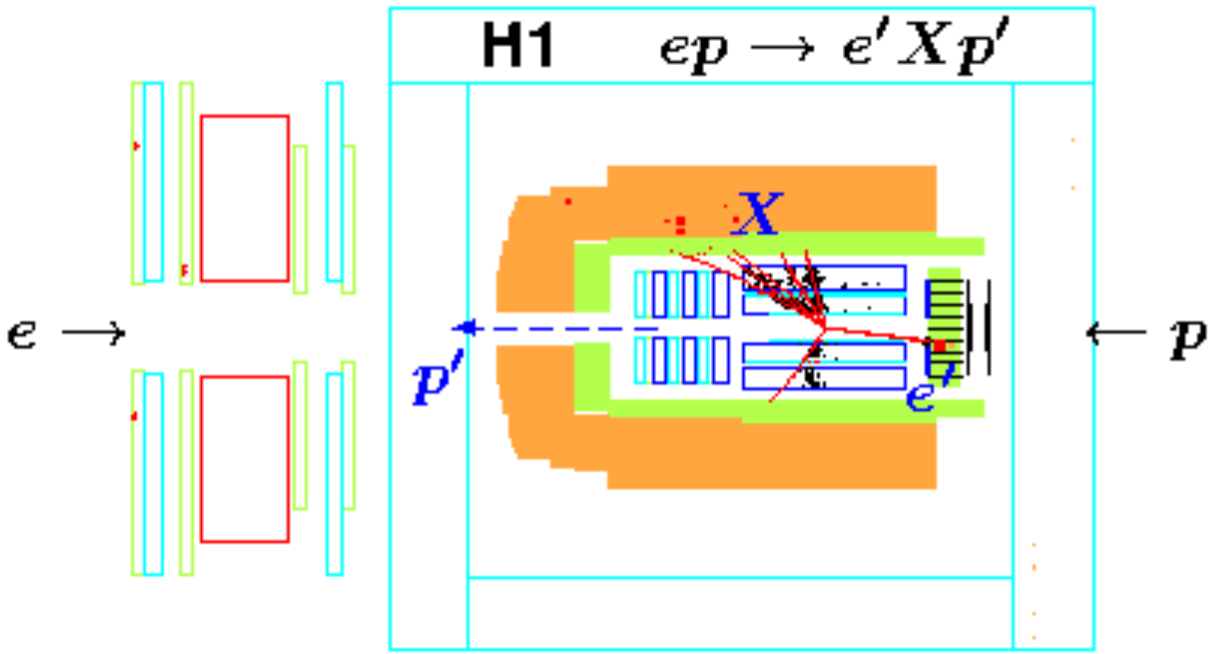
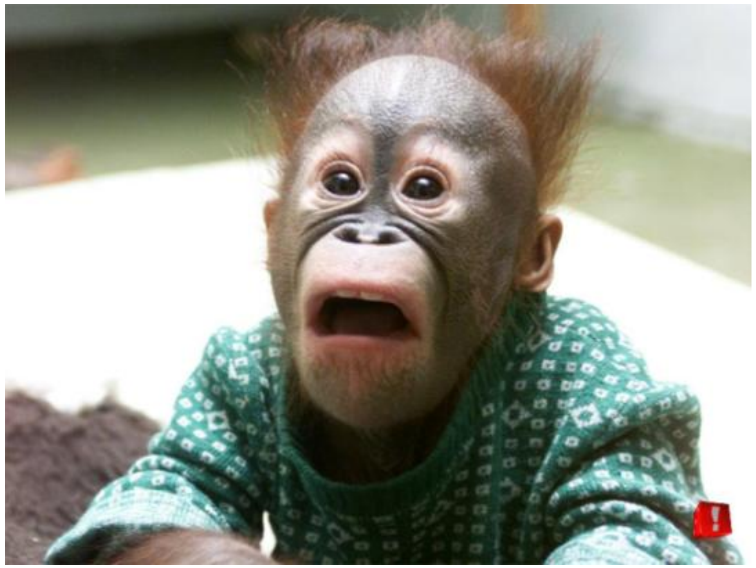


There are 'leading twist' diffractive processes with same Q^2 dependence as the bulk DIS cross section …





~10% of DIS events have no forward energy flow

Kinematics

Standard DIS variables …

x = momentum fraction q/p
Q^2 = |γ^* 4-momentum squared|

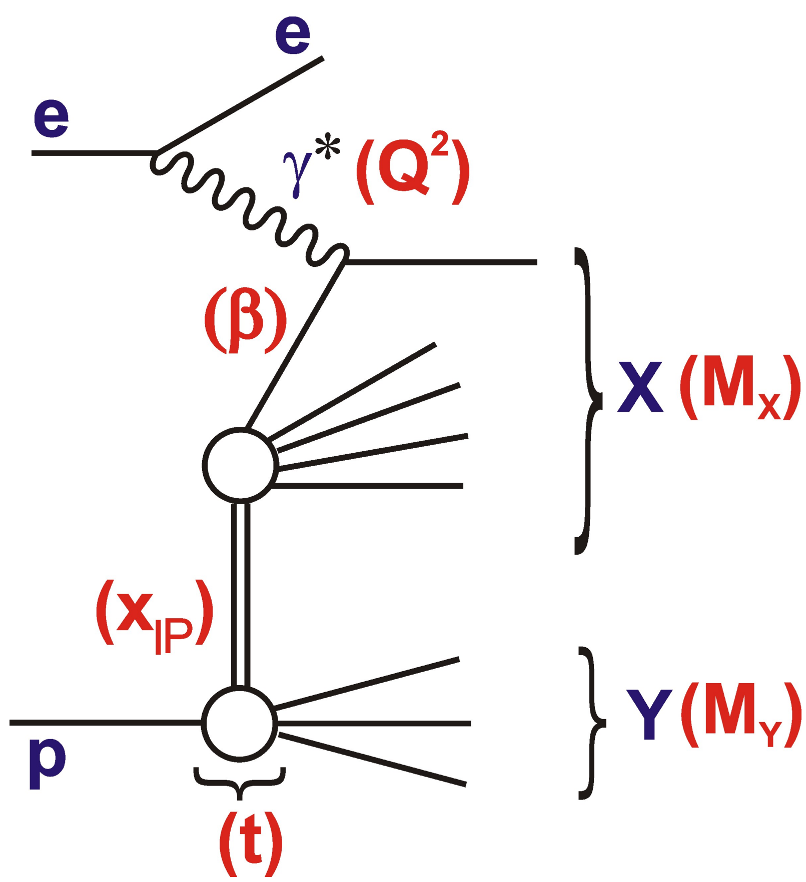
Additional variables for diffraction …

t = squared 4-momentum transfer at proton vertex

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

β = x / x_{IP} (momentum fraction q / IP)

Most generally ep→eXY …



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

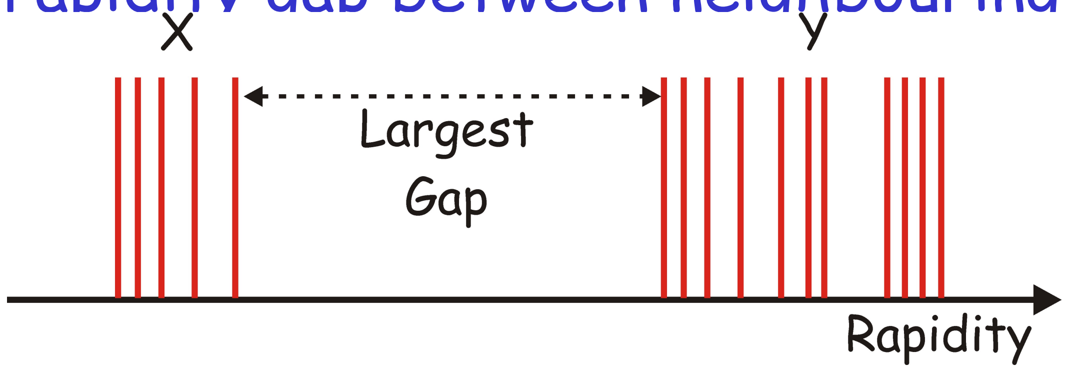
Definition of Diffraction

Definitions in terms of hadron-level observables …

- For SD ($\gamma p \rightarrow Xp$), can be done in terms of a leading proton
- More general definition to accommodate DD ($\gamma p \rightarrow XY$)

  …can be applied to any diff or non-diff final state …

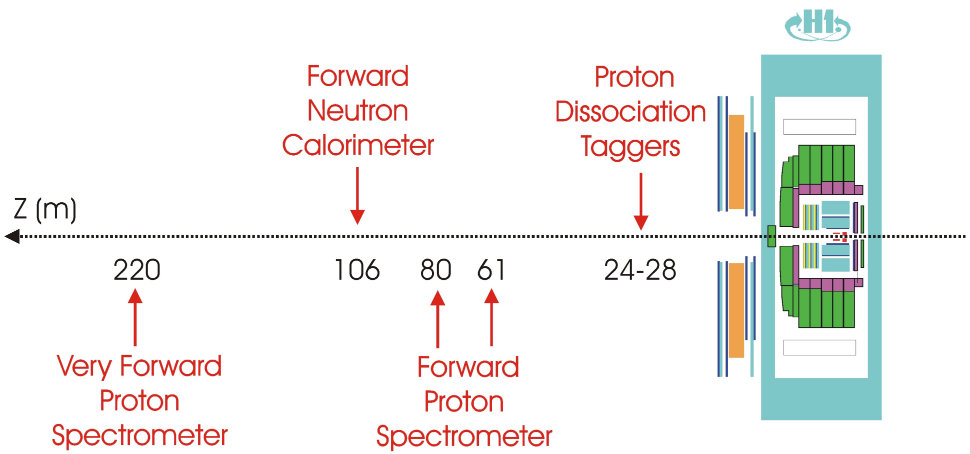
  - Order all final state particles in rapidity
  - Define two systems, X and Y, separated by the largest rapidity gap between neighbouring particles.



Many tests at HERA show leading proton & gap defs equivalent

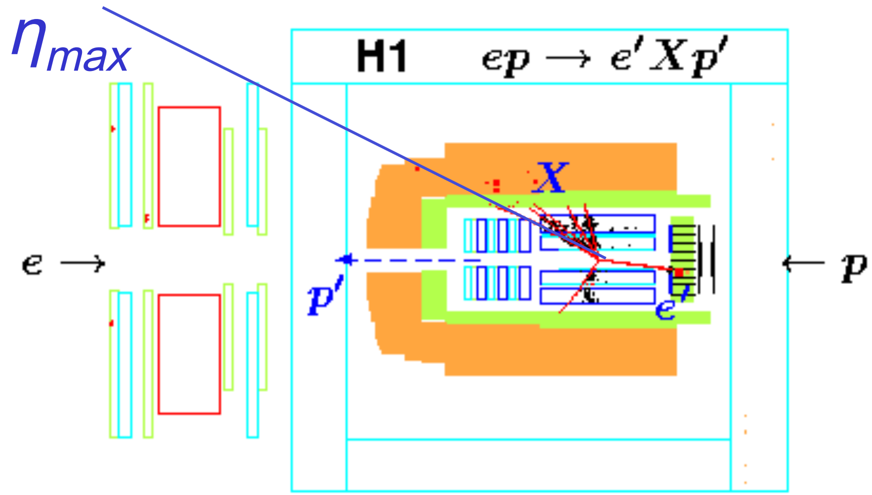
Signatures and Selection Methods

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



Limited by statistics and p-tagging systematics

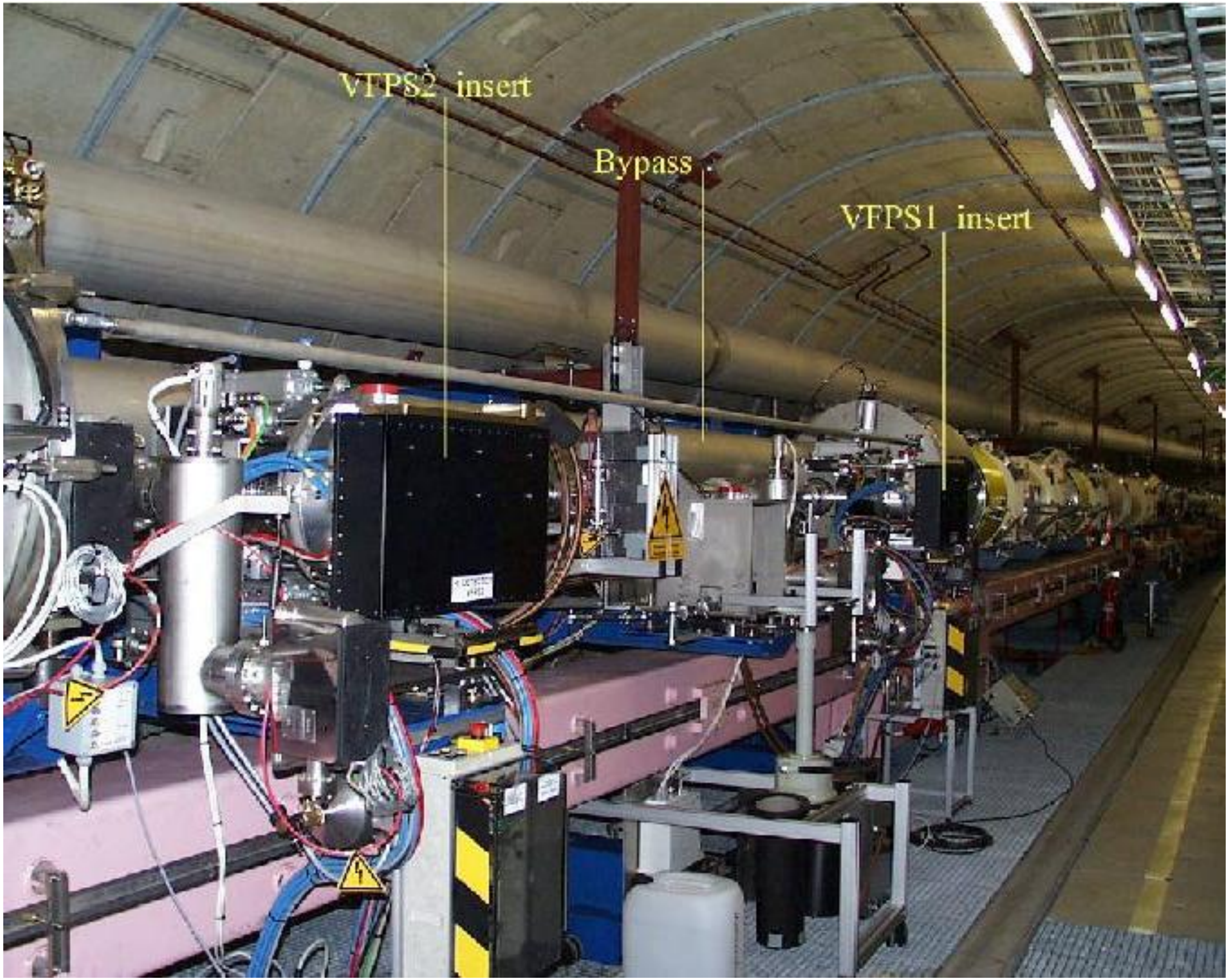
'Large Rapidity Gap' **(LRG)** adjacent to outgoing (untagged) proton



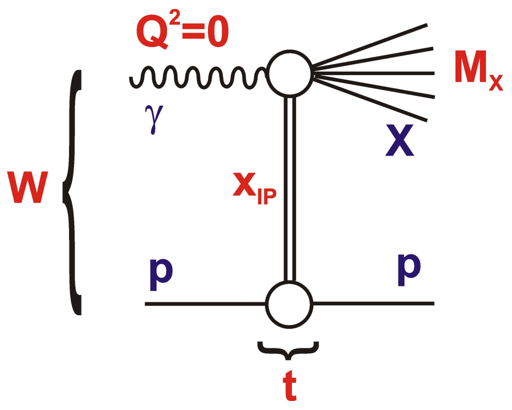
Limited by p-diss systematics

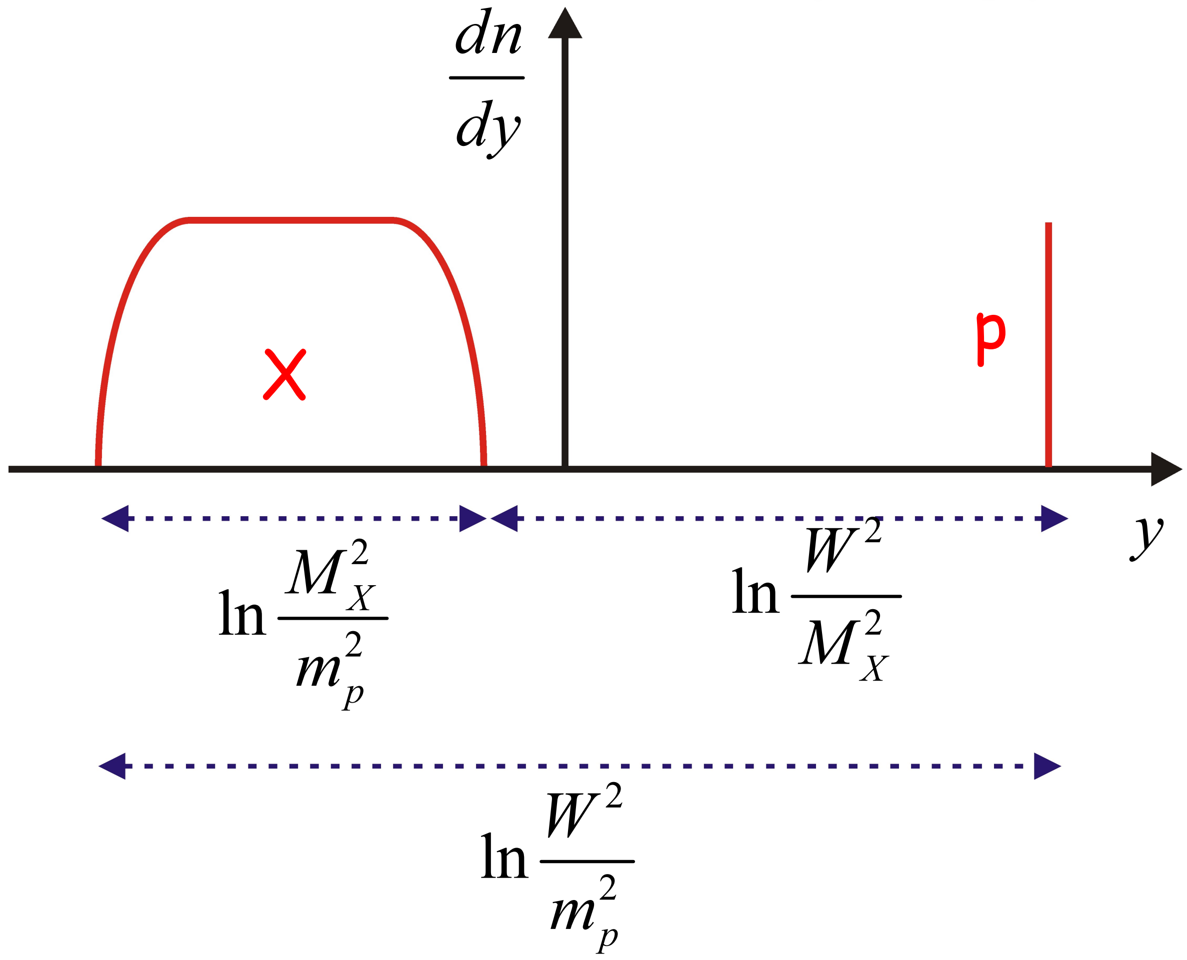
- The 2 methods have very different systematics
- Both experiments also have Zero Degree Calorimeters for forward neutron measurements

Example Roman Pots (H1 VFPS)



Basic Single Diffractive Event Topology



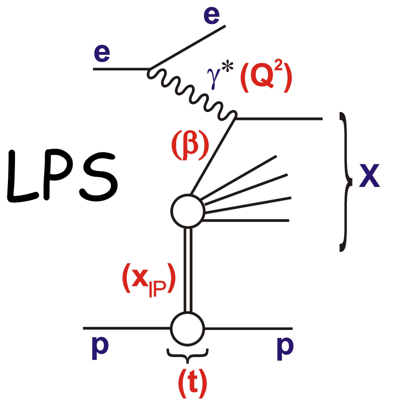


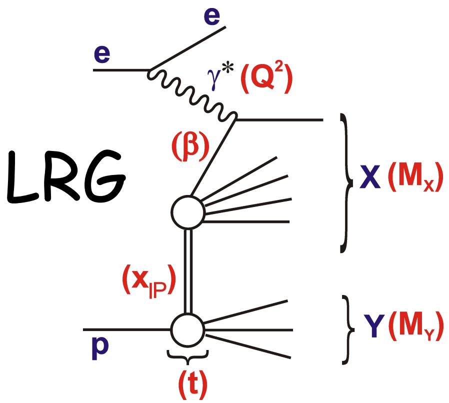
γp system of invariant mass W fragments to produce particles over rapidity range ~ $\ln(W^2/m_p^2)$

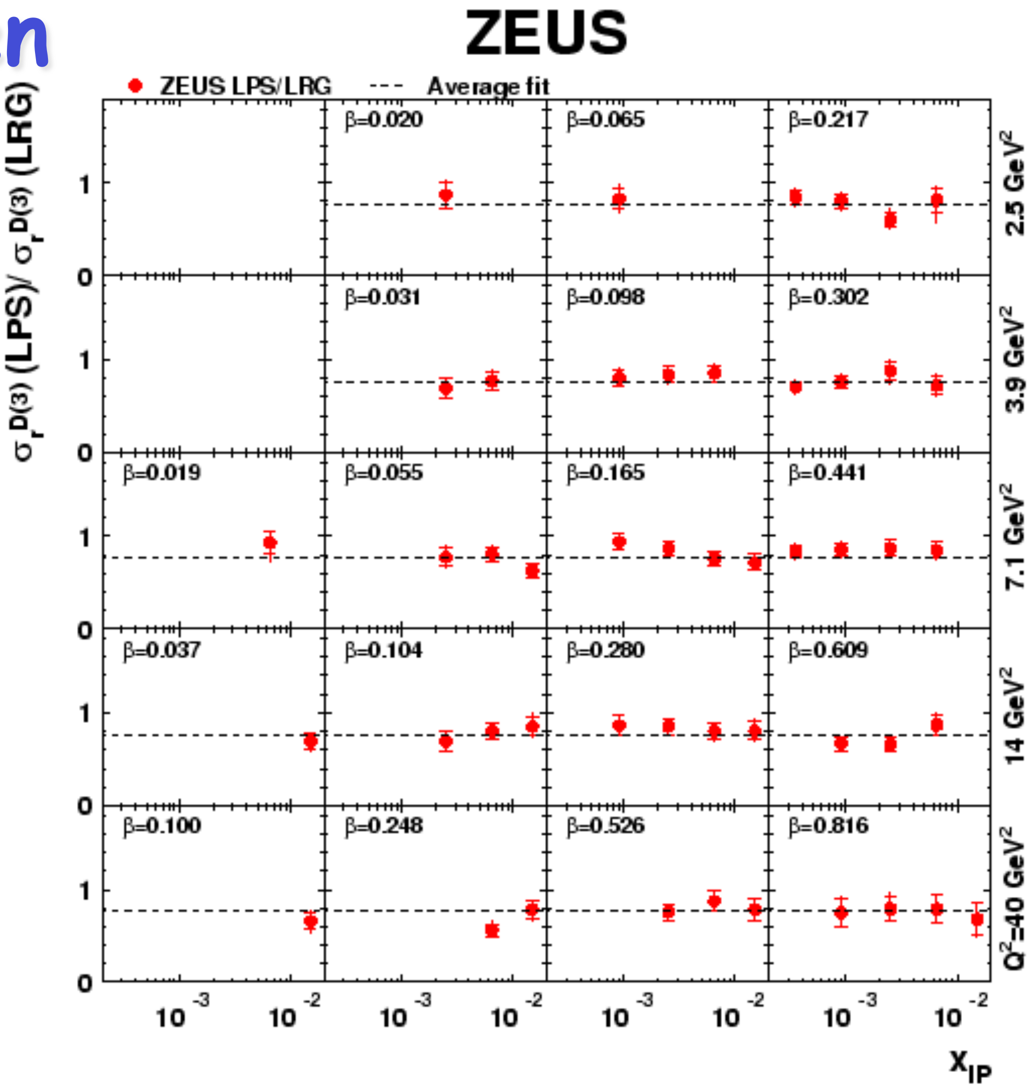
Similarly, diffractive system of mass M_X fragments over rapidity range ~ $\ln(M_X^2/m_p^2)$ leaving rapidity gap of size ~$\ln(W^2/M_X^2)$ ~ $-\ln x_{IP}$

Particle production within X shows similar patterns to ND

Comparisons between Methods

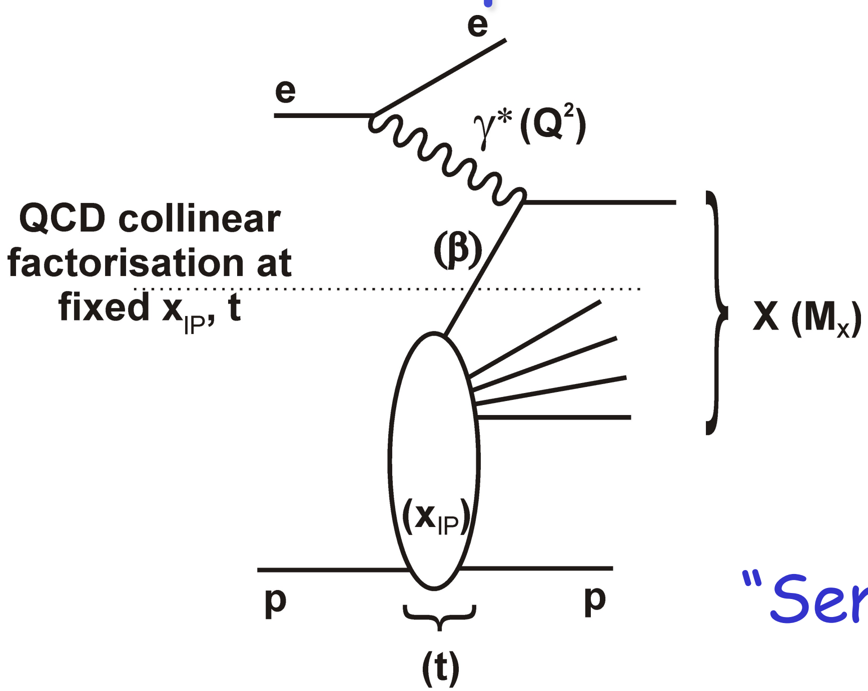






- LRG selections contain typically 20% p diss
- No significant dependence on any variable
- **… well controlled, precise measurements**

The "Proper" Theory



"Semi-inclusive QCD Factorisation"

QCD hard scattering collinear factorisation proved for diffraction at fixed scattered proton 4-vector (Collins 1997)

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

i.e. can define **diffractive PDFs (DPDFs), f_i^D**…

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

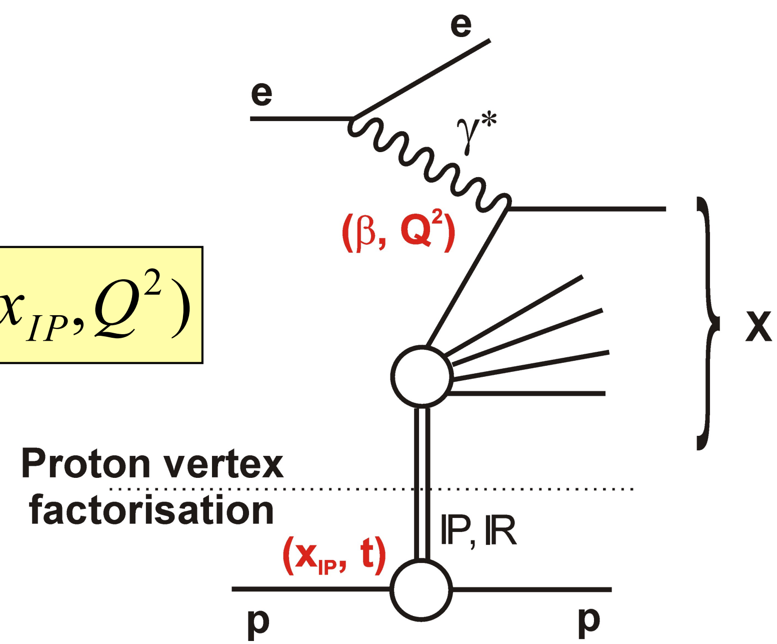
But we don't know how DPDFs change with (x_{IP}, t)

A deeper factorisation?

'Proton vertex' factorisation

… completely separate (x_{IP}, t) from (β, Q^2) dependences.

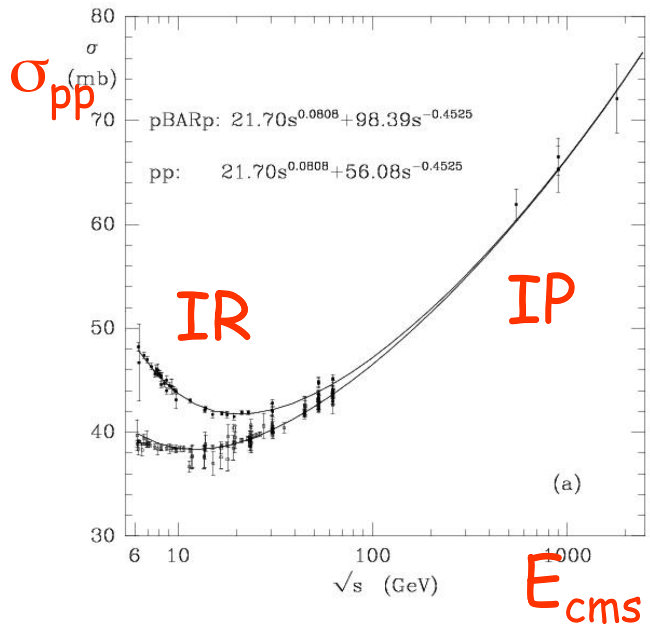
$$f_i^D(x,Q^2,x_{IP},t) = f_{IP/p}(x_{IP},t) \cdot f_i^{IP}(\beta = x/x_{IP},Q^2)$$



No firm QCD basis, but consistent with all experimental data!

DPDFs at fixed x_{IP} and t then measure partonic structure of the exchanged system (IP)

… in fact there a `sub-leading' (IR) exchange is also present at high x_{IP} (as for total, elastic pp cross sections)

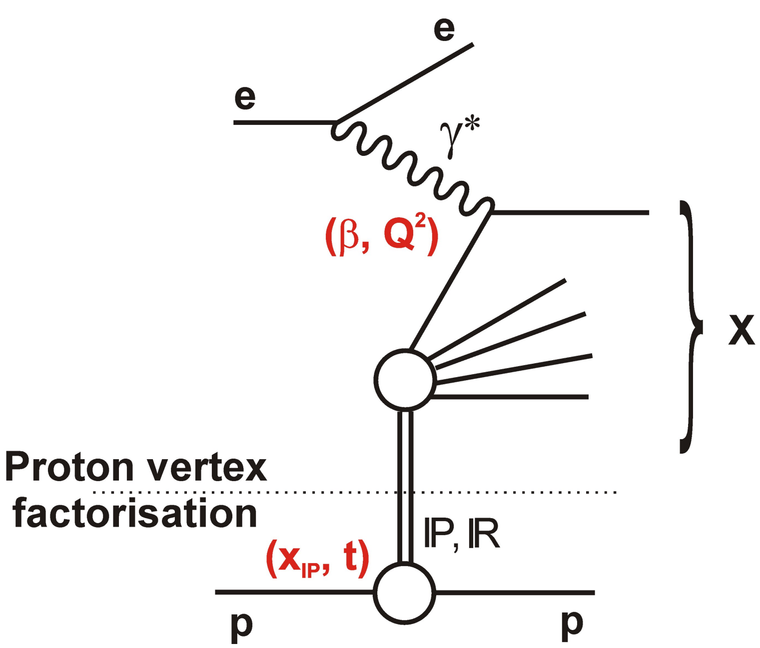


Measurements and Observables

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!

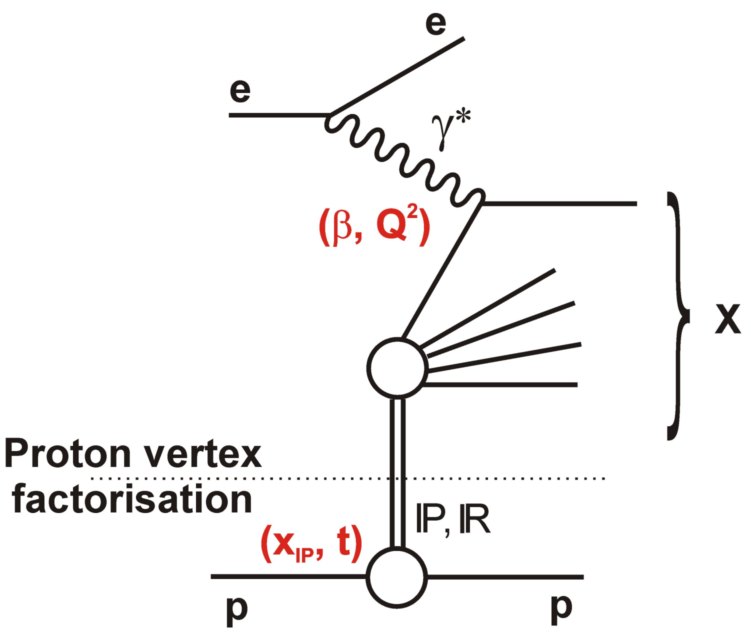


- (x_{IP}, t) dependences at fixed (β, Q^2) for soft (Pomeron) physics

- (β, Q^2) dependences at fixed (x_{IP}, t) for hard (QCD) physics
… Diffractive quarks and gluons

Factorisation Properties of Diffractive DIS

Proton vertex factorisⁿ hypothesis survived many HERA tests



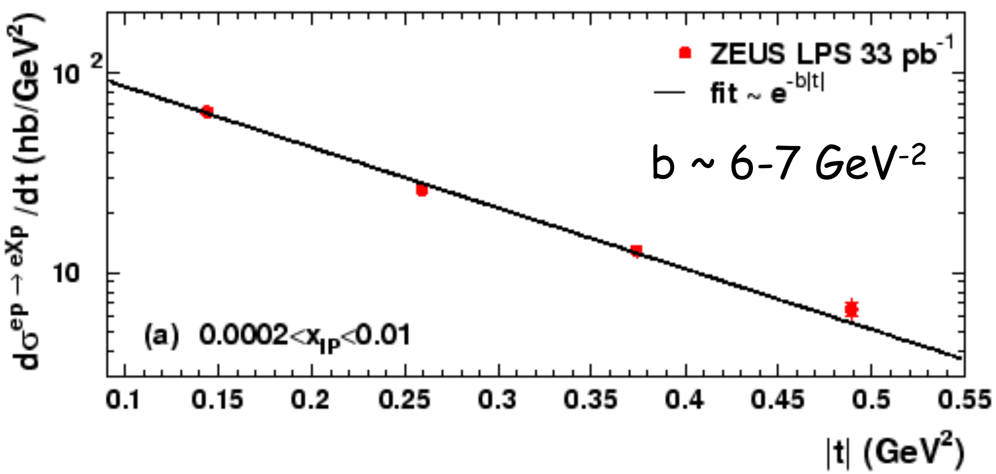
Total electron - pomeron DIS cross section $\sigma\left(e\, IP \rightarrow eX\right)$ described in terms of Diffractive Parton Densities (DPDFs), $f_i\left(\beta, Q^2\right)$

Pomeron flux $f_{IP/p}$ exhibits exponential t dependence

x_{IP} dependence well modelled by Regge phenomenology

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

$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP}\, t$$



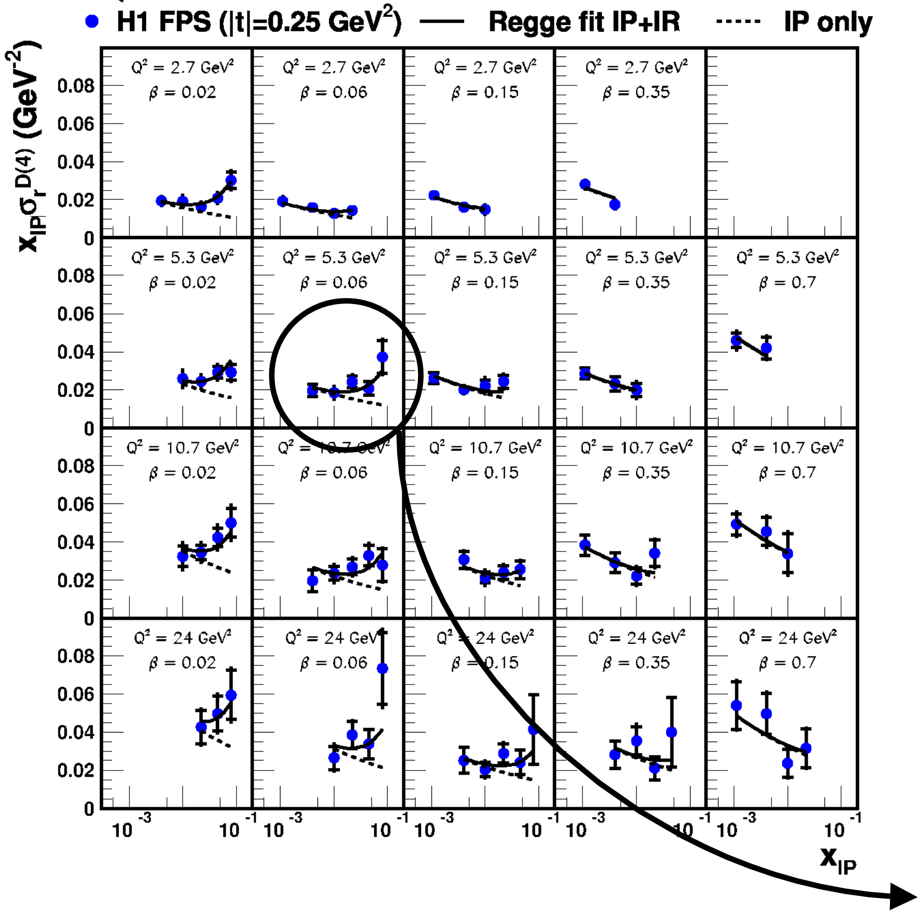
ep → eXY Data

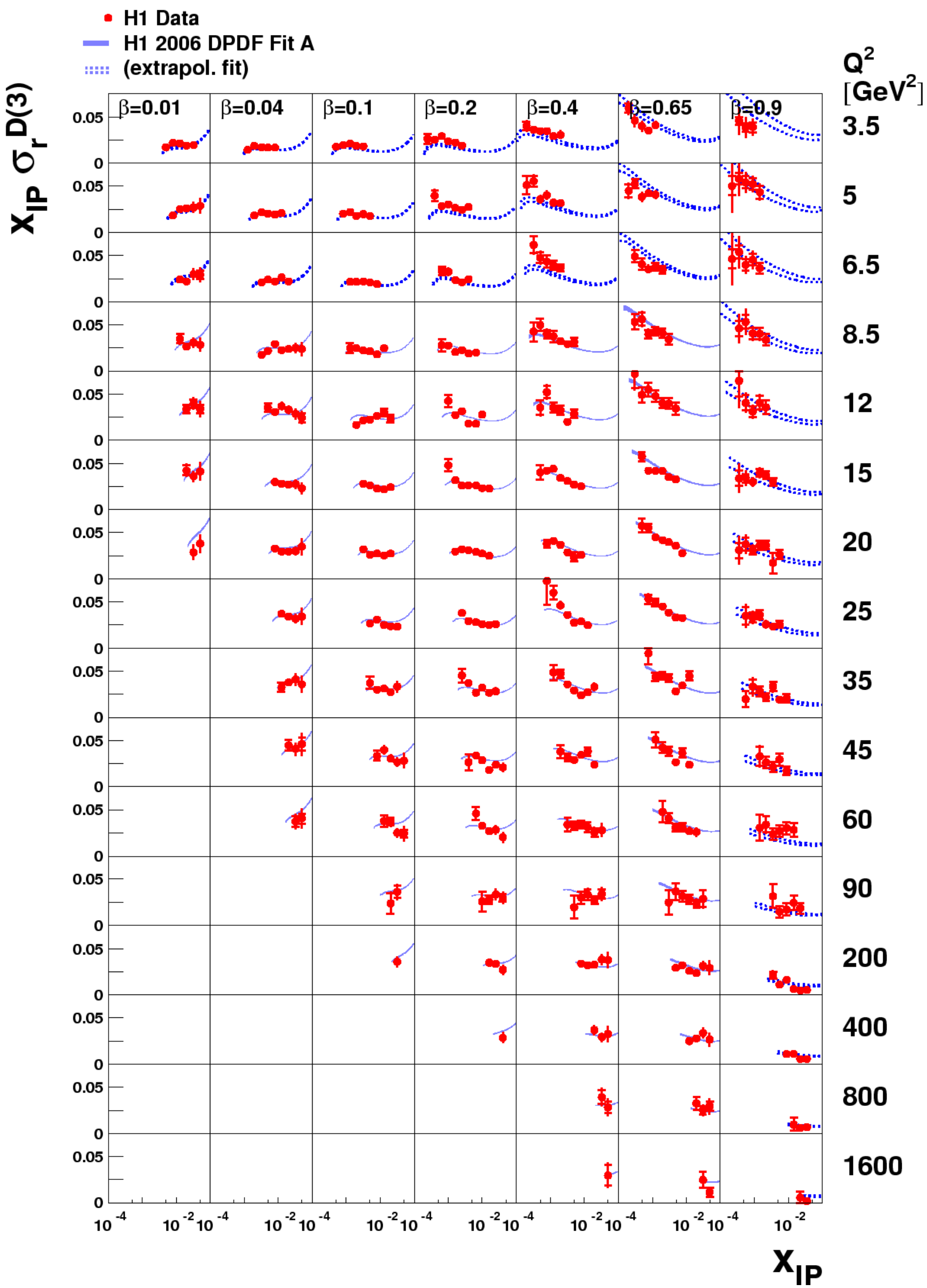
LRG: M_Y < 1.6 GeV →

$$3.5 \le Q^2 \le 1600\ \mathrm{GeV}^2$$

FPS: Y=p

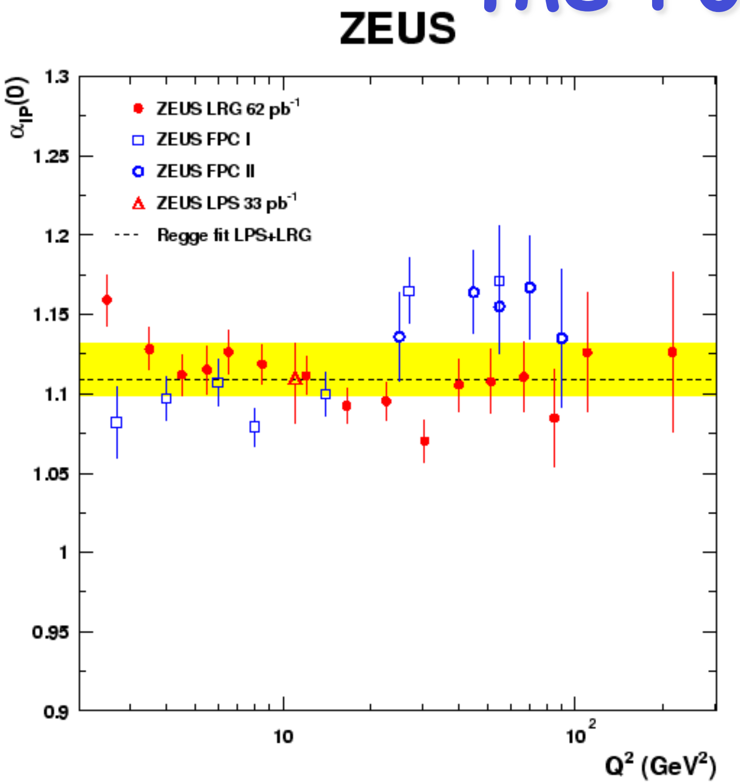
$$2.7 \le Q^2 \le 24\ \mathrm{GeV}^2$$

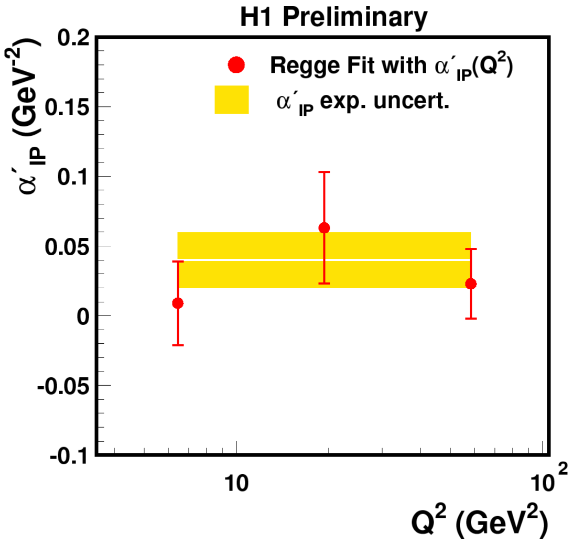


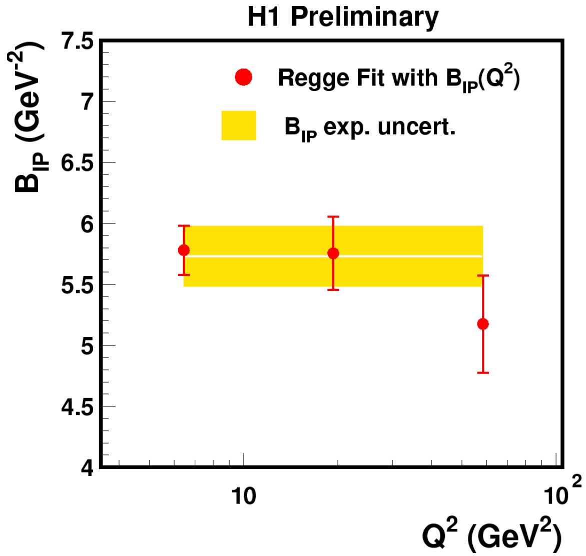


x_{IP} dependence shows clear IP+IR structure

Evidence for Proton Vertex Factorisation & the Pomeron Flux Factor







Excellent consistency between experiments and methods.

e.g. From H1 FPS data:

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

$$\alpha'_{IP} = 0.04 \pm 0.02\ (\text{exp.}) \pm 0.03\ (\text{model})\ \text{GeV}^{-2}$$

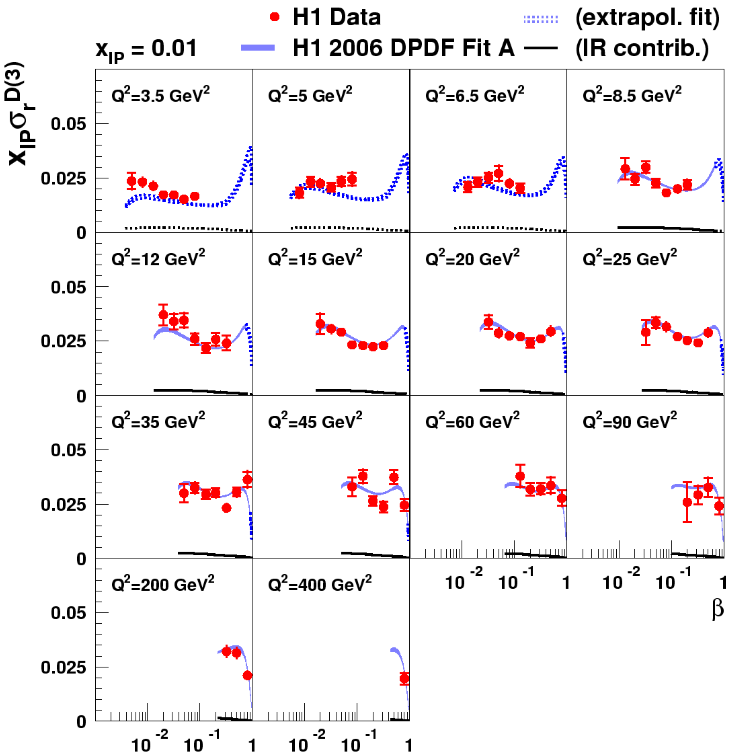
$$B_{IP} = 5.7 \pm 0.3\ (\text{exp.}) \pm 0.6\ (\text{model})\ \text{GeV}^{-2}$$

$\alpha_{IP}(0)$ consistent with soft IP → Dominantly soft exchange
α_{IP}' smaller than soft IP → Absorptive effects?...

Diffractive Parton Densities

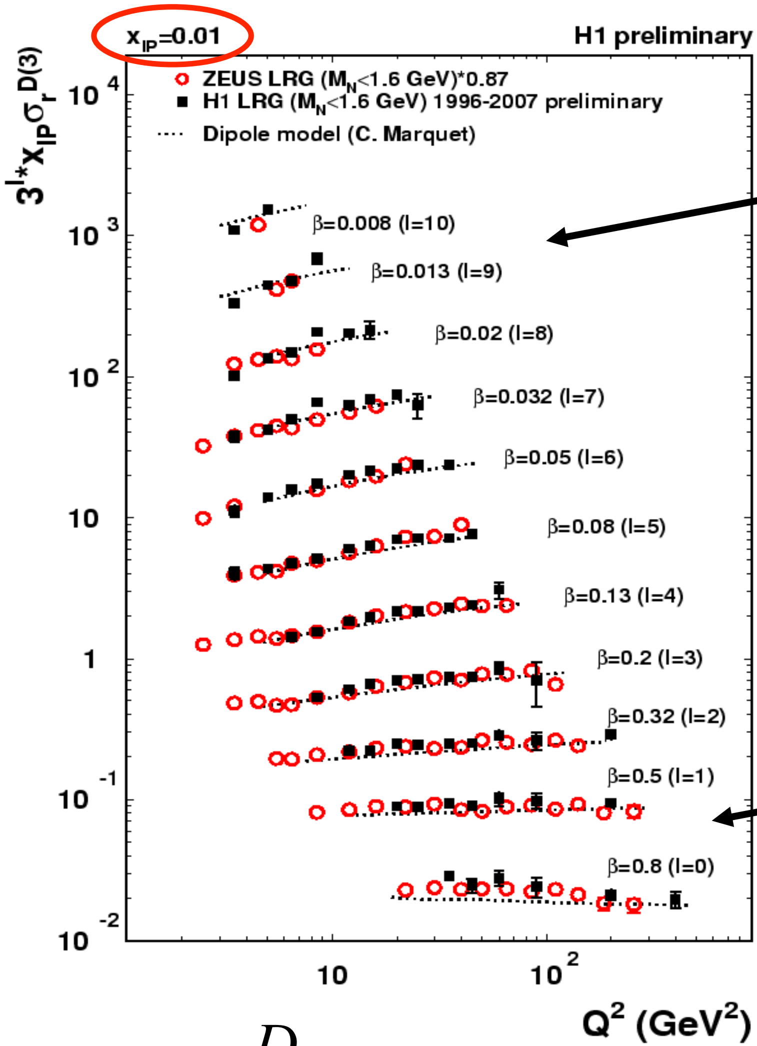
Sensitivity to Diffractive Quarks & Gluons

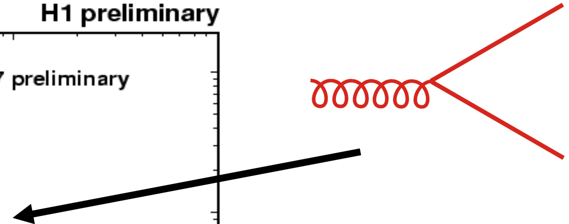
Similarly to Inclusive DIS …

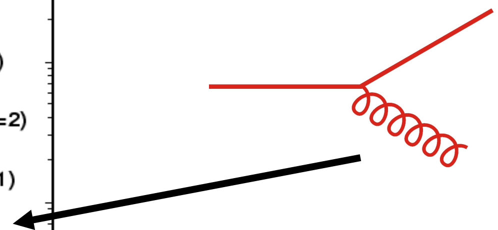


Diffractive cross section measures quark density

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



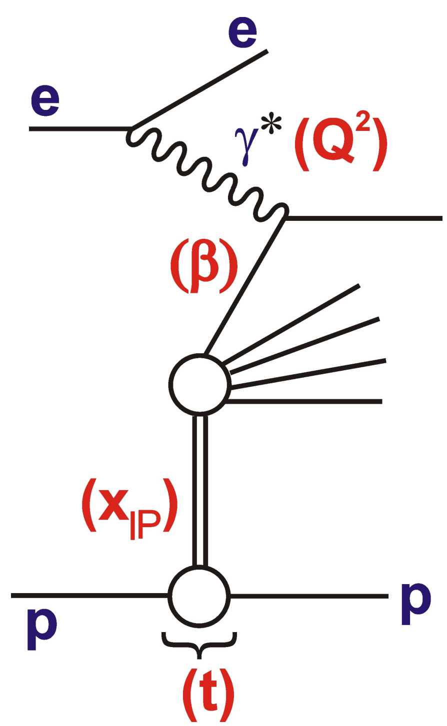




Q^2 dependence tells us gluon density via DGLAP eqns

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

Extracting the Quarks and Gluons



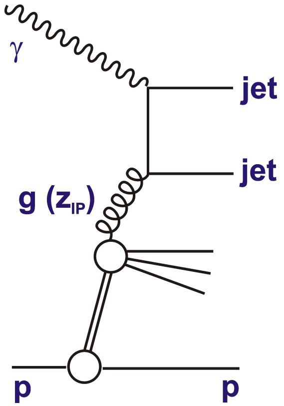
- Fit β and Q^2 dependence of LRG data from fixed x_{IP} binning scheme (χ^2 minimisation)

- Parameterise DPDFs at starting scale Q_0^2 for QCD evolution …
… evolve to higher Q^2 using NLO DGLAP equations (massive charm) and fit β and Q^2 dependence for DPDFs

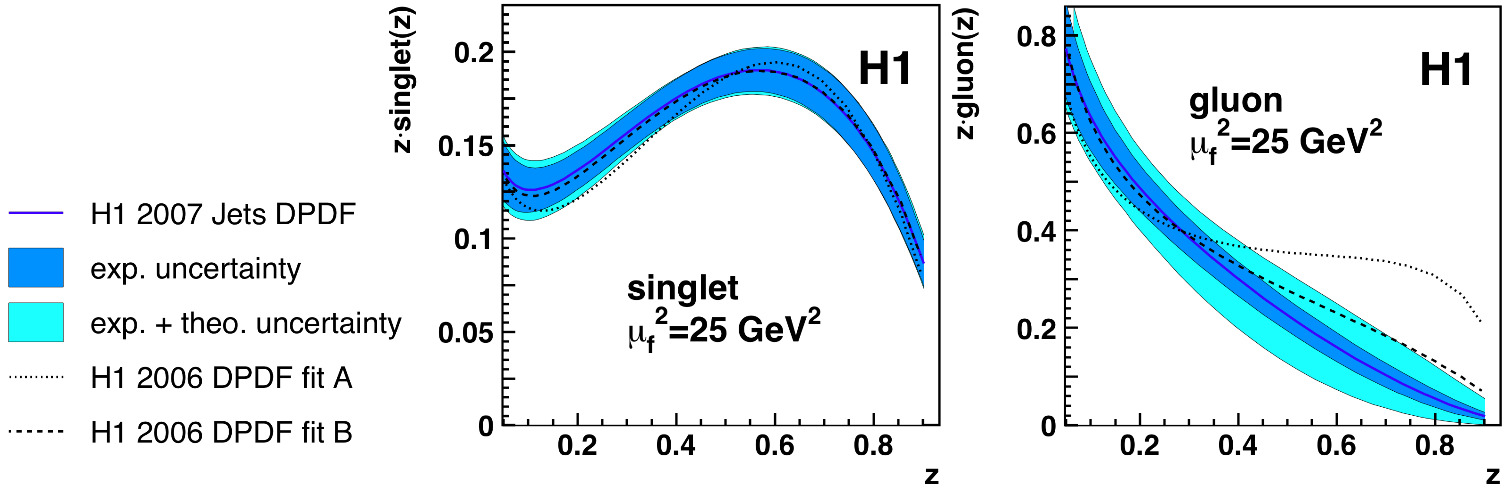
- Use proton vertex factorisation with $\alpha_{IP}(t)$ from FPS and LRG data to relate data from different x_{IP} values with complementary β, Q^2 coverage.

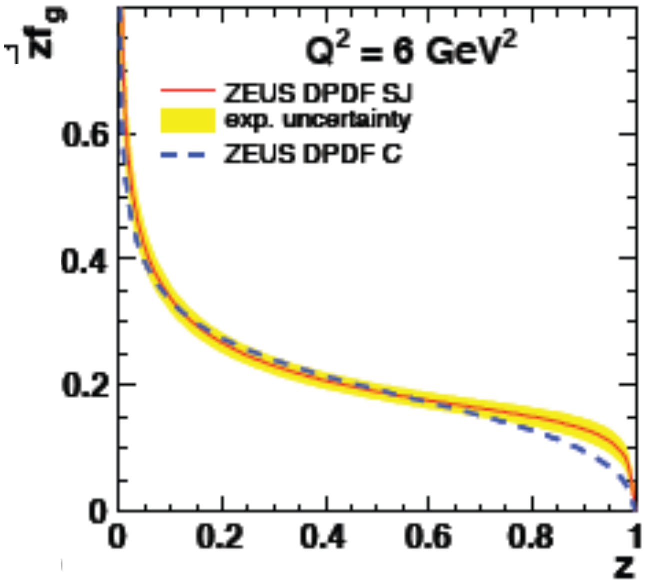
- Exclude data with low M_X or high β (higher twist region) and with low Q^2 (NLO insufficient?)

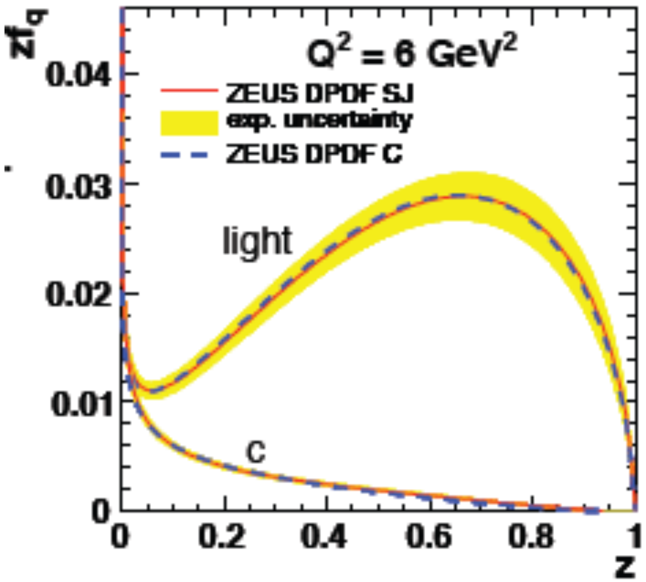
Some Recent DPDF sets



3 early H1 fits





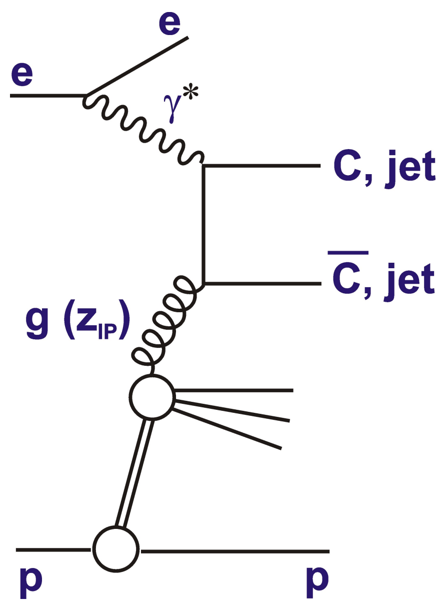


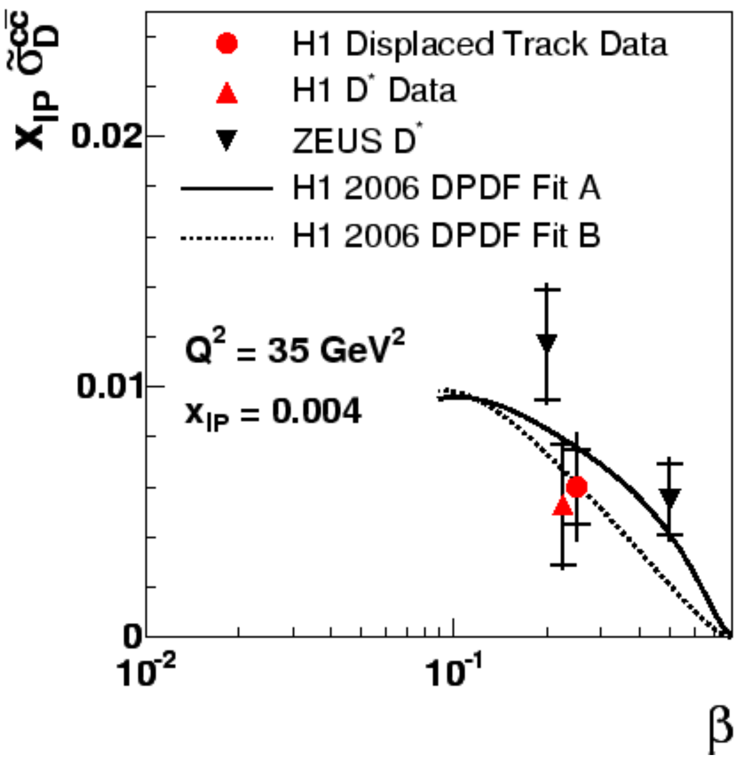
- Recent ZEUS fits to higher stats LRG & LPS data. With improved heavy flavour treatment

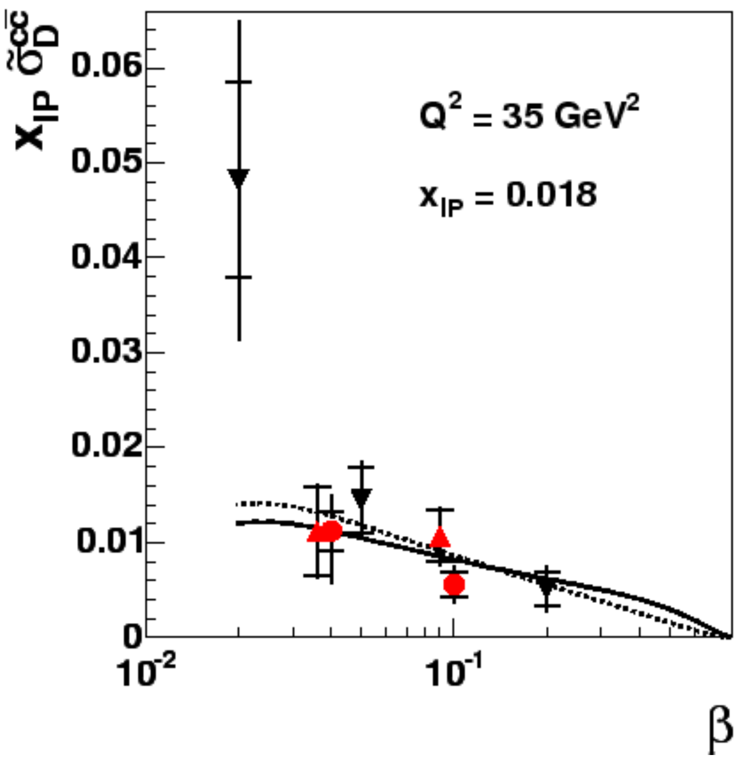
DPDFs dominated by a gluon density which extends to large z

Testing Factoris^n and the Gluon with Charm

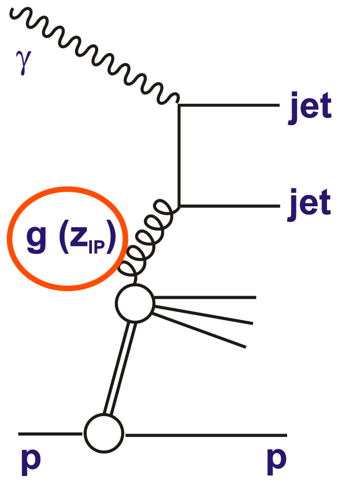
- Measure diffractive charm cross section by two different methods
- Charm production up to 30% of total diffractive cross section!
- Well described by prediction from DPDFs

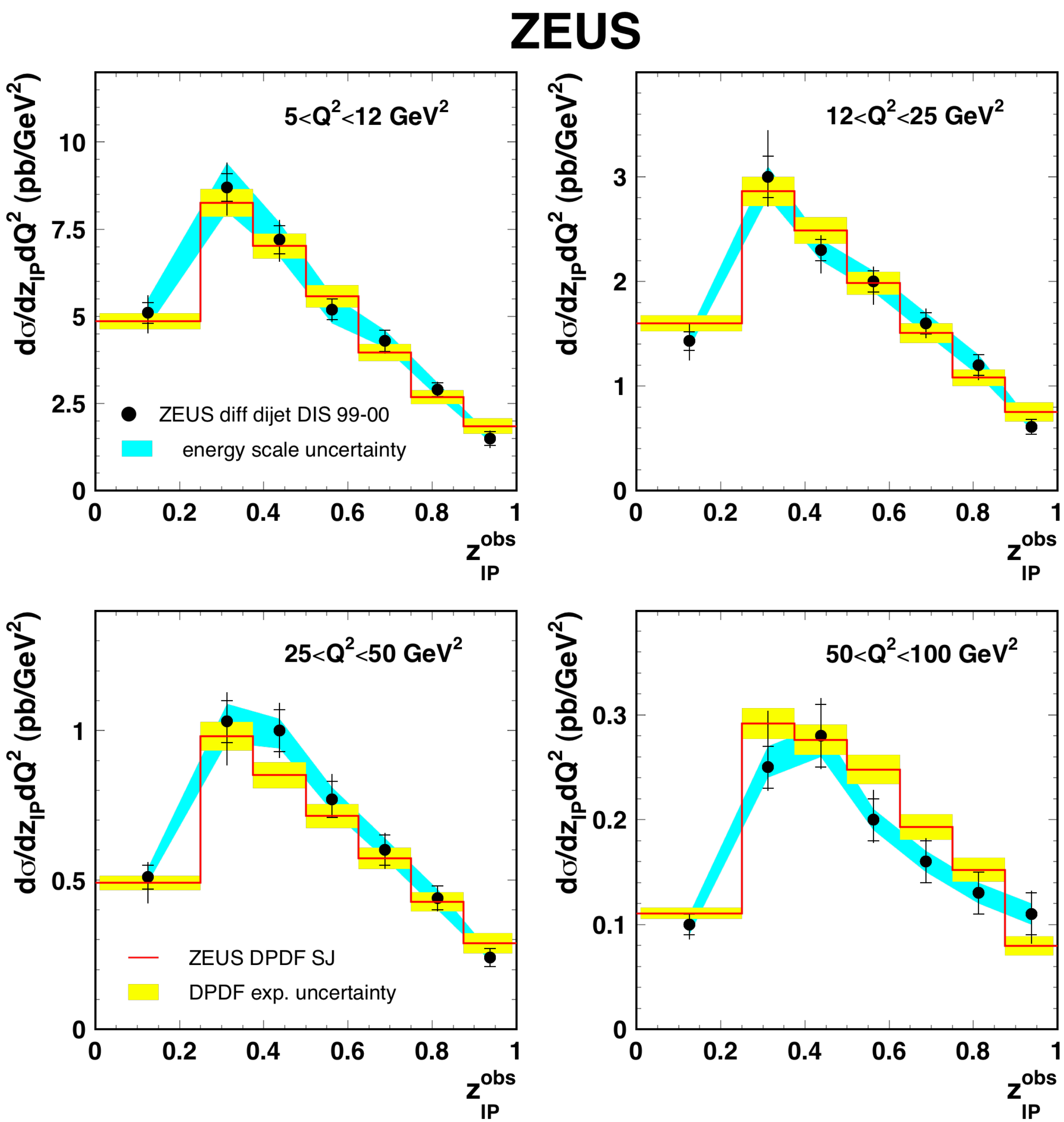






Testing Factorisation / Gluon with Jet Data





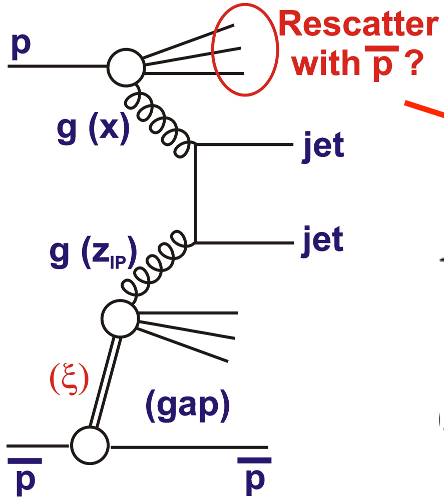
- Successful descriptions of diffractive final state data in DIS … Jets, Charm …

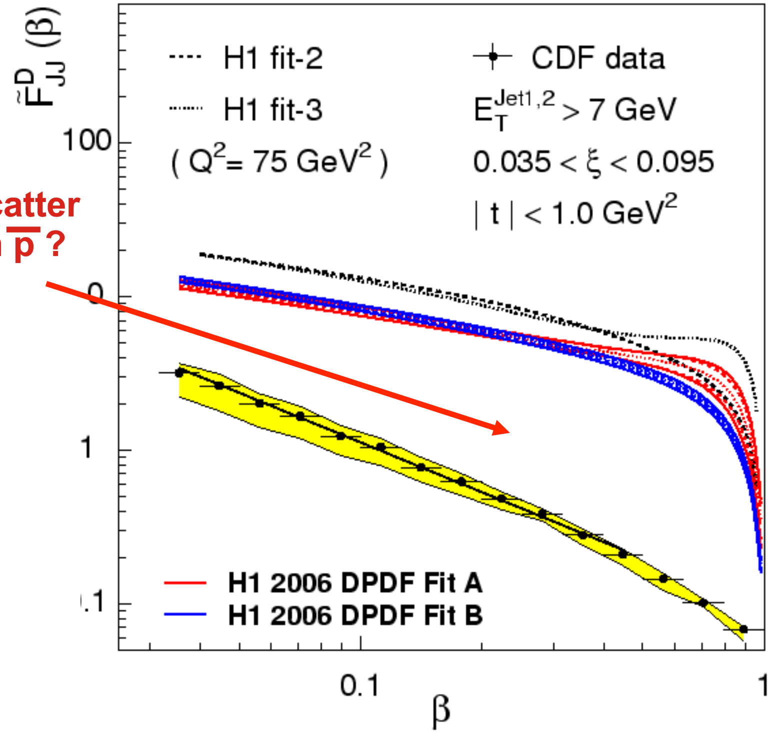
- Factorisation works in diffractive DIS as expected

Factorisation Breaking and Rapidity Gap Survival Probabilities

.. meanwhile in pp(bar) …

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

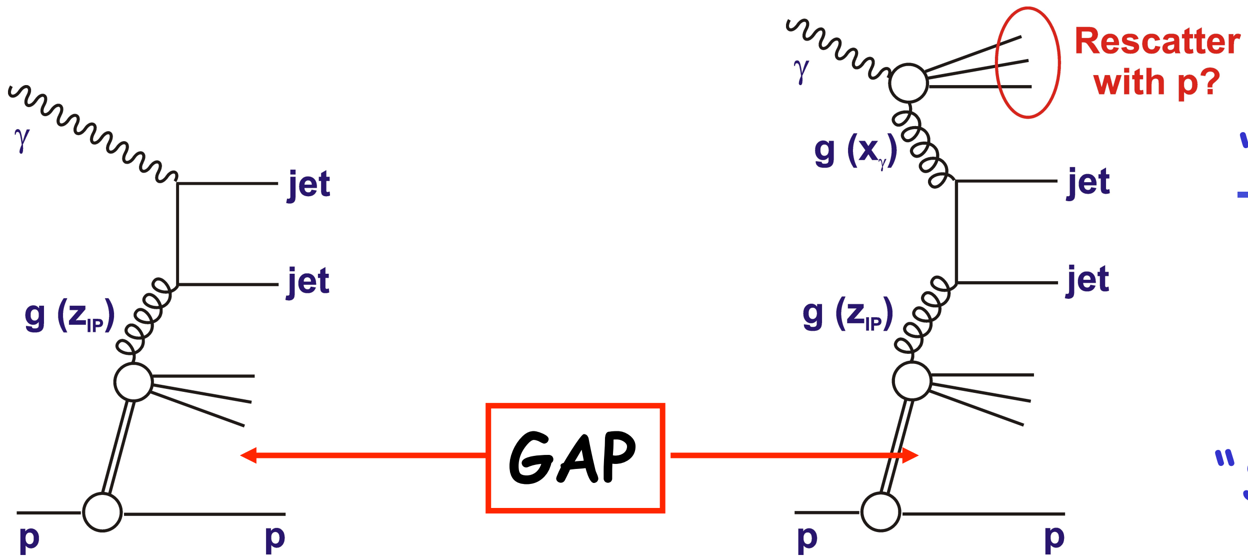




… photoproduction jets as the perfect control experiment?…

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

"$S^2 = 1$"



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

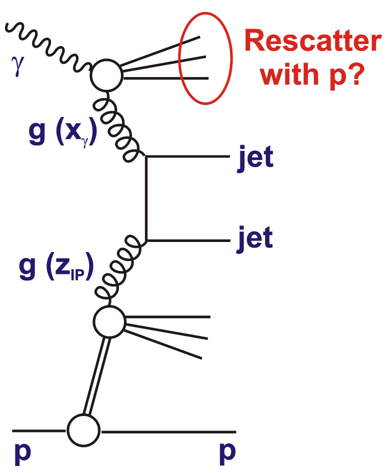
"$S^2 \sim 0.34$?"

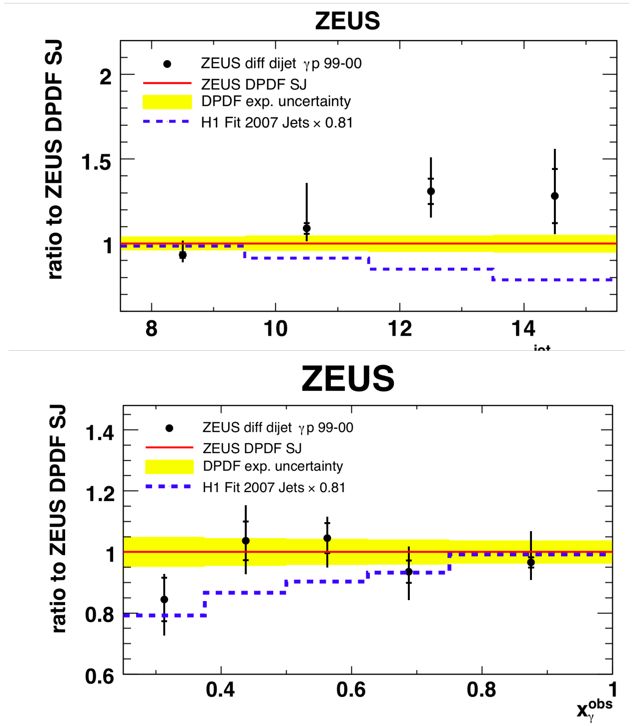

ZEUS

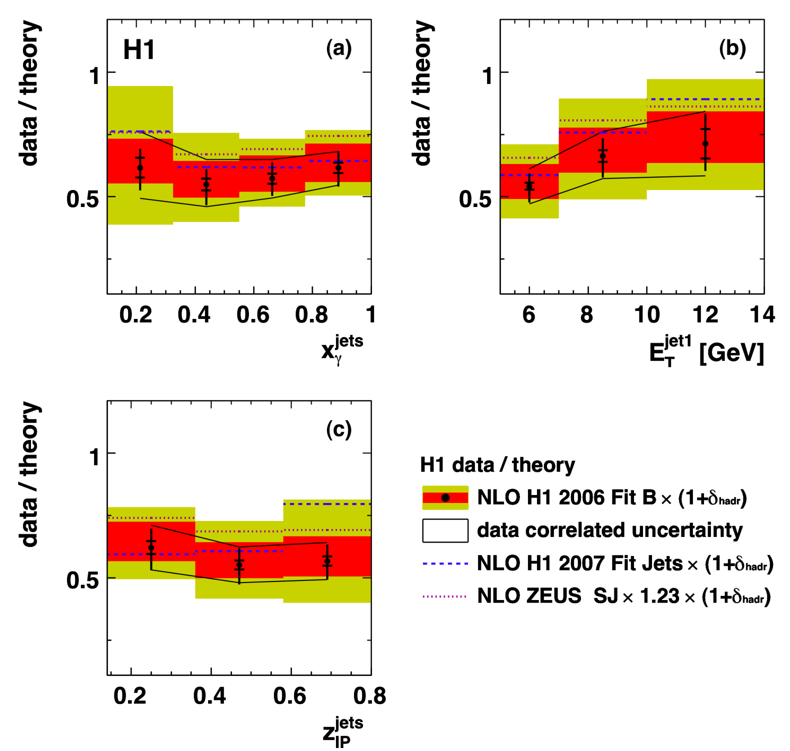
Rapidity Gap Survival Probability in Diffractive Dijet Photoproduction

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?

Refined gap Survival Model (KKMR)

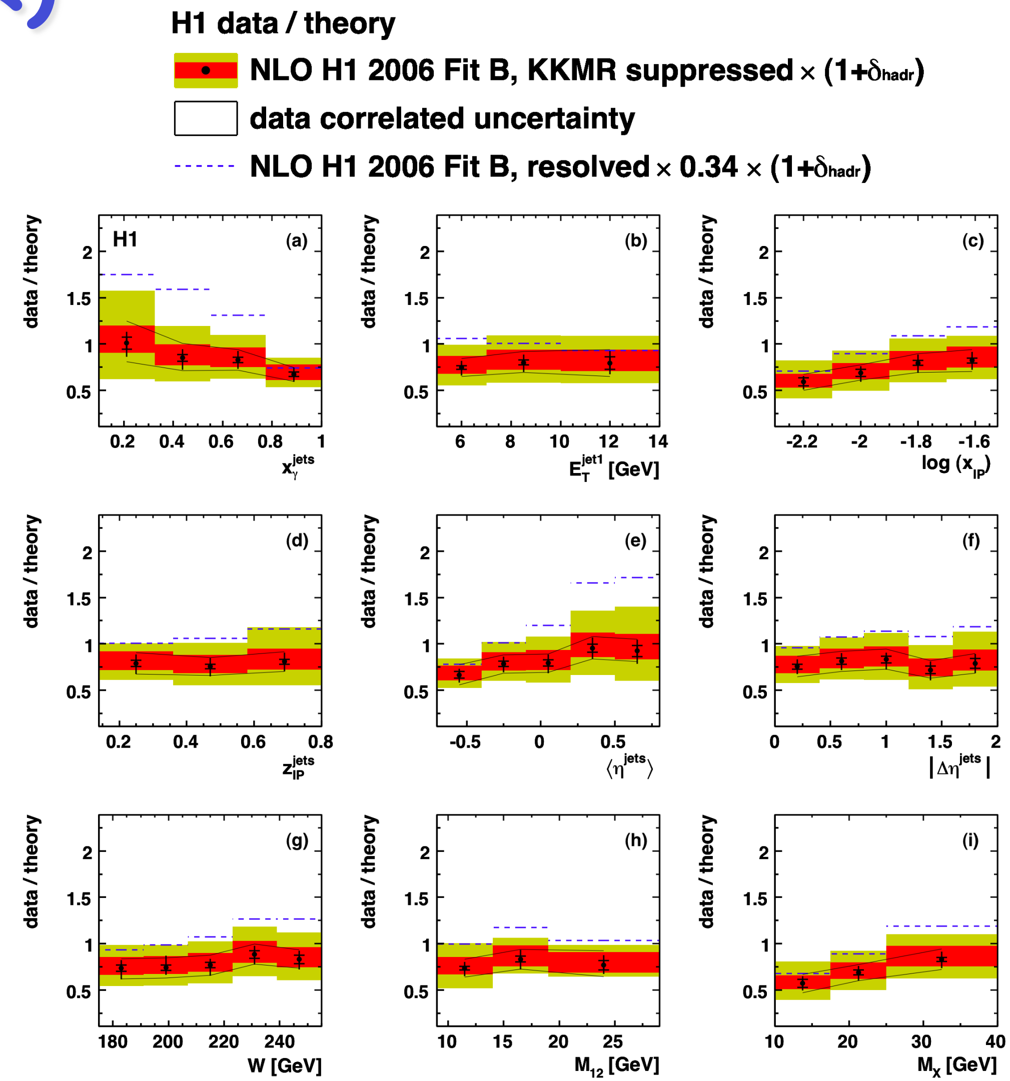
[hep-ph/0911.3716]

Direct contribution remains unsuppressed

Suppression factor 0.34 applies to Hadron-like (VMD) part of photon structure only (low $x_\gamma < 0.1$)

Point-like (anomalous) part of photon structure has less suppression (~0.7-0.8)

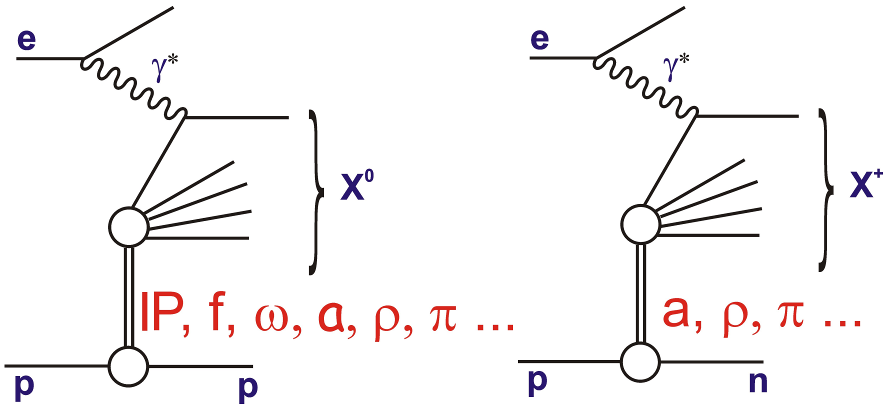
Smaller gap destruction effects with some E_T dependence



Fair agreement with both H1 and ZEUS data …

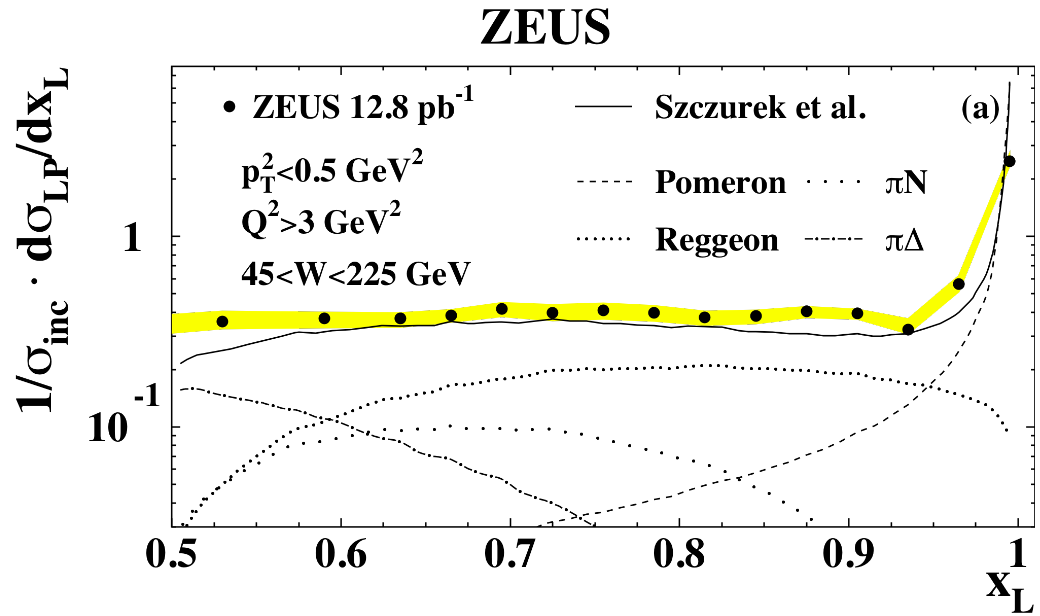
Sub-Leading (non-pomeron) Exchanges

Going beyond the diffractive forward peak



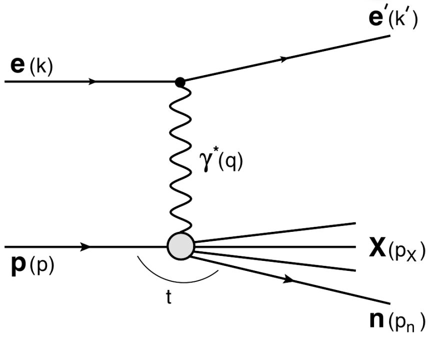
As x_L (= $1 - x_{IP}$) decreases ...
- Sub-leading exchanges important for leading protons
- Leading neutrons produced via charge exchange reactions

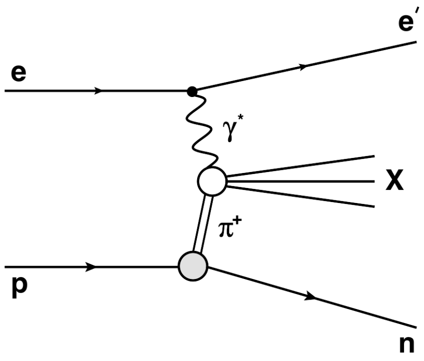
Regge analysis suggest leading proton production beyond diffractive peak dominated by isoscalar meson exchanges with $\alpha_{IR}(0) \sim 0.5 \rightarrow$ ω, f rather than isovector a, ρ

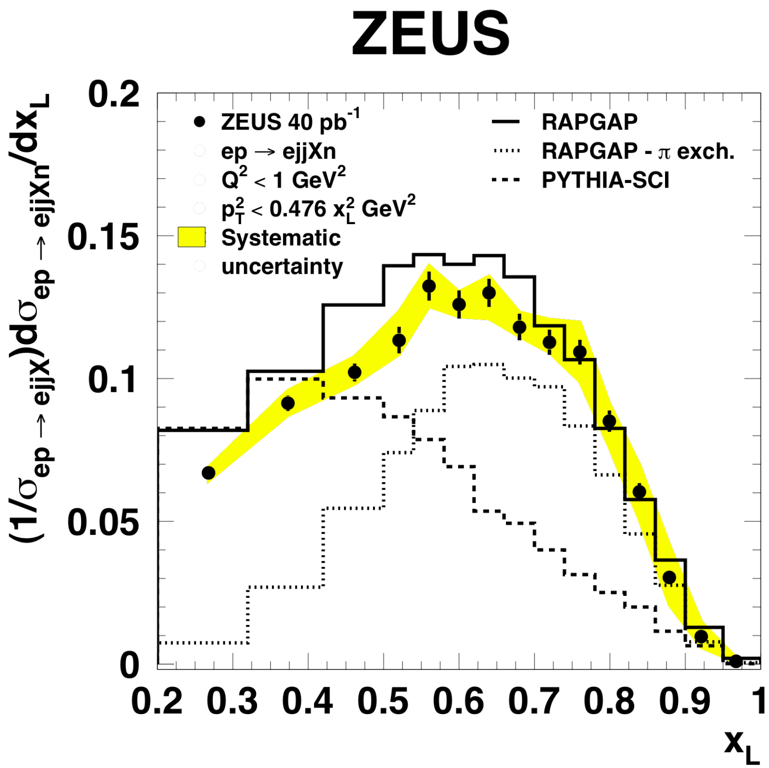


"Large" x_L leading neutron contributions expected to be due to π exchange [$\alpha_\pi(0) \sim 0$] competing with standard baryon fragmentation at lower x_L

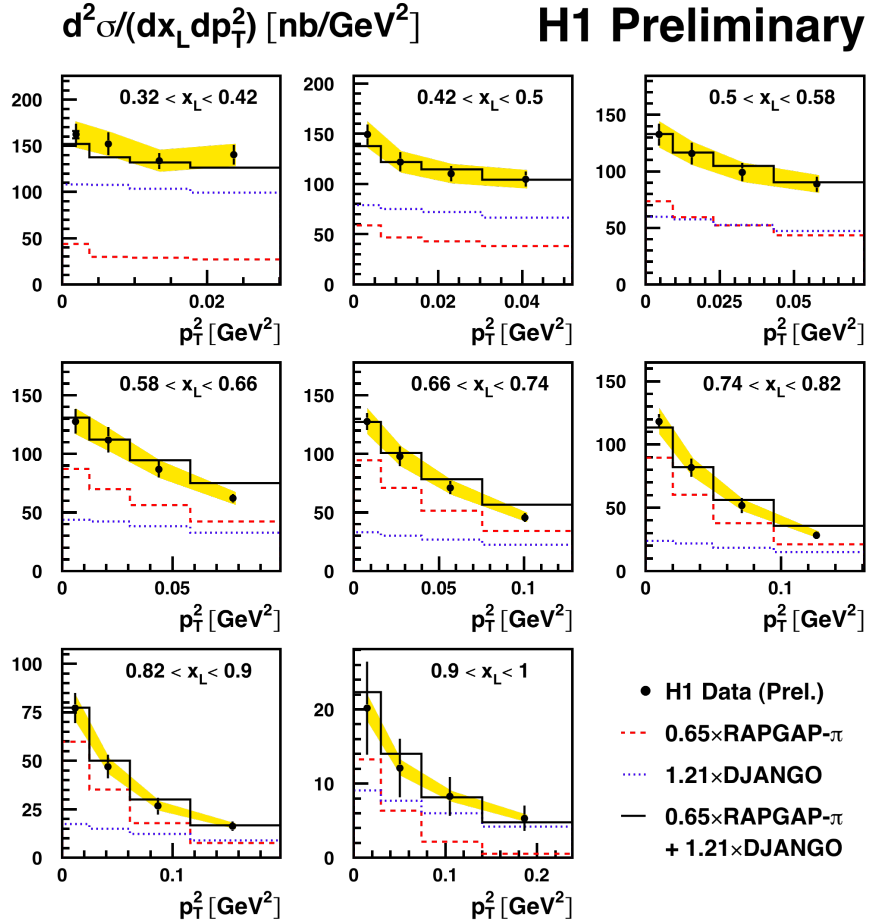
Leading Neutrons at Low x_L: π-exchange & fragmentation







[For π-excahnge, $|t-t_{min}| = p_t^2$]



… mixing MCs describing π-exchange and standard fragmentation gives good description of x_L and p_t dependences for inclusive neutrons and sample accompanied by jets

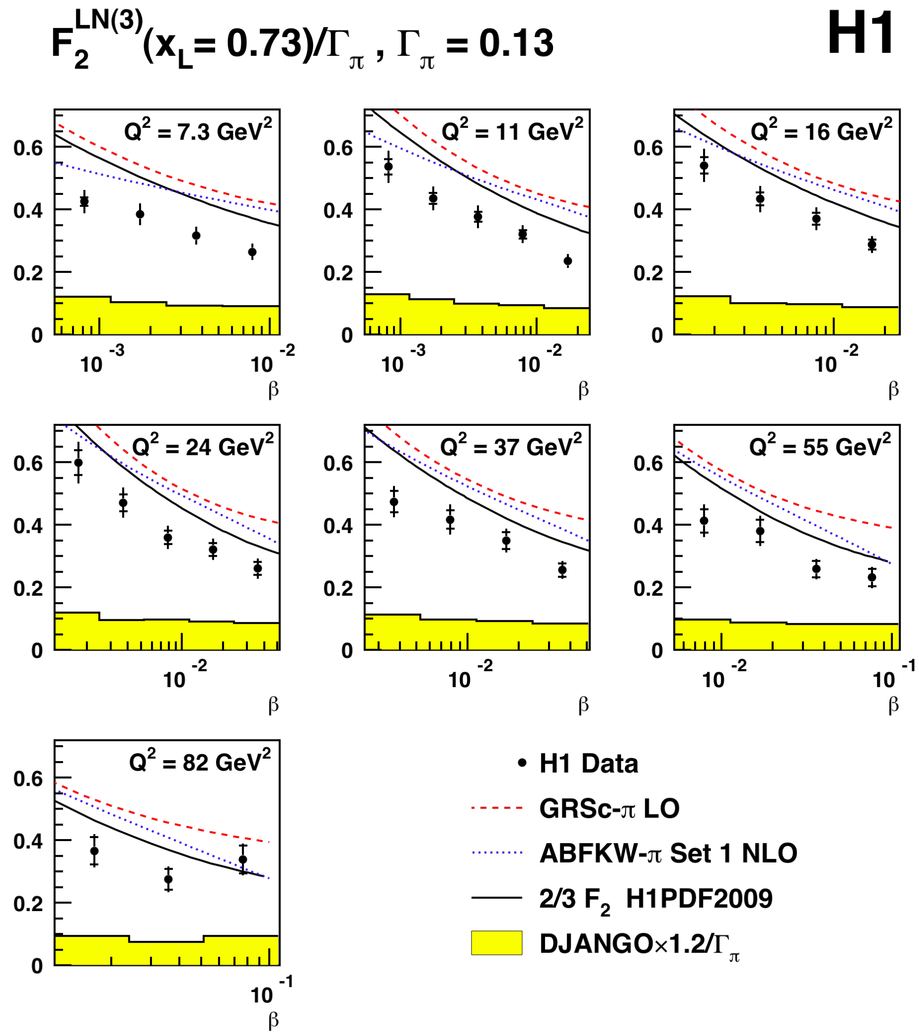
Leading Neutrons and F_2^{π}

… sensitivity at large x_L to pion structure function F_2^{π} after taking out a pion flux factor …

$\Gamma_{\pi} \sim 0.13$ +/- 0.04 (model)

25-35% residual fragmentation component

Other exchanges neglected



Fair agreement with parameterisations of pion structure.

$F_2^{\pi} = 2/3\ F_2^{p}$ (valence quark counting) also in fair agreement

Summary

• HERA diffractive and related data continue to arrive … unique sensitivity to strong colour-singlet exchange in pQCD regime

• Proton vertex factorisation with $\alpha_{IP}(t) \sim 1.10\ (+\ \delta t)$ & $b \sim 6\ GeV^{-2}$ is good model for the 'soft' physics

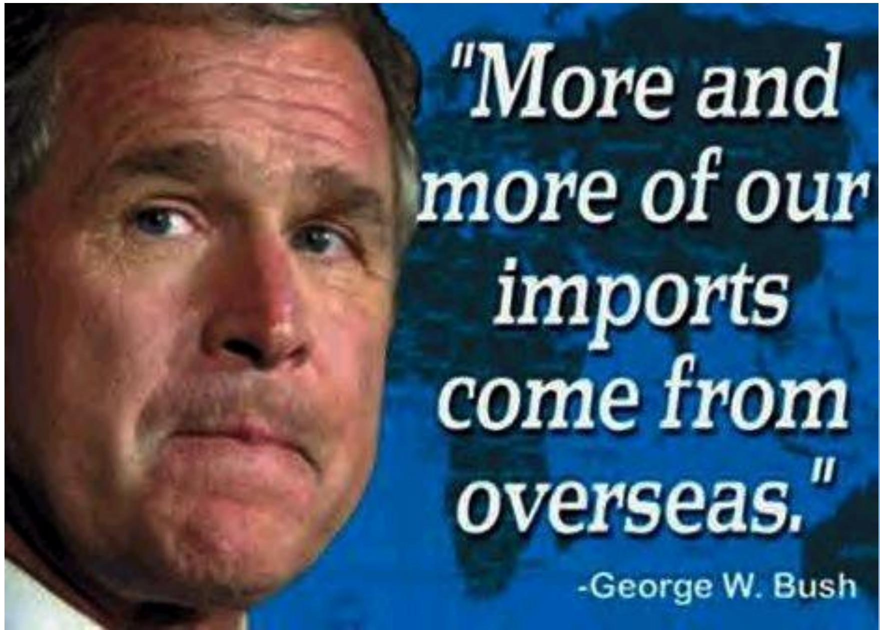
• DPDFs well constrained & tested

• Progress in understanding rapidity gap survival in photoproduction

• Leading Neutron Spectra Beyond diffractive peak constrain F_2^{π}

• Input to diffraction, multi-parton interactions, ZDC … @ LHC

George's Summary …

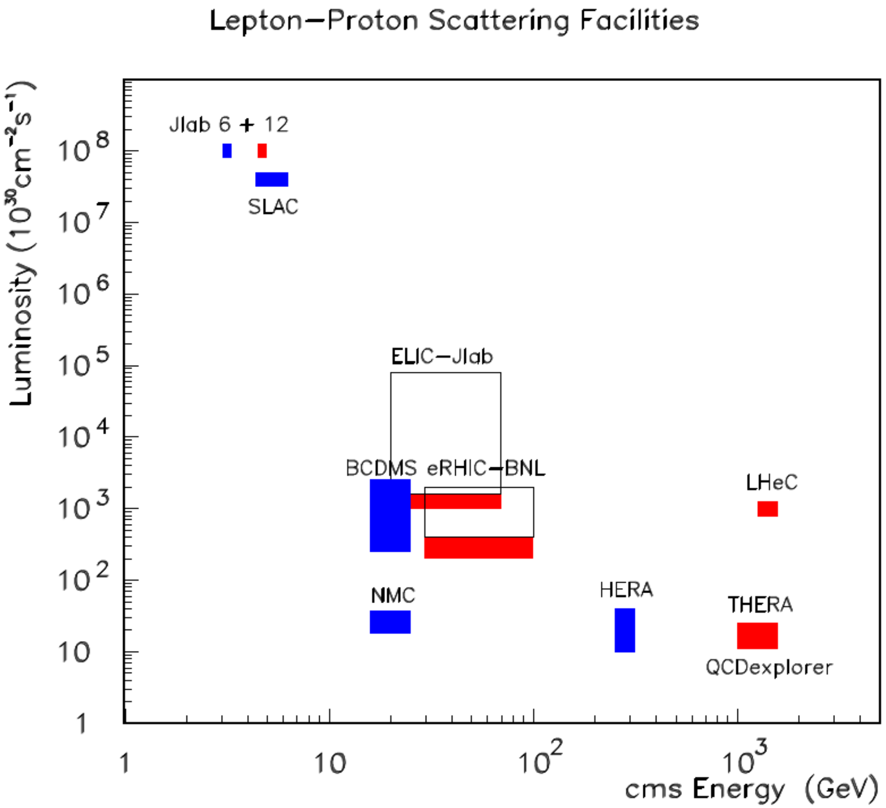


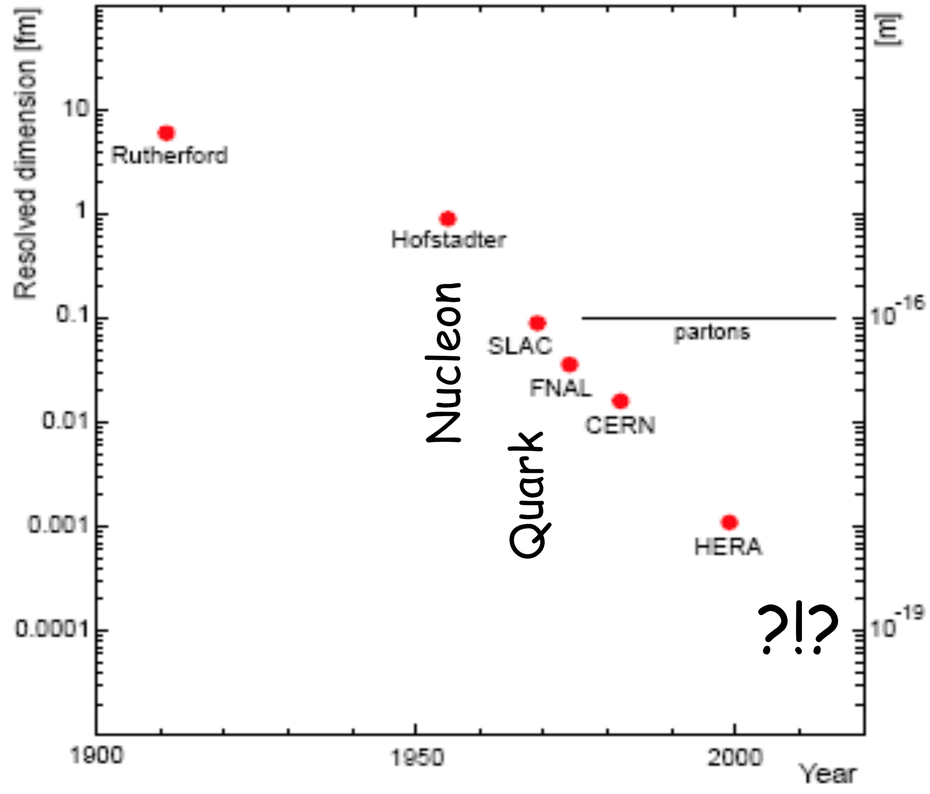
A possible future?

No high energy ep Physics Approved beyond 2007!..

LHeC: Latest of several proposals to take ep physics into the TeV energy range …

… but with unprecedented lumi!

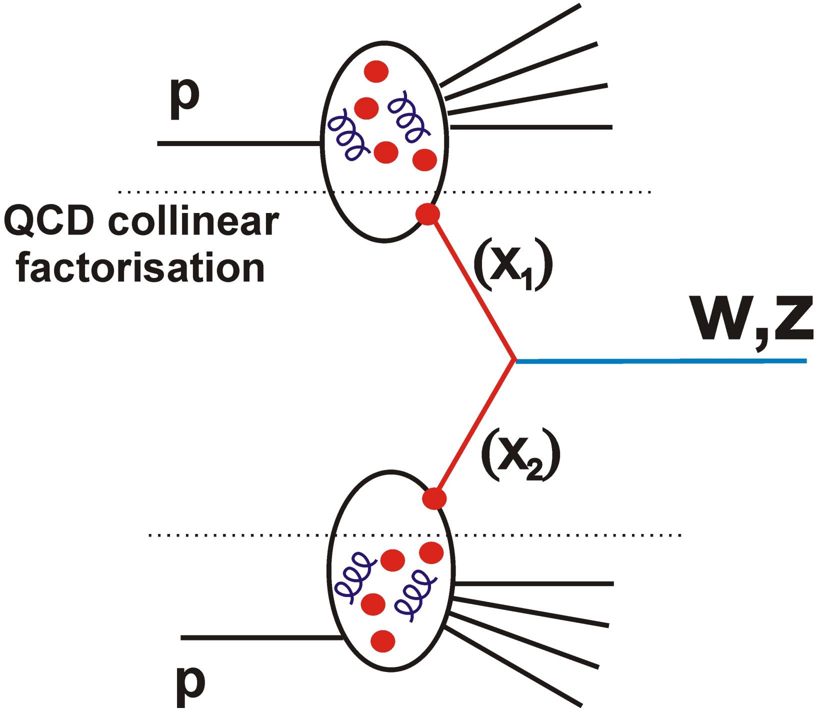




- Combining LHC protons with a new electron beam (70 GeV) Is technically possible and pushes frontiers of ep physics:

… $x \rightarrow 10^{-7}$, $M_{eq} \rightarrow 1.4$TeV,
Resolved dimension $\rightarrow 10^{-19}$m

Factorising away the Unknown

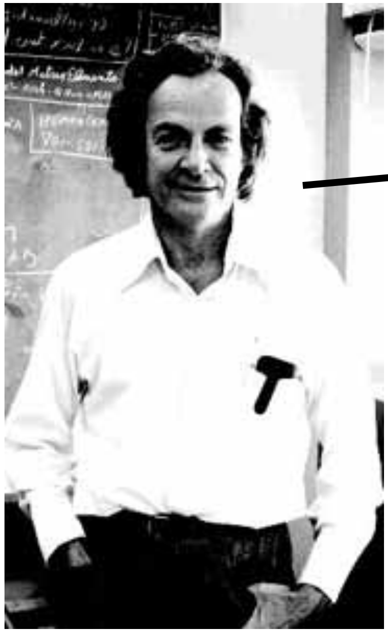


- **QCD factorisation theorem** allows us to define universal parton density functions (PDFs), same for proton in all contexts.

- **QCD evolution (`DGLAP' approx^n)** tells us how the partons evolve as scale (e.g. mass produced) changes. … i.e, we just need to know the x dependence at a single scale …

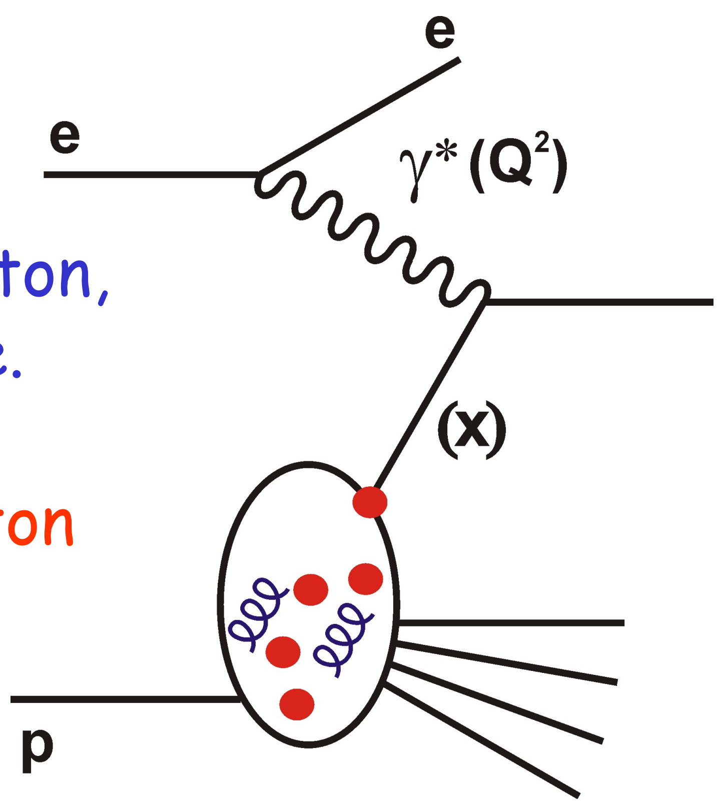
We cannot calculate PDFs (maybe one day on lattice)
… so we have to determine the PDFs experimentally

Parton Densities from Experiment… DIS



"You don't find out how a watch works by throwing other watches at it!"

Most precise information on PDFs comes from **`Deep inelastic lepton-nucleon Scattering'** …
Point-like probe, which doesn't feel strong colour field … a `snapshot' of proton, mainly via photon exchange.



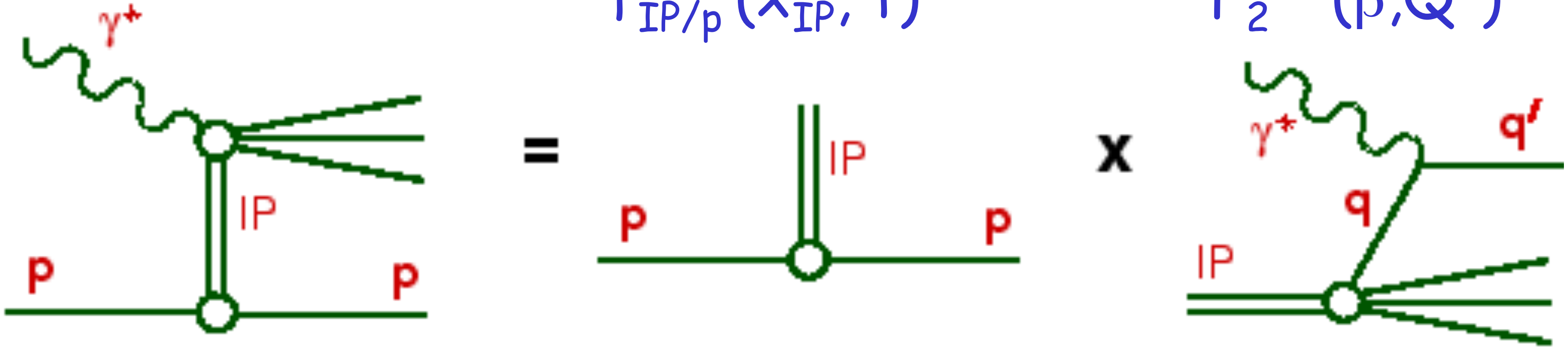
x = Momentum fraction of struck parton
Q^2 = Exchanged boson virtuality … scale or resolving power!

Proton Vertex Factorisation and 'Pomeron Flux'

If proton vertex factorisation works, we can factorise out x_{IP}, t (and M_Y) dependence into a `flux factor'

MEASUREMENT = IP FLUX x IP STRUCTURE

$f_{IP/p}(x_{IP}, t)$ $F_2^{IP}(\beta, Q^2)$



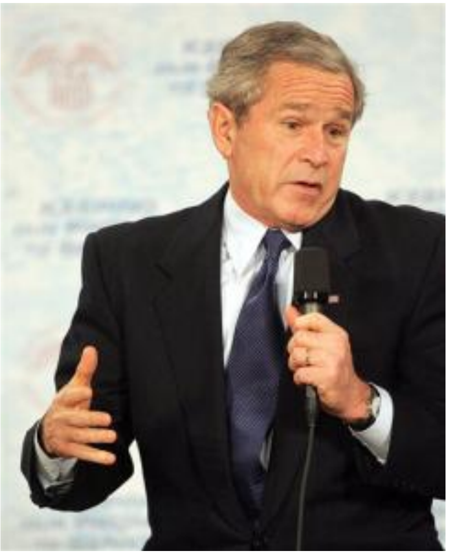
'Flux' parameterisation inspired By Regge theory …

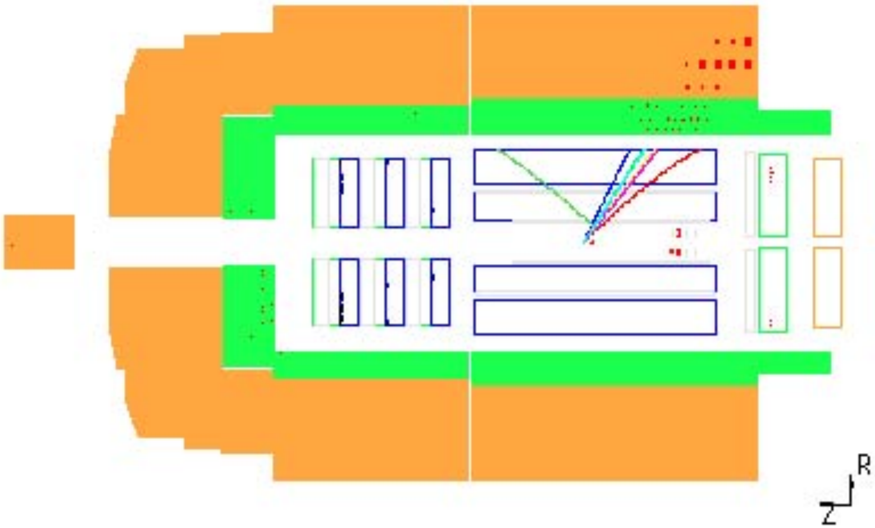
$$f_{IP/p}(x_{IP}, t) = \frac{e^{B_{IP}t}}{x_{IP}^{2\alpha_{IP}(t)-1}}$$

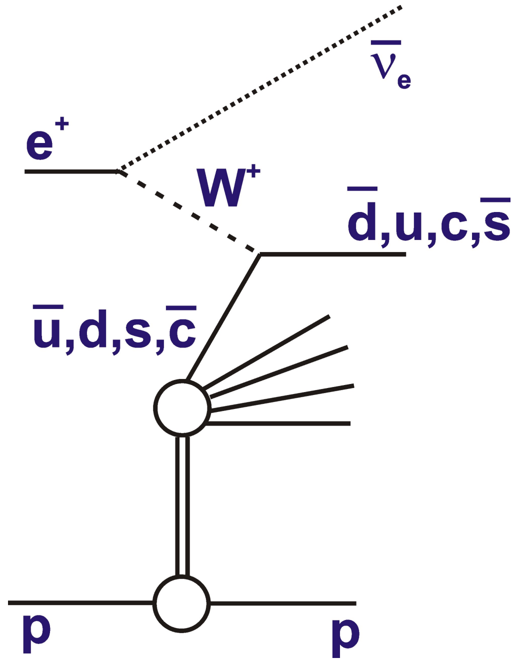
Free parameters - pomeron `trajectory' $\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP}t$

Testing Factorisation and Quark Density with Diffractive Charged Current Scattering

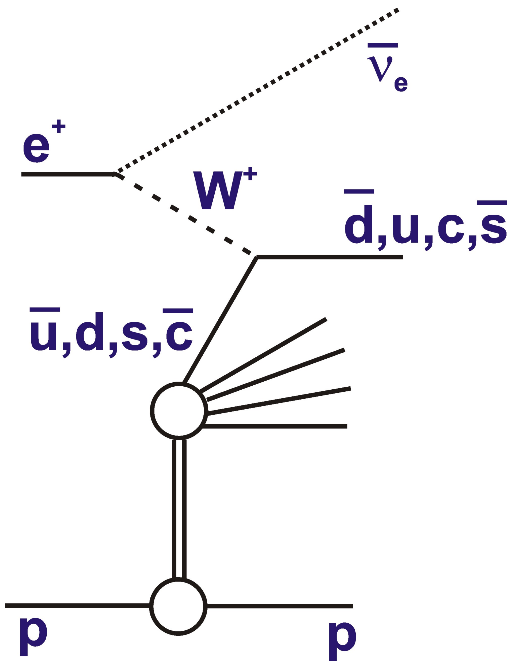
First observation of diffractive charged current events
… sensitive to flavour decomposition of quark density
(completely unconstrained by neutral current data)

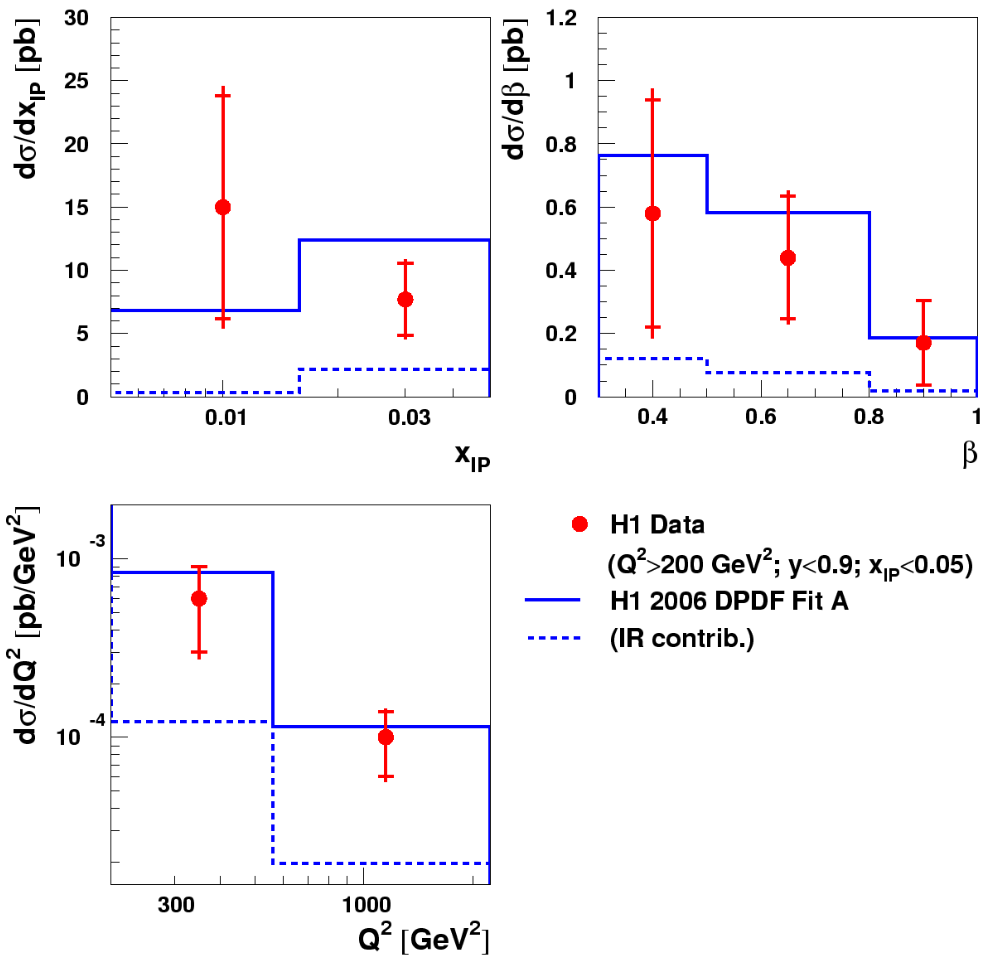






Diffractive Charged Current Cross Section



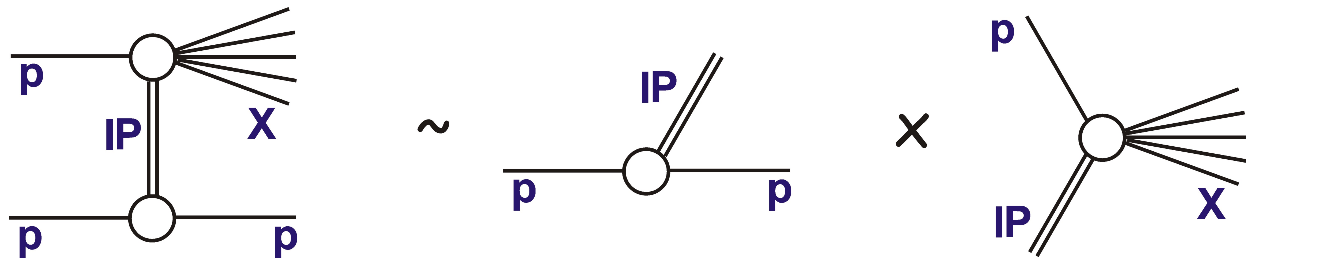


Very similar method of measurement to Neutral Current case.

Good agreement with fit prediction (assumes $u = d = s = \bar{u} = \bar{d} = \bar{s}$ and c from BGF) though statistical precision limited so far

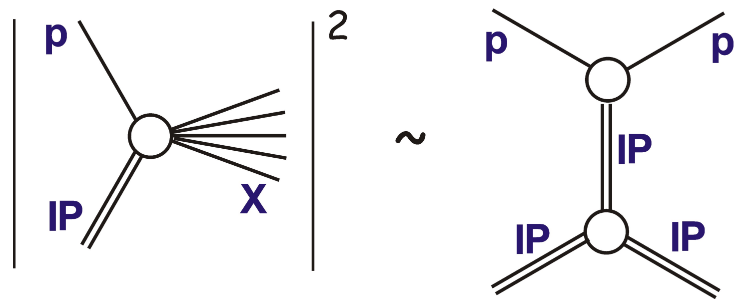
Diffractive Dissociation: Mueller's Generalisation of the Optical Theorem

1) Factorise SD into a pomeron (IP) flux and a total p+IP cross section

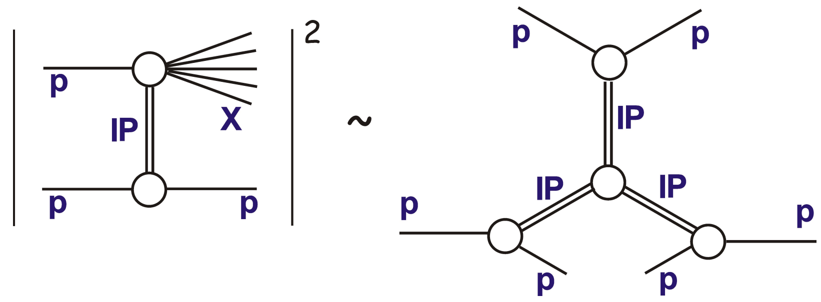


$f_{IP/p}(\xi,t)$ $\sigma_{tot}(IP+p\to X)$

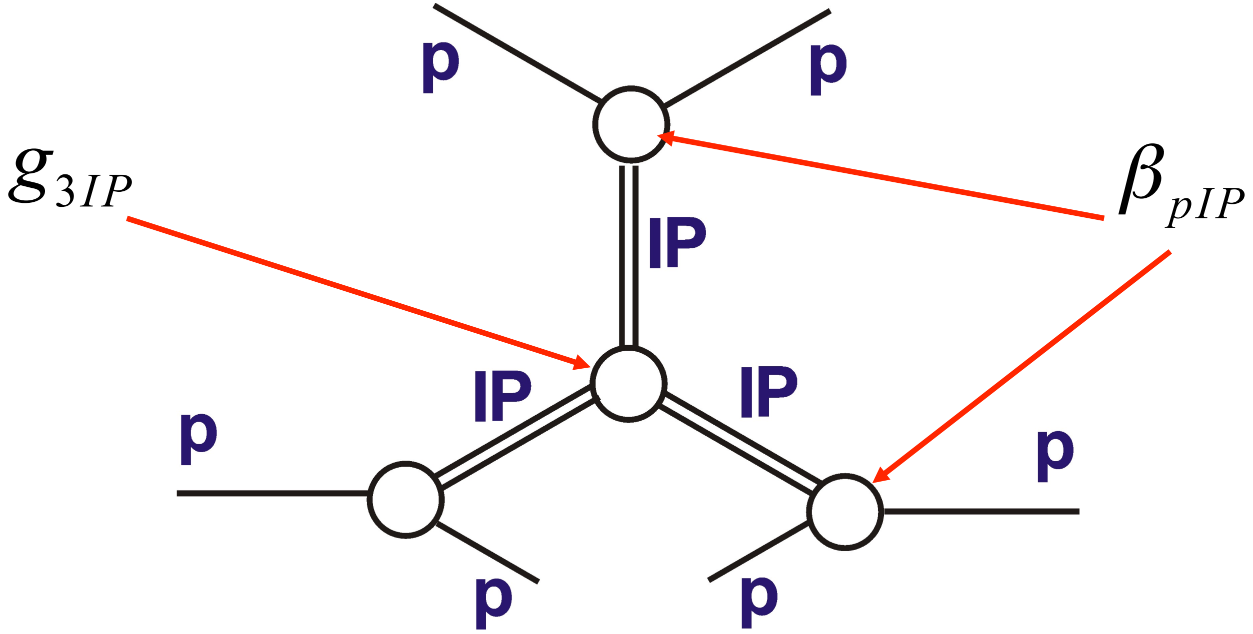
2) Similarly to total pp cross section, relate total p+IP cross section to forward elastic amplitude via optical theorem



3) Calculate SD cross sections from <u>triple</u> pomeron amplitudes



Calculating Triple Pomeron Amplitudes



Need to know triple pomeron coupling $g_{3IP}(t)$ and pomeron proton coupling $\beta_{pIP}(t)$.

Pomeron `propagators' give dependences on M_X^2 and s via pomeron trajectory $\alpha(t) \sim 1.08 + 0.25\,t$

$$\frac{d\sigma}{dt\,dM_X^2} = \frac{1}{16\pi}\, g_{3IP}(t)\, \beta_{pIP}(t)^3\, s^{2\alpha(t)-2}\, M_X^{2[\alpha(0)-2\alpha(t)]} \xrightarrow[t\to 0]{} s^{0.16} \left(\frac{1}{M_X^2}\right)^{1.08} e^{B(\xi)t}$$