Perturbative and non-perturbative diffraction at HERA

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On behalf of the H1 and ZEUS Collaborations

Physics in Collisions 2010

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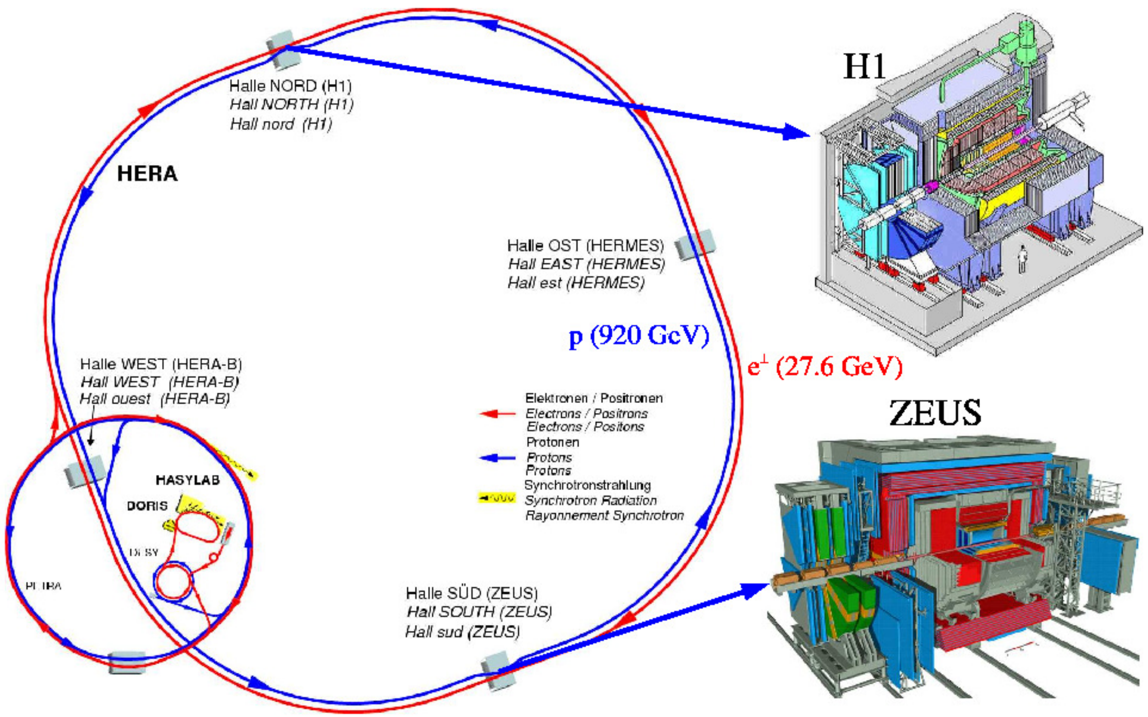
HERA colliding experiments

27.5 GeV leptons on 920 GeV protons



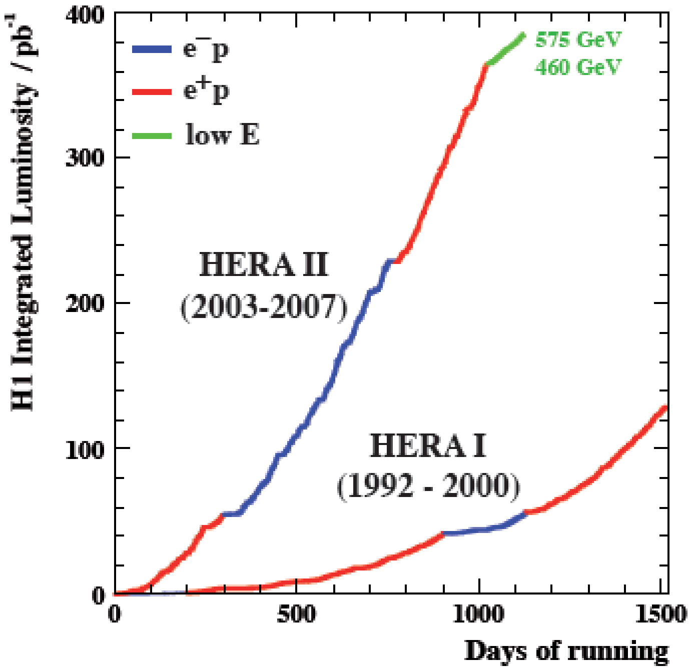
Detectors not originally designed for diffractive physics. Forward instrumentation added:

ZEUS LPS for HERA I only

H1 FPS for HERA I and II

H1 VFPS for HERA II

HERA I + HERA II ~0.5 fb^{-1}

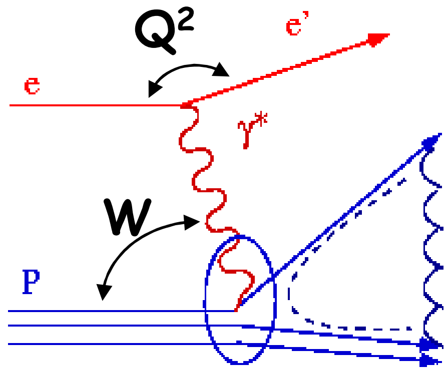


Lots of results achieved in diffraction at HERA:

- ✓ Inclusive diffraction
- ✓ Exclusive diffraction
- ✓ Leading Baryons

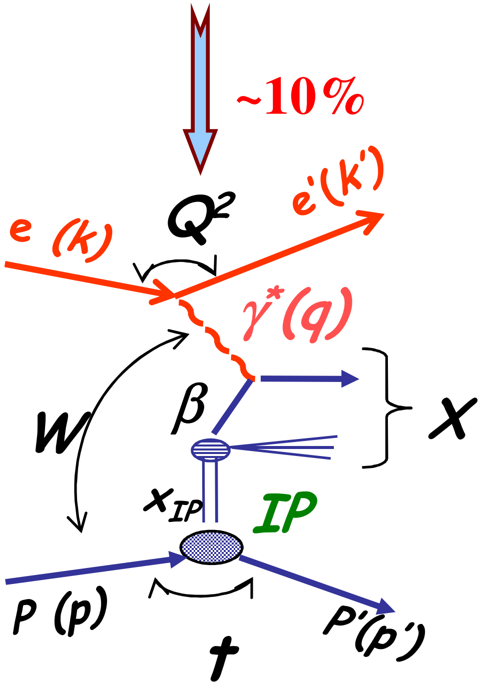
and many analyses ongoing

Inclusive Diffraction at HERA



Standard Deep Inelastic Scattering

DIS probes the partonic structure of the proton



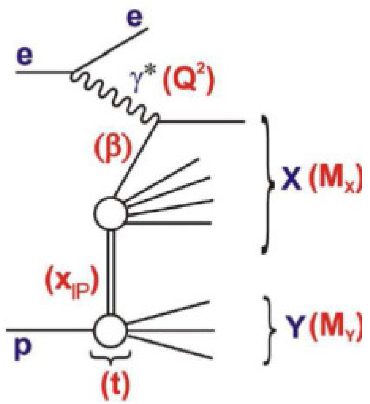
Diffractive DIS

Diff DIS probes the partonic structure of colour singlet exchange: DPDFs

- ✓ exchange of colour singlet producing a rapidity gap in the particle flow → LRG method
- ✓ the scattered proton intact or quasi-intact (low-mass state) → Proton tagger method

The object exchanged carrying the vacuum quantum numbers (IP)

Kinematic variables



Standard DIS variables

W = γ*-proton centre of mass energy

Q^2 = γ* 4-momentum squared

x = fraction of proton's momentum carried by struck quark ≈ Q^2/W^2

Diffractive variables

t = squared 4-momentum transfer at proton vertex = $(p-p')^2$

x_{IP} = fraction of the *p* mom carried by the *IP* $x_{IP} = \frac{q\cdot(p-p')}{q\cdot p} \approx \frac{Q^2+M_X^2}{Q^2+W^2}$

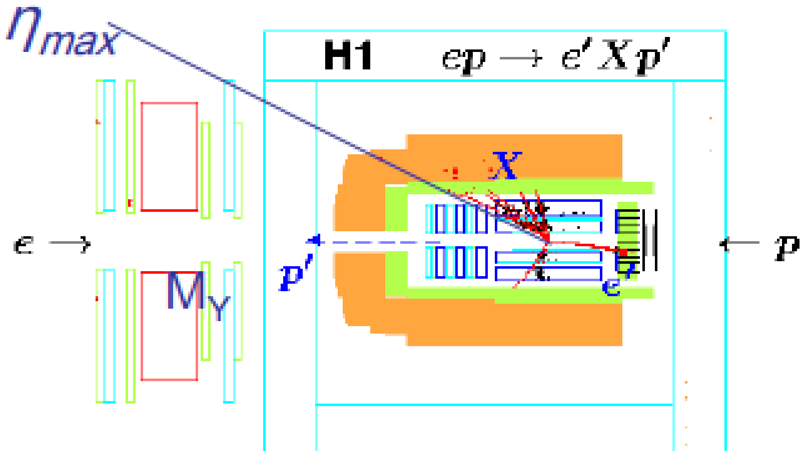
β = fraction of the *IP* mom carried by the struck quark $\beta = \frac{Q^2}{2q\cdot(p-p')} \approx \frac{Q^2}{Q^2+M_X^2} = \frac{x}{x_{IP}}$

reduced cross section — diffractive structure function

$$\frac{d^4\sigma}{d\beta\, dQ^2 dx_{IP} dt} = \frac{4\pi\alpha^2}{\beta Q^4}\left[1-y+\frac{y^2}{2}\right]\sigma_r^{D(4)}(\beta,Q^2,x_{IP},t) \qquad \sigma_r^{D(4)}(\beta,Q^2,x_{IP},t) = F_2^{D(4)} - \frac{y^2}{2(1-y+y^2/2)}F_L^{D(4)}$$

$F_2^{D(3)}$ integrated over t needed for LRG comparisons

Selection methods

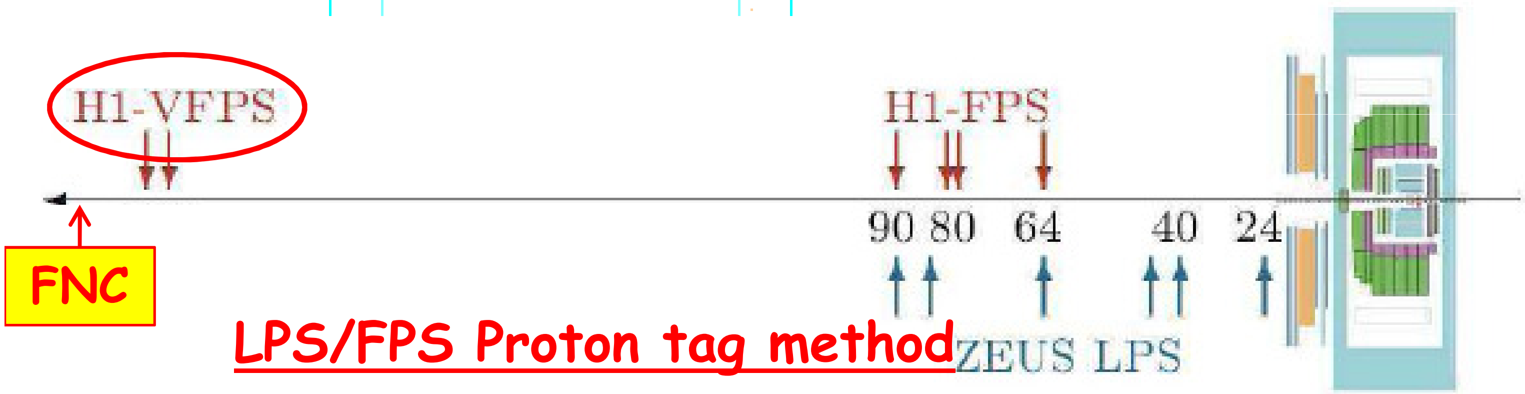


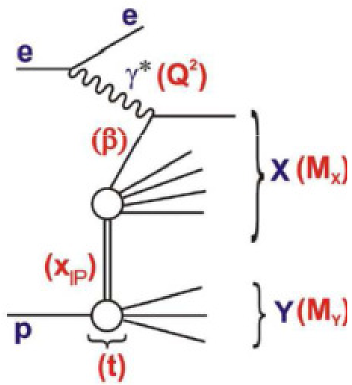
LRG method

Large rapidity gap method (H1 and ZEUS):
→ No activity in the forward direction

High statistics, p-diss (~20%)

Measurements integrated over t





LPS/FPS Proton tag method

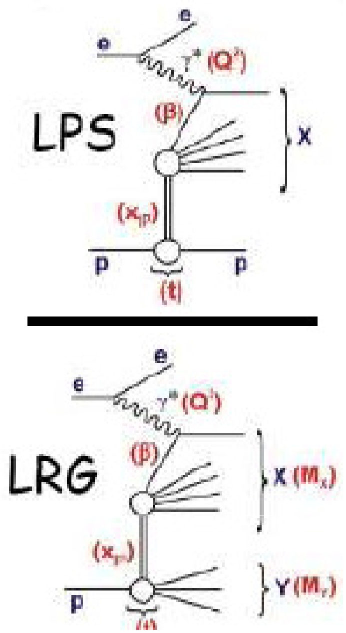
Dedicated detectors:
ZEUS-LPS for HERA I only
H1-FPS for HERA I and II
H1-VFPS for HERA II

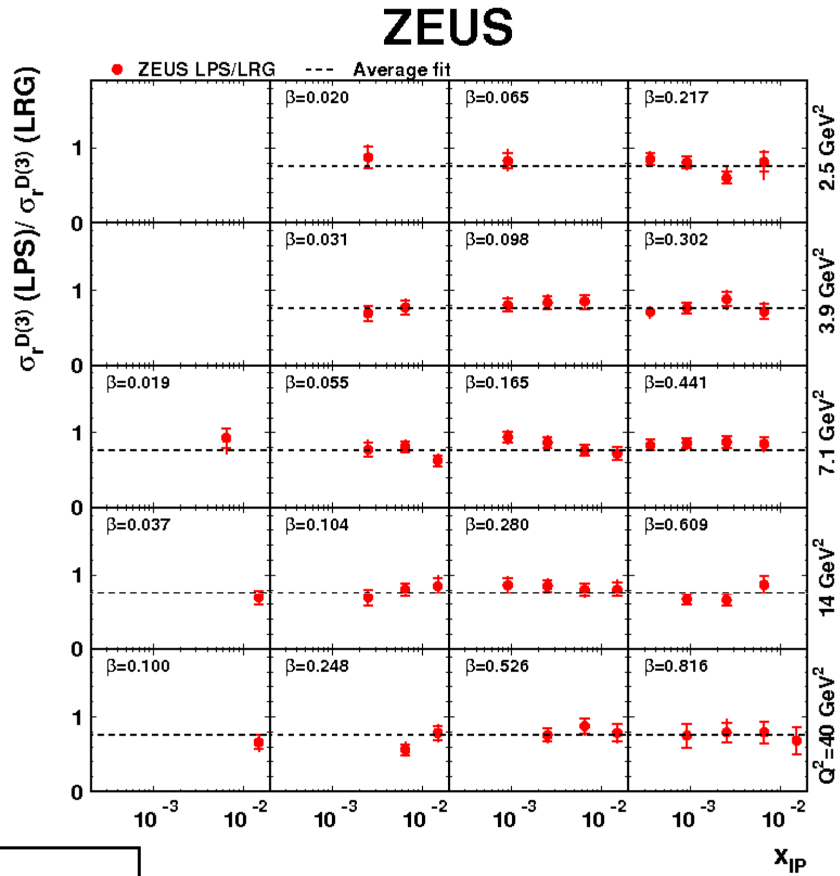
Low statistics but no p-diss bkg and $M_Y = m_p$

Measurements of x_{IP} and t

Methods comparison →

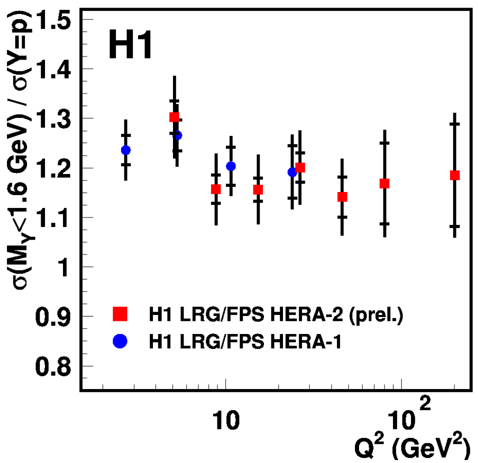
Comparison between methods





ZEUS estimate of p-diss fraction about 20%

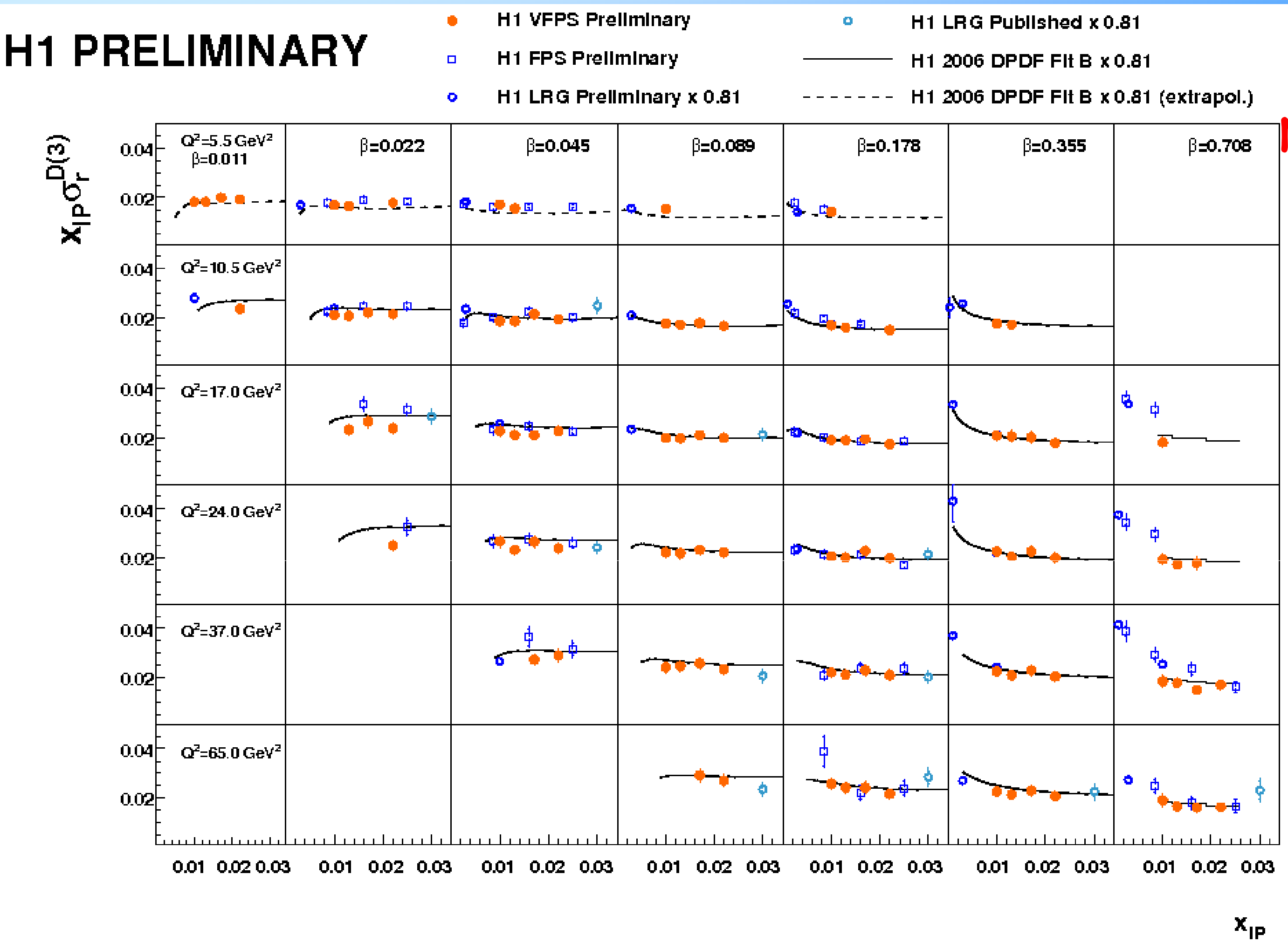
No significant dependence on β, Q^2 and x_{IP}



Same conclusions from H1
Combining FPS HERA I and HERA II data p-diss contribution about 20%
(H1prelim-09-012)

New measurements from H1!

First results from H1 VFPS



New results released!

VFPS:
(H1-prelim-10-14)
$5 < Q^2 < 100$ GeV^2
95 pb^{-1}

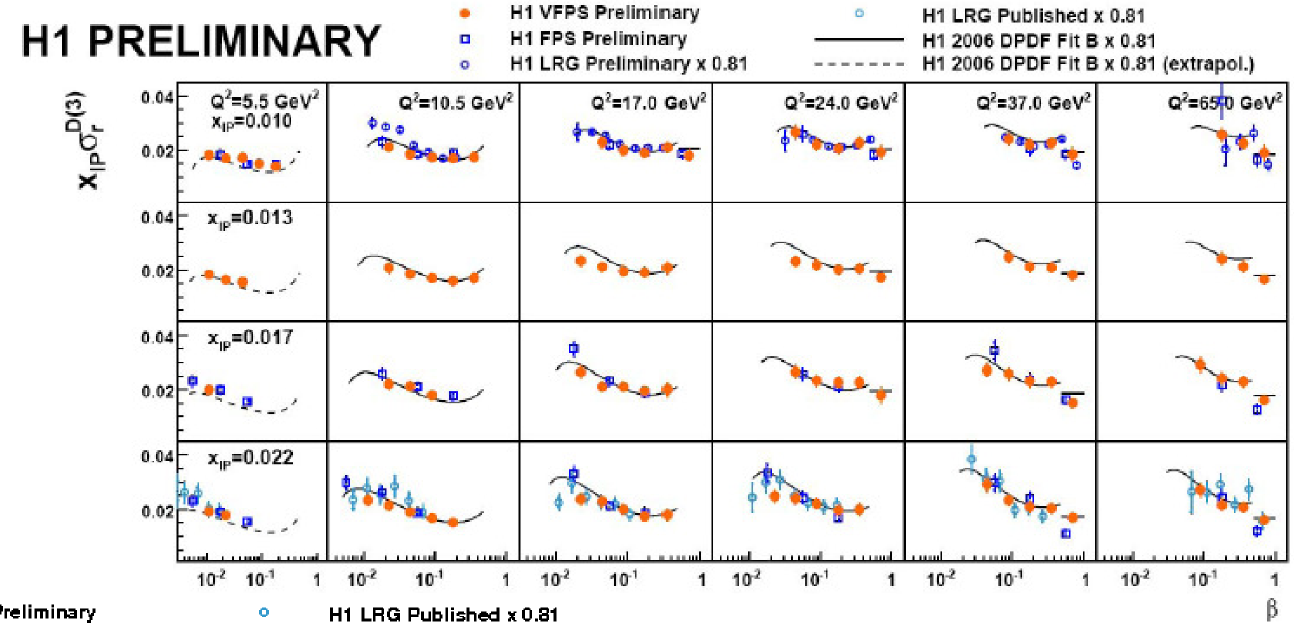
FPS:
(H1-prelim-10-12)
$5 < Q^2 < 200$ GeV^2
157 pb^{-1}

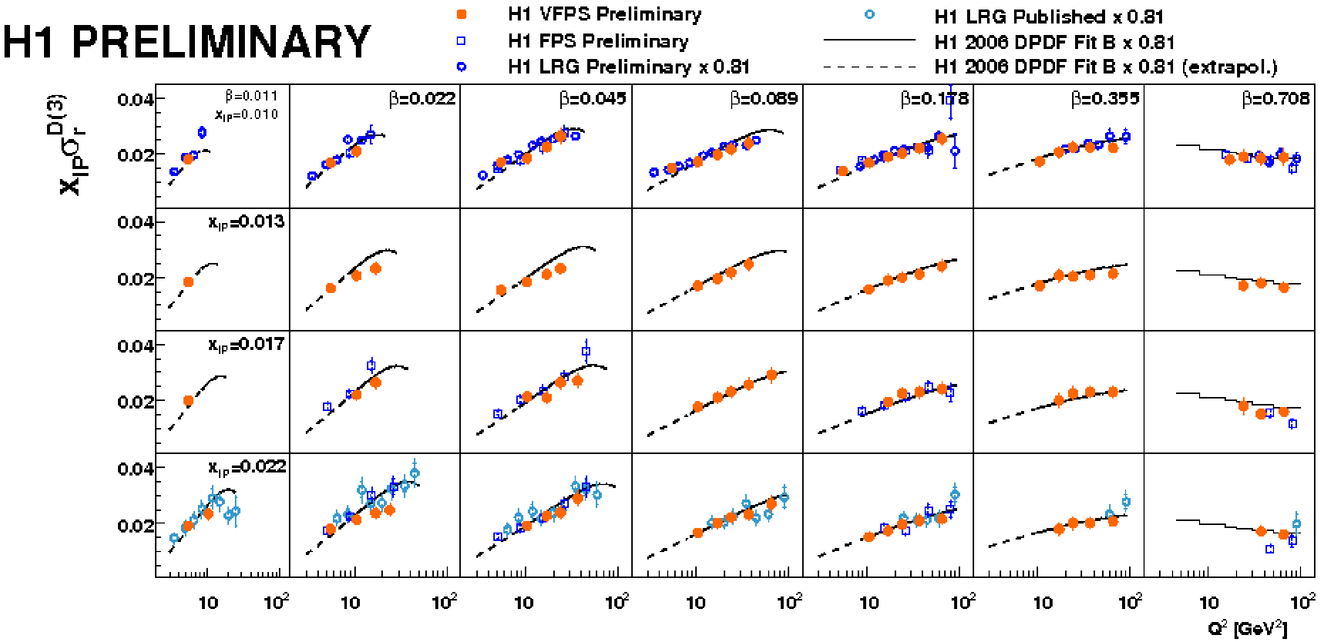
LRG:
(H1-prelim-10-11)
$Q^2 > 3.5$ GeV^2
370 pb^{-1}

VFPS: Covers complementary x_{IP} range w.r.t. LRG analysis, 20 times higher statistics than HERA I data, VFPS normalisation uncertainty 5%, low background contamination < 2%

All the measurements in agreement with H1 2006 DPDF fit B

First results from H1 VFPS



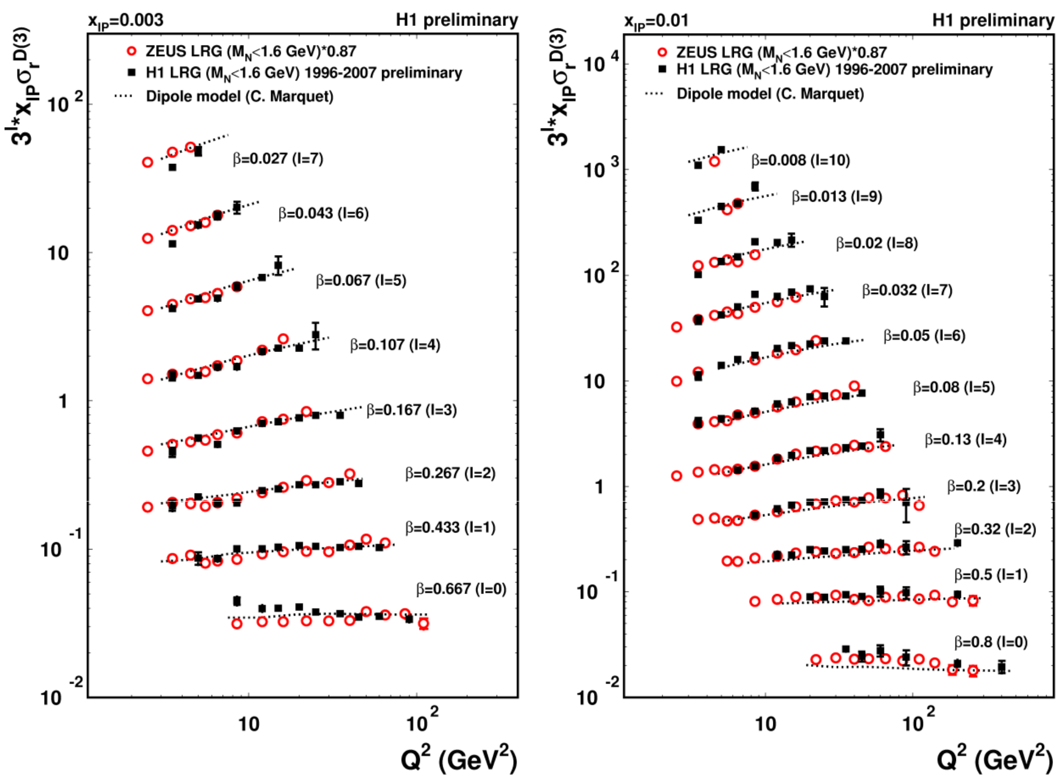


Positive scaling violations visible: a lot of gluons in DDIS

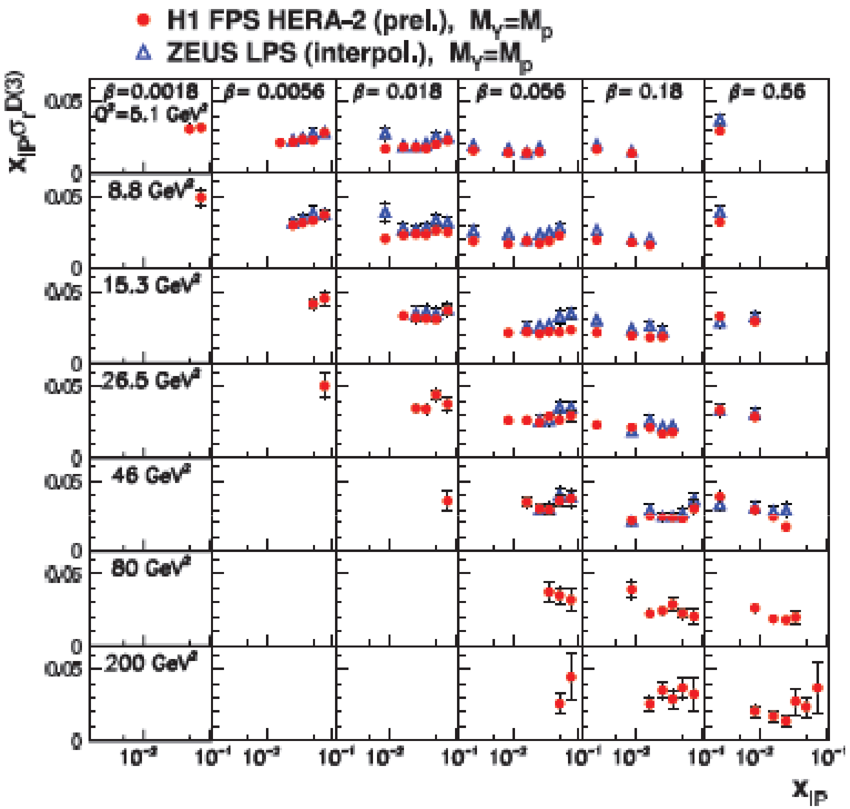
All the measurements in agreement with H1 2006 DPDF fit B

Comparison between experiments

LRG



LPS/FPS



ZEUS LRG 62pb^{-1} pub. (High stat precision)
Compared with new prel H1 LRG 370 pb^{-1}
13% difference in overall normalisation compatible within uncertaintes

Good agreement, 15% difference in overall normalisation compatible within uncertainties

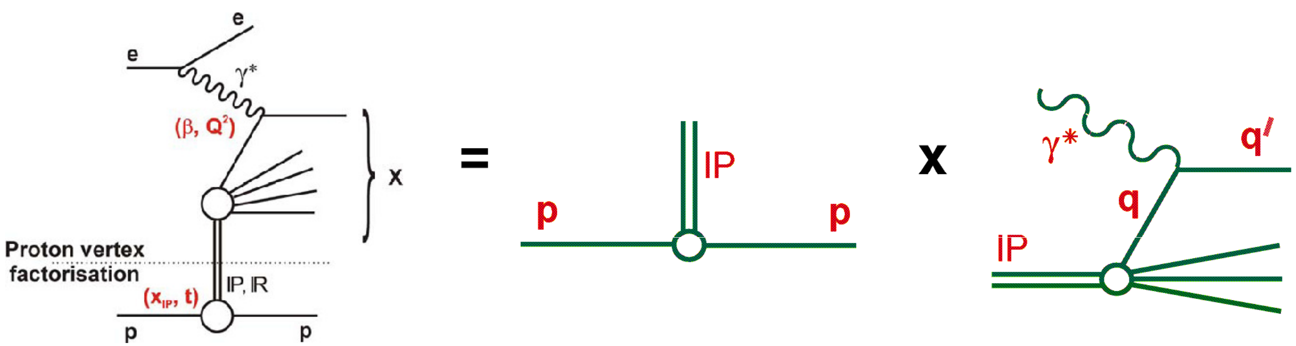
Both H1 and ZEUS inclusive data used to extract DPDFs →

Diffractive PDFs

QCD collinear factorization theorem proved also for DDIS (Collins 1998):

$$\sigma(\gamma^* p \to Xp) \approx f_i(z,Q^2,x_{IP},t) \otimes \hat{\sigma}_{\gamma^* i}(z,Q^2)$$

variables describing proton vertex (x_{IP},t) factorize from those at photon vertex (β, Q^2) to good approximation



$$\sigma(\gamma^* p \to Xp) \approx f_{IP}(x_{IP},t) \times f_i(z,Q^2) \otimes \hat{\sigma}_{\gamma^* i}(z,Q^2)$$

Regge motivated pomeron flux: $f_{IP}(x_{IP},t) = \frac{e^{Bt}}{x_{IP}^{2\alpha(t)-1}}$

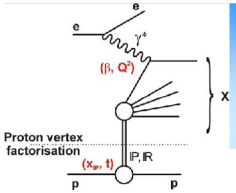
$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP} t$$

B and a(t) extracted from HERA data

DPDFs:

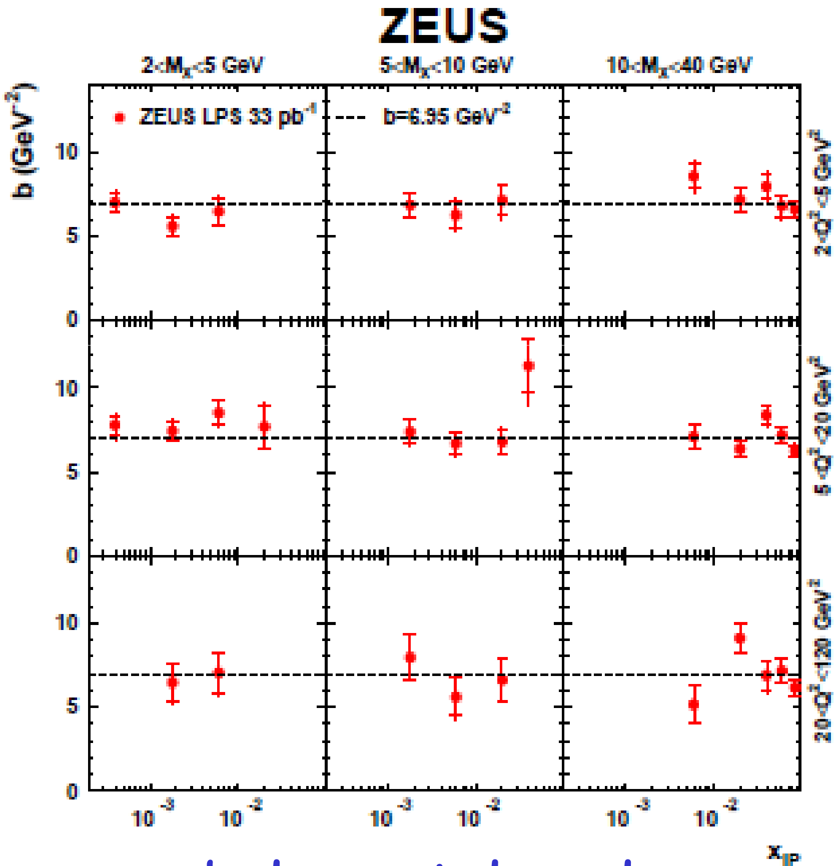
Universal partonic distribution function, obey evolution equations, apply when vacuum quantum numbers are exchanged

z is a generalisation of β: fraction of the *IP* mom carried by the struck parton

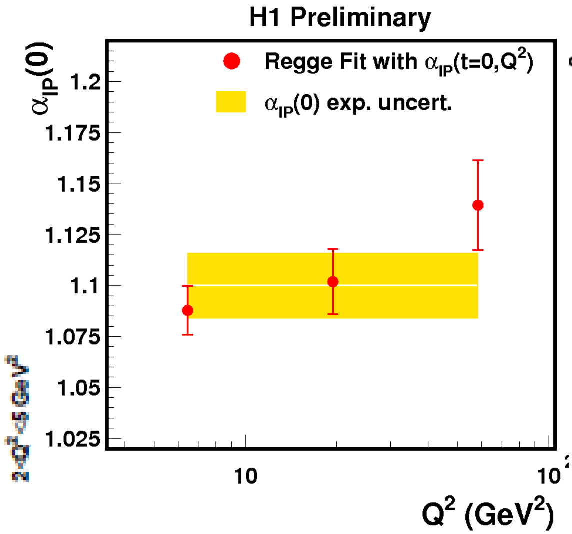


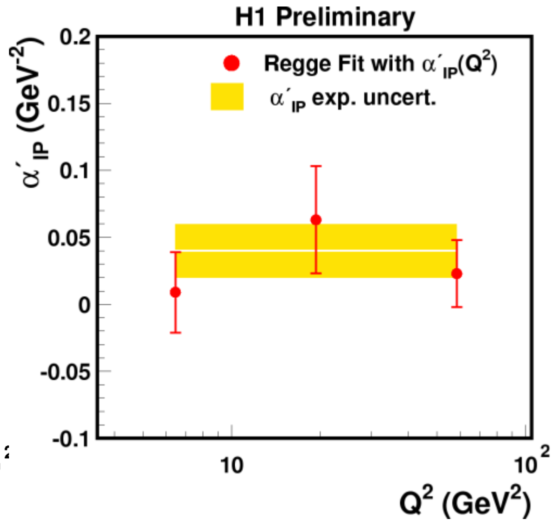
Proton vertex factorization: $f_{IP}(x_{IP},t)$

$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$



b does not depend
on β, Q^2 at fixed x_{IP}:
consistent with factorization





Regge fit results:

ZEUS:

$$\alpha_{IP}(0) = 1.11 \pm 0.02(stat.) \pm 0.02(syst.) \pm 0.02(\text{mod})$$

$$\alpha'_{IP} = -0.01 \pm 0.06(\text{exp.})^{+0.04}_{-0.08}(systy.) \pm 0.04(\text{mod.})\, GeV^{-2}$$

$$b = 7.1 \pm 0.7(stat.)^{+1.4}_{-0.7}(syst)\, GeV^{-2}$$

H1-FPS:

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

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

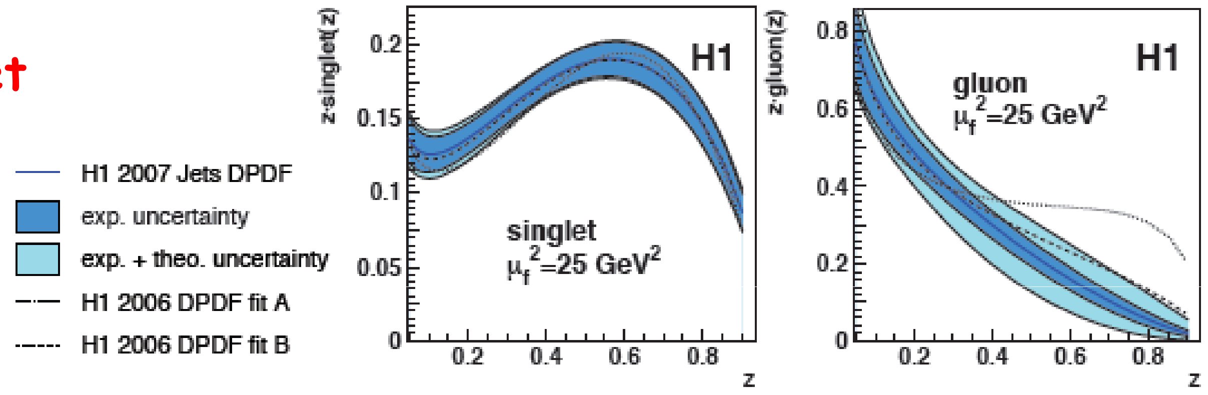
$$b = 5.7 \pm 0.3(\text{exp.}) \pm 0.6(\text{mod.})\, GeV^{-2}$$

DL: $\alpha_{IP}(t) = 1.08 + 0.25t$

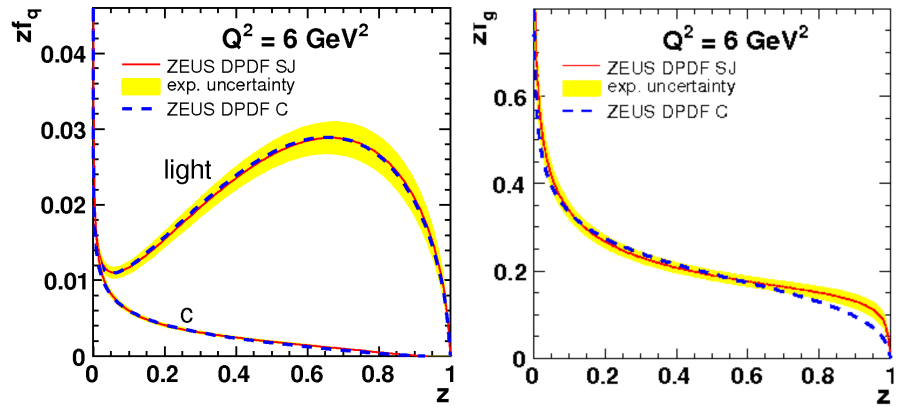
HERA Diffractive Parton densities

The vertex factorisation allow to extract DPFs fitting β, Q^2 dependance at fixed x_{IP} from a fit to the HERA data (inclusive+jets): evolution in Q^2 with DGLAP equations, parameterise q and g densities at initial scale Q_0^2

Combining inclusive and dijet data constrains g and q densities with comparable precision for all z

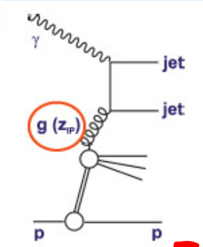


Reasonable agreement ZEUS and H1
A final data set of inclusive data is now available from H1 and ZEUS: plan to extract HERA DPDFs from the H1+ZEUS combined (reduction of exp. uncertainties)

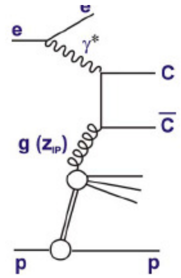


H1: EPJ C48 (2006) and JHEP 710 (2007).

ZEUS: NPB 816 (2009) and EPJ C52 (2007)

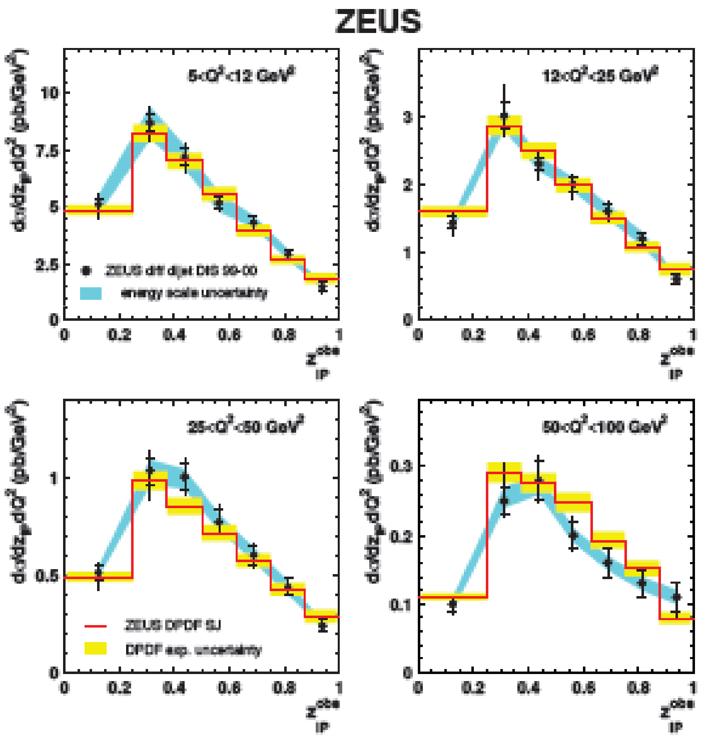


Several QCD factorisation tests…

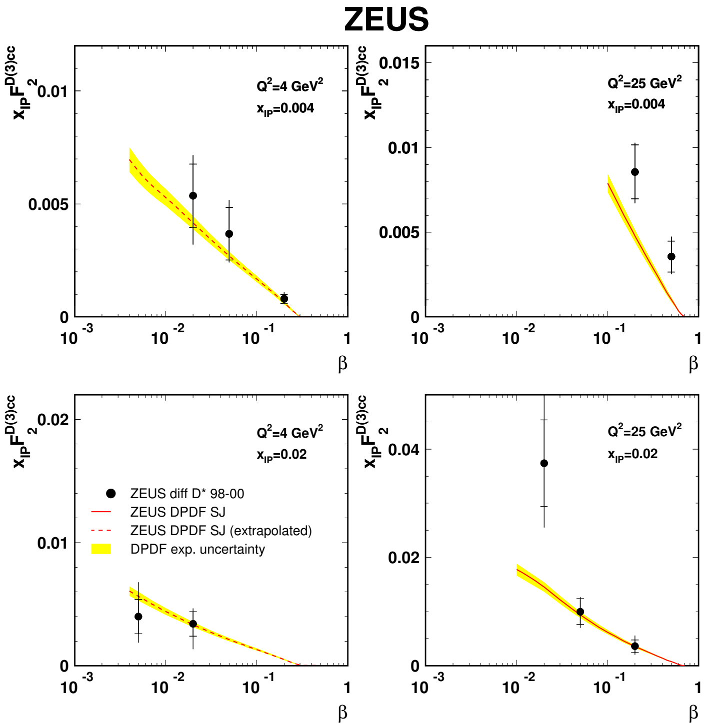


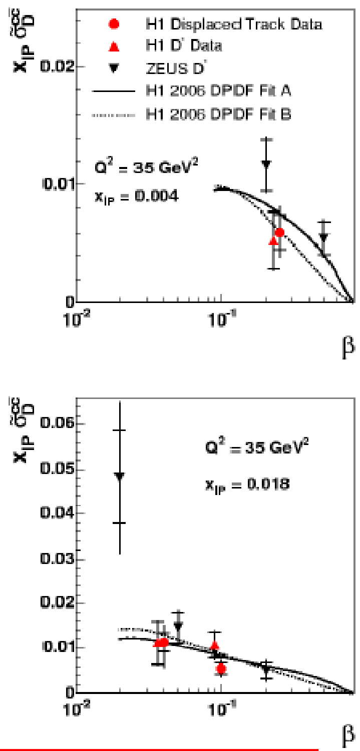
Final states with a hard scale, sensitive to gluons are a good test!

Dijets in DIS



Charm in DIS





ZEUS DPDF SJ and H1 Fit describe well the diffractive Dijets and charm production data (although still statistically limited)

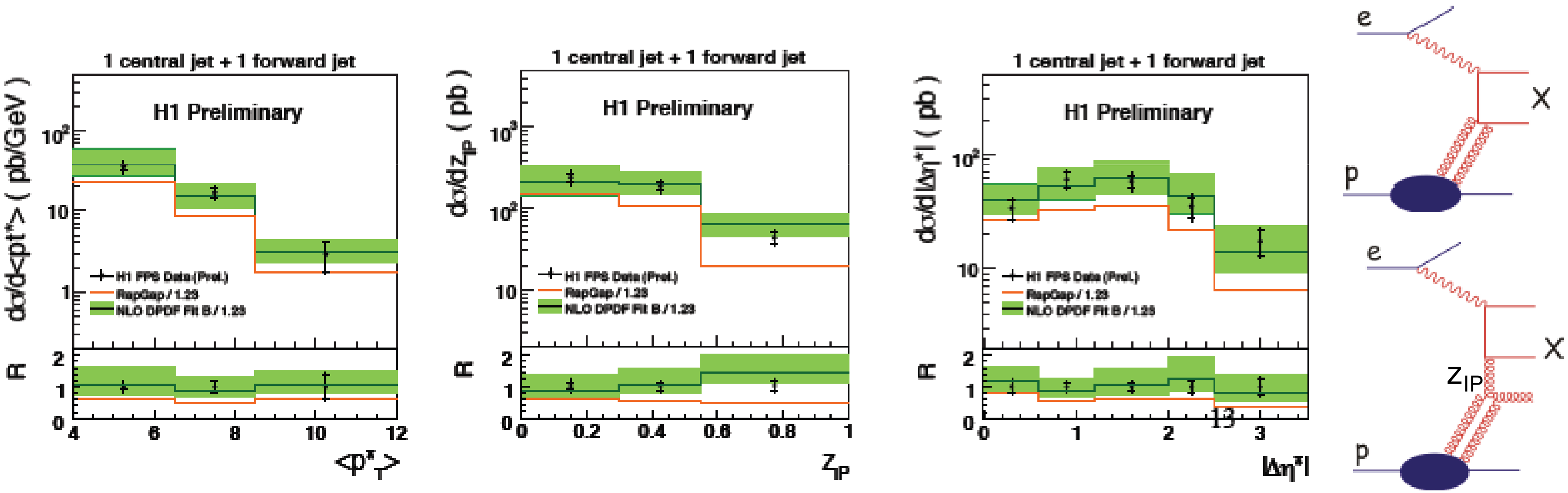
The factorization holds in DDIS!

Forward jets in DDIS

1 central jet + 1 forward jet + FPS proton

New H1 results on DDIS using FPS in a wider x_{IP} and η_{jet} range

No evidence for effects beyond NLO DGLAP (pQCD contributions breaking DGLAP p_T ordering at low x → BFKL)

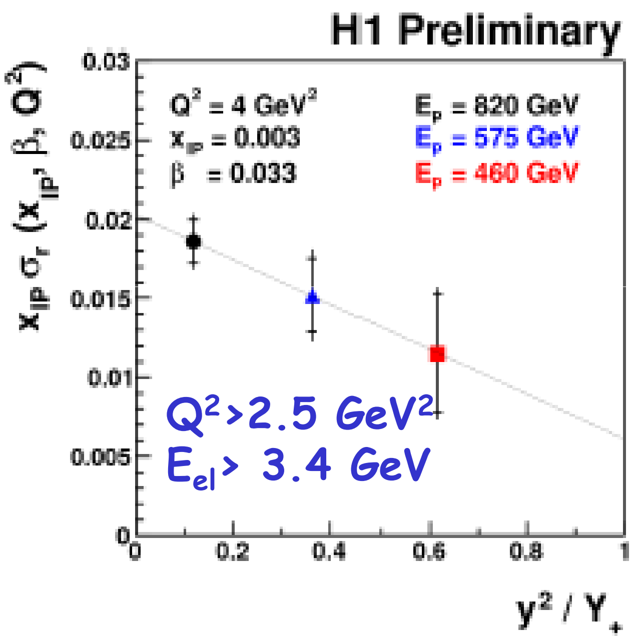


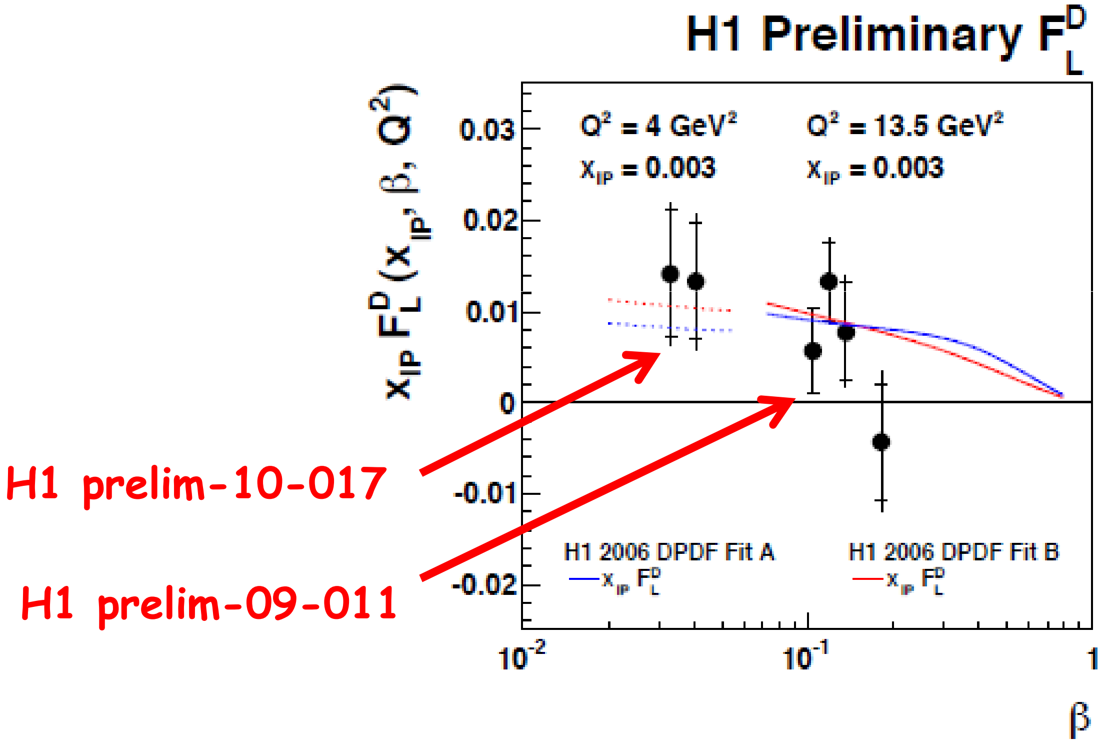
(H1 prelim-10-013)

New F_L^D measurements at low Q^2

At fixed β, Q^2 and x_{IP} F_L^D can be extract with a linear fit

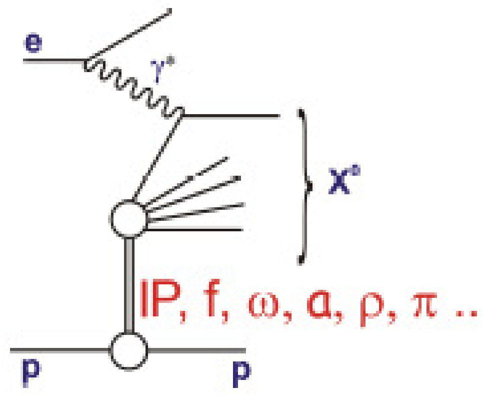
$$\sigma_r^{D(3)}(\beta, Q^2, x_{IP}) = F_2^{D(3)}(\beta, Q^2, x_{IP}) - \frac{y^2}{Y^+} F_L^{D(3)}$$



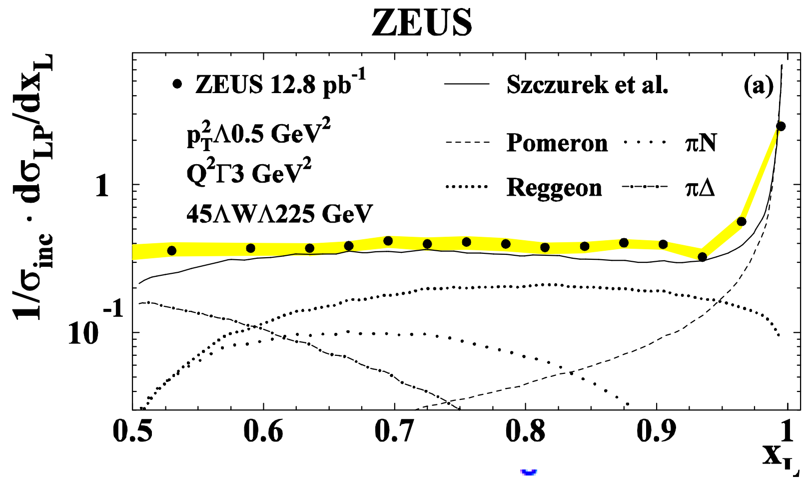


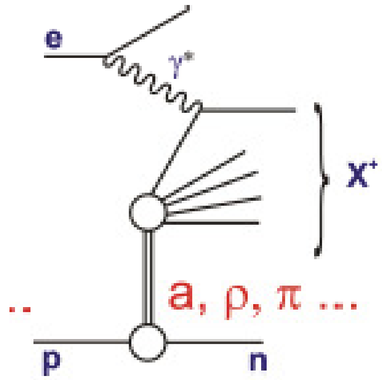
- F_L^D probes directly the diffractive gluon density
- Measurements are consistent with NLO QCD fits

Leading Baryon

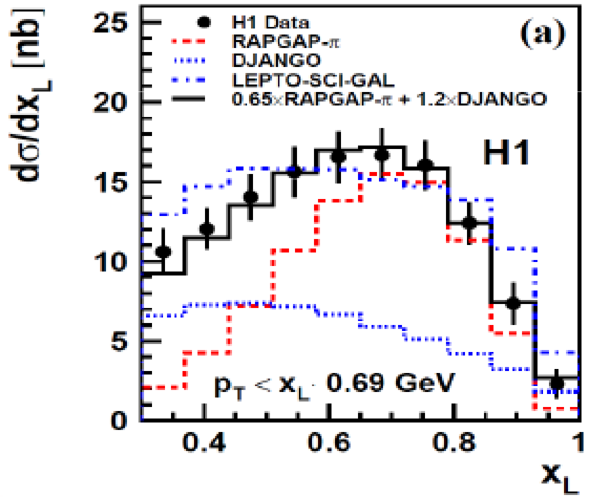


LP produced via exchange IP, IR, π^0. IR exchange dominates at medium x_L





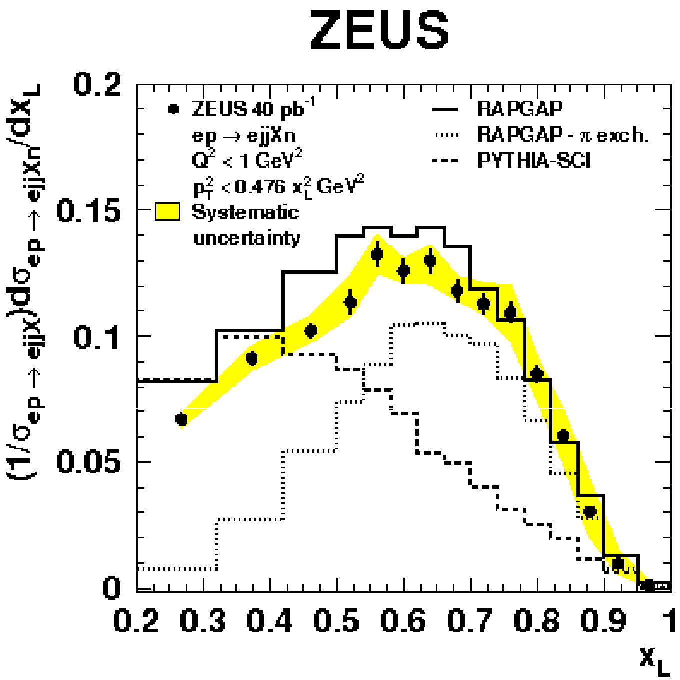
LN produced via charged exchange reactions π^+, ρ^+, a_2. Dominated at large x_L by π^+ exchange and at low x_L by standard baryon fragmentation



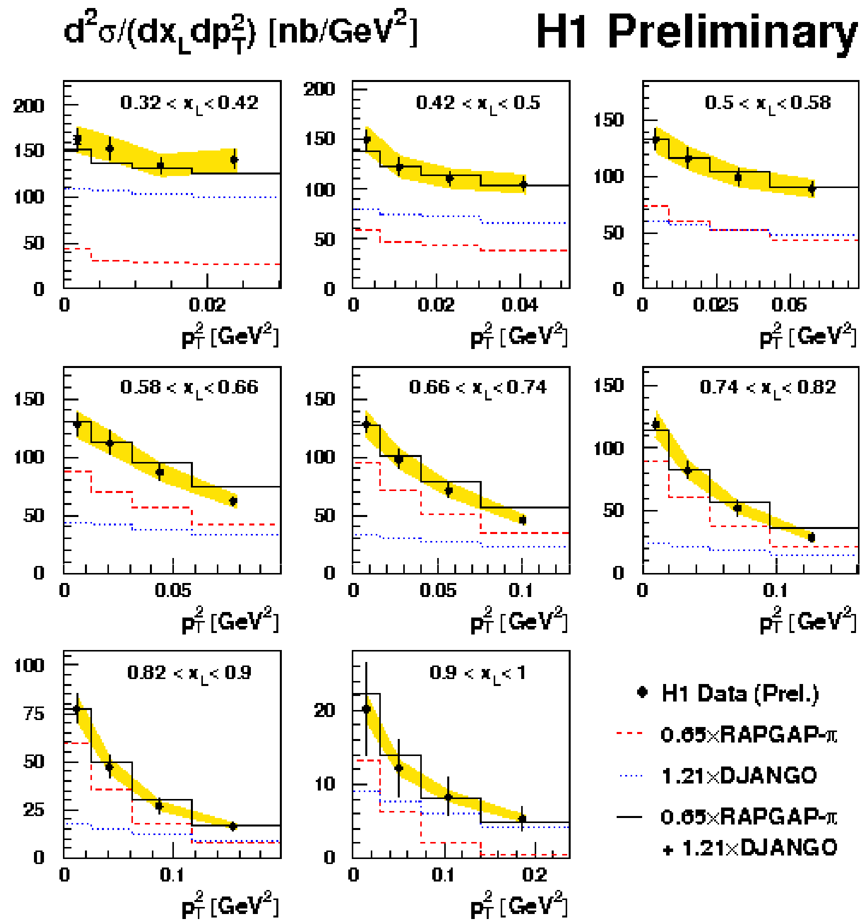
ZEUS: LP DESY 08-176 JHEP06(2009)074
LN DESY 09-139 Nucl. Ph. B 827 (2010) 1-33
LN DESY 07-011 Nucl. Ph. B 776 (2007) 1-37
H1: LN DESY-09-185
LN H1-prelim 10-113

$x_L = 1 - x_{IP}$
fraction of the p mom carried by the LB

LN x_L and p_T distributions



ZEUS pub-09-139
LN+Dijets PHP



H1 prelim-10-113
$6 < Q^2 < 100$ GeV^2

MC mix of π-exchange and standard fragmentation gives a good description of x_L and p_T dependences for inclusive neutrons and dijets+neutrons

LN structure function

$$\sigma_r^{LN(3)}(\beta,Q^2,x_L) = F_2^{LN(3)}(\beta,Q^2,x_L) - \frac{y^2}{Y^+} F_L^{LN(3)}$$

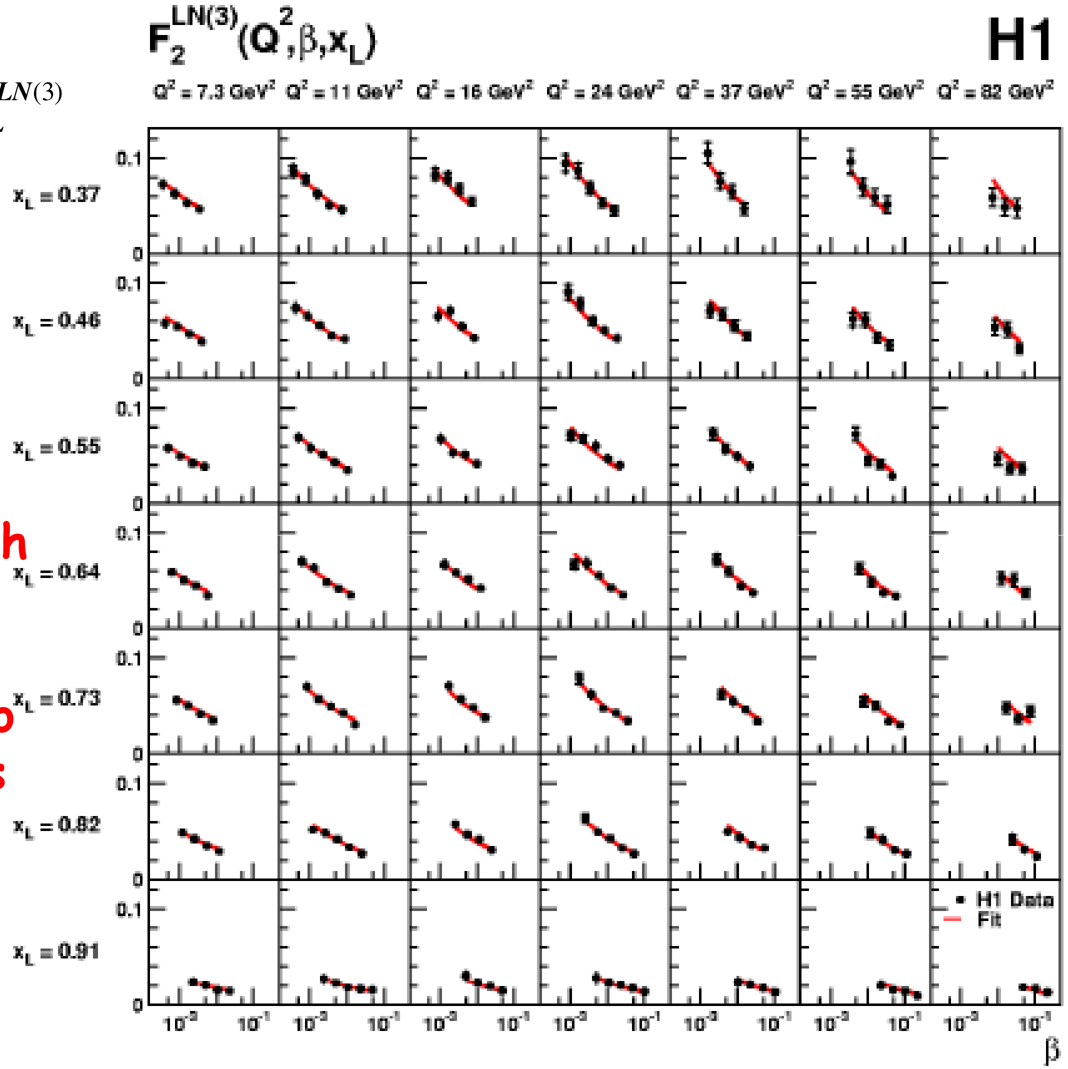
Assuming p vertex factorisation:

$$F_2^{LN(3)}(\beta,Q^2,x_L) = f(x_L) \cdot F_2^{LN(3)}(\beta,Q^2)$$

Fitting F_2^{LN} with $\sim\beta^{-\lambda}$:

λ indipendent to x_L (consistent with vertex factorisation)

- λ increases with Q^2 from 0.23 to 0.3 (similar of proton F_2) which is consistent with the hypothesis of limiting fragmentation



Pion structure function

Assuming proton vertex factorisation and the dominance of π^+-exchange at high x_L we estimate pion structure function from $F_2^{LN(3)}$ at $0.68<x_L<0.77$

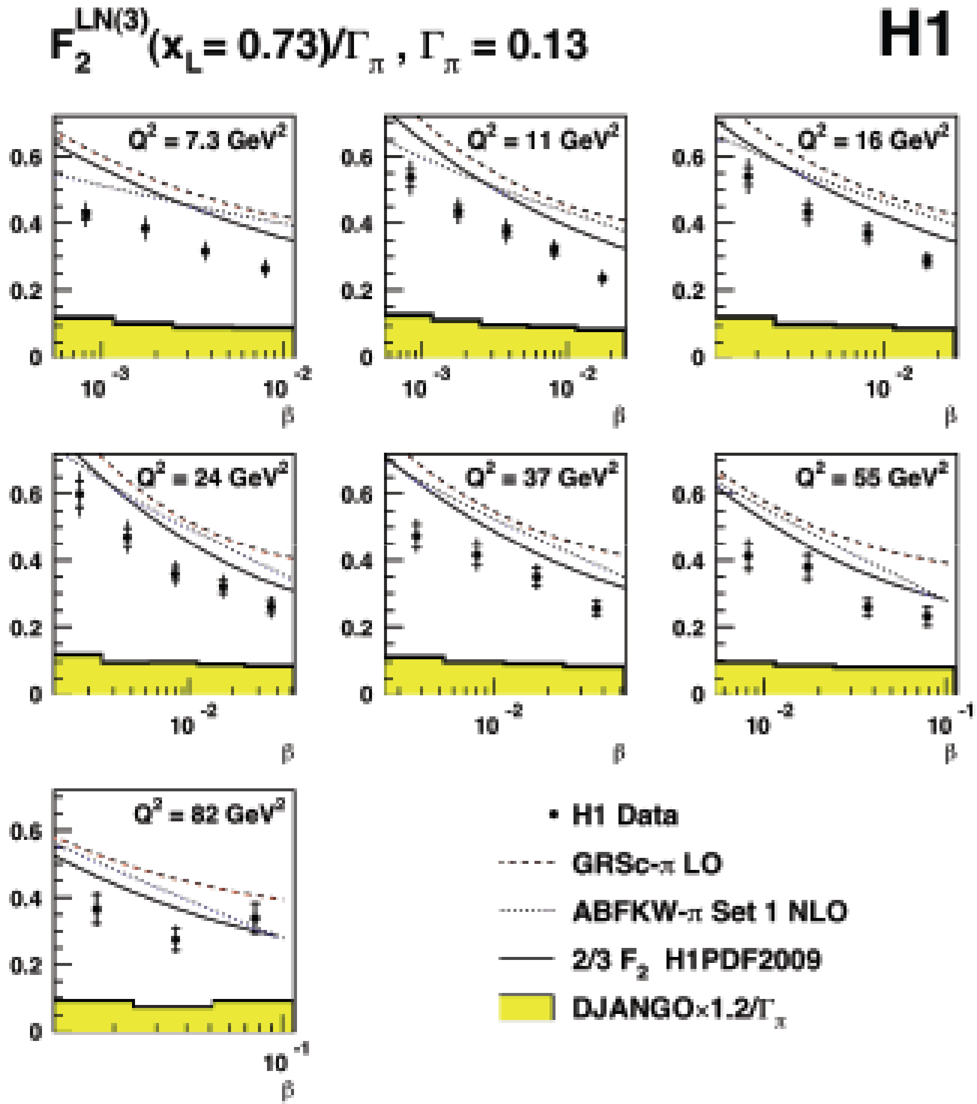
$$F_2^{\pi}(\beta,Q^2) = F_2^{LN(3)}(\beta,Q^2,x_L)/\Gamma_\pi(x_L)$$

$$\Gamma_\pi = \int f_{\pi/p}(x_L=0.73,t)\,dt \approx 0.13$$

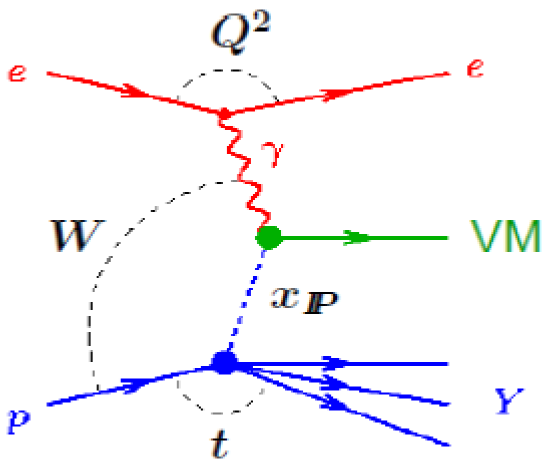
Pion flux parameterisation uncertainty ~30%

Contribution of neutrons from fragmentation (estimated by DJANGO) is ~25-30% and β, Q^2 independent

Contribution from ρ or other bkg negligible in this x_L bin

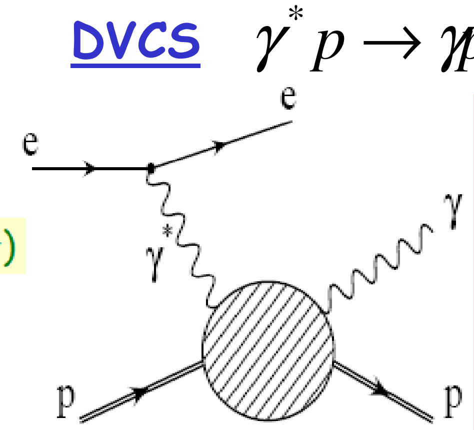


Exclusive diffraction



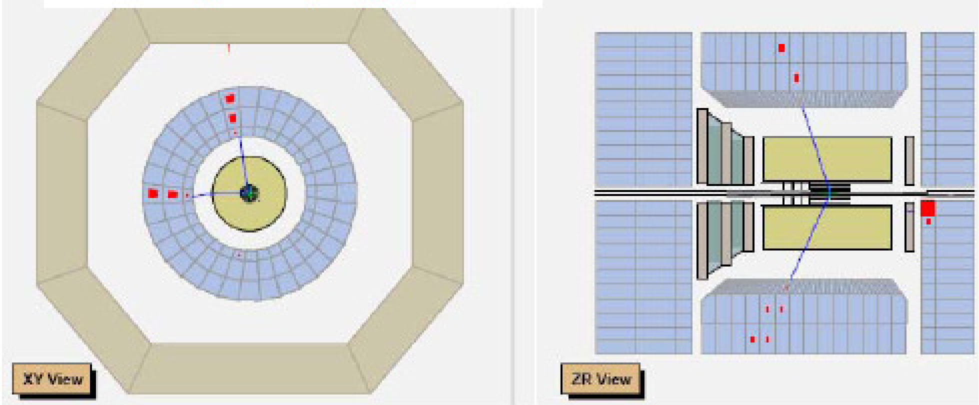
VM $(\rho, \omega, \phi, J/\psi, \Upsilon, \gamma)$

DVCS $\gamma^* p \to \gamma p$



- ✓Fully calculable in QCD
- ✓ Gives access to GPDs
- ✓ no uncertainty due to VM wave function

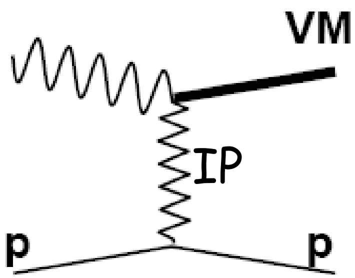
ZEUS: ep→e'+ρ⁰+p, ρ→π⁺π⁻



Signature:
VM decay particle and nothing else in the main detector!

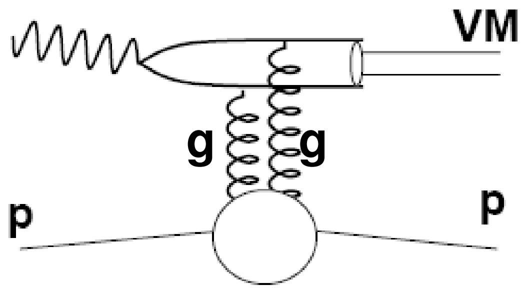
W and *t* cross section dependence for VM and DVCS to investigate the transition from soft to hard at HERA

Soft and hard diffraction



'soft'

Pomeron trajectory:
$\alpha(t)=\alpha(0) + \alpha' t$



'hard'

2-gluon exchange
(pQCD) at LO

Gluon density in the proton

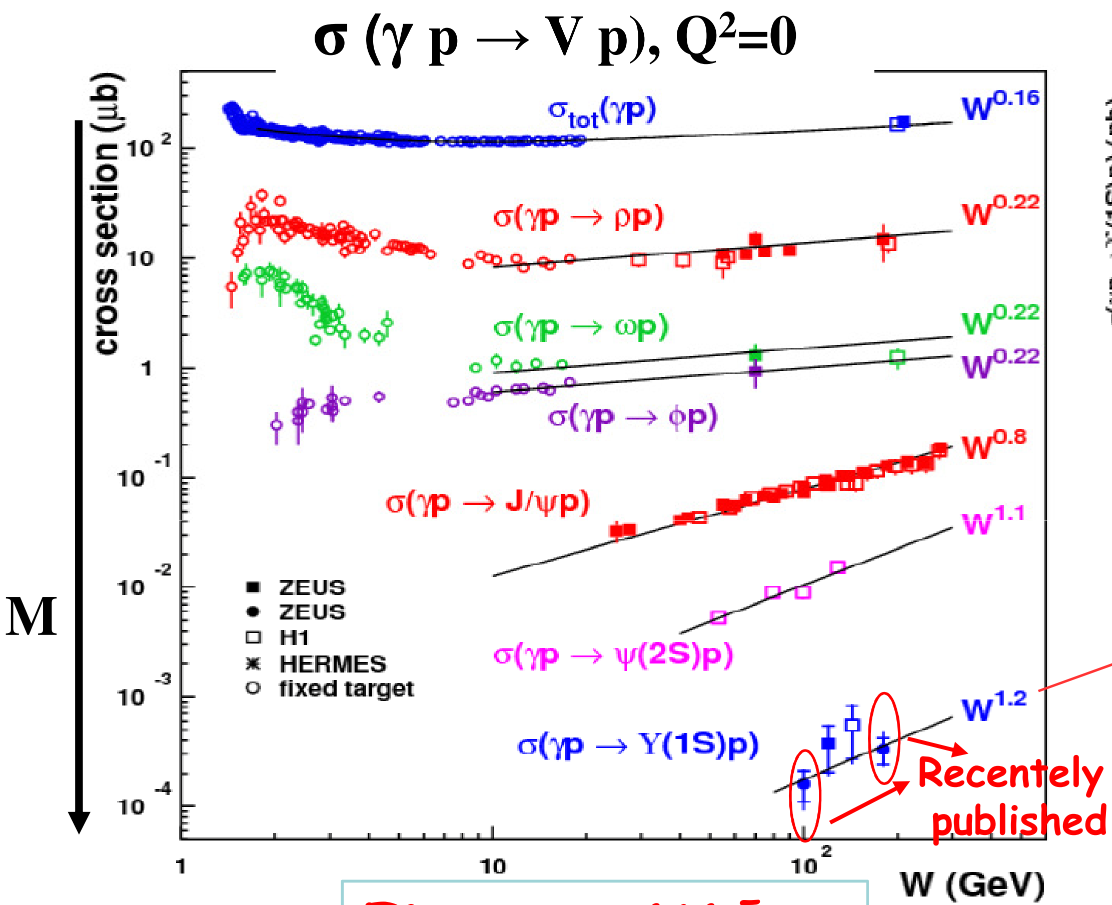
$$\begin{cases} \sigma \propto [x g(x,\mu^2)]^2 \\ \mu^2 \propto (Q^2 + M_V^2) \end{cases}$$

Fast increase of cross section proportional to probability of finding 2 gluons in the proton

$\sigma(W) \propto W^{\delta}$ → δ Expected to increase from soft (~0.2, "soft Pomeron") to hard (~1., "hard Pomeron")

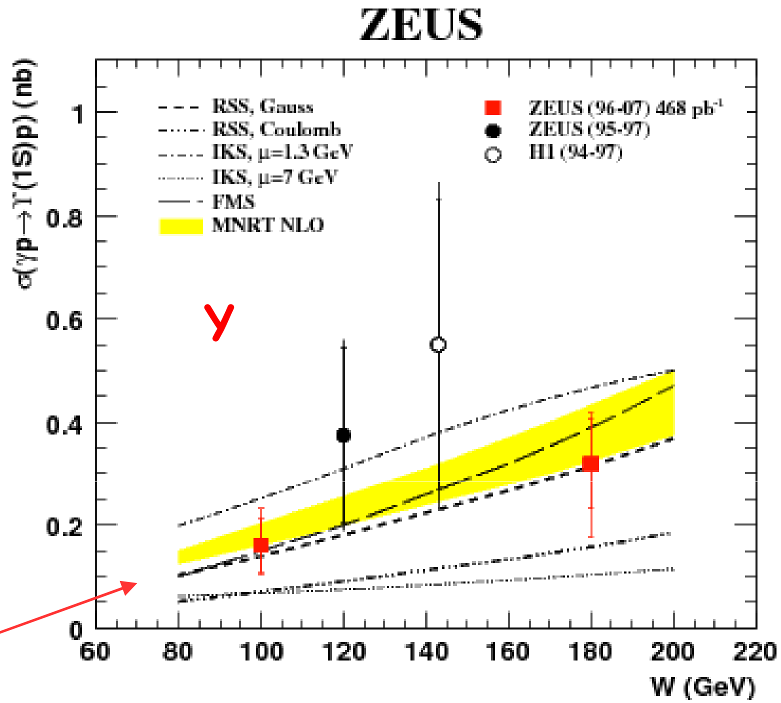
$\frac{d\sigma}{dt} \propto e^{-b|t|}$ → b expected to decrease from soft (~10 GeV^{-2}) to hard (~4-5 GeV^{-2})

VM photoproduction: W-dependence



Fit: $\sigma \sim W^{\delta}$

Phys. Lett. B 680 (2009) 4-12



Υ:

$\delta = 1.2 \pm 0.8$

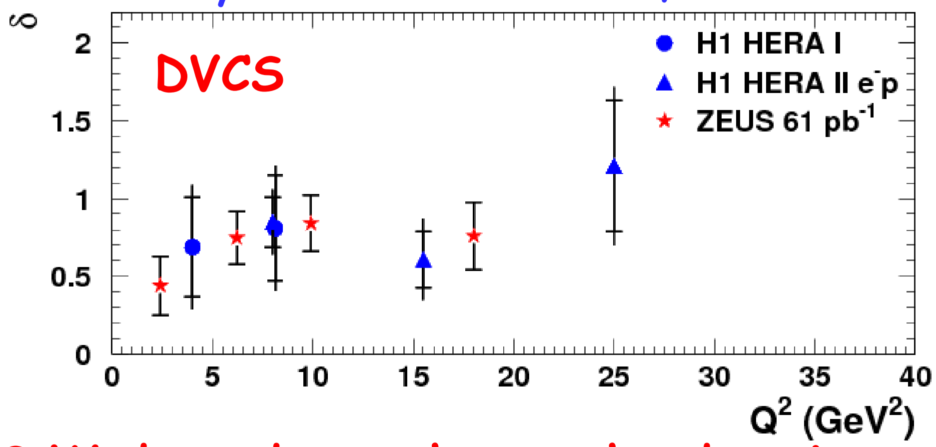
As the VM mass increases, the process gets harder: large M_V supplies a scale for hard processes → apply pQCD models

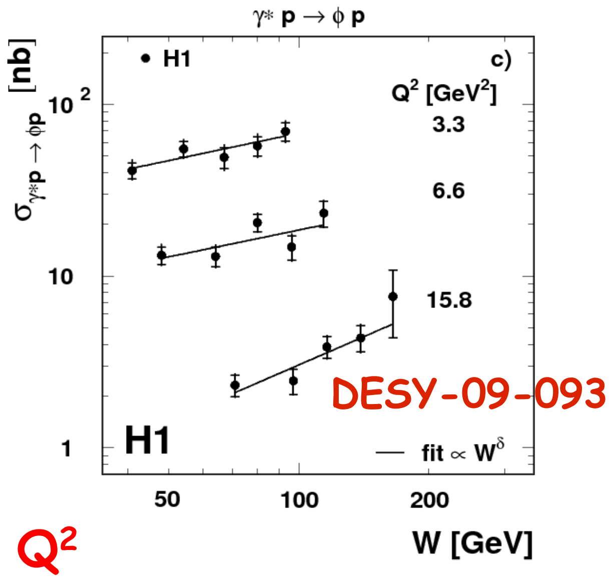
Consistent comparison with pQCD models
Sensitive to VM wave function (Gaussian-like light-cone WF favoured)

W-dependence in DIS

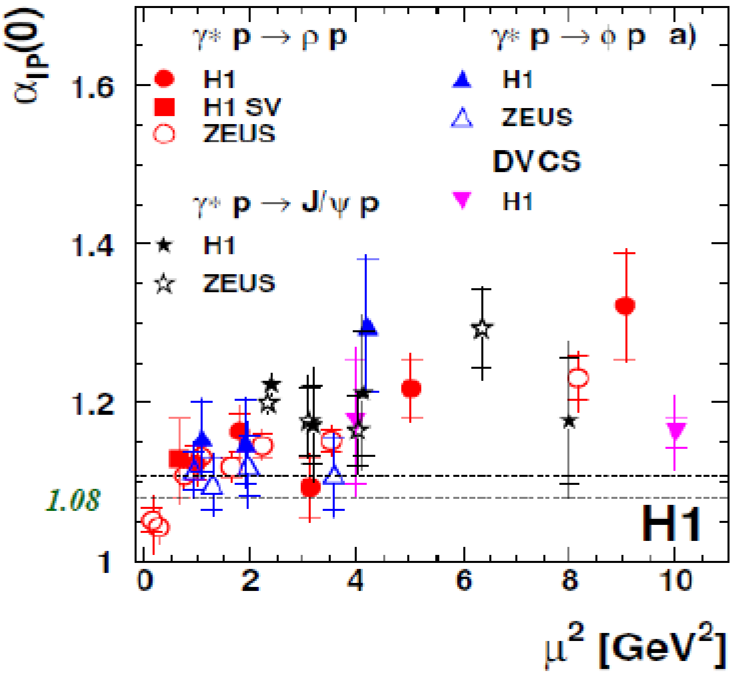
ZEUS: JHEP05(2009)108
H1: Phys.Lett.B659:796-806,2008

Fit: $\sigma \sim W^{\delta}$





DVCS W dependence shows a hard regime even at low Q^2

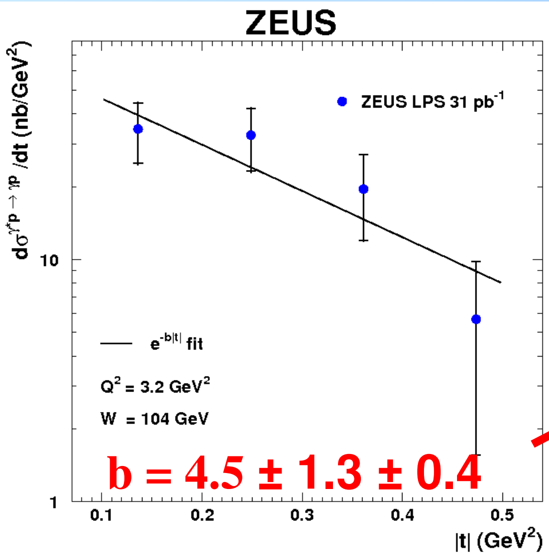


$$\begin{cases} \sigma(W) \propto W^{\delta} \\ \delta(t) = 4(\alpha_{IP}(t) - 1) \end{cases} \rightarrow \begin{cases} \alpha_{IP}(0) = 1 + \delta/4 + \alpha'_{IP}/\langle|t|\rangle \\ \mu^2 = (Q^2 + M^2)/4 \end{cases}$$

Common hardening of $\alpha_{IP}(0)$ with μ^2

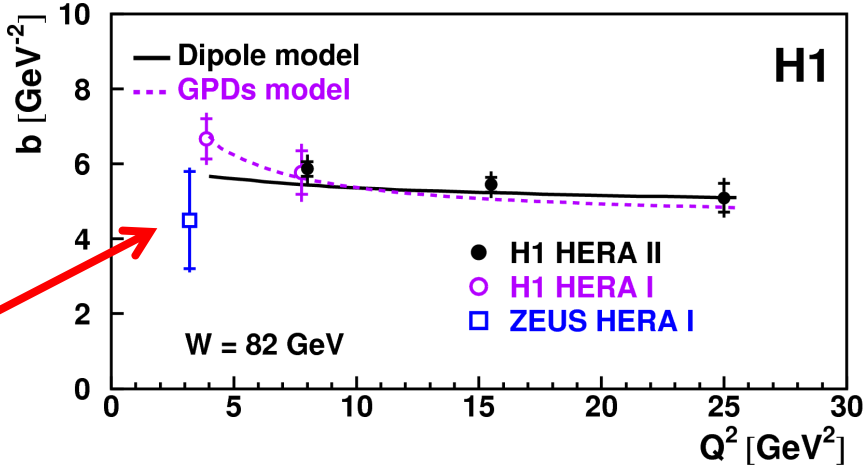
δ encreases with μ^2
(from soft to hard)

t dependence

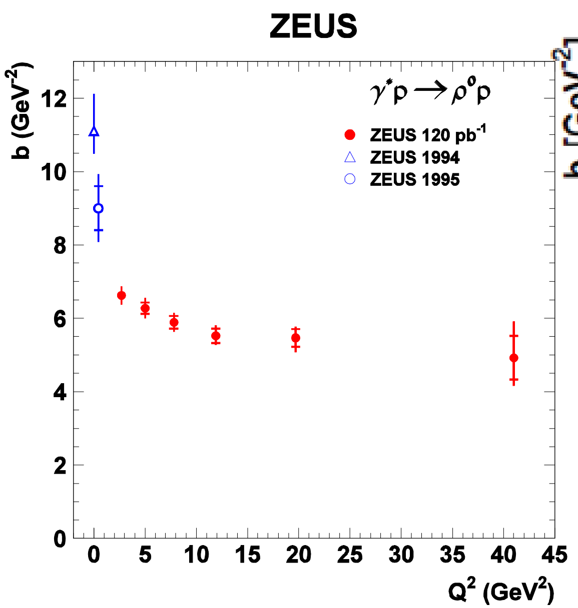


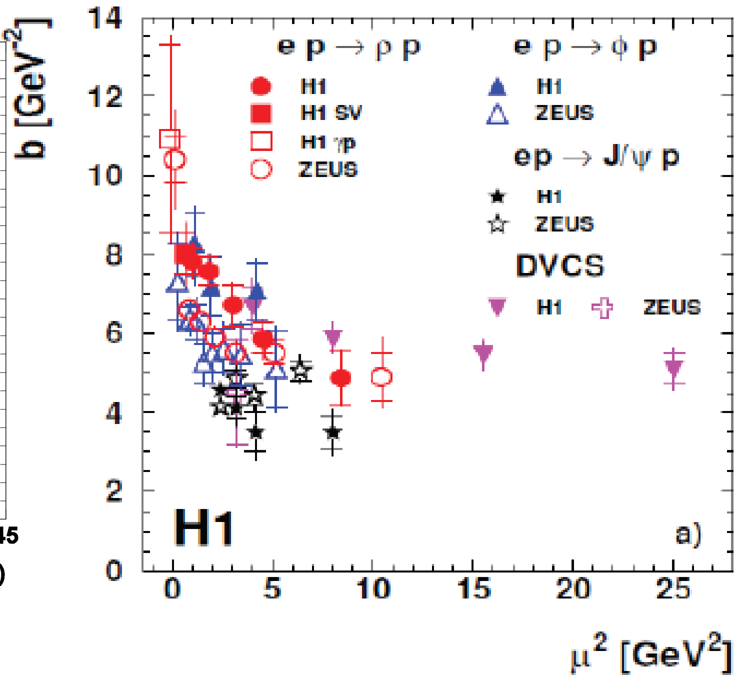
b = 4.5 ± 1.3 ± 0.4

DVCS



Same slope for all VM vs μ^2



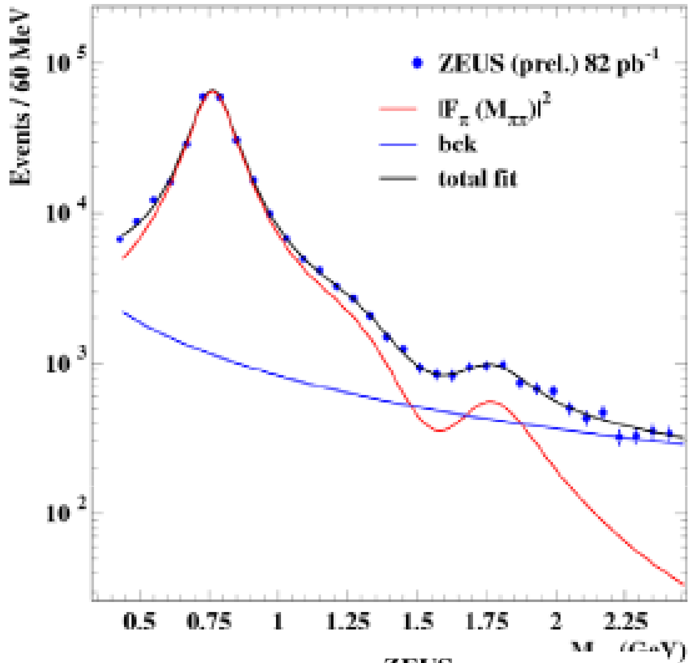


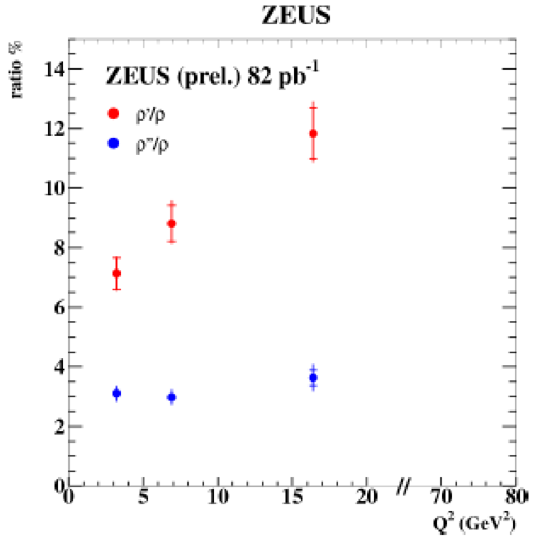
- b characterize the size of interaction, large dipole for light VM, the size became smaller with scale
- b decreases with μ^2 (from soft to hard)

Two pion electroproduction

ZEUS-prel-10-012

Two pion mass $0.4<M_{\pi\pi}<2.4$ GeV - $2<Q^2<80$ GeV^2





Fit with 3 resonances: ρ, ρ', ρ''

- $$\frac{dN(M_{\pi\pi})}{dM_{\pi\pi}} = N\left[|F_\pi(M_{\pi\pi})|^2 + \frac{B}{M^n_{\pi\pi}}\right]$$
- $$F_\pi(M_{\pi\pi}) = \frac{BW(\rho)+\beta BW(\rho')+\gamma BW(\rho'')}{1+\beta+\gamma}$$

Parameter	ZEUS (prel.)	PDG
M_ρ (GeV)	$772 \pm 2^{+2}_{-1}$	775.49 ± 0.34
Γ_ρ	$155 \pm 5 \pm 2$	149.4 ± 1.0
β	$-0.27 \pm 0.02 \pm 0.02$	
$M_{\rho'}$ (GeV)	$1360 \pm 20^{+20}_{-30}$	1465 ± 25
$\Gamma_{\rho'}$	$460 \pm 30^{+40}_{-45}$	400 ± 60
γ	$0.10 \pm 0.02^{+0.02}_{-0.01}$	
$M_{\rho''}$ (GeV)	$1770 \pm 20^{+15}_{-20}$	1720 ± 20
$\Gamma_{\rho''}$	$310 \pm 30^{+25}_{-35}$	250 ± 100

Q^2 dependence:
ρ'/ρ increases with Q^2
(consistent with pQCD expectation: Martin, Ryskin, Teubner Phys.Rev. D56, 3007, 1997)

ρ''/ρ flat with Q^2

Summary

A lot of data analysed and new measurements are coming:

- New inclusive measurements presented (first H1 measurements with VFPS)
- NLO predictions using HERA DPDFs agree very well with the data (see charm, dijet, forward jet, etc.) fact holds at HERA
- Combinations of H1 and ZEUS final results underway

- Precise measurements of LN (x_L and P_T^2) presented in PHP with jets and in DIS
- Pion structure function estimated from F_2^{LN}

- New exclusive measurements presented (two pion production)
- VM measurements allow the study the transition from the soft to the hard regime

HERA represents a powerful 'instrument' to understand diffraction in perturbative regime and to complete the mapping of the proton structure

Backup

ZEUS diffractive QCD fits

Regge factorization assumption →

$$F_{2/L}^{D(4)}(x_{IP},t,Q^2,\beta)$$
$$= f(x_{IP},t)F_{2/L}^{IP}(Q^2,\beta) + f(x_{IR},t)F_{2/L}^{IR}(Q^2,\beta)$$

DGLAP evolution equations

(QCDNUM)

Heavy quarks contribution treated

within TR-VFNS scheme (H1 FFNS)

DPDFs (q and g) parametrized

at the starting scale Q_0^2=1.8 GeV^2 as:

$$zf_{d,u,s}(z,Q_0^2) = A_q z^{B_q}(1-z)^{C_q}$$
$$zf_g(z,Q_0^2) = A_g z^{B_g}(1-z)^{C_g}$$

Fit C (constant) gluon parameters: B_g=C_g=0 (~H1 FitB)

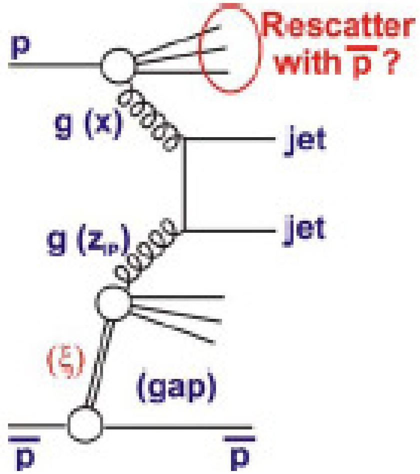
Fit S (standard) gluon parameters: B_g,C_g fitted

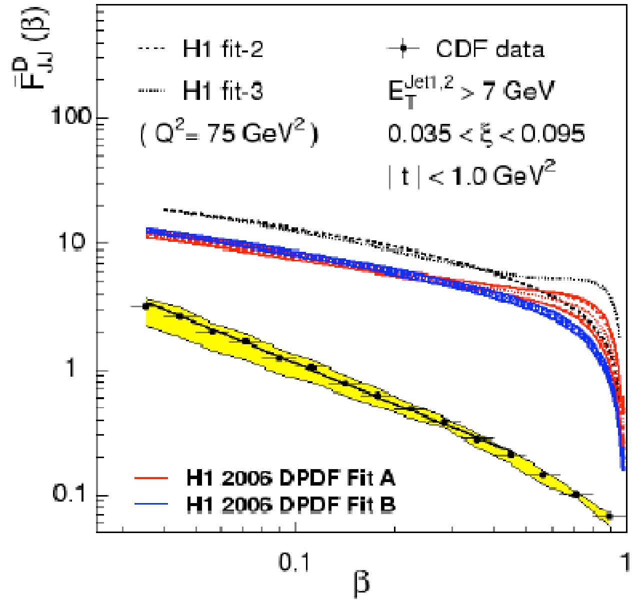
Fit SJ (standard+dijet) gluon parameters: B_g,C_g fitted

Q^2_{min}>5 GeV^2 (H1: Q^2_{min}>8.5 GeV^2)

Diffractive Dijet Photoproduction

TEVATRON →

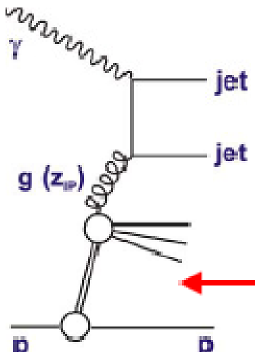




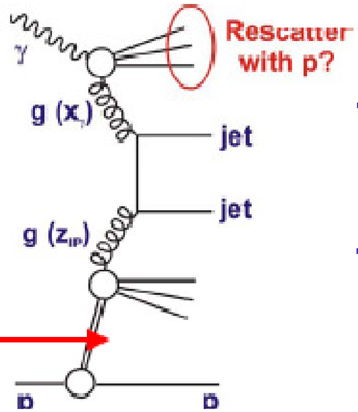
Rapidity Gap Survival probability S^2~0.1: Multi-Pomeron exchange absorptive effect, etc...

'Direct" photon ($x_\gamma \rightarrow 1$)

"S^2 = 1"



Resolved photon ($x\gamma$<1)

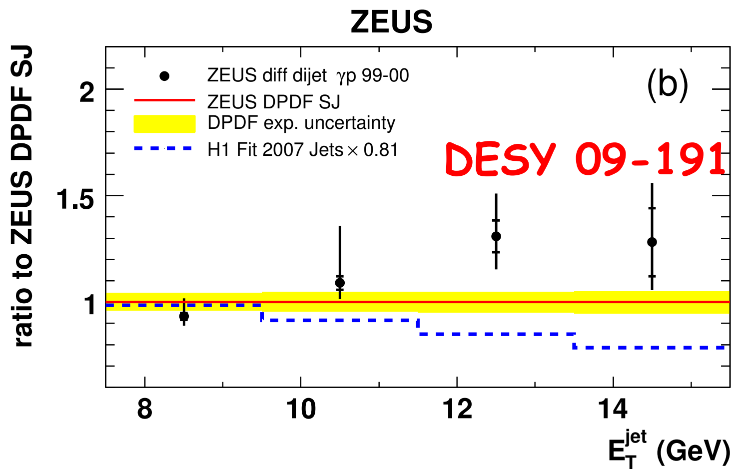


GAP

→ HERA

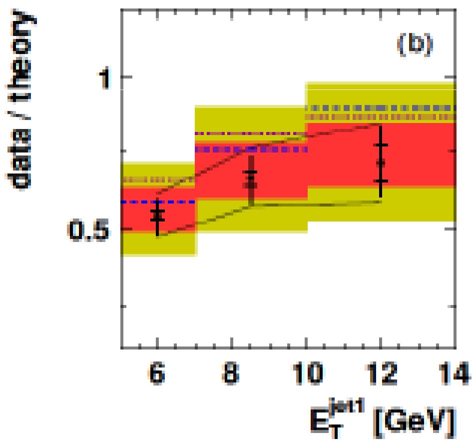
The strong suppression observed at Tevatron can be studied also at HERA using dijet cross sections in resolved dijet PHP

Diffractive Dijet Photoproduction



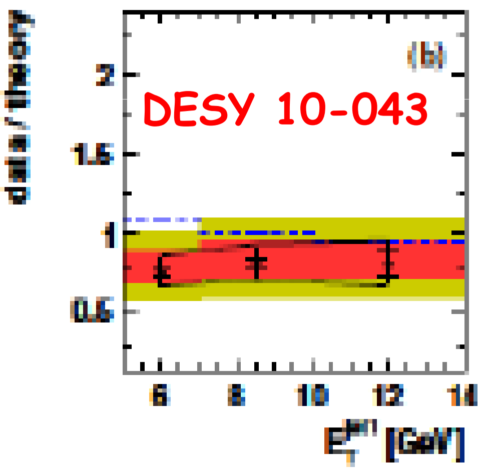
ZEUS: E_T ^{jet1} > 7.5 GeV

Good description with no evidence for suppression on any variable



H1 data / theory

- NLO H1 2006 Fit B × (1+δ$_{had}$)
- data correlated uncertainty
- NLO H1 2007 Fit Jets × (1+δ$_{had}$)
- NLO ZEUS SJ × 1.23 × (1+δ$_{had}$)



H1 data / theory

- NLO H1 2006 Fit B, KKMR suppressed × (1+δ$_{had}$) [hep-ph/0911.3716]
- data correlated uncertainty
- NLO H1 2006 Fit B, resolved × 0.34 × (1+δ$_{had}$)

H1: E_T ^{jet1} > 5 GeV
σ(data)/σ(theory)~0.6±0.2

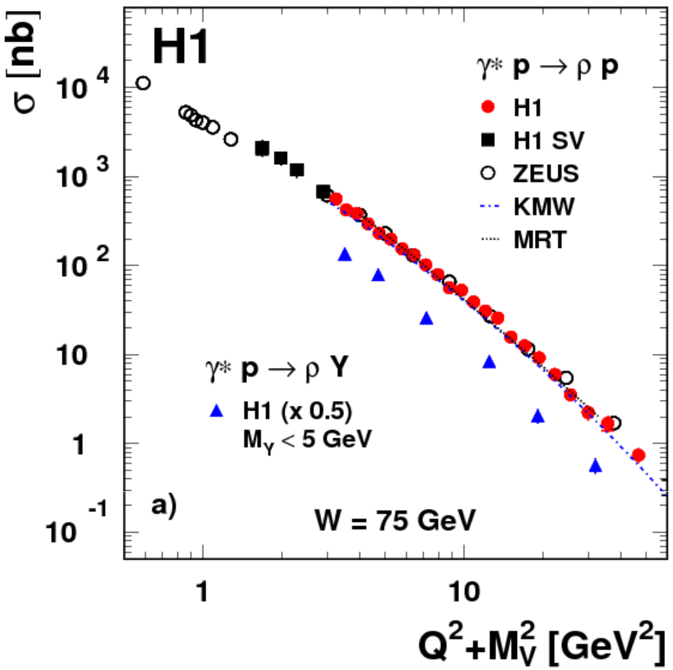
Results compatible (~2σ) with ZEUS

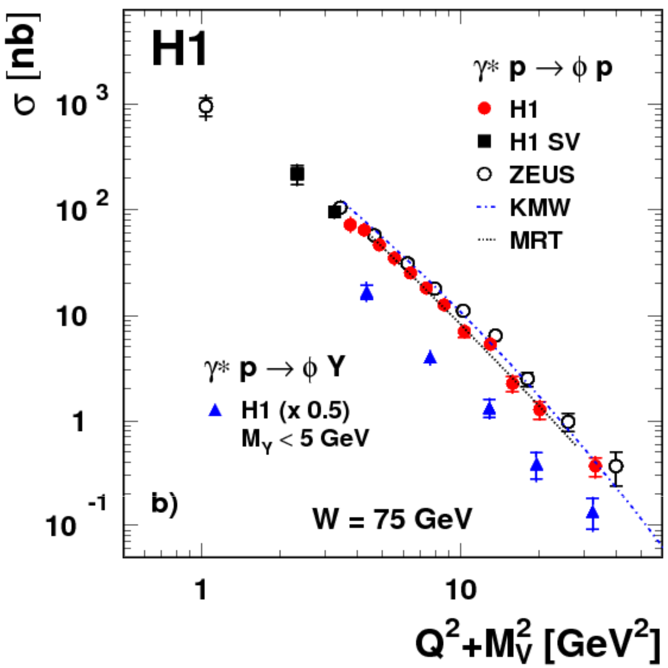
Results also compared with a refined gap survival model (KKRM) hep-ph/0911.3716

Q2-dependence

DESY-09-093

ρ^0 ($M^2\rho$ = 0.5 GeV^2) φ^0 ($M^2\varphi$ = 1 GeV^2)





$$\sigma \propto \left(Q^2 + M^2\right)^{-n}$$

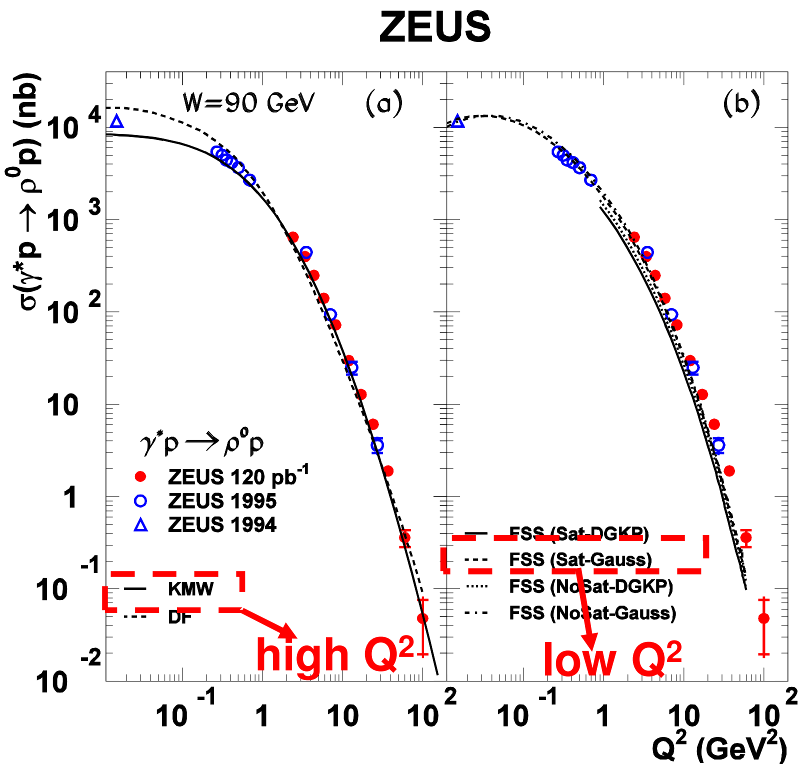
Fit to whole Q^2 range gives bad χ^2/df

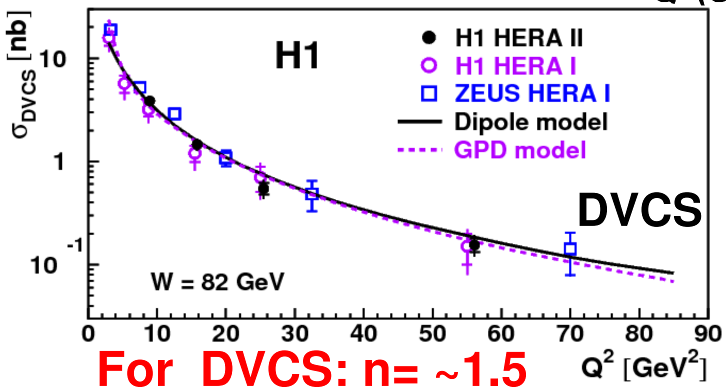
Good H1/ZEUS agreement

- $Q^2 \geq 0$ GeV^2, n≈2.00±0.01, $\chi^2/ndf \sim 10$ (n ≠ const)
- $Q^2 \geq 10$ GeV^2, n≈2.50±0.02, $\chi^2/ndf \sim 1.5$

- high precision for elastic ρ,φ cross sections
- good agreement between H1/ZEUS
- Steep decrease of σ with increasing Q^2+M^2
- similar for p-dissociation

Q^2-dependence

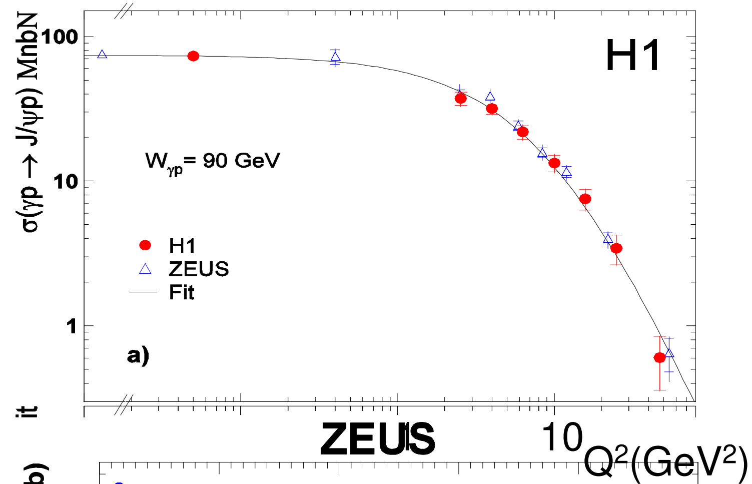


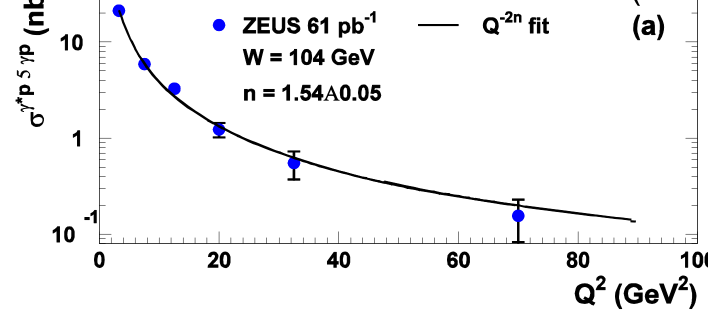


For DVCS: n= ~1.5

Fit to whole Q^2 range gives bad χ^2/df (~70)

n increasing with *Q^2* appears to be favored



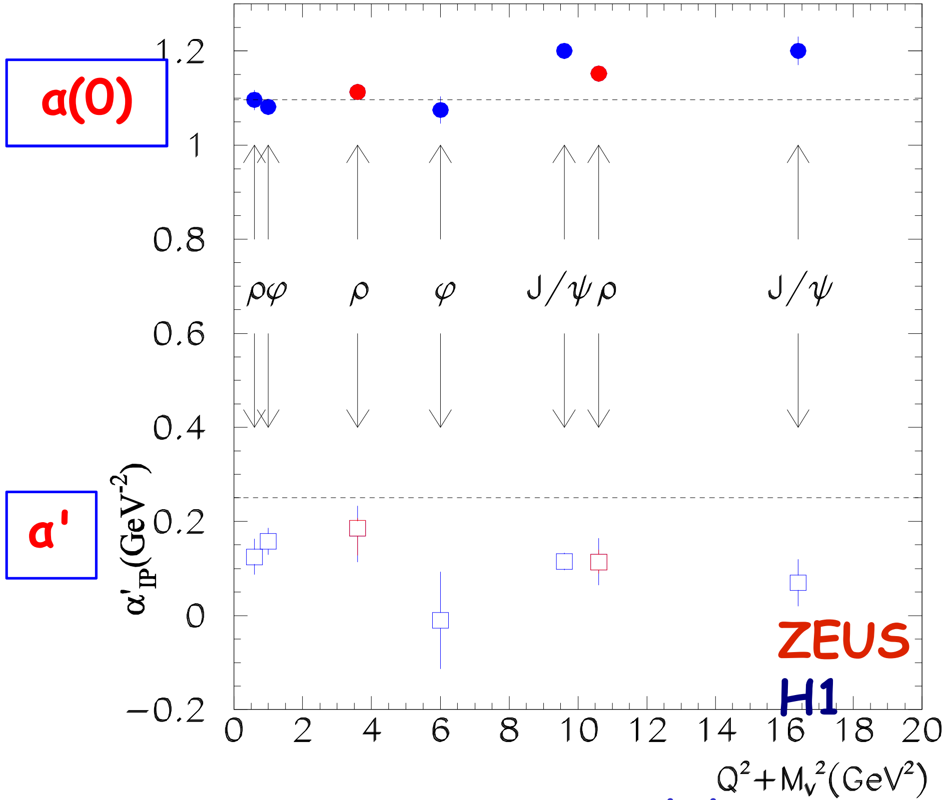


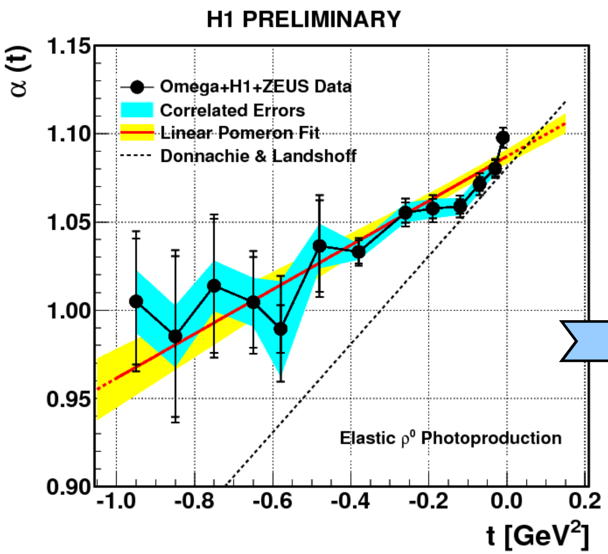
Pomeron trajectory in ep collisions

From SOFT to HARD.....

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

In electron-proton interactions:
As the scale gets harder the intercept grows up to 1.2
The Pomeron slope is around ~0.1





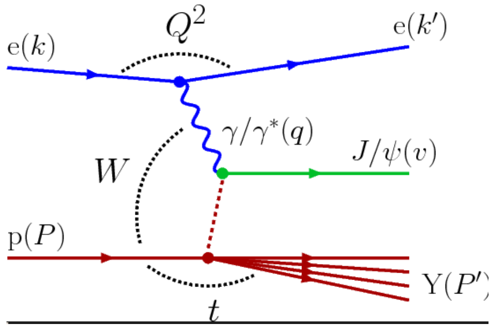
H1-prelim-09-016

ρ (light VM); elastic production (low |t|):

$\alpha(0) = 1.087 \pm 0.003 \pm 0.003$
$\alpha' = 0.126 \pm 0.013 \pm 0.012\ GeV^{-2}$

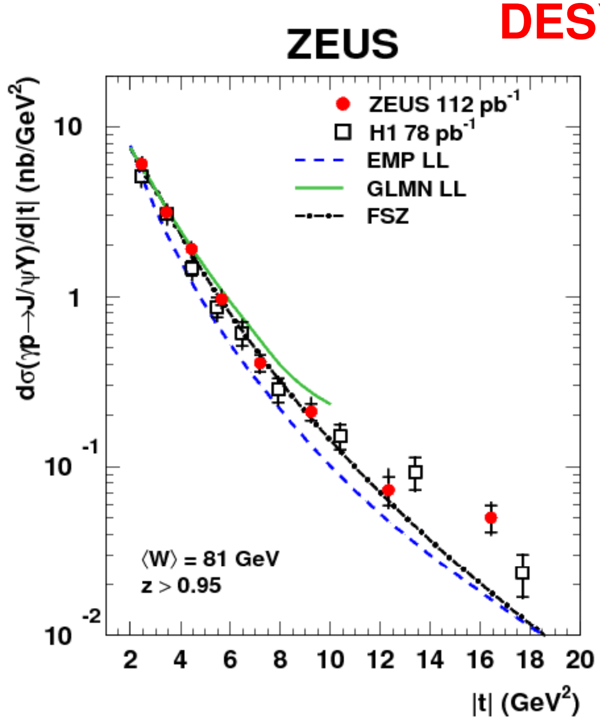
$$\alpha_{IP}(t) = 1.08 + 0.25t$$ measured in hh scattering

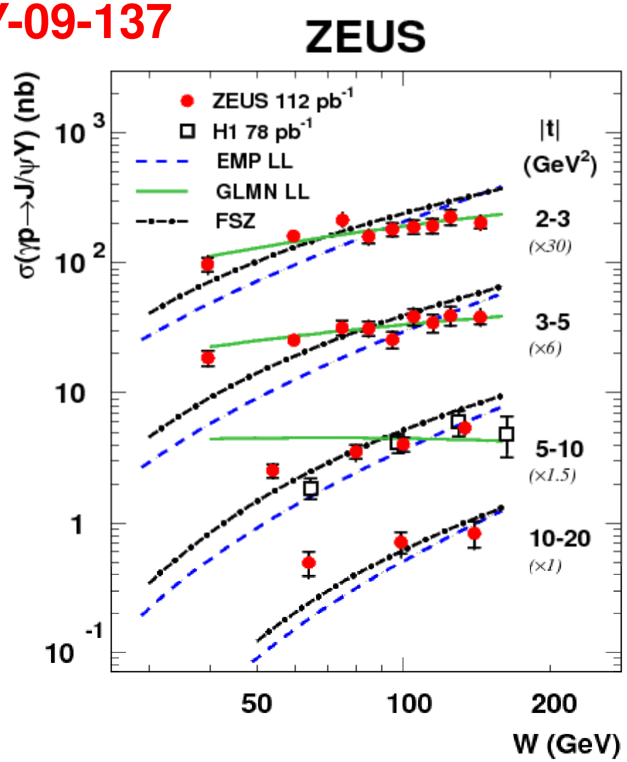
High |t| measurement of J/ψ



- Hard scale provided by t
- t dependence no longer exponential

DESY-09-137





Fit: $\frac{d\sigma}{d|t|} \sim t^n$

n = -1.9 ± 0.1, $2 < |t| < 4$ GeV^2
n = -3.0 ± 0.1, $4 < |t| < 16$ GeV^2

- σ vs W in t ranges: data rise with W for all t
- EMP *(BFKL)* below data
- GLMN *(DGLAP)* fails at $|t|>5$GeV^2
- FSZ *(W dependence of σ depends on the gluon distribution)*: describes data up to $|t|=12$ GeV^2
- None of the models describes the data over the full t-range