CRIMEA-2007
New Trends in High Energy Physics
Yalta, 15-22 September 2007

QCD measurements at HERA

Armen Bunyatyan

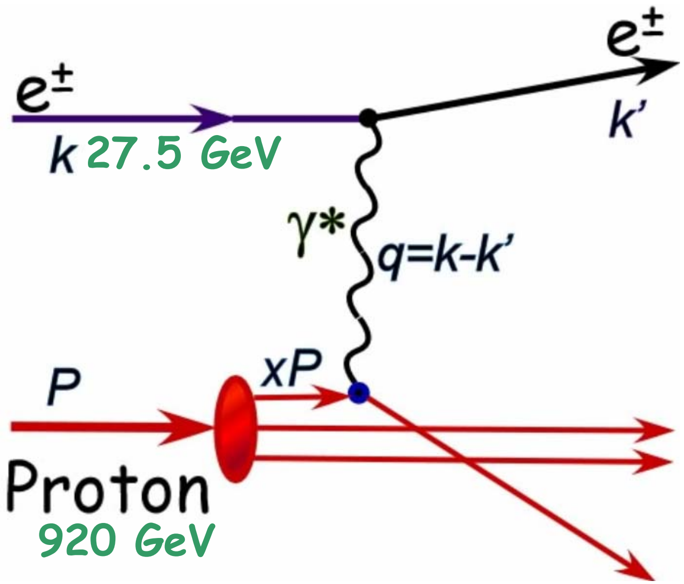
MPI-K, Heidelberg and YerPhI,Yerevan

On behalf of the H1 and ZEUS Collaborations

Outline:

- Deep Inelastic Scattering & Proton Structure
- Hadronic final states, Jets, Measurements of α_S
- Heavy quark production
- Inclusive diffraction, hadronic final states, vector mesons & DVCS

Deep Inelastic Scattering, Structure functions



$Q^2=-(k-k')^2$ - virtuality of exchanged boson $=2E_eE_e'(1+\cos\theta_e)$

$y=p\cdot q/p\cdot k$ - inelasticity variable $=1-E_e'(1+\cos\theta_e)/2E_e$

$x=Q^2/2p\cdot q$ - fraction of proton momentum carried by struck quark $=Q^2/Sy$

$W=[Q^2(1-x)/x]^{1/2}$ – invariant mass of γ^*p system

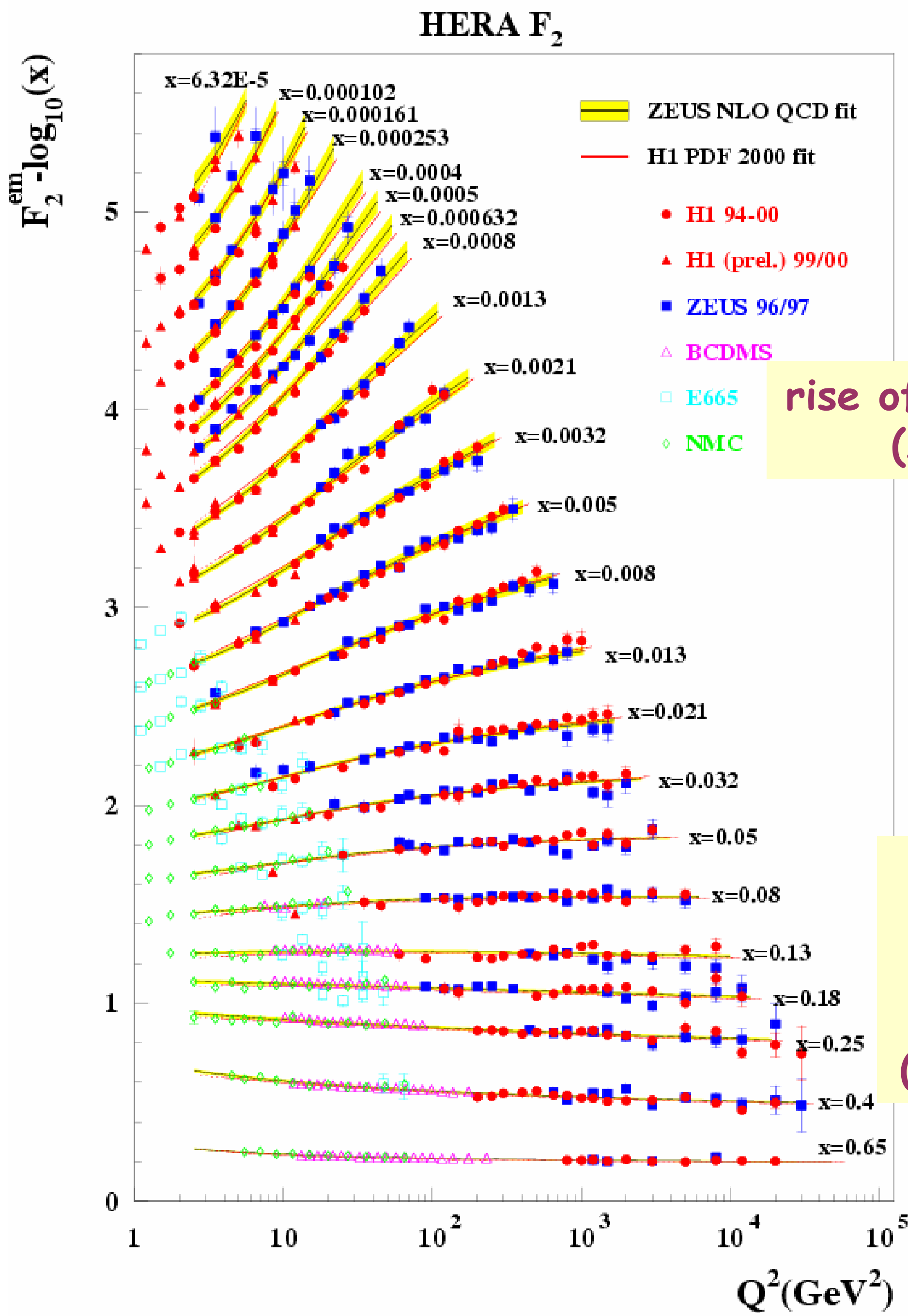
$$\frac{d^2\sigma^{NC}_{e^\pm p}}{dx\,dQ^2}=\frac{2\pi\alpha^2Y_+}{xQ^4}\cdot\underbrace{\left(F_2-\frac{y^2}{Y_+}F_L\mp\frac{Y_-}{Y_+}xF_3\right)}_{\text{reduced cross section}\equiv\tilde{\sigma}(x,Q^2)}\quad,\ Y_\pm=1\pm(1-y)^2$$

$F_2=x\sum e_q^2\left[q(x)+\bar{q}(x)\right]$ dominant contribution to cross section

F_L =0 at leading order; proportional to gluon density at higher orders

xF_3 important only at high Q^2

HERA F_2 structure function



- High precision data (2÷3% for bulk of data)

NLO QCD describes F_2 over 4 orders in x,Q^2

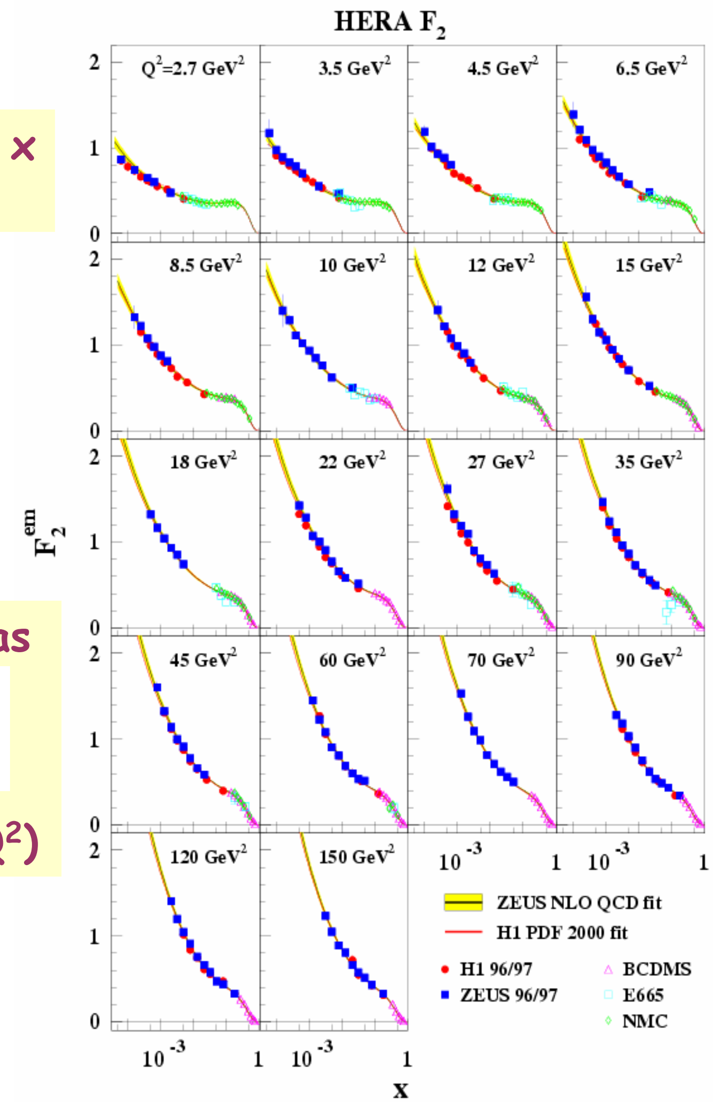
rise of F_2 with Q^2 at low x (scaling violation)

$$\frac{dF_2}{d\ln Q^2} \sim g$$

rise of F_2 at $x \to 0$ as

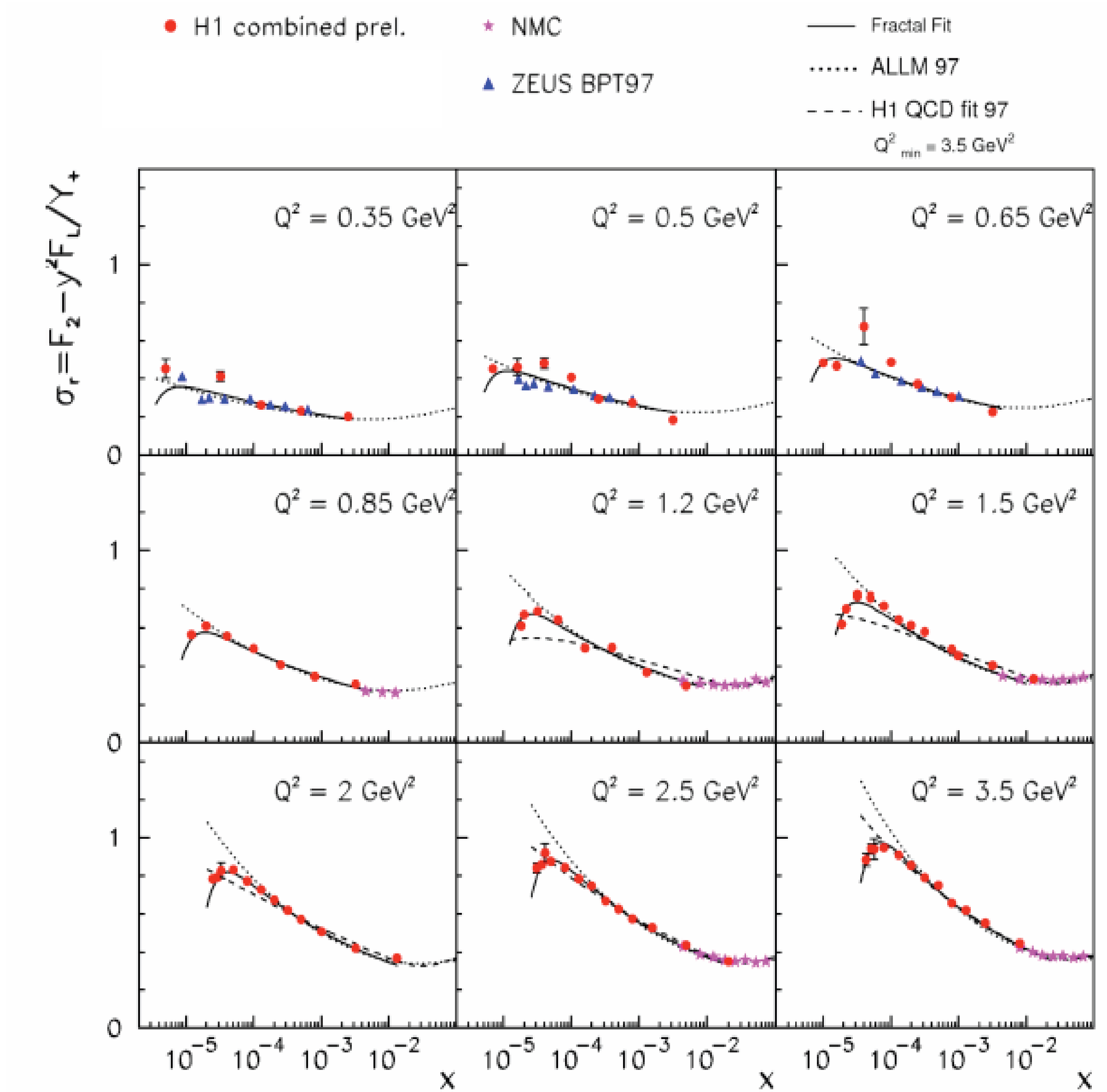
$$F_2 \sim x^{-\lambda(Q^2)}$$

(λ increasing with Q^2)



Cross section measurements at very low Q^2

New measurements in the transition region (Q^2~1 GeV^2) between DIS and γp.
Precision ~2÷3%, for Q^2>3 GeV^2 ~1.5%



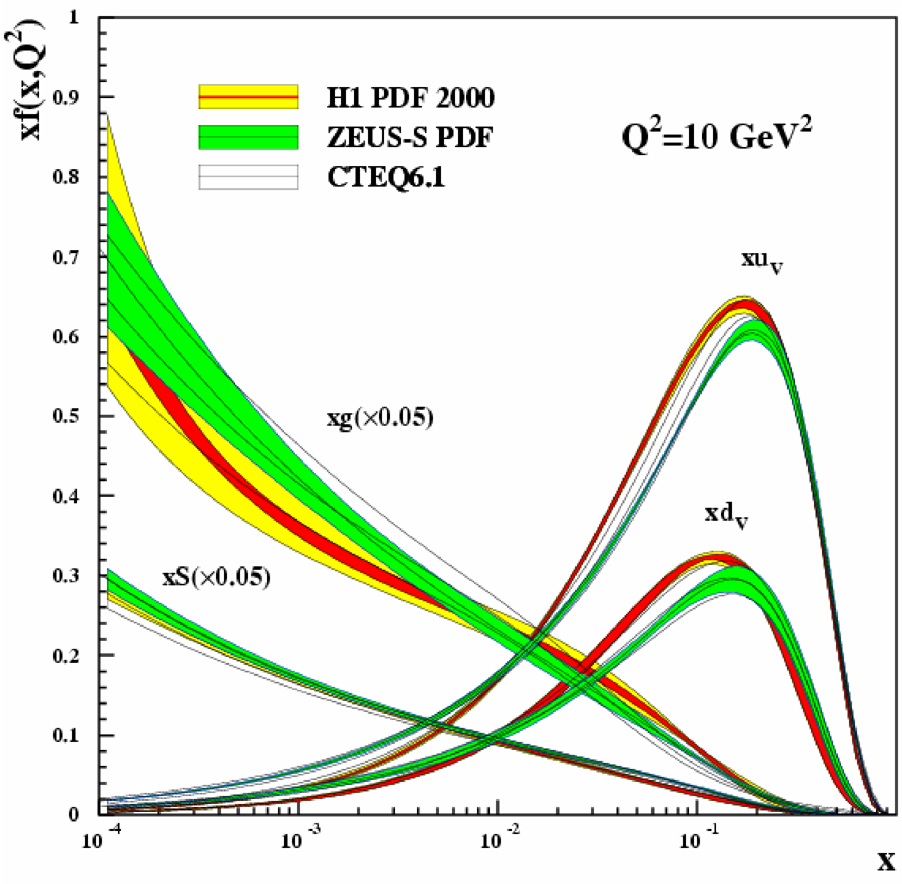
Proton PDFs from HERA – NLO QCD DGLAP fit

F_2 data from HERA allow to extract individual quark flavours, gluon density can be obtained from scaling violation

→ quark and gluon distributions-
$xq(x,Q^2)$, $x\bar{q}(x,Q^2)$, $xg(x,Q^2)$

- Valence quarks u_v, d_v determine proton structure at high x, sea and gluons important at low x
 F_2 data constrain the low-x sea quarks and gluons ($x = 10^{-1} \div 10^{-4}$)

- Some difference between fits
- largest uncertainties at low x gluon density
 → room for improvement (additional input from high y and F_L measurements will push down the uncertainties)



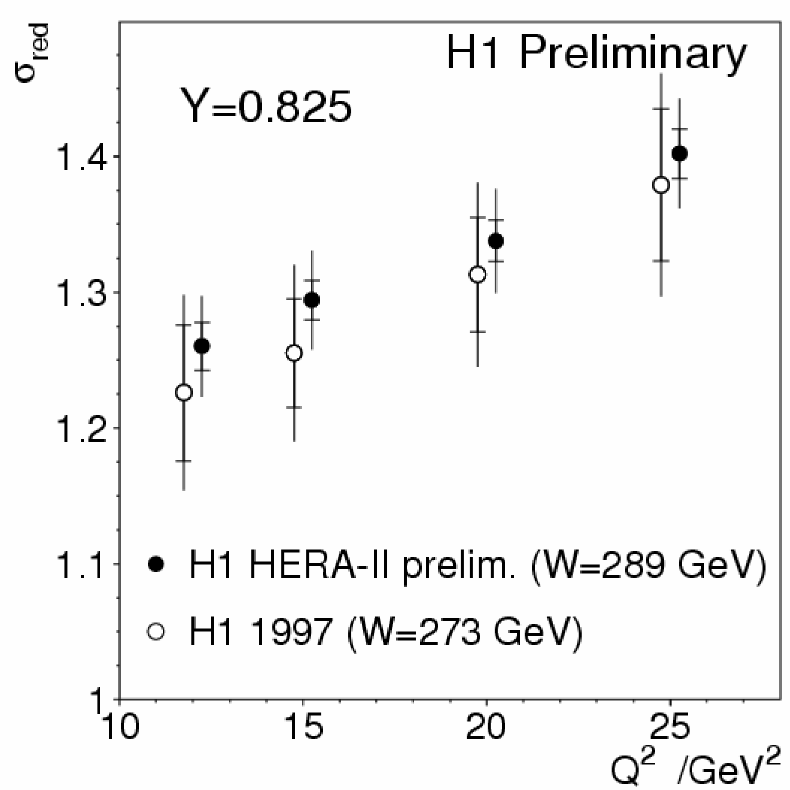
Measurements at high y and F_L

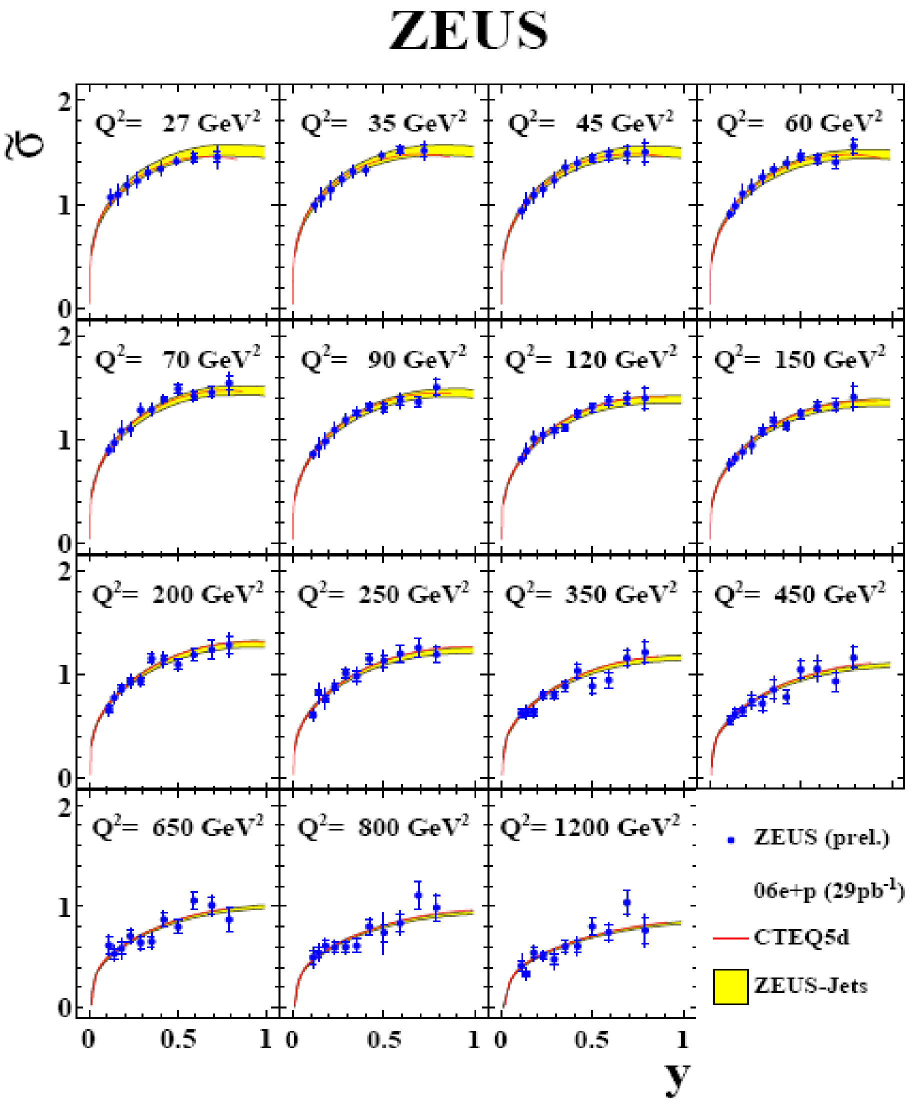
(scattered electron at low energy)

Sensitive to F_L (e.g. to gluons)

$F_L \sim \alpha_s \cdot g(x,Q^2)$:

$$\sigma_r = F_2 - y^2/[1+(1-y)^2]\cdot F_L$$



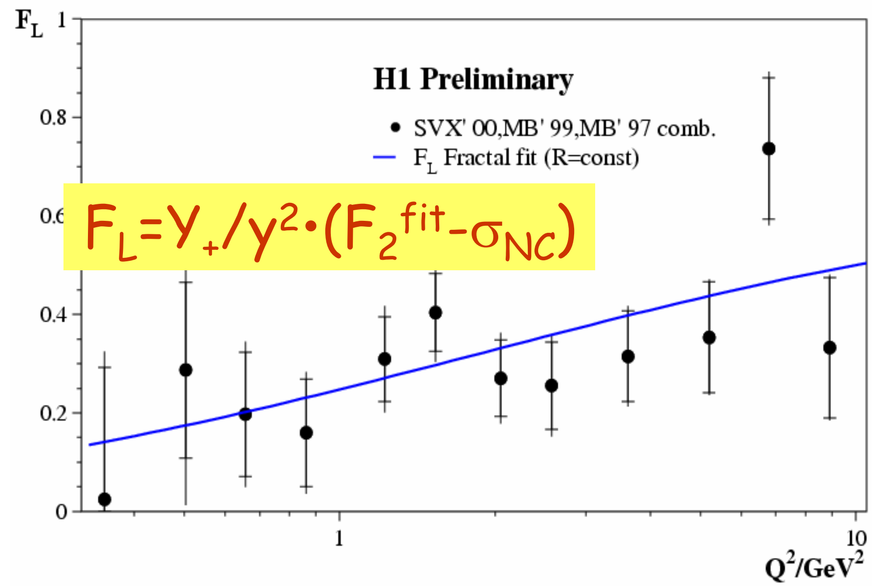


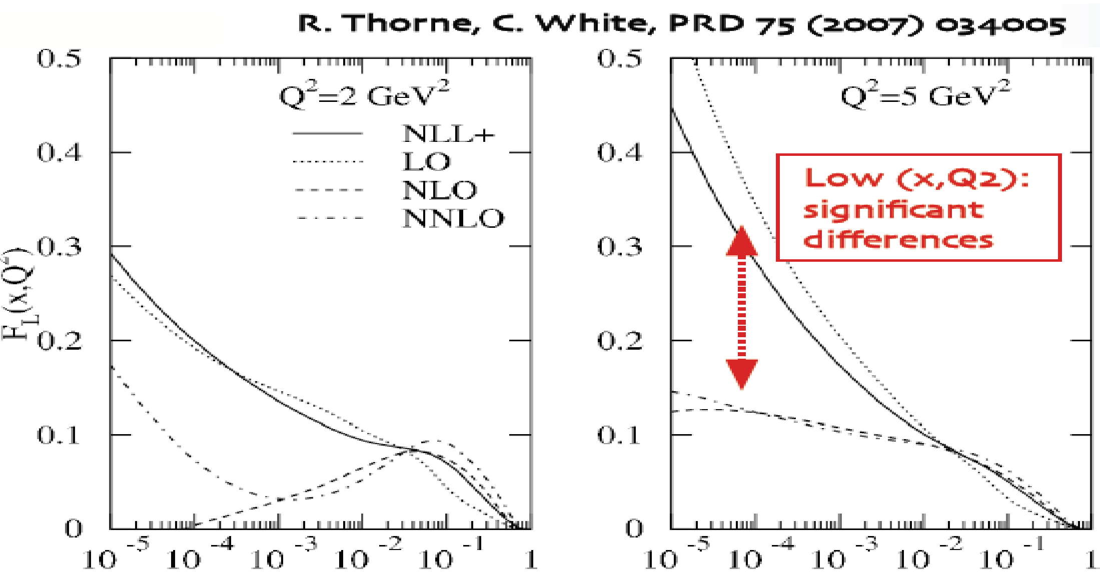
measurements extended to higher y,
total errors- 2÷3% (factor ~2 improvement in precision)

F_L measurements

F_L is directly sensitive to gluon PDF

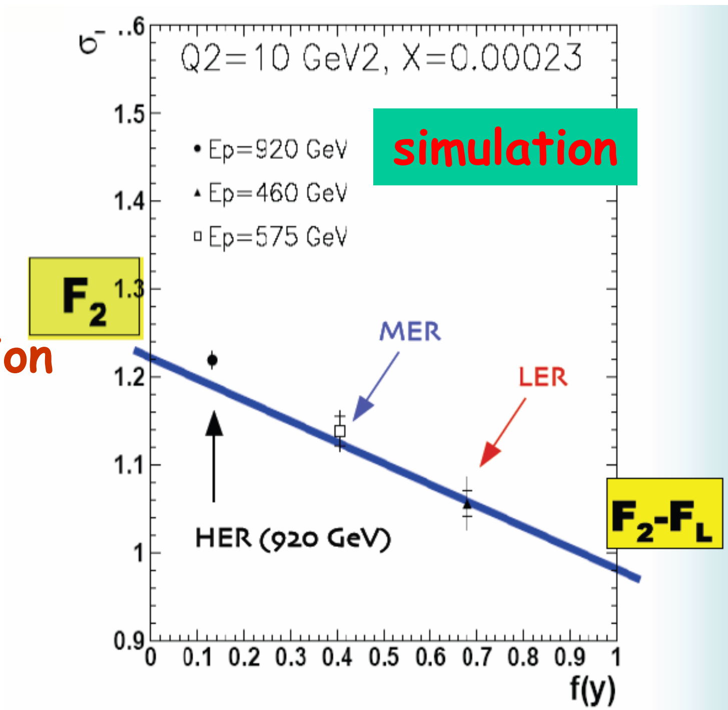
$F_L \sim \alpha_s \cdot g(x,Q^2)$





So far only indirect measurement was possible (fit F_2 and extrapolate to low x) → model dependence

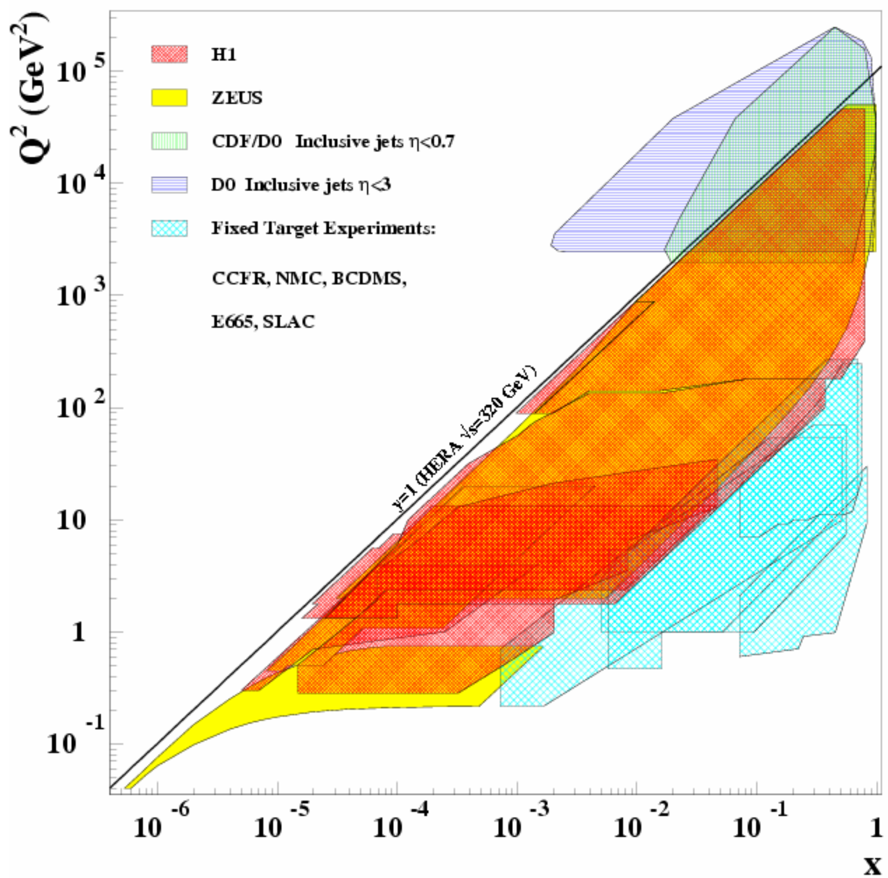
Direct measurement of F_L requires measuring cross section at the same Q^2,x but at different y (different beam energies) $\sigma_r = F_2 - y^2/Y_+ \cdot F_L$

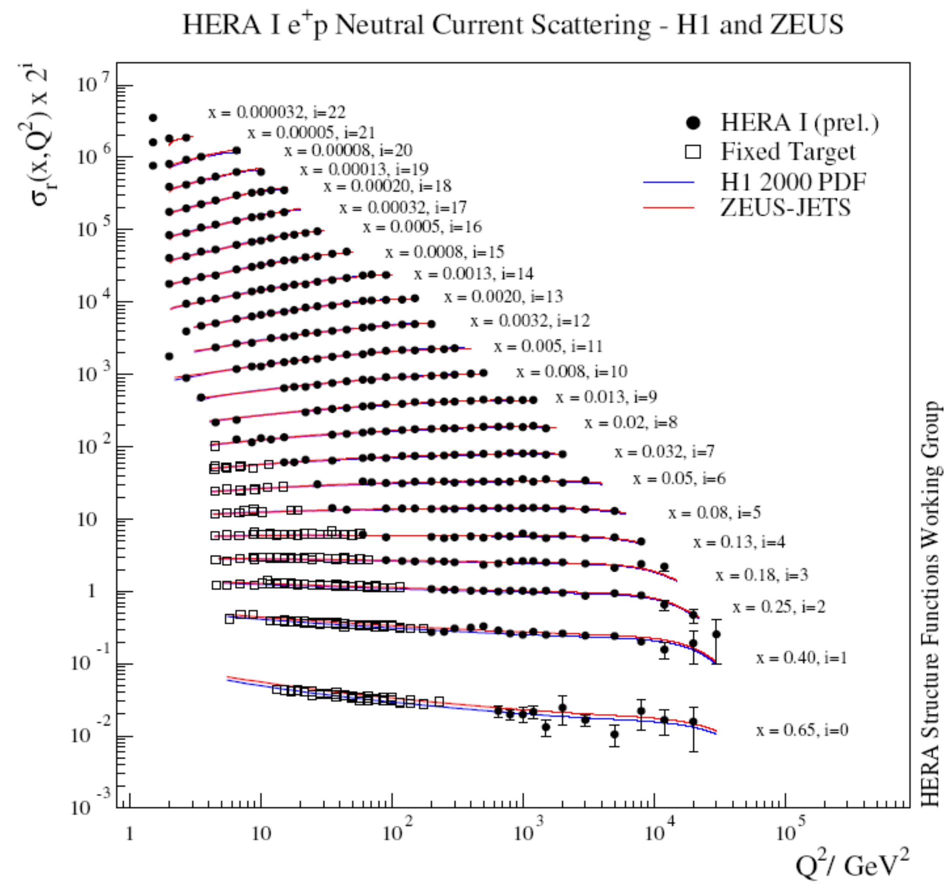


Last 3 months of HERA were dedicated to this measurement: HERA delivered ~14pb^{-1} at Ep=460 GeV and 7pb^{-1} at Ep=575 GeV.

Conclusions on structure functions

- HERA experiments provide unique information on proton structure at low x,
→crucial input for LHC physics !
- Precision of HERA measurement reached 2÷3% level, (aim is 1÷1.5%)
- Direct measurement of longitudinal str.function F_L will provide an important check of the theory and a new handle on the gluon density
- H1 and ZEUS initiated work on HERA average cross sections
  - -model independent check of consistency
  - -cross-calibrate each other, reduce systematical errors



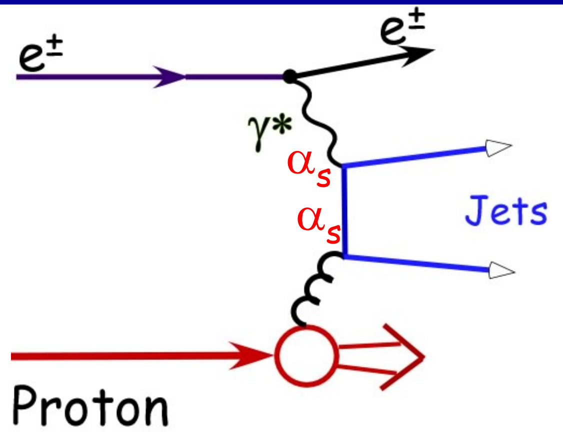


Physics with Jets at HERA

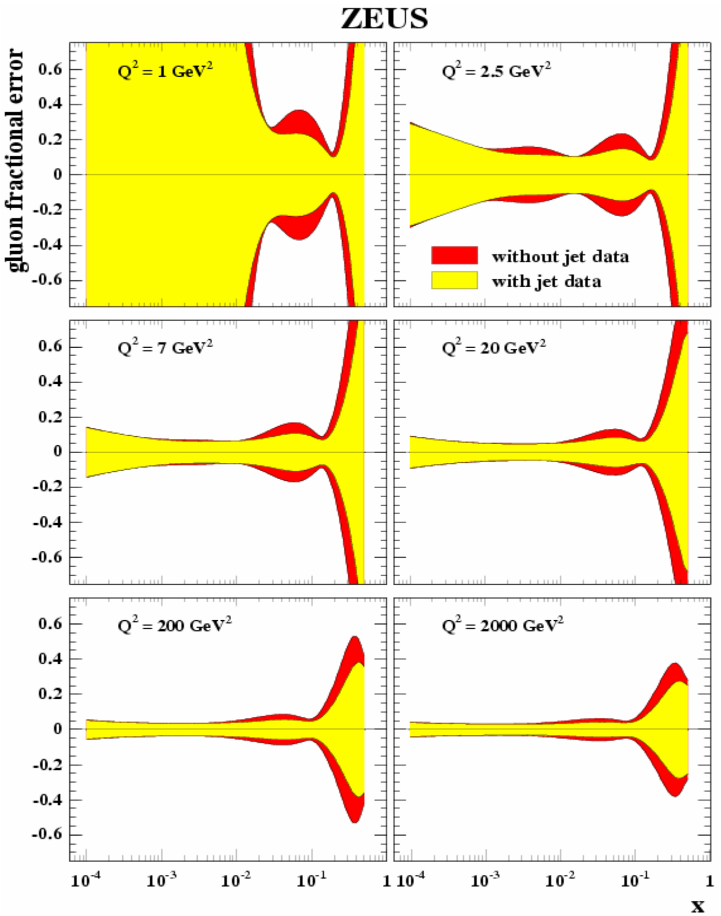
- Provides a testing ground for QCD
- Jets are directly sensitive to gluons: $\sigma \sim \alpha_s \cdot g(x)$

→ help to improve constraining gluon density

→ extract strong coupling α_s with high precision



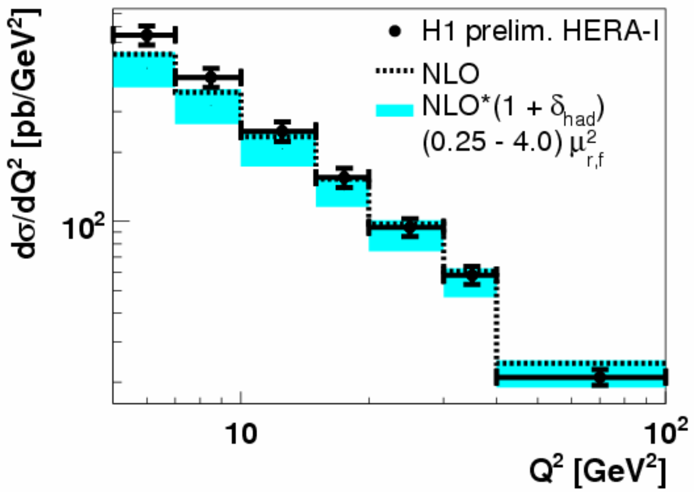
HERA-1 data in inclusive DIS and dijet photoproduction already successfully used to constrain high x gluon

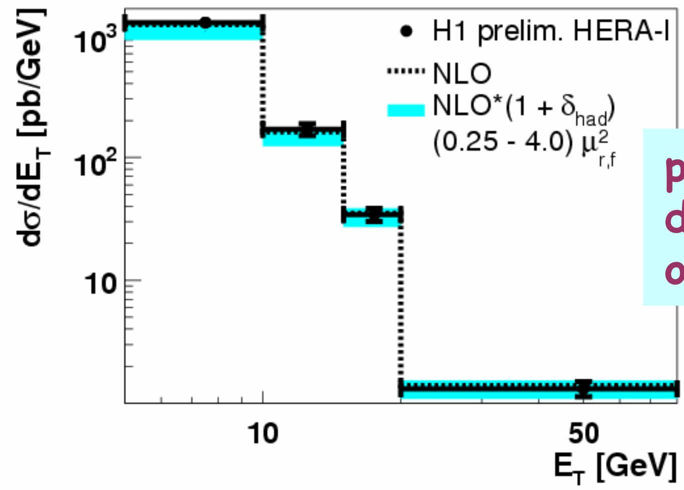


Wealth of new jet data from HERA available to provide further constrains on gluon PDF at medium and high x

Jet production at low Q^2 DIS ($5<Q^2<100$ GeV^2)

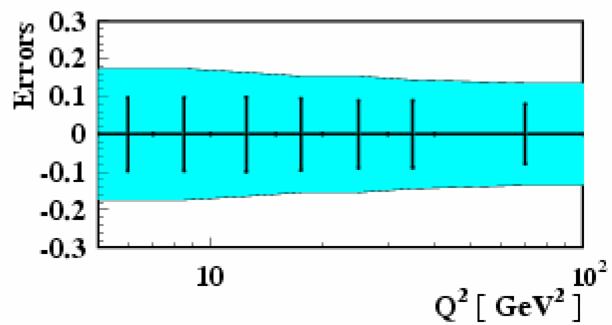
Inclusive jet cross sections $d\sigma/dQ^2$, $d\sigma/dE_t^{jet}$

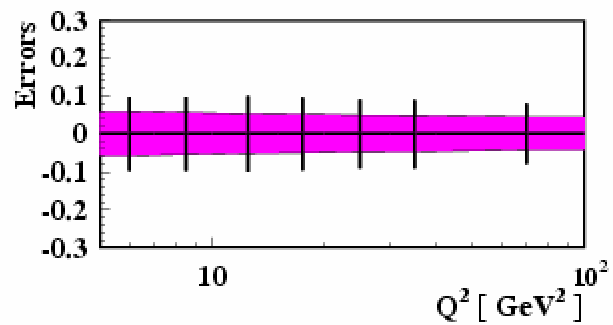


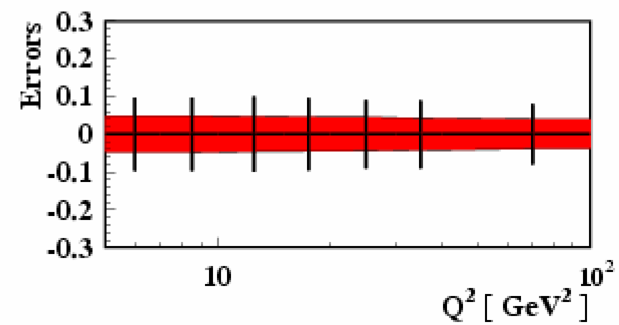


pQCD at NLO provides a good description for $Q^2>10$ GeV^2 or $E_t^{jet}>10$ GeV

Theoretical uncertainties of NLO calculations







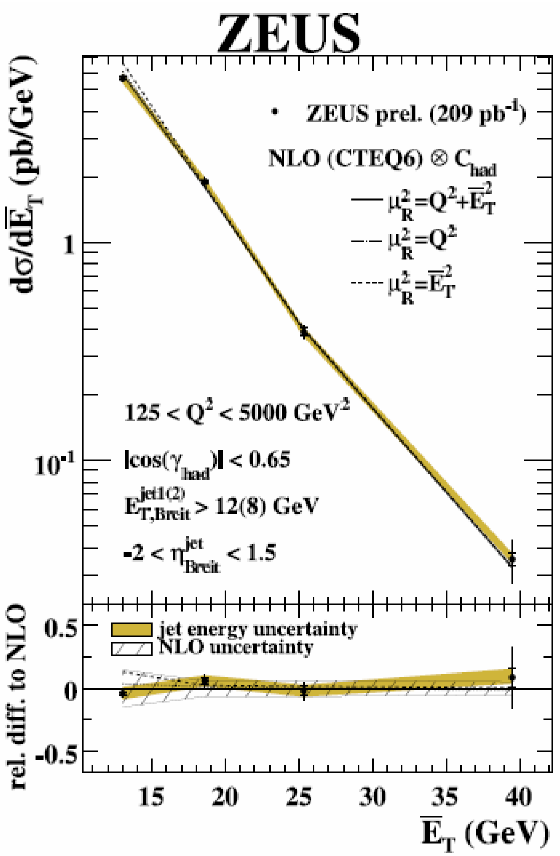
μ_R unc. → up to ±20%

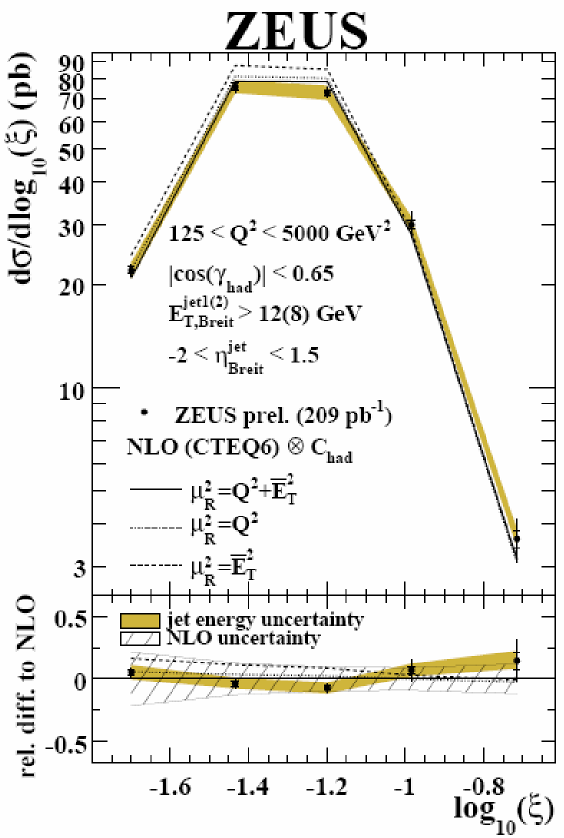
PDF unc. → ±5%

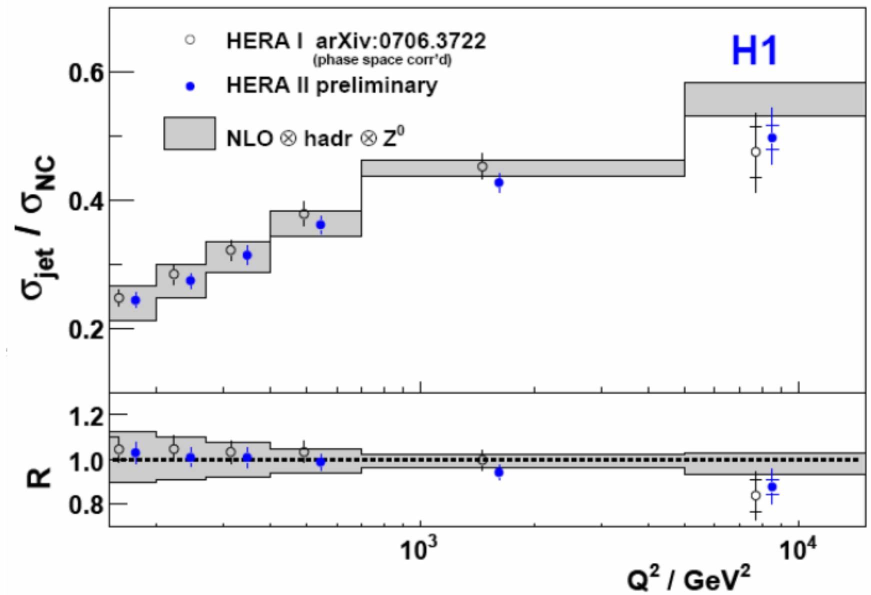
$\alpha_s(M_z)$ unc. → ±5%

The largest contribution to uncertainties are from terms beyond NLO
→ NNLO is needed to describe jets data at low Q^2 region

New high statistics results – HERA-1 + HERA-2 data





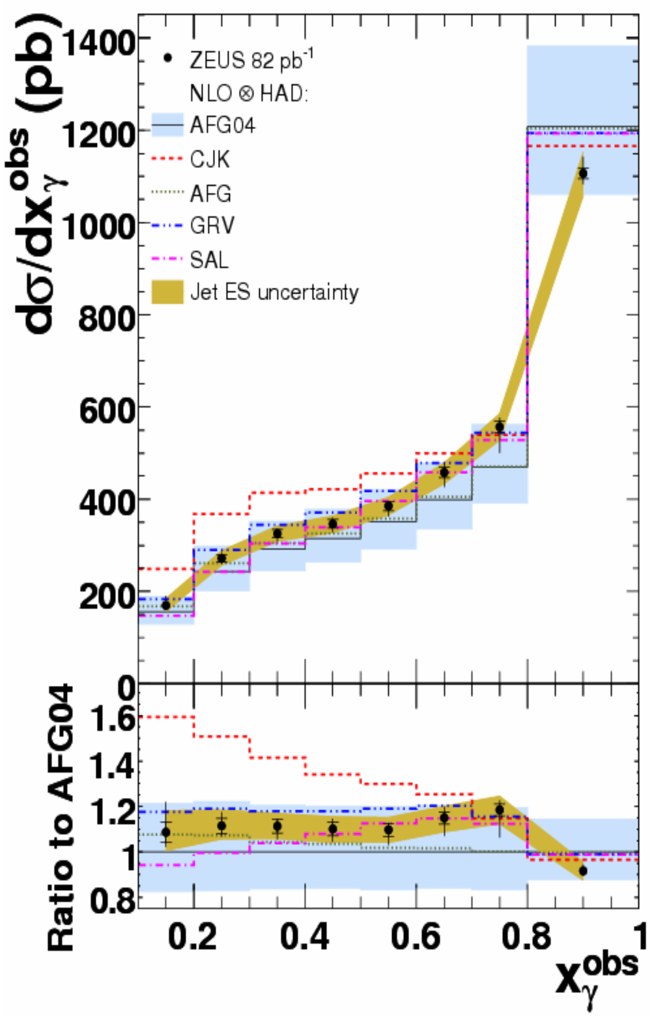


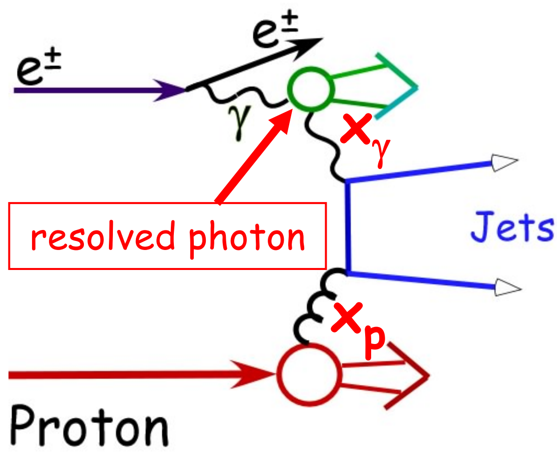
(ξ-fraction of the proton momentum carried by the interacting parton)

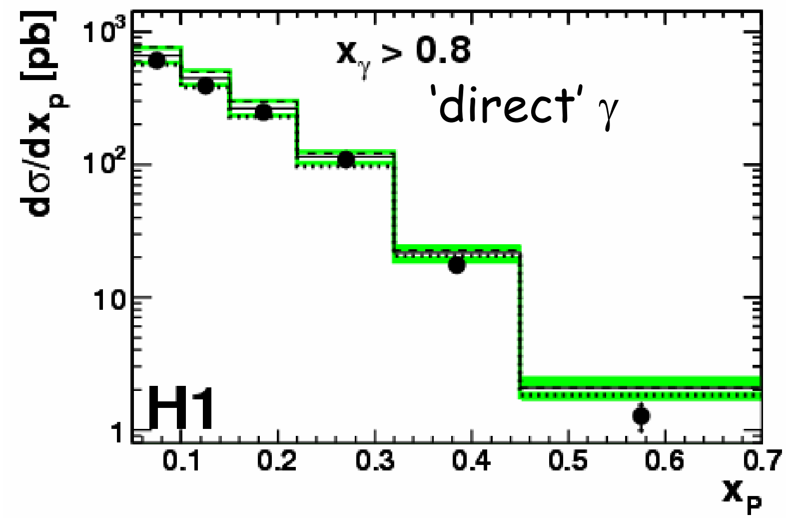
- Gluon density probed up to high momentum fraction
- Good description by NLO QCD

High E_t jets in photoproduction

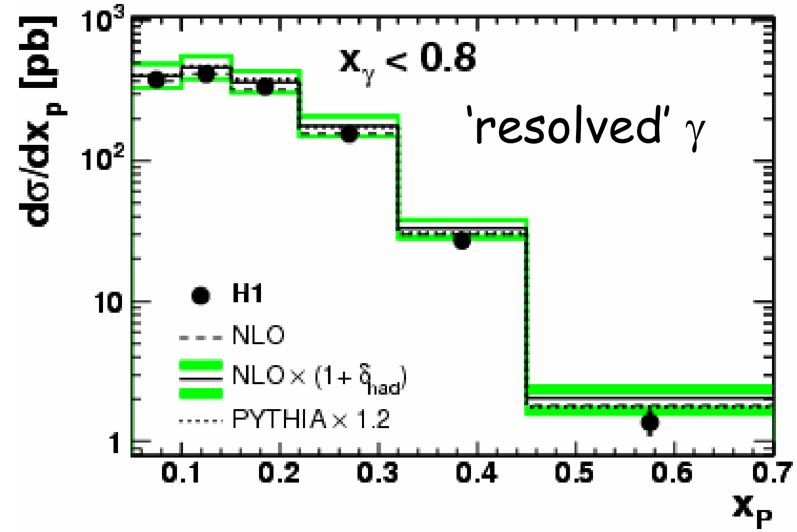
Direct and resolved photons sensitive to gluons in the proton and in the photon
→help to improve constraining parton densities







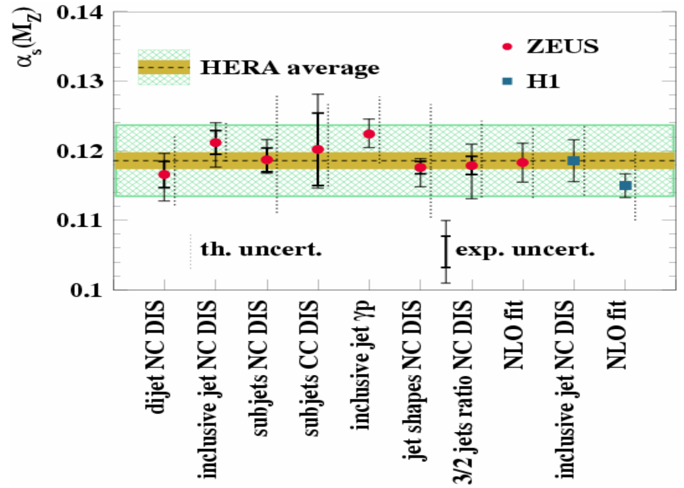
High x_γ - 'direct' photon
→ gluon in the proton
Low x_γ - 'resolved' photon
→ gluon in the photon



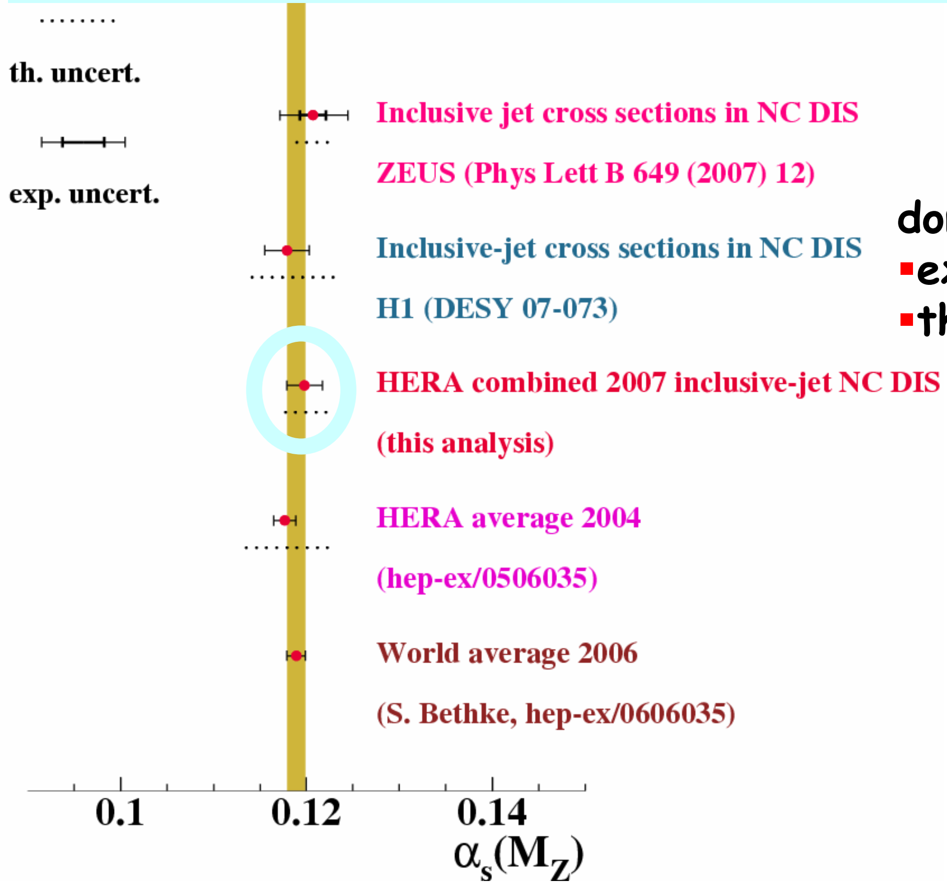
New HERA $\alpha_s(M_Z)$ combination from inclusive jet cross sections

Several precise determinations of α_s at HERA from different observables (jets, structure functions, jet substructure ..)

New precise $\alpha_s(M_Z)$ combination from the simultaneous fit to the H1 and ZEUS inclusive jet cross sections at high Q^2

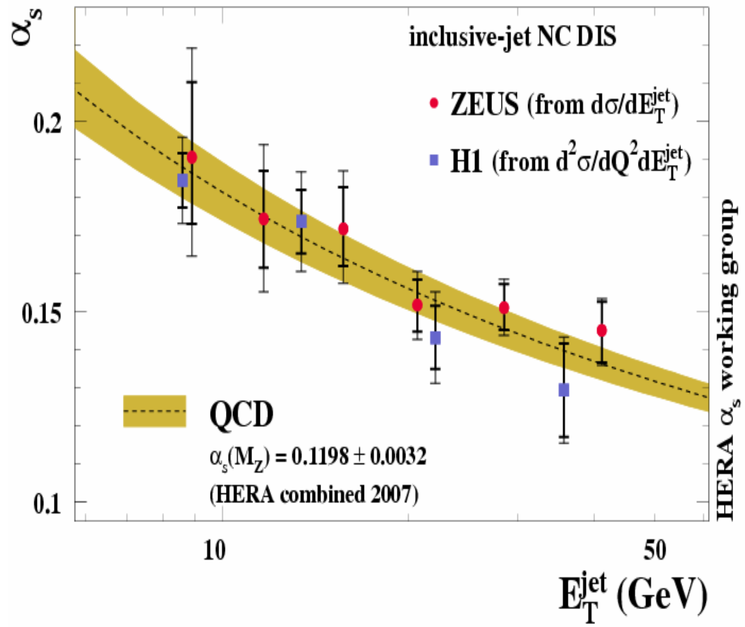


$\alpha_S(M_Z)=0.1198\pm0.0019\ (\text{exp.})\pm0.0026(\text{th.})$



dominant uncertainties:

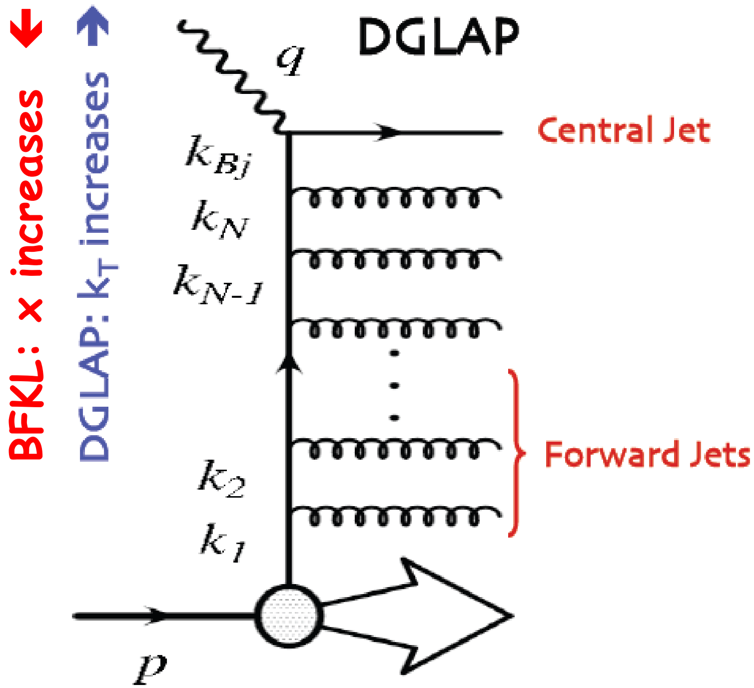
- **experimental- energy scale and model dependence**
- **theory - terms beyond NLO**

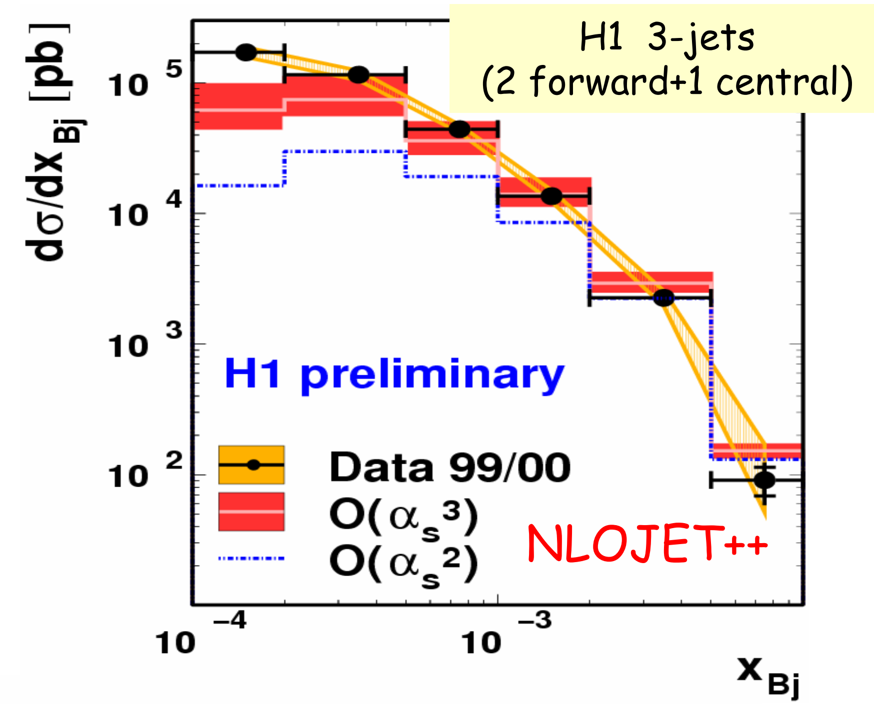


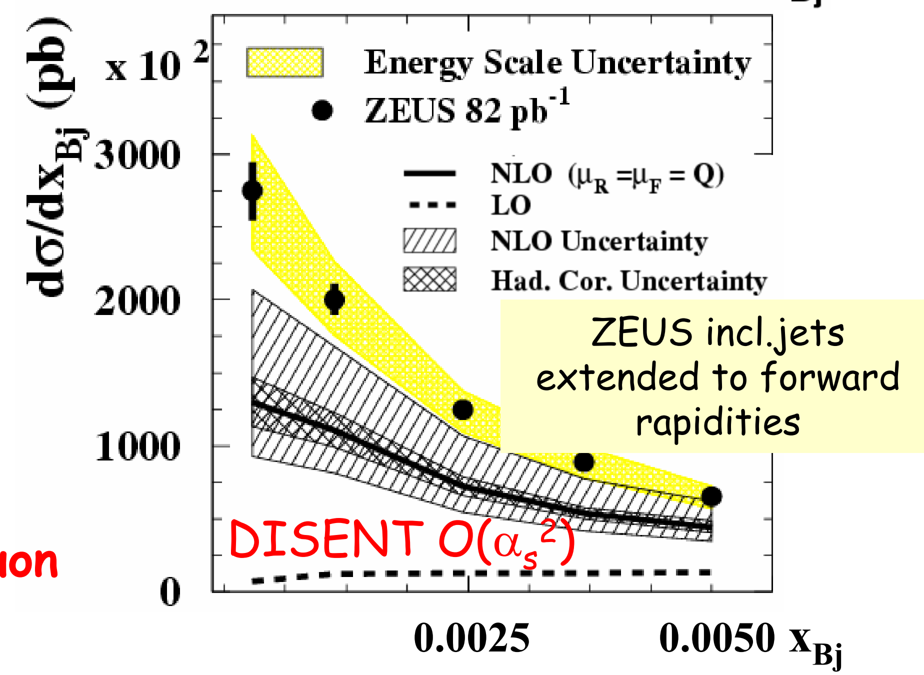
Measurements consistent with each other and with the world average

Running α_S over a large range in the scale

Parton dynamics with multijets and forward jets in DIS







DGLAP– strong k_t ordering

$k_{T,1}^2 \ll k_{T,2}^2 \ll \ldots \ll k_{T,N}^2 \ll Q^2$

➔ low probability for forward jet with $E_t \sim Q$

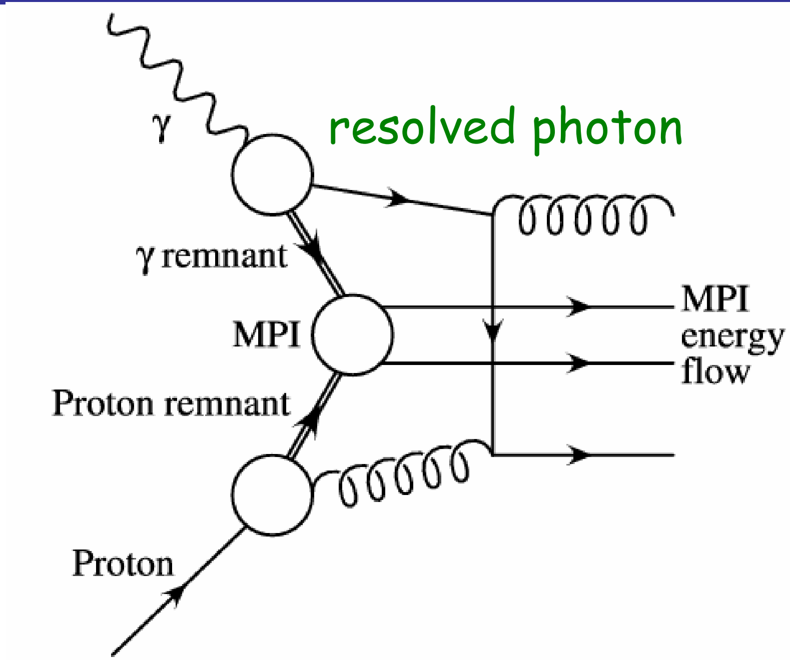
BFKL– no k_t ordering

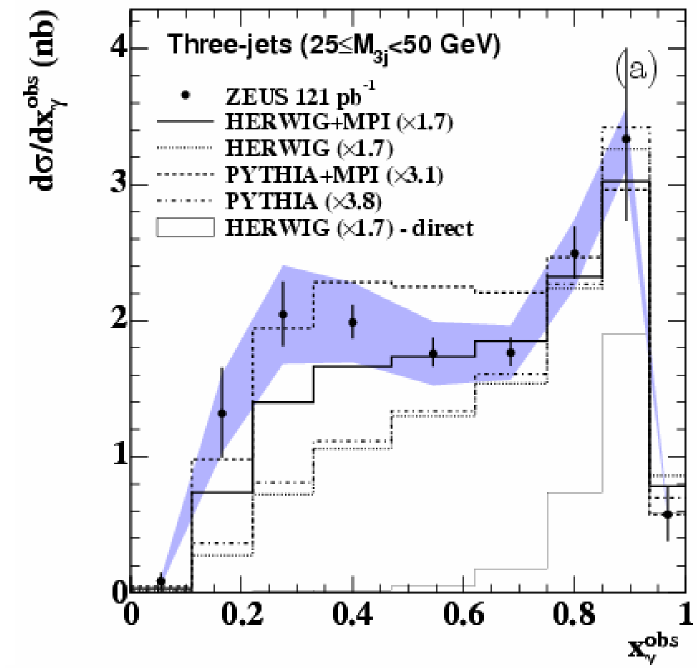
$x_1 \gg x_2 \gg \ldots\ldots x_N \gg x$

➔ expect more energetic jets in forward region

Data show a strong hint for k_t unordered gluon emission.

Multijets in photoproduction and Underlying event

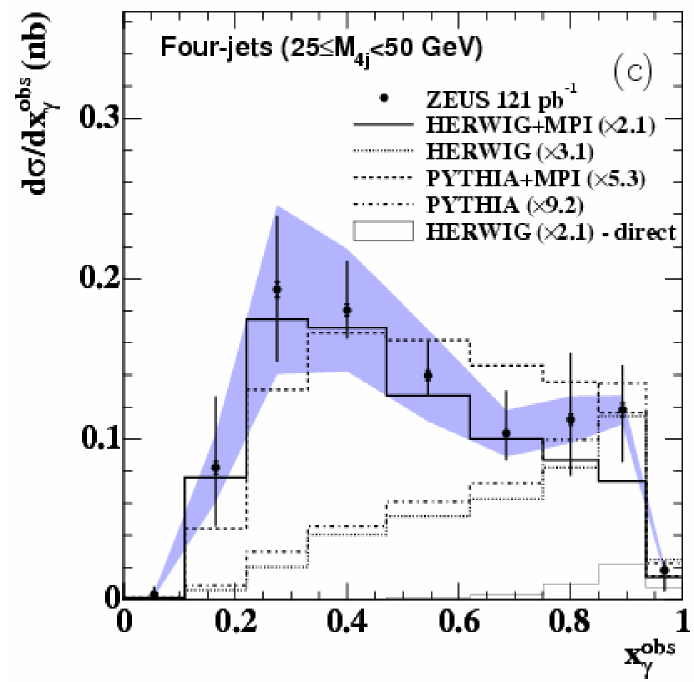




▪Multiple interactions and multi-jet final states will be abundant at LHC
→**need to understand and correct the underlying event**

▪Test pQCD at higher order of α_s
▪Test MC models (LP+PS) & Multiple Parton interactions

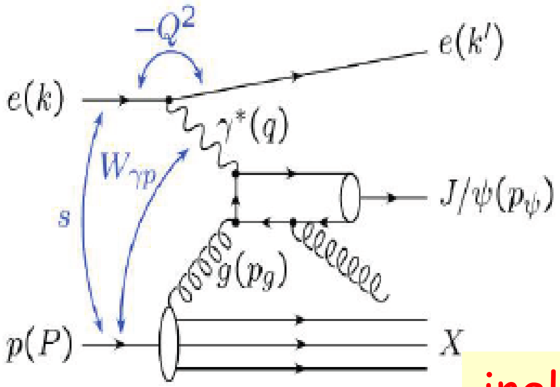
-Models without multiple interactions underestimate cross sections at low x_γ (resolved photons).
-Models with multiple interactions describe the measurements much better



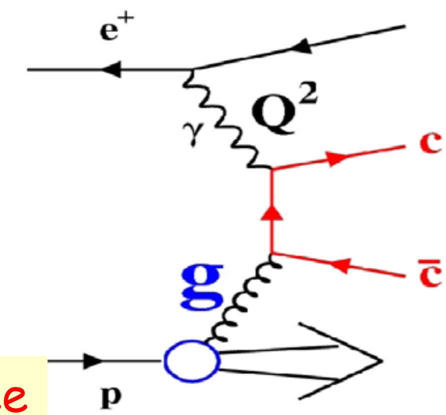
Heavy Flavours at HERA

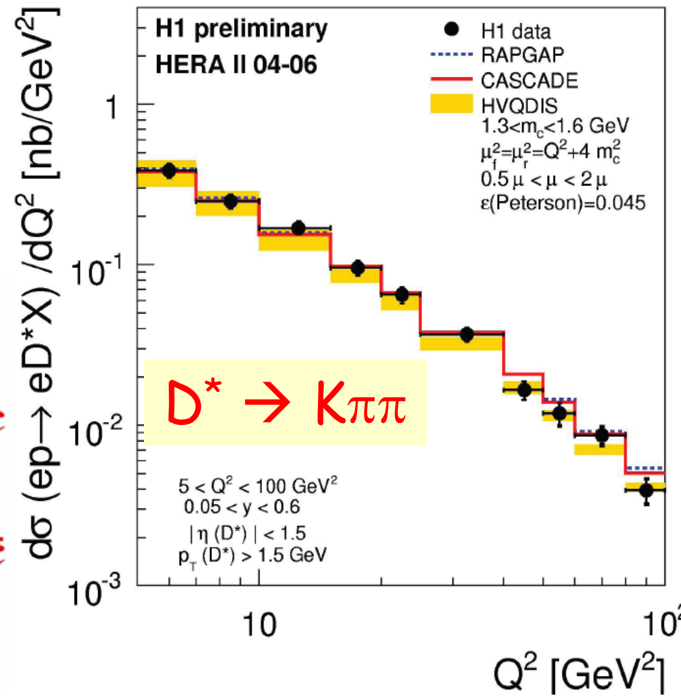
- Study of pQCD with additional hard scale (m_c, m_b)
- Provides information on HQ production mechanism
- Is sensitive to the gluon content of the proton

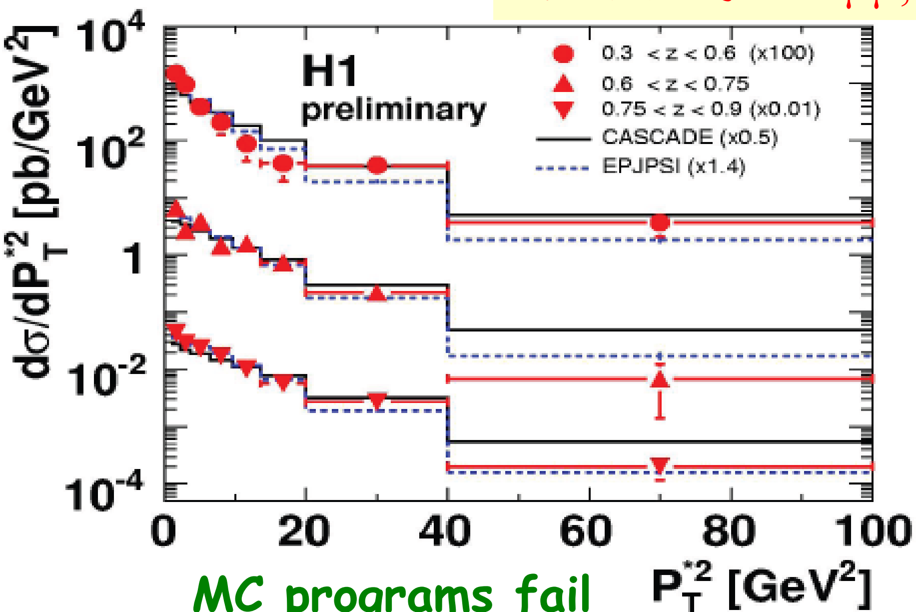
Wealth of new precision data on charm (J/Ψ, $D^{\pm}$, D^0, D^*)
Improved experimental measurement (Si trackers)



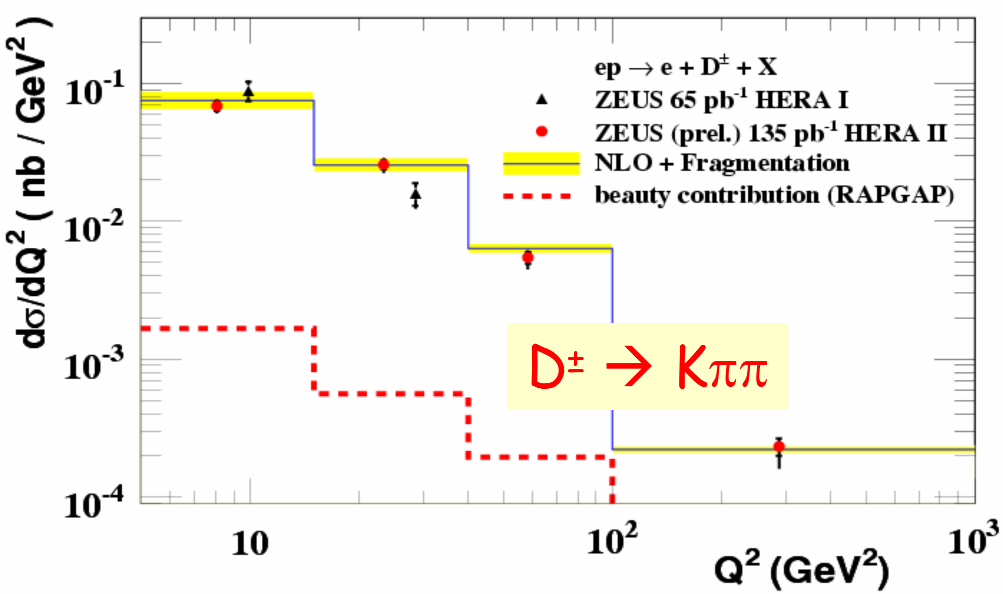
inelastic $J/\Psi \to \mu\mu, ee$





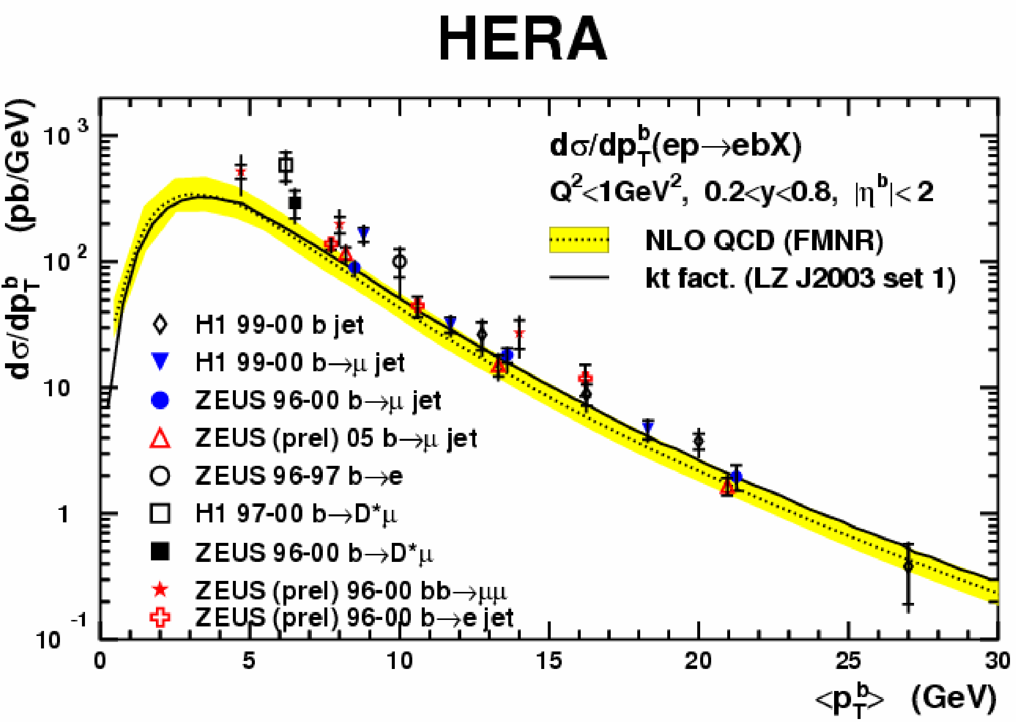


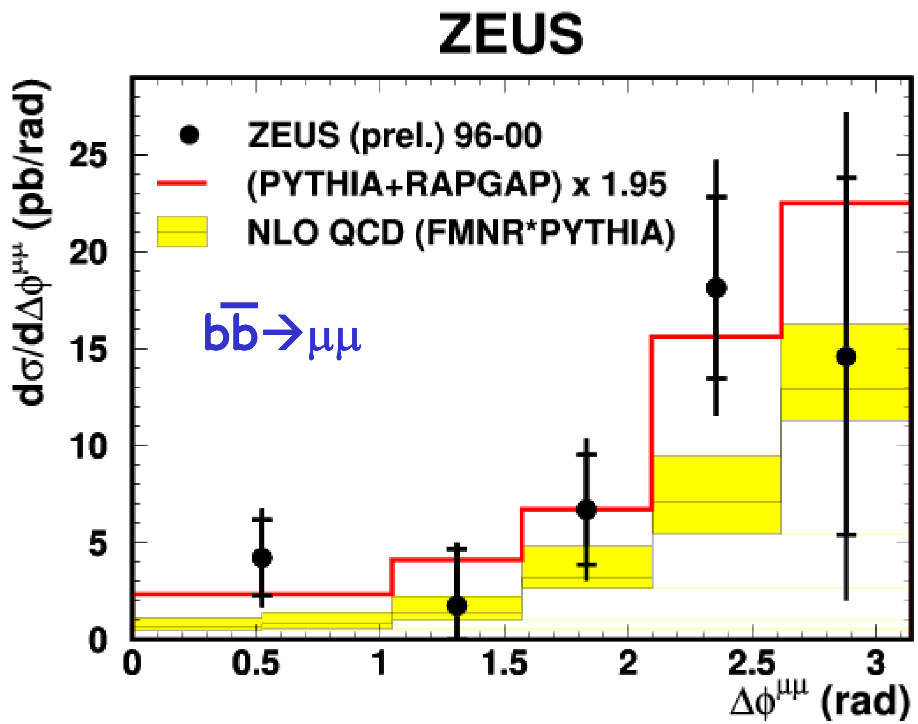
MC programs fail



NLO QCD describes well

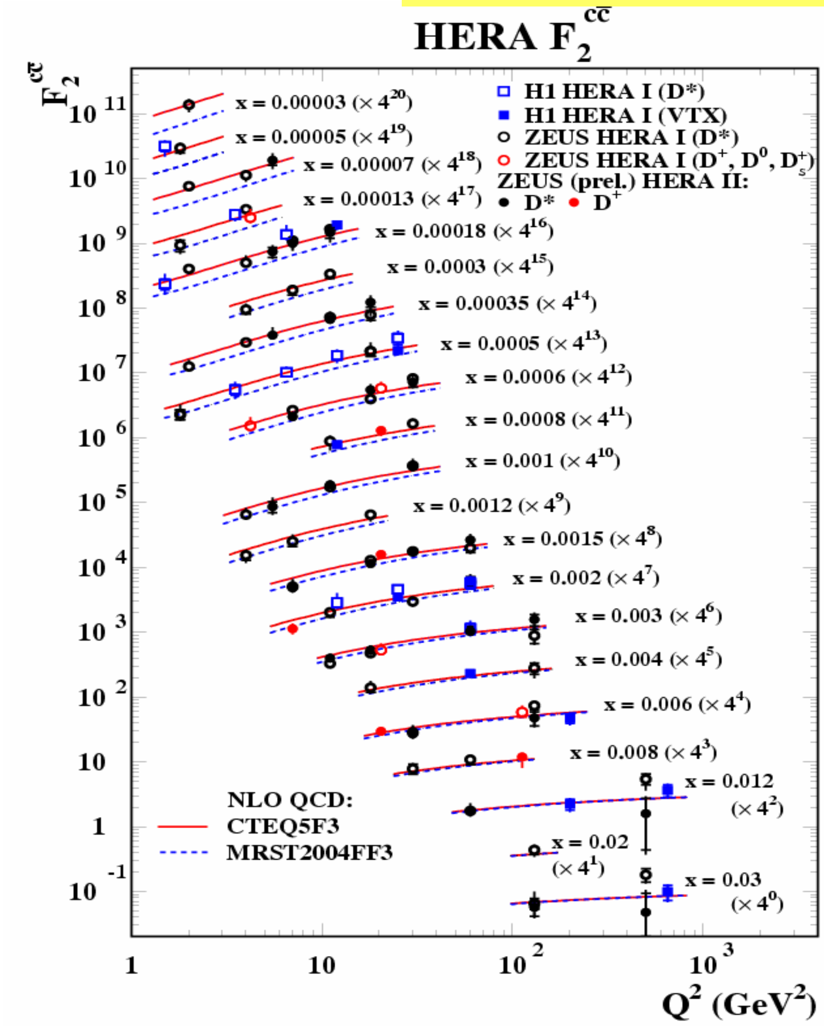
- Measure in variety of channels, e.g. $b \to c\mu(e)\nu$; $b\bar{b} \to \mu\mu$, $b \to D^{*}\mu$
- Good agreement between the different methods
- shapes well described by NLO QCD

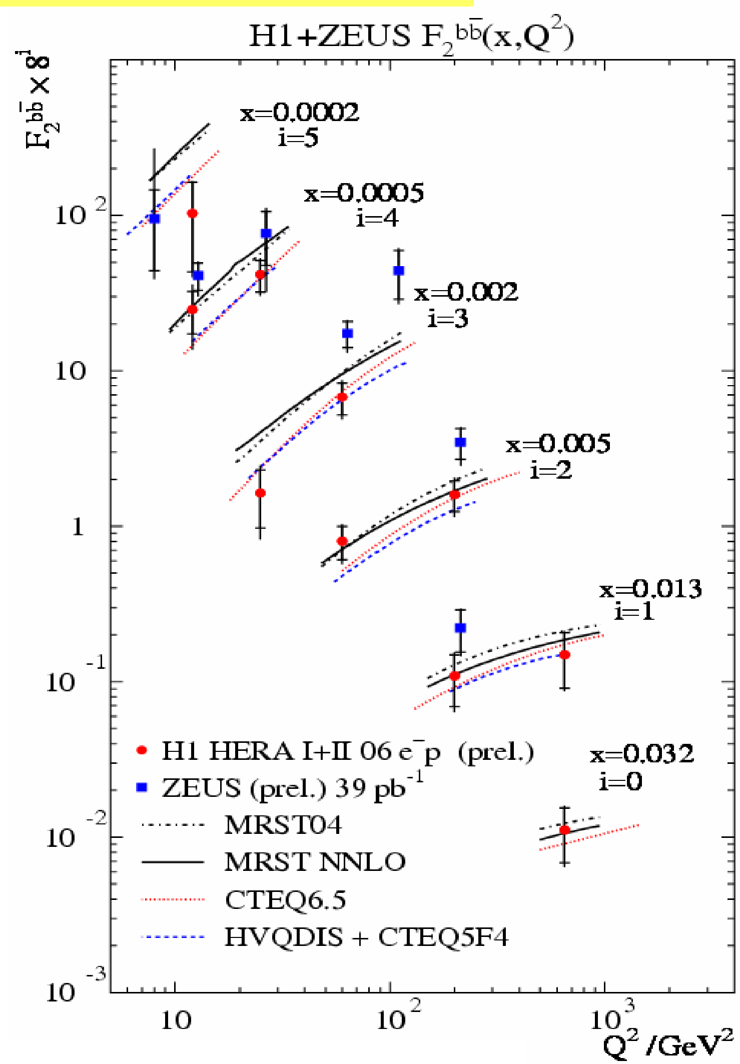




Charm and Beauty contribution to proton F_2

$$\sigma^{c\bar{c},b\bar{b}} \sim Y_+ F_2^{c\bar{c},b\bar{b}}(x,Q^2) - y^2 F_L^{c\bar{c},b\bar{b}}(x,Q^2)$$



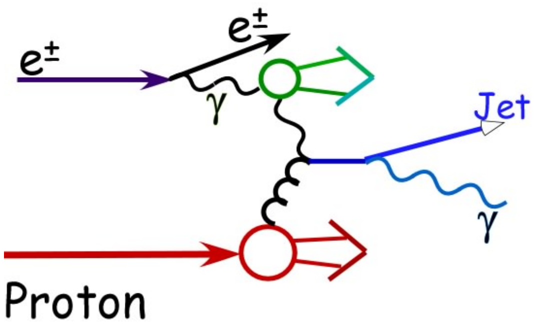


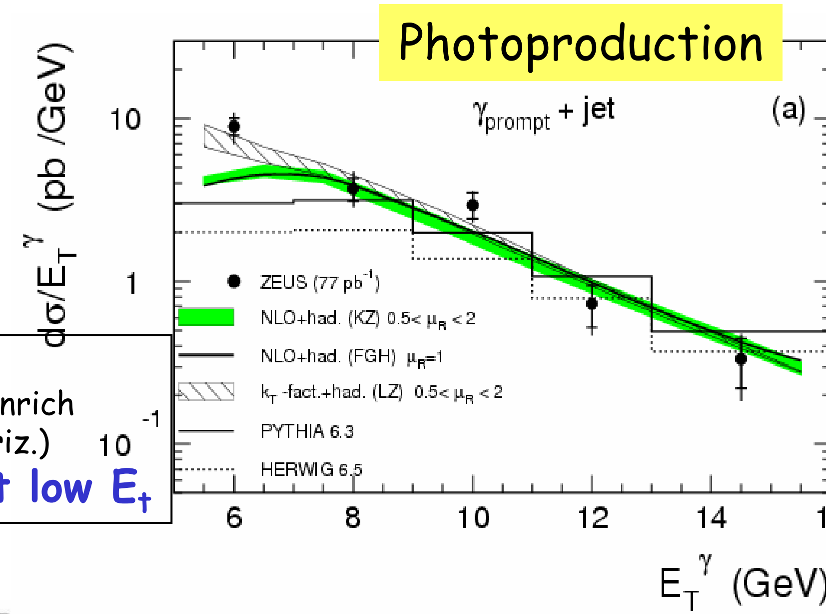
- **first measurement of $F_2^{b\bar{b}}$**
- scaling violation in charm and beauty → gluons !
- $F_2^{c\bar{c},b\bar{b}}$ data can constrain the proton gluon density at small x
- large spread in theoretical predictions

Prompt Photons at HERA

ep→ γ (prompt) + jet +X

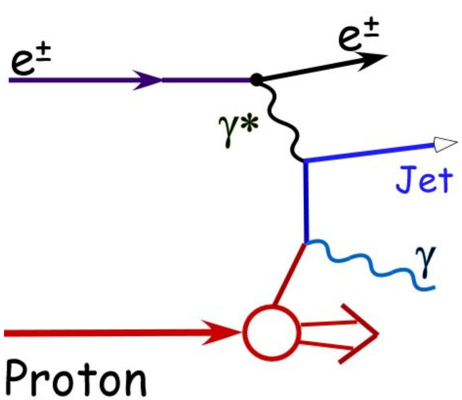
- Clean probe of QCD
- Constraints on proton and photon PDFs
- Understanding of photon rates relevant for searches at LHC

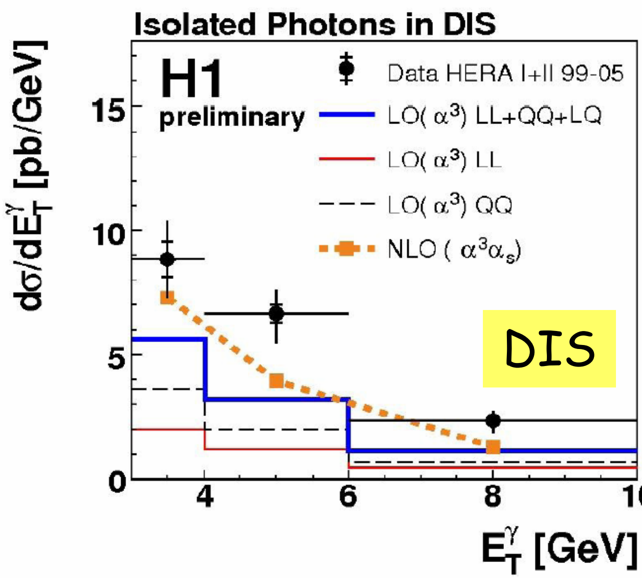


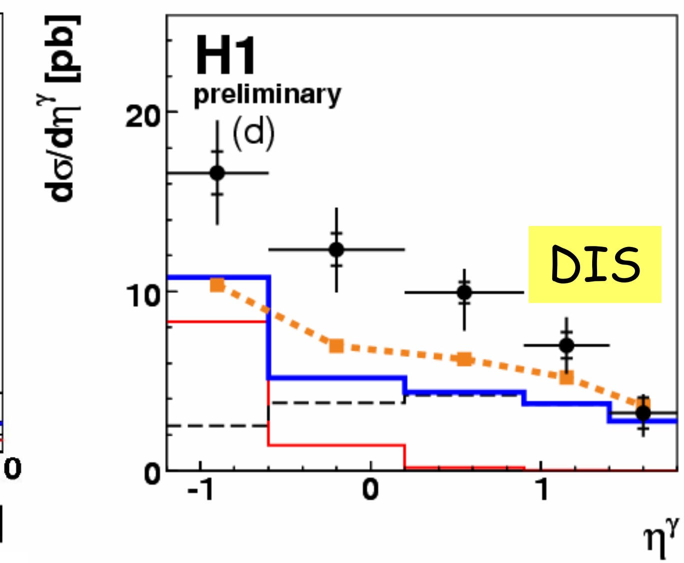


NLO-KZ M.Krawczyk,A.Zembrzuski
NLO-FGH-M.Fontanaz,J.P.Guillet,G.Heinrich
LZ- A.Lipatov,N.Zotov (kt factoriz.)

Theory predictions differ at low E_t



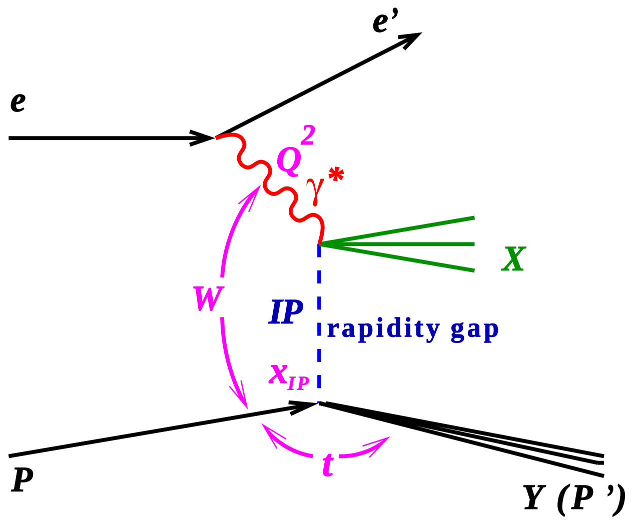


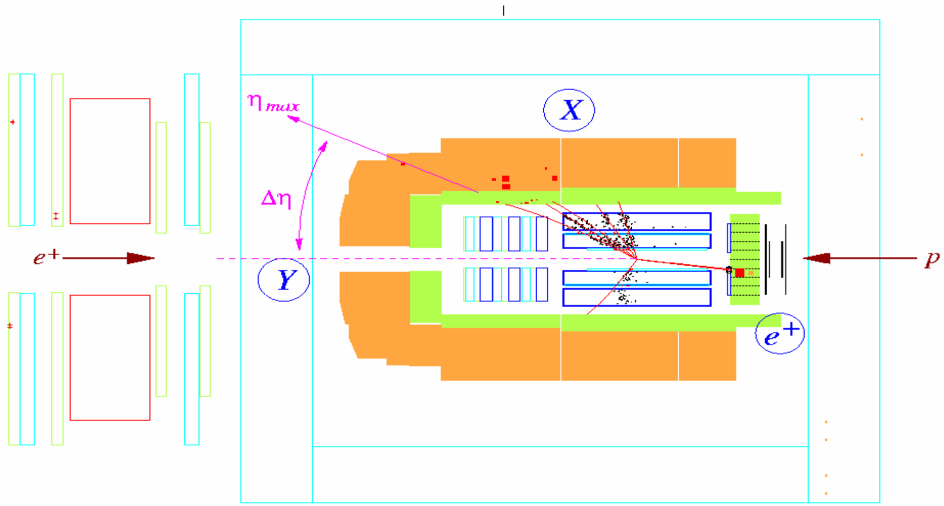


LO $\alpha^3\alpha_s$ calculation (Gehrmann et al.)
NLO $\alpha^3\alpha_s$ calculation (G.Kramer, H.Spesberger)

- In DIS radiation from the quark dominates
- LO calculation underestimates the measurements
- NLO QCD does not describe well, particularly at low E_t^γ

~10% of DIS events at HERA are diffractive





- proton survives the collision intact or dissociates to low mass state, $M_Y \sim O(m_p)$
- No activity in forward direction (rapidity gap)
- small *t* (four-momentum transfer) and x_{IP} (fraction of proton momentum), $M_X \ll W$

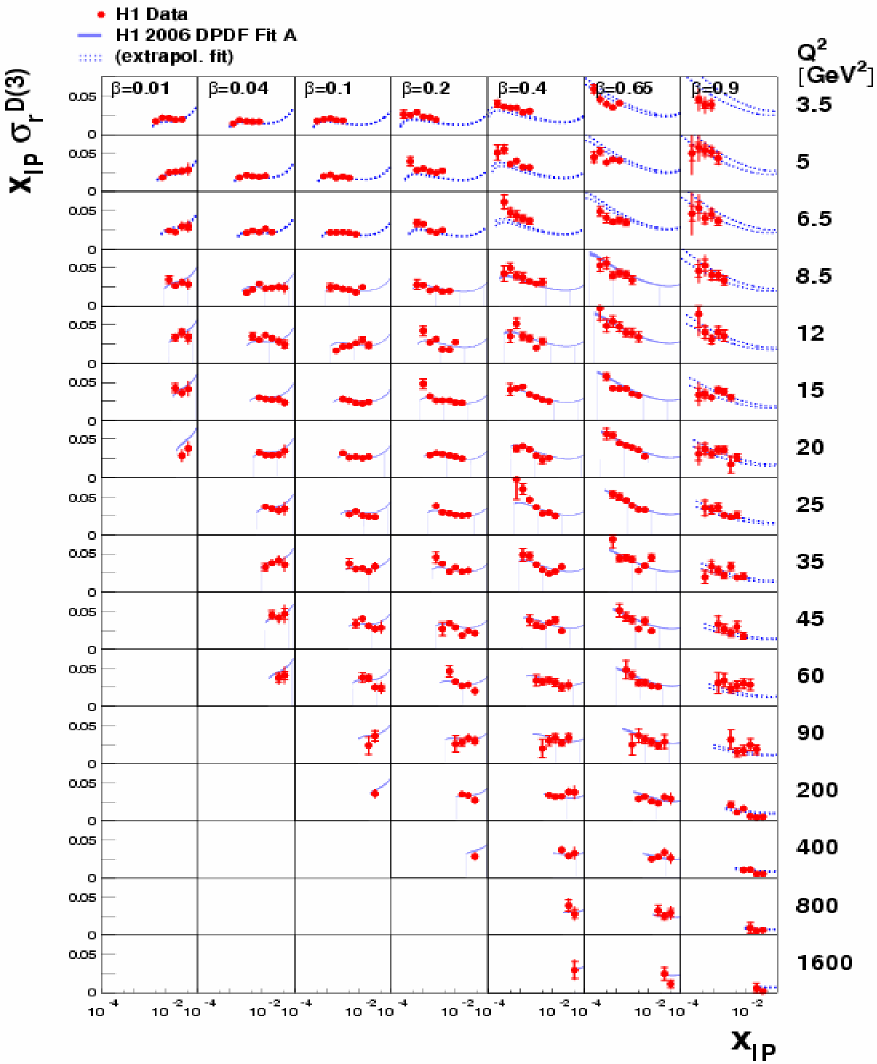
If no hard scale – Q^2, $|t| \approx 0$: similar to soft hadron-hadron interactions
Regge: diffraction is *exchange of Pomeron*

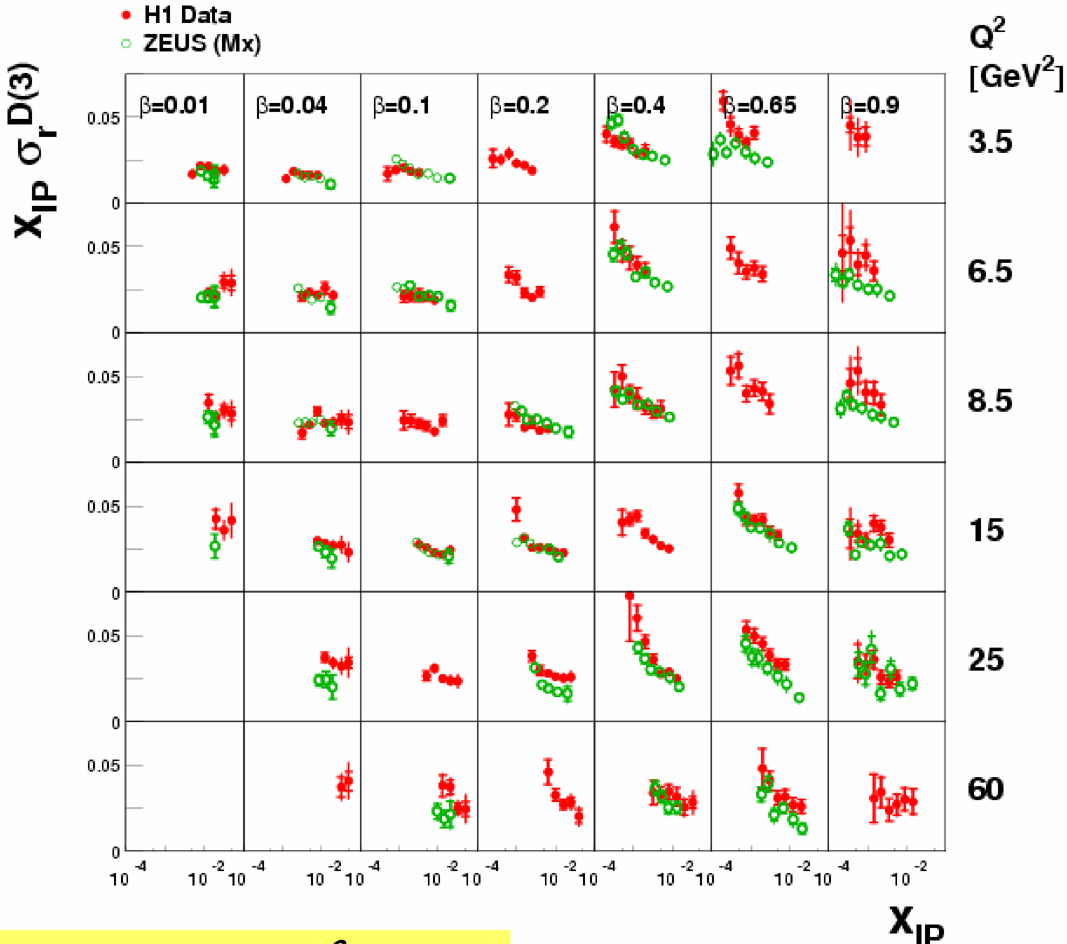
If hard scale (large Q^2, $|t|$, p_T^{jet}, m_Q): study diffractive phenomena in terms of QCD
probe the structure of exchanged object

HERA data allow to study transition from soft to hard regime and to probe partonic content of diffractive exchange.

Diffractive reduced cross section $\sigma_r^{D(3)}$ - x_{IP}, β and Q^2 dependence

$(x_{IP} \approx 1 - E_Y/E_p\ ,\ \beta = x/x_{IP})$

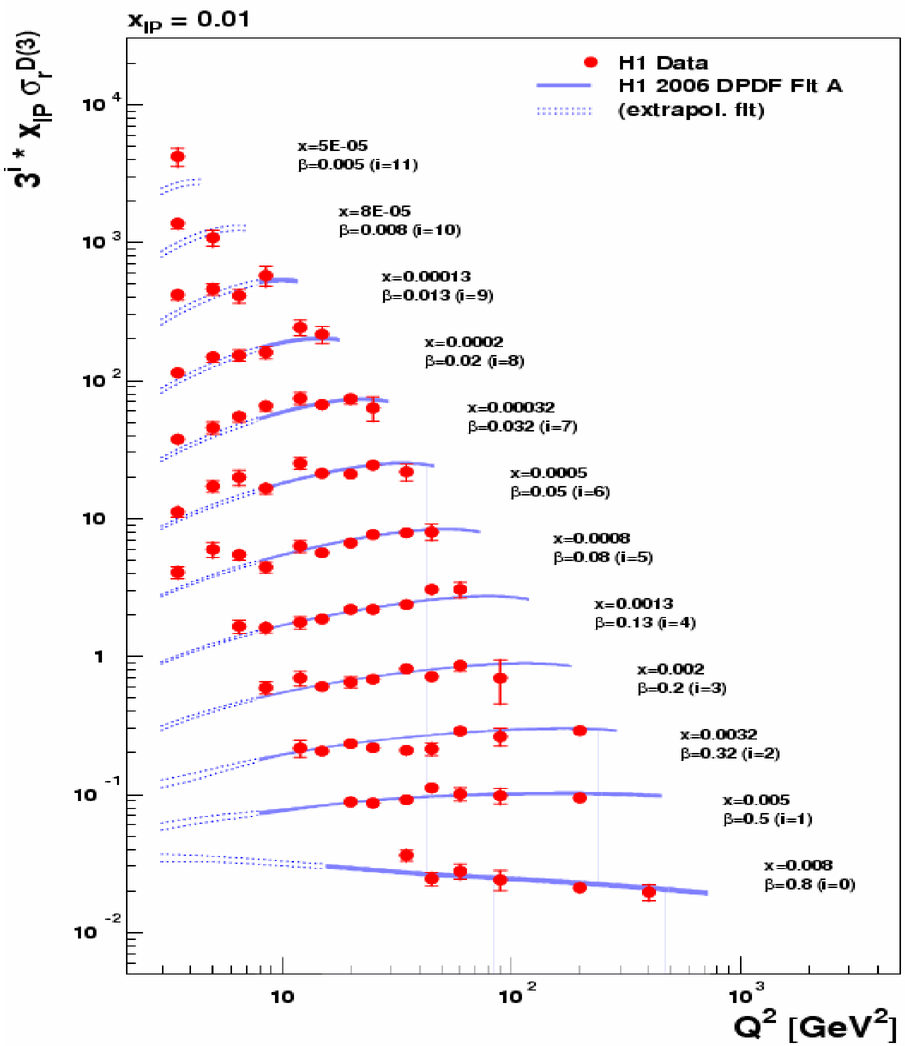


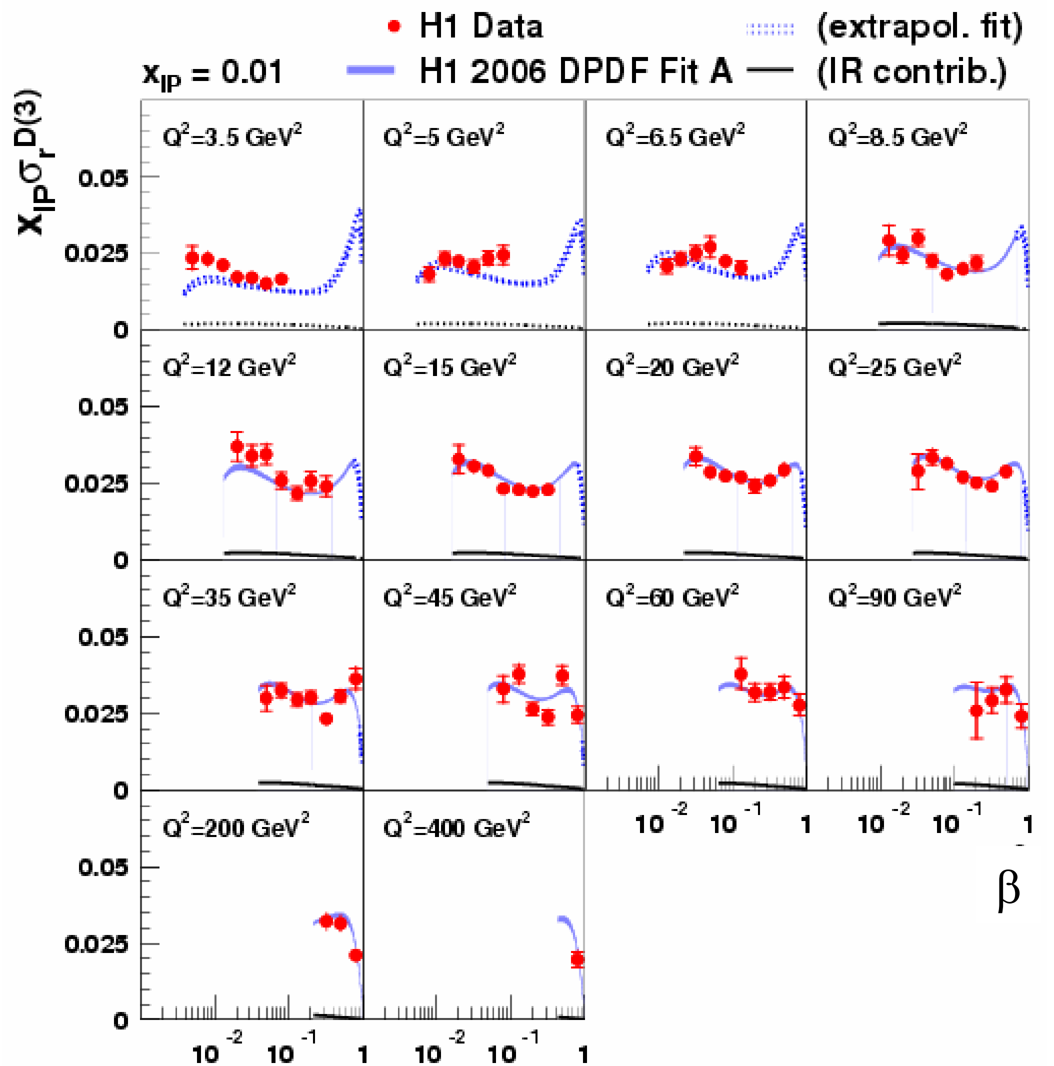


$$\sigma_R^D = F_2^D - \frac{y^2}{1+(1-y)^2} F_L^D$$

- large kinematic region covered $1.5 < Q^2 < 1600$ GeV^2 ,large statistical precision
- fair agreement between two experiments and different selection methods
- at closer look there is a difference between the two measurements at high β

β and Q^2 dependences of diffractive structure function

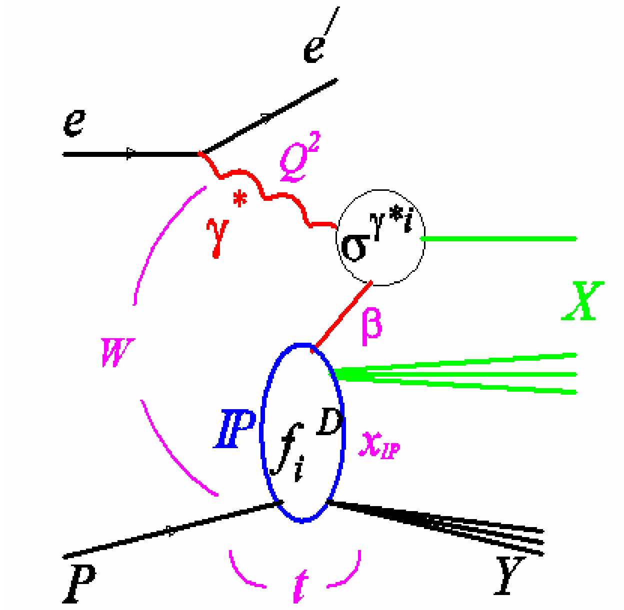




- positive scaling violation (rise with Q^2) up to large β → different from F_2^p
- β-dependence relatively flat

➔ large gluon component

Diffractive PDFs



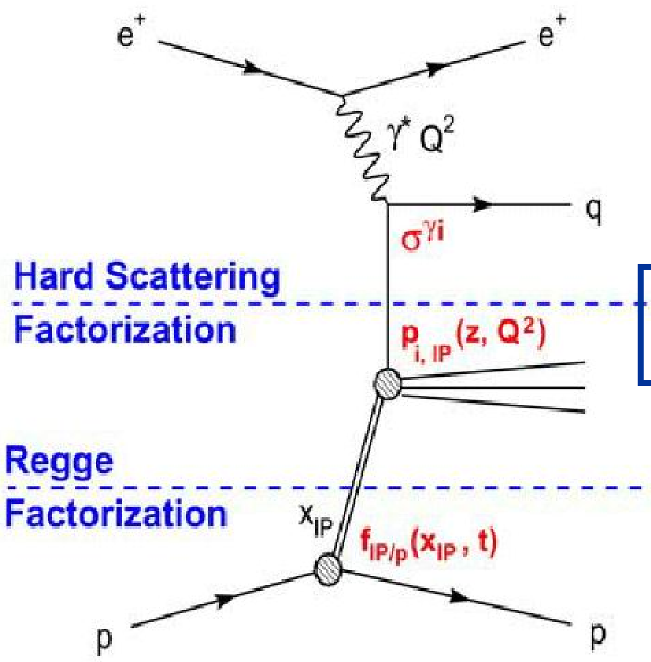
QCD factorization in diffractive DIS (Collins 1997)

$$\sigma^D\left(\gamma^* p \to Xp\right) \propto \sum_i f_{i,p}^D(x_{IP}, t, x, Q^2) \otimes \sigma^{\gamma^*, i}\left(x, Q^2\right)$$

$f_{i,IP}^D$ -diffractive parton distribution function – conditional proton parton probability distributions with final state proton at fixed x_{IP}, t

$\sigma^{\gamma^*, i}$ -universal hard scattering cross section

---



Regge factorization (assumption- no firm basis in QCD):

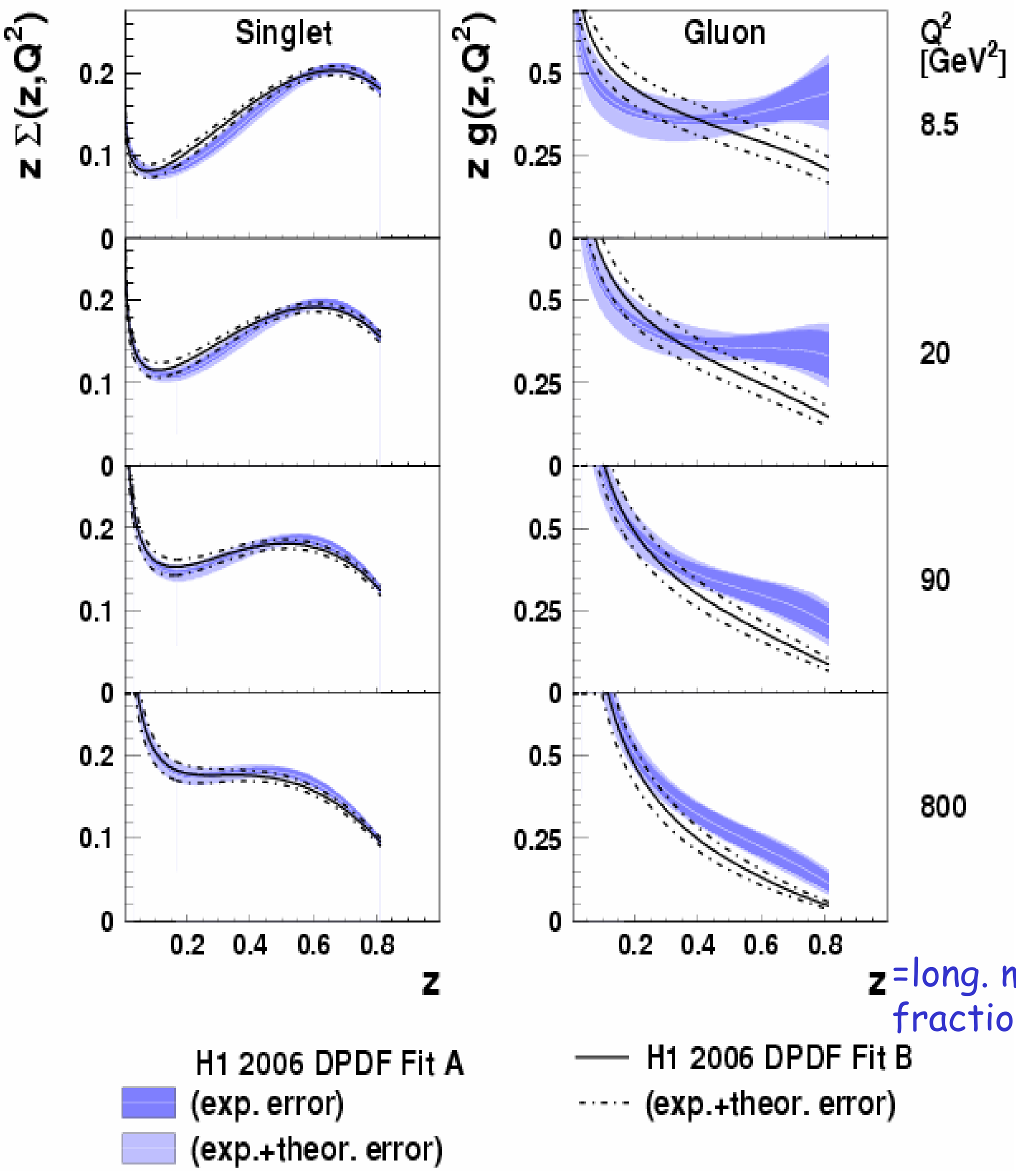
PDF = Pomeron-flux × Pomeron-PDF

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

where **Pomeron flux**

$$f_{IP/p}(x_{IP}, t) = \frac{e^{Bt}}{x_{IP}^{2\alpha(t)-1}}, \alpha(t) = \alpha(0) + \alpha'(t)$$

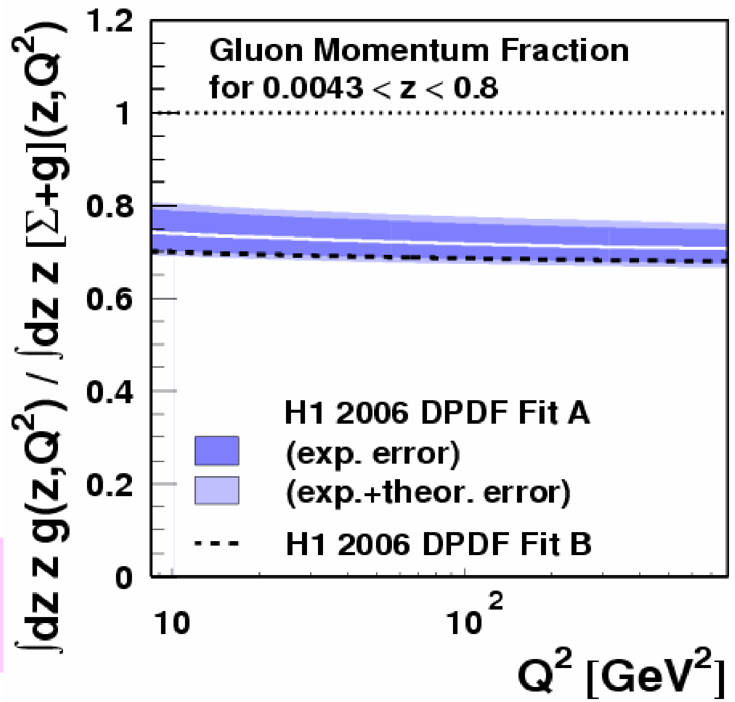
Diffractive PDFs: H1 NLO QCD fit



z =long. momentum fraction of exchange

- assume Regge factorization, apply NLO QCD DGLAP analysis technique to Q^2 and β dependencies of F_2^D
- quark density from F_2^D, gluon density from scaling violation

- **H1 DPDFs FitA, FitB** (different starting parameterizations)
- Well constrained singlet
  Weakly constrained gluons (at high β)
- low *z* behavior similar to F_2
- hard gluon distribution extended to high *z*



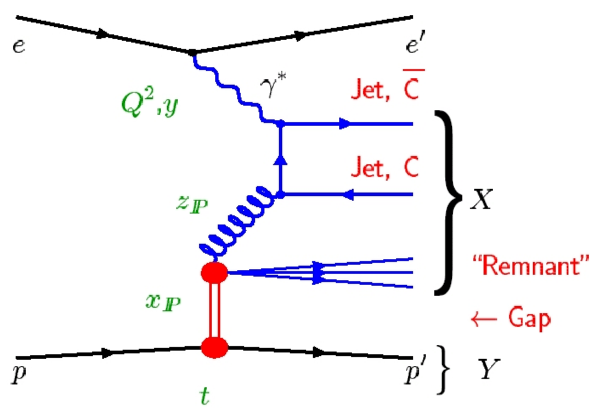
gluon carries ~70% of diffractive exchange

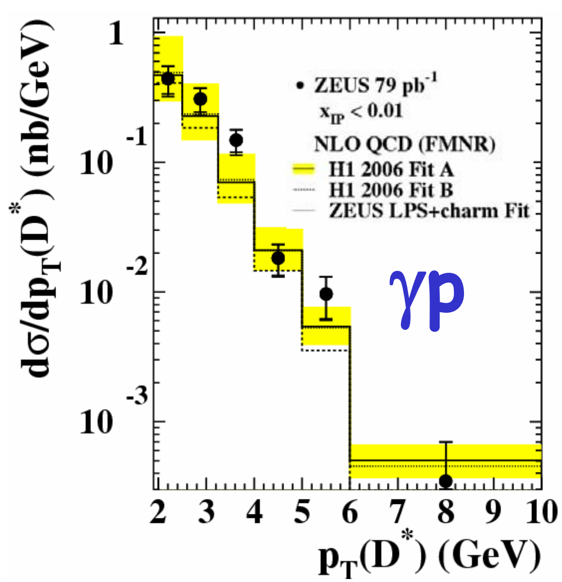
Check factorization with charm and jets in diffractive γp and DIS

- cross sections calculable in pQCD
- production mechanisms directly sensitive to the gluon content of colour singlet exchange

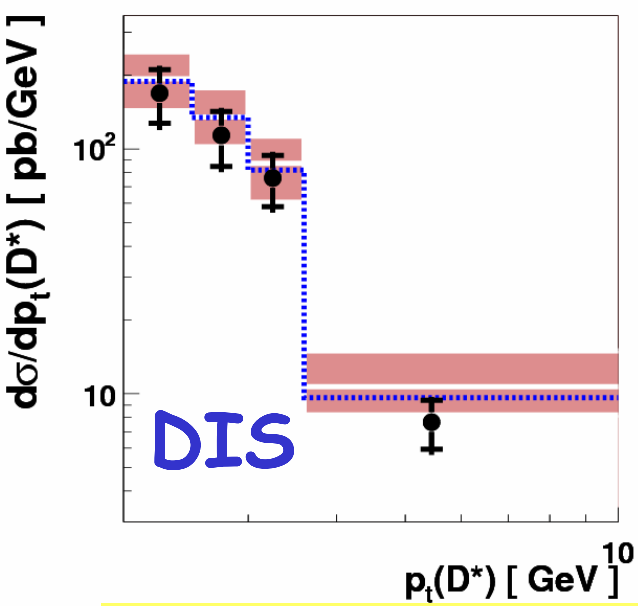
→ can be compared to theoretical models and approaches

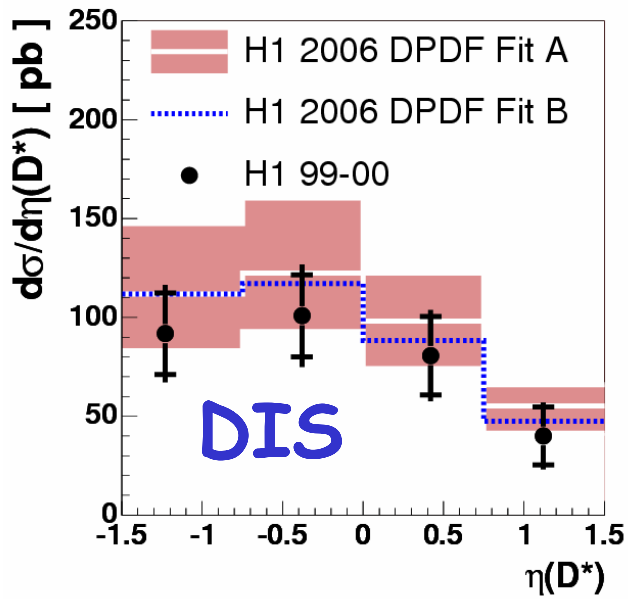
→ constrain the gluon density

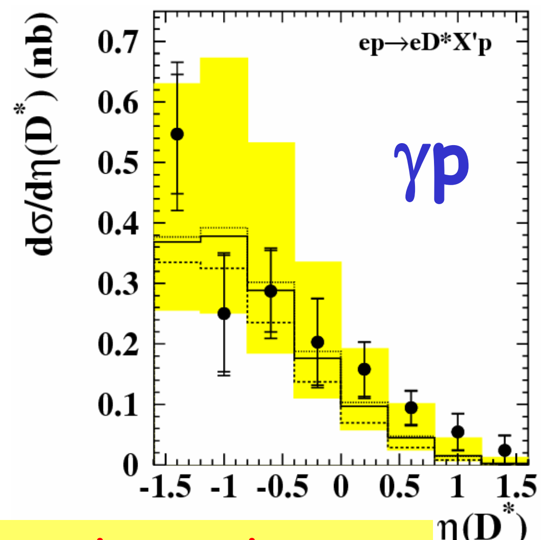




$D^* \rightarrow K\pi\pi_s$







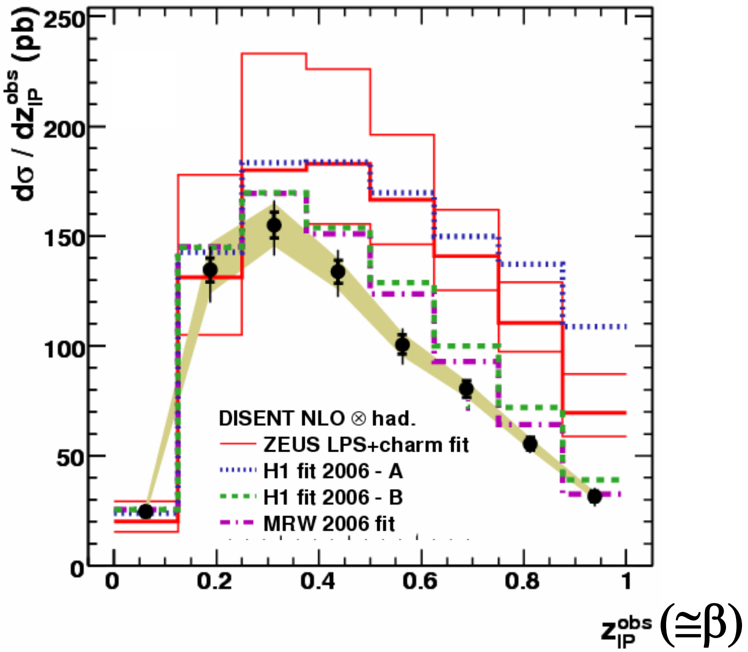
NLO calculations (HVQDIS for DIS and FMNR for γp) provide good description of diffractive charm data → support QCD factorization

DPDFs: compare to diffractive dijets in DIS

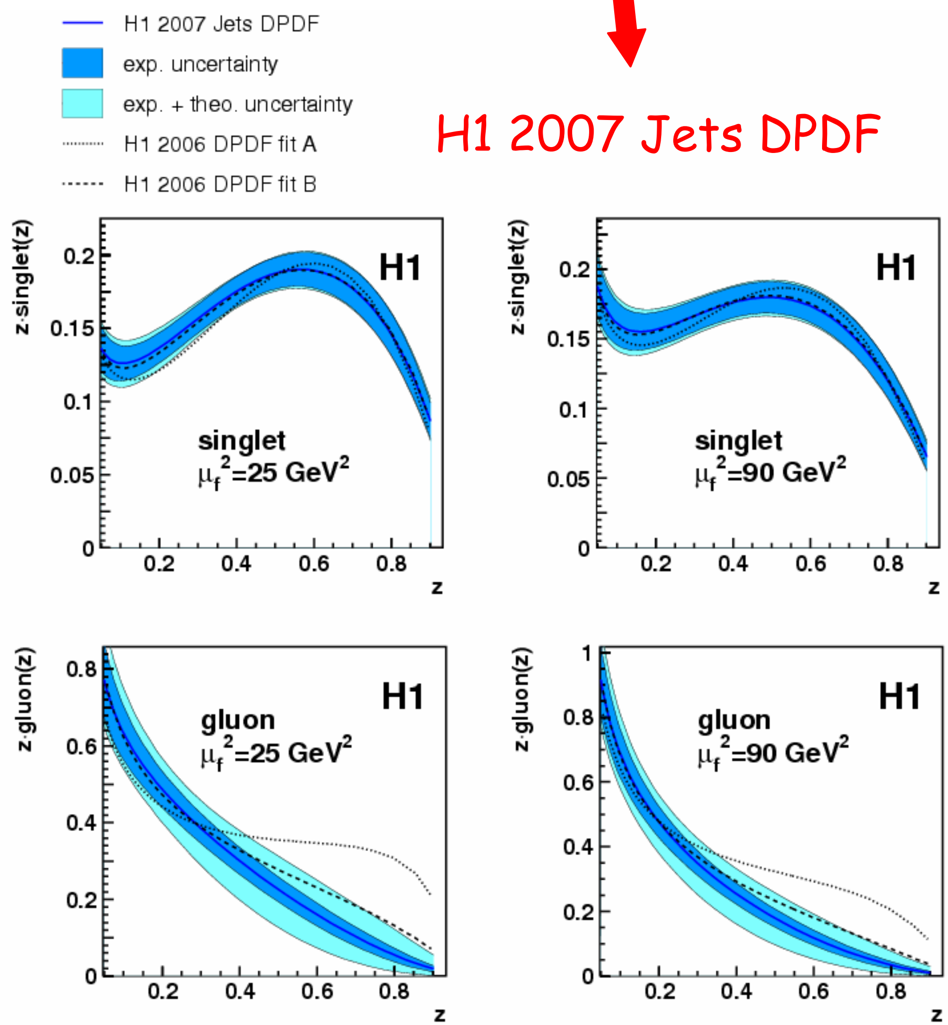
- At low β (<0.3) fit A and fit B similar
- At high β diffractive dijets clearly prefer fit B (less gluons)

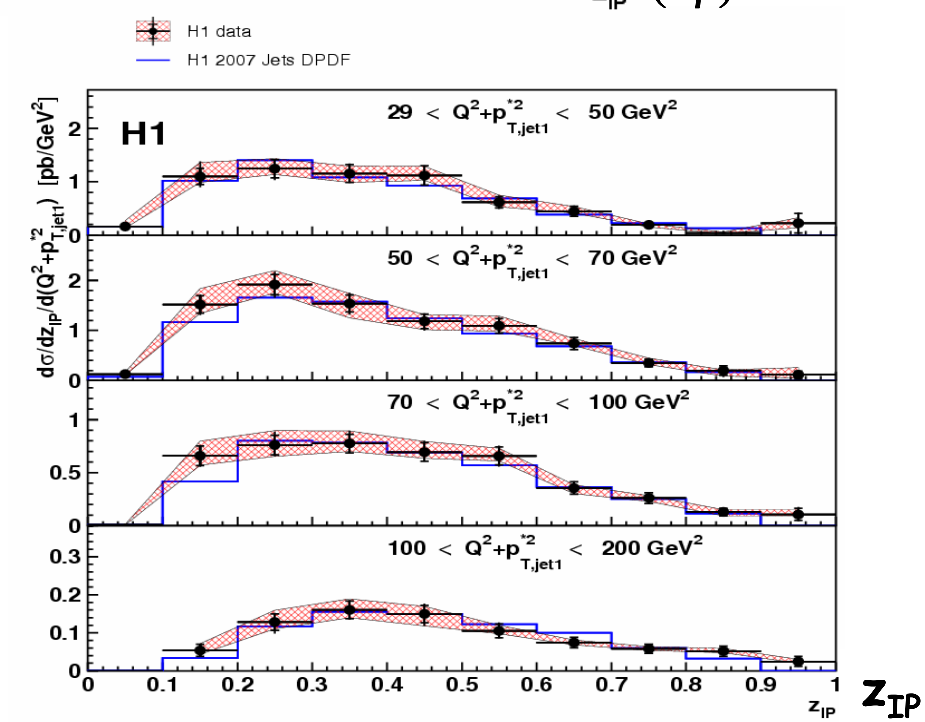
➔ improve g(β,Q²) at high β using dijet data

➔ consistent with QCD factorization



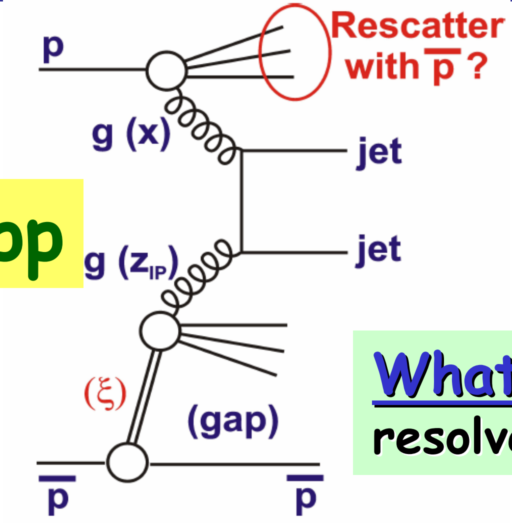
H1 2007 Jets DPDF





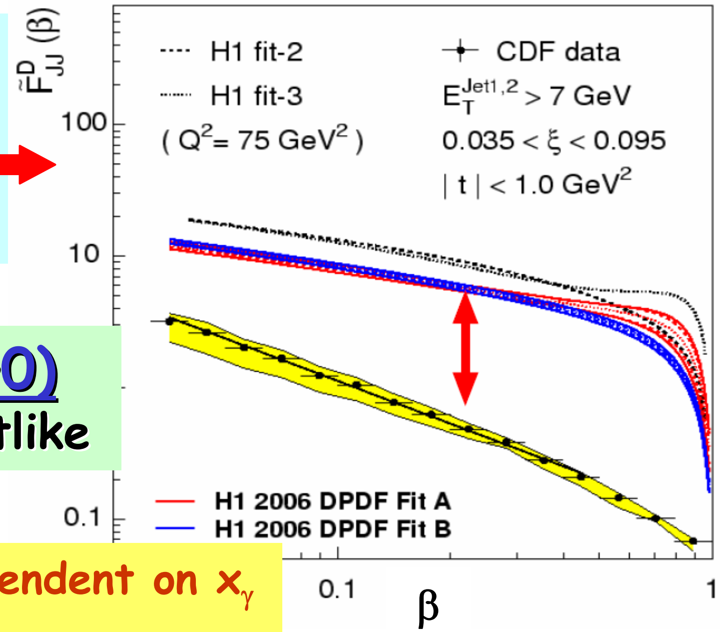
Diffractive jet photoproduction - does QCD factorization hold ?

pp



Factorization not expected to hold in pp scattering

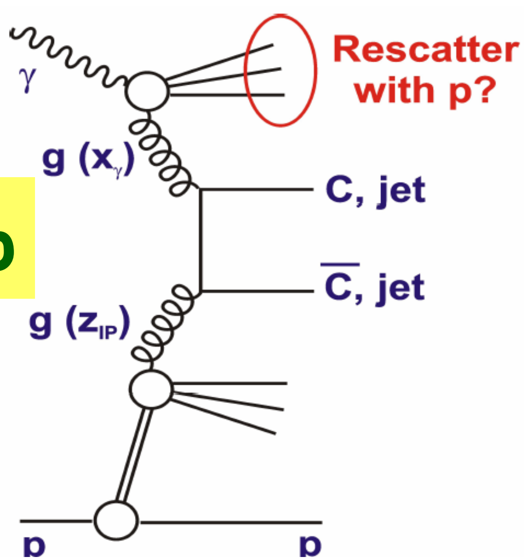
'gap survival probability' ~0.1

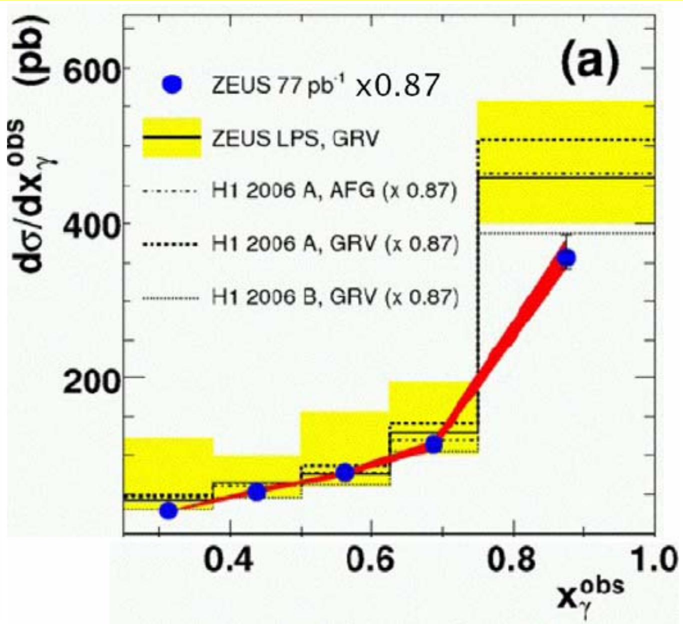


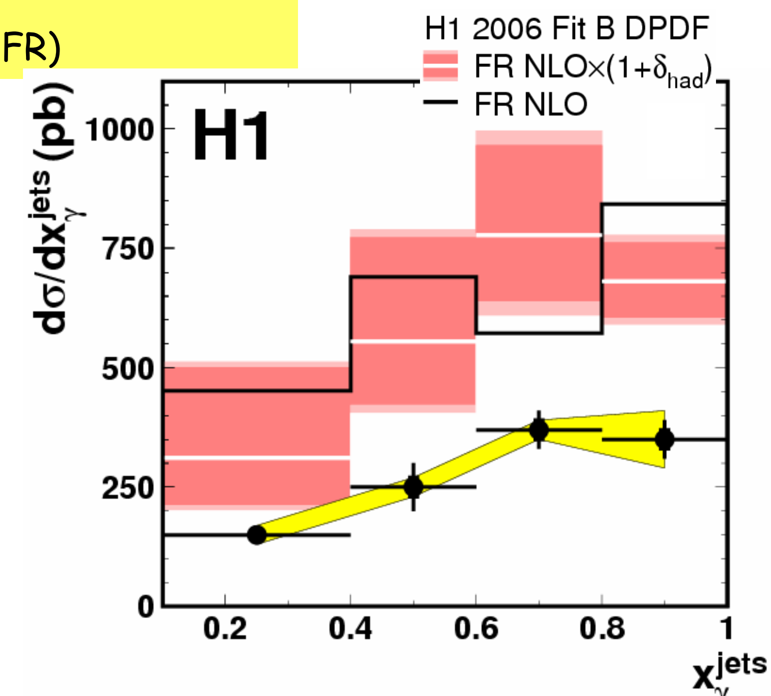
What about γ–p scattering? (Q^2~0)
resolved γ- like hadron, direct γ- pointlike

-H1-data vs NLO (Frixione,Ridolfi) → suppression ~0.5, independent on x_γ
-ZEUS-data vs NLO (Klasen,Kramer)→ suppression ~0.8
difference between H1/ZEUS results may be due to differences in jet cuts (H1- E_t>5 GeV, ZEUS- E_t>7.5 GeV) or in NLO calculations (KK vs FR)

γp

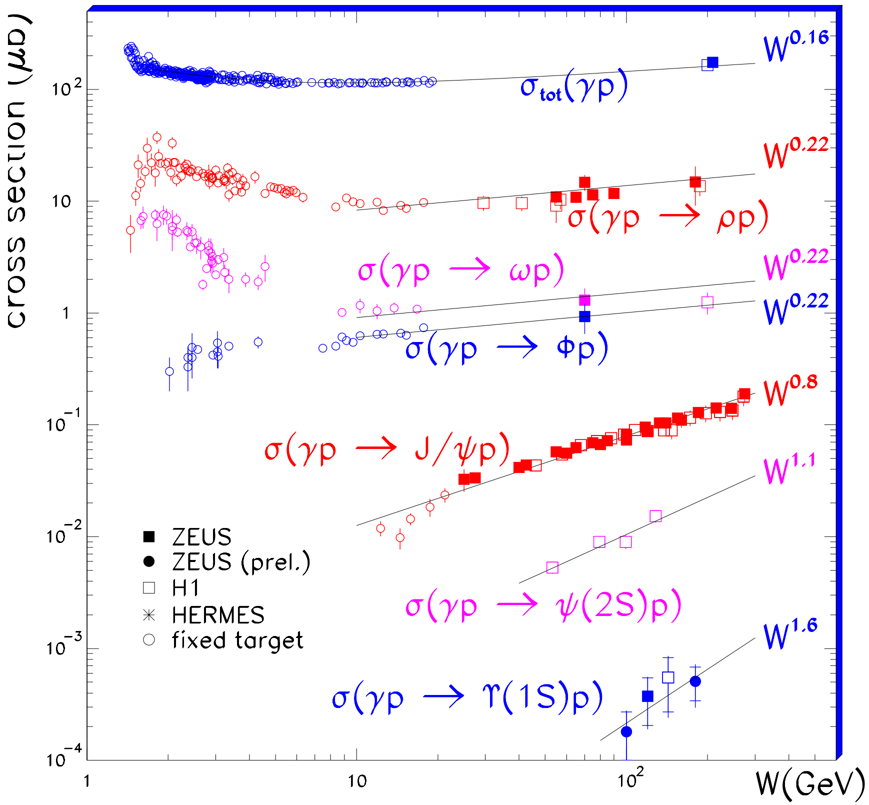


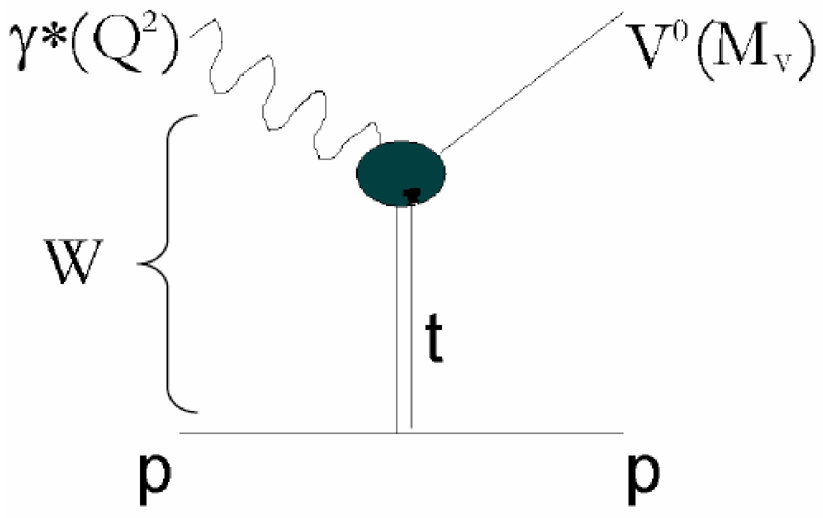


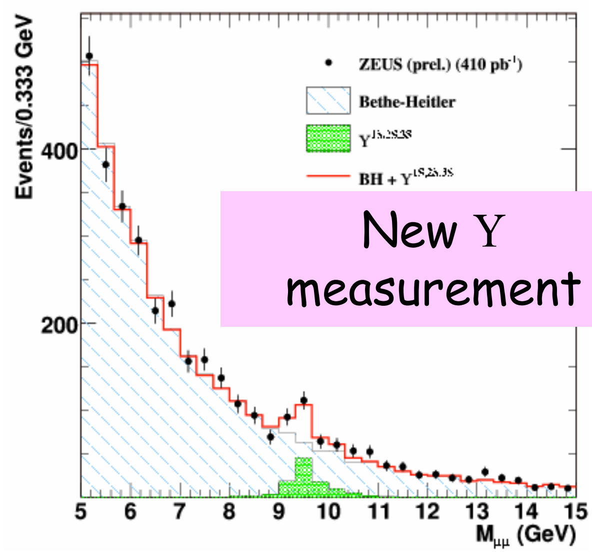


Elastic Vector Meson production

$\gamma^* p \rightarrow V^0 + p$ ($V^0 = \rho, \phi, J/\Psi, \Upsilon$)







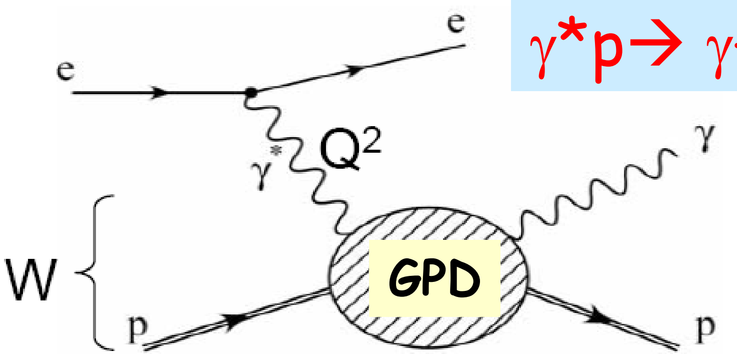
New Υ measurement

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

W is sensitive to gluons
→ δ increases from 'soft' (~0.2) to 'hard' (~0.8)

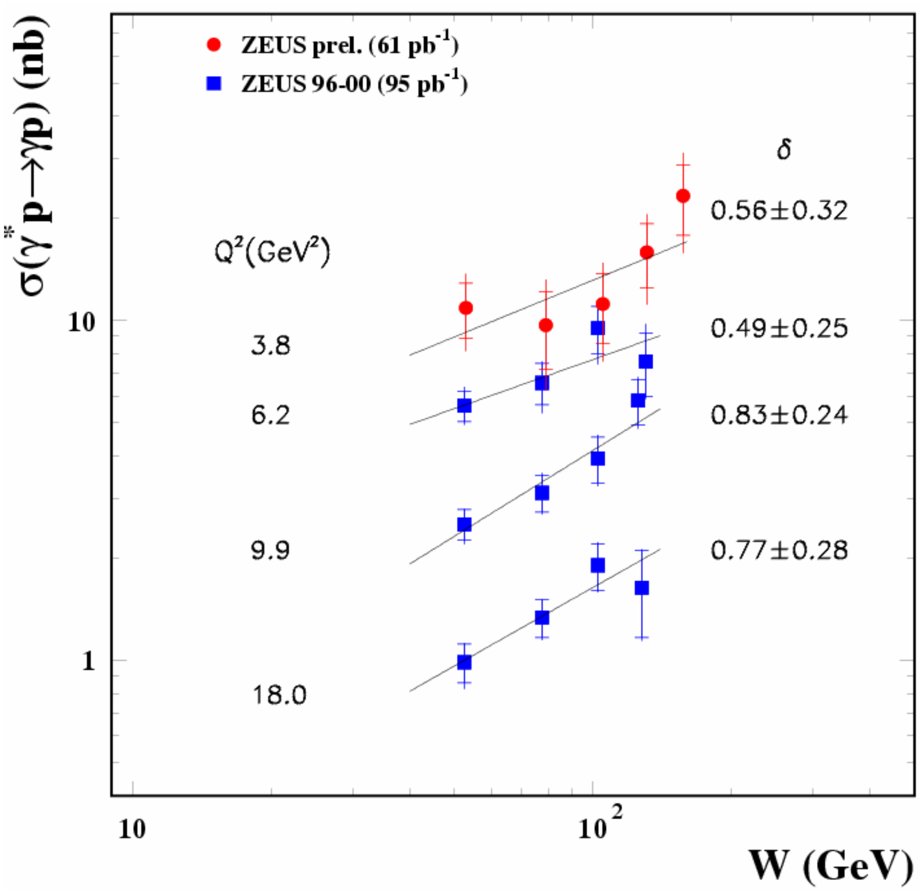
VM mass sets hard scale of interaction
Process becomes hard (steeper W dependence) as scale becomes larger

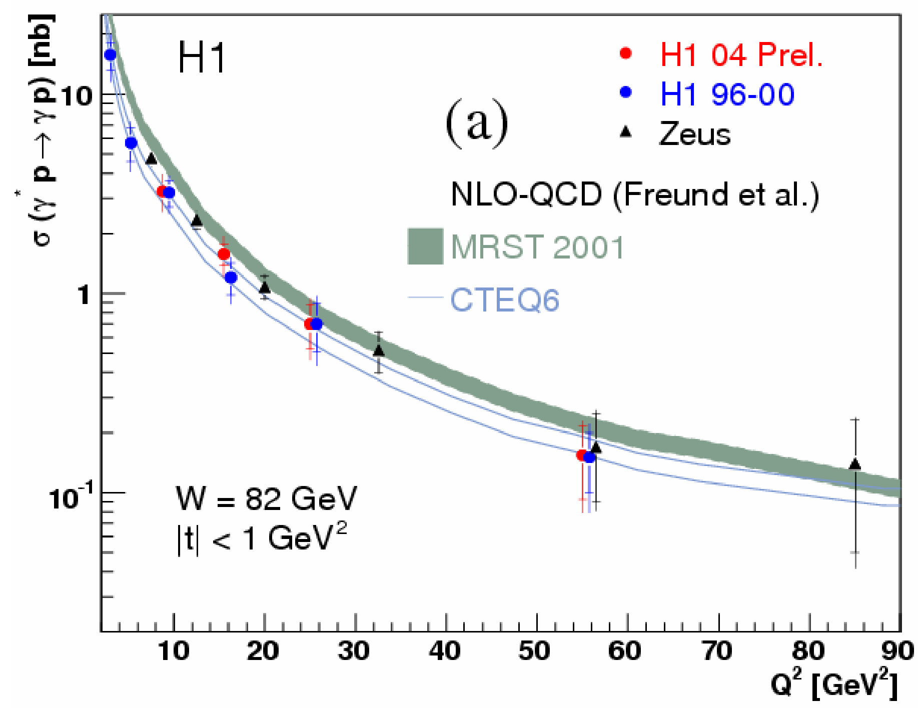
Deeply Virtual Compton Scattering (DVCS)



$\gamma^* p \rightarrow \gamma + p$

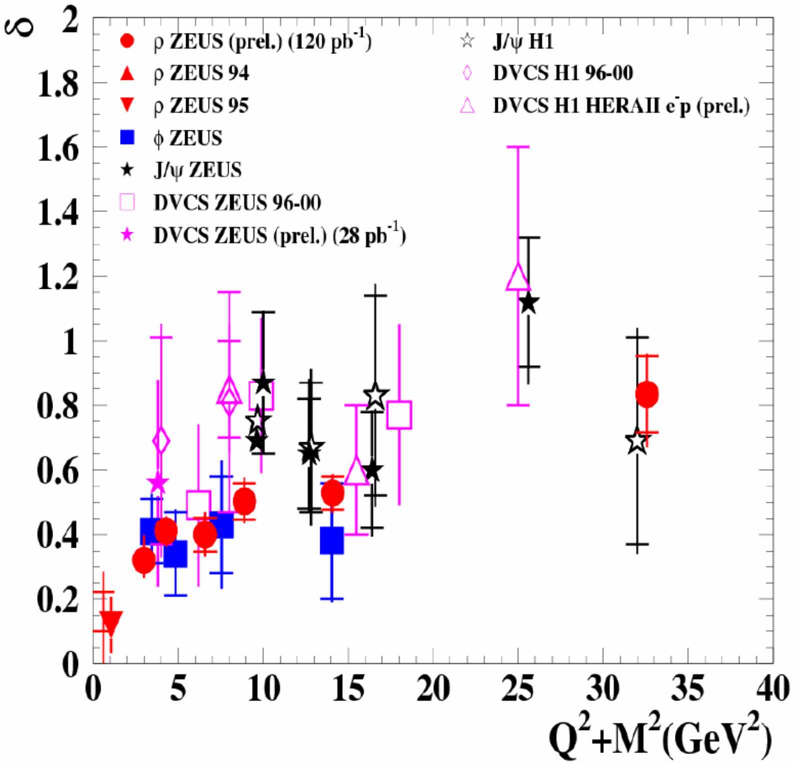
- -Elastic scattering of virtual photon off a proton
- -clean experimental signature, fully calculable in QCD
- -sensitive to generalized parton distributions (GPD)

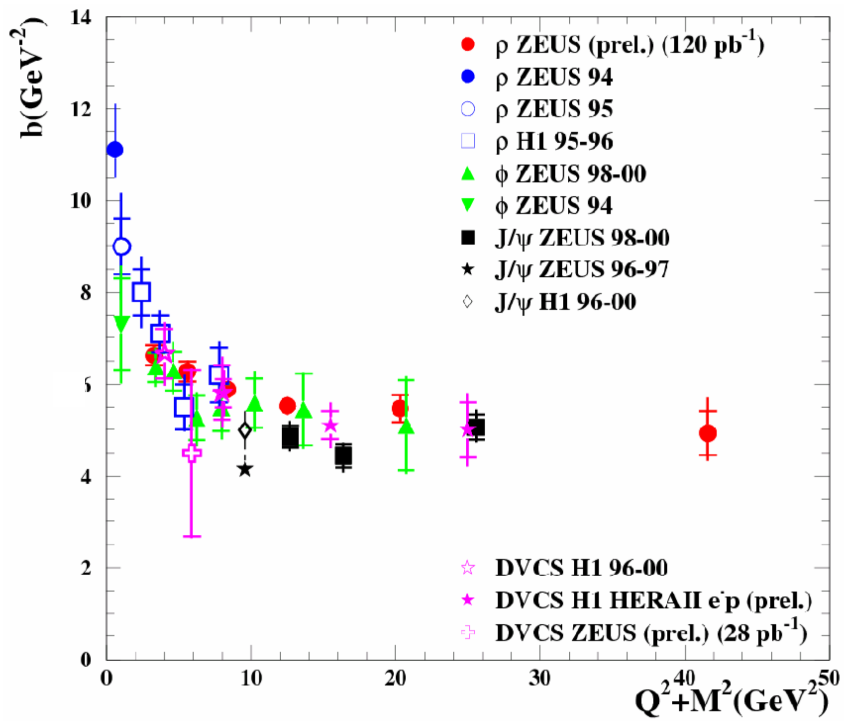




- -steep rise with energy
- -good description by NLO QCD models

Elastic VM production- energy dependence, t-slope





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

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

- Expect δ to increase from 'soft' (~0.2) to 'hard' (~0.8)
- ***b*** characterize the size of interaction, expect ***b*** to decrease from 'soft' to 'hard'

W dependence – process becomes hard as scales (VM mass or Q^2) become larger

b-slope size of scattered VM getting smaller with Q^2+M^2

➔ transverse extension of hard gluons in proton r_g~0.6 fm, compared to charge radius of the proton~0.8 fm

Summary

- **30.06.2007 – end of unique machine**

  An integrated luminosity of 1 fb^{-1} was taken by both H1 and ZEUS experiments together during the 15 years of HERA

- High precision and extended kinematic reach:
  - new constrains on proton structure: gluon density, charm and beauty
  - new HERA precision α_S
- Wealth of new jet and heavy flavour data from HERA available
  - need theoretical calculations to higher order
- The partonic structure of diffraction is measured with improved precision and extended kinematical range

  diffractive PDFs extracted from the NLO fits to the data:

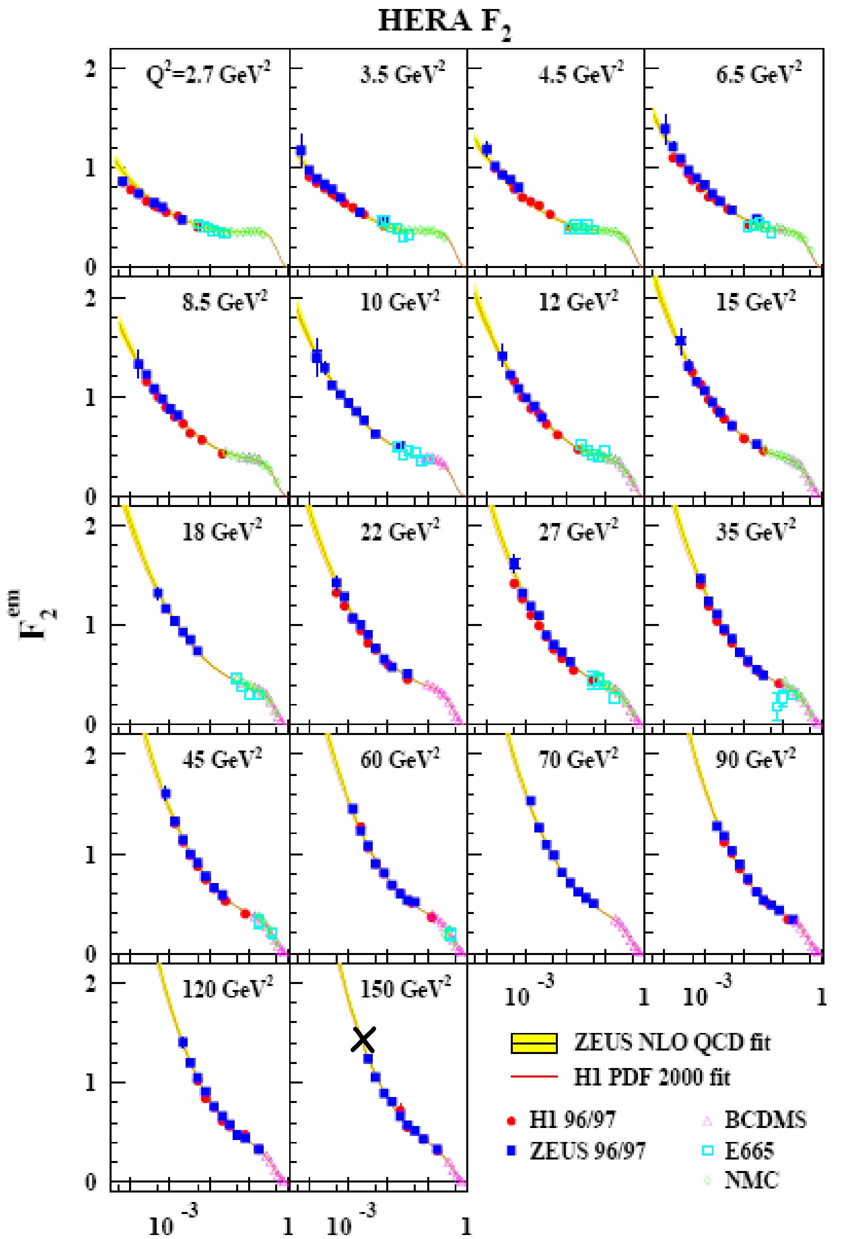
  QCD factorization, NLO DGLAP evolution, dominated by gluons

- New phase of H1 and ZEUS mutual collaboration: combined data, structure functions, α_S, …
- HERA has a reach program that should be completed.

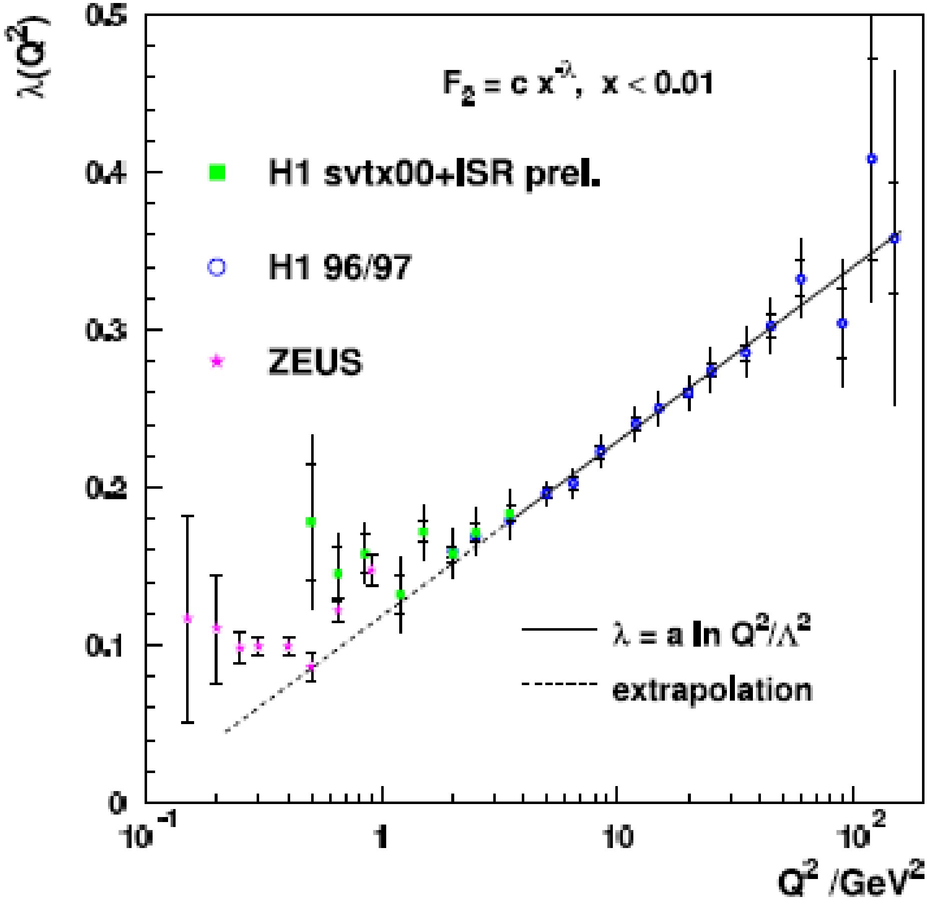
  Precision measurements at HERA provide crucial input for LHC physics !

- Many more results to come !

Cross section measurements at low x



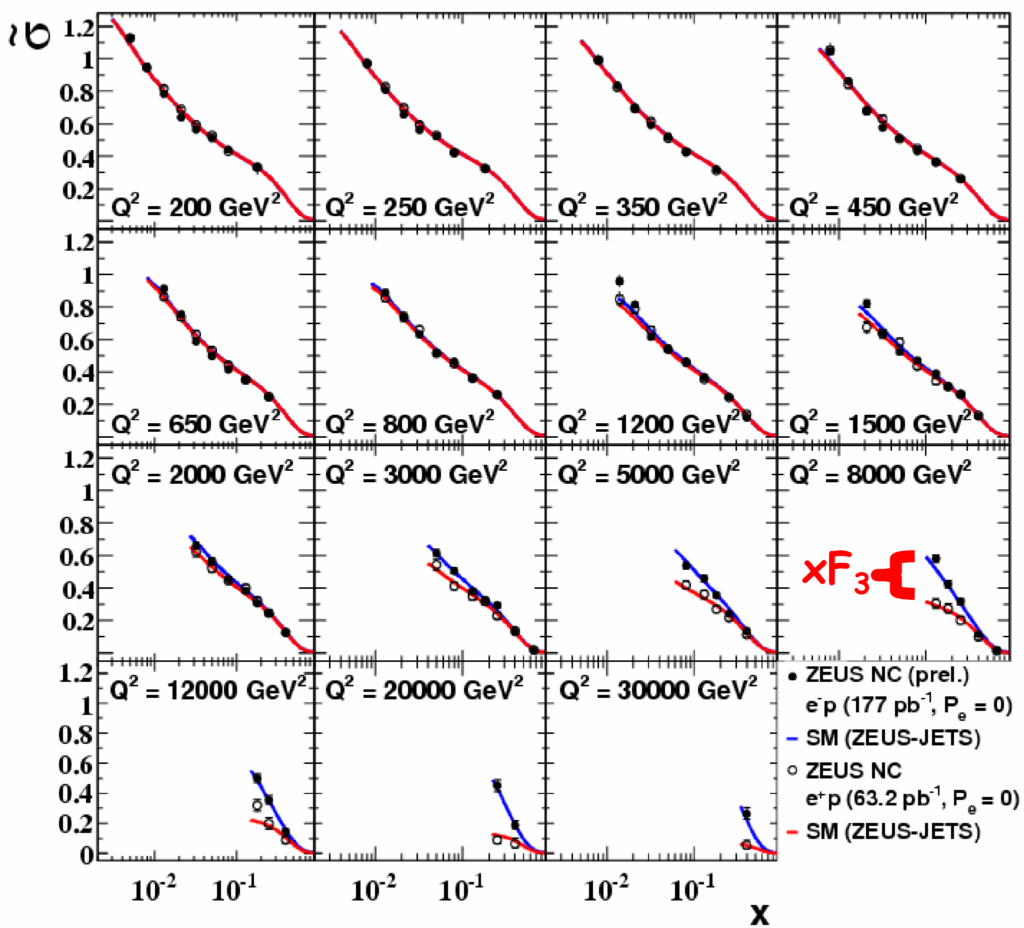
For each Q^2 bin a fit $F=cx^{-\lambda}$ is performed to quantify the rise

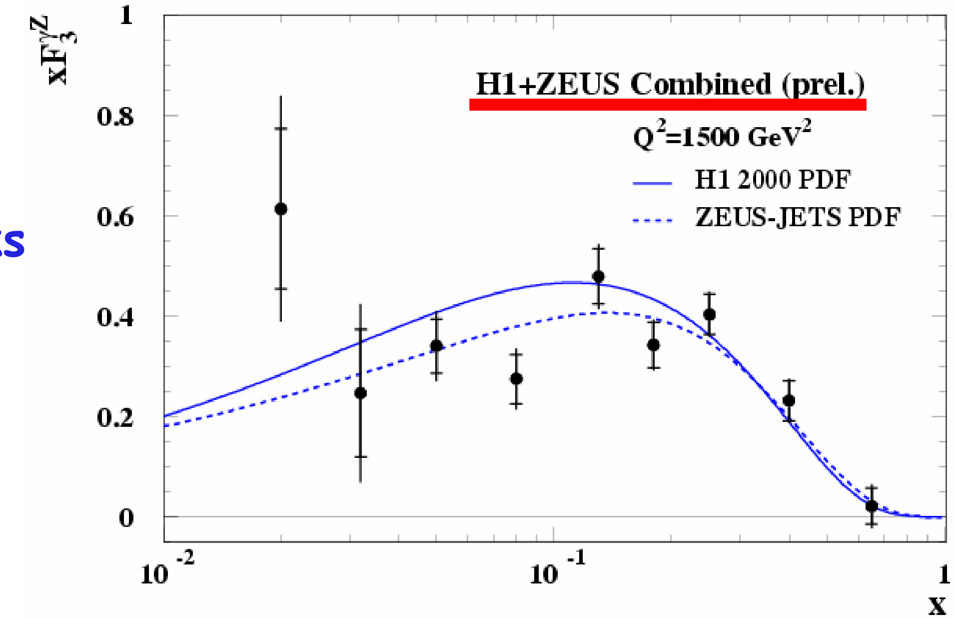


Valence quarks and xF_3

Large increase of e^-p high Q^2 data with HERA-2 allows to improve precision of the F_3 structure function

→ **Add to the knowledge of valence quarks in the proton (x<0.1)**





$$\tilde{\sigma}_{NC}(e^{\pm}p) \sim Y_+F_2 \mp Y_-xF_3$$

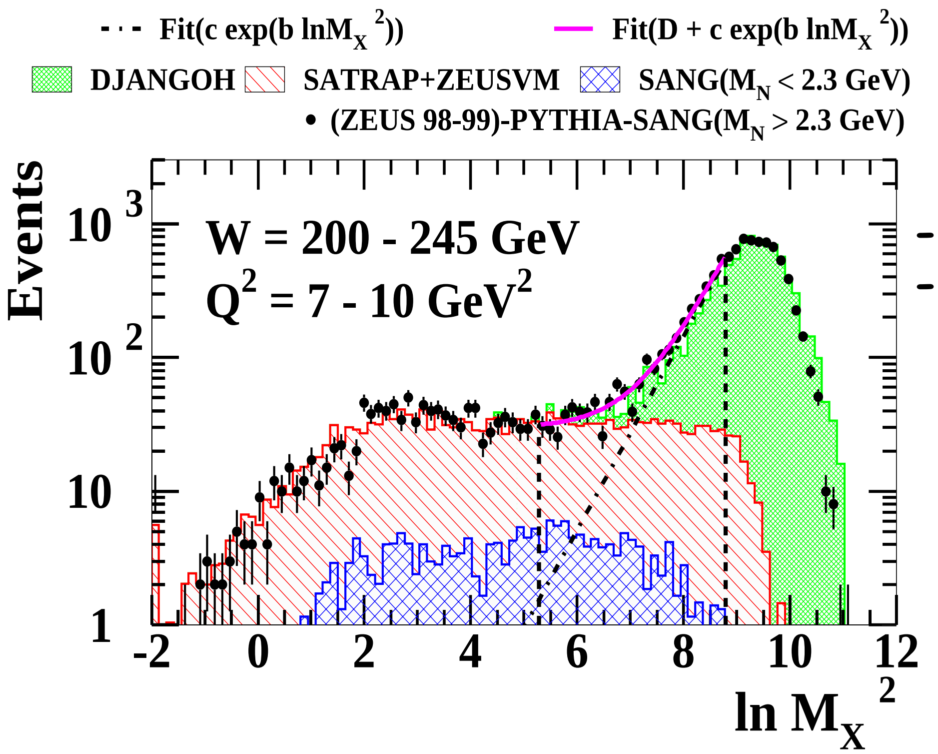
$$xF_3 \sim \sigma(e^-p) - \sigma(e^+p)$$

no-enhancement for low x

- **'Leading proton' method (LPS)**– scattered proton detected in 'Roman Pots' (LPS,FPS)
  free of p-diss.background, *t* and x_{IP} measurement, but low acceptance/statistics

- **Large Rapidity Gap' method (LRG)**
  t is not measured, some p-diss. background (for H1 measurements M_Y<1.6 GeV)

- **'M_X' method**- non-diffractive contribution subtracted from fit to M_X distribution
  t is not measured, some p-diss. background (for ZEUS measurements M_Y<2.3 GeV)



$$\frac{dN}{d\ lnM_X^2} = D + c \cdot exp(b \cdot lnM_X^2)$$

- exponential rise with M_X for non-diffr.events
- flat behavior vs ln M_X^2 for diffractive events