Workshop on Hadron-Hadron & Cosmic-Ray
Interactions at multi-TeV Energies
ECT* - Trento, Nov 29th - Dec 3rd, 2010

QCD results from HERA

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On behalf of the H1 and ZEUS Collaborations

Outline:
- Introduction to HERA
- Deep Inelastic Scattering & Proton Structure
- Heavy quark production
- Jets, α_s ,underlying event
- Diffraction
- Leading baryons

HERA and Cosmic Rays

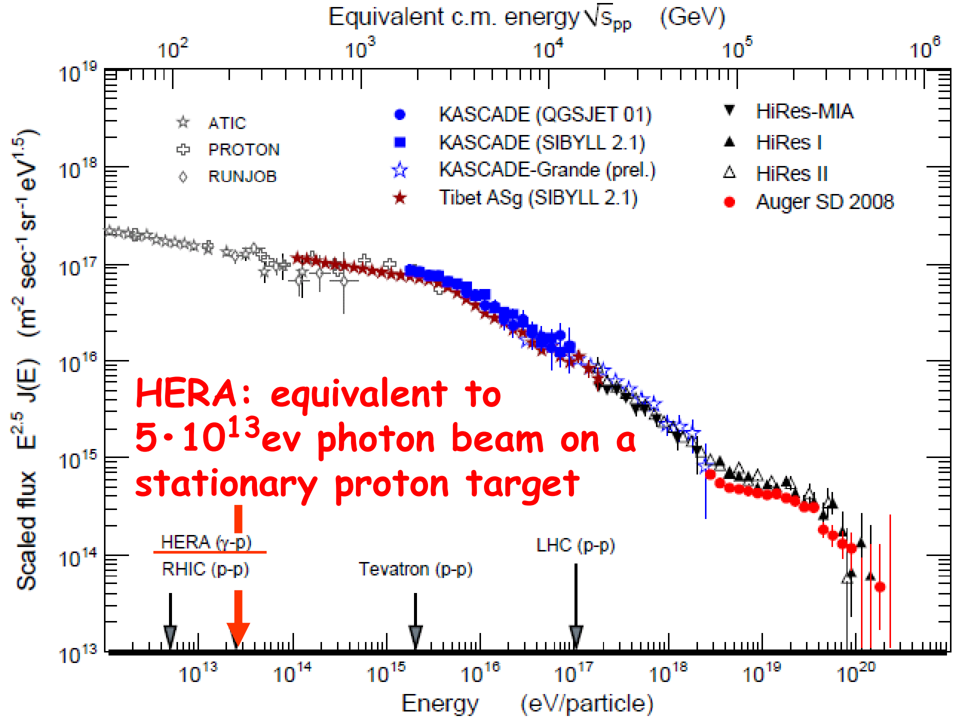
It is difficult to directly relate particle production measurements at collider with the data obtained by very high energy CR experiments:

- very different energy domains;
- collider expts.- mainly central rapidity range; CR- mainly projectile fragmentation region
- at colliders the primary particles are known; CR particles are detected via air showers, determination of their energy and mass relies on the <u>modeling</u> of hadronic interactions

➔ need experimental measurements to tune the models

Considering the underlying theory entering the models, almost all measurements at colliders are relevant for understanding of very high energy CR interactions.

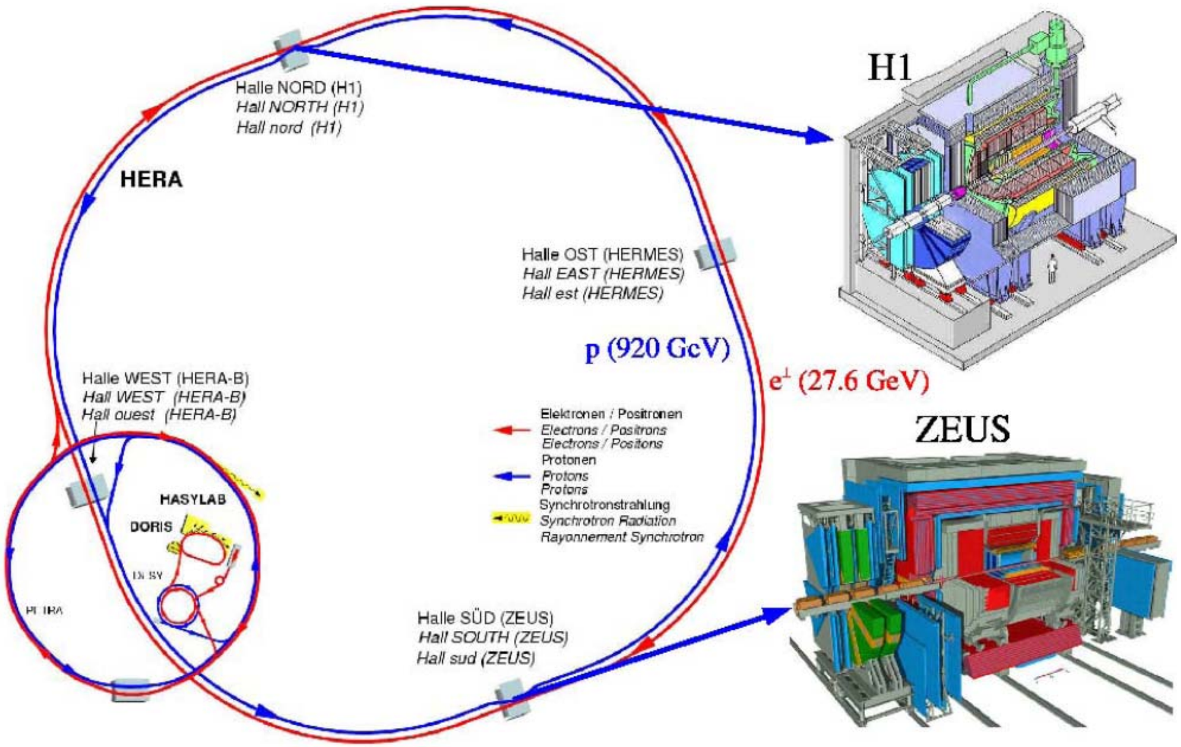
- parton densities, low-x dynamics, jets, transition between hard and soft regimes, heavy flavour production, forward hadron production, etc… are important for the basic structure of the models

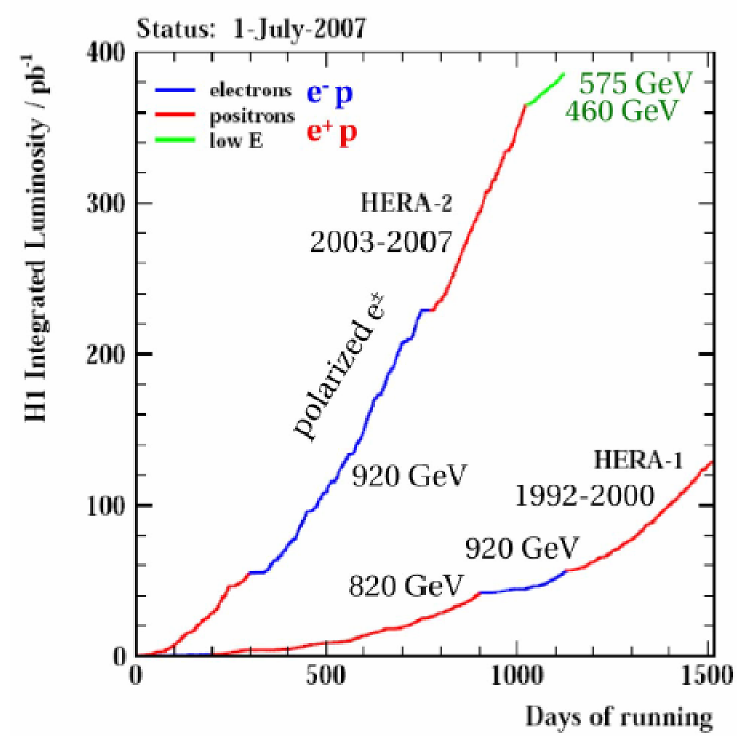


The world's only electron/positron-proton collider at DESY, Hamburg

E_e = 27.6 GeV E_p = 920 GeV (also 820, 460 and 575 GeV)

(total centre-of-mass energy of collision up to $\sqrt{s} \approx 320$ GeV)





HERA- the QCD machine

H1+ZEUS: extensive and precision studies of different aspects of QCD, Heavy Flavour production, Physics Beyond the Standard Model, Diffraction,…

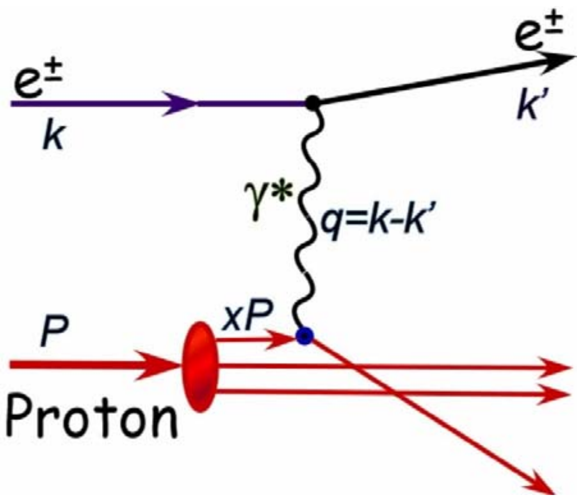
HERA-1: 1992 – 2000

HERA-2: 2003 - 2007

total lumi: 0.5 fb^{-1} per experiment

Deep Inelastic Scattering, Structure functions

DIS – a probe of proton structure



$Q^2=-(k-k')^2$ - virtuality of exchanged boson

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

$y=p\cdot q/p\cdot k$ - inelasticity variable

$Q^2=xys$ → at fixed $\sqrt{s}$ two independent variables

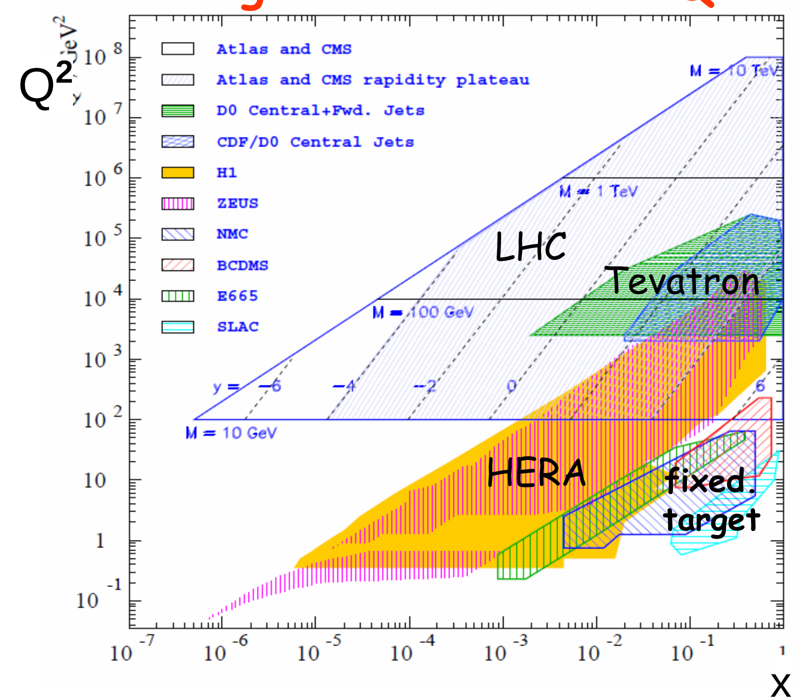
$$\frac{d^2\sigma^{NC}_{e^\pm p}}{dx\,dQ^2}=\frac{2\pi\alpha^2 Y_+}{xQ^4}\cdot\underbrace{\left(F_2-\frac{y^2}{Y_+}F_L\mp\frac{Y_-}{Y_+}xF_3\right)}_{\text{reduced cross section}\ \equiv\tilde{\sigma}_r(x,Q^2)},\quad Y_\pm=1\pm(1-y)^2$$

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

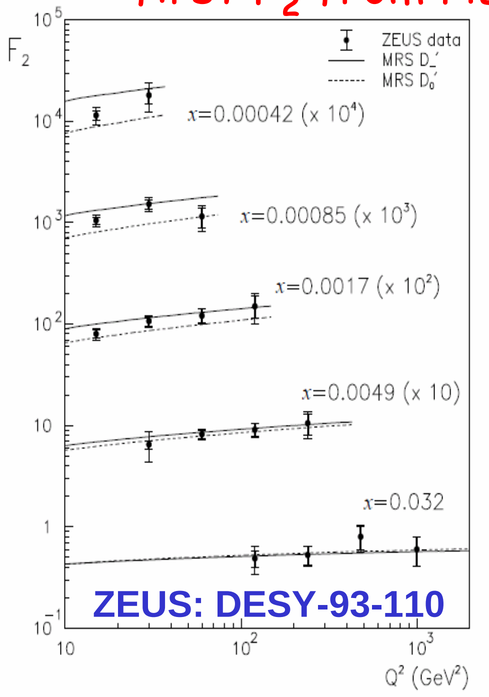
F_L =0 at leading order; proportional to gluon density at higher orders

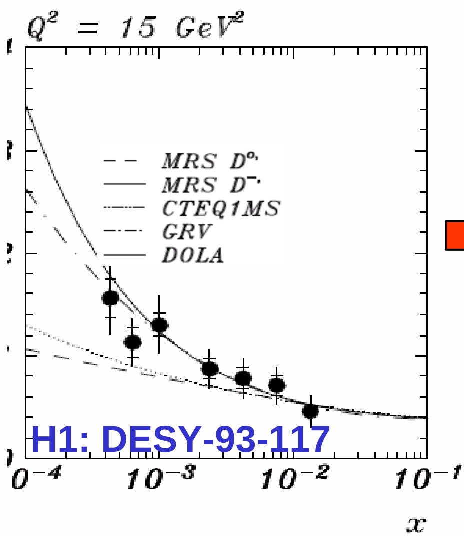
xF_3 important only at high Q^2

HERA: large reach in x and Q^2

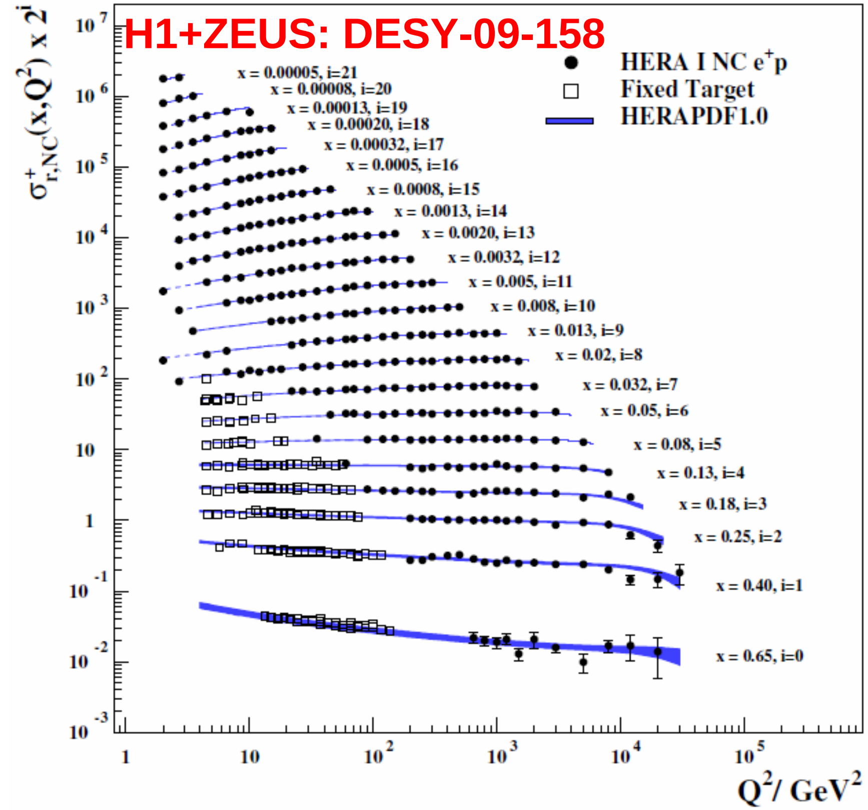


first F_2 from HERA (1993) …





recent publication (2009)



Combination of H1 and ZEUS measurements
(not only improvement of statistics – experiments 'cross-calibrate' each other, total uncertainties reduced)
Uncertainties below 1% for bulk of data

- **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 $x \to 0$**

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

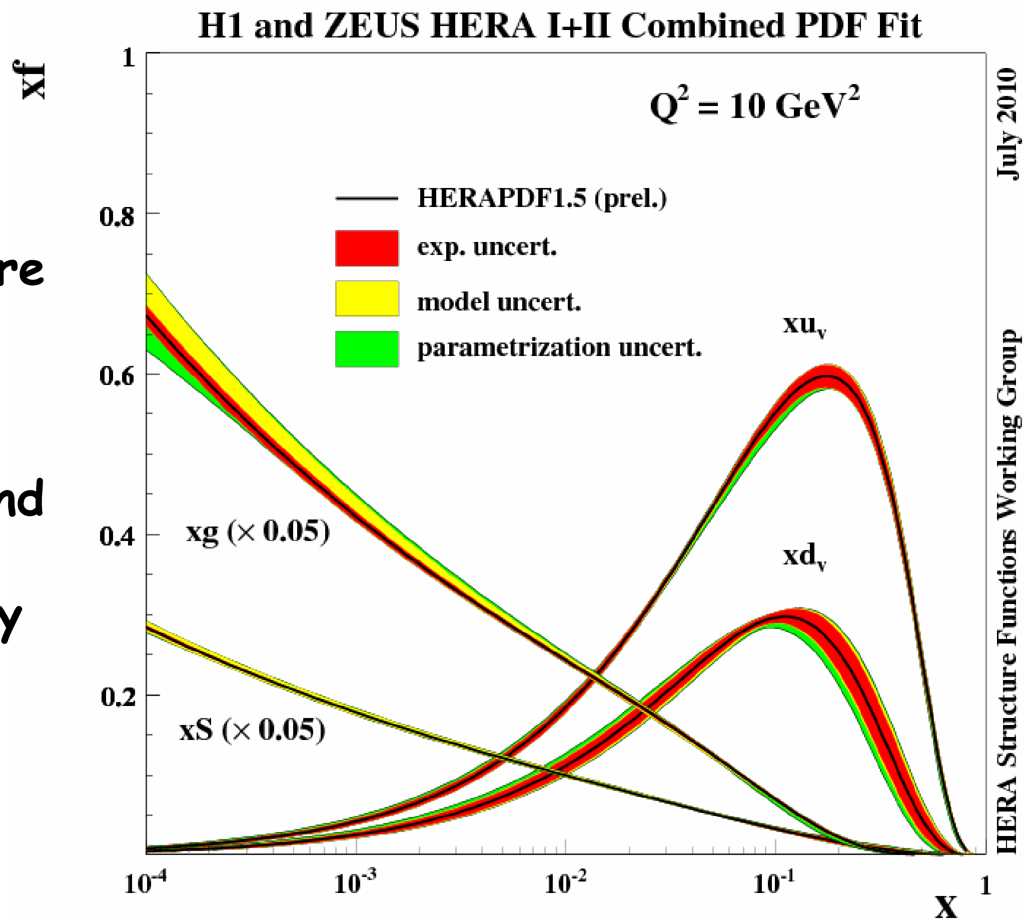
F_2 data from HERA allow to extract individual quark flavours;
gluon density - from scaling violation

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

- valence quarks determine proton structure at high x
- sea and gluons important at low x<0.01

- F_2 data constrain the low-x sea quarks and gluons ($x = 10^{-1} \div 10^{-4}$)

largest uncertainties at low x gluon density
→ reduce uncertainties using F_L (high y) measurements



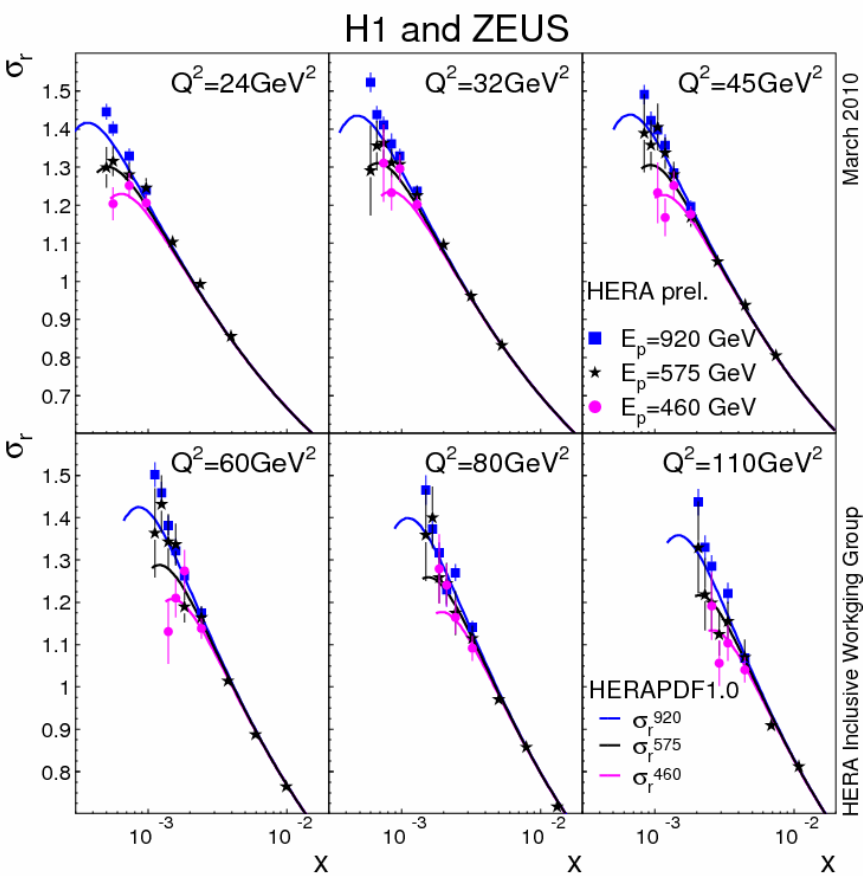
new prelim. PDF fits including HERA-II high Q^2 data (HERAPDF1.5)

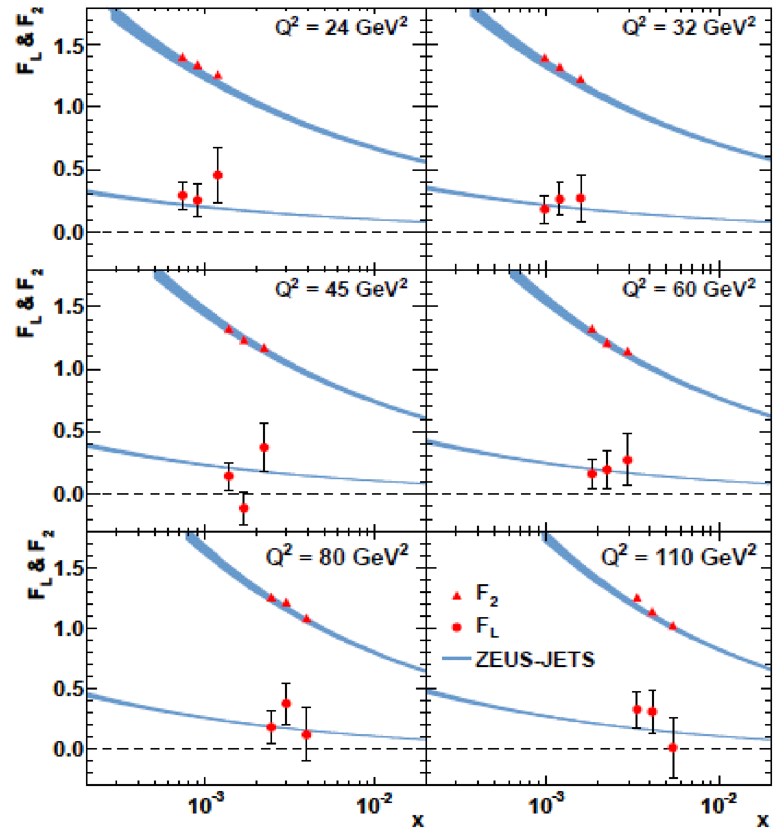
F_L is directly sensitive to gluon PDF:

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

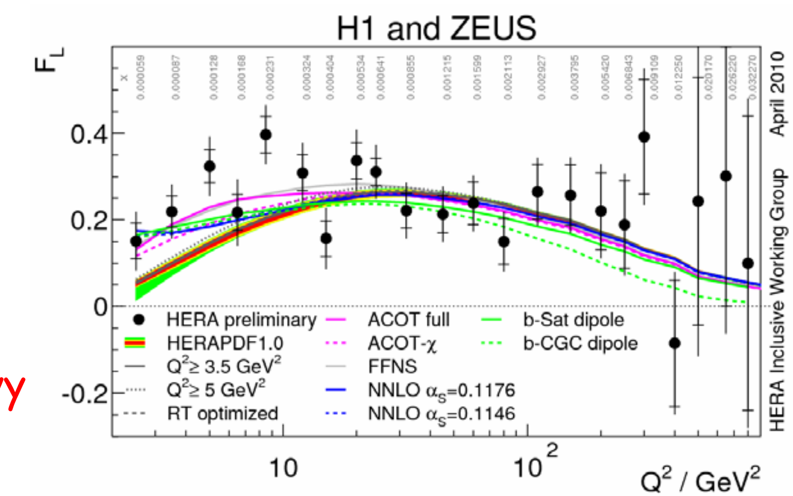
$\sigma_r = F_2 - y^2/[1+(1-y)^2] \cdot F_L$ → need to vary s to extract F_L in x,Q^2 bins ($y=Q^2/xs$)

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

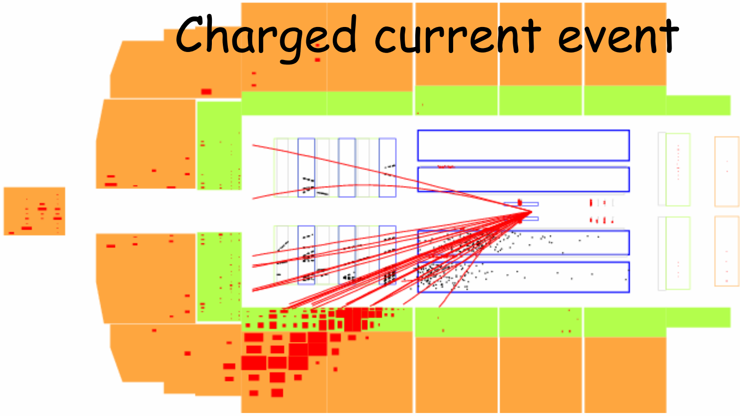


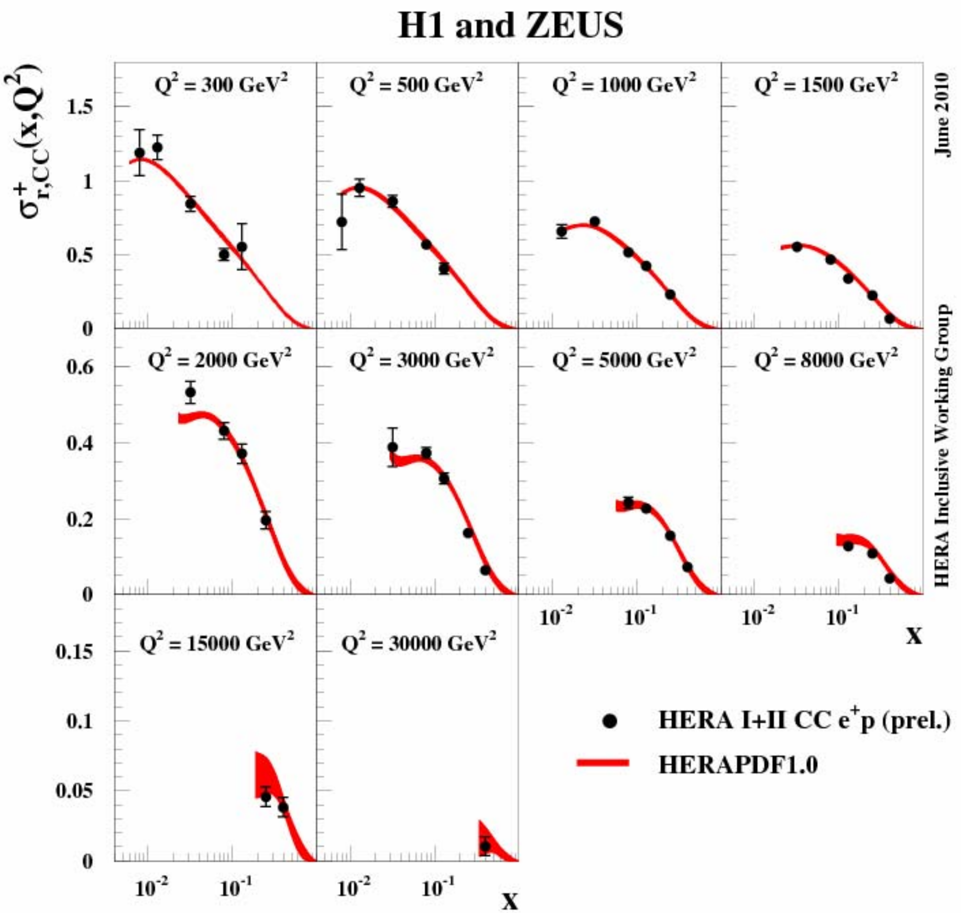


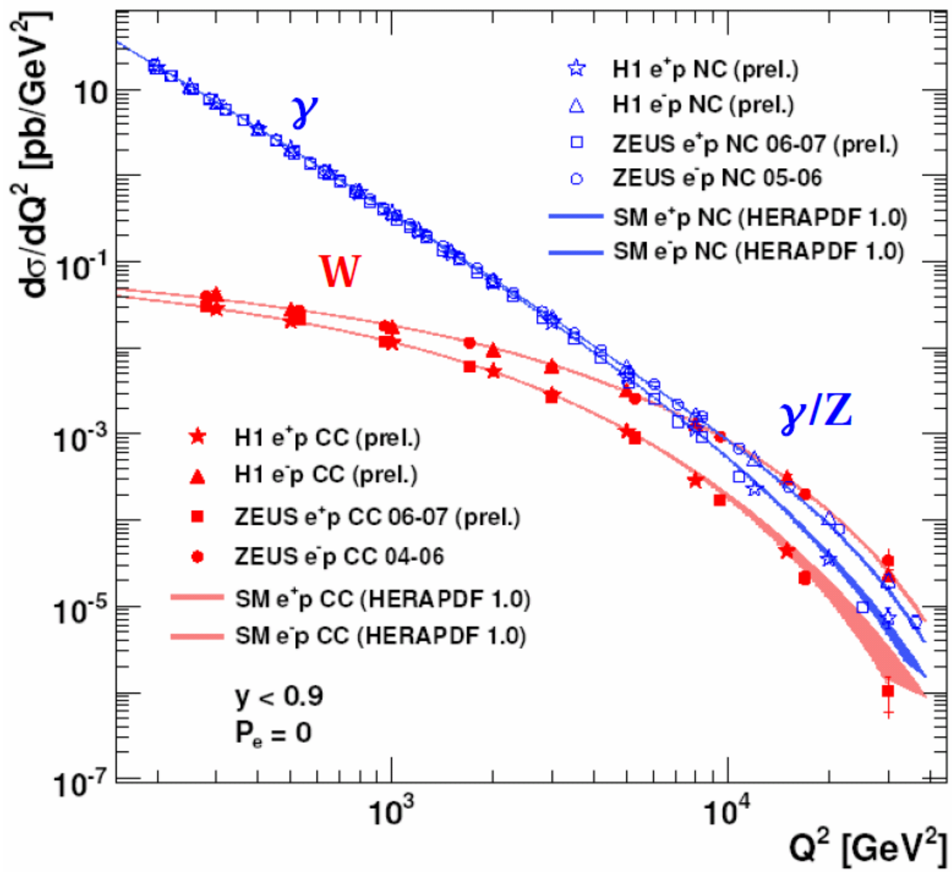
F_2 & F_L



Reasonable agreement with NLO and NNLO; sensitive to heavy flavour schemes



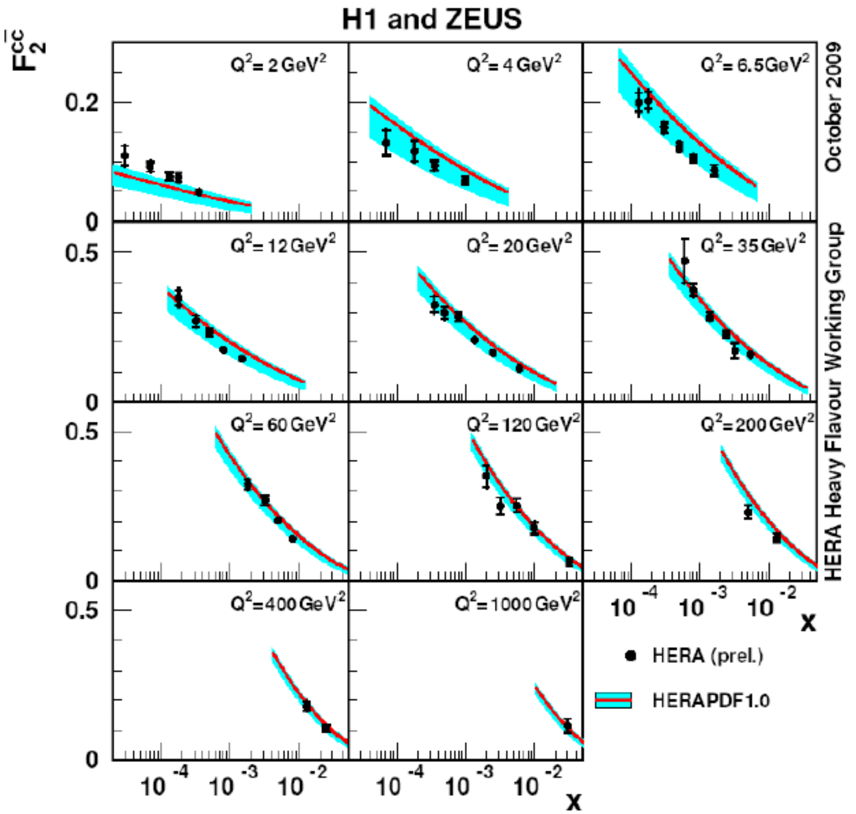


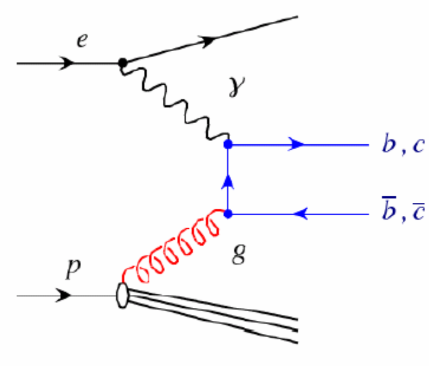


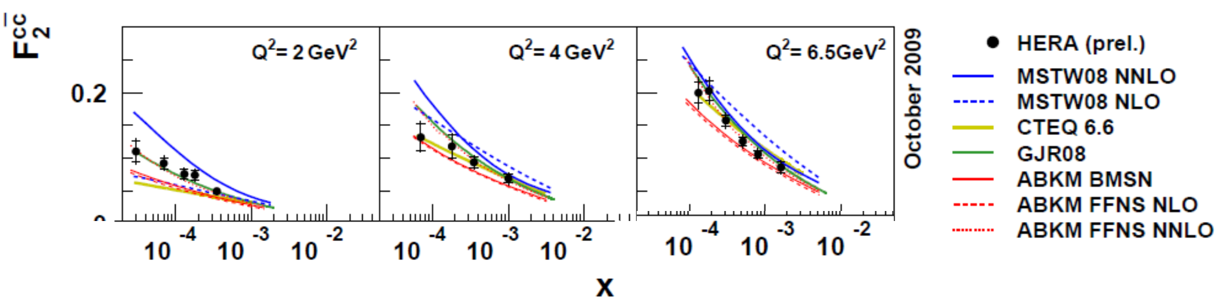
- Well described by SM over 6 orders
- Electroweak unification at $Q^2 \sim m_W^2$.

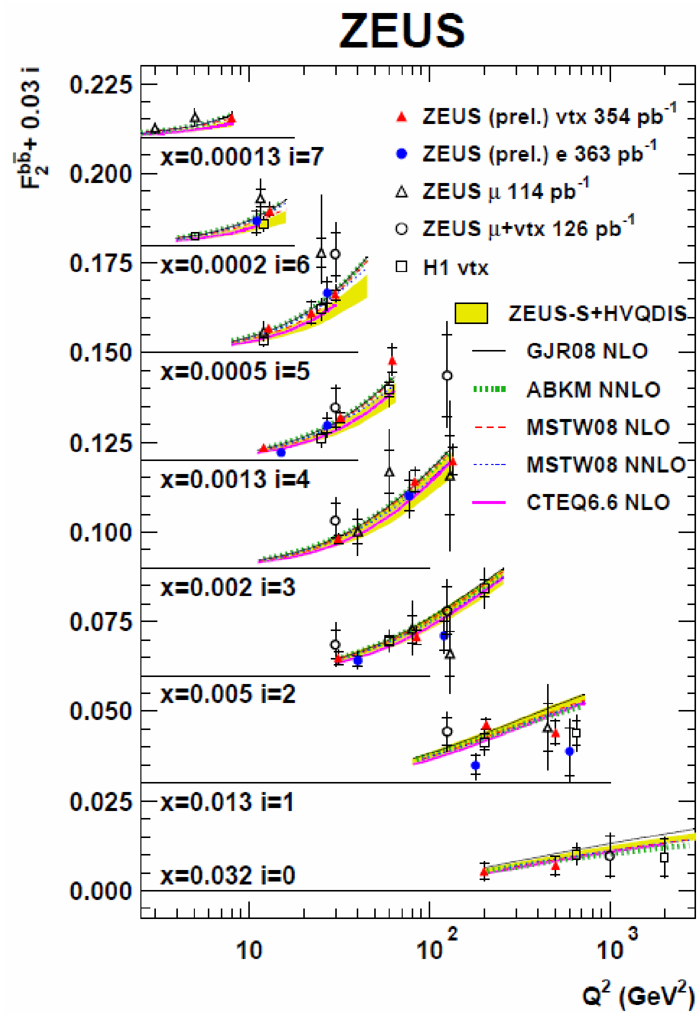
Charm and Beauty contribution to F_2

F_2^{cc}, F_2^{bb} - directly sensitive to gluon density
Up to 40% contribution to F_2









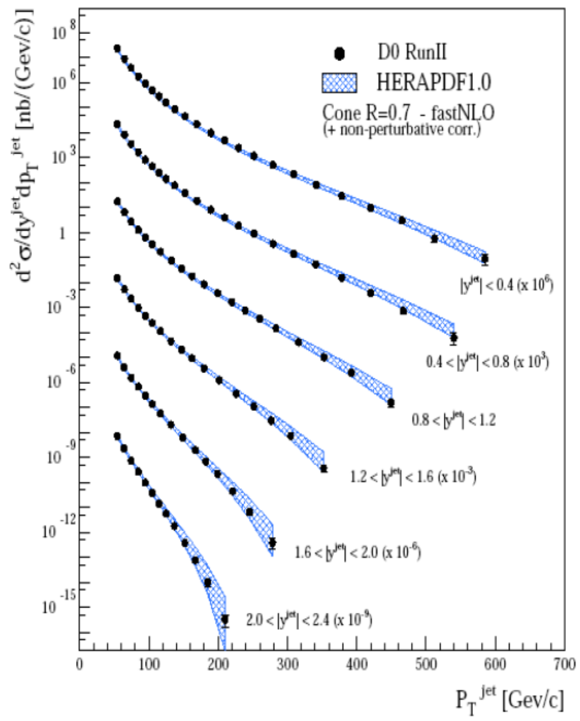
Reasonable agreement with NLO and NNLO, but sensitive to m_c (uncertainty band 1.25-1.65 GeV)

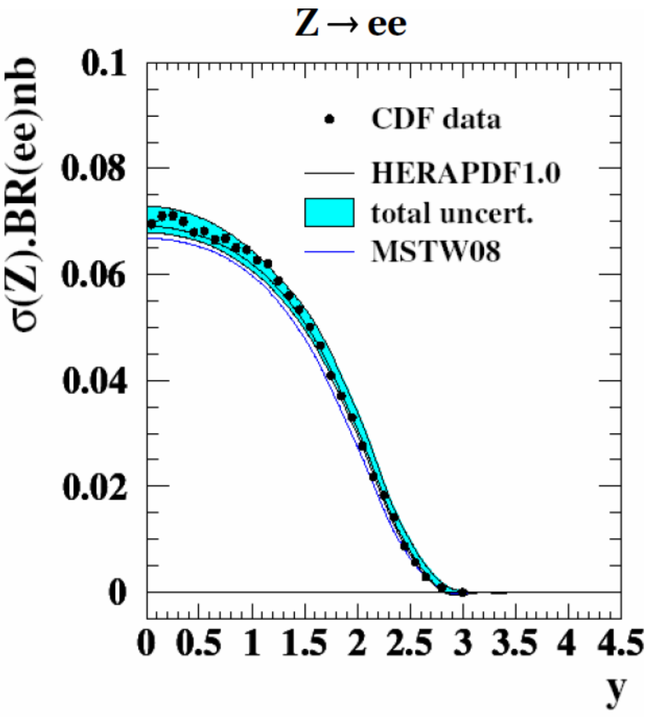
Sensitive to heavy flavour schemes

- **HERA experiments provide unique information on proton structure at low x**

- H1+ZEUS combined cross sections
  -model independent check of consistency
  -experiments cross-calibrate each other, reduce systematical errors
- Precision of HERA measurement reached 1÷2% level
- Direct measurement of F_L -important check of the theory and a new handle on the gluon density
- HERAPDFs – important input for the LHC physics

HERA PDFs vs Tevatron data



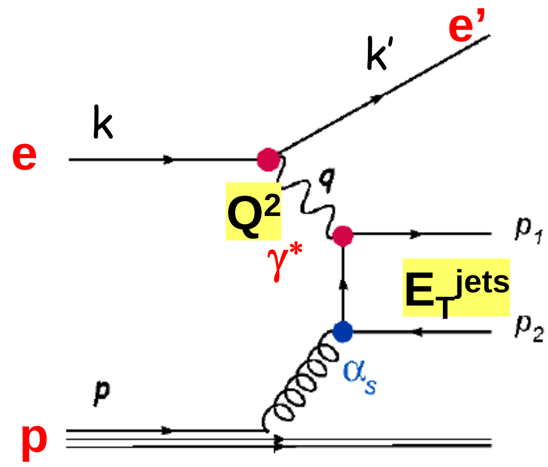


Jet measurements at HERA

- Provides a testing ground for pQCD.
  Cross section depends on: QCD matrix elements,
  strong coupling α_s, PDF of the proton (and the photon)

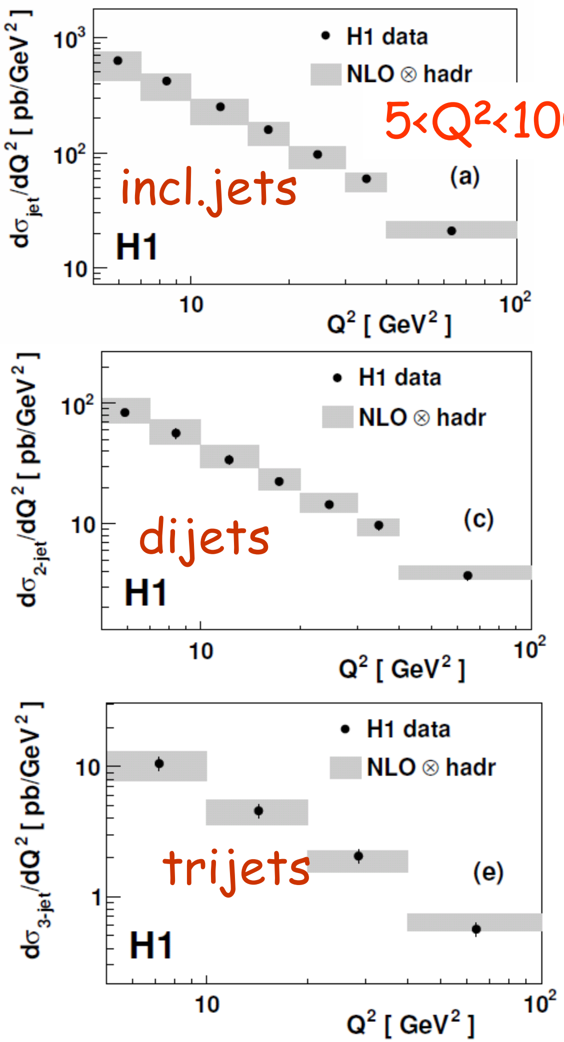
→ improve constraining gluon density

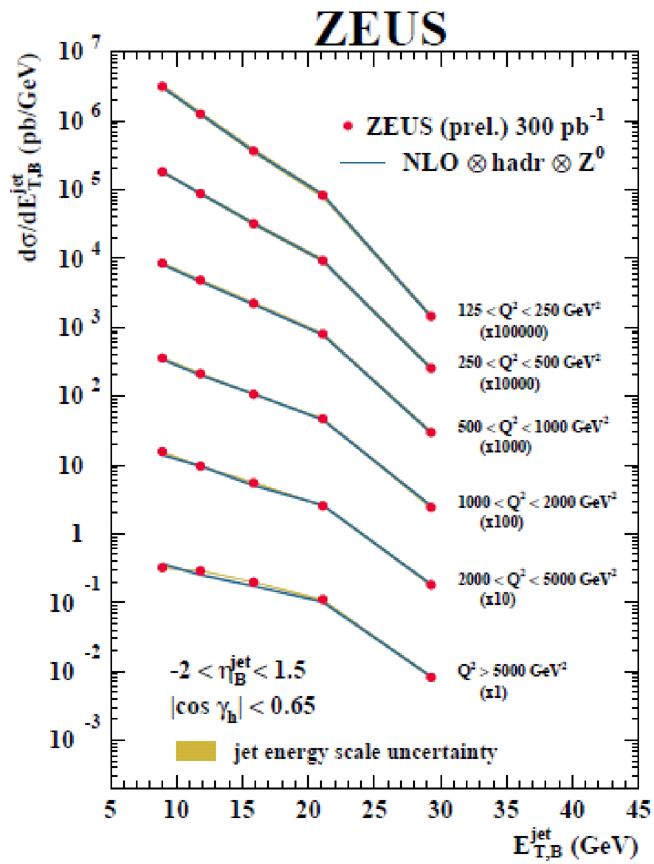
→ extract strong coupling α_s with high precision

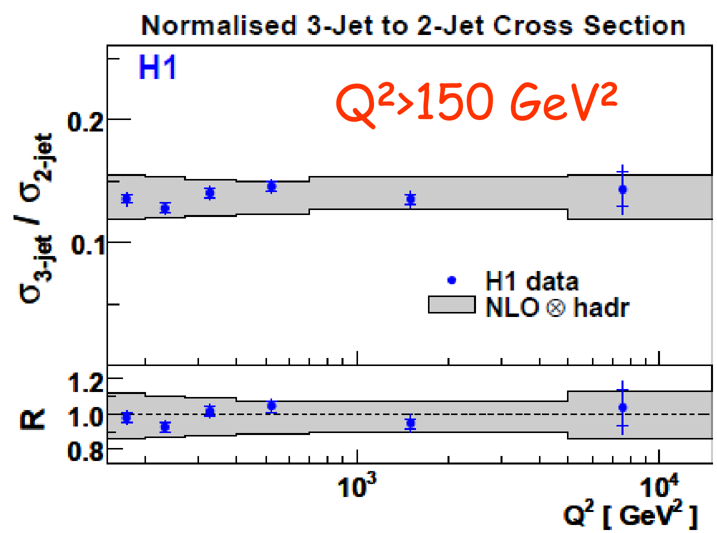


5<Q²<100 GeV²

Q²>125 GeV²

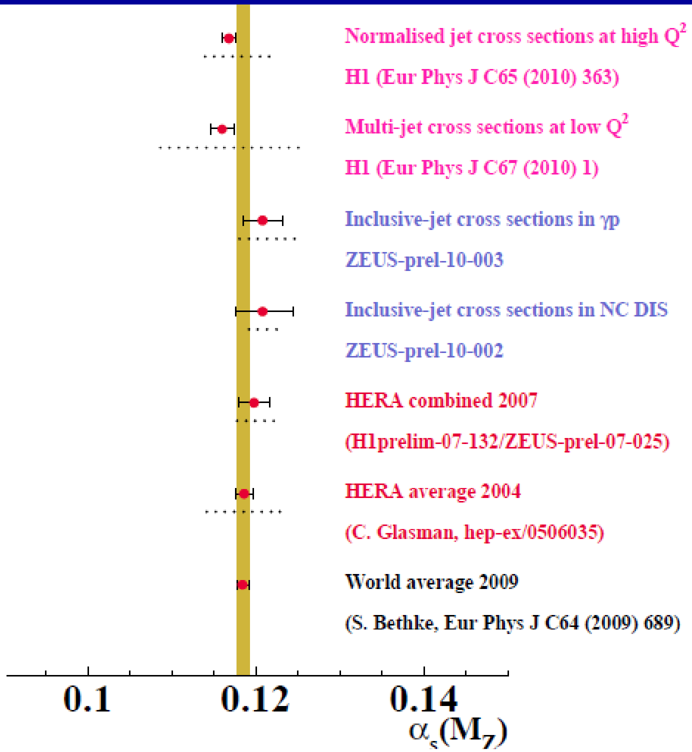






- High precision data
- Gluon density probed up to high momentum fraction
- Good description by NLO QCD

α_s measurements from jets at HERA

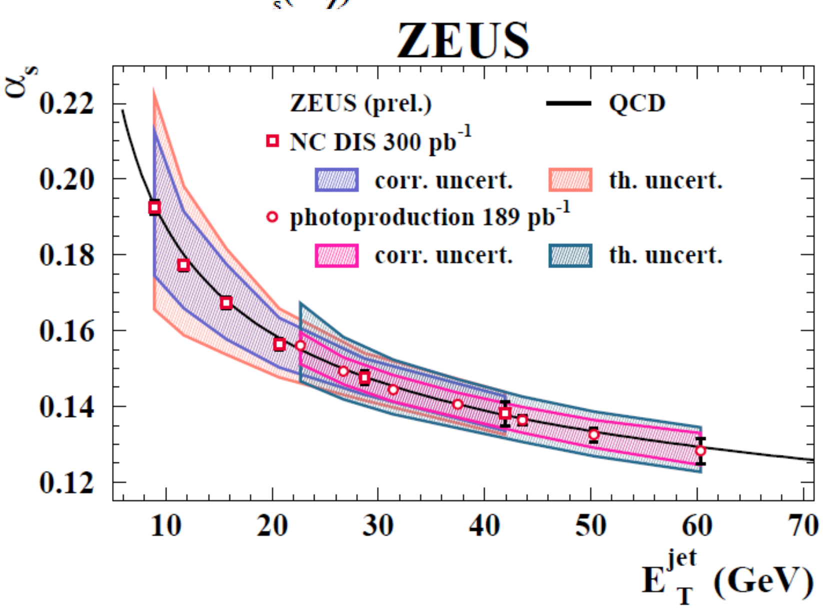


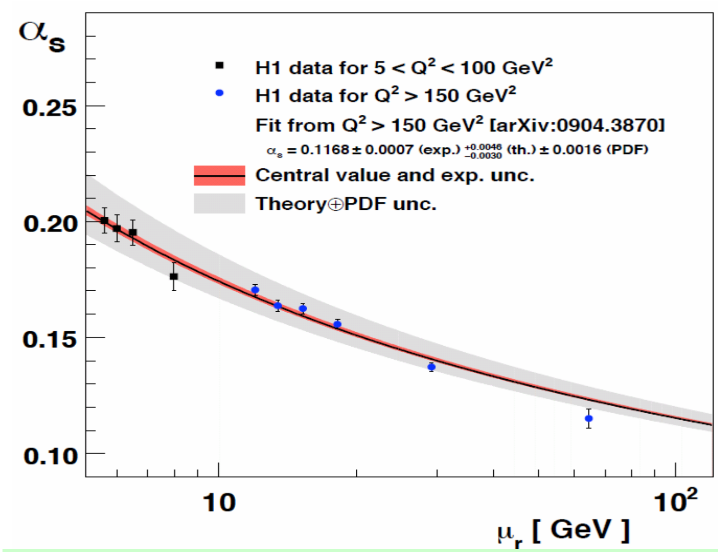
H1 $\alpha_s(M_Z) = 0.1168 \pm 0.0007\ (\text{exp.})^{+0.0049}_{-0.0034}\ (\text{th.})$

ZEUS $\alpha_s(M_Z) = 0.1208^{+0.0037}_{-0.0032}\ (\text{exp.})\ ^{+0.0022}_{-0.0022}\ (\text{th.})$

- Precise determination of α_s over the wide range of scale
- Uncertainties dominated by theory uncertainties
- From single HERA experiment the experimental error similar to world average

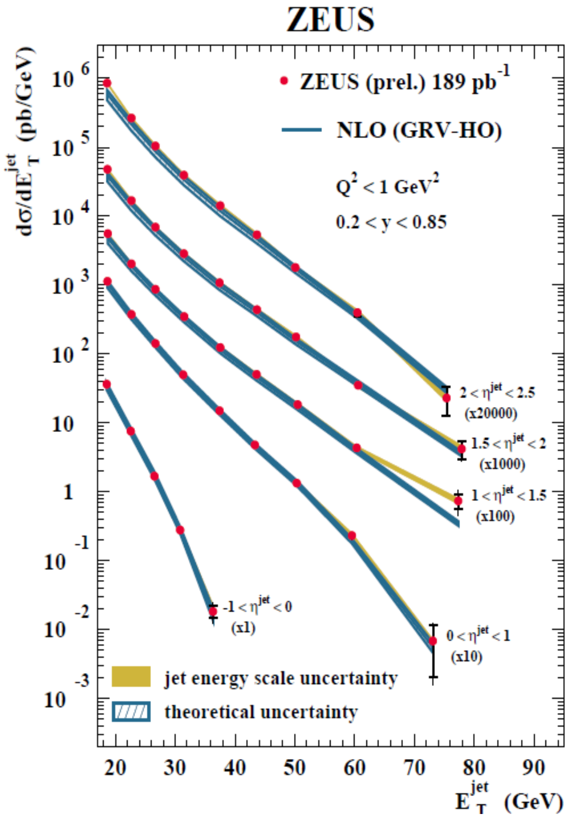
→ need to improve theory – need NNLO !

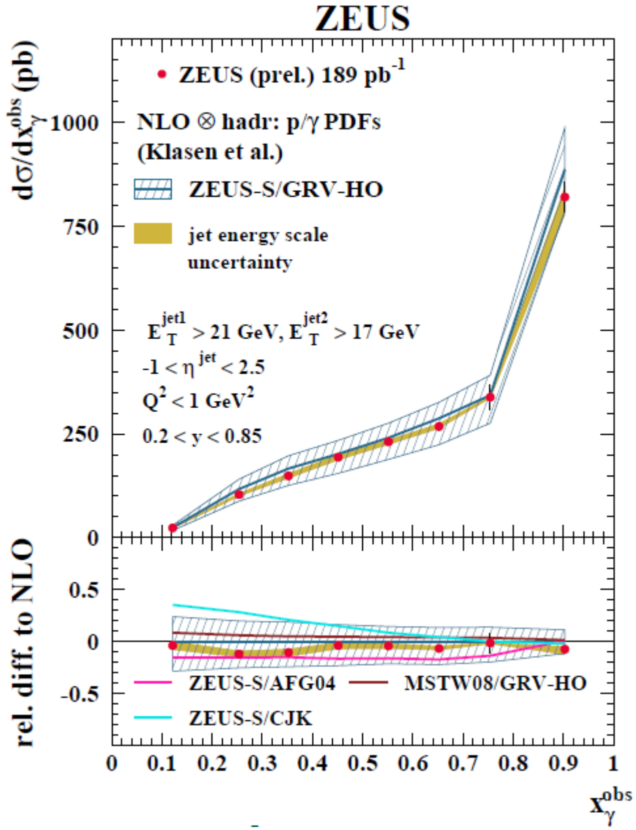




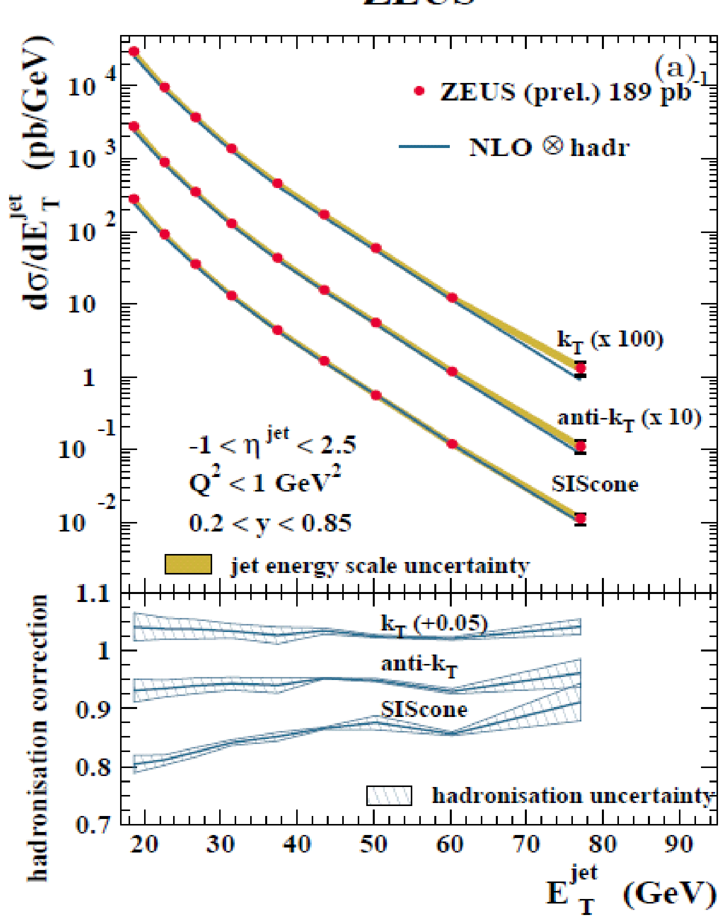
α_s running from single experiment

Jets in photoproduction (Q^2<1 GeV^2)

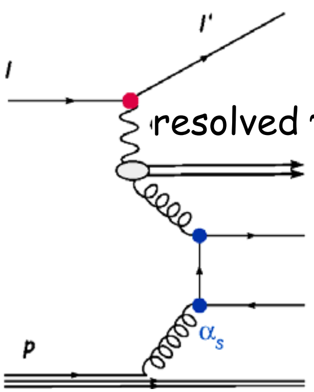


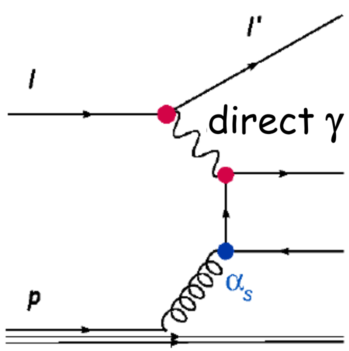


Testing jet algorithms: k_T, anti-k_T and SYScone



Good description of data by NLO QCD, except for low E_T^{jet}, high η^{jet}, low x_γ → sensitive to photon PDF

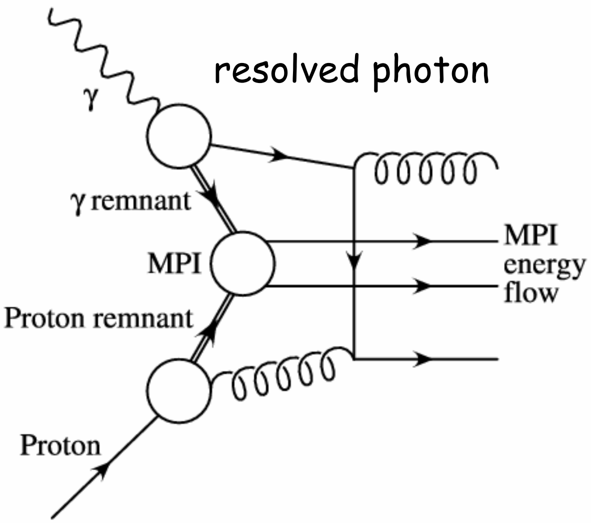


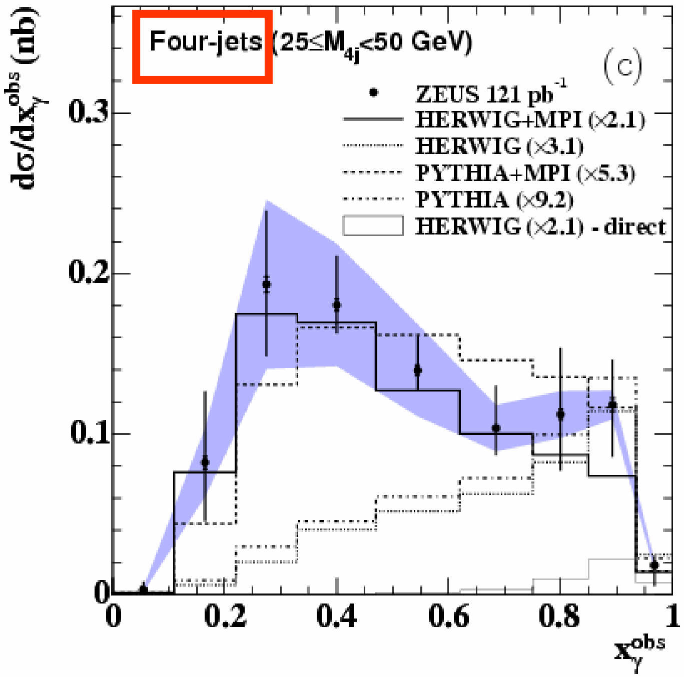


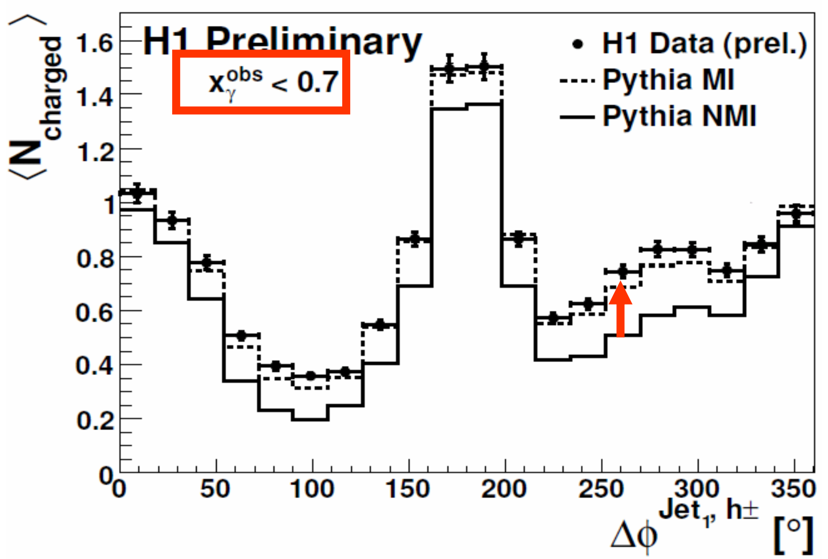
- Similar shape and normalisation for the three jet algorithms
- Bigger hadronisation corrections for SIScone

Multi-parton interactions (MI) and multi-jet final states:
in addition to the primary hard parton-parton interaction with large p_T:
- -remnant interactions (with lower p_T)
- -additional hard parton-parton interactions

➔ higher particle and jet multiplicity, energy offset







$\Delta\phi$ -angle between leading jet and charged particles

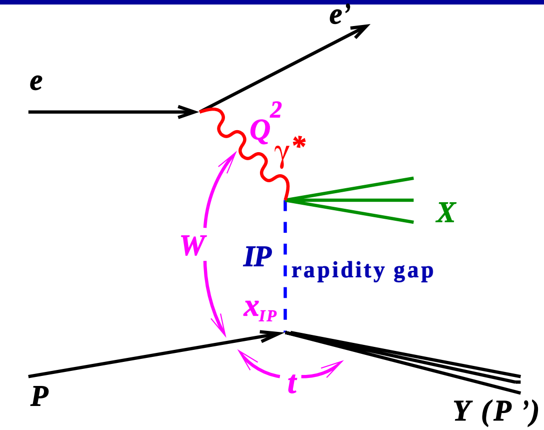
-Models without MI underestimate cross sections at low x_γ

-at low x_γ need MI describe the measurements

Low x physics - is the physics of very large gluon densities

Associated with a large (> 10%) diffractive content

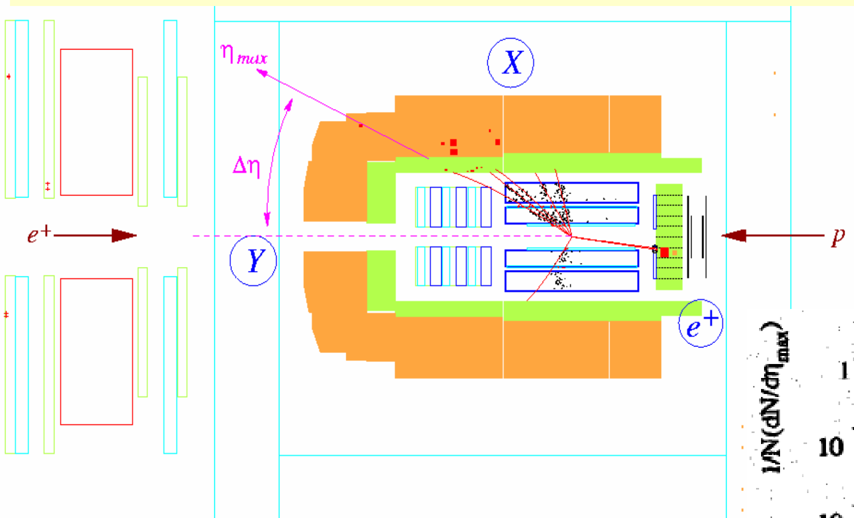
In $\gamma^* p \rightarrow XY$, virtual photon resolves structure of exchange.
-enormous progress in understanding diffraction in terms of partons
-essential for the predictions of diffractive cross sections
-related to non-linear evolution (low x saturation), underlying event (gap survival), confinement



$$t = (p - p_Y)^2 \qquad x_{IP} = \frac{q\cdot(p - p_Y)}{q\cdot p} \propto 1 - E_Y/E_p$$

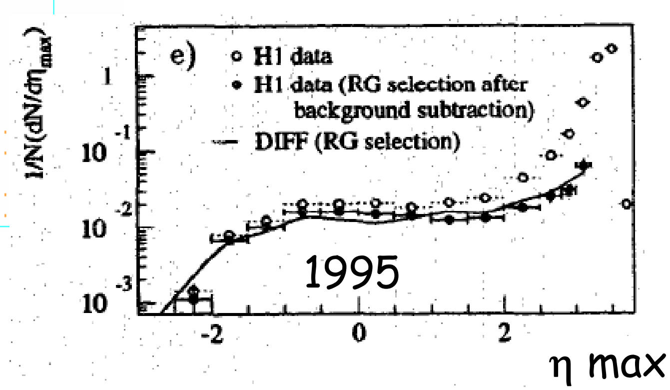
Diffractive event selection

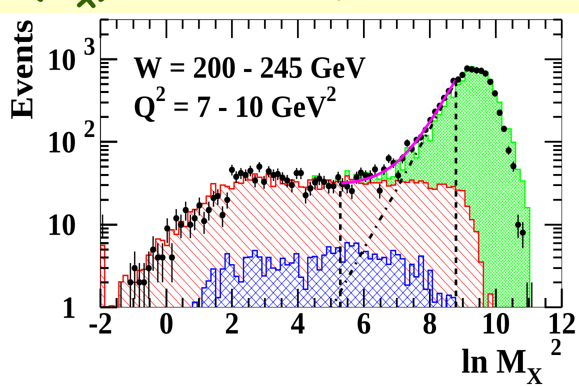
➢**Large Rapidity Gap' method (LRG)**
t is not measured, some p-diss. background



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

➢**'M_X' method–** subtract non-diffractive contribution using $\ln(M_X)$ distribution,

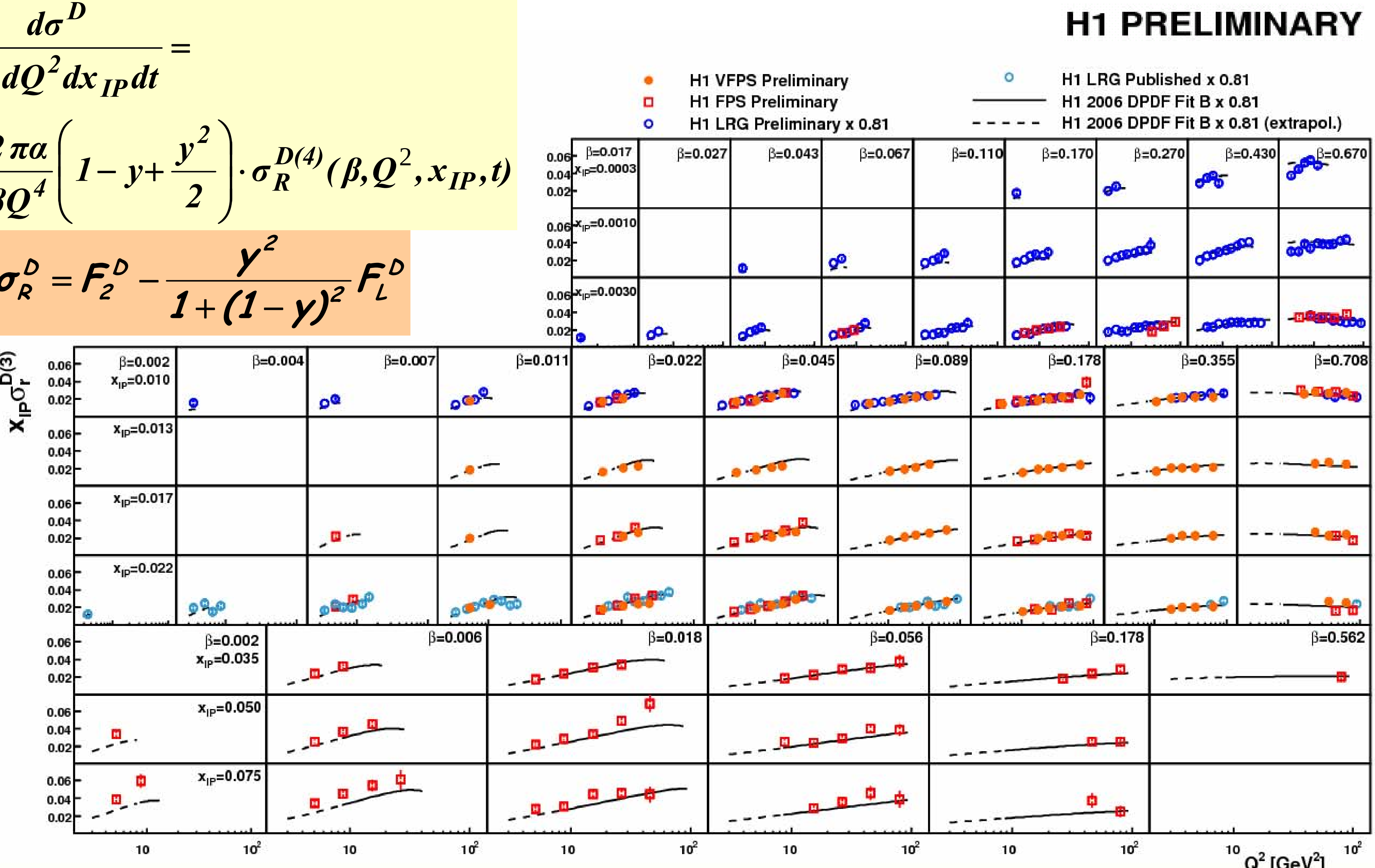




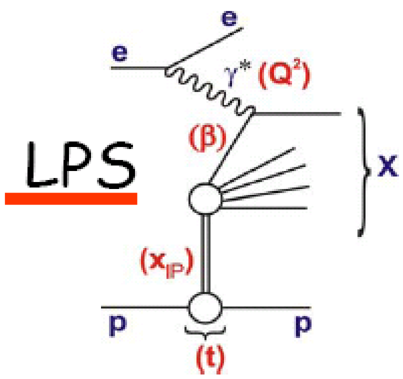
Diffractive reduced cross section $\sigma_r^{D(3)}$ - x_{IP}, β and Q^2 dependence

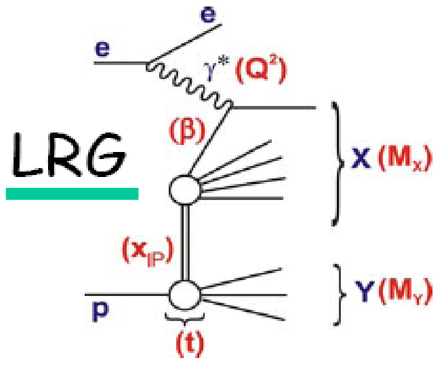
$$\frac{d\sigma^D}{d\beta\, dQ^2 dx_{IP} dt} = \frac{2\pi\alpha}{\beta Q^4}\left(1-y+\frac{y^2}{2}\right)\cdot\sigma_R^{D(4)}(\beta,Q^2,x_{IP},t)$$

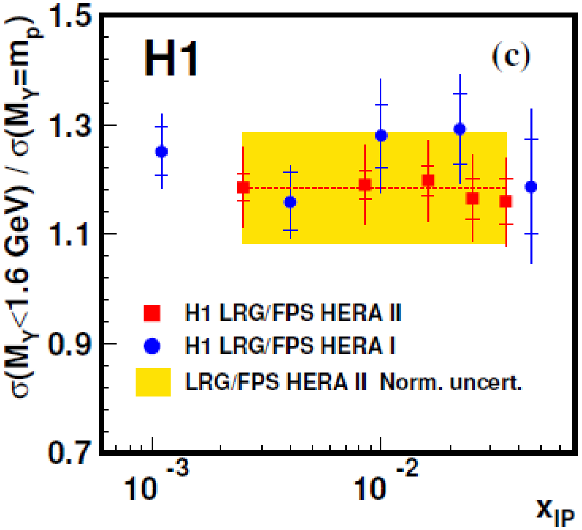
$$\sigma_R^D = F_2^D - \frac{y^2}{1+(1-y)^2}F_L^D$$



Different measurements cover large region of phase space in x_{IP}, β and Q^2
Agreement between different reconstruction methods in regions of overlap.

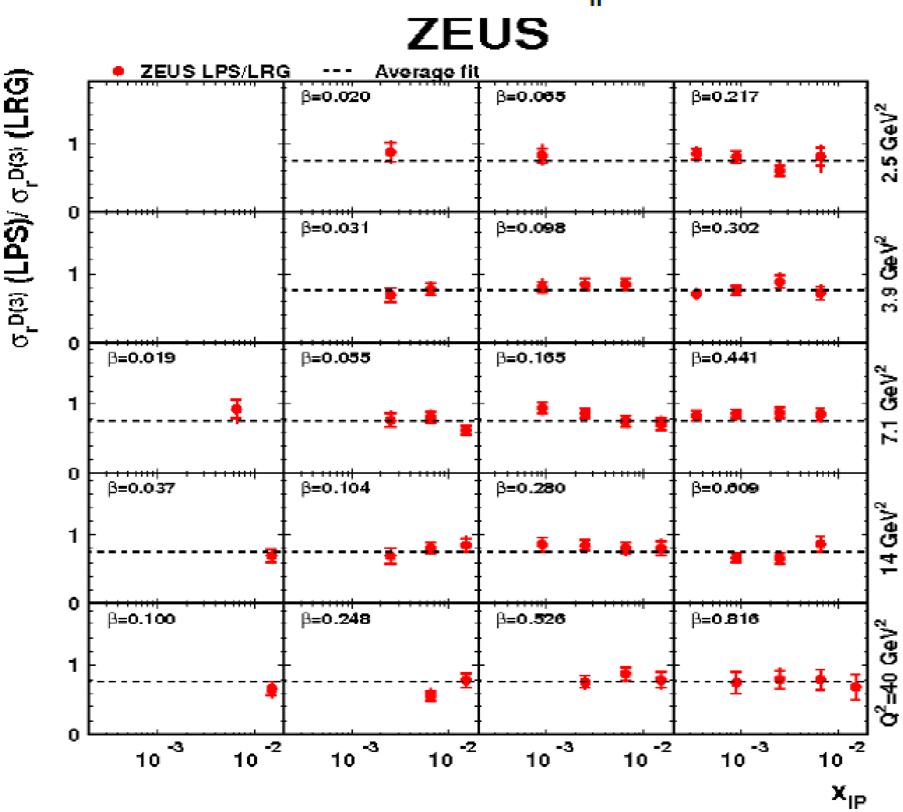






LRG data contains sizeable proton-dissociative contribution ~20-30%

Ratio LRG/LPS does not depend on Q^2, β, x_{IP}

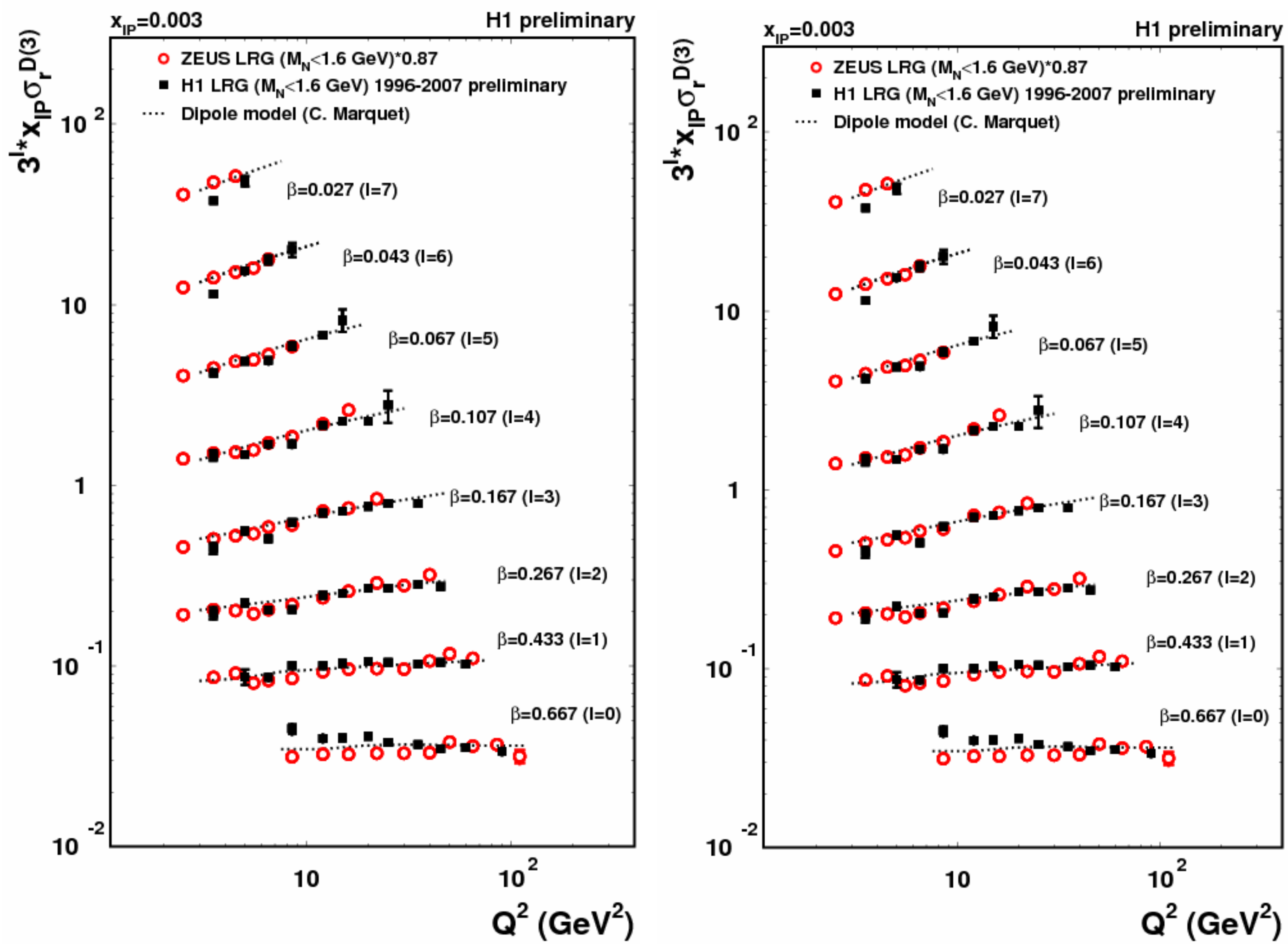


Large Rapidity Gap data : ZEUS vs H1

$\sigma_r^{D(3)}$ at x_{IP}=0.003, 0.01

Reasonable agreement between H1 and ZEUS measurements in most of phase space

~13% normalisation difference - within the uncertainties (dominant contribution from p-diss. background)

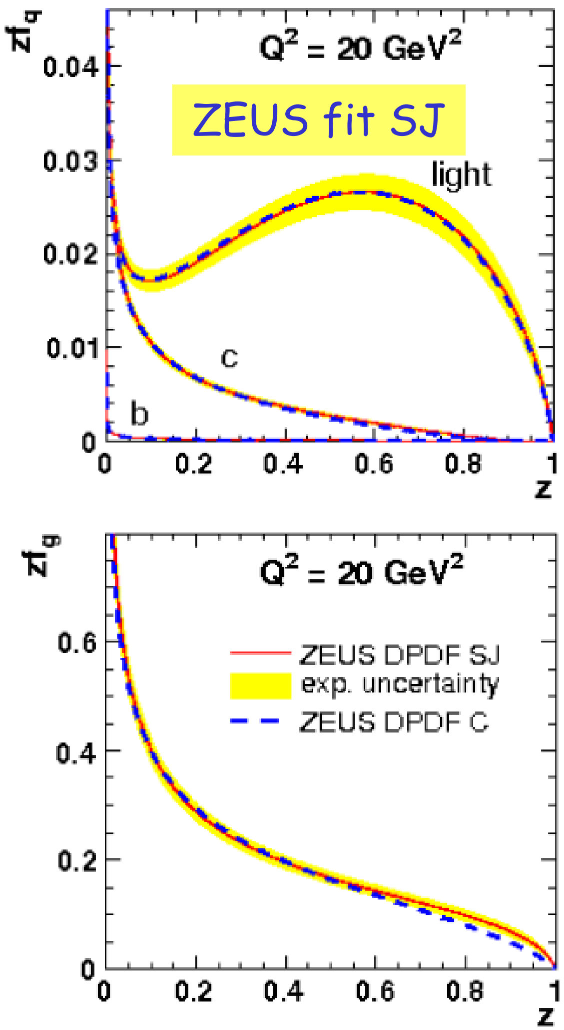


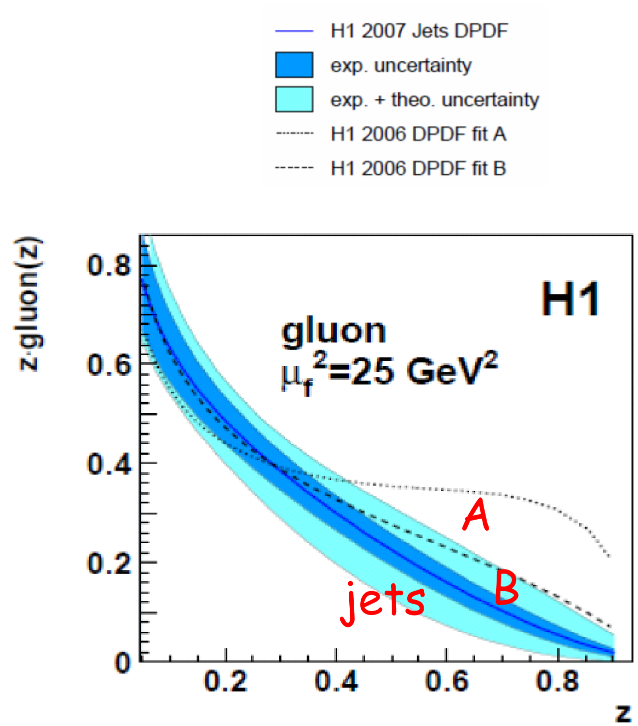
- F_2^D-positive scaling violation (rise with Q^2) up to large β → different from F_2
- β-dependence relatively flat

➔ large gluon component

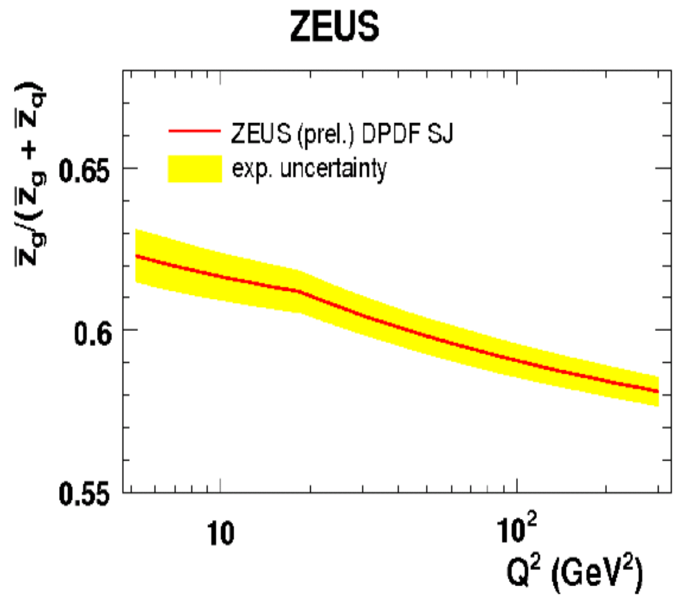
QCD fits to diffractive data $\sigma_r^{D(3)}$

- use NLO DGLAP evolution analysis technique to Q^2 and β dependences of diffractive cross sections.
- assume Regge factorisation
- F_2^D constrains quarks; gluons - from scaling violation; improvement of g(x) from the jet data



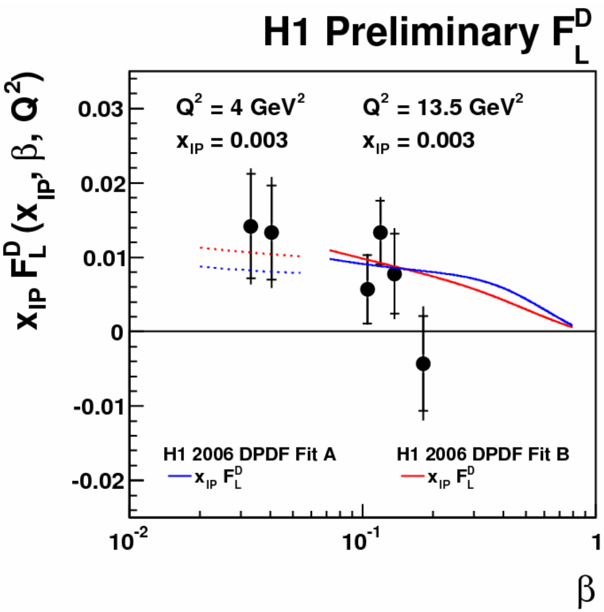


Gluon momentum fraction in diffractive excjhange ~ 60÷70%

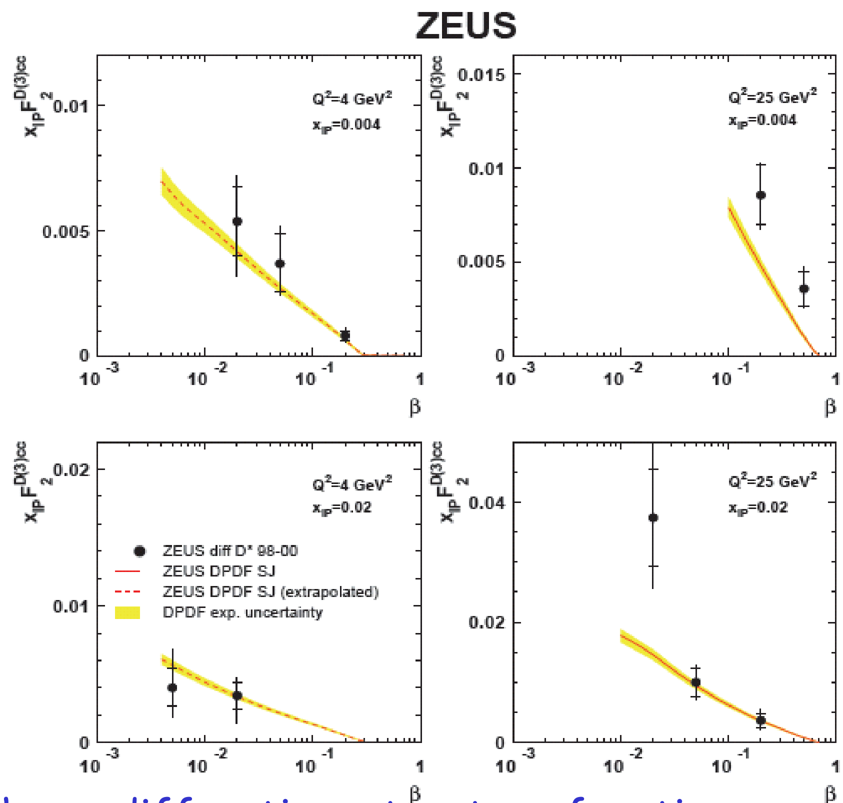


Test diffractive parton densities in diffractive DIS (F_L^D, jets and charm)

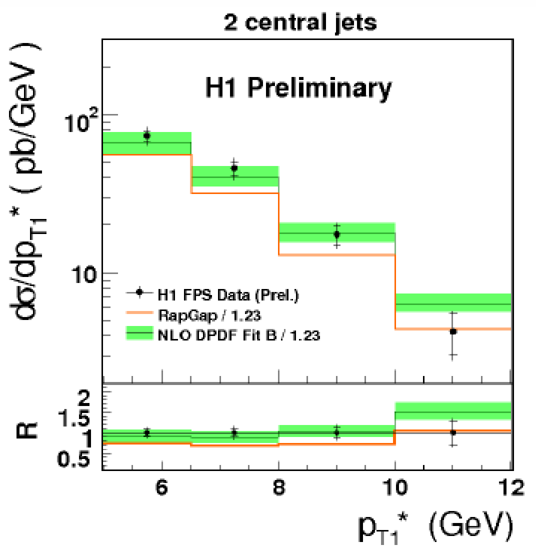
production mechanisms directly sensitive to the gluon content of colour singlet exchange → constrain the gluon density

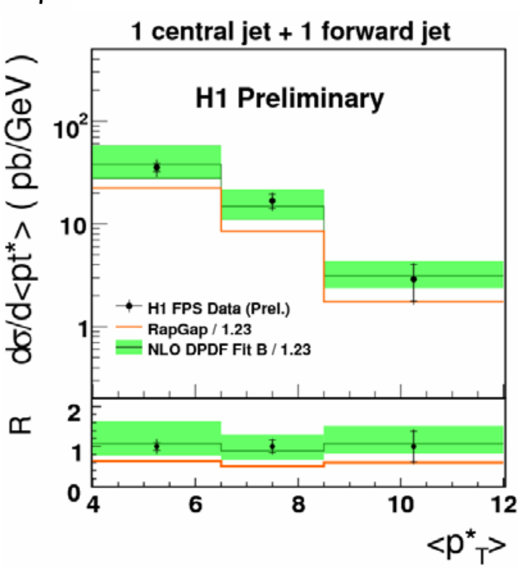


← F_L^D measured ~3σ from zero



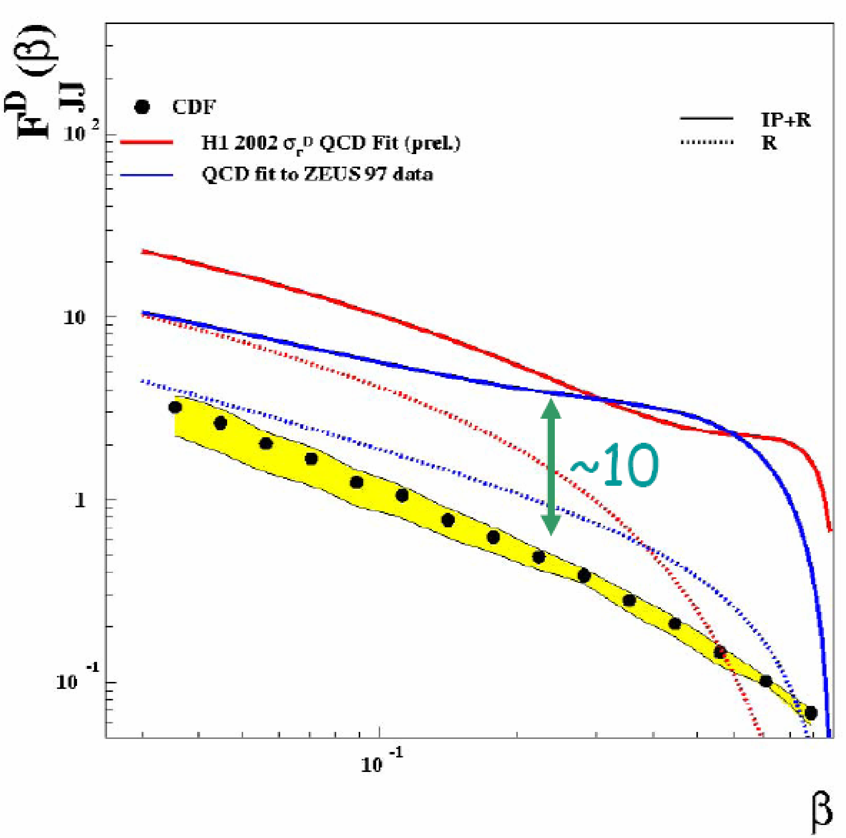
Charm diffractive structure function $x_{IP}F_2^{D(3)cc}$ compared to ZEUS DPDF fit SJ predictions





← Jet cross sections (2 central jets, 1 central+1 forward jets) compared to H1 DPDF FitB predictions

F_L^D, the charm and jet production in DIS- reasonable description by NLO QCD, using DPDFs and DGLAP

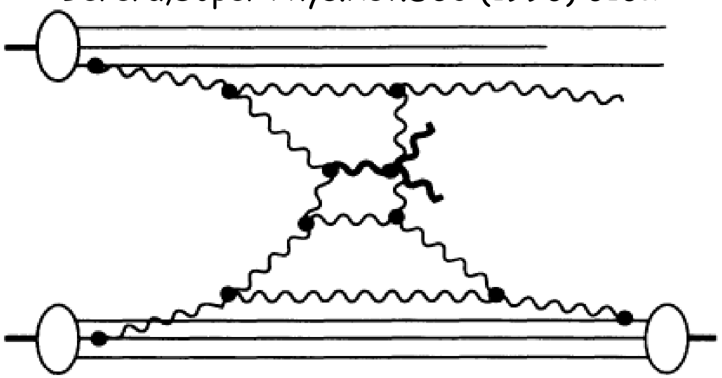


huge difference between the predictions based on the F_2^D fits from HERA and diffractive jet measurements at Tevatron !
Factorisation is broken in $p\bar{p}$

Violation of factorisation can be understood in terms of (soft) rescattering between the two hadrons and their remnants, in initial and final state, suppressing the large rapidity gap

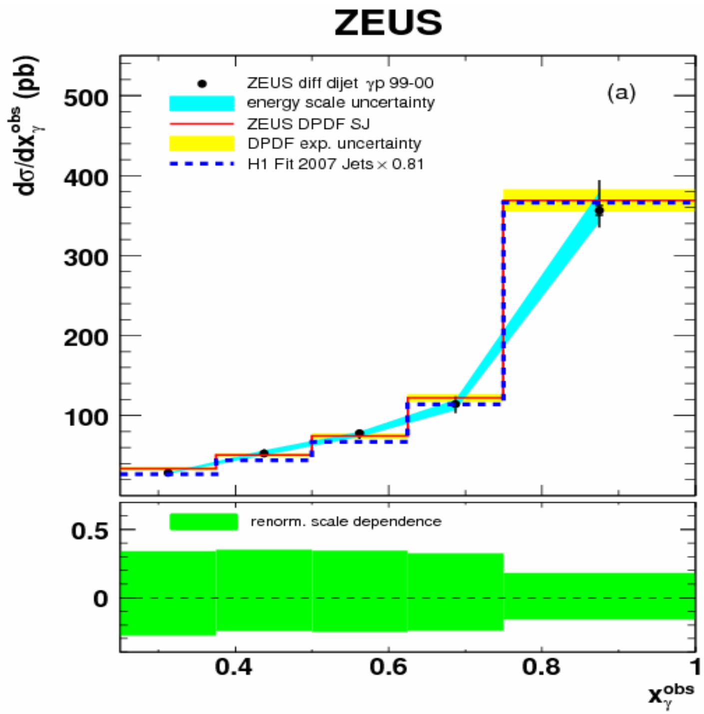
'Gap survival' factor S^2~0.1

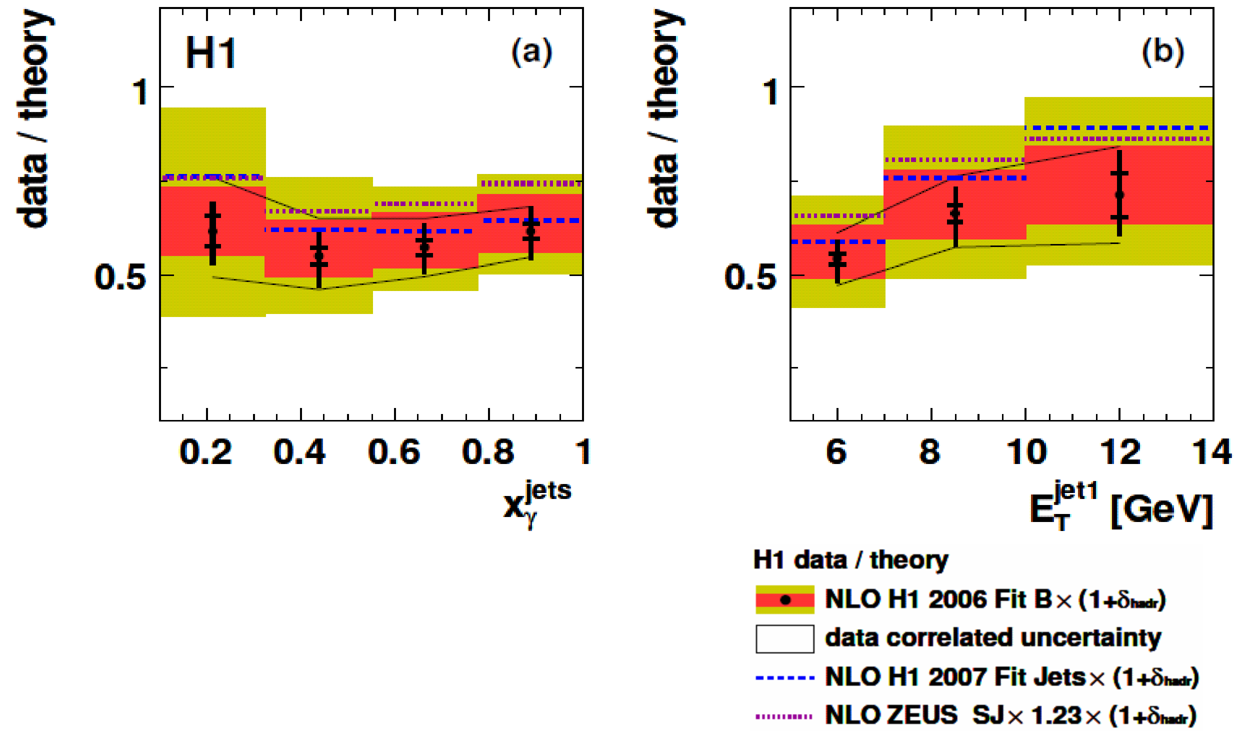
Berera,Soper Phys.Rev.D53 (1996) 6162



Very essential for the predictions for Diffractive Higgs production at the LHC

Photoproduction (Q^2~0) → photon has resolved component, like a hadron → expect some violation of factorisaton as in pp

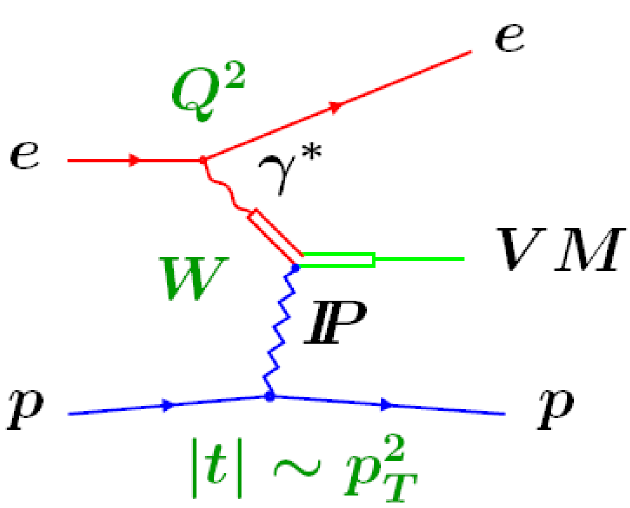




-ZEUS: E_t^{jet1} > 7.5 GeV → good description of jet data → no suppression

-H1: E_t^{jet1}> 5 GeV → suppression by factor ~2, no x_γ dependence (i.e. suppression also at high x_γ) . Suppression is E_t^{jet} dependent

Exclusive Vector Meson production



"soft" Regge theory and VDM model

"hard" pQCD description
in presence of hard scale: Q^2, M_{VM} or t

Energy *(W)* and *t* dependences:

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

$$\delta = 4(\alpha_{IP}(t) - 1)$$

$$\frac{d\sigma}{dt} \propto e^{-bt}$$

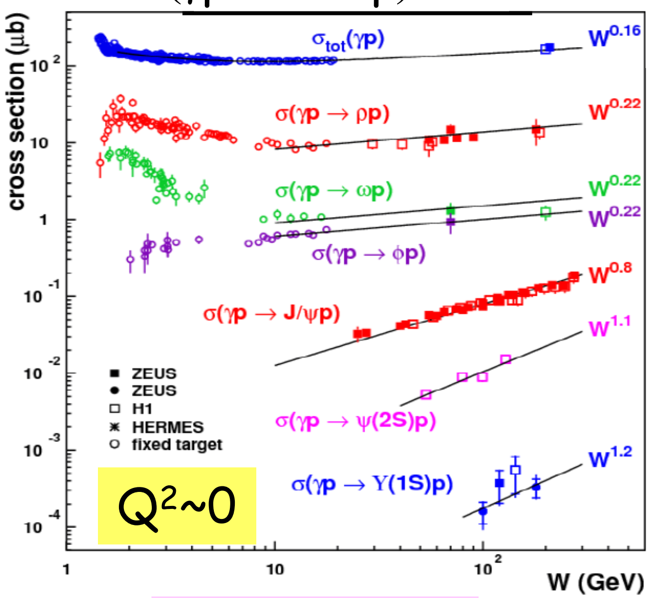
With HERA data it is possible to investigate the transition from "soft" to "hard" pomeron exchange processes with increasing of Q^2, M_{VM} or *t*.

- **Expect δ to increase from 'soft' (~0.2) to 'hard' (~0.8)**
  - for soft Pomeron: $\alpha_{IP}(t)=1.08+0.25\cdot t$ (DL)
  - for hard interaction: $\sigma \sim |xg(x,Q^2)|^2$ →fast increase of cross section with energy due to the gluon density in proton ($W^2 \sim 1/x$)

- **Expect b to decrease from 'soft' (~10 GeV^{-2}) to 'hard' (~4÷5 GeV^{-2})**
  (b is related to the size of interaction)

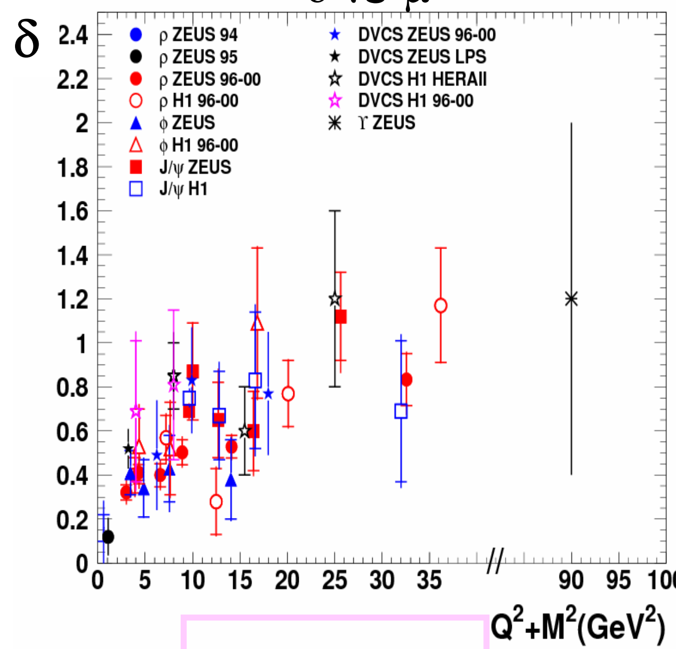
Exclusive Vector Meson production and DVCS

$\sigma(\gamma p \rightarrow VM+p)$ vs W



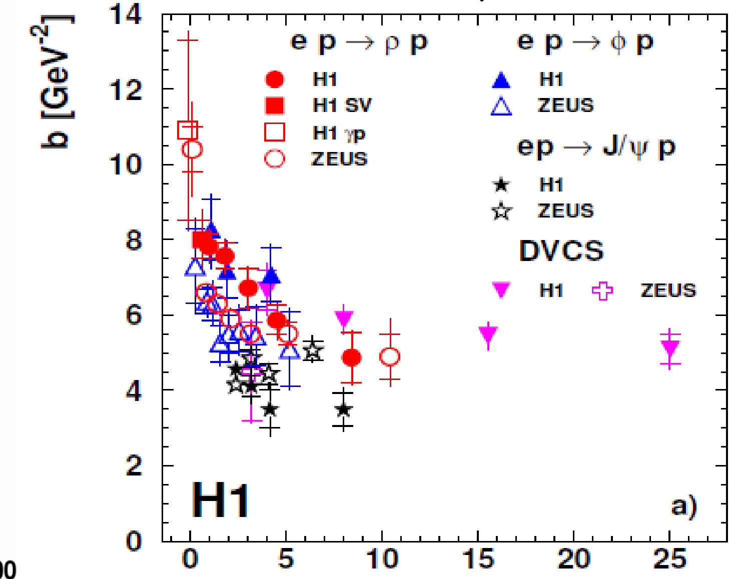
$$\sigma(W) \propto W^{\delta}$$

δ vs μ^2



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

b vs μ^2



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

μ^2 [GeV^2]

$\mu^2 = (Q^2 + M_V^2)/4$

(Q^2 for DVCS)

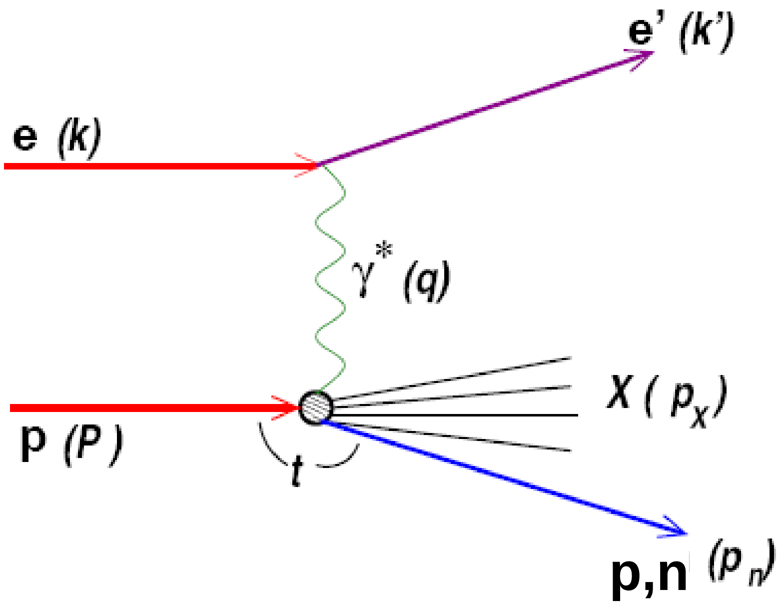
➔**Transition from soft to hard regime with increasing of hard scale**

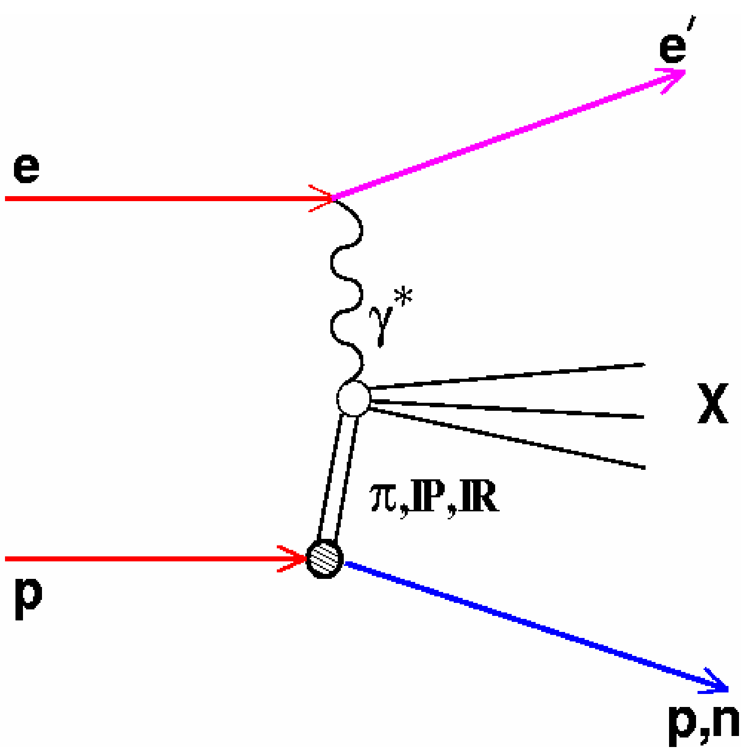
-In photoproduction - higher slope for heavy VM

-Similar behavior for all VMs and DVCS: hardening of W distribution (δ increase) with μ scale

-***b*** decreases from 5 GeV^{-2} to 10 GeV^{-2}: ➔ size of scattered VM getting smaller with scale

Significant fraction of *ep* scattering events contains in the final state a leading proton or neutron which carry a substantial portion of the energy of the incoming proton: e+p → e'+n+X or e'+p+X





'conventional' fragmentation of proton remnant (e.g. Lund string)

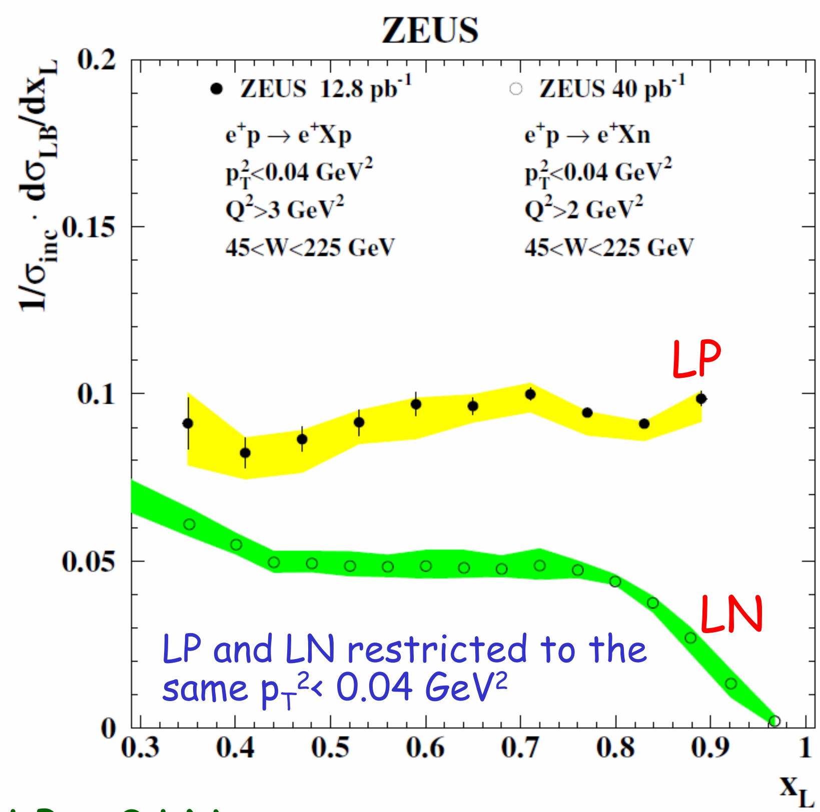
exchange of virtual particle

- **LP: neutral iso-scalar,iso-vector (π,IR,IP)**
- **LN: charged iso-vector ($\pi+$,$\rho+$,a_2..)**

In the exchange model the cross sections factorise, e.g. for π-exchange

$\sigma(ep\rightarrow e'NX) = flux(x_L,t) \times \sigma(e\pi\rightarrow e'X)$

LP and LN cross sections $(1/\sigma_{DIS} \times d\sigma/dx_L)$

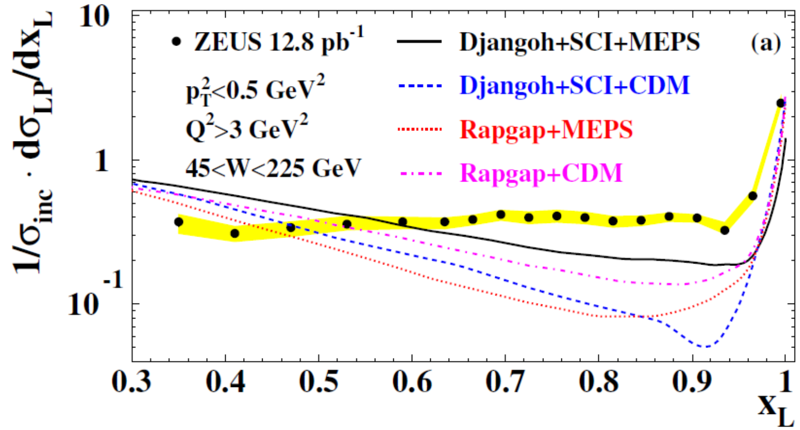


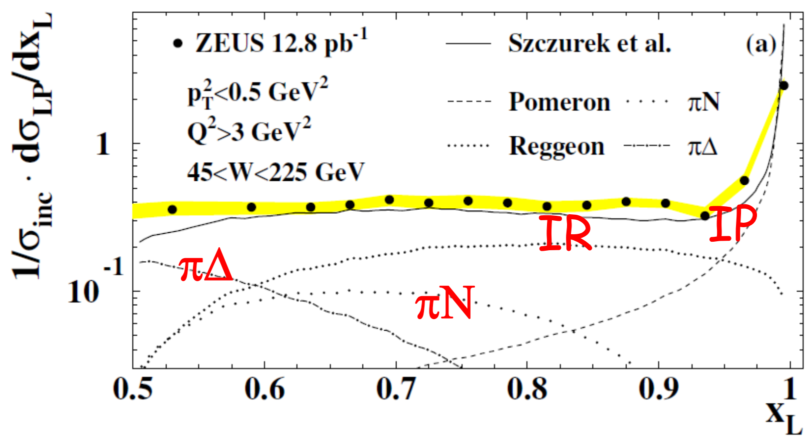
- LP ~ 2·LN

for pure isovector particle exchange (e.g. pion) one expects LP = ½·LN

➔more isoscalar exchanges contribute to the LP rates

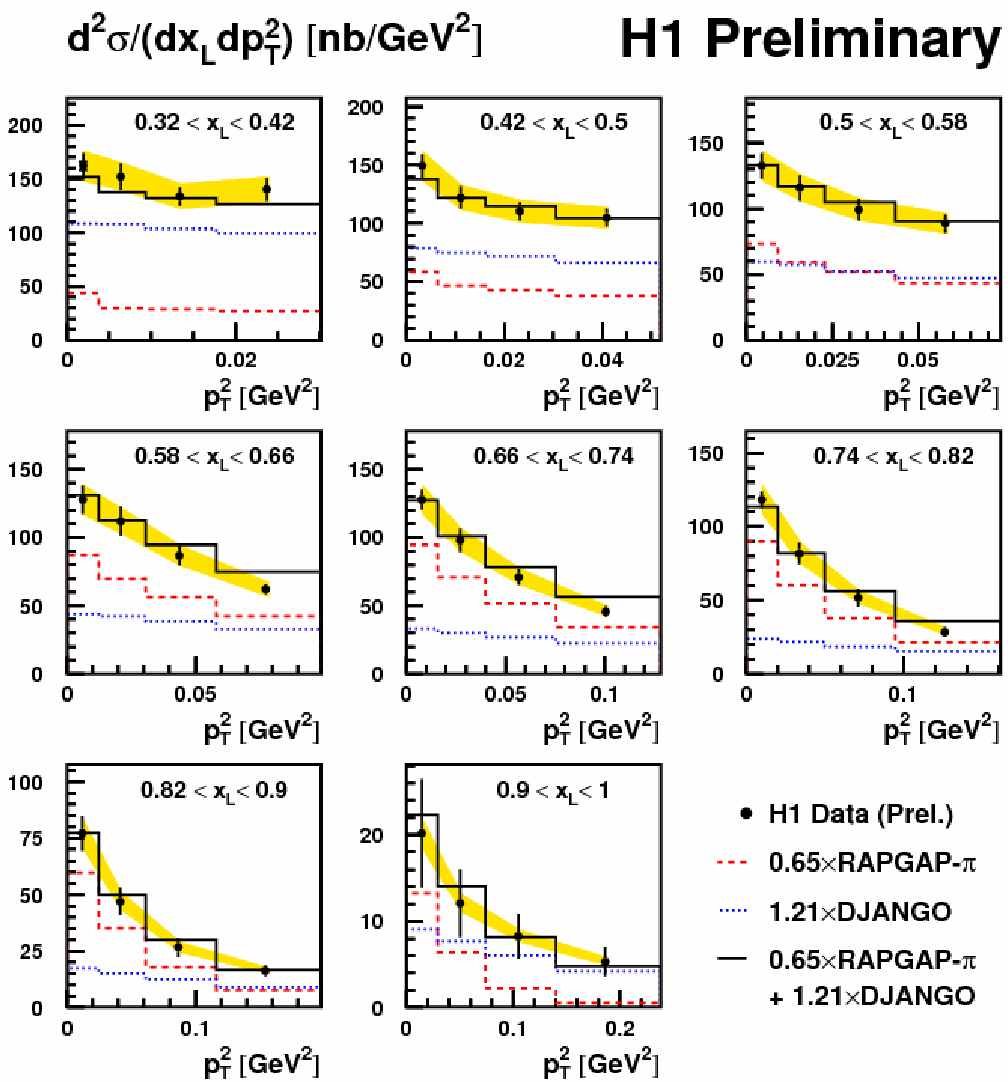
LP cross section

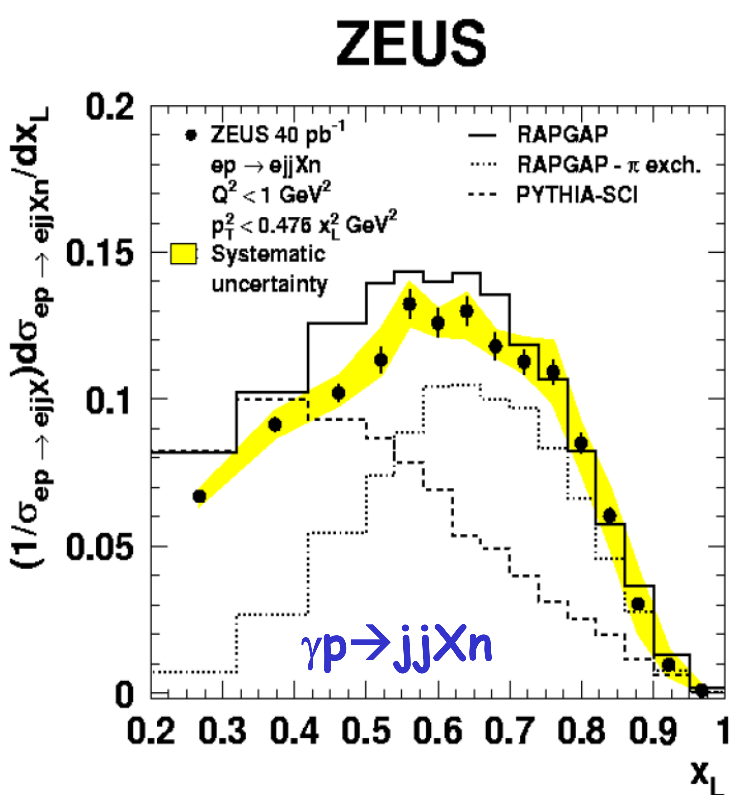




- diffractive peak at x_L=1 ; flat at x_L<0.95
- standard fragmentation MC models don't describe the data out of the diffractive peak
- good description by exchange models
- isoscalar reggeon dominant at intermediate x_L

LN production: comparison with fragmentation and exchange models:

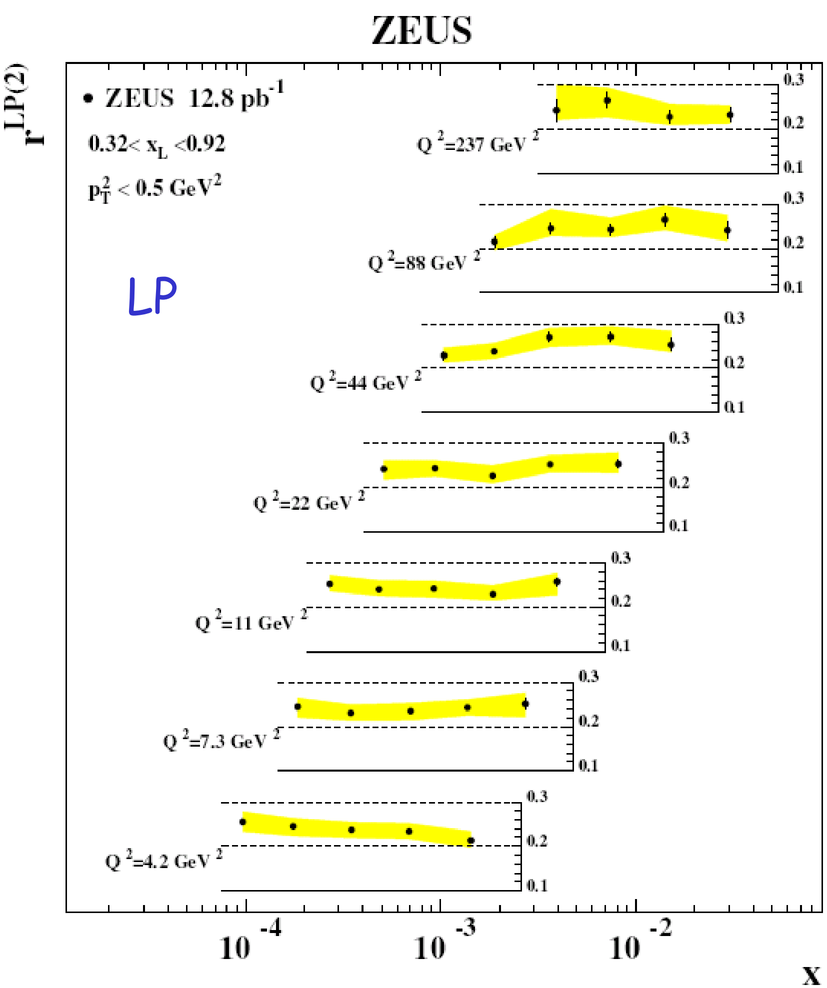


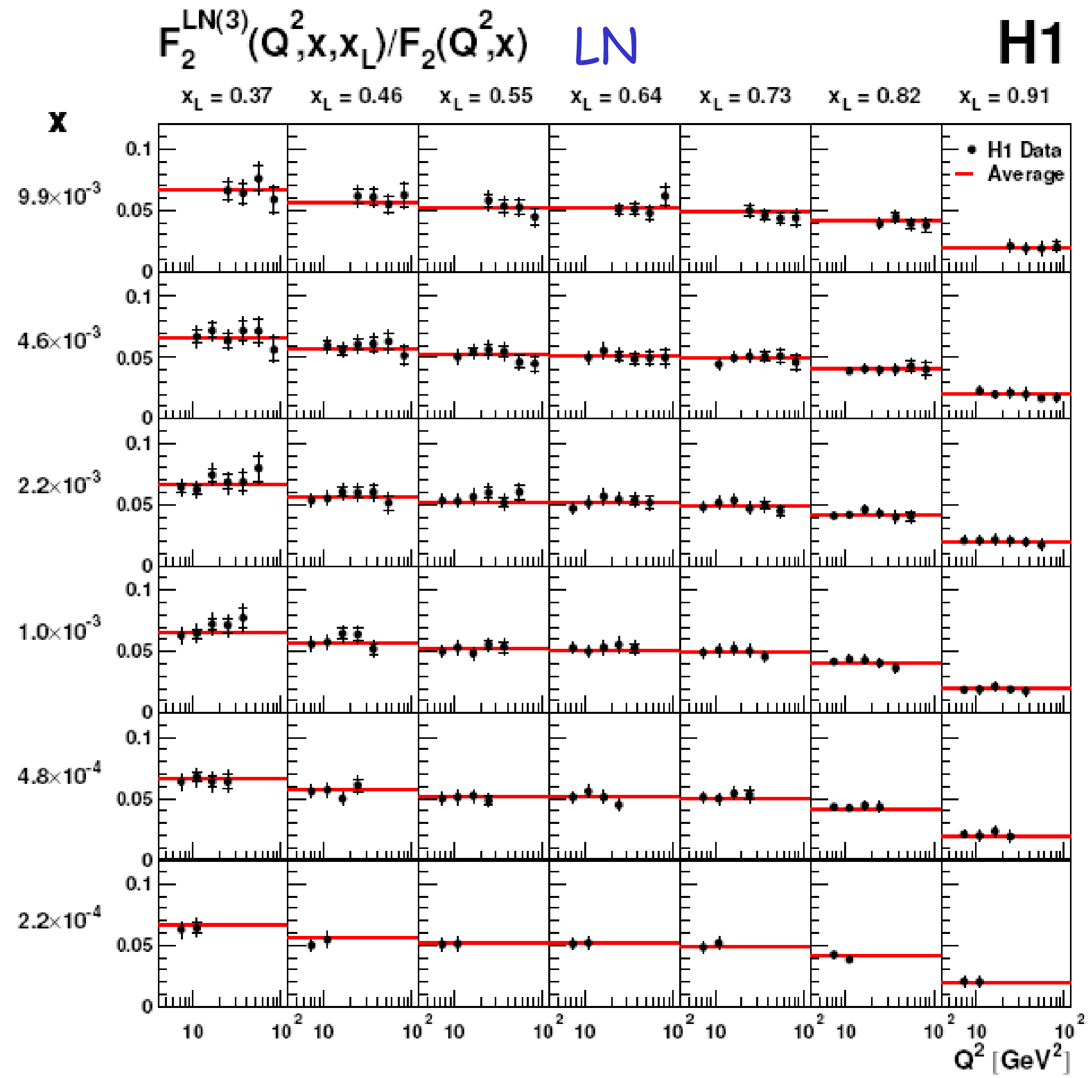


- all standard fragmentation models underestimate the neutron yield at high x_L
- best description of leading neutron data gives the mixing of π-exchange (RAPGAP) and standard fragmentation (e.g. DJANGO or PYTHIA)

Leading Baryon production rate in DIS: F_2^{LN} and F_2^{LP} ratio to F_2

$$\frac{d^3\sigma(ep \to eNX)}{dQ^2\,dx\,dx_L} = \frac{4\pi\alpha^2}{xQ^4}\left[1 - y + \frac{y^2}{2}\right] F_2^{LN}(Q^2, x, x_L)$$





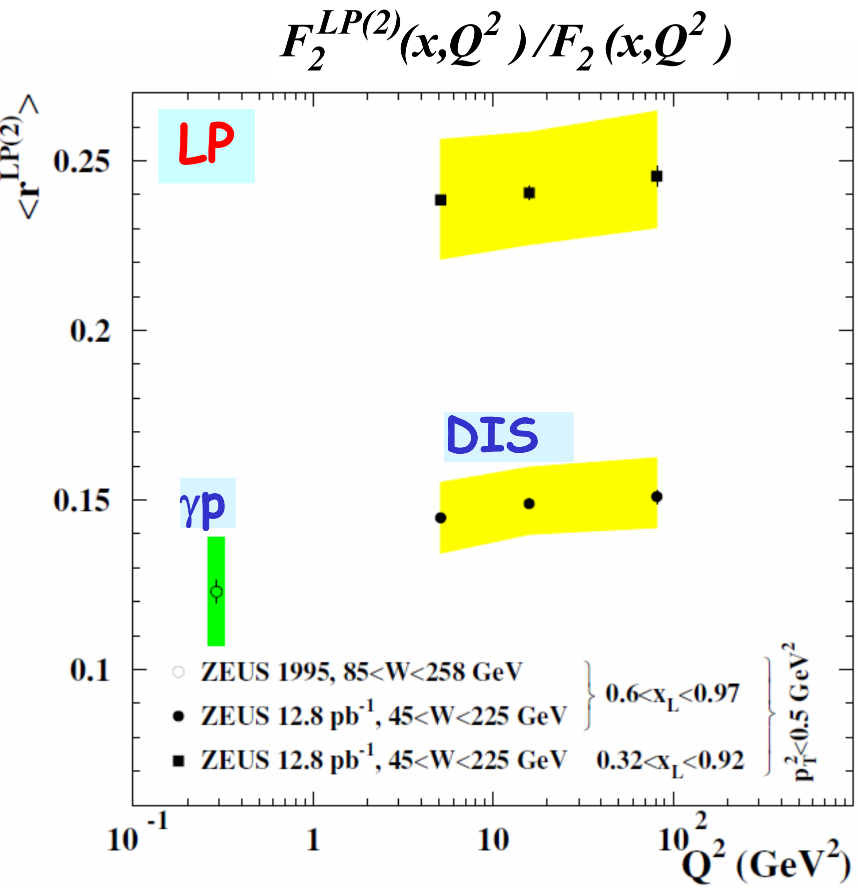
$F_2^{LP,LN}/F_2$ **is mostly flat in Q^2 and x**

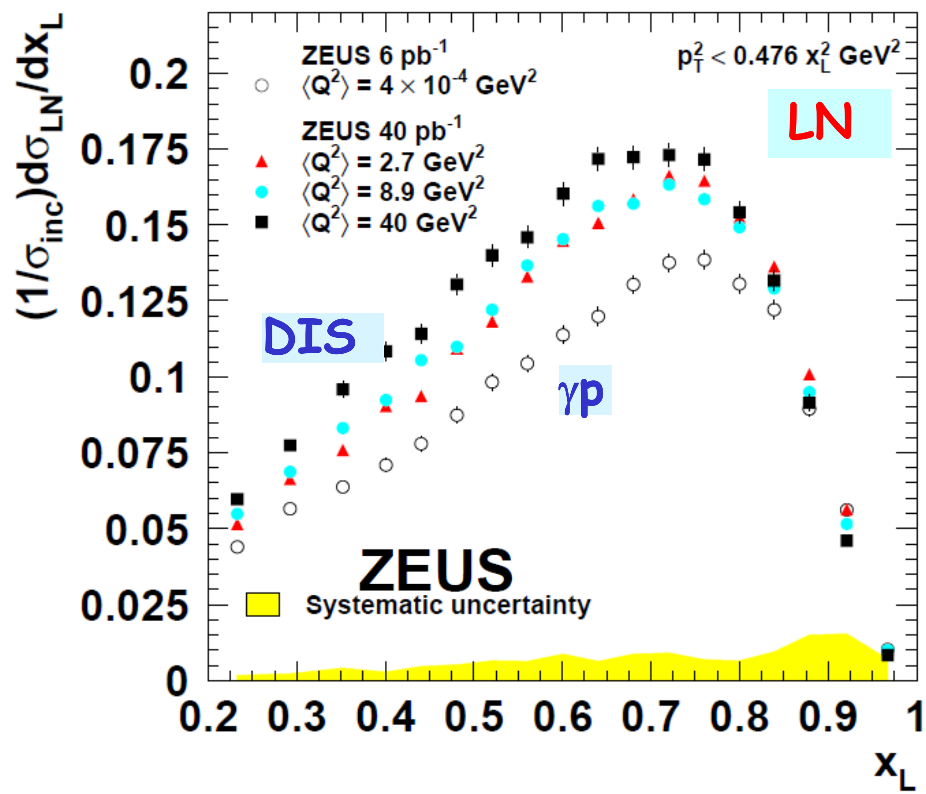
i.e. LB production rate, kinematics is approx. independent of (Q^2, x)

Proton/neutron absorption through rescattering - important ingredient to interpret the results in terms of particle exchange (in other language: multi-Pomeron exchange)

Expectation: suppression of LP,LN events in photoproduction:

higher Q^2 → smaller γ^* transverse size → less absorption → larger event yield

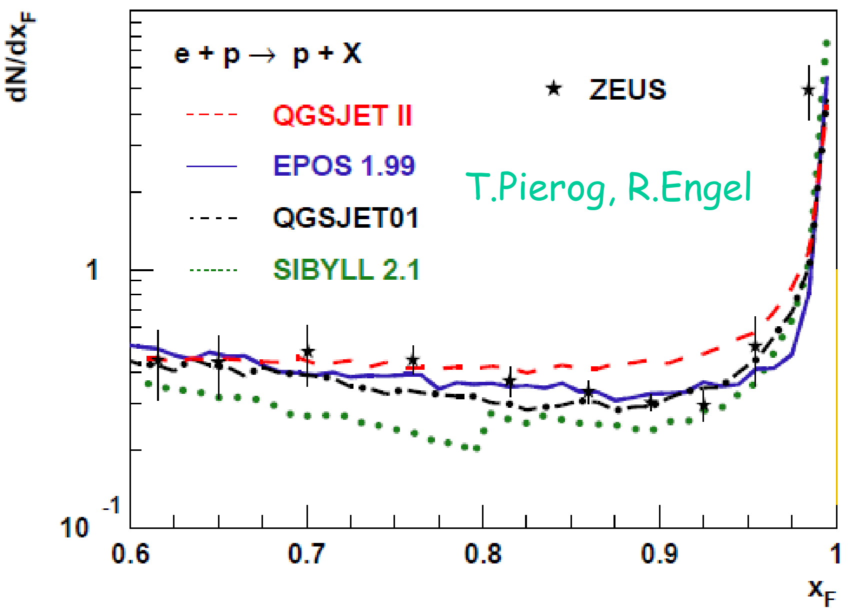


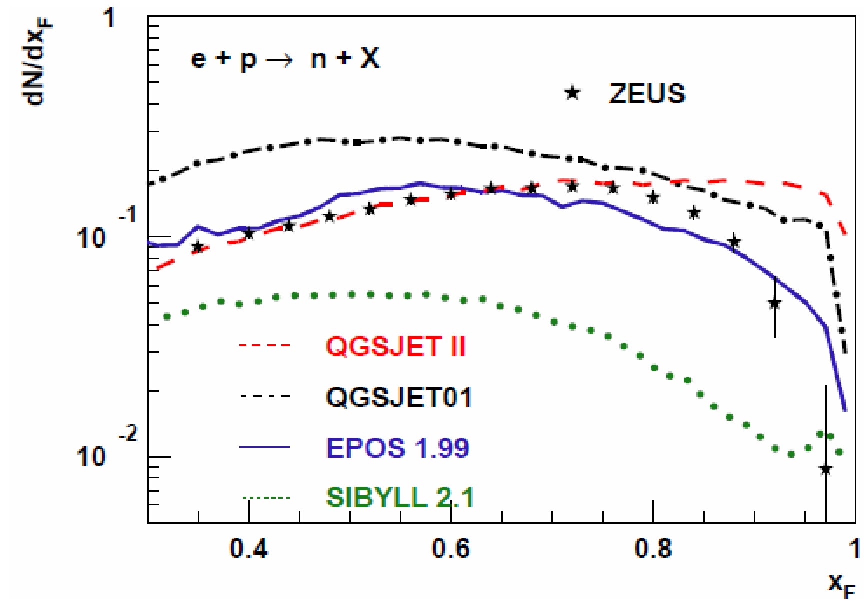


Increase of LP and LN rates from γp to DIS ➔ suggest violation of vertex factorisation

The tuning of CR interaction models crucially depends on the input from the measurements at accelerators

In particular, the forward measurements (baryons, γ's, π^0) are of the greatest importance for the model tuning, since the shower development is dominated by the forward, soft interactions.





- reasonable predictions for LP data (after model tuning)
- none of models describe LN data well

→ HERA can further contribute to the understanding of high energy cosmic rays

Summary

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

- New phase of H1 and ZEUS mutual collaboration:
  combined cross section measurements reach 1% precision

- HERAPDF- high precision and extended kinematic reach

- Wealth of new jet data from HERA available
  - high precision α_S → need theoretical calculations to higher order

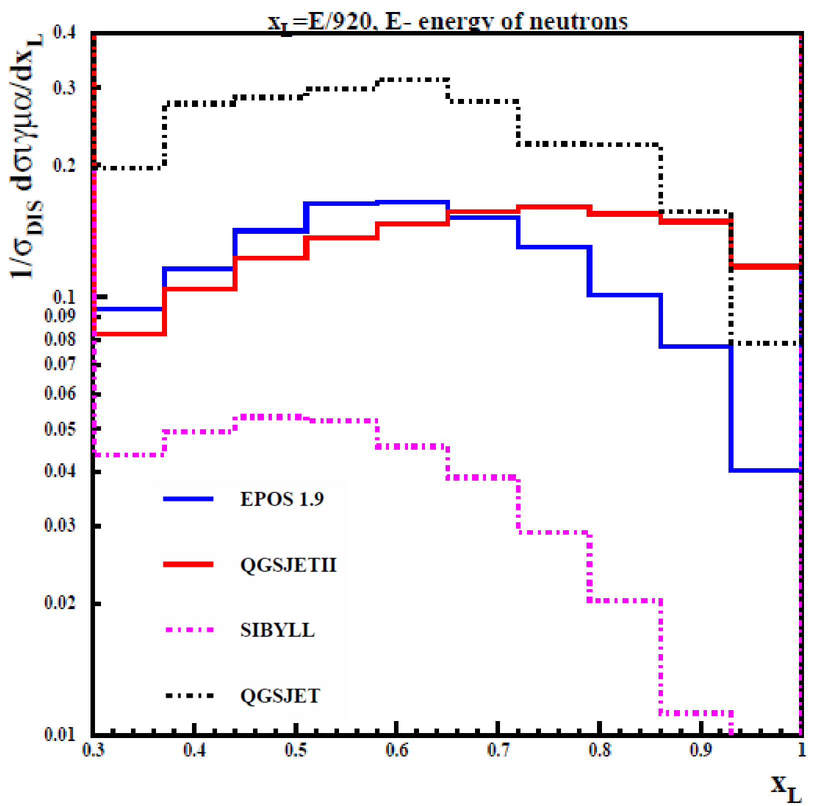
- The partonic structure of diffraction is measured with high precision. Diffractive PDFs are extracted from the NLO fits to the data.

- Leading baryon data important for an improved theoretical understanding of proton fragmentation mechanism: provide a useful input for models of CR interactions with matter.

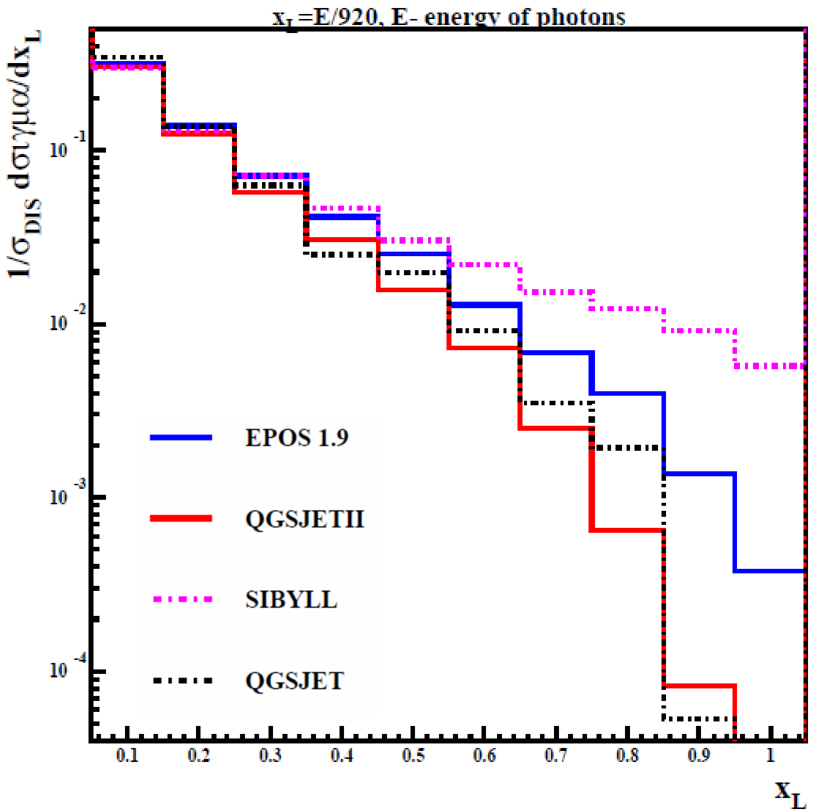
- HERA has a reach program that should be completed.

Backup

Predictions of CR models for forward neutrons and photons at HERA



Forward neutrons, theta<0.75 mrad



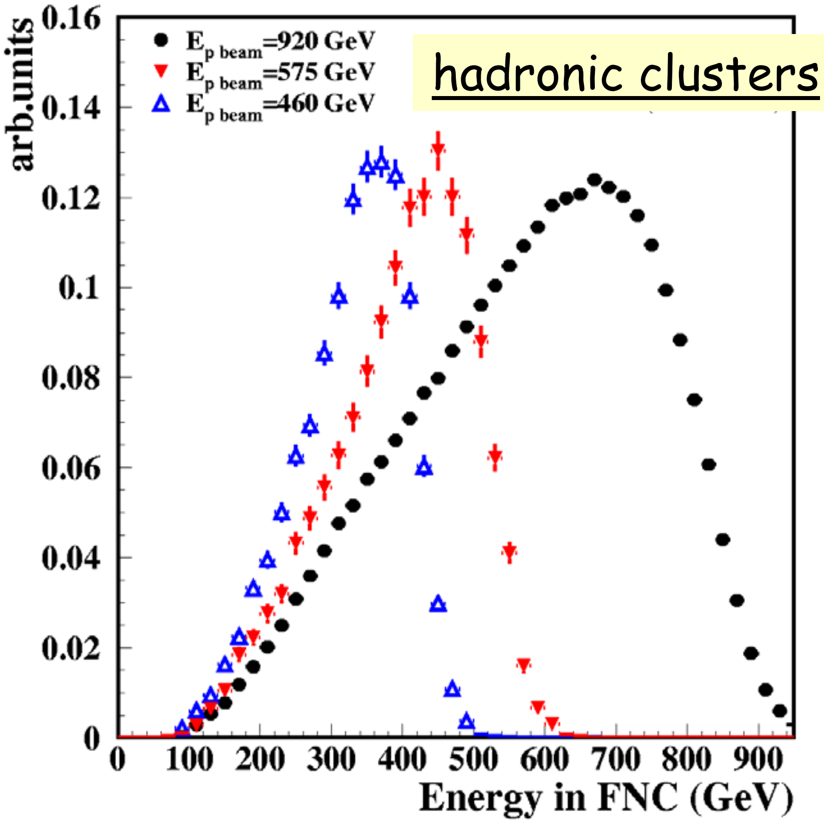
Sum of energy of forward photons within theta<0.75 mrad (η>7.9)

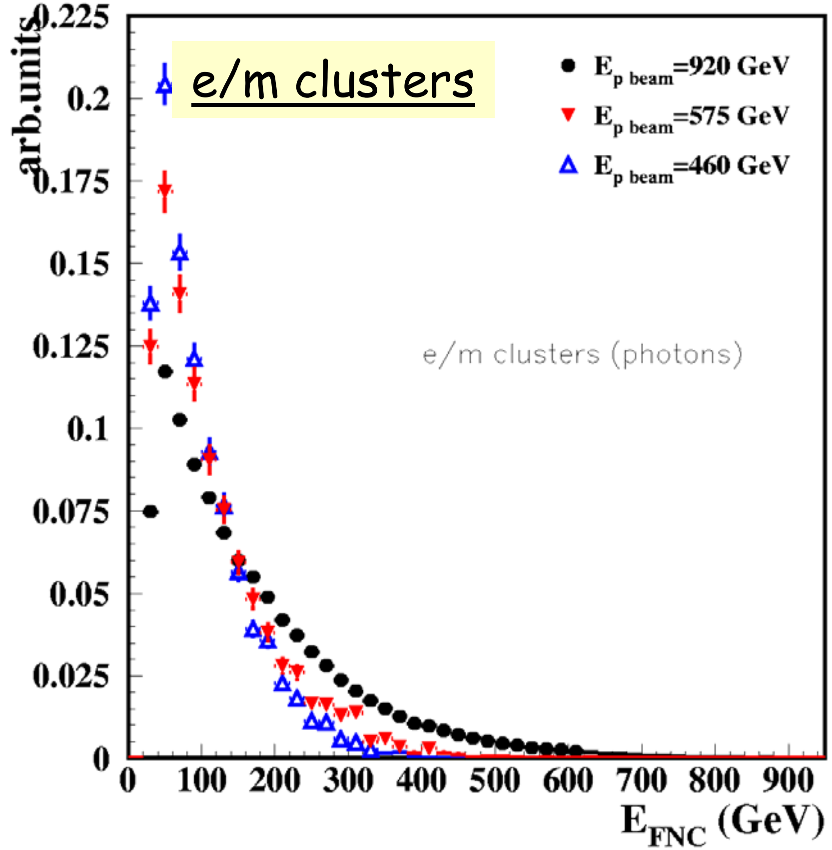
HERA can further contribute to the understanding of high energy cosmic rays

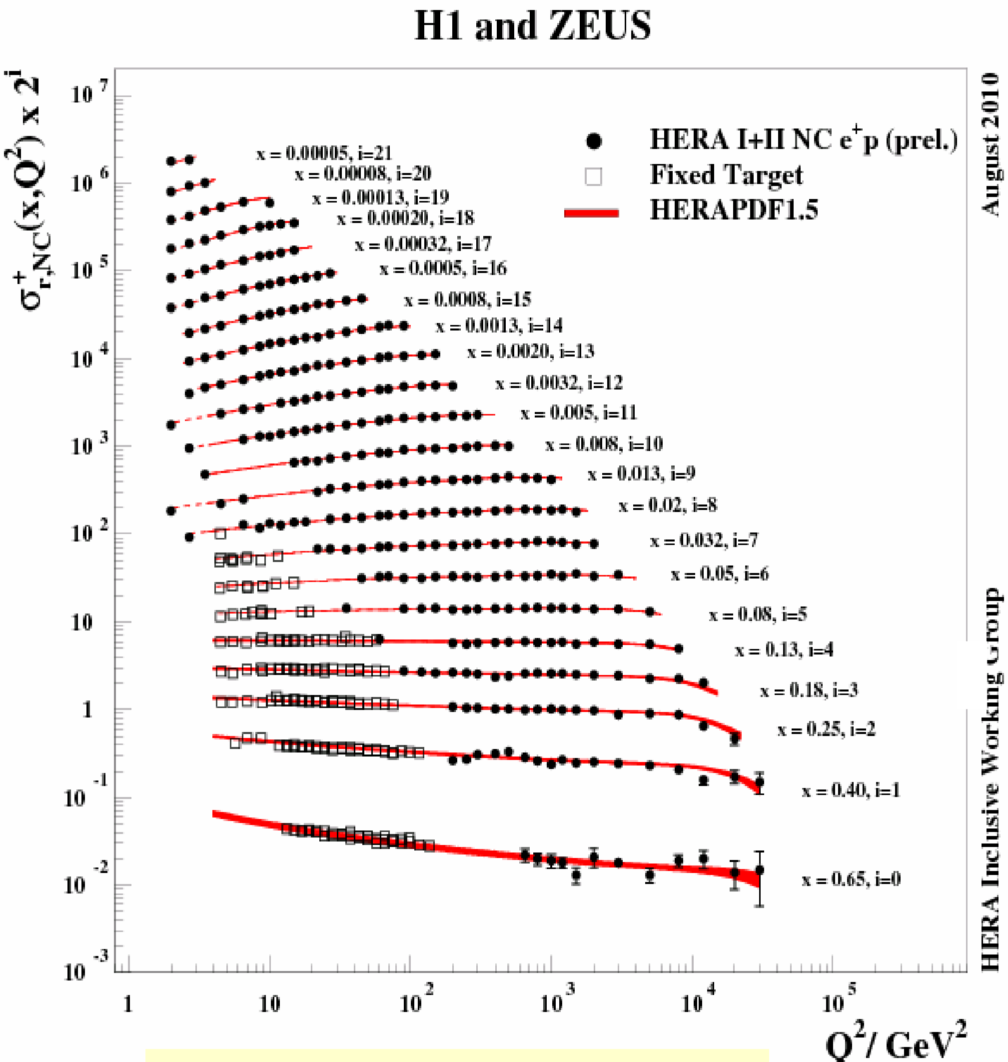
We measure the differential distributions of x_L and p_t for protons, neutrons and photons, in the photoproduction and DIS regimes

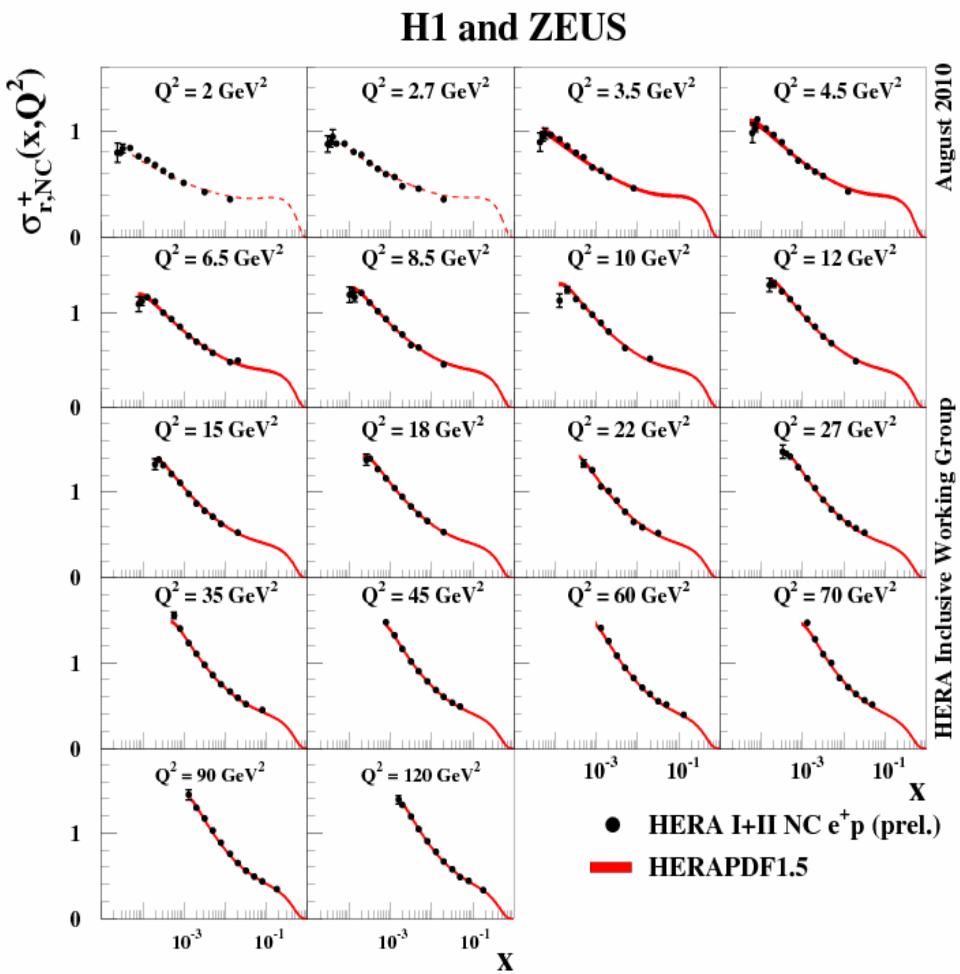
The measurements can be made also as a function of proton beam energy
(The last 3 months HERA was running with 460 GeV and 575 GeV protons.)

Energy distributions of electromagnetic (photons) and hadronic (neutron) clusters in H1-FNC at tree different proton beam energies (920, 575 and 460 GeV).









rise of F_2 with Q^2 at low x

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

(scaling violation)

rise of F_2 at x→0 as

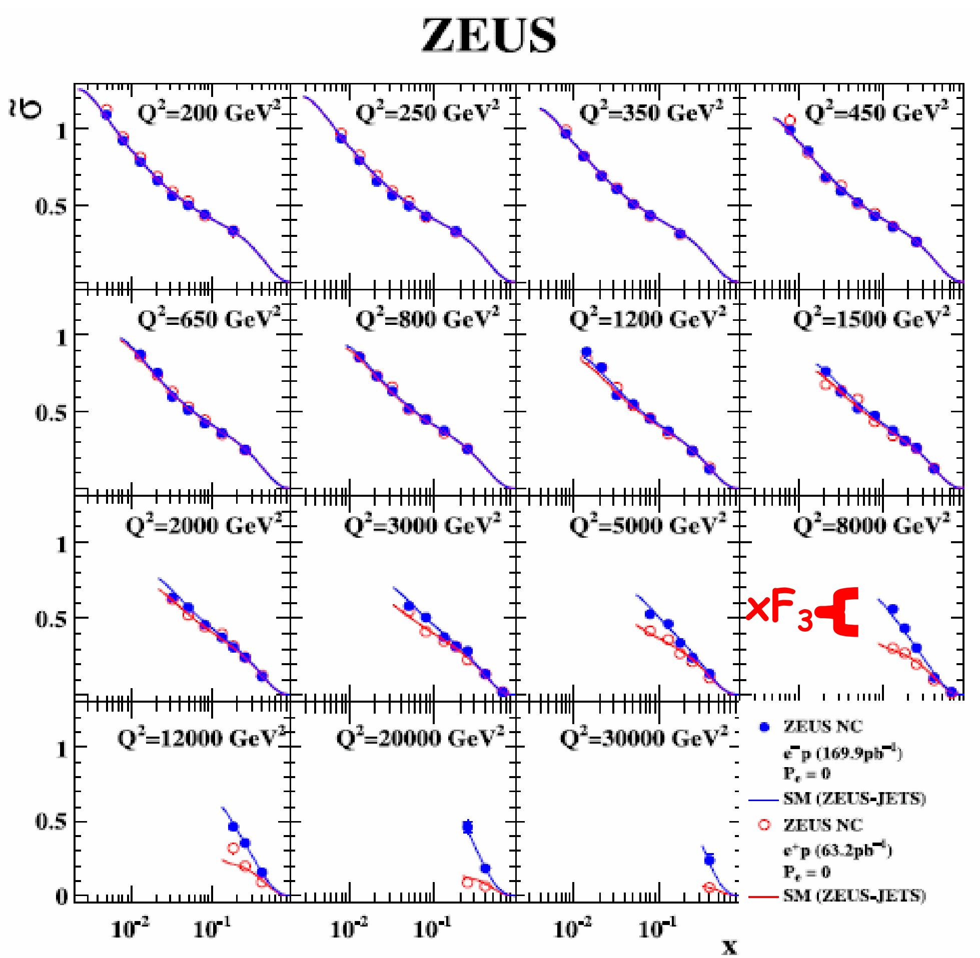
$$F_2 \sim x^{-\lambda(Q^2)}$$

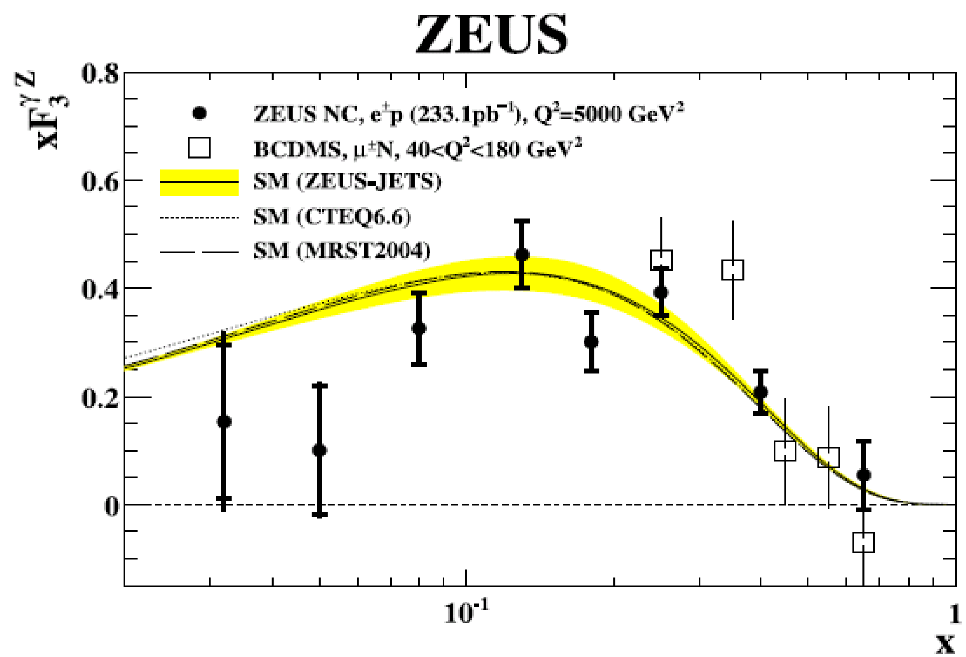
(λ increasing with Q^2)

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

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

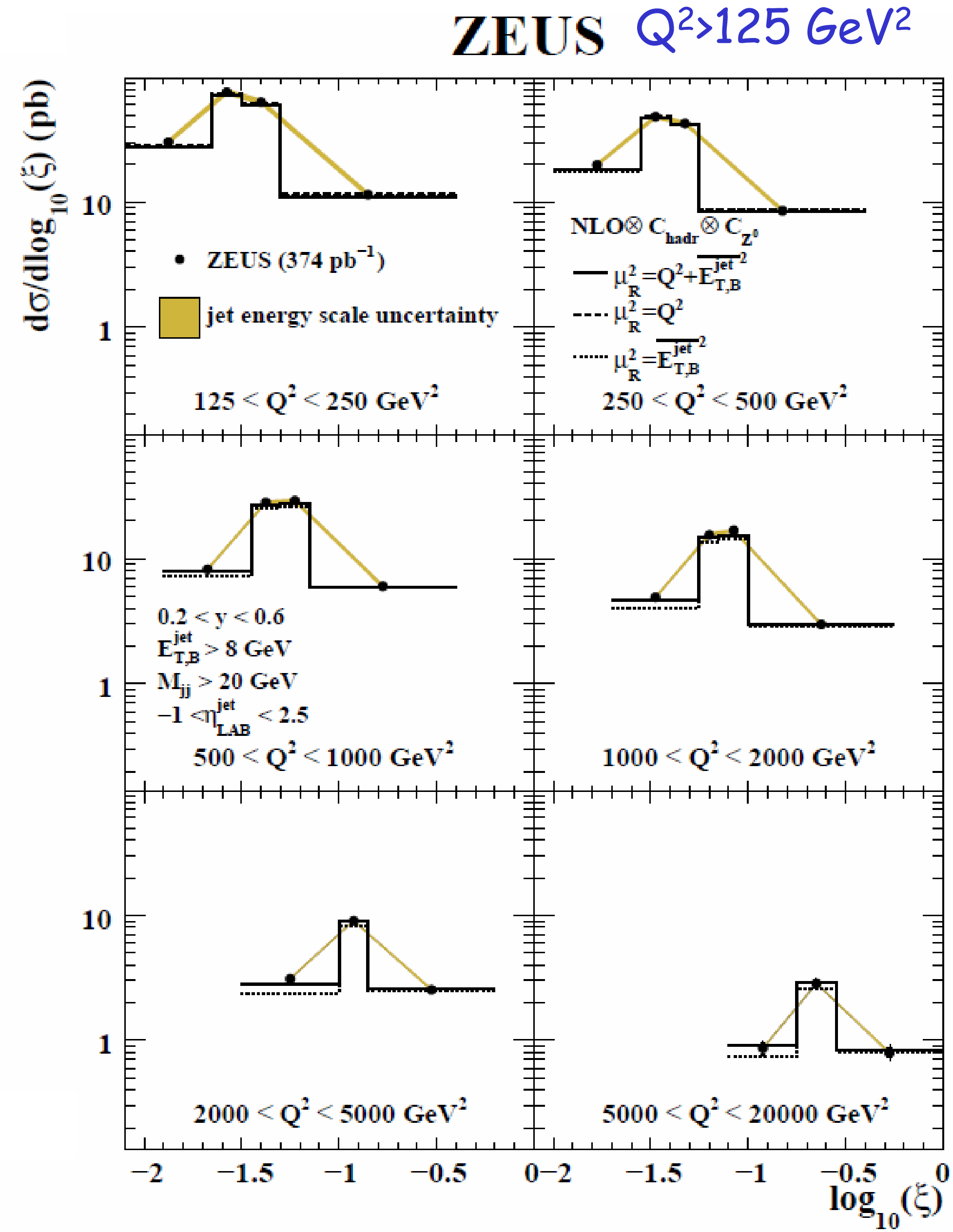
$$xF_3 \sim \sigma(e^- p) - \sigma(e^+ p)$$



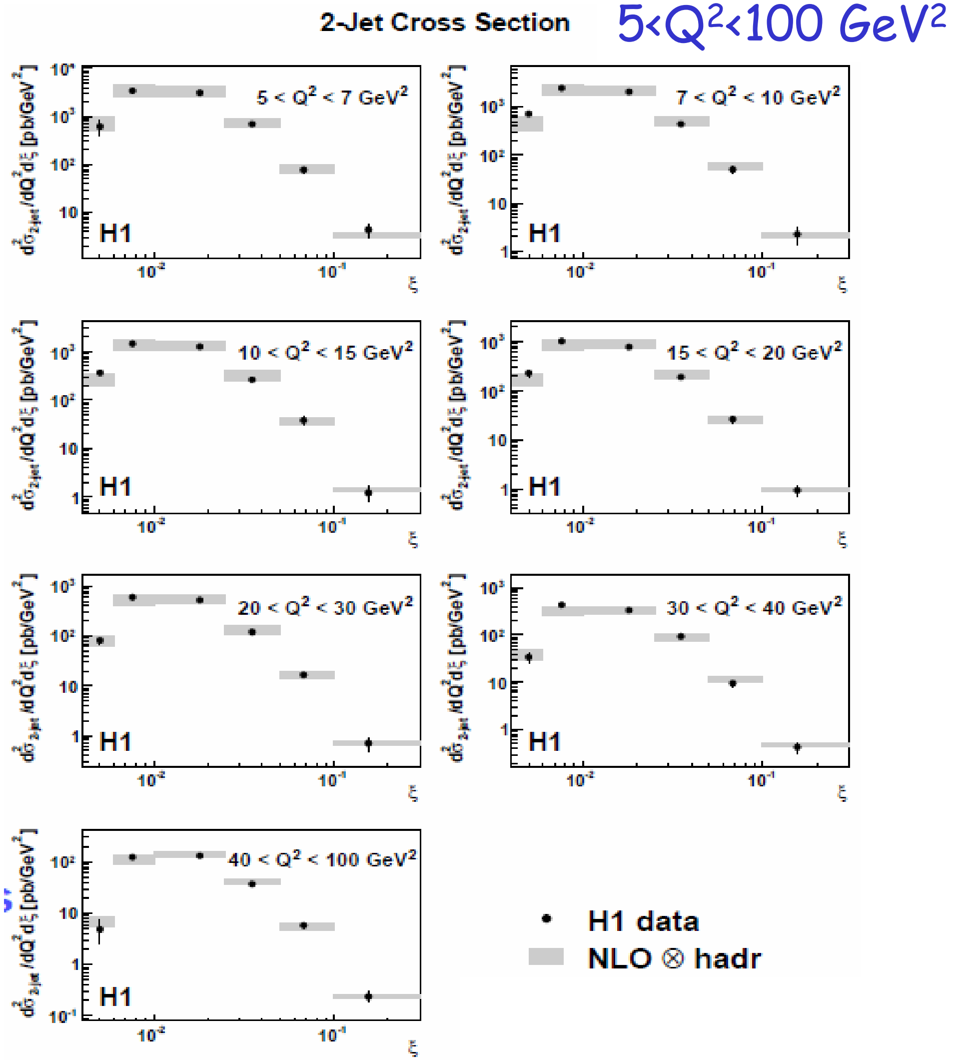


Dijet production – constraints on proton PDF

$Q^2 > 125\ GeV^2$



$5 < Q^2 < 100\ GeV^2$



$$\xi = x_{\mathrm{Bj}}(1 + (M^{\mathrm{jj}})^2 / Q^2)$$

estimator of the fraction of the proton momentum carried by the interacting parton