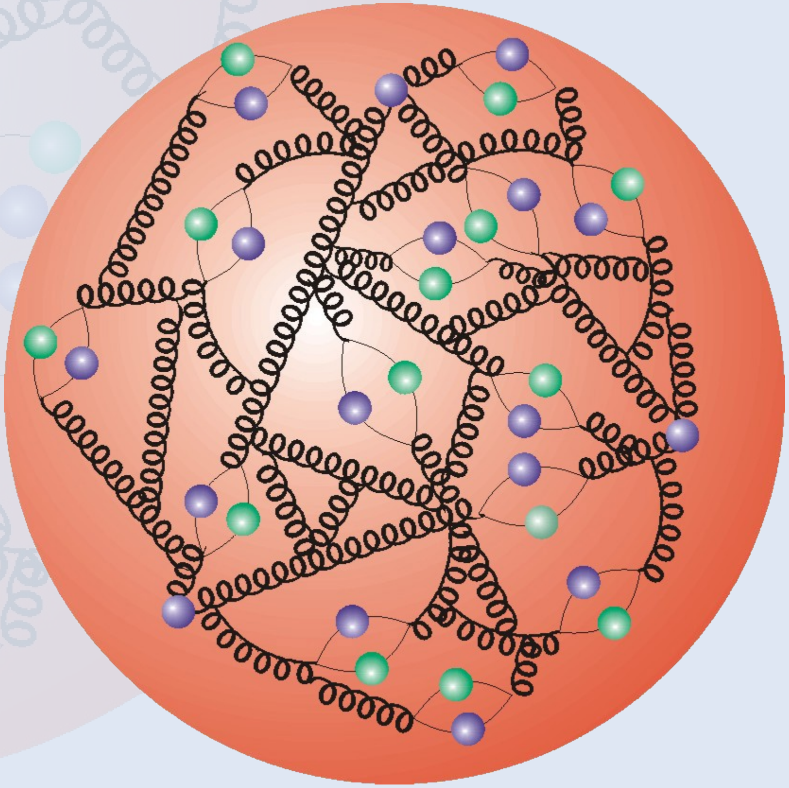
QCD at HERA

V. Boudry
Laboratoire Leprince-Ringuet,
École polytechnique,
Palaiseau, France

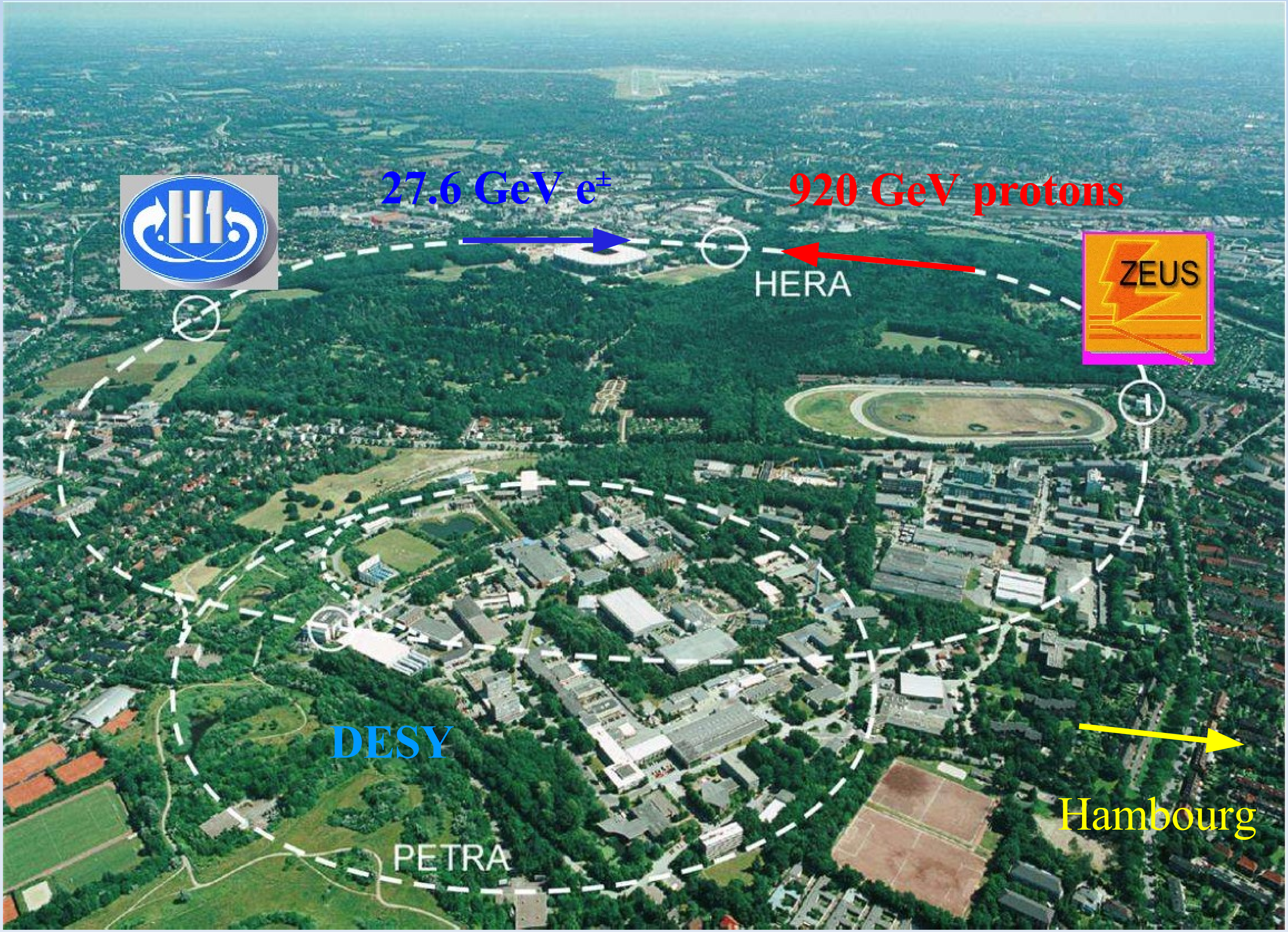
Introduction

- 15 years of ep scattering at high energy
- Main goal: study of proton structure
  - substructures ?
    higher 4-momentum transfert → smaller distance
    $Q^2 \sim 10^5$ GeV^2 → 10^{-18} m (1/1000 of the size of the p)
  - understanding of confinement ?
    low x → screening
- 2 most striking results of HERA from QCD:
  - Strong rise of F_2 at low x
  - Size of diffractive contributions in DIS
- Entering precision measurements:
  - Parton distribution function in the proton
  - α_s
  - Diffraction models
- → Many challenges for pQCD

Rem:
No EW
No BSM
results here

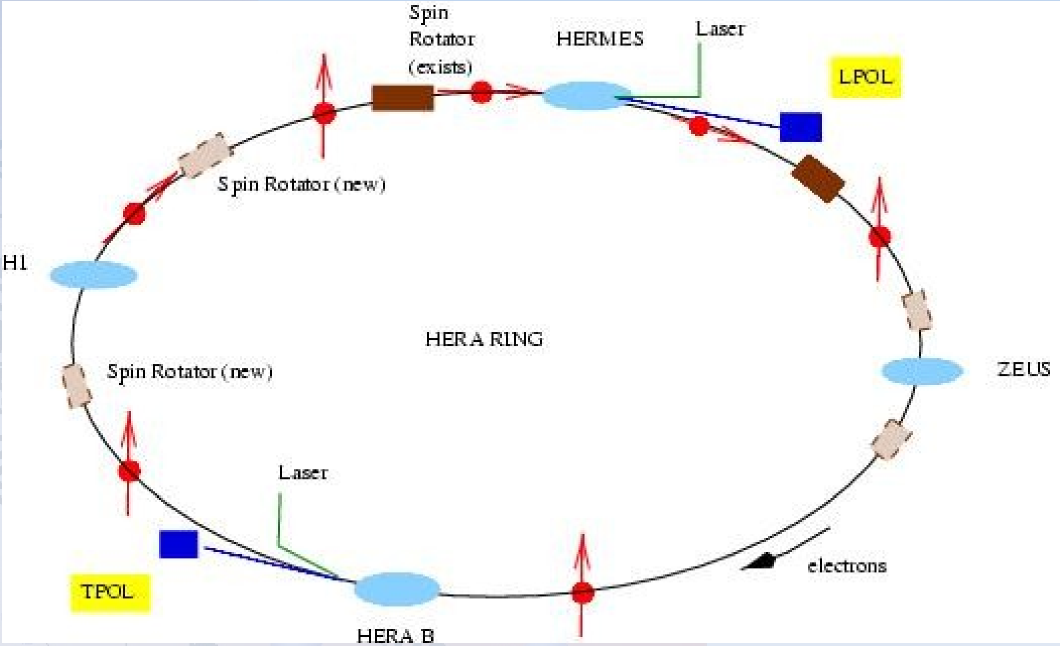


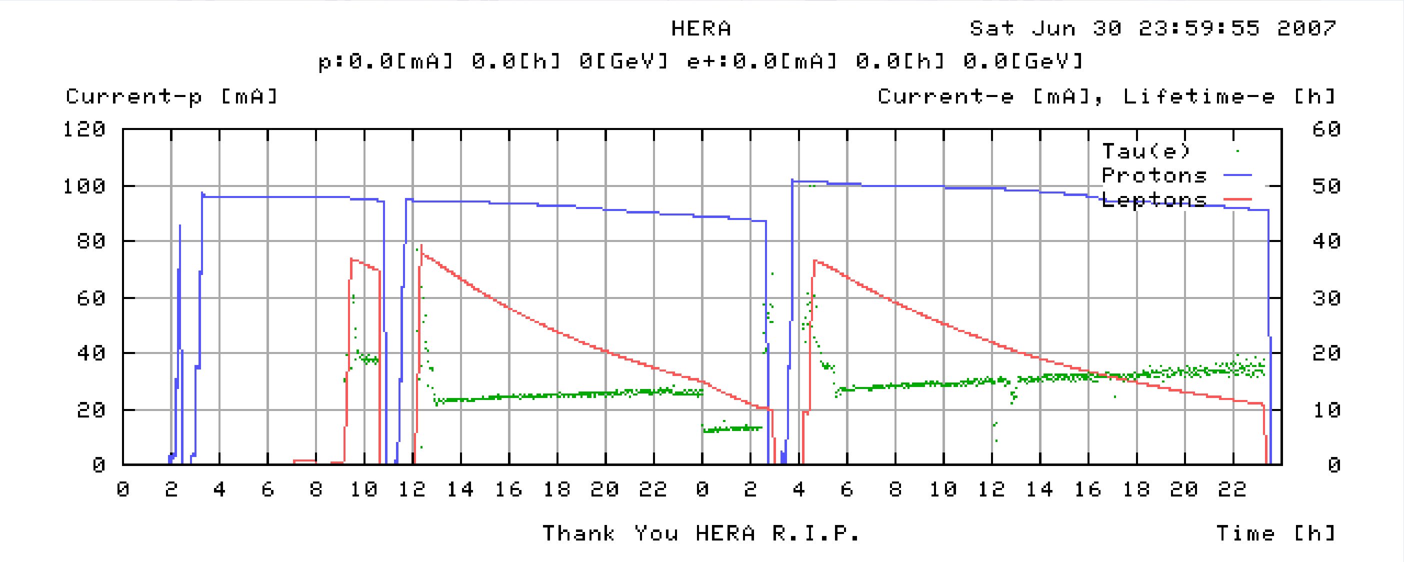
HERA



A unique machine

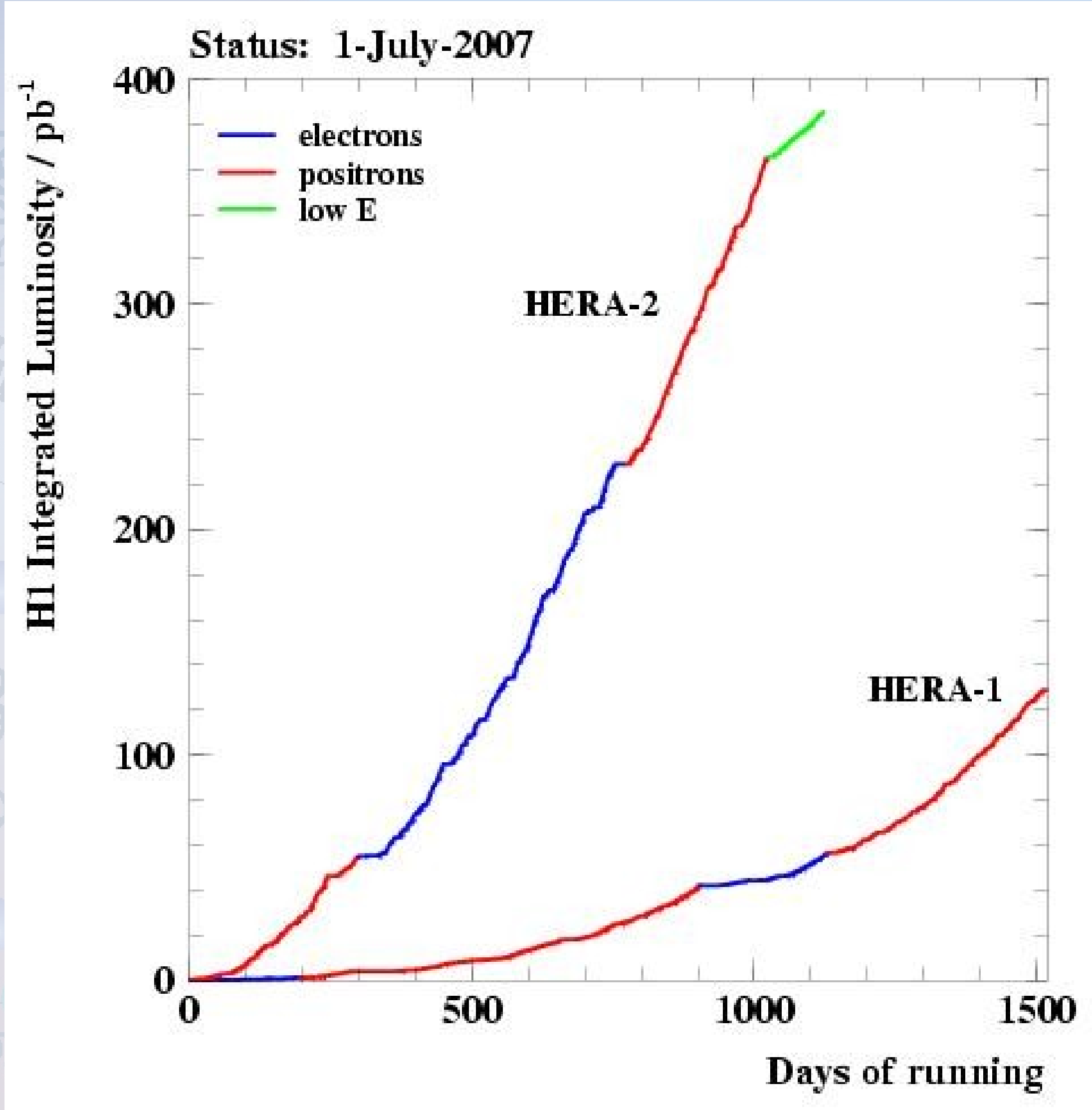
- Only hybrid ep collider
- Start 1992
- Upgrade 2000-2002
  - improved beam focusing
  - longitudinal polarization → H1 & ZEUS
- end 1/7/2007 (-few mins)





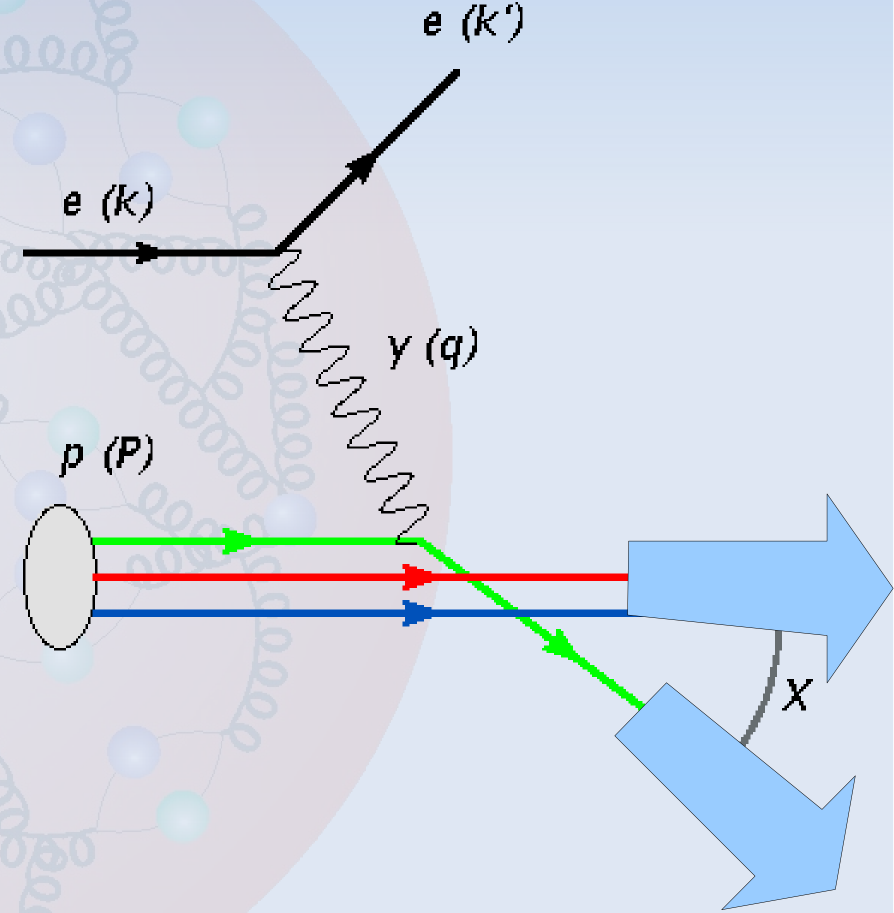
Collected luminosity

- High Energy Running ($\sqrt{s}$=300–320 GeV)
  - 1992 ⇥ March20th,2007
  - 758 pb^{-1} delivered by HERA
    - ~478 pb^{-1} for H1 physics
    - ~504 pb^{-1} for ZEUS physics
- Low Energy Running (E_p= 460 GeV, $\sqrt{s}$ = 225 GeV)
  - 16 pb^{-1} delivered
- Intermediate: (Ep = 575 GeV, $\sqrt{s}$ = 252 GeV)
  - 8.4 pb^{-1} delivered



DIS kinematics

- $Q^2 = -q^2$
  γ virtuality
- $x = Q^2/2\,P{\cdot}q$
  fraction of momentum struck quark
- $y = P{\cdot}q/P{\cdot}k = Q^2/xs$
  inelasticity (fraction of energy deposited in p rest frame)
- $W = (q+p)^2$
  cms energy of the γp system
- 2 indep^t variables inclusive measurement

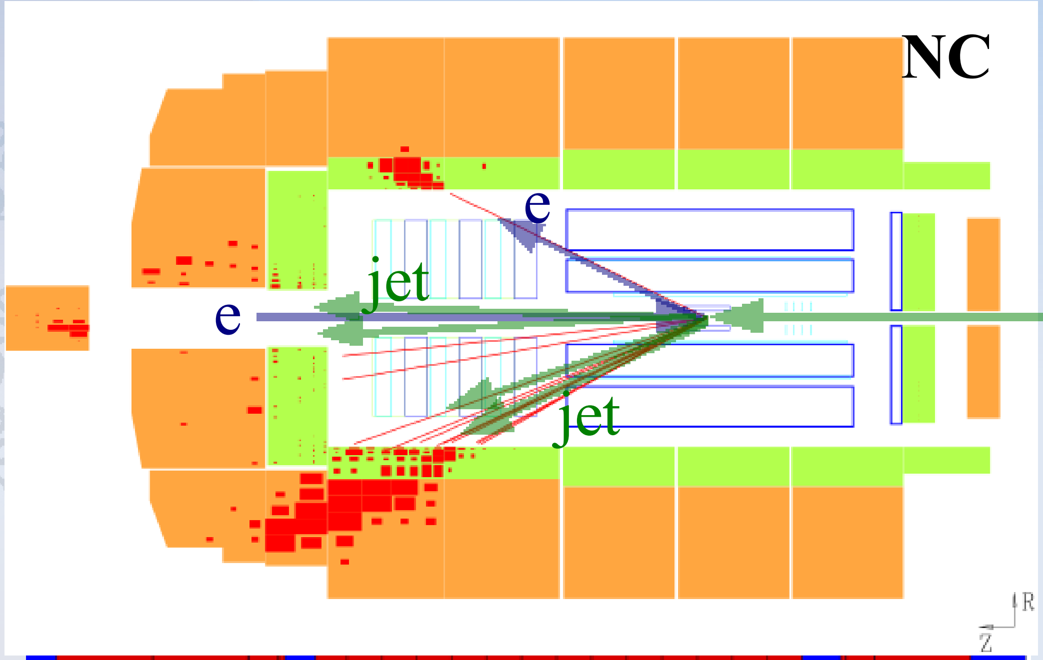


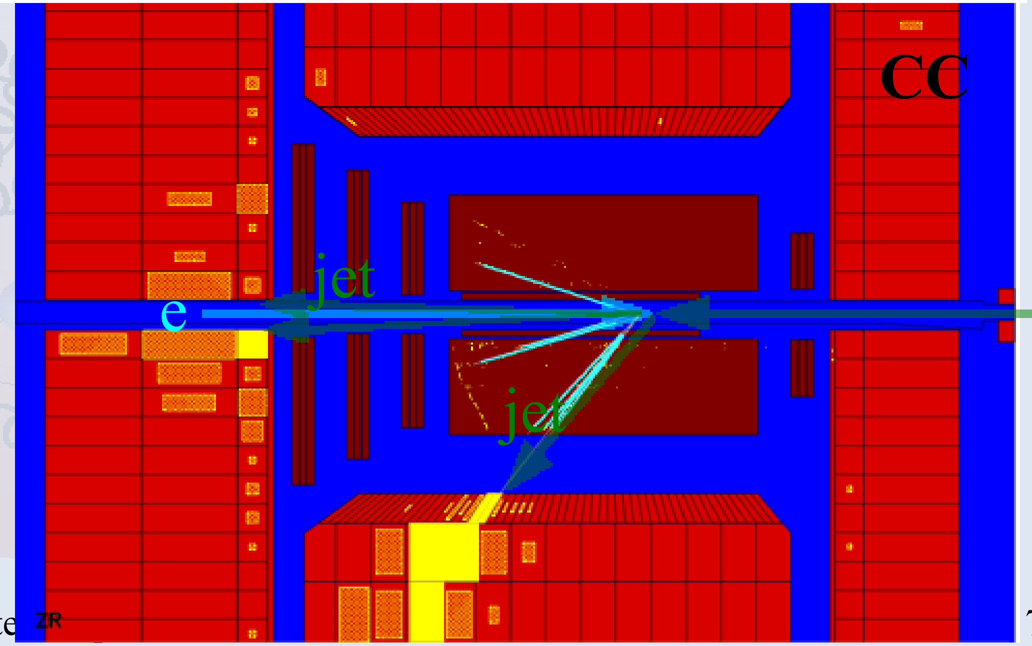
Deep Inelastic Scattering

- Main study of HERA
- → inclusive DIS NC & CC

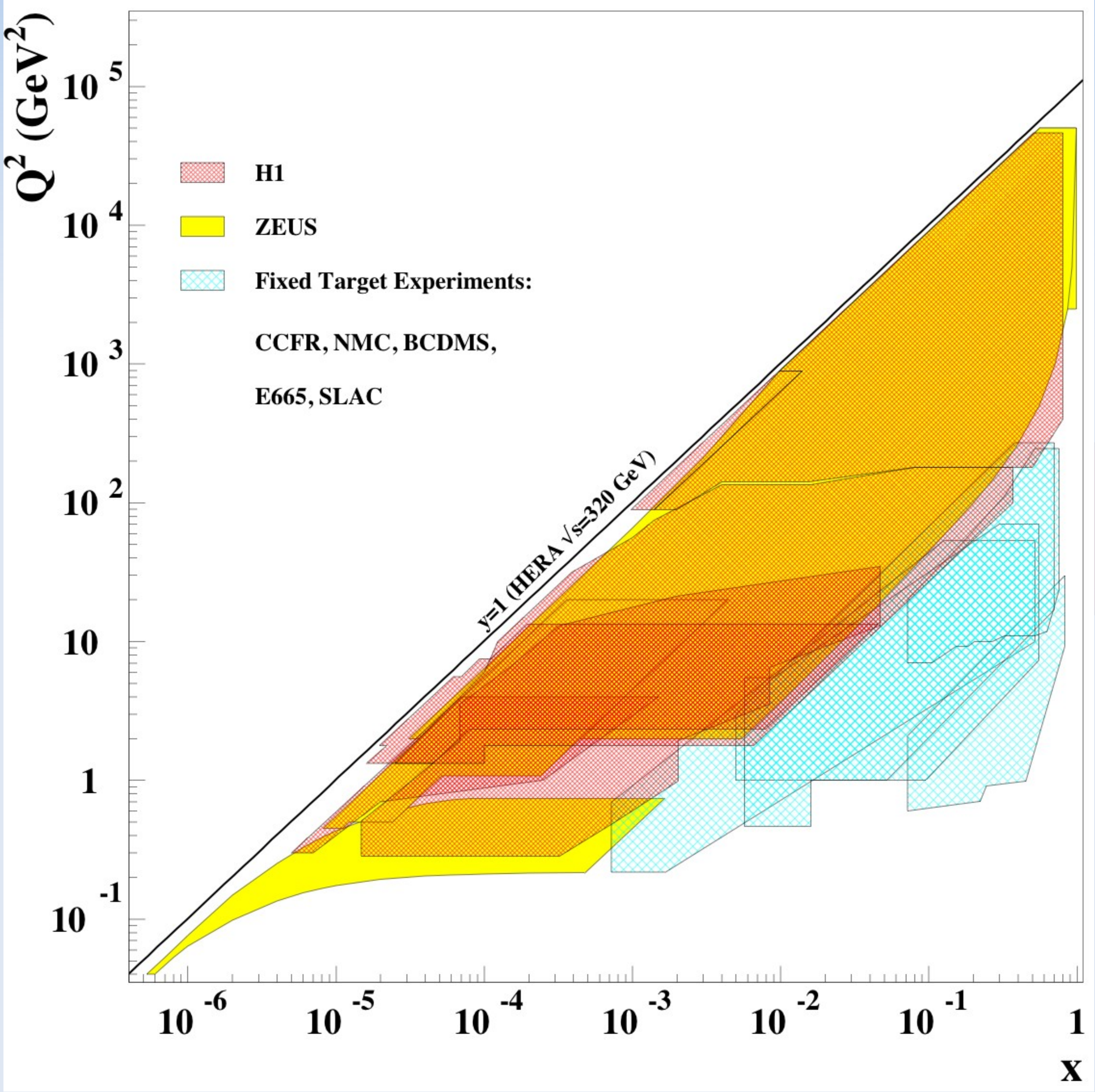
$$\frac{d^2\sigma(e^\pm p)}{dx\,dQ^2}$$

- (x, Q^2) from
  - electron (E_e, θ_e)
  - hadrons $((E\text{-}Pz)_h, \gamma_h)$
  - combination





Kinematics domain



Proton Structure Functions

$$\frac{d^2\sigma(e^\pm p)}{dx\,dQ^2}=\frac{2\pi\alpha^2}{xQ^4}\left[Y_+\ F_2(x,Q^2)-y^2F_L(x,Q^2)\mp Y_-\ xF_3(x,Q^2)\right](1+\delta_r);\quad Y_\pm=1\pm(1-y)^2$$

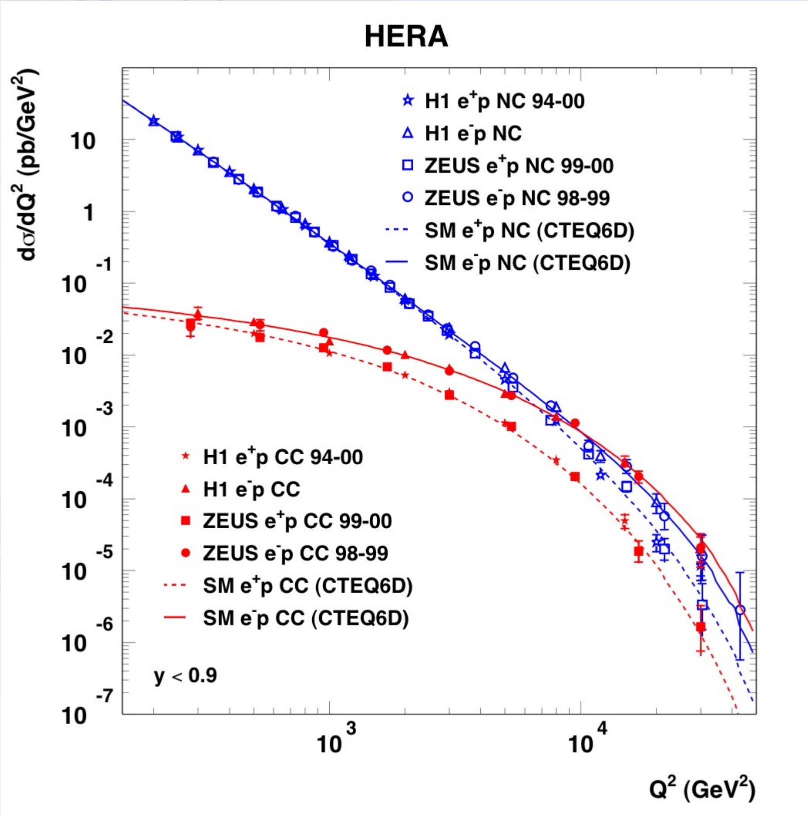
Spin effect

Longitudial structure function

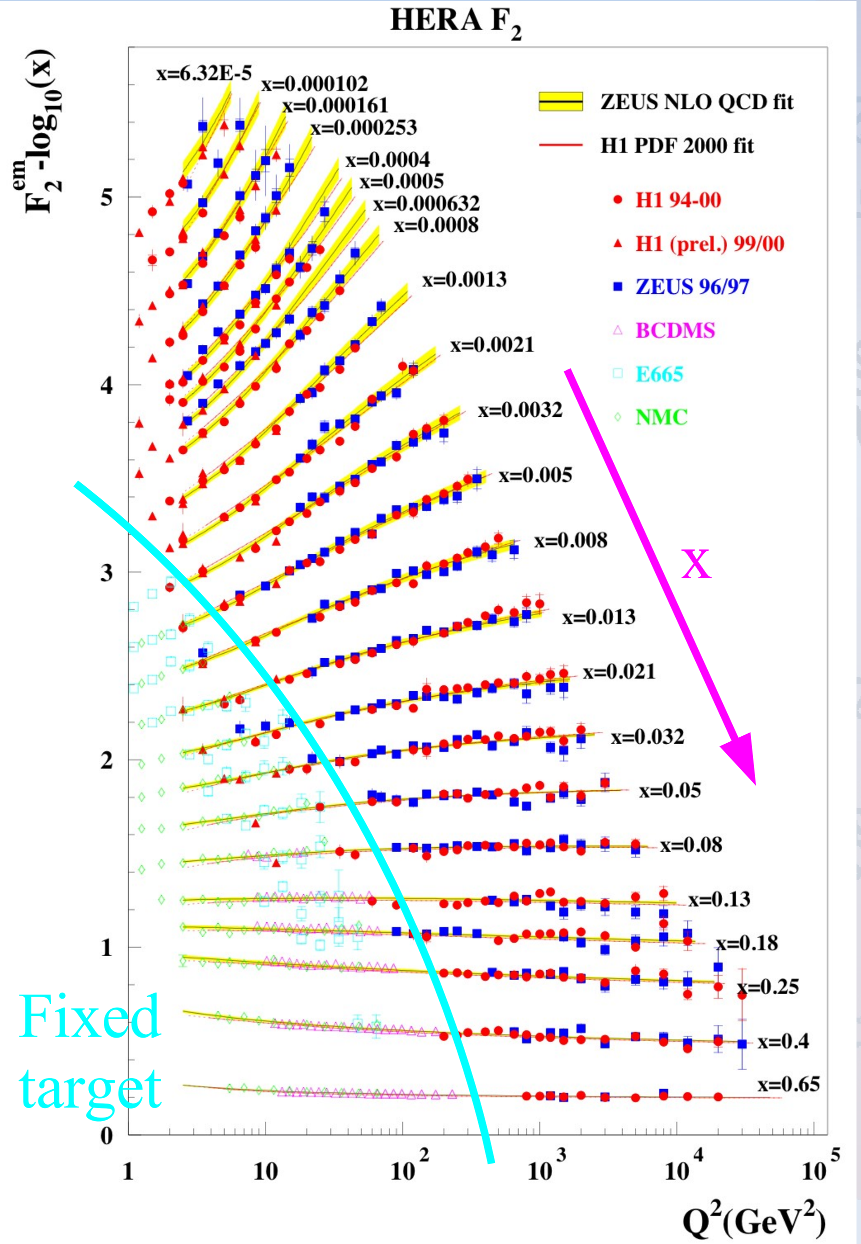
EW contributions

Radiative corrections

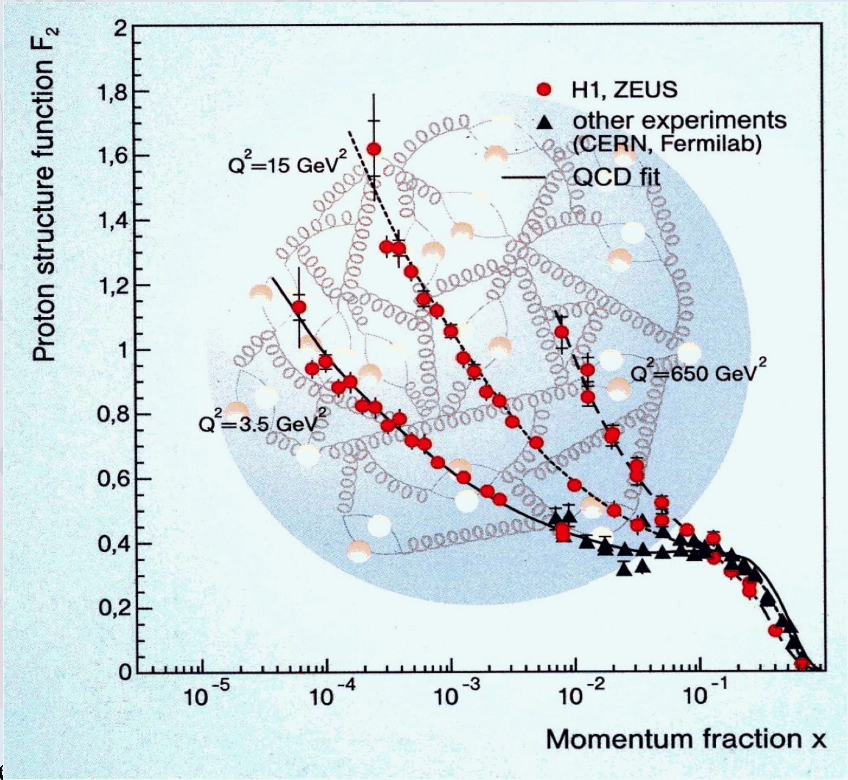
- F_2 dominates in most phase space (esp. pure em coupling)
- F_L contributes at high y
- F_3 ~ γZ interference → High Q^2



SF evolution

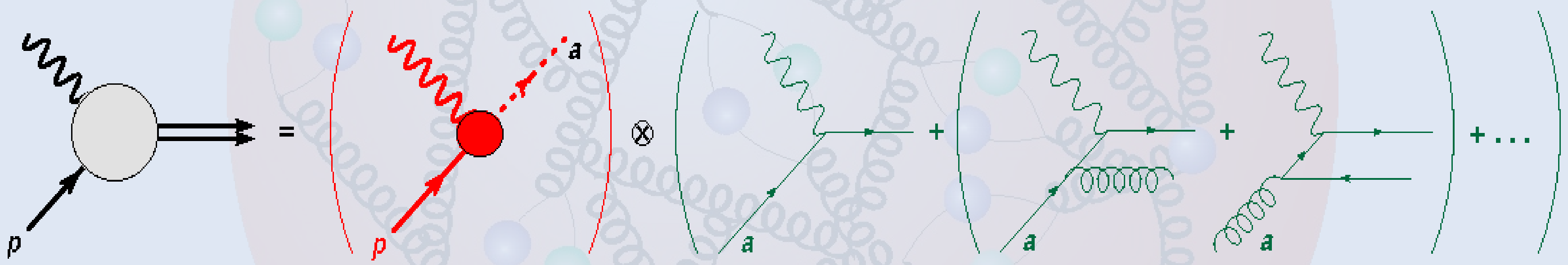


- In the Quark-Parton Model,
  → no Q^2 dependance
- with gluons (& sea quarks):
  More partons @ High Q^2
  → log Q^2 scaling violation
- → The opacity of the proton increases @ low x



Factorization:

- In the Quark-Parton Model:
  pdf $f_a(x, Q^2) = a(x)$ = probability to find a parton "a" with a fraction x for the proton, at a scale Q^2
  $a = q, \bar{q}$ *(u, d, s, …), g*
  - For the pure e.m. part: $F_2(x) = x \sum e_q^2 (q(x) + \bar{q}(x))$
- With QCD:



universal, scale dependent
Q^2 evolution by DGLAP eqs.

process dependent coeff.
pQCD in power series of $\alpha_s(Q^2)$

$$F_i(x, Q^2) = \sum_{a=q,\bar{q},g} f_a(x, Q^2) \otimes C_i^a(x, Q^2)$$

Determination of PDF at HERA

Procedure:

- Parametrization of a(x) at starting scale Q^2_0: valence q, sea q, g with all the constraints (sum rules)
- Evolution of a(x) → $f_a(x, Q^2)$ using NL DGLAP equations
- Convolution with pQCD predicted coefficients → σ
- Fit to data (⊃ all systematics)

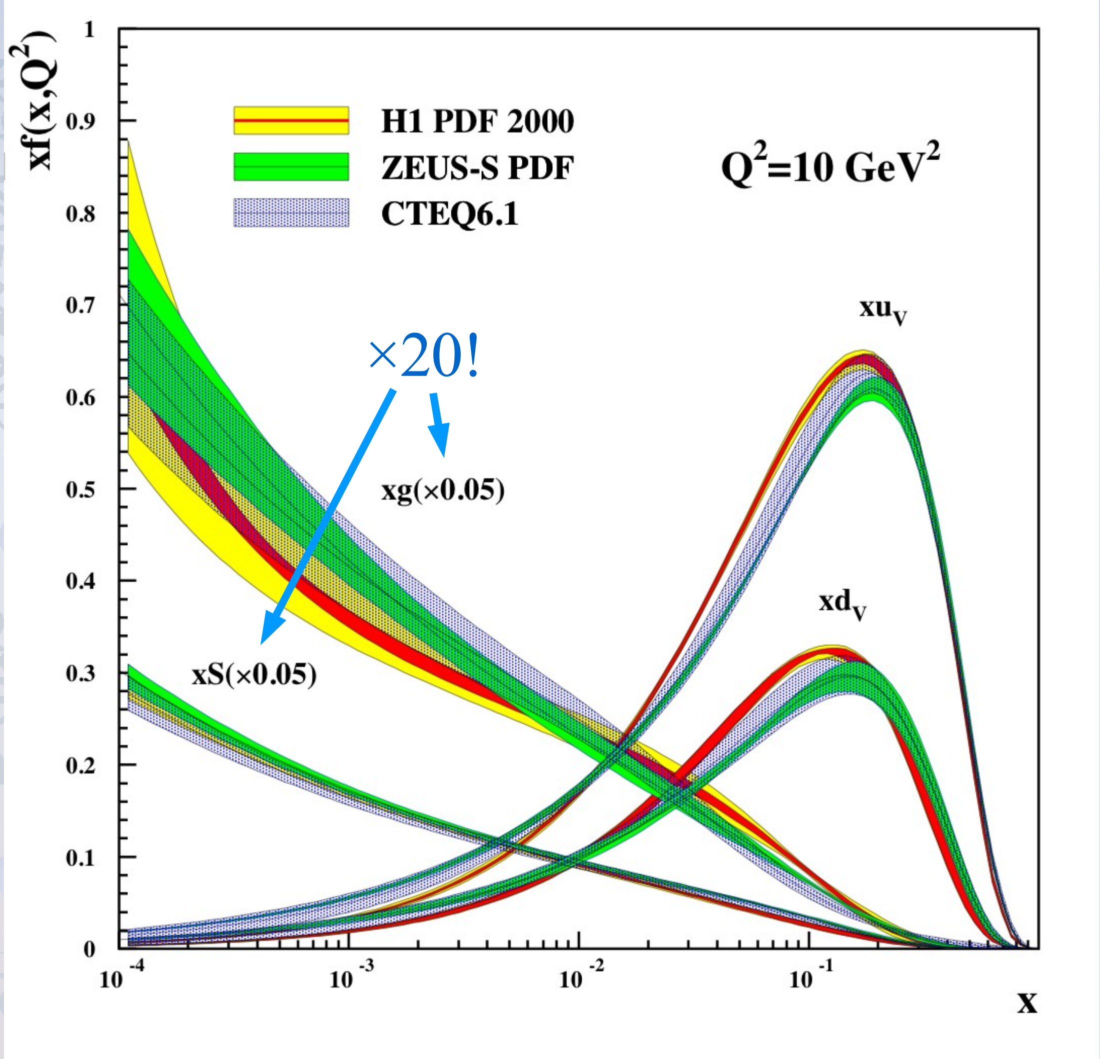
$$
\begin{aligned}
F_2 &= x \sum e_q^2 (q(x) + \bar{q}(x)) \\
xF_3 &= x \sum 2 e_q a_q (q(x) - \bar{q}(x)) \\
\sigma^{CC}_{e^+p} &\sim x(\bar{u} + \bar{c}) + x(1-y)^2 (d + s) \\
\sigma^{CC}_{e^-p} &\sim x(u + c) + x(1-y)^2 (\bar{d} + \bar{s})
\end{aligned}
$$

Analyses:

- low Q^2 inclusive NC → low x sea and g (indirect from scaling)
- High Q^2 NC & CC inclusive DIS → valence quarks density
- Jets production data → g at mid x

PDF from NLO Fits

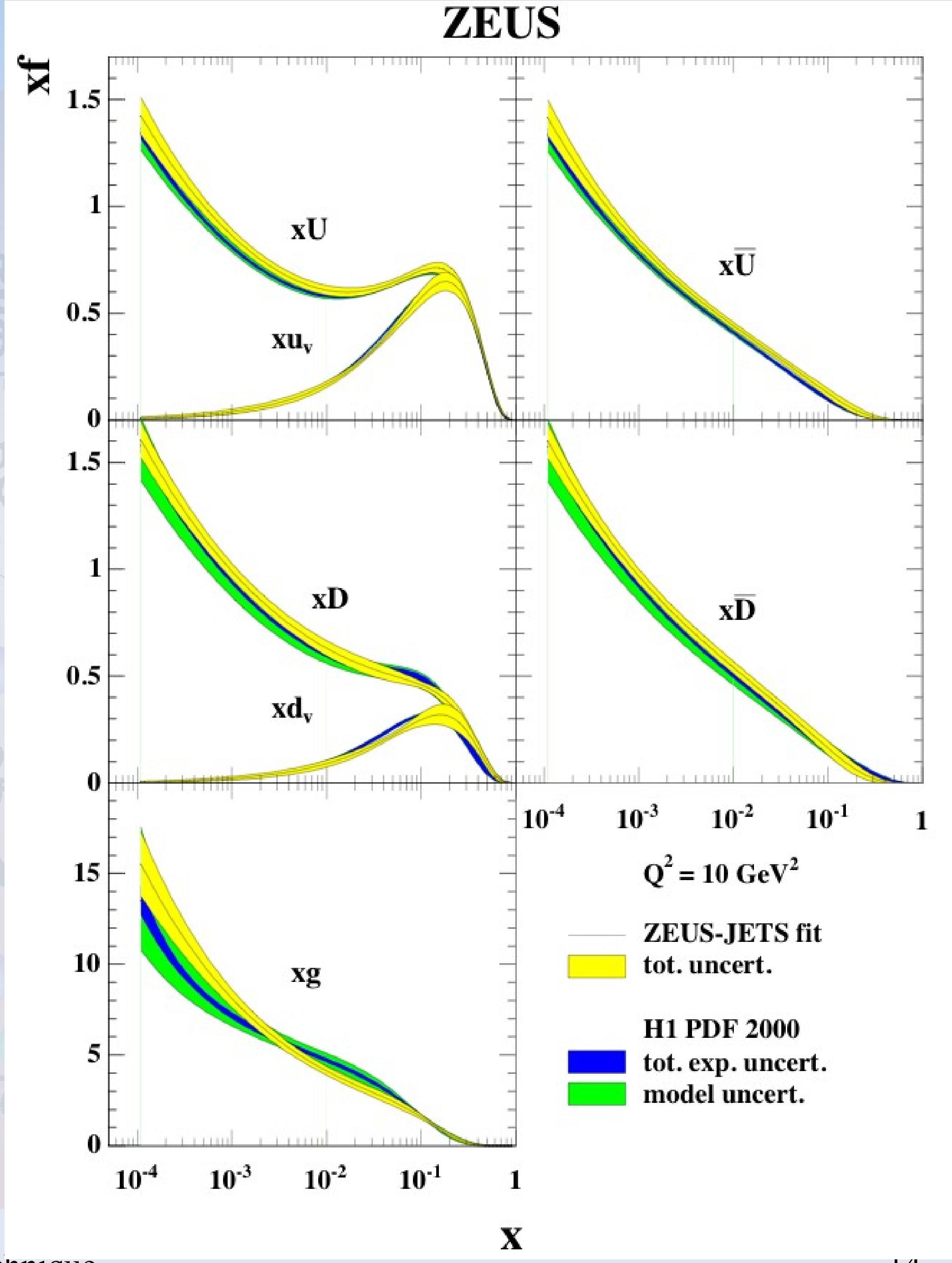
- From F2 data (H1 & ZEUS)
  - HERA-I data
  - well described by fits
  - 1.5—3% precision
- ⊃ fixed target (ZEUS)
- CC data
  - for valence quark at high x



- Good agreement
- low x dominated by gluons
- LHC ~ gg collider
- expects much improved precision from
- HERA-II data ($e^+p \times 3$, $e^-p \times 10$)
  - → 1 — 2% precision
- Combined DIS cross-sections

ZEUS-Jets Fits

- HERA-I data
- Simultaneous pdf's + α_s
- DIS NC data + jets
  - inclusive jets in DIS
  - dijets in photoproduction
  - ~2× precision on gluons at mid x (0.01 < x < 0.2)
- $xU = x(u+c); xD = x(d+s)$

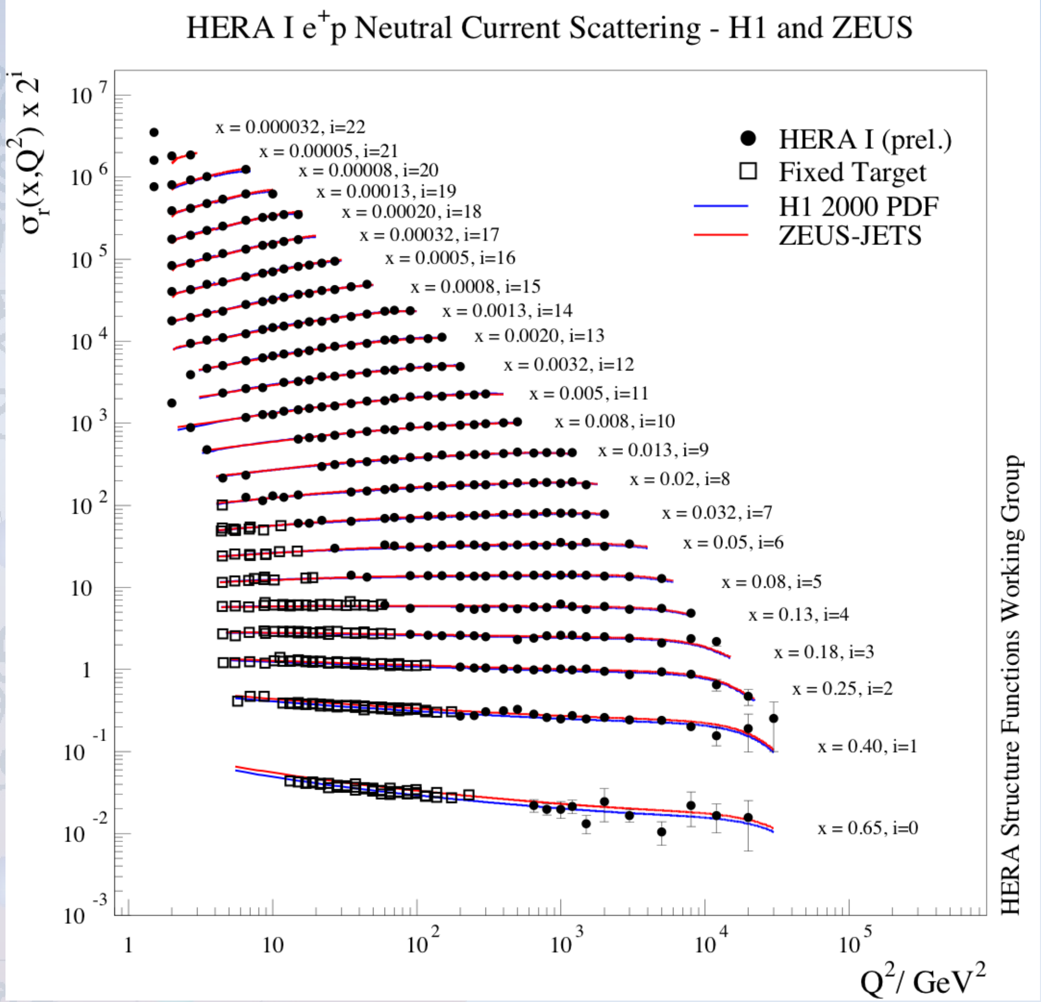


DESY-05-050; EPJ C42 (2005) 1-16

Combined DIS cross-section (H1 & ZEUS)

- From HERA-I (1996-2000) published data
- $Q^2 > 1.5\ GeV^2$
- Coherent approach of syst. error correlation
- Constraint due to X-calibration
  → Precision gain > pure stat. :
  ×2 (not √2)
- First step to more combinations
  - inclusion of HERA-II
  - pdf, QCD fits, ...

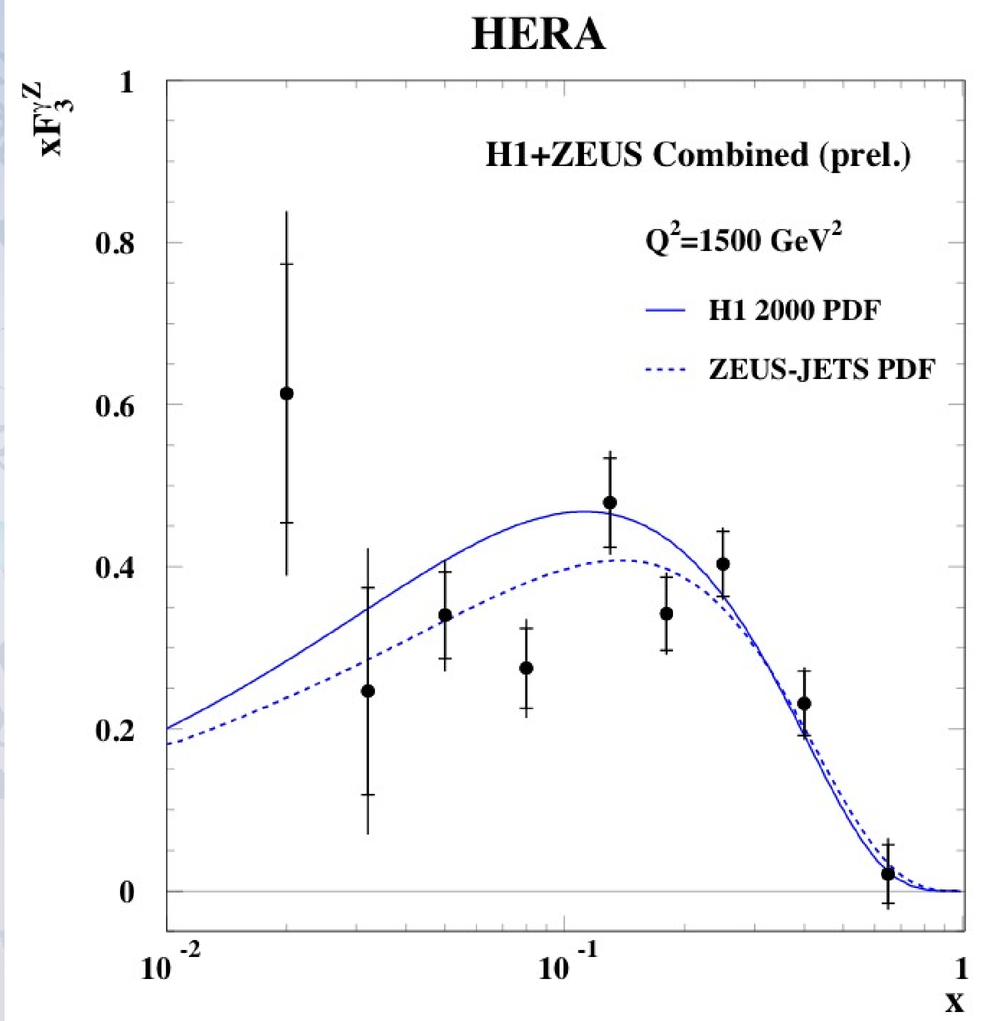
HERA Structure Functions Working Group



Combined xF_3

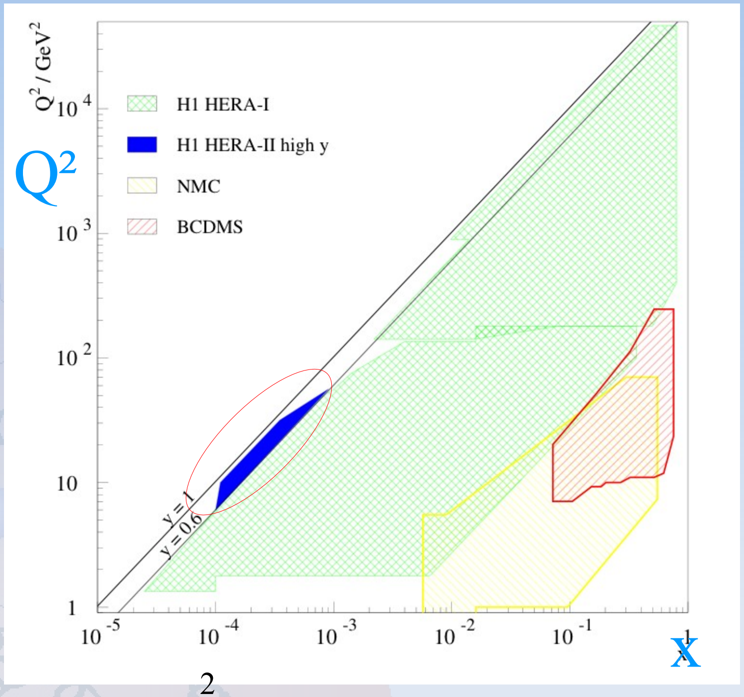
- First combined SF Combination of H1+ZEUS DIS NC cross-sections
- $xF_3 \propto \sigma(e^- p) - \sigma(e^+ p) \propto 2u_v + d_v$

  → measure of valence quarks
- $200 < Q^2 < 30000$ GeV^2
- $\mathscr{L} = 478.8$ pb^{-1} (HERA-I H1+ZEUS)
- Good agreement with pdf
  - esp. no increase at low x (sea q contributions ~0)



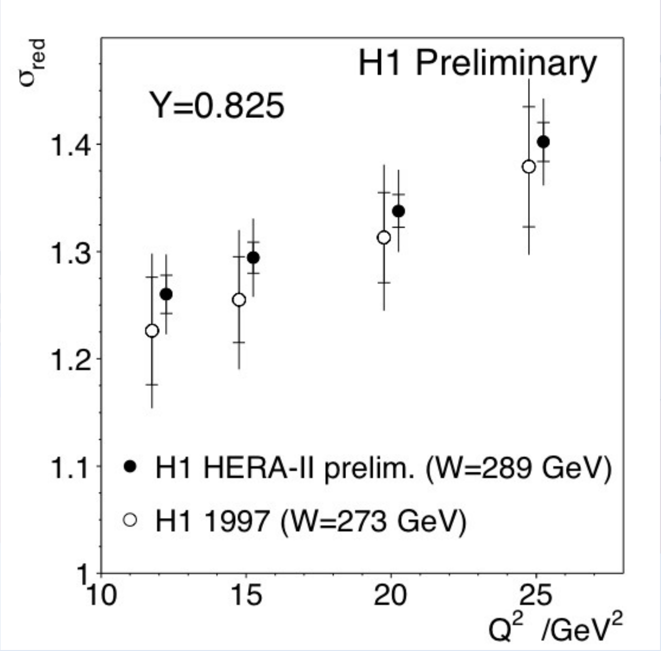
High y

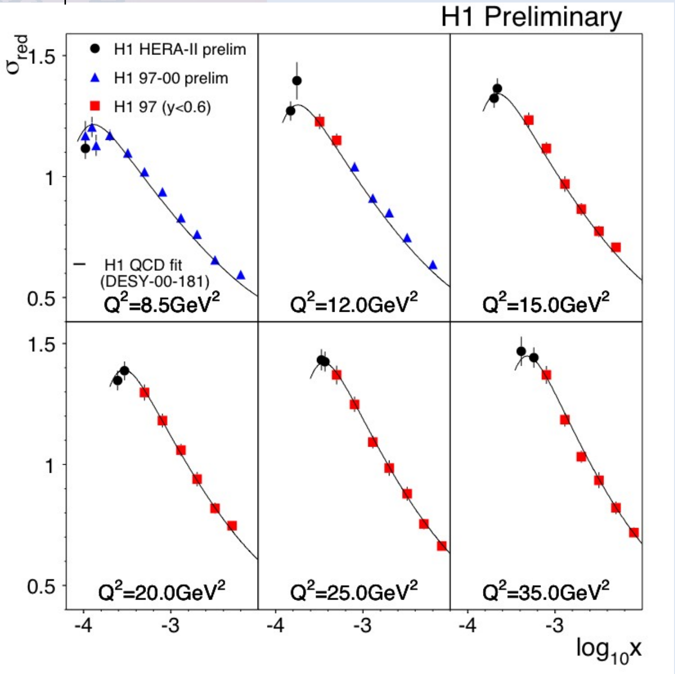
- 2003-2006 data ($e^{\pm}p$ data)
  - $\mathscr{L}$ = 96 pb^{-1}
- 12 GeV^2 < Q^2 < 150 GeV^2
- 0.75<y<0.9
- High Sensitivity to F_L
  - → constrains on DGLAP $F_L \sim xg$



$$\sigma_{red.} = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$

- 2× precision wrt previous data
- → prepares for low E F_L determination

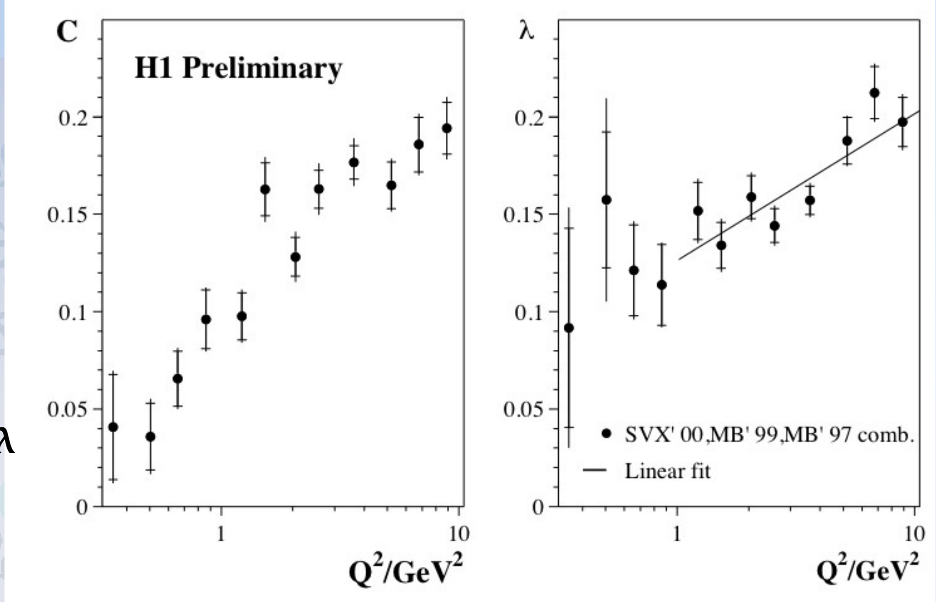


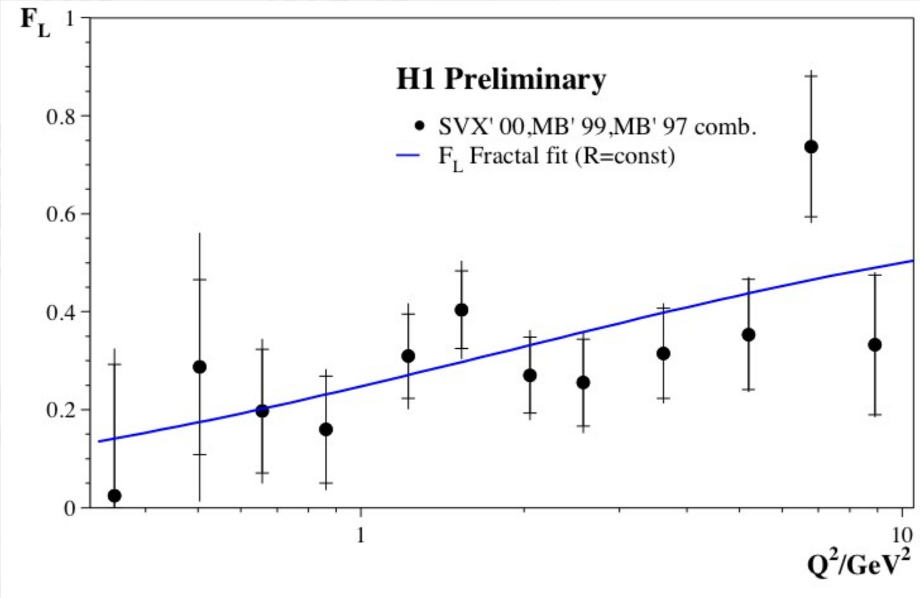


low x, low Q² measurement

- High precision from special run in 99/00
  - shifted vertex → lower θ_e
  - minimum bias trigger
- $0.2 < Q^2 < 12\ \text{GeV}^2$
- $4 \cdot 10^{-6} < x < 0.02$
  - ⊃ data with $y<0.85$
  - → sensitivity to F_L
- 2-3% precision

$$F_2 \propto C\, x^{-\lambda}$$

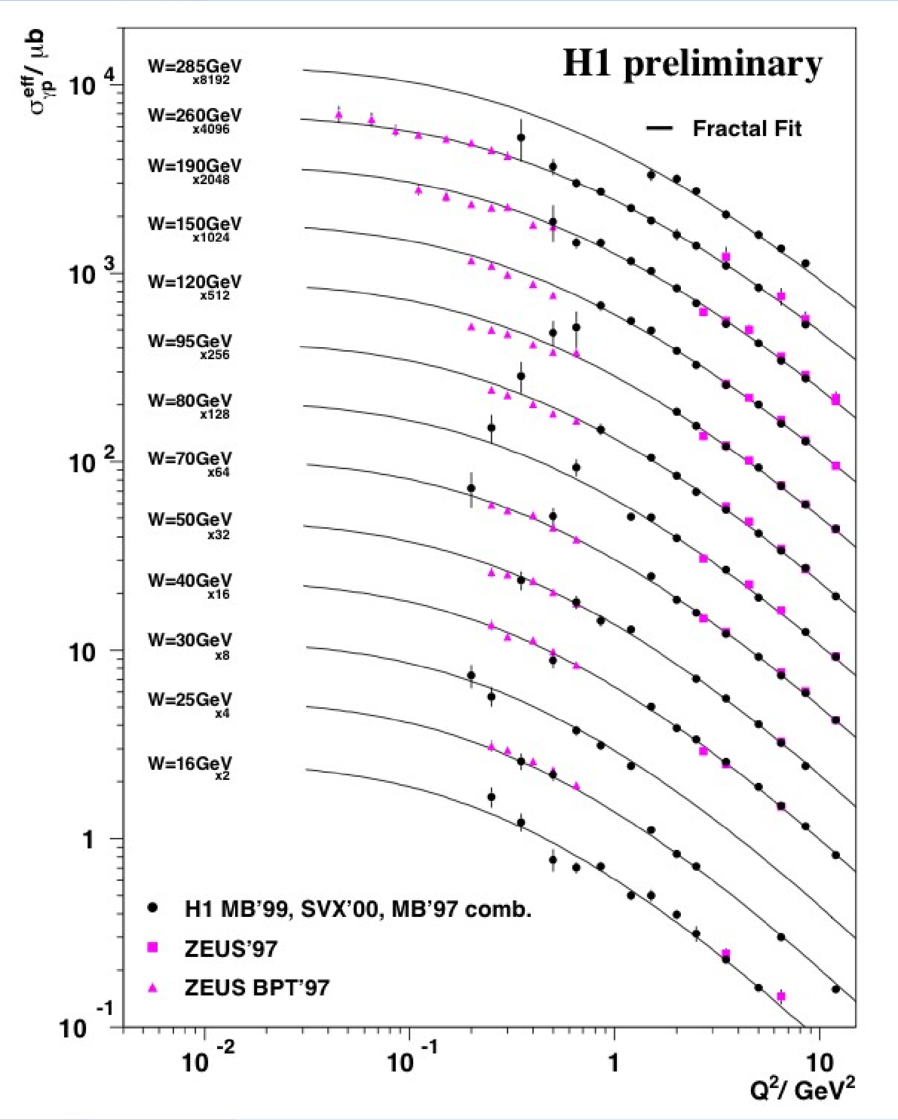




- Extended kin. domain (lower Q², larger x) by use of radiative correction
- → transition to the soft QCD
  - empirical predication: fractal fits, power laws

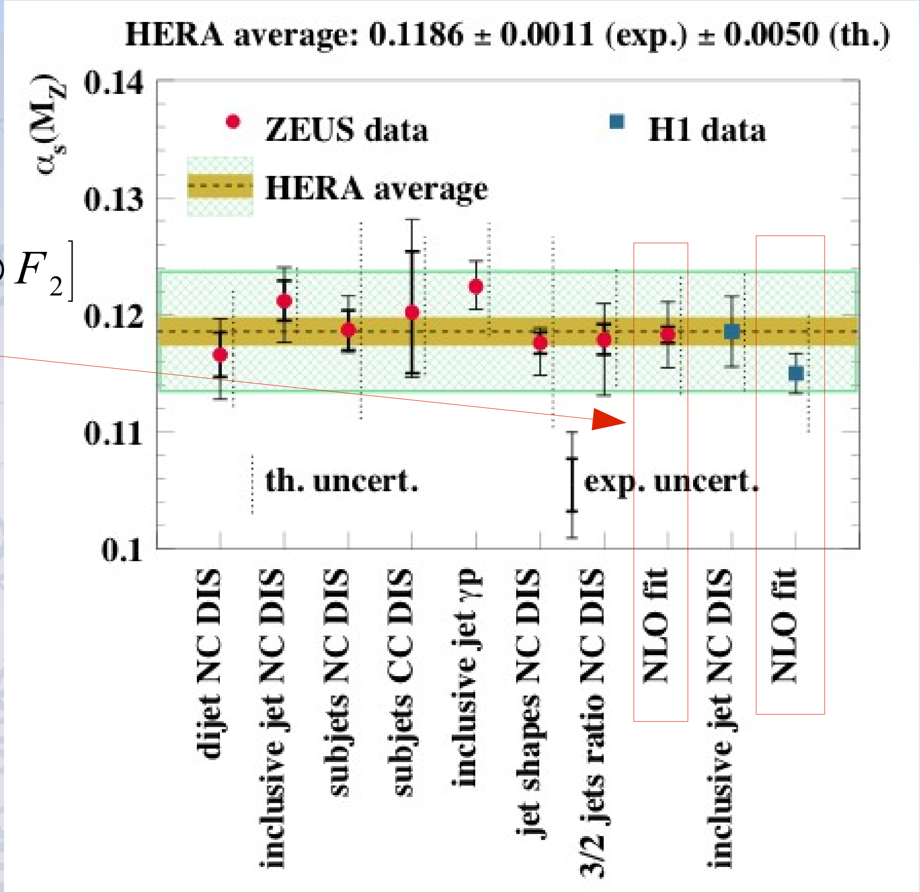
low Q² measurements

- At lowQ2,
  - F2 $\sim \sigma_T + \sigma_L$
  - $F_L \sim \sigma_L$
- New preliminary measurement of
  $$\sigma_{eff.} = \sigma_T + [1 - y^2/(1+(1-y)^2)]\sigma_L$$
- Fill the gap to photoproduction



Measures of $\alpha_s(M_Z)$

- Many methods:
  - Scaling violations $\left(\frac{\partial F_2}{\partial \ln Q^2}\right) \propto \alpha_s \left[P \otimes g + P \otimes F_2 \right]$
  - exclusive states (jets cross-sections, jet properties)
  - combined values to NLO
- All in good agreement



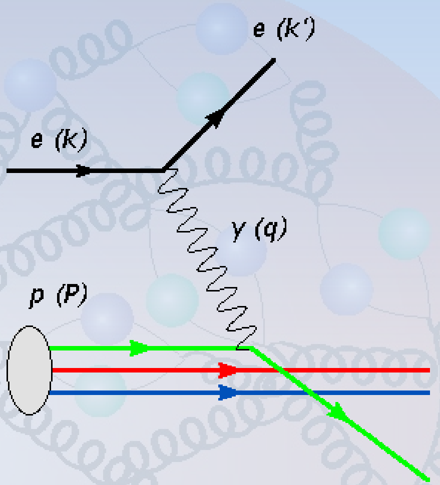
- Dominated by th. errors

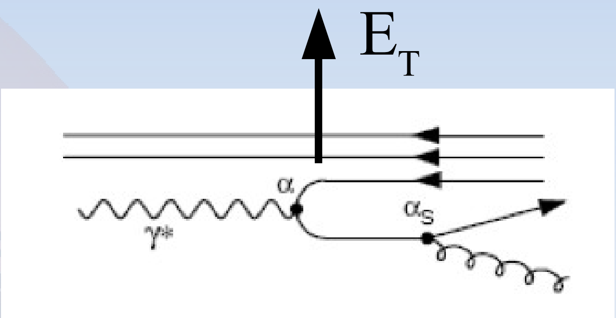
$\alpha_s(M_z) = 0.1186 \pm 0.0011 \text{ (exp)} \pm 0.005\text{(th) (H1 + ZEUS)}$

→ $\alpha_s(M_Z) = 0.1189 \pm 0.0010$ *(world average, Bethke 2006)*

α_s from Inclusive jets X-sections in NC DIS

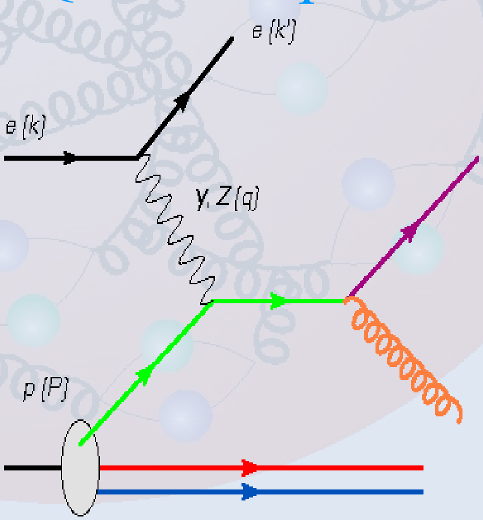
- High E_T jets
  → low experimental uncertainty
  → calc. in pQCD
- In the Breit frame (γ-p cms):
  - suppr. direct DIS (Born process)
  - suppr. of p remnants
- longitudinally inv.
  k_T jet algorithm
  - IR safe,
  - parton / hadron equi.
- Inclusive jets (≠ di-jets)
  - reduced th. uncertainties
  - IR safe
- NLO calc
  → low theoretical uncertainty
- need of precise pdf's



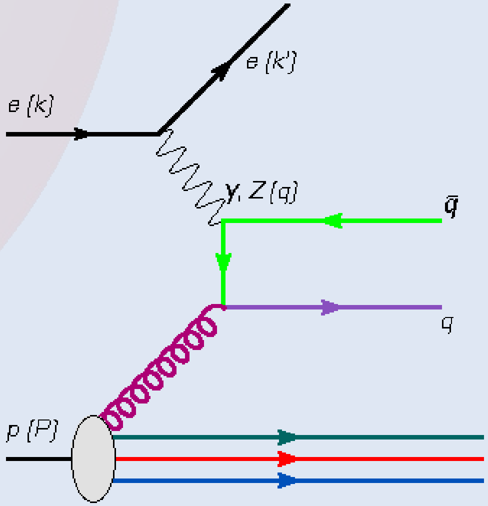


Leading Order:

QCD Compton

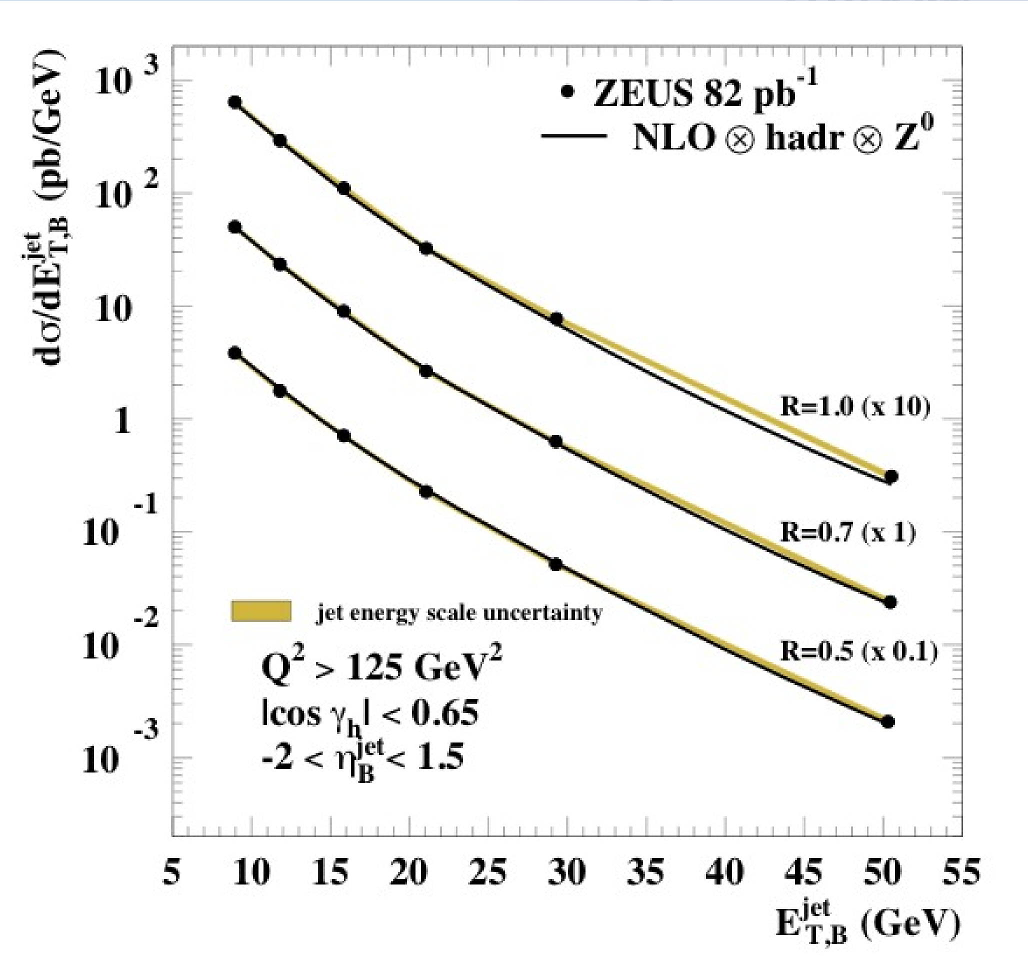


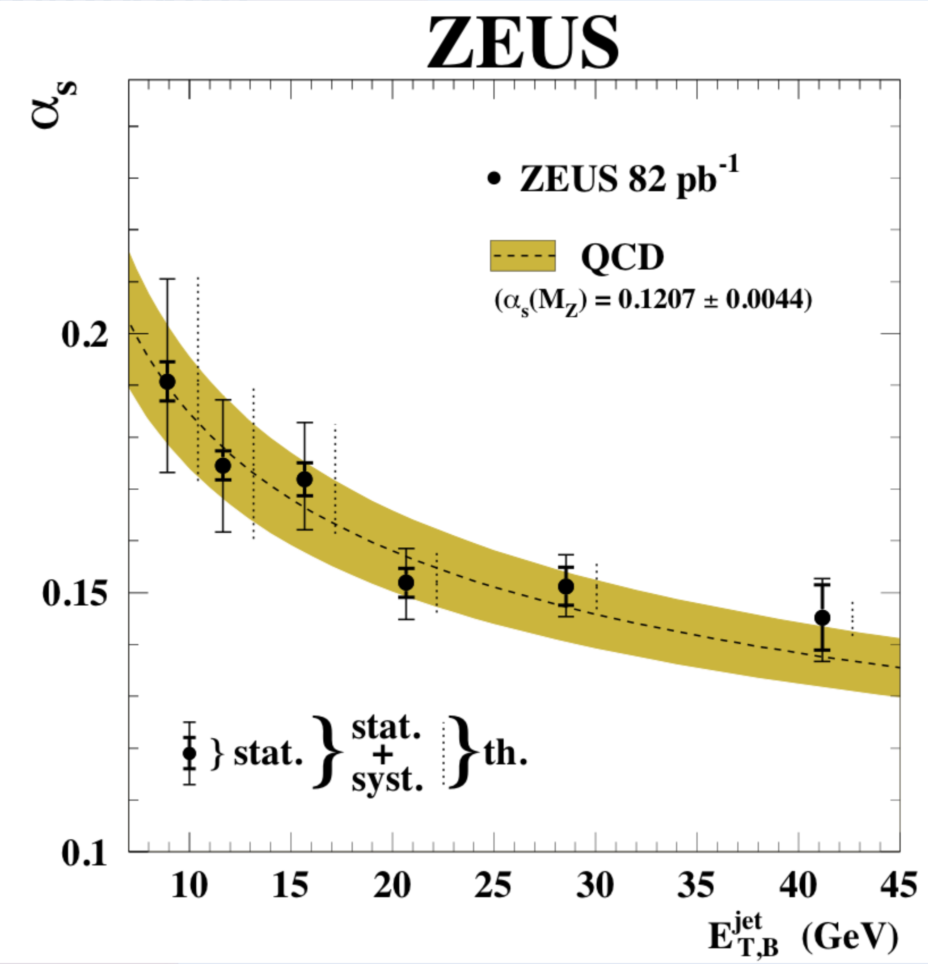
Boson-Gluon Fusion



Jets inclusive in NC DIS (ZEUS)

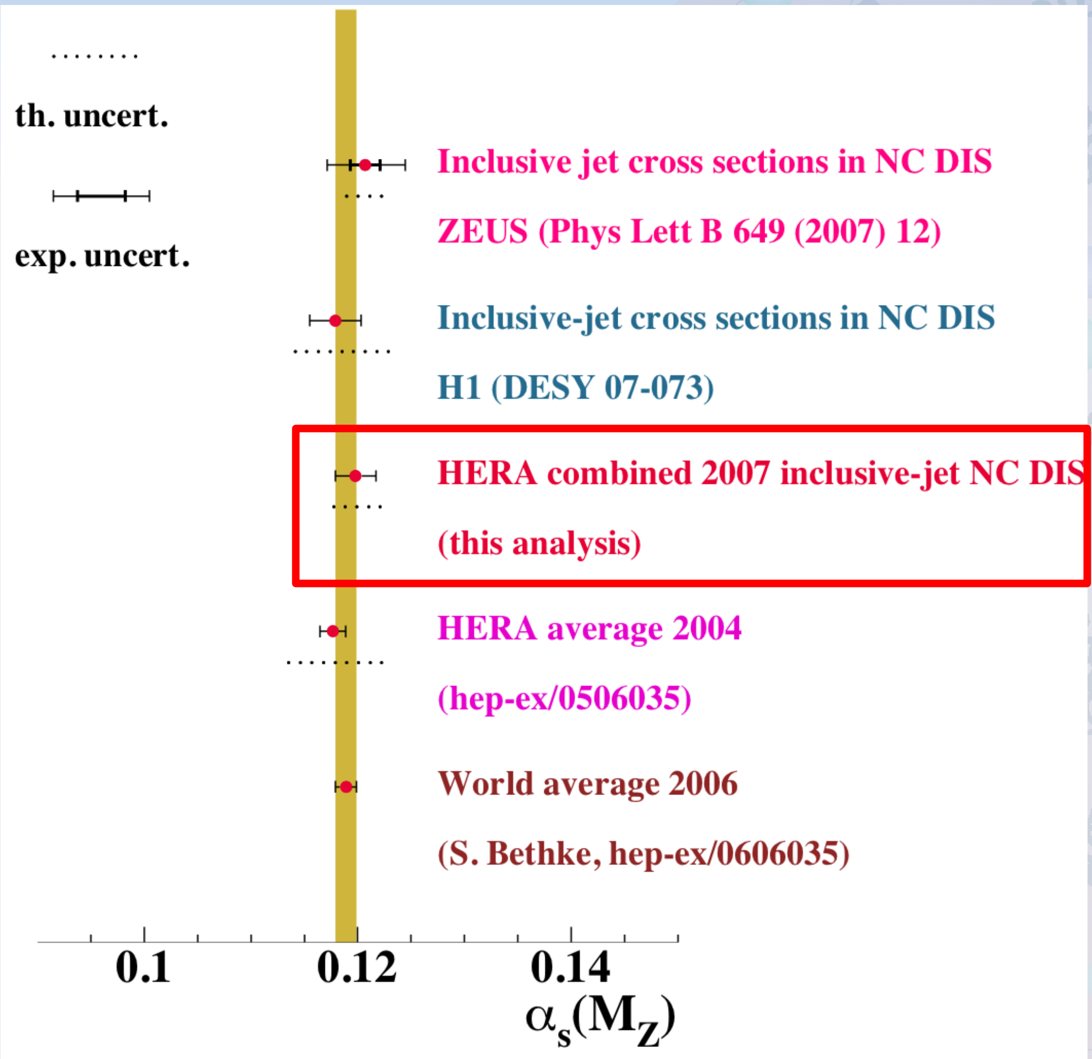
- Agreement for different jet Radius R
- E_t^{jet} = running scale for α_s





HERA 2007 combined α_s

HERA α_s Working Group
H1 and ZEUS Collaborations



Combine ***data*** of

DIS NC inclusive jets from

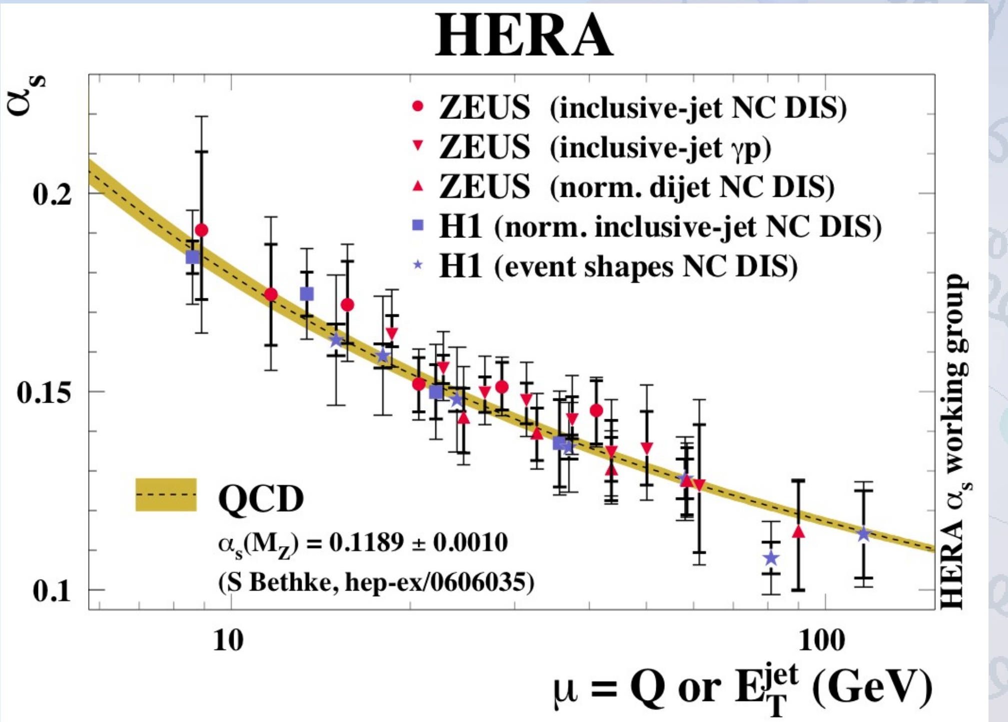
- ZEUS [Phys. Lett. B649(2007)12]
- H1 [hep-ex/0706.3722]

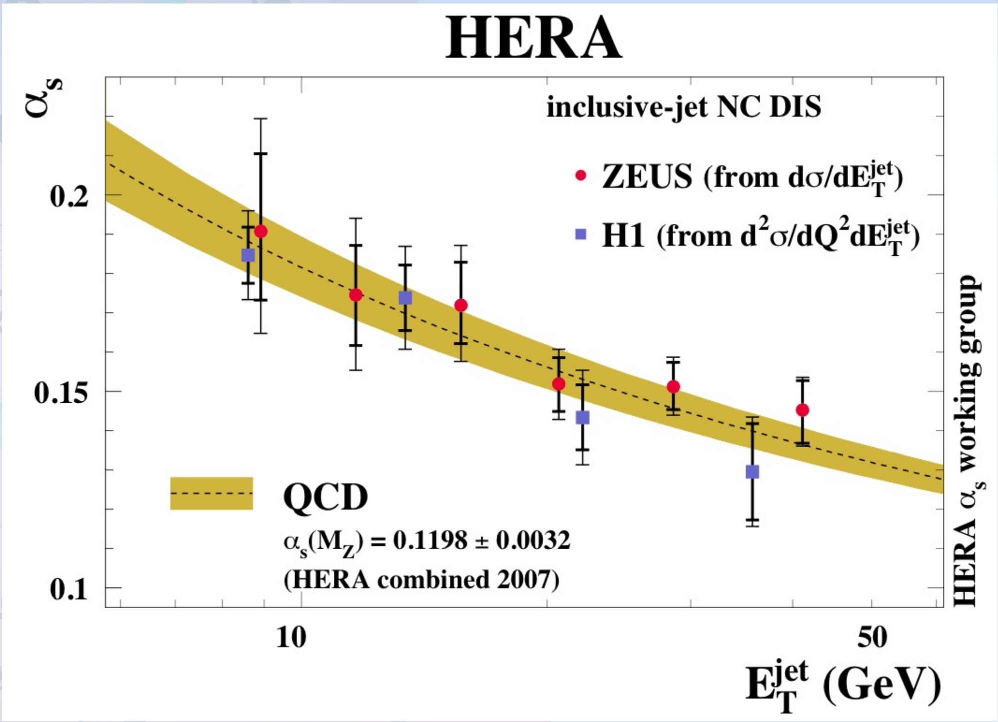
Consistent measurement

- 0.1198±0.0019(exp)±0.0026(th)
- 0.1186±0.0011(exp)±0.0050(th)
- 0.1189±0.0010

Running of α_s ...

... from HERA data alone



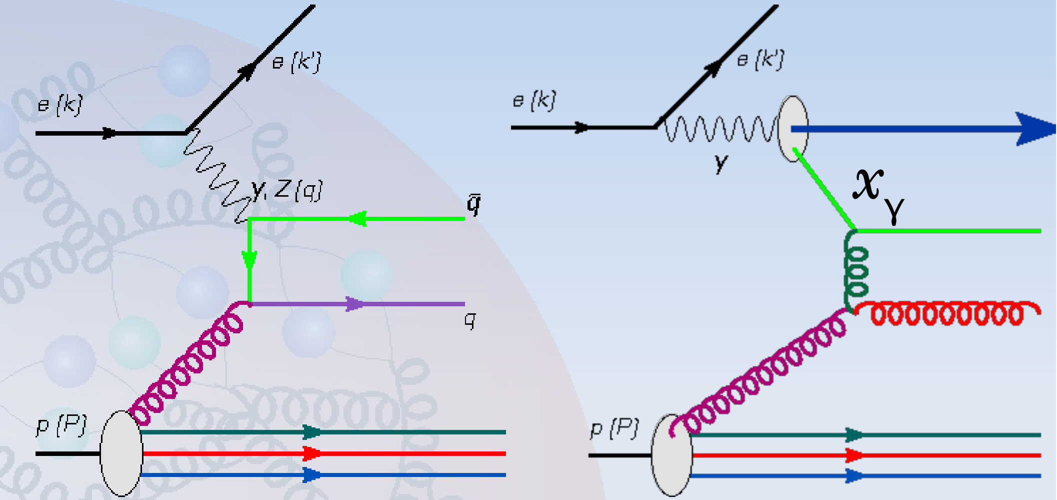


High E_T jets in photoproduction ($Q^2 \sim 0$)

→ parton density in the photon

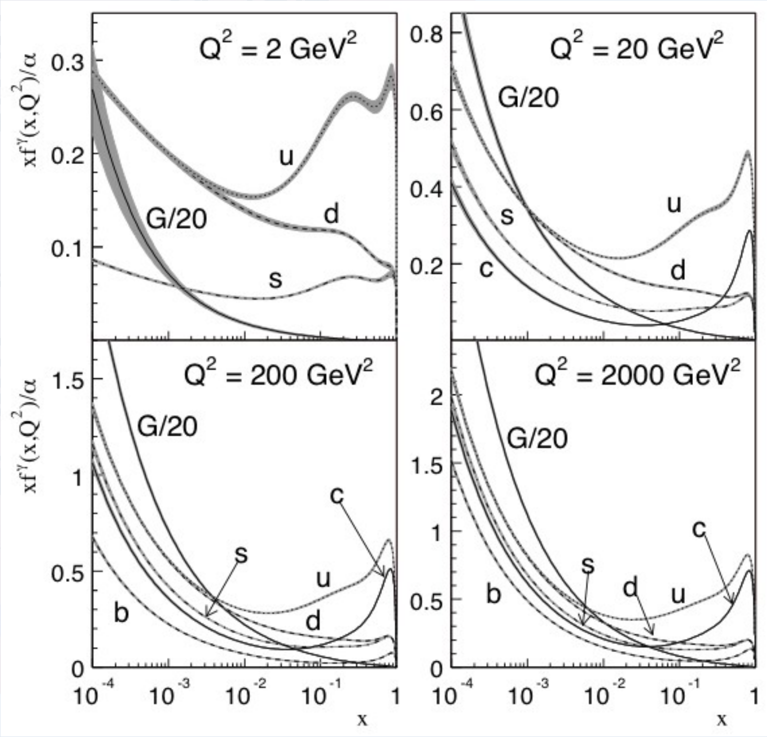
→ Gluon in the protons

- kin:
  $Q^2 < 1$ GeV²
  $142 < W_{\gamma p} < 293$ GeV
  $E_{jet\ 1(2)} > 20$ (15) GeV
  $-1 < \eta_{jet} < 3$ and $-1 < \eta_{jet} < 2.5$
- 82 pb^{-1} (98-00 data)



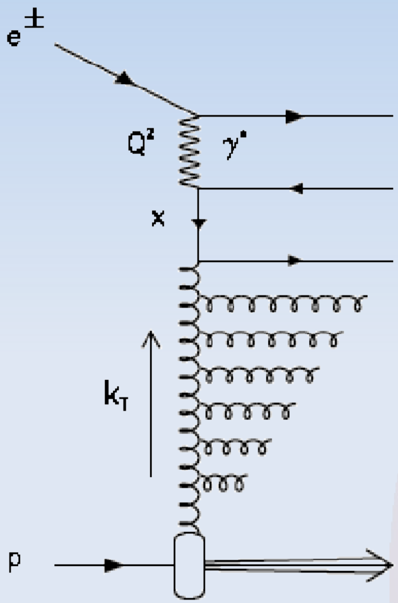
- High E_T 2j with
  $\gamma\gamma^* \to$ hadrons (ee),
  low-x $\gamma^* p \to$ hadrons

→ pdf in photons



W. Slominski, H. Abramowicz and A. Levy, Eur. Phys. J. C 45, 633 (2006).

BFKL vs DGLAP

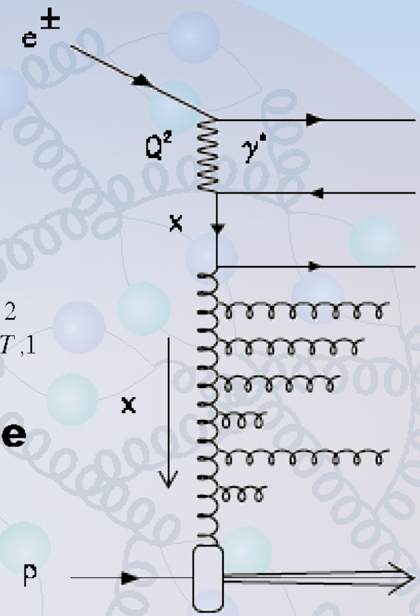


DGLAP

Evolution & resummation in powers of *lnQ2*

$$Q^2 >> k_{T,n}^2 >> \ldots >> k_{T,2}^2 >> k_{T,1}^2$$

The DGLAP gluon cascade is strongly ordered in k_T and ordered in x



BFKL

Evolution & resummation in powers of *ln(1/x)*

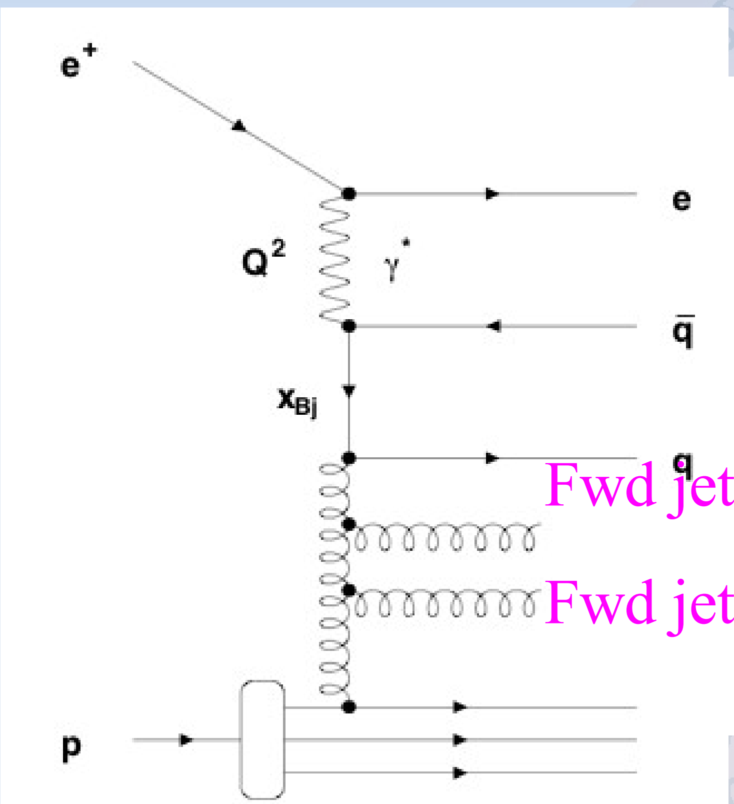
$$x_1 >> x_2 >> \ldots >> x_n >> x$$

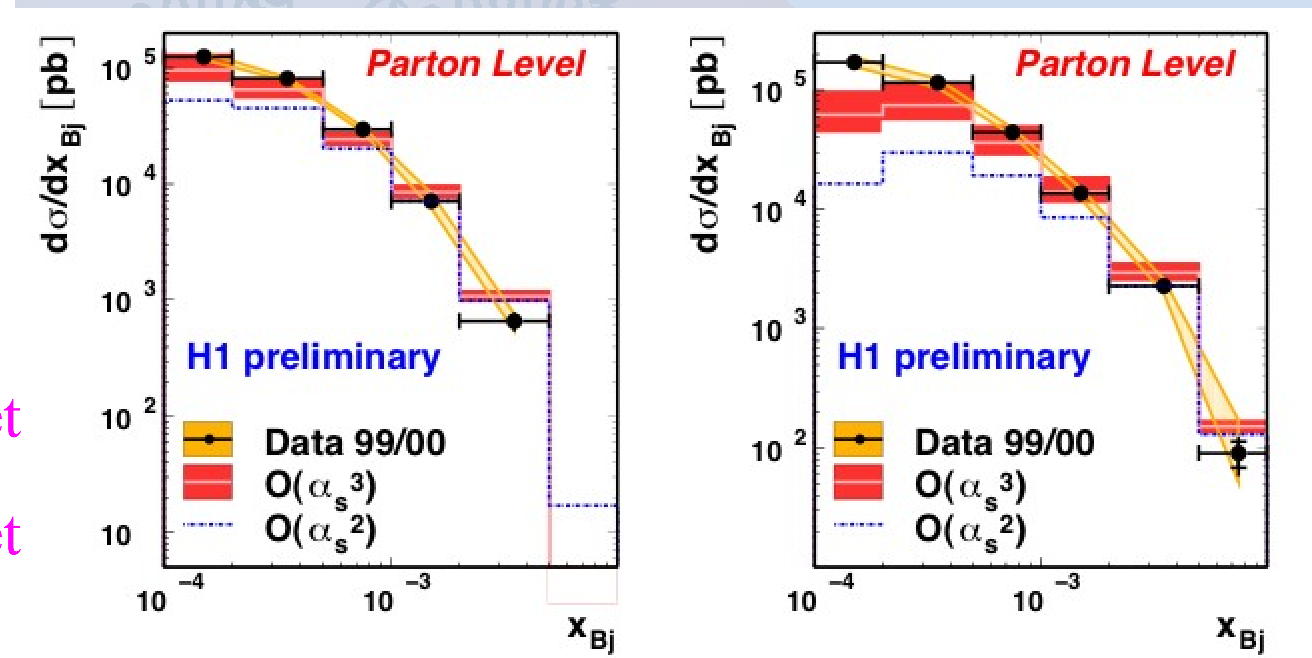
The BFKL is only strongly ordered in x

- **DGLAP** (**D**okshitzer-**G**ribov-**L**ipatov-**A**ltarelli-**P**arisi) is expected to break down at low x and Q^2 region
- **BFKL** (**B**alitsky-**F**adin-**K**uraev-**L**ipatov) can be applicable at low x
- **CCFM** (**C**iafaloni-**C**atani-**F**iorani-**M**archesini) describes an evolution in both Q^2 and x and approches BFKL at low x and DGLAP at high Q^2; angular ordering

First hints of a breakdown of DGLAP

- 3 jets dynamic at low x and low Q^2





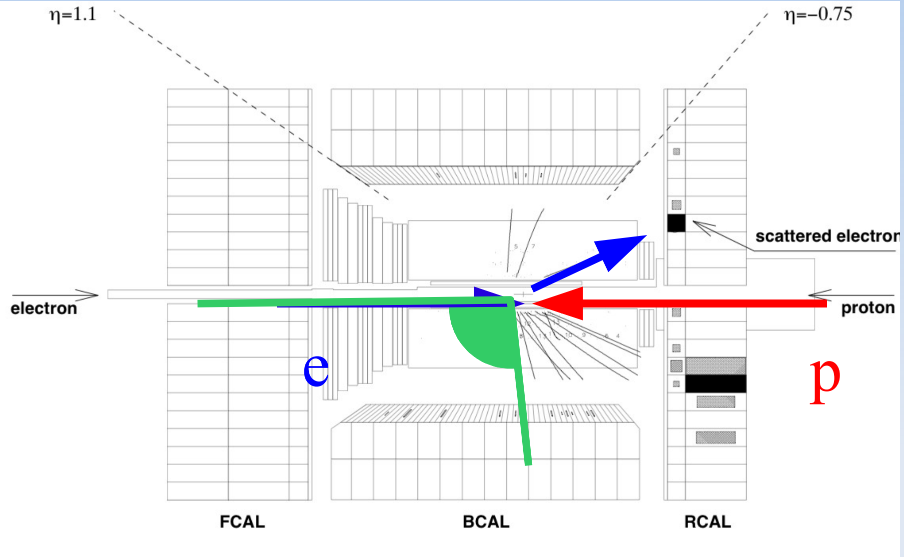
2 central jets | 2 forward jets

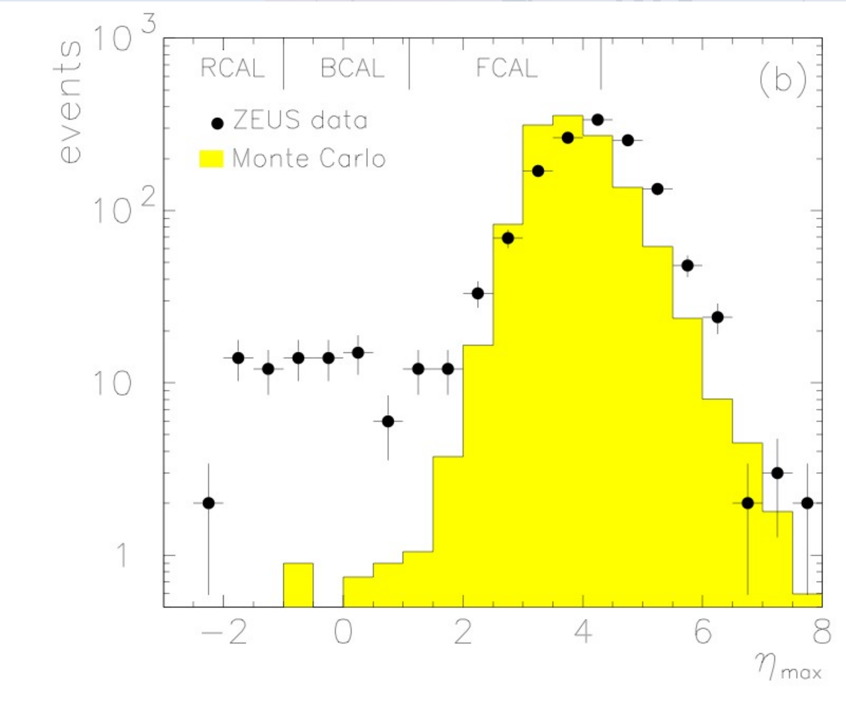
- fwd in the direction of the proton
- fwd jet = θ_{jet}<20° and $x_{jet} = E^*_{jet}/E_P$>0.035 *in γ*p cms*

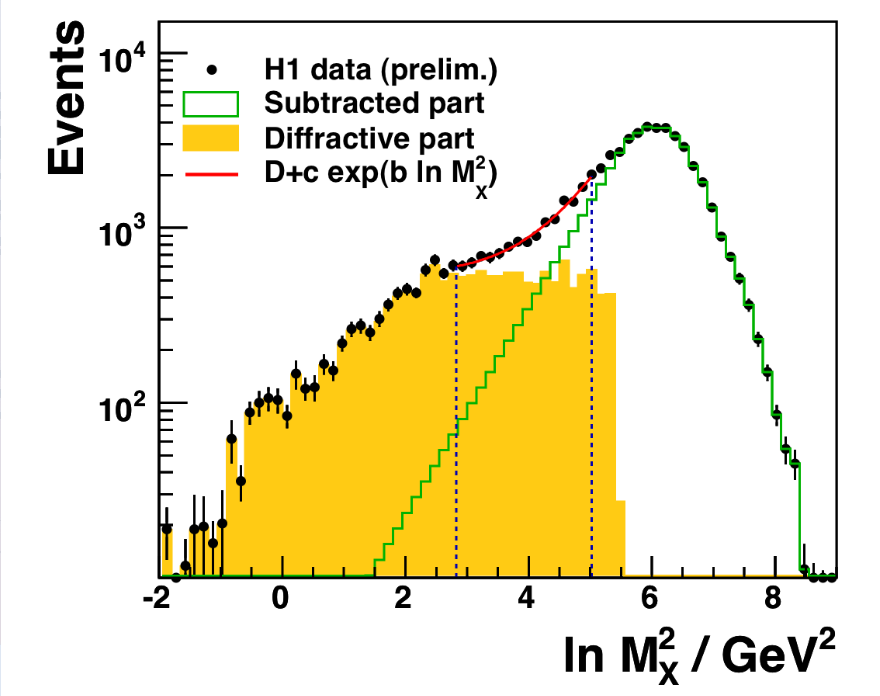
→ unordered k_T gluons emission ? typically BKFL

Diffraction re-discovery

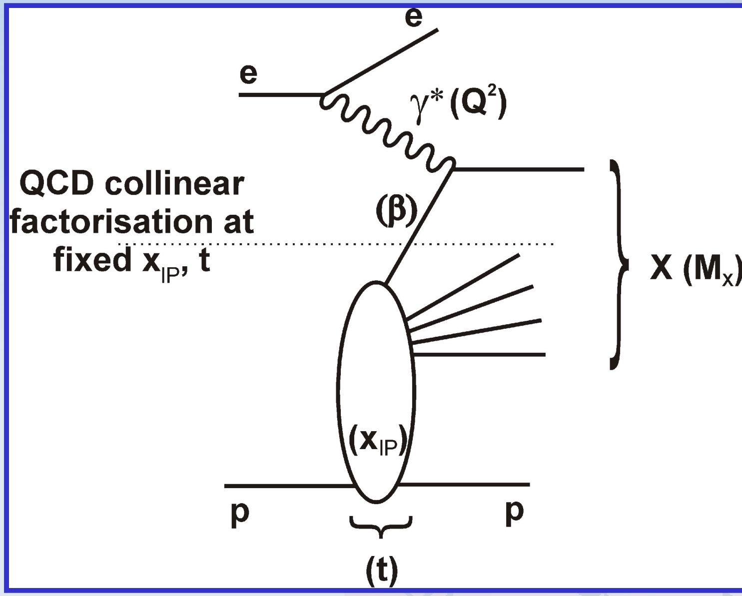
- re-discovery by ZEUS in 93:
  1/10 of DIS events present a large rapidity gap
- ep → eXp,
  → p barely touched
  - 1% of long. momentum exchanged
    P_T ~ 100 MeV.
- → Regge theory ("Vaccum exchange")

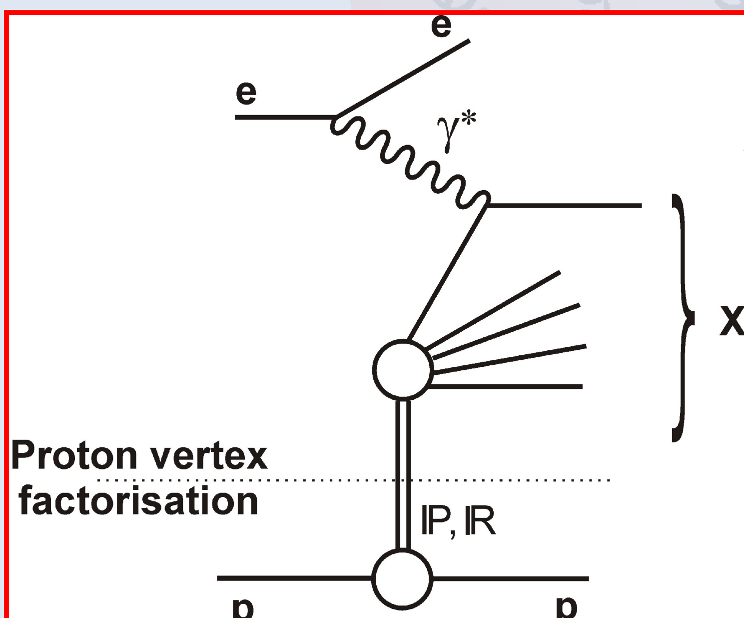






Regge Factorization





- DIS:

$$F_2(x, Q^2) = \sum_{a=q,\bar{q},g} f_a \otimes C_2^a$$

- Diffractive DIS:

$$F_2^{D(3)}(x_{IP}, \beta, Q^2) = \sum_{a=q,\bar{q},g} f_a^D \otimes C_i^a$$

- if Regge factorization holds:

$$f_a^D(x_{IP}, \beta, Q^2) = \mathrm{Flux}(x_{IP})\, f_a^{IP}(\beta, Q^2)$$

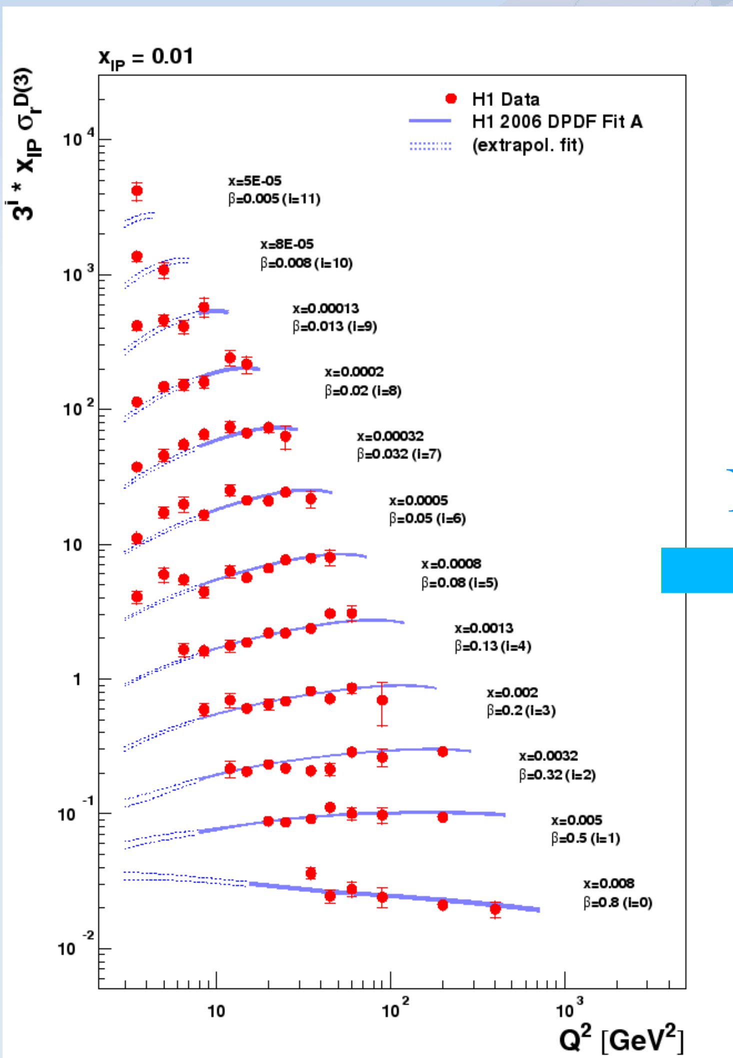
t = squared 4-mom. transfer to proton

x_{IP}(or ξ) = fractional proton mom. loss (mom. frac. IP/p)

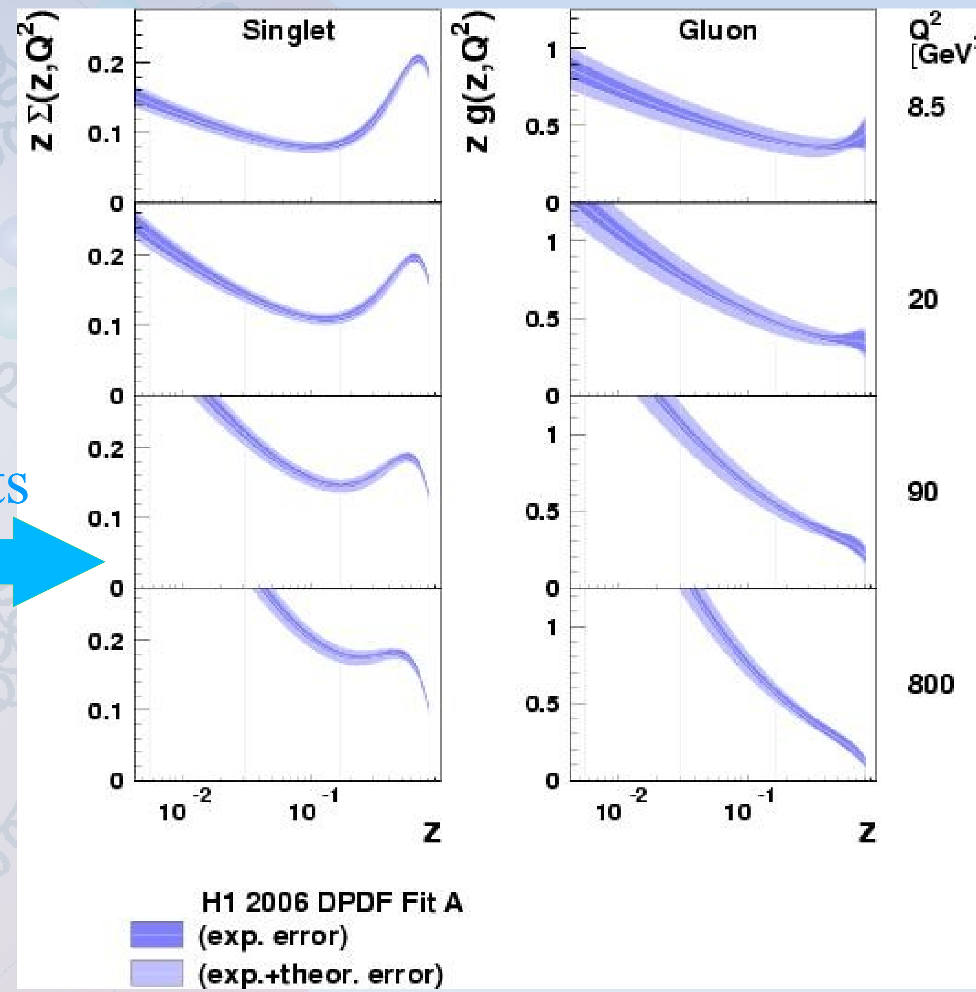
β(or z_{IP}) = fraction of total exchanged mom. entering hard scatter (mom. frac. q / IP or g / IP)

Hard Diffraction: PDF's

- If factorisation holds : Hard Diff → IP PDF's

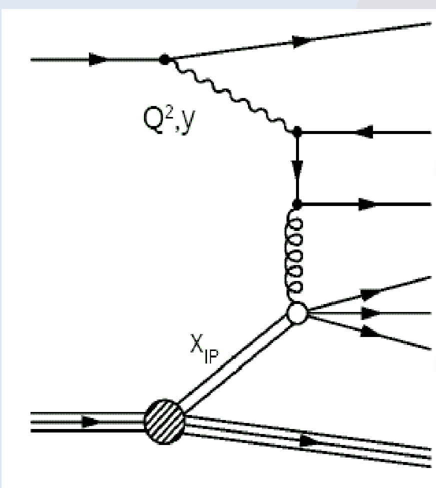


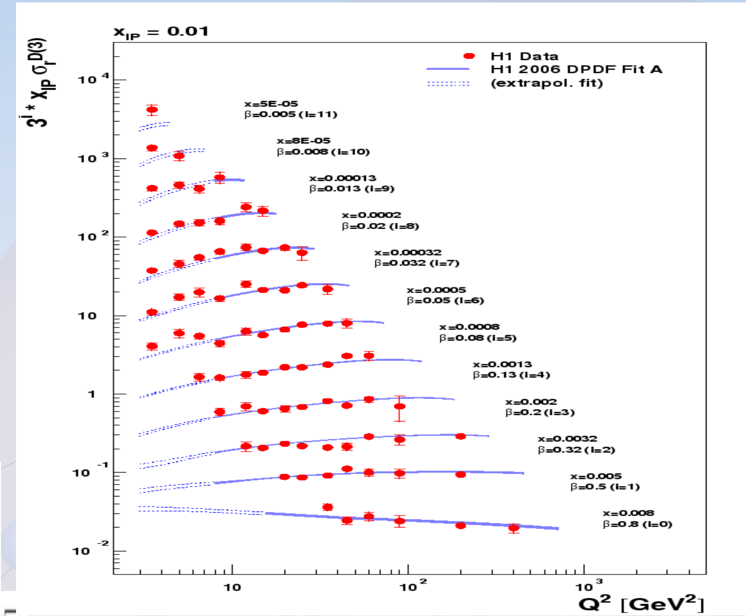
NLO fits

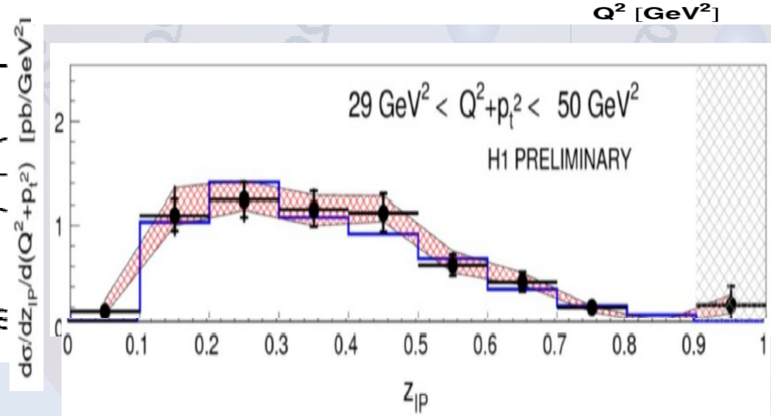


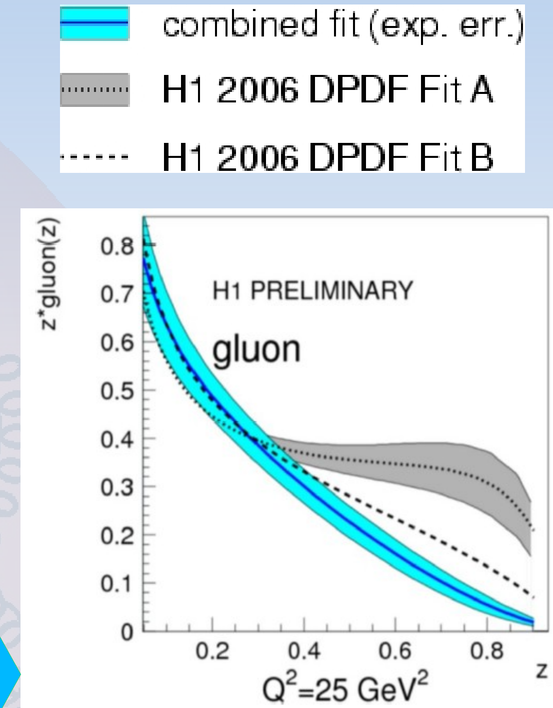
~70% gluons
Integrated over z

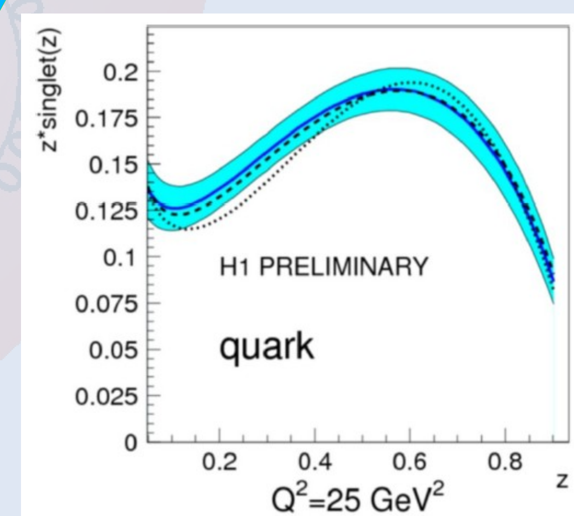
Diffractive PDF's (inclusive +2jets)







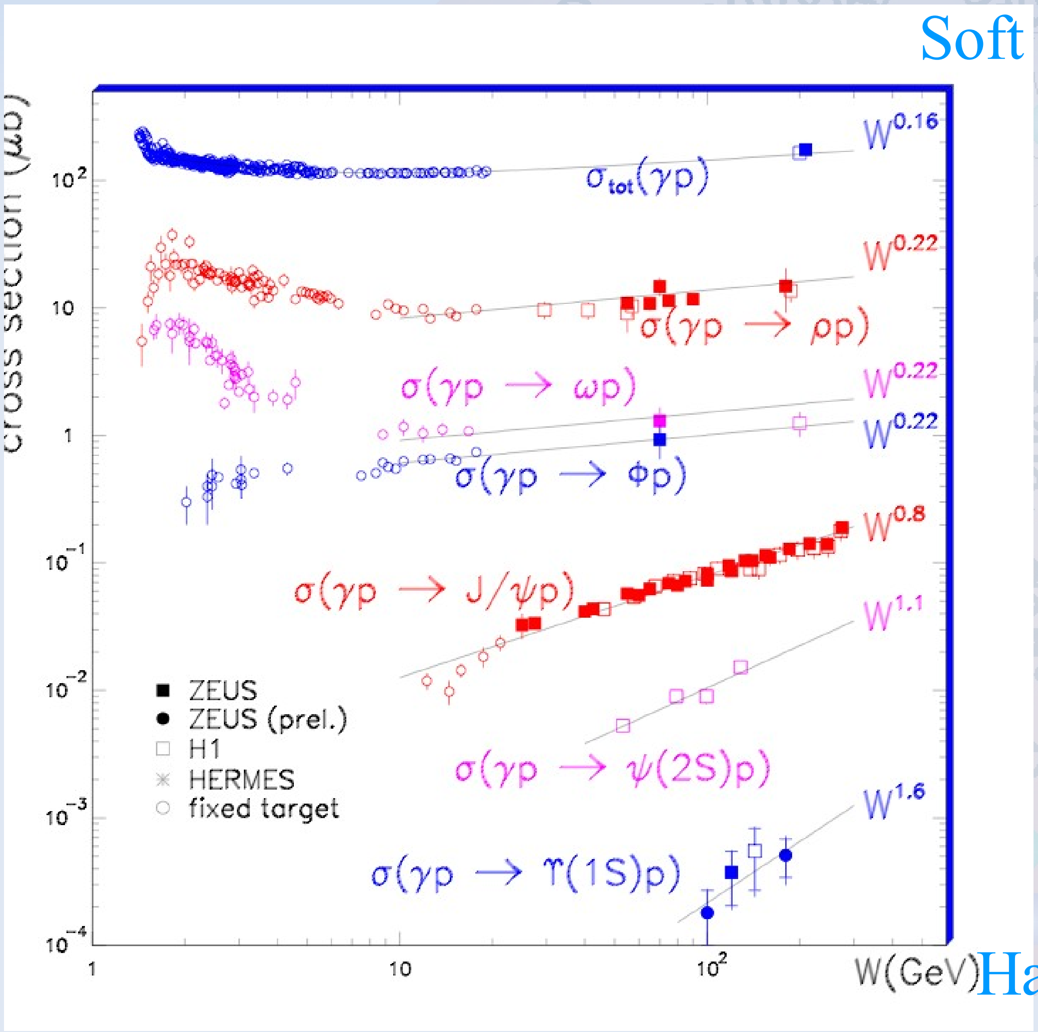


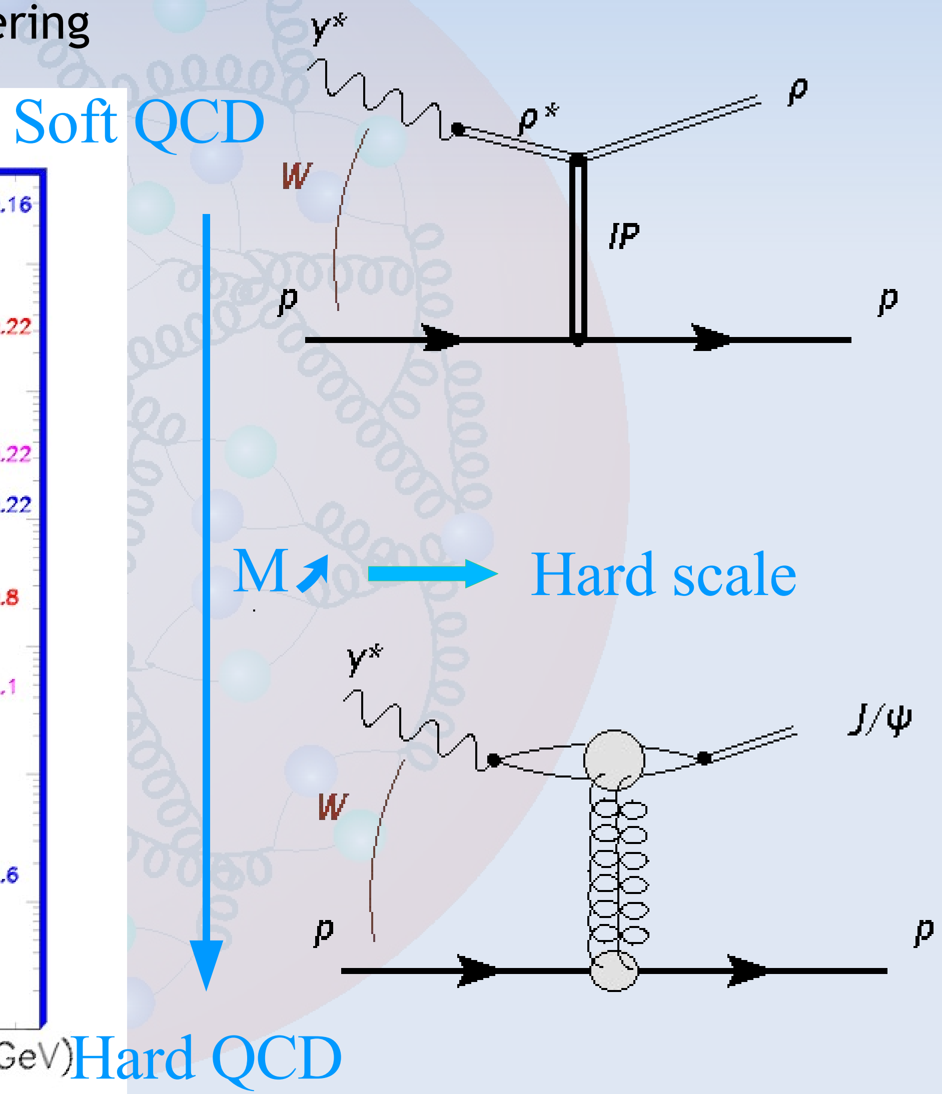


- Consistent picture
- Improved precision on gluon density
- *Spoiled by rescattering in photoproduction*

VM production

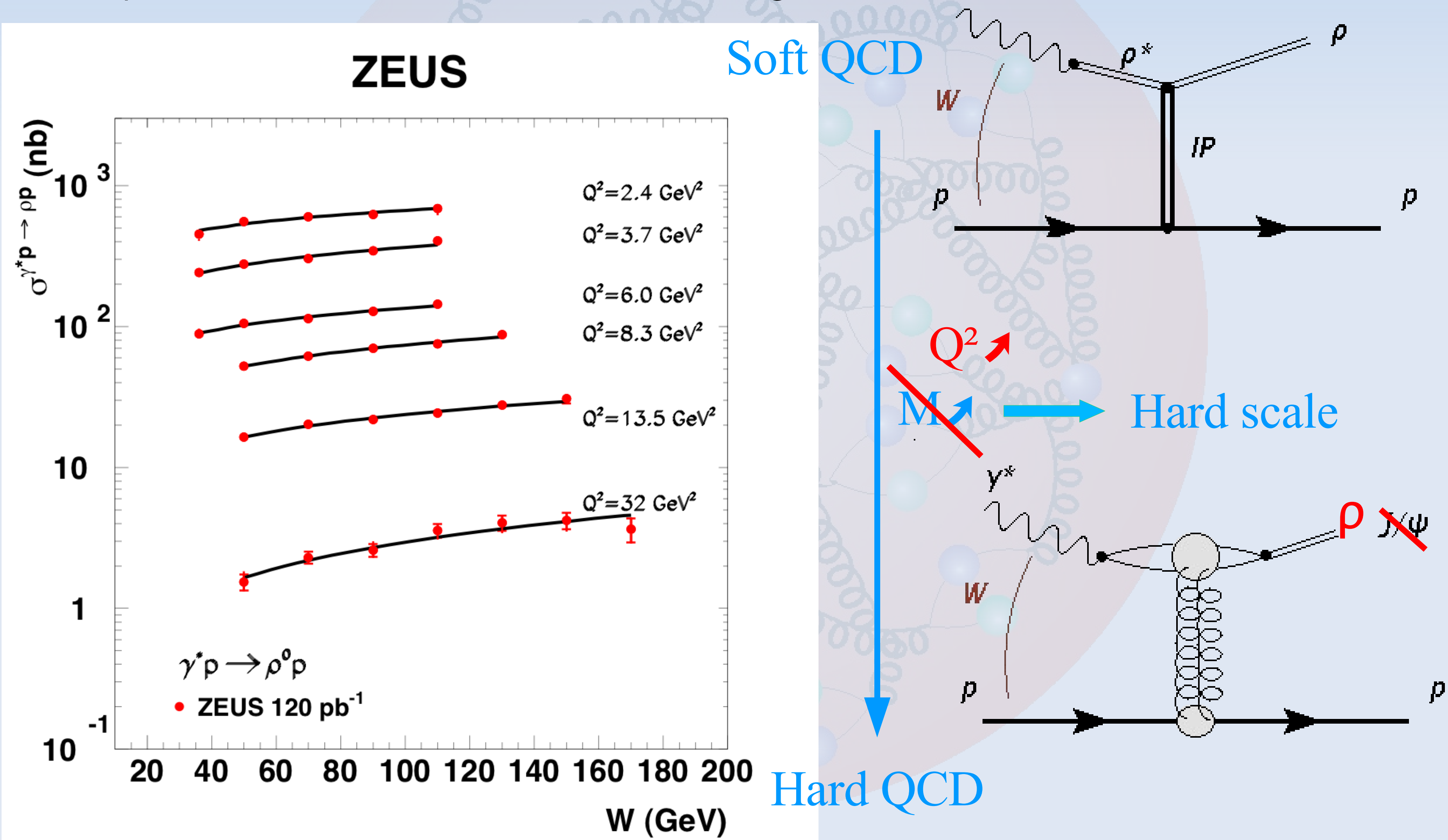
- Vector Mesons: (γ), ρ^0, ω, Φ, J/Ψ, ϒ
  - γ* fluctuate in VM + hadronic scattering





VM production

- Vector Mesons: (γ), ρ⁰, ω, Φ, J/Ψ, ϒ
  - γ* fluctuate in VM + hadronic scattering



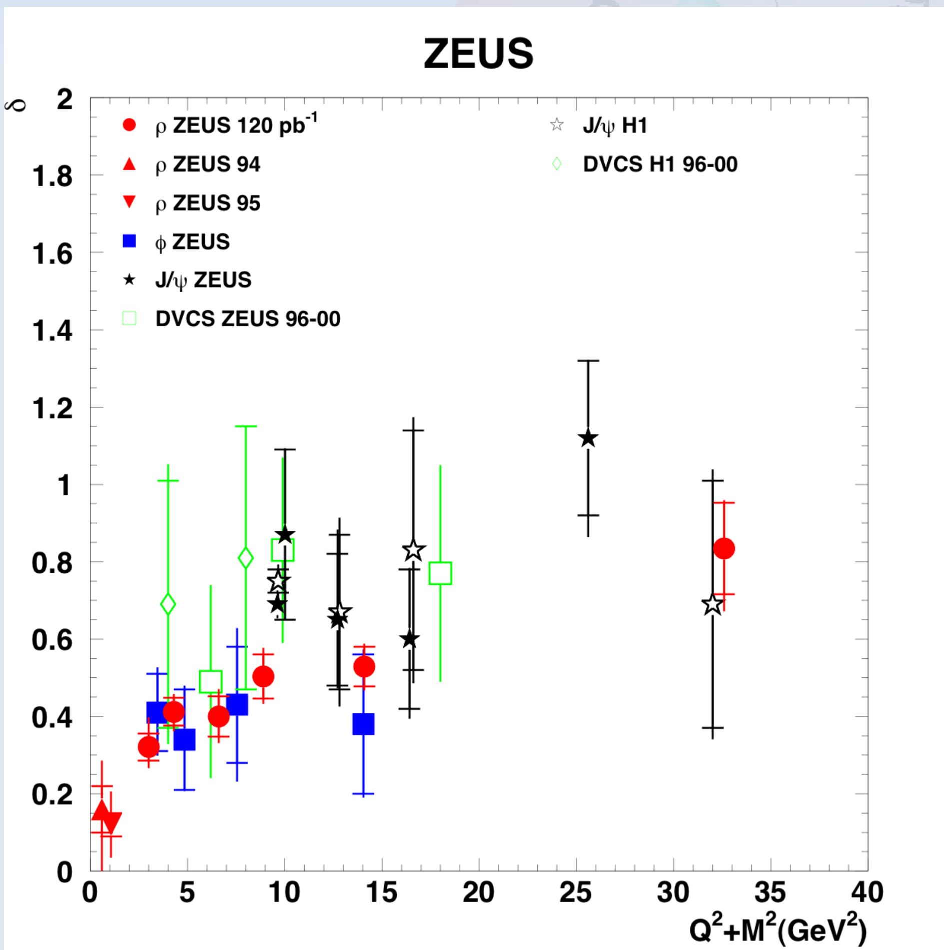
VM production vs hard scale

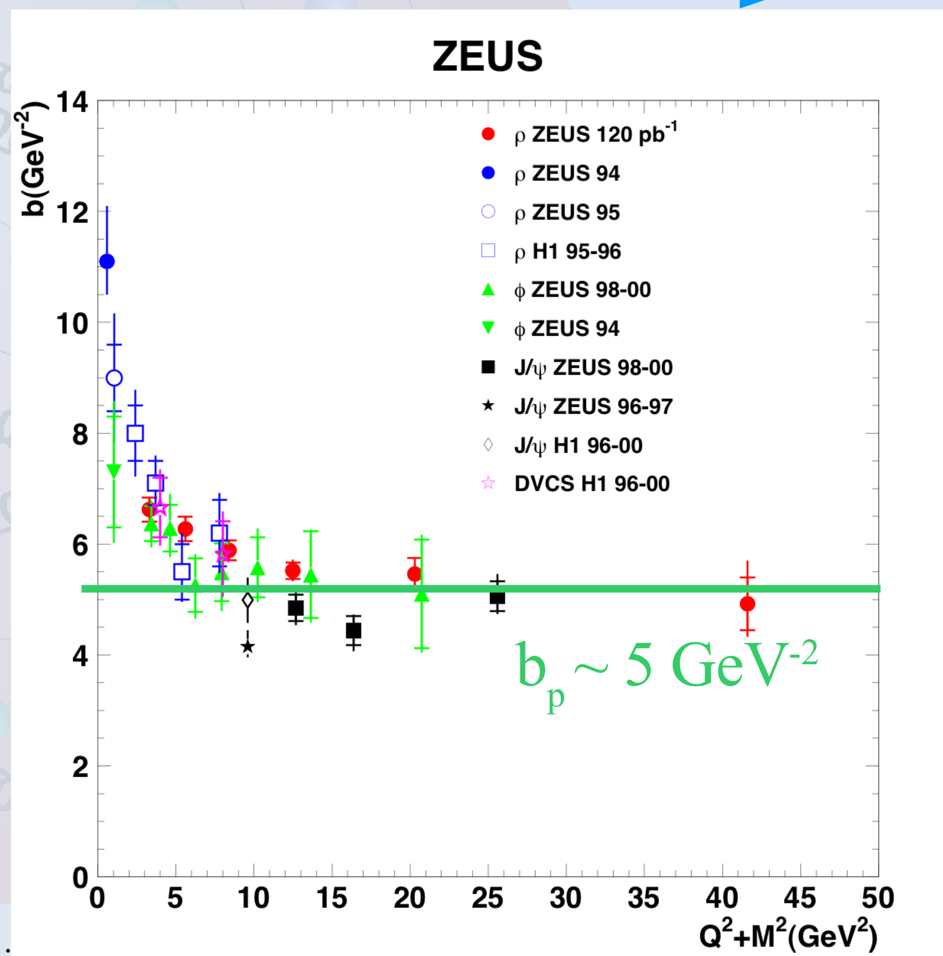
- Study at moderate Q^2
- $\sigma \sim W^{\delta}$

$$\delta = \delta_0 + 0.25 \ln(Q^2+M^2)$$

- $d\sigma/dt \sim e^{bt}$ at low $|t|$
  $b = b_v + b_p$
- $b_v \sim 1/(Q^2 + M^2)$

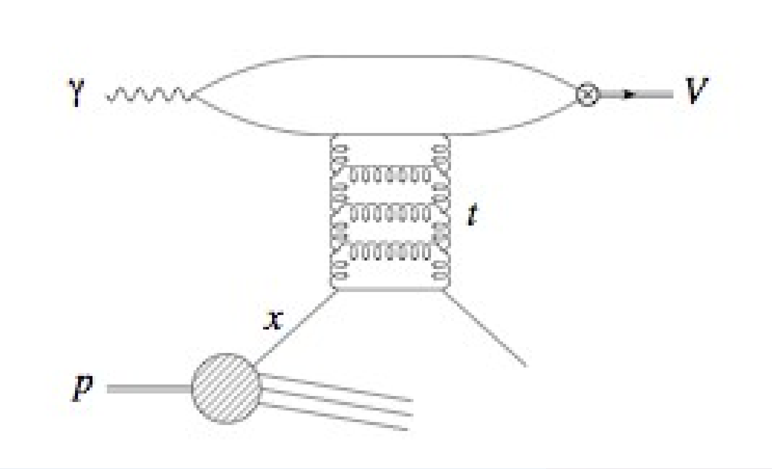
qqbar pair size

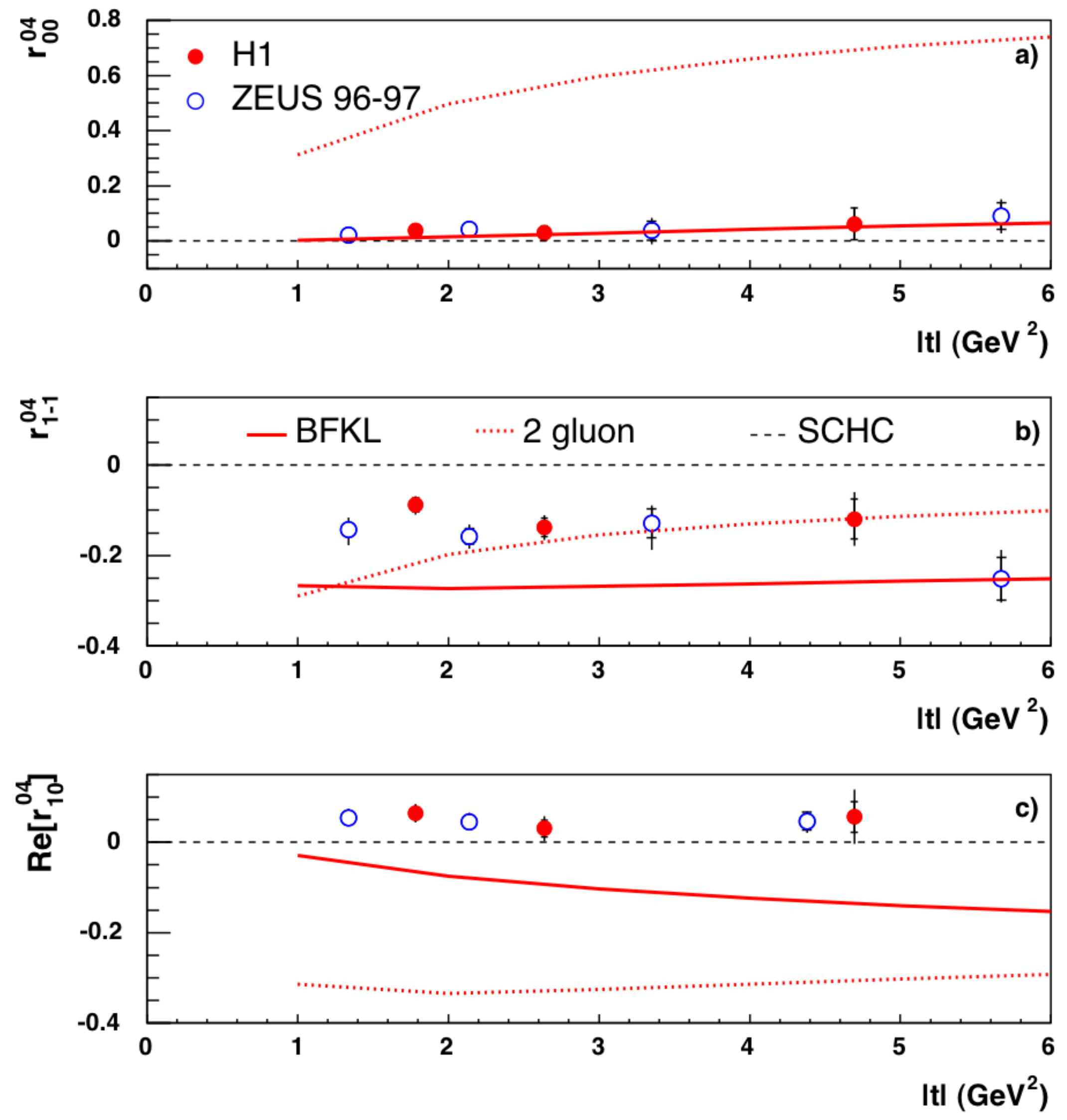




VM test of QCD dynamics

- $ep \rightarrow ep\rho^0$ @ high |t| (H1)
- spin analysis
- BFKL model
  - vs 2 gluons
  - vs Regge Model (helicity conservation)





Conclusions & Outlook

- Many "unmissable" topics uncovered
  - DVCS, Heavy Quarks, many many analysis...
- Huge progress on p structure function precision
  - extended precision in all of the kin.
    → low & high x, low & high Q^2, high y
- ... and in the QCD basis of diffraction
- Still a lot of work
  - combine H1 & ZEUS data started
  - HERA-II data "barely" touched
    → improvement of precision × ~2 expected
- and many new results to come,
  - direct measurements of $F_L \sim \alpha_s\, xg(x)$ from low energy runs
  - inclusion of charm and beauty data (F2cc and F2bb) in QCD fit
  - NNLO QCD fits
  - ...