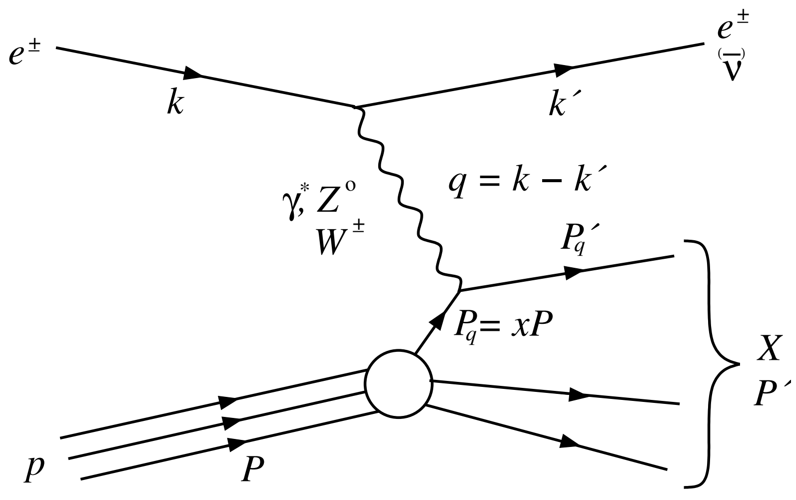
# $\alpha_s$ and $xg$ from Structure Functions, $F_L$

**Vladimir Chekelian** (*MPI for Physics, Munich*)

**Deep inelastic scattering (DIS)**
**Low $x$ at HERA**
**Inclusive DIS measurements and kinematic reach at HERA**
**Rise of $F_2$ at low $x$**
**Scaling violations at low $x$**
**NLO QCD fits**
**Gluon**
$\alpha_s$
**Charm & jets**
$F_L$
**Summary**

# Deep Inelastic Scattering (DIS)




$Q^2 = -q^2$ *virtuality of* $\gamma^*, Z^o, W^\pm$

$x = Q^2/2(pq)$ *Bjorken scaling variable*

$y = (Pq)/(pk)$ *inelasticity*

$Q^2 = xys$, $\sqrt{s}$ *is energy in the* $ep$ *cms*

$W^2 = (P+q)^2 = Q^2(1/x - 1)$ *hadronic mass*$^2$

## Neutral Current (NC) - $\gamma^*, Z^o$ exchange

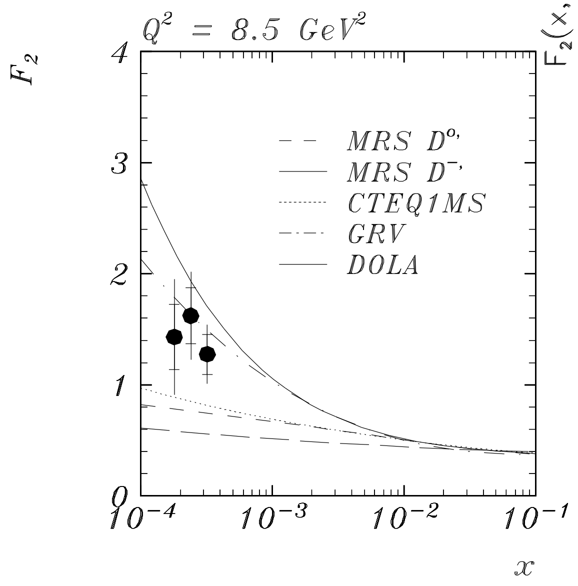
$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dx\, dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+ F_2(x,Q^2) \mp Y_- xF_3(x,Q^2) - y^2 F_L(x,Q^2)]\,, \quad Y_\pm \equiv 1 \pm (1-y)^2$$

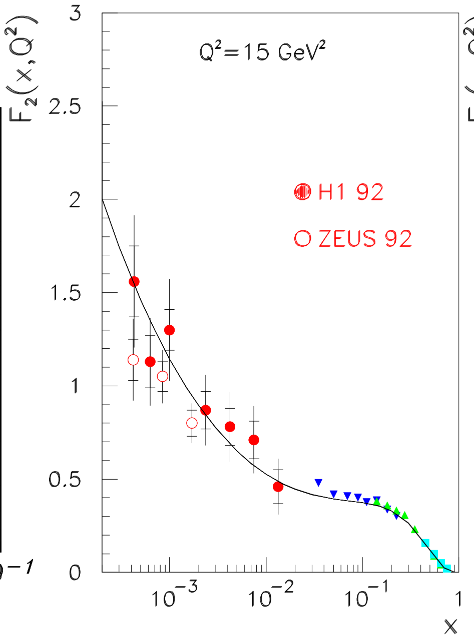
in QPM: $F_2 = x\sum A_i(q_i + \bar{q}_i)$, $xF_3 = x\sum B_i(q_i - \bar{q}_i)$, $F_L = 0$

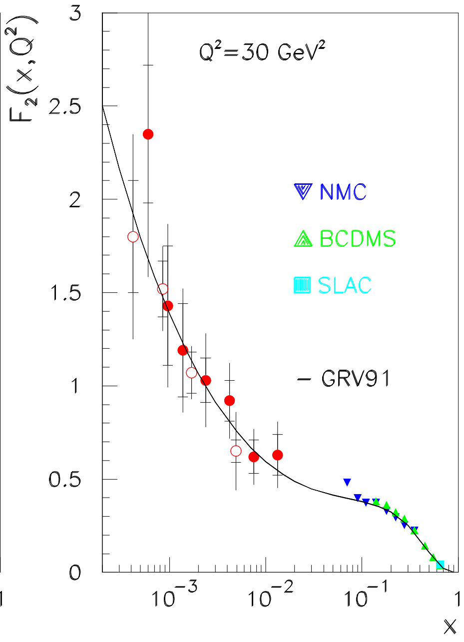
## Reduced cross section (NC)

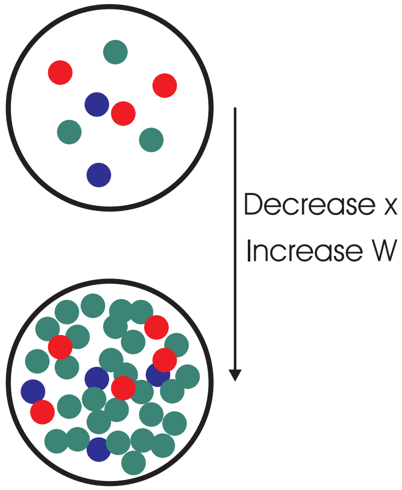
$$\tilde{\sigma}_{NC}(x,Q^2) \equiv \frac{1}{Y_+}\frac{Q^4\ x}{2\pi\alpha^2}\frac{d^2\sigma_{NC}}{dx dQ^2} = F_2(1 + \Delta_{F_2} + \Delta_{F_3} + \Delta_{F_L})$$

# Low $x$ at HERA



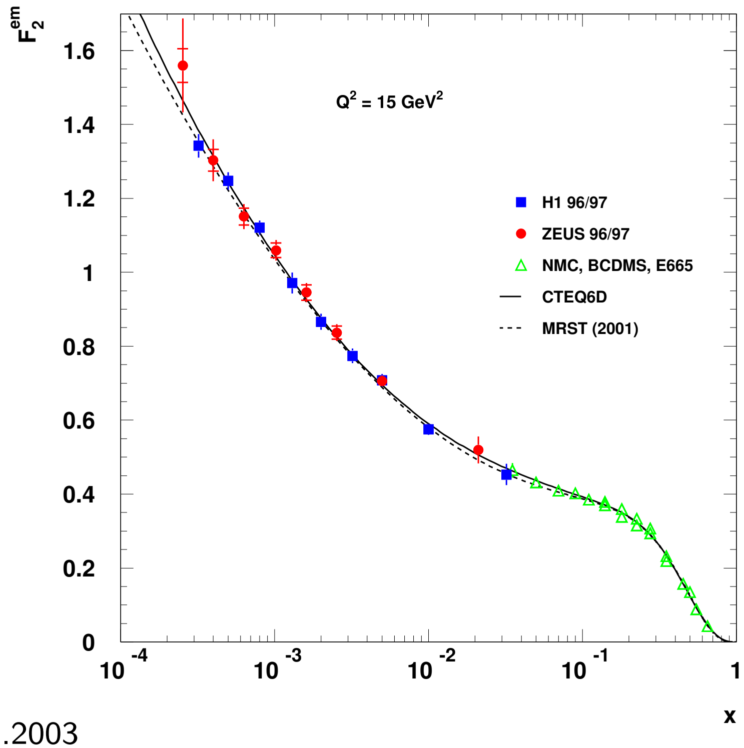

**the first HERA data:**

- *discovery of the $F_2$ rise at low $x$*

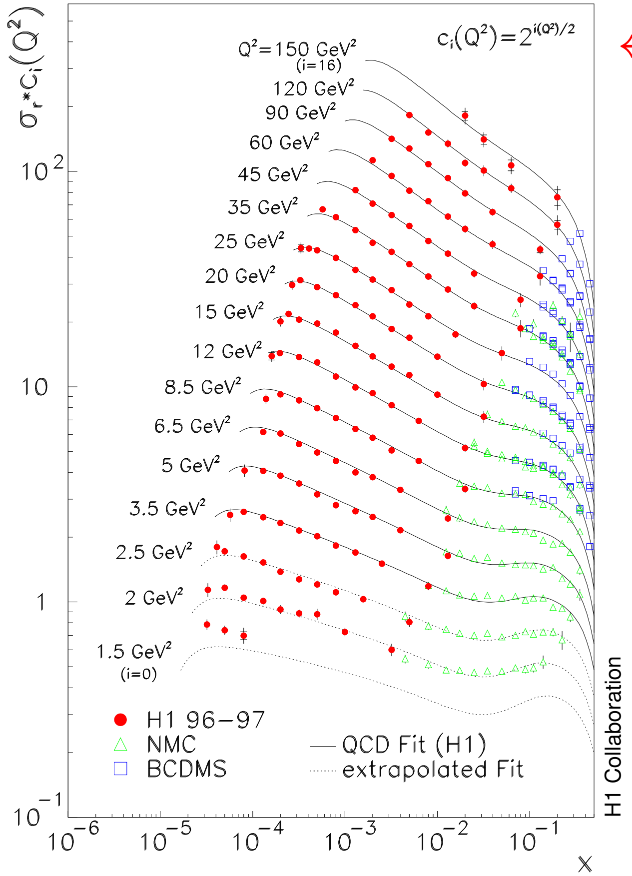
- **can not rise forever !**
- **search for new gluon dynamics (saturation effects)**

**after 11 years of HERA:**

- **precise data allowing to look for smallest deviations**

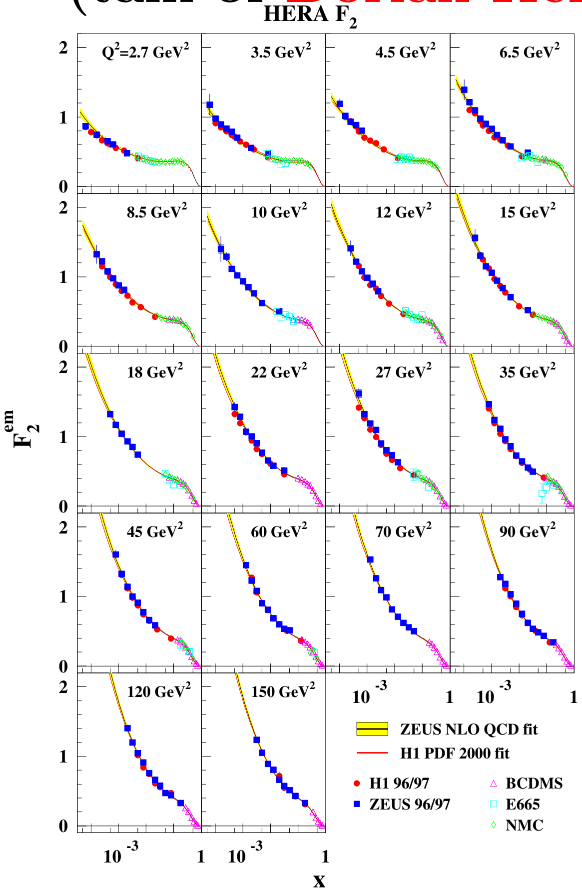


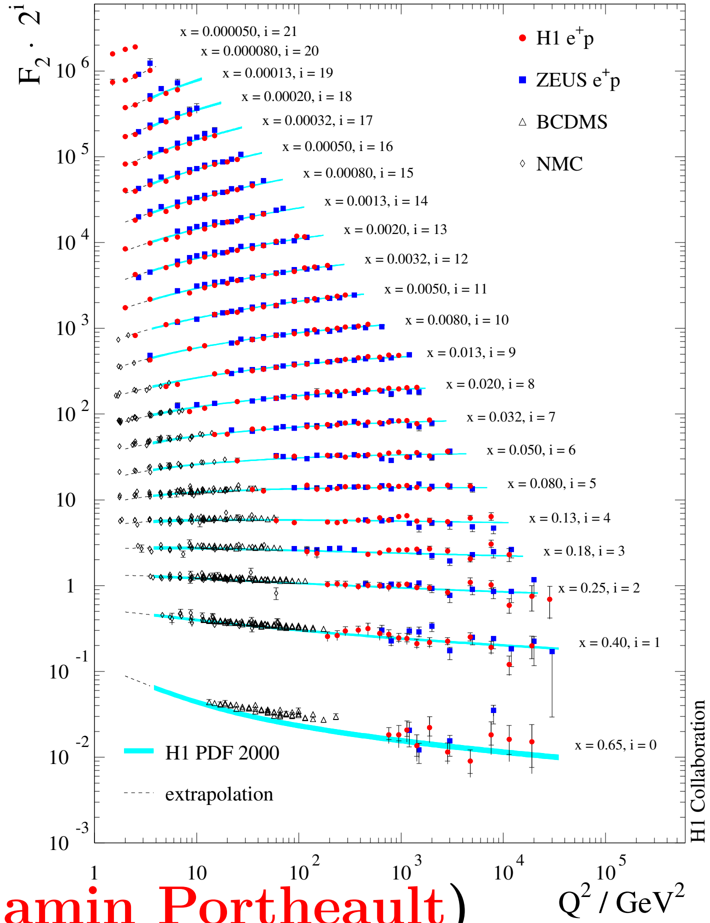
# Inclusive DIS Measurements at HERA




← **low $Q^2$**
**(talk of Dorian Kcira)**

*precision data ±2-3%*
*5 decades in $x$*
*5 decades in $Q^2$*

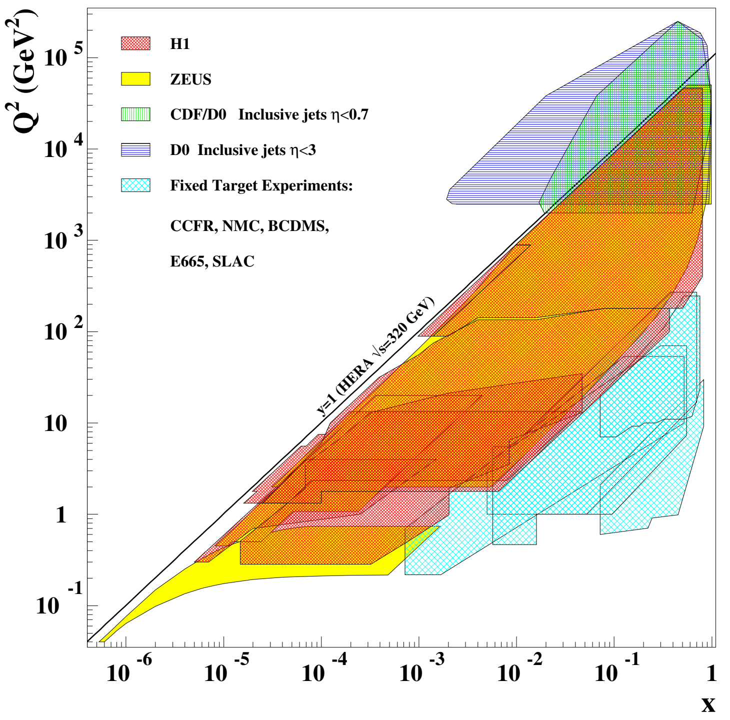


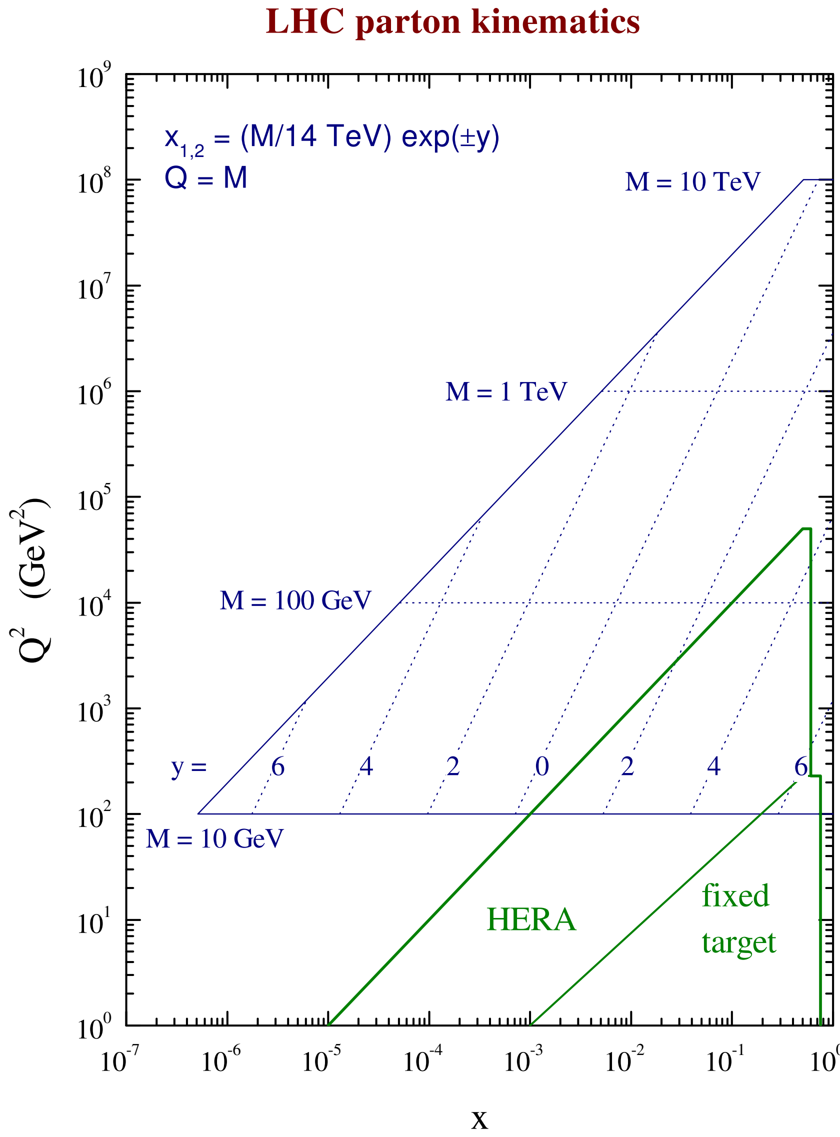




*rich possibilities to test QCD, transition to $\gamma p$,*
*models, search for saturation effects, ...*

**high $Q^2$** →
**(talk of Benjamin Portheault)**

# Kinematic Reach in DIS




*full HERA $x$ range needed for LHC*

$\boldsymbol{Q^2 \geq 1\ \mathrm{GeV}^2}$ **QCD** *evolution* ($\boldsymbol{xg}$&$\boldsymbol{\alpha_s}$)

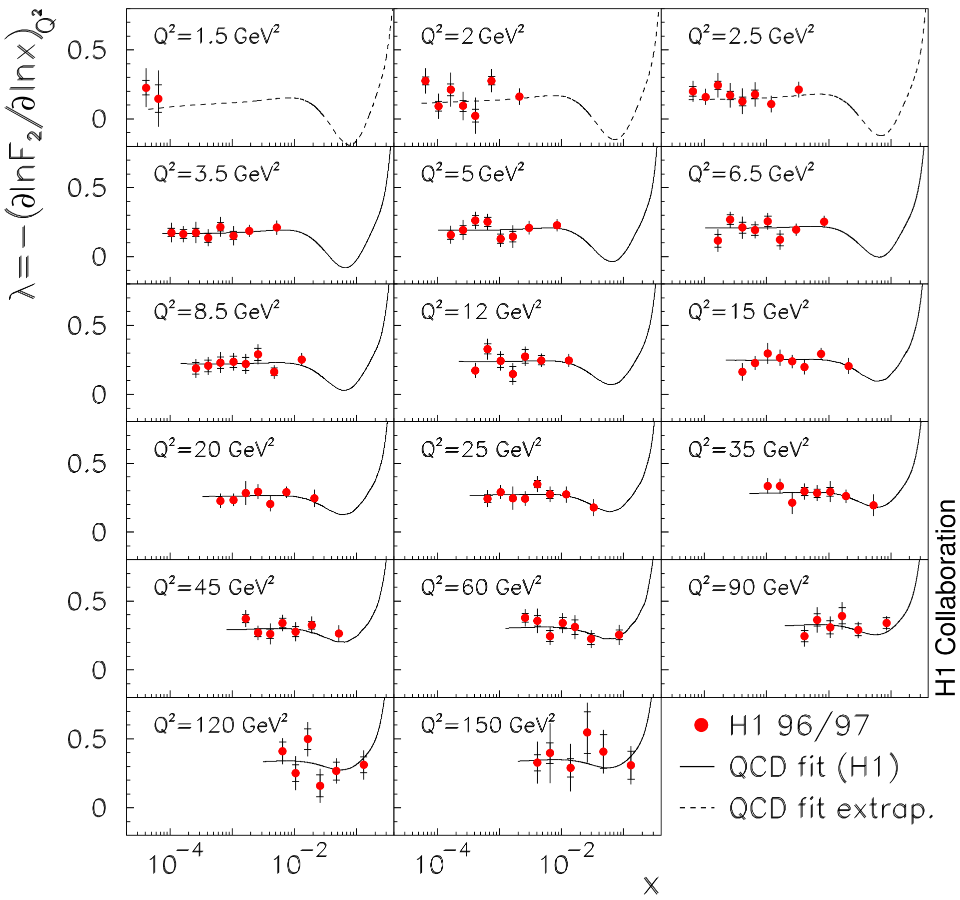
$\boldsymbol{x \to 0}$ *saturation (?)*

$\boldsymbol{y \to 1}$ *sensitivity to* $\boldsymbol{F_L}$

$\boldsymbol{Q^2 \to s}$ *electroweak physics*

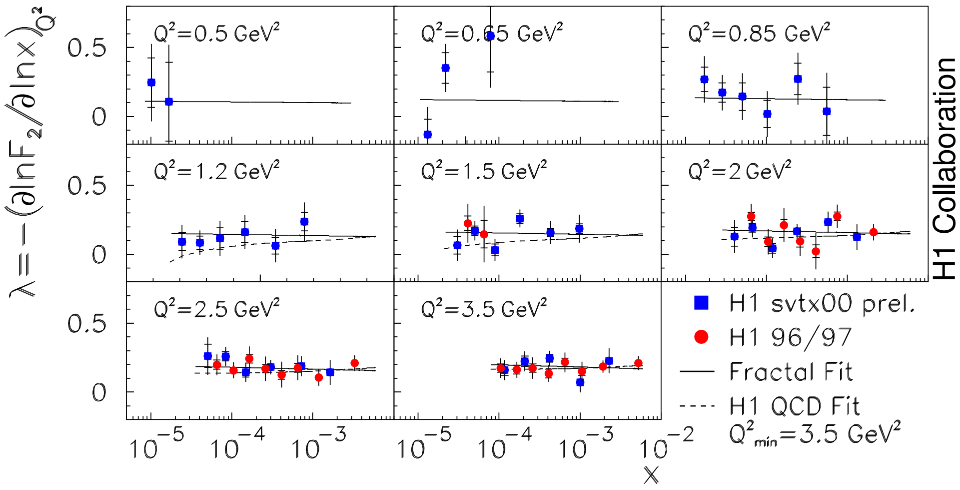
$\boldsymbol{x \to 1}$ *probe valence quarks*

# Partial Derivatives $(\partial F_2/\partial \ln x)_{Q^2}$



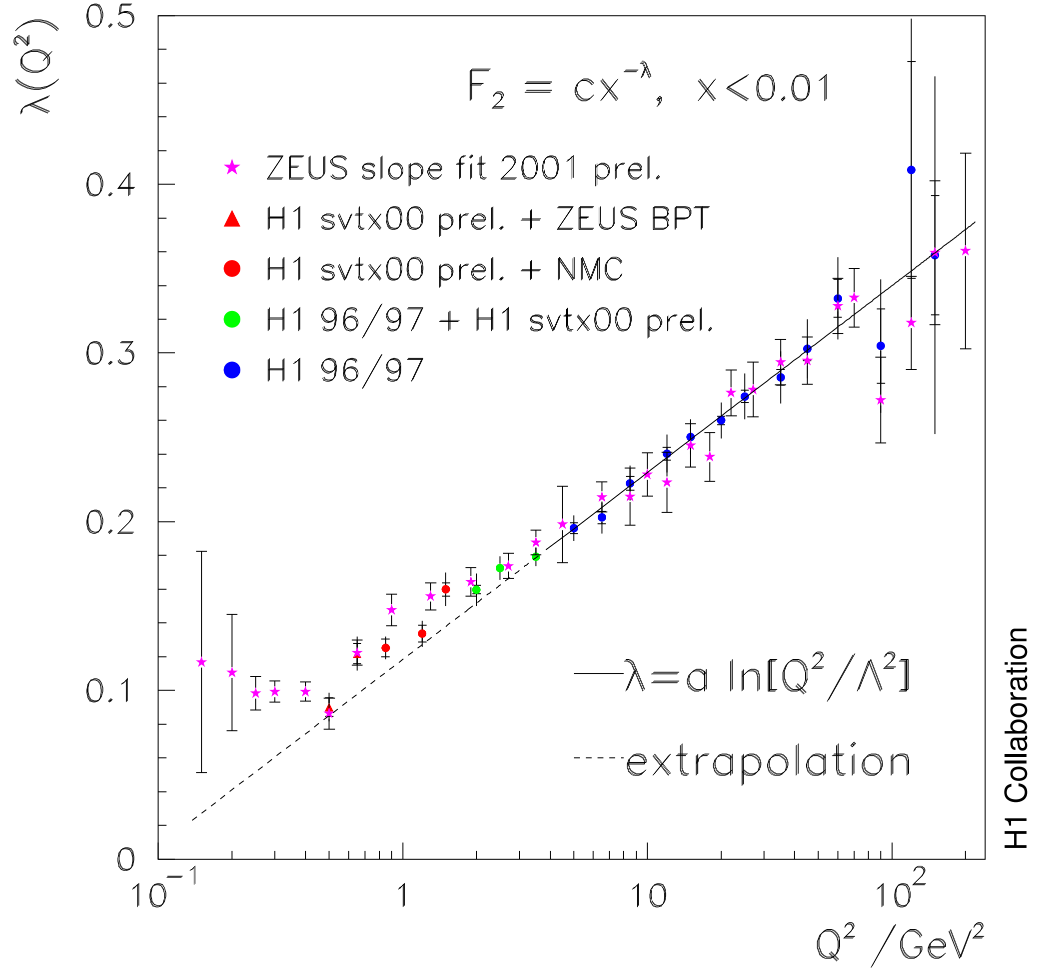

**Study rise of $F_2$ locally**

$$\lambda = -(\partial F_2/\partial \ln x)_{Q^2}$$




- $\lambda \approx$ *constant at fixed* $Q^2$ $(x < 0.01)$
- *no taming of rise of* $F_2$ *to low* $x$ *for* $Q^2 \geq 0.5\ \mathrm{GeV}^2$

# Rise of $F_2$ to Low $x$




$\leftarrow$ $\lambda(Q^2)$ from the fit:

$$F_2(x, Q^2) = c(Q^2)\ x^{-\lambda(Q^2)}$$

- $\lambda(Q^2)$ *depends linearly on* $\ln(Q^2)$
- *agrees with QCD for* $Q^2 > 2$ GeV$^2$
- *change of behavior at* $Q^2 \approx 1$ GeV$^2$
- *soft pomeron limit* $\lambda$=0.08 (DL)

$$\sigma_{tot}^{\gamma^* p} = 4\pi^2 \alpha F_2/Q^2,\ s = W^2 \propto Q^2/x$$

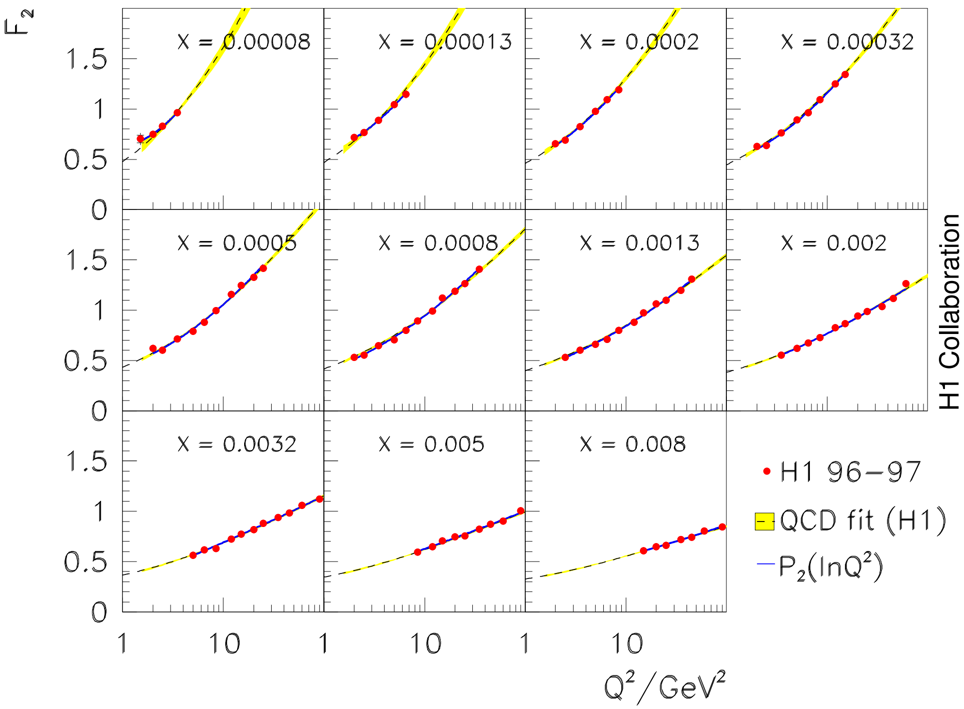
*Regge theory:* $\sigma_{tot} \propto s^{\alpha_{IP}(0)-1}$

$$F_2 \propto x^{-(\alpha_{IP}(0)-1)} \approx x^{-0.08}$$

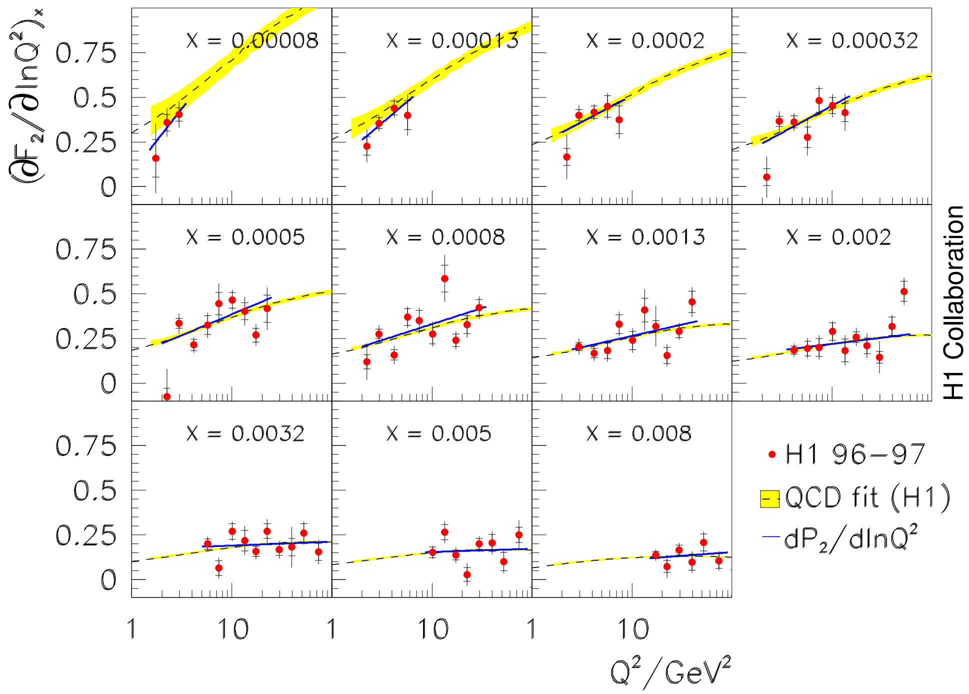
*more precision in the transition region*
*no evidence for saturation effects*

# Partial Derivatives $(\partial F_2/\partial \ln Q^2)_x$

## $F_2$ vs. $Q^2$




## Local derivatives

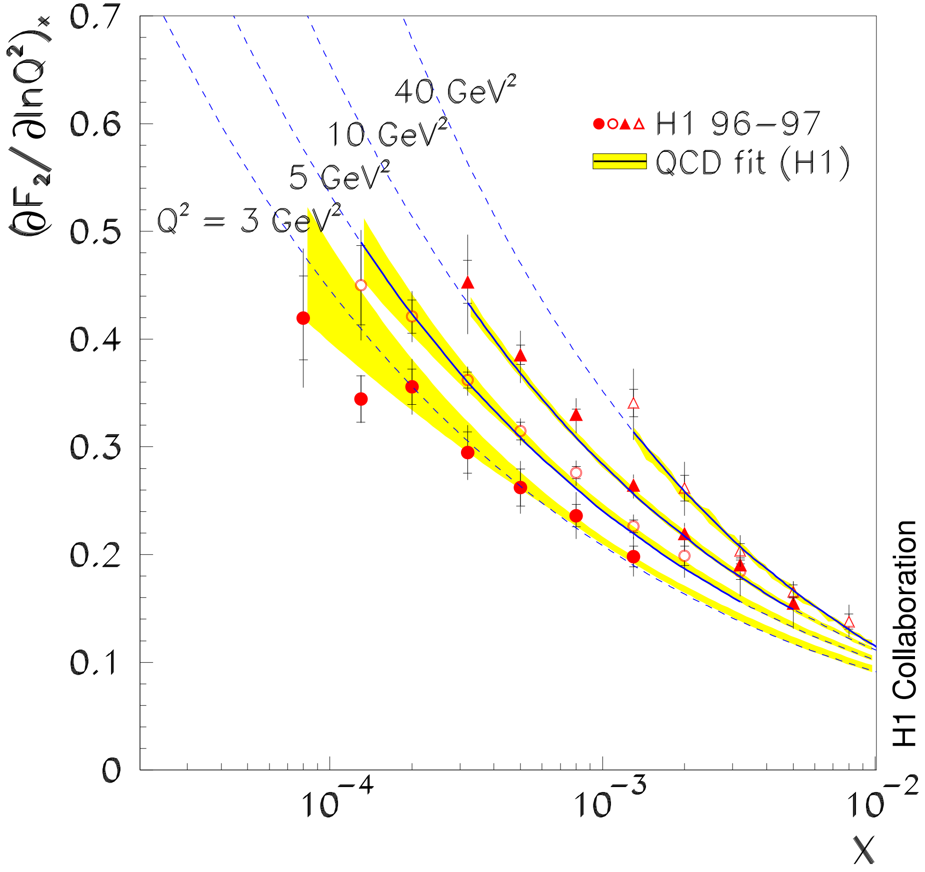


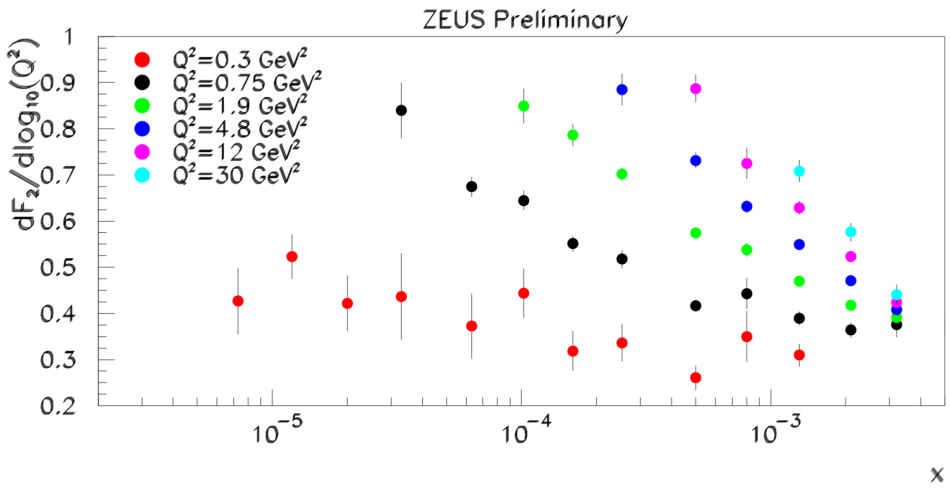

- *for local derivatives higher precision is desirable*
- *local derivatives are consistent with linear rise in* $\ln Q^2$
- *Quadratic fit to $F_2$:* $P_2(x,Q^2) = a(x) + b(x)\ln Q^2 + c(x)(\ln Q^2)^2$

$$P_2'(x,Q^2) = b(x) + 2c(x)\ln Q^2$$

# Scaling Violations at Low $x$

driven by gluon $(\partial F_2/\partial \ln Q^2)_x \propto \alpha_s(Q^2)xg(2x,Q^2)$ (LO)




- *continuous rise towards low* $x$
- *consistent with* QCD fit ($Q^2 \geq 3$ GeV$^2$)
- *no sign of new dynamics*

# The HERA NLO DGLAP QCD Fits

## $xg\&\alpha_s$ Fit of H1

$\overline{\text{MS}}$,massive,$F_2 = F_2^{n_f=3} + F_2^{c\bar{c}}$(NLO BGF)

only $ep$ H1 and $\mu p$ BCDMS ($y_\mu > 0.3$)

$xg, V \approx \frac{9}{4}u_v - \frac{3}{2}d_v, A \approx \bar{u} - \frac{1}{4}(u_v - 2d_v)$

$xP = a_p x^{b_p}(1-x)^{c_p}[1 + d_p\sqrt{x} + e_p x]$

$Q_o^2 = 4$ GeV$^2$

$3.5 \leq Q^2 \leq 3000$ GeV$^2$

momentum sum rule, $\int_0^1 V dx \approx 3$

## H1 PDF 2000

**→ talk of B.Portheault**

## ZEUS Global Fit

$\overline{\text{MS}}$, VFNS (Thorne, Roberts)

ZEUS, NMC, E665, BCDMS, CCFR

$xg, xu_v, xd_v, xS, x\Delta(norm)$

$xP = a_p x^{b_p}(1-x)^{c_p}[1 + e_p x]$

$Q_o^2 = 7$ GeV$^2$

$2.5 \leq Q^2 \leq 30000$ GeV$^2$

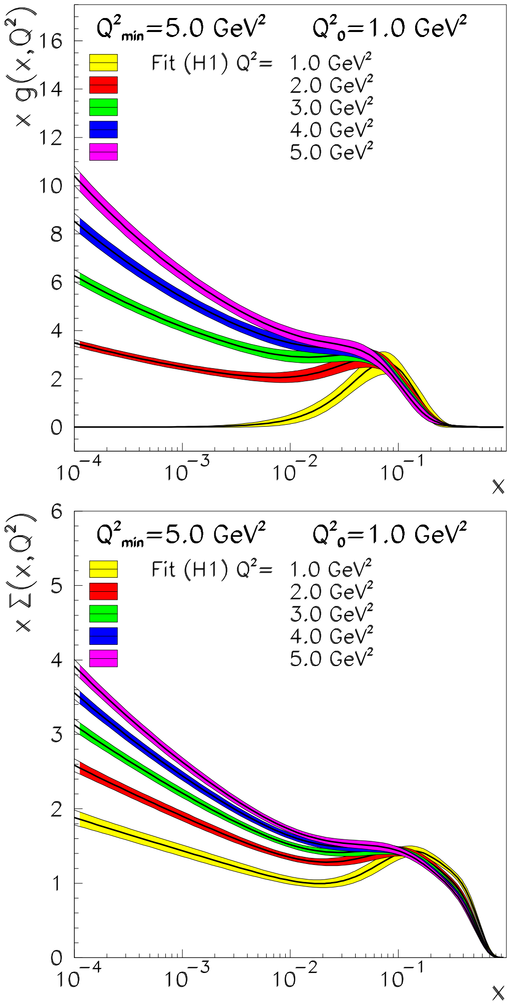
mom. sum rule, $\int_0^1 (u_v + d_v)dx = 3$

shape of $x\Delta = x(\bar{d} - \bar{u})$ from MRST

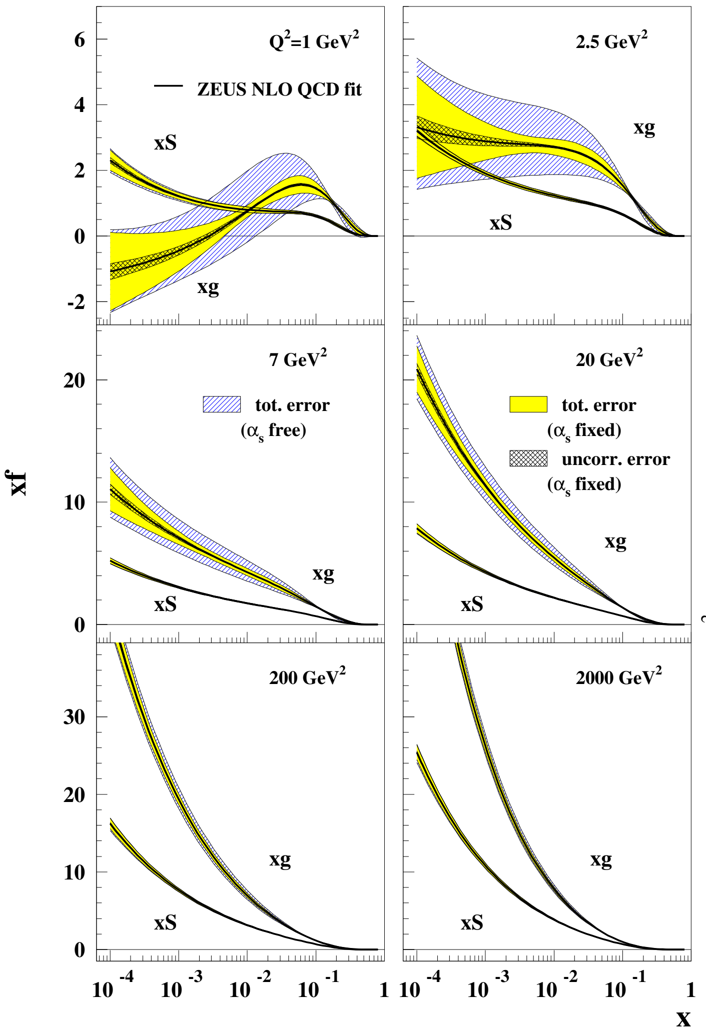
$b_{u_v} = b_{d_v} = 0.5$

# Gluon and Sea

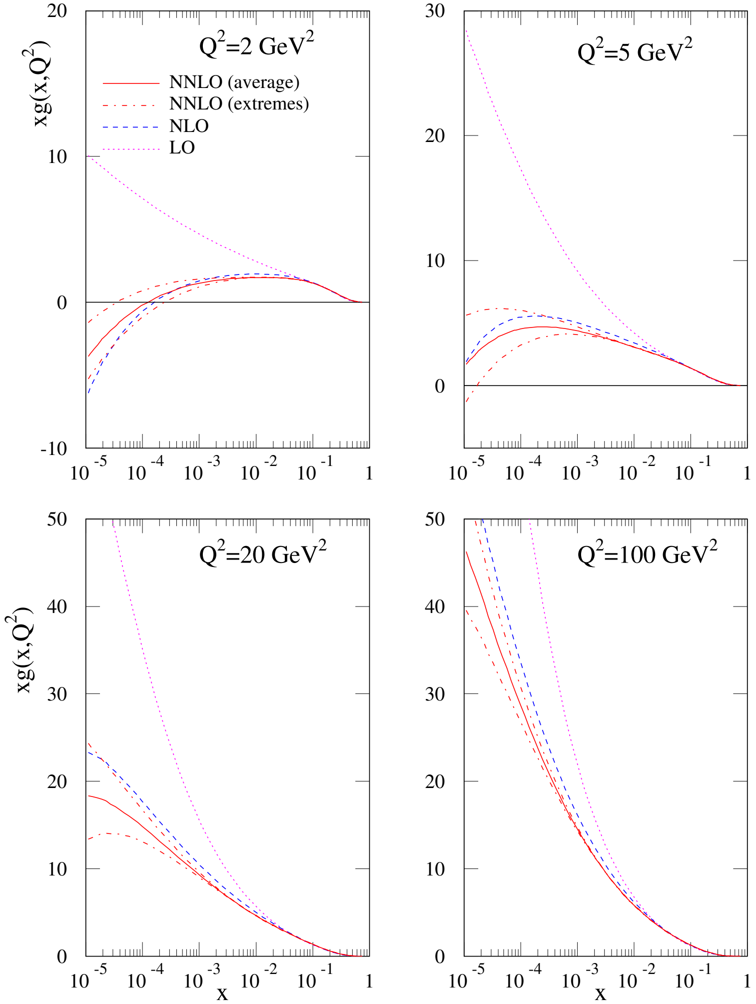
H1




ZEUS

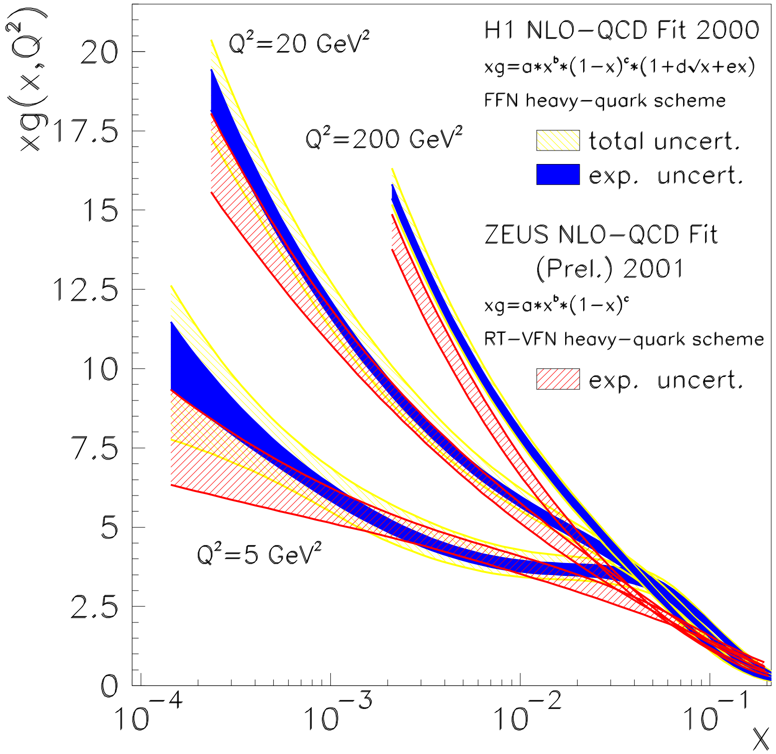


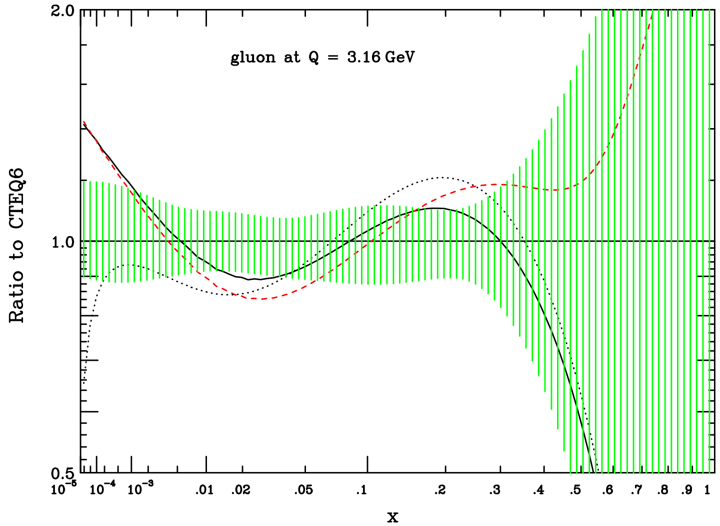

MRST

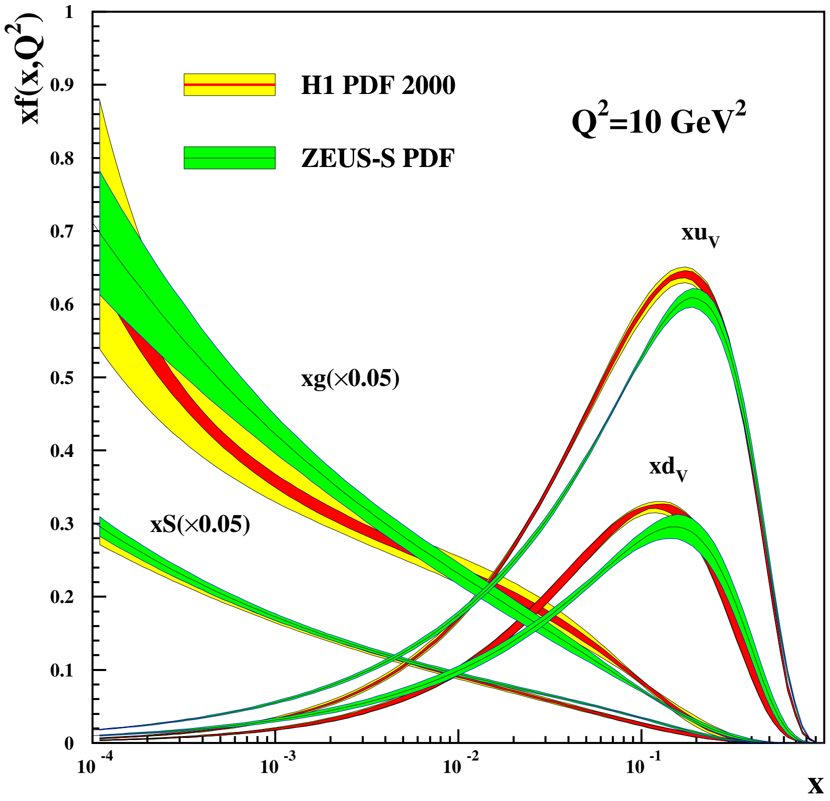



- *rise of the sea (driven by gluon) towards low $x$*
- *rise of gluon towards low $x$ for $Q^2 > 2 - 3$ GeV$^2$* - *similar to $F_2$, $(\partial F_2/\partial \ln Q^2)_x$*
- *flat or even negative gluon at smallest $Q^2$*

# Gluon



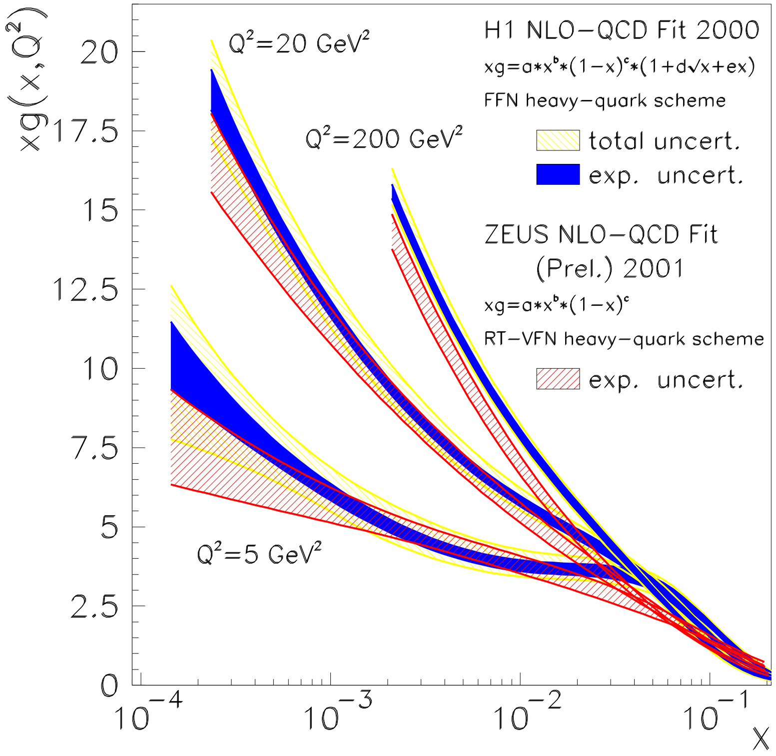



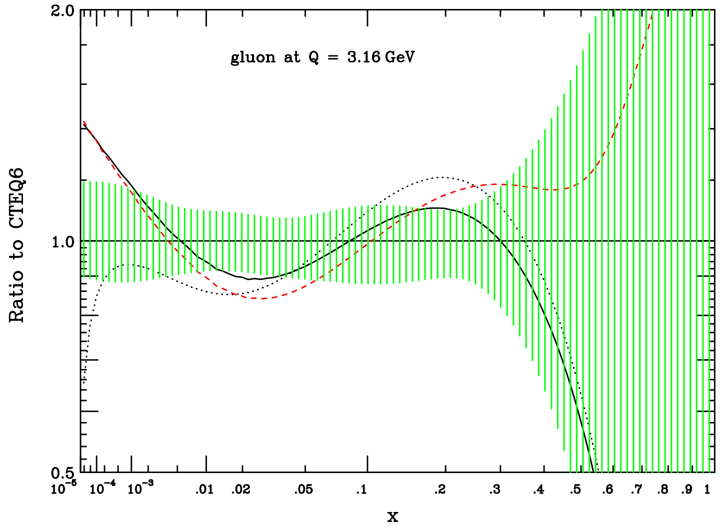

**Remaining uncertainties of PDFs:**

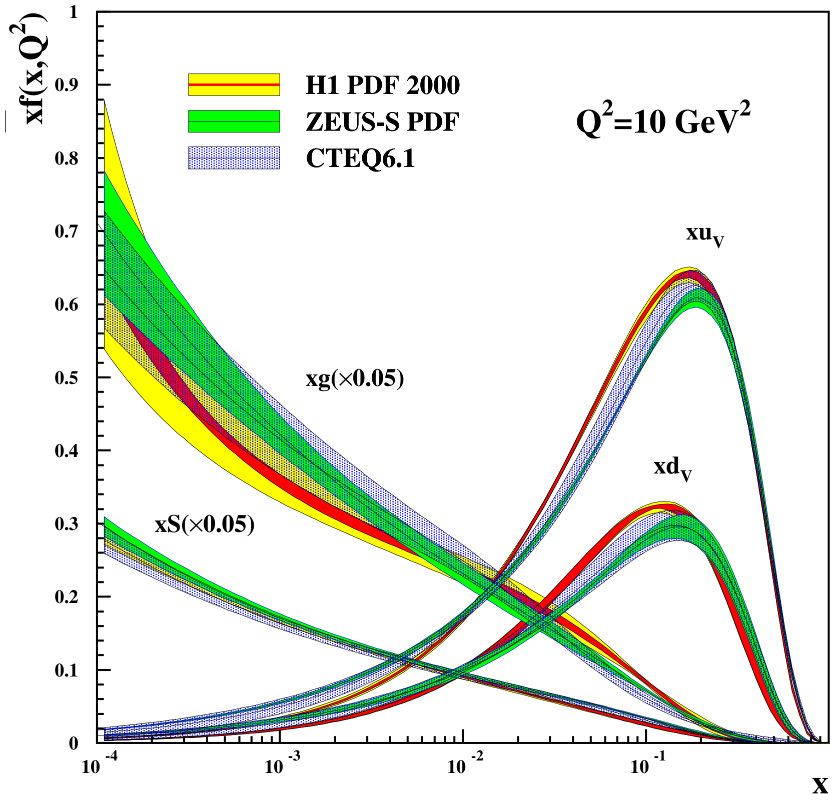
- *different assumptions*
- *parametric forms of PDFs*
- *missing pieces in theory*
- *consistency of data sets*

$\rightarrow$ *see talk of Jon Pumplin*

# Gluon




**Remaining uncertainties of PDFs:**

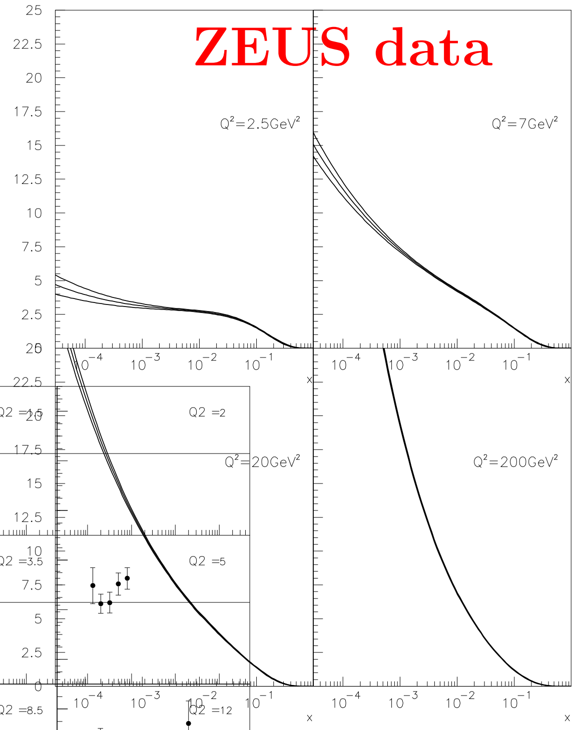
- *different assumptions*
- *parametric forms of PDFs*
- *missing pieces in theory*
- *consistency of data sets*

$\rightarrow$ *see talk of Jon Pumplin*

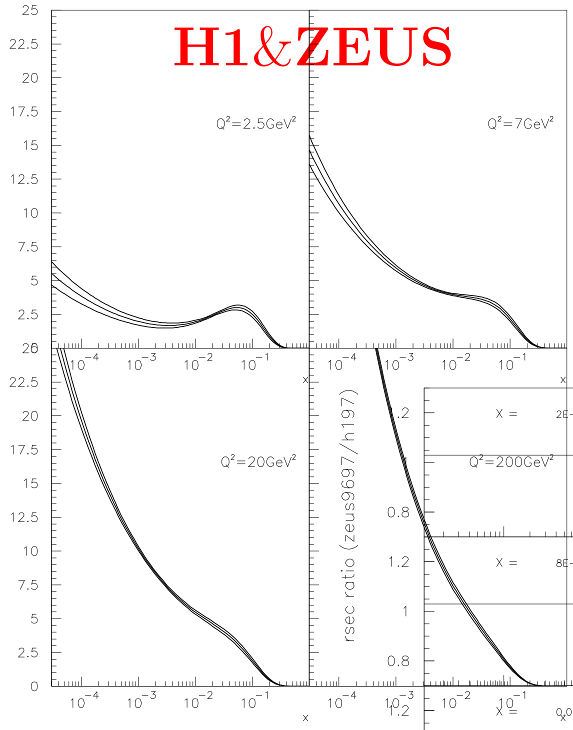
# More about H1&ZEUS Data and Gluon

$xg(x) \rightarrow$

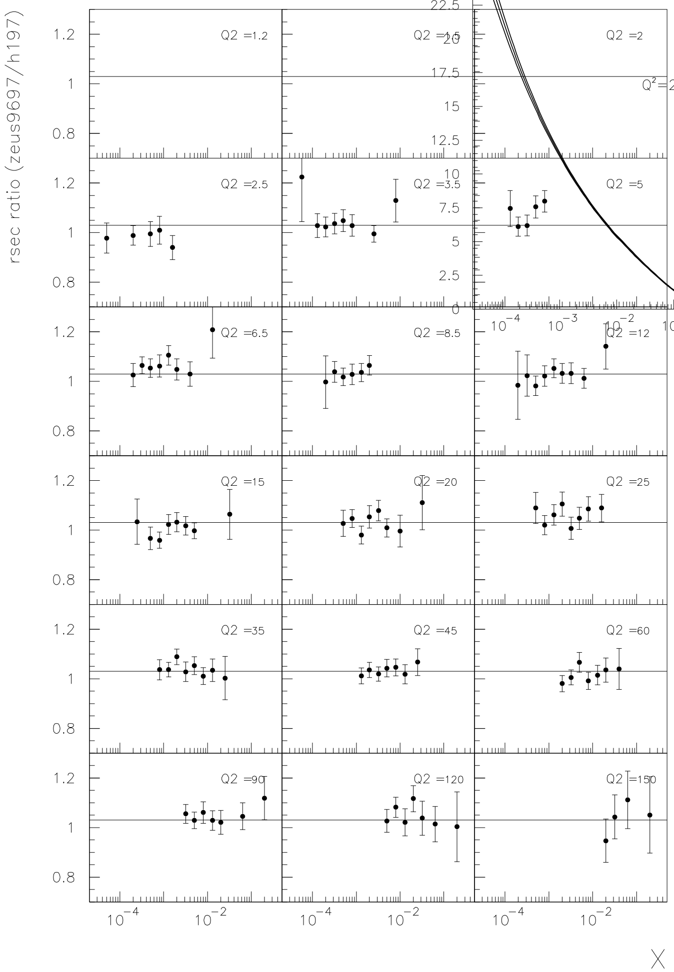
**ZEUS data**

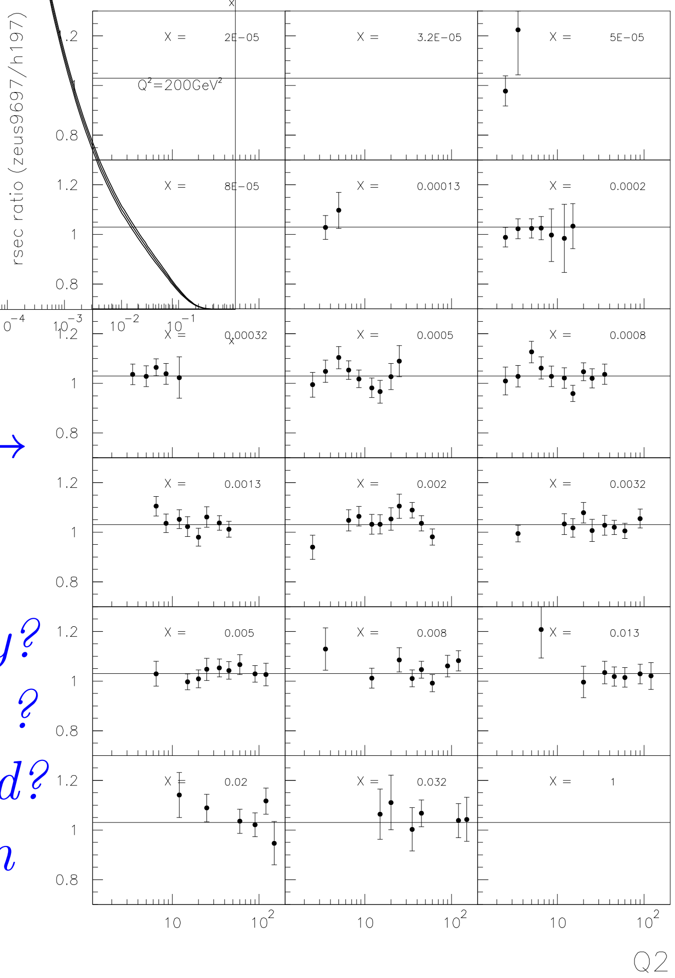


**H1&ZEUS**



**the same QCD fit procedure applied to H1, ZEUS data (A.Cooper-Sarkar)**





$\leftarrow$ $F_2$**(ZEUS/H1)** $\rightarrow$

- *data look very consistent*
- *gluon shows difference,why?*
- *sensitive to small features ?*
- *even more precision needed?*
- *under further investigation*

# $\alpha_s(M_Z^2)$ in the HERA NLO QCD Fits

## $xg\&\alpha_s$ fit of H1

$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0017(exp)^{+0.0009}_{-0.0005}(model)$$

$$\pm 0.005(theory)$$

| | $m_r^2 = 0.25$ | $m_r^2 = 1$ | $m_r^2 = 4$ |
|---|---|---|---|
| $m_f^2 = 0.25$ | $-0.0038$ | $-0.0001$ | $+0.0043$ |
| $m_f^2 = 1$ | $-0.0055$ | $--$ | $+0.0047$ |
| $m_f^2 = 4$ | $--$ | $+0.0005$ | $+0.0063$ |

## ZEUS fit

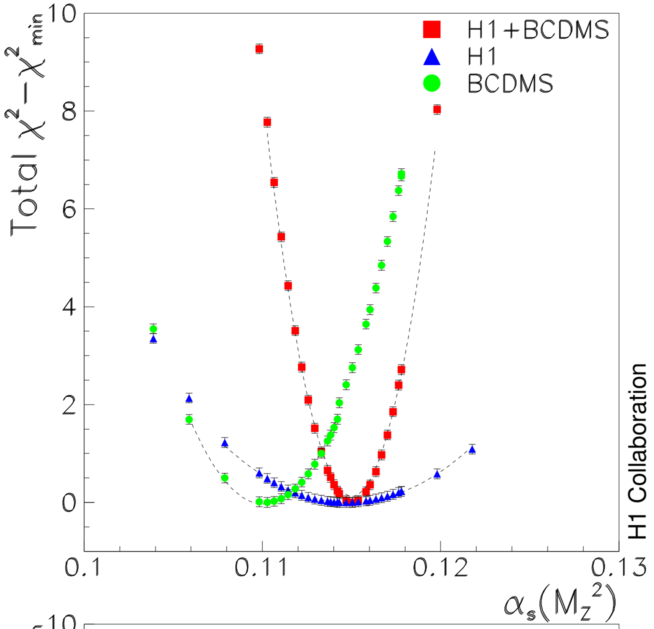
$$\alpha_s(M_Z^2) = 0.1166 \pm 0.0008(uncor) \pm 0.0032(cor) \pm 0.0036(norm) \pm 0.0018(model)$$

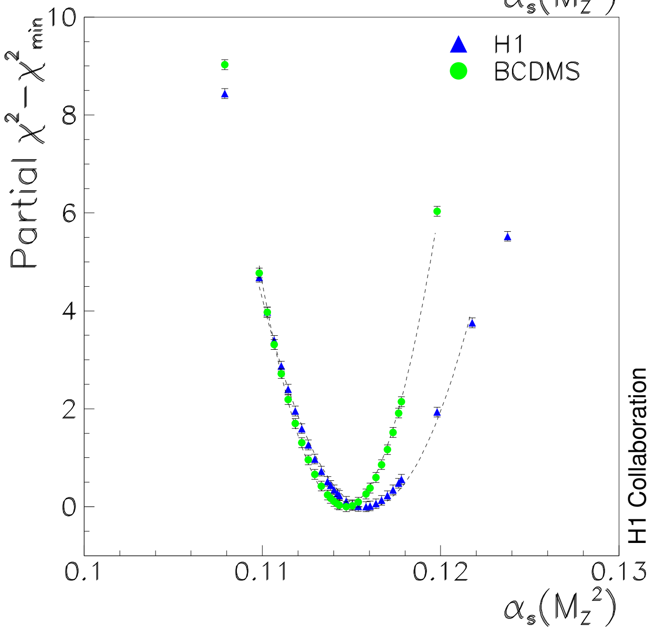
$$\pm 0.004(theory)$$

variation of $m_r^2, m_f^2$ by factor of 2

- *Exp. errors are competitive with the world average*
- *"Theory error" is by far dominating*
- *Large $\chi^2$ variations if ren. scale is varied (+20 units)*
- *Variation factors (4 or 2) are arbitrary*
- *$\alpha_s$ variations are reduced in NNLO*

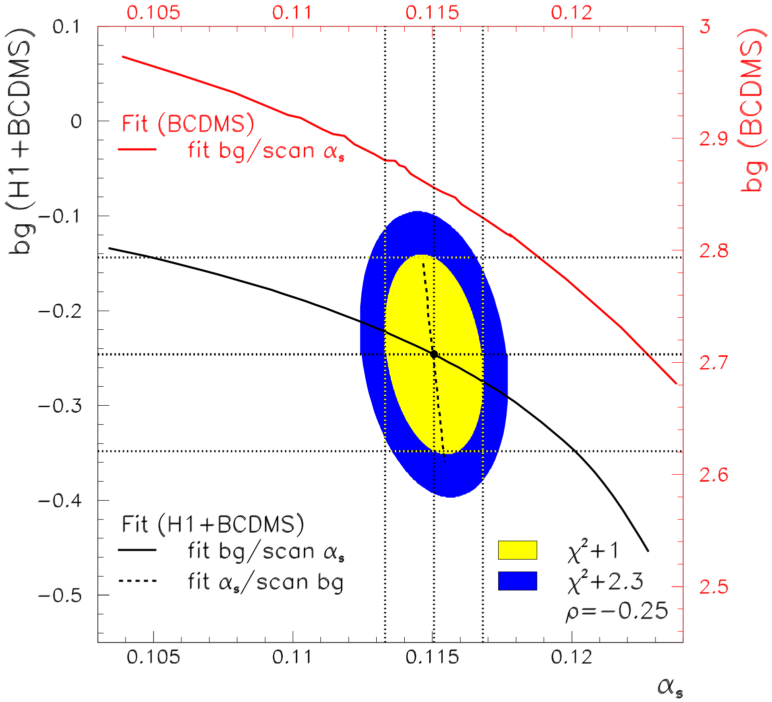
# Two Remarks about $xg\&\alpha_s$ Fit of H1




## H1, BCDMS, H1+BCDMS fits

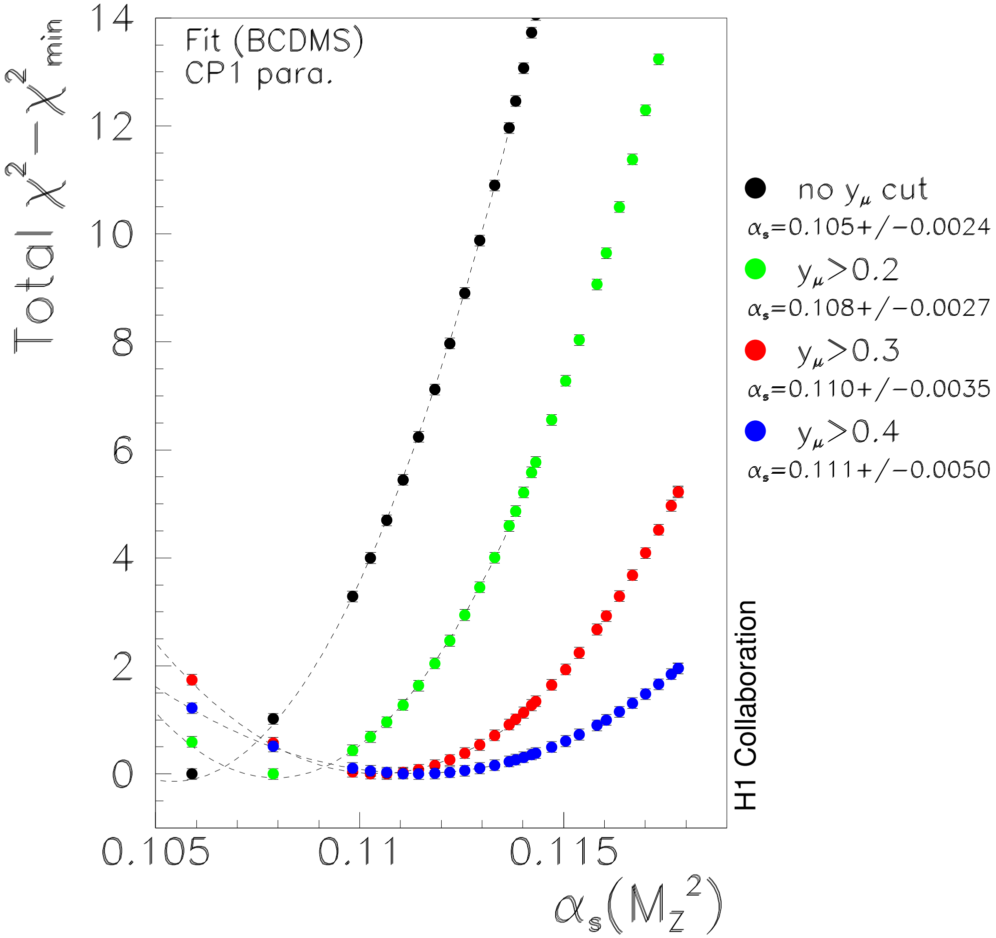
- *H1 pins down gluon at low $x$*, $xg(x) \propto x^{b_g}$ *and shifts $\alpha_s$(BCDMS)* $= 0.110 \rightarrow 0.115$



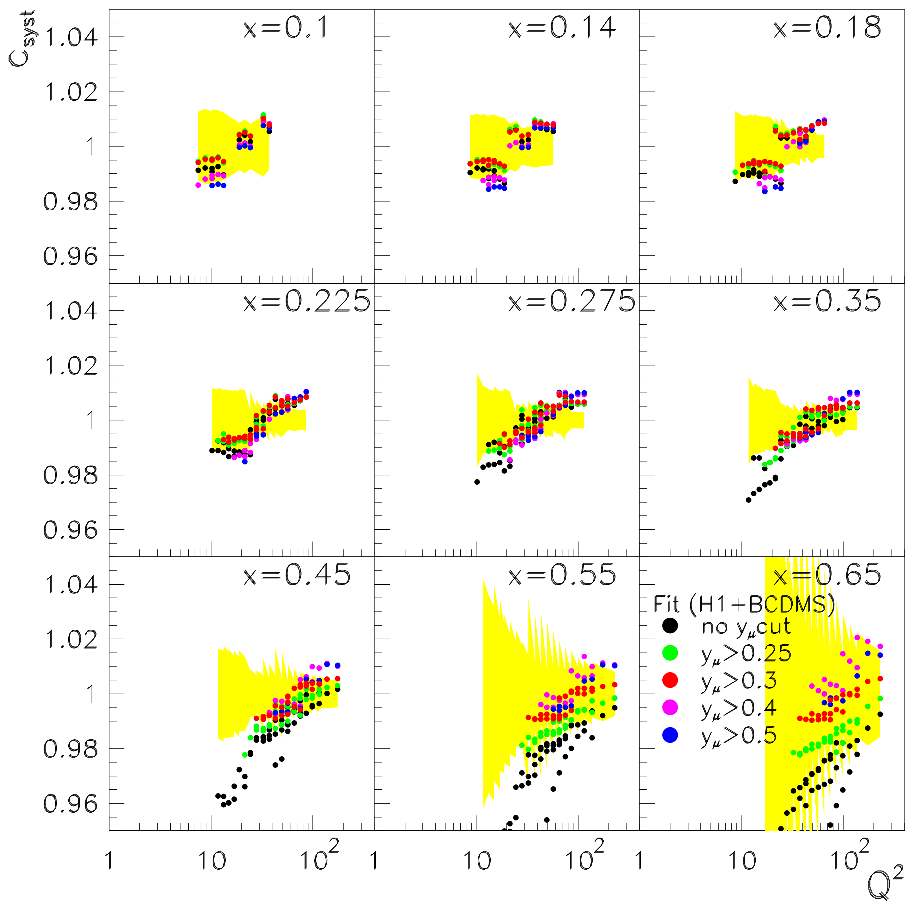

- *H1 and BCDMS data are fully consistent after cut* $y_{BCDMS} > 0.3$ *(see next slide* $\rightarrow$ *)*

# Treatment of the BCDMS Data

## $\alpha_s^{BCDMS}$ and cuts on $y$

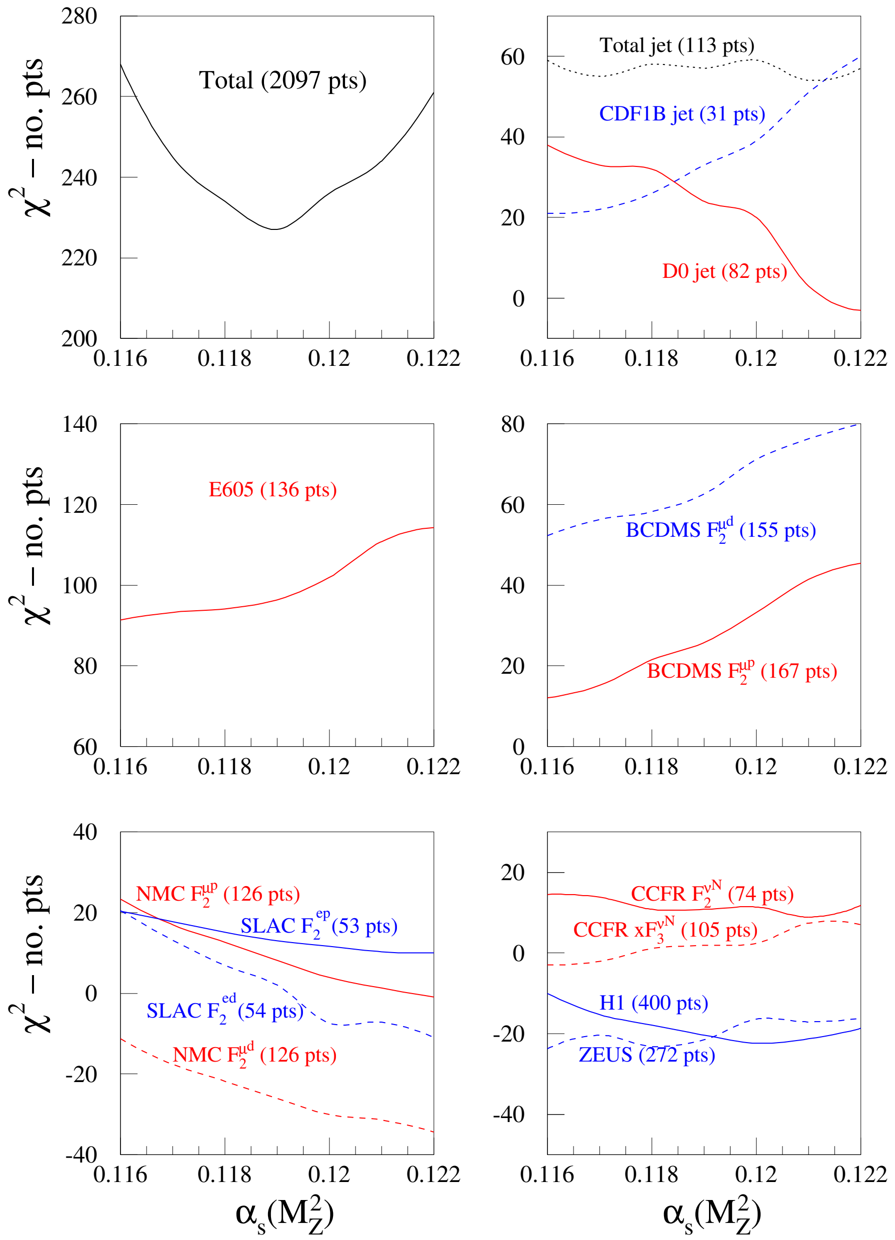


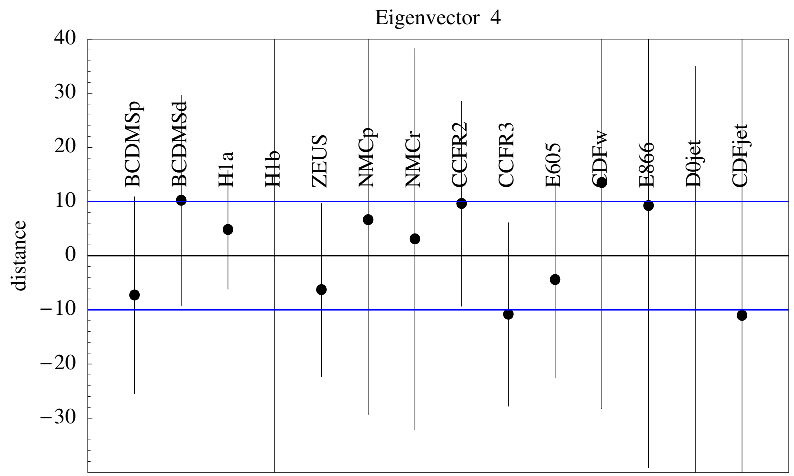

## Shifts imposed by QCD fits




- $\alpha_s^{BCDMS}$ *strongly* $y$ *dependent*
- *large systematics at low* $y$ *(large* $x$*)*
- *shifts are larger than systematics at lowest* $y$ $\rightarrow$ *apply cut* $y > 0.3$

# Consistency of Data Sets in Global Fits




- *reality: data sometimes* *inconsistent*
- *to be reflected in* *errors* *of QCD fits*
- *way out: modify the* $\Delta\chi^2$ *criterion*

$\longrightarrow$ *see talk of Jon Pumplin*

# $\alpha_s(M_Z^2)$ from QCD fits

## NLO

| | | | |
|---|---|---|---|
| **CTEQ6** | $\Delta\chi^2 = 100$ | $\alpha_s(M_Z^2) =$ | $0.1165 \pm 0.0065(exp)$ |
| **ZEUS** | $\Delta\chi^2 = 50$ | $\alpha_s(M_Z^2) =$ | $0.1166 \pm 0.0008(uncor) \pm 0.0032(cor) \pm 0.0036(norm)$ $\pm 0.0018(model) \pm 0.004(theory)$ |
| **MRST01** | $\Delta\chi^2 = 20$ | $\alpha_s(M_Z^2) =$ | $0.1190 \pm 0.002(exp) \pm 0.003(theory)$ |
| **H1** | $\Delta\chi^2 = 1$ | $\alpha_s(M_Z^2) =$ | $0.115 \pm 0.0017(exp)$ ${}^{+0.0009}_{-0.0005}(model) \pm 0.005(theory)$ |
| **Alekhin** | $\Delta\chi^2 = 1$ | $\alpha_s(M_Z^2) =$ | $0.1171 \pm 0.0015(exp) \pm 0.0033(theory)$ |
| **GKK** | $CL$ | $\alpha_s(M_Z^2) =$ | $0.112 \pm 0.001(exp)$ |

## NNLO

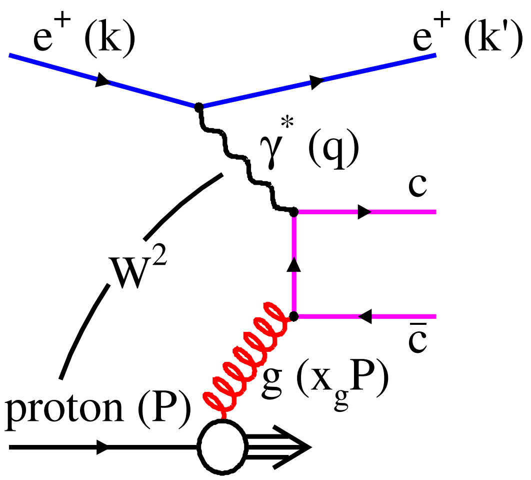
| | | | |
|---|---|---|---|
| **Alekhin** | $\Delta\chi^2 = 1$ | $\alpha_s(M_Z^2) =$ | $0.1143 \pm 0.0014(exp) \pm 0.0013(theory)$ |

- *theory uncertainty in NNLO expected to be small*

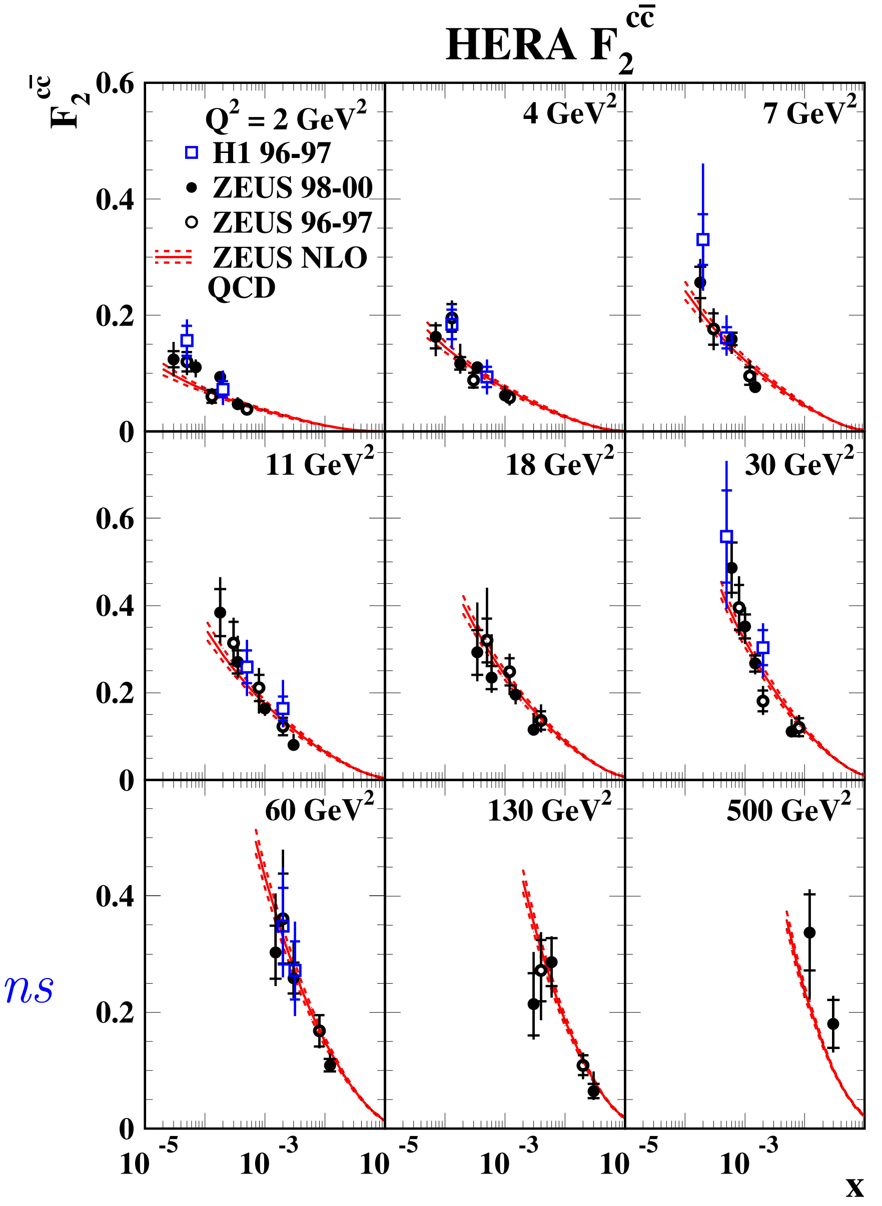
  $\rightarrow$ *more in talks of Sven Moch and Sergey Alekhin*

# Gluon and Open Charm Production

Boson Gluon Fusion (BGF)

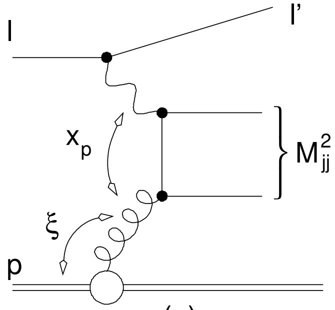



$$D^* \rightarrow D^0 \pi_{slow} \rightarrow K\pi\pi_{slow}$$




- *charm contribution up to 25 – 30%*
- *consistent with gluon from scaling violations*

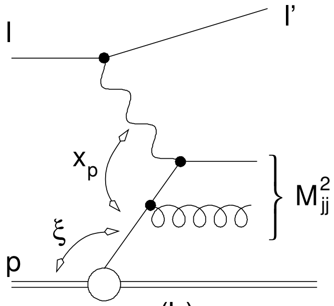
# $xg \& \alpha_s$ and Jets



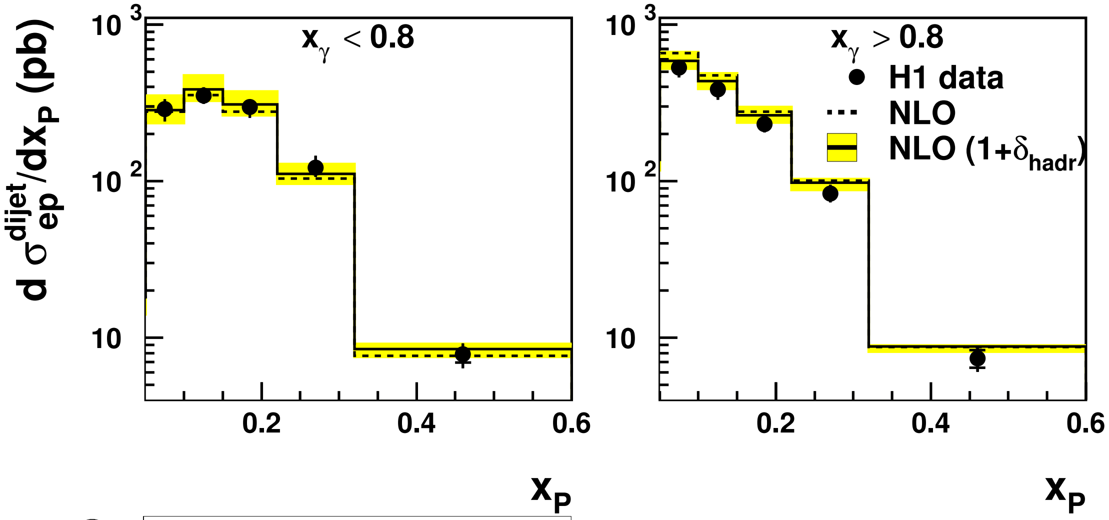
(c)

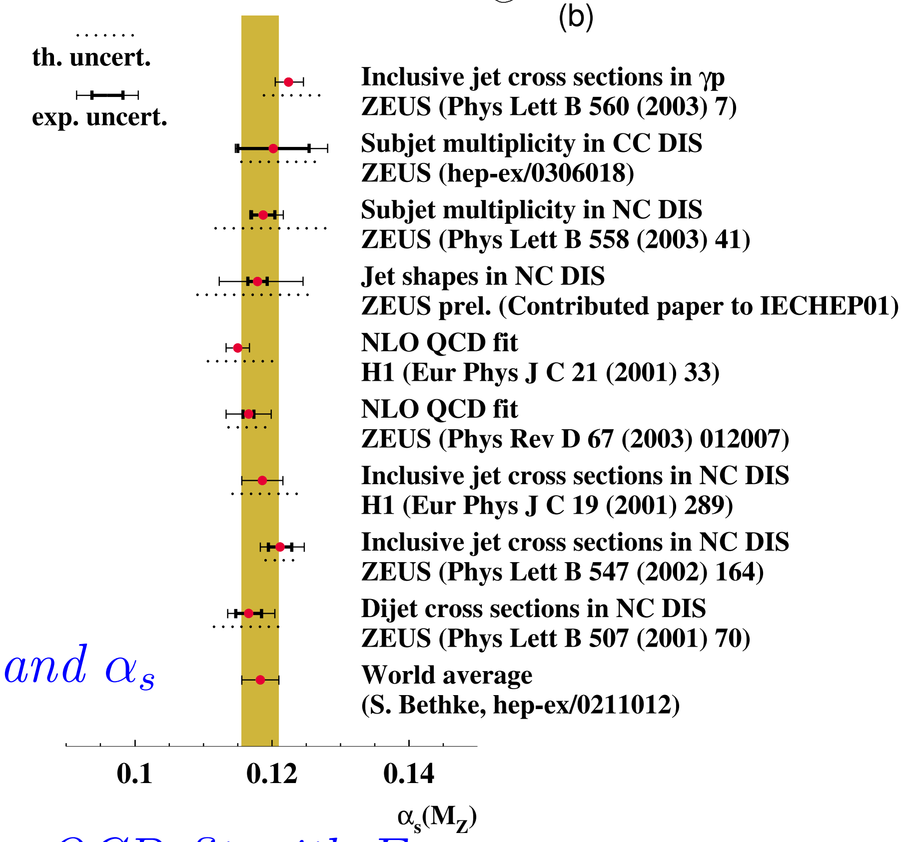
BGF: similar to $c\bar{c}$

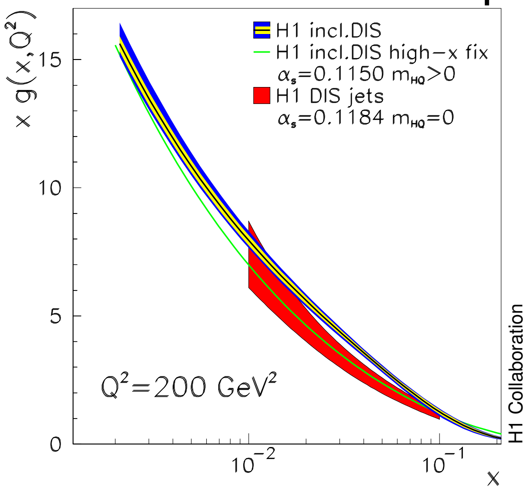
with $M_{jj} \gg M_{c\bar{c}}$



(b)



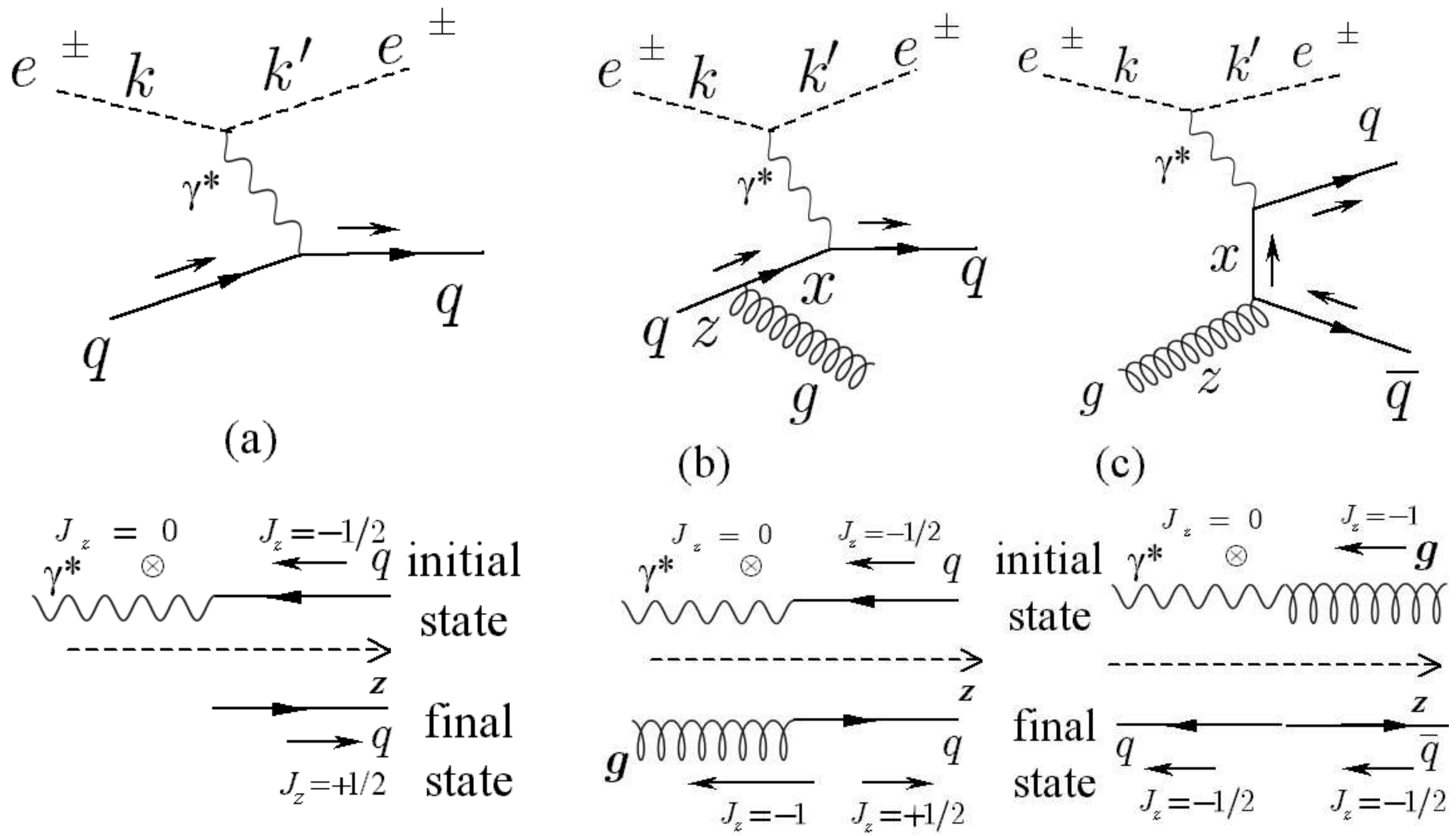




- *directly related to gluon and $\alpha_s$*
- *sensitivity to larger $x$*
- *include jets into common QCD fit with $F_2$*

# $F_L$ in QPM and QCD

## QPM | QCD




*helicity and angular momentum conservation:*

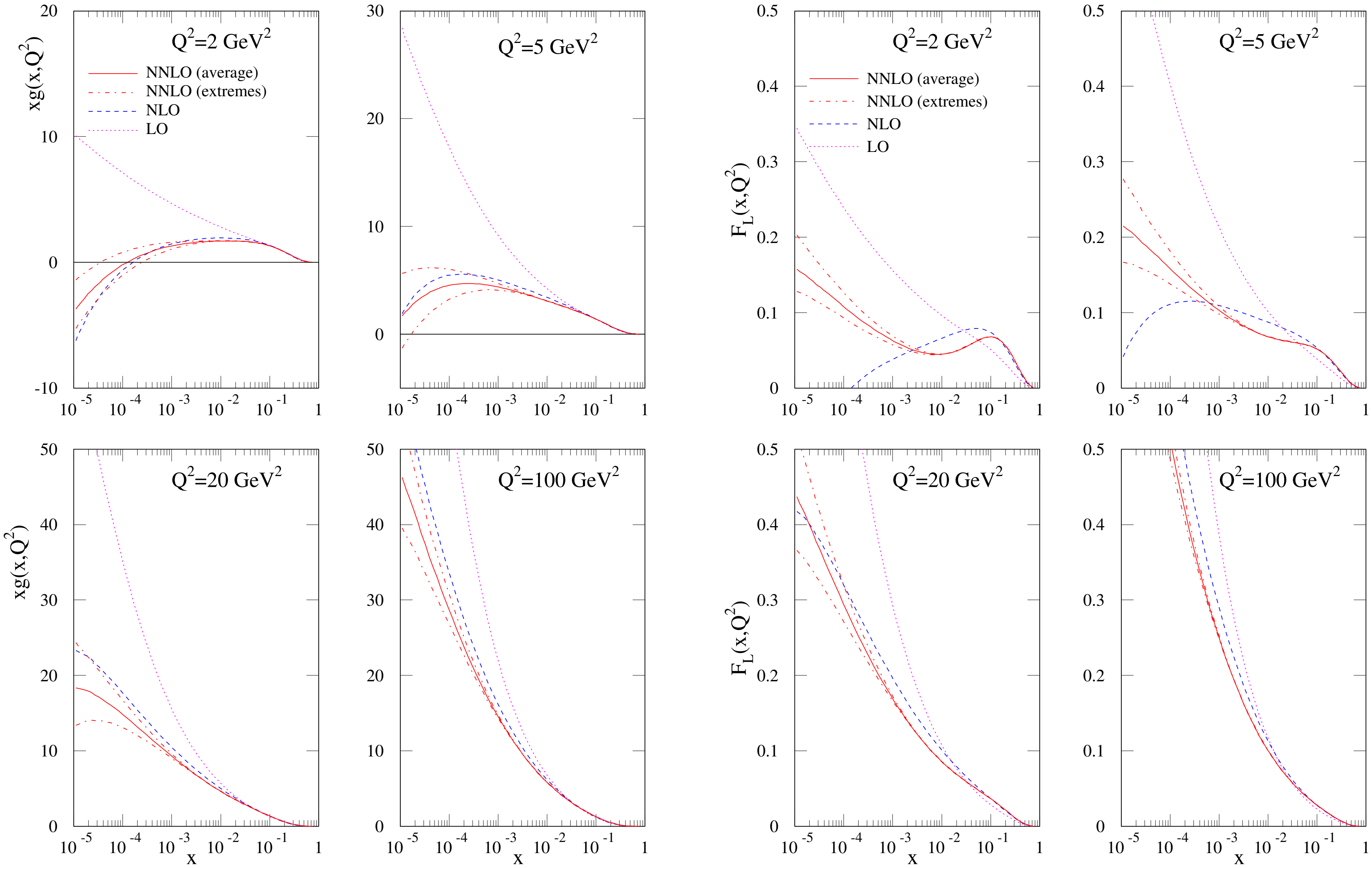
$J_z = 0 \;\&\; H^{ini} = H^{fin} : J_z^{ini} \neq J_z^{fin}$

$$\Rightarrow F_L \propto \sigma_L^{\gamma p} = 0$$

$J_z = 0 \;\&\; H^{ini} = H^{fin} : J_z^{ini} = J_z^{fin}$

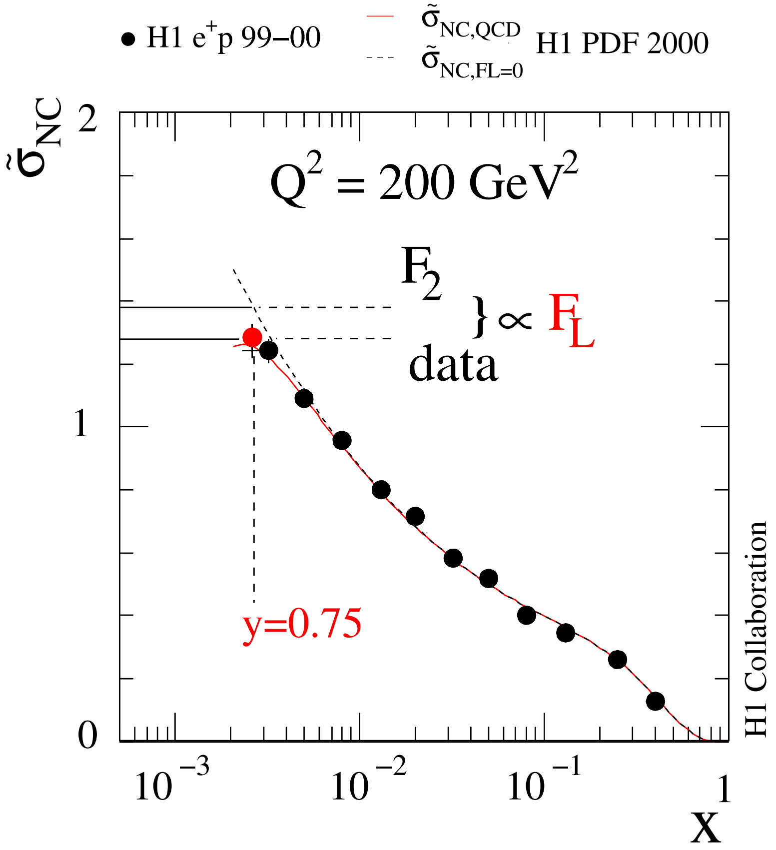
$$\Rightarrow F_L \propto \sigma_L^{\gamma p} \neq 0$$

# Gluon and $F_L$

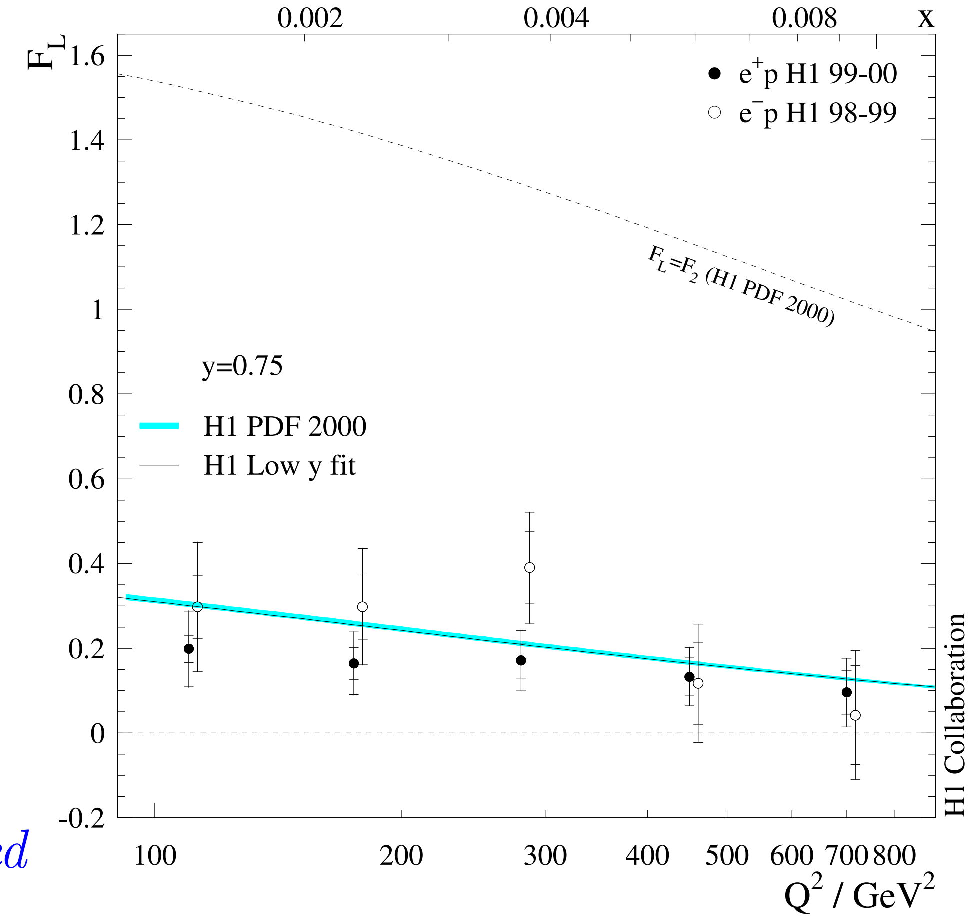



- *Large spread of theory calculations for $F_L$*
- *Critical corner - $xg$ at low $x$ and low $Q^2$*
- *Until $F_L$ is measured, the QCD program at HERA is not completed*

# $F_L$ at High $Q^2$ $(100 < Q^2 < 800\ \mathrm{GeV}^2)$



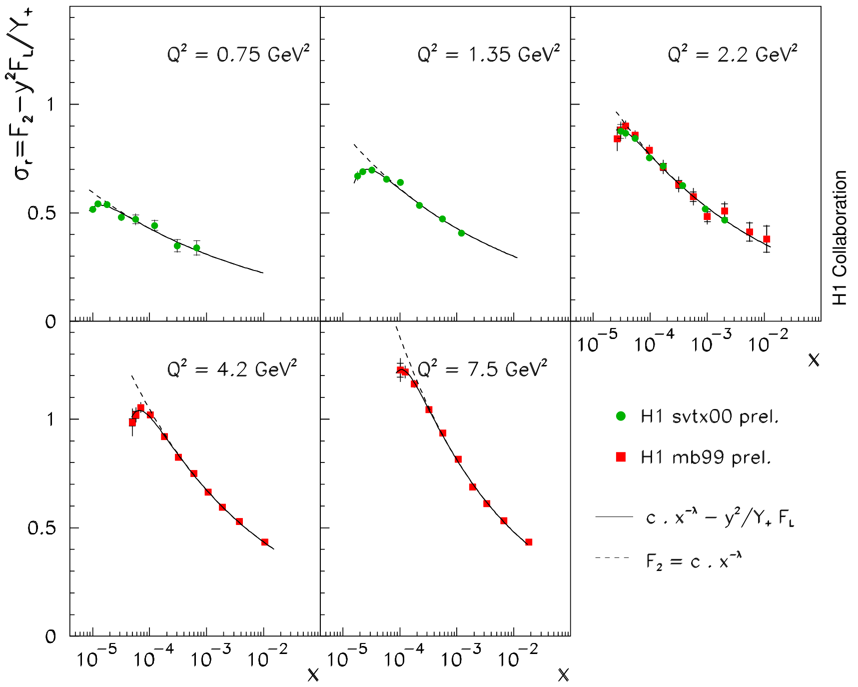

$$F_L = \frac{Y_+}{y^2}(F_2^{QCDfit} - \tilde{\sigma}_{NC})$$

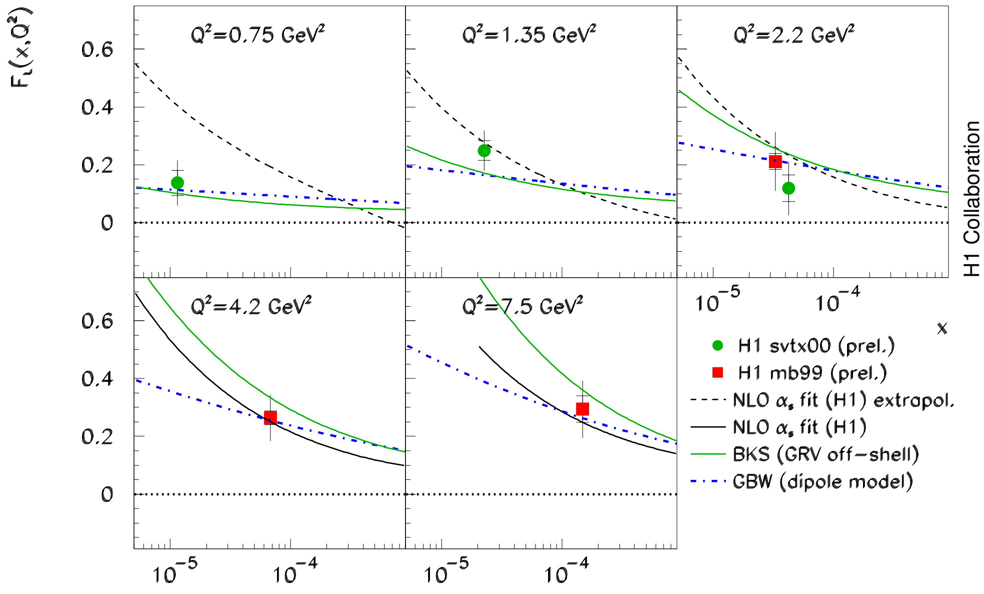



- *$e^+p$ and $e^-p$ results are in agreement*
- *extremes $(F_L = 0, F_L = F_2)$ are excluded*
- *consistent with NLO QCD calculations*

# $F_L$ at Low $Q^2$

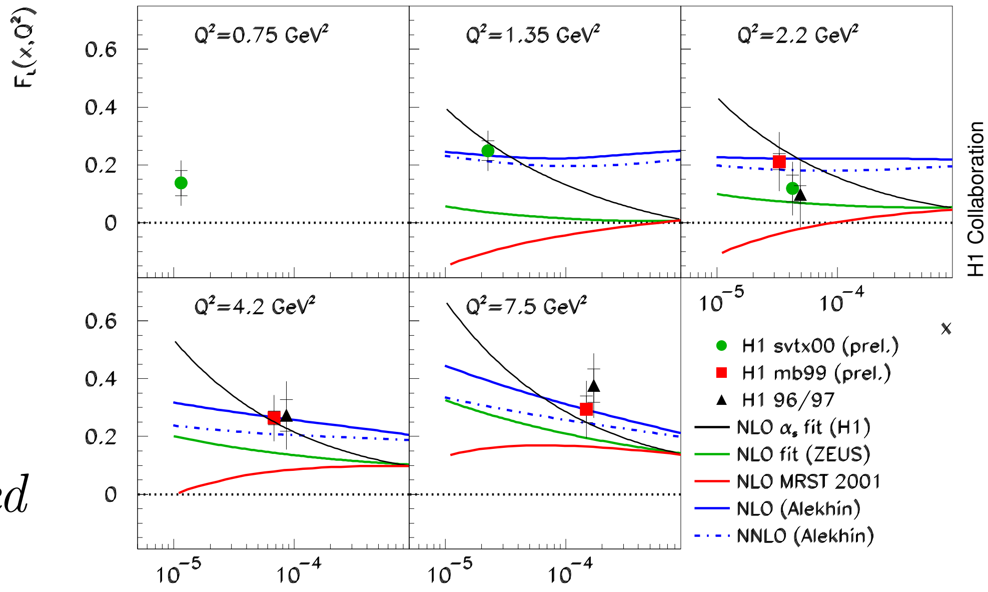
**shape of $\sigma_r$ at high $y$ driven by kin.factor $y^2/Y_+$ rather than $F_L$**




**Fit in each $Q^2$ bin:**

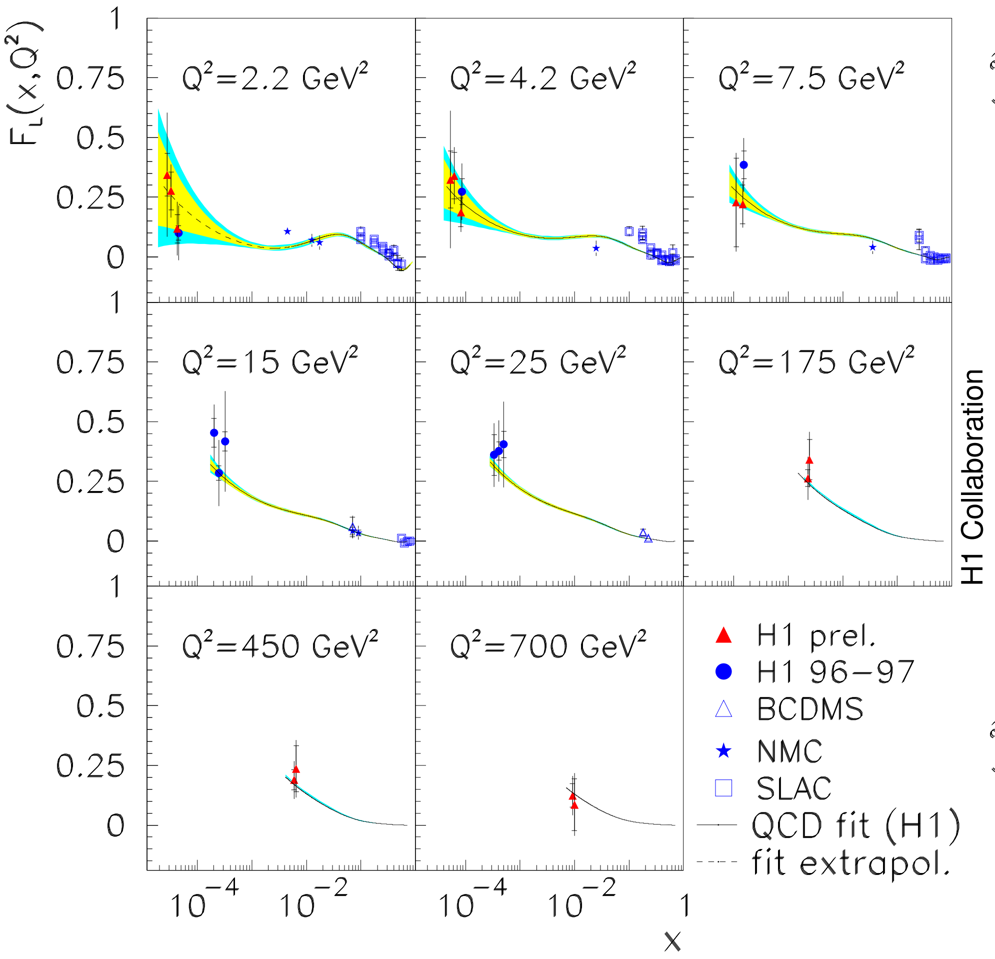
$$\sigma_{fit} = cx^{-\lambda} - \frac{y^2}{Y_+} F_L$$

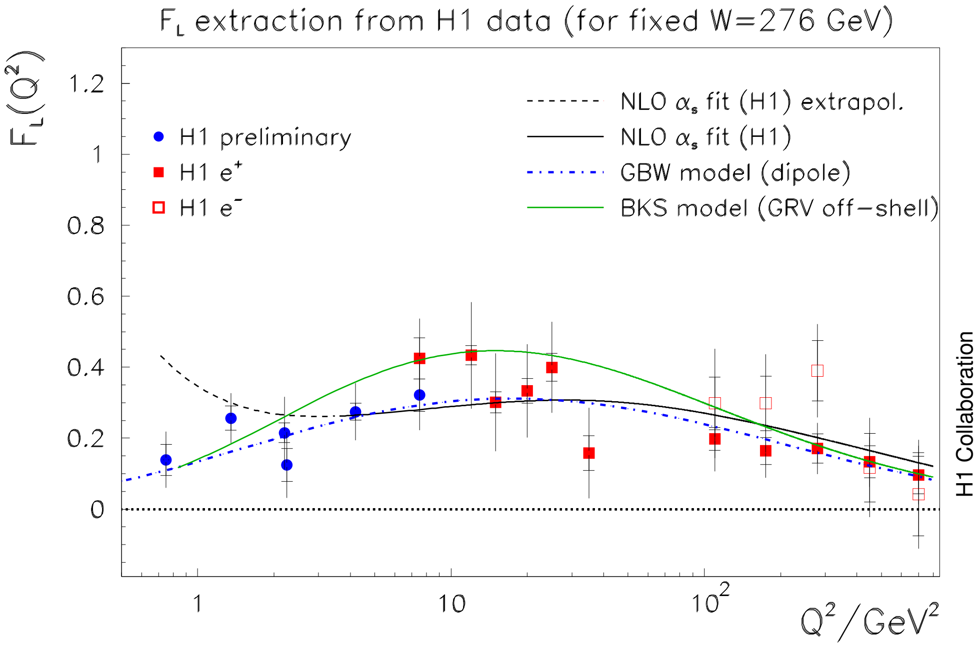


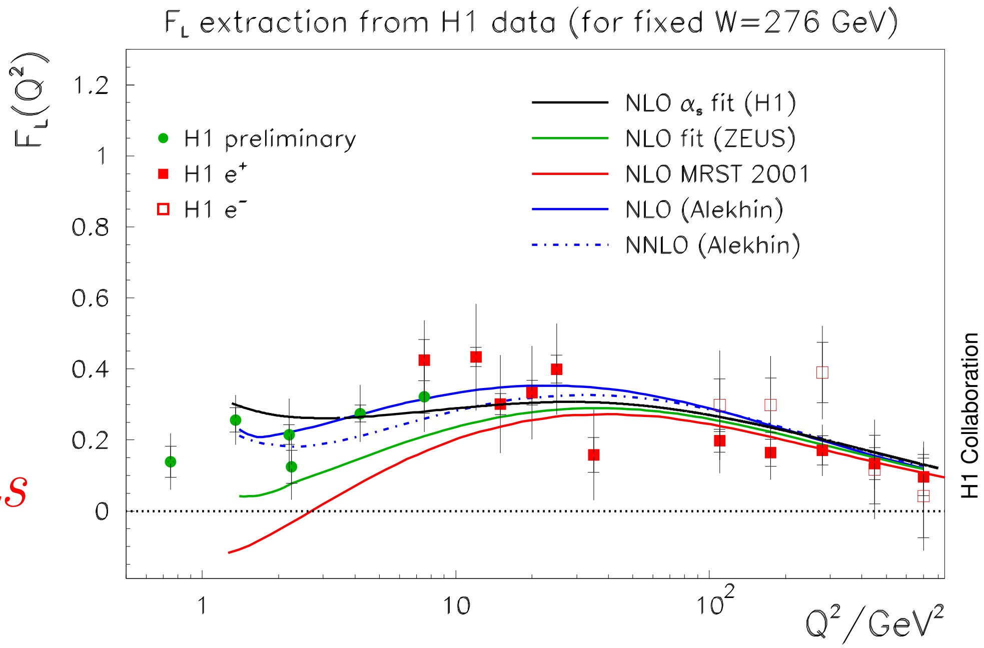

- *make use of $F_2 = cx^{-\lambda}$ behavior*
- *$F_L$ variation in narrow $x$ range neglected*

*$\rightarrow$ not possible to measure $x$ dependence*

# Summary for $F_L(x, Q^2)$

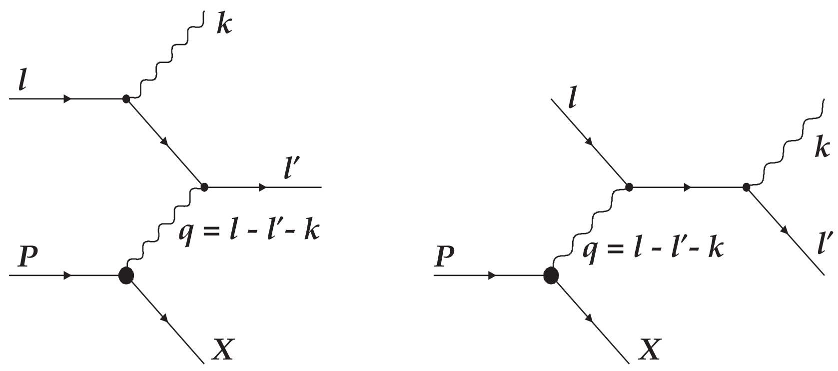


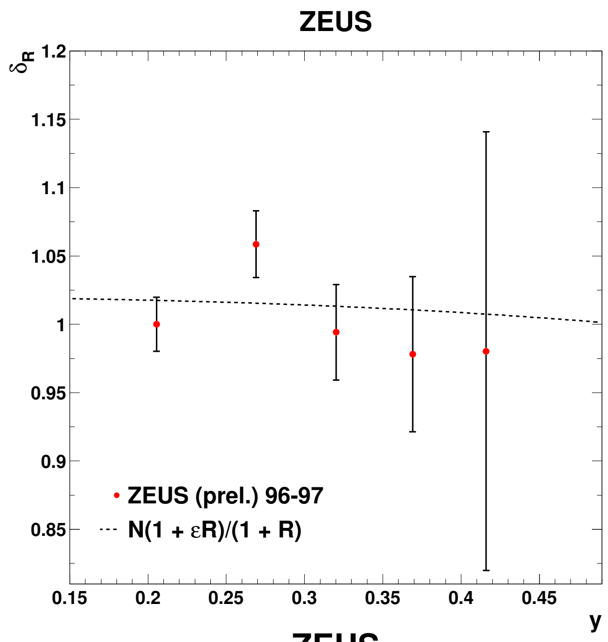




$\rightarrow$ *$F_L$ "determinations" start to discriminate QCD predictions*

# $F_L$ from ISR in ZEUS



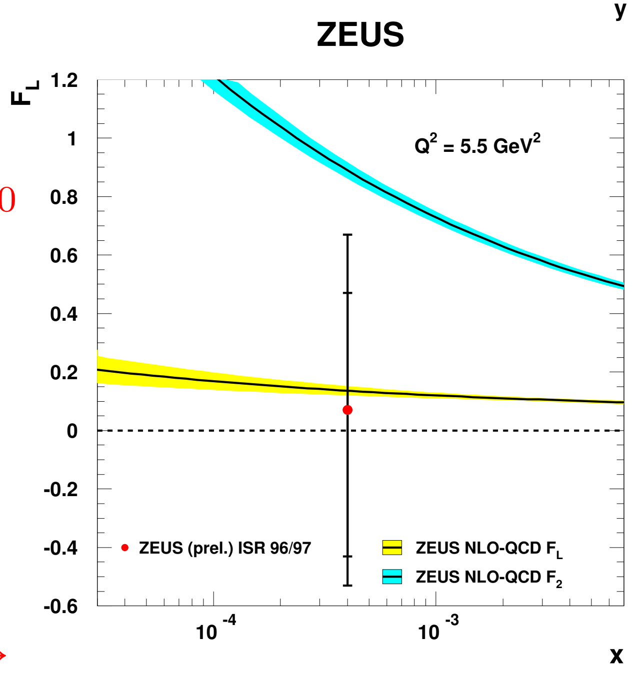




**Emission of ISR $\gamma \rightarrow$ reduction of $E_e$**

$$1 < Q^2 < 30 \text{ GeV}^2$$
$$0.11 < y_{HERA} < 0.23$$

**Fitting $y$ dependence of $\delta_R = N_{data}/N_{MC,F_L=0}$**
**($N_{MC,F_L=0} \propto F_2^{fit}$ taken from ALLM97)**

- *$F_L$ is in the allowed range ($0 < F_L < F_2$)*
- *experimentally very difficult measurement*




*can not replace low proton energy running,*
*see next slide →*

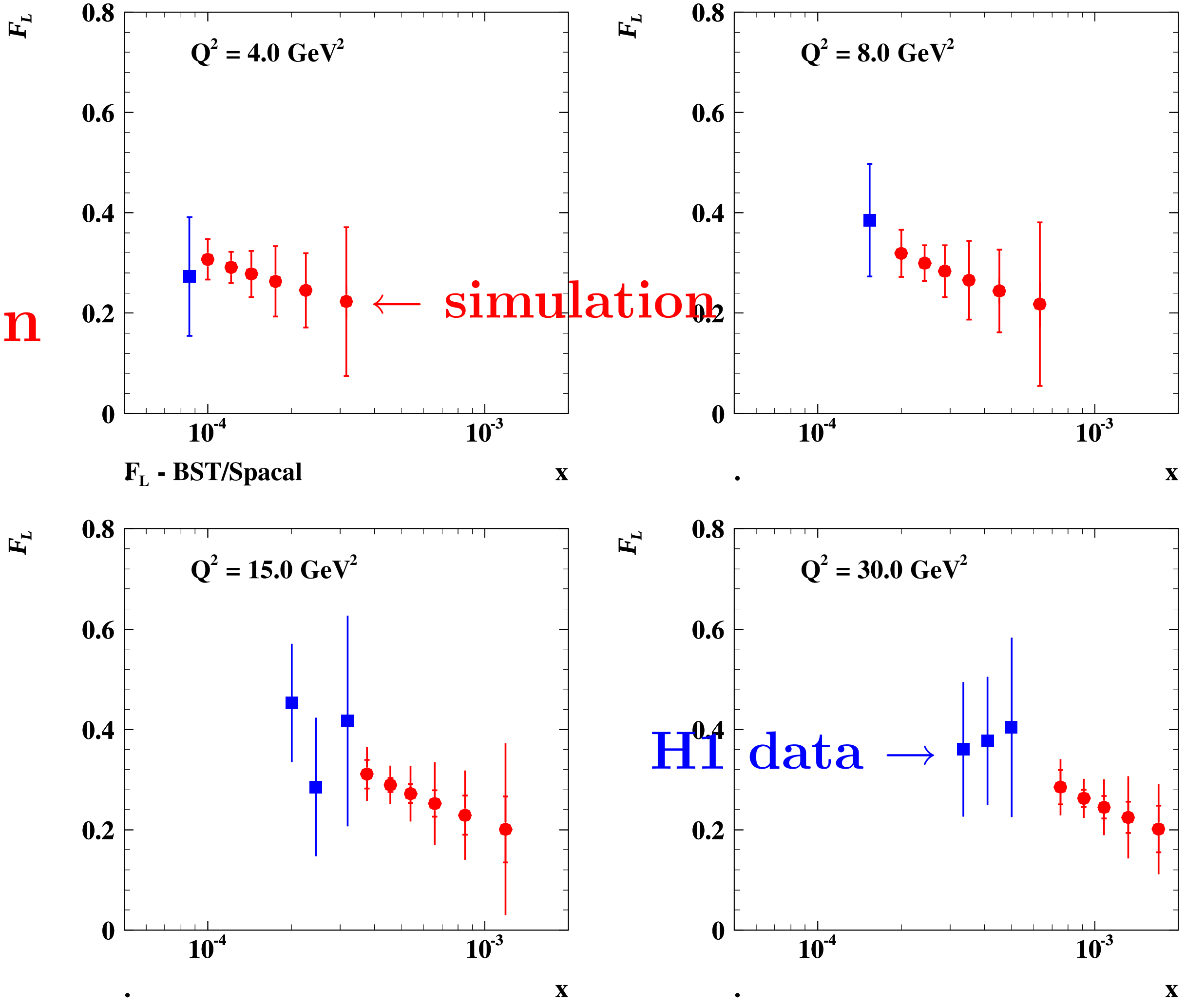
# $F_L$ Expectations From the Low Proton Energy Running

$F_L$ **precision estimation**

**assuming 3 energies:**

$E_p = 460, \quad 575, \quad 920$ **GeV**

$(20\text{pb}^{-1}, 10\text{pb}^{-1}, 200\text{pb}^{-1})$



# Summary

- **Very nice and precise inclusive cross section data from HERA I**
- **Comprehensive analysis of the data from different directions:**
  - **tests of perturbative QCD in NNLO**
    $\rightarrow$ *consistent picture / driven by gluon /* $F_2$, $F_L$, *charm, jets, ...*
  - **determination of PDFs, gluon density and** $\alpha_s$
    $\rightarrow$ *potentially very high precision of* $\alpha_s$ *in NNLO*
  - **search for new dynamics (saturation, ...)**
    $\rightarrow$ *no evidence yet (*$\rightarrow$ *HERA III ?)*
- **HERA II: new detectors, new lumi, new possibilities**
  $\rightarrow$ **including low** $E_p$ **running for direct** $F_L$ **measurements**
- **Aiming for common QCD fit to**
  $\rightarrow$ **inclusive xsec., jets, charm**