



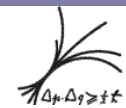
# Open Issues in DIS

## The High Energy Perspective

My private  
point of view  
using data  
from



- DIS in collider mode:  
Accelerator and Experiments
- HERA success story:  
Precision cross sections, structure  
functions and parton densities
- HERA outlook:  
What's still in the queue?
- Open Issues

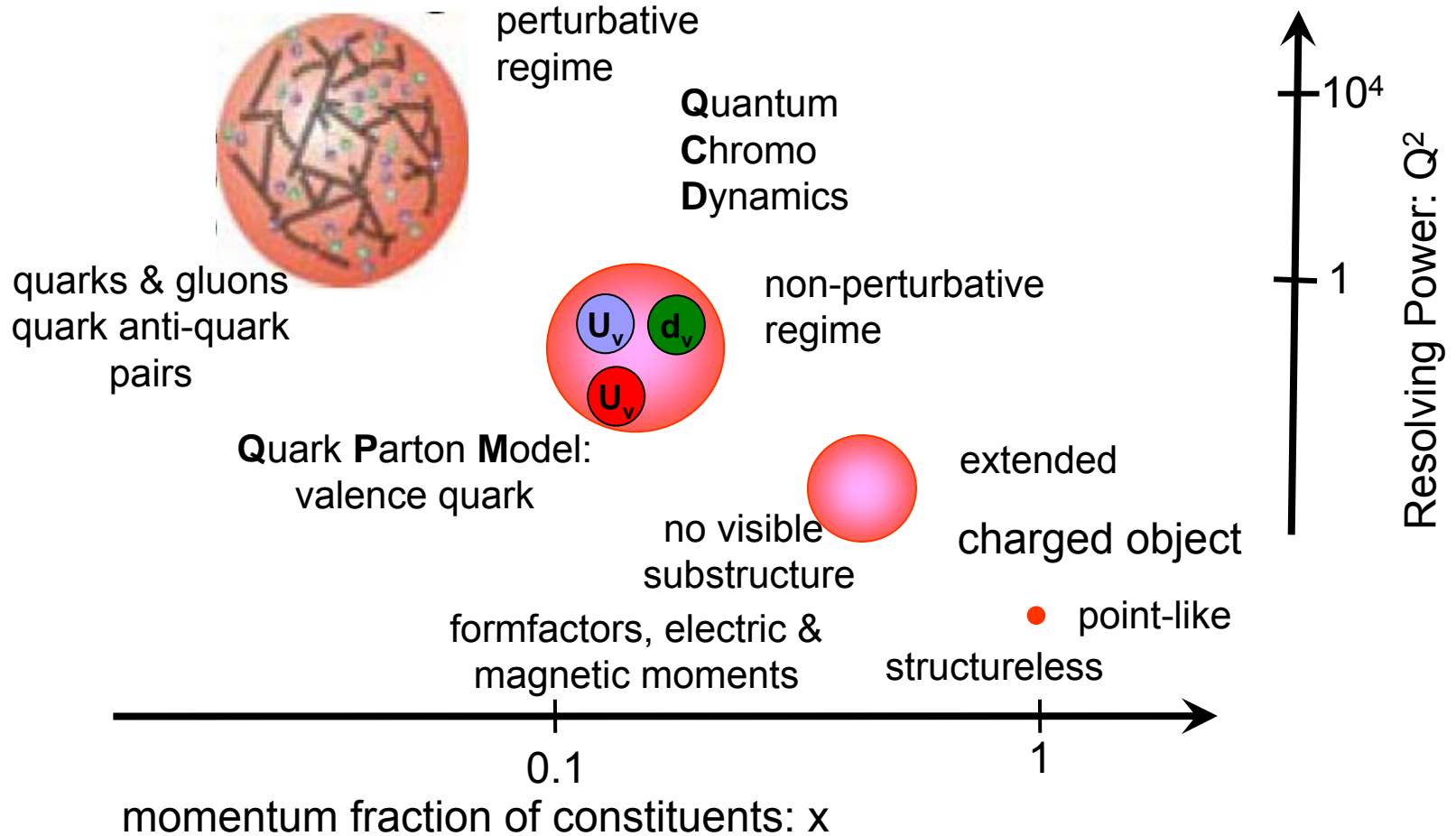


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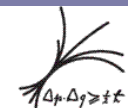
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# “Imaging” of the Proton



**Low  $Q^2$  : probing transition perturbative to non-perturbative QCD**  
**Low  $x$  : probing quarks and gluons at high density**  
 $\Delta E \Delta t \sim \hbar \rightarrow$  high  $Q^2$  “high resolution but time averaged picture”



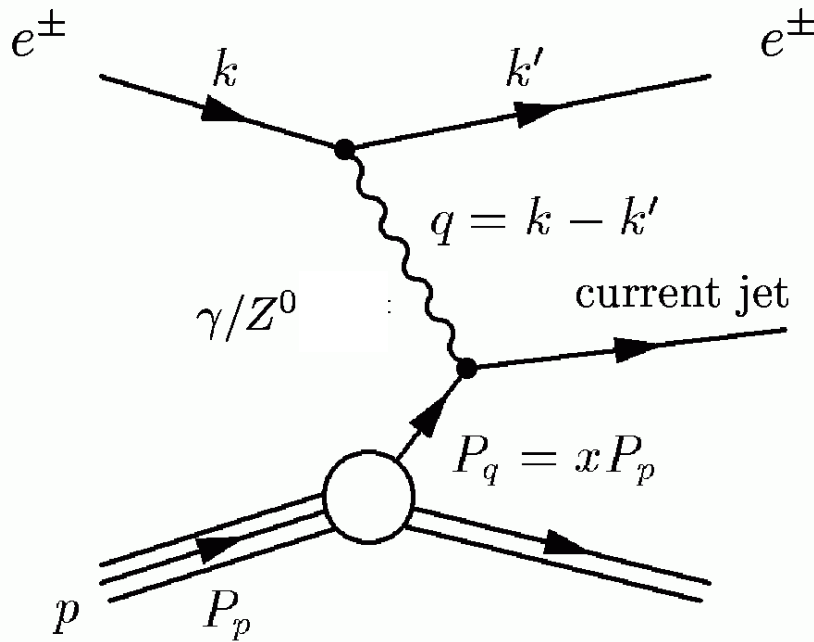
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# Deep Inelastic Scattering



## Kinematic Variables

- 4-momentum transfer resolving power  

$$Q^2 = -q^2 = -(k - k')^2$$

- Björken scaling variable momentum fraction of struck parton  

$$x = \frac{Q^2}{2p \cdot q}$$

- Inelasticity:  

$$y = \frac{p \cdot q}{p \cdot k}$$

Center of mass energy  $\sqrt{s}$ :  $s = (k + p)^2$  relation for fixed s:  $Q^2 = sxy$

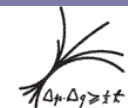
- Neutral current DIS cross section expressed by structure functions:

$$\frac{d^2 \sigma^{e^\pm p \rightarrow e^\pm X}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \underbrace{\left(1 + (1-y)^2\right)}_{Y_\pm = 1 \pm (1-y)^2} \cdot \left( F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) \mp \frac{Y_-}{Y_+} xF_3(x, Q^2) \right)$$

valence & sea quarks

gluons

valence quarks



# Mapping the Kinematic Plane

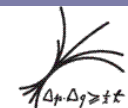
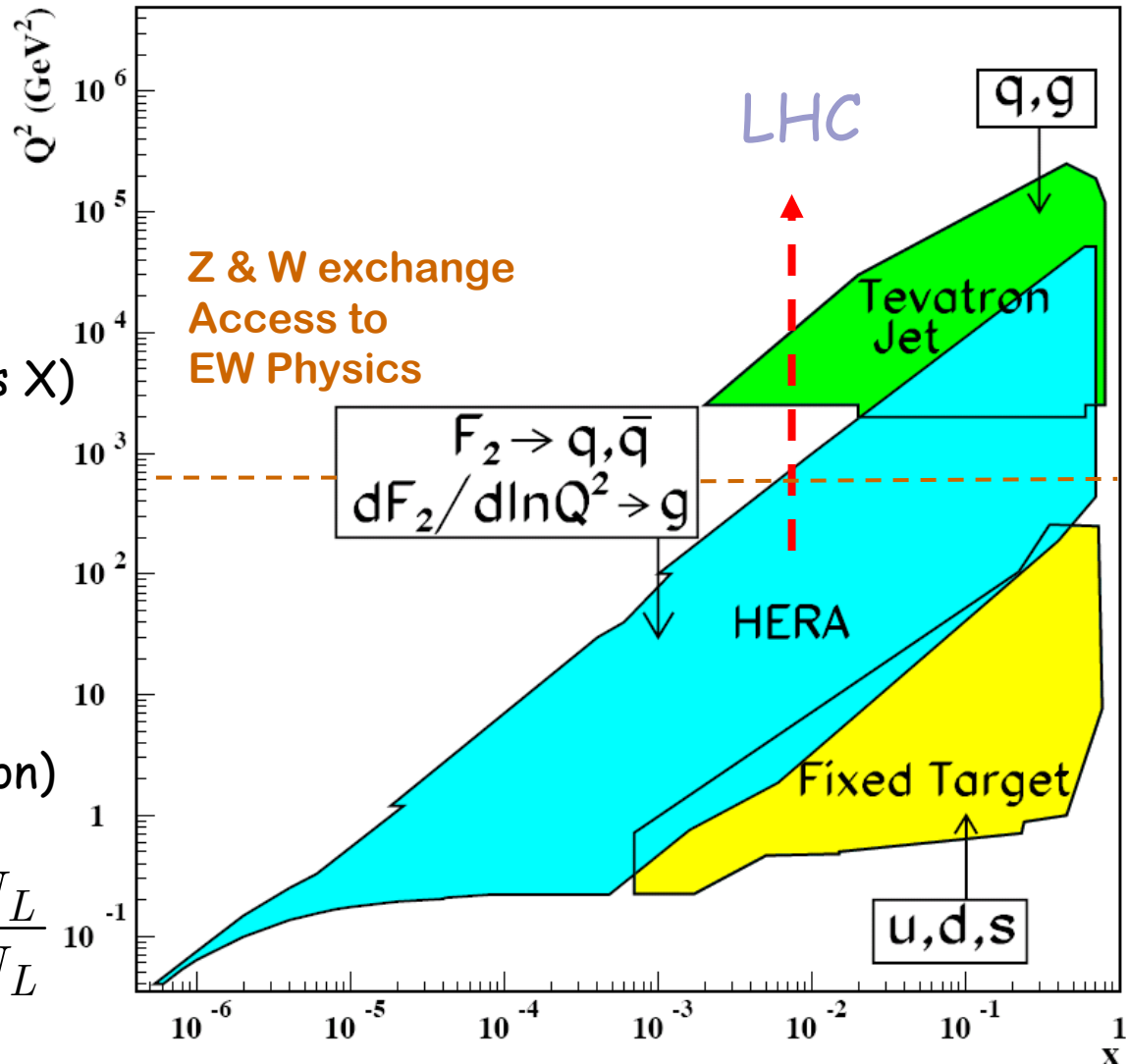
- large reach in  $x$
- large reach in  $Q^2$

“Inclusive” scattering  
(integrate over all  
hadronic final states  $X$ )

- pdf's of quarks  
from  $F_2$
- pdf of gluon from  
 $Q^2$  variation of  $F_2$   
(e.g. DGLAP evolution)

$$\text{HERA II: } P_e = \frac{N_R - N_L}{N_R + N_L}$$

longitudinal polarization



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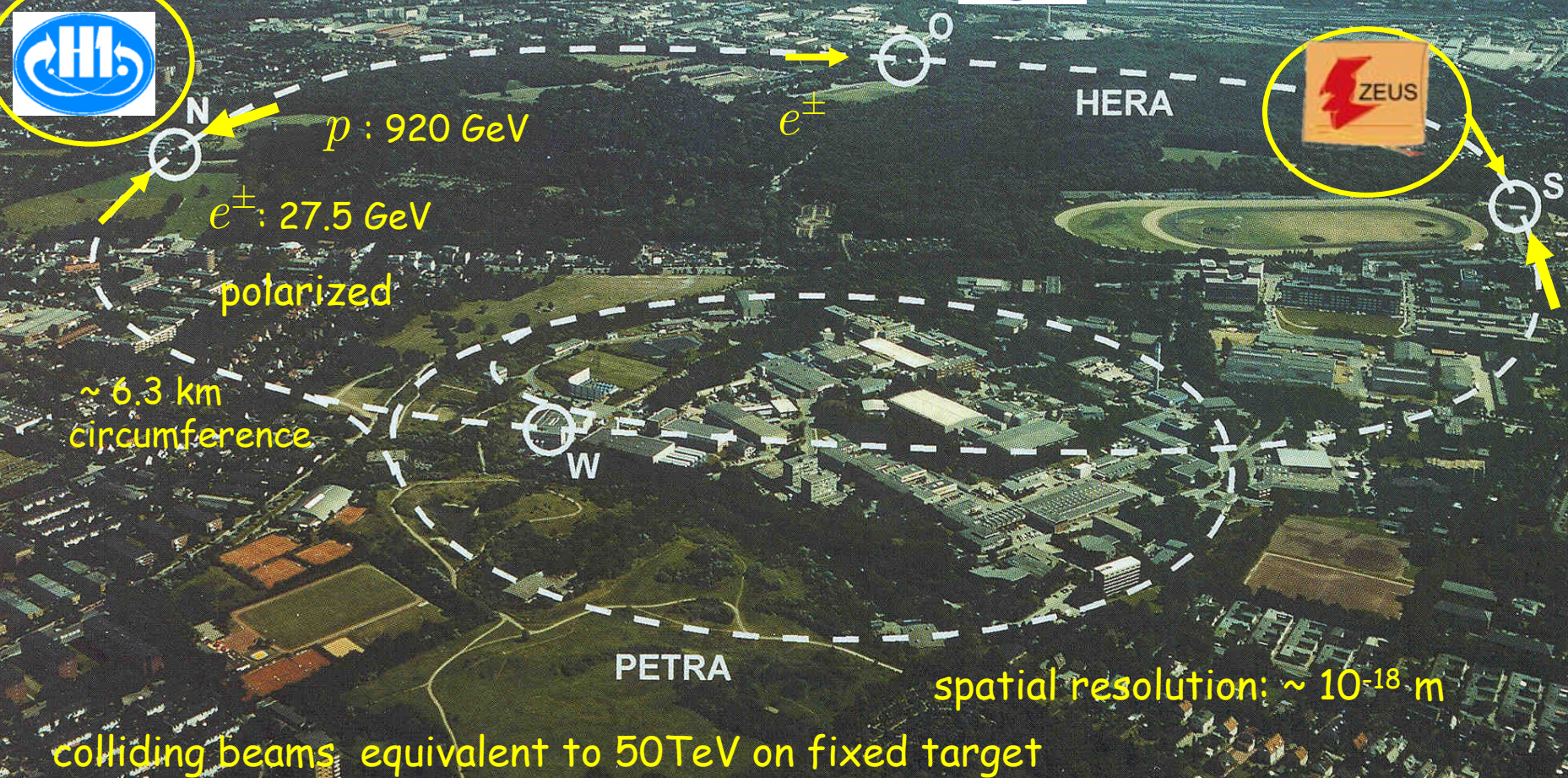
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# HERA - the world's largest electron microscope (Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany)

Shutdown on June 30, 2007, 23:00

HERA start: 1992  
upgraded in 2001: „HERA II“



~ 6.3 km circumference

PETRA

HERA

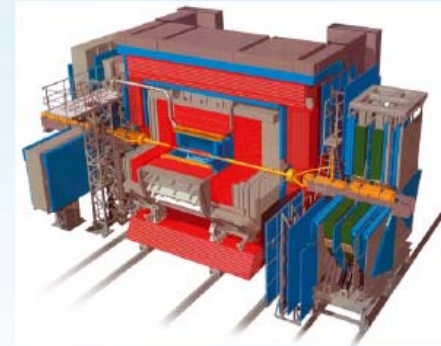
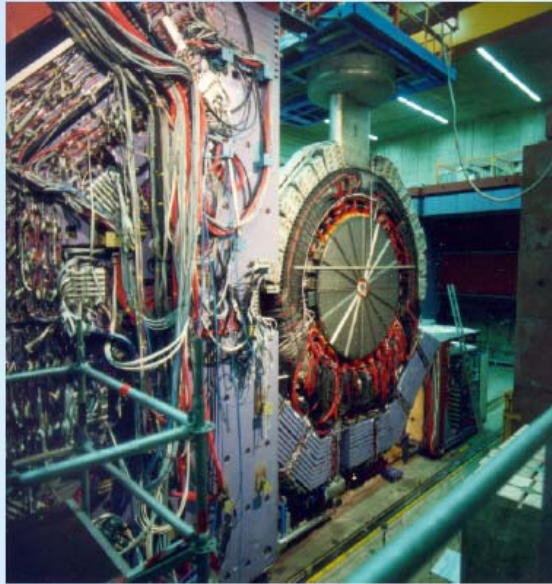
spatial resolution:  $\sim 10^{-18} \text{ m}$

colliding beams equivalent to 50 TeV on fixed target

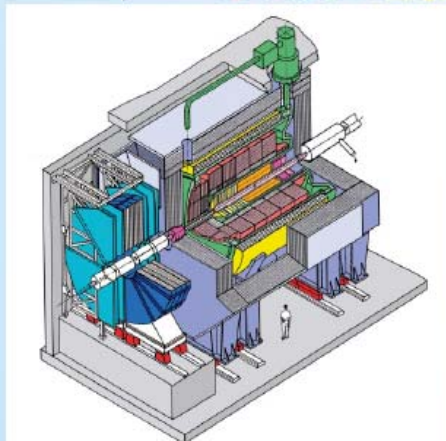


# Collider Experiments at HERA

**H1**  
went  
for  
LAr

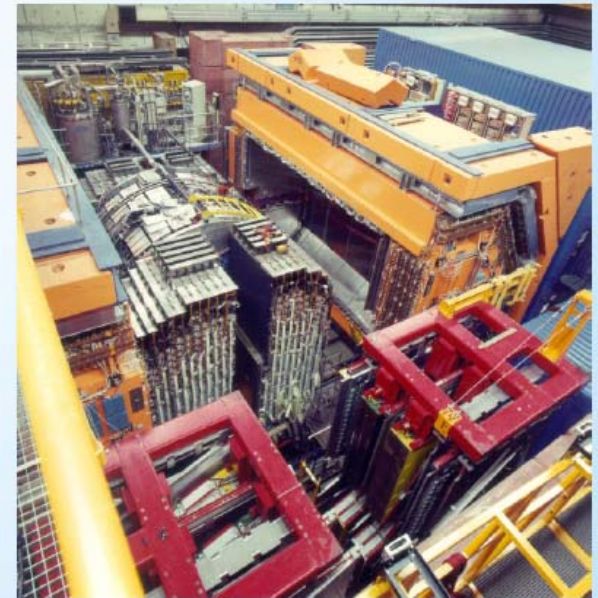


**ZEUS**  
went  
for  
compensation



**A final salute to  
our experiments**

**How we like to  
remember  
H1 and ZEUS**

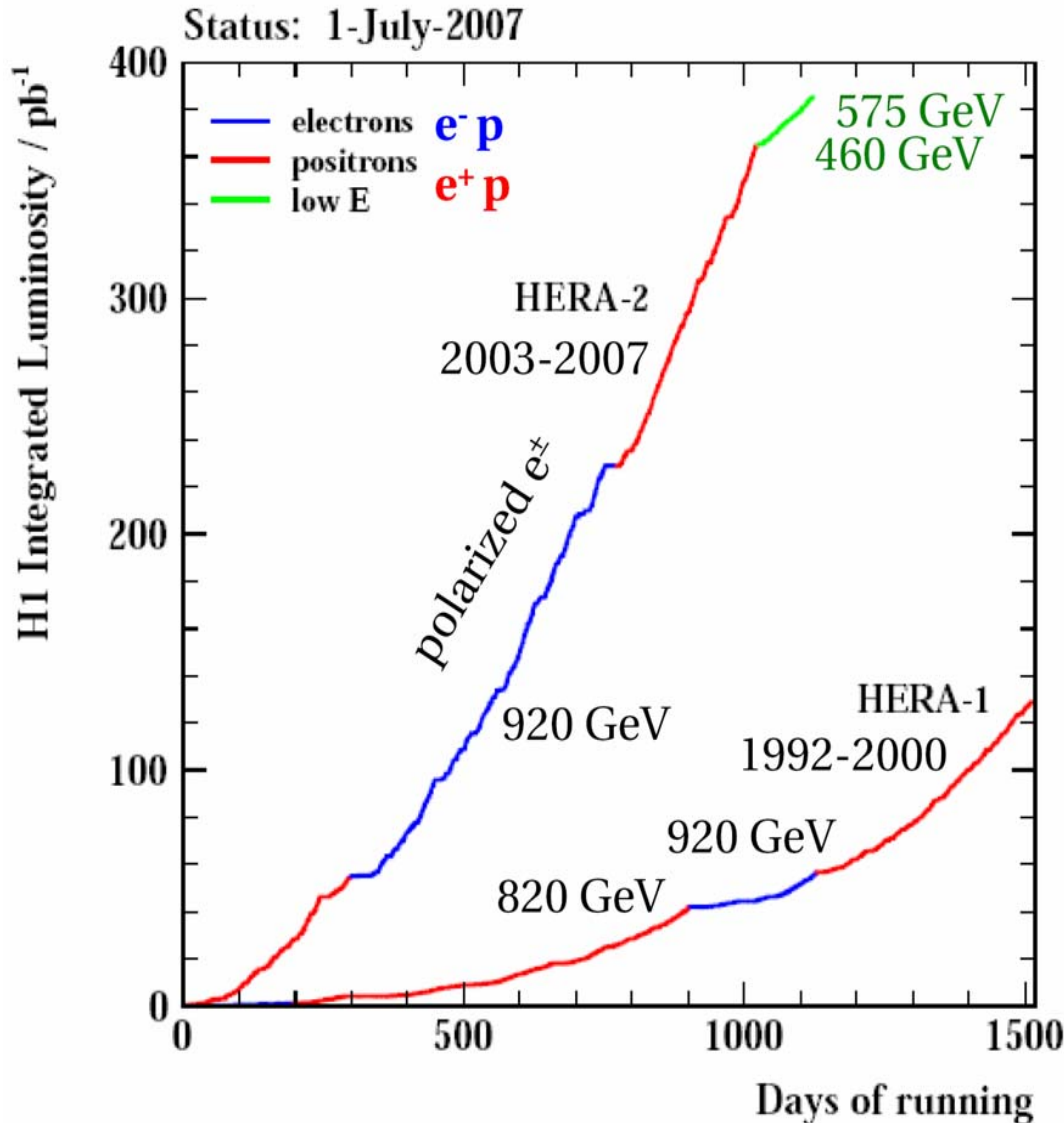


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# Hera Luminosity



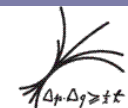
HERA I: 1992-2000

HERA II upgrade:

- luminosity
- longitudinal polarization of the lepton beams (spin rotator pairs around the interaction regions)
- massive upgrades also for the detectors



- running efficiently from 2003 onwards
- Luminosity  
 $L = 500 pb^{-1}$  per exp.

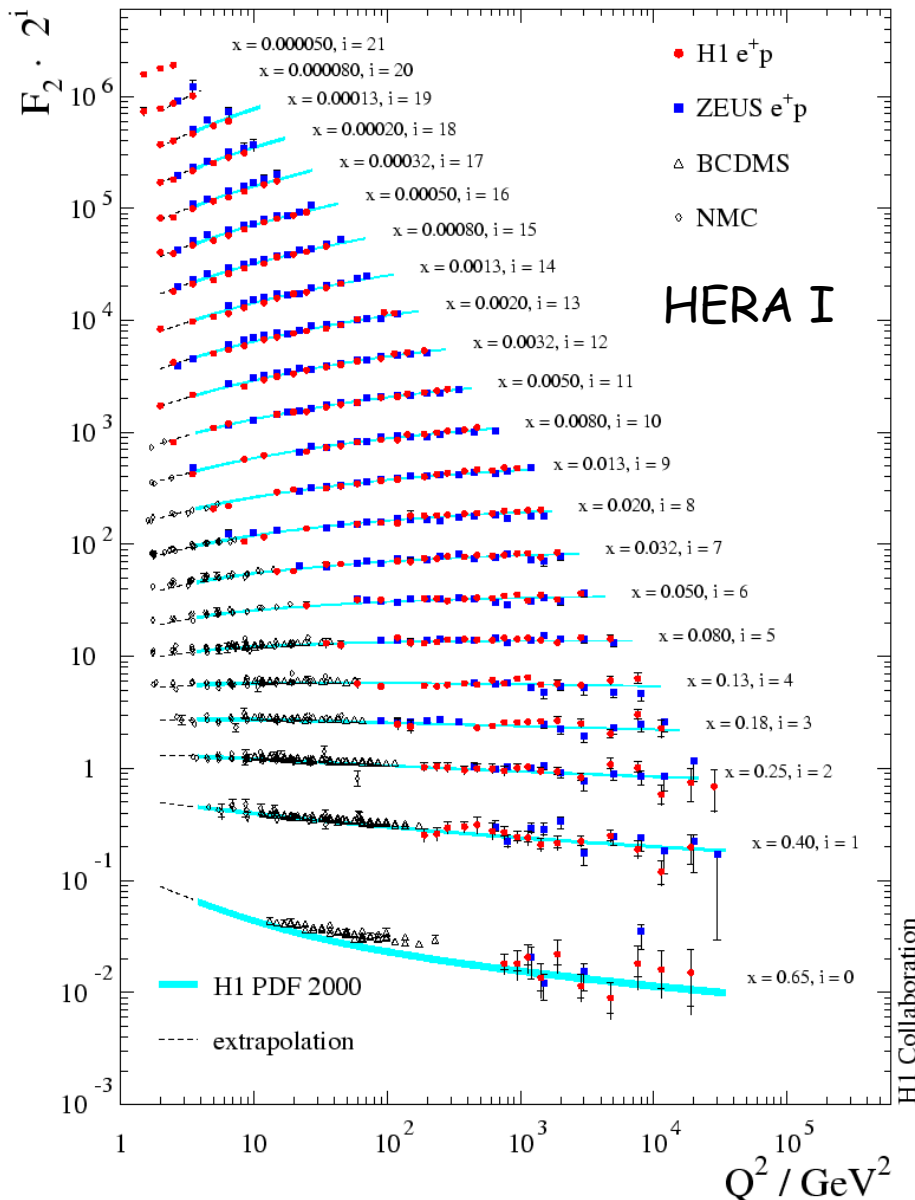


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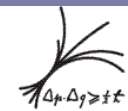
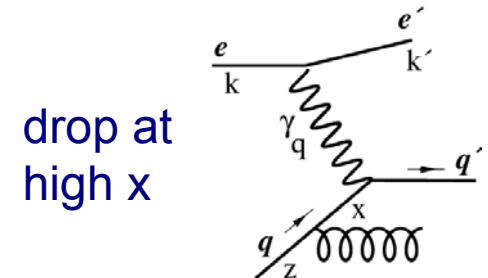
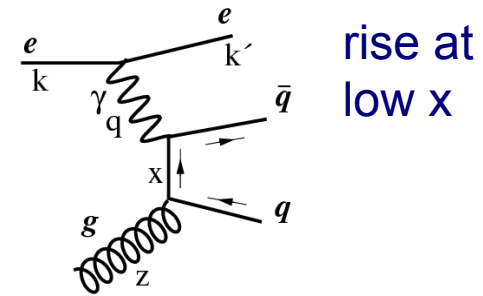
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# Structure Function $F_2$



- H1 & ZEUS extended fixed target kinematic regime in  $x$  and  $Q^2$  by 2 Orders
- Described by DGLAP
- Scaling violations



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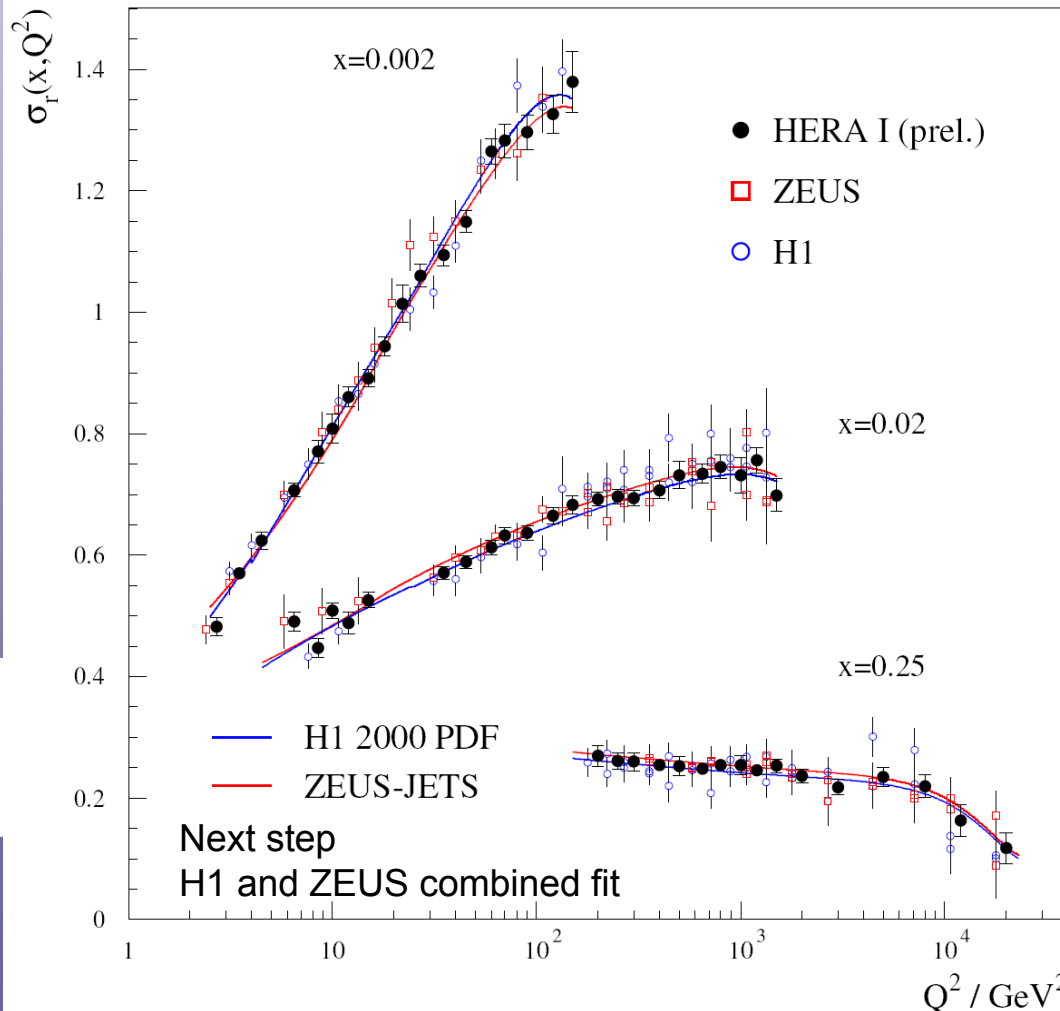
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# HERA Averaged NC cross sections

$$\sigma_r^{e^\pm p \rightarrow e^\pm X} = F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} xF_3$$

HERA I  $e^+p$  Neutral Current Scattering - H1 and ZEUS



- Precise measurements from two experiments

- For  $Q^2 \leq 100 \text{ GeV}^2$

$$\delta_{\text{stat}} \leq 1\%, \delta_{\text{sys}} \leq 3\%$$

- for  $Q^2 \geq 1000 \text{ GeV}^2$

$$\delta_{\text{stat}} > \delta_{\text{sys}}$$

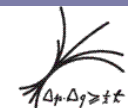
- Combine datasets from both experiments:

Key assumption

H1 and ZEUS measure the same cross section at the same  $x, Q^2, y$

- Improved precision of combined H1 and ZEUS datasets (stat and sys)

HERA Structure Functions Working Group



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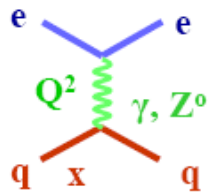
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# Input to HERA PDF Fits

■ **NC** 
$$\frac{d^2 \sigma^{e^\pm p \rightarrow e^\pm X}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \underbrace{\left(1 + (1-y)^2\right)}_{Y_\pm = 1 \pm (1-y)^2} \cdot \left( \tilde{F}_2(x, Q^2) - \frac{y^2}{Y_+} \tilde{F}_L(x, Q^2) \mp \frac{Y_-}{Y_+} x\tilde{F}_3(x, Q^2) \right)$$

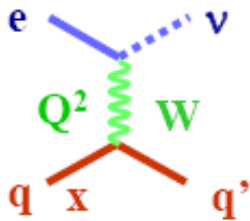


$$\tilde{F}_2 = \sum_i A_i(Q^2) [xq_i + x\bar{q}_i] \Rightarrow F_2^{em} = \frac{4}{9} x(u + \bar{u} + c + \bar{c}) + \frac{1}{9} x(d + \bar{d} + s + \bar{s})$$

$$x\tilde{F}_3 = \sum_i B_i(Q^2) [xq_i - x\bar{q}_i] \Rightarrow xF_3 = B_U x(u - \bar{u} + c - \bar{c}) + B_D x(d - \bar{d} + s - \bar{s})$$

Electroweak Coefficient Functions  $A_i(Q^2)$ ,  $B_i(Q^2)$  (QED:  $A_i = e_i^2$ )

■ **CC**

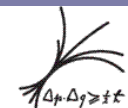


$$\sigma_{CC}(e^+ p) \propto x \left[ (1-y^2)(d+s) + (\bar{u} + \bar{c}) \right] \times (1 + P_e)$$

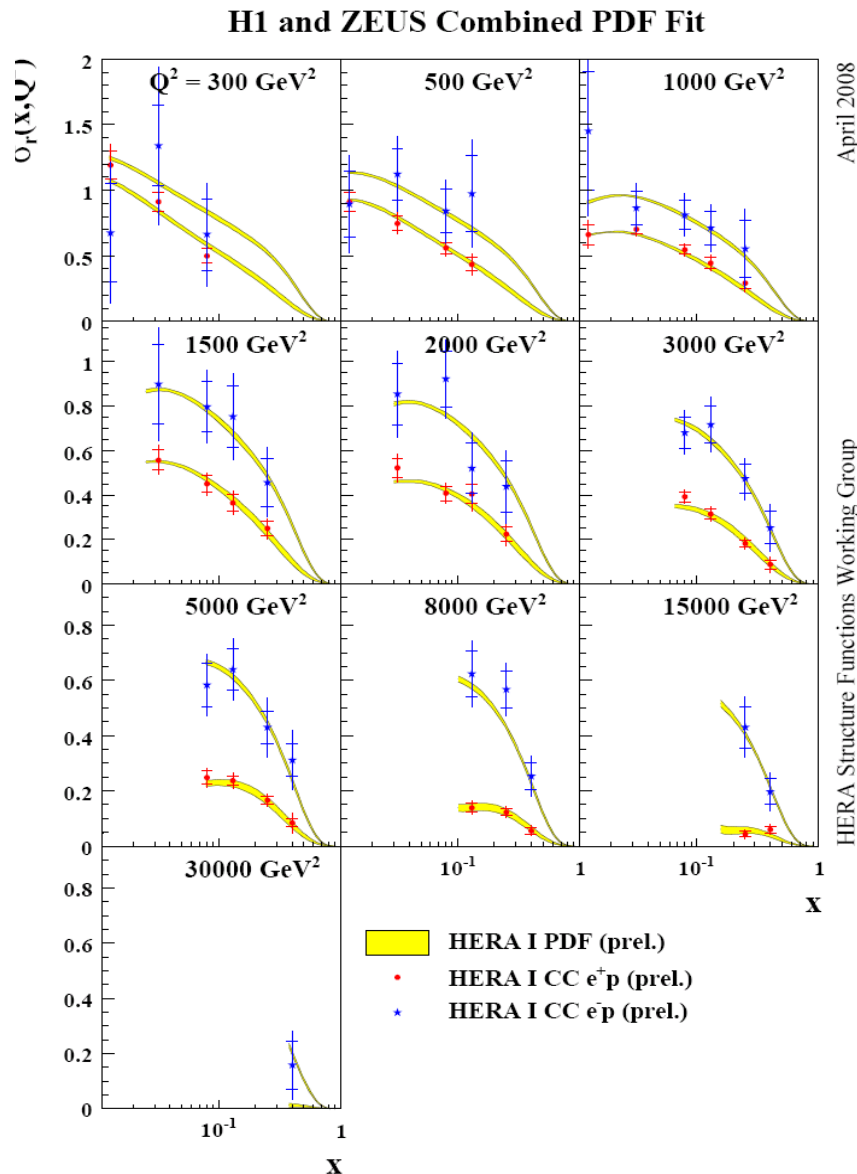
$$\sigma_{CC}(e^- p) \propto x \left[ (u+c) + (1-y^2)(\bar{d} + \bar{s}) \right] \times (1 - P_e)$$

**PDF general form:**  $xPDF = Ax^B (1-x)^C \cdot (1 + Dx + \dots)$

**Parameterize:**  $g$ ,  $u_v$ ,  $d_v$ ,  $\bar{U}(=\bar{u}+\bar{c})$ ,  $\bar{D}(=\bar{d}+\bar{s})$



# Charged Current Cross Section

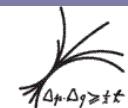


CC Cross section provide flavor sensible constrains at high x

$$\sigma_{CC}(e^+p) \propto x \left[ (1-y^2)D + \bar{U} \right]$$

$$\sigma_{CC}(e^-p) \propto x \left[ U + (1-y^2)\bar{D} \right]$$

Improved precision of  $\sigma_{CC}$   
By combining H1 and ZEUS



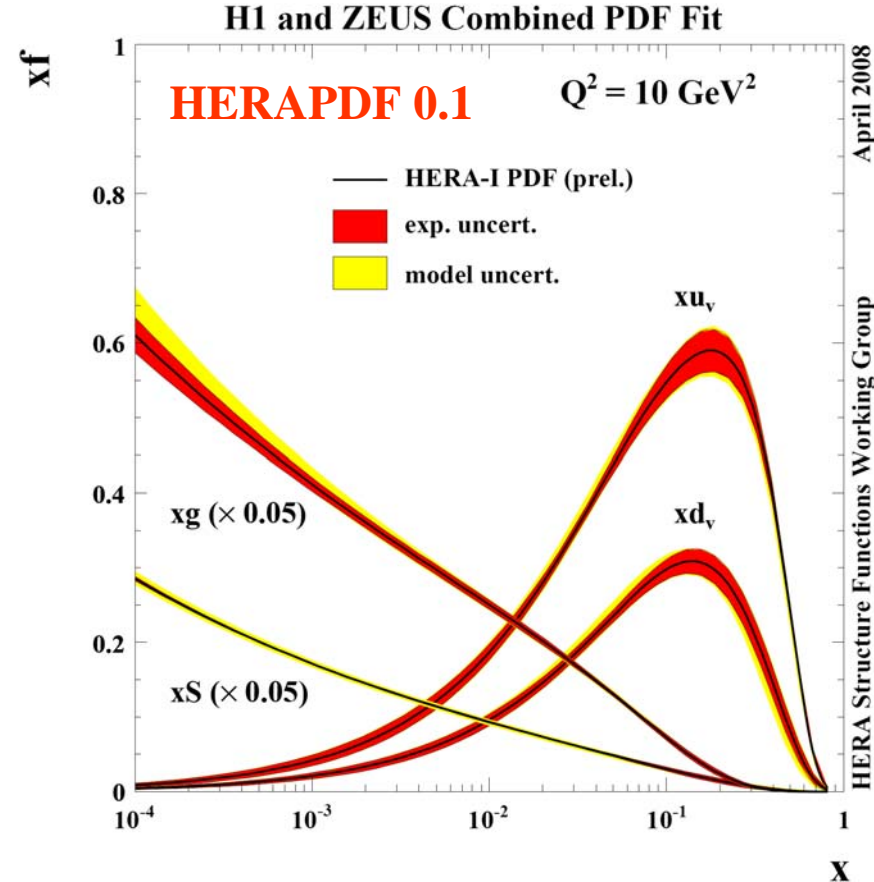
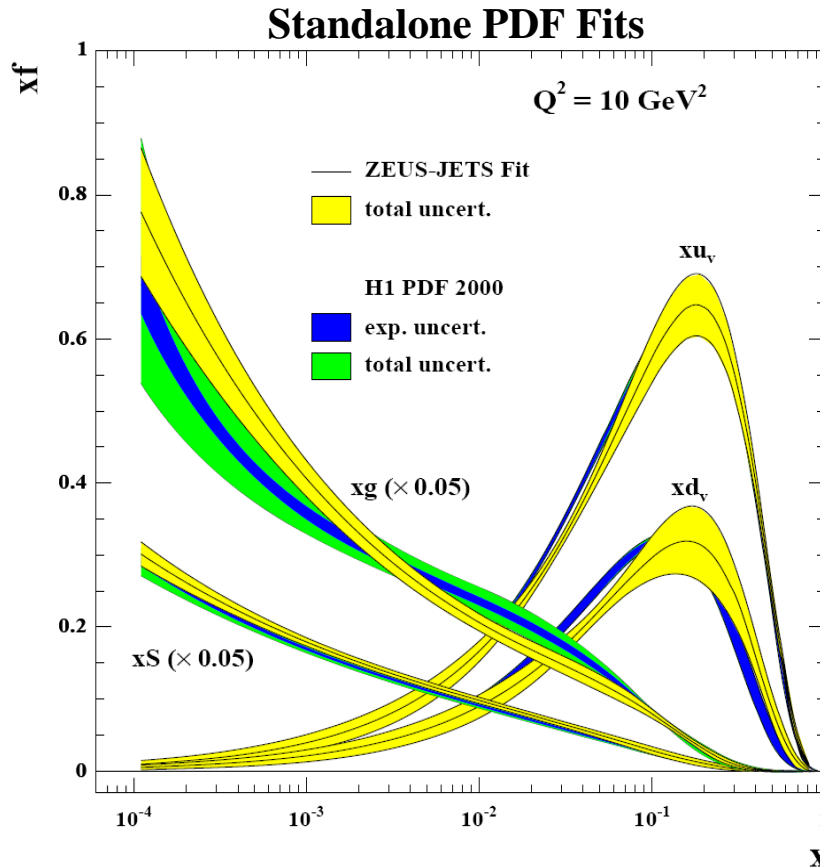
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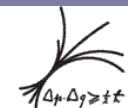


# PDF Fits on HERA I Data

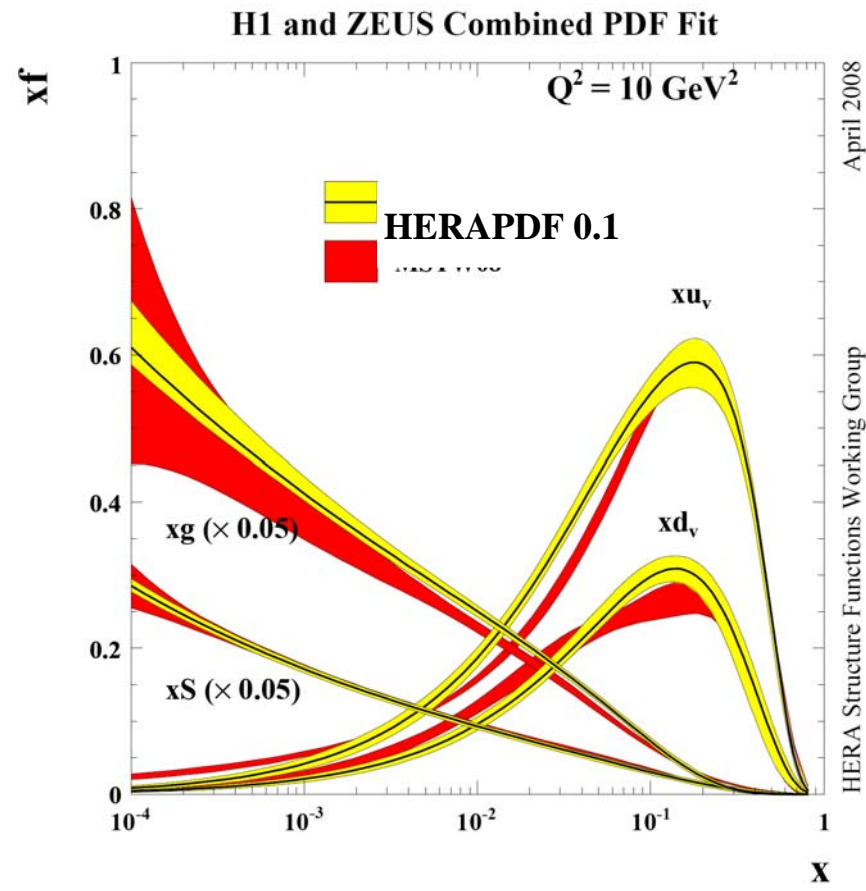
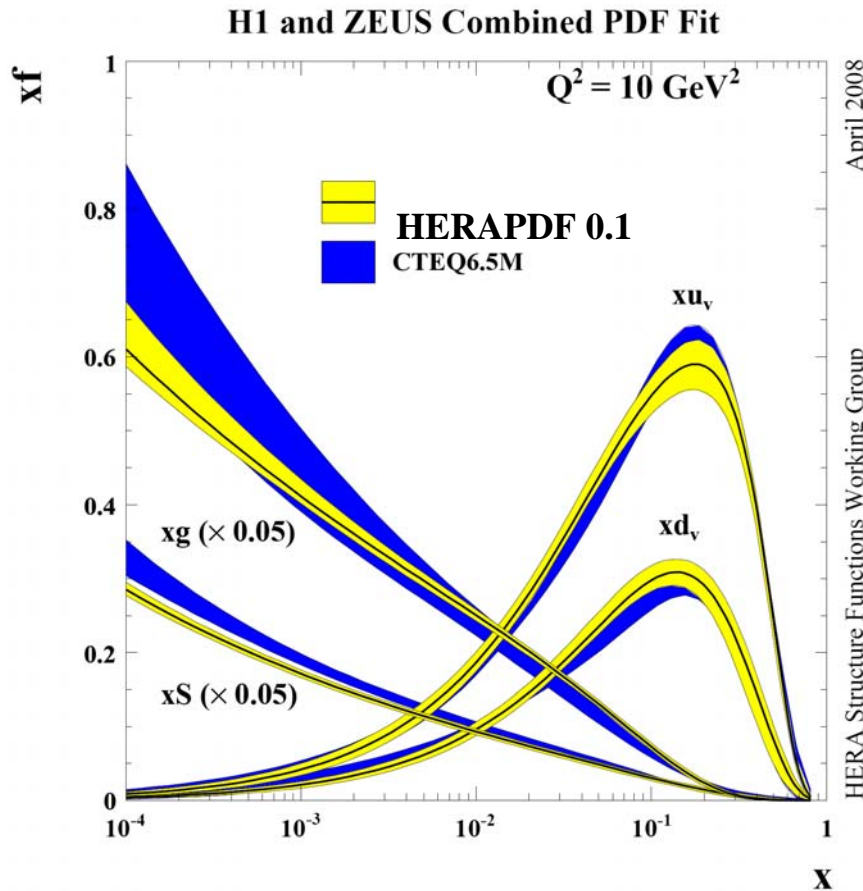


Impressive reduction of uncertainties of combined PDFs

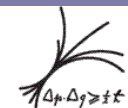
Model uncertainty: variation of charm and bottom mass, starting scale  $Q_0^2$ ,  $Q_{\min}^2$  of included data, strange and charm fraction at starting scale



# Comparison to Global Fits

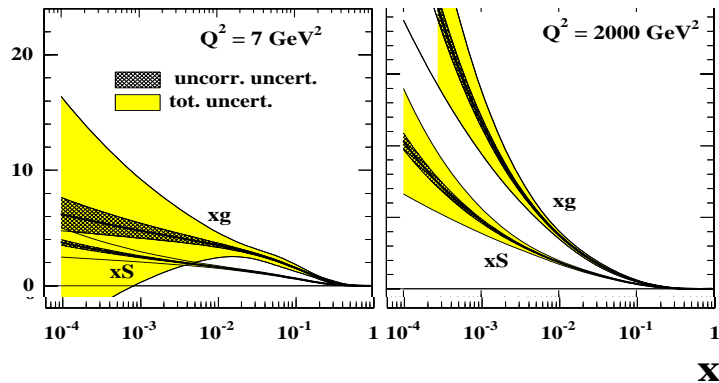


not a completely fair comparison:  
HERA combined data were not available to global fitters

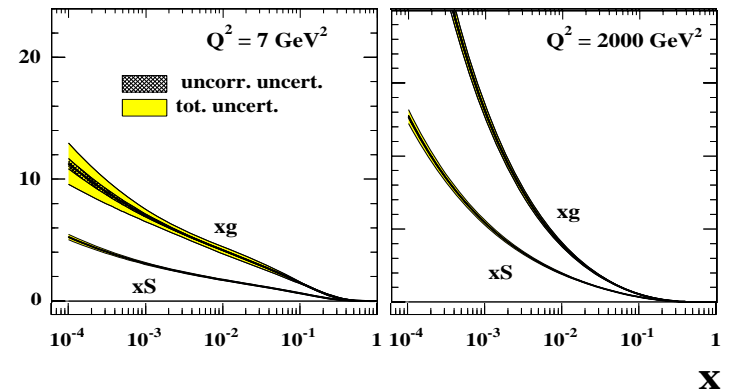


# Impact of HERA data

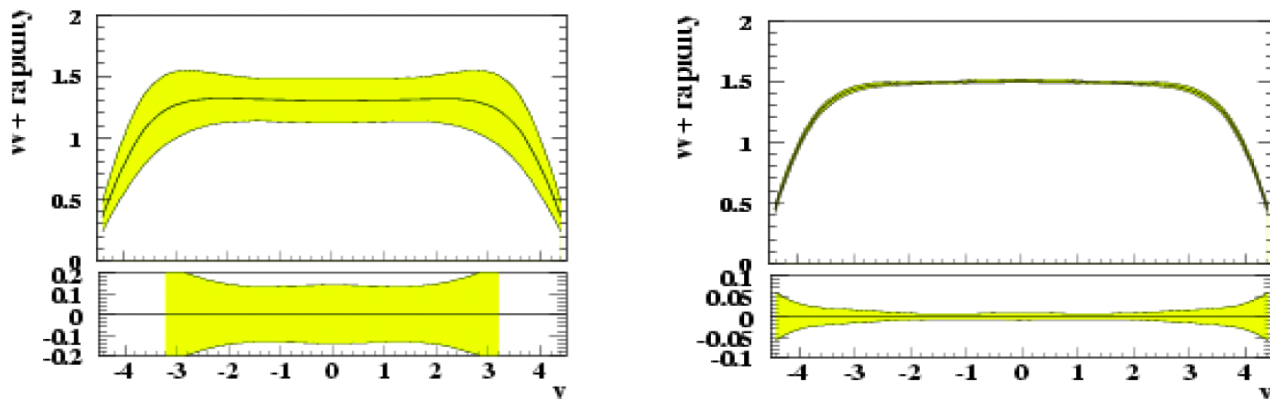
Pre-HERA uncert. in gluon/sea PDFs



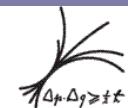
HERA PDFs combining H1 and ZEUS



Example:  $W^+$  production at the LHC (Study by A. Cooper-Sakar)



Note: Error bands are experimental uncertainties only  
model uncertainty will become increasingly important



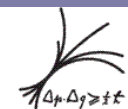
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# Future HERA PDF Fits

- So far only part of the inclusive HERA I were used → HERAPDF0.1
- Incorporate all NC and CC from HERA I&II
- Include jet cross sections
  - constrain high  $x$  gluon
- Include charm and beauty
  - flavor decomposition of the sea
- Charged & Neutral current cross sections with polarized  $e^\pm$  beams
  - constrain valence quark region

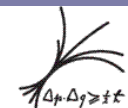
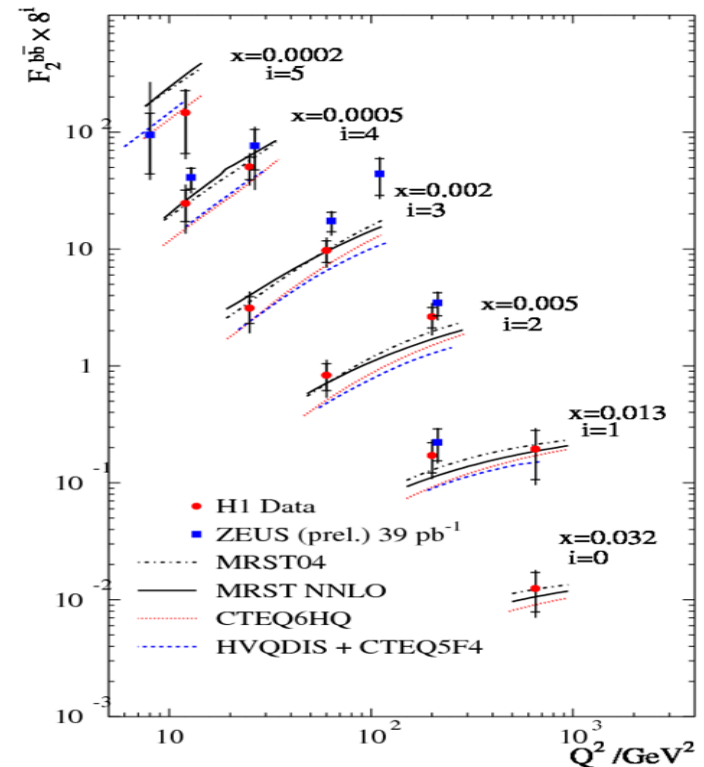
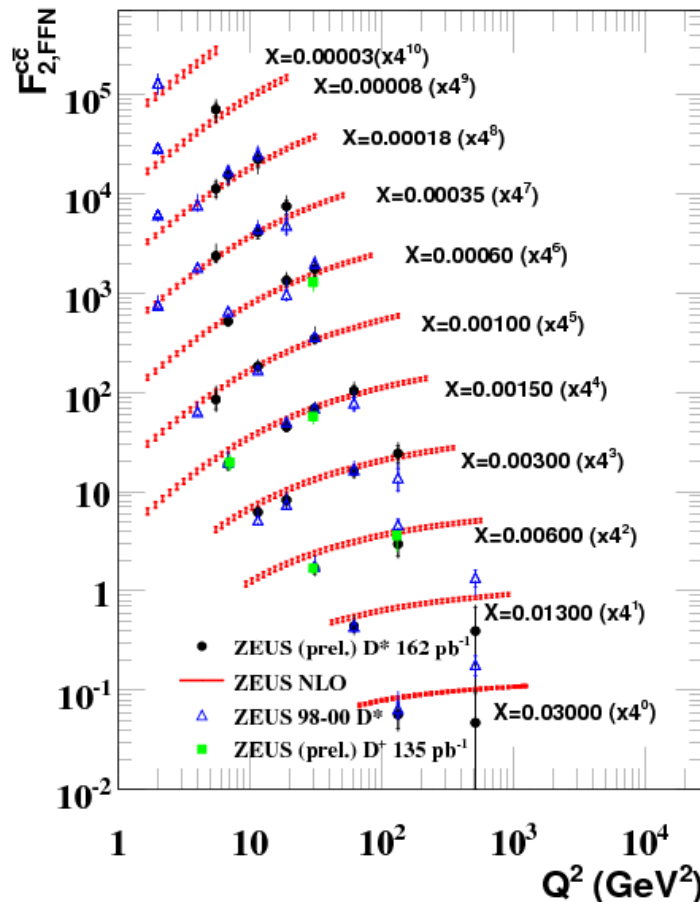
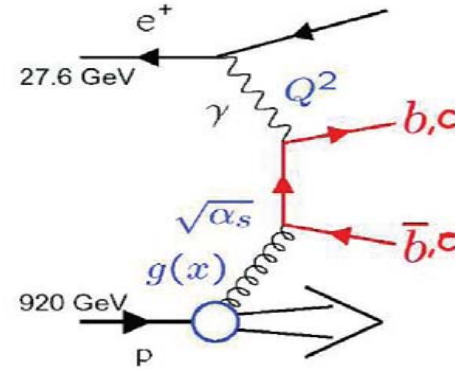


# Charm & Beauty Structure

Charm and Beauty production in DIS is driven by gluons in the proton

Charm tag: reconstruct D mesons

Beauty tag: displaced vertex, soft  $\mu$

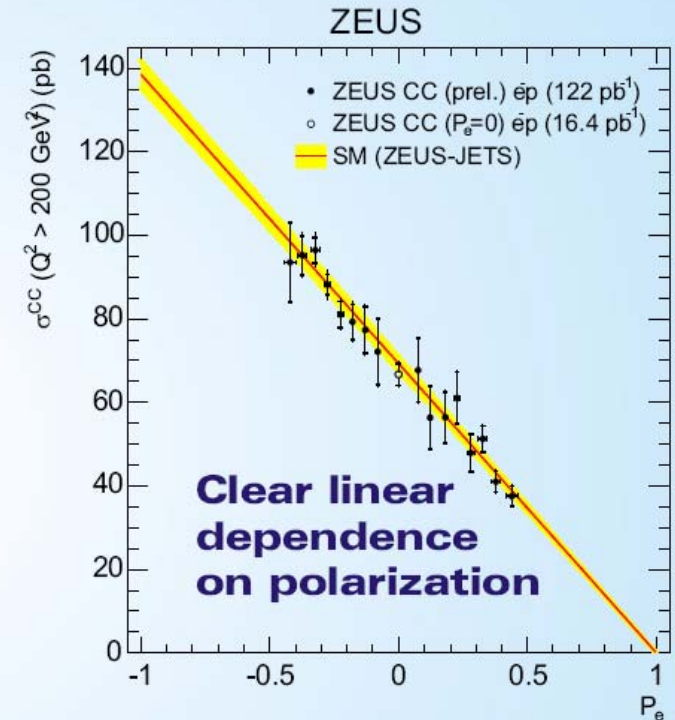
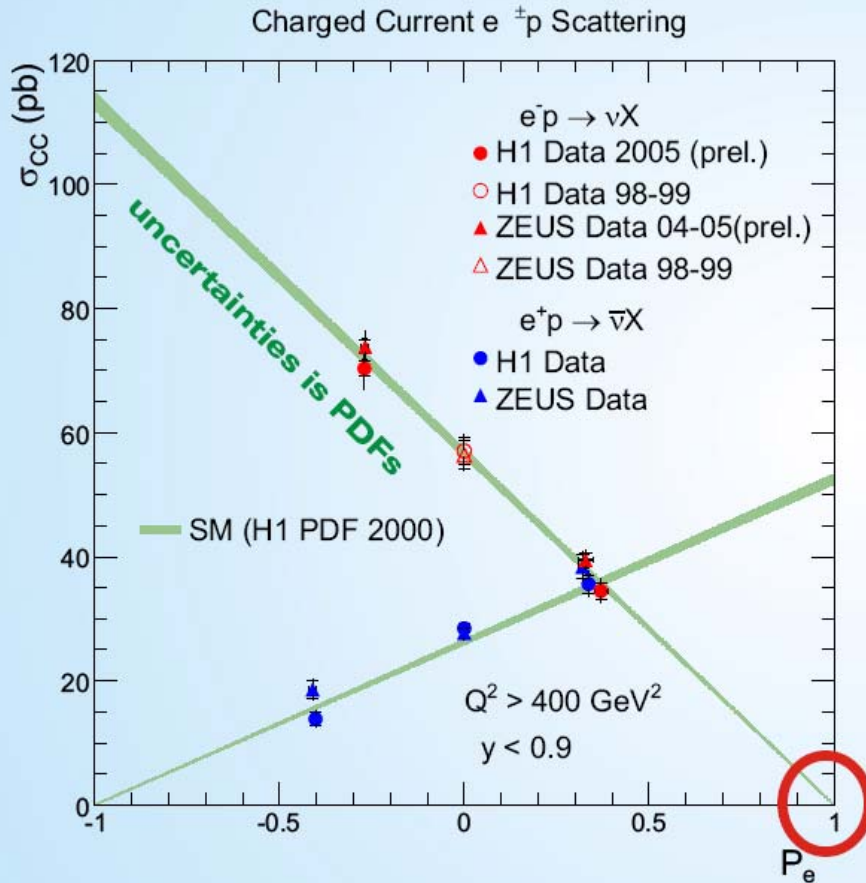


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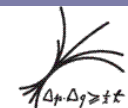
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# Polarization dependence of CC



**Consistent with SM prediction**  
 **$\sigma(\text{CCRH}) = 0$**

Input to PDF fits: Double differential CC  $e^\pm p$  cross sections



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# Polarisation Effects in NC

$$\begin{aligned}\tilde{F}_2 &= F_2^\gamma - (v_e \pm P_e a_e) \chi_Z F_2^{\gamma Z} + ((v_e^2 + a_e^2) \pm P_e 2v_e a_e) \chi_Z^2 F_2^Z \\ \tilde{F}_3 &= - (a_e \pm P_e v_e) \chi_Z F_3^{\gamma Z} + ((2v_e a_e \pm P_e (v_e^2 + a_e^2)) \chi_Z^2 F_3^Z\end{aligned}$$

Nb.:  $\chi F_3$  is written as  $F_3$  for simplicity

- Polarization modifies  $\gamma Z$  and  $Z$  terms:

- Axial in  $F_2$ , vector in  $F_3$
- dependent on size of  $P_e$

$$u_e \approx 0$$

- $F_2$  : 1<sup>st</sup> order,  $\sim \pm P_e a_e \chi_Z F_2^{\gamma Z}$
- $F_3$  : 2<sup>nd</sup> order only,  $\sim \pm P_e a_e^2 \chi_Z^2 F_3^Z$

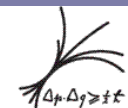
**Unpol:**

$$\sigma(e^+) - \sigma(e^-) \rightarrow F_3^{\gamma Z}$$

**Pol :**

$$\sigma(P_e \rightarrow) - \sigma(P_e \leftarrow) \rightarrow F_2^{\gamma Z}$$

- Polarization effects expected only at EW scale, i.e large  $Q^2$



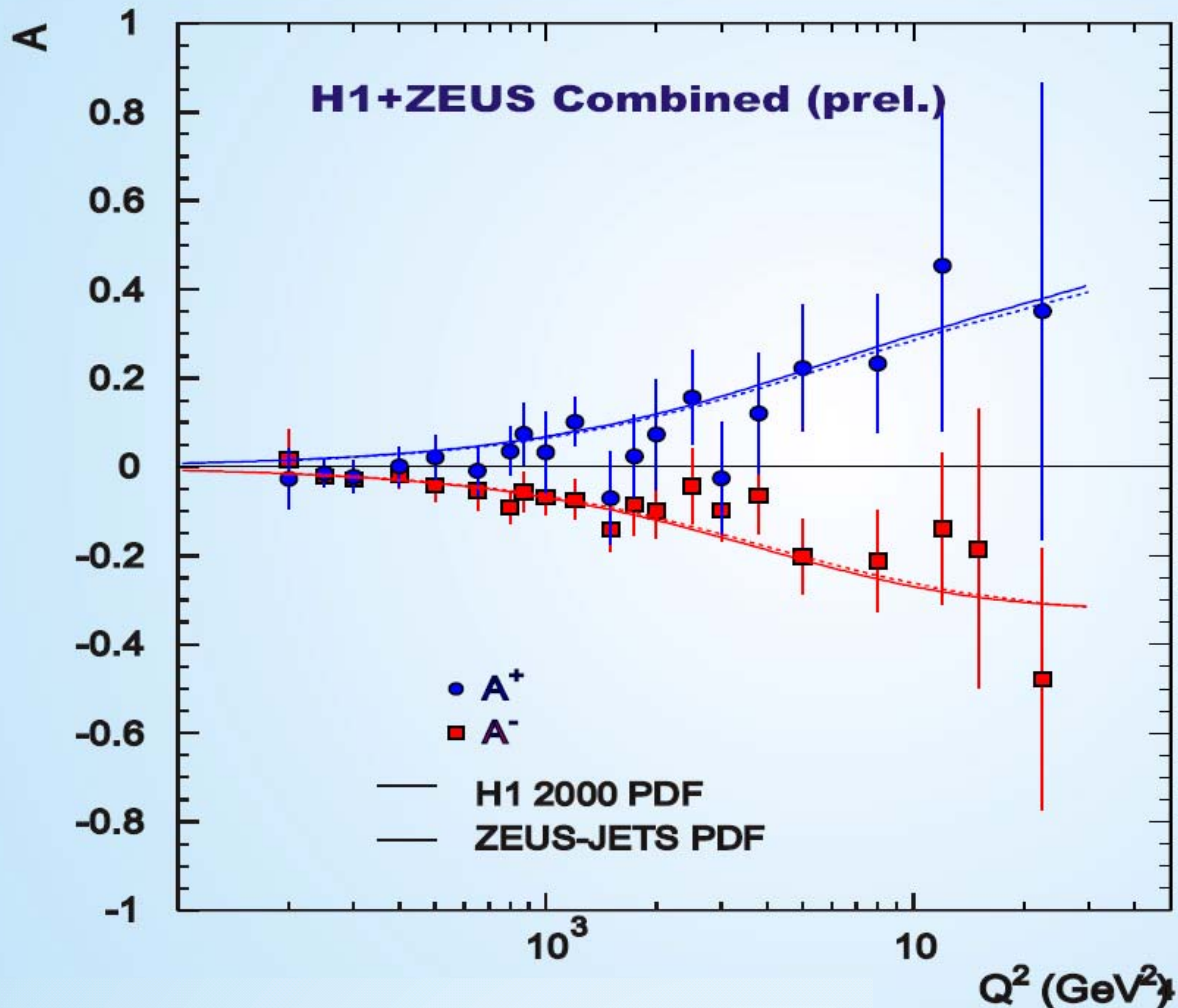
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# NC Cross Section Asymmetries



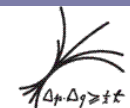
**Parity Violation  
 due to  $\gamma Z$   
 interference**

**At high  $x$ ,  
 assuming  
 SM couplings**

$$A_{\pm} \sim \frac{u_v + d_v}{4u_v + d_v}$$

**constrain  $d/u$**

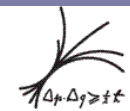
$$A_{\pm} = \frac{2}{P_R - P_L} \frac{\sigma_{\pm}(P_R) - \sigma_{\pm}(P_L)}{\sigma_{\pm}(P_R) + \sigma_{\pm}(P_L)}$$



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# OPEN ISSUES



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# Open Issues (I): high x

Inclusive cross sections at high x:

$$NC \quad e^\pm p : \sigma \propto \frac{4}{9} xu$$

$$CC \quad e^- p : \sigma \propto xu$$

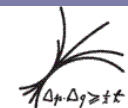
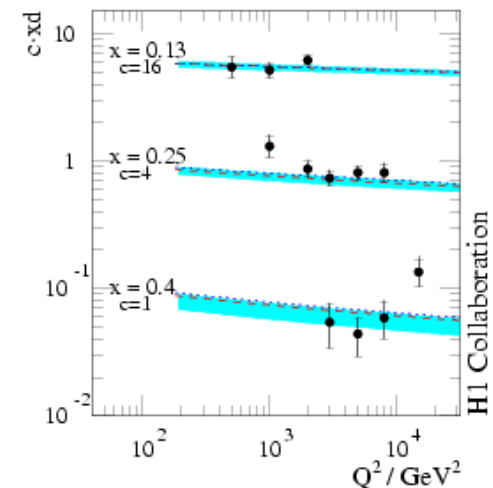
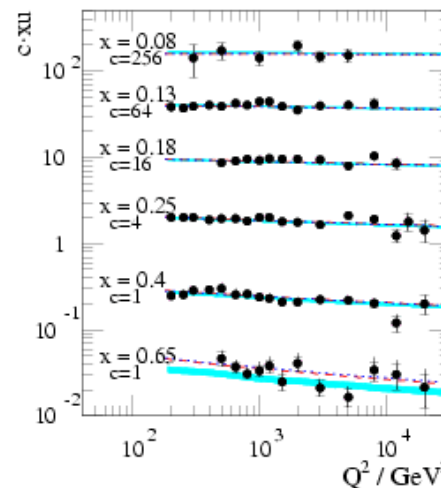
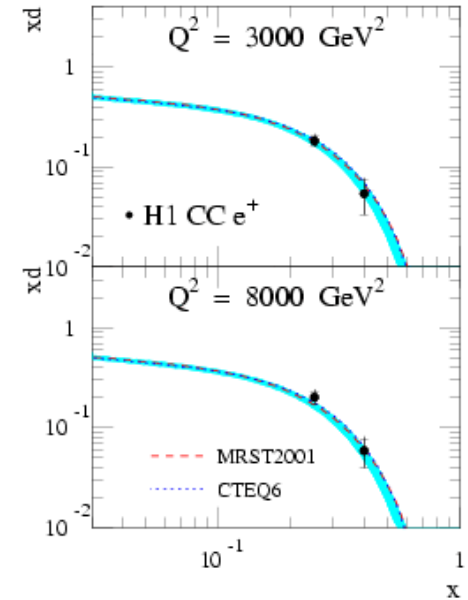
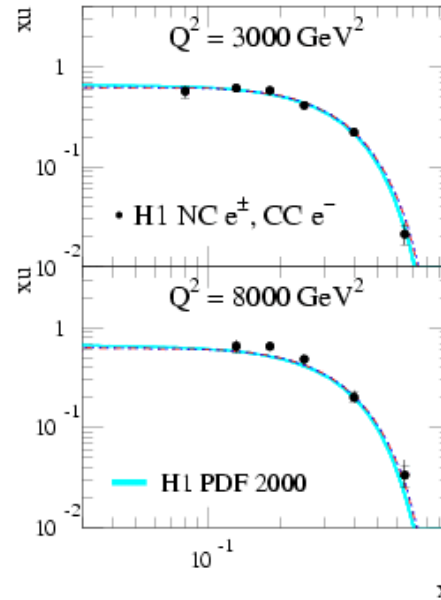
$$e^+ p : \sigma \propto (1 - y^2)xd$$

Quark distributions can be extracted with minimal corrections from QCD fits

Reach in x limited by detector acceptance, hadronic final state goes down the proton beam line

$$u: x_{\max} = 0.65$$

$$d: x_{\max} = 0.4$$



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# Open Issues(I): High x continued

Events at high x  
at acceptance limit

Poor resolution for x  
→ cannot measure  
differential  $\sigma$  at  
x, Q<sup>2</sup> point

Measure integrated  $\sigma$   
for  $x > x_{\text{limit}}$

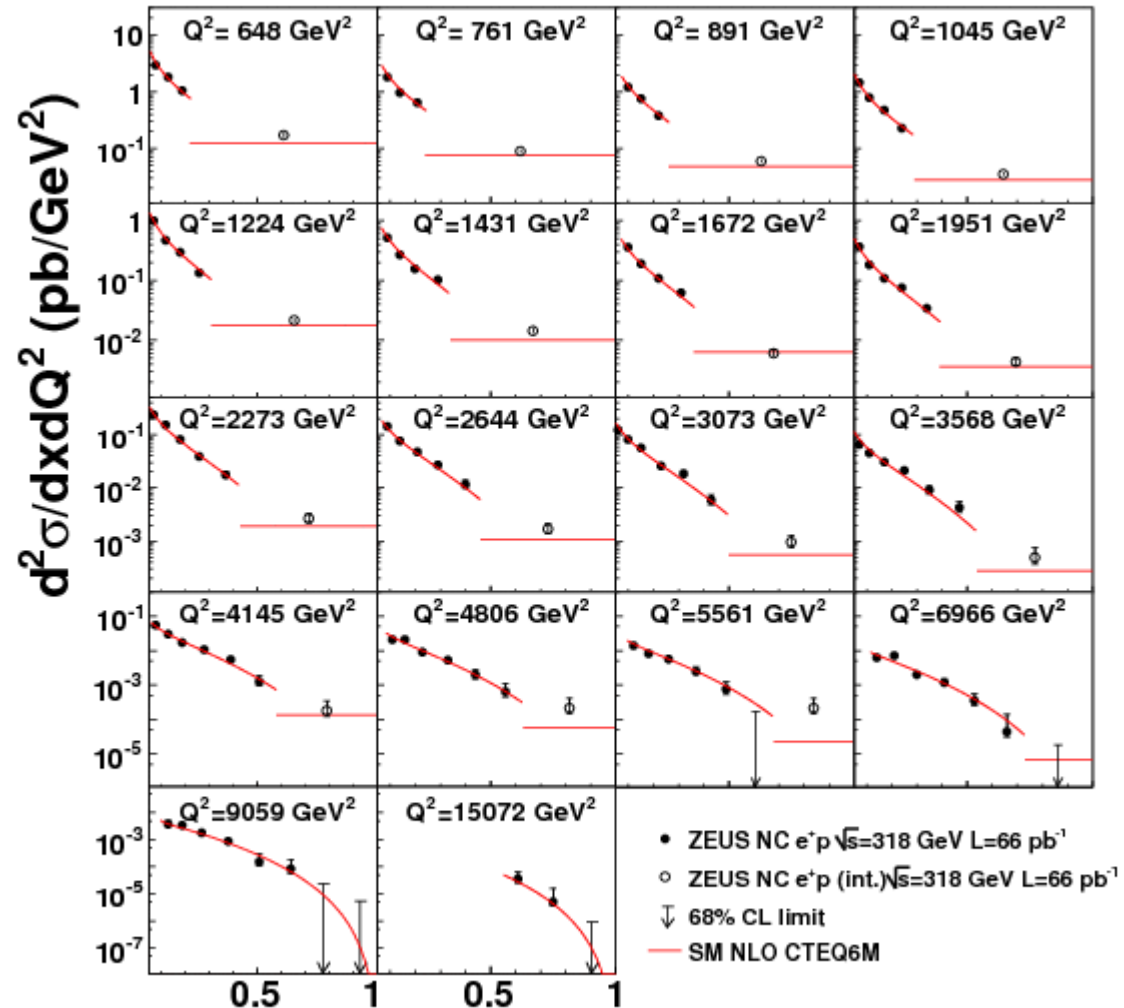
$\sigma$  larger than expected

PDFs at high x

$$f \propto (1-x)^C \Rightarrow f \xrightarrow{x \rightarrow 1} 0$$

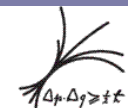
Constraint by shape  
→ underestimated  
uncertainty?

## ZEUS



Here HERA I e<sup>+</sup>p, e<sup>-</sup>p see backup

X



# Open Issues II: Light flavor decomposition of the $q\bar{q}$ sea

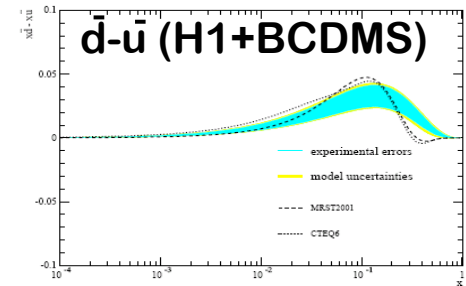
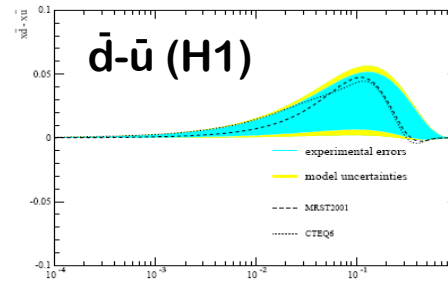
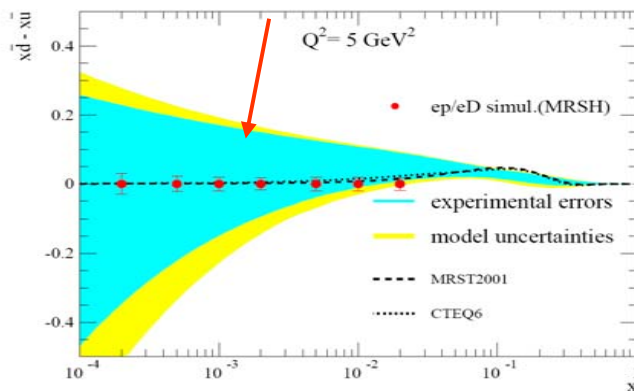
PDF fits conventionally assume

$$x\bar{d} - x\bar{u} \xrightarrow{x \rightarrow 0} 0$$

NMC found  $d \neq u$  at medium  $x$

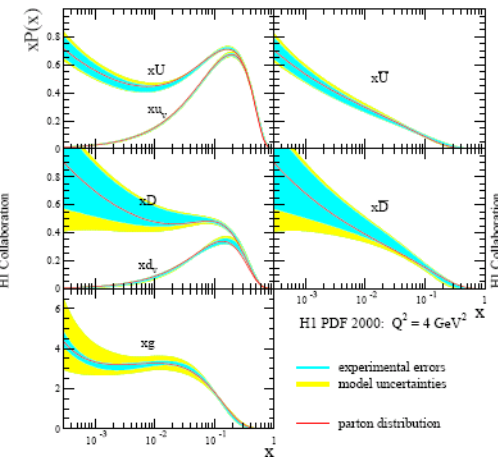
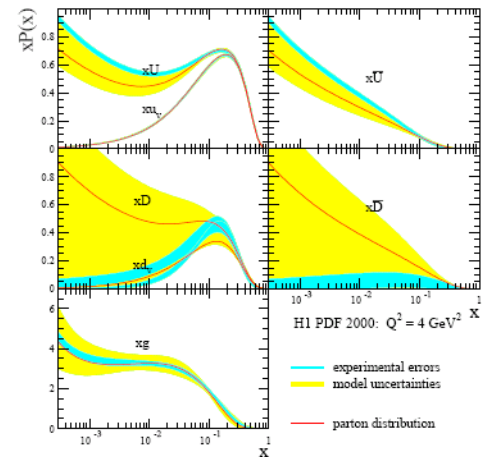
Here is what happens when  
the  $x\bar{d} - x\bar{u}$  constraint at low  $x$   
is relaxed

A deuteron run at HERA  
Could have disentangled  
the light flavor sea



H1 only (HERA I)

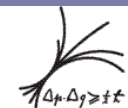
H1 +BCDMS



Poorly constrained

Fit stabilized by  
fixed target data  
(sum rules help)

Attempt to fit U and D  
Only one input:  $F_2$  ep



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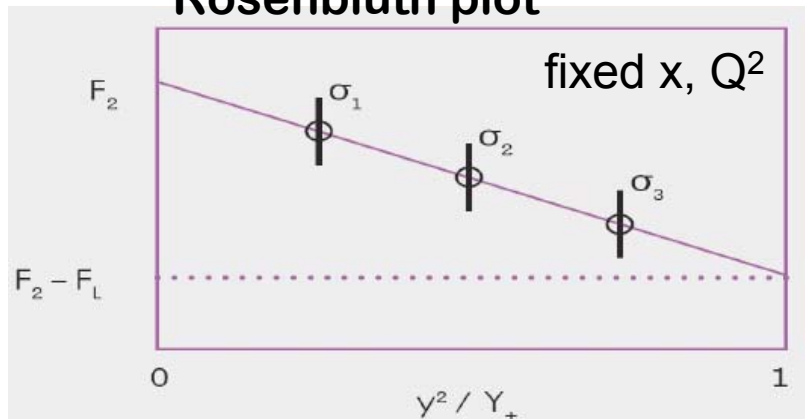
# Issues at low x? Low x = High y !

- Neutral current DIS cross section expressed by structure functions:

$$\frac{d^2\sigma^{e^\pm p \rightarrow e^\pm X}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \underbrace{\left(1 + (1-y)^2\right)}_{Y_\pm = 1 \pm (1-y)^2} \cdot \left( F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) \right)$$

$\tilde{\sigma}$  : Reduced cross section

Rosenbluth plot



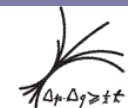
$$F_2(x, Q^2) = \sigma_r(x, Q^2, y=0)$$

$$F_L(x, Q^2) = - \frac{\partial \sigma_r(x, Q^2, y)}{\partial (y^2 / Y_+)}$$

Measure  $\sigma_r$  at fixed  $x, Q^2$  but varying  $y$

$$y = Q^2 / sx \quad \sqrt{s} = ep \text{ center-of-mass energy}$$

Varying  $y \rightarrow$  varying  $s \rightarrow$  dedicated low  $E_p$  runs at end of HERA



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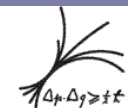
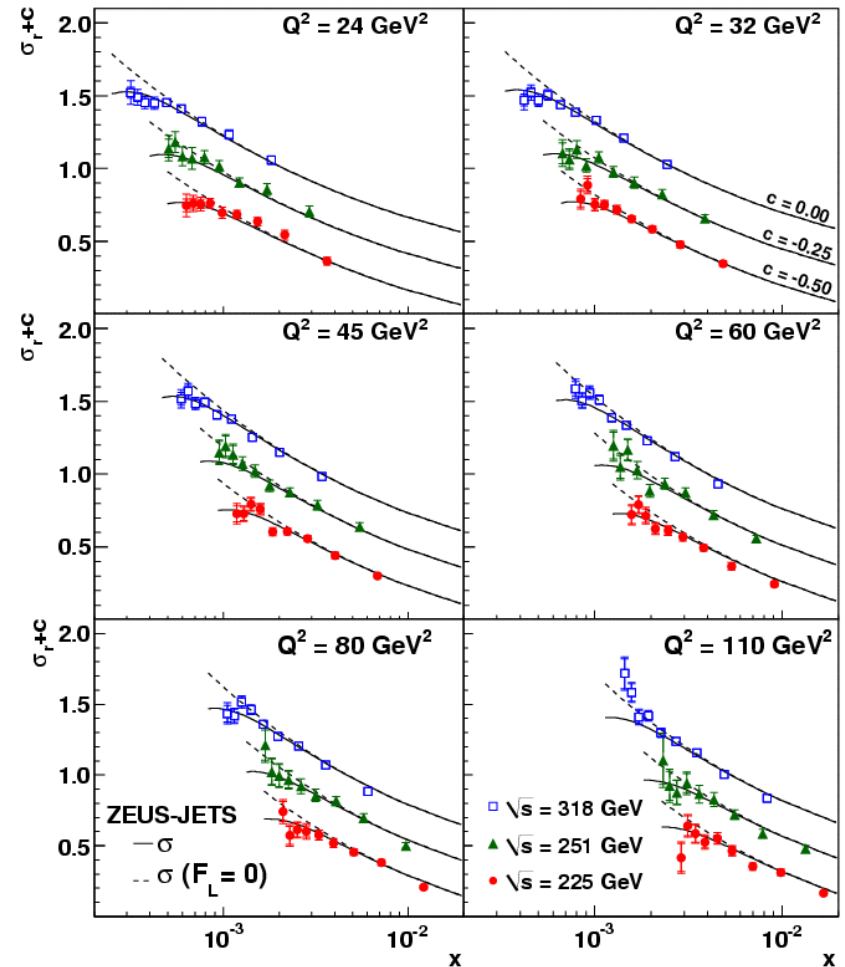
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# Cross Sections at low x, high y

- $\sigma_r$  measured at 3 different  $\sqrt{s}$
- comparison to ZEUS-JETS PDF prediction with  $F_L = F_L(\text{QCD})$  and  $F_L=0$
- $F_L$  causes suppression at low x
- Small effect but big enough to extract  $F_L$  and  $F_2$

## ZEUS

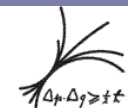
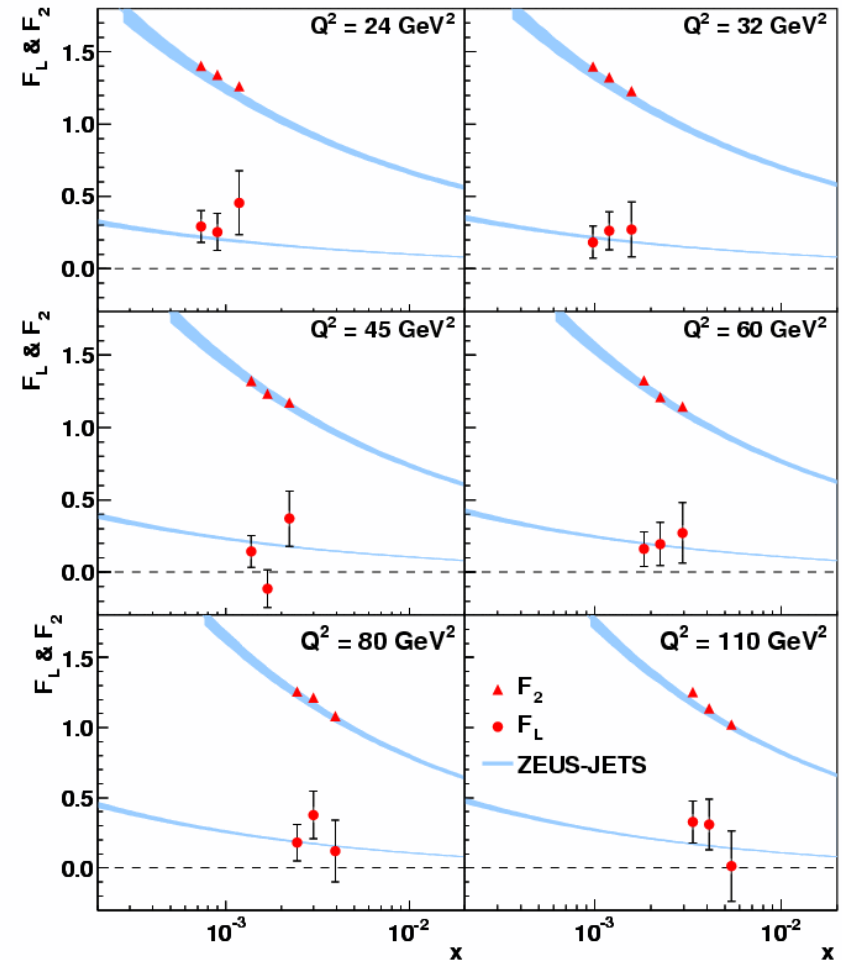




# Extracted Structure Functions

- Simultaneous extraction of  $F_L(x, Q^2)$  and  $F_2(x, Q^2)$
- Error bars: experimental errors (stat & syst)
- Data support non-zero  $F_L$
- Consistent with expectation from QCD

ZEUS

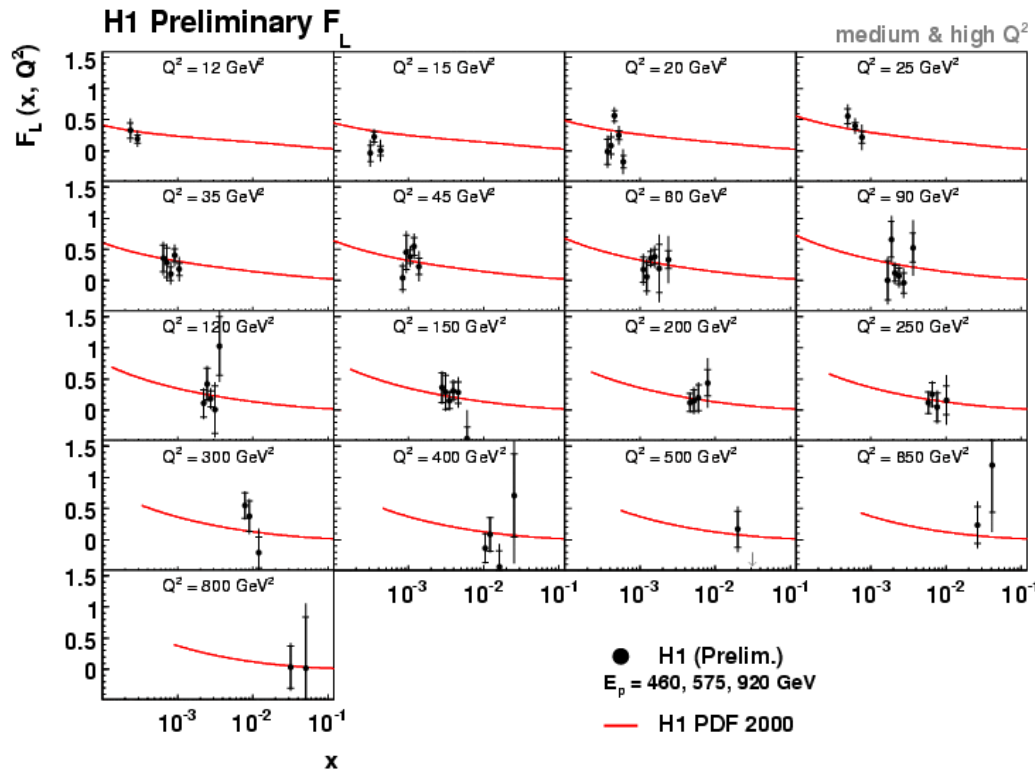


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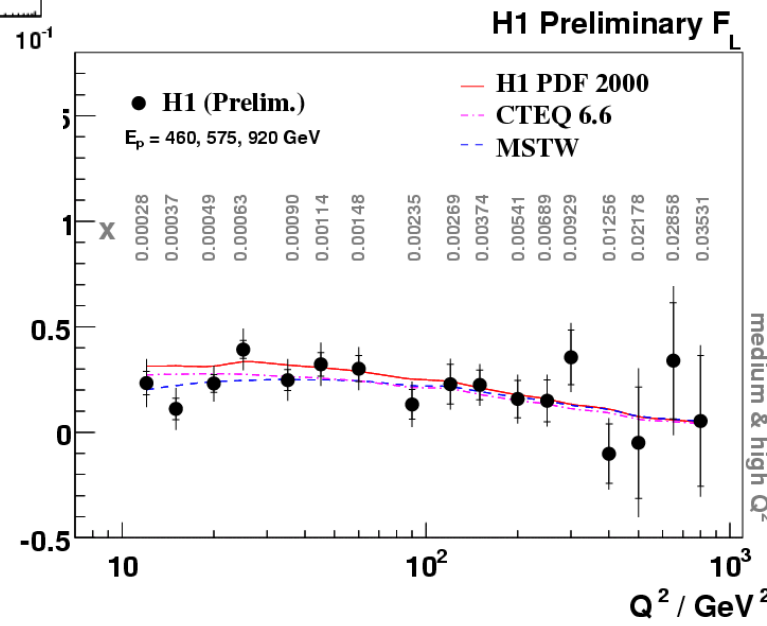
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# Longitudinal Structure Function from H1



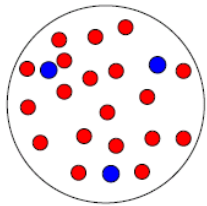
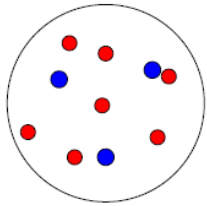
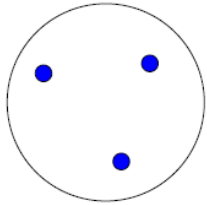
FL from medium (published) and high Q<sup>2</sup> analysis (prelim)



- Consistent results from H1 and ZEUS
- Very successful low  $E_p$  program at the end of the HERA era



# Low x, Large Parton Densities and Saturation



at fixed resolution scale ( $Q^2$ ) go to very large hadronic center of mass energy

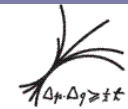
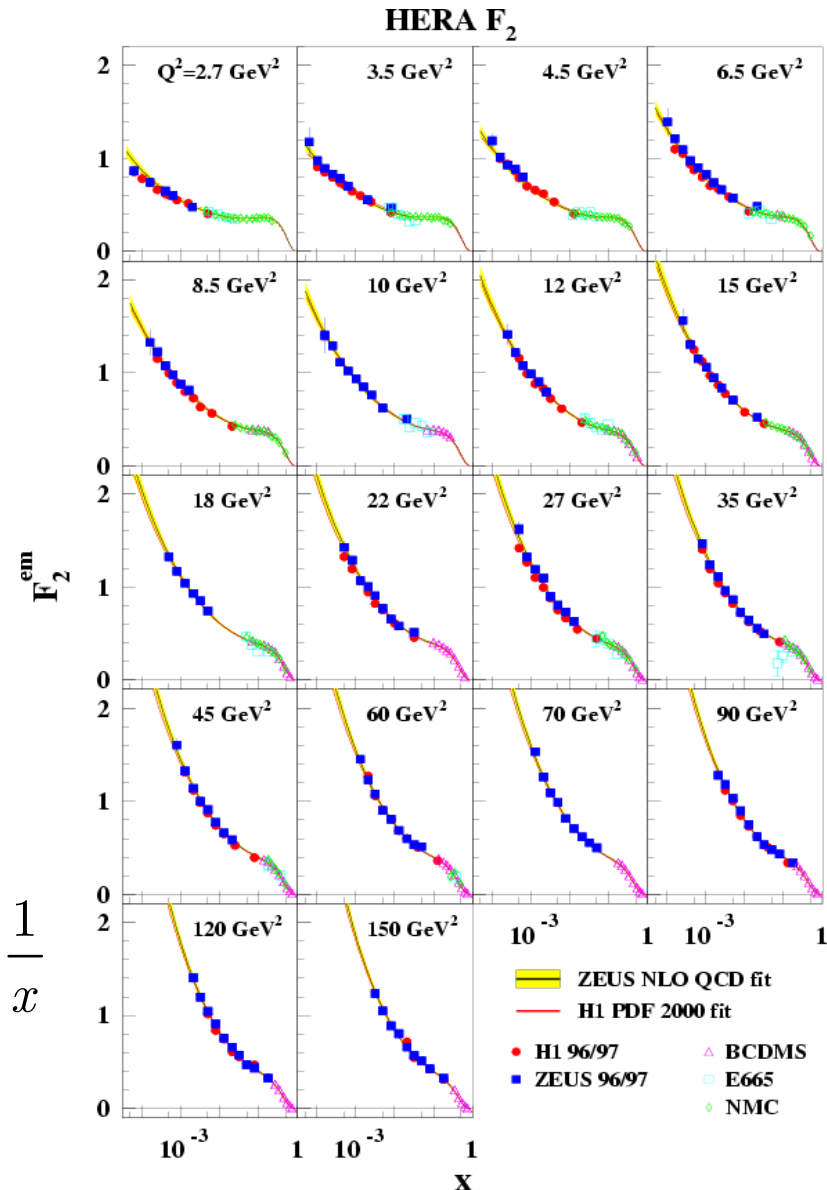
low  $x$  
$$x = \frac{Q^2}{Q^2 + W^2}$$

ultimately expect partons to overlap („saturation“)

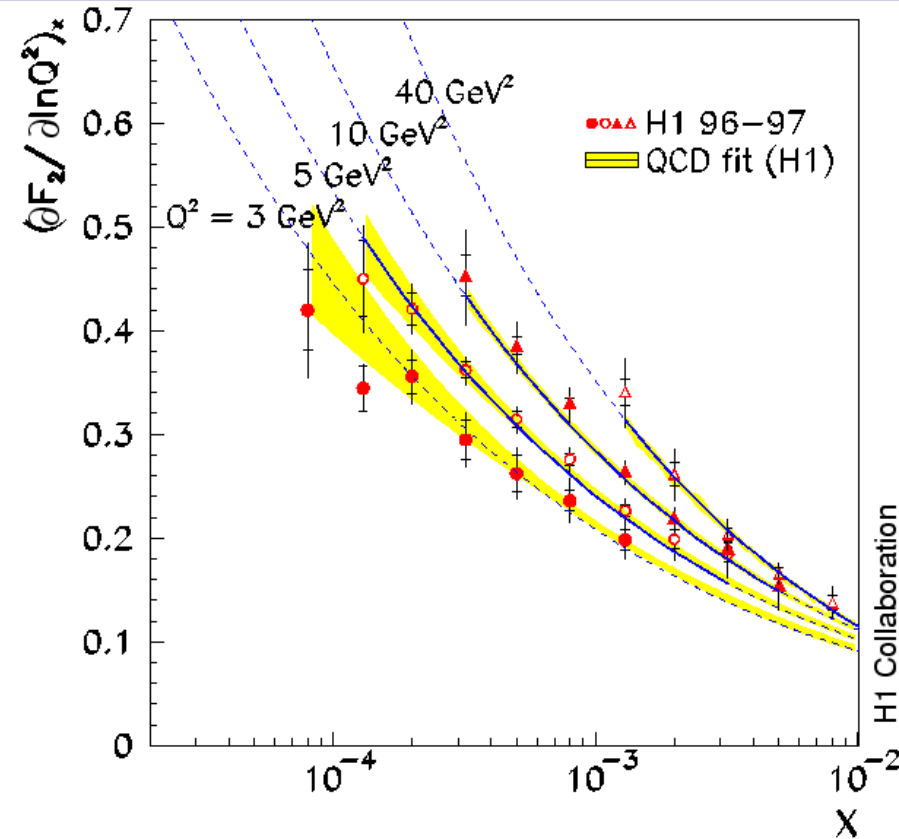
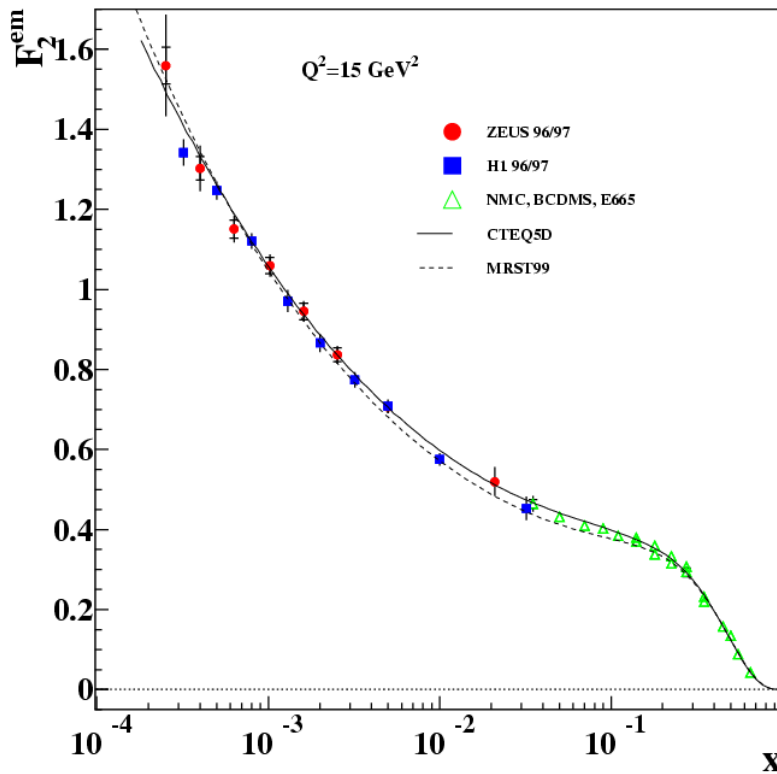
Rise of pdf should flatten with decreasing  $x$

$$\left(\frac{1}{x}\right)^\lambda \rightarrow \ln \frac{1}{x}$$

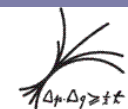
**No saturation observed at HERA**



# The Birth of Experimental Low x Physics



- Biggest HERA discovery: strong increase of quark density ( $F_2$ ) and gluon density ( $d F_2 / d \ln Q^2$ ) with decreasing  $x$  in newly explored regime.
- Low  $x$ , 'large'  $Q^2$  is high density, low coupling limit of QCD ...
- No saturation observed yet  $\rightarrow$  probe at even smaller  $x$



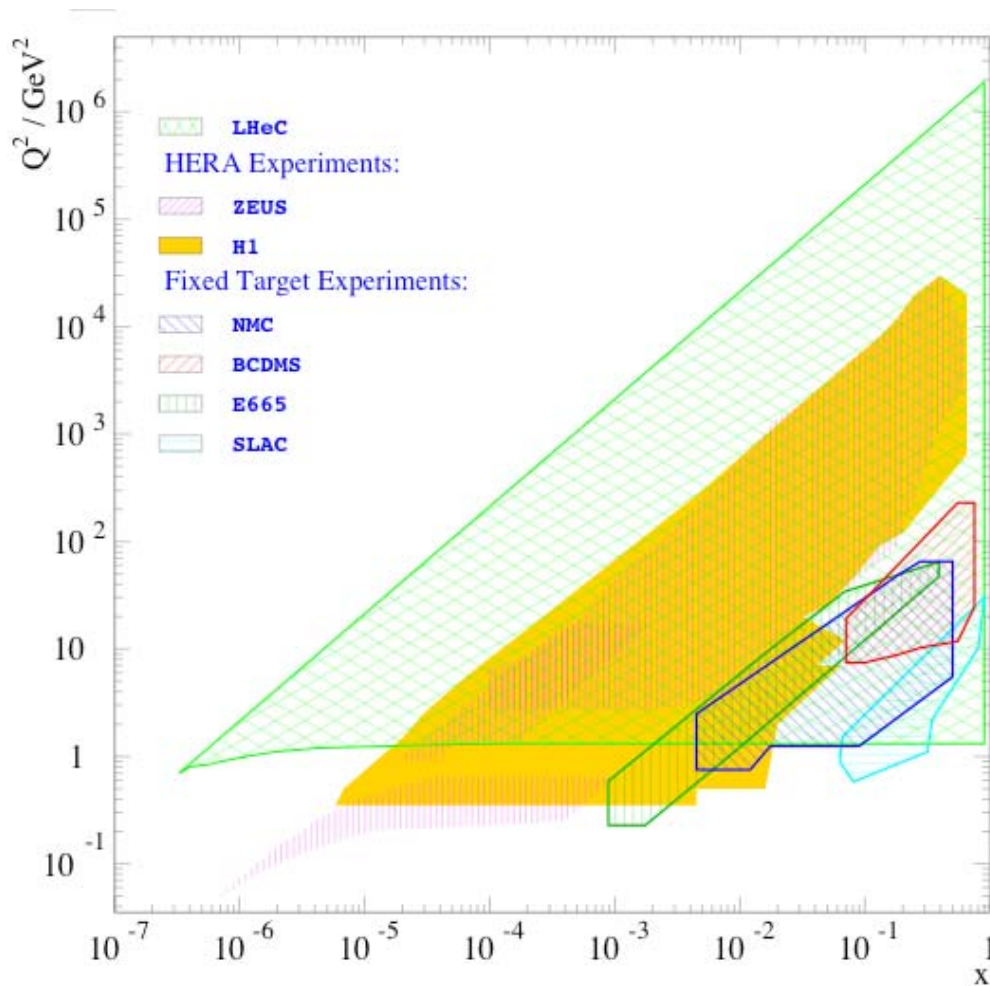
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# LHeC Inclusive Kinematics



$$E_e = 70 \text{ GeV}$$

$$E_p = 7 \text{ TeV}$$

$$\sqrt{s} = 1.4 \text{ TeV}$$

(5 x HERA)

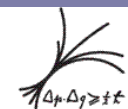
- Extension to higher  $Q^2$  in  $x$  range covered by HERA
- Extension of low  $x$  (high  $W$ ) frontier

$$W \leq 1.4 \text{ TeV}$$

$$x \geq 5 \cdot 10^{-7} \text{ at}$$

$$Q^2 \leq 1 \text{ GeV}^2$$

- Unprecedented lumi =  $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  !!!
- eA mode possible using LHC ion beam



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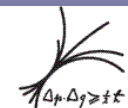
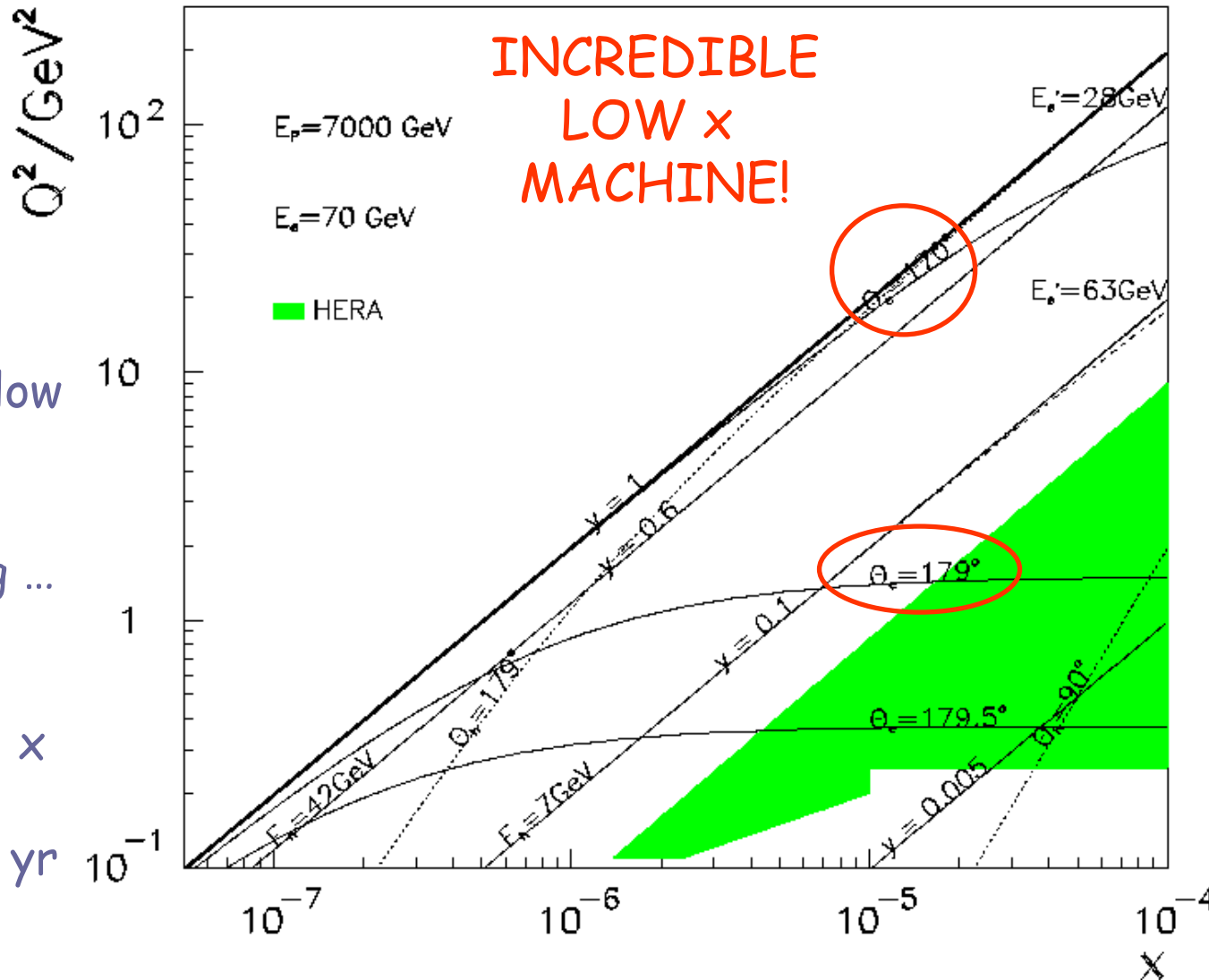
# The LHeC for Low x Investigations

2 modes considered:

LHeC – Low x Kinematics

1) Focusing magnet To optimise lumi ... detector acceptance to  $170^\circ$  ... little acceptance below  $Q^2=100 \text{ GeV}^2$

2) No focusing ... acceptance to  $179^\circ \rightarrow$  access to  $Q^2=1$  for all  $x$  ( $x > 5 \times 10^{-7}$ !) Lumi  $\sim 1 \text{ fb}^{-1} / \text{yr}$



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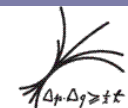
# Summary

## Precision measurements from HERA

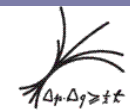
- inclusive NC & CC cross sections
- structure functions
- parton densities

## Issues:

- **valence quarks** constrained by NC & CC at high  $Q^2$   
 $d_v$  will remain less precise than  $u_v$
- **sea quarks** obtained from  $F_2$  at low  $x$   
possibility of an asymmetric light flavor sea  $\bar{d}-\bar{u}\neq 0$
- **gluons** from scaling violations,  $F_L$ , jets, vector mesons,  $c\bar{c}$   $b\bar{b}$   
ultimately precision to be seen, final uncertainty at high  $x$ ?
- **high  $x$** : extrapolating towards  $x\rightarrow 1$   
How to assess uncertainties?
- **low  $x$** : When does the strong rise saturate?



# Backup Slides



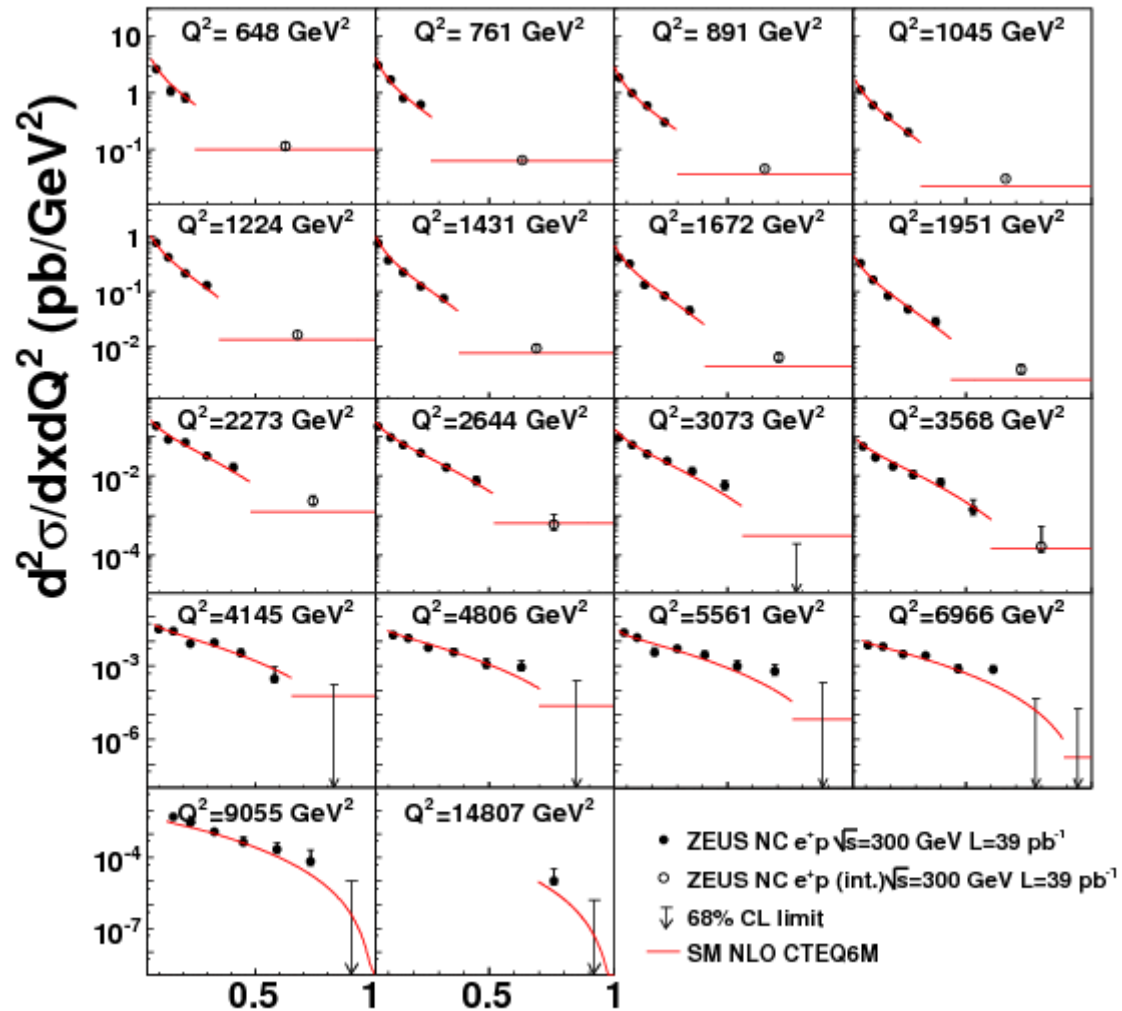
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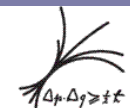
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# ZEUS



X



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