The Structure of the Proton and HERA

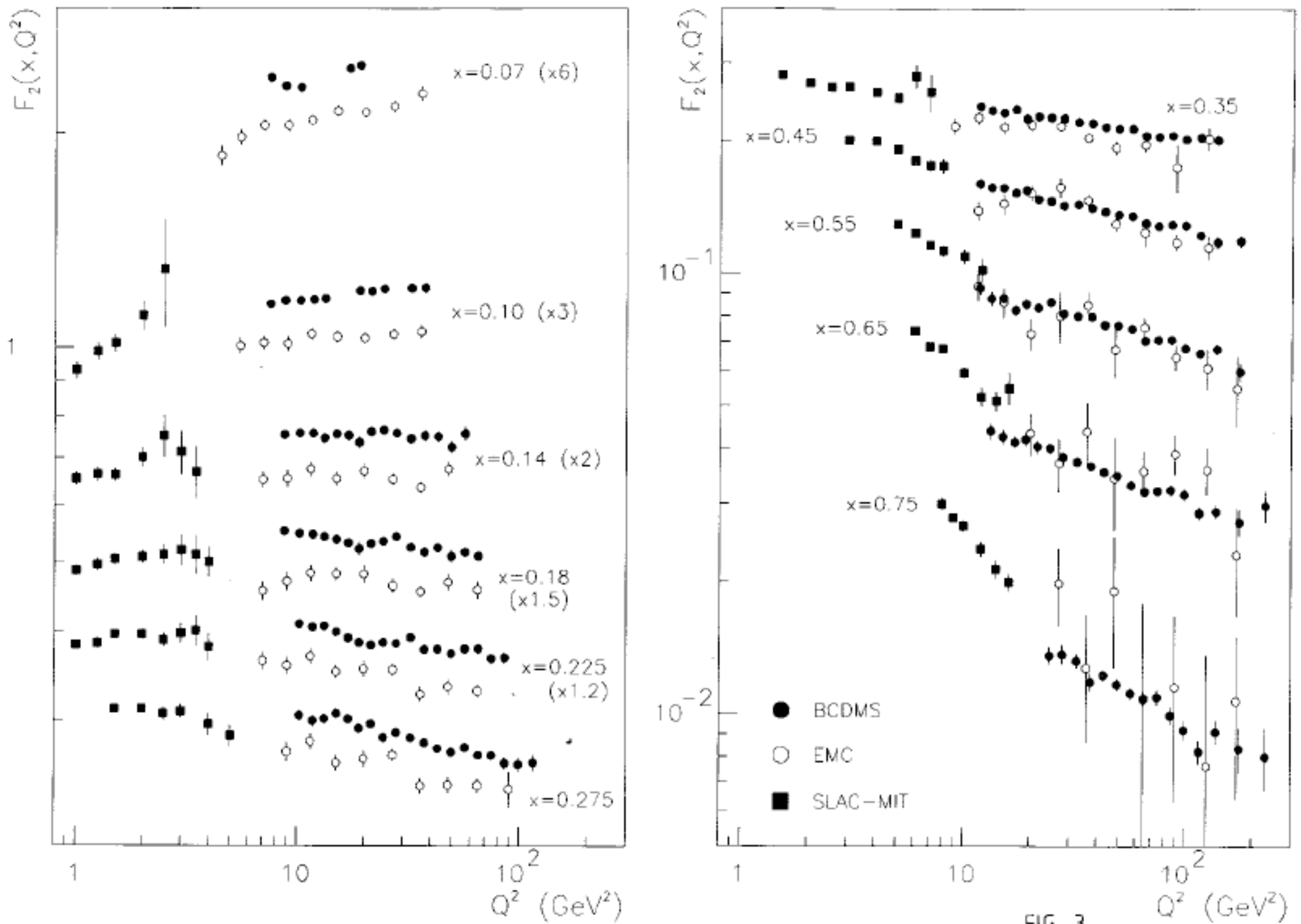
Proton structure and what have we learnt from HERA

1989 – before HERA
The first years
Some of today's results
Summary

Max Klein
(H1 and ATLAS)

UNIVERSITY OF LIVERPOOL

1989 – BCDMS (μp) – F_2



CERN-EP/89-06
January 17th, 1989

FIG. 3

x=0.07-0.75
Q^2=9-230 GeV^2

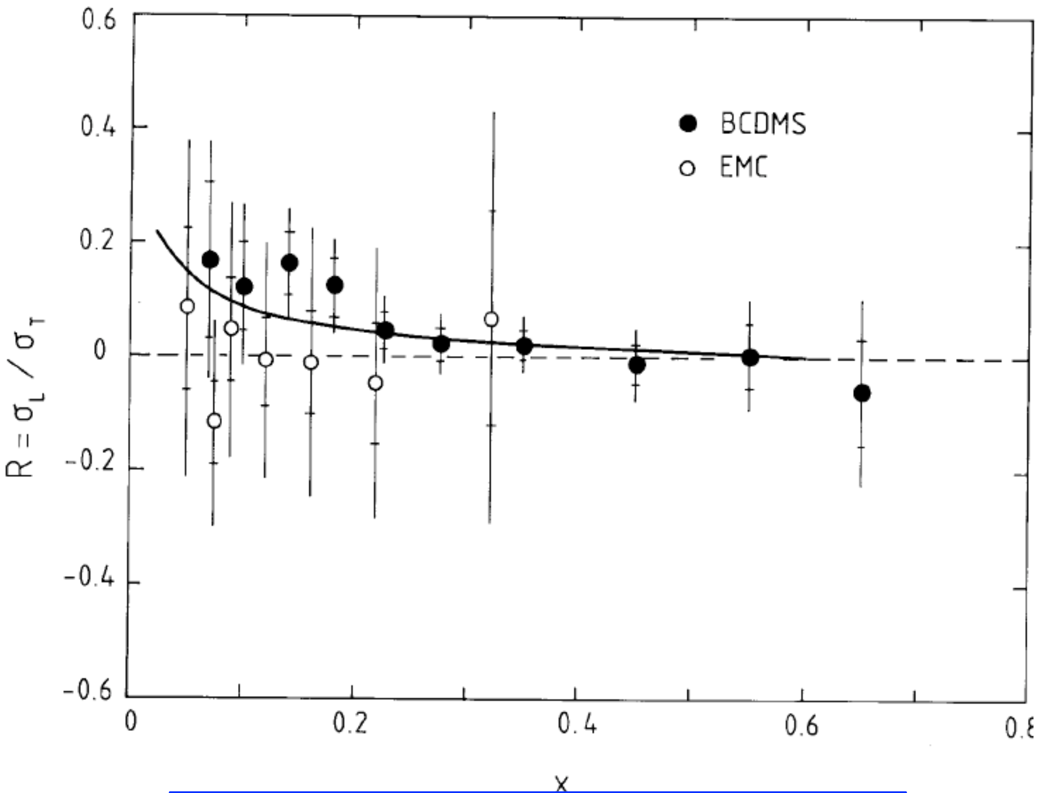
EMC?

High x – low y?

~2% accurate

p and d data

1989 – BCDMS (μp) – R and xg

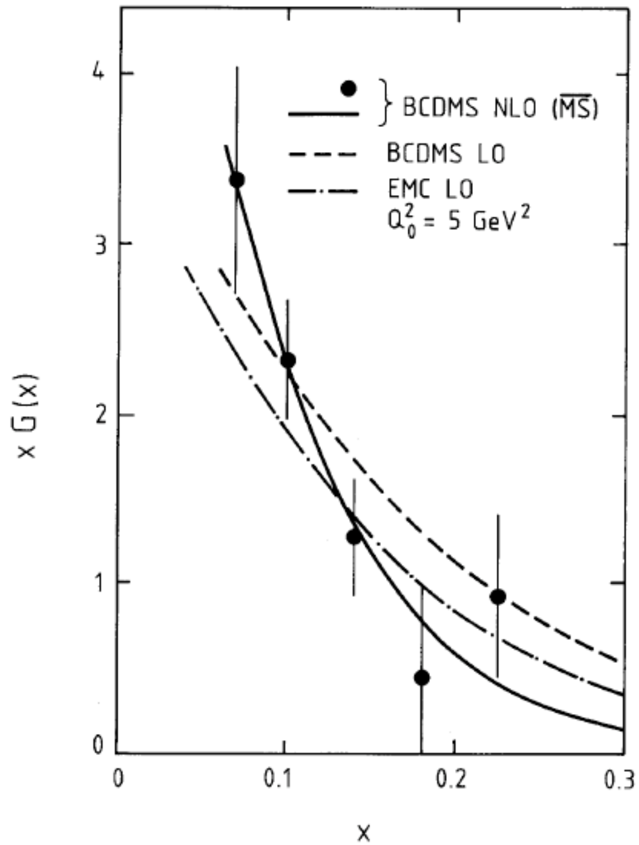


Curve: NLO QCD with

$$xG(x,Q_0^2) = 4.5(1-x)^8 \text{ at } Q_0^2 = 5 \text{ GeV}^2$$

NLO QCD: y > 0.14
Non-singlet: x>0.275 (xg=0)
Singlet+non-singlet (xg ~$(1-x)^c$)

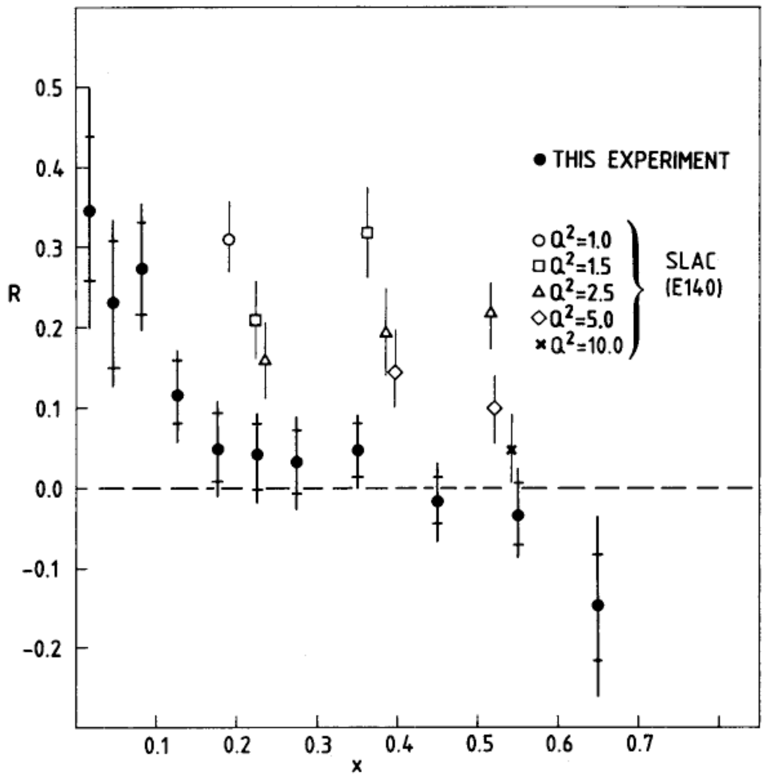
Λ = 220 ± 15 (st)± 50(sy) MeV



CERN-EP/89-07
January 17th, 1989

1989 – CDHS (νFe) – structure functions

$$\frac{d^2\sigma^{\bar{\nu}N}}{dxdy} - (1-y)^2\frac{d^2\sigma^{\nu N}}{dxdy} = \sigma_0\{[1-(1-y)^4]\bar{q}^{\bar{\nu}} + [(1-y)-(1-y)^3]F_L\}$$



CERN-EP/89-103
15 August 1989

CDHS
F_2, xF_3 , F_L

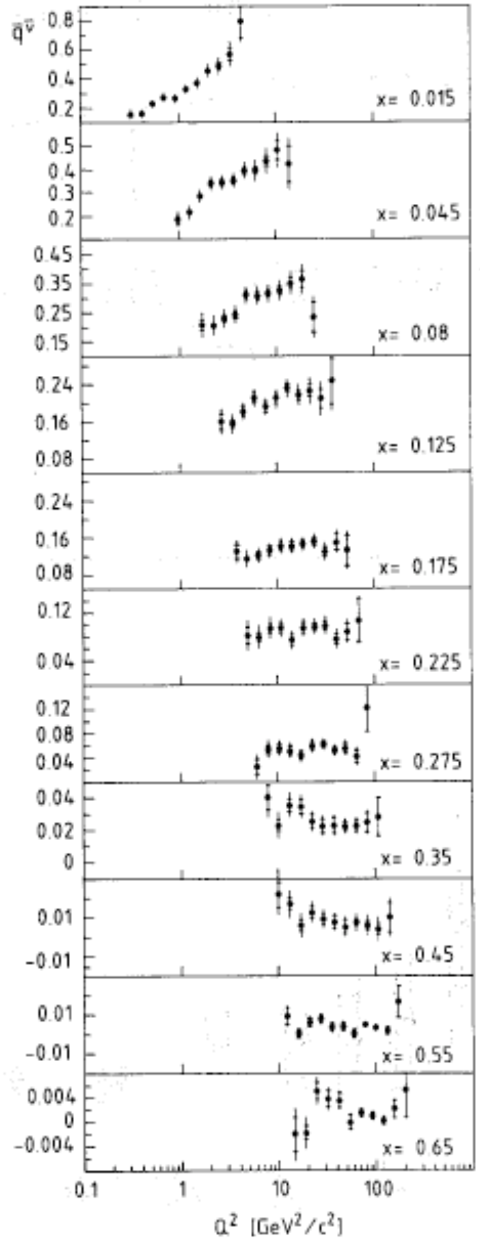
x=0.015-0.65
Q^2=0.8-210 GeV^2

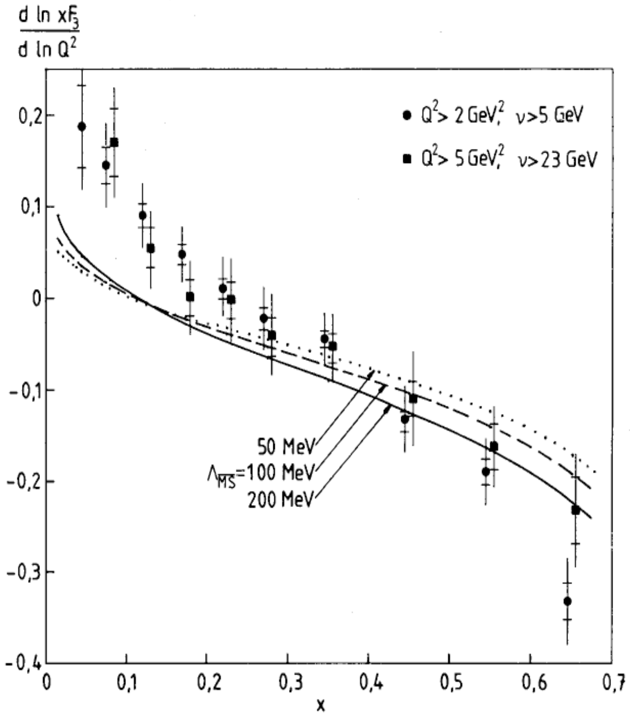
Iron target

Confirm BCDMS over EMC

Large scaling viol's at low x

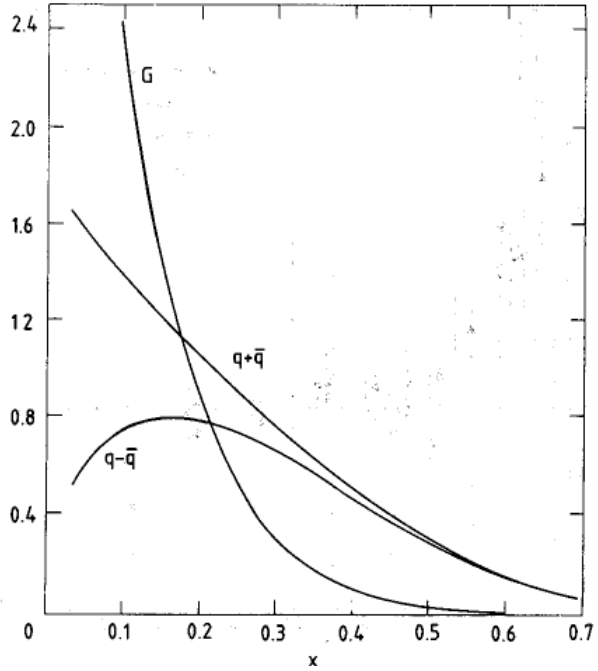
F_L from y dependence





CDHS (νFe)

NLO - QCD

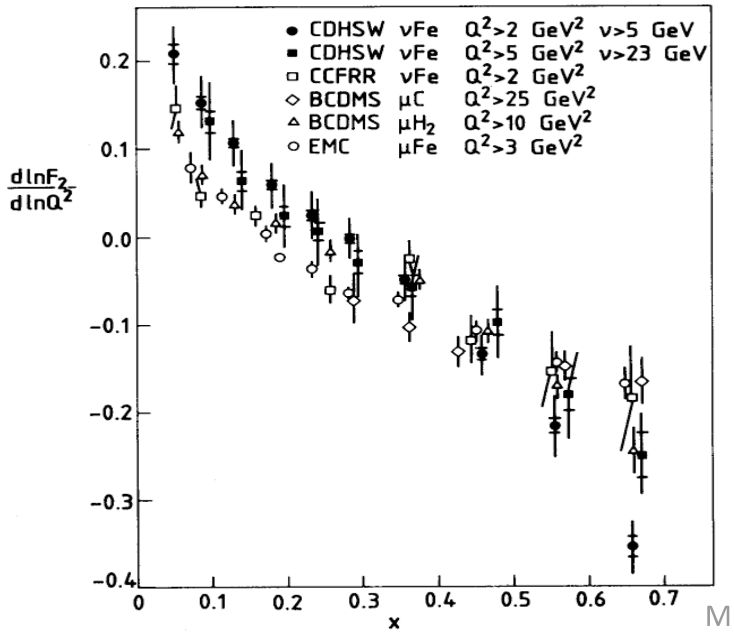


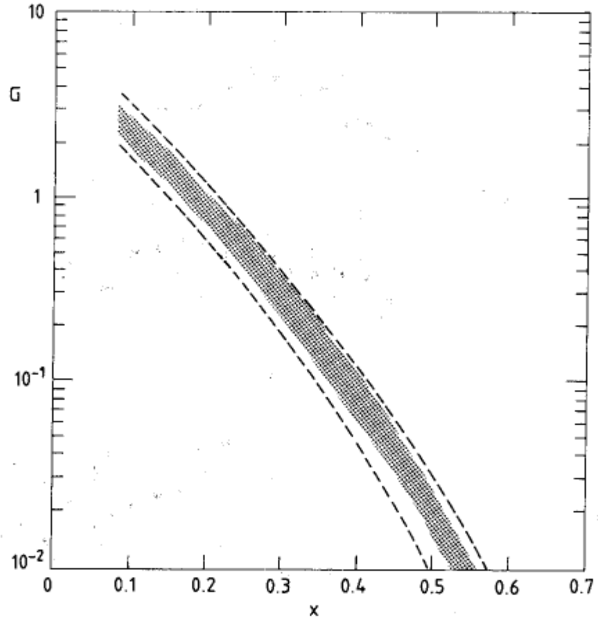
xg ~ $(1-x)^c$
with error band

q=x(u+d+s+c)
q-qbar=$x(u_v+d_v)$

c=0

derivative – QCD??





Parton Distributions from a Global QCD Analysis of Deep Inelastic Scattering and Lepton-Pair Production*

Jorge G. Morfín[1,3] and Wu-Ki Tung[1,2]

FERMILAB-Pub-90/74

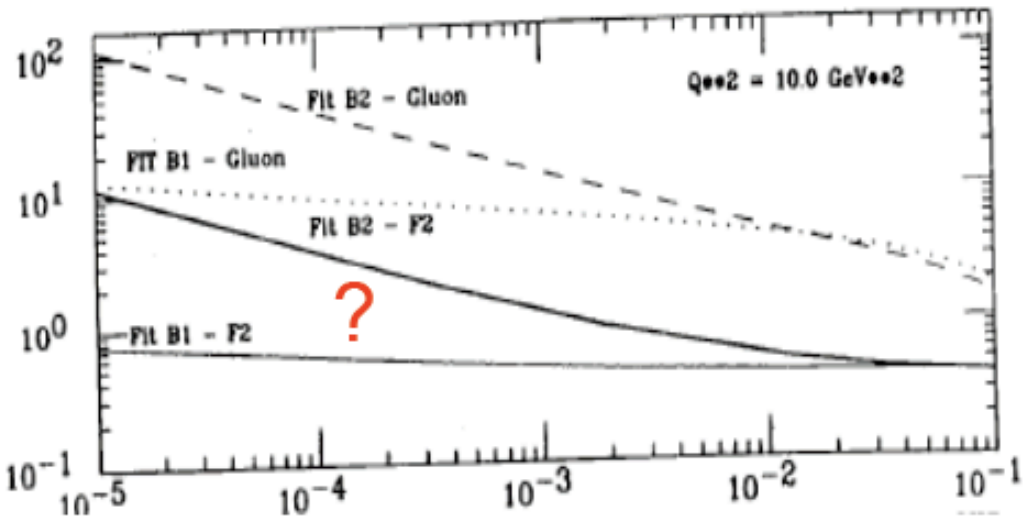
April 1990

* Submitted to Z. Phys. C.

$$f(x,Q) = e^{A_0} x^{A_1} (1-x)^{A_2} \ln^{A_3} x \ln^{A_4}(1-x)$$

"A_1 changes rapidly with Q^2" ICHEP Singapore 1990

Low x Extrapolation: F2(x,Q) and xG(x,Q)



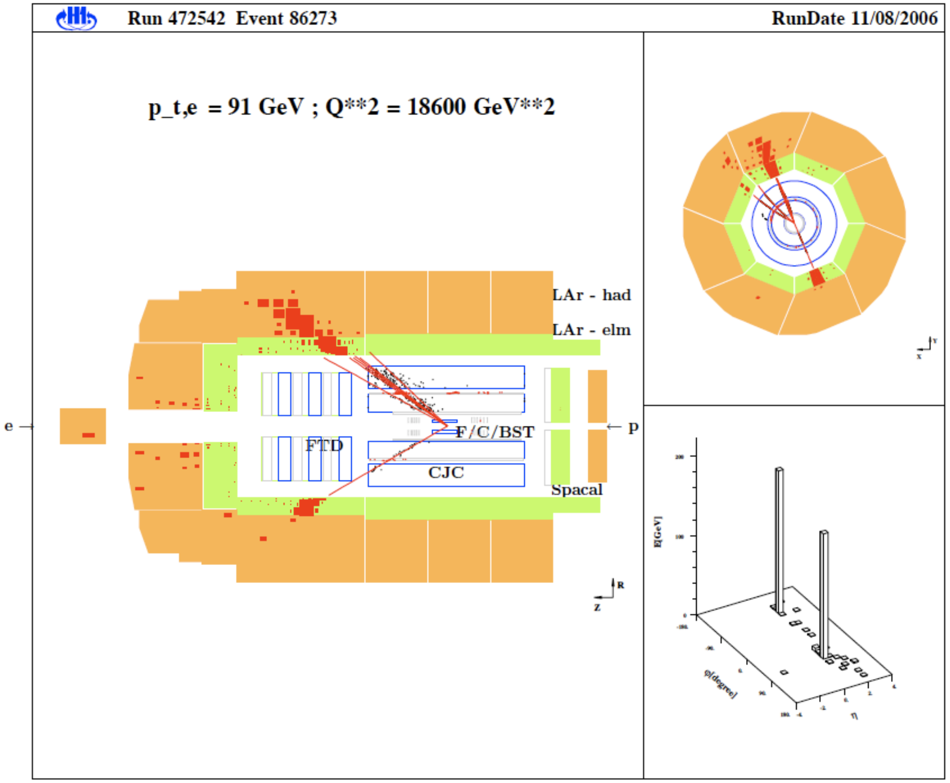
Global
Functional forms
Systematic errors
Kinematic ranges
Heavy target corr's
LO-NLO
Renorm. Schemes

No HERA
No heavy quarks
No error bands
No NNLO

In lively dispute with MRS (T)

A.D. Martin, R.G. Roberts & W.J. Stirling, Mod. Phys. Lett. A4 1135 (1989)

A neutral current DIS event in the H1 detector



LAr (Pb –elm, SS –hadr) σ_{had} =50%/√E
SpaCal (elm+hadr) σ_{elm} =12%/√E
B/C/FST
CIP
Driftchamber (CJC) …
Trigger: LAr, CIP, FTT, BST

Alignment (trackers, Comptons)
Calibration (kinem. peak, DA)
Luminosity: ep →epγ (1%)
MC simulation GEANT3 + physics

Redundant reconstruction of the kinematics from e and h final state. 'Removal' of Radiative Corrections.

$$E - p_z = E'_e(1-\cos\theta_e) + \sum_i (E_i - p_{z,i}) = \Sigma_e + \Sigma_h$$

$$y_e = 1 - \frac{\Sigma_e}{2E_e} \qquad Q^2_e = \frac{p^2_{t,e}}{1-y_e}$$

$$y_h = \frac{\Sigma_h}{2E_e} \qquad Q^2_h = \frac{p^2_{t,h}}{1-y_h}$$

$$y_\Sigma = \frac{\Sigma_h}{E-p_z} \qquad Q^2_\Sigma = \frac{p^2_{t,e}}{1-y_\Sigma}$$

Uranium/Sc –elm and hadronic

σ_{elm} =18%/√E, σ_{had} =35%/√E

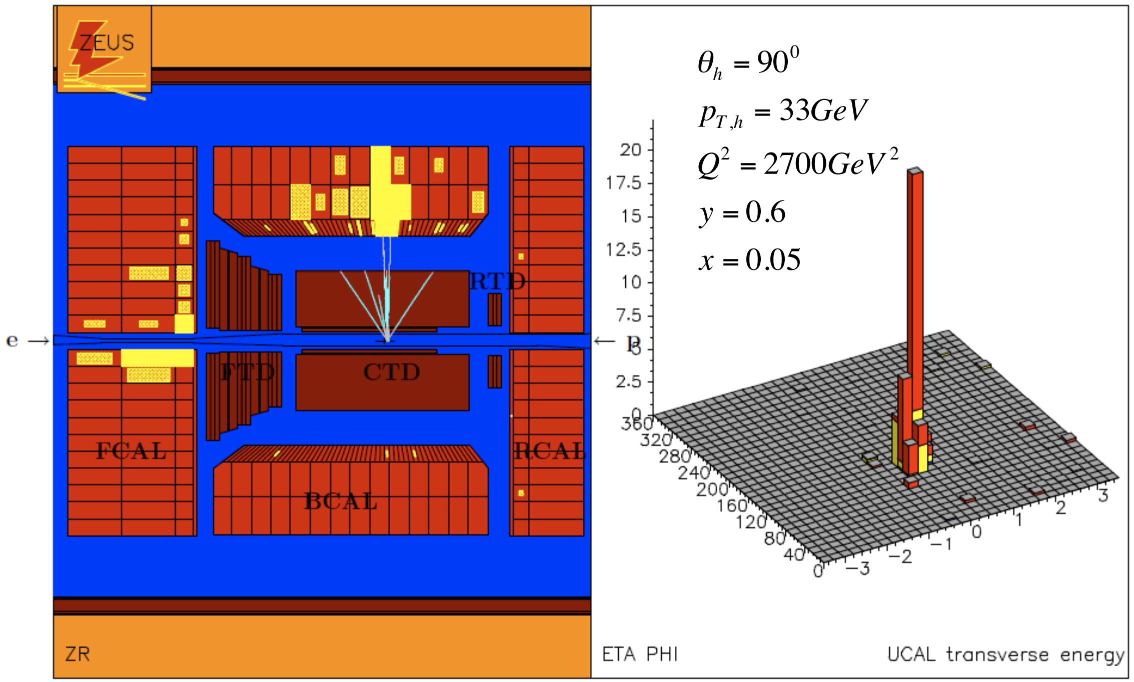
MVD (fwd, central)

Driftchamber (CTD) …

Trigger: Calorimeter

A charged current DIS event in the ZEUS detector

$$y_{DA} = \frac{\tan(\theta_h/2)}{\tan(\theta_e/2) + \tan(\theta_h/2)}$$



$$Q^2_{DA} = 4E_e^2 \cdot \frac{\cot(\theta_e/2)}{\tan(\theta_e/2) + \tan(\theta_h/2)}$$

$$\tan\frac{\theta_{PT}}{2} = \frac{\Sigma_{PT}}{P_{T,e}}$$

$$\Sigma_{PT} = 2E_e \frac{C(\theta_h, P_{T,h}, \delta_{PT}) \cdot \Sigma_h}{\Sigma_e + C(\theta_h, P_{T,h}, \delta_{PT}) \cdot \Sigma_h}$$

Calibration and alignment methods and L measurement similar as for H1. Kinematic reconstruction different, which is at the origin of a systematic error compensation in the combination of the H1 and ZEUS cross section data.

Inverse neutrino and anti-neutrino scattering off p's

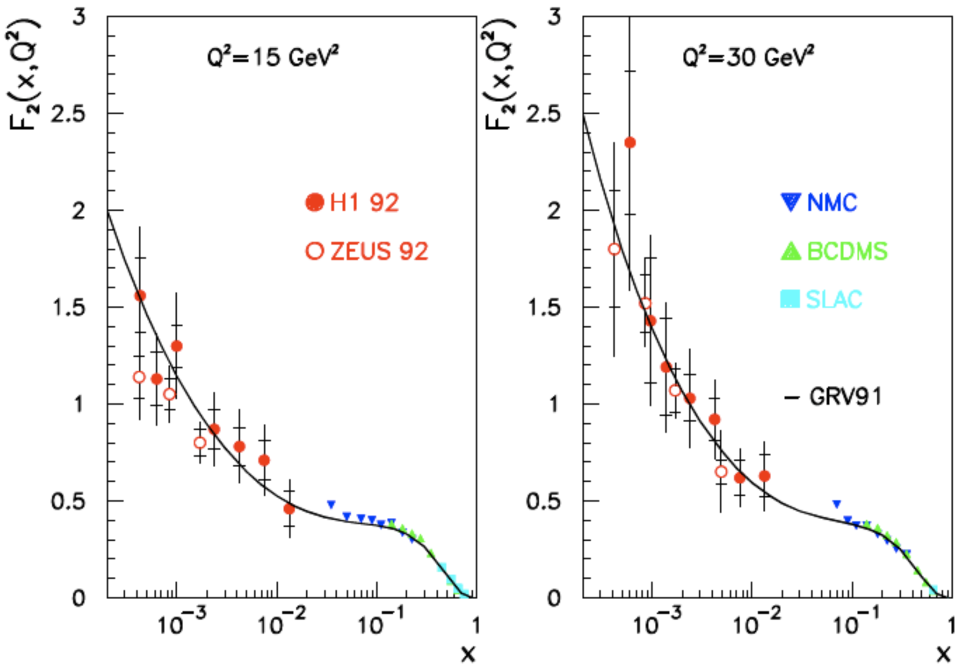
The first papers

ZEUS		H1	
• PL B293 (92) 465	• $\sigma_{tot}(\gamma p)$	PL B299 (93) 374	S
PL B297 (92) 404	• Hard Scattering in γp	• PL B297 (92) 205	S
	• Hadronic final state in DIS	• PL B298 (93) 469	S
• PL, accepted (A) DESY 93-030	• 2 jet production in DIS		
PL B303 (93) 183	• Deep Inelastic Sc. at low x	• PL B299 (93) 385	S
• DESY 93-017 PL	• Leptoquark Search	DESY 93-029 NPhys B.	A

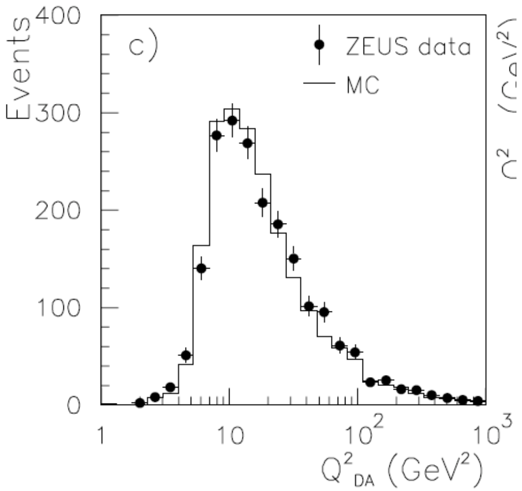
S summer data $\sim 2 nb^{-1}$

A autumn data $\sim 25 nb^{-1}$

$F_2 = \nu W_2$

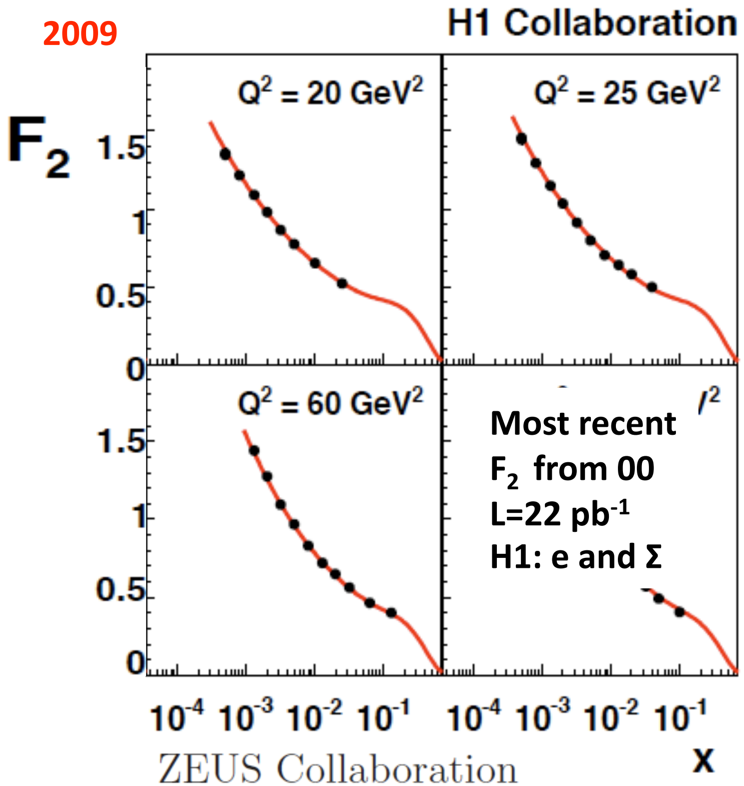


The F_2 structure function increases rapidly as x decreases.

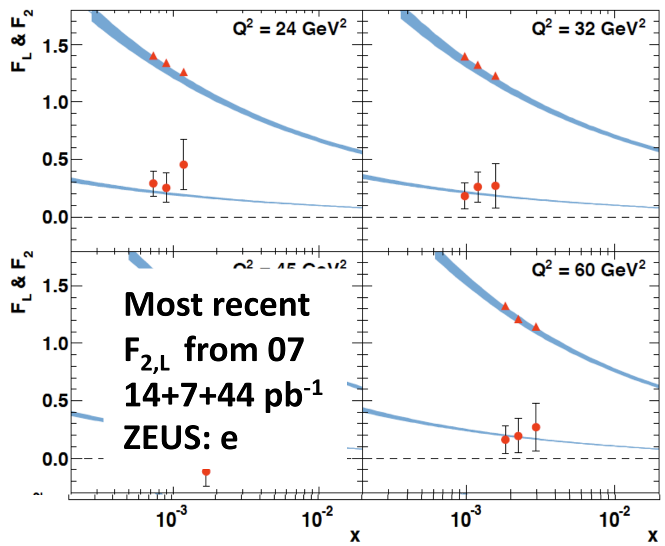


First F_2 data taken in 1992
L=0.03 pb^{-1}
H1: e and h
ZEUS: DA

2009



Most recent
F_2 from 00
L=22 pb^{-1}
H1: e and Σ



Most recent
$F_{2,L}$ from 07
14+7+44 pb^{-1}
ZEUS: e

systematic errors	e	m
E_e 2% and ±2% smearing	5-15%	3-6%
ϑ 5 mrad	4-12%	4-8%
y_{JB} fragmentation [D^*, PS vs HERWIG], 7% energy scale, $(y_{JB}-y_{Gen})/y_{Gen}$, thresholds	–	10-25%
z_{vtx} statistics, satellite bunch, comparison of methods I, II		7%
BPC, tracker cut, EBDi/ECRA, cluster-hit		6%
structure fct. D^-/D^0 (lowest x).		5-10%
radiative corrections (MC statistics for I) z_{vtx}, $E-p_z$ in MC	8%	2%
bin centre correction $(\alpha \sqrt{E}, \vartheta \to x, Q^2)$	5%	2%
	17-29%	18-29%

- statistics : 950 events
- Scale error: lumi 7% TOF, trigger → 9%

H1 July 1993

σ_r Errors in 2009

Spacal
Double angle calibration: 0.2%

BST /CJC/ BDC 0.2mrad

Noise at low y 3% at 0.01

z vertex 0.3%

eID: max 1%
BDC 0.5%

Iteration --

RC to alpha in MC 0.3%

Negligible

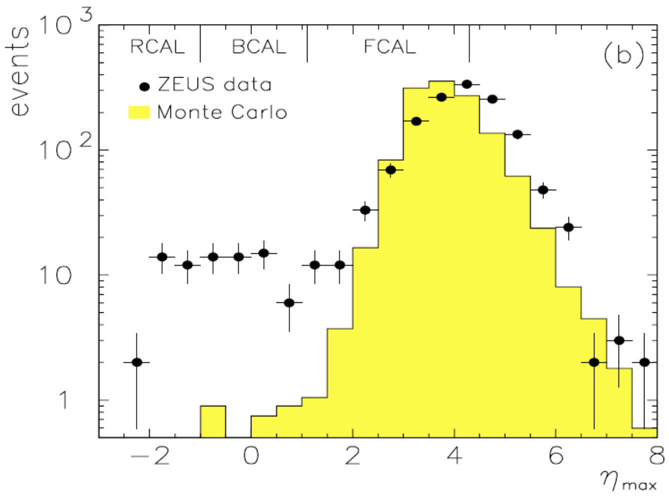
1.3-3%

~10^6

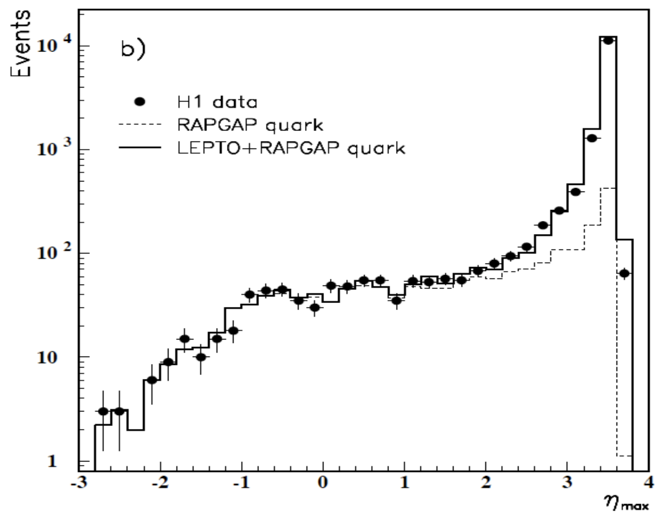
+ Lumi 1.2% trigger --

H1 April 2009

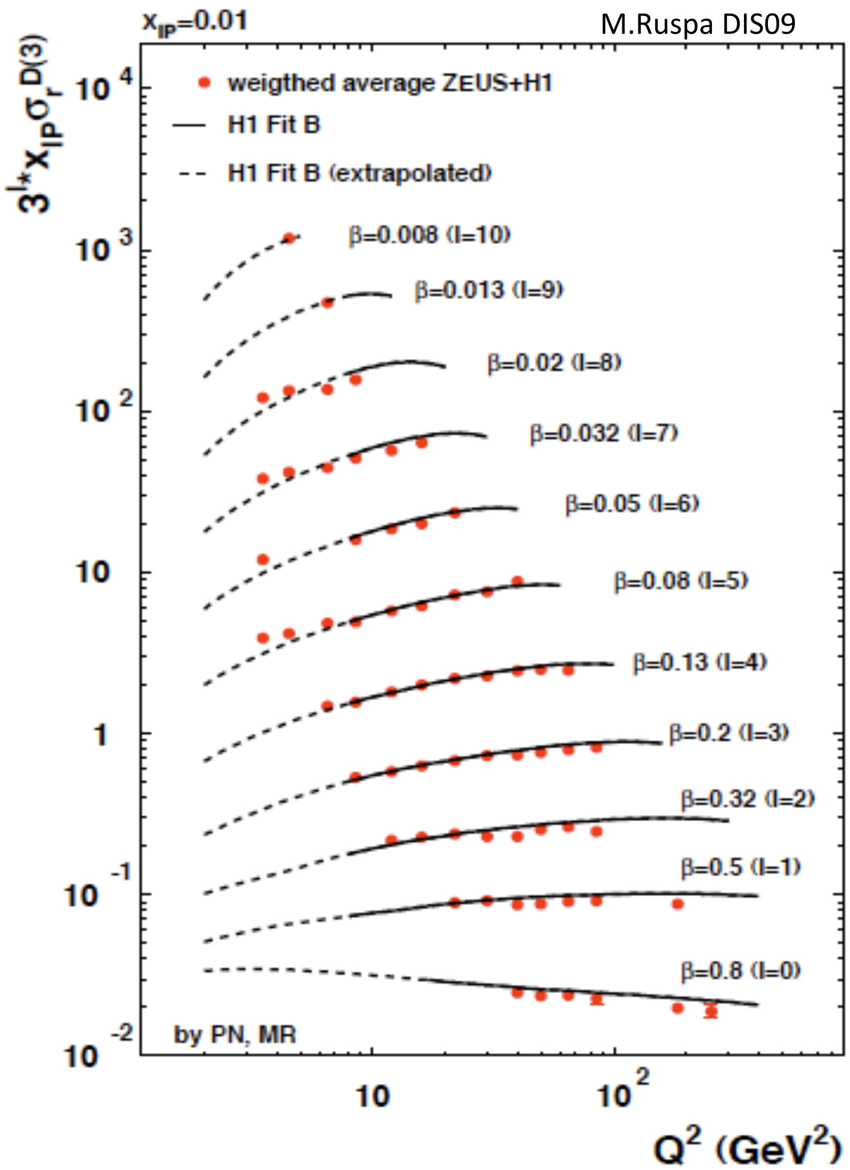
Rapidity Gaps → F_2^D



ZEUS DESY 93-093



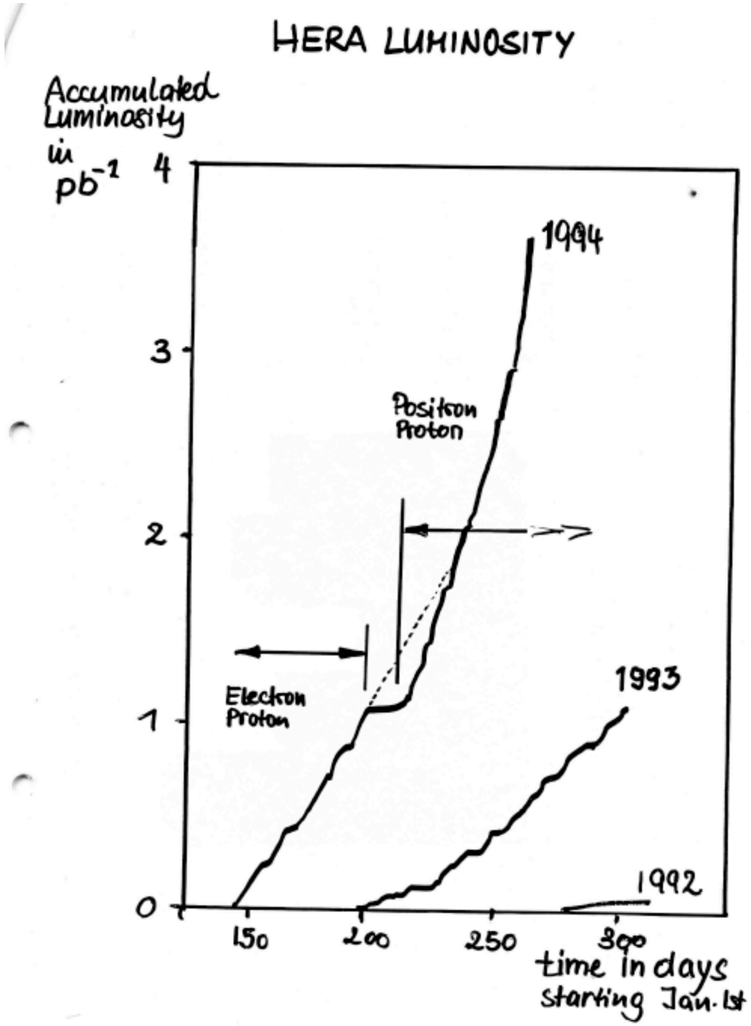
H1 DESY 94-133



Normalisations, LRG vs L/FPS

Regge + QCD. Dijets to fix xg at large β. **Cf P.Newman**

Meeting on the Future of HERA [24.9.1994]



F.Willeke [ε_{HERA}= 5 (93)—10 (94)—20 (9/94)%]

F.Sciulli: ep with high luminosity

M.K. First measurement of F_L

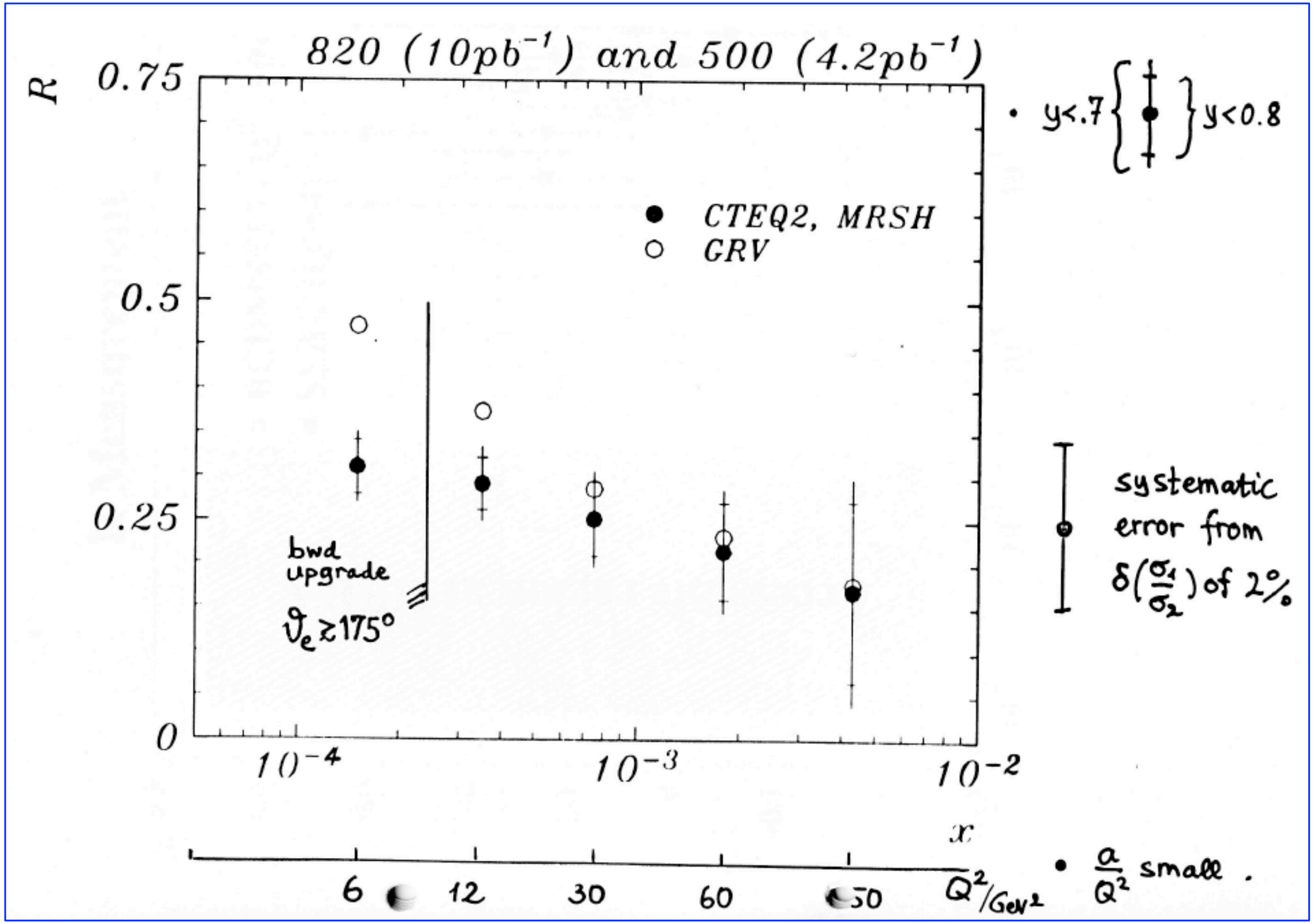
R.Brinkmann: HERA – e

F. Willeke: HERA – p

also HERMES and HERA-B talks

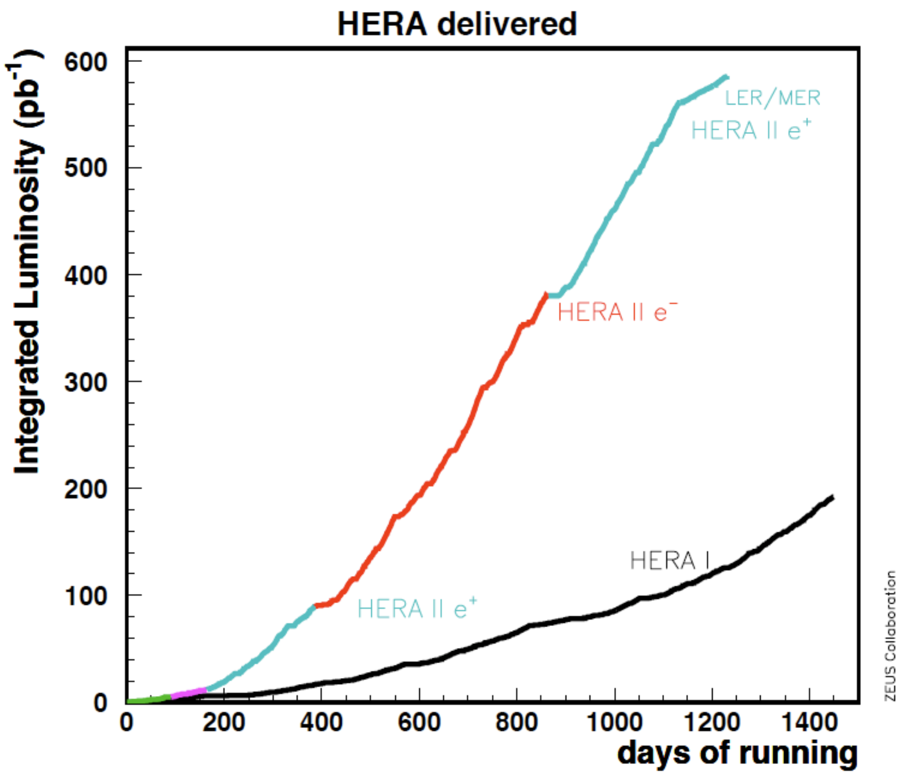
→Foundation of luminosity upgrade programme

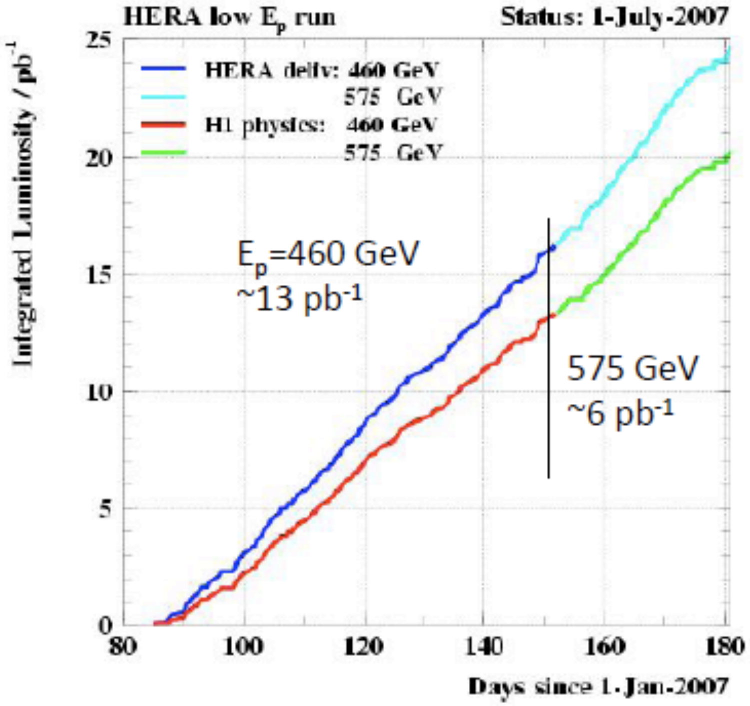
Simulated R in 1994..



MK future of HERA meeting

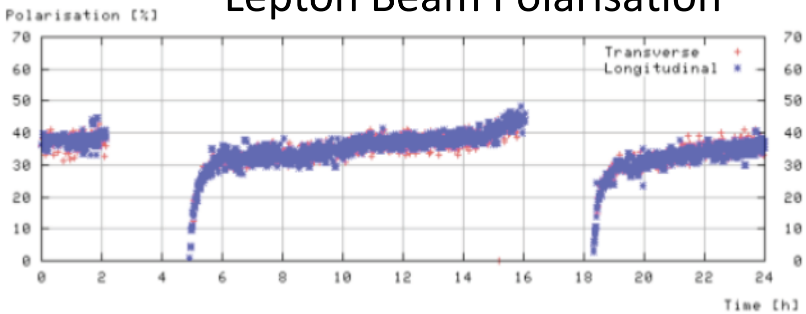
HERA 1992-2007

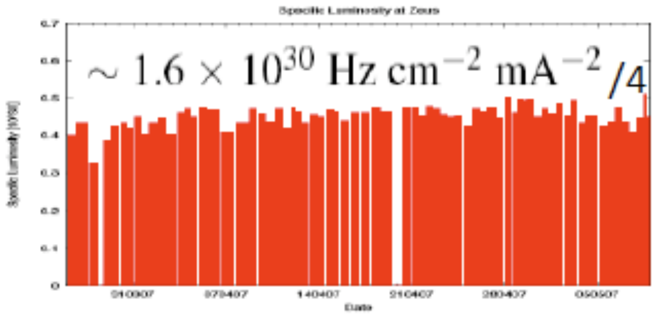




Luminosity over 4 months at lower E_p

Lepton Beam Polarisation



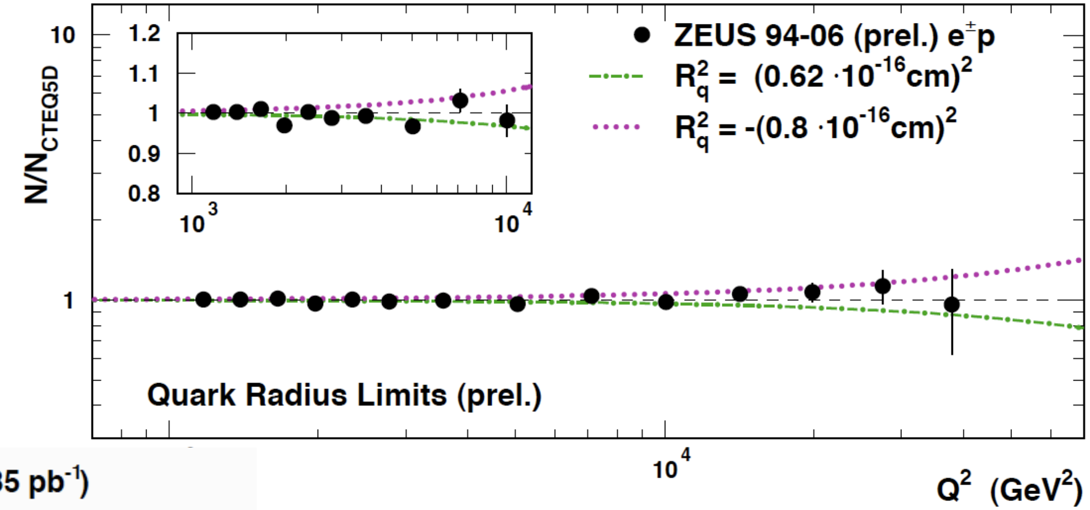


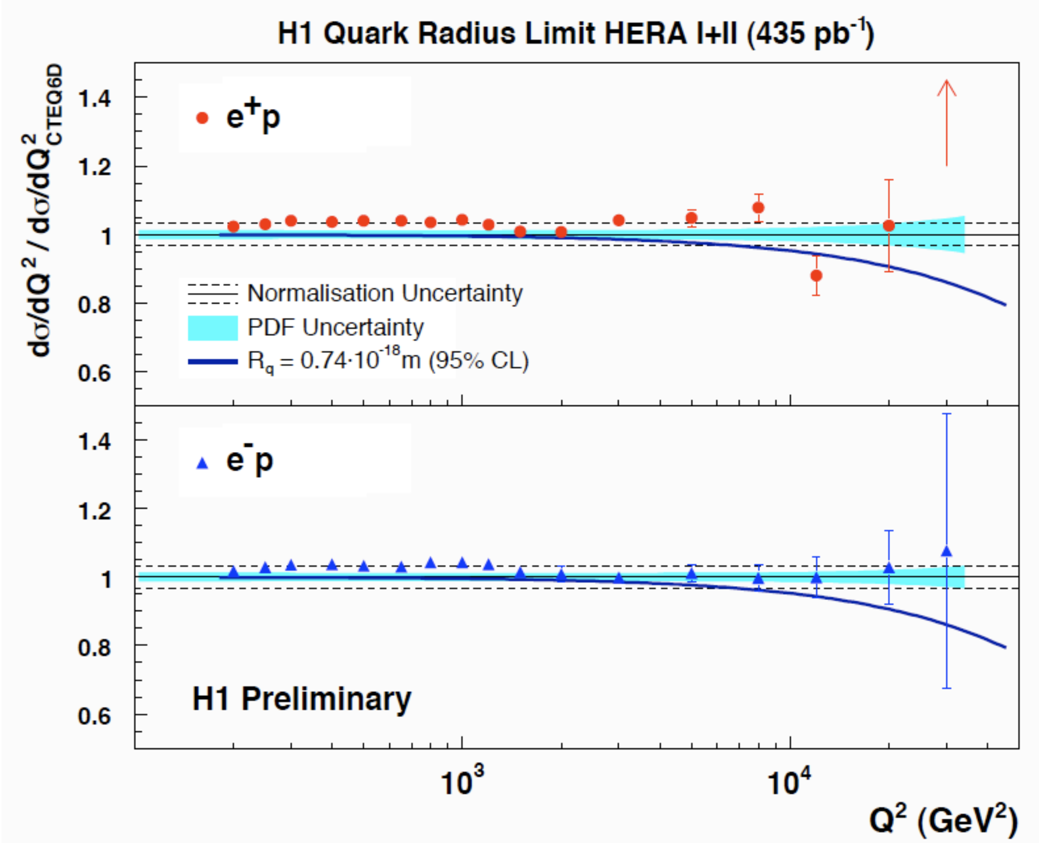
Specific luminosity over first 2 weeks

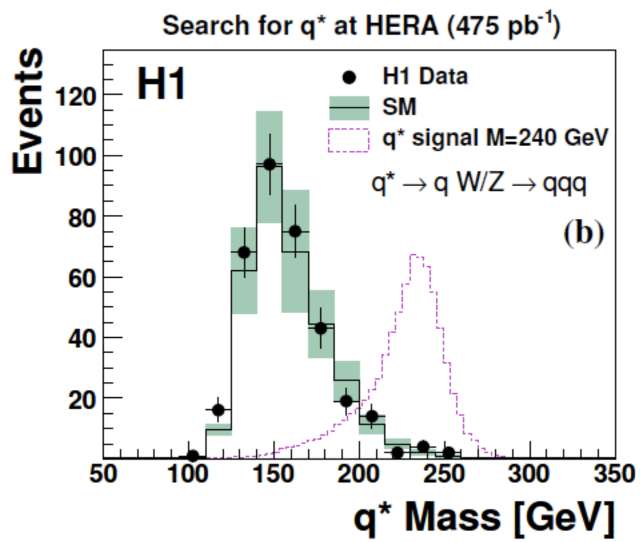
Quark Substructure?

Preliminary results based on full HERA statistics:

no substructure of quarks, no q*, corresponding limits on CI, ED,..







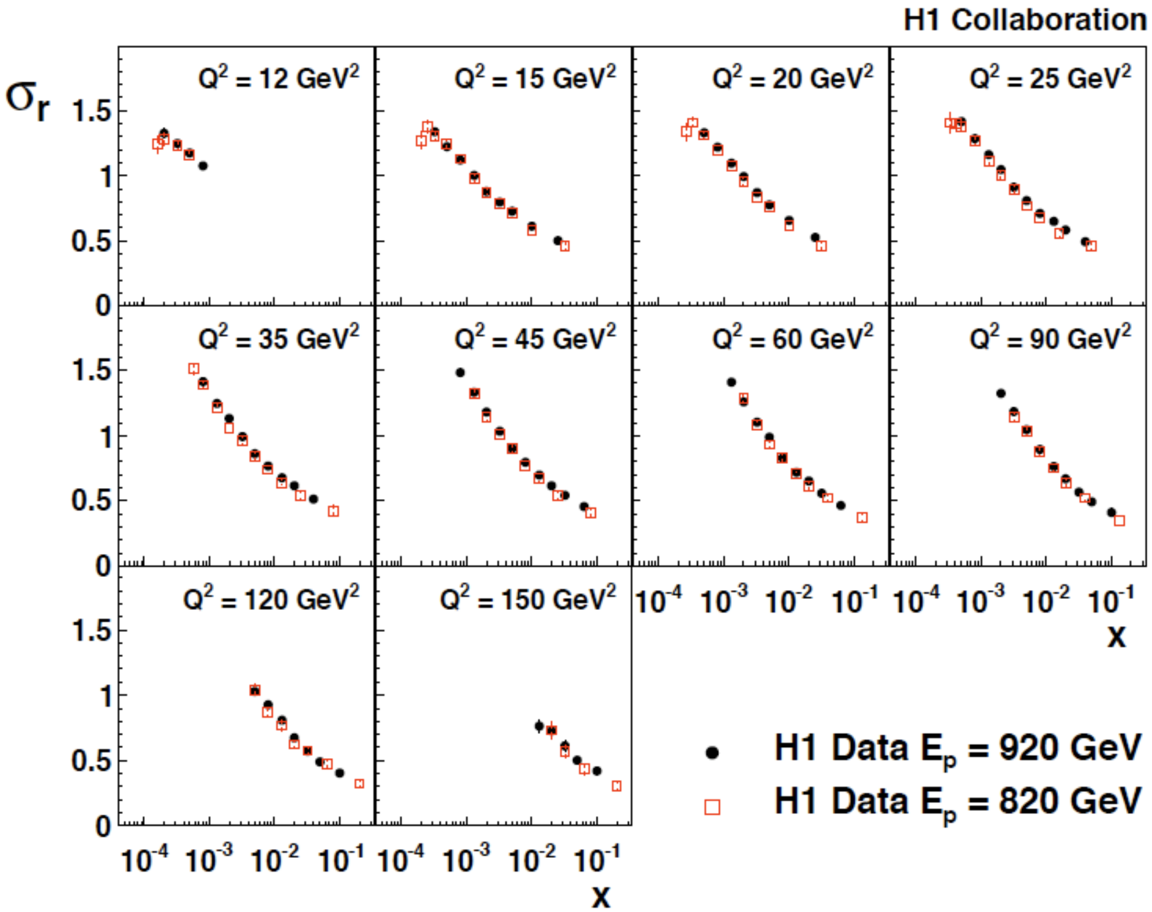
DESY 09-040

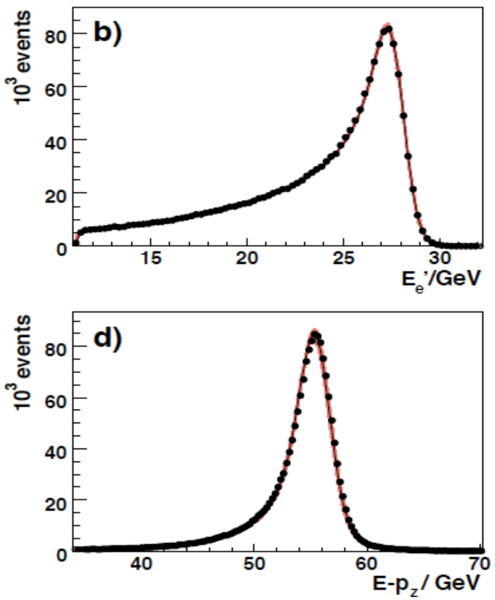
The most precise F_2 measurement, H1

H1: DESY 09-005

Based on methods detailed in 08-171, medium Q^2 accessed with maximum precision [1.3-2%]

Reanalysis of 97 (820 GeV) data, +0.5% (lumi) and small change of Q^2 dependence due to reweighting error. Both data sets combined to one.





Electron scattered into SpaCal ("backwards"). Track with BDC cross checked with CJC and BST. 920 data taken in 2000, just before break for the luminosity upgrade of HERA..

H1PDF2009

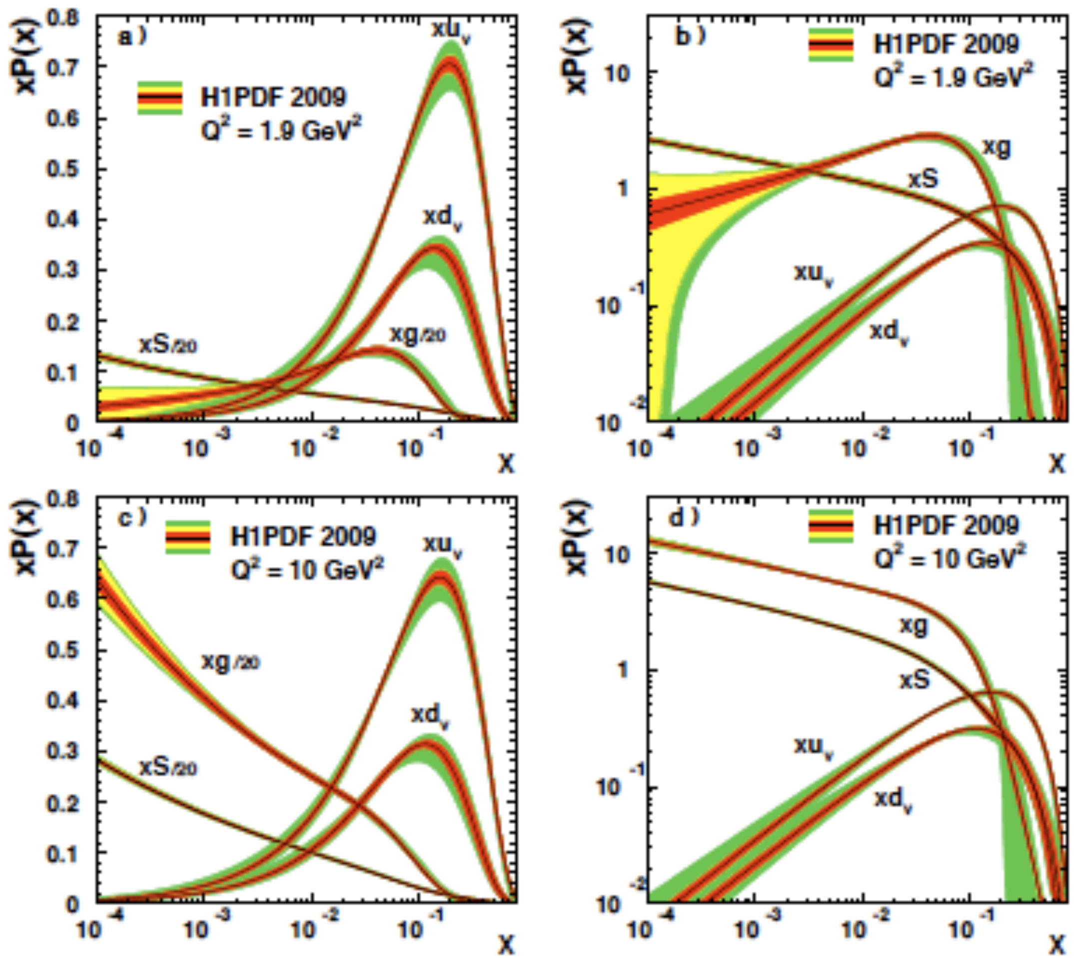
H1: DESY 09-005

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}\left[1+D_g x\right] \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}, \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}, \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

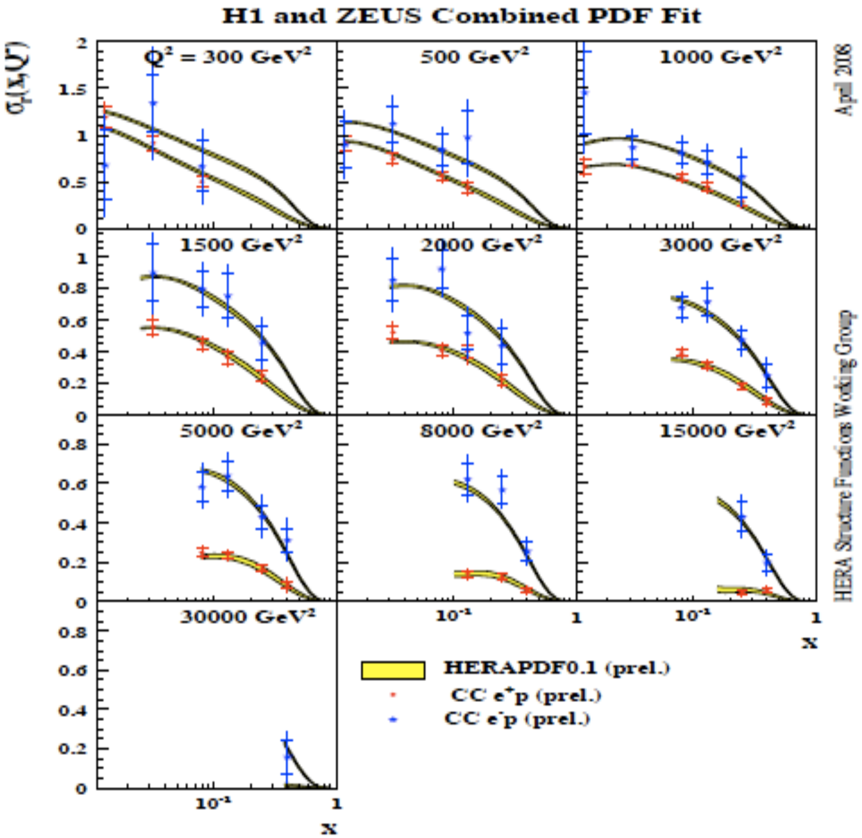
χ^2_{dof}=587/644, Q_0^2=1.9

xP	A_P	B_P	C_P	D_P
xg	5.66*	0.243	18.76	34.0
xu_v	5.15*	0.784	3.25	—
xd_v	3.29*	0.784*	4.77	—
$x\bar{U}$	0.105*	−0.177	2.42	—
$x\bar{D}$	0.152	−0.177*	3.42	—

Sea at low x fixed by F_2 (if d=u!)
Gluon at low Q^2,x uncertain, expressed via Q_0^2 variation; at high x too, expressed as parameterisation choice variation. Get astonishingly easy a high sea at large x..
Large uncertainties at high x (masses)



“p is glue for x < 0.1!”
for Q^2 > few GeV^2 (DIS)

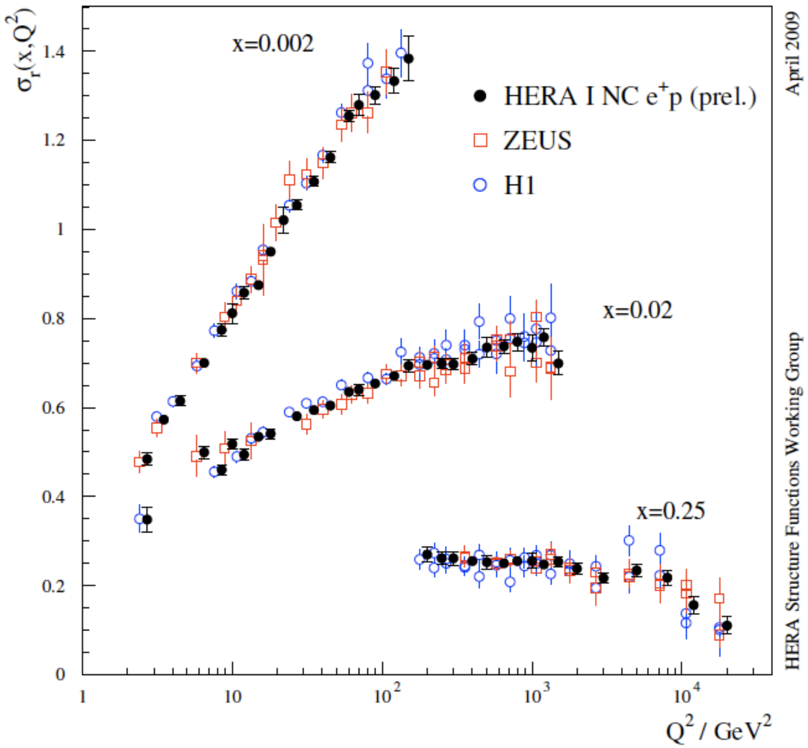


Combination of H1+ZEUS Data

$$\chi^2_{\rm exp}(\boldsymbol{m},\boldsymbol{a}) = \sum_i \frac{\left[m^i - \sum_j \frac{\partial \mu^i}{\partial \alpha_j}\left(a_j - \alpha_j\right) - \mu^i\right]^2}{\Delta_i^2} + \sum_j \frac{\left(a_j - \alpha_j\right)^2}{\Delta^2_{\alpha_j}}$$

$$\chi^2_{\rm tot}(\boldsymbol{m},\boldsymbol{b}') = \chi^2_{\rm min} + \sum_{i=1}^{N_M} \frac{\left[m^i - \sum_{j=1}^{N_S} \Gamma_j^{i,\rm ave} b'_j - \mu^{i,\rm ave}\right]^2}{\Delta^2_{i,\rm ave}} + \sum_{j=1}^{N_S} (b'_j)^2$$

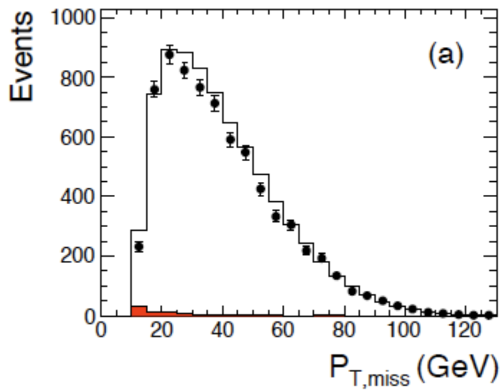
Minimisation for more than one data set with possible systematic error correlations among the sets (>100 sources in H1/ZEUS). Being used for data combination and QCD fit (as in H1 F_2 papers)



Combinations: 06/07 high Q^2 mainly
DIS08: attempt for full systematic analysis including joint QCD fit to combined data.

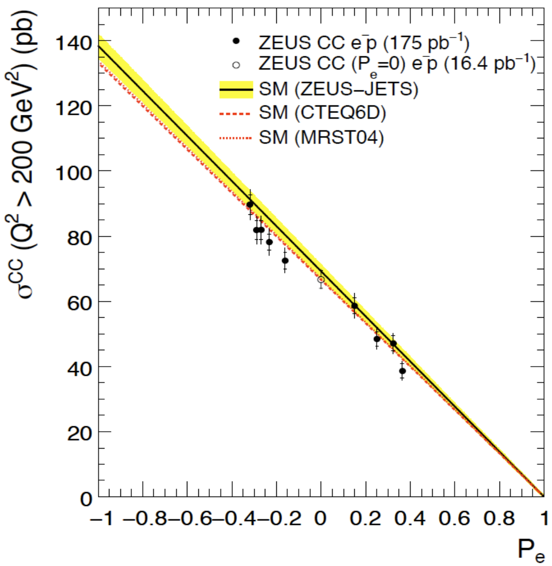
DIS09: Madrid, end of April: new preliminary: adapt to modified χ^2, include new H1 data (which are 1.3-2% accurate in the bulk region). Fit close to H1pdf09: VFNS, Q_0^2,parameterisation and uncertainties

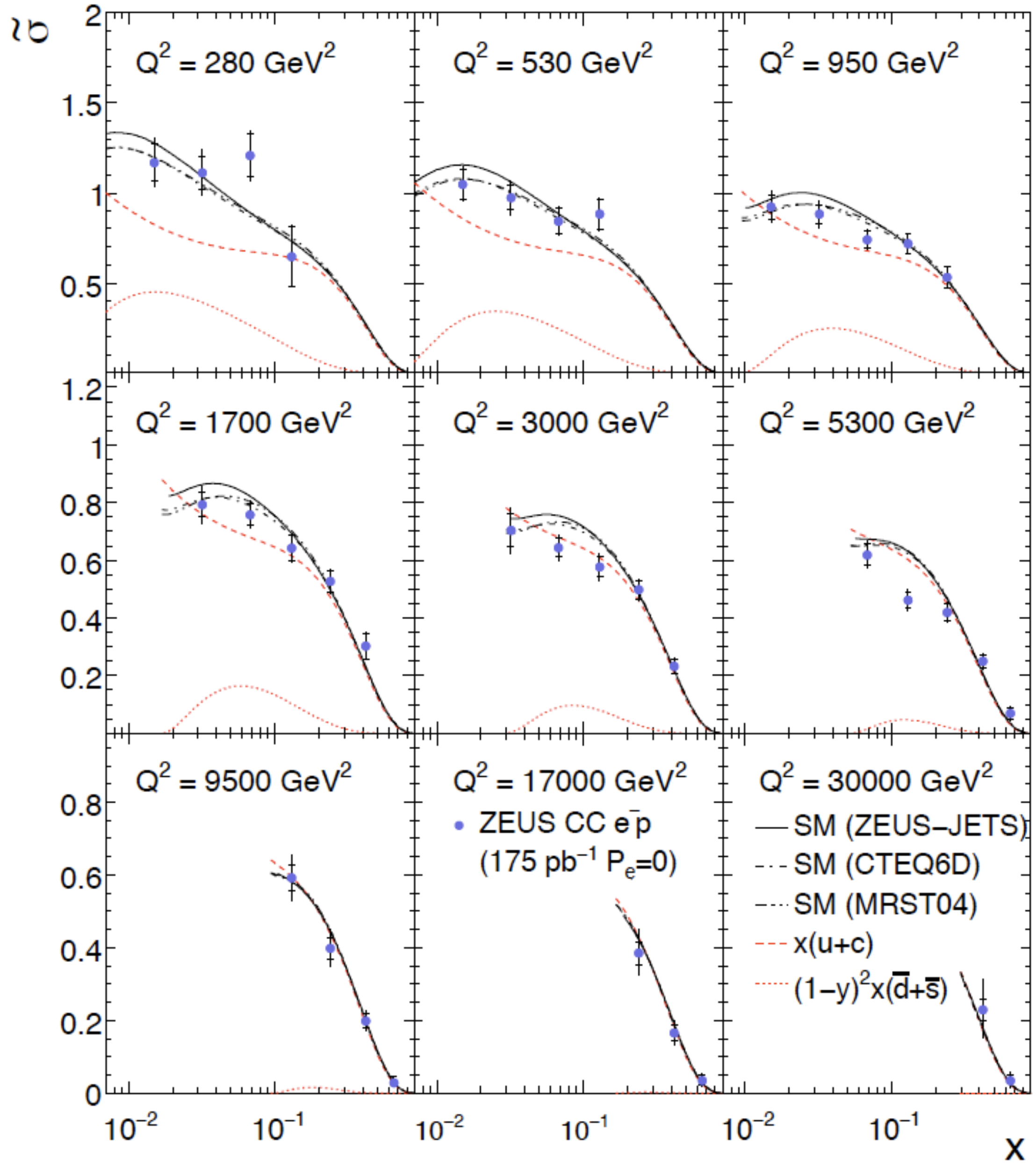
The new high Q^2 CC ($e^-p \rightarrow \nu X$) measurement by ZEUS



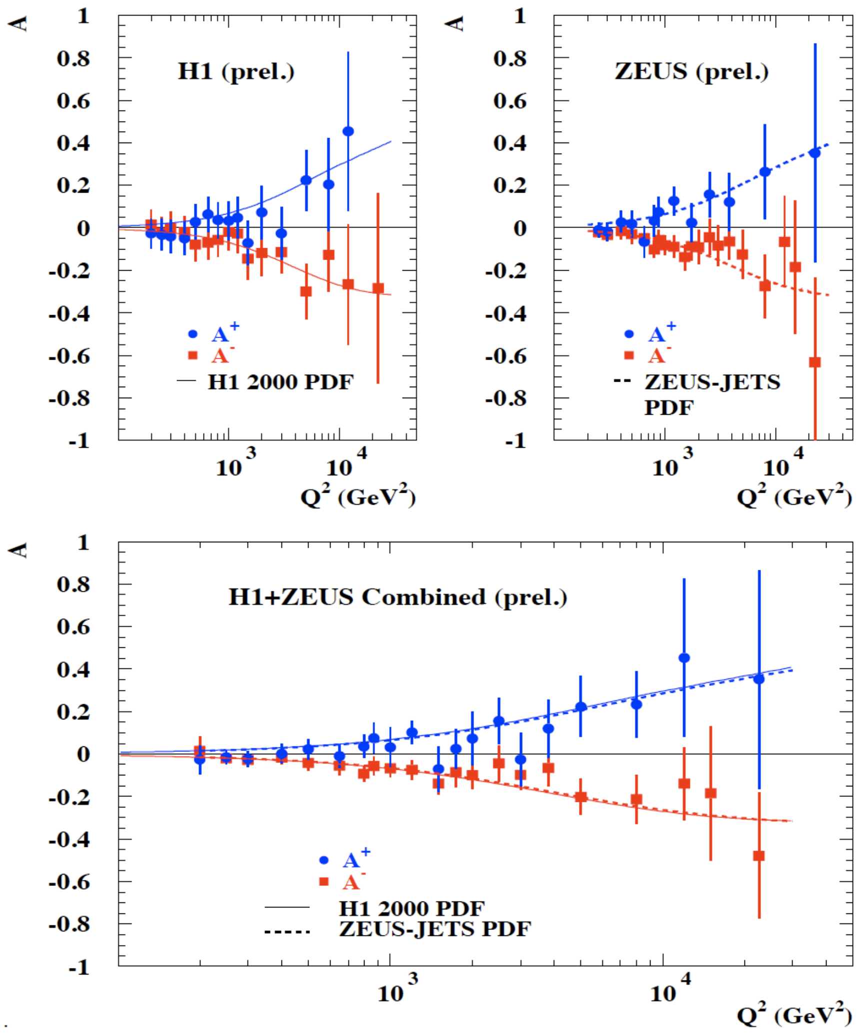
DESY 08-177, submitted
HERA II, 175 pb^{-1}

CC depends linearly on P





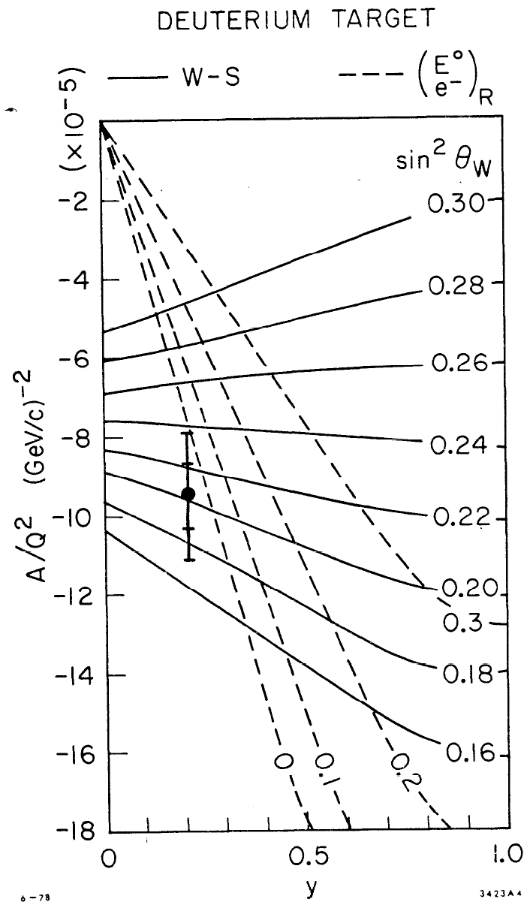
u/d at large x - parity violation $A^{\pm}$



ICHEP06, H1prel. 06-142, ZEUSprel. 06-022

$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}$$

$$A^{\pm} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$

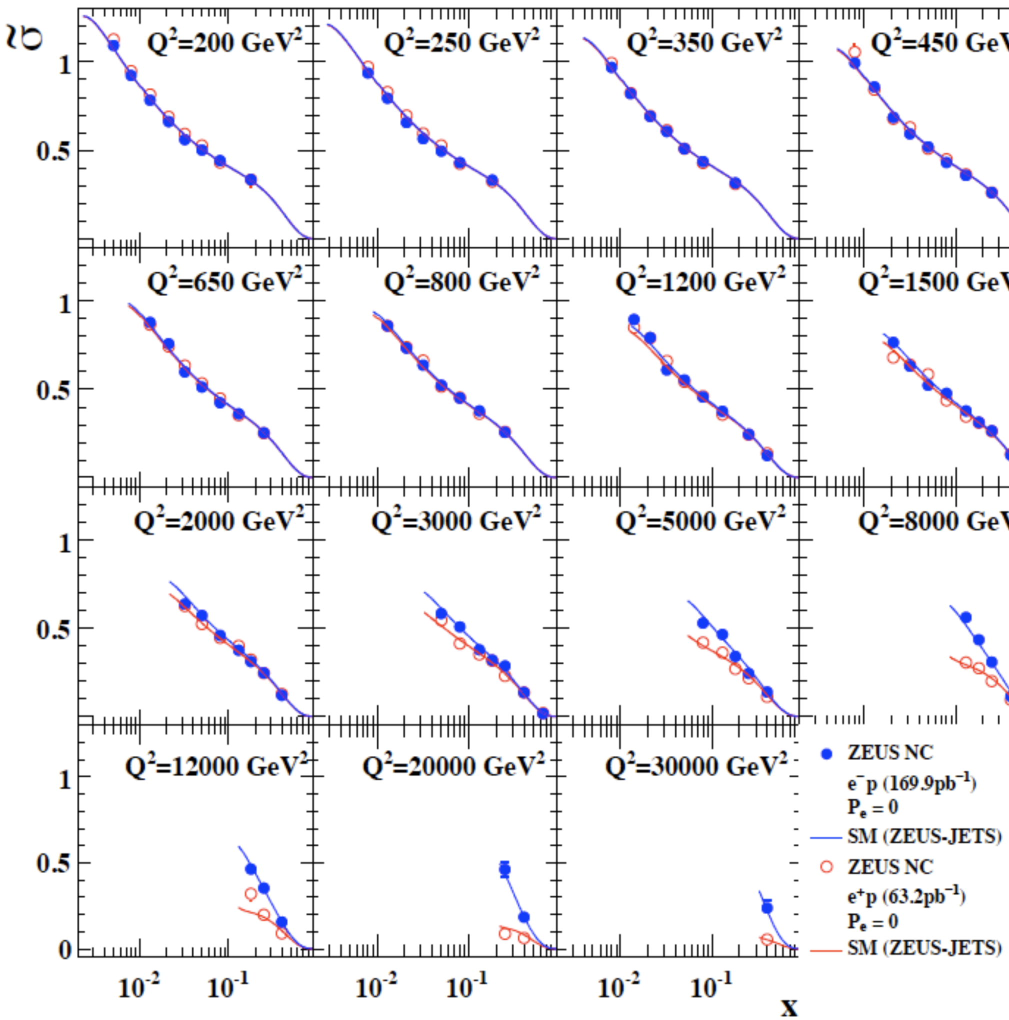


Q^2 =1..2 GeV^2

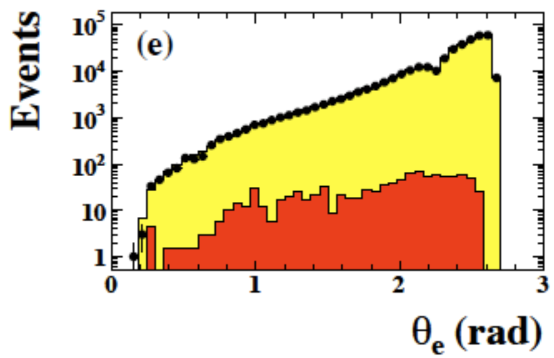
SLAC-PUB-2148
July 1978

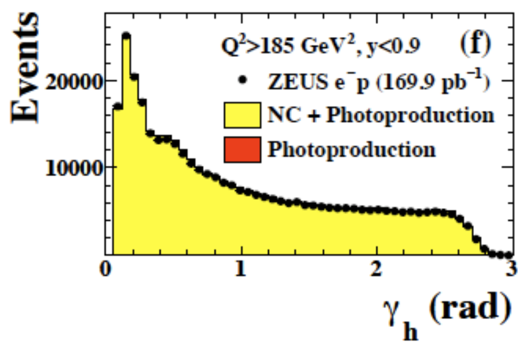
Cf L.Stanco

The new high Q^2 NC ($e^-p \rightarrow e^-X$) measurement by ZEUS

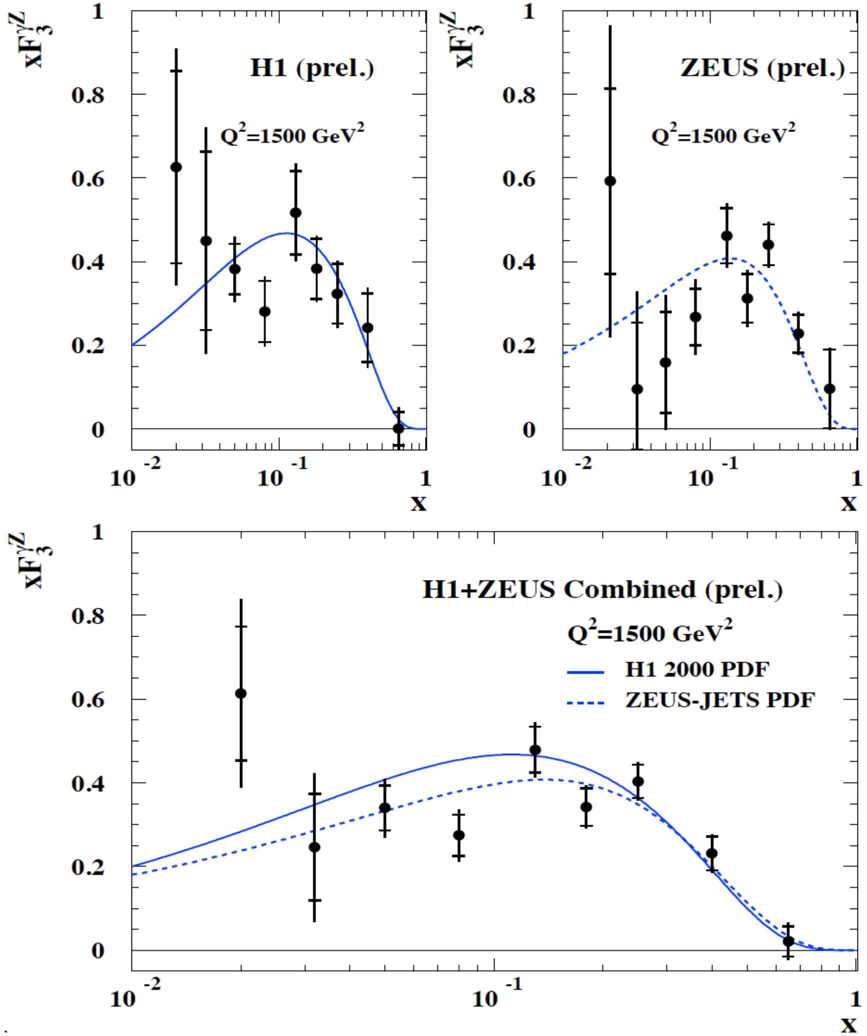


DESY 08-202, submitted
HERA II, 169 pb^{-1}
polarised e$^-$ beam
Double angle method:





Valence Quarks – xF_3

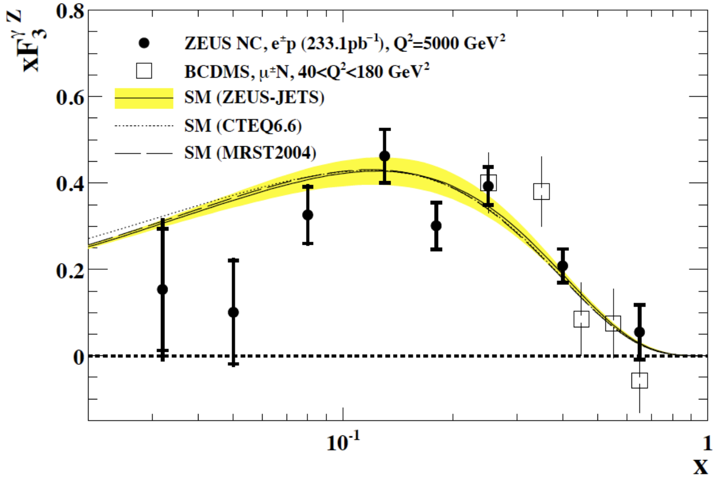


ICHEP06, H1prel. 06-142, ZEUSprel. 06-022

$$\tilde{\sigma}^- - \tilde{\sigma}^+ = 2\frac{Y_-}{Y_+}(-a_e \cdot kxF_3^{\gamma Z} + 2v_e a_e \cdot k^2 xF_3^Z)$$

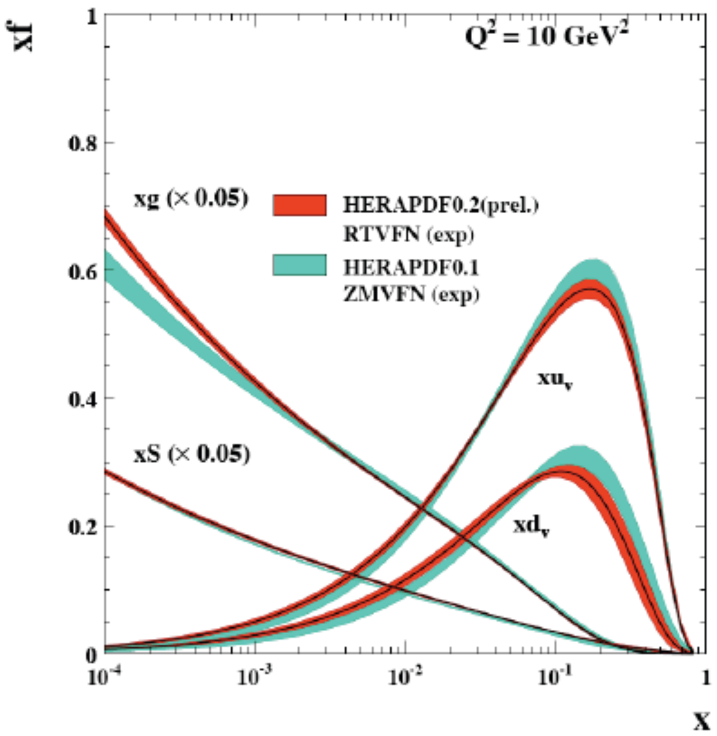
$$xF_3^{\gamma Z} = 2x[e_u a_u(U - \overline{U}) + e_d a_d(D - \overline{D})]$$

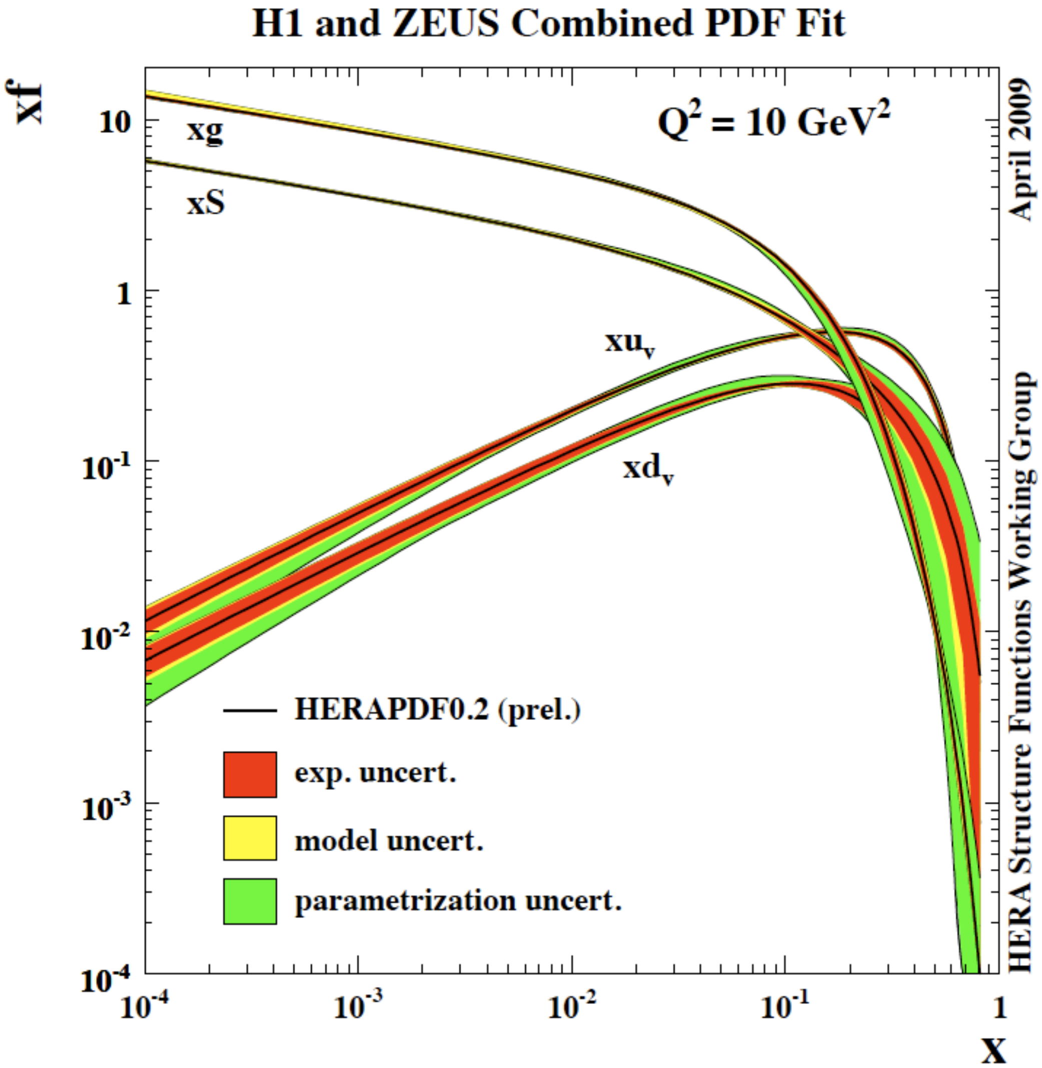
Measurement of valence quarks $[2u_v+d_v]/3$
down to low x, unless $q_{sea} \neq$ anti-q
Difficult to measure at HERA, needs high Q^2
and contributes only at high y as $Y_-=1-(1-y)^2$



Update of xF_3 by ZEUS, DESY 08-202

HERAPDF0.2



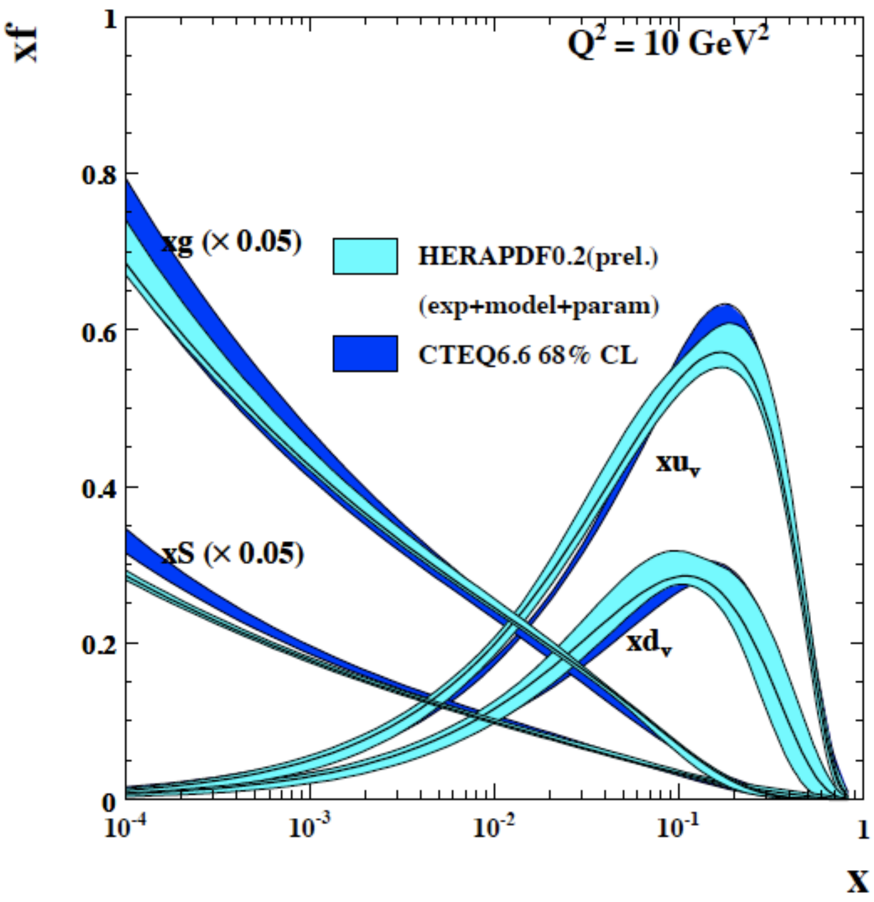


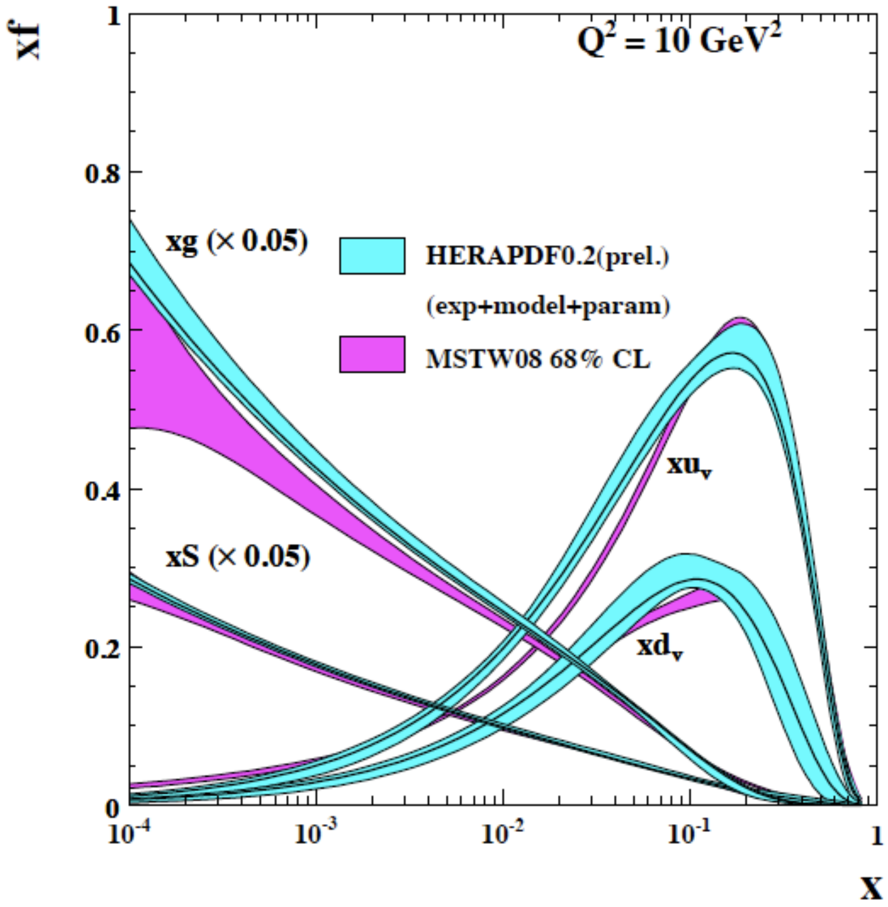
New precision H1 data in.
Variable flavour scheme
Pdf uncertainties
9 parameters (Q_0^2=1.9GeV^2)
Based on HERA I alone.
Publication this year.

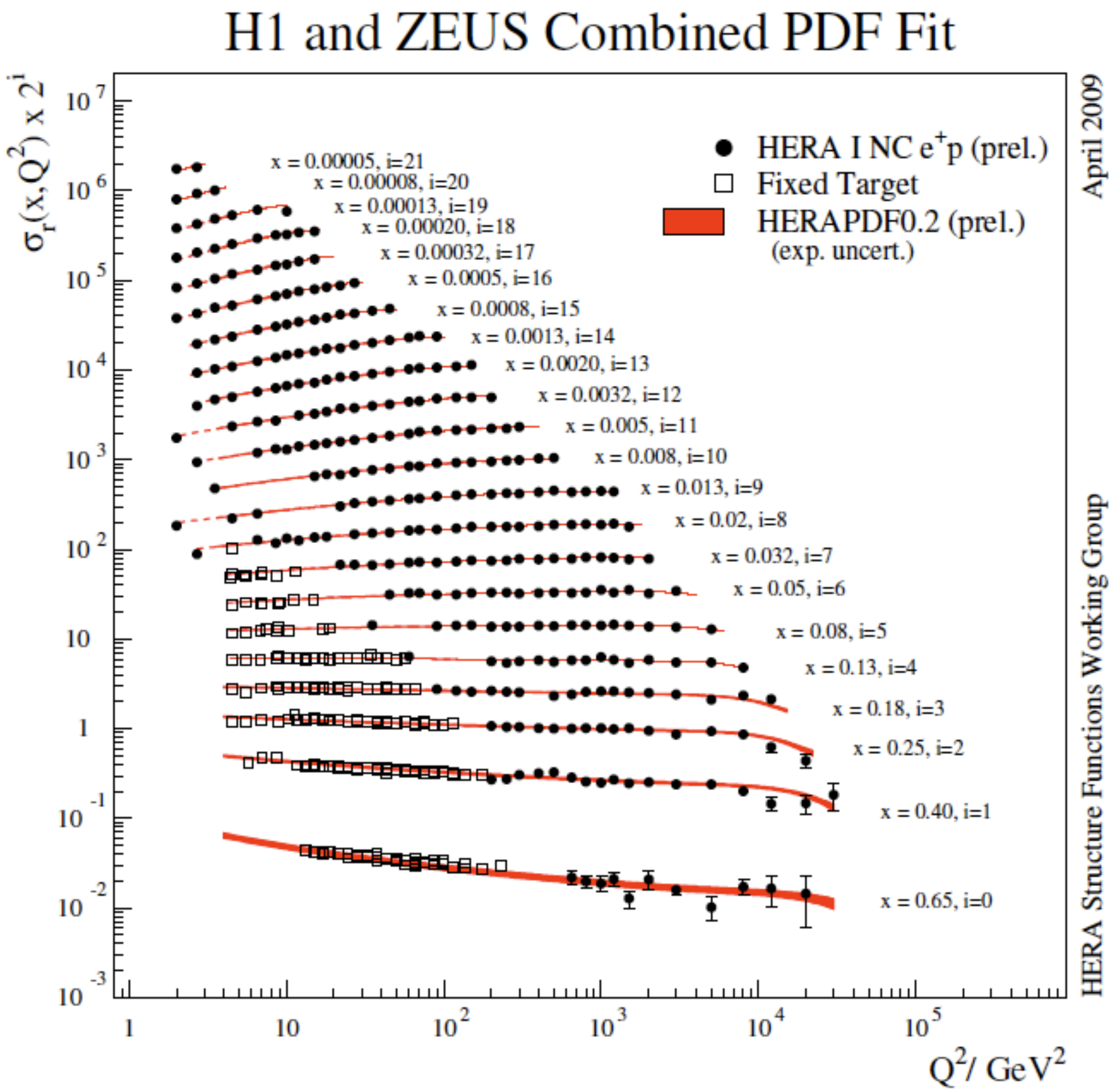
Assumptions on: strange, u/d at low x
Dynamic generation of c,b. uncertainties
at large x:. parameterisation, input data, xg

V.Radescu DIS09

HERApdf vs GLOBALs



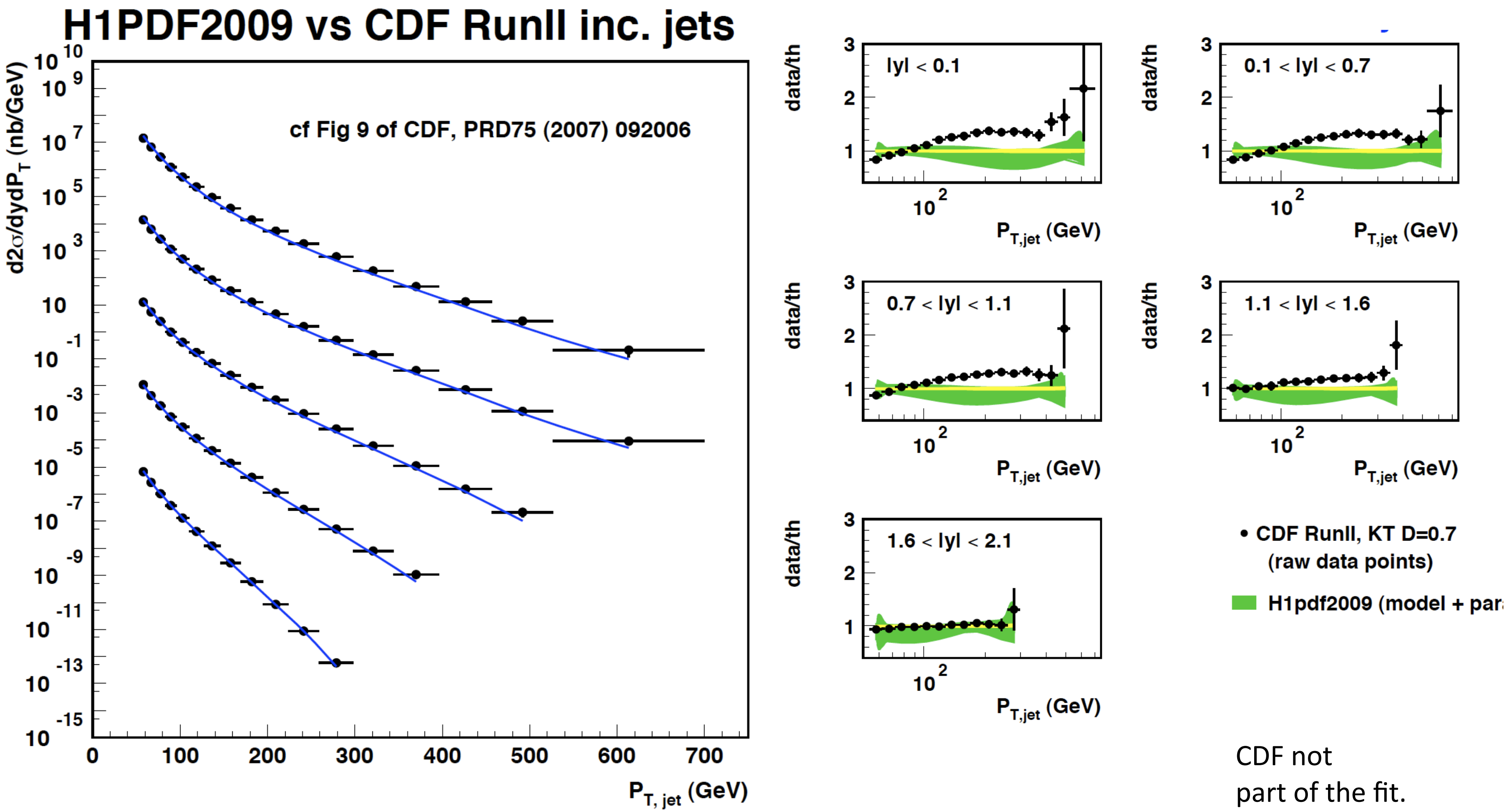




BCDMS not part of the fit.

α_s to NNLO for the final analysis.

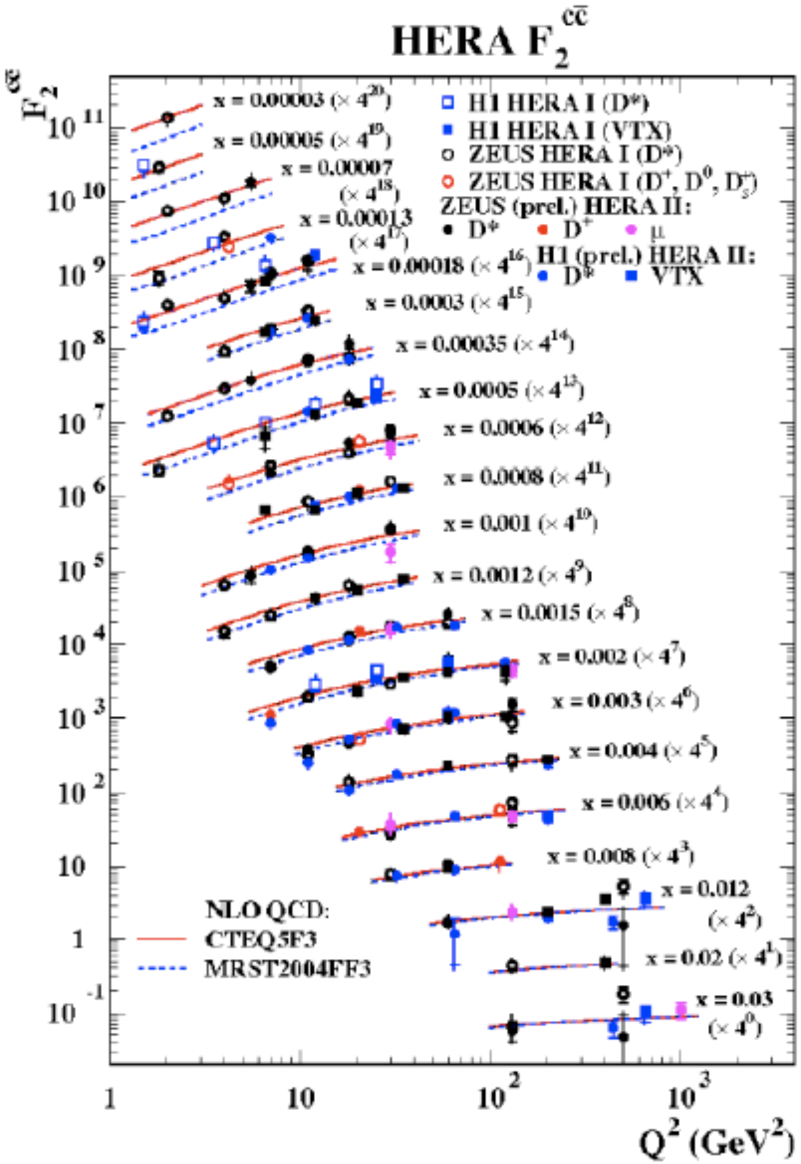
Comparison with Tevatron

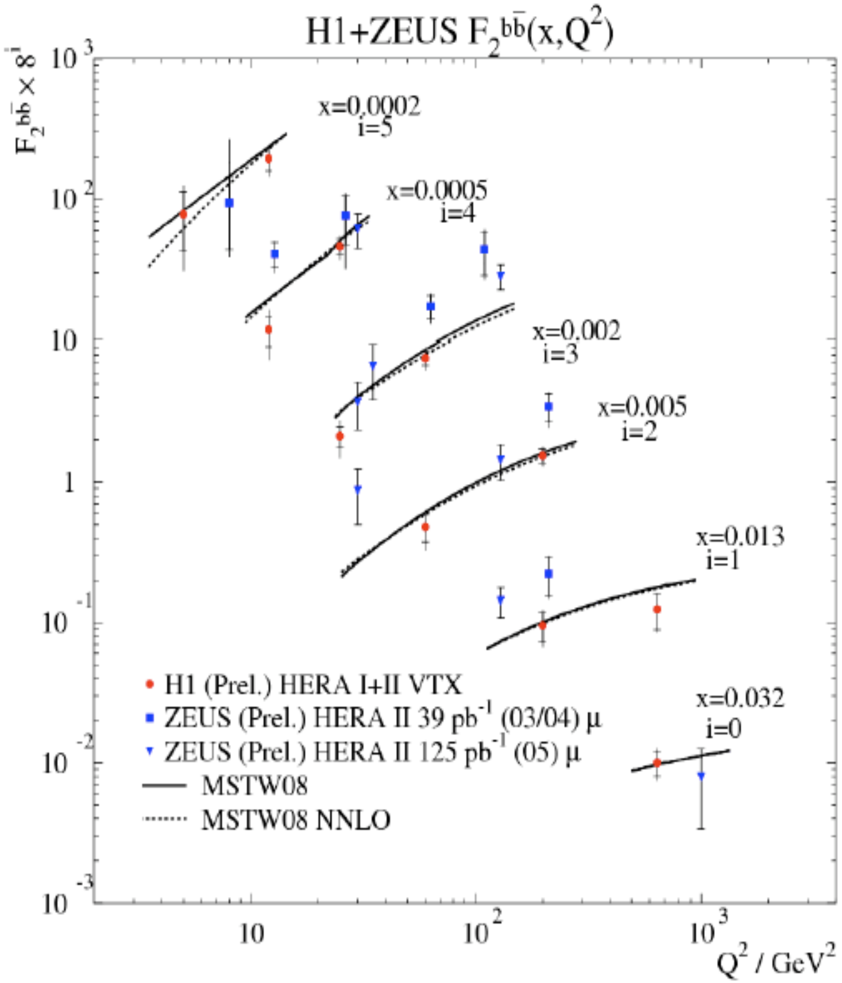


CDF not
part of the fit.

E.Perez

charm and beauty

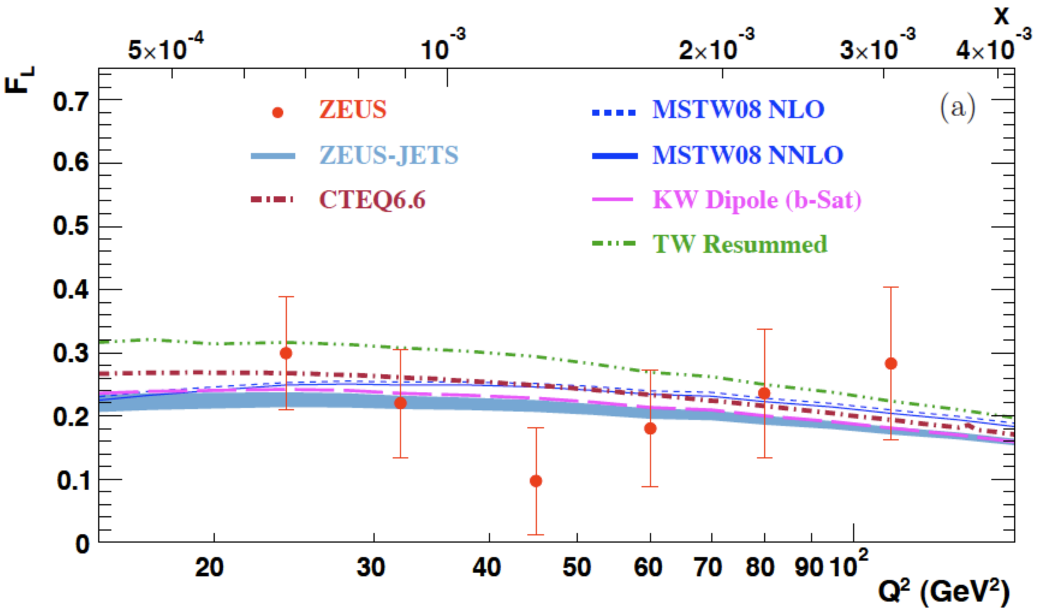




In recent fits c and b are dynamically generated,
i.e. the predictions are absolute [VFNS]
Remember c=0, 20 years ago (EMC)

cf G.Grindhammer

The Longitudinal Structure Function - ZEUS



DESY 09-046.

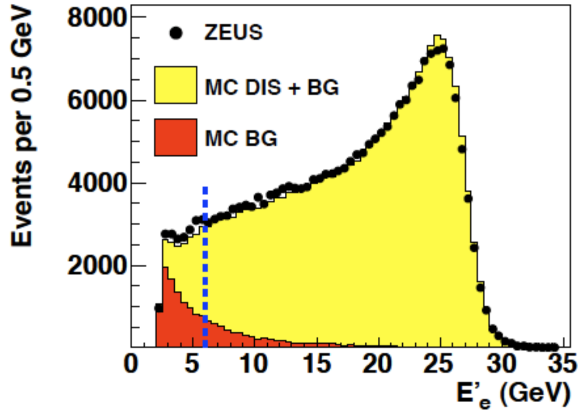
Errors from joint fit allowing changes of systematics.

Published both F_L and F_2

R=0.18+0.07-0.05

remember R=0.18+-0.10 from SLAC-PUB-815 April 1971

J.Grebeniuk, DIS09



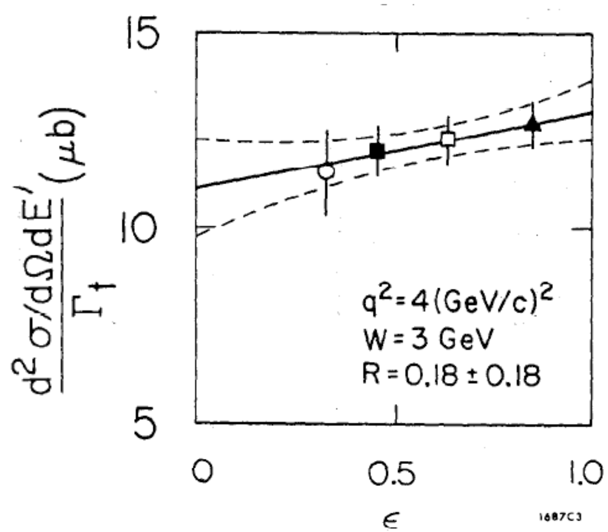
$E_e' > 6$ GeV.

eID with NN based on shower shape,

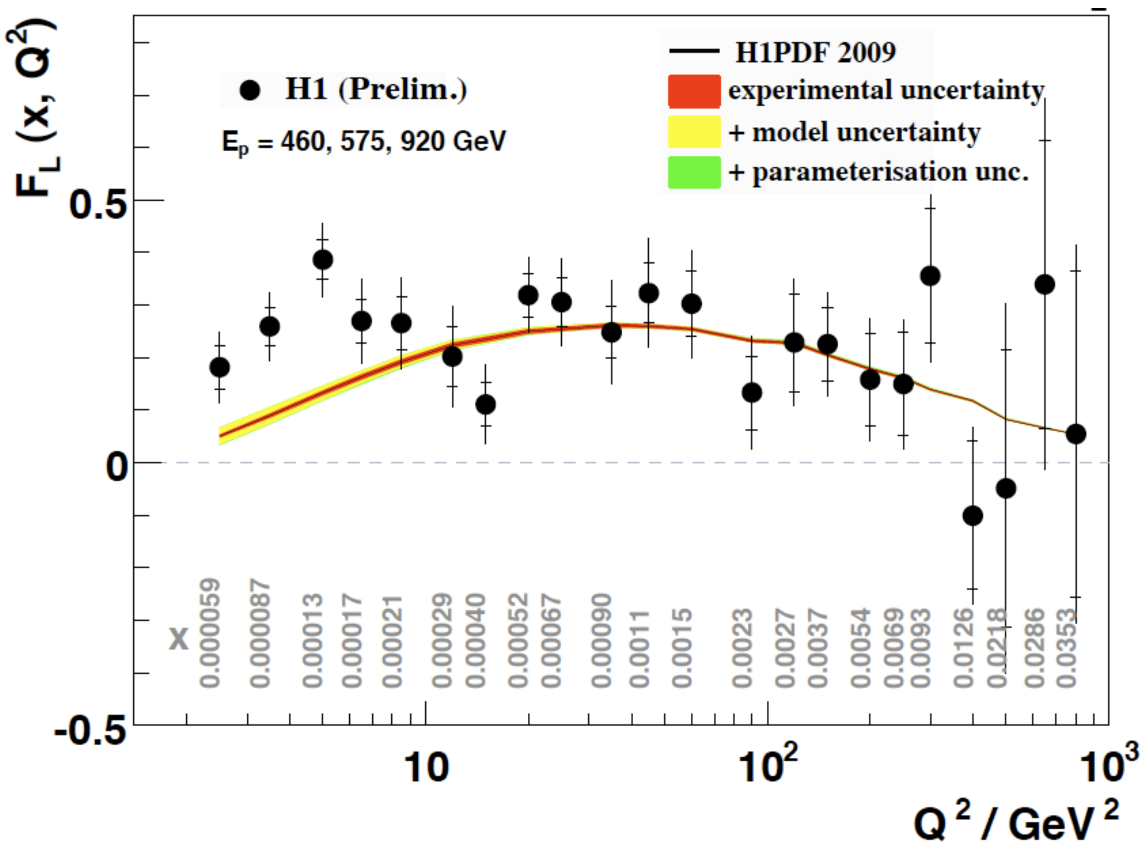
some hit requirement (MVD, CTD)

outside track reconstruction acc.

Monte Carlo used for background subtraction



The Longitudinal Structure Function F_L - H1



Backward Silicon   Central Jet Chamber

E_e' > 3 GeV
eID with max. p_T
BST/CJC track and
charge determination
to remove γp bgd

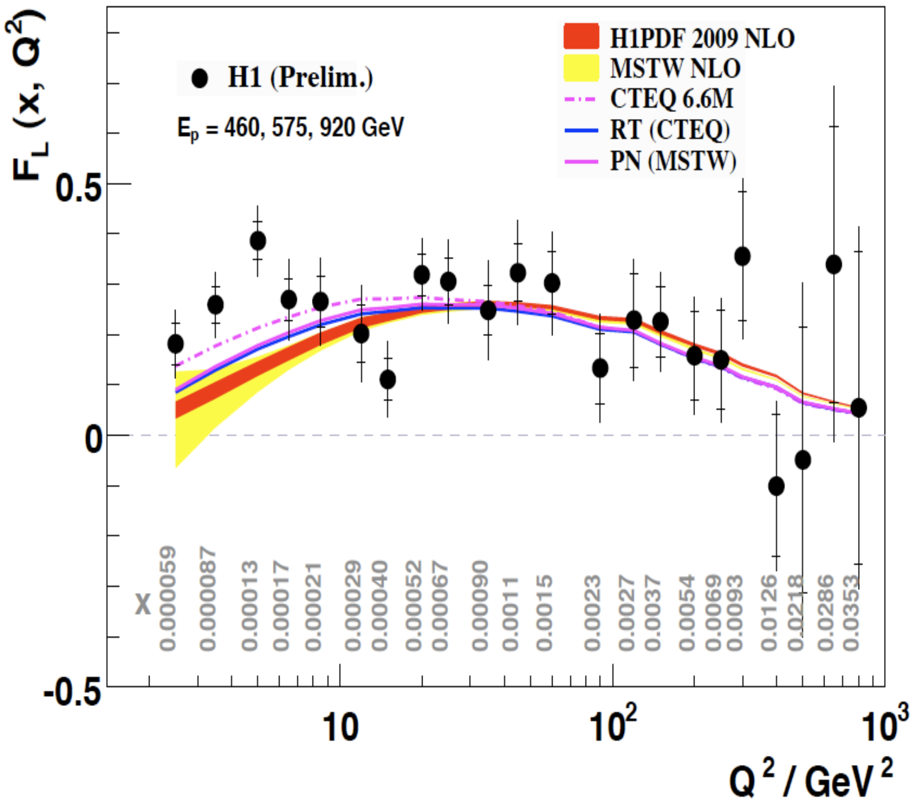
Values extracted point
by point assuming
uncorrelated errors
at this stage.

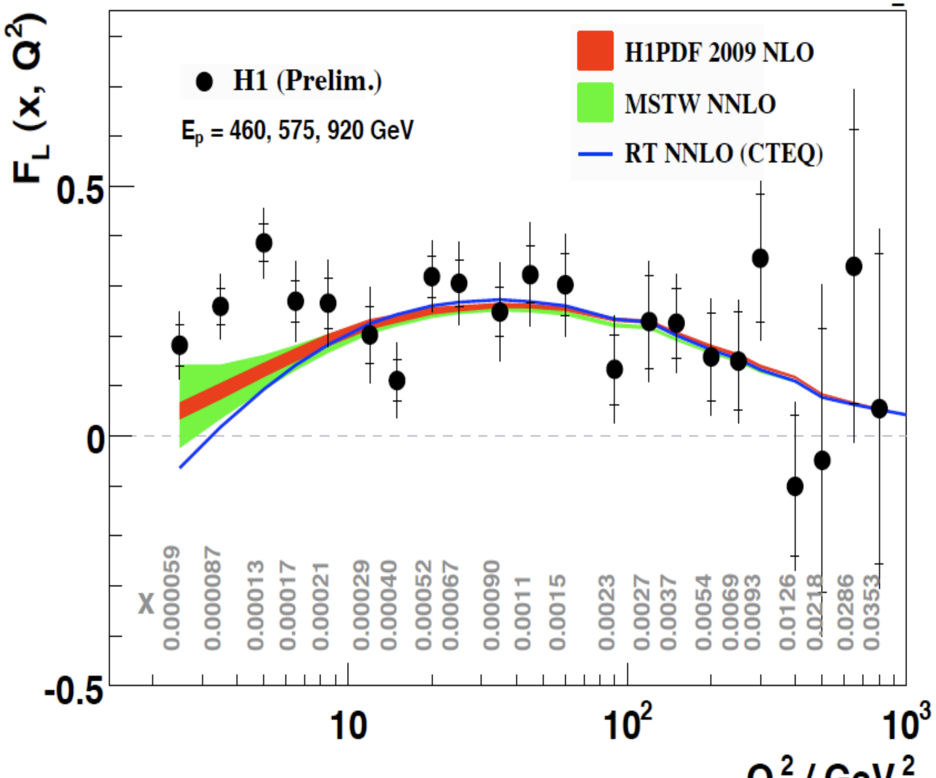
Results at medium Q^2
are consistent with ZEUS
but error treatment differs.

Improvement over
first F_L publication:
F.D. Aaron et al.,
Phys. Lett. B 665, 139 (2008)

A.Glazov, DIS09

F_L at low x – some puzzles





MSTW =H109 (NLO)
CTEQ6.6 higher
Use CTEQ prescription to calculate F_L:
MSTW moves up !

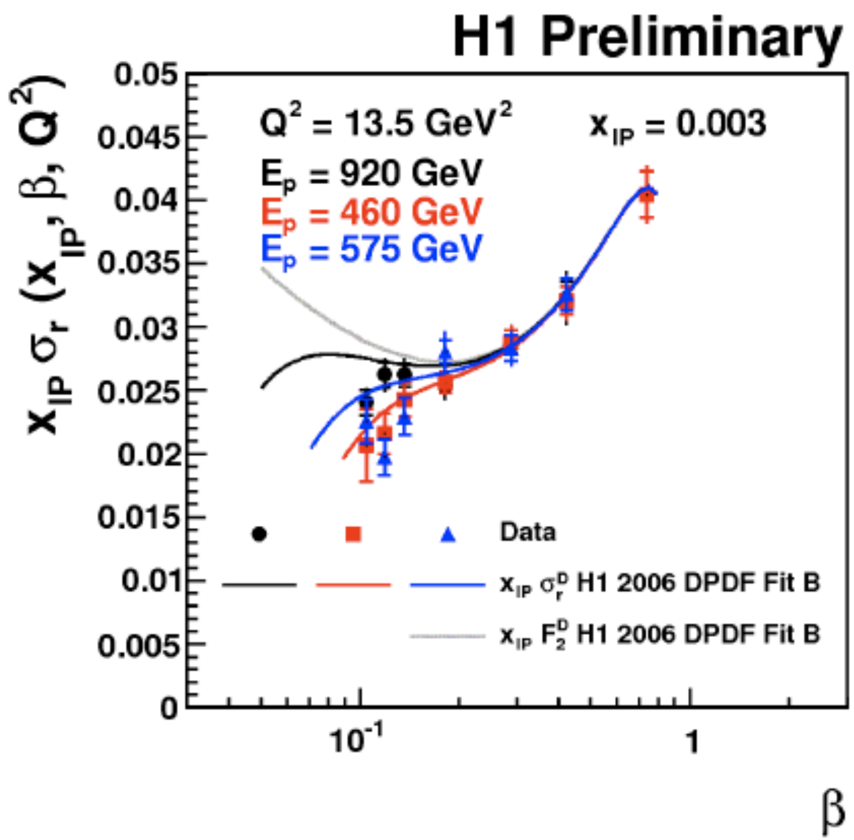
NNLO: MSTW(NLO)=MSTW(NLO)
but CTEQ moves down…

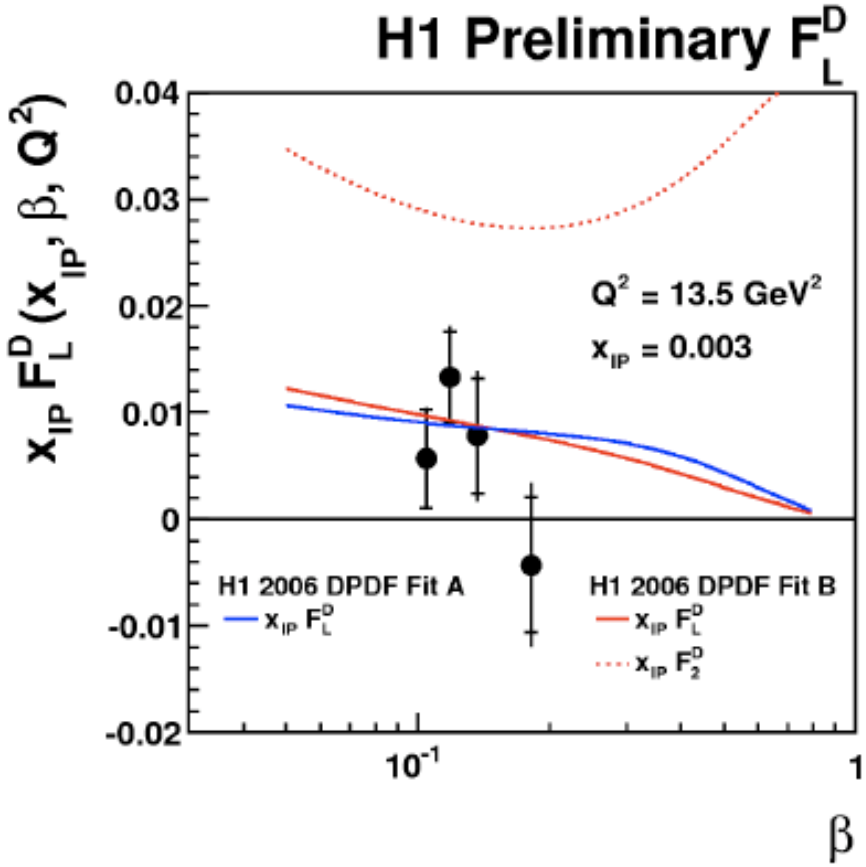
Need best possible measurement at low x,Q^2
To help understanding h.o. QCD

Dipole models work.

P.Nadolsky, R.Thorne, E.Perez

$\sigma_r = F_2^D - f(y) F_L^D$





$$\frac{d^3\sigma^{ep\rightarrow eXY}}{dx_{IP}\, d\beta\, dQ^2} = \frac{2\pi\alpha^2}{\beta Q^4} Y_+ \sigma_r^D(x_{IP}, \beta, Q^2)$$

David Šálek DIS09

Summary

-Below x=0.1 the proton structure in the DIS region is gluon dominated.

-Quarks are pointlike down to 0.7 10^{-18} m – HERA was the best microscope of mankind

-Broadly, the observations (here F_2(inclusive, charm, beauty, diffractive) and F_L(inclusive, diffractive) can be understood by NLO QCD

-A great development in the understanding of qg dynamics with new concepts as parton amplitudes, unintegrated distributions and the new area of high parton densities

-The HERA data and inclusive QCD fits are able to describe fixed target and Tevatron jet data, and yield predictions for the LHC (W,Z,Higgs)

-Next steps:

- completion of data analysis (high Q^2, y, F_L,…)
- Studies of QCD at low x, Q^2 (stability of α_s, F_L)
- Coupling constant and pdf's at NNLO ..

HERA was a remarkable success
and so have been the collaborations: H1-ZEUS, HERA, Theory.

A review: M.K. and Rik Yoshida, Collider Physics at HERA, Prog. Part. Nucl. Phys. 61,343 (2008)

1989/90

MUON EXPERIMENTS			
	BCDMS	BFP	EMC
Target	C and H_2	Fe	H_2 D_2 Fe
Energy	100 - 280	93, 215	120 - 280
x-range	.06 - .80	.08 - .65	.03 - .65
Q^2-range	25 - 280	5 - 220	3 - 200
# events	C: 680K	690K	Fe: 1080K
$R(x,Q^2)$	Expt.	0.0	0.0

Table III-1: Major recent Muon Experiments.

NEUTRINO EXPERIMENTS				
	BEBC	CCFRR	CDHSW	CHARM
Target	Ne H	Fe	Fe	Marble
Energy	10 - 200	30 - 250	30 - 300	10 - 200
x-range	.025 - .80	.02 - .65	.02 - .65	.02 - .55
Q^2-range	2 - 70	1 - 200	0.2 - 200	0.2 - 100
$R(x, Q^2)$	R(QCD)	R(QCD)	R(QCD)	0.1
# Events	25K	170K	940K	160K
SU(3) symmetry	$\bar{s} = 0.25\,(\bar{u} + \bar{d})$, $c = \bar{c} = 0$		$\bar{s} = 0.2\,(\bar{u} + \bar{d})$, $c = \bar{c} = 0$	
Charm	slow rescale: m = 1.5		No correction	

Table III-2: Major recent charged-current Neutrino Experiments.

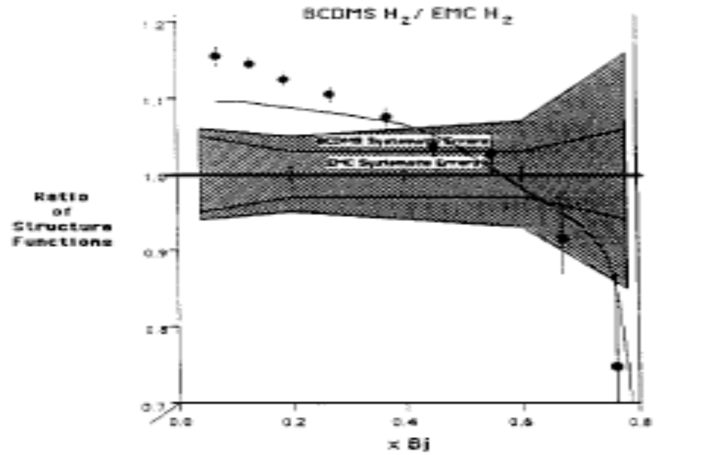
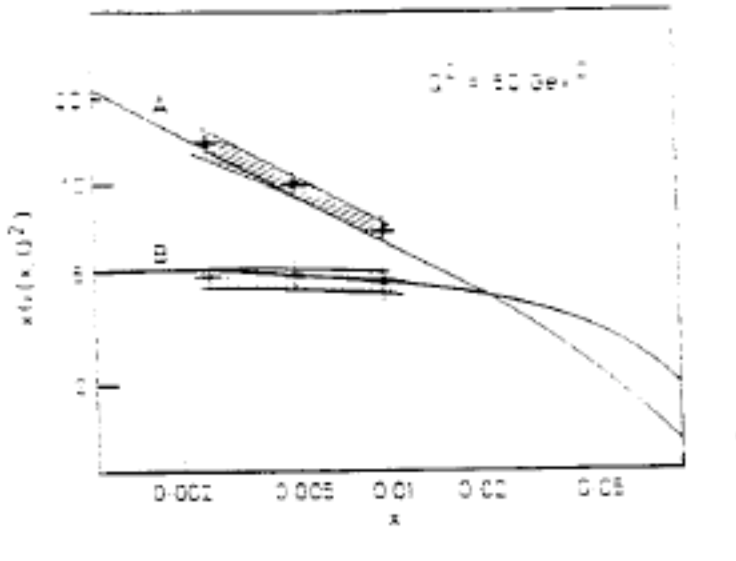


Fig.III-6: The Ratio of $F^2(x,Q)$ measured by BCDMS and EMC on hydrogen target (see text).

The anticipated resolving power



FERMILAB-Conf-89/26

Wu-Ki Tung[a,b,c], J. G. Morfín[b], H. Schellman[b], S. Kunori[d], A. Caldwell[e], F. Olness[f]