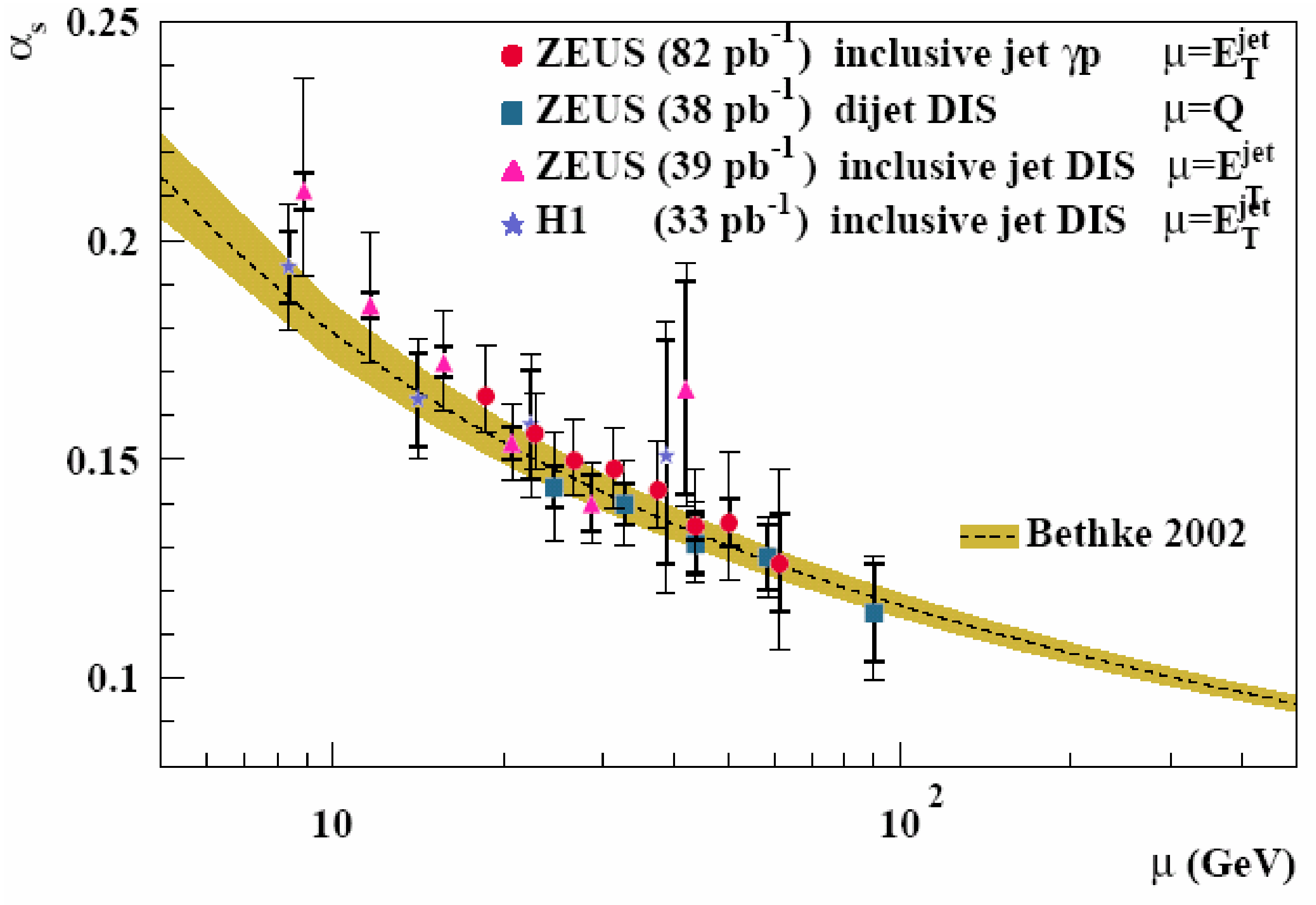
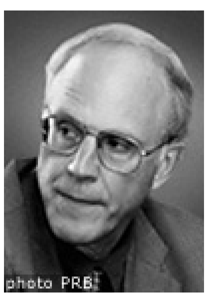
Precision Measurements at HERA

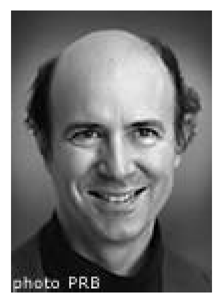
M. Klein (DESY)

- Why Precision?
- How Precise?
- Strong Coupling Constant
- Gluon Momentum Distribution
- Diffraction
- Light Quarks
- Charm and Beauty
- Remarks

HERA and the LHC – Workshop 12.10.2004 @ CERN
[Some intermediate considerations and results]

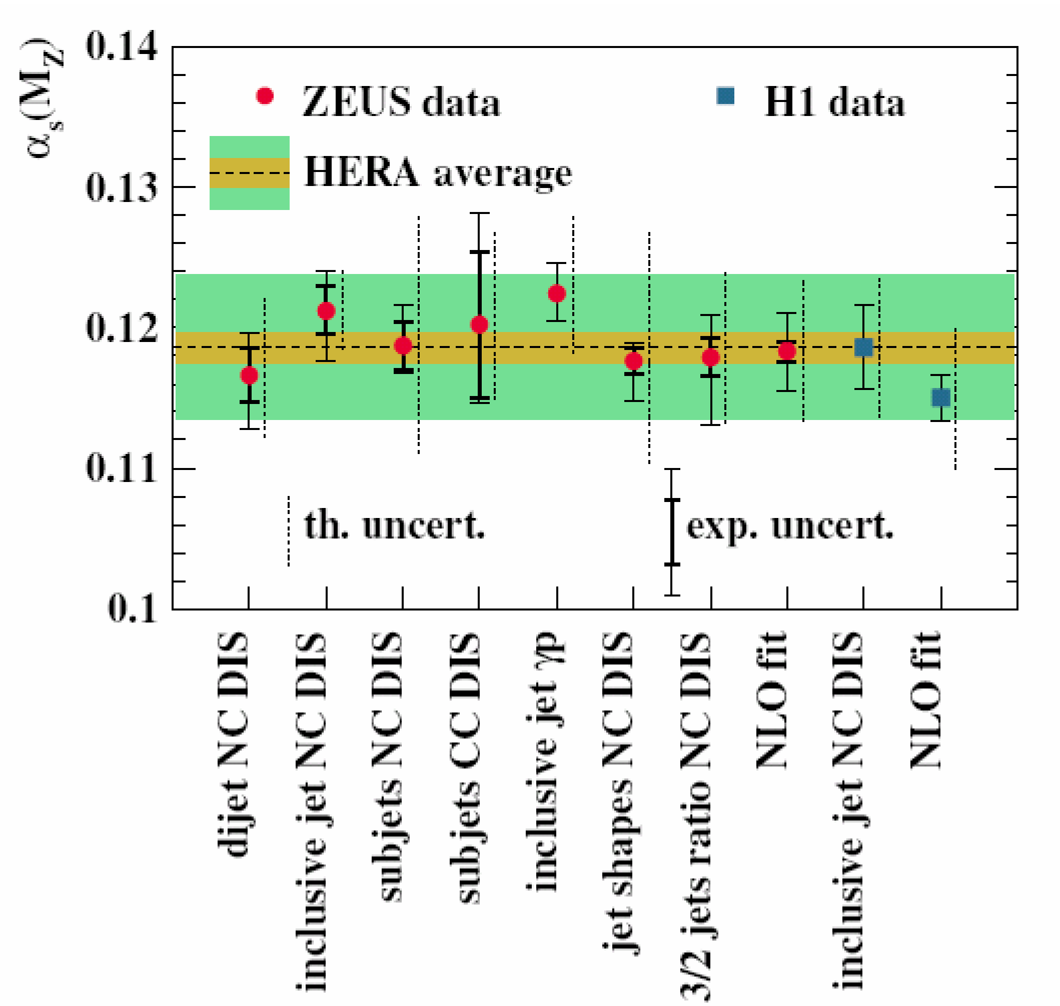




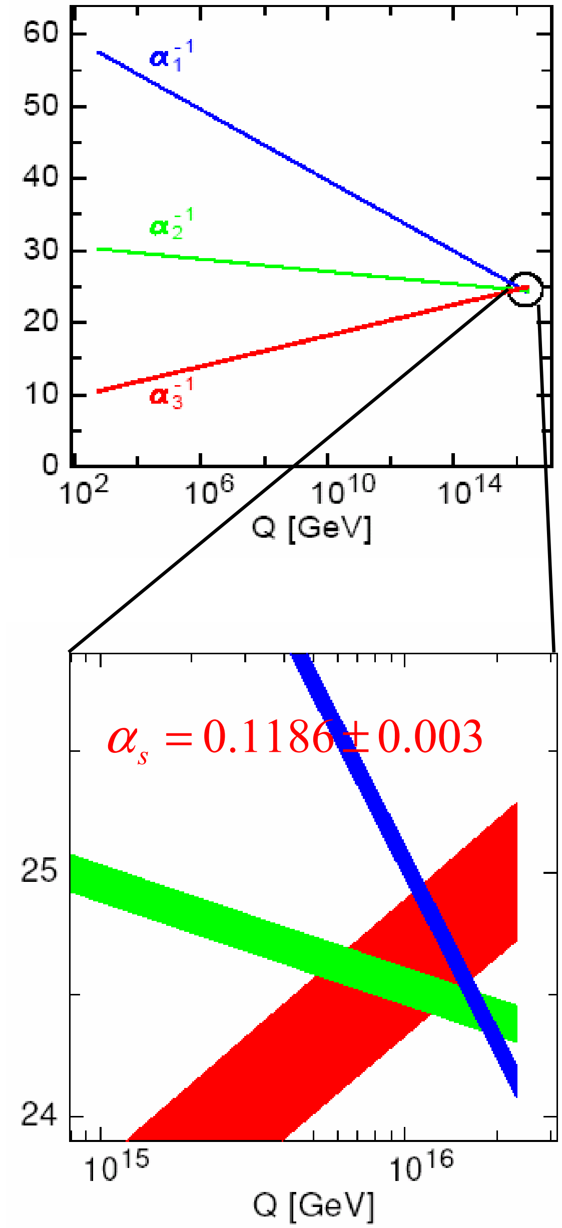


no doubt it "runs" - BUT
how large is the coupling?
and is the field so simple?

$HERA(prel.) - \alpha_s(M_Z^2) = 0.1186 \pm 0.0011(\exp) \pm 0.005(thy)$

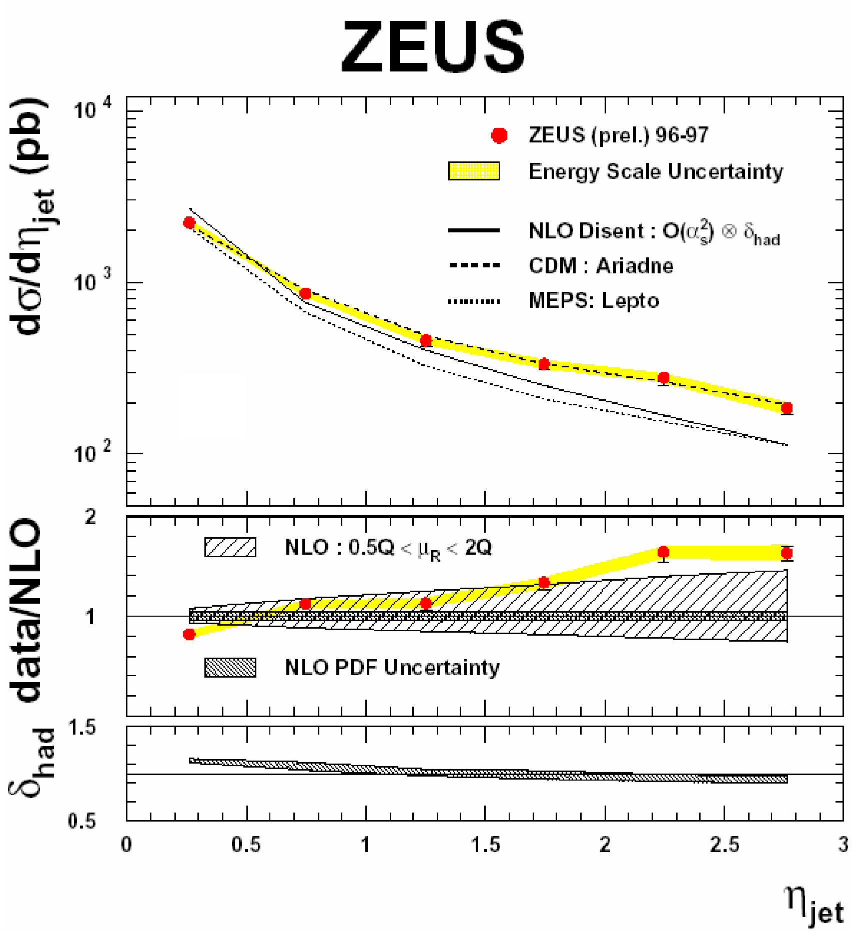


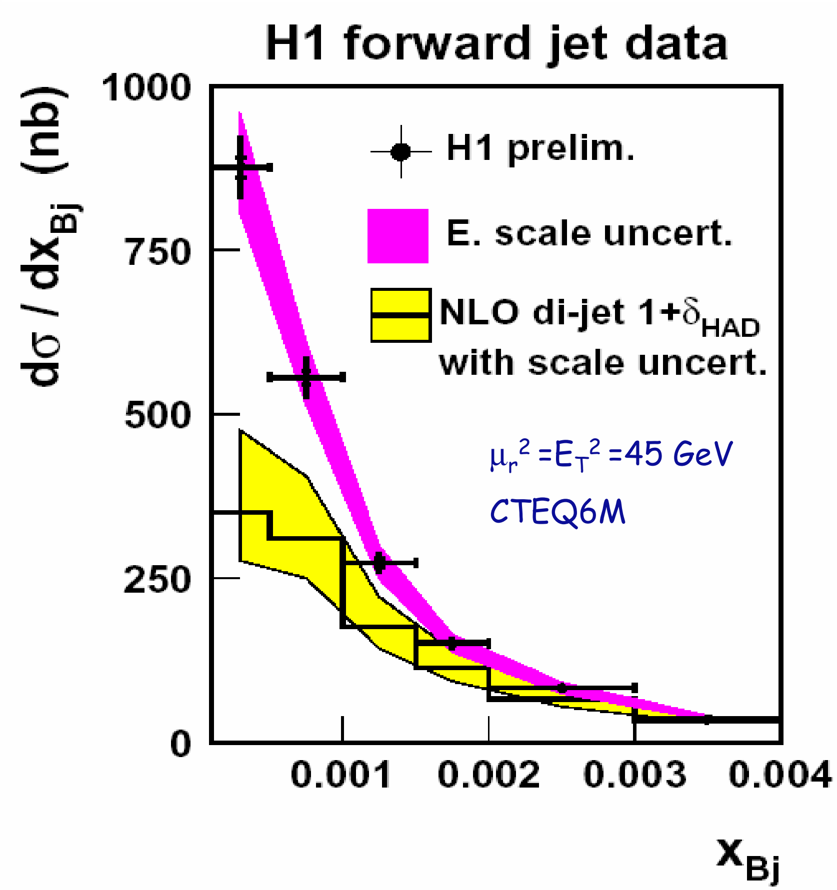
$$\alpha_s(M_Z^2) = 0.1209 \pm 0.0015(\exp) \pm^{0.0048}_{0.0049} (thy) - ZEUS$$
$$\alpha_s(M_Z^2) = 0.1160 \pm 0.0016(\exp) \pm^{0.0058}_{0.0046} (thy) - H1$$



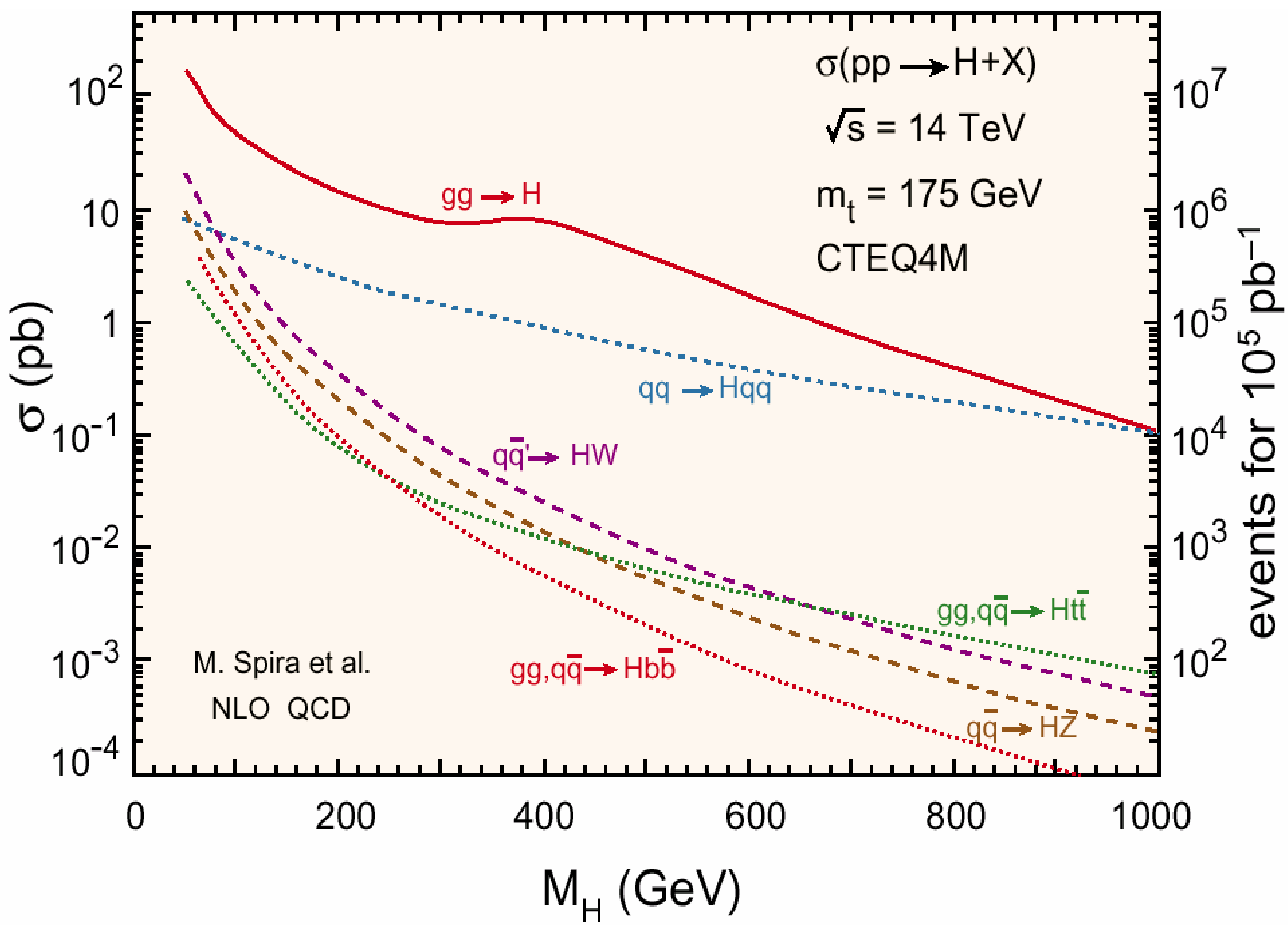
hep-ph/0407067 B.Allanach … P.Zerwas

Forward jet production in deep inelastic scattering





- Standard NLO pQCD prescription poor at lowest x for jets in forward direction where scale uncertainty is largest (higher orders? different radiation mechanism? best described by Ariadne – CDM – “BFKL like”)



σ(pp → H+X)
√s = 14 TeV
m_t = 175 GeV
CTEQ4M
gg → H
qq → Hqq
qq̄' → HW
gg,qq̄ → Htt̄
gg,qq̄ → Hbb̄
qq̄ → HZ
M. Spira et al.
NLO QCD
σ (pb)
events for 10^5 pb^-1
M_H (GeV)
0
200
400
600
800
1000
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^7
10^6
10^5
10^4
10^3
10^2

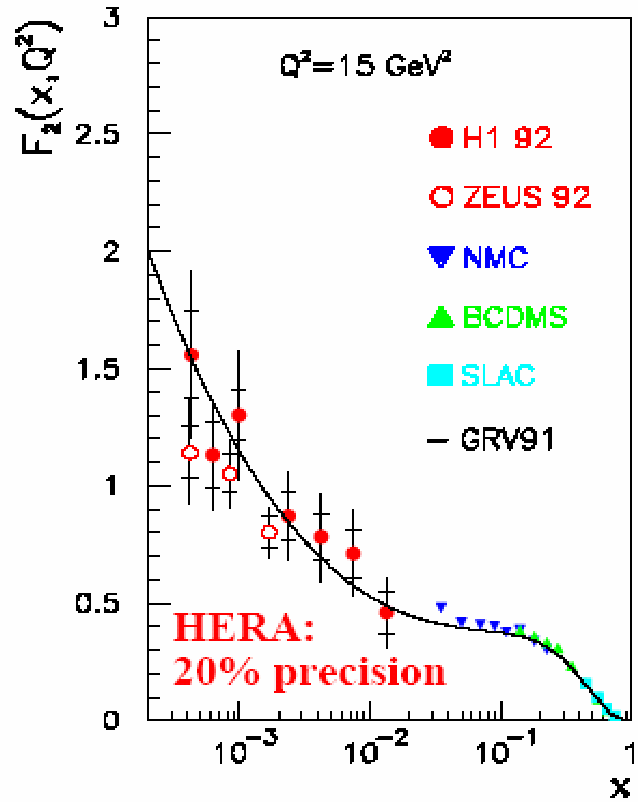
Three reasons for precision at HERA

- measure α_s, the gluon and quark distributions
  [inclusive NC and CC scattering, c, b – F_L and eD] - precision
- verify or/and falsify DGLAP QCD → develop QCD at high densities
  [low x physics, diffraction, jets, photon structure…] - exploration
- help understanding pp collisions (TeVatron and the LHC)
  [W,Z luminosity, PP→ H,…] – this workshop

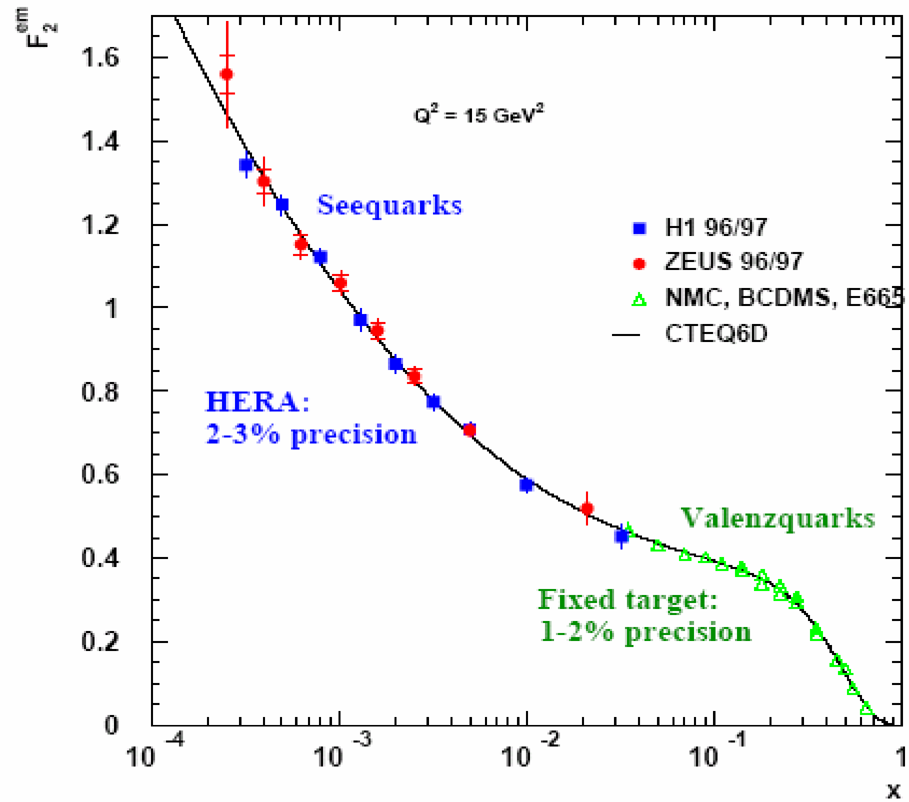
for overview on HERA physics:
cf. DIS04 and ICHEP04, 100 papers by ZEUS&H1
for explorations see also the many talks at this workshop

2. How Precise?

1992 data ~30nb-1

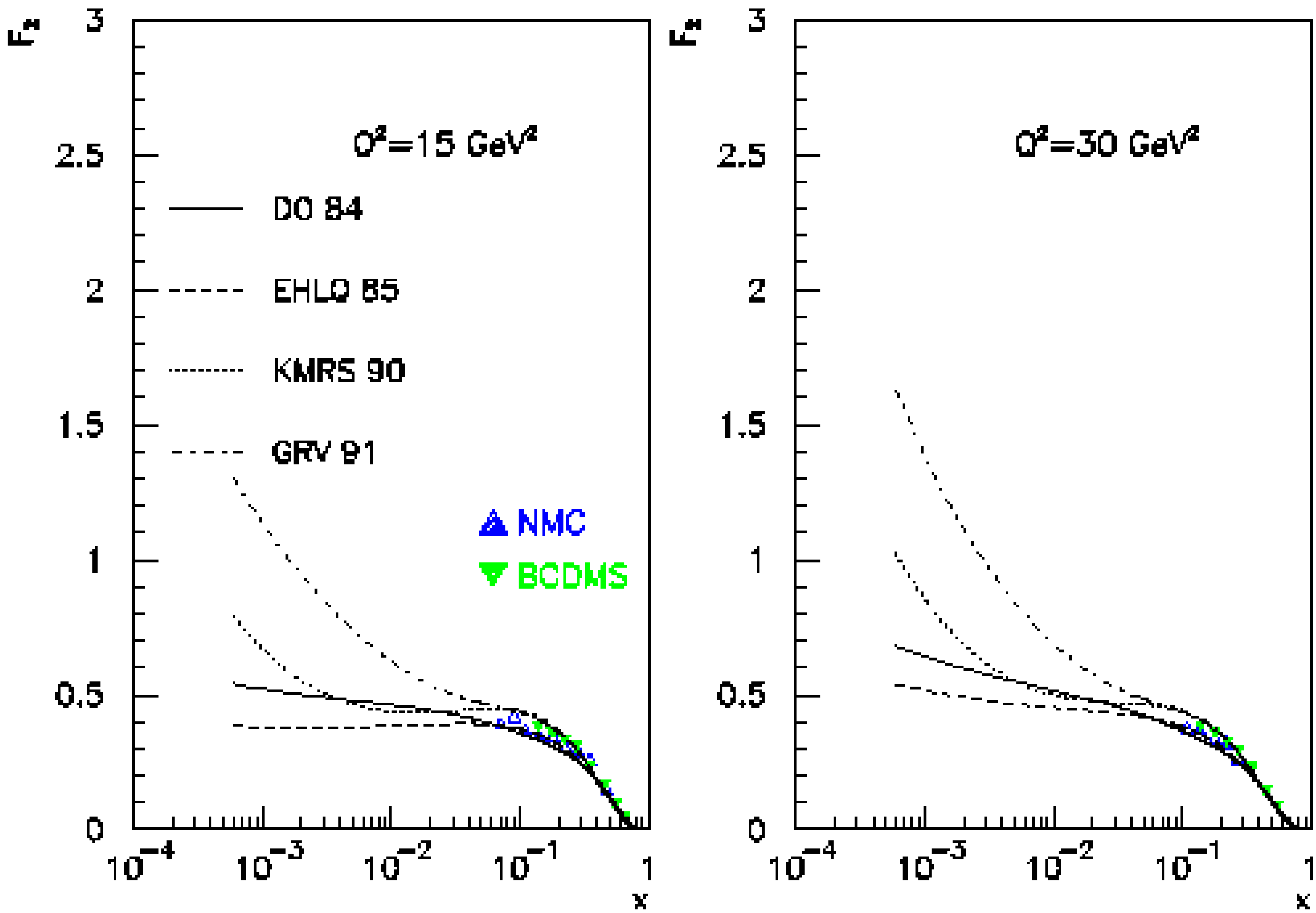


1997 data ~30pb-1



consequences, regarding the pointwise evolution of structure functions, were derived. The most dramatic of these, that protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was only clearly verified at HERA twenty years later.

F. Wilczek



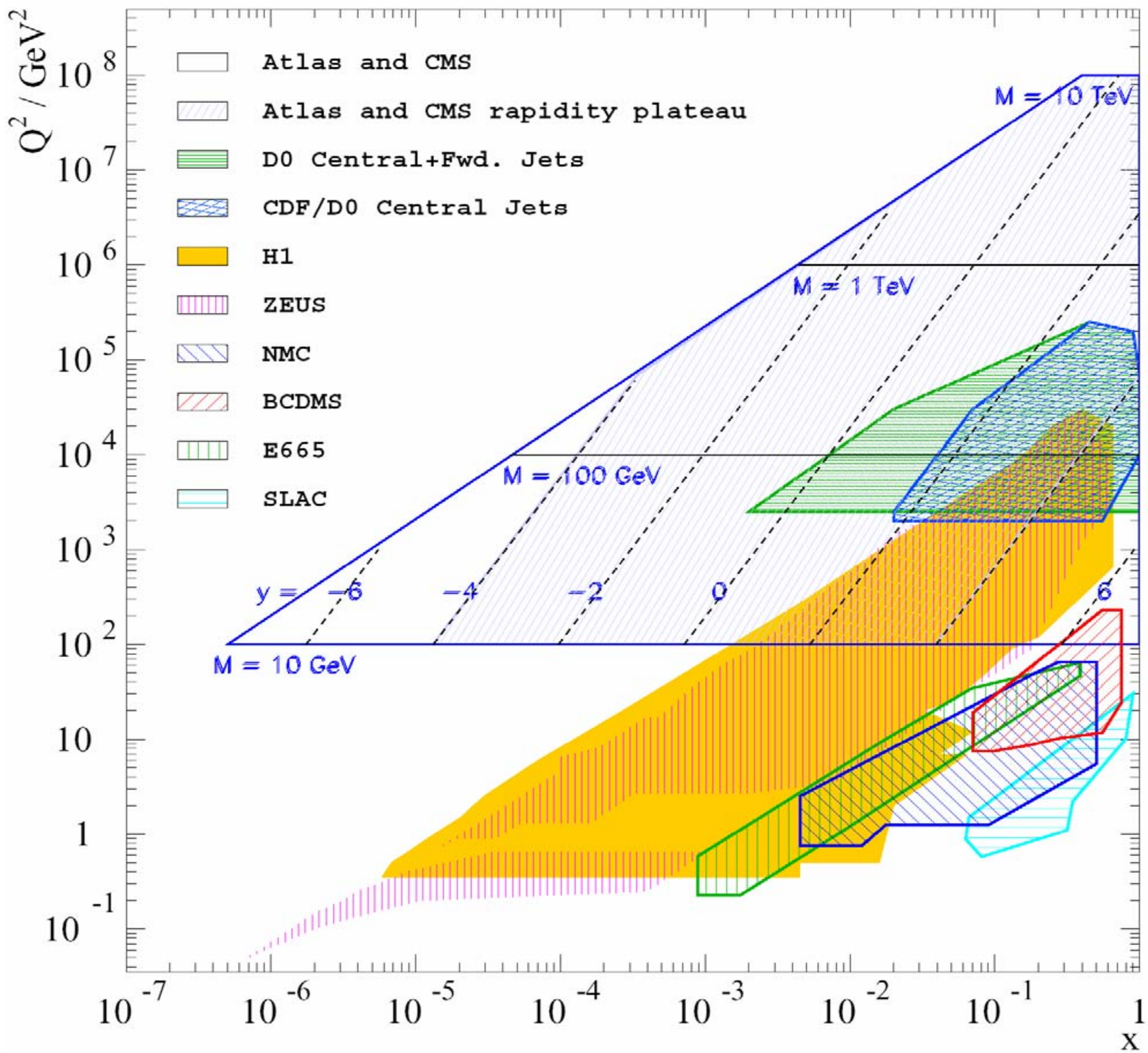
impossible to do fits without HERA

HERA collider experiments are precision experiments because

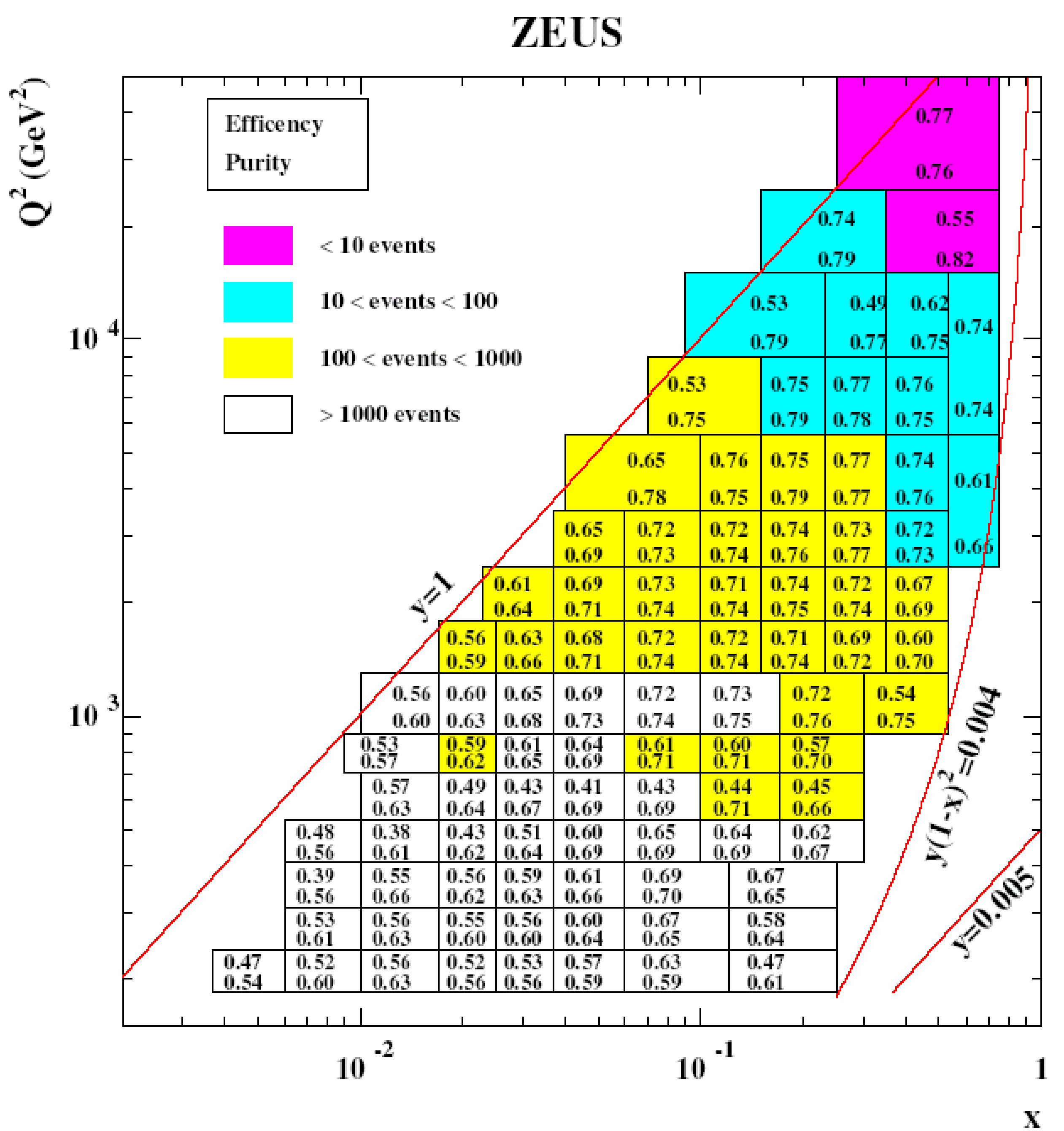
- Measure E'_e, θ_e, E_h, θ_h → Reconstruct x, Q^2: Kinematics is overconstrained
- Highly efficient, 4π Detectors (Calorimeters, Chambers in solenoidal field)
- Energy calibration: double angle method and kinematic peak constraint
  [high resolution calorimeters: 12%...35%/$\sqrt{E'_e}$ and 30-50%/$\sqrt{E_h}$]
- Energy momentum conservation (E-pz): reduces radiative (QED) corrections
- Polar angle measurement using redundant trackers. Run vertex accurate
  [drift chambers: 200μm and Si trackers: 20μm resolution]
- Luminosity from Bethe Heitler scattering [ep → epγ] to 1%.

HERA uses lepton (photon) to probe the proton

- Precision: takes time, needs patience, luck, ingenuity and dedication



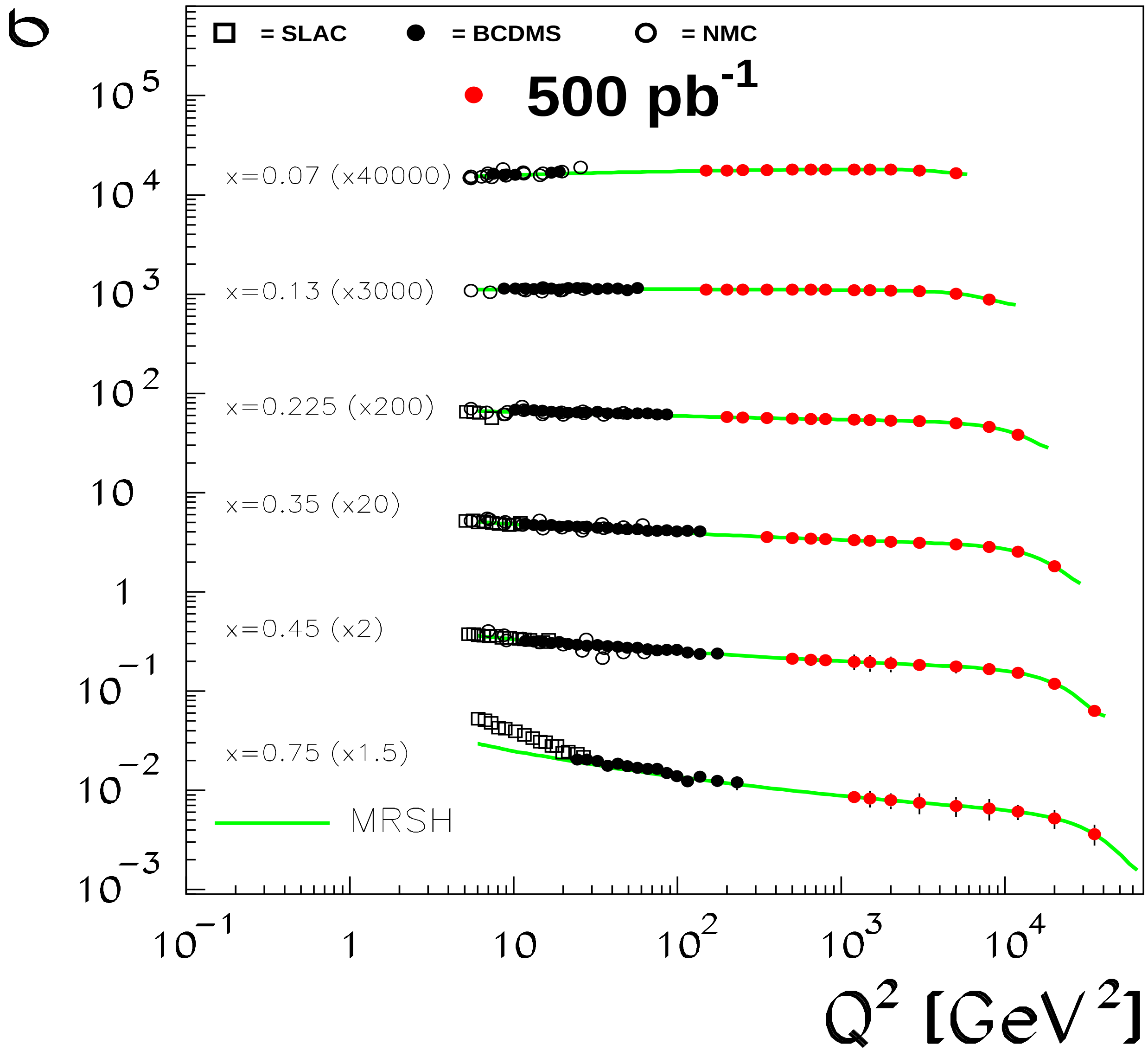
HERA accuracy limit about 1% in the bulk region (~LHC y plateau) for incl. xsection
[~2% at high y (low x) and perhaps 5% at large x, ~1/(1-x)]



← L upgrade

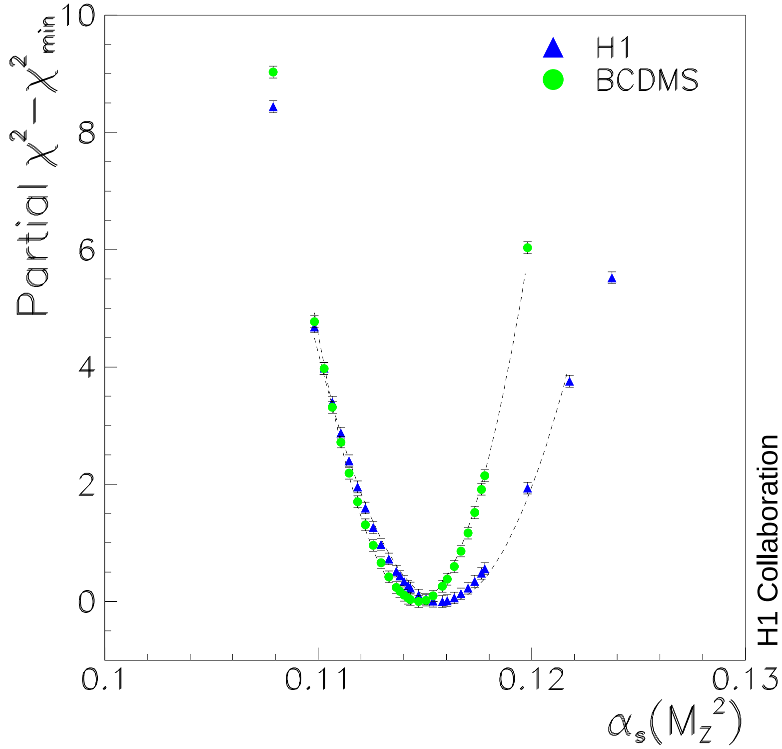
← MC + Det upgrade

ep→eX
63pb-1
DESY03-214

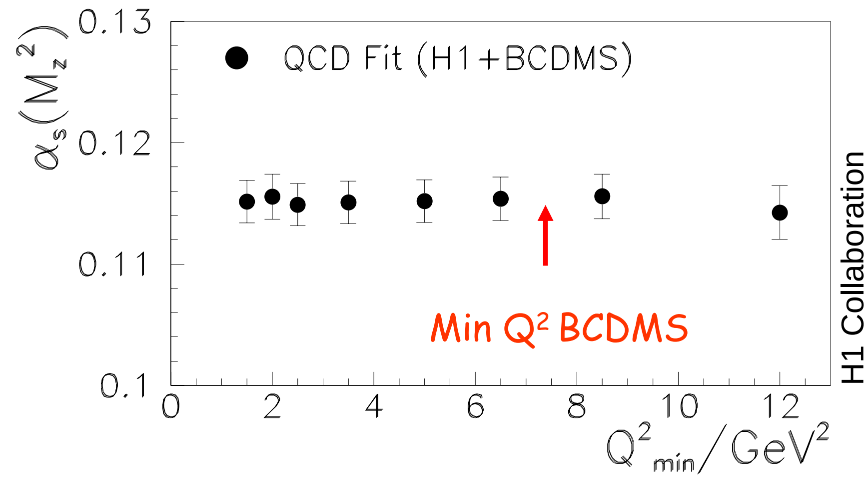


•10% uncertainty for Q^2 > 15000 GeV^2

3. Measurement of α_s in Deep Inelastic Scattering



→ χ^2+1 well defined with two consistent data sets



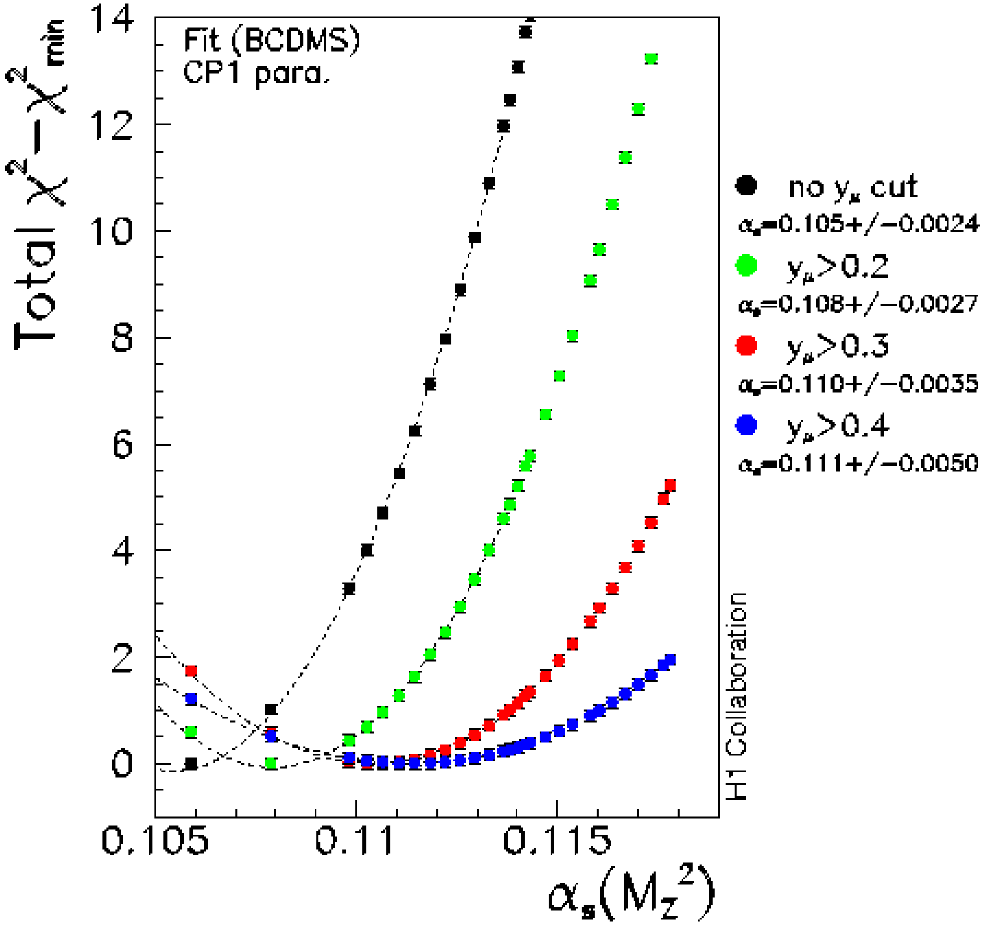
joint determination of alphas, xg, V,A
no interest in quarks → two pdfs only

$$9\,F_2 = 3\,xV + 11\,xA = 4xU + xD$$

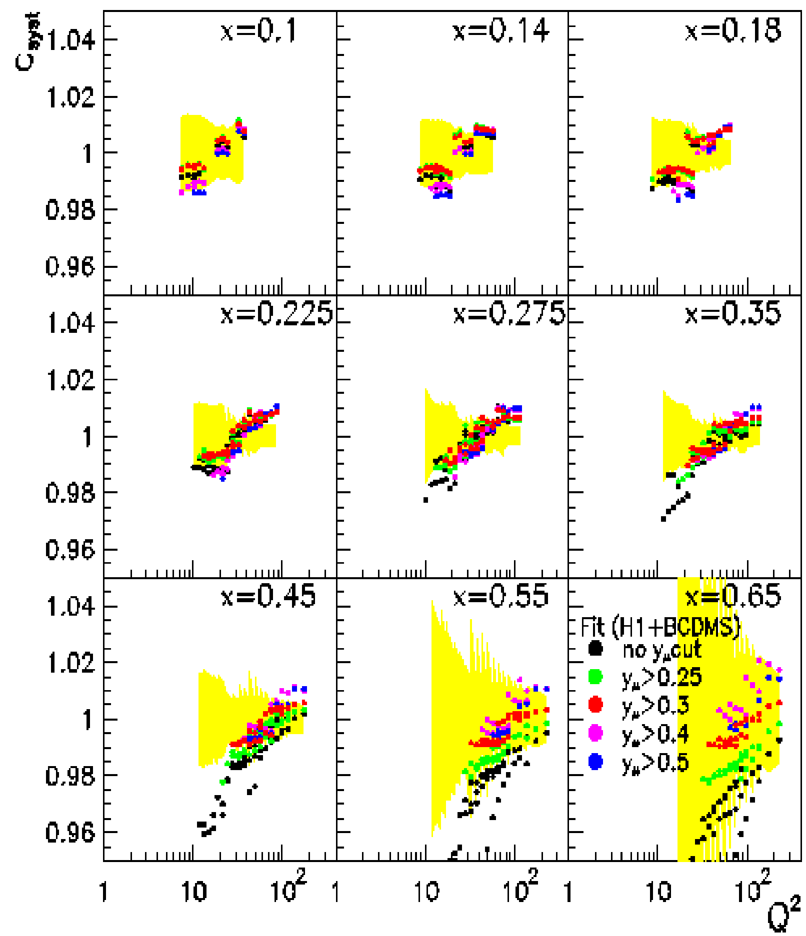
$$V \xrightarrow[\bar{u}=\bar{d}]{} \frac{3}{4}(3u_v - 2d_v)$$

$$A \xrightarrow[\bar{u}=\bar{d}]{} \bar{u} - \frac{1}{4}(u_v - 2d_v)$$

The BCDMS data determines all DIS determinations of the strong coupling, **BUT**



shifts imposed by QCD fit to BCDMS data



alphas (BCDMS) very low and strongly y dependent („electron method")

low y – large x region in conflict with SLAC F2

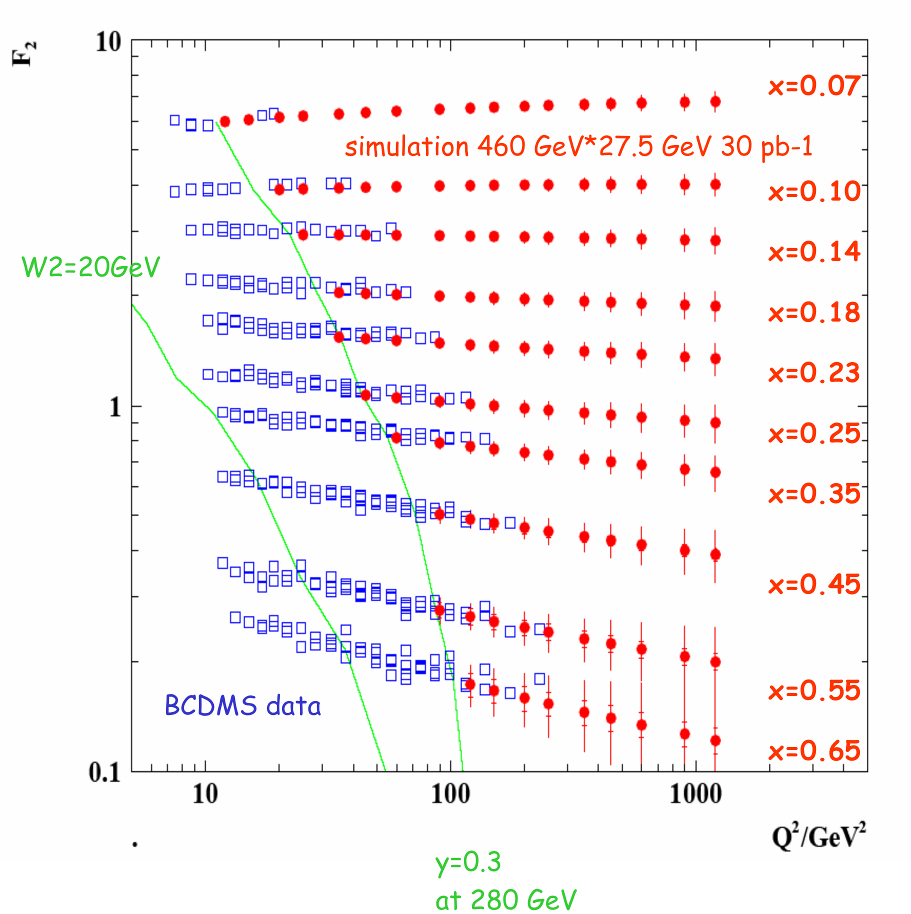
systematic errors of BCDMS data

H1 EPJ C21(01)33 R.Wallny Thesis 01-058

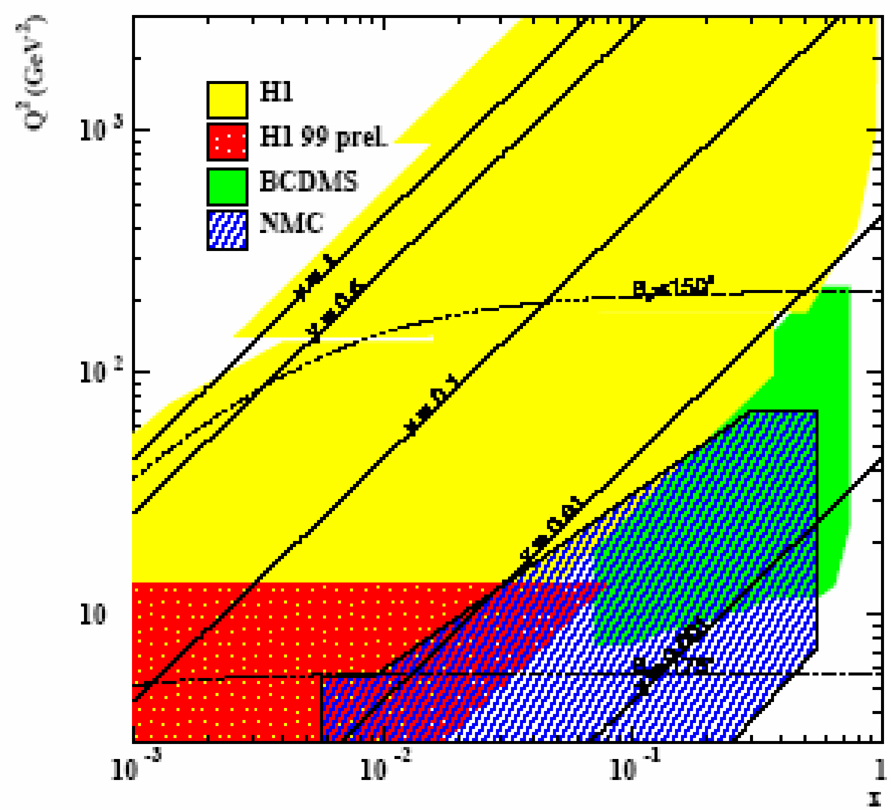
→ High x needs to be remeasured at medium Q^2: low Ep at HERA, COMPASS

Run at reduced proton beam energy

access large x at lower Q^2



•Low E_p kinematics



Improvements for Measurements at Low y:

- Improved simulation of resonance region
- Upgraded low noise calorimetry
- New/extended forward tracking
- Backward tracking (scattered e)

0.1150 +- 0.0017(exp) +- 0.0009 (model)

analysis uncertainty	$+\delta\ \alpha_s$	$-\delta\ \alpha_s$
$Q^2_{min} = 2$ GeV^2		0.00002
$Q^2_{min} = 5$ GeV^2	0.00016	
parameterisations	0.00011	
$Q^2_0 = 2.5$ GeV^2	0.00023	
$Q^2_0 = 6$ GeV^2		0.00018
$y_e < 0.35$	0.00013	
$x < 0.6$	0.00033	
$y_\mu > 0.4$	0.00025	
$x > 5 \cdot 10^{-4}$ →	0.00051	
uncertainty of $\overline{u} - \overline{d}$	0.00005	0.00005
strange quark contribution $\epsilon = 0$	0.00010	
$m_c + 0.1$ GeV →	0.00047	
$m_c - 0.1$ GeV		0.00044
$m_b + 0.2$ GeV	0.00007	
$m_b - 0.2$ GeV		0.00007
total uncertainty	0.00088	0.00048

Deep-Inelastic Inclusive ep Scattering at Low x and a Determination of α_s

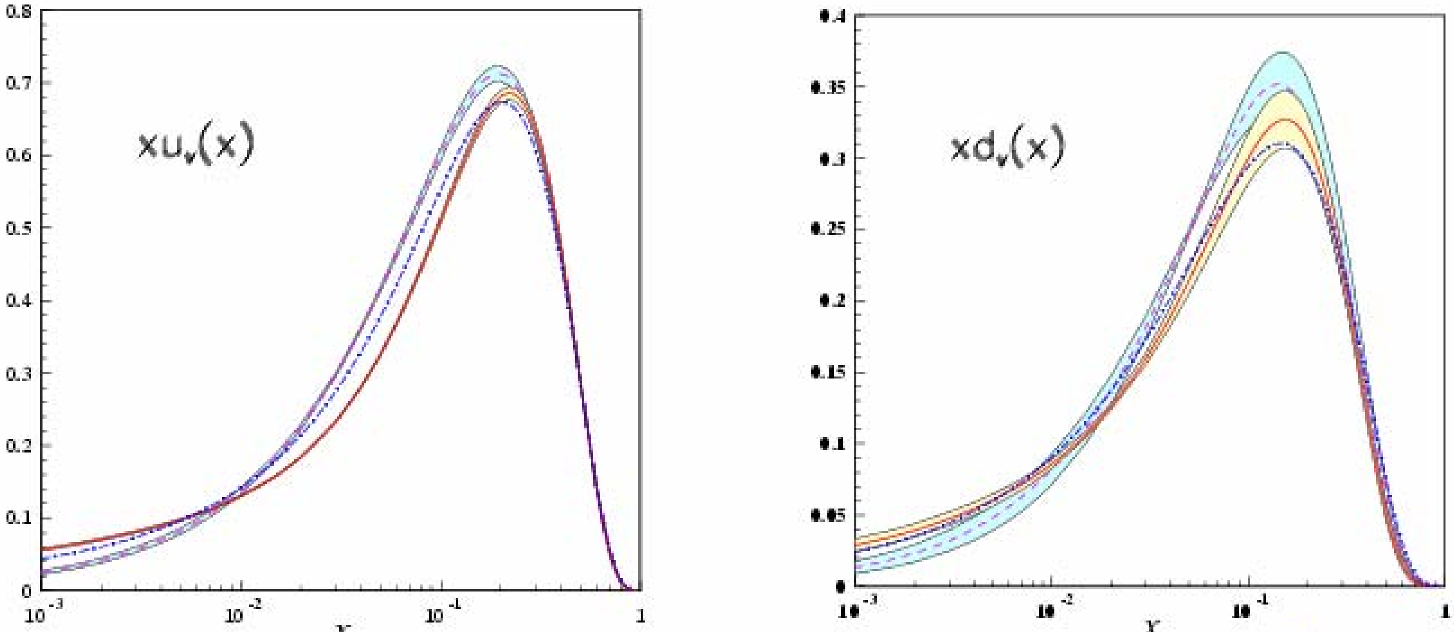
H1 Collab. EPJ C21(01)33

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

- Scale error: why $Q^2/4$ … $4Q^2$??
  use NNLO (MVV)

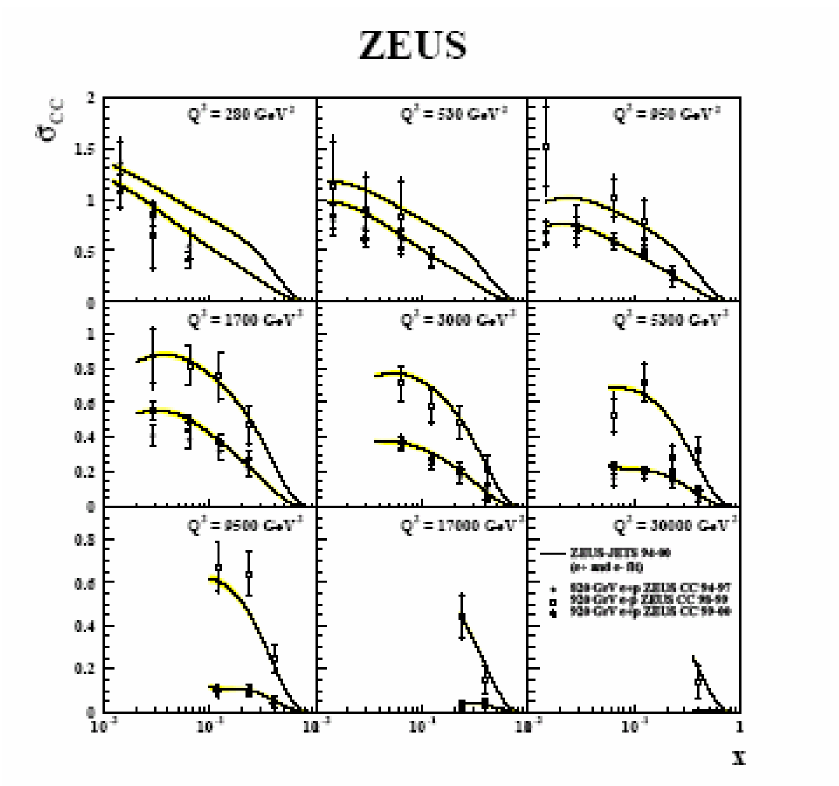
- if: systematic errors are not fitted: +0.0005
- NMC replaces BCDMS 0.116+-0.003 (exp)
- 4 light flavours: +0.0003
- BCDMS deuteron data added: 0.1158 +- 0.0016 (exp)

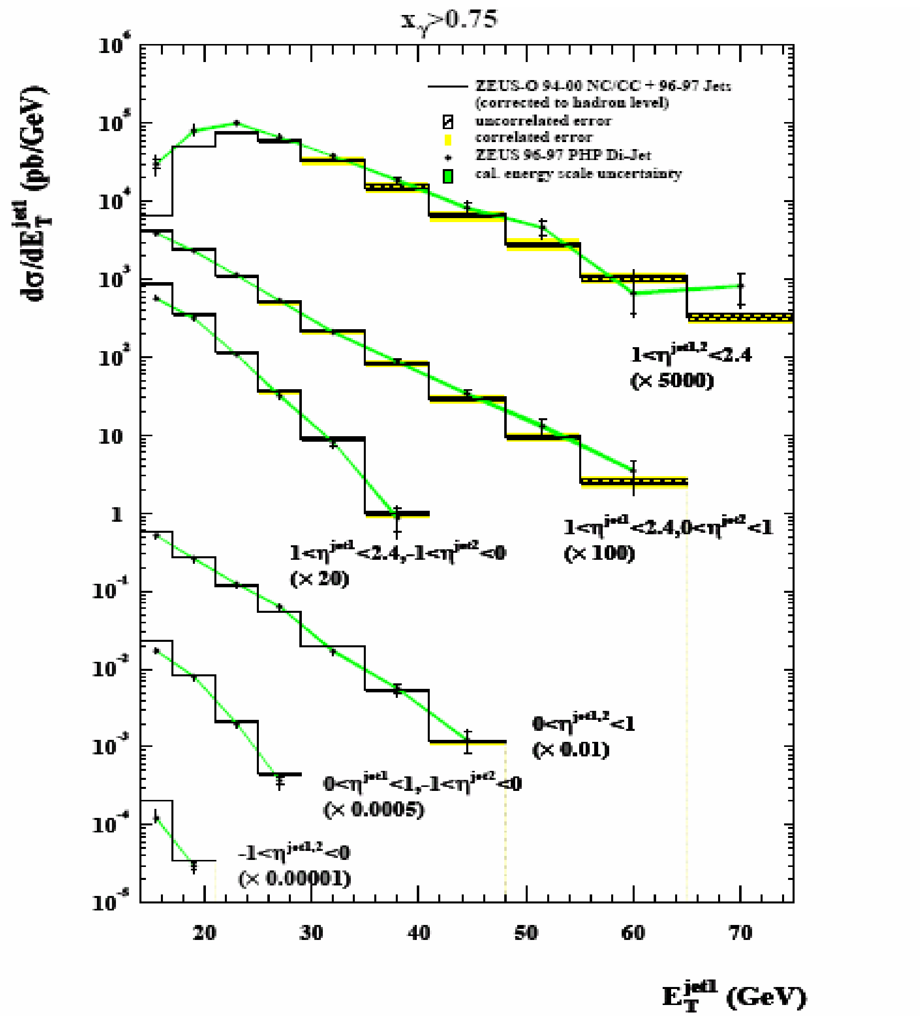
NNLO non-singlet QCD analysis of structure function data



- Fully correlated 1σ statistical error bands for xu_v and xd_v at $Q_0^2 = 4.0\ \mathrm{GeV}^2$
  - extracted values (solid) Blümlein, Böttcher, Guffanti `hep-ph/0407089` with $\alpha_s = 0.1135^{+0.0023}_{-0.0026}(\mathrm{exp})$
- Comparision with combined singlet/non-singlet fits
  - (dashed) Alekhin `hep-ph/0211096` with $\alpha_s = 0.1143 \pm 0.0014(\mathrm{exp}) \pm 0.0009(\mathrm{th})$
  - (dashed–dotted) Martin, Roberts, Stirling, Thorne `hep-ph/0307262` with $\alpha_s = 0.1153 \pm 0.0020(\mathrm{exp}) \pm 0.0030(\mathrm{th})$

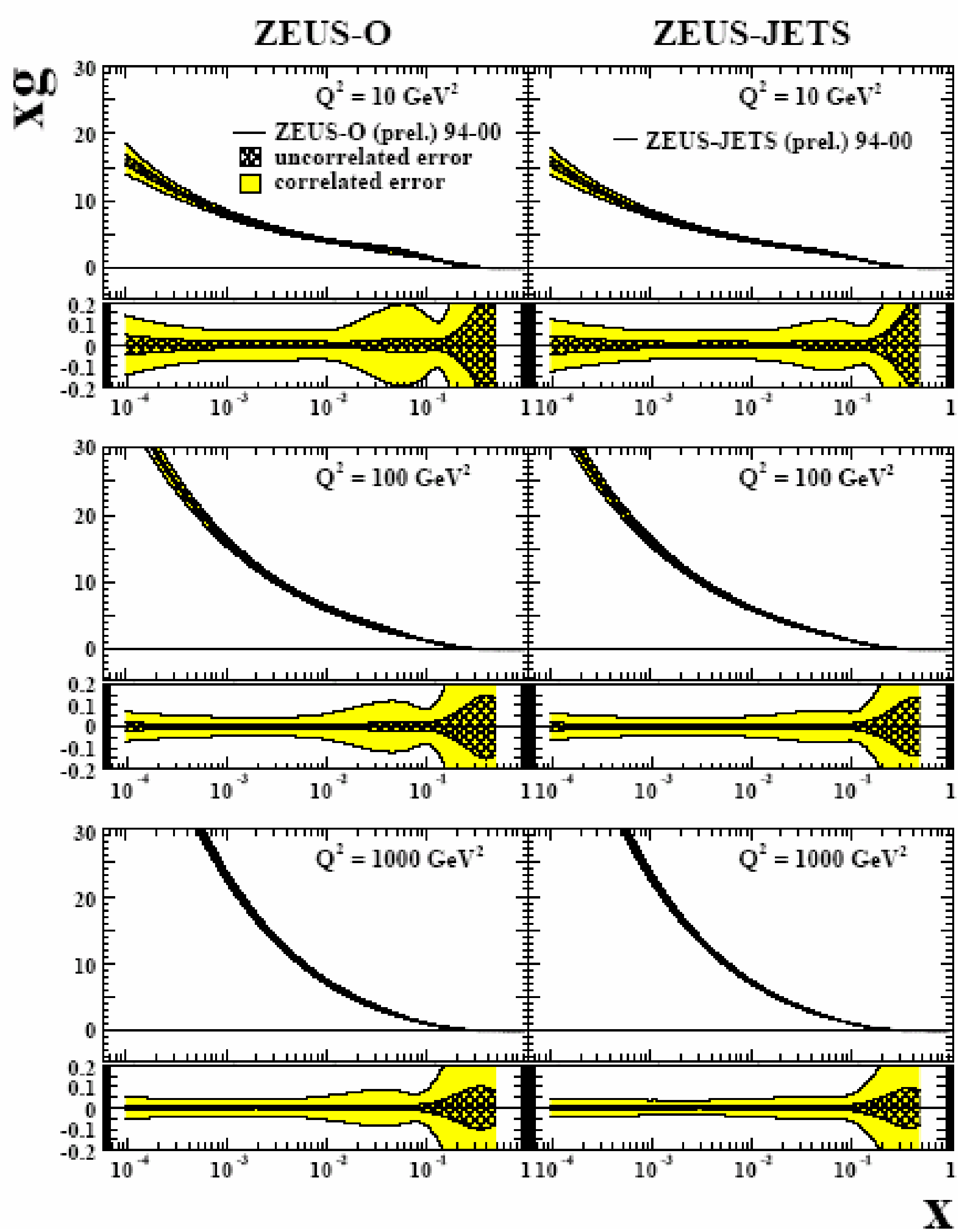
$\alpha_s(M_Z) = 0.1183 \pm 0.0007(\text{uncorr}) \pm 0.0027(\text{corr}) \pm 0.0008(\text{model})$





ZEUS fit NC, CC, and dijet HERA data
jets improve much the α_s determination

- 5% cross section accuracy, based on 1% energy scale error
- larger Et with higher statistics, leads to larger x for xg (up to 0.3)
- use OFFSET method (vs HESSIAN)
- no ‘tension’ of HERA jet data vs low x NC data (as in ‘conservative’ MRST analysis with Tevatron jets)



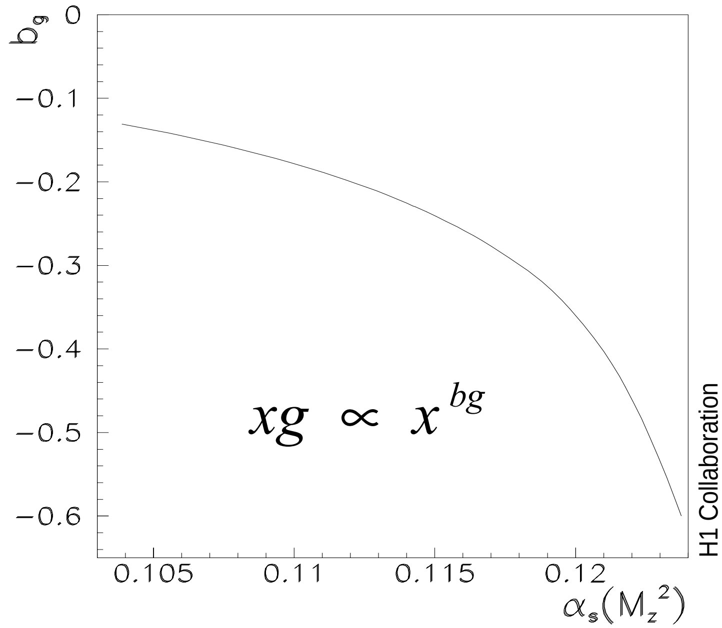
4. Measurement of xg

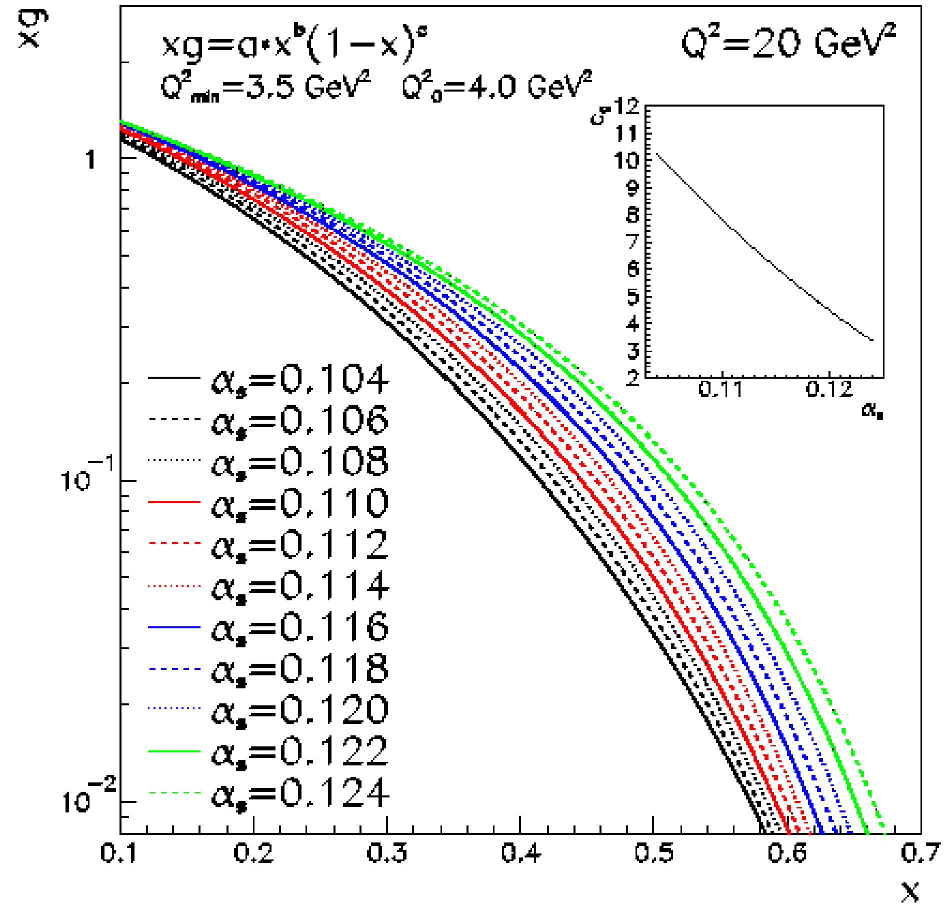
improved xg at medium x,
between 0.1 and 0.01

cf ZEUS paper to ICHEP04
Claire Gwenlan @ Beijing 8/04
Mandy C.Sarkar @ Low x Prague 9/04

Correlation of α_s and xg is resolvable in DIS fits including HERA data

$$xg \leftrightarrow \alpha_s$$

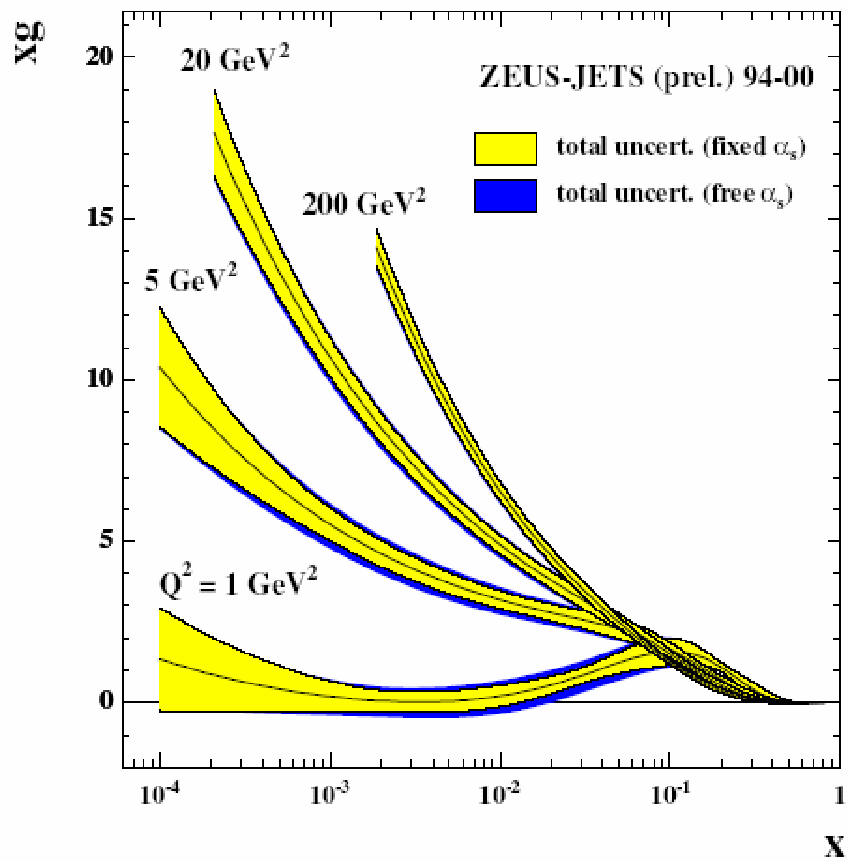




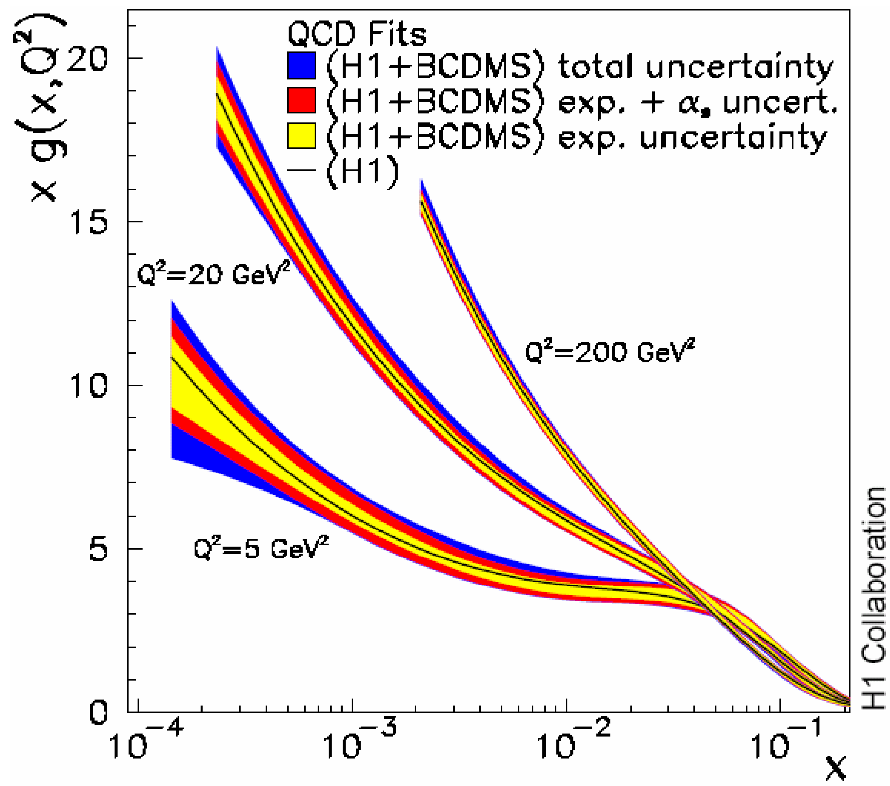
bg=0 in BCDMS (MV) analysis
bg>0 in fit to BCDMS alone

inclusive DIS fits yield very small gluon density at large x → must underestimate Tevatron jets

ZEUS inclusive NC+CC & jets



H1 inclusive NC+CC

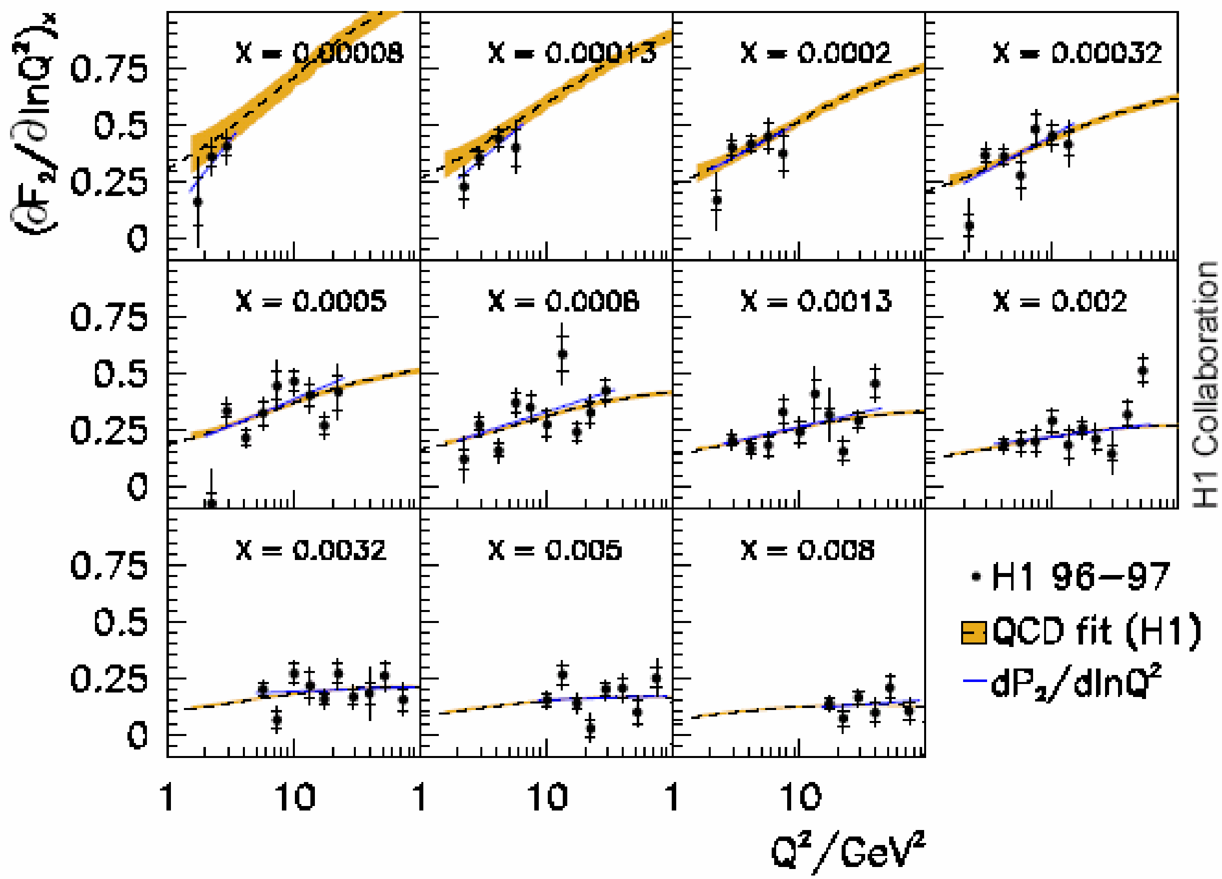


STATUS of ICHEP04

xg is NOT an observable. Charm treatment important (ZEUS: VFNS RT, H1: FFNS)

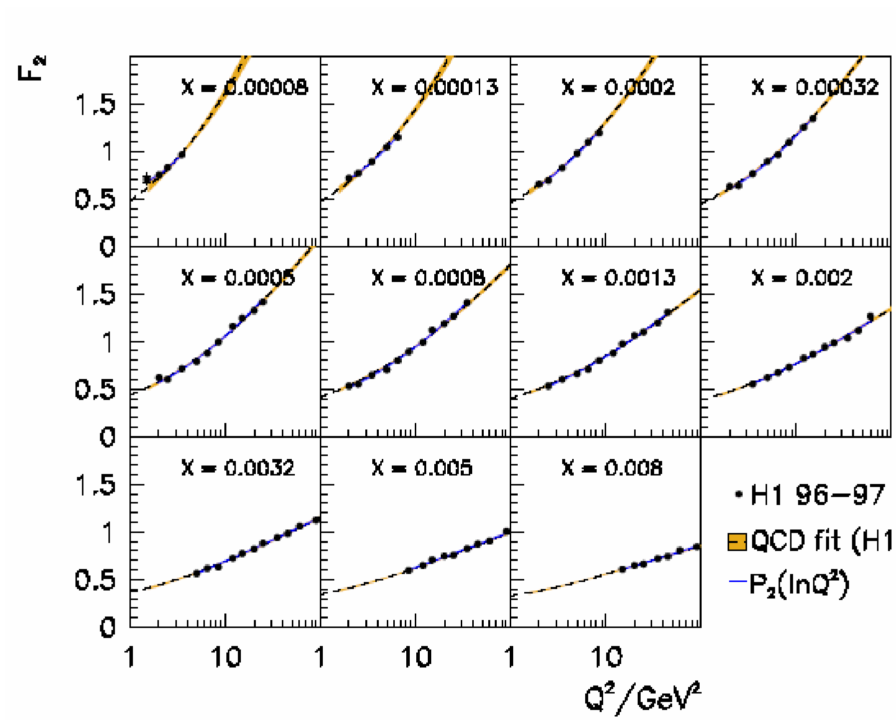
In the region of low x and $Q^2 \sim 1$ GeV² the gluon distribution becomes very small

→ transition from hadronic to partonic behaviour at about 0.3 fm

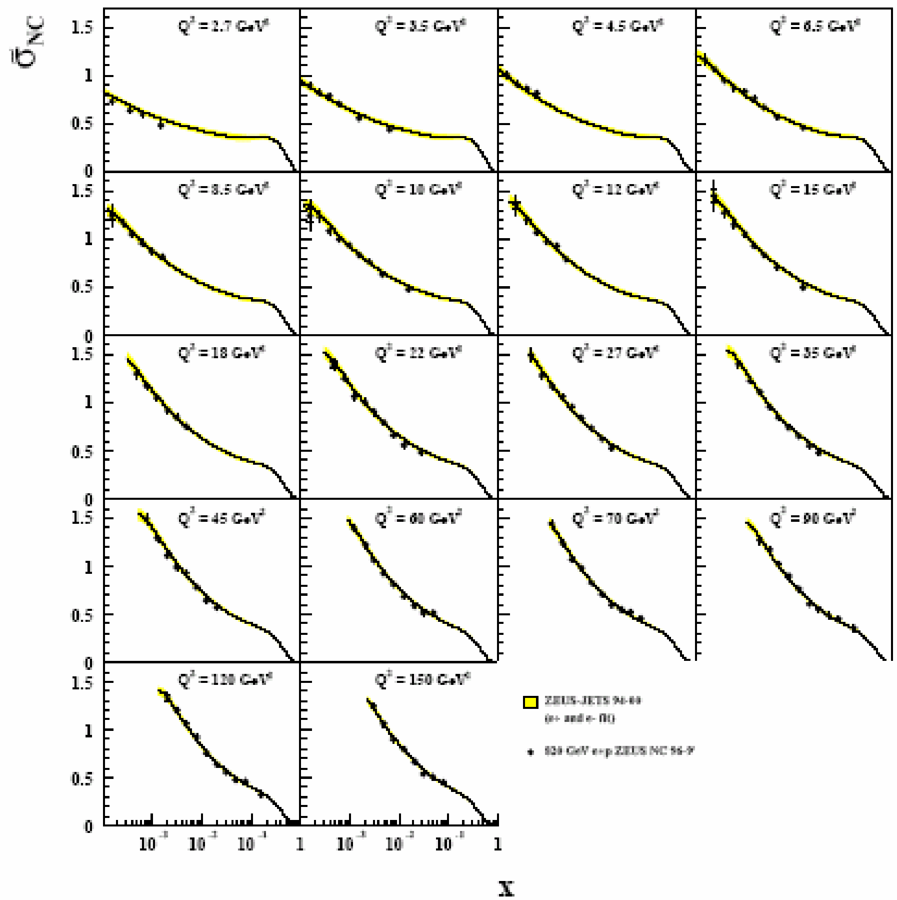


At low x gluon is determined by lnQ2 derivative of F2
This has been measured to rise with Q2 which is
NOT in conflict with DGLAP NLO analyses.
Not very accurate and few data only at low x, Q2 <10 GeV2!

H1



ZEUS



- F_2 itself looks much nicer

Predictions for the longitudinal structure function

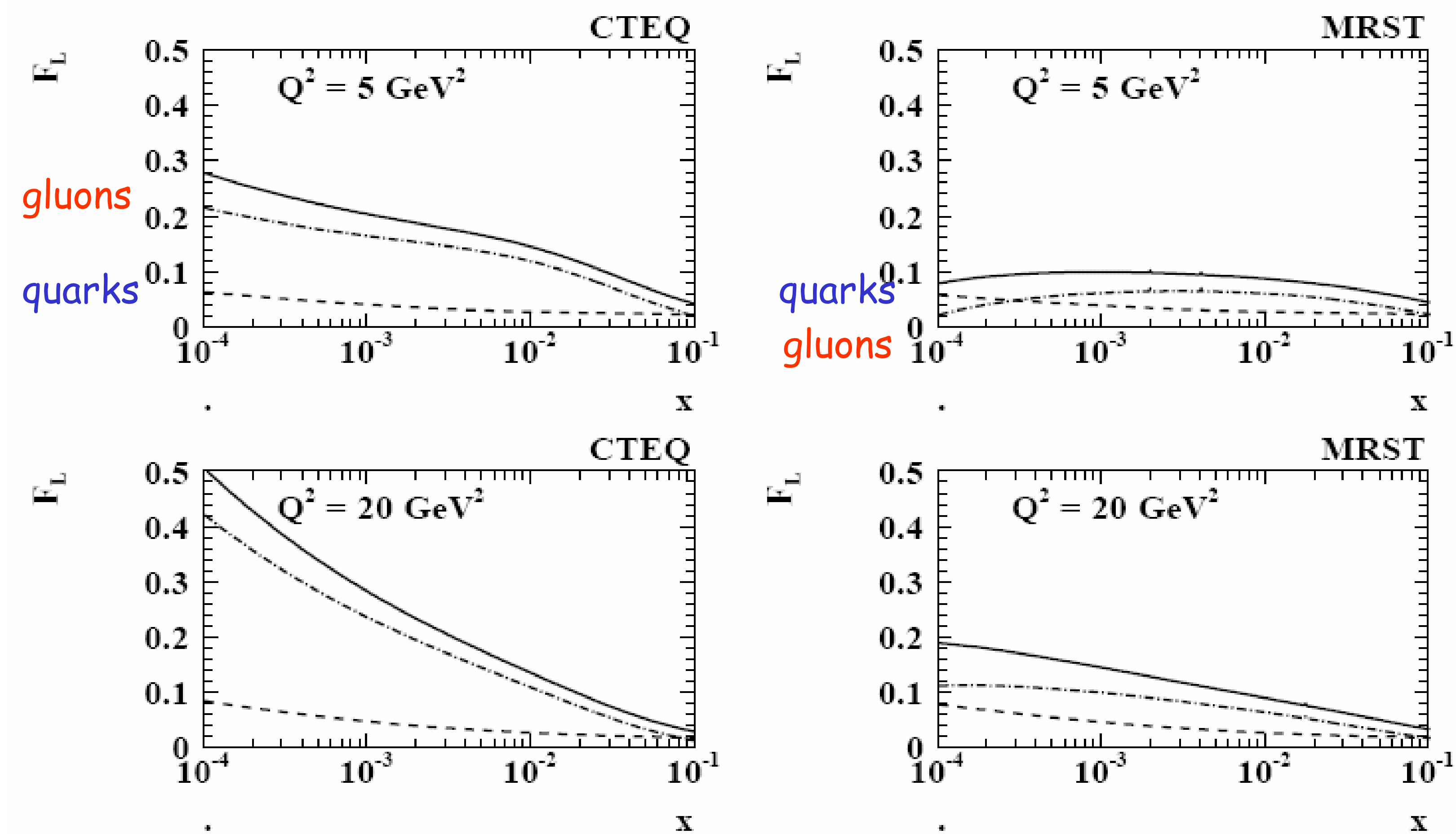
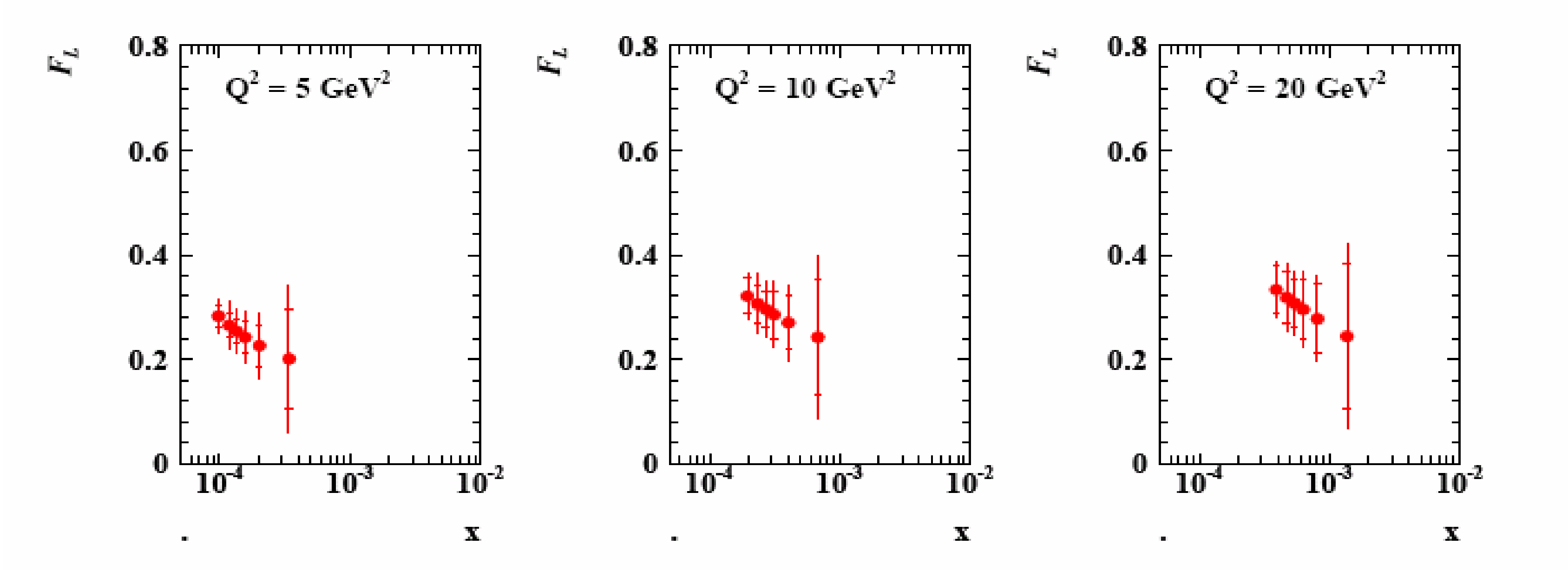


Figure 2. Calculation of the longitudinal structure function $F_L(x, Q^2)$ (solid lines) using the CTEQ6 (left) and the MRST2002 (right) parton distributions and Eq.2 for 4 flavours and α_s to NLO. Note that not only the predicted values for F_L differ but as well drastically the relative contributions from gluons (dashed dotted lines) and sea quarks (dashed lines). For MRST at low x, contrary to common belief, $F_L(x, Q^2)$ is not gluon dominated. Both sets of parton distributions describe the H1 data on F_2 well.

G. Altarelli and G. Martinelli, Phys.Lett. B76 (1978) 89.

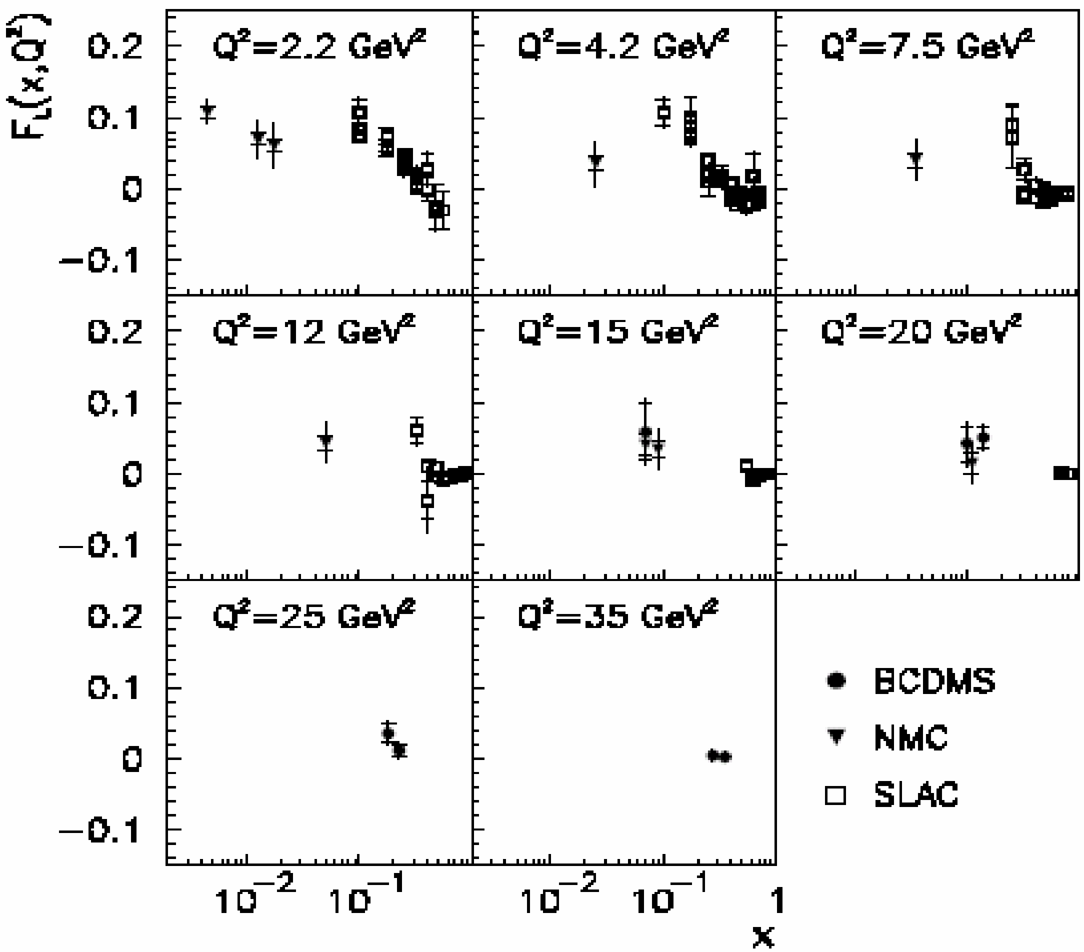
$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \cdot \left[\frac{16}{3} F_2 + 8 \sum e_q^2 \left(1 - \frac{x}{z} \right) zg \right]$$



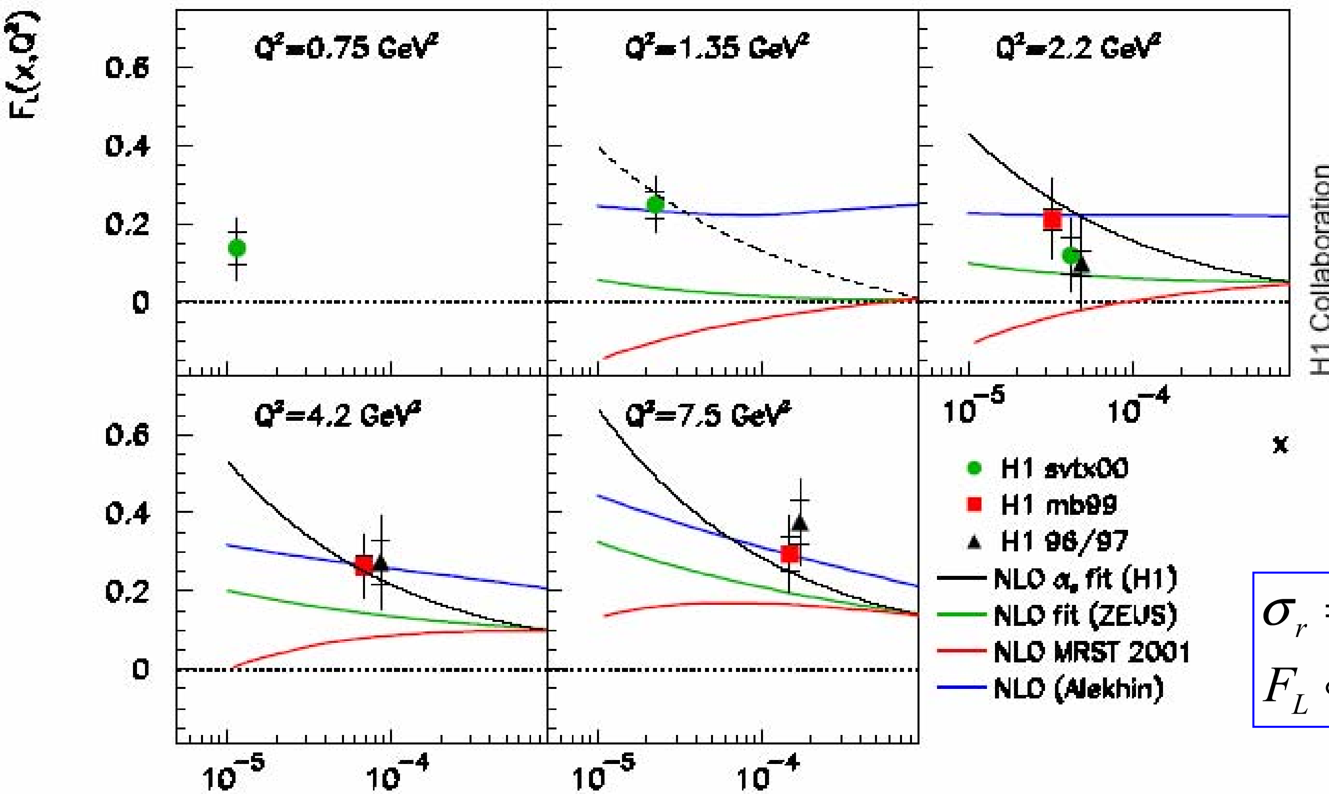
Simulation of FL measurement at HERA with four Ep runs
to complement low x data from H1 from high Ep data.

•Ep = 920, 575, 465, 400 GeV L = 10, 5, 3, 2 pb^{-1}, resp.

y>0.9, cross sections to 1-2%, challenging measurement cf: MK DIS04 proc.
case study!



- FL measurements of fixed target DIS lp experiments. CG: FL=0
- It is difficult to measure the longitudinal structure function.



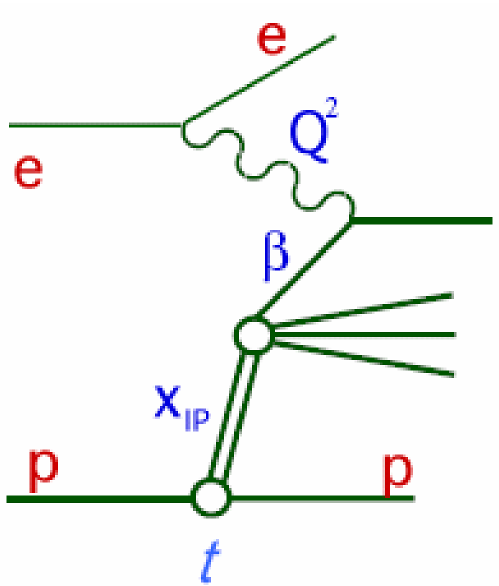
$$\sigma_r = F_2 - f(y)F_L$$
$$F_L \propto \alpha_s xg$$

F_L data point to positive gluon distribution at low Q^2.

Low E_p measurements determine x dependence and improve accuracy. Disentangle F_2 and F_L comme il faut and thereby pin down the gluon distribution at low x.

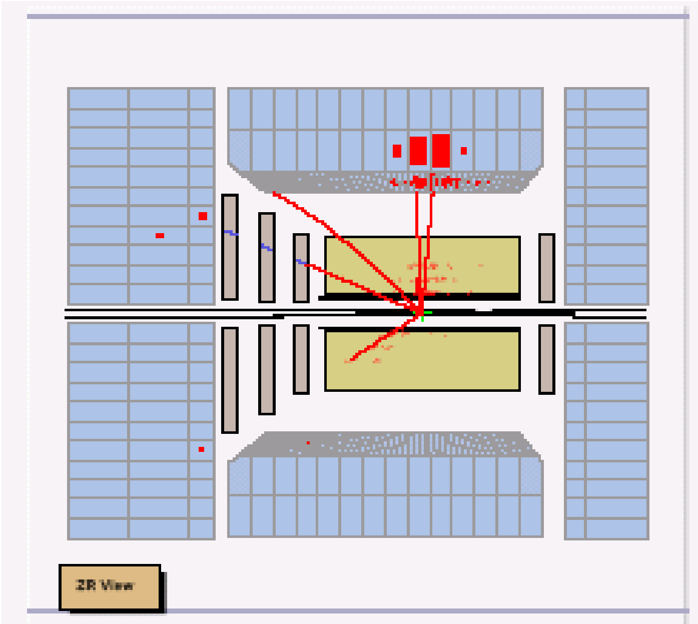
4. Diffraction

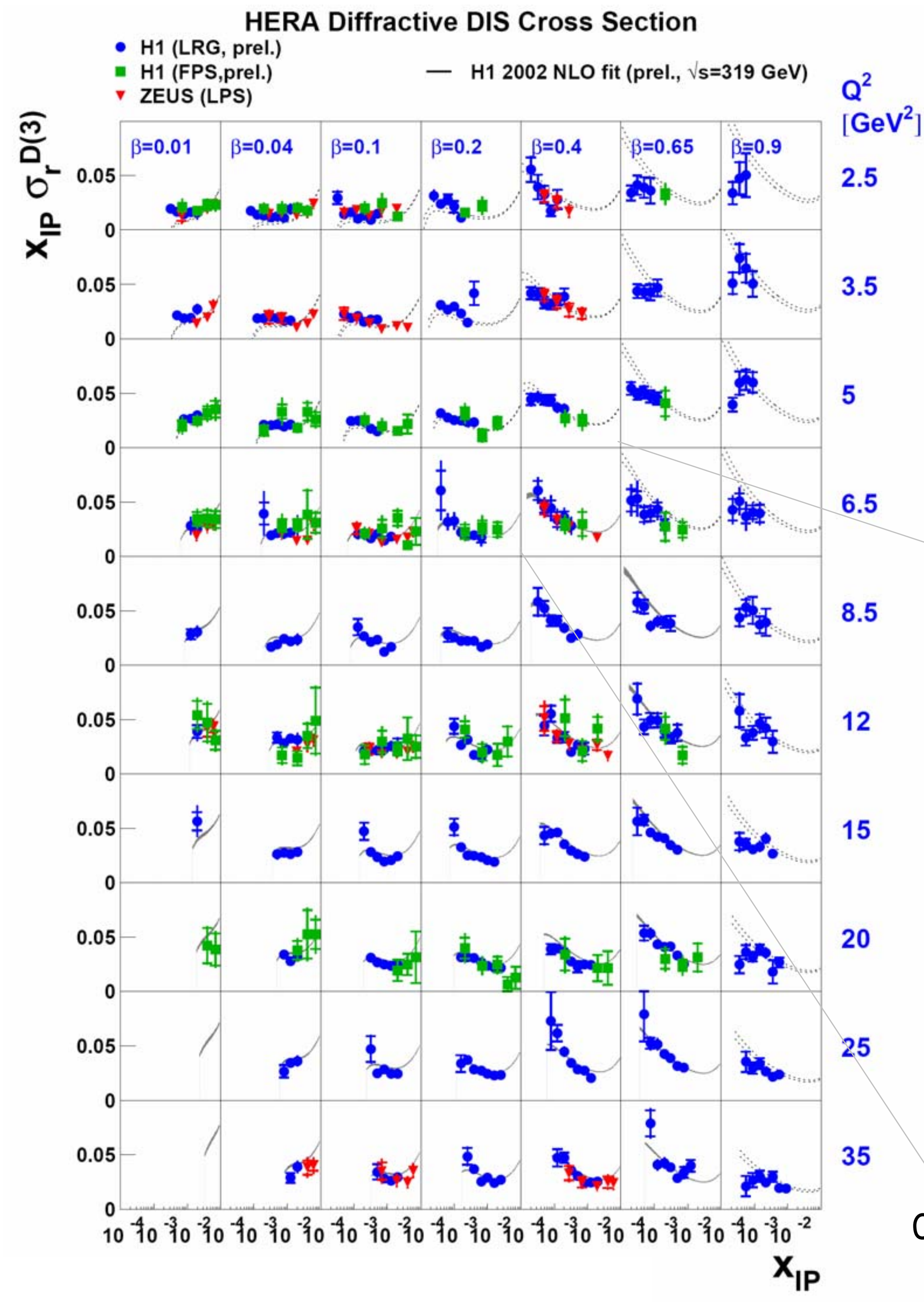
~10% of NC DIS events have gap between p and central tracks. Measure gap or detect p with LPS/VFPS



$$\frac{d\sigma^{NC}_{diff}}{dx_{IP}dtd\beta dQ^2} \propto \frac{1}{Q^4} F_2^{D(4)}(x_{IP}, t, \beta, Q^2)$$

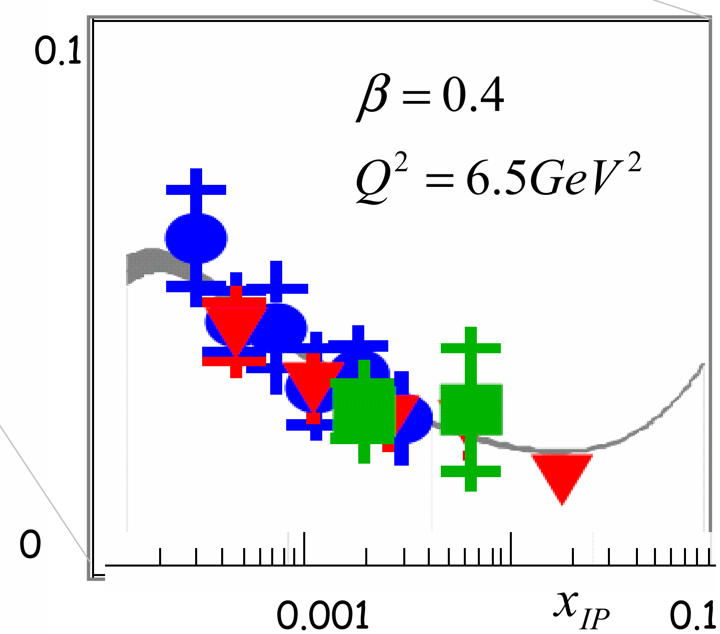
First observation by ZEUS and H1 of diffraction in charged current scattering at high Q^2: 2-3%

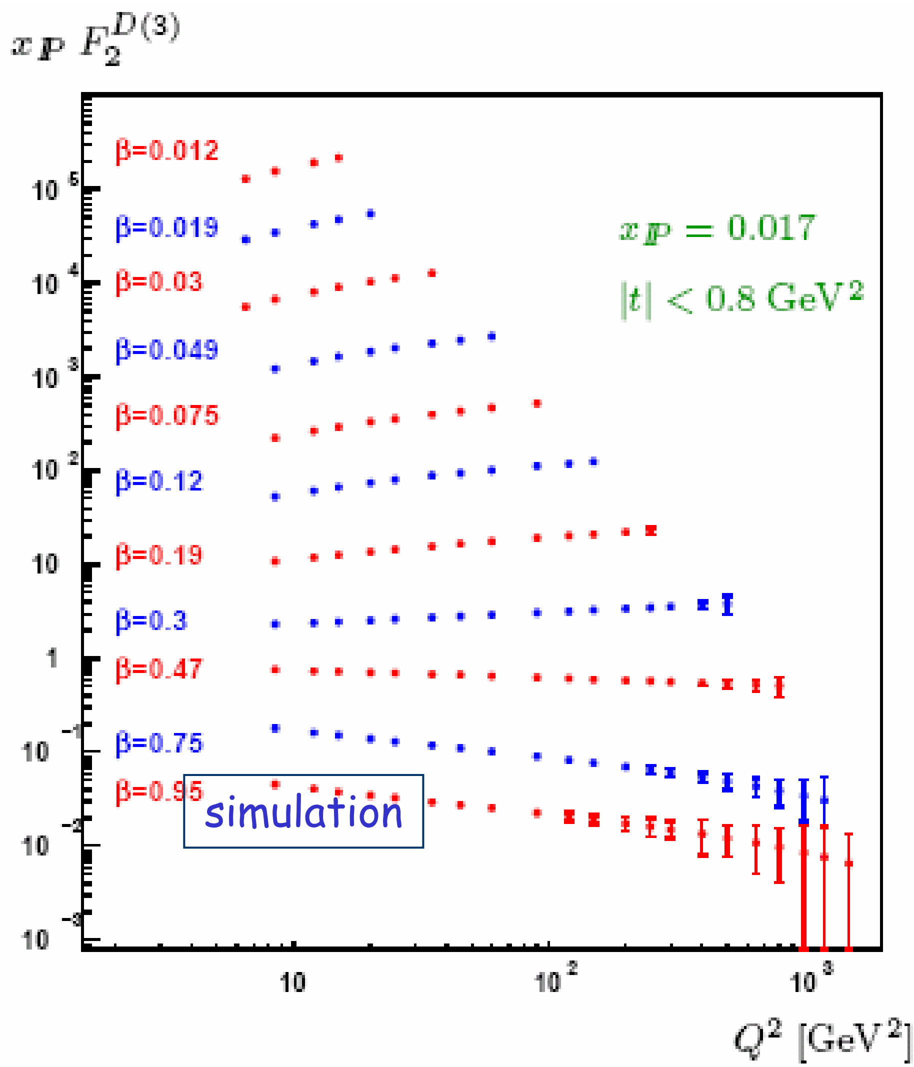


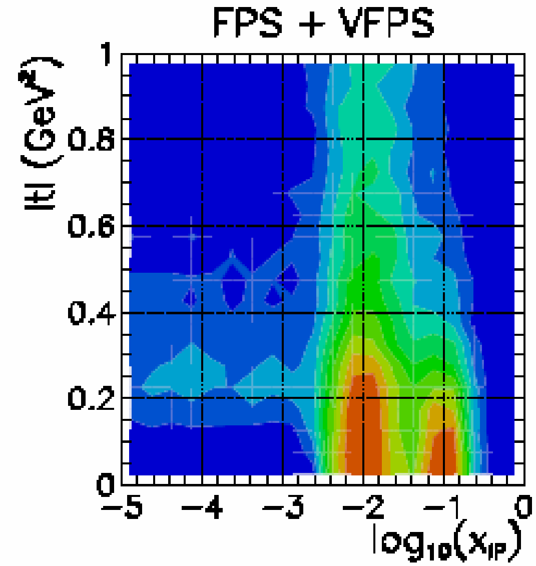


- New diffractive DIS data tagged with:
  - Large rapidity gap i.e. forward detector veto.
  - Tagged proton using Forward p Spectrometer FPS (H1) Leading p Spectrometer LPS (ZEUS)
- Good agreement between all data

$$x_{IP}\sigma_r^{D(3)} = x_{IP}[F_2^{D(3)} - f(y)F_L^{D(3)}]$$







10^6 Events for $Q^2 > 5\ \mathrm{GeV}^2$

$\longrightarrow$ Study t dependence

$\longrightarrow F_2^{D(4)}(Q^2, \beta, x_{I\!P}, t)$

Uncorrelated systematic errors can reach 2-3 %
(similar to F_2 precision)

$\longrightarrow$ Extract diffractive pdf's at fixed $x_{I\!P}$ and t and predict final states at same $x_{I\!P}$ and t to test factorization theorem

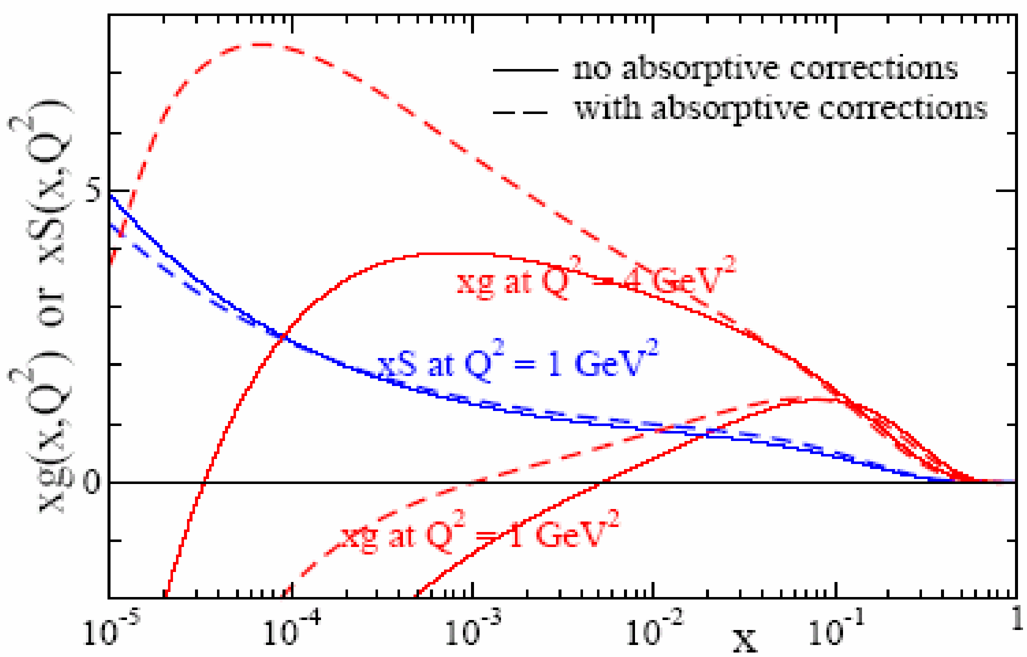
F2D4 (4 Q2, 4 beta, 5 xpom , 3 t bins) ->
4-10% stat error,

- M.Kapishin - || March04
- X.Janssen - DIS04

Gluon and sea quark PDFs

$$xg(x,Q^2=1\ \mathrm{GeV}^2) = A_g\, x^{-\lambda_g} (1-x)^{3.7} (1 + \varepsilon_g x^{0.5}) - A_- x^{-\delta_-} (1-x)^{10}$$

$$xS(x,Q^2=1\ \mathrm{GeV}^2) = A_S\, x^{-\lambda_S} (1-x)^{7.1} (1 + \varepsilon_S x^{0.5})$$



χ^2/d.o.f.	
F_2	$F_2^{D(3)}$
1.15	1.16
1.09	1.17

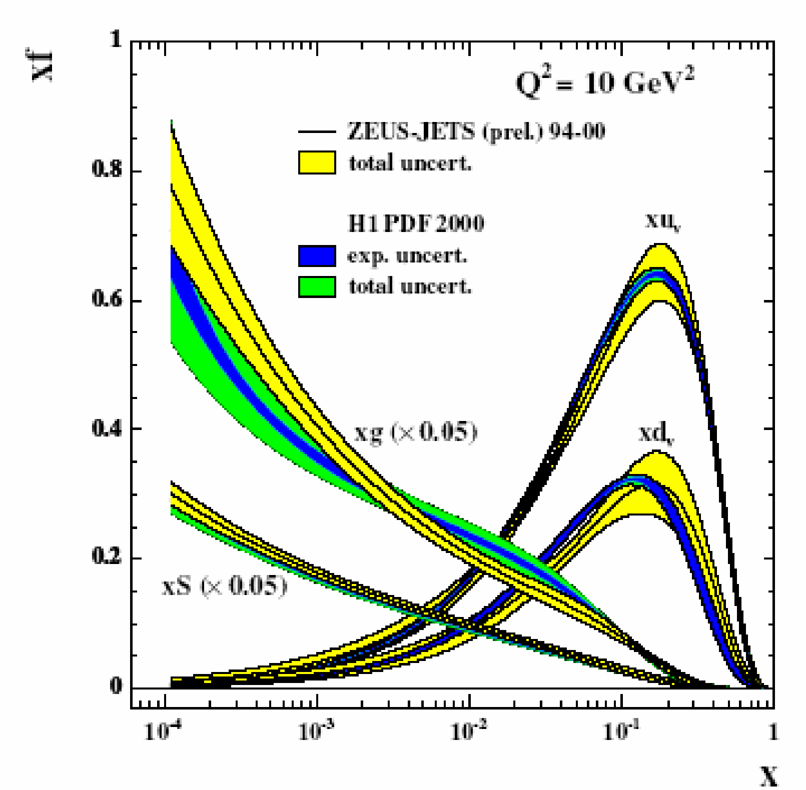
? "help" FL?

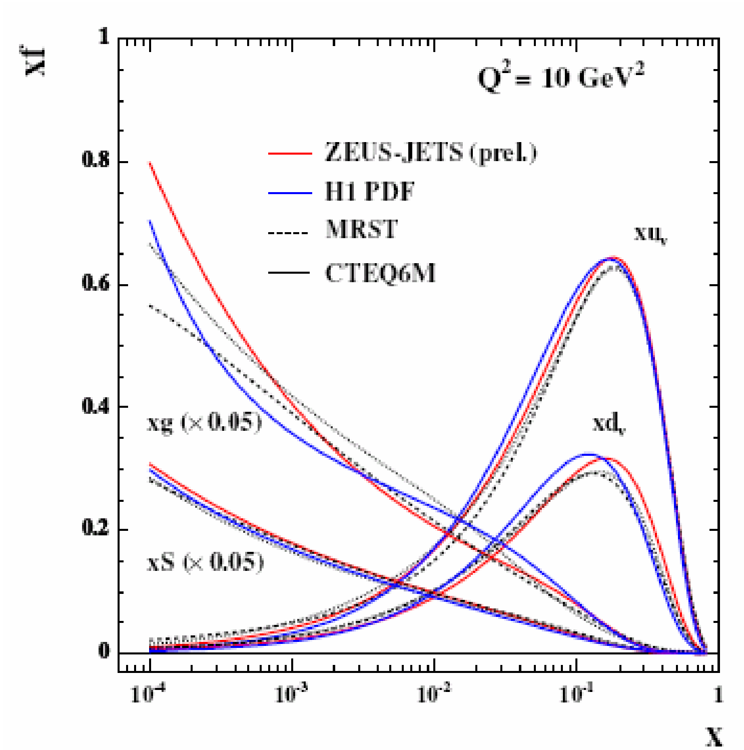
- Take +ve input gluon parameterisation ($A_- = 0$):
  - no absorptive corrections $\chi^2/\mathrm{d.o.f.} = 1.57$
  - with absorptive corrections $\chi^2/\mathrm{d.o.f.} = 1.10$

•Martin, Ryskin, Watt: absorptive corrections to F2. analysis of F2 and F2D3 → xg ??

5. Measurement of light quark distributions

Parton distributions unfolded with H1 data and with ZEUS data only, compared with global fits.





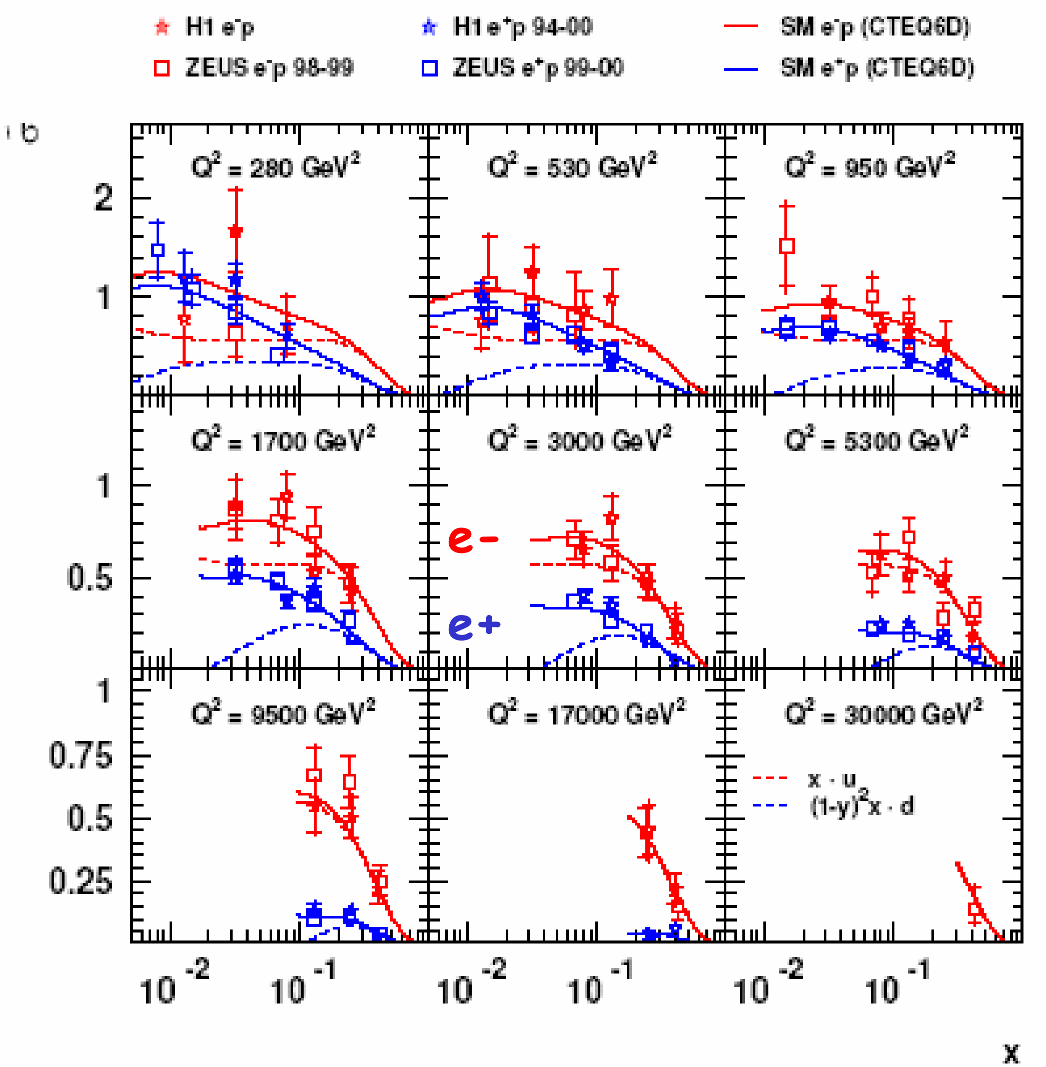
- H1 and ZEUS parton distributions are in agreement
- HERA experiment's fits agree with global fits
- Treatment of systematic, model and theoretical errors subject to conventions

QCD fits parameterise initial PDFs

H1 $U,\bar{U},D,\bar{D},xg \leftrightarrow V,A,xg-\alpha_s$

ZEUS $u_v,d_v,\bar{u}\pm\bar{d},xg-\alpha_s$

Reduced charged current scattering cross section

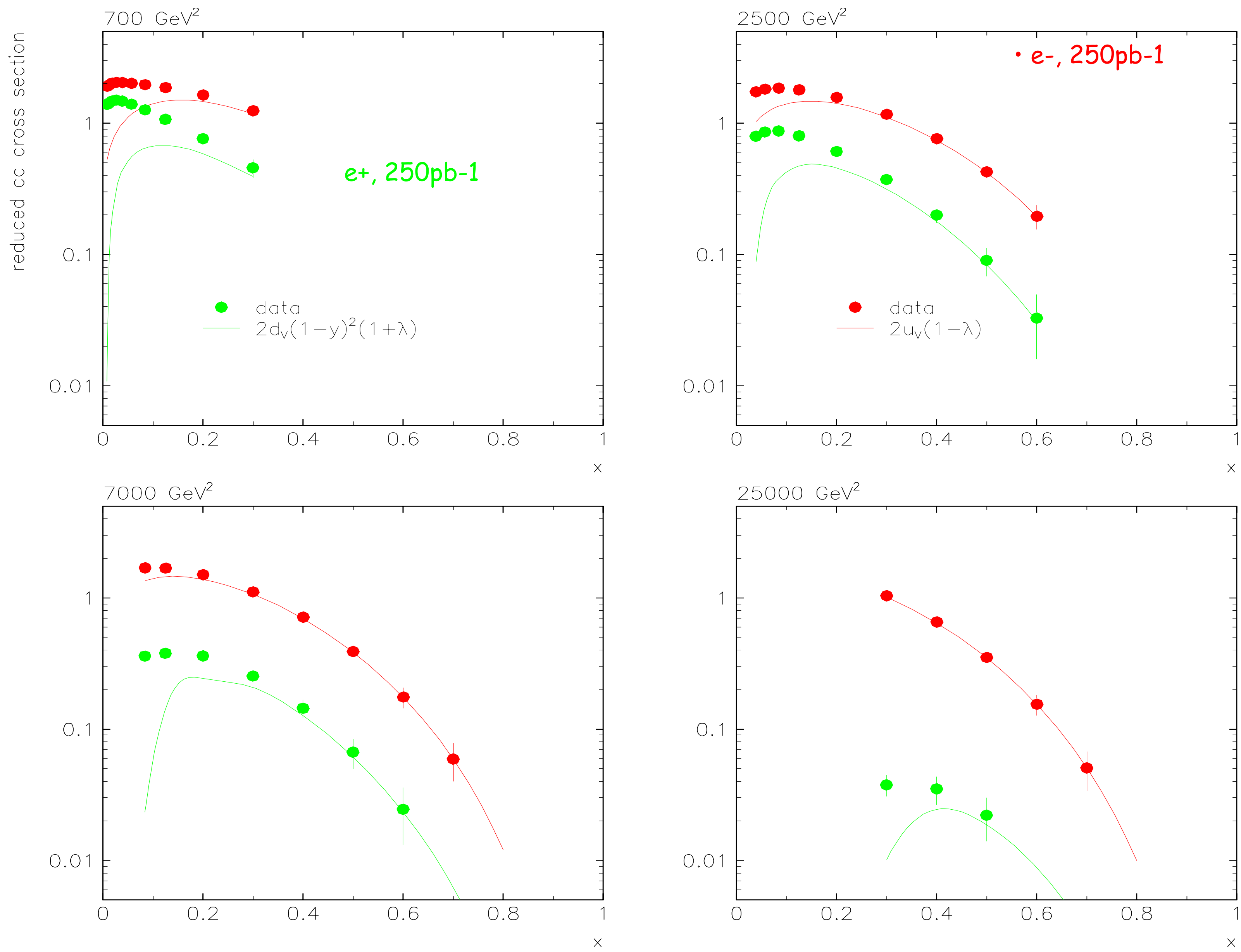


$$\sigma_{CC}^{-} \sim xU + (1-y)^2 x\overline{D} \rightarrow xu_v$$

$$\sigma_{CC}^{+} \sim x\overline{U} + (1-y)^2 xD \rightarrow (1-y)^2 xd_v$$

HERA can disentangle parton distributions at large Q^2 and large x > 0.01 within single experiments, independently of nuclear corrections and free of higher twists

Future CC cross section measurements at HERA in e±p



eD at HERA

if we want to study the structure of the neutron in the HERA kinematic range and if we want to distinguish up from down quarks, accurately at high x and precisely at low x, then HERA has to run with deuterons.

+ high x: Fermi motion: tag spectator proton

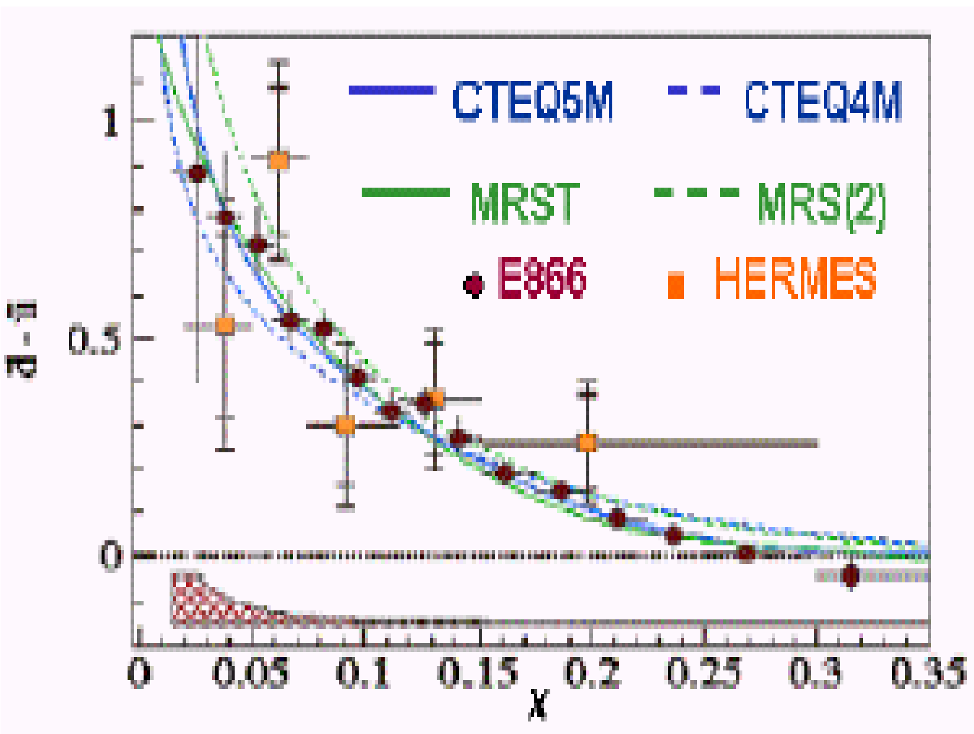
+ low x: shadowing: measure diffraction to control shadowing to ~2%

→ electron-deuteron scattering at HERA is much more powerful and attractive than at fixed target experiments

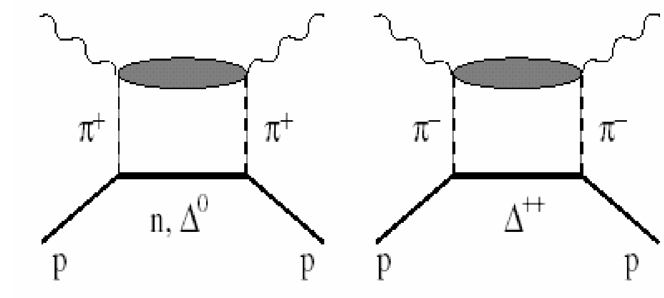
LoI: Electron-Deuteron Scattering with HERA: DESY 03-194
(cf also for beam related remarks. L ~L(ep)/2)
also: A New Experiment for the HERA Collider: MPI-2003-06

$\bar{d} \neq \bar{u}$?

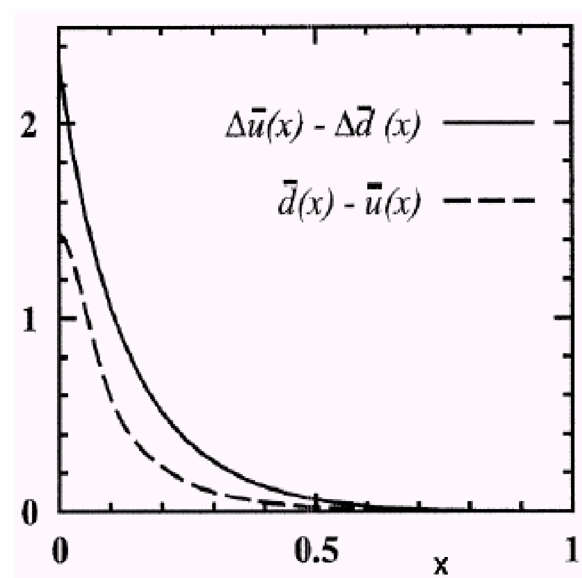
- extractions of PDFs assume $\bar{d} = \bar{u}$ at low x.
- plausible as both m_u ~ 3 MeV and m_d ~ 6 MeV << Λ_{QCD}.
- but look at available data…



•Sullivan model

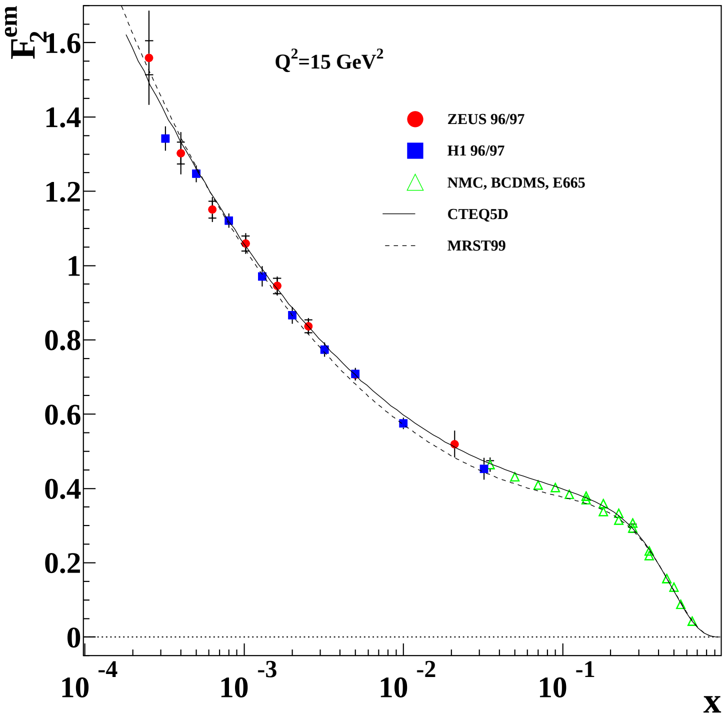


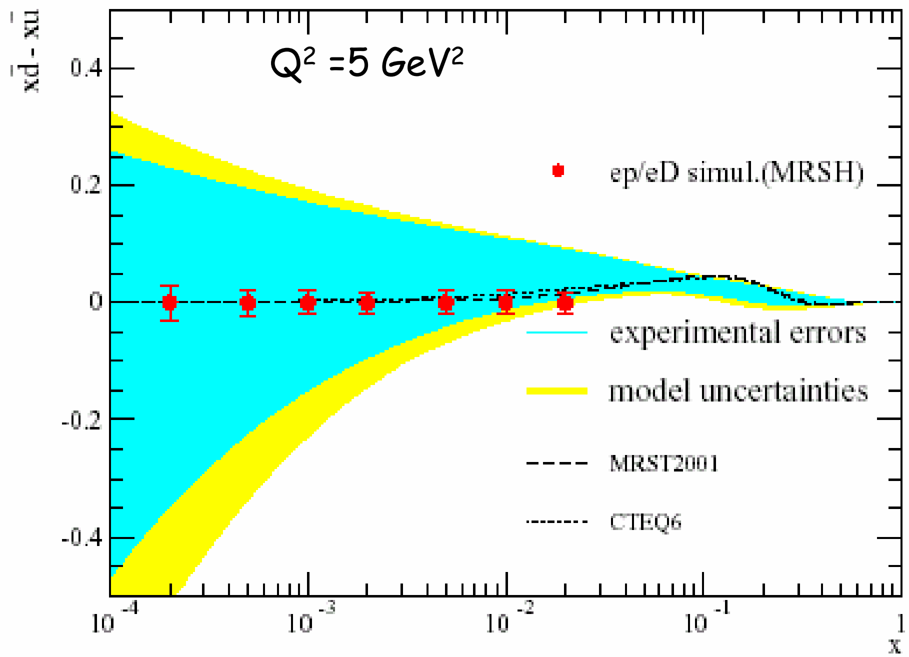
•Chiral soliton model



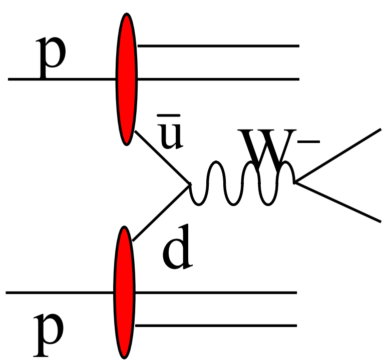
Exploration of the rising F2(x,Q2)

$$\tfrac{1}{2}\left(F_2^{\,p} + F_2^{\,n}\right) - F_2^{\,p}$$
$$= x\left(\tfrac{1}{6}d_v - \tfrac{1}{6}u_v + \tfrac{1}{3}\bar{d} - \tfrac{1}{3}\bar{u}\right)$$
$$\approx \tfrac{1}{3}x\left(\bar{d} - \bar{u}\right) \text{ at low } x.$$





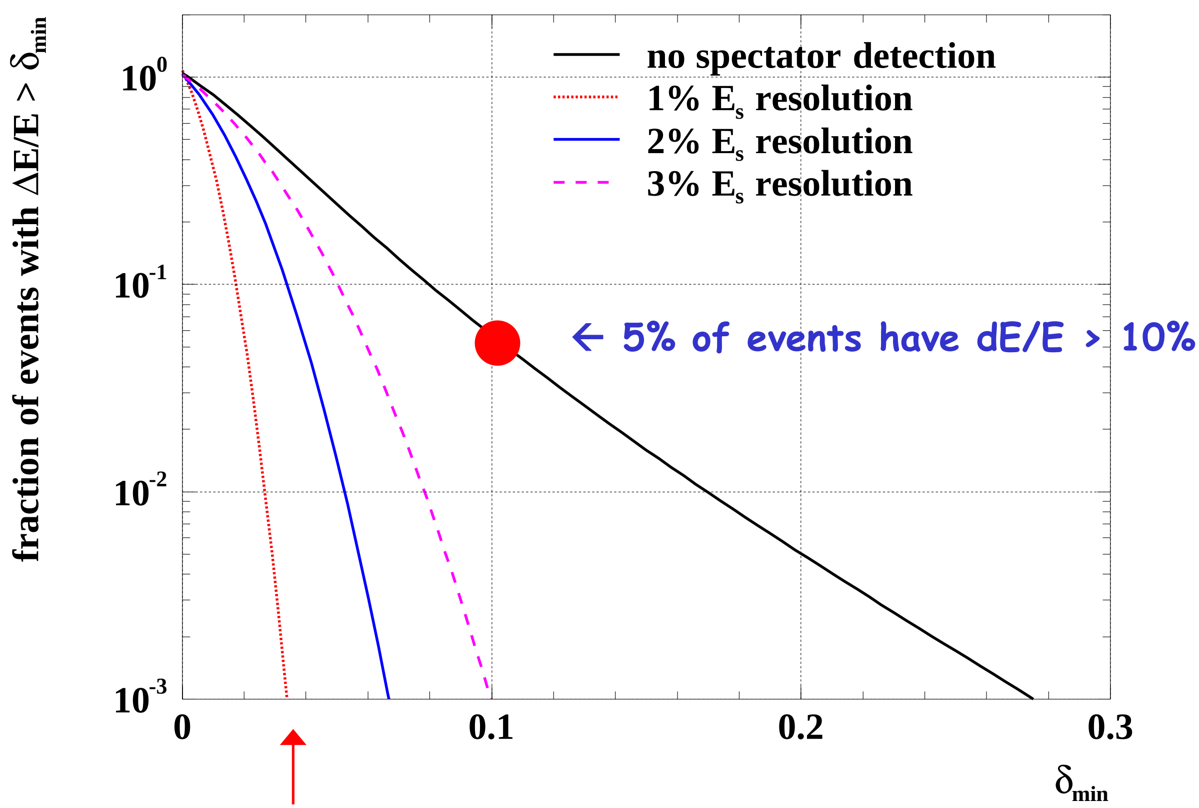
simulated accuracy (20pb^{-1} eD, 40 ep)



Affects parton luminosity at the LHC
Want 2% accuracy for δm_t = 2 GeV

Tagging of p,n,D

reconstruct en kinematics (reduce Fermi motion) by measuring spectator proton

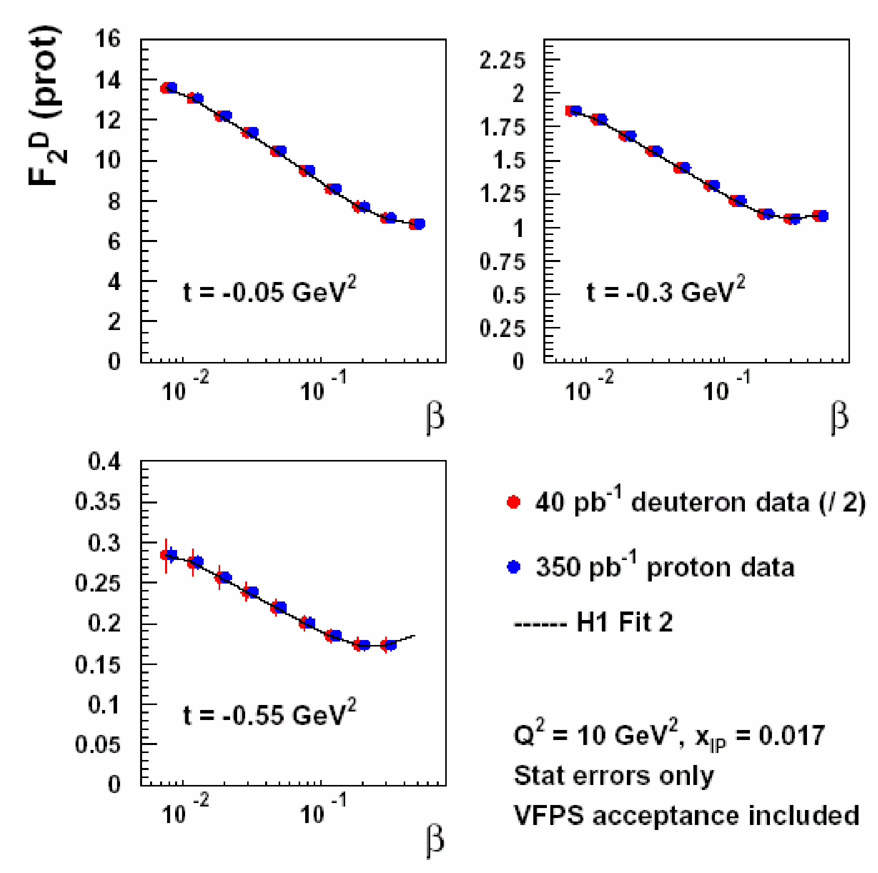


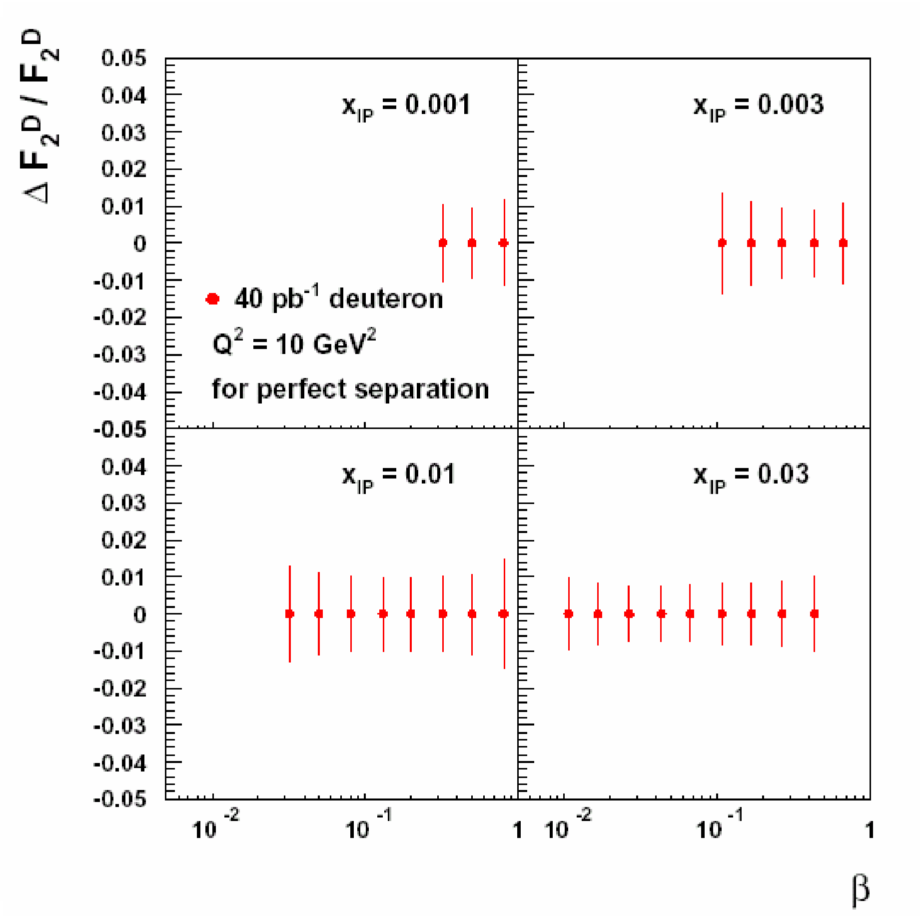
aim for 1% momentum resolution

calibration with kinematic peak at p=E/2 and resonances in central detector

optics: from VFPS and FPS

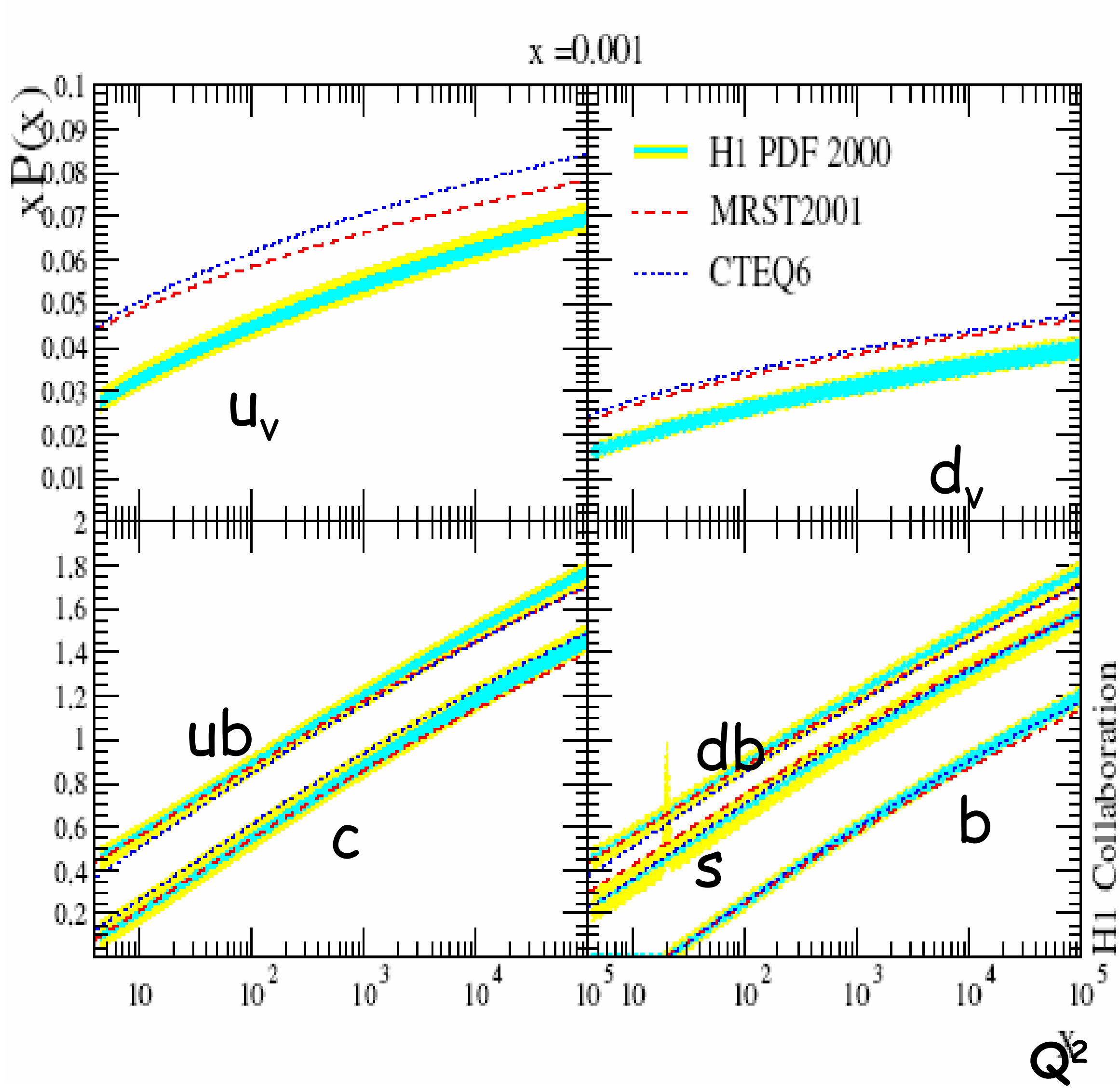
Diffraction on either p, n or D (coherent)





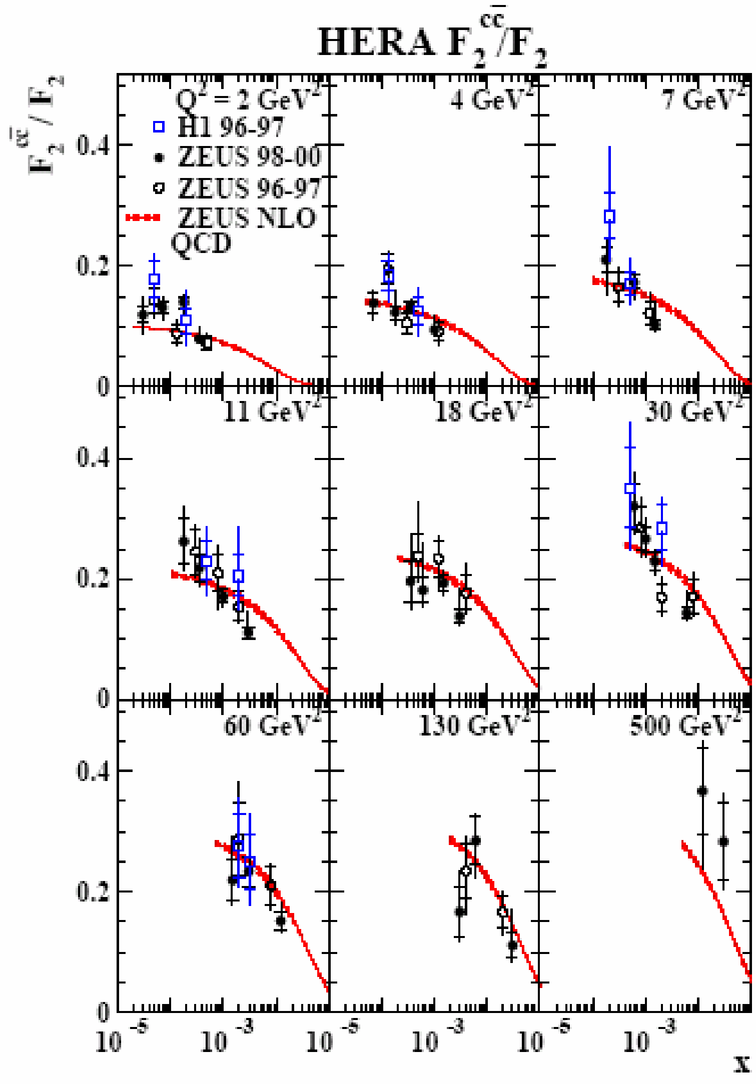
- is isospin conserved?
- expect increasing fraction of diffraction with larger A (bbl)

HERA and global parton distributions extrapolated to ~rapidity plateau at LHC

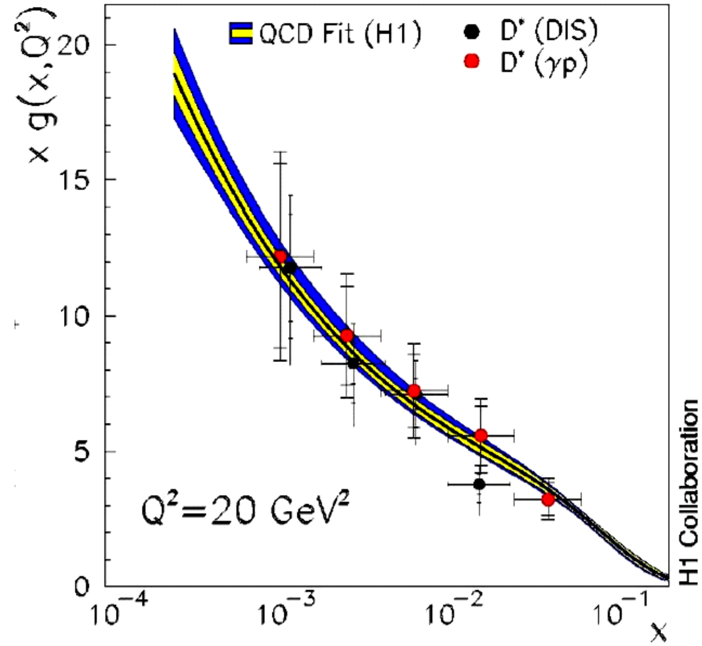


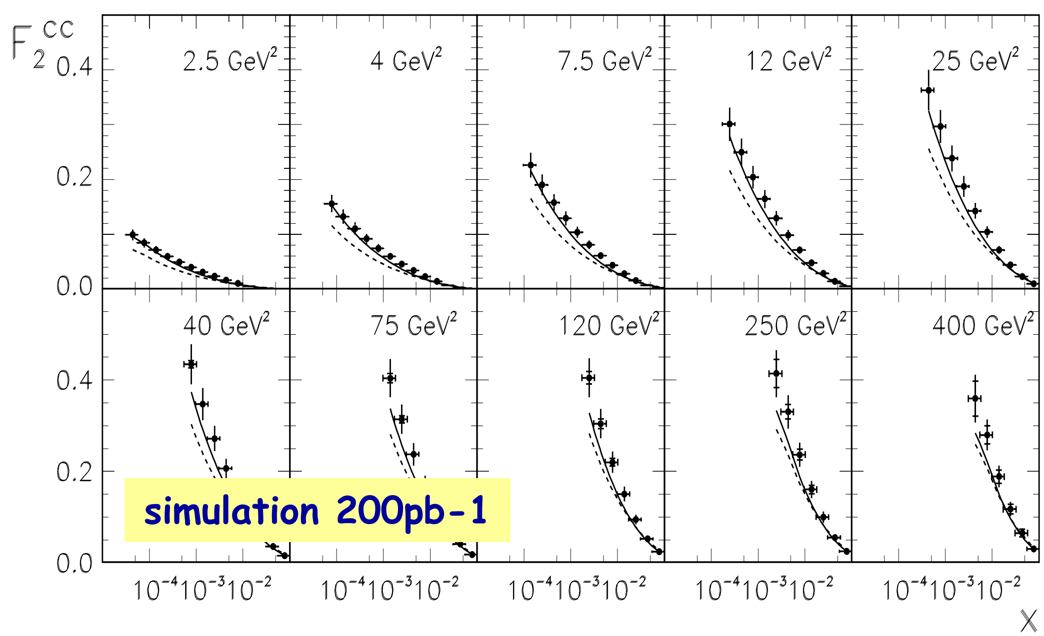
Heavy flavours become relatively large as compared to HERA → need to be well constrained

6. Charm and Beauty



large part of the xsection





simulation 200pb-1

- Increase Statistics: 2%
- New Si in fwd/bwd for high/low x
- Measure Fragmentation: 3%
- Develop MC@NLO
- Use Lifetime, more channels
- Fits to F2cc and $\sigma_{vis}(D^*)$
- Measure mc
- …

→few % F2cc and xg [K. Daum]

→ ~10% for F2bb

Uncertainties in extrapolation

Factors for extrapolating to full phase space in $p_T(D^*)$ and $\eta(D^*)$ are 4.7 at low Q^2 and 1.5 at high Q^2

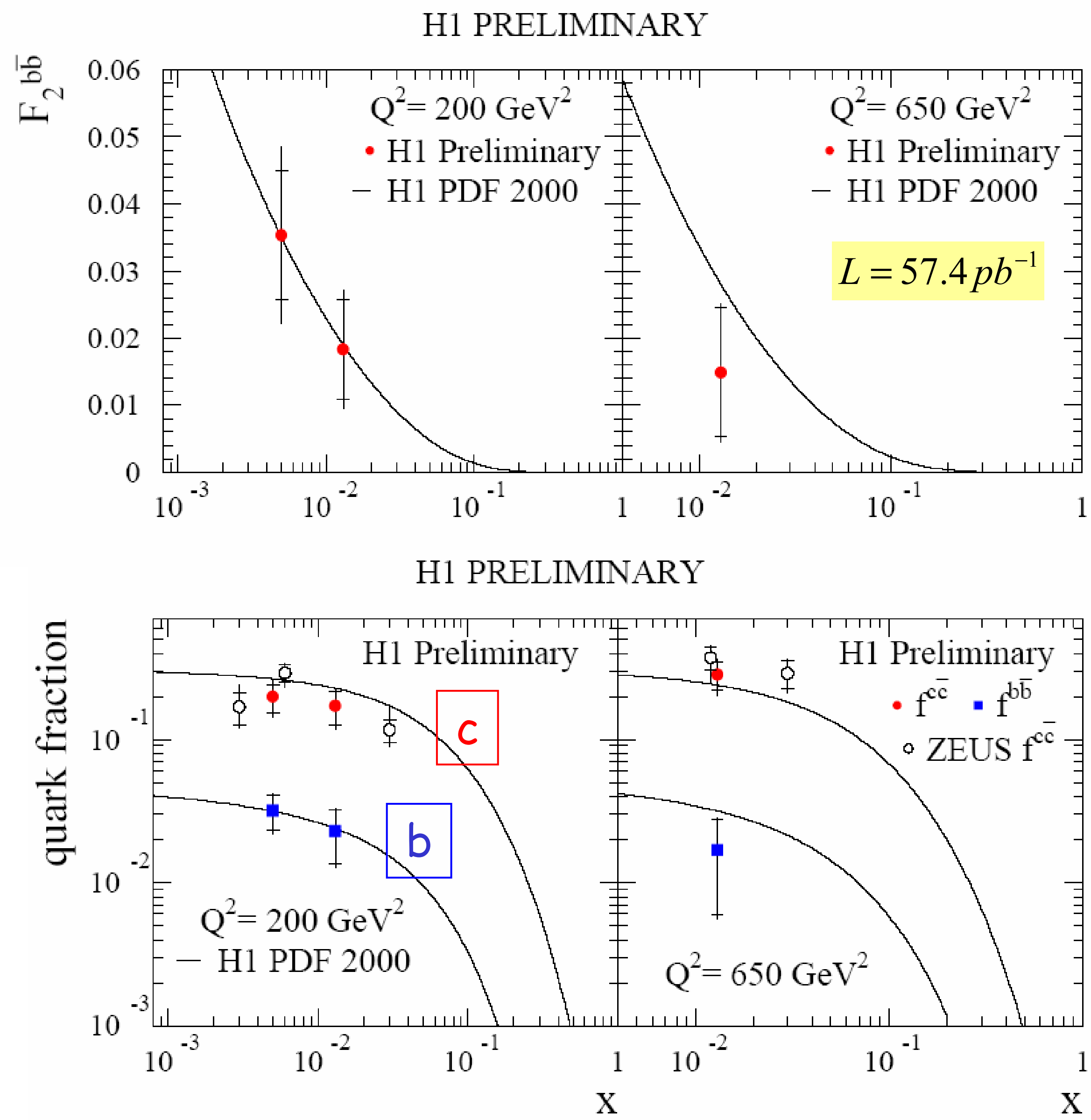
Uncertainties in the extrapolation are:

- using AROMA fragmentation instead of Peterson fragmentation - typically less than 10%, but less than 20%. Most significant at high x for given Q^2
- changing the charm mass by $\pm$ 0.15 GeV - differences of 5% at lower x and negligible elsewhere
- upper and lower predictions from the uncertainty on the ZEUS NLO PDF - typically less than 1%
- varying the b component by factor of 2 - typically less than 1−2% and 8% at high Q^2

Using CTEQ5F3 gave uncertainties of less than 10% for low Q^2 and less than 5% for $Q^2 > 11$ GeV^2

M. Wing (March 04 ||)

Inclusive beauty production in deep inelastic scattering



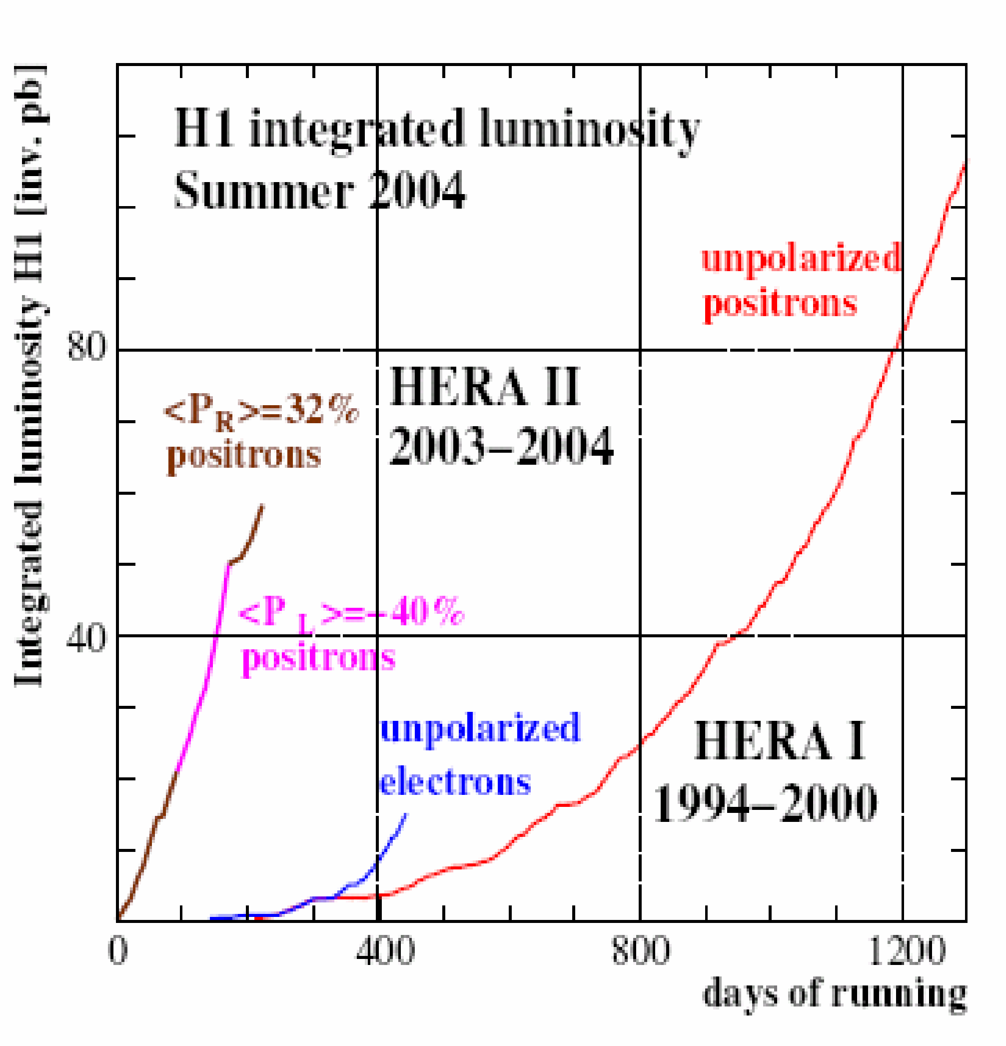
First measurement of bottom structure function, uses b lifetime tagging.

Charm F_2 data with D* (ZEUS) and tagging (H1) agree. Reach now high Q2

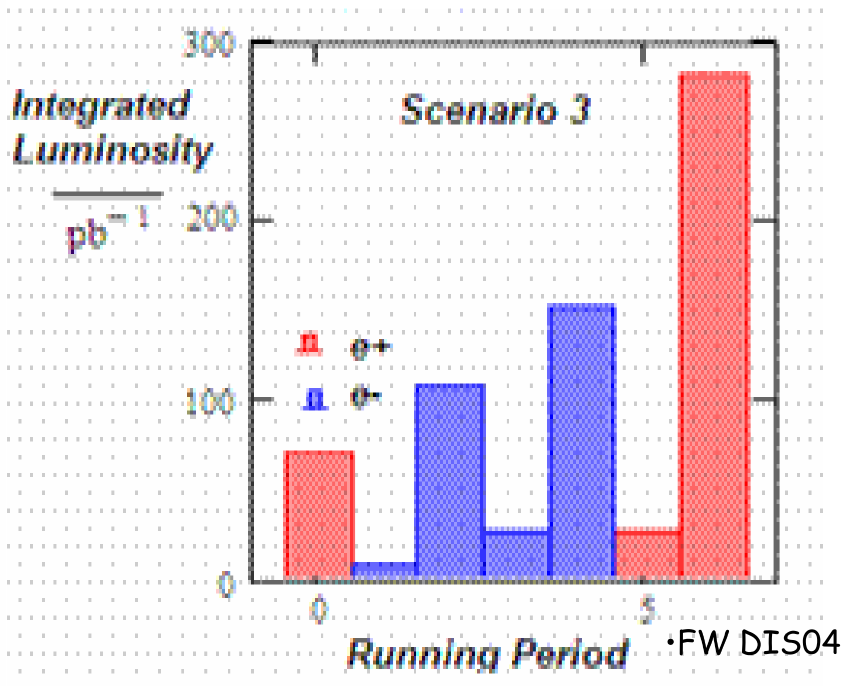
Charm is 20% of F_2. Beauty only 2%, below valence quark region

7. Remarks

HERA II has begun



a scenario for 3 years



•FW DIS04

HERA is an energy frontier machine, not 'only' a QCD machine. There are hints for events beyond the standard model which need to be clarified with highest luminosity, which also QCD requires.

HERA can determine with still increasing precision all parameters relevant to QCD and proton structure and use+demand theory developments to NNLO. HERA can determine the complete set of pdfs and determine the strong coupling with unique accuracy.

An exciting [exp+thy!] programme is being performed to develop QCD at low x - final states, diffraction, unintegrated pdf's… (cf. further talks, Small x Coll. hep-ph/0312333)
At low x the extrapolations may be misleading as an incomplete theory may be used!

Proton structure will be explored in 3 dimensions (GPD's, DVCS, p holography..)

A clearer view is necessary from the LHC as to which HERA information is necessary to be obtained given that the HERA lifetime is 3 years from now and very hard to extend.

The low energy runs are time consuming since $L \sim E_p^2$. The machine has to produce >100pb-1 in less than a year to allow efficient data taking at low energy. Yet then we talk about the best time for the high L programme (searches). On the other hand we will have operated HERA for 15 years with (almost) no change of beam energies. For now we look fwd to e-.

The eD programme is not part of HERAII which is scheduled to end mid 2007. The LoI's were not approved since PETRA is promised to the synchrotron radiation community. A continuation needs a new injector for which a plan exists.

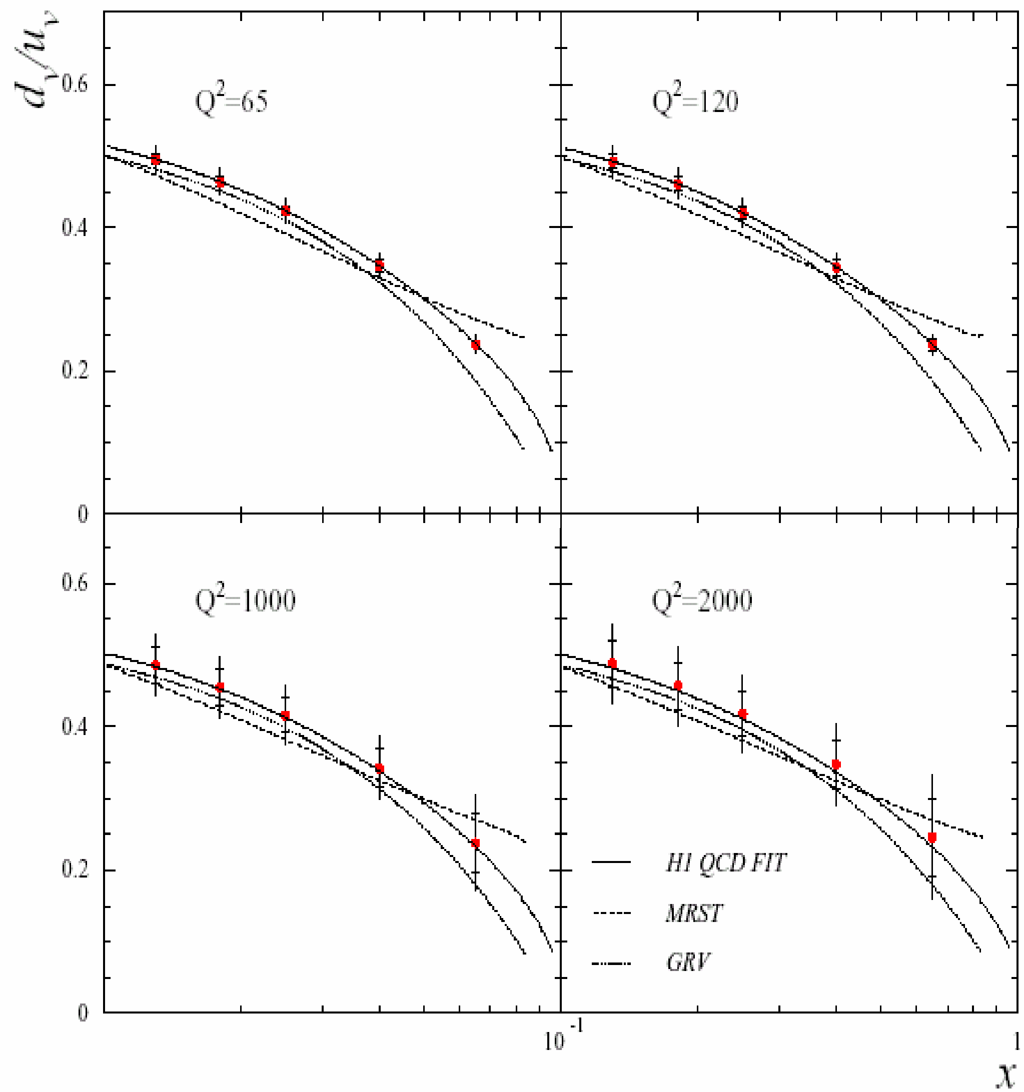
Very basic questions [low x, confinement, saturation, spin (ΔG)] may survive HERA.

The HEP community has to plan for DIS at the TeV scale. ILC-p ring? e-LHC?

•Thanks [and apologies] to many colleagues for help and information (MCS, KD, MK, ..)

Backup slides

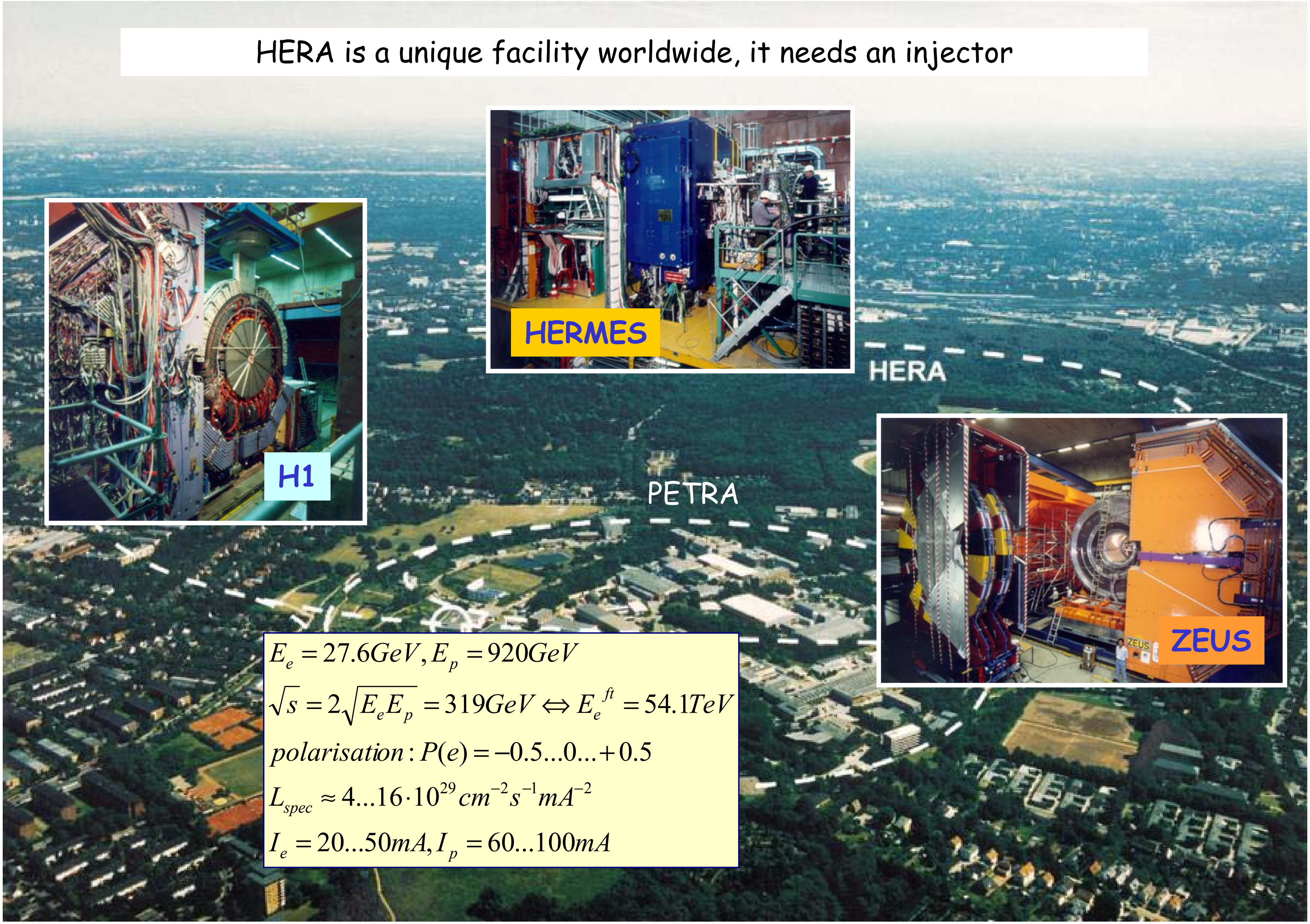
d/u = 0 scalar diquark dominance.
d/u = ½, naïve SU(6)



at high x

d/u from eD (50pb-1)
and from CC (500pb-1)

HERA is a unique facility worldwide, it needs an injector



$$E_e = 27.6GeV, E_p = 920GeV$$

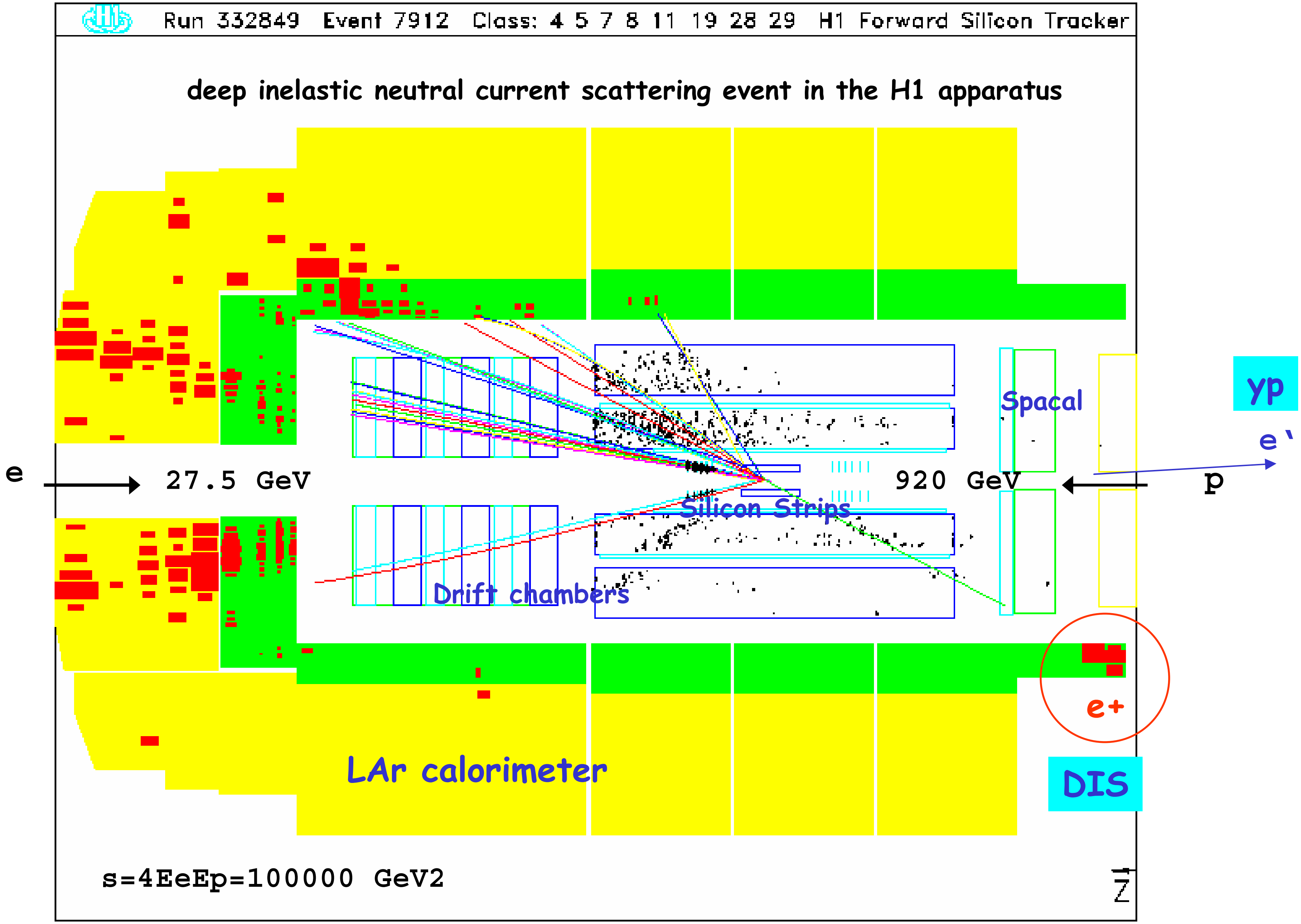
$$\sqrt{s} = 2\sqrt{E_e E_p} = 319GeV \Leftrightarrow E_e^{ft} = 54.1TeV$$

$$polarisation: P(e) = -0.5...0...+0.5$$

$$L_{spec} \approx 4...16 \cdot 10^{29} cm^{-2} s^{-1} mA^{-2}$$

$$I_e = 20...50mA, I_p = 60...100mA$$

ep-collider expts H1, ZEUS @319GeV and polarised target expt HERMES @7GeV


Run 332849 Event 7912 Class: 4 5 7 8 11 19 28 29 H1 Forward Silicon Tracker
deep inelastic neutral current scattering event in the H1 apparatus
e
27.5 GeV
920 GeV
p
γp
e`
Spacal
Silicon Strips
Drift chambers
LAr calorimeter
e+
DIS
s=4EeEp=100000 GeV2
Z

Aims of the Workshop:

To identify and prioritize those measurements to be made at HERA which have an impact on the physics reach of the LHC.

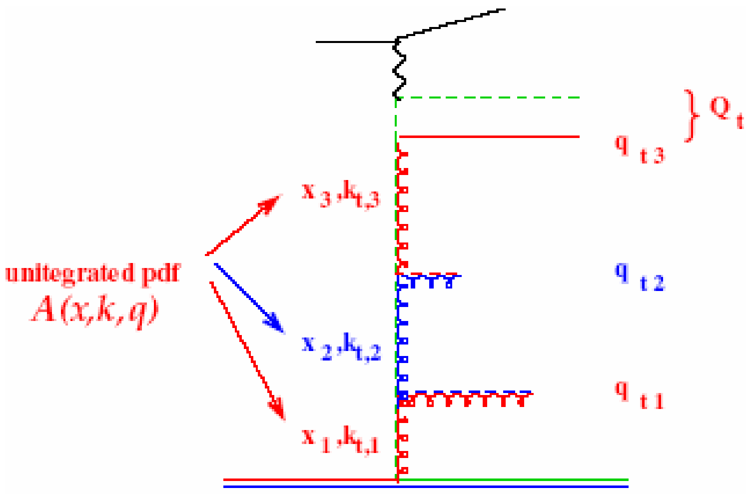
To encourage and stimulate theory and phenomenological efforts related to the above two goals.

To examine and improve theoretical and experimental tools related to the above three goals.

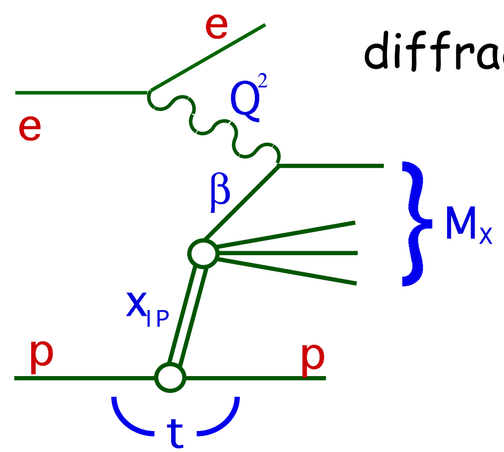
To increase the quantitative understanding of the implication of HERA measurements on LHC physics

Low x and the evolving view on parton dynamics

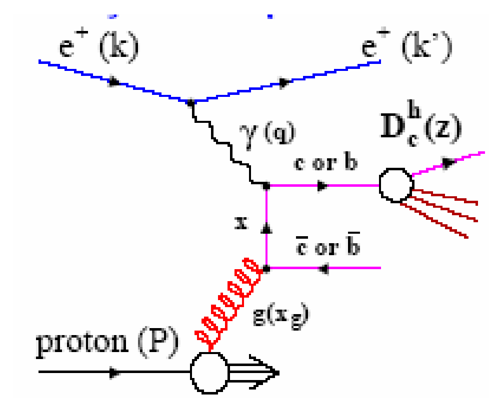
high density low x and parton emission



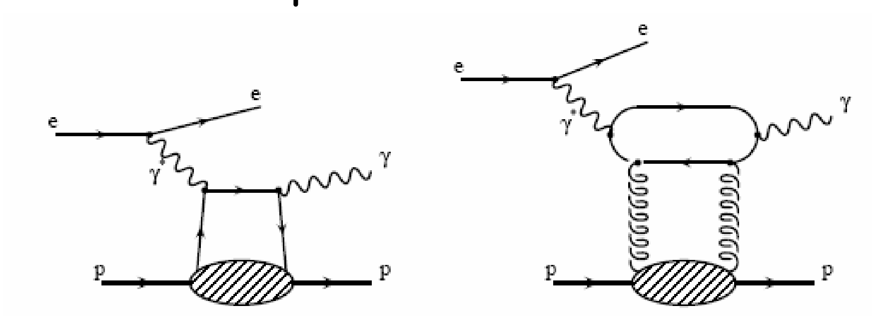
diffraction

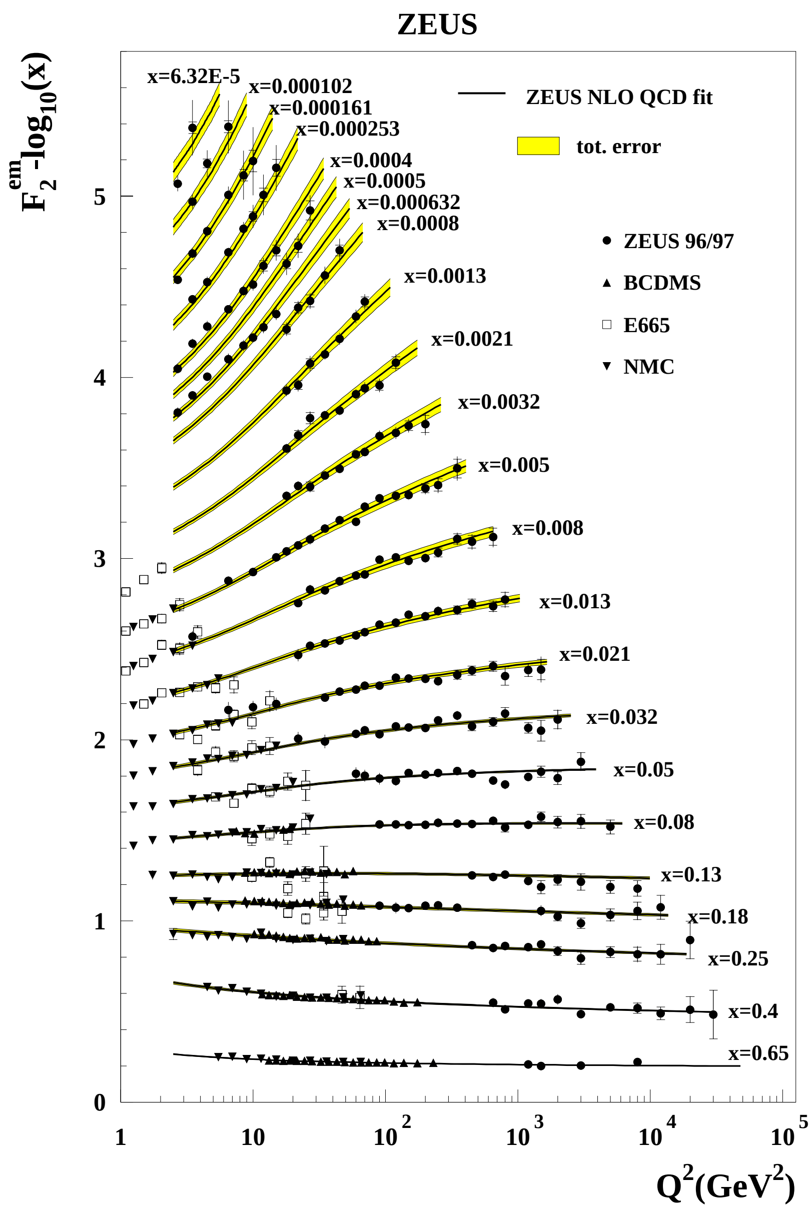


heavy flavours

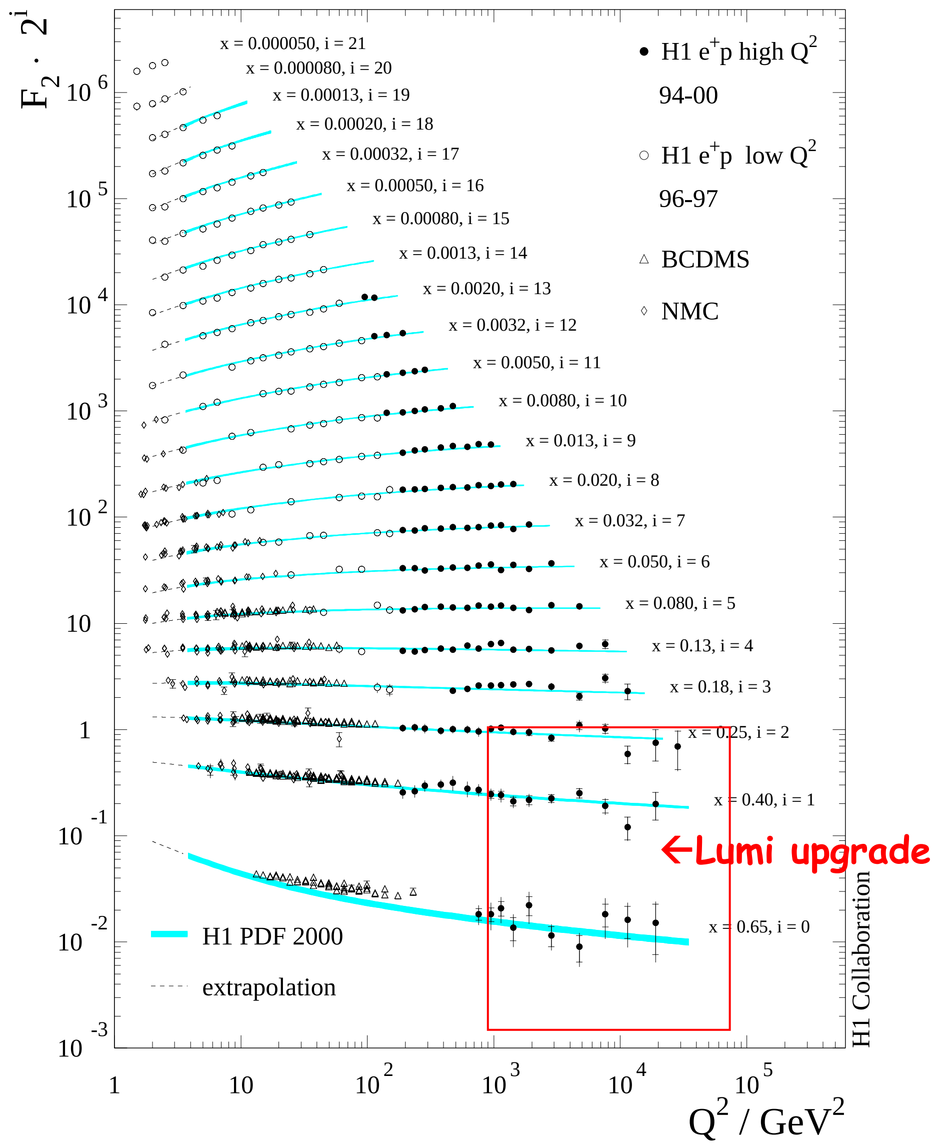


skewed parton distributions



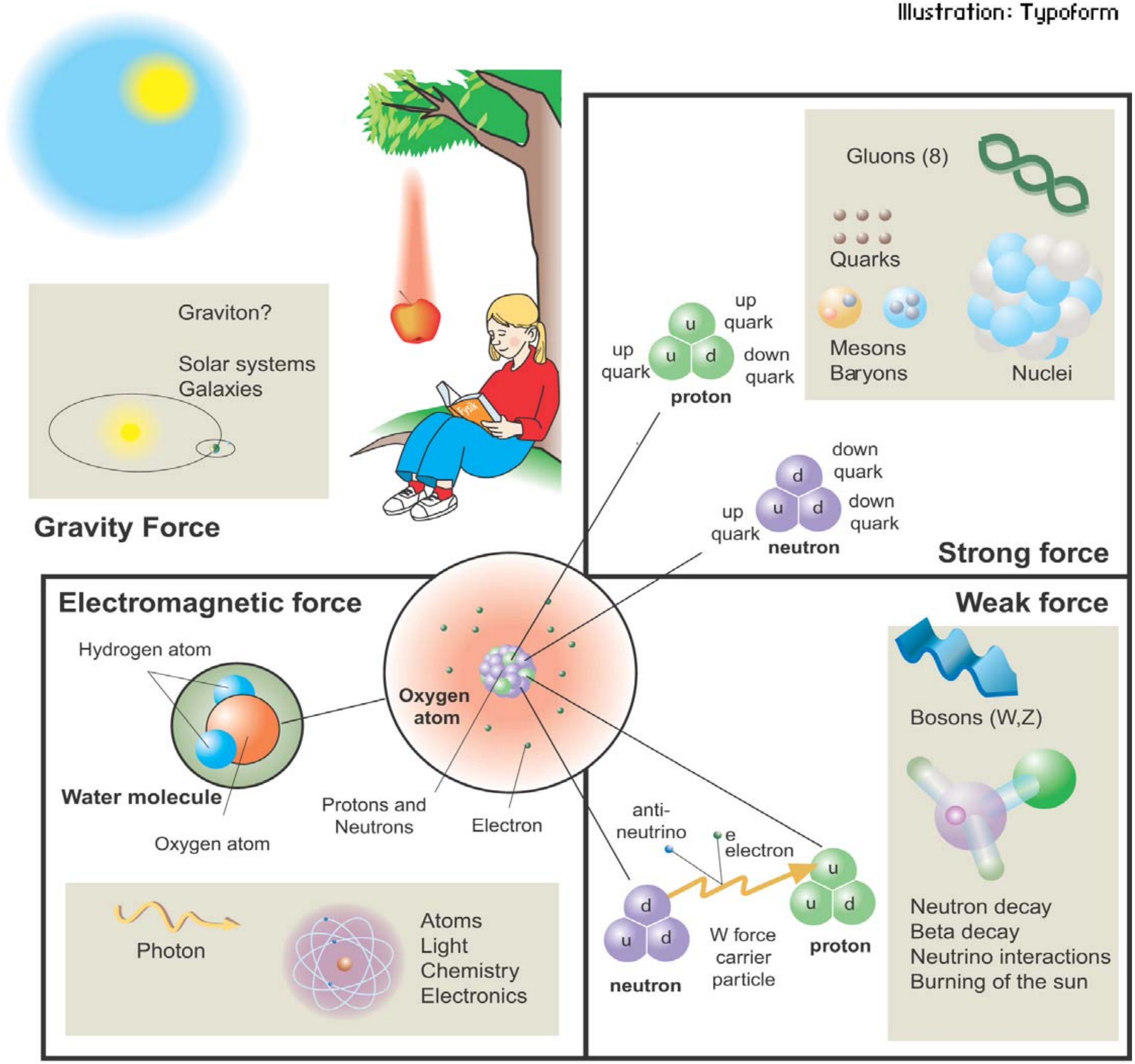


ZEUS 96-97, DESY 02-105, Phys.Rev. D67(2003)012007



H1 94-00, DESY 03-038, EPJ C30(2003)1

Illustration: Typoform



The end