Deep Inelastic Lepton-Proton Scattering

CTEQ School, Rhodos, July 1st, 2006.

Max Klein (DESY) klein@ifh.de

The role of DIS

Lepton-nucleon scattering was born in 1956, 50 years ago, when Hofstatter et al. performed the first elastic ep scattering experiments and found a finite radius of the proton. About 10 years later it became 'deep inelastic' when experiments at 20 times higher energies, at SLAC, established the partonic nature of the proton. Since then DIS has a dual role: in the search for the appropriate gauge field theory, remember the decisive role of polarised ep scattering in 1978 to establish Weinberg's 'Model of Leptons' as the correct, GWS, electroweak theory or recall the importance in the verification and development of QCD from 1974 till now, and in the highest resolution of the inner structure of matter. For the LHC, as for the Tevatron, the predictions of cross sections based on the unique DIS measurements are a necessity to find new physics. With a TeV ep collider the physics of electron-quark scattering may be pursued to possibly establish new interactions, to find new states of baryonic matter and to reach an unprecedent range and level of accuracy.

This lecture sketches:

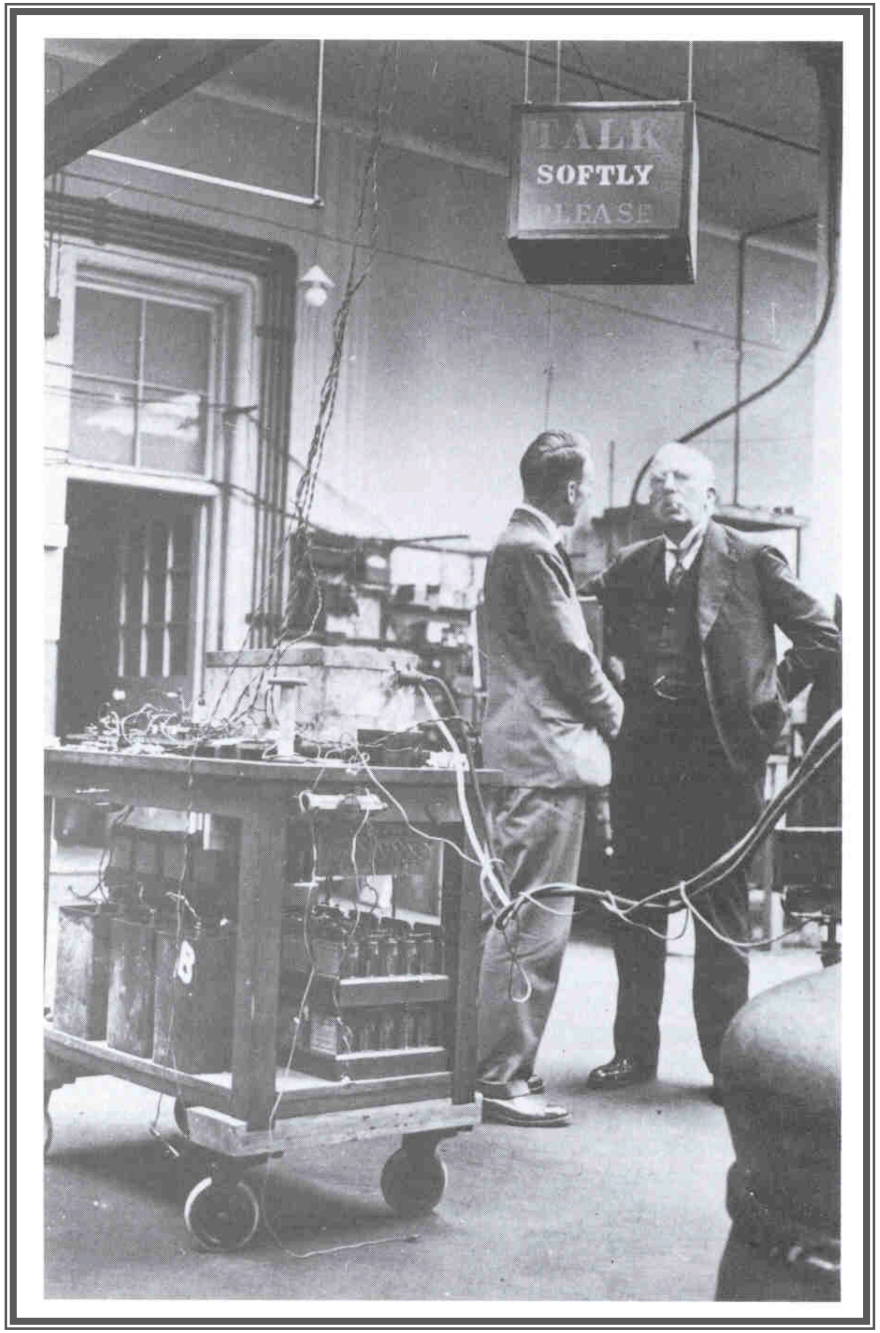
This development
HERA - detectors and physics
The link of DIS and the LHC
QCD analyses from H1 and ZEUS
DIS subjects (heavy flavour, diffraction,..)
A proposal for DIS at TeV energies

Deep Inelastic Scattering

Max Klein

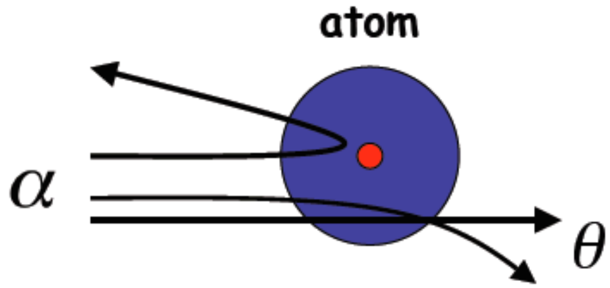
klein@ifh.de

CTEQ, Rodos, 1.7.2006



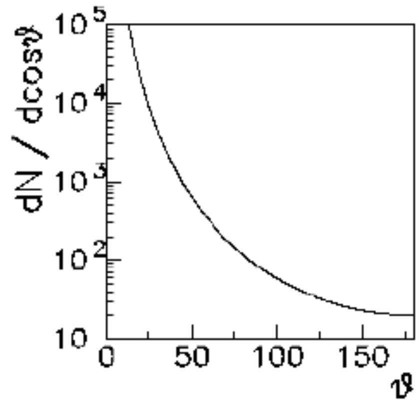
GMR

Discovery of the atomic nucleus 1909



positively charged massive atomic nucleus

$$r_{\text{nucleus}} \approx r_{\text{atom}} / 10000 \approx 10^{-14}\,\text{m}$$

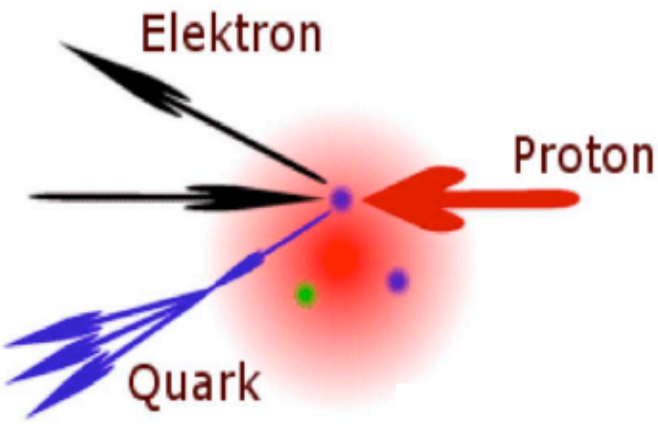


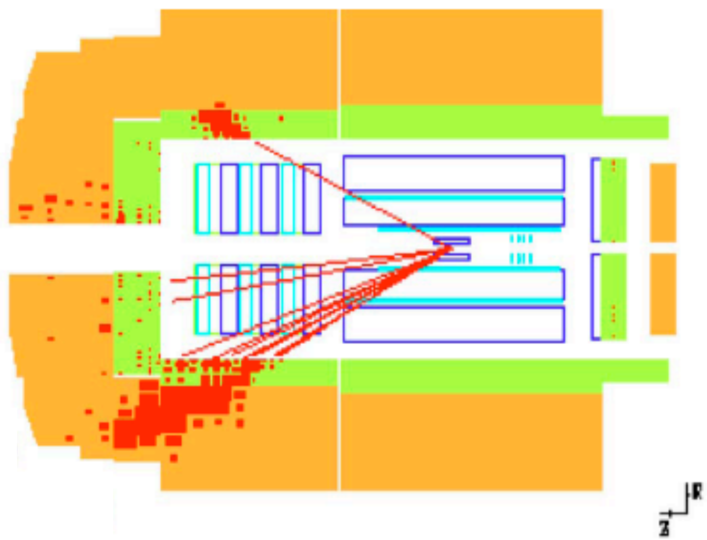
$$\frac{dN}{d\Omega} \propto \frac{Z^2}{E^2} \frac{1}{4\sin^4 \theta / 2}$$

$$\boxed{E_\alpha = 5.5\,\text{MeV}}$$

Rutherford backscattering at HERA

An ep scattering event in H1 1999





1 GeV = 1.6 10^{-10}Nm

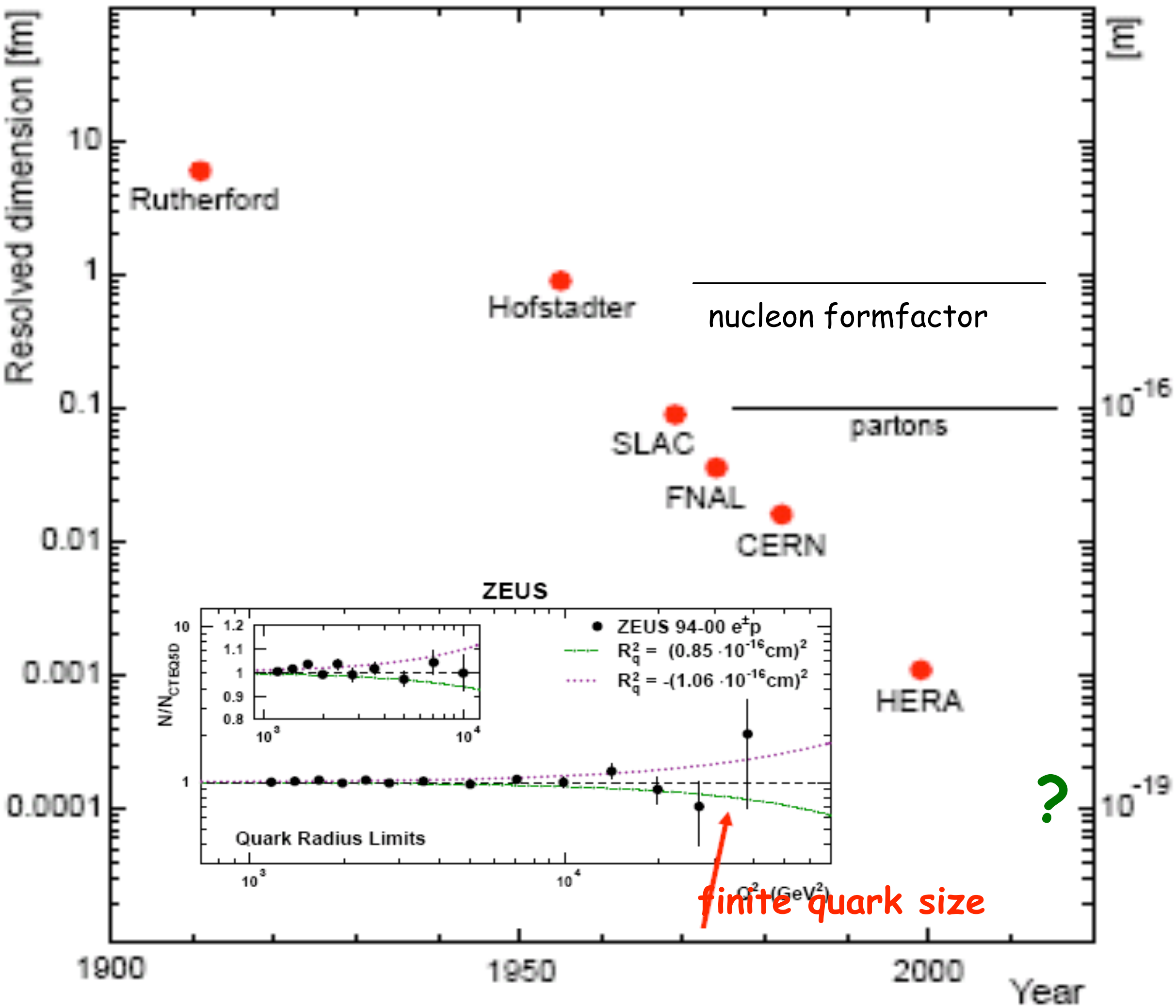
M_p=0.94 GeV = 1.67 10^{-27}kg

r_p = 1 fm = 10^{-15}m

r_A= 1 fm $A^{1/3}$

$r\sqrt{Q^2}$=h -->0.2 fm=1/GeV
high 4-momentum transfer Q,
i.e. large beam energy,
resolves small dimensions r

HERA: quarks are pointlike down to proton radius/1000



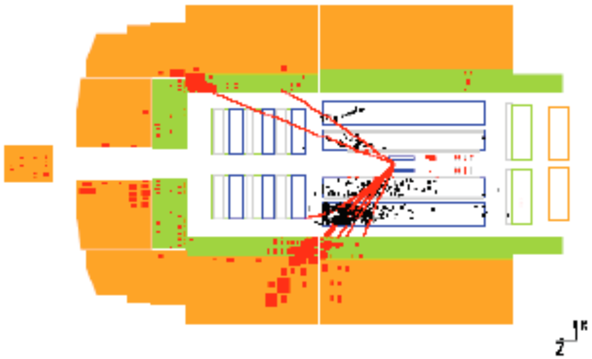
Inclusive cross section ep -> eX exhibits no extra formfactor
-> Limits on SUSY, leptoquarks, extra dimensions, quark radius…

present limits

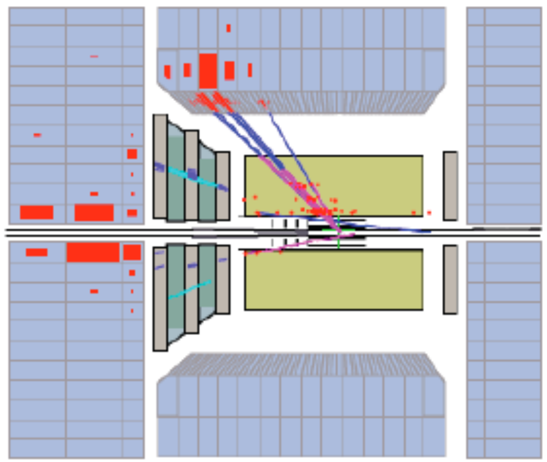
ZEUS r < 0.85
H1 r < 1.0 10^{-18}m

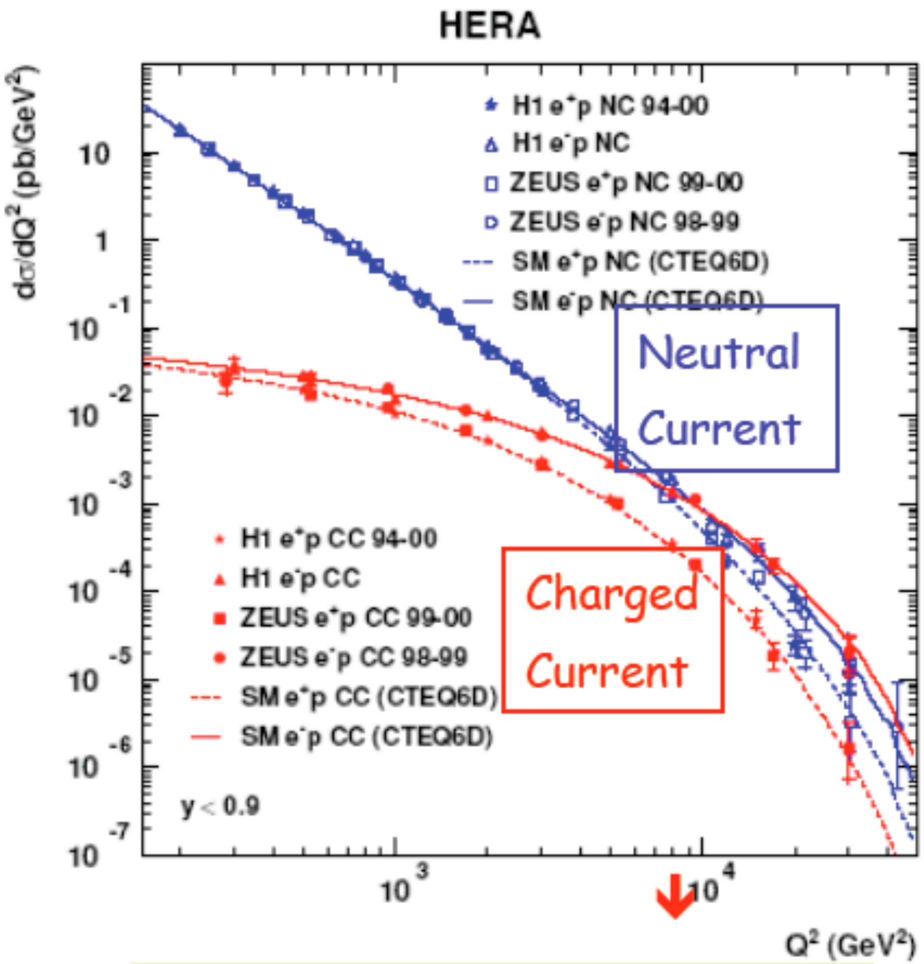
Electromagnetic and Weak Interactions

Neutral current $e^+ p \to e^+ X$



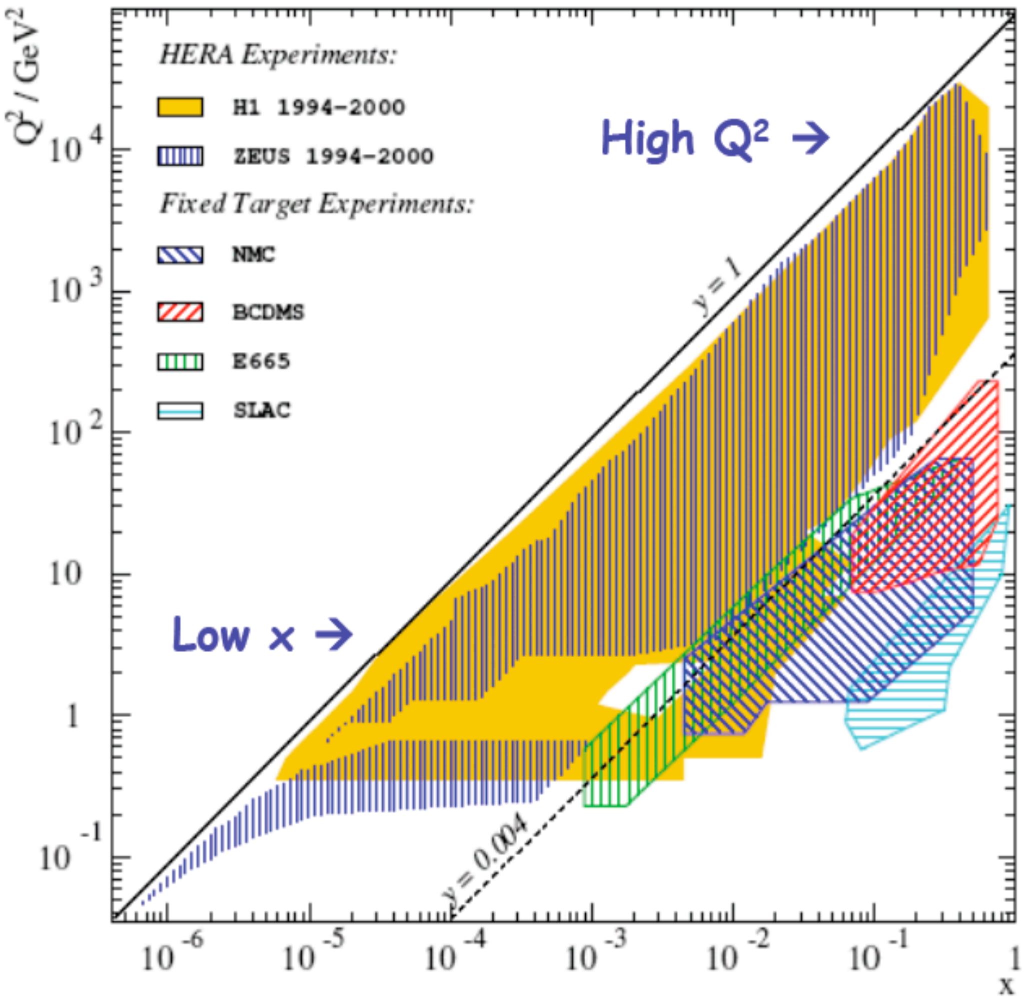
Charged current $e^+ p \to \bar{\nu} X$

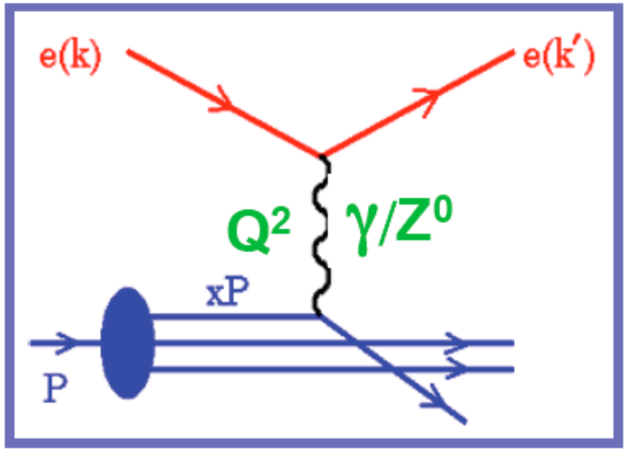




$$\sigma^{\pm}_{NC} \approx \sigma^{\pm}_{CC} \leftrightarrow Q^2 \approx M_Z^2 \approx 10^4\, GeV^2$$

HERA Kinematics





$E_e = 27.6 GeV, E_p = 920 GeV$

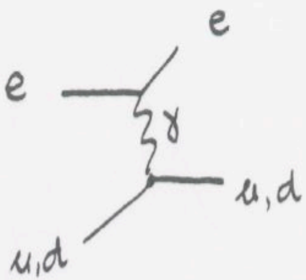
$\sqrt{s} = 2\sqrt{E_e E_p} = 319 GeV$

$\Leftrightarrow E_e^{ft} = 54.100 GeV$

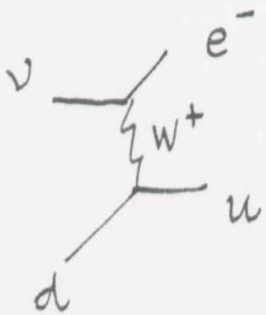
$Q^2 = sxy - high$

$x = Q^2 / sy - low$

Verification of the Quark-Parton Model - Fractional Electric Charges



neutral current (elm: γ)



charged current (weak!)

HERA:

inverse charged current.

$$F_2 = x \sum e_q^2 (q+\bar{q})$$

proton: uud

neutron: ddu

$e_u = 2/3 \quad e_d = -1/3$

$$F_2^{\nu p} = 2x\left[d+\bar{u}\right]$$

$$F_2^{\nu n} = 2x\left[u+\bar{d}\right] \qquad F_2^{\nu N} = x\left[u+\bar{u}+d+\bar{d}\right]$$

$$F_2^{p} = x\left[e_u^2(u+\bar{u}) + e_d^2(d+\bar{d})\right]$$

$$F_2^{n} = x\left[e_d^2(u+\bar{u}) + e_u^2(d+\bar{d})\right]$$

$$\rightarrow \frac{F_2^{eN}}{F_2^{\nu N}} = \frac{1}{2}\left(e_u^2+e_d^2\right) = \frac{5}{18} \simeq 0.28$$

$$\frac{1}{2}\left(F_2^{ep}+F_2^{en}\right) = F_2^{eN}$$

$$= x\,\frac{e_u^2+e_d^2}{2}\left[u+\bar{u}+d+\bar{d}\right]$$

$$\frac{\text{GGM } \nu N}{\text{SLAC } eN} : \; 0.29 \pm 0.05$$

Verifications of the Quark-Parton Model - Valence and Sea Quarks

$u = u_V + u_{sea}\ ,\ u_s = \bar{u}$

$d = d_V + d_s\ ,\ d_s = \bar{d} \underset{(?)}{=} \bar{u}$

$F_2^{\nu} = 2x\ \Sigma(q+\bar{q})\ .\ V$

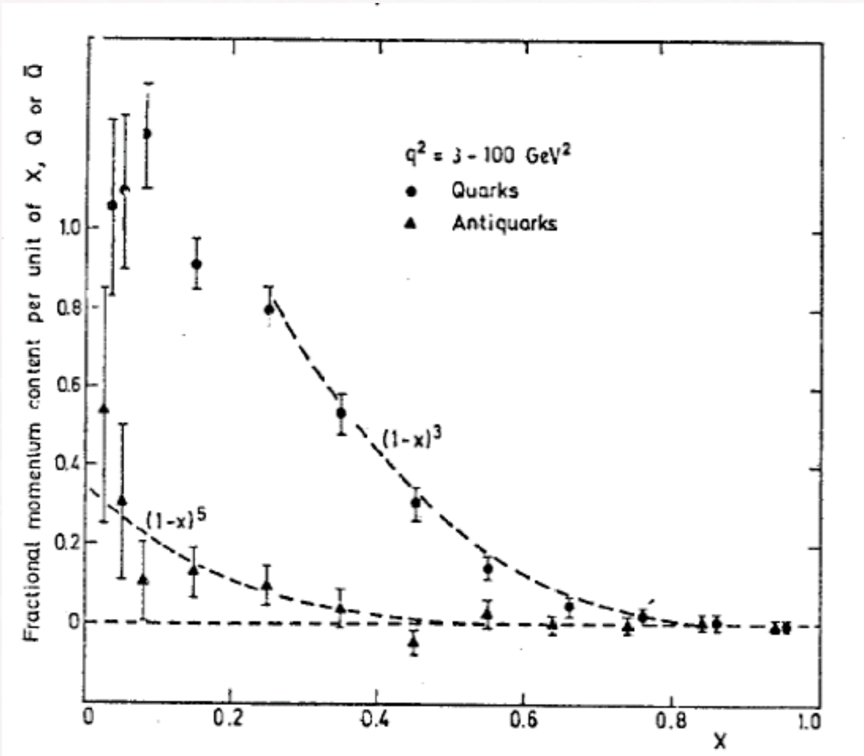
$xF_3^{\nu} = 2x\ \Sigma(q-\bar{q})\ .\ A$

$xF_3^{\nu p} = 2x d_V\ .\ xF_3^{\nu N} = 2x u_V$

$$\int_0^1 x F_3^{\nu N} \frac{dx}{x} = \int_0^1 (u_V + d_V)\,dx$$

Gross Llewellyn Smith : = 3

Gargamelle 3.2 ± 0.6



$$\frac{d\sigma^{\nu N}}{dx\,dy} = \frac{G^2}{\pi} 2ME x \left[u + d + (\bar{u} + \bar{d})(1-y)^2 \right]$$

$$\frac{d\sigma^{\bar{\nu} N}}{dx\,dy} = \left[\bar{u} + \bar{d} + (u+d)(1-y)^2 \right]$$

Extension and Surprise to the Quark-Parton Model - Gluons

- momentum conservation

$$\frac{1}{2}\int (F_2^p + F_2^n)\,dx = \frac{e_u^2+e_d^2}{2}\underbrace{\int_0^1 x\sum(q+\bar{q})\,dx}$$

νN GGM : 0.49 ± 0.07

eN : SLAC 0.14 ± 0.05

→ half of p's momentum not carried by quarks.

- colour

$$R = \frac{\sum \sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \sum e_q^2$$

$= \frac{11}{9}$ for u, d, s, c, b

$\sqrt{s} > 10$ GeV

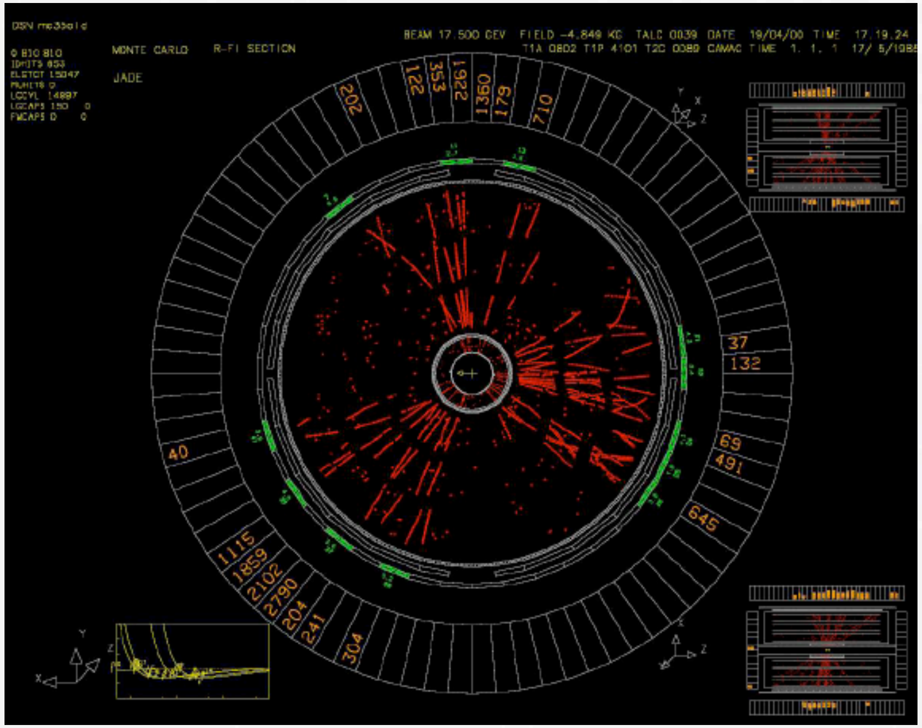
$q\bar{q}$

$q\bar{q}$

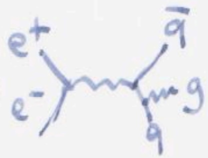
$q\bar{q}$

measured $\sim \frac{11}{3}$

A 3 jet event at PETRA



discovery of gluons



3 jet events.

Adapting to new, hypothetical theories?

"… when I reported these things here in Göttingen, they laughed at me that I should take such fantasies seriously"

R.Courant to N.Bohr, 1922, December, 8

Fermi's "A Tentative Theory of ß Decay" refused to publish in Nature

cited by Pontecorvo

1962: Gell Mann predicts the Omega minus (sss state)
" The paper looks crazy, but if I accept it and it is nonsense, everyone will blame Gell-Mann and not Physics Letters. If I reject it and it turns out to be right, I will be ridiculed."

cited by Lipkin

" …we know that … mesons and baryons are mostly, if not entirely, made up out of one another. The probability that a meson consists of a real quark pair rather than two mesons… must be quite small"

Gell-Mann XIII ICHEP Berkeley, 1967

Zweig, who invented the Quark Model with Gell Mann in 1964, could not get a paper published describing his quark theory until the mid 70ies.

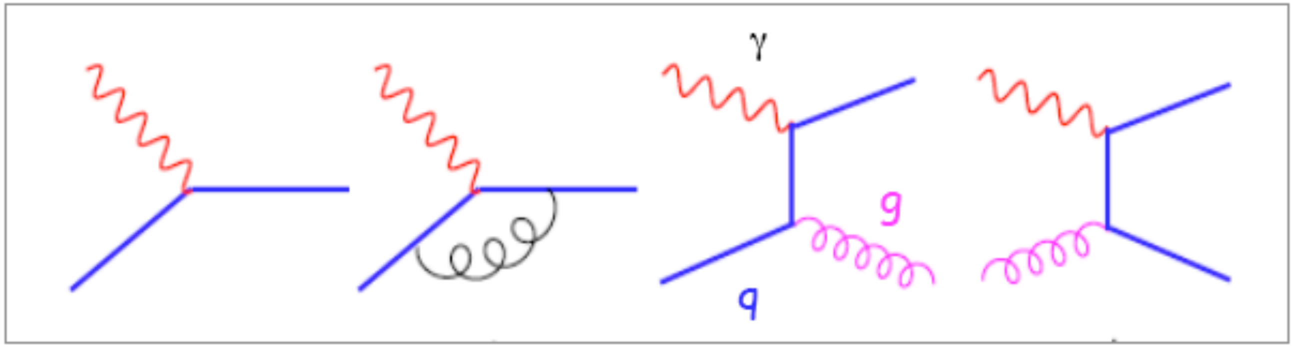
cited by H.Kendall

"The correct theory will not be found within the next 100 years"

F.Dyson 1960

Factorisation and the Q^2 evolution of parton distributions f_p

$$F_{i\{=2,3,L\}}^{V\{=\gamma,Z,W\}}(x,Q^2) = \sum_{p=q,\bar{q},g} \int_0^1 dz f_p(z,\mu) \cdot C_a^V(\frac{x}{z},\frac{Q}{\mu},\alpha_s(\mu)) + \ldots$$

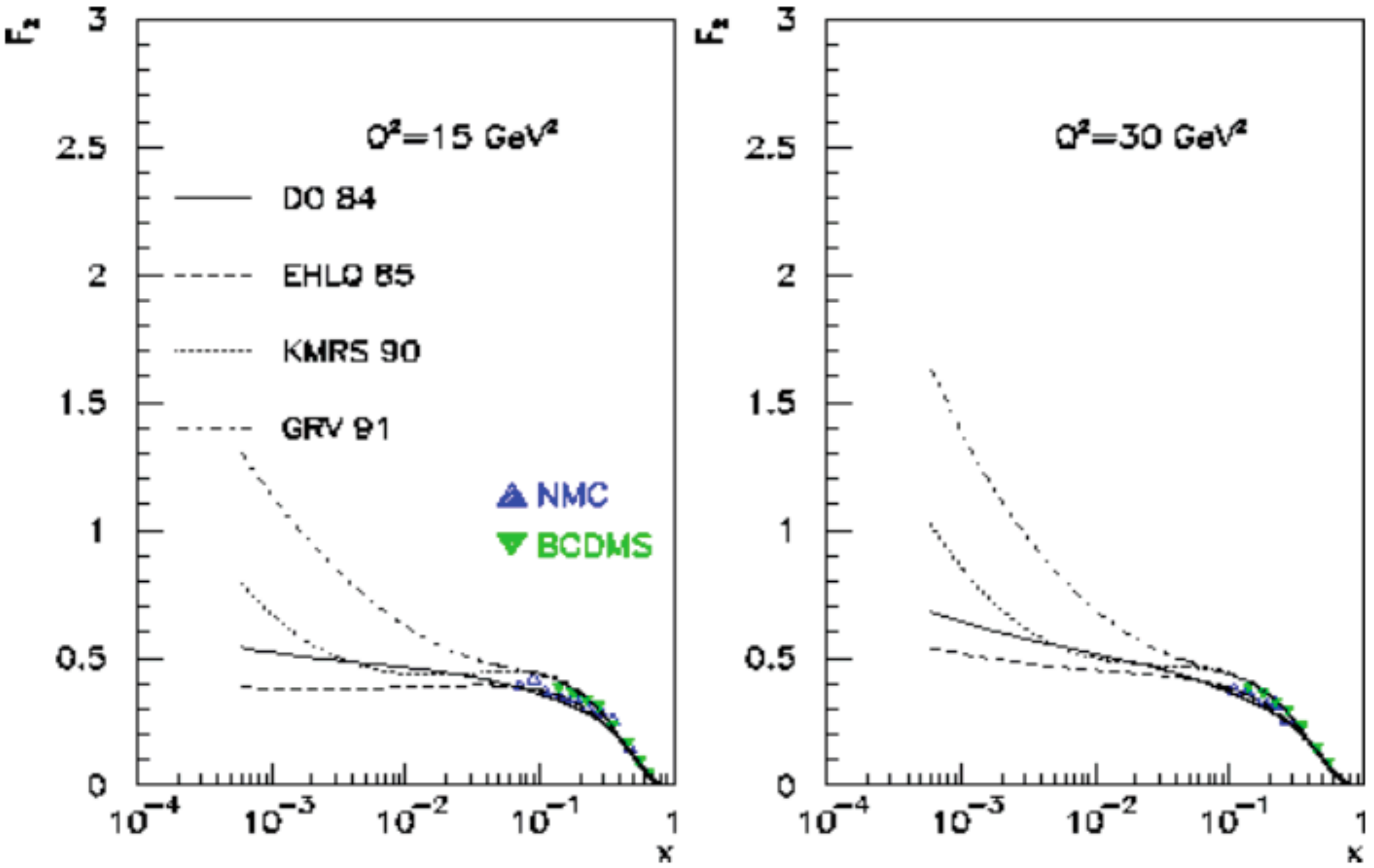


$$\frac{d}{d\ln\mu} f_p(x,\mu) = \sum_{p'} \int_x^1 \frac{dz}{z} P_{p,p'}(\frac{x}{z},\alpha_s) f_{p'}(z,\mu)$$

DGLAP equations

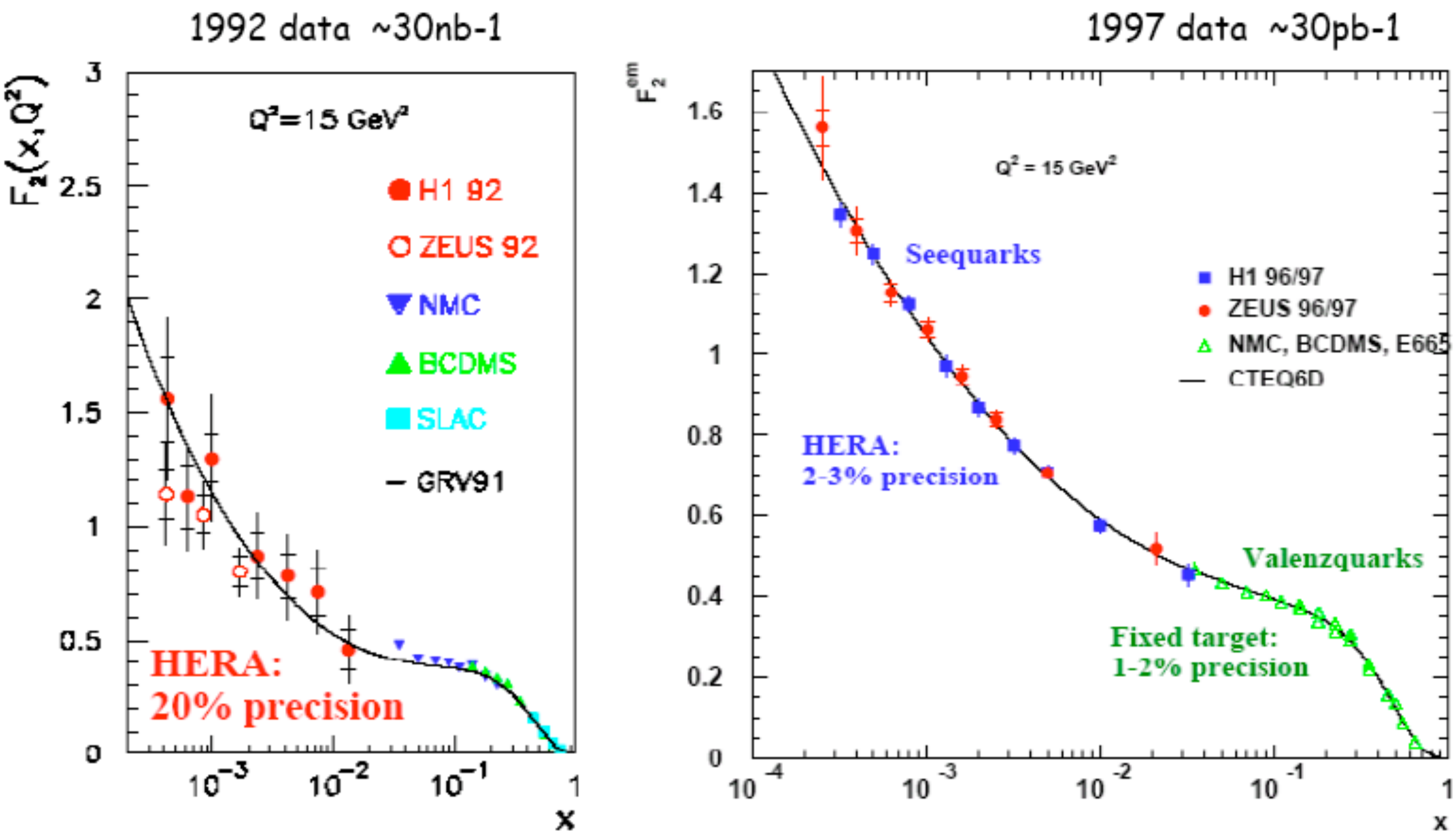
QCD predicts not the [long distance] parton distributions but their evolution.
The coefficient functions C and splitting functions P are calculated to NNLO.

·Expectations on the density of partons before HERA



$$F_2 = x\sum e_q^2[q+\bar{q}]$$

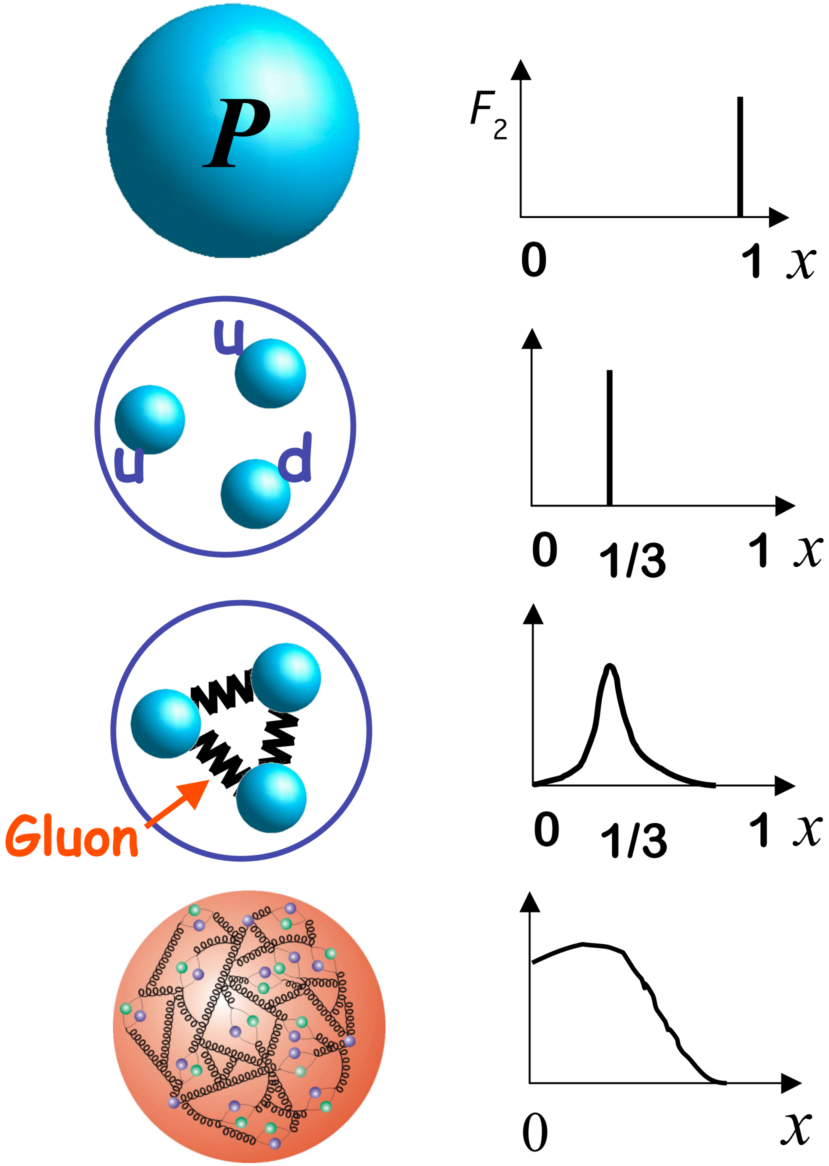
$$u = u_v + u_s, \bar{u} = u_s, d, s = \bar{s}, c = \bar{c}, \ldots$$



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

[redacted] – The function characterising the proton's structure



no substructure

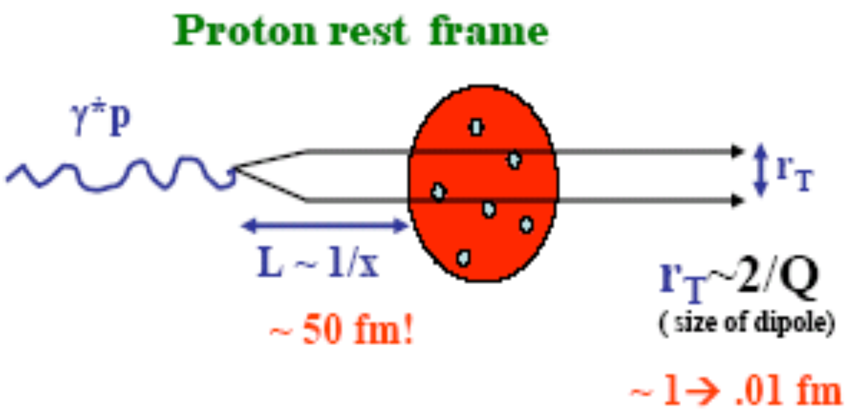
3 free valence quarks

3 bound quarks

Valence quarks
Sea quarks
gluons

[redacted]

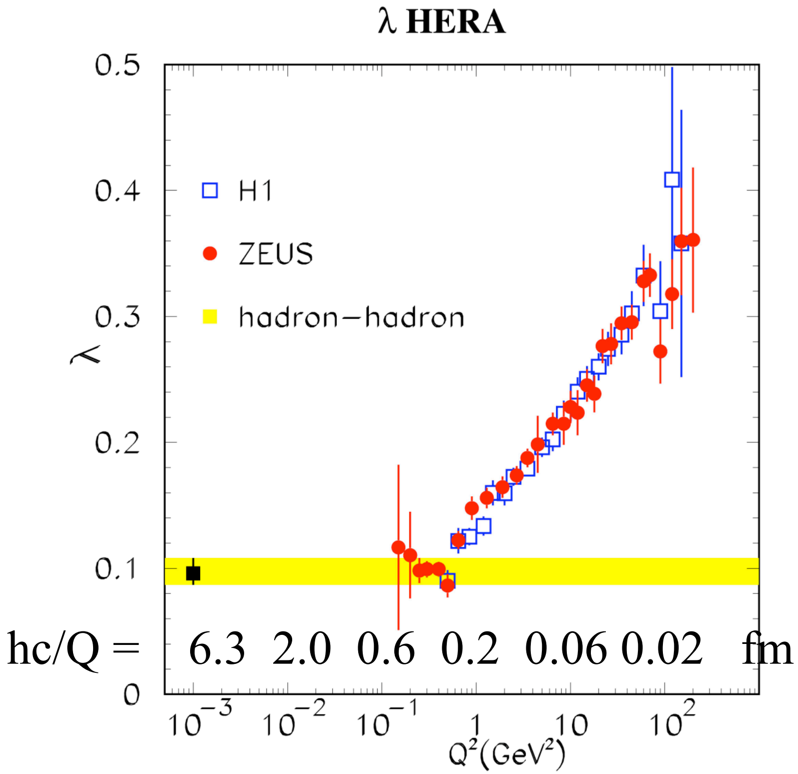
Low x Dynamics in the Colour Dipol Picture



At low x<0.01 a color dipole of variable size 2/Q interacts with the proton at high CM energy $s^{\gamma p} = W^2 \approx Q^2/x \approx 1000 \div 90000\ \mathrm{GeV}^2$

Low x = high energy scattering!

Q^2 steers the transition from hard collisions (perturbative QCD) to soft hadron physics.



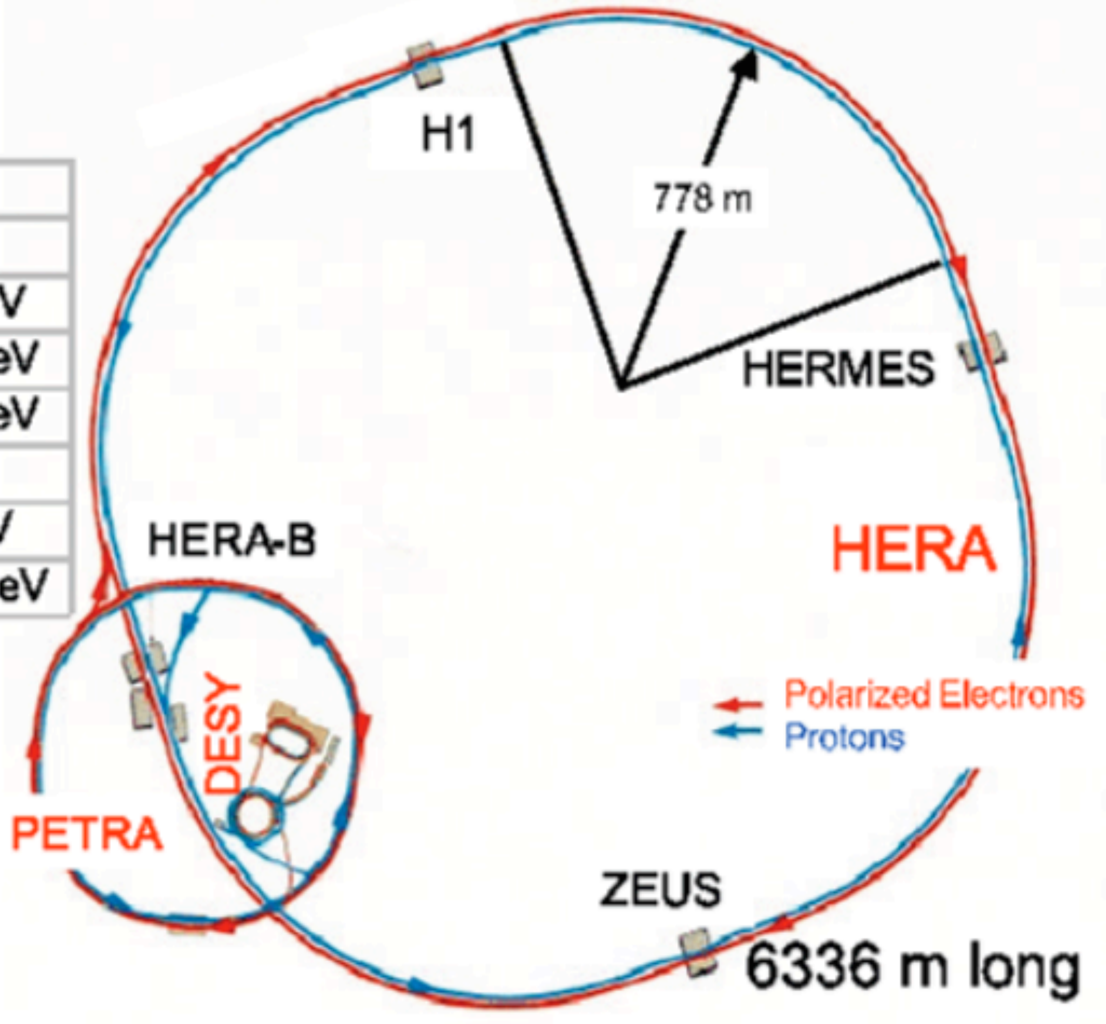
$F_2 \propto x^{-\lambda}$ at small x

CDM is universal - explored in diffractive and final state physics

HERA and its Pre-Accelerator Chain

	Protons	Electrons	
20 keV	Source	Source	150 keV
750 keV	RFQ	Linac II	450 MeV
50 MeV	Linac III	Pia	450 MeV
8 GeV	DESY III	DESY II	7 GeV
40 GeV	PETRA	PETRA	12 GeV
920 GeV	HERA-p	HERA-e	27.5 GeV

$$E_e = 15..30 GeV, E_p = 400..1000 GeV$$
$$polarisation: P(e) = -0.5...0...+0.5$$
$$L_{spec} \approx 0.4...2 \cdot 10^{30} cm^{-2} s^{-1} mA^{-2}$$
$$I_e = 20...50 mA, I_p = 60...100 mA$$



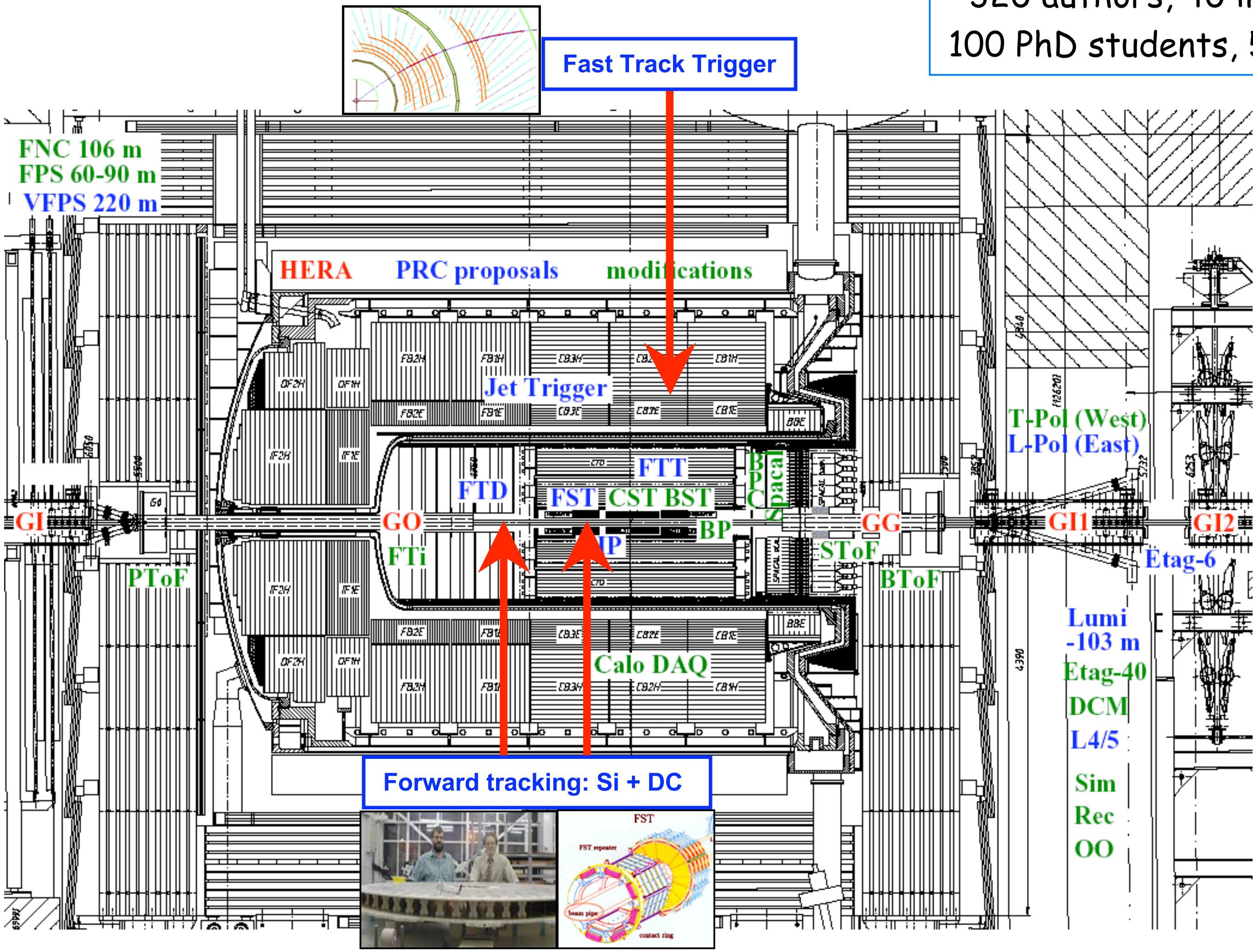
H1
ZEUS
HERA
protons 920 GeV
electrons 27.6 GeV
PETRA

The H1 Detector

320 authors, 40 institutes
100 PhD students, 50 engineers

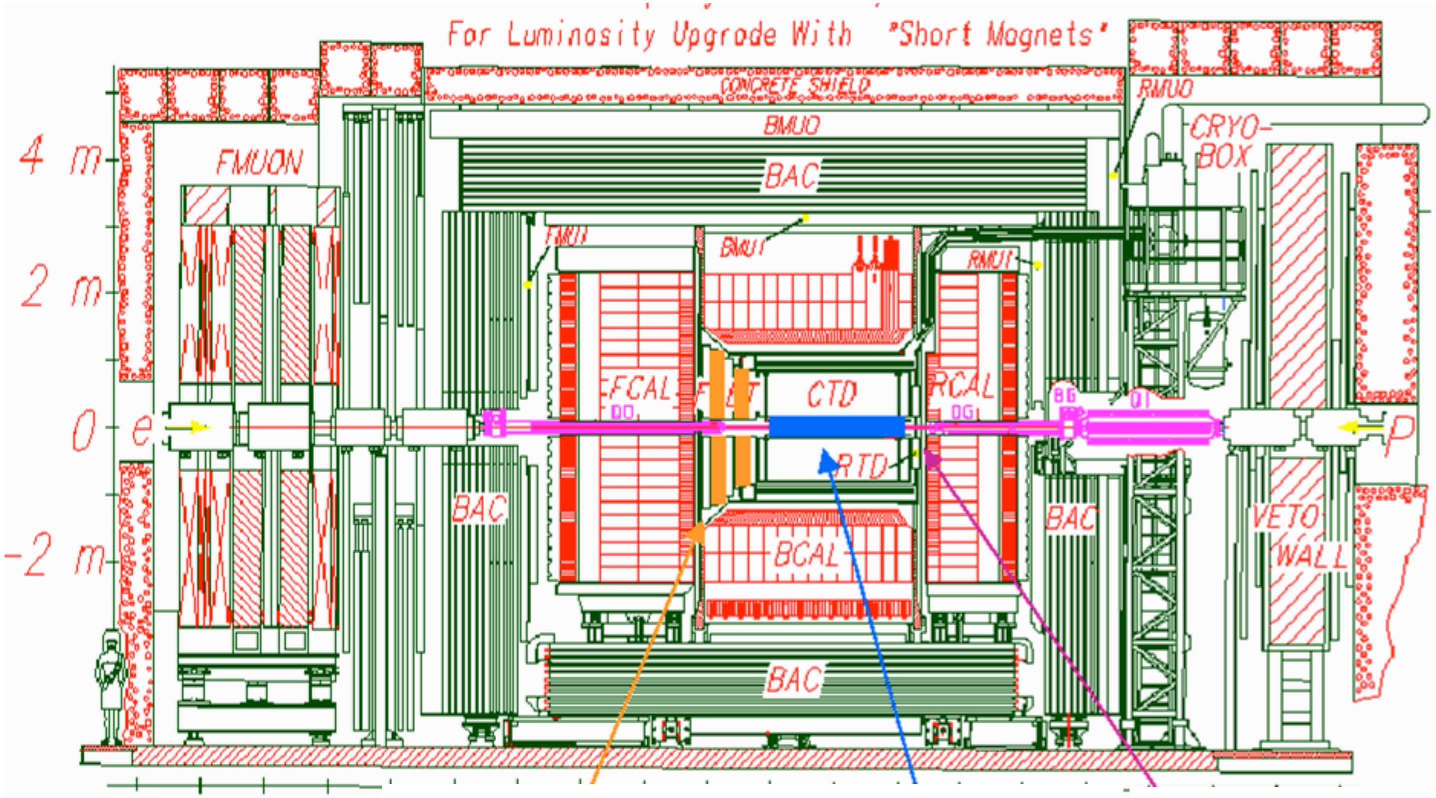
Forward Proton and Neutron Spectro- meters

e
27.5 GeV



Luminosity spectrometer

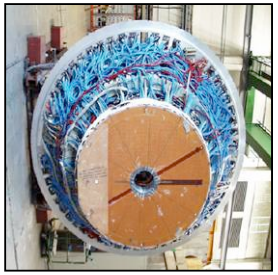
p
920 GeV



Straw Tube Forward Tracker

Micro Vertex Detector

Beam Pipe Magnets



Luminosity spectrometer

350 authors
~35 institutes

The ZEUS Detector

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: 10%...35%/$\sqrt{E'_e}$ and 30-50%/$\sqrt{E_h}$]
- Energy momentum conservation ($E-p_z$): 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 [$ep \to ep\gamma$] to 1%.

Precision, HERA and QCD: all require time, patience, luck, ingenuity and dedication

Physics at HERA (the expected and the unexpected)

•classic DIS

•QCD

•Searches

•elweak

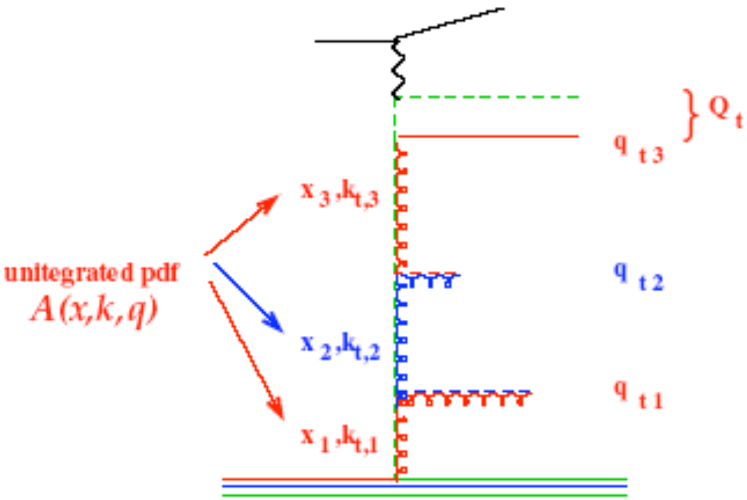
- Inclusive ep measurements (NC, CC-inverse neutrino i.a.) -> pdf's, gluon,
- Low x physics: small coupling and high density of partons -> "CGC, BFKL.."
- Heavy flavour physics (c and b: production and fragmentation dynamics)
- Final state physics (parton emission,,jets, γ structure, dijet correlations)
- Diffraction [all related: e.g. "the structure of charm jets in diffraction"]
- Parton amplitudes (DVCS)
- Searches for exotic states (pentaquarks) and less? exotic ones (instantons)
- Searches: substructure, leptoquarks, SUSY, isolated lepton events (17/5)
- Electroweak physics (spacelike region)

for HERA physics see also:

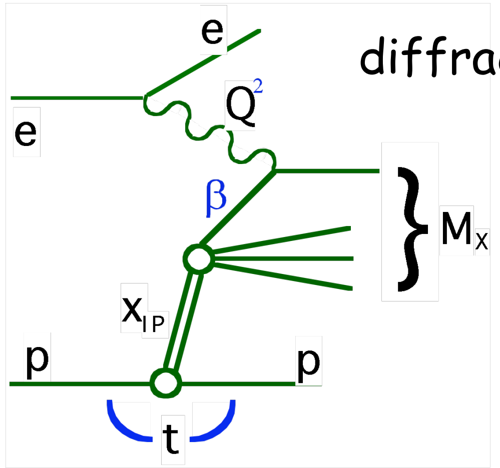
- Talks at DIS05, Madison, DIS06, Tsukuba
- Ringberg Workshop (2003/05) Proceedings ed by G.Grindhammer, B.Kniehl, G.Kramer

Low x and the evolving view on parton dynamics

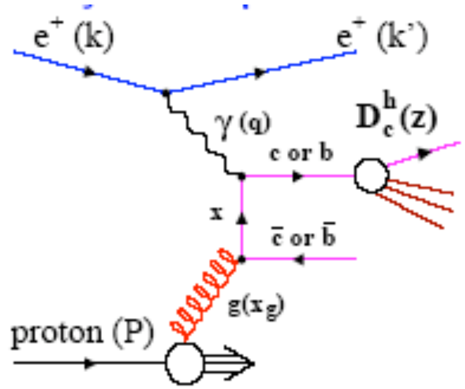
high density low x and parton emission



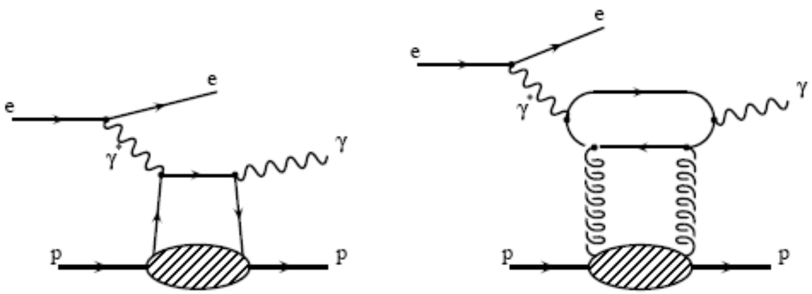
diffraction



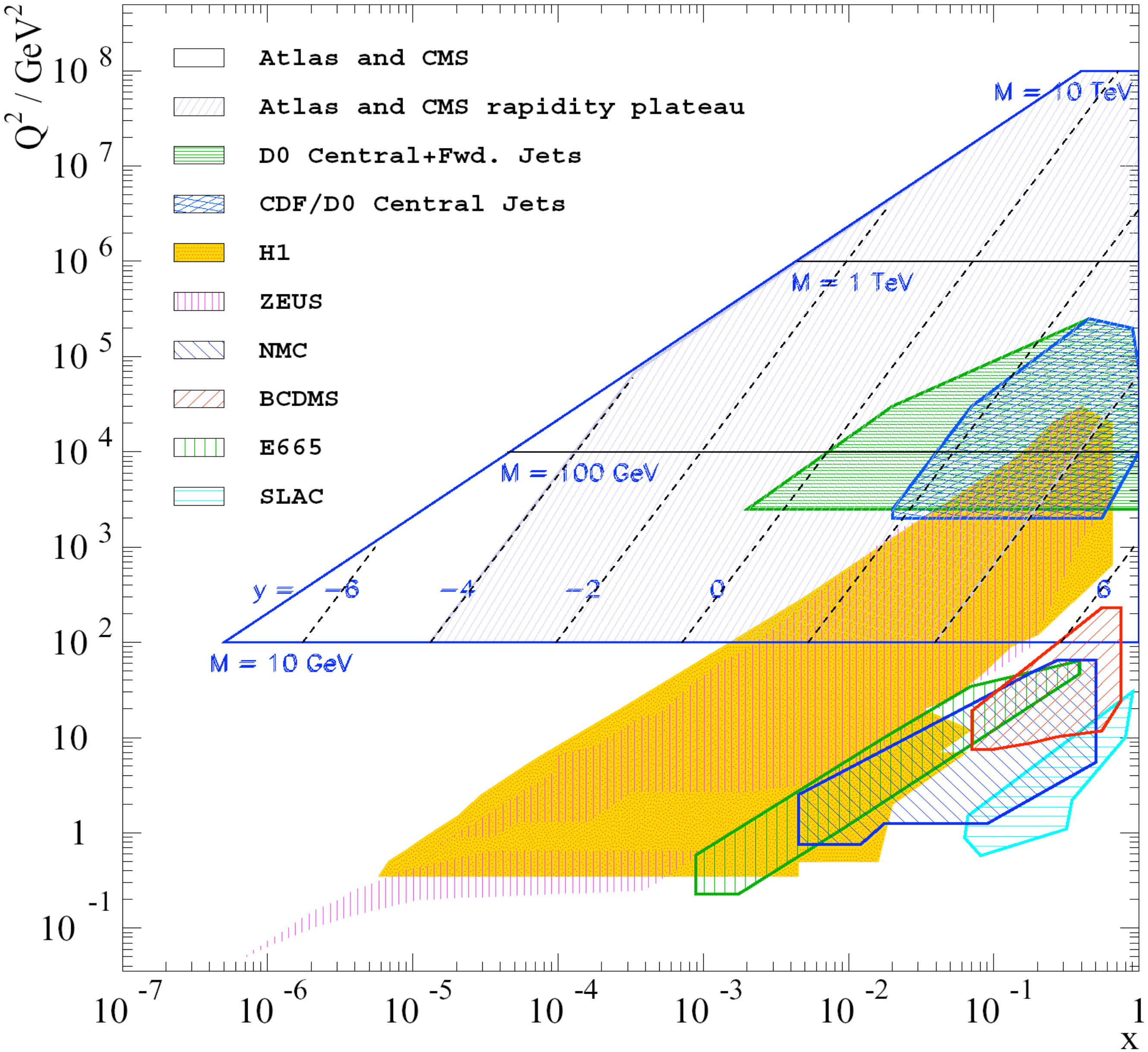
heavy flavours



skewed parton distributions

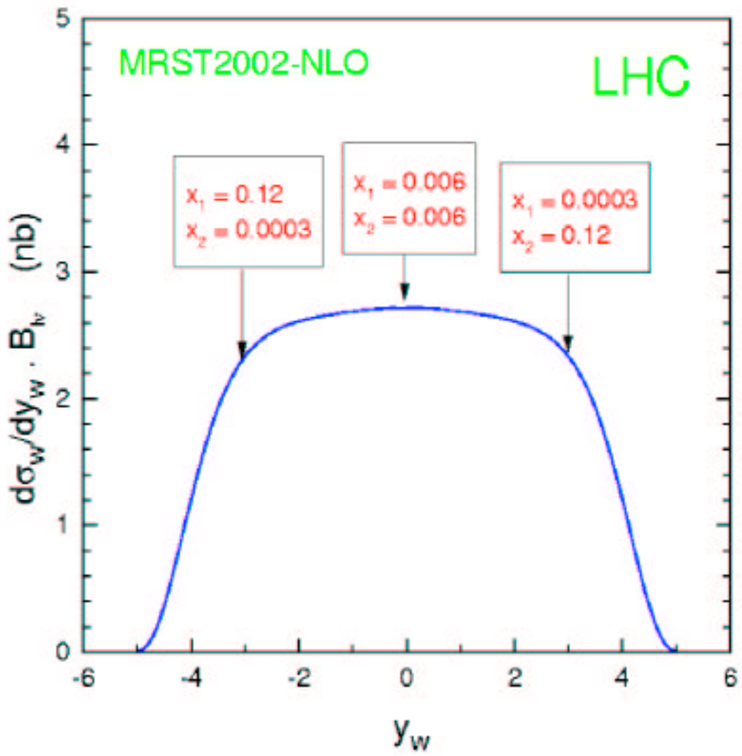


DIS and the LHC



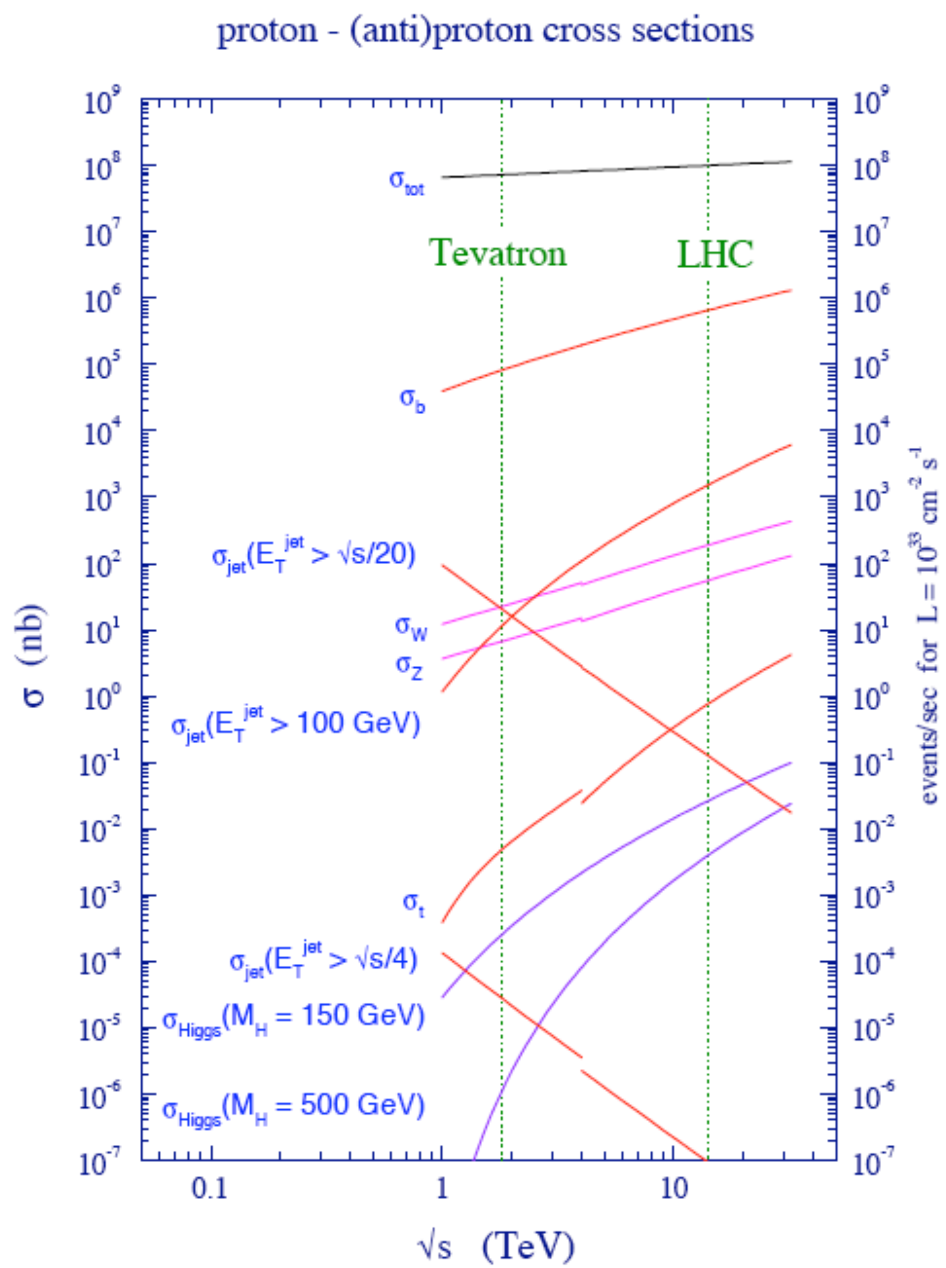
HERA accuracy limit about 1% in the bulk region (~LHC y plateau) for incl. xsection
[~2% at high y (low x) and perhaps 5% at large x, ~1/(1-x)]

Cross sections at the LHC



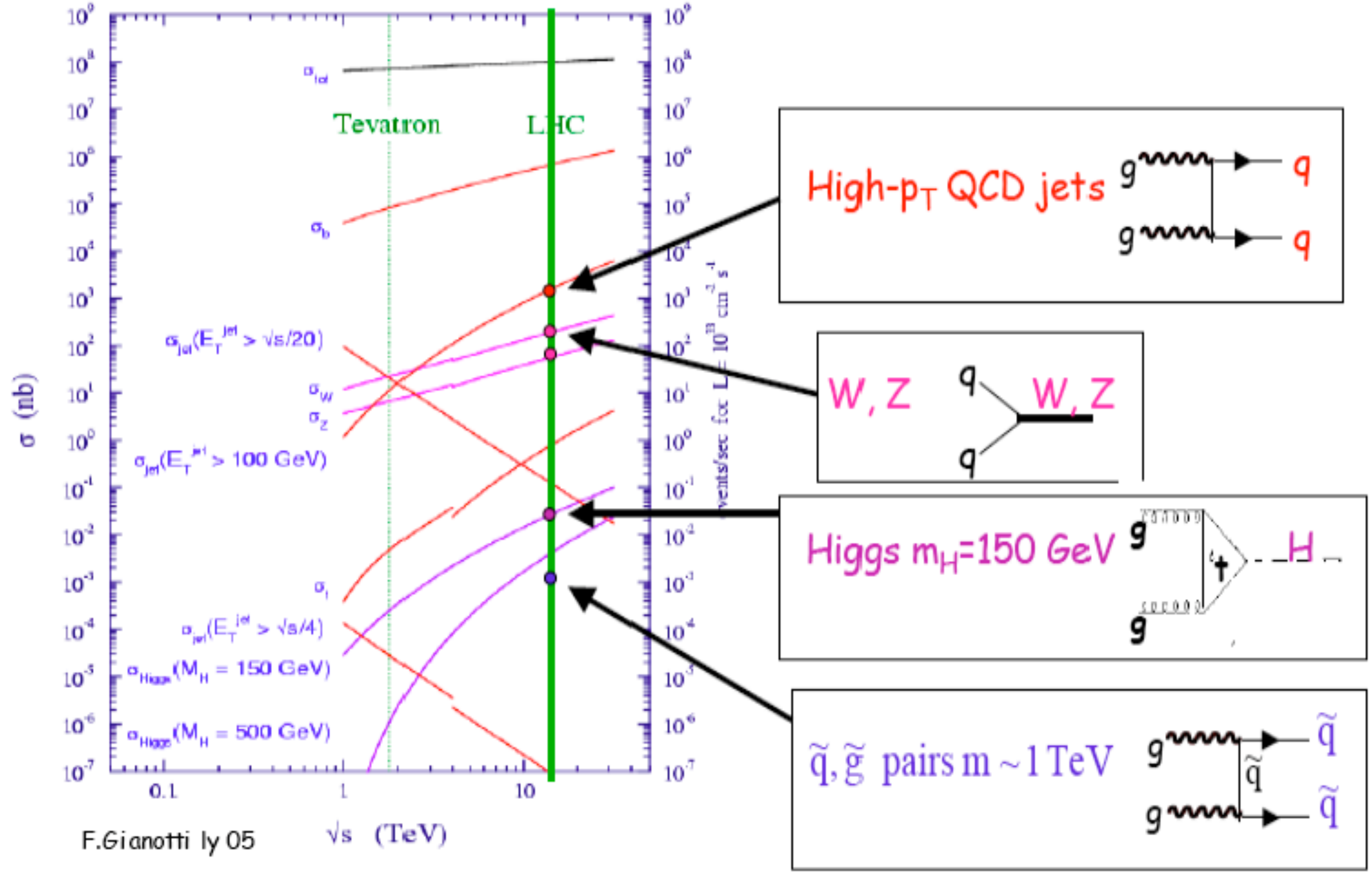
Low and high x are linked.
Likely cancellations in ratios

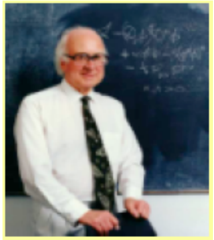
$$R_\pm = \frac{\sigma(W^+)}{\sigma(W^-)} \simeq \frac{u(x_1)\bar{d}(x_2)}{d(x_1)\bar{u}(x_2)} \simeq \frac{u(x_1)}{d(x_1)}$$

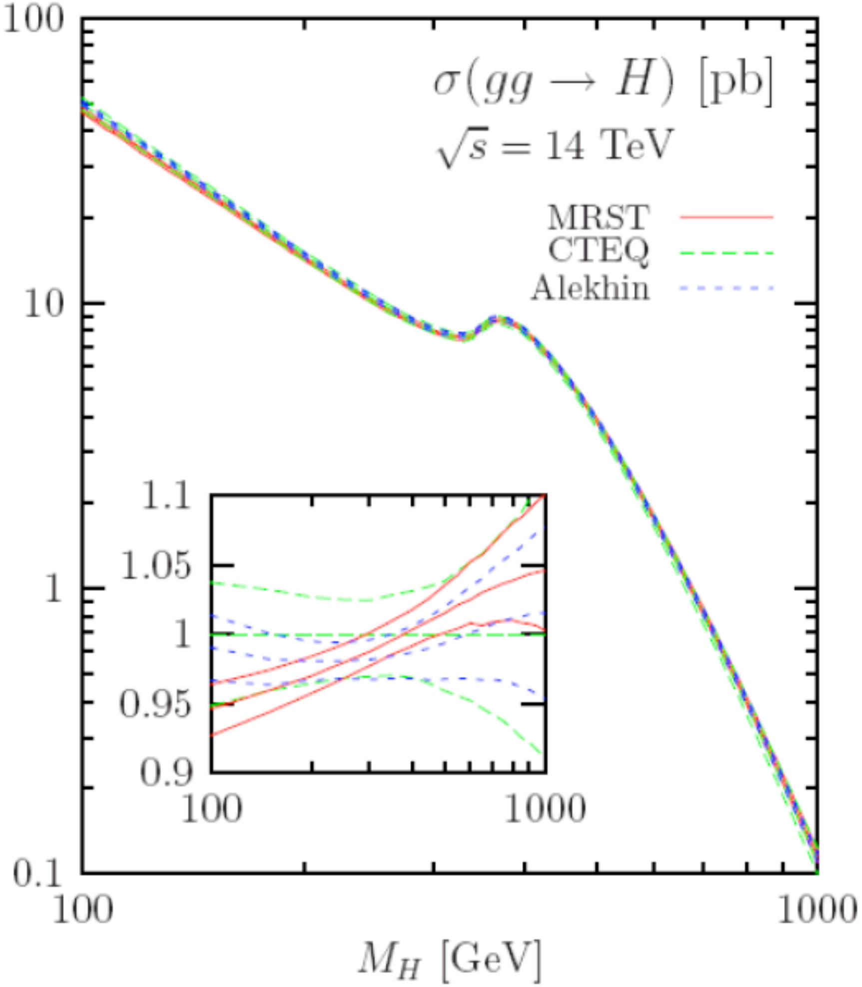


W.Stirling, Binn Workshop 10/2003

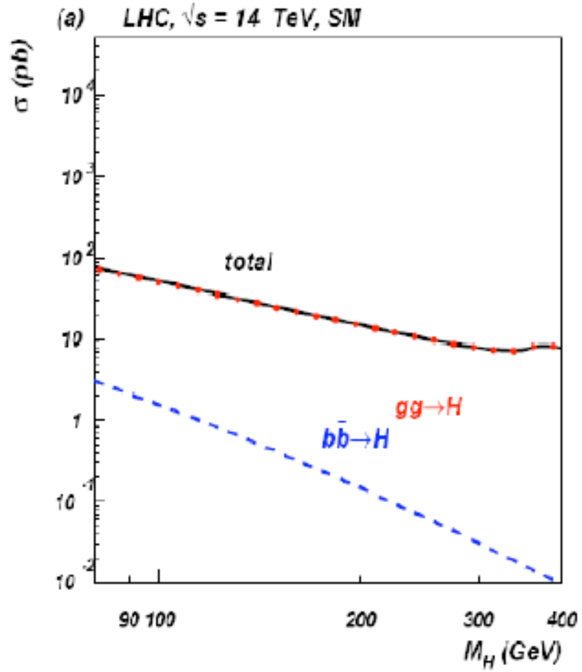
The LHC is a discovery machine based on developping QCD



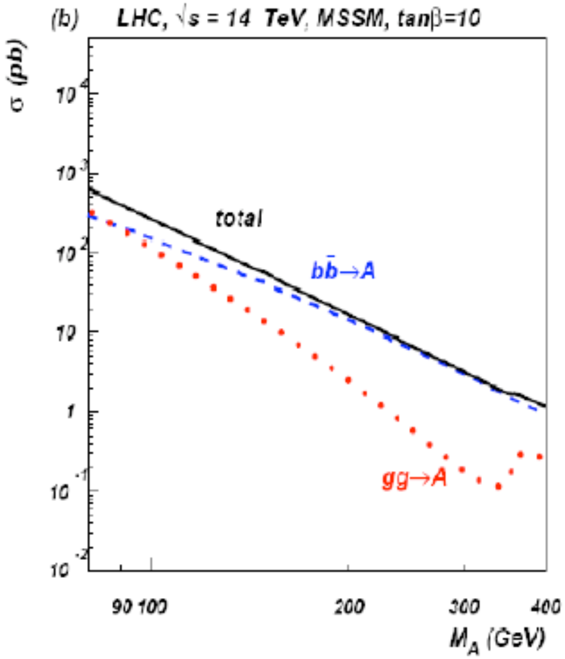




σ(gg → H) [pb]
√s = 14 TeV
MRST
CTEQ
Alekhin
M_H [GeV]



(a) LHC, √s = 14 TeV, SM
σ (pb)
total
gg→H
bb̄→H
M_H (GeV)



(b) LHC, √s = 14 TeV, MSSM, tanβ=10
σ (pb)
total
bb̄→A
gg→A
M_A (GeV)

beauty density at the LHC

The bottom quark can enter, in the form of a PDF, a number of interesting processes:

b g --> t W

Process	Interest	Accuracy
single-top t-channel	SM, top EW couplings and polarization, V_{tb}. Anomalous couplings.	NLO
single-top + W		NLO
Wbj	SM, bkg to single top	(NLO)
gamma+b	SM, SUSY bkg, b-pdf	NLO
Z+b		NLO
inclusive h,A	SUSY discovery/ measurements at large tan(beta)	NNLO
h,A+b		NLO
H^{+} + t	SUSY discovery, couplings	NLO

Standard processes

Searches (discoveries?)

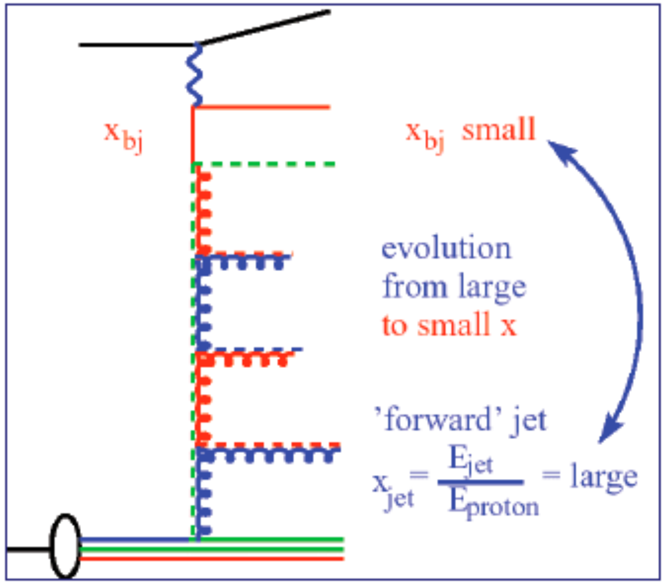
A. Tonazzo Study in ATLAS.

F. Maltoni

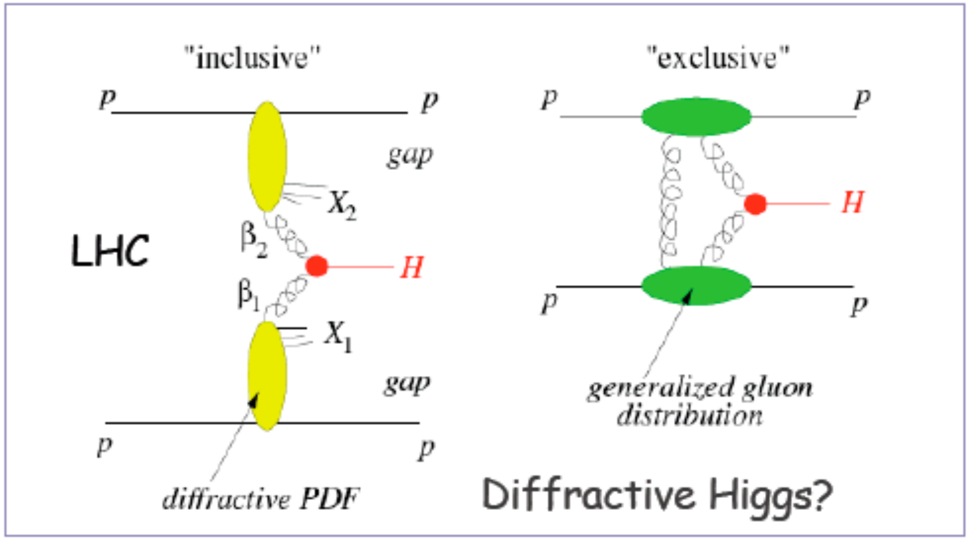
b is 5% of pp to Z

thus <20% accuracy required for 1% accurate cross section

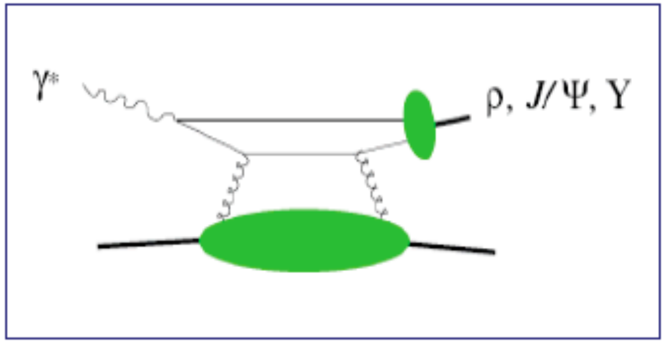
Low x Physics - Forward at the LHC - rich of unknowns and new developments



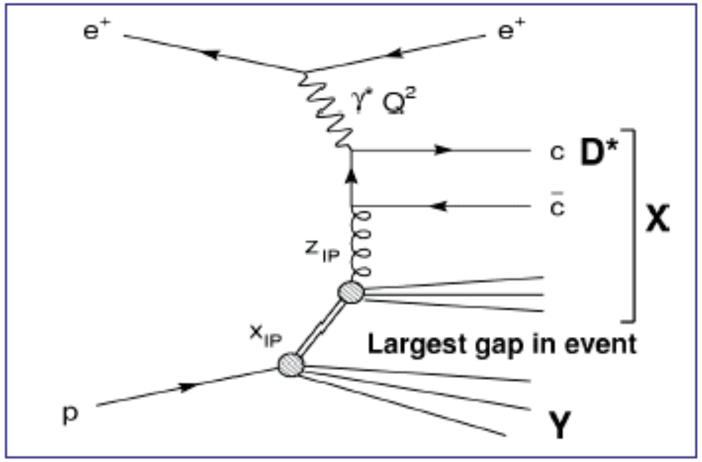
Parton radiation dynamics



Diffractive Higgs?



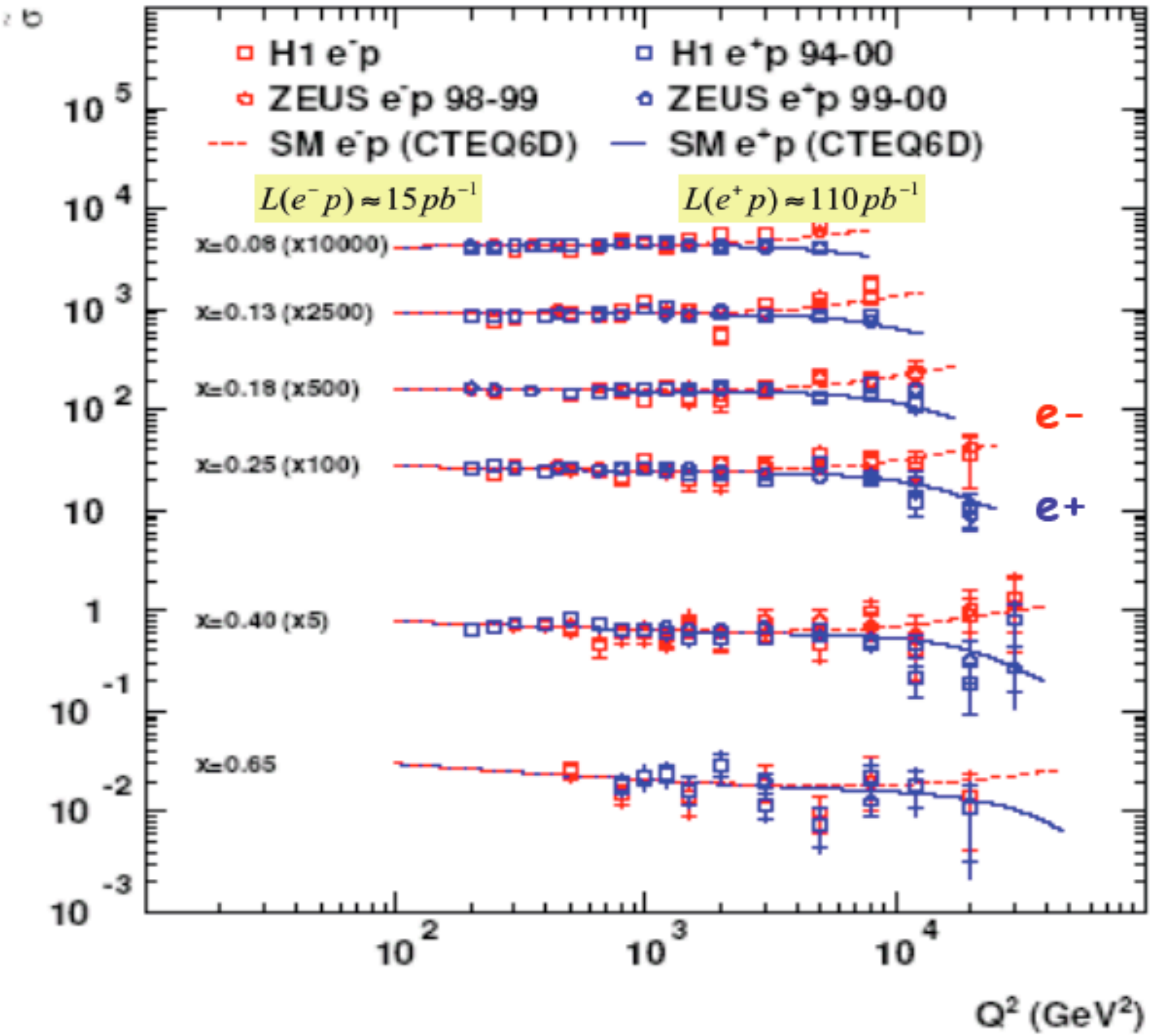
Generalised Parton Distributions



Diffractive Factorisation? dpdf's?

Neutral and Charged Currents in ep

HERA Neutral Current at high x



$$\sigma_{NC}^{\pm}(x,Q^2) \sim F_2 \mp f(y) xF_3$$

$$F_2 = e_u^2 x(U + \overline{U}) + e_d^2 x(D + \overline{D})$$

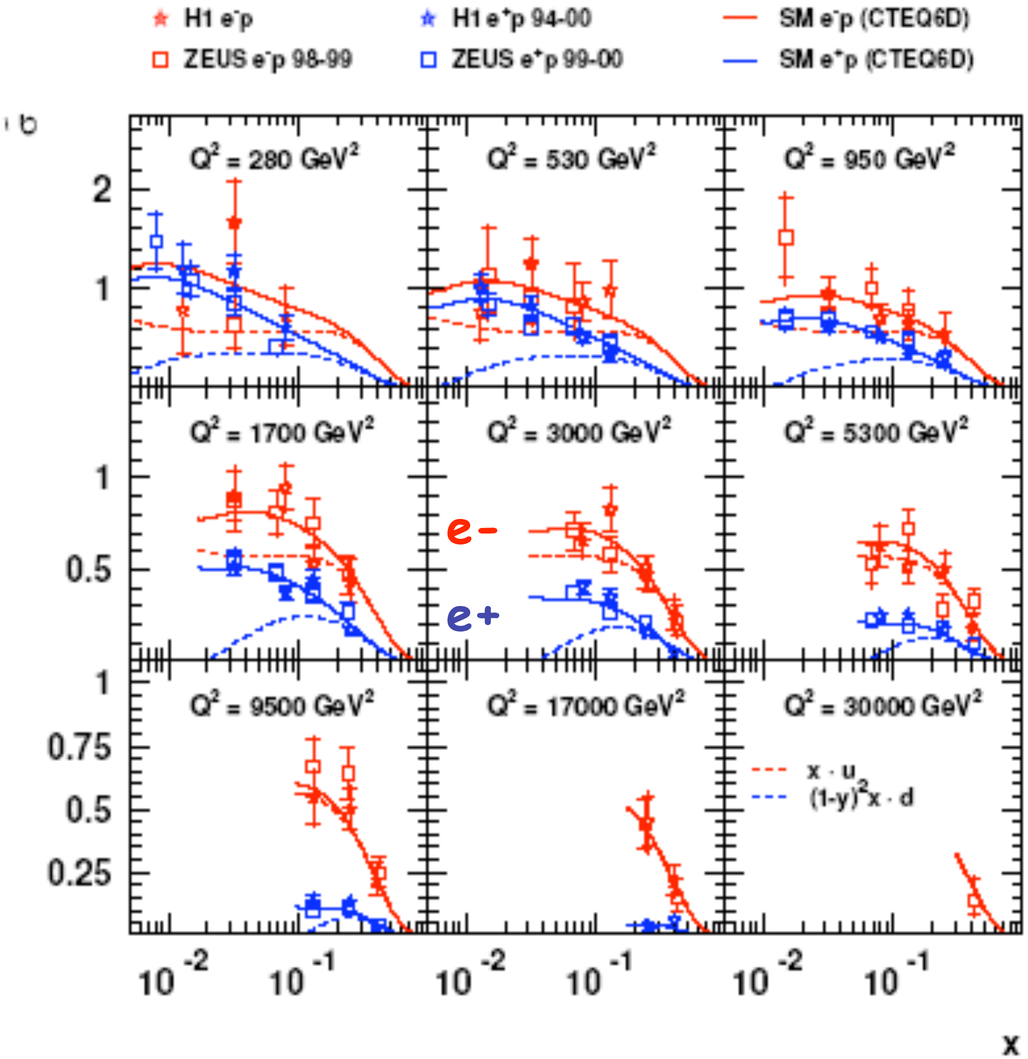
$$xF_3^{\gamma Z} = x(2u_v + d_v)/3$$

$$U = u + c$$

$$D = d + s + b$$

Z exchange enhances electron proton cross section and reduces positron proton cross section at large Q2

Reduced charged current scattering cross section

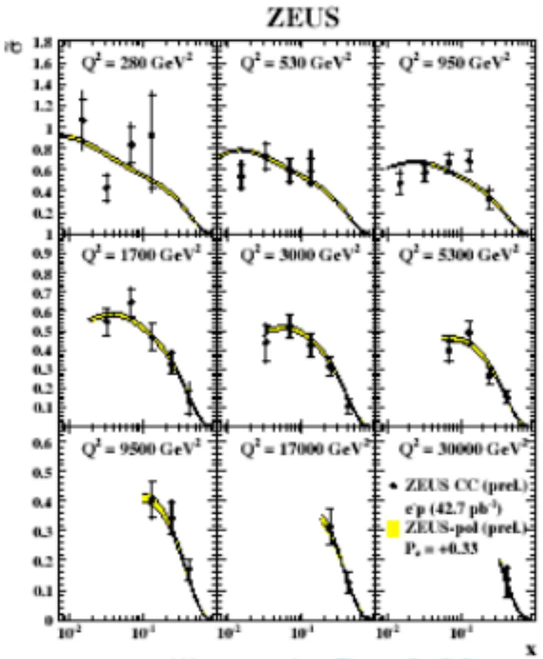


$$\sigma_{CC}^{-} \sim xU + (1-y)^2 x\overline{D} \rightarrow xu_v$$

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

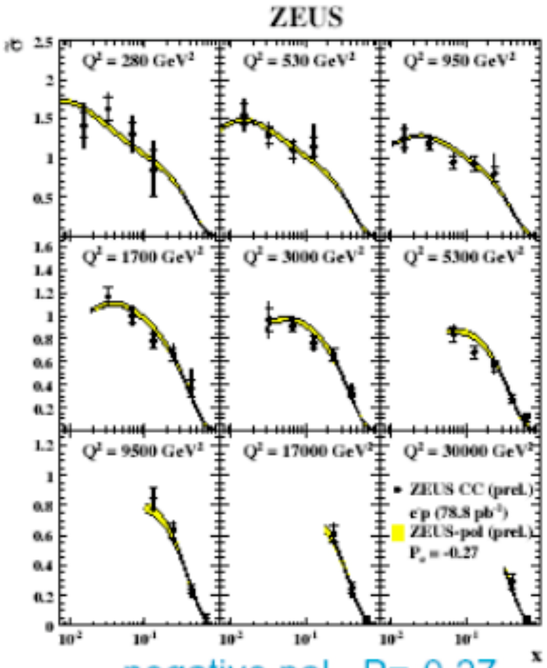
HERA can disentangle parton distributions at large Q^2 and large x > 0.01 within single experiments, independently of nuclear corrections and free of higher twists

New CC Data from 2004-2006



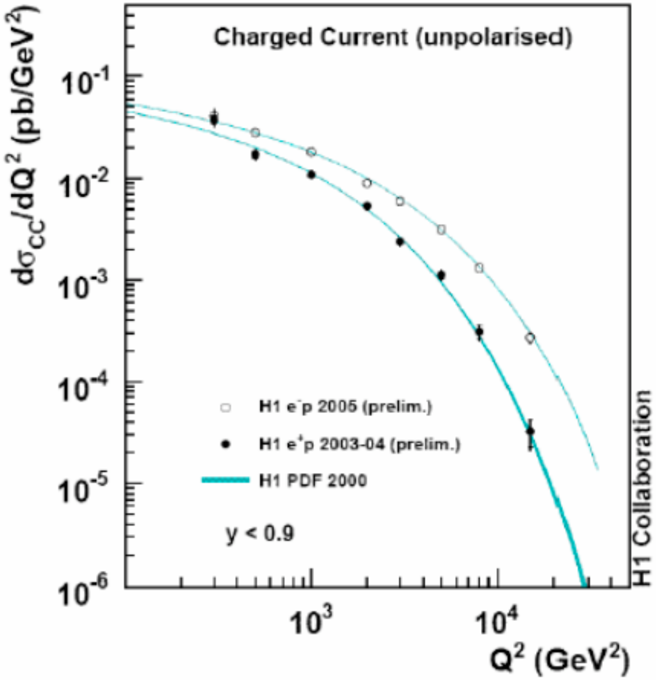
positive pol. $P=+0.33$

43 pb^{-1}

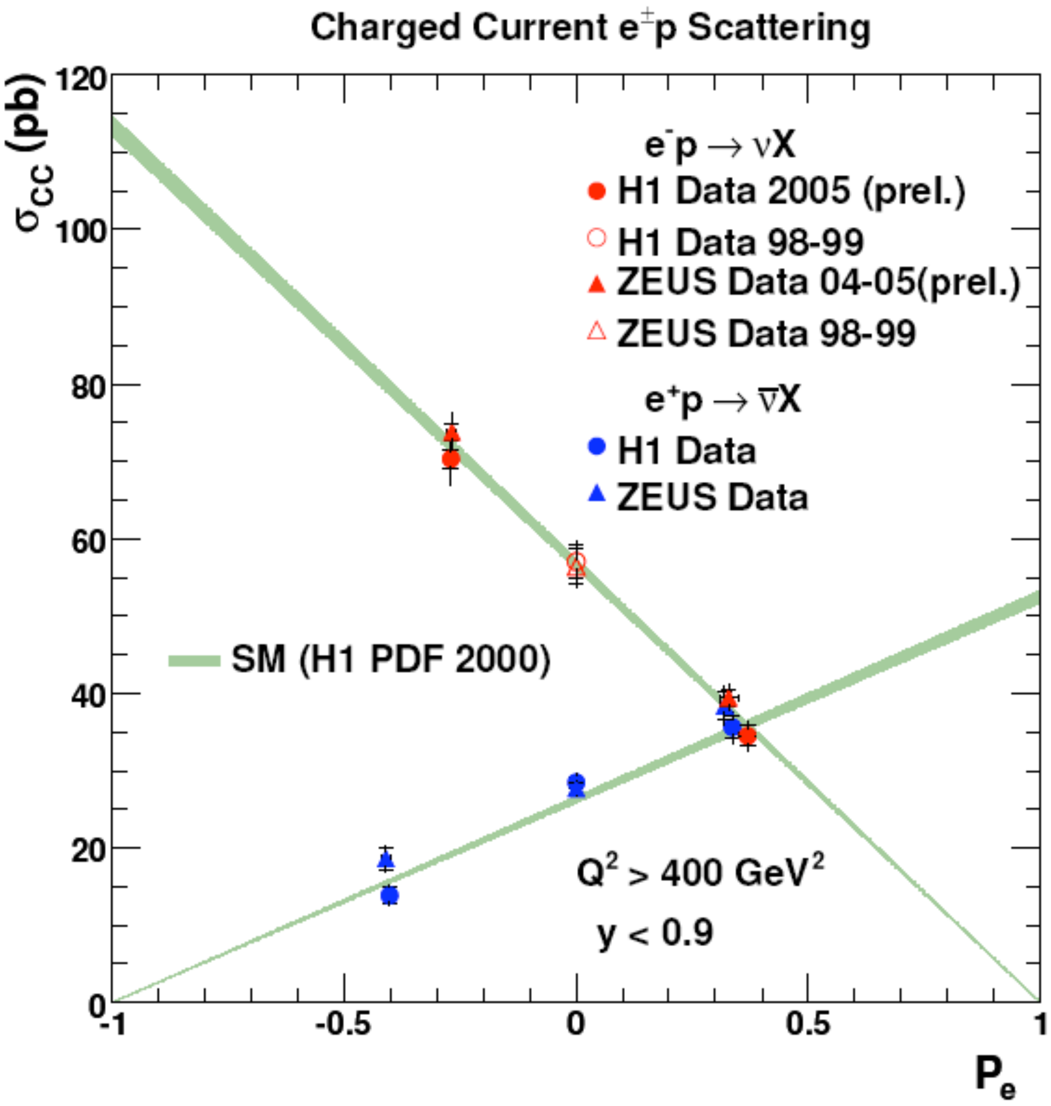


negative pol. $P=-0.27$

79 pb^{-1}



Polarisation dependence of CC cross section



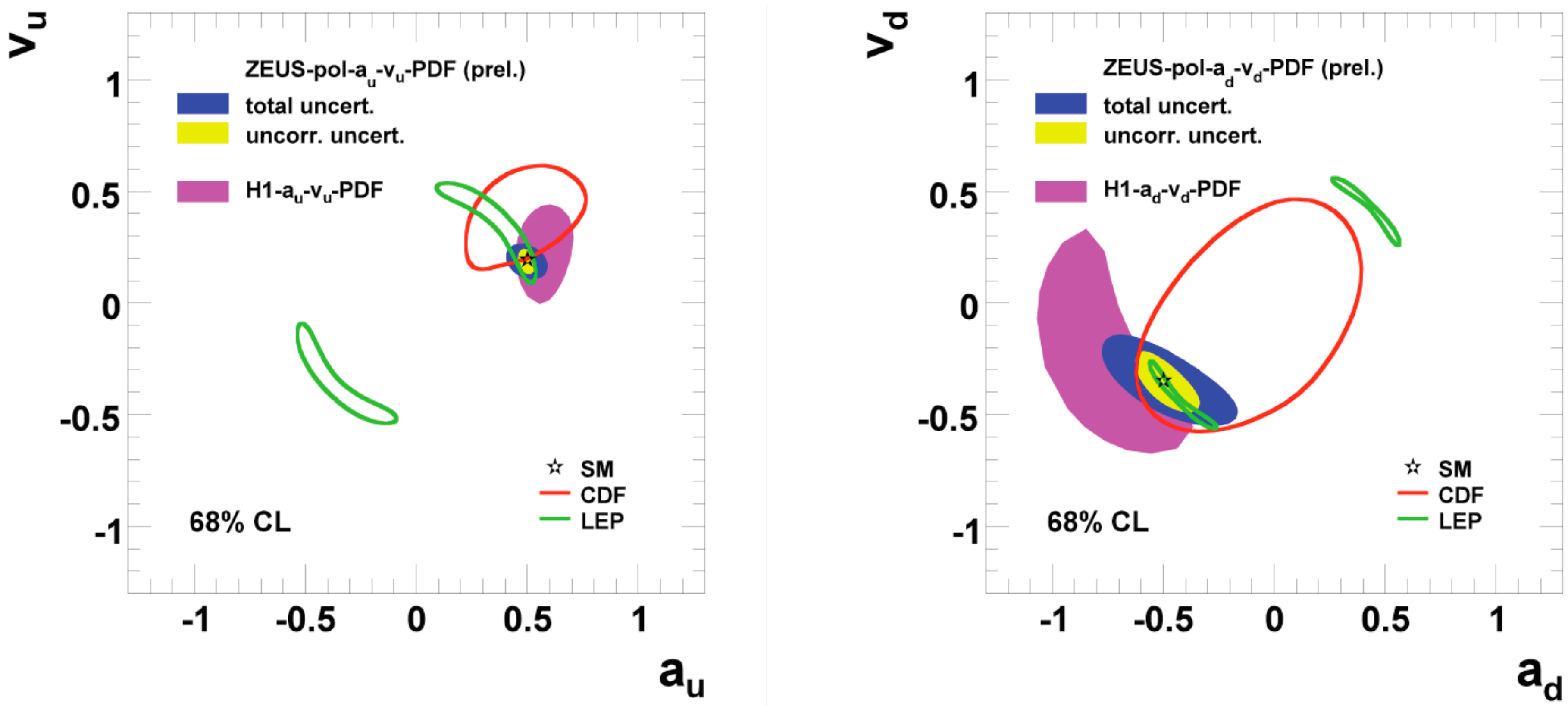
$$\frac{d^2\sigma_{cc}^{e^{\pm}p}}{dxdQ^2} = [1 \pm P]\frac{G_F^2}{2\pi x}\left[\frac{M_W^2}{Q^2 + M_W^2}\right]^2 \phi_{cc}^{\pm}$$

HERA polarised collider

No indication for rh currents

Long awaited textbook plot

Electroweak Physics at HERA



Weak couplings of light quarks [from joint pdf - v,a fits to NC,CC]
CC vs polarisation
NC polarisation asymmetries ~ va: parity violation at 10^{-18} m
Searches for new physics (as r.h currents, anomalous couplings..)

“QCD Fits” - Determination of pdf’s and α_s

cf Mandy Cooper Sarkar

QCD Fit H1 - I

Goal: measure strong coupling constant and the gluon distribution

$$F_2 = \frac{4}{9} \cdot xU + \frac{1}{9} \cdot xD$$

$$\Sigma = U + D$$

singlet

$$F_2 = \frac{2}{9} \cdot x\Sigma + \frac{1}{3} \cdot x\Delta$$

$$\Delta = (2U - D)/3$$

non-singlet

$$\boxed{F_2 = \frac{1}{3} xV + \frac{11}{9} xA}$$

$$A = \frac{1}{4}(2D - U) = \overline{d} + \overline{s} - \frac{1}{2}\overline{u} - \frac{1}{4}u_v + \frac{1}{2}d_v$$

$$V = \frac{3}{4}(3U - 2D) = \frac{9}{4}u_v - \frac{3}{2}d_v + \frac{9}{2}\overline{u} - 3(\overline{d} + \overline{s})$$

Two quark distribution functions, valence and sea like (min number of parameters for quarks)

Fit to proton data only (no nuclear corrections)

$$V = \frac{3}{4} \cdot \frac{1}{1+\epsilon}[(3+2\epsilon)u_v - 2d_v + (5+2\epsilon)(\overline{u} - \overline{d})]$$

$$\delta = \int(\overline{u} - \overline{d})dx$$

$$s + \overline{s} = (\frac{1}{2} + \epsilon) \cdot (\overline{u} + \overline{d})$$

$$\int_0^1 V dx = 3 + \delta \cdot \frac{3}{4} \cdot \frac{5+2\epsilon}{1+\epsilon} = v(\epsilon, \delta)$$

Note notation clash, here U,D include quark and antiquark parts

NC

$$\frac{d^2\sigma^{\pm}_{NC}}{dx\, dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\phi^{\pm}_{NC}\left(1+\Delta^{\pm,weak}_{NC}\right),$$

with $\phi^{\pm}_{NC} = Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\,,$

$$[F_2, F_2^{\gamma Z}, F_2^{Z}] = x\sum_q [e_q^2, 2e_qv_q, v_q^2+a_q^2]\{q+\overline{q}\}$$

$$[xF_3^{\gamma Z}, xF_3^{Z}] = 2x\sum_q [e_qa_q, v_qa_q]\{q-\overline{q}\} \underset{?}{=} 2x\sum_{q=u,d}[e_qa_q, v_qa_q]q_v$$

below bottom threshold

$$\begin{aligned} xU &= x(u+c) \\ x\overline{U} &= x(\overline{u}+\overline{c}) \\ xD &= x(d+s) \\ x\overline{D} &= x(\overline{d}+\overline{s}) \end{aligned}$$

$$xu_v = x\left(U-\overline{U}\right), \quad xd_v = x\left(D-\overline{D}\right)$$

QCD Fit H1 - II (PDF 2000)

CC

$$\frac{d^2\sigma^{\pm}_{CC}}{dx\, dQ^2} = \frac{G_F^2}{2\pi x}\left[\frac{M_W^2}{Q^2+M_W^2}\right]^2\phi^{\pm}_{CC}\left(1+\Delta^{\pm,weak}_{CC}\right)$$

with $\phi^{\pm}_{CC} = \frac{1}{2}(Y_+W_2^{\pm} \mp Y_- xW_3^{\pm} - y^2W_L^{\pm})\,,$

$$W_2^+ = x(\overline{U}+D)\,, \quad xW_3^+ = x(D-\overline{U})$$

$$W_2^- = x(U+\overline{D})\,, \quad xW_3^- = x(U-\overline{D})$$

$$\phi^+_{CC} = x\overline{U} + (1-y)^2 xD, \quad \phi^-_{CC} = xU + (1-y)^2 x\overline{D}$$

Goal: disentangle the quark distributions (required assumptions on low x)

The low x limit of the parton distributions determined in H1 fits

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} \cdot [1+D_g x] \\
xU(x) &= A_U x^{B_U}(1-x)^{C_U} \cdot [1+D_U x+F_U x^3] \\
xD(x) &= A_D x^{B_D}(1-x)^{C_D} \cdot [1+D_D x] \\
x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}}(1-x)^{C_{\overline{U}}} \\
x\overline{D}(x) &= A_{\overline{D}} x^{B_{\overline{D}}}(1-x)^{C_{\overline{D}}},
\end{aligned}
$$

B_g not well constrained
-0.05 … -.8
D related to B

Polynomial determined from χ^2 saturation

At low x have only one measurement: $F_2 = \frac{4}{9} x\,(U+\overline{U}) + \frac{1}{9} x\,(D+\overline{D})$

assume that quark and anti-quark distributions are equal at low x, and u=d

$$B_U = B_D = B_{\overline{U}} = B_{\overline{D}} \equiv B_q$$

$A_{\overline{U}} = A_{\overline{D}} \cdot (1-f_s)/(1-f_c)$, which imposes that $\bar{d}/\bar{u} \to 1$ as $x \to 0$.

QCD Fits ZEUS

ZEUS S

Zeus-S(tandard) and Zeus-α_s fits:

- μ-induced F_2 from BCDMS,NMC,E665
- Deuterium-target data from NMC and E665
- The NMC data on the F_2^D/F_2^p
- CCFR xF_3 data

  (nb $0.1 < x < 0.65$)
- ZEUS 96-97 NC cross sections

ZEUS O[nly] (similar to the H1 fit II)

ZEUS+jets (uses inclusive and jet data)

QCD Fit ZEUS

$$\left\{\begin{array}{c} xg \\ xS \equiv 2x\left(\bar{d}+\bar{u}+\bar{s}+\bar{c}\right) \\ x\Delta \equiv x\left(\bar{d}-\bar{u}\right) \\ xd_V \equiv x\left(d-\bar{d}\right) \\ xu_V \equiv x\left(u-\bar{u}\right) \end{array}\right\} = p_1 x^{p2}(1-x)^{p3}(1+p_4\sqrt{x}+p_5 x)$$

4 quark distributions

assumptions

Assume: $2x\bar{s} = 0.2xS$

- p_2= 0.5 for both valence dist.
- p_1 only free param. for $x\Delta$
  $p_1(\Delta)$=0.5, $p_3(\Delta)=p_3(S)+2$,$p_5(\Delta)$=0
- p_5=0 for xg

All these assumptions were varied during the model uncertainty study

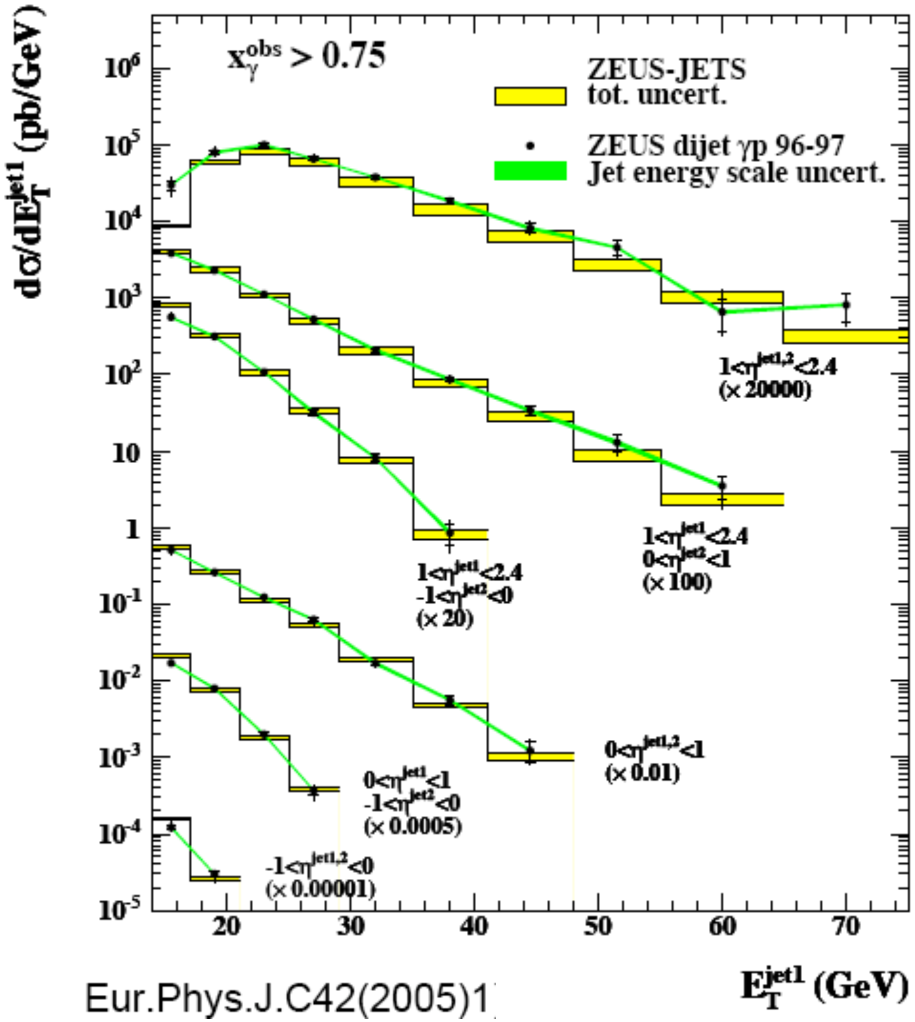
Sum rules

$$\int_0^1 (xg + x\Sigma)dx = 1, \quad \int_0^1 d_V dx = 1, \quad \int_0^1 u_V dx = 2$$

with $\quad x\Sigma = xS + xu_V + xd_V$

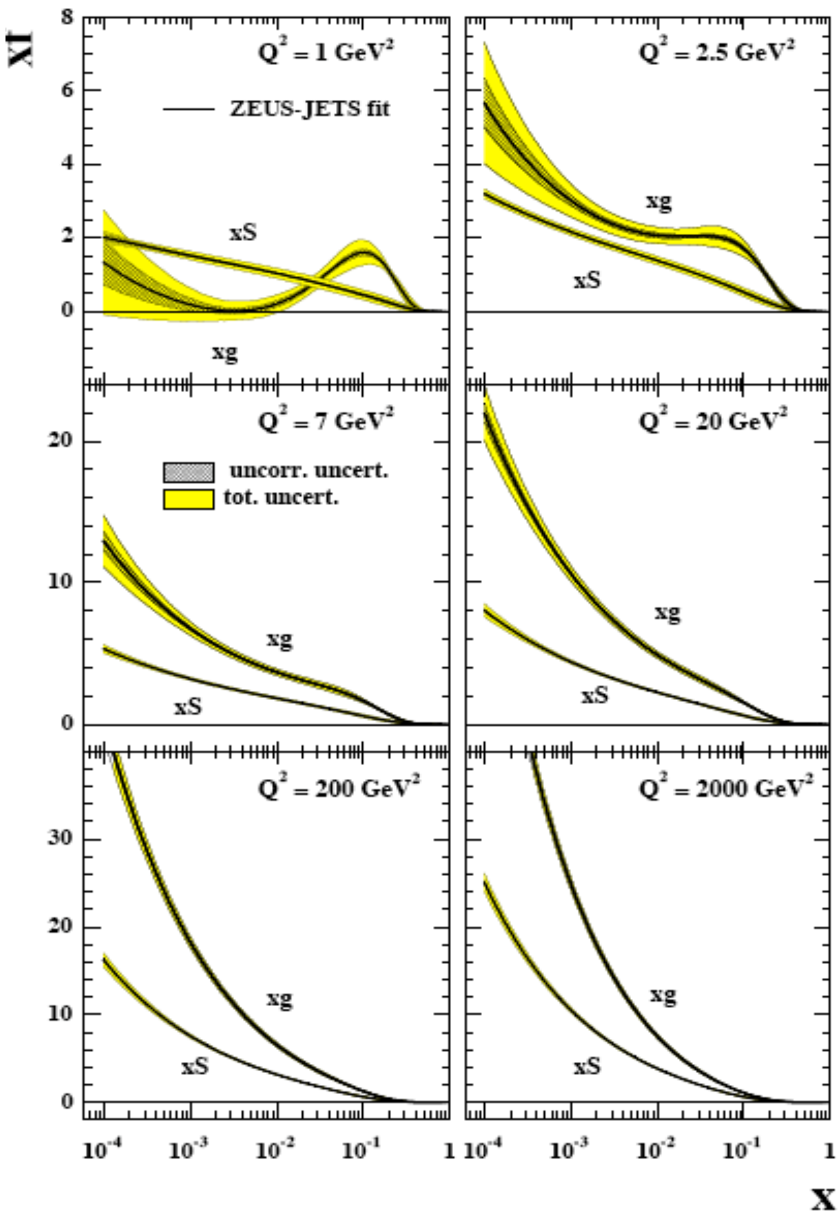
From E.Tassi CTEQ 2003

Dijets in direct photoproduction ($Q^2 \sim 0$)



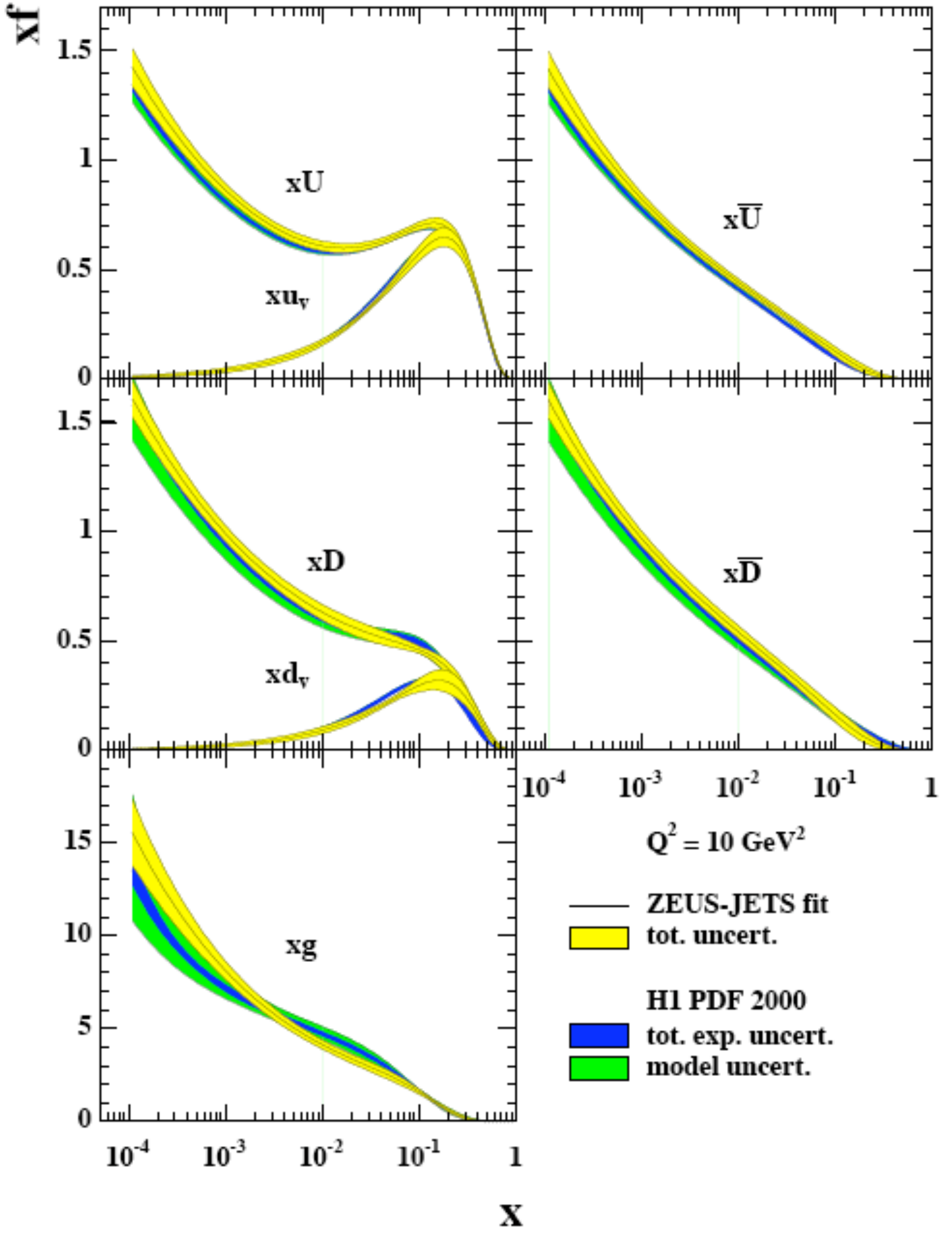
Eur.Phys.J.C42(2005)1

Sea and gluon dynamics



ZEUS fit NC, CC, and dijet HERA data jets improve much the α_s determination and somewhat the accuracy of xg at $x \sim 0.05$

Parton Distributions from H1 and ZEUS

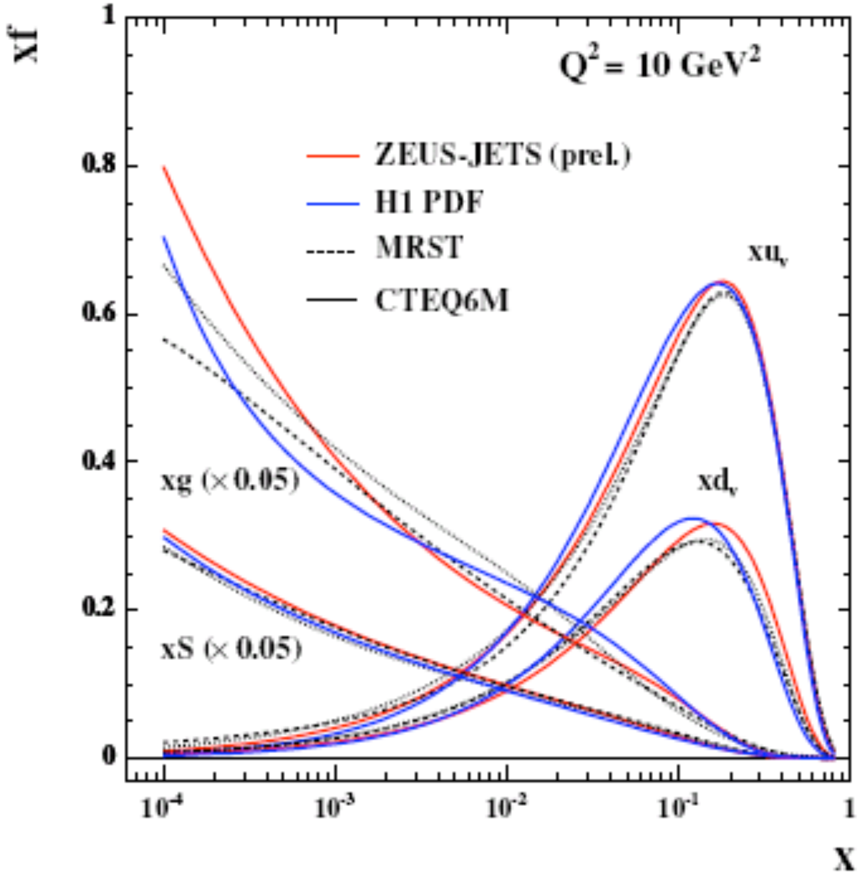


Broad agreement from independent approaches: different data, different flavour decompositions, different error treatments, different HQ treatment, different programs

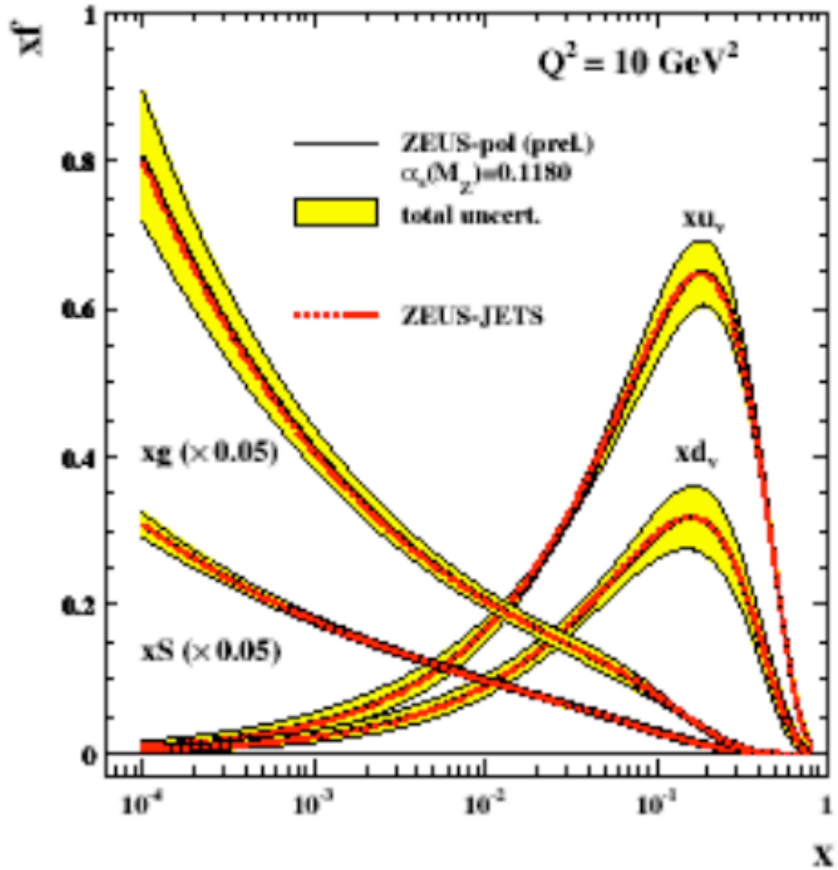
Next: more accurate data at high x,Q2, and low x, F_L , combined H1+ZEUS data and possibly unified treatment of the QCD fit problem, NNLO

Goal: most accurate pdf's for proton's structure and for understanding QCD at the Large Hadron Collider leading to new physics

Valence and sea quarks from HERA

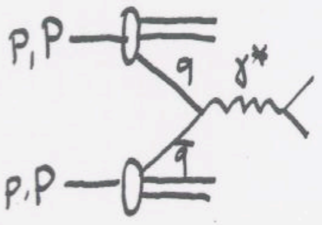


Most recent: ZEUS incl, jets and pol data



Low x dominated by sea and gluon, large x by valence quarks
Accuracy improving with more data and better thy understanding

Partons in pp Scattering



Drell-Yan 1970

$\sqrt{s} = 2P = 14$ TeV @ LHC

$Q^2 = M^2 = s\, x_q x_{\bar{q}}$

$$\frac{d\sigma}{dQ^2} = \sum_q \int dx_q \int dx_{\bar{q}}\; q(x_q) \cdot \frac{d\tilde{\sigma}_{q\bar{q}}}{dQ^2}\, \bar{q}(x_{\bar{q}})$$

$$\frac{d\tilde{\sigma}}{dQ^2} = \frac{4\pi\alpha^2}{3N_c Q^2 s} \cdot e_q^2\, \delta\left(\frac{Q^2}{s} - x_q x_{\bar{q}}\right)$$

rapidity variable of γ^* : $x = \frac{M}{\sqrt{s}}\, e^{\pm y}$

for vector boson or Higgs production

M^2 and $\frac{M}{\sqrt{s}} e^{\pm y}$ are equivalent to Q^2, x in DIS

factorisation in pp scattering

--> $\boxed{\sigma = \sum_{p,p'} f_p(\mu^2) \otimes f_{p'}(\mu^2) \otimes \tilde{\sigma}_{pp'}(\mu)}$

W, Z production

jets

direct photons

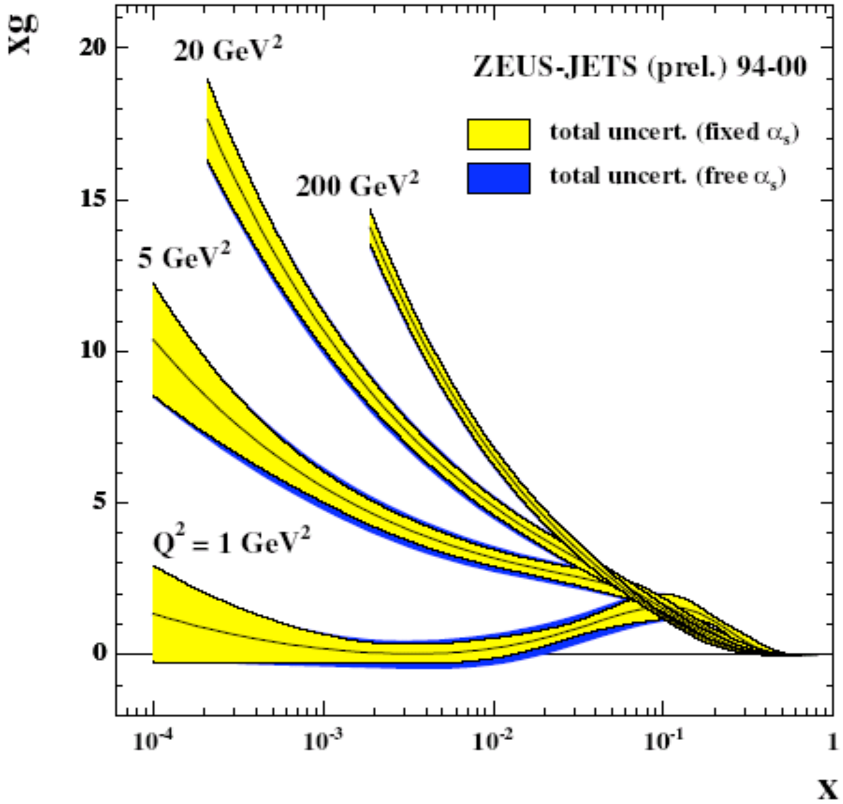
need to know the parton distribution functions (pdf's):

from DIS : HERA

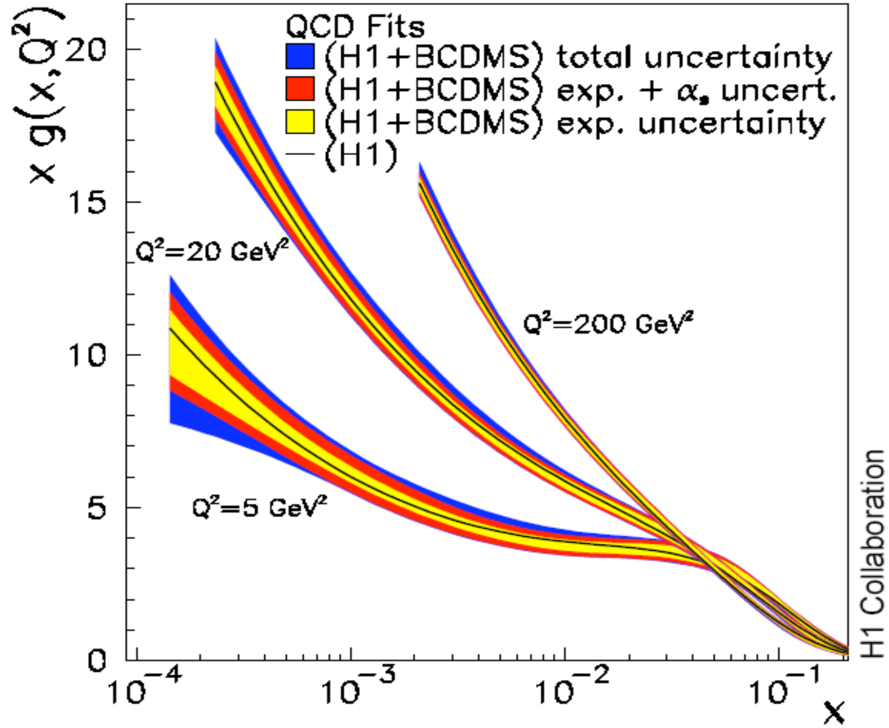
$\boxed{\text{measure } \sigma, \text{ pdf's, calculate } \tilde{\sigma} \underset{?}{\to} \mathcal{L}_{pp}}$

The Gluon Distribution from HERA

ZEUS inclusive NC+CC & jets



H1 inclusive NC+CC



$$xg \leftrightarrow \alpha_s$$

- Further improvements from: more accurate scaling violations, charm, jets, F_L
- xg is NOT an observable. Charm treatment important (ZEUS: VFNS RT, H1: FFNS)
- at large x > 0.1, the gluon distribution is not well known.

$$\frac{dG(x,t)}{dt} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[\cancel{\sum_i^{2f} q^i(y,t)\, P_{Gq}\left(\frac{x}{y}\right)} + G(y,t)\, P_{GG}\left(\frac{x}{y}\right)\right]$$

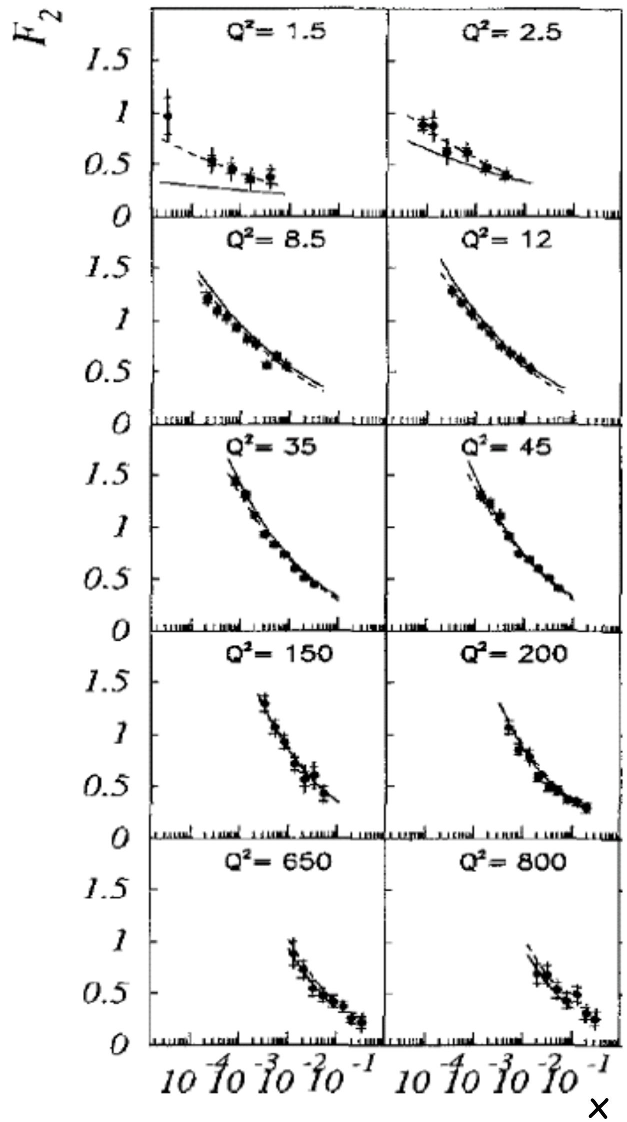
$$\frac{d\sum_i^{2f} q^i(x,t)}{dt} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[\cancel{\sum_i^{2f} q^i(y,t)\, P_{qq}\left(\frac{x}{y}\right)} + G(y,t)\, 2f\, P_{qG}\left(\frac{x}{y}\right)\right]$$

if at low x the gluon dominates, we can solve the DGLAP equation and determine the gluon distribution. This provides $F_2(x,Q^2;\ Q_0^2,\Lambda)$

$$F_2(x,Q^2) = N_f e^{\gamma\sqrt{T\ln(1/x)}}$$

$$T = \ln\frac{\ln(Q^2/\Lambda^2)}{\ln(Q_o^2/\Lambda^2)} = \ln\frac{\alpha_s(Q^2)}{\alpha_s(Q_0^2)}$$

$$\gamma^2 = 12/(11-2n_f/3),\ N_f = \sqrt{\gamma/\pi}\,5n_f/324$$



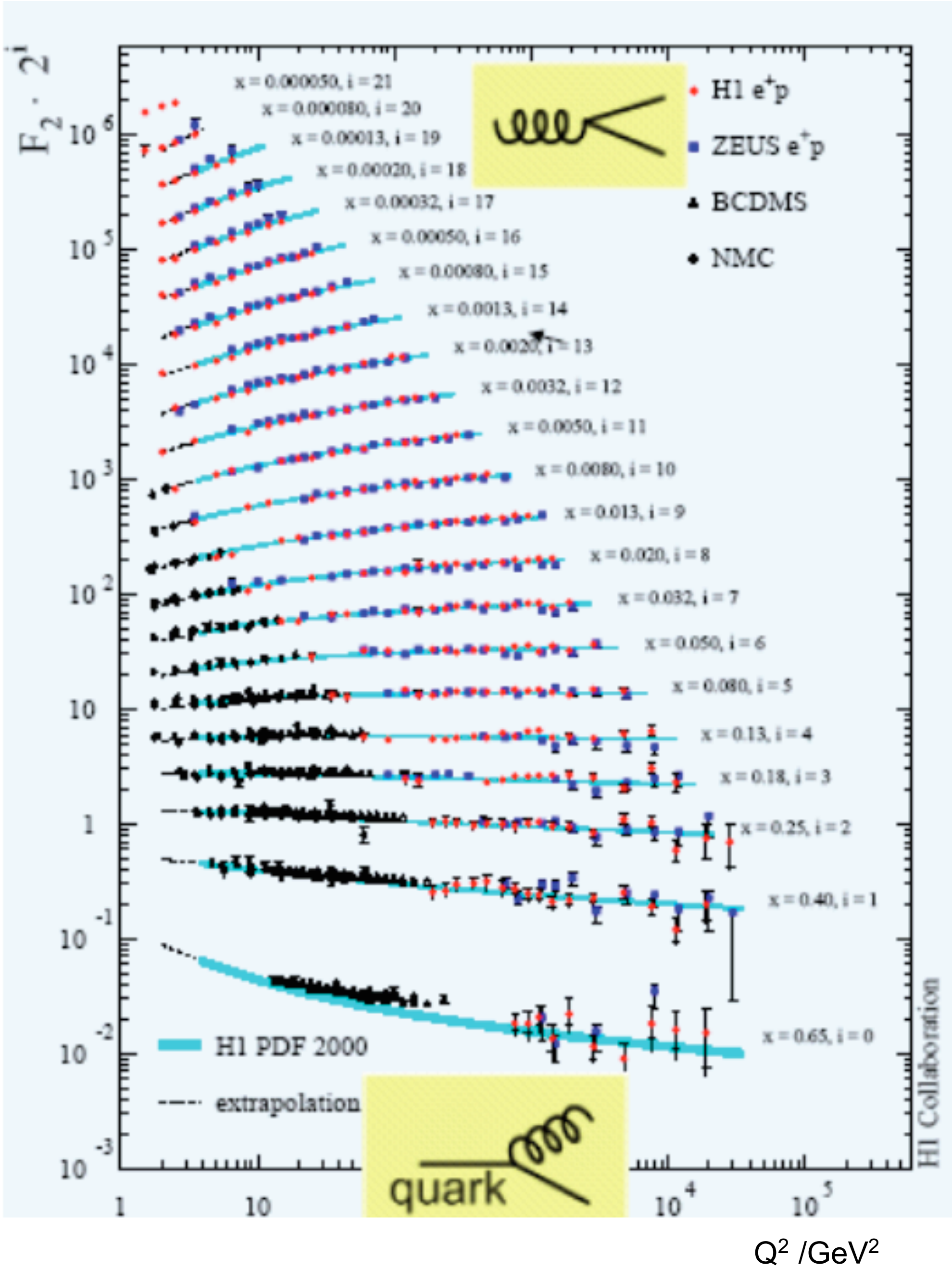
Physics Letters B 385 (1996) 411
A.DeRoeck, M.K. T.Naumann

→At low x the QCD vacuum determines the proton structure
→Many scaling expressions for the proton structure functions

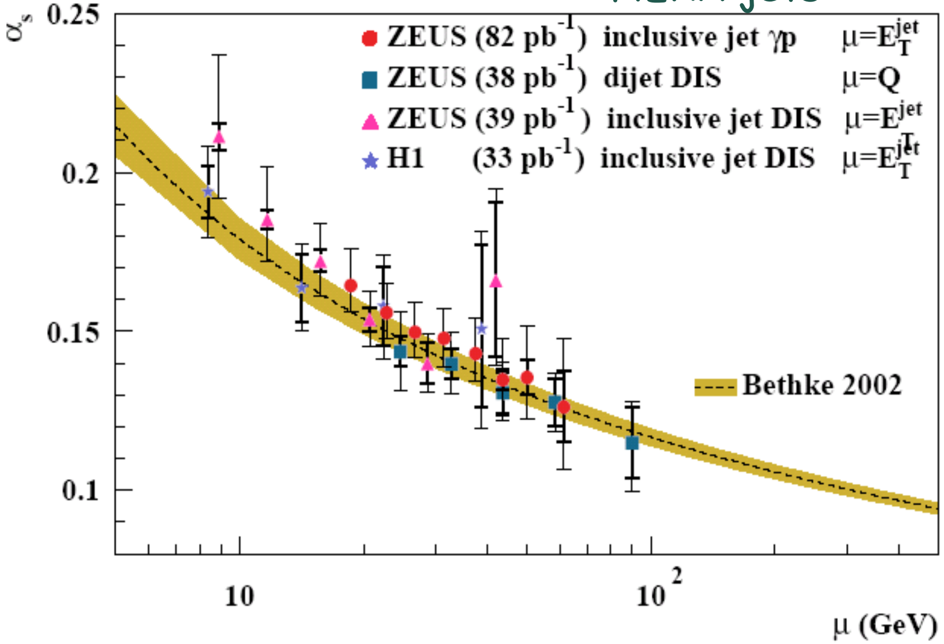
$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s(Q^2) x g(x,Q^2)$$

resolve correlation of coupling and gluon by accessing wide range of x and Q2

$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s(Q^2) q(x,Q^2)$$



Asymptotic Freedom



$$\mu \frac{dg(\mu)}{d\mu} = \beta(g(\mu))$$ RGE

$$\beta(g) = -g[\frac{\alpha_s}{4\pi}\beta_1 + (\frac{\alpha_s}{4\pi})^2\beta_2 + \ldots]$$

$$\beta_1 = (11N_c - 2n_f)/3$$

gluon & quark loops

$$\beta_2 = 102 - 38n_f/3$$

$$\frac{\alpha_s}{4\pi} = \frac{1}{\beta_1 \ln(\mu^2/\Lambda^2)} - \frac{\beta_2 \ln(\ln \mu^2/\Lambda^2)}{\beta_1^3 \ln^2(\mu^2/\Lambda^2)} + \ldots$$

leading and next-to-leading order (NLO)

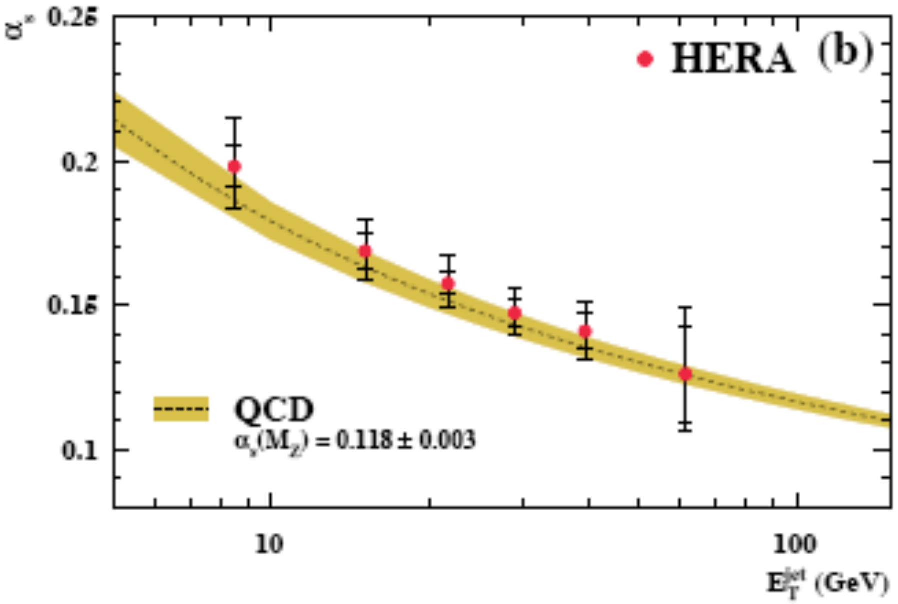
Prediction confirmed in many reactions [cf Tung]
Nobel price 2004 (Gross, Politzer, Wilczek)

At small distances < fm quarks are free
QPM restored in the limit of perturbative QCD

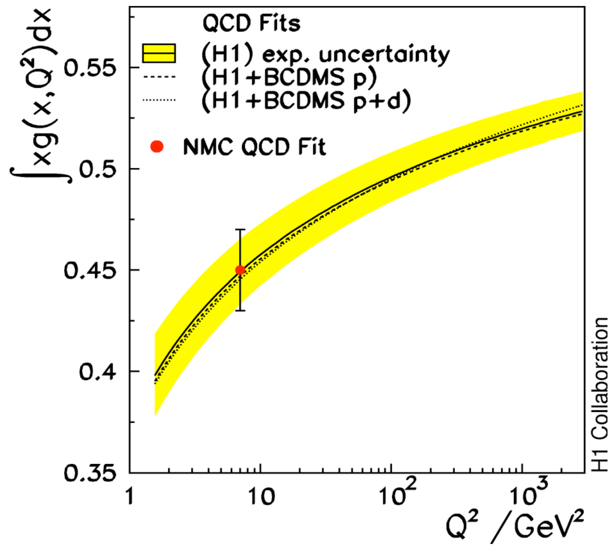
At large distances, quarks are confined.(?)
Lattice, string theories, nonperturbative regime

There is a 3rd region discovered at HERA, where the coupling is small BUT the densities are large (low x physics, AA, superhigh energy neutrino physics, forward physics at the LHC)

The strong interaction gets larger at small distances [asymptotic freedom] and gluons carry half of proton's momentum: QCD non Abelian qg field theory



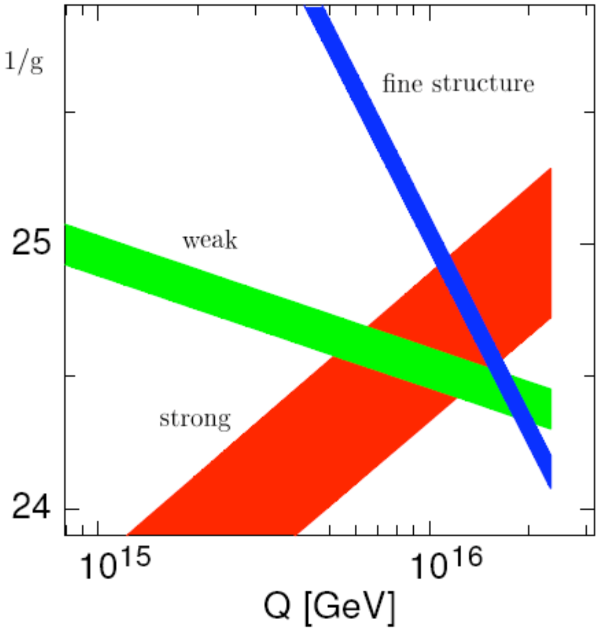
quarks carry only about 1/2 of the nucleon momentum:



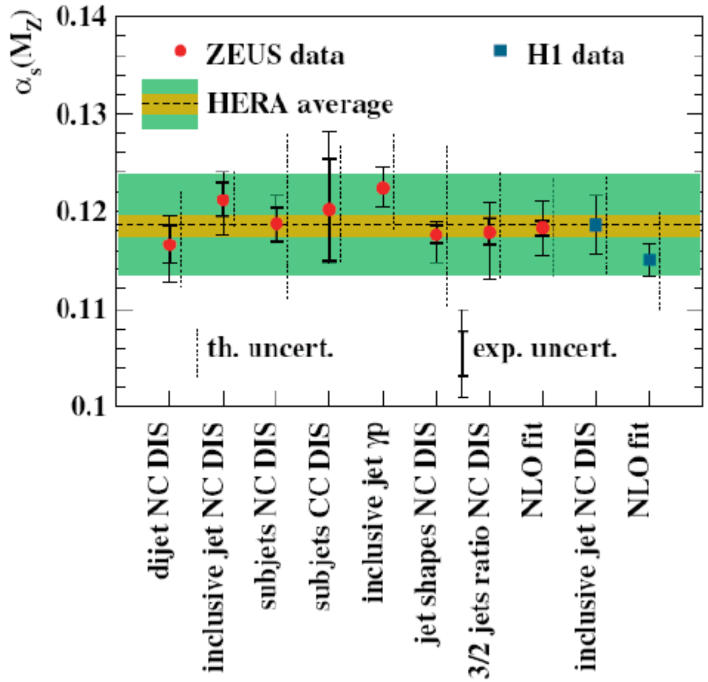
•Nobel prize 2004: Gross, Politzer, Wilczek

no doubt α_s "runs" - BUT how large is the coupling? and is the field so simple? HERA has a fundamental role to answer these ?'s

- 2006 α @ 10^{-9}
- 2006 G_F @ 10^{-5}
- 2006 G @ 0.02%
- 2006 α_s @ 1-2%
- LHeC ® α_s few/mil



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



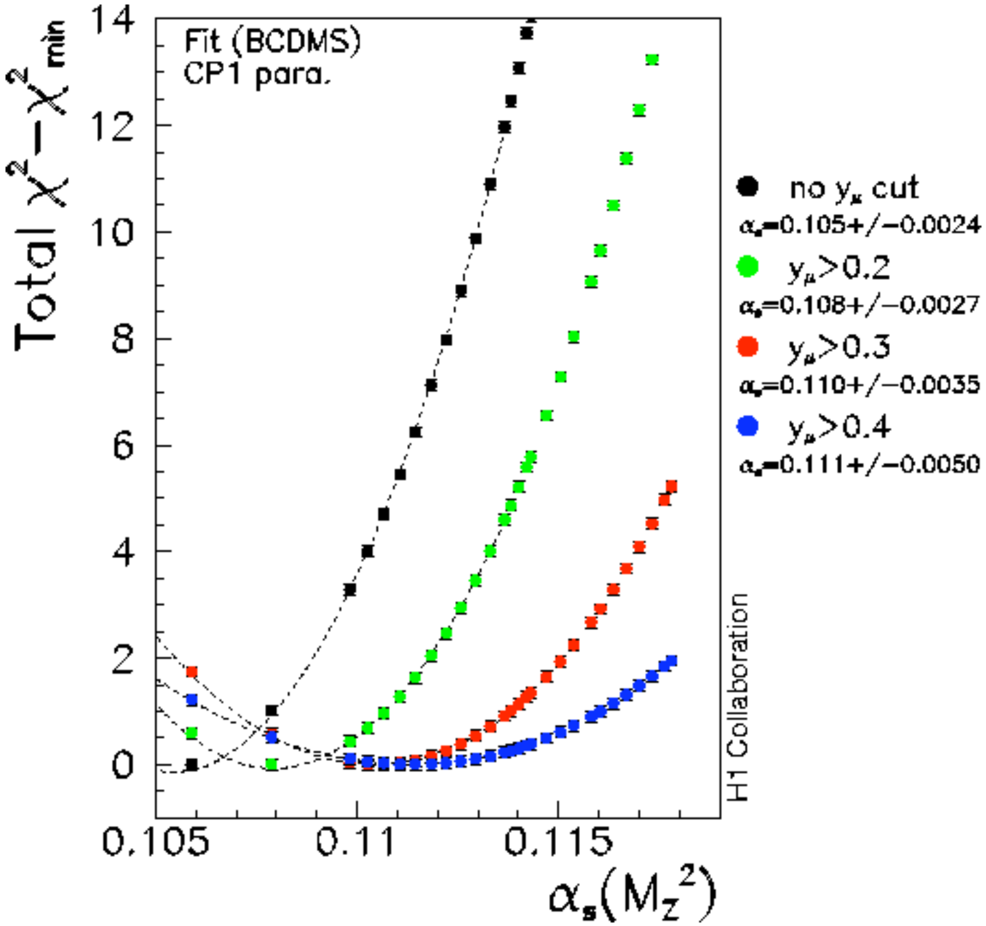
$$\alpha_s(M_Z^2) = 0.1209 \pm 0.0015(\exp) \pm^{0.0048}_{0.0049}(thy) - ZEUS$$
$$\alpha_s(M_Z^2) = 0.1160 \pm 0.0016(\exp) \pm^{0.0058}_{0.0046}(thy) - H1$$

C. Glasman, hep-ex/0506035

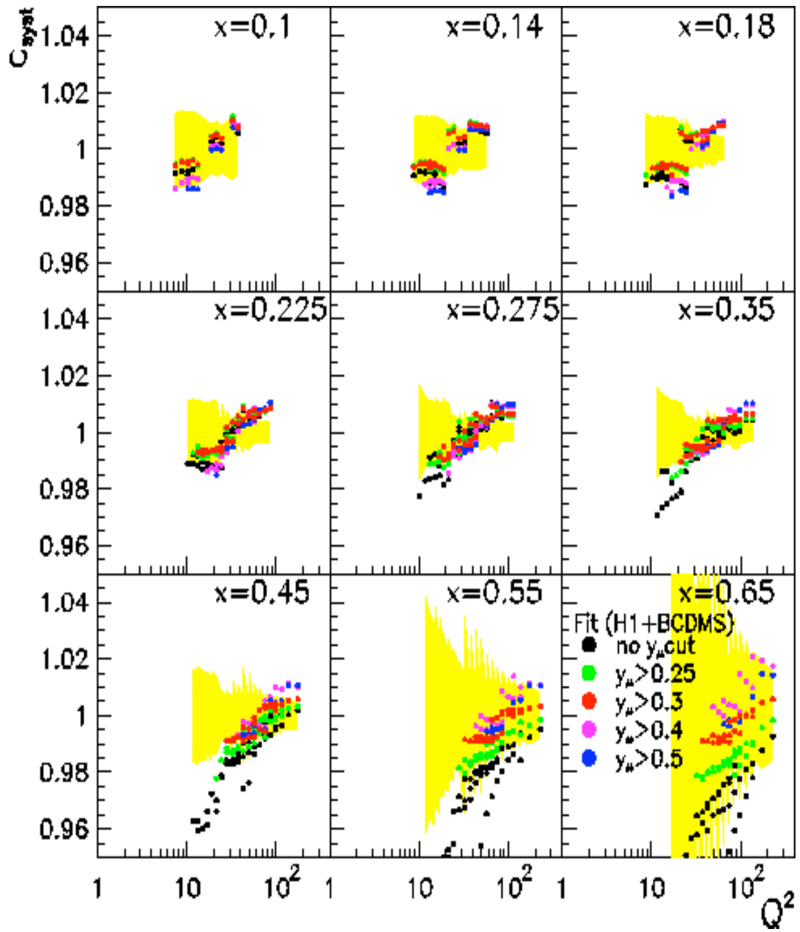
Improved accuracy with more and more accurate data (statistics and systematics), inclusive and jets

Theory uncertainty: NNLO, $\mu/2$?

The BCDMS data determines most 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

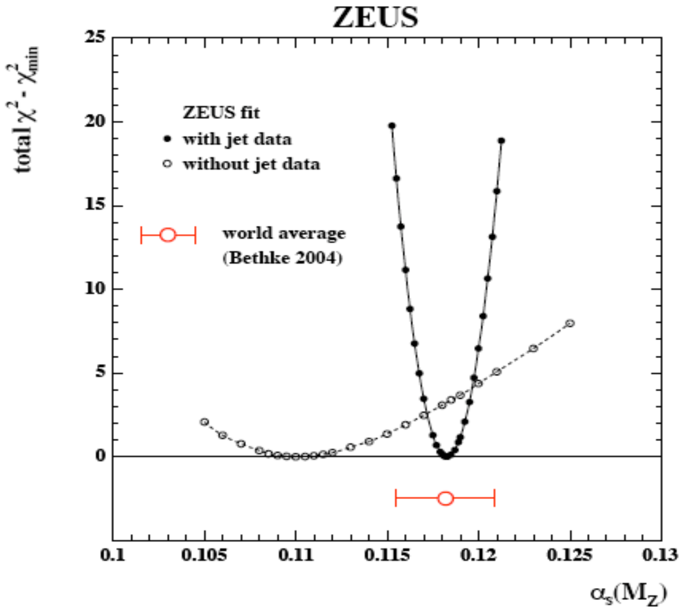
H1 EPJ C21(01)33 R.Wallny Thesis 01-058

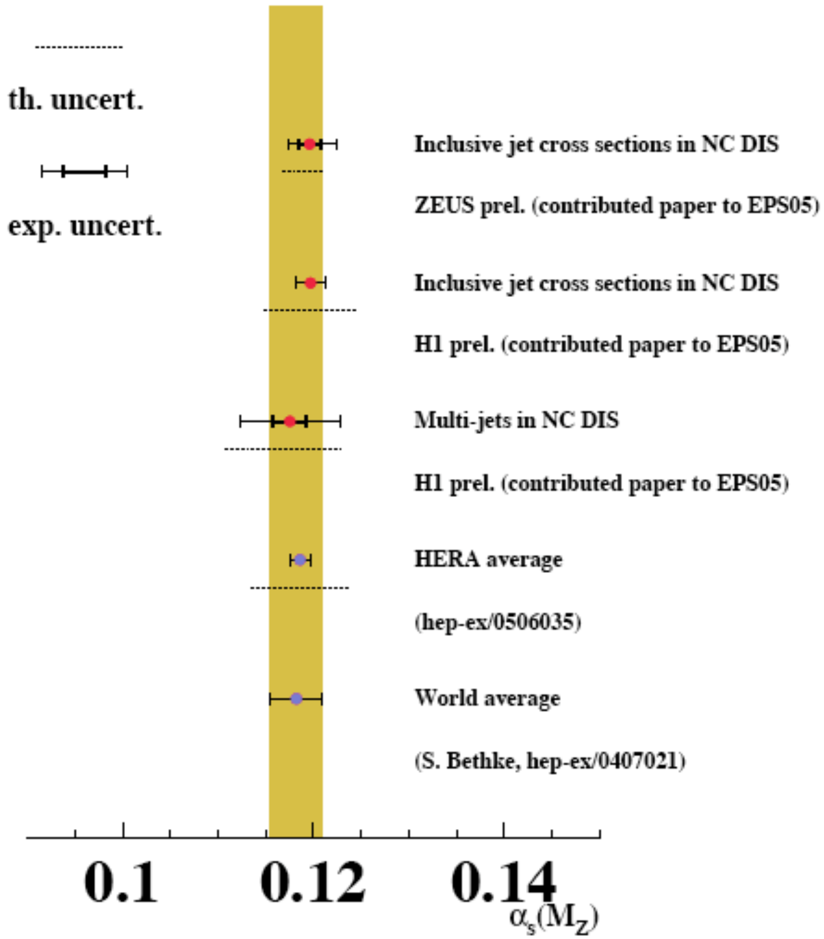
Further on the Strong Coupling Constant

α_s determination

	$\alpha_s(M_Z^2)$	expt	theory
NNLO			
MRST03	0.1153	± 0.0020	± 0.0030
A02	0.1143	± 0.0014	± 0.0009
SY01(ep)	0.1166	± 0.0013	
SY01(νN)	0.1153	± 0.0063	
BBG	0.1134	$^{+0.0019}_{-0.0021}$	
World Average	0.1182	± 0.0027	

H1 0.1155+-0.0017+-0.005



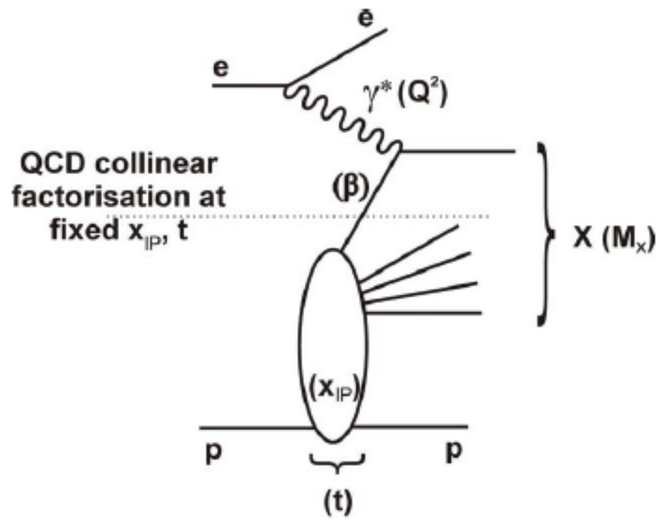


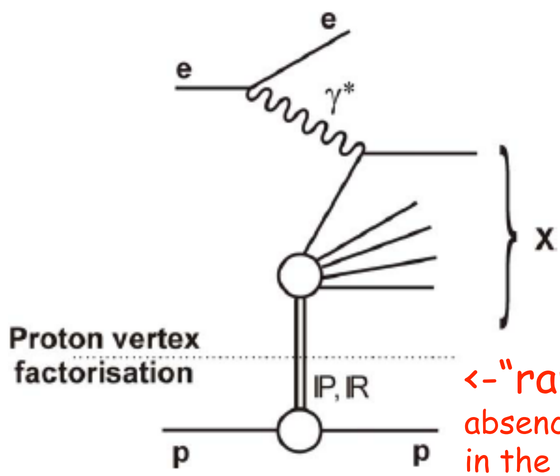
High precision will tell whether the analysis of inclusive DIS data only leads to a significantly smaller α_s

Further DIS Subjects

Deep Inelastic Diffractive ep Scattering

Huge amount of data obtained by the HERA collider experiments





<-"rapidity gap"
absence of fwd activity
in the main detector for
about 10% of DIS events

Diffractive, universal?
conditional q,g densities

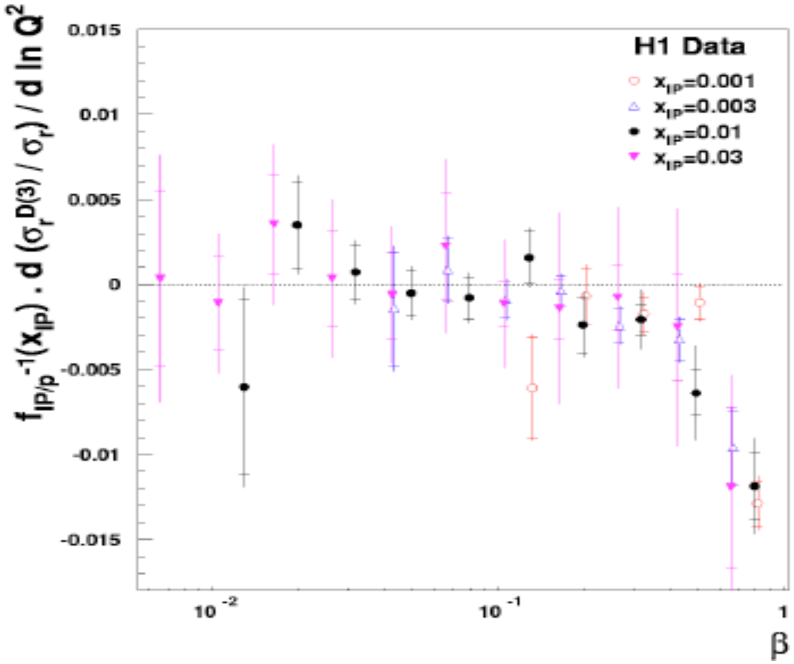
$$f_i^D(x,Q^2,x_{I\!P},t) = f_{I\!P/p}(x_{I\!P},t)\cdot f_i^{I\!P}(\beta = x/x_{I\!P},Q^2)$$

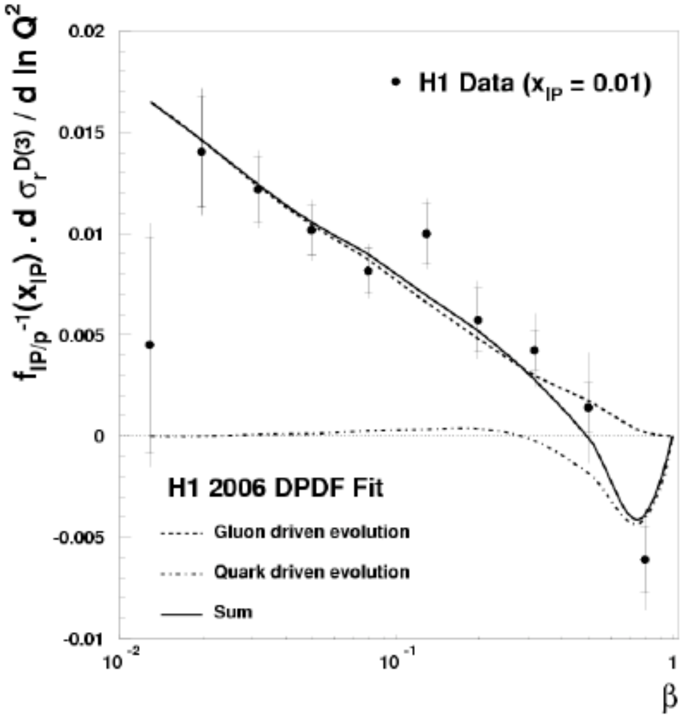
QCD

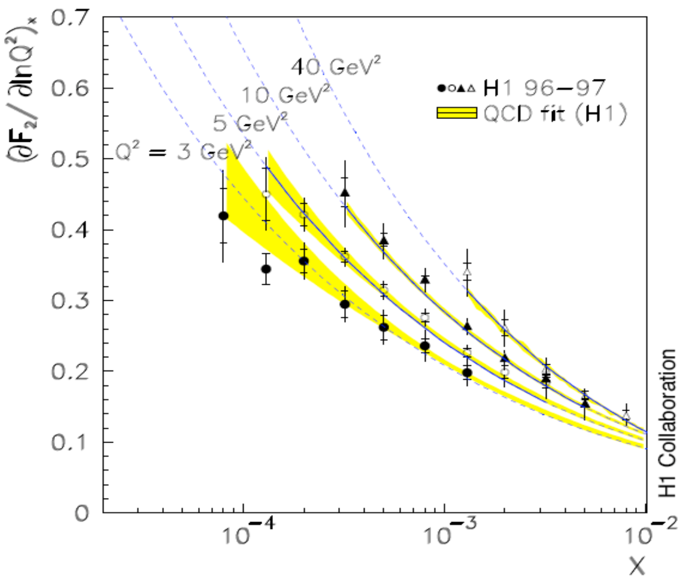
phenomenology

Tagged and rapidity gap data to check

Diffraction resembles inclusive DIS

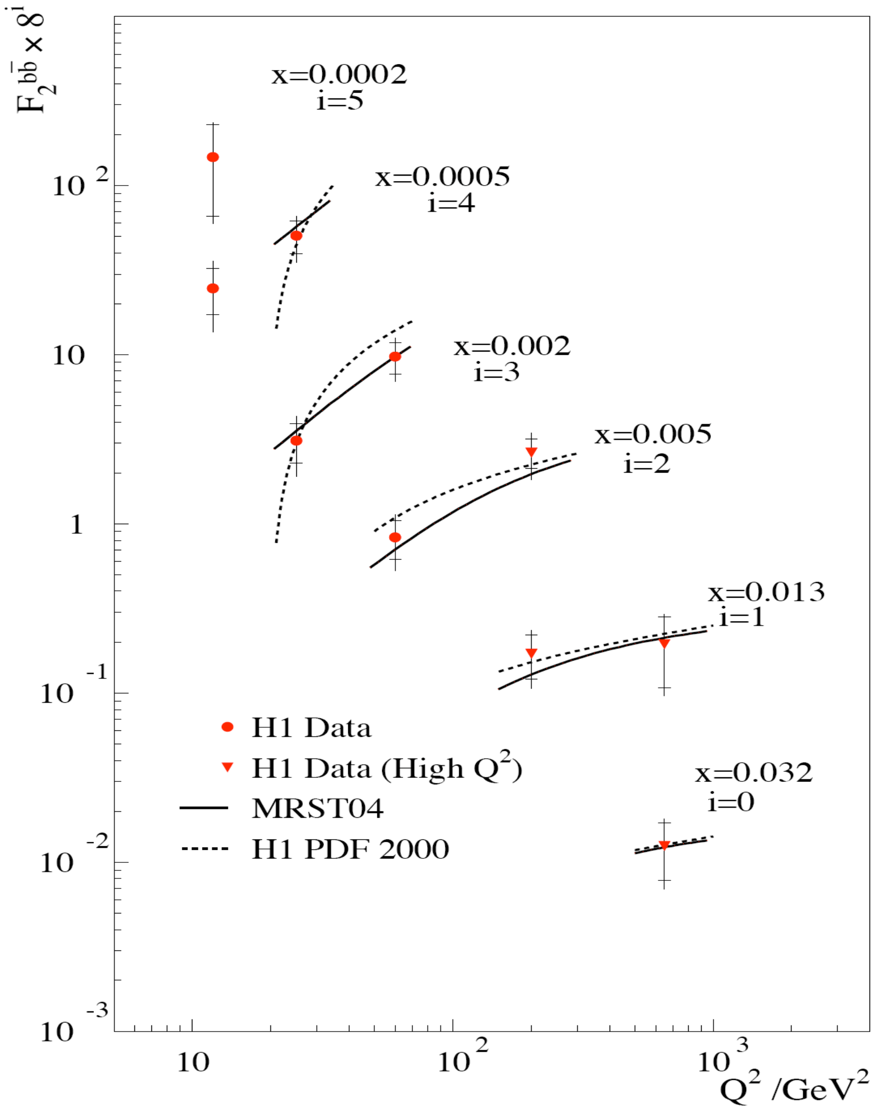




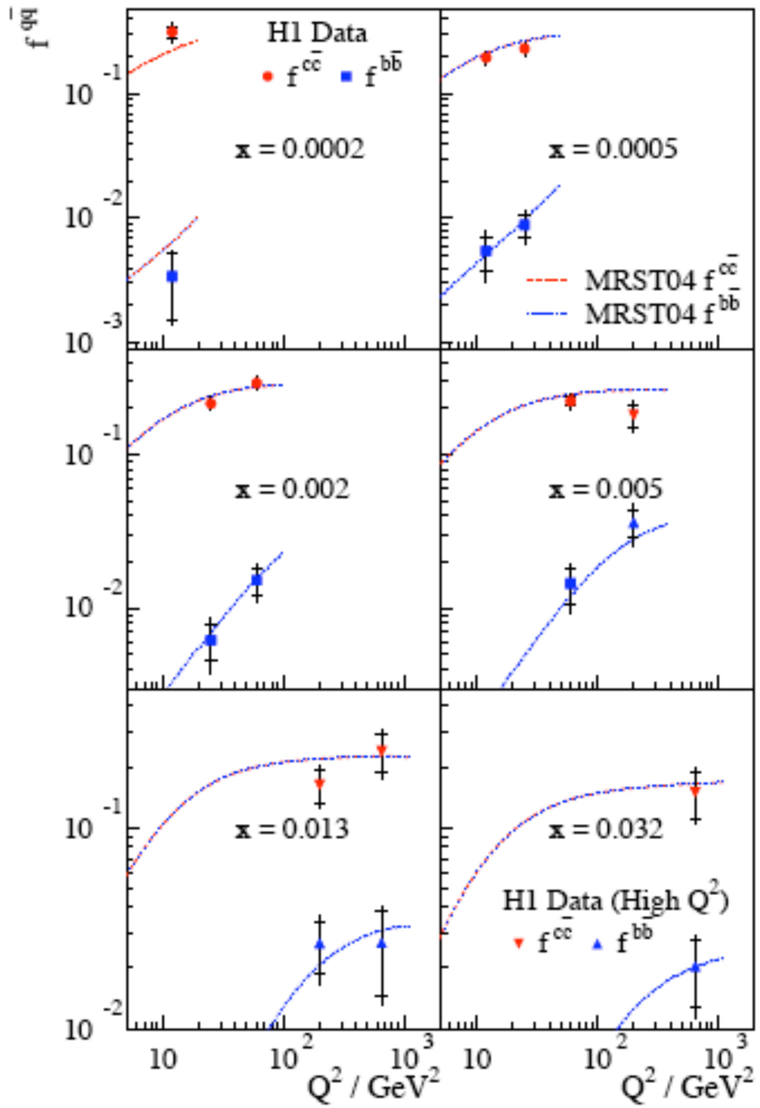


$$\text{If } \frac{d(\sigma_r^D/\sigma_r)}{d\ln Q^2} \sim 0 \text{ , then } \frac{1}{\sigma_r^D}\frac{d\sigma_r^D}{d\ln Q^2} \approx \frac{1}{\sigma_r}\frac{d\sigma_r}{d\ln Q^2}$$

Beauty Quark Density

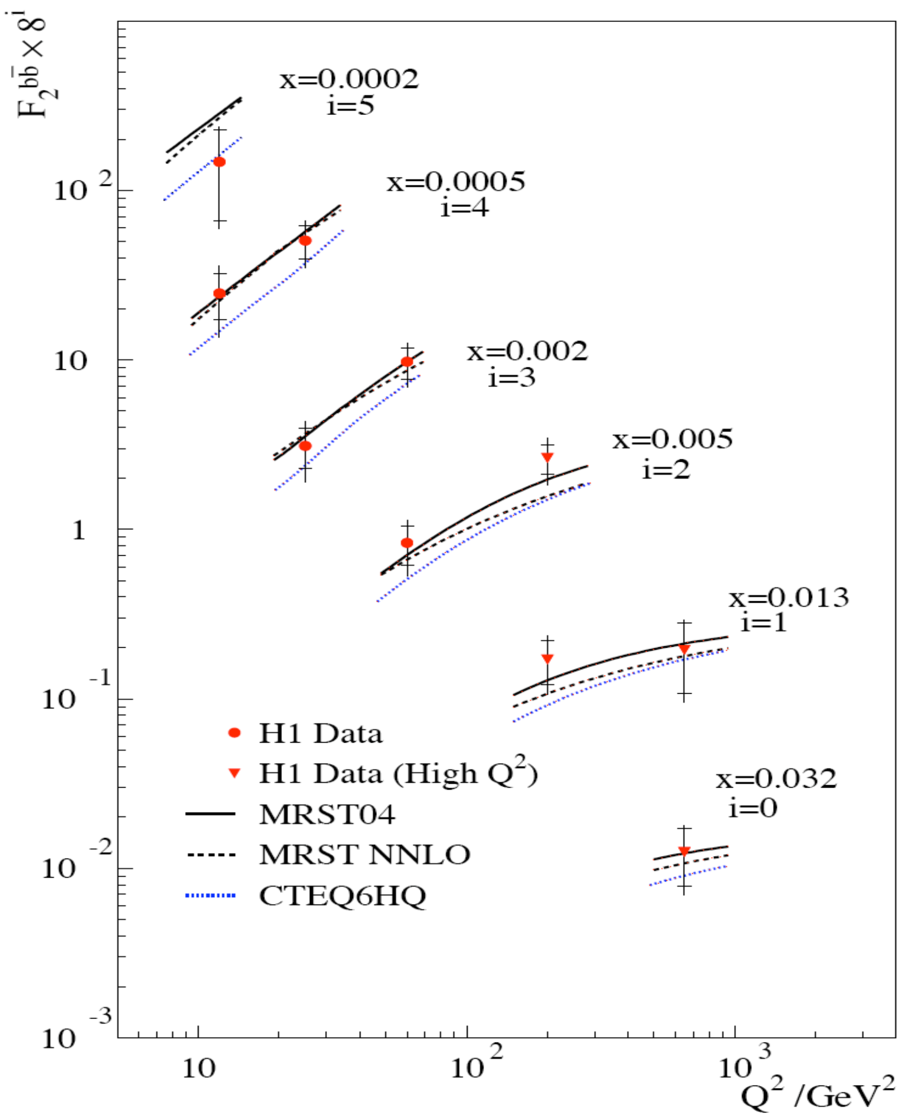


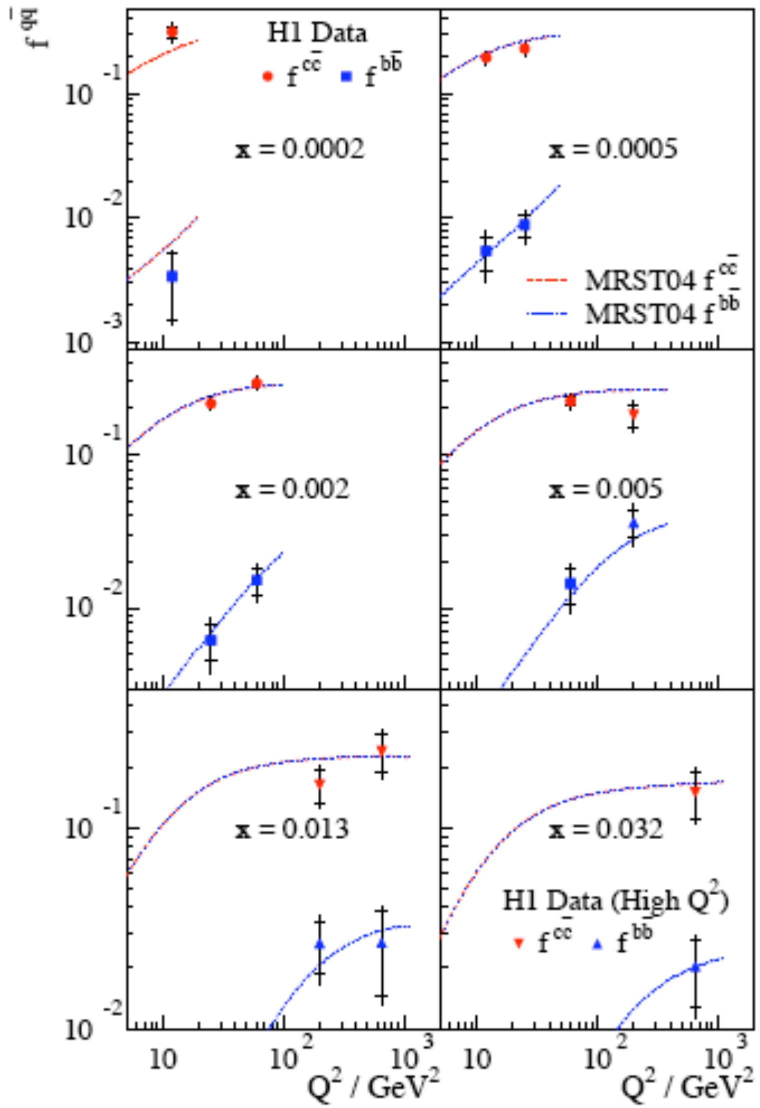
fractions of c and b



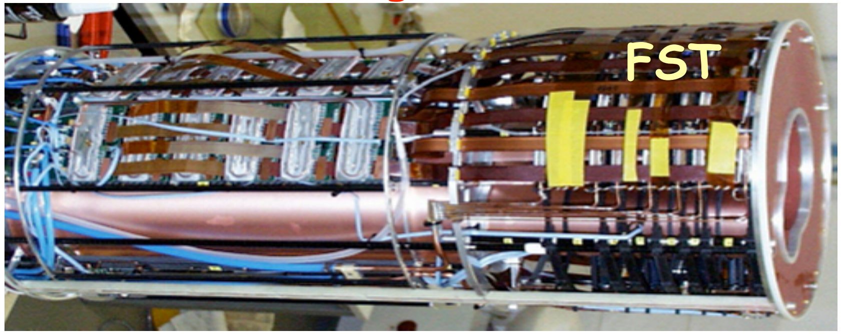
Beauty Quark Density

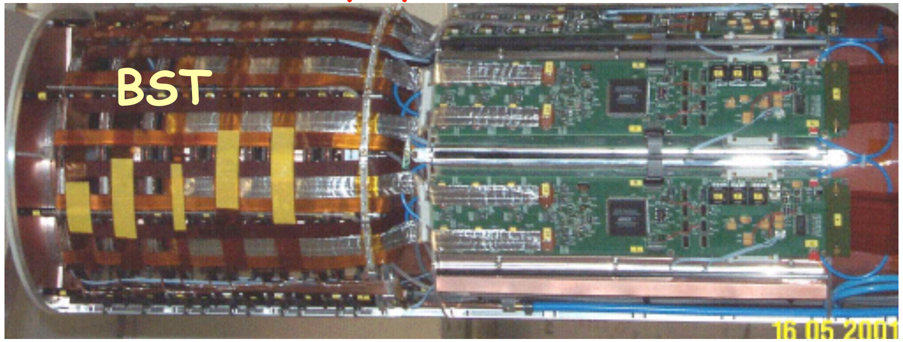
fractions of c and b





New tracking detectors of H1 and ZEUS for HF physics in HERA II



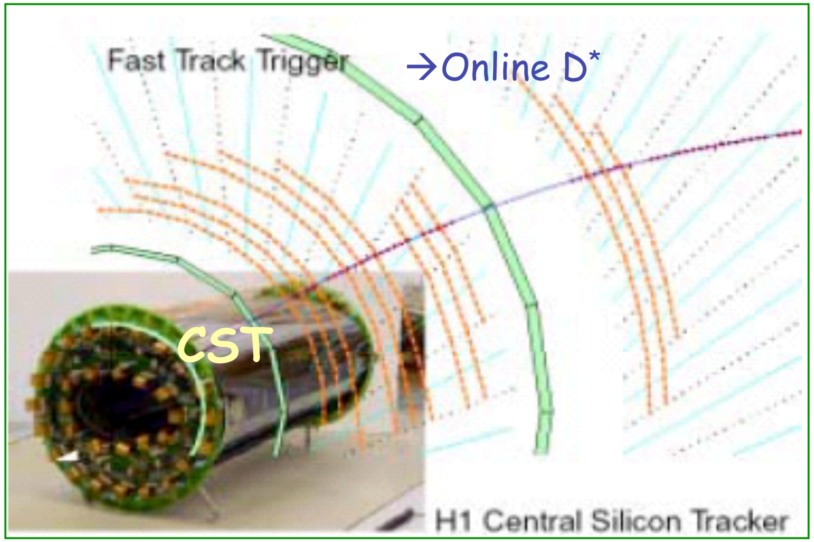


charm and beauty

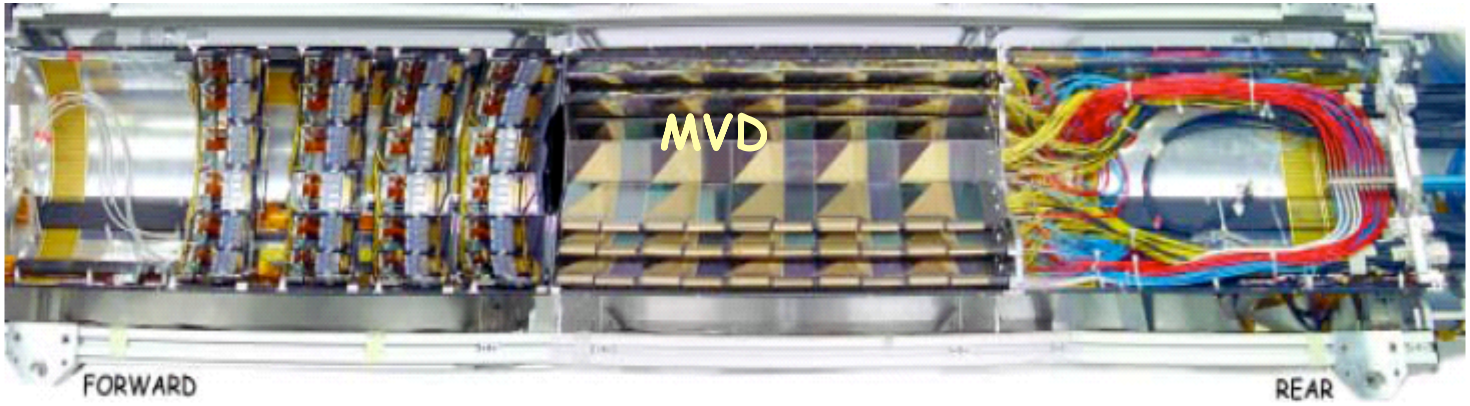
evt vtx (lo and hi y)

eID (DVCS, J/Ψ, searches)

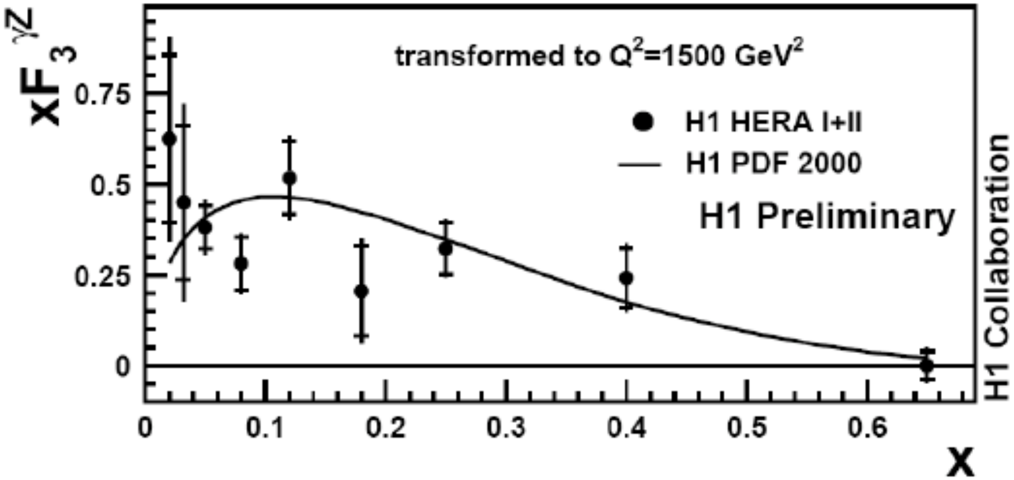
F_L



Huge investments for high lumi phase by H1 and ZEUS & fwd chambers



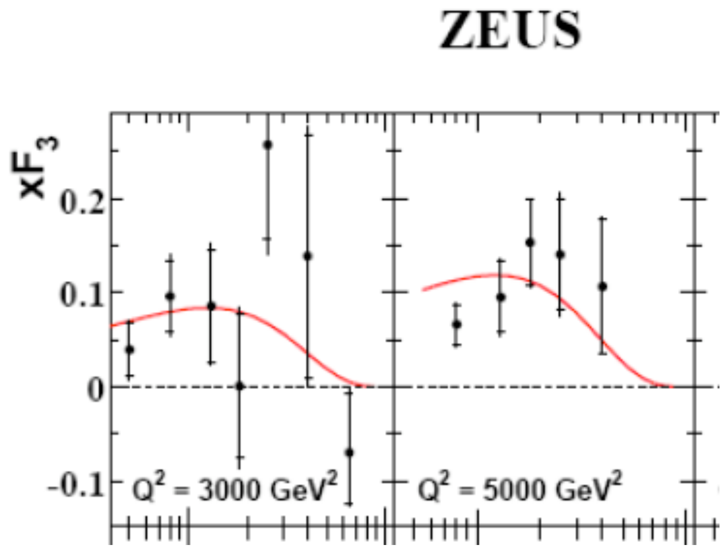
xF_3 and the sea quark symmetry



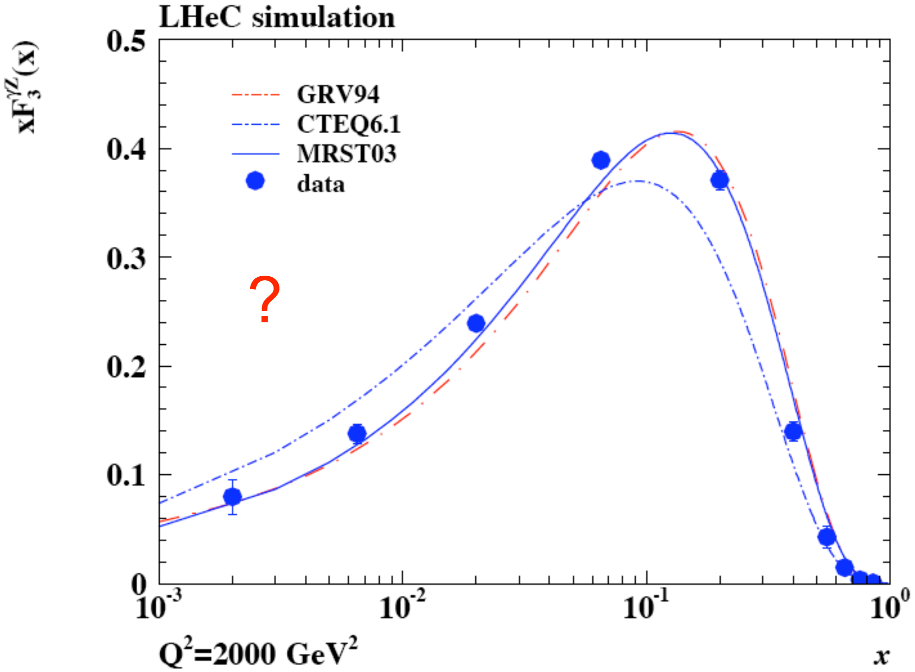
$$\sigma_{NC}^{\pm} \sim F_2 \mp f(y)xF_3$$

$$2x[a_u e_u(U - \overline{U}) + a_d e_d(D - \overline{D})]$$

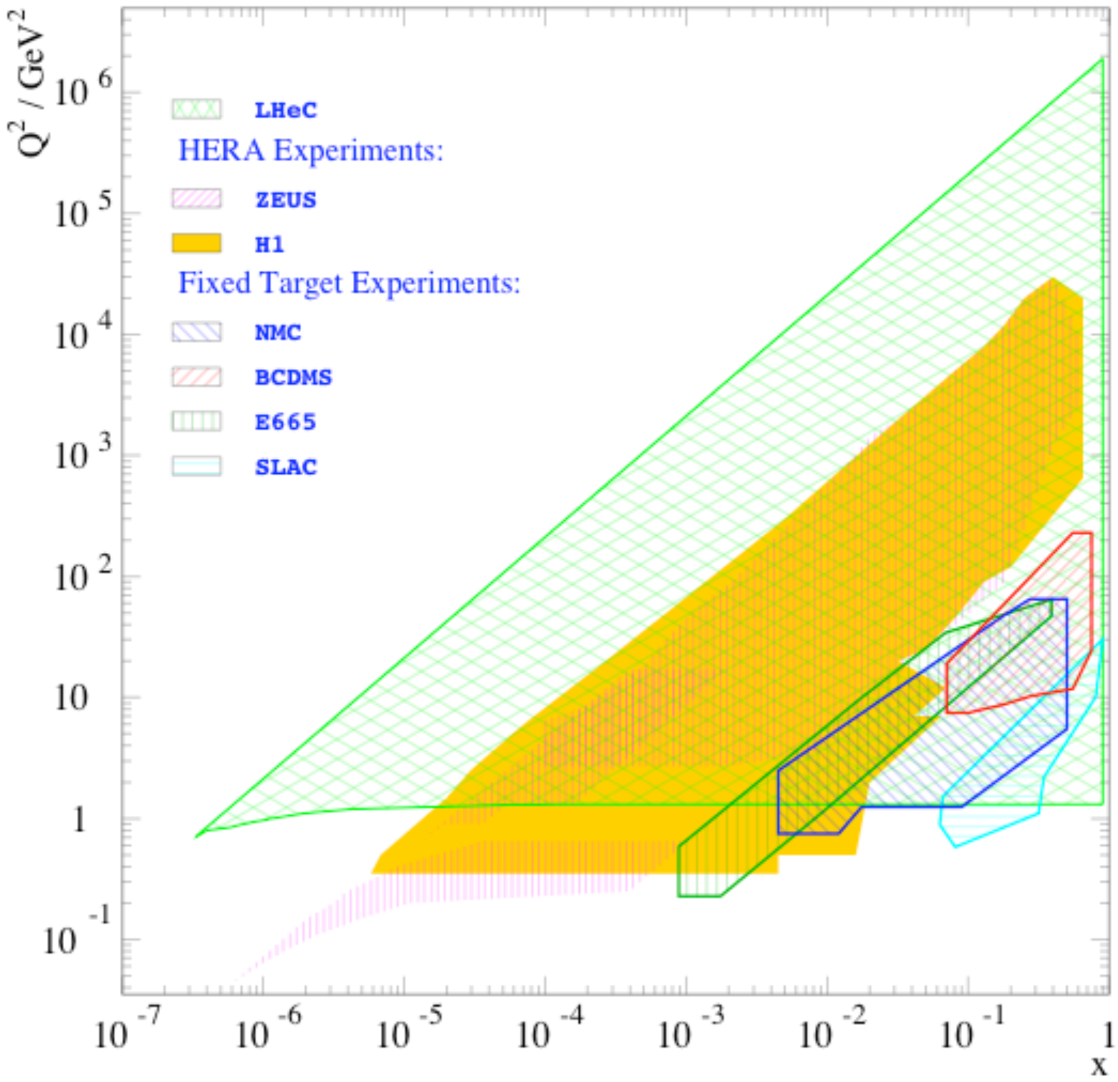
$$q_s(x,Q^2) = \bar{q}(x,Q^2)\,?$$



and higher Q^2



Particle physics moves to the TeV Scale, how about ep?



$s = 4E_eE_p$

$LHeC: 70 \cdot 7000 \rightarrow 2 \cdot 10^6 GeV^2$

$HERA: 27.6 \cdot 920 \rightarrow 10^5 GeV^2$

$s = 2M_pE_l$

$BCDMS: 280 \rightarrow 500 GeV^2$

$SLAC: 20 \rightarrow 40 GeV^2$

$Q^2 = sxy$

$x = \frac{Q^2}{sy}$

$Bjorken - x \leq 1$

$inelasticity - y \leq 1$

$Q^2 \leq s$

hep-ex/0306016 → JINST

DESY 06-006
Cockcroft-06-05

Deep Inelastic Electron-Nucleon Scattering at the LHC*

J. B. Dainton[1], M. Klein[2], P. Newman[3], E. Perez[4], F. Willeke[2]

[1] Cockcroft Institute of Accelerator Science and Technology, Daresbury International Science Park, UK
[2] DESY, Hamburg and Zeuthen, Germany
[3] School of Physics and Astronomy, University of Birmingham, UK
[4] CE Saclay, DSM/DAPNIA/Spp, Gif-sur-Yvette, France

Abstract

The physics, and a design, of a Large Hadron Electron Collider (LHeC) are sketched. With high luminosity, $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and high energy, $\sqrt{s} = 1.4$ TeV, such a collider can be built in which a 70 GeV electron (positron) beam in the LHC tunnel is in collision with one of the LHC hadron beams and which operates simultaneously with the LHC. The LHeC makes possible deep-inelastic lepton-hadron (ep, eD and eA) scattering for momentum transfers Q^2 beyond $10^6\,\mathrm{GeV}^2$ and for Bjorken x down to the 10^{-6}. New sensitivity to the existence of new states of matter, primarily in the lepton-quark sector and in dense partonic systems, is achieved. The precision possible with an electron-hadron experiment brings in addition crucial accuracy in the determination of hadron structure, as described in Quantum Chromodynamics, and of parton dynamics at the TeV energy scale. The LHeC thus complements the proton-proton and ion programmes, adds substantial new discovery potential to them, and is important for a full understanding of physics in the LHC energy range.

*Contributed to the Open Symposium on European Strategy for Particle Physics Research, LAL Orsay, France, January 30th to February 1st, 2006.

ep collider in the LHC tunnel

70 * 7000 GeV^2

further studies at forthcoming workshop

cost estimate and design study ready by about 2010

an attractive option for upgrading the LHC

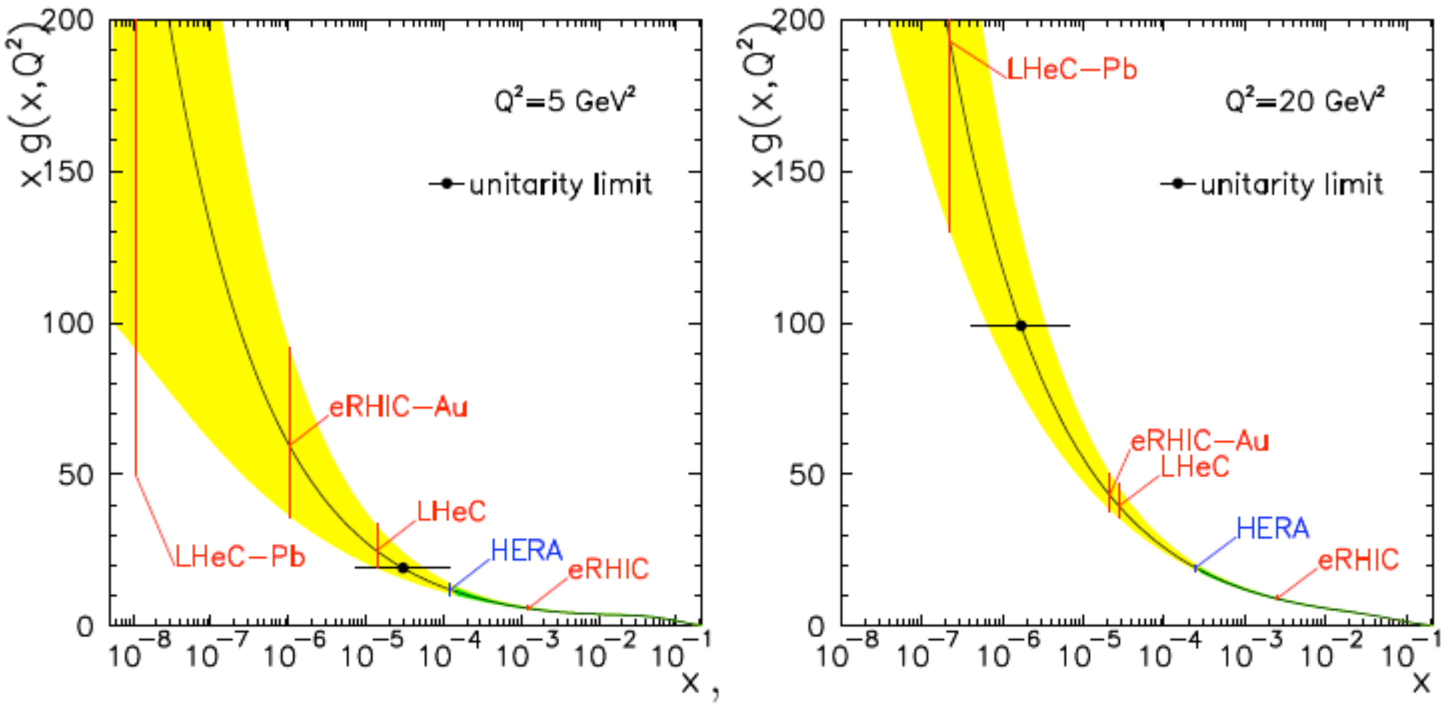
physics

Search for and spectroscopy of new particles (eq states)

Exploration of high density QCD

High precision ep in LHC range

High density states



High density $$\frac{g_A/\pi r_A^2}{g_p/\pi r_p^2} = A^{1/3}\frac{g_A}{Ag_p}$$

Unitarity $$\boxed{xg(x,Q^2) \leq \frac{1}{\pi N_c \alpha_s(Q^2)} Q^2 R^2 \simeq \frac{Q^2}{\alpha_s}}$$

Striking effects predicted:

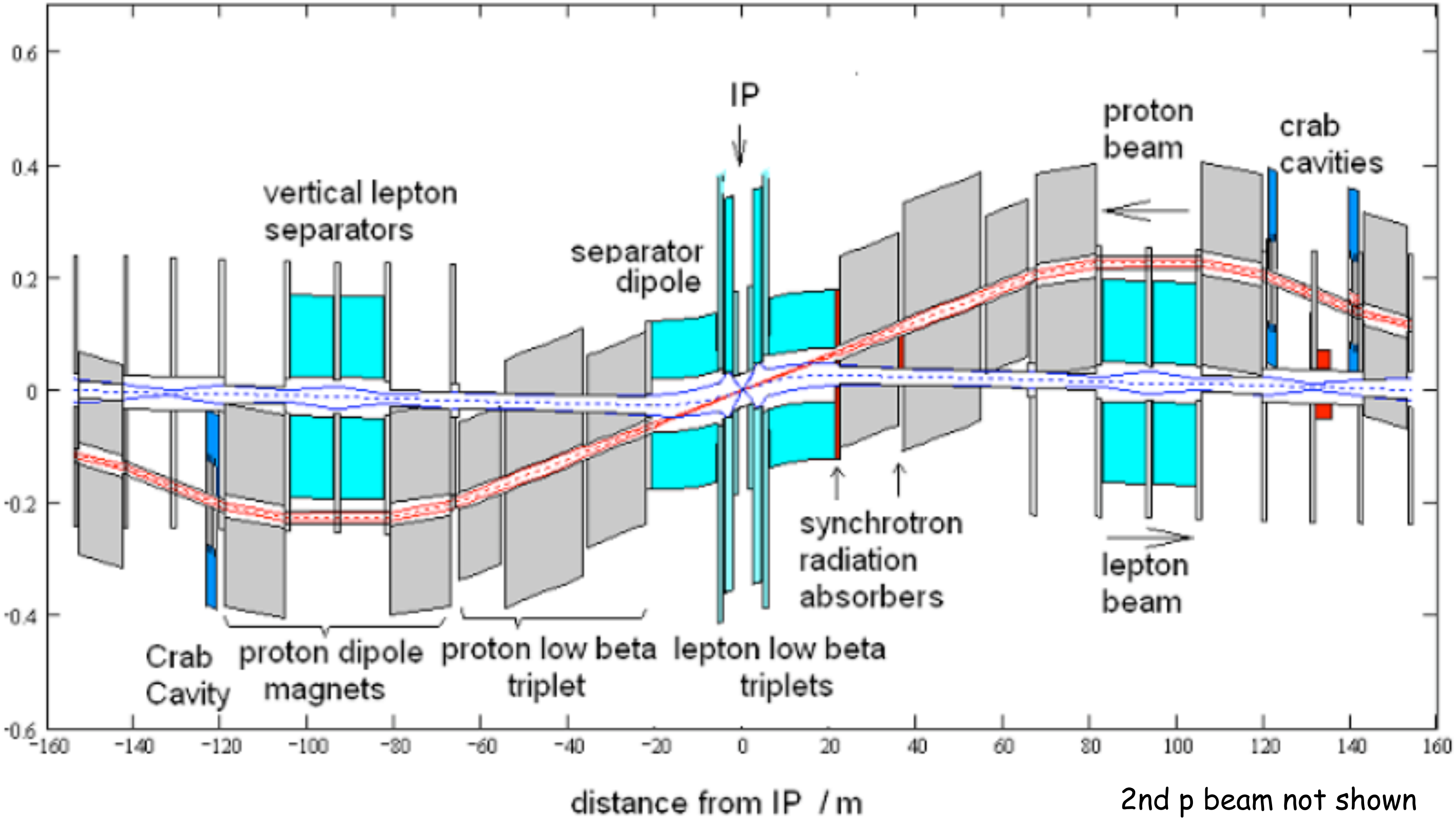
bj -> black disc limit $F_2 \rightarrow Q^2 \ln(1/x)$

~50% diffraction

colour opacity, change of $J/\Psi(A)$

Understanding the possible observation of QGP in AA with eA

LHeC - top view of IR



2nd p beam not shown

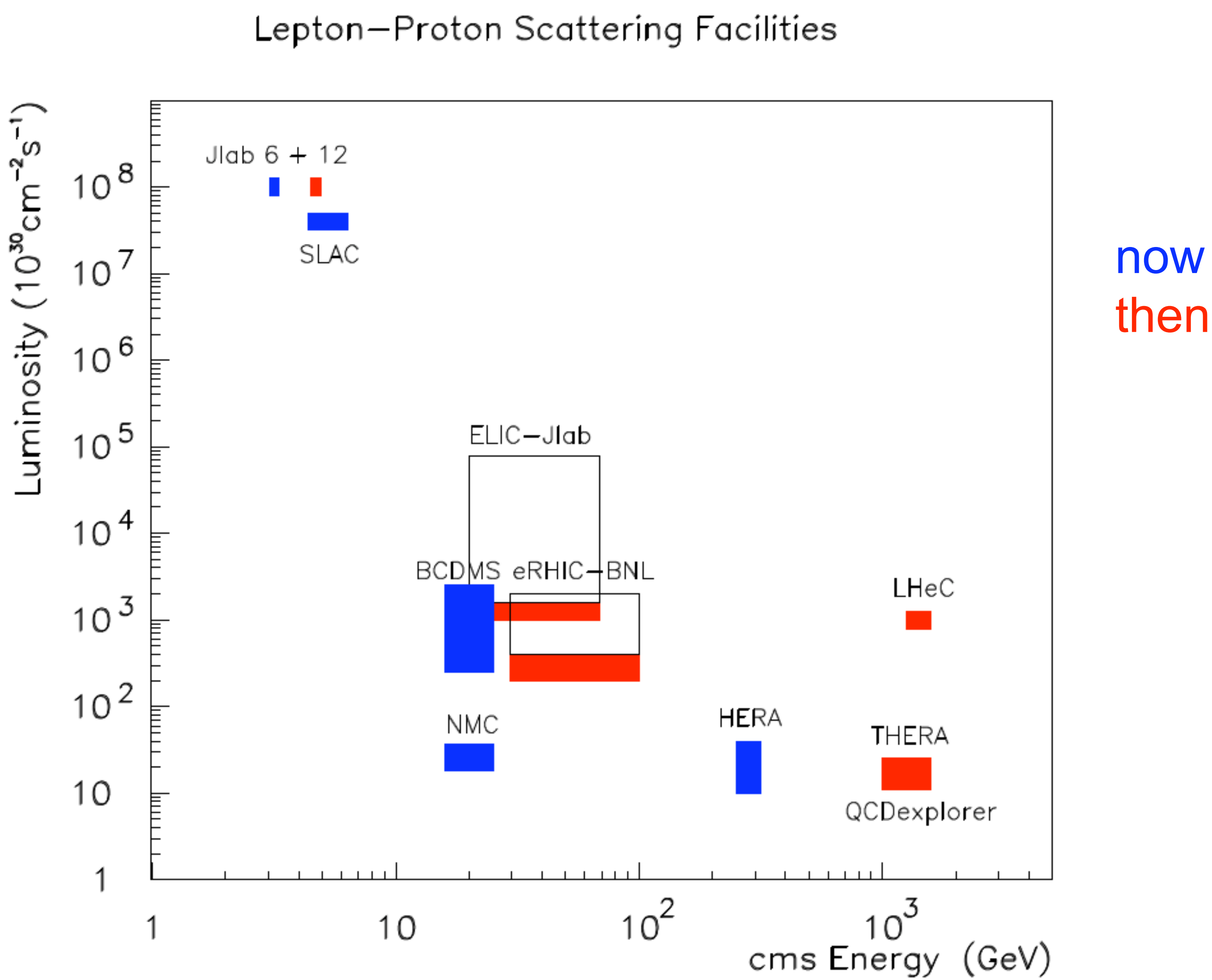
Design foresees to run in parallel with pp and e around ATLAS+CMS
Further, more detailed studies required but so far encouraging

LHeC parameters

Table 3: *Main Parameters of the Lepton-Proton Collider*

Property	Unit	Leptons	Protons
Beam Energies	GeV	70	7000
Total Beam Current	mA	74	544
Number of Particles / bunch	10^{10}	1.04	17.0
Horizontal Beam Emittance	nm	7.6	0.501
Vertical Beam Emittance	nm	3.8	0.501
Horizontal β-functions at IP	cm	12.7	180
Vertical β-function at the IP	cm	7.1	50
Energy loss per turn	GeV	0.707	$6 \cdot 10^{-6}$
Radiated Energy	MW	50	0.003
Bunch frequency / bunch spacing	MHz / ns	40 / 25	
Center of Mass Energy	GeV	1400	
Luminosity	$1.1 \cdot 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.04	

Compare with HERA: maximum reached was 0.05 10^{33} $cm^{-2}s^{-1}$
Estimated luminosities of linac-ring ep colliders below HERA


Lepton−Proton Scattering Facilities
Luminosity ($10^{30}cm^{-2}s^{-1}$)
cms Energy (GeV)
Jlab 6 + 12
SLAC
ELIC−Jlab
BCDMS
eRHIC−BNL
LHeC
NMC
HERA
THERA
QCDexplorer
now
then

The role of DIS

Lepton-nucleon scattering was born in 1956, 50 years ago, when Hofstatter et al. performed the first elastic ep scattering experiments and found a finite radius of the proton. About 10 years later it became 'deep inelastic' when experiments at 20 times higher energies, at SLAC, established the partonic nature of the proton. Since then DIS has a dual role: in the search for the appropriate gauge field theory, remember the decisive role of polarised ep scattering in 1978 to establish Weinberg's 'Model of Leptons' as the correct, GWS, electroweak theory or recall the importance in the verification and development of QCD from 1974 till now, and in the highest resolution of the inner structure of matter. For the LHC, as for the Tevatron, the predictions of cross sections based on the unique DIS measurements are a necessity to find new physics. With a TeV ep collider the physics of electron-quark scattering may be pursued to possibly establish new interactions, to find new states of baryonic matter and to reach an unprecedent range and level of accuracy.

This lecture sketched:

This development
HERA - detectors and physics
The link of DIS and the LHC
QCD analyses from H1 and ZEUS
DIS subjects (heavy flavour, diffraction,..)
A proposal for DIS at TeV energies

Deep Inelastic Scattering

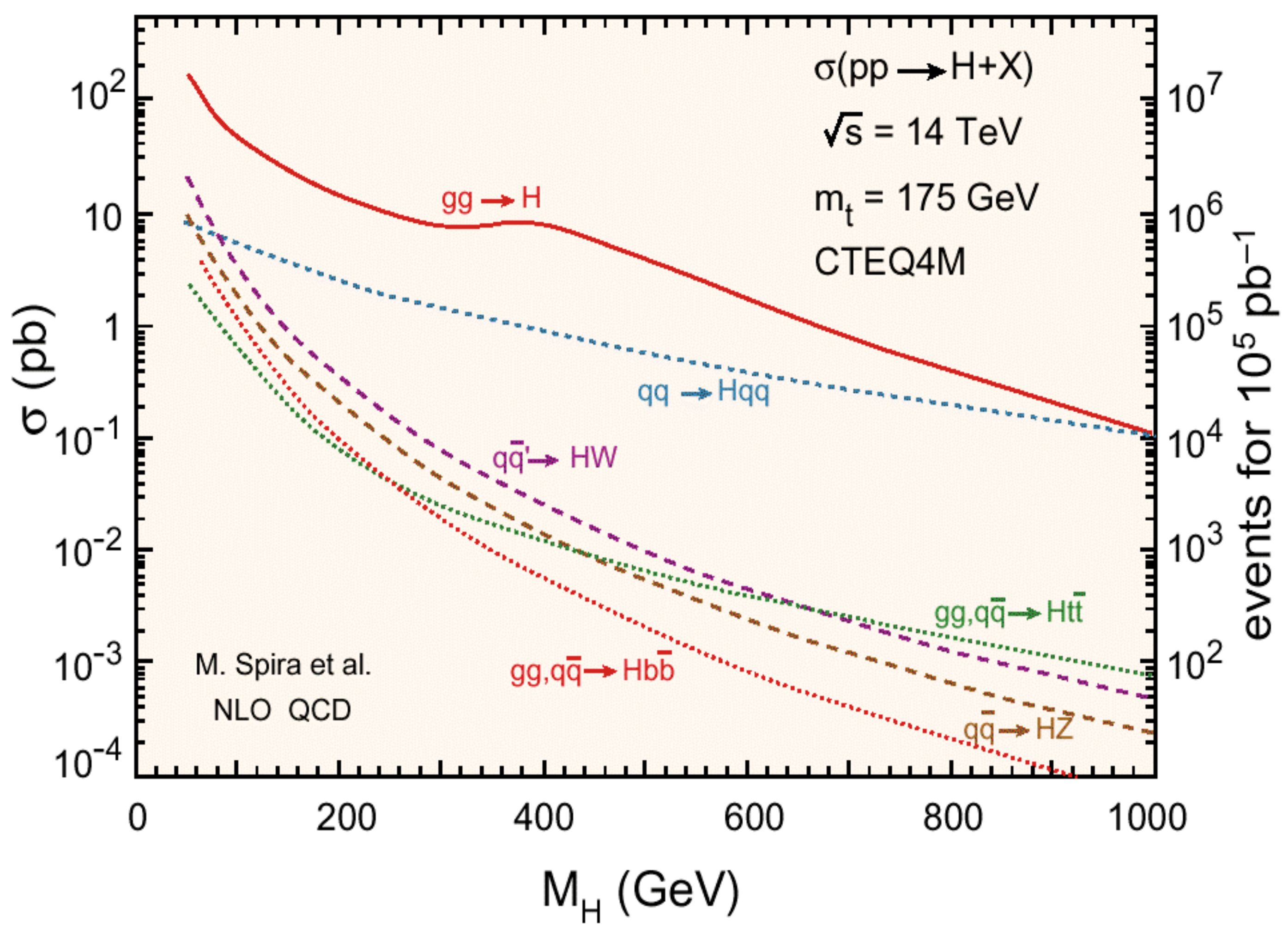
has been and can remain to be

a most fascinating subject

HERA, polarised lN, JLab
MINERVA, JPARC, LHeC..

Backup slides

Higgs production reactions at the LHC

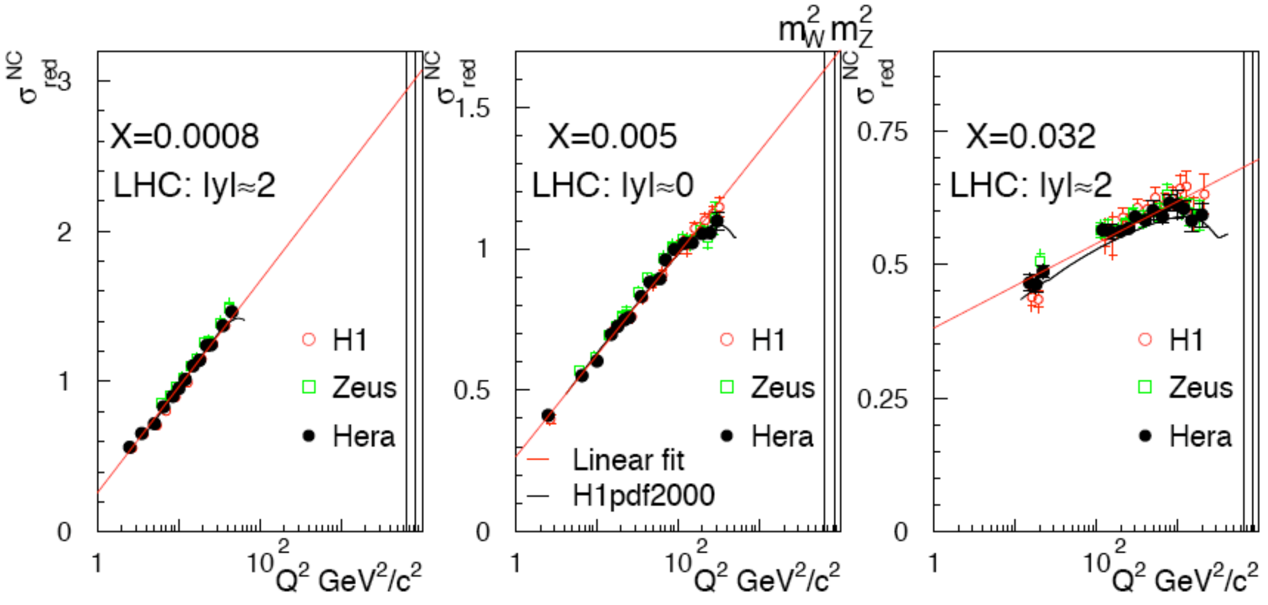


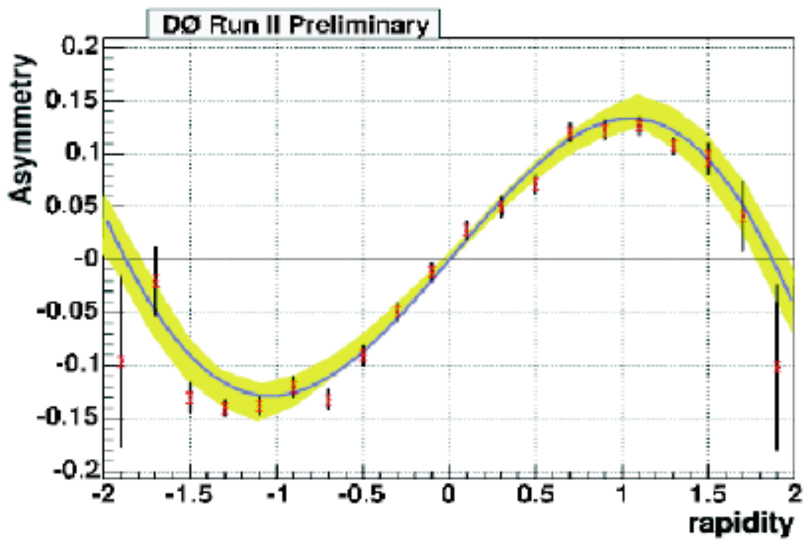
Any jet, Higgs or exotic particle production in pp needs HERA's partons and theory understood!
Forward particle production (double diffraction) at the LHC may help to find the Higgs particle.

Towards the LHC

W,Z physics

-QCD@LHC
-luminosity
-calibration

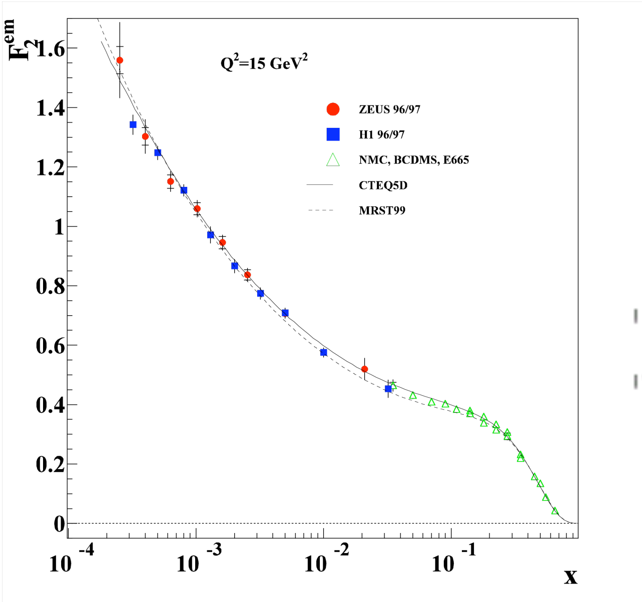


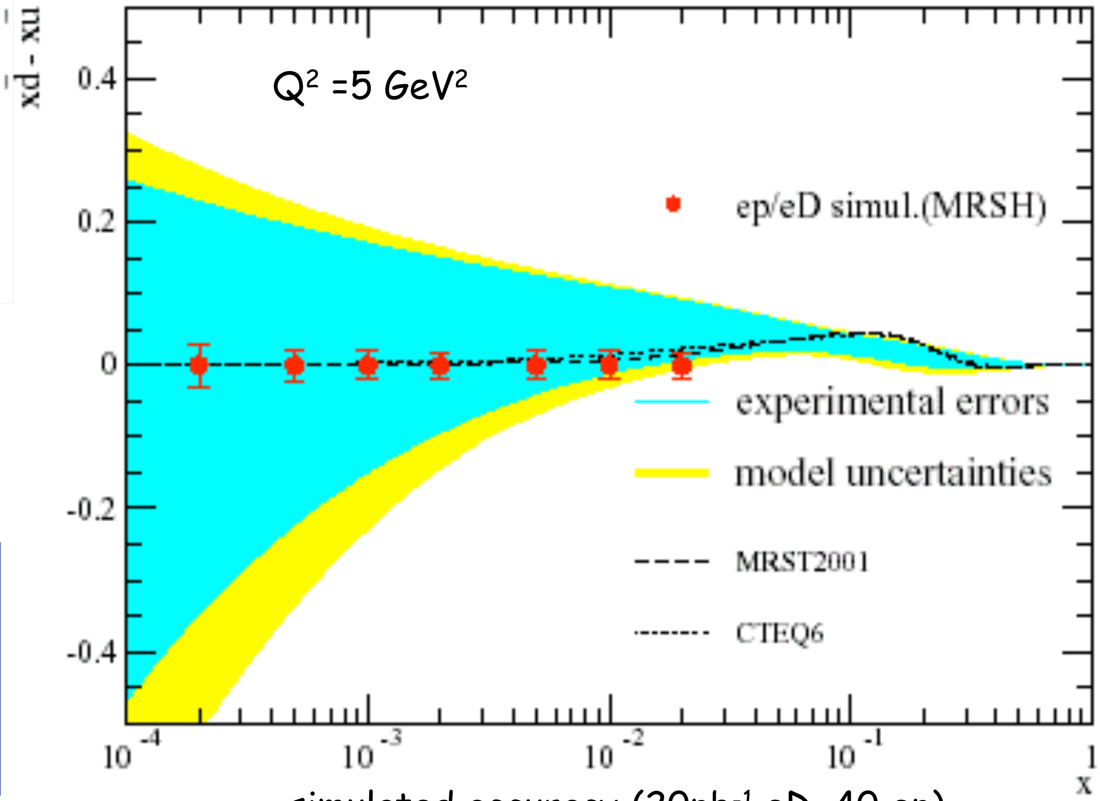


'F_2 corresponds to W,Z production'
extrapolation from HERA needs pQCD
combine H1+Z data and measure well

$$A = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy} \approx \frac{d}{u}$$

The light sea quark asymmetry is expected and has been assumed to vanish at low x. However, F_2 rises strongly towards low x which deserves to be studied.



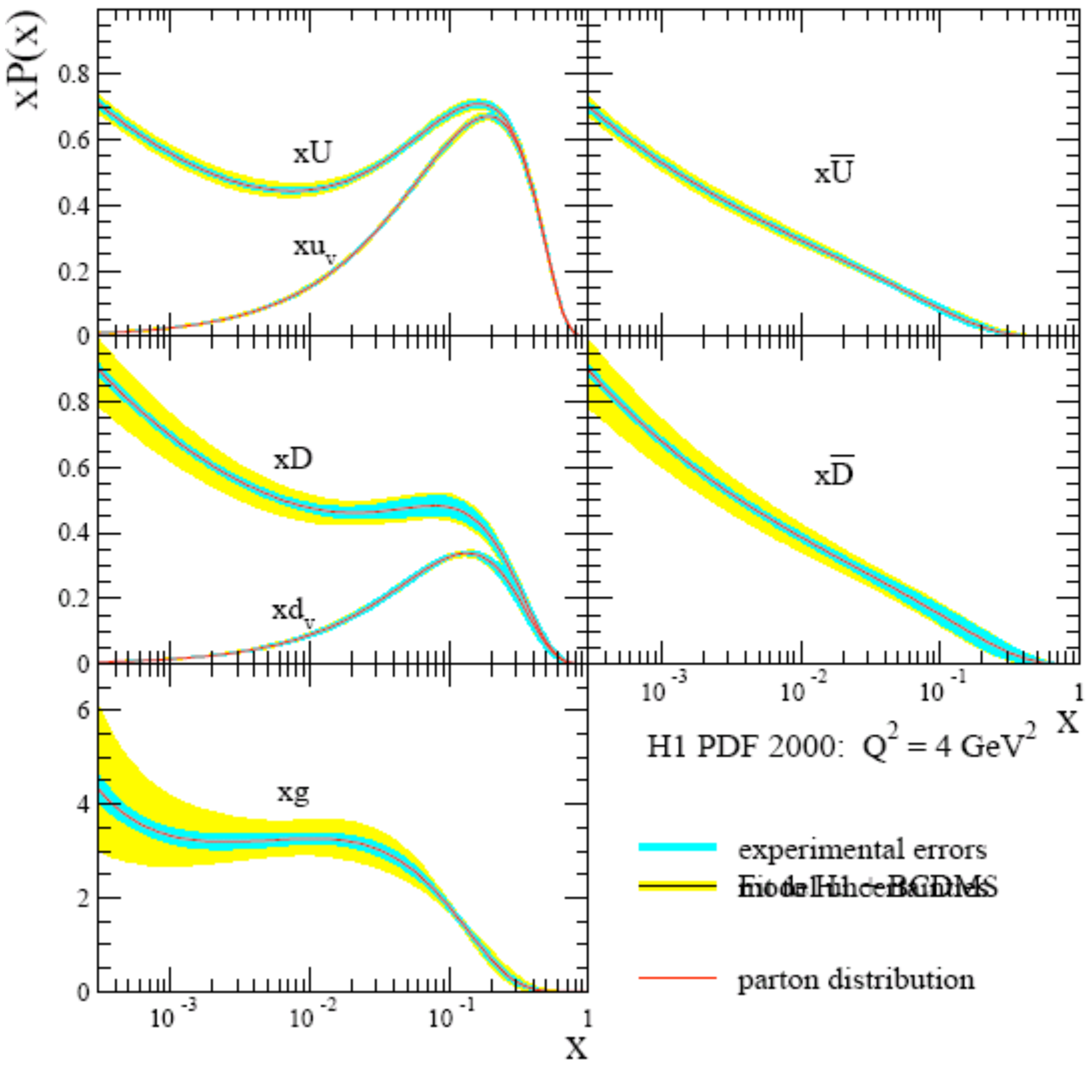


simulated accuracy (20pb^{-1} eD, 40 ep)

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

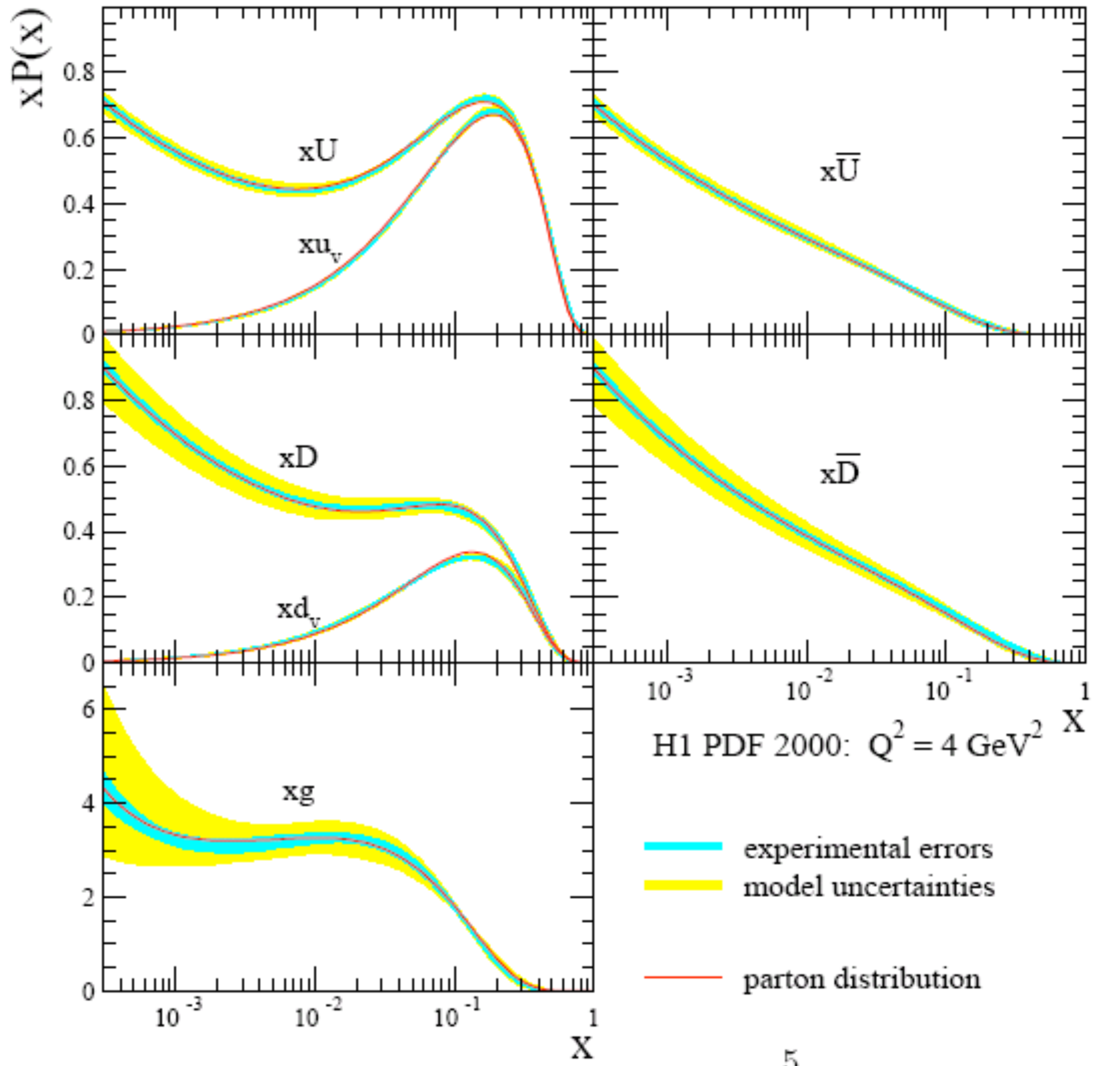
H1 + BCDMS

default assumptions - H1 data only



Fit published in:
hep-ex/0304003
EPJ C30(2003)1

Default assumptions - H1 + BCDMS (p,d) data



$$F_2^N = \frac{5}{18}\,x\left(U + \overline{U} + D + \overline{D}\right) + \frac{1}{6}\,x\left(c + \overline{c} - s - \overline{s}\right)$$

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

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

H1 Collab. EPJ C21(01)33

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

	$m_r = 0.25$	$m_r = 1$	$m_r = 4$
$m_f = 0.25$	-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: systematíc 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)