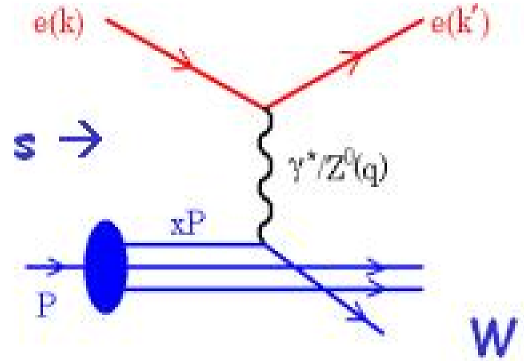
Deep Inelastic Scattering
Глубоко-неупругое Рассеяние
Status and Future

Max Klein - DESY/H1

DIS prior to HERA

HERA - a new Frontier in DIS
'The Rise' towards low Bjorken x
Quark Momentum Distributions
The Strong Coupling Constant and xg
A Holographic View of the Proton

HERA III and the EIC
ep Scattering in the TeV region
Remarks



centre-of-mass energy squared:
$s = (k + p)^2 = 4\ Ee\ Ep$

$Q^2 = -q^2 = -(k - k')^2 = s\,x\,y$
four-momentum transfer

$x = Q^2 / (2P \cdot q)$ Bjorken-x
momentum fraction of struck parton

$y = (P \cdot q)/(P \cdot k)$ Inelasticity
relative energy transfer to the proton

Hadronic energy squared:
$W^2 = (q + xP)^2 = s\,y$

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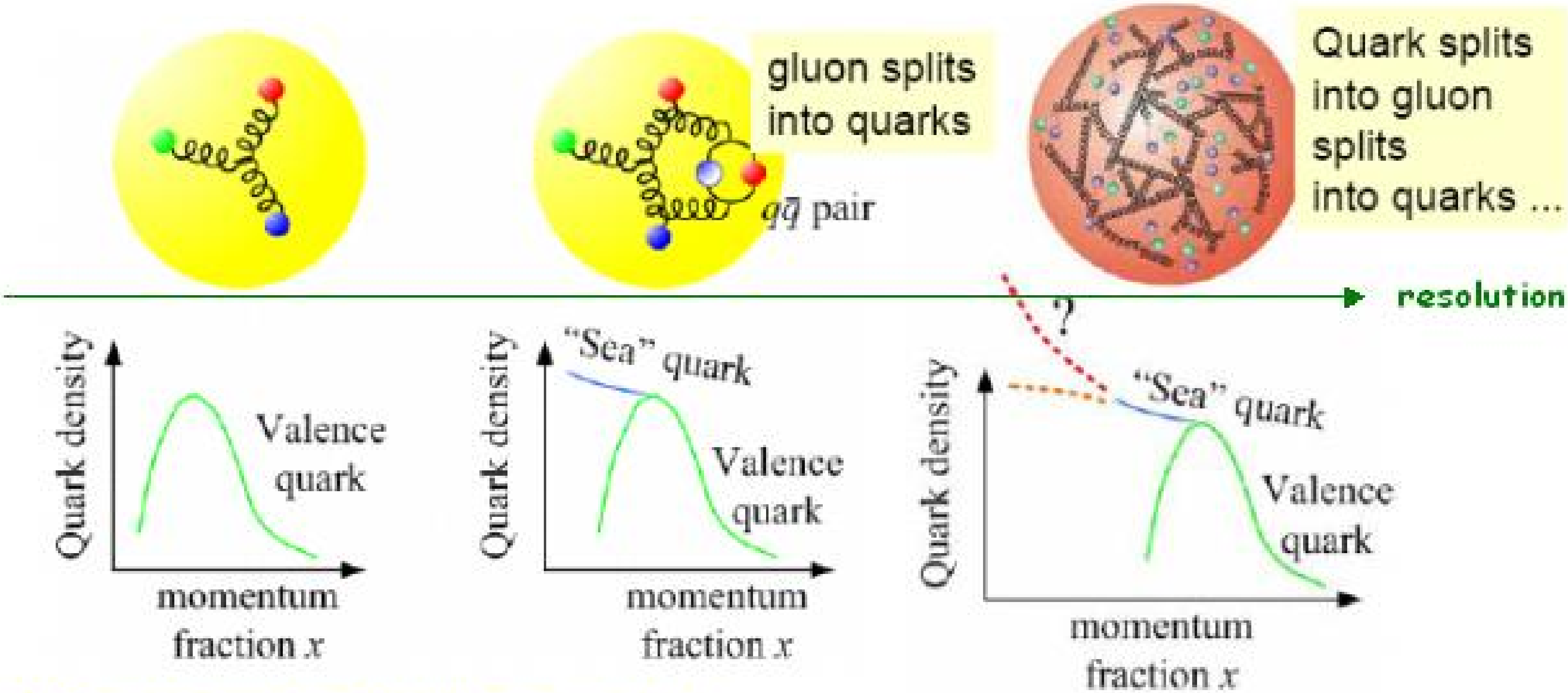
1. Deep Inelastic Lepton-Nucleon Scattering

1970	→	2000
DIS:	ep: Bjorken scaling - quarks, PV	hi density QCD
	μp: scaling violations - QCD	gluon
	νN: QPM: valence and sea quarks	diffraction
e+e-:	J/Ψ	three neutrinos
	gluons - 3jet events	electroweak theory
hh:	open charm, bottom quark	top quark
	W,Z	

Quark and neutrino mixing and searches at the energy frontier

$$SU(2)_L \times U(1) \times SU(3)_c$$

the standard model emerged as a result of decades of joint research in e+e-, ep, hh.



- DIS cross section depends on x and Q2
- two formfactors (el + magn) → two structure functions
- F2(x) scaling observed at SLAC at x ~ 0.2

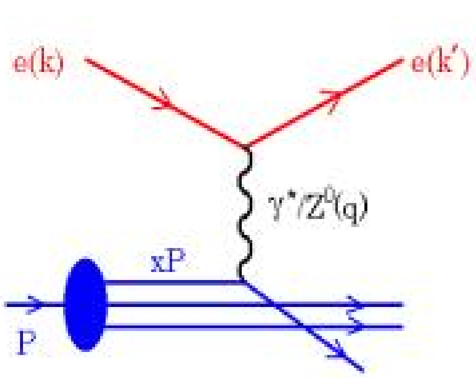
$$F_2 = x\sum e_q^2[q+\bar{q}]$$

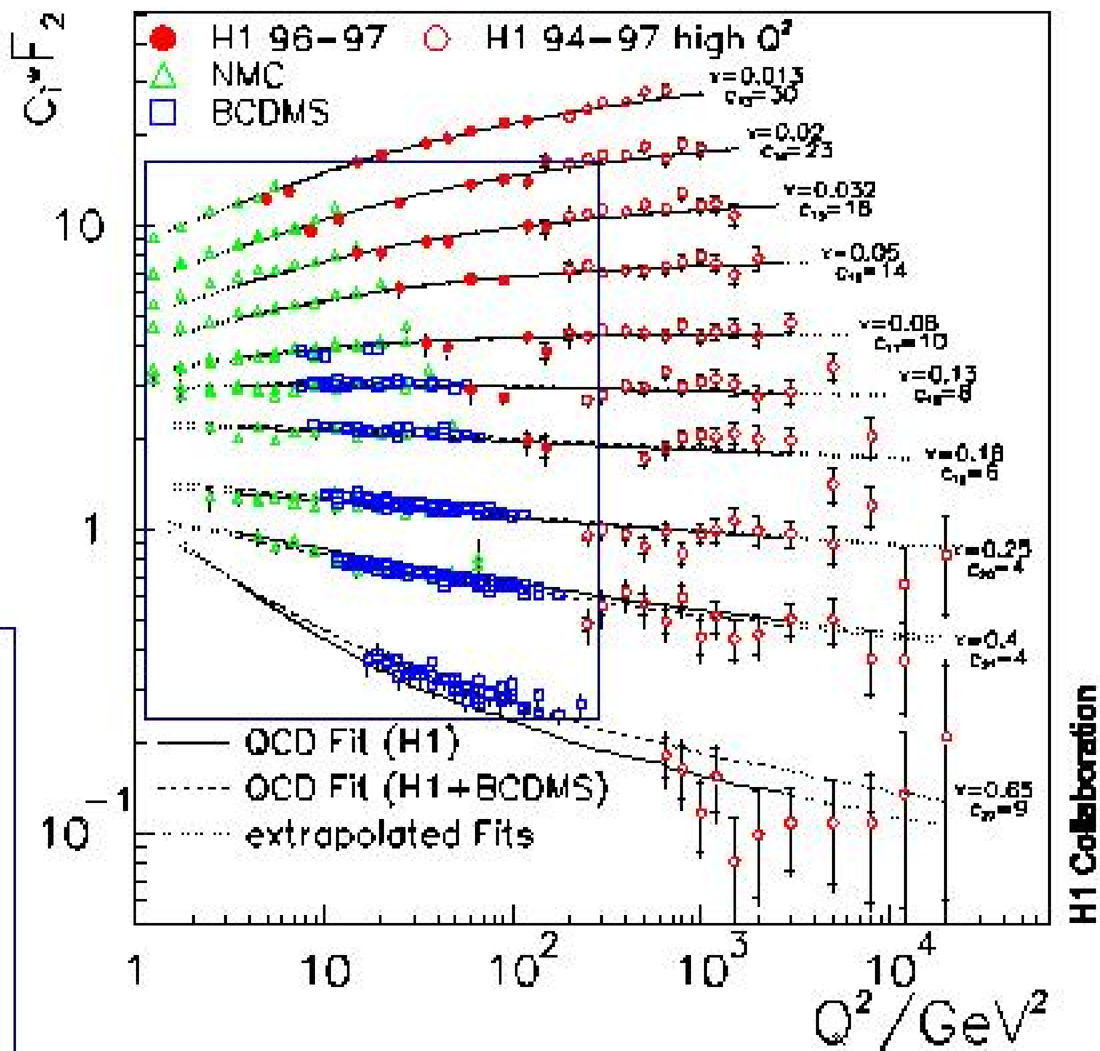
$$u = u_v + u_s, \bar{u} = u_s, d, s = \bar{s}, c = \bar{c}, \ldots$$

- F2(x,Q2) scaling violated (evolution equations):

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

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





- Electron
  - SLAC
- Muon
  - FNAL,CERN
- Neutrino
  - FNAL, CERN, IHEP

Scattering off nucleons

[fixed target experiments]

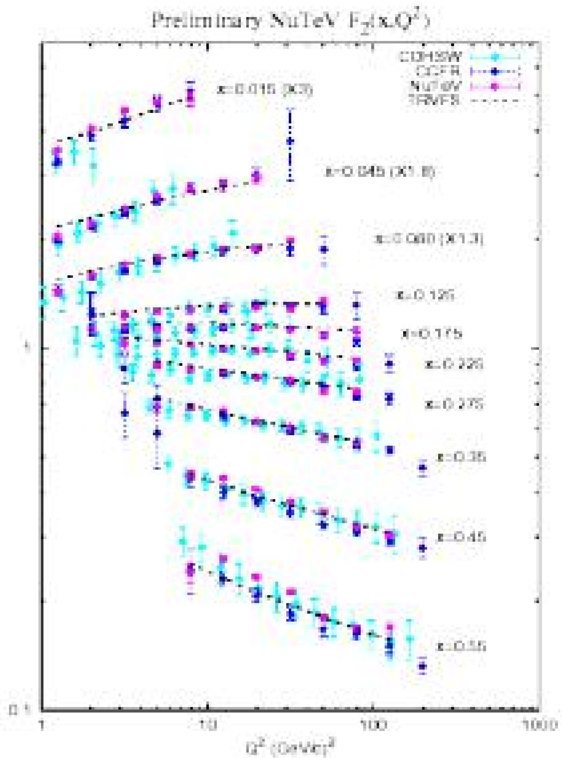
$$Q^2 \le s = 2M_pE_l << 4E_eE_p, x = \frac{Q^2}{sy}$$

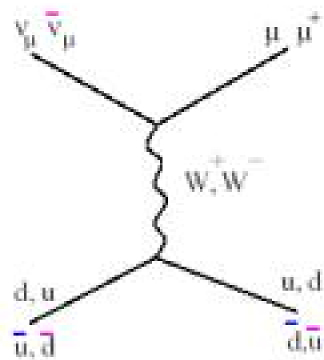
$F_2^{\nu N}$ new high stat data from improved ν and $\overline{\nu}$ beams $xF_3^{\nu N}$

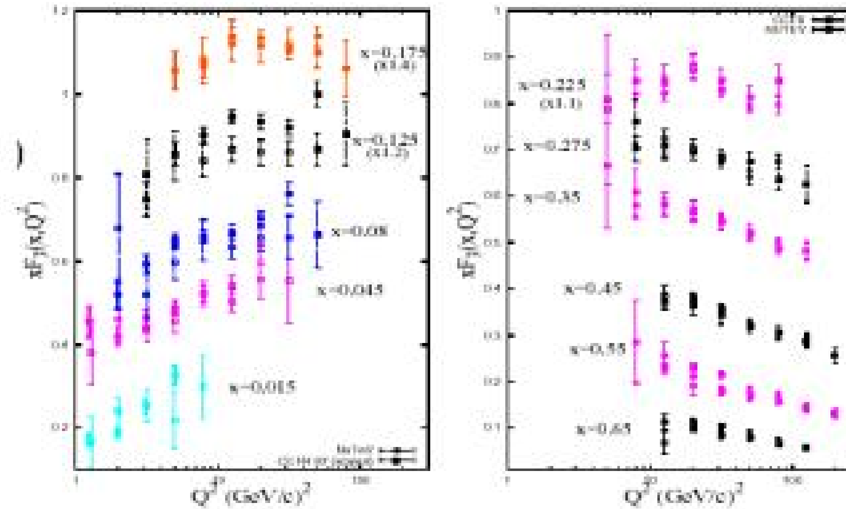
better control of largest systematics: E_μ and E_{Had}

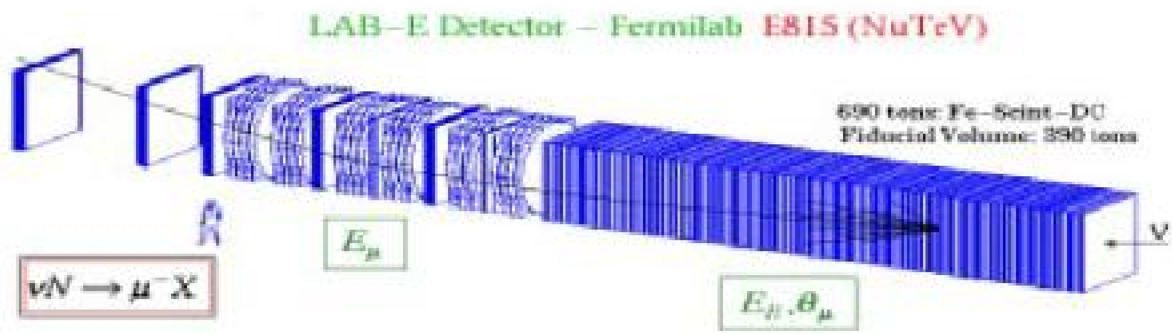
$$F_2^{\nu(\overline{\nu})} = \Sigma x(q + \overline{q} + 2k)$$

$$xF_3^{\nu(\overline{\nu})} = \Sigma x(q - \overline{q}) \pm 2x(s - c)$$









Data taken in 1996-97

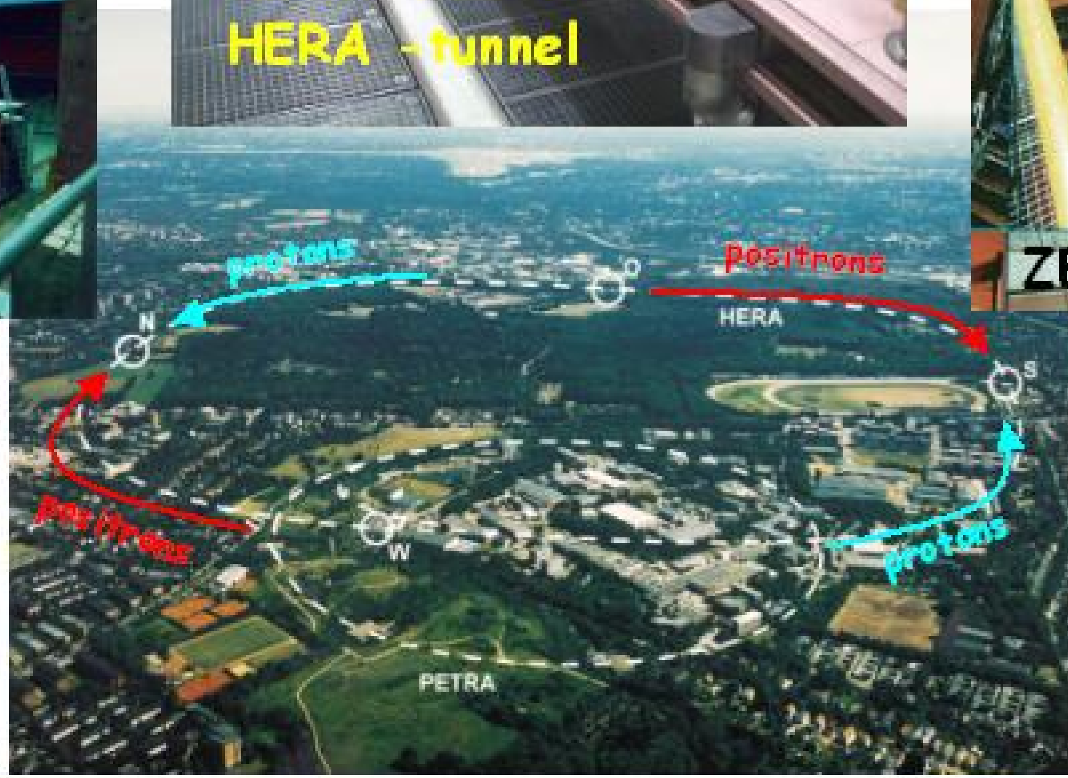
DIS03 NuTeV → MINOS at FNAL

2. HERA

protons: 920 GeV

positrons: 27.6 GeV

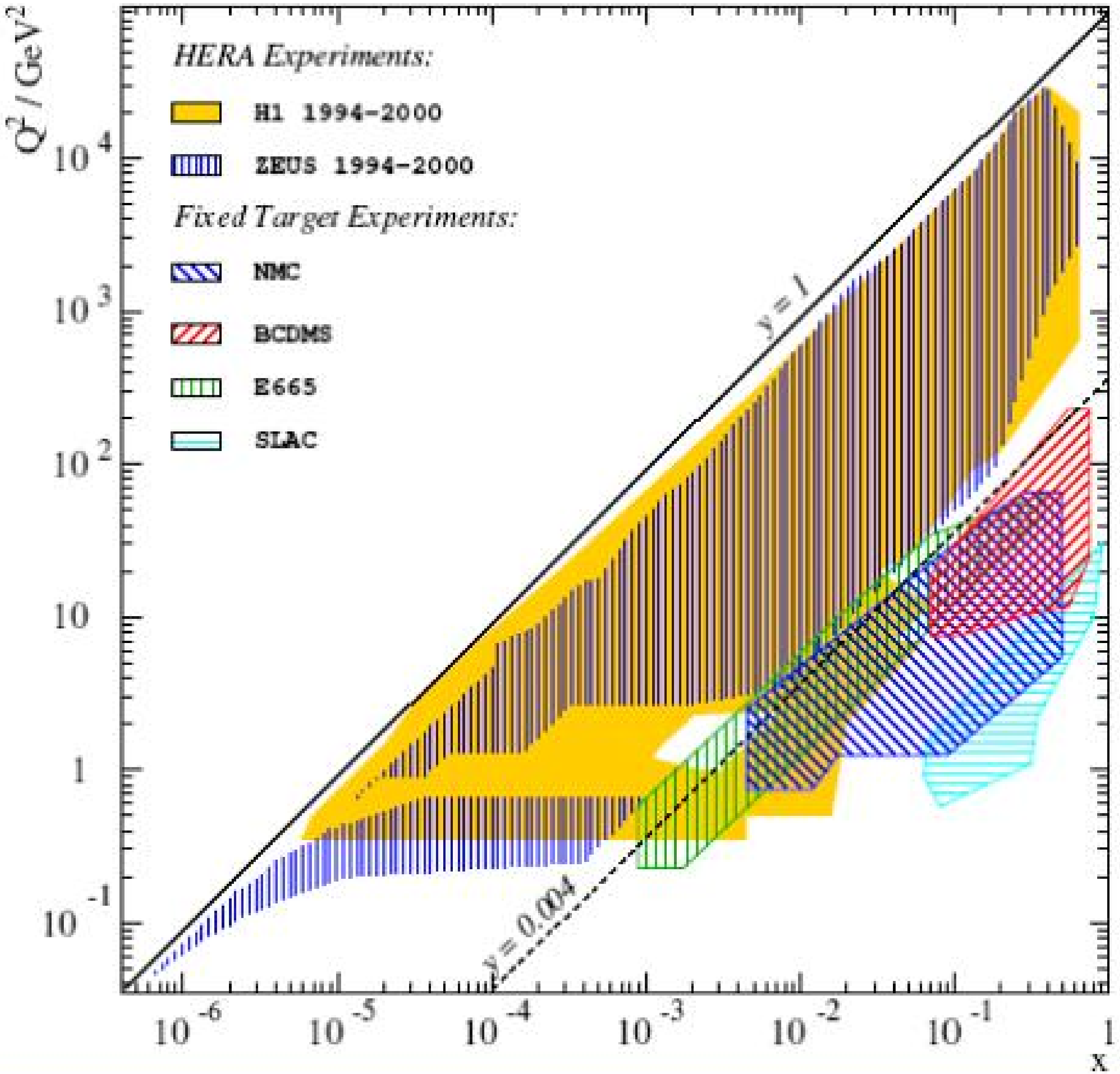
circumference: 6.3 km



the world's
highest
resolution
microscope

- 1000 authors on
- H1, ZEUS,HERMES,
- 14% from DESY
- About 1.-1.5 BEuro investments & 20k person years

huge extension of kinematic range: DIS and searches at energy frontier

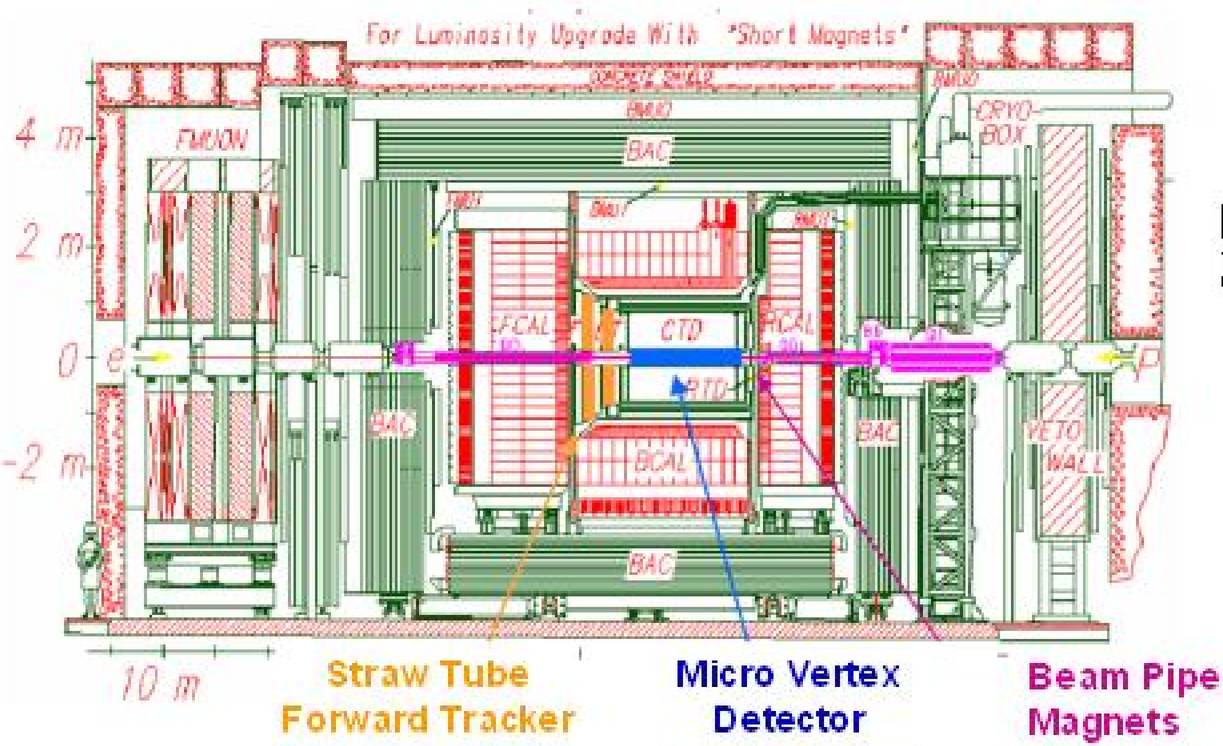


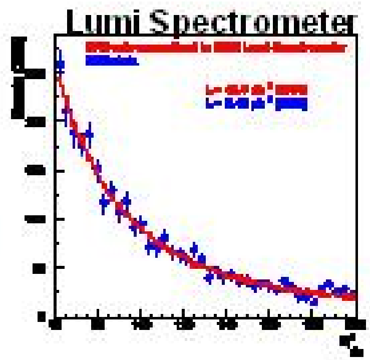
Q2: -four momentum transfer^2 from e to p

x: parton fraction of proton momentum

redundant reconstruction of the kinematics using scattered electron and the hadronic final state

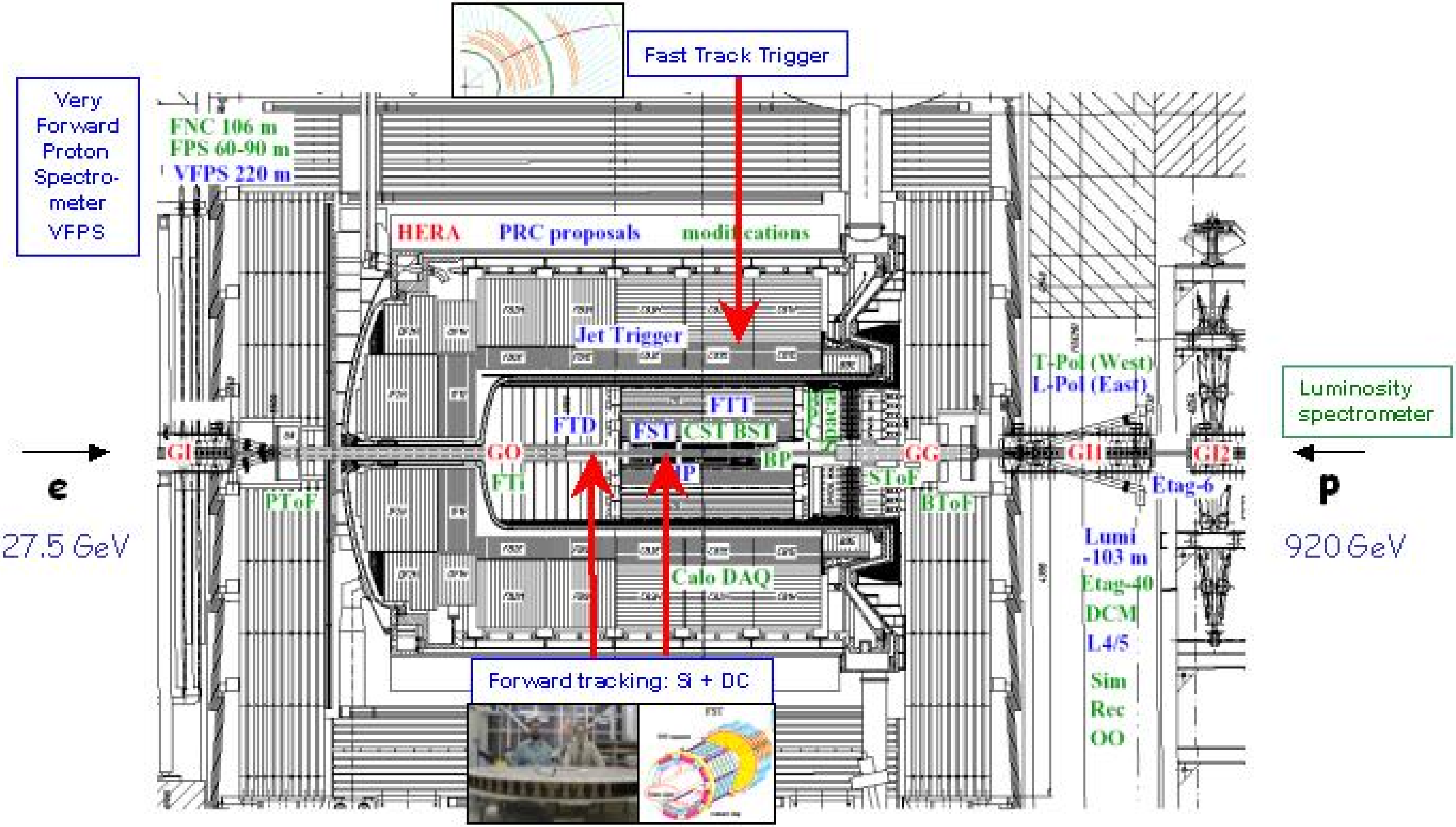
ZEUS and its Upgrades

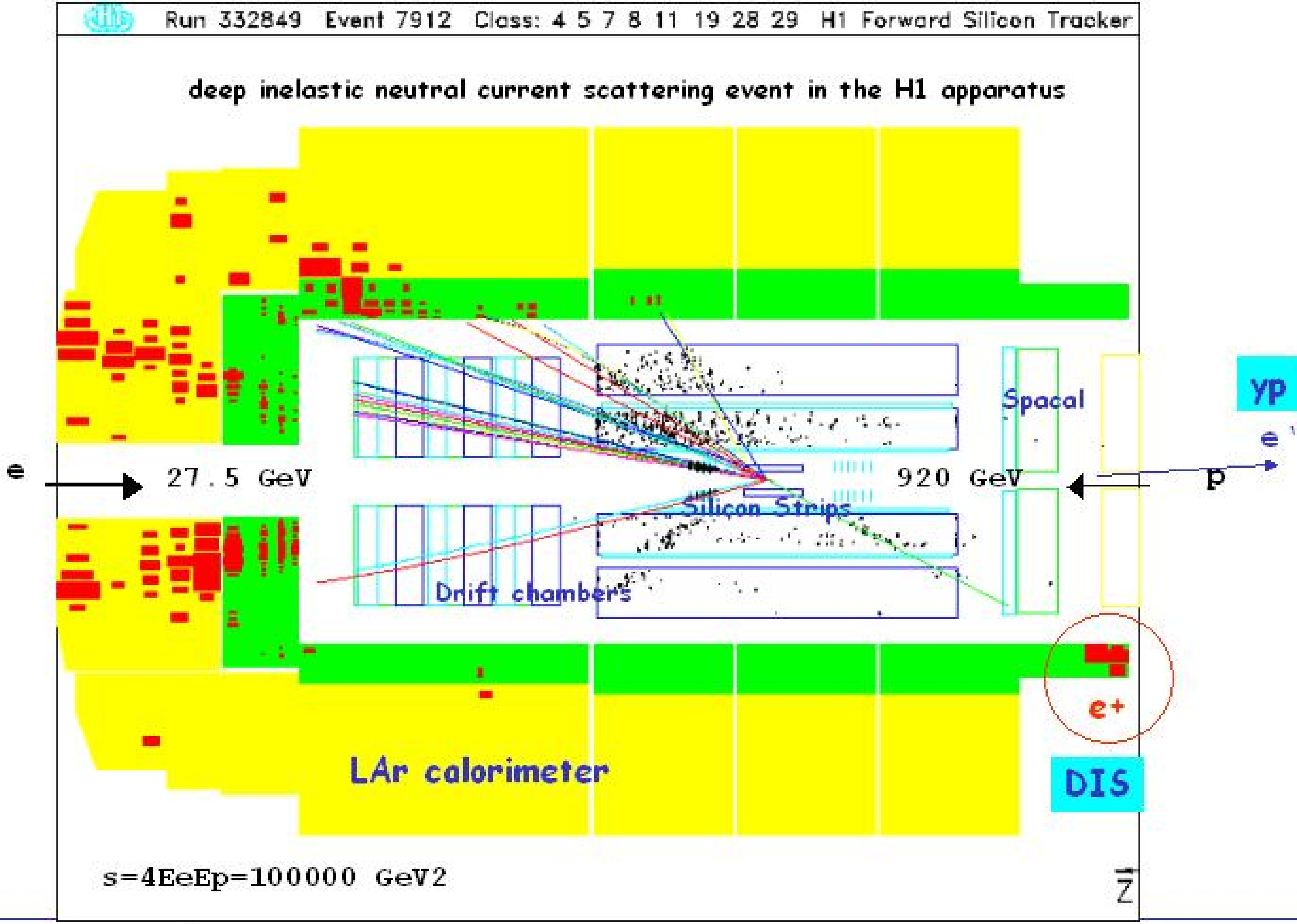




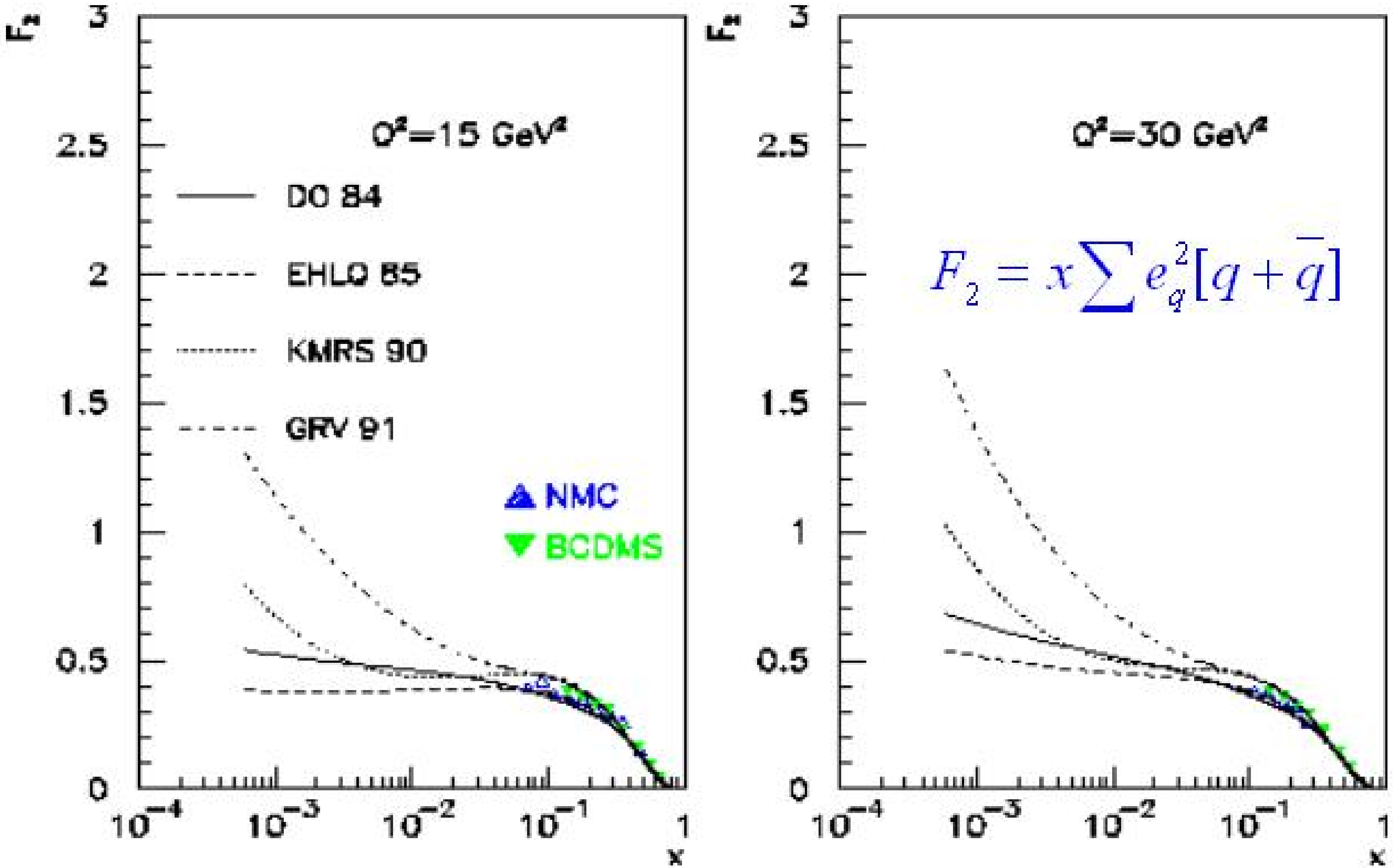
HERA I: 1992-2000: 100pb-1
HERA II: 2003-07: 1000pb-1

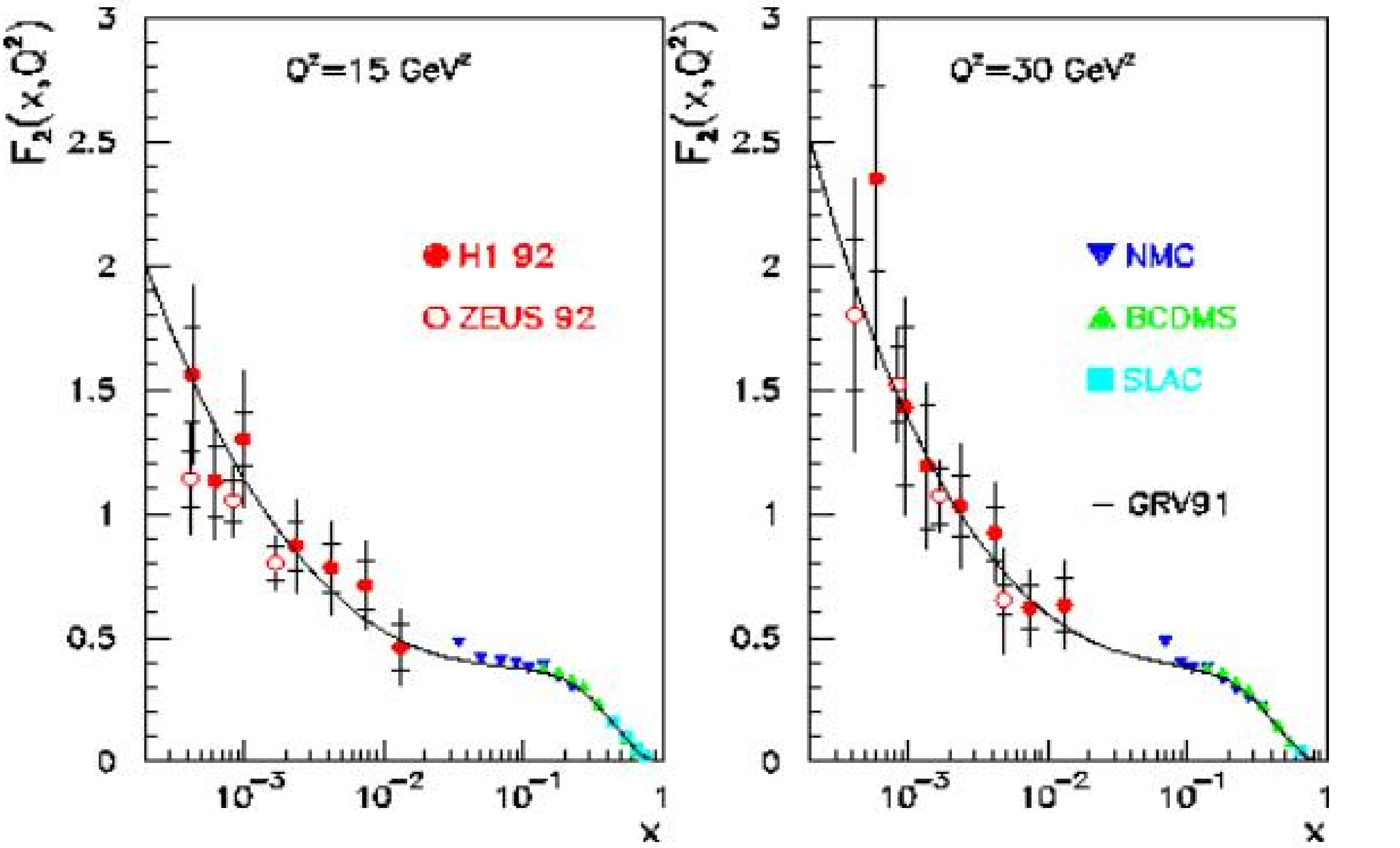
The H1 Detector for HERA II



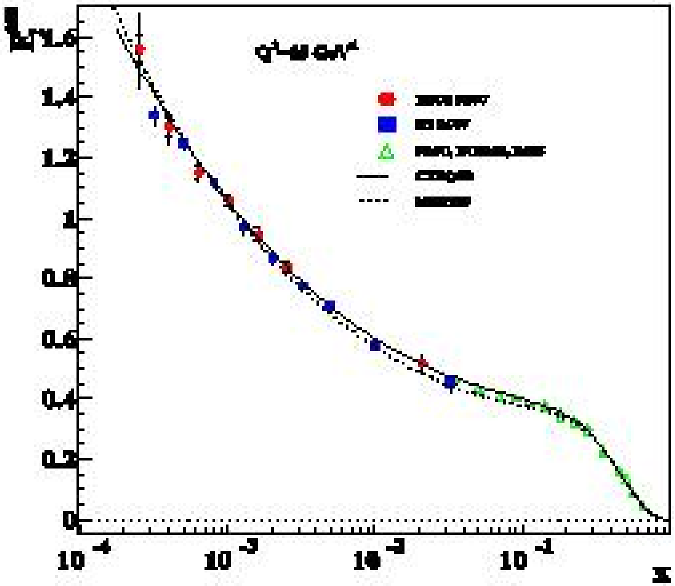

Run 332849 Event 7912 Class: 4 5 7 8 11 19 28 29 H1 Forward Silicon Tracker
deep inelastic neutral current scattering event in the H1 apparatus
e
27.5 GeV
920 GeV
p
e'
γp
Spacal
Silicon Strips
Drift chambers
LAr calorimeter
e+
DIS
s=4EeEp=100000 GeV2
Z

3. The Rise towards and Physics at Low x





HERA: F2 is rising towards low Bjorken x - observed with 200nb-1 (ФИАН)

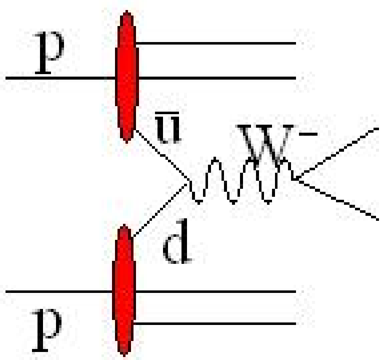


rise confirmed up to 2-3%!

Q2 0.3-30 000 GeV2

sea (a)symmetry important for ν

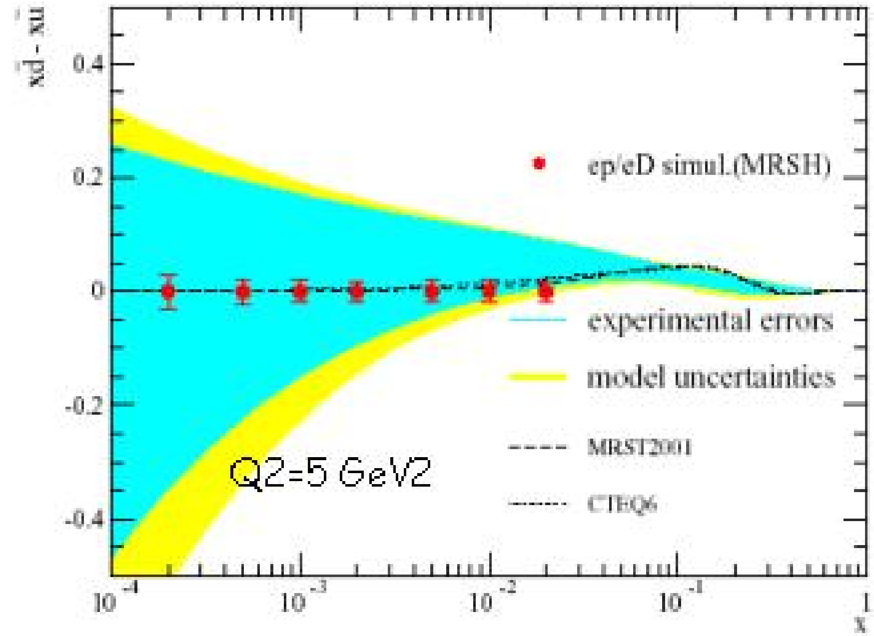
astrophysics at UHE <--> small x



parton luminosity problem at the LHC

Is this behaviour the same for d&u??

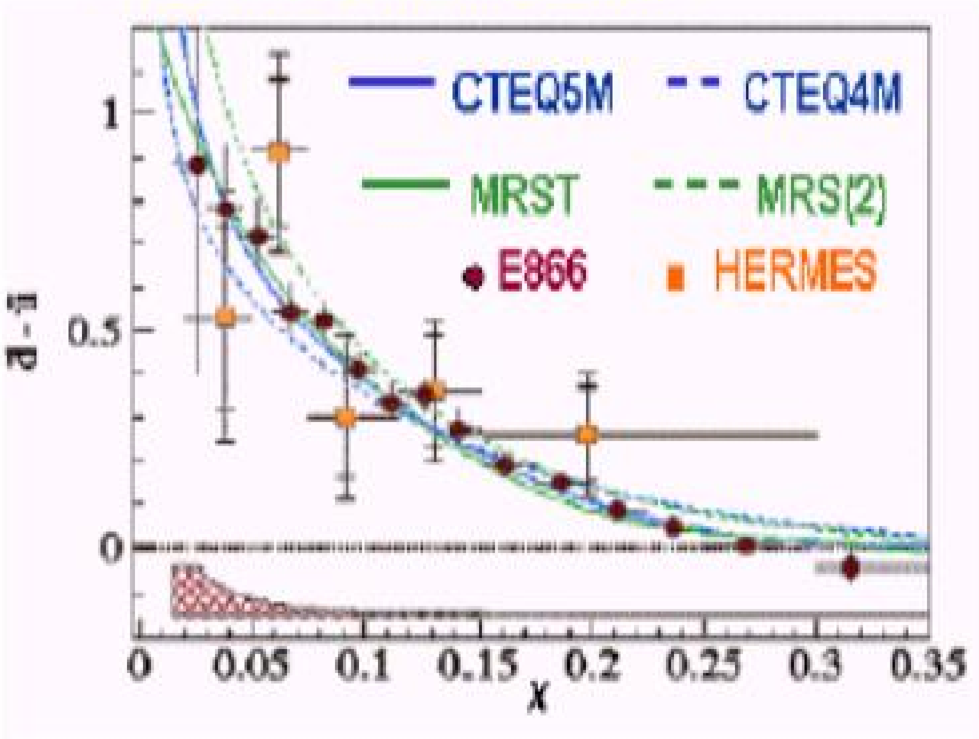
$$\frac{1}{2}\left(F_2^p + F_2^n\right) - F_2^p$$
$$= x\left(\frac{1}{6}d_v - \frac{1}{6}u_v + \frac{1}{3}\bar{d} - \frac{1}{3}\bar{u}\right)$$
$$\approx \frac{1}{3}x\left(\bar{d} - \bar{u}\right) \text{ at low } x.$$



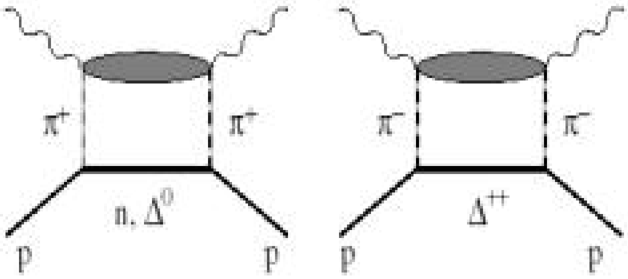
requires to operate HERA with deuterons

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

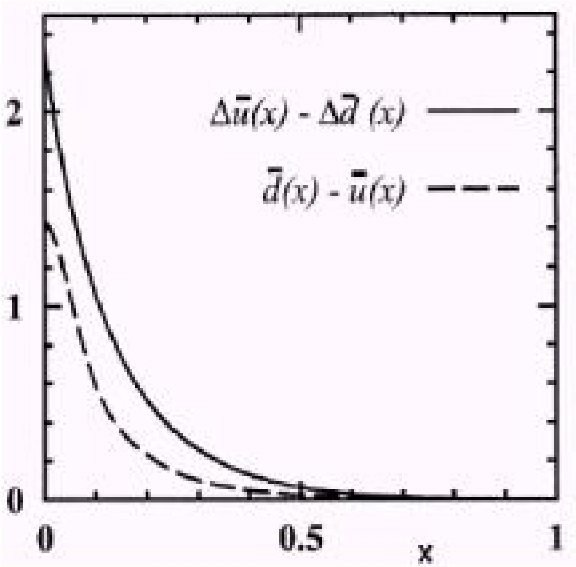
- extractions of PDFs assume $\bar{d} = \bar{u}$ at low x.
- plausible as both m_u ~ 3 MeV and m_d ~ 6 MeV << Λ_{QCD}.
- but look at available data...



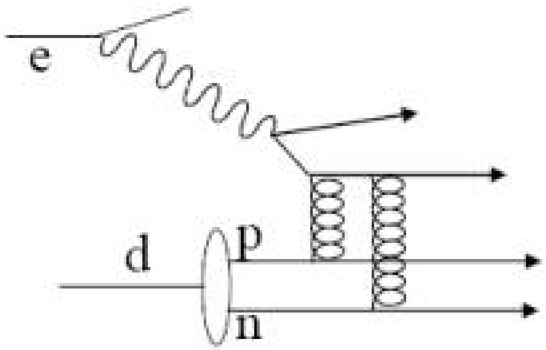
•Sullivan model



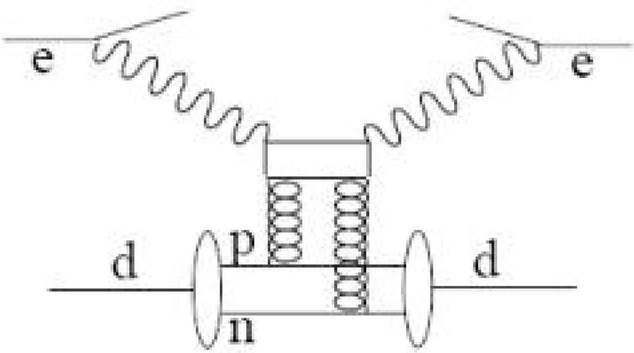
•Chiral soliton model



Gribov: shadowing is



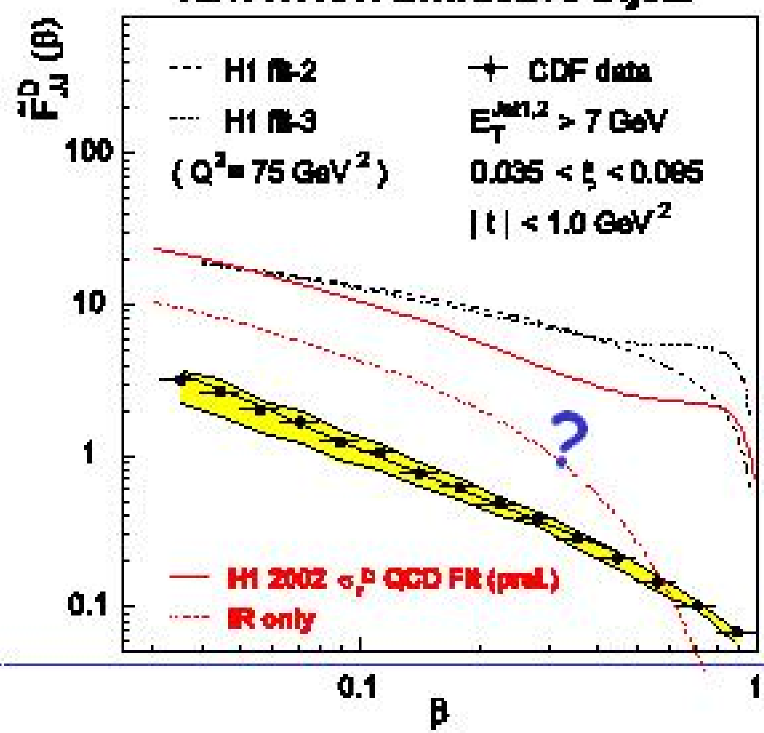
related to diffraction



cf: H1 LoI for eD at HERA, DESY 2003

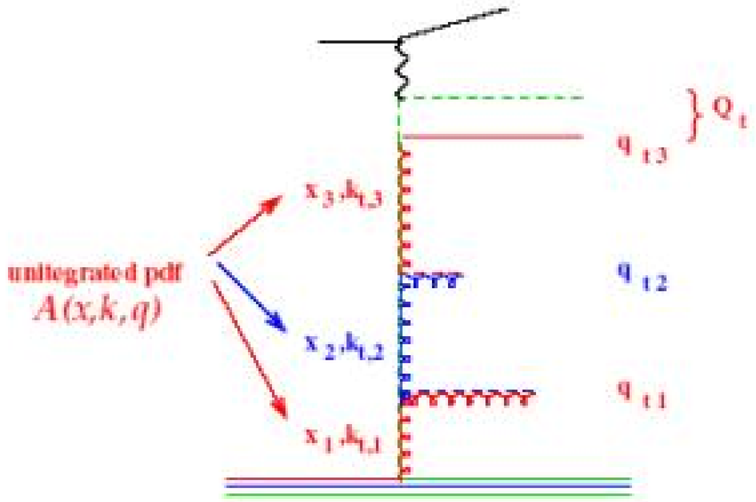
- with p, n, D tagging learn much more about diffraction and the n structure in the HERA range
- Diffraction constrains shadowing → high precision low x en data
- Tagging of spectator p removes nuclear corrections at high x → determine uv/dv at large x

TEVATRON Diffractive Dijets

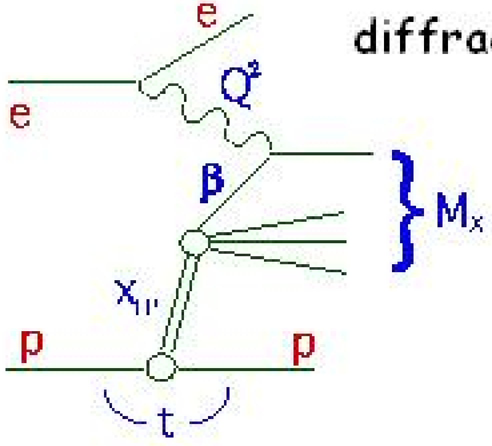


Many refined measurements are being done to understand low x

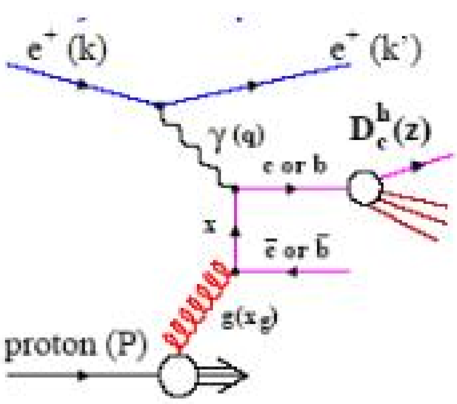
high density low x and parton emission



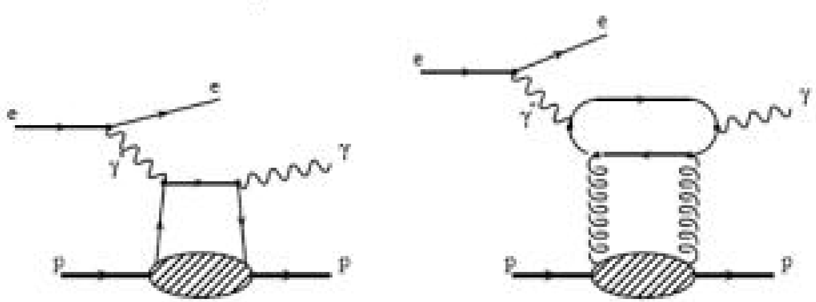
diffraction



heavy flavours



skewed parton distributions

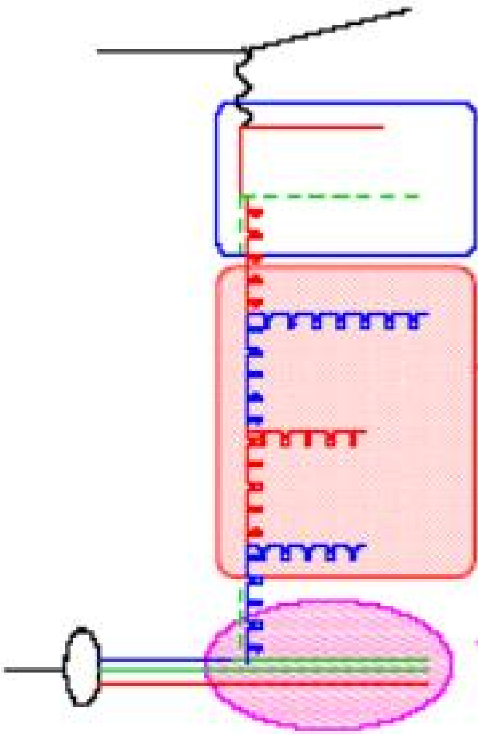


Unintegrated gluon density to describe parton radiation at small x

CCFM

CCFM (one loop)

- angular ordering

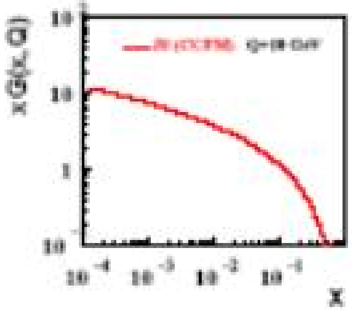


BGF matrix element off mass shell

evolution of parton cascade with DGLAP splitting fct.

$\tilde{P} = \bar{\alpha}_s \left(\frac{1}{1-z} + \frac{1}{z} \right)$

initial distribution:



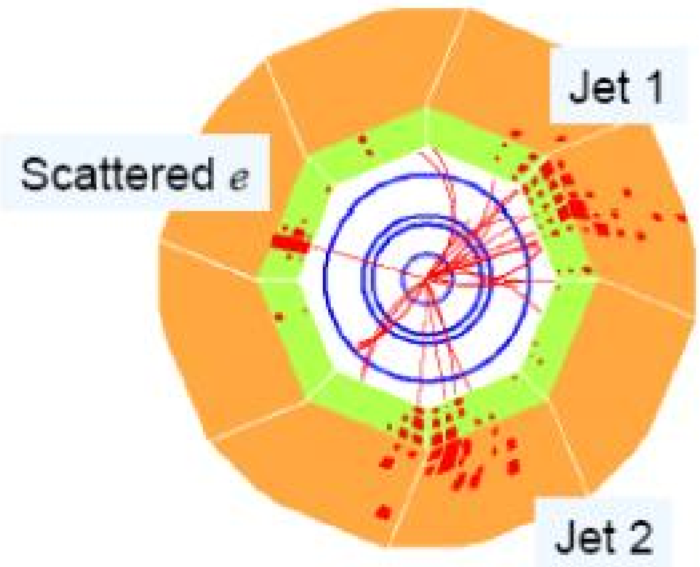
$$\sigma(ep \to e'q\bar{q}) = \int \frac{dy}{y} d^2Q \frac{dx_g}{x_g} \int d^2k_t \hat{\sigma}(\hat{s}, k_t, Q) x_g \mathcal{A}(x_g, k_t, \bar{q})$$

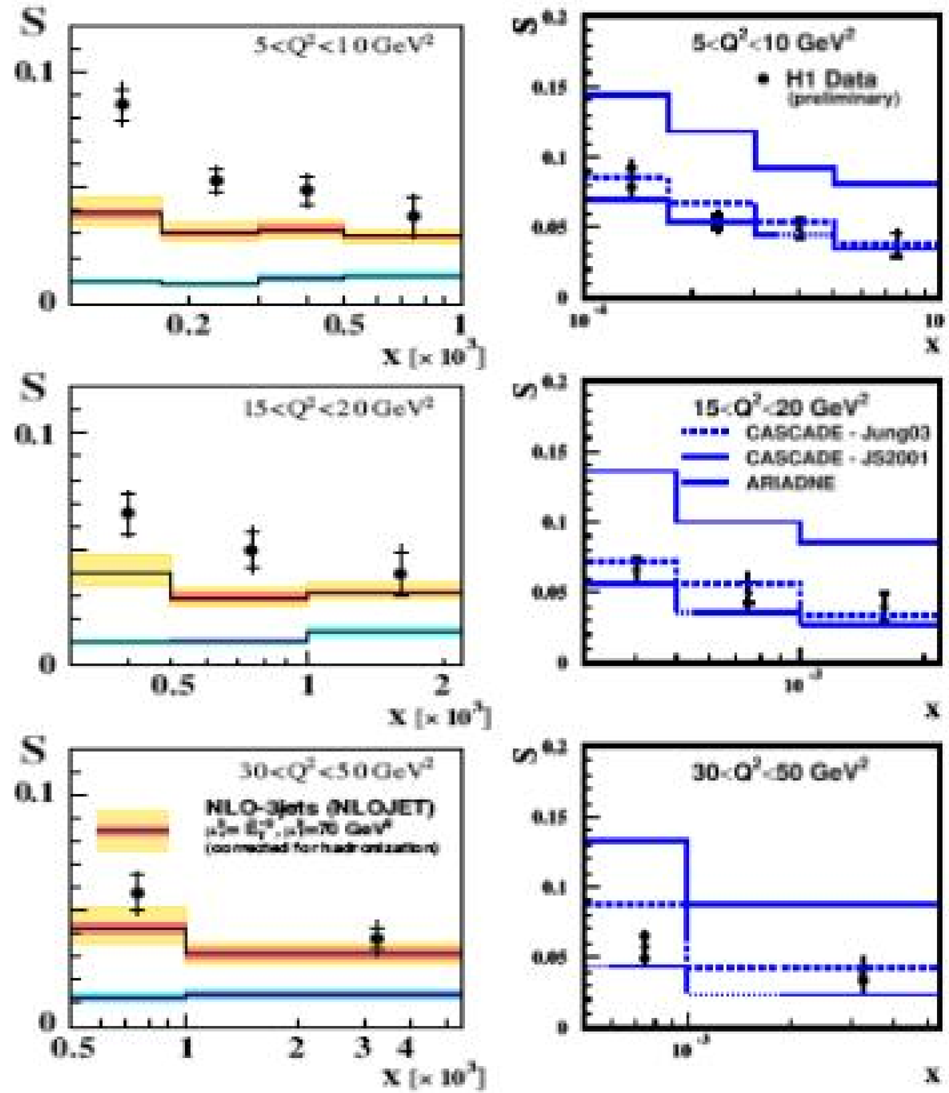
with $\int d^2k_t x_g \mathcal{A}(x_g, k_t, \bar{q}) \simeq x_g G(x_g, Q^2)$

Jet azimuthal correlations to study parton radiation - DGLAP or not at low x?

$$S(\alpha) = \frac{\int_0^{\alpha} N_{dijet}(\Delta\Phi^*, x, Q^2)\, d\Delta\Phi^*}{\int_0^{\pi} N_{dijet}(\Delta\Phi^*, x, Q^2)\, d\Delta\Phi^*}$$

$\alpha = 120^\circ$





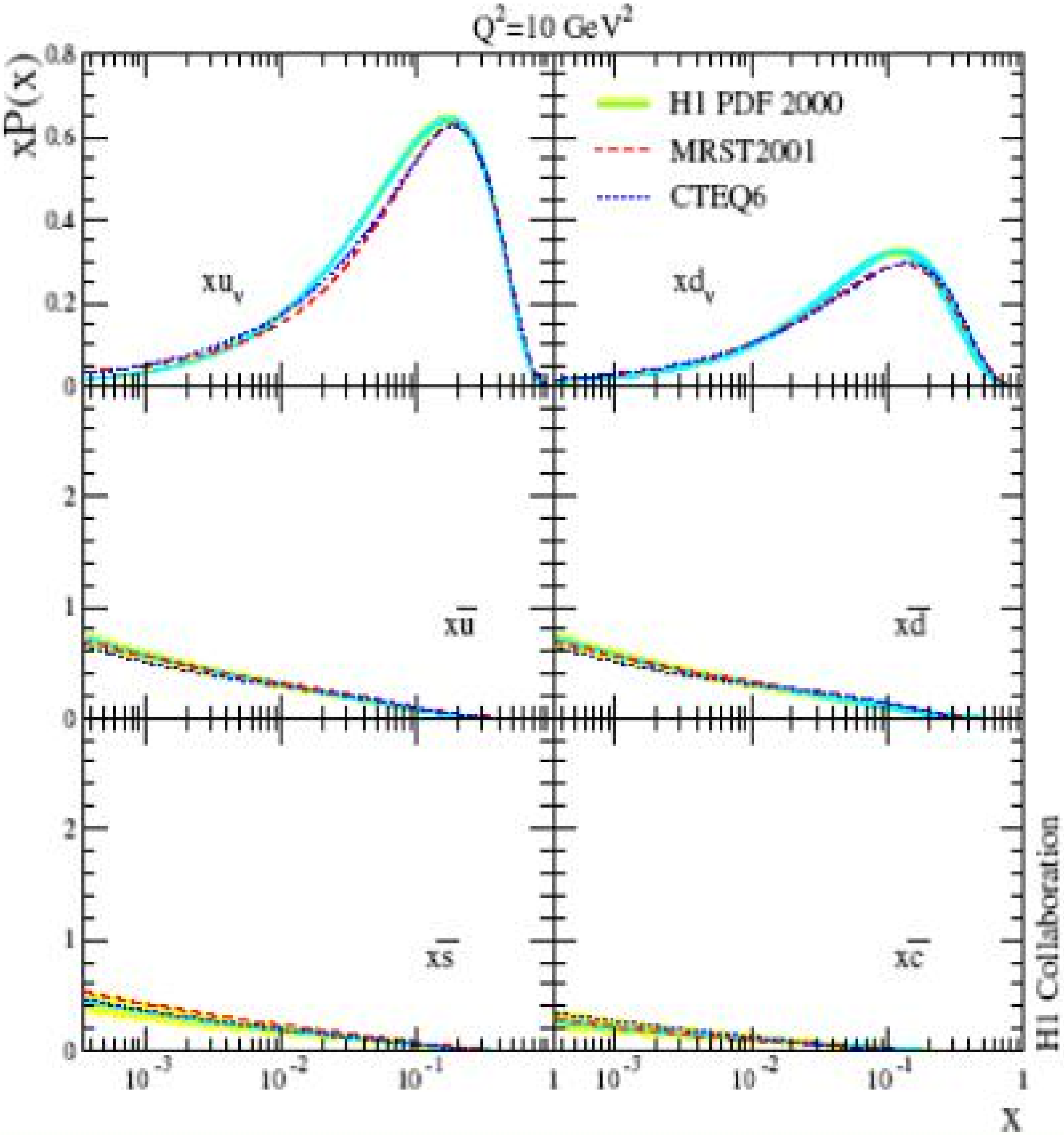
NLO 3-jets in trouble at lowest x   CCFM (unintegrated g) and CDM ok

Low x physics needs very accurate measurements
in inclusive scattering ($ep \rightarrow eX$) and in final states.

It is not 'done' but requires much more HERA input

for ingenuitive theorists to formulate QCD
at high densities and small couplings
which describes a new phase of matter.

4. Quark Distributions



exp uncertainties of H1 pdfs

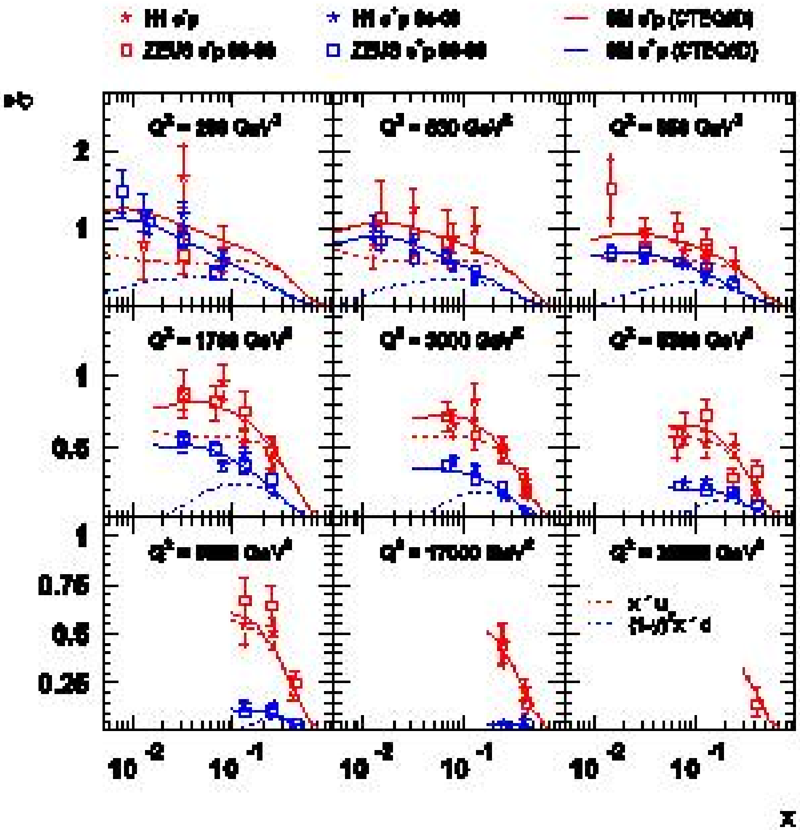
x	0.01	0.4	0.65
xU	1%	3%	7%
xD	2%	10%	30%

quark distributions
from pQCD fit to H1 data

Assumptions	To do:
$\bar{c} = f_c \overline{U}$	•F2c
$\bar{s} = f_s \overline{D}$	•Ws→c
$\bar{s} = s, \bar{c} = c$	•?
$\bar{u} - \bar{d} \to 0$	•eD
	•F2b

Accuracy (L) to be increased!

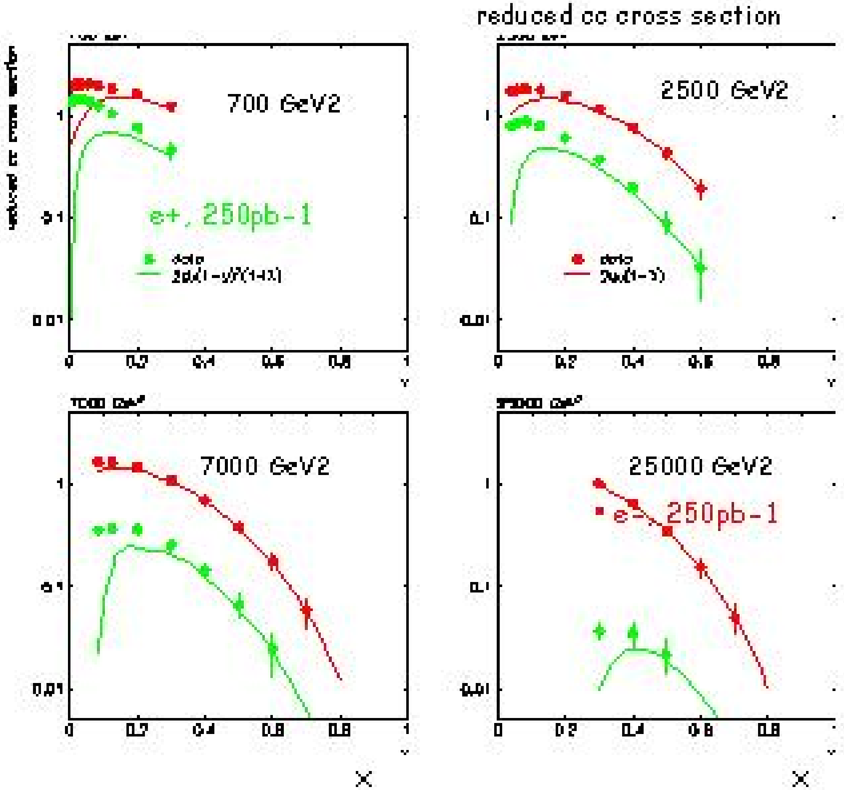
Measured at HERA 94-00



Charged currents ep →νX

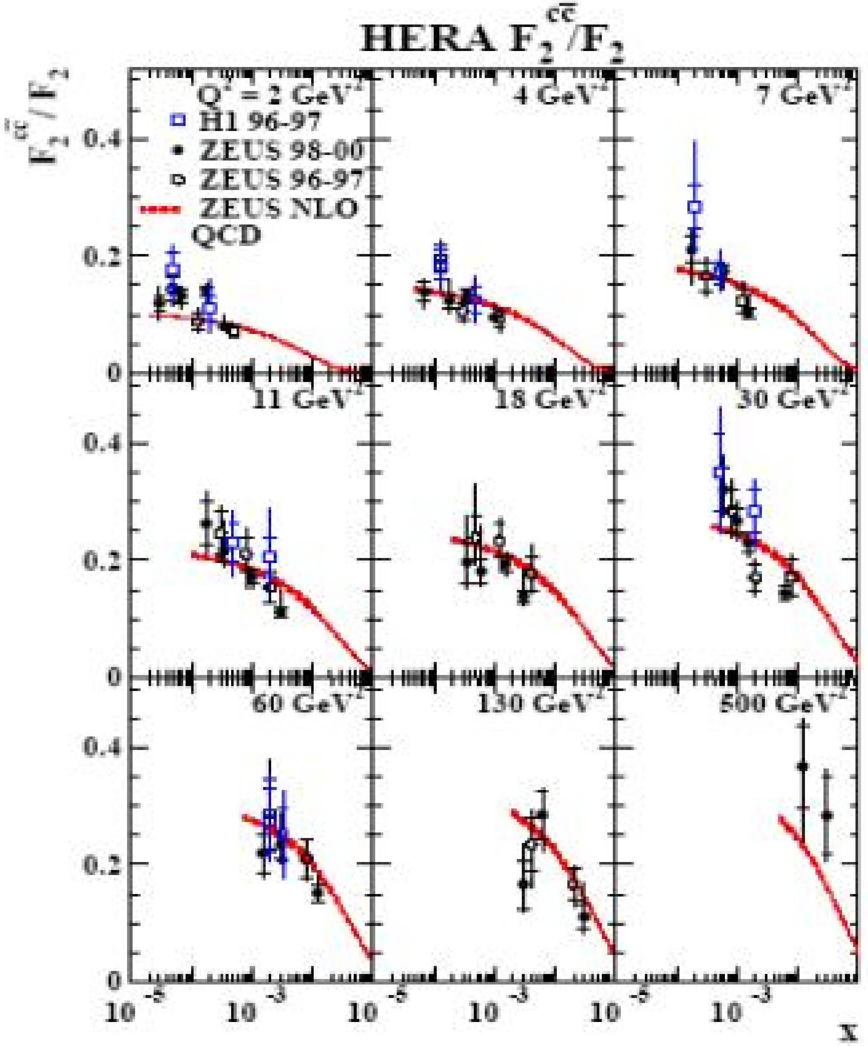
inverse neutrino scattering,
sensitive to quark flavours

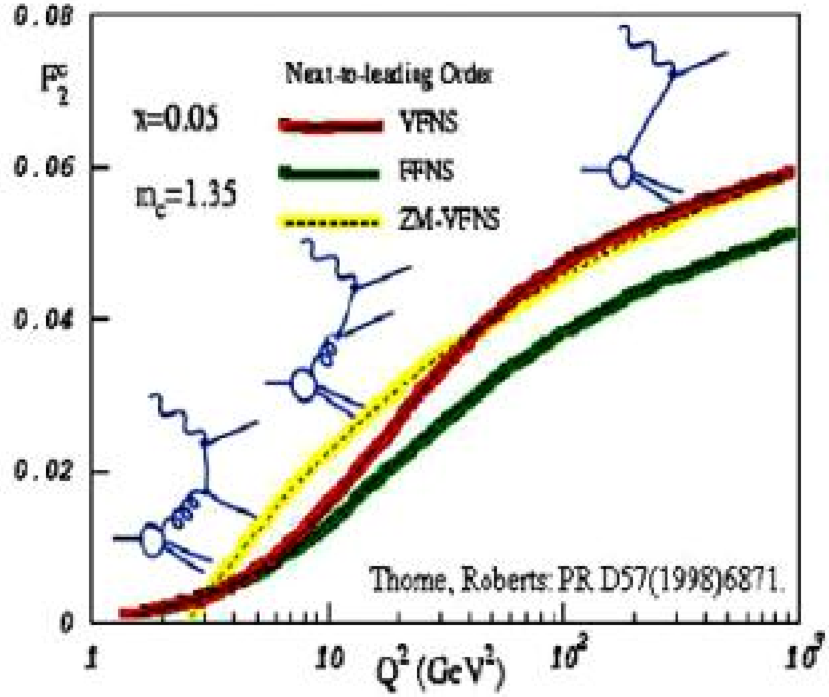
Expectation for HERA 04-07



--- $\sigma(e^-p) \sim x(u+c) + (1-y^2)\, x(\overline{d}+\overline{s})$

--- $\sigma(e^+p) \sim x(\overline{u}+\overline{c}) + (1-y^2)\, x(d+s)$





charm quark distribution in the proton?
NLO QCD - theory of heavy flavour
complementary probe of gluon distribution

- expect improved accuracy in coming years (Si, Lumi)

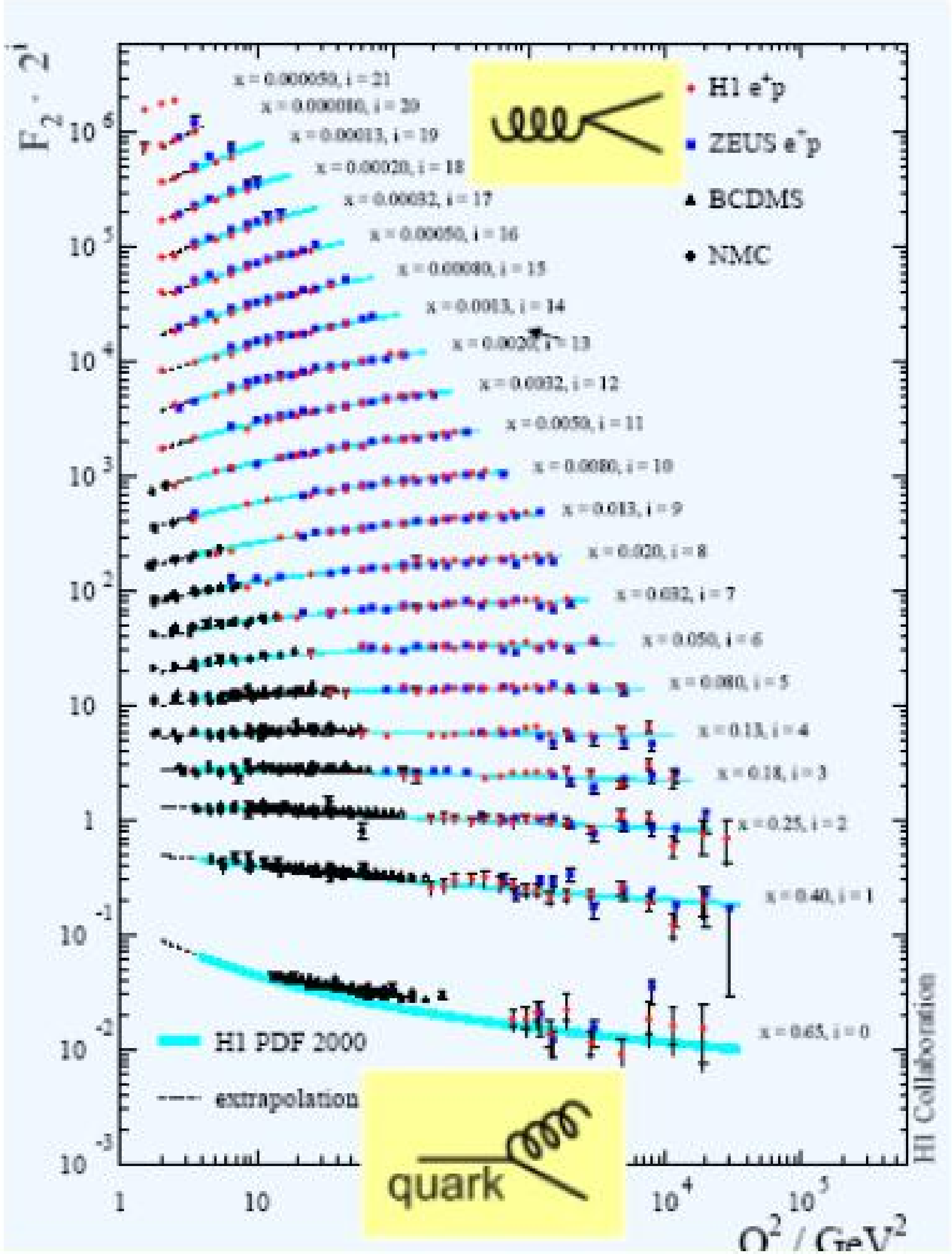
note: at the LHC [c ~ u], HERA [c < u].

5. The Gluon Distribution and the Strong Coupling

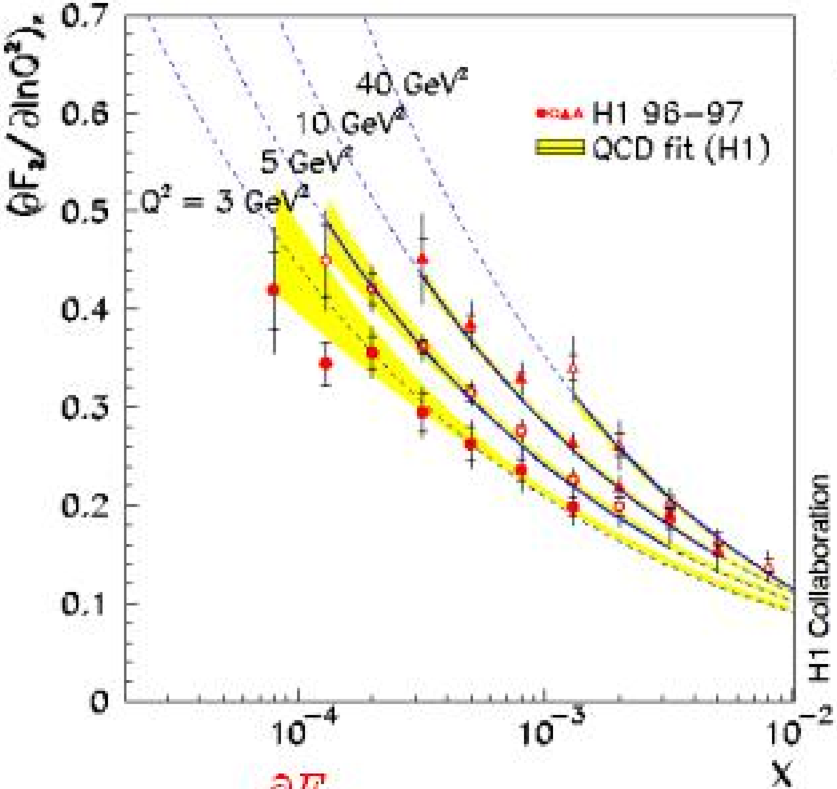
$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s(Q^2) x g(x, Q^2)$$

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

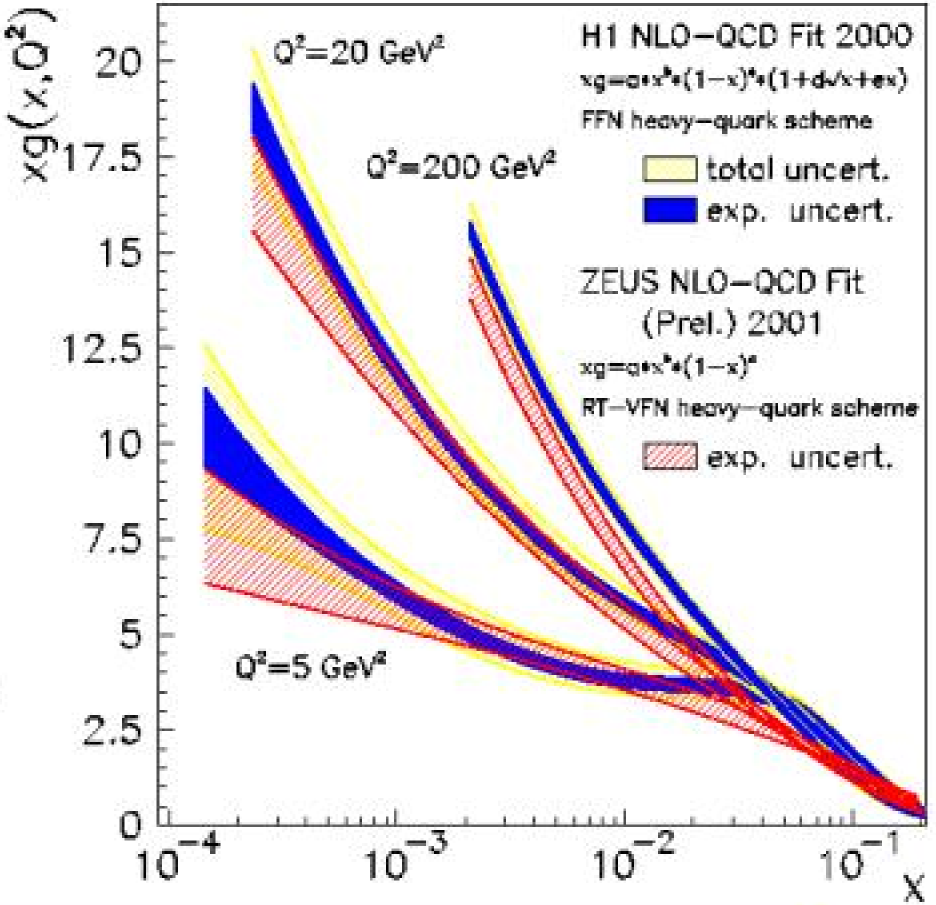
$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s(Q^2) q(x, Q^2)$$



strong scaling violations at low x lead to very large gluon momentum density



$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s \cdot xg$$



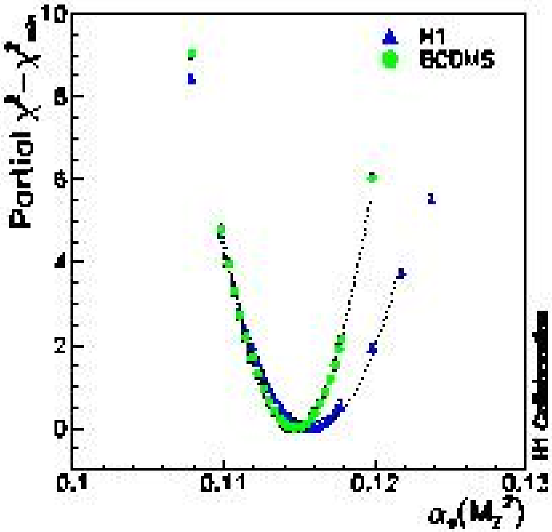
xg depends on charm treatment!

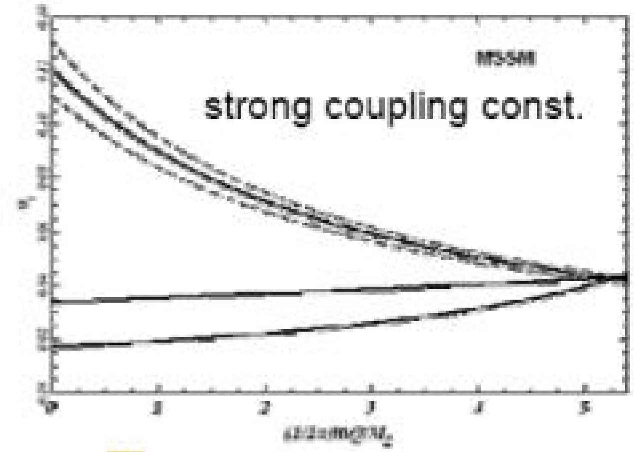
xg is not an observable → no unique determination and still uncertain at low x, Q2!

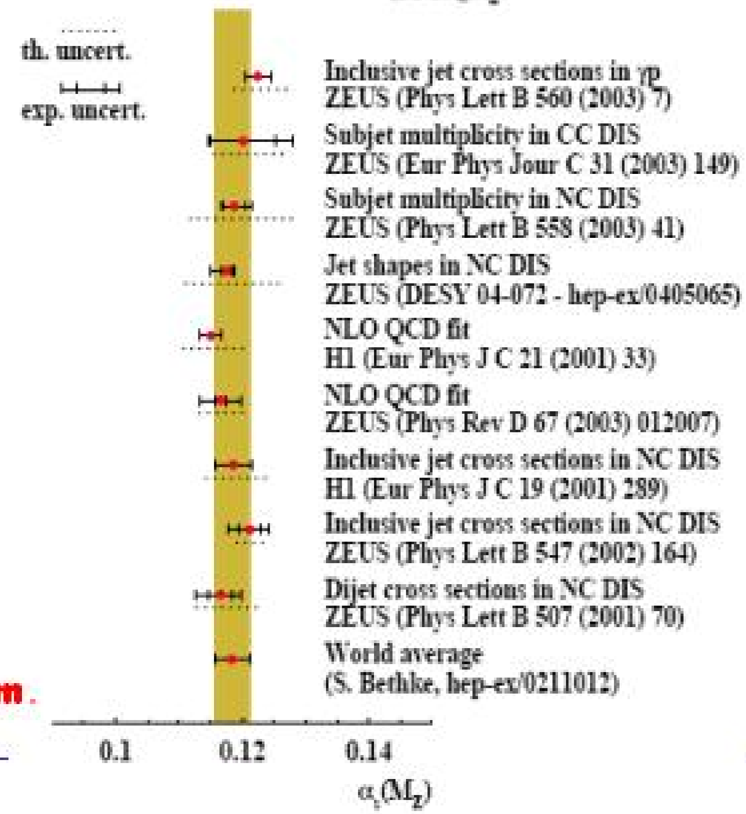
Understand + consider the role of diffraction and absorptive corrections!

DIS measurement of α_s - with H1 and BCDMS data

0.1150 ± 0.0019 (exp+fit) ± 0.0050 (ren.scale)







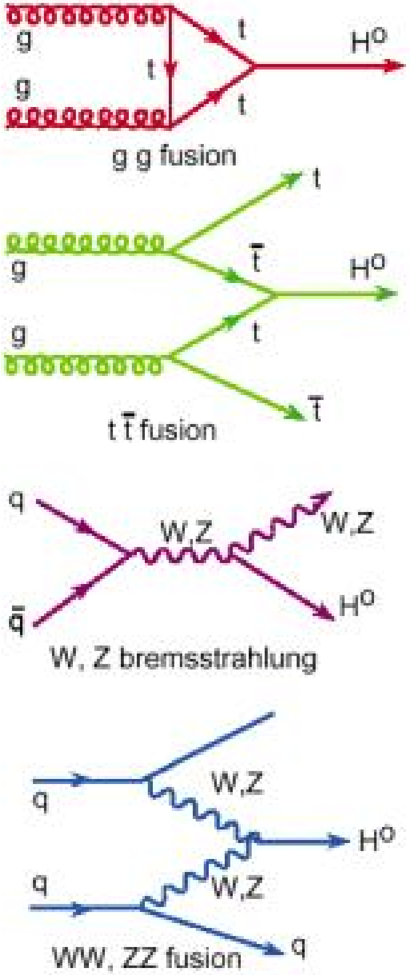
Potentially the best measurement

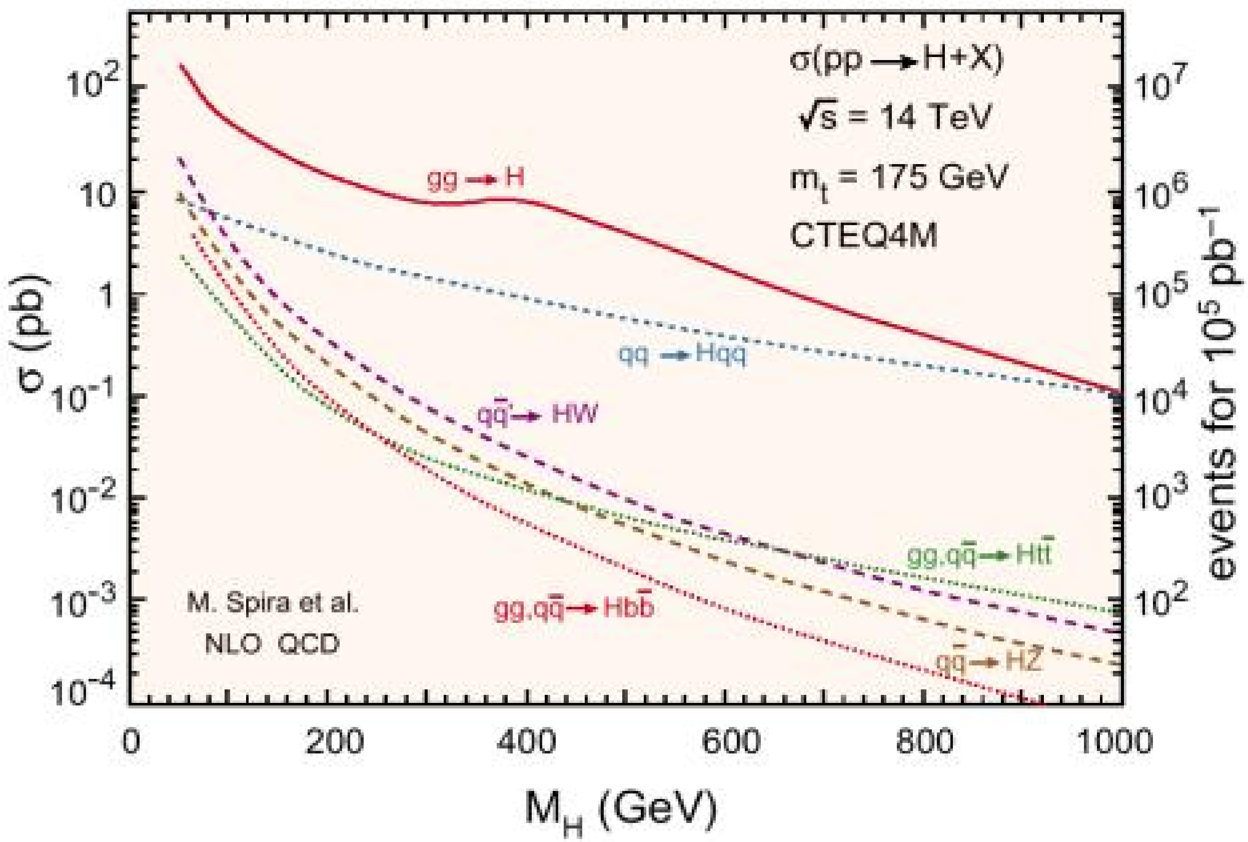
Theory now calculated to NNLO [Vermaseren, Moch, Vogt]

Exp accuracy to 1% possible…?

More constraints on the gluon -FL,jets charm.

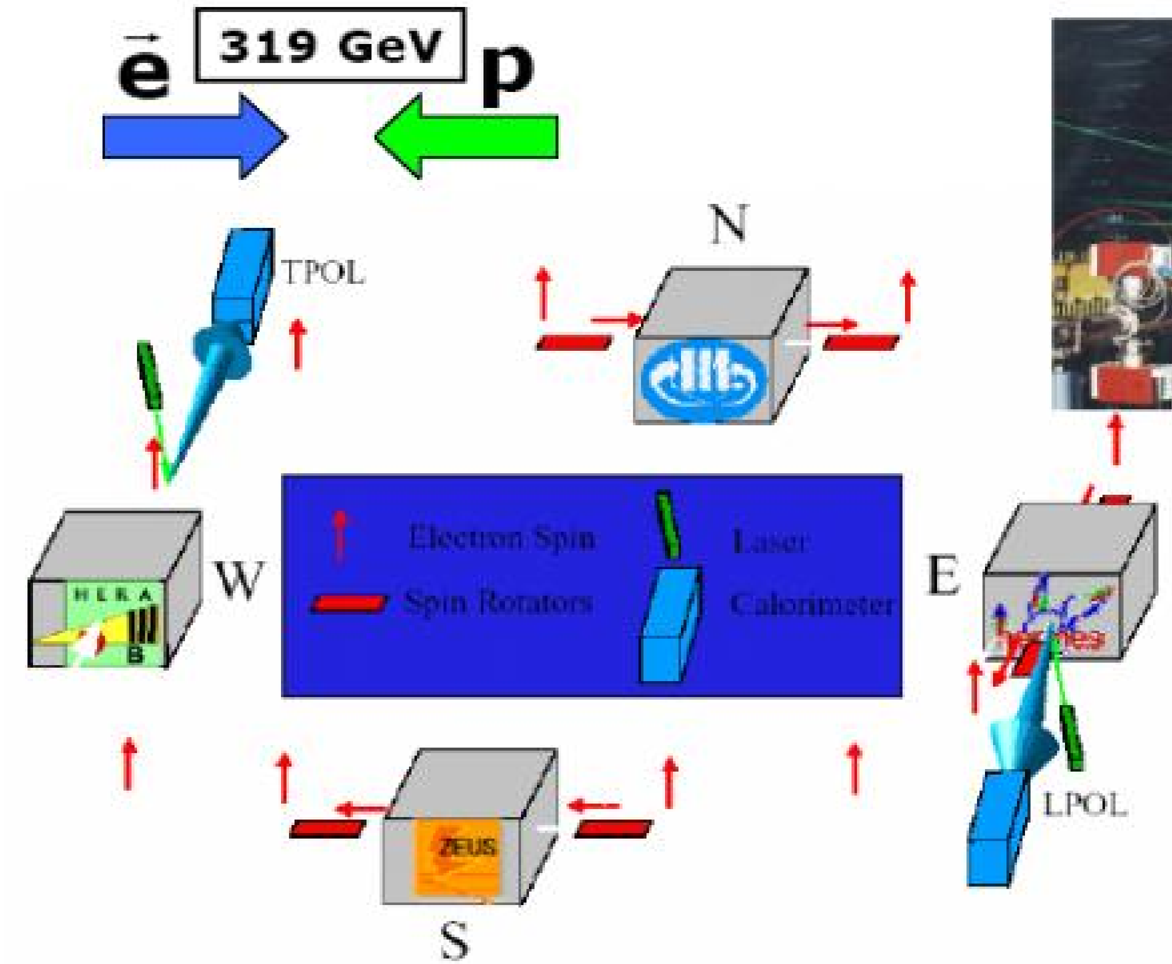
SM Higgs at the LHC

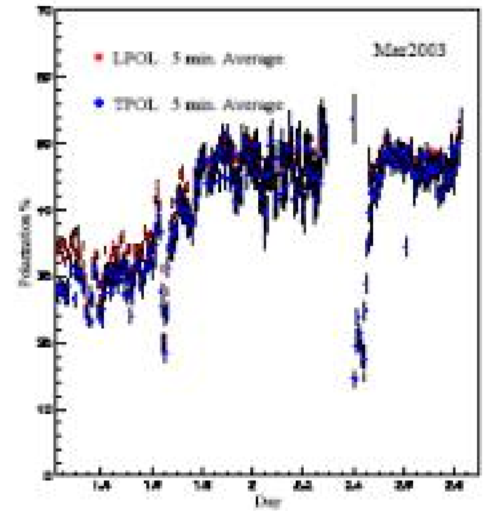




LHC leads from QCD to Higgs & BSM, from HERA to the LC

6. Proton structure - a holographic view





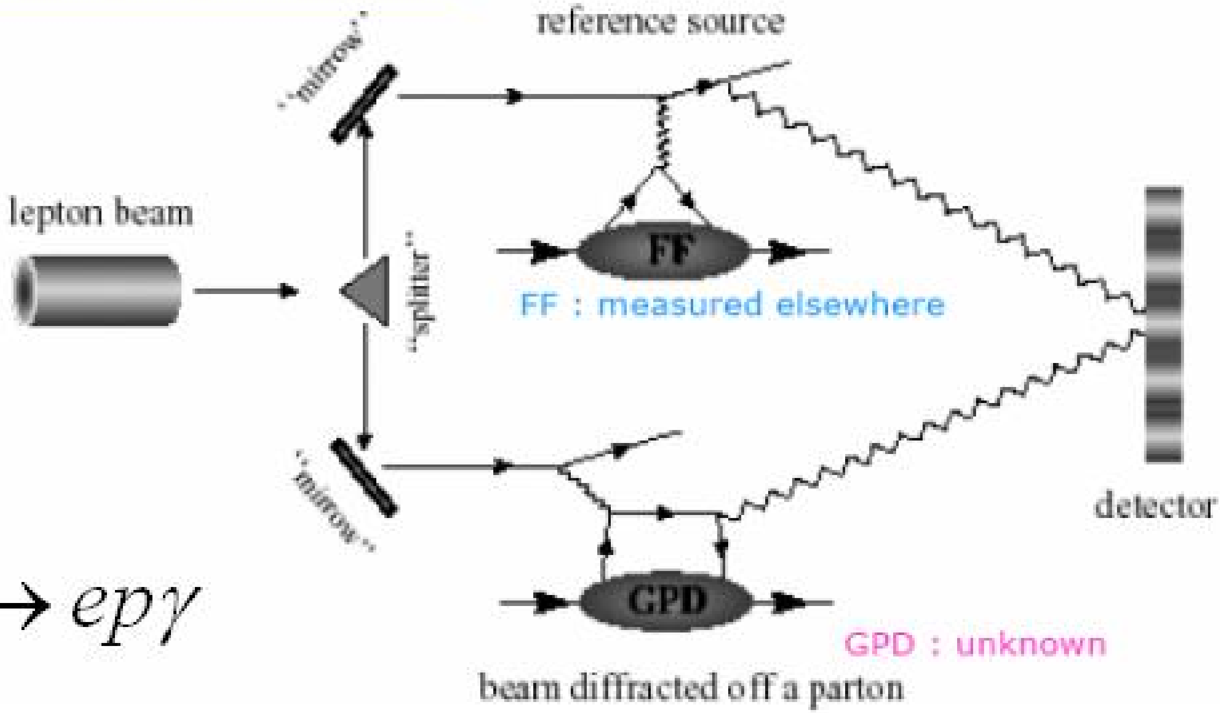
Classic electroweak measurements: charged currents, parity violation, v,a(u,d)

Measure vector meson and photon production for different charge and beam helicity

[V.Belitsky, D.Müller,hep-ph/0206306]

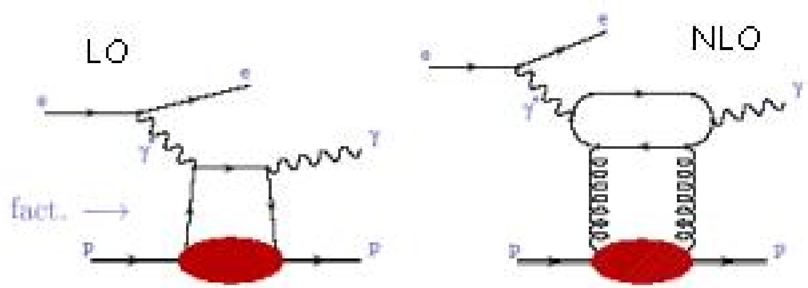
nucleon hologram with leptoproduction: interference of Bethe-Heitler (reference) and DVCS (sample) amplitudes

map transverse
proton size: access
parton amplitudes (GPD)

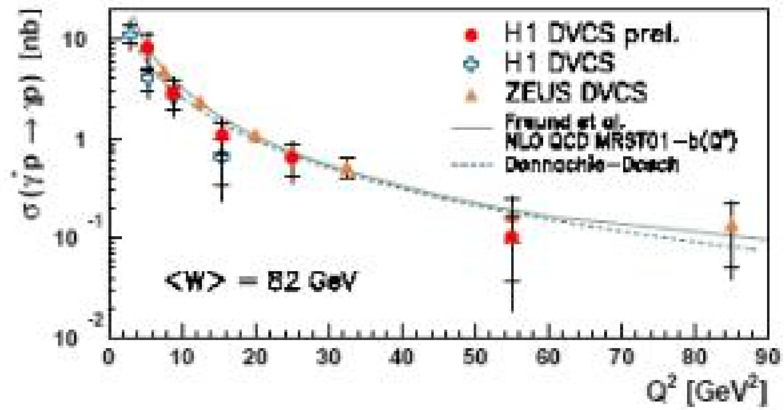


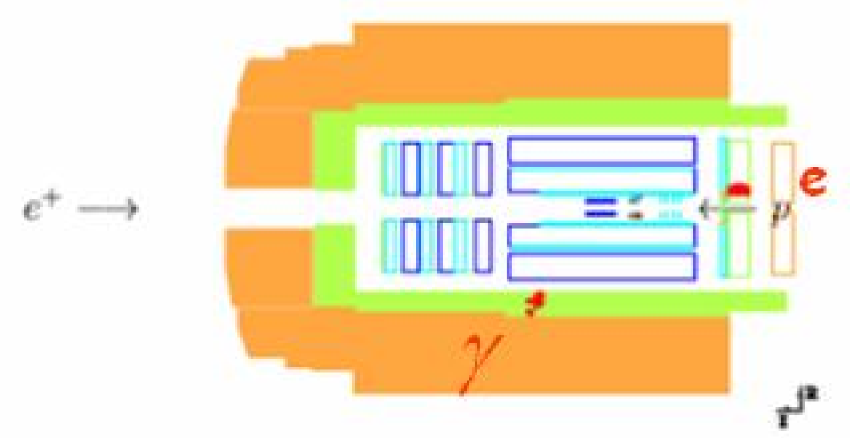
$$ep \to ep\gamma$$

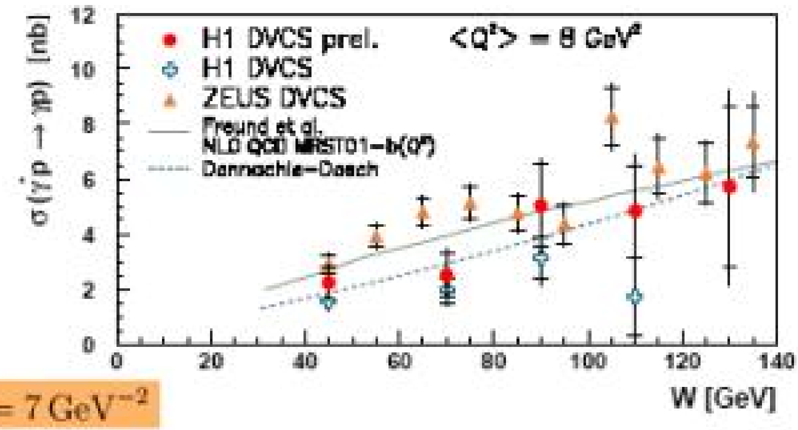
Deeply Virtual Compton Scattering



beautiful events, signature interferes with Bethe Heitler

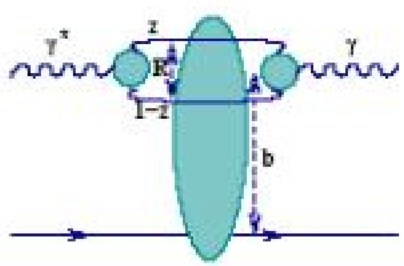






$b = 7\,\mathrm{GeV}^{-2}$

Colour Dipol Models



$$GPD(x,\xi,Q^2,t) \sim \frac{PDF(\frac{x-\xi/2}{1-\xi/2},Q^2)}{1-\xi/2} \times e^{-b|t|}$$

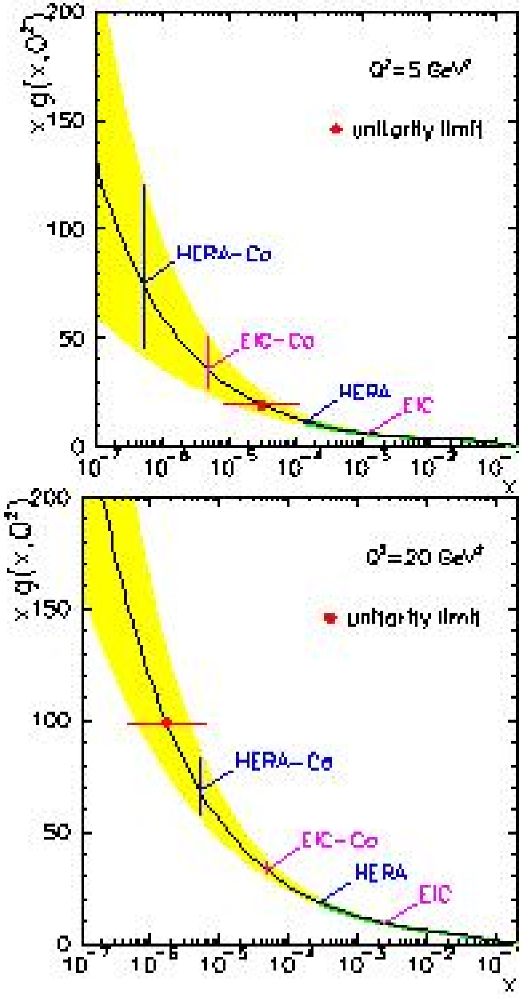
Generalised Parton Distributions

Large asymmetries predicted (A. Freund)

7. HERA III and eRHIC

- Low x ~ 10^-4: high density QCD at small coupling (CQC)
  - A new phase of matter. QCD is at the origin of mass
- Diffraction (p,n,D,A)
  - A key to confinement and the Higgs?
- Mapping the 3D structure of strong interactions, GPD's
  - A new detailed view on nucleon structure
- Precision measurements of parton densities (gluon, sea, valence)
  - A must for the LHC and an unresolved problem
- Parton dynamics and forward emission - BFKL?
  - A necessity to develop low x theory and find the limits of DGLAP
- Saturation and nuclear parton densities - the black body limit
  - A long predicted limit and a need to understand RHIC+ALICE
- HERA as a spin collider (low x Delta G, high Q2, ...)
  - A new world of hard QCD spin physics as in unpolarised case

Two Letters of Intent (45+24 institutes) published in 2003, signed by LPI



eA scattering at HERA

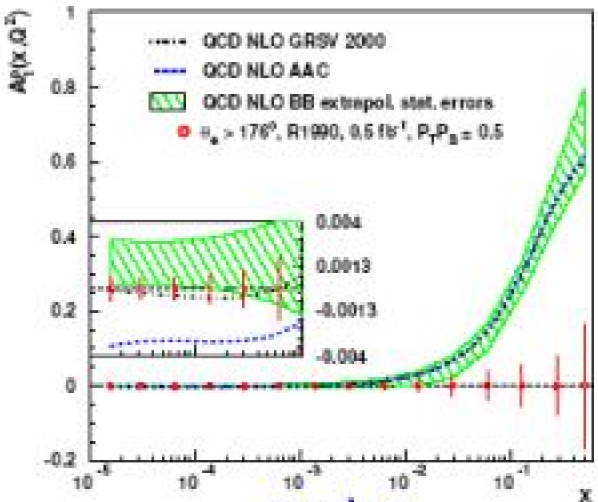
- low x - field strength high, large Q2 - coupling weak
  → unitarisation effects
  → new phase of matter CGC
- deconfinement
- nuclear parton distributions (RHIC, Alice)
- bj → black body limit
  - $F_2 \propto Q^2 \ln(\delta / x)$
  - large diffractive cross section
  - no colour transparency
  - $\sigma(J/\psi)[A]_x$

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

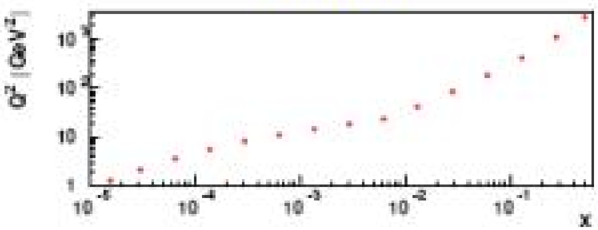
$$xg(x,Q^2) \leq \frac{1}{\pi N_c \alpha_s(Q^2)} Q^2 R^2 \simeq \frac{Q^2}{\alpha_s}$$

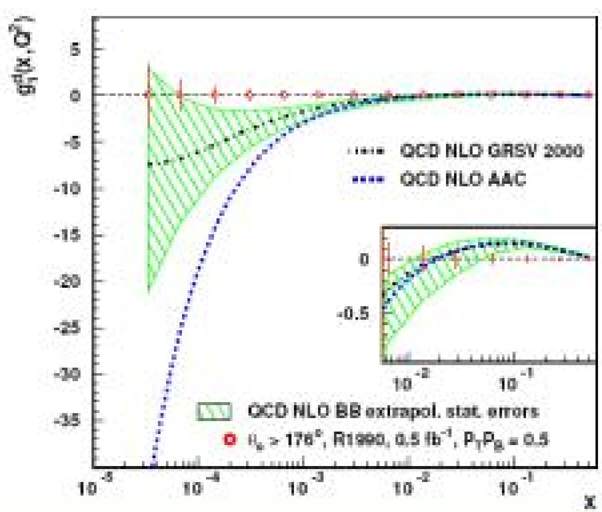
- $d, \vec{d}, {}^{16}O, {}^{40}Ca, Hg$ with $5 pb^{-1} / A$

exploratory at lowest x - unique due to high beam energies



proton





$\vec{e}\,\overleftarrow{N}$

small asymmetries at low x
require huge statistics
→ Sources
→ HERA Lumi upgrade

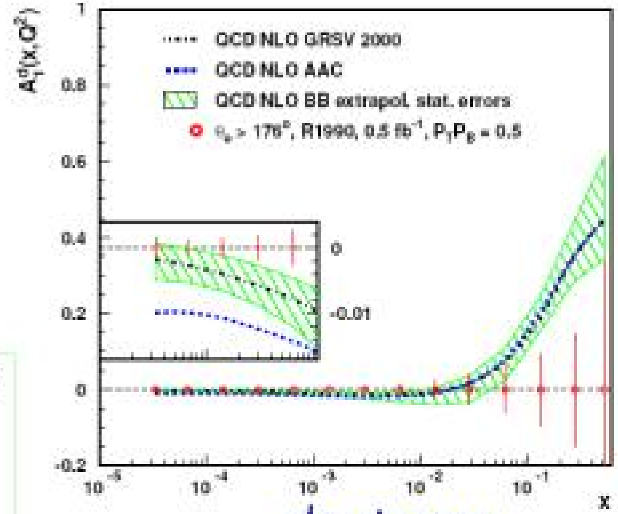
large asymmetries in CC

(also interesting for
transversity - cf R.Jakobs
MPI workshop Dec 02)

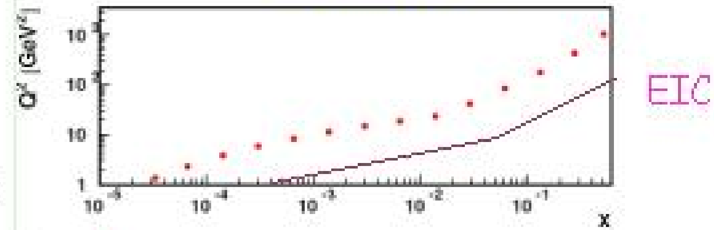
heavy flavour
diffraction
Searches

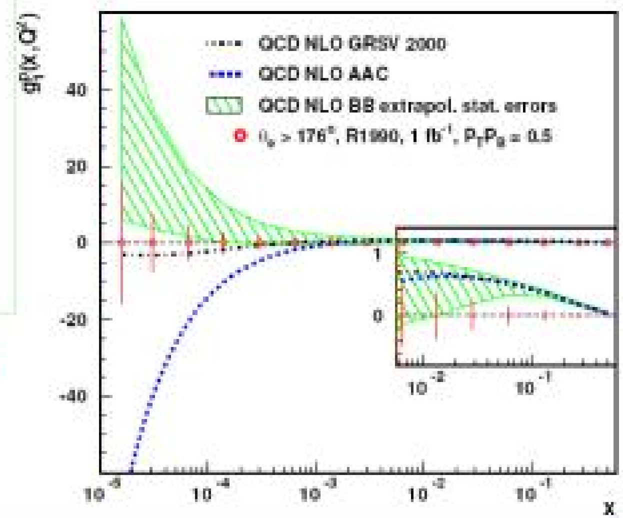
high rate to trigger

A polarised collider is the next step to explore the proton's spin composition

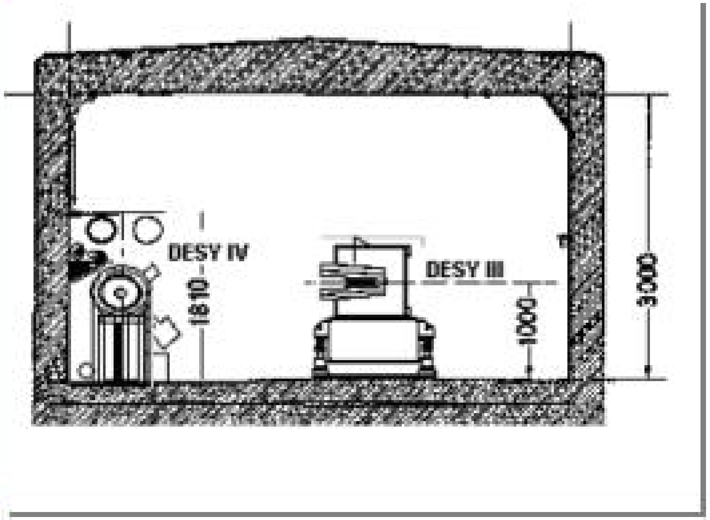


deuteron





HERA beyond 2007 - possible new injectors



Possible site for a new HERA p-injector

Preliminary ideas:

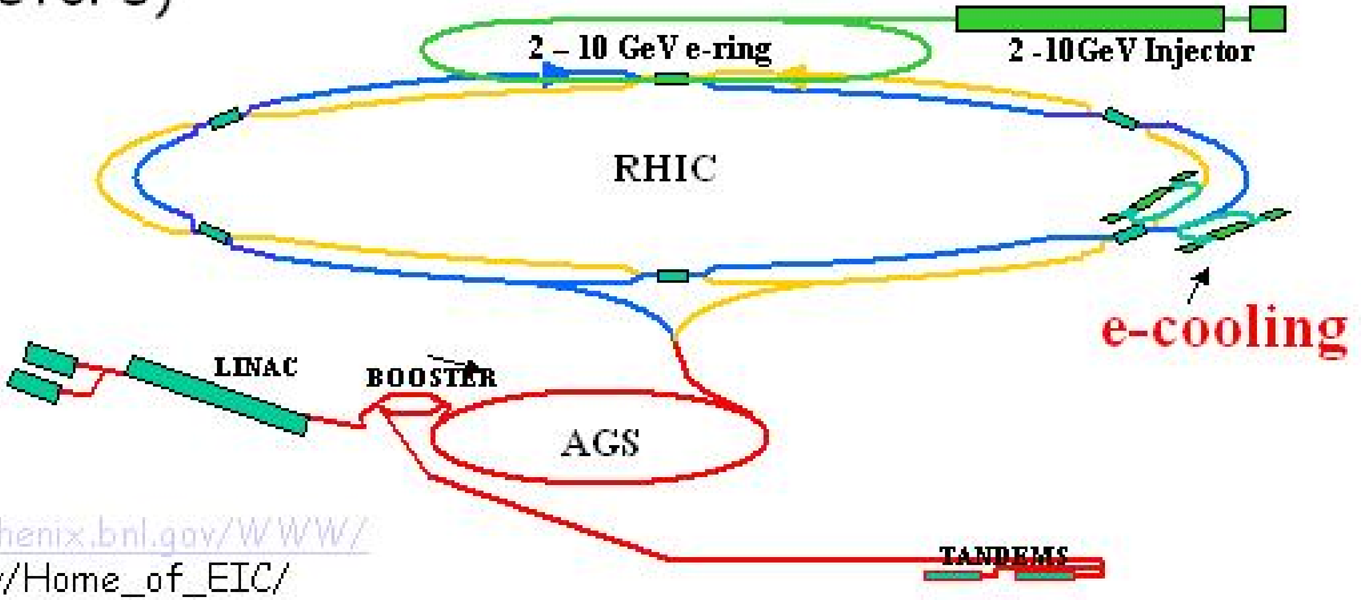
- Direct injection from DESY II into HERA-e (alternatively via a damping ring in the DESY tunnel)
- New tunnel for DESY III and a new superconducting 40GeV Proton Booster

→ Needs more study to assure feasibility & determine costs

Design study carried out by HERA III users envisioned

2-10 x 250 GeV2 eRHIC layout 4 10^32 cm-2s-1

- Collisions at 12 o'clock interaction region
- 10 GeV, 0.5 A e-ring with ¼ of RHIC circumference (similar to PEP II HER)
- Inject at full energy 2 - 10 GeV
- Existing RHIC interaction region allows for typical asymmetric detector (similar to HERA or PEP II detectors)



http://www.phenix.bnl.gov/WWW/publish/abhay/Home_of_EIC/

•R.Milner at DIS04

8. ep Scattering in the TeV Region

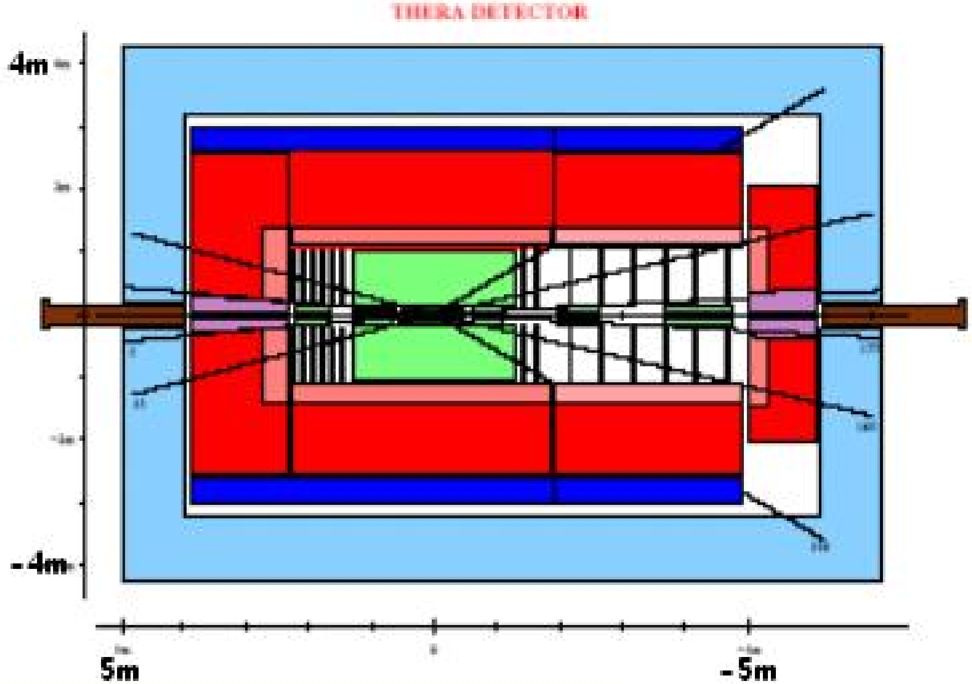
DESY 01-123F vol. 4
DESY-LC-REV-2001-062
December 2001

Physics and Experimentation at a Linear Electron–Positron Collider

Volume 4: The THERA Book. Electron–Proton Scattering at $\sqrt{s} \sim 1$ TeV

e

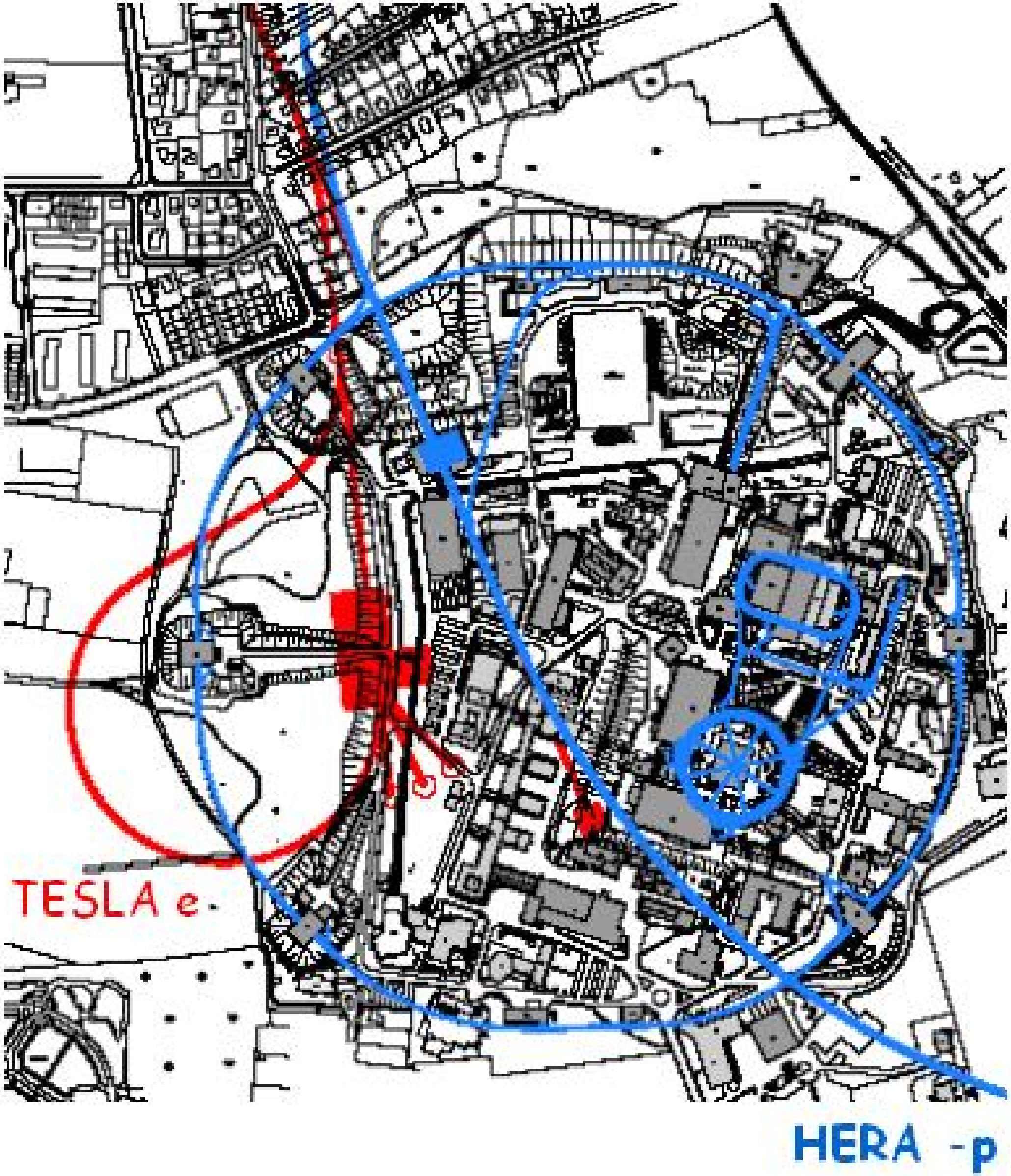
250-800 GeV



p

400-1000 GeV

Editors: U. Katz, M. Klein, A. Levy and S. Schlenstedt



√s up to 2TeV
x down to 10-6 in DIS region

e can be highly polarised
→ LQ spectroscopy

Luminosity up to 4 10^31
depending on Ee=Ep
and IR layout (dynamic focus)
note: I(e) is constant with time
[40 .. 200 pb-1 per year, 50%]

Cavity should be cold:
-standing wave type: acc. in
both directions to double E(e)
-time structure of few 100ns fits
to HERA and Tevatron bc time

→ THERA or TESLA-Tevatron

9. Remarks

Deep Inelastic scattering has made an enormous development over the past decades, in particular due to HERA, H1 and ZEUS.

The Physics at HERA is by far not exploited and vital elements of QCD need to be developed further. This already lead to completely unforeseen new developments [low x physics, hard diffraction, GPD's].

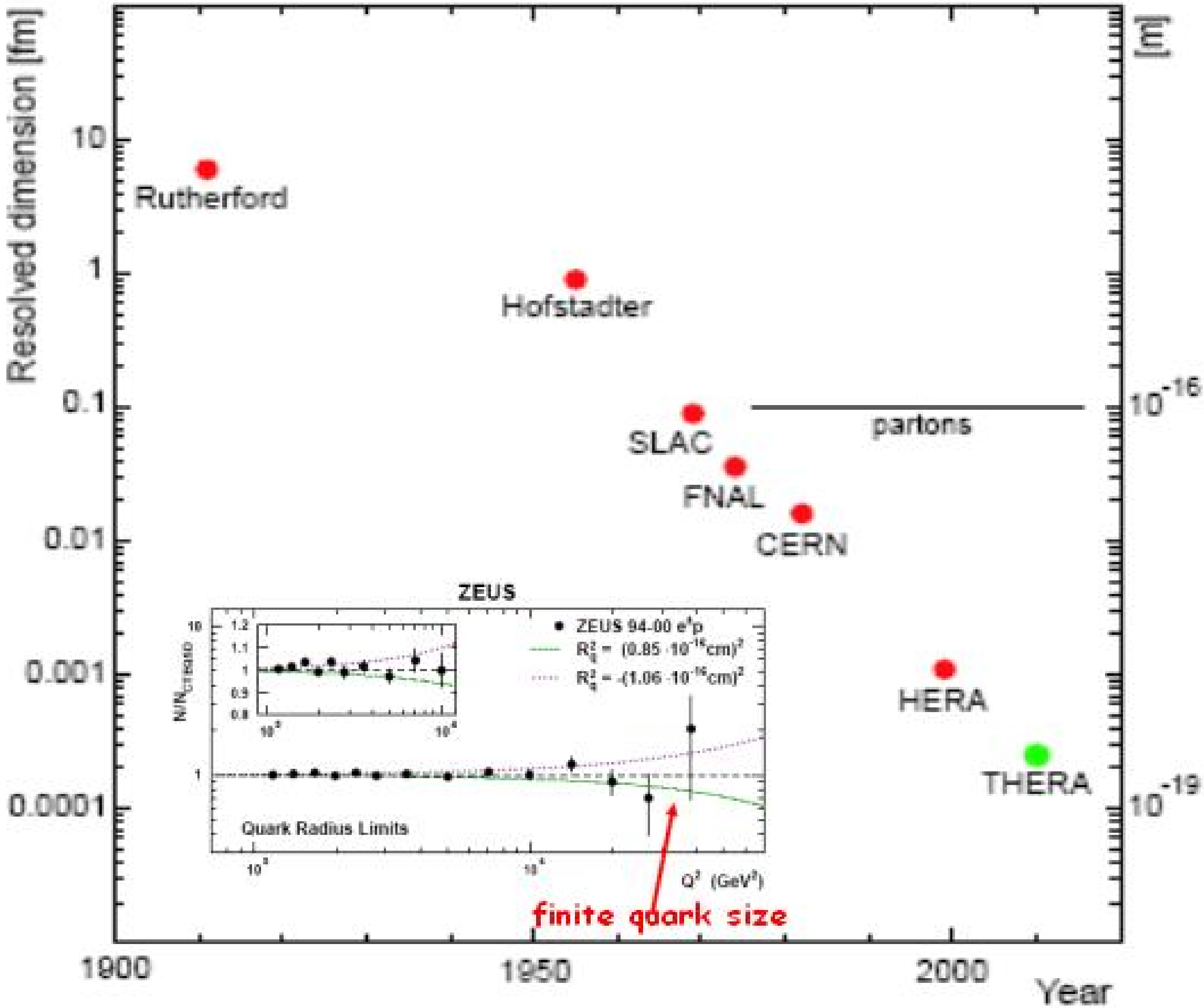
With high luminosity and further improved accuracy, HERA may still radically change our view on the smallest structure and find sth. BSM.

Non perturbative phenomena [sea asymmetry, instantons, odderons,PQ,..] and the transition to the DIS region are still to be explored.

If HERA operation would end in 2007, it would be the only DIS experiment which did neither change the beam energy (low Ep?) nor the nucleon type. The loss in investment and physics is huge and quantified.

The physics at the TeV scale is richer than the Higgs search and a TeV energy ep collider a neccessity to develop QCD and parton theory and to maintain the e+e-, pp and ep symbiosis which established the SM and will overcome it by a more profound theory. This has to include QCD.

100 years of exploring the inner structure of matter



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