Deep Inelastic ep Scattering at High Energies

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H1 and ATLAS

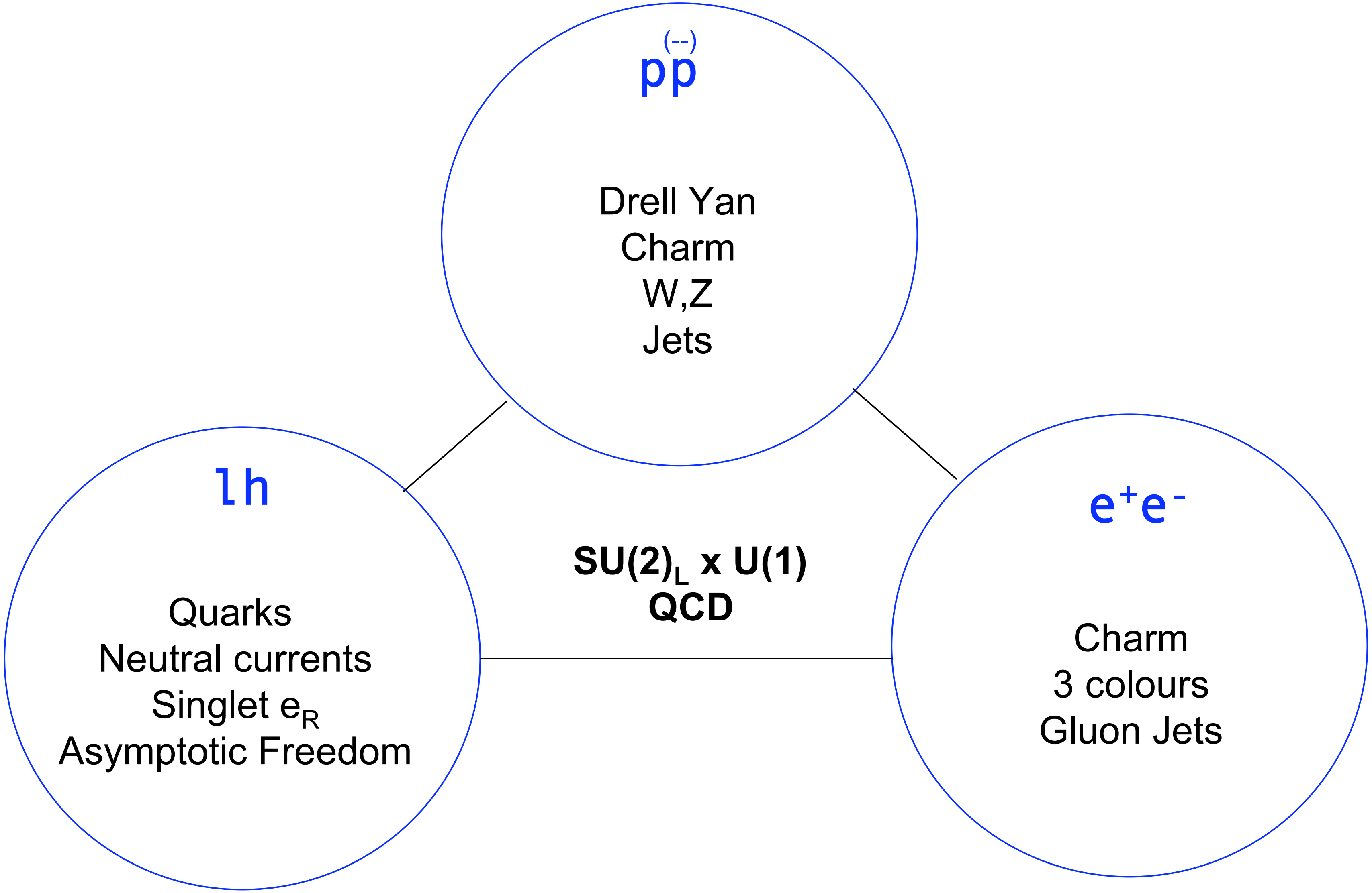
From the **H**och-**E**nergie-**R**ing-**A**nlage to the **L**arge **H**adron **e**lectron **C**ollider

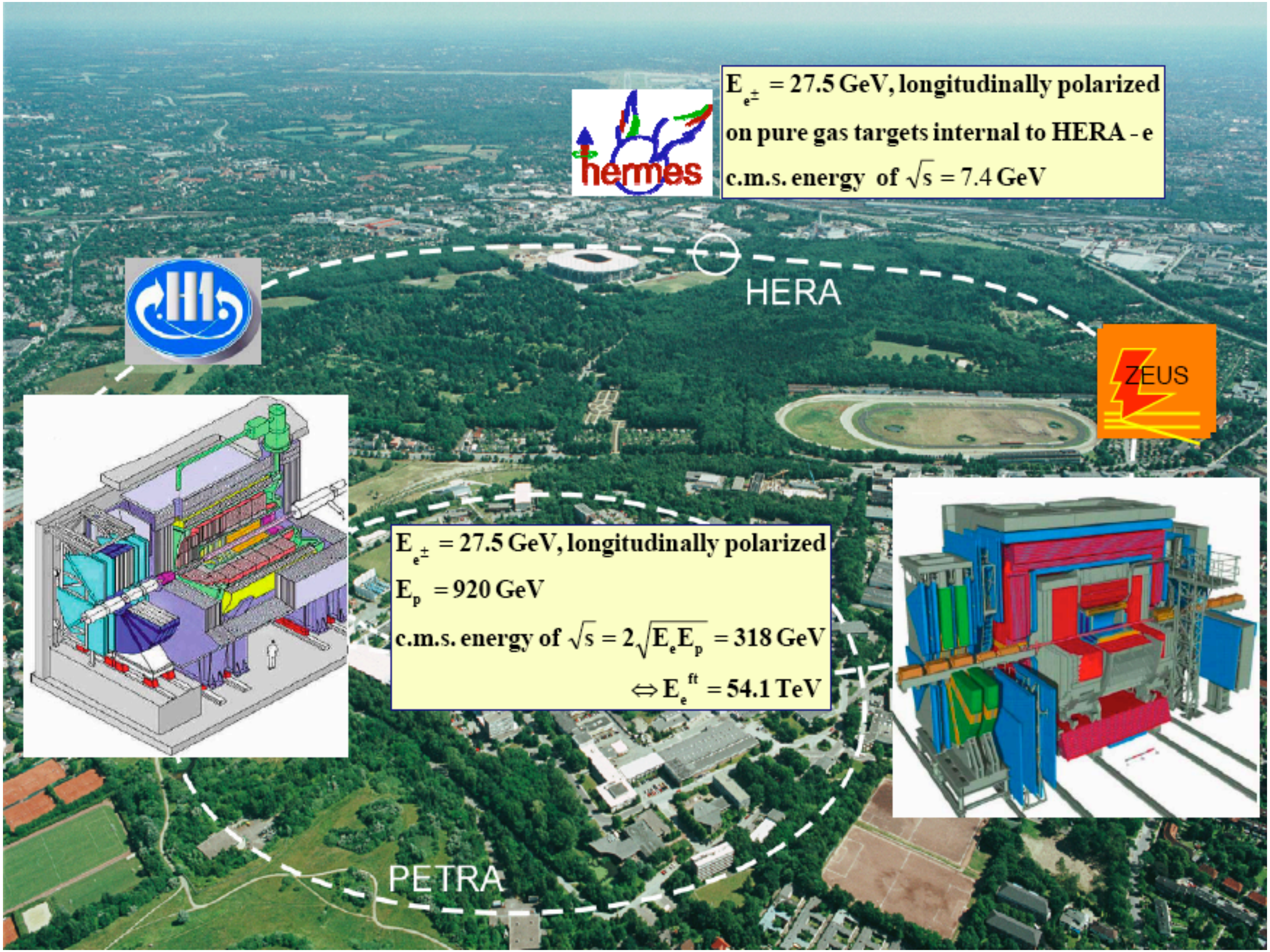
"Now we are entering the post-TeV era, jumping not one but two orders of magnitude to a lab equivalent of order 50 TeV at HERA. If the LHC is successfully commissioned in the LEP tunnel in 1997, then we may hope to see collisions between electrons from LEP and protons from the LHC in the next millenium giving a lab equivalent around 10^3 TeV (1 PeV). "

F.Close Singapor 1990

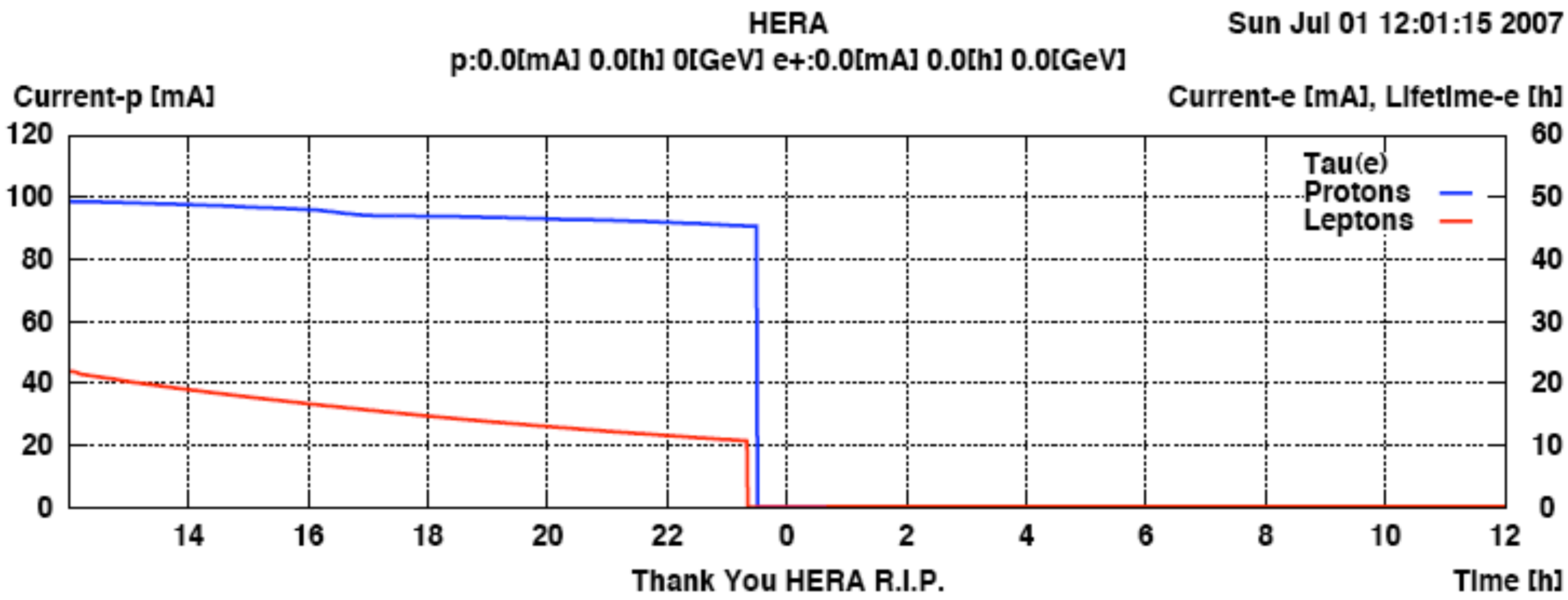
Seminar at the University of Manchester, January 30th , 2008

The 10-100 GeV Energy Scale [1968-1986]




hermes
$E_{e^\pm}$ = 27.5 GeV, longitudinally polarized
on pure gas targets internal to HERA - e
c.m.s. energy of $\sqrt{s}$ = 7.4 GeV
HERA
ZEUS
$E_{e^\pm}$ = 27.5 GeV, longitudinally polarized
E_p = 920 GeV
c.m.s. energy of $\sqrt{s} = 2\sqrt{E_e E_p}$ = 318 GeV
$\Leftrightarrow E_e^{ft}$ = 54.1 TeV
PETRA

HERA’s last day



HERA did end with a 3 month operation at reduced proton beam energies in order to measure the longitudinal proton structure function directly, which provides a crucial test of QCD at higher orders and an independent measure of the gluon density at low x.

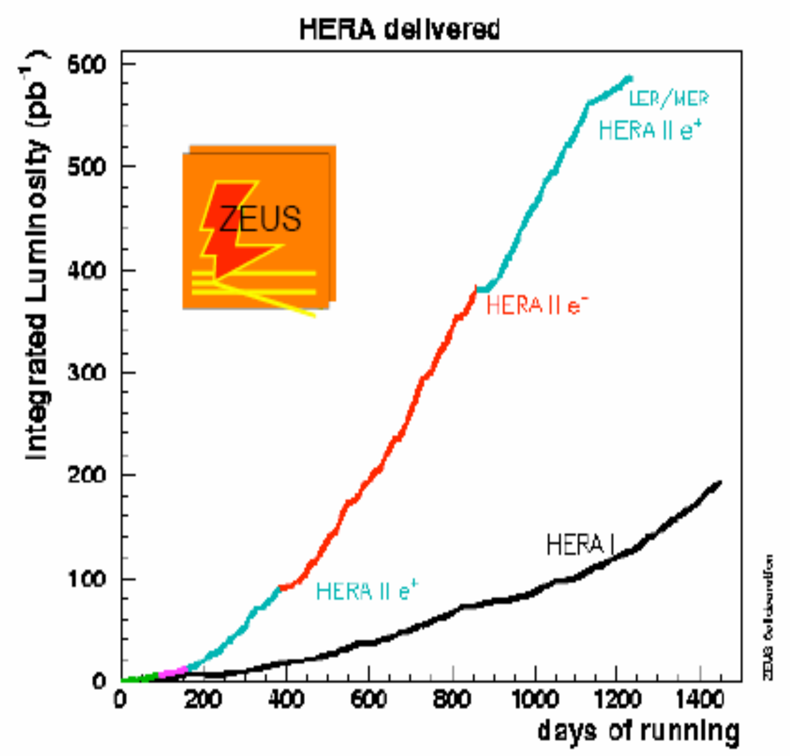
HERA Performance

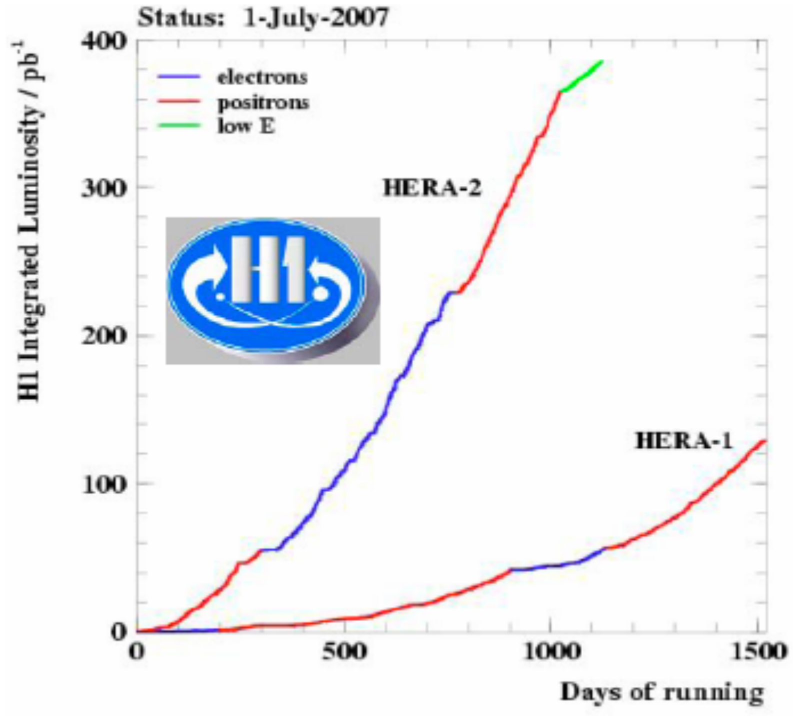
About 1 fb^{-1} collected data

	for H1	+ ZEUS	
high E	478	496	pb^{-1}
575 GeV	6.5	7.8	pb^{-1}
460 GeV	12.3	13.2	pb^{-1}

F_L

HERA I : 1992-2000
HERA II: 2003-2007



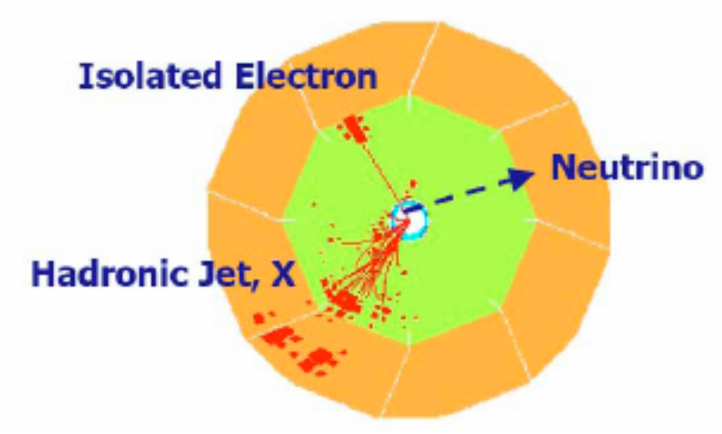


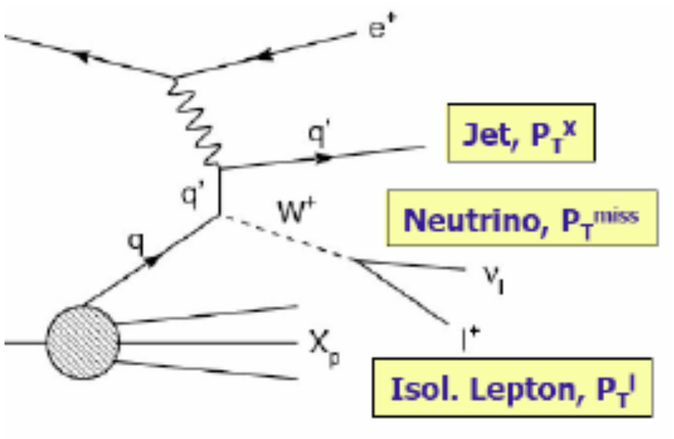
Two years of fight for HERA's existence (2002/2003) in what was called 'upgrade'..

The most puzzling observation (for long)

$p_T^X > 25$ GeV

	H1+ZEUS
e^+p (0.58 fb^{-1})	**23/14.6±1.9**
e^-p (0.39 fb^{-1})	**6/10.6±1.4**





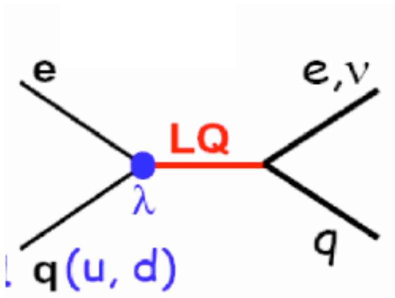
H1 still sees excess (2.9σ) in e^+p data
and ZEUS does not

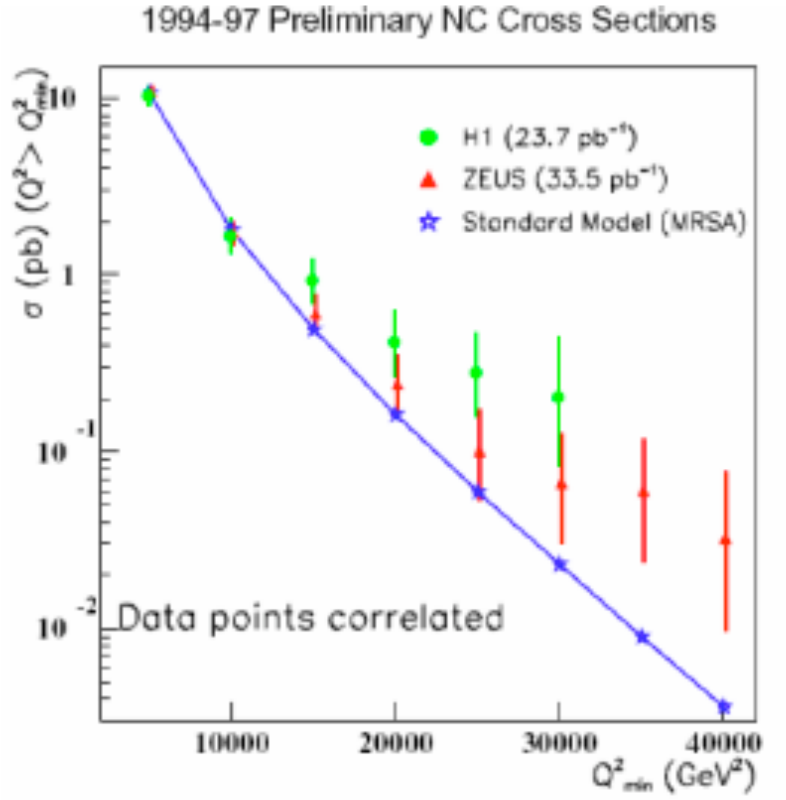
Consistency of experiments: 2σ

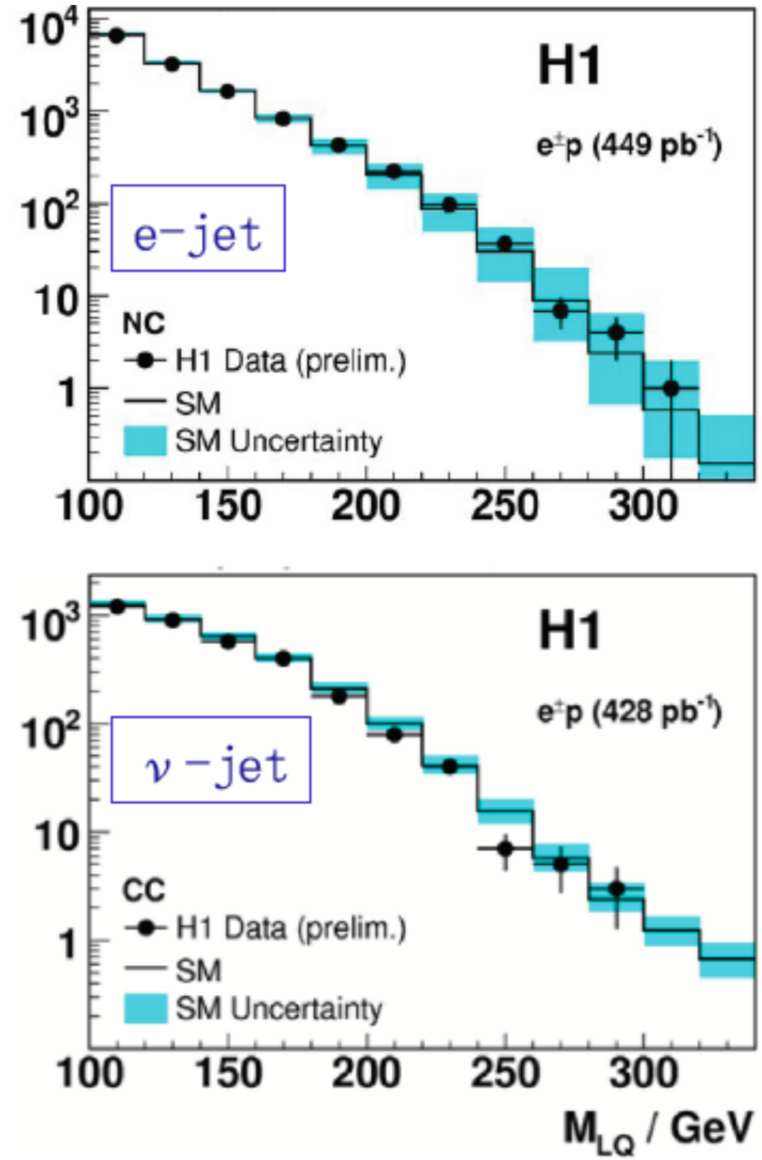
Combined significance of excess 1.8σ

The most spectacular fluctuation

EPS07

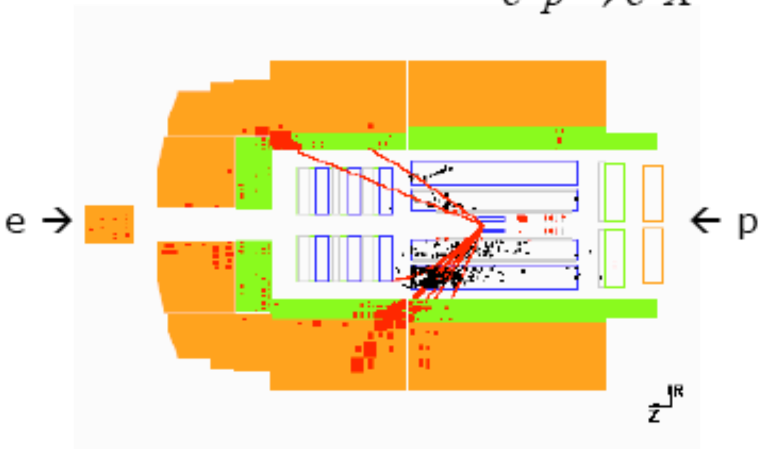




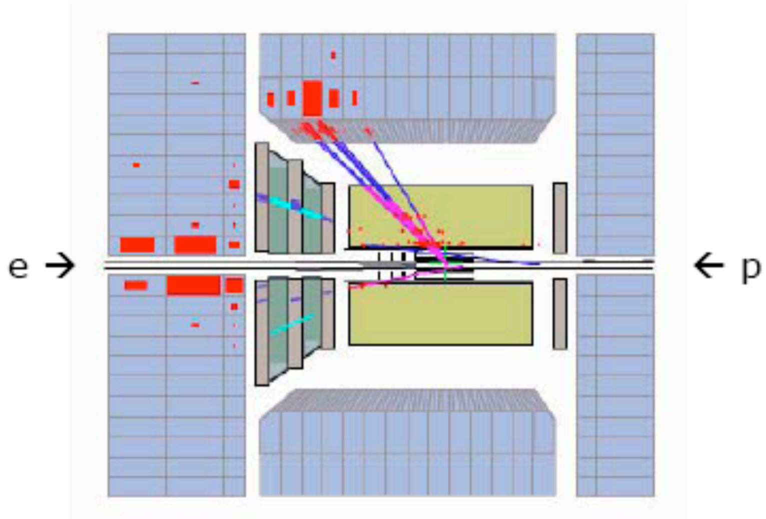


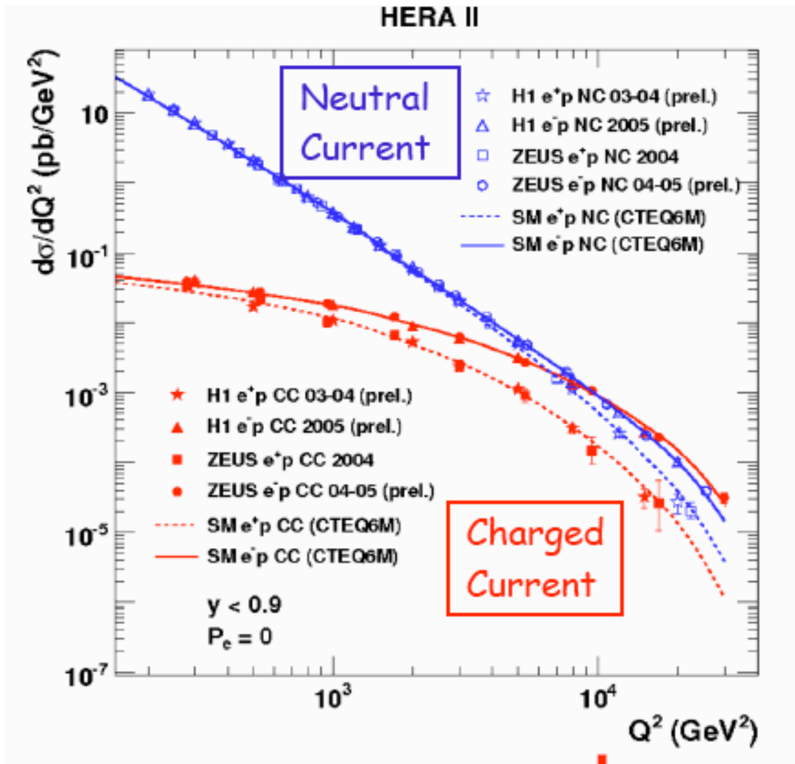
Weak and Electromagnetic Interactions

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



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

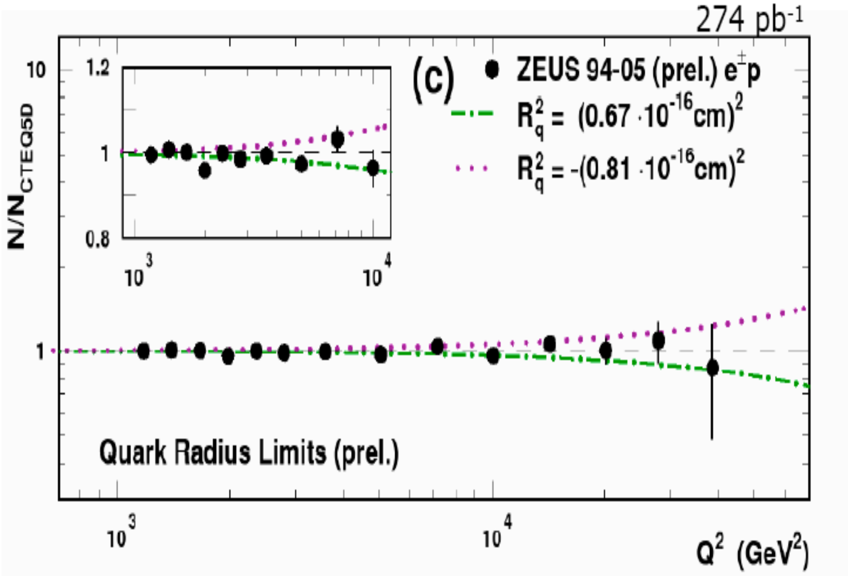




$$\sigma^{\pm}_{NC} \approx \sigma^{\pm}_{CC} \leftrightarrow Q^2 \approx M_Z^2 \approx 10^4\,\mathrm{GeV}^2$$

A major question in the early 80ies, would the weak and the electro-magnetic interactions “unify”?

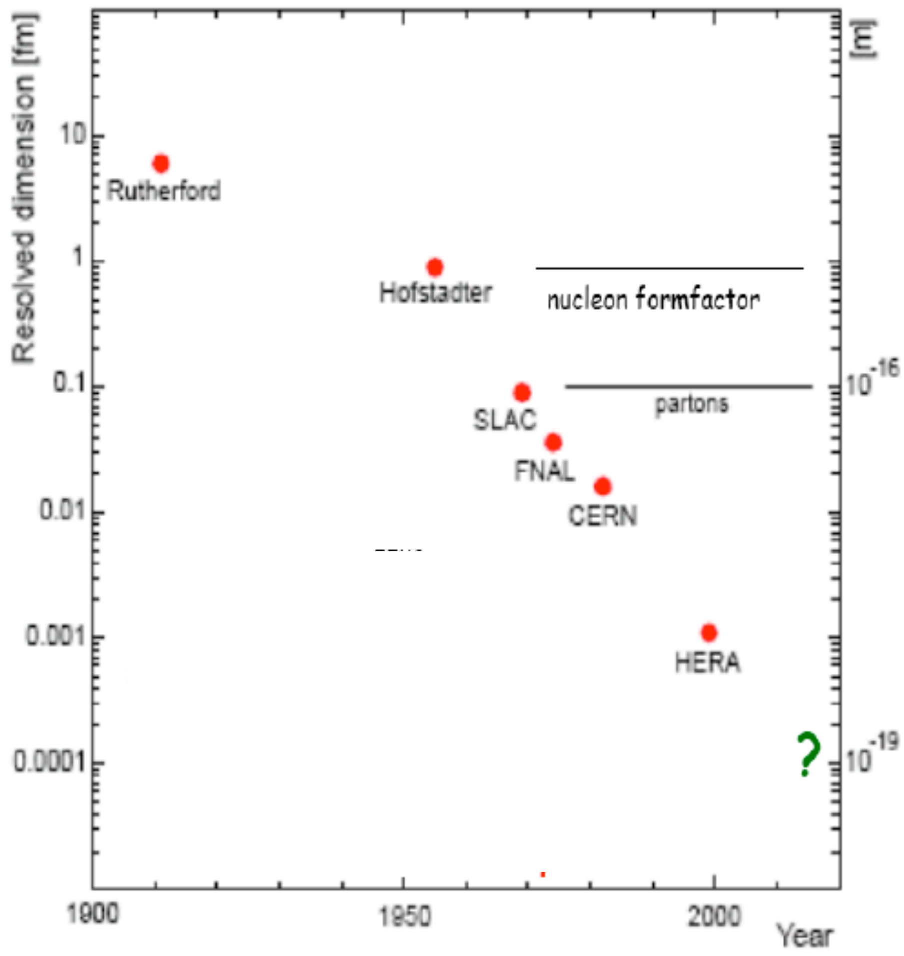
Subsubstructure of matter?



$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2}\left(1 - \frac{R_e^2}{6}\right)^2 \left(1 - \frac{R_q^2}{6}\right)^2$$

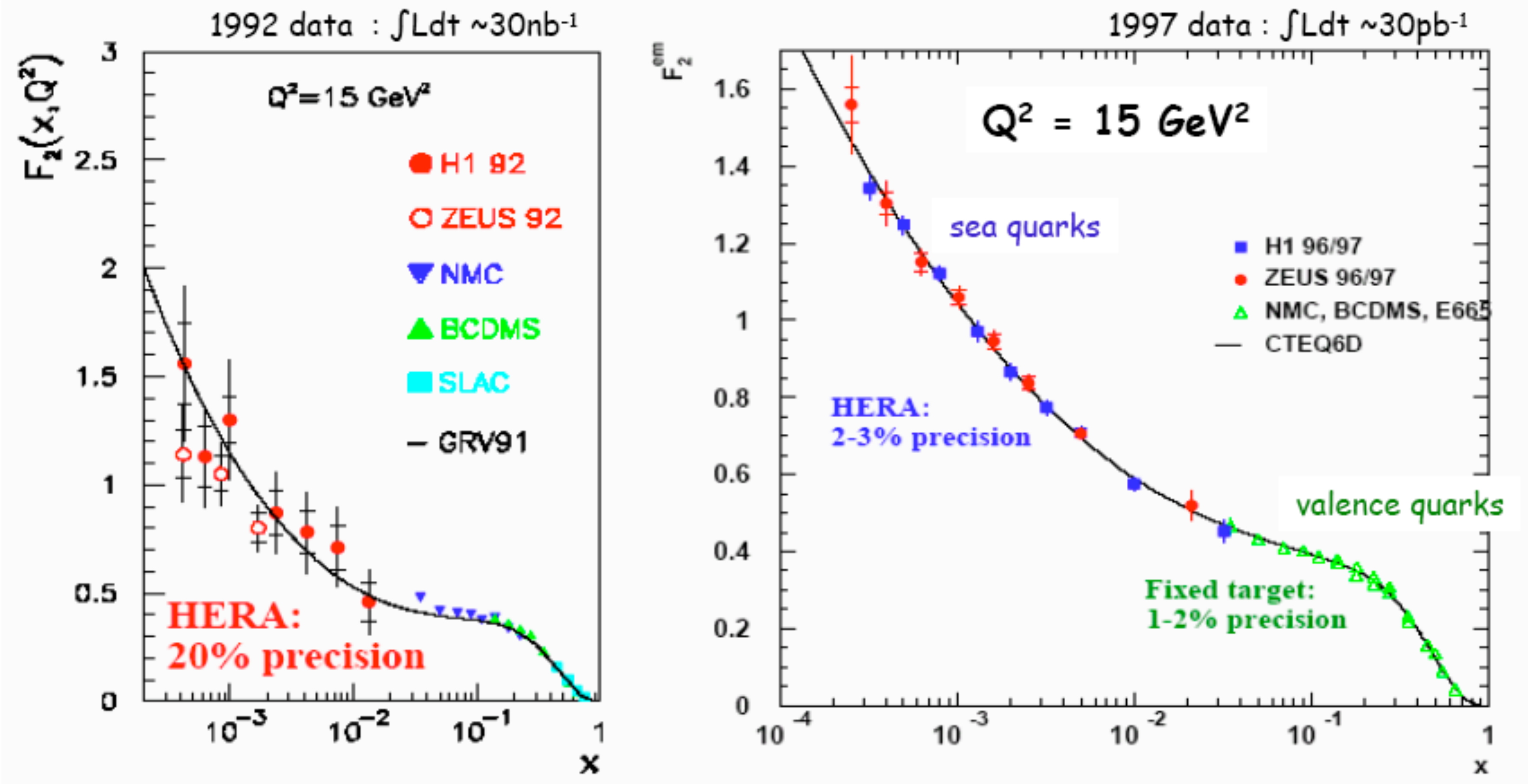
$$R_q < 0.67 \times 10^{-3}\ \mathrm{fm}$$

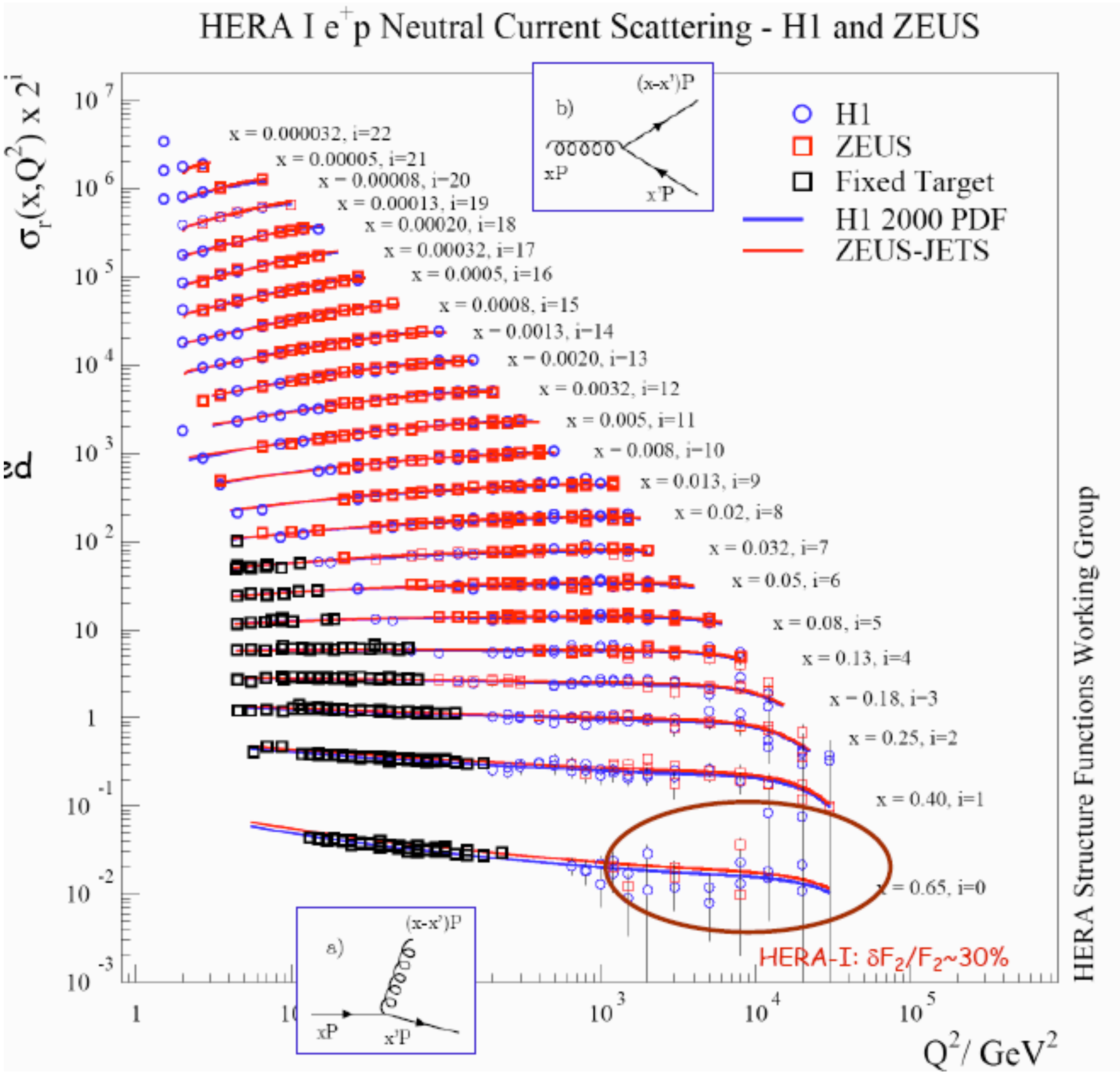
Quarks are point-like up to $0.67\text{x}10^{-3}$ fm (H1 : $0.74\text{x}10^{-3}$ fm).
No evidence of contact interactions up to limits of ~ 5 TeV.



A new phase of matter (high parton densities and small coupling)

$$F_2 = \frac{4}{9}x(U+\overline{U}) + \frac{1}{9}x(D+\overline{D})$$



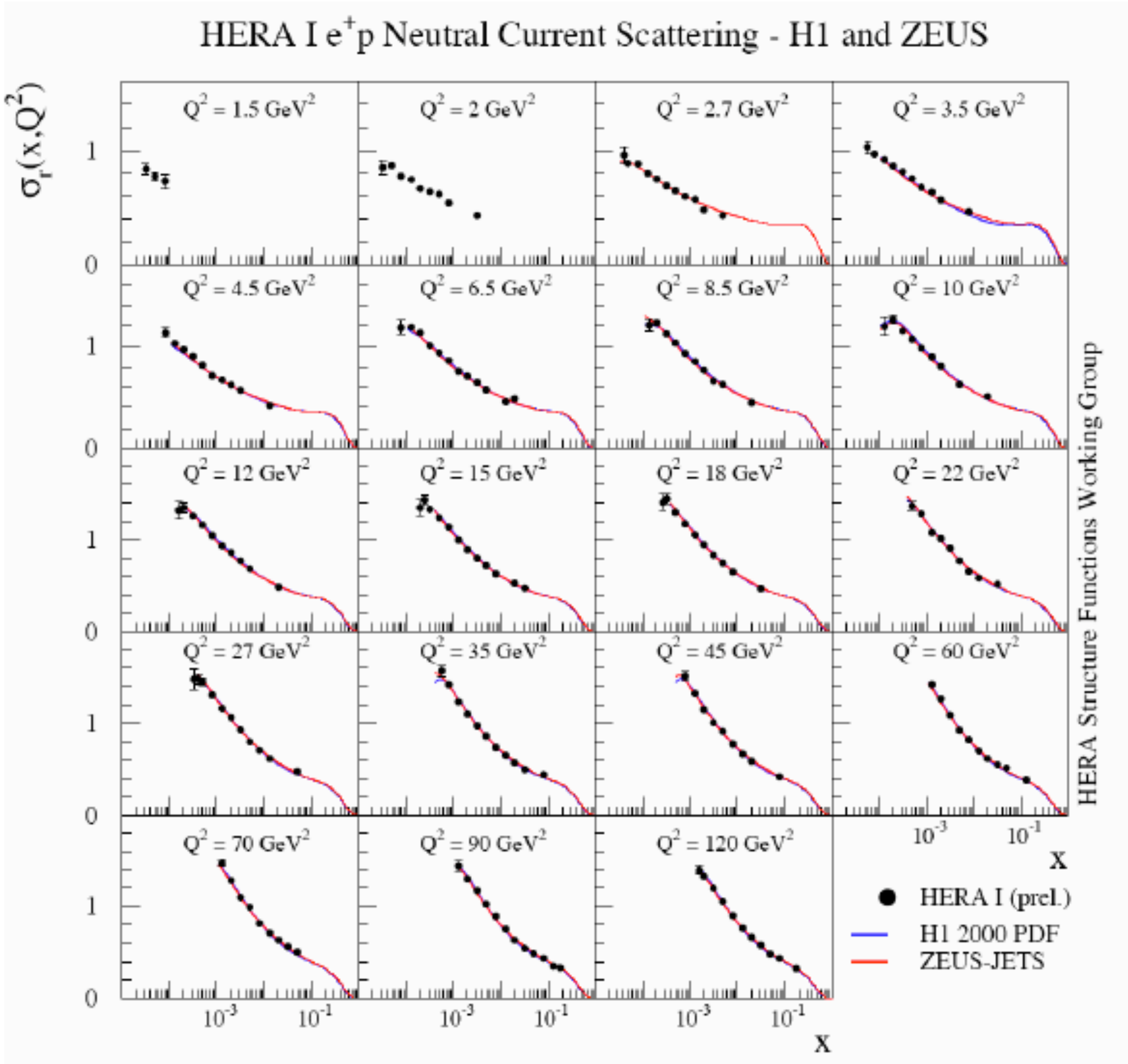


Low x is gluon dominated

HERA very precise in the LHC rapidity plateau region

You can never have enough luminosity at high x and Q2

H1&ZEUS now cooperate really



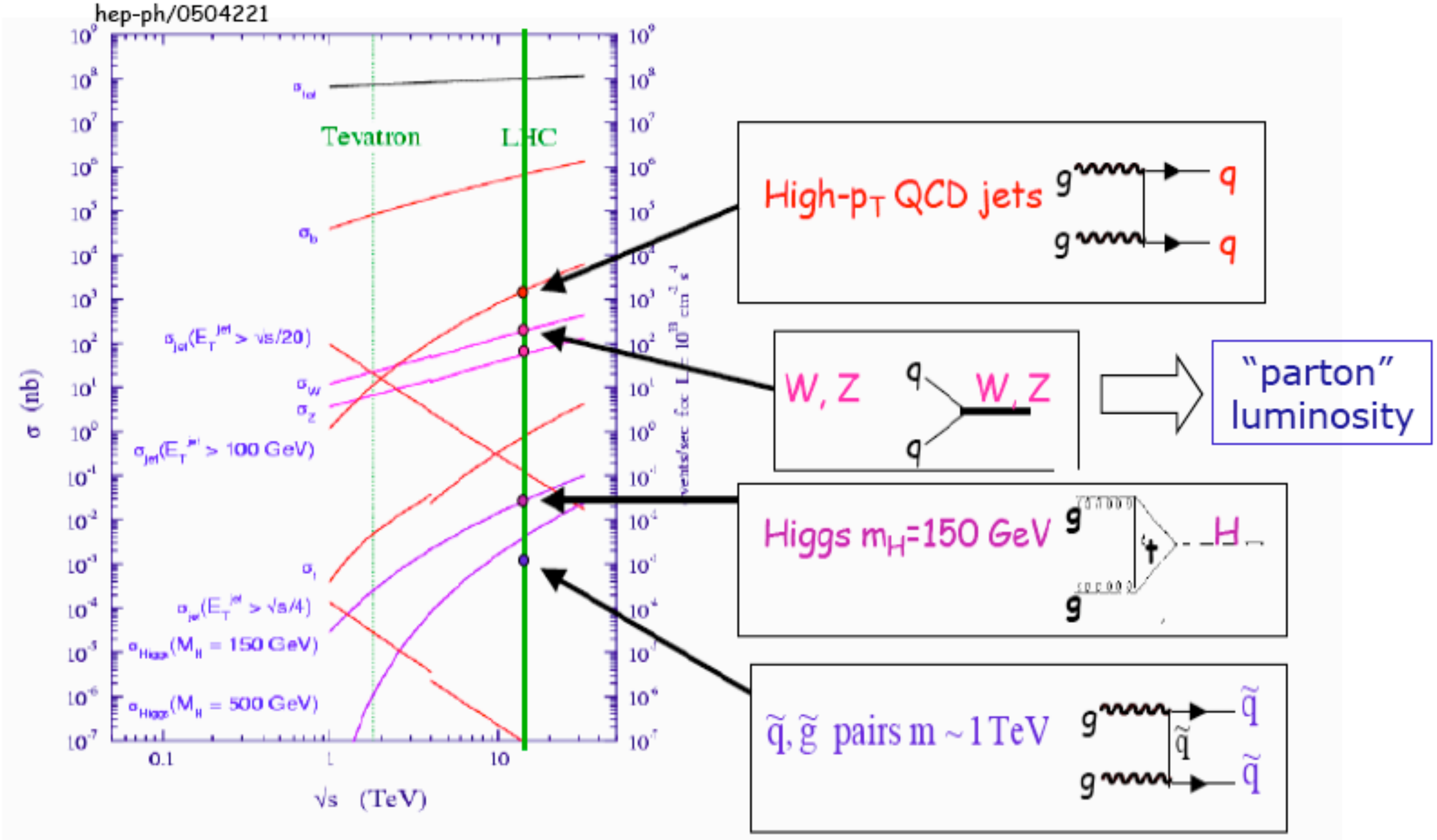
Data from H1 +ZEUS, combined, as published from HERA I

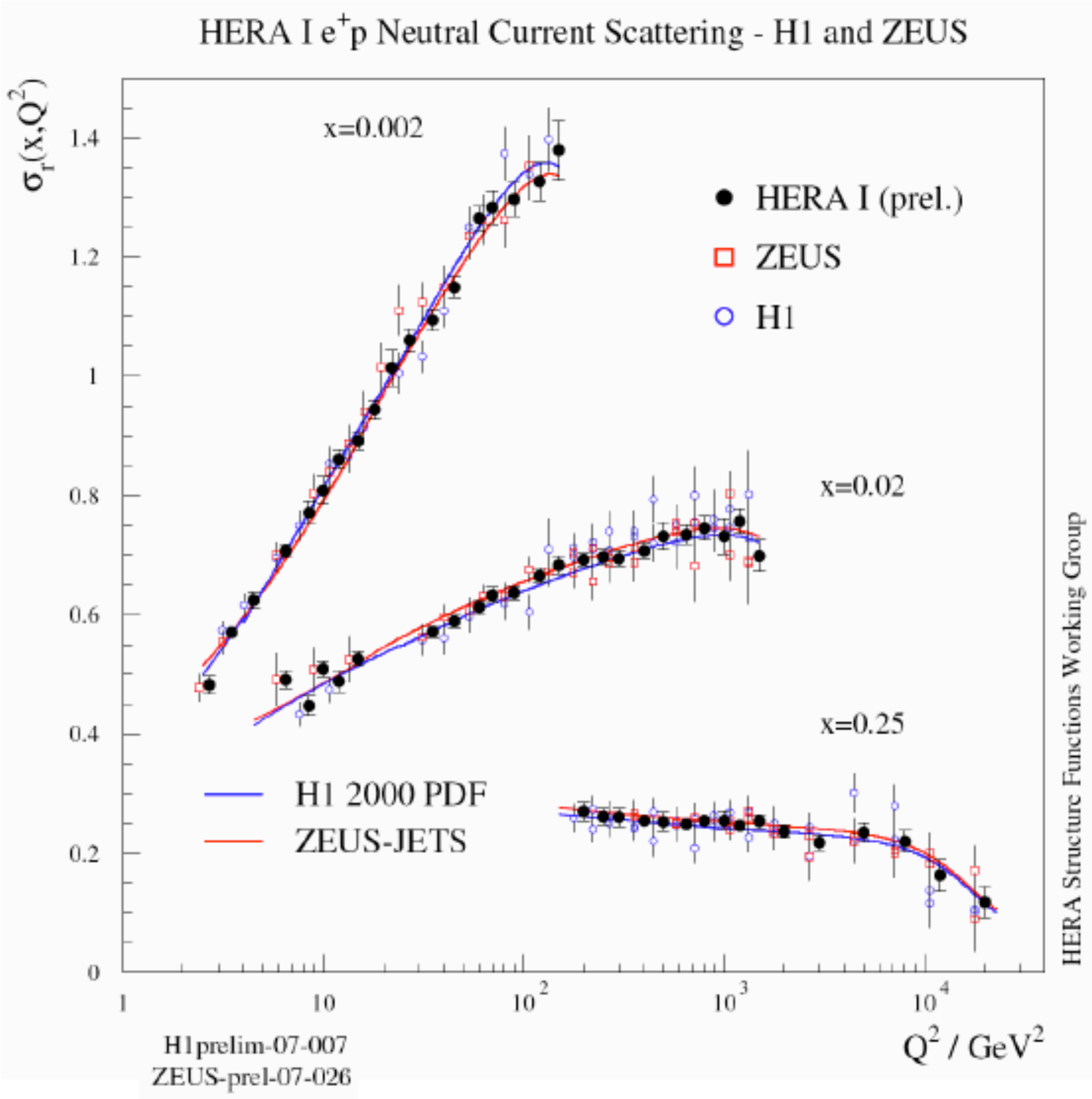
Data are consistent, with few % normalisation issues being resolved.

More recent H1 data (from 1999/2000) and HERA II still being/ to be analysed.

Final goal: 1% accuracy for bulk region, which leads to few % accuracy in the rapidity plateau for LHC [$x = 0.006 = M^2_W/s$]

The knowledge of the pdfs (HERA) is crucial for LHC





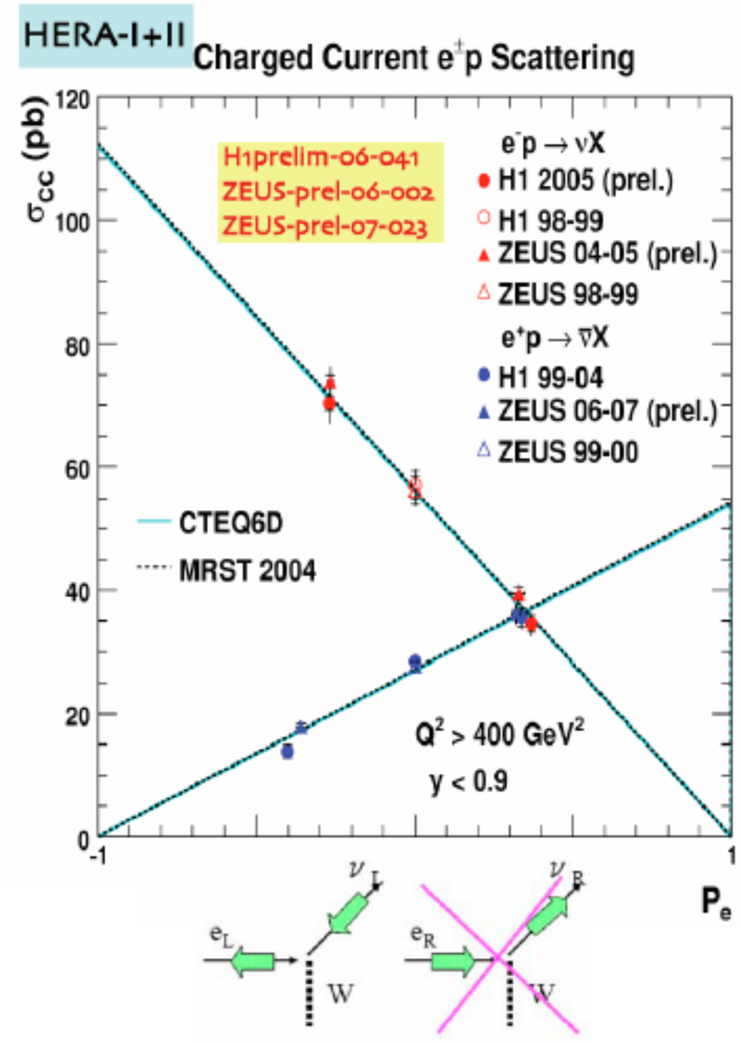
Combination of cross section measurements from joint χ^2 minimisation for optimum systematics and correct average.

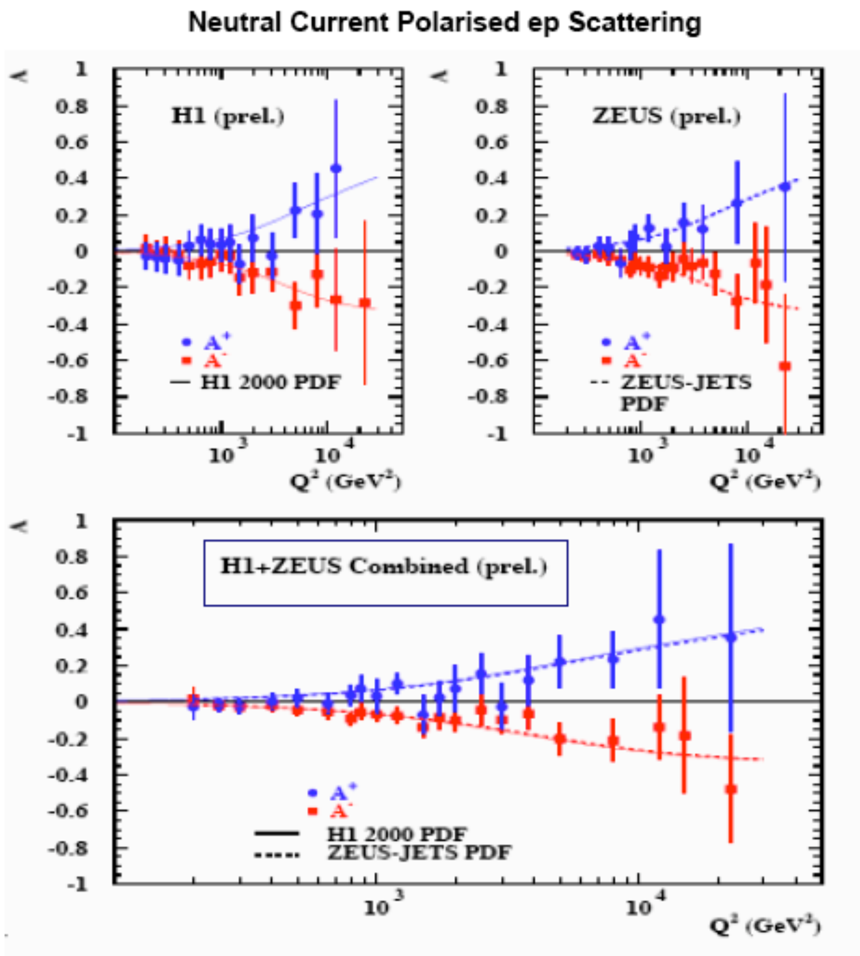
Assumes H1 and ZEUS measure the same, thus requires consistent input.

General : Such an approach leads to higher accuracy than the statistical average due to cross calibration of different detectors.

Advantage : H1 and ZEUS use different reconstruction methods.

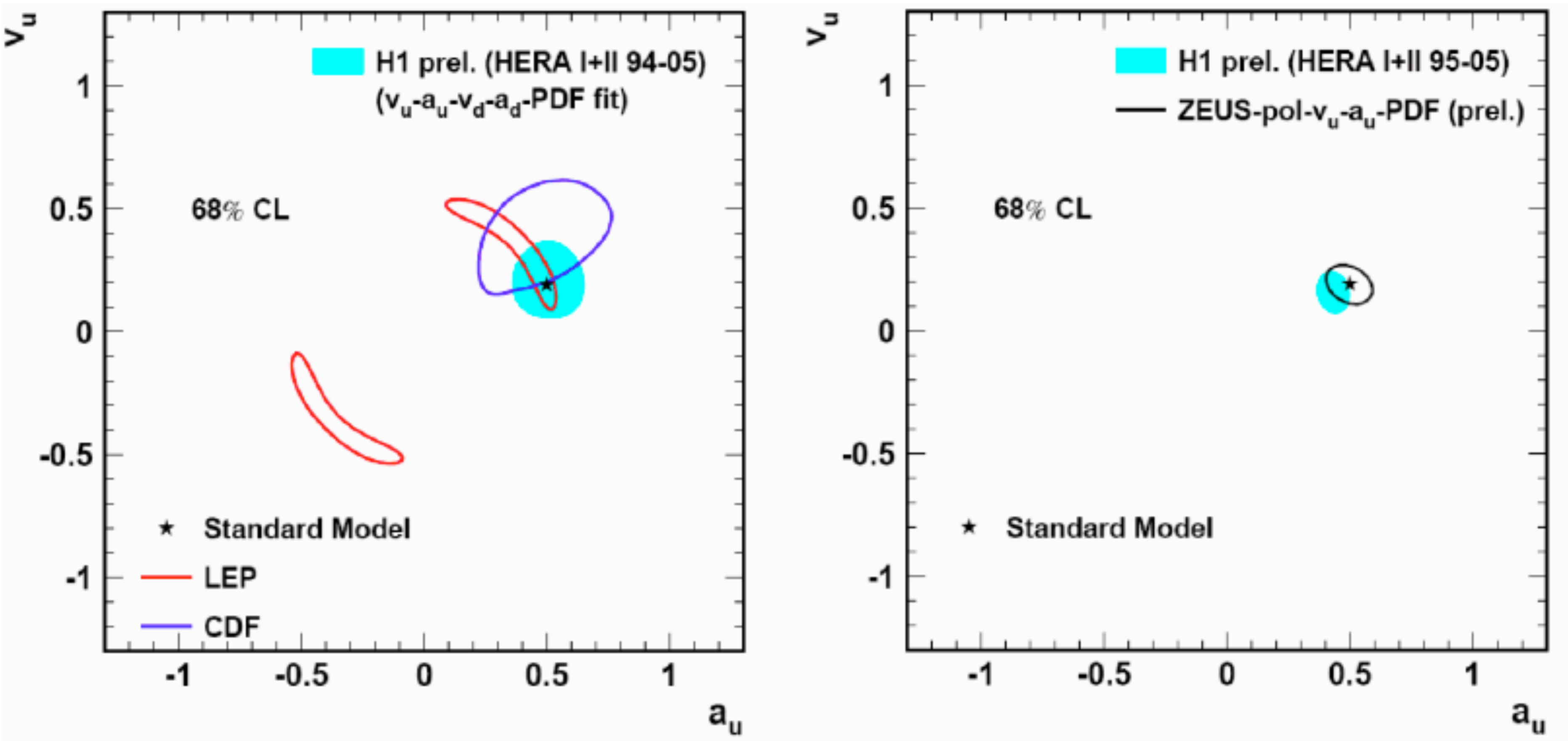
Electroweak Measurements at HERA





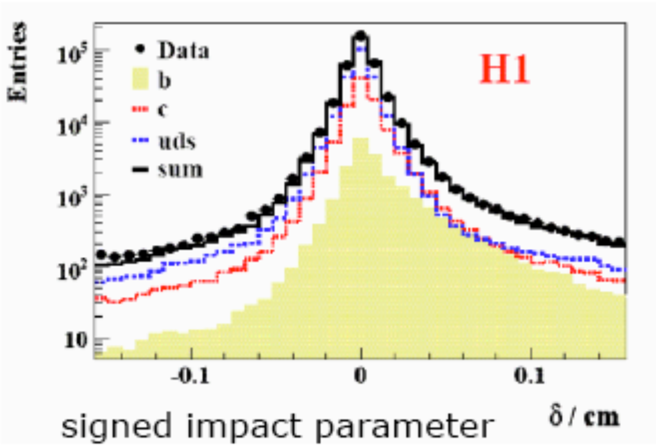
NC: parity violation at ~10^{-18} m

Fit to PDFs and u,d couplings   Fit to PDFs and u couplings *only*

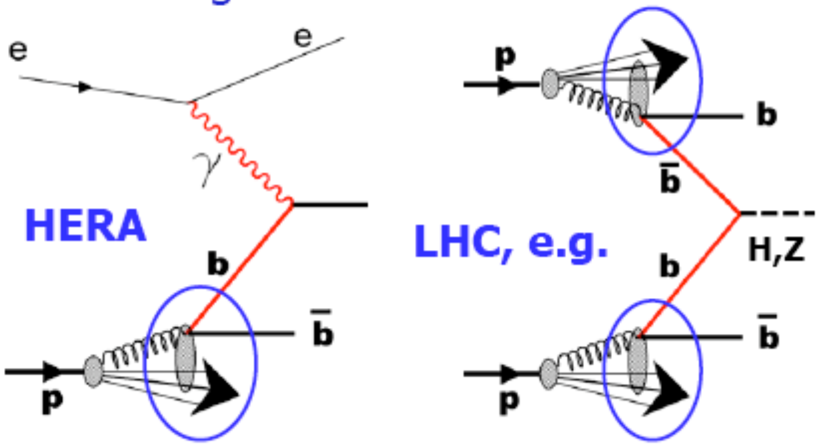


Joint NLO QCD fit of PDFs and light quark neutral current couplings
World's best precision on up quark coupling. Down competitive.
Uses so far half of HERA's data, may still improve further.

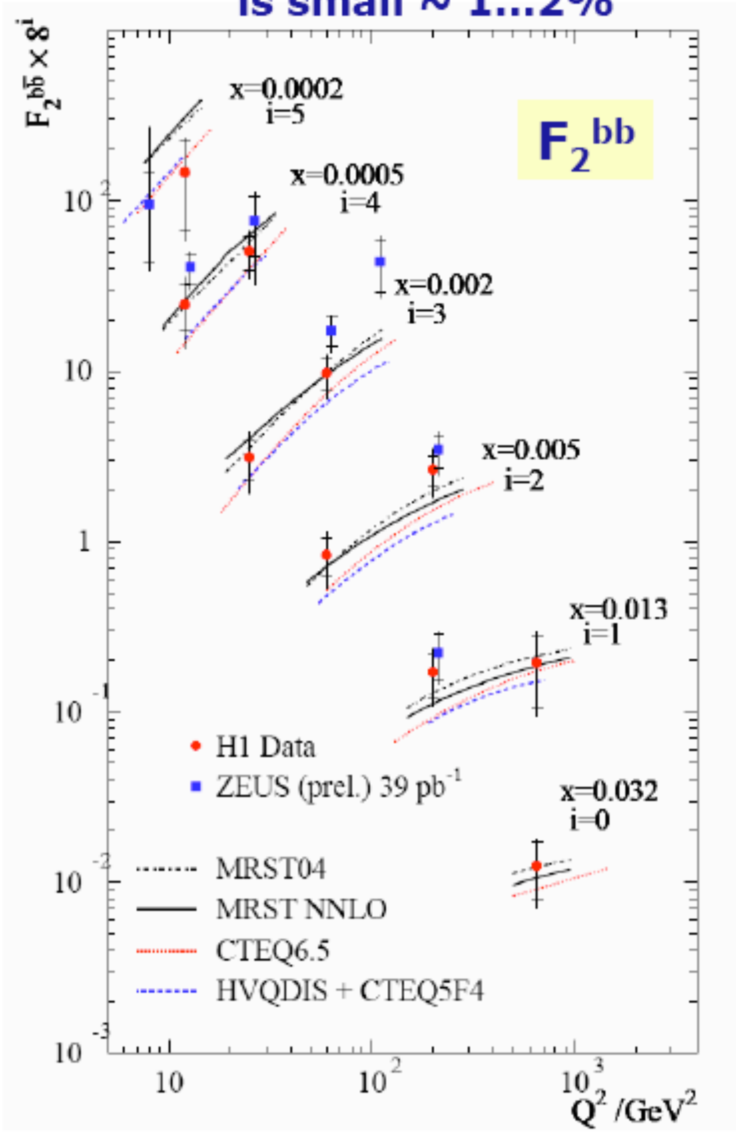
Impact parameter tagged
with Si-vertex detector



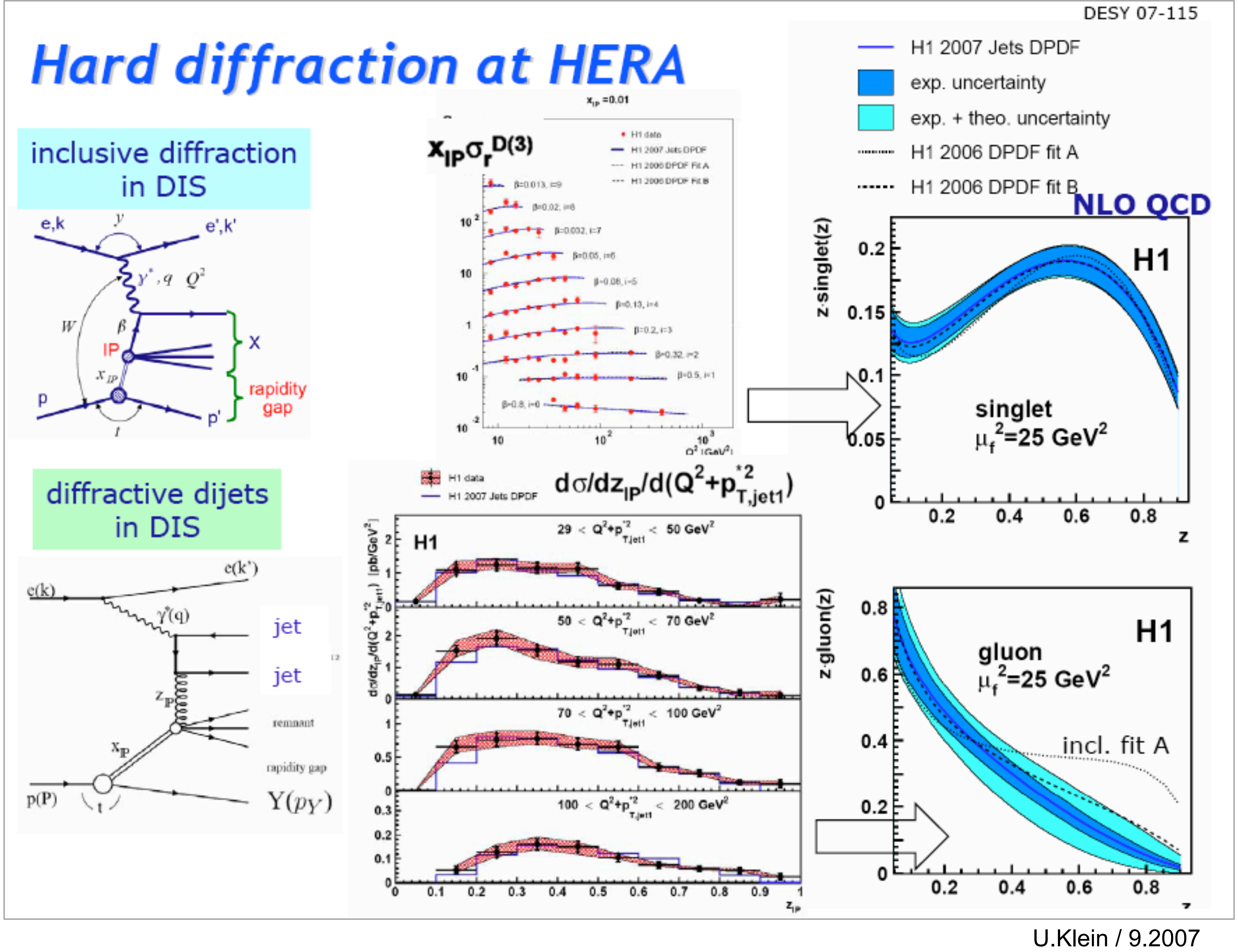
-> very promising measurements
a challenge for HERA II



Beauty contribution to F_2 is small ~ 1…2%



Hard diffraction at HERA

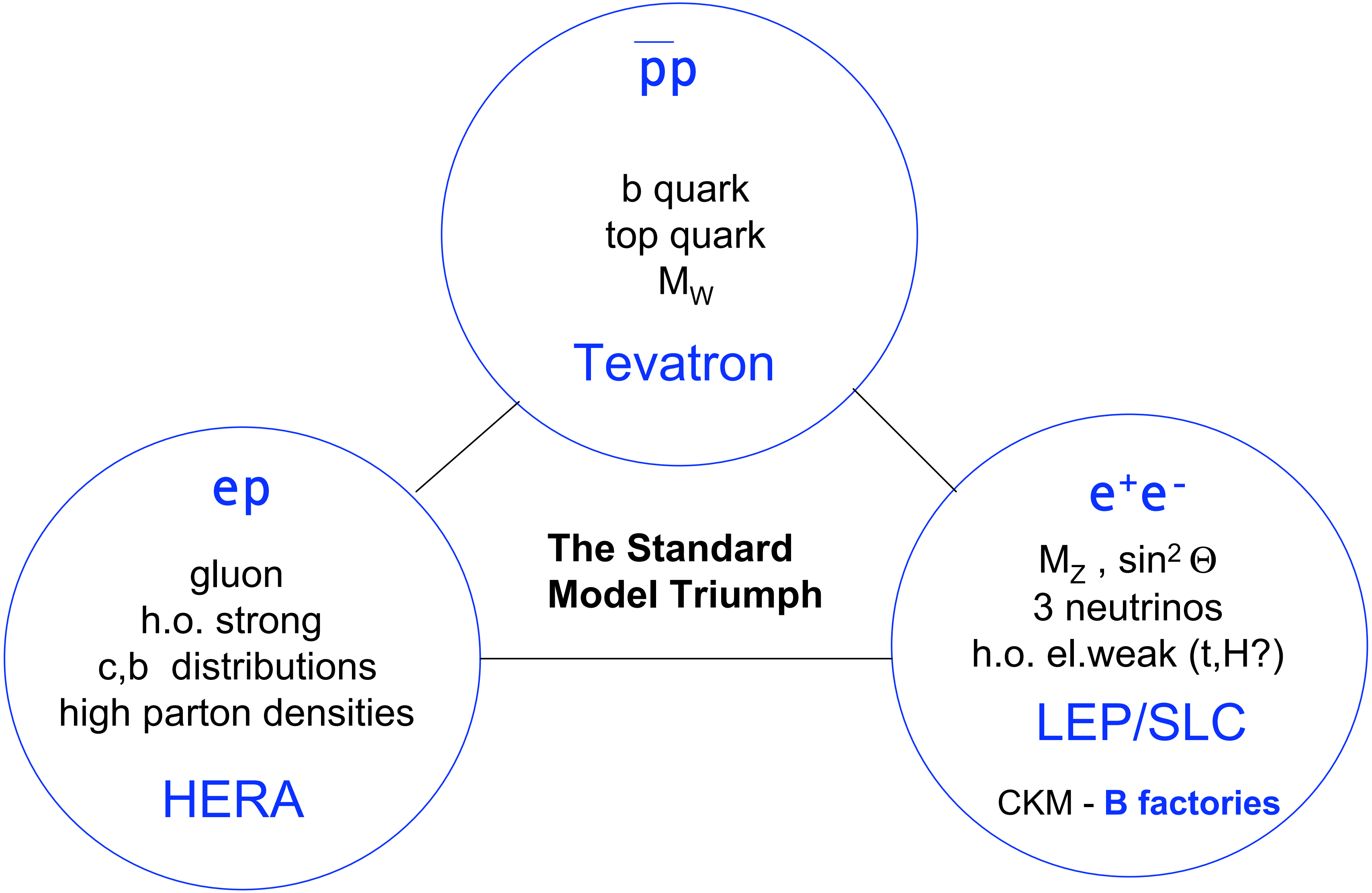


MANY more important results from HERA

Hard Diffraction (the return of the IP)
Vector Mesons
Deeply Virtual Compton Scattering (Parton Amplitudes!)
Transverse Size of the Gluon
Charm Structure Function
Jets
Strong Coupling "Constant"
Low x Parton Dynamics ("fwd jets", azimuthal decorr.'s)
Pion Structure Function
Partonic Structure of the Photon …

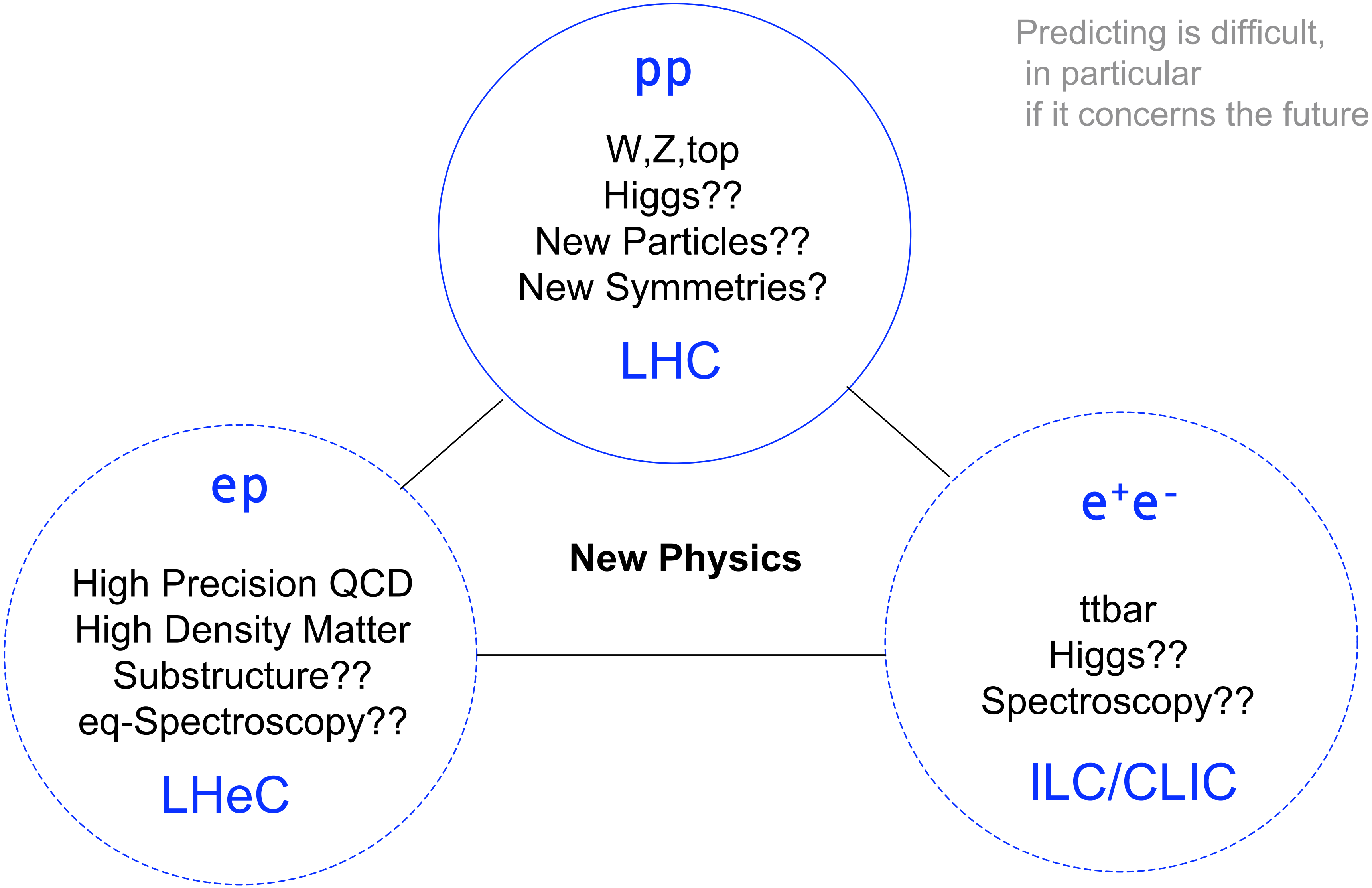
HERA has delivered much more than was expected.
The final results are being worked on (+3 years)

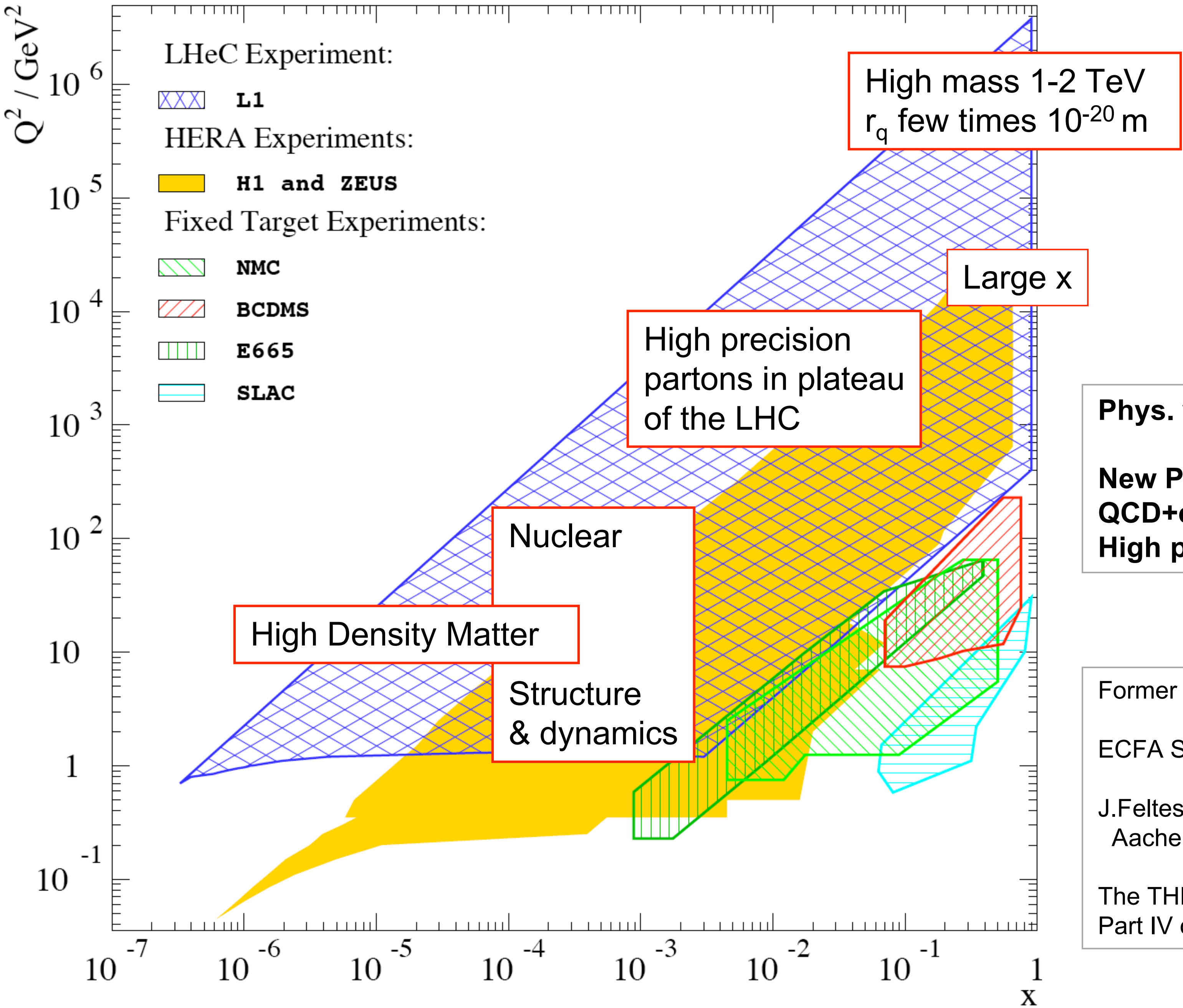
The Fermi Scale [1985-2010]



The TeV Scale [2008-2033..]

Predicting is difficult,
in particular
if it concerns the future.





Phys. working groups

New Physics
QCD+electroweak
High parton densities

Former considerations:

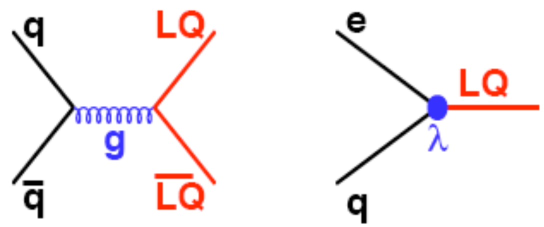
ECFA Study 84-10

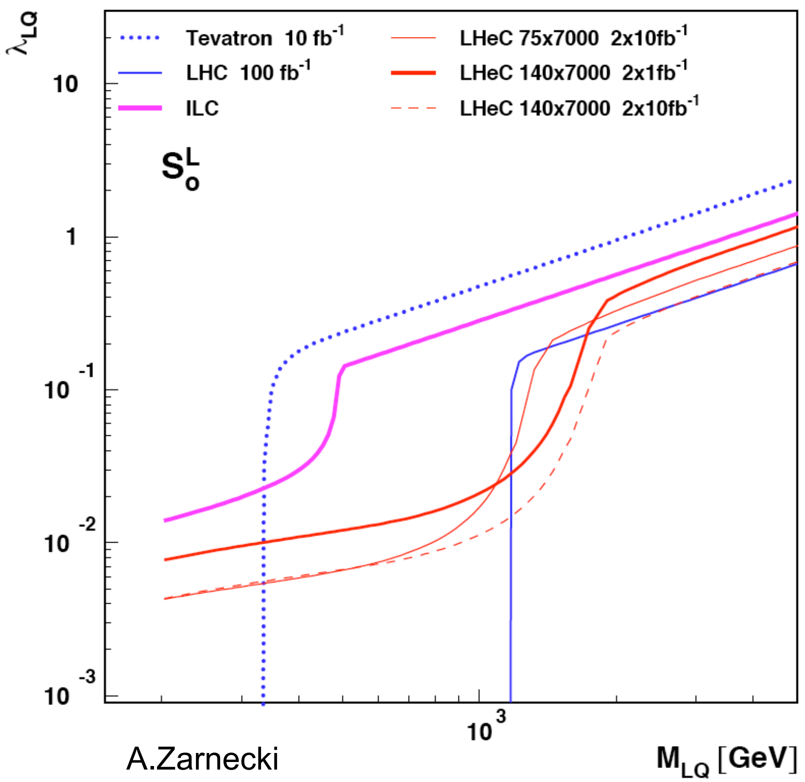
J.Feltesse, R.Rueckl:
Aachen Workshop (1990)

The THERA Book (2001)&
Part IV of TESLA TDR

New Physics - Electron-Quark Resonances

Appear in many extensions of the SM,
e.g. RP violating SUSY.
Scalar or vector colour triplet bosons
Symmetry between q and l sector.
B, L violation?





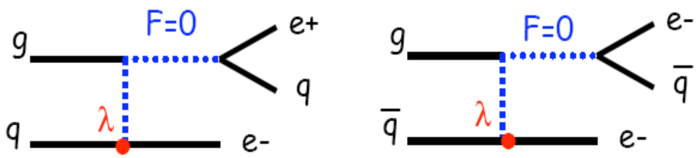
Could be discovered via pair production at LHC up to masses of 1-1.5 TeV

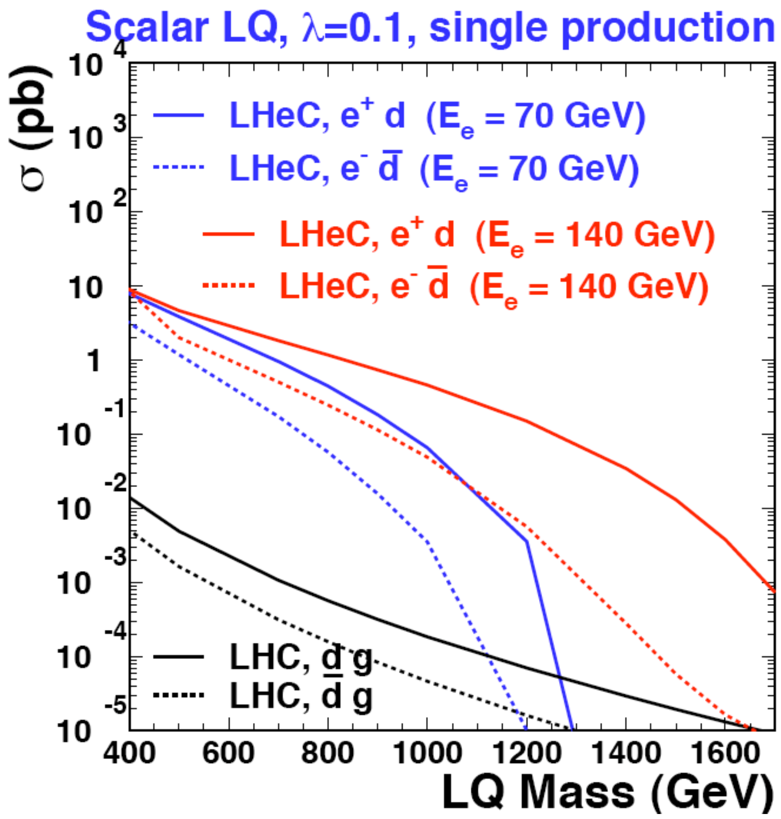
ep		pp		
eq	νq	llqq	lνqq	ννqq
NC DIS	CC DIS	Z/DY + jj QCD	W + jj	W/Z + jj QCD

SM: (row above)

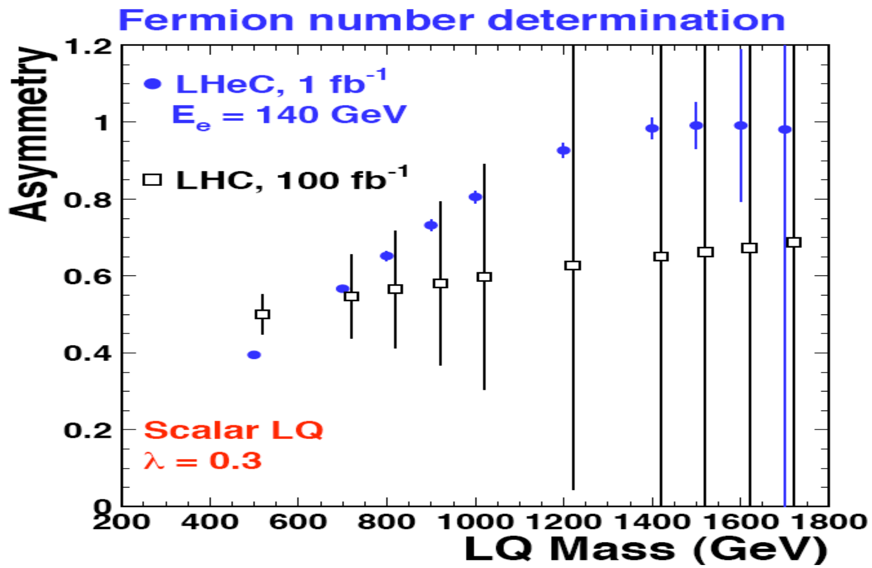
Charge, angular distribution, polarisation:
quantum numbers may be determined in ep.
Similarly: If the LHC sees some CI, you may need pp and ep and ee to resolve the new i.a..

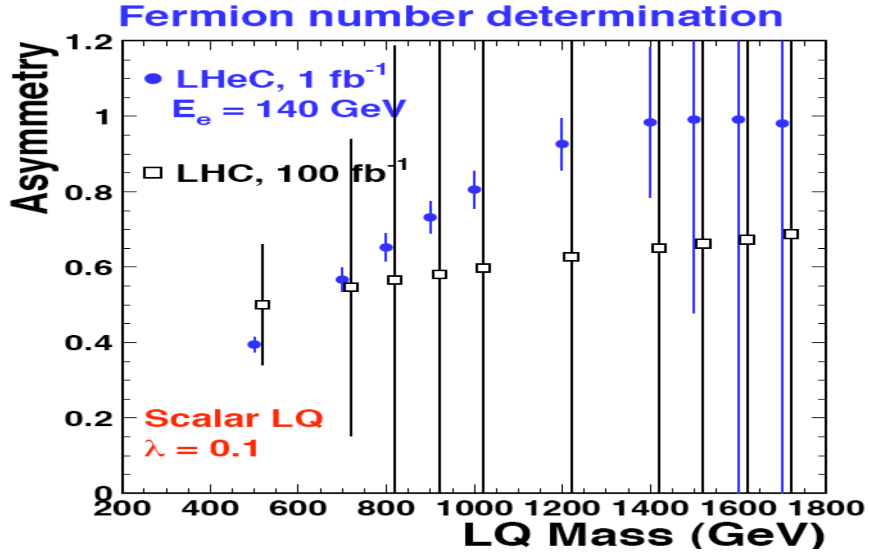
Quantum Numbers





E.Perez, DIS07

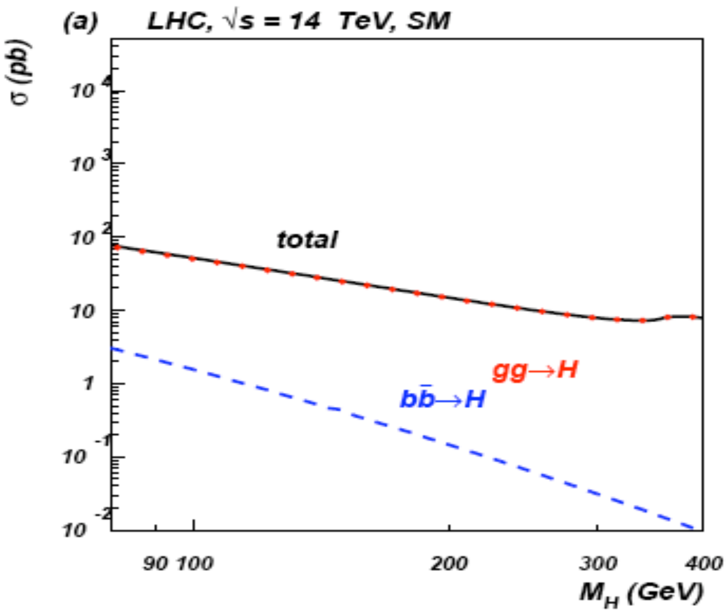




Charge asymmetry much cleaner in ep than in pp. Similar for simultaneous determination of coupling and quark flavour

Gluon

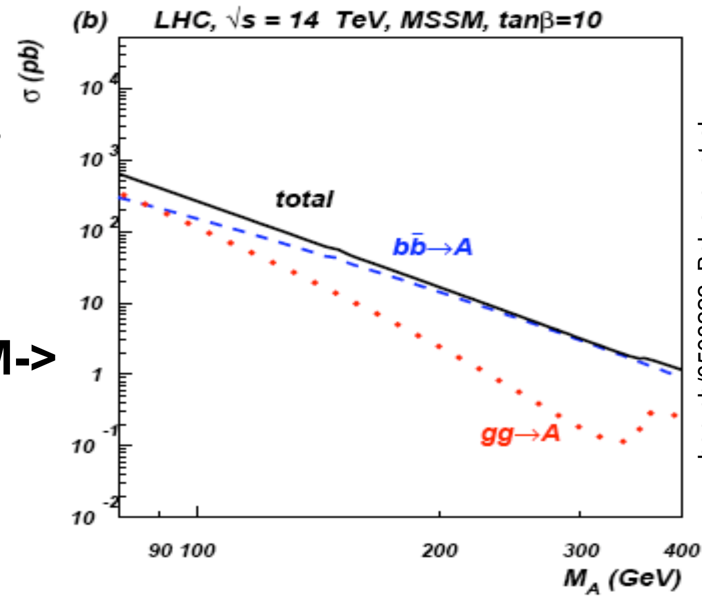
Beauty



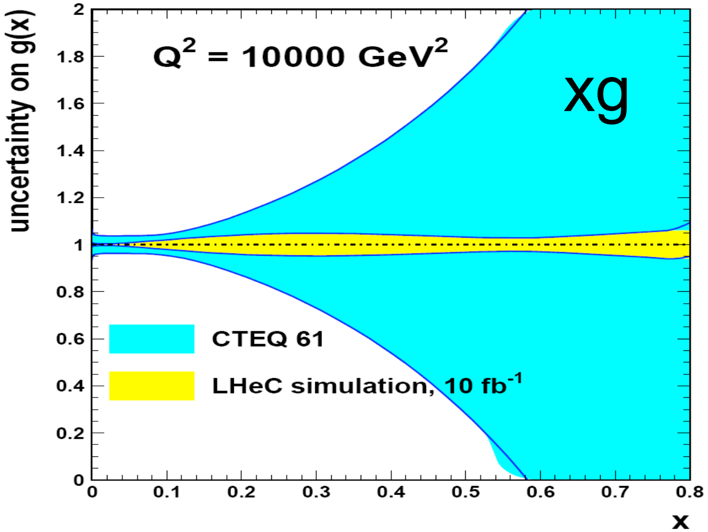
Higgs

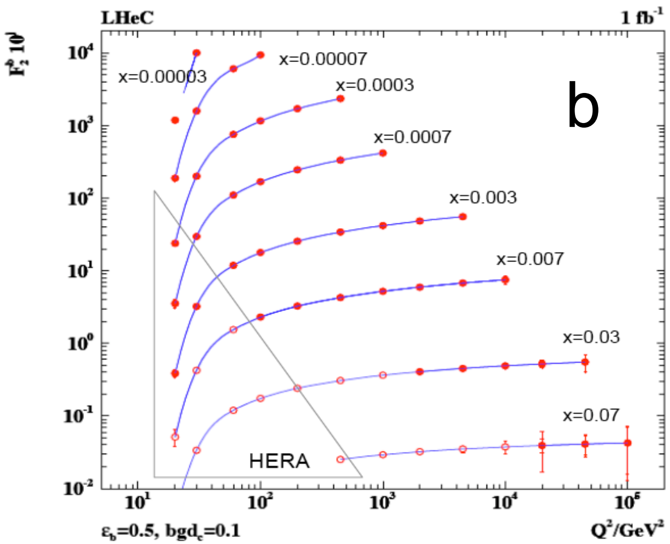
<-SM

MSSM->

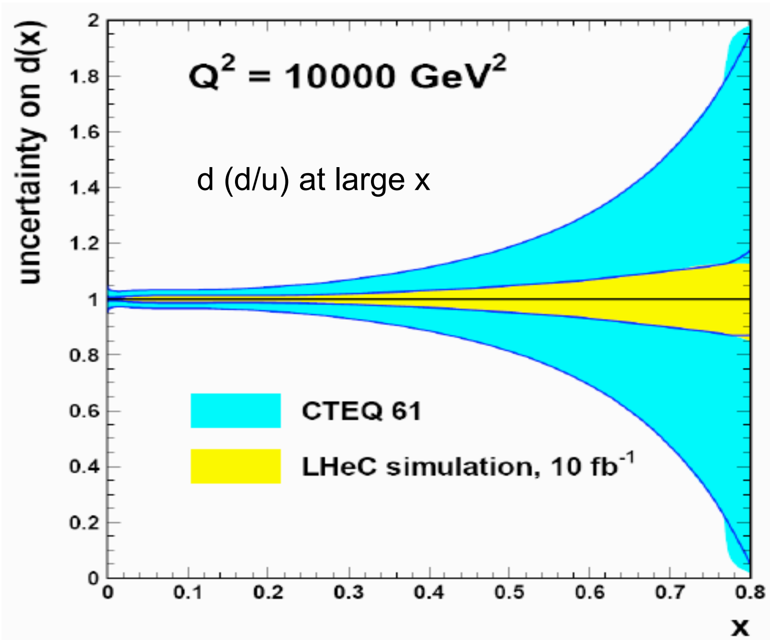


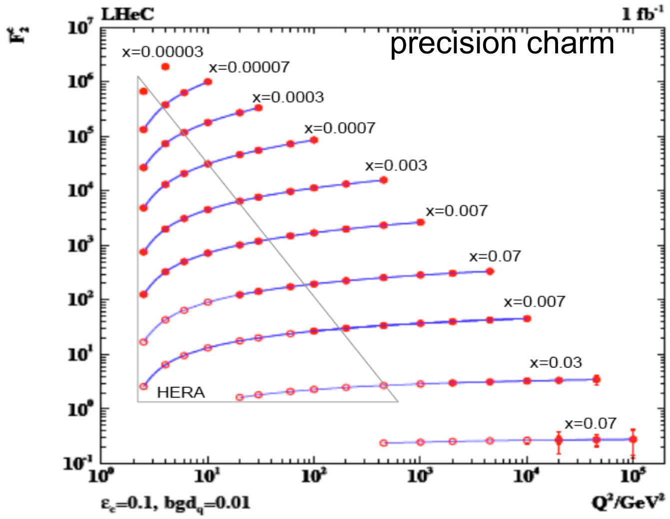
hep-ph/0508222, Belyayev et al

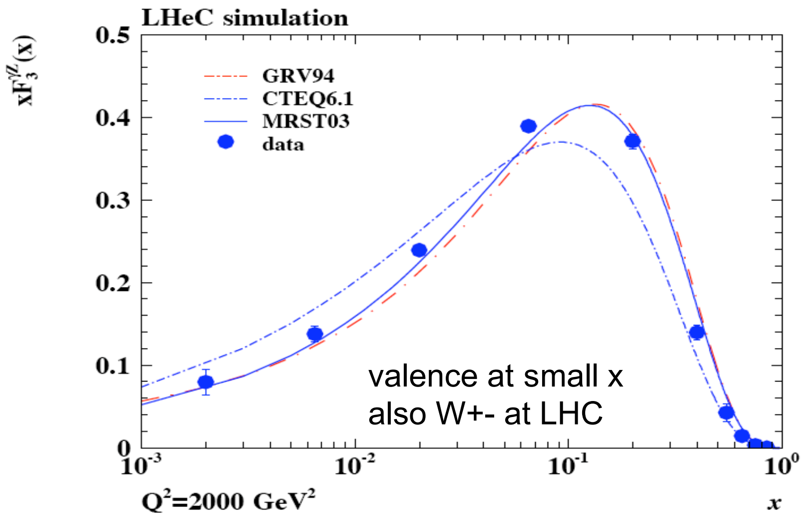


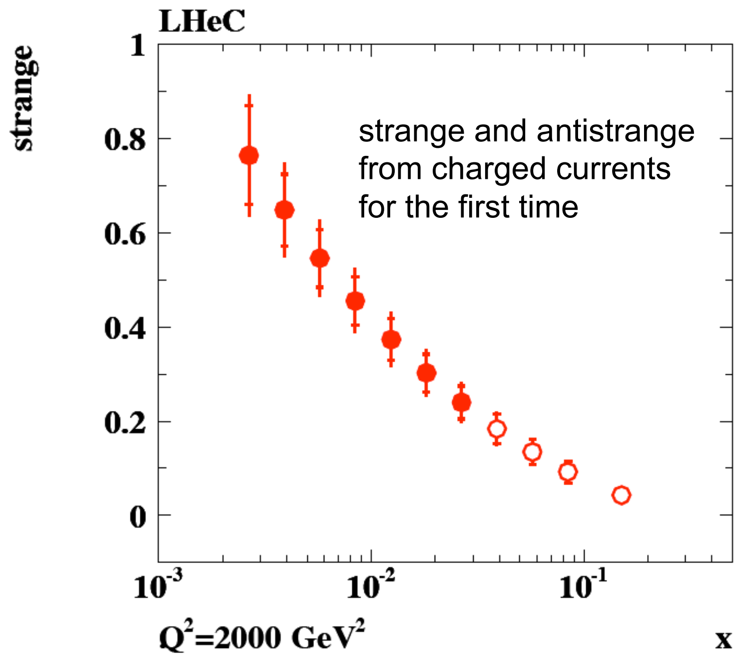


Complete Unfolding of the Quark Content of the Nucleon (NC,CC) at PeV energies

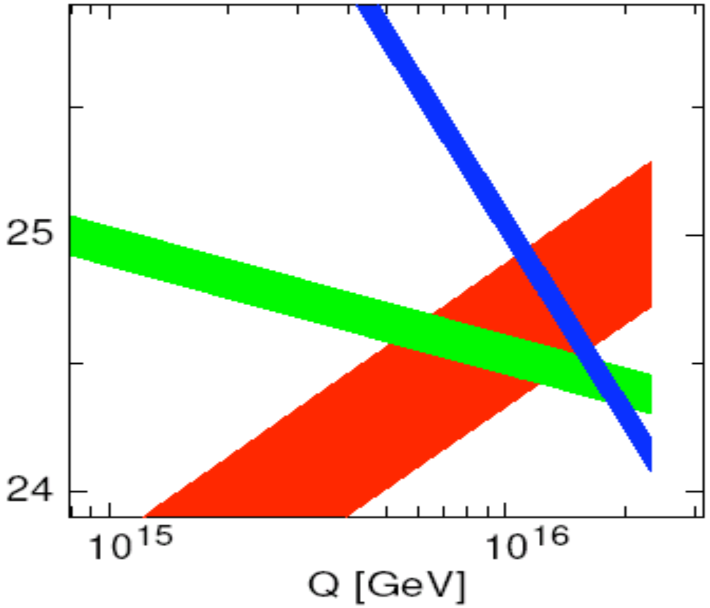


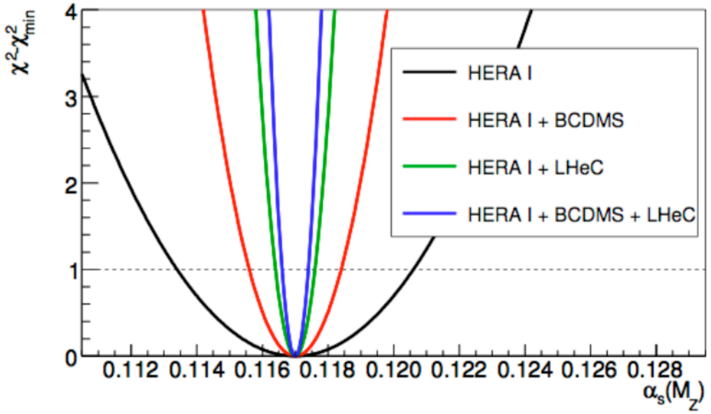






Strong Coupling





T.Kluge, MK, DIS07

Detector Requirements

	LHeC	HERA
Largest possible acceptance	1-179°	7-177°
High resolution tracking	0.1 mrad	0.2-1 mrad
Precision electromagnetic calorimetry	0.1%	0.2-0.5%
Precision hadronic calorimetry	0.5%	1%
High precision luminosity measurement	0.5%	1%

The strong coupling constant is the worst of all measured couplings. The LHeC leads to a per mille level of exp. accuracy, a new challenge to pert. and lattice QCD.

QCD - a rich theory

(3) The lepto-production of multiple jets at LHeC can probe the three and four gluon vertices. The one-loop PQCD corrections have many anomalous features [3].

Multijets: fwd jets, low x, LHC

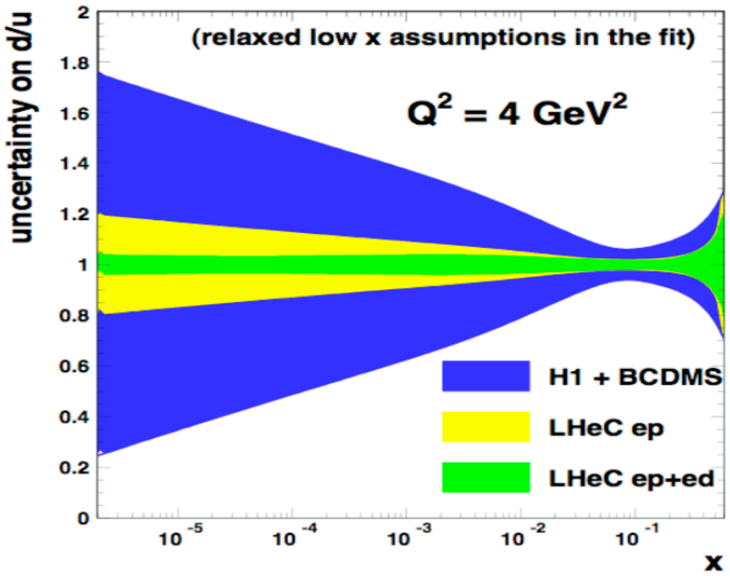
(7) Production of the Higgs boson in $ep \to eHX$. A remarkable consequence of the intrinsic charm and bottom Fock states of the proton is the production of the Higgs boson with more than 80% of the proton's momentum [7]. This necessitates detectors with forward acceptance in the proton fragmentation region [8].

Heavy flavours & hadron structure

Stan Brodsky's 13 Questions

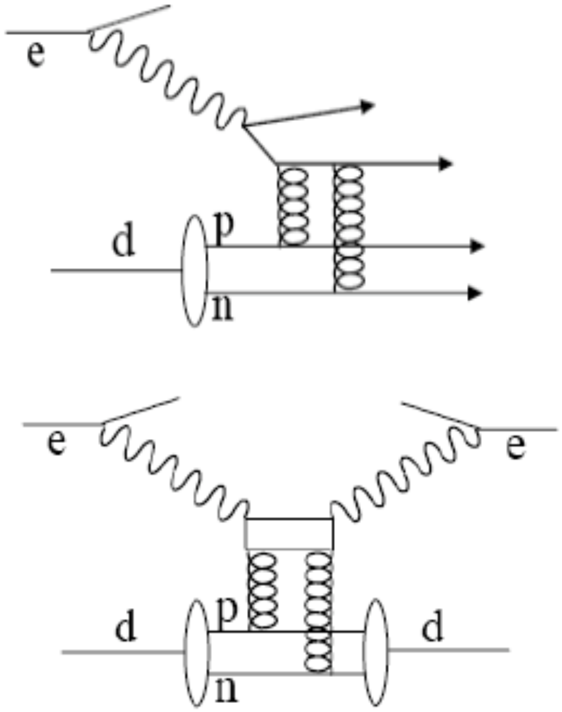
Neutron Structure (ed → eX)

d/u at low x from deuterons

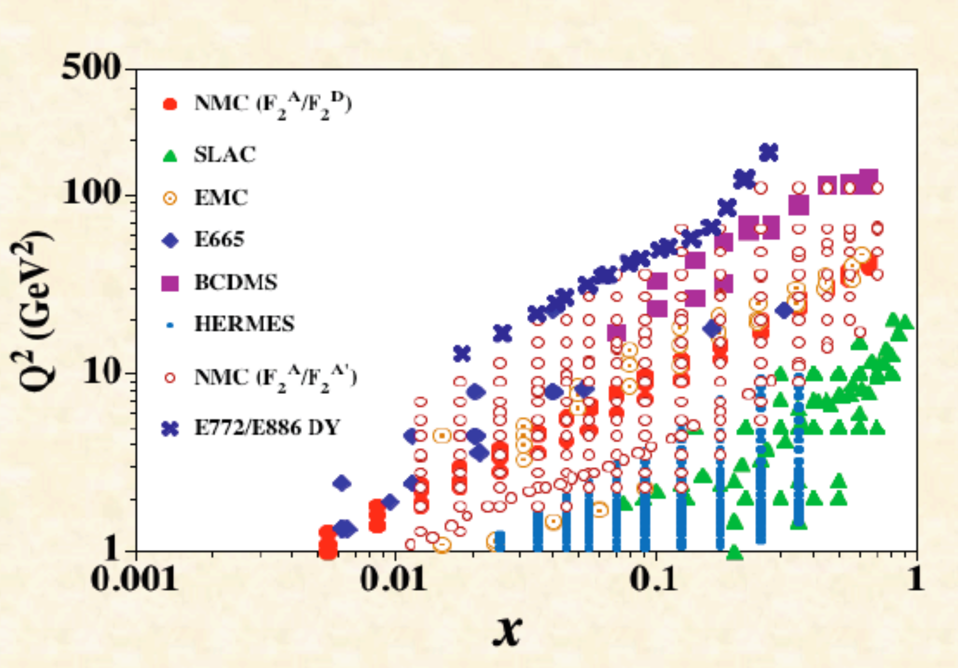


(13) There are five color-singlet combinations of the deuteron wavefunction in QCD, only one of which is the standard proton-neutron state. The "hidden color" [13] components will lead to high multiplicity final states in deep inelastic electron-deuteron scattering.

crucial constraint on evolution (S-NS), improved α_s



In eA at the collider, test Gribovs relation between shadowing and diffraction, control nuclear effects at low Bjorken x to high accuracy



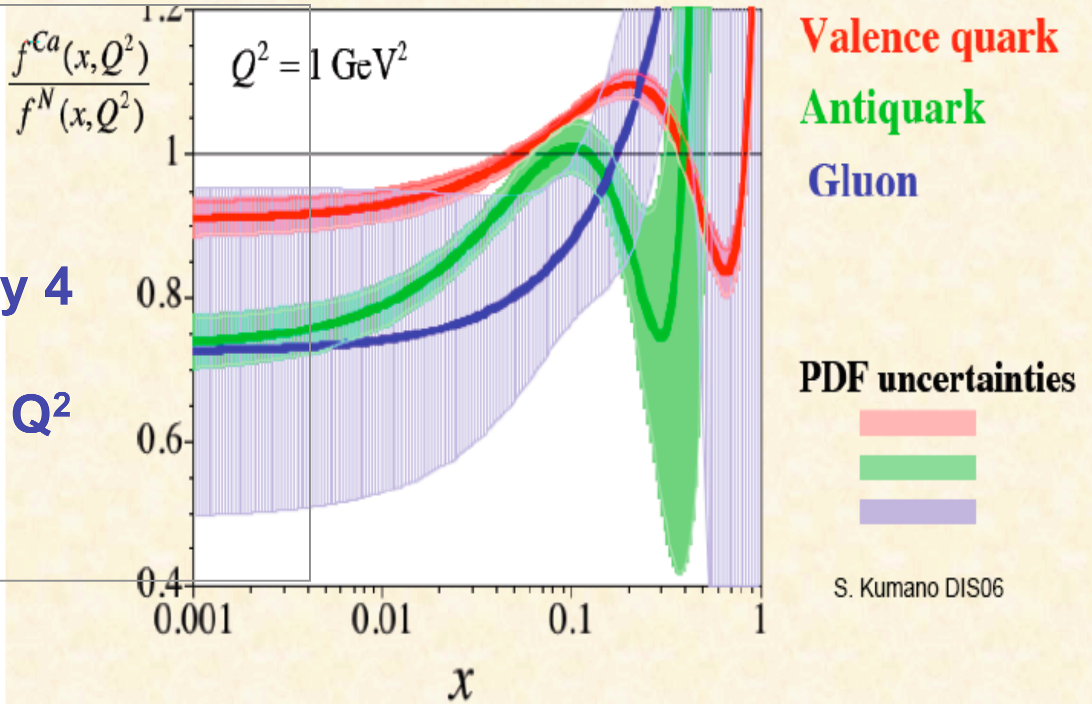
Nuclear Structure

Striking effects predicted:
bj -> black disc limit $F_2 \to Q^2 \ln(1/x)$
~50% diffraction
colour opacity, change of J/Ψ(A)

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

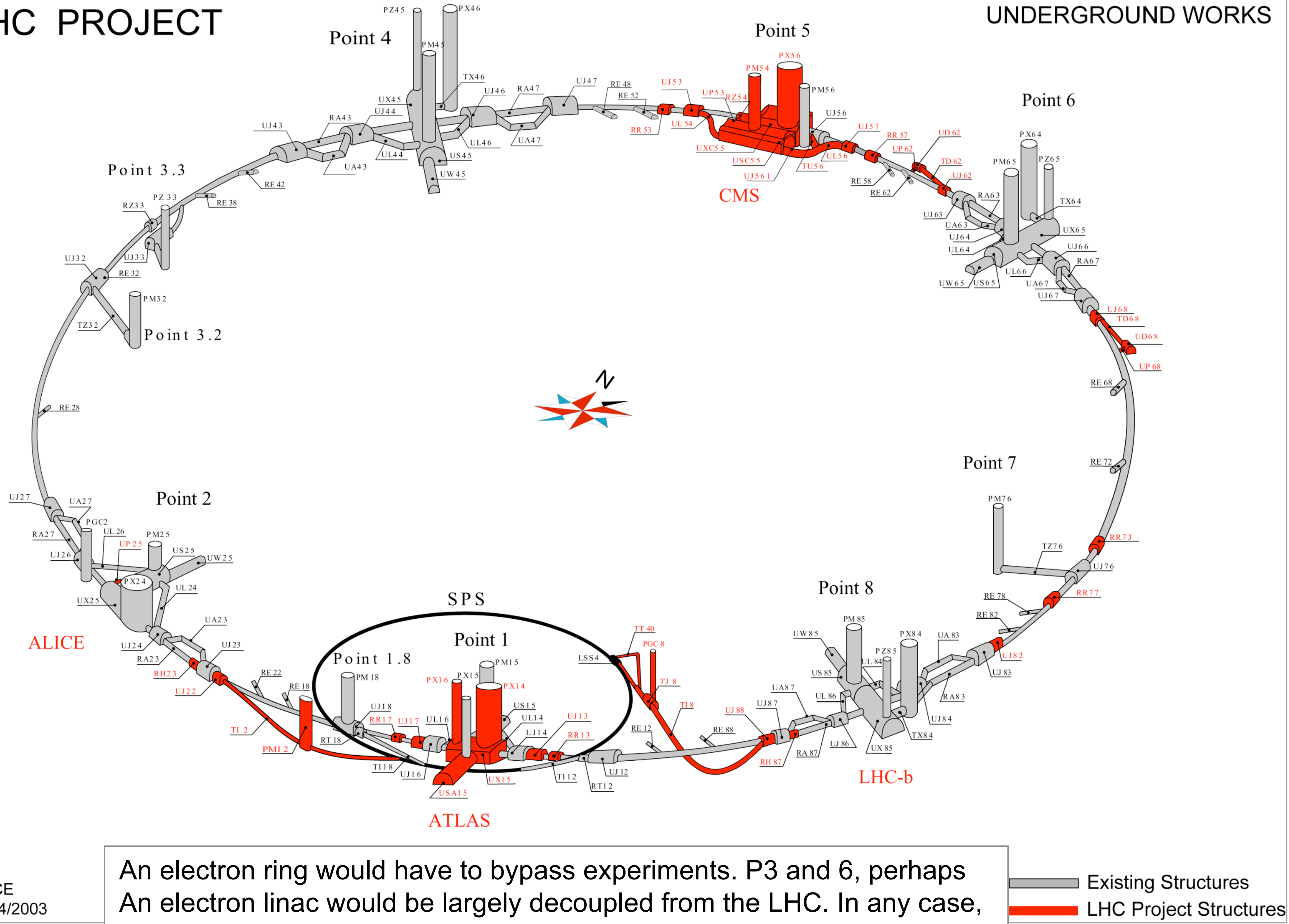
unitarity limit

extension of x range by 4 orders of magnitude and huge extension in Q^2



LHC PROJECT

UNDERGROUND WORKS



ST-CE
18/04/2003

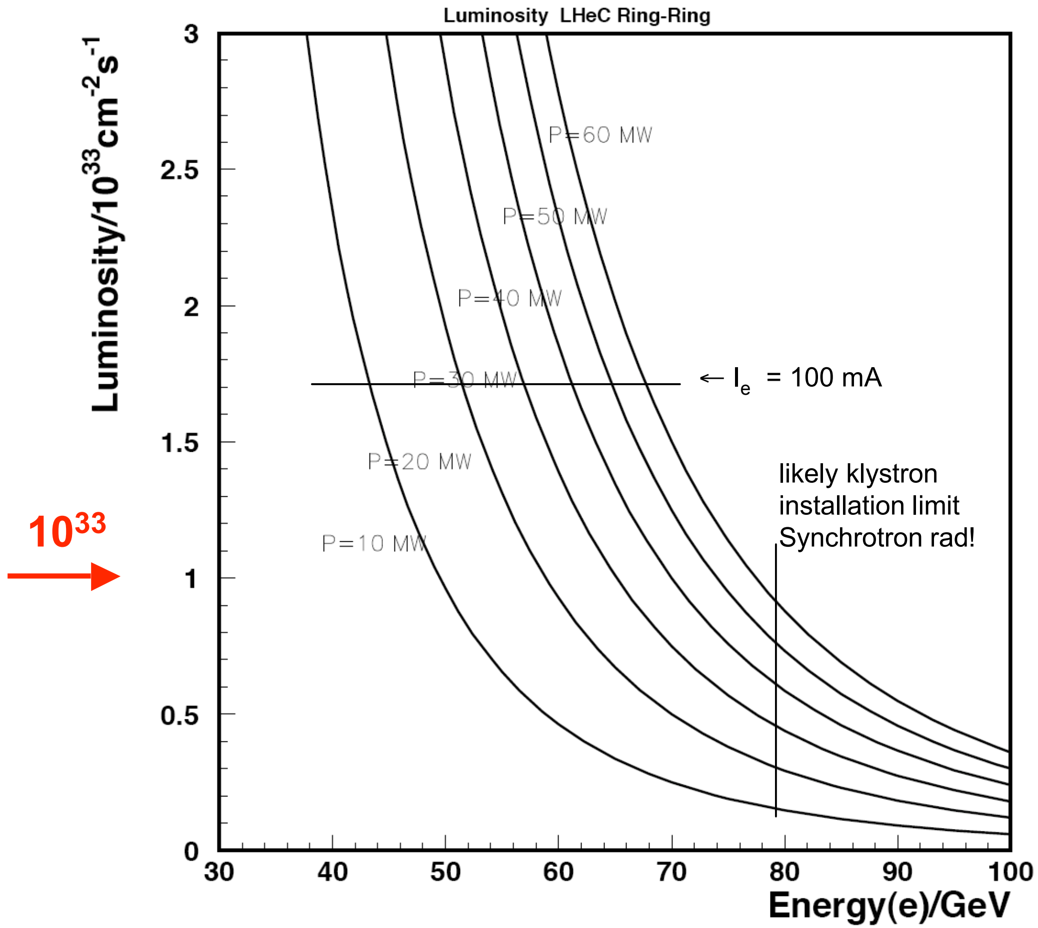
An electron ring would have to bypass experiments. P3 and 6, perhaps
An electron linac would be largely decoupled from the LHC. In any case,
an ep/eA interaction region by then would have to be in P2 or/and P8.

Luminosity: Ring-Ring

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}} = 8.3 10^{32} \cdot \frac{I_e}{50mA} \frac{m}{\sqrt{\beta_{px}\beta_{pn}}} cm^{-2}s^{-1}$$

$$\varepsilon_{pn} = 3.8\mu m$$
$$N_p = 1.7 \cdot 10^{11}$$
$$\sigma_{p(x,y)} = \sigma_{e(x,y)}$$
$$\beta_{px} = 1.8m$$
$$\beta_{py} = 0.5m$$

$$I_e = 0.35mA \cdot \frac{P}{MW} \cdot \left(\frac{100GeV}{E_e}\right)^4$$



10^{33} can be reached in RR
E_e = 40-80 GeV & P = 5-60 MW.

HERA was 1-4 10^{31} cm^{-2} s^{-1}
huge gain with SLHC p beam

F.Willeke in hep-ex/0603016:
Design of interaction region
for 10^{33} : 50 MW, 70 GeV

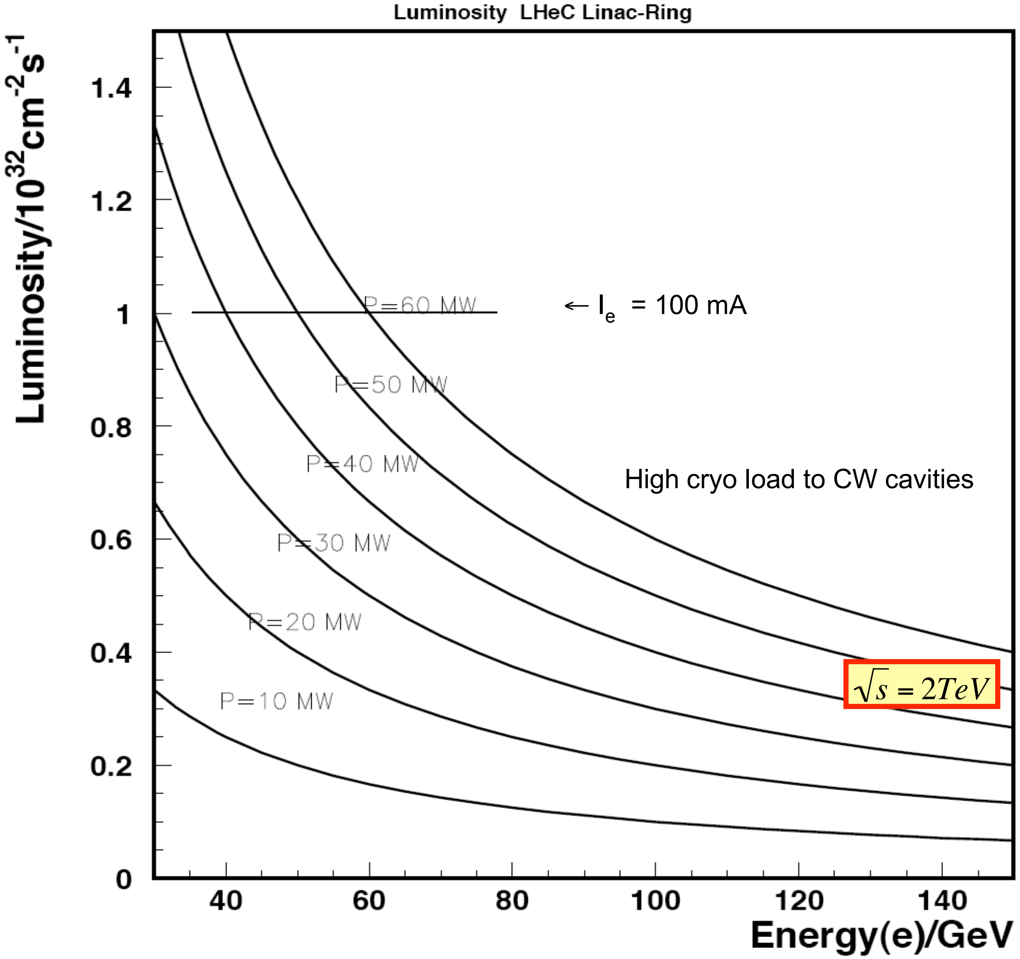
May reach 10^{34} with ERL in
bypasses, or/and reduce power.
R&D performed at BNL/eRHIC

cf also A.Verdier 1990, E.Keil 1986

Luminosity: Linac-Ring

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn} \beta^*} \cdot \frac{P}{E_e} = 1 \cdot 10^{32} \cdot \frac{P / MW}{E_e / GeV} cm^{-2} s^{-1}$$

$$\varepsilon_{pn} = 3.8 \mu m$$
$$N_p = 1.7 \cdot 10^{11}$$
$$\beta^* = 0.15 m$$



$$I_e = 100 mA \cdot \frac{P}{MW} \cdot \frac{GeV}{E_e}$$

LHeC as Linac-Ring version
can be as luminous as HERA II:

4 10^{31} can be reached with LR:
E_e = 40-140 GeV & P=20-60 MW
LR: average lumi close to peak

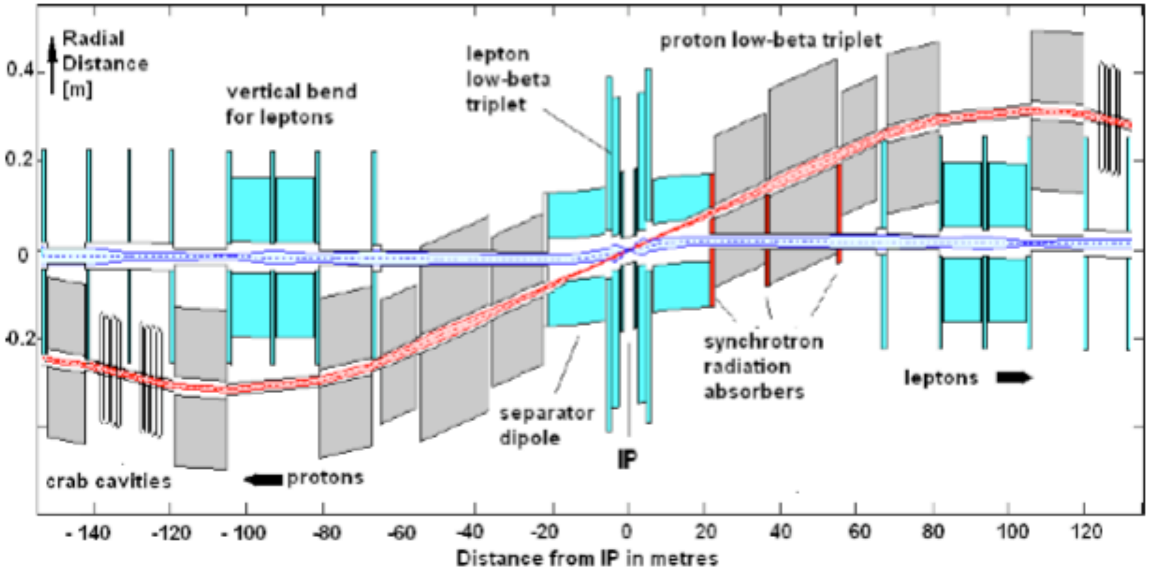
140 GeV at 23 MV/m is 6km +gaps

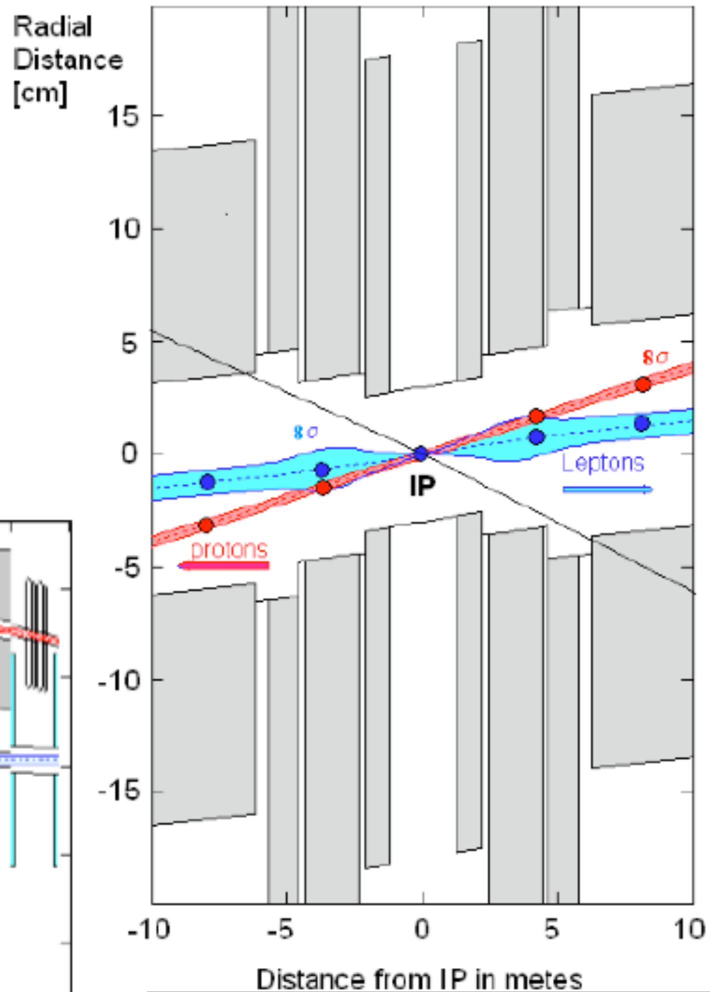
Luminosity horizon: high power:
ERL (2 Linacs?)

Ring-Ring LHeC Interaction Region Design

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

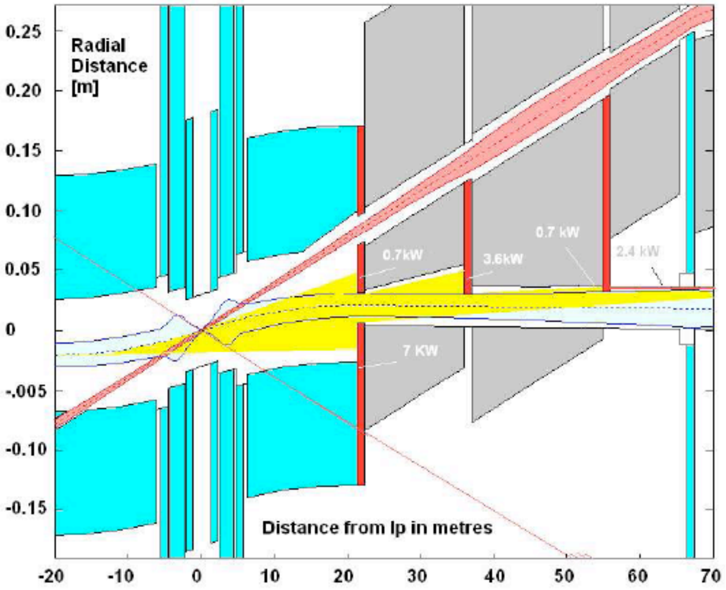
Property	Unit	Leptons	Protons
Beam Energies	GeV	70	7000
Total Beam Current	mA	74	544
Number of Particles / bunch	10^{10}	1.04	17.0
Horizontal Beam Emittance	nm	7.6	0.501
Vertical Beam Emittance	nm	3.8	0.501
Horizontal β-functions at IP	cm	12.7	180
Vertical β-function at the IP	cm	7.1	50
Energy loss per 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	$10^{33}cm^{-2}s^{-1}$	1.1	

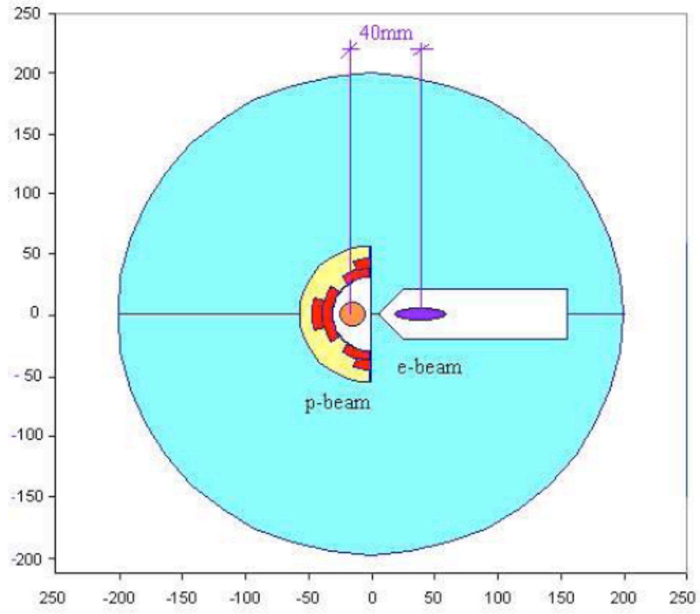




foresees simultaneous operation of pp and ep

Design Details





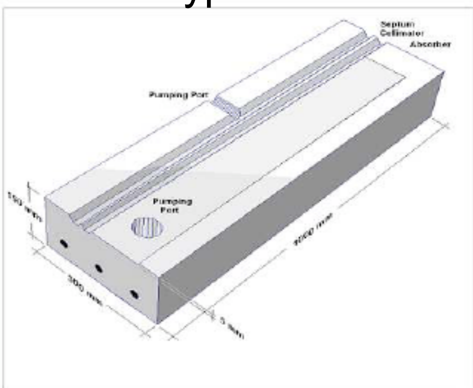
Synchrotron radiation fan

and HERA type absorber

$9.1kW$

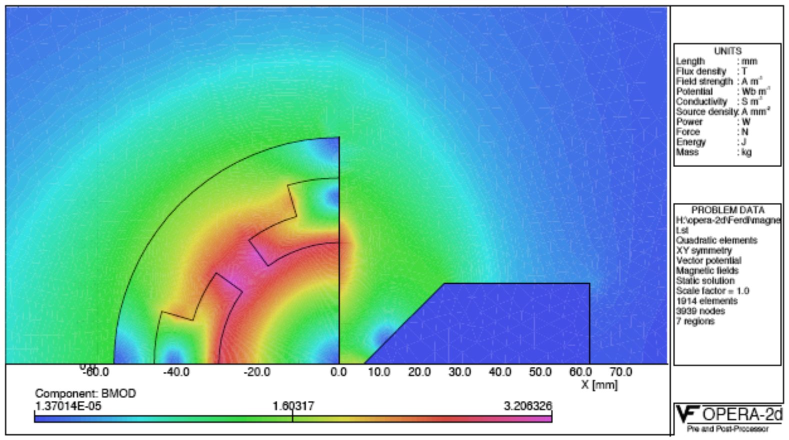
$E_{crit} = 76keV$

First p beam lens: septum quadrupole.
Cross section and Field calculation



100W/mm^2

cf also W.Bartel
Aachen 1990



Accelerator (RR) questions considered

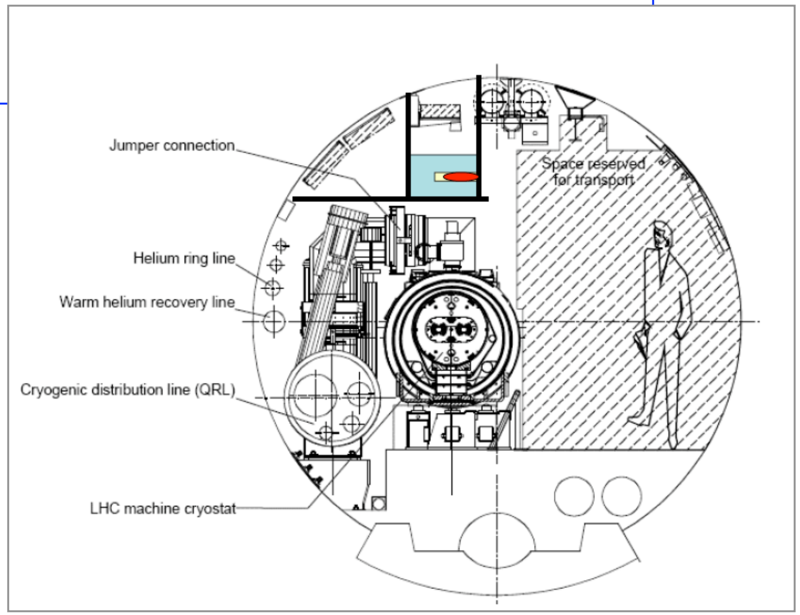
Power: 25ns: nx40MHz rf frequency. Imax 100 mA: 60 klystrons with 1.3MW coupler of perhaps 0.5MW, 66% efficient… need space for rf in bypasses

Injection: LEP2 was N= 4 10^{11} in 4 bunches, LHeC is 1.4 10^{10} in 2800 bunches may inject at less than 20 GeV. Injection is no principal problem regarding power and technology (ELFE, KEK, direct?)

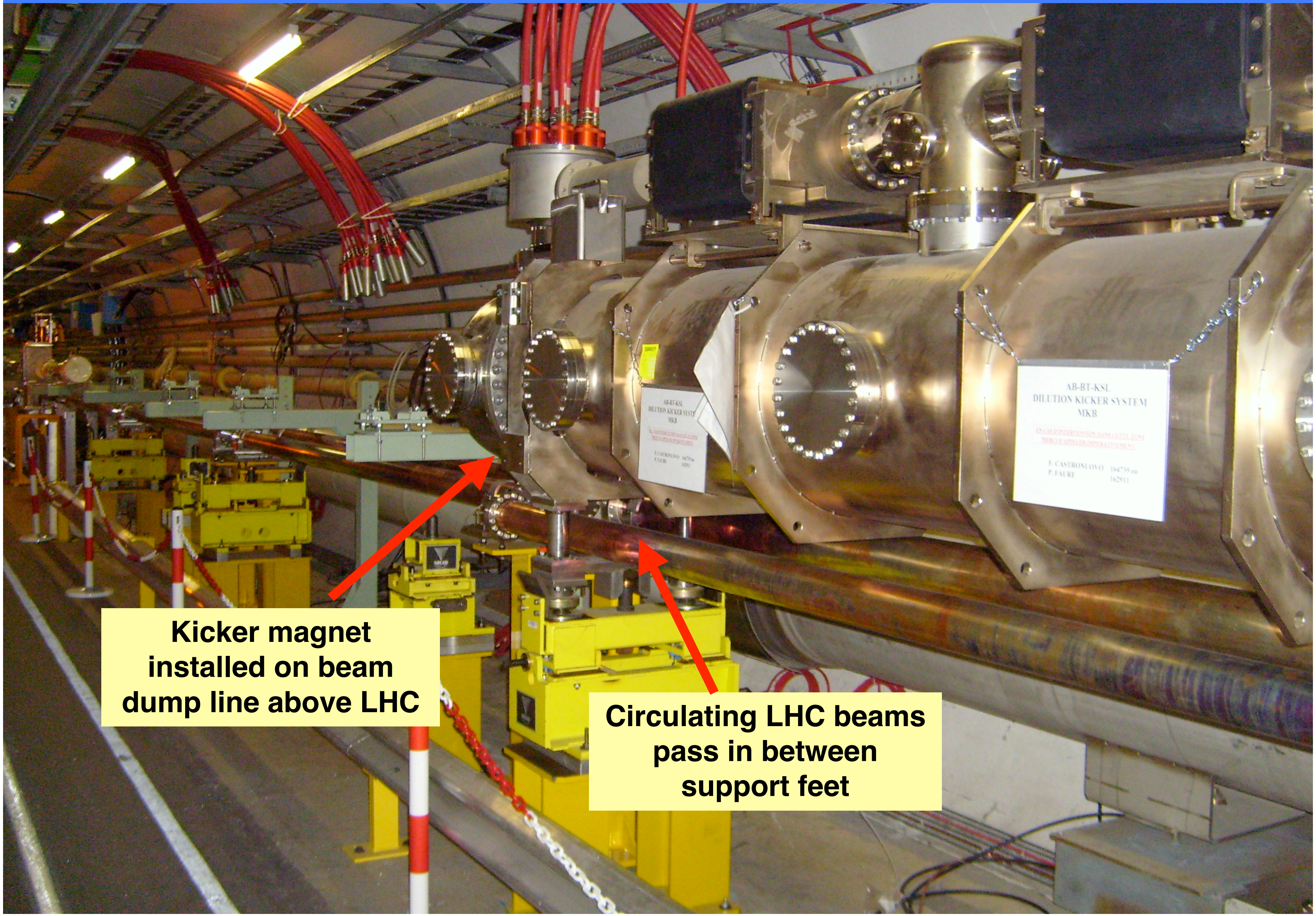
Synchrotron load to LHC magnets: can be shielded (water cooled Pb)

Bypasses: for ATLAS and CMS but also for further Pi. l~500m start in the arcs. May ensure same length of e ring as p with ~ -20cm radius of e ring.

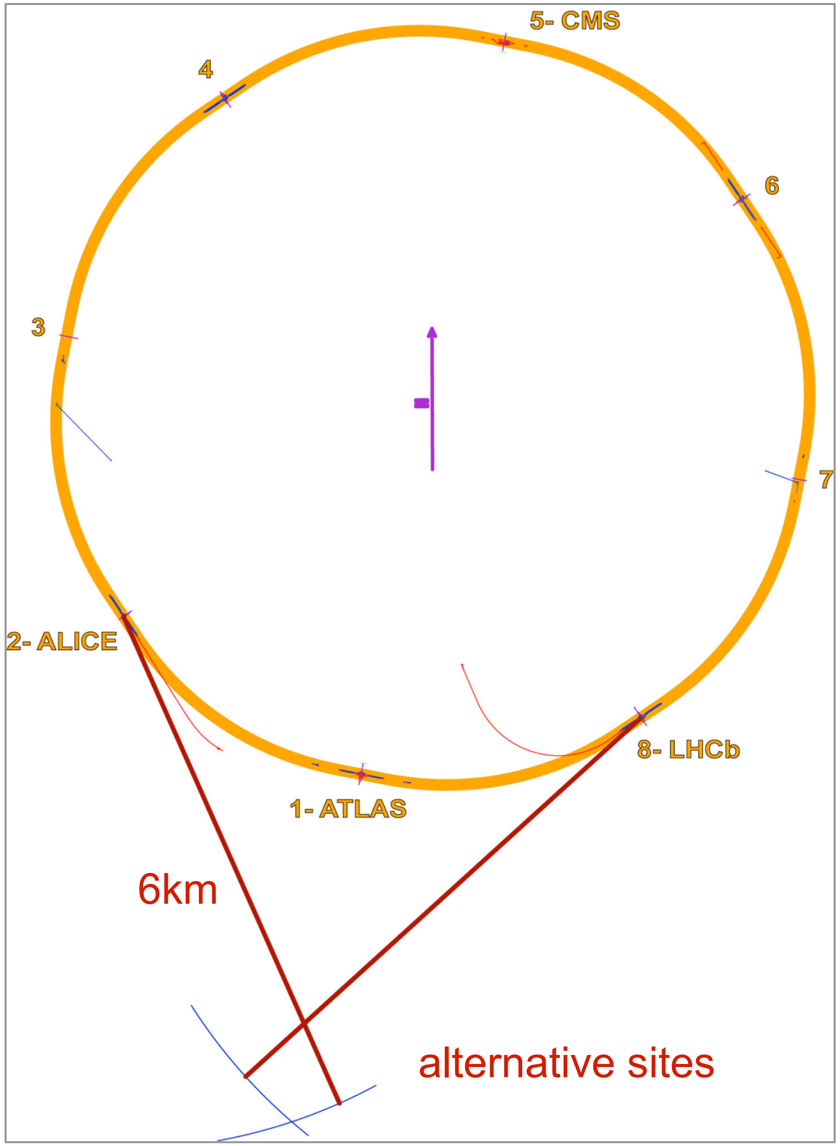
Space: first look at the installation on top of LHC



Passing equipment above installed LHC beamlines….



$e^{\pm}$ Linac - p/A Ring



		ring-linac pulsed		ring-linac, cw , ~99% energy recovery	
	units	e-	p	e-	p
energy	GeV	70	7000	70	7000
punch population	10^{10}	2	17	2	17
σ_z	cm	0.03	7.55	0.03	7.55
beam current (pulsed)	mA	101	858	101	858
emittance $\varepsilon_{x,y}$	nm	0.5, 0.5			
$\beta^*_{x,y}$	cm	15, 15			
spacing	ns	25			
e-linac/ring length	km	3.5		7 (2 linacs)	
e- pulse length		1 ms		cw	
repetition rate		5 Hz		continuous	
e- beam power	MW	35		7000	
peak luminosity	**10^{32} $cm^{-2}s^{-1}$**	**0.6**		**2x110**	

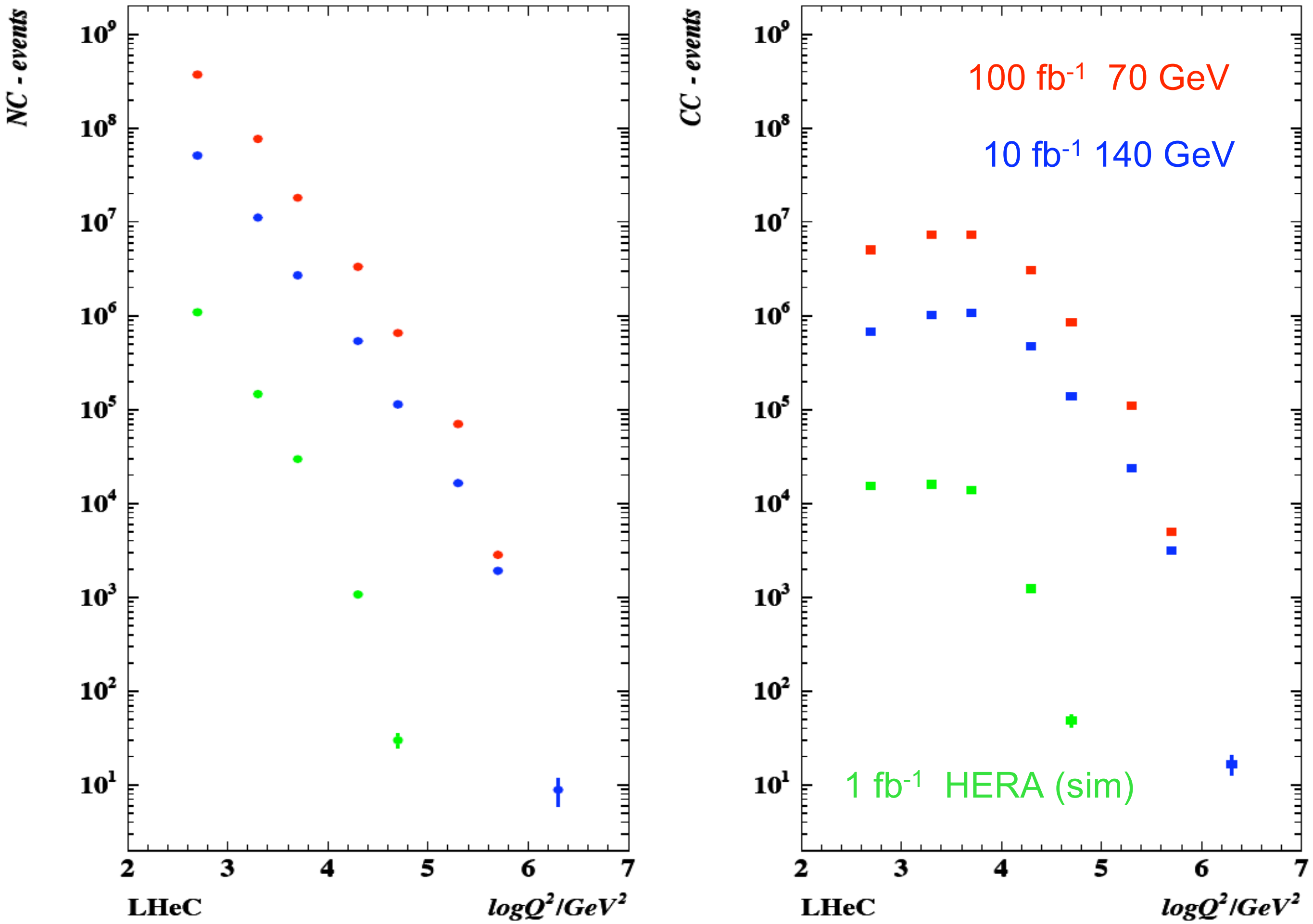
S. Chattopadhyay (Cockcroft), F.Zimmermann (CERN), et al.

Comparison Linac-Ring and Ring-Ring

	Linac-Ring	Ring-Ring
Energy / GeV	40-140	40-80
Luminosity / 10^{32} cm^{-2} s^{-1}	0.5	10
Mean Luminosity, relative	2	1 [dump at L_{peak} /e]
Lepton Polarisation	60-80%	30% [?]
Tunnel / km	6	2.5=0.5 * 5 bypasses
Biggest challenge	CW cavities	Civil Engineering Ring+Rf installation
Biggest limitation	luminosity (ERL,CW)	maximum energy
IR	not considered yet one design? (eRHIC)	allows ep+pp 2 configurations [lox, hiq]

DIS events

Neutral Currents ep ->eX　　　Charged Currents ep ->νX



The strong decrease of the DIS cross section with Q^2 requires highest possible luminosity.

Statistics at LHeC for up to ~10^5 GeV^2 is rich.

No statistics problem for low x physics - two versions of IR and instrumentation possible, though not really desired.

Highest scales: large energy counts for discovery range.

The LHeC is a huge step from HERA into the TeV range.

At very large Q^2 10 times less L is compensated by 2 E_e .

The Goal of the ECFA-CERN Workshops is a CDR by end of 2009:

Accelerator Design [RR and LR]

Closer evaluation of technical realisation: injection, magnets, rf, power efficiency, cavities, ERL…

What are the relative merits of LR and RR? Recommendation.

Interaction Region and Forward Detectors

Design of IR (LR and RR), integration of fwd detectors into beam line.

Infrastructure

Definition of infrastructure - for LR and RR.

Detector Design

A conceptual layout, including alternatives, and its performance [ep and eA].

New Physics at Large Scales

Investigation of the discovery potential for new physics and its relation to the LHC and ILC/CLIC.

Precision QCD and Electroweak Interactions

Quark-gluon dynamics and precision electroweak measurements at the TERA scale.

Physics at High Parton Densities [small x and eA]

QCD and Unitarity, QGP and the relations to nuclear, pA/AA LHC and SHEν physics.

Scientific Advisory Committee (SAC)

Accelerator Experts
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Research Directors+ECFA
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Paul Newman	(Birmingham)
Emmanuelle Perez	(CERN)
Wesley Smith	(Wisconsin)
Bernd Surrow	(MIT)
Katsuo Tokushuku	(KEK)
Urs Wiedemann	(CERN)

First workshop: xx.8/yy.9. 2008 (near CERN)

Summary and Proposal endorsed by ECFA 30.11.07

As an add-on to the LHC, the LHeC delivers in excess of 1 TeV to the electron-quark cms system. It accesses high parton densities ‘beyond’ what is expected to be the unitarity limit. Its physics is thus fundamental and deserves to be further worked out, also with respect to the findings at the LHC and the final results of the Tevatron and of HERA.

First considerations of a ring-ring and a linac-ring accelerator layout lead to an unprecedented combination of energy and luminosity in lepton-hadron physics, exploiting the latest developments in accelerator and detector technology.

It is thus decided to hold two workshops (2008 and 2009), under the auspices of ECFA and CERN, with the goal of having a Conceptual Design Report on the accelerator, the experiment and the physics. A Technical Design report will then follow if appropriate.

Electron-proton colliders open new horizons on all three of the fundamental questions: the spectroscopy of fundamental fermions, the spectroscopy of gauge bosons, and the problem of hadron structure. In addressing these issues, the ep collider is approaching the same physics as is studied in e^+e^- and $\bar{p}p$ colliders, but in a complementary way, with emphasis on the t-channel. Each technique has its own strengths and weaknesses, which I leave you to contemplate.

Chris Quigg
Fermi National Accelerator Laboratory

FERMILAB-Conf-81/52-THY

The success of HERA and the LHC are the basis for designing a new ep collider. Its physics is unique and it may become reality if we wish so.

More on HERA + LHeC

HERA:

Talks at EPS07 (Manchester…)

U.Klein HERA Summary at DESY Theory Workshop 9/2007

M.Klein and R.Yoshida, Collider Physics at HERA, to appear

The H1 and ZEUS Webpages

LHeC: http://www.lhec.ac.uk
J.Dainton et al, JINST 1 (2006) 10001

Thanks for the invitation and yesterday's reminder…

Fundamental questions in lepton-nucleon scattering

Is there one form of matter or two,
is there substructure of quarks and leptons?

Do lepton-quark resonances exist?

Do the fundamental interactions unify?

What is the dynamics of quark-gluon interactions
which is the origin of visible mass?

What is the quark-gluon structure of the nucleon?

How are quarks confined?

Is the Pomeron (really) related to the graviton??

Quarks and gluons in hadronic matter?

DIS is the cleanest, high resolution microscope in the world.
Thus, DIS over decades has been a cornerstone of HEP.