A Large Hadron electron Collider at the LHC

40-140 GeV on 1-7 TeV e±p, also eA

Deep Inelastic Scattering

Physics with the LHeC

Machine Considerations

ECFA Workshops: Towards a CDR

Max Klein
for the LHeC Steering Group

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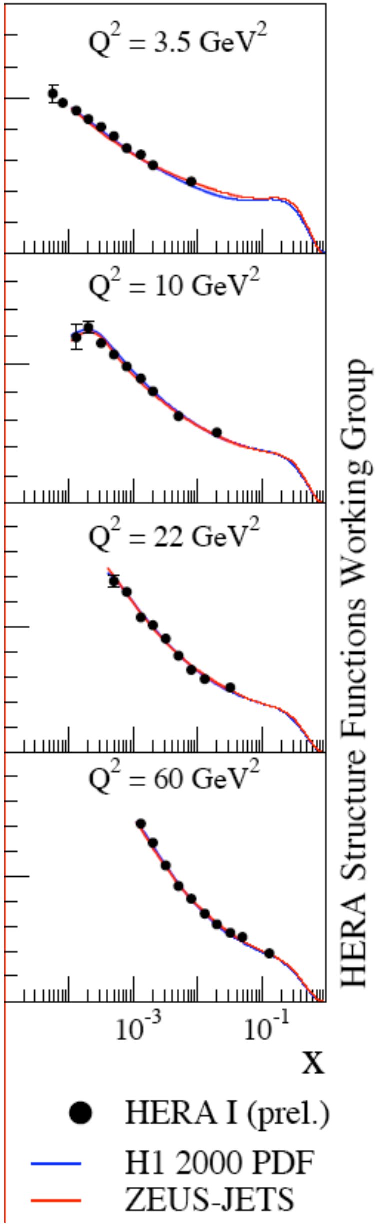
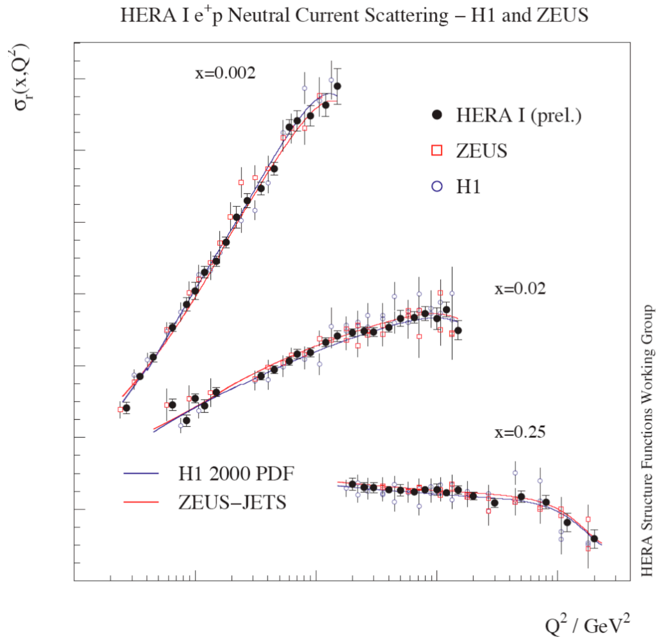
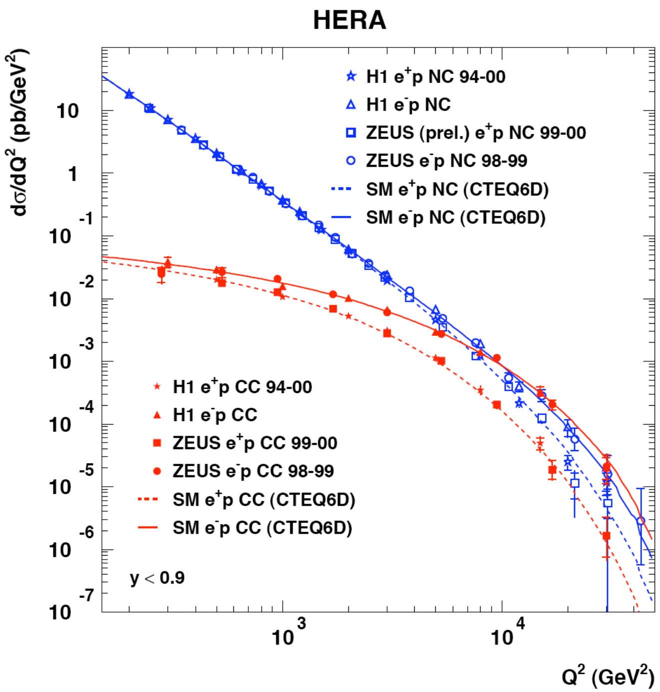
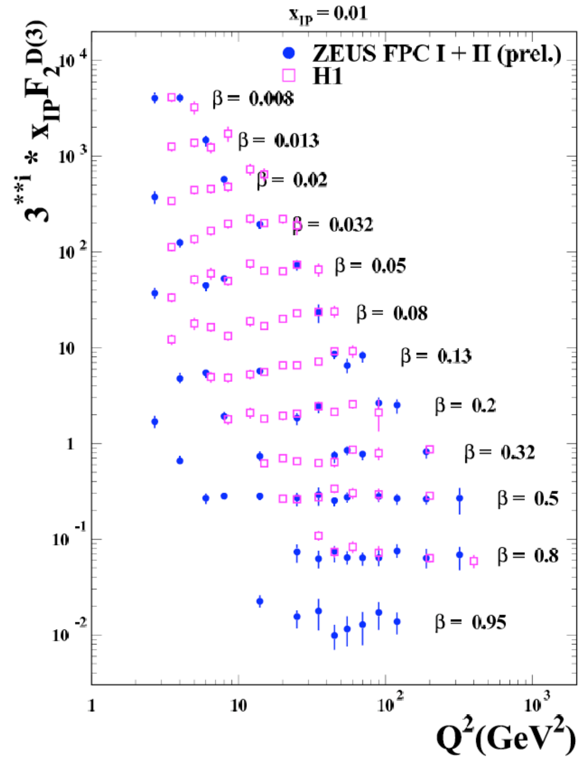




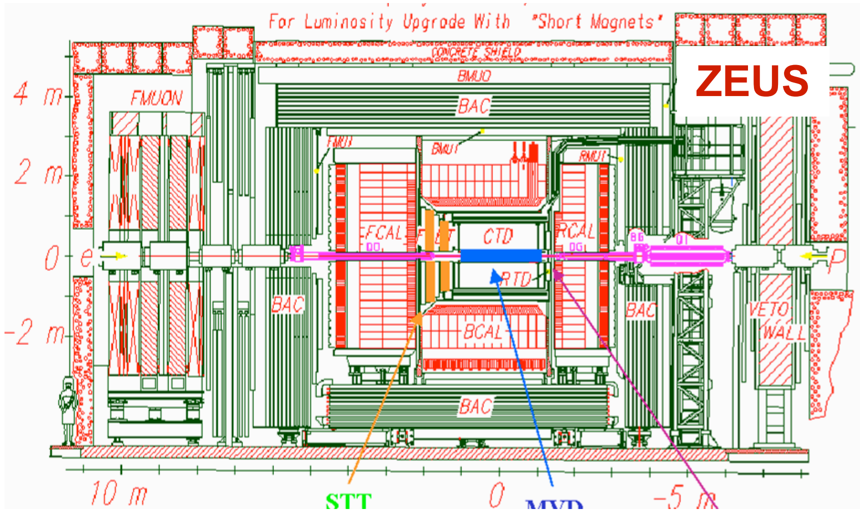




rising sea
huge glue
hard diffraction
quark radius < 7 10^{-18} m
electroweak unification

HERA 1992-2007

HERA - the first ep collider

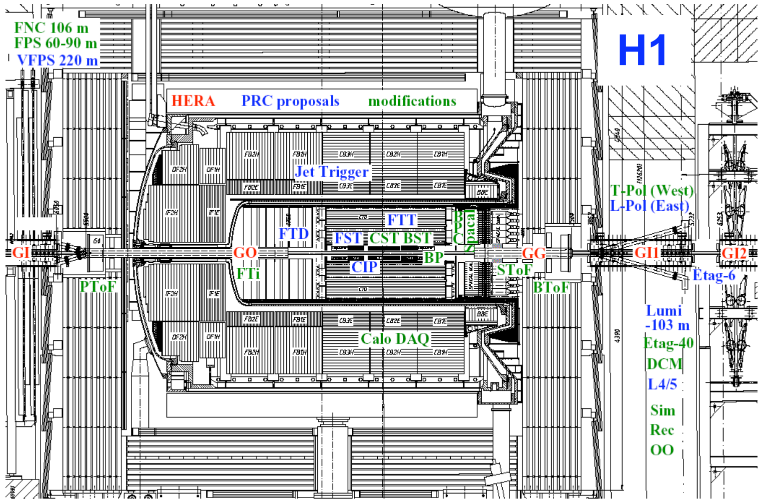


quark+gluon densities in the proton
photon-quark/gluon physics
parton amplitudes
multijets, …

$\vec{e}$ and p fixed target experiments

No neutron structure explored
No nuclear structure explored

In the accessed energy range:
No SUSY
No leptoquarks
No extra dimensions



1000 physicists for 25 years
developed the techniques of ep scattering at high energies, the accelerator, the collider experiments, the theory and analysis techniques. **800 PhD's, 350 publications**

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?

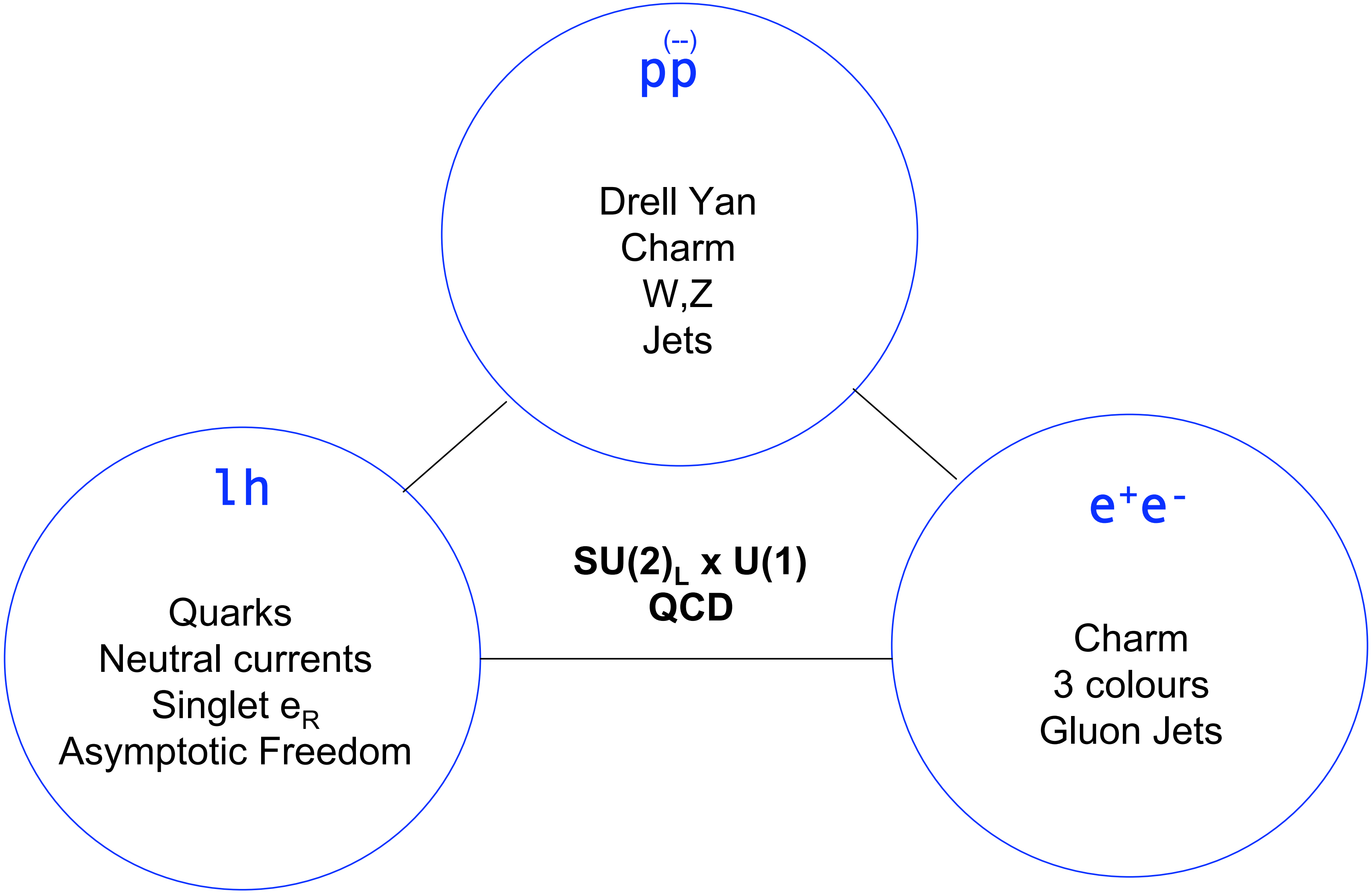
How are quarks confined?

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.

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



The Fermi Scale [1985-2010]

$\bar{p}p$

b quark
top quark
M_W

Tevatron

ep

gluon
h.o. strong
c,b distributions
high parton densities

HERA

The Standard Model Triumph

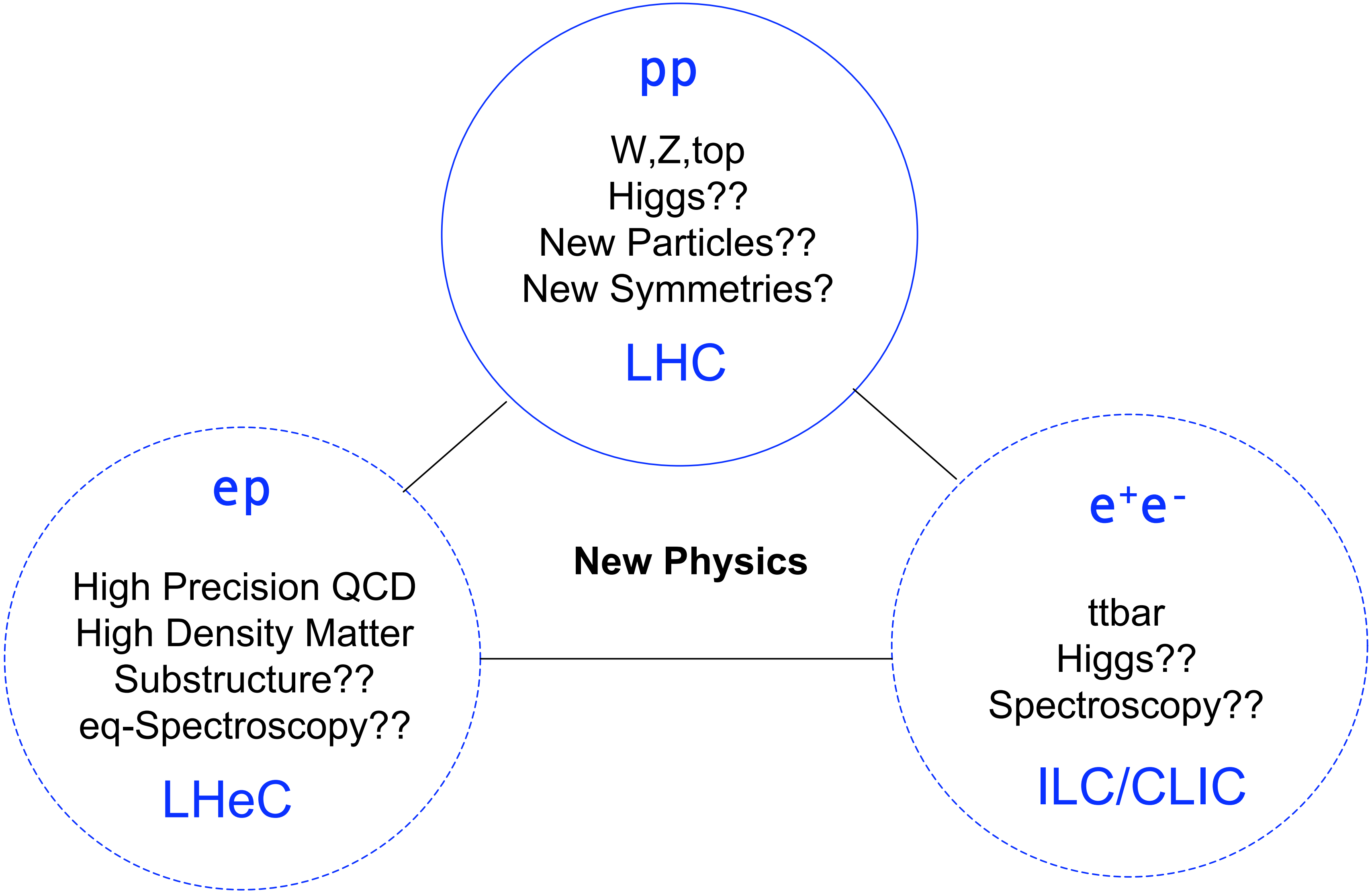
e^+e^-

M_Z , $\sin^2 \Theta$
3 neutrinos
h.o. el.weak (t,H?)

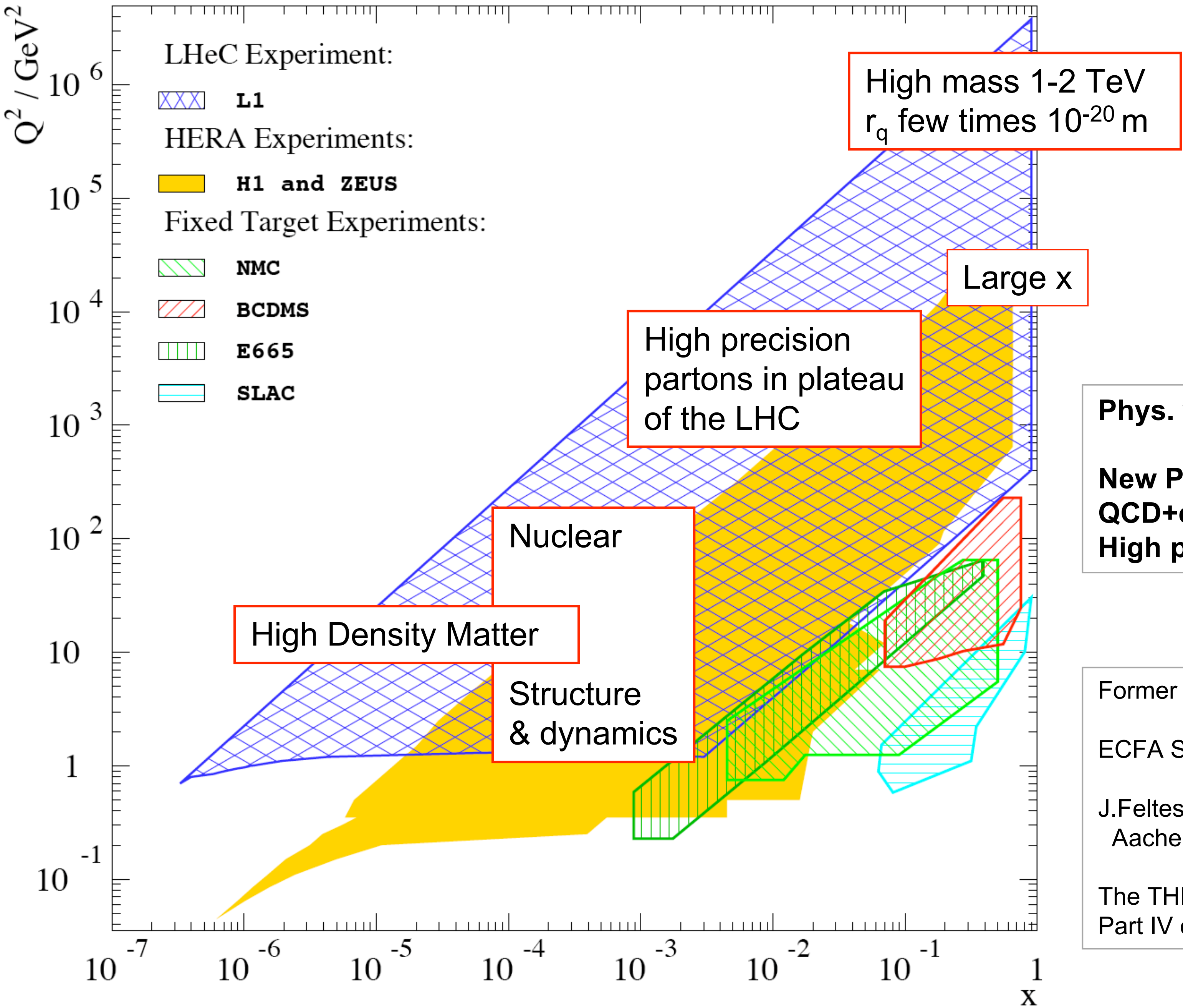
LEP/SLC

CKM - **B factories**

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:

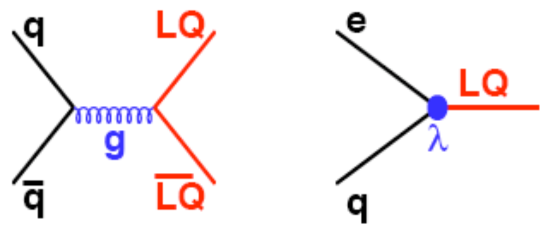
ECFA Study 84-10

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

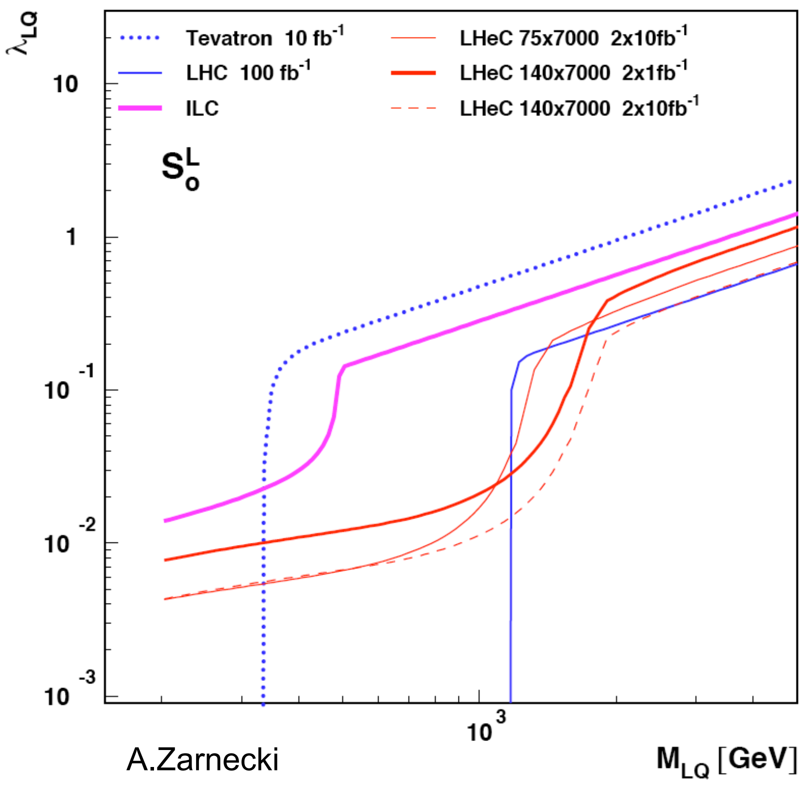
The THERA Book (2001)& Part IV of TESLA TDR

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

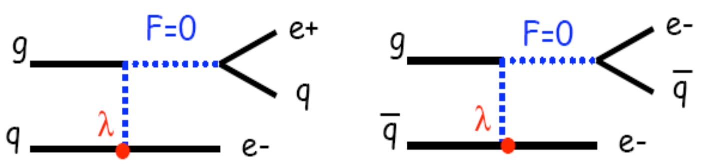


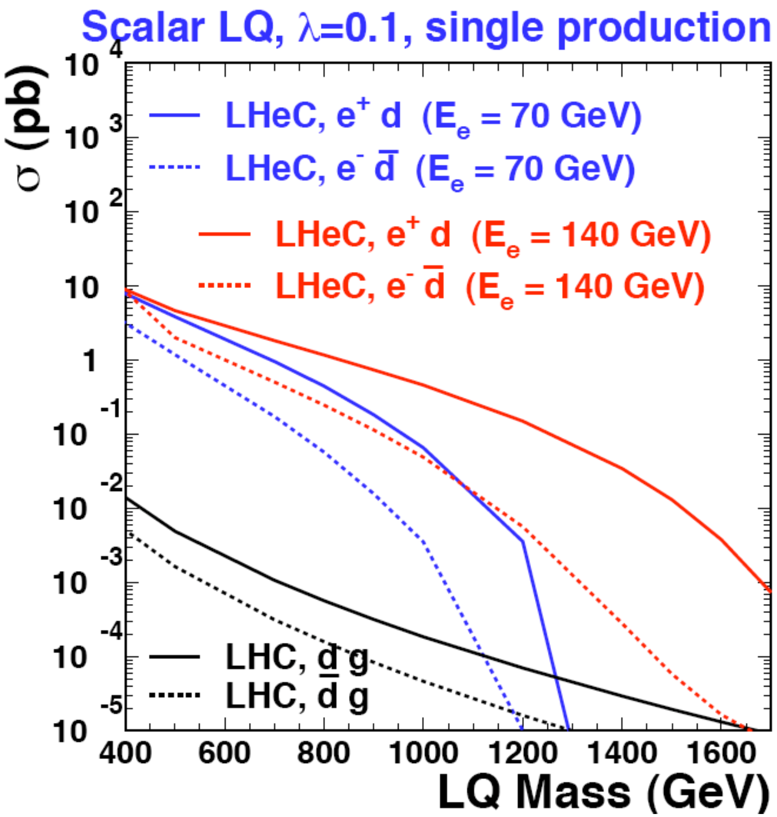
A.Zarnecki

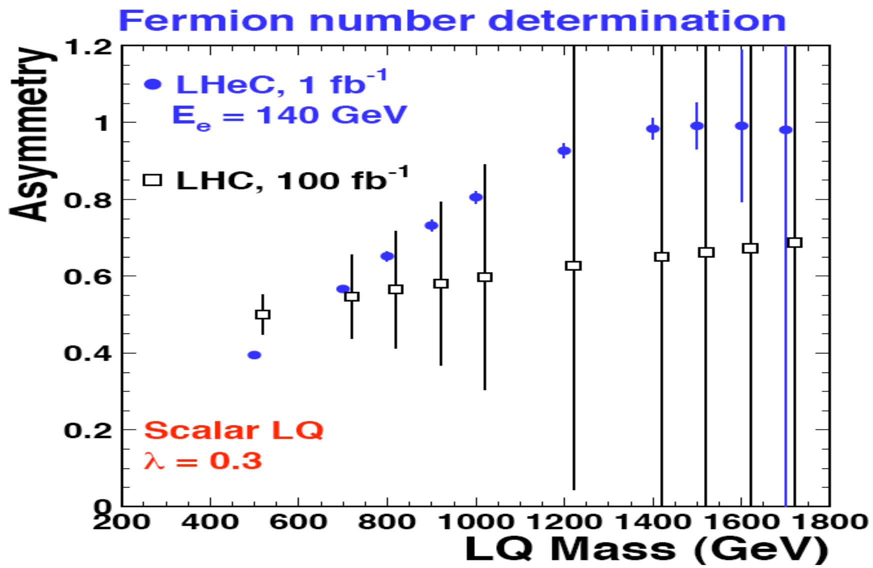
	ep		pp		
	eq	νq	llqq	lνqq	ννqq
SM:	NC DIS	CC DIS	Z/DY + jj QCD	W + jj	W/Z + jj QCD

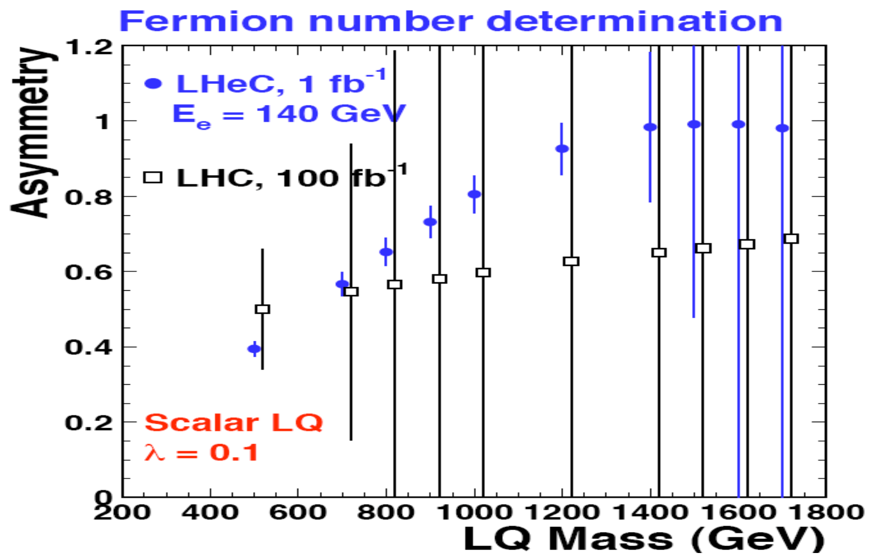
Charge, angular distribution, polarisation: quantum numbers may be determined in ep.
Similarly: If the LHC sees some CI, you may need pp and ep and ee to resolve the new i.a..

Quantum Numbers







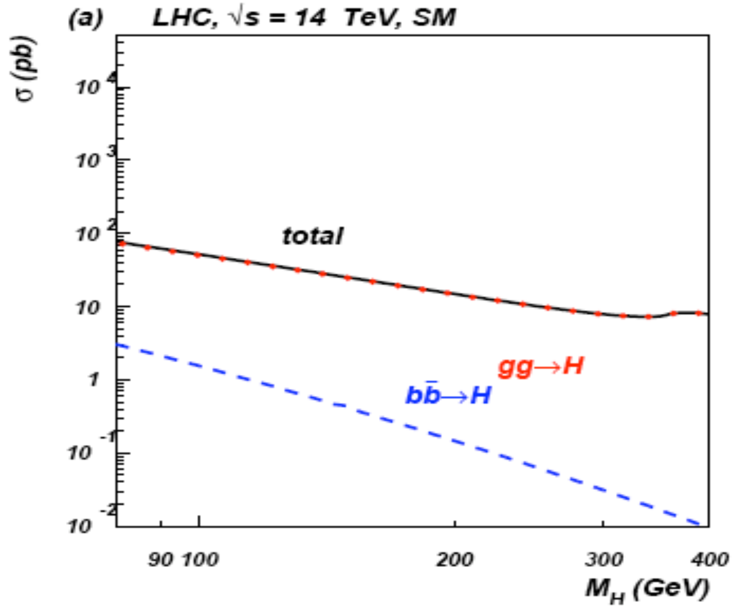


E.Perez, DIS07

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

Gluon

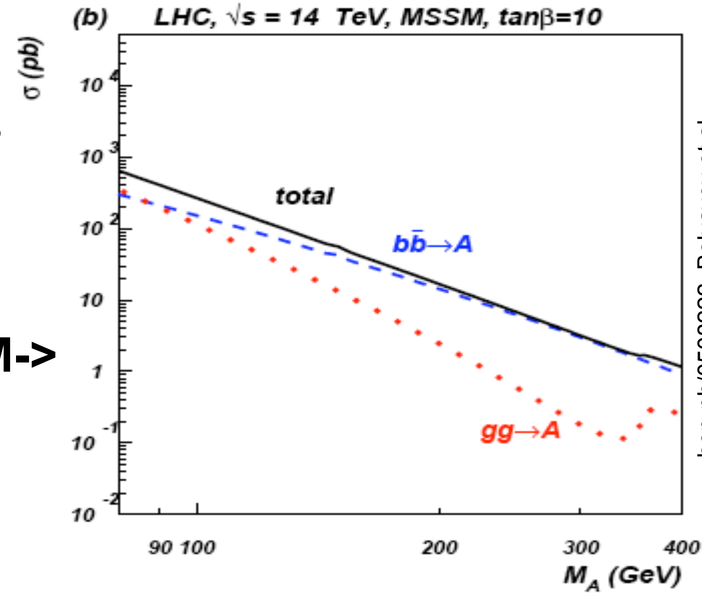
Beauty



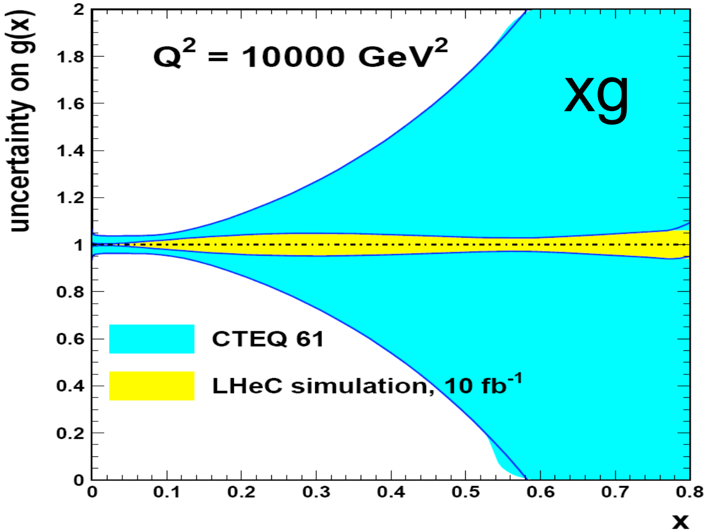
Higgs

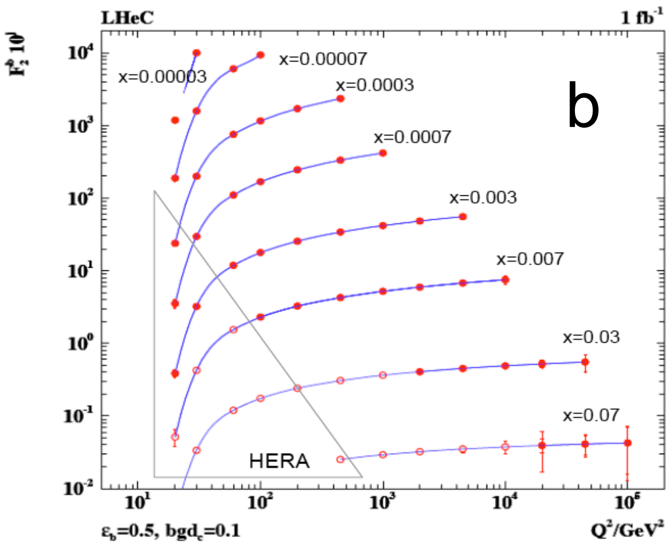
<-SM

MSSM->

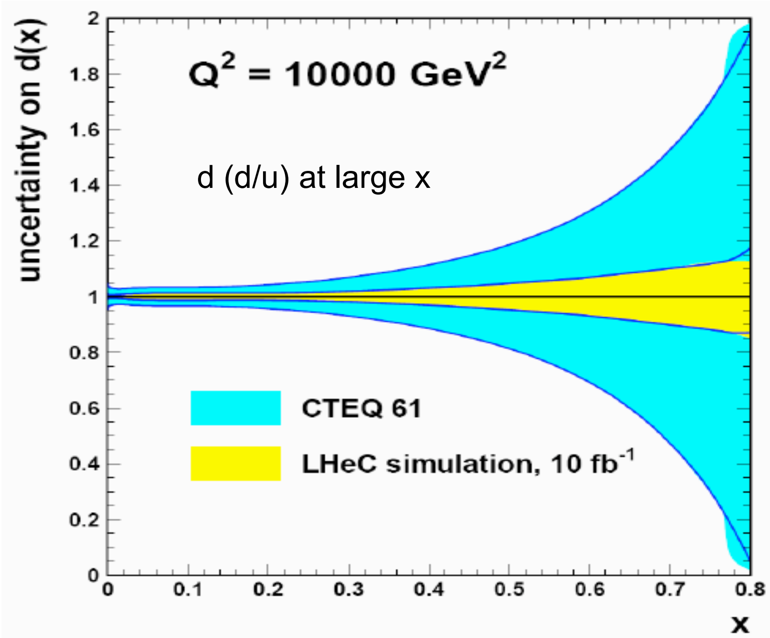


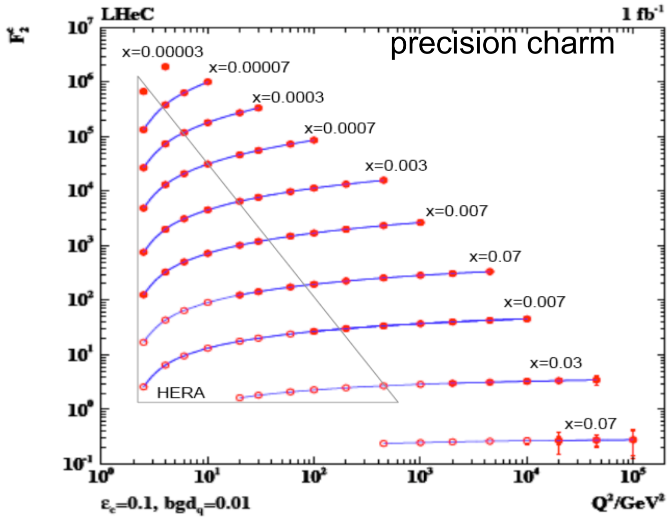
hep-ph/0508222, Belyayev et al

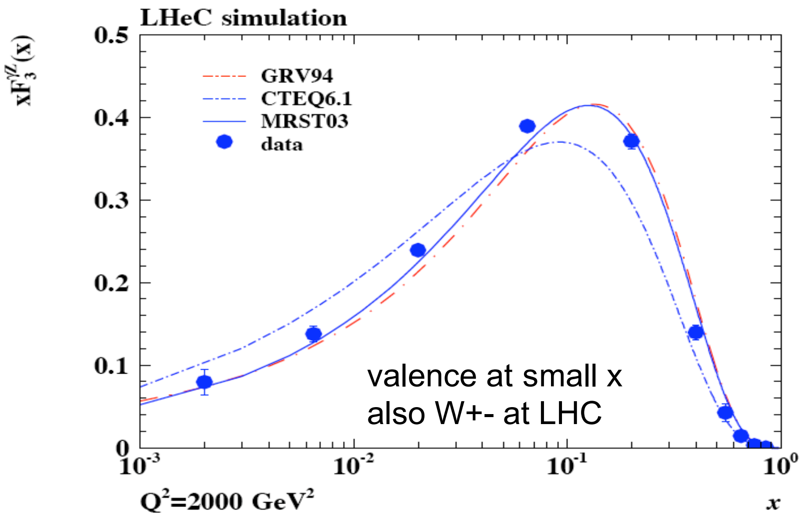


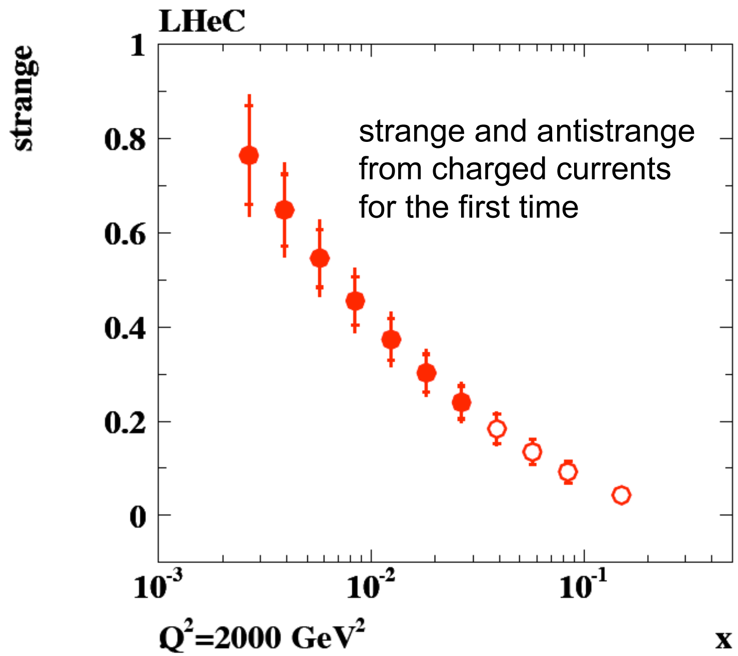


Complete Unfolding of the Quark Content of the Nucleon (NC,CC) at PeV energies

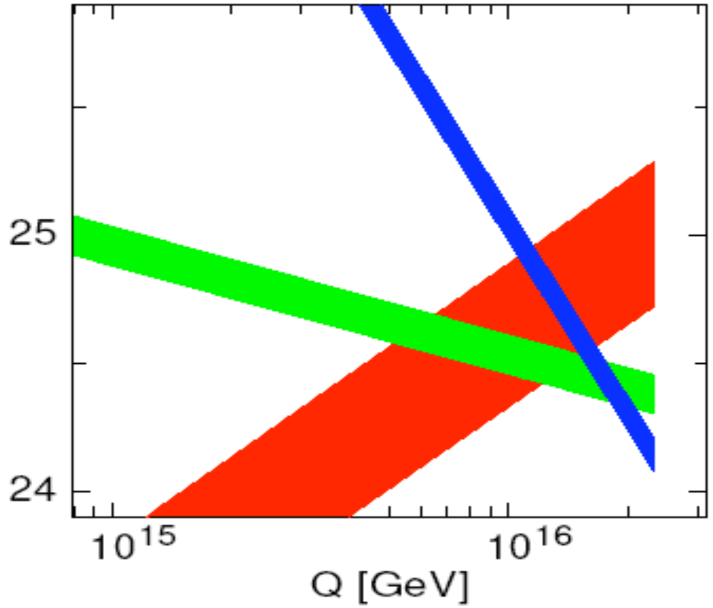


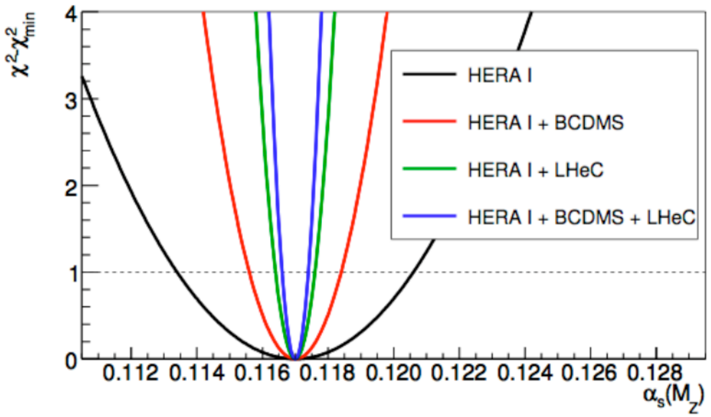






Strong Coupling





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

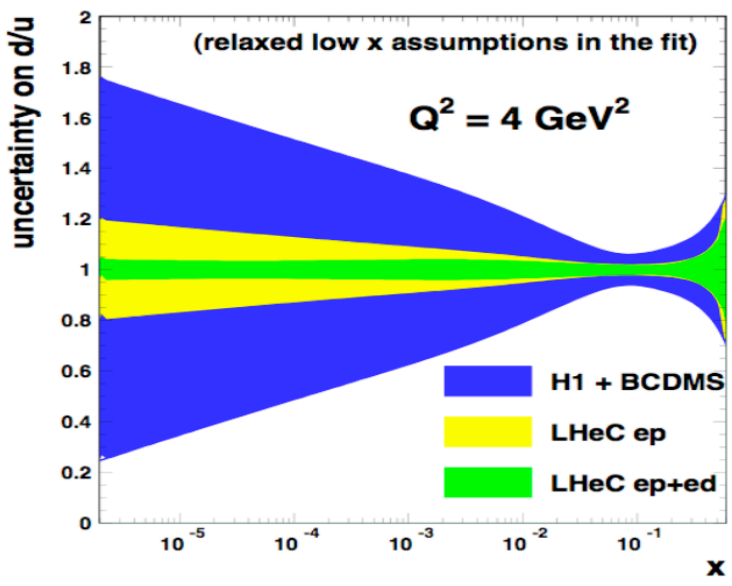
(7) Production of the Higgs boson in $ep \to eHX$. A remarkable consequence of the intrinsic charm and bottom Fock states of the proton is the production of the Higgs boson with more than 80% of the proton's momentum [7]. This necessitates detectors with forward acceptance in the proton fragmentation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

Heavy flavours & hadron structure

Stan Brodsky's 13 Questions

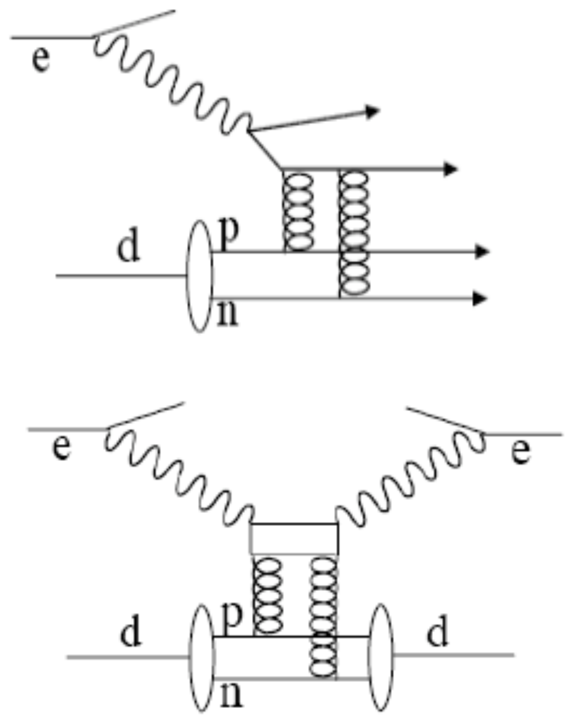
Neutron Structure (ed → eX)

d/u at low x from deuterons

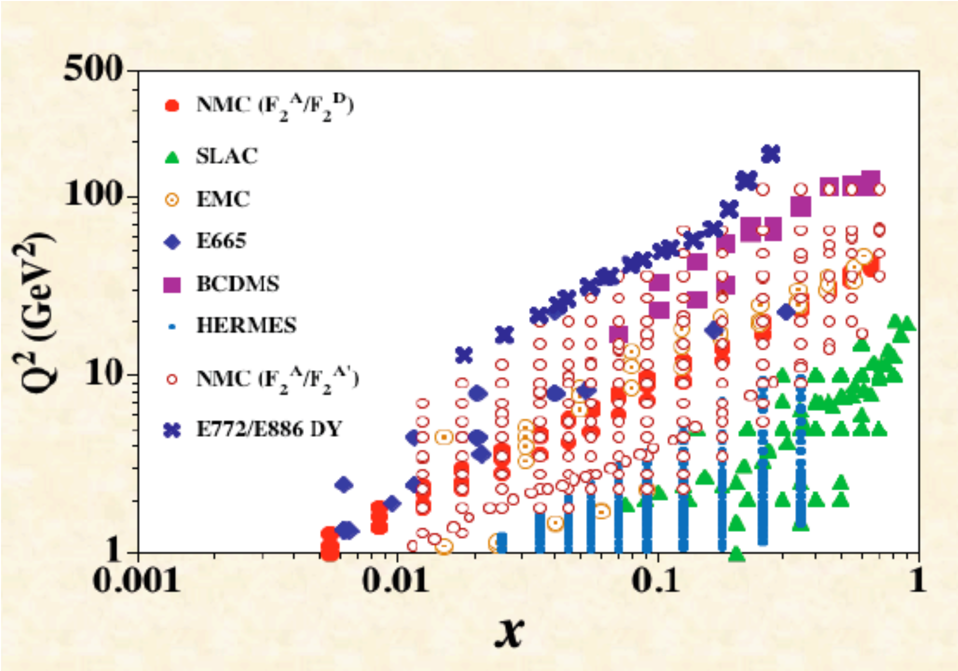


(13) There are five color-singlet combinations of the deuteron wavefunction in QCD, only one of which is the standard proton-neutron state. The "hidden color" [13] components will lead to high multiplicity final states in deep inelastic electron-deuteron scattering.

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



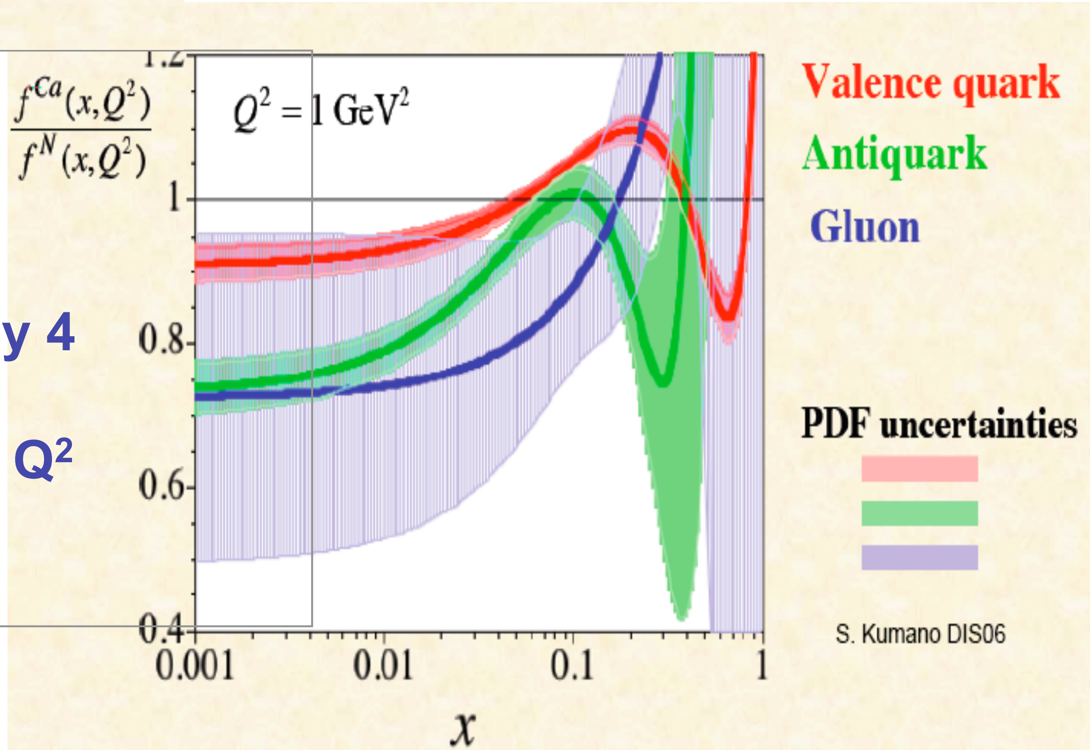
Nuclear Structure

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

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

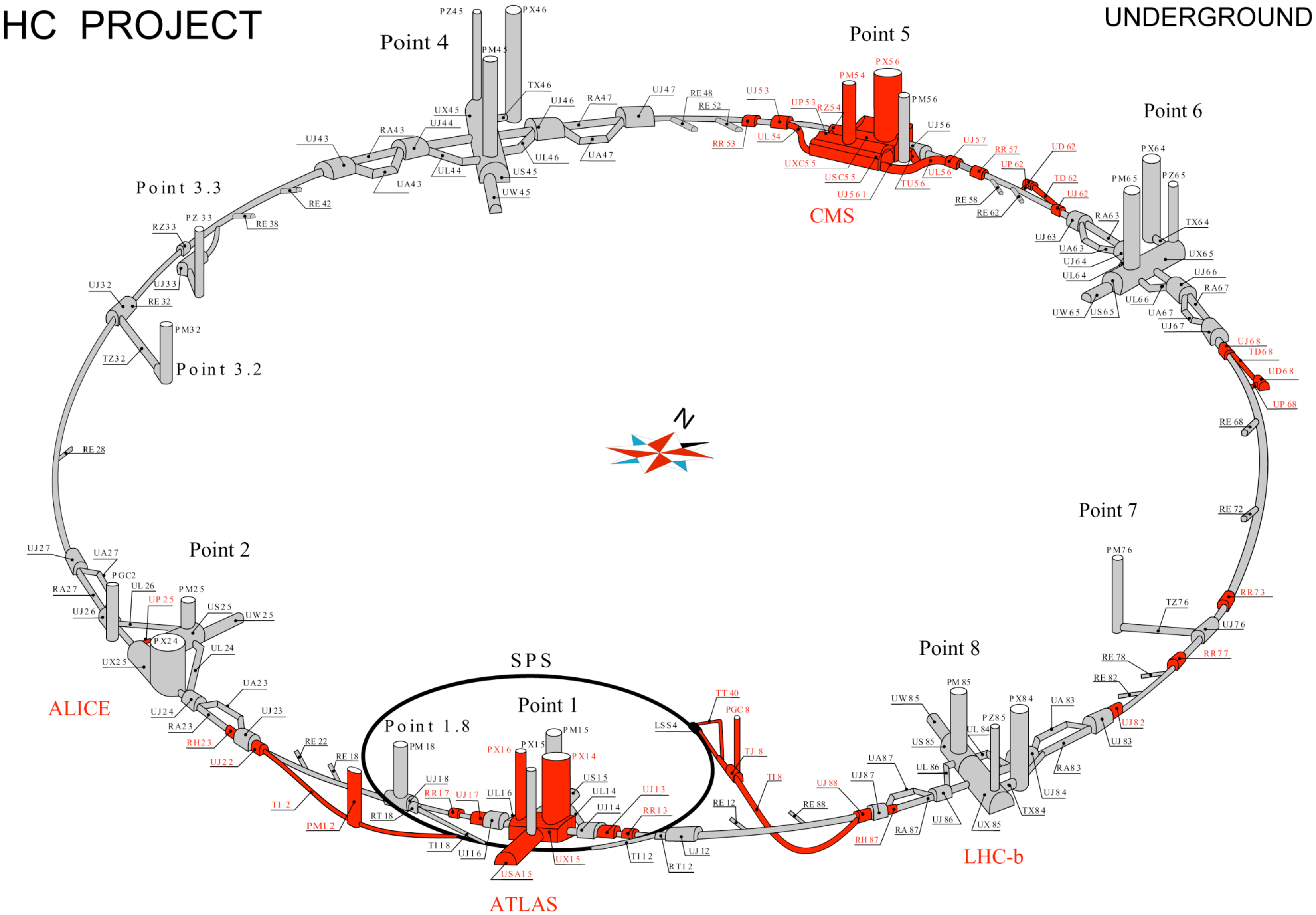
unitarity limit

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.

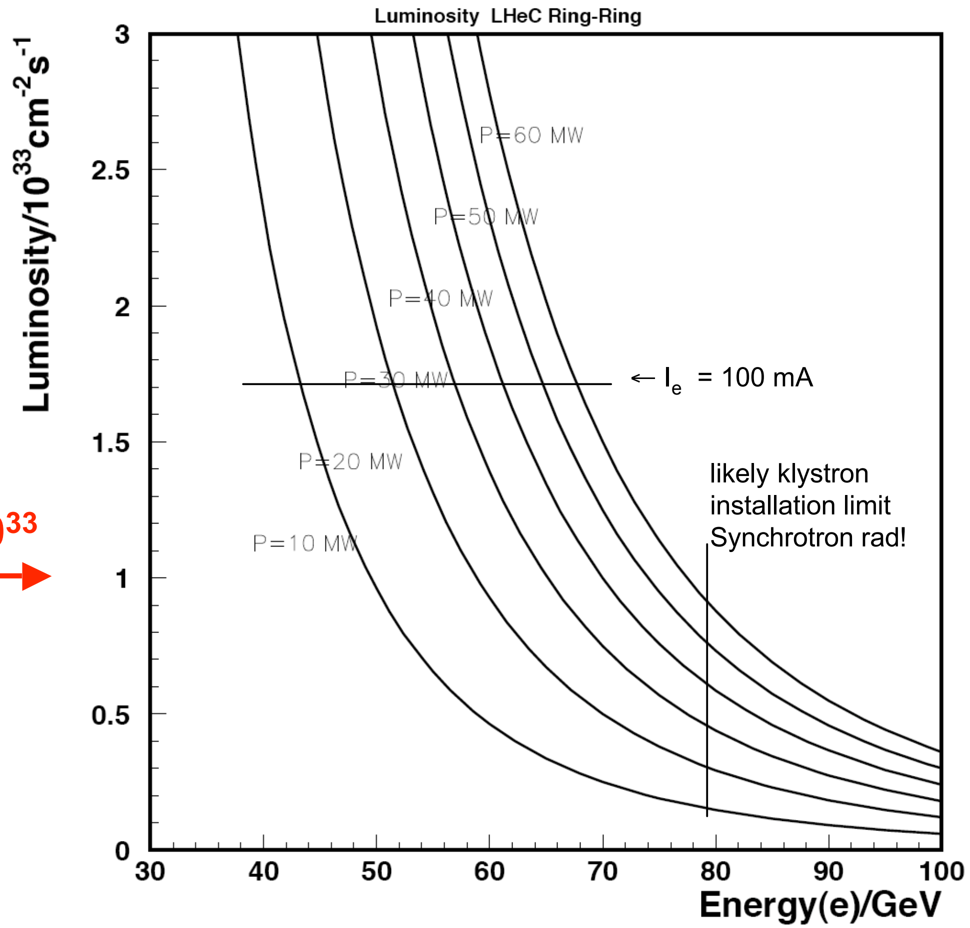
Luminosity: Ring-Ring

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

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

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

10^{33} →



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

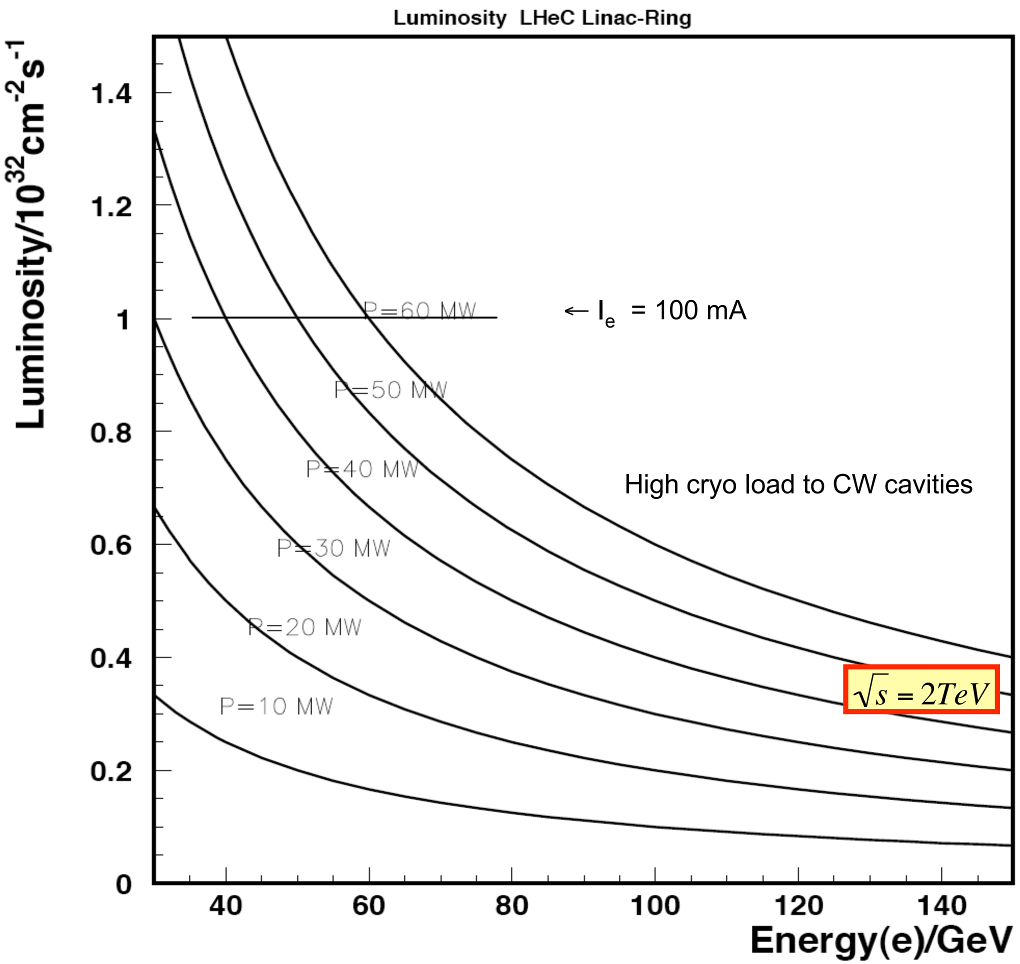
May reach 10^{34} with ERL in bypasses, or/and reduce power. R&D performed at BNL/eRHIC

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

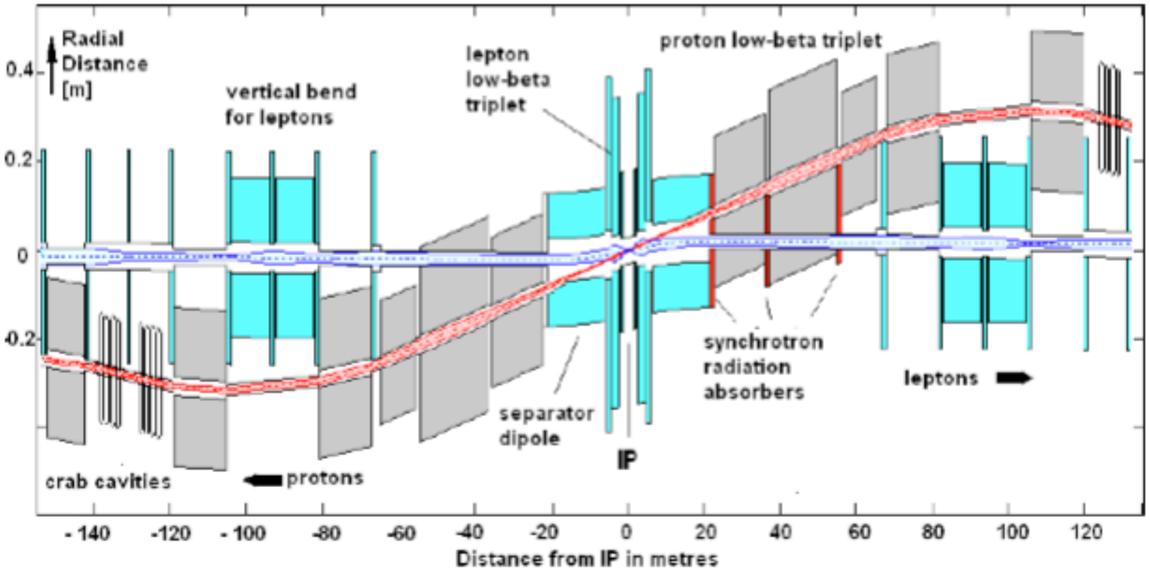
140 GeV at 23 MV/m is 6km +gaps

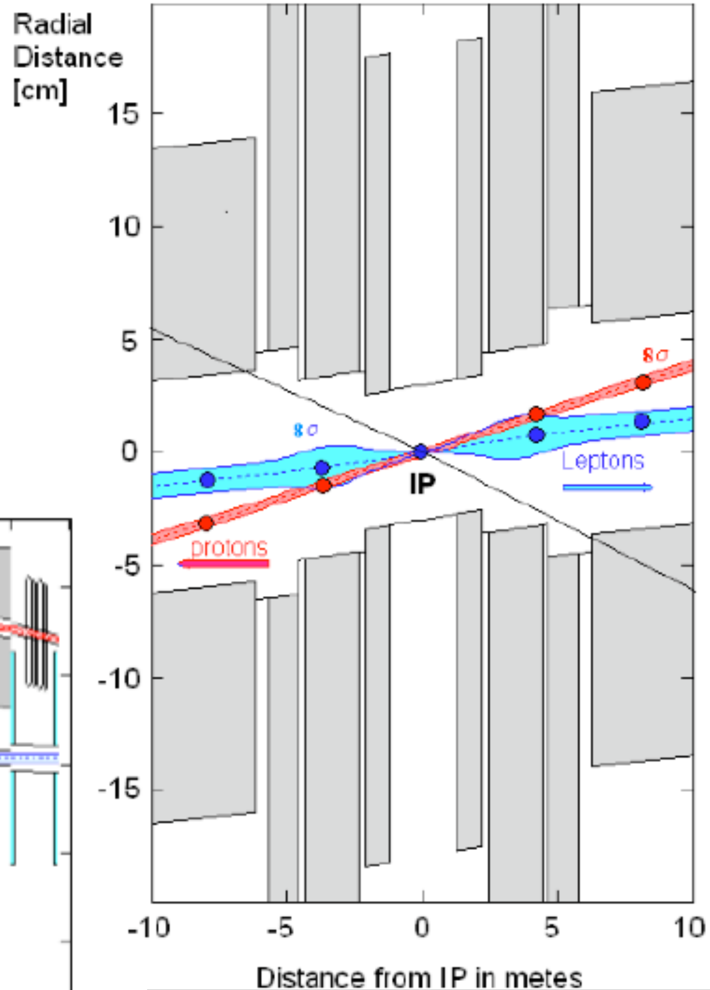
Luminosity horizon: high power:
ERL (2 Linacs?)

Ring-Ring LHeC Interaction Region Design

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

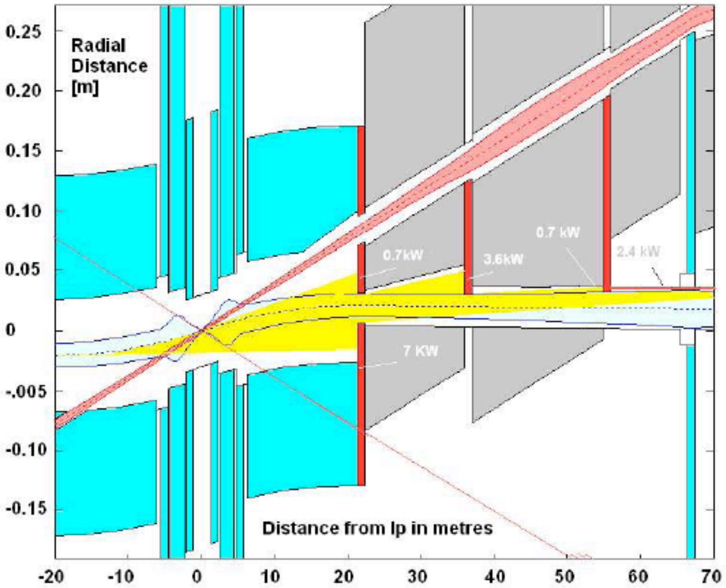
Property	Unit	Leptons	Protons
Beam Energies	GeV	70	7000
Total Beam Current	mA	74	544
Number of Particles / bunch	10^{10}	1.04	17.0
Horizontal Beam Emittance	nm	7.6	0.501
Vertical Beam Emittance	nm	3.8	0.501
Horizontal β-functions at IP	cm	12.7	180
Vertical β-function at the IP	cm	7.1	50
Energy loss per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





foresees simultaneous operation of pp and ep

Design Details

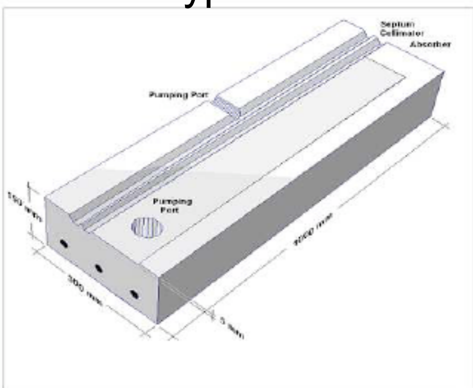


Synchrotron radiation fan

and HERA type absorber

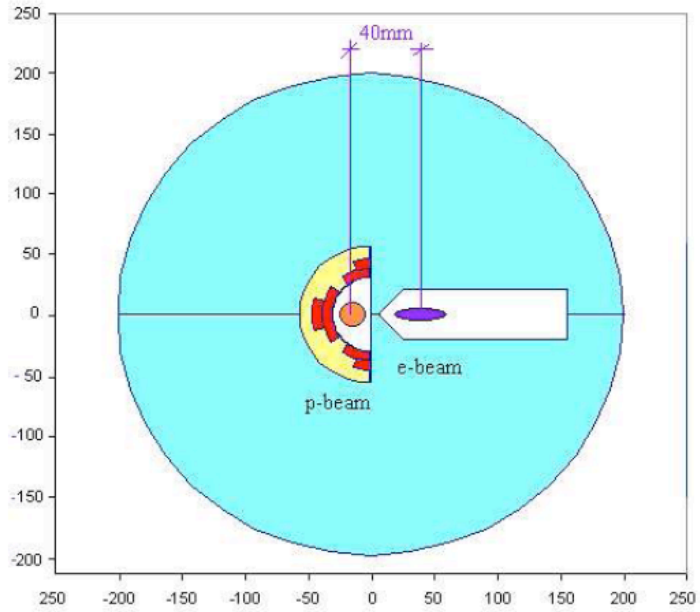
$9.1kW$

$E_{crit} = 76keV$

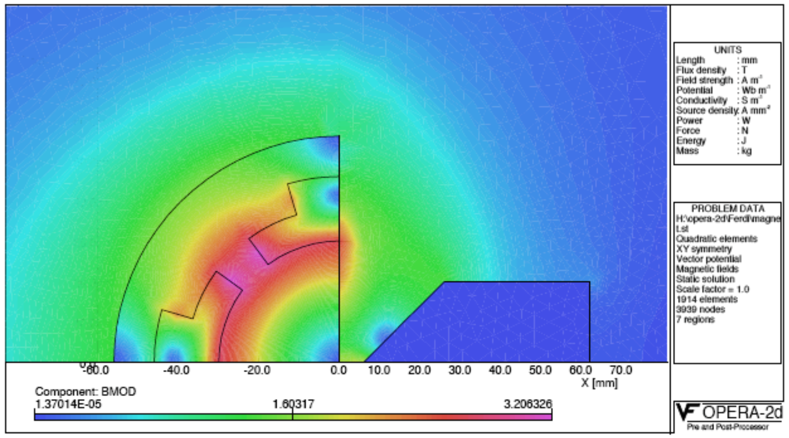


100W/mm^2

cf also W.Bartel Aachen 1990



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



Accelerator (RR) questions considered

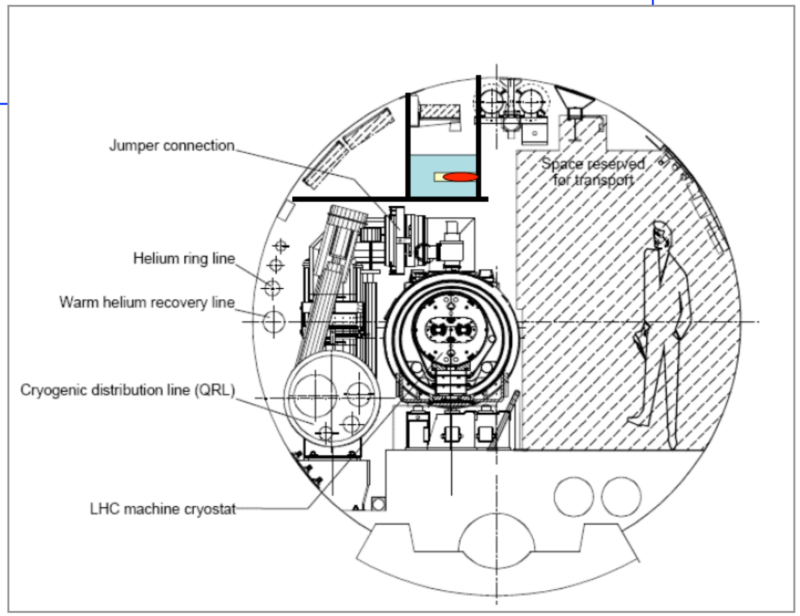
Power: 25ns: nx40MHz rf frequency. Imax 100 mA: 60 klystrons with 1.3MW
coupler of perhaps 0.5MW, 66% efficient… need space for rf in bypasses

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?)

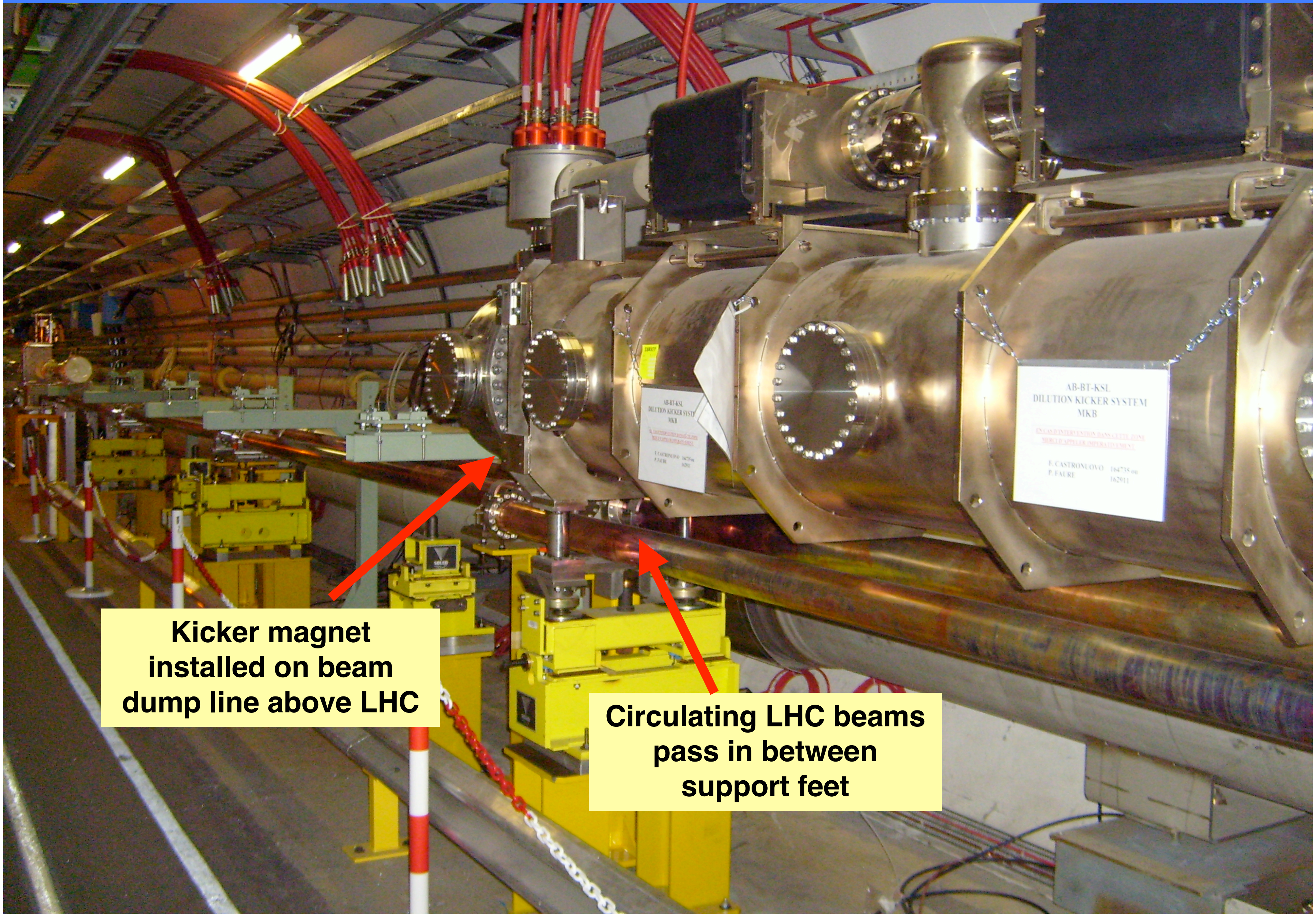
Synchrotron load to LHC magnets: can be shielded (water cooled Pb)

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.

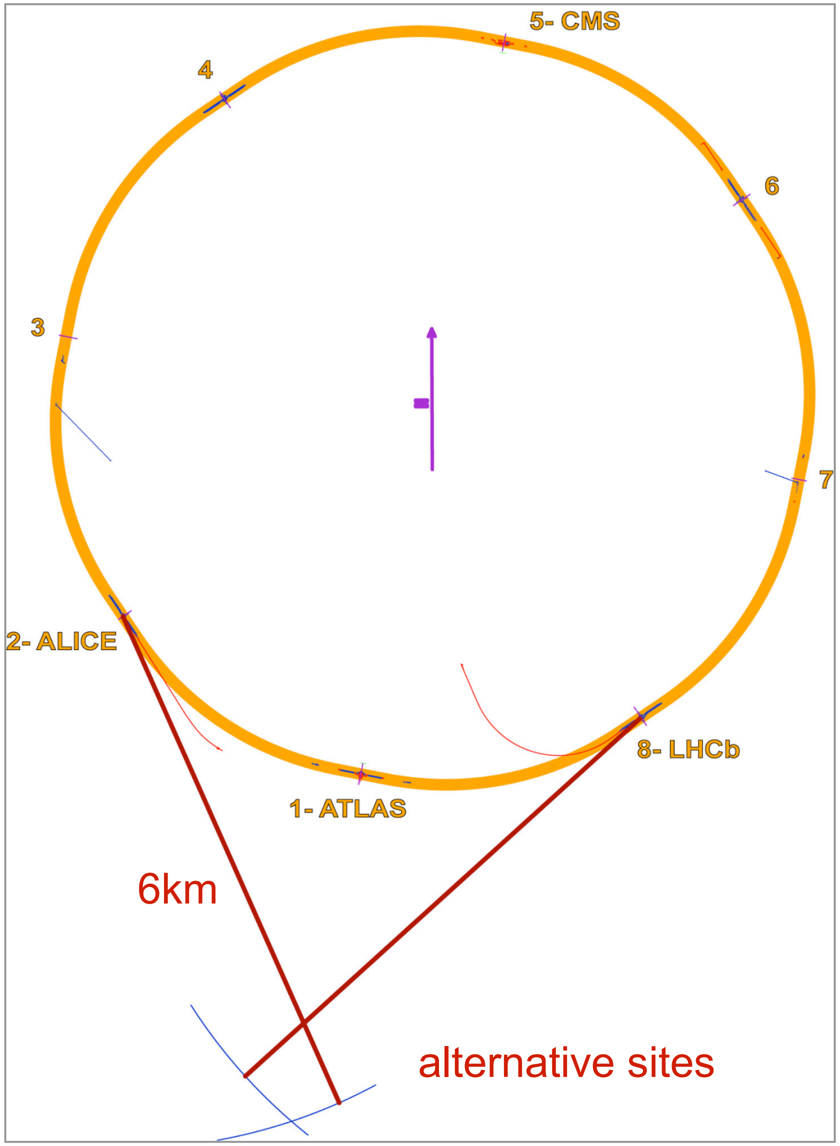
Space: first look at the installation on top of LHC



Passing equipment above installed LHC beamlines….



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



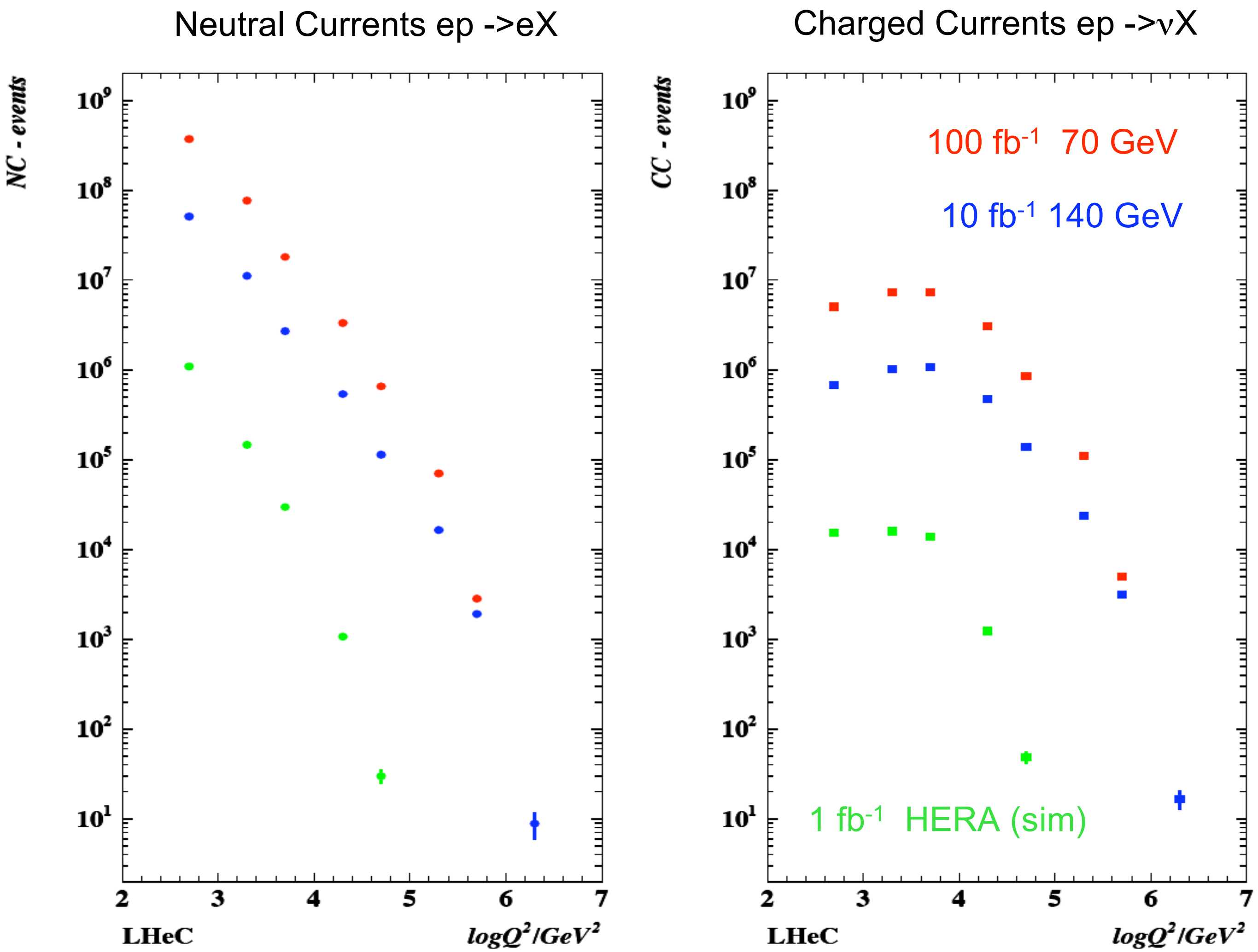
		ring-linac pulsed		ring-linac, cw , ~99% energy recovery	
	units	e-	p	e-	p
energy	GeV	70	7000	70	7000
punch population	10^{10}	2	17	2	17
σ_z	cm	0.03	7.55	0.03	7.55
beam current (pulsed)	mA	101	858	101	858
emittance $\varepsilon_{x,y}$	nm	0.5, 0.5			
$\beta^*_{x,y}$	cm	15, 15			
spacing	ns	25			
e-linac/ring 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



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 .

Part IV - Towards a Conceptual Design Report

Scientific Advisory Committee (SAC)

Accelerator Experts
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John Dainton	(Cockcroft)
Albert DeRoeck	(CERN)
Stefano Forte	(Milano)
Max Klein - chair	(Liverpool)
Paul Newman	(Birmingham)
Emmanuelle Perez	(CERN)
Wesley Smith	(Wisconsin)
Bernd Surrow	(MIT)
Katsuo Tokushuku	(KEK)
Urs Wiedemann	(CERN)

Working Group Structure

Accelerator Design [RR and LR]

Interaction Region and Forward Detectors

Infrastructure and Cost

Detector Design

New Physics at Large Scales

Precision QCD and Electroweak Interactions

Physics at High Parton Densities [small x and eA]

Convenors are being or will be invited

The Goal of the ECFA Workshop(s) 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.

Summary and Proposal to ECFA

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.

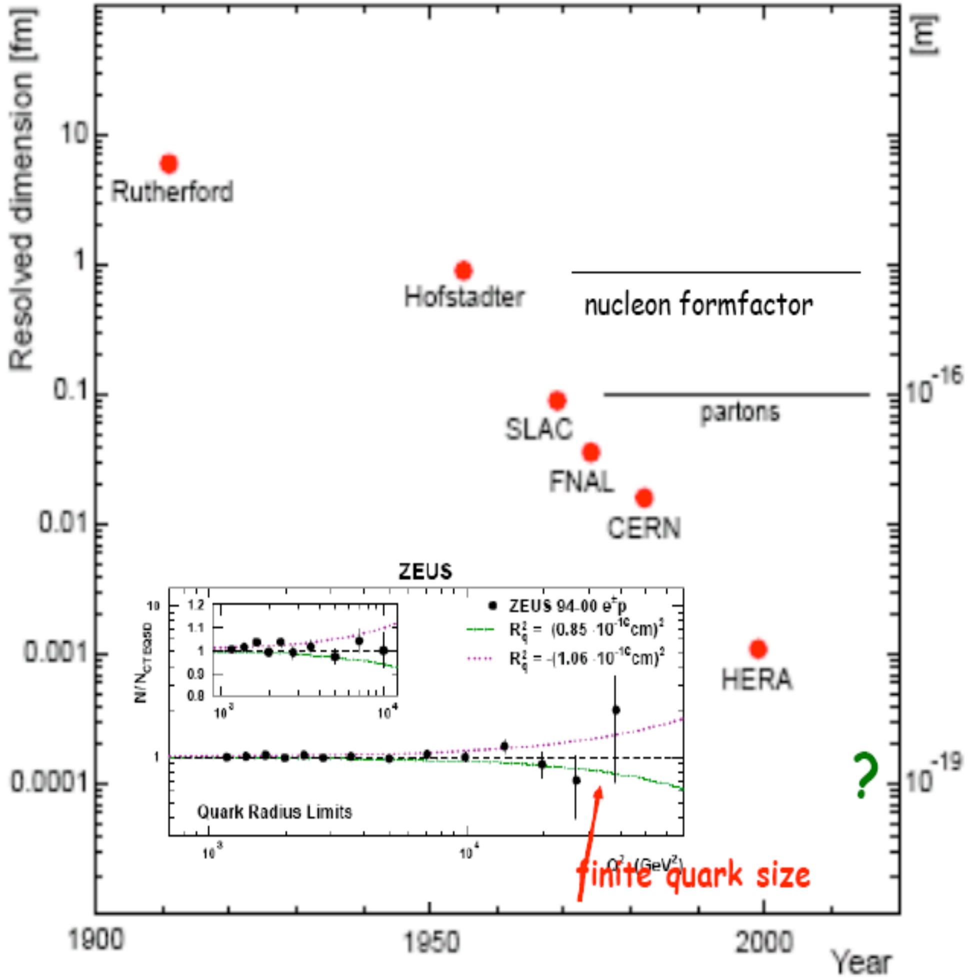
It is thus proposed to hold two workshops (2008 and 2009), under the auspices of ECFA, with the goal of having a Conceptual Design Report on the accelerator, the experiment and the physics. A Technical Design report will then follow if appropriate.

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

History and Thanks



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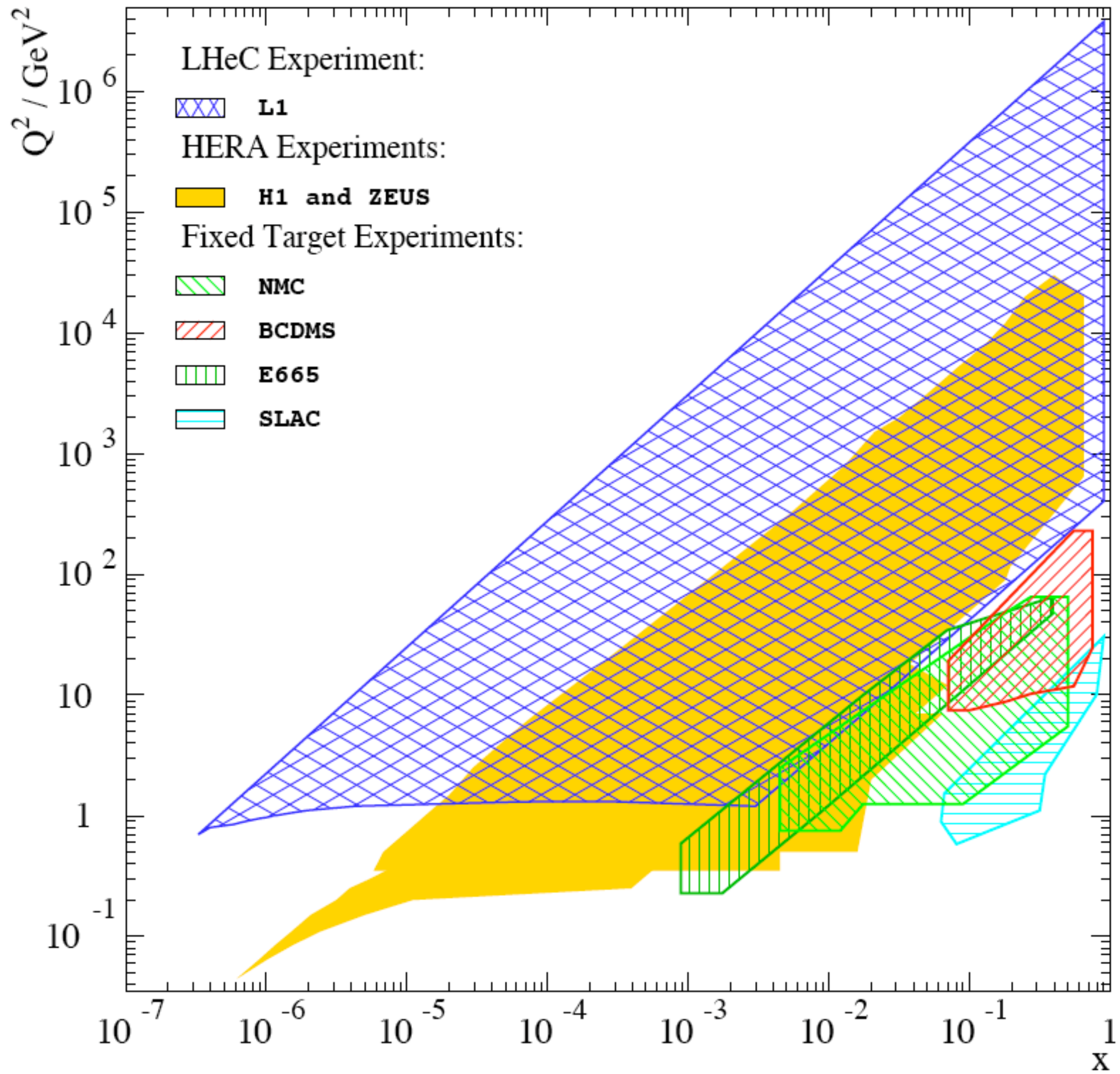
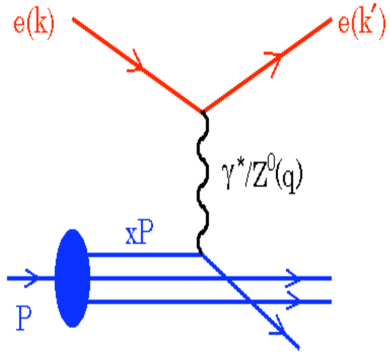
http://www.lhec.org.uk

Backup

Kinematic coverage: lp scattering





$$s = 4E_e E_p$$

$$Q^2 = sxy$$

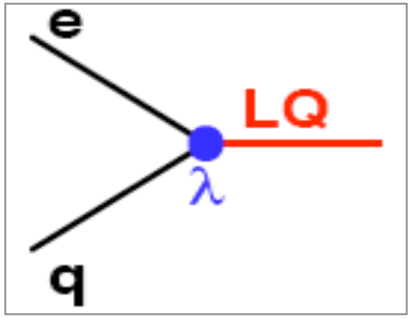
x – Bjorken

y – inelasticity

$$M_{\gamma^* p} = W \approx \sqrt{sy} = \sqrt{\frac{Q^2}{x}}$$

$$M_{eq} = \sqrt{sx}$$

Electron-Quark Resonances



ep facilities lead to the
possible formation of
eq resonances
at masses as high as
$M^2 = sx$.
With high energy (s),
high luminosity (large x)
and variation of lepton beam
charge and polarisation
eq resonance spectroscopy
can be studied, should new
states exist (LQ, RPV SUSY)

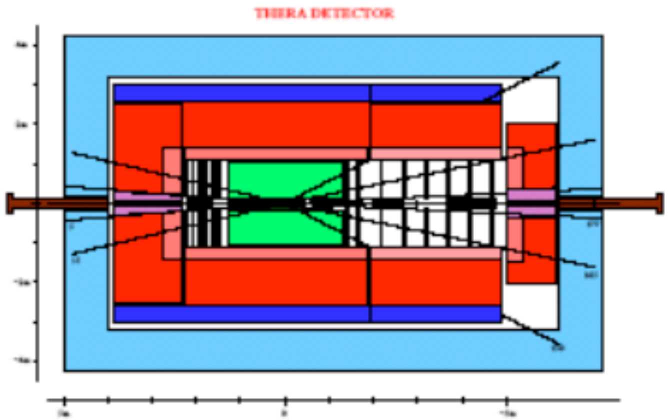
Model	Fermion number F	Charge Q	$BR(LQ \rightarrow e^{\pm}q)$ β	Coupling		Squark type
S_0^L	2	$-1/3$	$1/2$	$e_L u$	νd	$\tilde{d}_R$
S_0^R	2	$-1/3$	1	$e_R u$		
$\tilde{S}_0$	2	$-4/3$	1	$e_R d$		
$S_{1/2}^L$	0	$-5/3$	1	$e_L \bar{u}$		
		$-2/3$	0		$\nu \bar{u}$	
$S_{1/2}^R$	0	$-5/3$	1	$e_R \bar{u}$		
		$-2/3$	1	$e_R \bar{d}$		
$\tilde{S}_{1/2}$	0	$-2/3$	1	$e_L \bar{d}$		$\overline{\tilde{u}_L}$
		$+1/3$	0		$\nu \bar{d}$	$\overline{\tilde{d}_L}$
S_1	2	$-4/3$	1	$e_L d$		
		$-1/3$	$1/2$	$e_L u$	νd	
		$+2/3$	0		νu	
V_0^L	0	$-2/3$	$1/2$	$e_L \bar{d}$	$\nu \bar{u}$	
V_0^R	0	$-2/3$	1	$e_R \bar{d}$		
$\tilde{V}_0$	0	$-5/3$	1	$e_R \bar{u}$		
$V_{1/2}^L$	2	$-4/3$	1	$e_L d$		
		$-1/3$	0		νd	
$V_{1/2}^R$	2	$-4/3$	1	$e_R d$		
		$-1/3$	1	$e_R u$		
$\tilde{V}_{1/2}$	2	$-1/3$	1	$e_L u$		
		$+2/3$	0		νu	
V_1	0	$-5/3$	1	$e_L \bar{u}$		
		$-2/3$	$1/2$	$e_L \bar{d}$	$\nu \bar{u}$	
		$+1/3$	0		$\nu \bar{d}$	

DIS at the TeV scale

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



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LEP-LHC

A. Verdier LHC Workshop Aachen 90, p.820

E. Keil LHC Project Report 93 (1997)

THERA

R. Brinkmann, F. Willeke THERA book
and Proceedings Snowmass 2001

QCD explorer (CLIC-LHC')

D. Schulte, F. Zimmermann CLIC 608

LHEC

F. Willeke (a study)

M.Klein, 30. 04. 2005 DIS05 Madison

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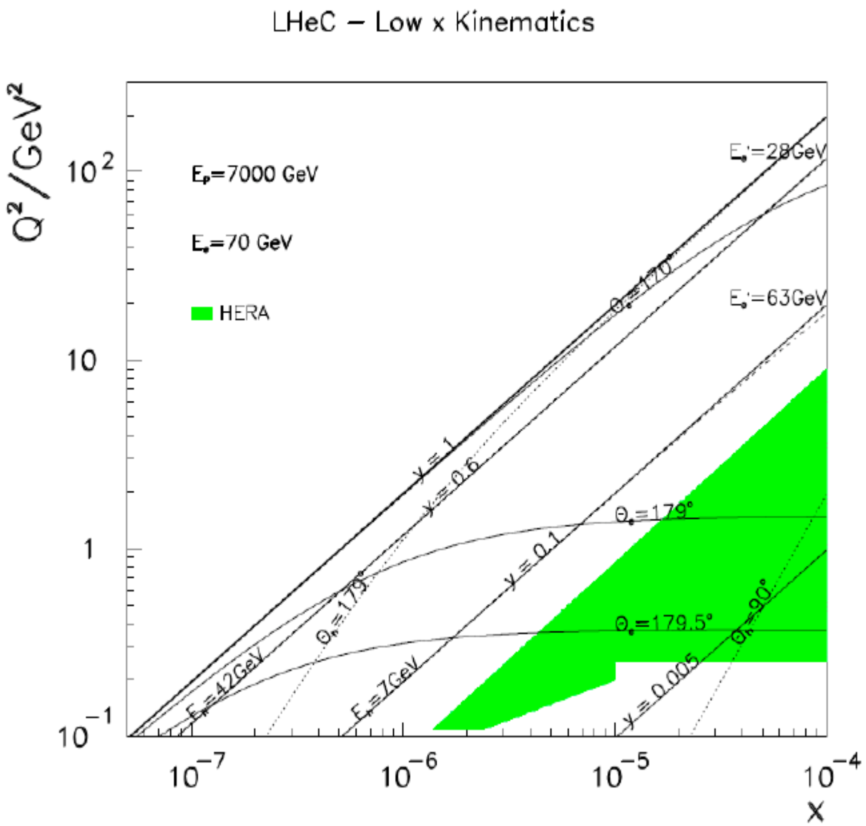
Deep inelastic electron-nucleon scattering at the LHC

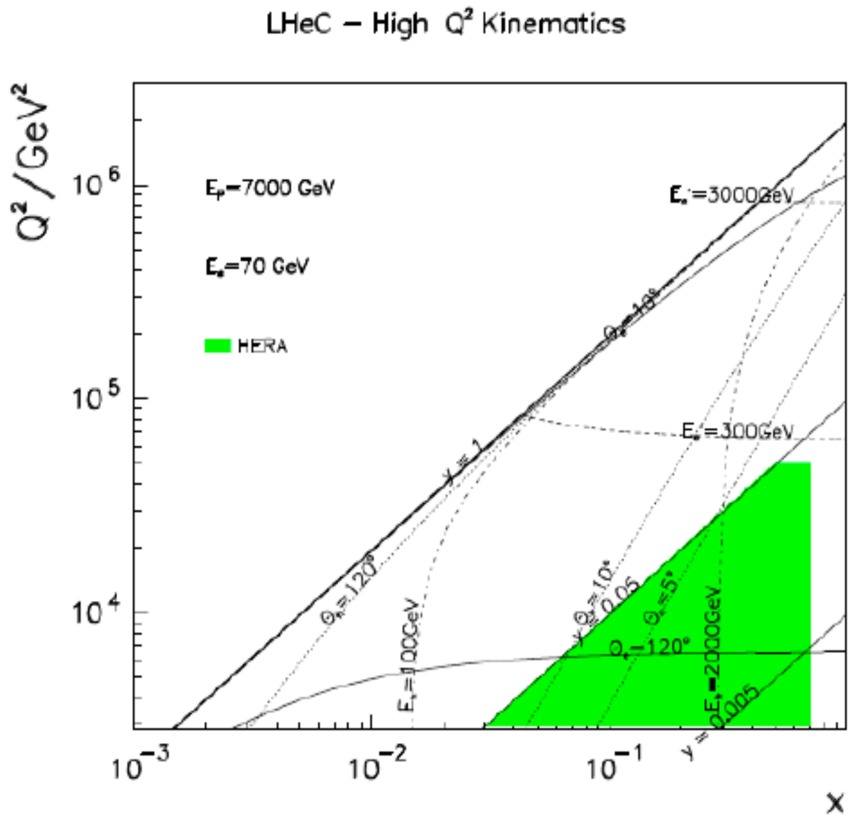
J.B. Dainton,[a] M. Klein,[b*] P. Newman,[c] E. Perez[d] and F. Willeke[b]

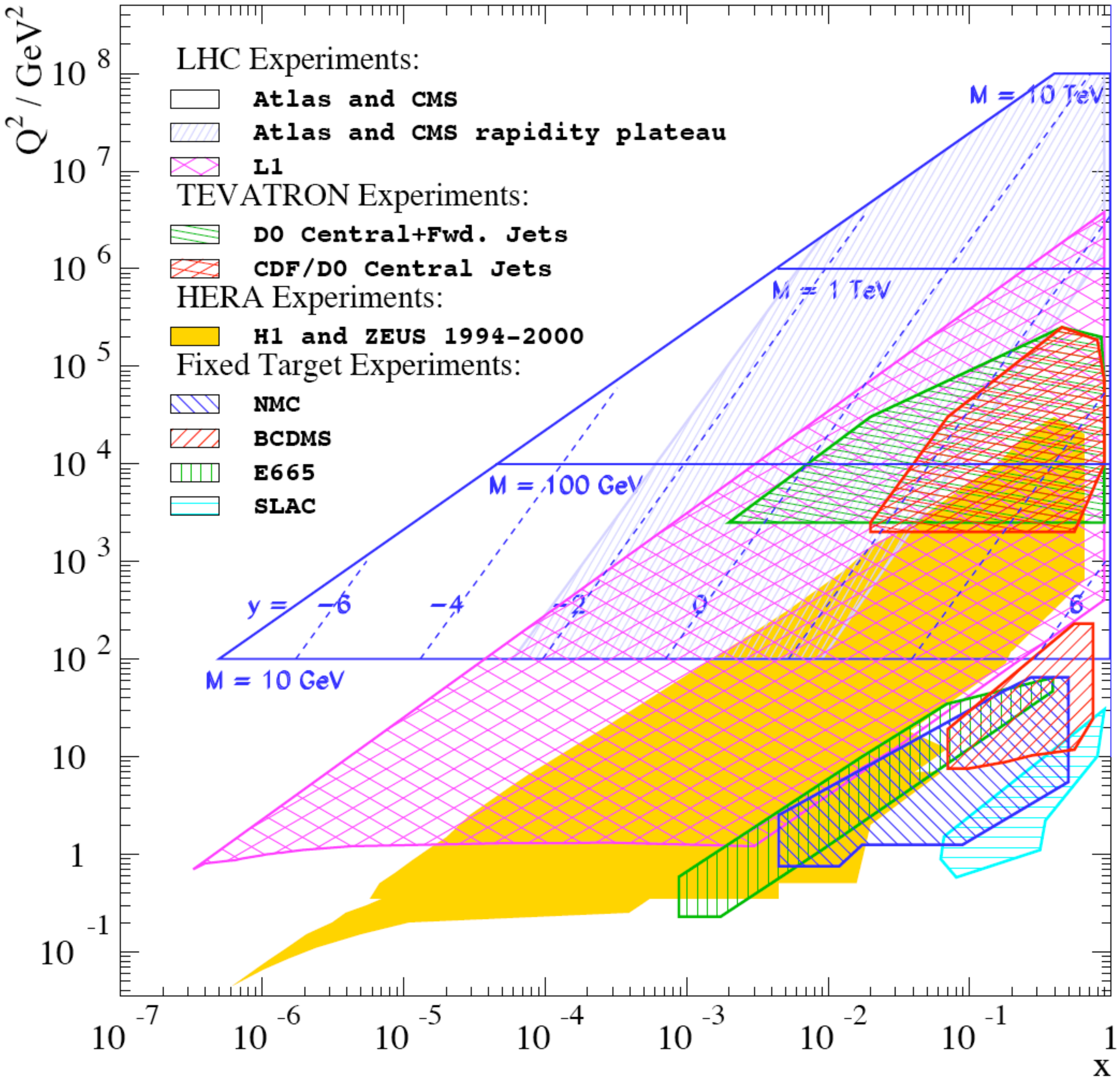
Close

“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 TeV (1 PeV). “ F.Close Singapor 1990

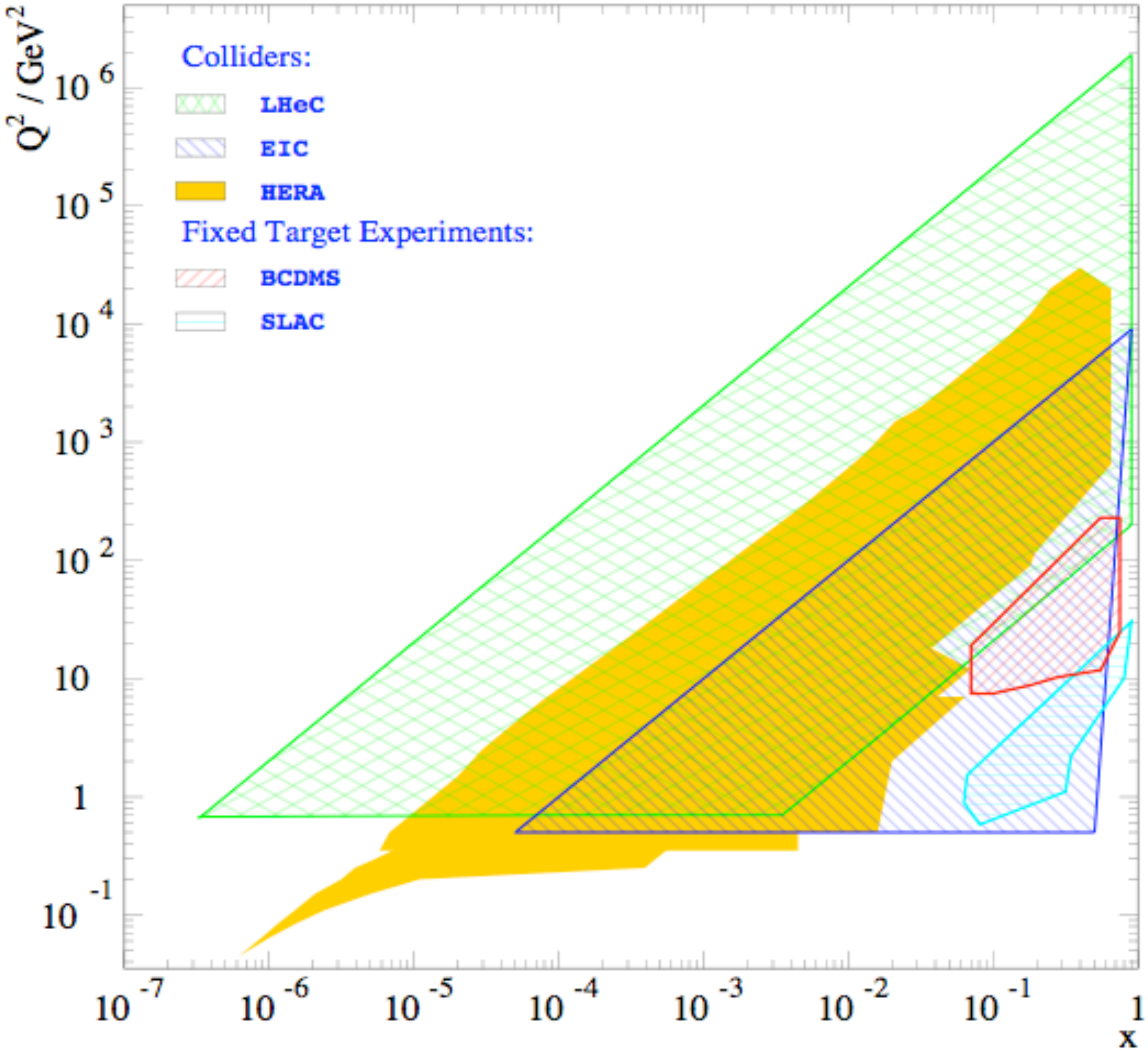
Interaction Region - Kinematics



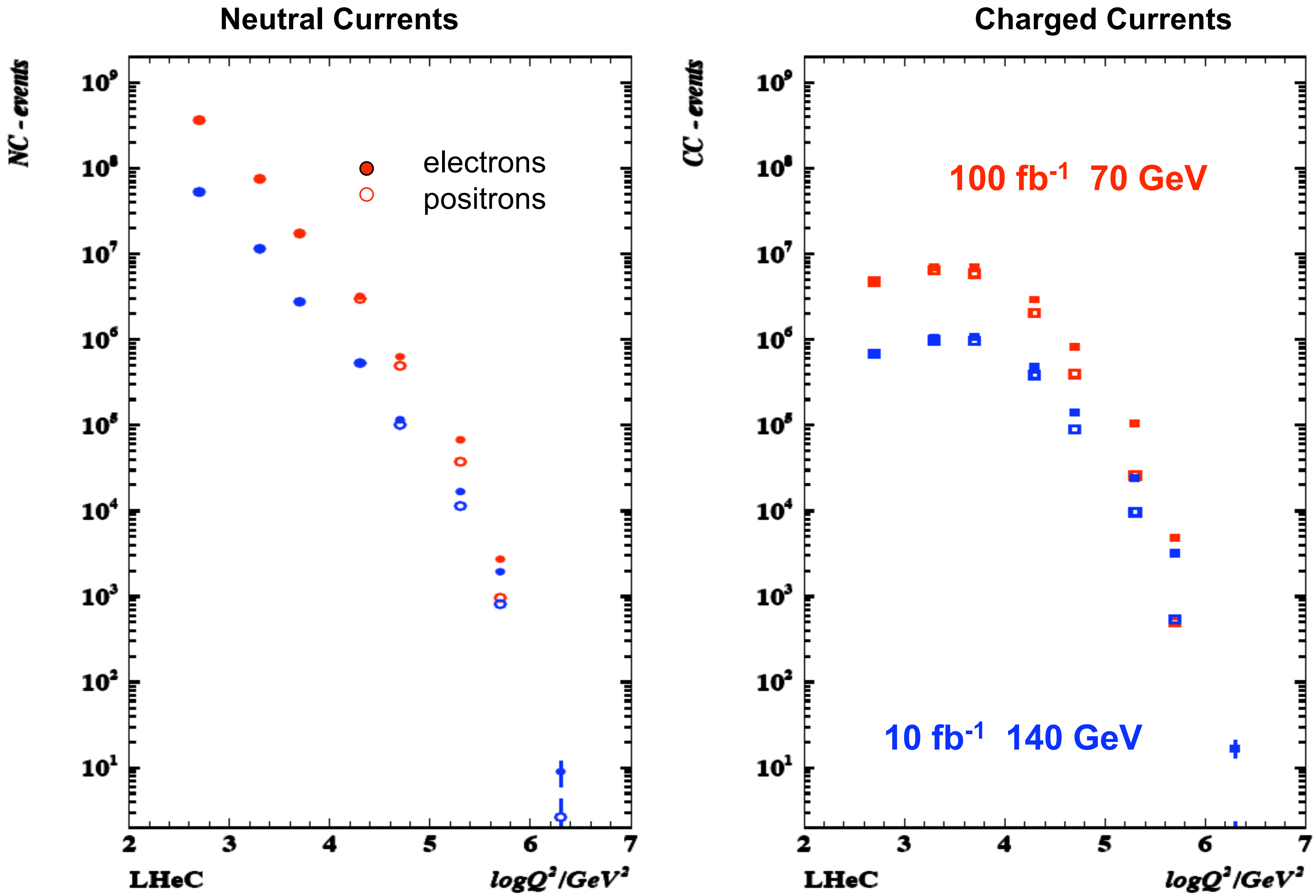



Q^2 / GeV^2
LHC Experiments:
Atlas and CMS
Atlas and CMS rapidity plateau
L1
TEVATRON Experiments:
D0 Central+Fwd. Jets
CDF/D0 Central Jets
HERA Experiments:
H1 and ZEUS 1994-2000
Fixed Target Experiments:
NMC
BCDMS
E665
SLAC
M = 10 TeV
M = 1 TeV
M = 100 GeV
M = 10 GeV
y = -6 -4 -2 0 2 4 6
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
1
x

LHeC, HERA and EIC



Event Rates: E_e x 7000 GeV



2 times E_e compensates for 10 times the energy at highest Q^2