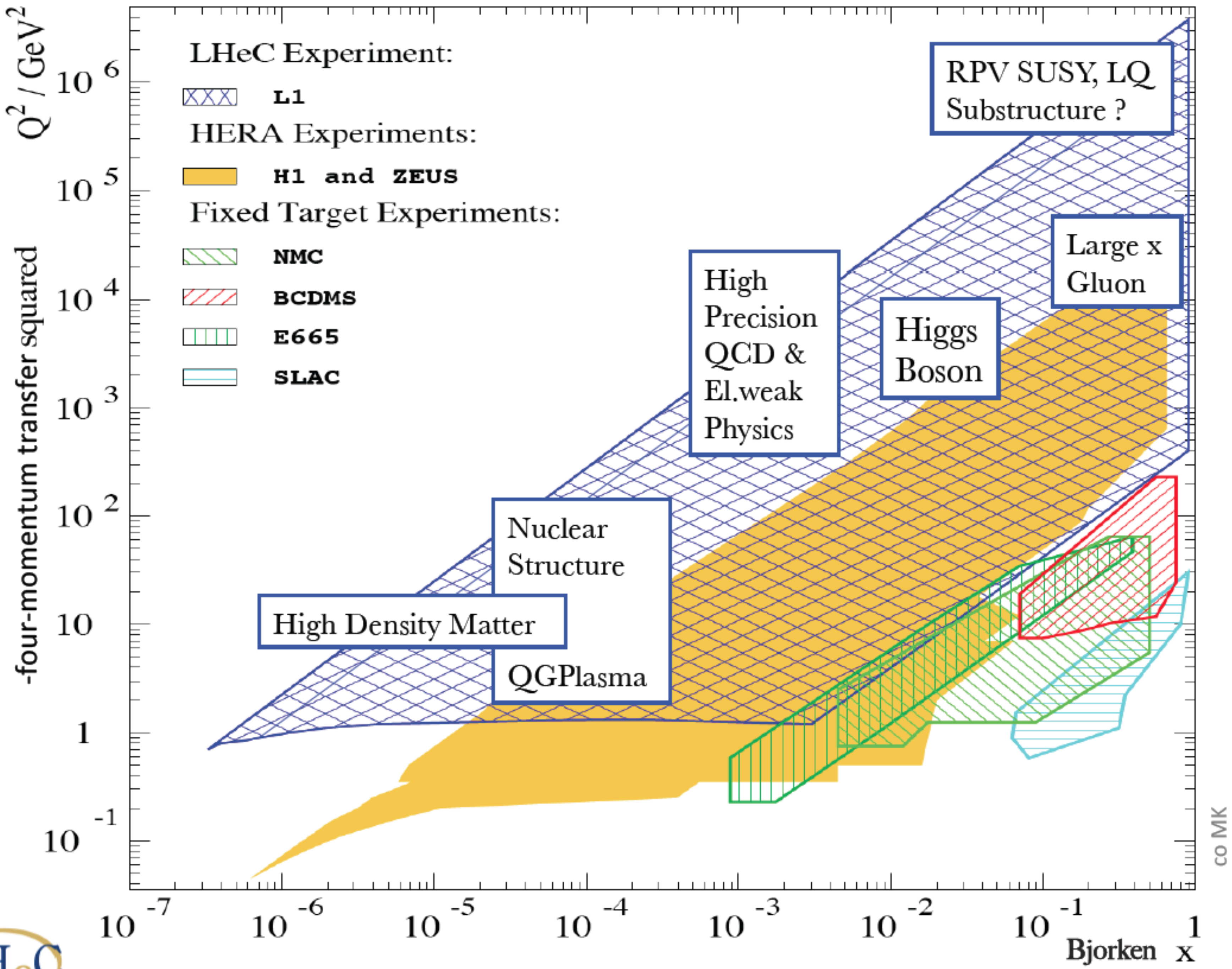
The Large Hadron Electron Collider Project

Conceptual Design and Project Status
Deep Inelastic Scattering?
Partons (ep,en,eA)
Higgs "Factory"
Next Steps

Max Klein
UNIVERSITY OF LIVERPOOL

http://cern.ch/lhec

Seminar at Glasgow, Scotland, June 13th, 2013


LHeC Experiment:
L1
HERA Experiments:
H1 and ZEUS
Fixed Target Experiments:
NMC
BCDMS
E665
SLAC
RPV SUSY, LQ
Substructure ?
Large x
Gluon
High
Precision
QCD &
El.weak
Physics
Higgs
Boson
Nuclear
Structure
High Density Matter
QGPlasma
Q^2 / GeV^2
-four-momentum transfer squared
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-7}
10^{-6}
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-Conceptual Design Report-

LHeC Collaboration
Default Linac-Ring Design
Physics
Detector
Time Schedule
CDR
CERN Mandate
ECFA Statement

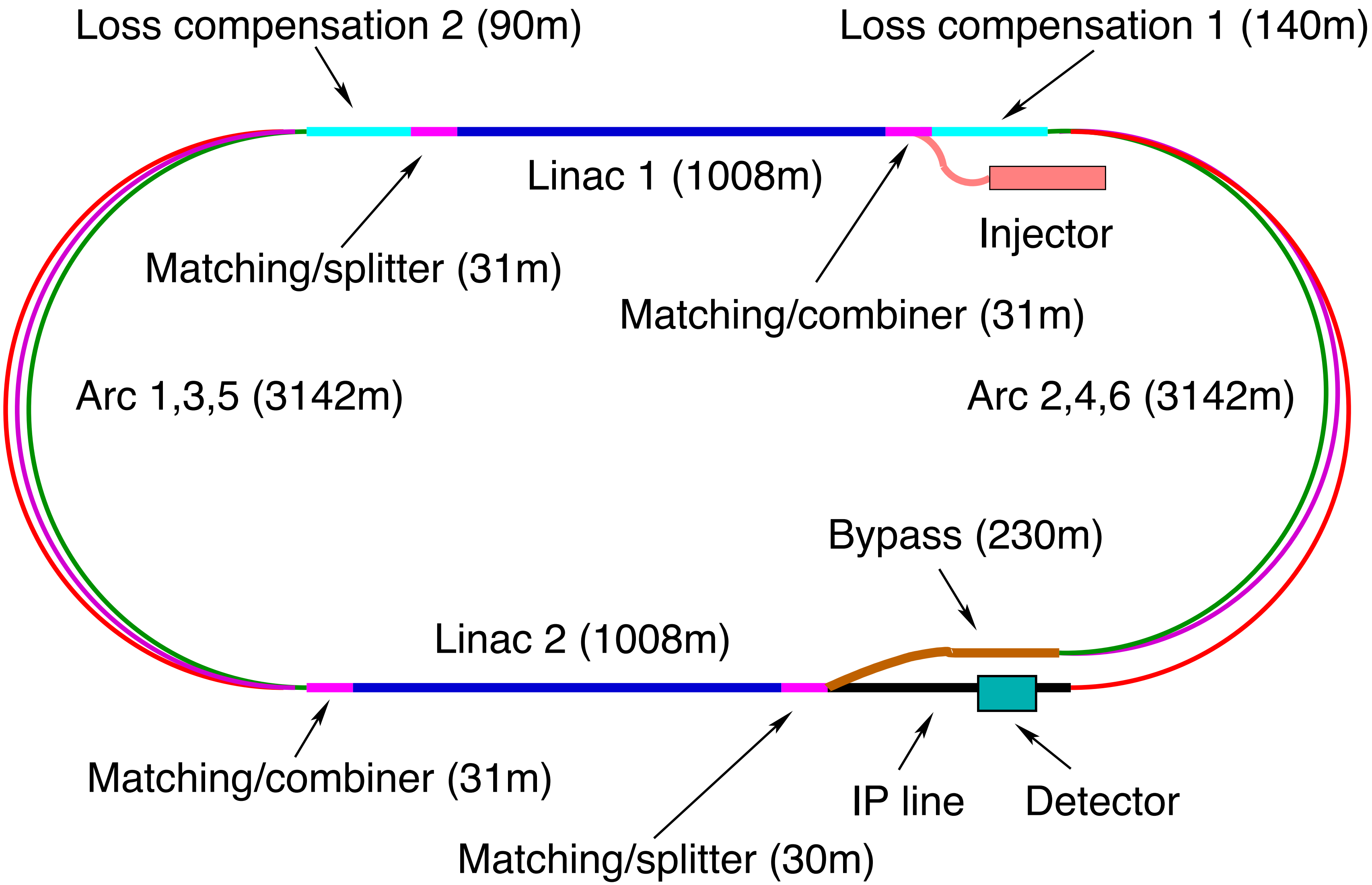
http://cern.ch/lhec

LHeC

J.L.Abelleira Fernandez[16,23], C.Adolphsen[57], P.Adzic[74], A.N.Akay[03], H.Aksakal[39], J.L.Albacete[52], B.Allanach[73], S.Alekhin[17,54], P.Allport[24], V.Andreev[34], R.B.Appleby[14,30], E.Arikan[39], N.Armesto[53,a], G.Azuelos[33,64], M.Bai[37], D.Barber[14,17,24], J.Bartels[18], O.Behnke[17], J.Behr[17], A.S.Belyaev[15,56], I.Ben-Zvi[37], N.Bernard[25], S.Bertolucci[16], S.Bettoni[16], S.Biswal[41], J.Blümlein[17], H.Böttcher[17], A.Bogacz[36], C.Bracco[16], J.Bracinik[06], G.Brandt[44], H.Braun[65], S.Brodsky[57,b], O.Brüning[16], E.Bulyak[12], A.Buniatyan[17], H.Burkhardt[16], I.T.Cakir[02], O.Cakir[01], R.Calaga[16], A.Caldwell[70], V.Cetinkaya[01], V.Chekelian[70], E.Ciapala[16], R.Ciftci[01], A.K.Ciftci[01], B.A.Cole[38], J.C.Collins[48], O.Dadoun[42], J.Dainton[24], A.De.Roeck[16], D.d'Enterria[16], P.DiNezza[72], M.D'Onofrio[24], A.Dudarev[16], A.Eide[60], R.Enberg[63], E.Eroglu[62], K.J.Eskola[21], L.Favart[08], M.Fitterer[16], S.Forte[32], A.Gaddi[16], P.Gambino[59], H.García Morales[16], T.Gehrmann[69], P.Gladkikh[12], C.Glasman[28], A.Glazov[17], R.Godbole[35], B.Goddard[16], T.Greenshaw[24], A.Guffanti[13], V.Guzey[19,36], C.Gwenlan[44], T.Han[50], Y.Hao[37], F.Haug[16], W.Herr[16], A.Hervé[27], B.J.Holzer[16], M.Ishitsuka[58], M.Jacquet[42], B.Jeanneret[16], E.Jensen[16], J.M.Jimenez[16], J.M.Jowett[16], H.Jung[17], H.Karadeniz[02], D.Kayran[37], A.Kilic[62], K.Kimura[58], R.Klees[75], M.Klein[24], U.Klein[24], T.Kluge[24], F.Kocak[62], M.Korostelev[24], A.Kosmicki[16], P.Kostka[17], H.Kowalski[17], M.Kraemer[75], G.Kramer[18], D.Kuchler[16], M.Kuze[58], T.Lappi[21,c], P.Laycock[24], E.Levichev[40], S.Levonian[17], V.N.Litvinenko[37], A.Lombardi[16], J.Maeda[58], C.Marquet[16], B.Mellado[27], K.H.Mess[16], A.Milanese[16], J.G.Milhano[76], S.Moch[17], I.I.Morozov[40], Y.Muttoni[16], S.Myers[16], S.Nandi[55], Z.Nergiz[39], P.R.Newman[06], T.Omori[61], J.Osborne[16], E.Paoloni[49], Y.Papaphilippou[16], C.Pascaud[42], H.Paukkunen[53], E.Perez[16], T.Pieloni[23], E.Pilicer[62], B.Pire[45], R.Placakyte[17], A.Polini[07], V.Ptitsyn[37], Y.Pupkov[40], V.Radescu[17], S.Raychaudhuri[35], L.Rinolfi[16], E.Rizvi[71], R.Rohini[35], J.Rojo[16,31], S.Russenschuck[16], M.Sahin[03], C.A.Salgado[53,a], K.Sampei[58], R.Sassot[09], E.Sauvan[04], M.Schaefer[75], U.Schneekloth[17], T.Schörner-Sadenius[17], D.Schulte[16], A.Senol[22], A.Seryi[44], P.Sievers[16], A.N.Skrinsky[40], W.Smith[27], D.South[17], H.Spiesberger[29], A.M.Stasto[48,d], M.Strikman[48], M.Sullivan[57], S.Sultansoy[03,e], Y.P.Sun[57], B.Surrow[11], L.Szymanowski[66,f], P.Taels[05], I.Tapan[62], T.Tasci[22], E.Tassi[10], H.Ten.Kate[16], J.Terron[28], H.Thiesen[16], L.Thompson[14,30], P.Thompson[06], K.Tokushuku[61], R.Tomás García[16], D.Tommasini[16], D.Trbojevic[37], N.Tsoupas[37], J.Tuckmantel[16], S.Turkoz[01], T.N.Trinh[47], K.Tywoniuk[26], G.Unel[20], T.Ullrich[37], J.Urakawa[61], P.VanMechelen[05], A.Variola[52], R.Veness[16], A.Vivoli[16], P.Vobly[40], J.Wagner[66], R.Wallny[68], S.Wallon[43,46,f], G.Watt[69], C.Weiss[36], U.A.Wiedemann[16], U.Wienands[57], F.Willeke[37], B.-W.Xiao[48], V.Yakimenko[37], A.F.Zarnecki[67], Z.Zhang[42], F.Zimmermann[16], R.Zlebcik[51], F.Zomer[42]

LHeC Study group and CDR authors (Dec.2012)

About 200 Experimentalists and Theorists from 76 (+3) Institutes



Loss compensation 2 (90m)

Loss compensation 1 (140m)

Linac 1 (1008m)

Injector

Matching/splitter (31m)

Matching/combiner (31m)

Arc 1,3,5 (3142m)

Arc 2,4,6 (3142m)

Bypass (230m)

Linac 2 (1008m)

Matching/combiner (31m)

IP line

Detector

Matching/splitter (30m)

60 GeV electron beam energy, $L = 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$, $\sqrt{s} = 1.3$ TeV: $Q^2_{max} = 10^6\ \text{GeV}^2$, $10^{-6} < x < 1$
Recirculating linac (2 * 1km, 2*60 cavity cryo modules, 3 passes, energy recovery)
Ring-ring as fall back. “SAPHIRE” 4 pass 80 GeV option to do mainly: $\gamma\gamma \rightarrow H$

LHeC

Accelerator Design: Participating Institutes

CERN

SLAC
NATIONAL ACCELERATOR LABORATORY

NTNU
Norwegian University of Science and Technology

ECFA

clic

The Cockcroft Institute
of Accelerator Science and Technology

Jefferson Lab
Thomas Jefferson National Accelerator Facility

ANKARA ÜNİVERSİTESİ

NİĞDE ÜNİVERSİTESİ 1992

ULUDAĞ ÜNİVERSİTESİ 1975

TOBB ETU

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

DESY

Physique des accélérateurs

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

UNIVERSITY OF LIVERPOOL

KEK

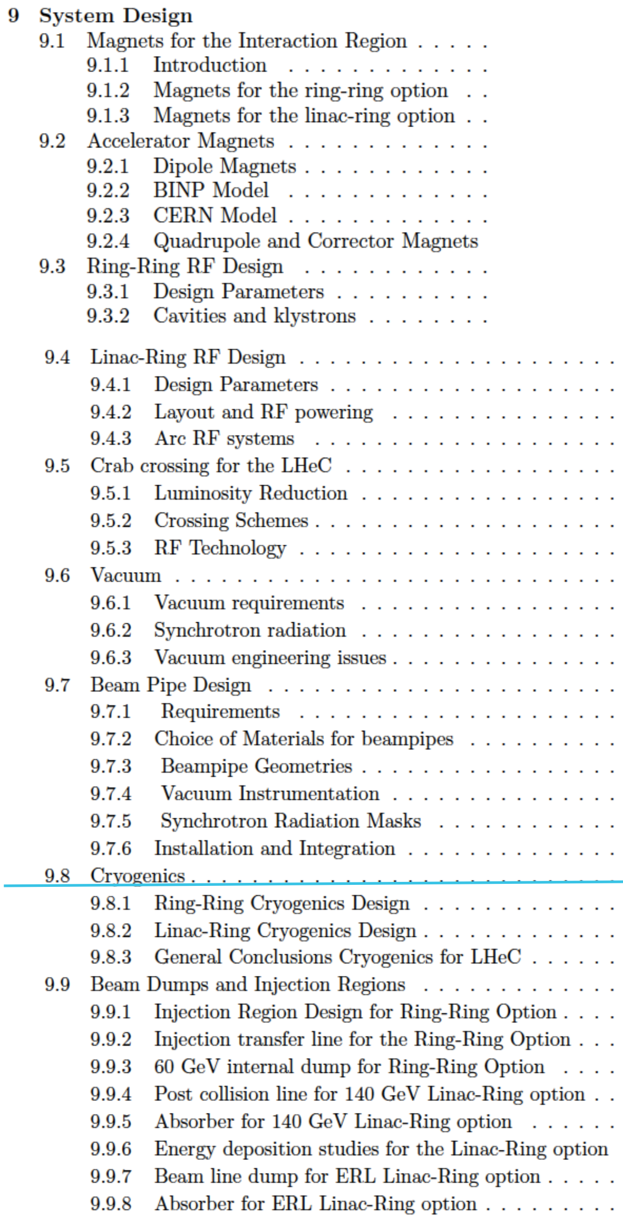
BROOKHAVEN
NATIONAL LABORATORY

СИБИРСКОЕ ОТДЕЛЕНИЕ РАН
ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
им. Г.И.Будкера
630090 Новосибирск

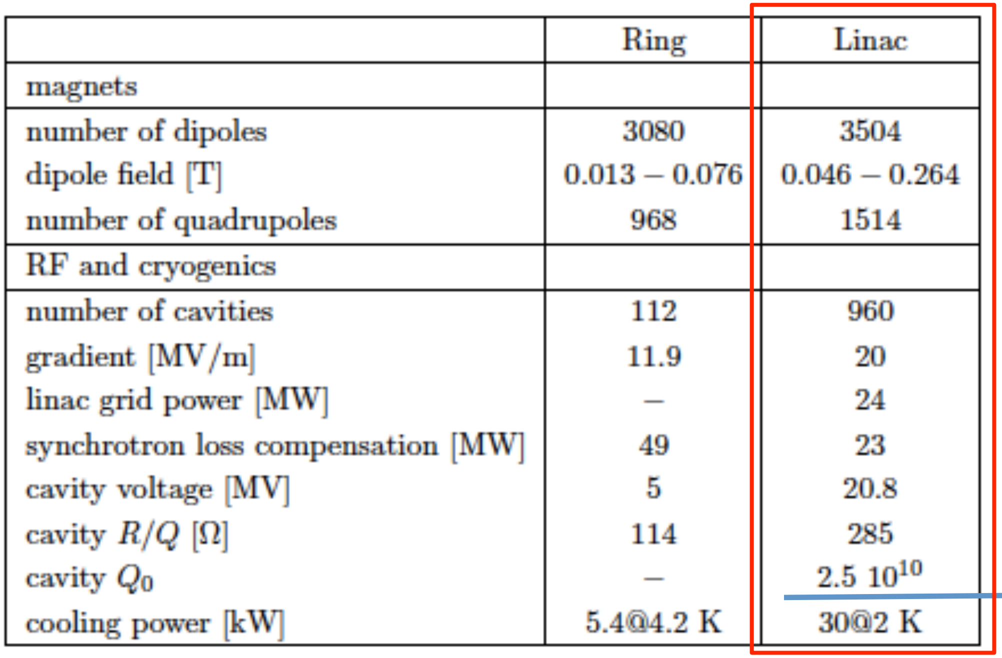
Source	Power [MW]
Cryogenics (linac)	21
Linac grid power	24
SR compensation	23
Extra RF cryopower	2
Injector	6
Arc magnets	3
Total	**78**

Components and Cryogenics

Chapter 9 of CDR

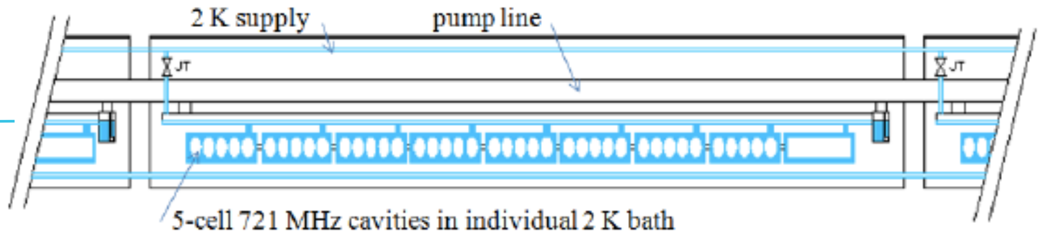


9 System Design

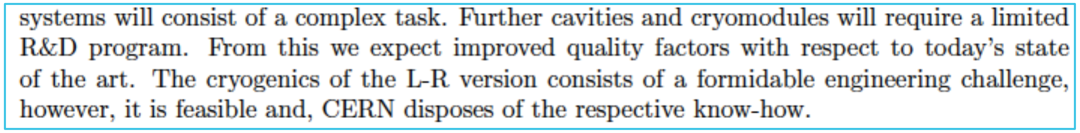


	Ring	Linac
magnets		
number of dipoles	3080	3504
dipole field [T]	0.013 – 0.076	0.046 – 0.264
number of quadrupoles	968	1514
RF and cryogenics		
number of cavities	112	960
gradient [MV/m]	11.9	20
linac grid power [MW]	–	24
synchrotron loss compensation [MW]	49	23
cavity voltage [MV]	5	20.8
cavity R/Q [Ω]	114	285
cavity Q_0	–	2.5 10^{10}
cooling power [kW]	5.4@4.2 K	30@2 K

Jlab:
4 10^{11}



Need to develop LHeC cavity (cryo-module)

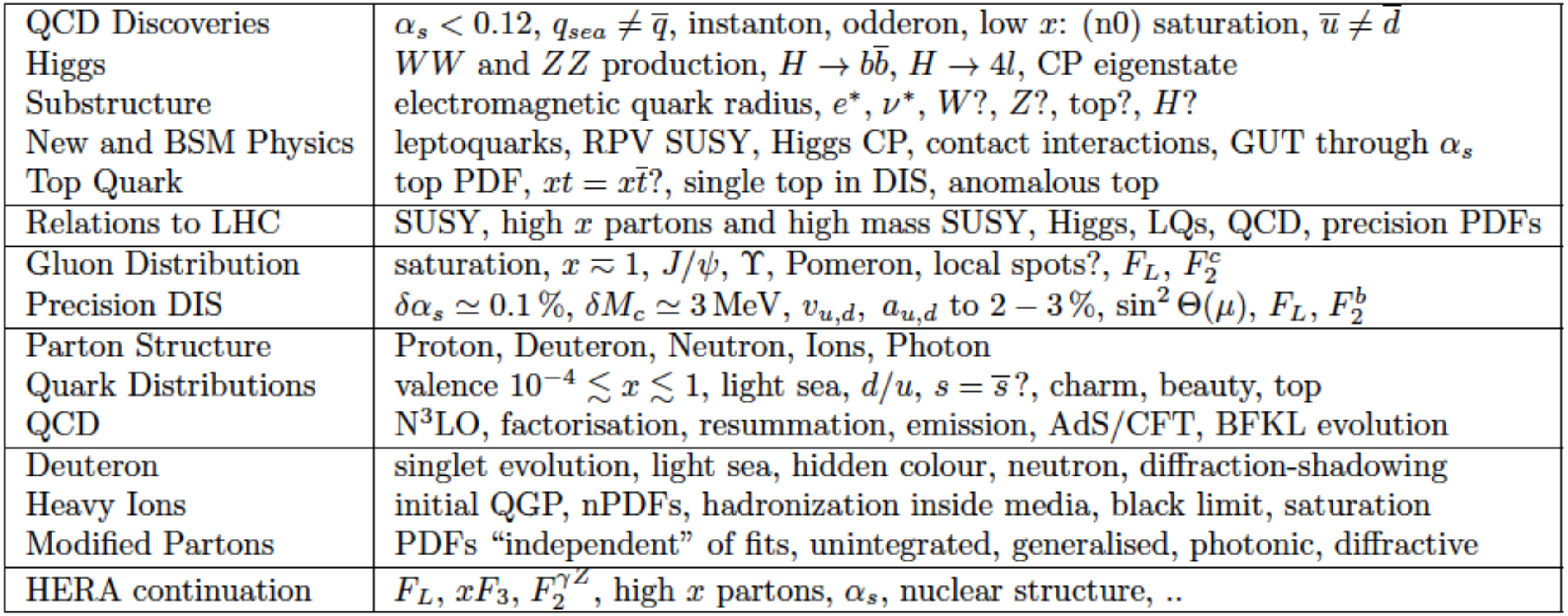


systems will consist of a complex task. Further cavities and cryomodules will require a limited R&D program. From this we expect improved quality factors with respect to today's state of the art. The cryogenics of the L-R version consists of a formidable engineering challenge, however, it is feasible and, CERN disposes of the respective know-how.

from CDR LHeC

LHeC Physics Programme

CDR, arXiv:1211.4831 and 5102
http://cern.ch/lhec

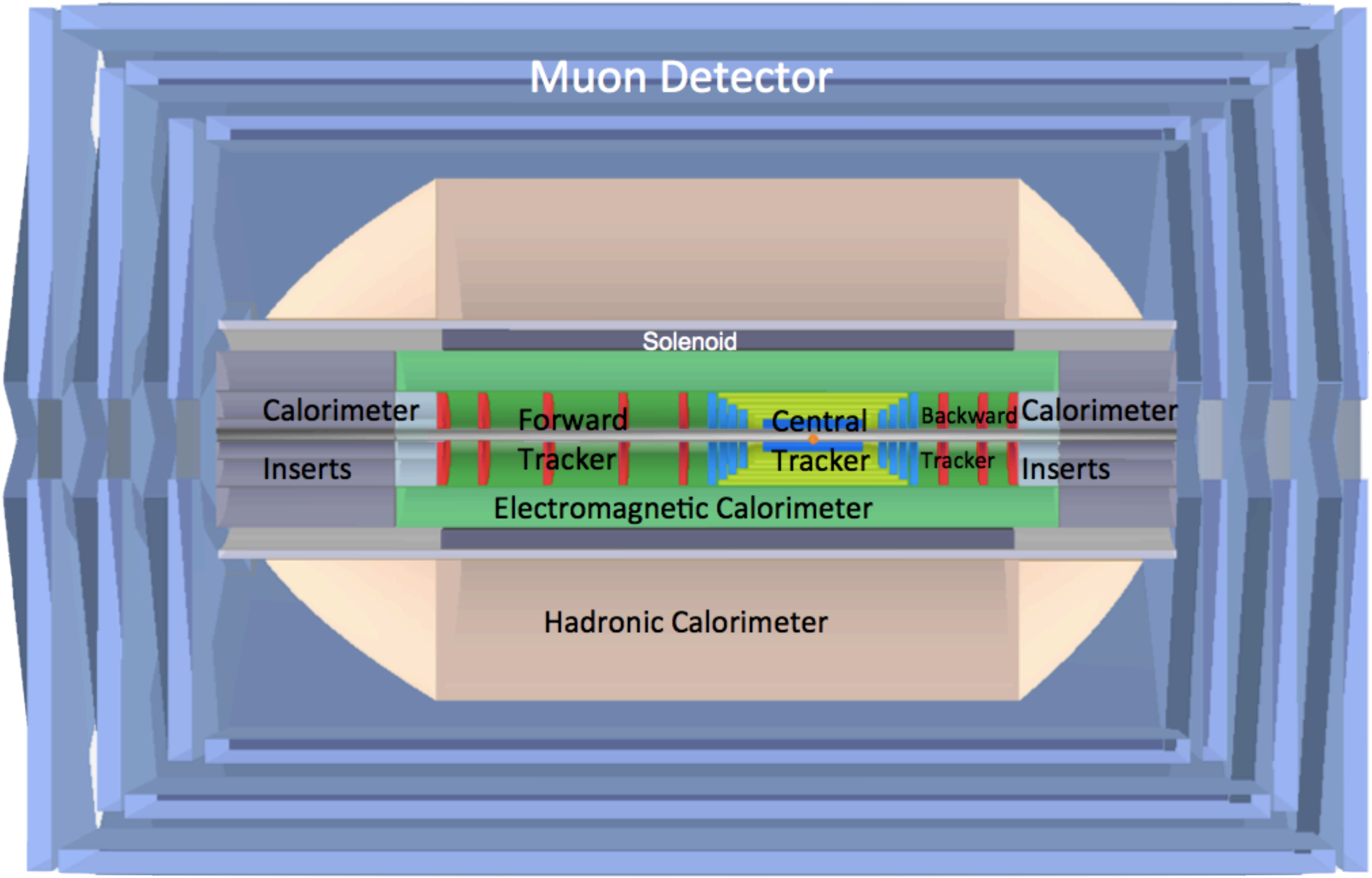


QCD Discoveries	$\alpha_s < 0.12$, $q_{sea} \neq \overline{q}$, instanton, odderon, low x: (n0) saturation, $\overline{u} \neq \overline{d}$
Higgs	WW and ZZ production, $H \rightarrow b\overline{b}$, $H \rightarrow 4l$, CP eigenstate
Substructure	electromagnetic quark radius, e^*, ν^*, W?, Z?, top?, H?
New and BSM Physics	leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through α_s
Top Quark	top PDF, $xt = x\overline{t}$?, single top in DIS, anomalous top
Relations to LHC	SUSY, high x partons and high mass SUSY, Higgs, LQs, QCD, precision PDFs
Gluon Distribution	saturation, $x \approx 1$, J/ψ, Υ, Pomeron, local spots?, F_L, F_2^c
Precision DIS	$\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\mathrm{MeV}$, $v_{u,d}$, $a_{u,d}$ to $2-3\,\%$, $\sin^2\Theta(\mu)$, F_L, F_2^b
Parton Structure	Proton, Deuteron, Neutron, Ions, Photon
Quark Distributions	valence $10^{-4} \lesssim x \lesssim 1$, light sea, d/u, $s = \overline{s}$?, charm, beauty, top
QCD	N^{3}LO, factorisation, resummation, emission, AdS/CFT, BFKL evolution
Deuteron	singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing
Heavy Ions	initial QGP, nPDFs, hadronization inside media, black limit, saturation
Modified Partons	PDFs "independent" of fits, unintegrated, generalised, photonic, diffractive
HERA continuation	F_L, xF_3, $F_2^{\gamma Z}$, high x partons, α_s, nuclear structure, ..

Ultra high precision (detector, e-h redundancy) - new insight
Maximum luminosity and much extended range - rare, new effects
Deep relation to (HL-) LHC (precision+range) - complementarity

Summarised for the European Strategy Debate (summary 1211.4831 and link to LHC .5102)

LHeC Detector Overview

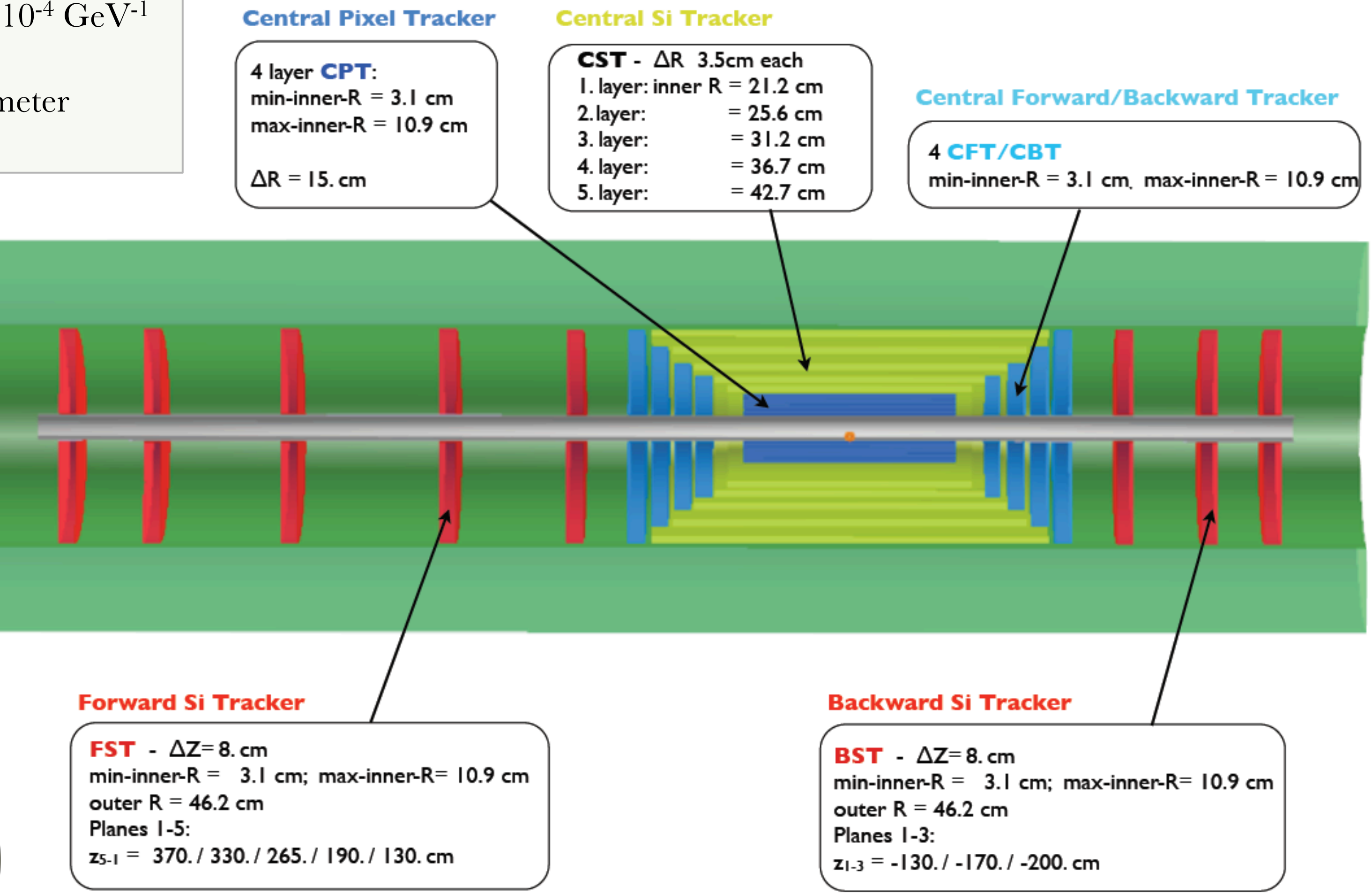


Detector option 1 for LR and full acceptance coverage

Forward/backward asymmetry in energy deposited and thus in geometry and technology
Present dimensions: LxD =14x9m^2 [CMS 21 x 15m^2, ATLAS 45 x 25 m^2]
Taggers at -62m (e),100m (γ,LR), -22.4m (γ,RR), +100m (n), +420m (p)

Silicon Tracker and EM Calorimeter

Transverse momentum $\Delta p_t/p^2_t$ → 6 10^{-4} GeV^{-1}
transverse
impact parameter
→ 10μm



Central Pixel Tracker

4 layer **CPT**:
min-inner-R = 3.1 cm
max-inner-R = 10.9 cm

ΔR = 15. cm

Central Si Tracker

CST - ΔR 3.5cm each
1. layer: inner R = 21.2 cm
2. layer: = 25.6 cm
3. layer: = 31.2 cm
4. layer: = 36.7 cm
5. layer: = 42.7 cm

Central Forward/Backward Tracker

4 **CFT/CBT**
min-inner-R = 3.1 cm, max-inner-R = 10.9 cm

Forward Si Tracker

FST - ΔZ= 8. cm
min-inner-R = 3.1 cm; max-inner-R= 10.9 cm
outer R = 46.2 cm
Planes 1-5:
z_{5-1} = 370. / 330. / 265. / 190. / 130. cm

Backward Si Tracker

BST - ΔZ= 8. cm
min-inner-R = 3.1 cm; max-inner-R= 10.9 cm
outer R = 46.2 cm
Planes 1-3:
z_{1-3} = -130. / -170. / -200. cm

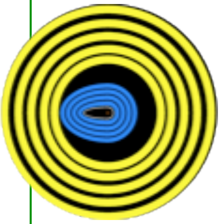
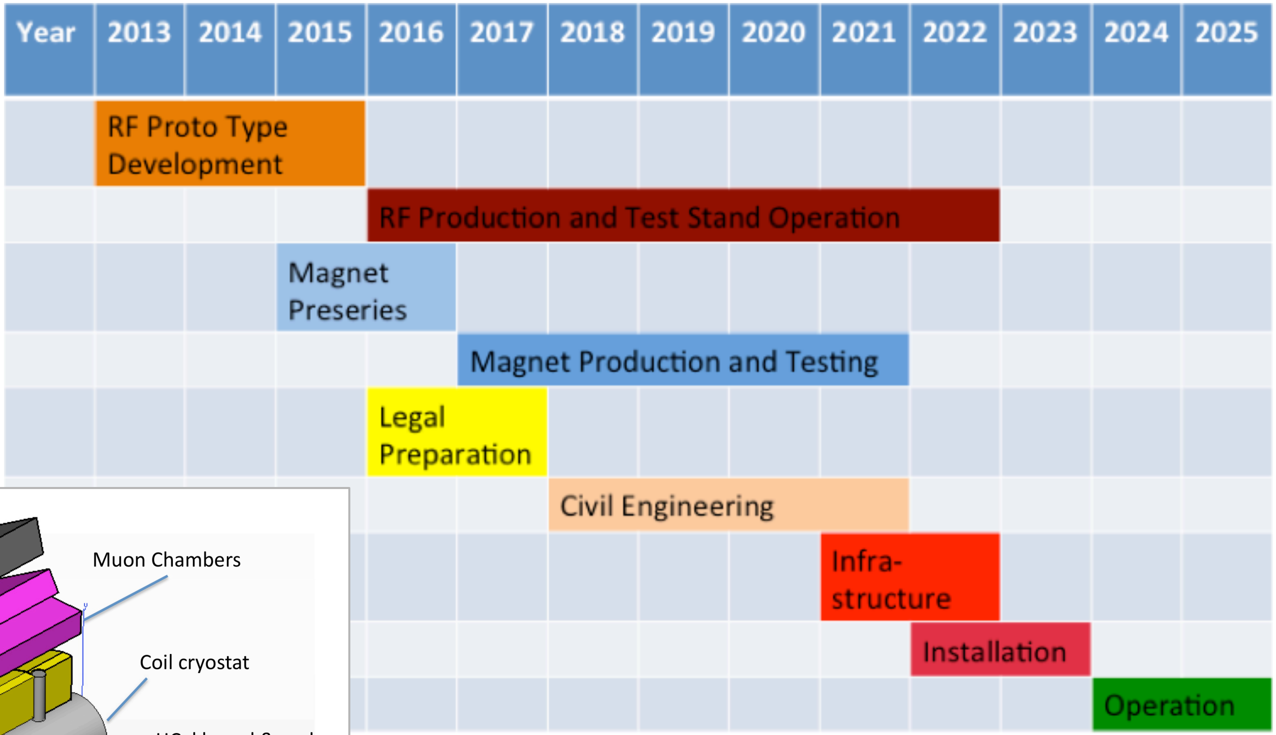


Figure 13.18: Tracker and barrel Electromagnetic-Calorimeter rz view of the baseline detector (Linac-Ring case).

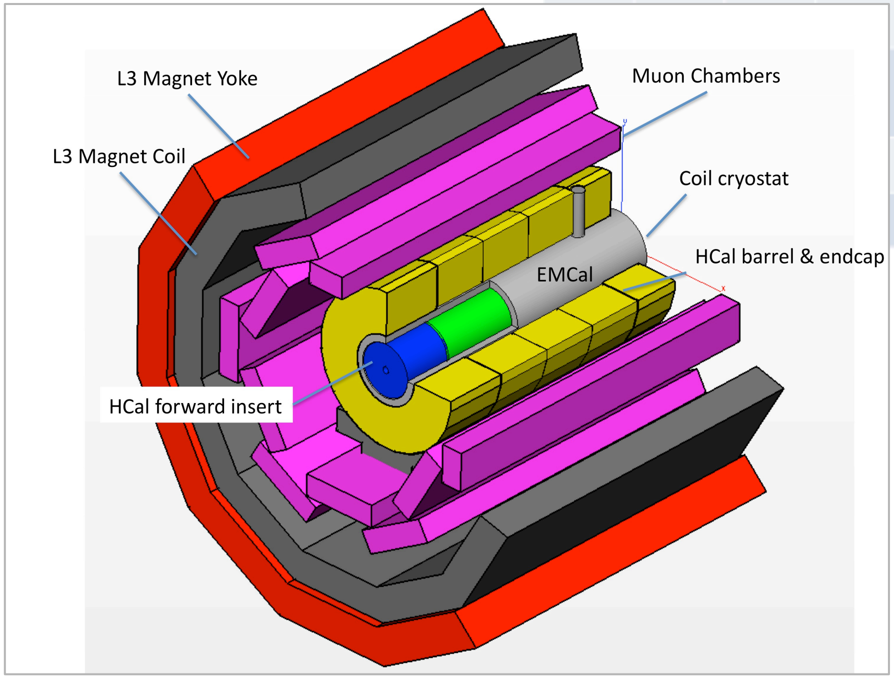
LHeC-LHC: no pile-up, less radiation, smaller momenta apart from forward region

Time Schedule*)



Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
	RF Proto Type Development												
				RF Production and Test Stand Operation									
			Magnet Preseries										
					Magnet Production and Testing								
				Legal Preparation									
						Civil Engineering							
									Infra-structure				
										Installation			
												Operation	

Detector installation study for IP2, reuse of L3 magnet as support for LHeC. Estimated 30 months

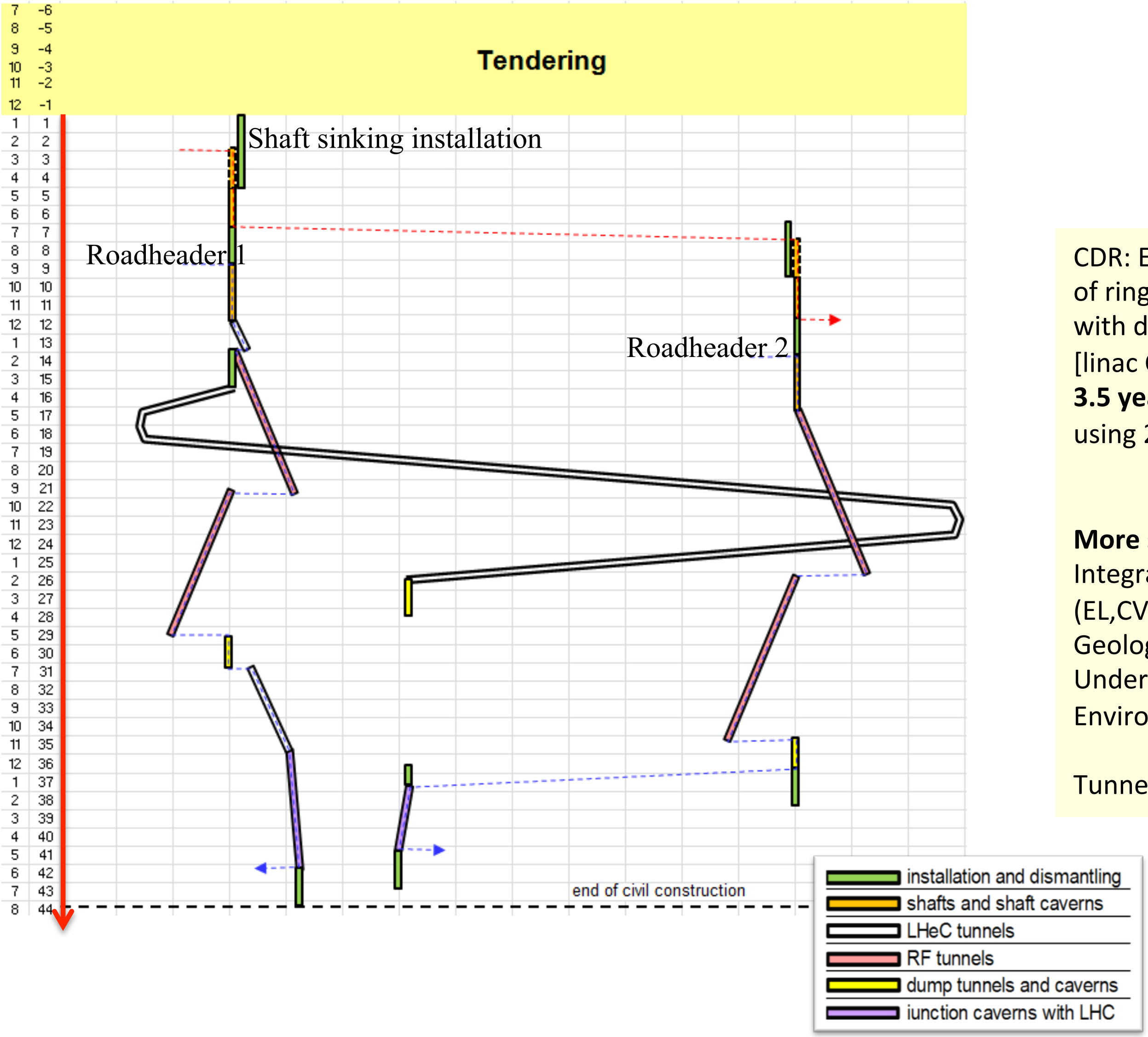


LHeC is to operate synchronous with HL-LHC

LS3 requires 2-3 years for ATLAS+. It is the one extended time period, which will allow installation and connection of LHeC

*) LS3 → schedule most likely shifted by +2 years

Civil Engineering

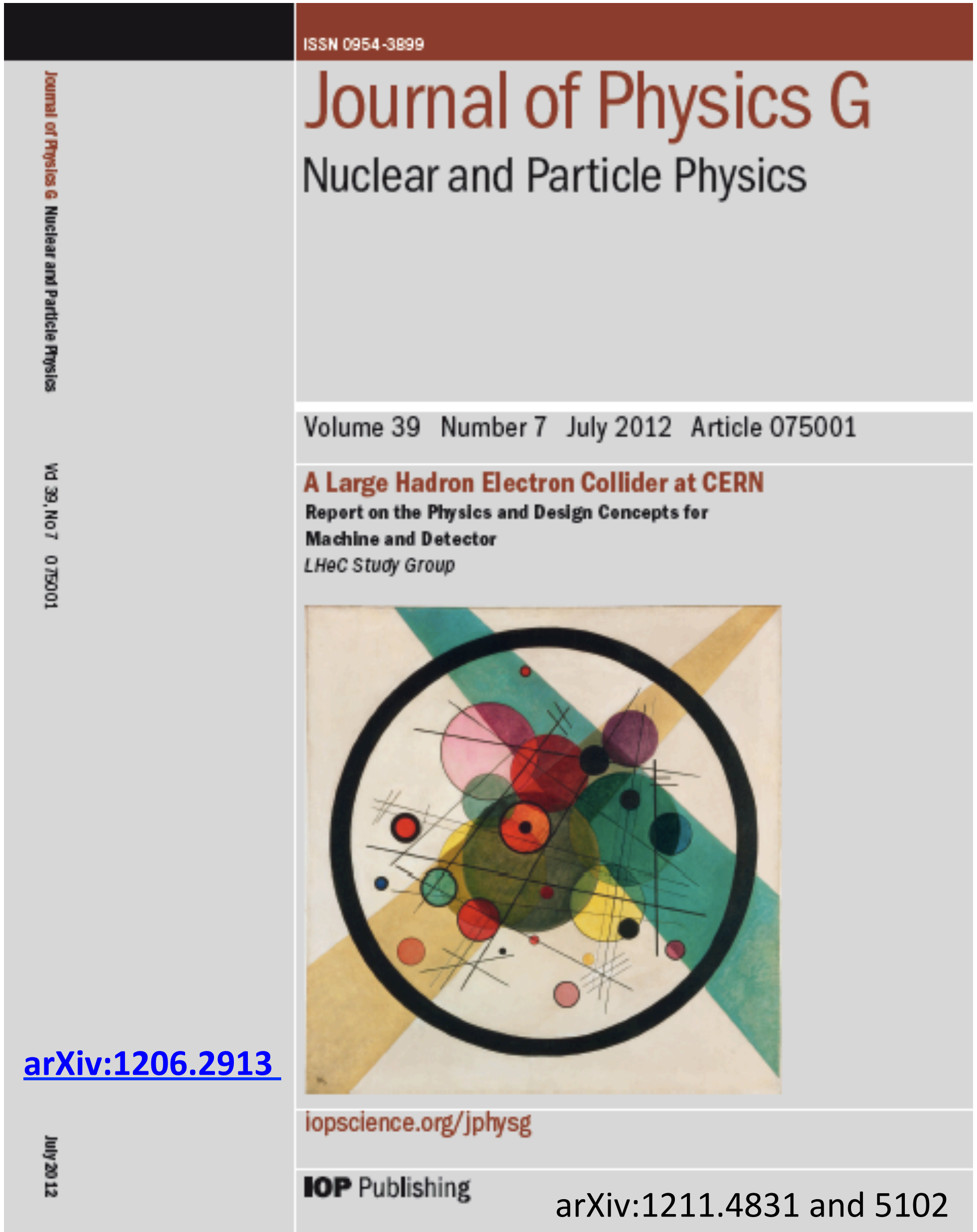


CDR: Evaluation of CE, analysis of ring and linac by Amber Zurich with detailed cost estimate [linac CE: 249,928 kSF..] and time: **3.5 years for underground works** using 2 roadheaders and 1 TBM

More studies needed for
Integration with all services (EL,CV, transport, survey etc).
Geology
Understanding vibration risks
Environmental impact assessment

Tunnel connection in IP2

J.Osborne, Chavannes



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Nuclear and Particle Physics

Volume 39 Number 7 July 2012 Article 075001

A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group

iopscience.org/jphysg

IOP Publishing

arXiv:1206.2913

arXiv:1211.4831 and 5102

CERN Referees

Ring Ring Design
Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)
Linac Ring Design
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)
Energy Recovery
Georg Hoffstaetter (Cornell)
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Magnets
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Interaction Region
Daniel Pitzl (DESY)
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Detector Design
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Installation and Infrastructure
Sylvain Weisz (CERN)
New Physics at Large Scales
Cristinel Diaconu (IN2P3 Marseille)
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Precision QCD and Electroweak
Guido Altarelli (Roma)
Vladimir Chekelian (MPI Munich)
Alan Martin (Durham)
Physics at High Parton Densities
Alfred Mueller (Columbia)
Raju Venugopalan (BNL)
Michele Arneodo (INFN Torino)

Published 600 pages conceptual design report (CDR) written by 150 authors from 60 Institutes. Reviewed by ECFA, NuPECC (long range plan), Referees invited by CERN. Published June 2012.

“BFKL evolution and Saturation in DIS”

“Critical gravitational collapse”

Circles in a circle
V. Kandinsky, 1923
Philadelphia Museum of Art

5d tiny black holes and perturbative saturation
Talk by A.S.Vera at LHeC Workshop 2008

http://cern.ch/lhec
event-lhec-workshop@cern.ch

CERN-ECFA-NuPECC

Workshop on the LHeC

Electron-proton and electron-ion collisions at the LHC

14-15 June 2012

Chavanne-de-Bogis, Switzerland

Scientific Advisory Committee

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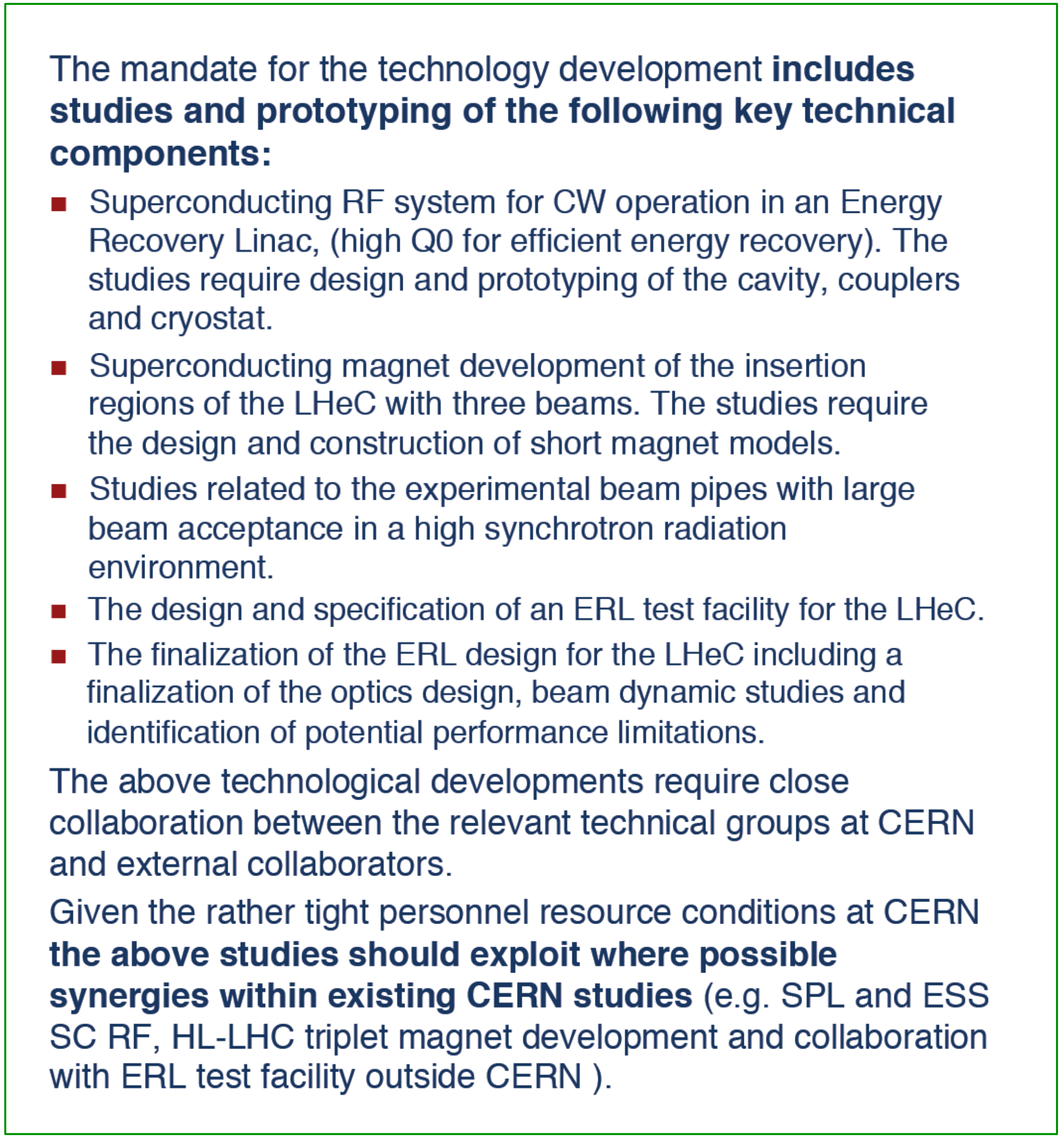
Four main results of a sunny workshop:

- **Higgs** close to be discovered
  [WW→ H re-emphasised
  and LHeC physics reviewed]
- Decision for **Linac-Ring**
  [Ring-Ring as backup, doable
  but challenging installation]
- Confirmation of **Detector Concept**
  [detailed reviews of tracking,
  magnets, IR and calorimetry]
- **Mandate of CERN to proceed**
  [preparations of key technologies
  for project decision in ~2017]

CERN Mandate – TDR by ~2015



The mandate for the technology development **includes studies and prototyping of the following key technical components:**

- Superconducting RF system for CW operation in an Energy Recovery Linac, (high Q0 for efficient energy recovery). The studies require design and prototyping of the cavity, couplers and cryostat.
- Superconducting magnet development of the insertion regions of the LHeC with three beams. The studies require the design and construction of short magnet models.
- Studies related to the experimental beam pipes with large beam acceptance in a high synchrotron radiation environment.
- The design and specification of an ERL test facility for the LHeC.
- The finalization of the ERL design for the LHeC including a finalization of the optics design, beam dynamic studies and identification of potential performance limitations.

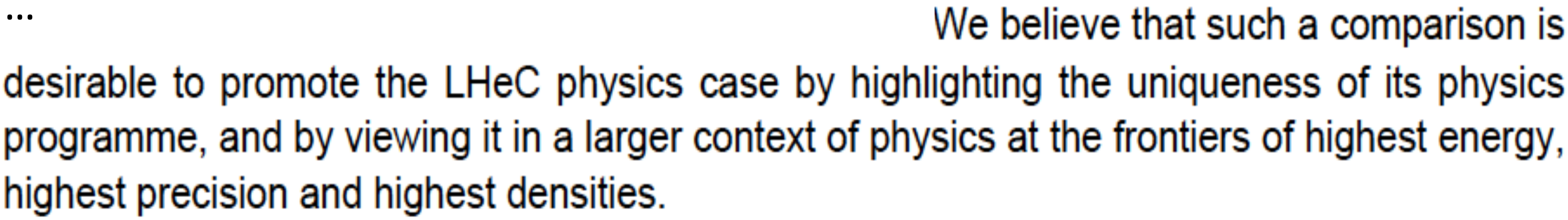
The above technological developments require close collaboration between the relevant technical groups at CERN and external collaborators.

Given the rather tight personnel resource conditions at CERN **the above studies should exploit where possible synergies within existing CERN studies** (e.g. SPL and ESS SC RF, HL-LHC triplet magnet development and collaboration with ERL test facility outside CERN).

S.Bertolucci at Chavannes workshop 6/12 based on
CERN directorate's decision to include LHeC in the MTP

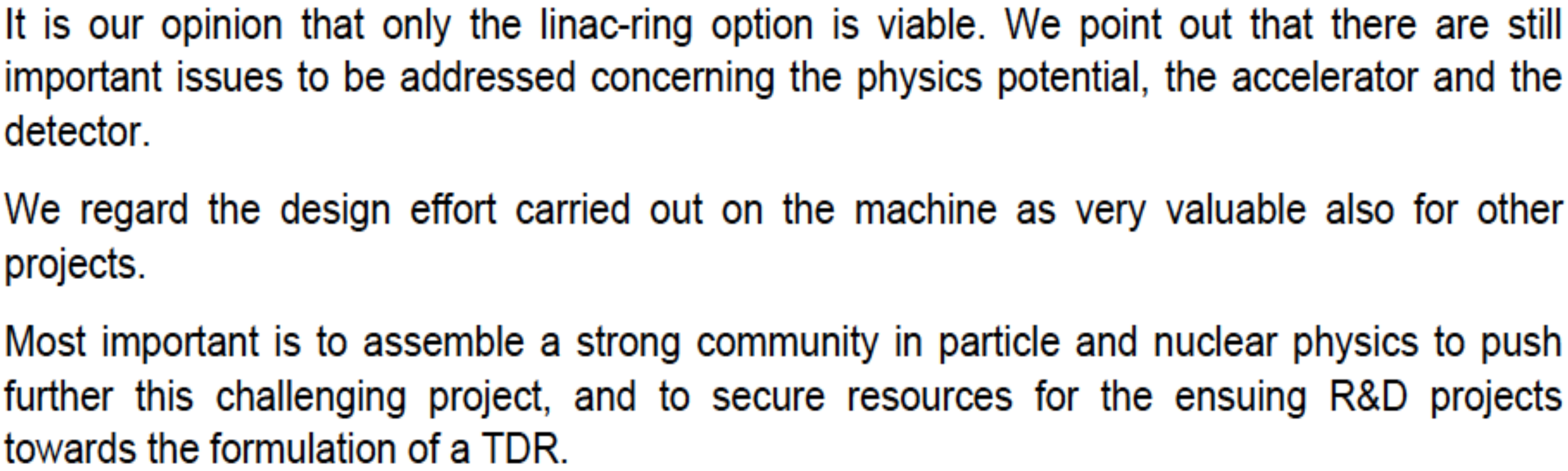
ECFA Review 2007-2012

CERN SPC, [r]ECFA Mandate given in 2007 to work out the LHeC physics, detector and accelerator design(s) – looking back to 1994 CDR and referee process carefully evaluated by ECFA committee



… We believe that such a comparison is desirable to promote the LHeC physics case by highlighting the uniqueness of its physics programme, and by viewing it in a larger context of physics at the frontiers of highest energy, highest precision and highest densities.

Stressed: Link to LHC physics and operation, link to HEP, cost estimates, R&D, DIS community



It is our opinion that only the linac-ring option is viable. We point out that there are still important issues to be addressed concerning the physics potential, the accelerator and the detector.

We regard the design effort carried out on the machine as very valuable also for other projects.

Most important is to assemble a strong community in particle and nuclear physics to push further this challenging project, and to secure resources for the ensuing R&D projects towards the formulation of a TDR.

ECFA Statement ECFA/12/279 December 2012

-the value of DIS and the LHeC-

DIS discoveries
HERA
Beyond HERA
LHeC discovery potential
High Q^2 and huge luminosity
Higgs discovered
HL LHC requirements
ep - pp - ee

Early ep Scattering

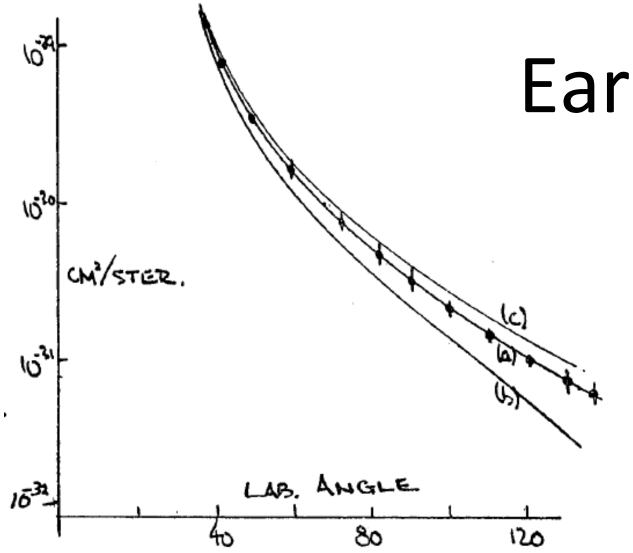
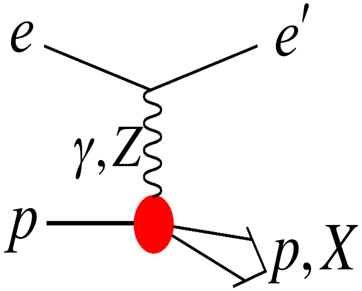
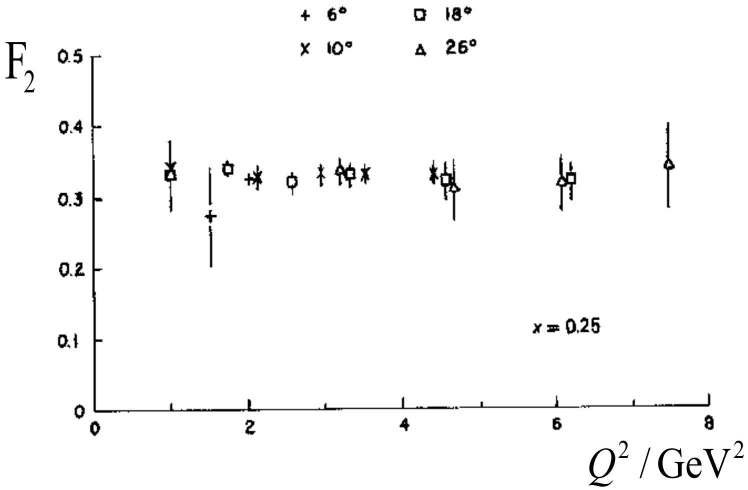


Fig. 2

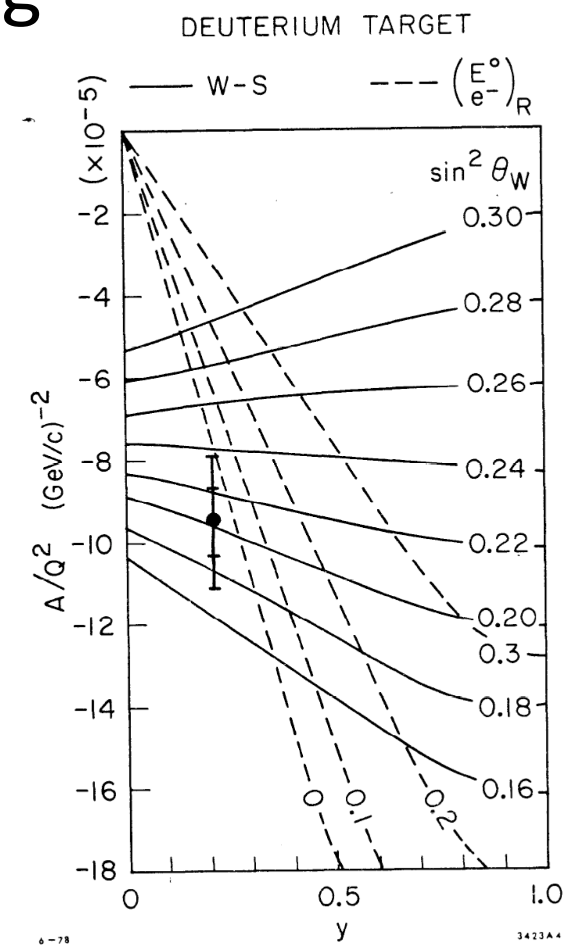
Hofstadter et al, 1955, r_p=0.74±0.20fm





SLAC-MIT 1968 Bj Scaling → Partons

In DIS the x and Q^2 scales are prescribed by the electron kinematics

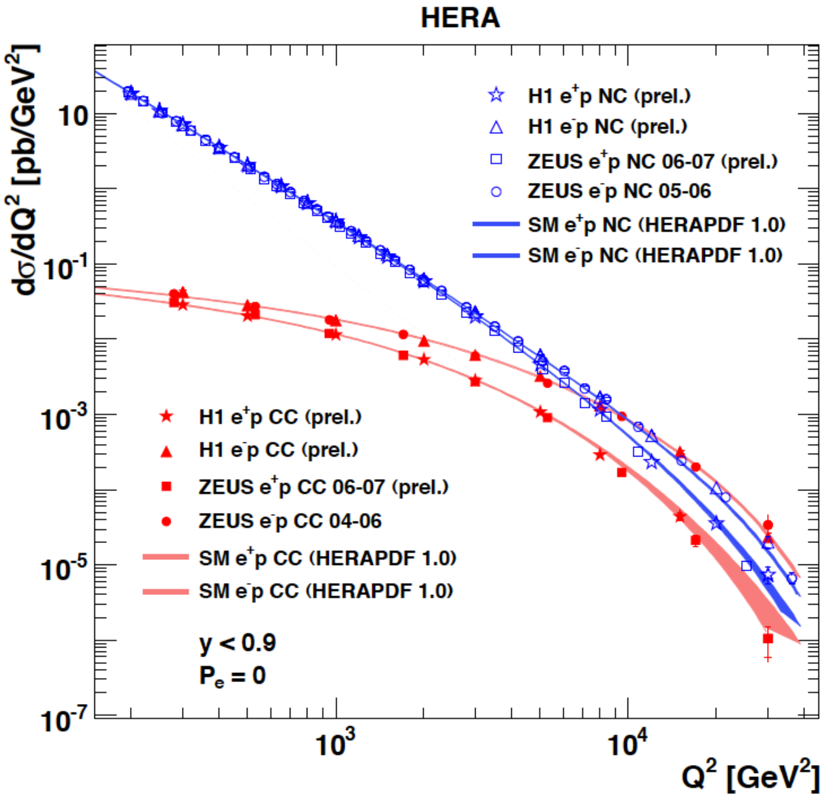


$$A^{\pm} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$

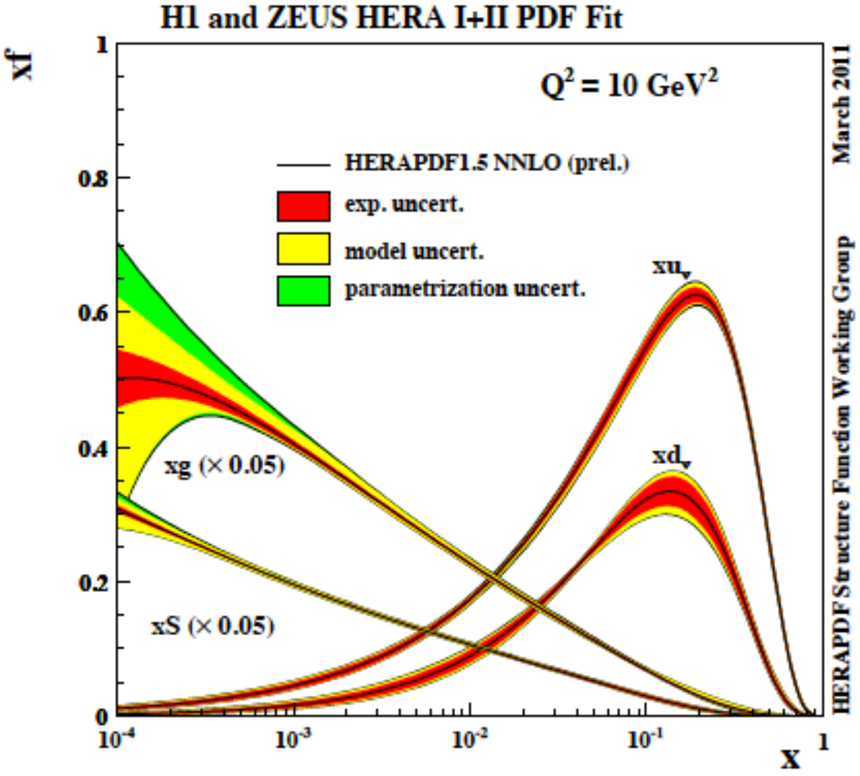
SLAC-PUB-2148
July 1978

Prescott et al, 1978, $I_{3,R}^e$=0

Results from HERA



The weak and electromagnetic interactions reach similar strength when $Q^2 \geq M^2_{W,Z}$



F_2 rises towards low x, and xg too.
Parton evolution - QCD to NNLO

Measurements on α_s, Basic tests of QCD: longitudinal structure function, jet production, γ structure
Some 10% of the cross section is diffractive (ep → eXp) : **diffractive partons; c,b quark distributions**
New concepts: unintegrated parton distributions (k_T) , generalised parton distributions (DVCS)
New limits for leptoquarks, excited electrons and neutrinos, quark substructure, RPV SUSY
Interpretation of the Tevatron measurements (high Et jet excess, M_W, searches..), + **base for PDF fits**..

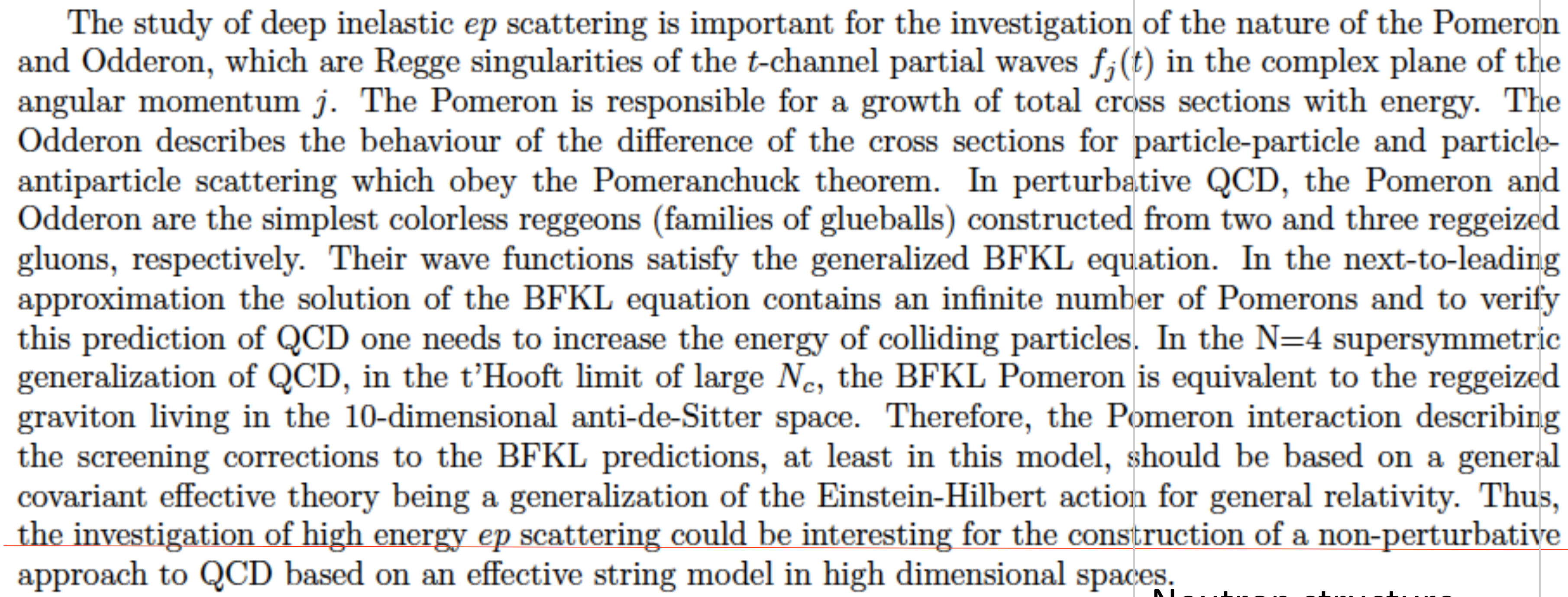
M.Klein, R.Yoshida: **Collider Physics at HERA** Prog.Part.Nucl.Phys. 61 (2008) 343-393 and recent H1,ZEUS results
A Recent review of **The Theory of Deep Inelastic Scattering**: J.Bluemlein arXiv:1208.6087 ProgPartNuclPhys 69(2013)28

What HERA could not do or has not done

Test of the isospin symmetry (u-d) with eD - no deuterons
Investigation of the q-g dynamics in nuclei - no time for eA
Verification of saturation prediction at low x – too low s
Measurement of the strange quark distribution – too low L
Discovery of Higgs in WW fusion in CC – too low cross section
Study of top quark distribution in the proton – too low s
Precise measurement of F_L – too short running time left
Resolving d/u question at large Bjorken x – too low L
Determination of gluon distribution at hi/lo x – too small range
High precision measurement of α_s – overall not precise enough
Discovering instantons, odderons – don't know why not
Finding RPV SUSY and/or leptoquarks – may reside higher up
…

Candidates for Surprises and Discoveries

- PDFs (t, s, q-$\bar{q}$, val, xg)
- Odderon
- Instanton
- (no) saturation, QCD
- QGP initial state



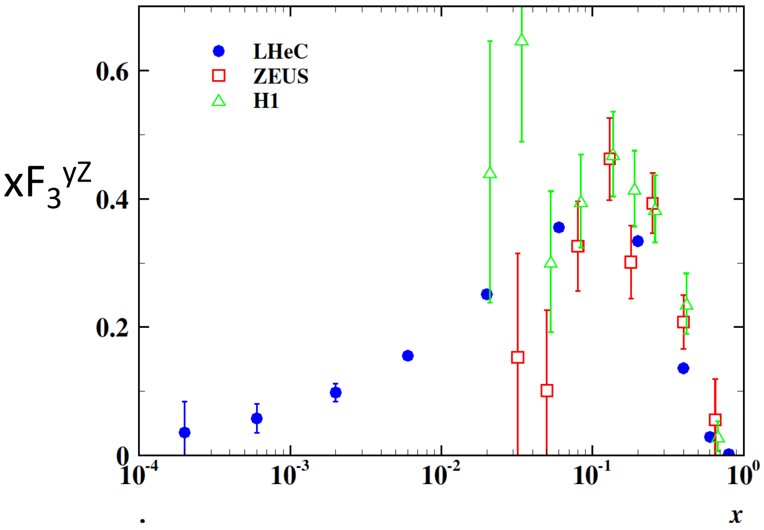
The study of deep inelastic *ep* scattering is important for the investigation of the nature of the Pomeron and Odderon, which are Regge singularities of the t-channel partial waves $f_j(t)$ in the complex plane of the angular momentum j. The Pomeron is responsible for a growth of total cross sections with energy. The Odderon describes the behaviour of the difference of the cross sections for particle-particle and particle-antiparticle scattering which obey the Pomeranchuck theorem. In perturbative QCD, the Pomeron and Odderon are the simplest colorless reggeons (families of glueballs) constructed from two and three reggeized gluons, respectively. Their wave functions satisfy the generalized BFKL equation. In the next-to-leading approximation the solution of the BFKL equation contains an infinite number of Pomerons and to verify this prediction of QCD one needs to increase the energy of colliding particles. In the N=4 supersymmetric generalization of QCD, in the t'Hooft limit of large N_c, the BFKL Pomeron is equivalent to the reggeized graviton living in the 10-dimensional anti-de-Sitter space. Therefore, the Pomeron interaction describing the screening corrections to the BFKL predictions, at least in this model, should be based on a general covariant effective theory being a generalization of the Einstein-Hilbert action for general relativity. Thus, the investigation of high energy *ep* scattering could be interesting for the construction of a non-perturbative approach to QCD based on an effective string model in high dimensional spaces.

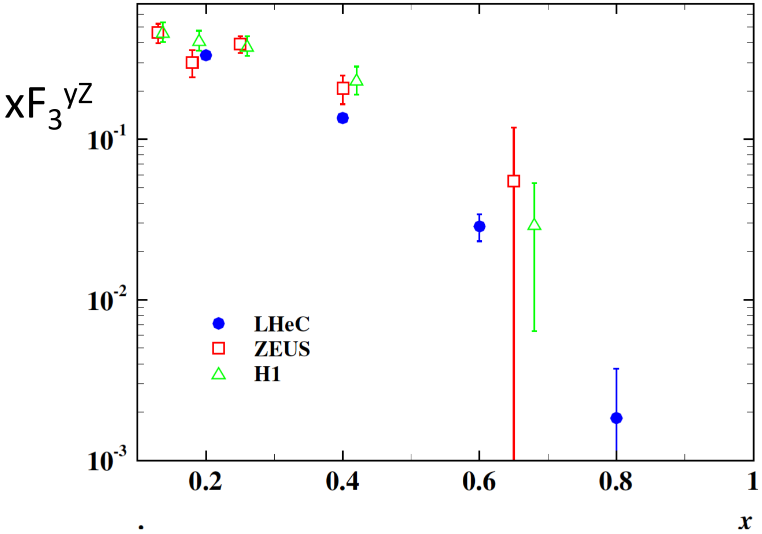
Lev Lipatov in the CDR…

- Neutron structure
- Factorization pp-ep
- LQs, RPV SUSY
- e^*
- Higgs CP
- α_s indeed small (GUT)

Ultra high precision (detector, e-h redundancy) - new insight
Maximum luminosity and much extended range - rare, new effects
Deep relation to (HL-) LHC (precision+range) - complementarity
→ **LHeC brings a substantial enrichment of LHC physics**

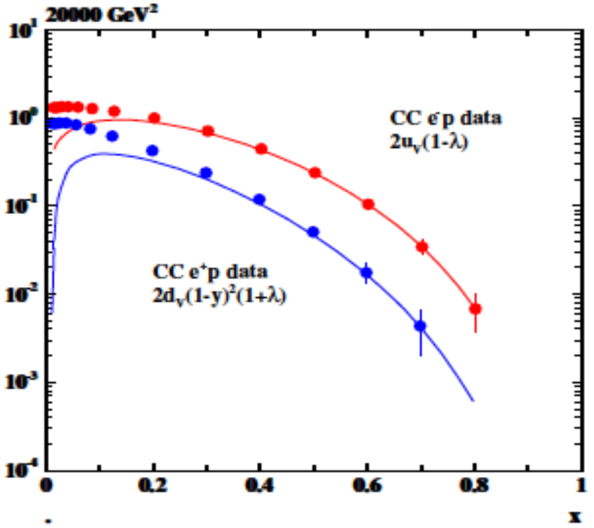
Primary measurements – simulated – high Q^2

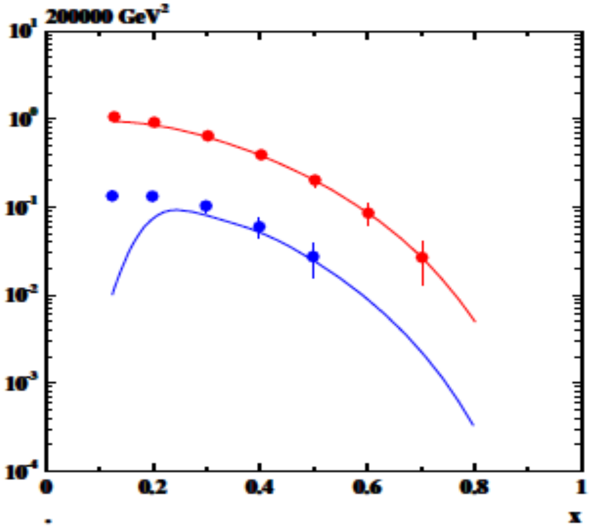




Precision electroweak measurements
PV with polarisation, $F_2^{b,Z}$, NC couplings..

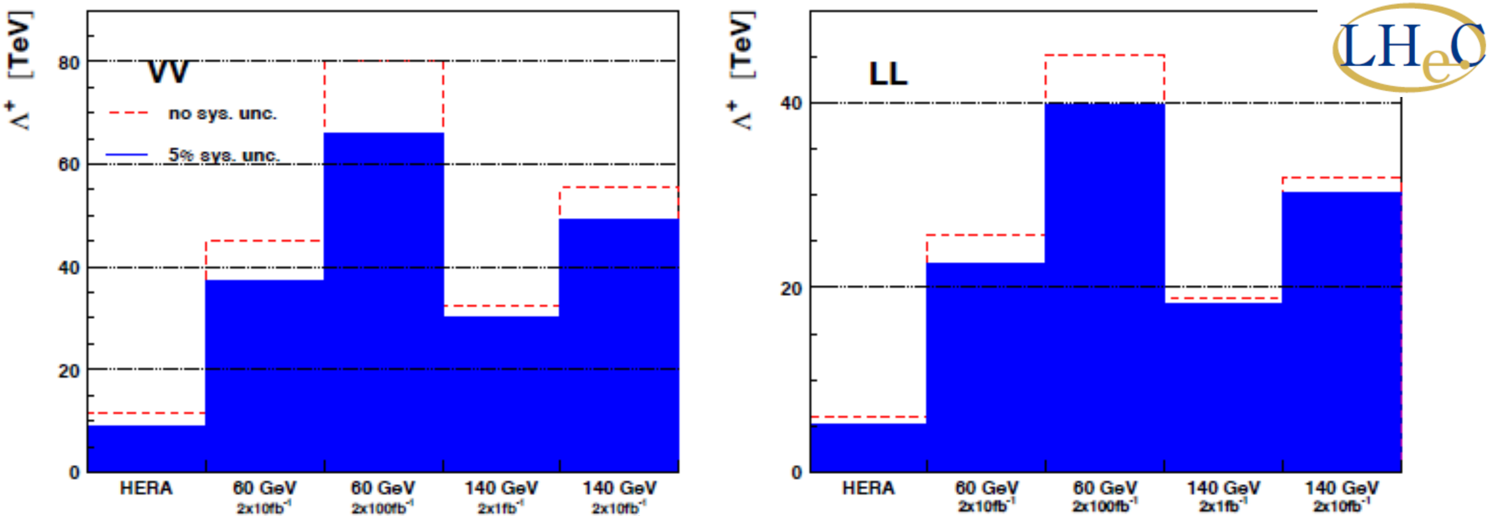
Precision CC measurements: top [10pb]
valence quarks, high x, V_{tb}, strange, ..



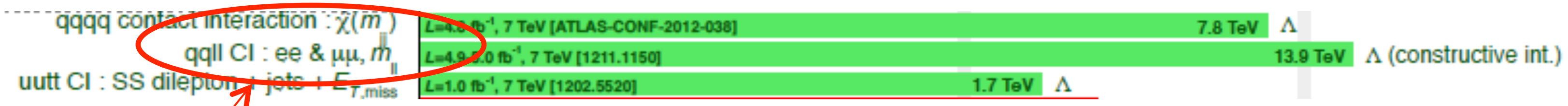


Contact interactions (eeqq)

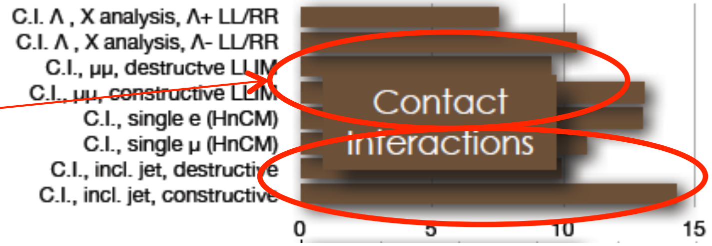
- New currents or heavy bosons may produce indirect effect via new particle exchange interfering with γ/Z fields.
- Reach for Λ (CI eeqq): 25-45 TeV with 10 fb^{-1} of data depending on the model



Similar to LHC



ATLAS and CMS constraints on eeqq CI (expected up to 30-40 TeV at c.o.m. 14 TeV LHC)

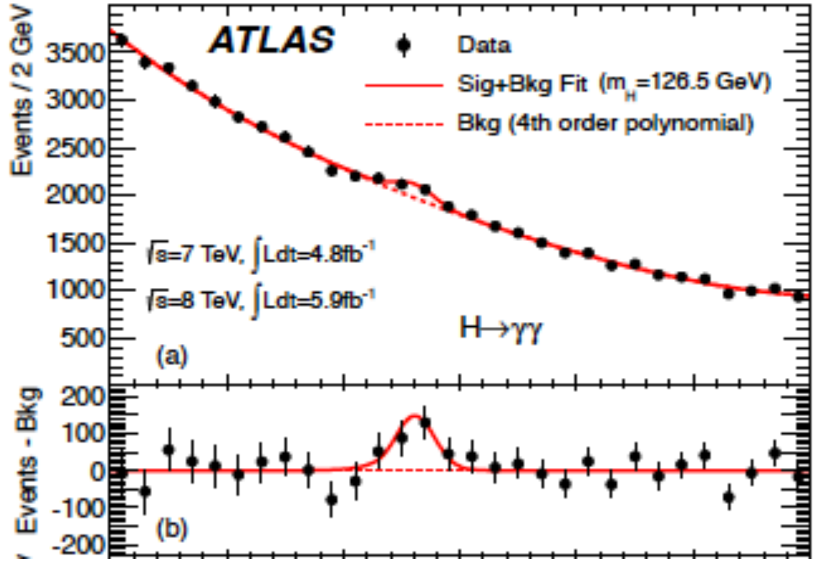


H → γγ

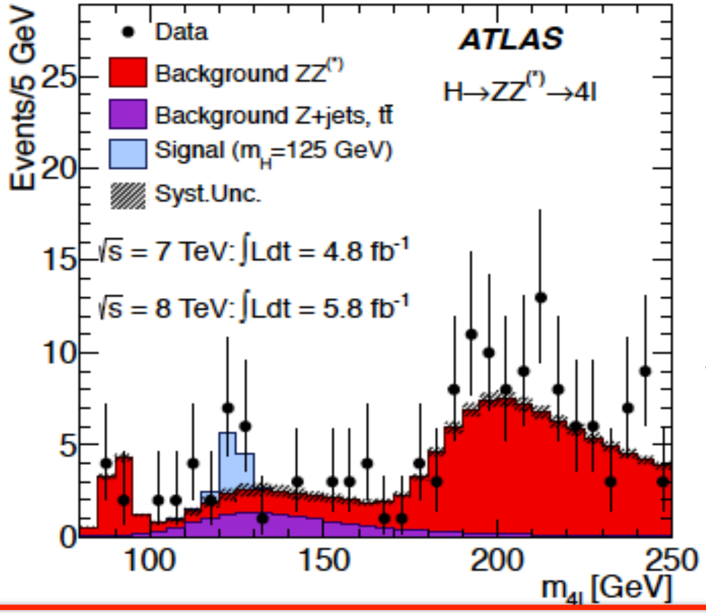
Discovery of H

H→ ZZ* → 4l

4.7.2012 ICHEP Melbourne

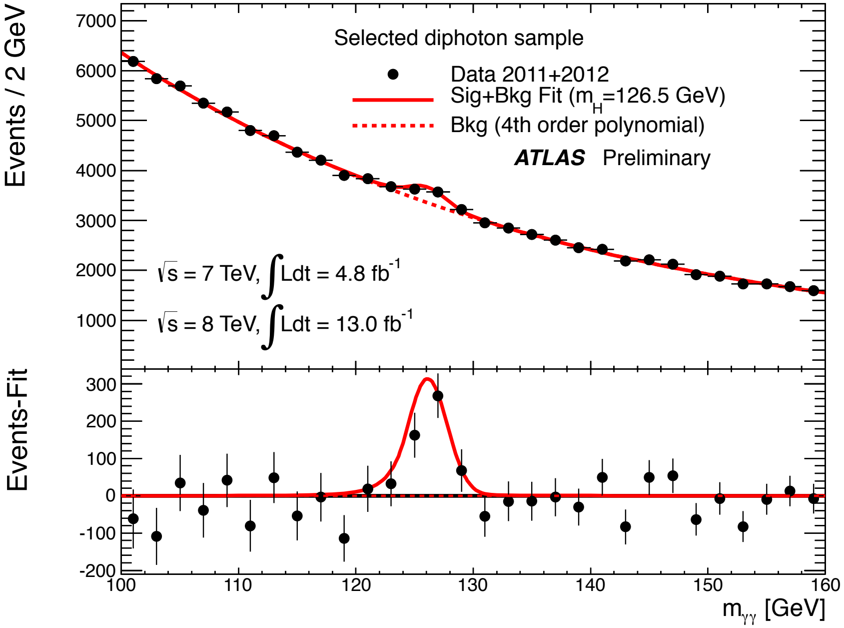


arXiv:1207.7214

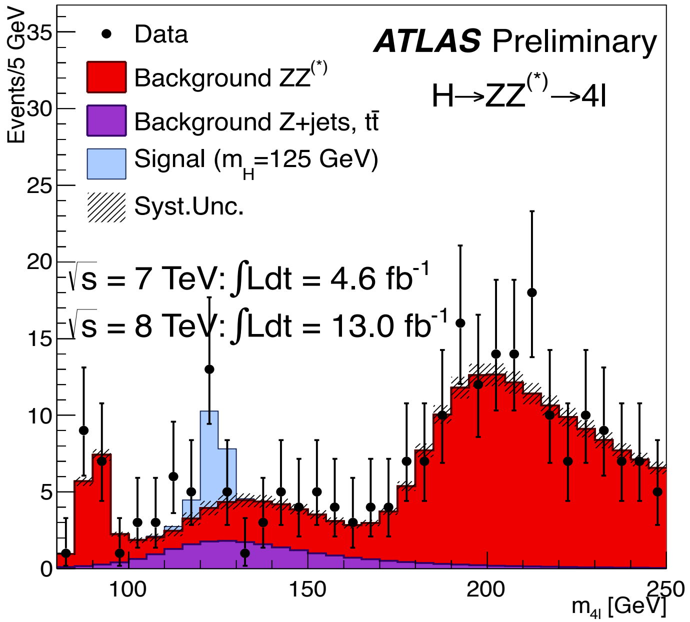


arXiv:1207.7214

13.12.2012 CERN Council



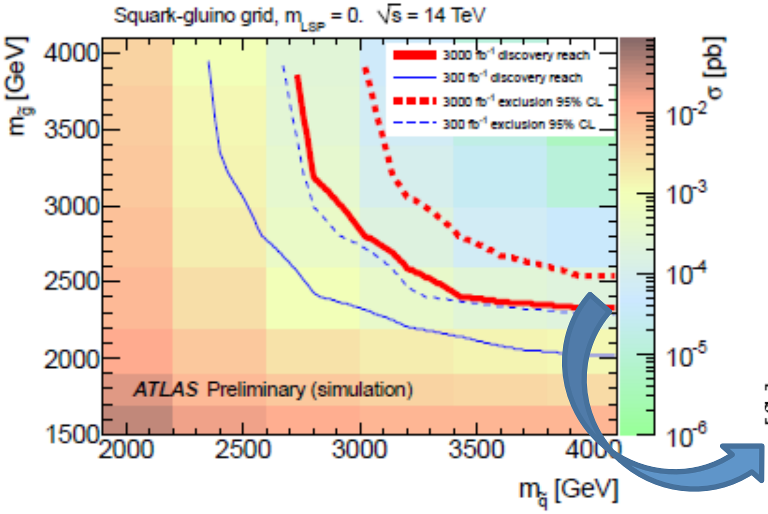
ATLAS CONF 2012-168



ATLAS CONF 2012-169

Impact on discovery/exclusion reach

- PDF uncertainties impact discovery / exclusion reach:
  - Total yields
  - Shape variations on discriminating quantities (in progress)

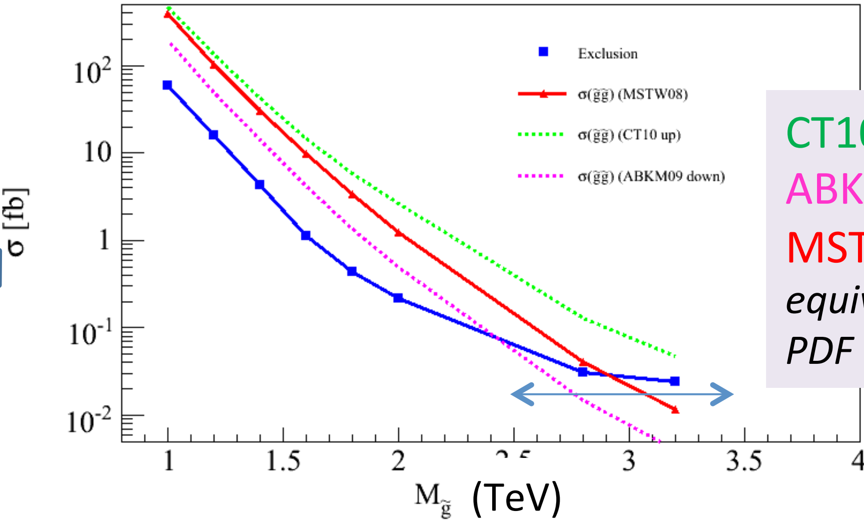


Caution: **very very** preliminary, mostly as illustration

(UL for gl-gl courtesy of G.Redlinger)

Impact on discovery/exclusion contours under various PDF hypothesis in progress

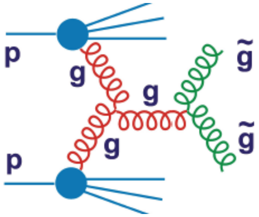
LHC @ 14 TeV 3 ab-1, M(squark) > 4 TeV

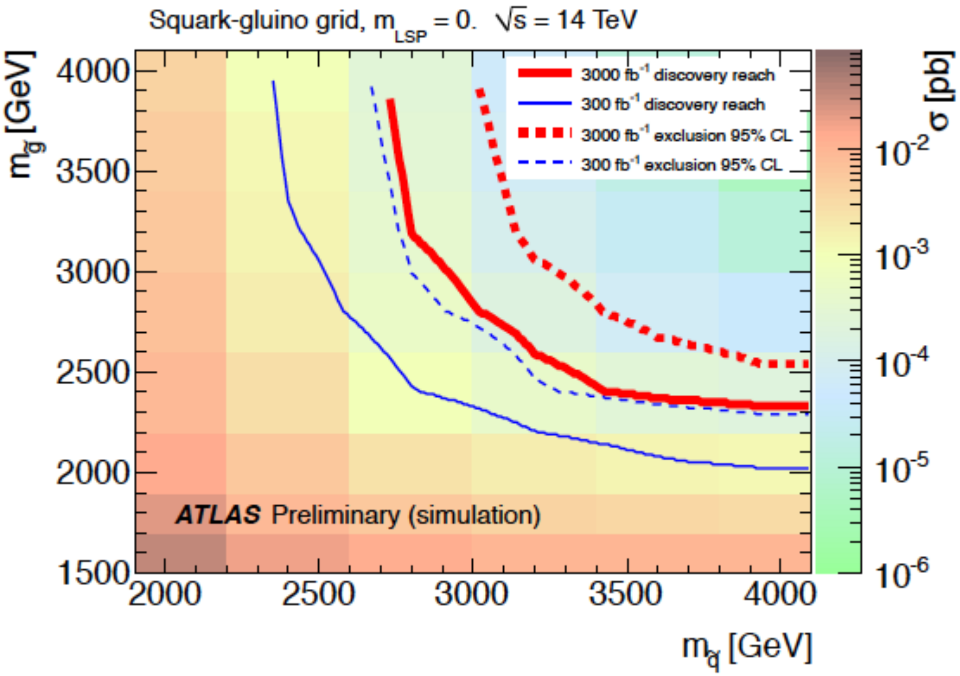


CT10 up
ABKM09 down
MSTW08
equivalent to LHeC PDF

Note: impact of PDF uncertainties on SM background also not negligible
However → mitigated by usage of Control Regions and semi data-driven estimate

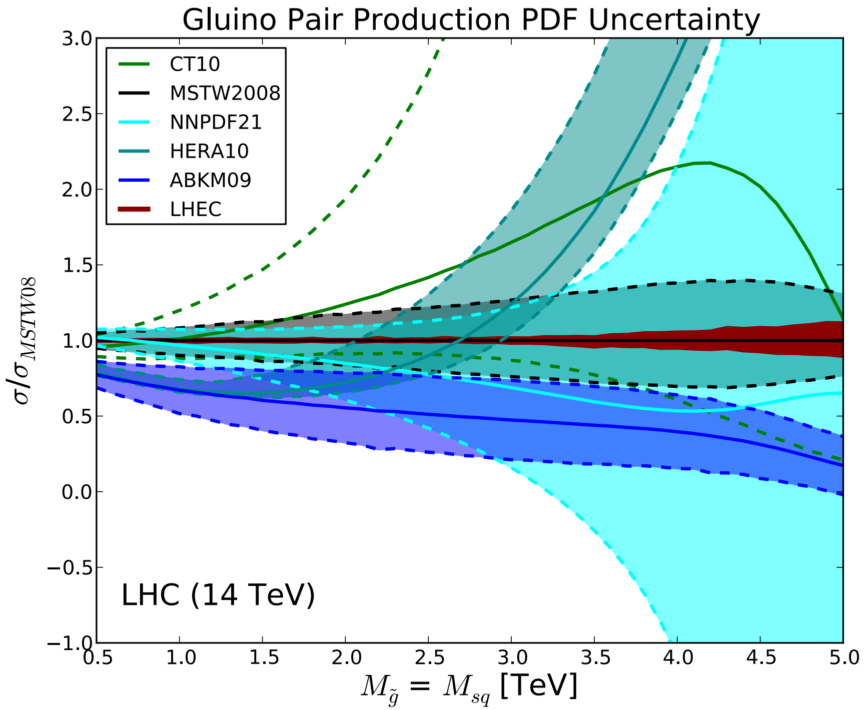
Link to HL LHC, e.g. High Mass SUSY





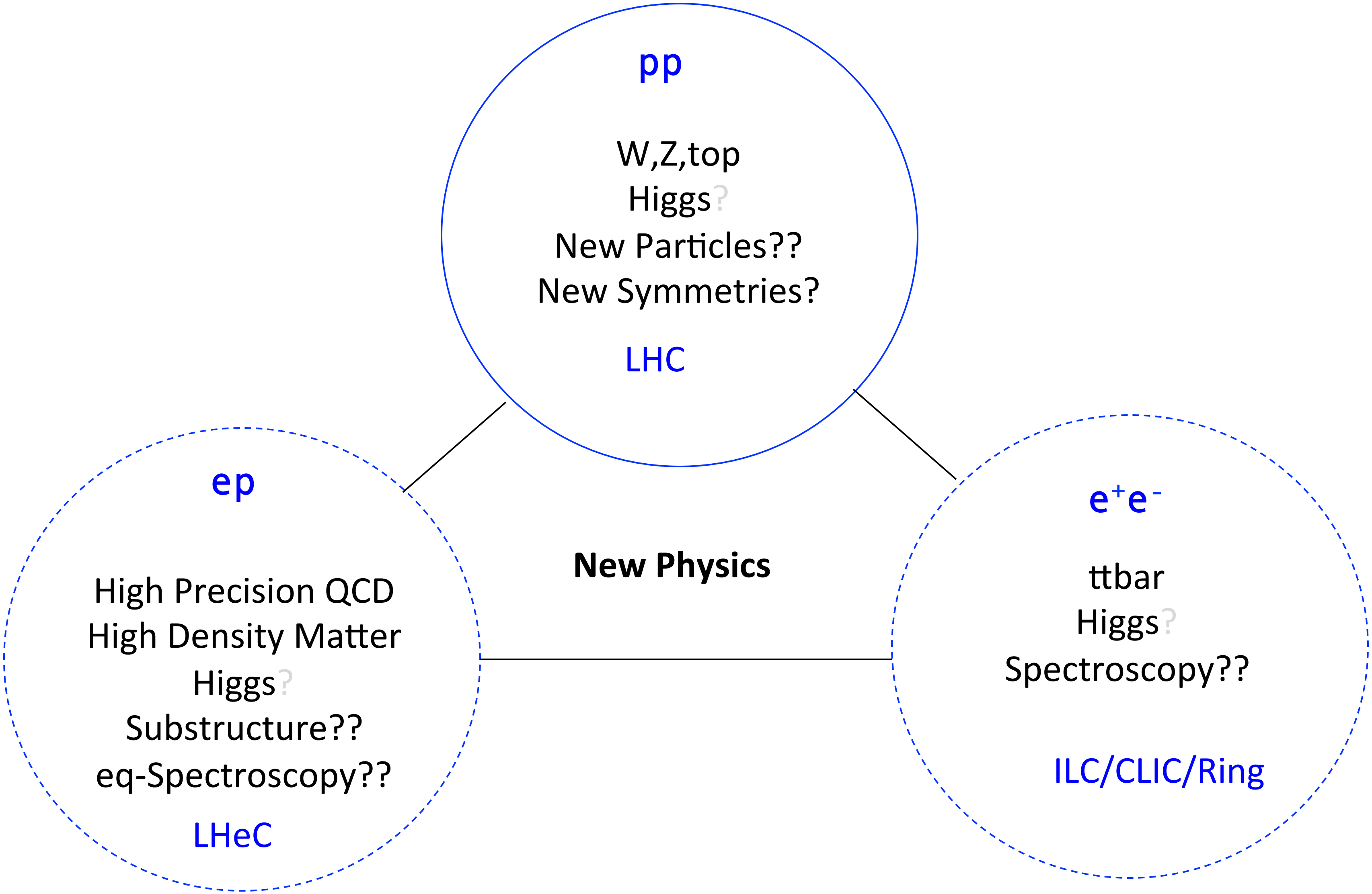
ATLAS October 2012 “Physics at High Luminosity”

LHeC: arXiv:1211.5102



With high energy and luminosity, the LHC search range will be extended to high masses, up to 4-5 TeV in pair production, and PDF uncertainties come in ~ 1/(1-x), CI effects?

The TeV Scale [2012-2035..]



pp

W,Z,top
Higgs?
New Particles??
New Symmetries?

LHC

ep

High Precision QCD
High Density Matter
Higgs?
Substructure??
eq-Spectroscopy??

LHeC

New Physics

e^+e^-

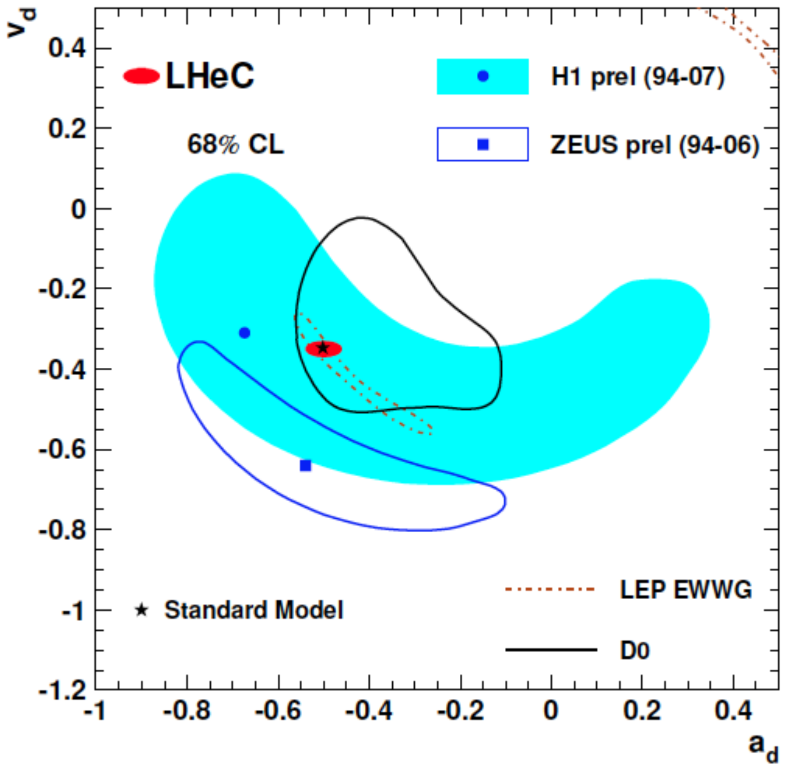
ttbar
Higgs?
Spectroscopy??

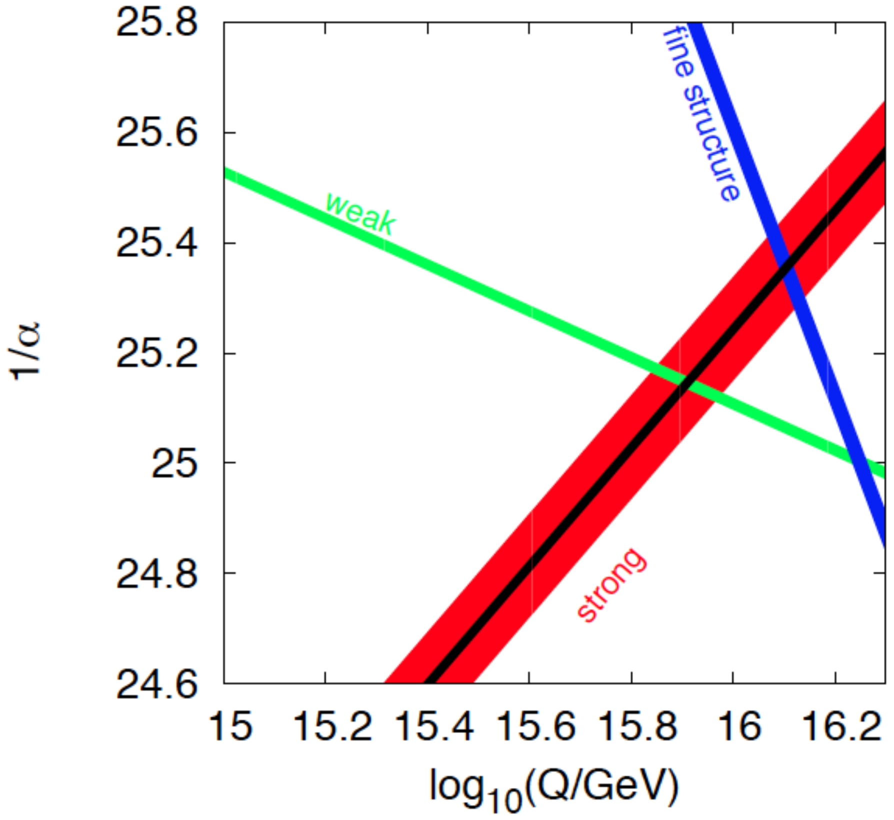
ILC/CLIC/Ring

-some simulated results-

Weak and strong couplings [GUT]
Gluon at low and high x
Unfolding partons (NC,CC and deuterons)
Strange, Charm and Beauty
Gluon Saturation?
Nuclear PDFs
Hadronisation..

High Precision DIS



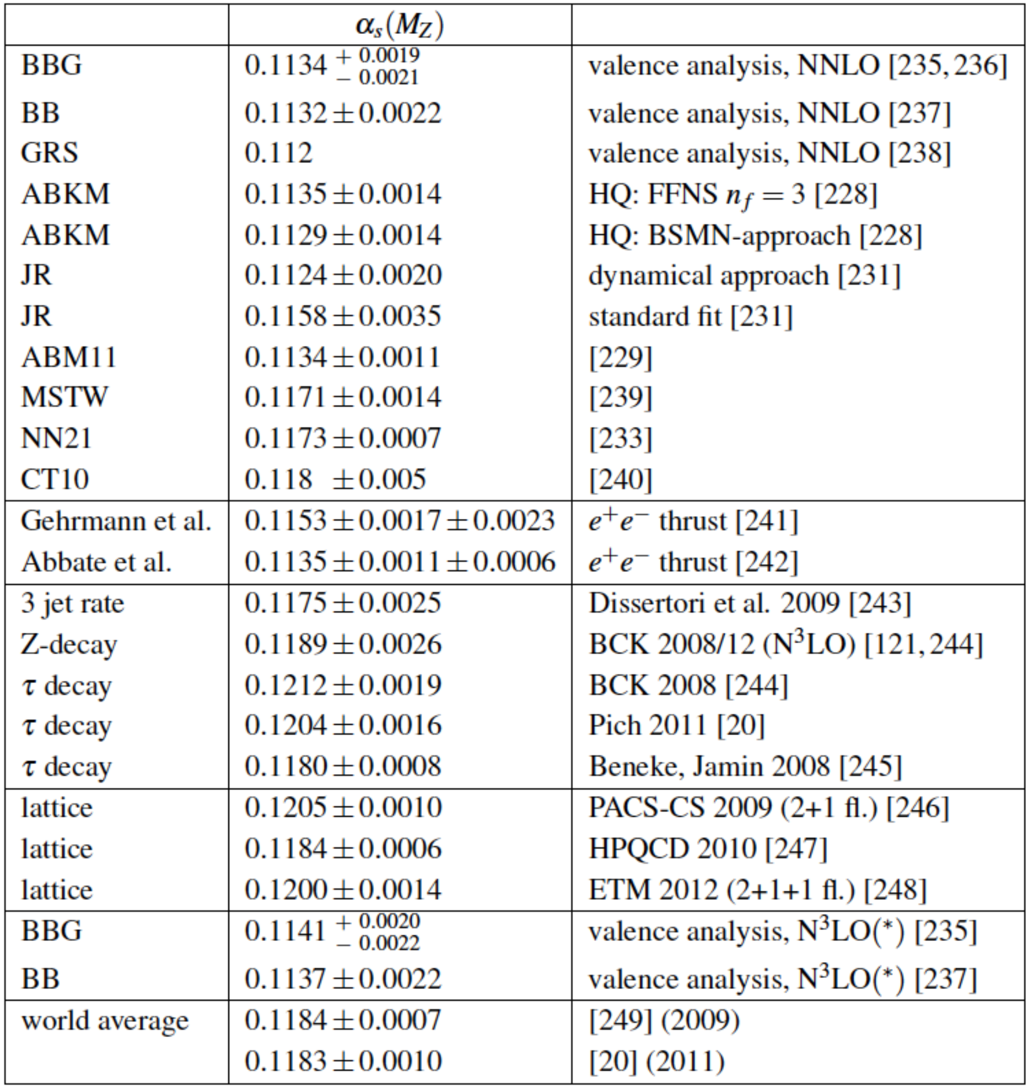


$Q^2 >> M_{Z,W}^2$, high luminosity, large acceptance
Unprecedented precision in NC and CC
Contact interactions probed to 50 TeV
Scale dependence of $\sin^2\theta$ left and right to LEP

→ A renaissance of deep inelastic scattering ←

Solving a 30 year old puzzle:
α_s small in DIS or high with jets?
Per mille measurement accuracy
Testing QCD lattice calculations
Constraining GUT (CMSSM40.2.5)
Charm mass to 3MeV, N^3LO

The strong coupling constant



	$\alpha_s(M_Z)$	
BBG	$0.1134 {}^{+0.0019}_{-0.0021}$	valence analysis, NNLO [235, 236]
BB	0.1132 ± 0.0022	valence analysis, NNLO [237]
GRS	0.112	valence analysis, NNLO [238]
ABKM	0.1135 ± 0.0014	HQ: FFNS $n_f = 3$ [228]
ABKM	0.1129 ± 0.0014	HQ: BSMN-approach [228]
JR	0.1124 ± 0.0020	dynamical approach [231]
JR	0.1158 ± 0.0035	standard fit [231]
ABM11	0.1134 ± 0.0011	[229]
MSTW	0.1171 ± 0.0014	[239]
NN21	0.1173 ± 0.0007	[233]
CT10	0.118 ± 0.005	[240]
Gehrmann et al.	$0.1153 \pm 0.0017 \pm 0.0023$	e^+e^- thrust [241]
Abbate et al.	$0.1135 \pm 0.0011 \pm 0.0006$	e^+e^- thrust [242]
3 jet rate	0.1175 ± 0.0025	Dissertori et al. 2009 [243]
Z-decay	0.1189 ± 0.0026	BCK 2008/12 (N^3LO) [121, 244]
τ decay	0.1212 ± 0.0019	BCK 2008 [244]
τ decay	0.1204 ± 0.0016	Pich 2011 [20]
τ decay	0.1180 ± 0.0008	Beneke, Jamin 2008 [245]
lattice	0.1205 ± 0.0010	PACS-CS 2009 (2+1 fl.) [246]
lattice	0.1184 ± 0.0006	HPQCD 2010 [247]
lattice	0.1200 ± 0.0014	ETM 2012 (2+1+1 fl.) [248]
BBG	$0.1141 {}^{+0.0020}_{-0.0022}$	valence analysis, $N^3LO(^*)$ [235]
BB	0.1137 ± 0.0022	valence analysis, $N^3LO(^*)$ [237]
world average	0.1184 ± 0.0007	[249] (2009)
	0.1183 ± 0.0010	[20] (2011)

α_s is the worst measured fundamental coupling constant. Is there grand unification?

In DIS, values (NNLO) range from 0.113 to 0.118.

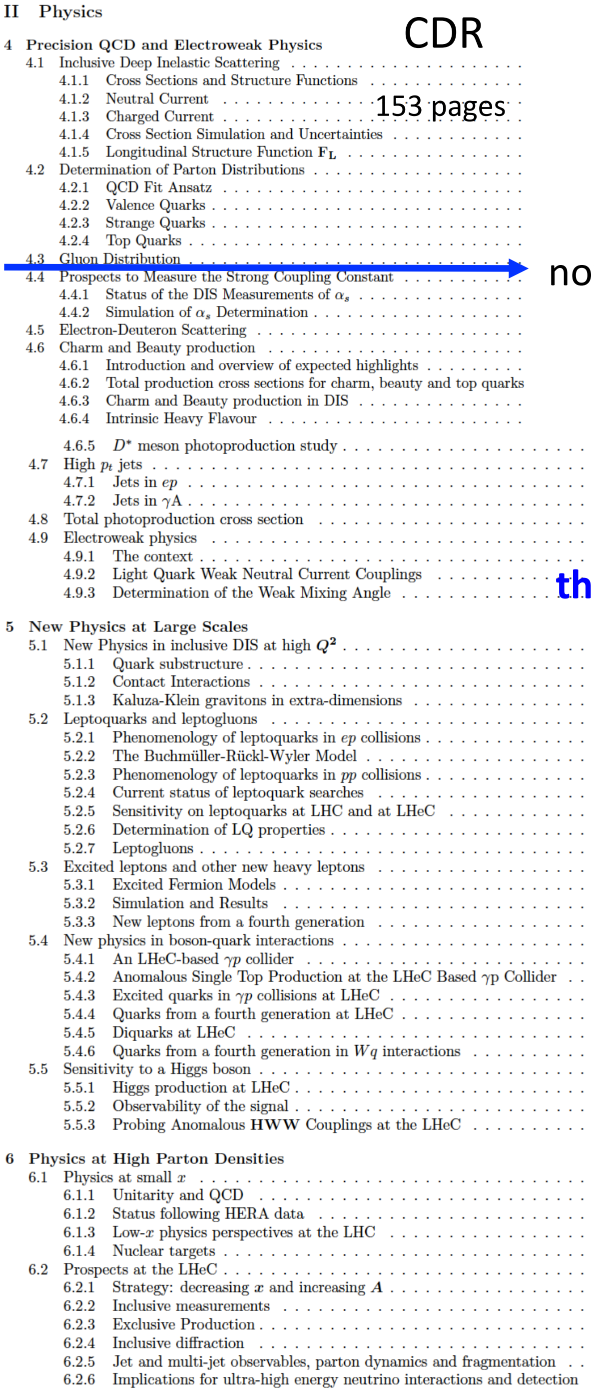
τ leads to about 0.120

Lattice predictions seem to determine the world average.

The LHeC has the potential to measure αs to permille accuracy (0.0002) from a consistent data set. This leads to high precision understanding of all related effects (low x, δM_c=3MeV) and pQCD at N^3LO

J.Bluemlein, Why Precision, arXiv:1205.4991

Gluon Distribution

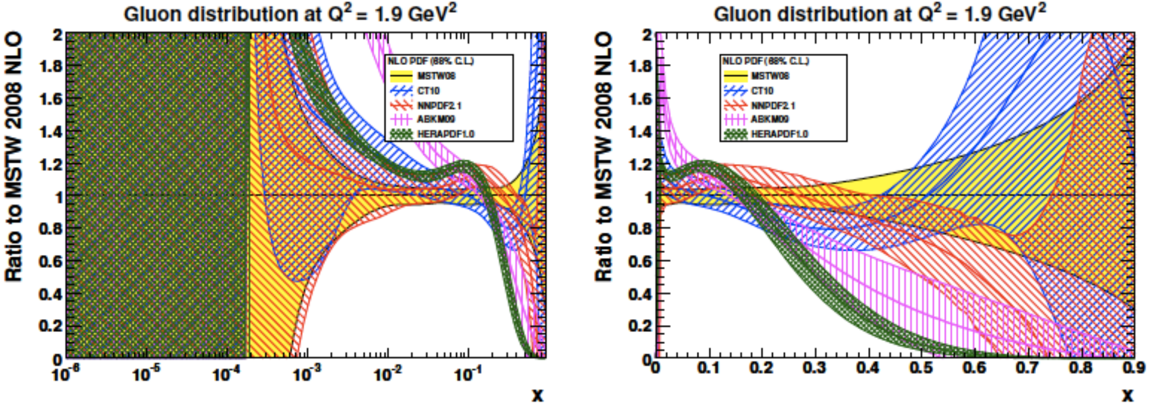


CDR

153 pages

now

then



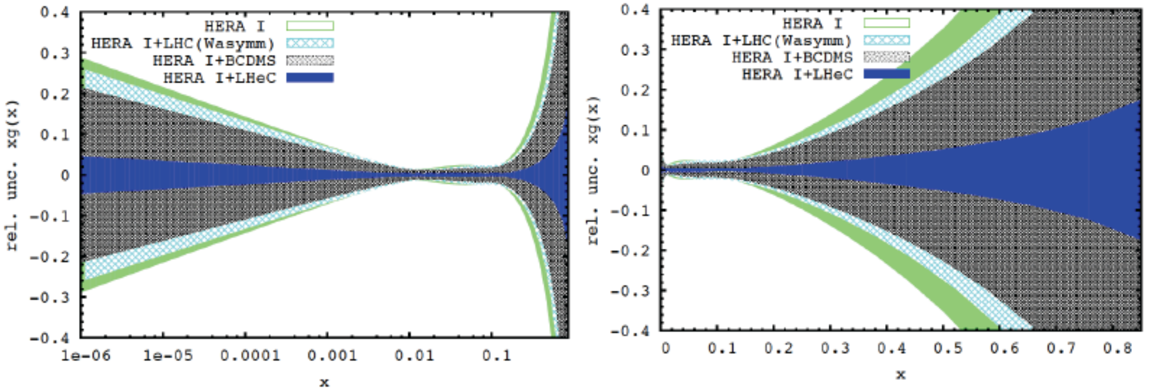
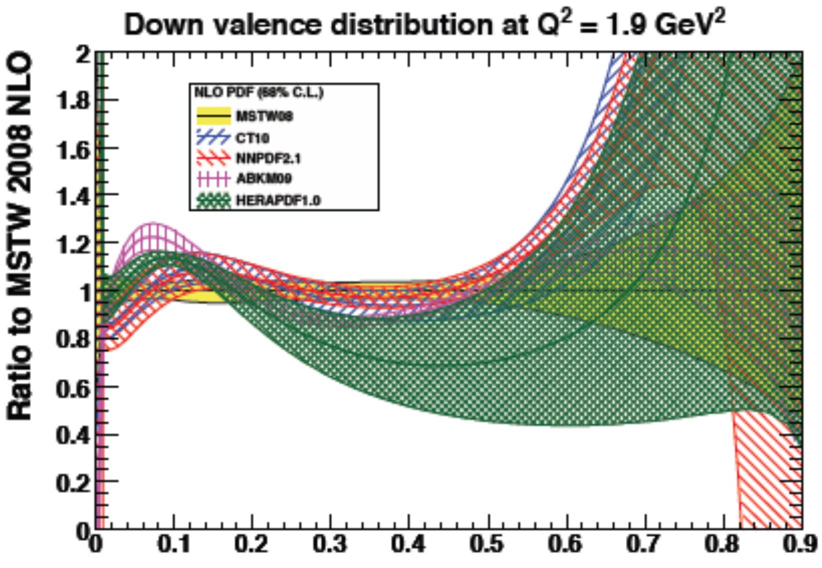
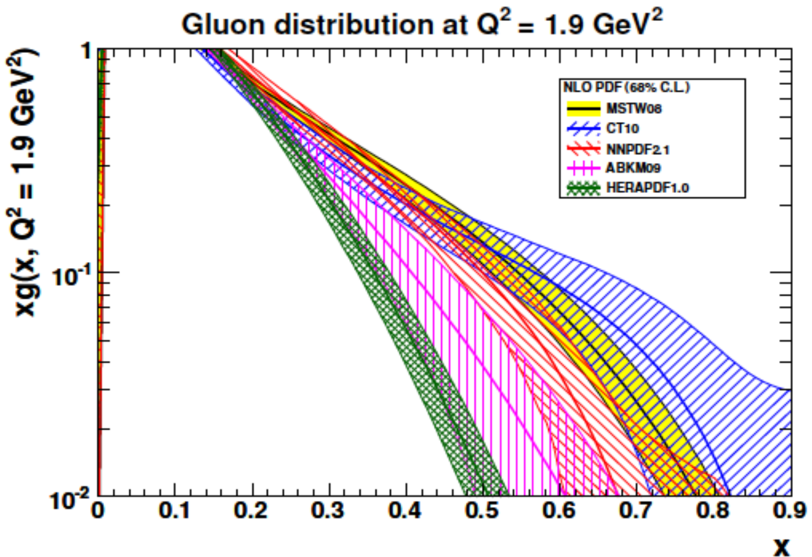


Figure 4.17: Relative uncertainty of the gluon distribution at $Q^2 = 1.9\,\mathrm{GeV}^2$, as resulting from an NLO QCD fit to HERA (I) alone (green, outer), HERA and BCDMS (crossed), HERA and LHC (light blue, crossed) and the LHeC added (blue, dark). Left: logarithmic x, right: linear x.

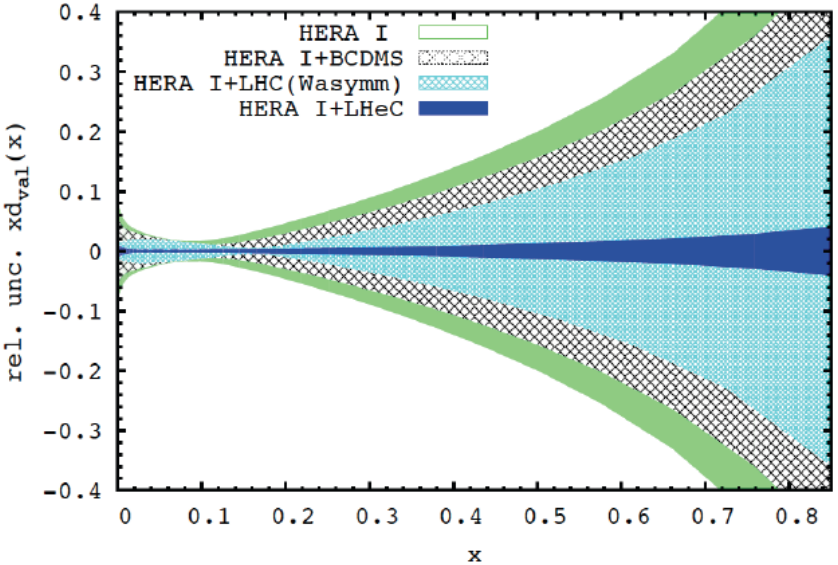
Precision measurement of gluon density to extreme x → α_s
Low x: saturation in ep? Crucial for QCD, LHC, UHE neutrinos!
High x: xg and valence quarks: resolving new high mass states!
Gluon in Pomeron, odderon, photon, nuclei.. Local spots in p?
Heavy quarks intrinsic or only gluonic?

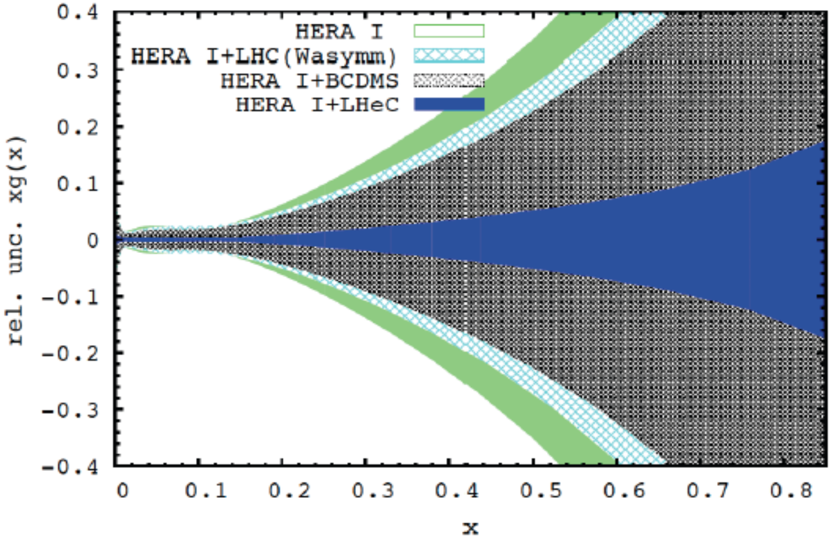
PDFs at Large x



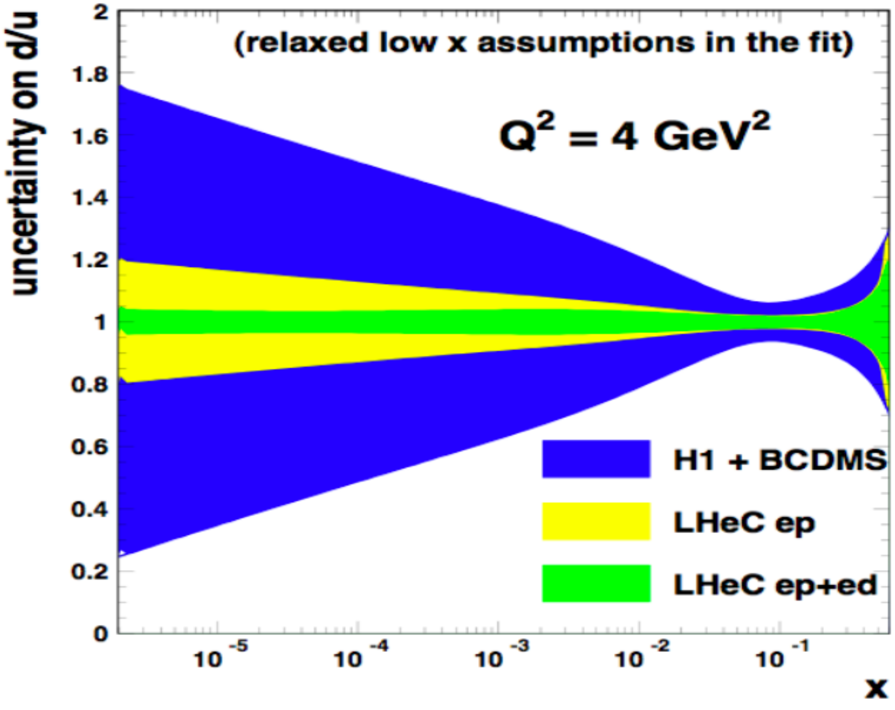


No higher twist corrections, free of nuclear uncertainties, high precision test of factorisation

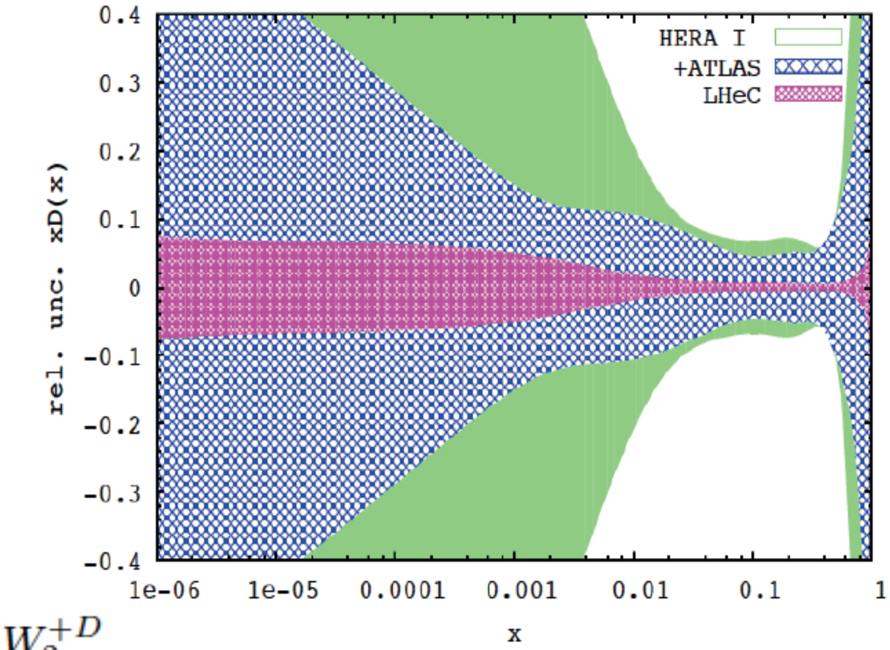




Deuterons and Light Sea Quark Asymmetry


d/u at low x from deuterons

D="total down" from LHeC (ep) fit with FREE d-u difference, including simulated high precision LHC W,Z


CDR

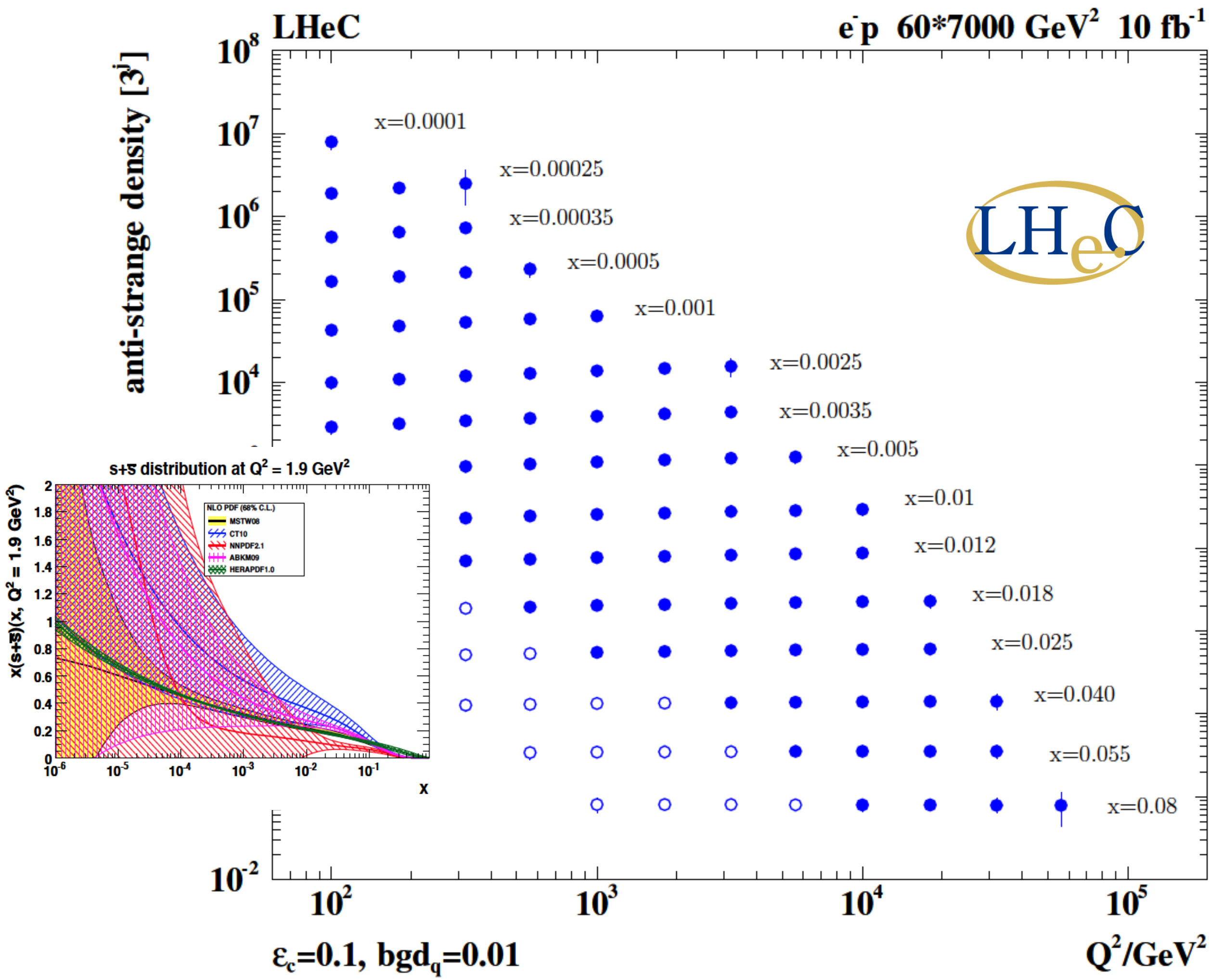
Deuterons: Crucial for

- NS-S decomposition
- Neutron structure
- Flavour separation

$$R^- = 2\frac{W_2^{-D} - W_2^{+D}}{W_2^{-p} + W_2^{+p}}$$

Nice: Gribov relation and spectator tagging to get rid off shadowing and Fermi motion!!

Strange Quark Distribution



High luminosity

High Q^2

Small beam spot

Modern Silicon

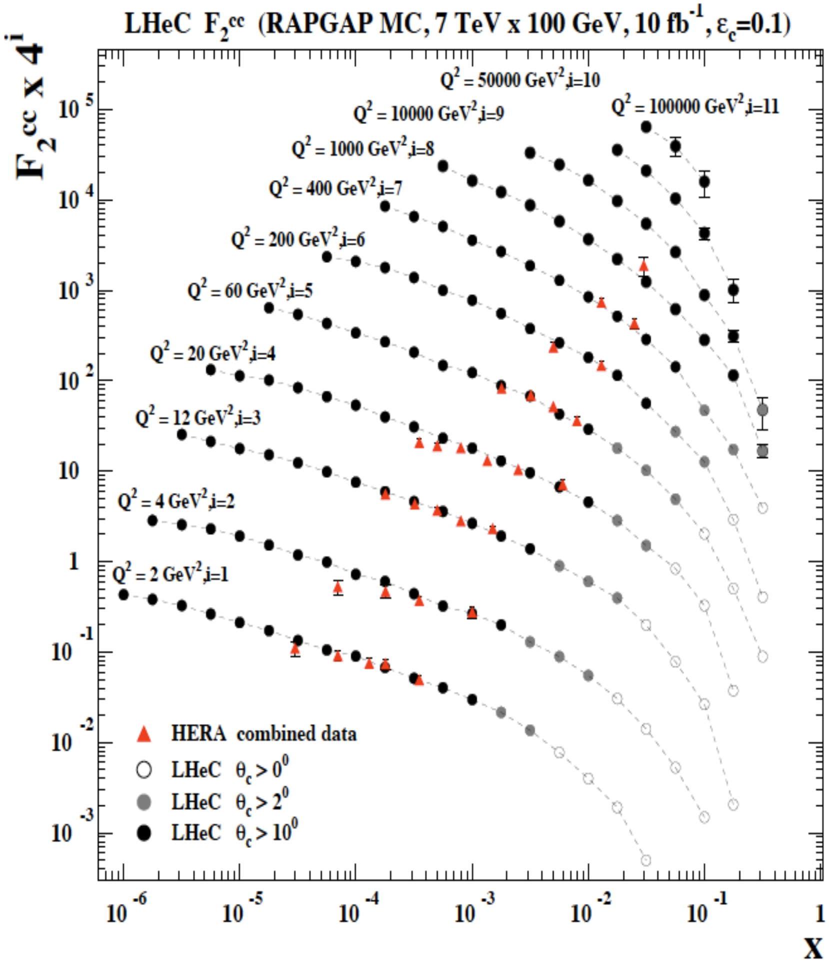
NO pile-up..

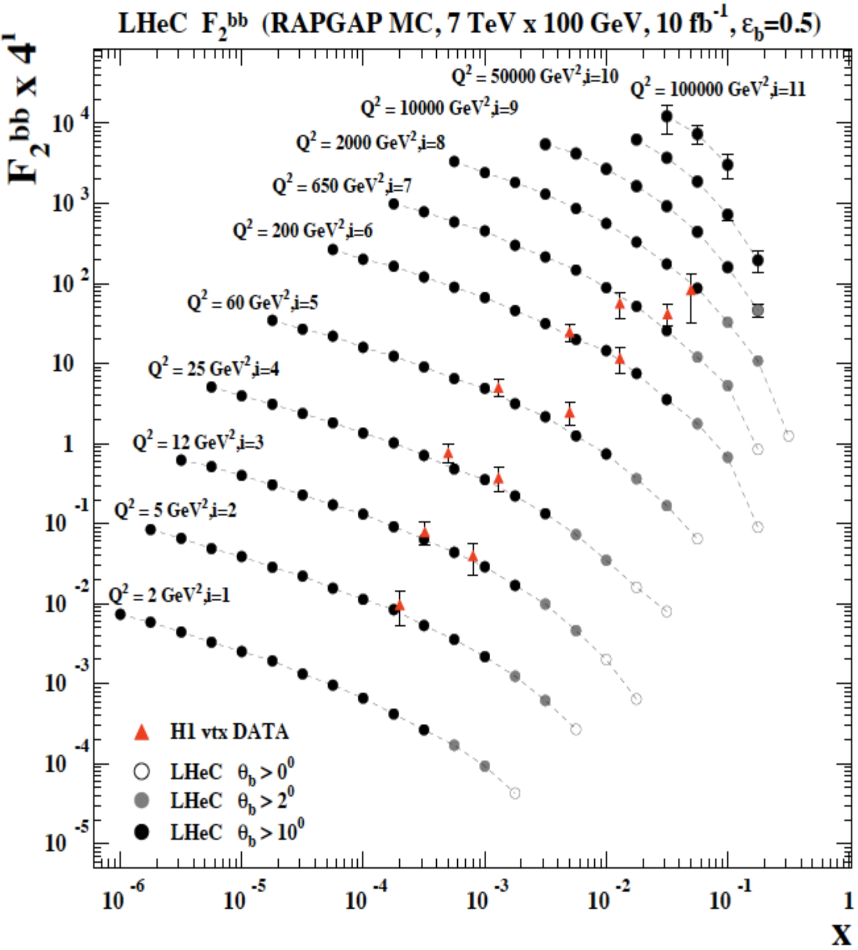
→ First (x,Q^2) measurement of the (anti-)strange density, HQ valence?

x = 10^{-4} .. 0.05
Q^2 = 100 – 10^5 GeV^2

Initial study (CDR): Charm tagging efficiency of 10% and 1% light quark background in impact parameter

F_2^{charm} and F_2^{beauty} from LHeC

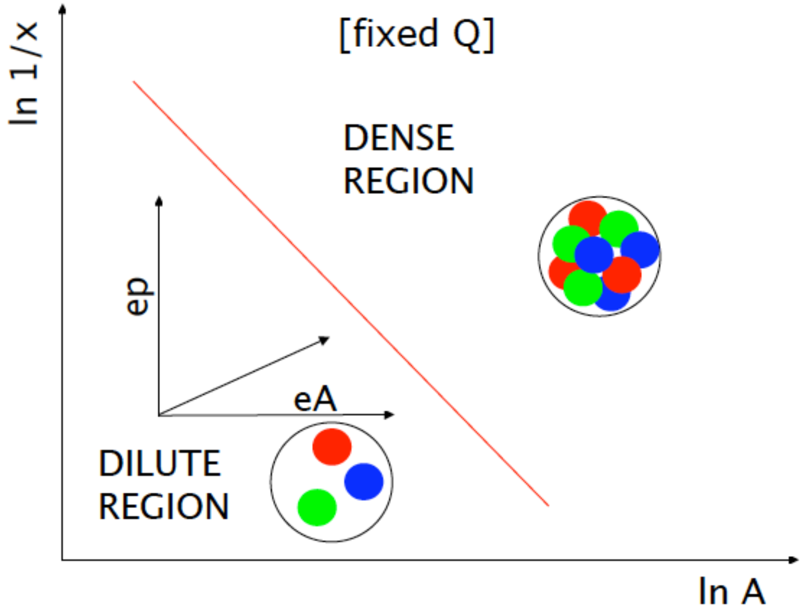


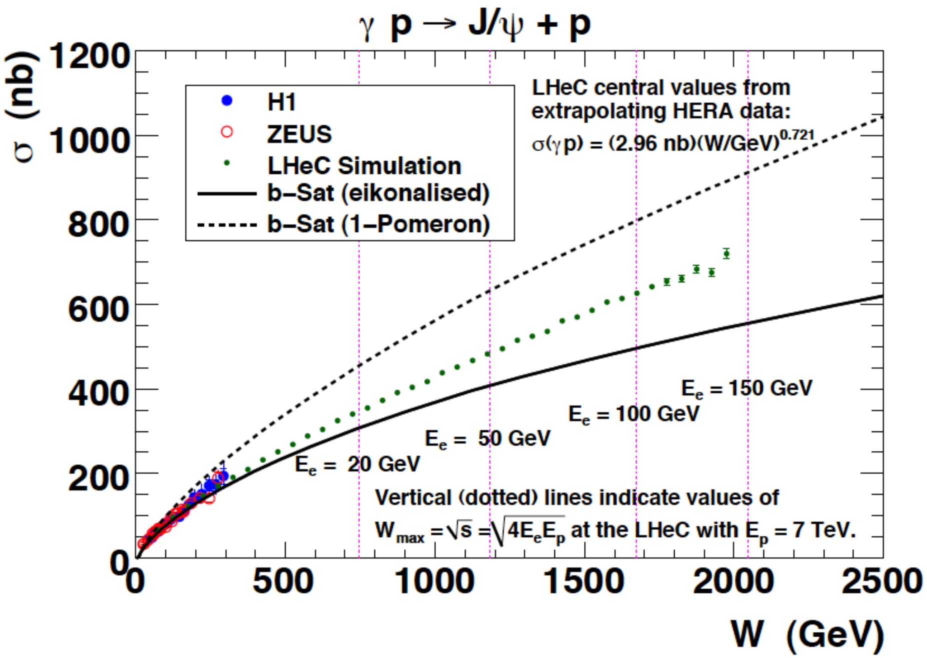


Hugely extended range and much improved precision (δM_c=60 HERA → 3 MeV)
will pin down heavy quark behaviour at and far away from thresholds, crucial for precision t,H..
In MSSM, Higgs is produced dominantly via bb → H (Pumplin et al) , but where is the MSSM..

Low x Physics – Gluon Saturation?

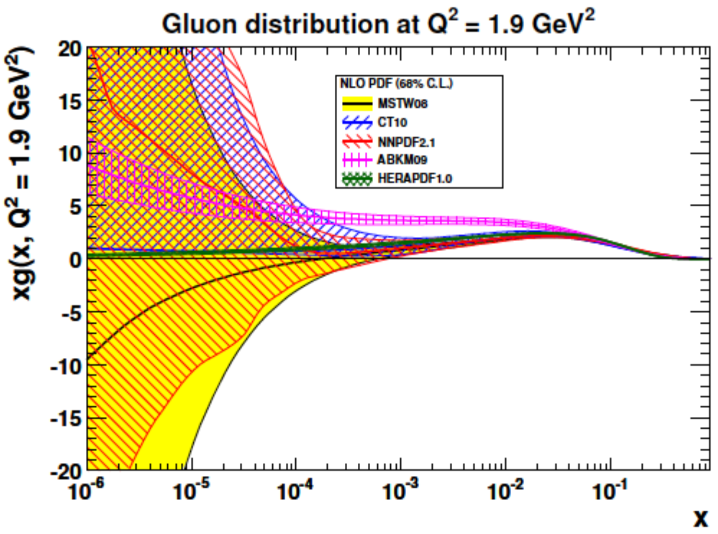
Precision Measurements of various
crucial observables (F_2, F_L, J/ψ, diffraction

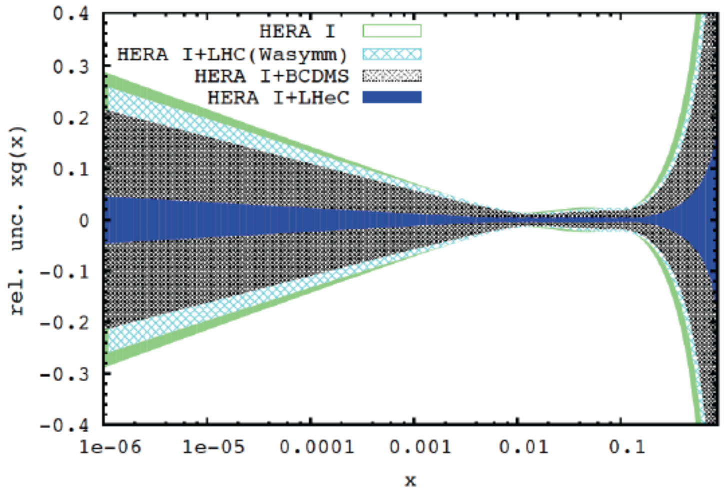


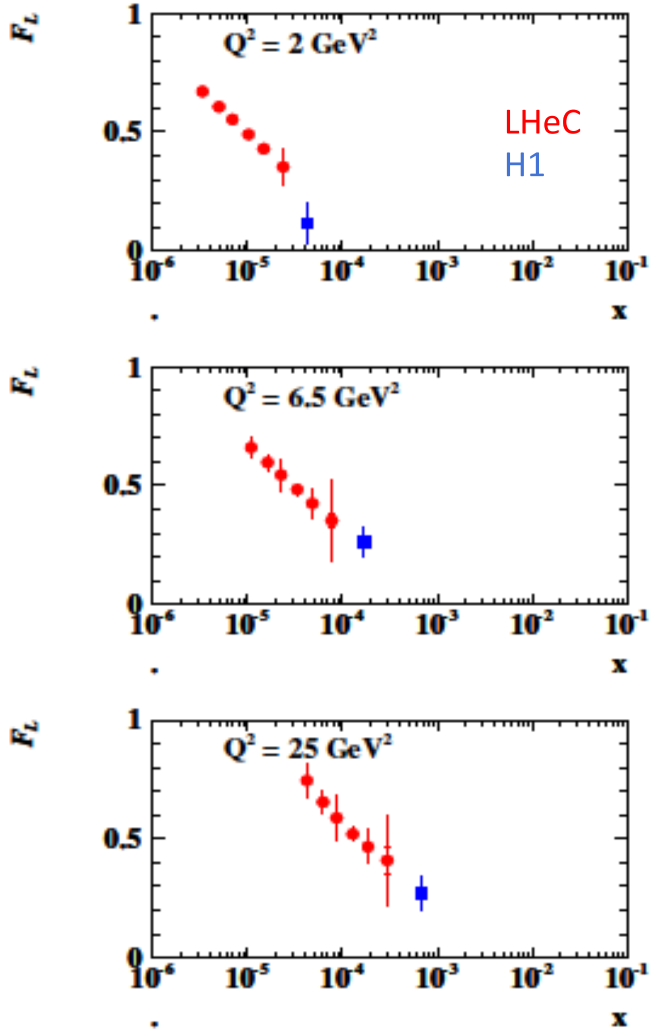


also GPDs with polarisation, charge asymmetries..

Gluon at Low x



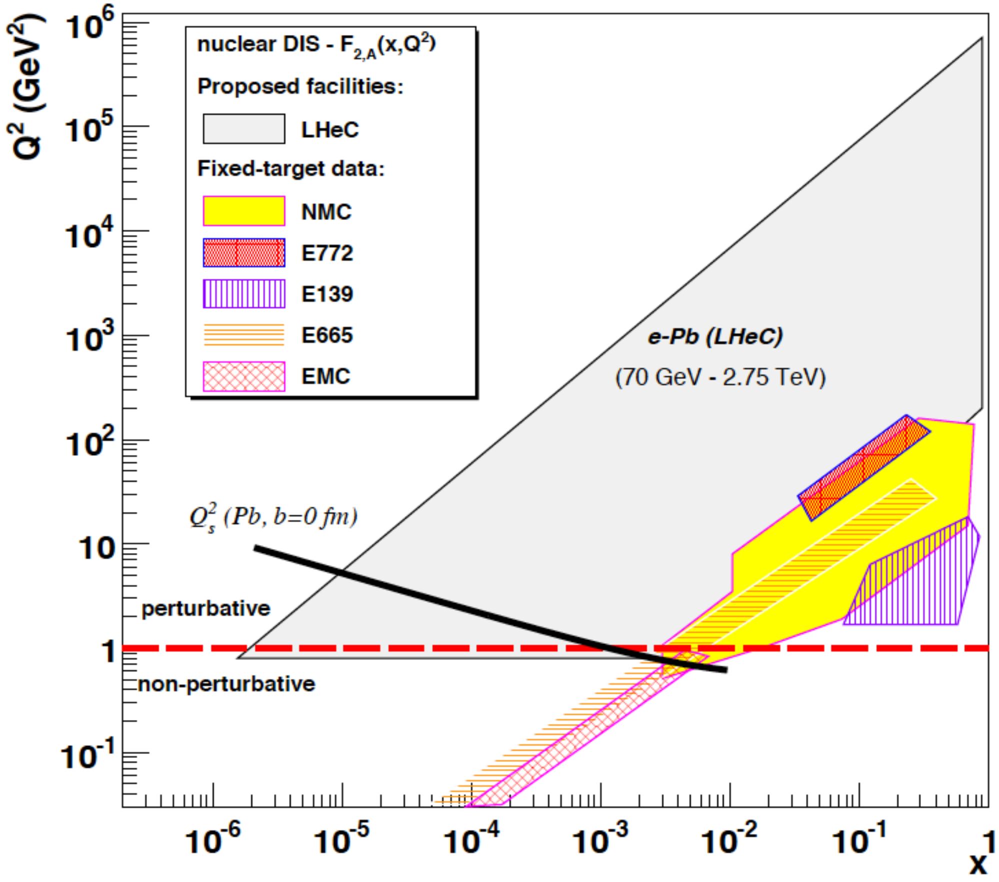




Gluon measurement down to x=10^{-5}, **Saturation or no saturation** (F_2 and precise F_L)
Non-linear evolution equations? Relations to string theory, and **SUSY at ~10 TeV**?

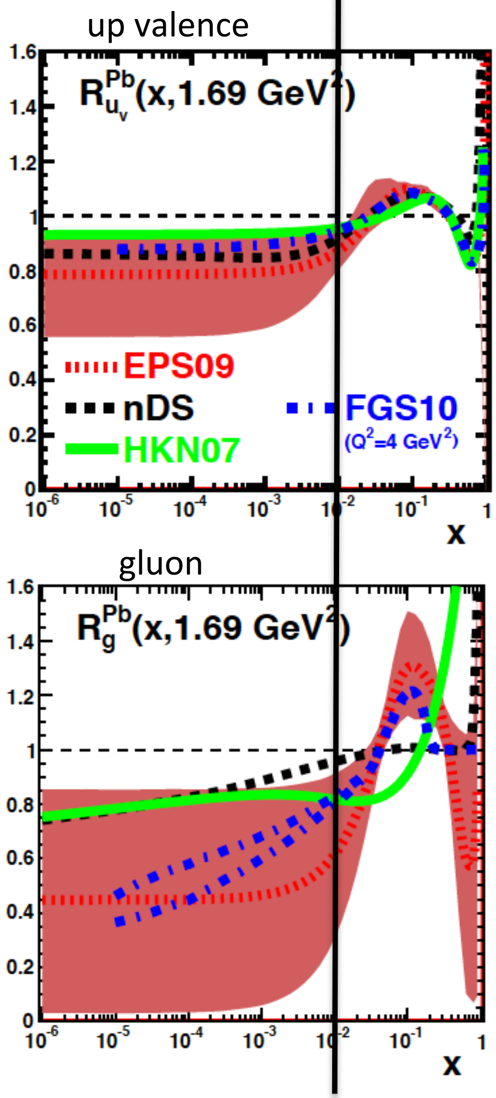
cf H.Kowalski, L.Lipatov, D.Ross, arXiv:1205.6713

LHeC as an electron-ion collider



3-4 orders of magnitude extension of lA kinematic range

→ LHeC has huge discovery potential for new HI physics
(bb limit, saturation, deconfinement, hadronisation,QGP..)
will put nPDFs on completely new ground



unmeasured | known?

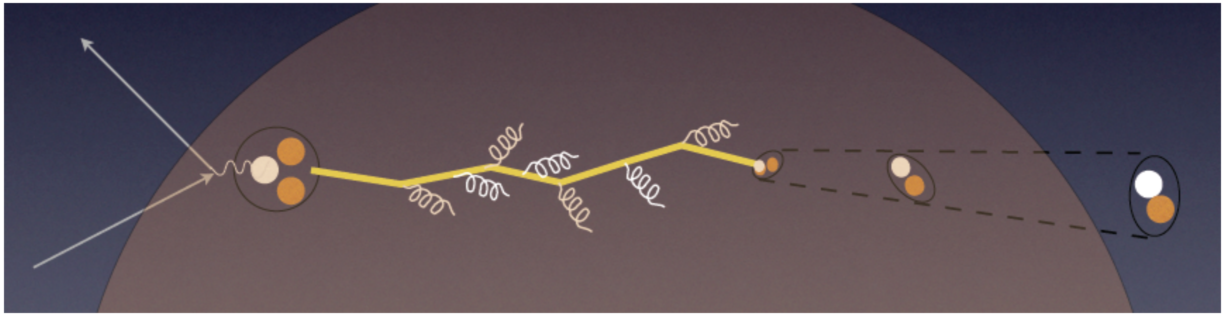
In-medium Hadronisation

The study of particle production in eA (fragmentation functions and hadrochemistry) allows the study of the space-time picture of hadronisation (the final phase of QGP).

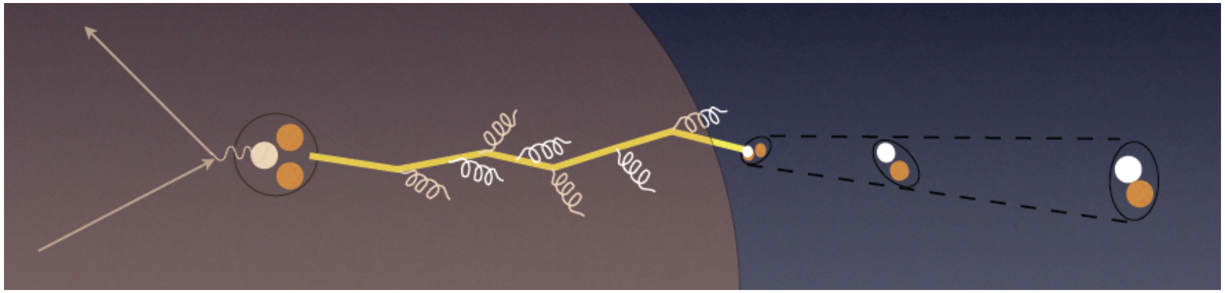
Low energy (ν): need of hadronization inside.

Parton propagation: pt broadening

Hadron formation: attenuation



High energy (ν): partonic evolution altered in the nuclear medium.



W.Brooks, Divonne09

LHeC :

+ study the transition from small to high energies in much extended range wrt. fixed target data

+ testing the energy loss mechanism crucial for understanding of the medium produced in HIC

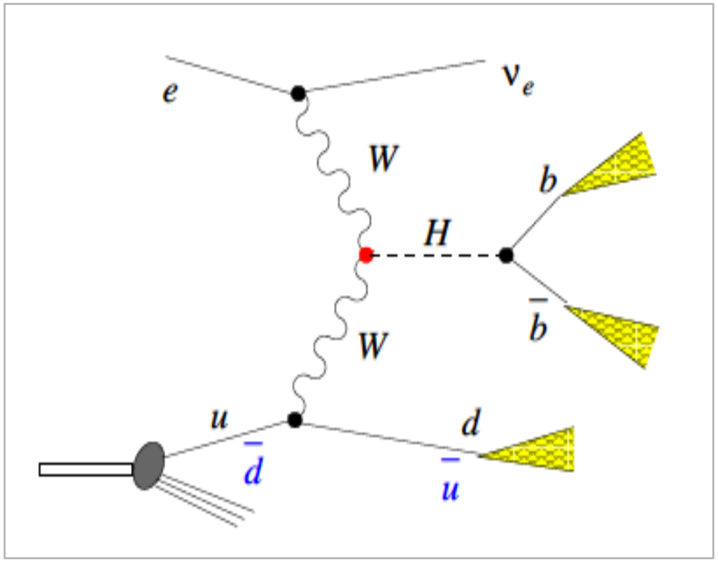
+ detailed study of heavy quark hadronisation …

-Higgs and ep-

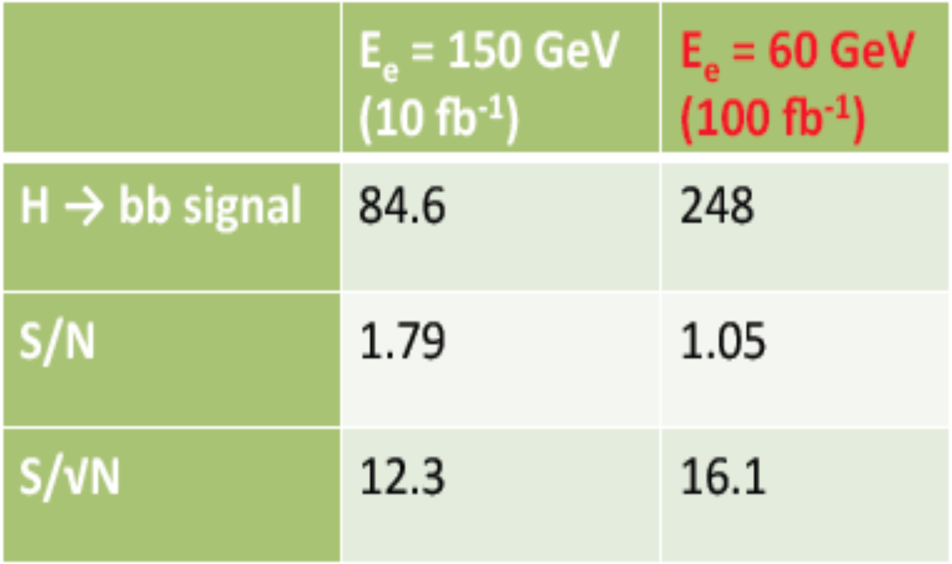
Higgs production
Higgs to bbar with S/B=1
CP
LHeC as Higgs “Factory”
Rates [→ more work ..]
H in e^+e^-
Precision xg and gg→ H at the LHC

Higgs at the LHeC

Clean final state, no pile-up, low QCD bgd, uniquely WW and ZZ, small theory unc.ties



Default



	E_e = 150 GeV (10 fb^{-1})	E_e = 60 GeV (100 fb^{-1})
H → bb signal	84.6	248
S/N	1.79	1.05
S/√N	12.3	16.1

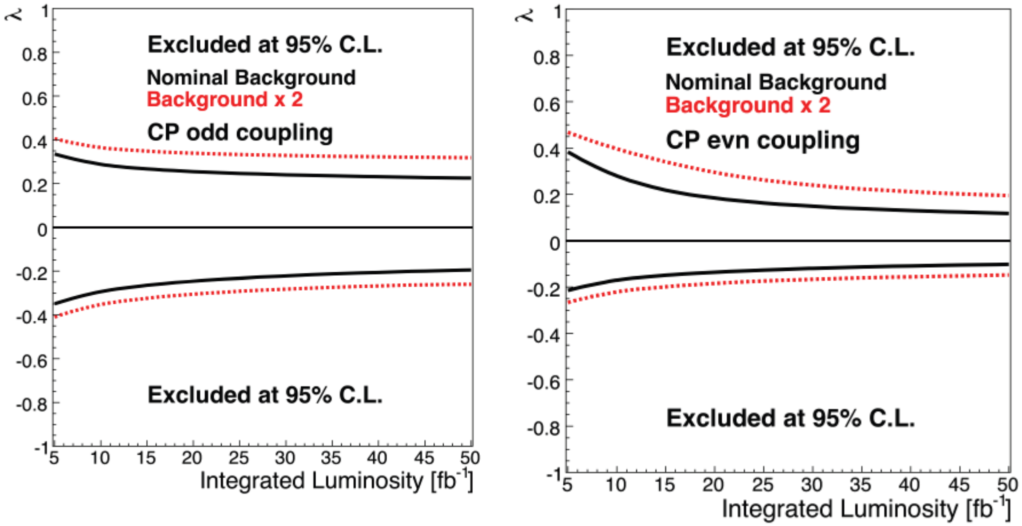
U. Klein, ICHEP12, Melbourne for the LHeC

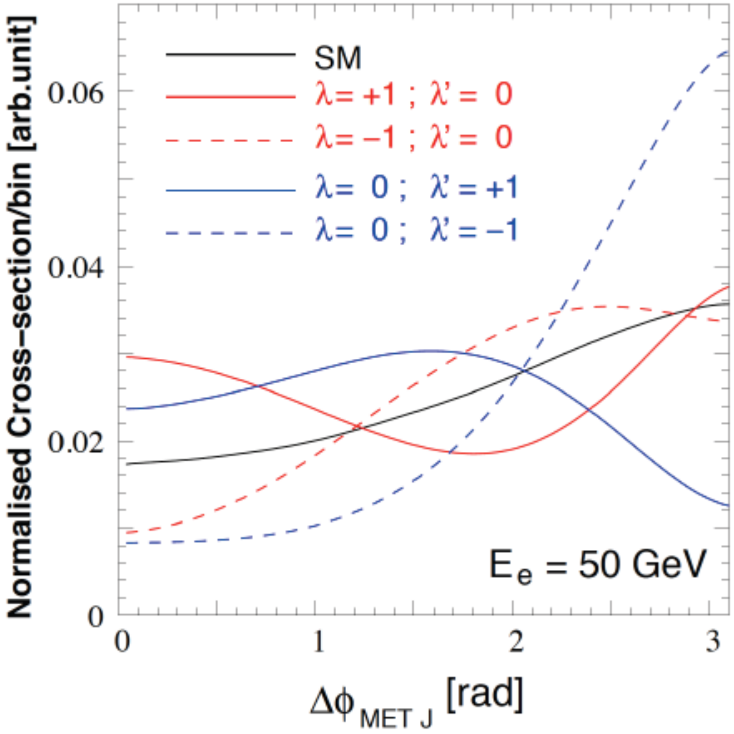
Full simulation of ep → nu H X → nu bbar X: reconstruction efficiency of 2.5%

With **polarised** electrons, 100fb^{-1} - bb coupling measurement precision of 2-3%.

CP Higgs at the LHeC

In the SM the Higgs is a $J^{PC}=0^{++}$ state. One needs to measure the EV if CP is conserved, and the mixture of even and odd states if it is not.





λ (λ') anomalous CP (non) conserving terms

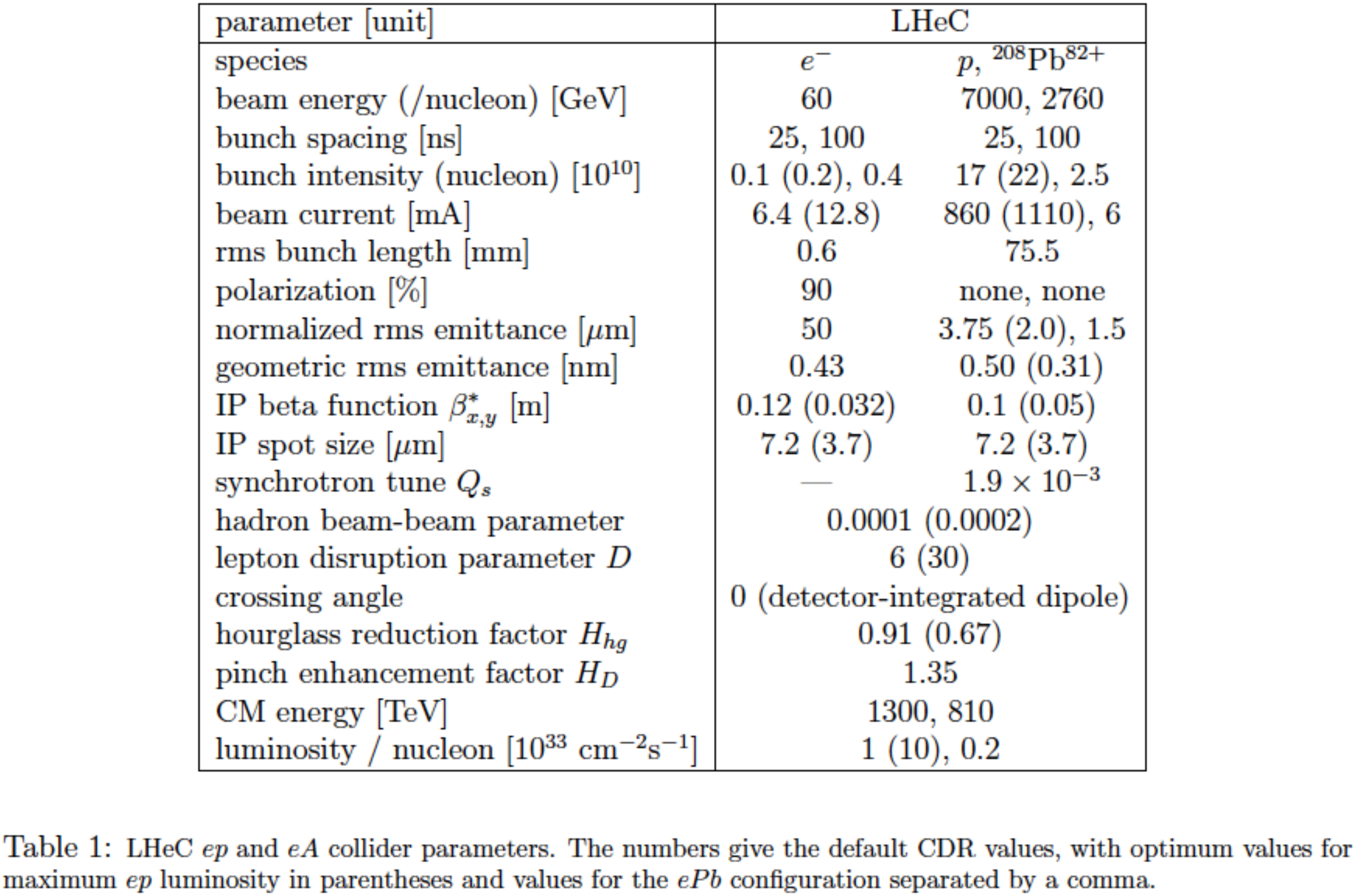
$$\mathcal{L}_{\text{int}} = -gM_W \left(W_\mu W^\mu + \frac{1}{2\cos\theta_W} Z_\mu Z^\mu \right) H$$

$$\Gamma^{\mu\nu}_{(\text{SM})}(p,q) = \ -gM_W\, g^{\mu\nu}$$

$$\Gamma^{\text{BSM}}_{\mu\nu}(p,q) = \frac{g}{M_W} \left[\lambda \left(p \cdot q\, g_{\mu\nu} - p_\nu q_\mu \right) + i\, \lambda'\ \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma \right]$$

S.Biswal et al, PhysRevLett.109.261801

LHeC at 10^{34} Luminosity

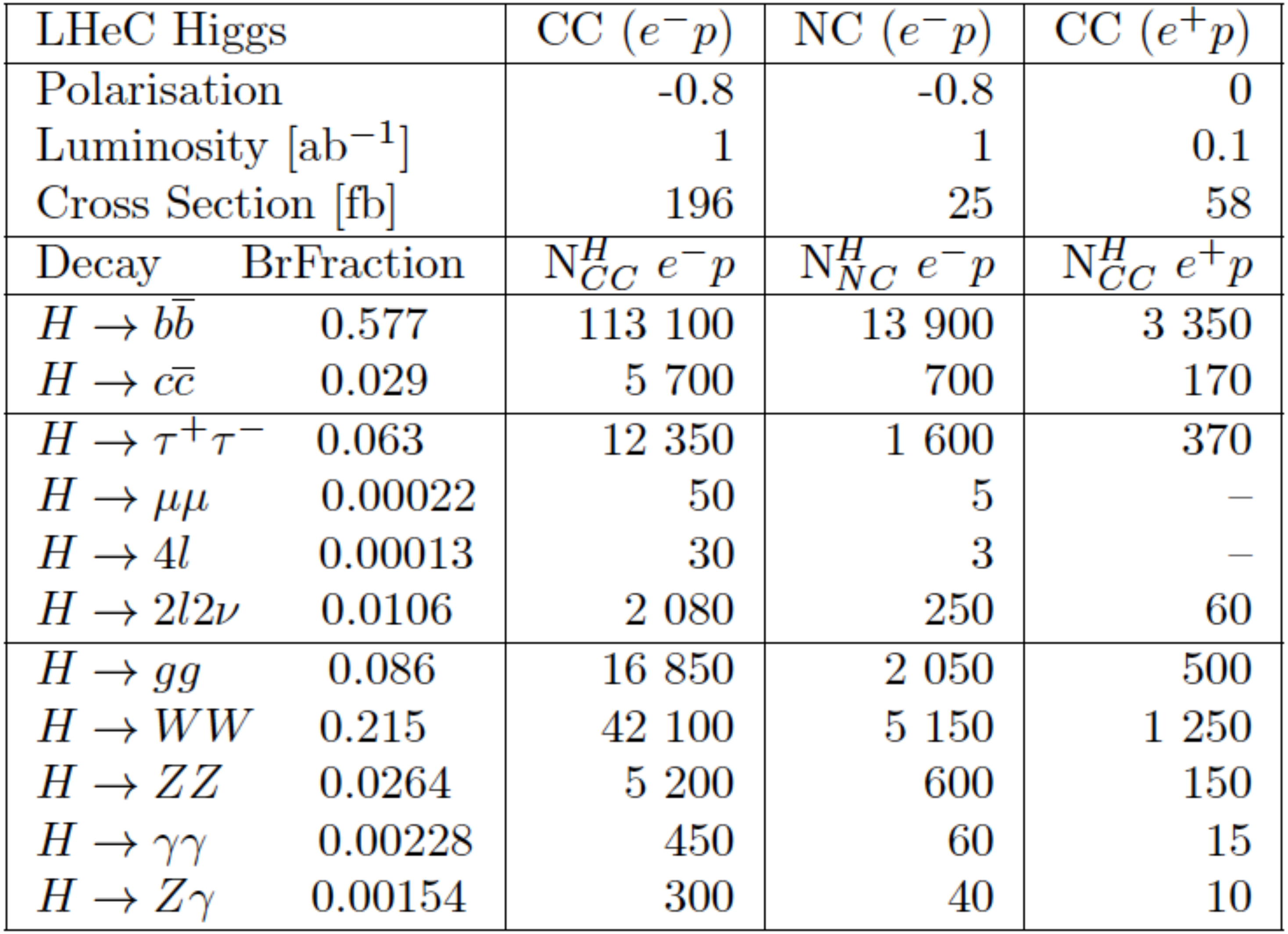


parameter [unit]	LHeC	
species	e^-	p, $^{208}\mathrm{Pb}^{82+}$
beam energy (/nucleon) [GeV]	60	7000, 2760
bunch spacing [ns]	25, 100	25, 100
bunch intensity (nucleon) [10^{10}]	0.1 (0.2), 0.4	17 (22), 2.5
beam current [mA]	6.4 (12.8)	860 (1110), 6
rms bunch length [mm]	0.6	75.5
polarization [%]	90	none, none
normalized rms emittance [μm]	50	3.75 (2.0), 1.5
geometric rms emittance [nm]	0.43	0.50 (0.31)
IP beta function $\beta^*_{x,y}$ [m]	0.12 (0.032)	0.1 (0.05)
IP spot size [μm]	7.2 (3.7)	7.2 (3.7)
synchrotron tune Q_s	—	1.9×10^{-3}
hadron beam-beam parameter	0.0001 (0.0002)	
lepton disruption parameter D	6 (30)	
crossing angle	0 (detector-integrated dipole)	
hourglass reduction factor H_{hg}	0.91 (0.67)	
pinch enhancement factor H_D	1.35	
CM energy [TeV]	1300, 810	
luminosity / nucleon [10^{33} cm^{-2}s^{-1}]	1 (10), 0.2	

Table 1: LHeC *ep* and *eA* collider parameters. The numbers give the default CDR values, with optimum values for maximum *ep* luminosity in parentheses and values for the *ePb* configuration separated by a comma.

LHeC Collaboration arXiv:1211:5102, see also O.Bruening and M.Klein arXiv:1305.2090

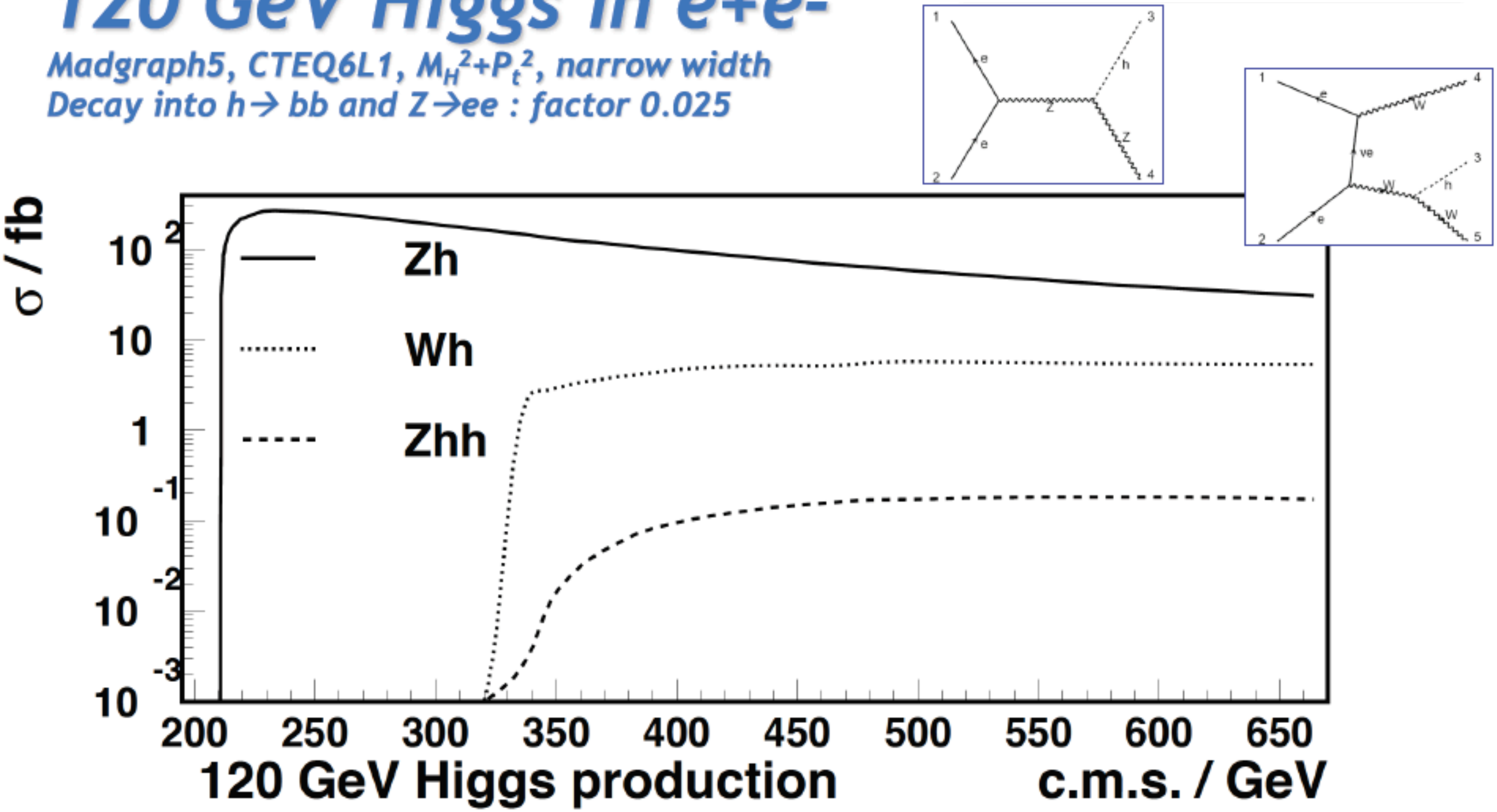
LHeC Higgs Rates

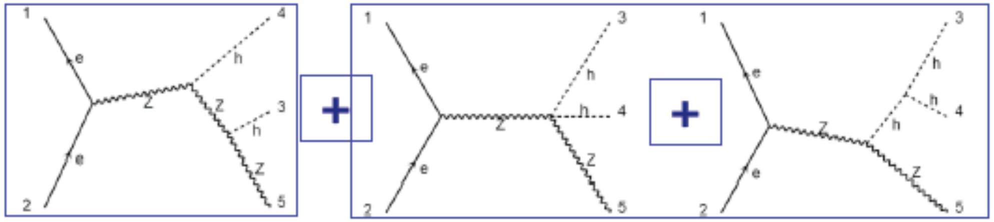


LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation		-0.8	-0.8	0
Luminosity [ab^{-1}]		1	1	0.1
Cross Section [fb]		196	25	58
Decay	BrFraction	N^H_{CC} e^-p	N^H_{NC} e^-p	N^H_{CC} e^+p
$H \to b\bar{b}$	0.577	113 100	13 900	3 350
$H \to c\bar{c}$	0.029	5 700	700	170
$H \to \tau^+\tau^-$	0.063	12 350	1 600	370
$H \to \mu\mu$	0.00022	50	5	–
$H \to 4l$	0.00013	30	3	–
$H \to 2l2\nu$	0.0106	2 080	250	60
$H \to gg$	0.086	16 850	2 050	500
$H \to WW$	0.215	42 100	5 150	1 250
$H \to ZZ$	0.0264	5 200	600	150
$H \to \gamma\gamma$	0.00228	450	60	15
$H \to Z\gamma$	0.00154	300	40	10

120 GeV Higgs in e+e-

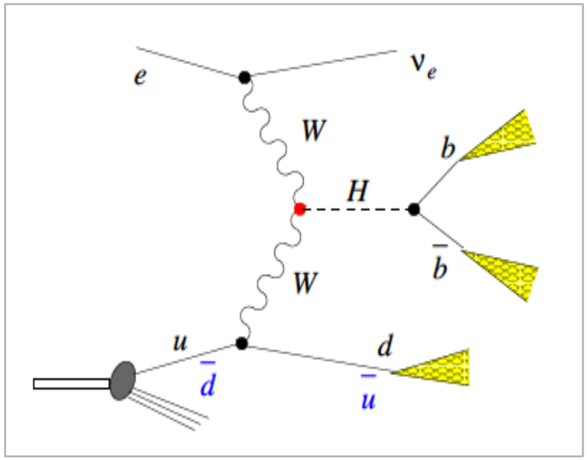
Madgraph5, CTEQ6L1, $M_H^2+P_t^2$, narrow width
Decay into h→ bb and Z→ee : factor 0.025



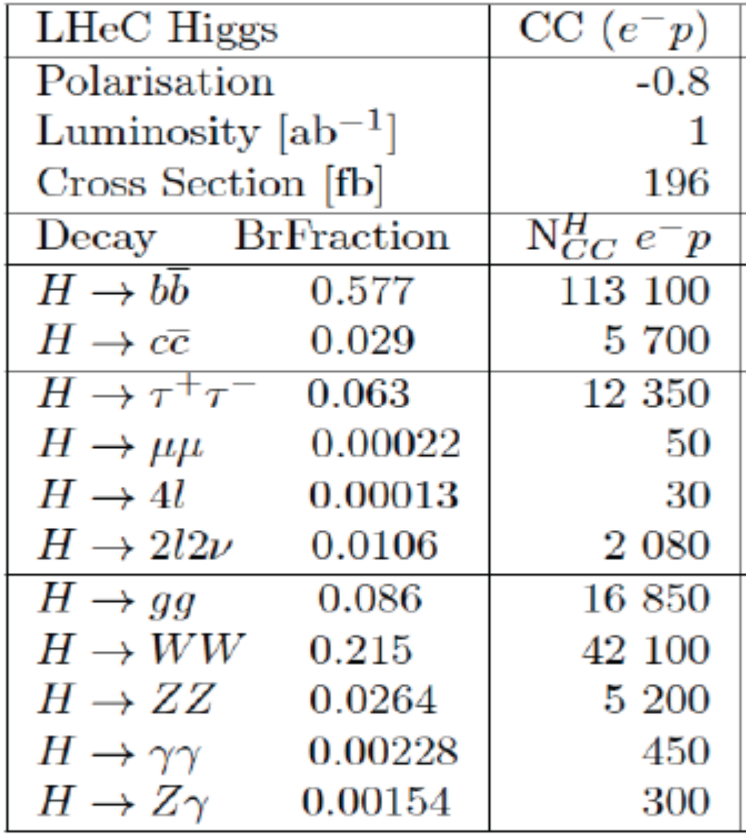


Zh threshold
at 211 GeV
= (120+91) GeV

Higgs with the LHeC



ZZ → H ~10 times lower rate



LHeC Higgs		CC (e^-p)
Polarisation		-0.8
Luminosity [ab^{-1}]		1
Cross Section [fb]		196
Decay	BrFraction	N^H_{CC} e^-p
$H \to b\bar{b}$	0.577	113 100
$H \to c\bar{c}$	0.029	5 700
$H \to \tau^+\tau^-$	0.063	12 350
$H \to \mu\mu$	0.00022	50
$H \to 4l$	0.00013	30
$H \to 2l2\nu$	0.0106	2 080
$H \to gg$	0.086	16 850
$H \to WW$	0.215	42 100
$H \to ZZ$	0.0264	5 200
$H \to \gamma\gamma$	0.00228	450
$H \to Z\gamma$	0.00154	300

Unique production mechanism (WW,ZZ)
Clean experimental conditions:
No pileup, simpler final state …

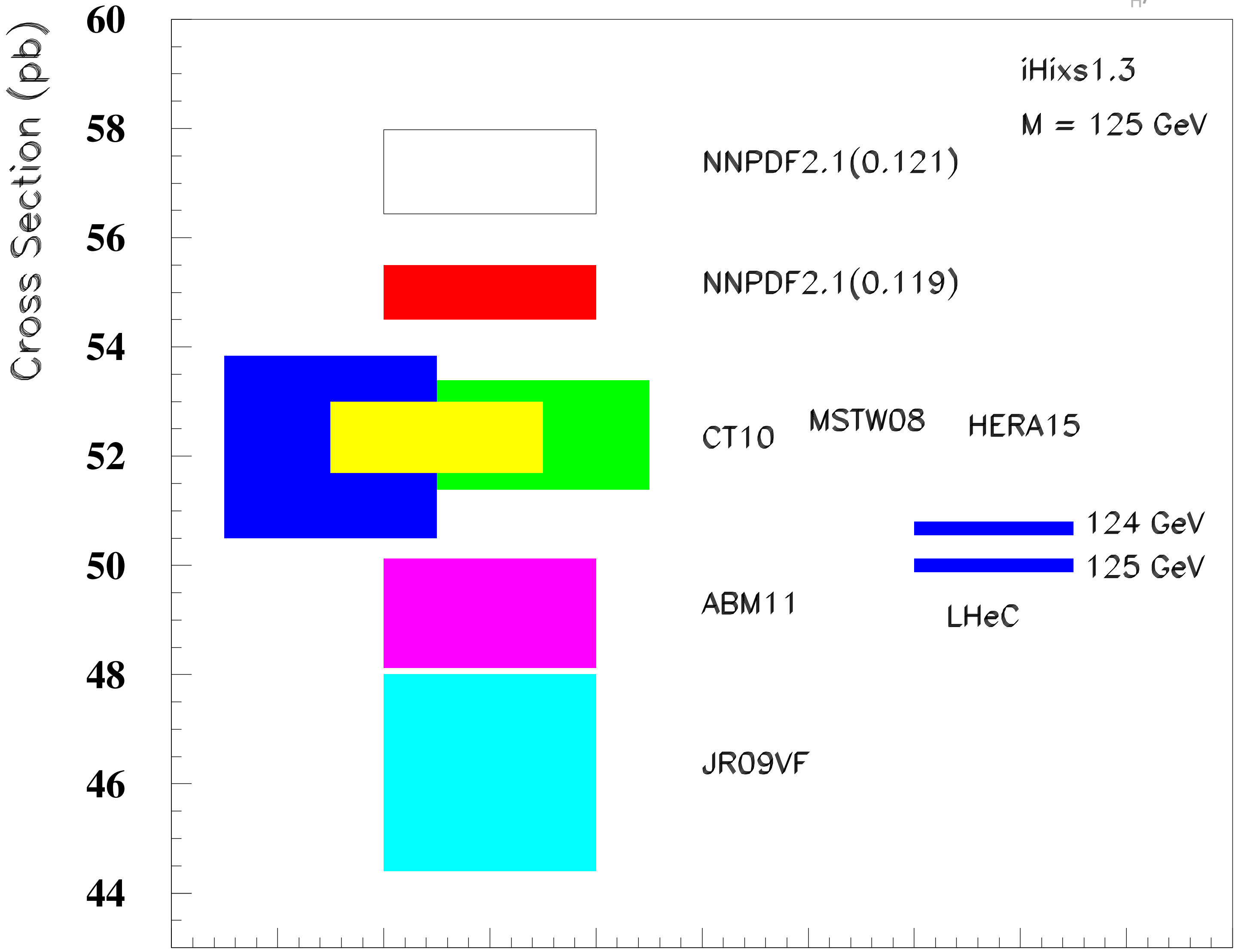
LHeC at 10^{34}cm^{-2}s^{-1} : arXiv:1211:5102
Nb: Cross section and luminosity as large as are projected for the ILC. Access to difficult channels (ττ, cc – under study)

With its unique Higgs measurements and precision N^{3}LO PDFs and $\delta\alpha_s$,
ep upgrade transforms the LHC facility into a precision Higgs factory.
[cf arXiv:1211:5102 + OB, MK: arXiv:1305:2090]

Rates for E_e=60 GeV, proportional to E_e
Initial study for CDR:
H →bbar: selection efficiency: ~2.5%
which gives 5000 events with S/B=1.
corresponding to 0.7% coupling precision.
[cf: CDR, U.Klein ICHEP12, B.Mellado LPCC]

NNLO pp−Higgs Cross Sections at 14 TeV

Calculated for scale of $M_H/2$



co MK

Exp uncertainty of LHeC Higgs cross section is 0.25% (sys+sta), using LHeC only.

Leads to mass sensitivity..

Strong coupling underlying parameter (0.005 – 10%). LHeC: 0.0002

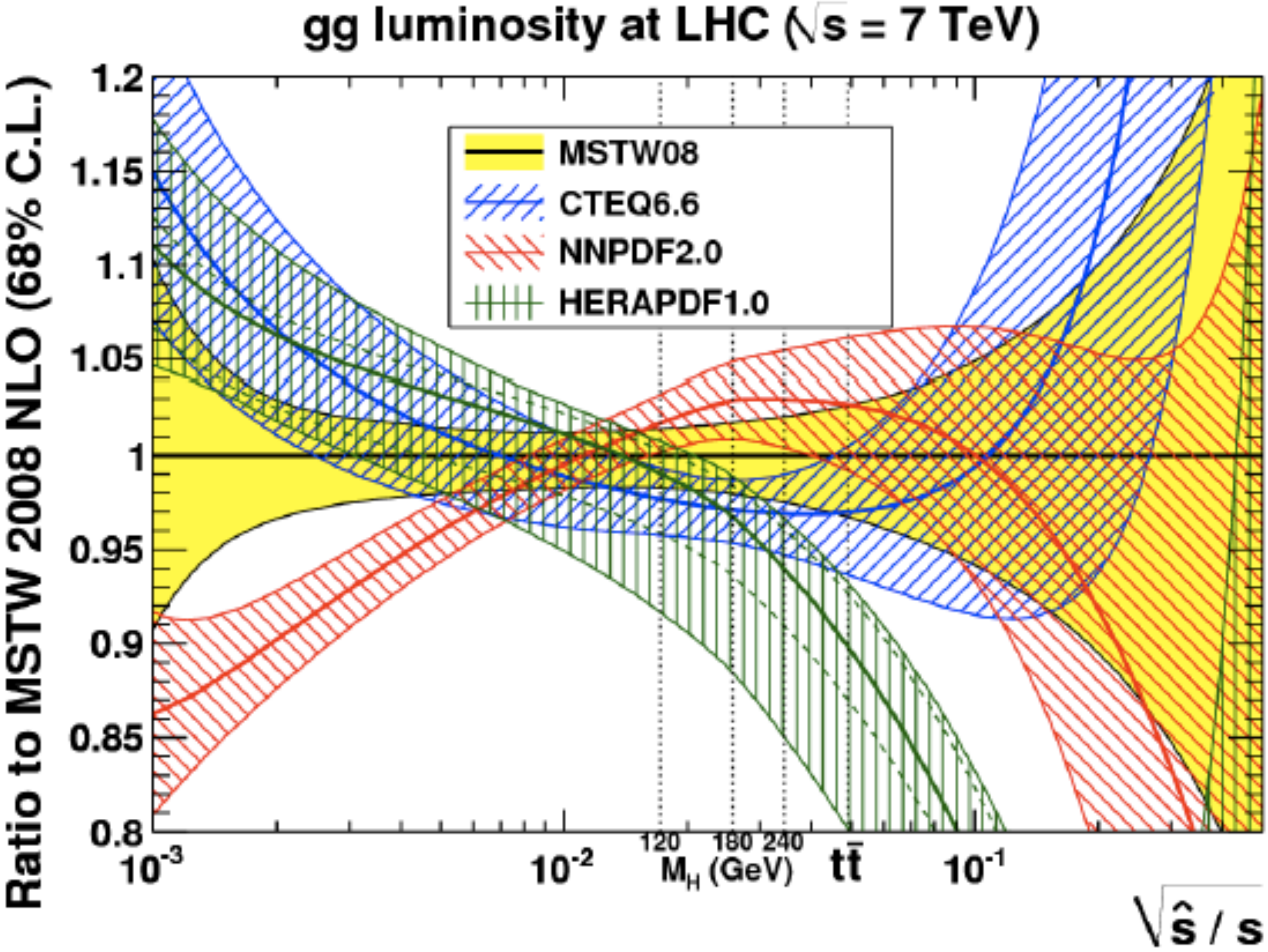
Needs N^{3}LO

HQ treatment important

PRECISION σ(H)

Higgs production (gg) at the LHC is $\propto \alpha_s^2(M_H^2)xG(x,M_H^2) \otimes xG(x,M_H^2)$

Bandurin (ICHEP12) Higgs physics at the LHC is limited by the PDF knowledge


gg luminosity at LHC (√s = 7 TeV)
Ratio to MSTW 2008 NLO (68% C.L.)
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
MSTW08
CTEQ6.6
NNPDF2.0
HERAPDF1.0
10^{-3}
10^{-2}
120
180
240
M_H (GeV)
$t\bar{t}$
10^{-1}
$\sqrt{\hat{s}/s}$

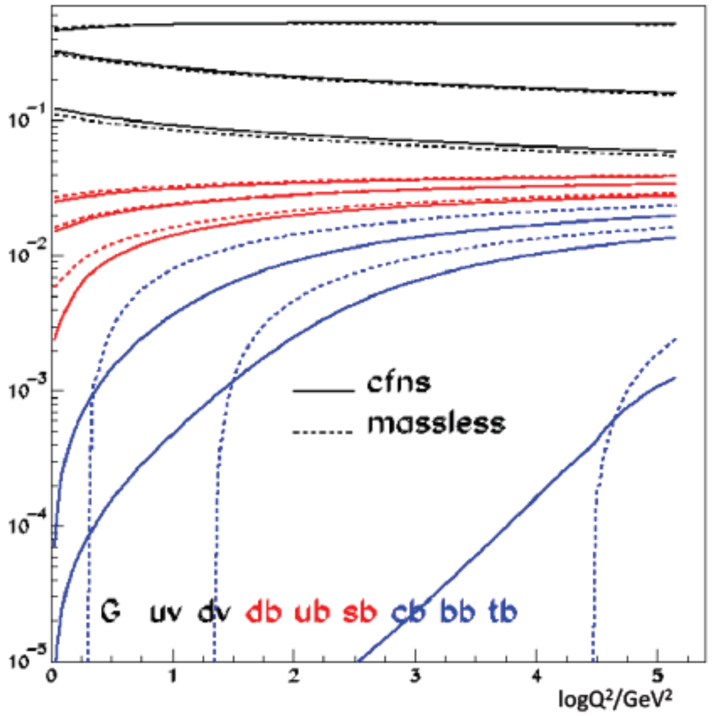
-next steps and final remarks-

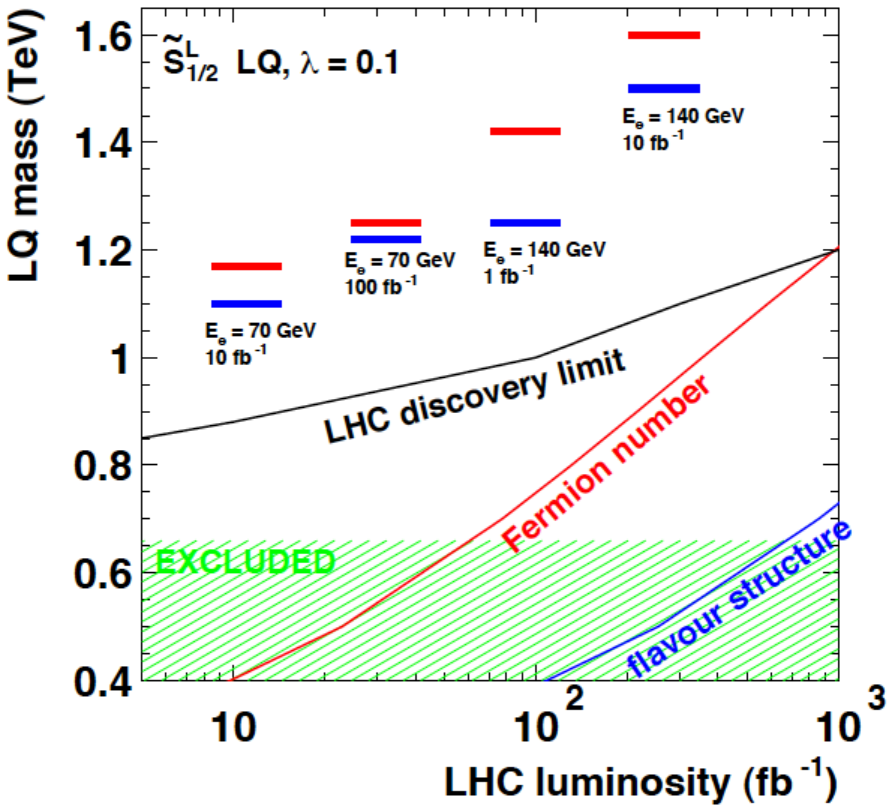
Physics studies and further LHC discoveries
Interaction region
Detector simulation (not shown)
LHeC Test Facility
Magnet designs

Theory and experiment
Future ep colliders and the energy frontier
A Summary

Top Quark and Leptoquarks

The LHeC is a (single) top quark production factory, via Wb → t. Top was never observed in DIS. With ep: top-PDF → 6 flavour VFNS, precision M_t direct and from cross section, anomalous couplings [to be studied]

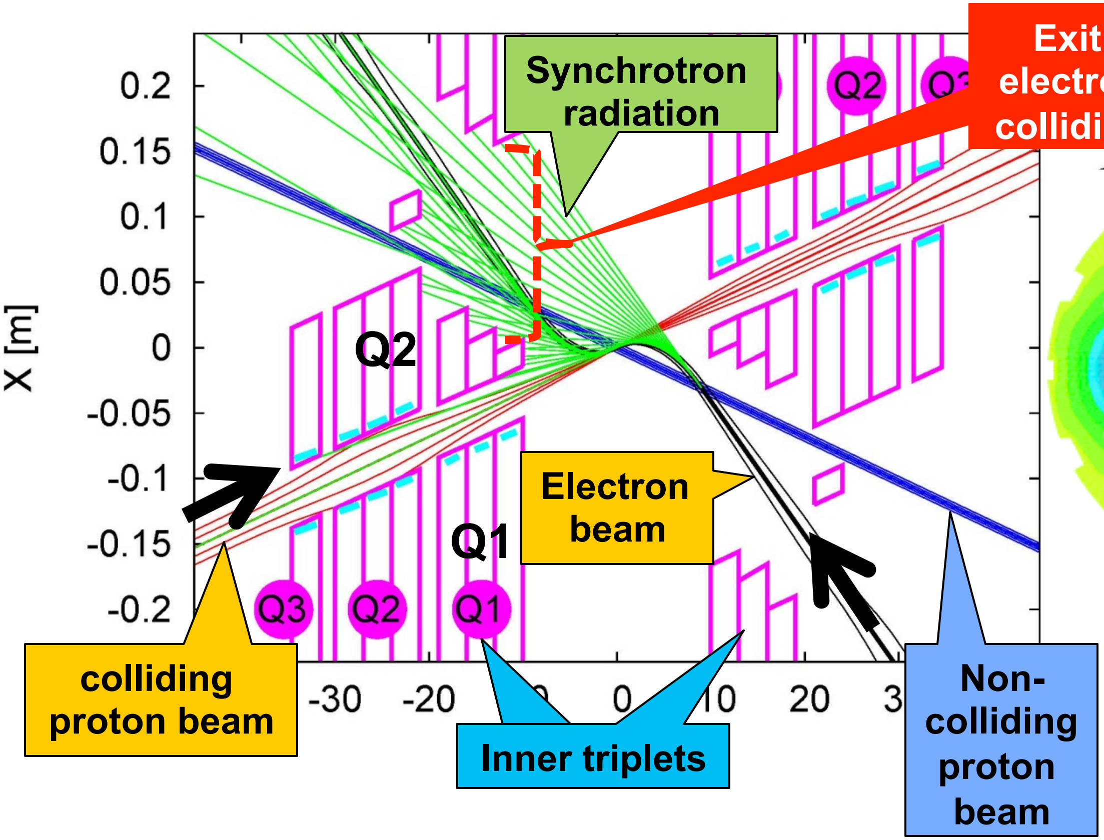




Leptoquarks (-gluons) are predicted in RPV SUSY, E6, extended technicolour theories or Pati-Salam.

The LHeC is the appropriate configuration to do their spectroscopy, should they be discovered at the LHC.

LR LHeC IR layout & SC IR quadrupoles



Synchrotron radiation

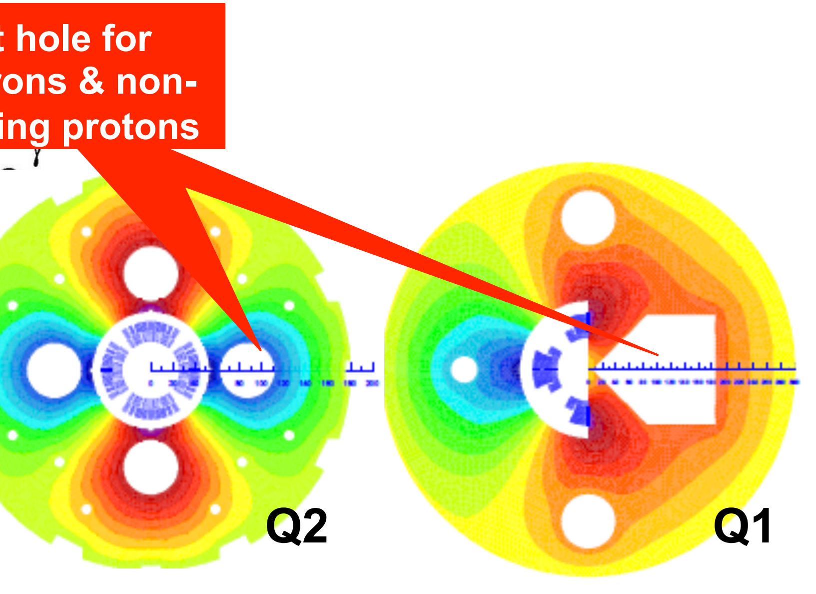
Exit hole for electrons & non-colliding protons

Electron beam

colliding proton beam

Inner triplets

Non-colliding proton beam



Nb_3Sn (HFM46): 5700 A, 175 T/m, 4.7 T at 82% on LL (4 layers), 4.2 K	Nb_3Sn (HFM46): 8600 A, 311 T/m, at 83% LL, 4.2 K
46 mm (half) ap., 63 mm beam sep.	23 mm ap.. 87 mm beam sep.
0.5 T, 25 T/m	0.09 T, 9 T/m

High-gradient SC IR quadrupoles based on Nb_3Sn for colliding proton beam with common low-field

As shown by F. Zimmermann at Chamonix12

Towards an LHeC ERL Test Facility at CERN

Contribution to IPAC13

STRAWMAN OPTICS DESIGN FOR THE LHeC ERL TEST FACILITY

A. Valloni[*], O. Bruning, R. Calaga, E. Jensen, M. Klein, R.Tomas, F. Zimmermann,
CERN, Geneva, Switzerland
A. Bogacz, D. Douglas, Jefferson Lab, Newport News Virginia

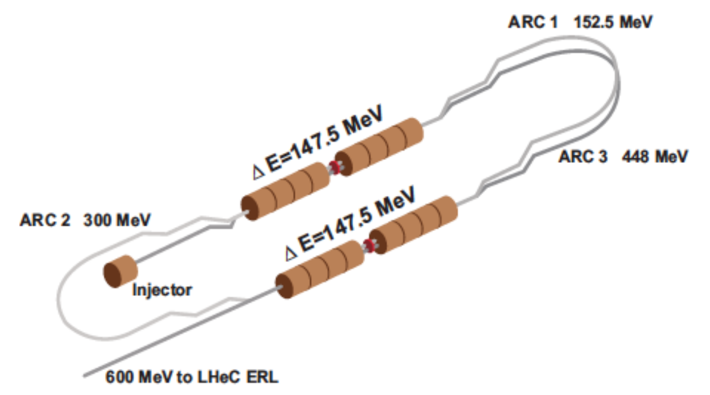


Figure 2: Consequent upgrade to LHeC pre-accelerator. By modifying the machine backleg to include a second full cryomodule, the recirculator can deliver higher beam energy of 600 MeV.

Proposal for an LHeC ERL Test Facility at CERN

R. Calaga, E. Ciapala, E. Jensen
CERN, Geneva, Switzerland

CERN-LHeC-Note-2012-001 ACC
October 17, 2012
Rama.Calaga@cern.ch

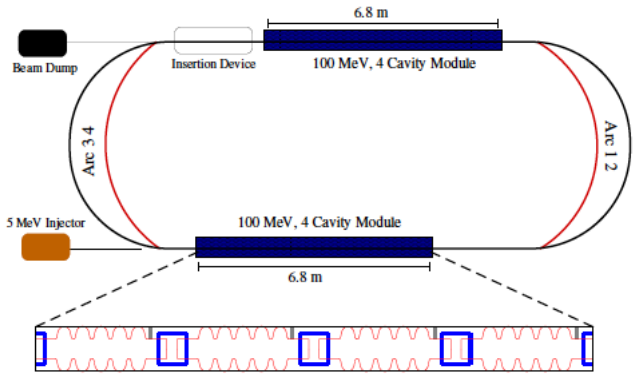


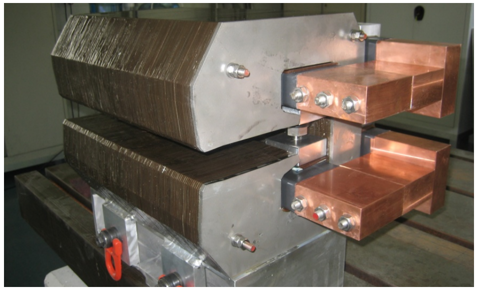
Table 3: Future ERLs for electron-hadron colliders

Parameter	JLab MEIC	BNL eRHIC	CERN LHeC
Energy [GeV]	5-10	20	60
Frequency [MHz]	750	704	n×40
# of passes	-	6	3
Current/pass [mA]	3	50	6.6
Charge [nC]	4	3.5	0.3
Bunch Length [mm]	7.5	2.0	0.3

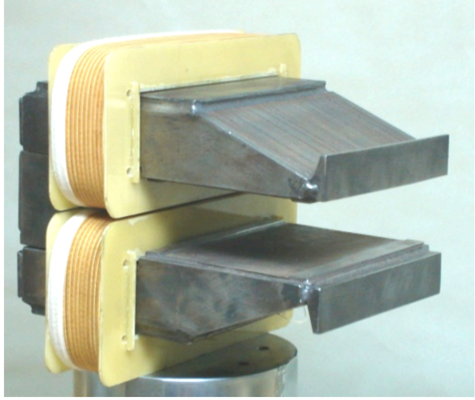
Daresbury Workshop:

- Collaboration: CERN, AsTEC, CI, JeffersonLab, U Mainz, +
- LHeC Parameters (C,Q,source,I) rather conservative
- Test Facility to develop full technology, key: cavity
- RF frequency chosen

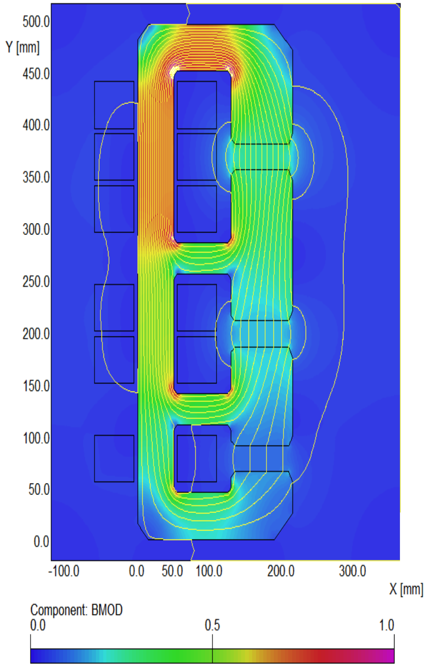
Magnets Developments



Prototypes for Ring dipoles
Fabricated and tested by
CERN (top) and Novosibirsk



LR recirculator dipoles and quadrupoles
New requirements (aperture, field)?
Combined apertures?
Combined functions (for example, dipole + quad)?
LR linac quadrupoles and correctors
New requirements (aperture, field)?
More compact magnets, maybe with at least two families for quadrupoles?
Permanent magnets / superconducting for quads?
A.Milanese, Chavannes workshop



1/2m dipole model
Full scale prototype
Quadrupole for Linac

Magnets for ERL test stand

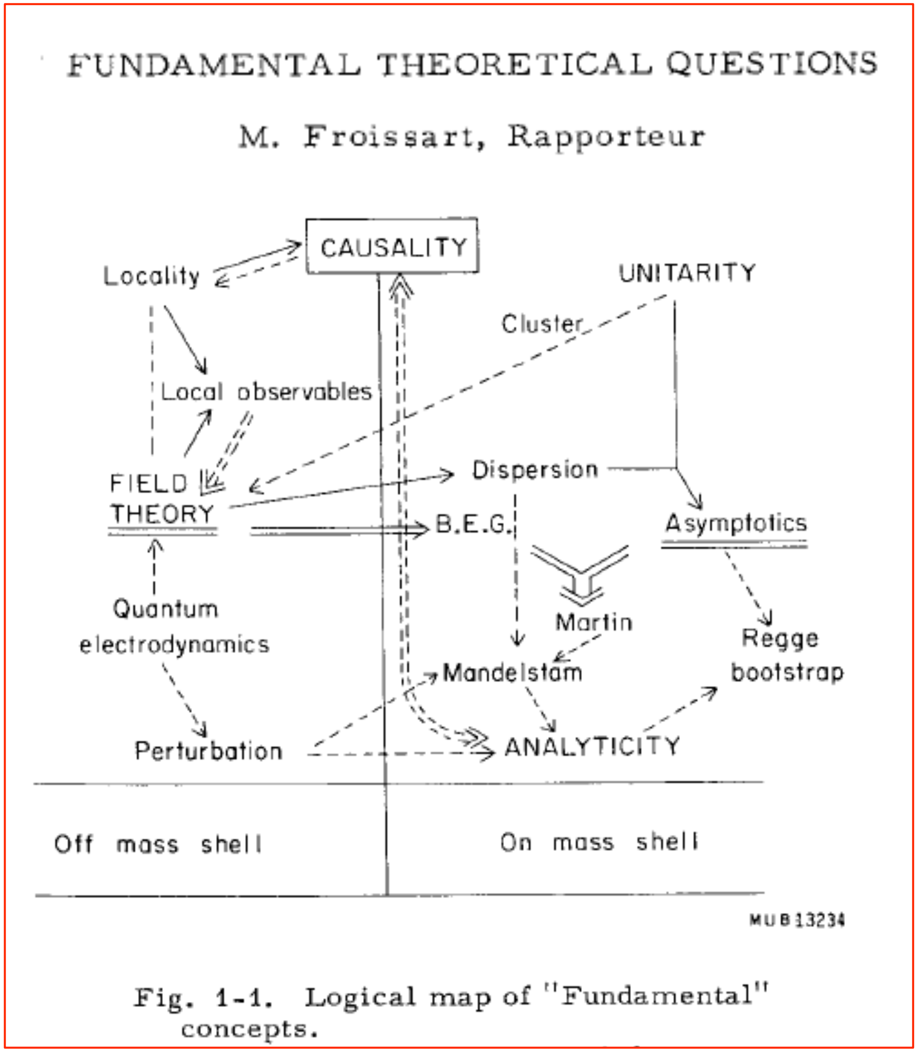
Collaboration of CERN, Beijing, Daresbury, Novosibirsk)

flux density in the gaps	0.264 T 0.176 T 0.088 T
magnetic length	4.0 m
vertical aperture	25 mm
pole width	85 mm
number of magnets	584
current	1750 A
number of turns per aperture	1 / 2 / 3
current density	0.7 A/ mm^2
conductor material	copper
resistance	0.36 mΩ
power	1.1 kW
total power 20 / 40 / 60 GeV	642 kW
cooling	air

M.Froissart ICHEP (“Rochester”) 1966

THEORY

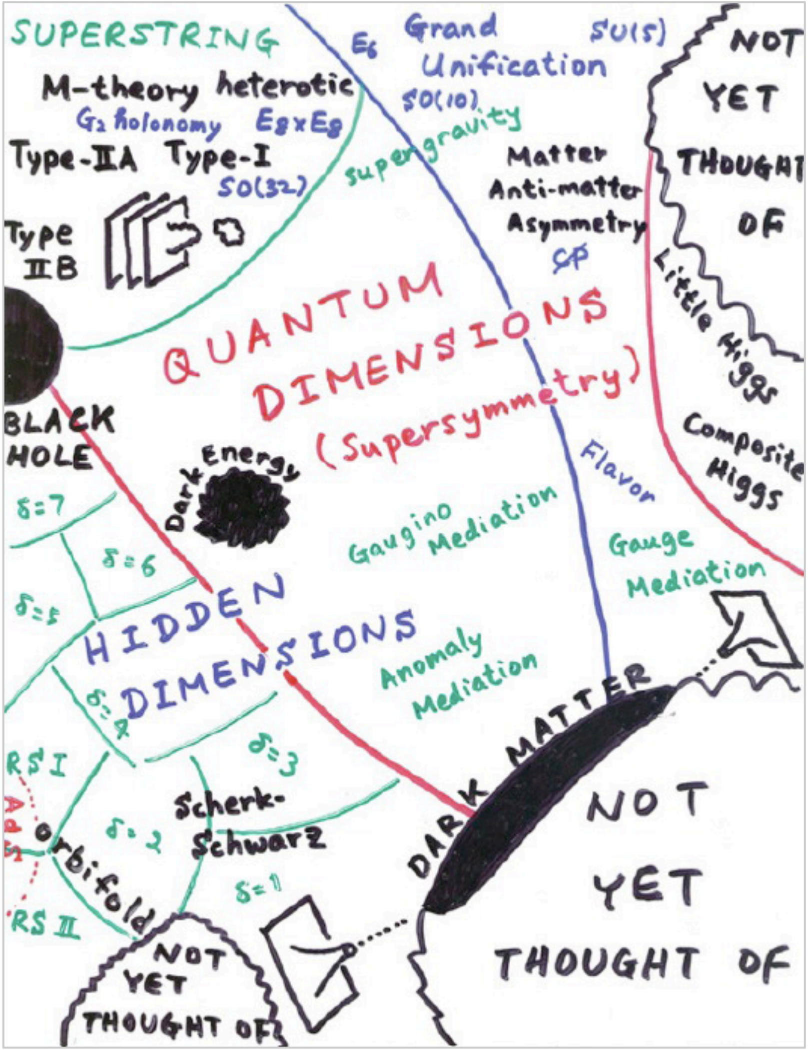
H.Murayama – ICFA11



FUNDAMENTAL THEORETICAL QUESTIONS

M. Froissart, Rapporteur

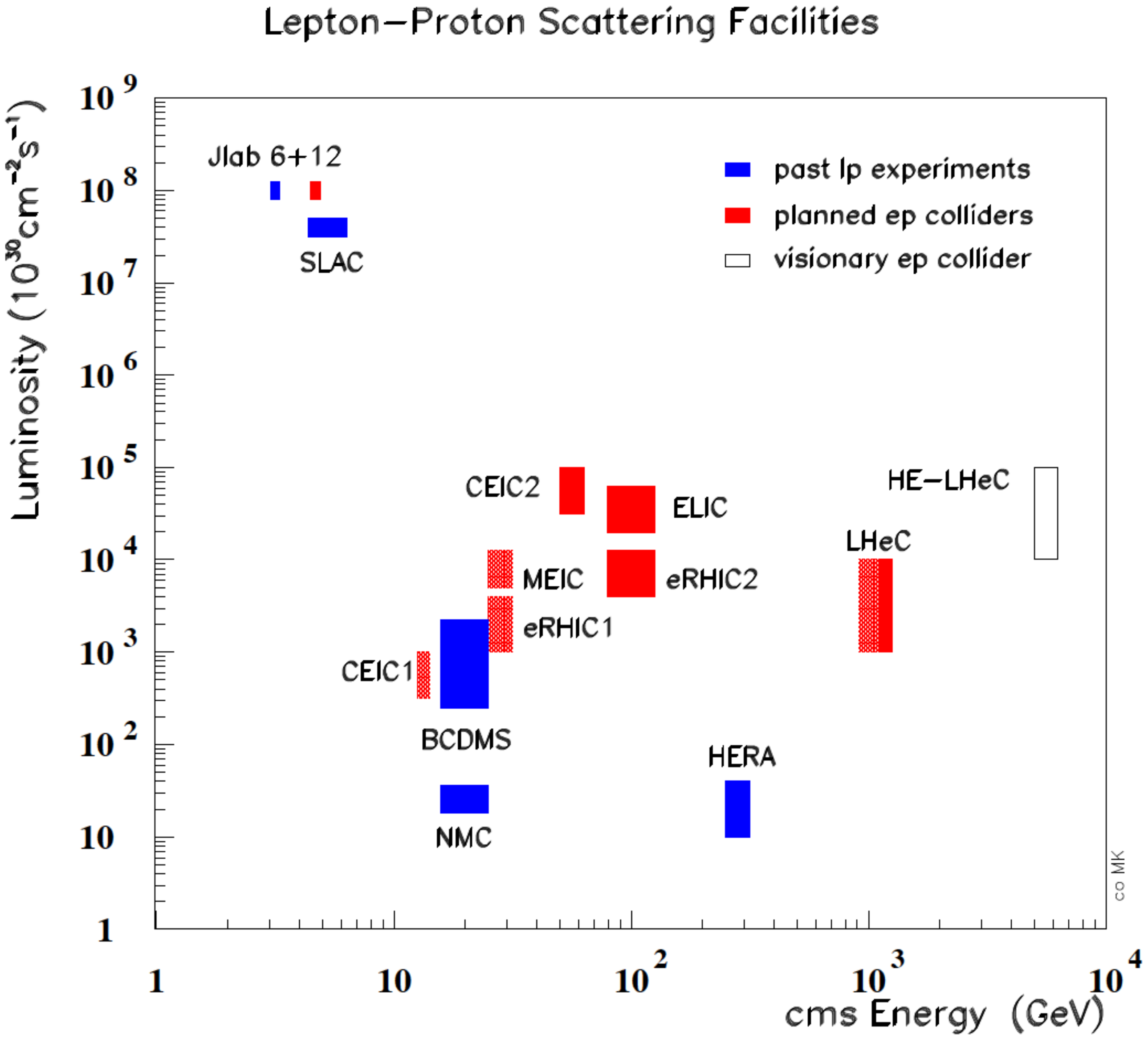
Fig. 1-1. Logical map of "Fundamental" concepts.



→ Quarks in 1969

→ ?in 2015+?

We like to see particle physics as driven by experiment … Burt Richter



Energy frontier deep inelastic scattering - following HERA with the LHC
LHeC: A new laboratory for particle physics, a 5th large LHC experiment

Summary

1. The LHeC is the natural (and the only possible) successor of the energy frontier exploration of deep inelastic scattering with fixed target experiments and HERA at 10, 100 and then 1000 GeV of cms energy.

2. Its physics programme has key topics (WW→ H, RPV SUSY, α_s , gluon mapping, PDFs, saturation, eA…) which ALL are closely linked to the LHC (Higgs, searches for LQ and at high masses, QGP ..). With the upgrade of the LHC by adding an electron beam, the LHC can be transformed to a high precision energy frontier facility, which is crucial for understanding new+"old" physics and its sustainability.

3. The LHeC will deliver vital information to future QCD developments (N^3LO, resummation, factorisation, non-standard partons, neutron and nuclear structure, AdS/CFT, non-pQCD, SUSY..) and as a gigantic next step into DIS physics it promises to find new phenomena (no saturation, instantons, substructure of heavy elementary particles ??).

4. The default LHeC configuration is a novel ERL (with < 100MW power demand) in racetrack shape which is built inside the LHC ring and tangential to IP2. This delivers multi-100fb^{-1} (> 100 * HERA) and a factor of larger than 10^3 increased kinematic range in lN DIS, accessing the range of saturation at small α_s in ep+eA.

5. The LHeC is designed for synchronous operation with the LHC (3 beams) and has to be operational for the final decade of its lifetime. This gives 10-12 years for its realisation, as for HERA or CMS.

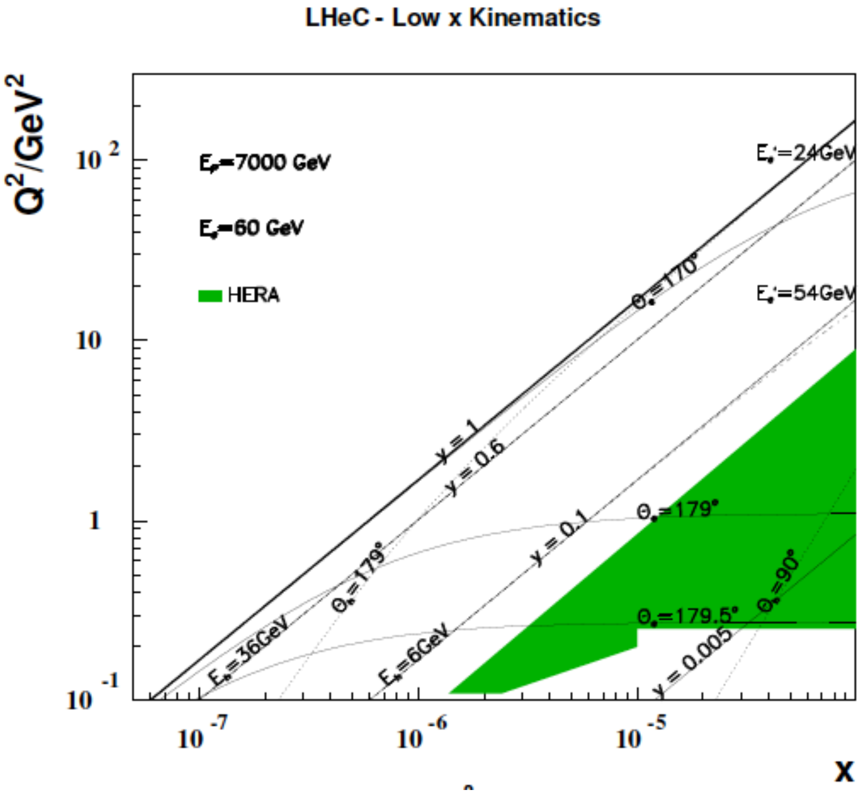
6. A detector concept is described in the CDR suitable for the Linac-Ring IR and to obtain full coverage and ultimate precision. This can be realised with a collaboration of 500 physicist.

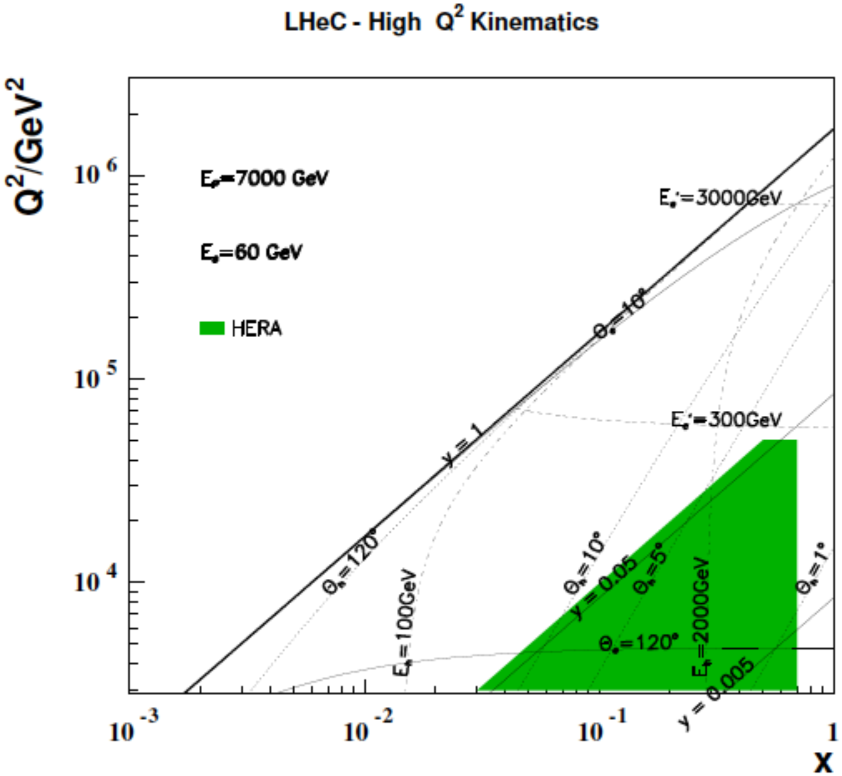
7. Half of the LHeC is operational. The other half requires next: an ERL test facility at CERN, IR related proto-typing (Q1, pipe), to develop the LHC-LHeC physics links, to simulate and preparing for building the detector.

-backup-

Kinematics - LHeC and HERA

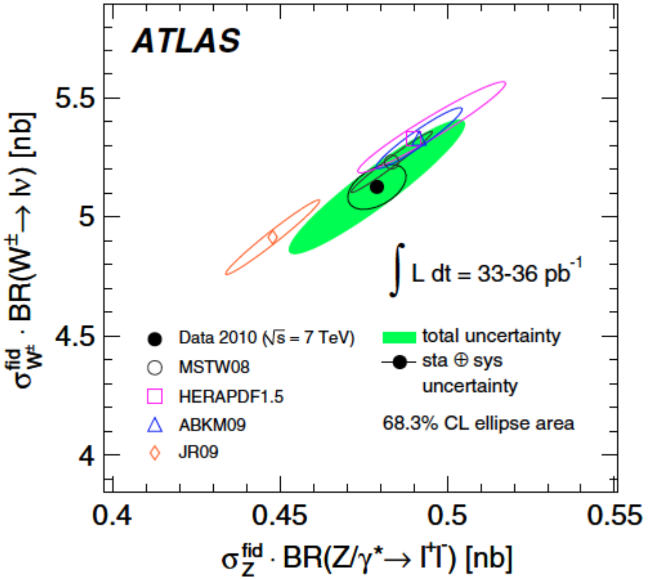
Access to "saturation" (?) region
in DIS ($Q^2 > 1$ GeV^2) and ep





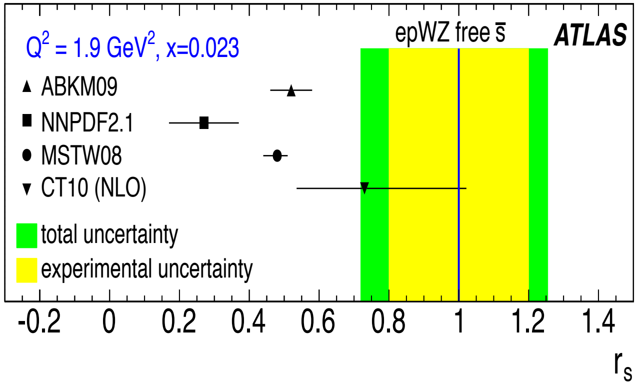
Extending beyond the Fermi scale with precision Z and W exchange data → high x, top PDF, flavour & new physics,

PDF constraints from LHC - Di-Lepton Production

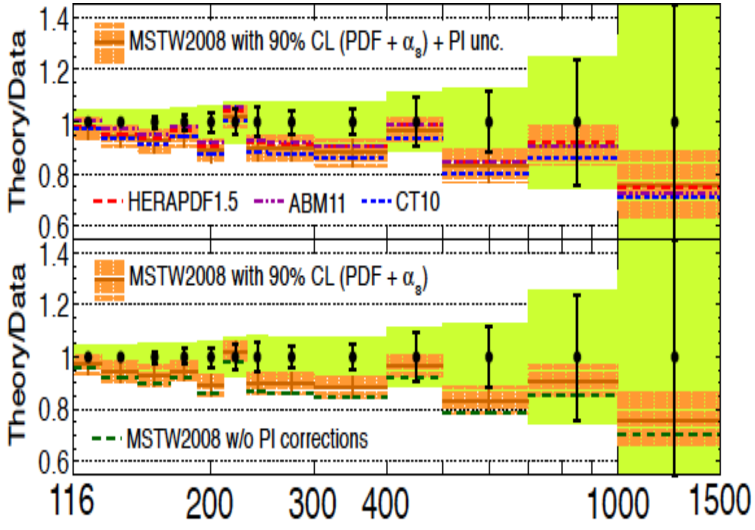


PRD D85 (2012) 072004

Precision Drell-Yan (W,Z) data constrain PDFs

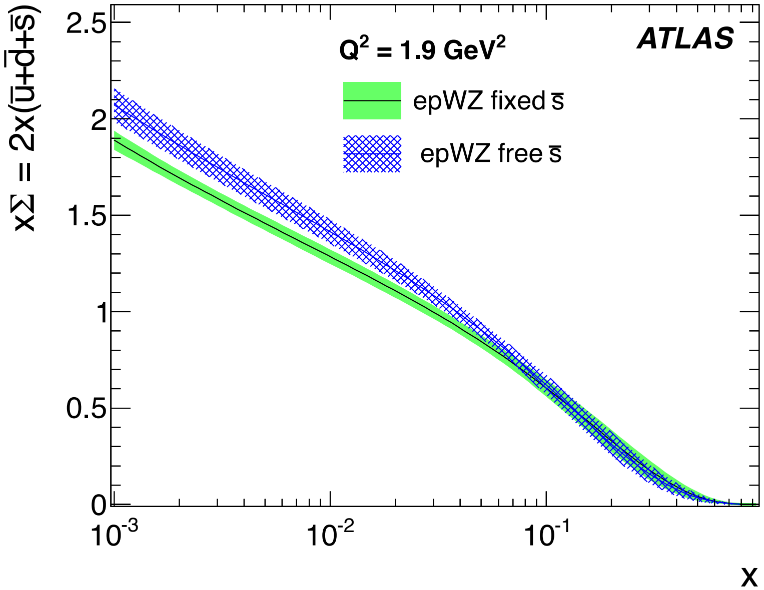


according to the ATLAS data and HERA+ATLAS QCD analysis: s = d !



ATLAS-CONF-2012-159

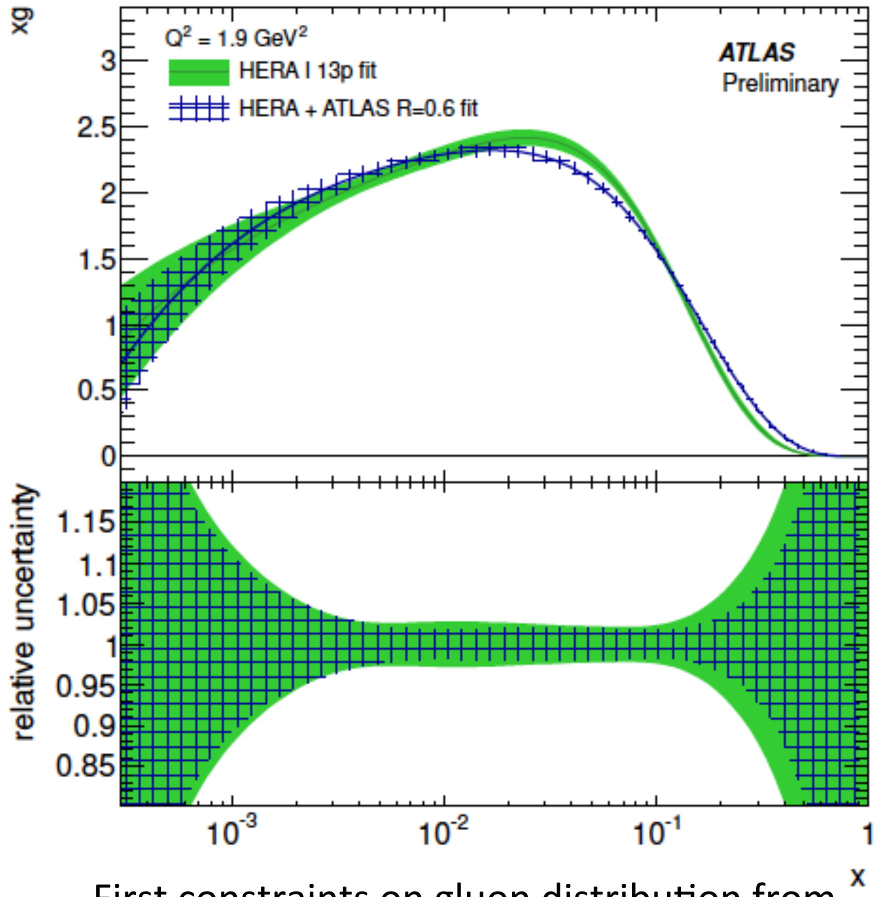
Very high precision required for any constraint on PDFs



PRL 109(2012)012001

Change of strange affects sea - UHE ν

PDF constraints from LHC – Jets

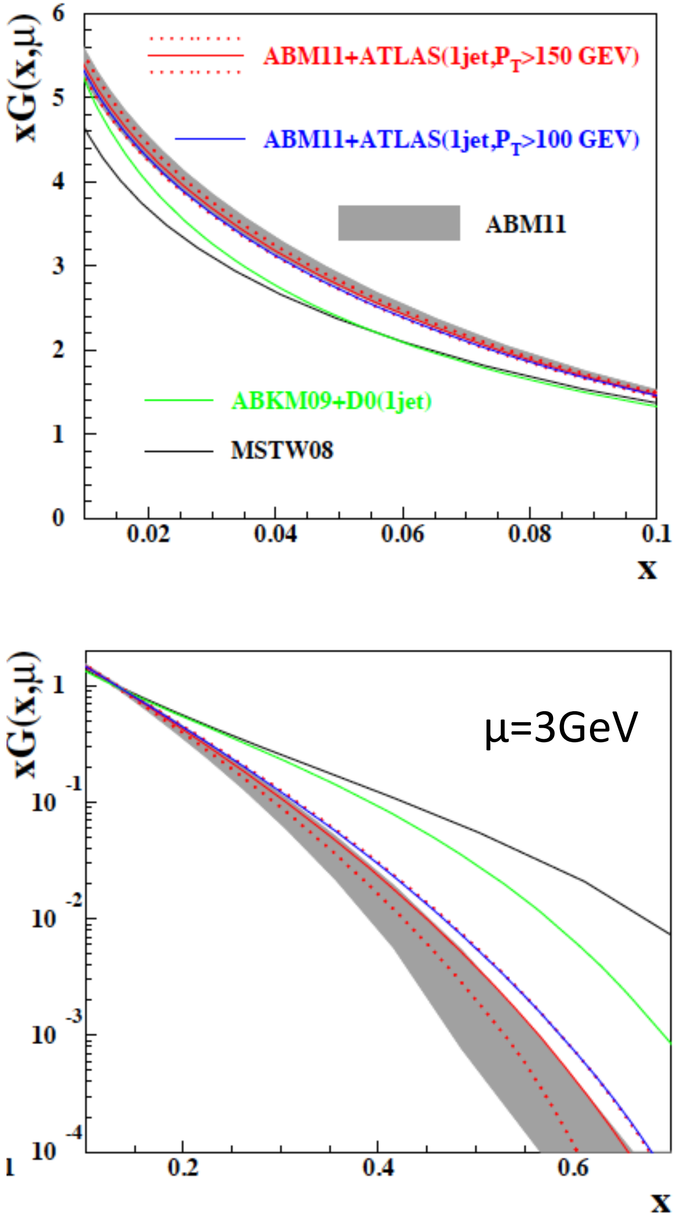


ATLAS-CONF-2012-128

First constraints on gluon distribution from jets: cross sections and ratios 2.7/7 TeV

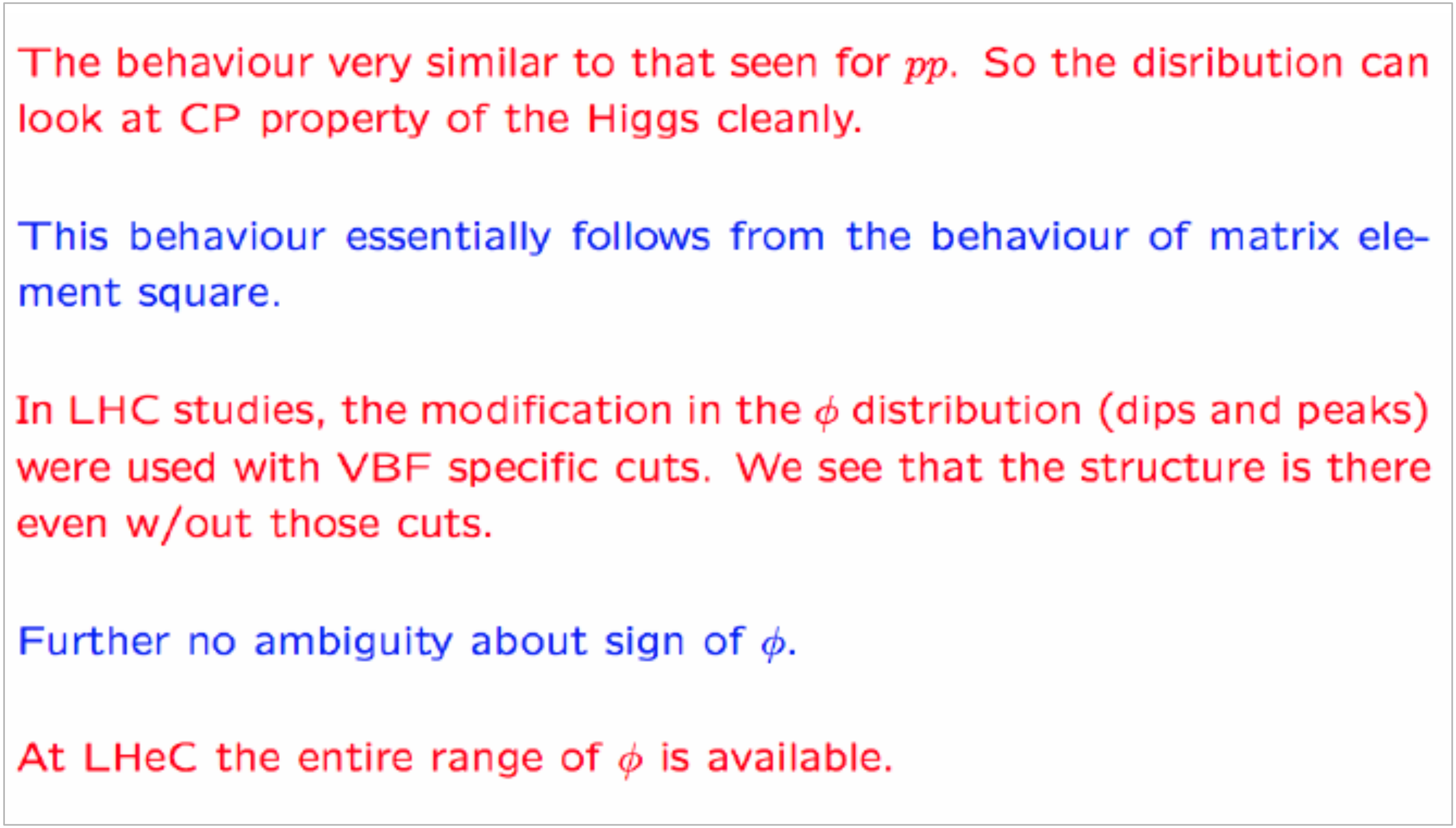
Will improve, but depends on energy scales, jet definition, non-perturbative effects ..

Similar results from CMS (W±, DY, top..)



S.Moch 6th Terascale Workshop (Hamburg, 3.12.12)

CP Properties



The behaviour very similar to that seen for pp. So the disribution can look at CP property of the Higgs cleanly.

This behaviour essentially follows from the behaviour of matrix element square.

In LHC studies, the modification in the ϕ distribution (dips and peaks) were used with VBF specific cuts. We see that the structure is there even w/out those cuts.

Further no ambiguity about sign of ϕ.

At LHeC the entire range of ϕ is available.

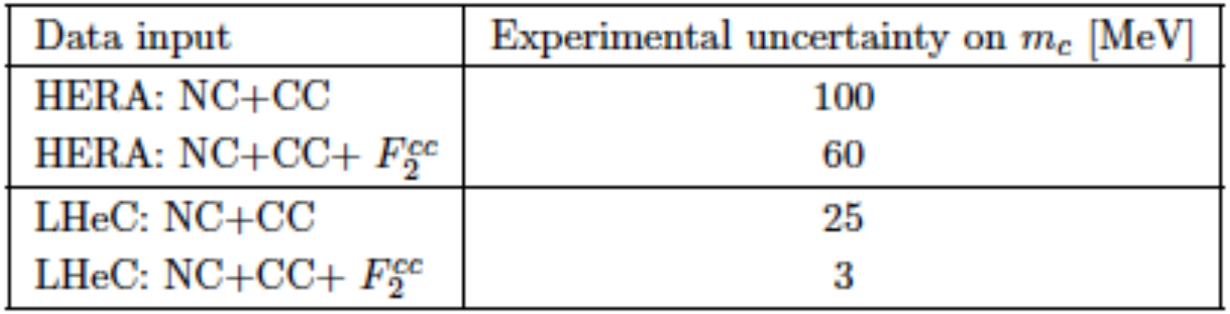
B.Mellado at LPCC 3/13

BSM Summary and outlook

- LHeC provides complementarities to the LHC SUSY search program in the twenties
  - Ideal to search and study properties of new bosons with couplings to electron-quark
  - Direct searches for CI, excited fermions, leptoquark, RPV SUSY, RPC SUSY in specific scenarios such as compressed, non-degeneracy for squarks
  - Interplay with HL-LHC to constraints on PDF crucial for model testing in case of observed deviations → an independent precision measurement of PDFs will be important for an efficient use of the high luminosity for setting reliable high mass limits

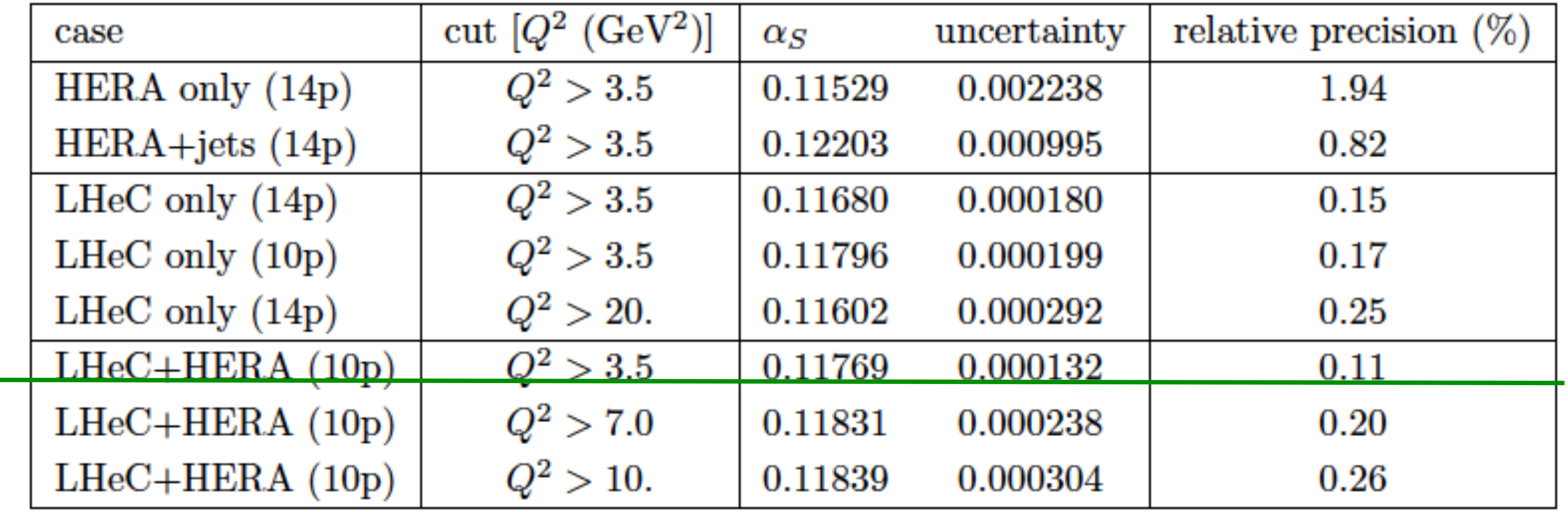
α_s

Per mille precision
NNNLO PDFs
Heavy quarks →
Full set of PDFs



Data input	Experimental uncertainty on m_c [MeV]
HERA: NC+CC	100
HERA: NC+CC+ F_2^{cc}	60
LHeC: NC+CC	25
LHeC: NC+CC+ F_2^{cc}	3

Full exp. error

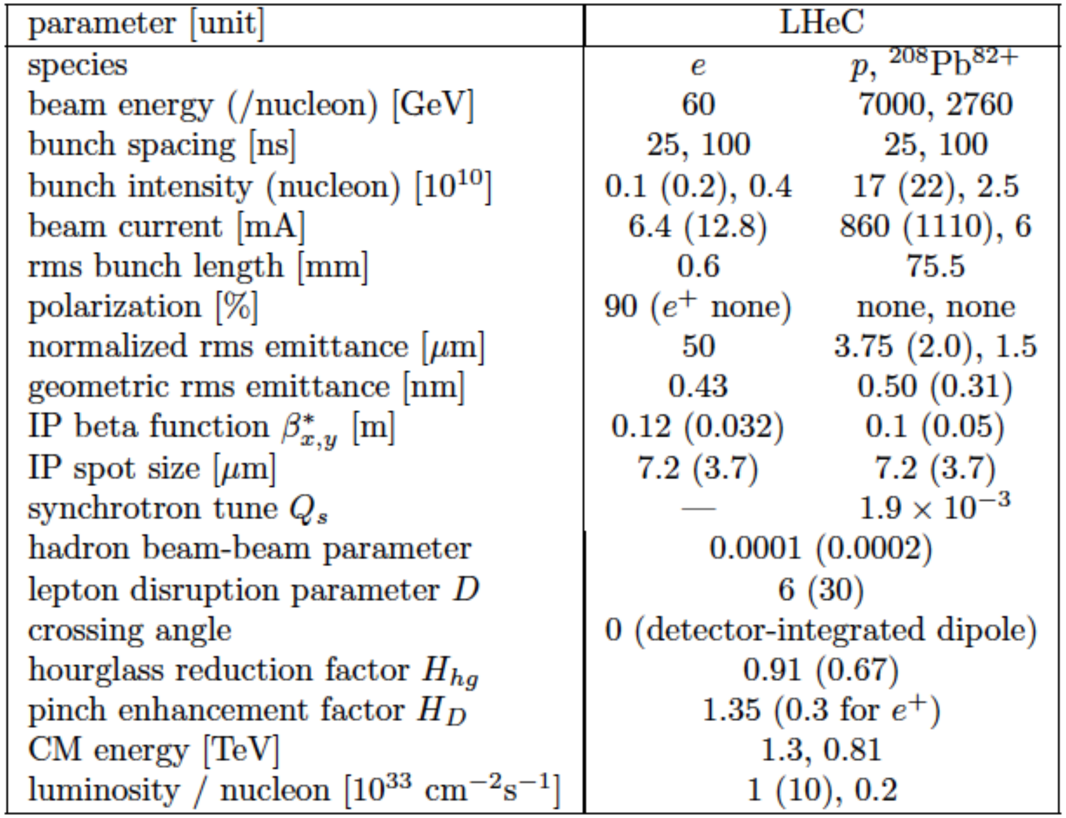


case	cut $[Q^2\ (\mathrm{GeV}^2)]$	α_S	uncertainty	relative precision (%)
HERA only (14p)	$Q^2 > 3.5$	0.11529	0.002238	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.12203	0.000995	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.11680	0.000180	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.11796	0.000199	0.17
LHeC only (14p)	$Q^2 > 20.$	0.11602	0.000292	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11769	0.000132	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.11831	0.000238	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.11839	0.000304	0.26

From LHeC CDR

Parameters and Design

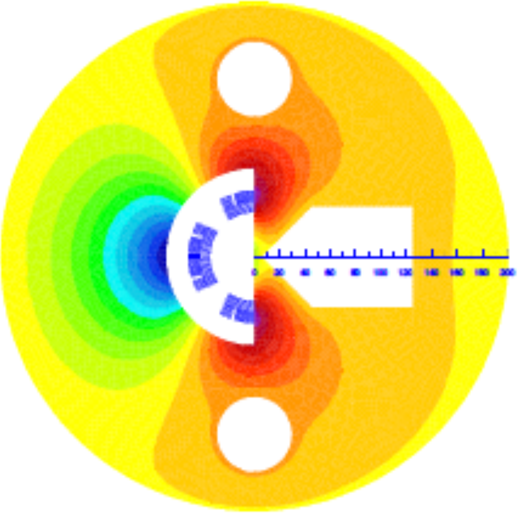
257 pages of technical design
in the CDR arXiv:1206:2913, e.g.



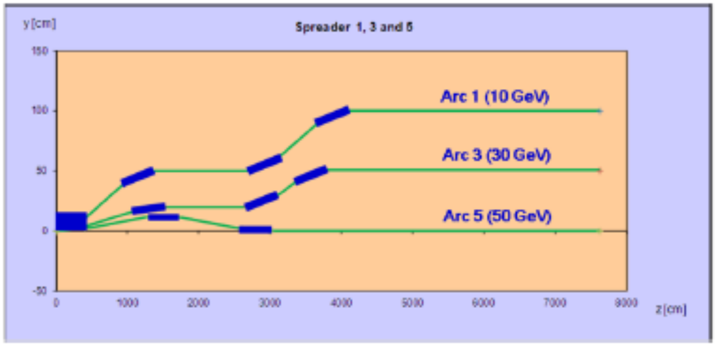
parameter [unit]	LHeC	
species	e	p, $^{208}\mathrm{Pb}^{82+}$
beam energy (/nucleon) [GeV]	60	7000, 2760
bunch spacing [ns]	25, 100	25, 100
bunch intensity (nucleon) [10^{10}]	0.1 (0.2), 0.4	17 (22), 2.5
beam current [mA]	6.4 (12.8)	860 (1110), 6
rms bunch length [mm]	0.6	75.5
polarization [%]	90 (e^+ none)	none, none
normalized rms emittance [μm]	50	3.75 (2.0), 1.5
geometric rms emittance [nm]	0.43	0.50 (0.31)
IP beta function $\beta^*_{x,y}$ [m]	0.12 (0.032)	0.1 (0.05)
IP spot size [μm]	7.2 (3.7)	7.2 (3.7)
synchrotron tune Q_s	—	1.9×10^{-3}
hadron beam-beam parameter	0.0001 (0.0002)	
lepton disruption parameter D	6 (30)	
crossing angle	0 (detector-integrated dipole)	
hourglass reduction factor H_{hg}	0.91 (0.67)	
pinch enhancement factor H_D	1.35 (0.3 for e^+)	
CM energy [TeV]	1.3, 0.81	
luminosity / nucleon [10^{33} cm^{-2}s^{-1}]	1 (10), 0.2	

Update of parameter table in view of H - arXiv:1211:5102

Designed for synchronous ep and pp operation



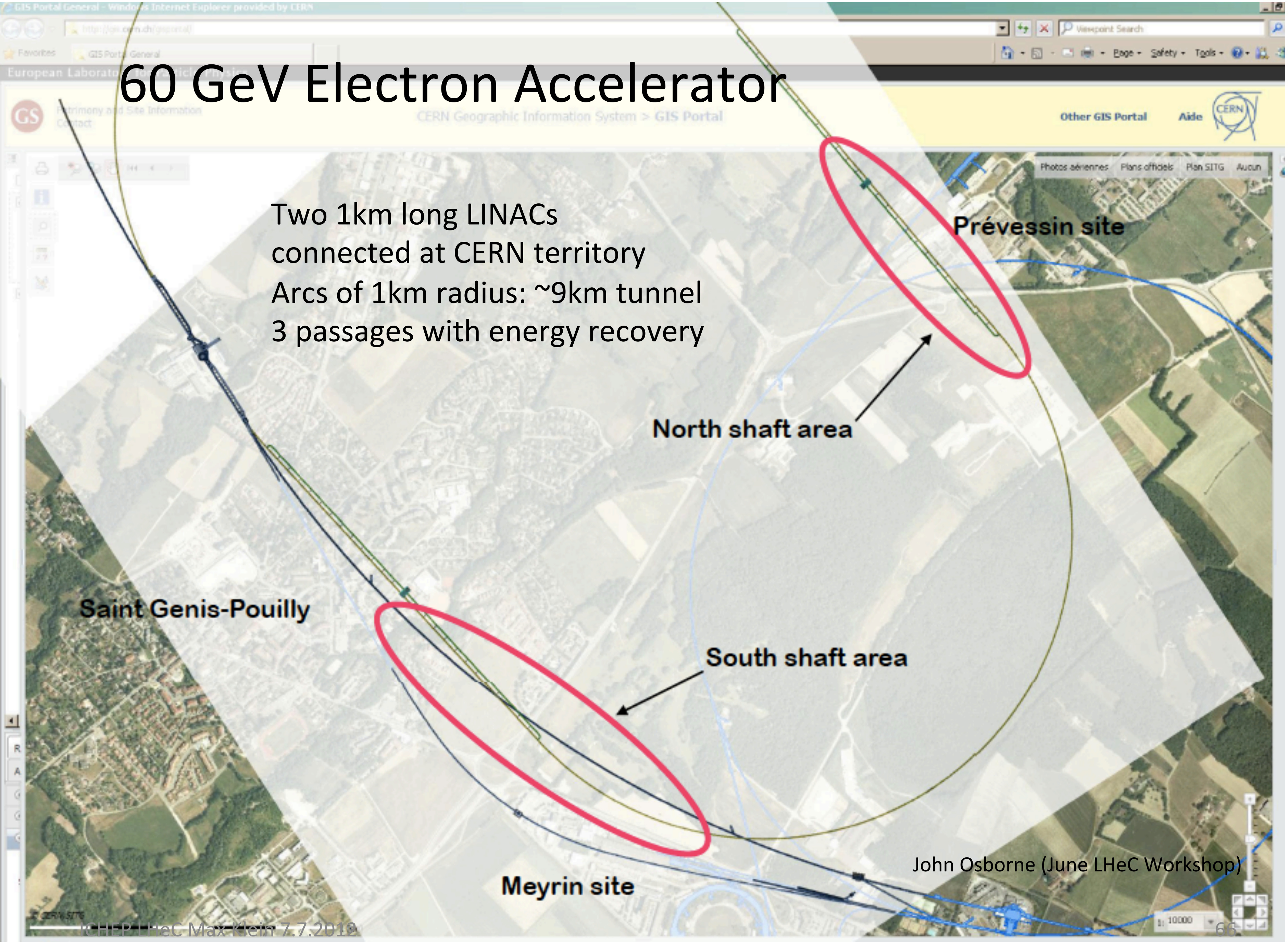
“Q1” SC 3-beam IR magnet



1→3 beam spreader design

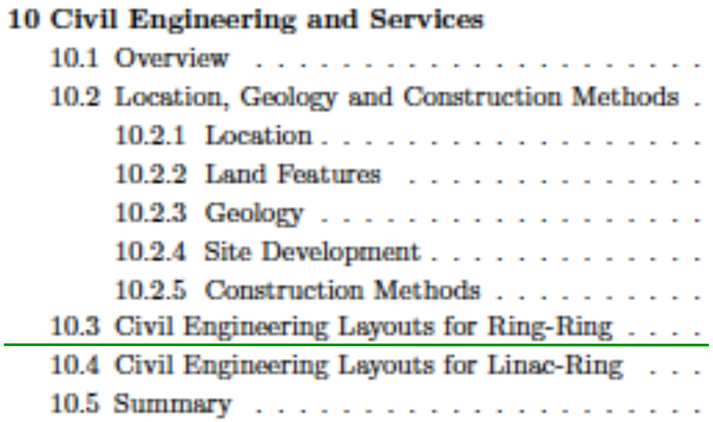
60 GeV Electron Accelerator

Two 1km long LINACs
connected at CERN territory
Arcs of 1km radius: ~9km tunnel
3 passages with energy recovery

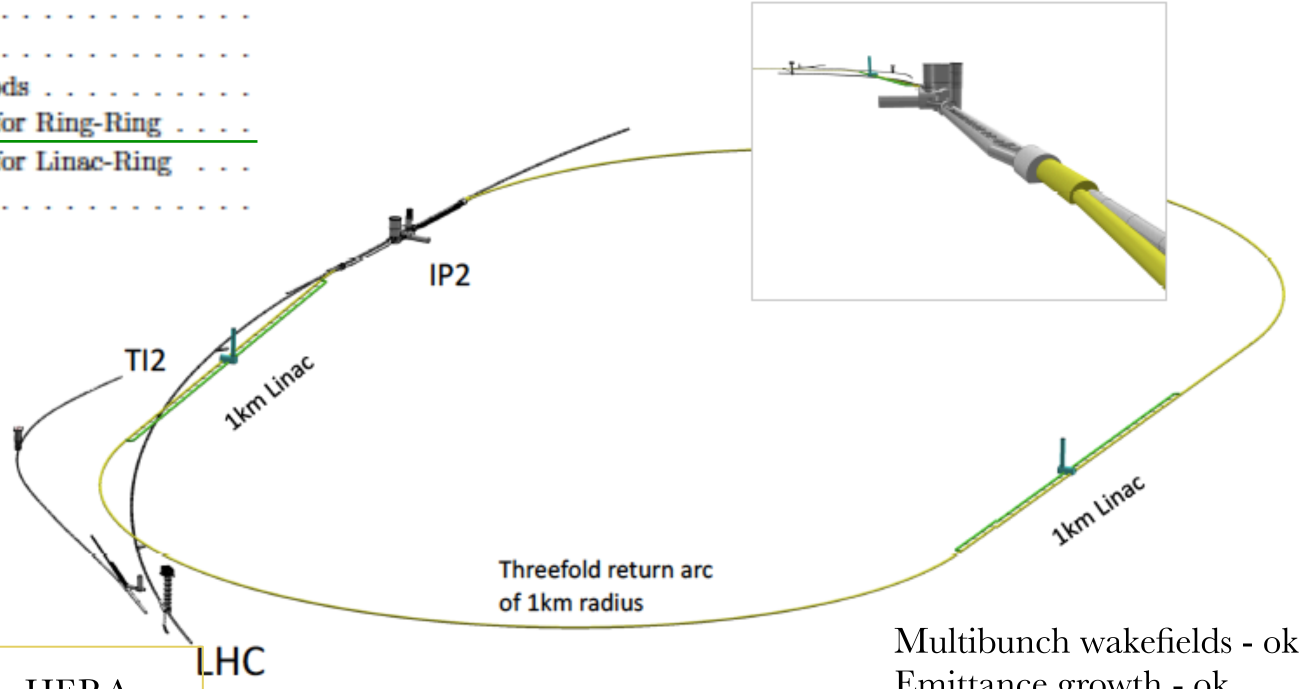


John Osborne (June LHeC Workshop)

Linac Characteristics



10 Civil Engineering and Services

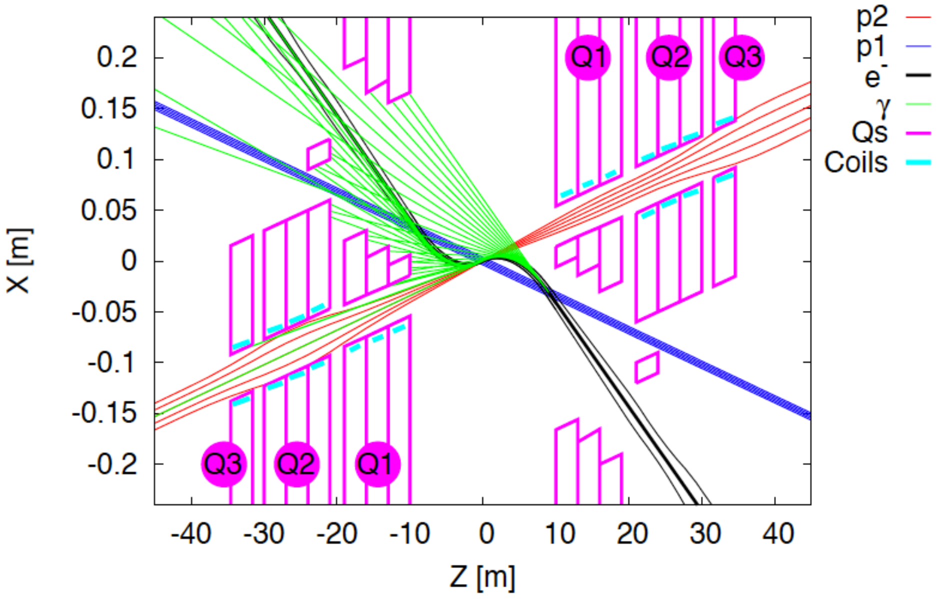


$U_{LHeC}=U_{LHC}/3$: 1.5 x HERA
Tunneling: 150m per week – 60 weeks
Two 1km linacs with 59 cryomodules
of 8 cavities each → 1000 cavities

Multibunch wakefields - ok
Emittance growth - ok
[ILC 10nm, LHeC 10μm]
36σ separation at 3.5m - ok
Fast ion instability - probably ok
with clearing gap (1/3)

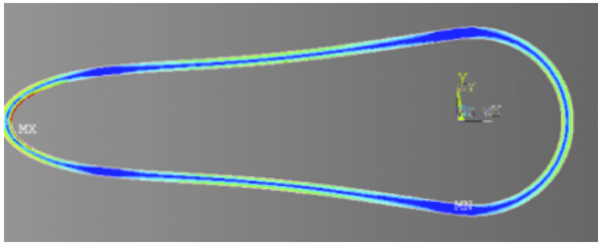
Figure 10.11: View on the ERL placed inside the LHC ring and tangential to IP2. TI2 is the injection line into the LHC. The insert shows the view towards IP2, which currently houses the ALICE experiment, from the direction of the protons colliding with the electron beam incoming from behind.

Interaction Region Developments



Beam pipe: in CDR 6m, Be, ANSYS calculations

Composite material R+D, prototype, support..
→ Essential for tracking, acceptance and Higgs



Have optics compatible with LHC and β*=0.1m
Head-on collisions mandatory →
High synchrotron radiation load, dipole in detector

Specification of Q1 – NbTi prototype (with KEK?)
Revisiting SR (direct and backscattered),
Masks+collimators
Beam-beam dynamics and 3 beam operation studies

Optimisation: HL-LHC uses IR2 quads to squeeze IR1
(“ATS” achromatic telescopic squeeze) Start in IR3 – 10cm ok.

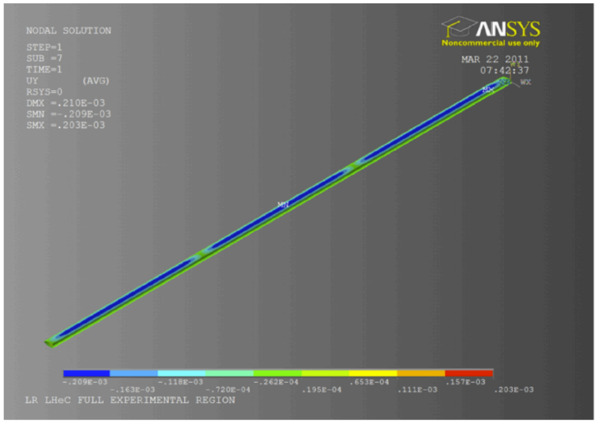


Figure 9.32: 3-D view of the LR geometry showing contours of bending displacement [m].

Liquid Argon Electromagnetic Calorimeter

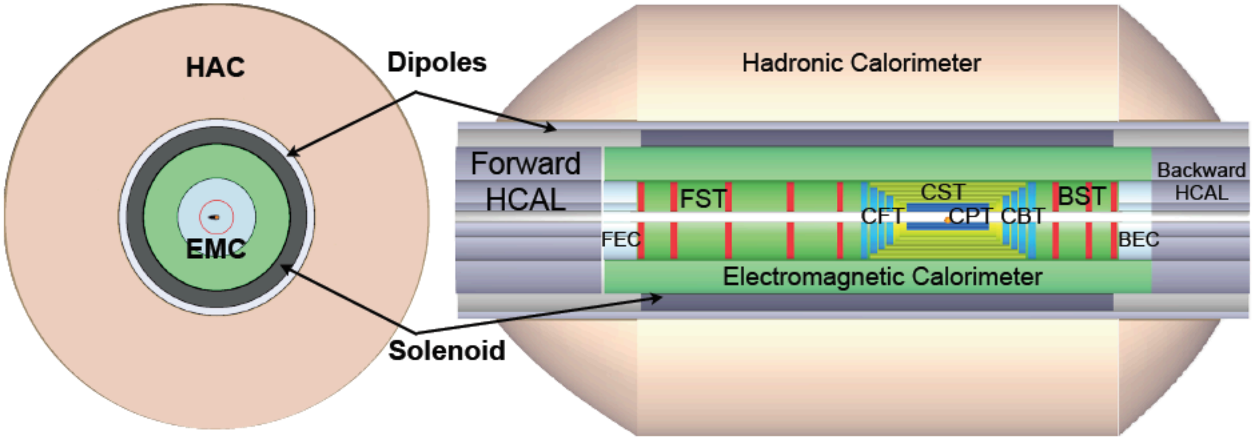


Figure 13.30: x-y and r-z view of the LHeC Barrel EM calorimeter (green).

Inside Coil
H1, ATLAS
experience.

Barrel: Pb, 20 X_0 , 11m^3

fwd/bwd inserts:

FEC: Si -W, 30 X_0 ,0.3m^3

BEC: Si -Pb, 25 X_0,0.3m^3

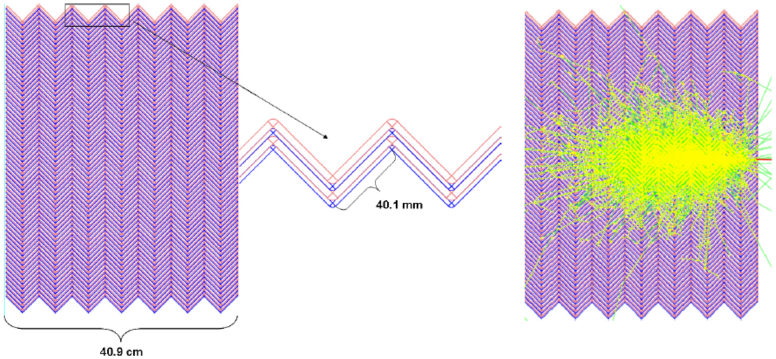


Figure 13.35: View of the parallel geometry accordion calorimeter (left) and simulation of a single electron shower with initial energy of 20 GeV (right).

GEANT4 Simulation

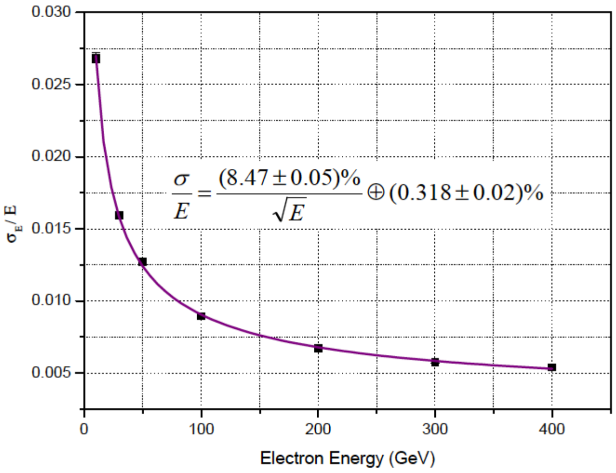
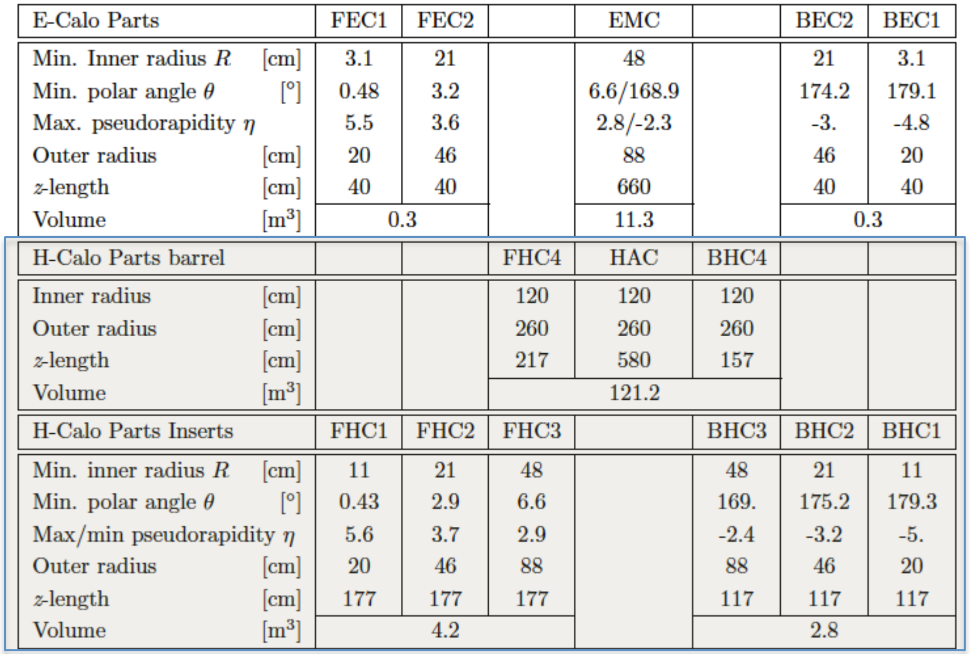


Figure 13.36: LAr accordion calorimeter energy resolution for electrons between 10 and 400 GeV.

Hadronic Tile Calorimeter

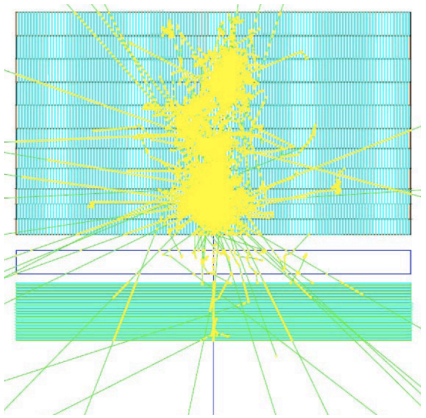
Outside Coil: flux return

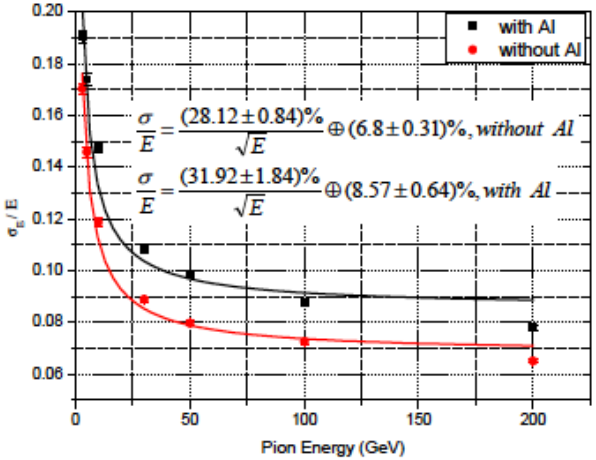
Modular. ATLAS experience.



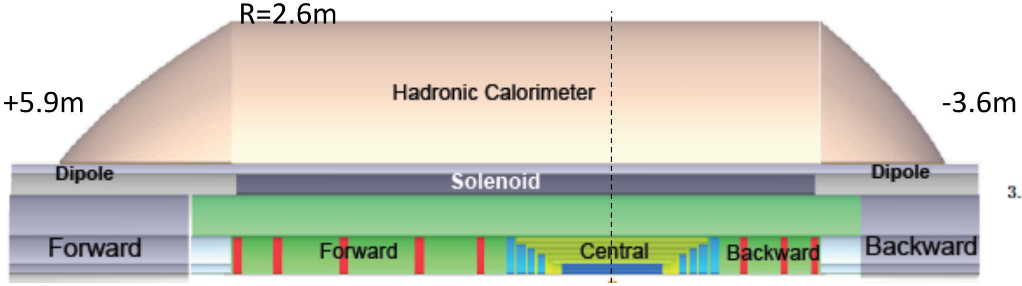
E-Calo Parts	FEC1	FEC2		EMC		BEC2	BEC1
Min. Inner radius R [cm]	3.1	21		48		21	3.1
Min. polar angle θ [°]	0.48	3.2		6.6/168.9		174.2	179.1
Max. pseudorapidity η	5.5	3.6		2.8/-2.3		-3.	-4.8
Outer radius [cm]	20	46		88		46	20
z-length [cm]	40	40		660		40	40
Volume [m^3]	0.3			11.3		0.3	
H-Calo Parts barrel			FHC4	HAC	BHC4		
Inner radius [cm]			120	120	120		
Outer radius [cm]			260	260	260		
z-length [cm]			217	580	157		
Volume [m^3]			121.2				
H-Calo Parts Inserts	FHC1	FHC2	FHC3		BHC3	BHC2	BHC1
Min. inner radius R [cm]	11	21	48		48	21	11
Min. polar angle θ [°]	0.43	2.9	6.6		169.	175.2	179.3
Max/min pseudorapidity η	5.6	3.7	2.9		-2.4	-3.2	-5.
Outer radius [cm]	20	46	88		88	46	20
z-length [cm]	177	177	177		117	117	117
Volume [m^3]	4.2				2.8		

Table 13.6: Summary of calorimeter dimensions.
The electromagnetic barrel calorimeter is currently represented by the barrel part EMC (LAr-Pb module); the setup reaches $X_0 \approx 25$ radiation length) and the movable inserts forward FEC1, FEC2 (Si-W modules ($X_0 \approx 30$) and the backward BEC1, BEC2 (Si-Pb modules; $X_0 \approx 25$).
The hadronic barrel parts are represented by FHC4, HAC, BHC4 (forward, central and backward - Scintillator-Fe Tile modules; $\lambda_I \approx 8$ interaction length) and the movable inserts FHC1, FHC2, FHC3 (Si-W modules; $\lambda_I \approx 10$), BHC1, BHC2, BHC3 (Si-Cu modules, $\lambda_I \approx 8$) see Fig. 13.9.





3.37: Accordion and Tile Calorimeter energy resolution for pions with and without 14cm Al block.



Combined GEANT4 Calorimeter Simulation

Project Development

2007: Invitation by SPC to ECFA and by (r)ECFA to work out a design concept

2008: First CERN-ECFA Workshop in Divonne (1.-3.9.08)

2009: 2nd CERN-ECFA-NuPECC Workshop at Divonne (1.-3.9.09)

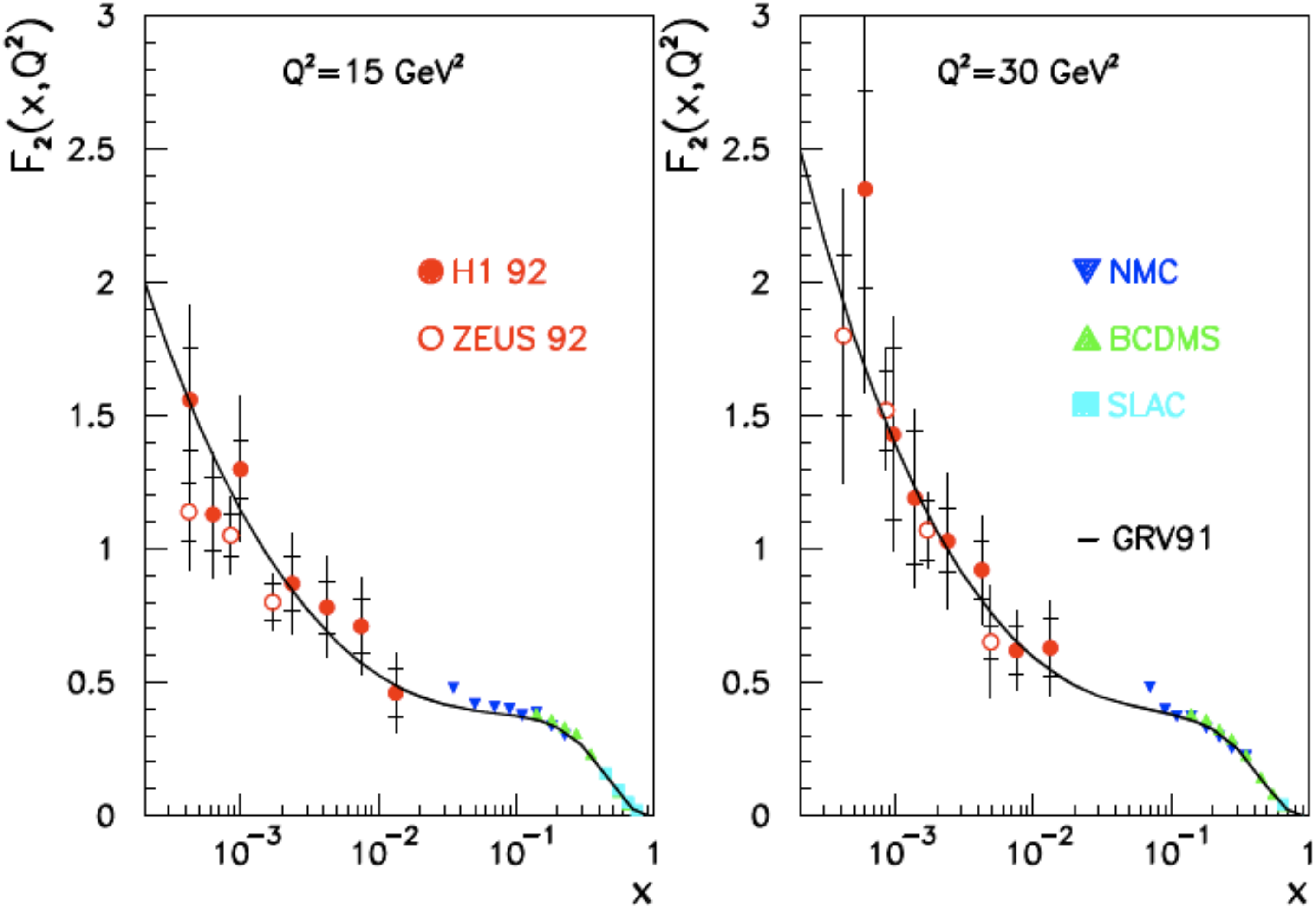
2010: Report to CERN SPC (June)
3rd CERN-ECFA-NuPECC Workshop at Chavannes-de-Bogis (12.-13.11.10)
NuPECC: LHeC on Longe Range Plan for Nuclear Physics (12/10)

2011: Draft CDR (530 pages on Physics, Detector and Accelerator) (5.8.11)
refereed and being updated

2012: Discussion of LHeC at LHC Machine Workshop (Chamonix)
Publication of CDR + 2 Contributions to European Strategy [arXiv]
Chavannes workshop (June14-15, 2012) – CERN: Linac+TDR Mandate
ECFA final endorsement of CDR
2013: EU Strategy places lower priority to the LHeC.
Workshop in early fall. Testfacility at CERN.

http://cern.ch/lhec

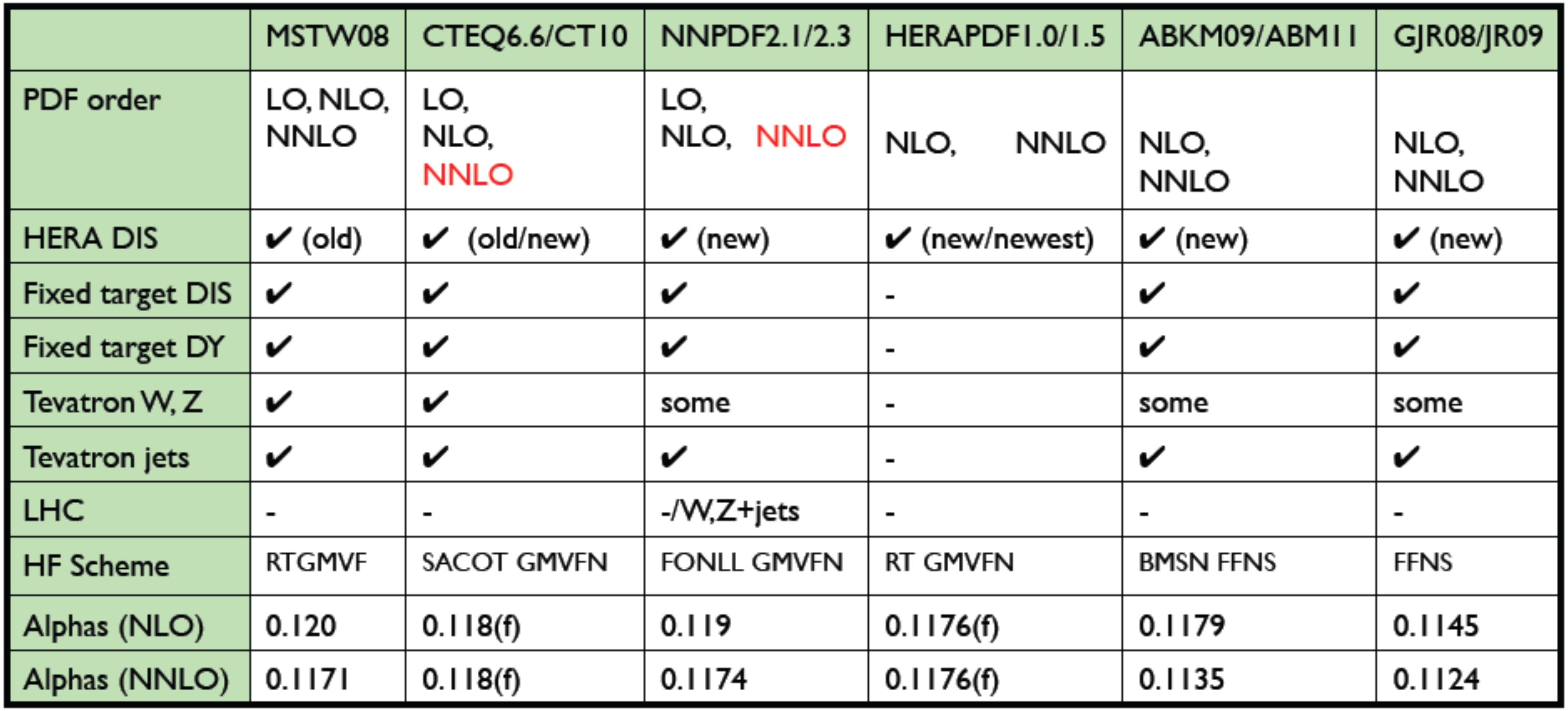
The first F_2 from HERA



H1 Collaboration, Nucl. Phys. B407 (1993) 515
ZEUS Collaboration, Phys. Lett. B316(1993) 412

Not too steep, not flat (Regge)
in accord with 1974 expectation
hidden in pioneering pQCD paper

Industry of PDF Determinations

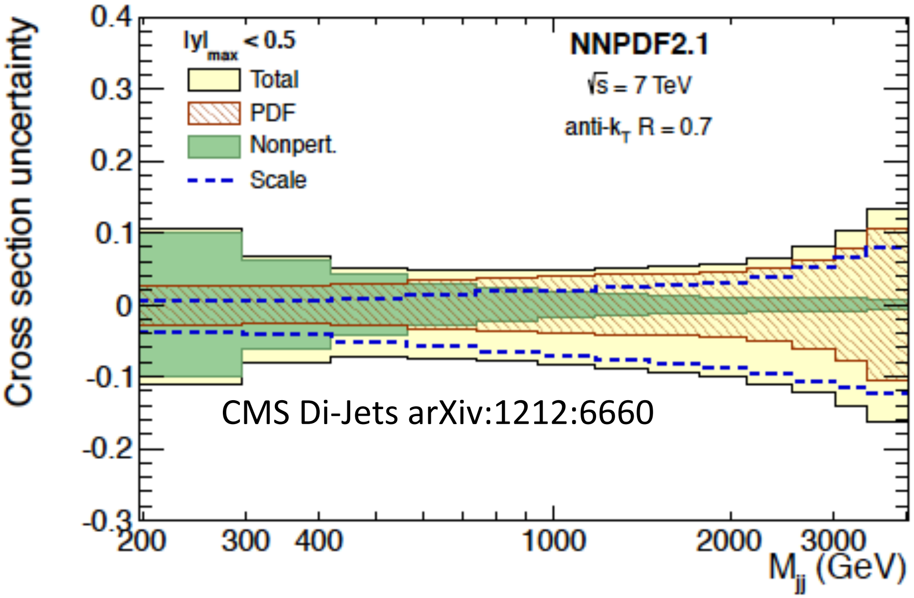


	MSTW08	CTEQ6.6/CT10	NNPDF2.1/2.3	HERAPDF1.0/1.5	ABKM09/ABM11	GJR08/JR09
PDF order	LO, NLO, NNLO	LO, NLO, NNLO	LO, NLO, NNLO	NLO, NNLO	NLO, NNLO	NLO, NNLO
HERA DIS	✔ (old)	✔ (old/new)	✔ (new)	✔ (new/newest)	✔ (new)	✔ (new)
Fixed target DIS	✔	✔	✔	-	✔	✔
Fixed target DY	✔	✔	✔	-	✔	✔
Tevatron W, Z	✔	✔	some	-	some	some
Tevatron jets	✔	✔	✔	-	✔	✔
LHC	-	-	-/W,Z+jets	-	-	-
HF Scheme	RTGMVF	SACOT GMVFN	FONLL GMVFN	RT GMVFN	BMSN FFNS	FFNS
Alphas (NLO)	0.120	0.118(f)	0.119	0.1176(f)	0.1179	0.1145
Alphas (NNLO)	0.1171	0.118(f)	0.1174	0.1176(f)	0.1135	0.1124

V.Radescu

The determination of the partonic contents of the proton is a subtle, complex task.
It often involves data which are barely compatible as is tolerated with χ^2 innovations..
Future high precision needs a new, complete PDF data basis and precision h.o. theory.
(cf arXiv:1310.1073,jb)

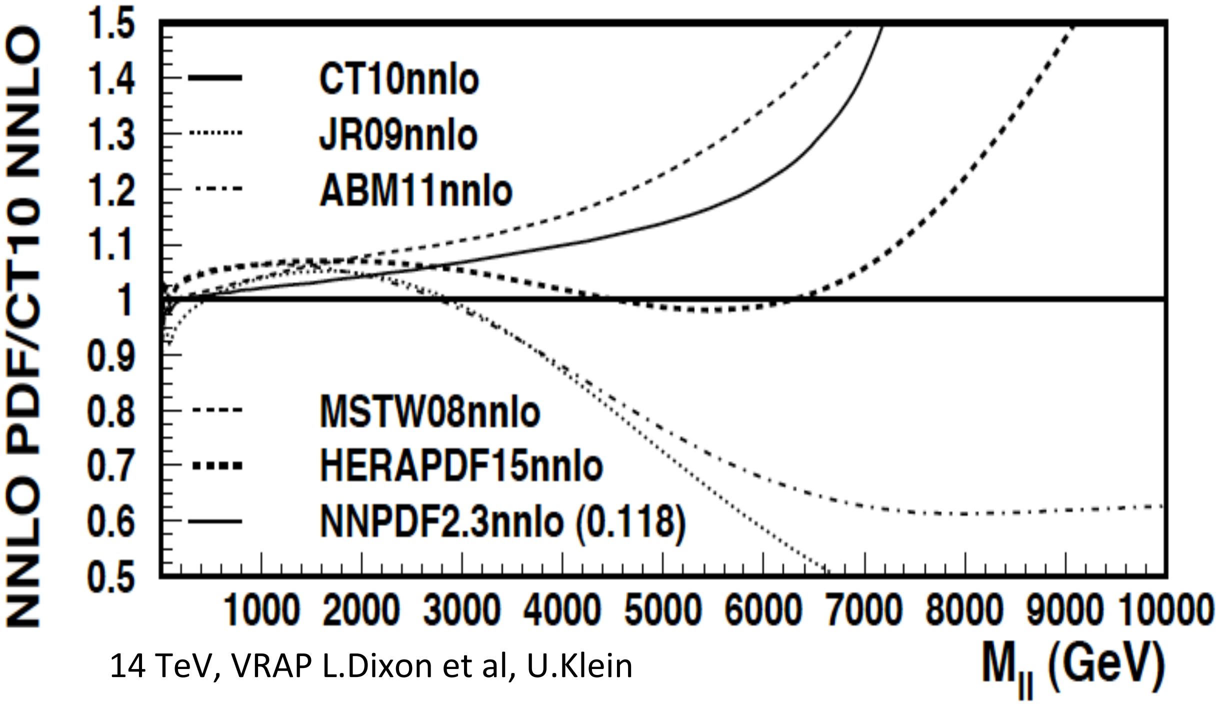
High Mass Drell Yan



CMS Di-Jets arXiv:1212:6660

Towards high mass the PDF uncertainties rise, strongly towards the edge (√s) x → 1…

For HL-LHC:
Need to study limits and interferences (ED?) in context with energy calibrations, and thy uncertainties, + PDFs vs BSM expectations



14 TeV, VRAP L.Dixon et al, U.Klein

Strong Coupling Constant

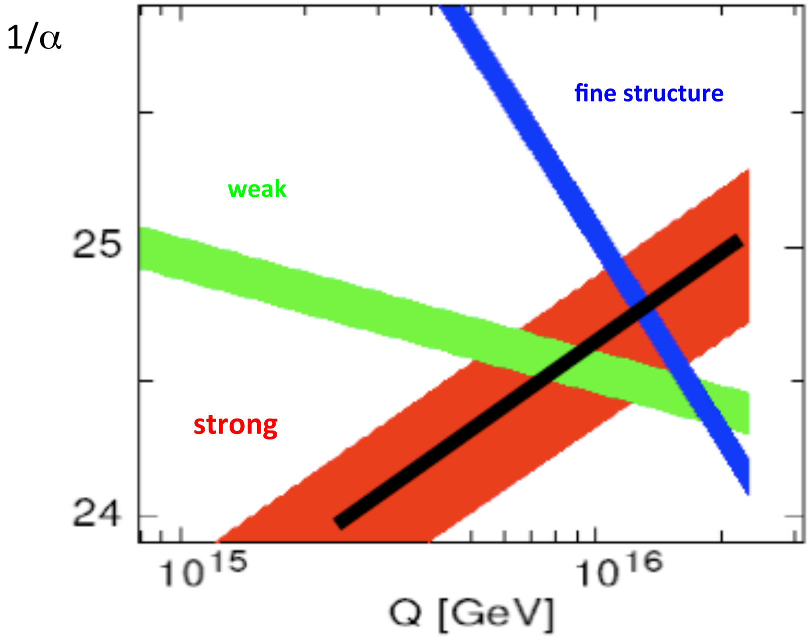
α_s least known of coupling constants

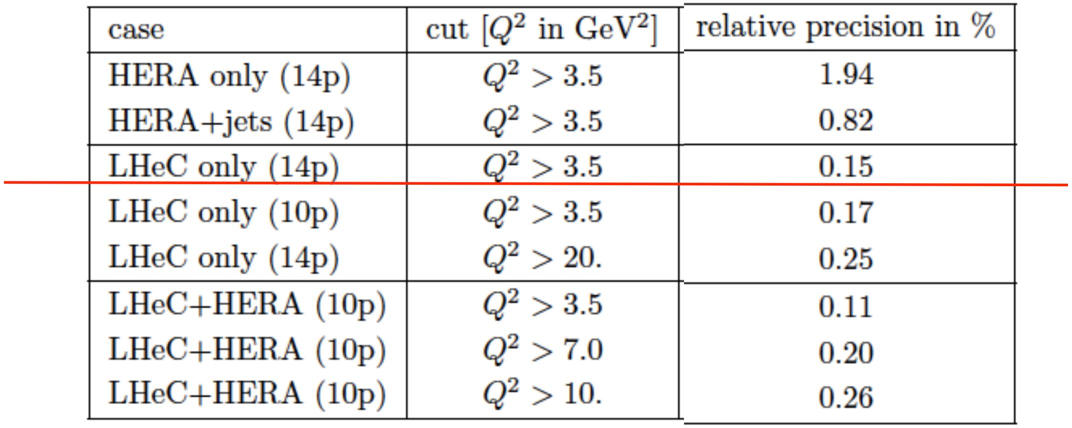
Grand Unification predictions suffer from $\delta\alpha_s$

DIS tends to be lower than world average (?)

LHeC: per mille - independent of BCDMS.

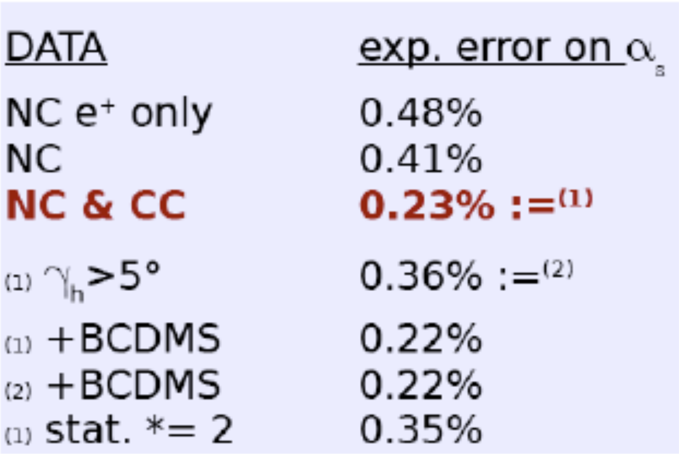
Challenge to experiment and to h.o. QCD →
A genuine DIS research programme rather than
one outstanding measurement only.





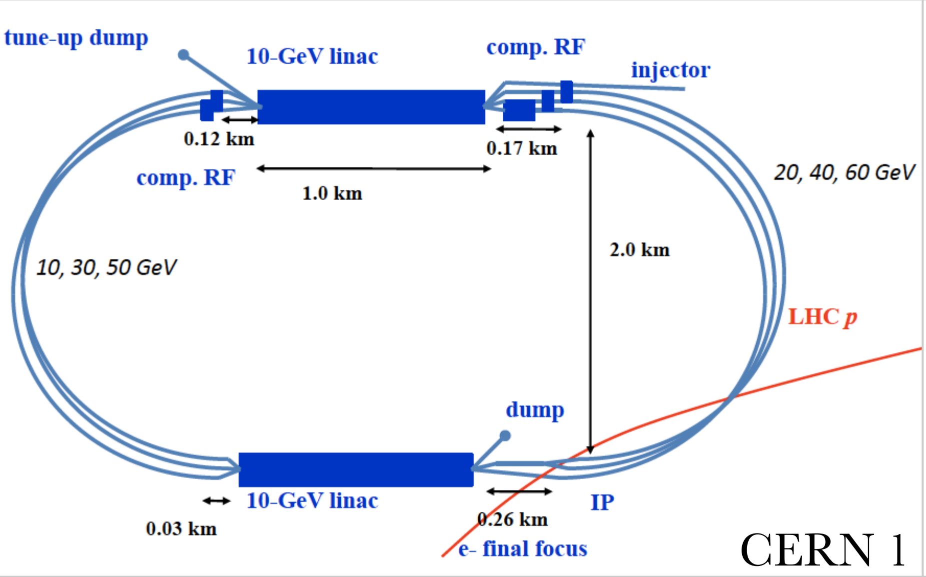
case	cut [Q^2 in GeV^2]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.26

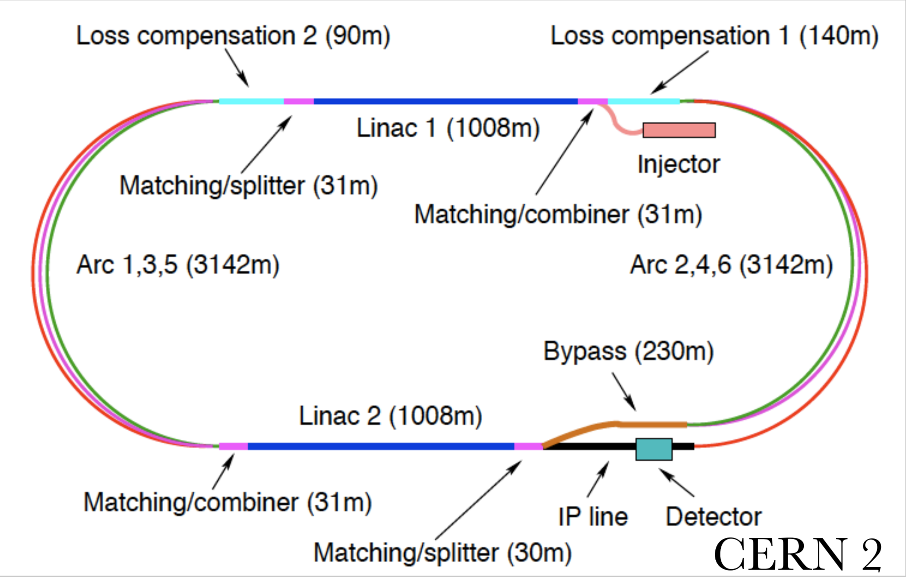
Two independent QCD analyses using LHeC+HERA/BCDMS

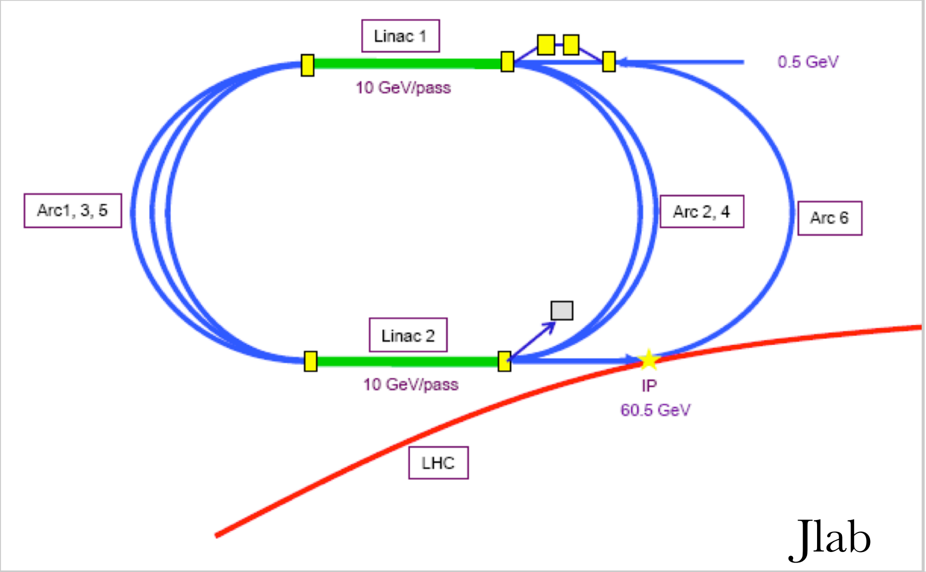


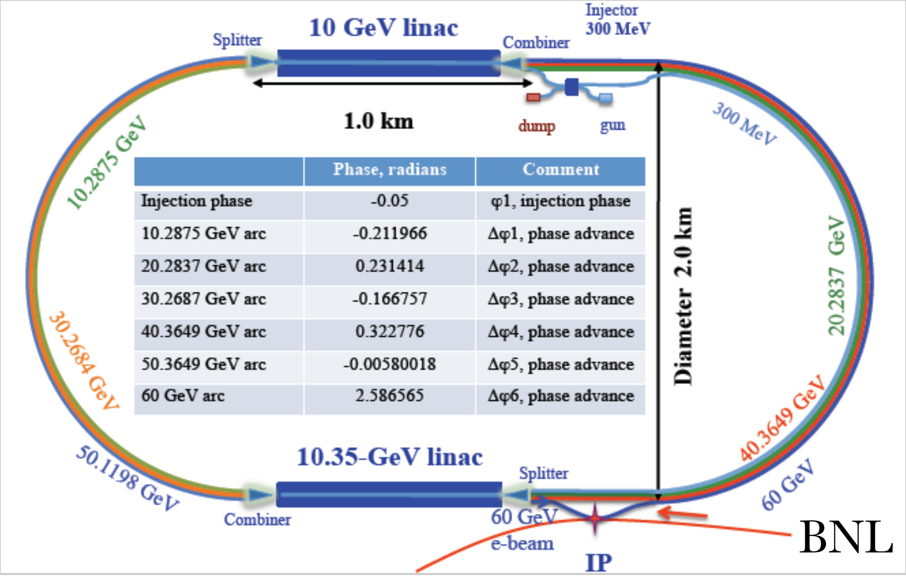
DATA	exp. error on α_s
NC e^+ only	0.48%
NC	0.41%
NC & CC	**0.23% :=$^{(1)}$**
(1) $\gamma_h > 5°$	0.36% :=$^{(2)}$
(1) +BCDMS	0.22%
(2) +BCDMS	0.22%
(1) stat. *= 2	0.35%

60 GeV Energy Recovery Linac





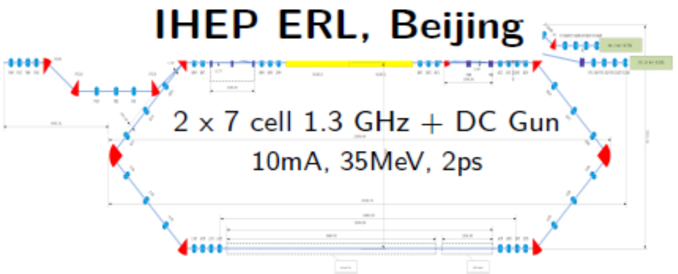




	Phase, radians	Comment
Injection phase	-0.05	φ1, injection phase
10.2875 GeV arc	-0.211966	Δφ1, phase advance
20.2837 GeV arc	0.231414	Δφ2, phase advance
30.2687 GeV arc	-0.166757	Δφ3, phase advance
40.3649 GeV arc	0.322776	Δφ4, phase advance
50.3649 GeV arc	-0.00580018	Δφ5, phase advance
60 GeV arc	2.586565	Δφ6, phase advance

Two 10 GeV energy recovery Linacs, 3 returns, 720 MHz cavities

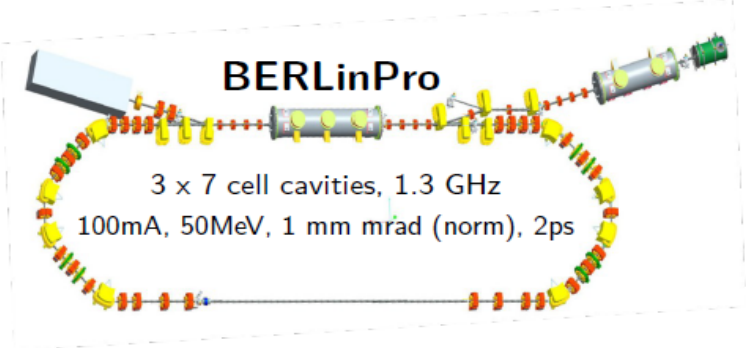
Collaboration on ERL



IHEP ERL, Beijing

2 x 7 cell 1.3 GHz + DC Gun

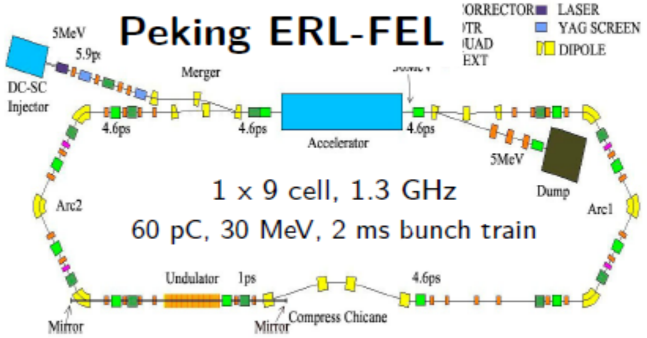
10mA, 35MeV, 2ps



BERLinPro

3 x 7 cell cavities, 1.3 GHz

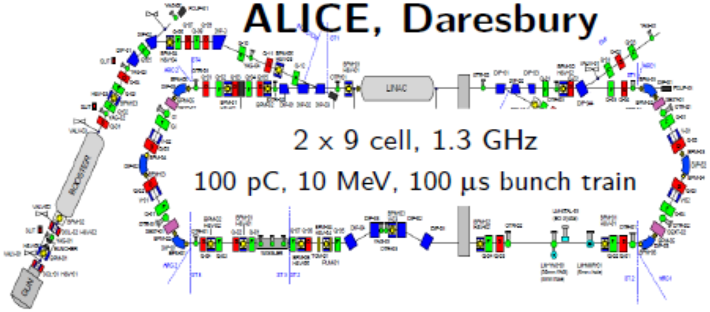
100mA, 50MeV, 1 mm mrad (norm), 2ps



Peking ERL-FEL

1 x 9 cell, 1.3 GHz

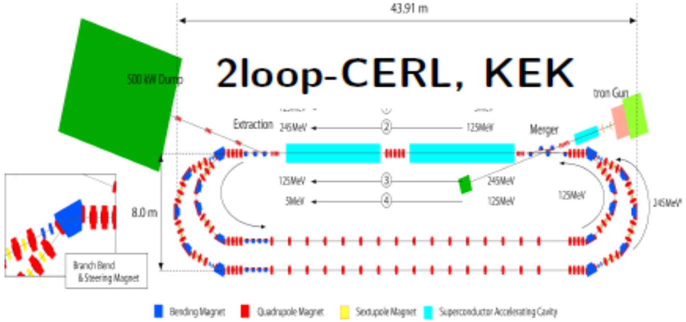
60 pC, 30 MeV, 2 ms bunch train



ALICE, Daresbury

2 x 9 cell, 1.3 GHz

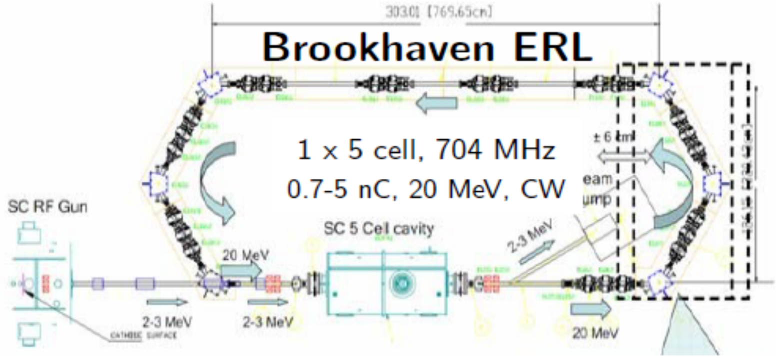
100 pC, 10 MeV, 100 μs bunch train



2loop-CERL, KEK

9 cell, 1.3 GHz cavities, 4 modules

77 pC, 245 MeV, 1-3 ps



Brookhaven ERL

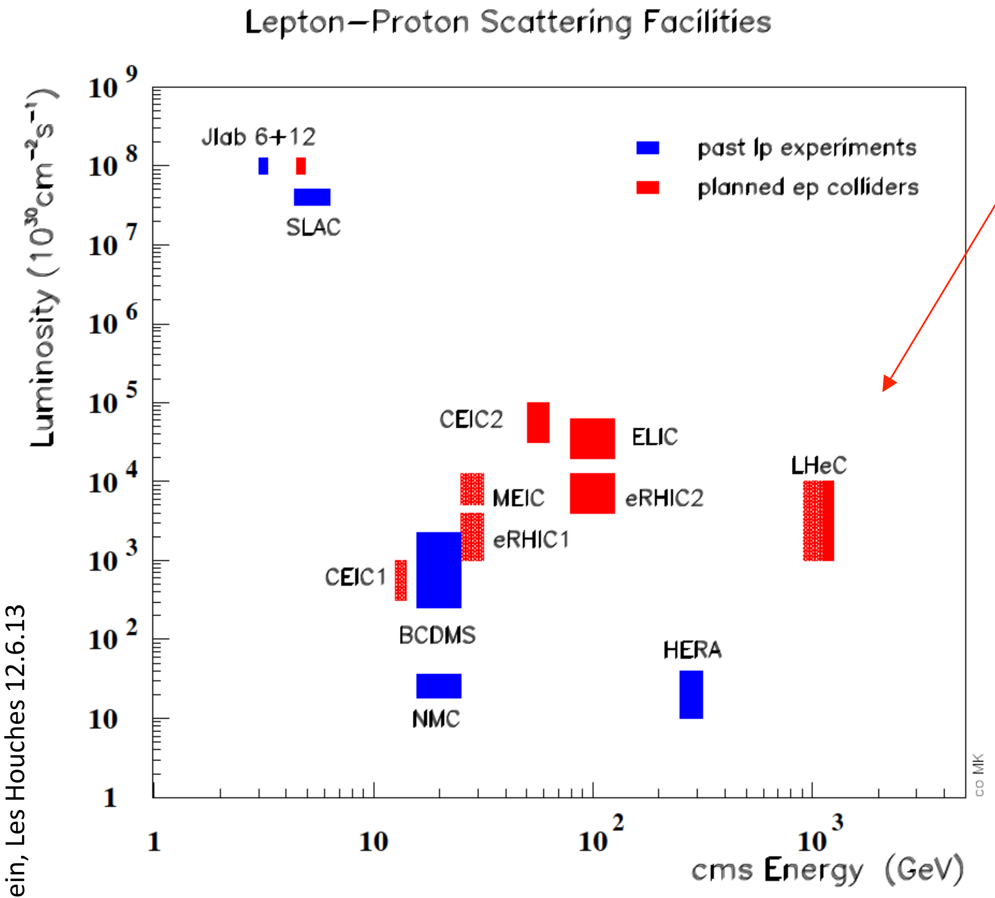
1 x 5 cell, 704 MHz

0.7-5 nC, 20 MeV, CW

Budker Institute

Large Hadron Electron Collider - LHeC

Information on http://cern.ch/lhec



ep/A synchronous to pp/AA

- LHC is the only place for TeV energy DIS
- ~60 GeV electron beam upgrade to the LHC
- DIS at TeV energies: $Q^2_{max}10^6$, $x > 10^{-6}$
- **A new Higgs facility** – new detector

Noteable:

- Unprecedent precision (α_s to per mille)
- Complete unfolding of PDFs (1st time)
- Precision electroweak measurements
- Novel precision input for LHC physics
- BSM (RPV SUSY, e*, CI, lq resonances?)
- Quark Gluon Plasma – initial formation

QCD

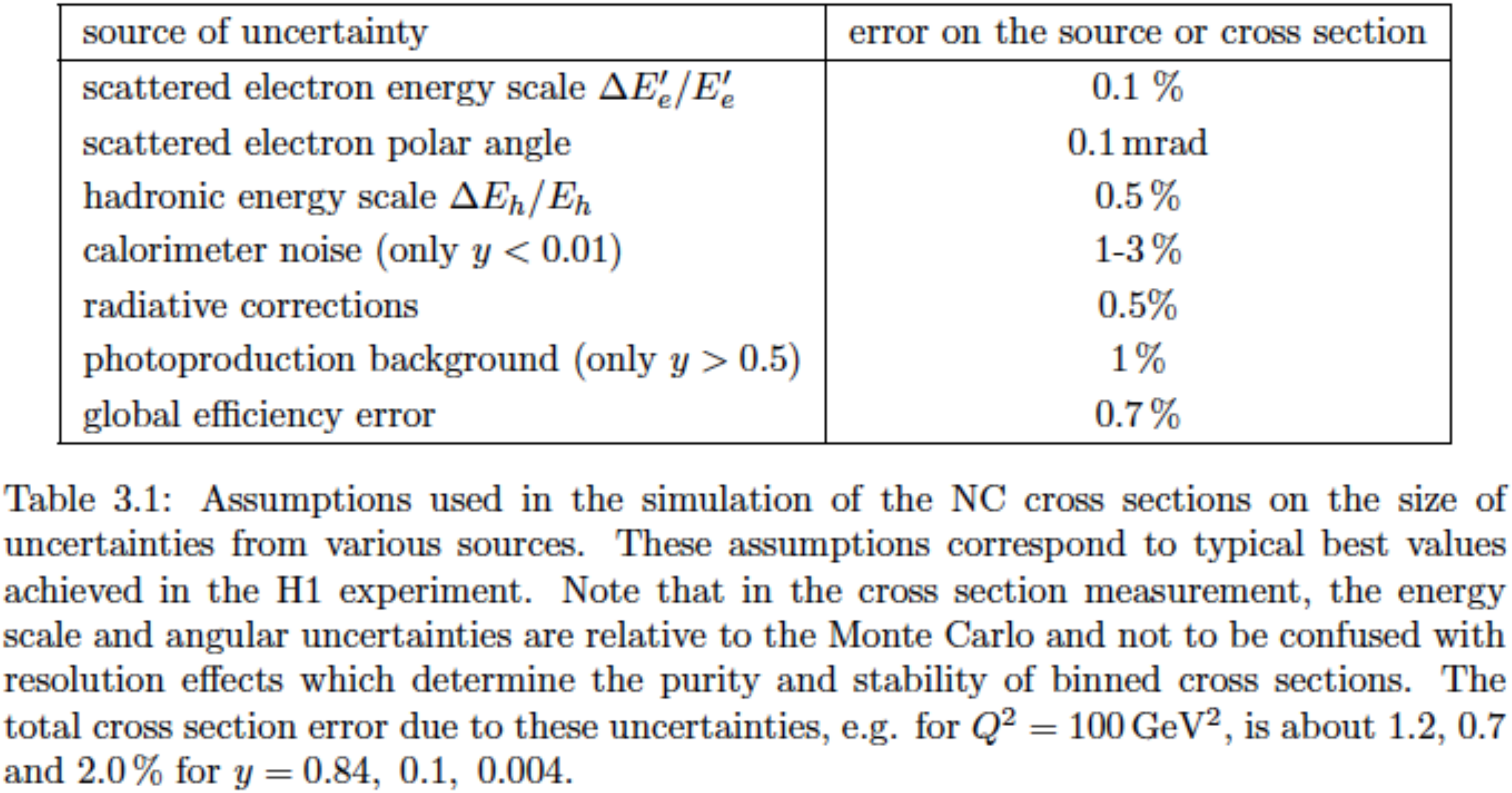
- Discovery/disproval of saturation at low x
- Less conventional partons (kt, diff., GPDs)
- Nuclear structure in huge kinematic range
- Top with 10pb cross section in DIS, tPDF

Max Klein, Les Houches 12.6.13

The LHeC is a new laboratory for energy frontier particle physics of unique character.

Ref's: CDR arXiv:1205:2913, summary: arXiv:1211.4831, relation to LHC: arXiv:1211:5102

Measurement Simulations



source of uncertainty	error on the source or cross section
scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale $\Delta E_h/E_h$	0.5 %
calorimeter noise (only $y < 0.01$)	1-3 %
radiative corrections	0.5%
photoproduction background (only $y > 0.5$)	1 %
global efficiency error	0.7 %

Table 3.1: Assumptions used in the simulation of the NC cross sections on the size of uncertainties from various sources. These assumptions correspond to typical best values achieved in the H1 experiment. Note that in the cross section measurement, the energy scale and angular uncertainties are relative to the Monte Carlo and not to be confused with resolution effects which determine the purity and stability of binned cross sections. The total cross section error due to these uncertainties, e.g. for $Q^2 = 100\,\mathrm{GeV}^2$, is about 1.2, 0.7 and 2.0 % for $y = 0.84,\ 0.1,\ 0.004$.

Full simulation of NC and CC inclusive cross section measurements including statistics, uncorrelated and correlated uncertainties – checked against H1 MC

L vs E_e

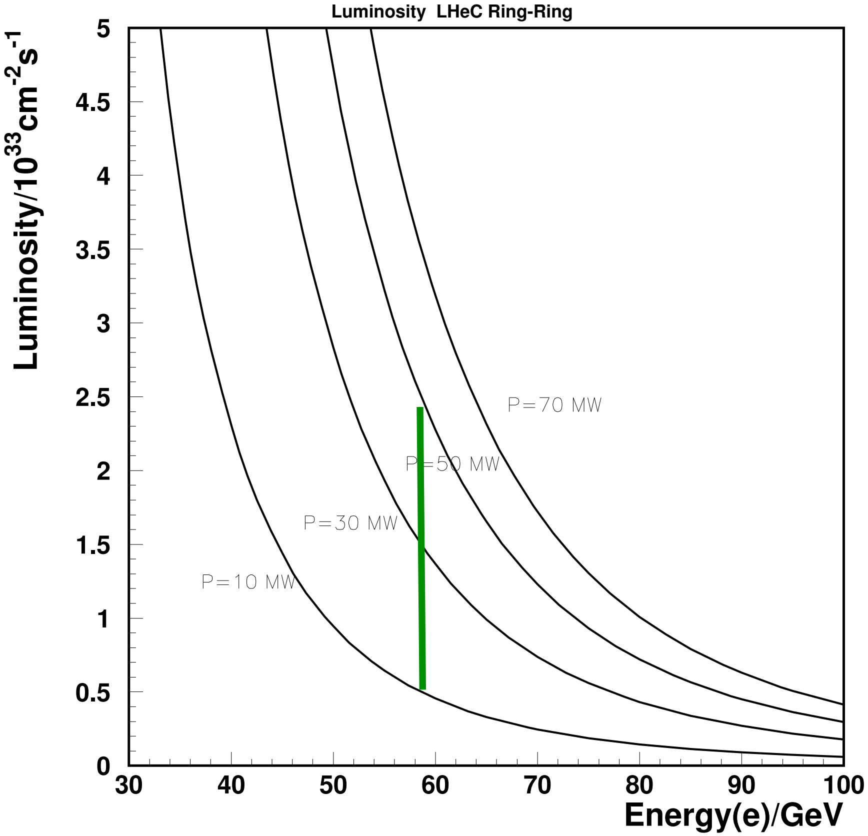
Storage Ring

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}}$$

$$N_p = 1.7\cdot 10^{11}, \varepsilon_p = 3.8\mu m, \beta_{px(y)} = 1.8(0.5)m, \gamma = \frac{E_p}{M_p}$$

$$L = 8.2\cdot 10^{32} cm^{-2}s^{-1}\cdot \frac{N_p 10^{-11}}{1.7}\cdot \frac{m}{\sqrt{\beta_{px}\beta_{py}}}\cdot \frac{I_e}{50mA}$$

$$I_e = 0.35mA\cdot P[MW]\cdot (100/E_e[GeV])^4$$


Luminosity LHeC Ring-Ring

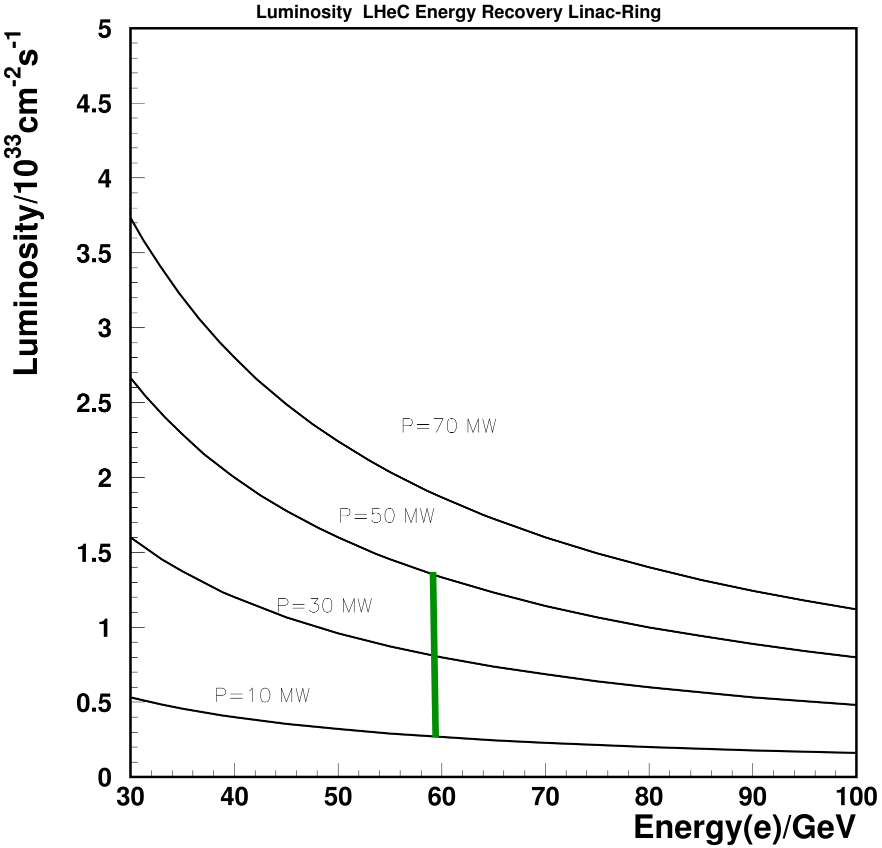
Energy Recovery Linac

$$L = \frac{1}{4\pi}\cdot\frac{N_p}{\varepsilon_p}\cdot\frac{1}{\beta^*}\cdot\gamma\cdot\frac{I_e}{e}$$

$$N_p = 1.7\cdot 10^{11}, \varepsilon_p = 3.8\mu m, \beta^* = 0.2m, \gamma = 7000/0.94$$

$$L = 8\cdot 10^{31} cm^{-2}s^{-1}\cdot\frac{N_p 10^{-11}}{1.7}\cdot\frac{0.2}{\beta^*/m}\cdot\frac{I_e/mA}{1}$$

$$I_e = mA\frac{P_E/MW}{E_e/GeV}, P_E = P/(1-\eta), \eta \approx 0.95$$


Luminosity LHeC Energy Recovery Linac-Ring

Detector Magnets

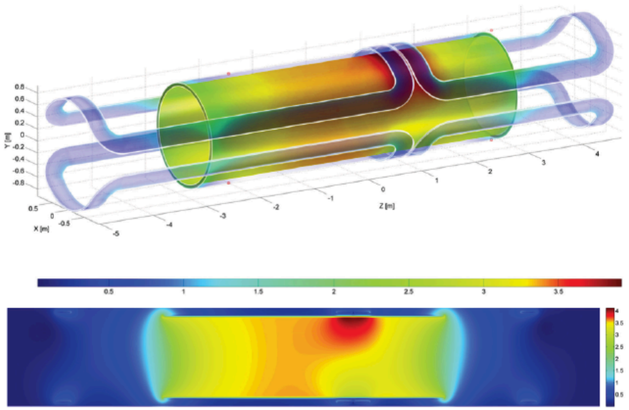


Figure 13.13: Magnetic field of the magnet system of solenoid and the two internal superconducting dipoles at nominal currents (effect of iron ignored). The position of the peak magnetic field of 3.9 T is local due to the adjacent current return heads on top of the solenoid where all magnetic fields add up.

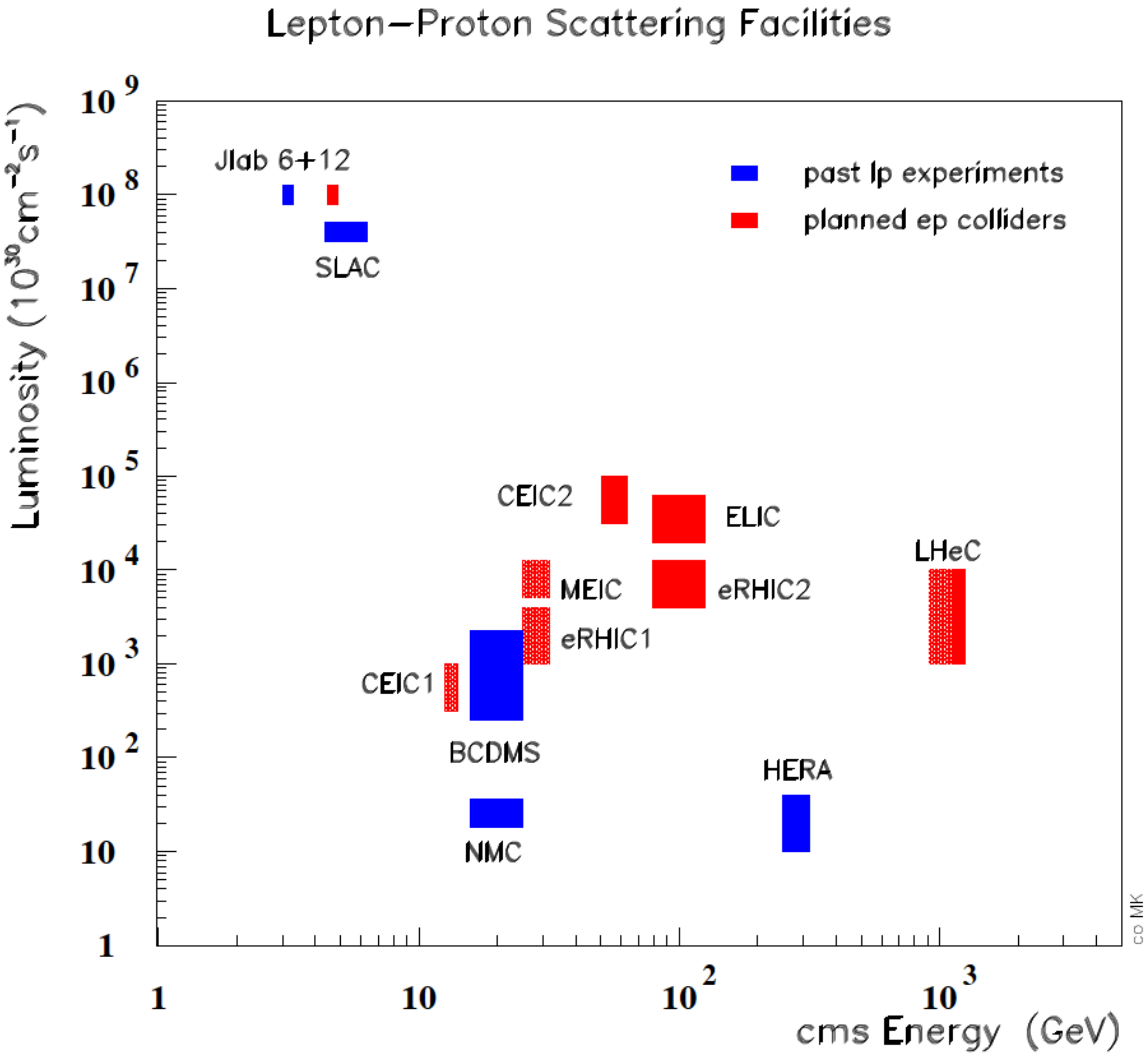
Dipole (for head on LR) and solenoid in common cryostat, perhaps with electromagnetic LAr

3.5T field at ~1m radius to house a Silicon tracker

Based on ATLAS+CMS experience

Property	Parameter	value	unit
Dimensions	Cryostat inner radius	0.900	m
	Length	10.000	m
	Outer radius	1.140	m
	Coil windings inner radius	0.960	m
	Length	5.700	m
	Thickness	60.0	mm
	Support cylinder thickness	0.030	m
	Conductor section, Al-stabilized NbTi/Cu + insulation	30.0×6.8	mm^2
	Length	10.8	km
	Superconducting cable section, 20 strands	12.4×2.4	mm^2
	Superconducting strand diameter Cu/NbTi ratio = 1.25	1.24	mm
Masses	Conductor windings	5.7	t
	Support cylinder, solenoid section + dipole sections	5.6	t
	Total cold mass	12.8	t
	Cryostat including thermal shield	11.2	t
	Total mass of cryostat, solenoid and small parts	24	t
Electro-magnetics	Central magnetic field	3.50	T
	Peak magnetic field in windings (dipoles off)	3.53	T
	Peak magnetic field in solenoid windings (dipoles on)	3.9	T
	Nominal current	10.0	kA
	Number of turns, 2 layers	1683	
	Self-inductance	1.7	H
	Stored energy	82	MJ
	E/m, energy-to-mass ratio of windings	14.2	kJ/kg
	E/m, energy-to-mass ratio of cold mass	9.2	kJ/kg
	Charging time	1.0	hour
	Current rate	2.8	A/s
	Inductive charging voltage	2.3	V
Margins	Coil operating point, nominal / critical current	0.3	
	Temperature margin at 4.6 K operating temperature	2.0	K
	Cold mass temperature at quench (no extraction)	∼ 80	K
Mechanics	Mean hoop stress	∼ 55	MPa
	Peak stress	∼ 85	MPa
Cryogenics	Thermal load at 4.6 K, coil with 50% margin	∼ 110	W
	Radiation shield load width 50% margin	∼ 650	W
	Cooling down time / quench recovery time	4 and 1	day
	Use of liquid helium	∼ 1.5	g/s

Table 13.1: Main parameters of the baseline LHeC Solenoid providing 3.5 T in a free bore of 1.8 m.



Energy frontier deep inelastic scattering - following HERA with the LHC
LHeC: A new laboratory for particle physics, a 5th large LHC experiment