The Large Hadron Electron Collider at CERN

An Introduction to the LHeC Project

Max Klein

University of Liverpool

Project

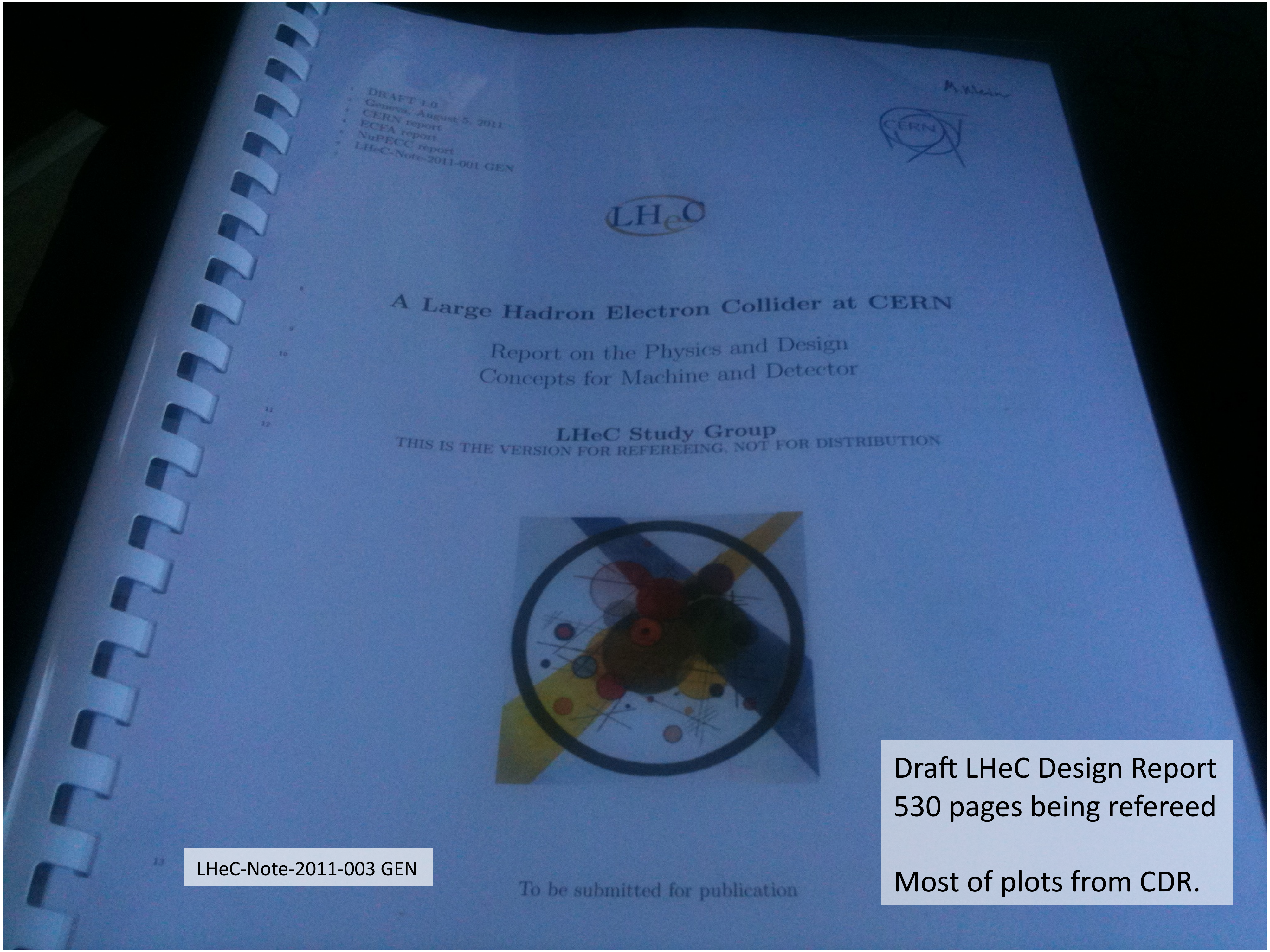
Deep Inelastic Scattering
Physics Programme

Two Accelerator Options
Detector Design

Outlook

http://cern.ch/lhec

Seminar at University of Prague, 12.01.2012



LHeC-Note-2011-003 GEN

Draft LHeC Design Report
530 pages being refereed

Most of plots from CDR.

http://cern.ch/lhec

LHeC Study Group

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About 150 Experimentalists and Theorists from 50 Institutes

Tentative **list of those who contributed to the CDR**

Supported by
CERN, ECFA, NuPECC

Project Milestones

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 puts LHeC to its Longe Range Plan for Nuclear Physics (12/10)

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

2012: Publication of CDR – European Strategy
New workshop (tentatively in May 10-11, 2012)

Goal: TDR by 2014
Perspective: Operation by 2023 (synchronous with pp)

Organisation for CDR

Review ongoing:

Scientific Advisory Committee

Guido Altarelli (Roma)
Sergio Bertolucci (CERN)
Stan Brodsky (SLAC)
Allen Caldwell (MPI Muenchen) - Chair
Swapan Chattopadhyay (Cockcroft Institute)
John Dainton (Liverpool)
John Ellis (CERN)
Jos Engelen (NWO)
Joel Feltesse (Saclay)
Roland Garoby (CERN)
Rolf Heuer (CERN)
Roland Horisberger (PSI)
Young-Kee Kim (Fermilab)
Aharon Levy (Tel Aviv)
Lev Lipatov (St. Petersburg)
Karlheinz Meier (Heidelberg)
Richard Milner (MIT)
Joachim Mnich (DESY)
Steve Myers (CERN)
Guenther Rosner (Glasgow)
Alexander N. Skrinsky (INP Novosibirsk)
Anthony Thomas (JLab)
Steve Vigdor (Brookhaven)
Ferdinand Willeke (Brookhaven)
Frank Wilczek (MIT)

LHeC

Steering Committee

Oliver Bruening(CERN)
John Dainton (Liverpool)
Albert De Roeck (CERN)
Stefano Forte (Milano)
Max Klein (Liverpool) - Chair
Paul Laycock (Liverpool)
Paul Newman (Birmingham)
Emmanuelle Perez (CERN)
Wesley Smith (Wisconsin)
Bernd Surrow (MIT)
Katsuo Tokushuku (KEK)
Urs Wiedemann (CERN)
Frank Zimmermann (CERN)

Working Group Convenors

Accelerator Design

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John Dainton (Liverpool)

Interaction Region

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Uwe Schneekloth (DESY)
Pierre van Mechelen (Antwerpen)

Detector Design

Peter Kostka (DESY)
Alessandro Polini (Bologna)
Rainer Wallny (Zurich)

New Physics at Large Scales

Georges Azuelos (Montreal)
Emmanuelle Perez (CERN)
Georg Weiglein (Hamburg)

Precision QCD and Electroweak

Olaf Behnke (DESY)
Paolo Gambino (Torino)
Thomas Gehrmann (Zurich)
Claire Gwenlan (Oxford)

Physics at High Parton Densities

Néstor Armesto (Santiago de Compostela)
Brian A. Cole (Columbia)
Paul R. Newman (Birmingham)
Anna M. Stasto (PennState)

CERN Referees

Ring Ring Design
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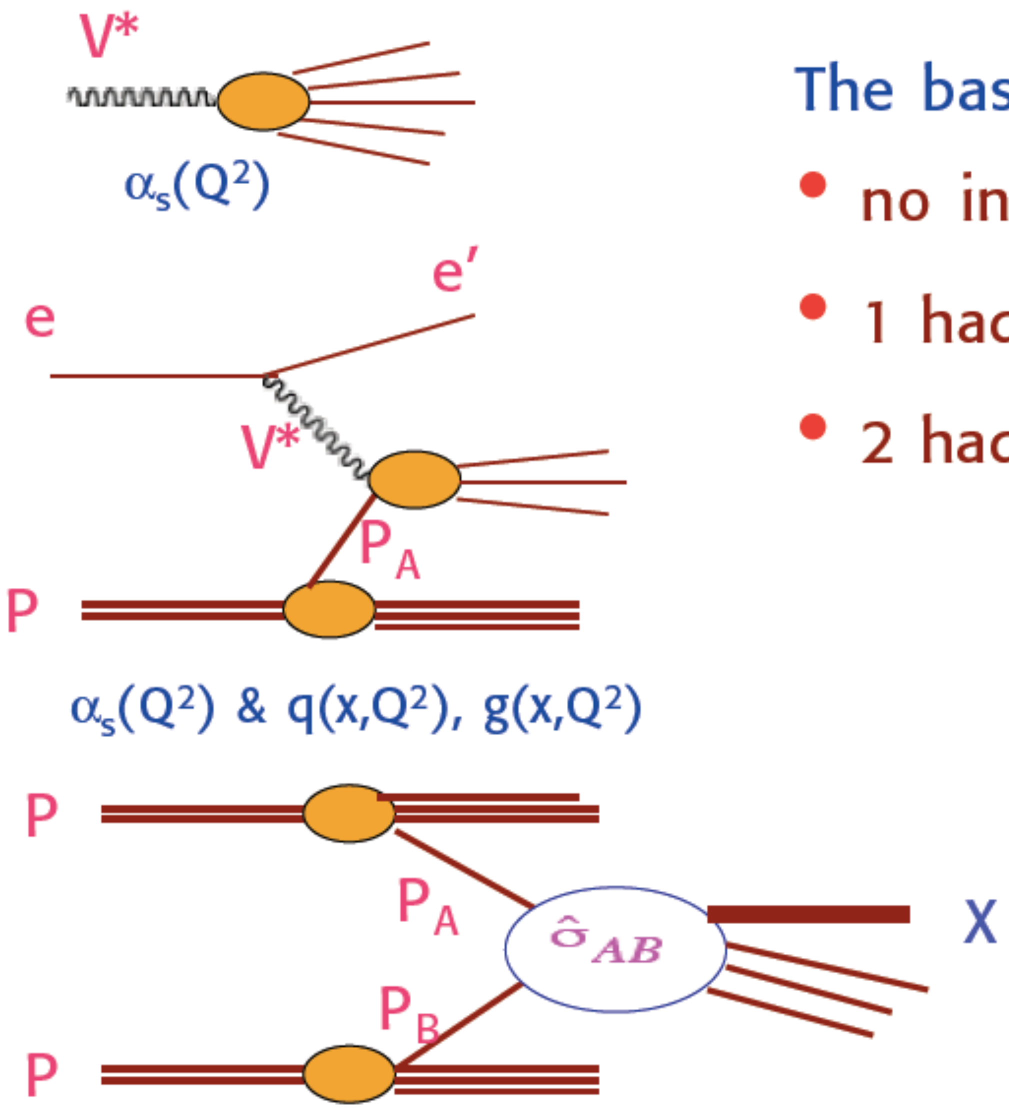
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)
Linac Ring Design
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)
Energy Recovery
Georg Hoffstaetter (Cornell)
Ilan Ben Zvi (BNL)
Magnets
Neil Marks (Cockcroft)
Martin Wilson (CERN)
Interaction Region
Daniel Pitzl (DESY)
Mike Sullivan (SLAC)
Detector Design
Philippe Bloch (CERN)
Roland Horisberger (PSI)
Installation and Infrastructure
Sylvain Weisz (CERN)
New Physics at Large Scales
Cristinel Diaconu (IN2P3 Marseille)
Gian Giudice (CERN)
Michelangelo Mangano (CERN)
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)

I. Deep Inelastic Scattering, HERA,LHC and Physics at the LHeC

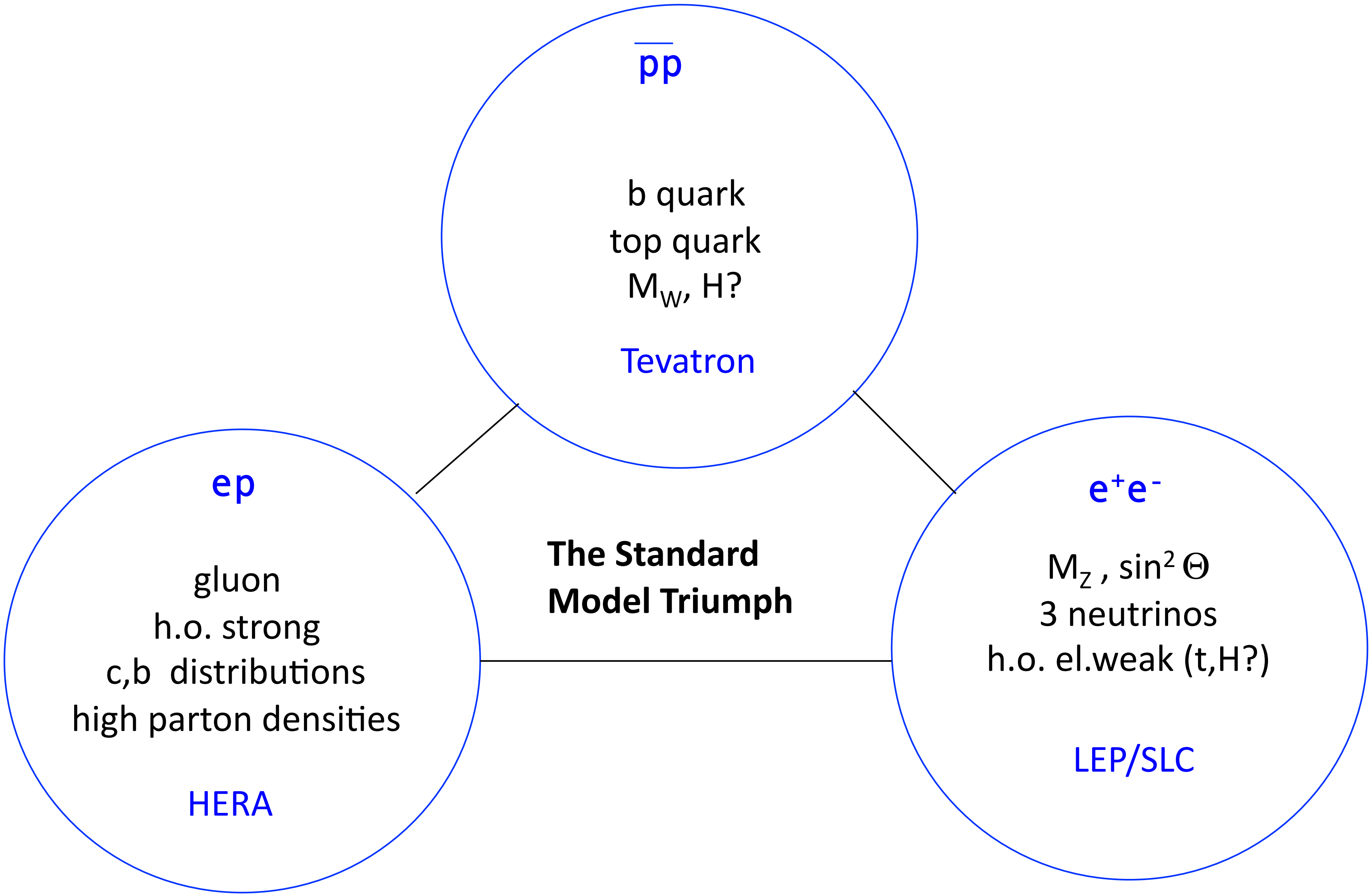


The basic experimental set ups:

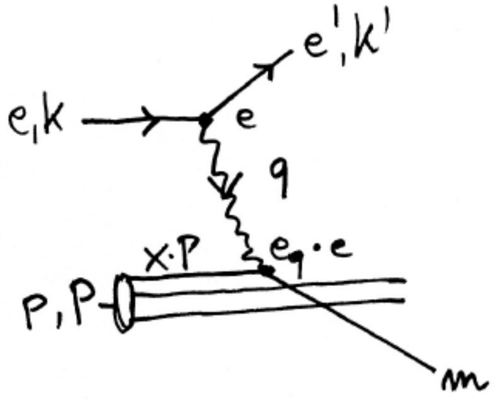
- no initial hadron (....LEP, ILC, CLIC)
- 1 hadron (....HERA, LHeC)
- 2 hadrons (....SppS, Tevatron, LHC)

Progress in particle physics needs their continuous interplay to take full advantage of their complementarity

The Fermi Scale [1985-2010]



Deep Inelastic Scattering



$$q = (k - k')$$
$$(xP + q)^2 = m^2, P^2 = M_p^2$$
$$Q^2 = -q^2 > 0$$
$$if: Q^2 >> x^2 M_p^2, m^2:$$
$$q^2 + 2xPq = 0:$$
$$x = \frac{Q^2}{2Pq}$$

"fixed target":

$$P = (M_p, 0,0,0)$$
$$2Pq = 2M_p(E - E')$$
$$= 2M_p E \cdot \frac{\nu}{E} \equiv s \cdot y$$
$$Q^2 = sxy \le s$$
$$s = 2M_p E$$
$$s = 4E_e E_p \quad \text{- ep collider}$$
$$x = \frac{Q^2}{sy}$$

$$\sigma(ep \to eX) = \frac{d^2\sigma}{dxdQ^2} \approx \frac{2\pi\alpha^2}{Q^4}(1 + (1-y)^2) \cdot F_2$$
$$F_2(x, Q^2) = x \sum_q e_q^2 (q + \bar{q}), q = u,d,s,c,b,t$$
$$q = q(x, Q^2)$$

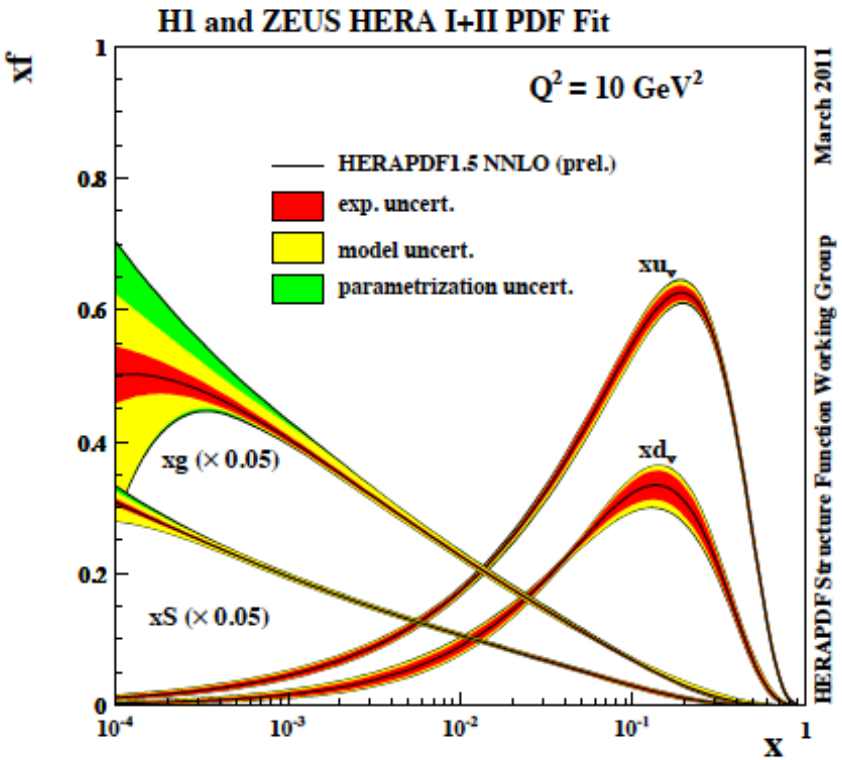
In DIS the inclusive cross section depends on two variables, the negative 4-momentum transfer squared (Q^2), which determines the resolving power of the exchanged particle in terms of p substructure, and the variable Bjorken x, which Feynman could relate to the fraction of momentum of the proton carried by a parton [in what he called the 'infinite momentum frame' in which the transverse momenta are neglected].

Feynman's partons were readily linked to Gell-Mann and Zweig's quarks.

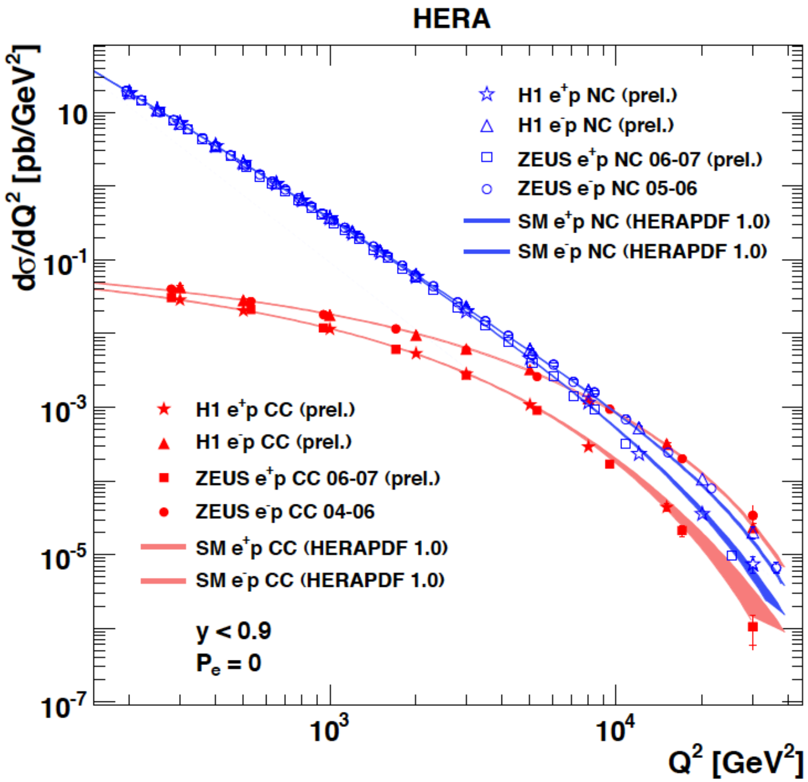
This process has been for 20 years recently been investigated at HERA.

Deep inelastic scattering resolves the nucleon structure. If s is high: produce new states
Kinematics is determined with scattered electron or with HFS → high precision due to redundancy

Results from HERA



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



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

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..)

M.Klein, R.Yoshida: Collider Physics at HERA Prog.Part.Nucl.Phys. 61 (2008) 343-393 and recent H1,ZEUS results

What HERA could not do or has not done

HERA in one box
the first ep collider

$E_p * E_e =$
$920 * 27.6 GeV^2$
$\sqrt{s} = 2\sqrt{E_e E_p} = 320$ GeV

$L = 1..4\ 10^{31} cm^{-2} s^{-1}$
→ $\Sigma L = 0.5 fb^{-1}$
1992-2000 & 2003-2007

$Q^2 = [0.1 -- 3 * 10^4]\ GeV^2$
-4-momentum transfer^2

$x = Q^2/(sy) \cong 10^{-4}$ .. 0.7
Bjorken x

$y \cong 0.005$ .. 0.9
inelasticity

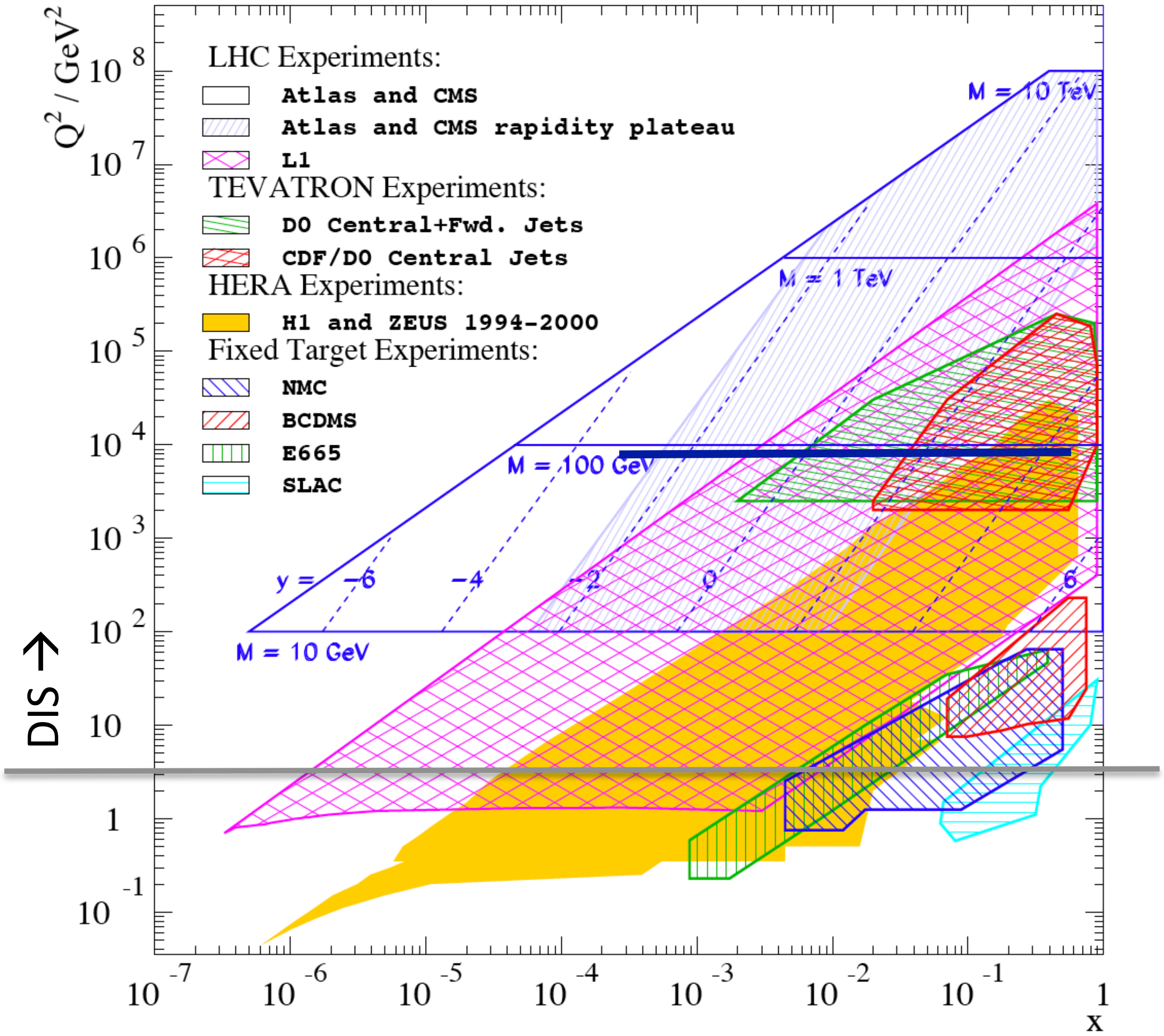
Test of the isospin symmetry (u-d) with eD - no deuterons
Investigation of the q-g dynamics in nuclei - no time for eA
Verification of saturation prediction at low x – too low s
Measurement of the strange quark distribution – too low L
Discovery of Higgs in WW fusion in CC – too low cross section
Study 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
…

The H1 and ZEUS apparatus were basically well suited
The machine had too low luminosity and running time

HEP needs a TeV energy scale machine with 100 times higher luminosity than HERA to develop DIS physics further and to complement the physics at the LHC. The Large Hadron Collider p and A beams offer a unique opportunity to build a second ep and first eA collider at the energy frontier.

LEP-LHC studies, J.Dainton et al. "DIS at the LHC", JINST 1 (2006) P10001

Complementing the LHC with ep/A



In Drell-Yan kinematics: mass and rapidity relate to Q^2 and x

LHC partons: W,Z +c,b new constraints but severely limited in x,Q^2 range

Discoveries at the LHC will be at high masses: large x and very high Q^2 which require high s, lumi of LHeC for precision PDFs (u,d,xg mainly)

If the Higgs exists, its study will become a major field of research:
ep: WW→ H → bbar (CP odd/even?)

top distribution in the proton TDF

IF RP is violated and LQ or RPV SUSY discovered: LHeC is uniquely suited

AA: QGP: study initial state in eA
Resolve parton distributions in nuclei

LHeC is unique in various areas, e.g.:
Low x and saturation physics
Strong coupling constant to 0.1% level

CDR

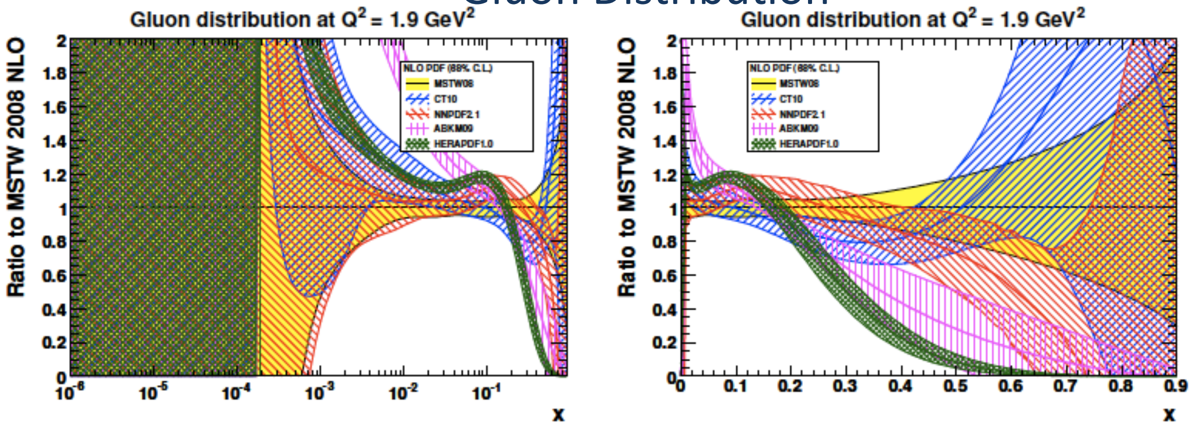
153 pages

II Physics

now

then

Gluon Distribution



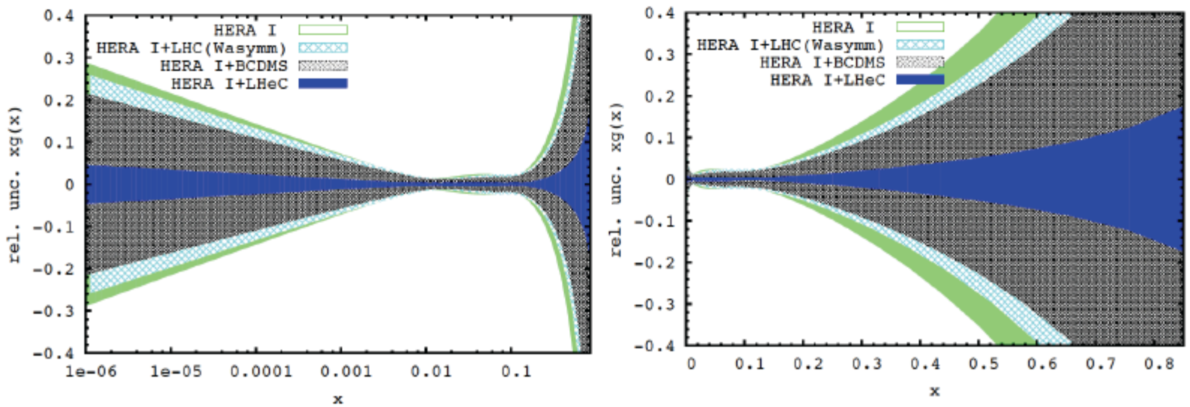


Figure 4.17: Relative uncertainty of the gluon distribution at $Q^2 = 1.9\,\mathrm{GeV}^2$, as resulting from an NLO QCD fit to HERA (I) alone (green, outer), HERA and BCDMS (crossed), HERA and LHC (light blue, crossed) and the LHeC added (blue, dark). Left: logarithmic x, right: linear x.

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?

Strong Coupling Constant

α_s least known of coupling constants

Grand Unification predictions suffer from $\delta\alpha_s$

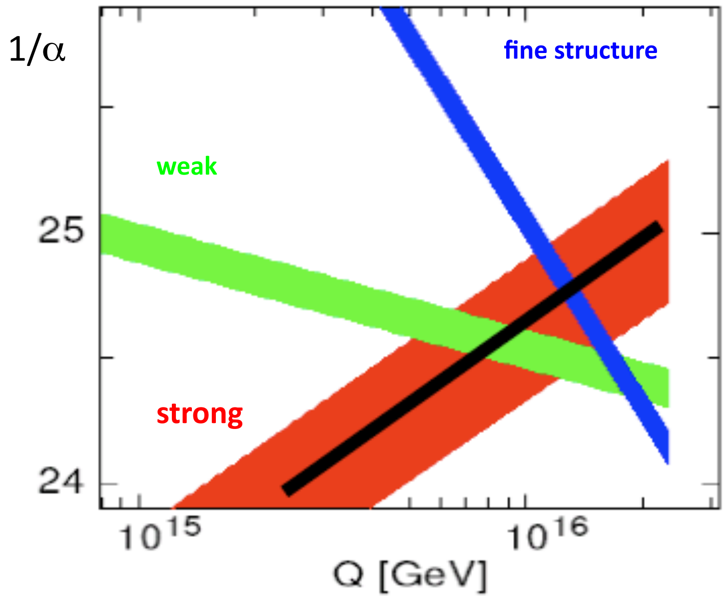
DIS tends to be lower than world average

Recently challenged by MSTW and NNPDF – jets??

LHeC: per mille accuracy - independent of BCDMS.

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

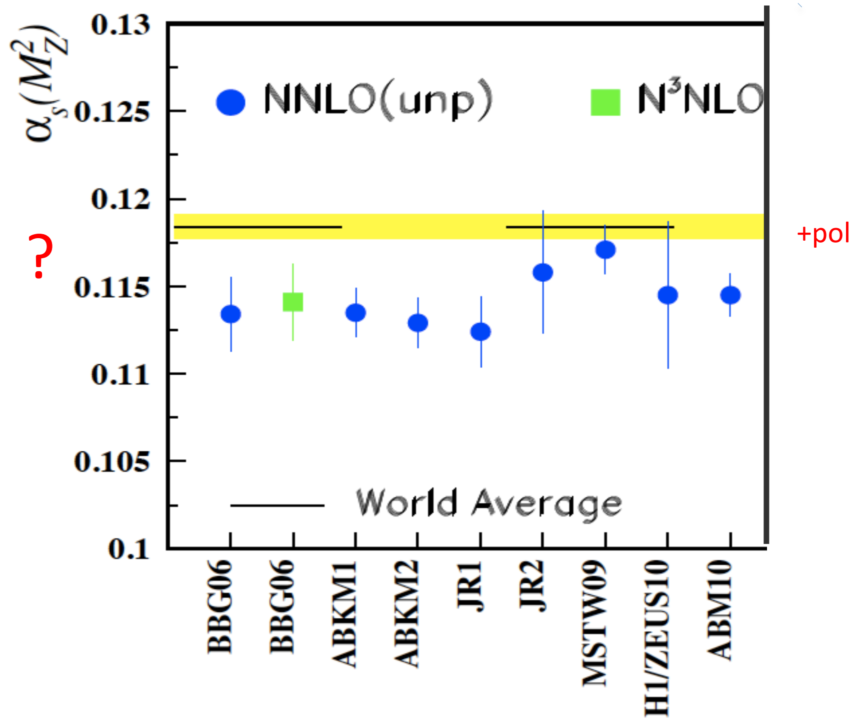
Simulation of α_s measurement at LHeC



MSSM - B.Allnach et al, hep-ex/0403133

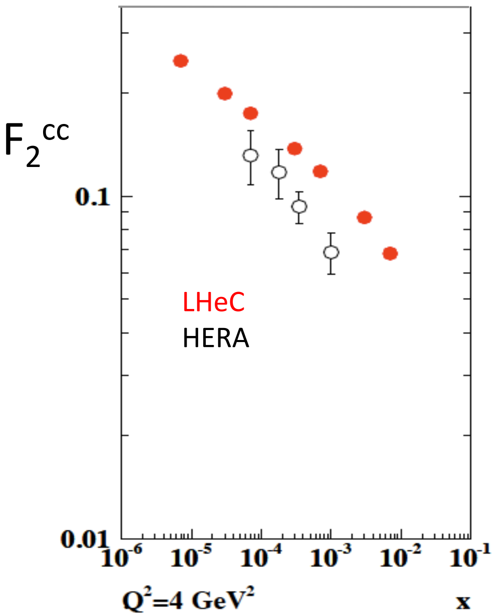
DATA	exp. error on α_s
NC e^+ only	0.48%
NC	0.41%
NC & CC	**0.23% :=(1)**
(1) $\gamma_h > 5°$	0.36% :=(2)
(1) +BCDMS	0.22%
(2) +BCDMS	0.22%
(1) stat. *= 2	0.35%

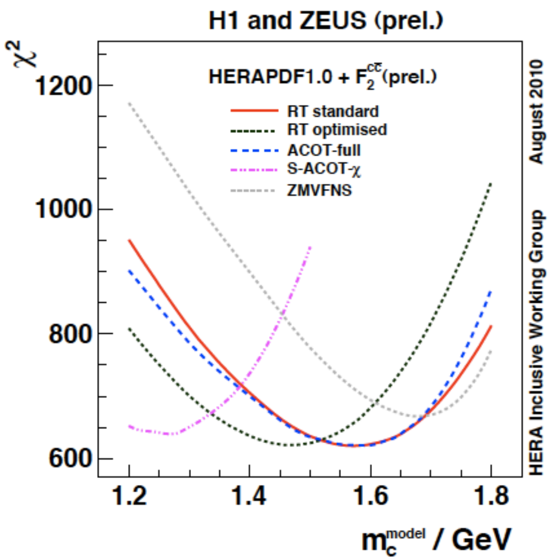
Two independent analyses performed

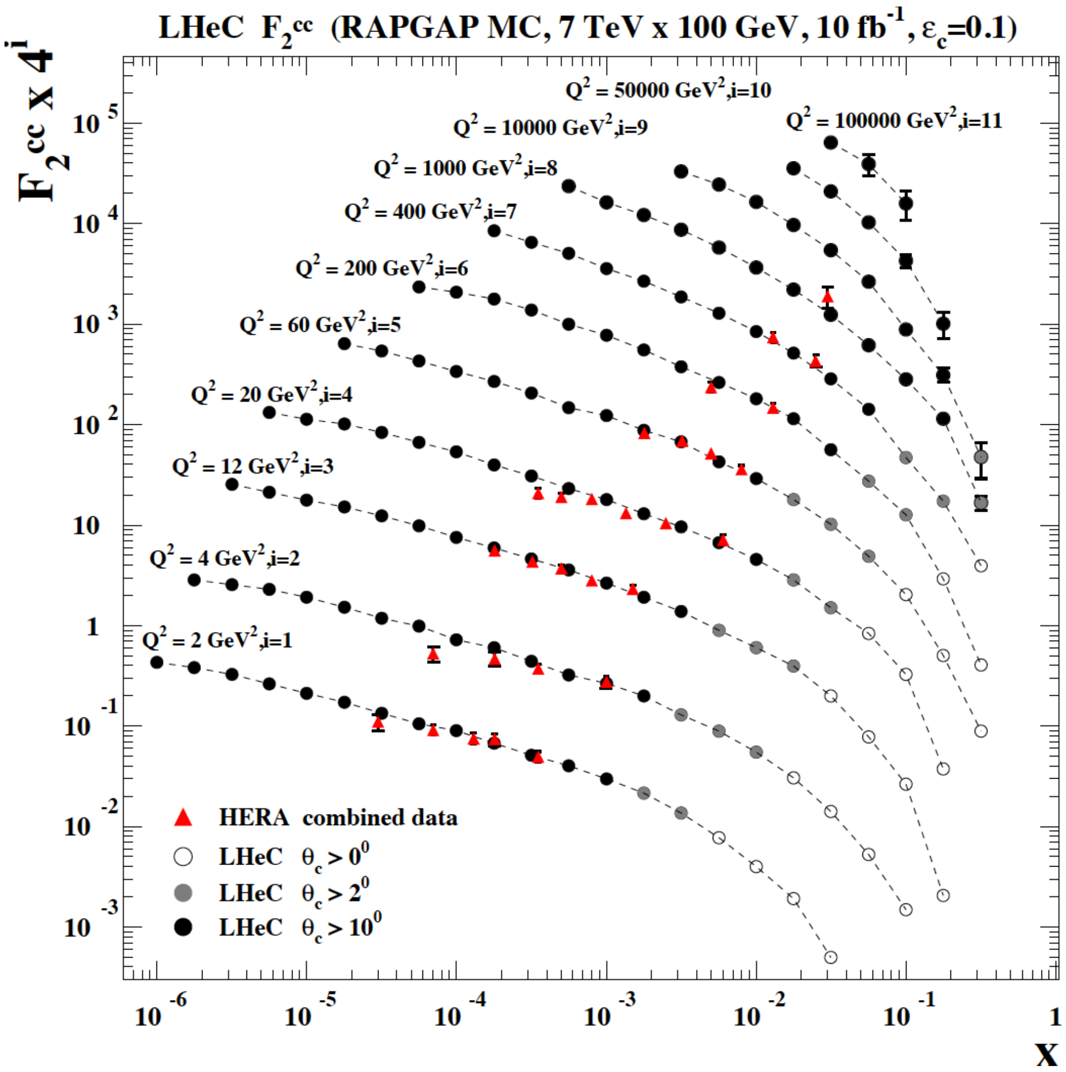


J.Bluemlein and H. Boettcher, arXiv 1005.3013 (2010)

Treatment of charm influences α_s





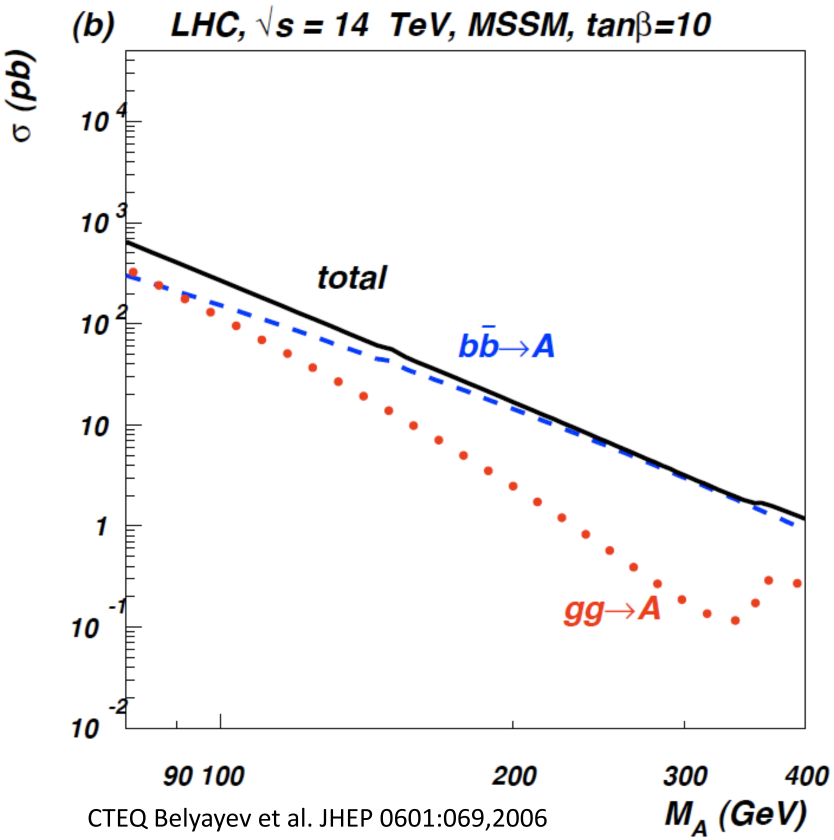


LHeC vs HERA: higher fraction of c, larger range, smaller beam spot, better Silicon detectors

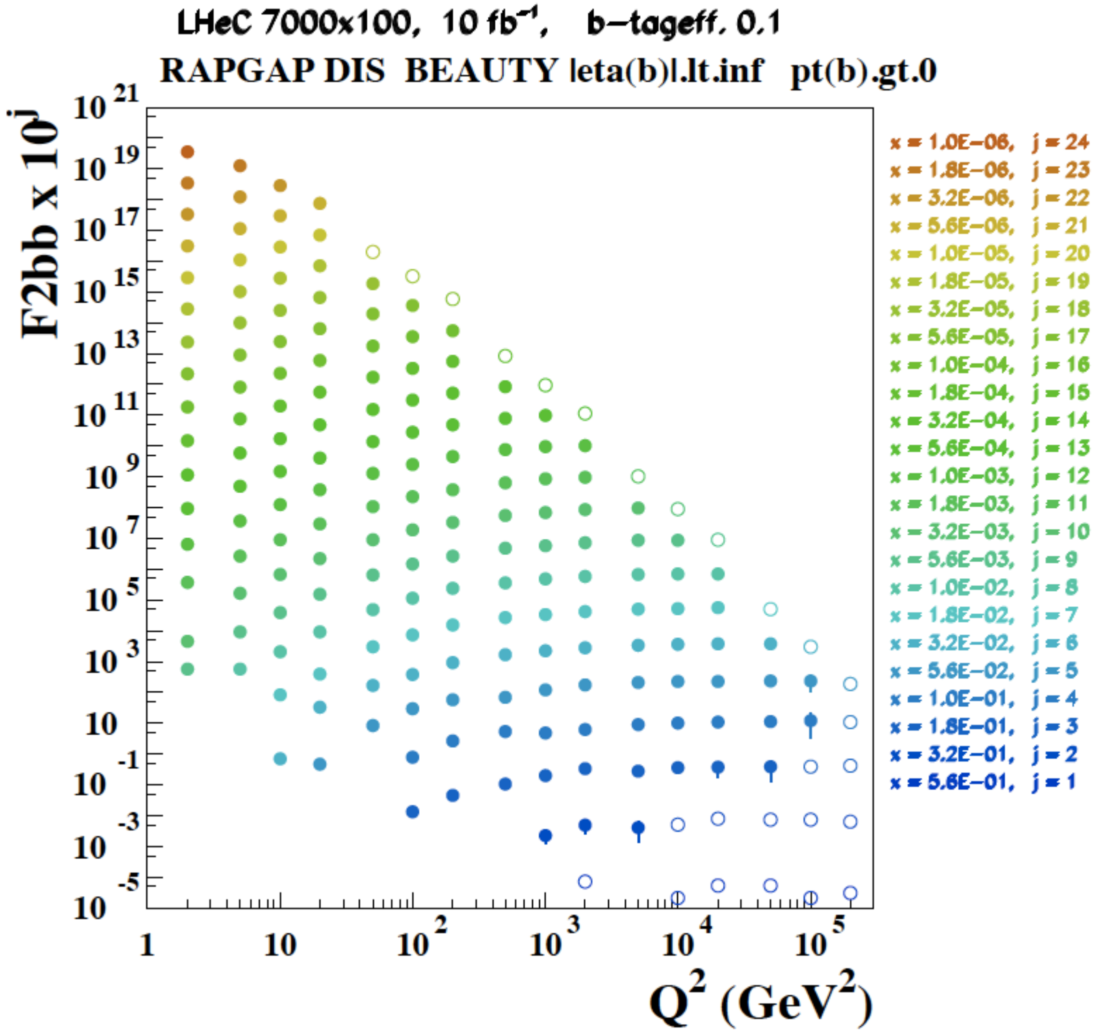
note: 100 MeV of m_c is about 1% on α_s

CDR

Beauty - MSSM Higgs



CTEQ Belyayev et al. JHEP 0601:069,2006

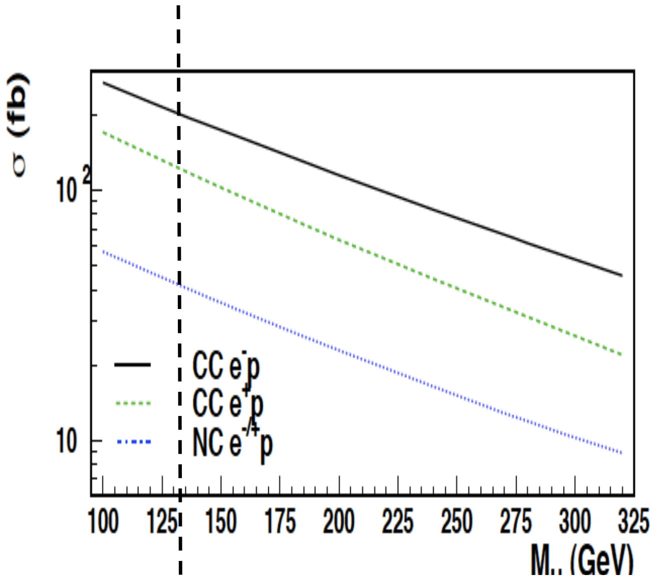


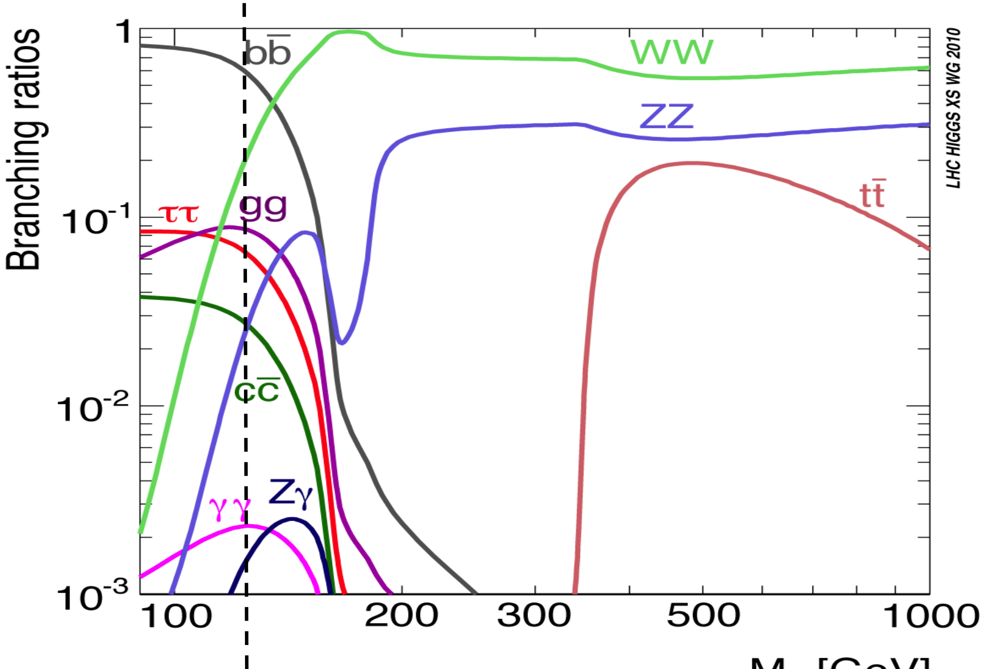
In MSSM Higgs production is b dominated

HERA: First measurements of b to ~20%
LHeC: precision measurement of b-df

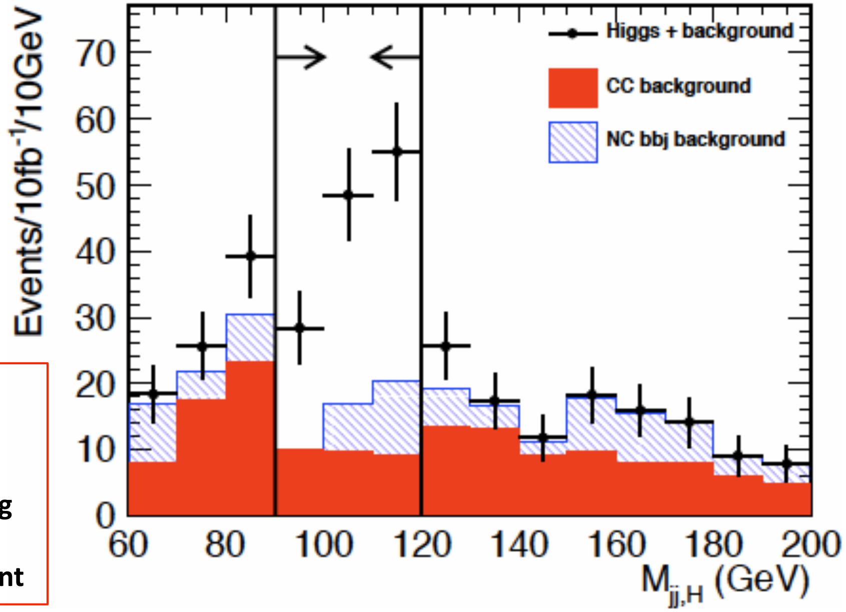
LHeC: higher fraction of b, larger range, smaller beam spot, better Si detectors

Higgs

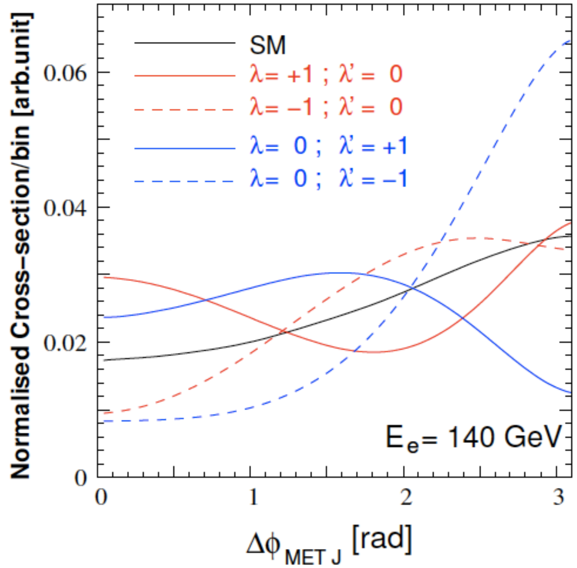




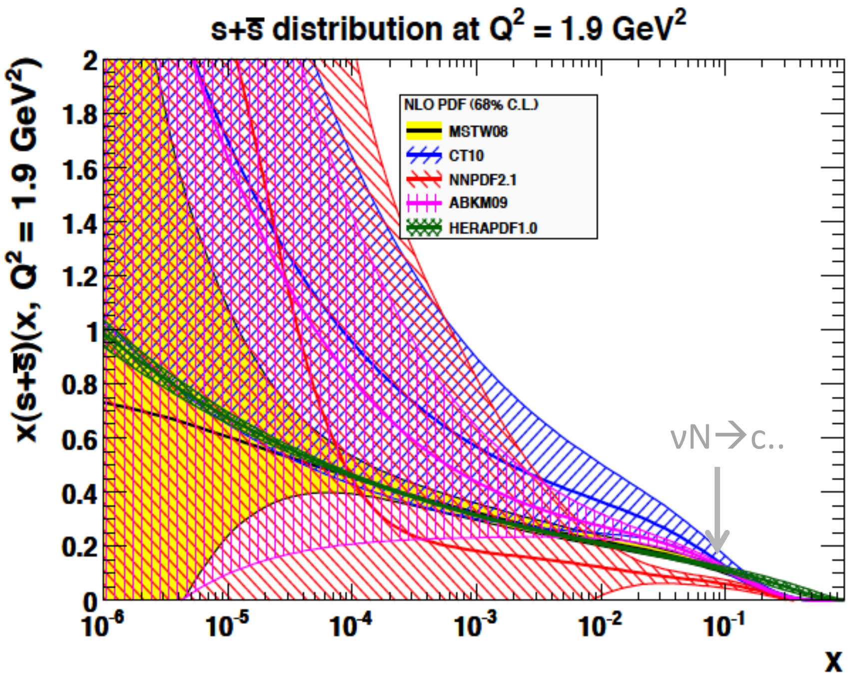
Process determines much of detector acceptance and calibration and b tag (also single top) and L/E_e requirement

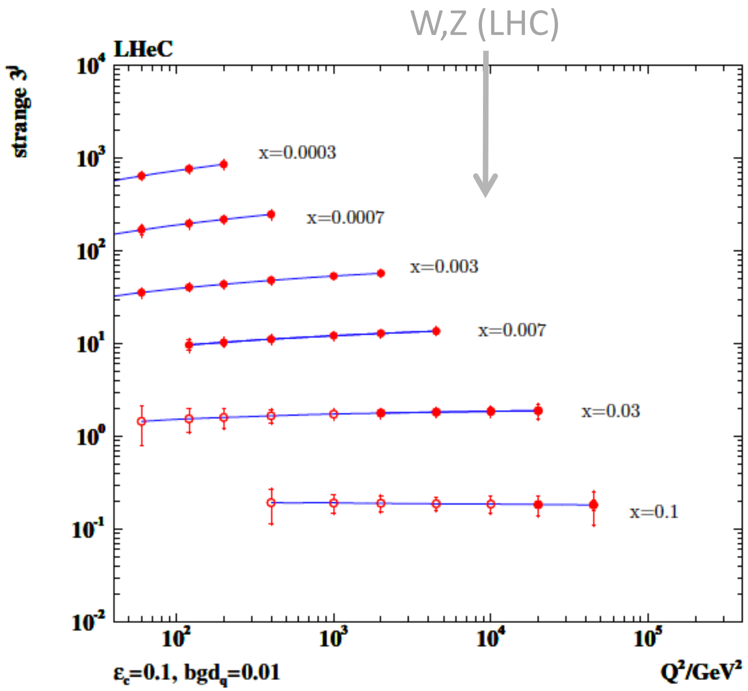


Higgs is light (or absent), CC: WW→H→bb
CP even: SM, CP odd: nonSM, mixture?



Strange and Valence Quarks



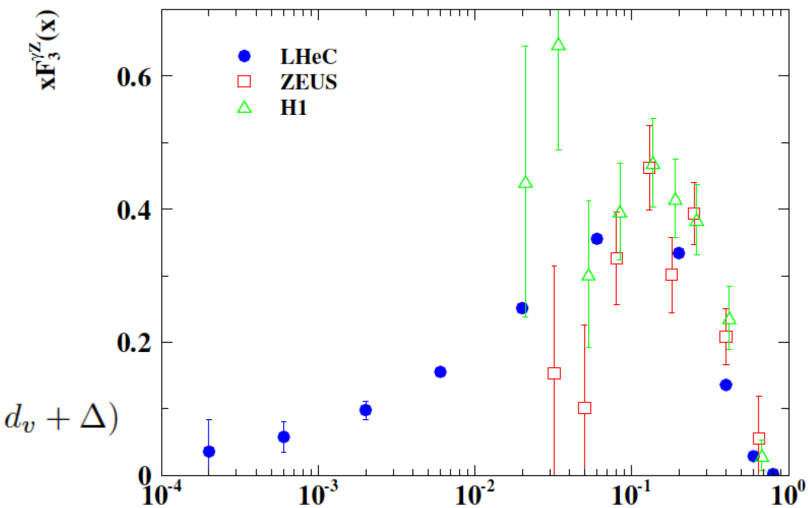


Strange quark density unknown
at low x and controversial at high x~0.1

Low x sea to be unfolded with LHeC
CC and ep and eD measurements
down to x=$10^{-4..6}$

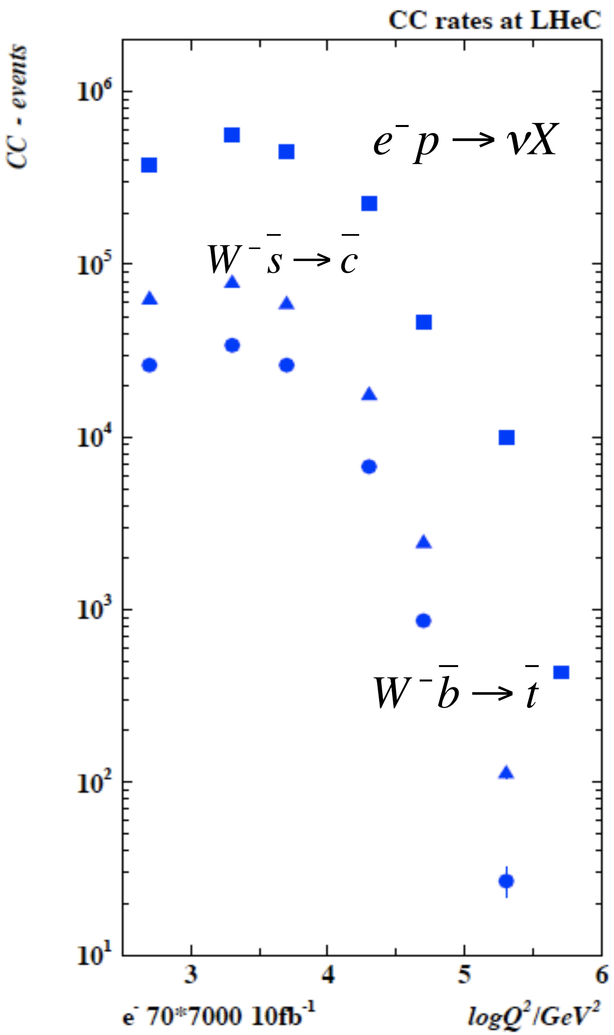
$$xF_3^{\gamma Z} = \frac{x}{3}(2u_v + d_v + \Delta)$$

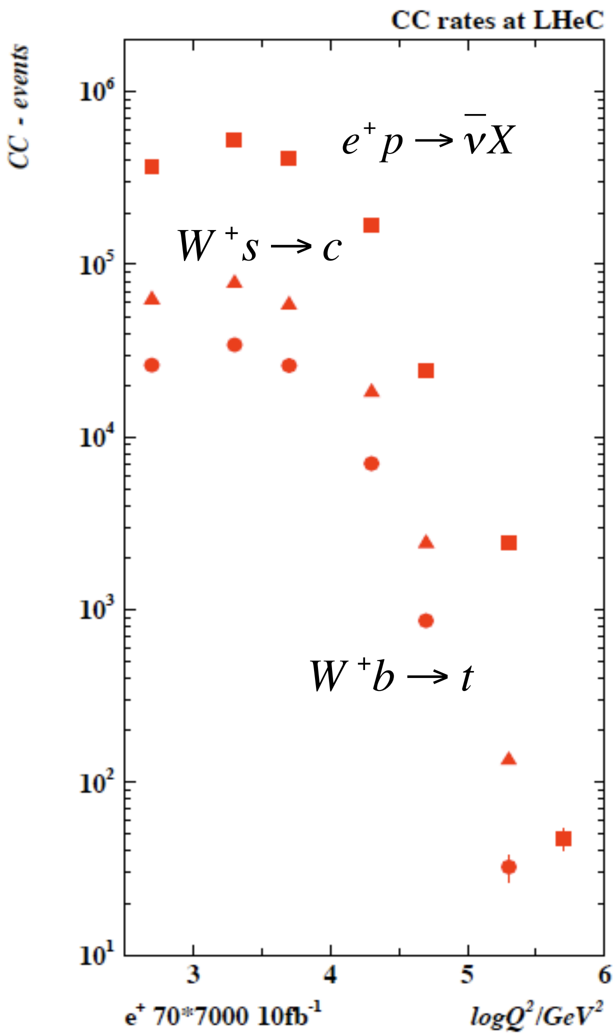
Sea Quarks=Antiquarks? Need u_v,d_v

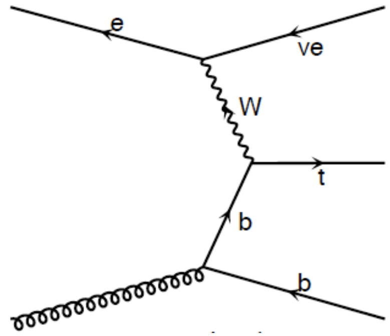


LHeC: much extended range and 100 * L (HERA)

$\overline{\text{Top}}$ and Top Production in Charged Currents







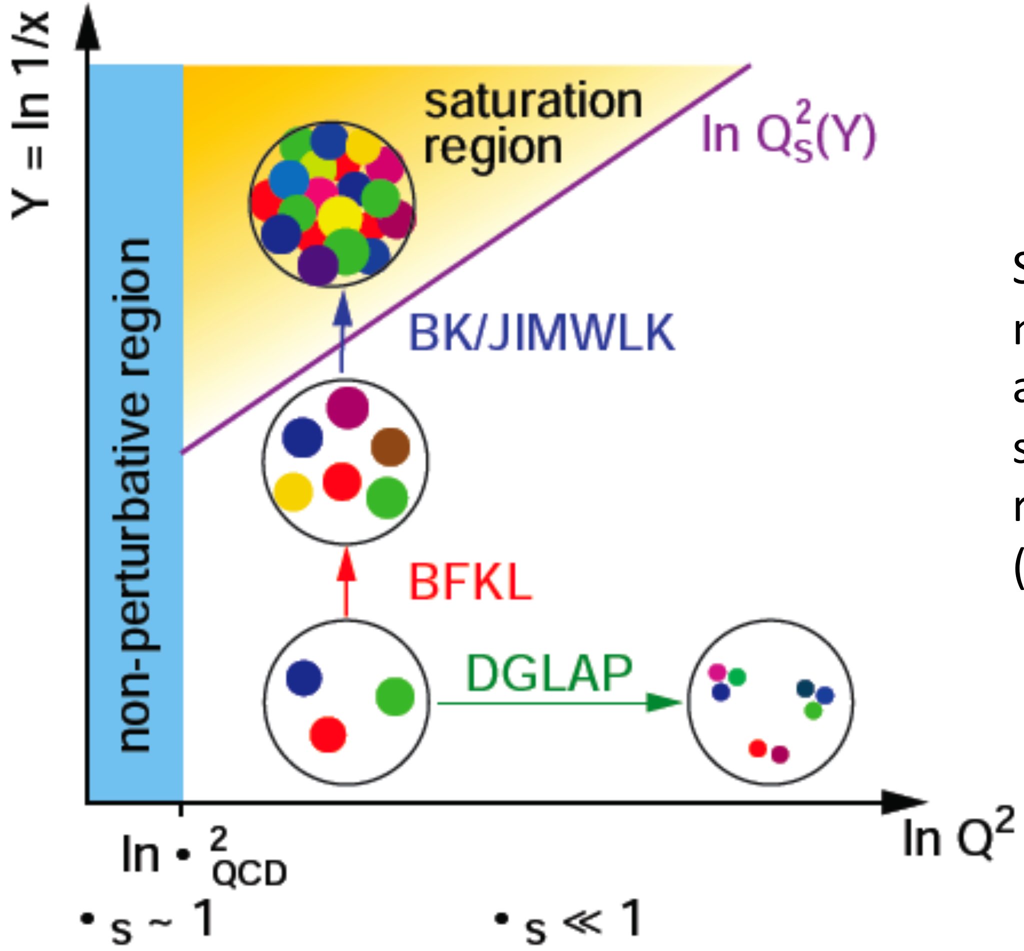
LHeC copious single top and anti-top quark production

with a CC cross section of O(10) pb

Study Q^2 evolution of top quark onset – 6 quark CFNS
(Pascaud at DIS11)

m_{top}
Not yet simulated..

High Parton Densities



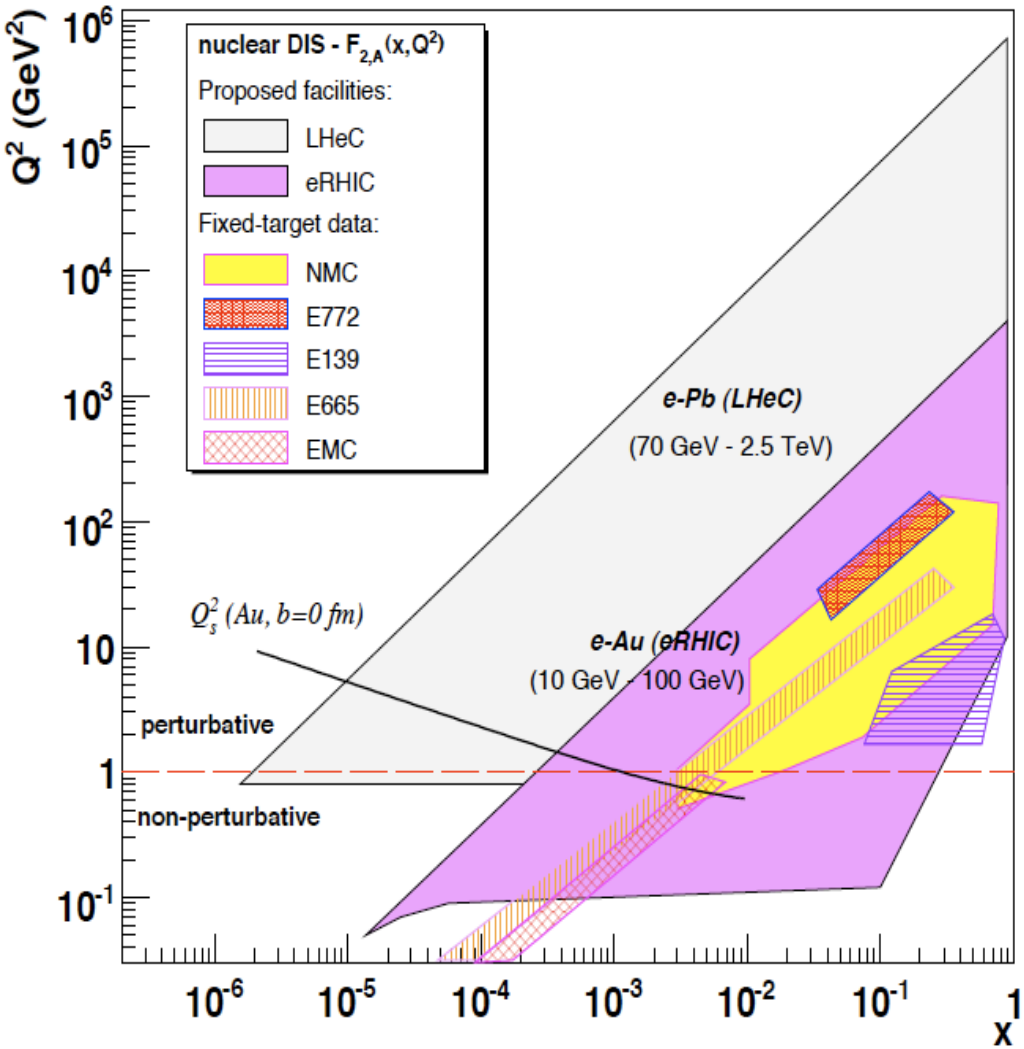
Should lead to
non-linear evolution
and eventually
saturation of
rise of cross section
(unitarity limit)

CDR $L_{eN} \cong 3 * 10^{31}$ $cm^{-2}s^{-1}$ for D,A - not optimised

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…

Electron-Ion Scattering



EIC programme:
see recent workshop arXiv:1108.1713 [nucl-th]

Dipole models predict **saturation** which resummation in pQCD moves to lower x..
It requires highest energy, low x, $Q^2 > M_p^2$

Saturation at the LHeC is predicted to be observed both in ep AND in eA.
This combination is crucial to disentangle nuclear from unitarity effects.

Expect **qualitative changes of behaviour**

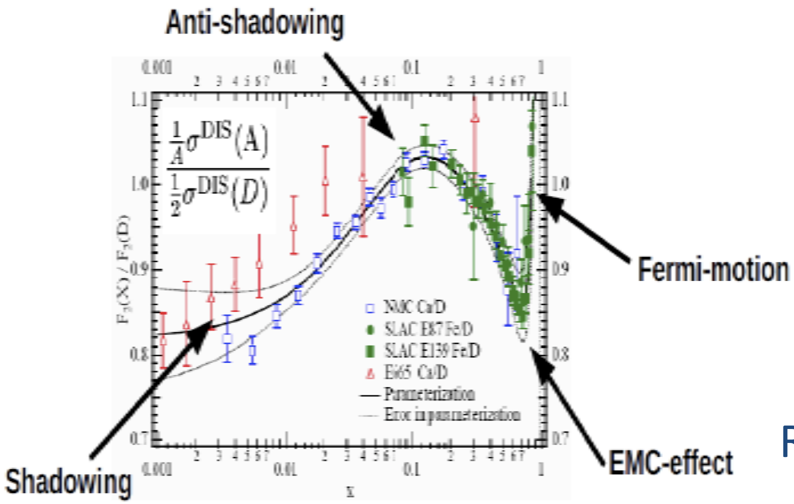
- Black body limit of F_2
- Saturation amplified with $A^{1/3}$
- Rise of diffraction to 50%? ….

Below x ~ 10^{-2}: DIS data end. NO flavour separation yet. However indications are that e.g. shadowing is flavour dependent.

Deuterons: tag spectator,
relate shadowing-diffraction (Gribov)!
stabilise QCD evolution (singlet!)

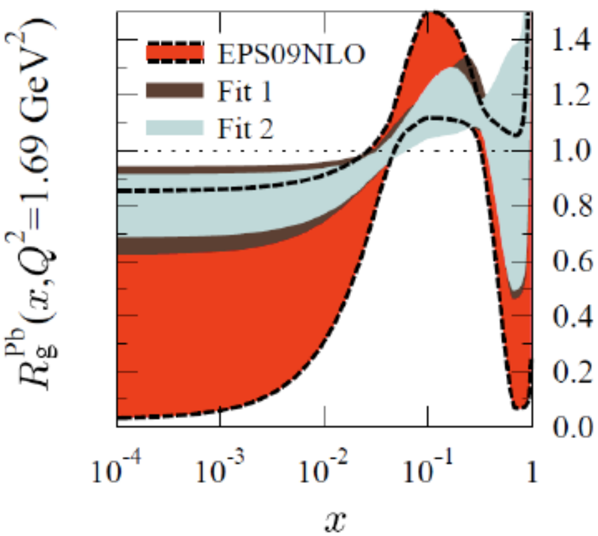
Neutron (light sea, UHE neutrinos, QPM)

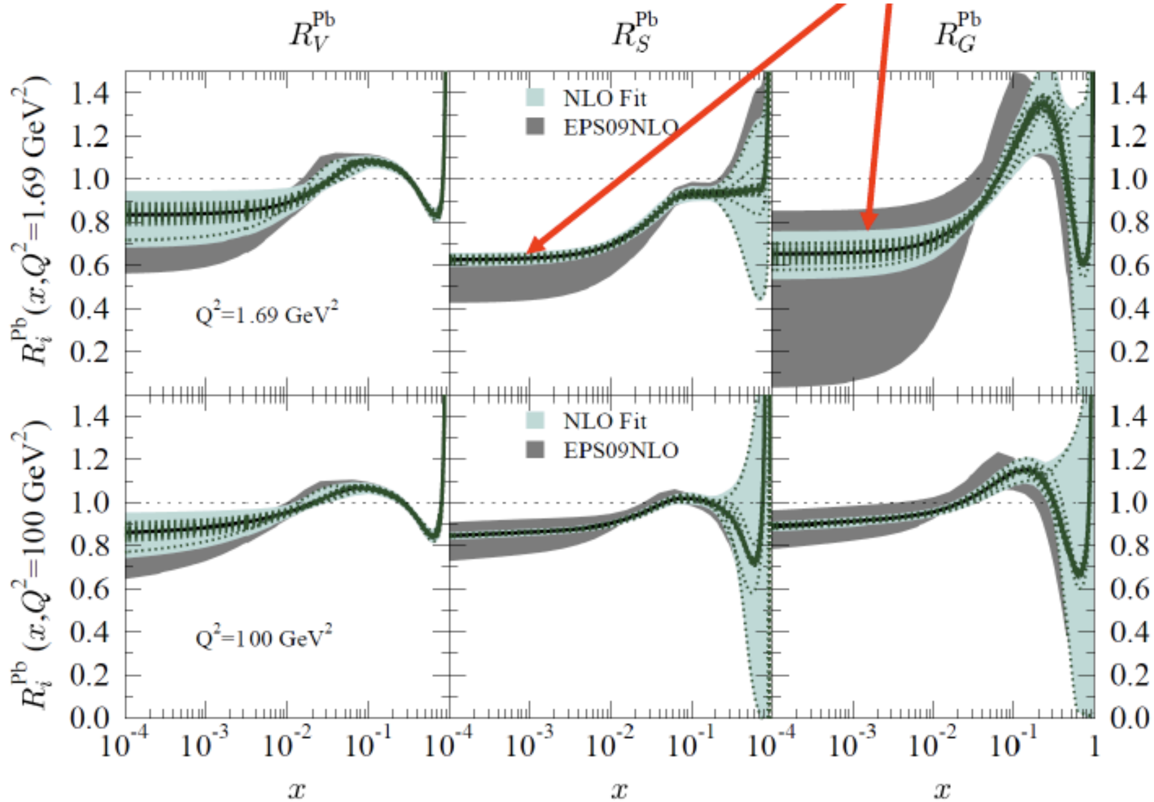
Nuclear Parton Distributions



Study using eA LHeC pseudodata

R=q^{Pb}/q^{p}





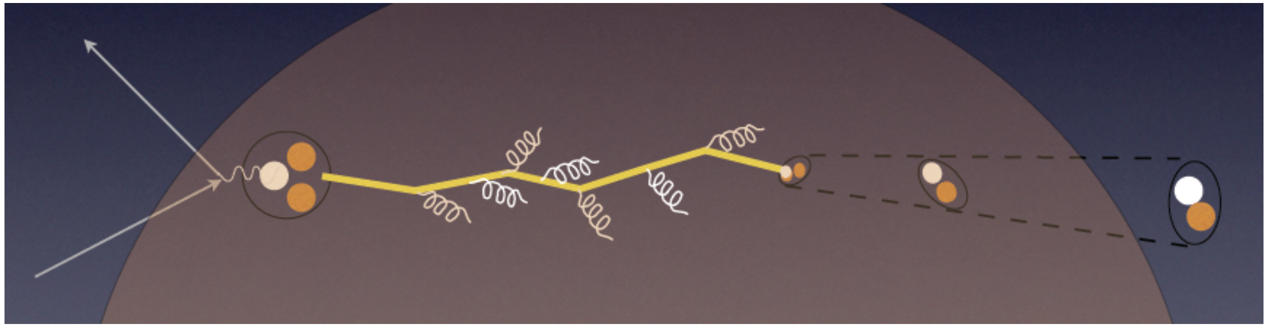
K.Eskola, H.Paukkunen, C.Salgado, Divonne09

→A complete determination of nPDFs in grossly extended range, into nonlinear regime certainly more diverse than in V,S,G terms and cleaner than pA at the LHC

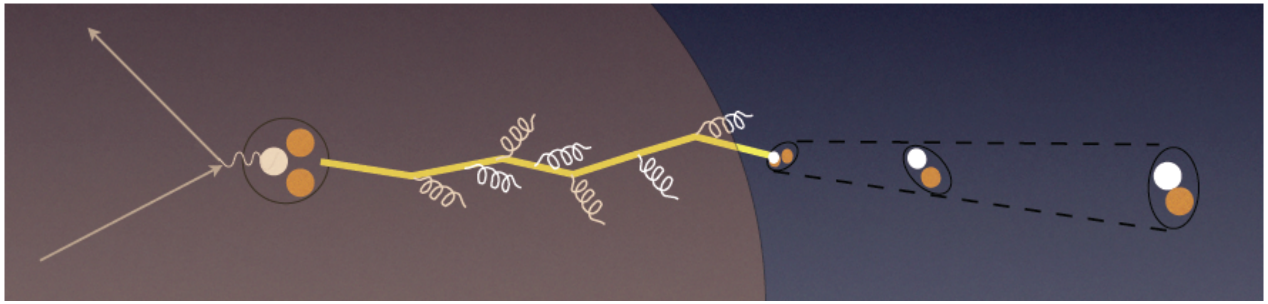
In-medium Hadronisation

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



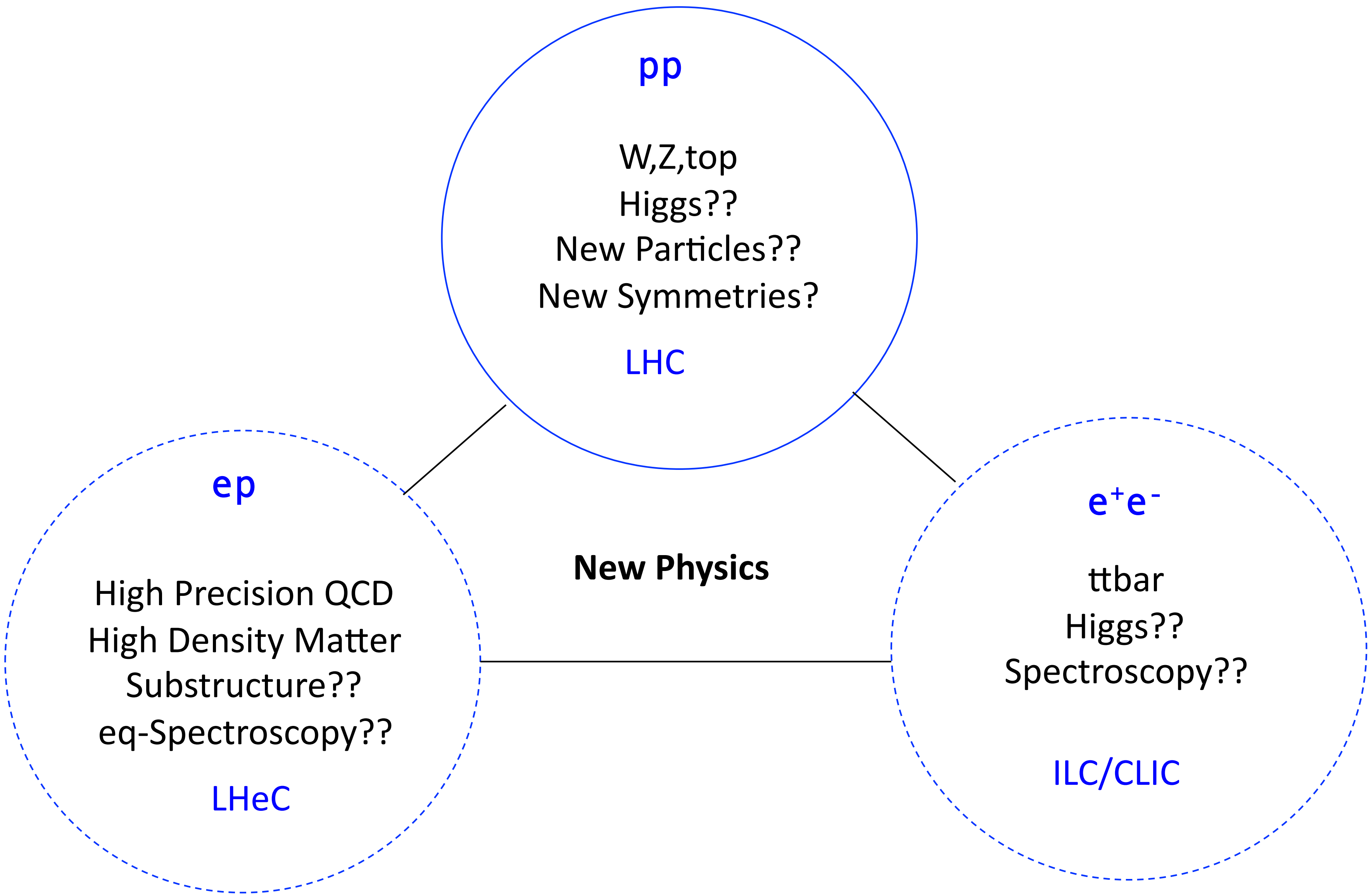
High energy (ν): partonic evolution altered in the nuclear medium.



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 ...

The TeV Scale [2010-2035..]



II. Accelerator and Detector

LHeC Accelerator Design: Participating Institutes

CERN

SLAC NATIONAL ACCELERATOR LABORATORY

NTNU
Norwegian University of Science and Technology

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

LAL Physique des accélérateurs

ECFA

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

UNIVERSITY OF LIVERPOOL

BROOKHAVEN NATIONAL LABORATORY

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

KEK

Electron Beam -Two Options

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

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

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

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

Ring-Ring

Power Limit of 100 MW wall plug

“ultimate” LHC proton beam

60 GeV e± beam

→L = 2 10^{33} $cm^{-2}s^{-1}$ → O(100) fb^{-1}

LINAC Ring

Pulsed, **60 GeV**: ~10^{32}

High luminosity:

Energy recovery: P=P_0/(1-η)

β*=0.1m

[5 times smaller than LHC by reduced l*, only one p squeezed and IR quads as for HL-LHC]

L = 10^{33} $cm^{-2}s^{-1}$ → O(100) fb^{-1}

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

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

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

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

Synchronous ep and pp operation (small ep tuneshifts)

The LHC p beams provide 100 times HERA’s luminosity

e Ring- p/A Ring

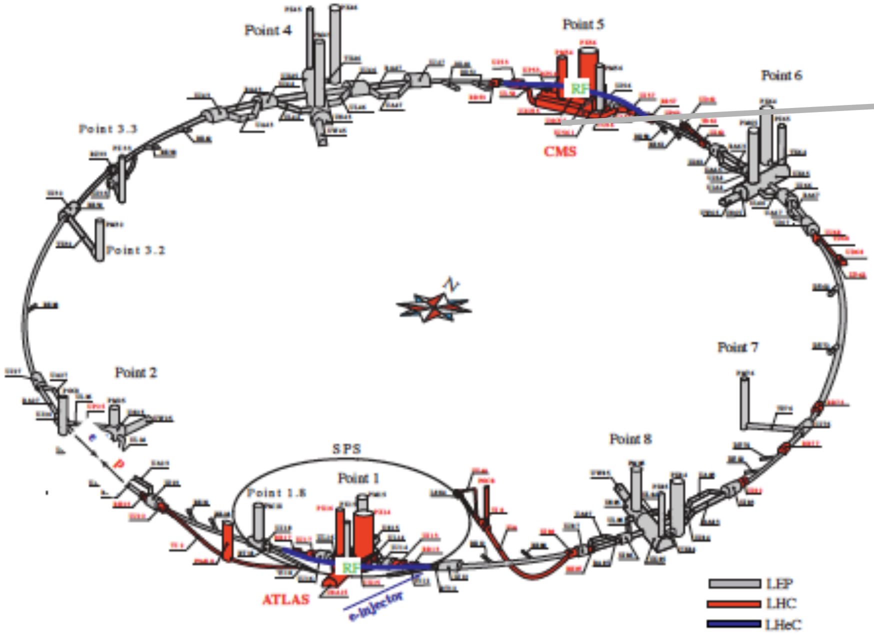
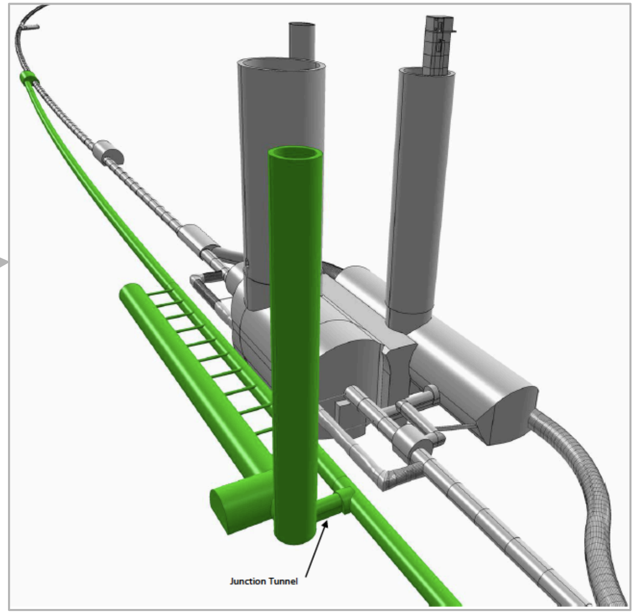
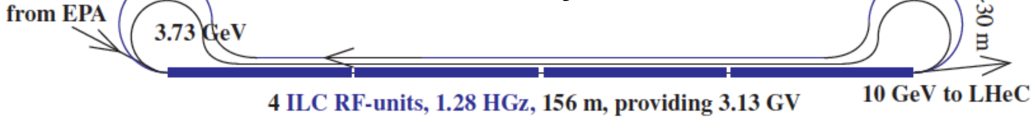
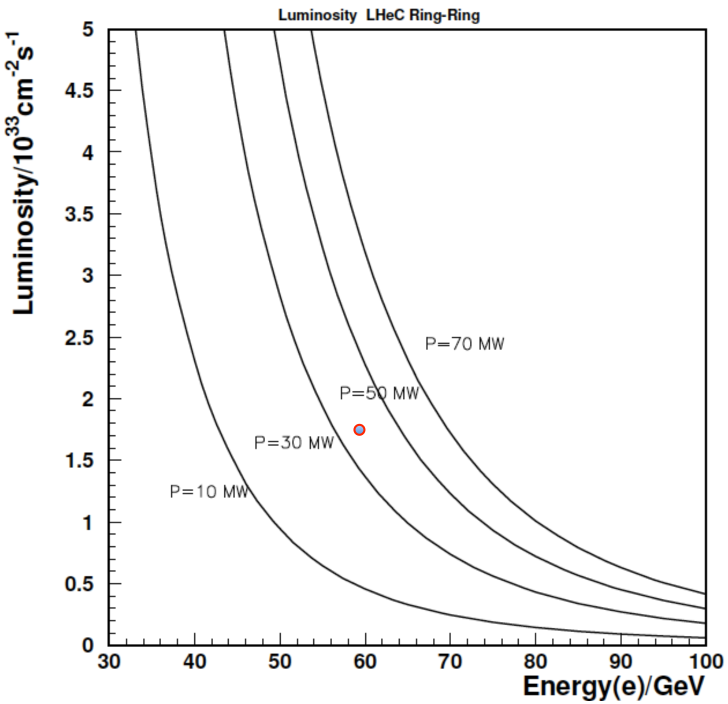


Figure 1: Schematic Layout of the LHC (grey/red) with the bypasses of CMS and ATLAS for the ring electron beam (blue) in the RR version. The e injector is a 10 GeV superconducting linac in triple racetrack configuration which is considered to reach the ring via the bypass around ATLAS.

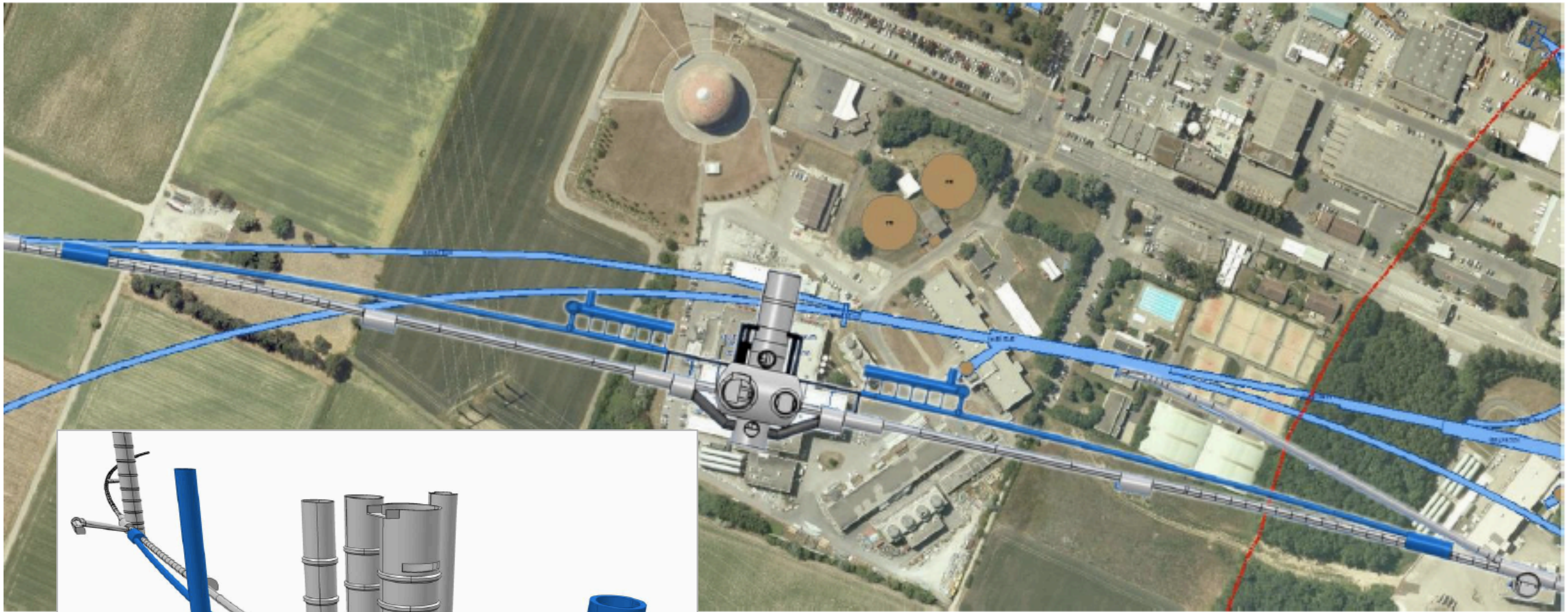


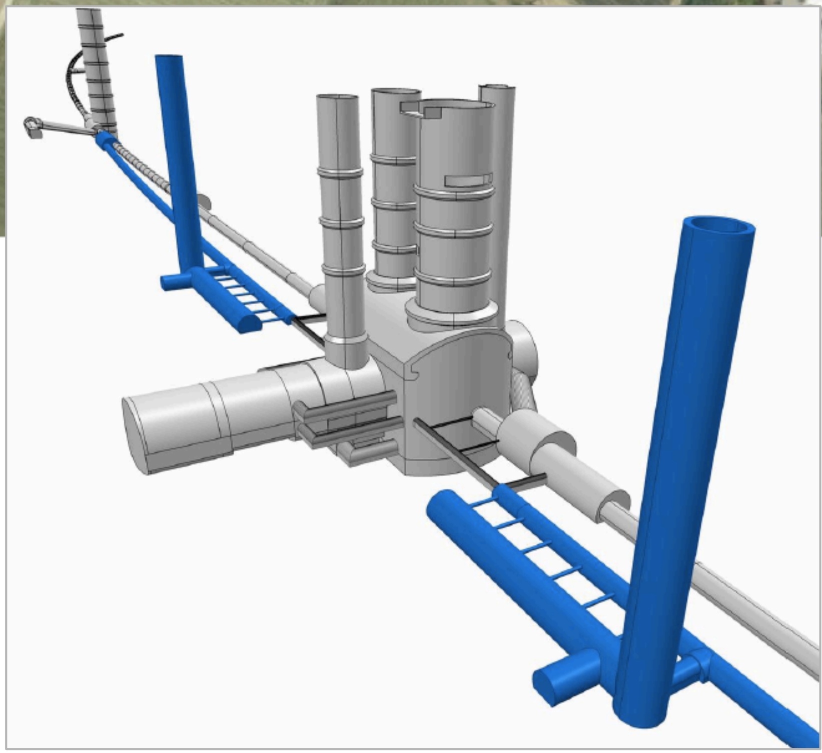
10 GeV injector





Bypassing ATLAS





For the CDR the bypass concepts were decided to be confined to ATLAS and CMS

Magnets

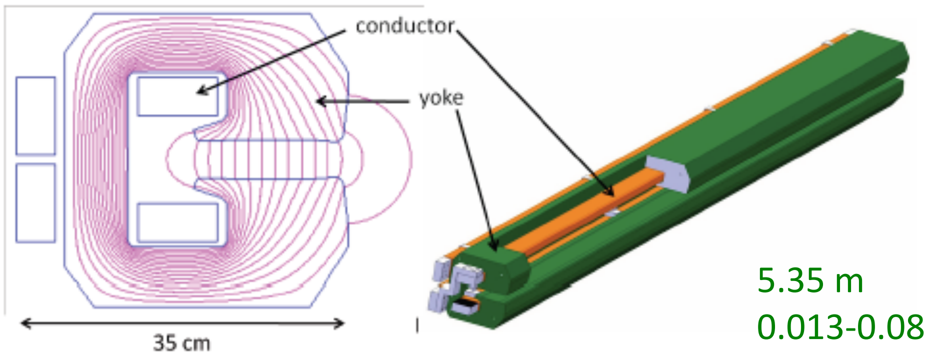
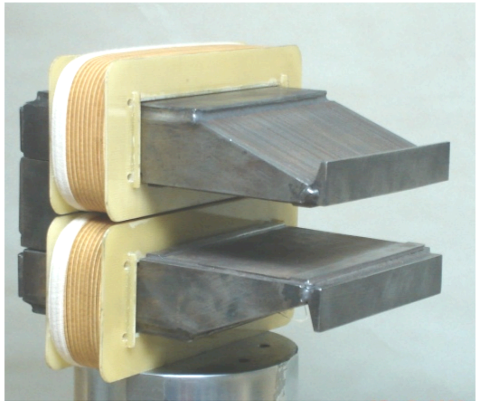


Fig. 2. Field lines and artistic view of a LHeC arc dipole.

5.35 m
0.013-0.08 T
~200kg/m



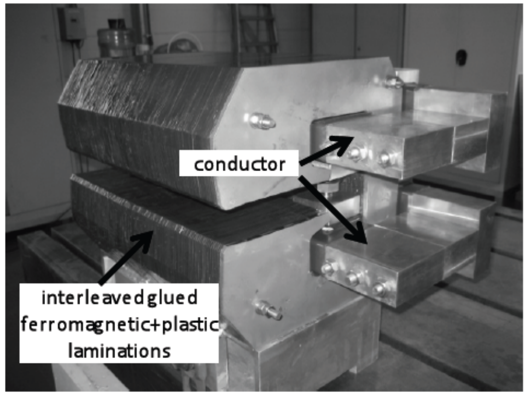
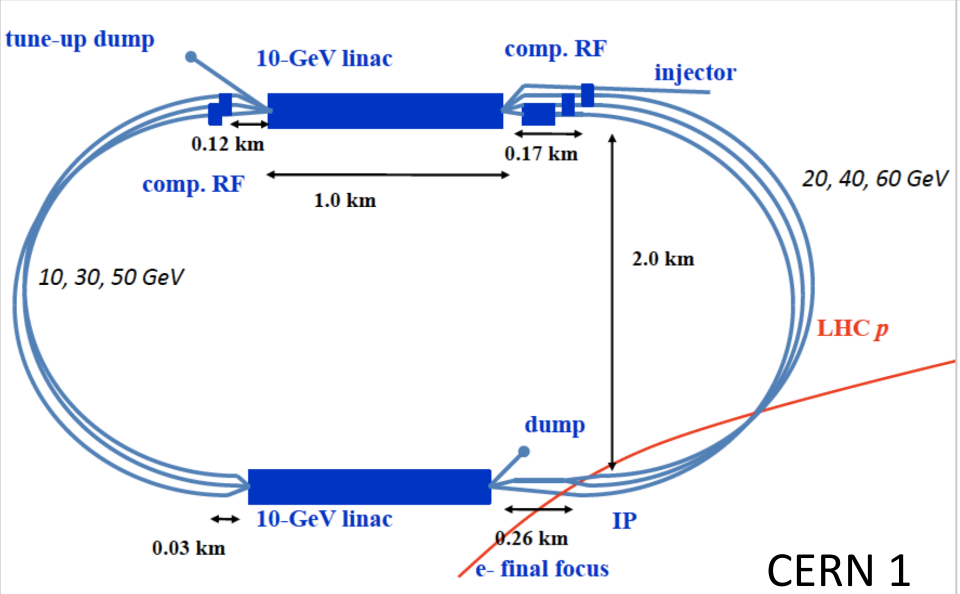


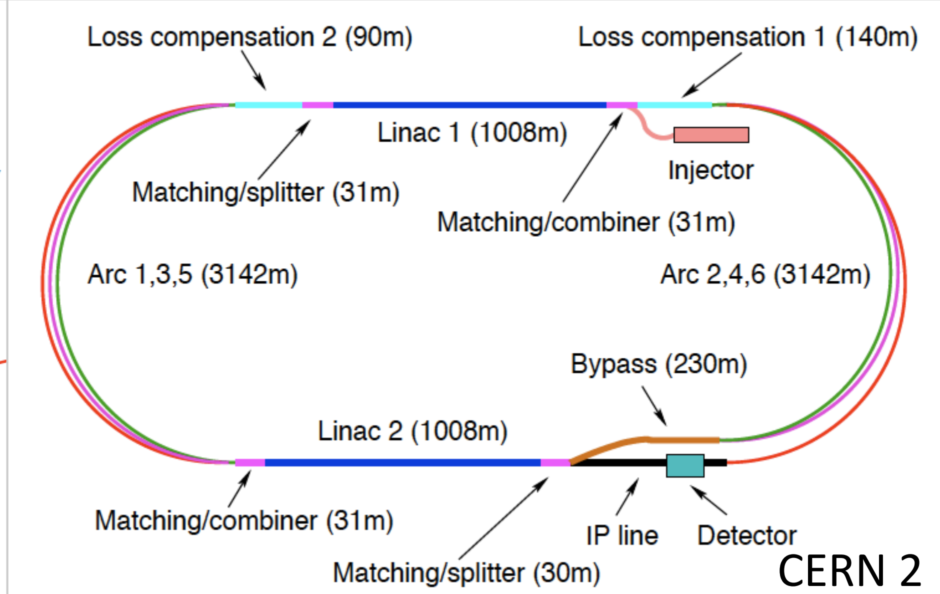
TABLE II REPRODUCIBILITY OF MAGNETIC FIELD OVER 8 CYCLES

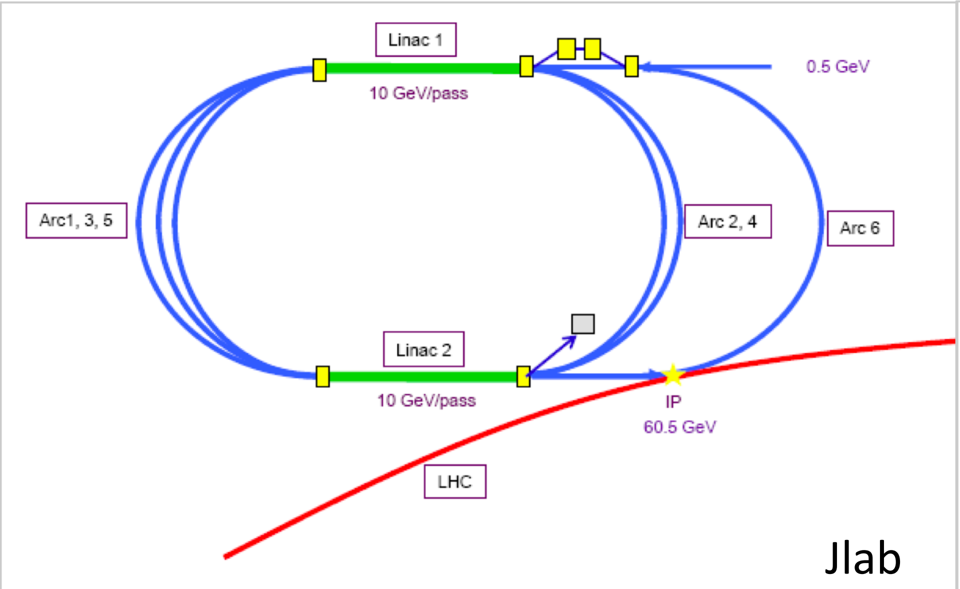
Model	Low field	High fields
Maximum Relative Deviation from Average		
Model 1 (NiFe steel)	$5\cdot10^{-5}$	$4\cdot10^{-5}$
Model 2 (Low carbon steel)	$6\cdot10^{-5}$	$6\cdot10^{-5}$
Model 3 (Grain oriented 3.5% Si steel)	$4\cdot10^{-5}$	$6\cdot10^{-5}$
Standard Deviation from Average		
Model 1 (NiFe steel)	$3\cdot10^{-5}$	$3\cdot10^{-5}$
Model 2 (Low carbon steel)	$4\cdot10^{-5}$	$5\cdot10^{-5}$
Model 3 (Grain oriented 3.5% Si steel)	$2\cdot10^{-5}$	$4\cdot10^{-5}$

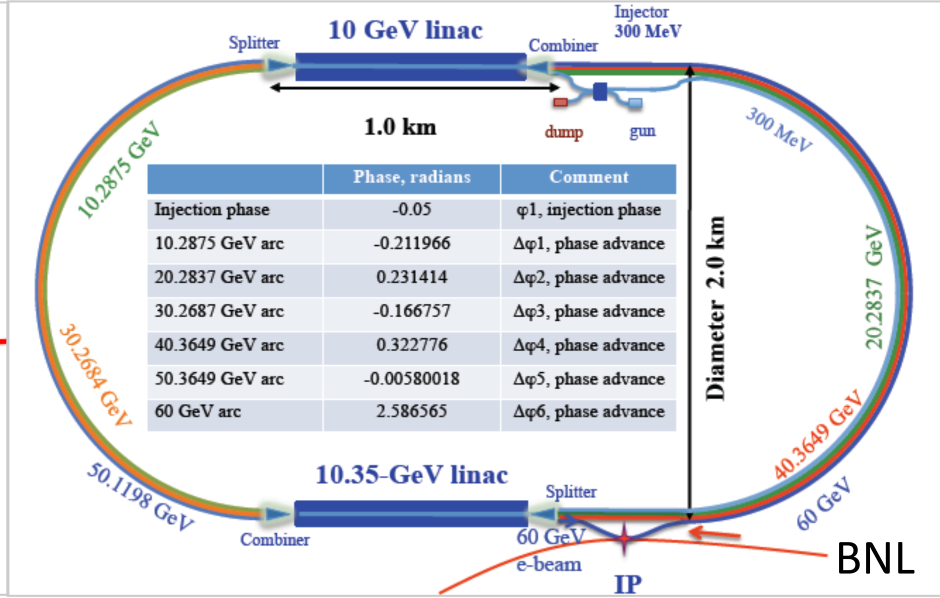
Prototypes from BINP and CERN: function to spec's

60 GeV Energy Recovery Linac







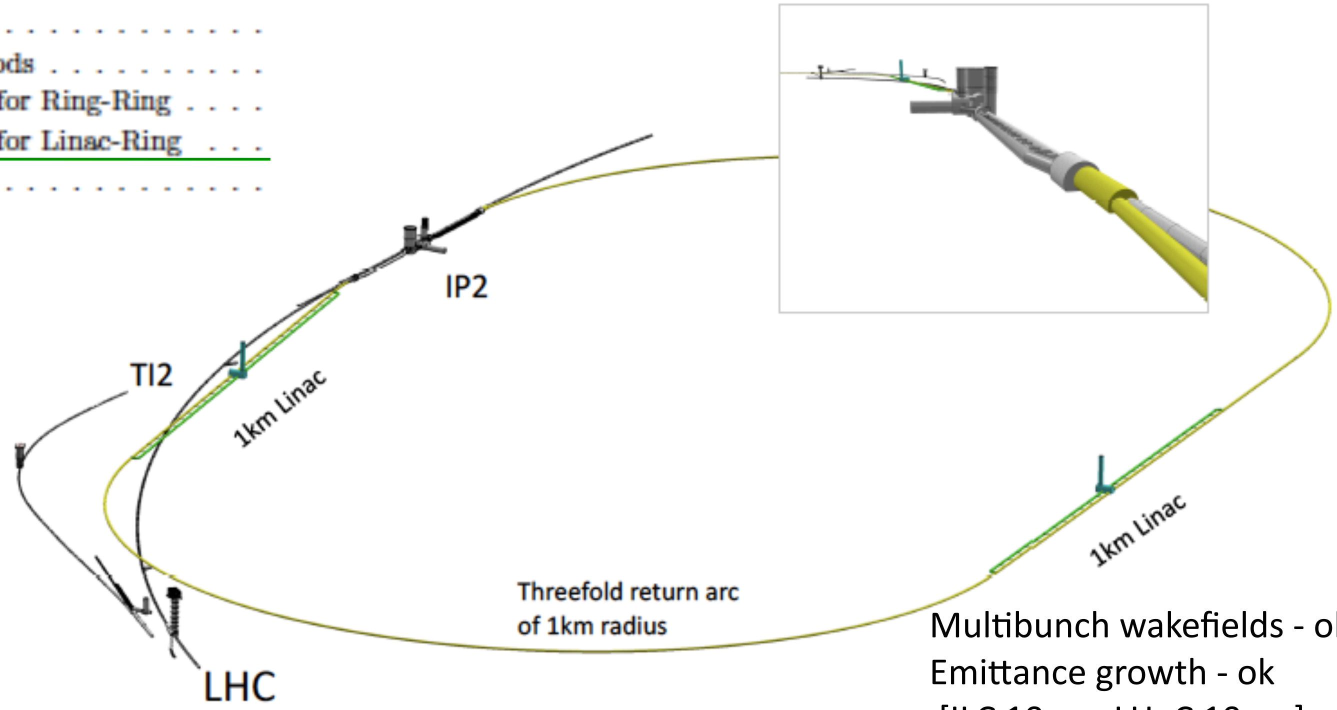


	Phase, radians	Comment
Injection phase	-0.05	φ1, injection phase
10.2875 GeV arc	-0.211966	Δφ1, phase advance
20.2837 GeV arc	0.231414	Δφ2, phase advance
30.2687 GeV arc	-0.166757	Δφ3, phase advance
40.3649 GeV arc	0.322776	Δφ4, phase advance
50.3649 GeV arc	-0.00580018	Δφ5, phase advance
60 GeV arc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

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

Linac Infrastructure

$U_{LHeC} = U_{LHC}/3$: 1.5 x HERA



944 cavities
59 cryo modules per linac
721 MHz
20 MV/m CW

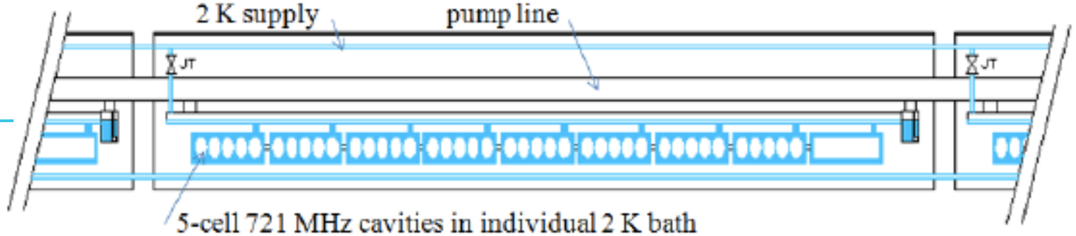
Multibunch wakefields - ok
Emittance growth - ok
[ILC 10nm, LHeC 10µm]
36σ separation at 3.5m - ok
Fast ion instability - probably ok
with clearing gap (1/3)

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.

Cryogenics

Table 2: Components of the Electron Accelerators

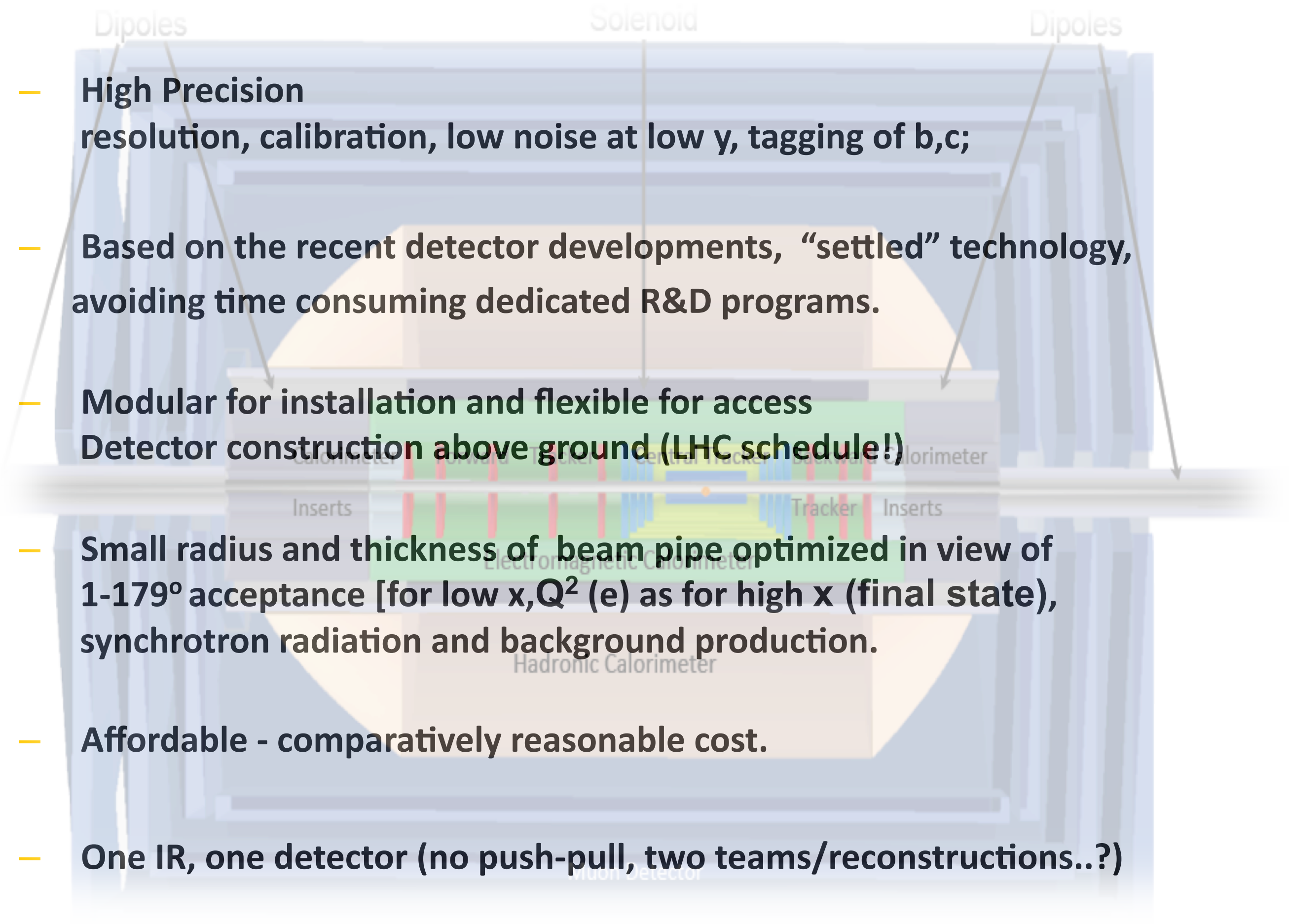
	Ring	Linac
magnets		
beam energy	60 GeV	
number of dipoles	3080	3600
dipole field [T]	0.013 – 0.076	0.046 – 0.264
total nr of quads	866	1588
RF and cryogenics		
number of cavities	112	944
gradient [MV/m]	11.9	20
RF power [MW]	49	39
cavity voltage [MV]	5	21.2
cavity R/Q [Ω]	114	285
cavity Q_0	–	$2.5\ 10^{10}$
cooling power [kW]	5.4@4.2 K	30@2 K



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.

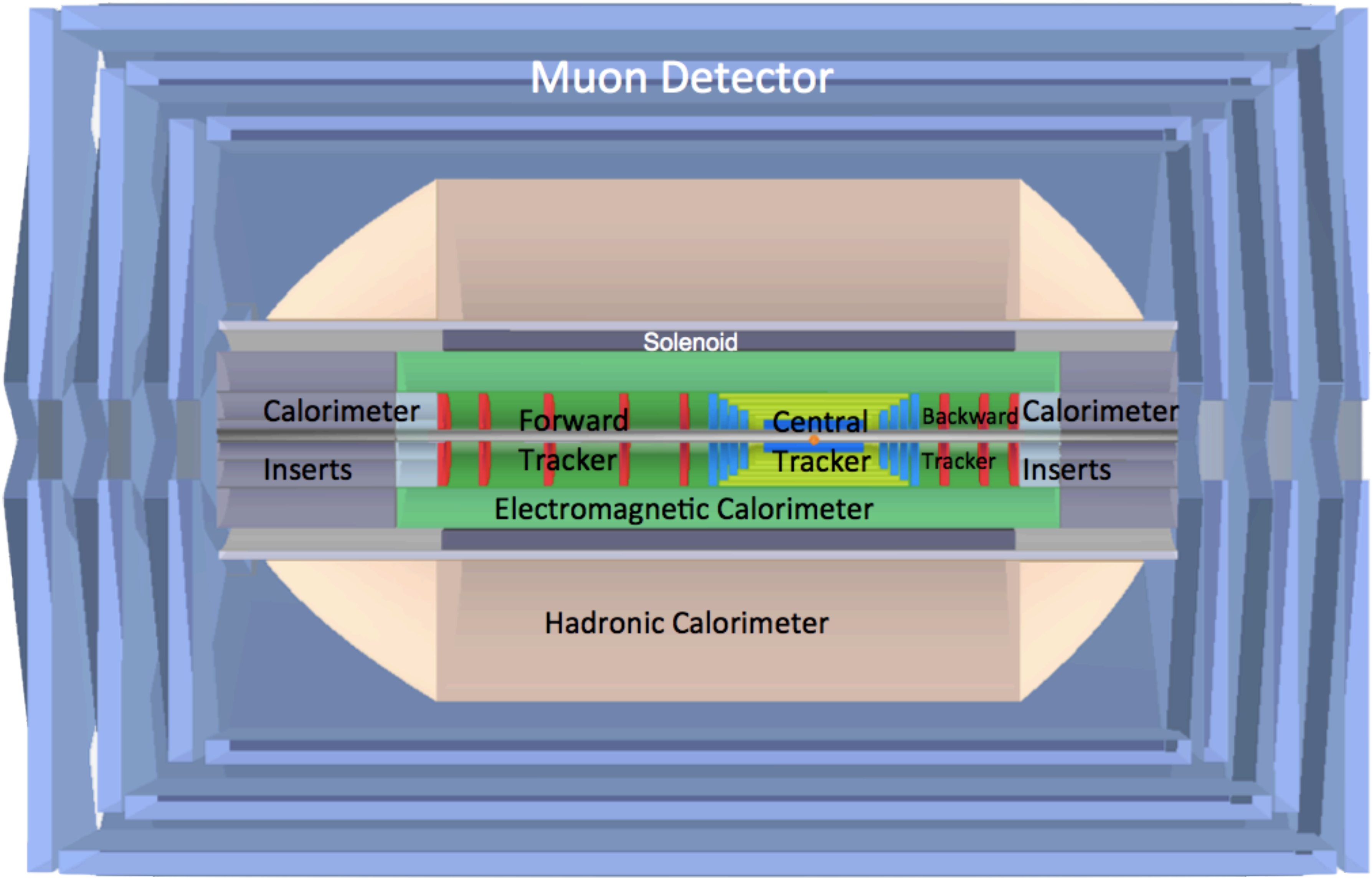
from CDR LHeC

Detector Requirements



- **High Precision**
  resolution, calibration, low noise at low y, tagging of b,c;
- **Based on the recent detector developments, "settled" technology, avoiding time consuming dedicated R&D programs.**
- **Modular for installation and flexible for access**
  Detector construction above ground (LHC schedule!)
- **Small radius and thickness of beam pipe optimized in view of 1-179° acceptance [for low x,Q^2 (e) as for high x (final state), synchrotron radiation and background production.**
- **Affordable - comparatively reasonable cost.**
- **One IR, one detector (no push-pull, two teams/reconstructions..?)**

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)

Detector Magnets

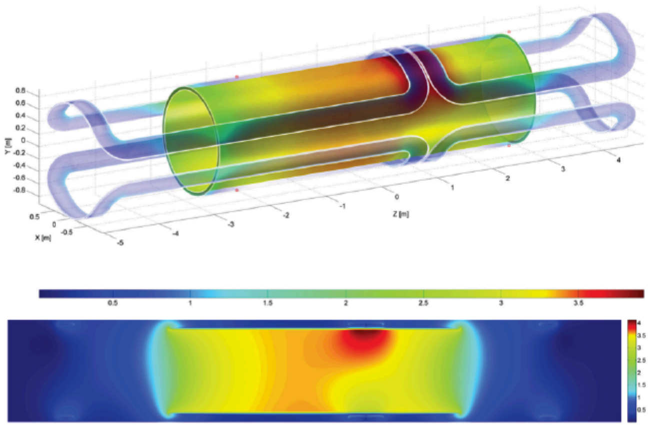


Figure 13.13: Magnetic field of the magnet system of solenoid and the two internal superconducting dipoles at nominal currents (effect of iron ignored). The position of the peak magnetic field of 3.9 T is local due to the adjacent current return heads on top of the solenoid where all magnetic fields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

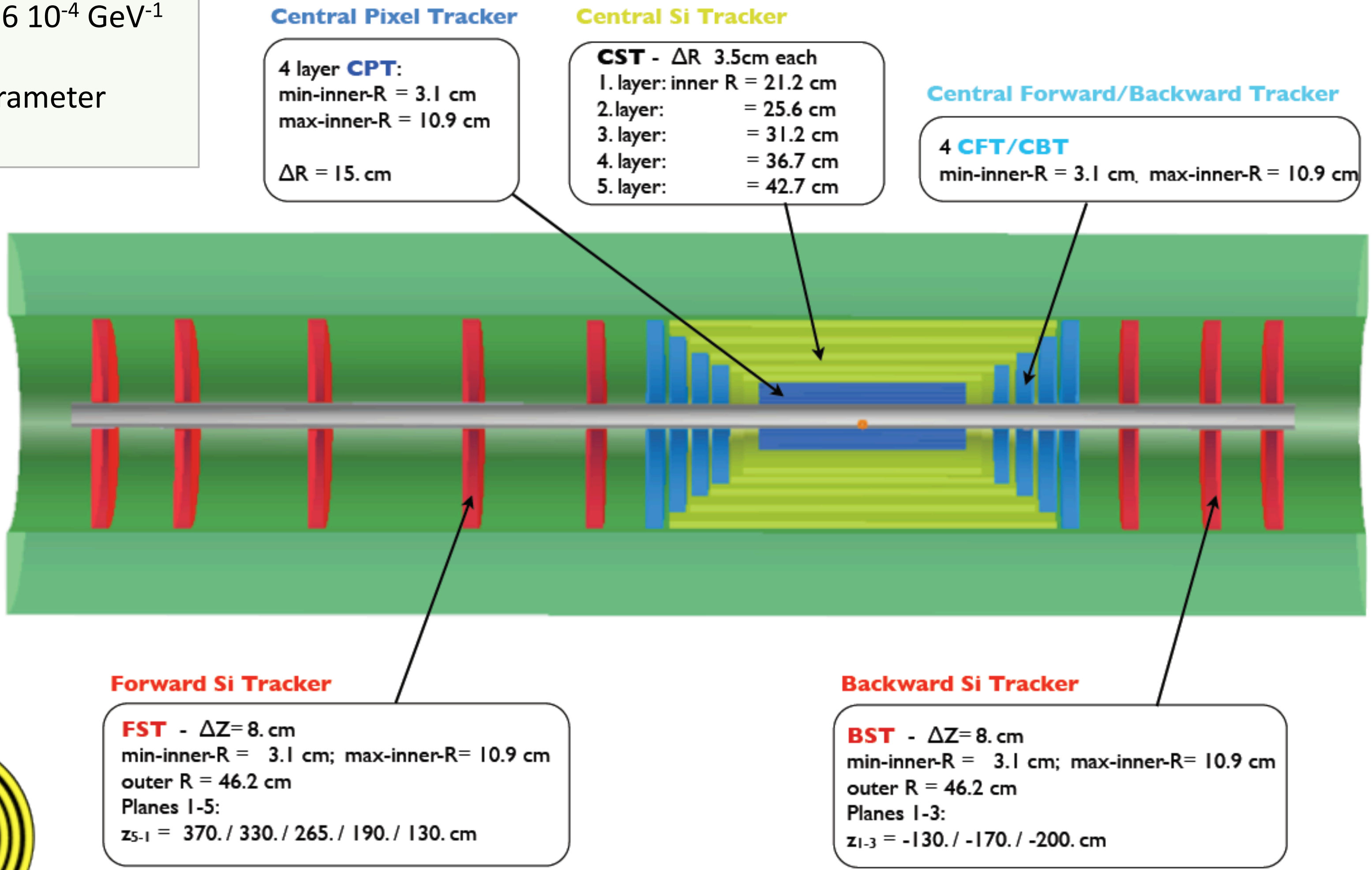
Based on ATLAS+CMS experience

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.

Silicon Tracker and EM Calorimeter

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



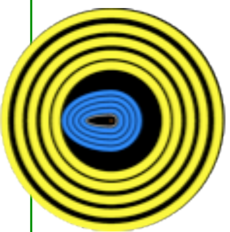


Figure 13.18: Tracker and barrel Electromagnetic-Calorimeter rz view of the baseline detector (Linac-Ring case).

Liquid Argon Electromagnetic Calorimeter

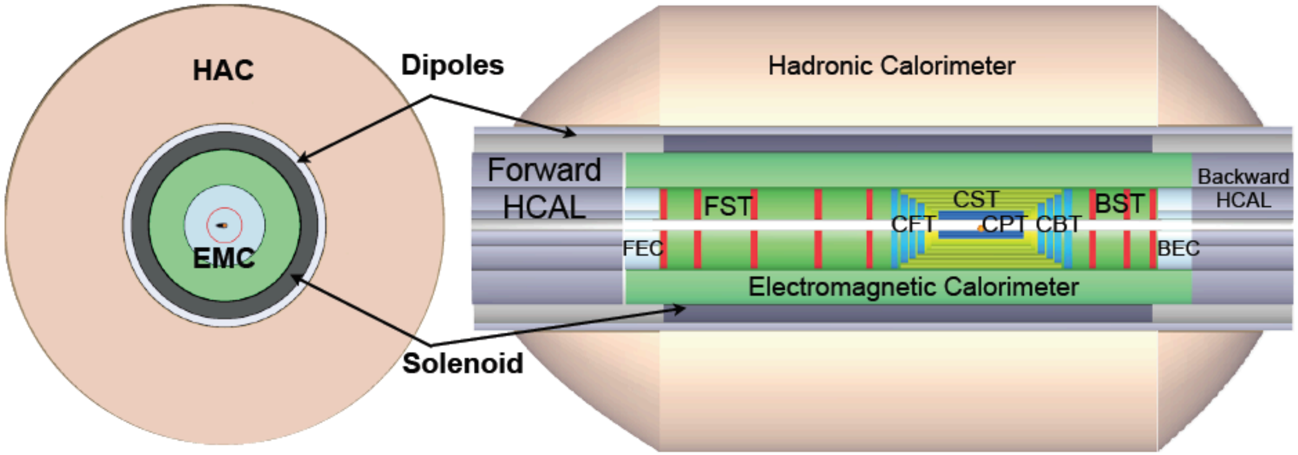


Figure 13.30: x-y and r-z view of the LHeC Barrel EM calorimeter (green).

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

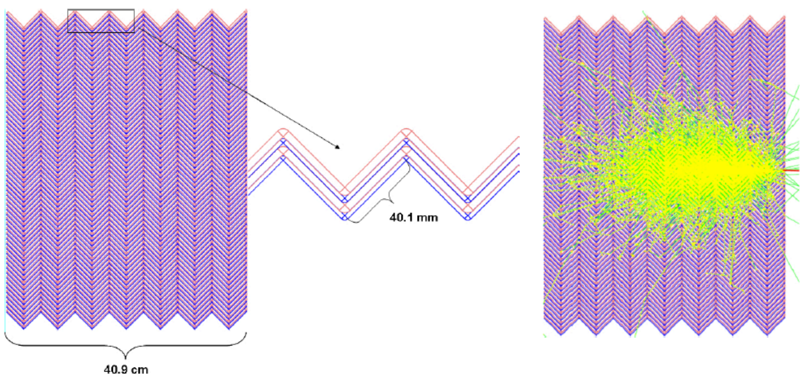


Figure 13.35: View of the parallel geometry accordion calorimeter (left) and simulation of a single electron shower with initial energy of 20 GeV (right).

GEANT4 Simulation

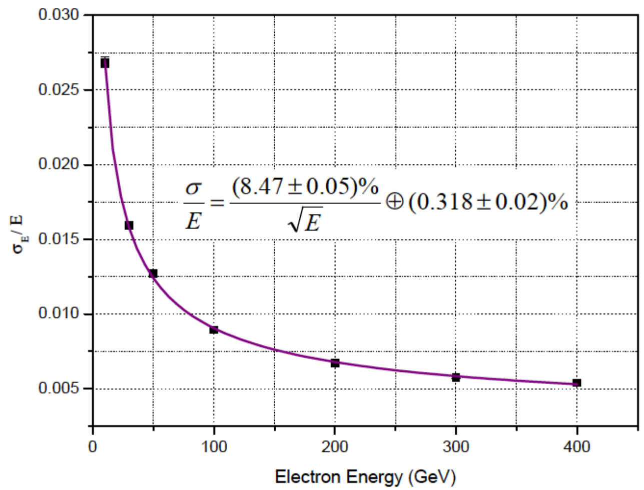


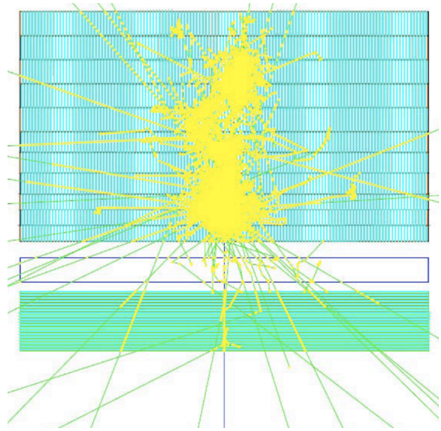
Figure 13.36: LAr accordion calorimeter energy resolution for electrons between 10 and 400 GeV.

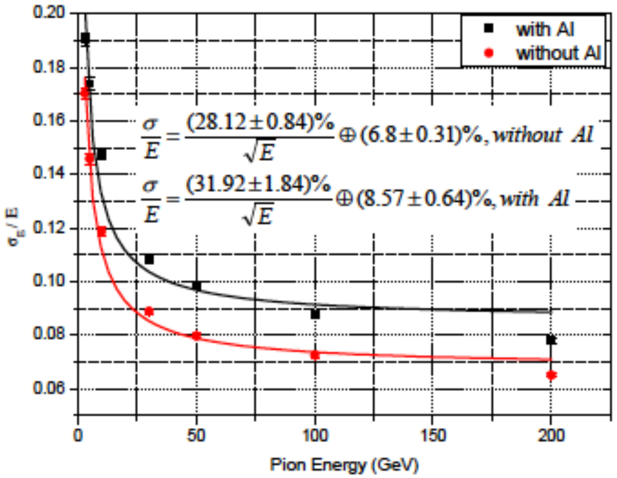
Hadronic Tile Calorimeter

Outside Coil: flux return
Modular. ATLAS experience.

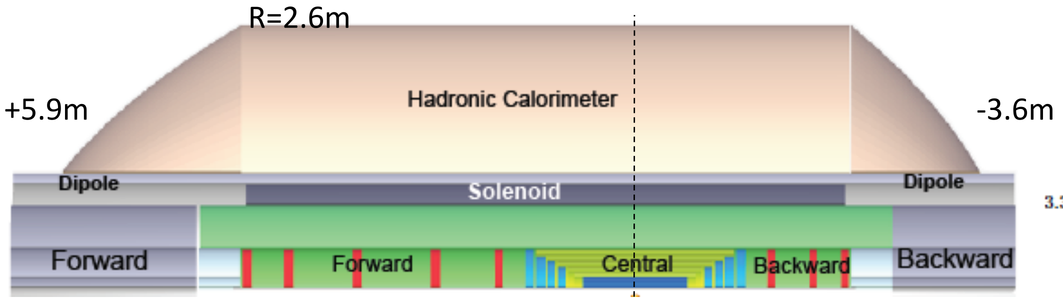
E-Calo Parts		FEC1	FEC2		EMC		BEC2	BEC1
Min. Inner radius R	[cm]	3.1	21		48		21	3.1
Min. polar angle θ	[°]	0.48	3.2		6.6/168.9		174.2	179.1
Max. pseudorapidity η		5.5	3.6		2.8/-2.3		-3.	-4.8
Outer radius	[cm]	20	46		88		46	20
z-length	[cm]	40	40		660		40	40
Volume	[m^3]	0.3			11.3		0.3	
H-Calo Parts 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.





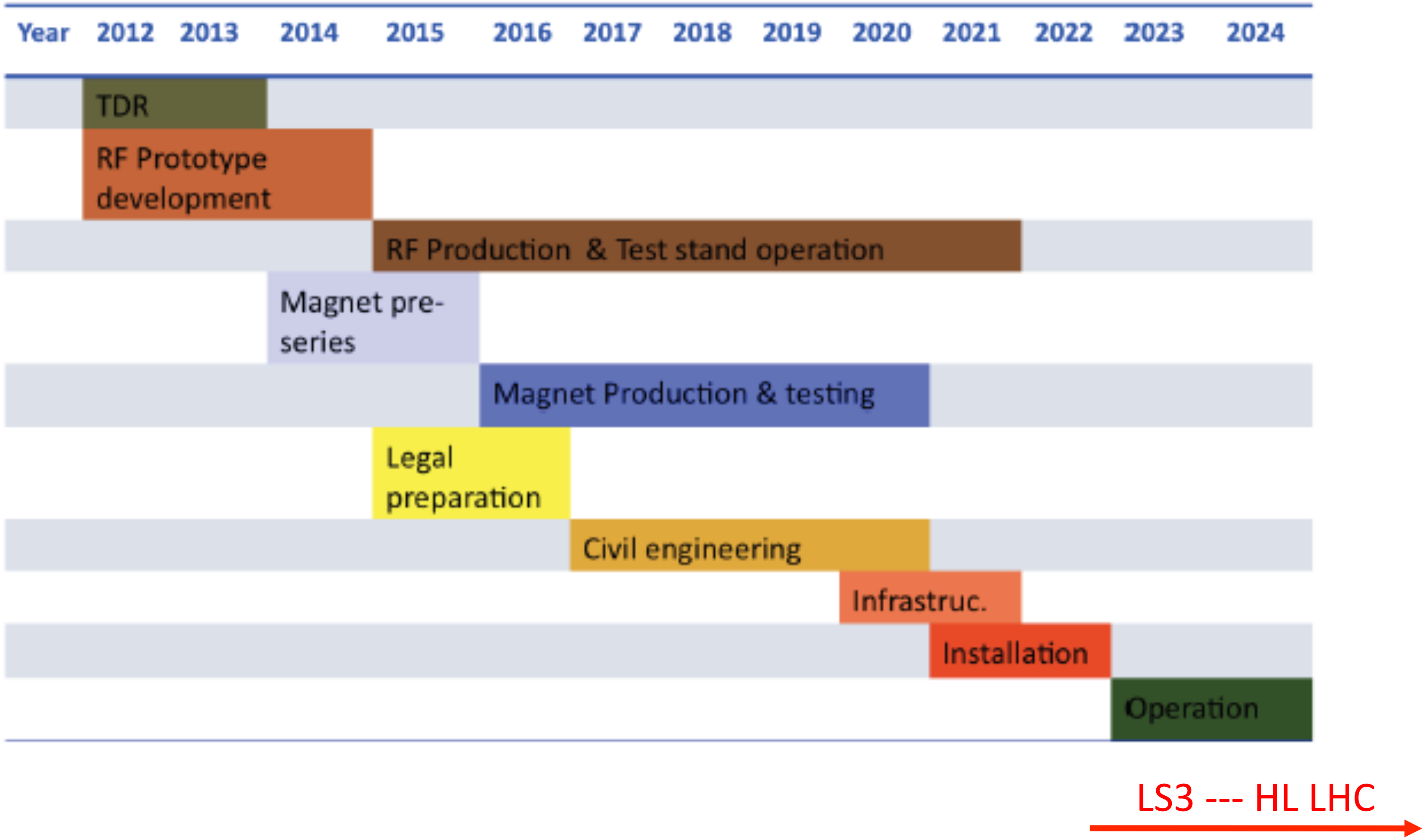
3.37: Accordion and Tile Calorimeter energy resolution for pions with and without 14cm Al block.



Combined GEANT4 Calorimeter Simulation

Outlook

Tentative Time Schedule



We base our estimates for the project time line on the experience of other projects, such as (LEP, LHC and LINAC4 at CERN and the European XFEL at DESY and the PSI XFEL)

from draft CDR

Draft LHC Schedule for the coming decade

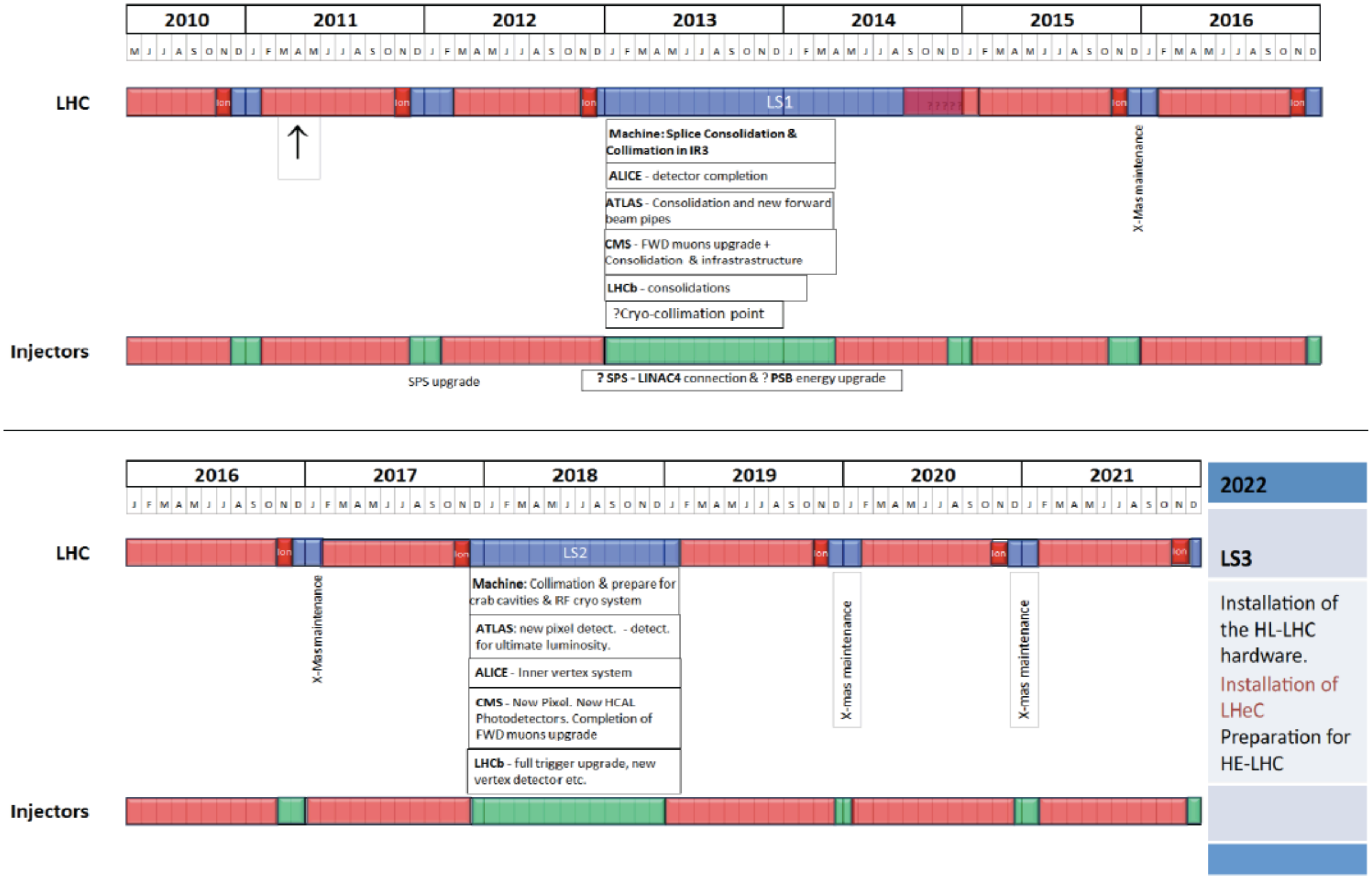


Figure 11.1: CERN medium term plan (MTP), draft as of July 2011

as shown by S. Myers at EPS 2011 Grenoble

Summary

Table 1: Parameters of the RR and RL Configurations

	Ring	Linac
electron beam		
beam energy E_e	60 GeV	
e^- (e^+) per bunch N_e [10^9]	20 (20)	1 (0.1)
e^- (e^+) polarisation [%]	40 (40)	90 (0)
bunch length [mm]	10	0.6
tr. emittance at IP $\gamma\epsilon^e_{x,y}$ [mm]	0.58, 0.29	0.05
IP β function $\beta^*_{x,y}$ [m]	0.4, 0.2	0.12
beam current [mA]	131	6.6
energy recovery intensity gain	–	17
total wall plug power	100 MW	
syn rad power [kW]	51	49
critical energy [keV]	163	718
proton beam		
beam energy E_p	7 TeV	
protons per bunch N_p	$1.7 \cdot 10^{11}$	
transverse emittance $\gamma\epsilon^p_{x,y}$	3.75 μm	
collider		
Lum e^-p (e^+p) [10^{32}cm^{-2}s^{-1}]	9 (9)	10 (1)
bunch spacing	25 ns	
rms beam spot size $\sigma_{x,y}$ [μm]	30, 16	7
crossing angle θ [mrad]	1	0
$L_{eN} = A\ L_{eA}$ [10^{32}cm^{-2}s^{-1}]	0.3	1

Both the ring and the linac are feasible and both come very close to the desired performance. The pleasant challenge is to soon decide for one.

CERN-ECFA-NuPECC:
CDR Draft (530pages) being refereed
Publish spring 2012

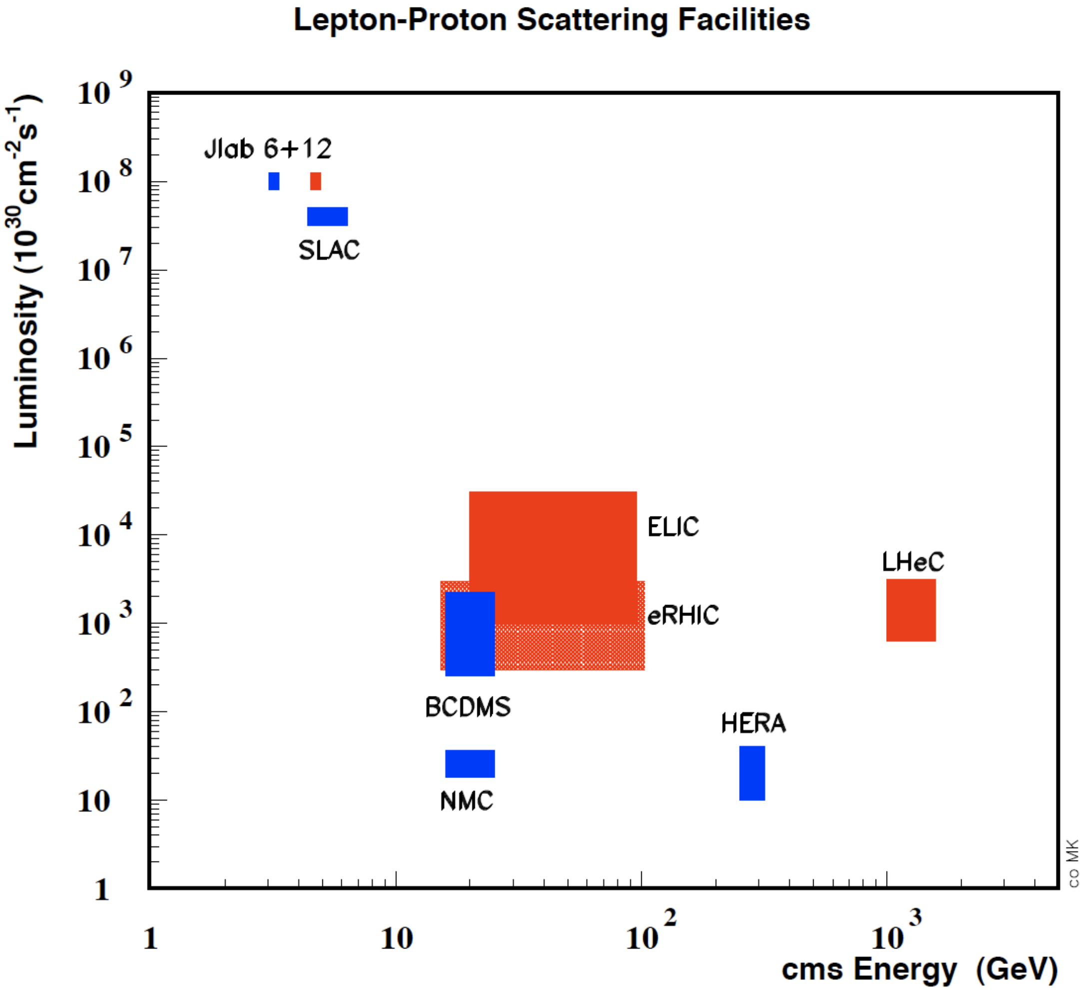
Steps towards TDR (tentative)
-Prototype IR magnet (3 beams)
-Prototype Dipole (1:1)
-Develop Cavity/Cryomodule
-Civil Engineering, …

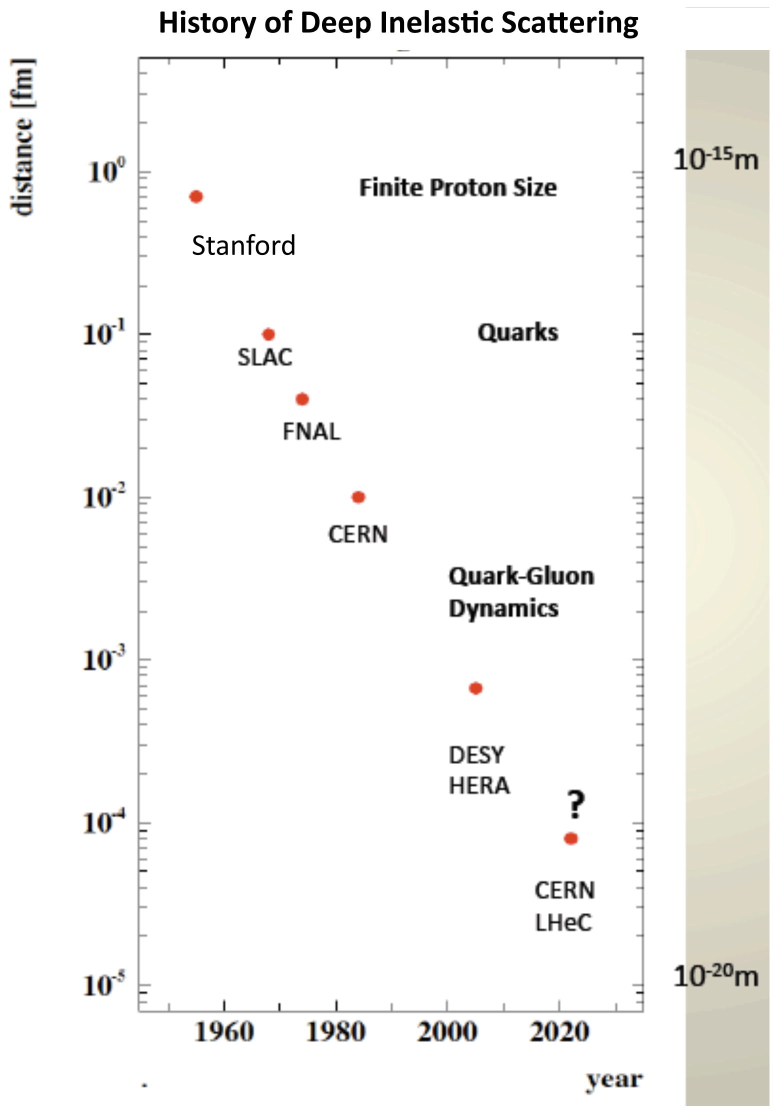
Build international collaborations for the accelerator and detector development. Strong links to ongoing accelerator and detector projects.

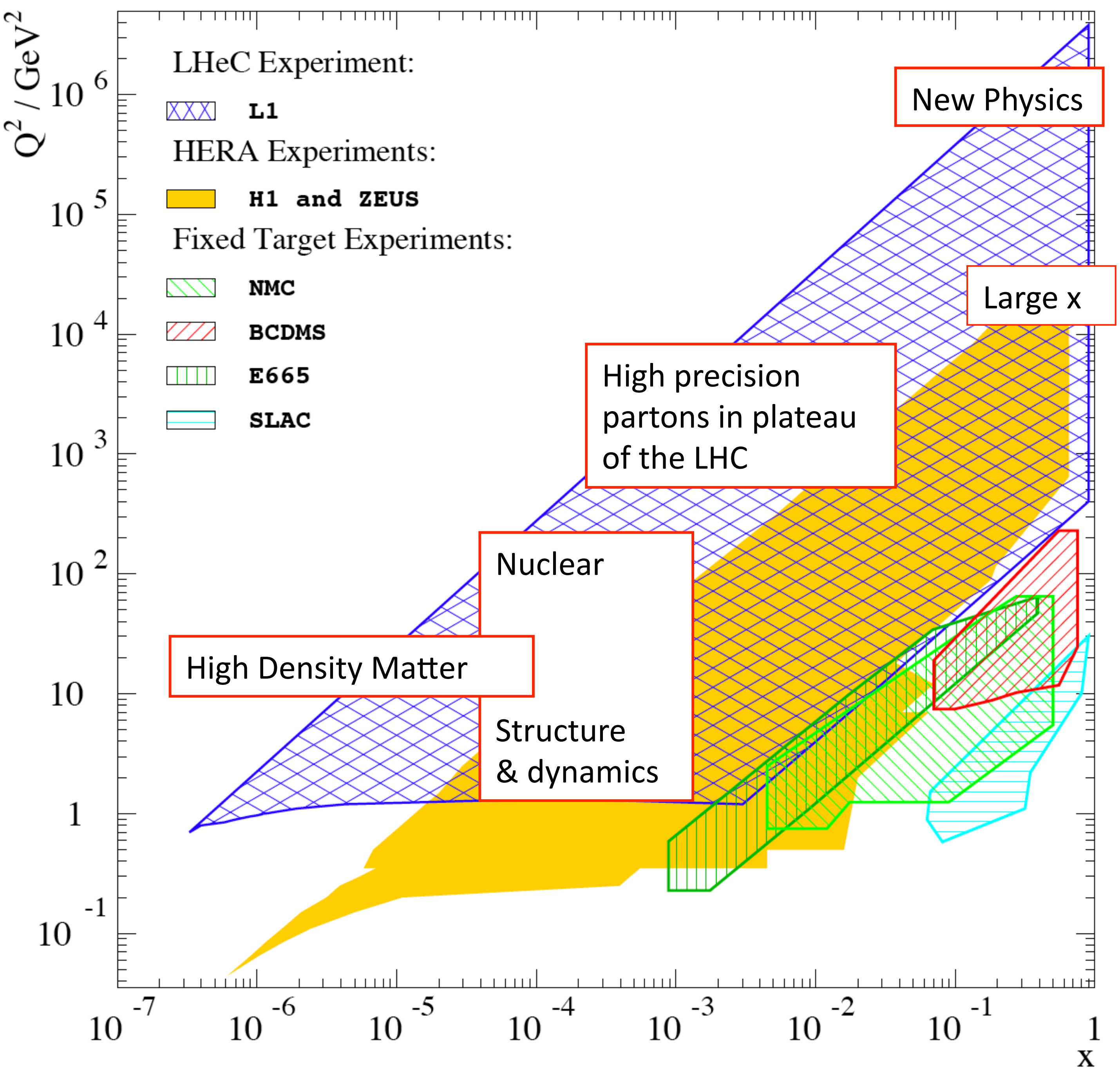
The LHC offers the unique perspective for a further TeV scale collider. The LINAC's are of about 2mile length, yet the Q^2 is 10^5 times larger than was achieved when SLAC discovered quarks. Particle physics needs pp, ll and ep.
Here is a realistic prospect to progress
You are cordially invited to join

backup

Deep Inelastic Scattering - History and Prospects







Q^2 = 4momentum transfer^2

x = Bjorken x: fraction of p's momentum

Why an ep/A Experiment at TeV Energies?

1. For resolving the quark structure of the nucleon with p, d and ion beams

   QPM symmetries, quark distributions (complete set from data!), GPDs, nuclear PDFs ..

2. For the development of perturbative QCD [37-28-15]

   N^kLO ($k\geq2$) and h.o. eweak, HQs, jets, resummation, factorisation, diffraction

3. For mapping the gluon field

   Gluon for $\sim10^{-5} < x < 1$, is unitarity violated? J/ψ, F_2^c, … unintegrated gluon

4. For searches and the understanding of new physics

   GUT (α_s to 0.1%), LQs RPV, Higgs (bb, HWW) … PDFs4LHC… instanton, odderon,..?

5. For investigating the physics of parton saturation

   Non-pQCD (chiral symm breaking, confinement), black disc limit, saturation border..

..For providing data which could be of use for future experiments [Proposal for SLAC ep 1968]

Summary of Design Parameters

electron beam	RR	LR	LR
e- energy at IP[GeV]	60	60	140
luminosity [10^{32} $cm^{-2}s^{-1}$]	17	10	0.44
polarization [%]	40	90	90
bunch population [10^9]	26	2.0	1.6
e- bunch length [mm]	10	0.3	0.3
bunch interval [ns]	25	50	50
transv. emit. $\gamma\varepsilon_{x,y}$ [mm]	0.58, 0.29	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [μm]	30, 16	7	7
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.18, 0.10	0.12	0.14
full crossing angle [mrad]	0.93	0	0
geometric reduction H_{hg}	0.77	0.91	0.94
repetition rate [Hz]	N/A	N/A	10
beam pulse length [ms]	N/A	N/A	5
ER efficiency	N/A	94%	N/A
average current [mA]	131	6.6	5.4
tot. wall plug power[MW]	100	100	100

High E_e Linac option (ERL?) if physics demands HE-LHC?

proton beam	RR	LR
bunch pop. [10^{11}]	1.7	1.7
tr.emit.$\gamma\varepsilon_{x,y}$ [μm]	3.75	3.75
spot size $\sigma_{x,y}$ [μm]	30, 16	7
$\beta^*_{x,y}$ [m]	1.8,0.5	0.1
bunch spacing [ns]	25	25

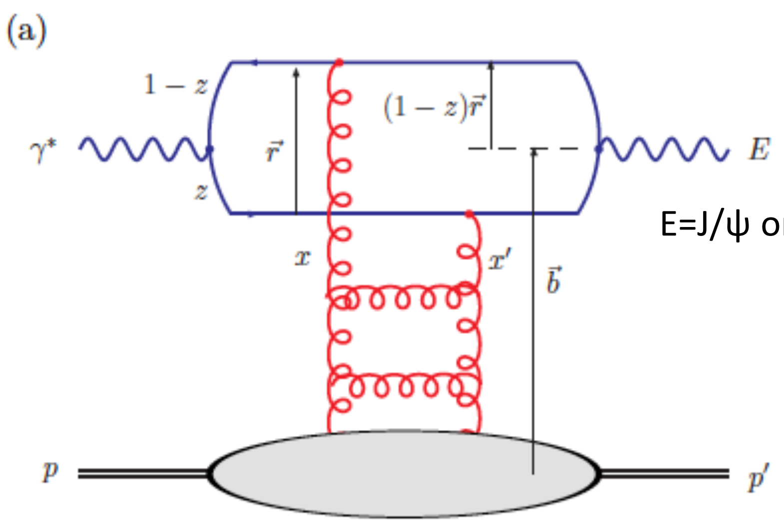
"ultimate p beam"
1.7 probably conservative
and emittance too

CDR has design also for
D and A ($L_{eN} \cong 3 * 10^{31}$ $cm^{-2}s^{-1}$)

RR= Ring – Ring
LR =Linac –Ring

Ring: use 1° as baseline : L/2
Linac: clearing gap: L*2/3

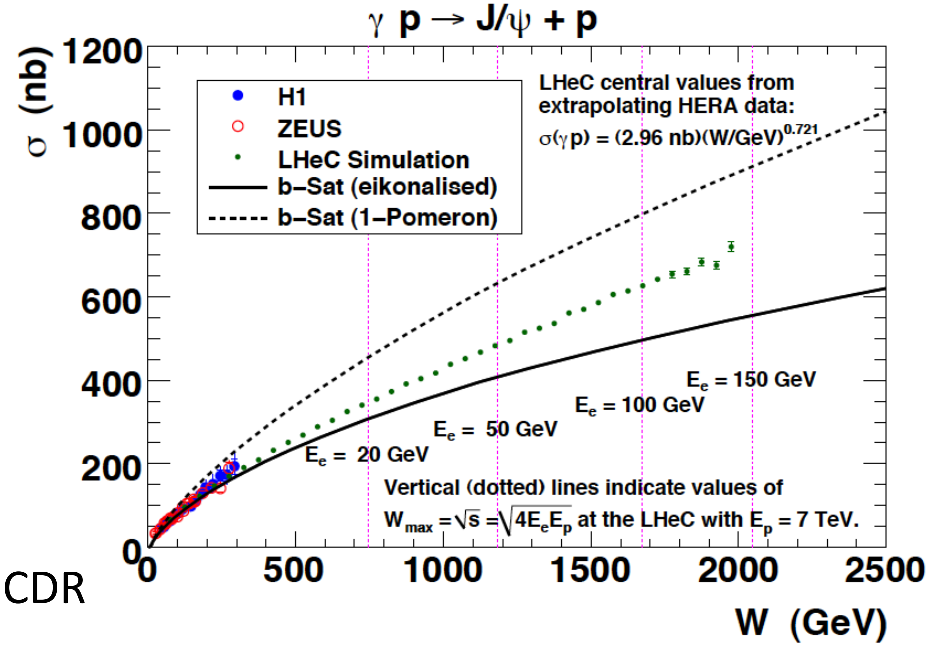
J/ψ in γ^*p/A



E=J/ψ or γ (DVCS)

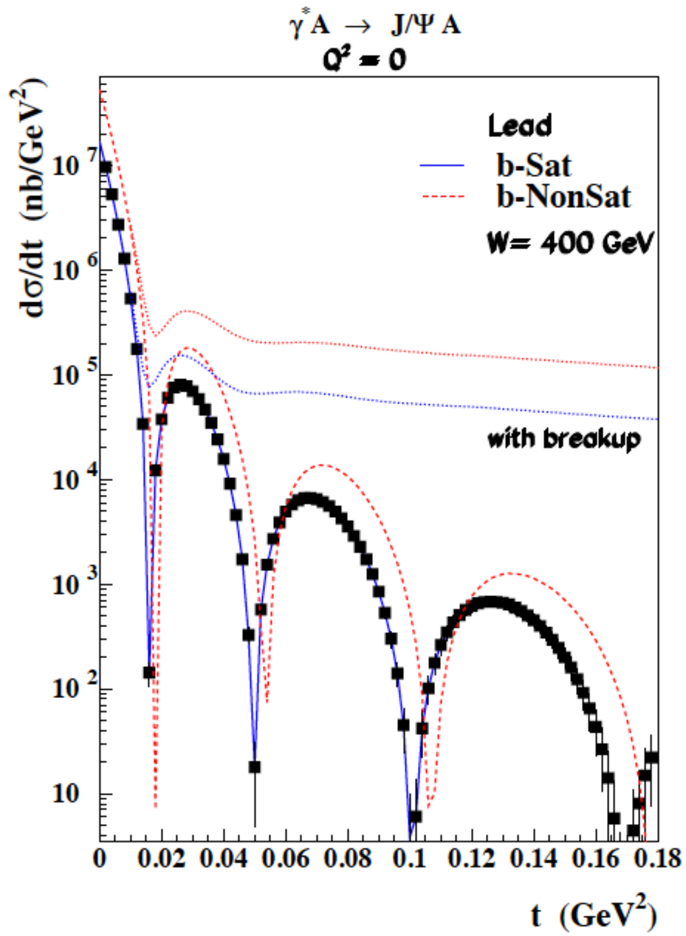
$$\sigma_{T,L}^{\gamma^* p}(x,Q) = \mathrm{Im}\,\mathcal{A}_{T,L}^{\gamma^* p\to\gamma^* p}(x,Q,\Delta=0) = \sum_f \int \mathrm{d}^2\boldsymbol{r} \int_0^1 \frac{\mathrm{d}z}{4\pi}(\Psi^*\Psi)_{T,L}^f \int \mathrm{d}^2\boldsymbol{b}\, \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\boldsymbol{b}}$$

Optical theorem relates J/ψ to $F_T=F_2-F_L$



CDR

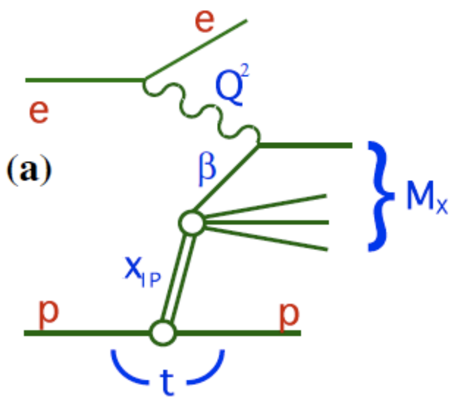
Test of saturation



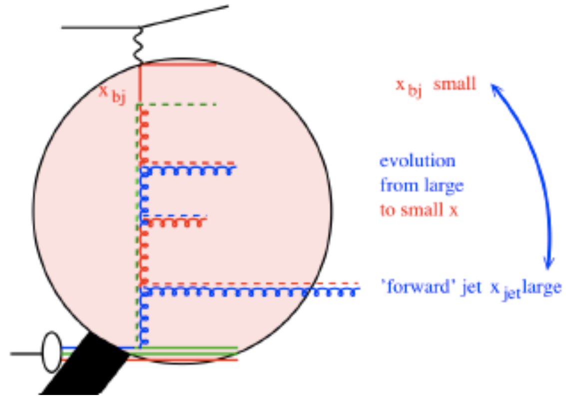
Coherent production in γ*A

Probing of nuclear matter

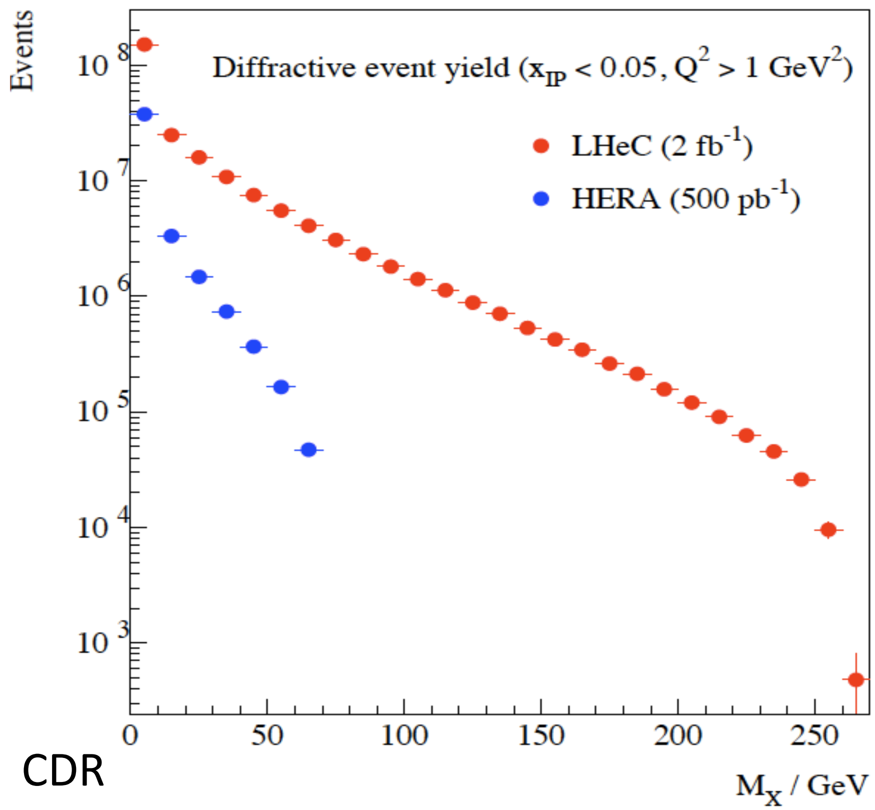
Quark-Gluon Dynamics - Diffraction and HFS (fwd jets)



Factorisation broken
(LHC fwd – LHeC diff)

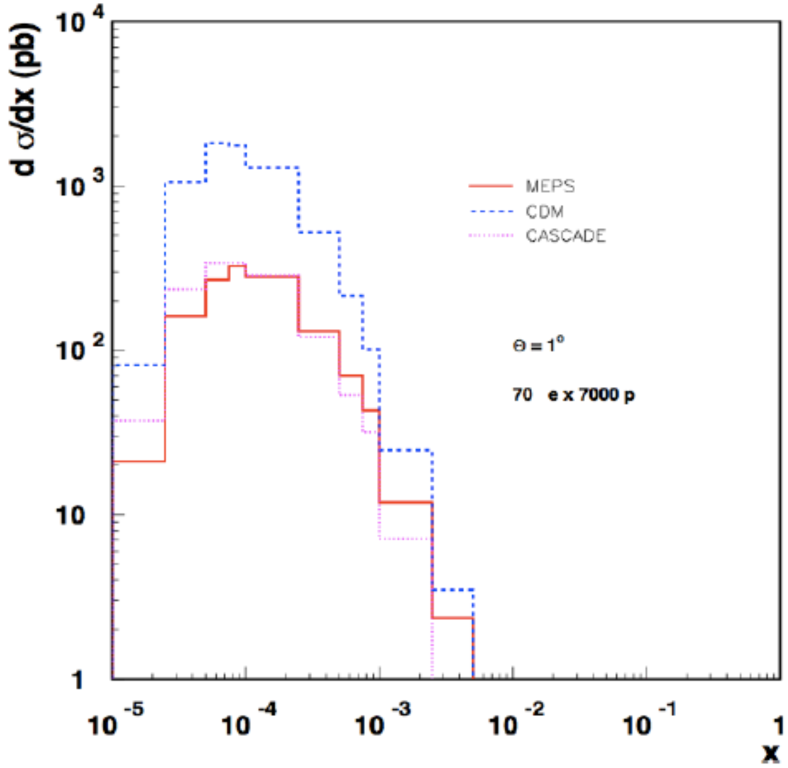


Production of high mass 1- states



CDR

Understand multi-jet emission (unintegr. pdf's), tune MC's



At HERA resolved γ effects mimic non-kt ordered emission