Development of the LHeC

Deep Inelastic ep/eA Scattering at the Energy Frontier (√s > 0.3TeV - HERA)

- Design Concept (CDR 2012)
- LHeC into the Higgs + HL LHC era
- Detector + Accelerator Studies
- Project Development – Next Steps

LHeC:
E_e=60 GeV
E_p= 7 TeV

Max Klein
University of Liverpool

for the LHeC Study Group

For references, please consult
lhec.web.cern.ch

LHeC CDR
arXiv:1206.2913
J.Phys. G39 (2012) 075001

FCC_eh:
E_e =60 GeV
E_p =50 TeV

HE LHC:
E_p=14 TeV

Bits of LHeC History (1984-2007)

Lausanne 1984: ep at CERN: Altarelli, Rueckl

Aachen 1990: LEP x LHC Study Group
Rubbia DG@ICHEP: pp in 1996, ep in 1998 …

HERA ($s=10^5$ GeV^2 at L= 1-4 10^{31}) 1992-2007 [F_L]

1997 E. Keil: ep at the LHC 10^{32} – LHC Report 93

HERA III (eD and eA, EIC@DESY) no - TESLA yes

THERA 2001 (1 x 0.5 TeV^2) with 10^{31} Luminosity..

Snowmass 2001 Interaction with EIC (AD et al)..

QCD explorer (CLIC x LHC', L ~ 10^{30}), ep with SPS?

DIS2005 at Madison: LHeC for the first time

Jinst
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PUBLISHED: *October 11, 2006*

Deep inelastic electron-nucleon scattering at the LHC

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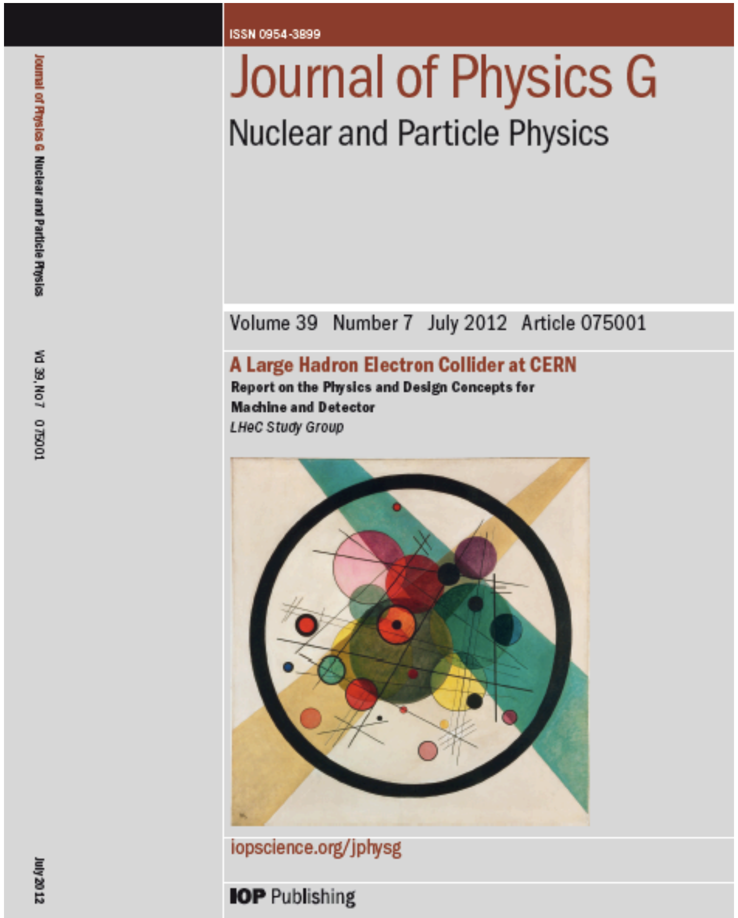
ABSTRACT: The physics, and a design, of a Large Hadron Electron Collider (LHeC) are sketched. With high luminosity, $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and high energy, $\sqrt{s} = 1.4$ TeV, such a collider can be built in which a 70 GeV electron (positron) beam in the LHC tunnel is in collision with one of the LHC hadron beams and which operates simultaneously with the LHC. The LHeC makes possible deep-inelastic lepton-hadron (*ep*, *eD* and *eA*) scattering for momentum transfers Q^2 beyond 10^6 GeV^2 and for Bjorken x down to the 10^{-6}. New sensitivity to the existence of new states of matter, primarily in the lepton-quark sector and in dense partonic systems, is achieved. The precision possible with an electron-hadron experiment brings in addition crucial accuracy in the determination of hadron structure, as described in Quantum Chromodynamics, and of parton dynamics at the TeV energy scale. The LHeC thus complements the proton-proton and ion programmes, adds substantial new discovery potential to them, and is important for a full understanding of physics in the LHC energy range.

→ Initialisation of the CERN-ECFA-NuPECC LHeC Study (2008-2012) → CDR arXiv:1206.2913

Design Report 2012



arXiv:1206.2913

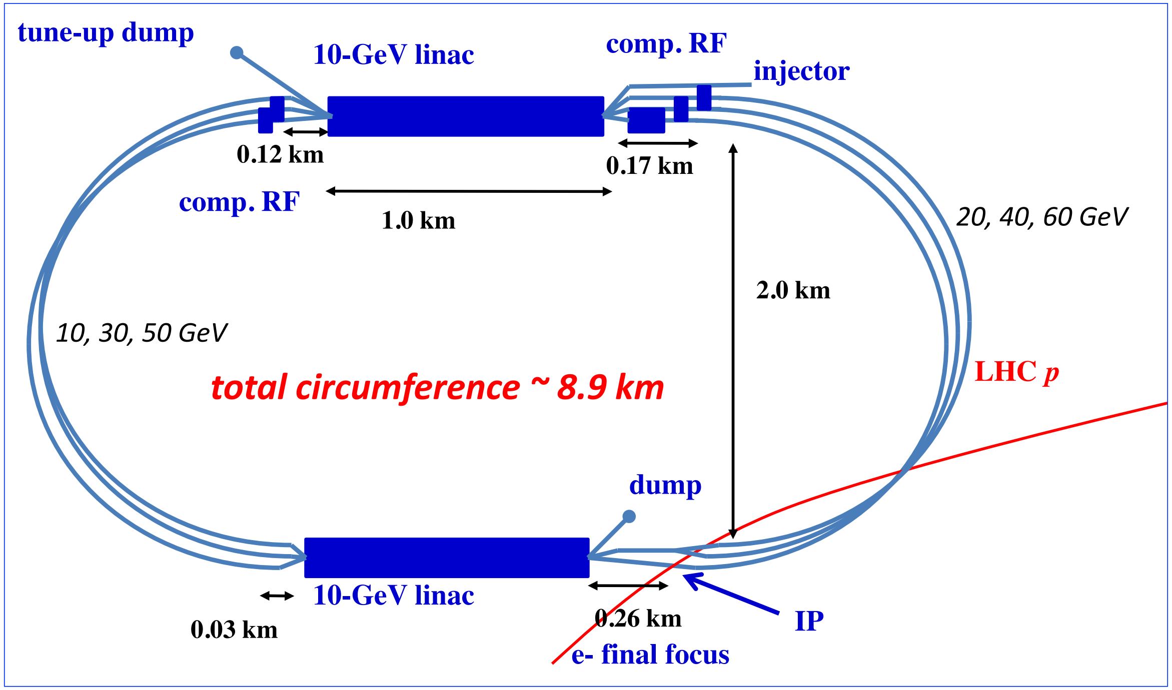
CERN Referees

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)
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)

600 pages. Physics, Detector and Two Accelerator Options
ring-ring which may be of interest in the HE-LHC context and linac-ring, the default LH(e)C

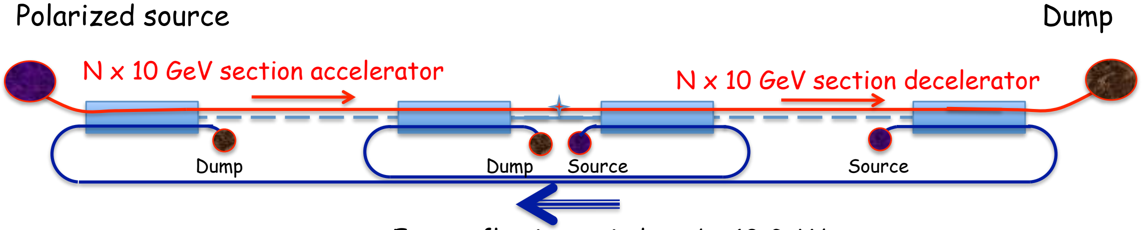
Default Electron Accelerator Concept

Conceptual Design Report: arXiv:1206.2913



LHeC: 60 GeV off 7 TeV, L(ep) $=10^{34}$ cm^{-2} s^{-1} (1000 x HERA) in synchronous ep+pp operation

Non default: An expensive generalisation to achieve E_e= 500 GeV or more



V Litvinenko

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

LAL Physique des accélérateurs

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

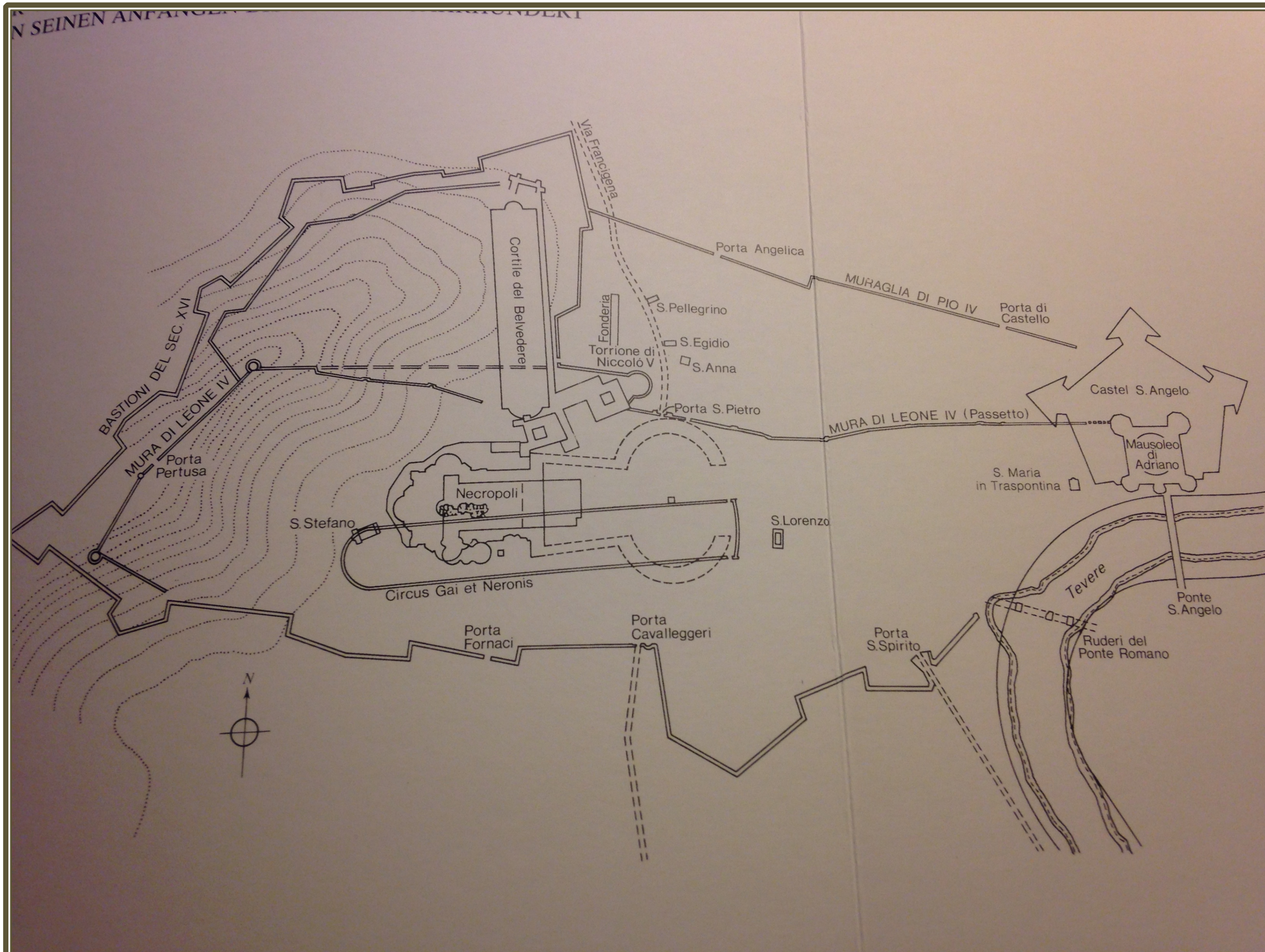
UNIVERSITY OF LIVERPOOL

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**



An early racetrack embedded in the Vatican (XV century)

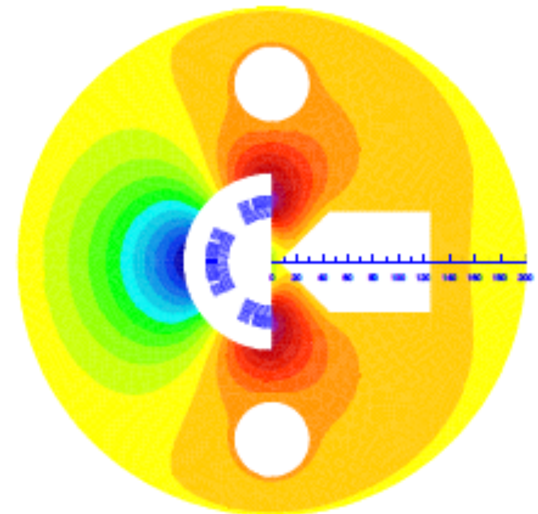
Parameters and Design

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

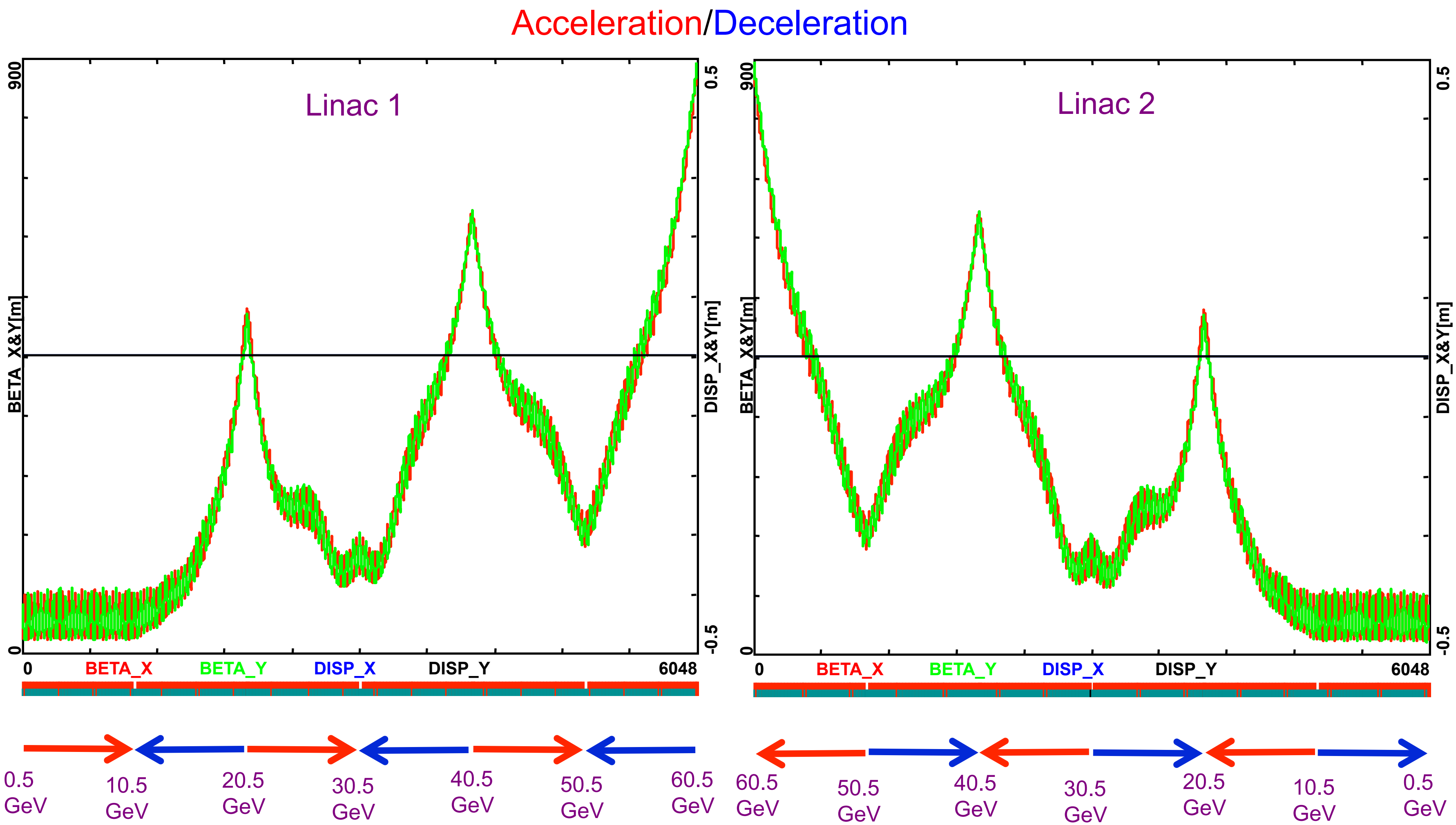
Designed for synchronous ep and pp operation



“Q1” SC 3-beam IR magnet

1→3 beam spreader design

Linac 1 and 2: Multi-pass ER Optics



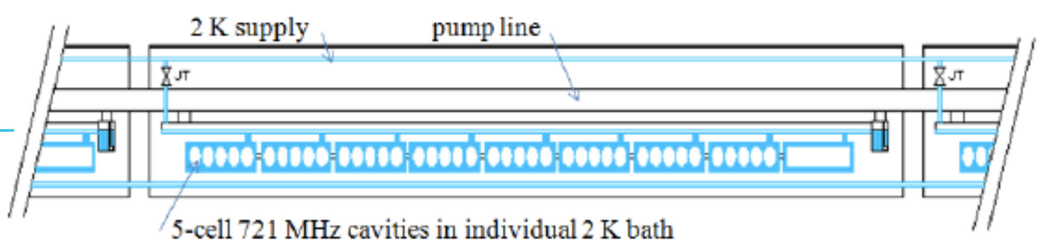
Arc optics: Emittance preserving flexible momentum compaction cell
3+3 arcs of normal conducting "standard" magnets

Alex Bogacz

Chapter 9 of CDR

Components and Cryogenics

	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



Need to develop LHeC cavity (cryo-module) *[2013]*

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

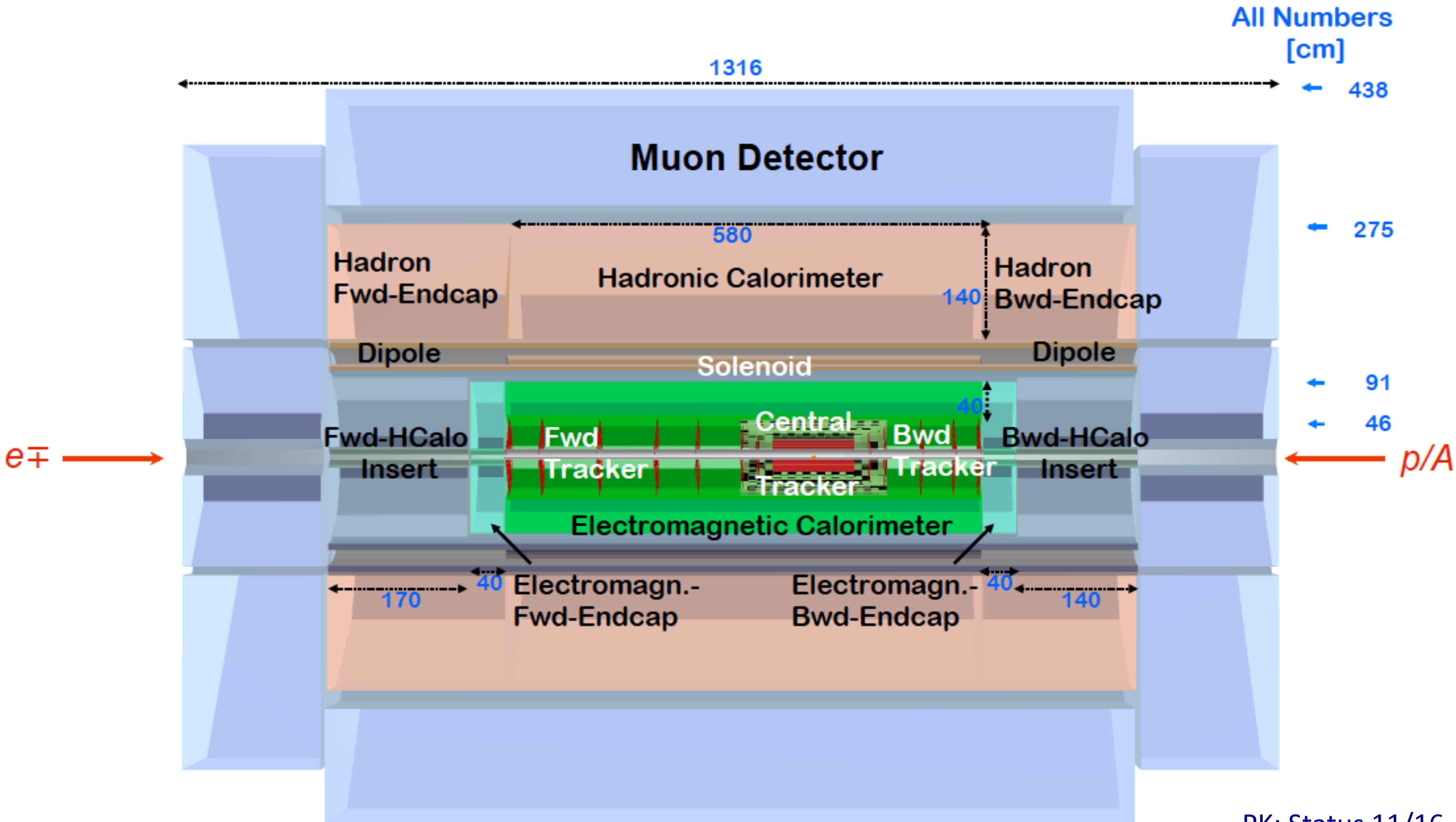
The LHeC Physics Programme

arXiv:1206.2913 (CDR) 1211.4831 and 5102

QCD Discoveries Higgs Substructure New and BSM Physics Top Quark	$\alpha_s < 0.12$, $q_{sea} \neq \overline{q}$, instanton, odderon, low x: (n0) saturation, $\overline{u} \neq \overline{d}$ WW and ZZ production, $H \to b\overline{b}$, $H \to 4l$, CP eigenstate electromagnetic quark radius, e^*, ν^*, W?, Z?, top?, H? leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through α_s 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 Precision DIS	saturation, $x \approx 1$, J/ψ, Υ, Pomeron, local spots?, F_L, F_2^c $\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\text{MeV}$, $v_{u,d}$, $a_{u,d}$ to $2-3\,\%$, $\sin^2\Theta(\mu)$, F_L, F_2^b
Parton Structure Quark Distributions QCD	Proton, Deuteron, Neutron, Ions, Photon valence $10^{-4} \lesssim x \lesssim 1$, light sea, d/u, $s = \overline{s}$?, charm, beauty, top N^{3}LO, factorisation, resummation, emission, AdS/CFT, BFKL evolution
Deuteron Heavy Ions Modified Partons	singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing initial QGP, nPDFs, hadronization inside media, black limit, saturation 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

LHeC Detector



PK: Status 11/16

Forward/backward asymmetry in energy deposited and thus in geometry and technology
Present dimensions: LxD =13x9m^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

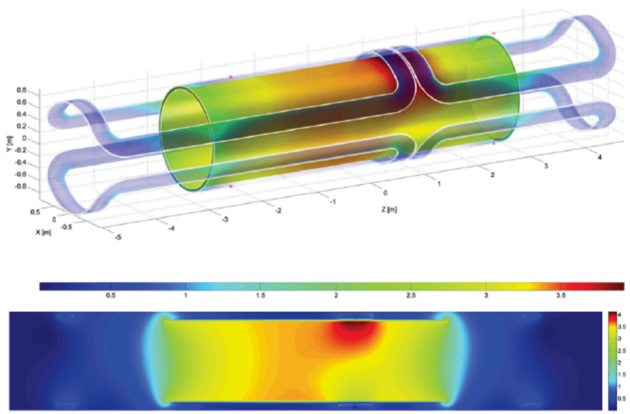


Figure 13.13: Magnetic field of the magnet system of solenoid and the two internal superconducting dipoles at nominal currents (effect of iron ignored). The position of the peak magnetic field of 3.9 T is local due to the adjacent current return heads on top of the solenoid where all magnetic fields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

Observations post CDR - 2012+

LHC brightness 2-3 times higher than expected

LHC lifetime now extended to 2037 ($4ab^{-1}$ until 2039)

Discovery of the Higgs: L(ep): $10^{33} \rightarrow 10^{34}$ $cm^{-2} s^{-1}$

No further discovery at the LHC (as yet)

Detector technology developments (LHC Det. Upgrades)

Strong ERL developments (cβ, Jlab, BerlinPRO, MESA..)
SC RF: 802 MHz (LHeC), enhanced Q_0 through Ni doping

EU strategy 13: exploit LHC, study Higgs, develop SCRF,
CERN: new accelerators "with emphasis on pp and ee"
Fine with the LHeC cost being a small fraction of ILC,CLIC,FCC

No decision on e^+e^- colliders, for how long?

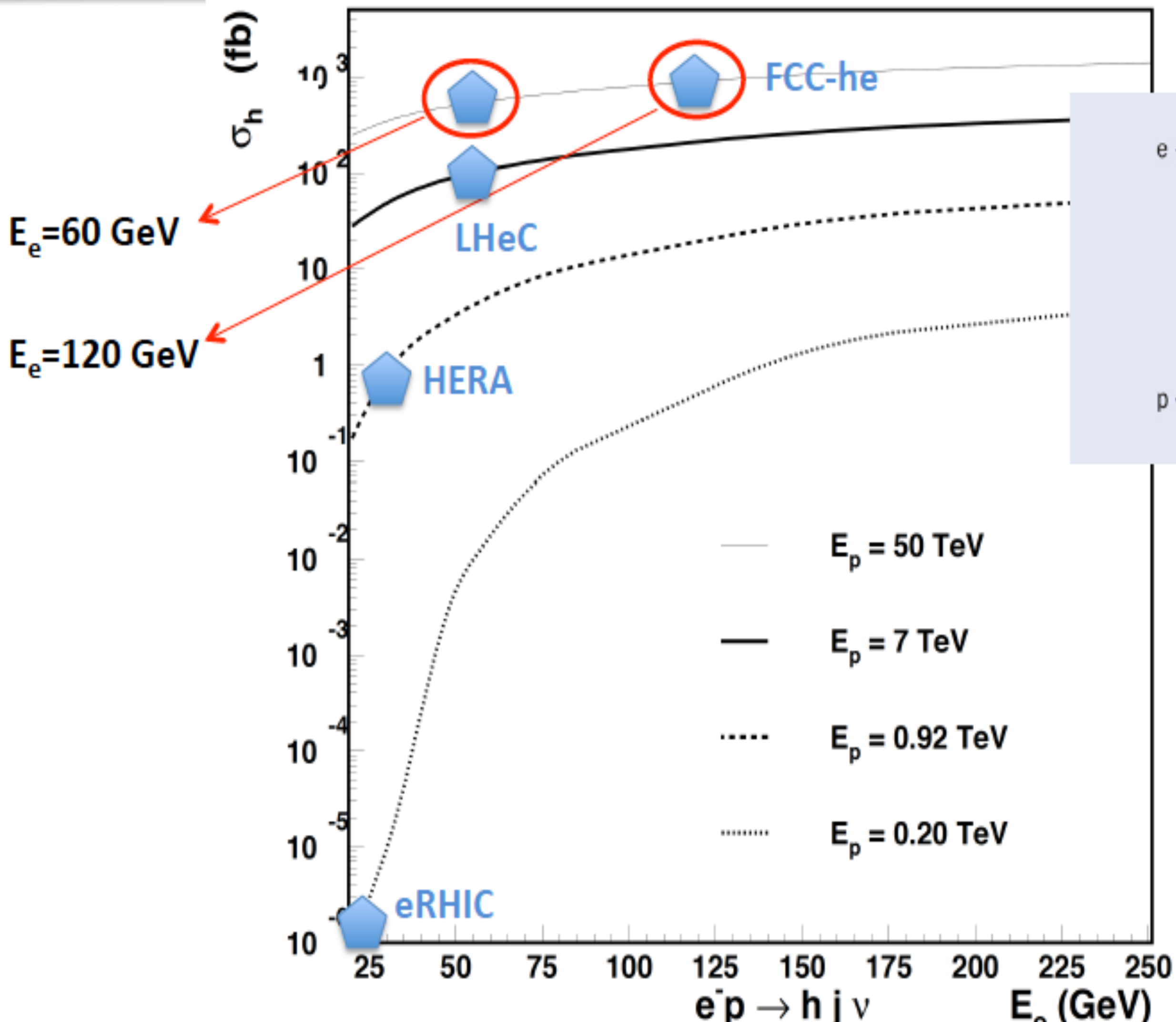
→ CERN set up a new LHeC organisation with a new
Mandate to prepare for the next EU strategy 19
Two main goals: Update of CDR for HL-LHeC + Testfacility

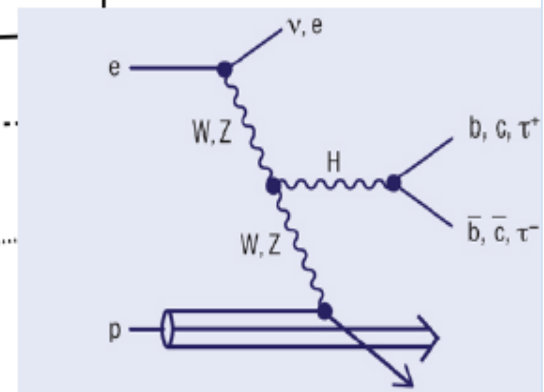
A New Era of Particle Physics

4.7.2012 greeting Melbourne from CERN

"The Higgs: So simple and yet so unnatural" G.Altarelli,arXiv:1308.0545

SM Higgs in ep → ν/e H X





LHeC / FCC-he: Sizeable charged current DIS unpolarised **ep cross sections**

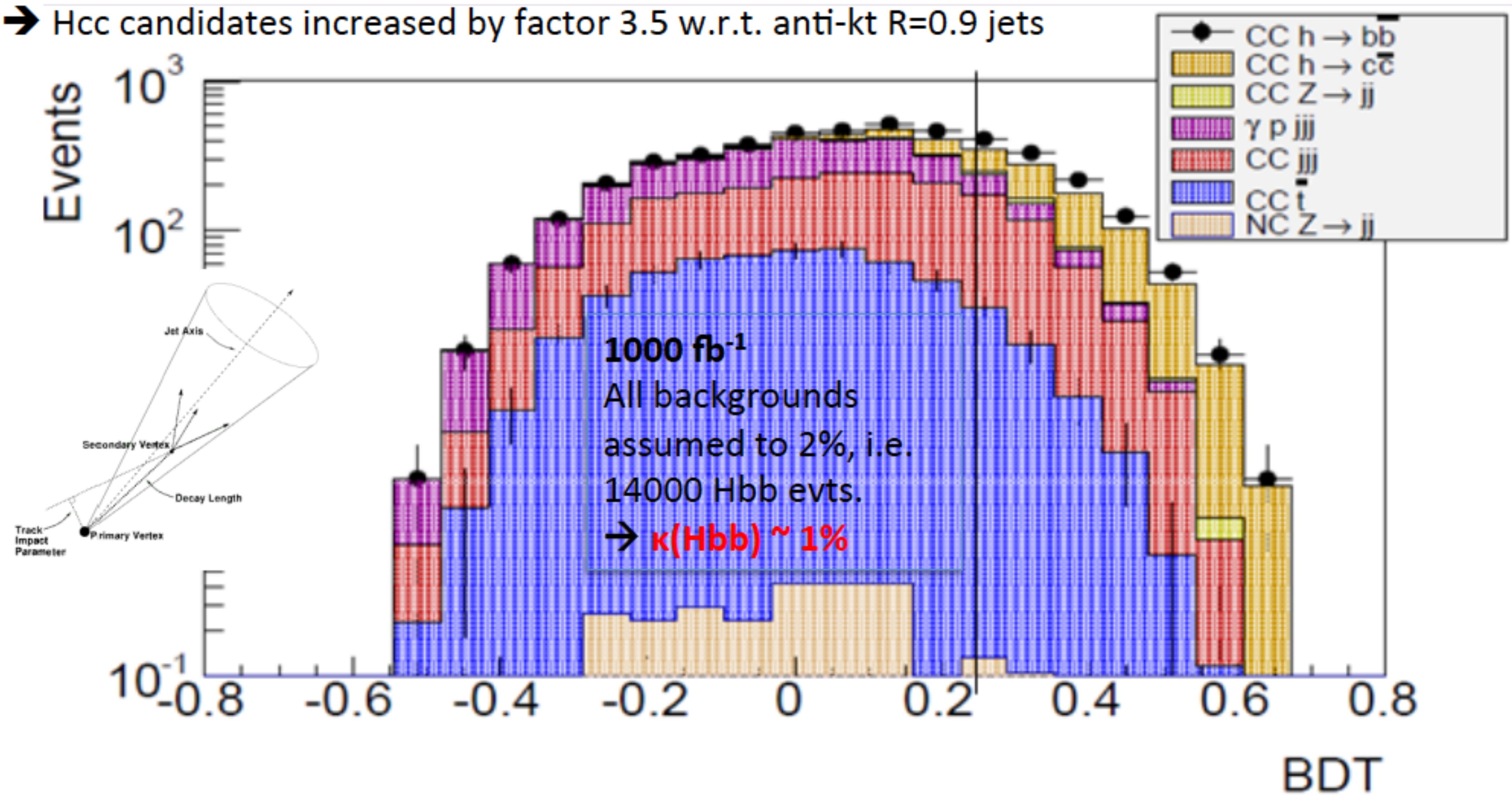
BDT Results Higgs→ cc

For analysis and variables, c.f. U Klein LHeC Workshop

U Klein and D Hampson.
May 2016

NEW : Using R = 0.5 anti-kt jets and ATLAS IBL vertex resolution (5 μm)

➔ Hcc candidates increased by factor 3.5 w.r.t. anti-kt R=0.9 jets



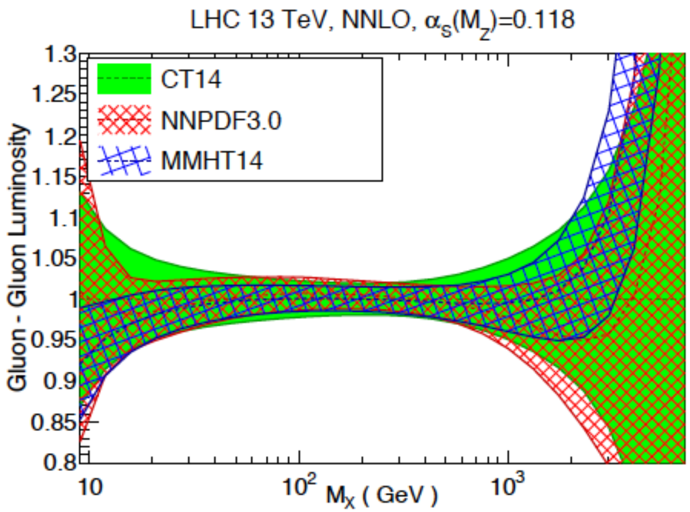
BDT cut >0.2: **Hcc Signal events : 474**

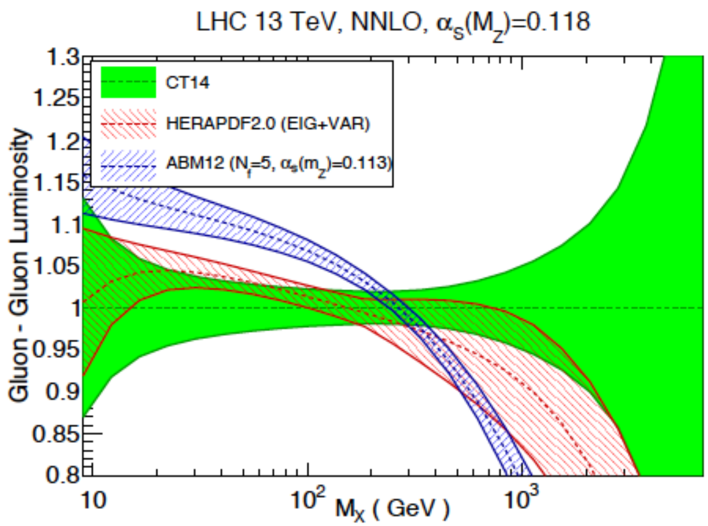
S/√S+B=12.8 ➔ κ(Hcc) = 5% for 1000 fb^{-1}

Clear potential to access the Higgs to charm decay channel at the LHeC.

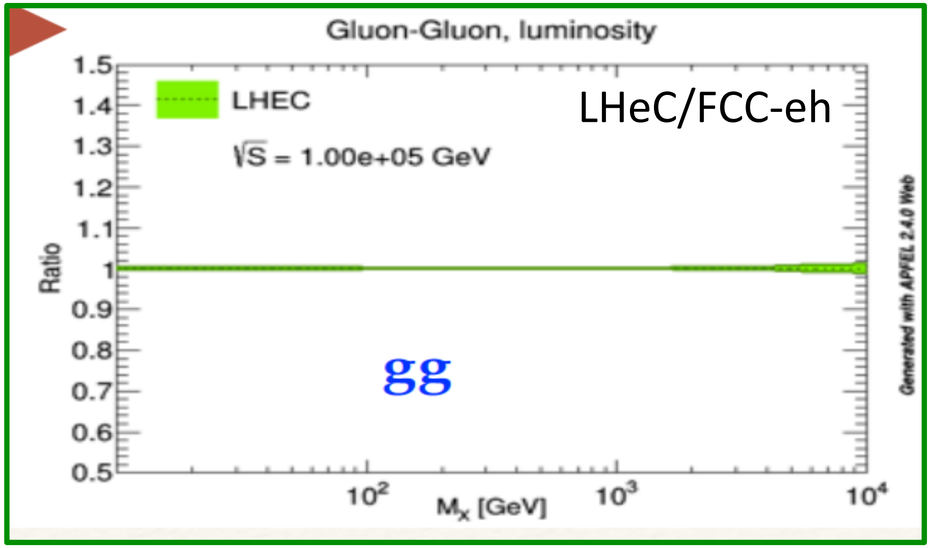
Gluon (gg) Luminosity

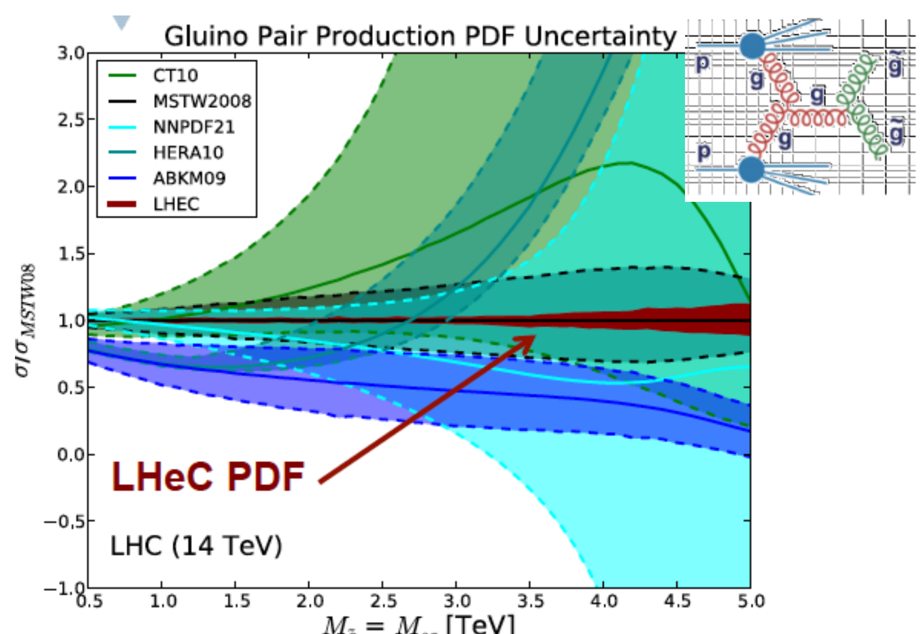
Present status





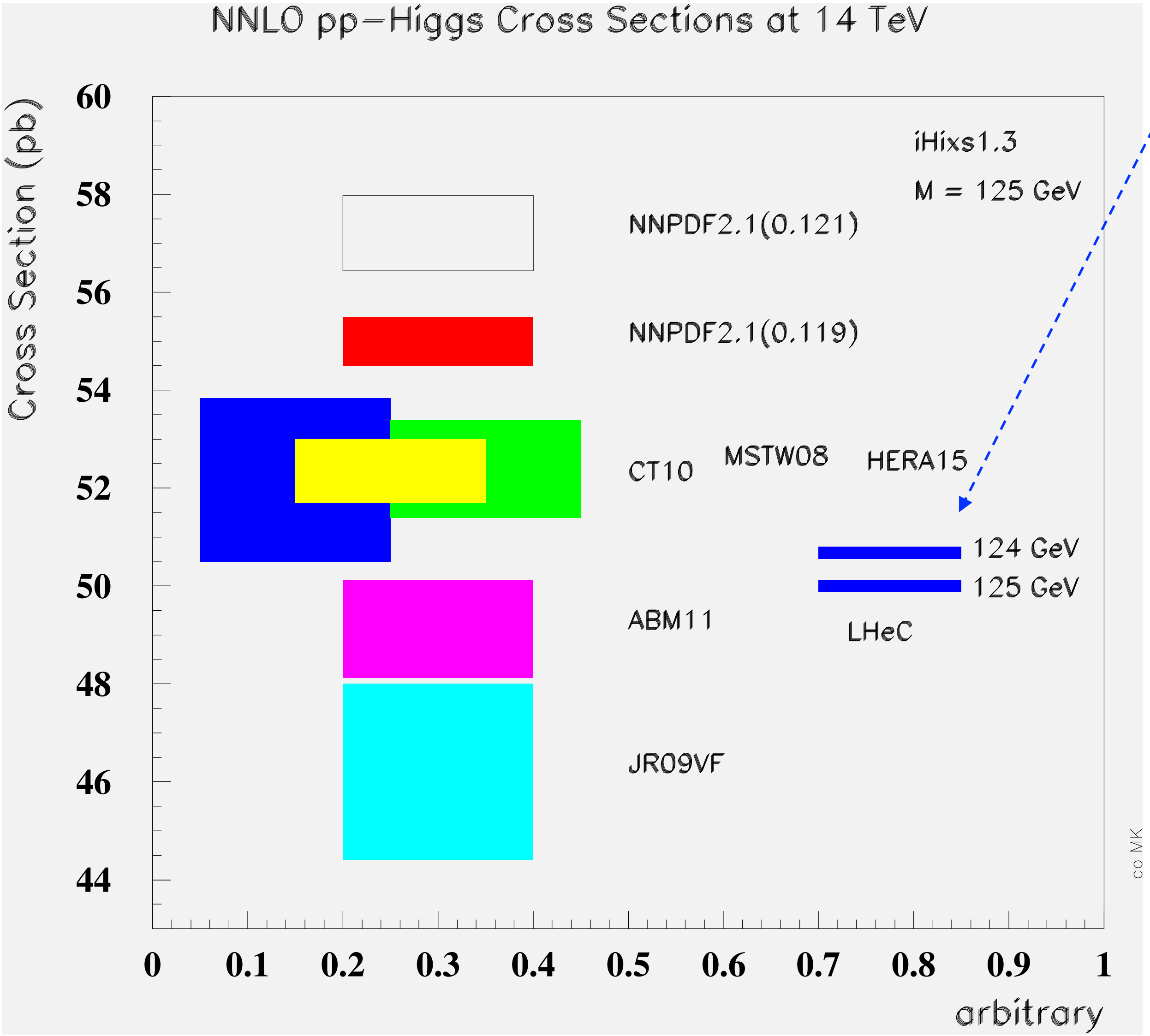
gg → H dominant process in pp
Crucial for SUSY searches/limits





arXiv:1211.5102

Precision PDFs for Higgs at the LHC



O.Brüning and M.K. arXiv:1305.2090, MPLA 2013

LHeC:

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

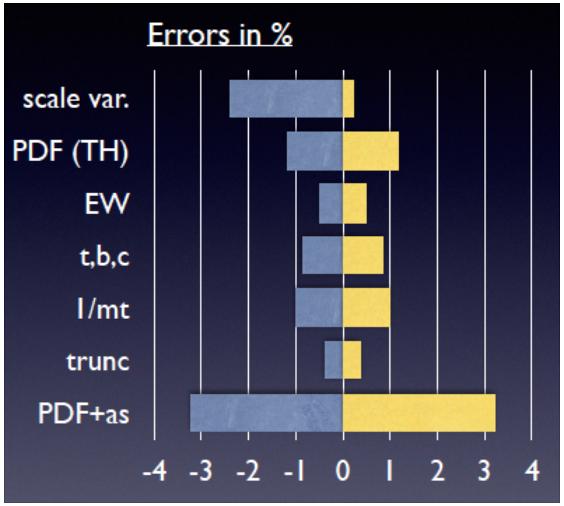
Leads to H mass sensitivity.

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

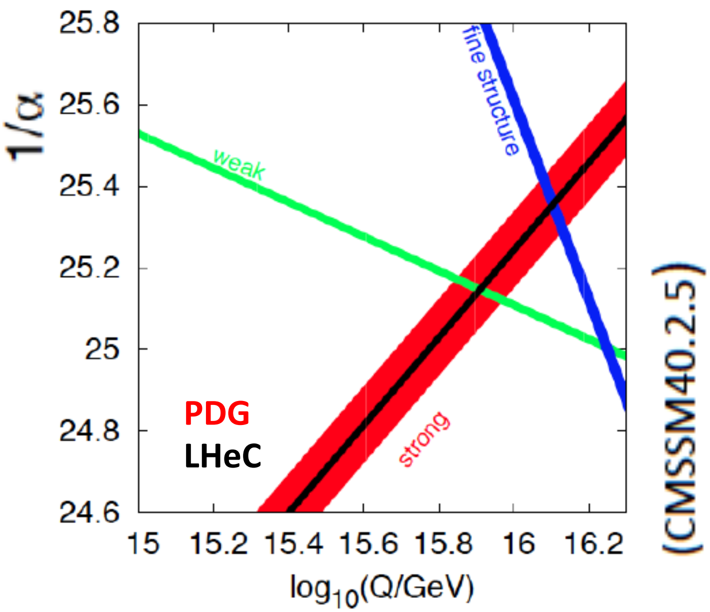
Needs N^{3}LO

HQ treatment important …

Strong Coupling Constant



Uncertainty on Higgs cross section
Giulia Zanderighi, Vietnam 9/16,
from C.Anastasiou et al, 1602.00695
who also discuss the ABM alpha_s..



- **α_s least known of coupling constants**
  Grand Unification predictions need smaller $\delta\alpha_s$
- **Is α_s(DIS) lower than world average (?)**
- **LHeC: per mille - independent of BCDMS!**
- **High precision from inclusive data – α_s(jets)??**
- **Challenge lattice QCD**

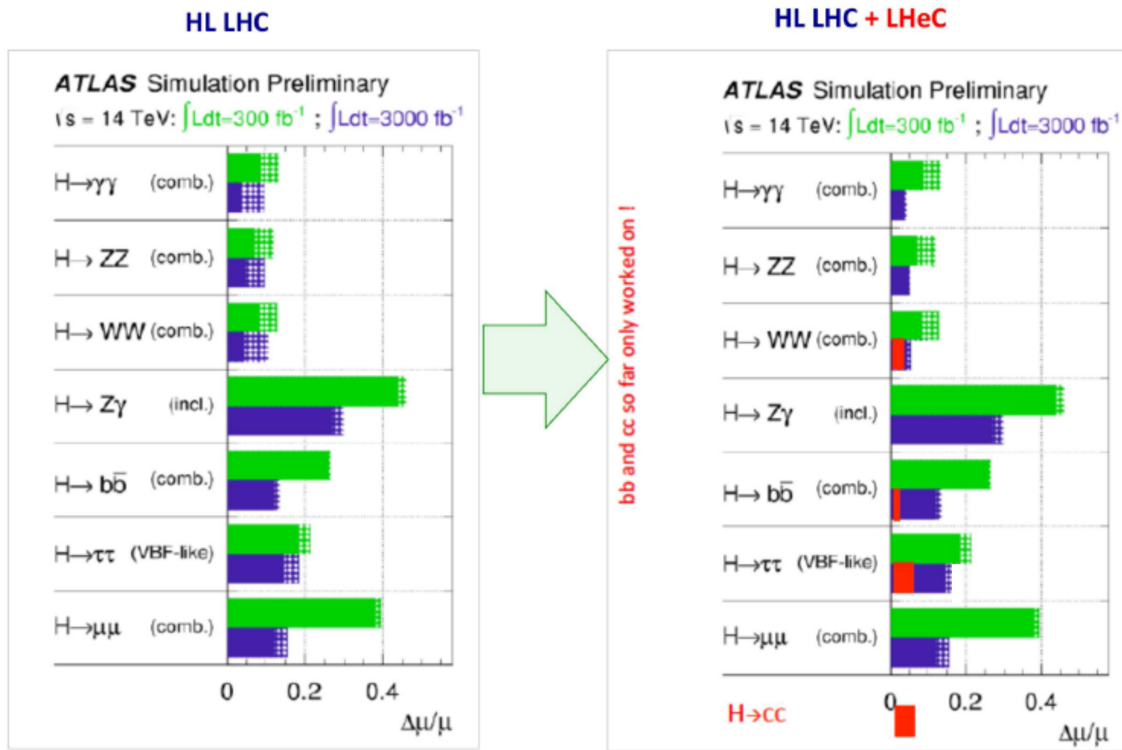
LHeC simulation, NC+CC inclusive, total exp error

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

HIGGS PHYSICS AT THE LHEC

SUMMARY



- GLUON FUSION AND W FUSION $\Rightarrow$ PDF+α_s UNCERTAINTY REMOVED (hatched bands)
- $H\bar{b}b$ MEASURED TO PERCENTAGE PRECISION;
- $\tau\tau$ AND $\bar{c}c$ ALSO MEASURABLE

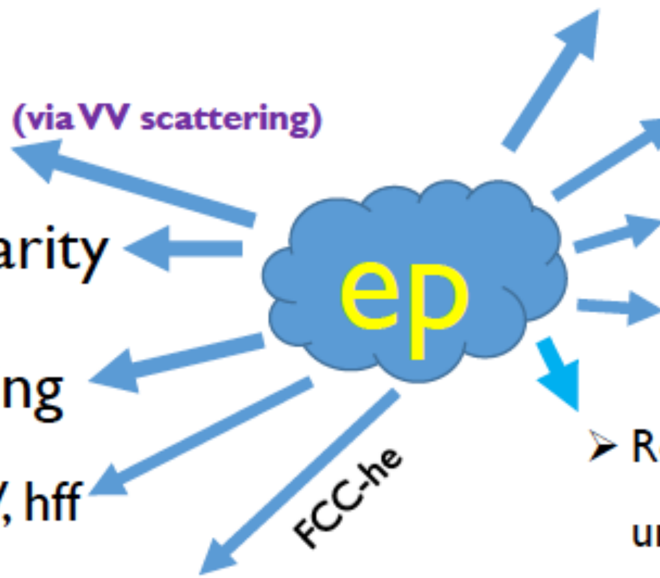
S.Forte ECFA 11/15

The exp. error on the Higgs cross section calculated with LHeC PDF is 0.3% → sensitive to mass

The Phenomenological Higgs Landscape (Revisited)

Future ep colliders could make important contribution to Higgs physics!

- Mass
- Width (via VV scattering)
- Spin-Parity
- Coupling
  - hVV, hff
  - 3h,4h, hhVV
  - FCNC coupling



- Exotic Higgs Decay
  - h to invisible
  - h to 4b
  - …

➢ Reducing PDF & Alpha_s uncertainties in Higgs measurements

➡ See talk given by Voica Radescu

Philosophy could be traced back to
Phys. Rev. D82 (2010) 016009 by T. Han and B. Mellado.

See also:
M. Kumar et al., 1509.04016
S. S. Biswal et al., Phys. Rev. Lett. 109 (2012) 261801
U. Klein, talk given at LHeC Workshop 2015

Chen Zhan 12.4.16 (talk at annual FCC week 2016, Rome)

LHeC at POETIC 7

N. Armesto: eA

C. Zhang: Higgs

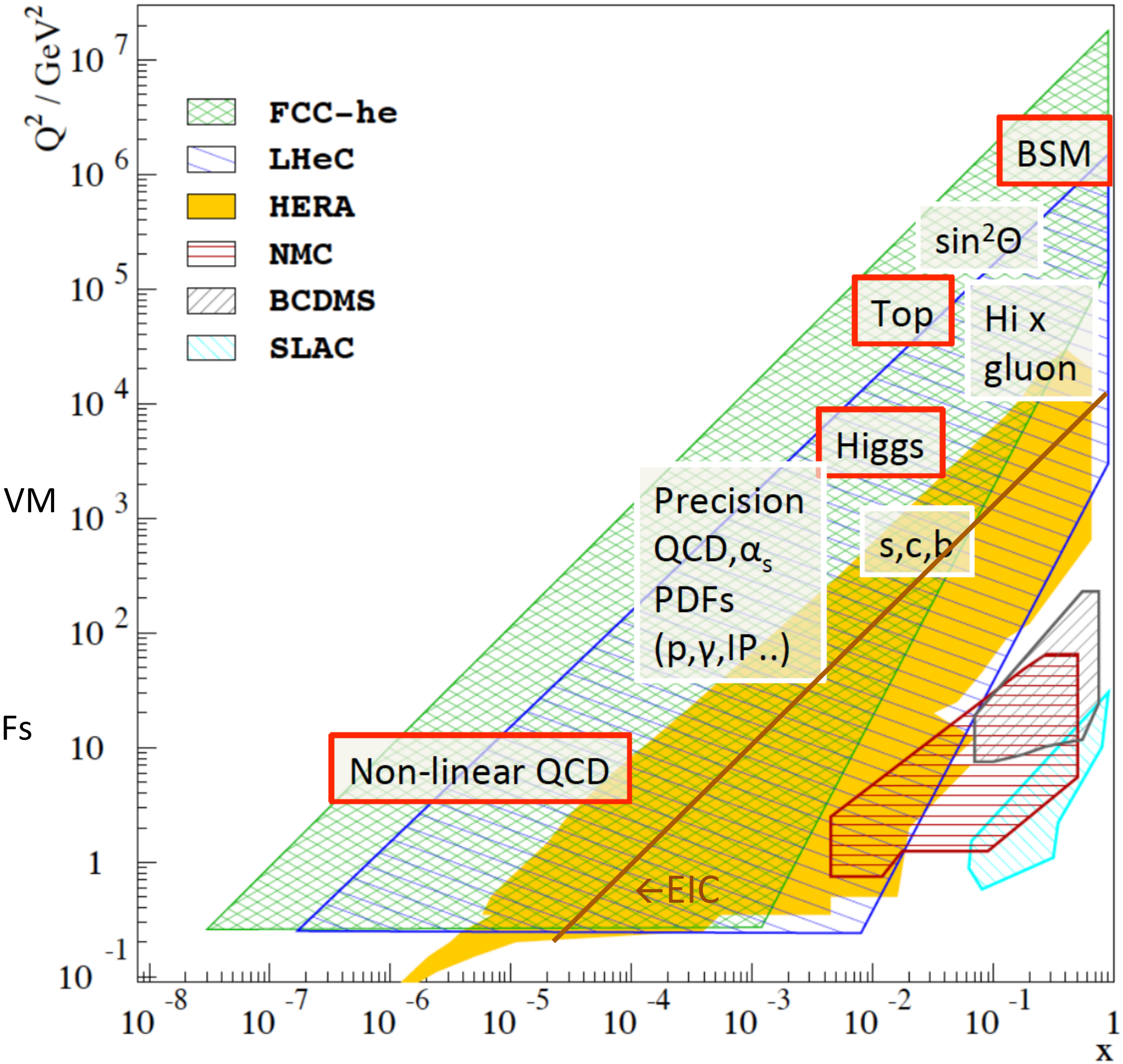
A. Stasto: Saturation, VM

C. Gwenlan:
Top, elweak + BSM

M. Cooper Sarkar: PDFs

M. Klein: EIC+LHeC
(in the CTEQ Part)

+

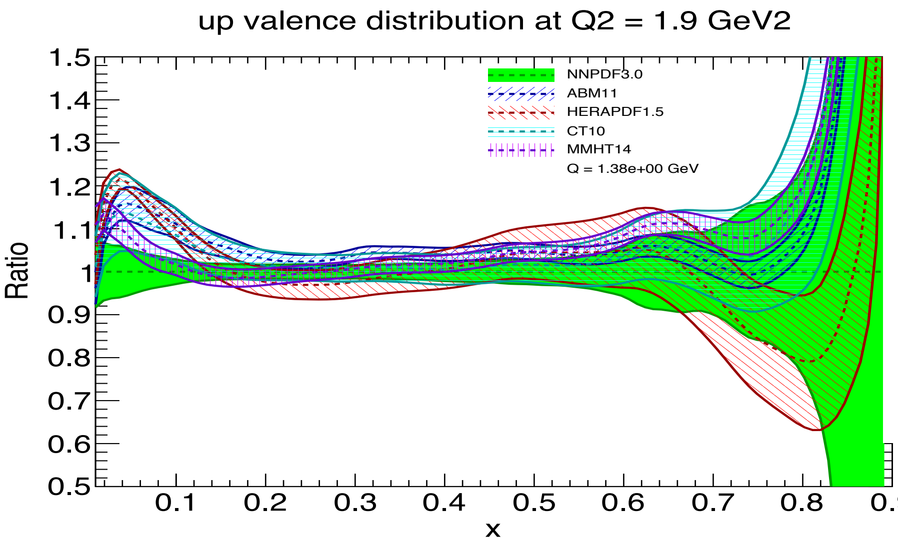


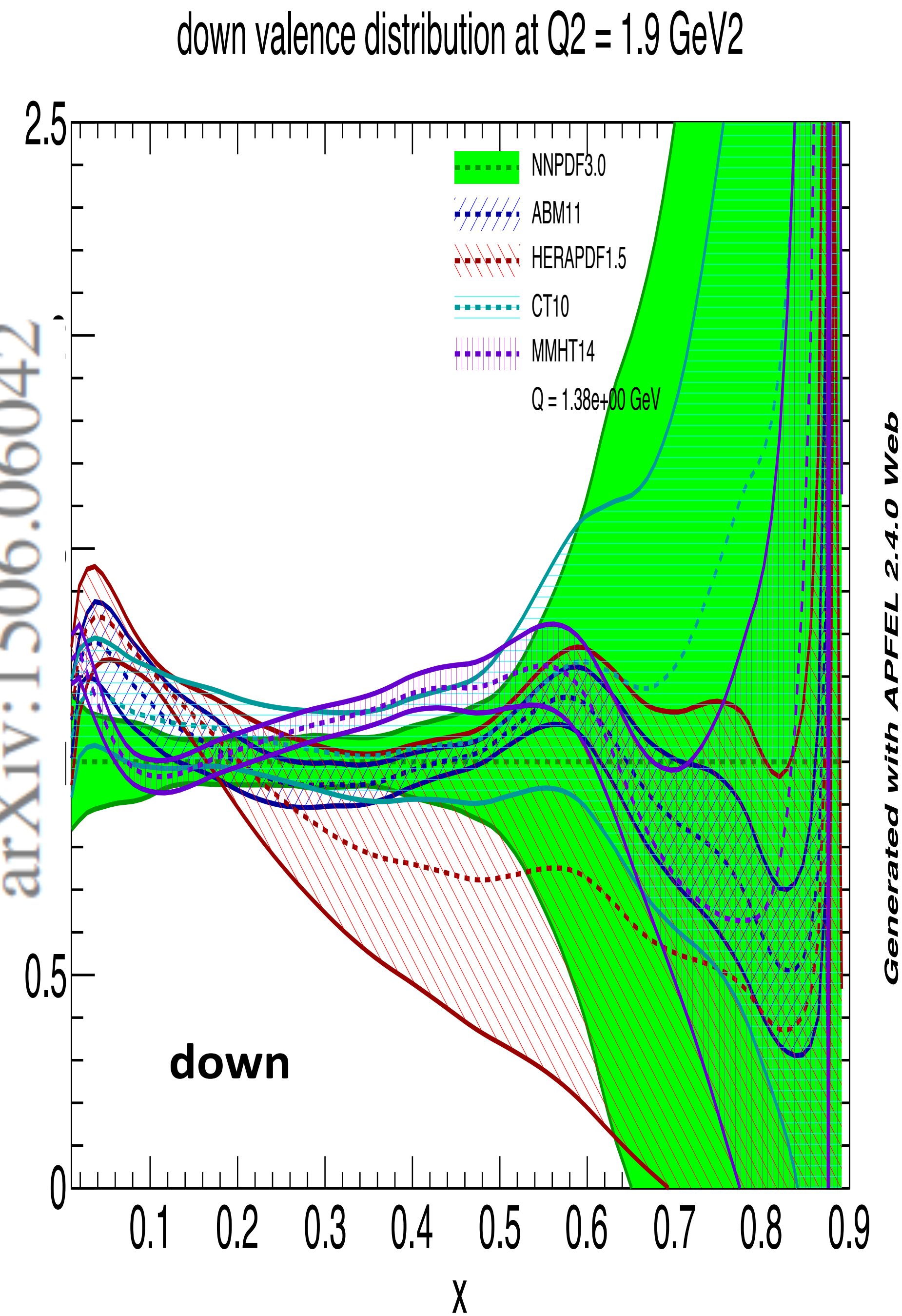
Novel LHeC physics studies focus on LHC complementarity and higher luminosity potential

Valence quarks

High x crucial for HL LHC searches
Related to DrellYan , W mass etc
d/u → 1 a classic question, still there

up

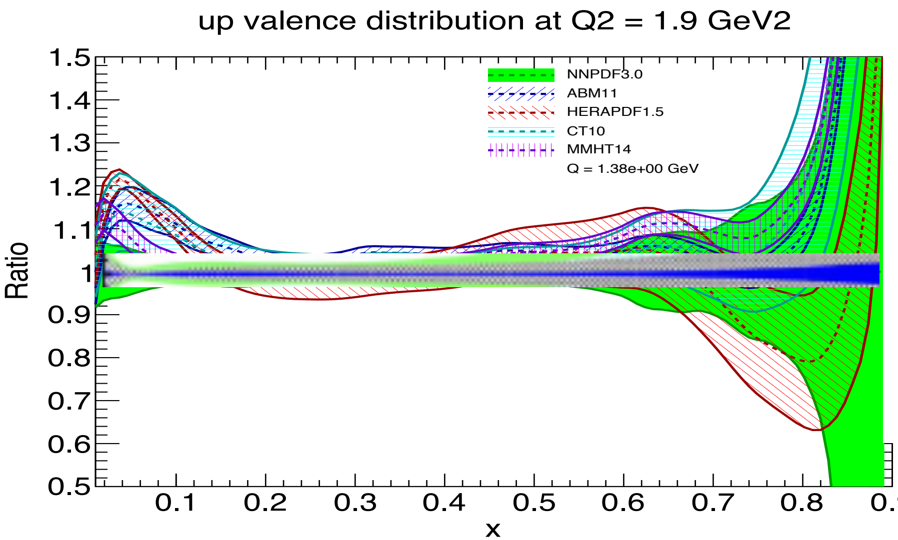


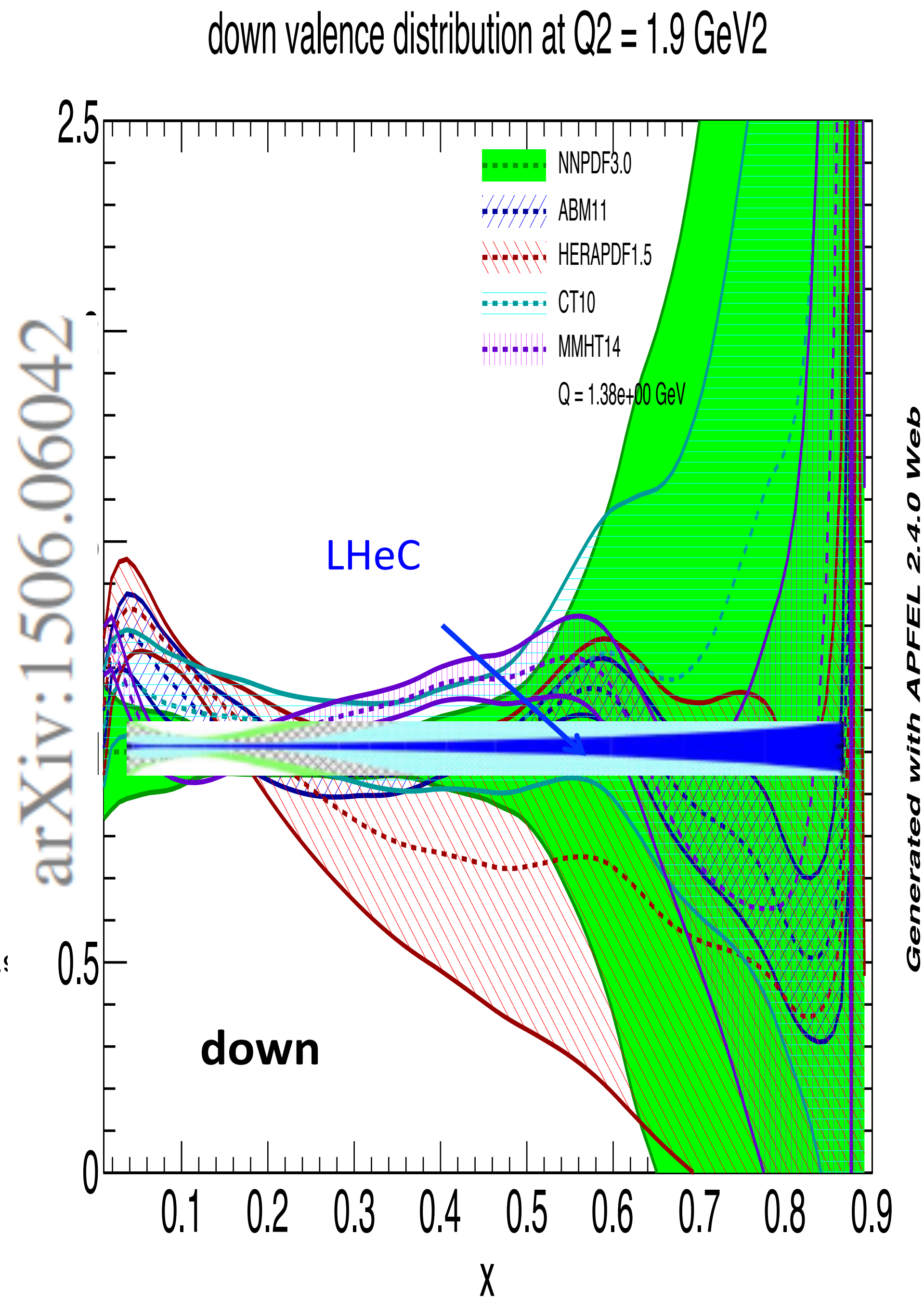


Valence quarks

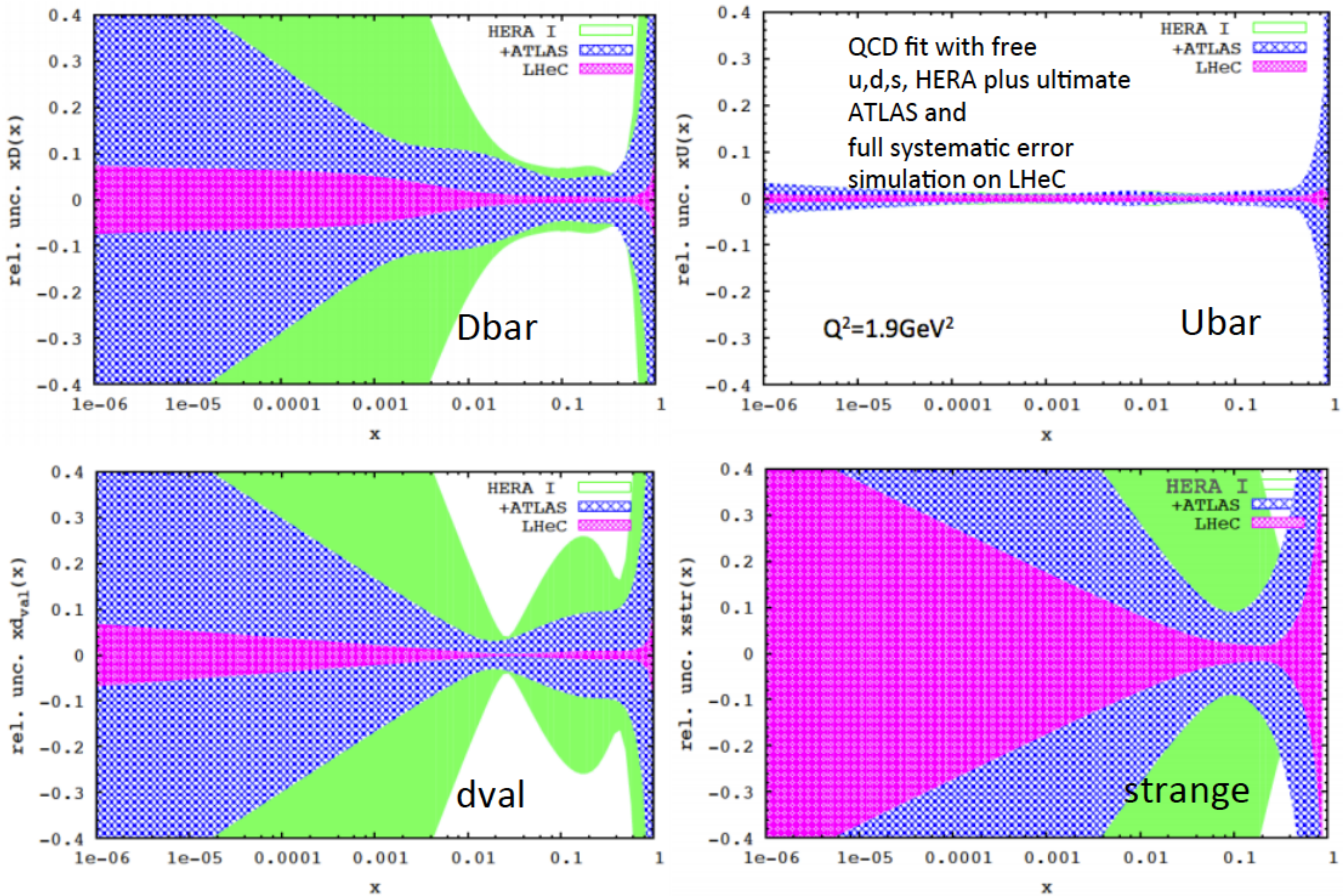
High x crucial for HL LHC searches
Related to DrellYan , W mass etc
d/u → 1 a classic question, still there

up





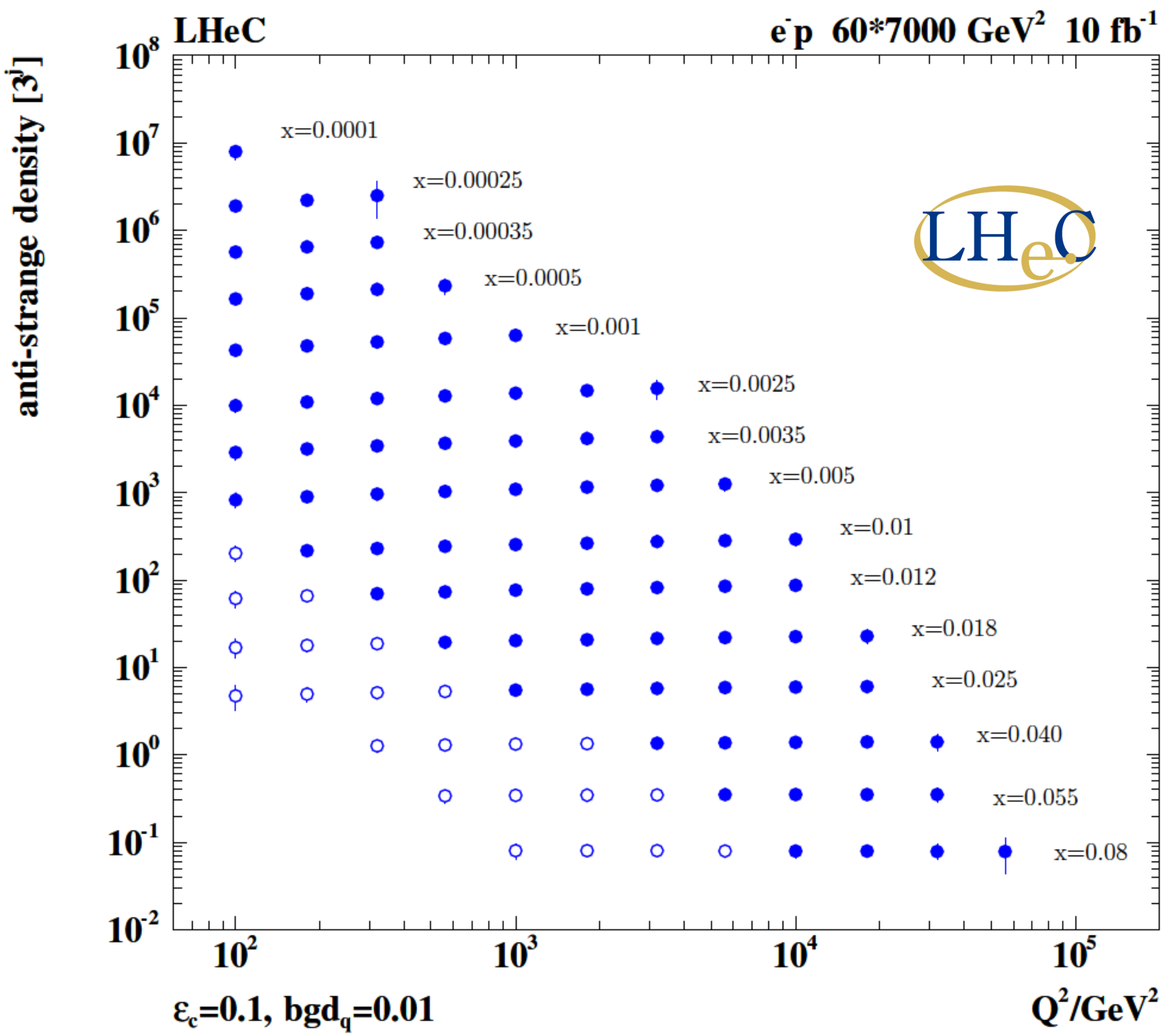
ep + pp and free fit to ū,d̄,s



Full unfolding of the PDFs (free of assumptions) including strange, charm, beauty, top, and the gluon

Leads much beyond extension of range and maximum precision in conventional analyses

Strange Quark Distribution from LHeC



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

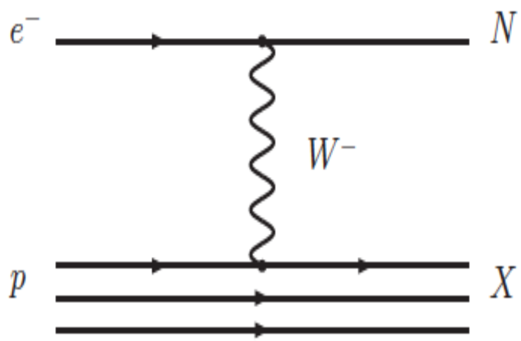
$x = 10^{-4}$ .. 0.05

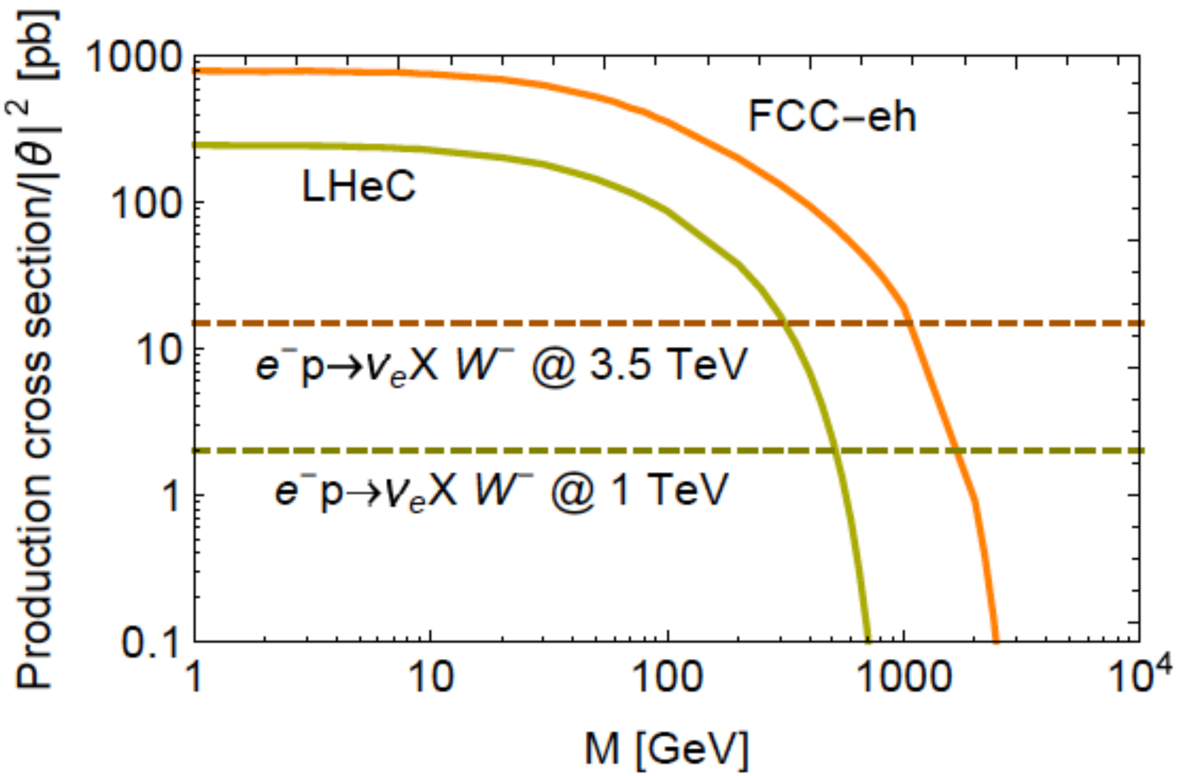
$Q^2 = 100 - 10^5\ \mathrm{GeV}^2$

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

Heavy Neutrino Search at FCC (ee,hh,eh)

Oliver Fischer
Rome Talk
Sterile Neutrinos

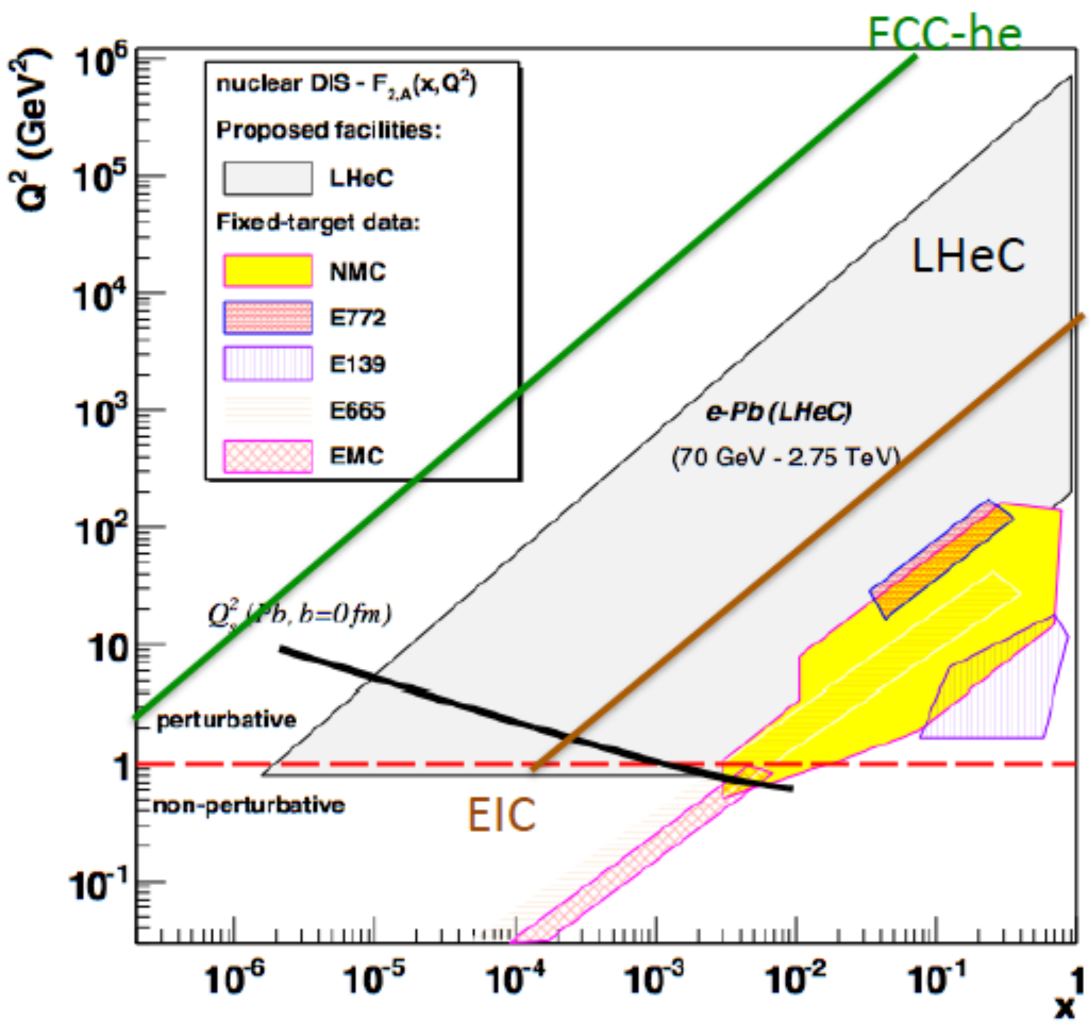




$\Rightarrow$ The FCCs provide great prospects for discovering the origin of neutrino masses.

- Future electron-proton colliders provide significant gain in mass reach and fairly "stable" production cross sections.

Future eA Colliders



Extension of kinematic range in lA by many orders of magnitude will change QCD view on nuclear structure and parton dynamics

May lead to genuine surprises…

- No saturation of xg (x,Q^2) ?
- Small fraction of diffraction ?
- Broken isospin invariance ?
- Flavour dependent shadowing ?

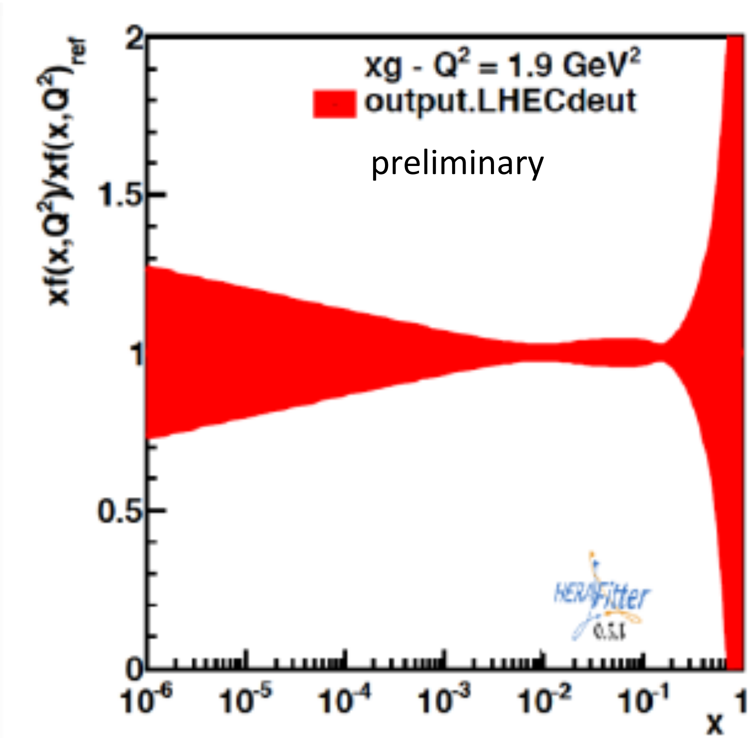
Relates to LHC Heavy Ion Physics
- Quark Gluon Plasma
- Collectivity of small nuclei (p)?
- ..

Saturation: needs large xg at small x
ep and eA

Future Nuclear PDFs with LHeC

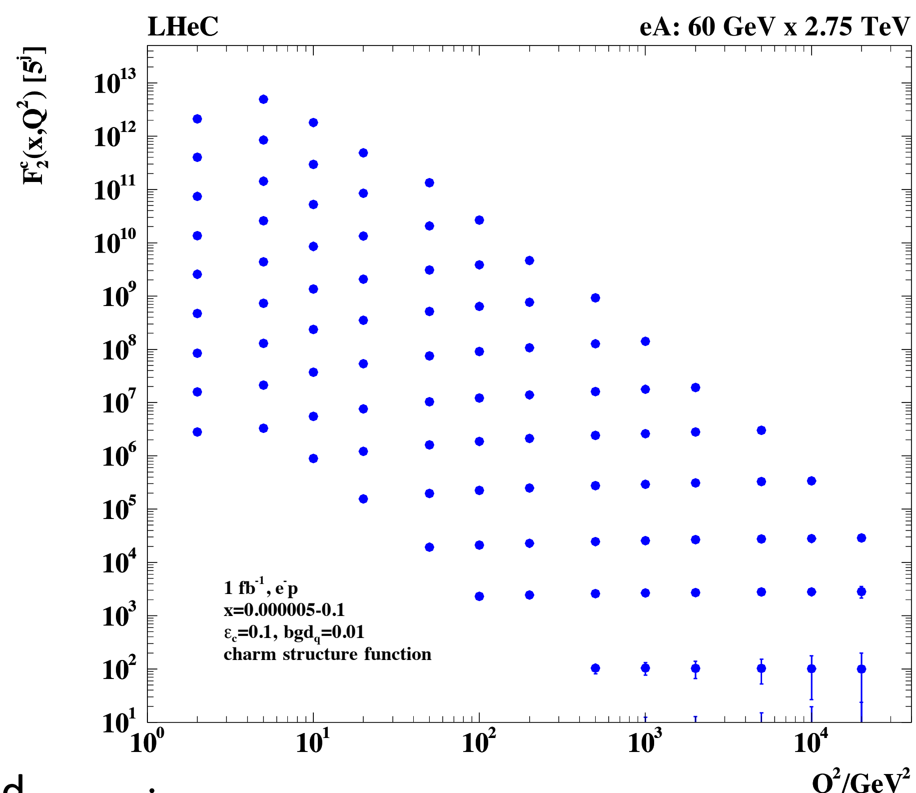
From an eA collider one can determine nuclear PDFs in a novel, the classic way.
Currently: use some proton PDF base and fit a parameterised shadowing term R.
Then: use the NC and CC eA cross sections directly and get $R(x,Q^2;p)$ as p/N PDFs.

Gluon density uncertainty in eA



1fb^{-1} of sole eA isoscalar data fitted

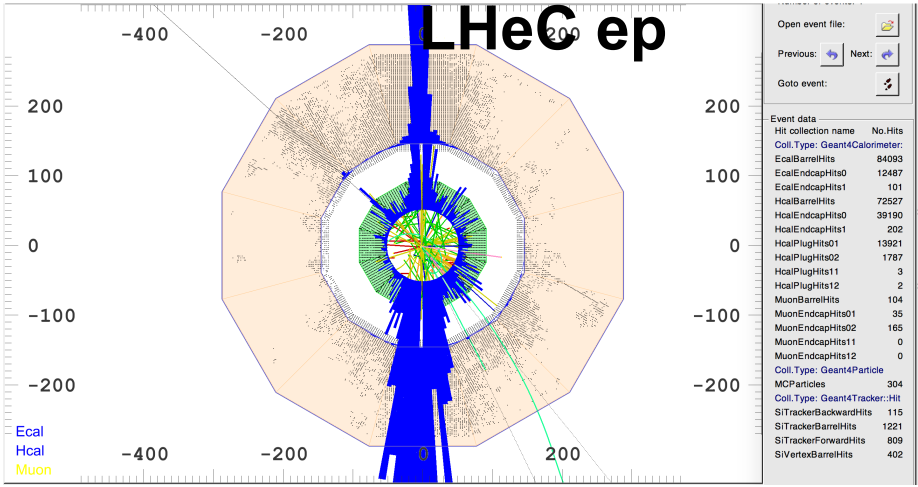
Charm density in nuclei

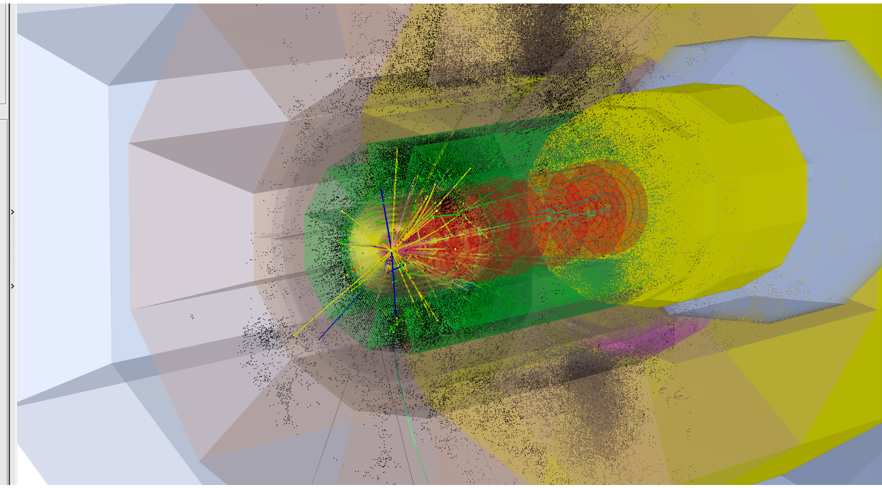


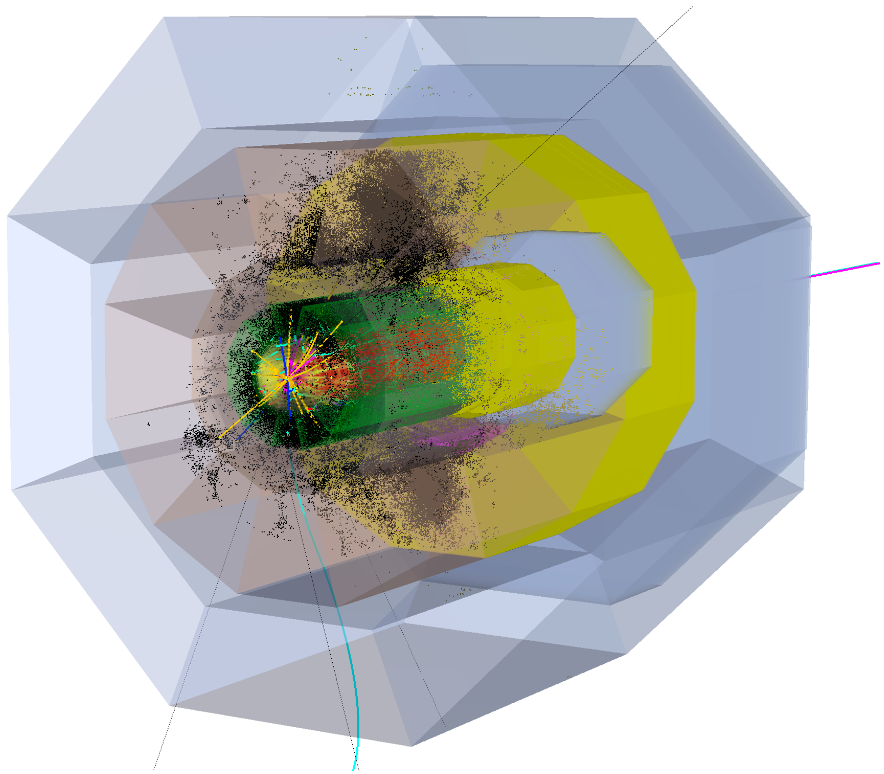
Impact parameter measurement in eA

Detector and Accelerator Studies

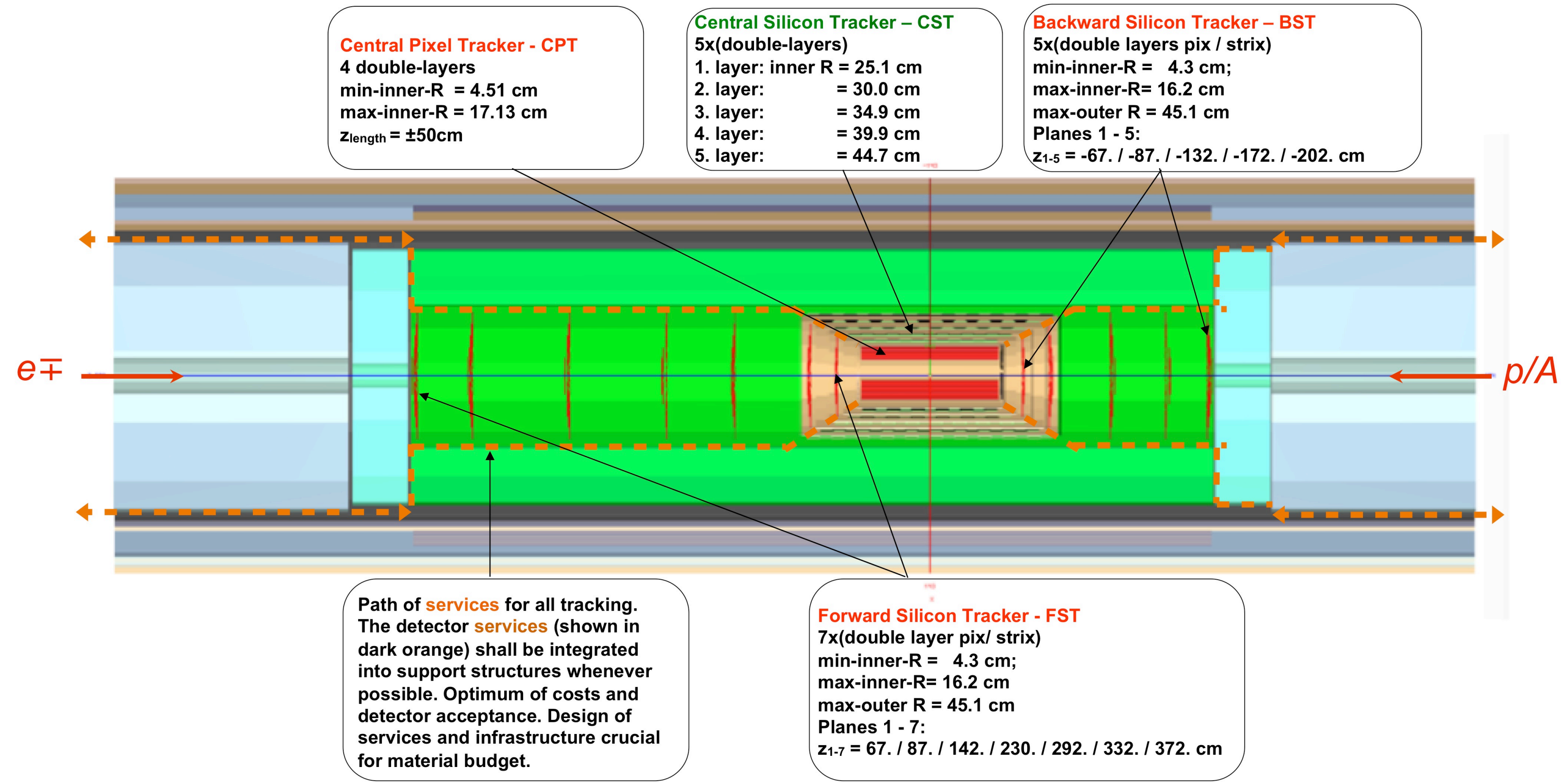
Simulation of Higgs →bb from LHeC ep





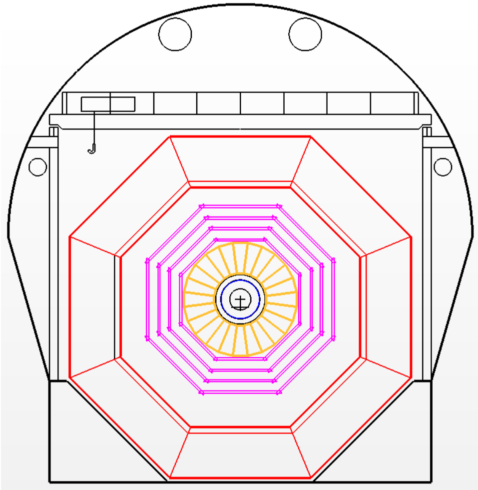


Detector design: Inner Silicon Tracker (status 3/16)

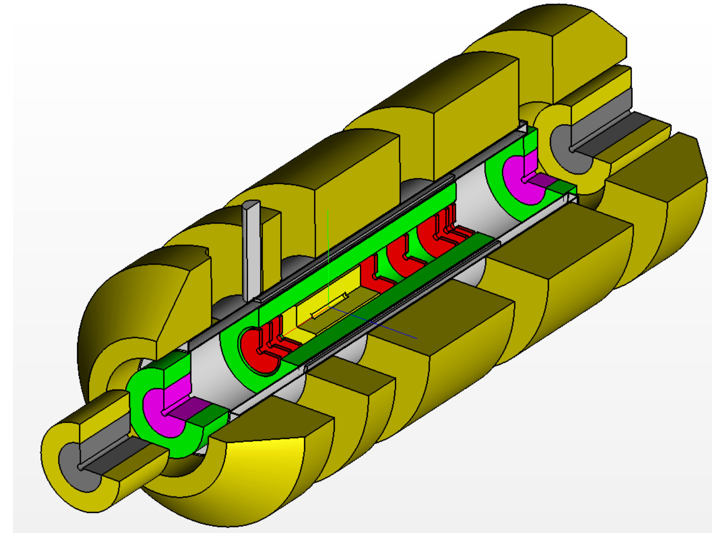


More detailed designs for other components too. DD4HEP software developments..
An opportunity for R+D and building a novel, challenging 4π detector in the twenties.
Profit from HL LHC detector upgrades, also ILC, with no pileup and small radiation load

Installation Study

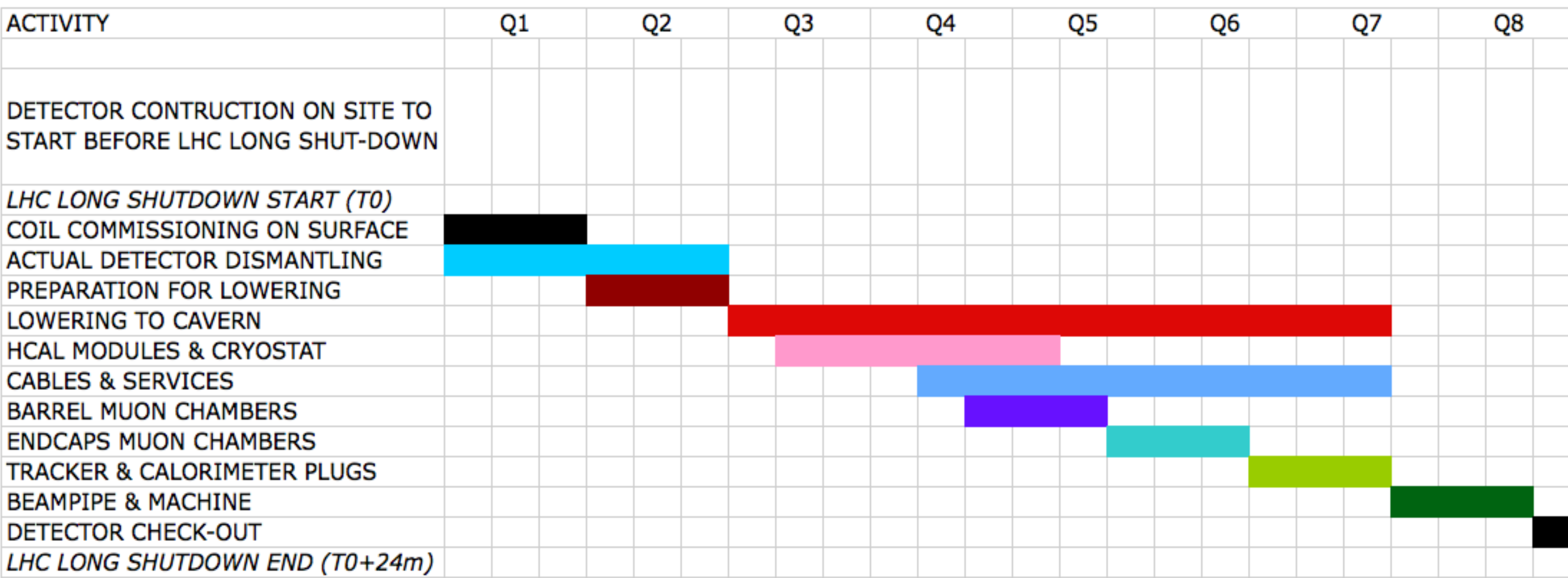


Detector fits in L3 magnet support

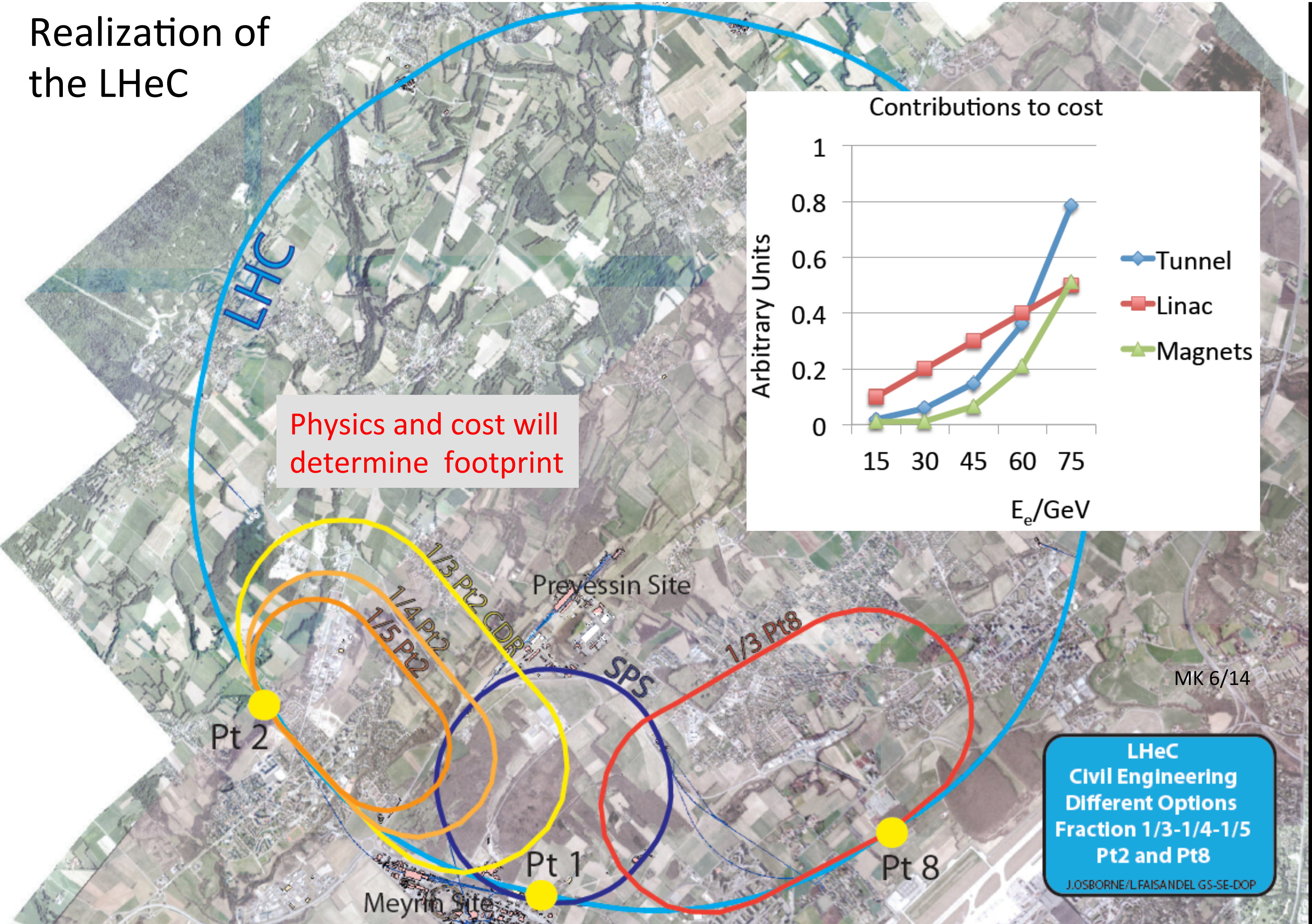


Modular structure

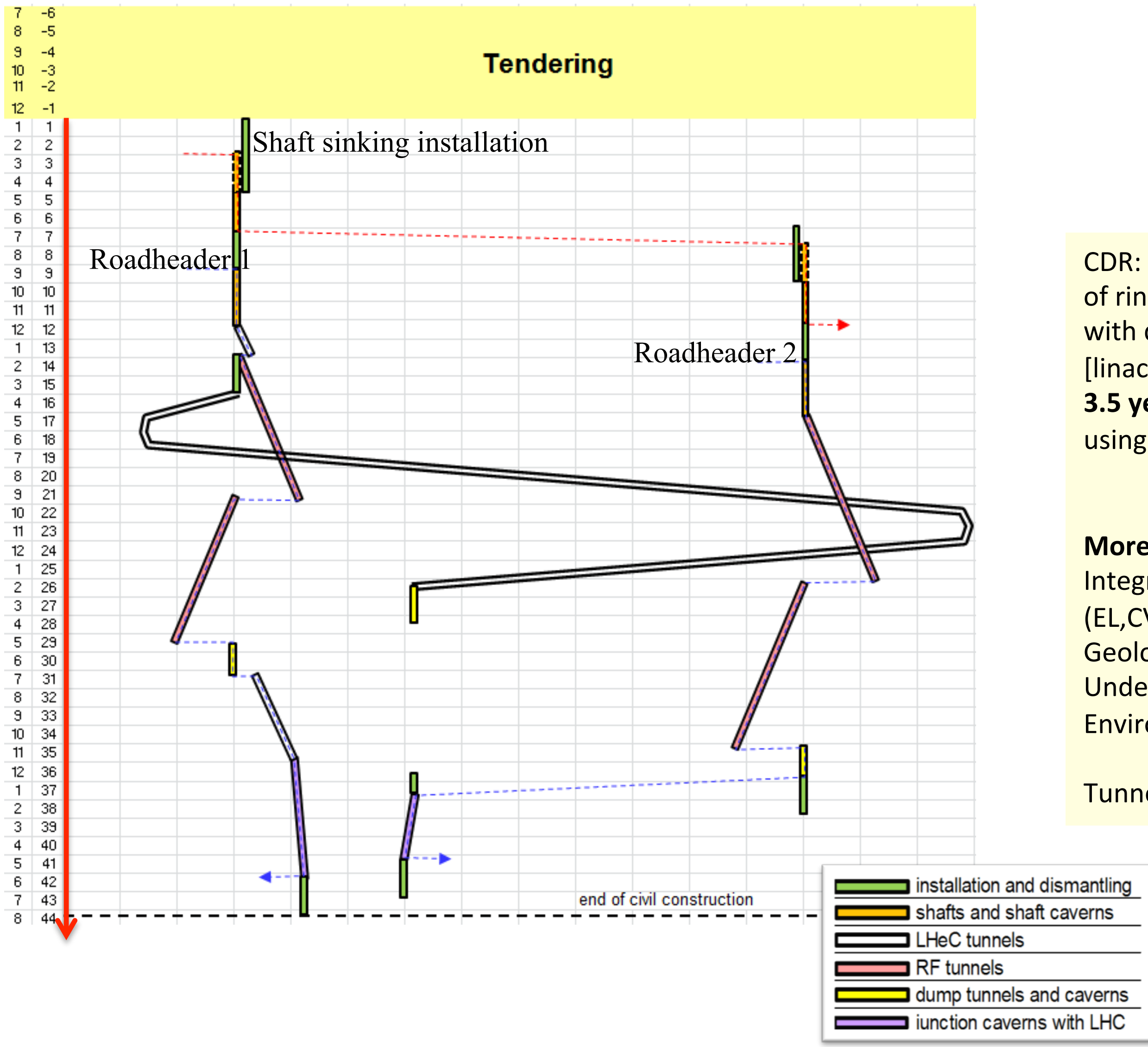
LHeC INSTALLATION SCHEDULE



Realization of the LHeC



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

Beam dynamics studies

Single particle/single bunch effects:

- *Synchrotron Radiation* in the arcs
  - 750 MeV are lost in arc 6,
  - induced energy spread (quantum excitation).
- *Beam-Beam effect*
  - Disruption of the electron beam (still need to be decelerated),
  - Stability of the proton beam (impact on the other LHC experiments).
- Short range wakefields and impedances (emittance growth).

Multi bunch effects:

- *Long range wakefields* (excitation of higher order modes in the cavities),
- Ion cloud build up.

cf Dario Pellegrini: Talk in August 2016
Accelerators for QCD, Thessaloniki

FCC-he Civil Engineering

FCC-he Point H

FCC Long Straight Section H

Tunnel Geology

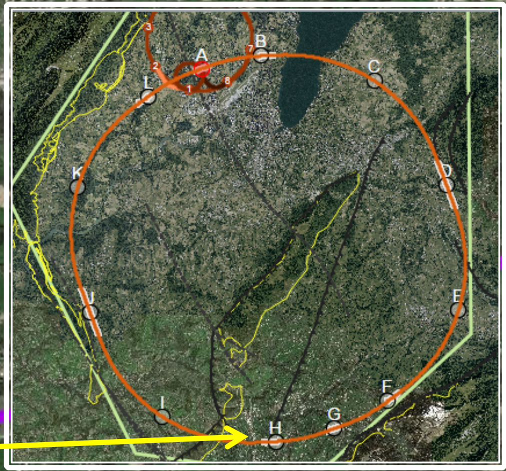
- Molasse rock (sandstone)

Construction

- Tunnel Boring Machine (TBM) in straight sections
- Roadheader in arcs

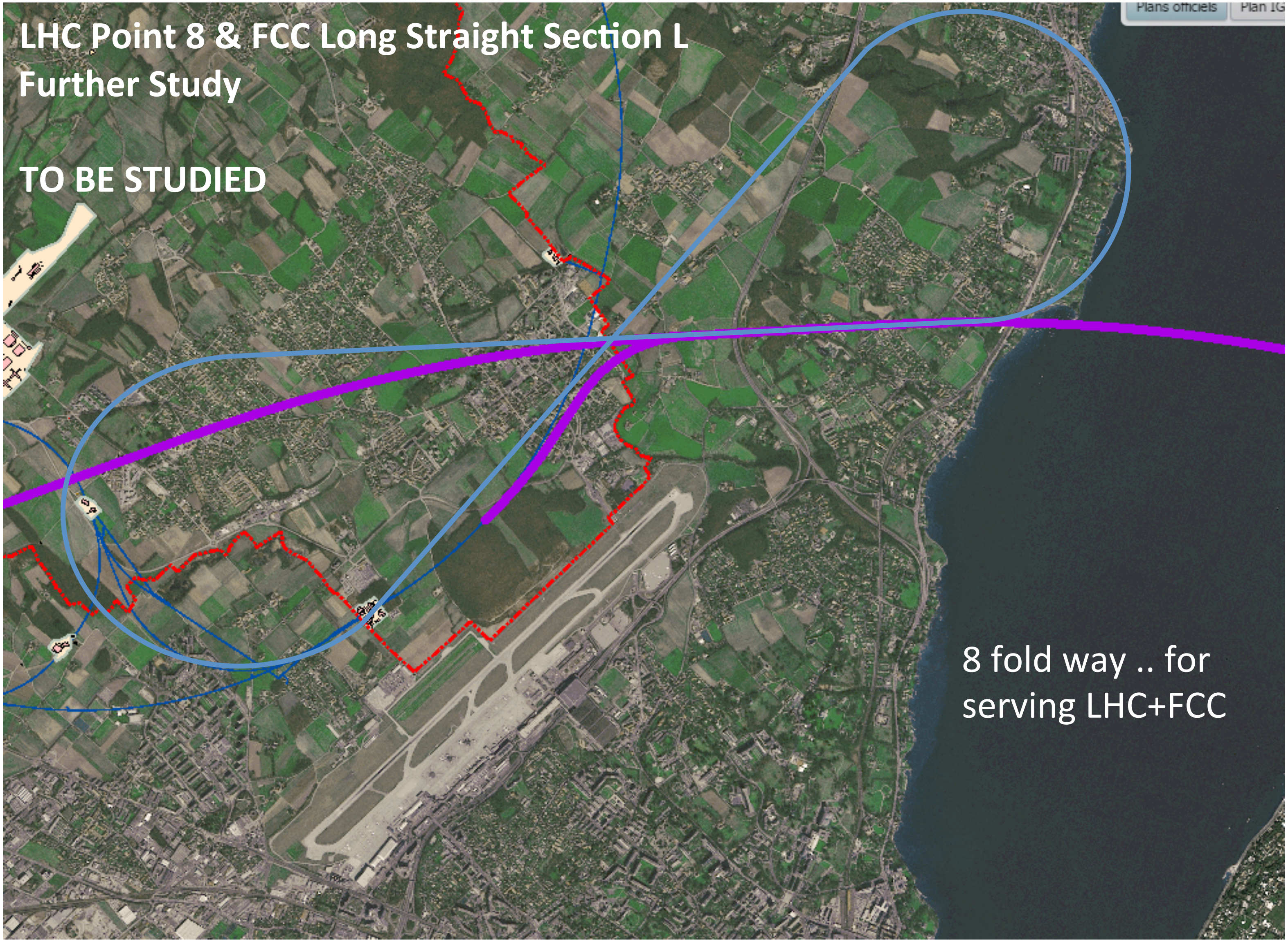
Civil Engineering challenges

- Low geological risk
- Interaction with main FCC tunnel(s)



CE: favoured eh site is point H

LHeC/FCC-he Civil Engineering



A Baseline for the FCC-he

Oliver Brüning[1] Max Klein[1,2], Daniel Schulte[1], Frank Zimmermann[1]
[1] CERN, [2] University of Liverpool
March 3rd, 2016

Table 1: Baseline parameters of future electron-proton collider configurations based on the ERL electron linac.

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	15	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.9	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.2	1
ϵ_p [μm]	3.7	2	2	2.2
electrons per bunch [10^9]	1	2.3	2.3	2.3
electron current [mA]	6.4	15	15	15
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3	1.3
luminosity [10^{33}cm^{-2}s^{-1}]	1.3	10.1	15.1	9.2

work in progress

May count on 1ab^{-1} in 10 years of OP, 1000xHERA in ep with HL LHC, with HE-LHC and with FCC_eh

Note CEPC+SEPC Options for ep in China

Project Development

Next decades

Rolf Heuer at
Aix Les Bains
1. 10. 2013

Road beyond Standard Model

LHC results vital to guide the way at the energy frontier

At the energy frontier through synergy of

hadron - hadron colliders (LHC, (V)HE-LHC?)

lepton - hadron colliders (LHeC ??)

lepton - lepton colliders (LC (**ILC** or CLIC) ?)

Mandate and Goals

LHeC: Following the CDR in 2012: 2014+16: CERN DGs issued Mandate to continue the study:

DG: Mandate to the International Advisory Committee 2015-2018

Advice to the LHeC Coordination Group and the CERN directorate by following the development of options of an ep/eA collider at the LHC and at FCC, especially with:

Provision of scientific and technical direction for the physics potential of the ep/eA collider, both at LHC and at FCC, as a function of the machine parameters and of a realistic detector design, as well as for the design and possible approval of an ERL test facility at CERN.

Assistance in building the international case for the accelerator and detector developments as well as guidance to the resource, infrastructure and science policy aspects of the ep/eA collider.

Chair: Herwig Schopper

Two major next goals:

-Design and build an LHeC ERL demonstrator (10mA, 3 turn, 802 MHz)

-Update of the CDR by 2018: LHC physics, 10^{34} lumi, detector and accelerator updates

FCC-eh: Utilize the LHeC design study to describe baseline ep/A option.
Emphasis: 3 TeV physics, IR and Detector: synchronous ep-pp operation.
Open to other configurations and new physics developments (750..)

Organisation*)

International Advisory Committee

"..Direction for ep/A both at LHC+FCC"

Sergio Bertolucci (CERN/Bologna)
Nichola Bianchi (Frascati)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Victor A Matveev (JINR Dubna)
Shin-Ichi Kurokawa (Tsukuba)
Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Herwig Schopper (CERN) – Chair
Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (STFC)

IAC being renewed by new DG
We lost Guido Altarelli.

*)August 2016

Coordination Group

Accelerator+Detector+Physics

Nestor Armesto
Oliver Brüning – Co-Chair
Stefano Forte
Andrea Gaddi
Erk Jensen
Max Klein – Co-Chair
Peter Kostka
Bruce Mellado
Paul Newman
Daniel Schulte
Frank Zimmermann

5(11) are members of the FCC coordination team

OB+MK: FCC-eh responsibles
MDO: physics co-convenor

Working Groups

PDFs, QCD
Fred Olness,
Voica Radescu
Higgs
Uta Klein,
Masahiro Kuze
BSM
Georges Azuelos,
Monica D'Onofrio
Top
Olaf Behnke,
Christian Schwanenberger
eA Physics
Nestor Armesto
Small x
Paul Newman,
Anna Stasto
Detector
Alessandro Polini
Peter Kostka

Electron-Hadron Scattering at the Energy Frontier –
A Higgs Physics Facility Resolving the Substructure of Matter

Draft Table of Contents (9. June 2016)

1. Introduction: The LHC, Modern Particle Physics and the Rôle of ep/eA
2. Physics: QCD/PDFs, Higgs, top, BSM, small x, eA at the LHeC; key items at 1.9/3.4 TeV
3. ERL electron beam: Design, Components, Injector, Dump, Civil Engineering ..
4. LHeC Performance: Collider Parameters, Luminosity, Joint Operation, Infrastructure..
5. Detector: Machine Interface (IR), Design and Performance, Components, Software
6. Installation of the Machine and Detector
7. Summary

Appendix:

- Status of the LHeC Demonstrator and ERL Developments
- Cost-Energy Relation and Cost Estimate for LHeC
- Detector Cost Estimate
- Extensions into the HE LHC Phase
- Electron-Hadron Scattering with the FCC (link to FCC CDR)

LHeC CDR update because:

- Lumi * 10
- LHC results
- Technology progress

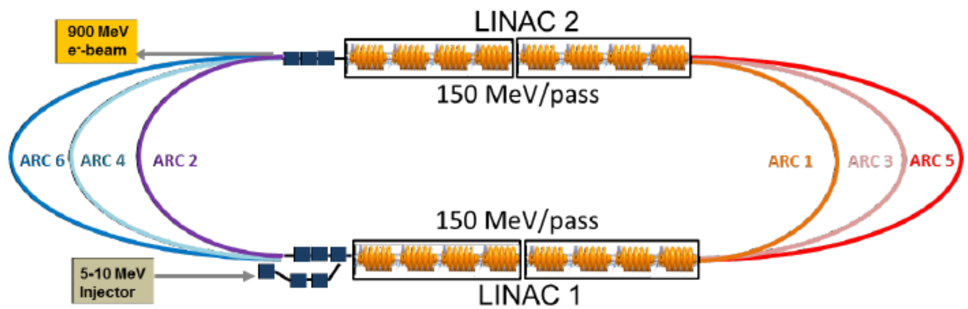
Open for any participation

Update of the LHeC CDR*) and input to EU Particle and Nuclear Physics Strategy

*) arXiv:1206.2913

PERLE

Powerful energy
recovery linac experiments



Conceptual Design Report

Draft 1.3 November 10^{th}, 2016

CELIA Bordeaux, MIT Boston, CERN, Cockcroft and Astec
Daresbury, TU Darmstadt, U Liverpool, Jefferson Lab
Newport News, BINP Novosibirsk, IPNO and LAL Orsay

CDR of ERL demonstrator, and test facility with physics applications and technology goals, soon out

Cf also ICFA beam Newsletter 68/2016

Physics
ep
R(p), $\sin^2\theta$
Dark photons
γp
1000*L(ELI)
Eγ>30keV
→ Unique photo-nuclear Physics

Technology
High Ie ~ 10mA
Multiturn ERL
SC RF
Cryomodules
Operation

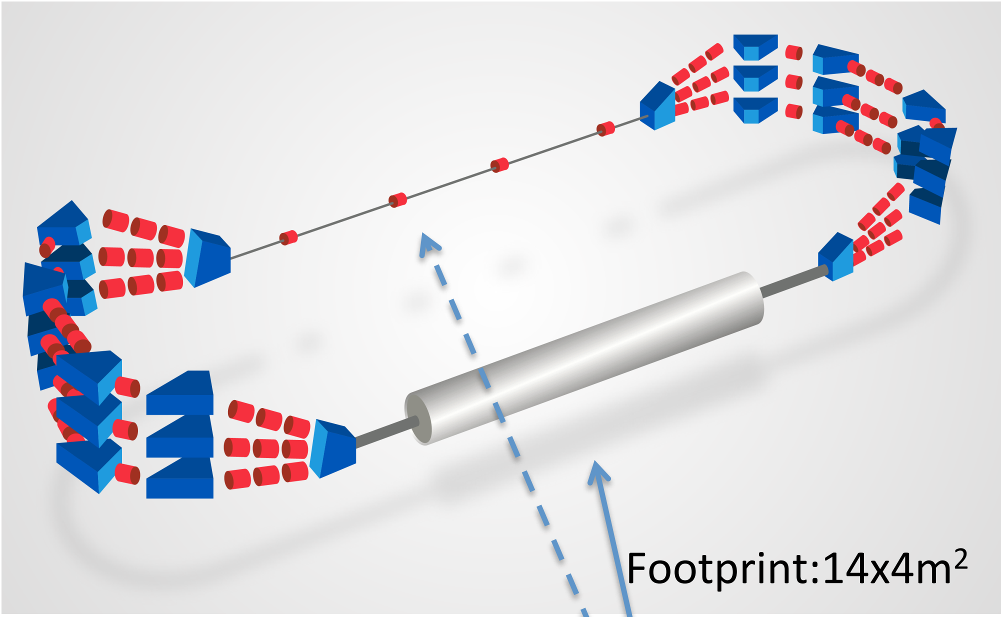
Testfacility 1^{st}
Userfacility 2^{nd}

ERL Testfacility

Demonstration of high current (10mA), multi(3)turn ERL

Test and development of 802MHz SCRF technology

E_e = 200 (400) MeV with 1(2) module which houses four 5-cell cavities



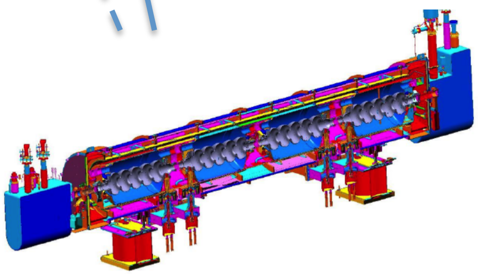


Figure 3.9: SNS high β module adapted to house β =1 5-cell cavities for LHeC.

Parameter	Value
Dipoles per arc Dipole length Max B Field	3/4 50 cm 1.1 T
Quadrupoles per arc Quadrupoles in straight lines	5 4
Dipoles in Spreader/Combiner Quads in Spreader/Combiner	1-3 3
Dipoles for Injection-Extraction	6

“PERLE” CDR to be published, ICFA Beam Newsletter 68 (2016)

BINP, CERN, Daresbury, Jlab, Liverpool, Orsay (LAL/IPN),+

Technical Design as next goal
802 MHz cavity soon produced

802 MHz Cavity Parameters

design to also test FCC-ee

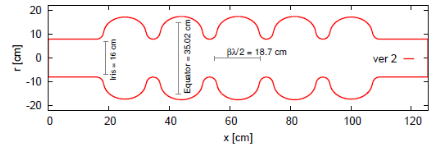
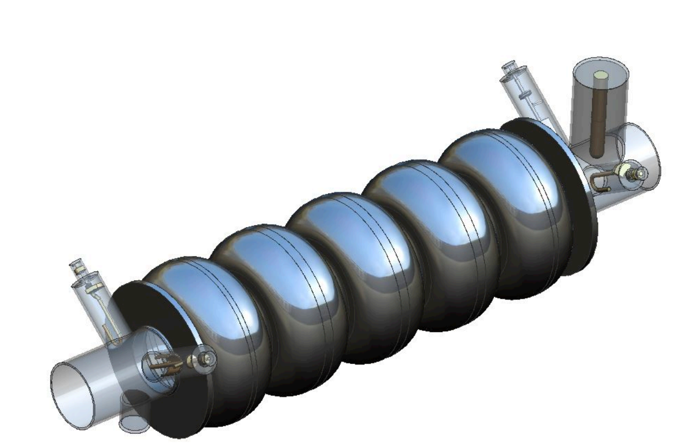


Fig. 6: Envelope of the second version of the five-cell ERL cavity at 802 MHz with 16 cm aperture.

CERN-ACC-NOTE-2015-xxx
28-05-2015
Rama.Calaga@cern.ch

Parameter	Unit	Value	Value	Value		Value	
cavity type		**LHeC prototype (2016)**	LHeC study (2015)	LHeC study (2015)		LHeC Ver. 1	LHeC Ver. 2
frequency	MHz	**801.58**	802	802		801.58	801.58
number of cells		**5**	5	5		5	5
L_{active}	mm	**917.91**	922.31	922.14		935	935
$R/Q = V_{eff}^2/(\omega * W)$	Ω	**523.7**	580.1	[illegible]	[illegible]	[illegible]	[illegible]
R/Q/cell	Ω	**104.7**	116.0	[illegible]	[illegible]	[illegible]	[illegible]
G	Ω	**274.6**	273.2	[illegible]	[illegible]	[illegible]	[illegible]
R/Q·G/cell		**28765**	31702	[illegible]	[illegible]	[illegible]	[illegible]
Eq. Diameter	mm	**327.95**	323.12	[illegible]	[illegible]	[illegible]	[illegible]
Iris Diameter	mm	**130**	115	[illegible]	[illegible]	[illegible]	[illegible]
Tube Diameter	mm	**130**	140	[illegible]	[illegible]	[illegible]	[illegible]
Eq./Iris ratio		**2.52**	2.81	[illegible]	[illegible]	[illegible]	[illegible]
Wall angle (mid-cell)	deg	**0**	0	[illegible]	[illegible]	[illegible]	[illegible]
E_{peak}/E_{acc} (mid-cell)		**2.26**	2.07	[illegible]	[illegible]	[illegible]	[illegible]
B_{peak}/E_{acc} (mid-cell)	mT/(MV/m)	**4.20**	4.00	4.00		4.77	4.92
k_{cc}	%	**3.22**	2.14	2.14		4.47	5.75
N^2/k_{cc}		**7.78**	11.71	11.71		5.59	4.35
cutoff TE_{11}	GHz	**1.35**	1.26	1.53		1.17	1.10
cutoff TM_{01}	GHz	**1.77**	1.64	2.00		1.53	1.43



Detail end group + flange locations → build

F.Marhauser, B.Rimmer, J.Henry (Jlab) + R.Calaga, E.Jensen, K. Schirm et al (CERN) [4.8.16]

"The future belongs to those who believe in the beauty of their dreams."

Anna Eleanor Roosevelt
(1884-1962)

Universal Declaration of Human Rights (1948)

cited by Frank Zimmermann at the FCC Meeting at Washington DC, March 2015

QCD - Developments and Discoveries

AdS/CFT

Instantons

Odderons

Non pQCD

QGP

N^kLO

Resummation

Saturation and BFKL

Non-conventional PDFs …

Breaking of Factorisation

Free Quarks

Unconfined Color

New kind of coloured matter

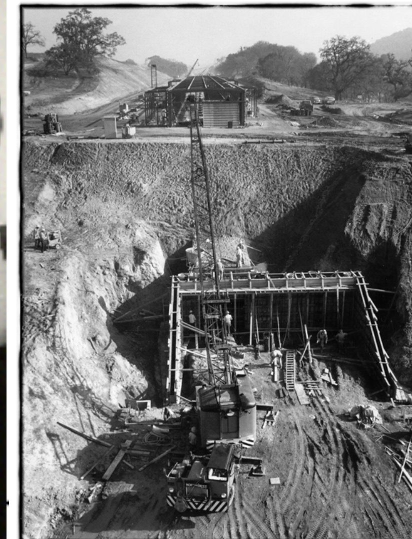
Quark substructure

New symmetry embedding QCD

QCD may break .. (Quigg DIS13)

QCD is the richest part of the Standard Model Gauge Field Theory and will (have to) be developed much further, on its own and as background.

can one build a 2 km long linac?

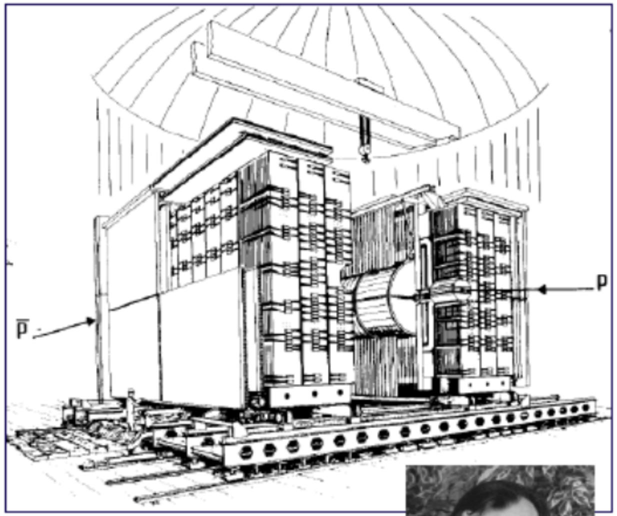


it has been done before

Courtesy F.Zimmermann

Can CERN host pp and DIS at once?

.. in the 80ies it successfully did



UA1

“ We have two tasks: kill Weinberg Salam, kill QCD”
Carlo Rubbia: 1978 BCDMS meeting at Dubna.
The failure to fulfill his task made Carlo famous…

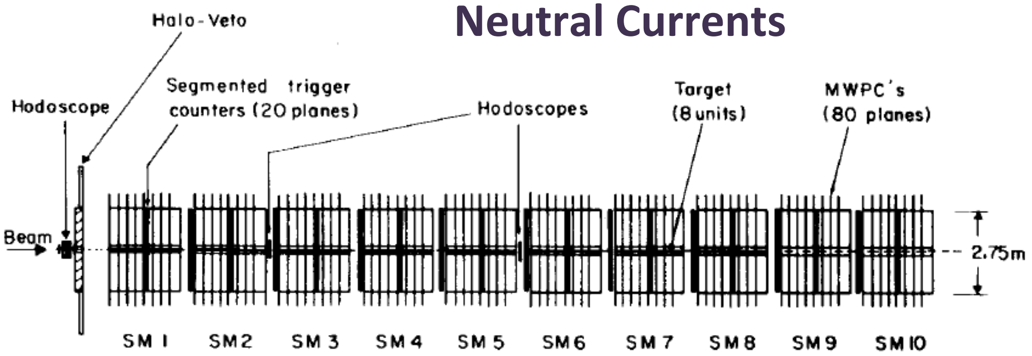
UA2

Pierre Darriulat
now in Vietnam

Charged Currents

BEBC, **CDHS(W)**, CHARM, CHORUS

Neutral Currents



BCDMS, EMC, SMC, COMPASS

Concluding Remarks

- The LHeC may be built as an ERL racetrack accelerator tangential to the LHC
- The current LHC schedule points to LS4, in 2028/29, for a possible installation
- The luminosity reach is $10^{34} cm^{-2} s^{-1}$ at 60 GeV, with $L \sim 1/E_e$ at fixed power
- The default energy is 60 GeV (for Higgs, top and low x physics).
- E_e may be larger if LHC discovers sth (750 GeV γγ was at the edge..)
- E_e may be chosen to be smaller for cost and effort and schedule reasons

- The LHeC would be the cleanest microscope the world may build and
- a unique Higgs laboratory enabling to transform the LHC into a precision facility
- The eA programme is set to revolutionize the QCD of nuclear dynamics+structure

- The linac-ring configuration allows for one novel detector (two teams?)
- The LHeC detector may be the next "GPD" apparatus PP can build
- A modular structure and on surface premounting enable installation in 2 years

- Following a CERN DG mandate, an organisation is established to lead to EU 2019
- The development of the LHC, physics and technology call for a CDR update by 18
- A 3 turn, 10mA, 802 MHz, 2-400 MeV ERL facility (PERLE) is under design
- PERLE is a development ground for the LHeC ERL concept and SCRF technology

- Physics (ep+eA) and technology make EIC and LHeC partners henceforth

Logo of the CDR

W.Kandinsky: "Circles in a cirle" (1923) Philadelphia (USA) Museum of Art

First shown in LHeC context in a talk by A.S.Vera Workshop 2008

Many thanks to all LHeC/FCC-eh collaborators, the IAC, to CERN and our labs

“BFKL evolution and Saturation in DIS”

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

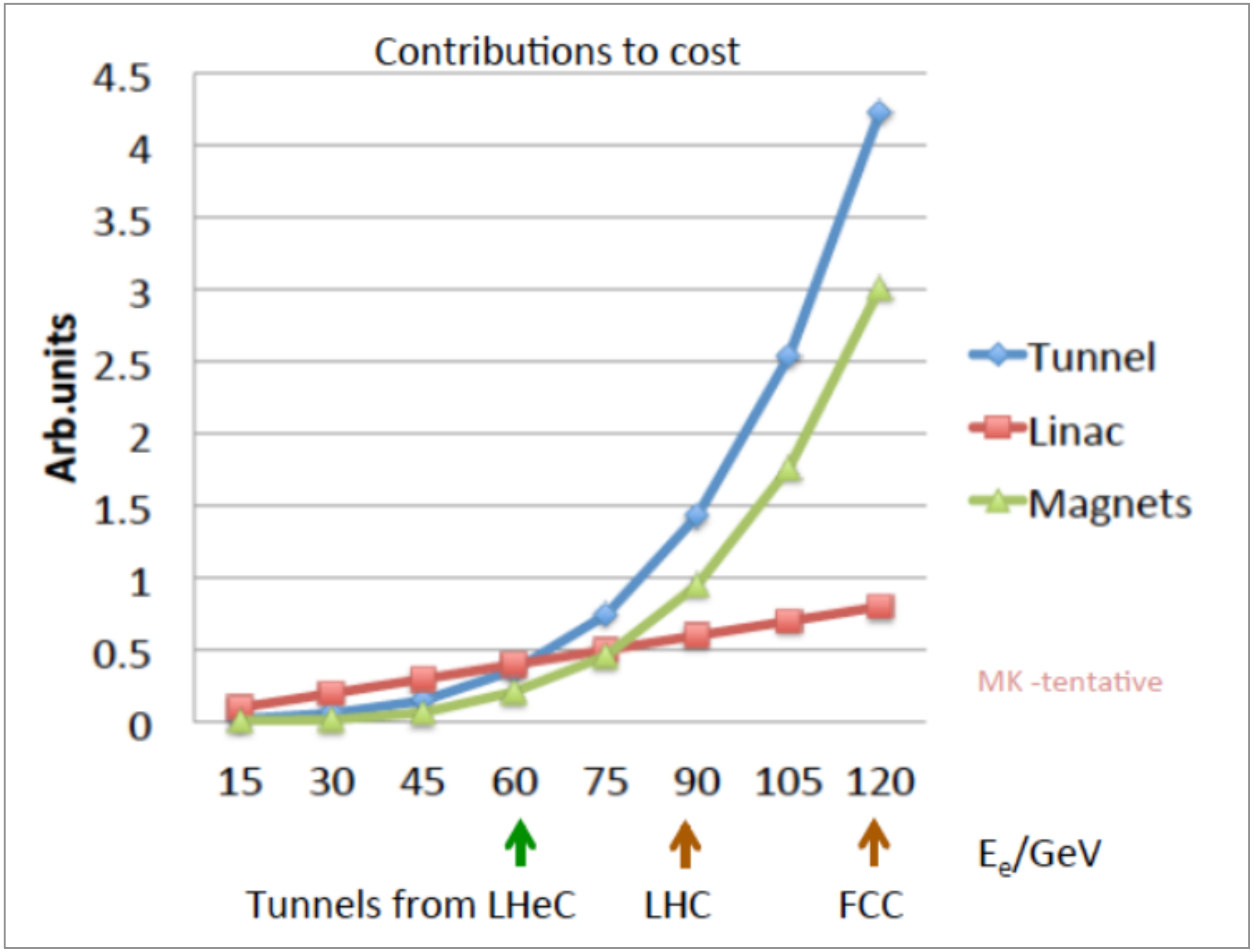
LHeC

“Critical gravitational collapse”

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

title

Choice of FCC_eh Baseline Configuration = f(cost,E_e,s)



→ Cost strongly rising with tunnel circumference. Presently stick to LHeC default.
→ Maximise independence of ring installation, design for synchronous ep and pp OP

Low x

xg for x < 10^{-4} not known, it is not unknown above.

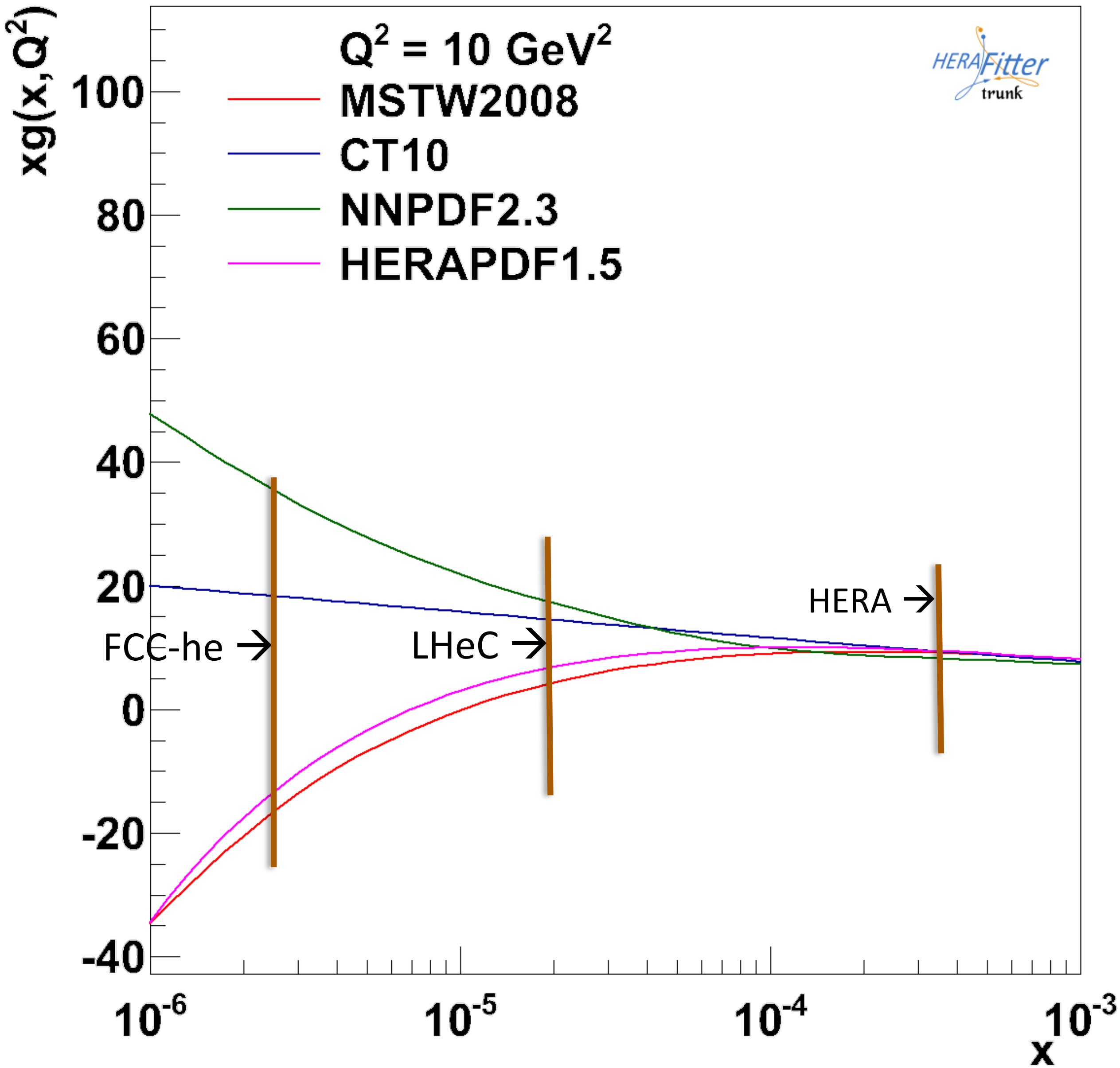
Low x evolution law unlikely linear DGLAP

HERA: where is BFKL?

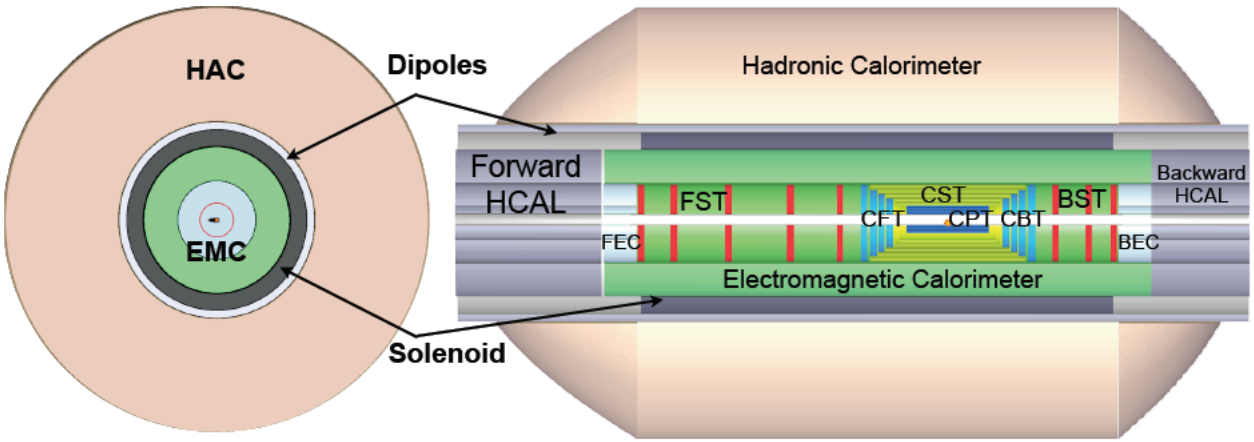
Needs precision F_2 and F_L in extended x range

Search for Saturation requires xg to be large and α_s to be small → Q^2 ought to be > 10 GeV^2

Affects pp rates because x=M/√(s) exp(+-y)



Liquid Argon Electromagnetic Calorimeter



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

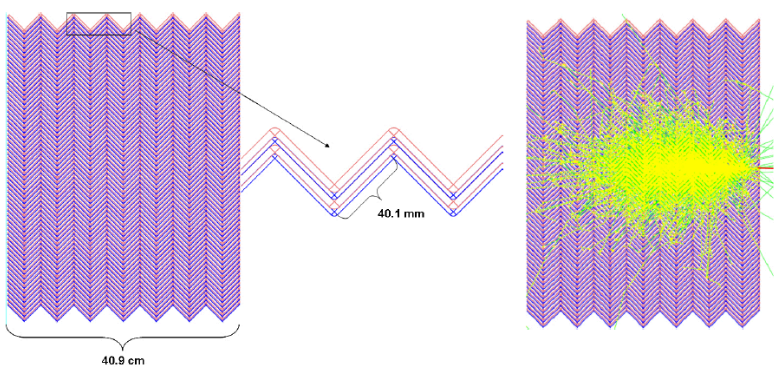


Figure 13.35: View of the parallel geometry accordion calorimeter (left) and simulation of a single electron shower with initial energy of 20 GeV (right).

GEANT4 Simulation

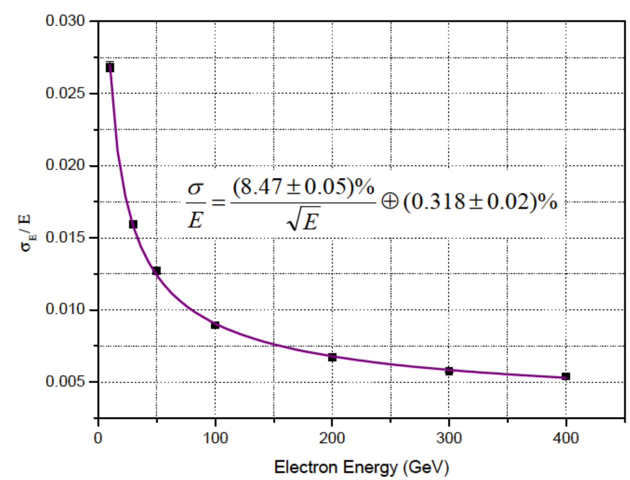


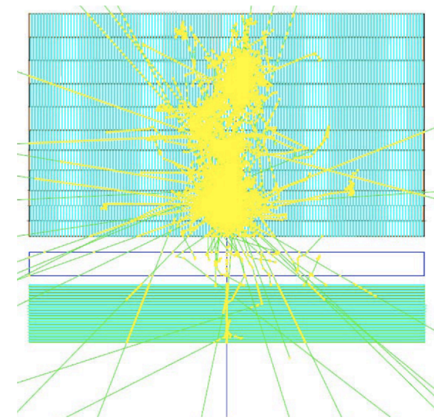
Figure 13.36: LAr accordion calorimeter energy resolution for electrons between 10 and 400 GeV.

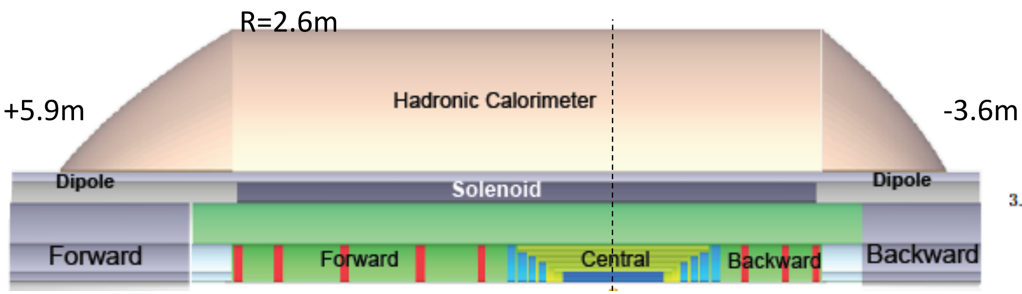
Hadronic Tile Calorimeter

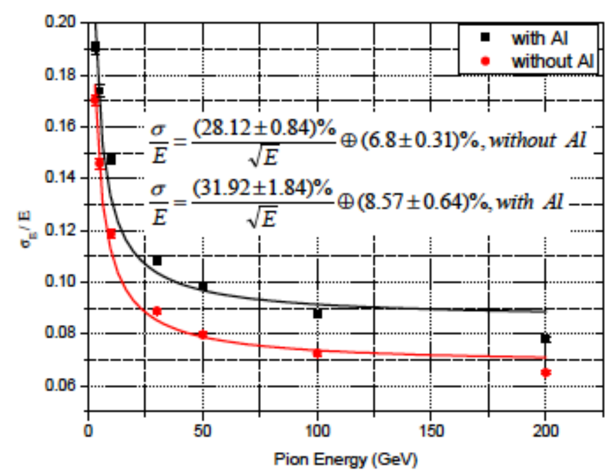
Outside Coil: flux return
Modular. ATLAS experience.

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.

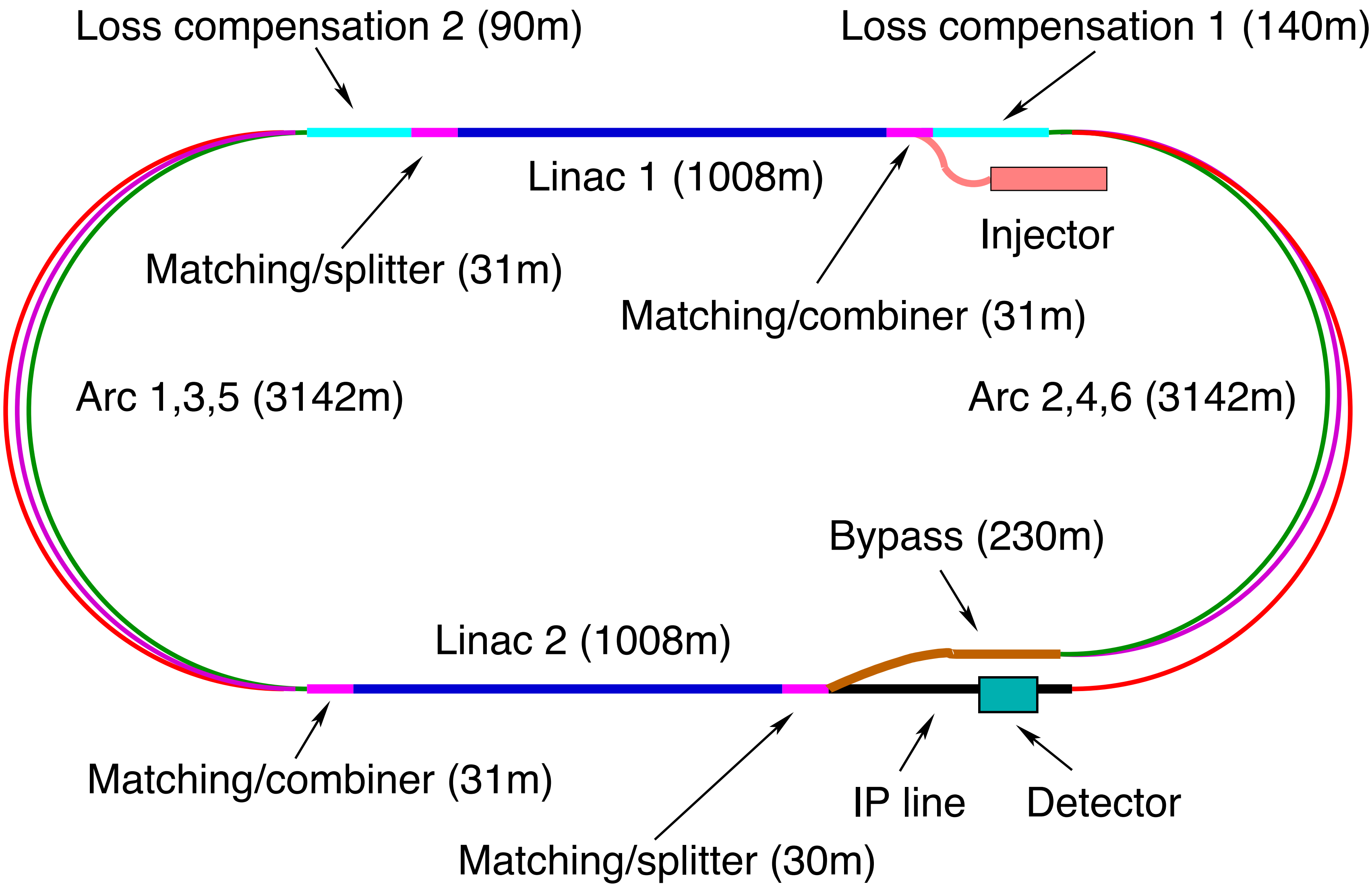






3.37: Accordion and Tile Calorimeter energy resolution for pions with and without 14cm Al block.

Combined GEANT4 Calorimeter Simulation



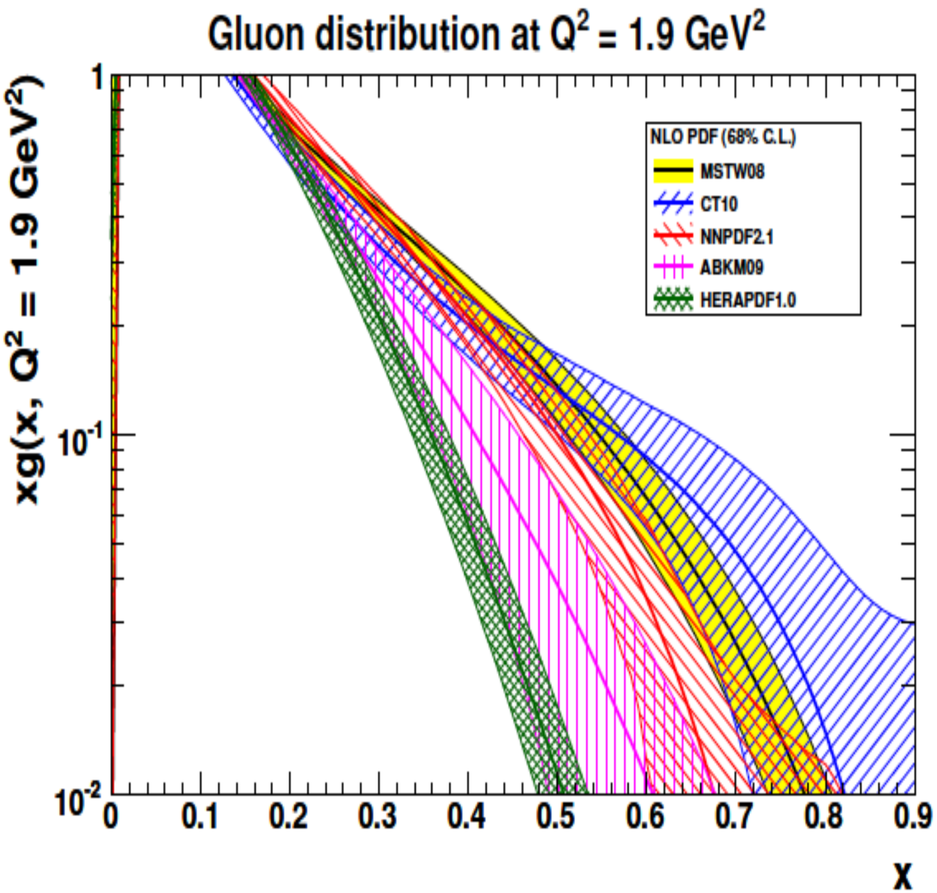
60 GeV electron beam energy, L= 10^{33-34} $cm^{-2}s^{-1}$, √s=1.3 TeV: Q^2_{max}= 2 10^6 GeV^2, ~10^{-6} < x< 1
Recirculating linac (2 * 1km, 2*60 cavity cryo modules, 3 passes, energy recovery)

A Revival of electron-proton (ion) colliders following HERA

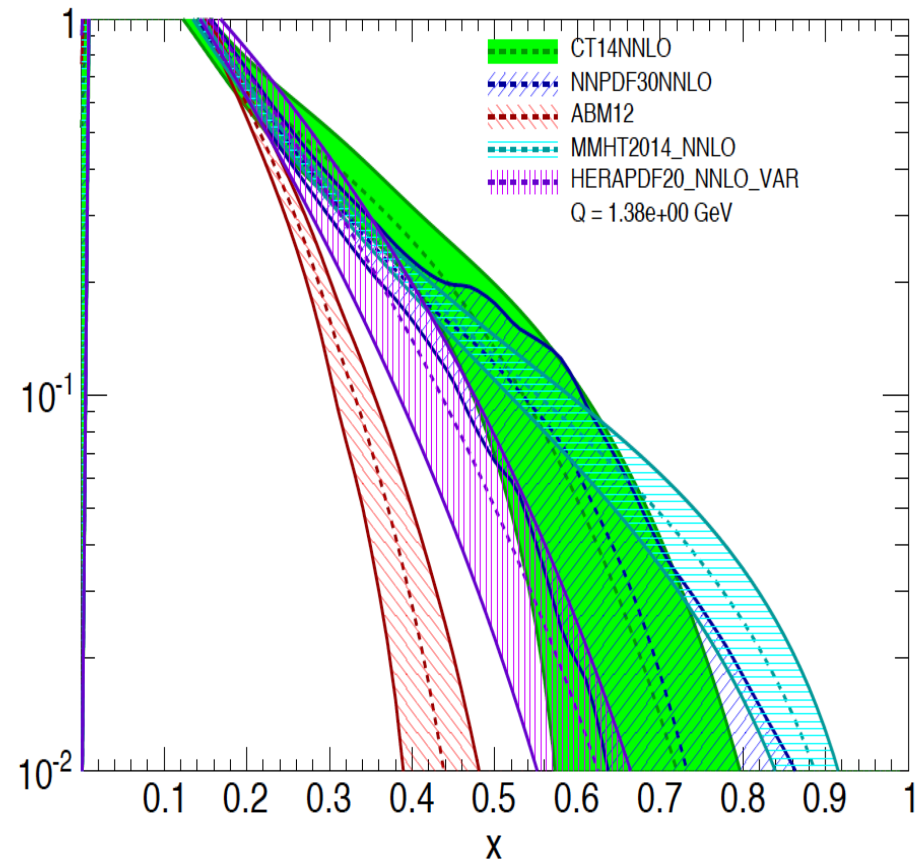
ep colliders 11.2014 Max Klein	CEPC	MEIC	eRHIC	HERA 92-07	CepC	LHeC	SepC	FCC-he
√s/GeV	**13**	**35**	**122**	**319**	**1000**	**1300**	**3375**	**3464**
$L/10^{33}$ $cm^{-2}s^{-1}$	0.4	5.6	1.5	0.04	4.8	16	8.9	10
E_e /GeV	3	5	15.9	27.6	120	60	80	60
E_p /GeV	15	60	250	920	2100	7000	35600	50000
f /MHz	500	750	9.4	10.4	20	40	40	40
$N_{e/p} 10^{10}$	3.7/0.54	2.5/0.42	3.3/3	3/7	1.3/16.7	0.4/22	3.3/5	0.5/10
$\varepsilon_{e/p}$ /µm	.03/.15	54/.35	32/.27	4.6/.09y	250/1	20/2.5	7.4/2.4	10/2
$\beta^*_{e/p}$/cm	10/2	10/2	5/5	28/18 y	4.2/10	10/5	9.3/75	9/40
comment	Lanzhou	full acc.	"Day1"	HERA II	Booster	ERL (H)	$E_e = M_W$	ERL (HH)
source	X.Chen July 14	McKoewn POETIC14	Litvinenko S.Brook 14	B.Holzer at CERN 2008	Y.Peng Oct. 2014	Frank Z. LHeC 2014	Y.Peng Oct. 2014	Frank Z. IPAC 2014

Gluon Density

High x



Gluon prior to LHC data (2011)



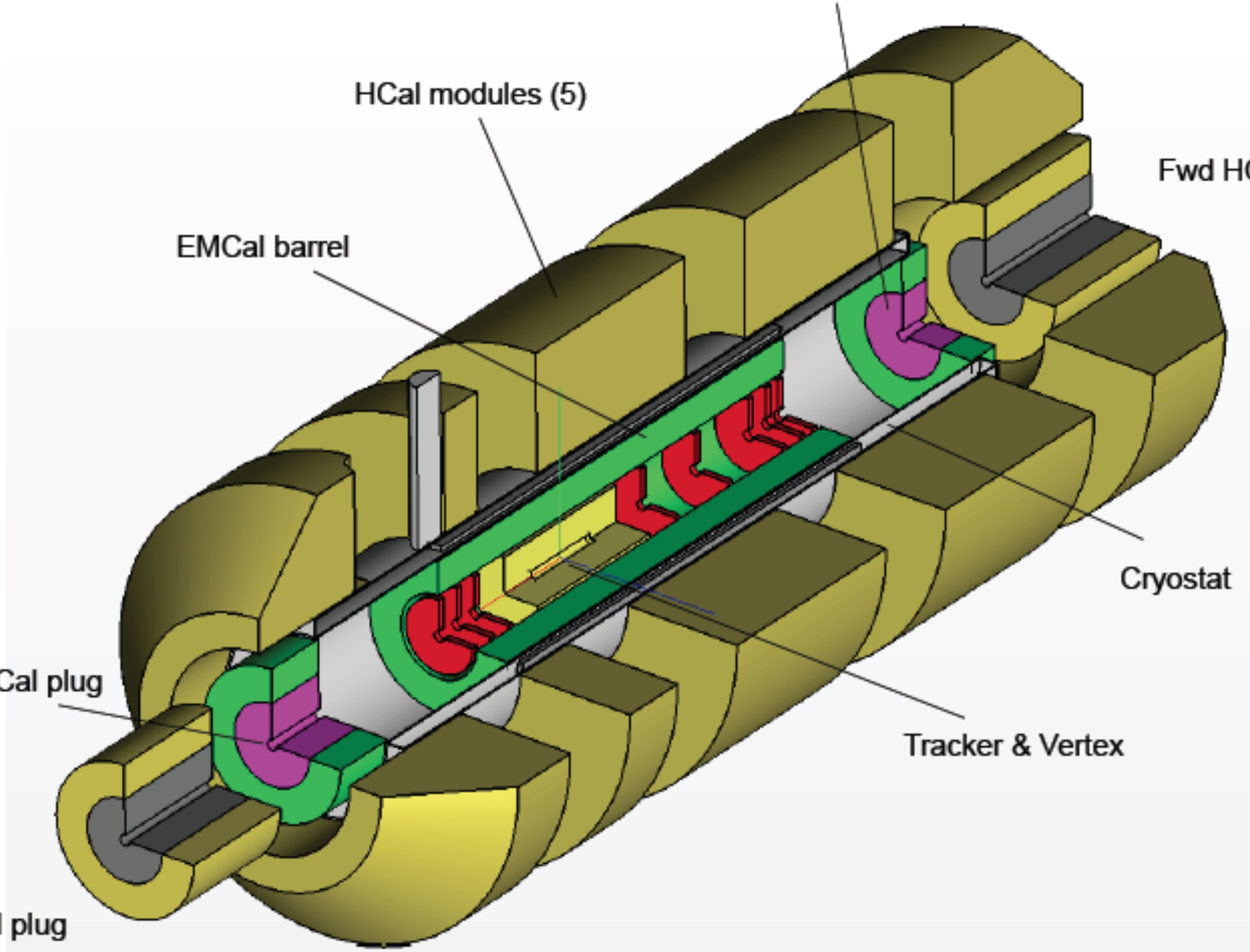
Gluon with (first) LHC data (2015)

used by CT14,NNPDF,MMHT

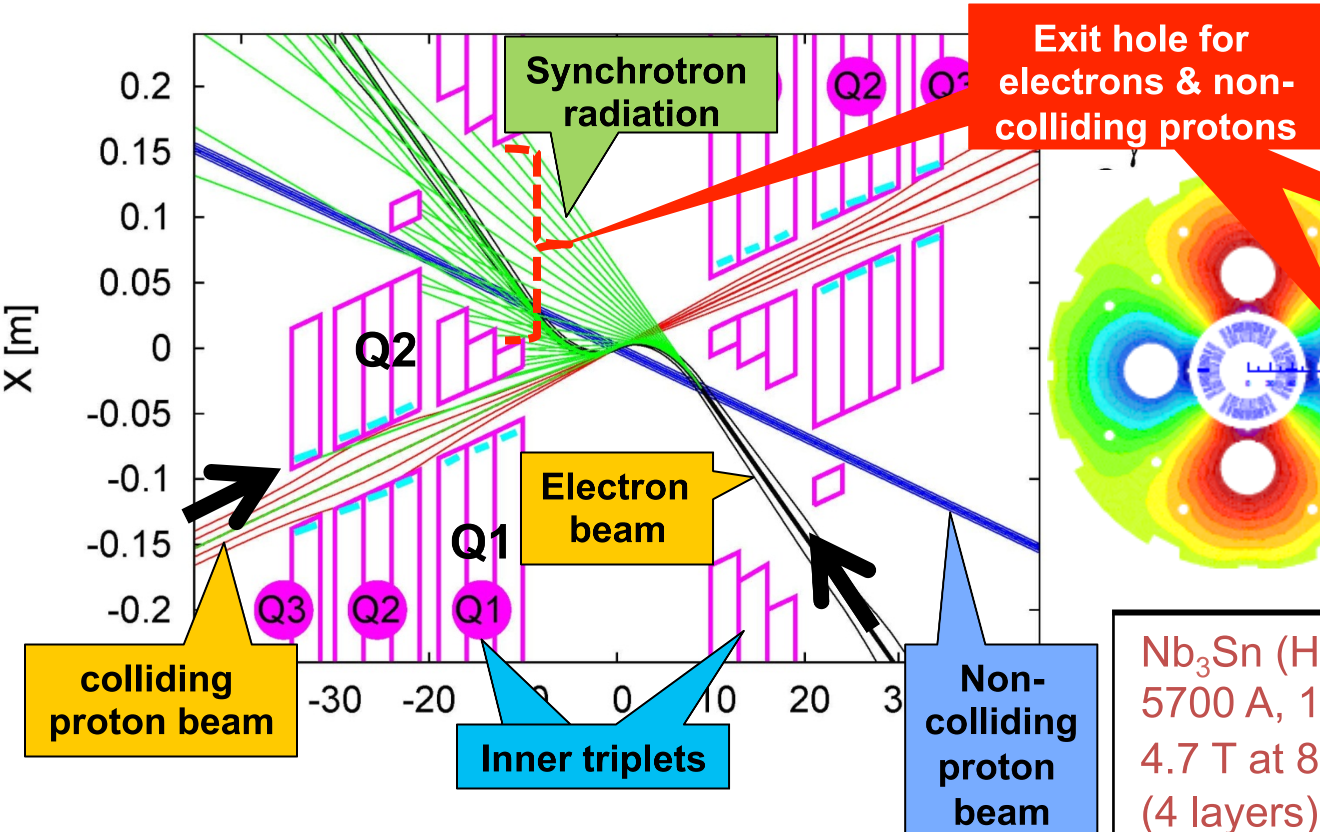
Rates of Higgs Production at the LHeC

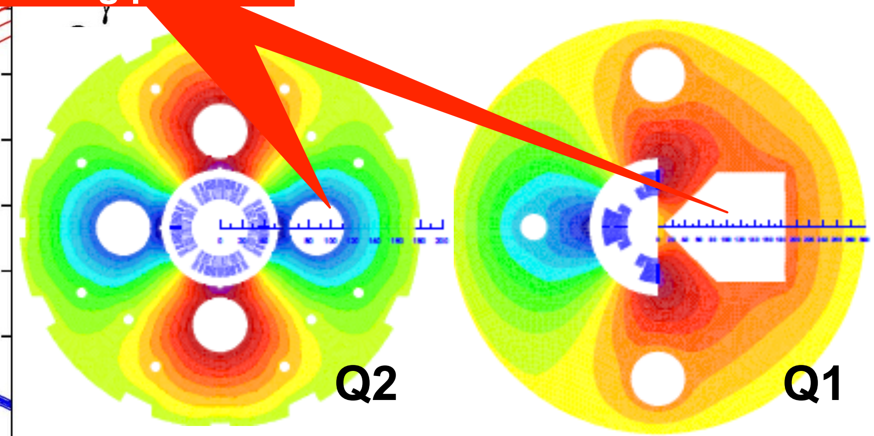
kinematic requirements	CC e^-p	CC e^+p	NC $e^\pm p$
cross section	109 fb	58 fb	20 fb
acceptance	0.92	0.94	0.93
H$\to bb$	6500	3500	1200
H$\to c\bar{c}$	330	180	60
H$\to gg$	900	480	160
H$\to WW$	1400	760	260
H$\to ZZ$	160	190	30
H$\to \tau\tau$	570	310	100
H$\to \gamma\gamma$	20	12	4

LHeC Detector baseline design.



LR LHeC IR layout & SC IR quadrupoles





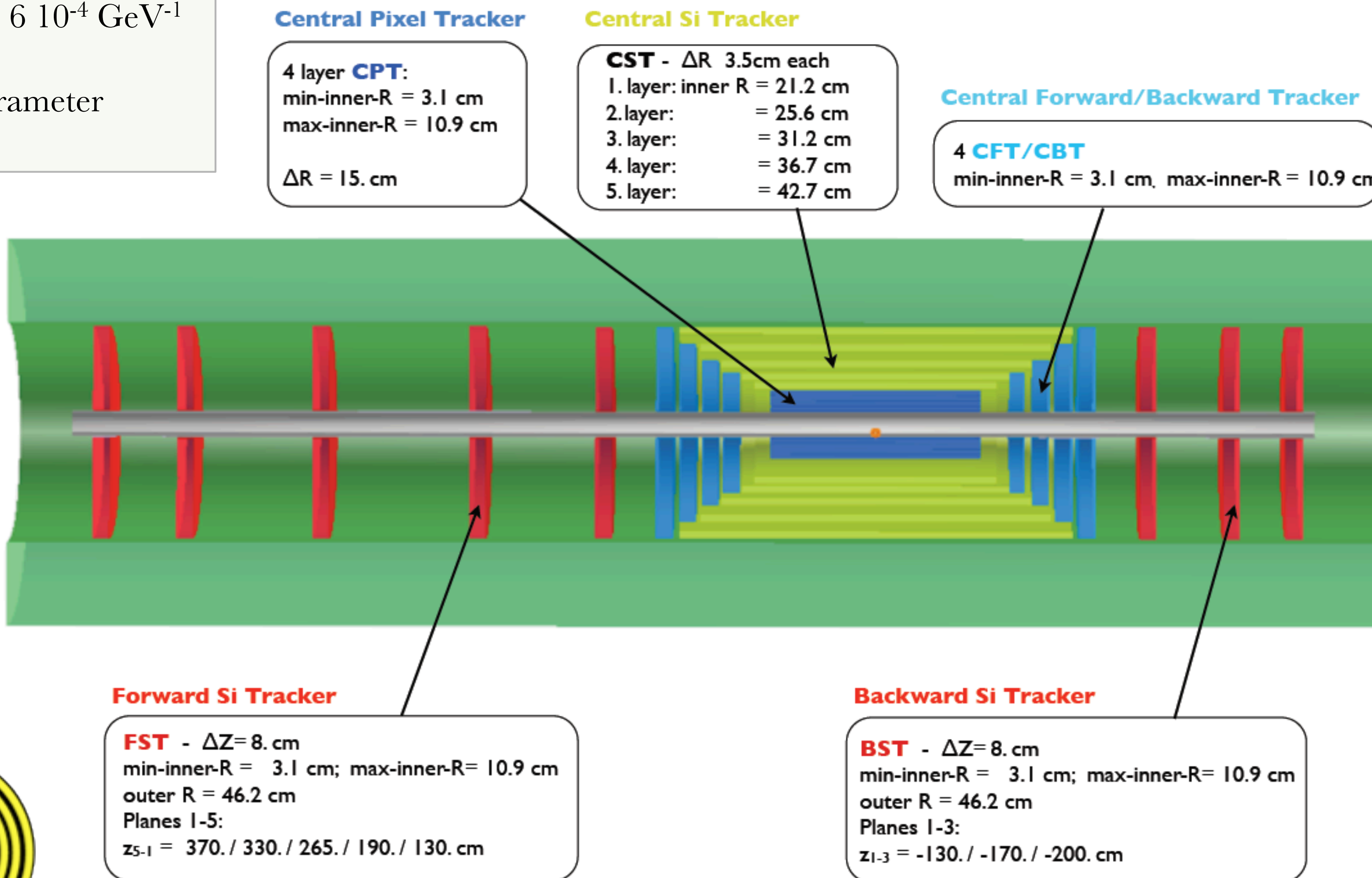
Nb_3Sn (HFM46): 5700 A, 175 T/m, 4.7 T at 82% on LL (4 layers), 4.2 K	Nb_3Sn (HFM46): 8600 A, 311 T/m, at 83% LL, 4.2 K
46 mm (half) ap., 63 mm beam sep.	23 mm ap.. 87 mm beam sep.
0.5 T, 25 T/m	0.09 T, 9 T/m

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

As shown by F. Zimmermann at Chamonix12

Silicon Tracker and EM Calorimeter

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



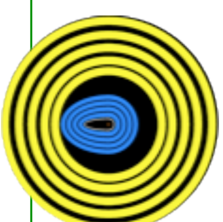
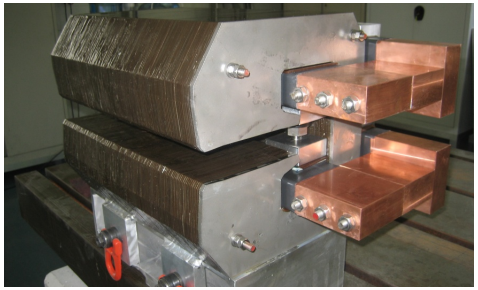


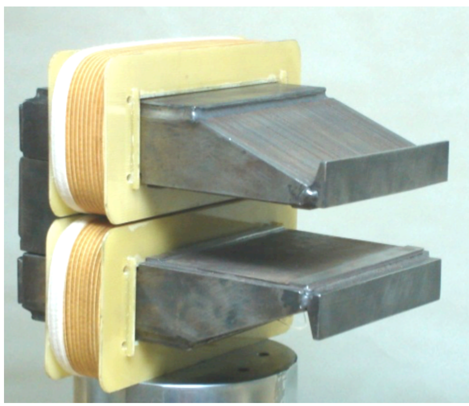
Figure 13.18: Tracker and barrel Electromagnetic-Calorimeter rz view of the baseline detector (Linac-Ring case).

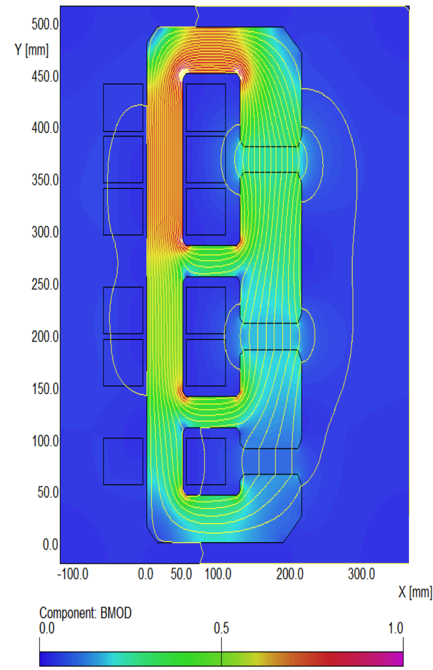
LHeC-LHC: no pile-up, less radiation, smaller momenta apart from forward region

Magnets Developments



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

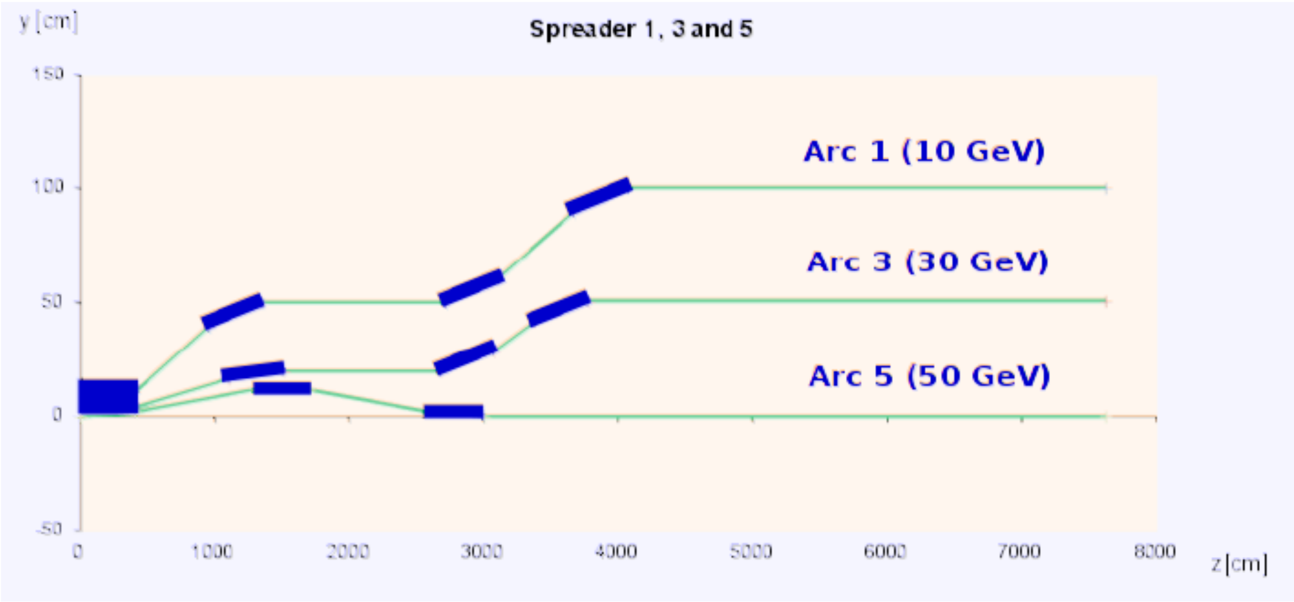
LR recirculator dipoles and quadrupoles
New requirements (aperture, field)?
Combined apertures?
Combined functions (for example, dipole + quad)?
LR linac quadrupoles and correctors
New requirements (aperture, field)?
More compact magnets, maybe with at least two families for quadrupoles?
Permanent magnets / 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, Daresbury and Budker (Novosibirsk)

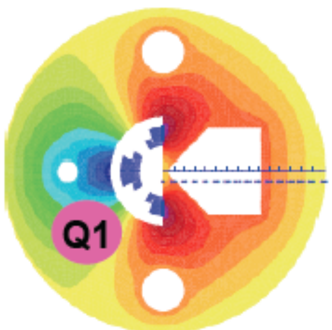
Spreader/Combiner

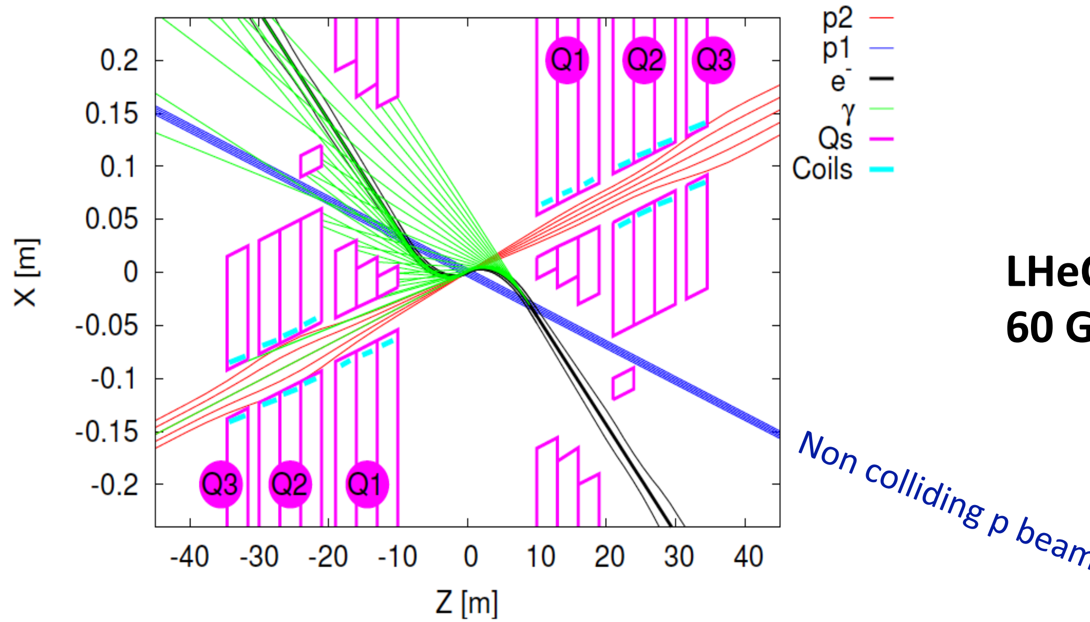


Arc Optics: Emittance Preserving Flexible Momentum Compaction Cell

- 1 km radius for all of them (total circumference 1/3 LHC),
- Same arrangement for each arc to simplify magnets installation in the tunnel,
- Tunable cells:
  - Highest energy arcs are tuned to minimize the energy spread induced by synchrotron radiation (quantum excitation),
  - Lowest energy arcs are tuned to contain the bunch length.

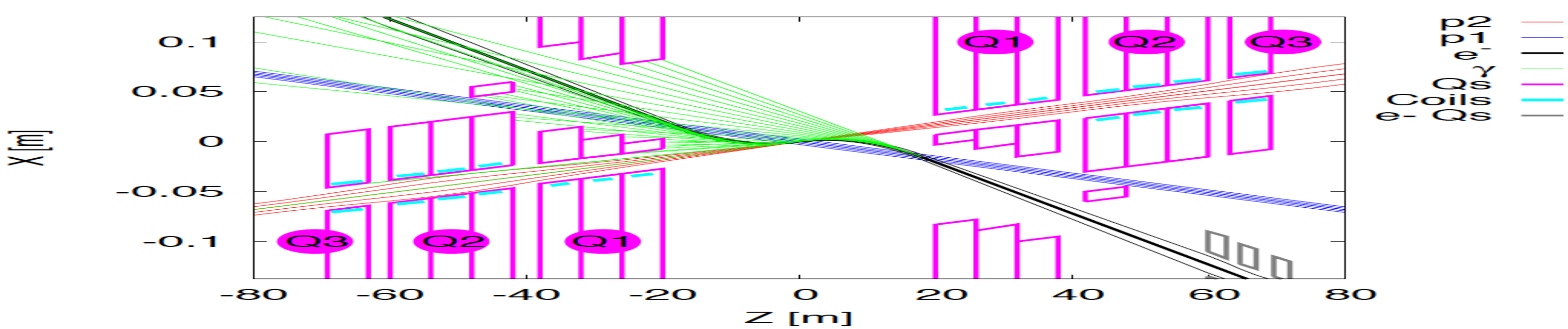
Interaction Regions for ep with Synchronous pp Operation





LHeC (CDR)
60 GeV * 7 TeV

Still work in progress:
may not need half
quad if L*(e) < L*(p)

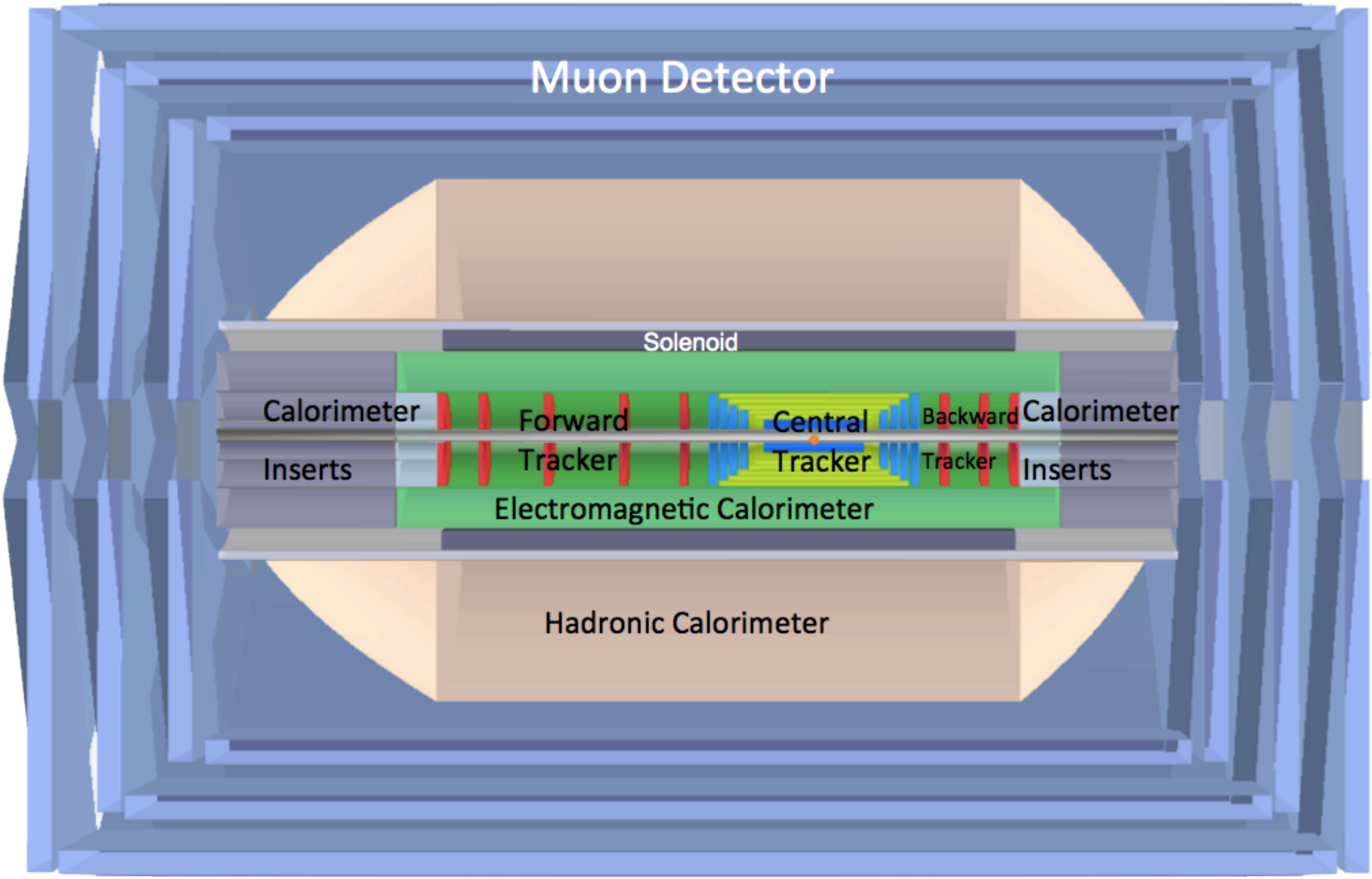


Tentative: ε_p=2μm, β*=20cm → σ_p=3μm ≈σ_e matched! ε_e=5μm ..

FCC-he (ERL)
60 GeV * 50 TeV

Rogelio Tomas et al

LHeC Detector CDR 2012



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)