

LHeC and FCC-eh to Snowmass

Introduction
European Strategy
Energy Recovery
Bits of Physics
White Paper
Summary

Large Hadron electron Collider:
e:10-60 GeV, p: 1-7 TeV (LHC)
 $s = 4 E_e E_p$

FCC-eh: Few TeV cms eh collider
e:10-60 GeV, p: 20 .. 50 TeV

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University of Liverpool, ATLAS, H1
For the LHeC/FCC-eh and PERLE Collaborations

For **LHeC**: see Conceptual Design Report arXiv:1206.2913 (J.Phys.G) and Update and plethora of talks and papers, Web site <http://lhec.web.cern.ch> (needs update)

For **FCC-eh** see FCC books 1 (physics) and 3 (FCC-hh with eh integrated)
See also the CDR presentation in March 2019: <https://indico.cern.ch/event/789349/>
with talks on FCC-eh machine (OB), Higgs in eh (UK) and QCD (MK).

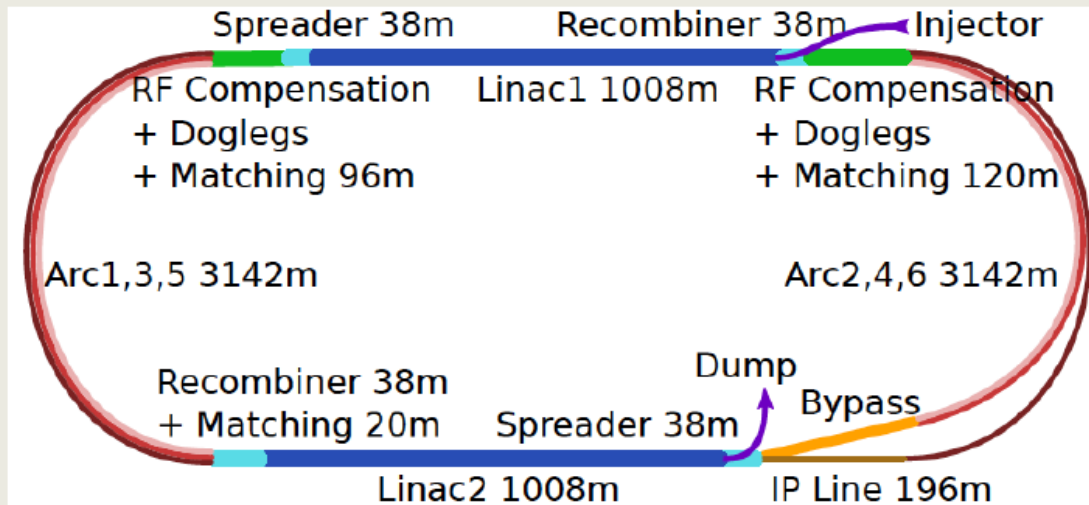
The Basic Concept

Energy $\sqrt{s} = \sqrt{4 E_e E_p} = 0.2-1.3 \text{ TeV}$

electrons: $E_e=10-60 \text{ GeV}$, protons: $E_p=1-7 \text{ TeV}$, ions Pb: $E=2.75 \text{ TeV}$

LHeC: a next generation TeV energy electron-proton collider.
 Large coverage of kinematic DIS range, down to 10^{-6} in x owing to high energy and approaching $x=1$ due to high luminosity.
 Electron-ion collisions extend the kinematic range by 3-4 orders of magnitude since HERA missed its electron-ion collider phase.

Default layout of the ERL configuration for the LHeC



An intense electron beam (20mA current) is accelerated in three passes through two 1km linacs in an energy recovery linac racetrack configuration, which is positioned tangentially to the LHC (at IP2, or L for FCC).

The electron-proton interaction does not disturb the proton beams in a noticeable manner. Thus the LHeC may operate synchronously with the LHC. The installation of the ERL is in a separate tunnel, while the detector installation requires a typical LHC shutdown length of two years. The whole project concept therefore is that of adding instrumentation and providing crucial new physics, i.e. of making the LHC physics richer and thus sustaining its HL phase.

Luminosity:

$10^{34} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow O(1) \text{ ab}^{-1} \text{ in 10 years}$

This is 1000 times higher than HERA, owing to the high beam brightness of the HL-LHC, the large electron current from the ERL and may be achieved through the interaction of matched e and p beams at a β^* below 10cm.

New default electron energy for LHeC: 50 GeV instead of 60 GeV to economise ~400 M SF and effort.

Thoughts about higher electron energy for FCC-eh, especially if E_p is lowered.

A recent review on the project and physics: MK, arXiv:1802.04317

Conceptual Design Report and beyond

Ring Ring Design

Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)

Linac Ring Design

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Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)

Energy Recovery

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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)

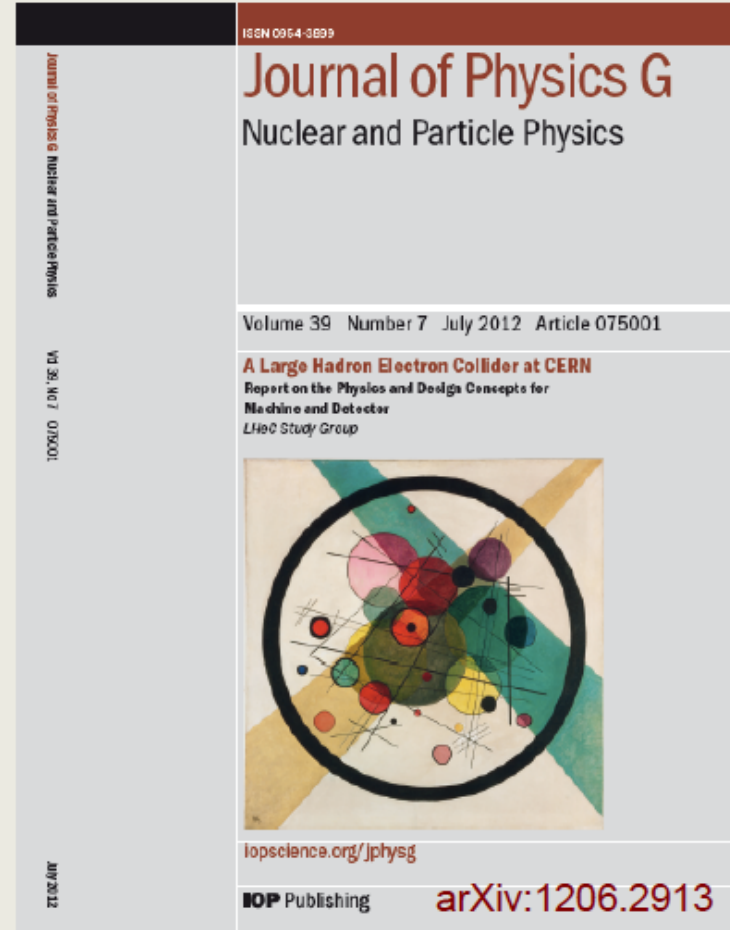
Precision QCD and Electroweak

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)



In 2012, parallel to the discovery of the Higgs boson by the ATLAS and CMS experiments at the LHC, a 500 pages report was published on the design of the LHeC. It was the summary of the work of a very large international collaboration for about 4 years, following mandates by ECFA, CERN and in collaboration with NuPECC. The report, on the physics, accelerator and a complete detector, was discussed for a year with referees, listed on the left, which CERN had invited. The report was for $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ luminosity obtainable in concurrent electron-proton and proton-proton operation. It contained a ring-ring and a linac-ring collider concept.

The European strategy in 2013 opened the path to a much enlarged luminosity and prolonged lifetime for the LHC. The Higgs boson set a more ambitious luminosity goal also for ep, where $ep \rightarrow \nu H X$ has a 200 fb cross section. The CERN directorates thus mandated a second phase of the LHeC design, for higher luminosity, with only the ERL version, and adapted to the evolving LHC physics.

The CDR in 2012 was very detailed and extensively refereed. It is time for an update, deadline November - this year.

High Luminosity Electron-Hadron Physics at TeV energy

The LHeC represents a new laboratory for high energy physics. Its programme comprises five major themes:

MICROSCOPE of substructure

By the nature of the high energy eh interaction, the LHeC is the cleanest high resolution microscope of matter, the Hubble telescope of substructure.

EMPOWERMENT of LHC physics

The LHC lacks crucial input on the proton structure and QCD dynamics. The clean, external input on partons will clarify the high mass predictions, and thus extend the reliability and range for BSM searches, and provide input required for precision QCD, electroweak and Higgs physics. This way, it empowers the LHC physics and utilises the LHC infrastructure optimally. It is the near detector for the GPDs.

A NOVEL HIGGS PHYSICS FACILITY

The clean final state, the absence of pile-up, the large Higgs production cross section and novel detection and analysis techniques enable precision input in all large decay channels, including $H \rightarrow cc$, which combined with pp , lead to percent level LHC Higgs coupling results, comparable to ee prospects.

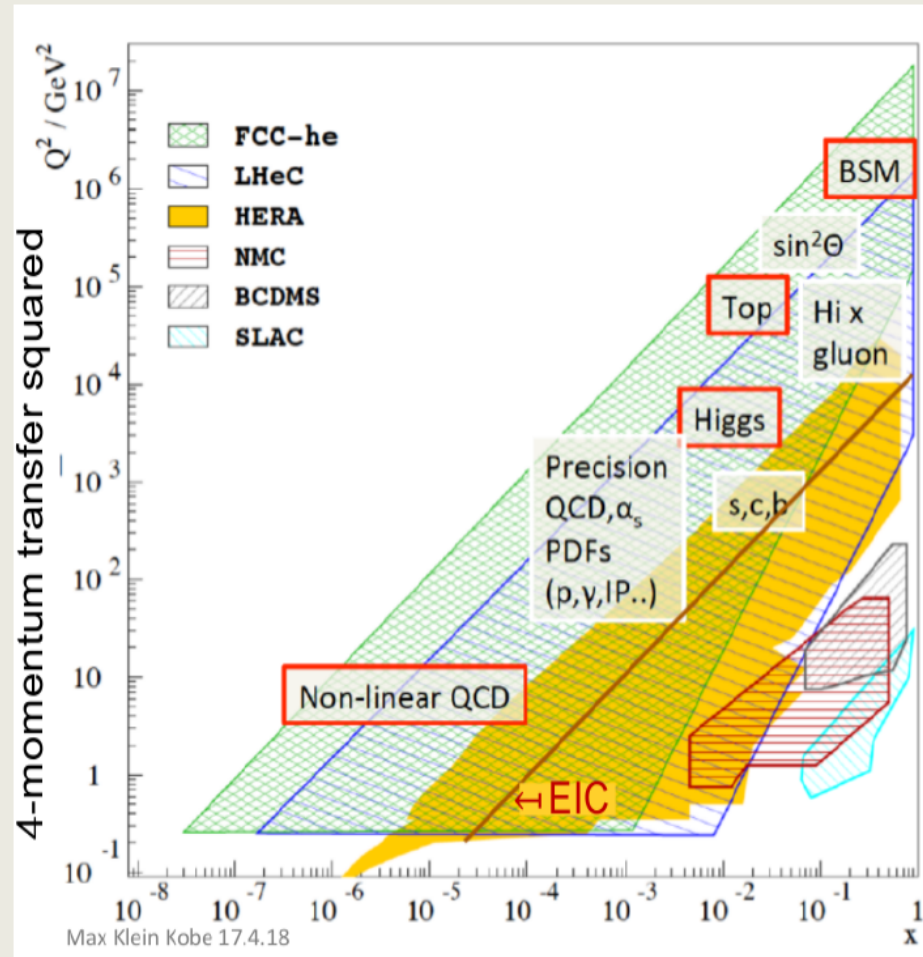
DISCOVERY of new physics

The LHeC is a TeV energy scale new configuration, it has large discovery potential in QCD (saturation), electroweak (Higgsinos, ν neutrinos), top and substructure physics.

REVOLUTION of nuclear particle physics

The partonic structure of nuclei is of an infant status like that of protons before HERA, it will be established in a huge range with stand-alone eA PDF one may then relate to those in ep. The understanding of the Quark-Gluon Plasma needs ep.

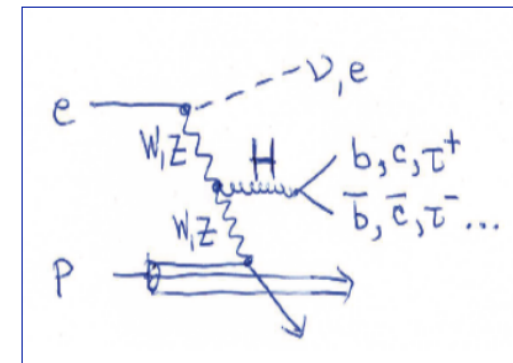
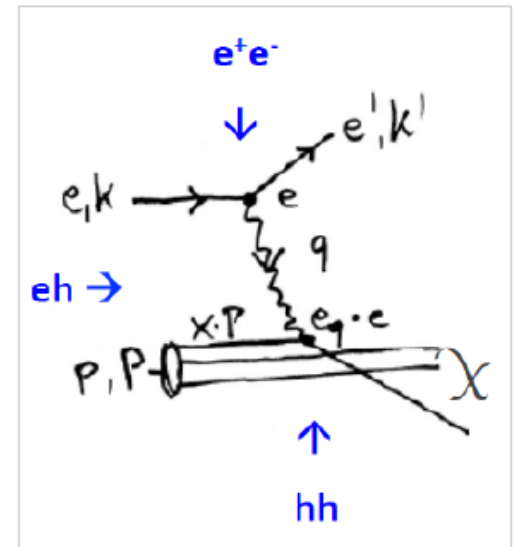
CERN-ACC-Note-2018-084, subm EU strategy, J.Phys.G to appear



Following HERA, deep inelastic scattering needs high energy (and also luminosity) to reach Higgs, top, BSM physics, to use charged currents for unfolding parton structure, independently of nuclear and higher twist effects, to clarify the existence of BFKL dynamics at small x , and prepare for FCC.

With polarised protons, there is a case for a lower (than HERA) energy eh collider, which also studies proton structure at medium Bjorken x , the EIC.

DIS: the cleanest high resolution microscope and a laboratory for new particles and new dynamics.



Organisation

International Advisory Committee

Mandate by CERN (2014+17) to define
“..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)

Eckhard Elsen (CERN)

Stefano Forte (Milano)

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

Juergen Schukraft (CERN)

Achille Stocchi (LAL Orsay)

John Womersley (ESS)

We miss Guido Altarelli.

Coordination Group

Accelerator+Detector+Physics

Gianluigi Arduini

Nestor Armesto

Oliver Brüning – Co-Chair

Andrea Gaddi

Erk Jensen

Walid Kaabi

Max Klein – Co-Chair

Peter Kostka

Bruce Mellado

Paul Newman

Daniel Schulte

Frank Zimmermann

**5(12) are members of the
FCC coordination team**

OB+MK: co-coordinate FCCeh

Working Groups

PDFs, QCD

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Monica D’Onofrio

Oliver Fischer

Top

Olaf Behnke,

Christian

Schwanenberger

eA Physics

Nestor Armesto

Small x

Paul Newman,

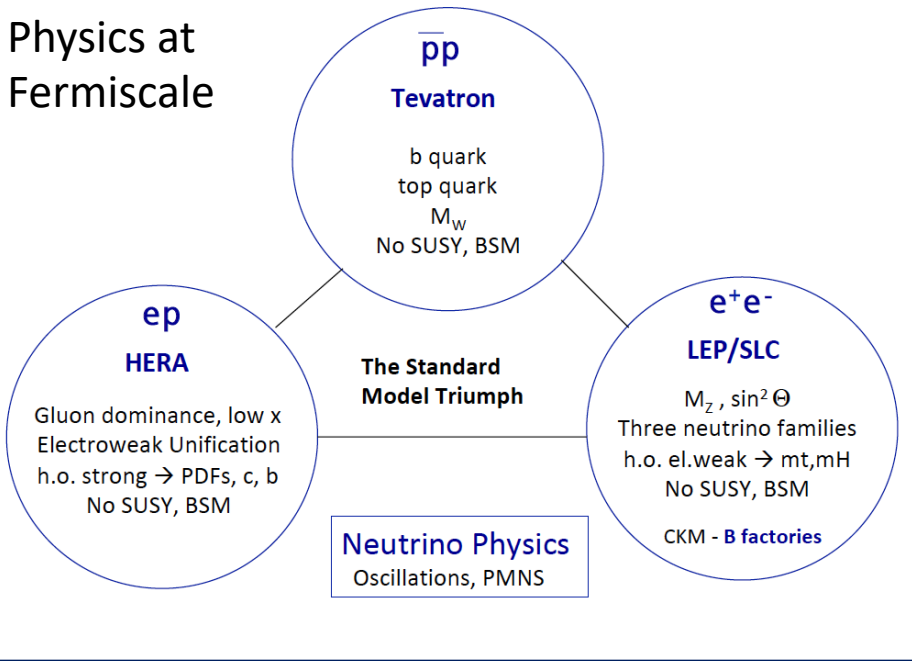
Anna Stasto

Detector

Alessandro Polini

Peter Kostka

Physics at Fermiscale



Strategy and Expectations

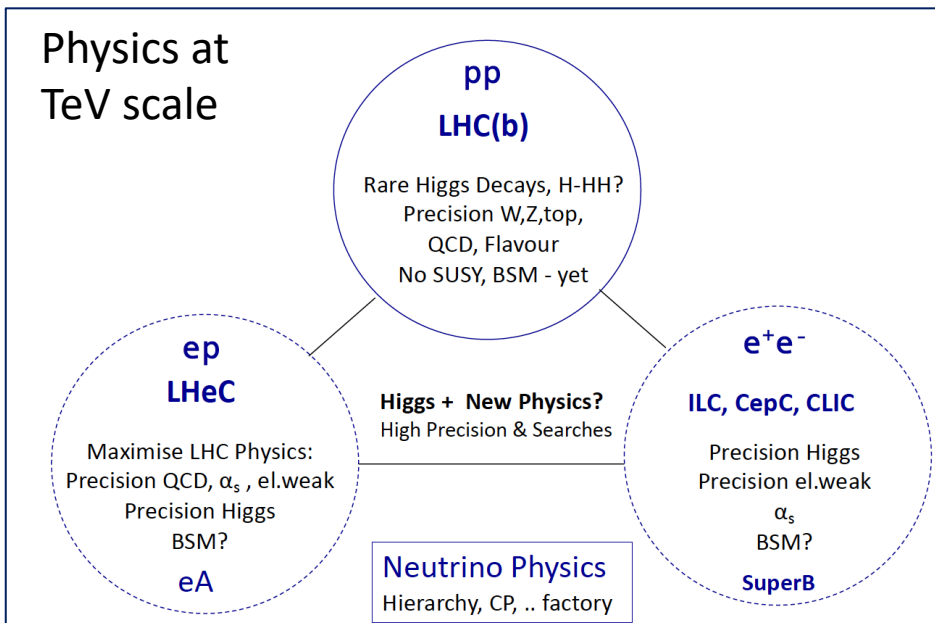
Recognition of the complementarity of pp/AA, ep/A and ee, and the special role of DIS to supplement hh, LHC/FCC

\rightarrow Support for technical (IR..) and detector developments

Recognition of energy recovery as a revolutionary, novel technology for next generation colliders of high impact

\rightarrow Support the development of ERL technology and the international PERLE Coll.

Physics at TeV scale



CERN/ESG/05
29 September 2019

	2020-2040	2040-2060	2060-2080
		1st gen technology	2nd gen technology
CLIC-all	HL-LHC	CLIC380-1500	CLIC3000 / other tech
CLIC-FCC	HL-LHC	CLIC380	FCC-h/e/A (Adv HF magnets) / other tech
FCC-all	HL-LHC	FCC-ee (90-365)	FCC-h/e/A (Adv HF magnets) / other tech
LE-to-HE-FCC-h/e/A	HL-LHC	LE-FCC-h/e/A (low-field magnets)	FCC-h/e/A (Adv HF magnets) / other tech
LHeC-FCC-h/e/A	HL-LHC + LHeC	LHeC	FCC-h/e/A (Adv HF magnets) / other tech

SUPPORTING NOTE FOR BRIEFING BOOK 2020

The future is under discussion (cf A Stocchi on Friday) and DIS has become part of it. The big question is on the next big machine.

The strategy puzzle as seen by the Chair of CERN Council, Ursula Bassler

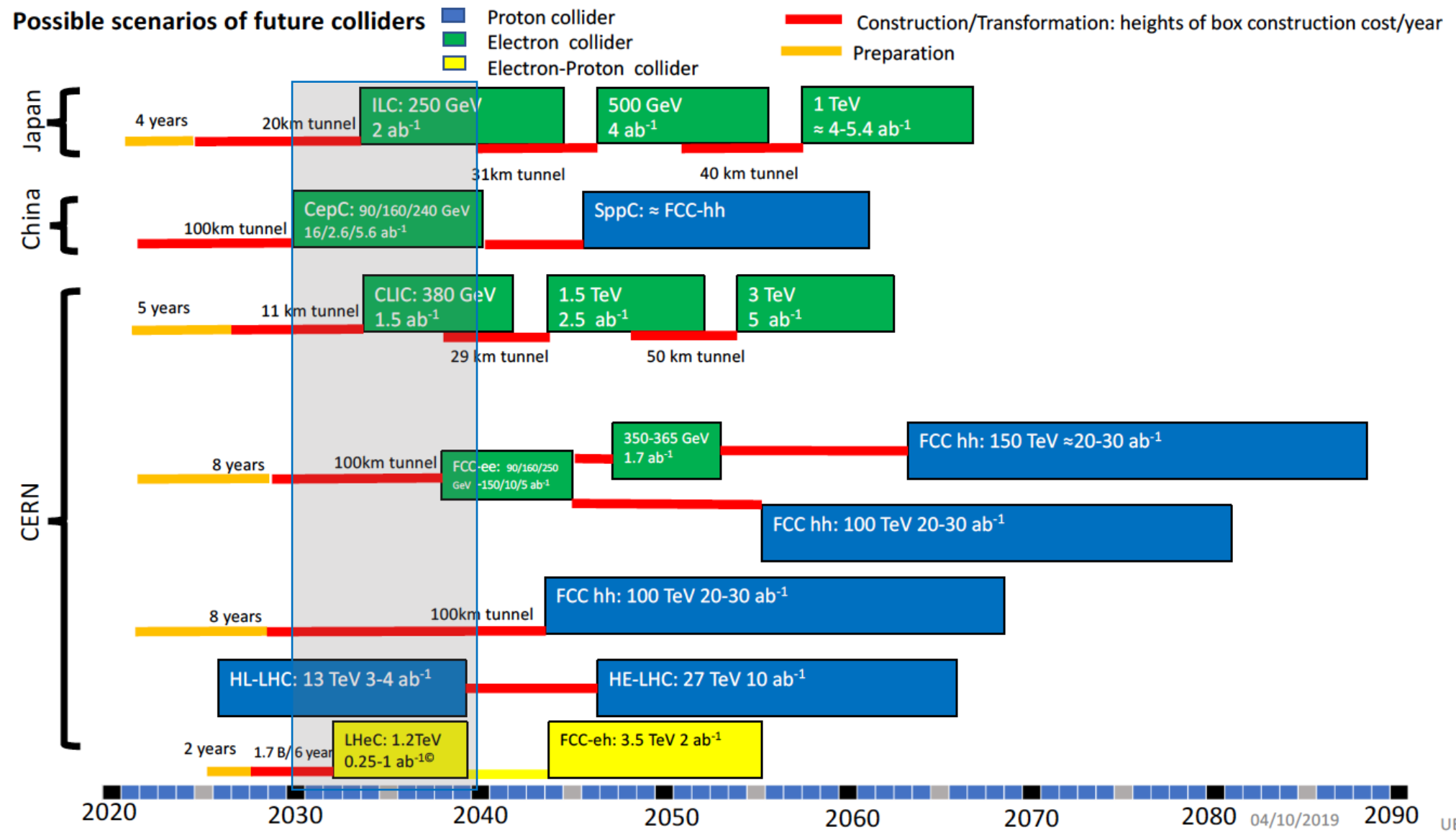


Figure 1 Timeline of Future Colliders as extracted from the submitted inputs (by U. Bassler)

High-energy DIS collider for QCD:



Hot & Dense QCD

A coherent and complementary “hot & dense QCD program” at the SPS brings valuable and unique contributions in the exploration of the QCD phase diagram.

An (HL-HE-)LHC/FCC based AA/pA/fixed-target program is unique and provides essential science at the frontline towards a profound understanding of particle physics.



Precision QCD

A globally concerted “precision QCD program” provides a unique avenue to find new physics that breaks the Standard Model.

A high-luminosity e^+e^- collider at the EW scale and a high-energy ep collider provide a unique environment for high-precision QCD, essential for most of our aspirations in particle physics.



Partonic Structure

A “hadronic structure program” exploring the complementarity of ep/pp/eA colliders provides vital ingredients for the high precision exploration in searches for new physics and as well steps into uniquely unknown territories of QCD.



Theory

It is vital to support coherently the QCD theory community to succeed in all these programs and to link QCD to the rest of the particle physics research program, especially for our HL-LHC exploration.



Organization

Strengthening the synergies in research and technology with adjacent fields will reinforce our efforts.

Global platforms, networks and institutes have the potential to enhance the research exchange among experts worldwide and to provide essential training opportunities.

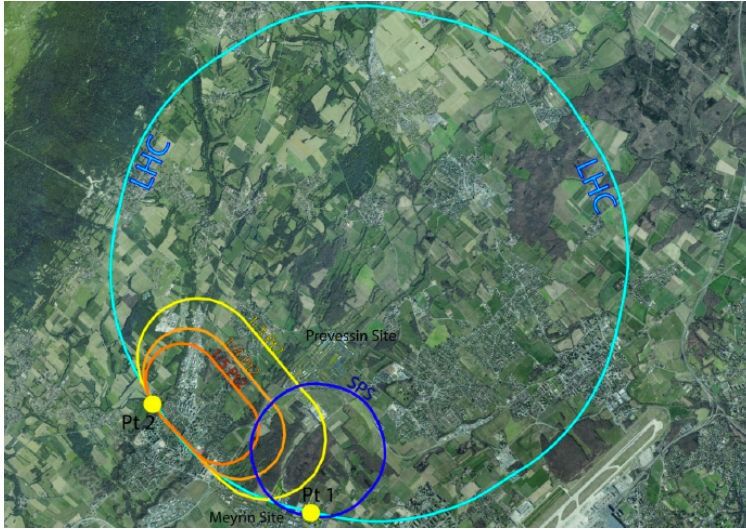
ERL: Accelerator Energy Frontier

CERN-ACC-Note-2020-0002

Version v1.0

Geneva, June 2, 2020

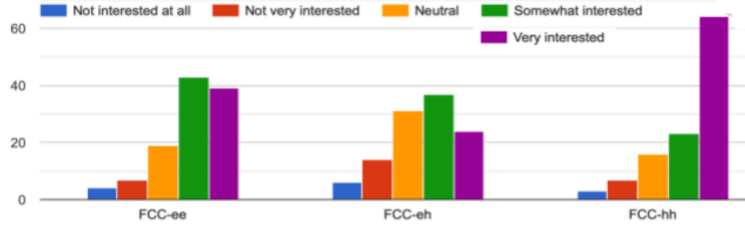
400 pages update of 2012 CDR - to appear



50 GeV to limit cost [1/4 or 1/5 of U(LHC)]
 Three pass ERL, two ~800m long linacs
 $I_e=20\text{mA}$ for 10^{34} luminosity, $f=801.58\text{ MHz}$
 (Erk at Daresbury 16, Frank M at Orsay 18)
 Operation concurrent to LHC (+dedicated)

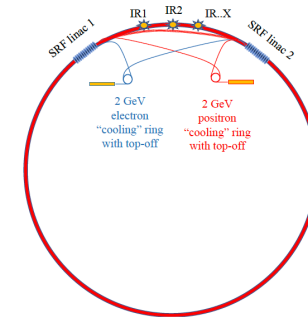
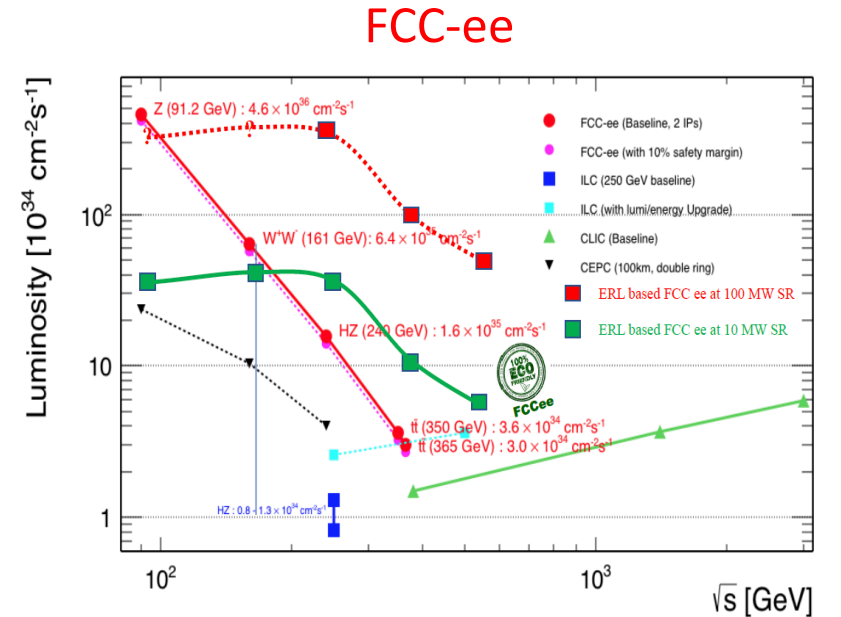
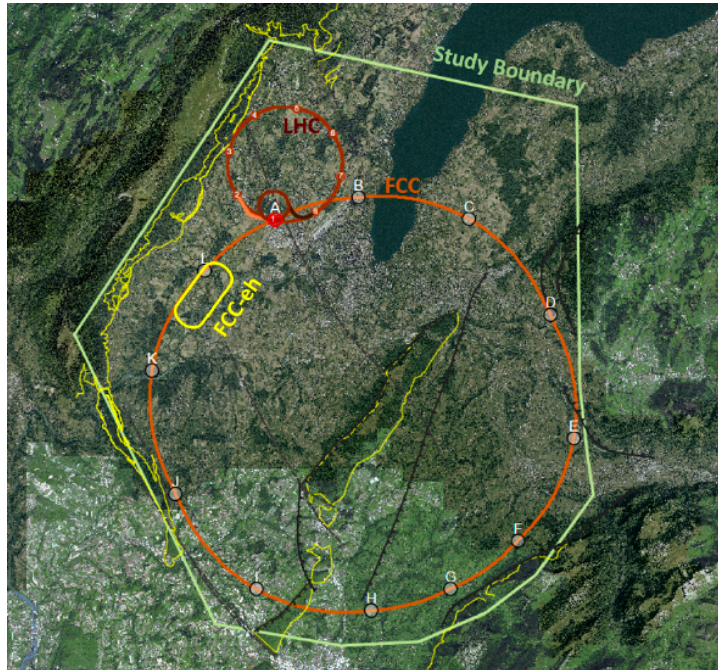
(when) will that happen.? We don't know
 I met Abhay Deshpande in Snowmass 2001,
 when he presented the EIC, not for the 1st time

HL-LHC dominates all of PP,
 Its programme will extend to 2040



ECFA: Interest of young scientists 2002.02837

60 GeV ERL design applied to FCC-he



4-6 turns

$$E/\text{linac} = M_{Z,\dots,HH} / (2 * N_{\text{turn}})$$

EIC: Polarised eh Collider at BNL

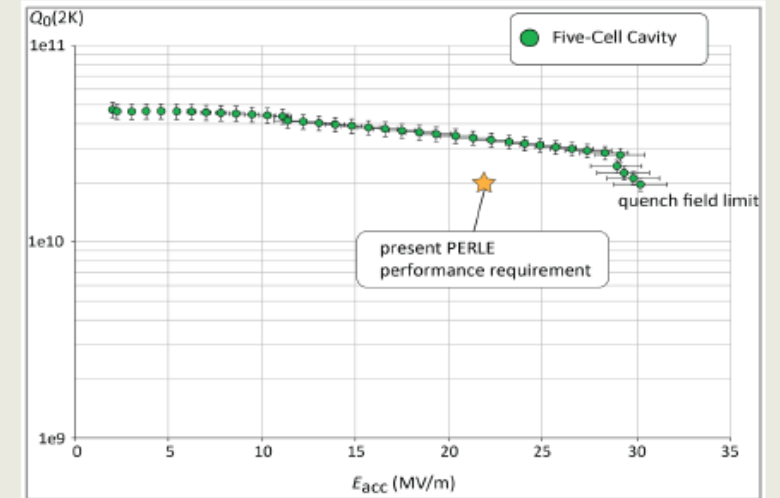
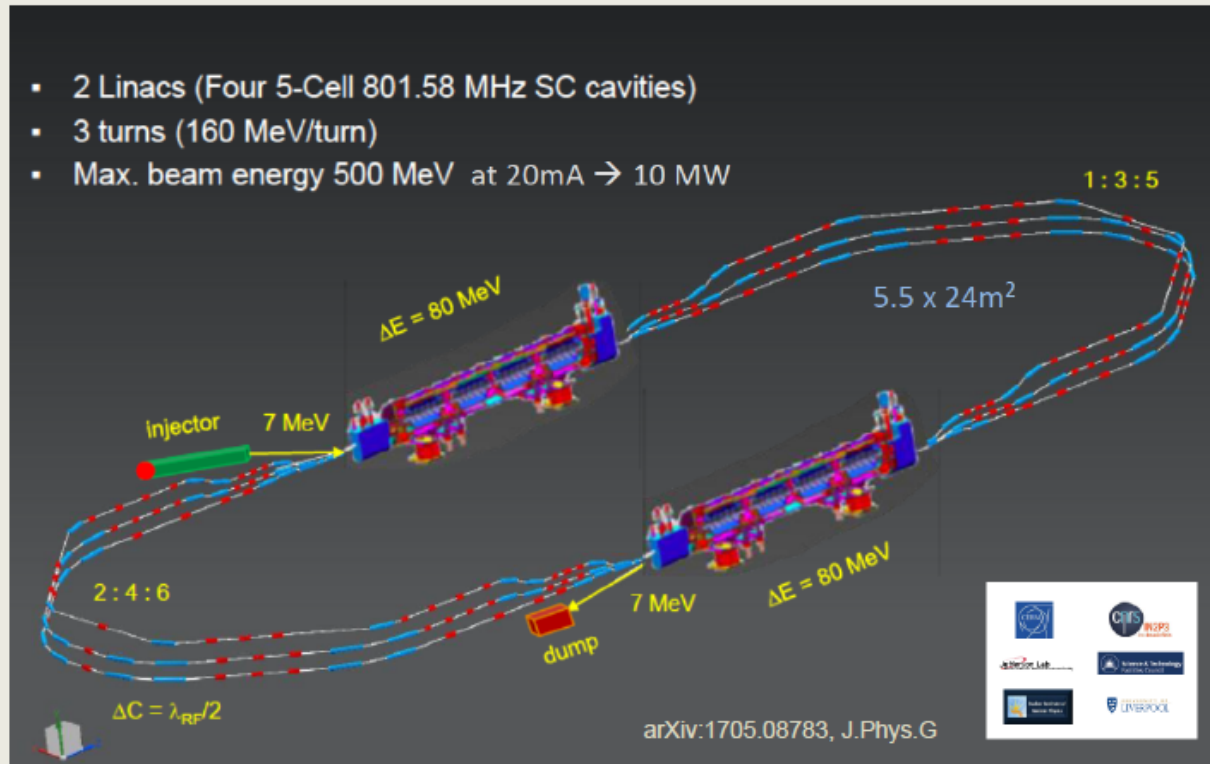
IBS: emittance growth: needs ERL 100mA (!)
 CW e beam cooling of p/A beam (for CBETA)
 cf e.g. F Willeke APS talk, April 2018

Coherent Electron Cooling

V.N. Litvinenko, Y.S. Derbenev, *PRL* **102**, 114801, 2009

PERLE powerful energy recovery linac for experiments

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV at 20mA → 10 MW



Test (Q_0 vs gradient) of 5-cell cavity built by:

Energy recovery is one of the few revolutionary concepts for accelerator design. A high energy collider application is for the LHeC (and possible successors with FCC). For stability, cost and CERN's RF, the frequency was chosen to be 802 MHz. A first 5-cell Niobium cavity, built at Jlab, reached a Q_0 of $3 \cdot 10^{10}$ with a large gradient stability margin (see right). **The PERLE Collaboration was built to realise a 500 MeV energy facility at Orsay**, for the development of ERL with LHeC conditions: high current and 3 passes. In a second phase it provides unique opportunity for intense low energy physics and industrial use.



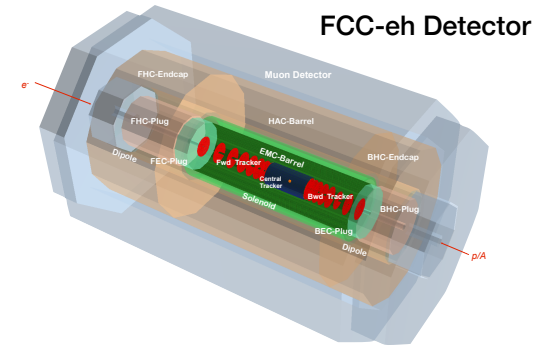
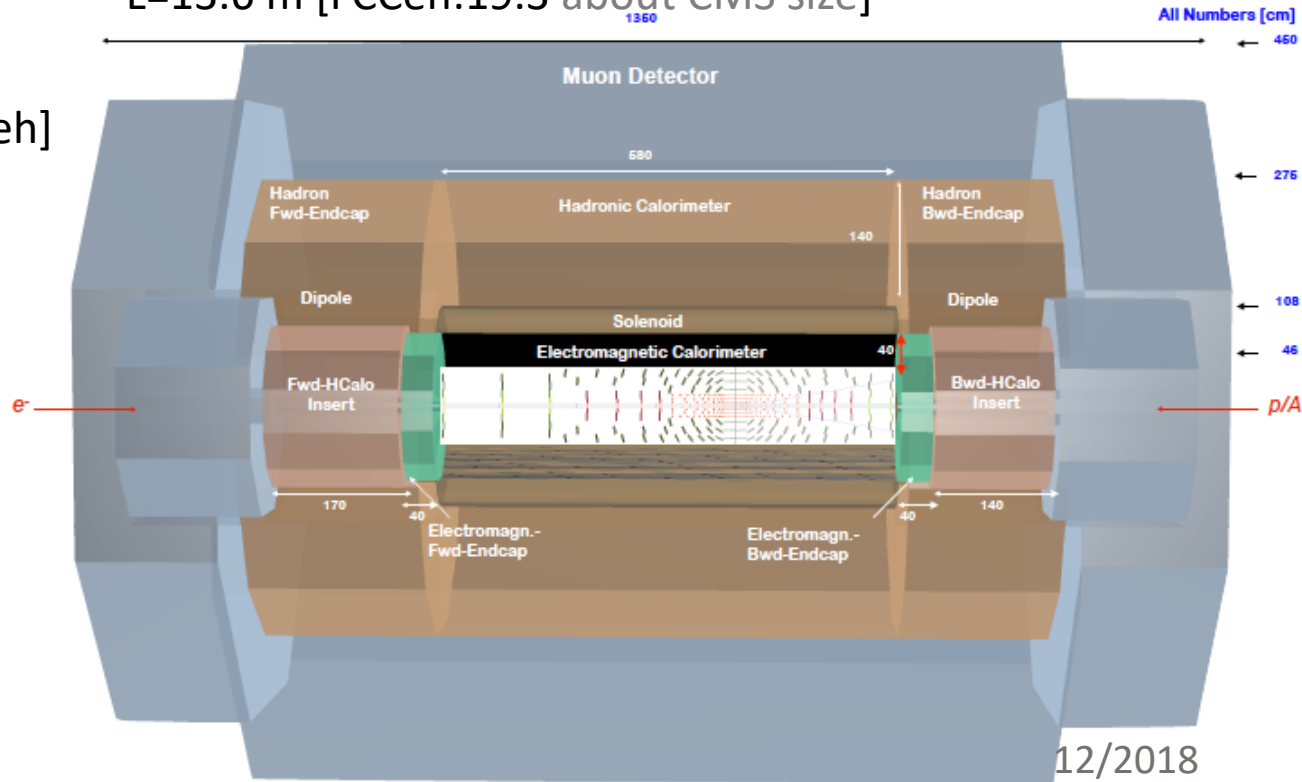
Thank you all

PERLE is progressing (source, injector, magnets, HOMs.. – radiation safety - in its recognition). International Collaboration

LHeC Detector

L=13.6 m [FCCeh:19.3 about CMS size]

R=4.6 m
[6.2 FCCeh]



Study of installation (sequence) of LHeC detector in IP2 cavern using L3 magnet support structure [commensurate with 2 year shutdown] A. Ghaddi et al, LHeC Workshop 2015

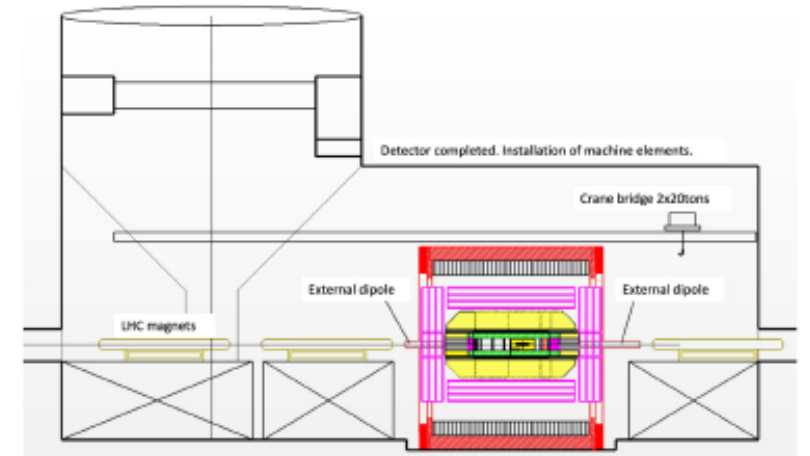


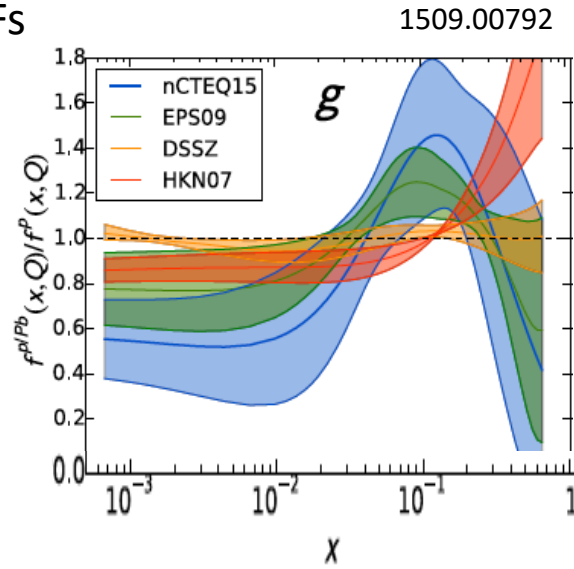
Figure 2: Current status of the LHeC central detector design. The detector is complemented by photon and electron taggers in the electron beam direction and by proton and neutron tagging forward spectrometers as were presented in the CDR [1].

Currently: increase radius of tracker, choose technology, summarise/simulate response: update this fall

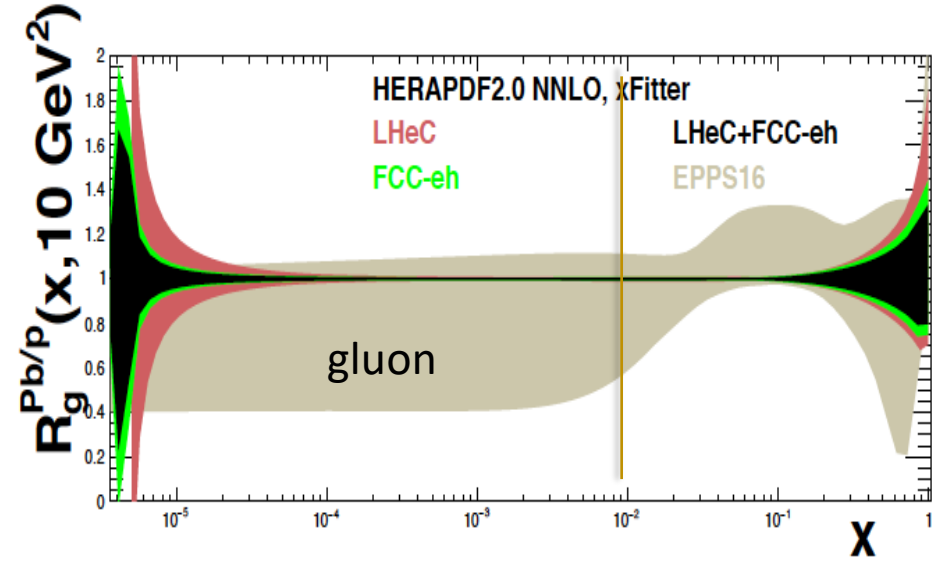
Unique nuclear/HI physics programme
 Extension of fixed target range by 10^{3-4}
 QCD of QGP, de-confinement, saturation..
 nPDFs independent of p PDFs

High
 luminosity
 $\sim 10^{33}$
 enables
 high statistics
 in short
 eA runs
 cf J Jowett et al

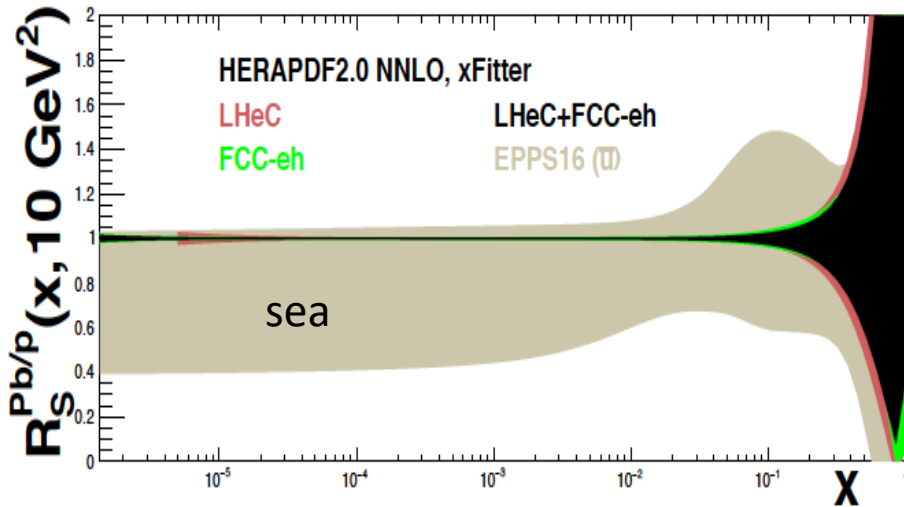
present
 status \rightarrow
 on xg
 Pb/p



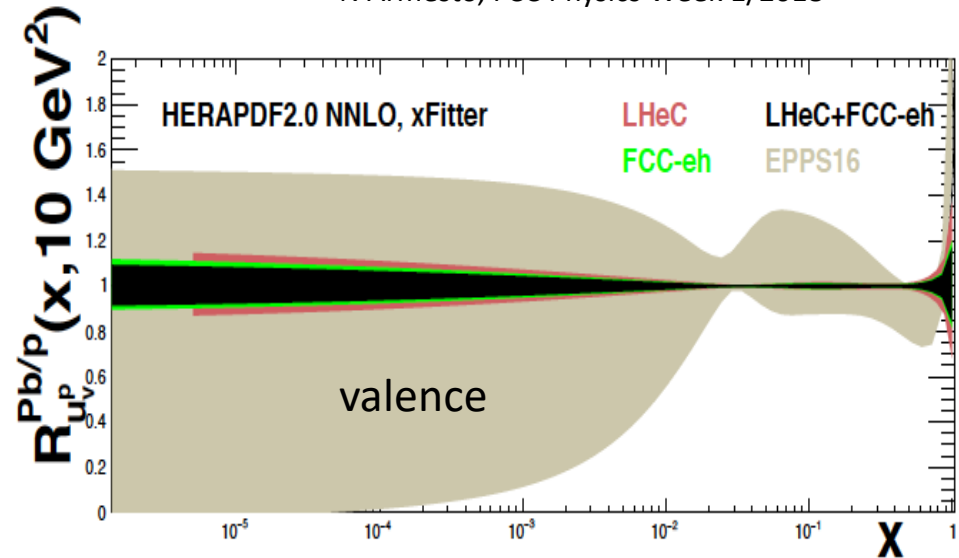
Nuclear PDFs at LHeC/FCCeh



N Armesto, FCC Physics Week 1/2018

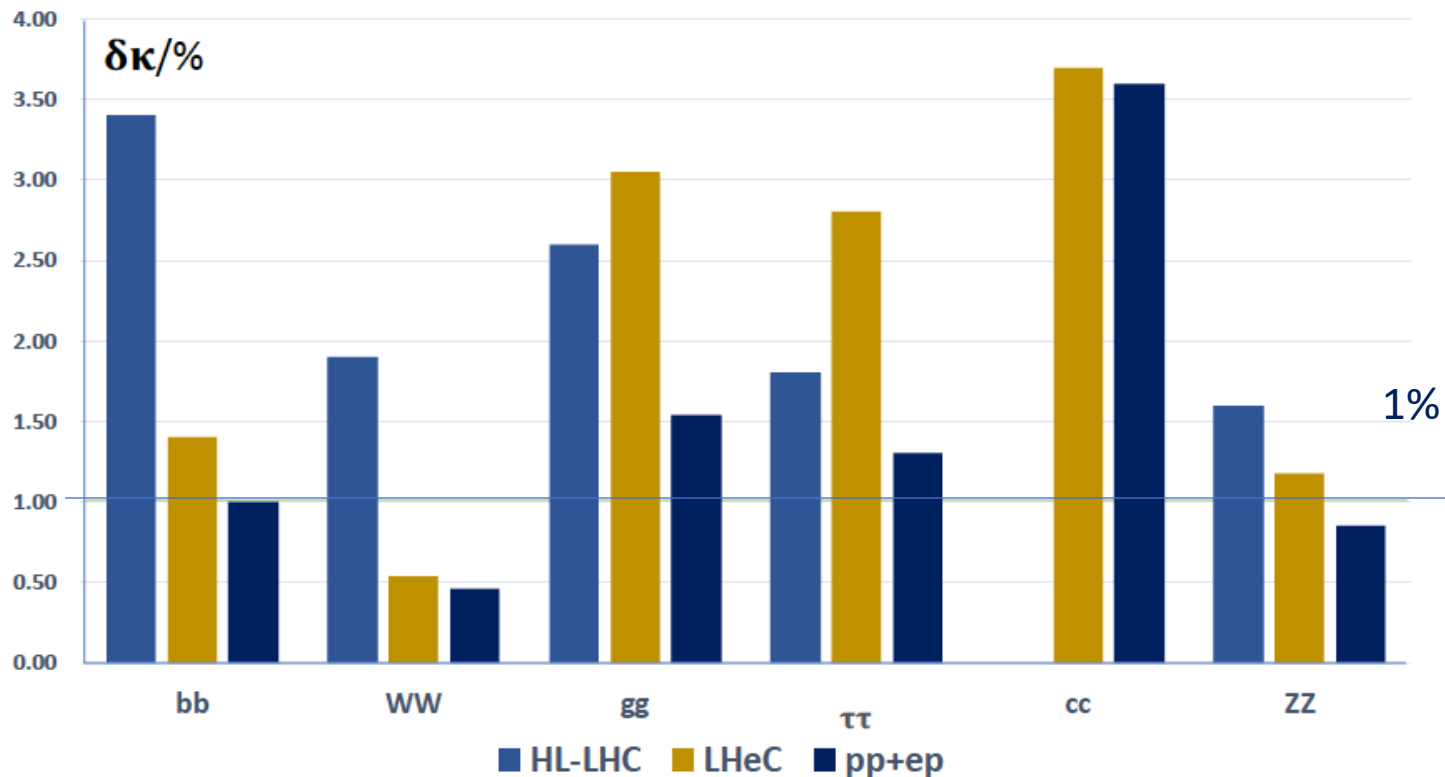


LHeC: Full error, $\Delta\chi^2=1$. EPPS $\Delta\chi^2=52$



Higgs in ep and pp [LHeC and HL-LHC]

Determination of SM Higgs couplings from pp + ep



The combined ep+pp at LHC reaches below 1% for dominant channels
 ep adds charm. Analysis in EFT framework work in progress (aTGCs in ep..)

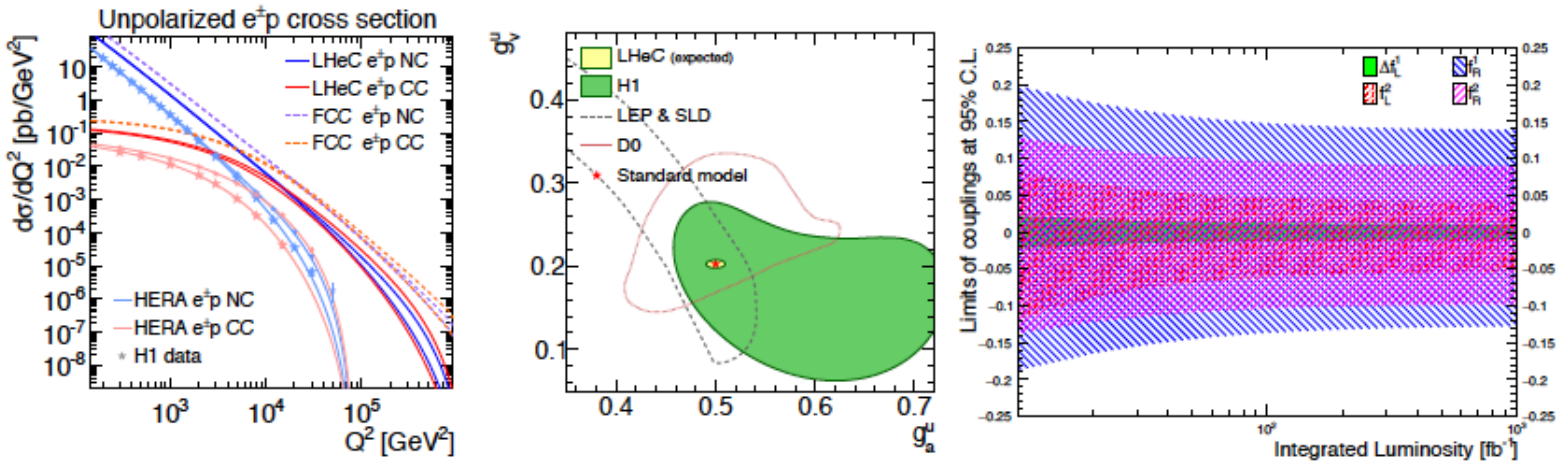
Results for FCC-eh at
 20 TeV E_p x 60 GeV E_e

Uncertainties on kappa
 Decay FCCep HL-LHC

bb	0.9	2.7
WW	0.3	1.2
gg	1.7	2.2
tau	1.5	1.6
cc	1.9	--
ZZ	0.5	1.0
yy	3.3	1.7

in percent. SM width.

Precision
Electroweak
Physics

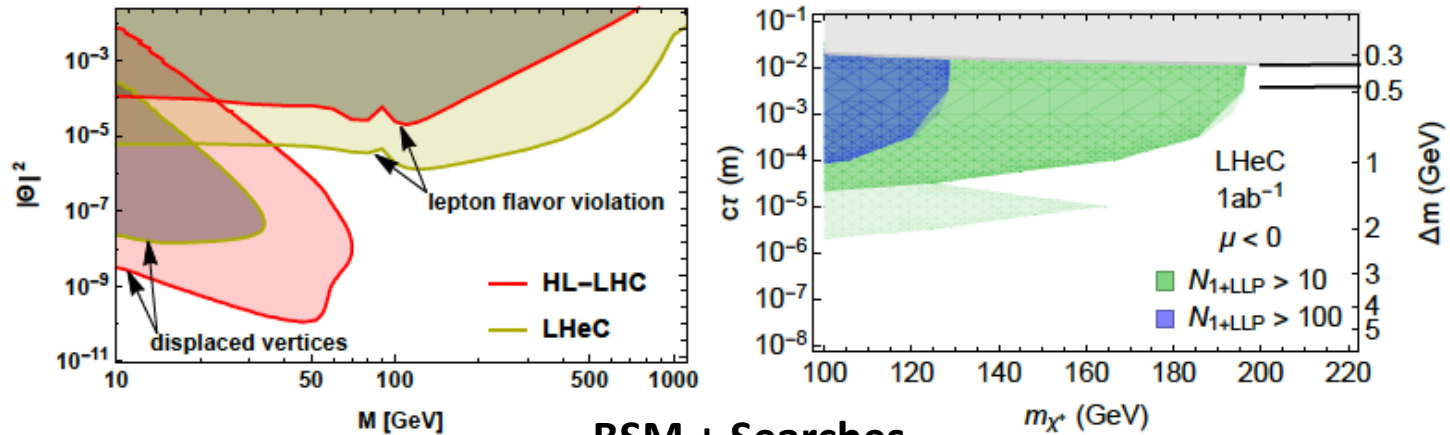


Electroweak+Top Physics

Figure 1: Left: Unpolarised inclusive NC and CC DIS cross sections as a function of Q^2 at the LHeC, in comparison to HERA (H1 [17]) and FCC-eh expectations; Middle: Determination of the up-quark weak neutral current vector and axial-vector couplings with LHeC (yellow) compared with current determinations; Right: Expected sensitivities as a function of the integrated luminosity on the SM and anomalous W_{tb} couplings [18].

Anomalous
 W_{tb} couplings

cf EPS talks by
D Britzger and
C Schwanenberger



BSM + Searches

Figure 4: Left: Prospects for direct right-handed neutrino searches at the LHeC, first estimates for HL-LHC prospects for comparison, based on [34]. Right: Reach for long-lived Higgsinos in the mass (m_{χ}) - lifetime ($c\tau$) plane, compared to disappearing tracks at the HL-LHC [35], shown by the black lines. Light shading indicates the uncertainty in the predicted number of events due to different hadronization and LLP reconstruction assumptions. For details, see [36].

Higgsinos

Heavy Neutrinos

MK at EPS 2019



The Large Hadron-Electron Collider at the HL-LHC

Preface	1
1 Introduction	9
1.1 The Context	9
1.1.1 Particle Physics - an unfinished Area of Fundamental Science	9
1.1.2 Deep Inelastic Scattering and HERA	11
1.2 The Paper	12
1.2.1 The LHeC Physics Programme	12
1.2.2 The Accelerator	14
1.2.3 PERLE	16
1.2.4 The Detector	16
1.3 Outline	17
2 LHeC Configuration and Parameters	18
2.1 Introduction	18
2.2 Cost Estimate, Default Configuration and Staging	19
2.3 Configuration Parameters	20
2.4 Luminosity	21
2.4.1 Electron-Proton Collisions	22
2.4.2 Electron-Ion Collisions	23
2.5 Linac Parameters	24
2.6 Operation Schedule	24
3 Parton Distributions - Resolving the Substructure of the Proton	27
3.1 Introduction	27
3.1.1 Partons in Deep Inelastic Scattering	28
3.1.2 Fit Methodology and HERA PDFs	29
3.2 Simulated LHeC Data	32
3.2.1 Inclusive Neutral and Charged Current Cross Sections	32
3.2.2 Heavy Quark Densities	35
3.3 Parton Distributions from the LHeC	37
3.3.1 Procedure and Assumptions	37
3.3.2 Valence Quarks	40
3.3.3 Light Sea Quarks	41
3.3.4 Strange Quark	43
3.3.5 Heavy Quarks	46
3.3.6 The Gluon PDF	48
3.3.7 Luminosity and Beam Charge Dependence of LHeC PDFs	49
3.3.8 Weak Interactions Probing Proton Structure	50

3.3.9 Parton-Parton Luminosities	56
3.4 The 3D Structure of the Proton	58
4 Exploration of Quantum Chromodynamics	65
4.1 Determination of the strong coupling constant	65
4.1.1 Strong coupling from inclusive jet cross sections	66
4.1.2 Pinning Down α_s with Inclusive and Jet LHeC Data	69
4.1.3 Strong coupling from other processes	72
4.2 Discovery of New Strong Interaction Dynamics at Small x	74
4.2.1 Resummation at small x	74
4.2.2 Disentangling non-linear QCD dynamics at the LHeC	77
4.2.3 Low x and the Longitudinal Structure Function F_L	83
4.2.4 Relation to Ultrahigh Energy Neutrino and Astroparticle physics	89
4.3 Diffractive Deep Inelastic Scattering at the LHeC	91
4.3.1 Introduction and Formalism	91
4.3.2 Pseudodata for diffractive structure functions	96
4.3.3 Potential for constraining diffractive PDFs at the LHeC and FCC-eh	97
4.3.4 Factorisation tests using Hadronic Final States in Diffractive DIS	99
4.4 Theoretical Developments	99
4.4.1 Prospects for Higher Order pQCD in DIS	99
4.4.2 Theoretical Concepts on the Light Cone	101
5 Electroweak and Top Quark Physics	106
5.1 Electroweak Physics with Inclusive DIS data	106
5.1.1 Electroweak effects in inclusive NC and CC DIS cross sections	106
5.1.2 Methodology of a combined EW and QCD fit	107
5.1.3 Weak boson masses M_W and M_Z	108
5.1.4 Further mass determinations	110
5.1.5 Weak Neutral Current Couplings	111
5.1.6 The neutral current ρ_{NC} and κ_{NC} parameters	112
5.1.7 The effective weak mixing angle $\sin^2 \theta_W^{\text{eff},\ell}$	113
5.1.8 Electroweak effects in charged-current scattering	115
5.1.9 Conclusion	115
5.2 Direct W and Z Production and Anomalous Triple Gauge Couplings	116
5.2.1 Direct W and Z Production	116
5.2.2 Anomalous Triple Gauge Couplings	118
5.3 Top Quark Physics	120
5.3.1 Wtq Couplings	120
5.3.2 Top Quark Polarisation	122
5.3.3 Top- γ and Top- Z Couplings	122
5.3.4 Top-Higgs Coupling	123
5.3.5 Top Quark PDF and the Running of α_s	124
5.3.6 FCNC Top Quark Couplings	124
5.3.7 Summary of Top Quark Physics	126
6 Nuclear Particle Physics with Electron-Ion Scattering at the LHeC	128
6.1 Introduction	128
6.2 Nuclear Parton Densities	130
6.2.1 Pseudodata	131
6.2.2 Nuclear gluon PDFs in a global-fit context	133

6.2.3 nPDFs from DIS on a single nucleus	135
6.3 Nuclear diffraction	140
6.3.1 Exclusive vector meson diffraction	140
6.3.2 Inclusive diffraction on nuclei	145
6.4 New Dynamics at Small x with Nuclear Targets	147
6.5 Collective effects in dense environments – the ‘ridge’	148
6.6 Novel QCD Nuclear Phenomena at the LHeC	148
7 Higgs Physics with LHeC	152
7.1 Introduction	152
7.2 Higgs Production in Deep Inelastic Scattering	153
7.2.1 Kinematics of Higgs Production	153
7.2.2 Cross Sections and Rates	155
7.3 Higgs Signal Strength Measurements	156
7.3.1 Higgs Decay into Bottom and Charm Quarks	158
7.3.2 Higgs Decay into WW	163
7.3.3 Accessing Further Decay Channels	166
7.3.4 Systematic and Theoretical Errors	167
7.4 Higgs Coupling Analyses	169
7.5 Parton Distributions and Higgs – $\text{raus} ???$	171
7.6 Measuring the Top-quark–Higgs Yukawa Coupling	172
7.7 Higgs Decay into Invisible Particles	177
8 Searches for Physics Beyond the Standard Model	180
8.1 Introduction	180
8.2 Extensions of the SM Higgs Sector	180
8.2.1 Modifications of the Top-Higgs interaction	181
8.2.2 Charged scalars	181
8.2.3 Neutral scalars	182
8.2.4 Modifications of Higgs self-couplings	183
8.2.5 Exotic Higgs boson decays	184
8.3 Searches for supersymmetry	184
8.3.1 Search for the SUSY Electroweak Sector: prompt signatures	185
8.3.2 Search for the SUSY Electroweak Sector: long-lived particles	186
8.3.3 R-parity violating signatures	187
8.4 Feebly Interacting Particles	188
8.4.1 Searches for heavy neutrinos	188
8.4.2 Fermion triplets in type III seesaw	189
8.4.3 Dark photons	190
8.4.4 Axion-like particles	191
8.5 Anomalous Gauge Couplings	192
8.5.1 Radiation Amplitude Zero	193
8.6 Theories with heavy resonances and contact interaction	193
8.6.1 Leptoquarks	194
8.6.2 Z' mediated charged lepton flavour violation	195
8.6.3 Vector-like quarks	196
8.6.4 Excited fermions (ν^*, e^*, u^*)	197
8.6.5 Colour octet leptons	197
8.6.6 Quark substructure and Contact interactions	197
8.7 Summary and conclusion	198

9	Influence of the LHeC on Physics at the HL-LHC	200		
9.1	Precision Electroweak Measurements at the HL-LHC	200		
9.1.1	The effective weak mixing angle	200		
9.1.2	The W -boson mass	202		
9.1.3	Impact on electroweak precision tests	205		
9.2	Higgs Physics	206		
9.2.1	Impact of LHeC data on Higgs cross section predictions at the LHC	206		
9.2.2	Higgs Couplings from a simultaneous analysis of pp and ep collision data	208		
9.3	Further precision SM measurements at the HL-LHC	211		
9.4	High Mass Searches at the LHC	215		
9.4.1	Strongly-produced supersymmetric particles	215		
9.4.2	Contact interactions	215		
9.5	PDFs and the HL-LHC and the LHeC	216		
9.5.1	PDF Prospects with the HL-LHC and the LHeC	217		
9.5.2	Parton luminosities at the HL-LHC	218		
9.5.3	PDF Sensitivity: Comparing HL-LHC and LHeC	219		
9.6	Impact of New Small- x Dynamics on Hadron Collider Physics	220		
9.7	Heavy Ion Physics with eA Input	222		
10	The Electron Energy Recovery Linac	226		
10.1	Introduction – Design Goals	226		
10.2	The ERL Configuration of the LHeC	227		
10.2.1	Baseline Design – Lattice Architecture	228		
10.2.2	30 GeV ERL Options	239		
10.2.3	Component Summary	239		
10.3	Electron-Ion Collisions	239		
10.4	Beam-Beam Interactions	241		
10.4.1	Effect on the electron beam	242		
10.4.2	Effect on the proton beam	244		
10.5	Arc Magnets	244		
10.5.1	Dipole magnets	244		
10.5.2	Quadrupole magnets	245		
10.6	LINAC and SRF	247		
10.6.1	Choice of Frequency	248		
10.6.2	Cavity Prototype	248		
10.6.3	Cavity-Cryomodule	251		
10.6.4	Electron sources and injectors	255		
10.6.5	Positrons	259		
10.6.6	Compensation of Synchrotron Radiation Losses	261		
10.6.7	LINAC Configuration and Infrastructure	262		
10.7	Interaction Region	263		
10.7.1	Layout	263		
10.7.2	Proton Optics	265		
10.7.3	Electron Optics	272		
10.7.4	Interaction Region Magnet Design	280		
10.8	Civil Engineering	284		
10.8.1	Placement and Geology	284		
10.8.2	Underground infrastructure	286		
10.8.3	Construction Methods	287		
			10.8.4	Civil Engineering for FCC-eh
			10.8.5	Cost estimates
			10.8.6	Spoil management
11	Technology of ERL and PERLE	292		
11.1	Energy Recovery Linac Technology – Status and Prospects	292		
11.1.1	ERL Applications	292		
11.1.2	Challenges	292		
11.1.3	ERL Landscape	295		
11.2	The ERL Facility PERLE	296		
11.2.1	Configuration	297		
11.2.2	Importance of PERLE towards the LHeC	297		
11.2.3	PERLE Layout and Beam Parameters	298		
11.2.4	PERLE Lattice	299		
11.2.5	The Site	301		
11.2.6	Staging Strategy and Time Schedule	301		
11.2.7	Concluding Remark	303		
12	Experimentation at the LHeC	304		
12.1	Introduction	304		
12.2	Overview of Main Detector Elements	306		
12.3	Inner Tracking	307		
12.3.1	Overview and Performance	307		
12.3.2	Silicon Technology Choice	311		
12.4	Calorimetry	312		
12.5	Muon Detector	317		
12.6	Forward and Backward Detectors	318		
12.6.1	Zero-Degree (Neutron) Calorimeter	318		
12.7	Detector Installation and Infrastructure	321		
12.8	Detector Design for a Low Energy FCC-eh	324		
13	Conclusion	328		
A	Statement of the International Advisory Committee	331		

Statement of the IAC (reproduced in CDR Update)

Members of the Committee

Sergio Bertolucci (Bologna)	Max Klein (Liverpool, coordinator)
Nichola Bianchi (INFN, now Singapore)	Shin-Ichi Kurokawa (KEK)
Frederick Bordy (CERN)	Victor Matveev (JINR Dubna)
Stan Brodsky (SLAC)	Aleandro Nisati (Rome I)
Oliver Brüning (CERN, coordinator)	Leonid Rivkin (PSI Villigen)
Hesheng Chen (Beijing)	Herwig Schopper (CERN, em.DG, Chair)
Eckhard Elsen (CERN)	Jürgen Schukraft (CERN)
Stefano Forte (Milano)	Achille Stocchi (Orsay)
Andrew Hutton (Jefferson Lab)	John Womersley (ESS Lund)
Young-Kee Kim (Chicago)	

In conclusion it may be stated

- The installation and operation of the LHeC has been demonstrated to be commensurate with the currently projected HL-LHC program, while the FCC-eh has been integrated into the FCC vision;
- The feasibility of the project as far as accelerator issues and detectors are concerned has been shown. It can only be realised at CERN and would fully exploit the massive LHC and HL-LHC investments;
- The sensitivity for discoveries of new physics is comparable, and in some cases superior, to the other projects envisaged;
- The addition of an ep/A experiment to the LHC substantially reinforces the physics program of the facility, especially in the areas of QCD, precision Higgs and electroweak as well as heavy ion physics;
- The operation of LHeC and FCC-eh is compatible with simultaneous pp operation; for LHeC the interaction point 2 would be the appropriate choice, which is currently used by ALICE;

- The development of the ERL technology needs to be intensified in Europe, in national laboratories but with the collaboration of CERN;
- A preparatory phase is still necessary to work out some time-sensitive key elements, especially the high power ERL technology (PERLE) and the prototyping of Intersection Region magnets.

Recommendations

- i) It is recommended to further develop the ERL based ep/A scattering plans, both at LHC and FCC, as attractive options for the mid and long term programme of CERN, resp. Before a decision on such a project can be taken, further development work is necessary, and should be supported, possibly within existing CERN frameworks (e.g. development of SC cavities and high field IR magnets).
- ii) The development of the promising high-power beam-recovery technology ERL should be intensified in Europe. This could be done mainly in national laboratories, in particular with the PERLE project at Orsay. To facilitate such a collaboration, CERN should express its interest and continue to take part.
- iii) It is recommended to keep the LHeC option open until further decisions have been taken. An investigation should be started on the compatibility between the LHeC and a new heavy ion experiment in Interaction Point 2, which is currently under discussion.

After the final results of the European Strategy Process will be made known, the IAC considers its task to be completed. A new decision will then have to be taken for how to continue these activities.

Herwig Schopper, Chair of the Committee,

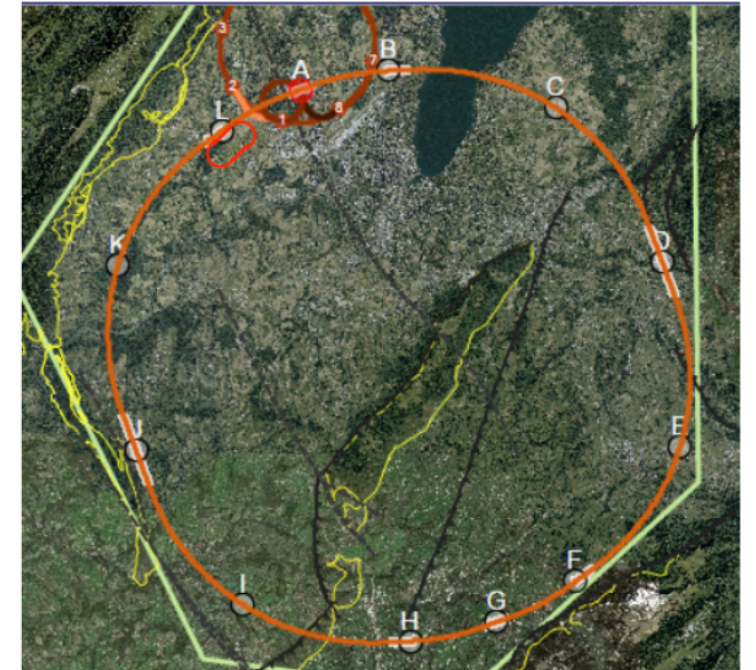
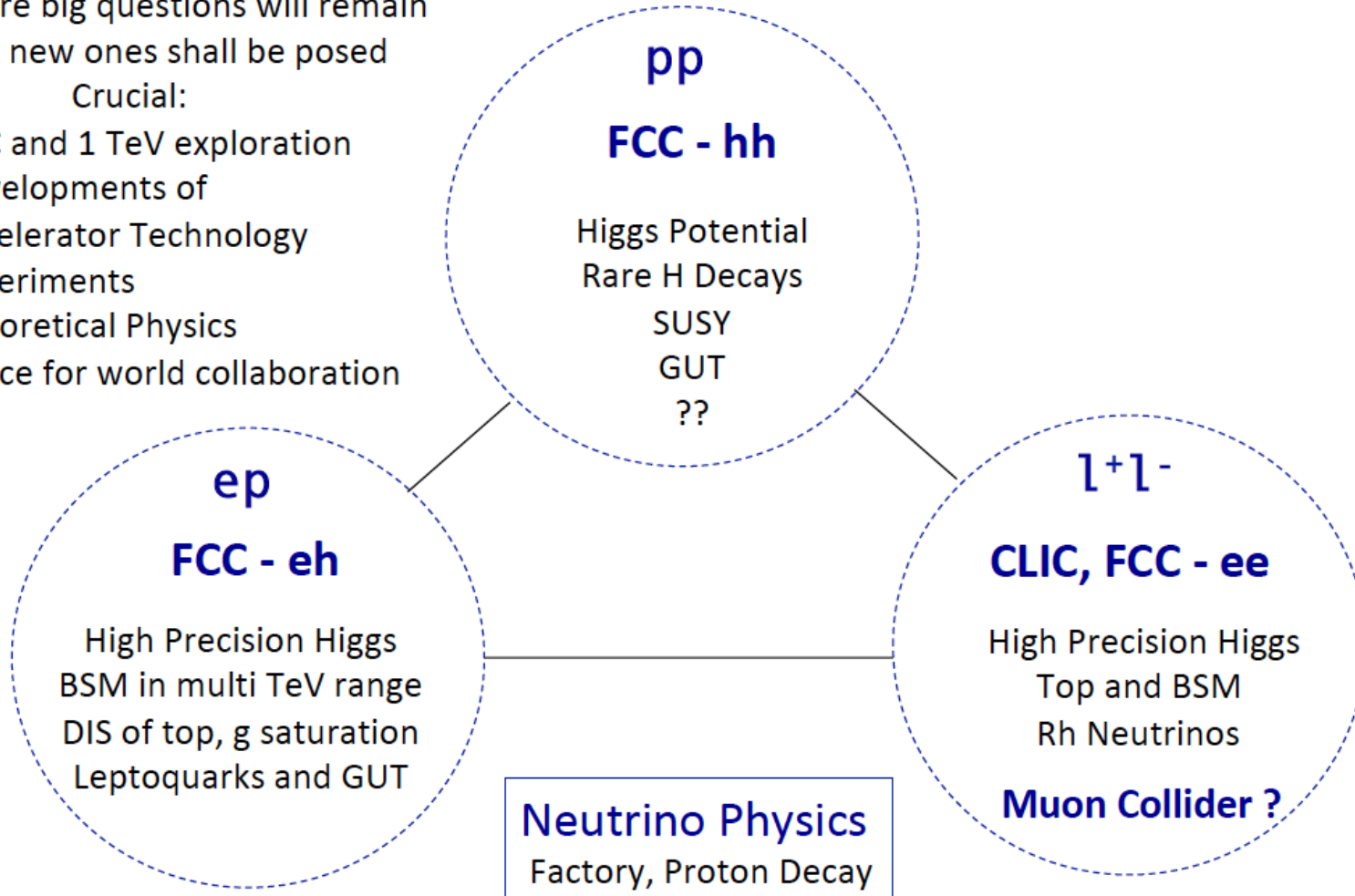
Geneva, November 4, 2019

Beyond the LHC/LHeC: FCC

The far future is least defined
There big questions will remain
and new ones shall be posed

Crucial:

LHC and 1 TeV exploration
Developments of
Accelerator Technology
Experiments
Theoretical Physics
Peace for world collaboration



Higher energy than 60 GeV ?

Particle Physics has a long term future,
many of its quests are unresolved,
Nr of families, GUT, substructure, DM..

Beyond Europe: eh in China ? and the EIC

CEPC e-p and e-A Options

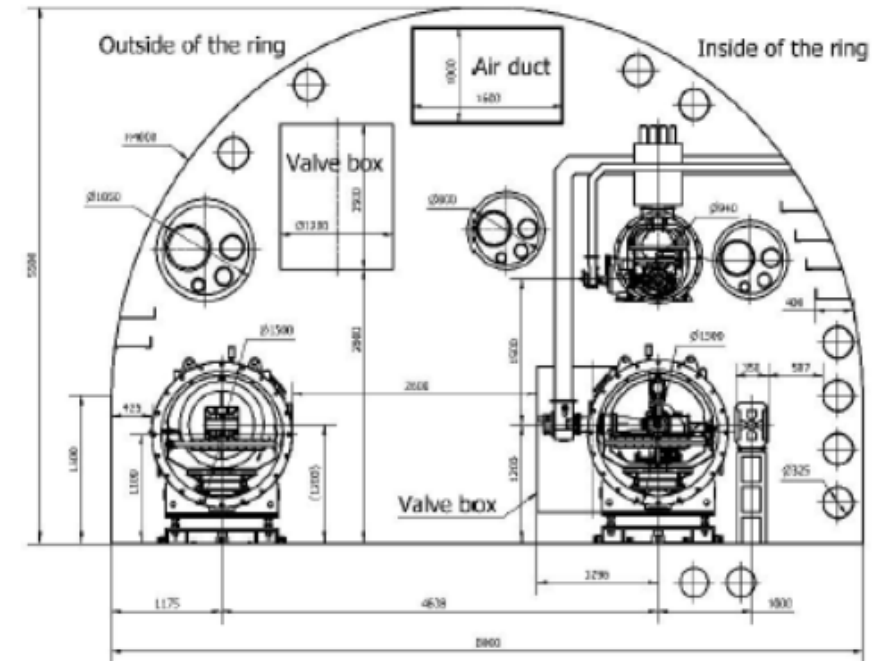
Y.H. Zhang

CEPC-SPPC e-p and e-A Design Parameters

Particle		Proton	Electron	Lead (²⁰⁸ Pb ⁸²⁺)	Electron
Beam energy	TeV	37.5	0.12	14.8	0.12
CM energy	TeV	4.2		2.7	
Beam current	mA	730	34.8	730	34.8
Particles per bunch	10 ¹⁰	15	0.72	0.18	0.72
Number of bunch		10080		10080	
Bunch filling factor		0.756		0.756	
Bunch spacing	ns	25	25	25	25
Bunch repetition rate	MHz	40	40	40	40
Norm. emittance, (x/y)	μm rad	2.35	282	0.22	282
Bunch length, RMS	Cm	7	0.5	7	0.5
Beta-star (x/y)	Cm	75	3.7	75	0.88
Beam spot size at IP (c/y)	Mm	6.6	6.6	3.25	3.25
Beam-beam per IP(x/y)		0.0004	0.12	0.0016	0.12
Crossing angle	mrad	~0.95		~0.95	
Hour-glass (HG) reduction		0.77		0.34	
Luminosity/nuclei per IP, with HG reduction	10 ³³ /cm ² /s			1.0	
Luminosity/nucleon per IP, with HG reduction	10 ³³ /cm ² /s	4.5		23.6	

Tunnel cross section at RF-section
Width: 8,000 mm. Height: 5,500 mm.

The Chinese 100km tunnel housing p and e



Jie Gao, HKUST Conference, 22.1.18

Max Klein, Chavannes, 24.10.2019

EICs in US and China: spin, eh complementary
US: expect support in CDi and site selection
→ CERN is the unique place for high energy eh

Remarks

LHeC and FCCeh are the only and unique possibilities to keep DIS as part of HEP in this century. A high responsibility of CERN.

The luminosity is 100-1000 times that of HERA and the kinematic range extends to $x=10^{-6}$ (LHeC) $\rightarrow 10^{-7}$ (FCC-eh)

With their BSM, PDF, small x , top, Higgs, HI .. programme they are different to EIC (like H1/ZEUS and HERMES/COMPASS) which is hosted by the NP community

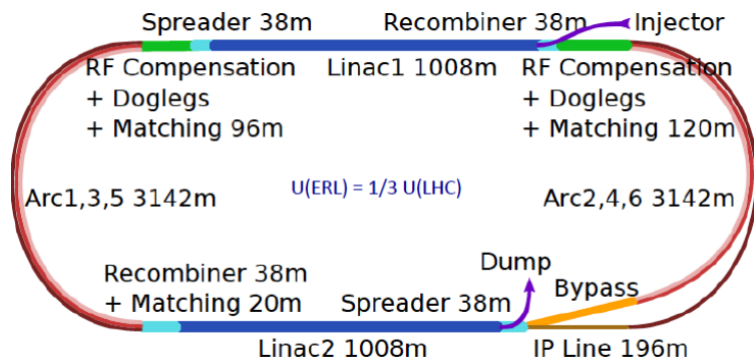
Organisation: contacts Nestor Armesto and Oliver Fischer

Talk on LHeC Machine: Oliver Bruening on 24.6. (today invited by V Shiltsev)

Many of us are interested to join

For these DIS projects to happen it will be crucial they are scrutinised and eventually supported by the US HEP community
European Strategy paper expected to be released in June.

backup



Sustainability and Cost

LHC:

- see: SM, Higgs and no BSM
- use: Investment of O(5) BSF
- run: HL LHC until ~2040

LHeC [1206.2913]

- 1.2 TeV ep/A for O(1)BSF

→ Establish novel ep+pp

Twin Collider Facility at CERN:

sustains HL LHC and bridges to CERN's long term future

For installation during LS4 (2030+) and long term use (HE LHC, FCCeh)

Three Raisons d'être of the LHeC

Physics

- **Microscope:** World's Cleanest High Resolution
- **Empowerment** of the LHC Physics Programme
- **Creation** of a high precision, novel Higgs facility
- **Discovery** Beyond the Standard Model
- **Revolution** of Nuclear Particle Physics

Technology

Accelerator: Novel SRF ERL, green power facility

Detector: Novel high tech (CMOS..) apparatus

→ Keep accelerator and detector base uptodate while preparing for colliders that cost O(10)BSF

With many thanks to

all collaborators from exp, acc + thy

CERN Directors

Advisory Committee and its Chair, H Schopper, em DG

Our home institutions and colleagues for supporting this engagement for the future

The LHeC/FCC coordinating groups and convenors

..

MK at EPS 2019

CERN-ACC-NOTE-2018-0084
December 18, 2018



Exploring the Energy Frontier with Deep Inelastic Scattering at the LHC
A Contribution to the Update of the European Strategy on Particle Physics

LHeC and PERLE Collaboration

LHeC also described in the ES paper by A.Caldwell, A.Levy, R.Ent, P.Newman and F.Olness

Summary
Papers
submitted
to the
European
Strategy
12/2018

CERN-ACC-NOTE-2018-0086

December 18, 2018

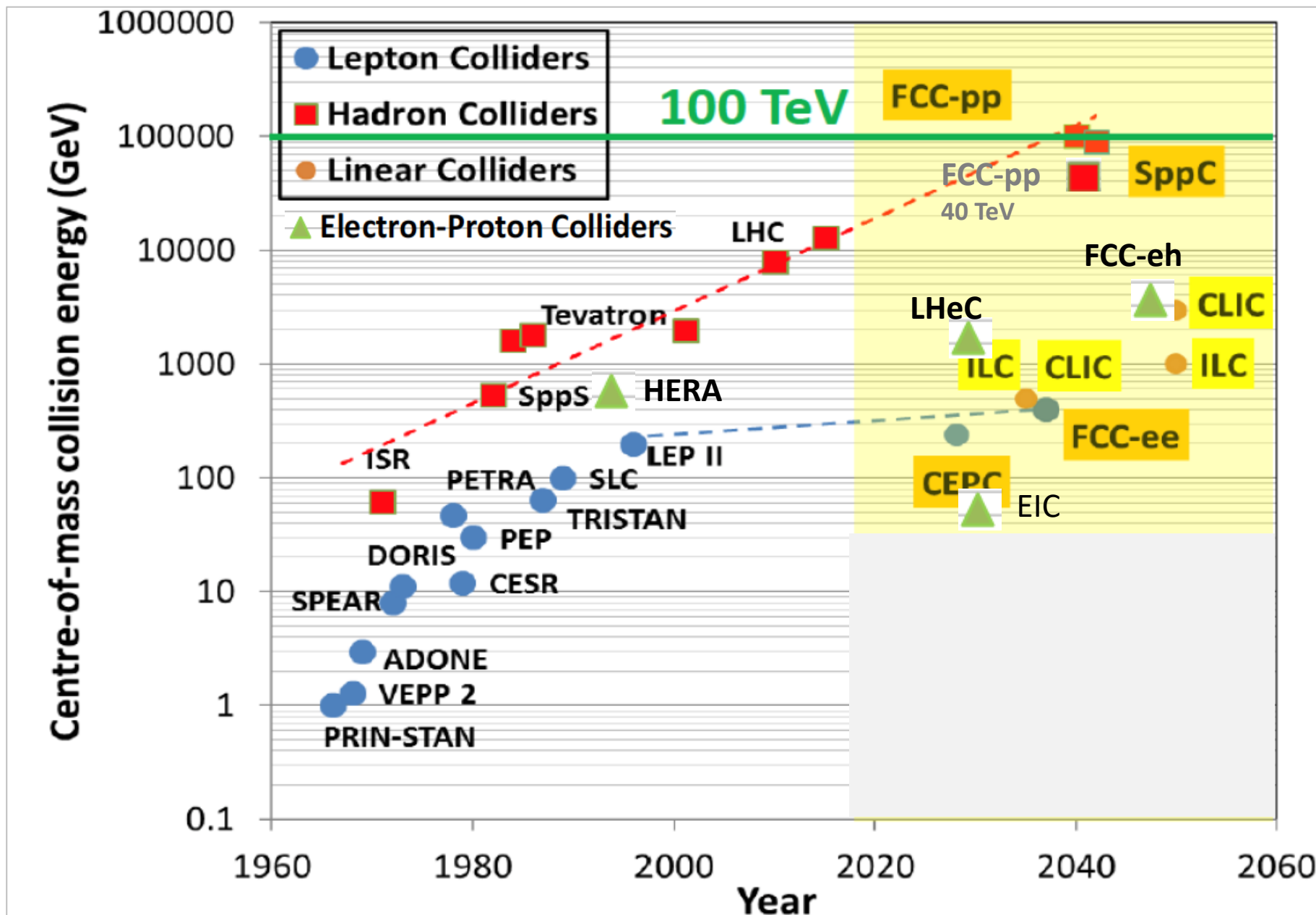


PERLE : A High Power Energy Recovery Facility for Europe

A Contribution to the Update of the European Strategy on Particle Physics

Cockcroft Institute, AsTEC Daresbury, TU Darmstadt, BINP Novosibirsk, CERN, Liverpool University,
IPN and LAL Orsay, Jefferson Laboratory, CEA Saclay

Hundred
Years of
HEP
Colliders

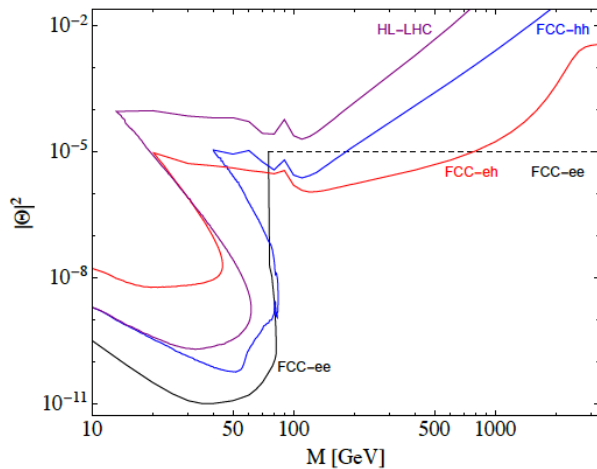


ep/A
Parameters:

FCC-eh in the CDR [V1 Physics and V3 hh]

Volume 1 had been the collaborative effort to present **the entity of FCC physics, in ee, pp and ep, including AA and eA**
Volume 3 on FCC hh contains a short summary of **the main characteristics of FCC-eh and the detector concept**

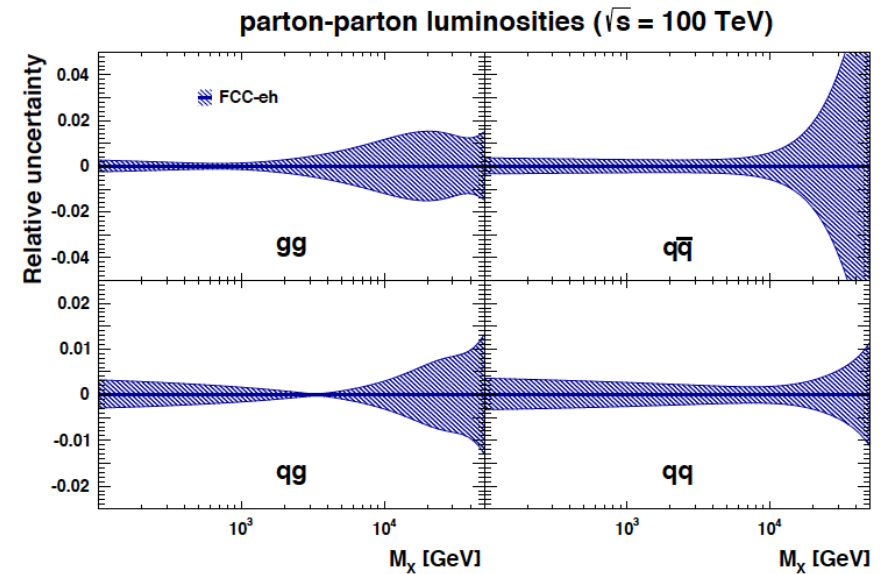
Some striking physics eh prospects are on searches and the high precision measurements on Higgs and proton structure:



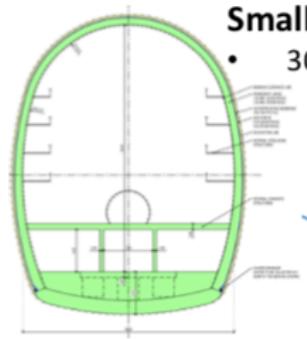
Complementary prospects to **discover rh massive neutrinos** in ee, ep and pp
 [mixing angle vs mass]

Collider	FCC-ee	FCC-eh
Luminosity (ab^{-1})	+1.5 @ 365 GeV	2
Years	3+4	20
$\delta\Gamma_H/\Gamma_H$ (%)	1.3	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	0.17	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	0.43	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	0.61	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	1.21	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.01	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	0.74	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	9.0	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	3.9	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	—	1.7
BR_{EXO} (%)	< 1.0	n.a.

Prospects for high precision measurements of **Higgs couplings at FCC ee and ep**. Note ee gets the width with Z recoil. ee is mainly ZHZ, while ep is mainly WWH: complementary also to pp



Unique resolution of partonic contents of and dynamics inside the proton, providing precise and independent parton luminosities for interpretation and searches on FCC-hh

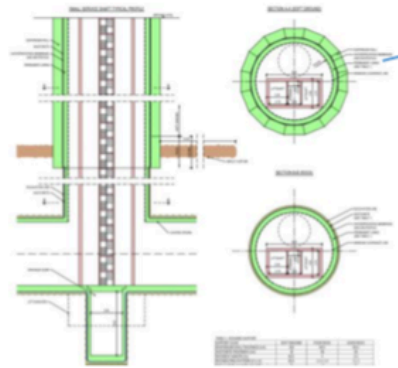


Small Experimental Caverns

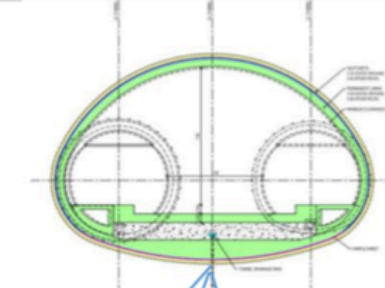
- 30 m x 35 m x 66m

Shafts:

2 x Service shafts:
9 m dia. x 175 m depth

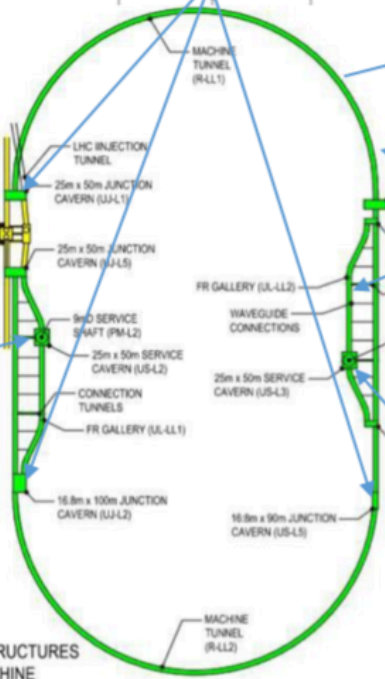


■ FCC STRUCTURES
■ EH MACHINE



Junction Caverns

- 16.8 m x 15 m x 100 m
- 25 m x 15 m x 50 m
- 16.8 m x 15 m x 90 m

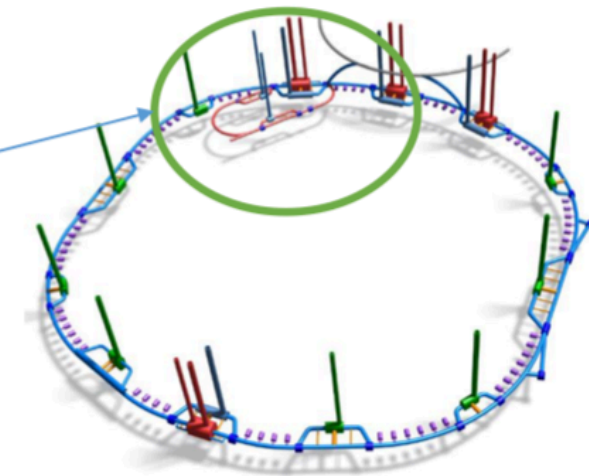
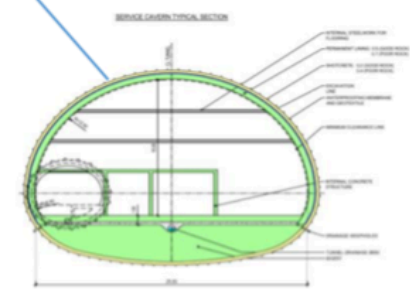


Tunnels:

- 9.091 km of 5.5m dia. machine tunnel.
- 2 x 1.04 km of 5.5m dia RF tunnel.

Service Caverns

- 25 m x 15 m x 50 m



title