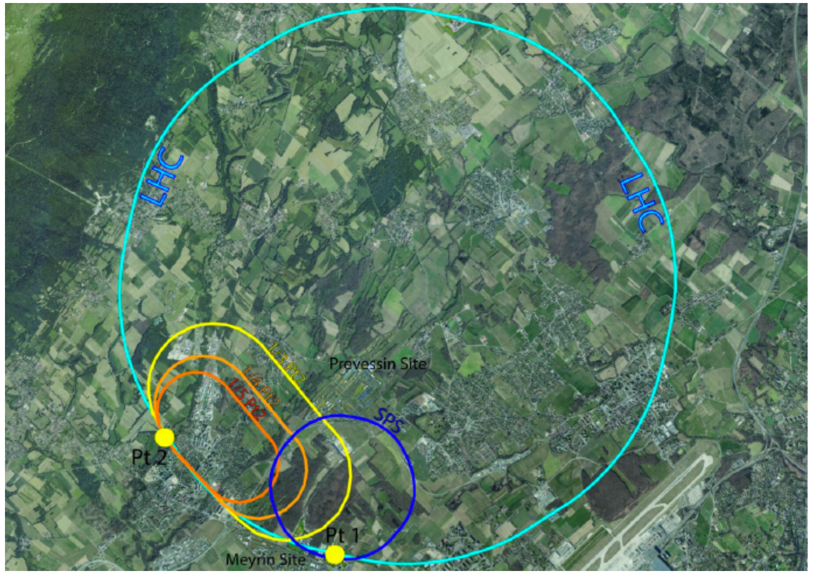
Max Klein (University of Liverpool)
for the LHeC/PERLE/FCCeh Collaboration
UK and FCC Meeting, 11.9.2020, Oxford online

LHeC, PERLE and FCC-eh



50 x 7000 GeV^2: 1.2 TeV ep collider

Operation: 2035+, Cost: O(1) BCHF

CDR: 1206.2913 J.Phys.G (550 citations)

Upgrade to 10^{34} cm^{-2}s^{-1}, for Higgs, BSM

CERN-ACC-Note-2018-0084 (ESSP)

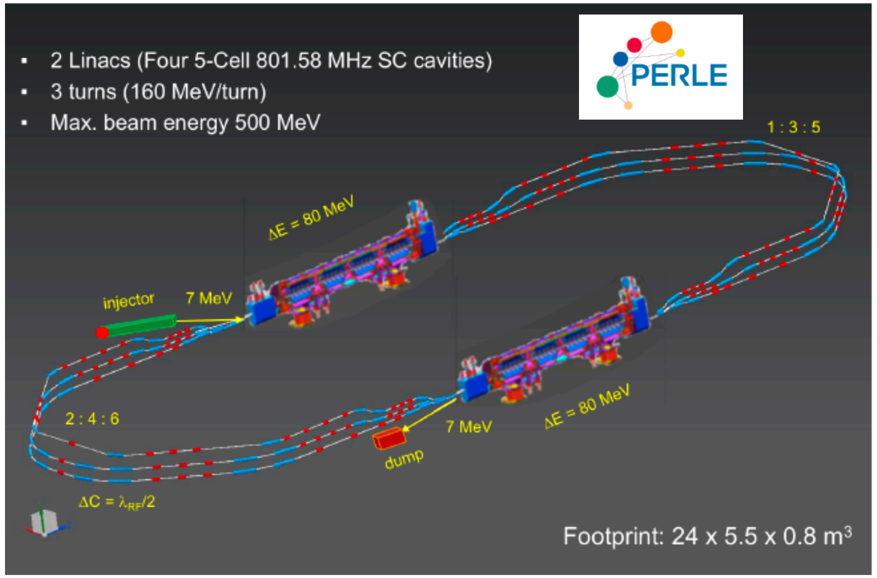
arXiv:2007.14491, subm J.Phys.G

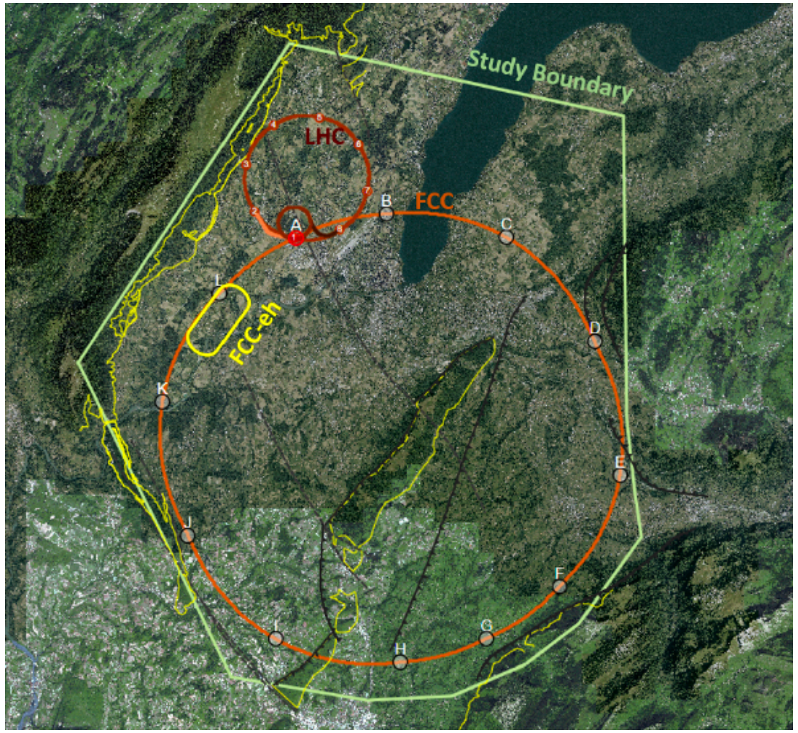
Powerful ERL for Experiments @ Orsay
CDR: 1705.08783 J.Phys.G
CERN-ACC-Note-2018-0086 (ESSP)

Operation: 2025+, Cost: O(20) MEuro

LHeC ERL Parameters and Configuration
I_e=20mA, 802 MHz SRF, 3 turns →
E_e=500 MeV → first 10 MW ERL facility

BINP, CERN, Daresbury, Jlab, Liverpool, Orsay (IJC), +





60 x 50000 GeV^2: 3.5 TeV ep collider

Operation: 2050+, Cost (of ep) O(1-2) BCHF

Concurrent Operation with FCC-hh

FCC CDR:
Eur.Phys.J.ST 228 (2019) 6, 474 Physics
Eur.Phys.J.ST 228 (2019) 4, 755 FCC-hh/eh

Future CERN Colliders: 1810.13022 Bordry+

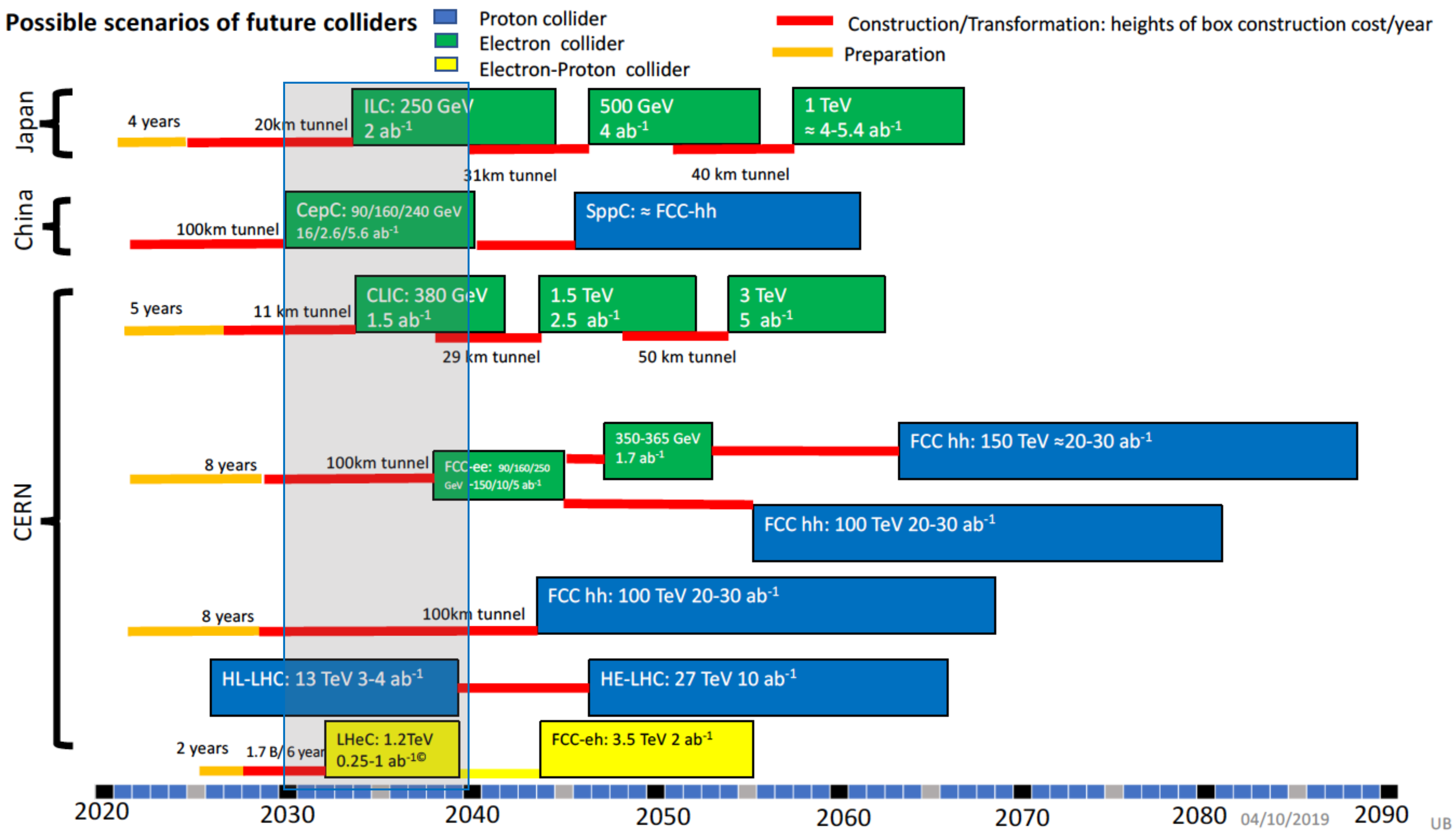


Figure 1 Timeline of Future Colliders as extracted from the submitted inputs (by U. Bassler)

CERN/ESG/05

The origin of deep inelastic scattering

Three Messages from the 2m LINAC at Stanford

Golden Past

-- **you do NOT need to promise to discover dark matter or know what new to expect when you increase the energy range** (we yet may have to readjust our perception about nature, its richness and as well our ability to predict and understand it. 'we like to see the field to be driven by experiment' – Burt Richter 2009)

-- **you can build a 2 mile electron linac in 3 years time, if you really want it**
of course we could build LHeC and FCC-eh when we decided to do so

-- **electron-proton scattering is the best means to explore the substructure of matter**
a necessary complement to the LHC/FCC and moreover, now a unique Higgs facility

50 years since the discovery of quarks by the SLAC-MIT ep scattering experiment

---

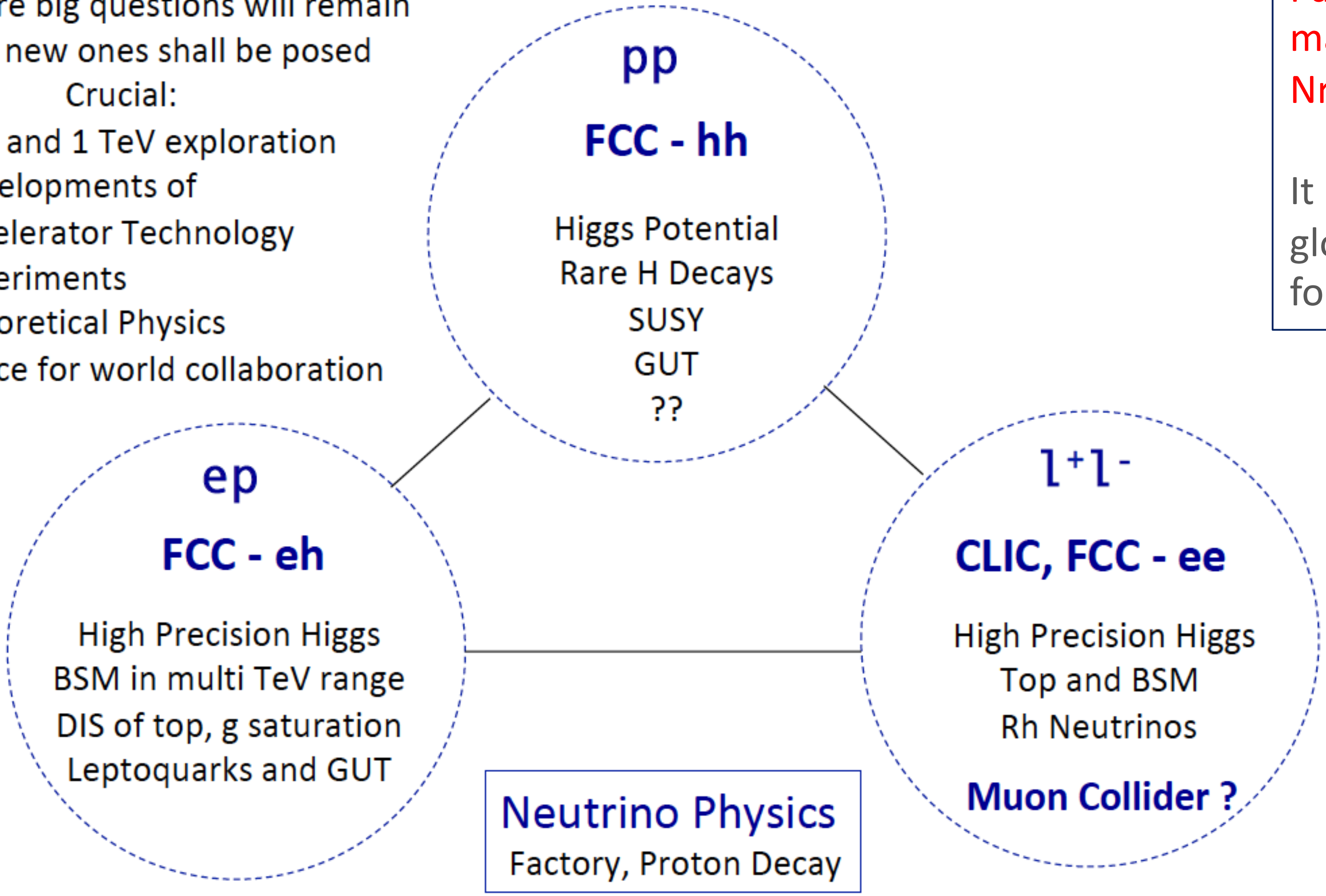
W.K.H. PANOFSKY   Vienna 8/1968   SLAC-PUB-502

Therefore theoretical speculations are focused on the possibility that these data might give evidence on the behaviour of point-like, charged structures within the nucleon.

Beyond the LHC/LHeC: FCC

Far Future

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



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

It has been and will be science at a global scale, with many question marks for USA, China and Japan at present.

Former times:

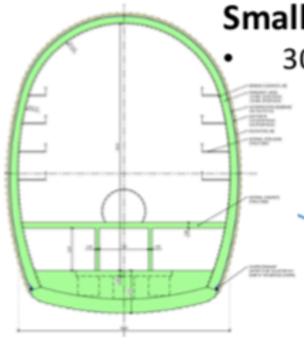
CDHS,BCDMS../SppS/PETRA,PEP

HERA/Tevatron/LEP,SLC

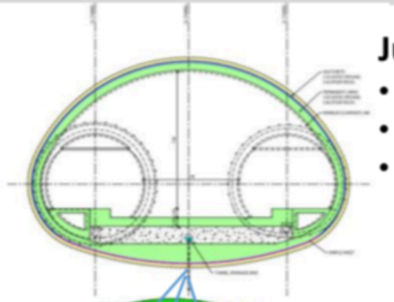
Nearer future, perhaps

LHeC/LHC/ILC,CepC

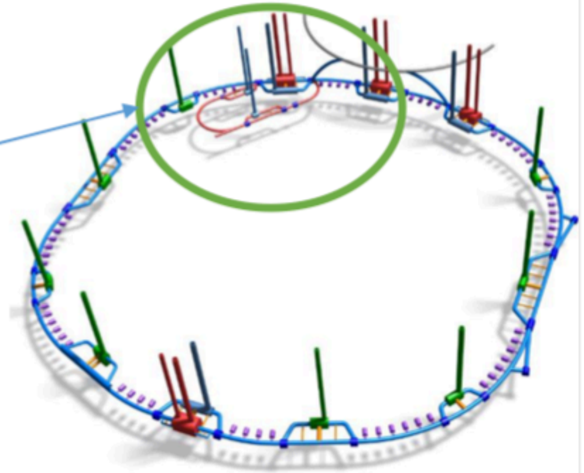
Scope of FCC-eh Structures

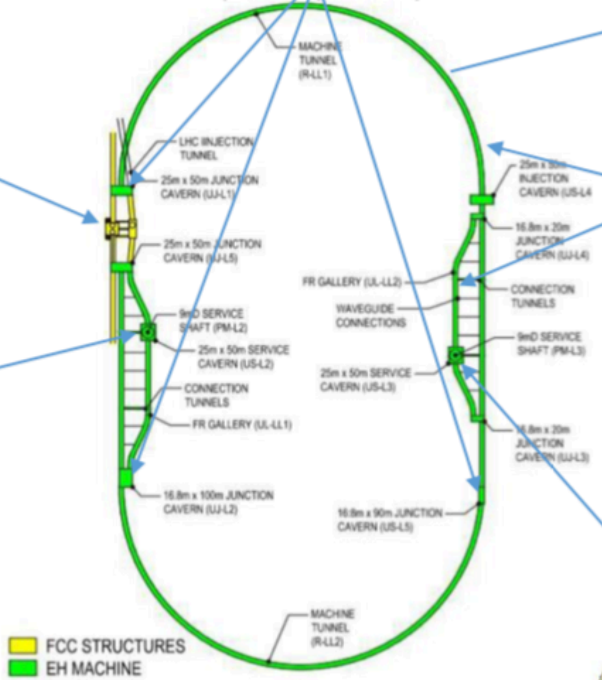


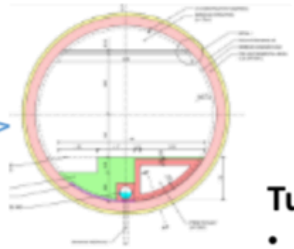
Small Experimental Caverns
- 30 m x 35 m x 66m



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

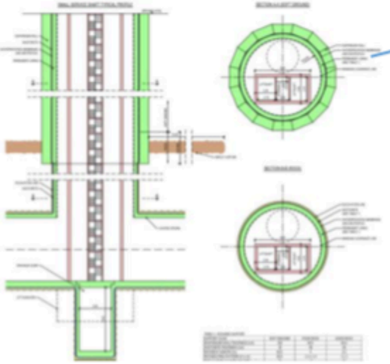


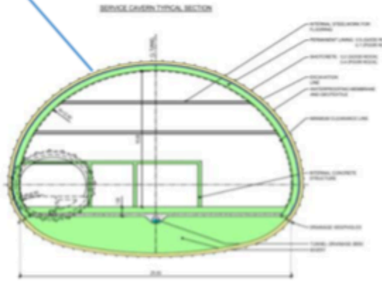




Tunnels:
- 9.091 km of 5.5m dia. machine tunnel.
- 2 x 1.04 km of 5.5m dia RF tunnel.

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

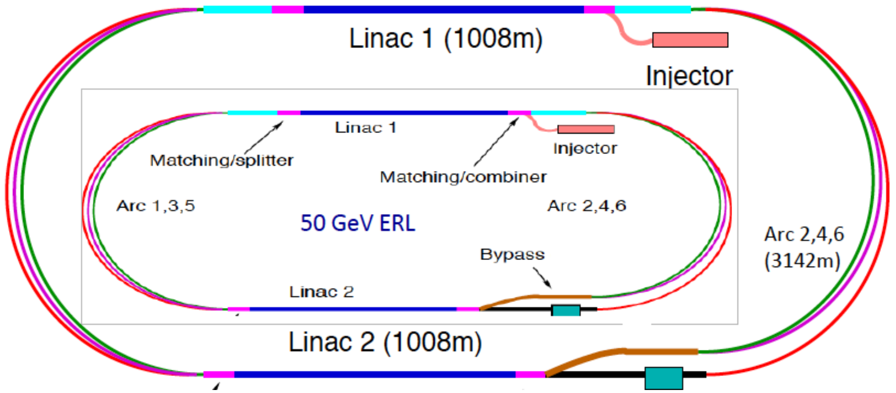




Service Caverns
- 25 m x 15 m x 50 m

Energy Recovery

today and tomorrow

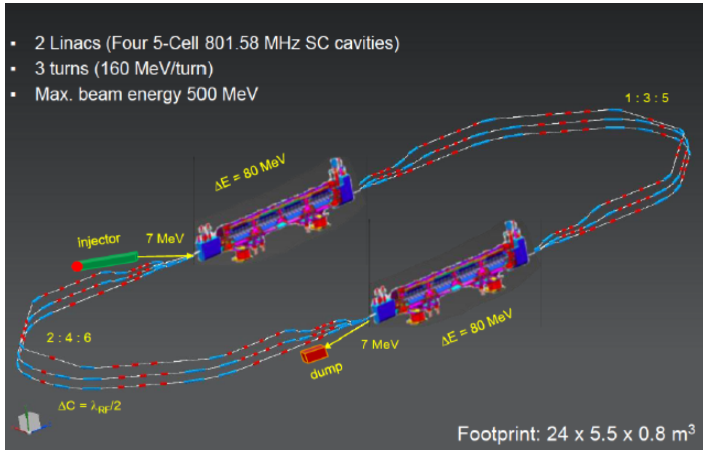


LHeC: 1 TeV ep collider with 10^{34} luminosity: P/10! Dump at injection.
Possible injector to FCC-ee in recirculating mode [O.Bruening]

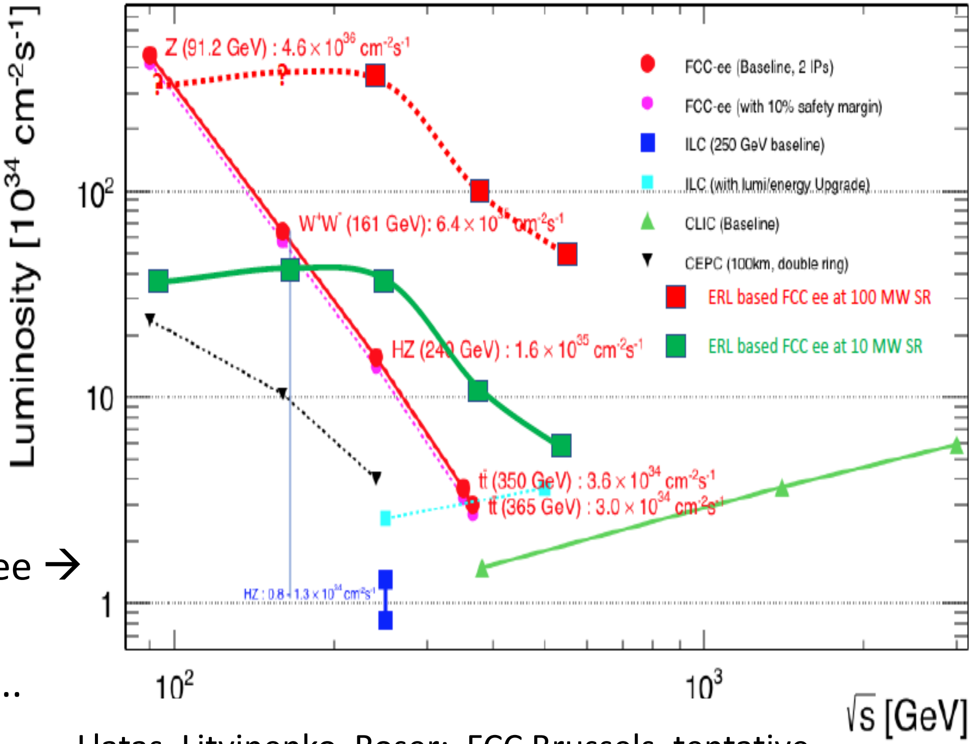
FCC-ee

- Joint 802 MHz cavity development [LHeC+FCC]

- New: Design of FCC-ee with ERL technique:
  [extension to higher energy, less SR power, higher lumi > WW]



ERL: A revolutionary technology ripe for real applications in HEP, low energy and industrial areas, of huge potential just evolving : to be recognised in strategy



Llatas, Litvinenko, Roser: FCC Brussels. tentative

PERLE BINP, CERN, Daresbury, Liverpool, Jlab, Orsay+. Could be 6 GeV injector to FCC-ee →

ERLs in: Berlin, BINP, Cornell, Daresbury, Darmstadt, Jlab, KEK, Mainz..

High current and E ~ 1GeV: low energy physics [1000 x L(ELI)!, lithography, photofission..

FCC-eh Detector Concept Design

Remarks/questions:

- Suitable design for precision DIS

- Muon tagger or spectrometer

- LAr or warm calo

- Beam pipe and Machine-detector Interface

- Final choices not now but later by a collaboration

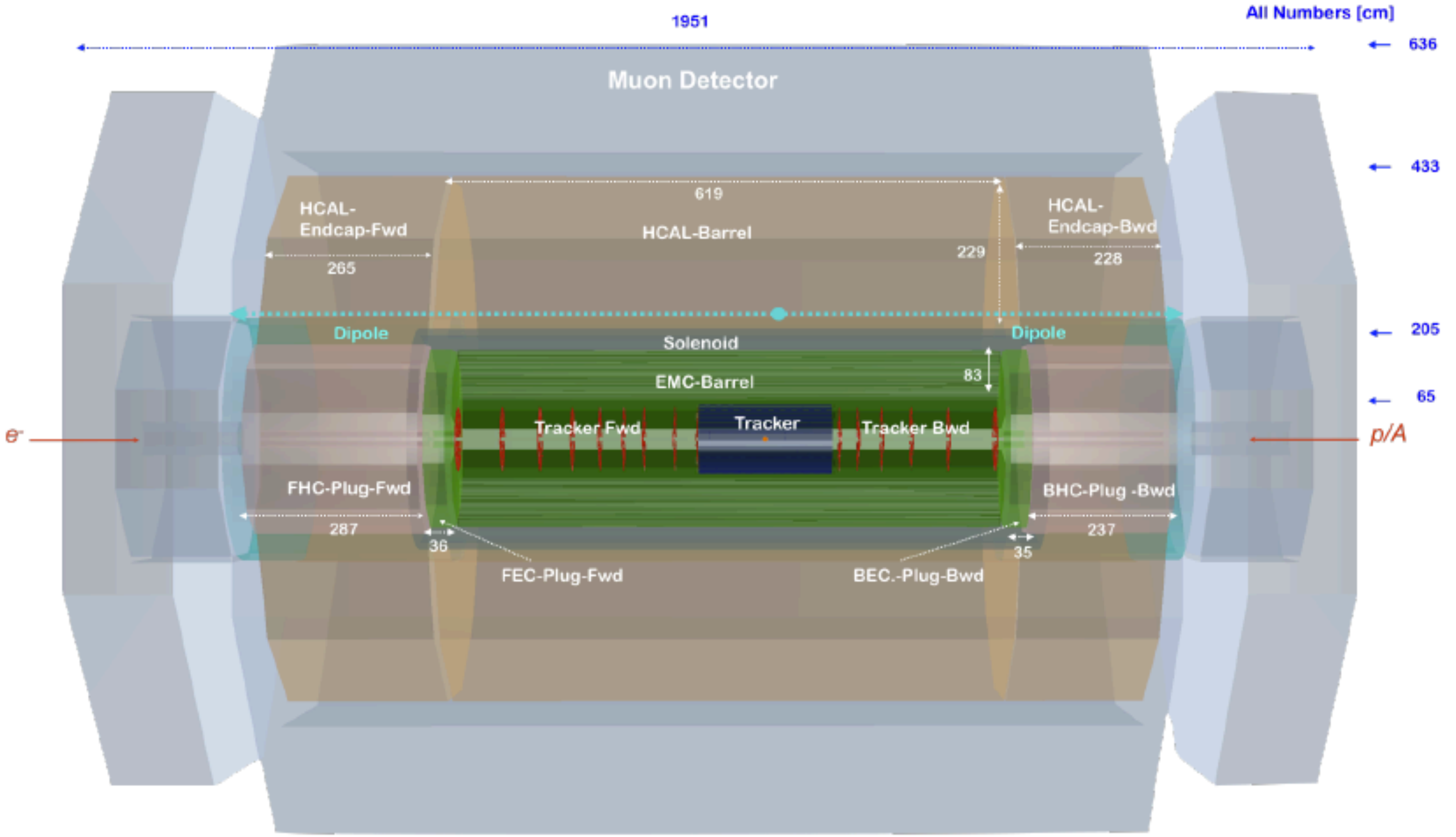


Figure 12.21: Side view of a low energy FCCeh ($E_p = 20$ TeV) concept detector, designed using the DD4hep framework [891], showing the essential features. The solenoid is again placed between the ECAL-Barrel and Hadronic-Barrel calorimeters and is housed in a cryostat in common with the beam steering dipoles extending over the full length of the barrel and plug hadronic calorimeters. The sizes have been chosen such that the solenoid/dipoles and ECAL-Barrel systems as well as the whole tracker are also suitable to operate after an upgrade of the beam energy to $E_p = 50$ TeV.

Clean FS

No pile-up

NC-CC-γp clearly separated

Radiation 1000 less than in pp

… "easy"

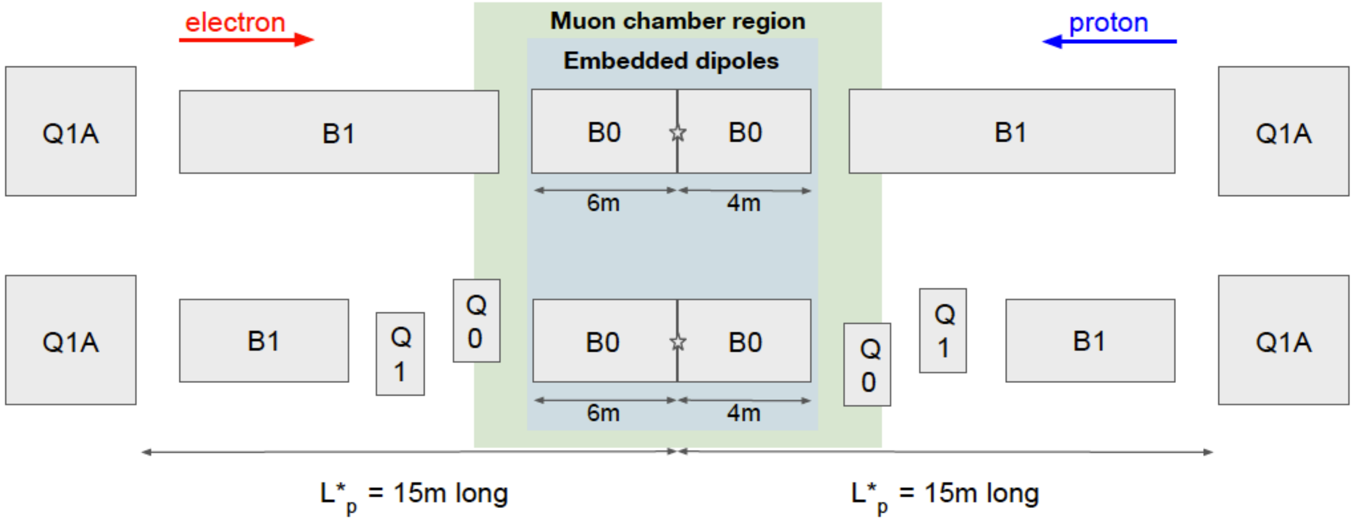
Challenge: IR and e-h

fwd region

From new paper: 2007:14491

Interaction Region – work in progress

FCC-eh magnet arrangement options (K Andre, FCC Brussels)



Recent optimisation with staggered quads

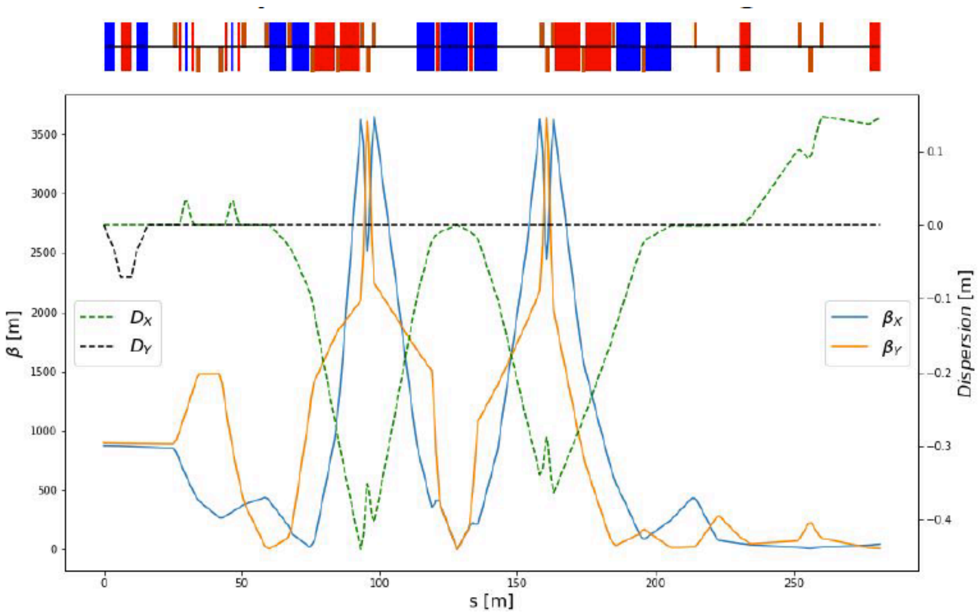
FCC-eh elonged version of LHeC IR

Prototyping for Nb_3SN under discussion

Next: masking, detector-machine interface

New question: IR with pp and ep collisions at 25ns/4 shifted IPs (for IP2 at LHC)

Electron optics with staggered quadrupoles



Down to 3 km beta max

Smaller beam size in the quadrupoles

Shorter quadrupoles

Natural chromaticity down to -80

Magnet parameters for LHeC Interaction Region

Magnet parameter	Unit	Magnet type			
		Q1A	Q1B	Q2 type	Q3 type
Superconductor type		Nb-Ti	Nb-Ti	Nb_3Sn	Nb_3Sn
Coil aperture radius R	mm	20	32	40	45
Nominal current I_{nom}	A	7080	6260	7890	9260
Nominal gradient g	T/m	252	164	186	175
Percentage on the load line	%	78	64	71	75
Beam separation distance S_{beam}	mm	106-143	148-180	233-272	414-452

Table 10.28: Main triplet magnet parameters

Machine Parameters and Operation - ep

CERN-ACC-Note-2020-0002 →arXiv (July)

Parameter	Unit	LHeC				FCC-eh	
		CDR	Run 5	Run 6	Dedicated	E_p=20 TeV	E_p=50 TeV
E_e	GeV	60	30	50	50	60	60
N_p	10^{11}	1.7	2.2	2.2	2.2	1	1
ϵ_p	μm	3.7	2.5	2.5	2.5	2.2	2.2
I_e	mA	6.4	15	20	50	20	20
N_e	10^9	1	2.3	3.1	7.8	3.1	3.1
β^*	cm	10	10	7	7	12	15
Luminosity	$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	9	23	8	15

Table 2.3: Summary of luminosity parameter values for the LHeC and FCC-eh. Left: CDR from 2012; Middle: LHeC in three stages, an initial run, possibly during Run 5 of the LHC, the 50 GeV operation during Run 6, both concurrently with the LHC, and a final, dedicated, stand-alone *ep* phase; Right: FCC-eh with a 20 and a 50 TeV proton beam, in synchronous operation.

No pileup

For comparison, HERA I operated at $10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and was upgraded by a factor of up to 4 for HERA II
The total luminosity delivered was 1 fb^{-1} over a running period of 15 years, including shutdowns.
LHeC may operate at 20 x 1000 GeV^2 and "repeat" all of HERA in a short running period.

The updated CDR considers a Ring-Ring ep collider as a back-up solution. May be revived for HE-LHC.

Machine Parameters - eA

Parameter	Unit	LHeC	FCC-eh (E_p=20 TeV)	FCC-eh (E_p=50 TeV)
Ion energy E_{Pb}	PeV	0.574	1.64	4.1
Ion energy/nucleon E_{Pb}/A	TeV	2.76	7.88	19.7
Electron beam energy E_e	GeV	50	60	60
Electron-nucleon CMS $\sqrt{s_{eN}}$	TeV	0.74	1.4	2.2
Bunch spacing	ns	50	100	100
Number of bunches		1200	2072	2072
Ions per bunch	10^8	1.8	1.8	1.8
Normalised emittance ϵ_n	μm	1.5	1.5	1.5
Electrons per bunch	10^9	6.2	6.2	6.2
Electron current	mA	20	20	20
IP beta function β^*_A	cm	10	10	15
e-N Luminosity	10^{32}cm^{-2}s^{-1}	7	14	35

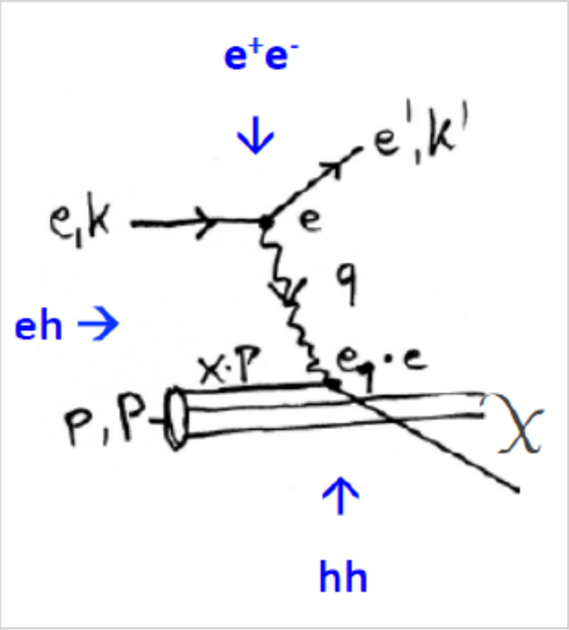
Table 2.4: Baseline parameters of future electron-ion collider configurations based on the electron ERL, in concurrent eA and AA operation mode with the LHC and the two versions of a future hadron collider at CERN. Following established convention in this field, the luminosity quoted, at the start of a fill, is the *electron-nucleon* luminosity which is a factor A larger than the usual (i.e. electron-nucleus) luminosity.

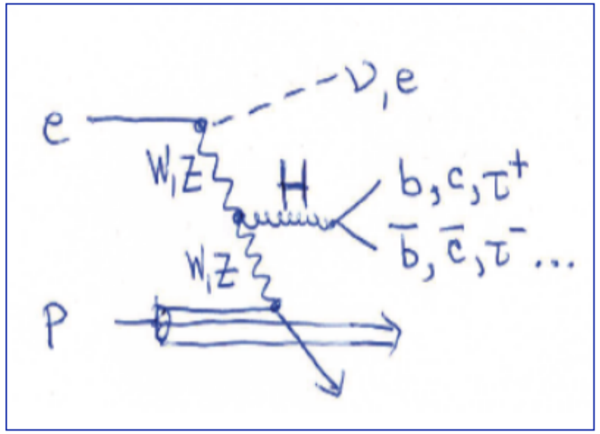
CERN-ACC-Note-2020-0002 →arXiv (July)

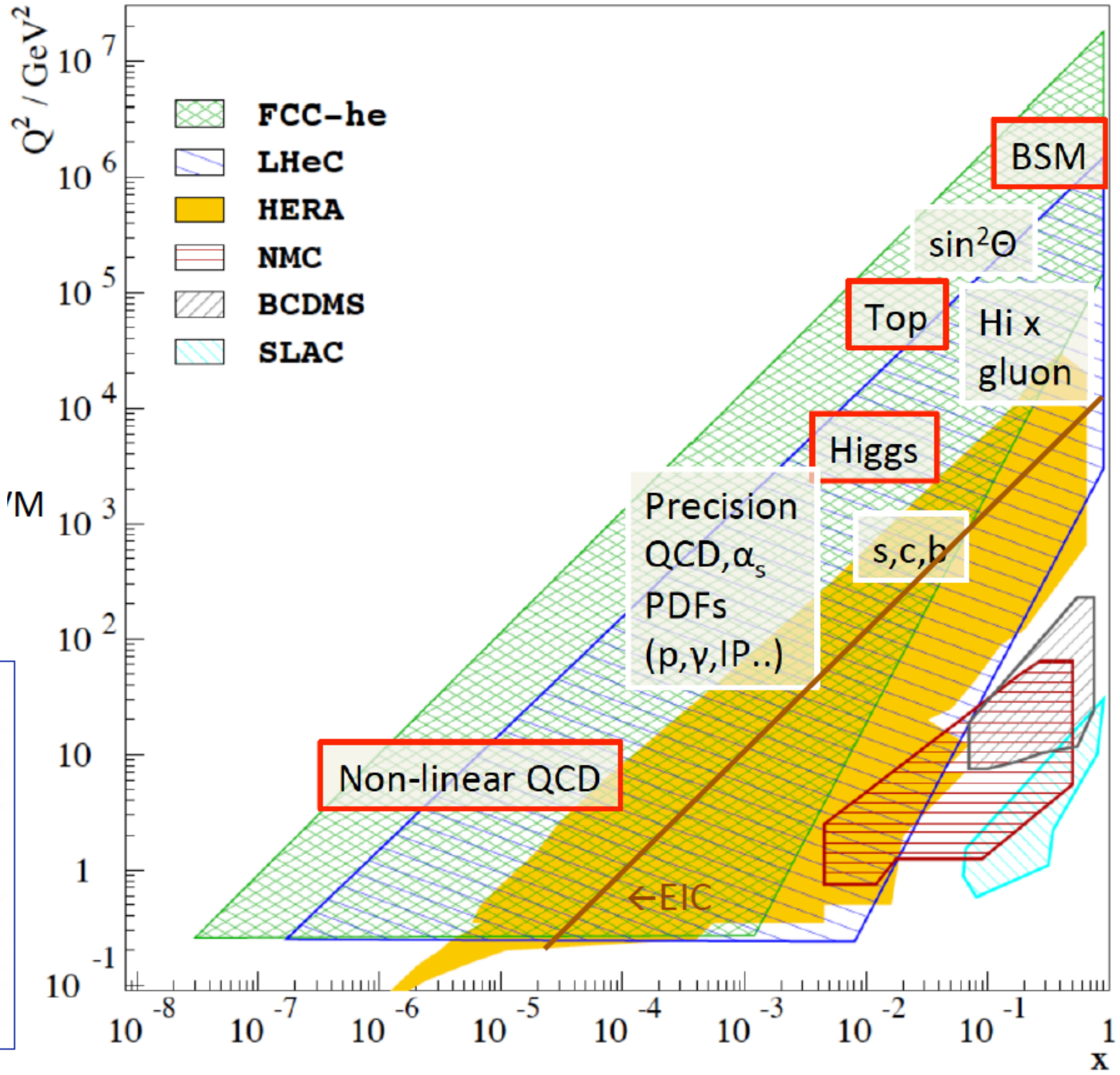
The LHeC and FCC-eh are the highest energy, most powerful electron-ion colliders the world may build.

Physics with Energy Frontier DIS

Deep Inelastic Scattering







Raison(s) d'etre of ep/eA at the energy frontier

Cleanest High Resolution Microscope: QCD Discovery

Empowering the LHC Search Programme

Transformation of LHC into high precision Higgs facility

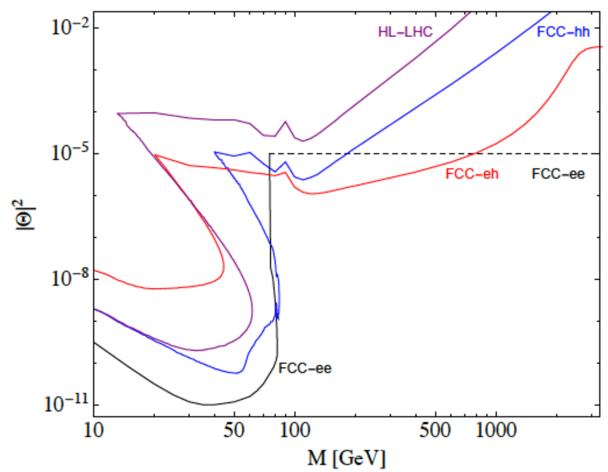
Discovery (top, H, heavy ν's..) Beyond the Standard Model

A Unique Nuclear Physics Facility

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**

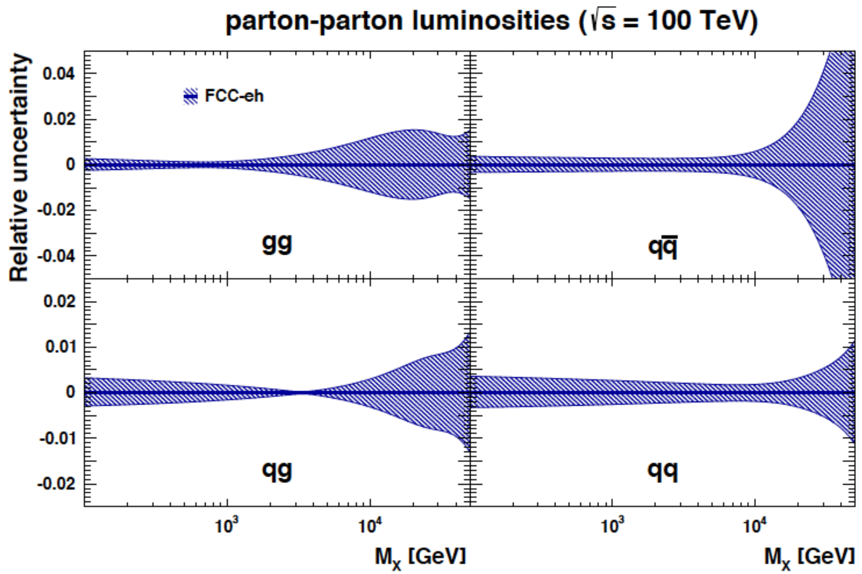
Some striking physics eh prospects are on searches and the high precision measurements on Higgs and proton structure:



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

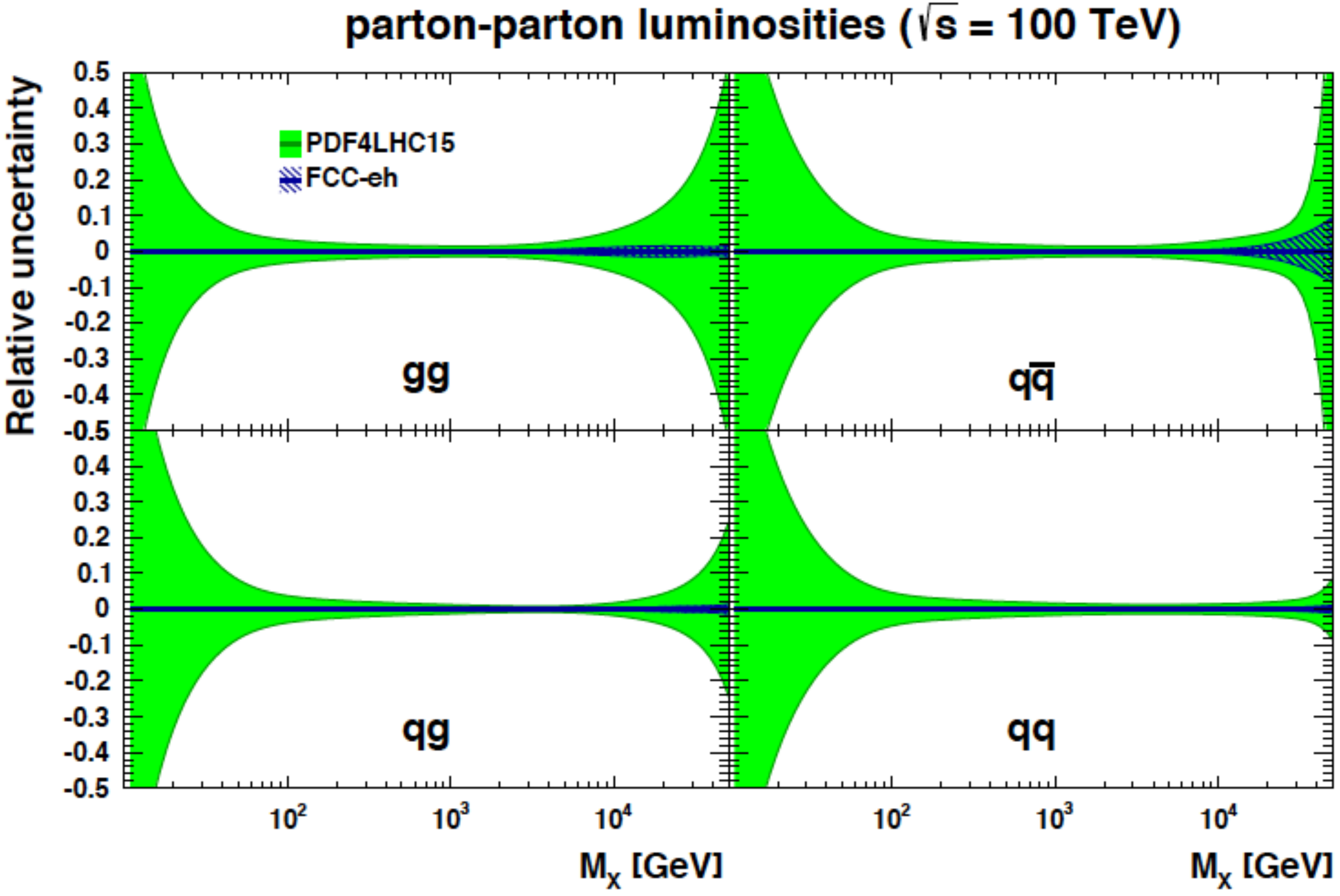
Collider	FCC-ee	FCC-eh
Luminosity (ab^{-1})	+1.5 @ 365 GeV	2
Years	3+4	20
$\delta\Gamma_H/\Gamma_H$ (%)	**1.3**	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	**0.17**	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	**0.43**	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	**0.61**	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	**1.21**	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	**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

Prospects FCCeh:



Ultimate prediction of pp interactions. external input. Decisive test of factorisation.

Synergy: example QCD

QCD in hh: a tool to understand the observations. Tests at unprecedented scales.
Through LHC QCD got a major boost (theory and phenomenology)

QCD in ee: strong coupling, perturbative parton radiation [jet substructure, fragmentation..]
non-perturbative parton radiation[colour reconnection, hadronisation..]..

QCD in ep: strong coupling to per mille, complete resolution of partonic proton contents
[also n,γ,IP and 3D] discovery of non-linear gg interactions, N^3LO prediction of H

QCD in eA: establish quantitative understanding of parton interactions in nuclei for the
first time. Disentangle nuclear from non-linear effects. The QGP in QCD

Higgs in ep and pp [LHC and FCC]

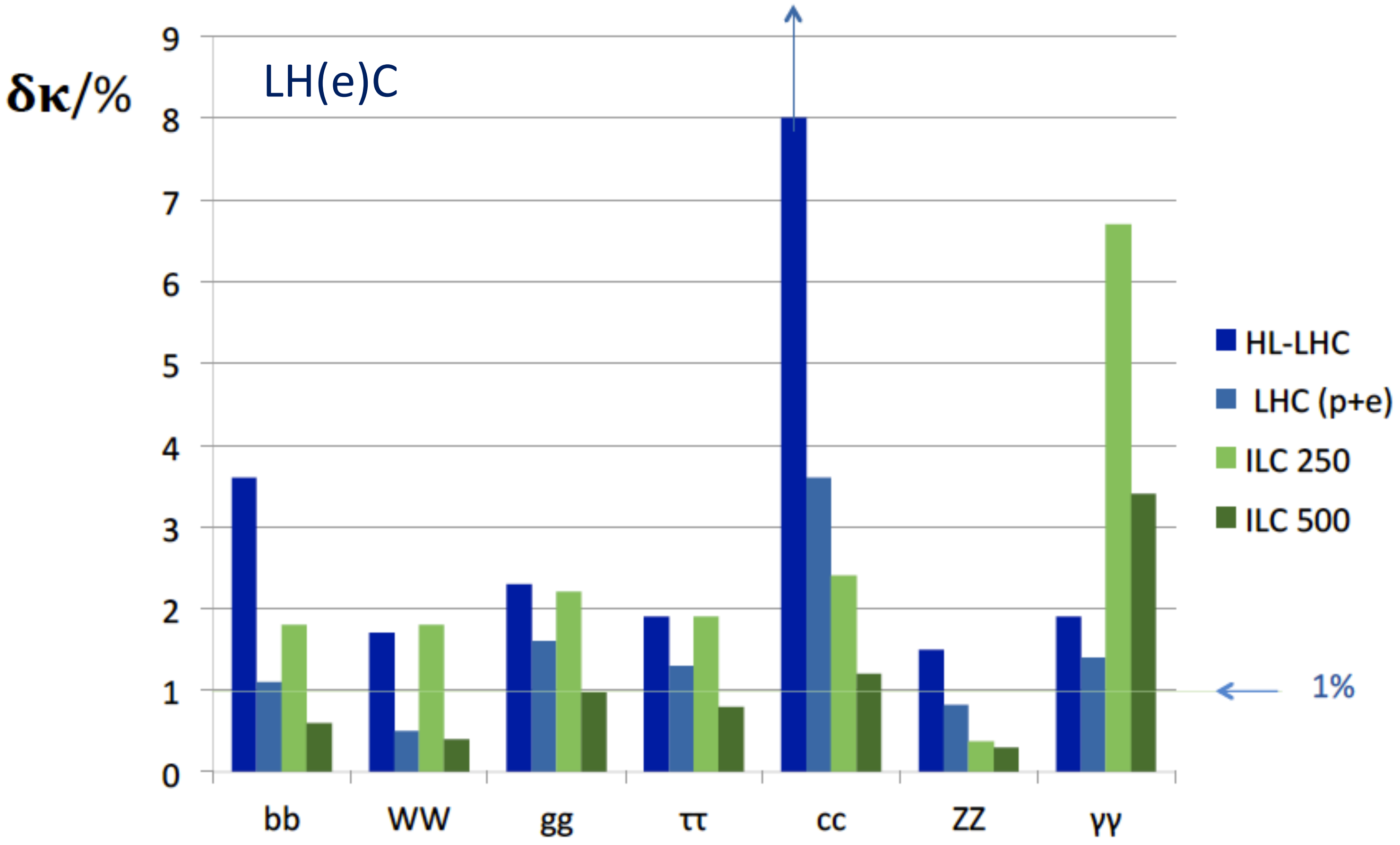


***Fig.1**: Results of prospect evaluations of the determination of Higgs couplings in the SM kappa framework for HL-LHC (dark blue), LHC with LHeC combined (p+e, light blue), ILC 250 (light green) and ILC-500 (dark green).*

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
γγ	3.3	1.7

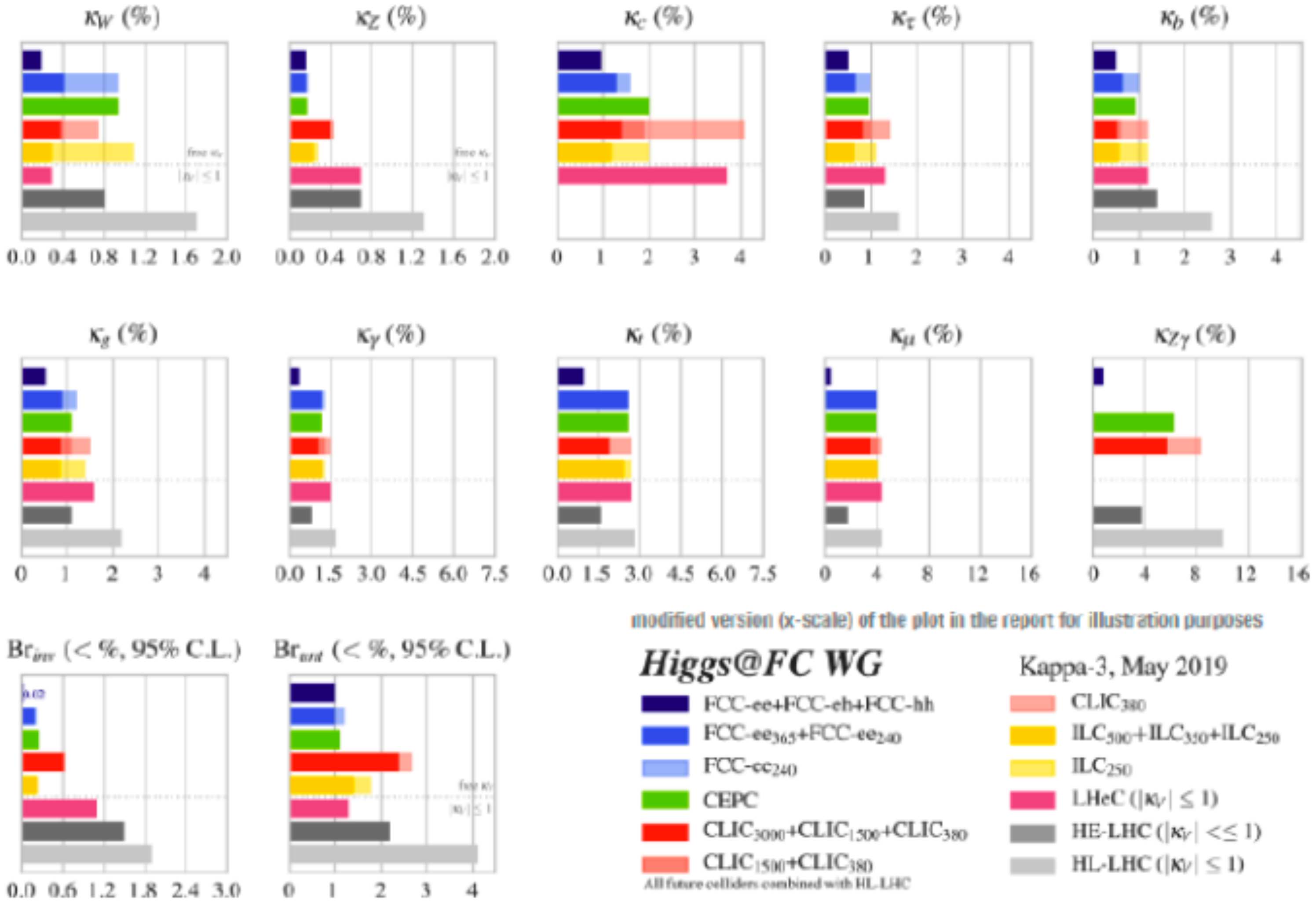
in percent. SM width.

Comparison of Colliders: kappa-framework

Some observations:

- **HL-LHC achieves precision of ~1-3% in most cases**
  - **In some cases model-dependent**
- **Proposed e^+e^- and ep colliders improve w.r.t. HL-LHC by factors of ~2 to 10**
- **Initial stages of e^+e^- colliders have comparable sensitivities (within factors of 2)**
- **ee colliders constrain $BR \rightarrow untagged$ w/o assumptions**
- **Access to κ_c at ee and eh**

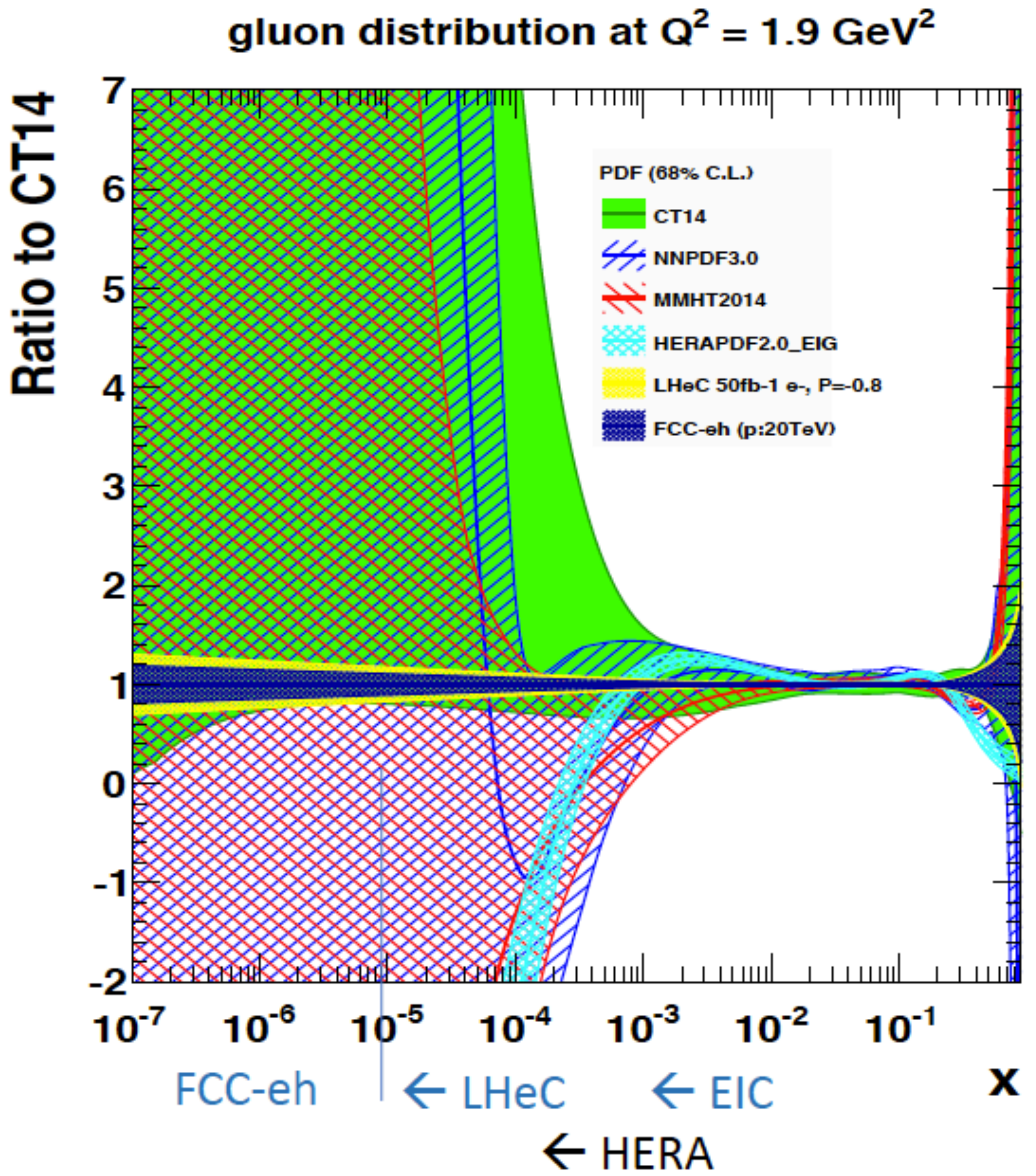
arXiv:1905.03764



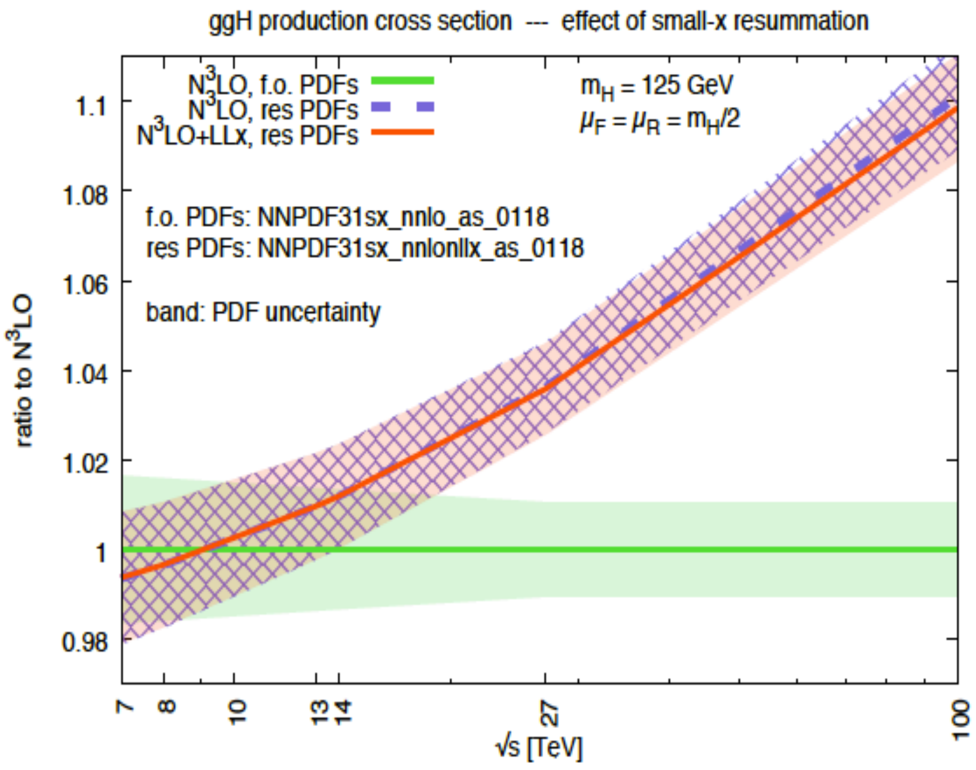
Low x Dynamics

1802.07758

Very large effects of small x dynamics at FCC-hh



HERA (and EIC) at too small energy to resolve low x



FCC-eh (LHeC) resolve low x BFKL-DGLAP question

FCC-hh is low x physics machine: there is no

Precision hh physics at FCC without ep

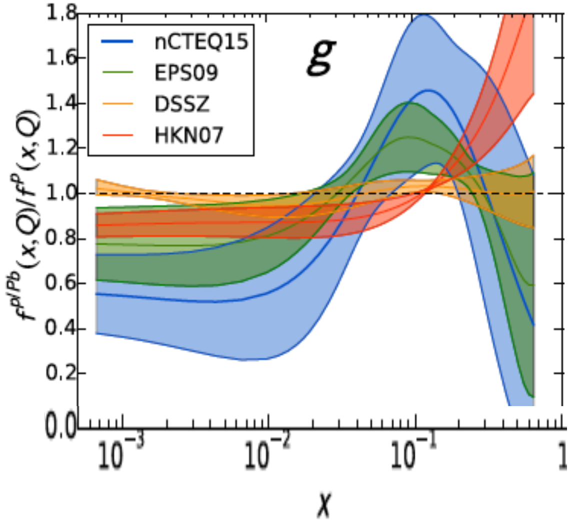
Unique nuclear/HI physics programme
Extension of fixed target range by 10^{3-4}
QCD of QGP, de-confinement, saturation..
nPDFs independent of p PDFs

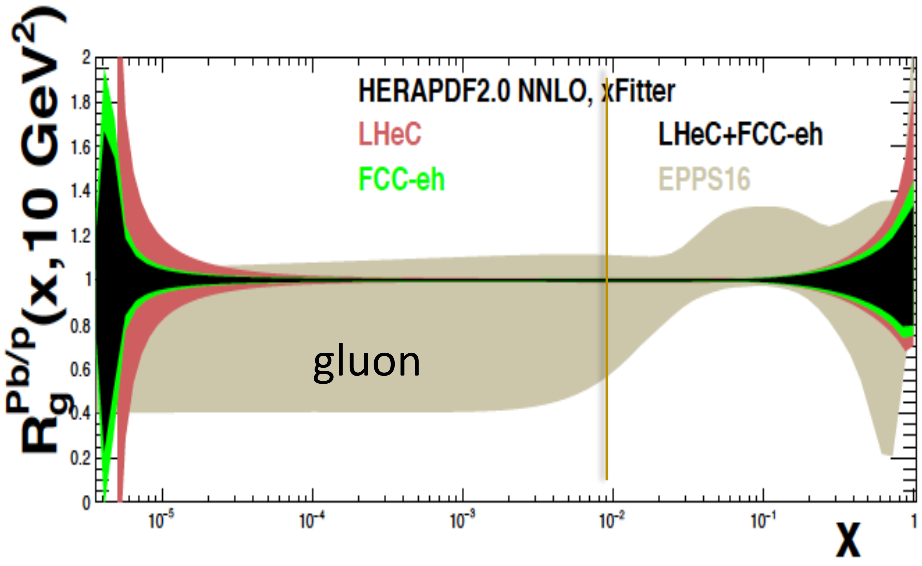
Nuclear PDFs at LHeC/FCCeh

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

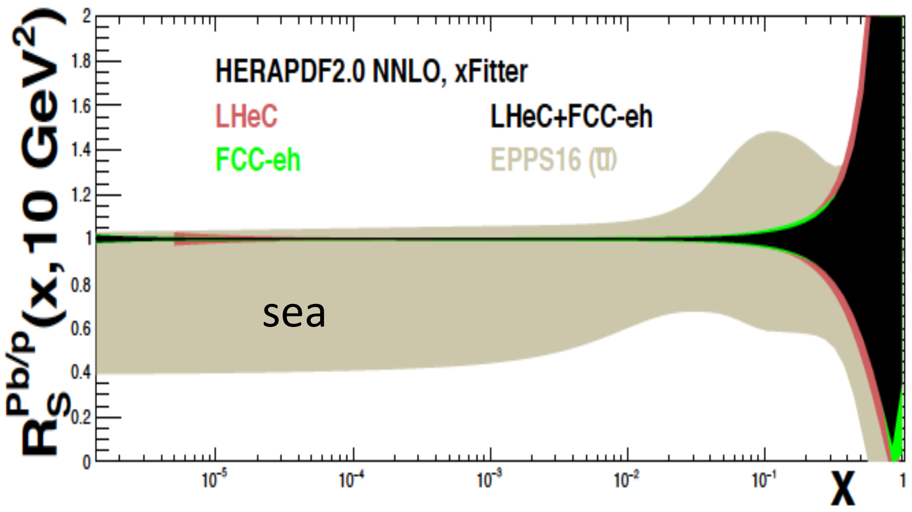
present status → on xg Pb/p

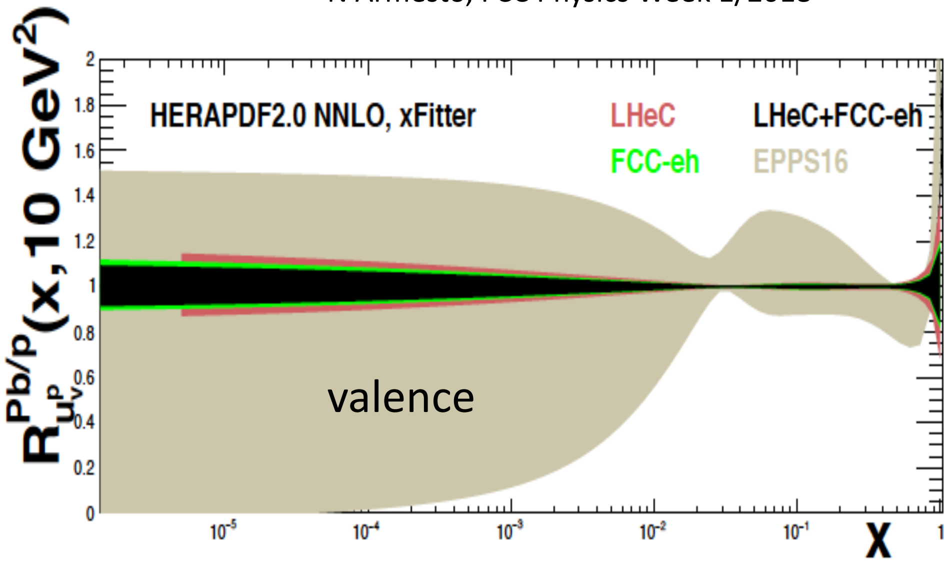
1509.00792





N Armesto, FCC Physics Week 1/2018





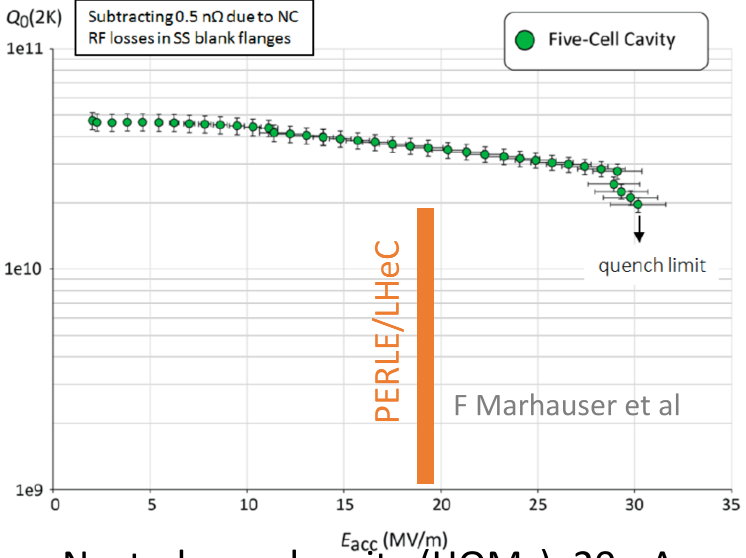
LHeC: Full error, $\Delta\chi^2 = 1$. EPPS $\Delta\chi^2 = 52$

Developments +Partners

Cf recent meeting: https://indico.cern.ch/event/923021/

SCRF: High Q_0, complete Cryomodule

Jointly with FCC-ee

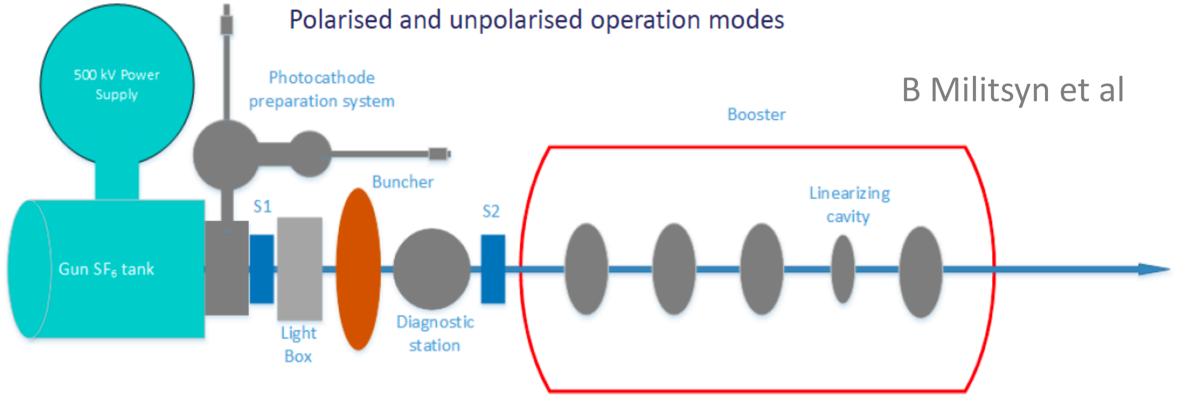


Next: dressed cavity (HOMs), 20mA
Adapt SPL Cryomodule for PERLE

CERN, Jlab, Orsay +

High Current Source (e^-, P, e^+)

ALICE gun upgraded and operates with GaAs photocathodes activated in the photocathode preparation system or with CsK_2Sb photocathodes prepared in the dedicated preparation facility.
Polarised and unpolarised operation modes

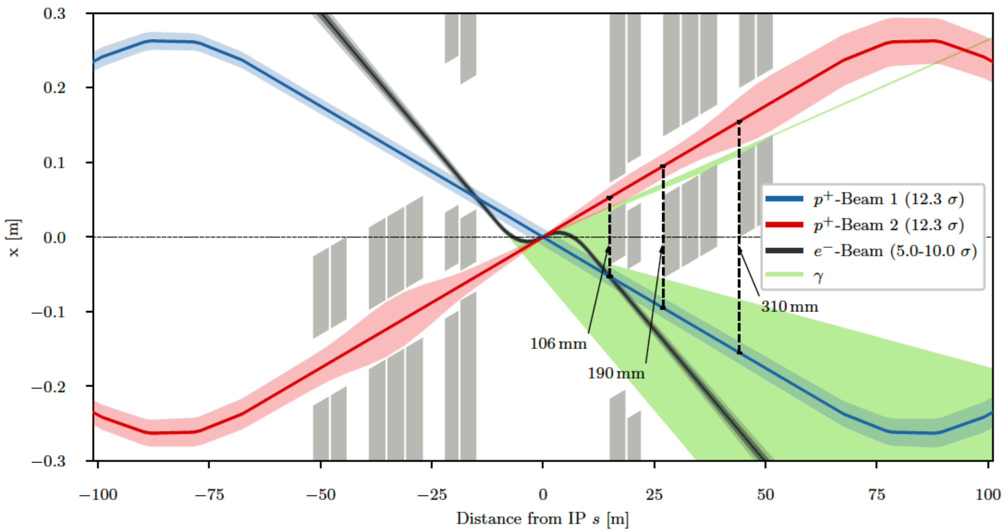


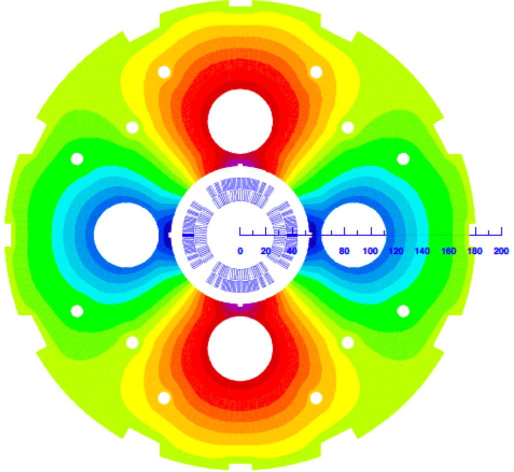
PERLE will begin with 5mA ALICE source, which has been transferred from Daresbury to Orsay while UK was in EU..

BINP, BNL/Cornell (cBETA), Daresbury, IJC, Jlab, +

Interaction Region Design and Q_1 Prototype:

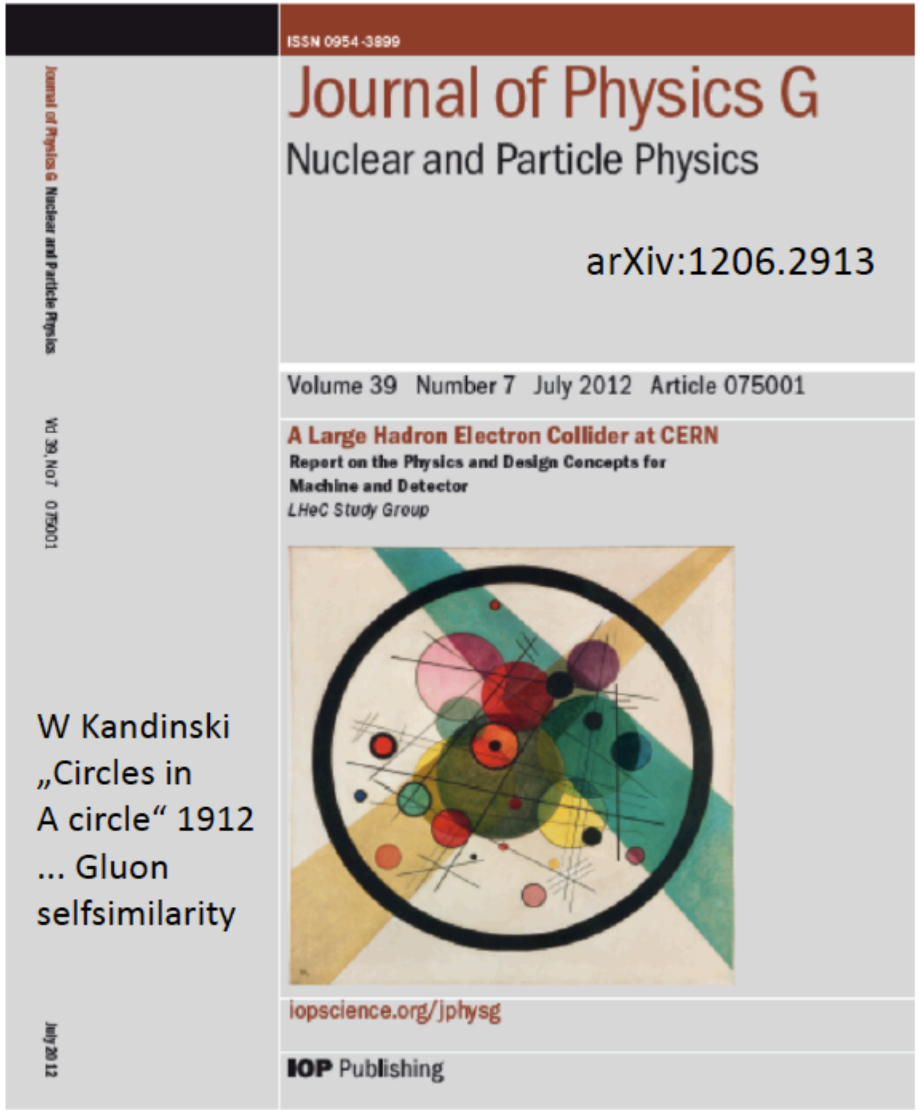
B Holzer, B Parker, S Russenschuck et al



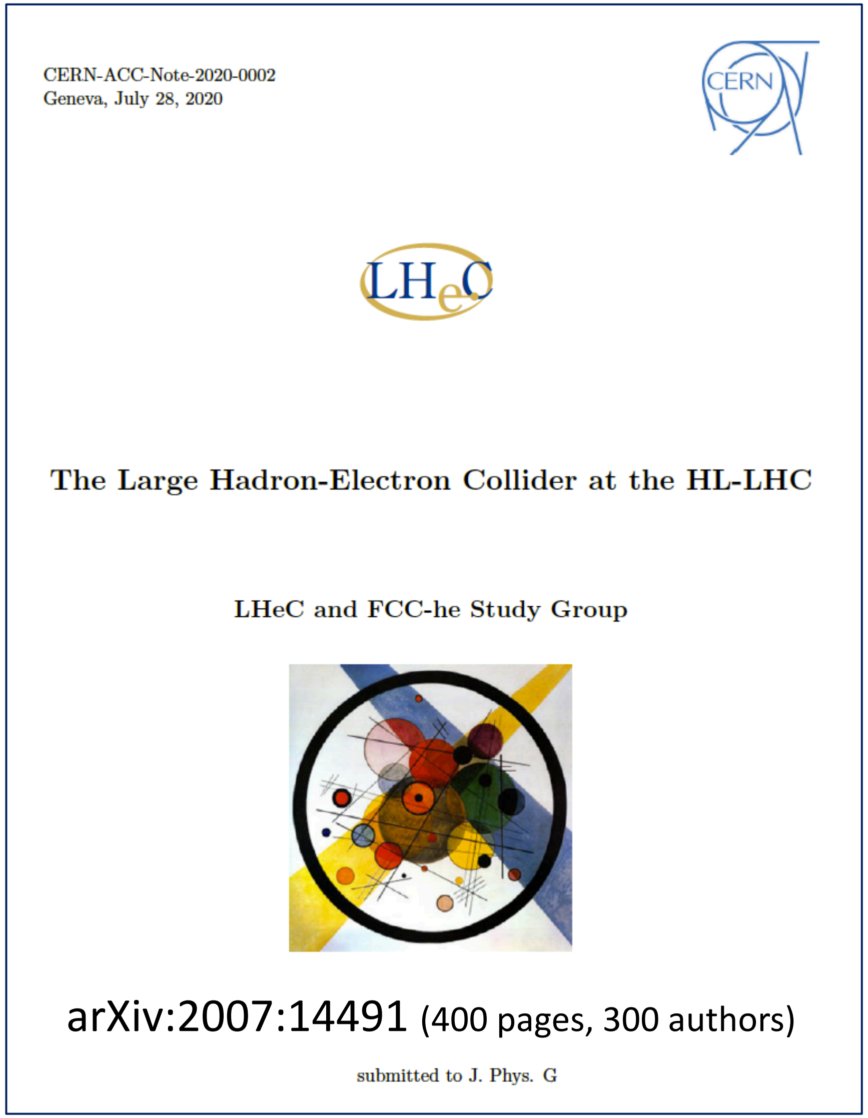


BNL, CERN, +

References



W Kandinski „Circles in A circle“ 1912 … Gluon selfsimilarity



FCC Workshops: CDR March 2019: https://indico.cern.ch/event/789349/

see: http://lhec.web.cern.ch (to be updated)

UK

DIS has strong tradition in UK: from BEBC, EMC to H1 and ZEUS

Various coordinators for Detector, H, QCD and BSM Physics are UK Physicists, including overall coordination

LHeC is a platform to develop FCC-eh

Accelerator focussed on PERLE: AsTEC, Cockcroft, Liverpool, with Novosibirsk, CERN, Jlab, Orsay:
PERLE at Orsay: Project leader W Kaabi (IJClab), Spokesperson M Klein (Liverpool)

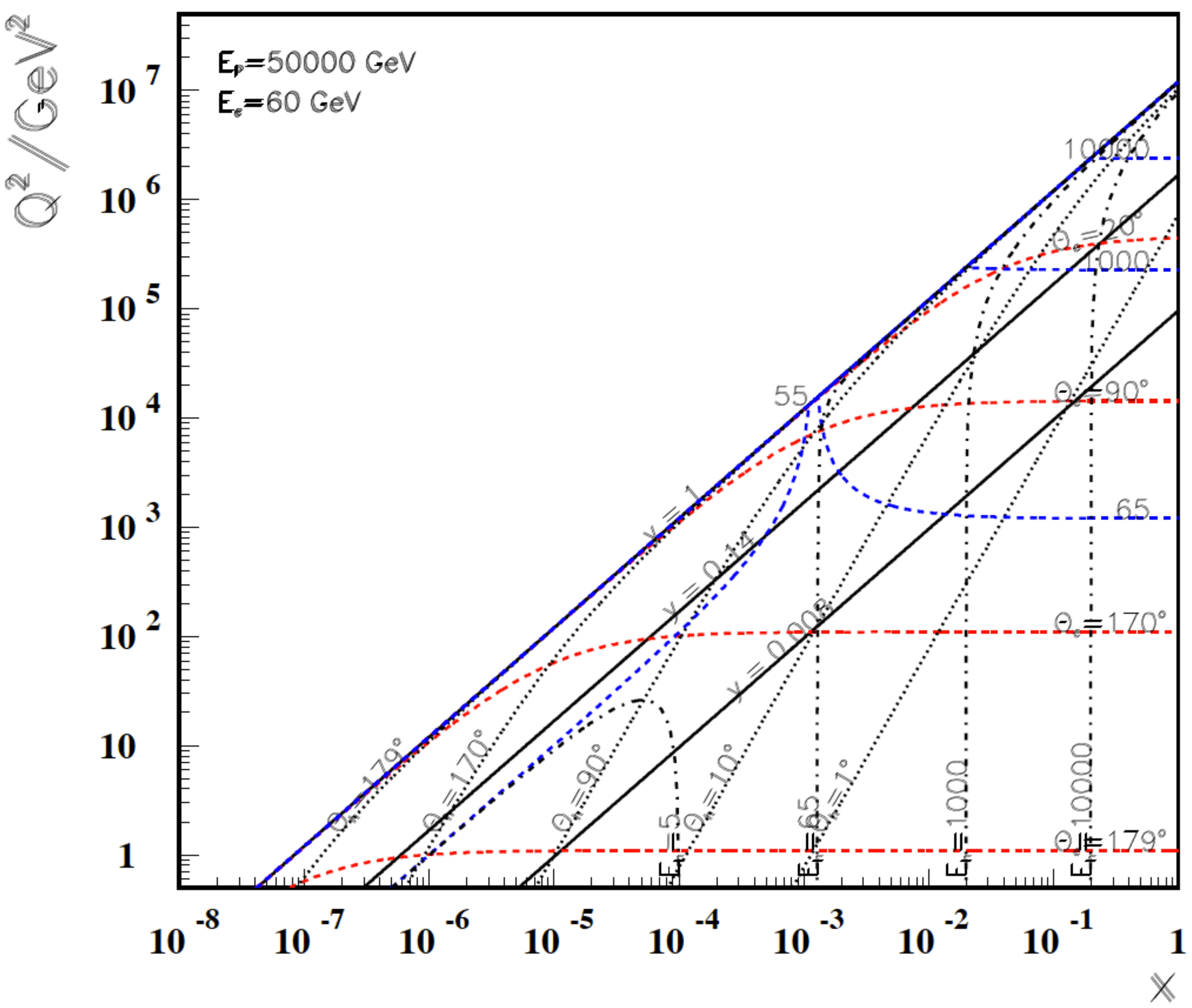
Detector design to be continued: Si tracker post ITK (ATLAS), low radiation: CMOS; and other topics

ep/eA is part of ee and pp/AA future for exploring nature and exploiting our investments (LHC and FCC)
It can operate concurrently with pp and should be further developed together with it.

The future may look undecided, uncertain but it offers research insight for decades (ee/hh/eh, neutrinos, fixed target)

backup

FCC−he Kinematic Range

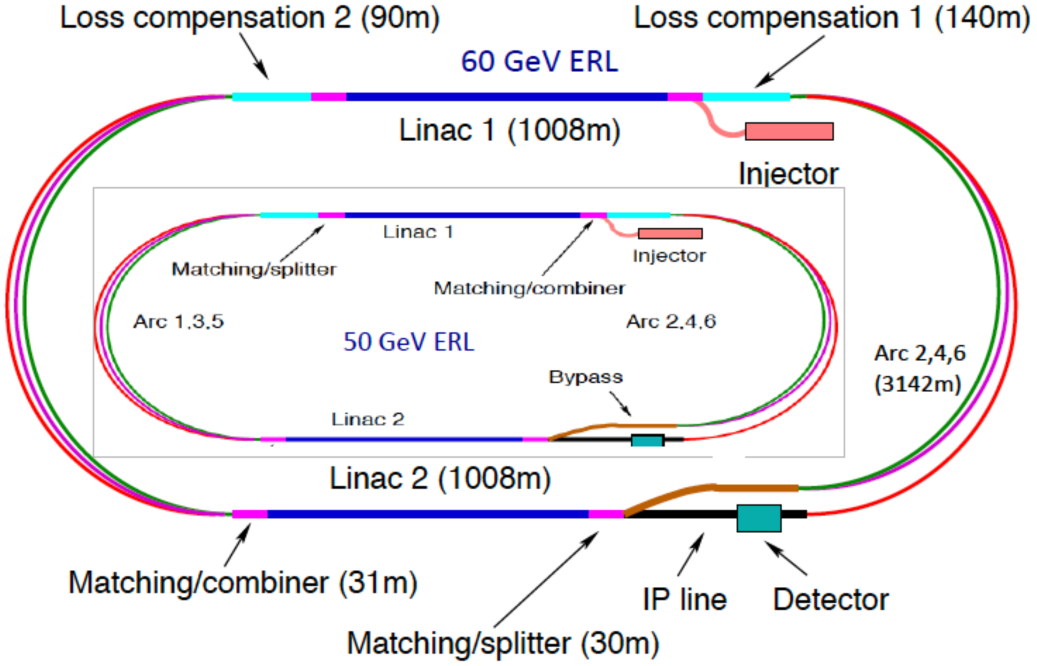


ERL in more Detail

Parameter	Unit	Value
Injector energy	GeV	0.5
Total number of linacs		2
Number of acceleration passes		3
Maximum electron energy	GeV	49.19
Bunch charge	pC	499
Bunch spacing	ns	24.95
Electron current	mA	20
Transverse normalized emittance	µm	30
Total energy gain per linac	GeV	8.114
Frequency	MHz	801.58
Acceleration gradient	MV/m	19.73
Cavity iris diameter	mm	130
Number of cells per cavity		5
Cavity length (active/real estate)	m	0.918/1.5
Cavities per cryomodule		4
Cryomodule length	m	7
Length of 4-CM unit	m	29.6
Acceleration per cryomodule (4-CM unit)	MeV	289.8
Total number of cryomodules (4-CM units) per linac		112 (28)
Total linac length (with with spr/rec matching)	m	828.8 (980.8)
Return arc radius (length)	m	536.4 (1685.1)
Total ERL length	km	5.332

Table 10.1: Parameters of LHeC Energy Recovery Linac (ERL).

Positrons: 500pC is 3 $10^9 e^-$/bunch → 20mA and 1.2 10^{17} e^-/s
LHeC programme needs e^-p predominantly (Higgs) and only smaller e^+p sample, ~fb^{-1} → $O(10^{15})$ e^+/s, still demanding!
High intensity with γγ or FEL options of LHeC (Frank Z)



- LHeC Configuration reduced from 60 to 50 GeV.
- LINAC: 112 cryomodules with 4 cavities each
  → Total number of cavities: 896 [ILC: $O(10^4)$]
- Configuration may be staged with less RF
- Tunnel is small part of cost and better not reduced further, synchrotron loss, upgrades..
- ERL reduces power to << GW and dumps at < GeV
  → novel, "green" accelerator technology