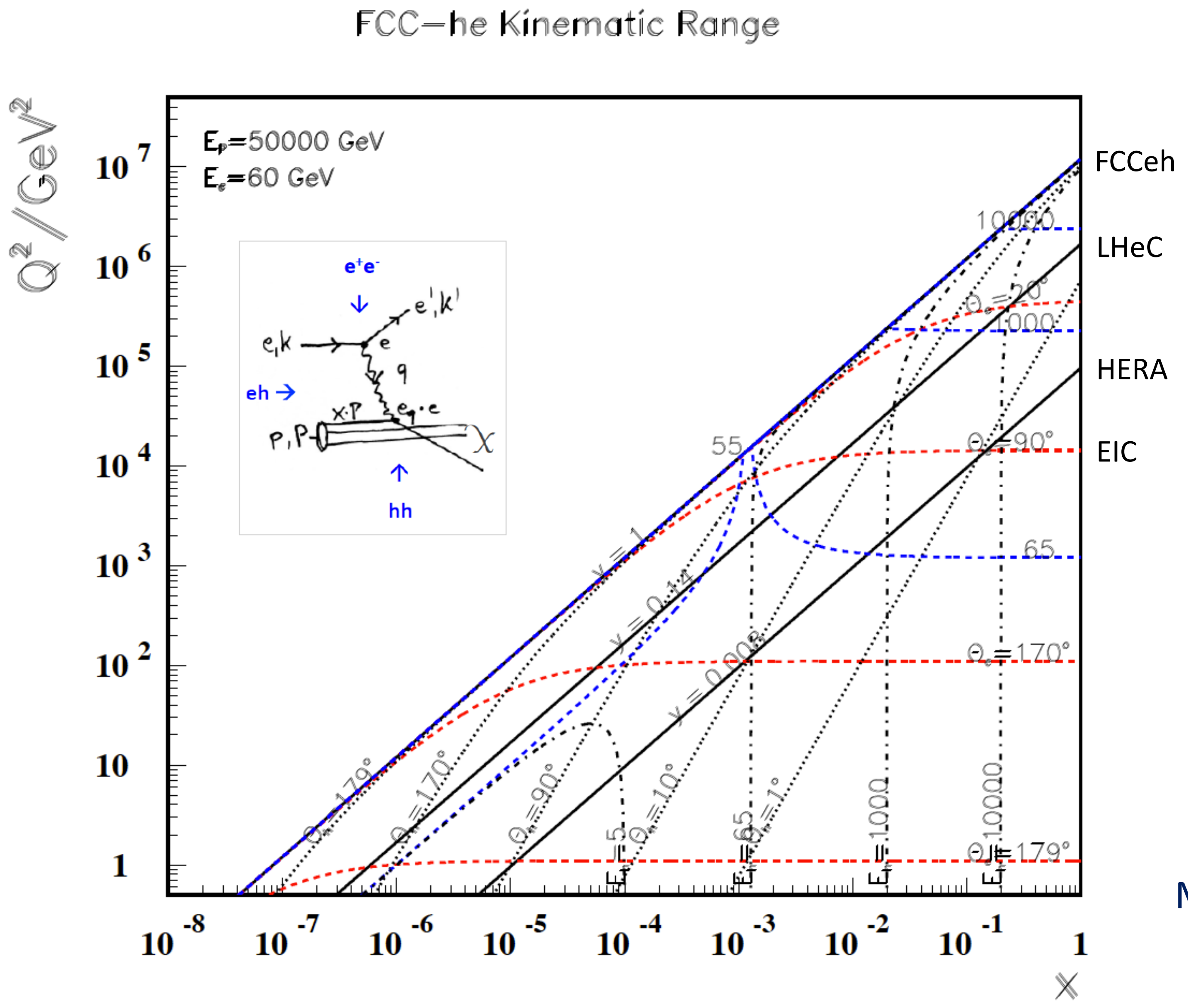
FCC-eh

Introductory Remarks



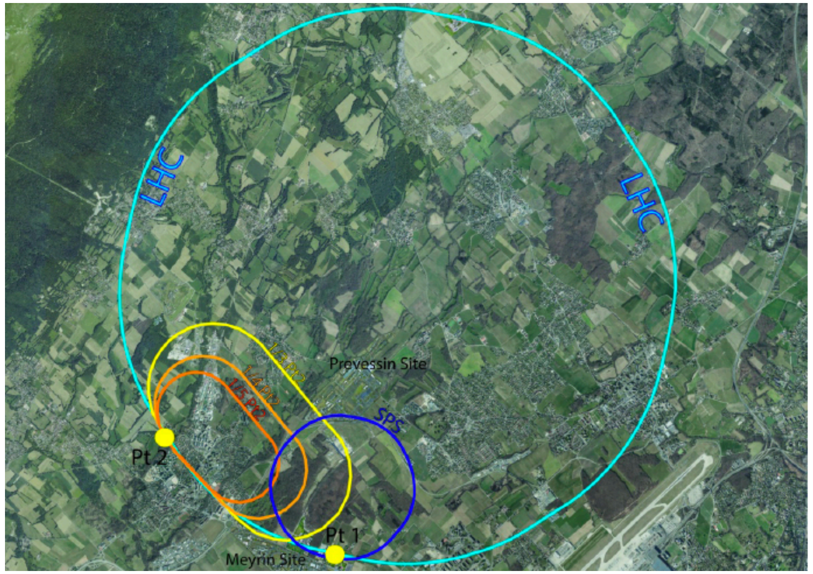
The most gigantic DIS experiment under consideration
Newton Microscope (Phil Yock) - Outreach on DIS !

- Projects: LHeC/PERLE/FCC-eh
- Energy Recovery Developments
- Particle Physics – Quo Vadis
- Physics on one page (more today)
- Examples of existing study (Det+IR today)
- Outlook

Max Klein (U Liverpool) and Oliver Bruening (CERN)

Max Klein and Oliver Bruening
for the LHeC/PERLE/FCCeh Collaboration
FCC Week, 30.6.2021, online

LHeC, PERLE and FCC-eh



50 x 7000 GeV^2: 1.2 TeV ep collider

Operation: Concurrent with HL-LHC
2035+, Cost: O(1) BCHF

CDR: 1206.2913 J.Phys.G

Upgrade to 10^{34} cm^{-2}s^{-1}, for Higgs, BSM
ESPPU: OB+MK, J.Phys.G 46 (2019) 12, 123001

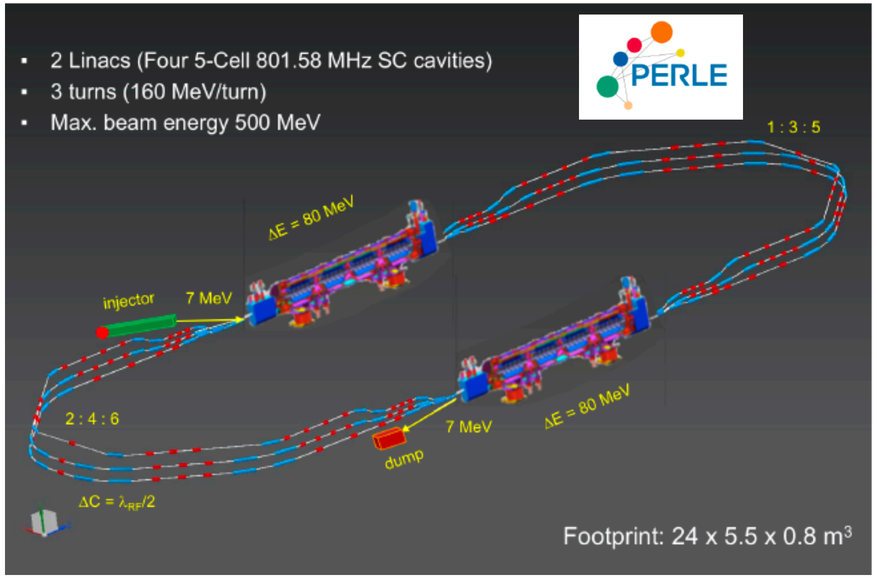
arXiv:2007.14491, J.Phys.G to appear

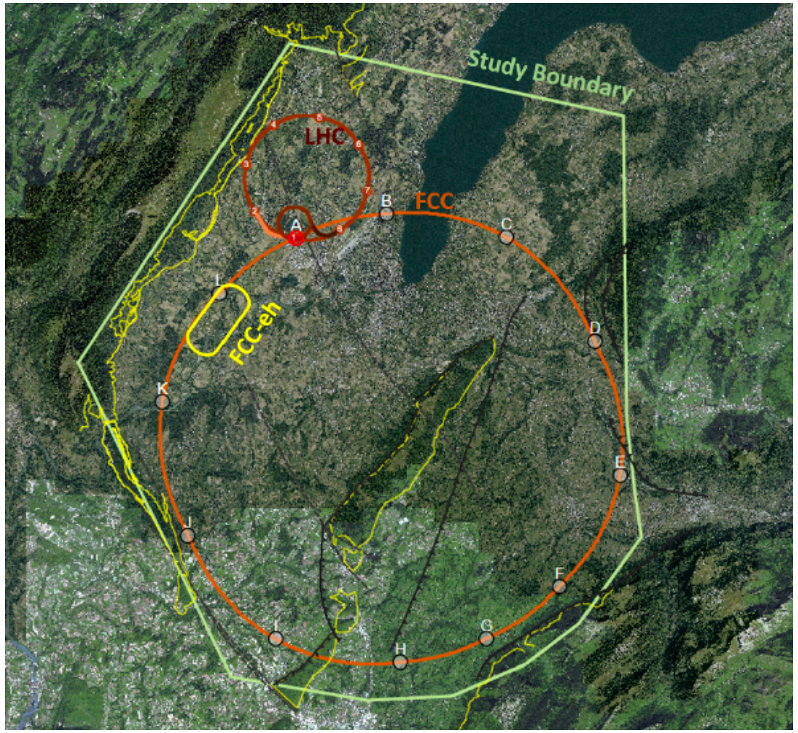
Powerful ERL for Experiments @ Orsay
CDR: 1705.08783 J.Phys.G
CERN-ACC-Note-2018-0086 (ESPPU)

TDR end of 2022, Operation: 2025+

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

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





60 x 50000 GeV^2: 3.5 TeV ep collider

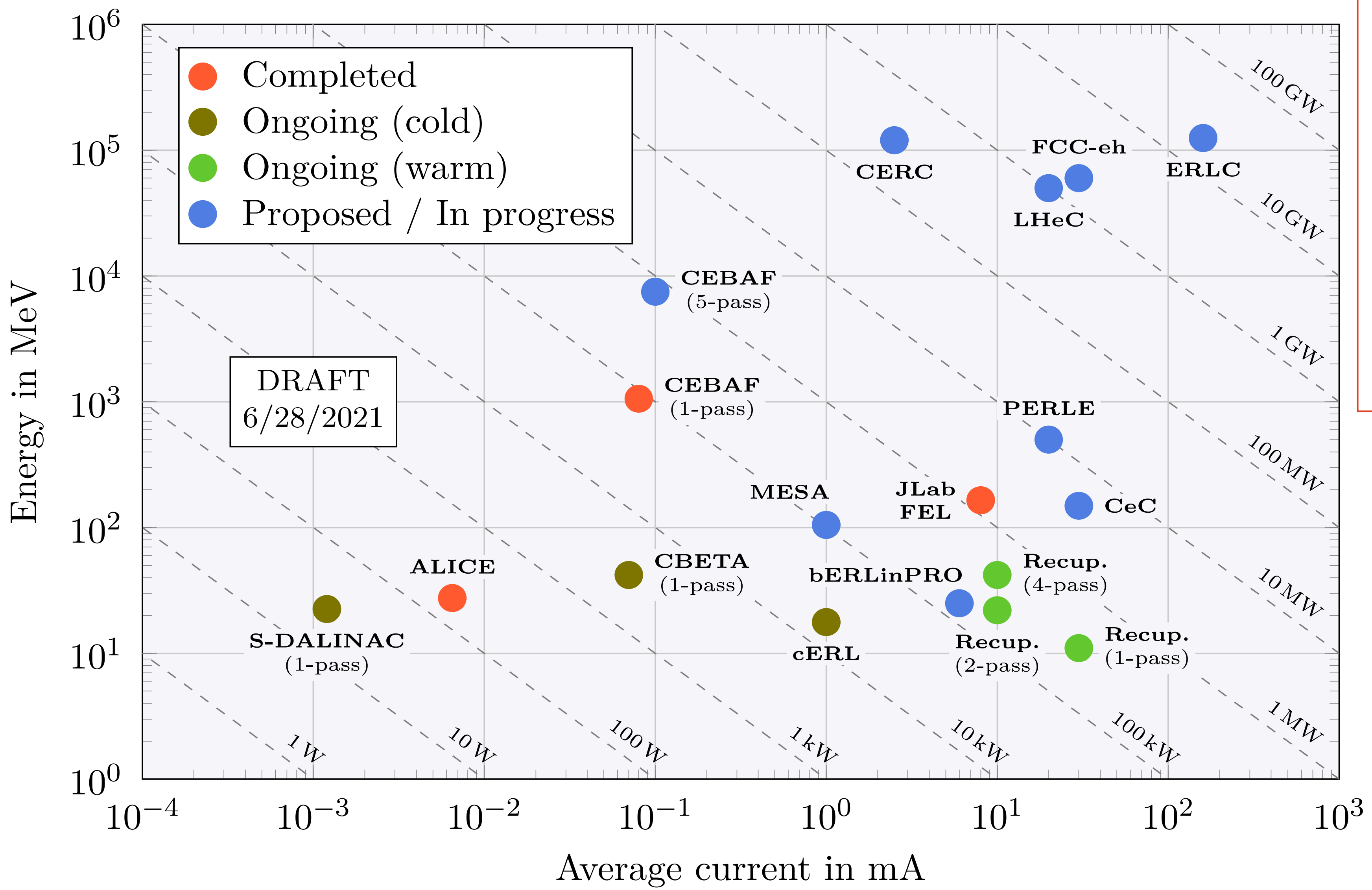
Operation: 2050+, Cost (of ep) O(1-2) BCHF

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+

A selection of past, present and proposed ERL facilities: Power = $E_e I_e$



From the ongoing work of the ERL Roadmap Panel, to be published

ERL Features:

Very high luminosity through high electron current and small preserved injector emittance. Economic use of power $P_o/(1-\eta)$ through recovery in multiple linac passing (recirculator or head-on). Non-radiative beam dump at injection energy. → orders of magnitude improved performance at same or reduced power, **a new era for accelerator, HEP, NP and applications**

"The ERL concept is well proven and the technology is well developed. Many demonstrator facilities exist worldwide with increasing sophistication. It needs a facility comprising all essential features simultaneously: high-current, multi-pass, optimised cavities and cryo-modules and a physics quality beam eventually for experiments". (Bob Rimmer at ERL Symposium, June 4, 2021)

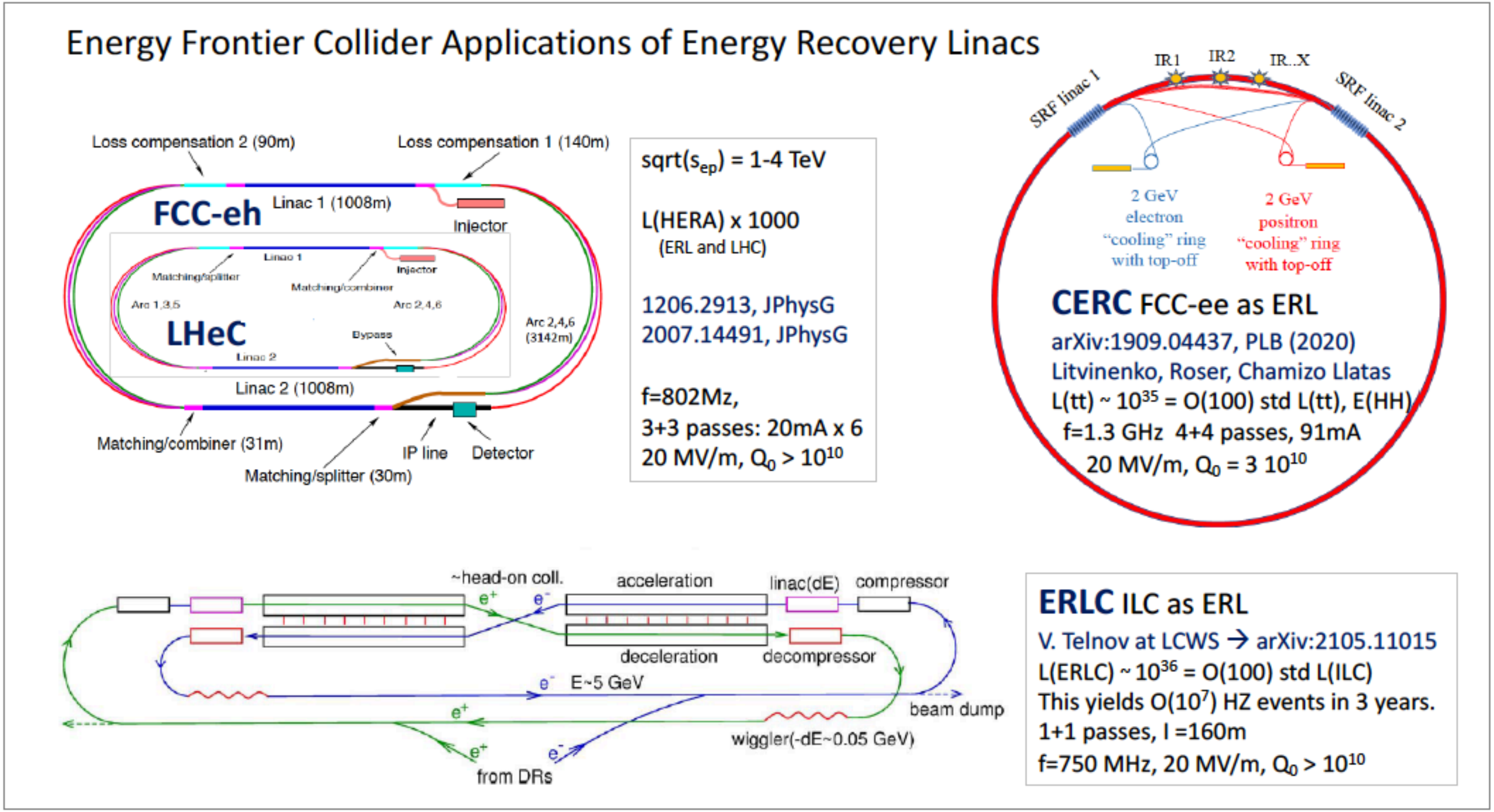


Figure 2: Sketch of possible future colliders based on ERLs: left top: LHeC and FCC-eh; right top: CERC; bottom: ERLC. For more information see the arXiv references displayed. [from report to LDG]

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

pp

FCC - hh

Higgs Potential
Rare H Decays
SUSY
GUT
??

ep

FCC - eh

High Precision Higgs
BSM in multi TeV range
DIS of top, g saturation
Leptoquarks and GUT

l^+l^-

CLIC, FCC - ee

High Precision Higgs
Top and BSM
Rh Neutrinos

Muon Collider ?

Neutrino Physics
Factory, Proton Decay

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.

“Turn the SM on its Head”
Steven Weinberg (CC15)

Former times: lh / hh / e+e-

CDHS,BCDMS../SppS/PETRA,PEP

HERA/Tevatron/LEP,SLC

A scenario for the nearer future

LHeC / HL-LHC / ILC or/and **CepC**

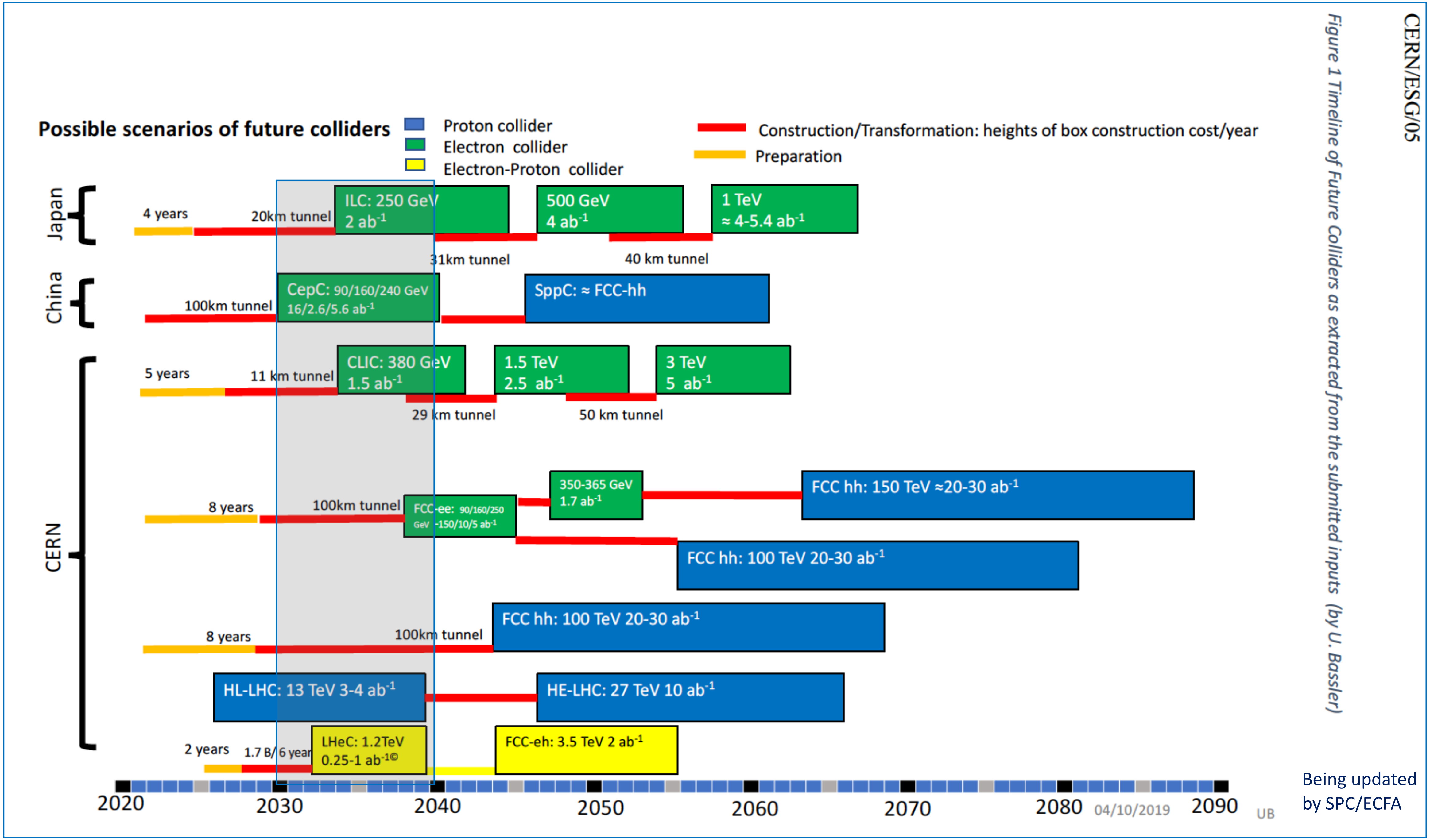
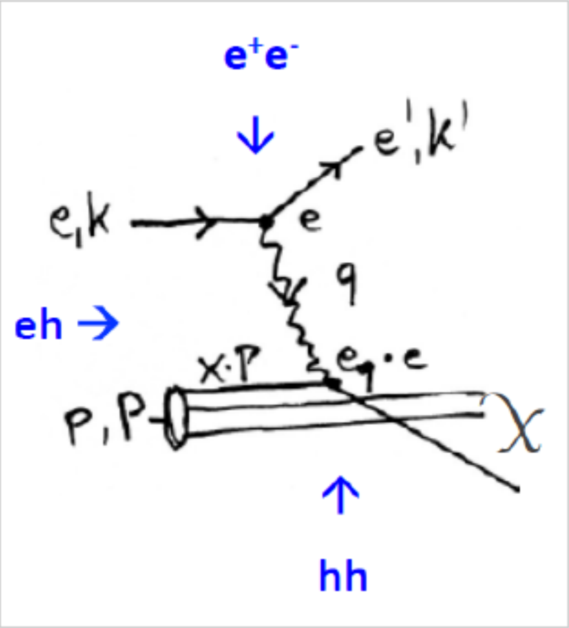
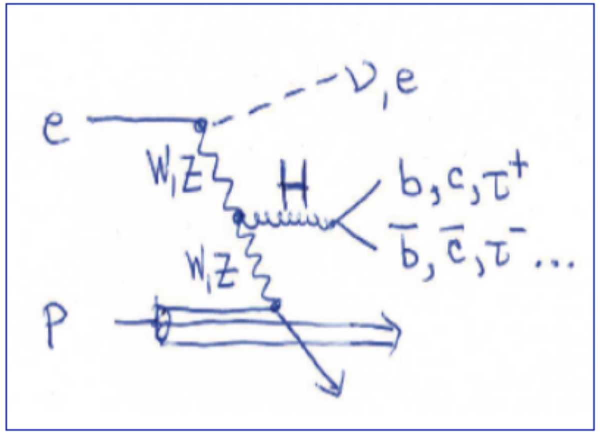


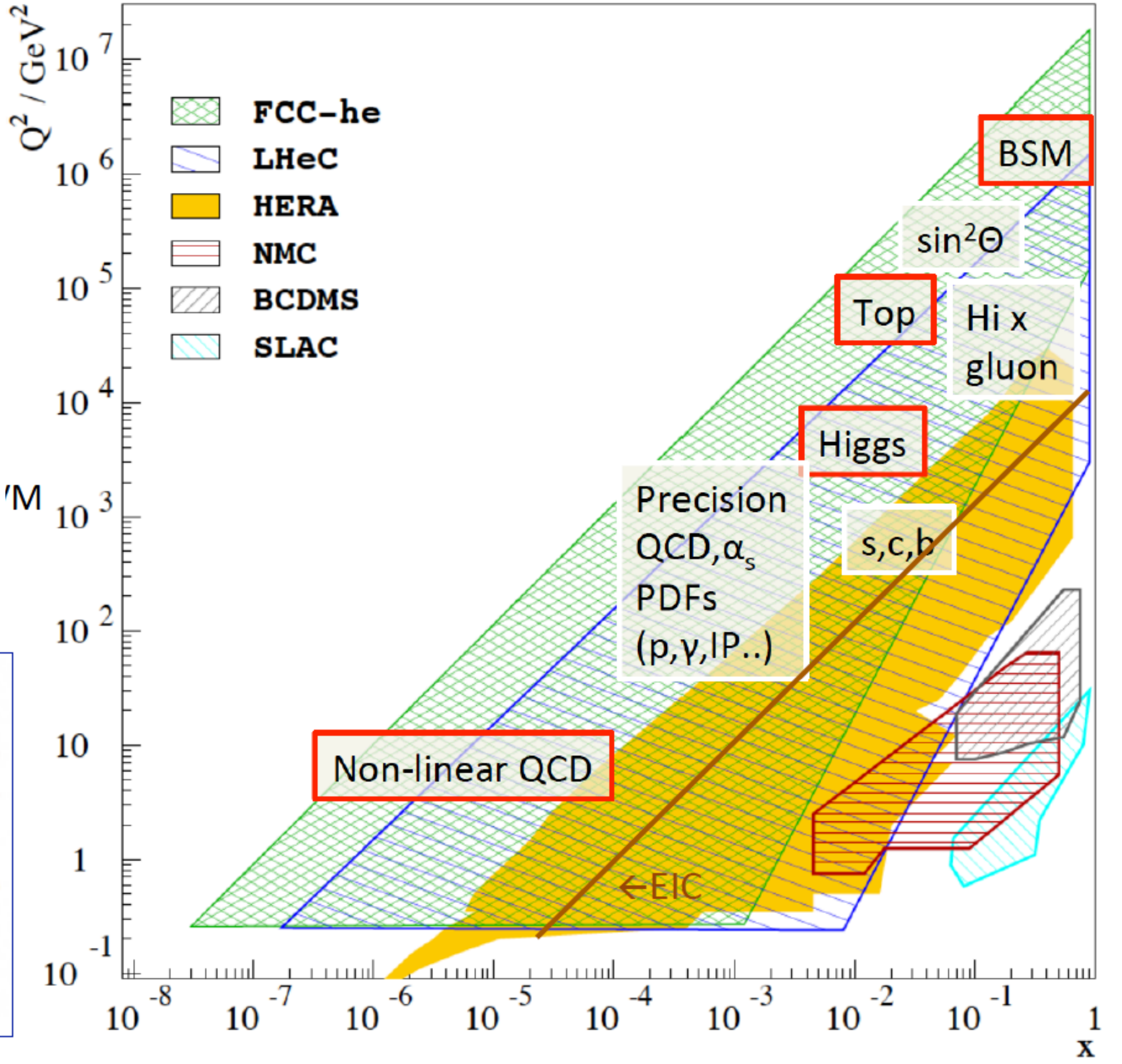
Figure 1 Timeline of Future Colliders as extracted from the submitted inputs (by U. Bassler)

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/FCC Search Programme

Transformation of LHC/FCC into high precision Higgs facility

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

A unique Nuclear Physics Facility for Discovery

Machine Parameters and Operation - ep

CERN-ACC-Note-2020-0002 →arXiv (July)

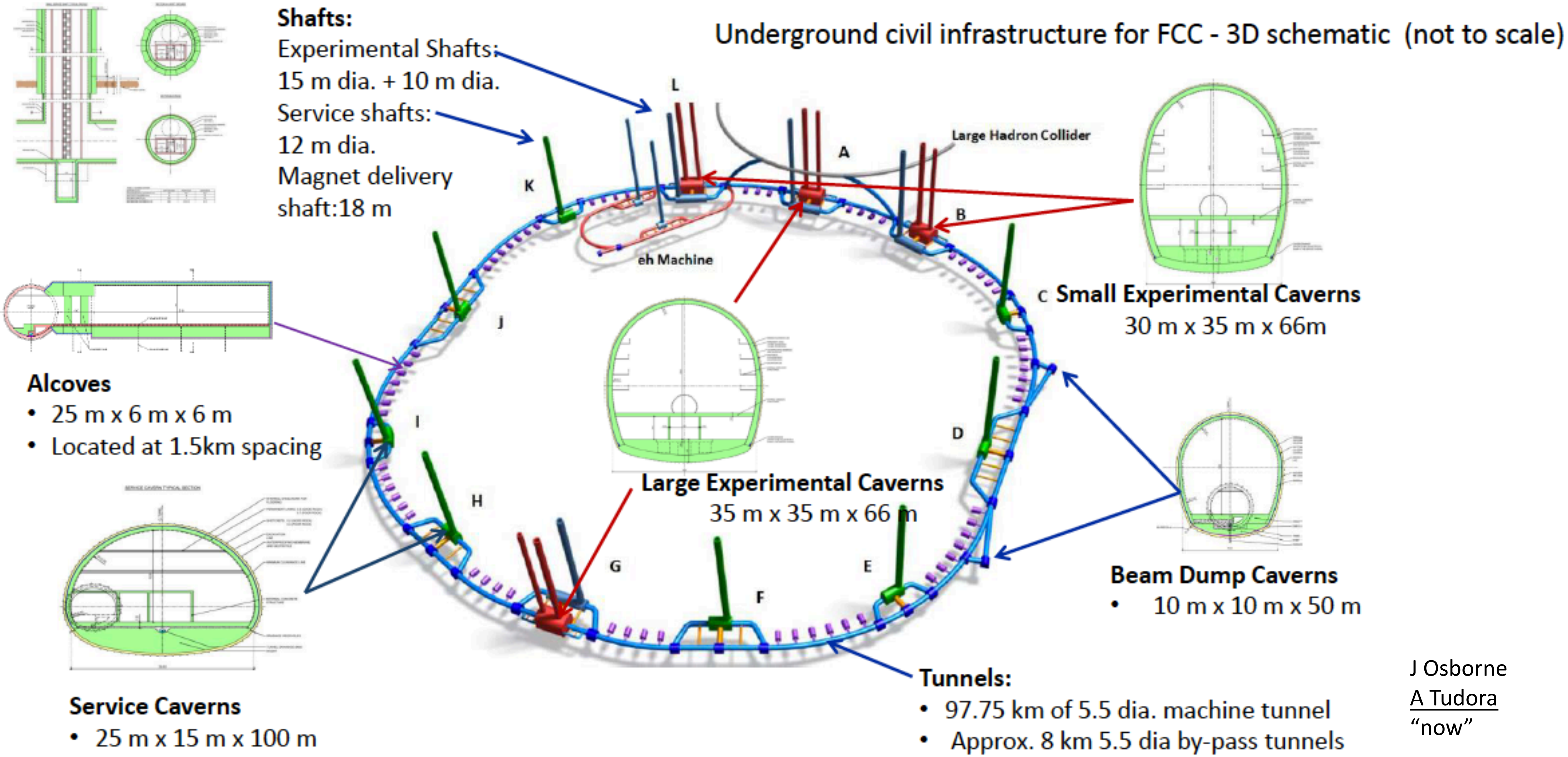
Parameter	Unit	LHeC				FCC-eh	
		CDR	Run 5	Run 6	Dedicated	E_p=20 TeV	E_p=50 TeV
E_e	GeV	60	30	50	50	60	60
N_p	10^{11}	1.7	2.2	2.2	2.2	1	1
ϵ_p	μm	3.7	2.5	2.5	2.5	2.2	2.2
I_e	mA	6.4	15	20	50	20	20
N_e	10^9	1	2.3	3.1	7.8	3.1	3.1
β^*	cm	10	10	7	7	12	15
Luminosity	10^{33} cm^{-2}s^{-1}	1	5	9	23	8	15

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}cm^{-2}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.

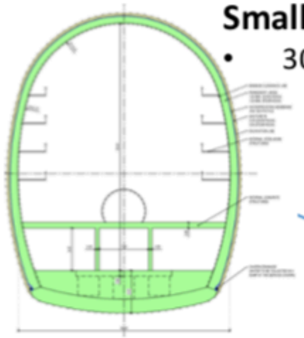
FCC Overview of Underground Structures
Conceptual design



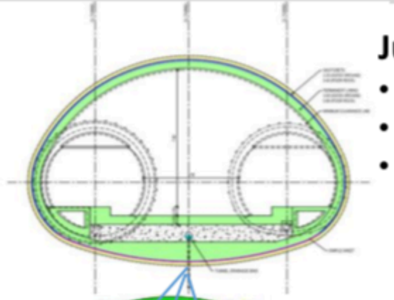
J Osborne
A Tudora
"now"

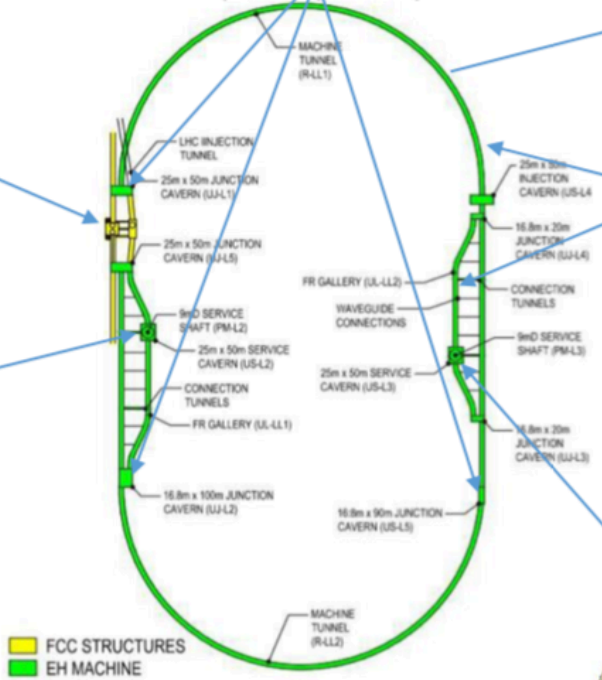
Scope of FCC-eh Structures

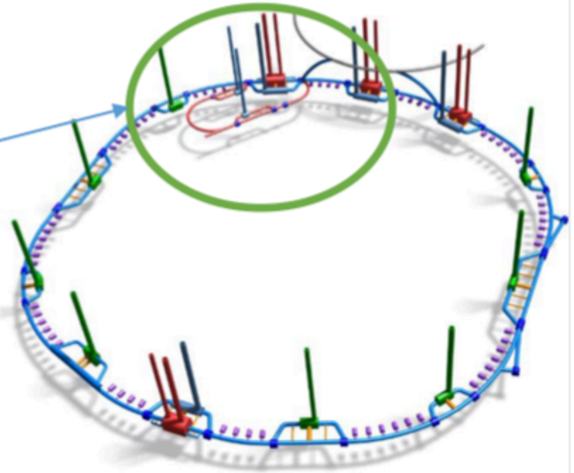
Small Experimental Caverns
- 30 m x 35 m x 66m



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

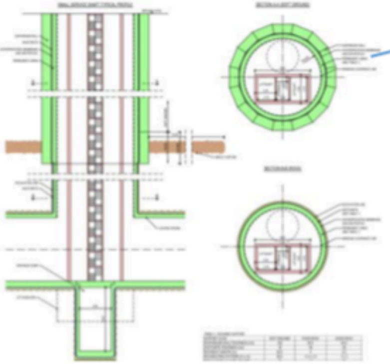


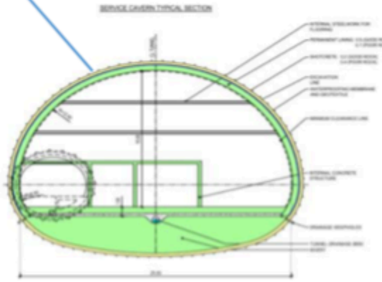




Tunnels:
- 9.091 km of 5.5m dia. machine tunnel.
- 2 x 1.04 km of 5.5m dia RF tunnel.

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



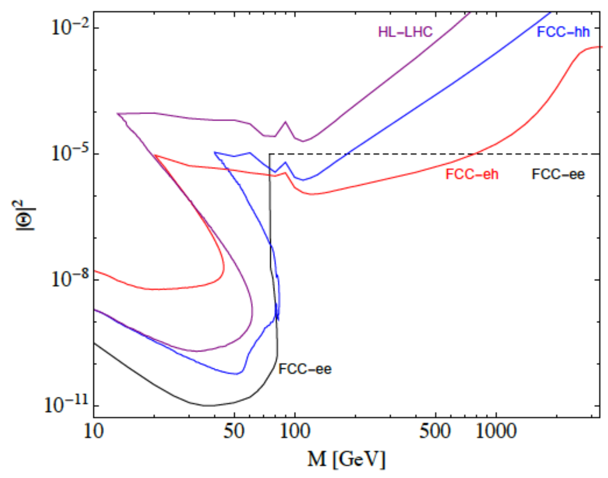


Service Caverns
- 25 m x 15 m x 50 m

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**

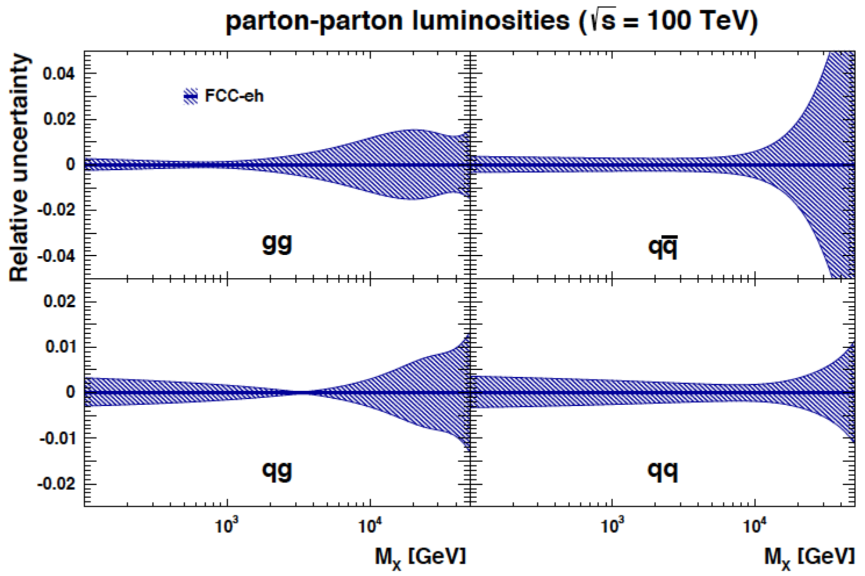
Some striking physics eh prospects are on searches and the high precision measurements on Higgs and proton structure:



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

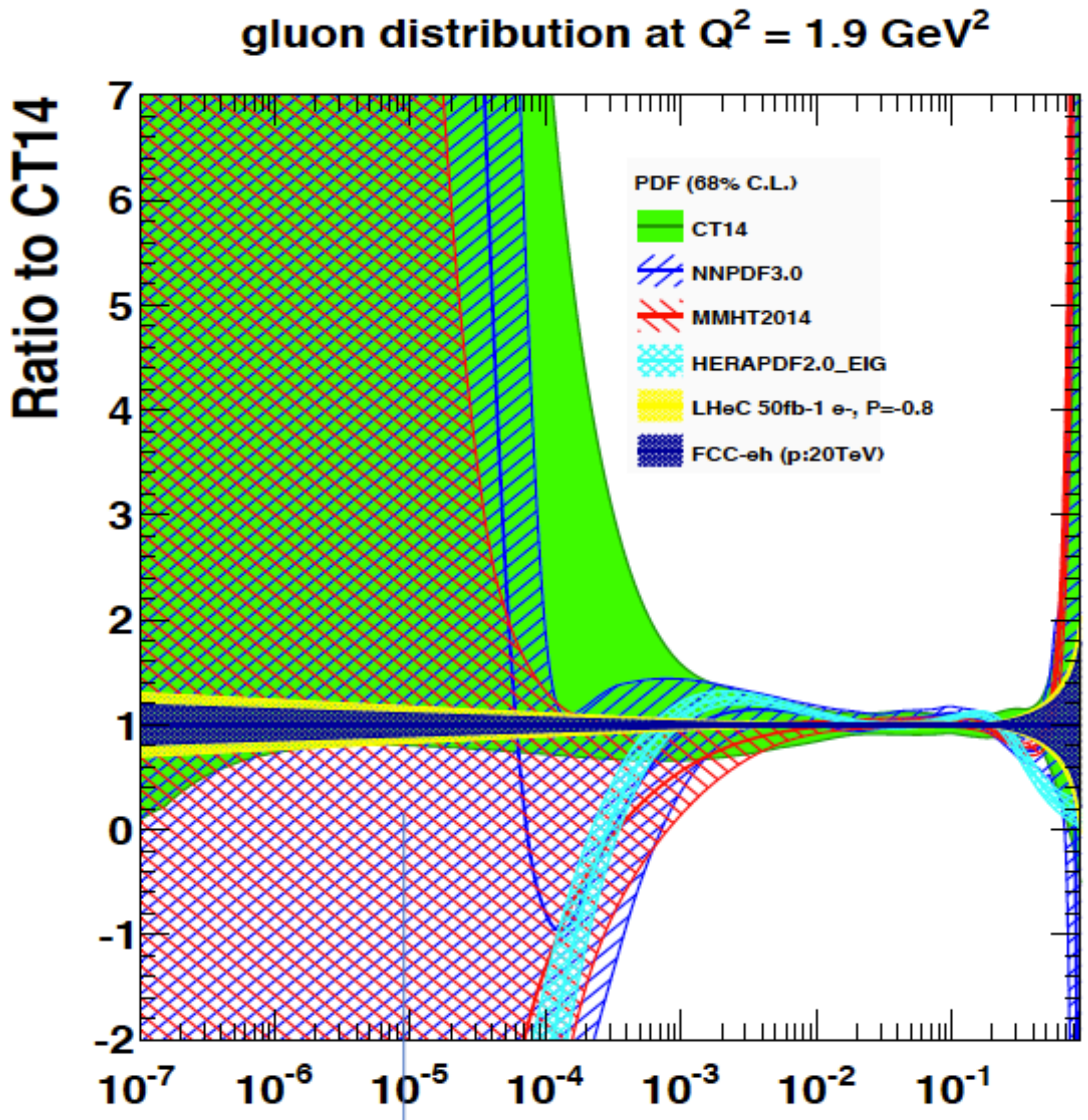
Collider	FCC-ee	FCC-eh
Luminosity (ab^{-1})	+1.5 @ 365 GeV	2
Years	3+4	20
$\delta\Gamma_H/\Gamma_H$ (%)	**1.3**	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	**0.17**	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	**0.43**	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	**0.61**	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	**1.21**	1.35
$\delta g_{Hgg}/g_{Hgg}$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

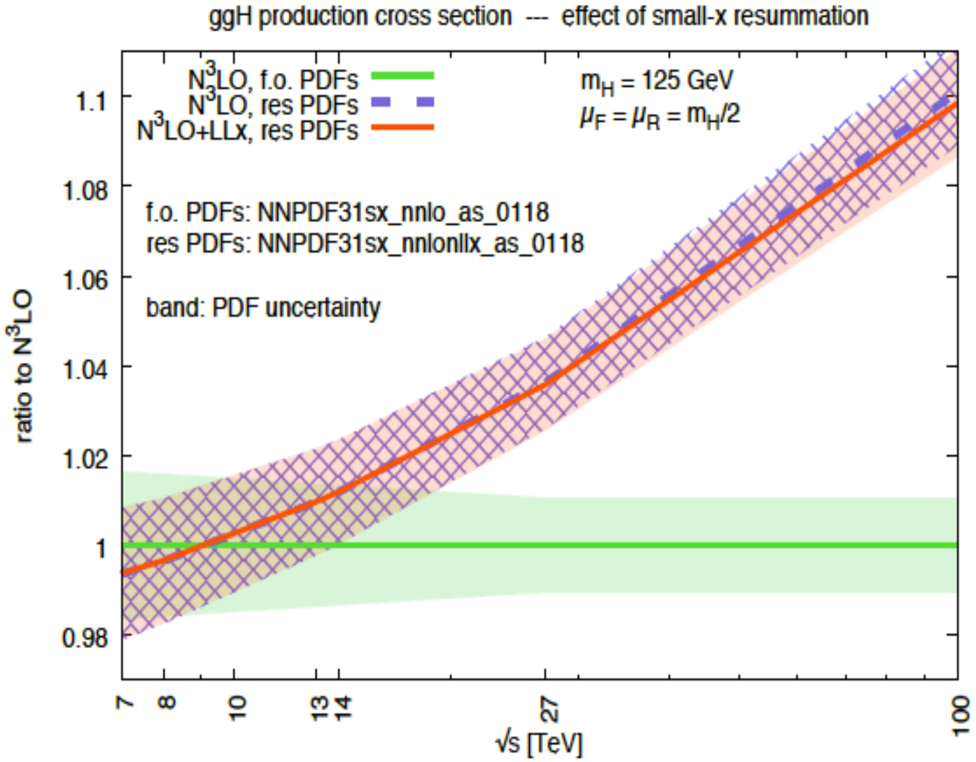
Low x Dynamics



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

1802.07758

Very large effects of small x dynamics at FCC-hh



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

Outlook

Today

Yannis Papaphilippou on LHeC Racetrack as Injector for FCC-ee
[an example of technical synergy, eg also: PERLE Linac as FCC-ee Demonstrator]

Kevin Andre on Accelerator Design
[IR perhaps the biggest challenge for ep / pp - for those who remember HERA]

Alessandro Polini on Detector Design
[based on LHeC Detector Paper, cf ECFA Detector R+D, topics for ep:
pipe, low mat solenoid, 5mu impact, timing?, fwd calorimetry, installation]

Ahmed Hammad on Heavy Neutrinos
Nathan Sherrill on Space Time Surprises
[two examples of novel physics studies and ideas, beyond genuine DIS]

The FCC-eh Development may move towards
a dedicated Conceptual Design Report (by 2023/24)

Physics: TeV Scale DIS and its Importance for hh

A Next Generation DIS Detector [of CMS size]

Accelerator: CE, Lattice, Parameters, Infrastructure..

- A useful base for the FCC-eh development
- Strong relation to LHeC and PERLE
- Emphasis on Unity of Physics

There is a scenario where FCC-hh comes without FCC-ee,
in a 100 km or the LHC tunnel. There comes a next strategy
discussion which is prepared to include the DIS future.

Comprehensive papers last longer than conferences.. :
The LHeC CDR arXiv:1206.2913 has by now 632 citations.

Needs careful thoughts and preparation and a human base..
Decision with next LHeC/PERLE/FCCeh workshop

P. Agostini[1], H. Aksakal[2], H. Alan[3], S. Alekhin[4,5], P. P. Allport[6], N. Andari[7], K. D. J. Andre[8,9], D. Angal-Kalinin[10,11], S. Antusch[12], L. Aperio Bella[13], L. Apolinario[14], R. Apsimon[15,11], A. Apyan[16], G. Arduini[9], V. Ari[17], A. Armbruster[9], N. Armesto[1], B. Auchmann[9], K. Aulenbacher[18,19], G. Azuelos[20], S. Backovic[21], I. Bailey[15,11], S. Bailey[22], F. Balli[7], S. Behera[23], O. Behnke[24], I. Ben-Zvi[25], M. Benedikt[9], J. Bernauer[26,27], S. Bertolucci[9,28], S. S. Biswal[29], J. Blümlein[24], A. Bogacz[30], M. Bonvini[31], M. Boonekamp[32], F. Bordry[9], G. R. Boroun[33], L. Bottura[9], S. Bousson[7], A. O. Bouzas[34], C. Bracco[9], J. Bracinik[6], D. Britzger[37], S. J. Brodsky[36], C. Bruni[7], O. Brüning[9], H. Burkhardt[9], O. Cakir[17], R. Calaga[9], A. Caldwell[37], A. Calıskan[38], S. Camarda[9], N. C. Catalan-Lasheras[9], K. Cassou[39], J. Cepila[40], V. Cetinkaya[41], V. Chetvertkova[9], B. Cole[42], B. Coleppa[43], A. 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Thanks to authors of 2007.14491, the FCC coordination and the International Advisoory Committee on LHeC and FCC-eh

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John Womersley (ESS Lund)

Recommendations

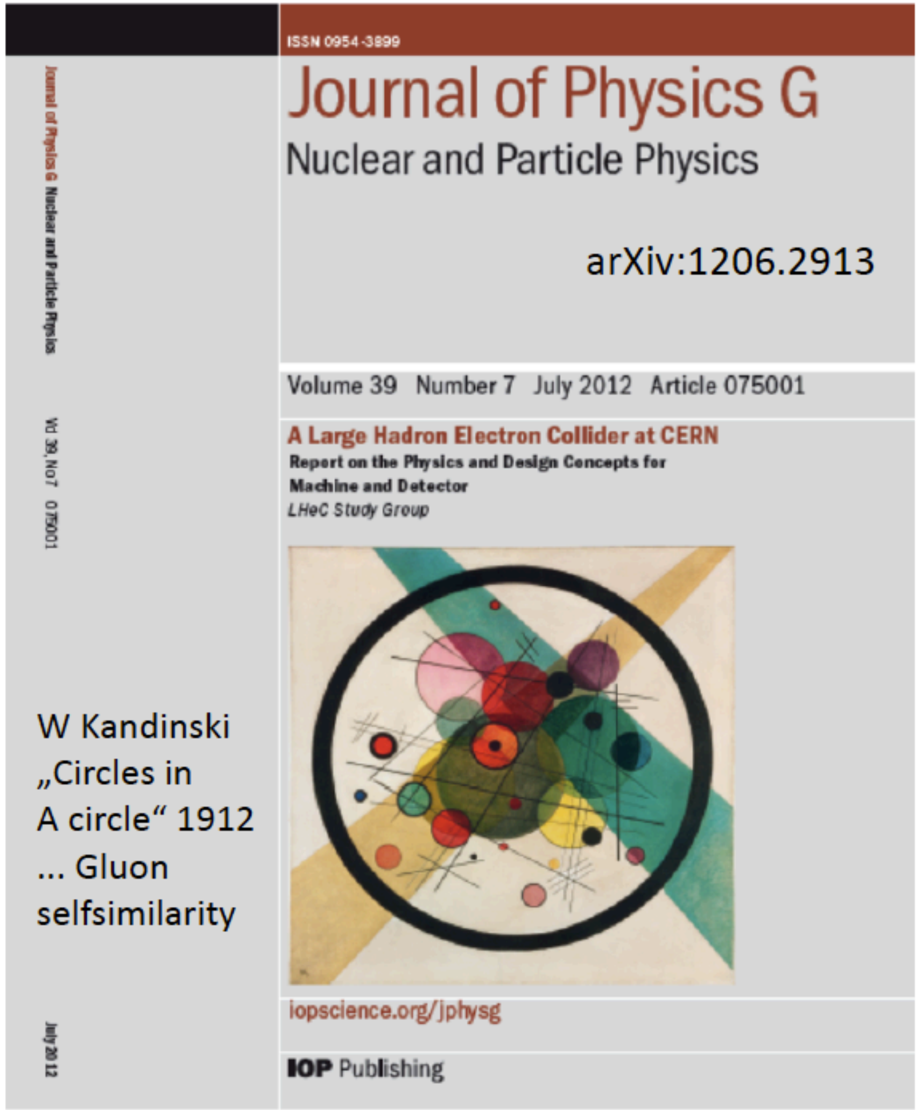
i) It is recommended to further develop the ERL based ep/A scattering plans, both at LHC and FCC, as attractive options for the mid and long term programme of CERN, resp. Before a decision on such a project can be taken, further development work is necessary, and should be supported, possibly within 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.

Full statement published in arXiv:2007.14491 (2020), J.Phys.G to appear

References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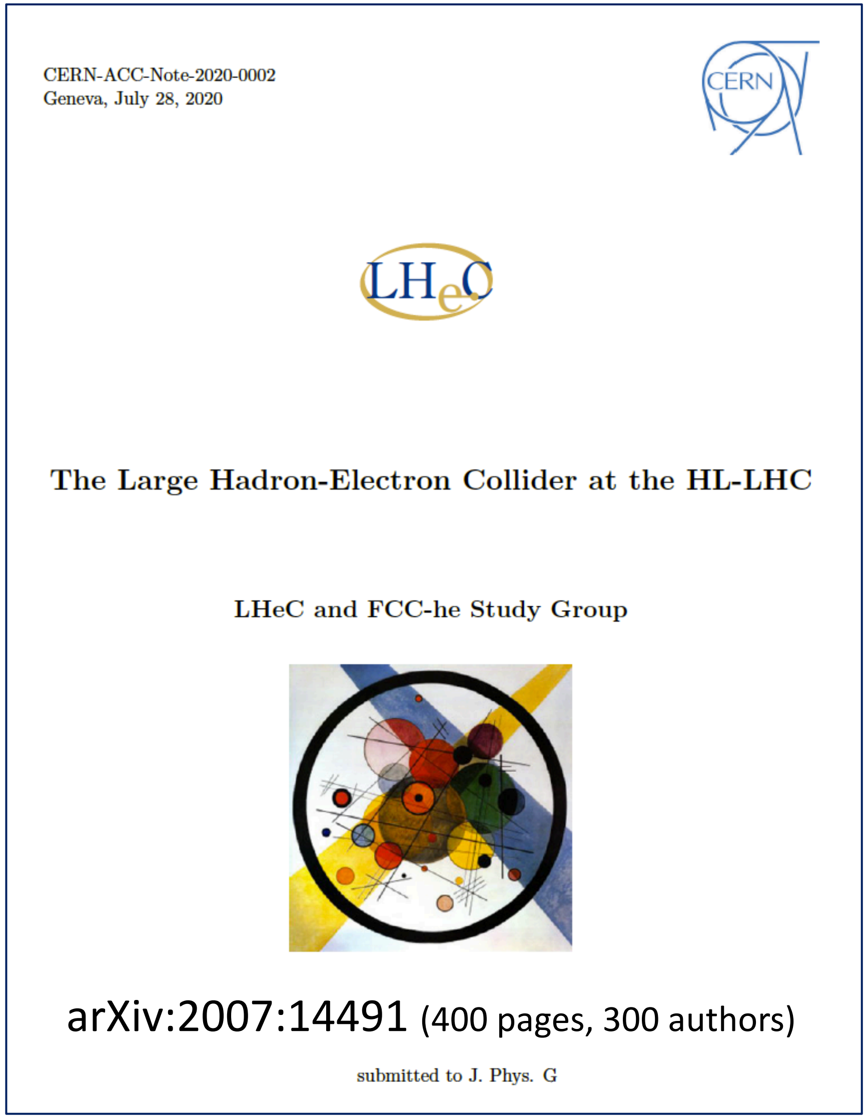
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Future of Particle Physics

much now resembles the fifties - theory provides questions, but no firm answers. Specifically, the SM has known, fundamental deficiencies: a proliferation of too many parameters, a missing explanation of the repetitive quark and lepton family pattern, an unresolved left-right asymmetry in the neutrino sector related to lepton-flavour non-conservation, an unexplained flavour hierarchy, the intriguing question of parton confinement and others. The Standard Model carries the boson-fermion asymmetry, it mixes the three interactions but has no grand unification, the proton is stable, it needs experiment to determine the parton dynamics inside the proton, has no prediction for the existence of a yet lower layer of substructure, and it does not explain the difference between leptons and quarks. Moreover, the SM has missing links to Dark Matter, possibly through Axions, and Quantum Gravity, while string theory still resides apart. The Standard Model is a phenomenologically successful theory, fine tuned to describe a possibly metastable universe [16].

Particle Physics: The Challenge Ahead

From ERL White Paper (draft), to be published

> Principally new theories would be required to "turn the SM on its head" while, as Steven Weinberg also stated not long ago: "There isn't a clear idea to break into the future beyond the Standard Model" [15], it remains the conviction, as Gian Giudice described it in his eloquent "imaginary conversation" with the late Guido Altarelli, that "A new paradigm change seems to be necessary" [17] in the "Dawn of the post naturalness era".

The Development of ERLs. draft

> Apparently, particle physics is as interesting, challenging and far reaching as it ever was in recent history. It yet needs revolutionary advances in insight, observation and technologies, not least for its accelerator base. It demands that new generation hadron-hadron, electron-hadron and pure lepton colliders be developed and realised. Hardly a new paradigm can be established with just one type of collider in the future. The field needs global cooperation, trust and complementarity of its techniques, a lesson learned from the exploration of the Fermi scale with the Tevatron, HERA and LEP/SLC,

High field magnets, SRF, ERL, Muon Collider, and Plasma Wakefield

The five acc. technology pillars identified last year and by Council/SPC/LDG.