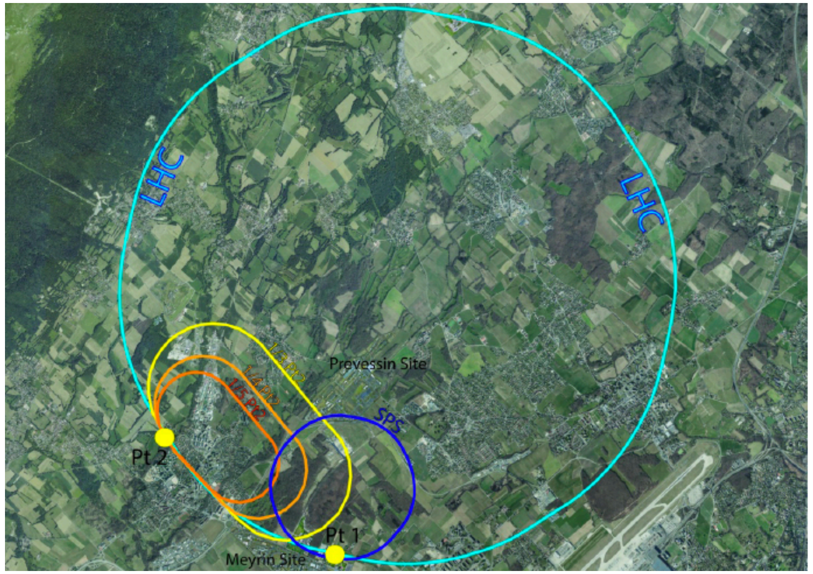
For Achille

Some slides on Project, Physics, Detector, ERL/PERLE

7.9.2021

Project and Accelerator

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)

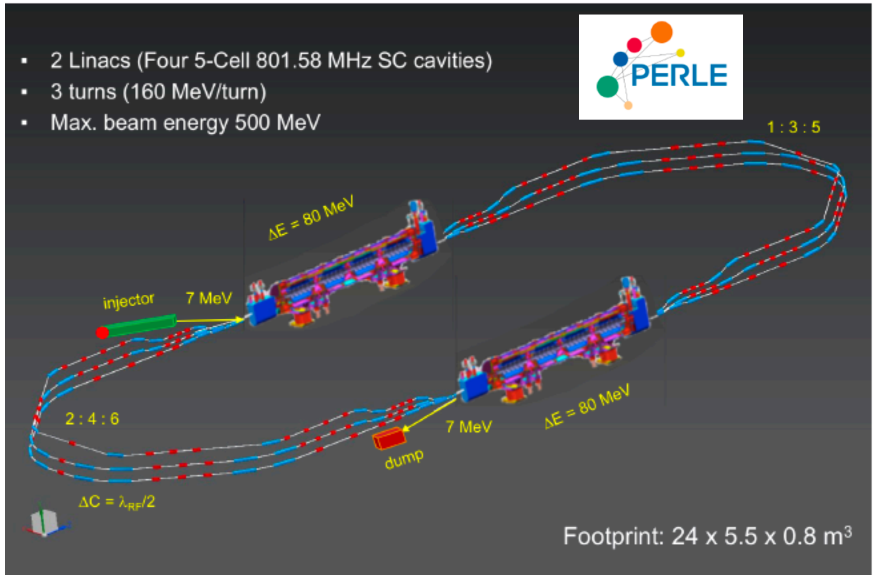
arXiv:2007.14491, J.Phys.G to appear

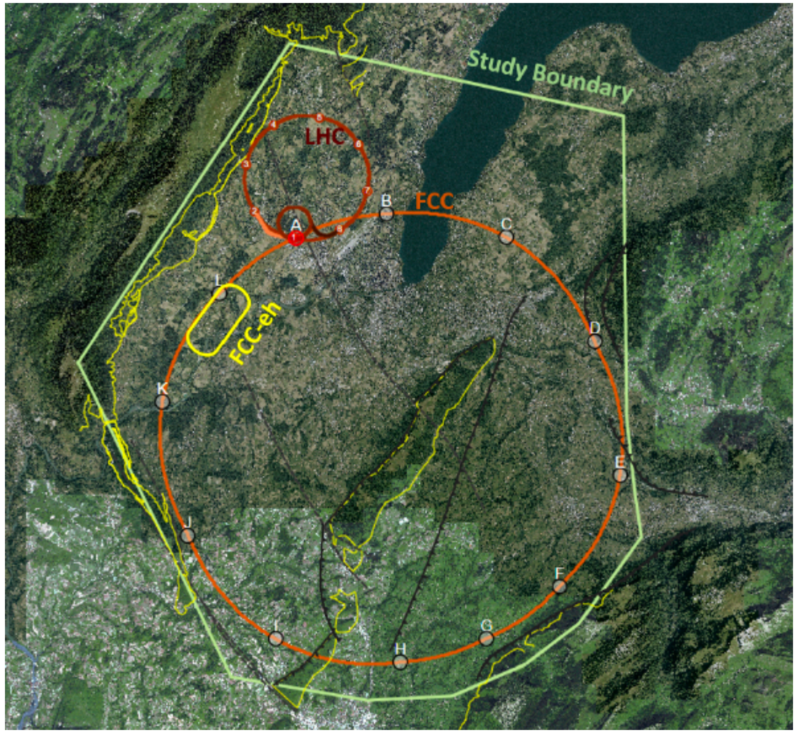
Powerful ERL for Experiments @ Orsay
CDR: 1705.08783 J.Phys.G
CERN-ACC-Note-2018-0086 (ESSP)

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

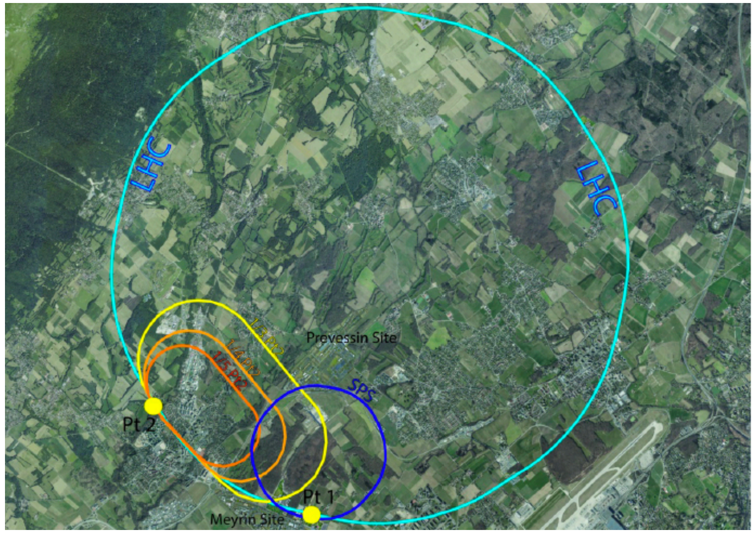
FCC CDR:
Eur.Phys.J.ST 228 (2019) 6, 474 Physics
Eur.Phys.J.ST 228 (2019) 4, 755 FCC-hh/eh

Future CERN Colliders: 1810.13022 Bordry+

ERL: Accelerator Energy Frontier

CERN-ACC-Note-2020-0002
Version v1.0
Geneva, June 2, 2020

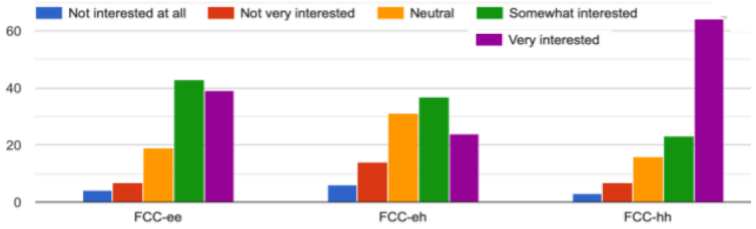
400 pages update of 2012 CDR - to appear



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

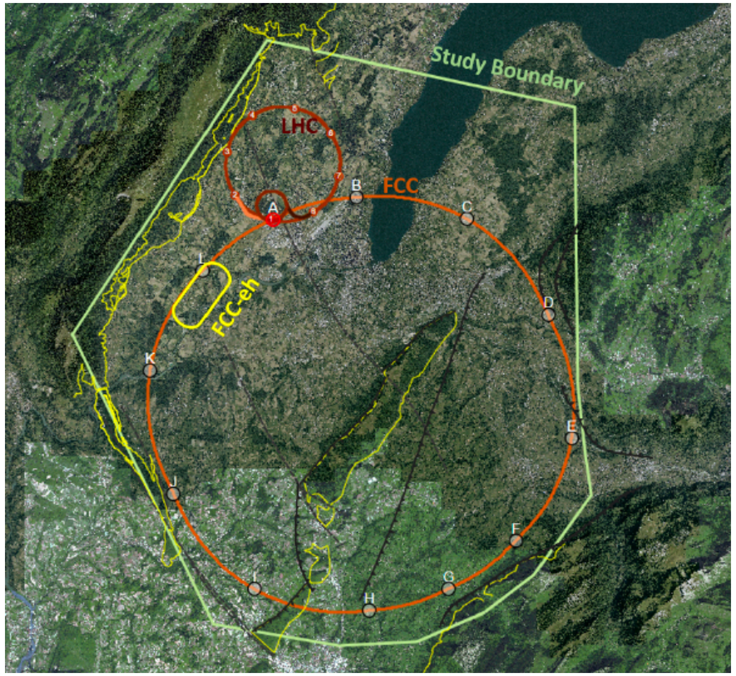
(when) will that happen.? We don't know
I met Abhay Deshpande in Snowmass 2001,
when he presented the EIC, not for the 1st time

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

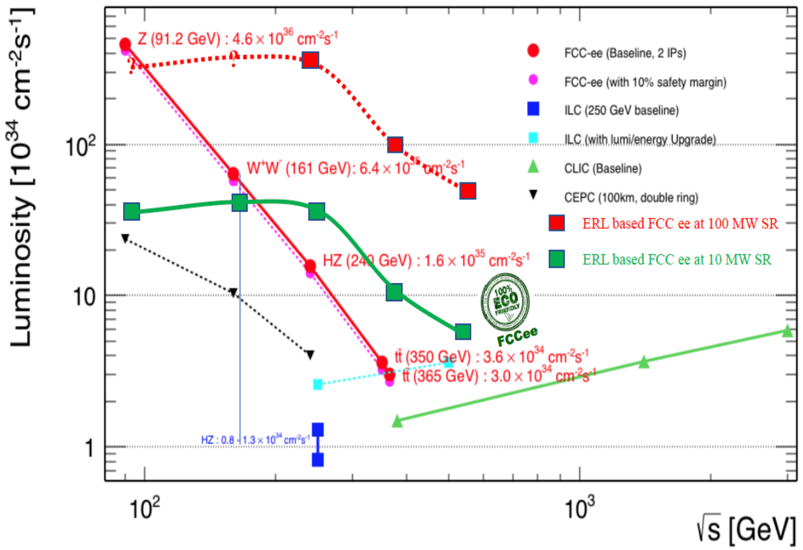


ECFA: Interest of young scientists 2002.02837

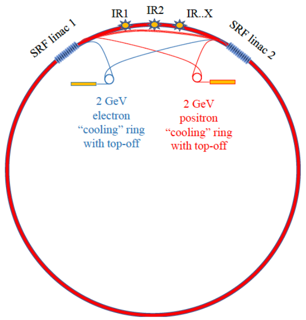
60 GeV ERL design applied to FCC-he



FCC-ee



Vladimir Litvinenko et al, 1909.04437



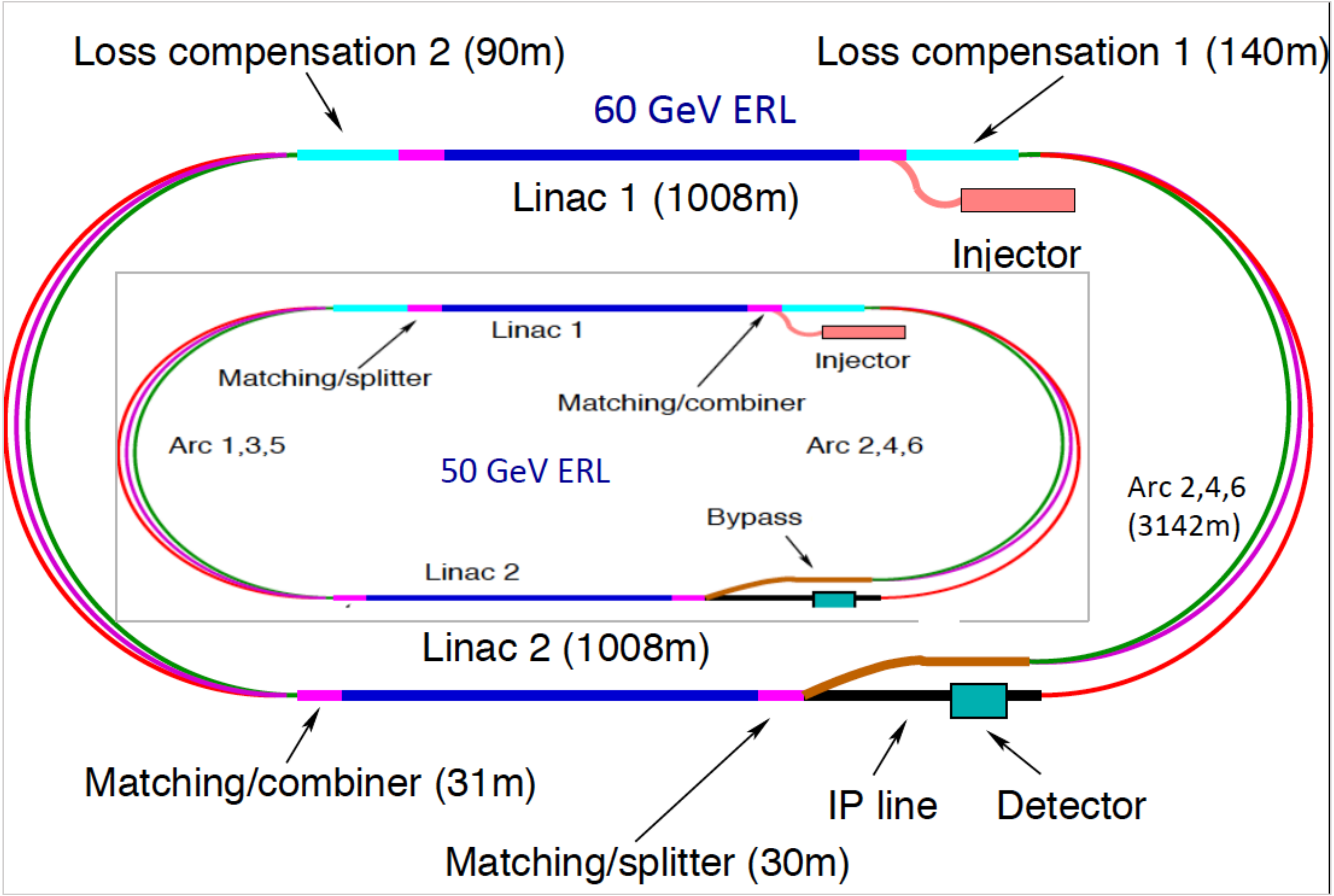
4-6 turns

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

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

LHeC Configuration (for two electron beam energies) [CERN, BNL, Jlab for CDR]



3-turn energy recovery racetrack configuration. Modular for LHeC/FCC-eh

Energy recovery linac(s)

20mA I_e

Concurrent ep + pp operation with LHC

Integrated luminosity in e^-p up to O(1) ab^{-1}

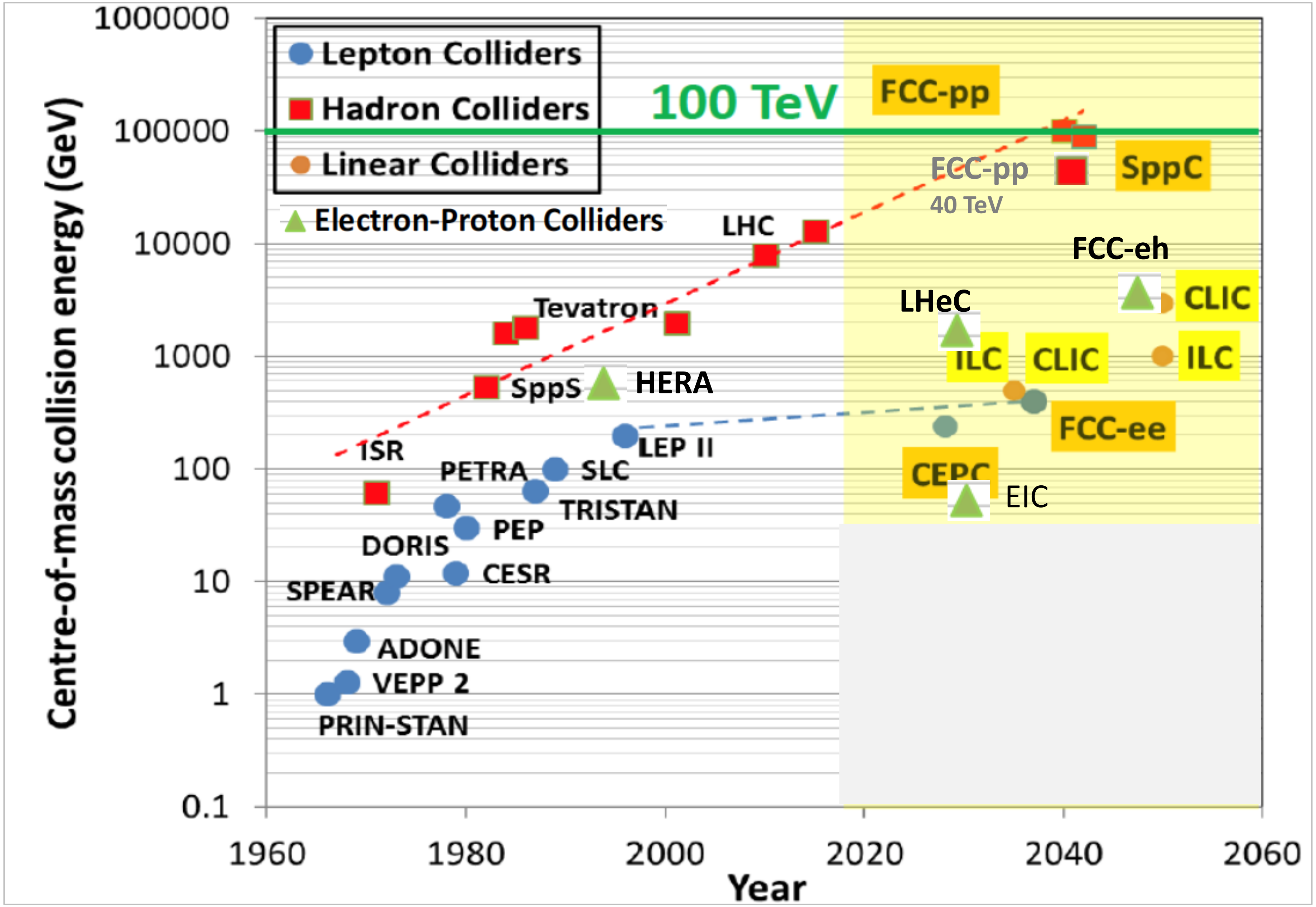
U(ep) = 1/n U(LHC)

Likely n=3 (CDR) → n=4 gains 20-30% cost. E< 60

H, BSM, top, low x.. require E > 50 GeV

Frequency set to 802 MHz, commensurate with LHC and 401/802 at CERN+FCC. also beam-beam stability

Hundred Years of HEP Colliders



ep/A Parameters:

Oliver Brüning[1], John Jowett[1], Max Klein[2], Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1] EDMS 17979910 | FCC-ACC-RPT-0012

MK EPS 7/19. adapted from M Benedikt (3/19)

Published in 2020

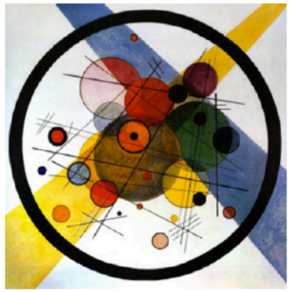
CERN-ACC-Note-2020-0002
Geneva, July 28, 2020

CERN

LHeC

The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group



arXiv:2007:14491 (400 pages, 300 authors)

To be submitted to J. Phys. G

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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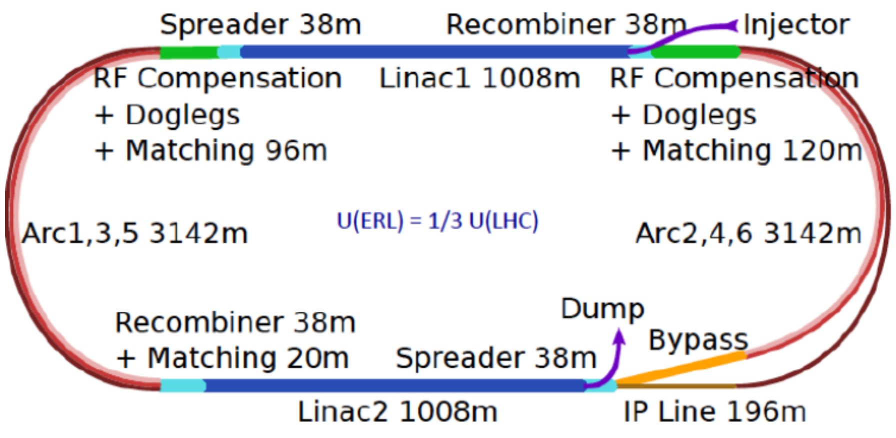
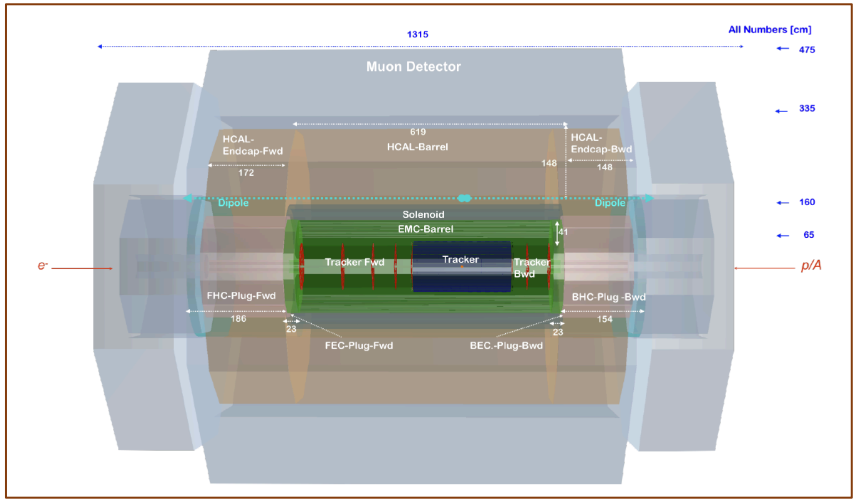
5 page summary: ECFA Newsletter Nr 5., August 20

https://cds.cern.ch/record/2729018/files/ECFA-Newsletter-5-Summer2020.pdf

156 Institutions involved

Concluding Remarks





This is indeed **affordable** - O(1) billion CHF for another TeV collider

It **sustains the HL-LHC** and exploits this massive O(5) BCHF investment

Physics: Unique: Microscope of substructure (not resolved!), empowers LHC searches and Higgs measurements challenging e^+e^-, Discovery in electroweak and strong i.a. sector, Revolution of HI physics

Technology: Accelerator: highest energy ERL application - green.
Detector: exciting place for new technology (CMOS, timing, thin calo.. etc) in classic DIS, low radiation environment, no pileup.
Exciting place also for known technology to reappear and work.

Merging LHeC with A3 resolves conceptual conflict on IP2 and promises to lead to new chapter of HI and accelerator physics (tentative)

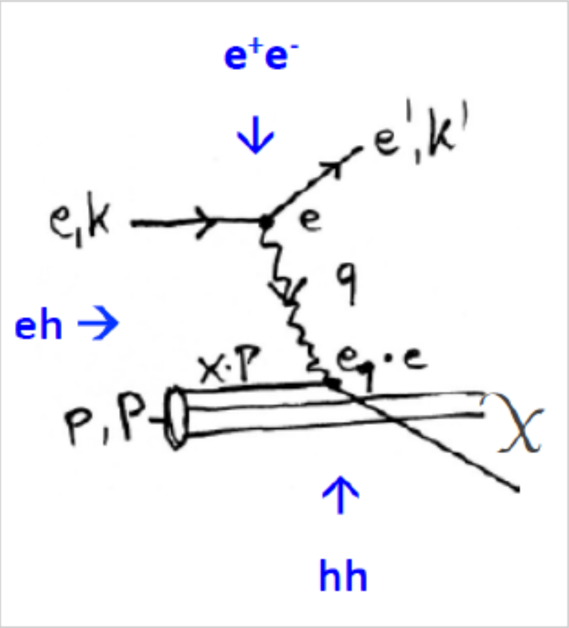
Next steps: PERLE facility at Orsay, considerations for a detector proposal to LHCC, embedded and subject to CERN's future, which is also related to that of the CEPC.

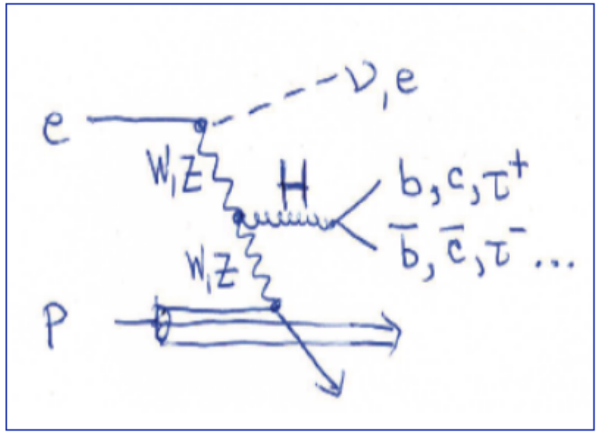
The LHeC group believes that **diversity** (at the energy frontier too) **is key** to help particle physics theory to restore its predictive power..

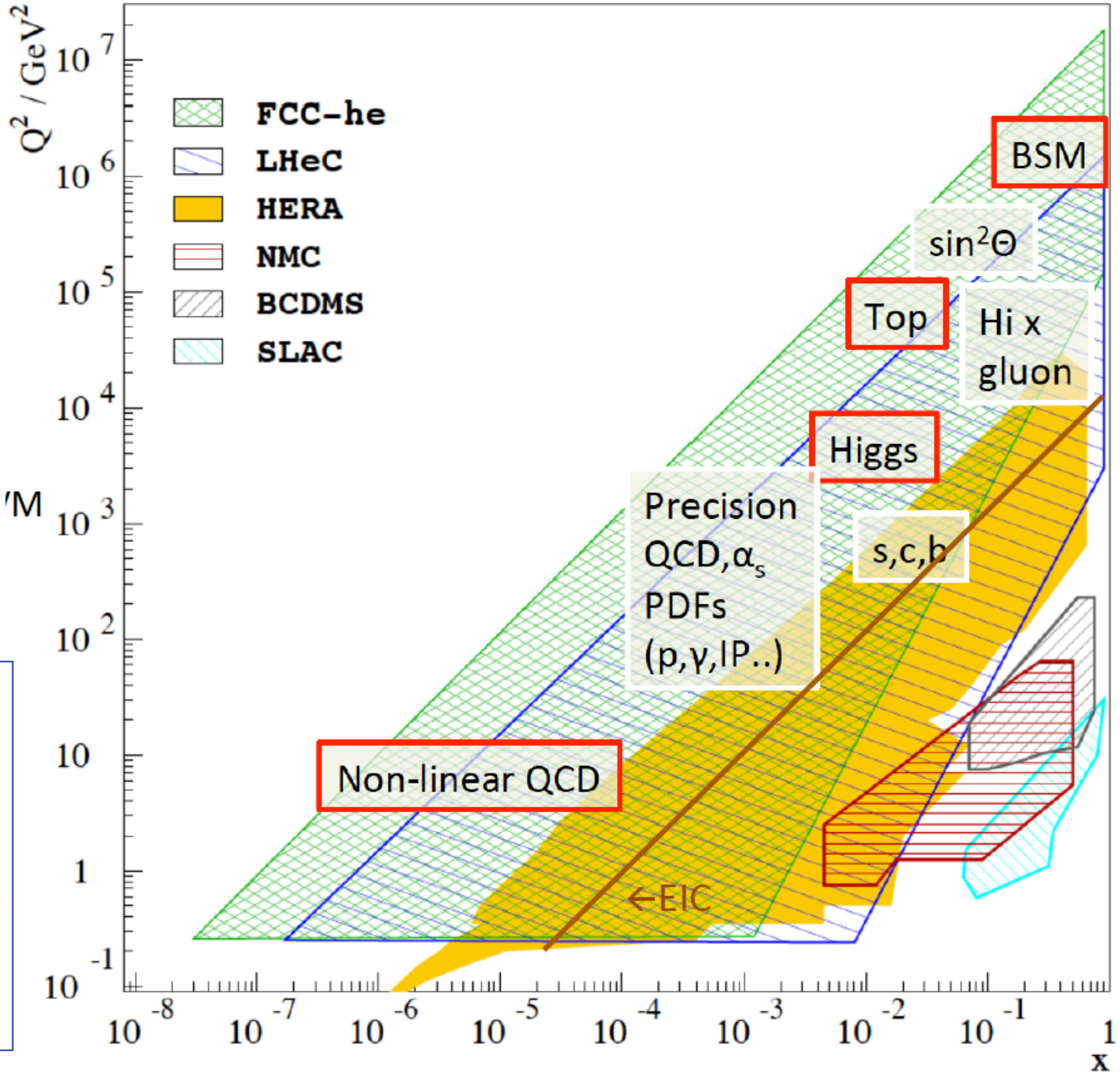
Physics

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

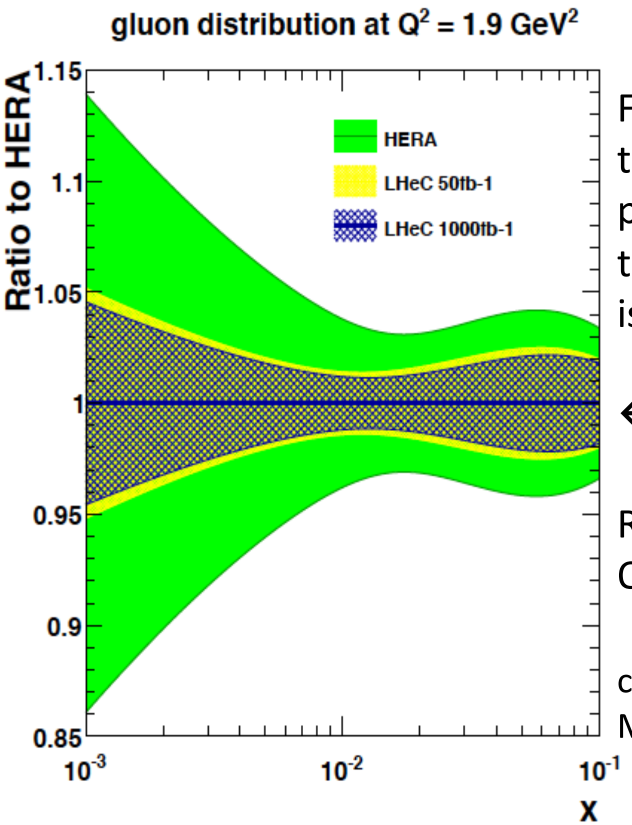
Transformation of LHC/FCChh into high precision Higgs facility

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

A Unique Nuclear Physics Facility

Parton Distributions

DIS: clean theory, light cone, redundant e/h FS reconstruction, ..



For LHC to have an impact on the search and precision physics program at HL-LHC it is crucial that PDF and QCD information is available early.

← PDF study with 50 vs 1000 fb^{-1}

Remove essential party of QCD uncertainties of gg→ H

cf C. Gwenlan, talk at DIS19 and M Cooper Sarkar yesterday at EPS

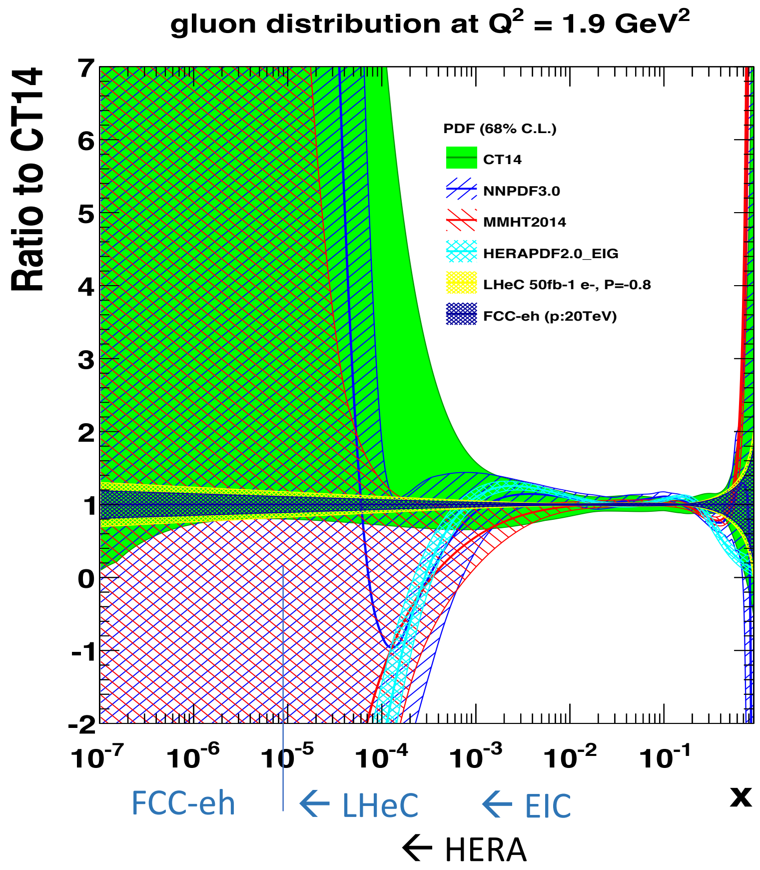
Figure 6: Uncertainty on the determination of the gluon distribution in the x range relevant for Higgs measurements at the LHC, based on the combined HERA data (outer band, green) and for the LHeC with the full data set (inner band, blue) and from the first running period (yellow, around the inner band. The LHeC uncertainties comprise full correlated systematic error estimates besides the statistics.

Note that $50fb^{-1}$ is 100 times H1's total luminosity: Low x needs $1fb^{-1}$.

Complete unfolding of parton contents in unprecedented kinematic range: u,d,s,c,b,t, xg
Strong coupling to permille accuracy (incl + jets):

Crucial for LHC:

- high precision eweak, Higgs measurements
- Extension of high mass search range
- Non-linear low x parton evolution; saturation?



Higgs in ep and pp [LHC and FCC]

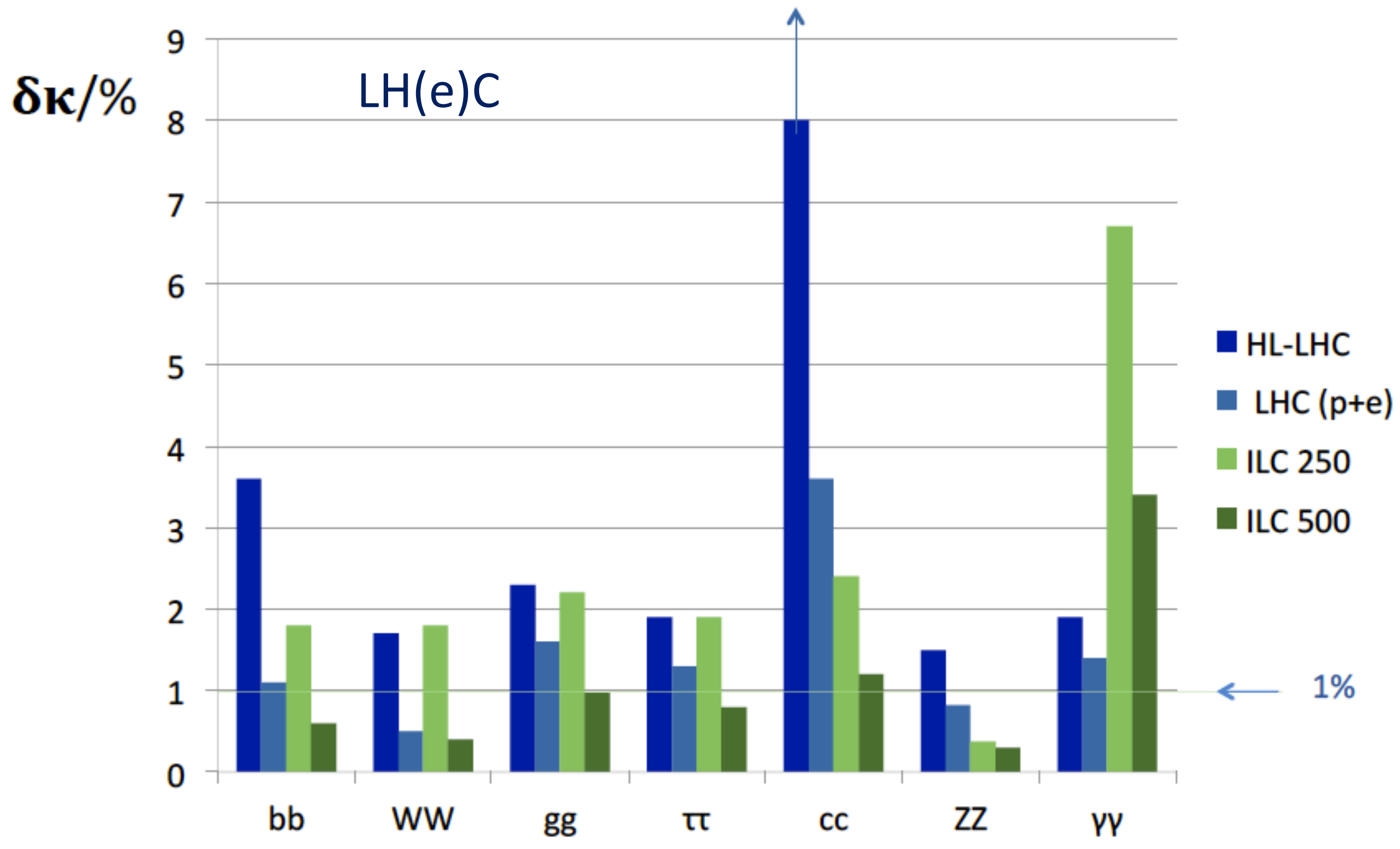
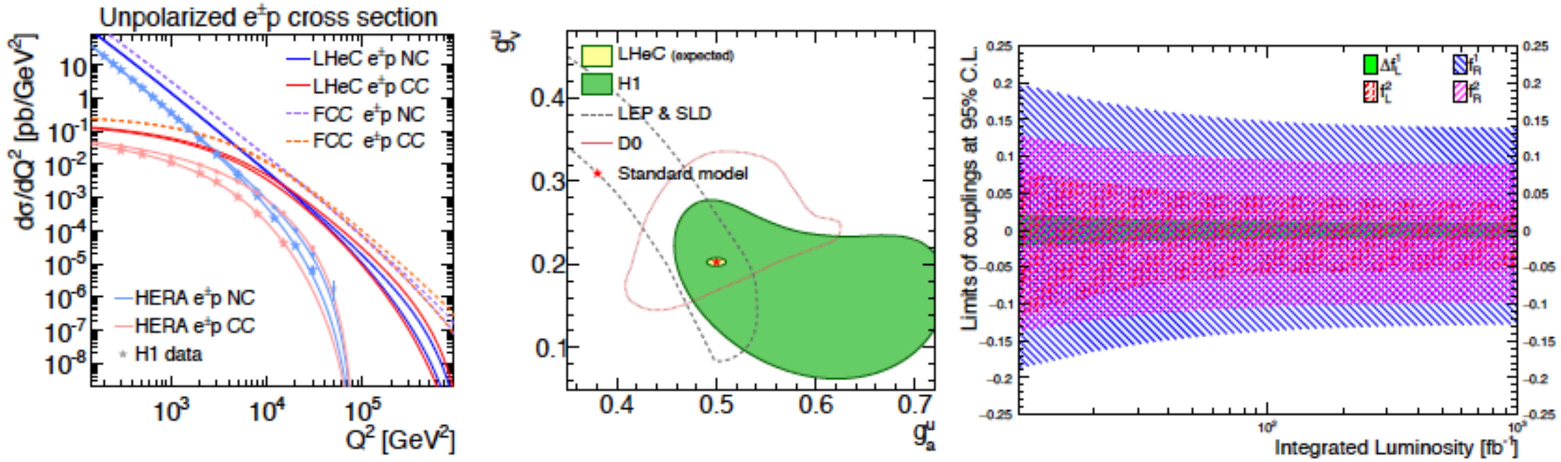


Fig.1*: Results of prospect evaluations of the determination of Higgs couplings in the SM kappa framework for HL-LHC (dark blue), LHC with LHeC combined (p+e, light blue), ILC 250 (light green) and ILC-500 (dark green).*

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

Precision Electroweak Physics



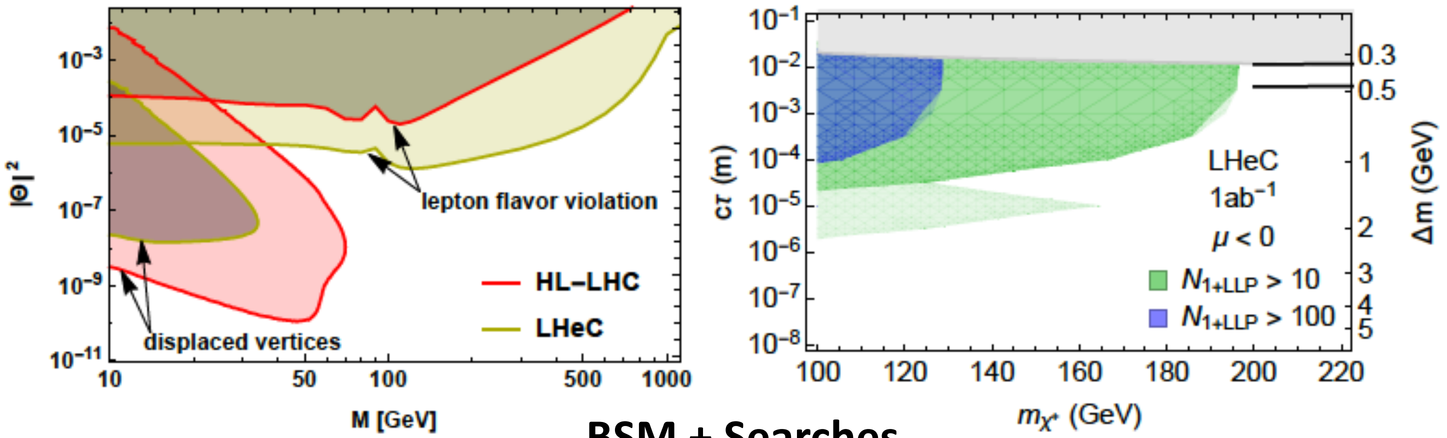
Anomalous Wtb couplings

Electroweak+Top Physics

cf EPS talks by
D Britzger and
C Schwanenberger

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].

Heavy Neutrinos



Higgsinos

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].

From LHeC strategy paper CERN-ACC-NOTE-2018-0084

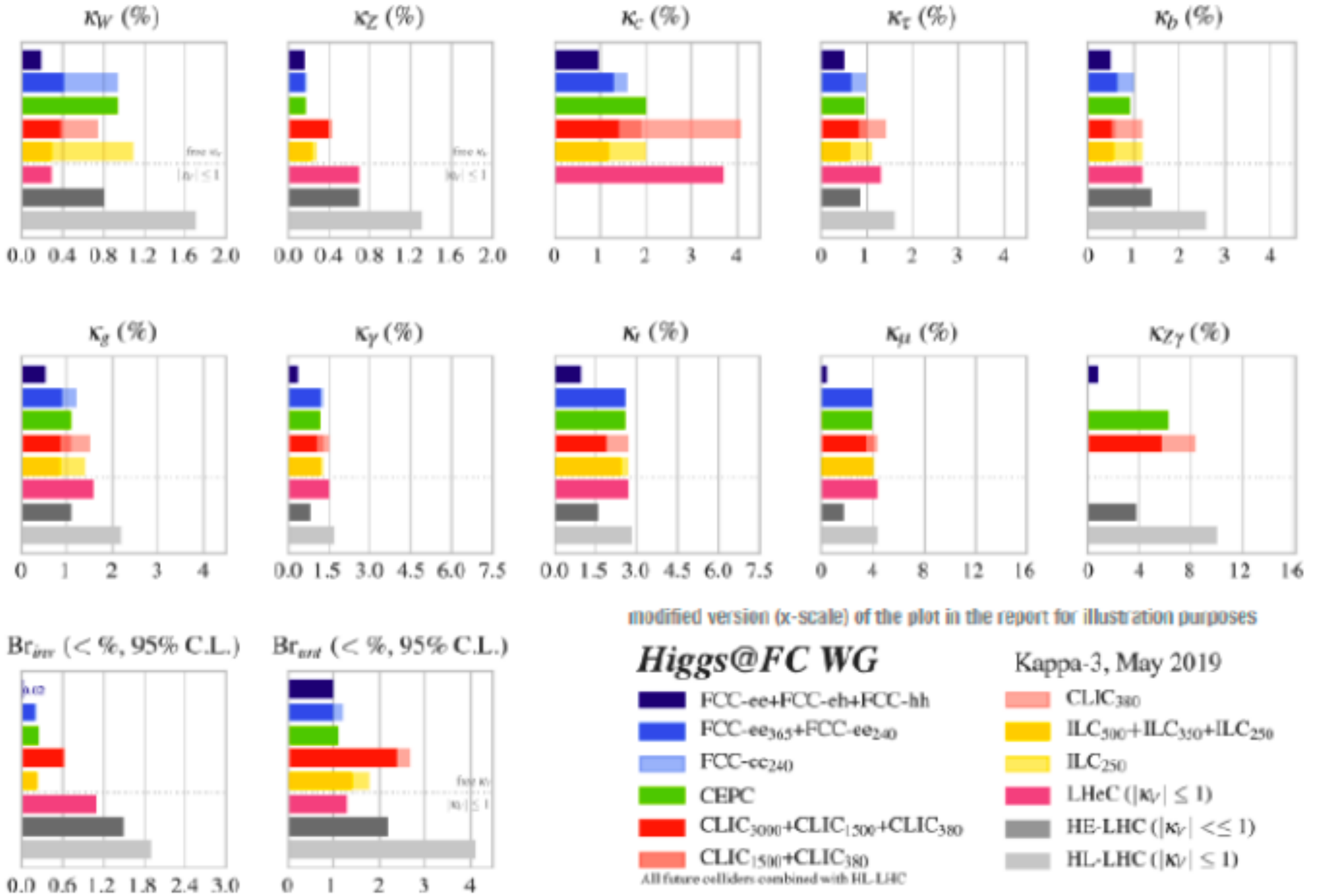
MK at EPS 2019

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



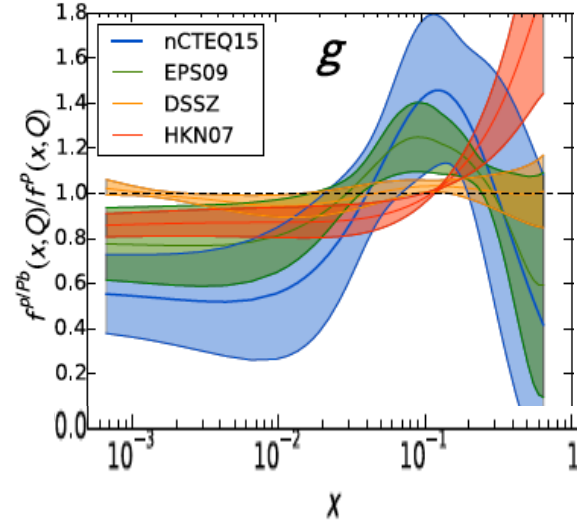
Nuclear PDFs at LHeC/FCCeh

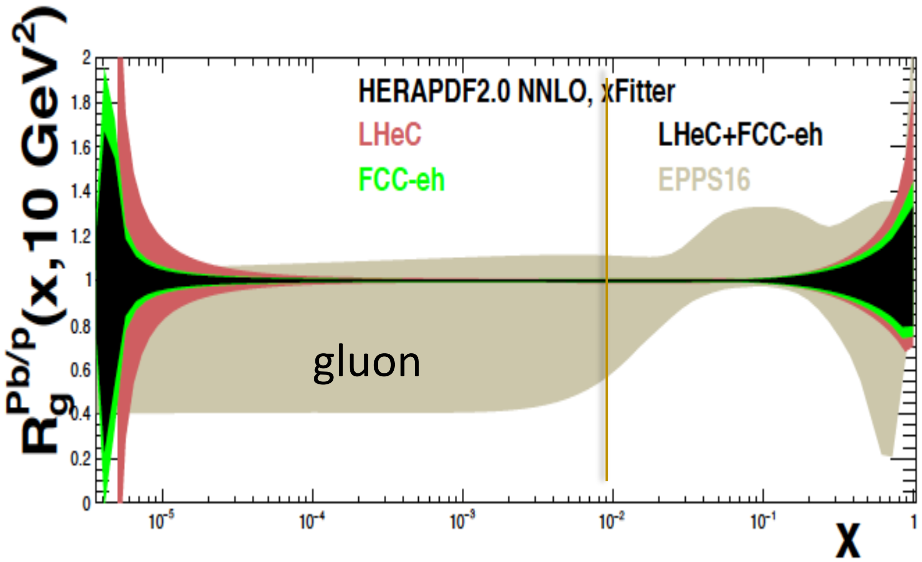
Unique nuclear/HI physics programme
Extension of fixed target range by 10 $^{3-4}$
QCD of QGP, de-confinement, saturation..
nPDFs independent of p PDFs

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

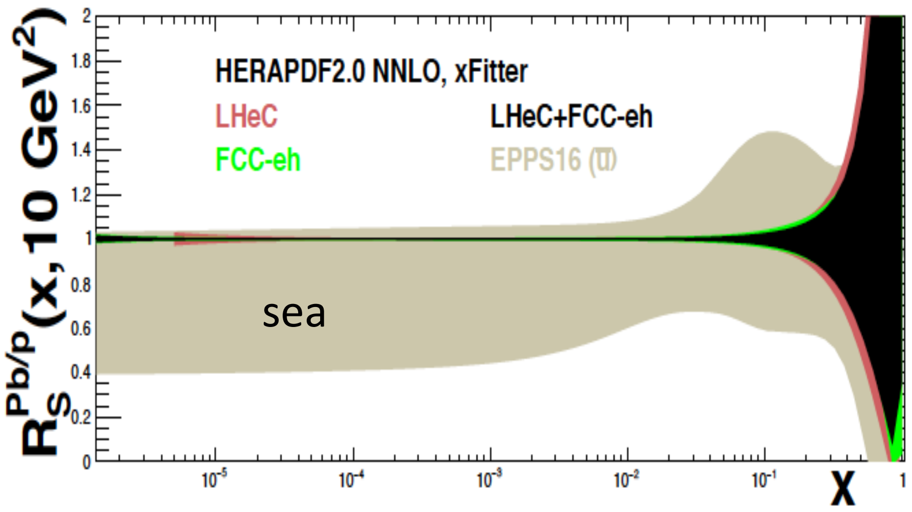
present status → on xg Pb/p

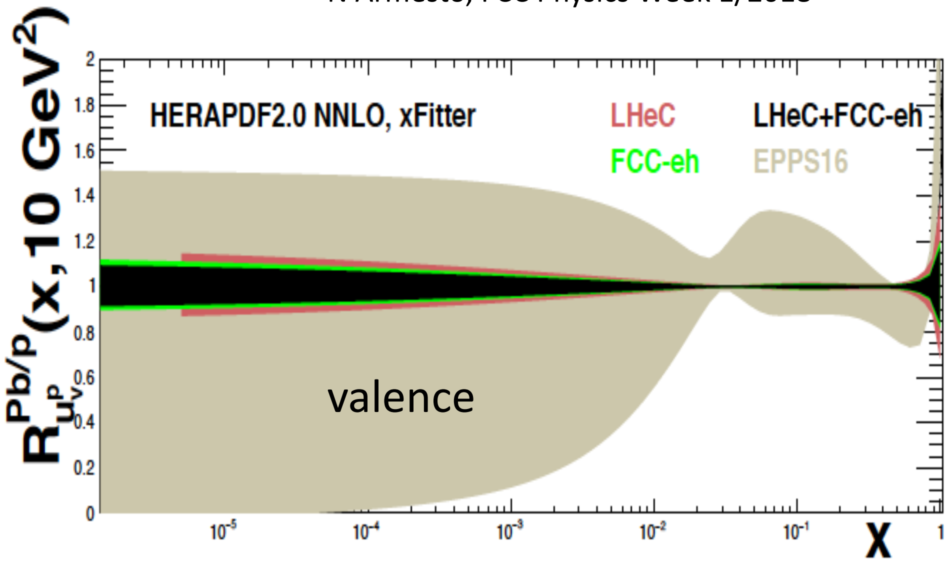
1509.00792





N Armesto, FCC Physics Week 1/2018



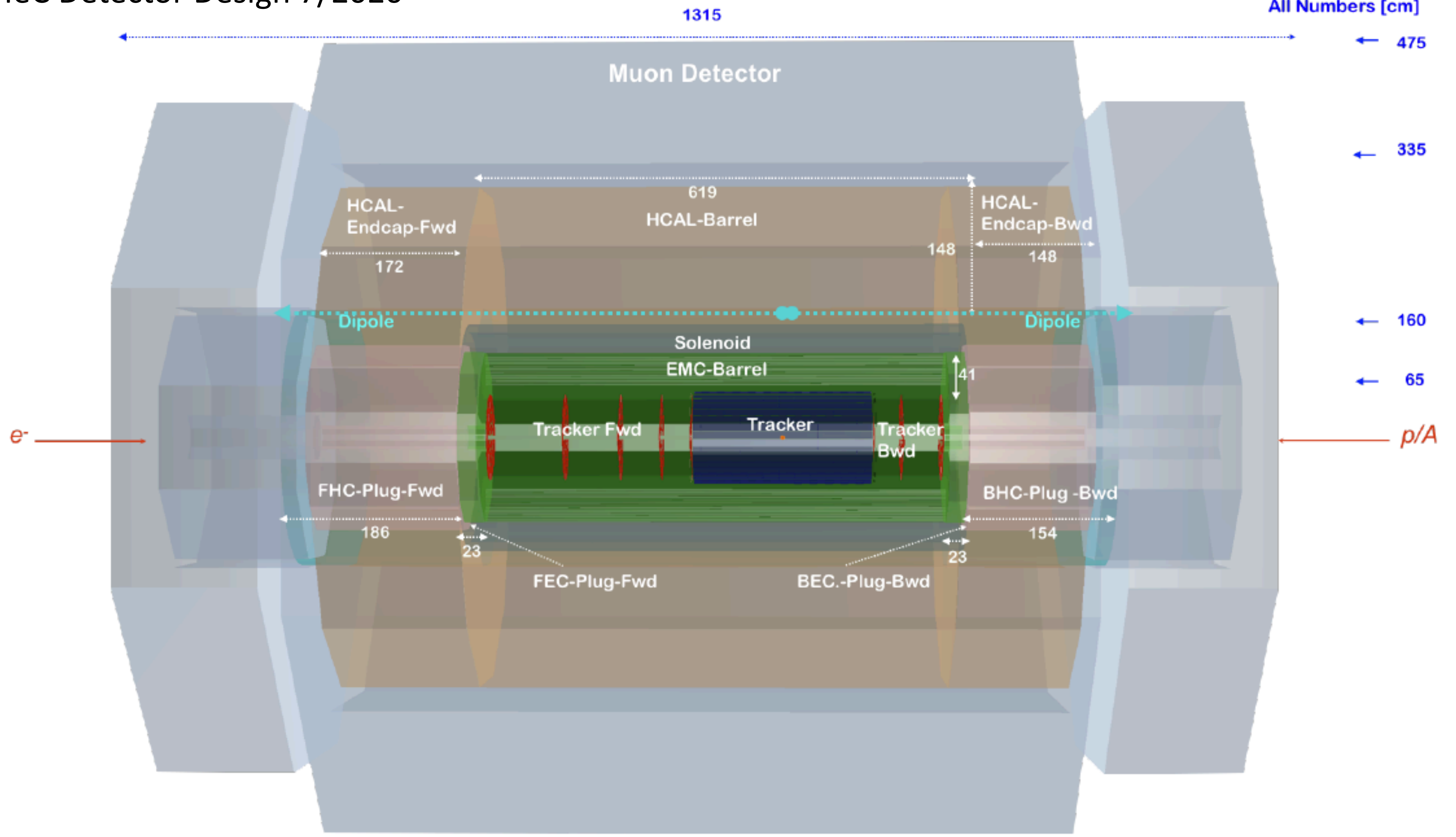


cf talk by A Stasto today

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

Detector

LHeC Detector Design 7/2020

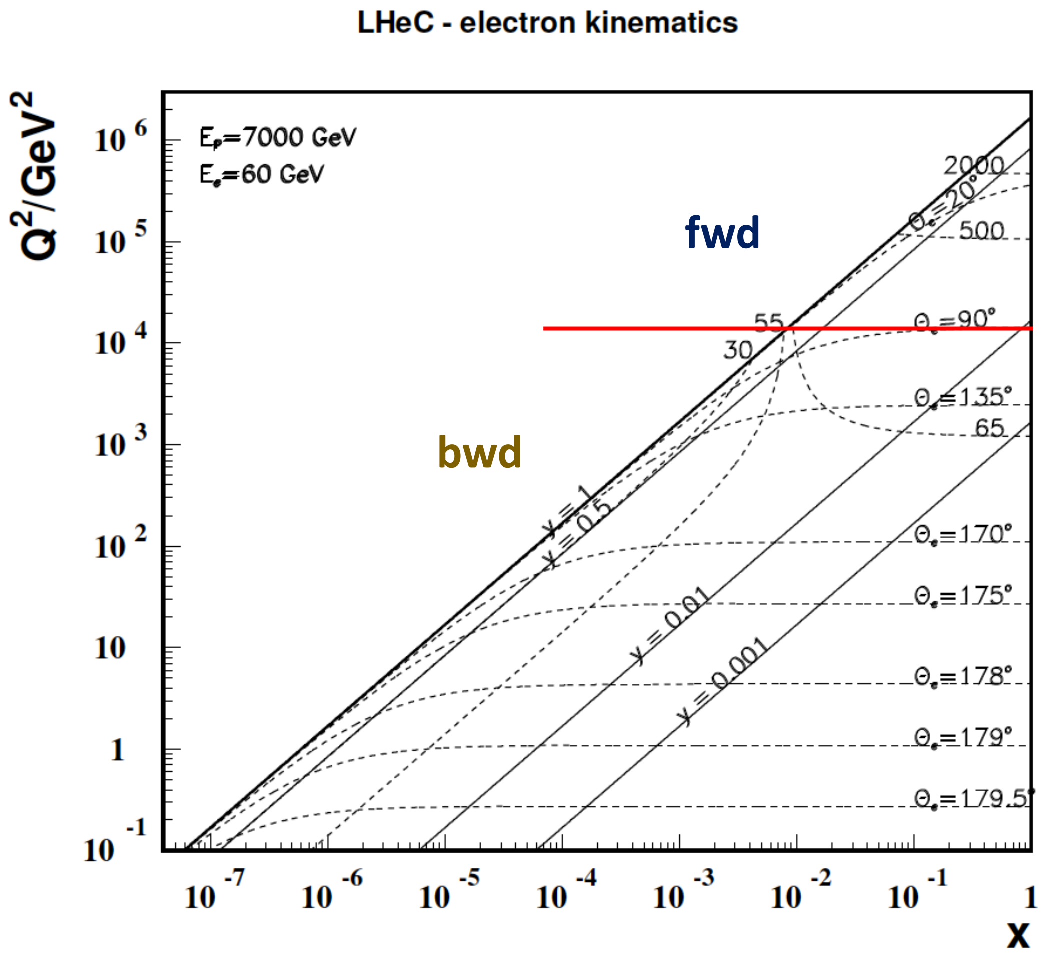


No pile up, low radiation wrt pp; high precision through overconstrained kinematics: e-h; modular for rapid installation

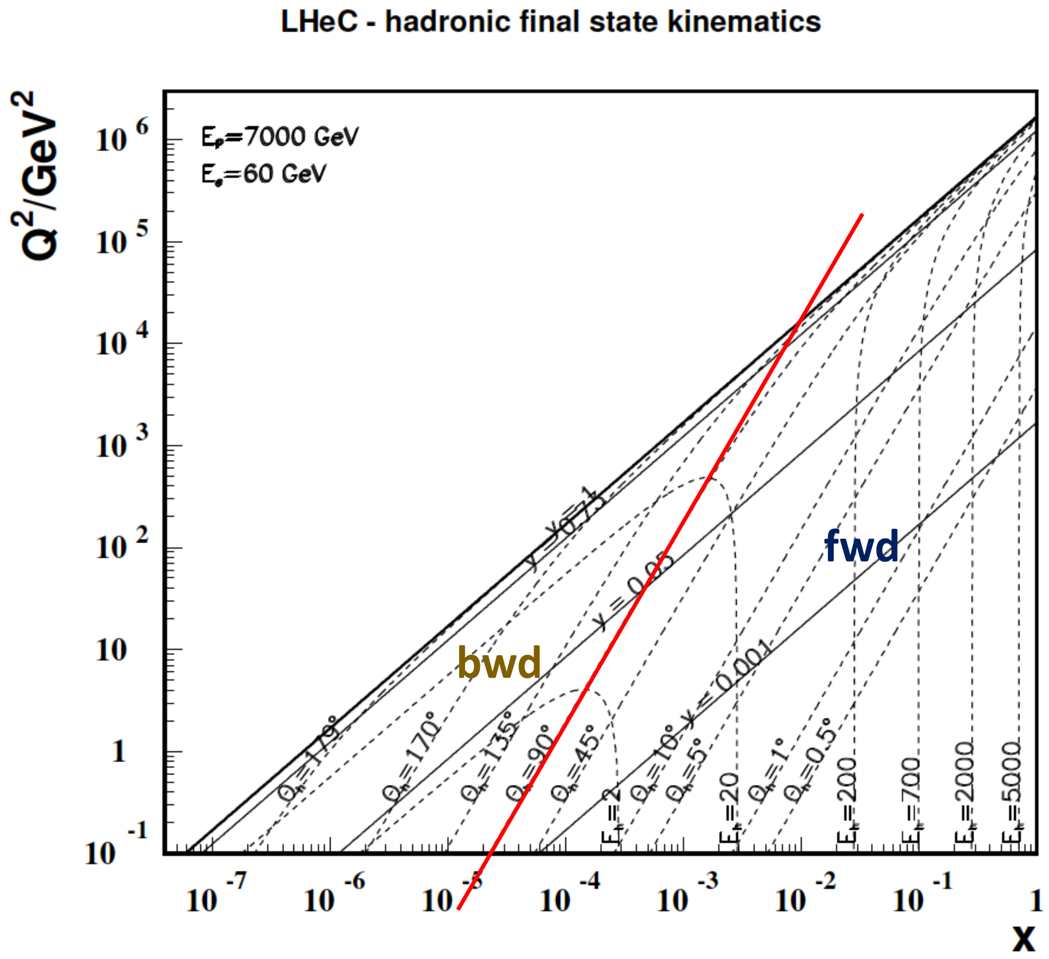
Tracker radius 40 → 60cm, B 3.5T; LxD =13 x 9m^2 [CMS 21 x 15m^2, ATLAS 45 x 25 m^2]..

arXiv:1206.2913+2007.14491

Kinematics: fwd: in p beam direction, bwd: e direction



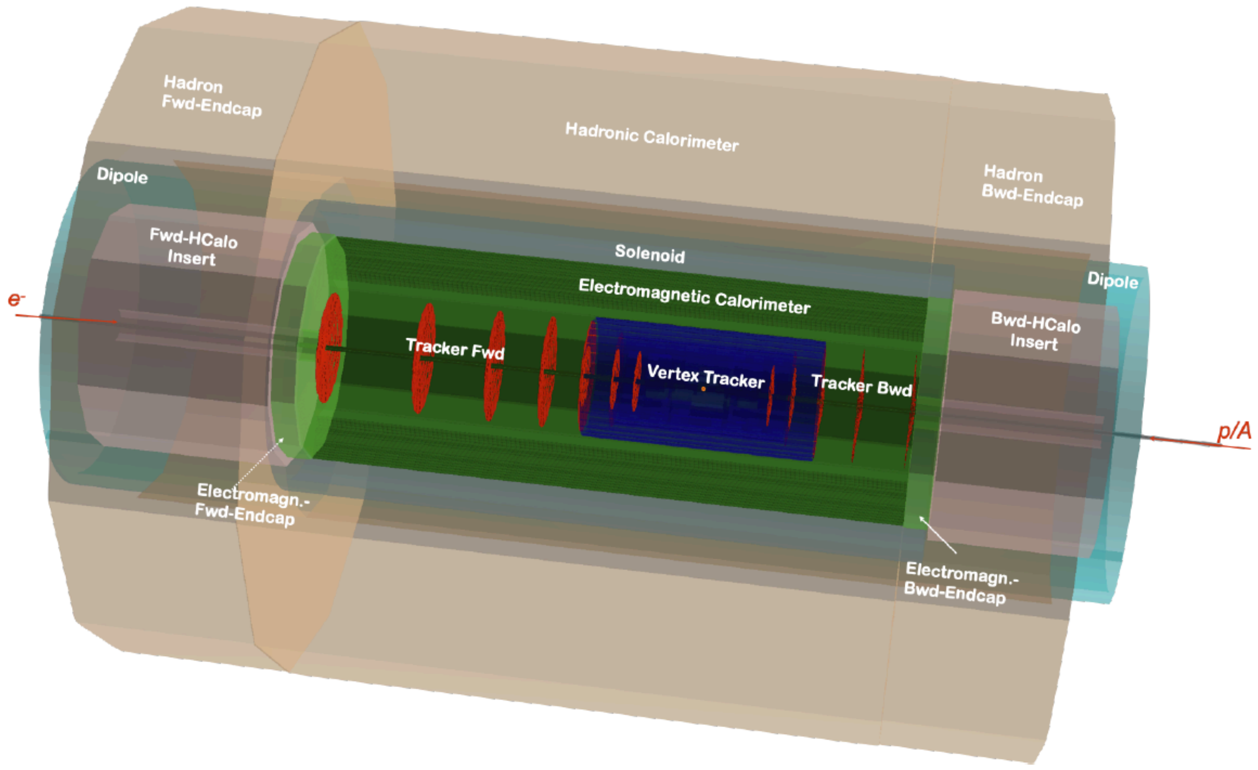
Electrons in bwd direction have low energy ($E'_e < E_e$ beam)
in fwd direction high energy up to Ep, Rutherford backscattering
Q^2=1 GeV^2 is 179°, or eta =4.74 = ln tan theta/2, ~ E_e^2 !



Hadrons in bwd direction have low energy $E_h < E_e$ beam
in fwd direction hadrons carry energy up to E_p beam

→ Asymmetric energy coverage of LHeC detector. Fwd region: resembles hh conditions

LHeC Calorimeters



Complete coverage to +- 5 in (pseudo)rapidity

Central Region: 2012: LAr, 2020 Sci/Fe option.

Forward Region: dense, high energy jets of few TeV

H → bb and other reactions demand resolution of HFS

Backward Region: in DIS only deposits of E < E_e

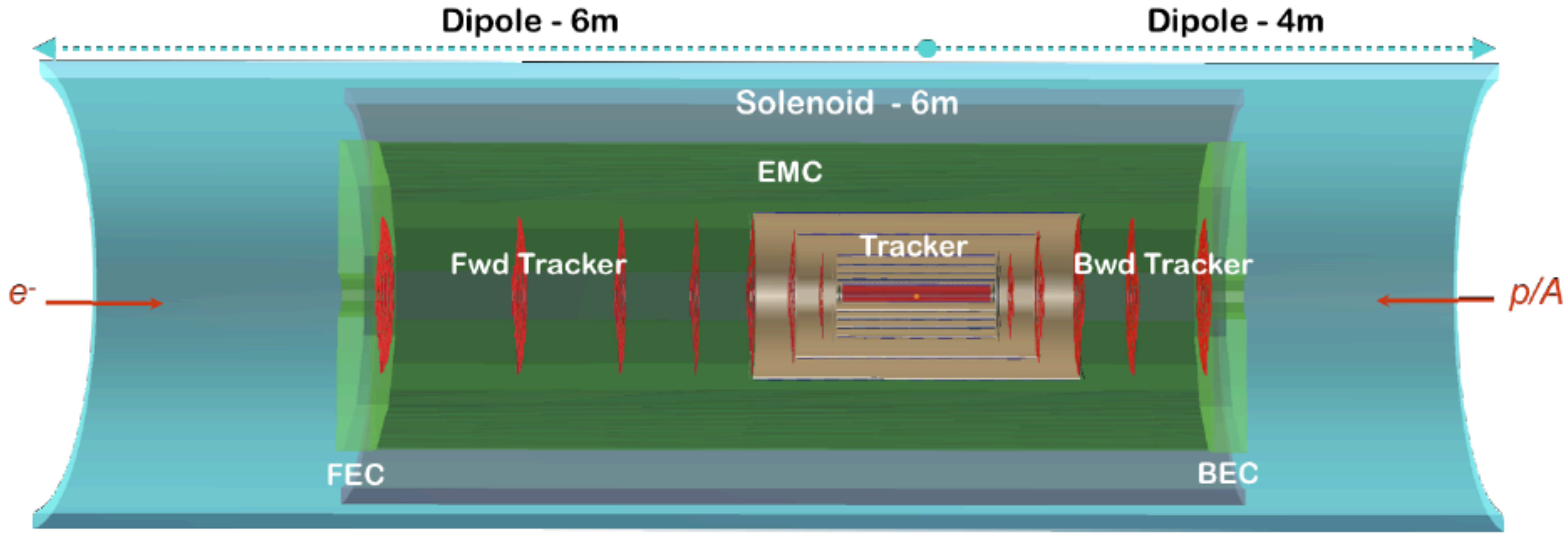
Barrel Calorimeters

Calo (LHeC)	EMC	HCAL		
	Barrel	Ecap Fwd	Barrel	Ecap Bwd
Readout, Absorber	Sci,Pb	Sci,Fe	Sci,Fe	Sci,Fe
Layers	38	58	45	50
Integral Absorber Thickness [cm]	16.7	134.0	119.0	115.5
η_{max}, η_{min}	2.4, −1.9	1.9, 1.0	1.6, −1.1	−1.5, −0.6
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	12.4/1.9	46.5/3.8	48.23/5.6	51.7/4.3
Λ_I / X_0	$X_0 = 30.2$	$\Lambda_I = 8.2$	$\Lambda_I = 8.3$	$\Lambda_I = 7.1$
Total area Sci [m^2]	1174	1403	3853	1209

Forward/Backward Calorimeters

Calo (LHeC)	FHC Plug Fwd	FEC Plug Fwd	BEC Plug Bwd	BHC Plug Bwd
Readout, Absorber	Si,W	Si,W	Si,Pb	Si,Cu
Layers	300	49	49	165
Integral Absorber Thickness [cm]	156.0	17.0	17.1	137.5
η_{max}, η_{min}	5.5, 1.9	5.1, 2.0	−1.4, −4.5	−1.4, −5.0
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	51.8/5.4	17.8/1.4	14.4/2.8	49.5/7.9
Λ_I / X_0	$\Lambda_I = 9.6$	$X_0 = 48.8$	$X_0 = 30.9$	$\Lambda_I = 9.2$
Total area Si [m^2]	1354	187	187	745

arXiv:2007.14491



Inner Tracker

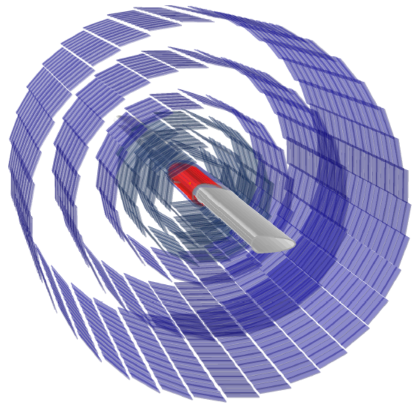
Rapidity to ~5

r_O = 60 cm

impact resolution 5-10 μm

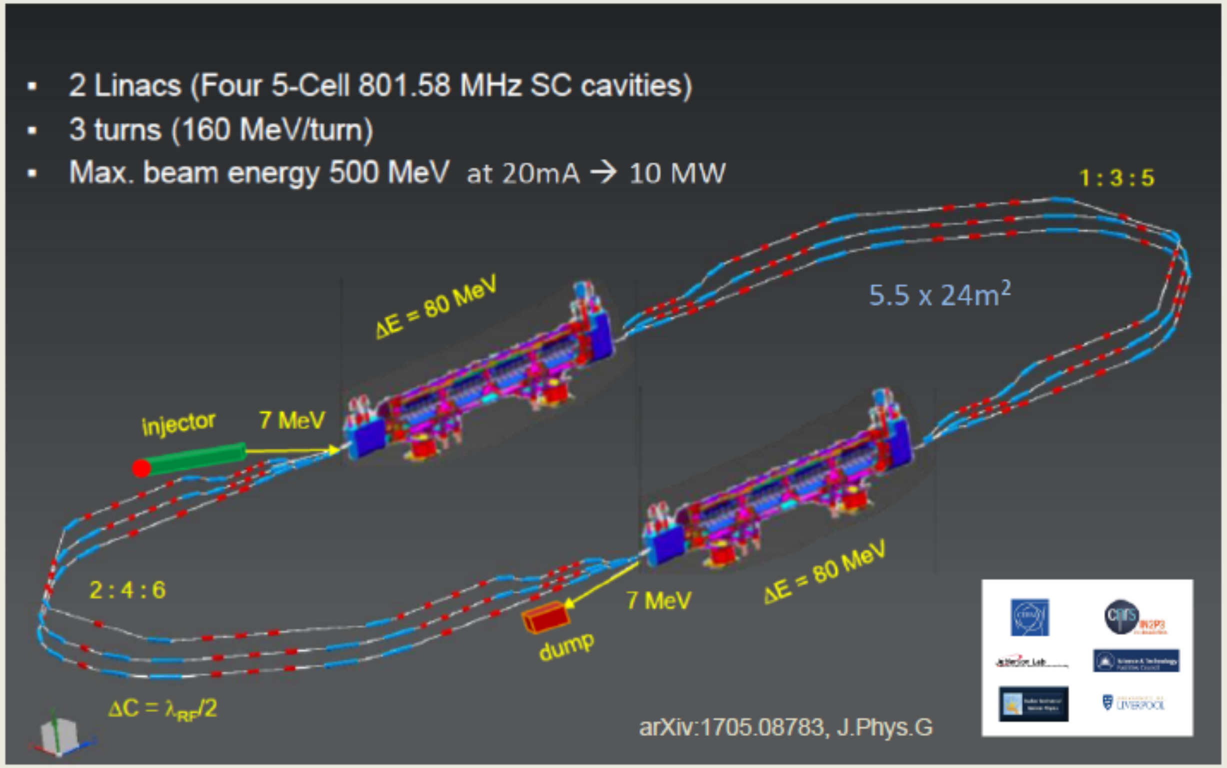
40.7 m^2 Si

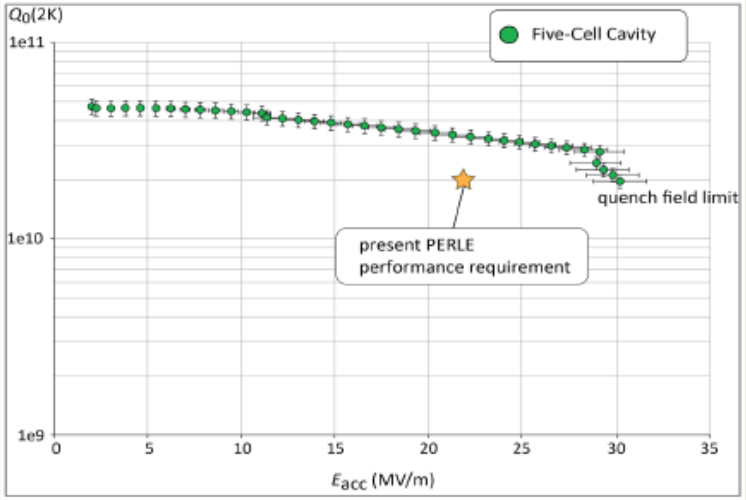
Tracker (LHeC)		Fwd Tracker			Bwd Tracker		Total
		pix	pix_{macro}	strip	pix_{macro}	strip	(incl. Tab. 12.1)
η_{max}, η_{min}		5.3,2.6	3.5,2.2	3.1,1.6	−4.6, −2.5	−2.9, −1.6	5.3,−4.6
Wheels		2	1	3	2	4	
Modules/Sensors		180	180	860	72	416	10736
Total Si area	[m^2]	0.8	0.9	4.6	0.4	1.8	40.7
Read-out-Channels	[10^6]	404.9	68.9	26.4	27.6	10.6	2934.2
$pitch^{r-\phi}$	[μm]	25	100	100	100	100	
$pitch^z$	[μm]	50	400	50k [2)]	400	10k [1)]	
Average X_0/Λ_I	[%]	6.7 / 2.1			6.1 / 1.9		
incl. beam pipe	[%]						40 / 25



PERLE

PERLE powerful energy recovery linac for experiments





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 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

SRF Cavities

ERLs, being somewhere between linacs and storage rings, have unique requirements for their RF systems and therefore need optimised designs to achieve the full potential of the concept. Proposed new machines operating with about 100 mA of current, either in single or multi-pass mode, need cavities with cell shapes optimised to avoid strong beam excitation of longitudinal higher order modes (HOMs), to minimise the power extracted from the beam, and strong HOM damping of all monopole and dipole HOMs to avoid beam break up instabilities.

Bob Rimmer

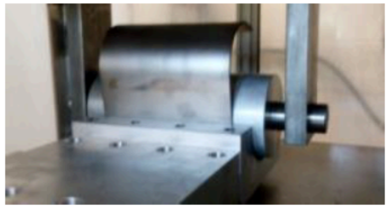
← f < 1 GHz

- We developed all tooling for cavity fabrication

Frank Marhauser et al. at Jlab (FM talk at PERLE workshop)

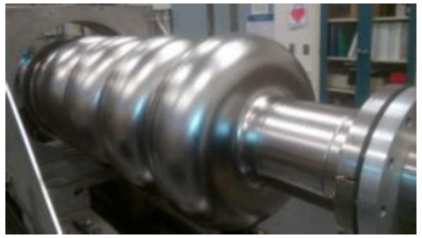

Fixture for female die with blank holder


Male die

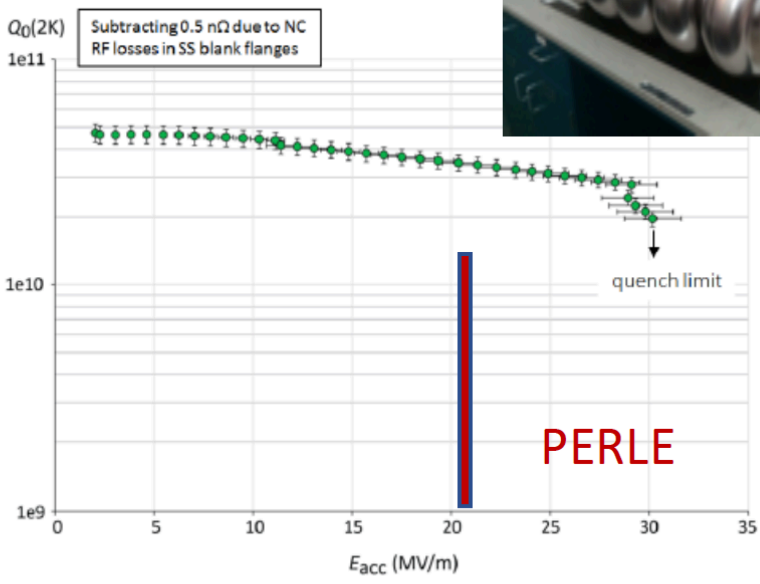

Beam tube rolling die

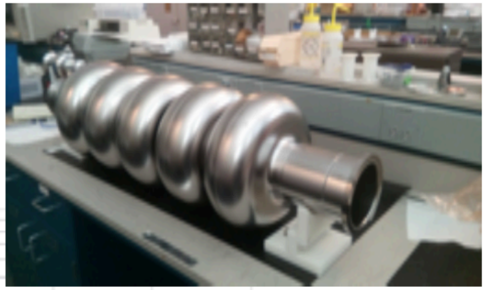

RF half cell/dumbbell measurements fixture


Five-cell cavity in EBW machine prepared for subsequent dumbbell and endgroup welding with both outside and inside welds in tilted position


Five-cell cavity on tuning bench

PERLE/LHeC (20 x 6 mA) and FCC-ee 802MHz Nb Cavity

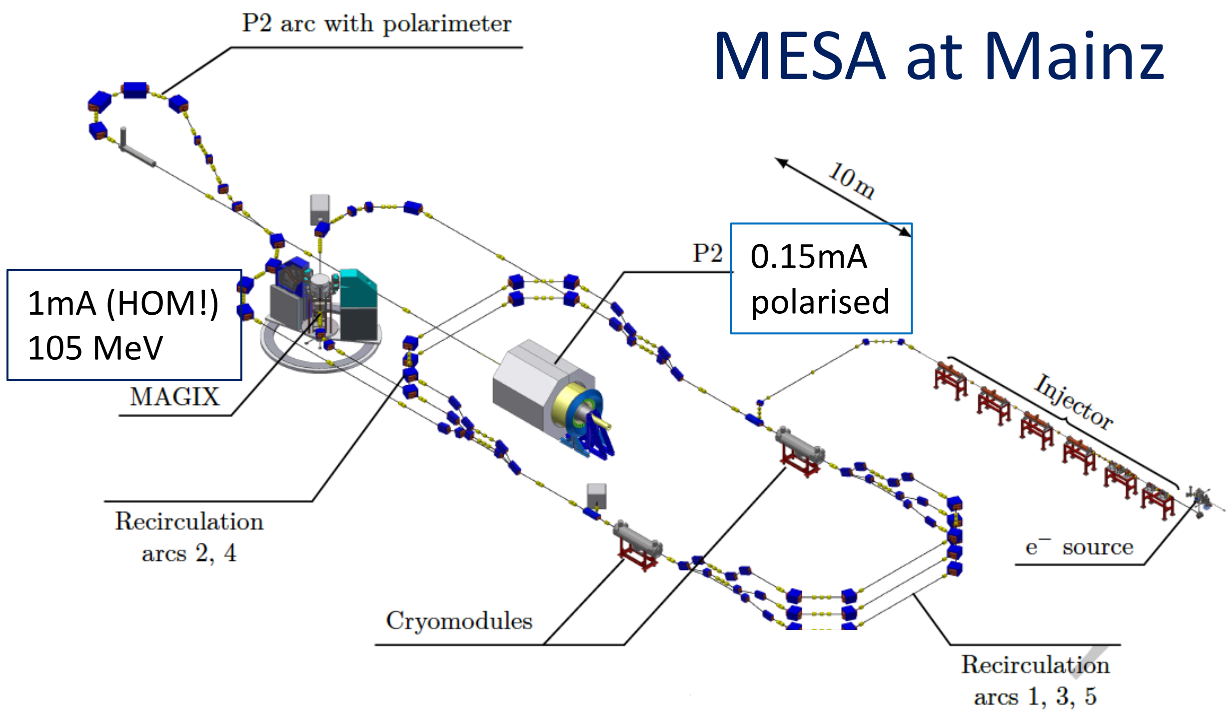




Low Energy Physics with ERLs

Three examples from Long Write-UP

MESA at Mainz

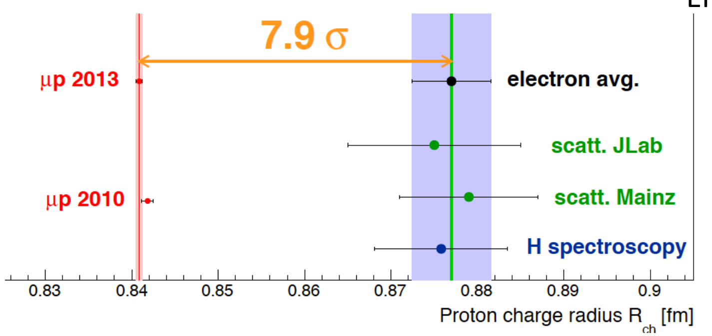


- 1.3 GHz, two ELBE type cryomodules, up to 3 passes
- New building, beam by 2024
- Polarimetry to 0.5% precision
- Current upgrade (unpolarised to 10 mA)

P2 – external target $\sin^2\Theta$, w/o energy recovery ("EB")
MAGIX – gas jet internal target, dark photons, p radius ("ER")

doi:10.18429/JACoW-ERL2019-MOCOXBS05

Proton Radius Puzzle [role for high intensity ERL, Jan Bernauer ERL Symposium 6/21



AMBER (CERN), MUSE (PSI), PRAD (Jlab), ULQ2 (Tohoku), Mainz .. ??

Nuclear Photonics [inverse γ's: L(PERLE) = O(10^3) L(ELI)]

Photonuclear reactions - from basic research to applications

A. Zilges[1], D. L. Balabanski[2], J. Isaak[3], N. Pietralla[3]

June 17, 2021, to appear

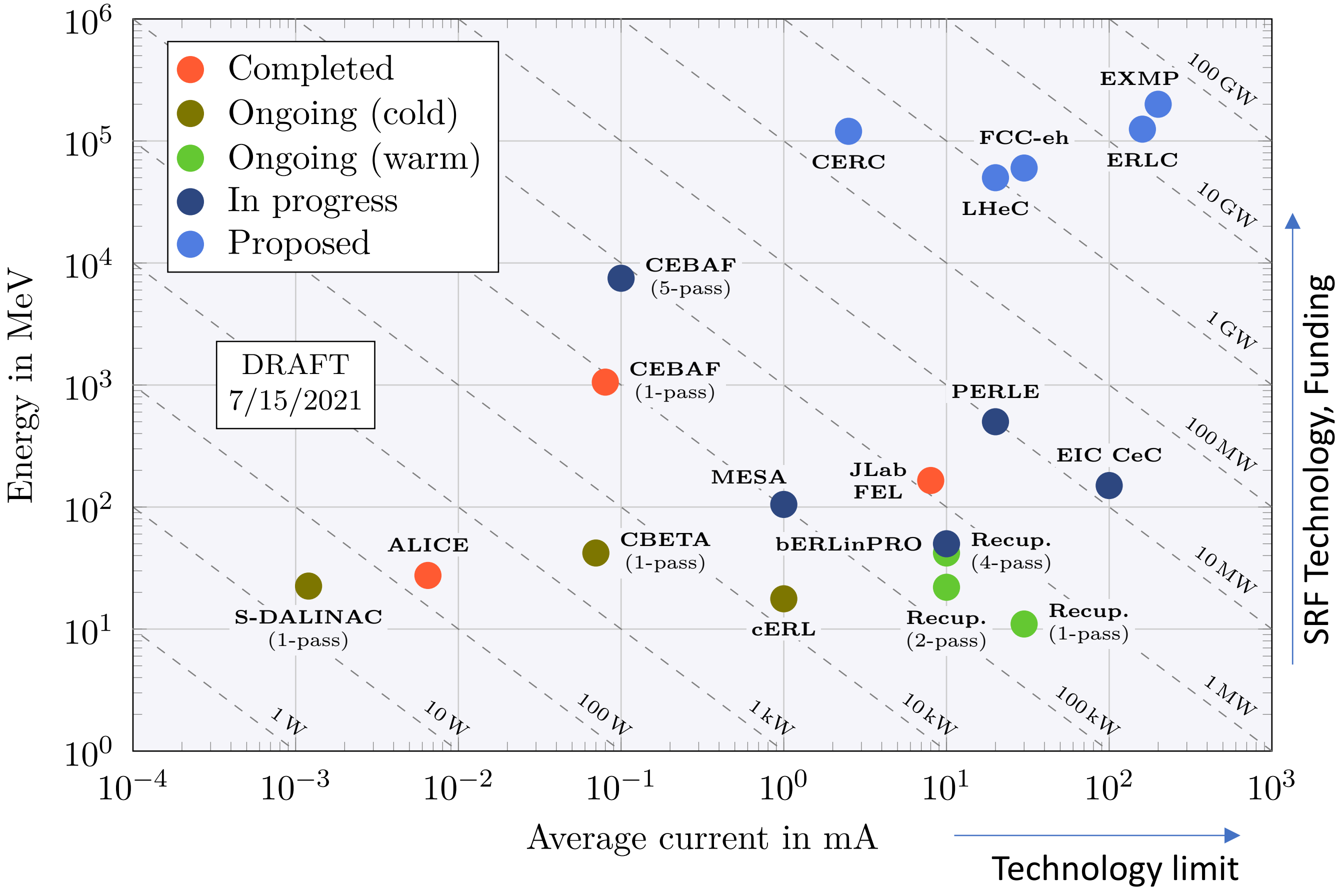
also: IGS: nuclear security, novel medical isotope research

Electrons Probing Exotic Nuclei

New field, pioneering: SCRIT@RIKEN, PRL 118, 2017
PERLE 500 MeV, 20mA, DESTIN project at Orsay
Outlook: eRI facility at GANIL (Caen, F) 200mA, ~2040

Facilities

Electron beam energy [MeV] vs current [mA]



Main goals of development and study:

High current sources, SRF to take ~100 mA load and high Q_0
CSR, HOMs, small emittance, efficient multi-turn operation

Current and coming activities [from an Interim ERL report 7/21]

– S-DALINAC (TU Darmstadt)
- establishment of a multi-turn SRF-ERL with high transmission (up to 70 MeV and 20 μA);
- quantification of phase-slippage effects in multi-cell-cavity-ERLs and counter-measures;
- characterisation of potential working points of individually-recirculating ERLs.

– Recuperator (BINP Novosibirsk)
- The current of the Novosibirsk ERL is now limited by the electron gun. A new RF gun was built and tested recently. It operates at a frequency of 90 MHz. An average beam current of more than 100 mA was achieved;
- Plans are to install this gun in the injector, while the existing electrostatic gun will be kept there. The RF gun beamline has already been manufactured and assembled on the test setup. The beam parameters were measured after the first bending magnet and at the beamline exit.

– CBETA (Cornell)
- improve transmission, which includes investigating better optics solutions;
- developing improved diagnostics for the decelerating passes;
- reducing halo by using a low halo cathode possibly in conjunction with beam collimation.

– bERLinPRO (HZB Berlin)
- Present activities are focused on the high-current SRF photoinjector and associated technologies. A dedicated diagnostic line capable of handling 10 mA is installed to characterise the beam;
- Following the upcoming booster installation, the beam can be transported through the merger to the high-power beam dump following the splitter section, allowing studies of emittance preservation, beam loss, and bunch length manipulation.

– cERL (KEK)
- Development of 10kW class powerful ERL -based EUV-FEL;
- Realisation of a 100% energy recovery operation with the beam current of 10mA at cERL and FEL light production experiment;
- Development of the irradiation line for industrial application (CNF, polymers and asphalt production) based on the CW cERL operation;
- Further, planning to develop a high efficiency high gradient Nb_3Sn acceleration cavity to realise a superconducting cryomodule based on the compact freezer.

– MESA
- Improving electron beam polarimetry to an accuracy $dP/P \leq 0.5\%$ in order to support the first physics measurements of electroweak observables, possibly including Hydro-Moeller polarimeter;
- Installing a second photo-source at the MESA injector with the potential to provide bunch charges > 10 pC with good beam quality;
- Improving the cavity HOM damping capabilities, for instance by coating of the HOM antennas by layers of high TC-material.