# LHeC: Status and Prospects

Large Hadron Electron Collider:
e:10-60 GeV, p: 1-7 TeV (LHC)

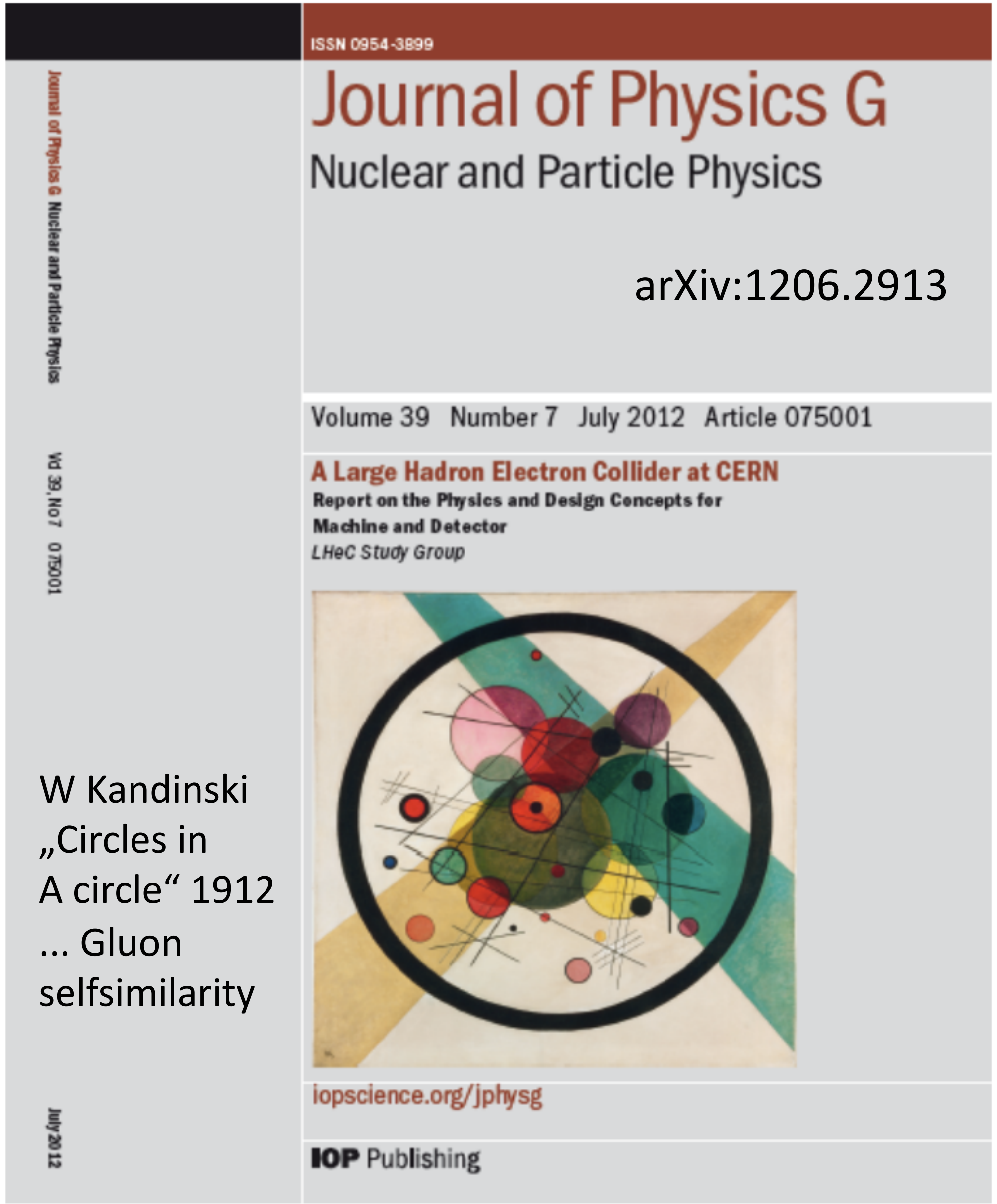
Overview
Physics
ERL
Machine
PERLE
Next Steps

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

Max Klein
University of Liverpool, ATLAS, H1
For the LHeC and PERLE Collaborations
EPS Conference, Ghent, 12.7.2019

further LHeC/FCC-eh talks at this conference:
D Britzger [eweak], M Cooper Sarkar [QCD/PDFs], U Klein [Higgs], C Schwanenberger [top/BSM], A Stasto [low x/eA]

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).
FCC Week at Brussels: Parallel Session [IR, cost, PERLE], summary by O Bruening




arXiv:1206.2913

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

CERN Referees

**Ring Ring Design**
Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)
**Linac Ring Design**
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)
**Energy Recovery**
Georg Hoffstaetter (Cornell)
Ilan Ben Zvi (BNL)
**Magnets**
Neil Marks (Cockcroft)
Martin Wilson (CERN)
**Interaction Region**
Daniel Pitzl (DESY)
Mike Sullivan (SLAC)
**Detector Design**
Philippe Bloch (CERN)
Roland Horisberger (PSI)
**Installation and Infrastructure**
Sylvain Weisz (CERN)
**New Physics at Large Scales**
Cristinel Diaconu (IN2P3 Marseille)
Gian Giudice (CERN)
Michelangelo Mangano (CERN)
**Precision QCD and Electroweak**
Guido Altarelli (Roma)
Vladimir Chekelian (MPI Munich)
Alan Martin (Durham)
**Physics at High Parton Densities**
Alfred Mueller (Columbia)
Raju Venugopalan (BNL)
Michele Arneodo (INFN Torino)

Published 600 pages conceptual design report (CDR) written by 200 authors from 60 Institutes and refereed by 24 world experts on physics, accelerator and detector, which CERN had invited.

## Conceptual Design Report

ep/eA with the LHC

[r]ECFA + CERN Mandate

← Result of a four year study and one year referee process.

Next generation ep [and first generation eA] collider following HERA (1992-2007) for extension of DIS energy frontier
60 GeV on 7 TeV [2.7 TeV Pb]
Lower energy: EICs, spin, 3D..

Then came Higgs, no SUSY ... from LHC, which worked admirably, and the decision for extending LHC to 2040

Choice for Linac Ring, new physics, tenfold higher Lumi..
→ **New Mandate by CERN**

# 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

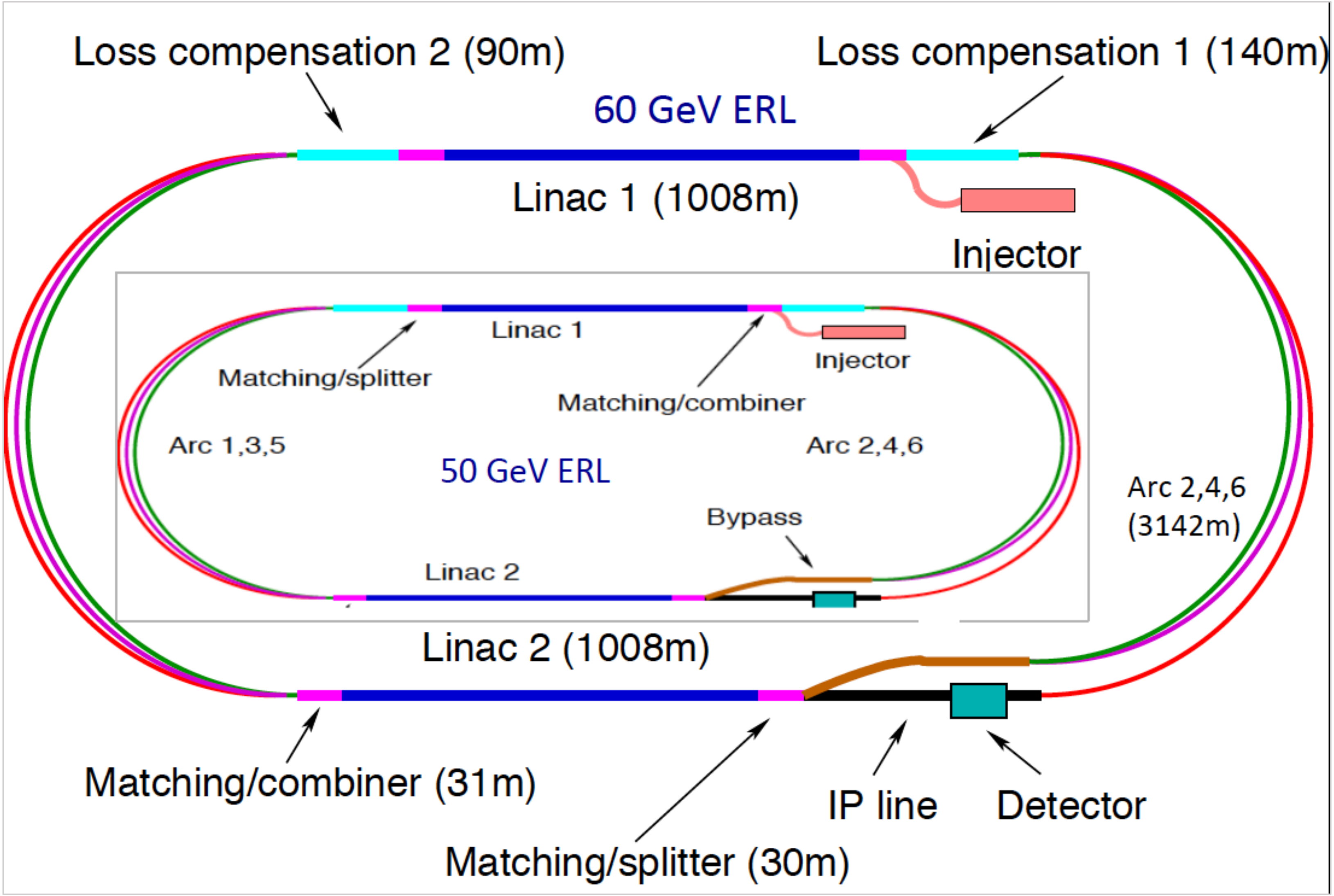
**5(12) are members of the FCC coordination team**

OB+MK: co-coordinate FCCeh

## Working Groups

**PDFs, QCD**
Fred Olness,
Claire Gwenlan
**Higgs**
Uta Klein,
Masahiro Kuze
**BSM**
Georges Azuelos,
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

# 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

Summary Papers submitted to the European Strategy 12/2018

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

LHeC

**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

CERN-ACC-NOTE-2018-0086 December 18, 2018

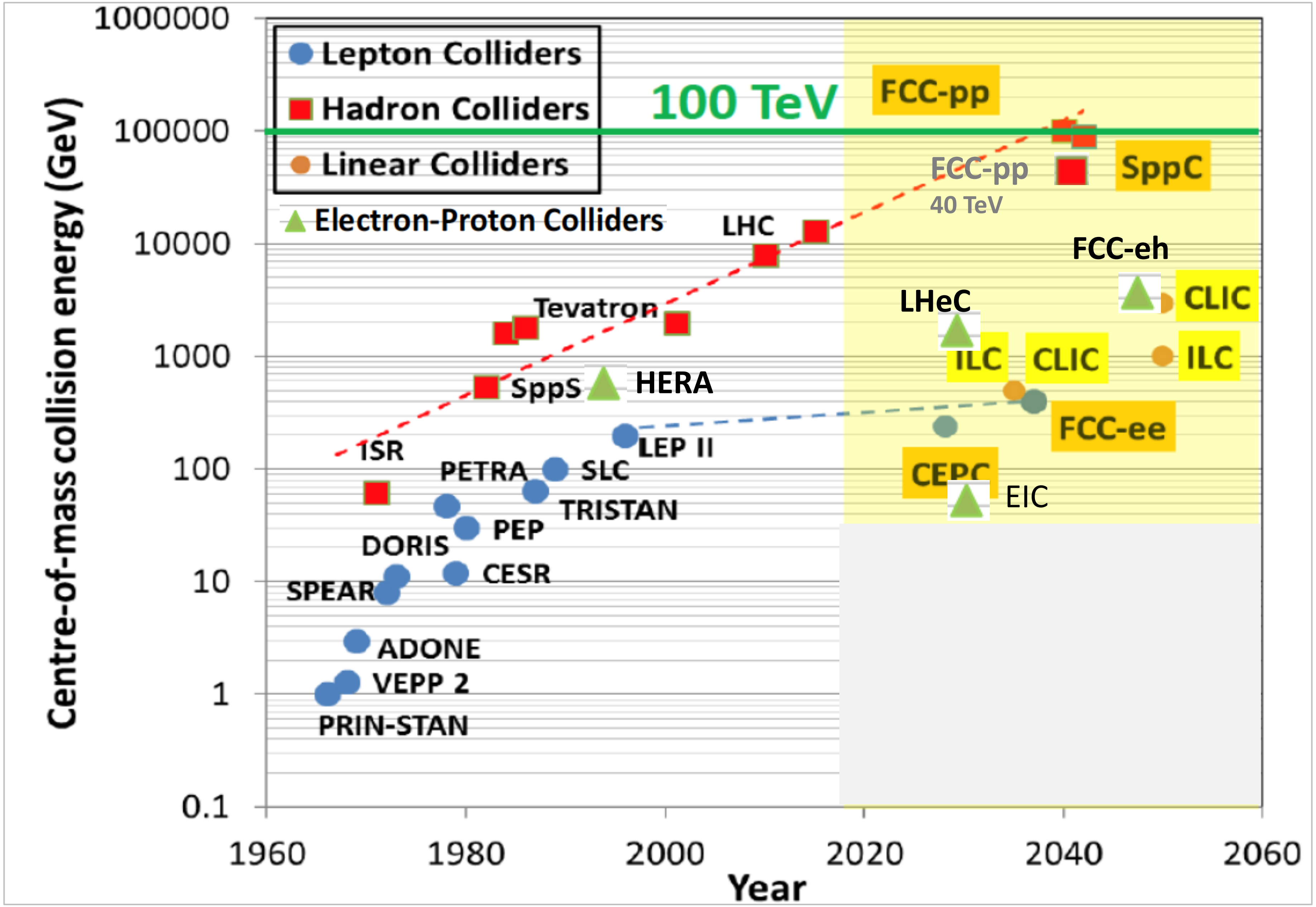
PERLE

**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



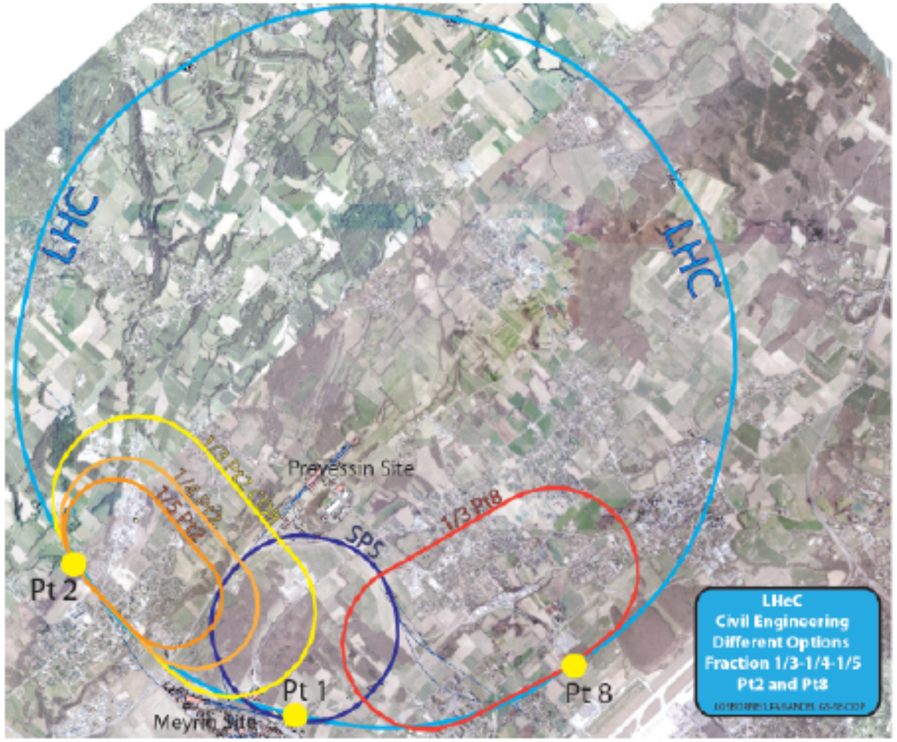

ep/A Parameters:

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)

# LHC (HL+HE) Footprint of ERL FCC



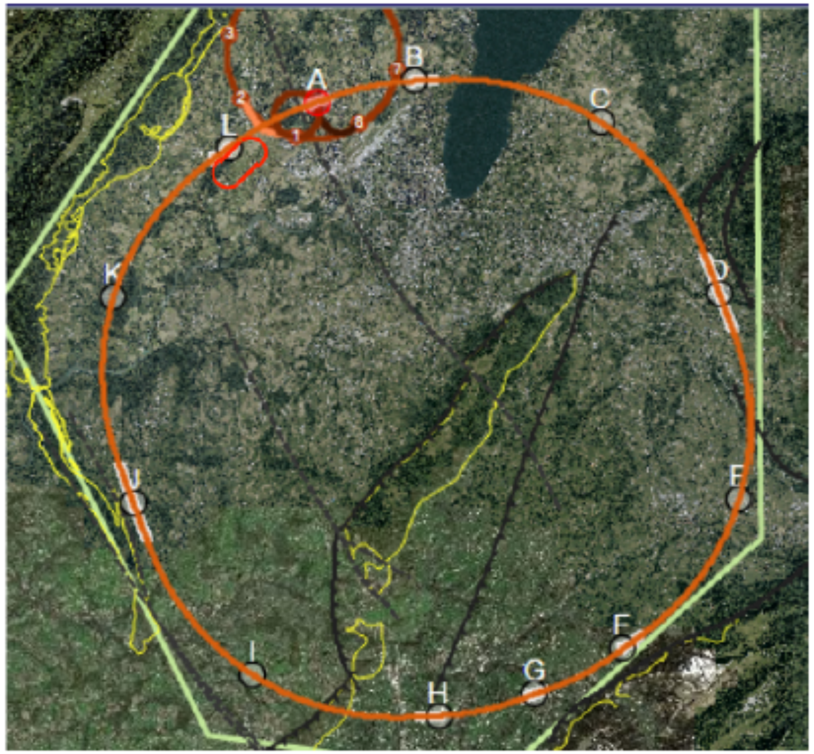
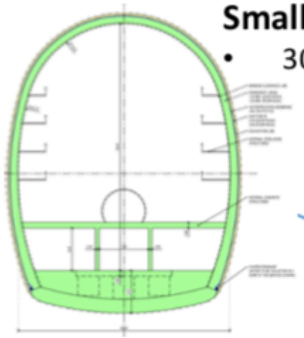



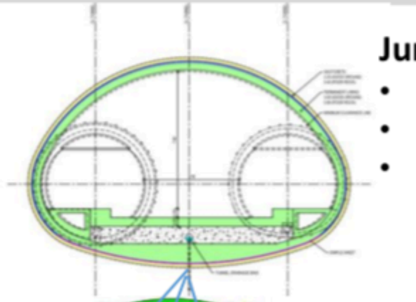

Figure 2: Possible locations of the ERL racetrack electron accelerator for the LHeC (left) and the FCC-he (right). The LHeC is shown to be tangential to Point 2 and Point 8. For Point 2 three sizes are drawn corresponding to a fraction of the LHC circumference of 1/3 (outer, default with $E_e = 60\,\mathrm{GeV}$), 1/4 (the size of the SPS, $E_e = 56\,\mathrm{GeV}$) and 1/5 (most inner track, $E_e = 52\,\mathrm{GeV}$). To the right one sees that the 8.9 km default racetrack configuration appears to be rather small as compared to the 100 km ring of the FCC. Present considerations suggest that Point L may be preferred as the position of the ERL, while two GPDs would be located at A and G.

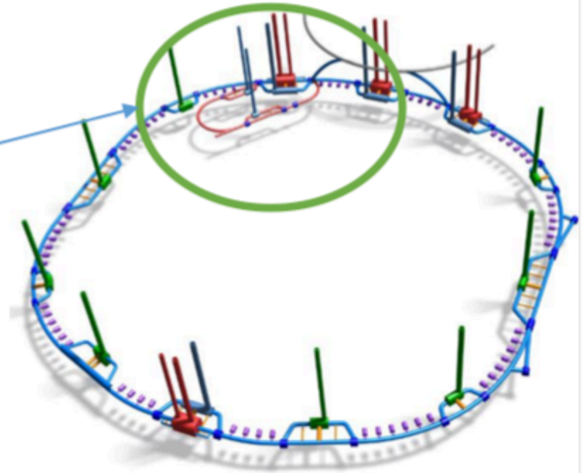
# Scope of FCC-eh Structures

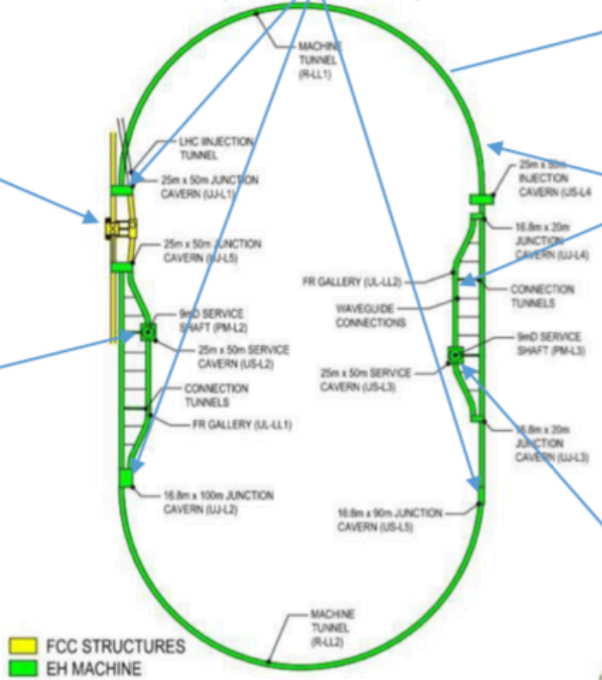
**Small Experimental Caverns**
- 30 m x 35 m x 66m



**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

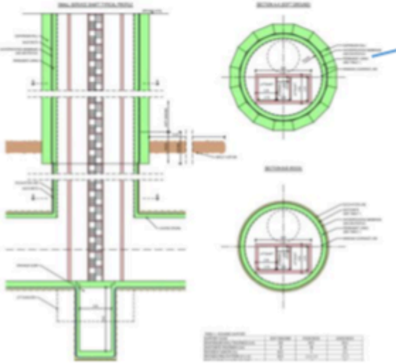


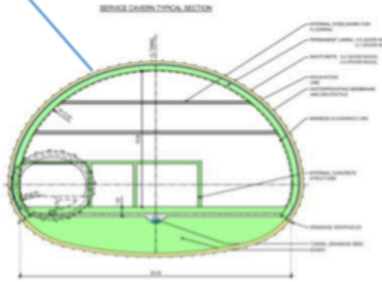





**Tunnels:**
- 9.091 km of 5.5m dia. machine tunnel.
- 2 x 1.04 km of 5.5m dia RF tunnel.

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

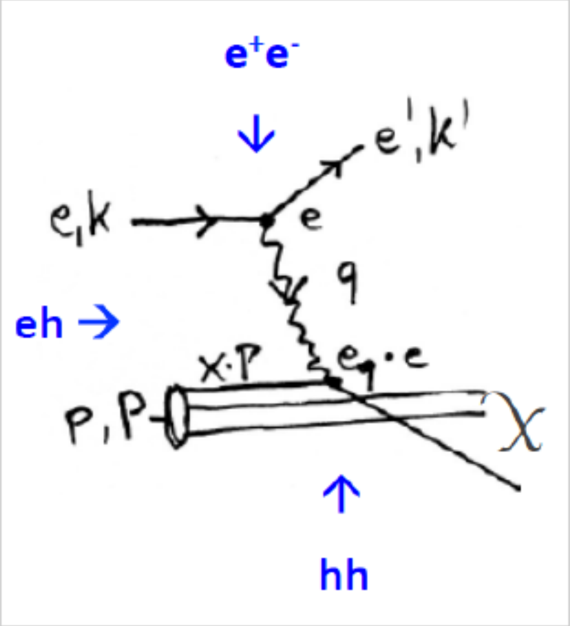


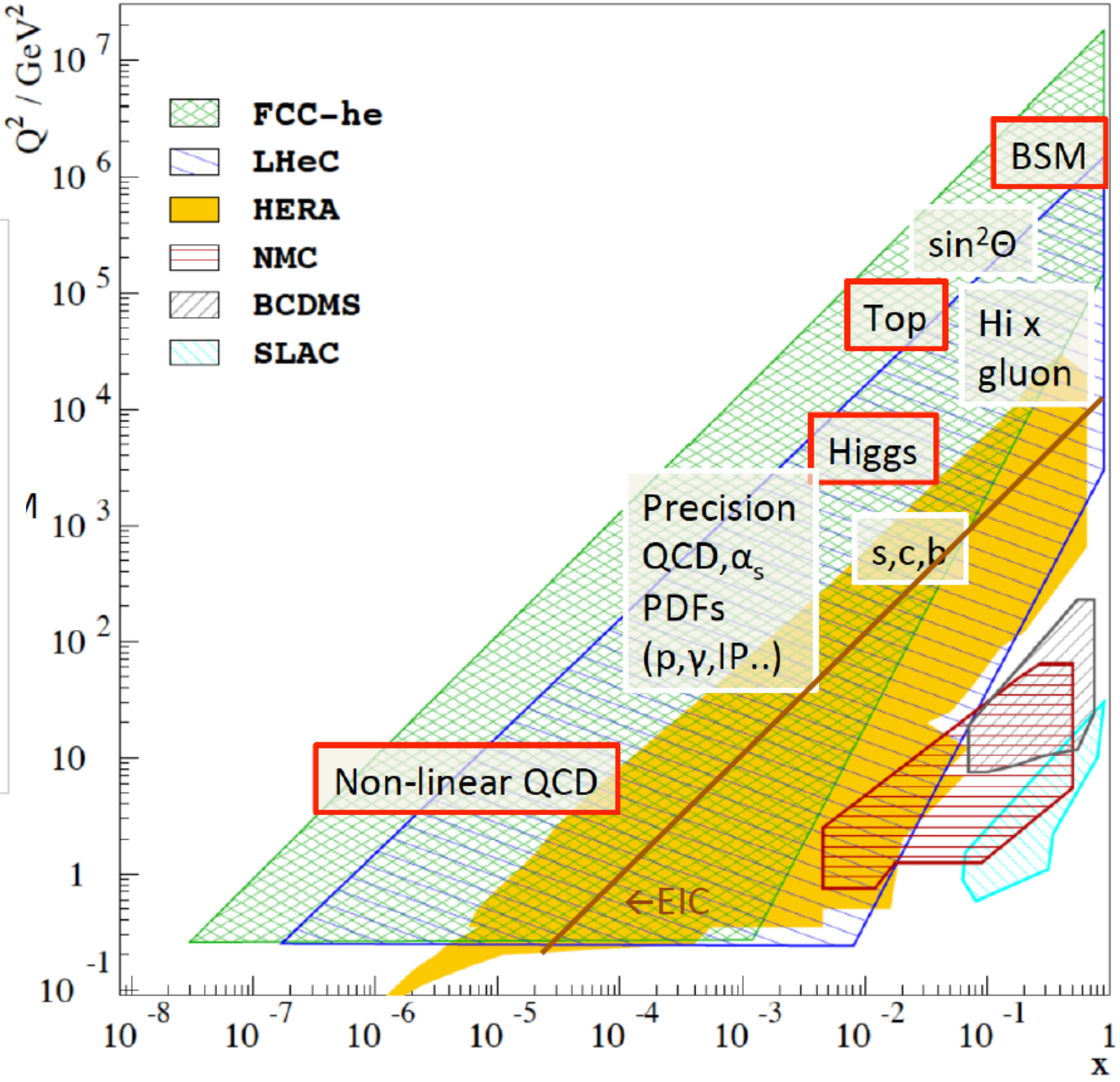


**Service Caverns**
- 25 m x 15 m x 50 m

# Physics with Energy Frontier DIS

Deep Inelastic Scattering




**Raison(s) d'etre of the LHeC**

Cleanest High Resolution Microscope: QCD Discovery

Empowering the LHC Search Programme

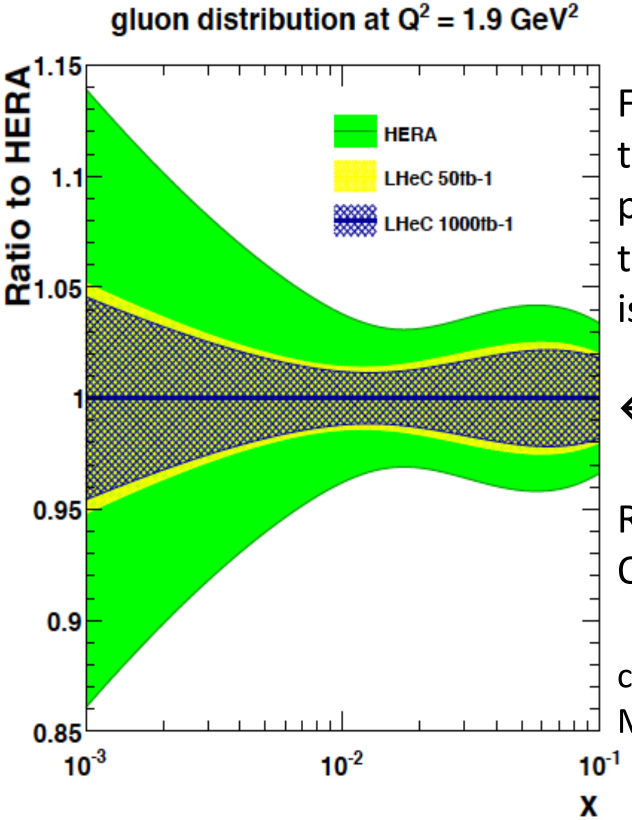
Transformation of LHC into high precision Higgs facility

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

A Unique Nuclear Physics Facility

# 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

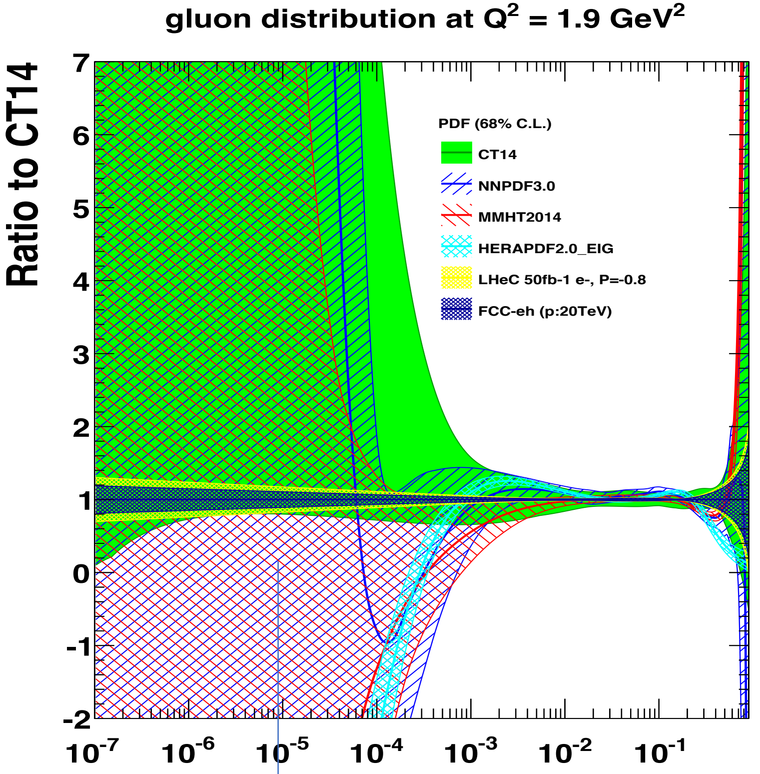
Figure 6: Uncertainty on the determination of the gluon distribution in the $x$ range relevant for Higgs measurements at the LHC, based on the combined HERA data (outer band, green) and for the LHeC with the full data set (inner band, blue) and from the first running period (yellow, around the inner 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?




FCC-eh ← LHeC ← EIC

← HERA

# High Precision Electroweak Physics with HL-LHC and LHeC

## ATLAS: Studies of HL-LHC+LHeC prospects

W Boson Mass: +-4 MeV (exp) +- 2 MeV (PDF)

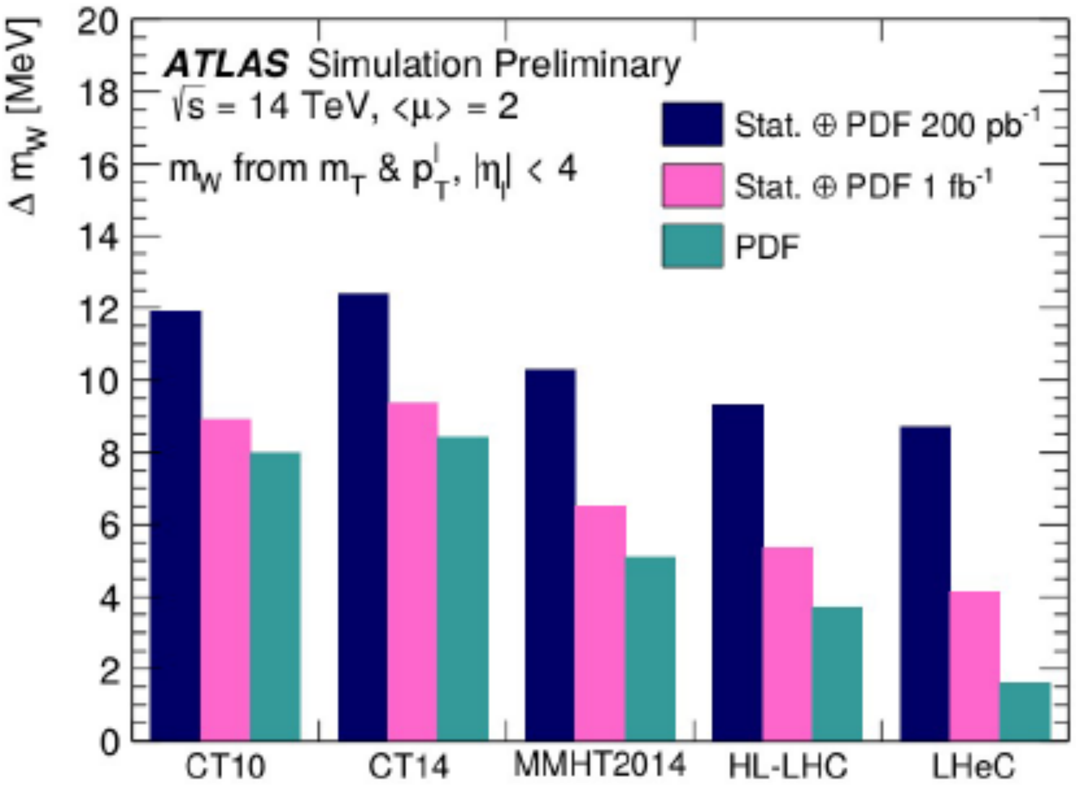
Weak mixing angle, PUB-2018-037: HL-LHC + LHeC
**0.23153 +- 0.00008** [LEP+SLD: +- …16]

Workshop on
Ultimate Precision at Hadron Colliders

Institut Pascal, Paris-Saclay

Nov. 25 – Dec. 6, 2019

Fabrice Balli, Louis Fayard, Marumi Kado,
Zhiqing Zhang, Maarten Boonekamp



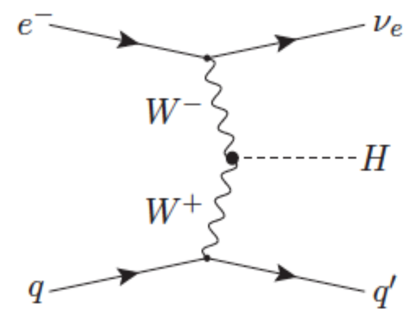
# Higgs in ep

Precision Higgs Physics at High-Energy Electron-Proton Colliders

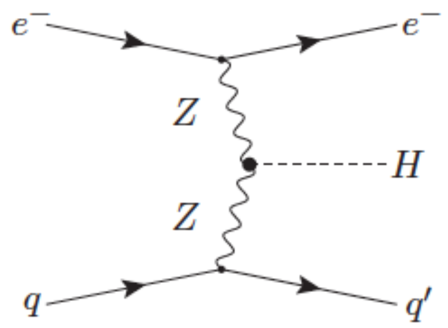
LHeC Higgs Study Group

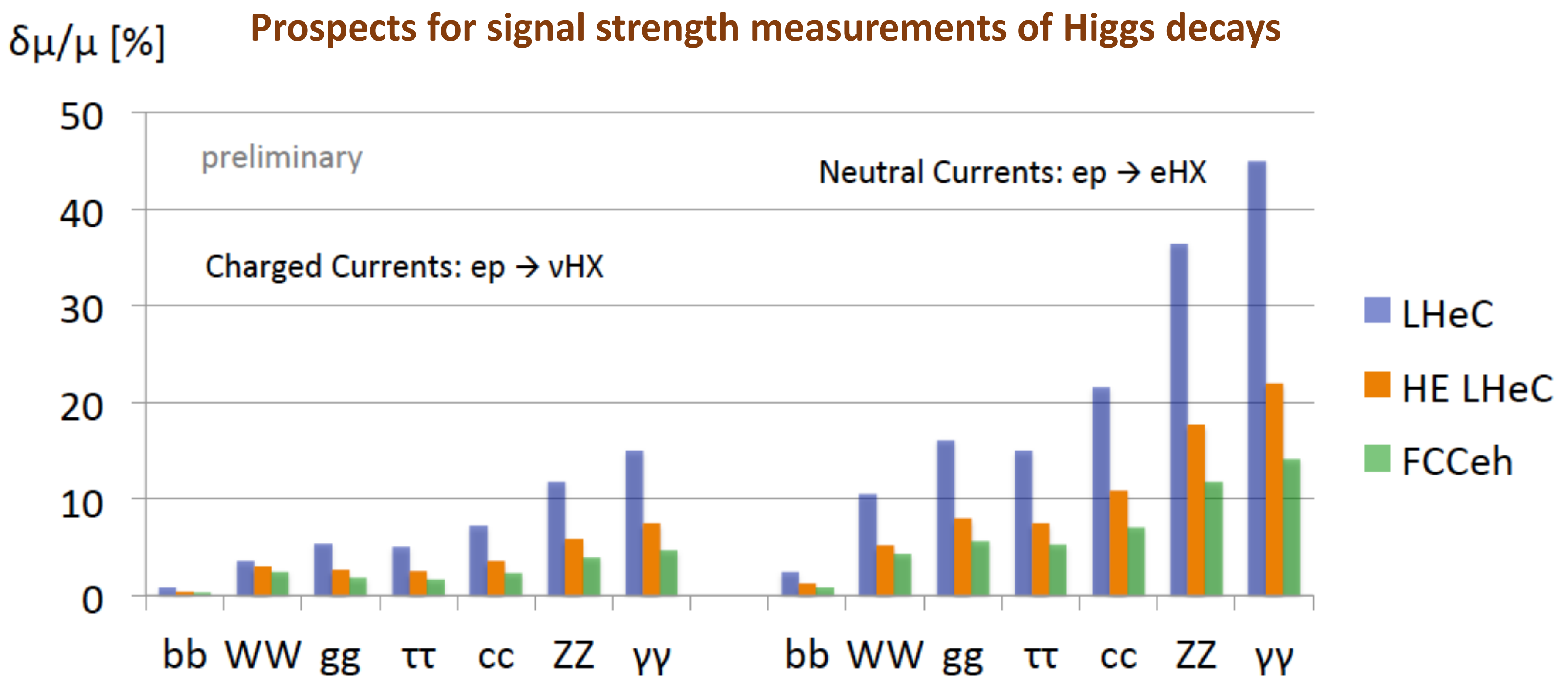
To be published

Charged Currents




Neutral Currents



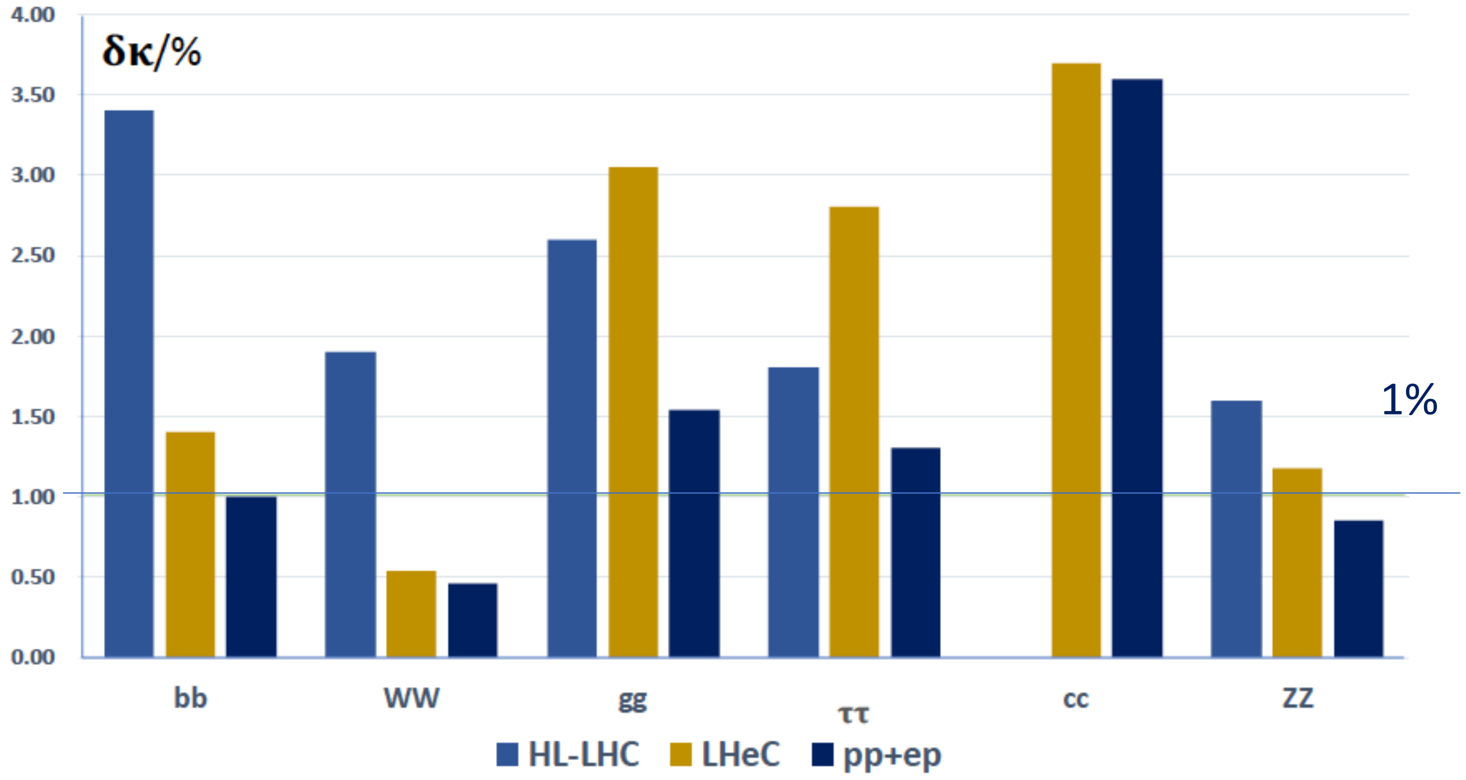




**LHeC:** $1ab^{-1}$, 7 TeV $E_p$
**HE LHeC**: $2ab^{-1}$, 13 TeV $E_p$
**FCC-eh:** $2ab^{-1}$, 50 TeV $E_p$

cf talk by U. Klein today at EPS

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

**Determination of SM Higgs couplings jointly 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 $E_e$

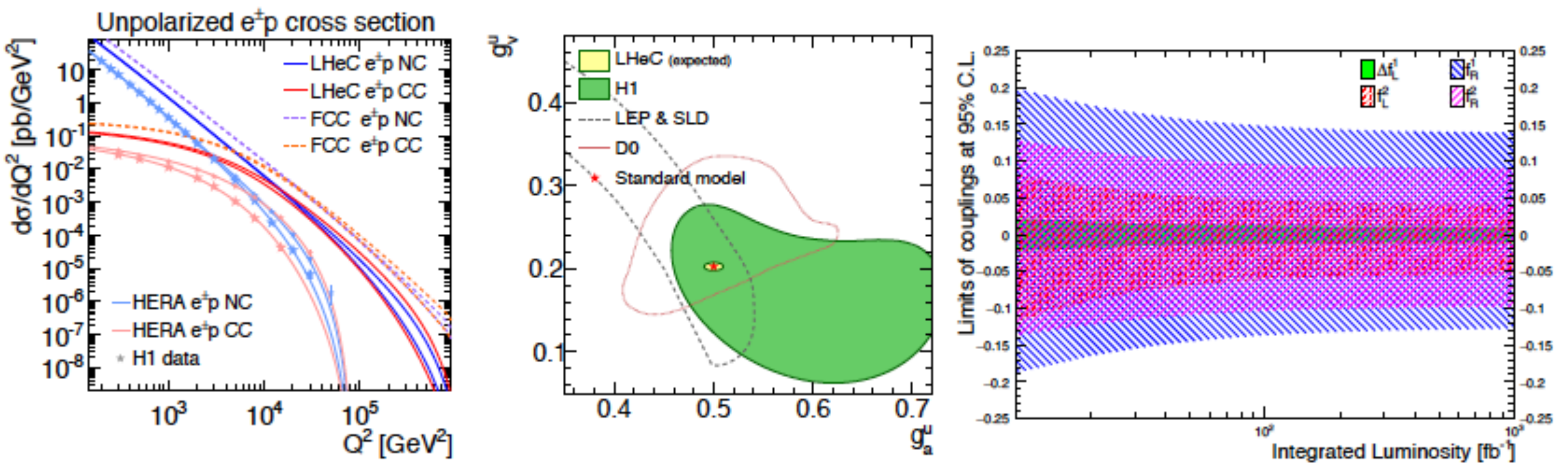
**Uncertainties on kappa**

| 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

Anomalous Wtb couplings



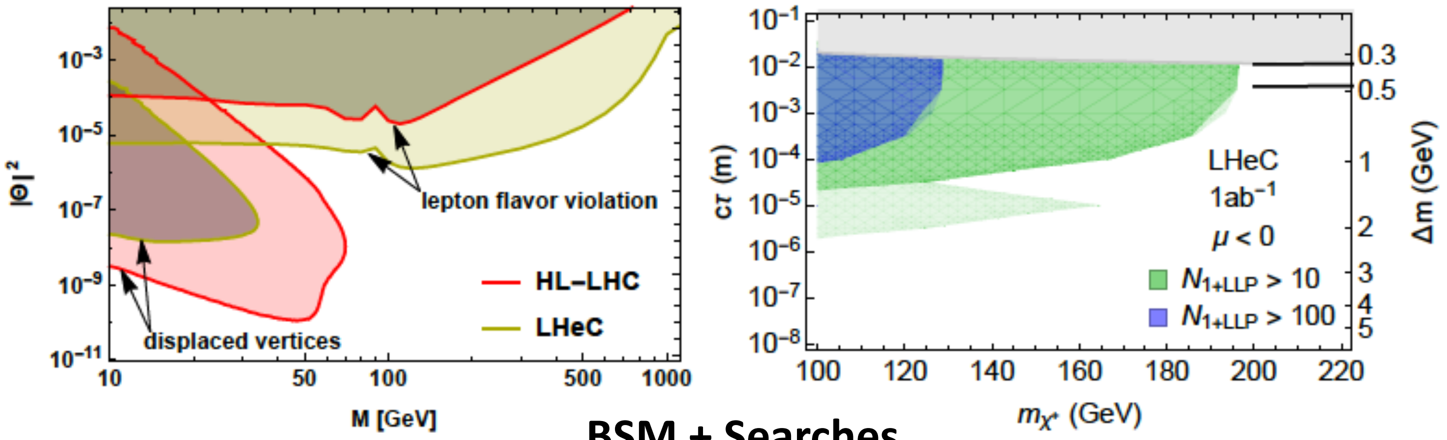

**Electroweak+Top Physics**

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].

cf today talks by
D Britzger and
C Schwanenberger

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 ($m_\chi$) - 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

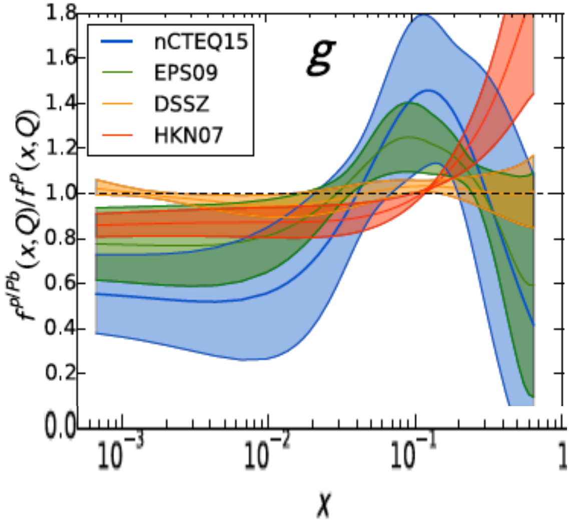
# Nuclear PDFs at LHeC/FCCeh

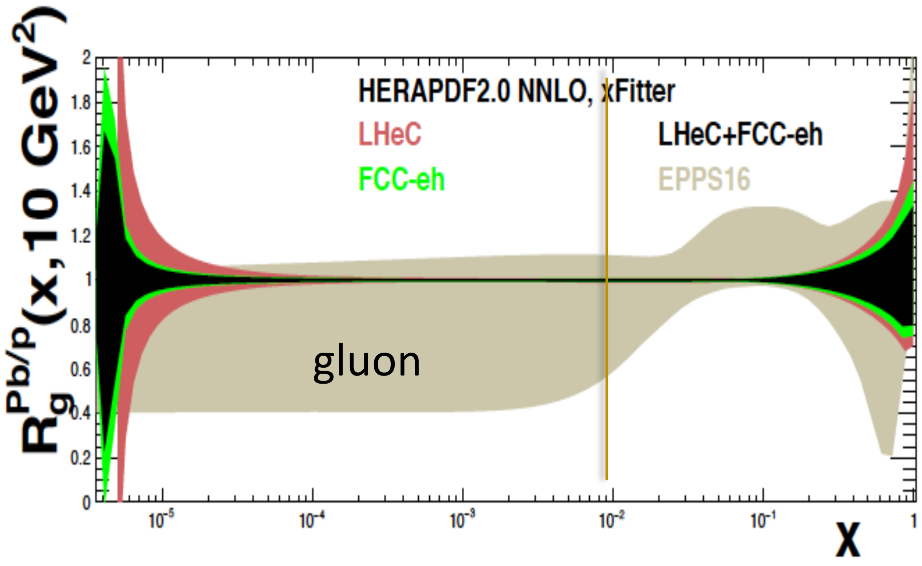
Unique nuclear/HI physics programme
Extension of fixed target range by $10^{3\text{-}4}$
QCD of QGP, de-confinement, saturation..
nPDFs independent of p PDFs

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

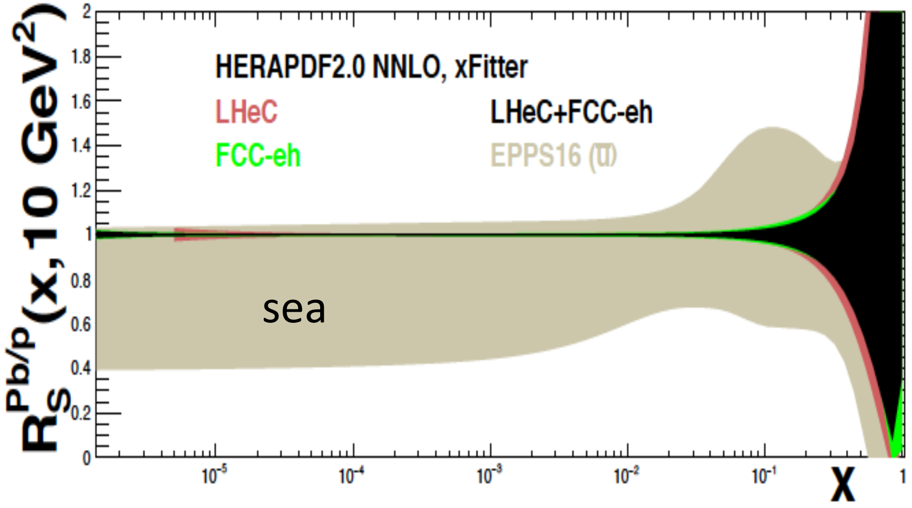
present status → on xg Pb/p

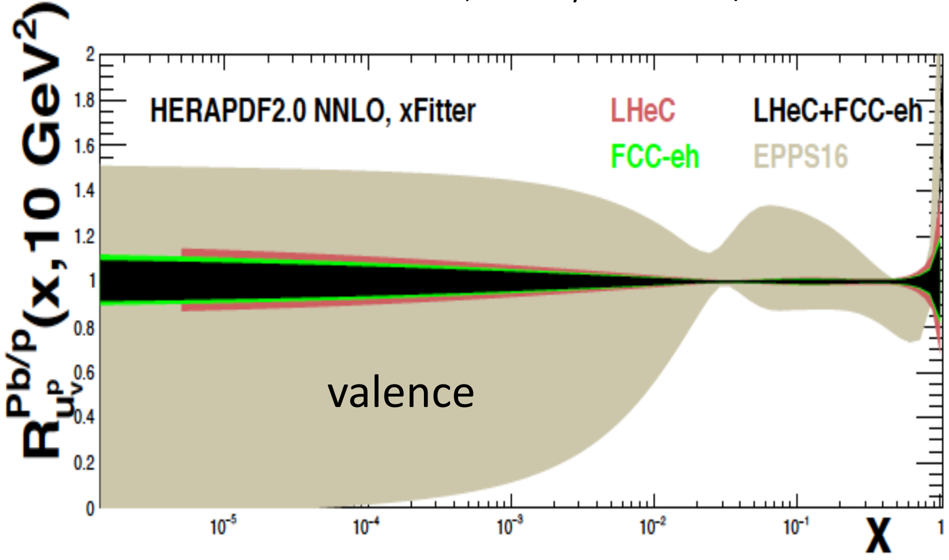
1509.00792




N Armesto, FCC Physics Week 1/2018



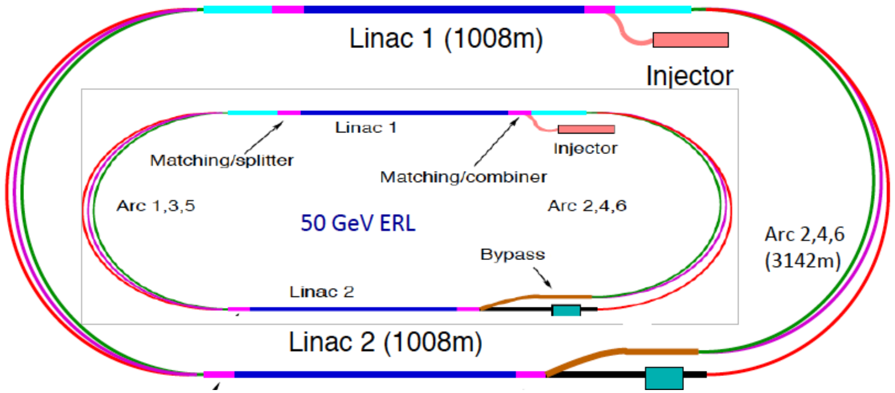




cf talk by
A Stasto today

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

# Energy Recovery

today and tomorrow

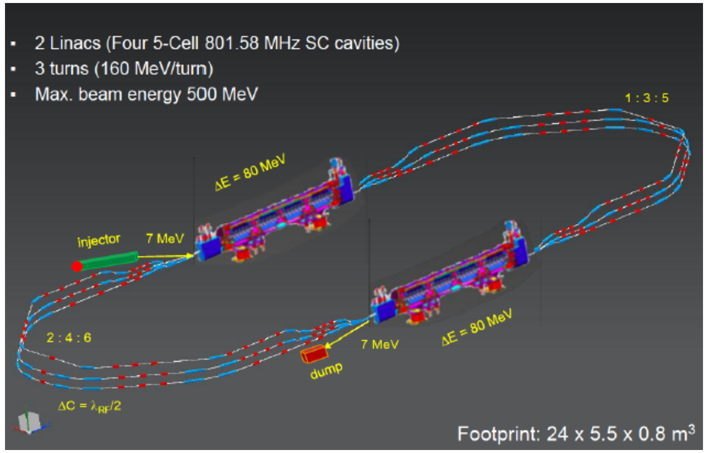



**LHeC:** 1 TeV ep collider with $10^{34}$ luminosity: P/10! Dump at injection.
Possible injector to FCC-ee in recirculating mode [O.Bruening]

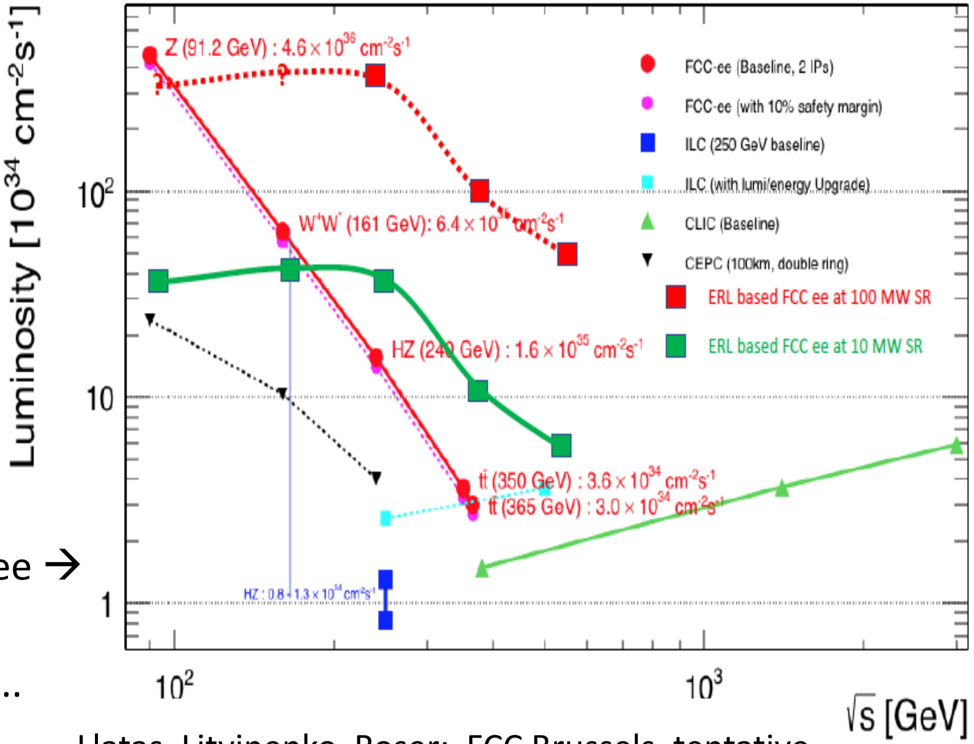
**FCC-ee**

- 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**




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

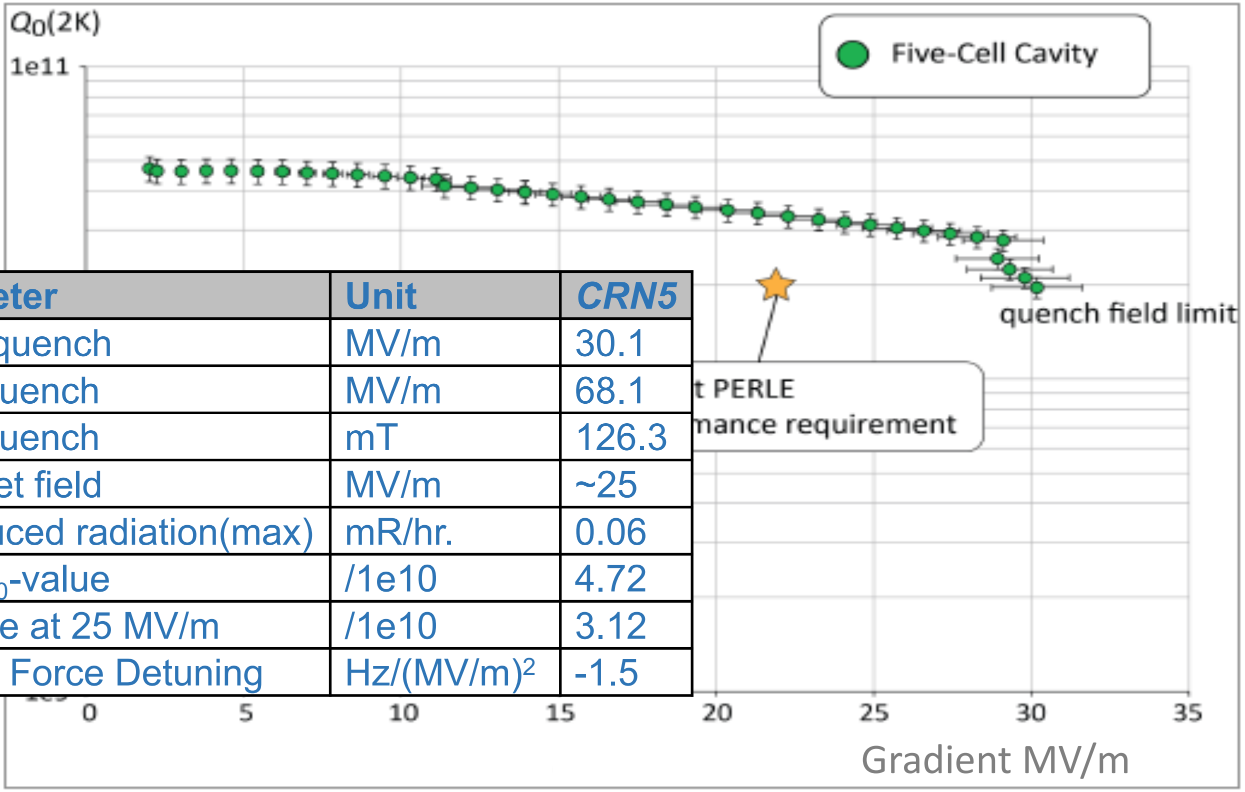
**ERLs** in: Berlin, BINP, Cornell, Daresbury, Darmstadt, Jlab, KEK, Mainz..

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

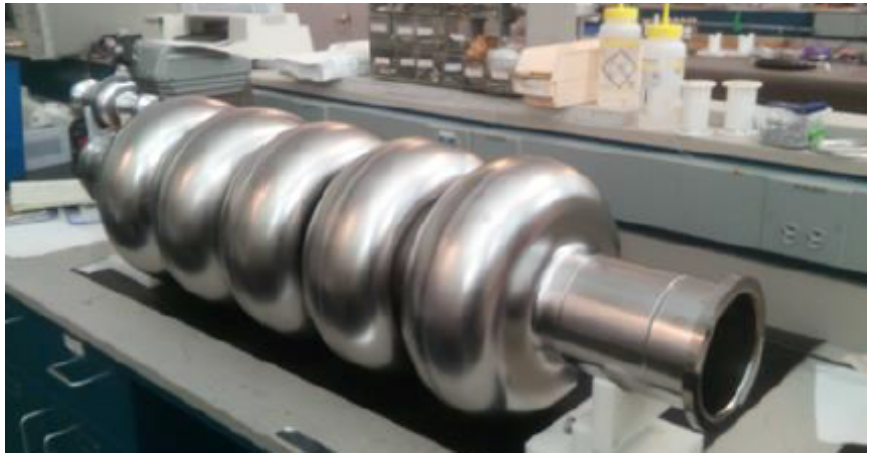
Llatas, Litvinenko, Roser: FCC Brussels. tentative

# Recent ERL achievements

$Q_0$



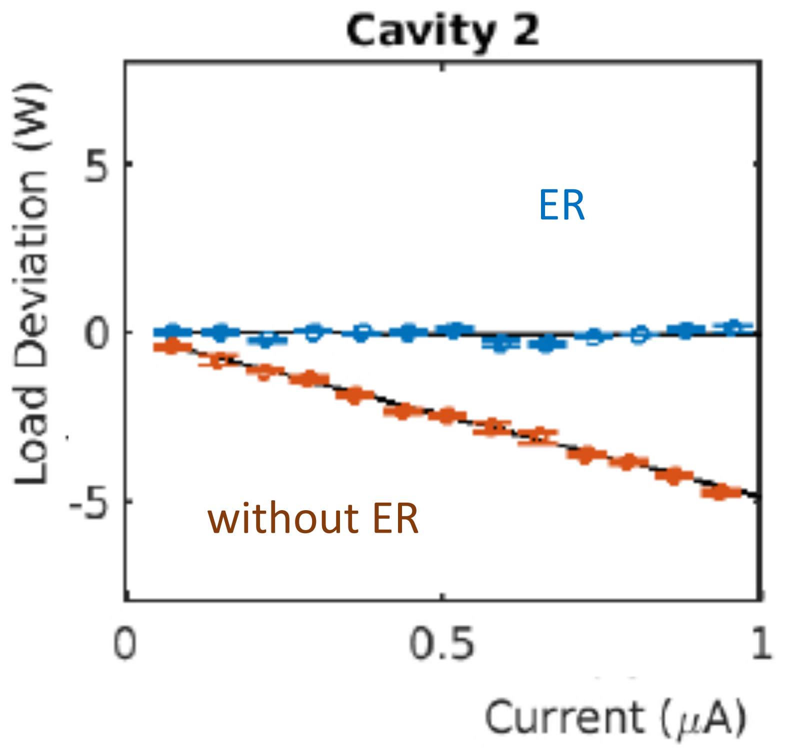

| Parameter | Unit | *CRN5* |
|---|---|---|
| $E_{acc}$ at quench | MV/m | 30.1 |
| $E_{pk}$ at quench | MV/m | 68.1 |
| $B_{pk}$ at quench | mT | 126.3 |
| FE onset field | MV/m | ~25 |
| FE-induced radiation(max) | mR/hr. | 0.06 |
| Max. $Q_0$-value | /1e10 | 4.72 |
| $Q_0$-value at 25 MV/m | /1e10 | 3.12 |
| Lorentz Force Detuning | Hz/(MV/m)$^2$ | -1.5 |



F Marhauser et al.
Jlab, CERN

**First 5 cell Niobium Cavity, 802 MHz**

High $Q_0$, high stability




**Demonstration of energy recovery in new cBETA facility at Cornell, with BNL**

G Hoffstaetter et al 19.6.2019

# Project staging strategy:

The PERLE configuration entails the possibility to construct PERLE in stages. We propose in the following two main phases to attend the final configuration.

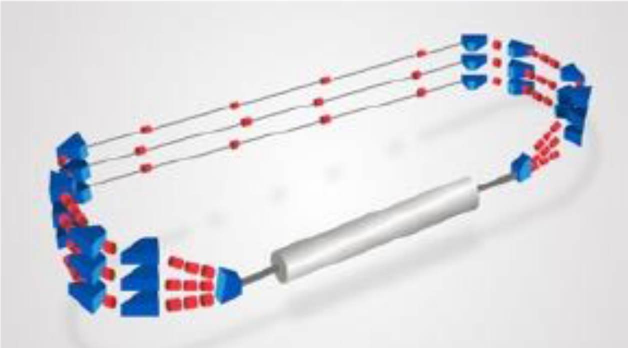
Phase 1: Installation of a single cryomodule in the first straight and three beam lines in the second (consideration motivated by the SPL cryomodule availability)

→ To allow a rather rapid realisation of a 250 MeV machine.

→ To test with beam the various SRF components.

→ To prove the multi-turn ERL operation.

→ to gain essential operation experience.



PERLE Phase 1 layout

Phase 2 : Realisation of PERLE at its design parameters as a 10MW machine:

→ Upgrade of the e- gun

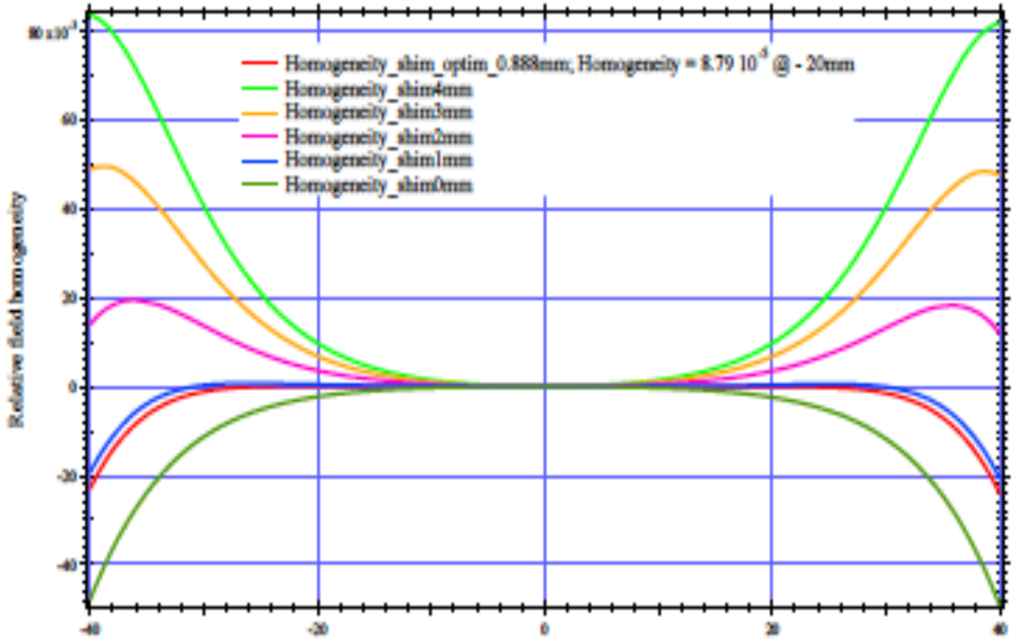
→ Installation of the 2nd Spreader and recombinar

→ Installation of the second cryomodule in the second straight.

PERLE Phase 2 layout

# Recent PERLE Progress

Field homogeneity 8 $10^{-2}$




Bending magnets: field homogeneity with optimized shim of 8.8 $10^{-5}$ at ± 20 mm (GFR), better than expected (5 $10^{-4}$).

LAL/IPNO and BINP-Novosibirsk applied for the H2020 European program (CRIMLINplus) and ask for fund for dipole design & prototyping and for a post-doc position.

Transfer of ALICE (Daresbury) gun + equipment to LAL (5/19)

Hiring of personell at Orsay

Design of source/booster/injector at Daresbury/Liverpool

Encouraging radiation protection survey at Orsay

...

arrival of the ALICE gun in the PERLE hall 10.5.19

cf Walid Kaabi 27.6. in FCCeh

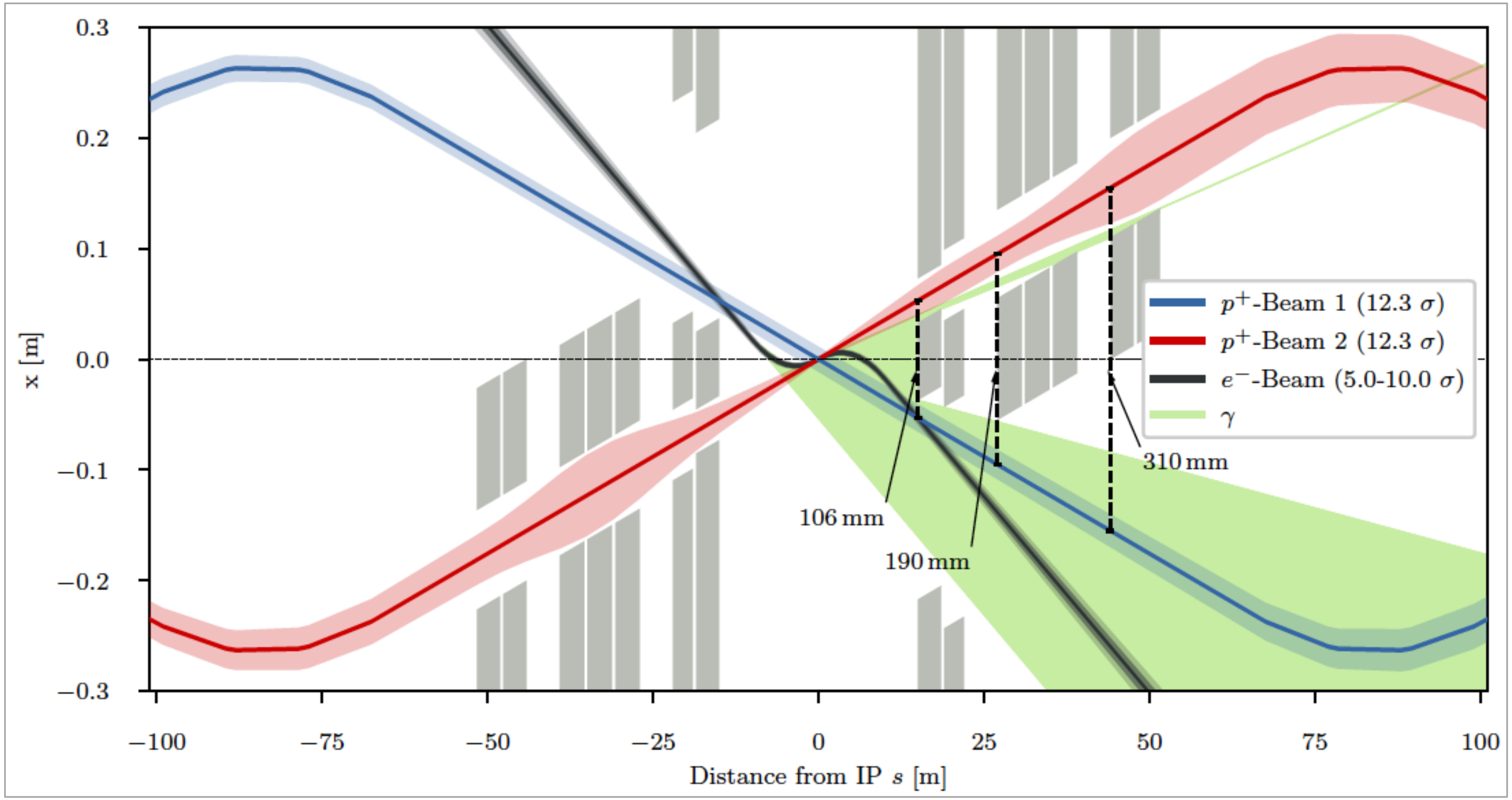
# **Magnet and RF Components of LHeC** ERL at 50 GeV, from full lattice simulation study [A.Bogacz]

| Section | Horizontal Dipoles | | | Vertical Dipoles | | | Quadrupoles | | | RF Cavities | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Number* | *Field* | *Mag. Length* | *Number* | *Field* | *Mag. Length* | *Number* | *Gradient* | *Mag. Length* | *Number* | *Frequency/Cell* | *RF Gradient* |
| LINAC 1 | | | | | | | 29 | 1.9 | 1.0 | 448 | 802/5 | 20.0 |
| LINAC 2 | | | | | | | 29 | 1.9 | 1.0 | 448 | 802/5 | 20.0 |
| Arc 1 | 344 | 0.039 | 4.0 | 8 | 0.51 | 4.0 | 158 | 9.3 | 1.0 | | | |
| Arc 2 | 294 | 0.077 | 4.0 | 6 | 0.74 | 4.0 | 138 | 17.7 | 1.0 | | | |
| Arc 3 | 344 | 0.123 | 4.0 | 6 | 0.92 | 4.0 | 158 | 24.3 | 1.0 | 6 | 1604/9 | 30.0 |
| Arc 4 | 294 | 0.181 | 4.0 | 6 | 1.23 | 4.0 | 138 | 27.2 | 1.0 | 6 | 1604/9 | 30.0 |
| Arc 5 | 344 | 0.189 | 4.0 | 4 | 0.77 | 4.0 | 156 | 33.9 | 1.0 | 18 | 1604/9 | 30.0 |
| Arc 6 | 344 | 0.226 | 4.0 | 4 | 1.49 | 4.0 | 156 | 40.8 | 1.0 | 30 | 1604/9 | 30.0 |
| **Total** | **1964** | | | **34** | | | **962** | | | **956** | | |

*Units: meter (m), Tesla (T), T/m, MHz, MV/m*

**Cost estimate for 60 / 50 / 30** [phase 1 of 50] **GeV $E_e$: 1.7 / 1.3/ 1.0 BSF. O Bruening: CERN-ACC-Note (2108).**
Conservative: in doubt took the conservative value. Resulting estimated for ILC 30% higher than default.
802 MHz four 5-cell cavity cryomodule: 112/linac: industrialisation will determine eventual cost. CE offer: 265 MSF

# Interaction Region




Roman Martin

Recent updates presented at FCC week in Brussels

Emilia Cruz, Kevin Andre

tentative:

| | | LHeC | HERA |
|---|---|---|---|
| $E_{crit}$ | keV | 270 | 150 |
| Synrad Power | kW | 30 | 28 |

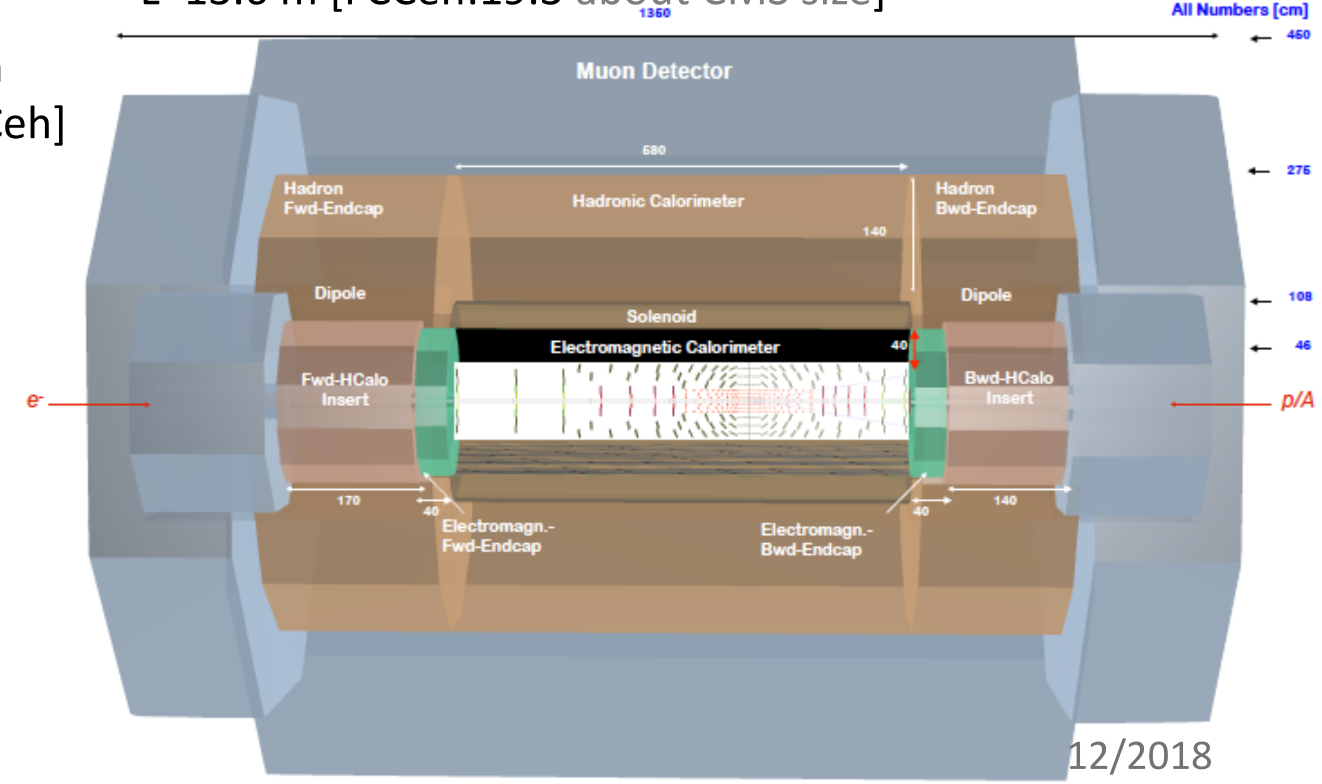
3 beams, needs head-on collisions. Design of Q1 ongoing and crucial for aperture and load

Study for LHeC and FCC-eh; reduction of synchrotron load with magnet alterations and 50 GeV
K Andre, E Cruz, B Holzer, R Martin, R Tomas, with B Parker, S Russenschuck. Work in progress

# LHeC Detector

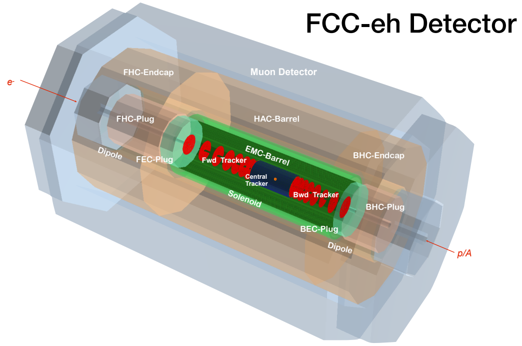
L=13.6 m [FCCeh:19.3 about CMS size]

R=4.6 m
[6.2 FCCeh]

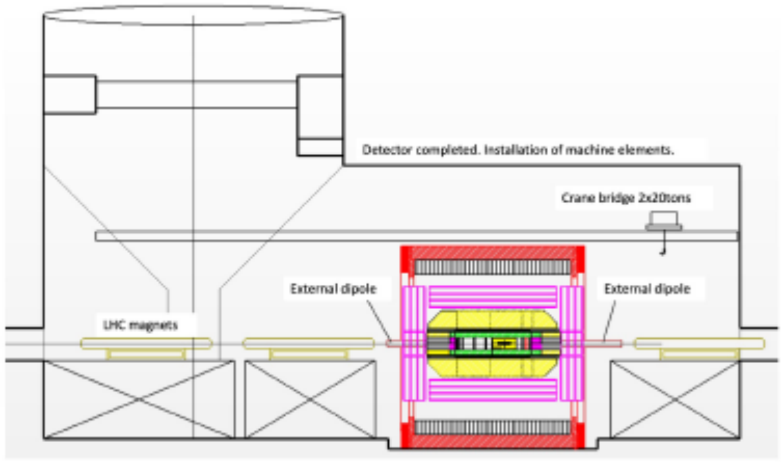



12/2018

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].



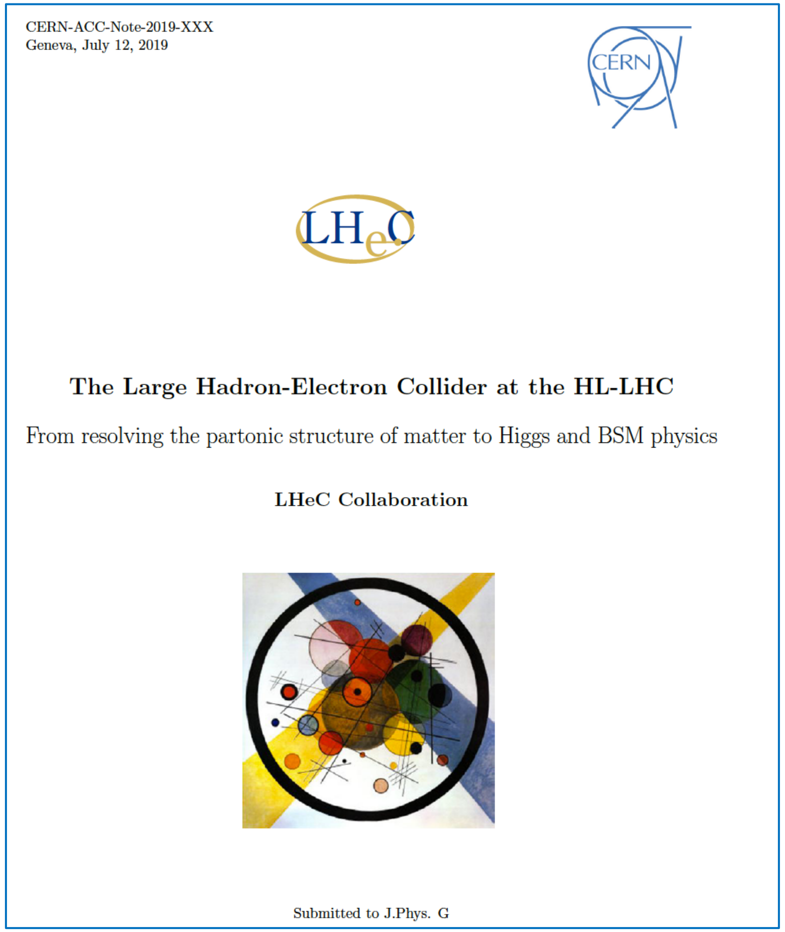

Study of installation (sequence) of LHeC detector in IP2 cavern using L3 magnet support structure [commensurate with 2 year shutdown] A. Ghaddi et al, LHeC Workshop 2015




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

# Remarks on Next Steps

CDR is 7 years old. New: Higgs, LHC physics and performance, technology, PERLE, FCC..
→ CDR on FCC-eh and Update on HL-LHeC
Comprehensive paper to appear end of 19


CERN-ACC-Note-2019-XXX
Geneva, July 12, 2019

The Large Hadron-Electron Collider at the HL-LHC

From resolving the partonic structure of matter to Higgs and BSM physics

LHeC Collaboration

Submitted to J.Phys. G

Workshop 24/25.10.2019 at Chavannes [http://lhec.web.cern.ch]

Beyond:

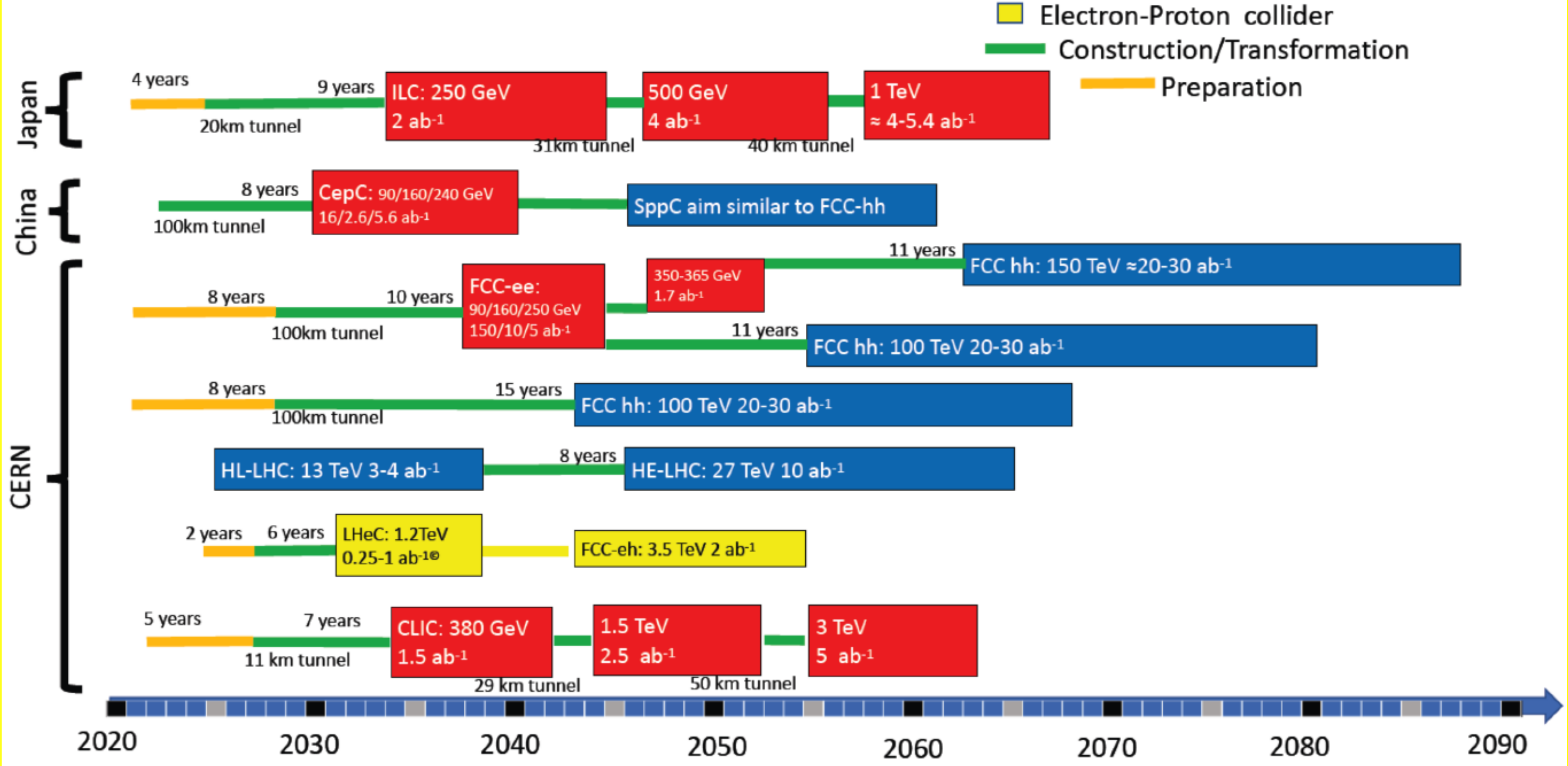
- Evolution of Physics, with LHC, theory..
- Design of the Interaction region
- Development of ERL technology
- PERLE at Orsay ..

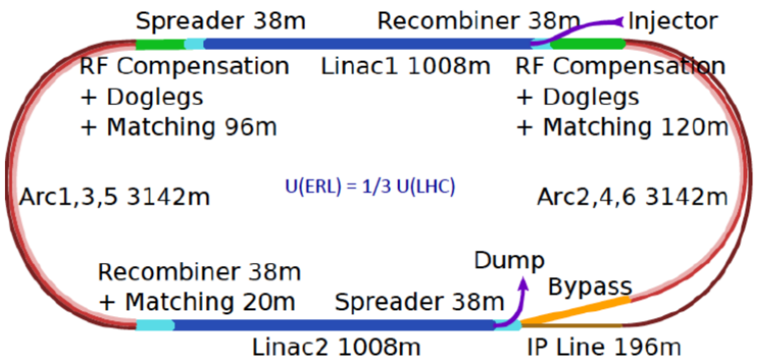
Future depends on strategy decisions and global HEP evolution

The physics and technology case of the LHeC is compelling
The cost is O(1) billion SF, not ten
The CERN hadron colliders are the only means for TeV scale DIS
Adding an ERL electron beam, transforms pp/AA physics
The future of particle physics requires a maximum of diversity

***If you want to discover a great taste, you will have to sample several:*** J de Hondt, slide 93 opening session

# Possible scenarios of future colliders






# Three Raisons d'etre of the LHeC

## 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)**

## 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

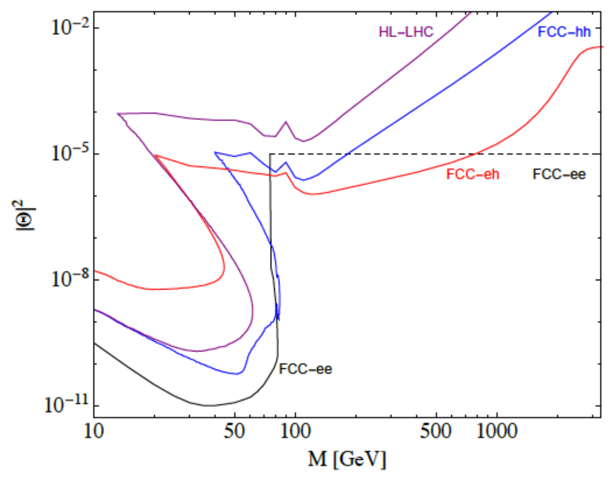
The LHeC/FCC coordinating groups and convenors
..

# backup

# 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**

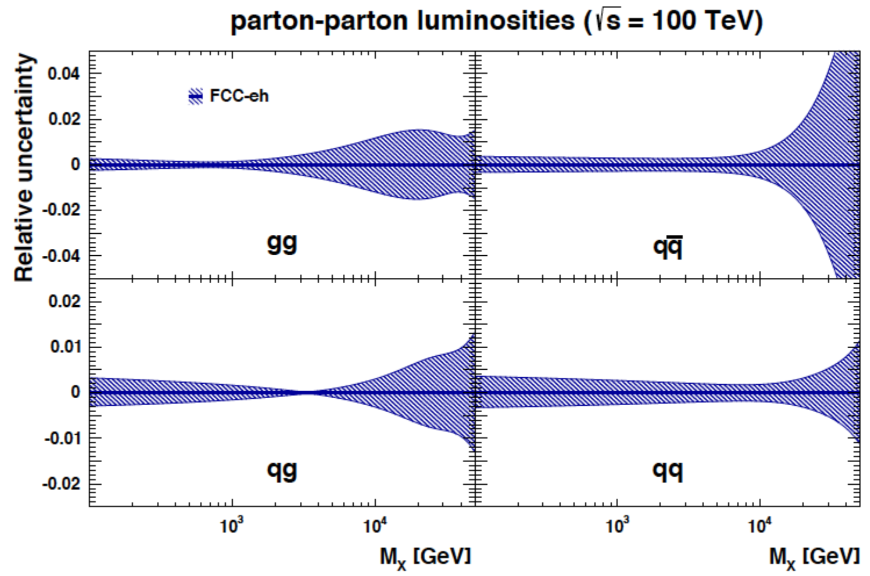
Some striking physics eh prospects are on searches and the high precision measurements on Higgs and proton structure:




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

# Energy and Luminosity ePb Prospects

Table 3: Baseline parameters of future electron-ion collider configurations based on the electron ERL, in concurrent $eA$ and $AA$ operation mode.

| parameter [unit] | LHeC (HL-LHC) | eA at HE-LHC | FCC-he |
|---|---|---|---|
| $E_{\mathrm{Pb}}$ [PeV] | 0.574 | 1.03 | 4.1 |
| $E_e$ [GeV] | 60 | 60 | 60 |
| $\sqrt{s_{eN}}$ electron-nucleon [TeV] | 0.8 | 1.1 | 2.2 |
| bunch spacing [ns] | 50 | 50 | 100 |
| no. of bunches | 1200 | 1200 | 2072 |
| ions per bunch [$10^8$] | 1.8 | 1.8 | 1.8 |
| $\gamma\epsilon_A$ [$\mu$m] | 1.5 | 1.0 | 0.9 |
| electrons per bunch [$10^9$] | 4.67 | 6.2 | 12.5 |
| electron current [mA] | 15 | 20 | 20 |
| IP beta function $\beta_A^*$ [cm] | 7 | 10 | 15 |
| hourglass factor $H_{geom}$ | 0.9 | 0.9 | 0.9 |
| pinch factor $H_{b-b}$ | 1.3 | 1.3 | 1.3 |
| bunch filling $H_{coll}$ | 0.8 | 0.8 | 0.8 |
| luminosity [$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$] | 7 | 18 | 54 |

Oliver Brüning[1], John Jowett[1], Max Klein[2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]

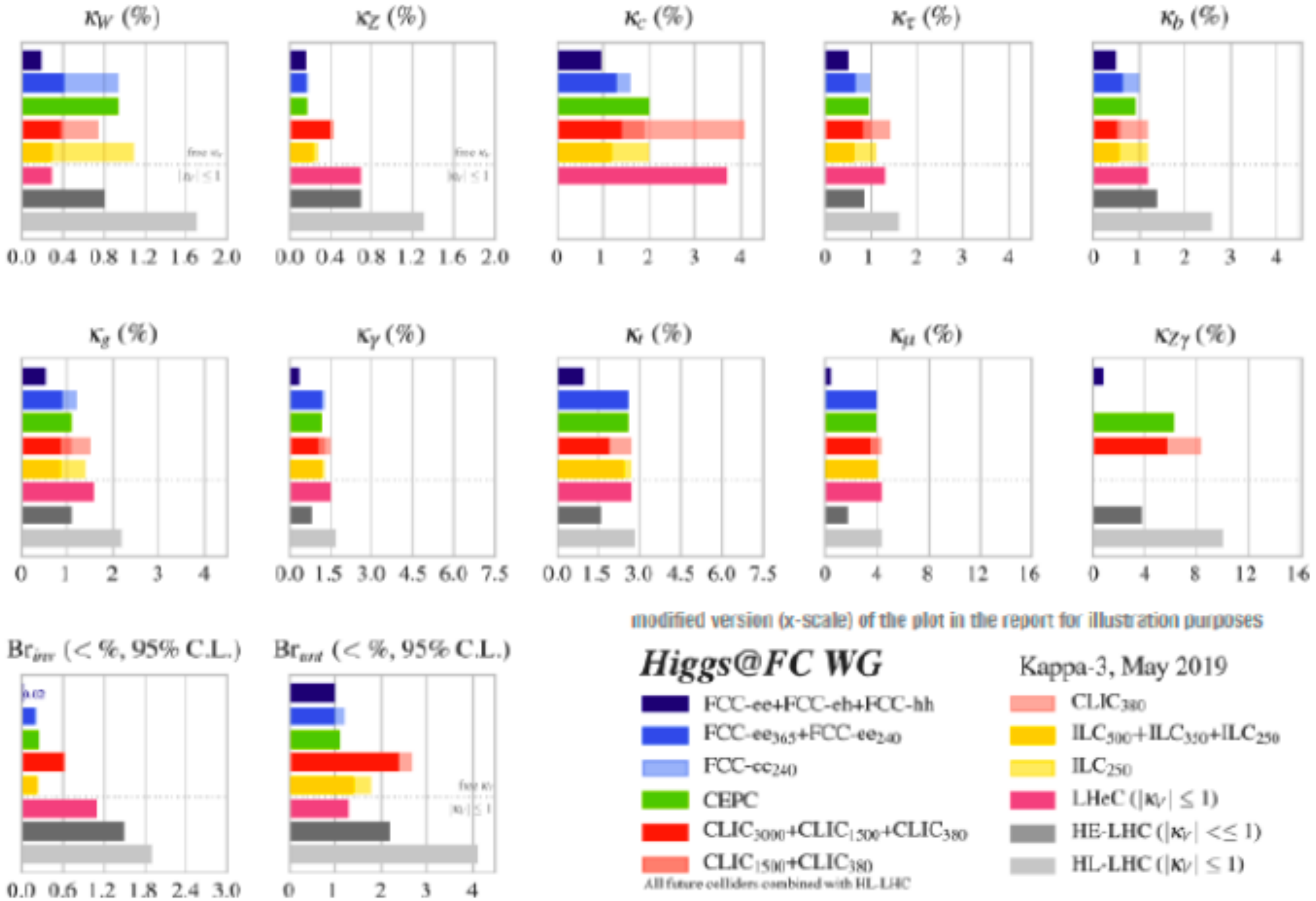
EDMS 17979910 | FCC-ACC-RPT-0012 2017

# Comparison of Colliders: kappa-framework

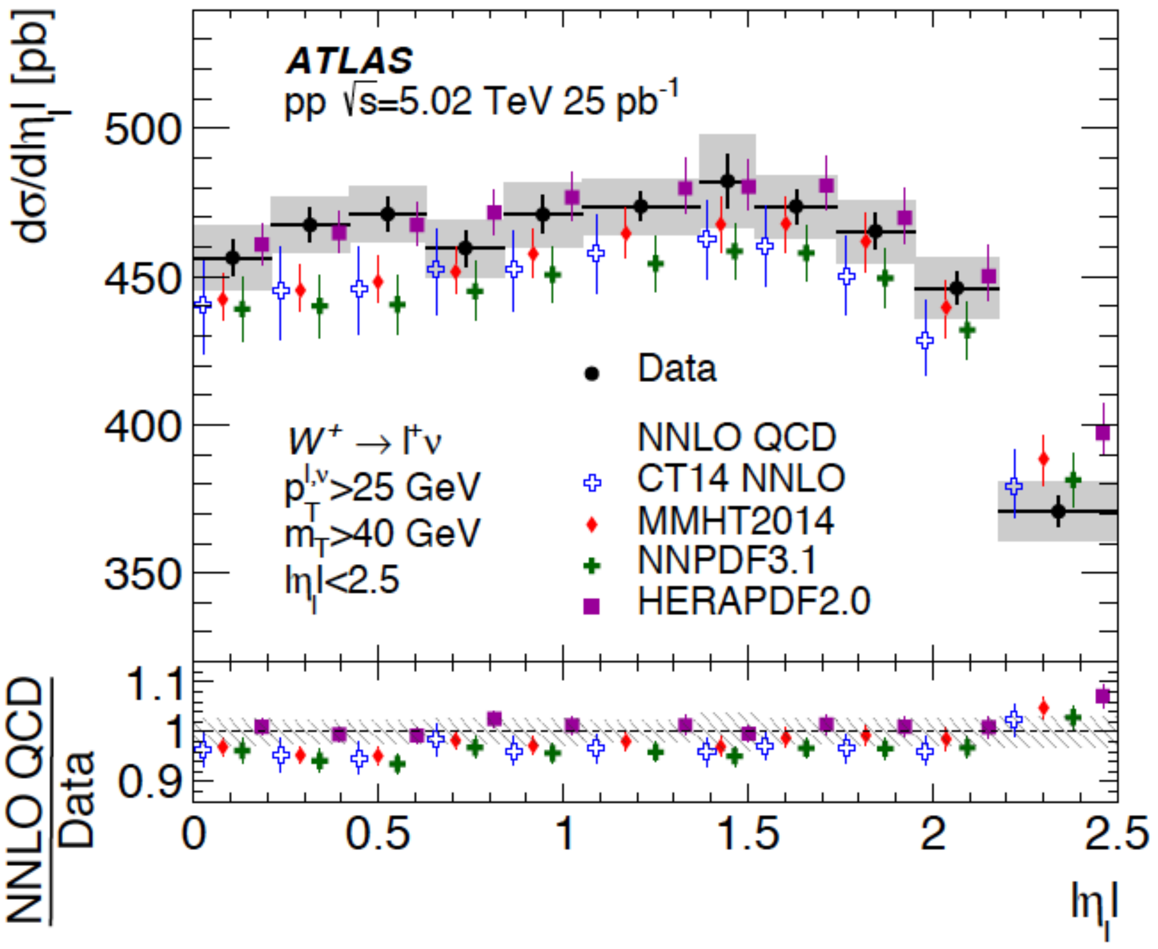
## Some observations:

- **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 $\kappa_c$ at ee and eh**

*arXiv:1905.03764*



# W and Z




ATLAS
5 TeV W,Z data
1810.08424

HERAPDF2.0 is best and very good while CT14 is worst, as are others.

**Ideal concept: import PDFs from ep and confront them with LHC data.**
**This tests QCD, avoids PDFs from pp and enables searches for BSM.**

# Jets

| Rapidity ranges | CT14 | MMHT2014 | NNPDF3.0 | HERAPDF2.0 |
|---|---|---|---|---|
| | $P_{obs}$ | | | |
| Anti-$k_t$ jets $R = 0.4$ | | | | |
| $\|y\| < 0.5$ | 44% | 28% | 25% | 16% |
| $0.5 \leq \|y\| < 1.0$ | 43% | 29% | 18% | 18% |
| $1.0 \leq \|y\| < 1.5$ | 44% | 47% | 46% | 69% |
| $1.5 \leq \|y\| < 2.0$ | 3.7% | 4.6% | 7.7% | 7.0% |
| $2.0 \leq \|y\| < 2.5$ | 92% | 89% | 89% | 35% |
| $2.5 \leq \|y\| < 3.0$ | 4.5% | 6.2% | 16% | 9.6% |
| Anti-$k_t$ jets $R = 0.6$ | | | | |
| $\|y\| < 0.5$ | 6.7% | 4.9% | 4.6% | 1.1% |
| $0.5 \leq \|y\| < 1.0$ | 1.3% | 0.7% | 0.4% | 0.2% |
| $1.0 \leq \|y\| < 1.5$ | 30% | 33% | 47% | 67% |
| $1.5 \leq \|y\| < 2.0$ | 12% | 16% | 15% | 3.1% |
| $2.0 \leq \|y\| < 2.5$ | 94% | 94% | 91% | 38% |
| $2.5 \leq \|y\| < 3.0$ | 13% | 15% | 20% | 8.6% |

Table 2: Observed $P_{obs}$ values evaluated for the NLO QCD predictions corrected for non-perturbative and electroweak effects and the measured inclusive jet cross-section of anti-$k_t$ jets with $R = 0.4$ and $R = 0.6$. Only measurements with $p_T > 100$ GeV are included. The predictions are evaluated for various PDF sets. The default scale choice $p_T^{jet,max}$ is used.

**NNPDF**
**1706.00428**

Impossible to achieve a good description of all rapidity bins with correlations included…

Used only central bin

**ATLAS: 1706.03192 8 TeV jet data**
"Tensions between the data and the theory predictions are observed"

**CT14 best, but not good, and HERAPDF2.0 worst, as opposed to W paper**

Very extensive studies on data correlations, including also 7 + 13 TeV

There is no simple pattern on how PDF sets describe LHC data. Using their projections as HL-LHC PDFs is indeed questionable.

# Cost estimate of ERL for LHeC and FCC-eh

## Nominal 60 GeV Configuration:

| Budget Item | Cost |
|---|---|
| SRF System | 805MCHF |
| SRF R&D and Proto Typing | 31MCHF |
| Injector | 40MCHF |
| Magnet and Vacuum System | 215MCHF |
| SC IR magnets | 105MCHF |
| Dump System and Source | 5MCHF |
| Cryogenic Infrastructure | 100MCHF |
| General Infrastructure and installation | 69MCHF |
| Civil Engineering | 353MCHF |
| Total | 1723MCHF |

## 30GeV to 50GeV Variation:

| Budget Item | Cost 30GeV | ➔ 50GeV |
|---|---|---|
| SRF System | 402MCHF | +268MCHF |
| SRF R&D and Proto Typing | 31MCHF | |
| Injector | 40MCHF | |
| Magnet and Vacuum System | 103MCHF | |
| SC IR magnets | 105MCHF | |
| Dump System and Source | 5MCHF | |
| Cryogenic Infrastructure | 41.5MCHF | +28MCHF |
| General Infrastructure and installation | 58MCHF | |
| Civil Engineering | 256MCHF | |
| Total | 1042MCHF | ➔ 1338MCHF |

➔ The scaled ERL circumference corresponds to 1/5$^{th}$ of the LHC circumference: 5.4km

ACC Note by Oliver Bruening: