Welcome to Chavannes

ELECTRONS FOR THE LHC: Workshop on the LHeC, FCC-eh and PERLE
Chavannes-de-Bogis, 24-25 October 2019

1. LHeC and PERLE – where do we stand?

Remarks around a poster (invited by Lepton-Photon Symposium, August 2019)

Energy Frontier Deep Inelastic Scattering at CERN
The LHeC and PERLE Collaborations
http://lhec.web.cern.ch

This poster is about the development, physics and realisation of the LHeC: a 50-60 GeV electron energy recovery linac (ERL) scattered concurrently off the LHC p/A

2. Strategy: Opportunity and Expectations

3. Beyond: this workshop [write-up], DIS [„impact“], the LHC [FCC]

Max Klein, for the coordination and organisers, Chavannes-de-Bogis, 24.10.2019

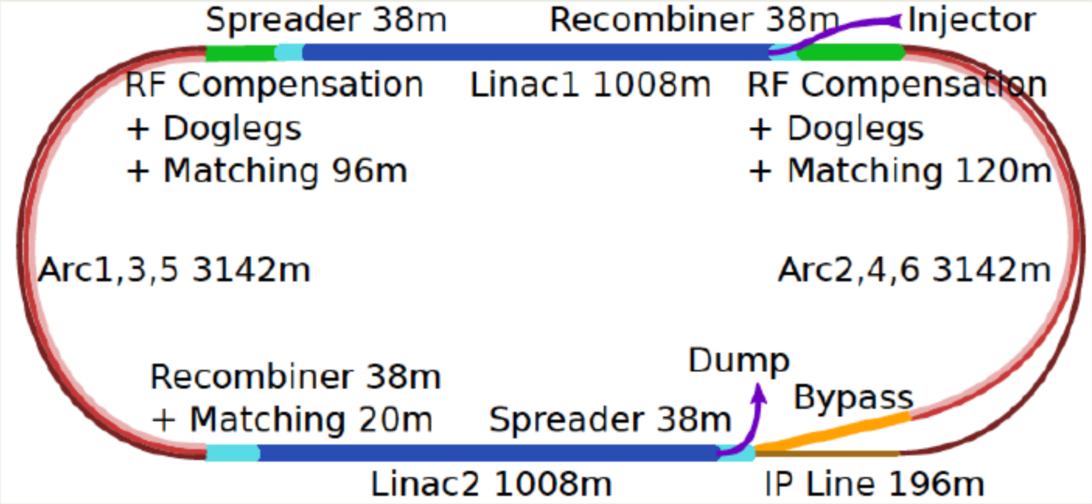
The Basic Concept

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

electrons: E_e=10-60 GeV, protons: E_p=1-7 TeV, ions Pb: E=2.75 TeV

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

Default layout of the ERL configuration for the LHeC



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

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

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

Luminosity:

10^{34} cm^{-2} s^{-1} → O(1) ab^{-1} in 10 years

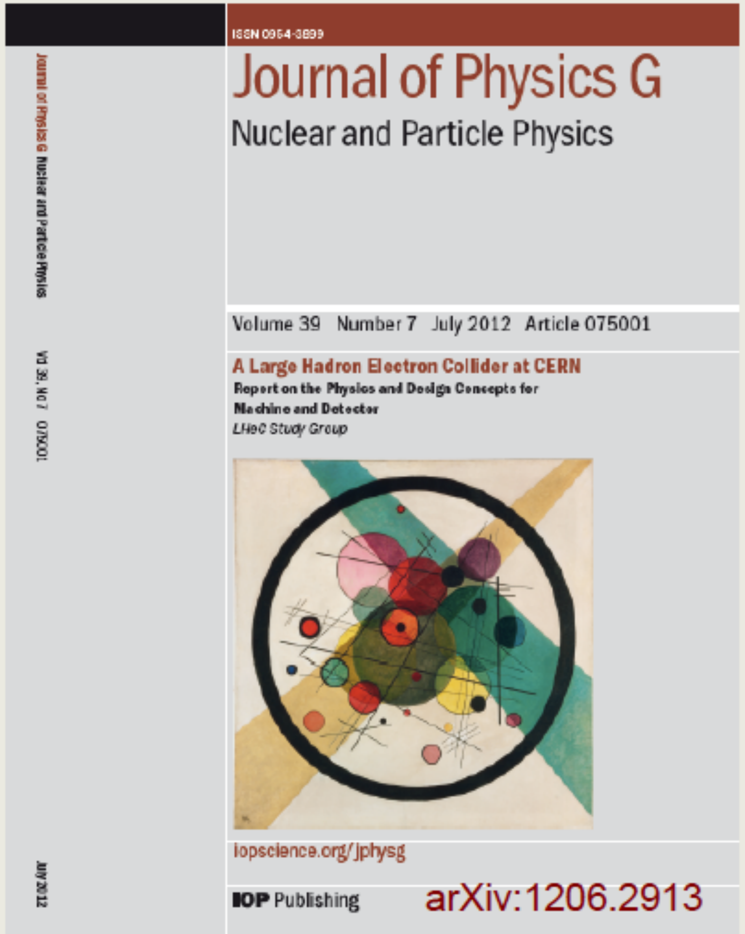
This is 1000 times higher than HERA, owing to the high beam brightness of the HL-LHC, the large electron current from the ERL and may be achieved through the interaction of matched e and p beams at a β* below 10cm.

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

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

Conceptual Design Report and beyond

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)



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

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

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

High Luminosity Electron-Hadron Physics at TeV energy

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

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

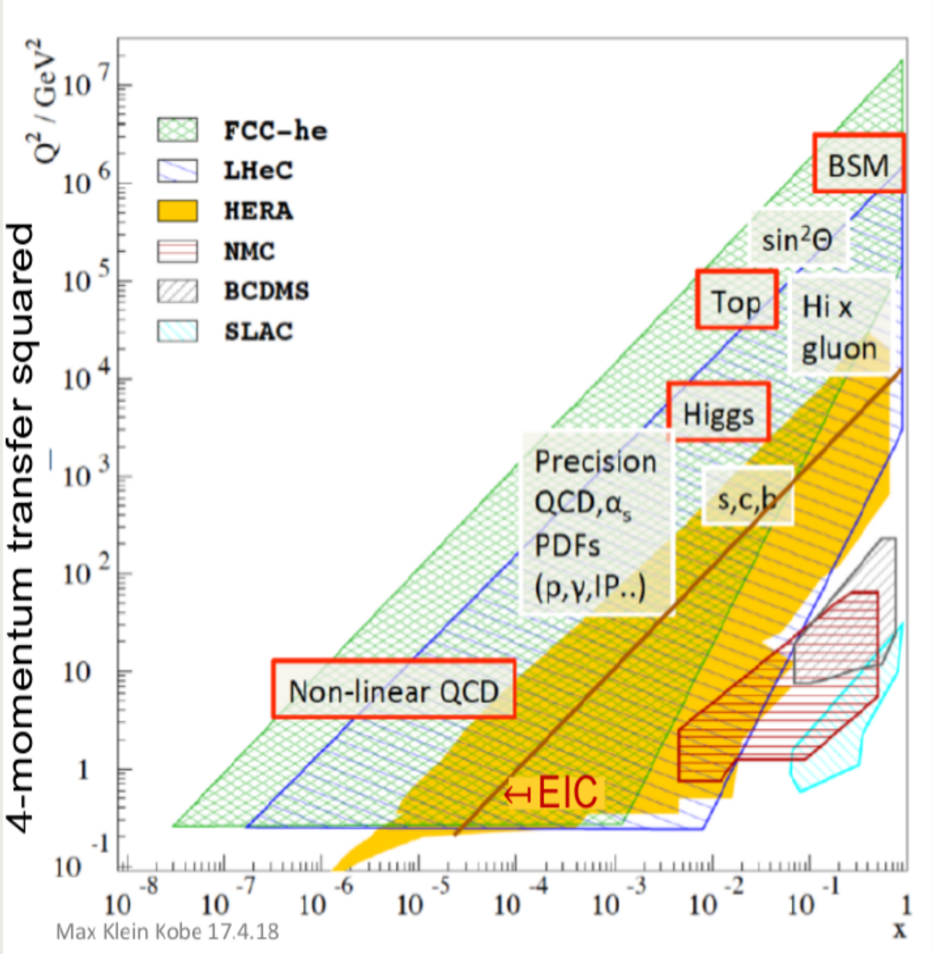
EMPOWERMENT of LHC physics
The LHC lacks crucial input on the proton structure and QCD dynamics. The clean, external input on partons will clarify the high mass predictions, and thus extend the reliablity and range for BSM searches, and provide input required for precision QCD, electroweak and Higgs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

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

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

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

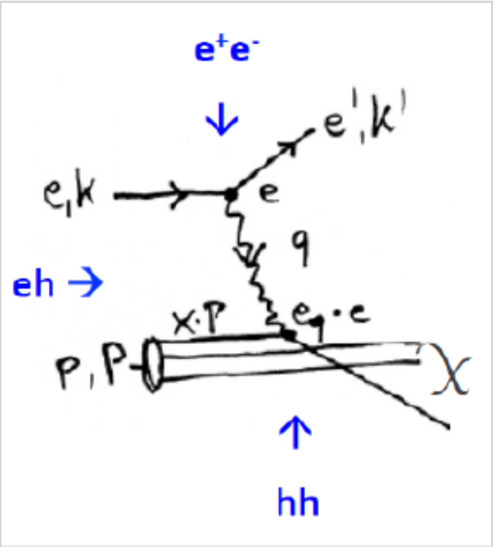
CERN-ACC-Note-2018-084, subm EU strategy, J.Phys.G to appear

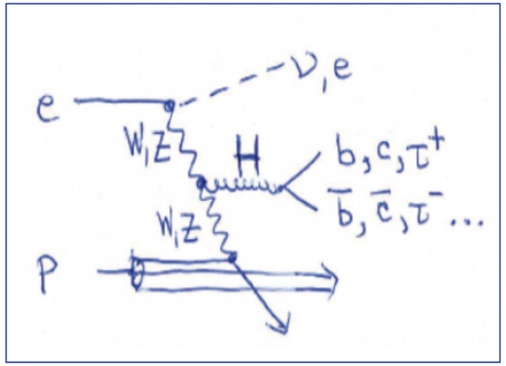


Following HERA, **deep inelastic scattering needs high energy** (and also luminosity) to reach Higgs, top, BSM physics, to use charged currents for unfolding parton structure, independently of nuclear and higher twist effects, to clarify the existence of BFKL dynamics at small x, and prepare for FCC.

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

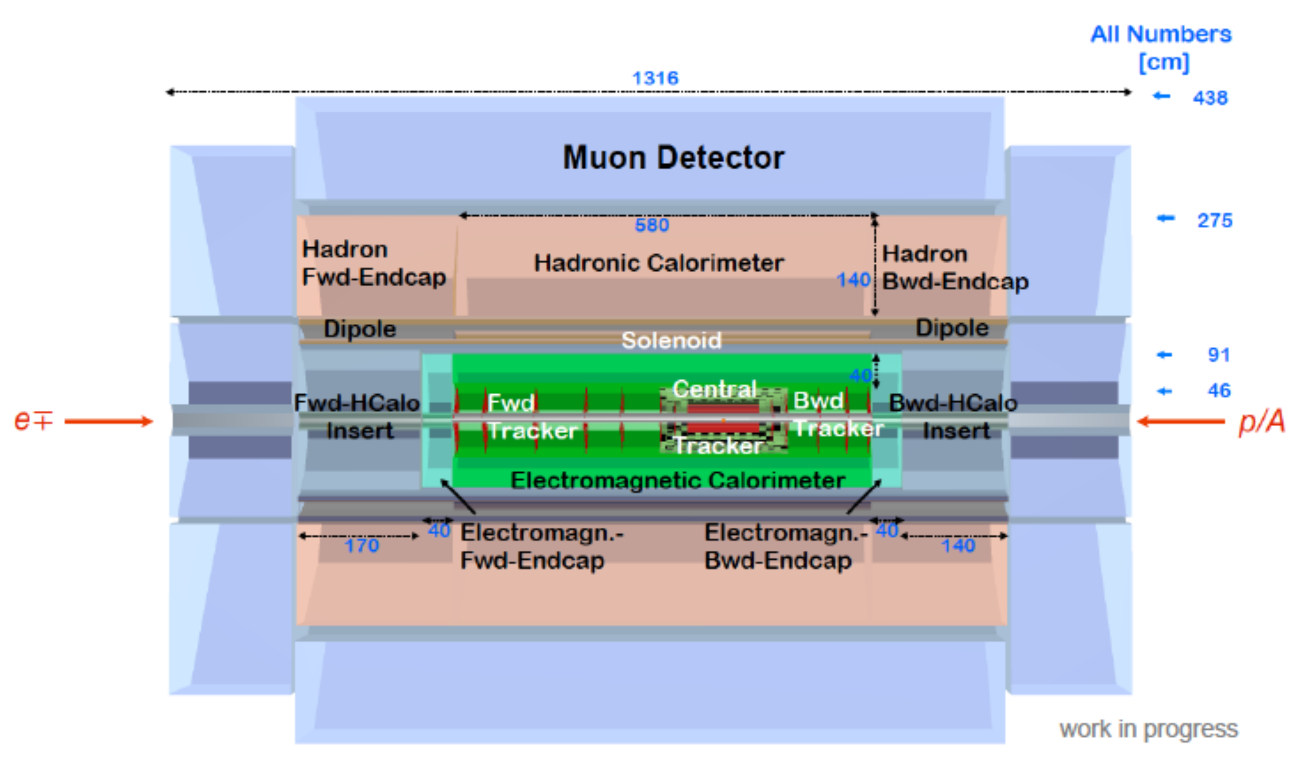
DIS: the cleanest high resolution microscope and a laboratory for new particles and new dynamics.





Detector Design

The LHeC detector (left below) is a large acceptance, precision device. Its design is determined by kinematics and high precision demands as from the H → bb reaction in CC. The low radiation (1/100 that of pp) enables sensitive technology such as HV CMOS to be used. The need to ensure head-on ep collisions introduces a long, low field dipole to be inserted before the HCAL, the solenoid (right below) is a rather conventional magnet. The detector is complemented by forward (p,n) and backward (e, γ) tagging detectors. Its dimensions are 13 x 9 m^2 (LxD) which one may compare with CMS: 21 x 15 m^2. The detector will have a modular structure to enable its rapid mounting in IP2.



We should think of when is the right time for forming a proto LHeC detector and experiment collaboration.

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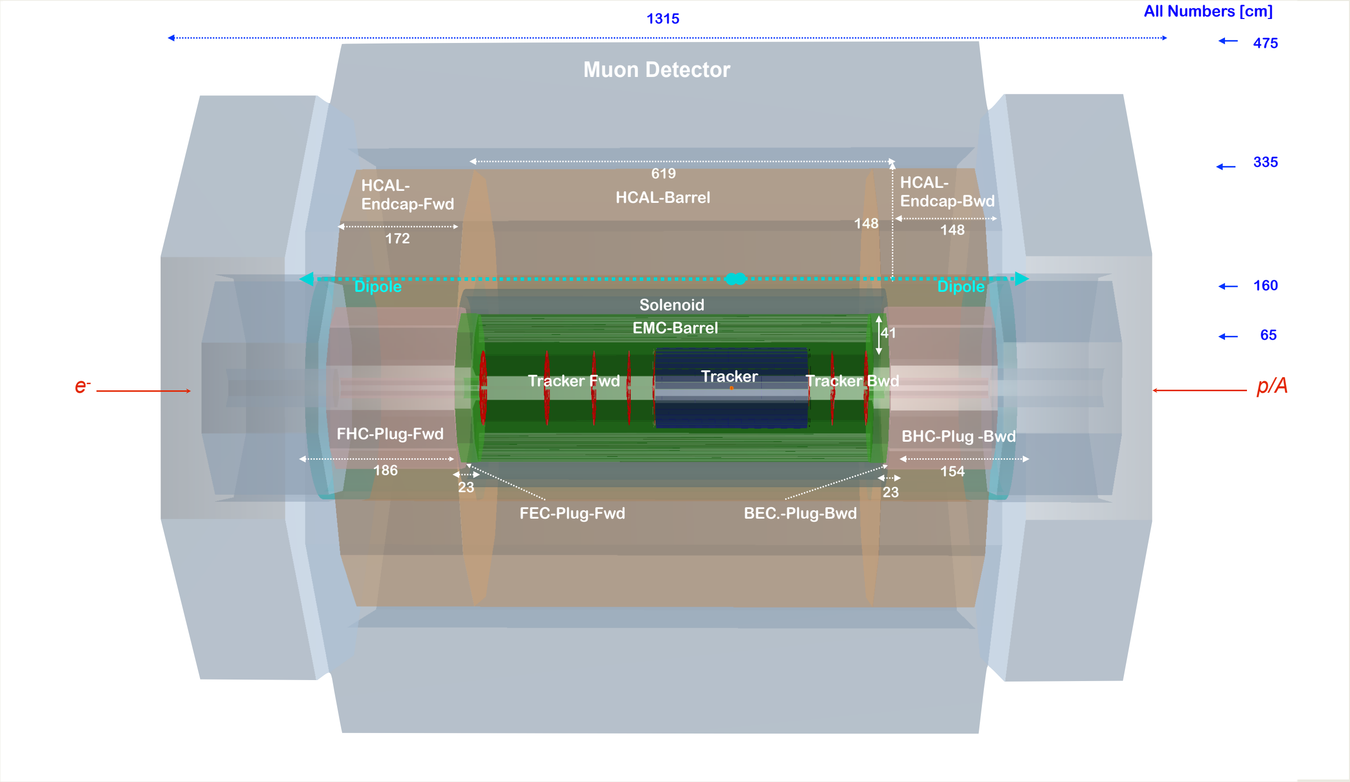


LHeC (CDR) Solenoid 3.5 T, 2.24 m OD, 7.1 m L

It will look like.........a stretched and squeezed ATLAS solenoid,

2 T scaled up to 3.5T (2 layer coil, slightly less free bore but a bit longer)

Relatively small bore but long, and efficient coil with 1.8 m free bore, 7.1 m long

- ≈ 11 km Al stabilized NbTi/Cu superconductor for 10 kA
- ≈ 80 MJ stored energy and ≈ 24 t mass including cryostat.

No specific R&D needed, except detailed analysis of the dipole load case

H ten Kate
EPRD Workshop
March 16, 2018

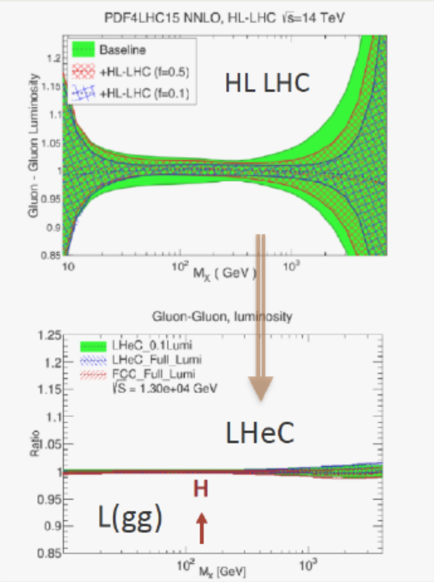
We should think of when is the right time for forming a proto LHeC detector and experiment collaboration.

LHeC Physics: Partons and Beyond

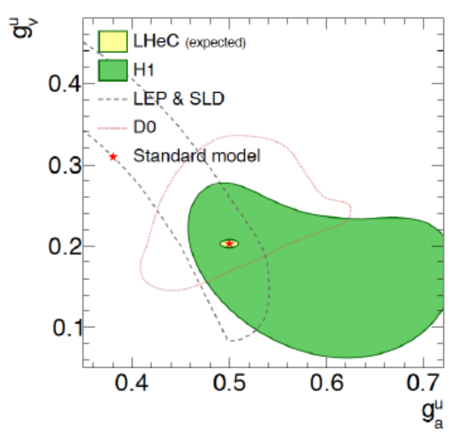
For the first time it will resolve the partonic structure of the proton and nuclei completely, i.e. determine the u_v, d_v, u, d, s, c, b, **the top and gluon momentum distributions** through neutral (NC) and charged current (CC) cross section and direct heavy quark (s,c,b,t) PDF measurements in a hugely extended kinematic range, from $x = 10^{-6}$ to 0.9 and from Q^2 about 1 to $10^6\,\mathrm{GeV}^2$.

Very high luminosity, an unprecedented precision from new detector technology and the redundant evaluation of the event kinematics from the lepton and hadron final states will lead to **extremely high PDF precision** and to the determination of the various PDF analysis parameters, such as m_c (to 3 MeV), m_b (to 10 MeV) and V_{cs} (to below 1 %), from the data themselves.

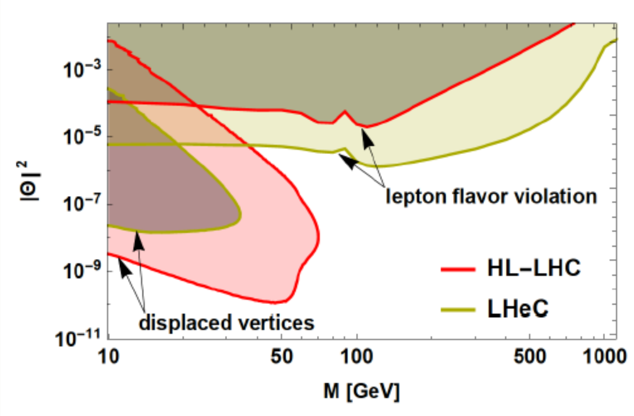
gg "luminosity" from HL-LHC and LHeC



The high energy, high luminosity accesses the weak neutral current DIS region down to small x. This enables **high precision electroweak measurements**, supported by the high electron beam polarisation.



The **cleanliness of the ep final state over the pp case** with large pile-up gives rise to additional BSM discovery potential as compared to the LHC, albeit its lower cms energy. Below the example for right-handed neutrinos:



Further examples for unique DIS physics are the resolution of p structure to 3D, precision diffraction, low x DGLAP-BFKL physics, novel, sensitive top measurements further BSM searches … and the new world of heavy ion physics with eA/ep input.

The LHeC is a new laboratory for the future of particle physics. Its cost, in the now considered version with a reduced circumference [1/4 U(LHC)], is estimated to be O(1) GSF. One therefore wonders, why sometimes "ep" is treated like the early Cinderella by some friends of its beautiful ee/pp sisters..

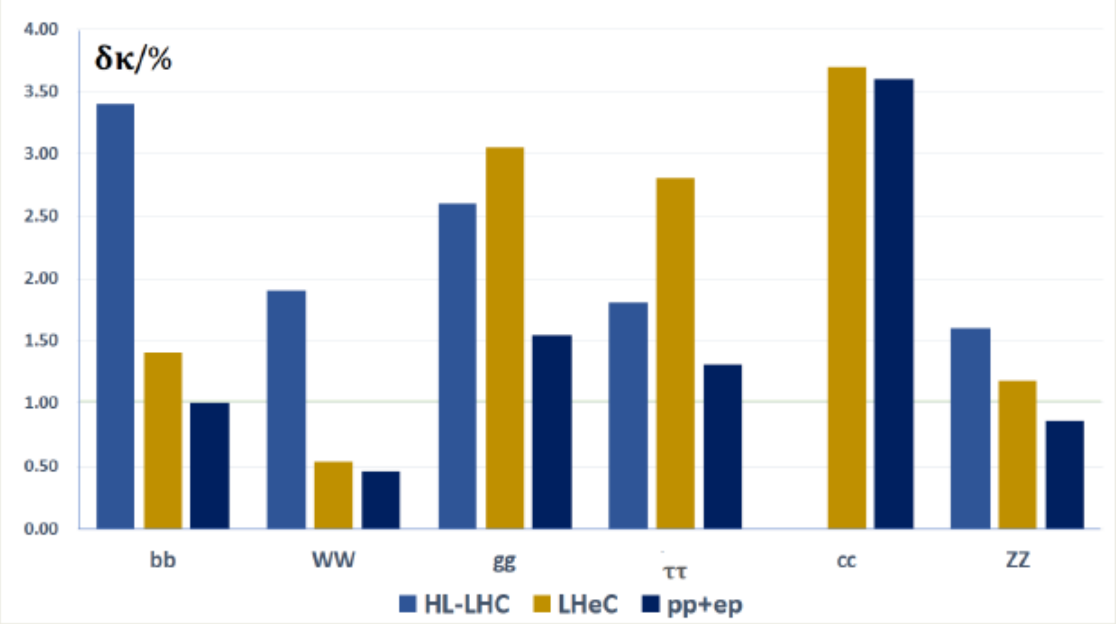
PDF text and physics examples from CERN-ACC-Note-2018-084, J.Phys.G to appear, and references therein. L(gg) C Gwenlan et al.

LHeC and FCC-eh are uniquely rich particle physics laboratories as will be illustrated at this workshop.

Parton distributions are known, but ep/eA with these powerful machines reaches out much further and to beyond the SM.

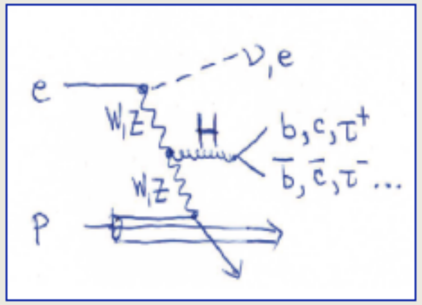
← Cinderella and her beautiful sisters ..

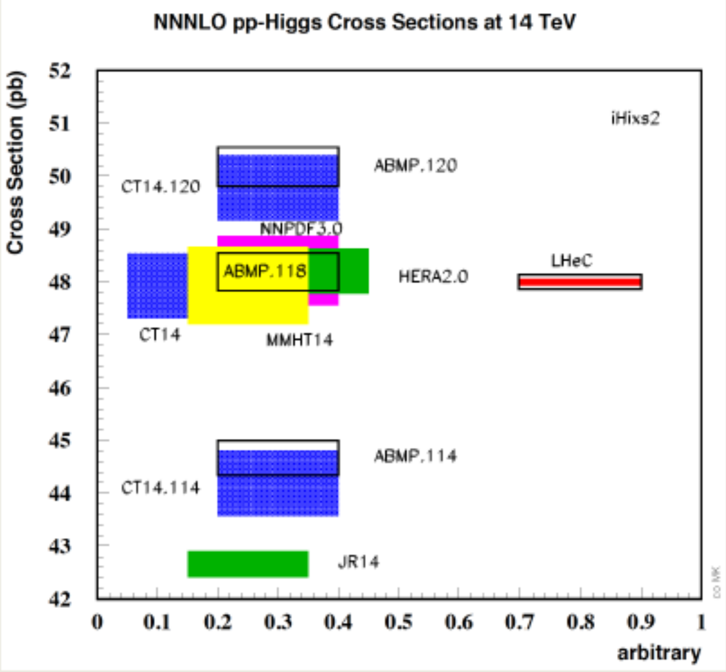
Higgs Physics with LHeC and LHC



Higgs physics at LHC is limited due to QCD uncertainties. LHeC determines α_s to permille accuracy and PDFs to N^{3}LO. This will give a major boost to pp Higgs physics as is illustrated below with the Higgs pp cross section predictions with current and LHeC PDFs.

Higgs production in ep. Each decay is measured in charged and neutral current scattering.



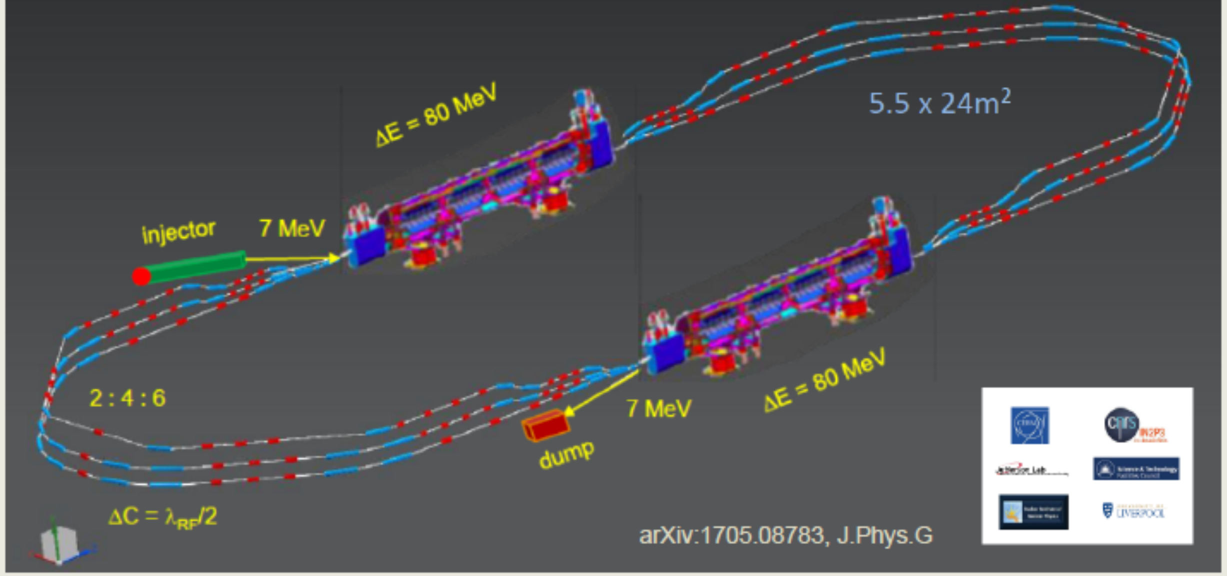


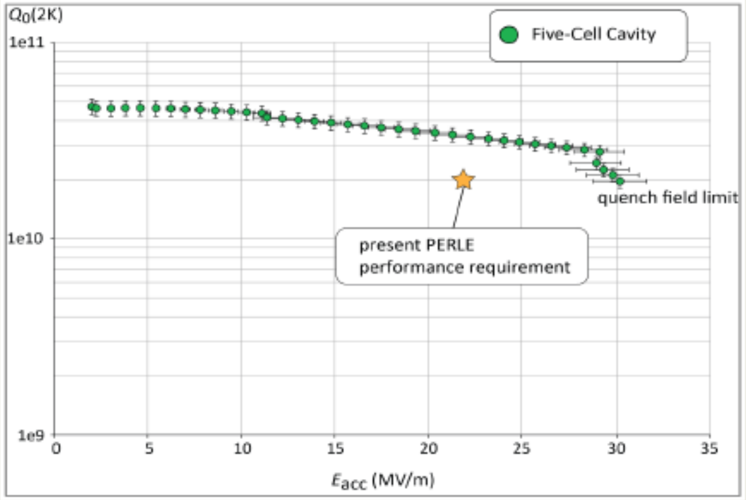
Recently, the HL-LHC prospects, ATLAS and CMS combined, have been re-evaluated (light blue). The LHeC provides an independent determination of the Higgs couplings, for the more abundant decays (golden). A combined (preliminary) analysis leads to per-cent level results, expressed as kappa parameters scaling the SM couplings.

LHeC and FCC-eh have unique Higgs physics potential on their own and in combination with pp.
Higgs Physics perhaps most interesting but surely not the only example for pp+ep physics synergy.

PERLE powerful energy recovery linac for experiments

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





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

Energy recovery is one of the few revolutionary concepts for accelerator design. A high energy collider application is for the LHeC (and possible successors with FCC). For stability, cost and CERN's RF, the frequency was chosen to be 802 MHz. A first 5-cell Niobium cavity, built at Jlab, reached a Q_0 of 3 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

Reasons to Proceed

The LHeC Collaboration is currently preparing the long write-up of a paper

"The Large Hadron Electron Collider for the HL-LHC"

for release in the fall 2019. This will be reviewed at a workshop, to be held near CERN, to which all interested colleagues are invited to attend.

Besides the physics in its five themes, **there have been many strategic reasons given which are supportive for the project to indeed go ahead.** In 2018, these had been briefly summarised as follows:

The uncertainty of HEP and its experience demand pp+ep+ee

The LHC HL Phase physics program would be transformed with ep/eA

CERN needs to build a new machine 20 years after LHC was built and 20 years before a next big machine may indeed be realised.

An ep detector would be a welcome task following the HL LHC.

There is a window of opportunity with the LHC lifetime, AA ending etc.

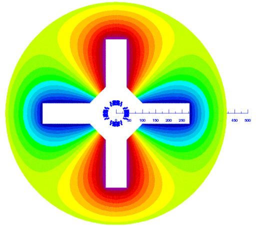
The ERL is green, high tech, innovative accelerator technology

When one came with a proposal to Vladimir Veksler and had several good reasons, he yet asked for one:

ep is the most precise and versatile microscope the world can build and CERN its place

For LHeC, time becomes a factor as it needs about ten years to be realised and > 5 years to operate.

Crucial developments especially for IR.



Brett Parker, Stefan Russenschuck

Needs strategic and community support, also for FCC-eh as an integral part of the FCC project. It is no sustainable option to plan for pp alone, we see this already with the LHC.

Input to the European Strategy on DIS + other papers

Summary Papers submitted to the European Strategy 12/2018

The LHeC paper is in print as topical J. Phys review publication.

We had also sent an addendum on cost etc. issues.

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

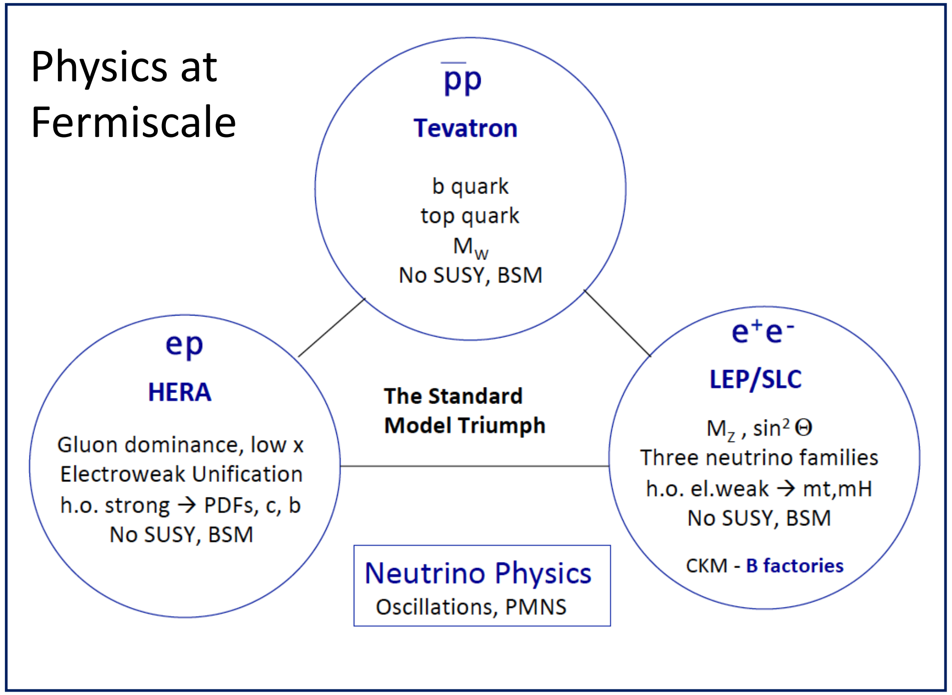
CERN-ACC-NOTE-2018-0086 December 18, 2018

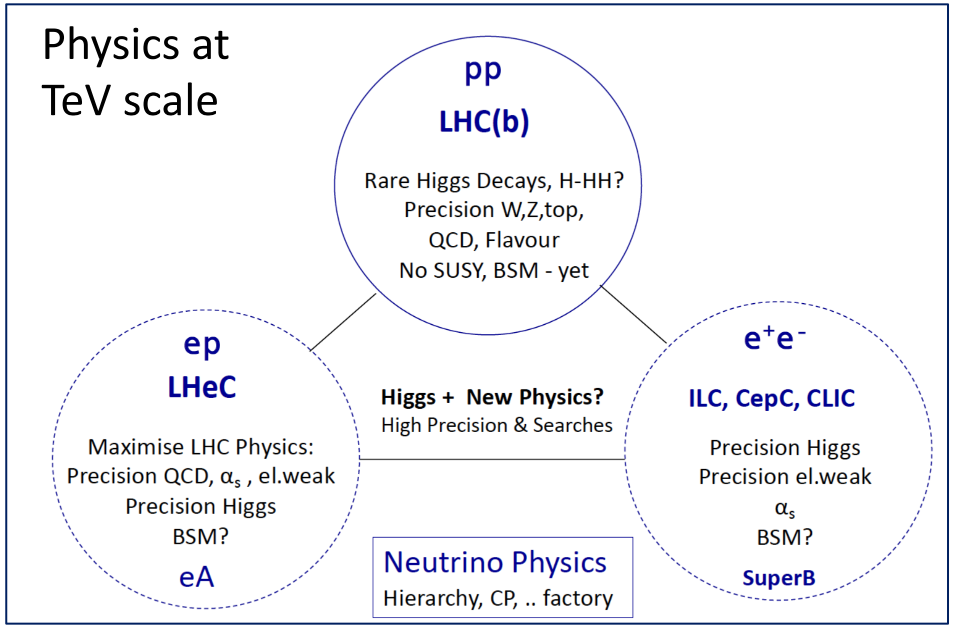
PERLE

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





Strategy and Expectations

Recognition of the complementarity of pp/AA, ep/A and ee, and the special role of DIS to supplement hh, LHC/FCC → Support for technical (IR..) and detector developments

Recognition of energy recovery as a revolutionary, novel technology for next generation colliders of high impact → Support the development of ERL technology and the international PERLE Coll.

CERN/ESG/05
29 September 2019

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

SUPPORTING NOTE FOR BRIEFING BOOK 2020

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

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

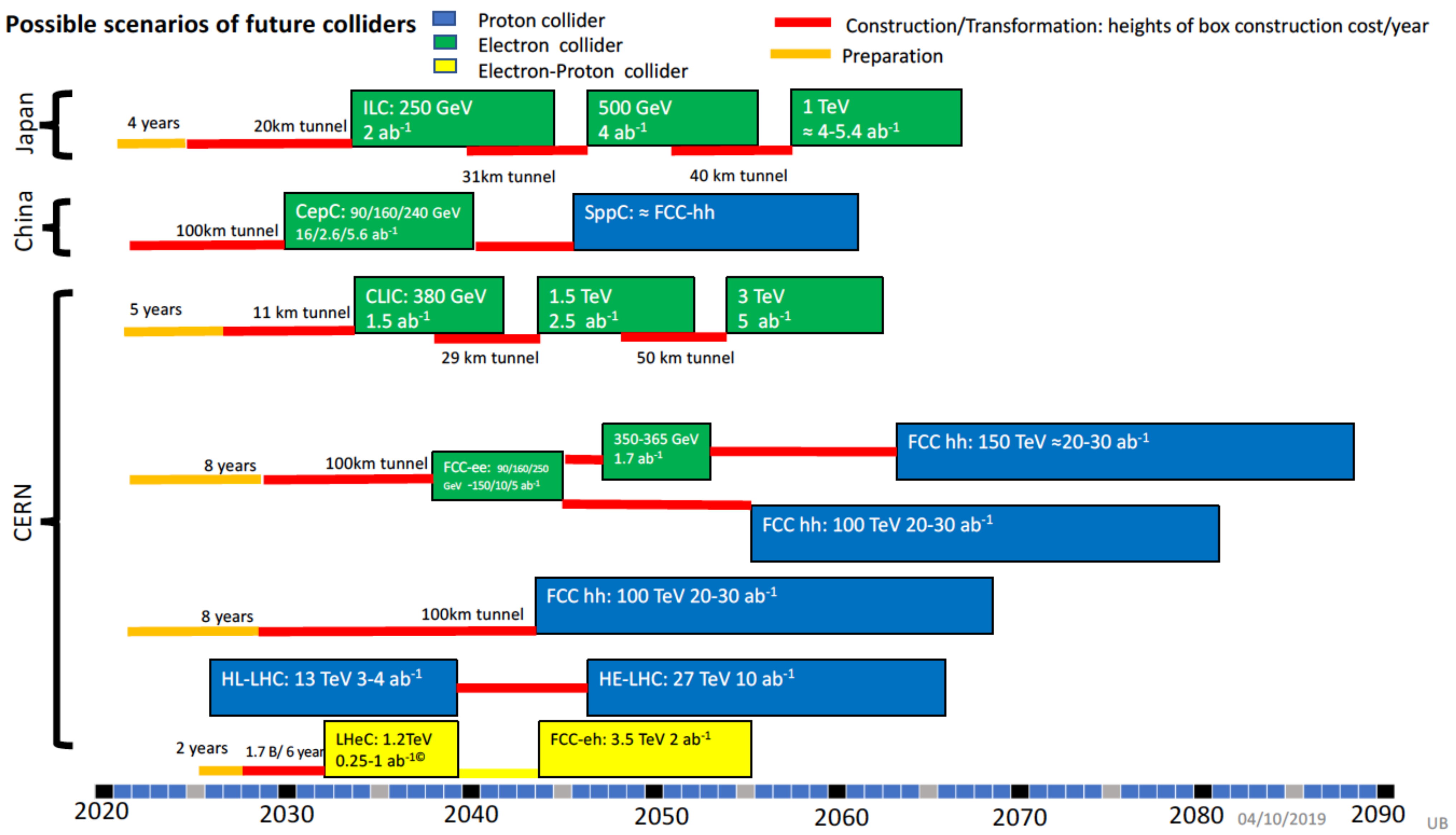
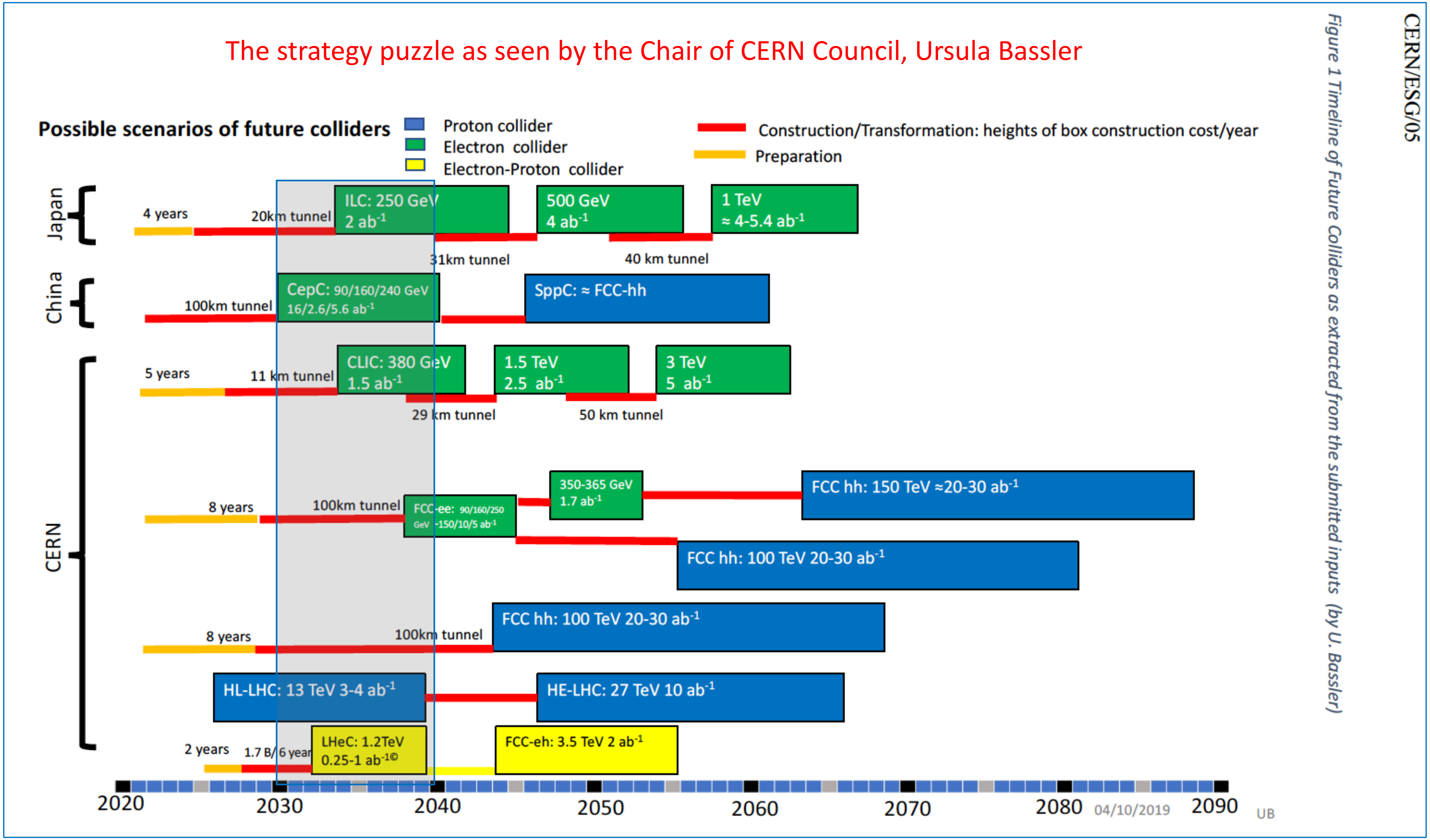


Figure 1 Timeline of Future Colliders as extracted from the submitted inputs (by U. Bassler)

CERN/ESG/05

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



High-energy DIS collider for QCD:

Hot & Dense QCD

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

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

Precision QCD

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

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

Partonic Structure

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

Theory

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

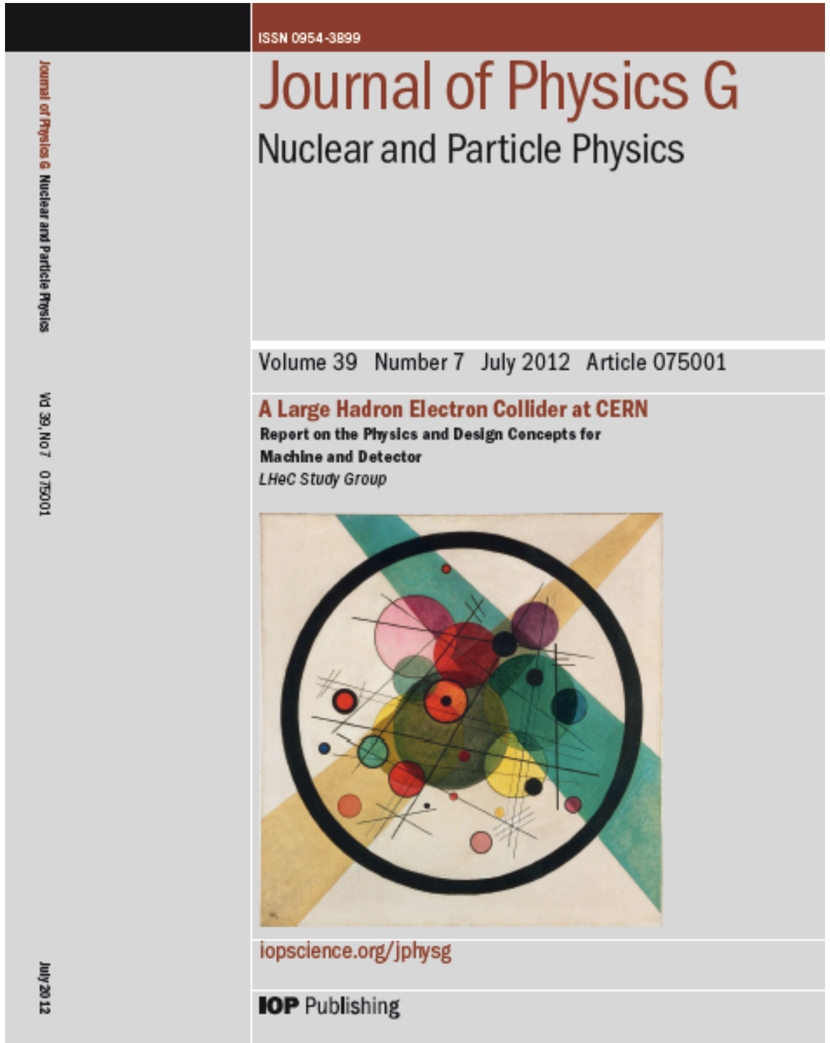
Organization

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

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

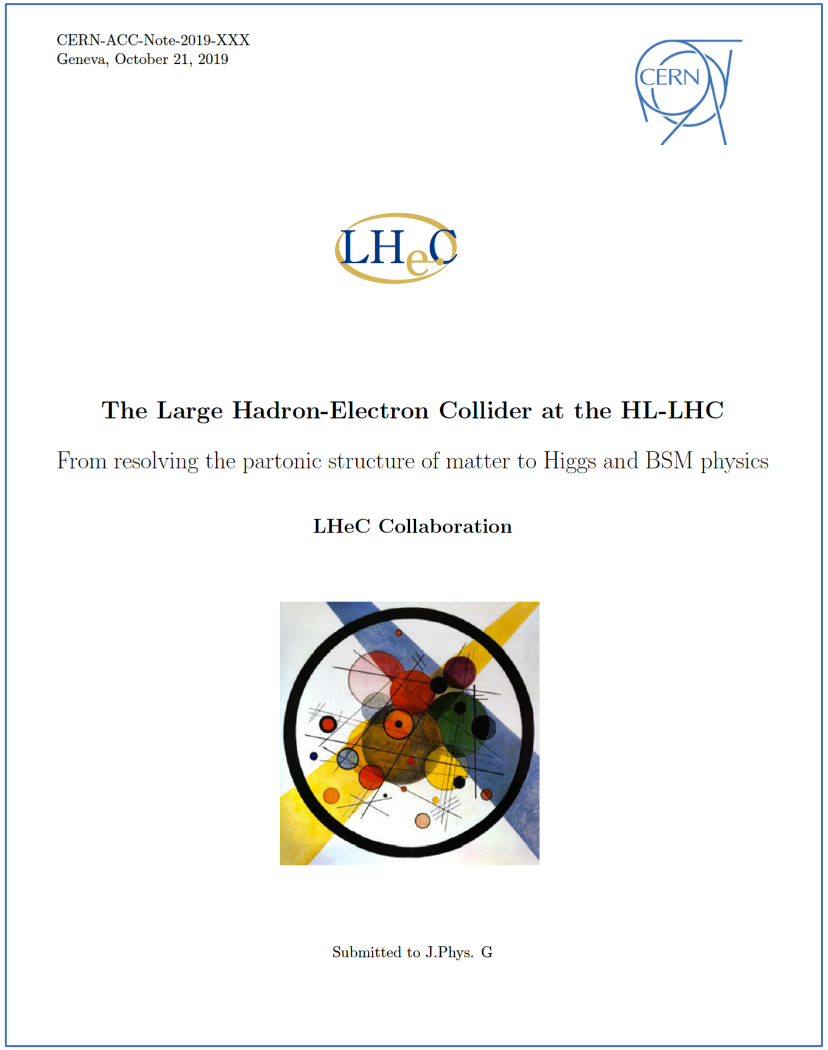
Summary on QCD of Jorgen D'Hondt and Krzysztof Redlich, Granada May 2019

Beyond what we documented: Write-up



CDR in 2012, prior to Higgs discovery

about 200 pages written,
to be submitted to JPhys
and arXiv this year.
Please converge by
mid November 19



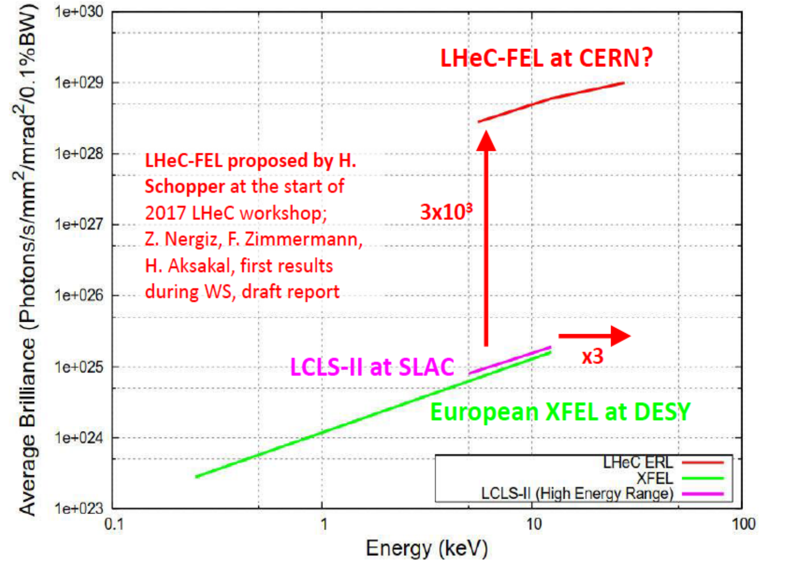
Update 2019, after the Higgs discovery

Beyond the LHeC and FCC-eh: Impact

The ERL technology and the multi-turn racetrack has huge possible impact beyond its LHeC application, for example:

highlight ARIES WP6.5 workshop *LHeC/FCC-eh*

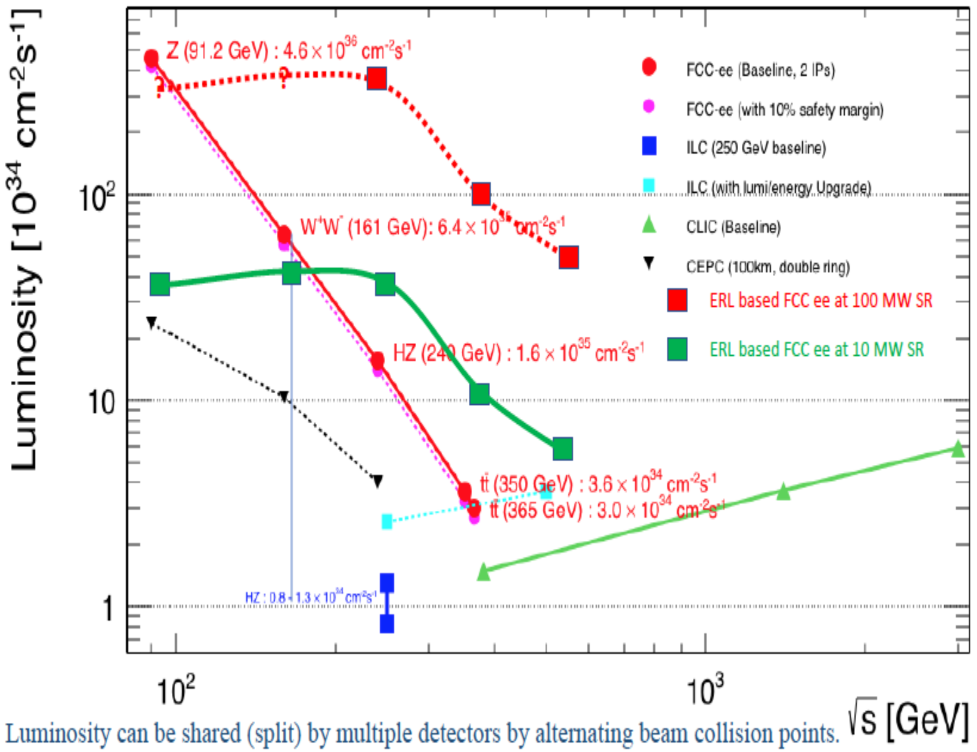
average brilliance, **LHeC-FEL** compared with state-of-the-art



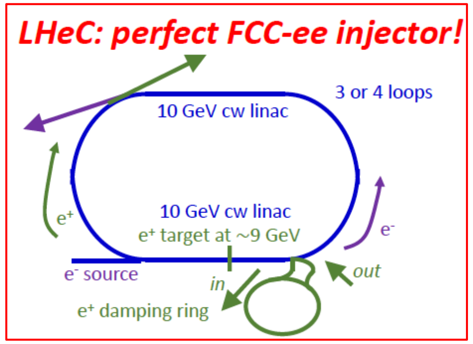
Frank Zimmermann, Orsay workshop 2018

PERLE and similar facilities: γN at I(1000) of ELI Lithography, Transmutation, Low energy nuclear and particle physics (PERLE CDR..)

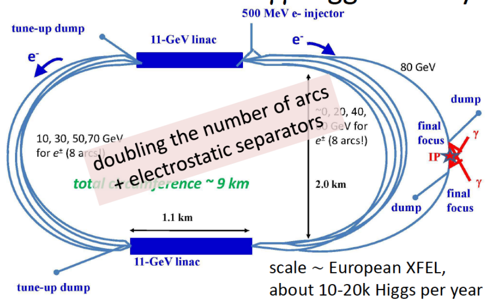
ERL based FCC-ee : higher luminosity at high E



Luminosity can be shared (split) by multiple detectors by alternating beam collision points.



SAPPHiRE: a Small γγ Higgs Factory



SAPPHiRE: Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons

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

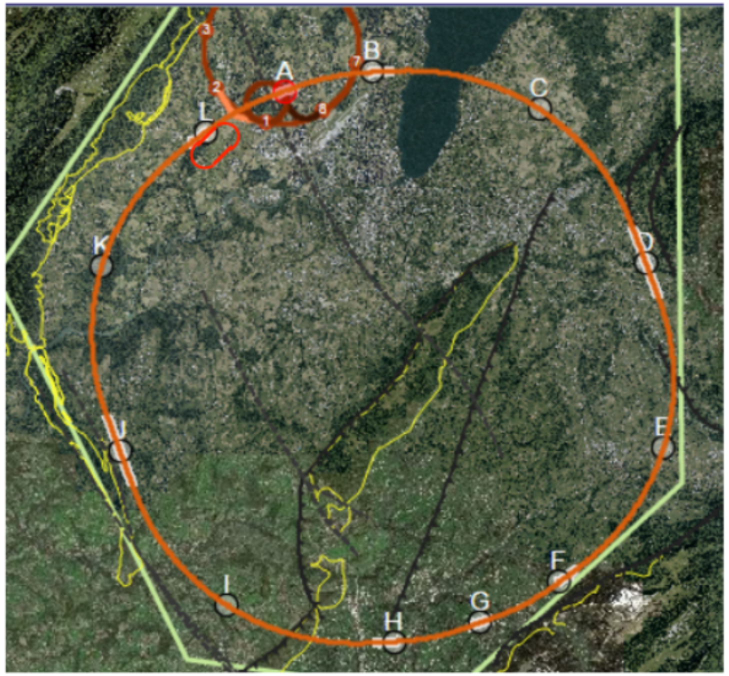
l^+l^-

CLIC, FCC - ee

High Precision Higgs
Top and BSM
Rh Neutrinos

Muon Collider ?

Neutrino Physics
Factory, Proton Decay



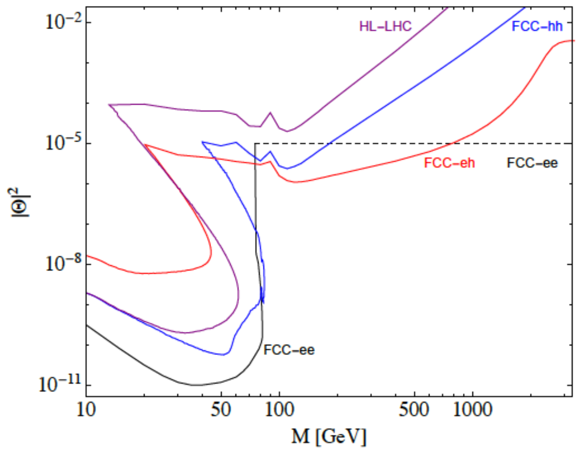
Higher energy than 60 GeV ?

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

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**

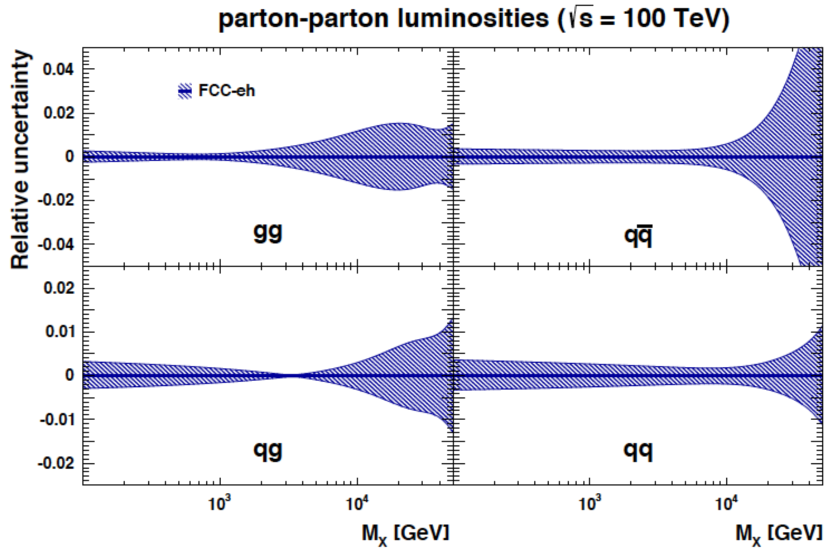
Some striking physics eh prospects are on searches and the high precision measurements on Higgs and proton structure:



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

Beyond Europe: eh in China ? and the EIC

CEPC e-p and e-A Options

Y.H. Zhang

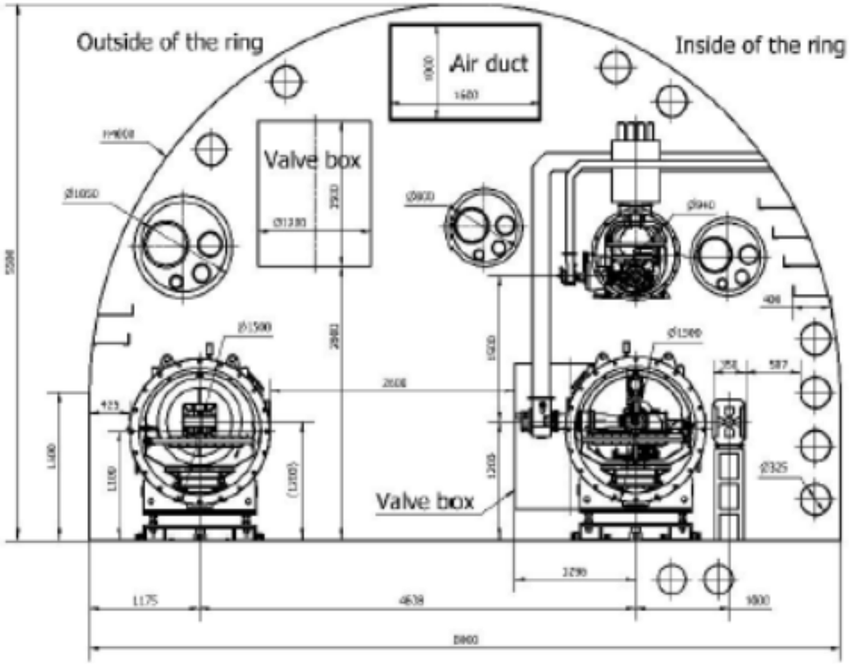
CEPC-SPPC *e-p* and *e-A* Design Parameters

Particle		Proton	Electron	Lead ($^{208}Pb^{82+}$)	Electron
Beam energy	TeV	37.5	0.12	14.8	0.12
CM energy	TeV	4.2		2.7	
Beam current	mA	730	34.8	730	34.8
Particles per bunch	10^{10}	15	0.72	0.18	0.72
Number of bunch		10080		10080	
Bunch filling factor		0.756		0.756	
Bunch spacing	ns	25	25	25	25
Bunch repetition rate	MHz	40	40	40	40
Norm. emittance, (x/y)	µm rad	2.35	282	0.22	282
Bunch length, RMS	Cm	7	0.5	7	0.5
Beta-star (x/y)	Cm	75	3.7	75	0.88
Beam spot size at IP (c/y)	Mm	6.6	6.6	3.25	3.25
Beam-beam per IP(x/y)		0.0004	0.12	0.0016	0.12
Crossing angle	mrad	~0.95		~0.95	
Hour-glass (HG) reduction		0.77		0.34	
Luminosity/nuclei per IP, with HG reduction	10^{33}/cm²/s			1.0	
Luminosity/nucleon per IP, with HG reduction	10^{33}/cm²/s	4.5		23.6	

Jie Gao, HKUST Conference, 22.1.18

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

The Chinese 100km tunnel housing p and e



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

This Workshop

Today: 4 sessions

Introduction and Physics

QCD

PERLE

Physics with ep+pp

Welcome Stan Brodsky

Dinner at 19.30

Tomorrow: 3 sessions

Accelerator (begins 8.30 am)

Detector and Physics

FCC-eh and Strategy

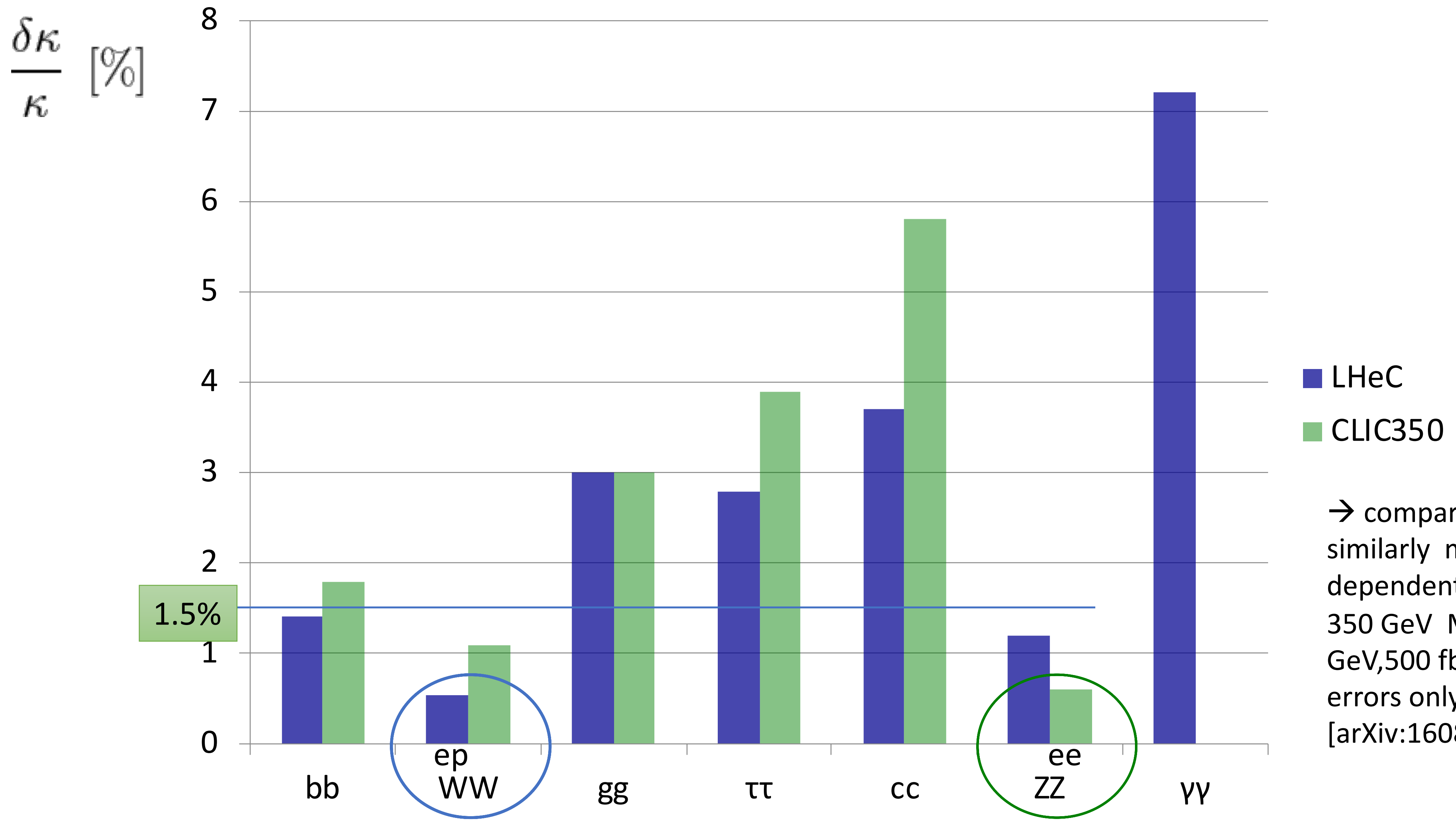
→ New ideas, more clarity, the white paper and a bright future through the strategy and CERN developments.

Thanks to:

Thank you for coming, thanks to the organising group, especially Alexia, Elodie and Valerie, and Bruno for the poster

backup

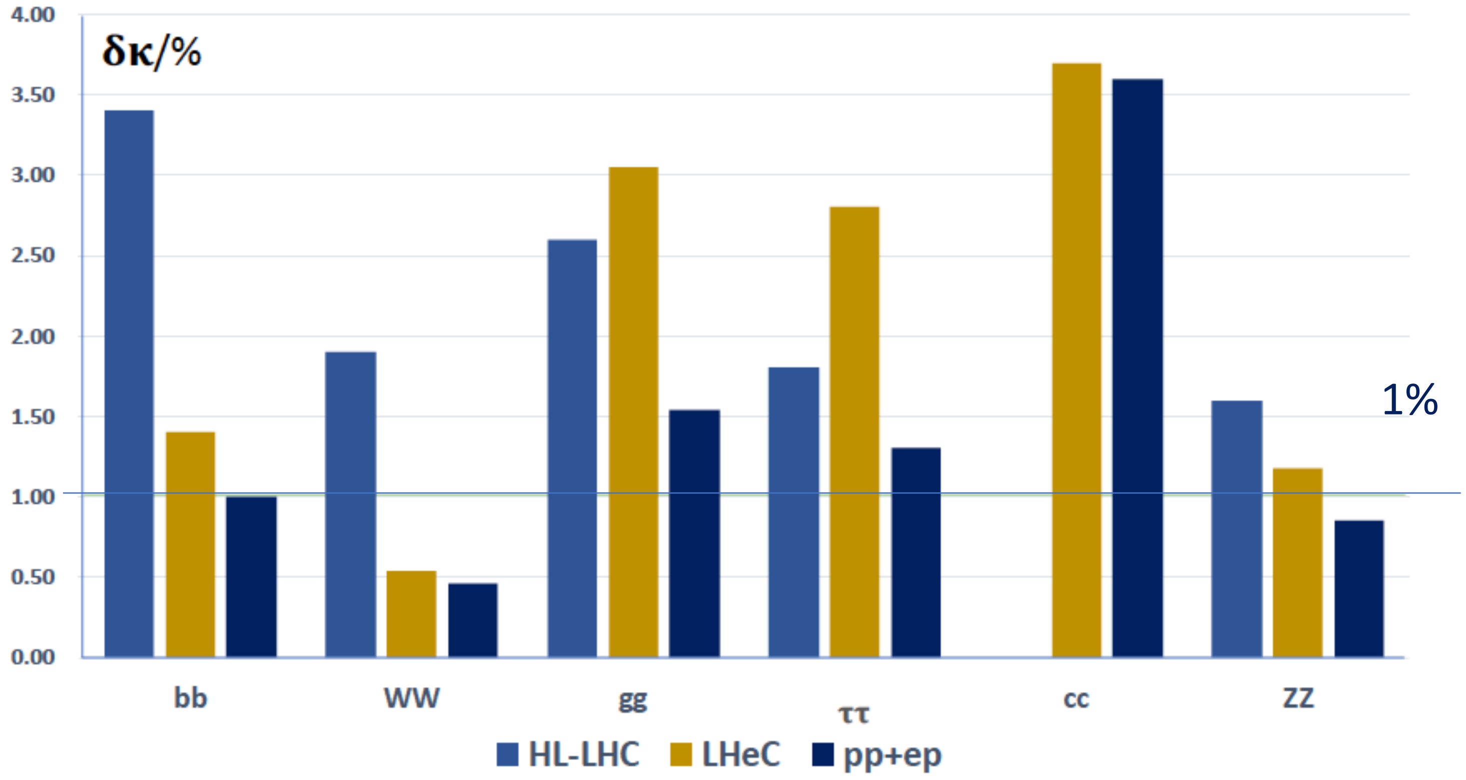
Model-dependent Coupling Fit [LHeC and CLIC]



→ compared to similarly model-dependent fit CLIC@ 350 GeV M_H=126 GeV,500 fb^{-1}, stats. errors only [arXiv:1608.07538]

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..)
DIS removes substantial part of theory uncertainties in HL-LHC prospects

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.