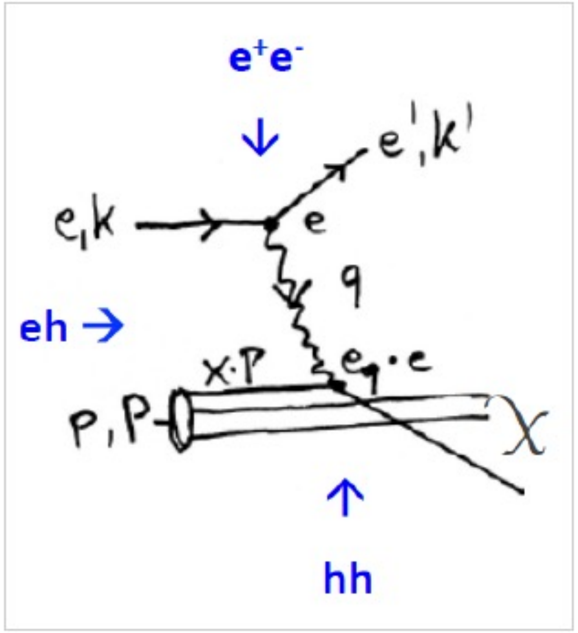
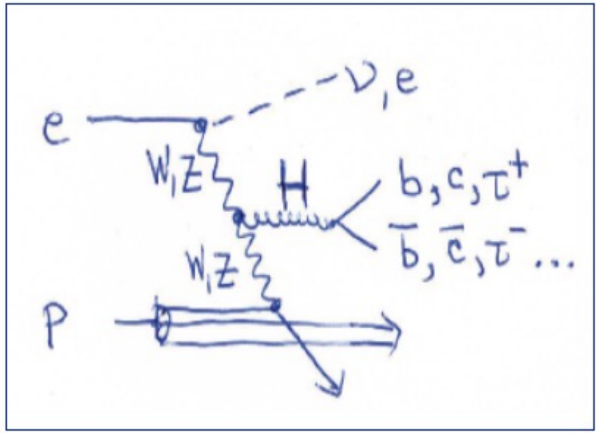
Uta Klein for FCC-eh,
May 1st, 2024

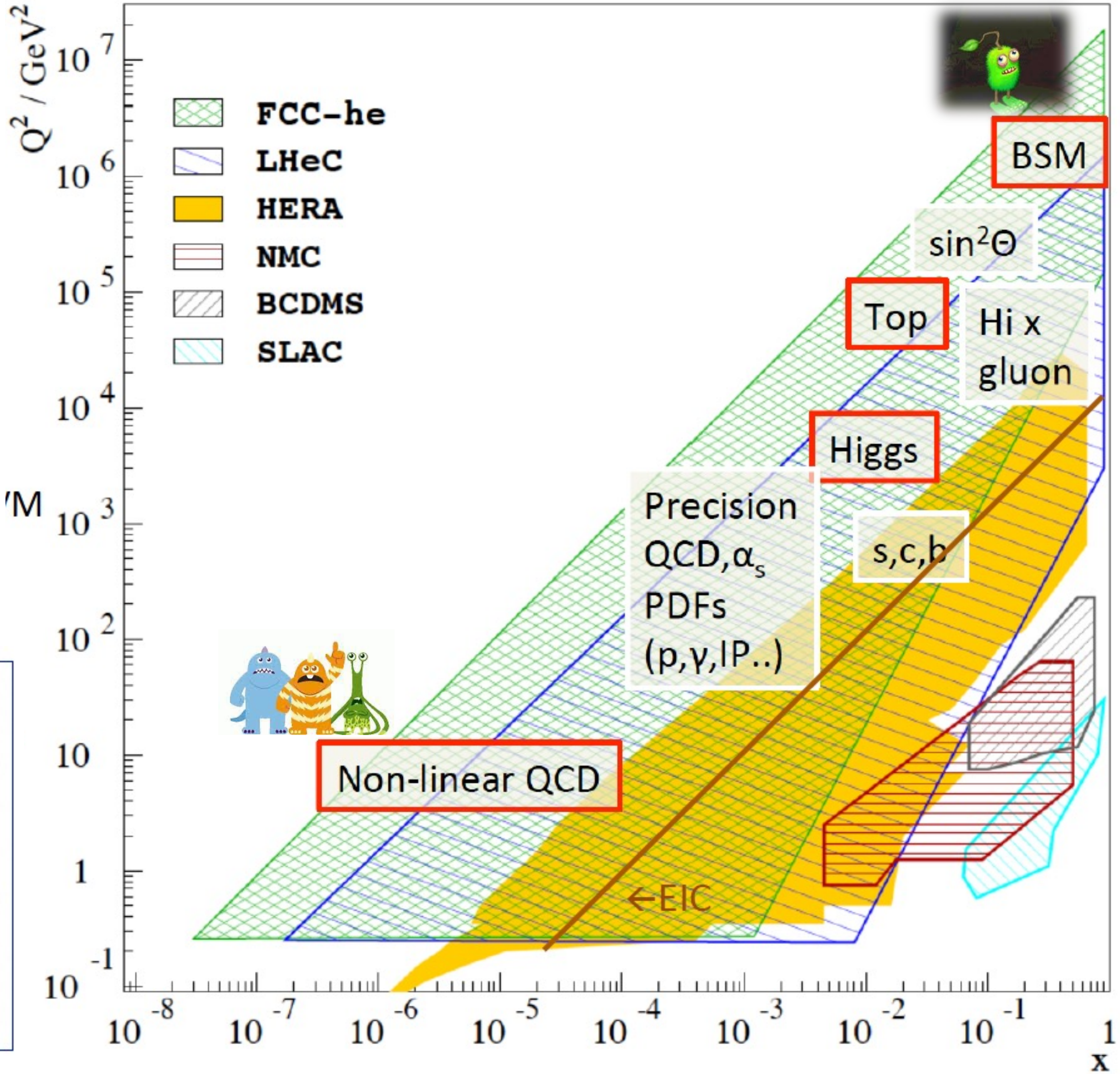
Super Microscopes FCC-eh and LHeC

UK Opportunities at European Strategy and Beyond

Deep Inelastic Scattering







+ **Cleanest High Resolution Microscope: QCD dynamics and discovery → *gluon saturation***
+BSM and Discovery (top, H, heavy ν's..), Leptoquarks
+ Unique *Nuclear* Physics Facility

+ **Empowering the LHC** pp & AA physics programme

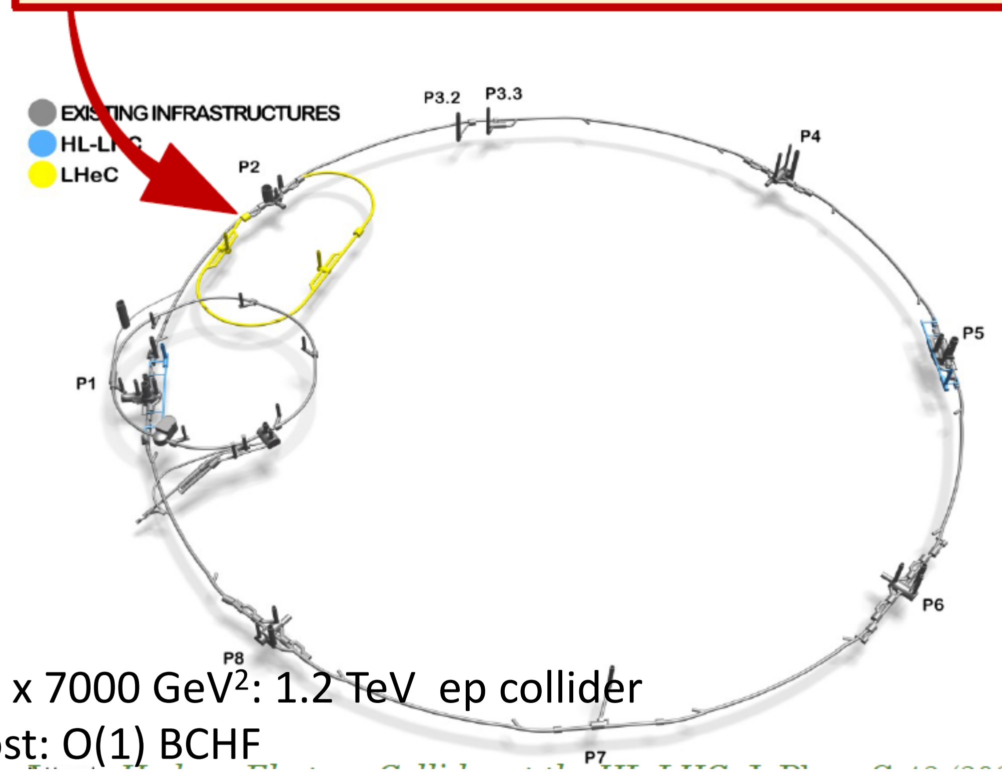
+**Transformation of FCC[LHC] pp**+ep into high precision Higgs facility

+ ***High Impact***
- ***sustainable:*** twin colliders
- ***energy recovery technology*** with industrial applications

LHeC (>50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳ Run5)

Twin Colliders of the Future
concurrent ep + pp

NEW



50 x 7000 GeV^2: 1.2 TeV ep collider
Cost: O(1) BCHF

L_{inst} =10^{34} $cm^{-2}s^{-1}$ for Higgs, BSM

CERN-ACC-Note-2018-0084 (ESSP)
CDR: 1206.2913 J.Phys.G (550 citations)
CDR update: J.Phys.G 48 (2021) 11, 110501 [arXiv:2007.14491]

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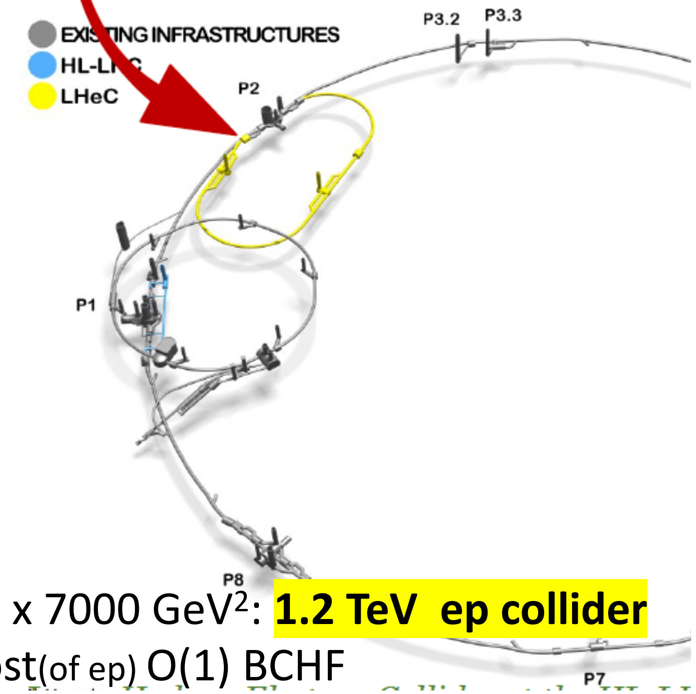

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Cost(of ep) O(1) BCHF

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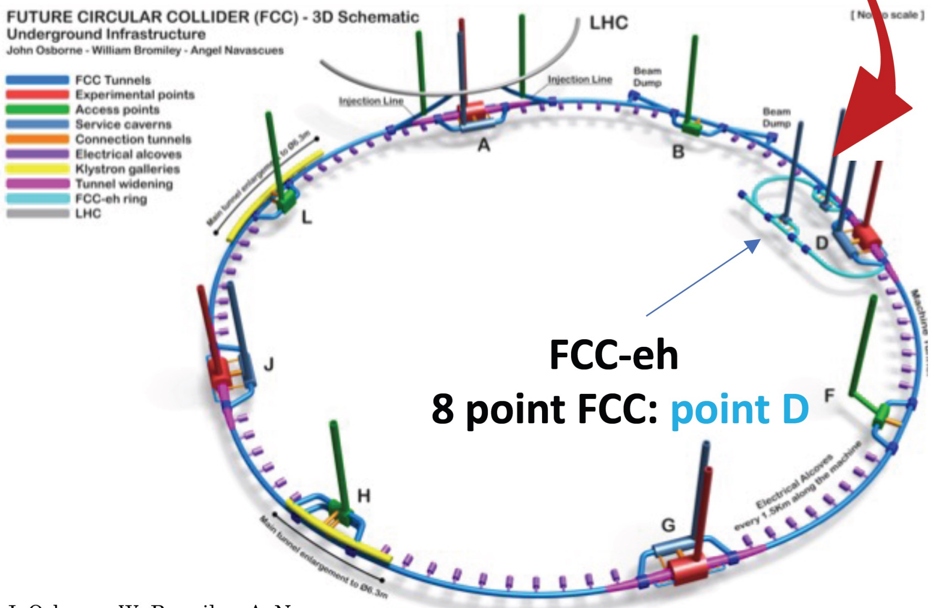
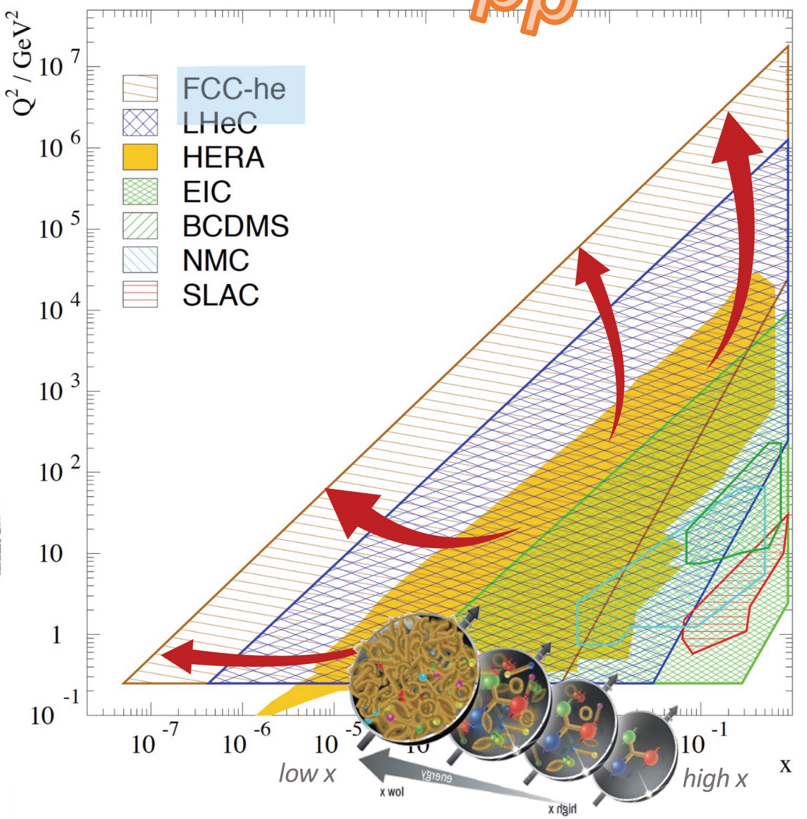
CDR update: J.Phys.G 48 (2021) 11, 110501 [2007.14491]

FCC-eh (60 GeV electron beams)
E_{cms} = 3.5 TeV, described in CDR of the FCC
run ep/pp together: FCC-hh + FCC-eh



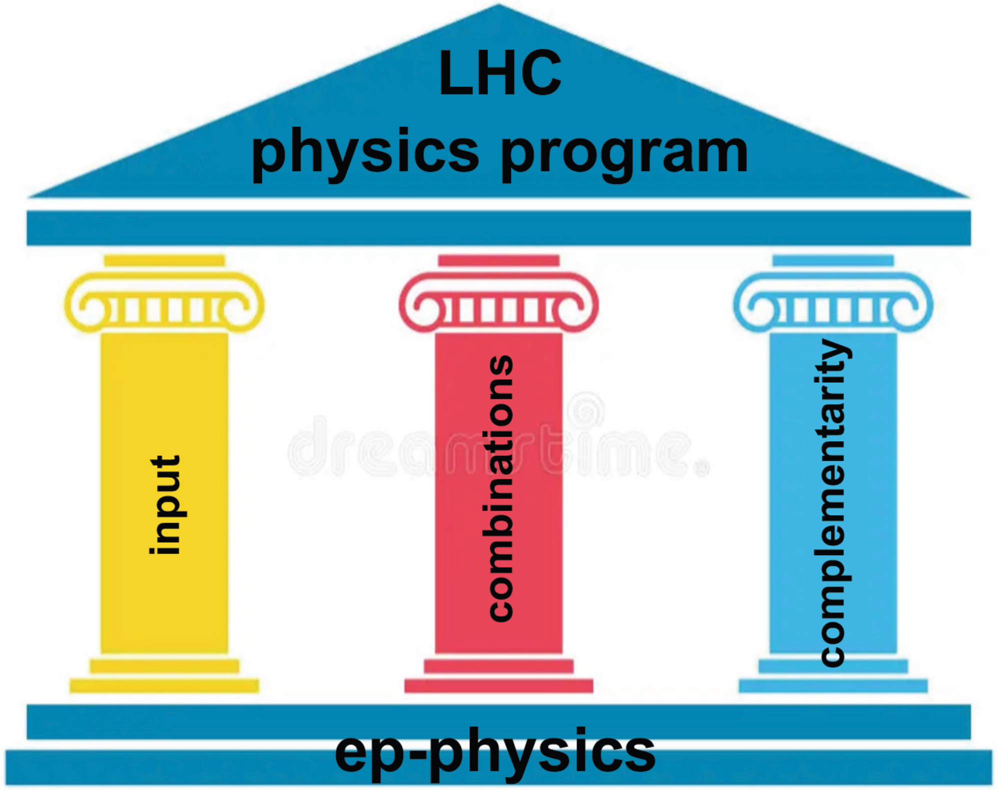
J. Osborne, W. Bromiley, A. Navascues



60 x 50000 GeV^2: **3.5 TeV ep collider** Cost (of ep) O(1-2) BCHF
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+

ep/eA-physics empowering pp/pA/AA-physics – Overview of Challenges

High precision *ep* measurements used as input in LHC analyses for their improvements



ep analyses with sensitivity complementary to LHC analyses to complete the overall LHC physics program

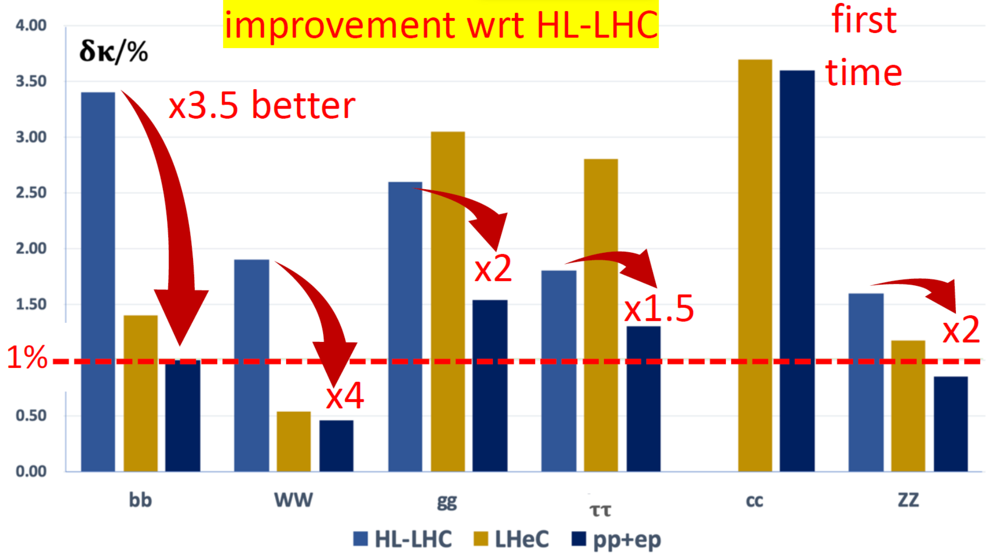
ep measurements to considerably improve LHC physics output, e.g. in final combinations

Some LHeC physics highlights achievable by ~2045

J.Phys.G 48 (2021) 11, 110501 [2007.14491]

Higgs physics — pp+ep

improvement wrt HL-LHC



EW physics — pp+ep

- Δm_W down to 2 MeV (today at ~10 MeV)
- $\Delta \sin^2\theta_W^{eff}$ to 0.00015 (same as LEP)

Top quark physics — ep

- $|V_{tb}|$ precision better than 1% (today ~5%)
- top quark FCNC and γ, W, Z couplings

DIS scattering cross sections — ep in 1 year

- PDFs extended in (Q^2,x) by orders of magnitude

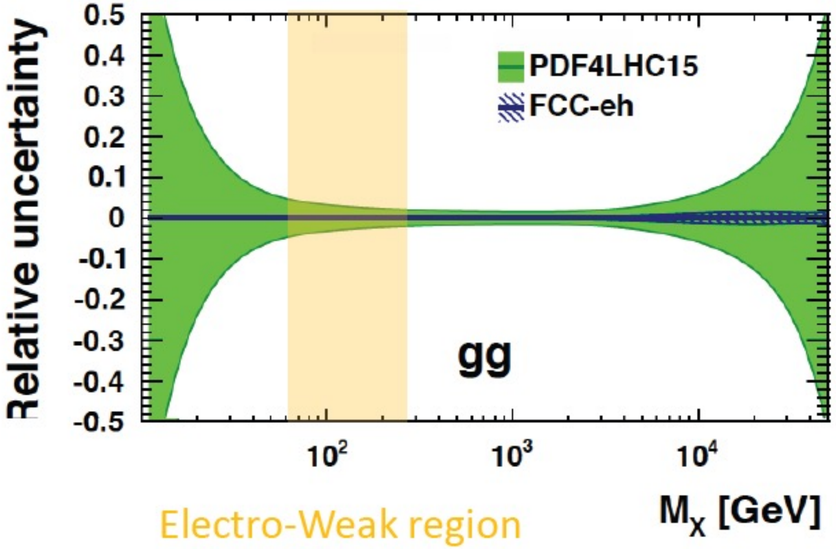
Strong interaction physics — ep in 1 year

- α_s precision of 0.2%
- low-x: a new discovery frontier

For LHC-pp: Precise Higgs cross section prediction with LHeC ep input: **$\delta\sigma$(pp→ Higgs)=[0.3 (PDF) + 0.2 (α_s)]%**

Empowering the FCC-hh program with the FCC-eh

pp @ 100 TeV



Electro-Weak region

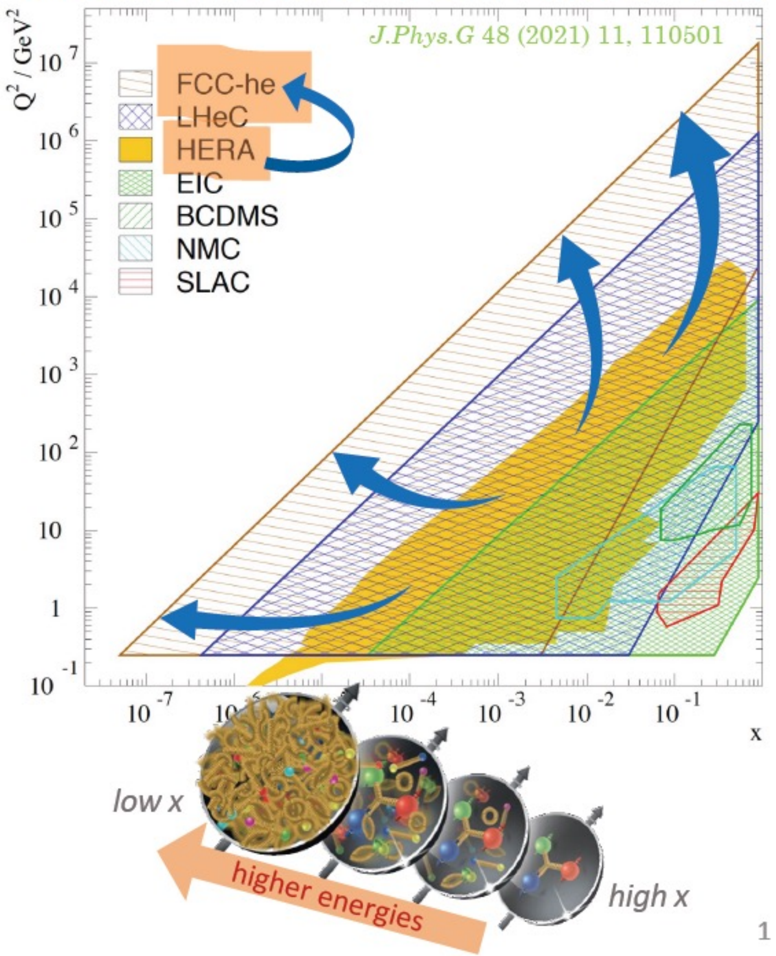
~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

with FCC-eh

~1% uncertainty on the σ(W,Z,H)

Kinematic range Parton Distribution Functions

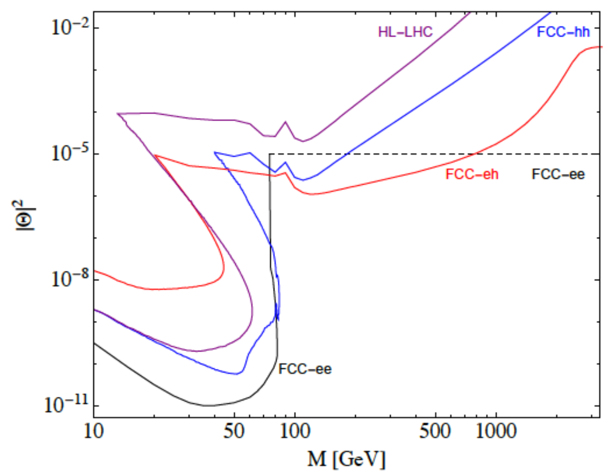


FCC-eh essential to unlock FCC-hh science potential

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**

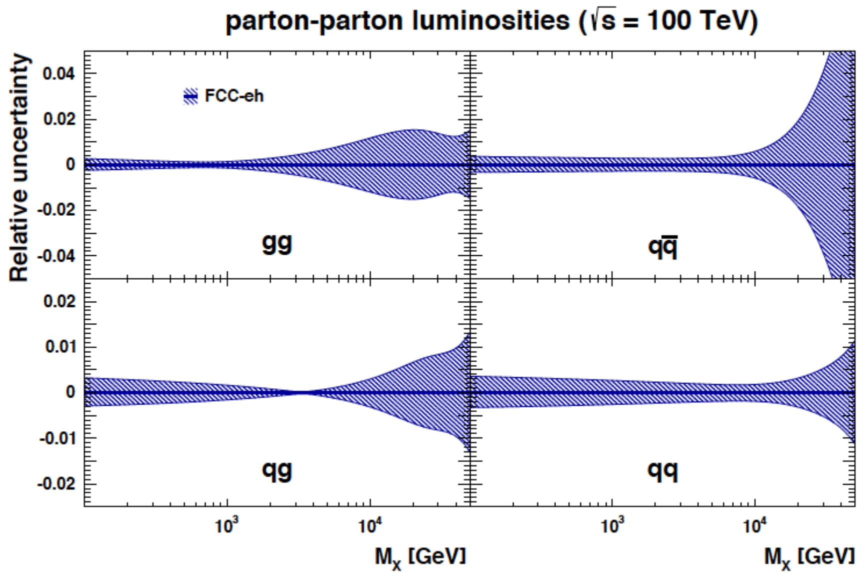
Some striking physics eh prospects are on searches and the high precision measurements on Higgs and proton structure:



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



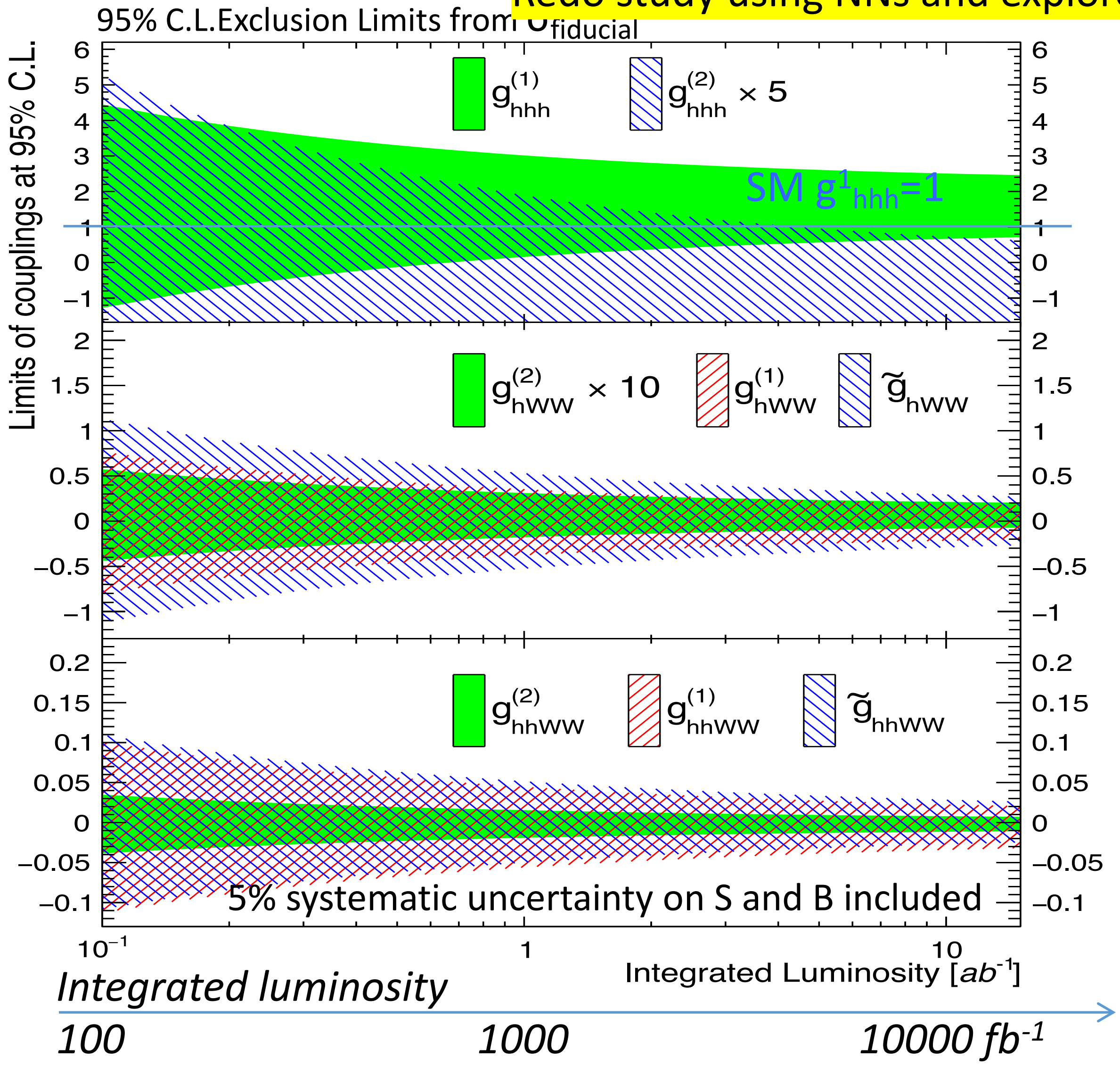
Unique resolution of partonic contents of and dynamics inside the proton, providing precise and independent parton luminosities for interpretation and searches on FCC-hh

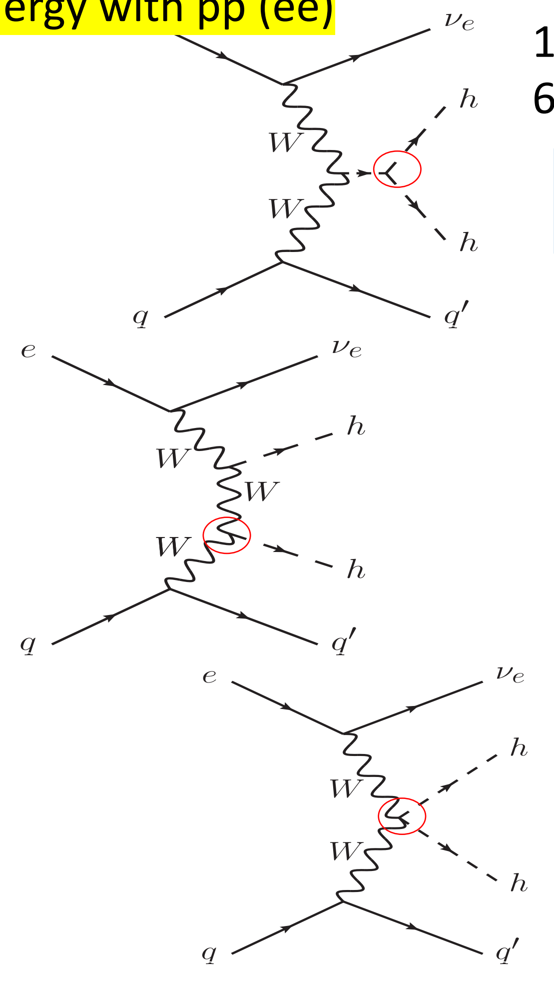
Example: Double Higgs Production

FCC-eh g_{HHH} ~ 20% in ep

Encouraging FCC-eh cut-based study; full Delphes-detector simulation; conservative HFL tagging

Redo study using NNs and explore synergy with pp (ee)





Here $g^{(i)}_{(\dots)}, i = 1, 2$, and $\tilde{g}_{(\dots)}$ are real coefficients corresponding to the CP-even and CP-odd couplings respectively, of the hhh, hWW and $hhWW$ anomalous vertices.

1σ for SM hhh for E_e 60 (120)GeV and 10ab^{-1}

$$g^{(1)}_{hhh} = 1.00^{+0.24(0.14)}_{-0.17(0.12)}$$

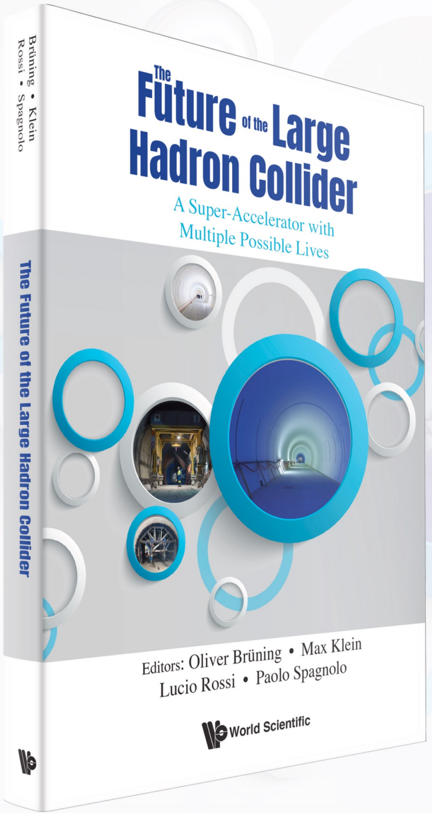
Probing anomalous couplings within Higgs EFT: limits are obtained by scanning one of the non-BSM coupling while keeping other couplings to their SM values.

➔ Very intriguing: How can HWW and Hbb from ep support HH discovery at HL-LHC?

Bands show the still allowed regions.

The Future of the Large Hadron Collider

A Super-Accelerator with Multiple Possible Lives



Editors:

Oliver Brüning
CERN, Switzerland

Max Klein
University of Liverpool, UK

Lucio Rossi
University of Milano, Italy & INFN, Italy

Paolo Spagnolo
INFN Pisa, Italy

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From ESPP 2020

“**Other essential scientific activities for particle physics …** An independent determination of the proton structure would be desirable to fully exploit the precision achievable with present and future hadron colliders. Detailed measurements of proton structure complement the investment in theoretical calculations and add sensitivity to searches for novel phenomena. A programme based on fixed-target experiments and on dedicated electron-proton machines, such as LHeC and FCC-ep, has been advocated in Europe.”

From ESPP 2020 to *ESPP 2025*: Opportunities

Detailed **physics** studies of the relation of *ep* and *pp*, as well as *eA* with *AA* (*pA*), physics to fully reveal synergies and benefits as e.g. for BSM and Higgs, in close Collaboration with theorists; N_3LO predictions and MC for TeV energy electron hadron scattering

→ see e.g., “Synergy workshop between ep/eA and pp/pA/AA physics experiments”
https://indico.cern.ch/event/1367865/overview

Accelerator technology ERL development: PERLE at Orsay. UK: **AsTEC, Cockcroft, Liverpool, also Lancaster**
International Collaboration: ESS Bilbao, CERN, Cornell, Grenoble, Jlab, Al-Najah Uni, Orsay *with iSAS project (kickoff in March 2023, funded by EU for sustainable RF and ERL technologies)*
PERLE at Orsay: Project leader W Kaabi (IJClab), Spokespersons M Klein (Liverpool) and A Stocchi (Director IJClab);
Linac cryomodule: ESS Lund, Cryo facility: Bessy (Berlin); Planned first beam in 2028.

Detector design in CDR update. to be continued: Si tracker post ITK (ATLAS), low radiation: CMOS; other topics
recent: Detector, Physics and IR paper on **joint ep/A and pp/AA operation with same detector: [2201.02436]**

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

Wrap Up

- *Energy frontier* ep would empower the physics potential of pp (non-resonant searches, EW, Higgs..) through high precision QCD measurements: flavour separated PDFs at N^3LO, α_S to per mille …
- Excellent opportunities for UK to contribute specifically to synergy prospects of pp+ep: physics, theory, as well as accelerator and detector in strong synergy with FCC-hh and ee

- *Our message: All three options ee, eh and hh belong together : This is "our task" to work this out in a sustainable and elegant way towards maximum physics insights for the benefit of the whole society.*

Combining pp with ep,
a very powerful twin facility can be established
at the HL-LHC already in the late 30ties
and later at the FCC eh+hh.

Wrap Up

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and later at the FCC eh+hh.

"It is difficult to make predictions, especially about the future."

Niels Bohr to Yogi Berra

"The Best Way to Predict the Future is to Create it."

Peter Drucker & Abraham Lincoln

How to get engaged?

The mandate for the high-energy ep/eA study at CERN was renewed in October 2022: "CERN continues to support studies for the LHeC and the FCC-eh as potential options for the future and to provide input to the next Update of the European Strategy for Particle Physics. The study is to further develop the scientific potential and possible technical realization of an ep/eA collider and the associated detectors at CERN, with emphasis on FCC."

In consultation with the International Advisory Committee, the Coordination Panel has developed new impact objectives for the ep/eA@CERN study, see also open kick-off meeting.

Coordination Panel members (May 2023): Nestor Armesto, Maarten Boonekamp, Oliver Brüning, Daniel Britzger, **Jorgen D'Hondt (spokesperson),** Monica D'Onofrio, Claire Gwenlan, Uta Klein, Paul Newman, Yannis Papaphilippou, Christian Schwanenberger, Yuji Yamazaki.

International Advisory Committee members (May 2023): Phil Allport, Diego Bettoni, **Frederick Bordry (chair),** Abhay Deshpande, Rohini Godbole, Beate Heinemann, Karl Jakobs, Young-Kee Kim, Max Klein, Eric Laenen, Jean-Philippe Lansberg, Tadeusz Lesiak, Dave Newbold, Vladimir Shiltsev, Johanna Stachel, Achille Stocchi.

New mailing lists have been created for each working group and with just a few clicks you can subscribe to them. Anyone with a CERN account or a light account can register via: *https://e-groups.cern.ch/* (use the search option, and search for "ep-eA-WG" in all e-groups).

WG 1: Proton and nuclear structure from EIC and HERA to LHeC and FCC-eh (conveners: N. Armesto, C. Gwenlan, P. Newman)

WG 2: General-purpose high-energy physics program with precision physics and searches (conveners: M. D'Onofrio, U. Klein, C. Schwanenberger)

WG 3: ep/eA-physics empowering pp/pA/AA-physics (conveners: M. Boonekamp, D. Britzger, C. Schwanenberger)
WG 4: Developing a general-purpose ep/eA detector (conveners: P. Newman, Y. Yamazaki)

WG 5: Developing a sustainable LHeC and FCC-eh collider program (conveners: O. Bruning, Y. Papaphilippou)

For FCC-UK: Please contact Paul <paul.richard.newman@cern.ch>, Claire c.gwenlan1@physics.ox.ac.uk, Mc <Monica.D'Onofrio@cern.ch> and me <Uta.Klein@liverpool.ac.uk> .

Additional material

WHY?

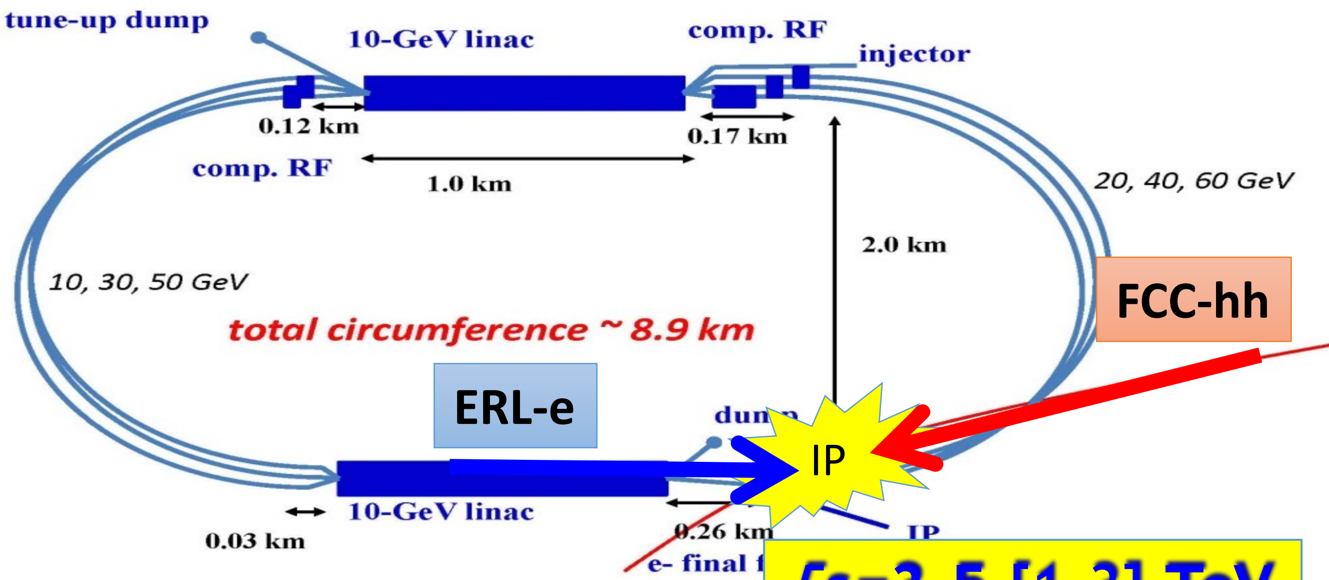
- Electron-hadron scattering at c.m.s. energies above 1 TeV@LHeC & 3 TeV@FCC-eh with luminosities of 100 fb^{-1} per year *building on great eh tradition in United Kingdom*
- Cleanest microscopes with which the substructure and theory of strong interactions, and its interplay with electroweak phenomena, may be probed principally with unprecedented reach and precision:
  - Unravelling of complete flavour-dependent parton dynamics at smallest hadron momentum fractions, 2-3 (4) orders of magnitude better than HERA&US-EIC for protons (nuclei).
  - Clear discovery potential for QCD phenomena: gluon saturation: yes or no?
  - Strong coupling at permille accuracy challenging lattice QCD results, synergy to ee
  - High precision, fundamental QCD and EW measurements like running sin2theta, quark couplings, CKM (V_{tb}).
  - High precision Higgs coupling measurements (Higgs cross sections comparable to ee).
  - Strong sensitivity for BSM physics (cleaner environment than hh, higher energy than ee).
- High impact:
  - Unique empowerment of hh physics potential.
  - Sustainable: World-new twin collider that ultimately exploit existing (LHC) and planned (FCC-hh) colliders by synchronous data taking of hh and eh data.
  - Novel energy recovery technology to generate electron beams of 20-60 GeV.
- High synergy effects in technology and further industrial applications also of low energy, high intense electron beams (PERLE in Orsay).

electrons for eh : ERL-e + FCC-hh [LHC]

- **Two 802 MHz Electron LINACs + 2x3 return arcs: using energy recovery in same structure: *sustainable* technology with power consumption < 100 MW** *instead of 1 GW for a conventional LINAC.*
- **Beam dump: no radioactive waste!**
- **high electron polarisation of 80-90%**

Concurrent eh and hh operation with same running time!

Genuine *Twin Collider* idea holds for LHC and FCC-hh.



$\sqrt{s}$=3.5 [1.3] TeV
E_e = 60 GeV
E_p = 50 [7] TeV

- **ep peak lumi 10^{34} cm s^{-2} s^{-1}** (based on existing HL-LHC design)
- **Operation scenario: F. Bodry et al.** CERN-ACC-2018-0037 [arXiv:1810.13022]
- **LHeC** [FCC-eh] **L= 1000** [2000] **fb^{-1} total collected in 10** [20] **years**
- **'No' pile-up**: <0.1@LHeC; ~1@FCCeh

ERL design detailed in LHeC CDR: J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001 [arXiv:1206.2913] and CDR update CERN-ACC-Note-2020-0002 [arXiv:2007.14491] accepted by J. Phys. G.

CERN-ACC-2018-0056

Higgs @ HL-LHC, ee and FCC-eh

within kappa framework; statistical errors only

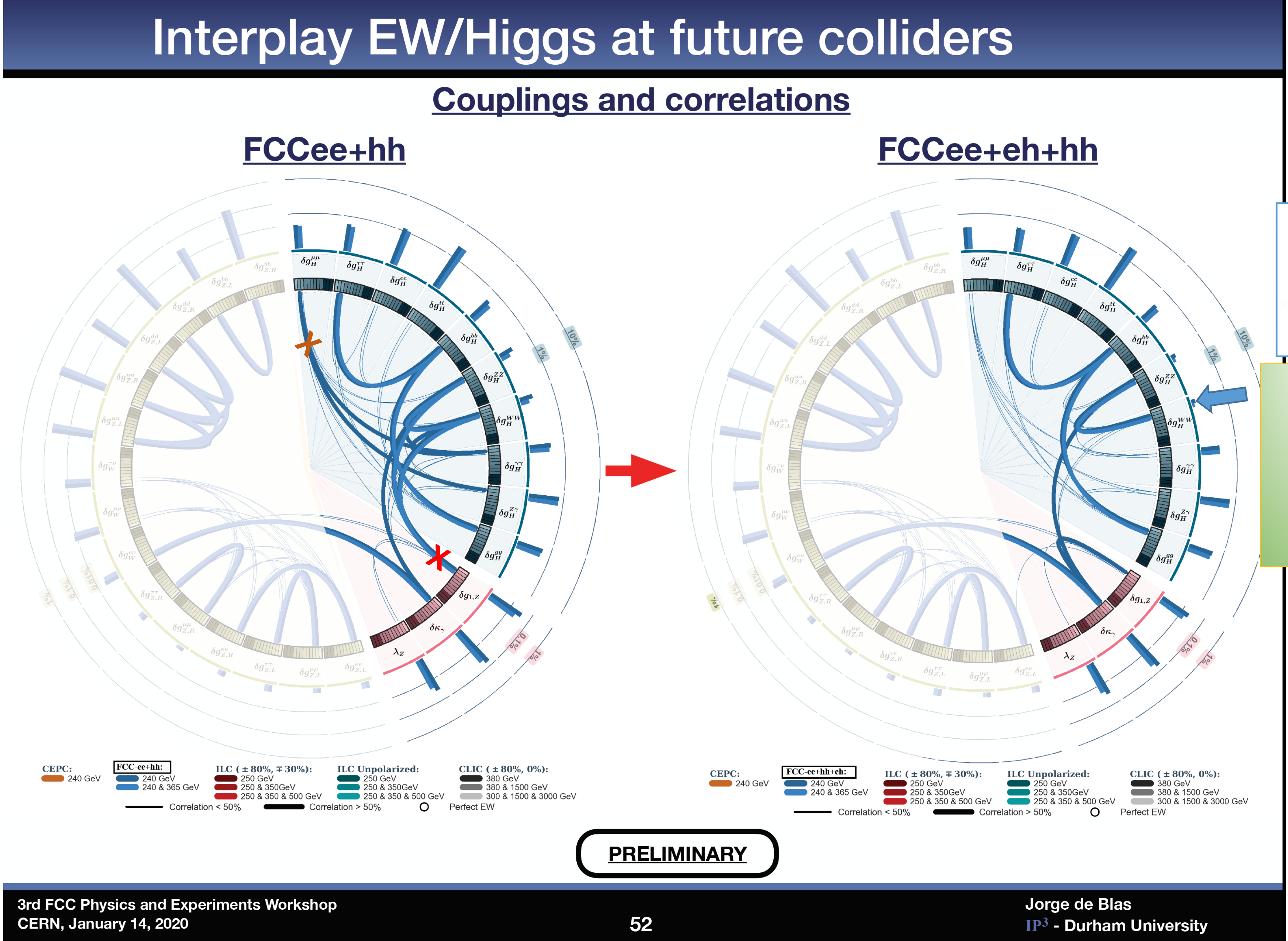
… to explore the synergy fully

FCC-eh

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	FCC-ee			FCC-eh
Luminosity (ab^{-1})	3	2	0.5	5 @ 240 GeV	+1.5 @ 365 GeV	+ HL-LHC	2
Years	25	15	7	3	+4	—	20
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.8	6.3	2.7	**1.3**	1.1	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.35	0.80	0.2	**0.17**	0.16	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.7	1.3	1.3	**0.43**	0.40	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.8	2.8	1.3	**0.61**	0.55	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	6.8	1.7	**1.21**	1.18	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	2.2	3.8	1.6	**1.01**	0.83	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.7	1.9	4.2	1.4	**0.74**	0.64	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	13	n.a.	10.1	**9.0**	3.9	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	6.4	n.a.	4.8	**3.9**	1.1	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	–	–	–	2.4	ttH 1.7
BR_{EXO} (%)	SM	< 1.8	< 3.0	< 1.2	$<$ **1.0**	< 1.0	n.a.

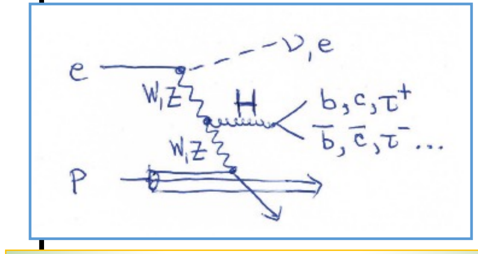
➔ Combine the complementary measurements for best physics outcome!
➔ FCC-hh will be the machine to pin down HH and all rare decays!

Higgs-inv.: 1.2%
HH ~20%



J de Blas at FCC WS 2020

See also Talk by Sally Dawson@DIS21, p13 Higgs at future colliders; Tables in backup & [arXiV: 1905.03764]



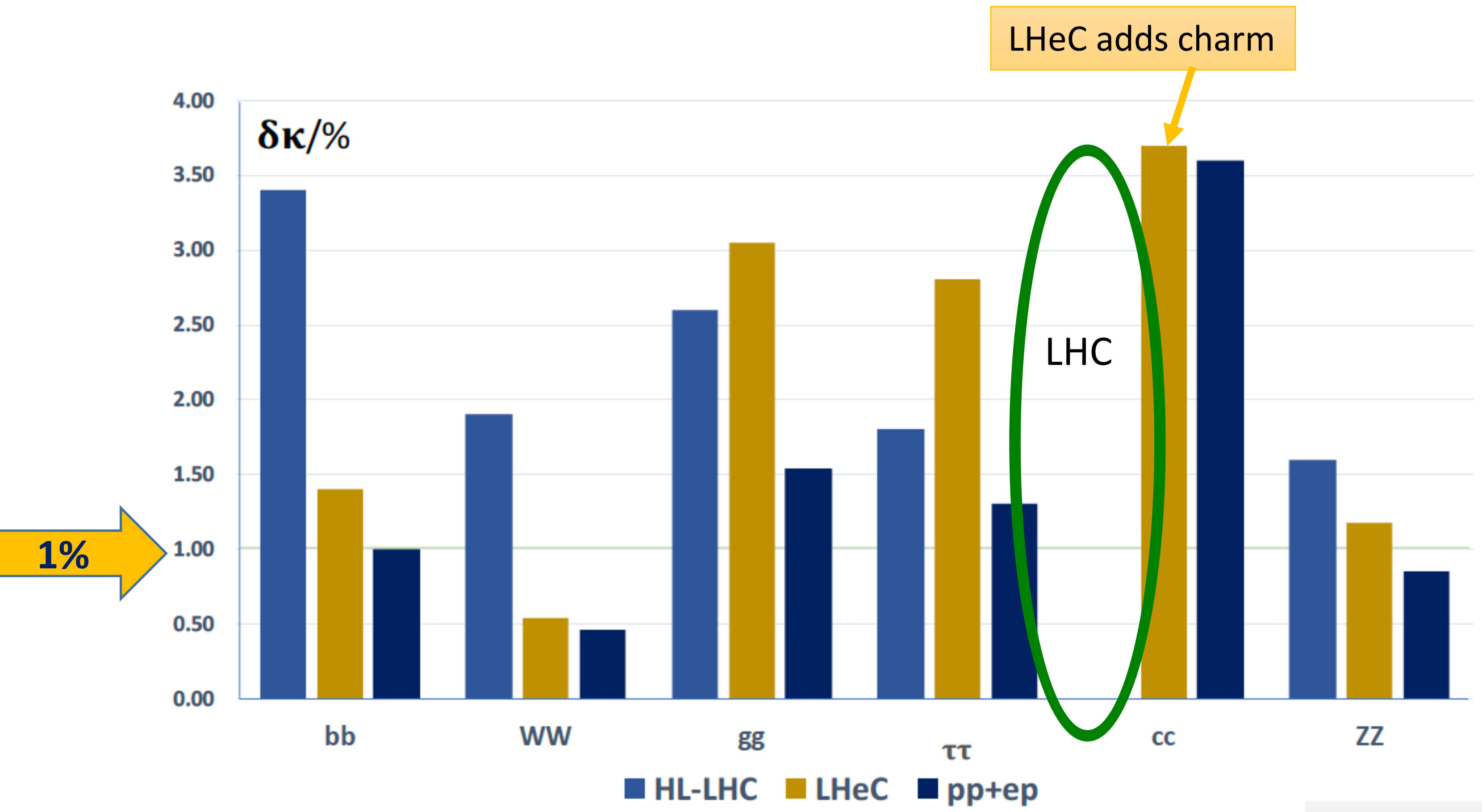
eh resolves HWW-HZZ correlation, see line marked with X on left plot, and reduces further correlations X

Higgs production in the three collider modes ee, ep, pp are also important for theory development

For the near future*: SM Higgs Couplings & $\delta\sigma_{\text{Higgs}}$ (pp)

Update of LHeC ES submission CERN-ACC-2018-0084 & CDR update [arXiv:2007.14491]

LHeC and HL-LHC prospects



Parameter	Uncertainty		
	HL-LHC	LHeC	HL-LHC+LHeC
κ_W	1.7	0.75	0.50
κ_Z	1.5	1.2	0.82
κ_g	2.3	3.6	1.6
κ_γ	1.9	7.6	1.4
$\kappa_{Z\gamma}$	10	–	10
κ_c	–	4.1	3.6
κ_t	3.3	–	3.1
κ_b	3.6	2.1	1.1
κ_μ	4.6	–	4.4
κ_τ	1.9	3.3	1.3

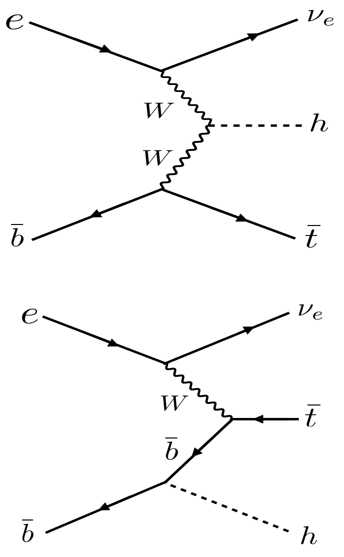
For LHC: Precise Higgs cross section prediction with LHeC input:

$\delta\sigma(pp \rightarrow \text{Higgs}) = [0.3\ (\text{pdf}) + 0.2\ (\alpha_s)]\%$

* see also backup slide

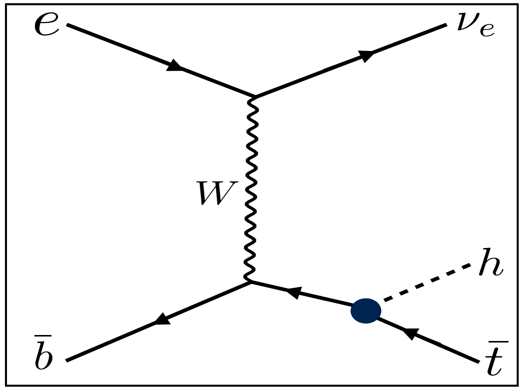
Top Yukawa Coupling @ LHeC

B.Coleppa, M.Kumar, S.Kumar, B.Mellado, PLB770 (2017) 335



SM:

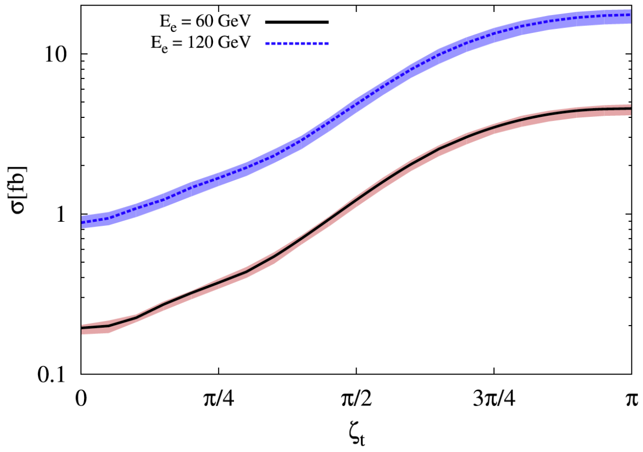
$$\mathcal{L}_{\text{Yukawa}} = -\frac{m_t}{v}\bar{t}th - \frac{m_b}{v}\bar{b}bh,$$



BSM: Introduce phases of top-Higgs and bottom-Higgs couplings

$$\mathcal{L} = -\frac{m_t}{v}\bar{t}\,[\kappa\cos\zeta_t + i\gamma_5\sin\zeta_t]t\,h$$
$$-\frac{m_b}{v}\bar{b}\,[\cos\zeta_b + i\gamma_5\sin\zeta_b]b\,h.$$

Enhancement of the DIS cross-section as a function of phase



CP even sign flip

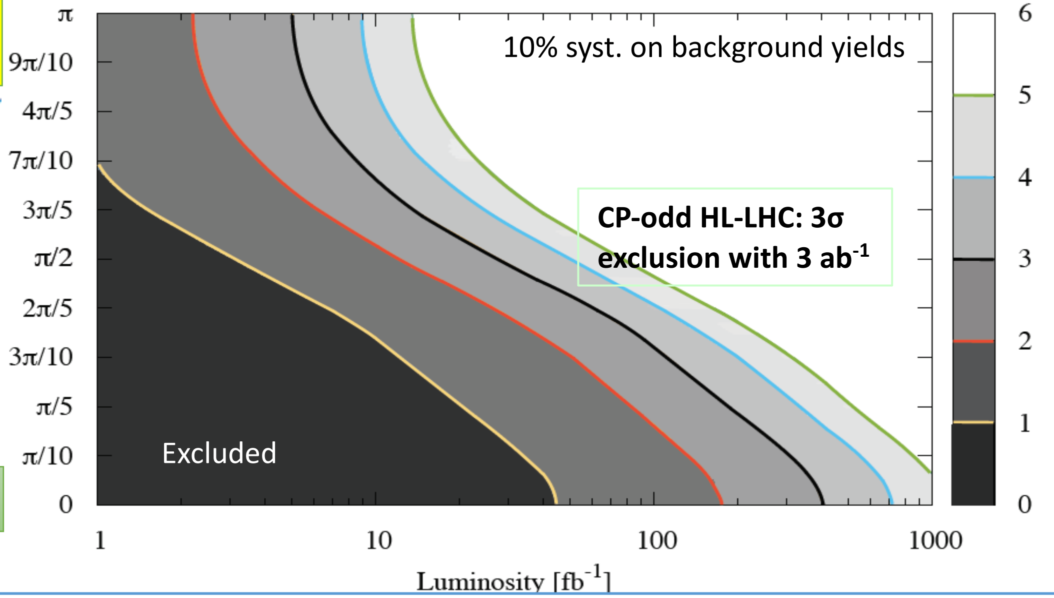
$\zeta_{t,b} = \pi$

CP odd

$\zeta_{t,b} = \frac{\pi}{2}$

CP even SM

$\zeta_t = 0$



Observe/Exclude non-zero phase to better than 4σ

➔ With Zero Phase: Measure **ttH** coupling with **17% accuracy at LHeC** ➔ **extrapolation to FCC-eh: ttH to 1.7%**