Future lepton-based colliders and ERL

- Impact on the physics program and potential (J. D'Hondt for M. Klein)
- ERL-based machine developments and plans (A. Hutton)

Andrew Hutton (Jefferson Laboratory)
Max Klein (Uni. Liverpool)

LDG Workshop on Future Accelerator R&D, Frascati, 11.7.2023, for the ERL Coordination Panel

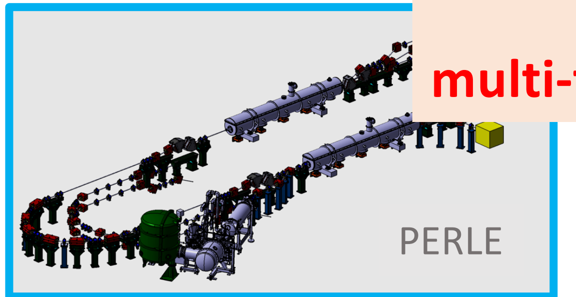
Potential impact of ERL technology

With stepping stones for innovations in technology to boost our physics reach

enables the ultimate upgrade of the LHC program

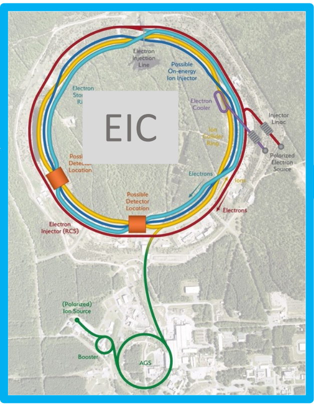
2020'ies

demonstrate multi-turn high-power ERL



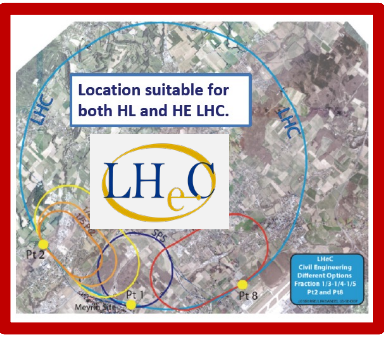
high-power ERL demonstrated

2030'ies



ERL application electron cooling

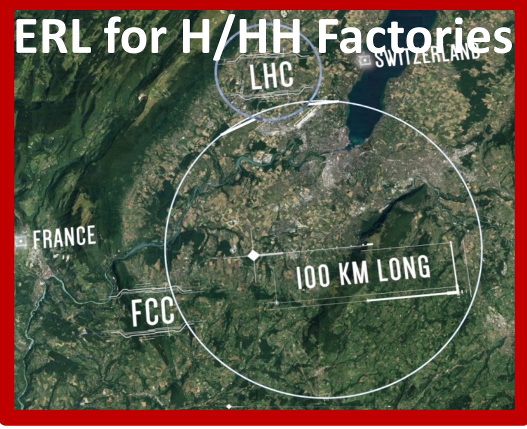
2030-2040'ies



1 ERL beam

high-power ERL e^- beam in collision (ep/eA @ LHC program)

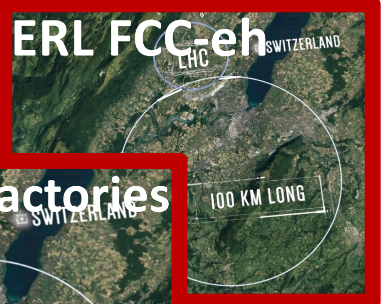
2040-2050'ies



2 ERL beams

high-power ERL for e^+e^- Higgs Factories (Z/W/H/top/HH program)

2070'ies

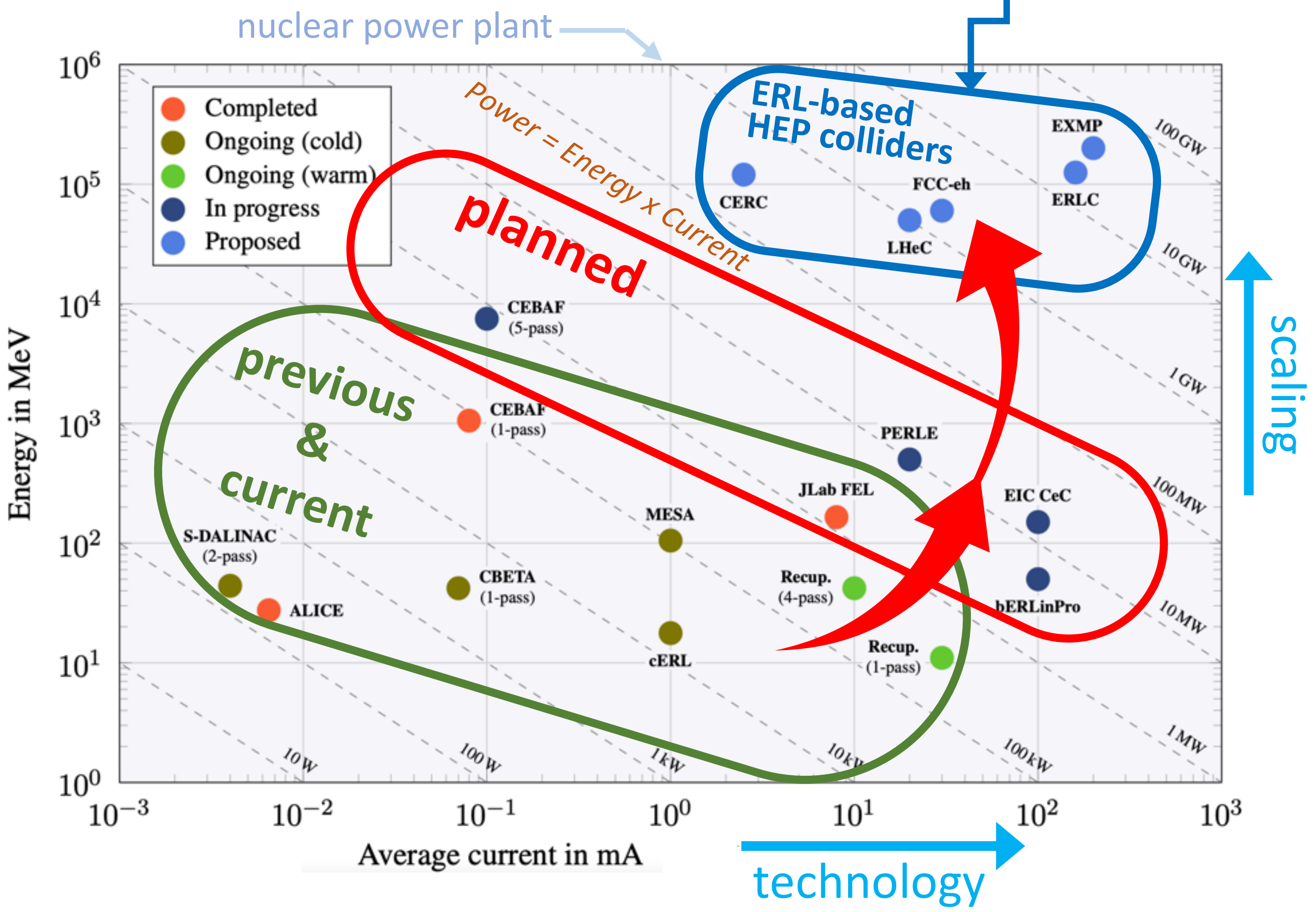


reuse ERL

increases the performance of the next major colliders

Lepton Based Colliders in the ERL Roadmap

ERL to enable high-power beams that would otherwise require one or more nuclear power plants



Three kinds of lepton based colliders are studied using ERL technology:

- **electron-positron Higgs facilities**
  CERC (FCC), *arXiv:2203.07358*
  ReLiC, *arXiv:2203.06476*
  ERLC (ILC), *arXiv:2302.09758*
  di-Higgs, *Roadmap, AH ERLWS22*

- **electron-proton colliders**
  LHeC/FCCeh, *arXiv:2007.14491*
  EIC, *e.g. F. Willeke EPS2021*

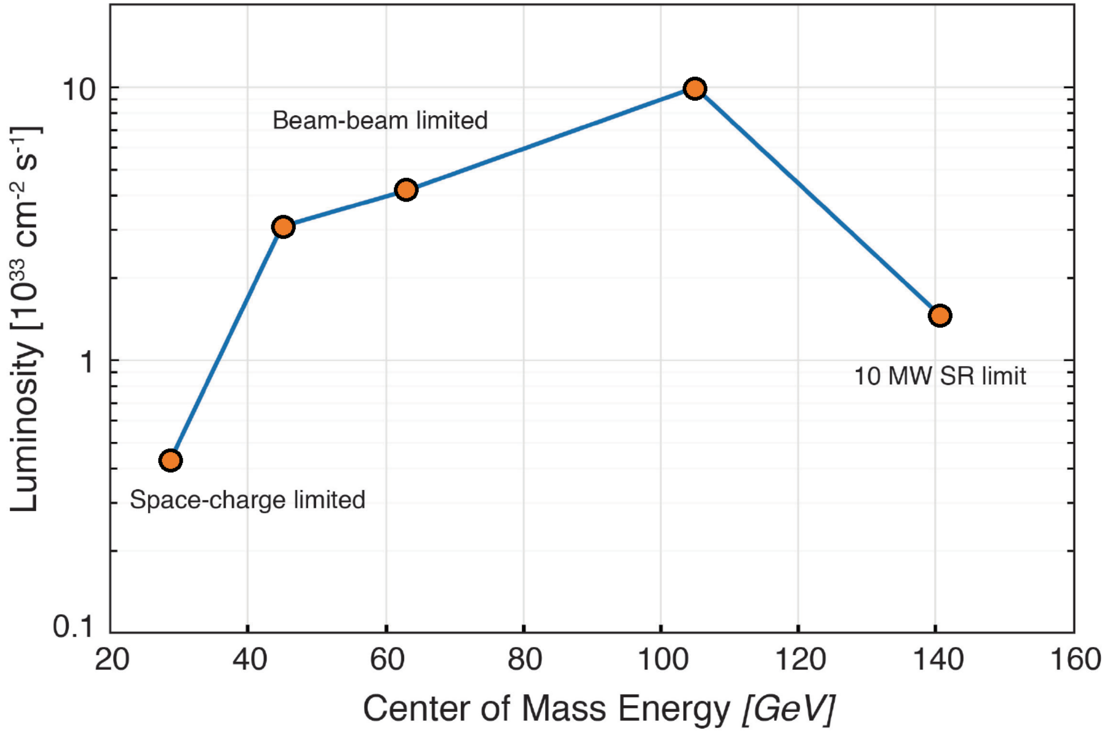
- **muon collider**
  EXMP, *arXiv:2106.03255 & 2304.08788*

High luminosity with reduced power, and focus on the exploration of the Higgs sector

ERL technology for the EIC

Electron Ion Collider

Plot from F.Willeke: EPS2021

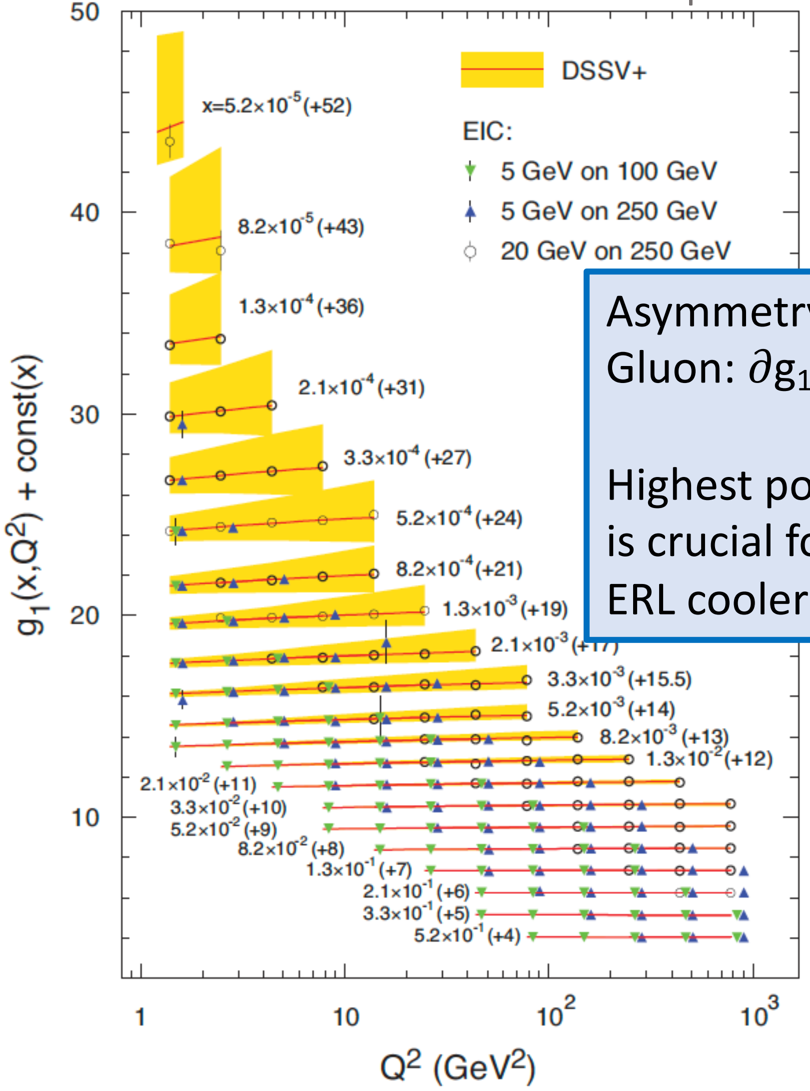


Optimised polarised ep luminosity vs cms energy
Peak luminosity at 105 GeV w/o cooler: 0.44 10^{34}

See also W.Fischer et al, eh luminosity optimisation, IPAC 2021
doi:10.18429/JACoW-IPAC2021-WEPAB004

$$g_1(x,Q^2) = \frac{1}{2}\sum e_q^2 \left[\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)\right]$$

arXiv:1212.1701 EIC White Paper

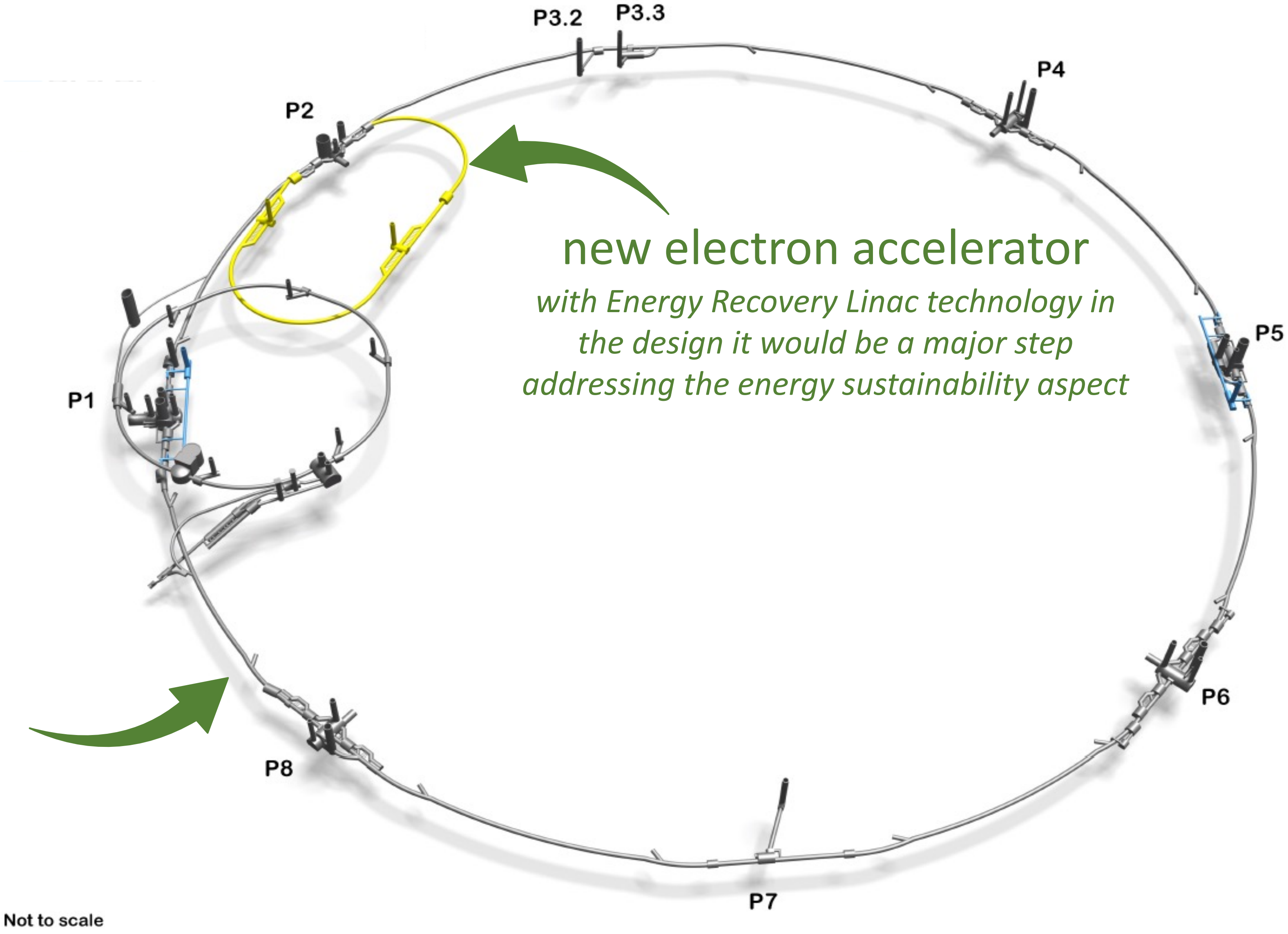


Asymmetry: $A_{||} \sim x$
Gluon: $\partial g_1/\partial \ln Q^2 \sim \Delta G$

Highest possible luminosity is crucial for spin program.
ERL cooler essential for EIC

ERL-based ep/eA colliders

A paradigm shift: high-energy electron-proton collions



new electron accelerator

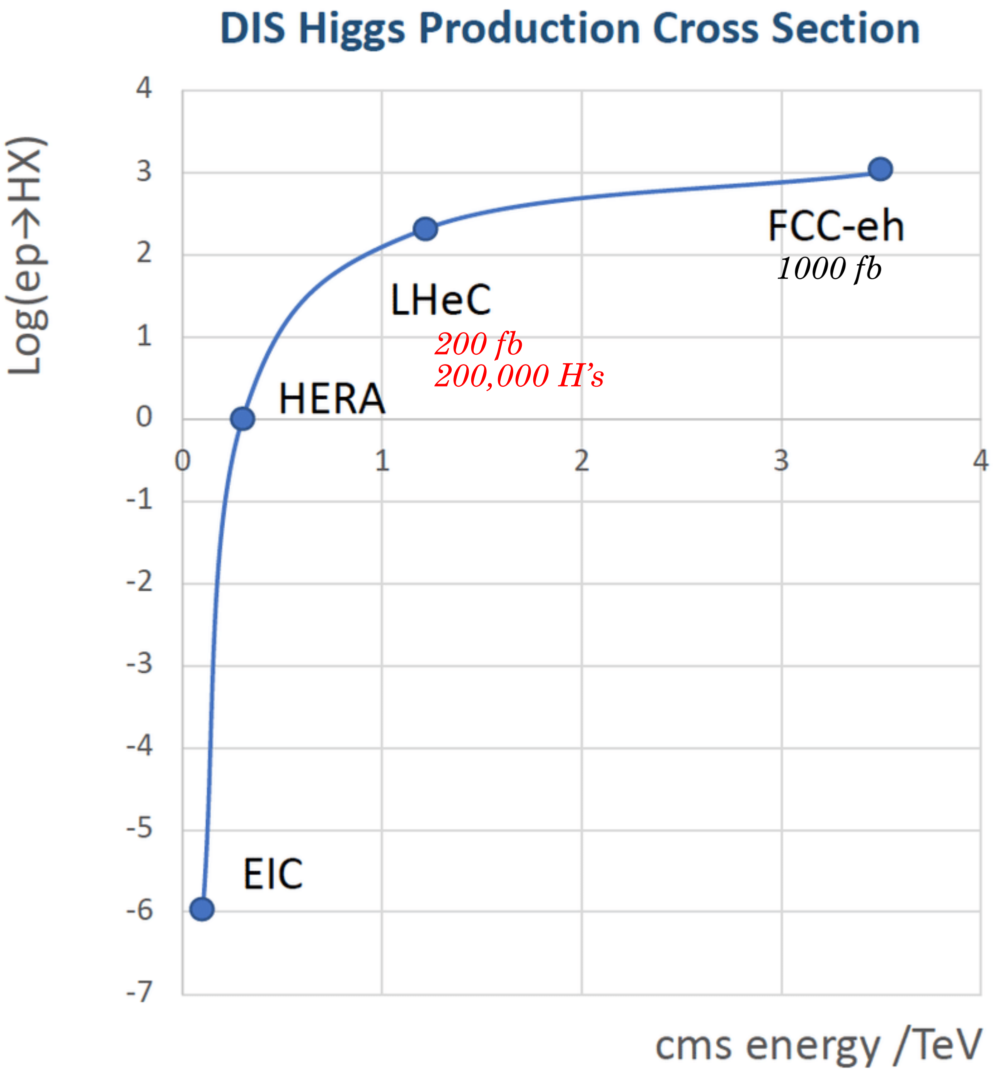
with Energy Recovery Linac technology in the design it would be a major step addressing the energy sustainability aspect

existing/future proton accelerator

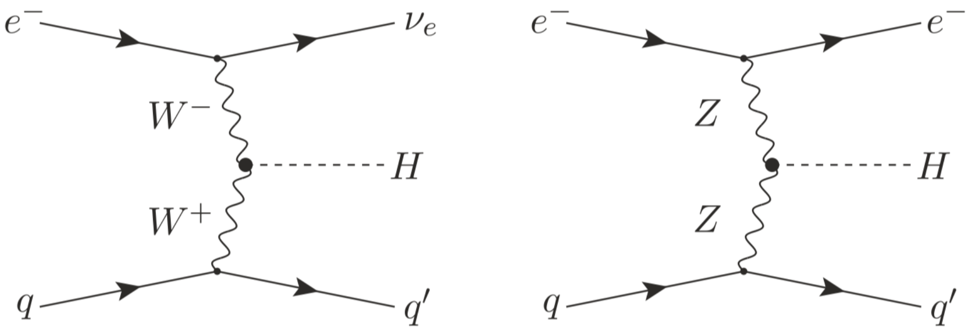
LHC and/or FCC

Collision energy above the threshold for EW/Higgs/Top

from mostly QCD-oriented physics to General-Purpose physics



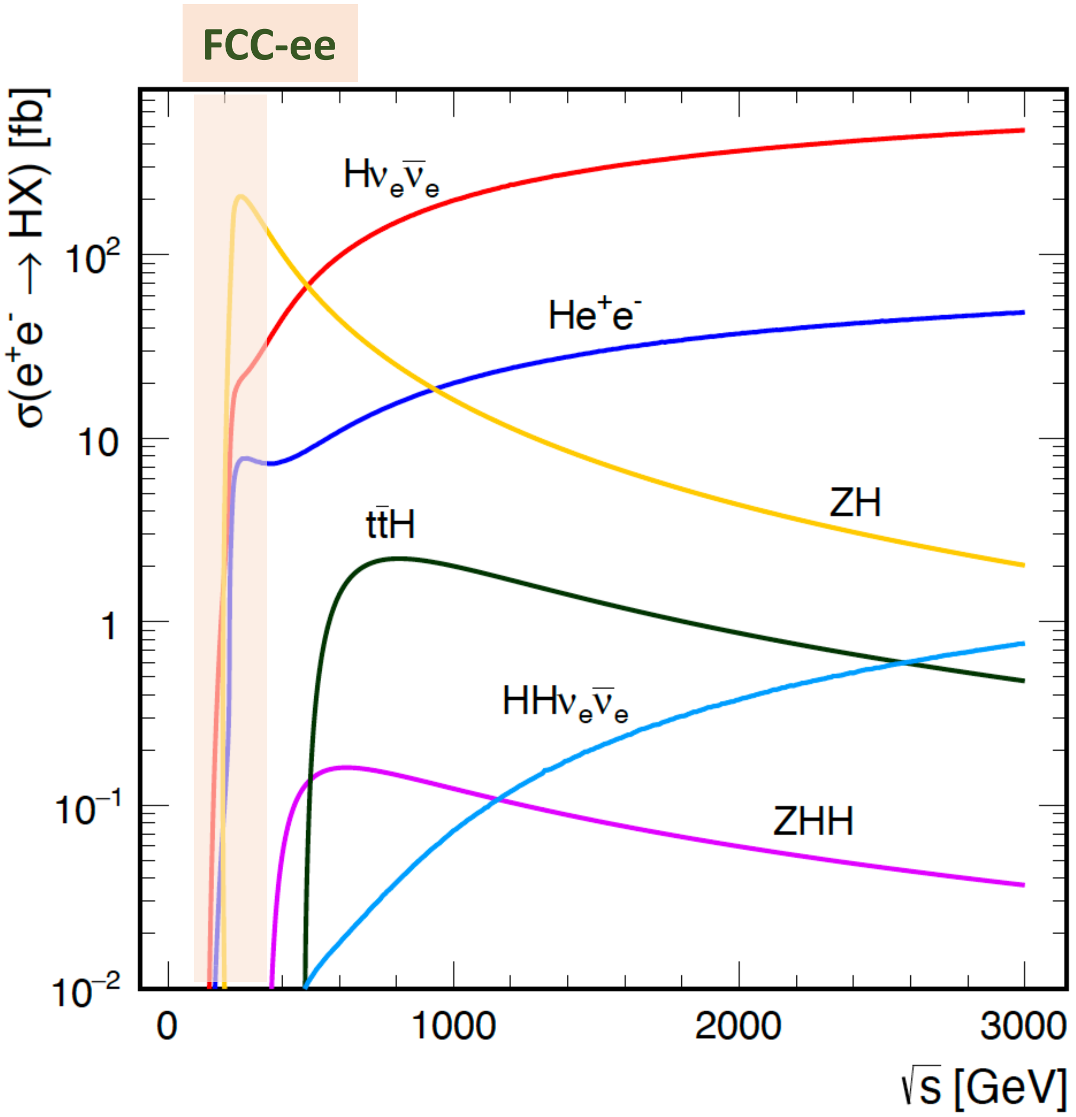
The real game change between HERA and LHC/FCC

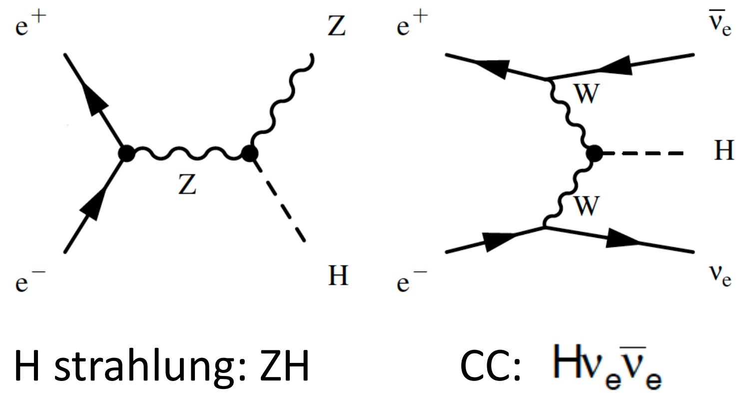


compared to proton collisions, these are reasonably clean Higgs events with much less backgrounds

at these energies and luminosities, interactions with all SM particles can be measured precisely

Higgs Production Cross Sections in e^+e^- and ep

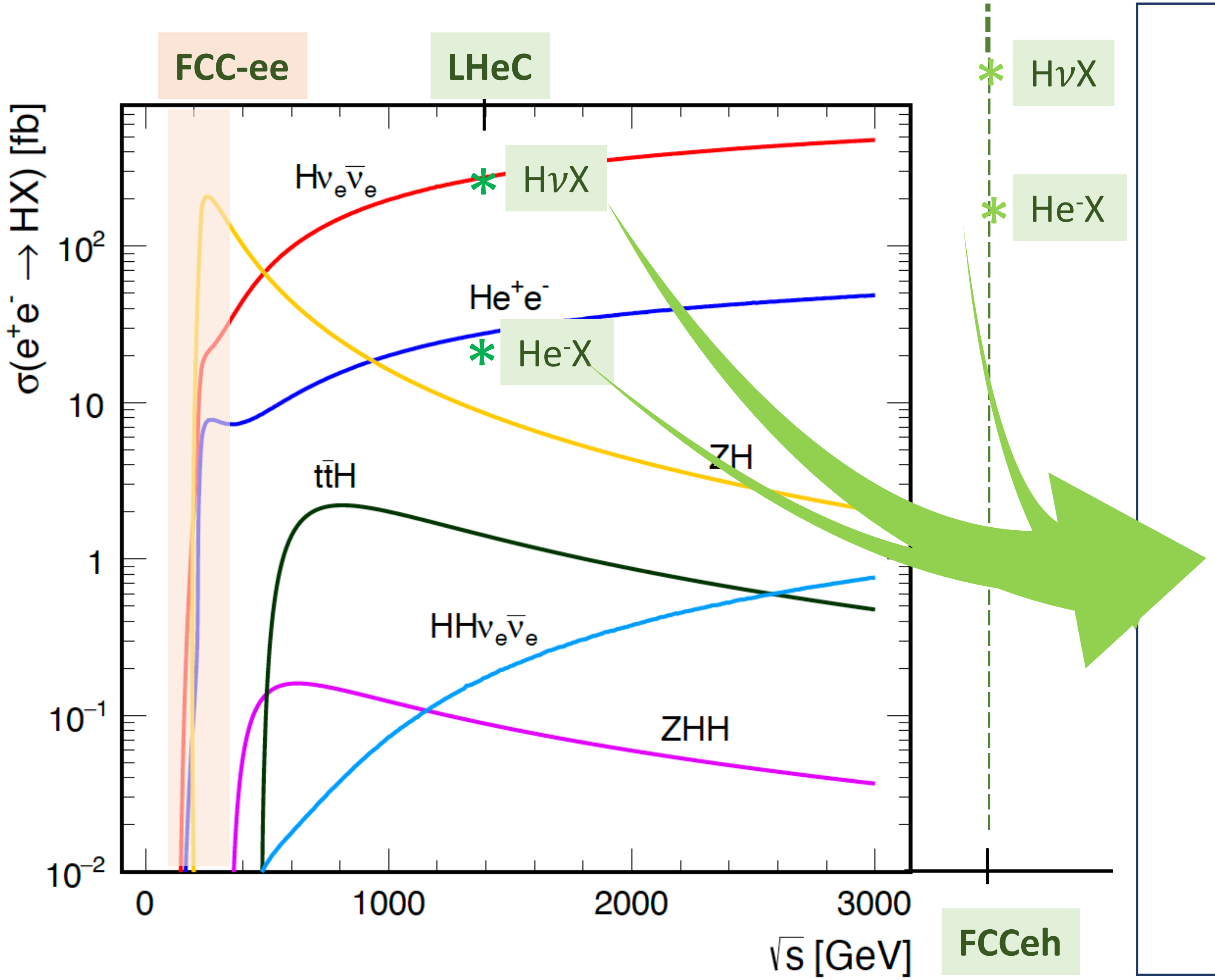


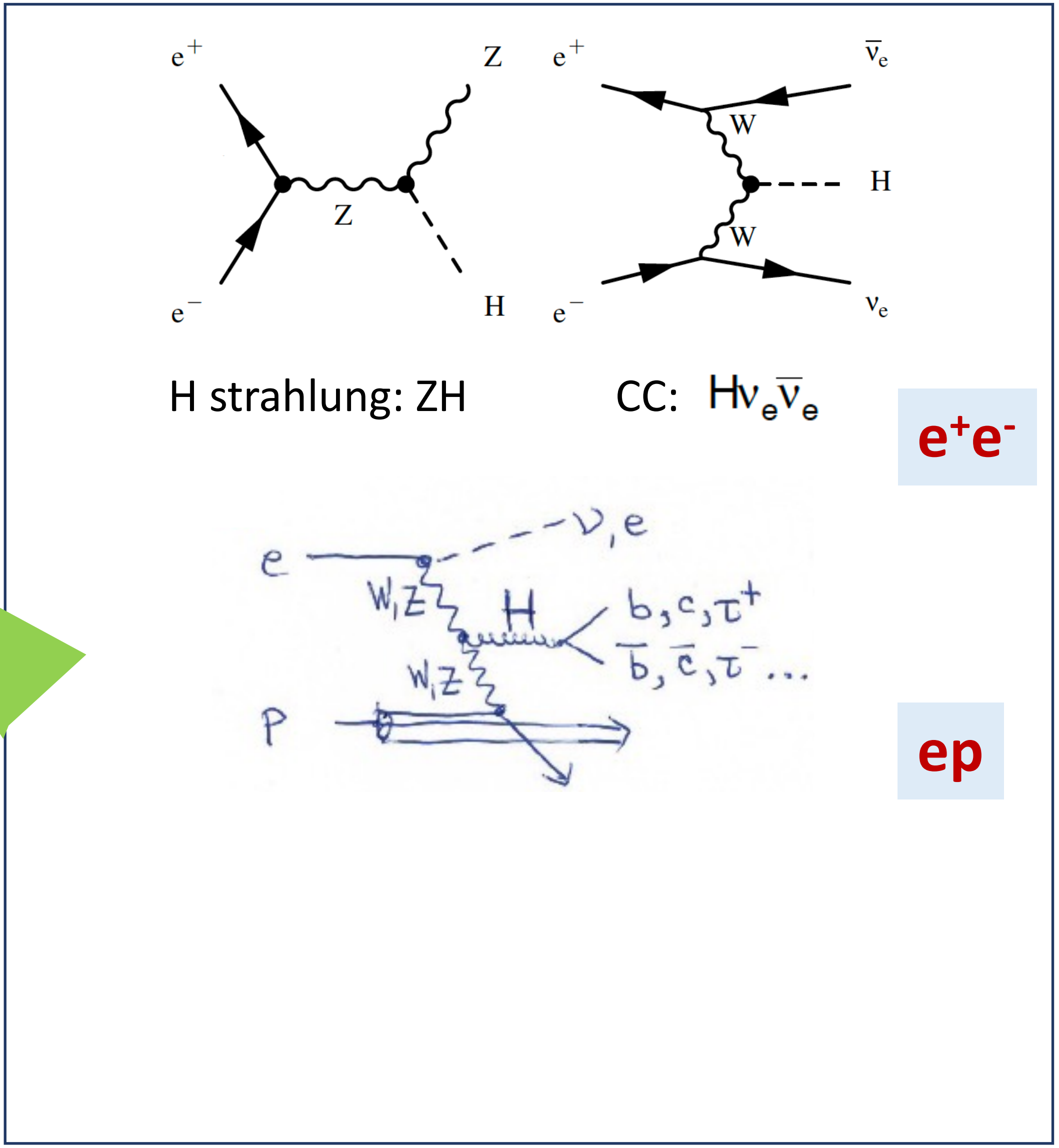


e^+e^-

e^+e^-: arXiv:1608.07538

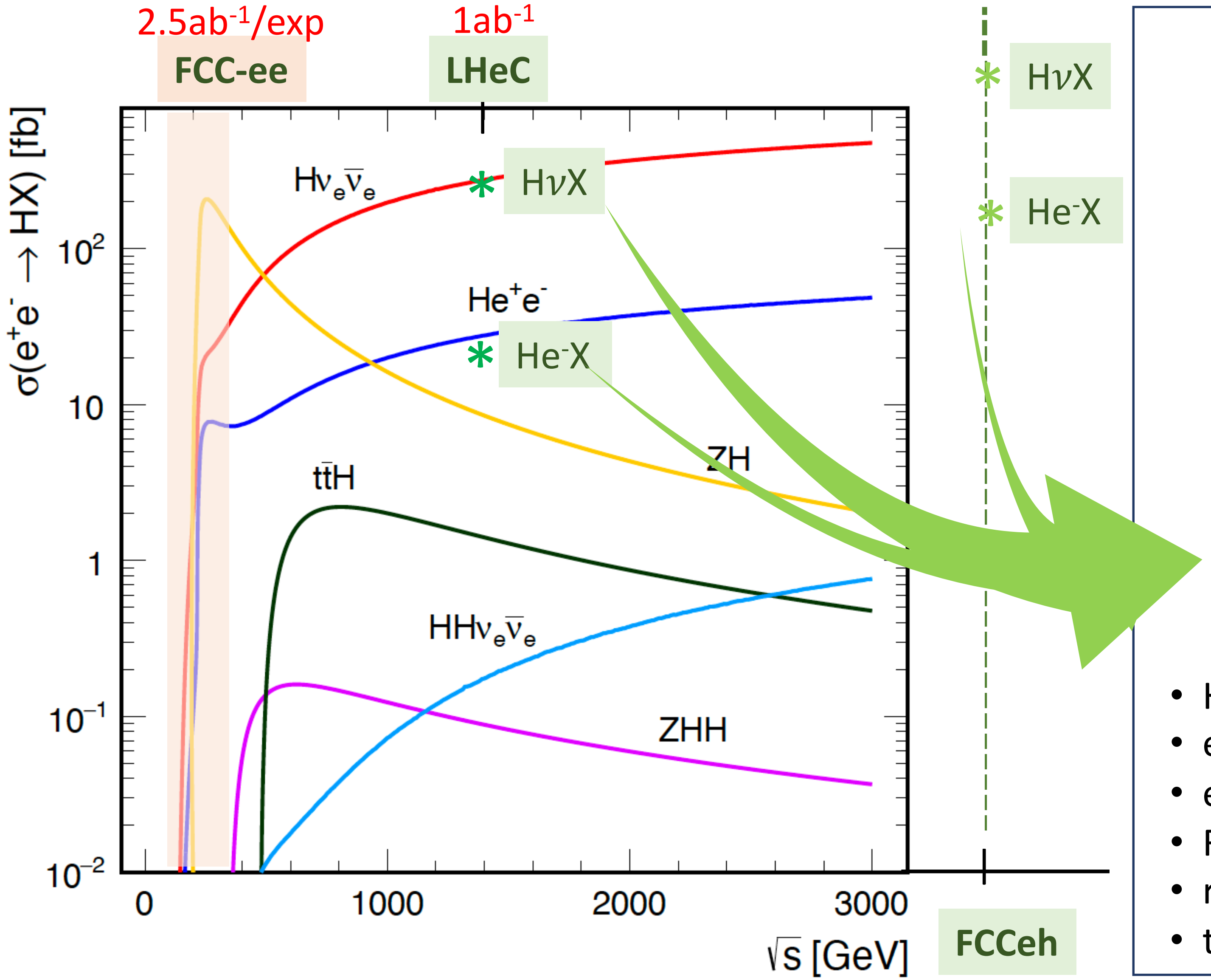
Higgs Production Cross Sections in e^+e^- and ep

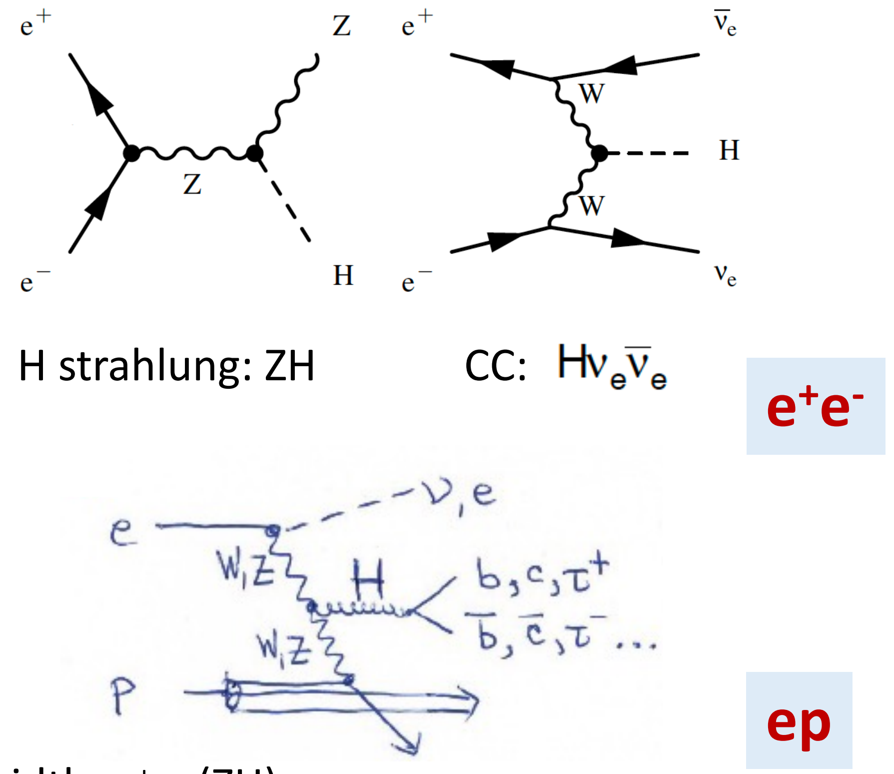




ee: arXiv:1608.07538, (*) ep: U.Klein arXiv:2007.14491

Higgs Production Cross Sections in e^+e^- and ep

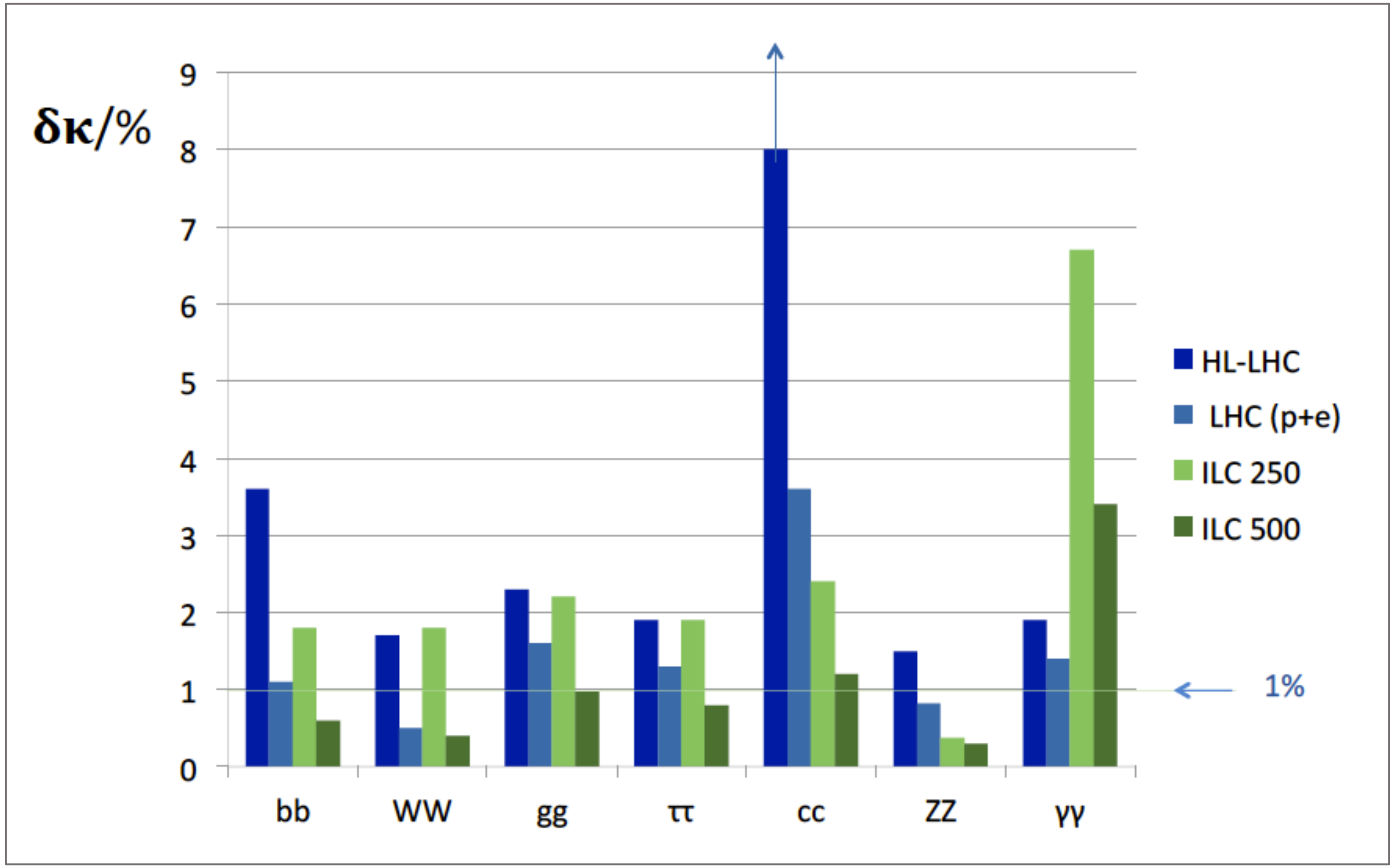




- H width: e^+e^- (ZH)
- $e^+e^-\oplus$ep get 99% of SM decays
- ep is reasonably clean from bck & no pile-up
- FCC-eh is as precise as FCC-ee
- rare decays for FCC-hh: needs ee/ep/pp
- trilinear coupling for hh/eh & high E$\oplus$Lumi e^+e^-

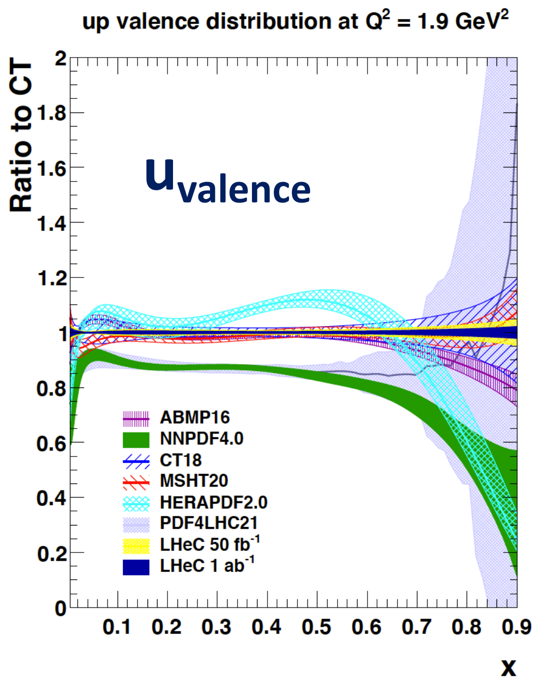
ee: arXiv:1608.07538, (*) ep: U.Klein arXiv:2007.14491

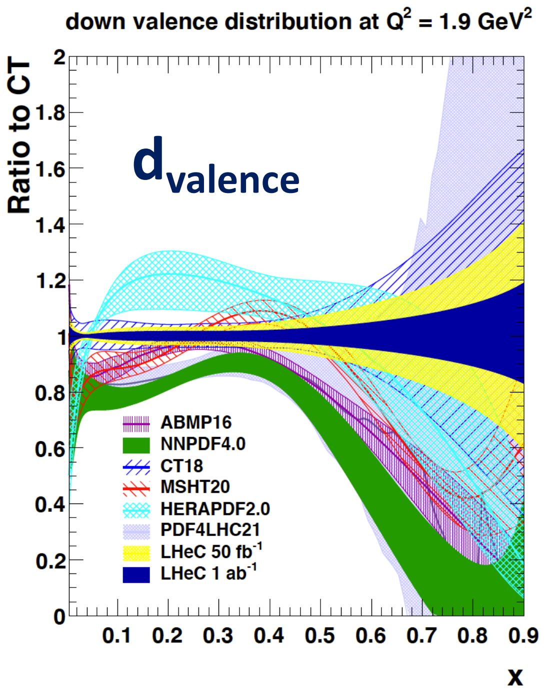
H couplings with LHC/LHeC & ILC



The HL-LHC⊕LHeC is performing very well compared to ILC250

LHeC Study Group arXiv:2007.14491 J.Phys.G and ECFA Newsletter 5/20



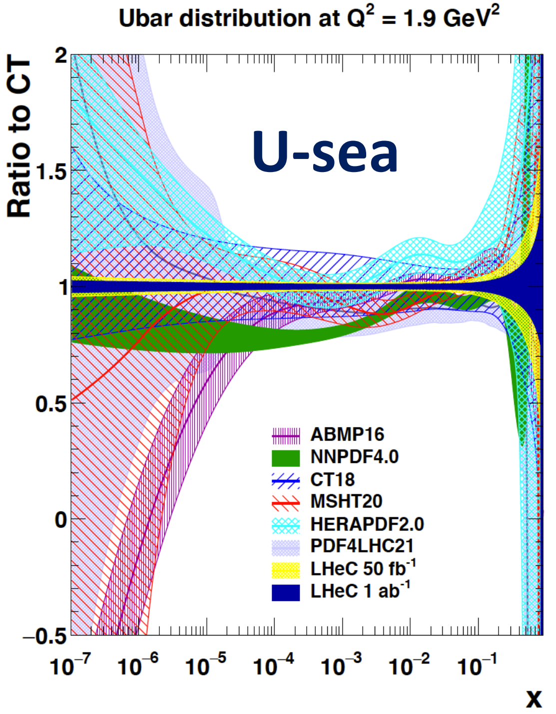


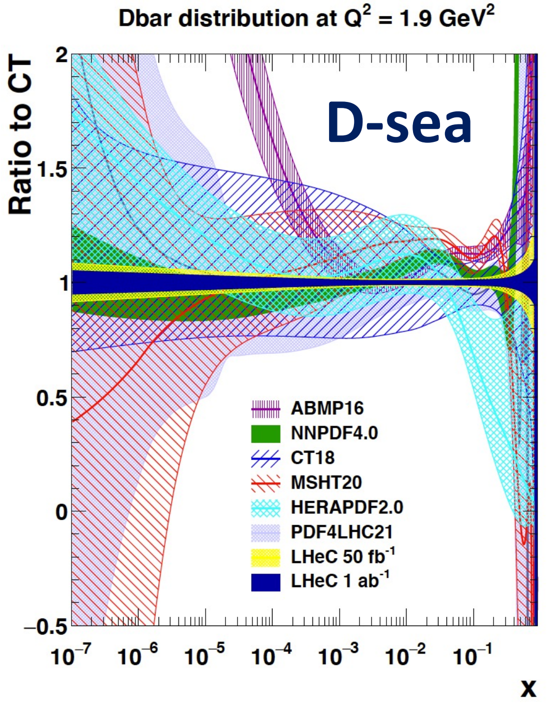
Uncharted QCD territory

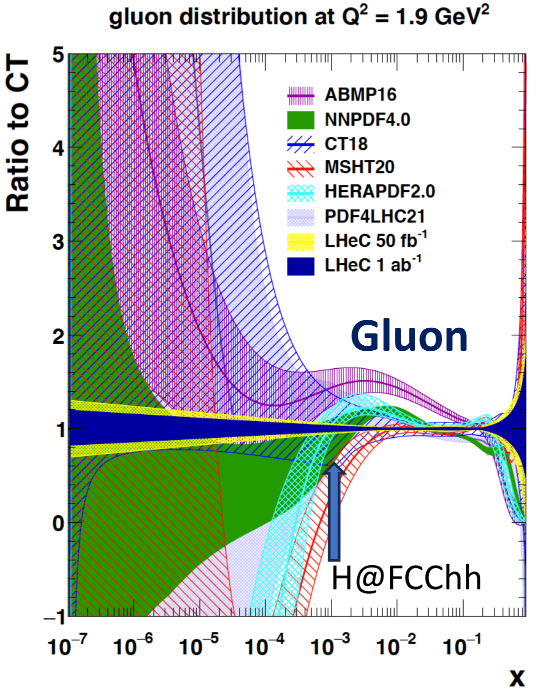
Parton Distribution Functions (PDF)

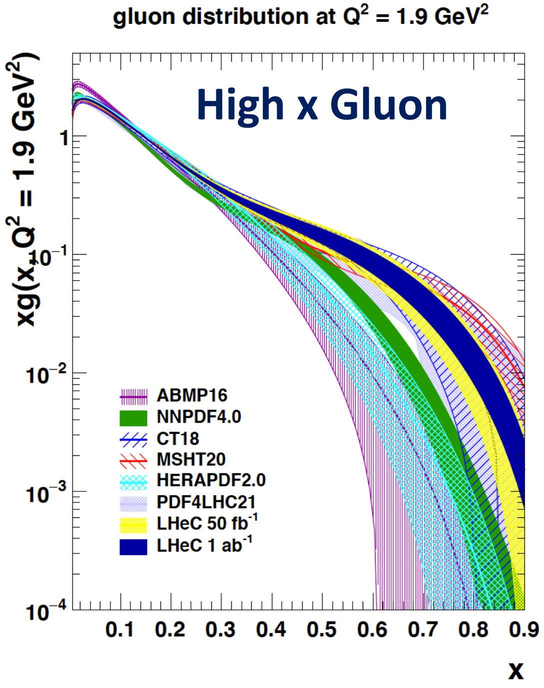
- QCD needs partonic contents to be resolved
- HL-LHC and FCC-hh are precision Higgs factories requiring accurate, N^{3}LO PDF and α_s input
- QCD dynamics at small x may be non-linear which would change many SM predictions for hh
- Global fits use inconsistent, hadronic data, which leads to spread of PDFs and uncertainty assumptions
- PDFs precisely determined only in high E/L DIS ep

For more information: see PDF chapter in LHeC CDR arXiv:2007.14491
update 10/22 C.Gwenlan, M.K. https://indico.ijclab.in2p3.fr/event/8623/



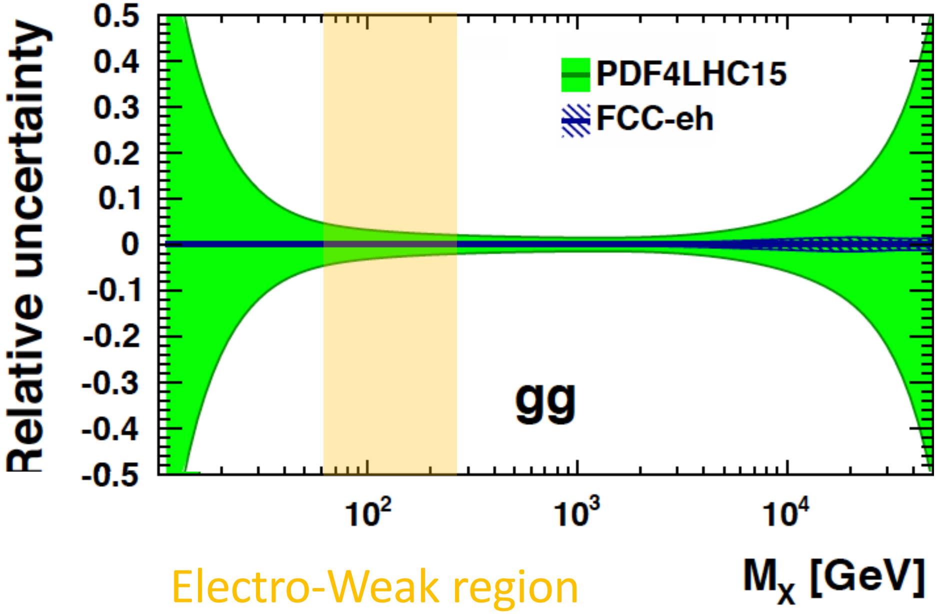






Empowering the FCC-hh program with the FCC-eh

pp @ 100 TeV

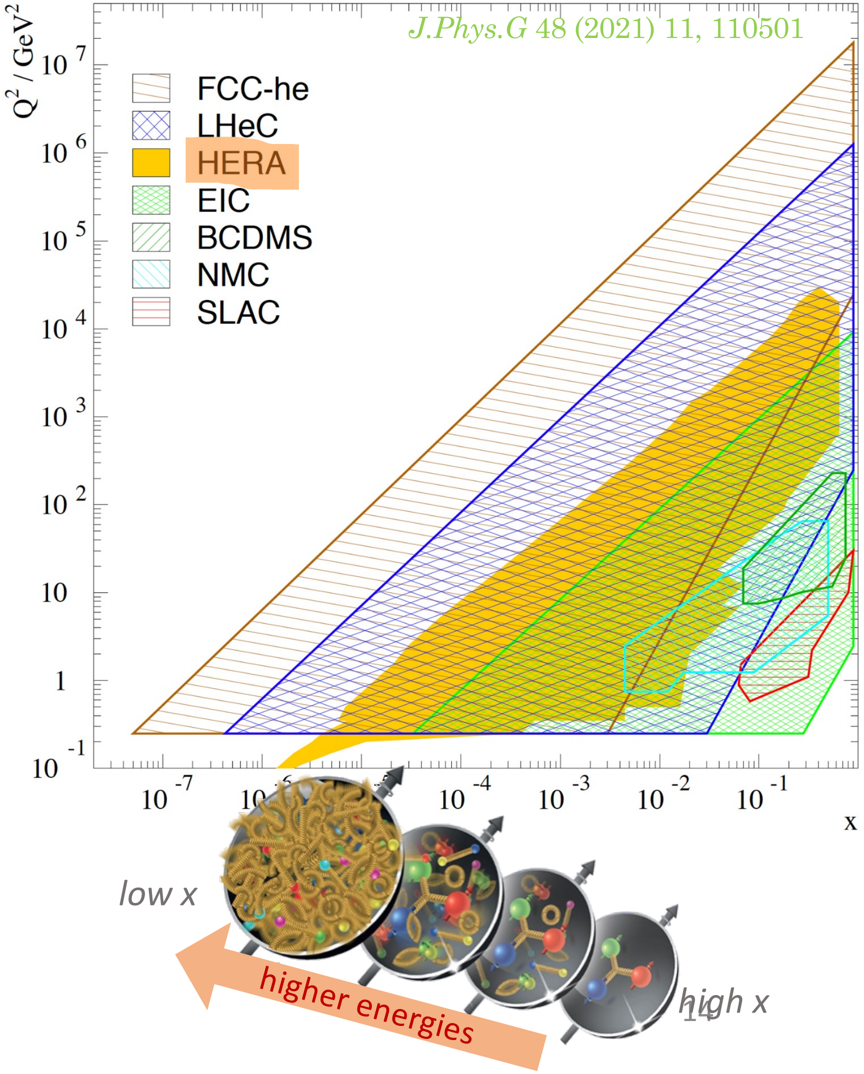


Electro-Weak region

~5-7% uncertainty on the σ(W,Z,H)

no FCC-eh

Kinematic range Parton Distribution Functions



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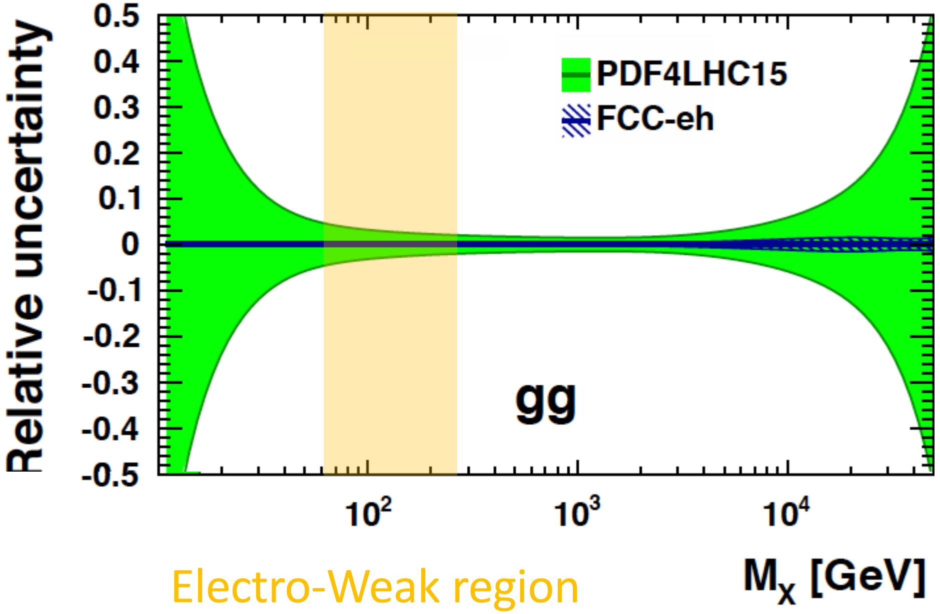


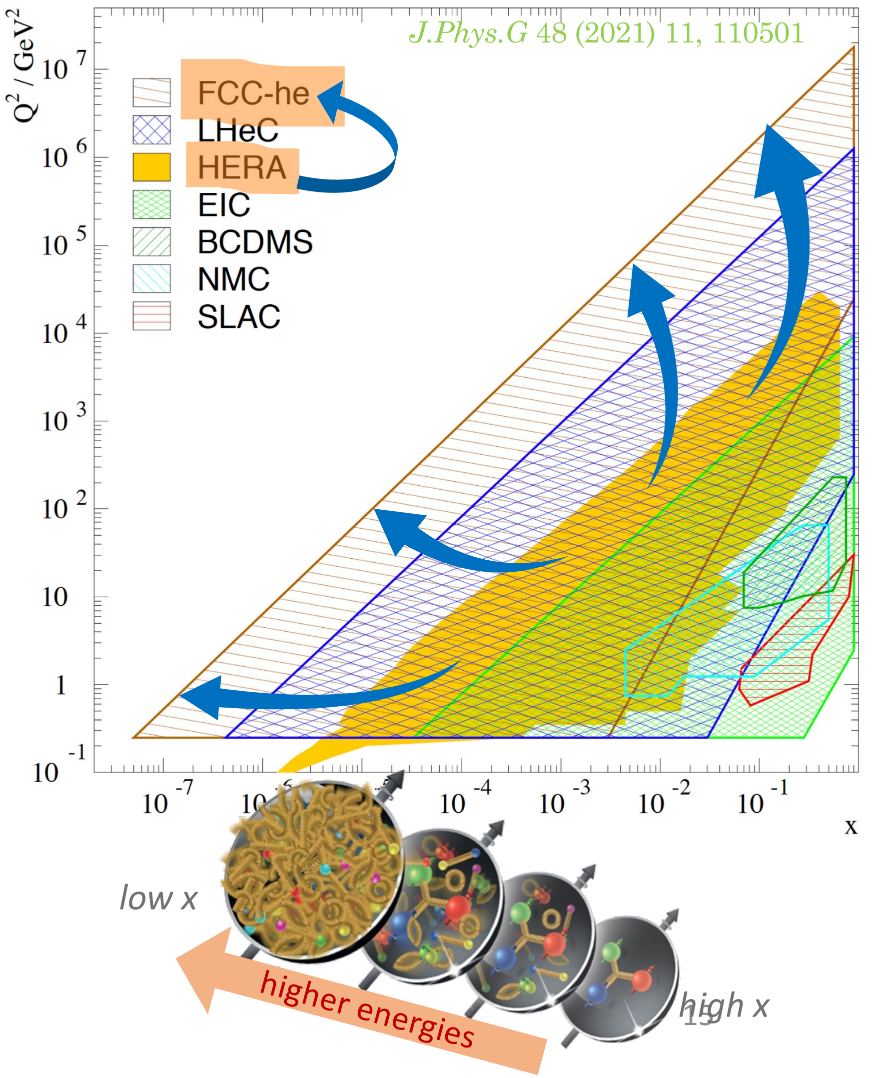
~5-7% uncertainty on the σ(W,Z,H)

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

Complementarity for Higgs physics in the FCC program

(Higgs coupling strength modifier parameters κ_i – assuming no BSM particles in Higgs boson decay)
(expected relative precision)

kappa-0-HL	HL+FCC-ee$_{240}$	HL+FCC-ee	HL+FCC-ee (4 IP)	HL+FCC-ee/hh	HL+FCC-eh/hh	HL+FCC-hh	HL+FCC-ee/eh/hh
κ_W [%]	0.86	0.38	0.23	0.27	0.17	0.39	0.14
κ_Z [%]	0.15	0.14	0.094	0.13	0.27	0.63	0.12
κ_g [%]	1.1	0.88	0.59	0.55	0.56	0.74	0.46
κ_γ [%]	1.3	1.2	1.1	0.29	0.32	0.56	0.28
$\kappa_{Z\gamma}$ [%]	10.	10.	10.	0.7	0.71	0.89	0.68
κ_c [%]	1.5	1.3	0.88	1.2	1.2	–	0.94
κ_t [%]	3.1	3.1	3.1	0.95	0.95	0.99	0.95
κ_b [%]	0.94	0.59	0.44	0.5	0.52	0.99	0.41
κ_μ [%]	4.	3.9	3.3	0.41	0.45	0.68	0.41
κ_τ [%]	0.9	0.61	0.39	0.49	0.63	0.9	0.42
Γ_H [%]	1.6	0.87	0.55	0.67	0.61	1.3	0.44

J. de Blas et al., JHEP 01 (2020) 139

FCC-ee prospect

FCC-pp/ep prospect

ALL COMBINED

only FCC-ee@240GeV

only FCC-hh

Ultimate Higgs Factory = {ee + eh + hh}

Future flagship at the energy & precision frontier

Current flagship (27km)

impressive programme up to ~2040

Future Circular Collider (FCC)

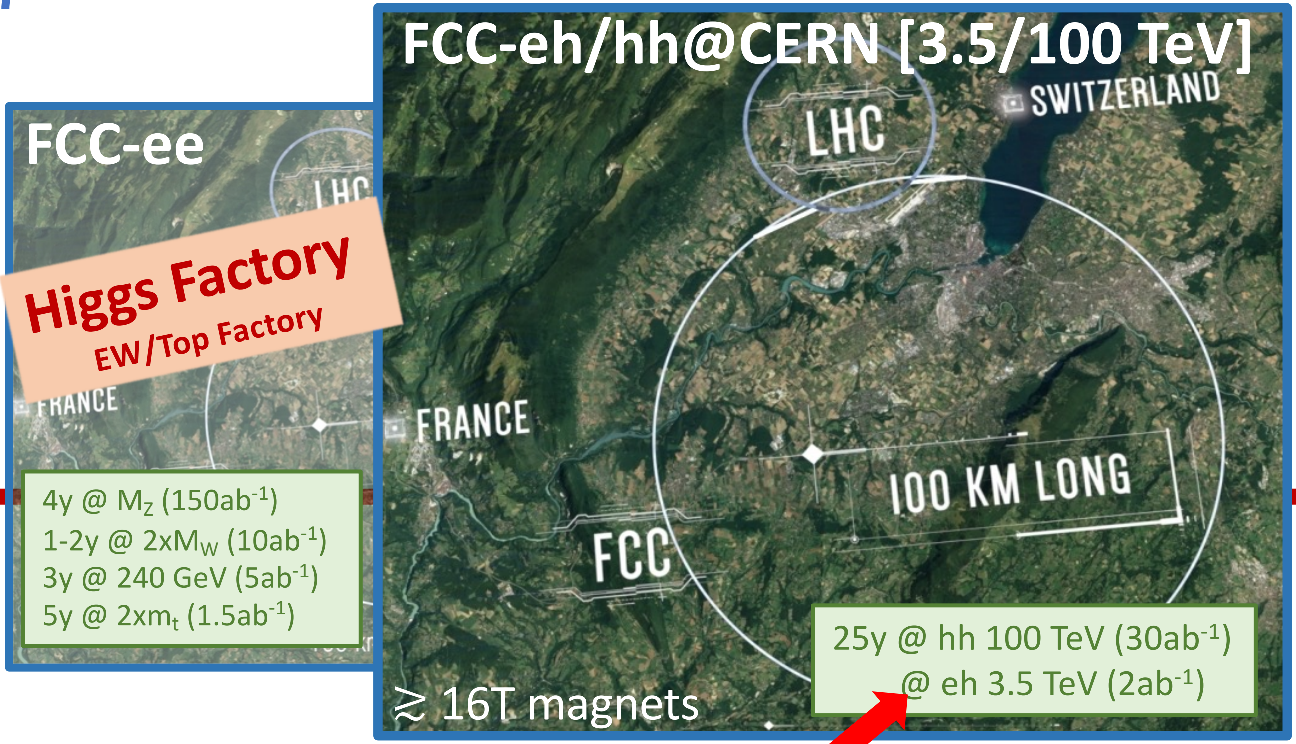
big sister future ambition (100km), beyond 2040

attractive combination of precision & energy frontier

ep-option with HL-LHC: LHeC

10y @ 1.2 TeV (1ab^{-1})

updated CDR: J.Phys.G 48 (2021) 11, 110501



numbers assume 2 IPs for each collider (only one for FCC-eh)

ERL-based H/HH Factories

Energy Recovery applications for HEP e^+e^- colliders

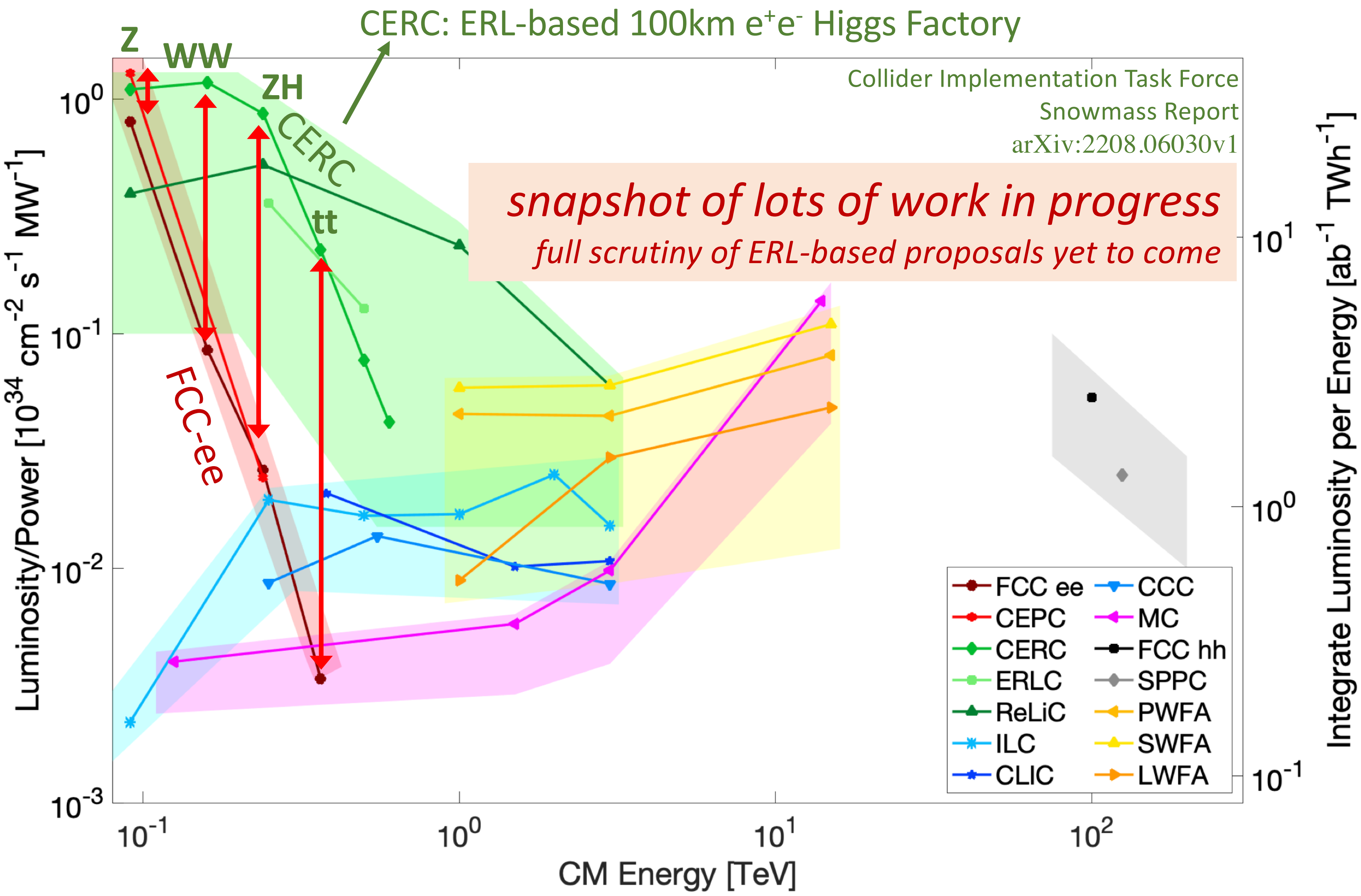
This plot <u>suggests</u> that with an ERL version of a Higgs Factory one might reach

x10 more H's

or

x10 less electricity costs

NOTE: several additional challenges identified to realise these ERL-based Higgs Factories



Refs for CERC: PLB 804 (2020) 135394 and arXiv:2203.07358

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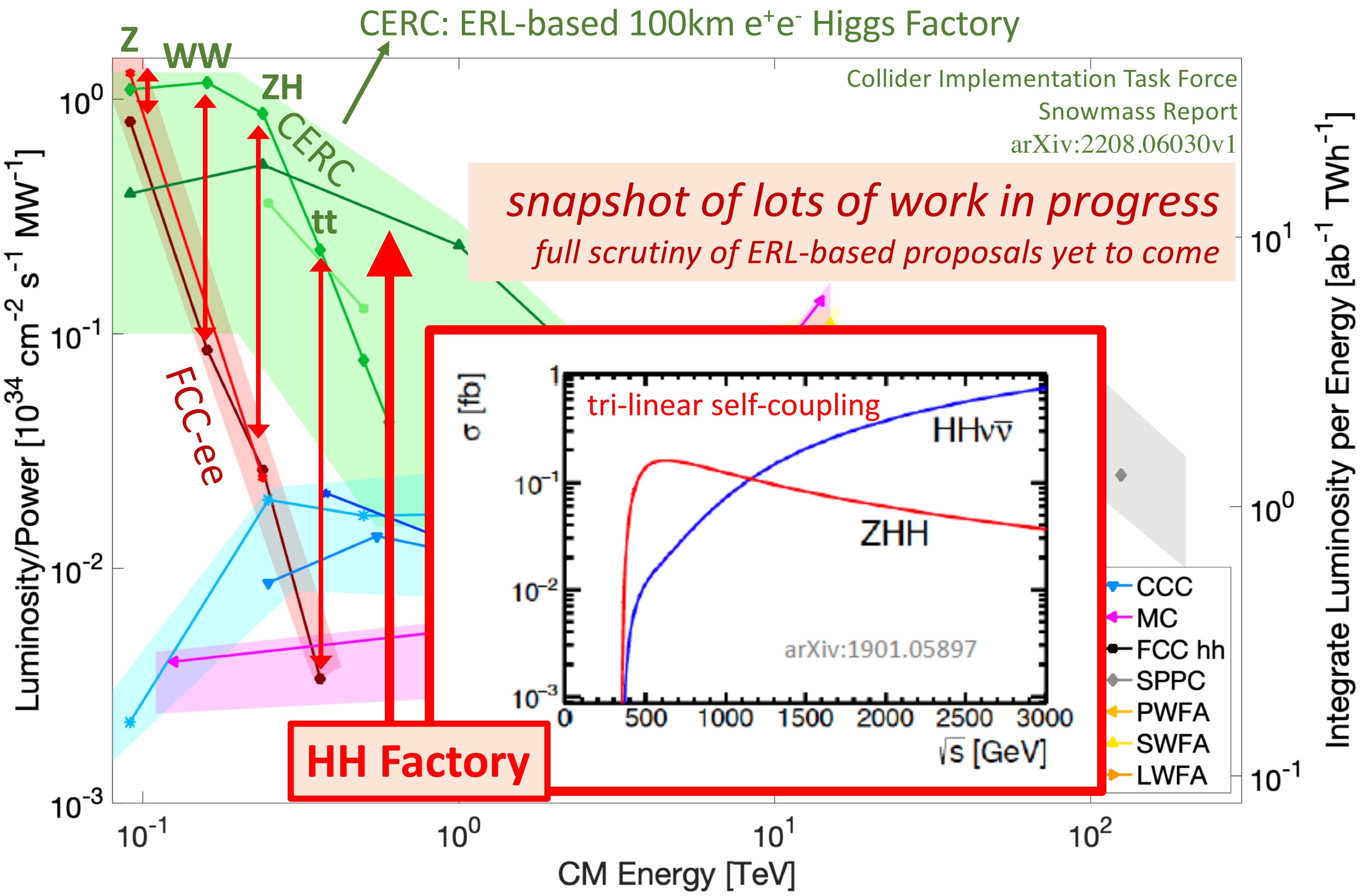


Refs for CERC: PLB 804 (2020) 135394 and arXiv:2203.07358

Tri-Linear Higgs Coupling in e^+e^-

Kinematic limit of e e → Z H H : M(Z) + 2 M(H) = 341 GeV

ZHH unpolarised cross section maximum at 500 GeV: O(0.1) fb

$O(10^{34})$ $cm^{-2}s^{-1}$ luminosity gives 1 ab^{-1} in ten years: 100 events (A=1)

$O(10^{36})$ $cm^{-2}s^{-1}$ luminosity should produce 10 000 events → few %
and 300 fb * 100 ab^{-1} = 3 10^7 ZH events,
→ opens rare H decay channel programme in e^+e^-

<u>This is a strong case for a next generation linear ee collider</u>

Gradient 20*f MV/m: two 25/f km linacs:

It needs: Twin cavities, 4.5K, Nb_3SN, Q_0 towards 10^{11}

MK/AH to LDG on October 12, 2021

The "Ghost" collider concept

https://doi.org/10.2172/1972705

Remarks – impact on the physics program and potential

ERL is a novel technology, that leads to an outstanding improvement of the performance of lepton-based colliders

This basically concerns superior luminosity performances at similar or even reduced power consumption.

It regards various new options: ERL versions of FCC-ee and ILC, new ERL designs for TeV energy e^+e^- colliders, high power updates of electron-proton designs for high energy (LHeC/FCC-eh) and increased luminosity (EIC) etc.

This way, ERL technology, under design worldwide and much advancing in Europe, will not only advance new sustainable accelerator techniques but directly improve the performance of forthcoming new colliders.

This, as has been illustrated with a few examples, will open new avenues for single and multiple Higgs production measurements, i.e. provide a complete and consistent view on the Higgs boson decays and verify the Higgs potential.

Further study of the principles, development of ERL technology and scrutinising the various Higgs and further physics opportunities is a task the ERL panel will pursue and invites to support and join.

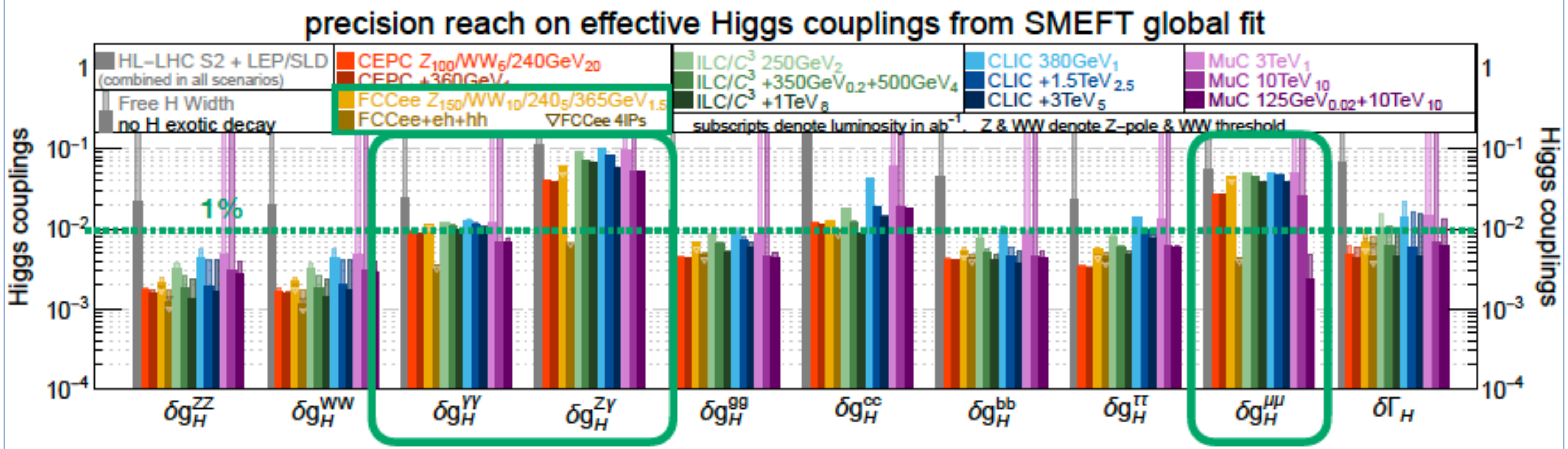
Sustainability is a requirement for our future work and energy recovery the best principle answer we have at hand.

NEXT (ANDREW HUTTON): INTEGRATING ERL IN THESE FUTURE COLLIDERS

backup

Higgs Physics with ee/pp/ep/$\mu\mu$ Colliders

Higgs interactions



HL-LHC+FCC-ee: Precision largely controlled by HL-LHC

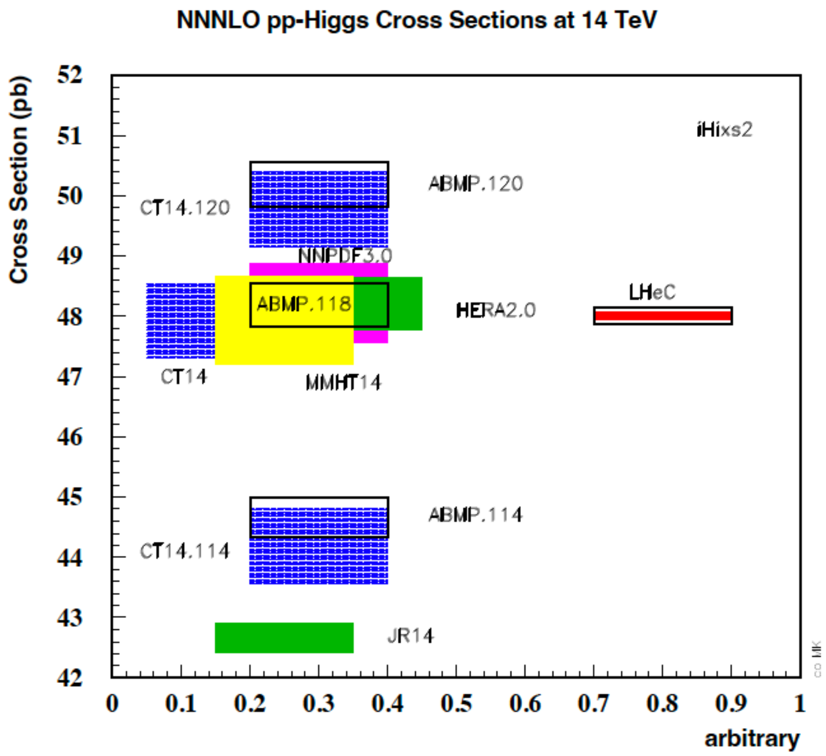
HL-LHC+FCC-ee+eh+hh: FCC-hh brings remaining H couplings below 1%

Note also improvement in HVV from combining with FCC-eh

Jorge deBlas at FCCweek, London, June 2023, based on arXiv:2206.08326 ``Global SMEFT Fit…”

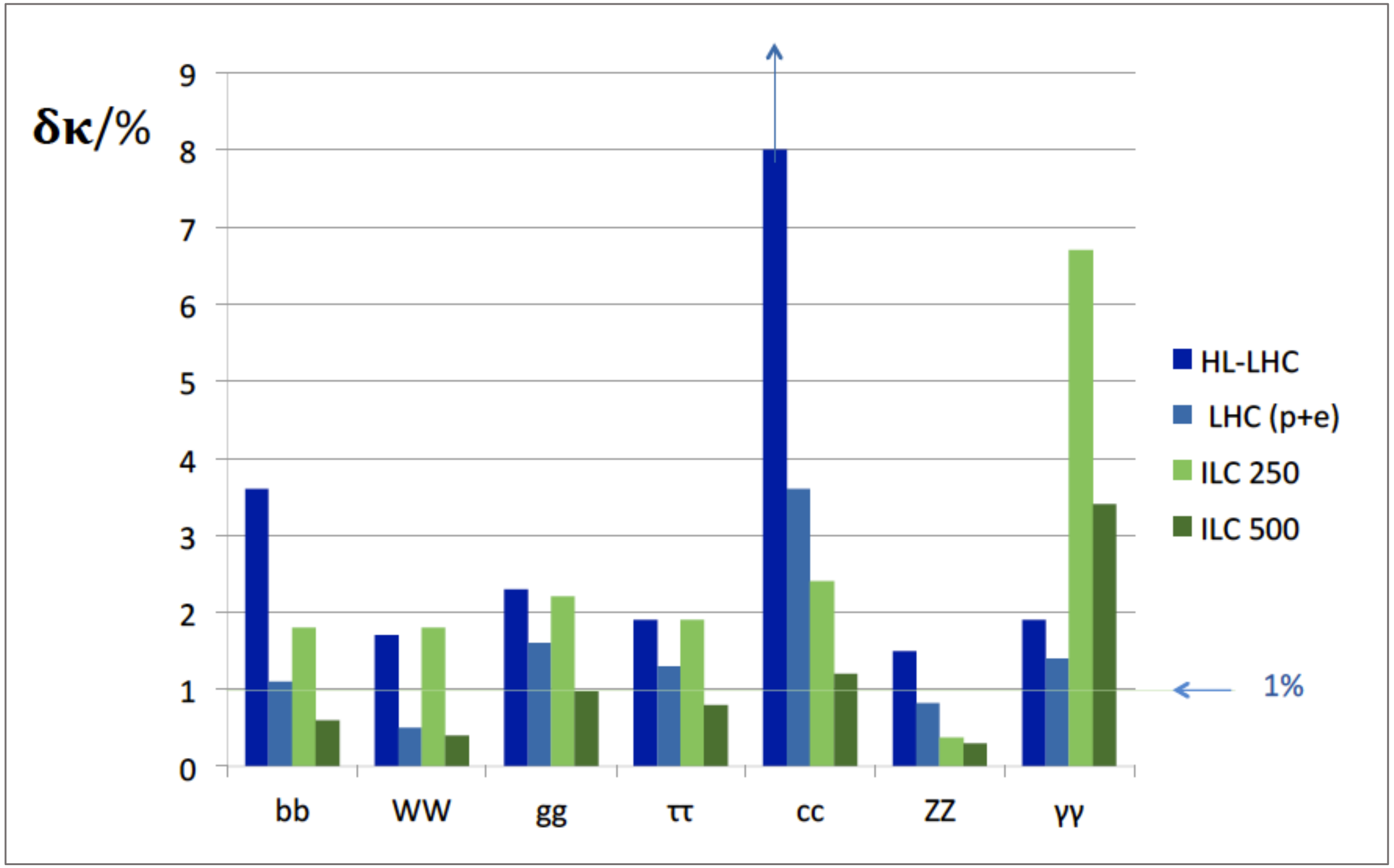
H couplings with LHC/LHeC & ILC

pp→HX cross sections and uncertainty



High precision control of pp→ H through PDFs from LHeC/FCCeh

LHeC: inner:PDFs, outer:with $\boldsymbol{\alpha}_s$

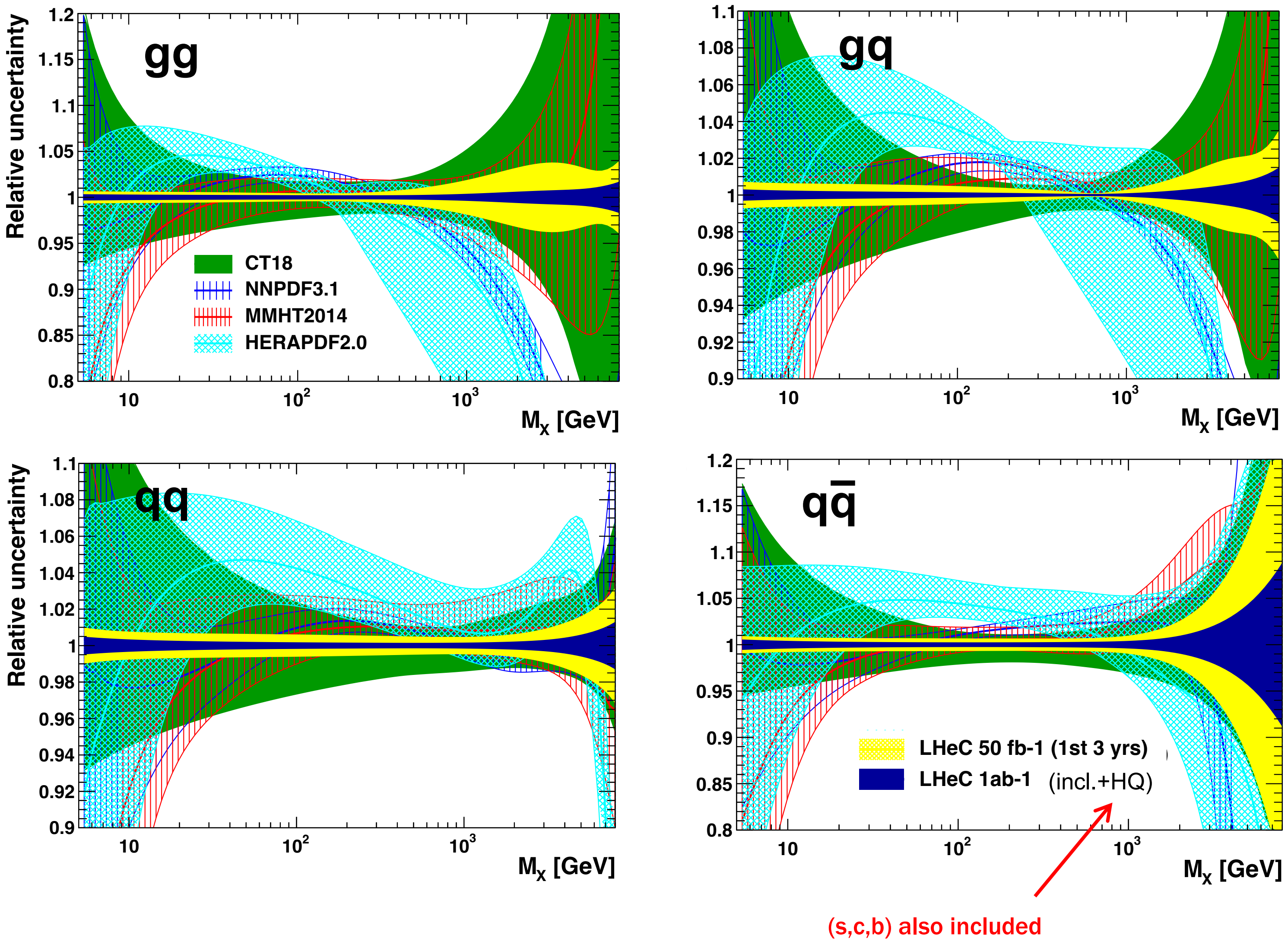


Determination of Higgs couplings in pp/ep and ILC500

Update of O.Bruening and M.K. arXiv:1305.2090 MPLA

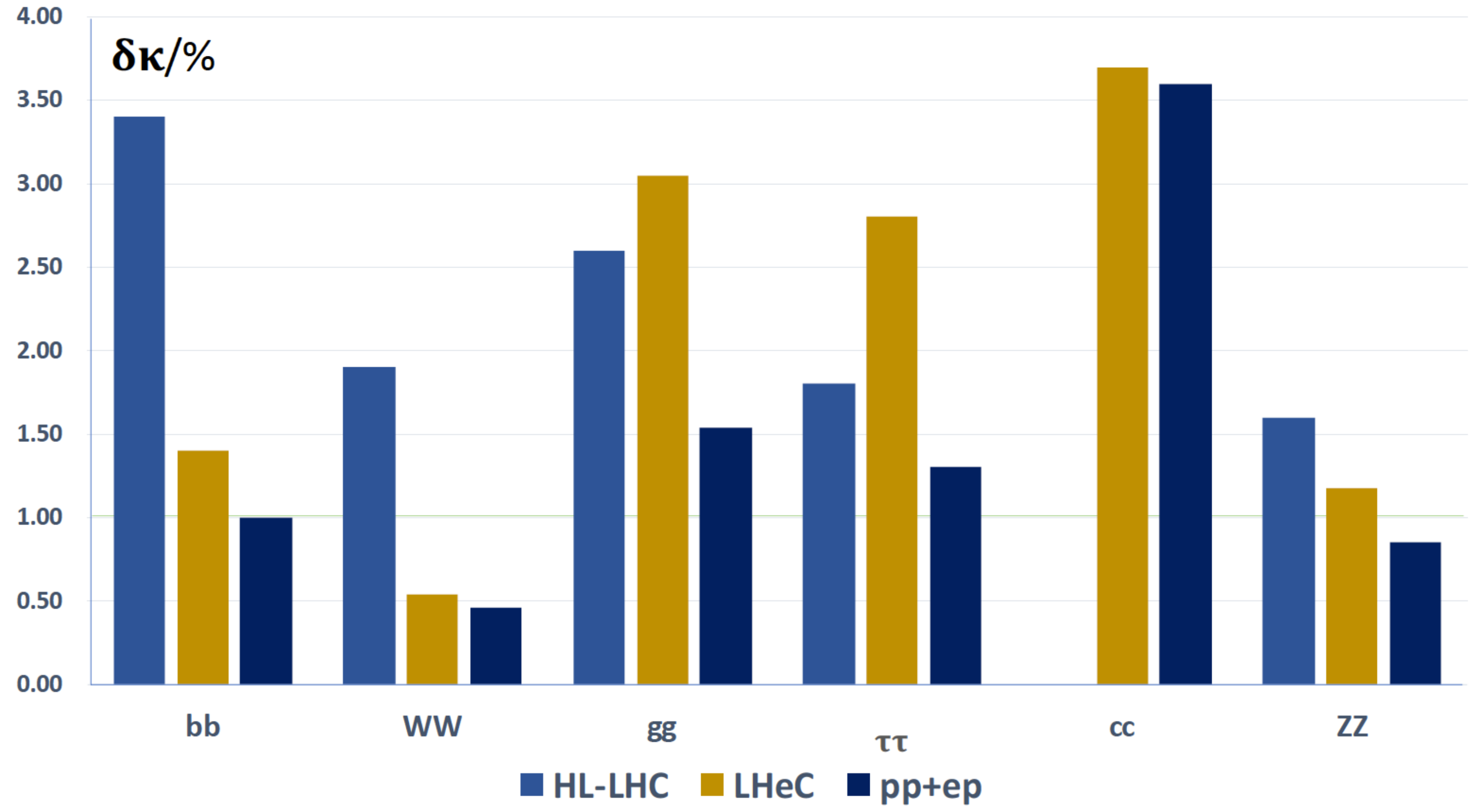
LHeC Study Group arXiv:2007.14491 J.Phys.G and ECFA Newsletter 5/20

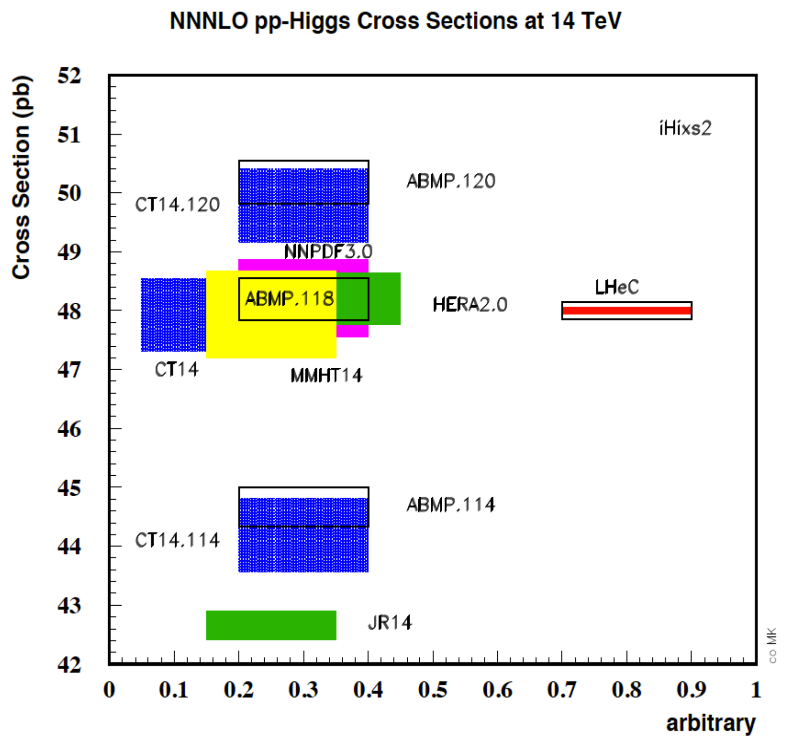
Parton-parton "luminosities" @ 14 TeV



arXiv:2007.14491

Precision Higgs Physics with pp and ep at the HL-LHC





High precision Higgs measurements in ep with LHeC (200fb) and FCC-he (1pb in CC H production)
Huge improvements vs LHC, especially for bb, WW, ZZ and cc results → 1% precision of LHC Higgs couplings and sub-percent for FCC-hh+he. 0.3% precision (strong coupling + PDFs) of pp → HX cross section, N^3LO

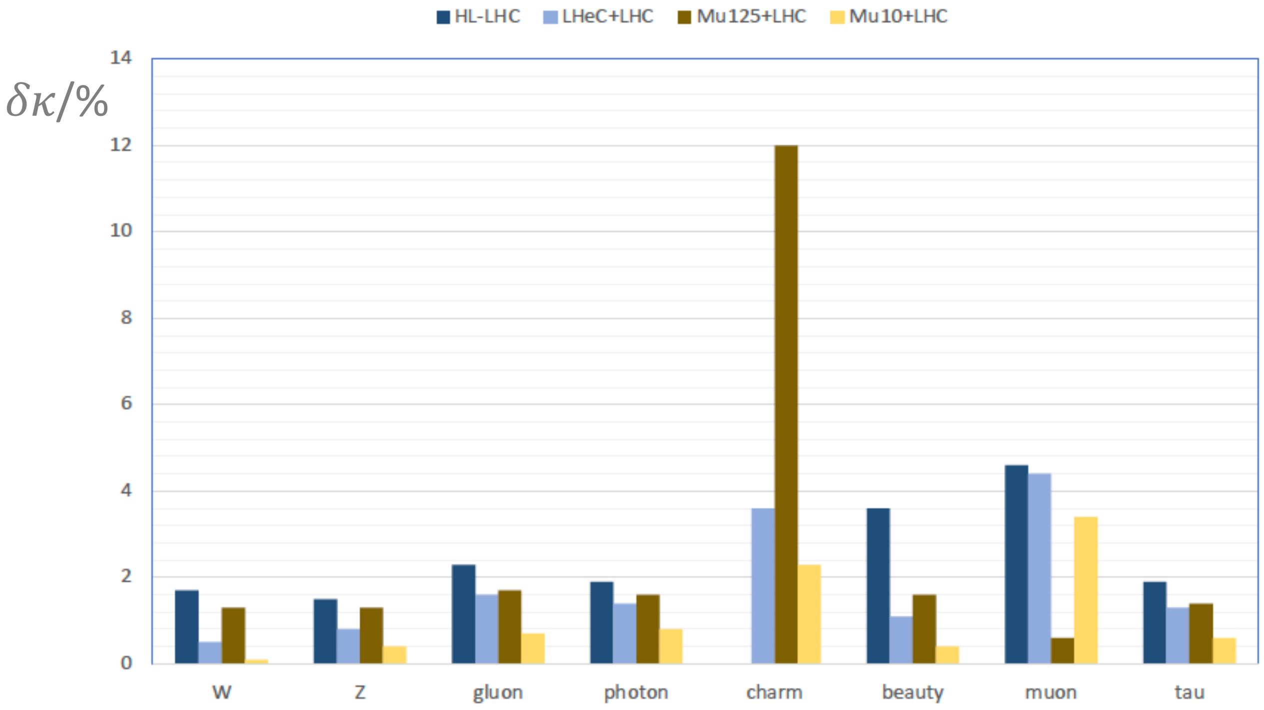
arXiv:2007.14491

ERL-based muon collider

Higgs Physics with Muon Collider

SM Higgs couplings in kappa framework

Higgs Coupling Uncertainties HL-LHC, +LHeC, +125MuC, +10TeVMuC



HL-LHC: $3ab^{-1}$, +LHeC: $1ab^{-1}$, +MuC125GeV: $5fb^{-1}$, +10TeV:$10ab^{-1}$

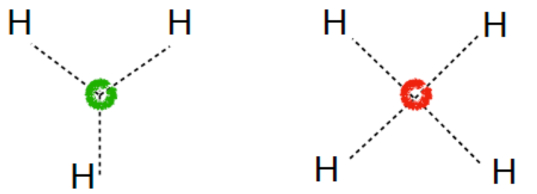
- **LHC improvement with ep better than muC125 (apart from muon)**
- **10 TeV with 10 ab^{-1} comparable to FCC expectations**

Muon collider: arXiv:2303.08533 - LHeC arXiv:2007.14491, J.PhysG

Tri (four) linear Higgs couplings: Potential

$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \boxed{\lambda_3} \frac{m_h^2}{2v} h^3 - \boxed{\lambda_4} \frac{m_h^2}{8v^2} h^4$$

$$\lambda_3^{SM} = \lambda_4^{SM} = 1$$



Determine the tri-linear Higgs coupling with about 20% precision at 3 TeV (1-2ab^{-1}) raised to 4% at 10 TeV MuC (10ab^{-1}) [HHH hard].
That is comparable to FCChh expectation and
A factor of two or so better than CLIC.
HH is very difficult for circular ee. Loops??
HH in HL-LHC/LHeC and FCCeh under study.

[arXiv:2303.08533 ``Towards a Muon Collider"
FCC-hh: 2004.03505, MLM, G.Ortona, M.Selvaggi]