Higgs boson prospects at future ee, pp and ep colliders

Andy Pilkington, University of Manchester

Completing the Higgs-saw, UK-HEP Forum, 22nd November 2023

Outline:

1) Future colliders of the circular variety

2) The core physics case: Higgs boson cross sections, couplings and total width

4) Beyond the core: Lorentz structures of Higgs boson interactions.

European Strategy: high priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

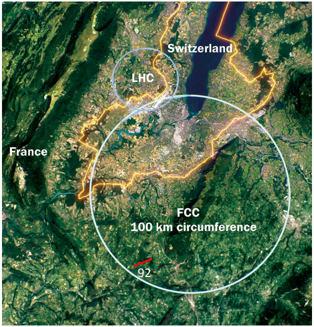
- ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.***

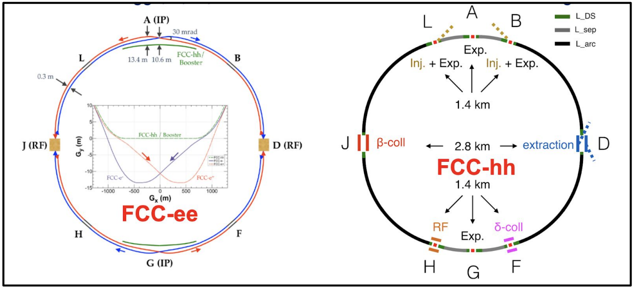
**European Strategy for Particle Physics Update (2020):* https://cds.cern.ch/record/2721370/

Future Circular Collider (FCC): integrated programme (I)

Based on the successful LEP-LHC programmes at CERN

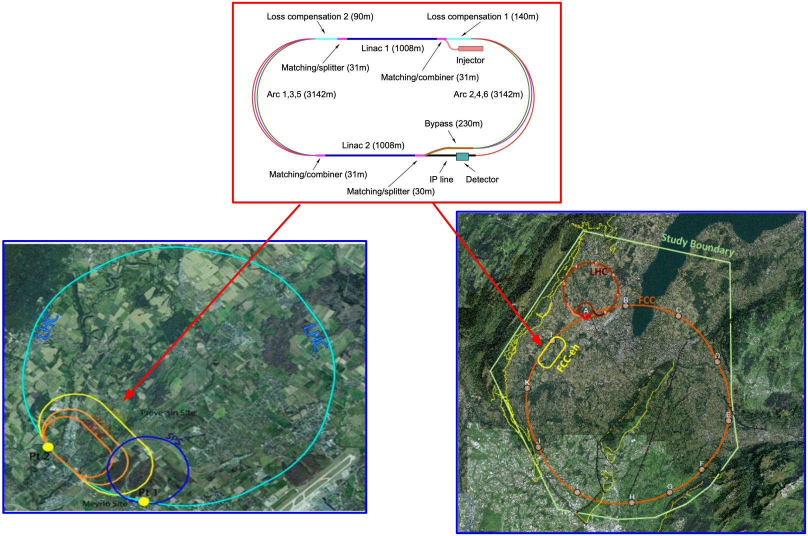
- complementary physics, common civil engineering and technical infrastructures
- building on, and reusing, CERN's existing infrastructure
- allows seamless continuation of collider-HEP after HL-LHC





- FCC-ee: electron-positron collider operating at $\sqrt{s}$ = 90, 160, 240, 365 GeV
- FCC-hh: proton-proton collider operating at $\sqrt{s}$ = 100 TeV

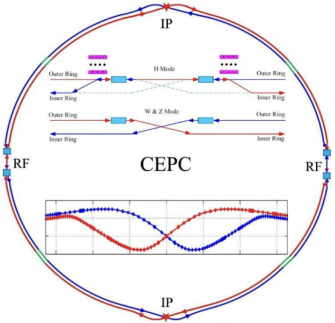
Electron-Proton Colliders: LHeC and FCC-eh



- Energy Recovery Linac (ERL) to provide electron beam with E = 60GeV
- Can run ep collider concurrently with (HL)LHC ($\sqrt{s}$=1.3TeV) or FCC-hh ($\sqrt{s}$=3.5TeV)

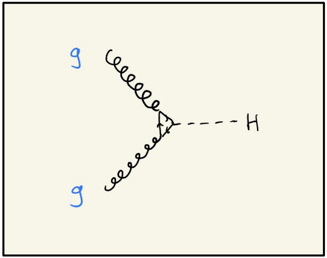
Circular Electron-Positron Collider (CEPC)

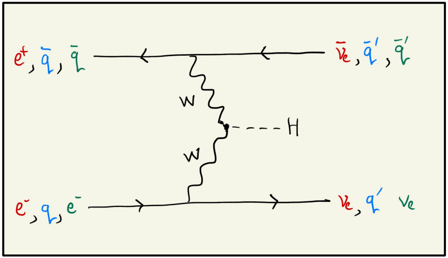
- Similar in scope to FCC-ee, proposed by the Chinese particle physics community.
- Smaller luminosity, limited by choice on SR power for energy costs. In principle, can be increased to match FCC-ee
- Tunnel can be re-used in the future for a proton-proton collider a.l.a FCC-hh

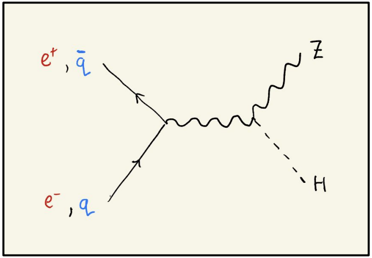


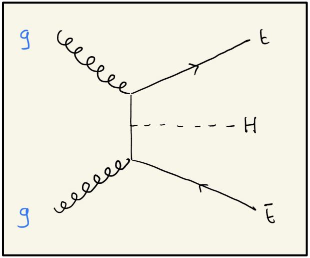
	FCC-ee				CEPC			
Running mode	Z	W	ZH	$t\bar{t}$	Z	W	ZH	$t\bar{t}$
Number of IPs	2				2			
Circumference (km)	91.2				100.0			
Beam energy (GeV)	45.6	80	120	182.5	45	80	120	180
Bunches/beam	12000	880	272	40	11951	1297	249	35
Beam current [mA]	1280	135	26.7	5.0	803.5	84.1	16.7	3.3
Lum. / IP [10^{34}cm^{-2}s^{-1}]	193	22.0	7.73	1.31	115	16	5	0.5
Synchr. Rad. Power [MW]	100				60			

Higgs production at future colliders



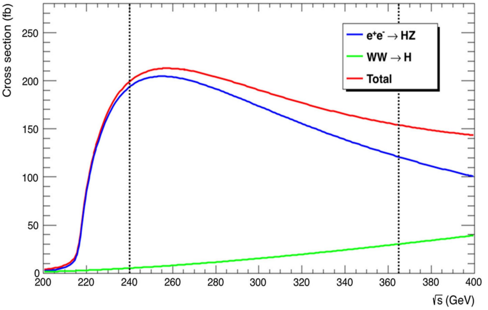


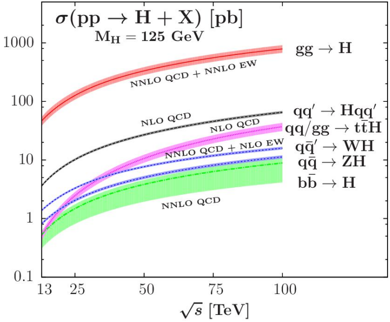




Higgs production cross sections

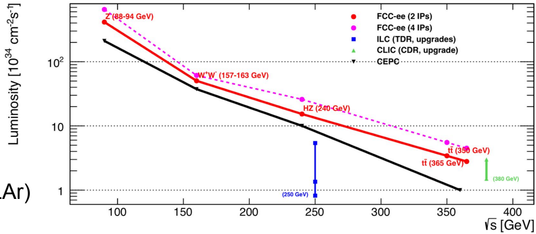
- Electron-positron colliders access the WW-fusion and ZH Higgstrahlung processes.
- Proton-proton colliders access more production mechanisms
  - but have larger theoretical uncertainties……
- Higgs production cross sections at FCC-hh are factors of 10-50 larger than at LHC.





Experimental considerations at ee colliders

- Lower √s runs for electroweak physics
- Clean environment (pile-up ~free)
- 4 IPs under serious consideration
- 3 FCC detector concepts (CLD, IDEA, LAr)



IDEA

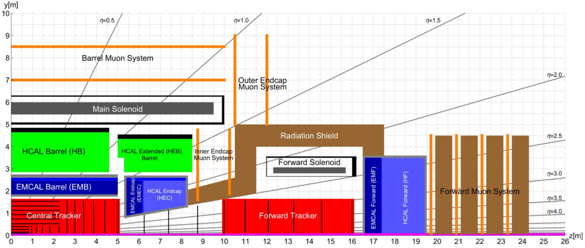
- (D)MAPS vertex detector (à la ALICE 3 ?);
- Drift chamber tracker;
- Silicon wrapper with time-of-flight (LGAD);
- Thin solenoid sharing ECAL cryostat;
- Scintillator + (return yoke) iron HCAL;
- Muon tagger.

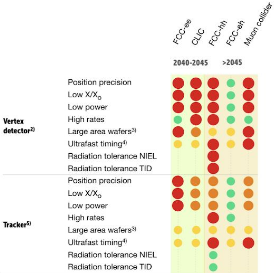
Working point	HZ	$t\bar{t}$	
$\sqrt{s}$ (GeV)	240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	8.5	0.95	1.55
Lumi/year (ab^{-1}, 2 IP)	1.7	0.2	0.34
Physics goal (ab^{-1})	5	0.2	1.5
Run time (year)	3	1	4
Number of events	10^6 HZ + 25k WW $\to$ H	10^6 $t\bar{t}$ +200k HZ +50k WW $\to$ H	

Experimental considerations at pp colliders

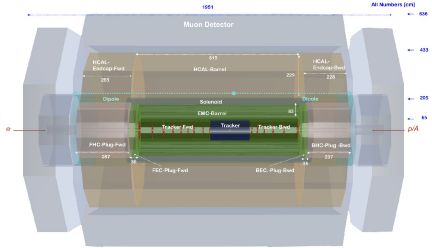
Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\,cm^{-2}\,s^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10 600
Goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel} [340]	mb	80	80	86	103
σ_{tot} [340]	mb	108	108	120	150
BC rate	MHz	31.6	31.0	31.6	32.5
Peak pp collision rate	GHz	0.8	4	14	31
Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950
Total number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm, est. (FLUKA)	$GHz\,cm^{-2}$	0.1	0.7	2.7	8.4 (10)
1 MeV-neq fluence at 2.5 cm, est. (FLUKA)	$10^{16}\,cm^{-2}$	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm, est. (FLUKA)	MGy	1.3	13	54	270 (300)
$dE/d\eta\|_{\eta=5}$ [340]	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0
90% $b\bar{b}$ $p_T^b > 30\,GeV/c$ [341]	$\|\eta\| <$	3	3	3.3	4.5
VBF jet peak [341]	$\|\eta\|$	3.4	3.4	3.7	4.4
90% VBF jets [341]	$\|\eta\| <$	4.5	4.5	5.0	6.0
90% $H \rightarrow 4l$ [341]	$\|\eta\| <$	3.8	3.8	4.1	4.8

- Unprecedented particle flux / radiation levels
- Detector requirements for physics are likely to be extreme and still under investigation
- O(1000) pile-up interactions per event
- Low-x collisions produce far-forward objects





- Lower fluxes and radiation levels compared to proton-proton colliders
- Manageable pile-up conditions
- Detector concepts similar at LHeC and FCC-eh



Parameters	Unit	LHeC	HE-LHeC	FCC-eh
E_{p}	TeV	7	13.5	50
$\sqrt{s}$ for $E_{\mathrm{e}} = 60\,\mathrm{GeV}$	TeV	1.3	1.7	3.5
Peak $\mathcal{L}$	$10^{33}\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	8	12	15
Bunch spacing	ns	25	25	25
Goal $\int \mathcal{L}$ electron–proton	ab^{-1}	1	2	2
Goal $\int \mathcal{L}$ electron–ion	fb^{-1}	10	20	20
Events per bunch crossing (pile-up)		0.1	0.2	1
1 MeV-neq fluence at $r = 2.5\,\mathrm{cm}$	$10^{15}\,\mathrm{cm}^{-2}$	1	2	5
DIS ep: $\sigma_{\mathrm{ep}\to\mathrm{e}X}$ $Q^2 \geq 1\,\mathrm{GeV}^2$	μb	3.0	3.4	4.6
DIS Pb: $\sigma_{\mathrm{e}N\to\mathrm{e}X}$/[nucleon,Pb] $Q^2 \geq 1\,\mathrm{GeV}^2$	μb	1.8	2.1	2.7
Top: $\sigma(\mathrm{ep} \to \nu\bar{\mathrm{t}}X)$, $p_T^j > 10\,\mathrm{GeV}$, $\lvert\eta\rvert < 6$	pb	0.9	2.4	11
Higgs: $\sigma(\mathrm{ep} \to \nu\mathrm{H}X)$, $P = -0.8$	pb	0.2	0.4	1

σ_{ZH}.BR measurements at $\sqrt{s}$ = 240 GeV

The Higgs peak can be reconstructed from the Z-boson decay products alone:

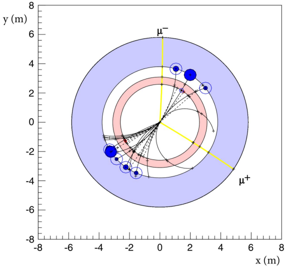
$$m^2_{\text{Recoil}} = s + m^2_{\text{Z}} - 2\sqrt{s}(E_{\ell^+} + E_{\ell^-})$$

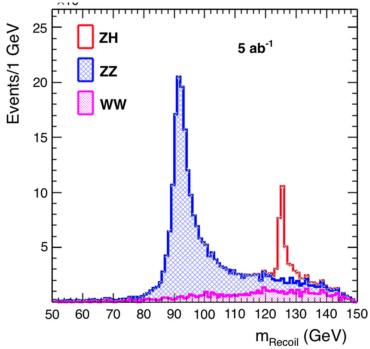
Count events and measure:

- σ_{ZH} determined when Higgs decays are ignored.
- σ_{ZH}.BR(H→XX) if the decay products are selected.

The Higgs mass can be measured from the recoil mass to an accuracy of 2.5%.

- Possible due to expected excellent beam energy resolution (0.1MeV)



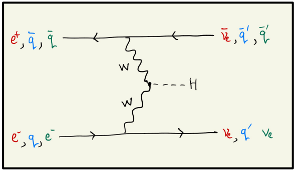


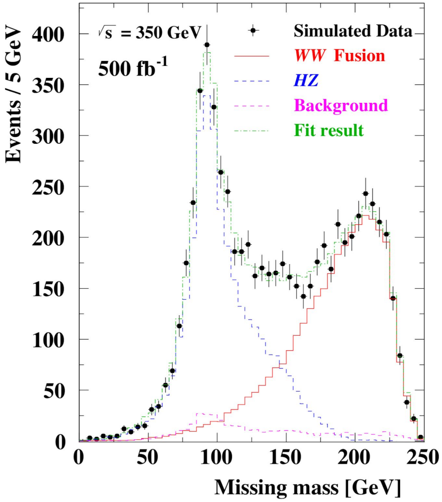
$\sigma_{WW\to H}$.BR measurements at $\sqrt{s}$ = 365 GeV

WW→H production accessed by selecting Higgs candidates in a specific decay channel and looking at the missing (i.e. recoil) mass

Contributions from ZH and WW→H peak in different regions:

- fit to extract each component.
- $\sigma_{WW\to H}$.BR(H→XX) then determined for each decay channel.





Summary of measurement accuracy in e^+e^- collisions

$\sqrt{s}$	240 GeV		365 GeV	
Int. Luminosity	5 ab^{-1}		1.5 ab^{-1}	
Channel	ZH	WWH	ZH	WWH
$H\to$ any	±0.5		±0.9	
$H\to b\bar{b}$	±0.3	±3.1	±0.5	±0.9
$H\to c\bar{c}$	±2.2		±6.5	±10
$H\to gg$	±1.9		±3.5	±4.5
$H\to W^+W^-$	±1.2		±2.6	±3.0
$H\to ZZ$	±4.4		±12	±10
$H\to \tau^+\tau^-$	±0.9		±1.8	±8
$H\to \gamma\gamma$	±9.0		±18	±22
$H\to \mu^+\mu^-$	±19		±40	
$H\to$ invisible	< 0.3		< 0.6	

Assumes:

- Luminosity uncertainty similar to LEP (<0.1%).
- Beam energy uncertainty of 0.1MeV via resonant depolarisation
- CMS-like detector resolutions and efficiencies

Higgs cross sections and coupling modifiers

$$\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \to X\overline{X}) \propto \frac{g^2_{\mathrm{HZZ}} \times g^2_{\mathrm{HX\overline{X}}}}{\Gamma_{\mathrm{H}}}$$

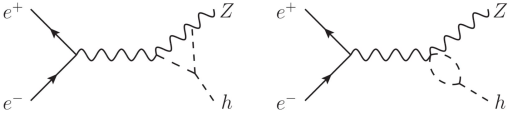
$$\sigma_{\mathrm{H}\nu_{\mathrm{e}}\overline{\nu}_{\mathrm{e}}} \times \mathcal{B}(\mathrm{H} \to X\overline{X}) \propto \frac{g^2_{\mathrm{HWW}} \times g^2_{\mathrm{HX\overline{X}}}}{\Gamma_{\mathrm{H}}}$$

- g_{HZZ} determined from σ_{ZH}
- g_{HWW} then determined from $\sigma_{WW\to H}$.BR(H→AA) / σ_{ZH}.BR(H→AA) ……[any A]
- Total width then determined from σ_{ZH}.BR(H→ZZ)
- All other g_{HAA} then determined from σ_{ZH}.BR(H→AA) and $\sigma_{WW\to H}$.BR(H→AA)

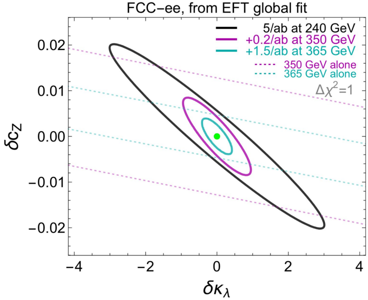
Higgs cross sections and coupling modifiers: results

Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-ee + HL-LHC
Int. Lumi (ab^{-1})	3	5 + 0.2 + 1.5	–
Years	10	3 + 1 + 4	–
g_{HZZ} (%)	1.5	0.18	0.17
g_{HWW} (%)	1.7	0.44	0.41
g_{Hbb} (%)	5.1	0.69	0.64
g_{Hcc} (%)	SM	1.3	1.3
g_{Hgg} (%)	2.5	1.0	0.89
$g_{\mathrm{H}\tau\tau}$ (%)	1.9	0.74	0.66
$g_{\mathrm{H}\mu\mu}$ (%)	4.4	8.9	3.9
$g_{\mathrm{H}\gamma\gamma}$ (%)	1.8	3.9	1.3
$g_{\mathrm{HZ}\gamma}$ (%)	11.	–	10.
g_{Htt} (%)	3.4	–	3.1
g_{HHH} (%)	50.	44.	33.
Γ_{H} (%)	SM	1.1	1.1

Higgs self coupling at ee colliders?

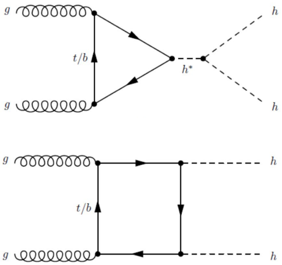


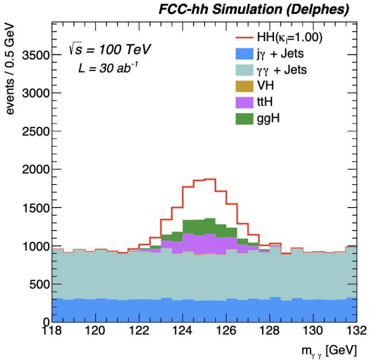
- Sensitivity to trilinear Higgs coupling via loop corrections (both ZH and WW→H)
- Requires global fit to all σ.BR measurements.
- Uncertainty of 42% from FCC-ee alone, reducing to 33% if HL-LHC measurements are included.

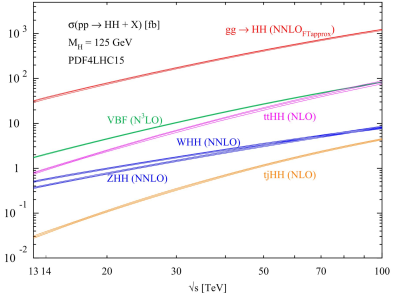


Higgs self-coupling in pp collisions (I)

- Sensitivity to trilinear Higgs coupling via measurements of diHiggs production.
- x300 event yield over LHC means that diHiggs production can be measured with high accuracy



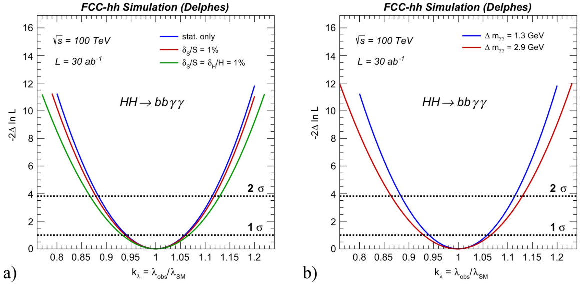




Higgs self-coupling in pp collisions (II)

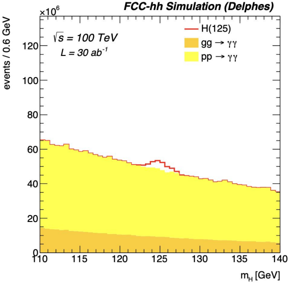
- Excellent sensitivity to modifications in the trilinear couplings in multiple channels.
- Assumptions:
  - Excellent b-tagging efficiency (85%) and light/charm mistag rate (1%/5%)
  - Backgrounds (non-resonant, single Higgs) known to 1% accuracy.

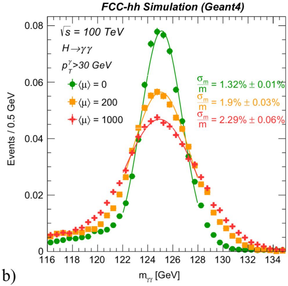
	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau\tau$	$b\bar{b}ZZ^*[\rightarrow 4\ell]$	$b\bar{b}WW^*[\rightarrow 2j\ell\nu]$	4b+jet
$\delta\kappa_\lambda$	6%	8%	14%	40%	30%



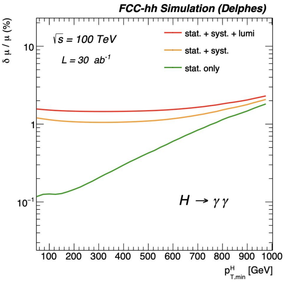
Rare decay channels in pp collisions: H→γγ

- Huge rates at proton-proton colliders allow rare decay channels to be measured accurately, and eventually limited by systematic precision.
- Target uncertainties:
  - 0.5% for object reconstruction
  - 1% for luminosity
  - 1% for production mechanism (for coupling modifier extraction)



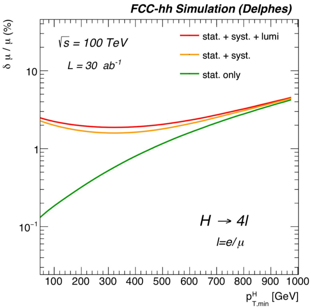


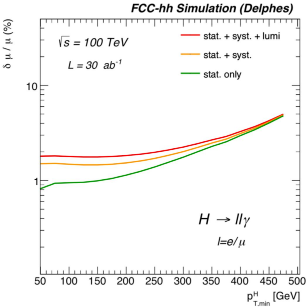
b)

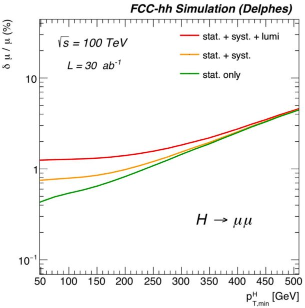


Rare decay channels in pp collisions: H→μμ, H→4l, H→llγ

	$H \to \gamma\gamma$	$H \to 4\ell$	$H \to \mu^+\mu^-$	$H \to \ell^+\ell^-\gamma$
p_T (H) > 0 GeV	50×10^6	3×10^6	5×10^6	2.5×10^6
p_T (H) > 200 GeV	900×10^3	50×10^3	90×10^3	40×10^3
p_T (H) > 500 GeV	100×10^3	6×10^3	10×10^3	5×10^3
p_T (H) > 1 TeV	4000	250	400	200

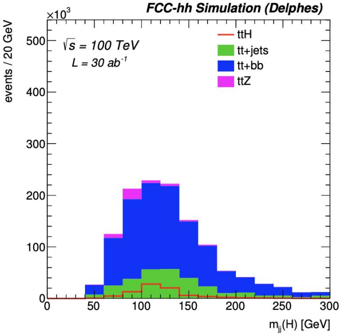


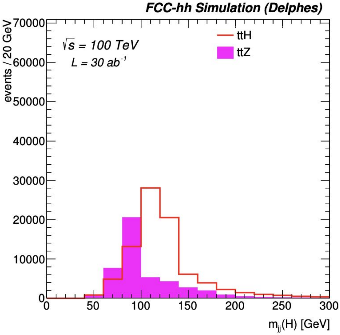




ttH production in pp collisions

- Utilises boosted-Higgs topologies where the ratio N_{tth}/N_{ttZ} can be measured to 1% accuracy (with cancellation of systematic uncertainties)
- Higgs-top Yukawa coupling then extracted assuming the ttZ coupling is measured to high accuracy in other decay channels.

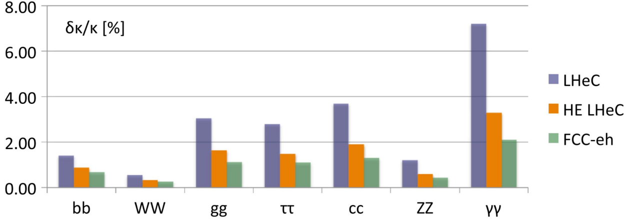




Higgs couplings at ep colliders

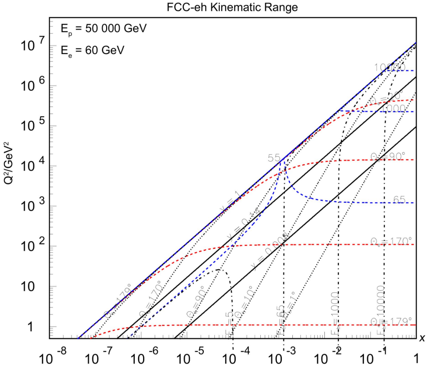
- Sensitivity to driven by cross section measurements of WW→H and ZZ→H.
- Clean environment and accurate theory calculations lead to excellent precision.

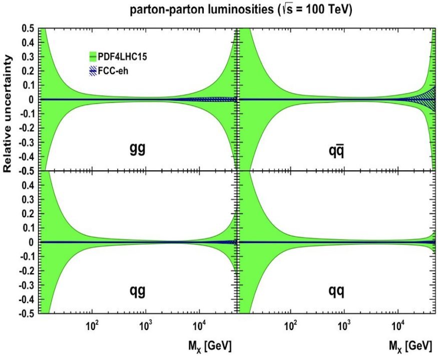
Collider	FCC-ee	FCC-eh
Luminosity (ab^{-1})	+1.5 @ 365 GeV	2
Years	3+4	20
$\delta\Gamma_H/\Gamma_H$ (%)	**1.3**	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	**0.17**	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	**0.43**	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	**0.61**	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	**1.21**	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	**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.



Additional input from ep colliders to Higgs couplings

- The entire FCC-hh programme relies on theoretical predictions accurate to 1%.
- Current PDF uncertainty on gluon fusion calculations is 3%
- DIS measurements at electron-proton colliders provide the necessary improvements.





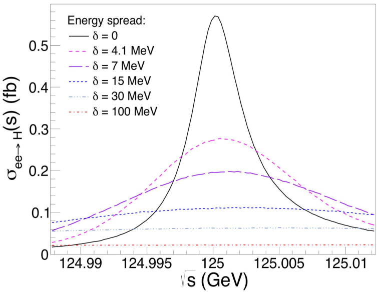
Summary of Higgs coupling modifier measurements

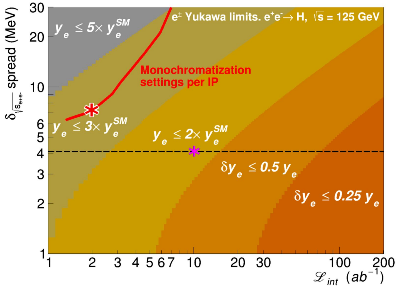
Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-ee + HL-LHC	FCC-INT	FCC-INT + HL-LHC
Int. Lumi (ab^{-1})	3	5 + 0.2 + 1.5	–	30	–
Years	10	3 + 1 + 4	–	25	–
g_{HZZ} (%)	1.5	0.18	0.17	0.17	0.16
g_{HWW} (%)	1.7	0.44	0.41	0.20	0.19
g_{Hbb} (%)	5.1	0.69	0.64	0.48	0.48
g_{Hcc} (%)	SM	1.3	1.3	0.96	0.96
g_{Hgg} (%)	2.5	1.0	0.89	0.52	0.5
$g_{\mathrm{H}\tau\tau}$ (%)	1.9	0.74	0.66	0.49	0.46
$g_{\mathrm{H}\mu\mu}$ (%)	4.4	8.9	3.9	0.43	0.43
$g_{\mathrm{H}\gamma\gamma}$ (%)	1.8	3.9	1.3	0.32	0.32
$g_{\mathrm{HZ}\gamma}$ (%)	11.	–	10.	0.71	0.7
g_{Htt} (%)	3.4	–	3.1	1.0	0.95
g_{HHH} (%)	50.	44.	33.	3–4	3–4
Γ_{H} (%)	SM	1.1	1.1	0.91	0.91

Factor 5-20 improvement in precision Higgs coupling modifiers

Electron Yukawa measurements in e^+e^- collisions?

- Can produce Higgs directly in electron-positron collisions at $\sqrt{s}$ = 125 GeV
- but low cross section due to small electron Yukawa
- Line shape is broadened significantly by ISR and beam energy spread ($\delta_{\sqrt{s}}$)
- If $\delta_{\sqrt{s}}$ is reduced to around Γ_H : sensitive the electron Yukawa at around SM expectations (this is 100x better than HL-LHC)





Examining the Lorentz structure of Higgs couplings

- Assuming that there is new physics at higher energy scales, the SM can be thought of as an effective field theory that is valid at low energy.

- The Lagrangian density is then written as:

$$\mathcal{L}_{\text{SMEFT}} \approx \underbrace{\mathcal{L}_{\text{SM}}^{(4)}}_{\text{SM Higgs boson interactions}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \underbrace{O_i^{(6)}}_{\text{Effective field theory operators}}$$

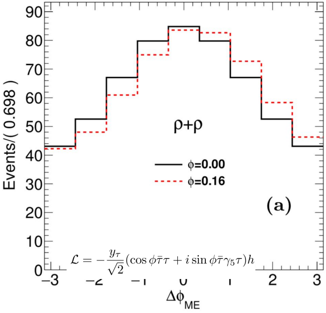
- The effective field theory operators induce anomalous Higgs boson interactions with different Lorentz structures to those in the Standard model
    - different kinematic properties, CP-violation …..

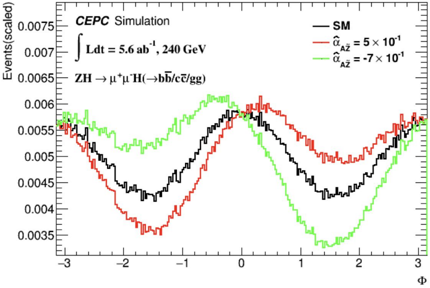
CP-violating Higgs interactions at e^+e^- colliders

- Smoking gun signature of CP violation is an asymmetry in a CP-odd observable

$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{d6}}) + |\mathcal{M}_{\mathrm{d6}}|^2,$$

- Typically measure angles between decay planes, e.g. ττ (left) or ZZ (right)

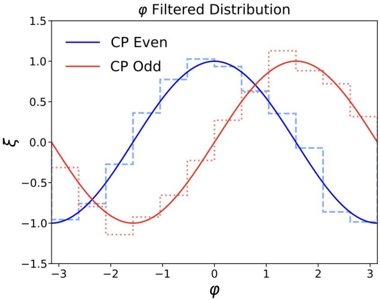


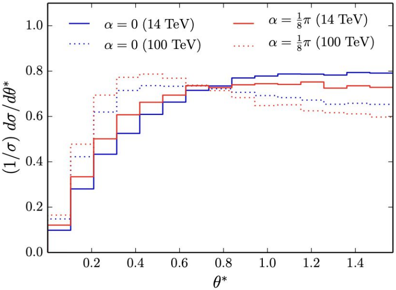


CP violation in Higgs interactions at proton-proton colliders

FCC-hh will build on and extend the CPV-Higgs programme that already exists at the LHC:

- Higher statistics measurements of CPV in ZZ/ττ decays and gluon-fusion / vector boson fusion
- First differential measurements of ZH production (left) and ttH production (right).
- Systematic uncertainties tend to cancel in asymmetries = enhanced sensitivity





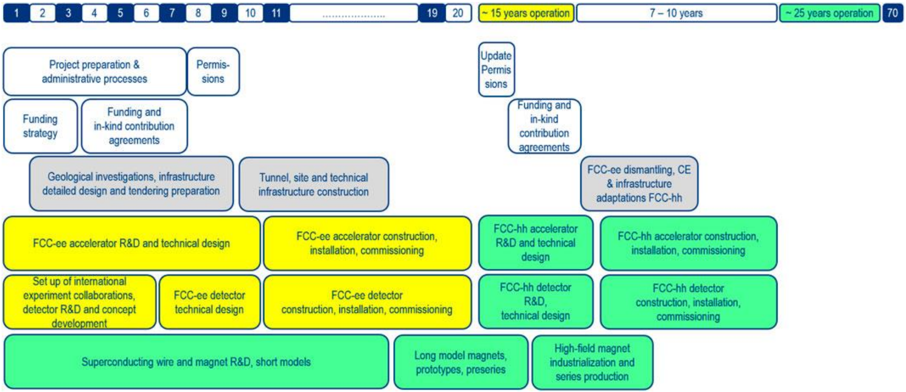
Summary

The European Strategy for Particle Physics calls for a coherent long-term collider programme to deliver:

- Factor of 5-10 improvement in HZZ, HWW, Htautau, Hbb, Hgg, Hmumu, Hyy, HZy couplings compared to HL-LHC.
    - Each will be known to better than 1% accuracy.
- First measurements of Hcc coupling and Higgs width; both to 1% accuracy
- Higgs self-coupling measured to 3% accuracy.

This collider programme will provide <u>much more</u> information than just the improvements above, probing the nature of the Higgs boson interactions far above the electroweak scale.

Future Circular Collider (FCC): integrated programme (I)



Integrated programme: https://www.frontiersin.org/articles/10.3389/fphy.2022.888078/full