Higgs boson measurements at Future Circular Colliders

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FUTURE CIRCULAR COLLIDER

29th July 2021

Outline

- Future Circular Colliders
- Higgs boson precision measurements on couplings, cross section, total width, mass
- Higgs boson self-coupling measurement

- Higgs boson coupling to electron
→ *see* *Electron Yukawa from s-channel resonant Higgs production at FCC-ee* *M. David d'Enterria 29/07/2021 16:30*

Future Circular Colliders

- Advantages of circular lepton colliders:
  - large luminosities
  - can later be replaced by very high energy pp colliders
- → Sequential implementation of a **lepton** and a **hadron** collider **maximises the physics reach** and covers more than 50 years of exploratory physics

- *see Experimental challenges towards a full exploitation of the FCC-ee potential Alain Blondel 26/07/2021 11:00*

Future Circular Colliders

FCC@CERN

- Future Circular Collider (FCC) at CERN: design study for a post-LHC collider installed in a tunnel with a circumference of 100 km
- In a first phase: **e^+e^- collider FCC-ee**

Collider	Type	$\sqrt{s}$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]\ \text{cm}^{-2}\text{s}^{-1}$	$\mathscr{L}$ $[\text{ab}^{-1}]$	Time [years]
FCC-ee	ee	M_Z	2	100/200	150	4
		$2M_W$	2	25	10	1-2
		240 GeV	2	7	5	3
		$2m_{top}$	2	0.8/1.4	1.5	5

- In a second phase: **pp-collider FCC-hh**

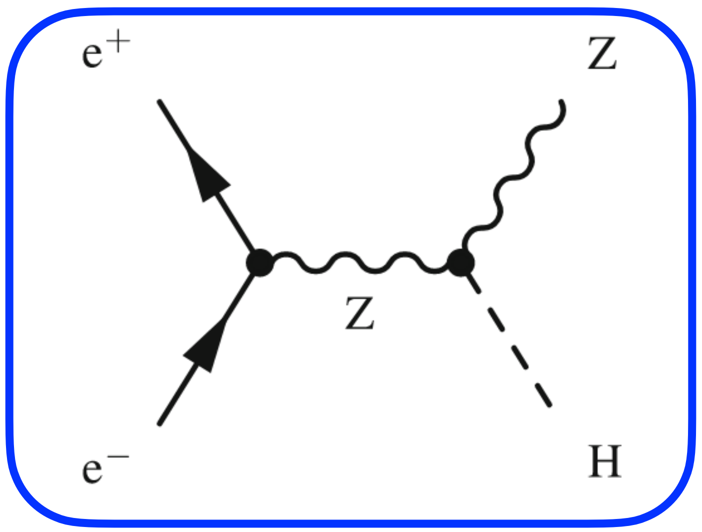
Collider	Type	$\sqrt{s}$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]\ \text{cm}^{-2}\text{s}^{-1}$	$\mathscr{L}$ $[\text{ab}^{-1}]$	Time [years]
FCC-hh	pp	100 TeV	2	30	30.0	25

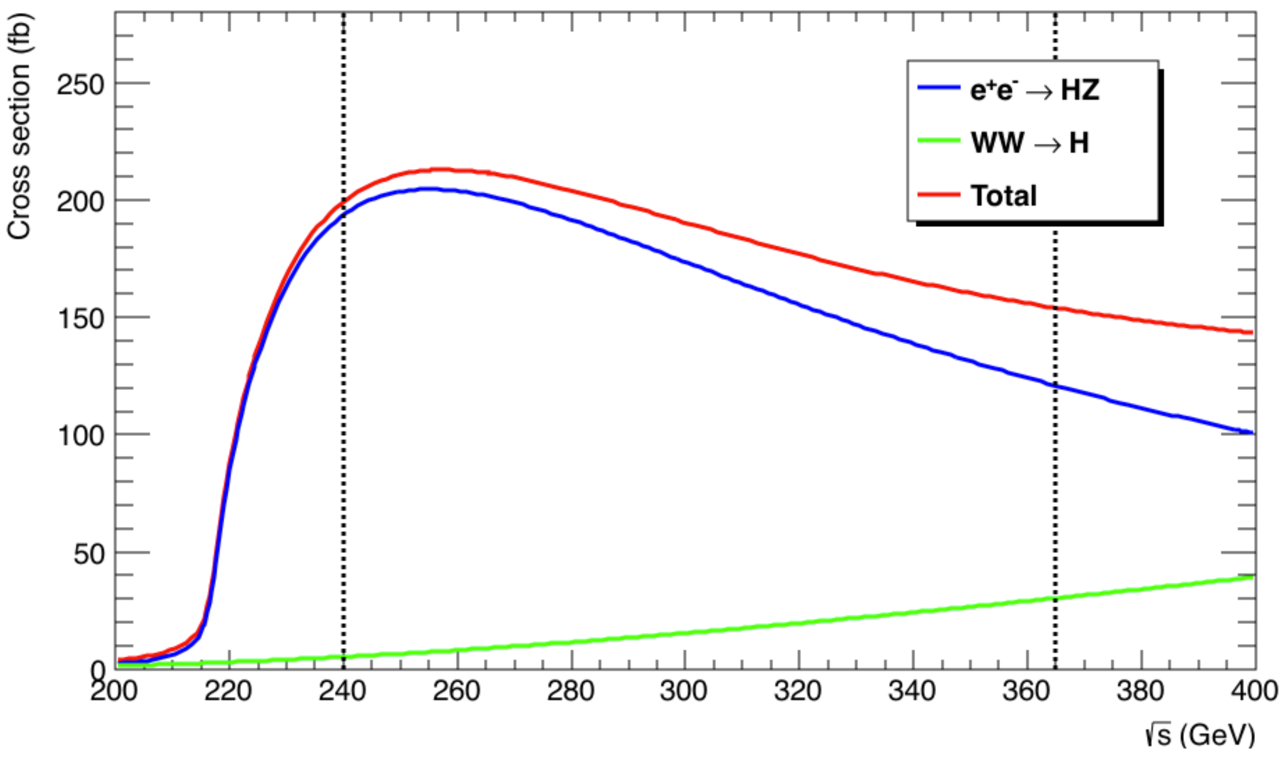
Higgs Boson Production at e^+e^- Colliders

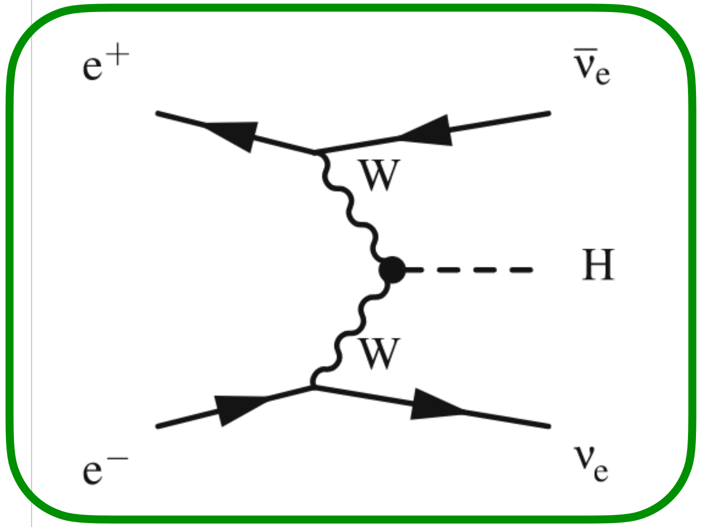
FCC-ee@CERN

	5 ab^{-1} @ $\sqrt{s}$ = 240 GeV	0.2 ab^{-1} @ $\sqrt{s}$ = 350 GeV 1.5 ab^{-1} @ $\sqrt{s}$ = 360 GeV
# H from HZ	1000000	200000
# H from VBF	25000	50000

- ~1.3· 10^6 Higgs bosons produced
- Clean environment and small backgrounds



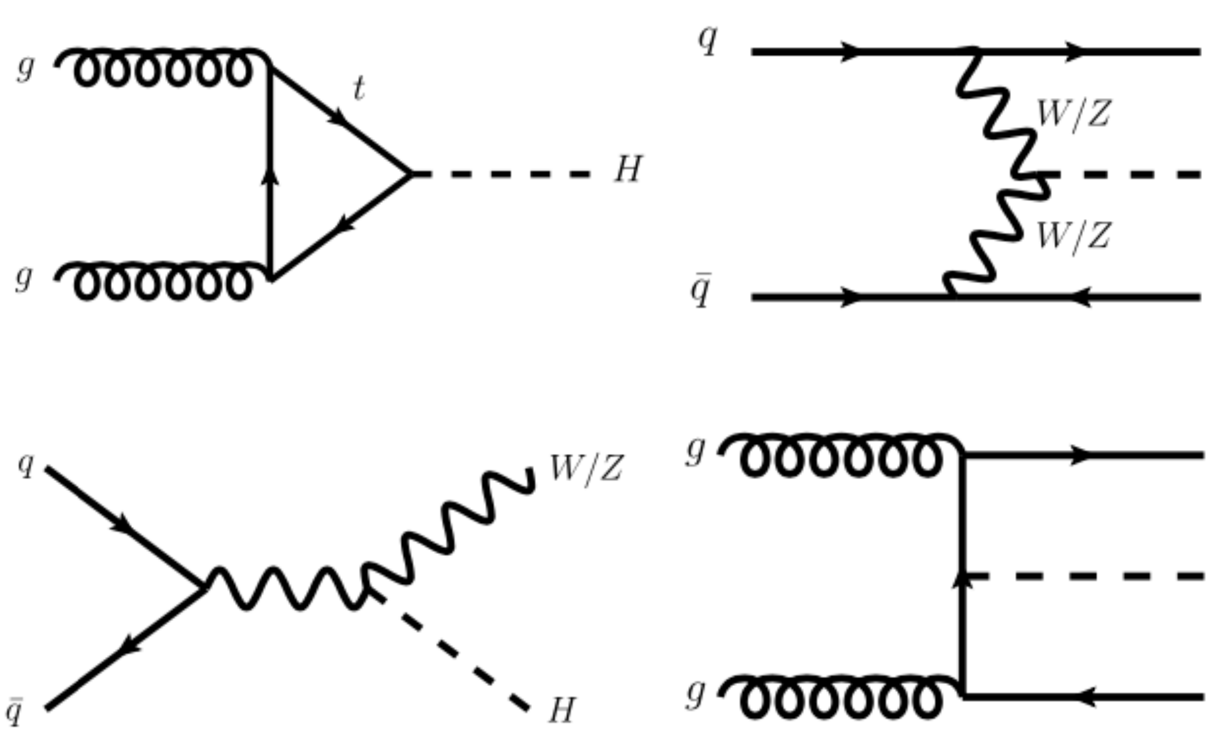


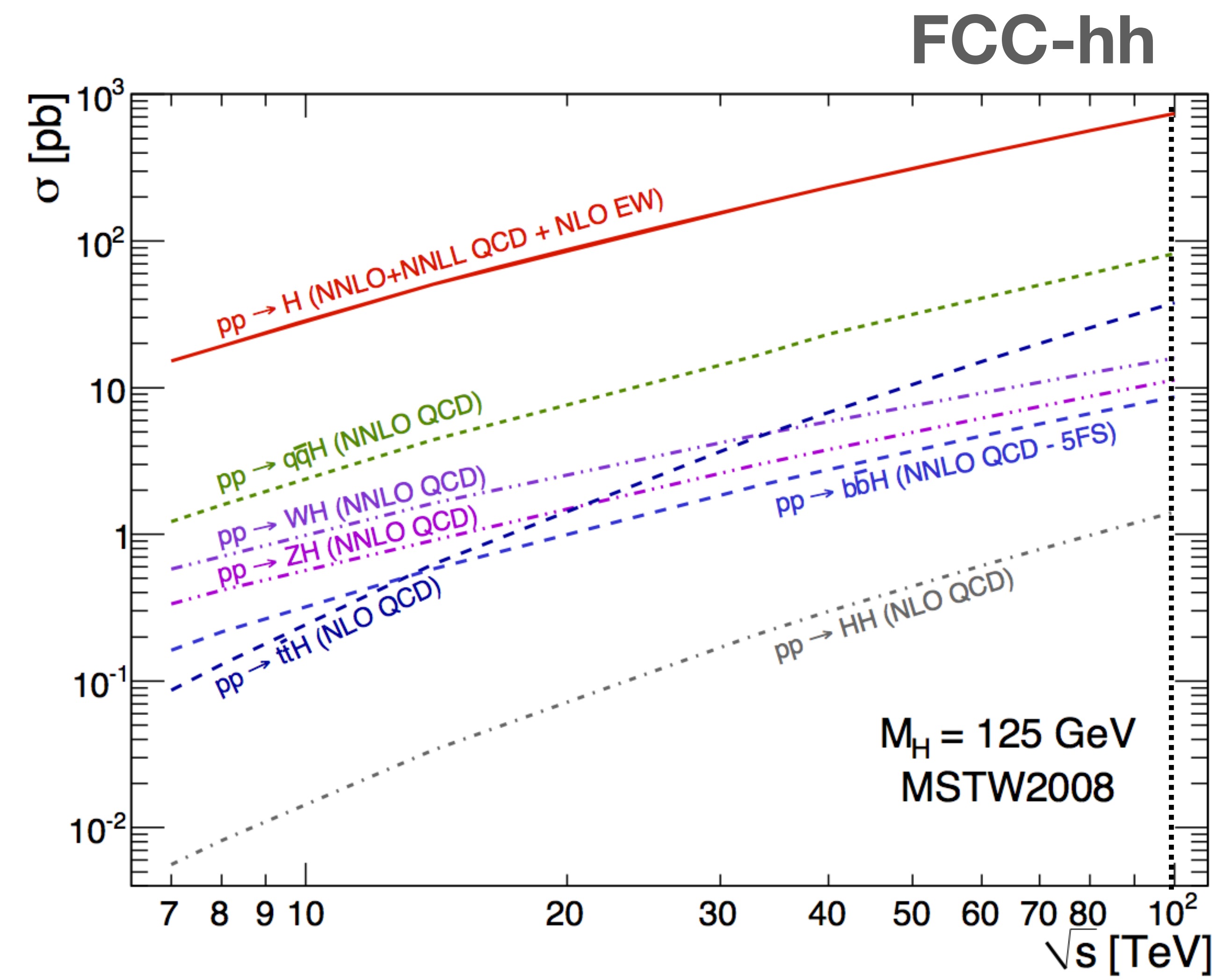


Higgs Boson Production at pp Colliders

FCC-hh@CERN

CERN-ACC-2018-0045





- High cross section (~1000 pb) and luminosity
  → **$3 \cdot 10^{10}$ Higgs bosons produced for L = 30 ab^{-1}**

	ggF	VBF	ttH	VH
$\sigma(100\text{TeV})(\text{pb})$	802	69	33	27
$\sigma(100\text{TeV})/\sigma(14\text{TeV})(\text{pb})$	16	16	52	11
$\text{N}(\sqrt{s}=100\text{ TeV}, 30\text{ ab}^{-1})$	25×10^9	2.5×10^9	10^9	7.5×10^8

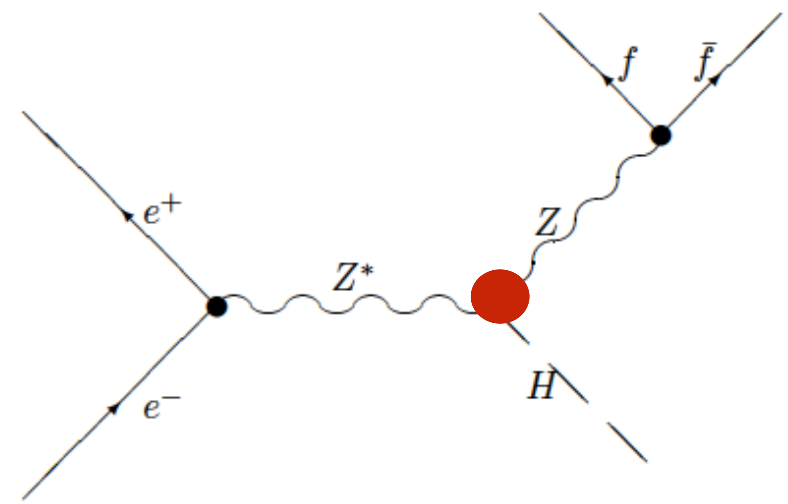
Higgs Boson Coupling to Z
@FCC-ee

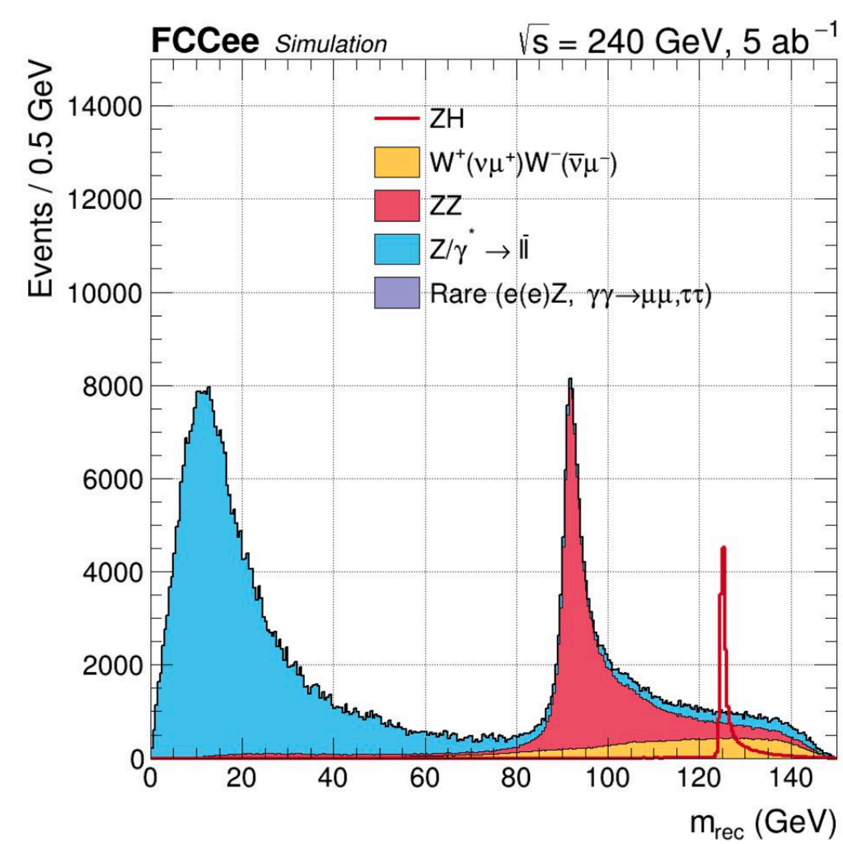
- Measurement through the recoil mass method in $e^+e^- \to HZ$ ($Z \to \ell^+ \ell^-$)
  - recoil mass distribution exhibits sharp peak at Higgs mass

$$m^2_{\rm recoil} = s + m^2_{\ell\ell} - 2\sqrt{s}(E_{\ell^+} + E_{\ell^-})$$

  → decay-mode independent measurement of the HZ coupling

- → expected relative precision on g_{HZZ} of **±0.17%**





Higgs Boson Couplings
@FCC-INT

arXiv:1905.03764

- Summary of the expected relative precision (%) of the Higgs boson couplings

kappa-3 scenario	CEPC	FCC-ee_{240}	FCC-ee_{365}	FCC-ee/eh/hh
κ_W [%]	0.88	0.88	0.41	0.19
κ_Z[%]	0.18	0.20	0.17	0.16
κ_g[%]	1.	1.2	0.9	0.5
κ_γ [%]	1.3	1.3	1.3	0.31
$\kappa_{Z\gamma}$ [%]	6.3	10.*	10.*	0.7
κ_c [%]	2.	1.5	1.3	0.96
κ_t [%]	3.1	3.1	3.1	0.96
κ_b [%]	0.92	1.	0.64	0.48
κ_μ [%]	3.9	4.	3.9	0.43
κ_τ [%]	0.91	0.94	0.66	0.46

- Most precise coupling measurements (to Z and W bosons) are measured to ±0.2-0.4%

Higgs Boson Invisible and Exotic Decays

@FCC-INT

arXiv:1905.03764

- Higgs boson to invisible decays are predicted in the Higgs-portal model of Dark Matter
  - Selection of events with a Z boson and nothing:
    $e^+e^- \rightarrow HZ$, $H \rightarrow$ invisible and $Z \rightarrow bb$, $\ell^+ \ell^-$
- → Upper limits at the 95% CL: **$BR_{inv} < 0.19\%$ @FCC-ee**
  - FCC-ee will improve upon HL-LHC by an order of magnitude (BRinv < 1.9% @HL-LHC)
  - FCC-hh by another order of magnitude (→ values below the SM value of 0.11%)

	CEPC	FCC-ee$_{240}$	FCC-ee$_{365}$	FCC-ee/eh/hh
BR_{inv} (<%, 95% CL)	0.27	0.22	0.19	0.024
BR_{unt} (<%, 95% CL)	1.1	1.2	1.	1.

- Upper limits at the 95% CL on exotic decays (final states that cannot be tagged as SM decays): **$BR_{unt} < 1\%$**

Higgs Boson Total Width Γ_H

arXiv:1905.03764

- Total Higgs boson Γ_H can be extracted from
  - **ZH inclusive cross section**
  - in combination with **exclusive Higgs decays**
- **$e^+e^- \rightarrow$ HZ, H $\rightarrow$ ZZ*** mostly @$\sqrt{s}$ = 240 GeV

$$\frac{\sigma(e^+e^- \to ZH)}{\mathrm{BR}(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{\mathrm{SM}} \times \Gamma_H$$

- Improvement using
  - other decays particularly **H → WW* and H → bb** decays and
  - vector boson fusion channel **e^+e^- → H**$\nu\nu$ mostly @$\sqrt{s}$ = 365 GeV
- → **Determination of Γ_H to ±1.1%**

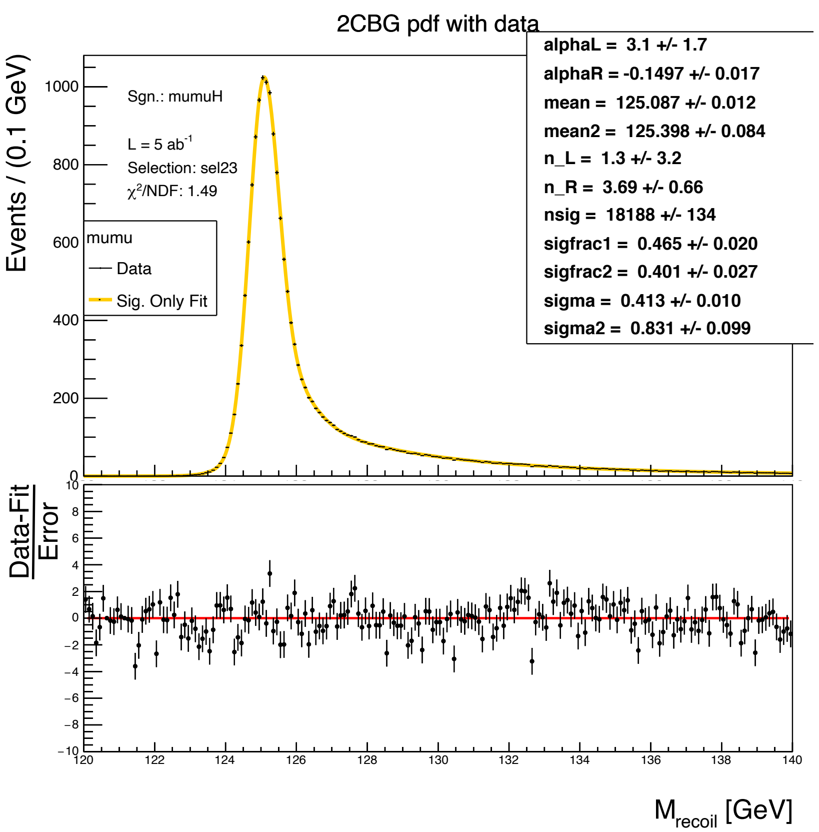
Higgs Boson Cross Section and Mass

Recent developments on the "recoil mass" method

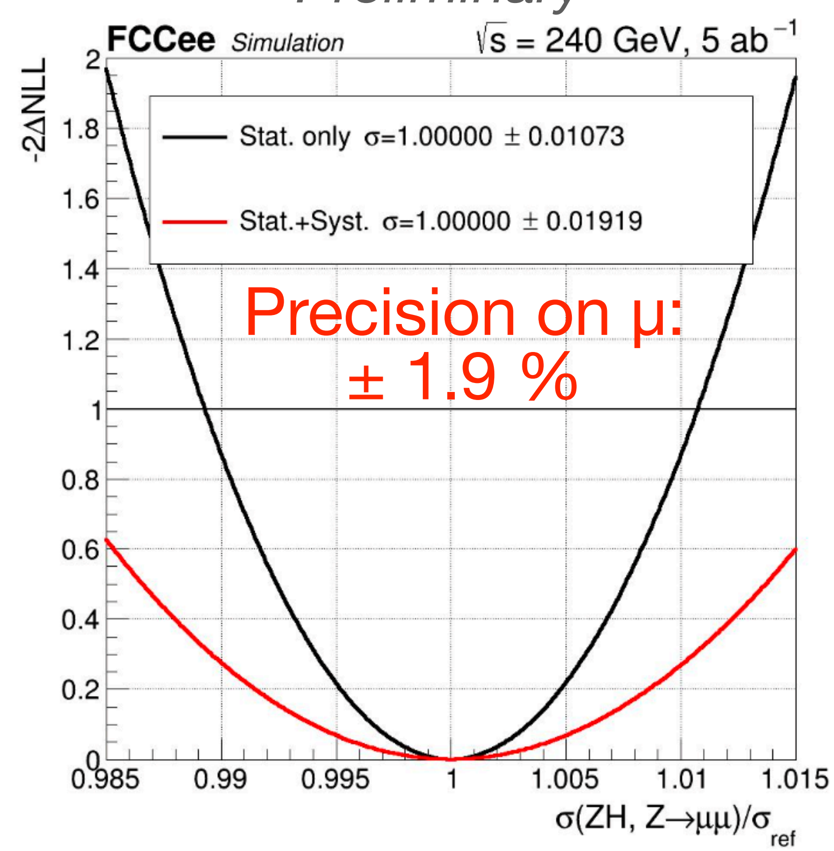
- Recent efforts to optimise and tune signal parameterisation (2 Crystal-Ball + Gaussian) and to include systematic uncertainties (BES, ISR, …)
- Negative log-Likelihood scans as a function of the signal strength and of the Higgs mass

J. Eysermans - talk at the FCC week - June 2021

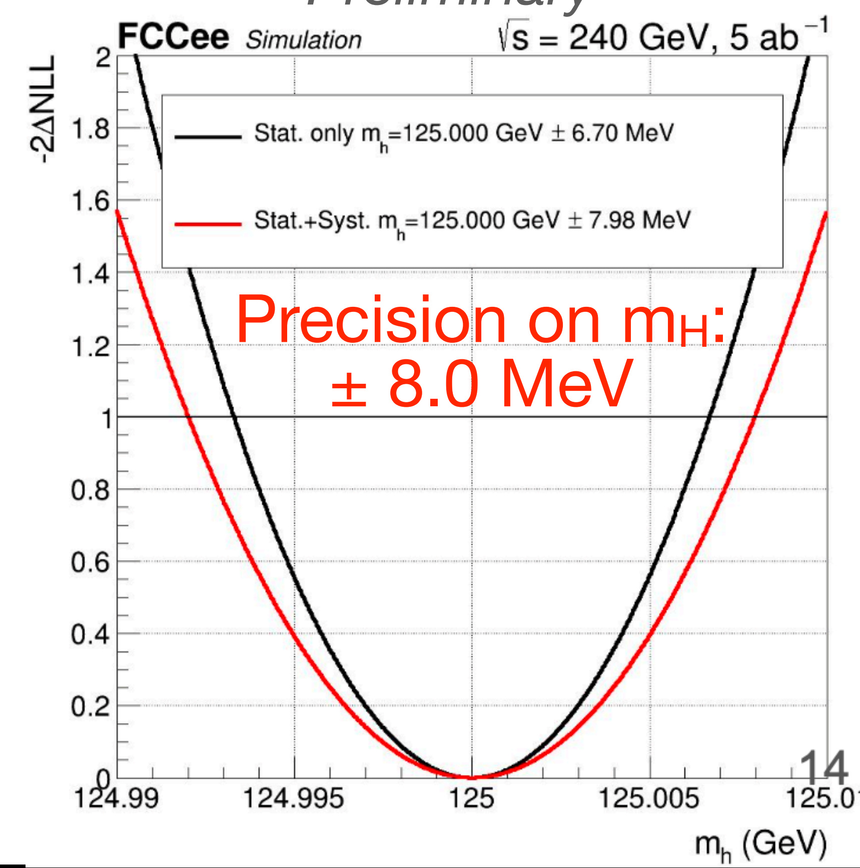
Preliminary



Preliminary



Preliminary



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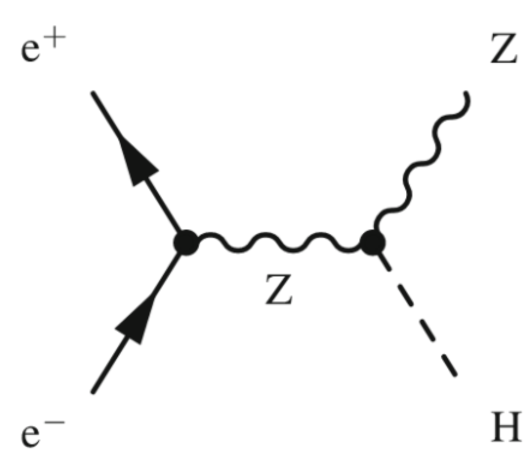
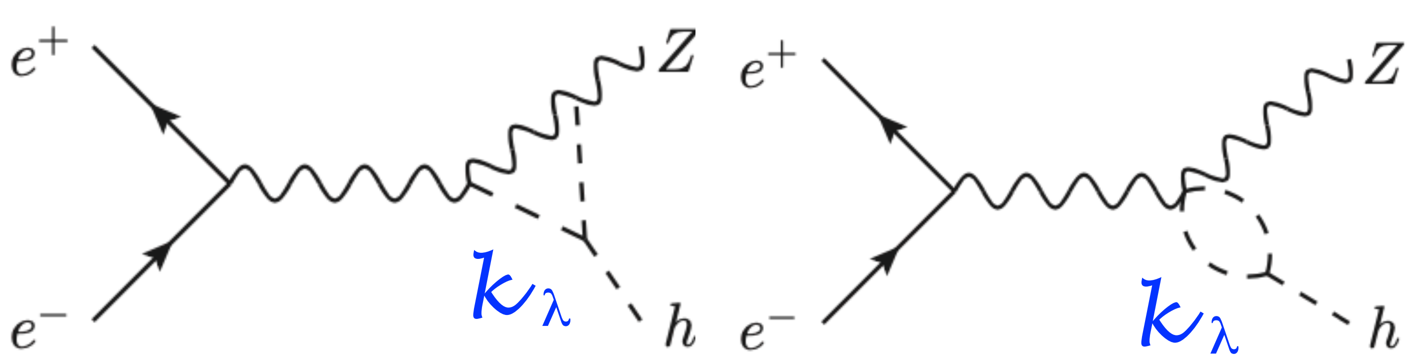
Higgs Boson Mass

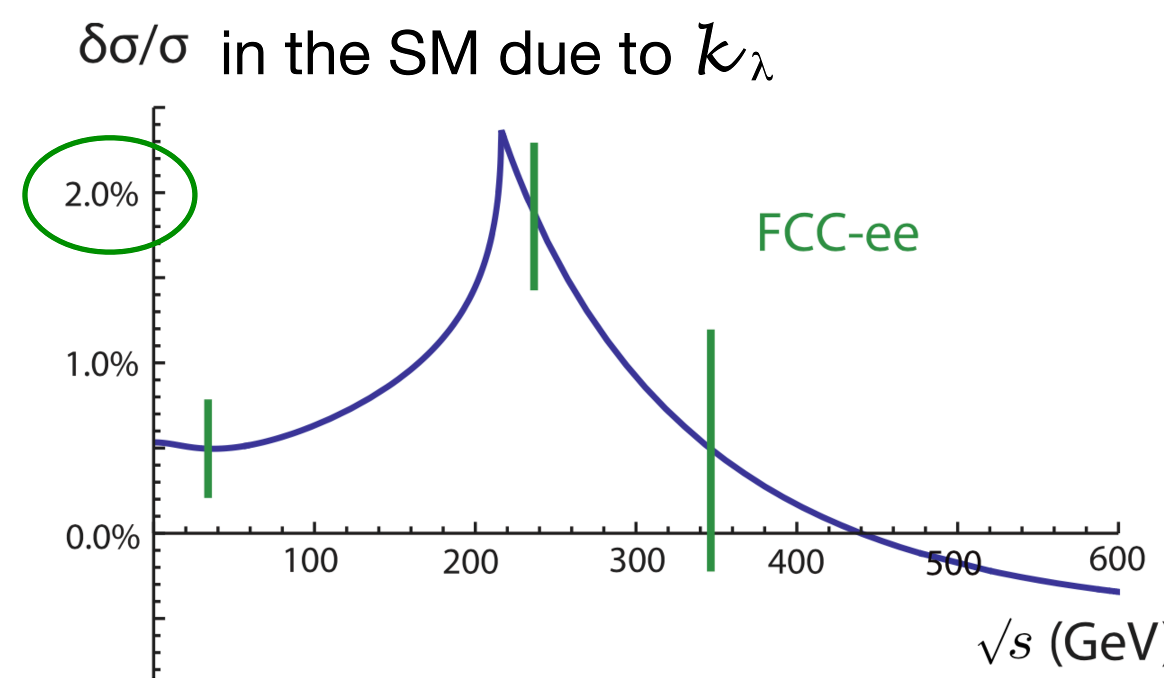
Scan of the HZ threshold @FCC-ee

arXiv:2106.15438

- **Deviation in the HZ Born cross section** due to the Higgs boson self-coupling
  - **relative enhancement maximal (~2%)** at the HZ production threshold







- With 5 ab^{-1} at $\sqrt{s} \simeq 217$ GeV → **statistical precision on m_H: ± 9 MeV**

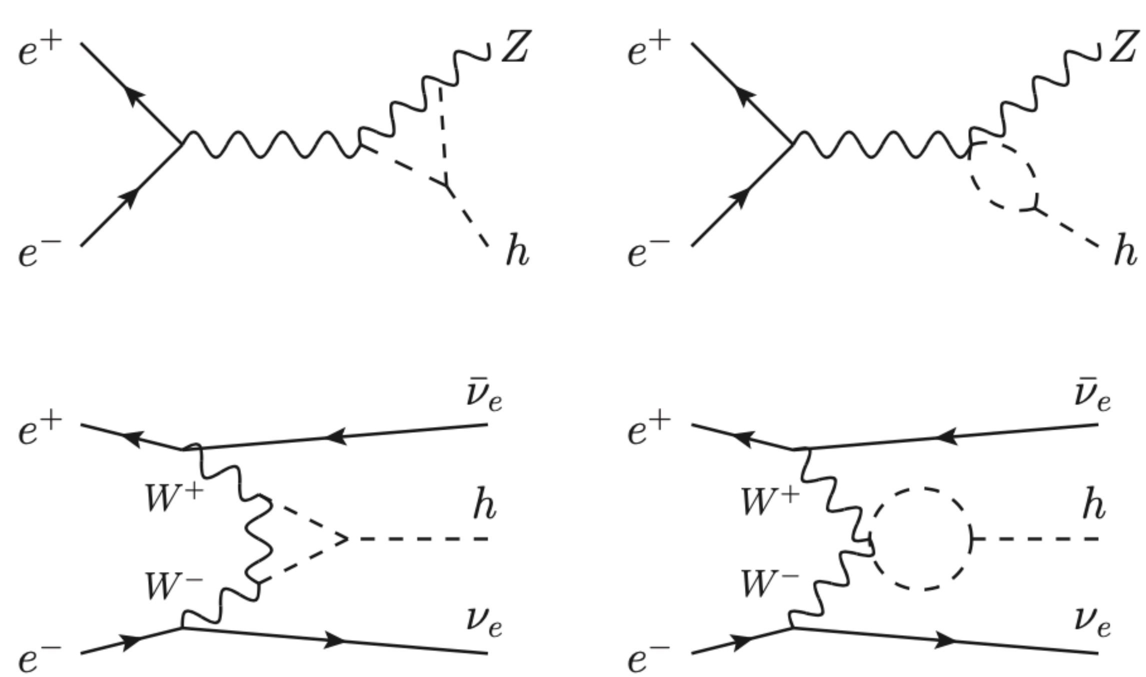
Higgs Boson Self-Coupling

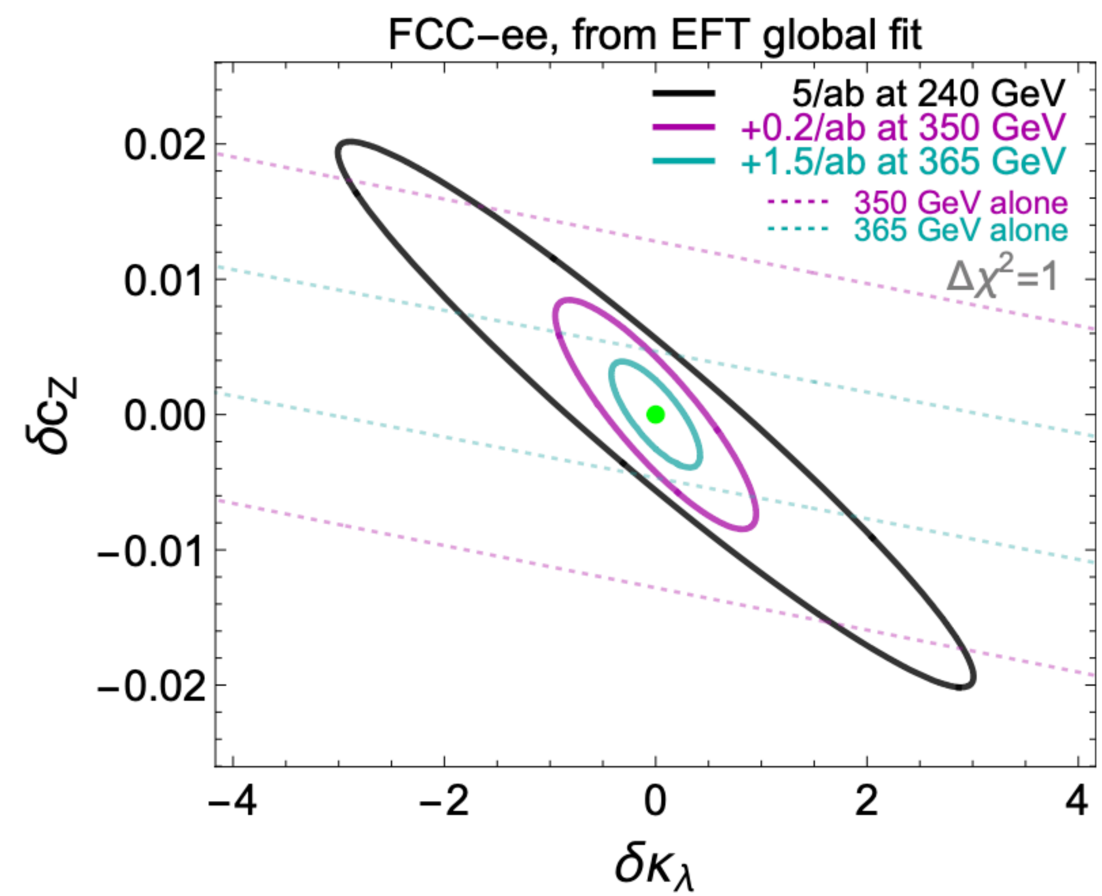
Single Higgs Production @FCC-ee

arXiv:2106.15438

- $\delta\sigma_{HZ}$ can constrain a linear combination of the deviations in the Higgs self-coupling (parameterised as δ_h) and g_{hZZ}/g_{hWW} couplings (parameterised as δ_Z)

$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

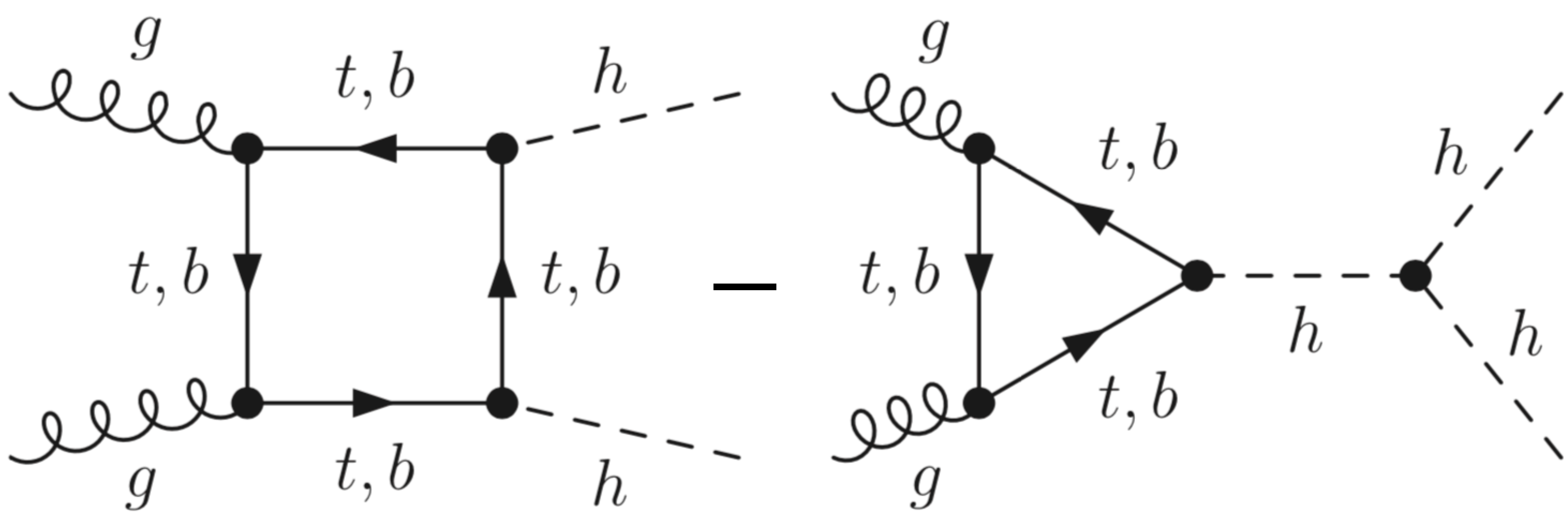




- → **g_{HHH} coupling measurement to ±33% with 2 IP**
  reduced to ±24% with 4 IP

Higgs Boson Self-Coupling

Di-Higgs Production @FCC-hh

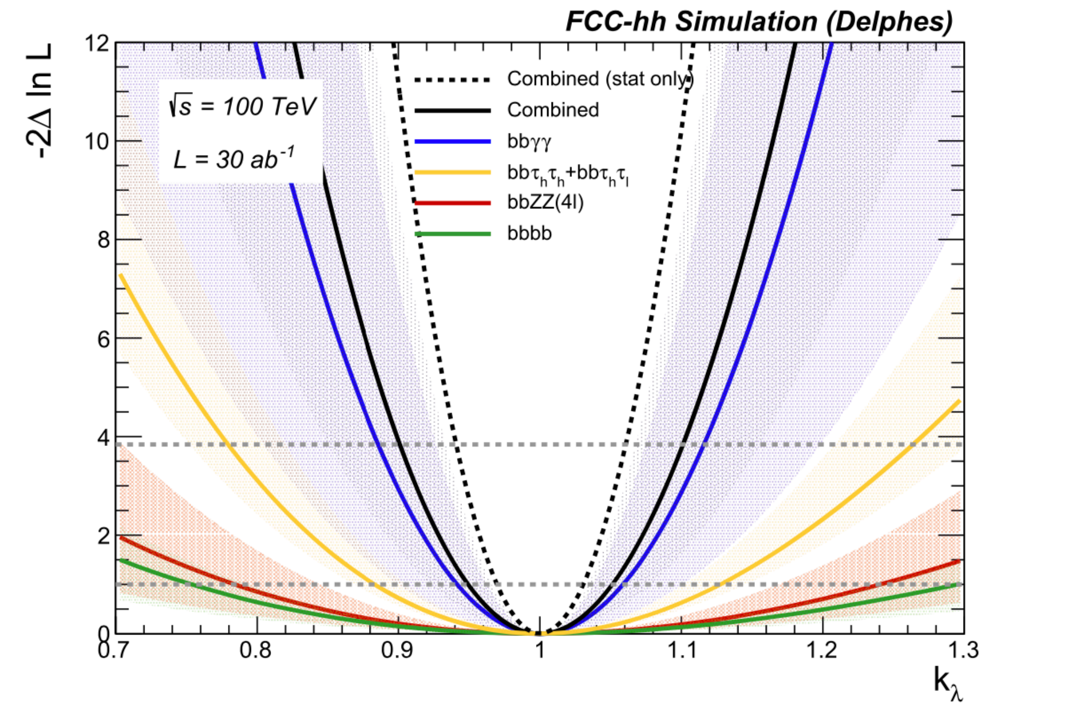


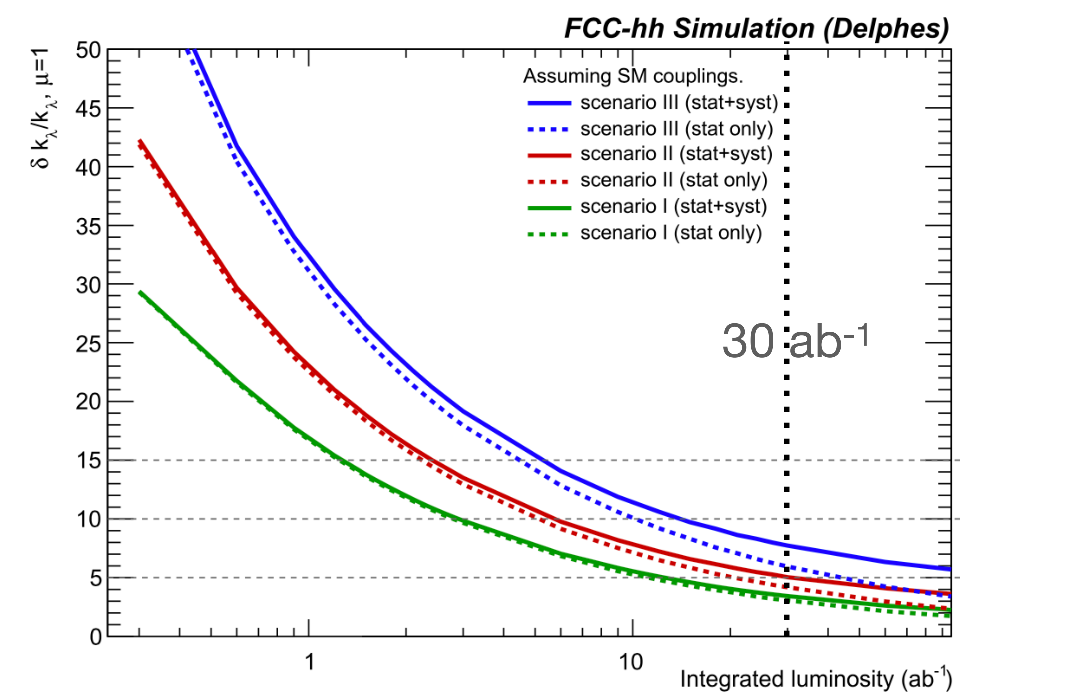
- Very large di-Higgs samples produced at FCC-hh
  - σ(100 TeV) / σ(14 TeV) ≅ 40
  - L(FCC-hh) / L(HL-LHC) ≅ 10
  - → Naively, factor 20 smaller statistical uncertainty

Higgs Boson Self-Coupling

Di-Higgs Production @FCC-hh

- Negative log-Likelihood scan as a function of the trilinear self-coupling modifier
- → Higgs self-coupling measurement with a precision in the range **[3.4 - 7.8]%** at 68% CL depending on the assumed detector performance and systematic uncertainties
  - only possible at a 100 TeV hadron machine
  - possible thanks also to precise BR measurements at FCC-ee





https://doi.org/10.1140/epjc/s10052-020-08595-3

Conclusions

- Fantastic prospects to probe the Higgs sector with FCC:
  - **Model-independent measurements of g_{HZZ} and Γ_H** with FCC-ee
  - **Sub-percent precision** on several Higgs couplings
    - only possible with FCC-ee
  - **Percent precision** on Higgs self-coupling
    - only possible with FCC-hh
- **Synergy** between **FCC-ee** and **FCC-hh** Higgs physics
  - FCC-ee and FCC-hh will provide **by far** the best possible Higgs measurements of any accelerator

Backup

Future Circular Colliders

- Several future colliders are proposed
  - Circular lepton colliders: **FCC-ee@CERN** and **CepC@China**
  - pp colliders: **FCC-hh@CERN** and **SppC@China**

HL-LHC
(CERN)

FCC design study for a post-LHC collider at CERN:
FCC-ee followed by **FCC-hh**
as recommended by the EPPSU

Need for a versatile machine capable to adjust to very different New Physics scenarios

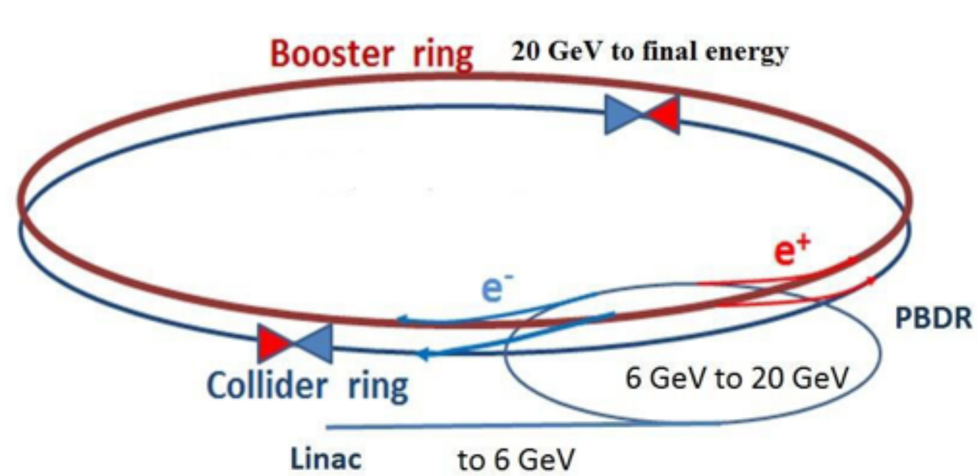
CepC/SppC
(China)

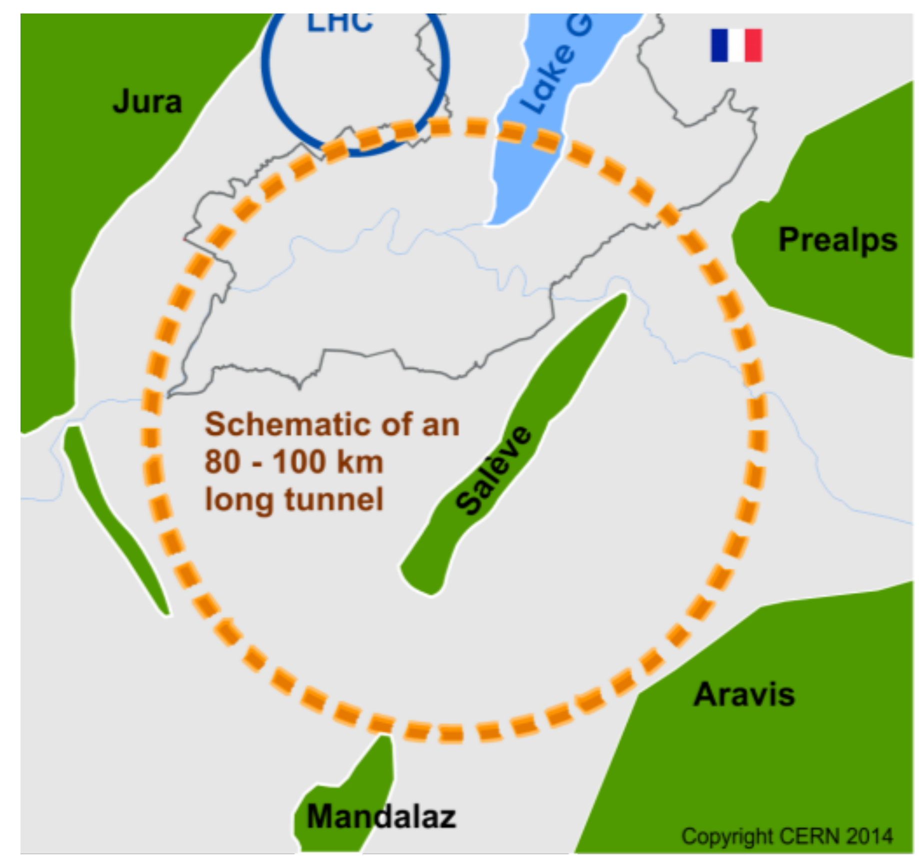
Future Circular Colliders

FCC@CERN

https://fcc-cdr.web.cern.ch/

- The Future Circular Collider (FCC) study: Collider installed in a tunnel with a circumference of 100 km
- The e^+e^- collider FCC-ee is a first step towards a pp collider FCC-hh





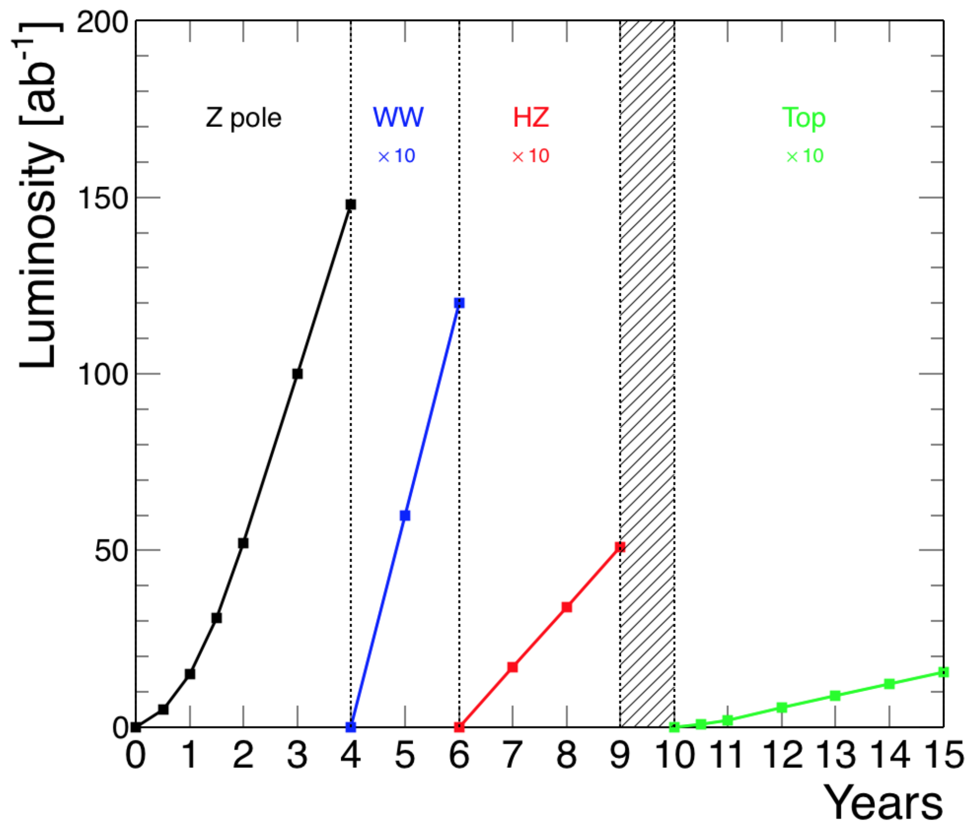
- *“Most effective and comprehensive approach to thoroughly explore the open questions in modern particle physics is a staged research programme, integrating in sequence lepton (FCC-ee) and hadron (FCC-hh) collision programmes”* M.Benedikt

Future Circular Colliders

FCC-ee@CERN

Collider	Type	$\sqrt{s}$	N(Det.)	$\mathcal{L}_{\text{inst}}$ $[10^{34}]\ \text{cm}^{-2}\text{s}^{-1}$	$\mathcal{L}$ $[\text{ab}^{-1}]$	Time [years]
FCC-ee	*ee*	M_Z	2	100/200	150	4
		$2M_W$	2	25	10	1-2
		240 GeV	2	7	5	3
		$2m_{top}$	2	0.8/1.4	1.5	5

	$\sqrt{s}$		
Z peak	91 GeV	5×10^{12}	$e^+e^- \to Z$
WW threshold	161 GeV	10^8	$e^+e^- \to WW$
ZH threshold	240 GeV	10^6	$e^+e^- \to ZH$
$t\bar{t}$ threshold	365 GeV	10^6	$e^+e^- \to t\bar{t}$

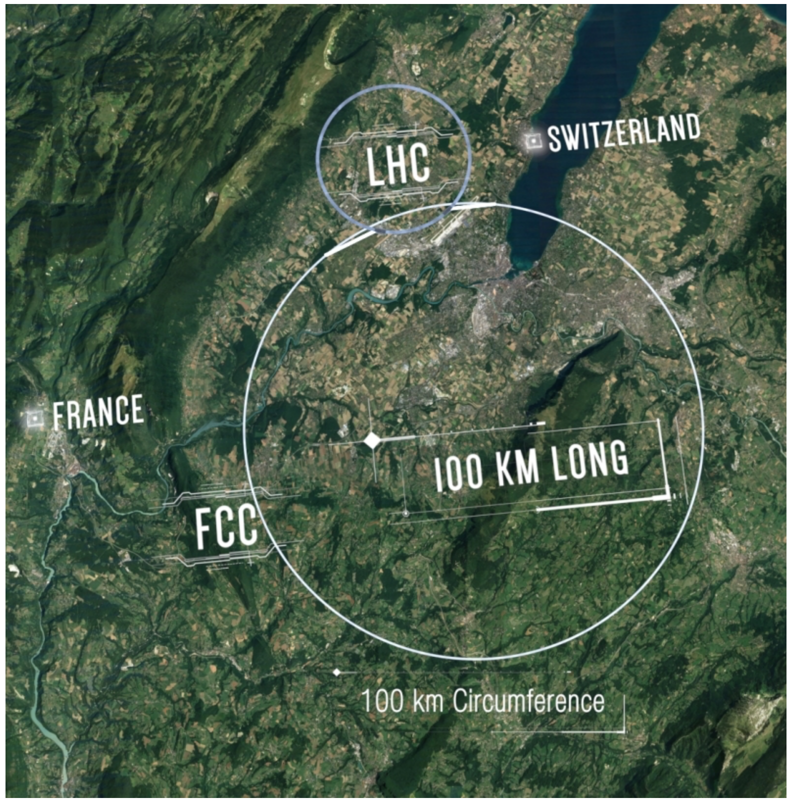


Future Circular Colliders

FCC-hh@CERN

- pp-collider FCC-hh @ 100 TeV in a second phase

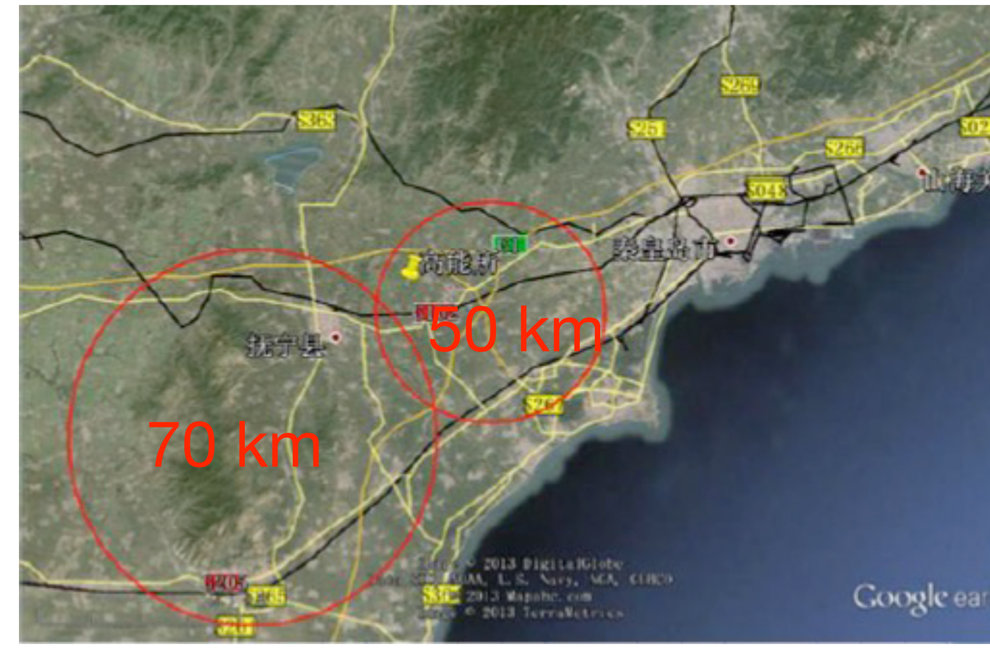
Collider	Type	$\sqrt{s}$	N(Det.)	$\mathcal{L}_{\text{inst}}$ $[10^{34}]\ \text{cm}^{-2}\text{s}^{-1}$	$\mathcal{L}$ $[\text{ab}^{-1}]$	Time [years]
FCC-hh	*pp*	100 TeV	2	30	30.0	25



Future Circular Colliders

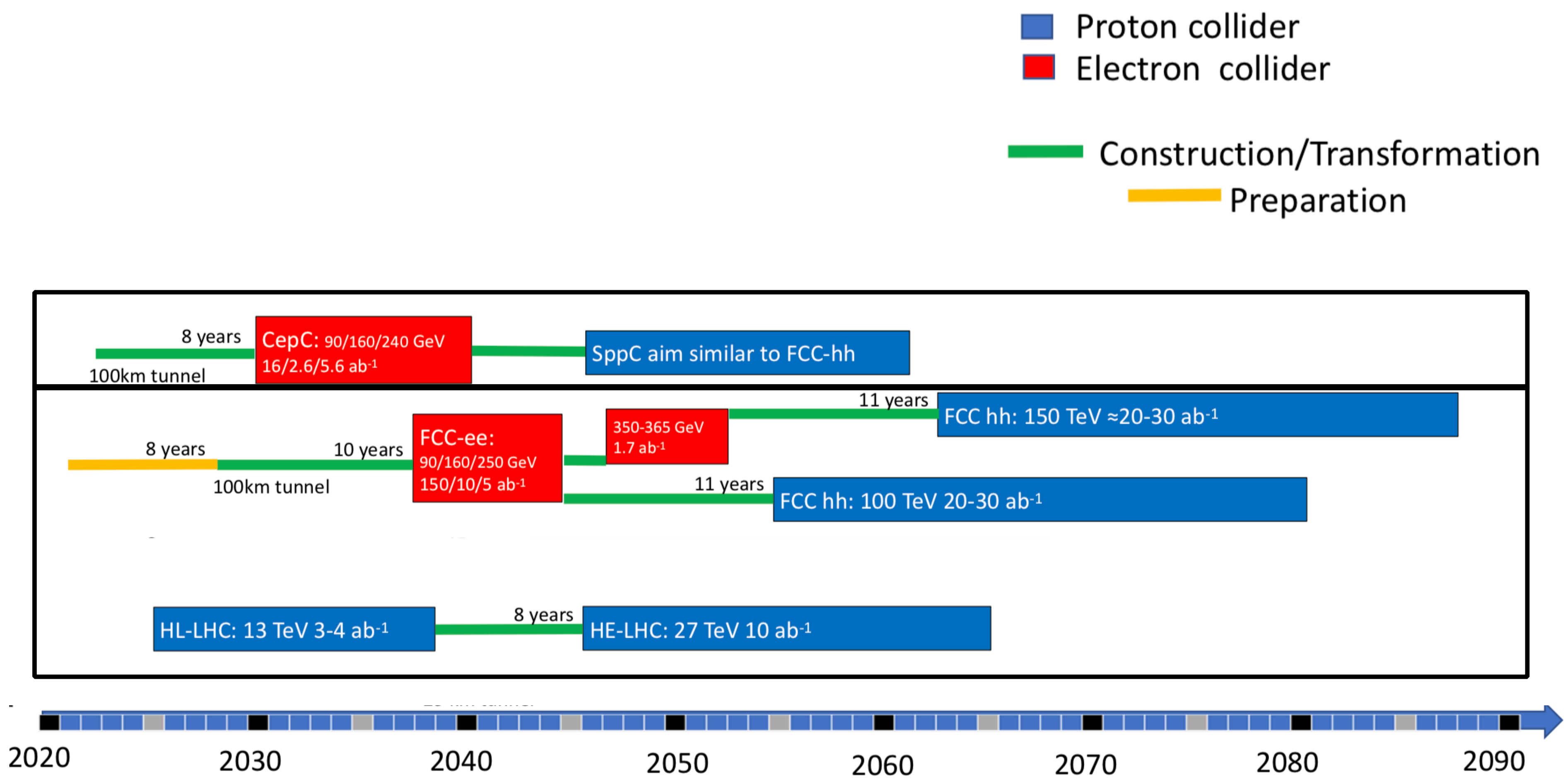
CepC/SppC@China

- First phase: a circular electron-positron collider in a tunnel with a circumference of 50-70 km



Collider	Type	$\sqrt{s}$	N(Det.)	$\mathcal{L}_{\text{inst}}$ $[10^{34}]\ \text{cm}^{-2}\text{s}^{-1}$	$\mathcal{L}$ $[\text{ab}^{-1}]$	Time [years]
CEPC	ee	M_Z	2	17/32	16	2
		$2M_W$	2	10	2.6	1
		240 GeV	2	3	5.6	7

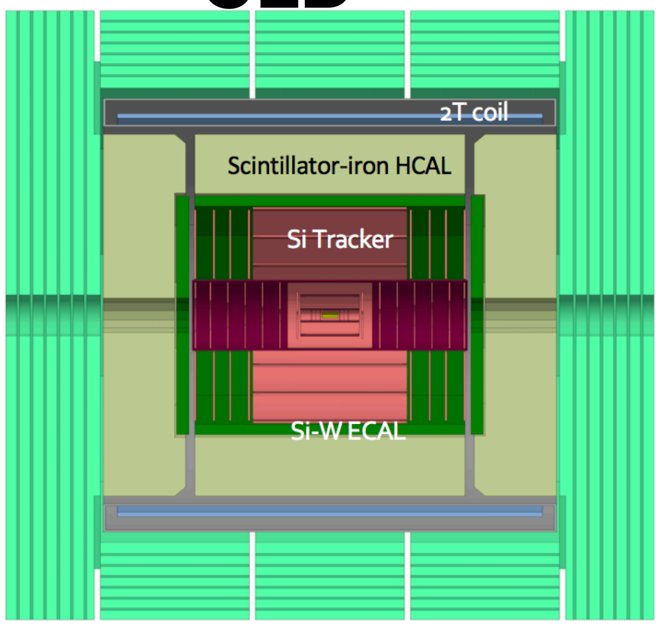
Future Circular Colliders



Detectors

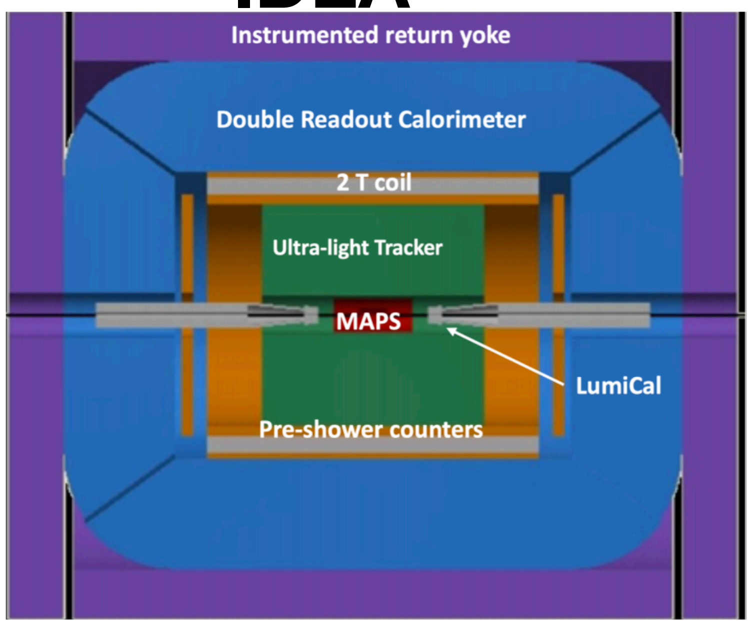
FCC-ee

CLD



- Consolidated option based on the detector design developed for CLIC: Proven concept, understood performance
  - 2 T solenoid
  - All silicon vertex detector and tracker
  - High granularity calorimeter system
  - Muon detector with RPCs

IDEA

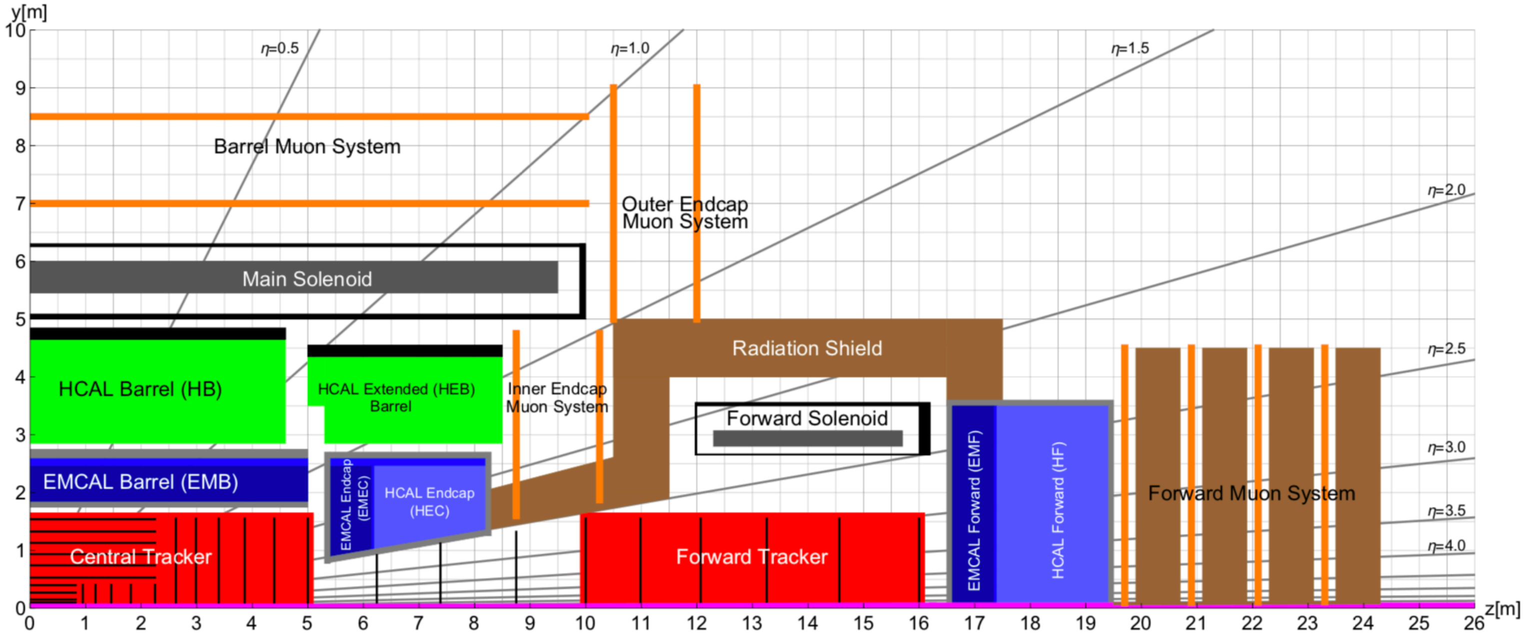


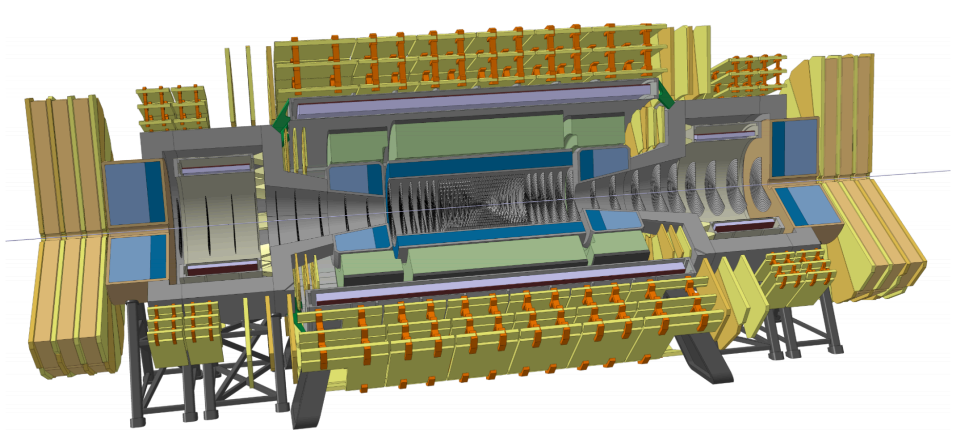
- New, innovative, probably more cost-effective design
- Thin and light 2 T solenoid coil inside calorimeter system
  - Silicon vertex detector
  - Short drift, ultra light wire chamber
  - Dual Readout calorimeter
  - MPGD-based muon detector

Detectors

FCC-hh

- Must be able to cope with:
  - Very large dynamic range of signatures: E = 20 GeV — 20 TeV
  - Hostile environment (1k pileup and up to 10^{18} cm^{-2} MeV neutron equivalent fluence)
- Characteristics:
  - Large acceptance (for low p_T physics)
  - Extreme granularity (for high p_T and pile-up rejection)
  - Timing capabilities
  - Radiation hardness





kappa and *EFT* Framework

arXiv:1307.1347

- ***Kappa* framework**
  - Characterisation of Higgs couplings in terms of a series of Higgs **coupling strength modifier parameters** k
    - defined as the ratios of the couplings of the Higgs bosons to particles *i* to their corresponding Standard Model values

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

- ***EFT* approach**
  - introduced to parametrise directly the new physics (rather than its effects) in terms of gauge invariant operators
  - global fit including not only Higgs but also di-boson and EWK precision observables

kappa Framework

arXiv:1209.0040

- Characterisation of Higgs couplings in terms of a series of Higgs **coupling strength modifier parameters** k
  - **defined as the ratios of the couplings of the Higgs bosons to particles *i* to their corresponding Standard Model values**

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

- Extension to allow the Higgs boson decays into **invisible** or all other **untagged BSM particles**

$$\Gamma_H = \frac{\Gamma_H^{\mathrm{SM}} \cdot \kappa_H^2}{1 - (BR_{inv} + BR_{unt})}$$

Higgs Boson Cross Section

@FCC-ee *arXiv:2106.15438*

- Relative uncertainty on $\sigma_{ZH} \cdot Br(H \to XX)$ and $\sigma_{H\nu\nu} \cdot Br(H \to XX)$
- → **Accuracy to ±0.5 %**

$\sqrt{s}$	240 GeV		365 GeV	
Integrated luminosity	$5\,ab^{-1}$		$1.5\,ab^{-1}$	
$\delta(\sigma\mathcal{B})/\sigma\mathcal{B}$ (%)	ZH	$\nu_e\bar{\nu}_e$ H	ZH	$\nu_e\bar{\nu}_e$ H
$H \to$ 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	

Higgs Boson Width Γ_H

arXiv:1905.03764

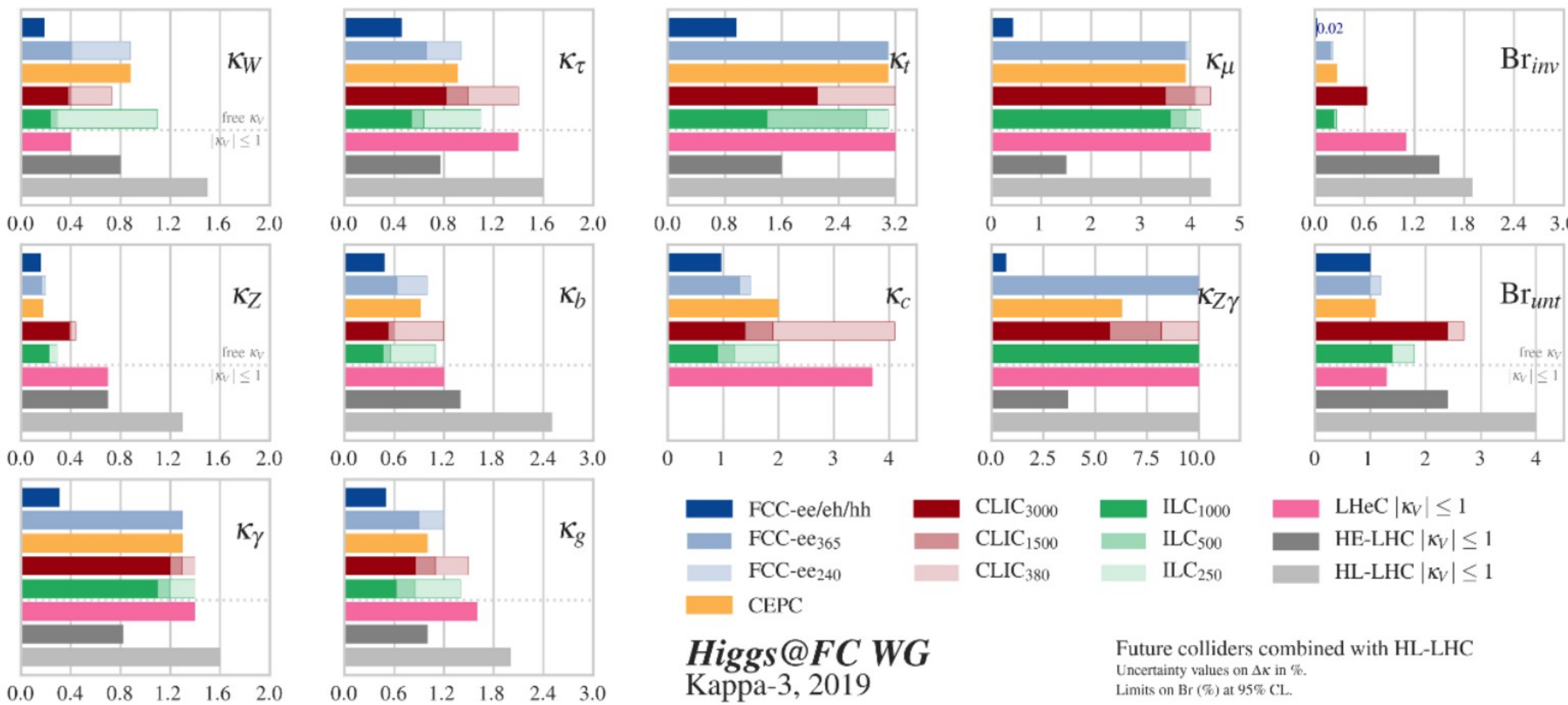
- With $\Delta k_Z / k_Z$ = 0.17% and under the same coupling assumption, one can extract the Higgs total width
- → **Determination of Γ_H to ±1.1%**

- Overview of expected precision

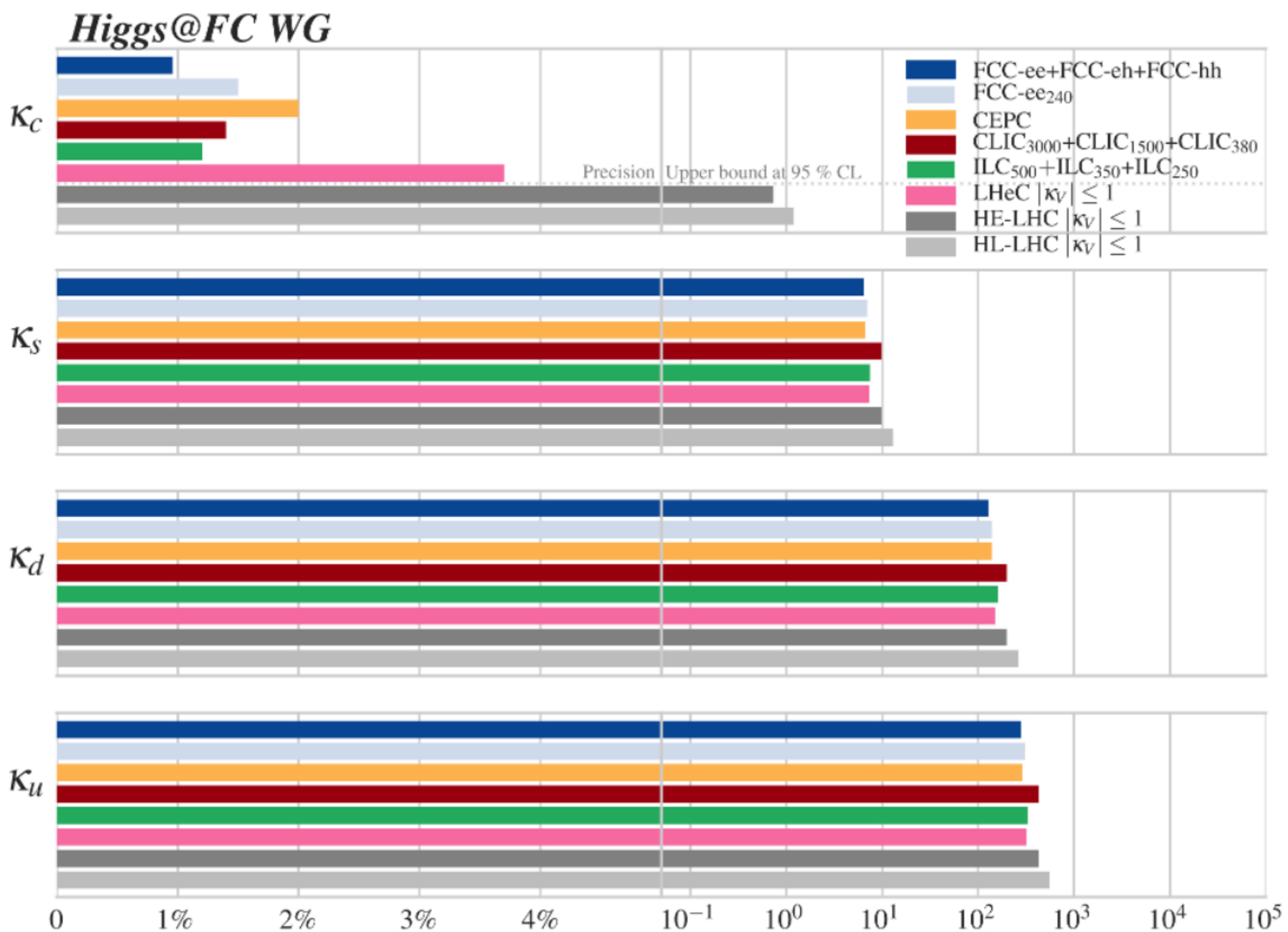
Collider	$\delta\Gamma_H$ [%] from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ [%] kappa-3 fit
CEPC	2.8	κ-framework [103, 104]	1.7
FCC-ee$_{240}$	2.7	κ-framework [1]	1.8
FCC-ee$_{365}$	1.3	κ-framework [1]	1.1

Higgs Couplings at Future Colliders

arXiv:1910.11775



Higgs Decays to Light Quarks



Higgs Boson Couplings

With/Without HL-LHC

- Precision on a few Higgs boson couplings g_{HXX} in the κ framework

P. Janot - 2nd FCC France Workshop 20-21 Jan 2021

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	$FCC\text{-}ee_{240\to365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years	10	11.5	8	7	3 + 1 + 4
g_{HZZ} (%)	1.5	0.30 / 0.29	0.50 / 0.44	0.19 / 0.18	0.18 / 0.17
g_{HWW} (%)	1.7	1.8 / 1.0	0.86 / 0.73	1.3 / 0.88	0.44 / 0.41
g_{Hbb} (%)	5.1	1.8 / 1.1	1.9 / 1.2	1.3 / 0.92	0.69 / 0.64
g_{Hcc} (%)	SM	2.5 / 2.0	4.4 / 4.1	2.2 / 2.0	1.3 / 1.3
g_{Hgg} (%)	2.5	2.3 / 1.4	2.5 / 1.5	1.5 / 1.0	1.0 / 0.89
$g_{H\tau\tau}$ (%)	1.9	1.9 / 1.1	3.1 / 1.4	1.4 / 0.91	0.74 / 0.66
$g_{H\mu\mu}$ (%)	4.4	15. / 4.2	– / 4.4	9.0 / 3.9	8.9 / 3.9
$g_{H\gamma\gamma}$ (%)	1.8	6.8 / 1.3	– / 1.5	3.7 / 1.2	3.9 / 1.2
$g_{HZ\gamma}$ (%)	11.	– / 10.	– / 10.	8.2 / 6.3	– / 10.
g_{Htt} (%)	3.4	– / 3.1	– / 3.2	– / 3.1	10. / 3.1
g_{HHH} (%)	50.	– / 49.	– / 50.	– / 50.	44./33. 27./24.
Γ_H (%)	SM	2.2	2.5	1.7	1.1
BR_{inv} (%)	1.9	0.26	0.65	0.28	0.19
BR_{EXO} (%)	SM (0.0)	1.8	2.7	1.1	1.1

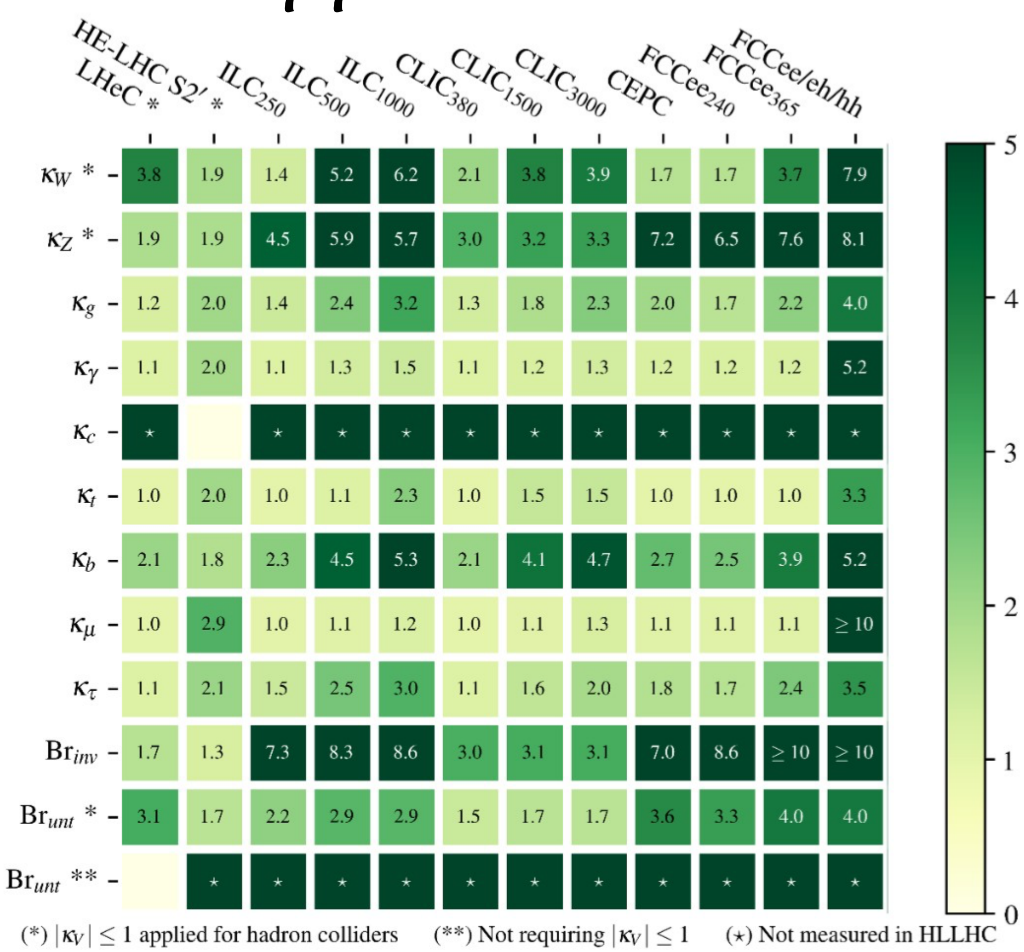
Collider	ILC_{500}	ILC_{1000}	CLIC	FCC-INT
g_{HZZ} (%)	0.24 / 0.23	0.24 / 0.23	0.39 / 0.39	0.17 / 0.16
g_{HWW} (%)	0.31 / 0.29	0.26 / 0.24	0.38 / 0.38	0.20 / 0.19
g_{Hbb} (%)	0.60 / 0.56	0.50 / 0.47	0.53 / 0.53	0.48 / 0.48
g_{Hcc} (%)	1.3 / 1.2	0.91 / 0.90	1.4 / 1.4	0.96 / 0.96
g_{Hgg} (%)	0.98 / 0.85	0.67 / 0.63	0.96 / 0.86	0.52 / 0.50
$g_{H\tau\tau}$ (%)	0.72 / 0.64	0.58 / 0.54	0.95 / 0.82	0.49 / 0.46
$g_{H\mu\mu}$ (%)	9.4 / 3.9	6.3 / 3.6	5.9 / 3.5	0.43 / 0.43
$g_{H\gamma\gamma}$ (%)	3.5 / 1.2	1.9 / 1.1	2.3 / 1.1	0.32 / 0.32
$g_{HZ\gamma}$ (%)	– / 10.	– / 10.	7. / 5.7	0.71 / 0.70
g_{Htt} (%)	6.9 / 2.8	1.6 / 1.4	2.7 / 2.1	1.0 / 0.95
g_{HHH} (%)	27.	10.	9.	5.
Γ_H (%)	1.1	1.0	1.6	0.91
BR_{inv} (%)	0.23	0.22	0.61	0.024
BR_{EXO} (%)	1.4	1.4	2.4	1.0

Higgs Boson Couplings

Improvements compared to HL-LHC

- Improvement is shown as the ratio of the precision at the HL-LHC over the precision at the future collider

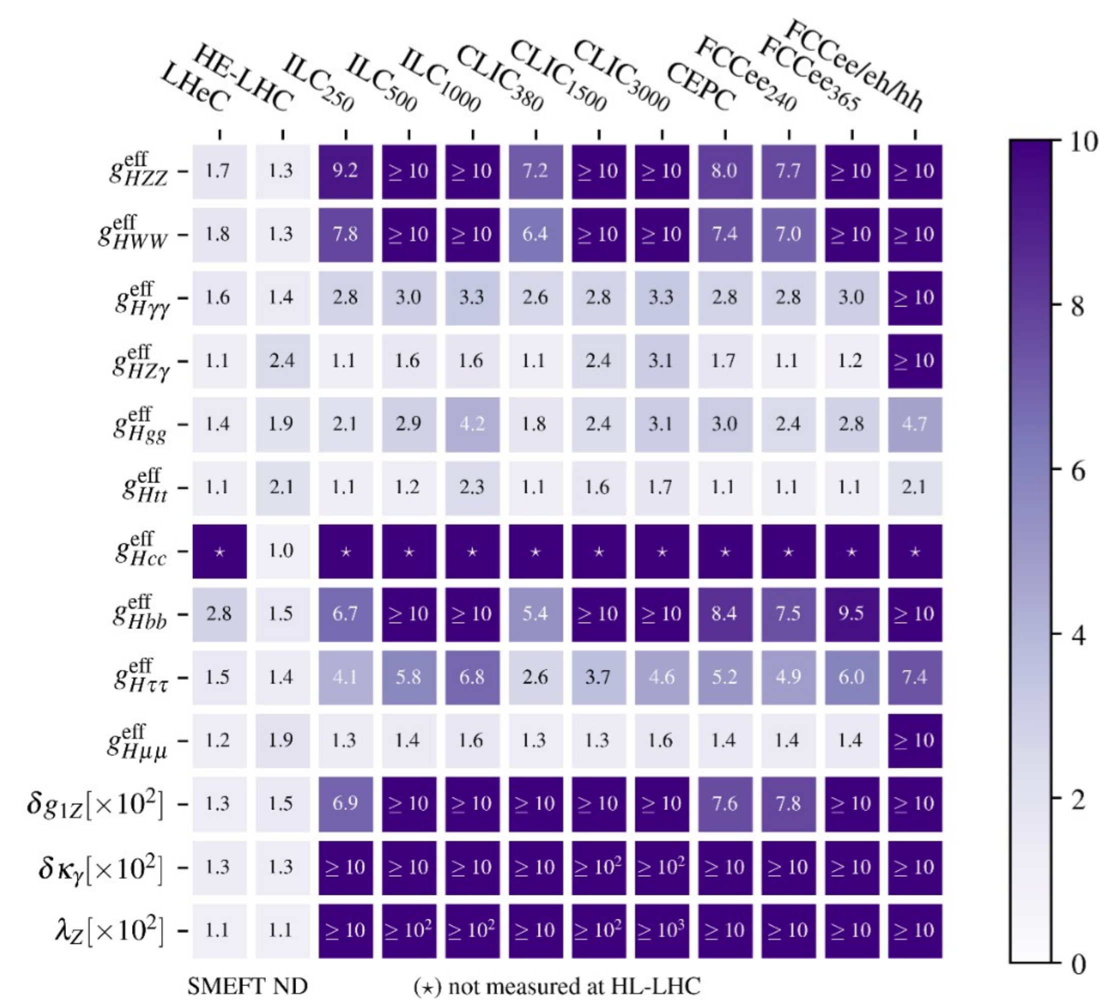
kappa framework



	LHeC *	HE-LHC S2′ *	ILC_{250}	ILC_{500}	ILC_{1000}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
κ_W *	3.8	1.9	1.4	5.2	6.2	2.1	3.8	3.9	1.7	1.7	3.7	7.9
κ_Z *	1.9	1.9	4.5	5.9	5.7	3.0	3.2	3.3	7.2	6.5	7.6	8.1
κ_g	1.2	2.0	1.4	2.4	3.2	1.3	1.8	2.3	2.0	1.7	2.2	4.0
κ_γ	1.1	2.0	1.1	1.3	1.5	1.1	1.2	1.3	1.2	1.2	1.2	5.2
κ_c	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
κ_t	1.0	2.0	1.0	1.1	2.3	1.0	1.5	1.5	1.0	1.0	1.0	3.3
κ_b	2.1	1.8	2.3	4.5	5.3	2.1	4.1	4.7	2.7	2.5	3.9	5.2
κ_μ	1.0	2.9	1.0	1.1	1.2	1.0	1.1	1.3	1.1	1.1	1.1	≥ 10
κ_τ	1.1	2.1	1.5	2.5	3.0	1.1	1.6	2.0	1.8	1.7	2.4	3.5
Br_{inv}	1.7	1.3	7.3	8.3	8.6	3.0	3.1	3.1	7.0	8.6	≥ 10	≥ 10
Br_{unt} *	3.1	1.7	2.2	2.9	2.9	1.5	1.7	1.7	3.6	3.3	4.0	4.0
Br_{unt} **		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆

(*) $|\kappa_V| \leq 1$ applied for hadron colliders (**) Not requiring $|\kappa_V| \leq 1$ (⋆) Not measured in HLLHC

SMEFT framework



	LHeC	HE-LHC	ILC_{250}	ILC_{500}	ILC_{1000}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
g^{eff}_{HZZ}	1.7	1.3	9.2	≥ 10	≥ 10	7.2	≥ 10	≥ 10	8.0	7.7	≥ 10	≥ 10
g^{eff}_{HWW}	1.8	1.3	7.8	≥ 10	≥ 10	6.4	≥ 10	≥ 10	7.4	7.0	≥ 10	≥ 10
$g^{eff}_{H\gamma\gamma}$	1.6	1.4	2.8	3.0	3.3	2.6	2.8	3.3	2.8	2.8	3.0	≥ 10
$g^{eff}_{HZ\gamma}$	1.1	2.4	1.1	1.6	1.6	1.1	2.4	3.1	1.7	1.1	1.2	≥ 10
g^{eff}_{Hgg}	1.4	1.9	2.1	2.9	4.2	1.8	2.4	3.1	3.0	2.4	2.8	4.7
g^{eff}_{Htt}	1.1	2.1	1.1	1.2	2.3	1.1	1.6	1.7	1.1	1.1	1.1	2.1
g^{eff}_{Hcc}	⋆	1.0	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
g^{eff}_{Hbb}	2.8	1.5	6.7	≥ 10	≥ 10	5.4	≥ 10	≥ 10	8.4	7.5	9.5	≥ 10
$g^{eff}_{H\tau\tau}$	1.5	1.4	4.1	5.8	6.8	2.6	3.7	4.6	5.2	4.9	6.0	7.4
$g^{eff}_{H\mu\mu}$	1.2	1.9	1.3	1.4	1.6	1.3	1.3	1.6	1.4	1.4	1.4	≥ 10
$\delta g_{1Z}[\times 10^2]$	1.3	1.5	6.9	≥ 10	≥ 10	≥ 10	≥ 10	≥ 10	7.6	7.8	≥ 10	≥ 10
$\delta \kappa_\gamma[\times 10^2]$	1.3	1.3	≥ 10	≥ 10	≥ 10	≥ 10	$\geq 10^2$	$\geq 10^2$	≥ 10	≥ 10	≥ 10	≥ 10
$\lambda_Z[\times 10^2]$	1.1	1.1	≥ 10	$\geq 10^2$	$\geq 10^2$	≥ 10	$\geq 10^2$	$\geq 10^3$	≥ 10	≥ 10	≥ 10	≥ 10

SMEFT ND (⋆) not measured at HL-LHC

kappa Framework

arXiv:1209.0040

- Characterisation of Higgs couplings in terms of a series of Higgs coupling strength modifier parameters κ
  - defined as the ratios of the couplings of the Higgs bosons to particles *i* to their corresponding Standard Model values

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

- Extension to allow the Higgs boson decays to invisible or untagged BSM particles
  - Higgs boson decays to BSM particles separated in two classes:
    - decays into invisible particles
    - decays into all other “untagged” particles

$$\Gamma_H = \frac{\Gamma_H^{\mathrm{SM}} \cdot \kappa_H^2}{1 - (BR_{inv} + BR_{unt})}$$

kappa Scenarios

Scenario	BR_{inv}	BR_{unt}	include HL-LHC
kappa-0	fixed at 0	fixed at 0	no
kappa-1	measured	fixed at 0	no
kappa-2	measured	measured	no
kappa-3	measured	measured	yes

Higgs Boson Width Γ_H

arXiv:1905.03764

- Total Γ_H can be extracted from a combination of measurements in a model independent way using
  - the inclusive cross section of the ZH process from the mass recoil method
  - in combination with measurements of exclusive Higgs decay cross sections
- **$e^+e^- \rightarrow$ HZ, H $\rightarrow$ ZZ* mostly at $\sqrt{s}$ = 240 GeV:**

$$\sigma\left(e^+e^- \rightarrow ZH, H \rightarrow ZZ\right) = \sigma\left(e^+e^- \rightarrow ZH\right)\frac{\Gamma_{H\rightarrow ZZ}}{\Gamma_H} \propto \frac{g^4_{HZZ}}{\Gamma_H}$$

$$\sigma\left(e^+e^- \rightarrow ZH\right) \propto g^2_{HZZ}$$

$$\Gamma_H \propto \frac{\sigma\left(e^+e^- \rightarrow ZH, H \rightarrow ZZ\right)^2}{\sigma\left(e^+e^- \rightarrow ZH\right)}$$

[limited by H→ZZ stat.]

Higgs Boson Width Γ_H

arXiv:1905.03764

- Improvement using
  - other decays particularly **H → WW* and H → bb** decays and
  - vector boson production channels **e+e- → H**νν **mostly at √s = 365 GeV**

$$\frac{\sigma(ee\to ZH)\cdot BR(H\to WW)\cdot\sigma(ee\to ZH)\cdot BR(H\to bb)}{\sigma(ee\to\nu\nu H)\cdot BR(H\to bb)}$$

$$\propto \frac{g_{HZ}^2\cdot \cancel{g_{HW}^2}}{\Gamma}\cdot\frac{g_{HZ}^2\cdot \cancel{g_{Hb}^2}}{\cancel{\Gamma}}\cdot\frac{\cancel{\Gamma}}{\cancel{g_{HW}^2}\cdot\cancel{g_{Hb}^2}} = \frac{g_{HZ}^4}{\Gamma}$$

Higgs Boson CP

arXiv:1905.03764

- Detecting non-zero CP-odd components in the Higgs interactions with SM particles would point to BSM physics
- Departures from the SM parametrised in terms of dimension-6 operators

$$\delta\mathscr{L}_{\rm CPV}^{hVV} = \frac{h}{v}\left[\tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu} + \tilde{c}_{aa}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{za}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}\tilde{Z}_{\mu\nu} + \tilde{c}_{ww}\frac{g^2}{2}W^+_{\mu\nu}\tilde{W}^-_{\mu\nu}\right]$$

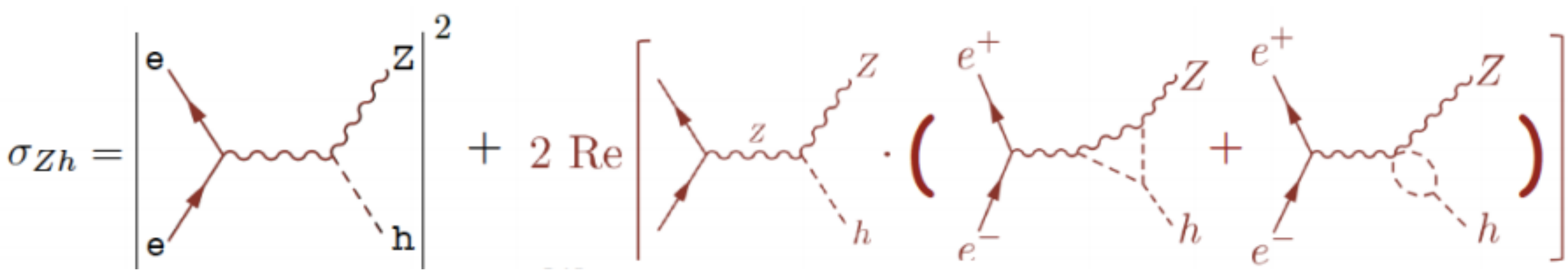
- CP-violating interactions of the Higgs boson with fermions can be parametrised as:

$$\mathscr{L}_{\rm CPV}^{hff} = -\bar{\kappa}_f m_f \frac{h}{v}\bar{\psi}_f(\cos\alpha + i\gamma_5\sin\alpha)\psi_f$$

  where angle α parametrizes the departure from the CP-even case
- @FCC-ee
  - Most promising direct probe of CP violation in fermionic Higgs decays is the $\tau\tau$ decay channel (relatively large branching fraction (6.3%)
- @FCC-eh: CP violation in the top quark interactions
  - a precision of 1.9% could be achieved on α_t

Higgs Boson Self-Coupling
@FCC-ee

- Higgs trilinear indirectly constrained through loop corrections to σ_{ZH}
- $\delta\sigma_{HZ}$ can constrain a linear combination of the deviations in the self-coupling (parameterised as δk_λ) and HZZ/HWW couplings (parameterised as δc_Z)



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

Higgs Boson Self-Coupling

Di-Higgs Production @FCC-hh

- Assumed detector performance and systematic uncertainties:

Table 2 Performance of physics objects for the various scenarios. Objects efficiencies and mistag rates are given for a representative $p_T \approx 50$ GeV. For b and τ-tagging (and their respective mistag rates) numbers for two different working points are given (medium and tight)

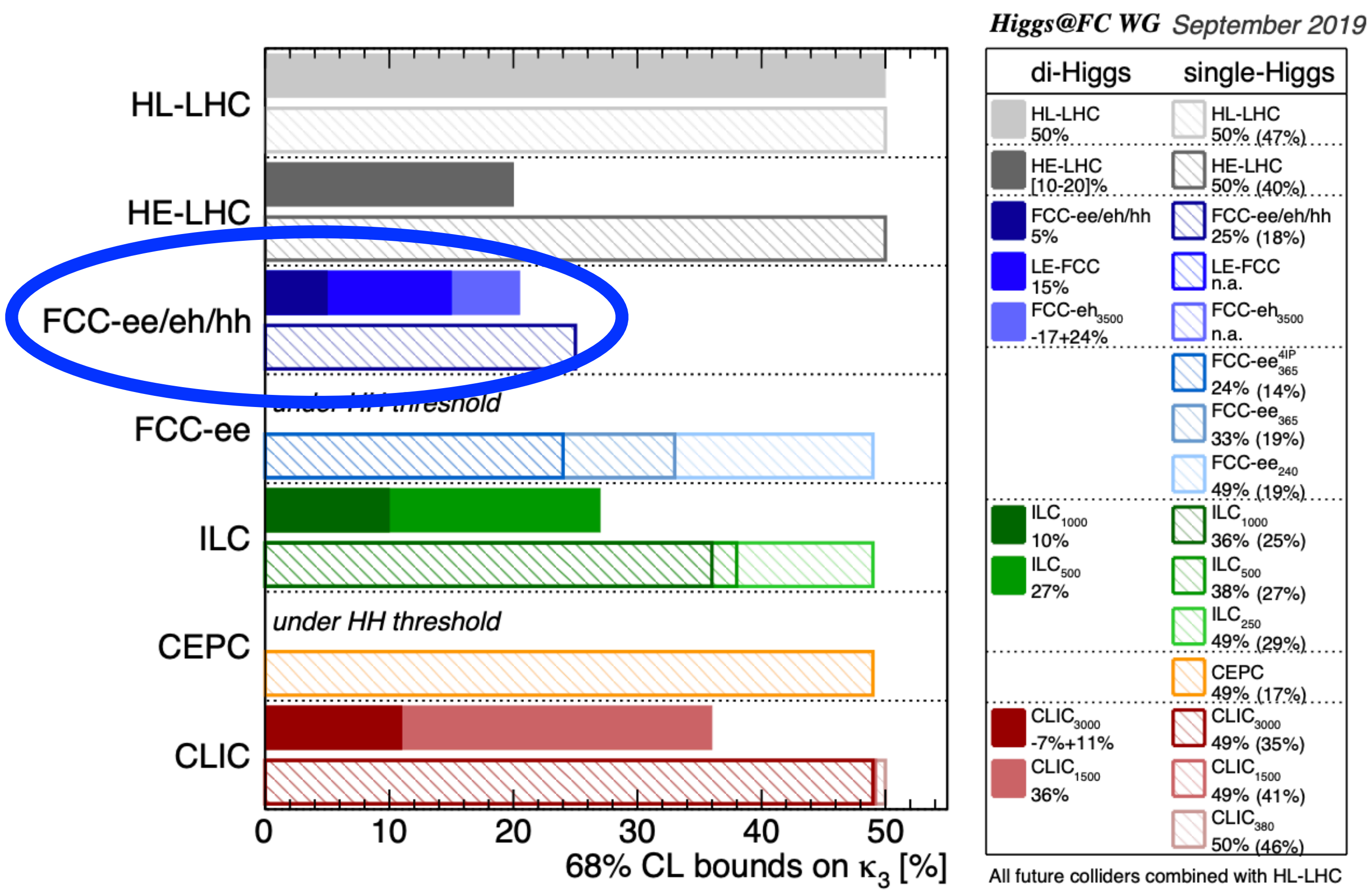
Parameterisation	Scenario I	Scenario II	Scenario III
b-jet ID eff.	82–65%	80–63%	78–60%
b-jet c mistag	15–3%	15–3%	15–3%
b-jet l mistag	1–0.1%	1–0.1%	1–0.1%
τ-jet ID eff	80–70%	78–67%	75–65%
τ-jet mistag (jet)	2–1%	2–1%	2–1%
τ-jet mistag (ele)	0.1–0.04%	0.1–0.04%	0.1–0.04%
γ ID eff.	90	90	90
jet $\rightarrow \gamma$ eff.	0.1	0.2	0.4
$m_{\gamma\gamma}$ resolution (GeV)	1.2	1.8	2.9
m_{bb} resolution (GeV)	10	15	20

https://doi.org/10.1140/epjc/s10052-020-08595-3

Higgs Boson Self-Coupling

Summary @FCC-INT

- 68% CL uncertainties on $\delta\kappa_\lambda$ with di-Higgs and single-Higgs
  (all combined with HL-LHC)
- k_λ **coupling measurement to ±5%**
  - only possible at a 100 TeV hadron machine
  - possible thanks also to precise BR measurements at FCC-ee



Higgs Boson Self-Coupling

Di-Higgs Production @FCC-hh

- Studied a number of final states: bbɣɣ most sensitive channel
- **Per-cent level precision of HHH coupling**
  - Only possible at a 100 TeV hadron machine
  - **$\delta\kappa_\lambda$ 5%** possible thanks also to precise BR measurements at FCC-ee