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Higgs boson measurements at Future Circular Colliders

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FUTURE
CIRCULAR
COLLIDER

24th August 2021

Outline

- Future Circular Colliders @ CERN
- Higgs boson precision measurements
    - couplings, total width, cross section and mass
    - self-coupling
    - Yukawa coupling to electrons

Future Circular Colliders

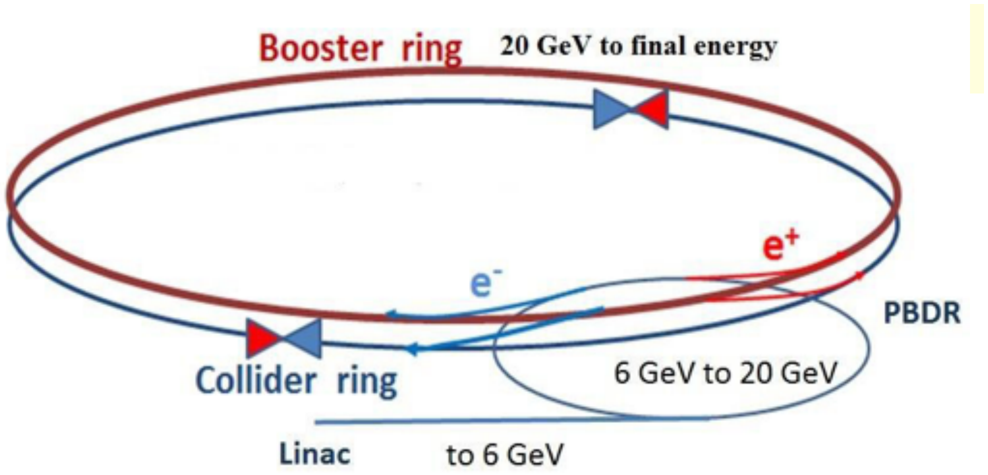
- Advantages of circular lepton colliders:
  - large luminosities
  - can later be replaced by very high energy pp colliders
- → Sequential implementation of a **lepton** and a **hadron** collider **maximises the physics reach**
- **Versatile machine capable to adjust to very different New Physics scenarios**

Future Circular Colliders

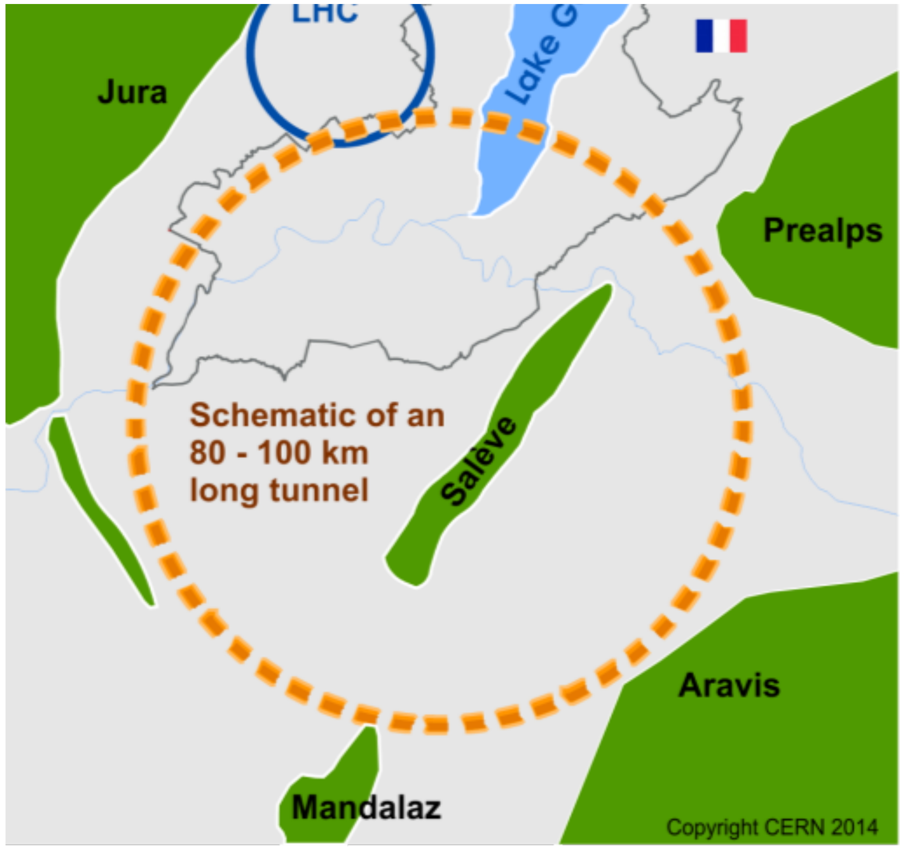
FCC@CERN

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

- Future Circular Collider (FCC) at CERN: design study for a post-LHC 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** (as recommended by the EPPSU) *https://home.cern/resources/brochure/cern/european-strategy-particle-physics*

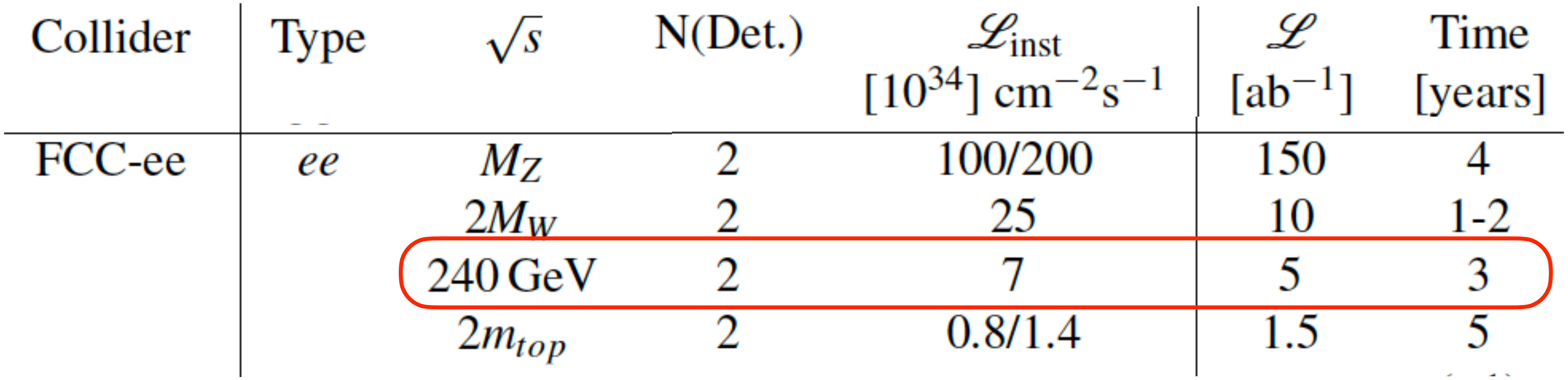


- *"Most effective and comprehensive approach to thoroughly explore the open questions in modern particle physics is a staged research programme, integrating in sequence lepton (FCC-ee) and hadron (FCC-hh) collision programmes"* M.Benedikt

Future Circular Colliders

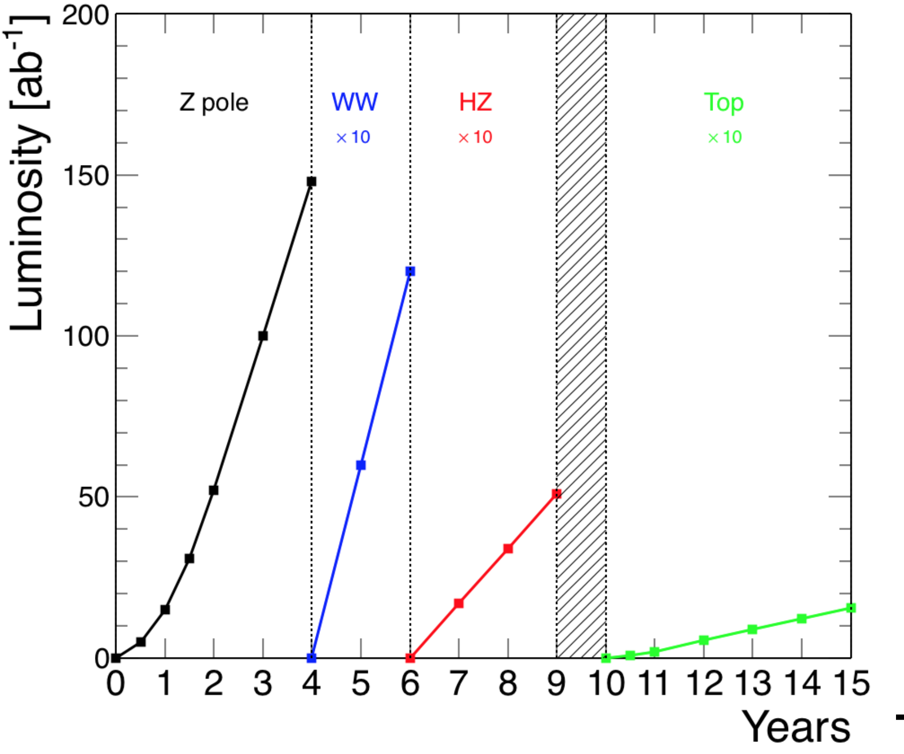
FCC-ee@CERN

- 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

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

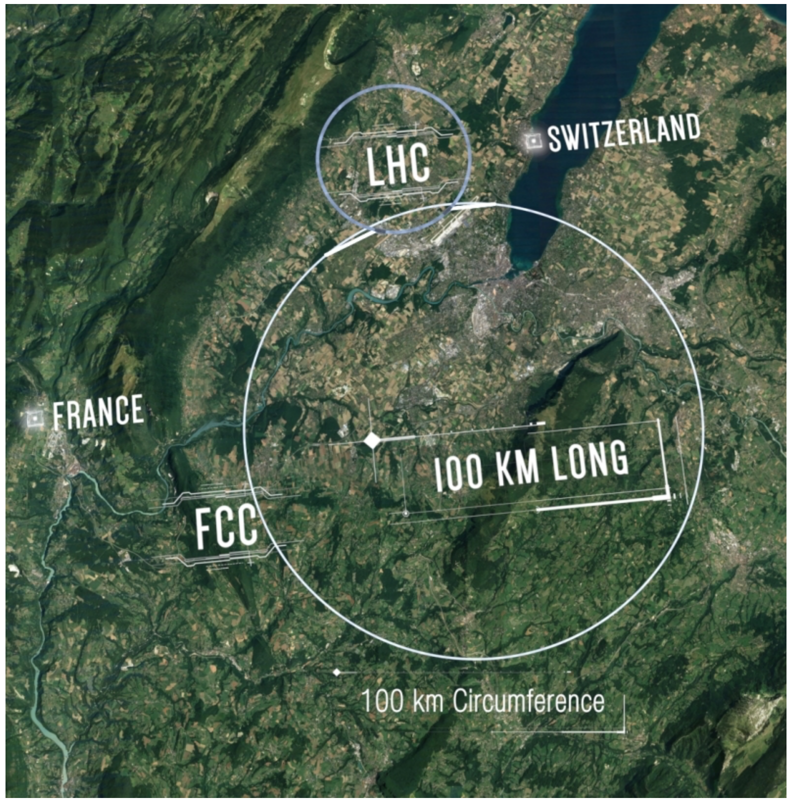


Future Circular Colliders

FCC-hh@CERN

- In a second phase: pp-collider **FCC-hh** @ 100 TeV

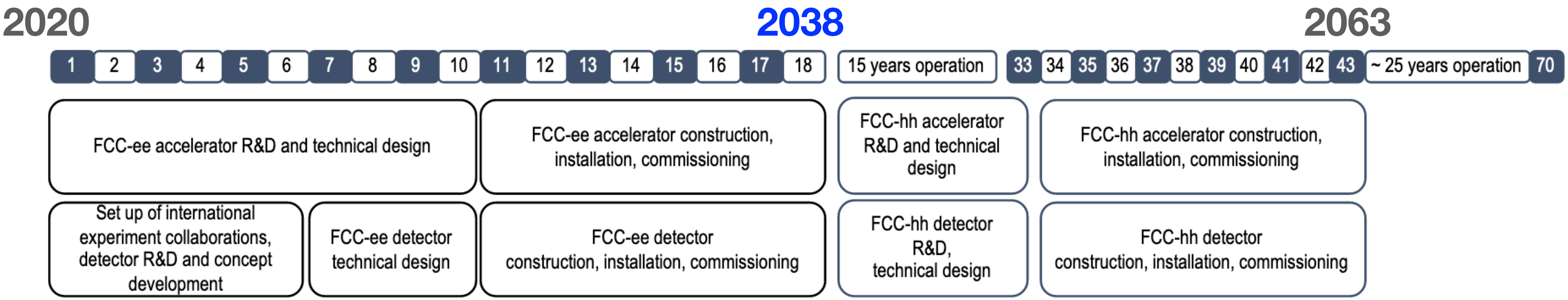
Collider	Type	$\sqrt{s}$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]\ \text{cm}^{-2}\text{s}^{-1}$	$\mathscr{L}$ $[\text{ab}^{-1}]$	Time [years]
FCC-hh	pp	100 TeV	2	30	30.0	25



Future Circular Colliders

Timeline for the integrated FCC program

- Overall project **duration** for implementation and operation of the integrated FCC is about **7 decades**
- Overview of implementation timeline for the integrated FCC-INT program starting in **2020** (numbers at the top indicate the year)
  - Physics operation for **FCC-ee** would start towards the **end-2030s** + 15 years operation
  - Physics operation for **FCC-hh** would start in the **mid-2060s** + 25 years operation



2020 2038 2063

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 | 15 years operation | 33 34 35 36 37 38 39 40 41 42 43 | ~ 25 years operation | 70

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

Set up of international experiment collaborations, detector R&D and concept development

FCC-ee detector technical design

FCC-ee detector construction, installation, commissioning

FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning

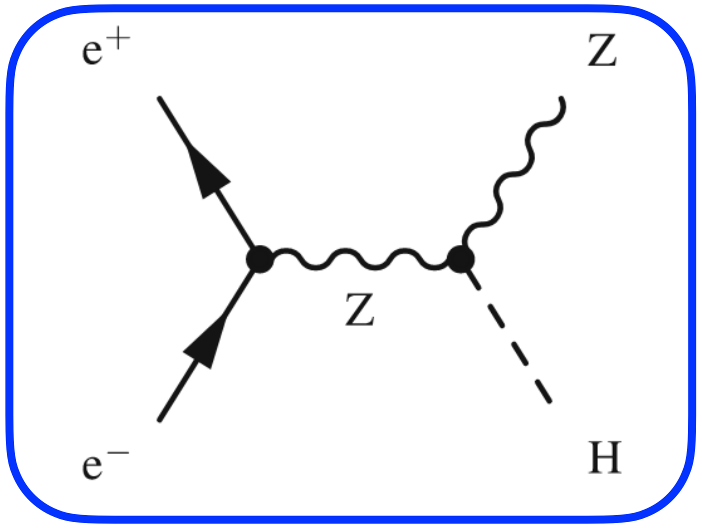
https://cds.cern.ch/record/2653673/files/CERN-ACC-2019-0007.pdf

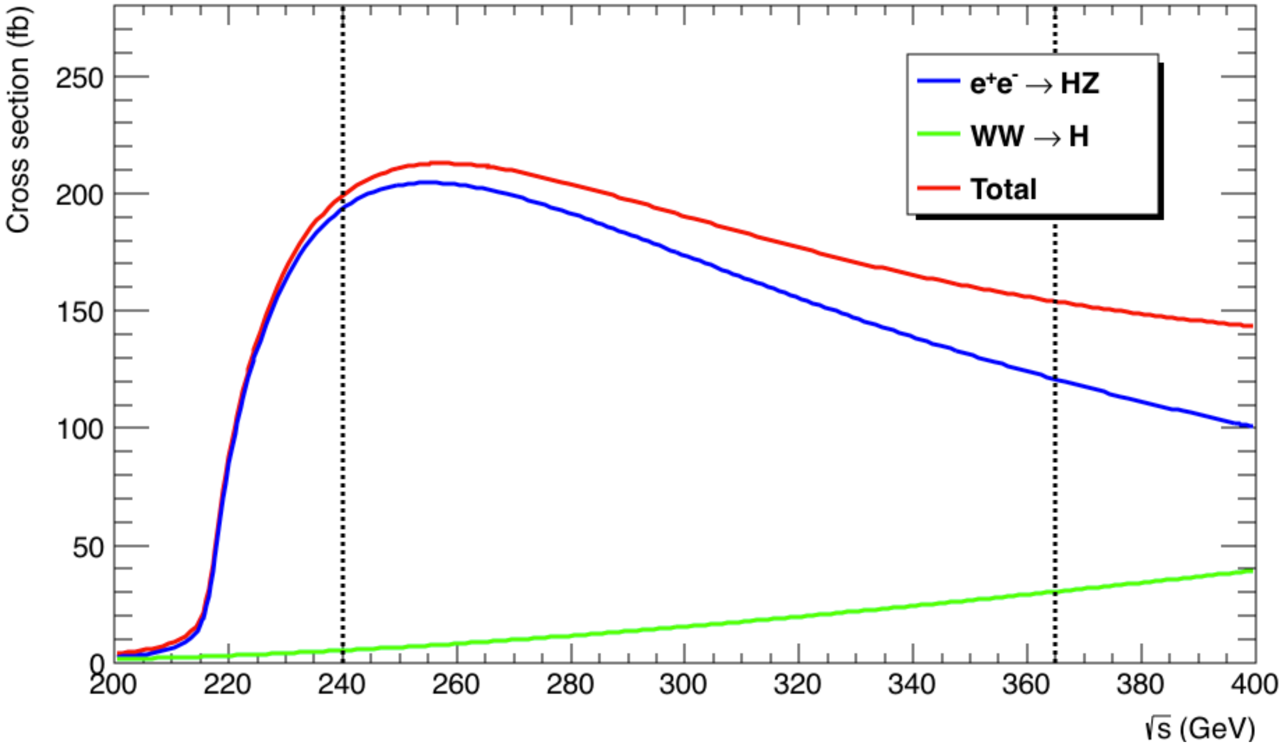
Higgs Boson Production at e^+e^- Colliders

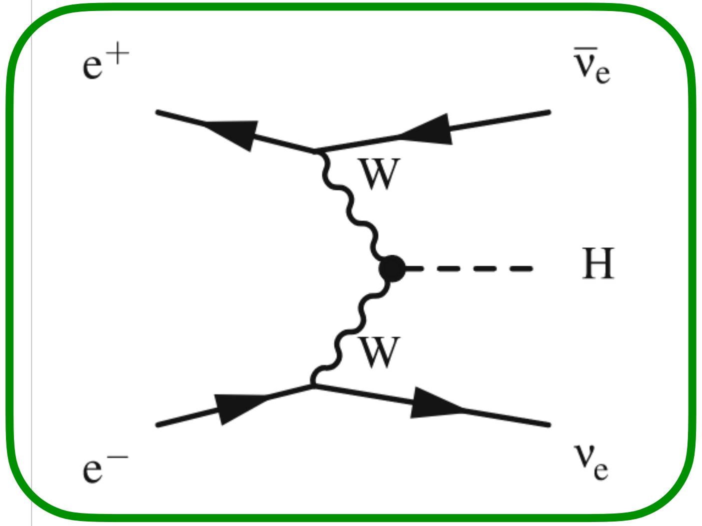
FCC-ee@CERN

	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



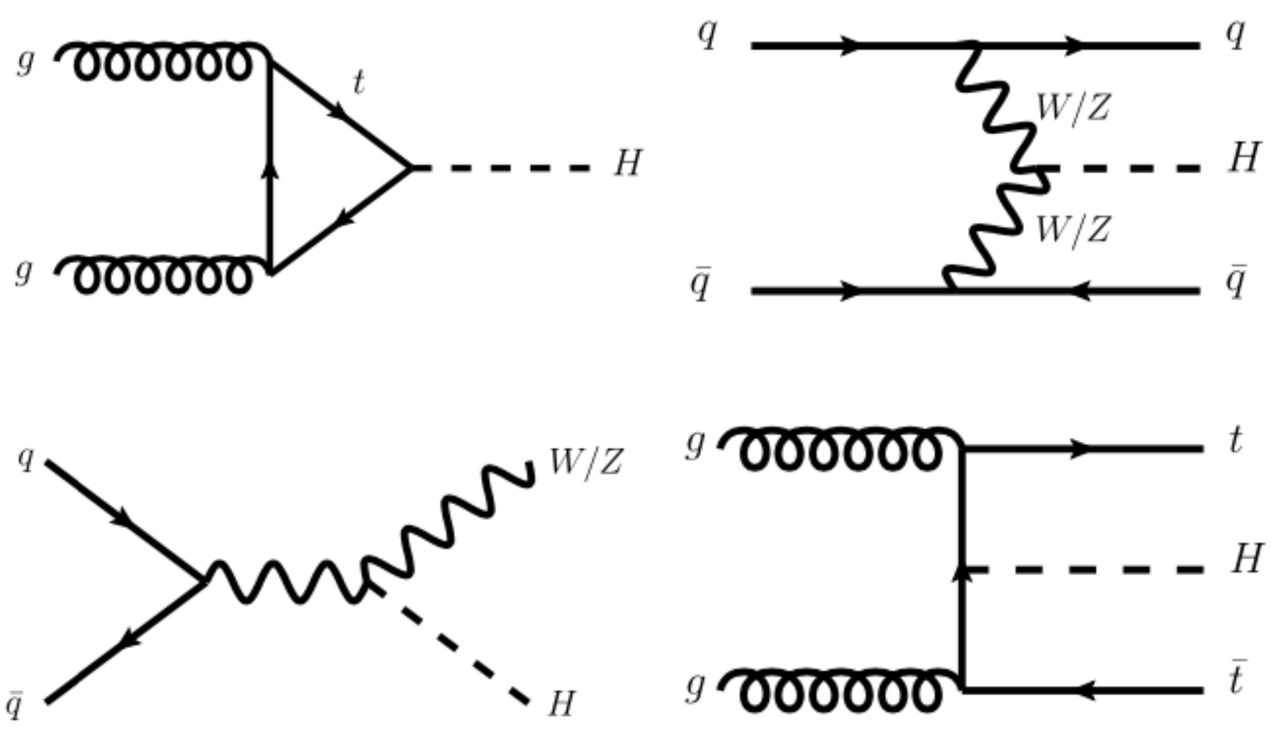




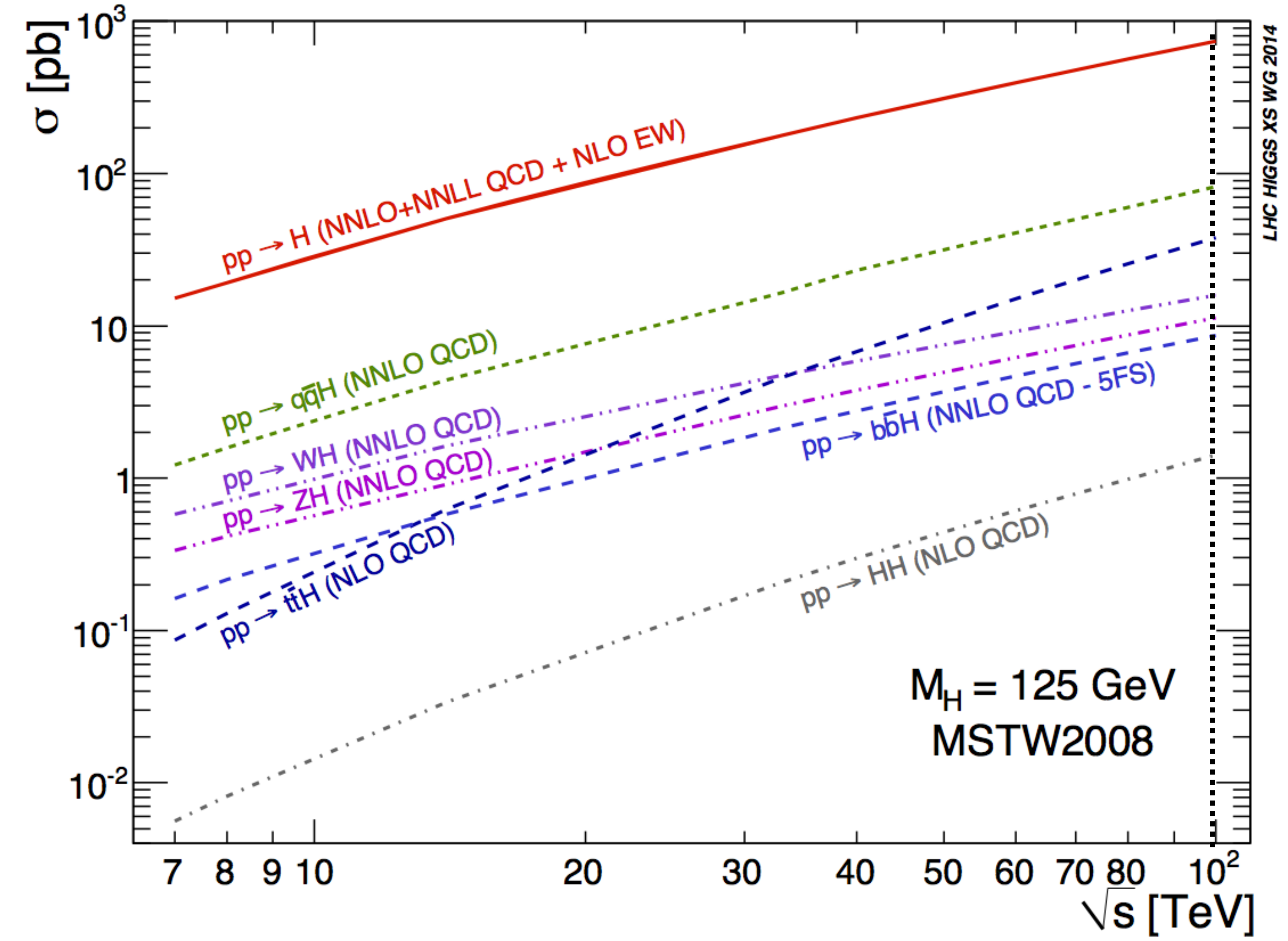
Higgs Boson Production at pp Colliders

FCC-hh@CERN

CERN-ACC-2018-0045



FCC-hh



- High cross section (~1000 pb) and luminosity → **~3·10^{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

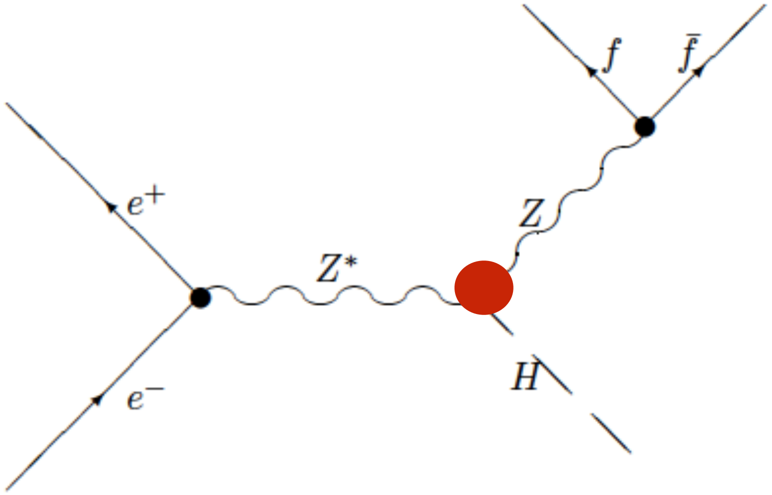
@FCC-ee

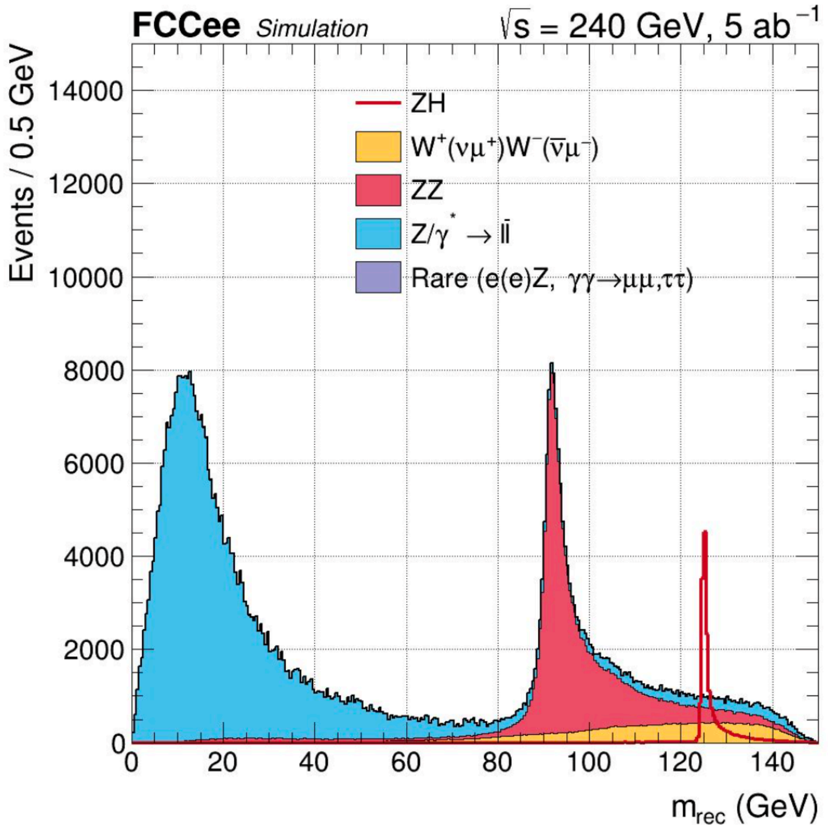
- Measurement through the recoil mass method in $e^+e^- \rightarrow HZ$ ($Z \rightarrow \ell^+ \ell^-$)
  - recoil mass distribution exhibits sharp peak at Higgs mass

$$m_{\text{recoil}}^2 = s + m_{\ell\ell}^2 - 2\sqrt{s}(E_{\ell^+} + E_{\ell^-})$$

→ decay-mode independent measurement of the HZ coupling

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



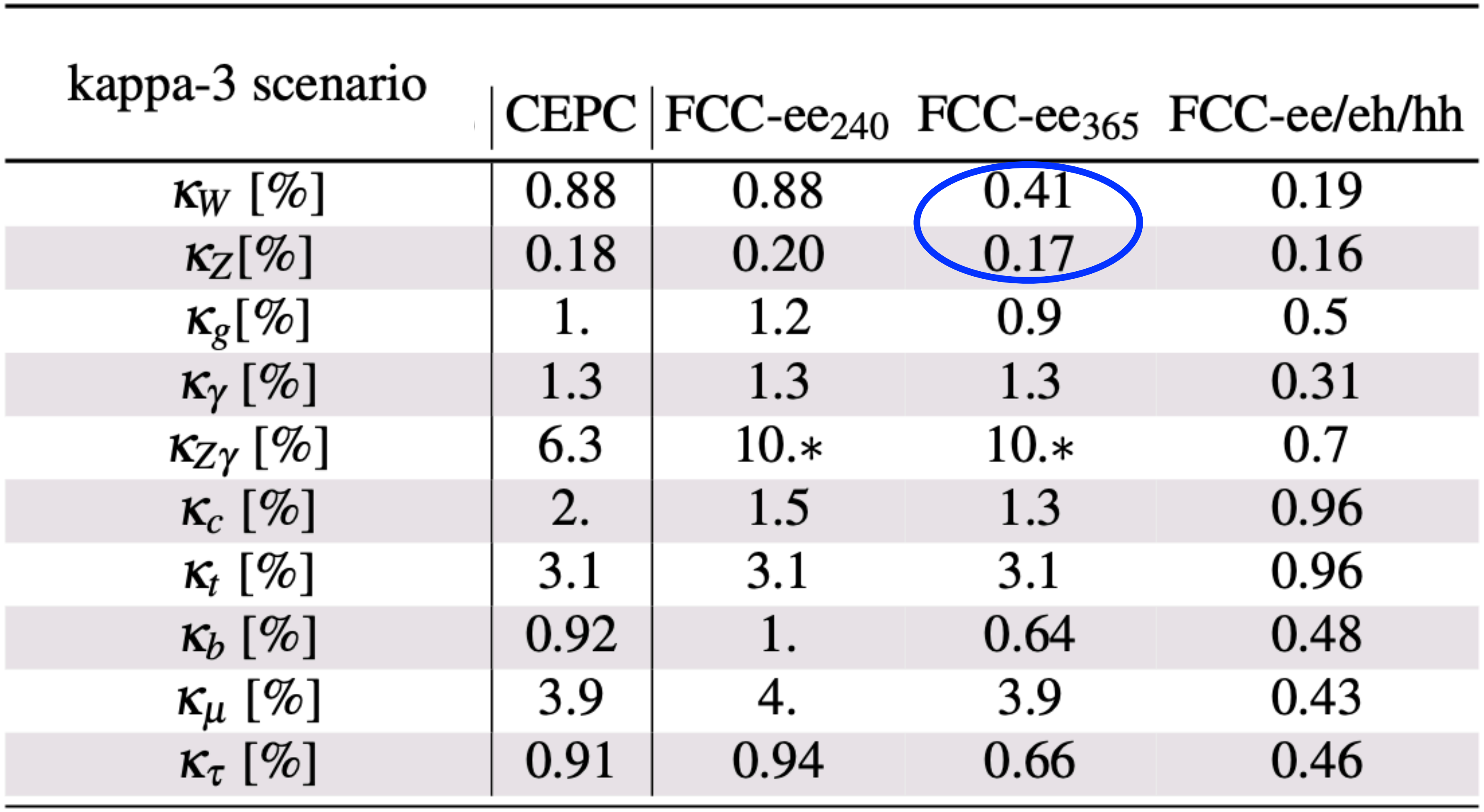


Higgs Boson Couplings

@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

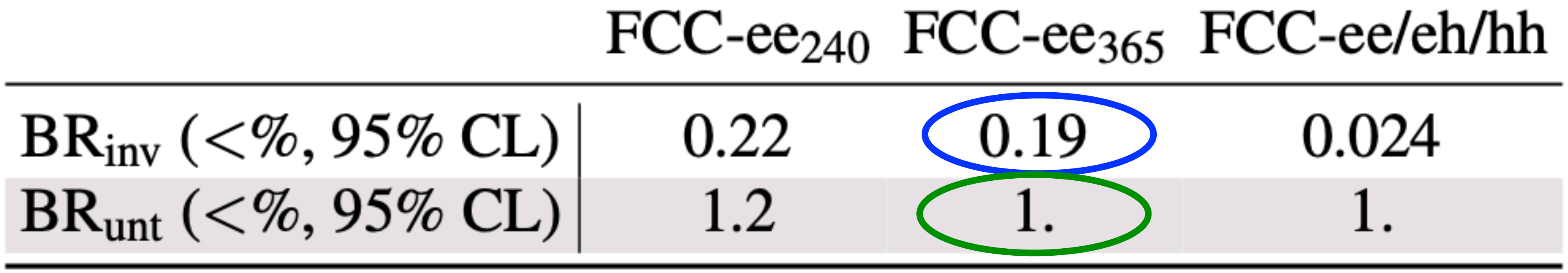
- Most precise coupling measurements (to Z and W bosons) are measured to ±0.2-0.4%

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 $Z \rightarrow b\bar{b}, \ell^+ \ell^-$
- → Upper limits at the 95% CL: **$BR_{inv} < 0.19\%$ @FCC-ee**
  - FCC-ee will improve upon HL-LHC by an order of magnitude ($BR_{inv} < 1.9\%$ @HL-LHC)
  - FCC-hh by another order of magnitude (→ values below the SM value of 0.11%)



	$FCC\text{-}ee_{240}$	$FCC\text{-}ee_{365}$	FCC-ee/eh/hh
BR_{inv} (<%, 95% CL)	0.22	0.19	0.024
BR_{unt} (<%, 95% CL)	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^- → HZ, H → 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%**

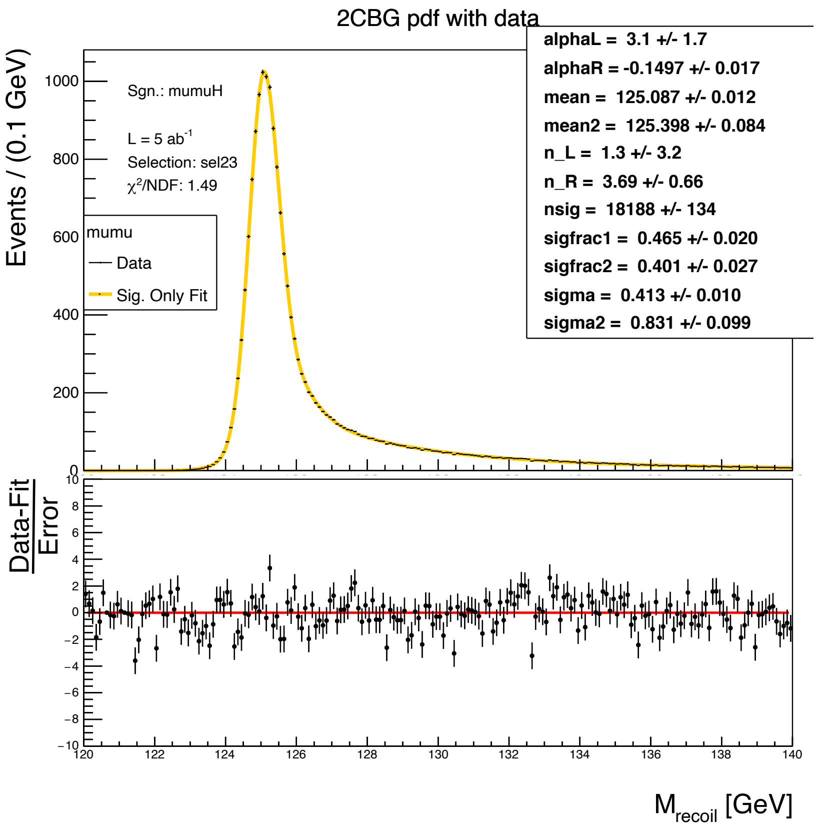
Higgs Boson Cross Section and Mass

Recent developments on the “recoil mass” method

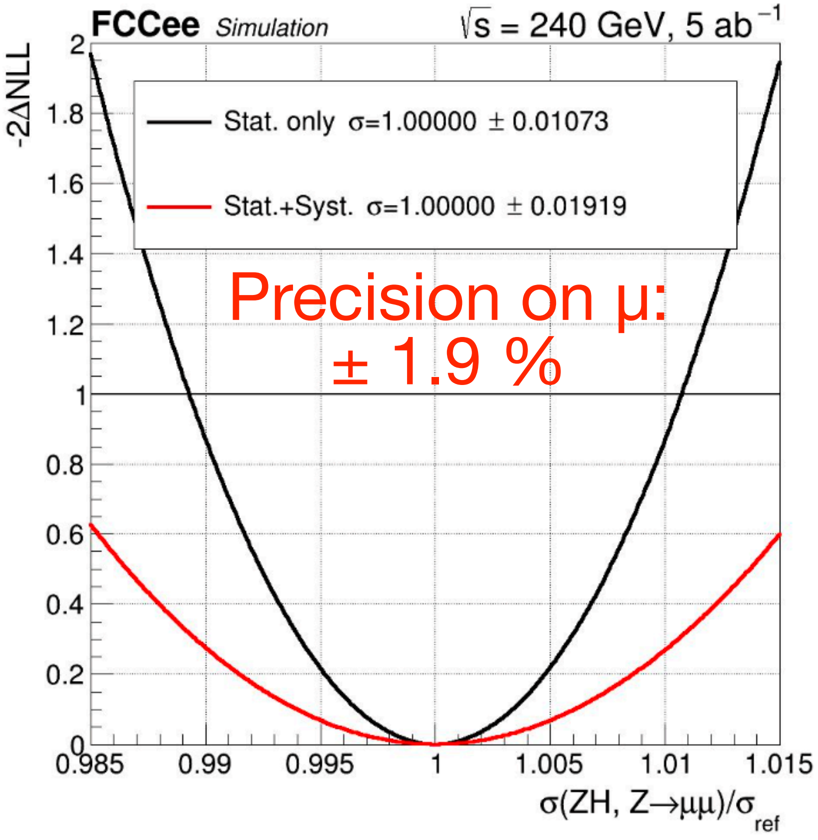
- Recent efforts to optimise and tune signal parameterisation (2 Crystal-Ball + Gaussian) and to include systematic uncertainties (BES, ISR, …)
- Negative log-Likelihood scans as a function of the signal strength and of the Higgs mass

[J. Eysermans - talk at the FCC week - June 2021](#)

Preliminary

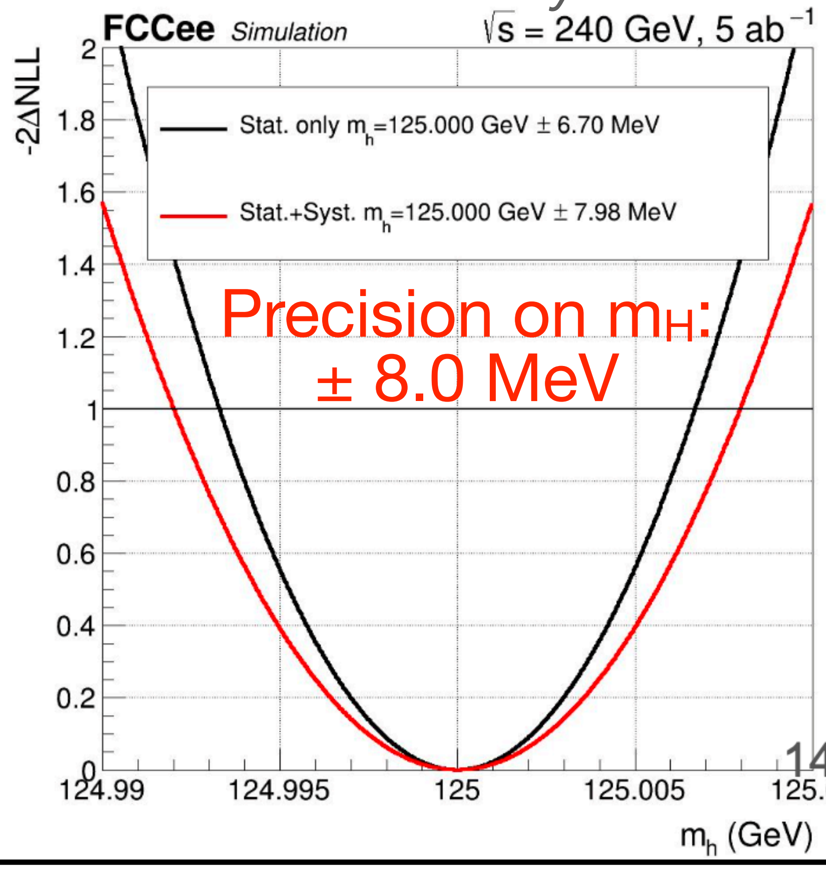


Preliminary



Precision on μ:
± 1.9 %

Preliminary



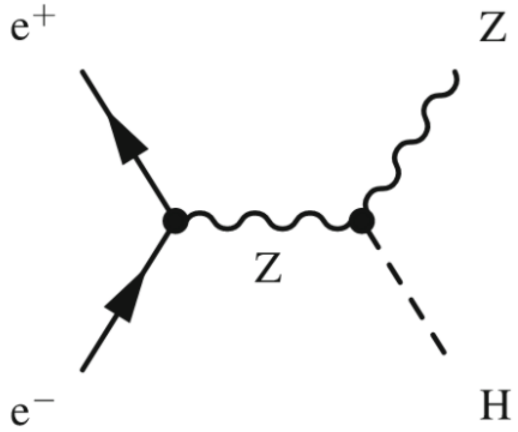
Precision on m_H:
± 8.0 MeV

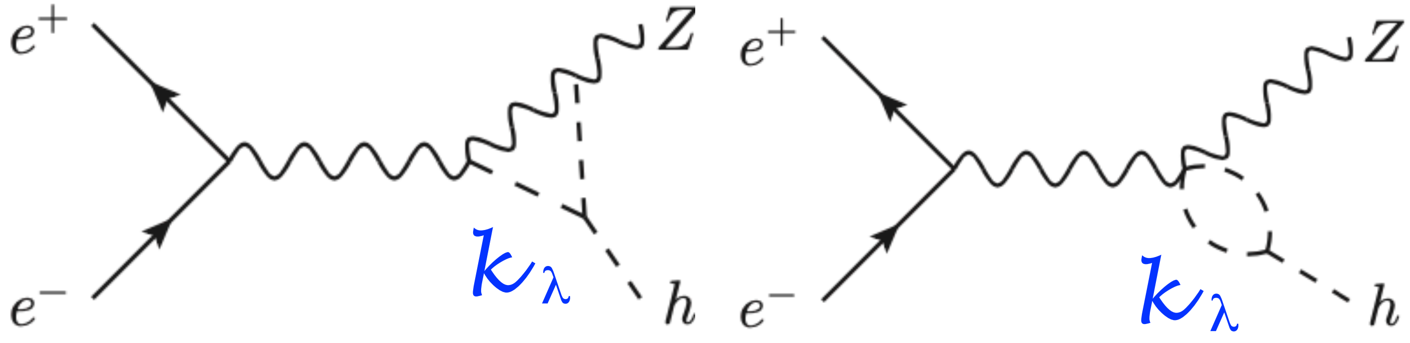
Higgs Boson Mass

Scan of the HZ threshold @FCC-ee

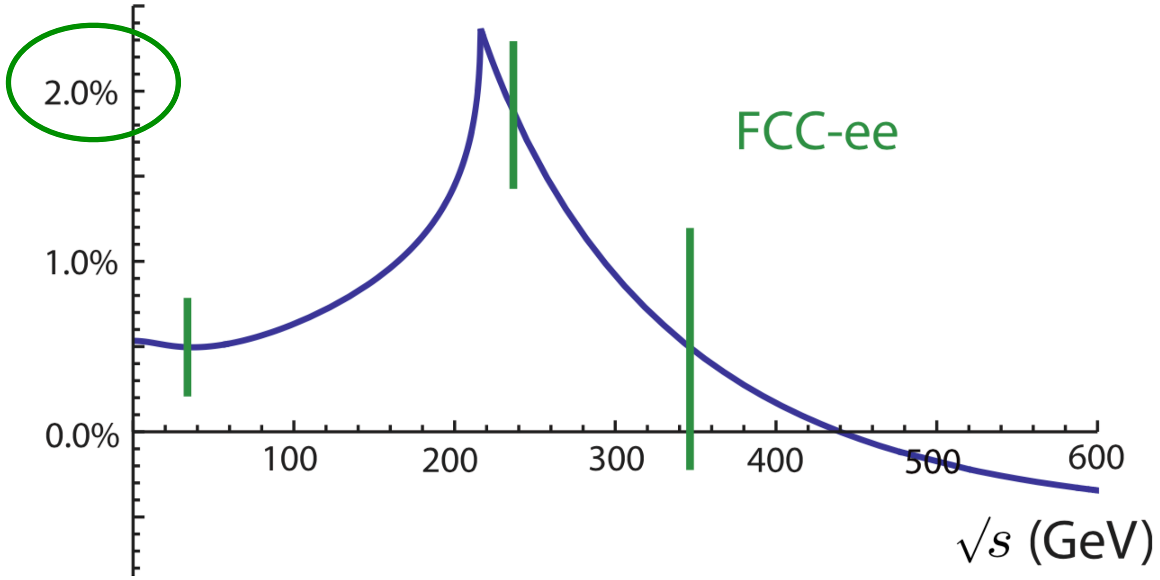
arXiv:2106.15438

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





δσ/σ or δΓ/Γ in the SM due to k_λ



- With 5 ab^{-1} at $\sqrt{s} \simeq 217$ GeV → **statistical precision on m_H: ± 9 MeV**
- *Collision energy point currently not foreseen in the baseline FCC-ee operation*

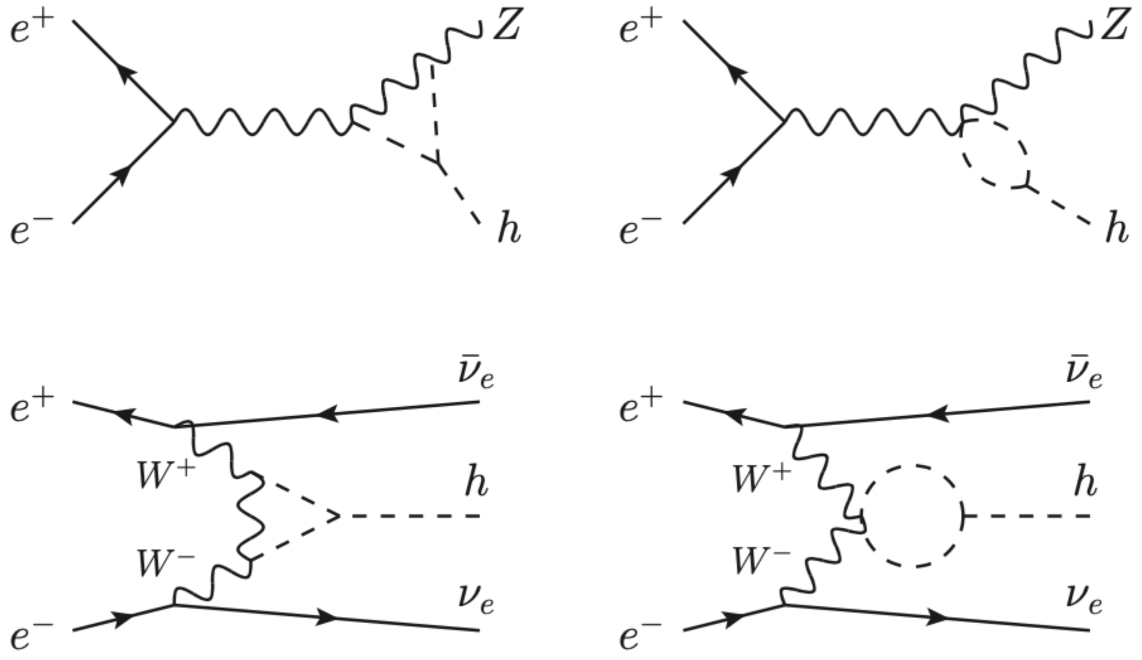
Higgs Boson Self-Coupling

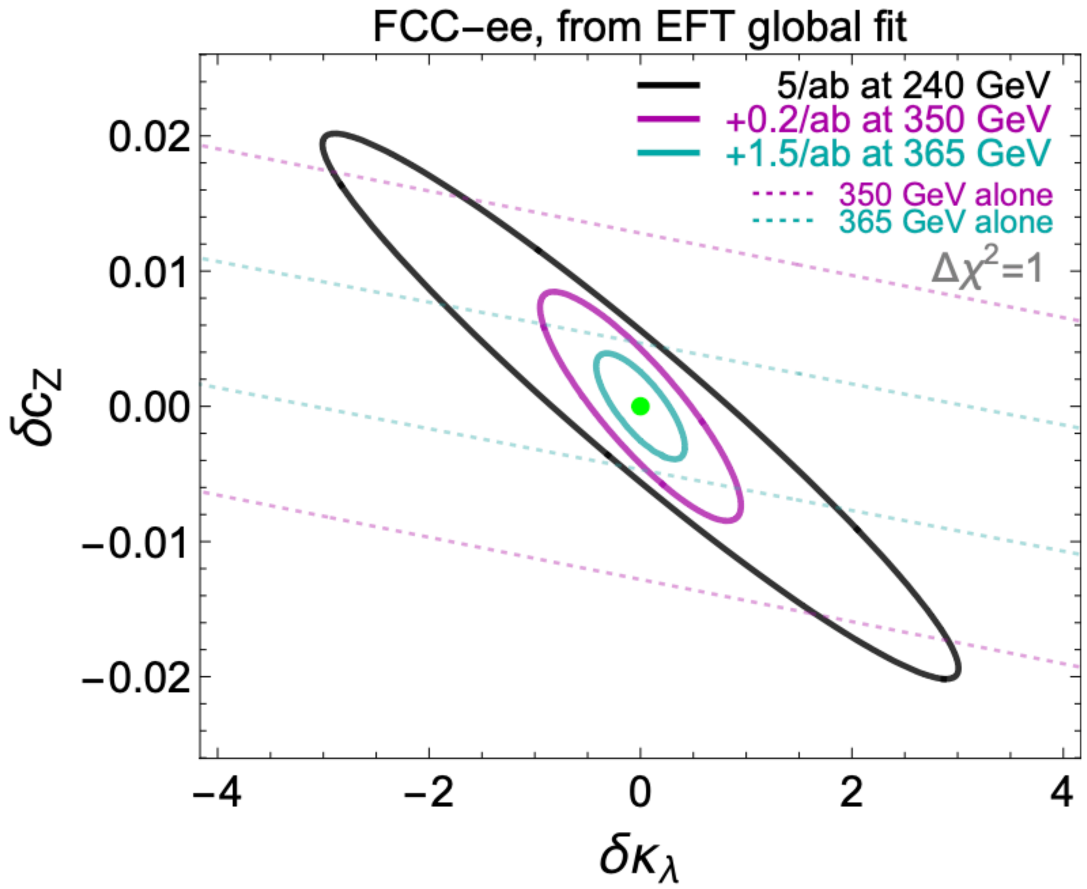
Single Higgs Production @FCC-ee

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)

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

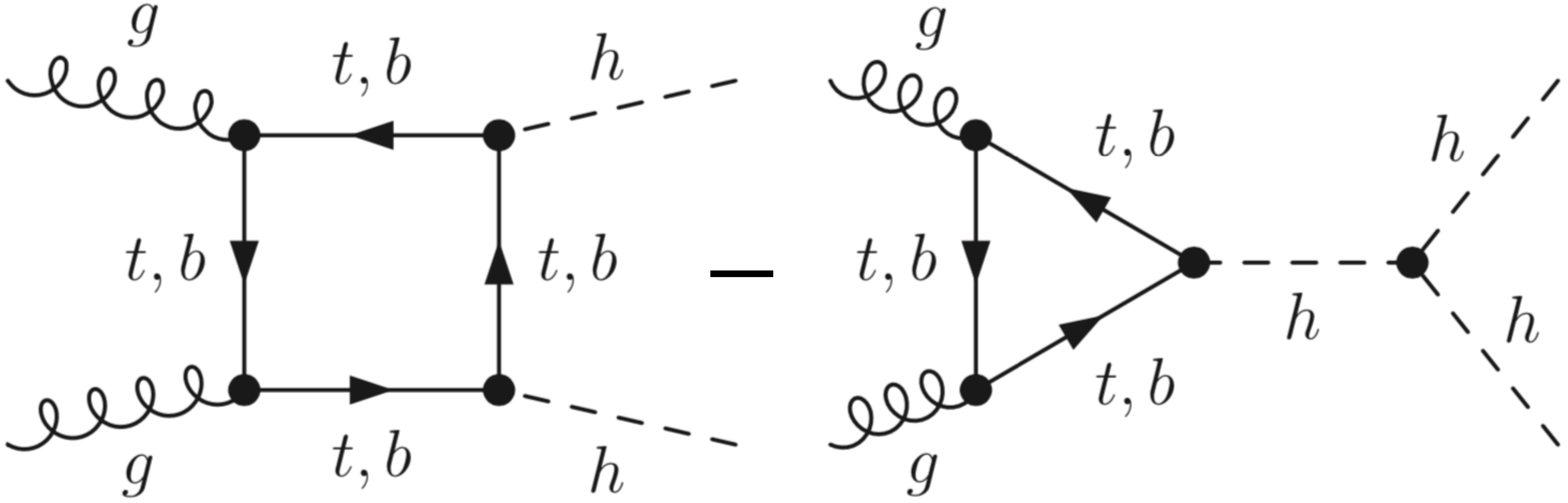




- → **g_{HHH} coupling measurement to ±33% with 2 IP**
  reduced to ±24% with 4 IP

Higgs Boson Self-Coupling

Di-Higgs Production @FCC-hh

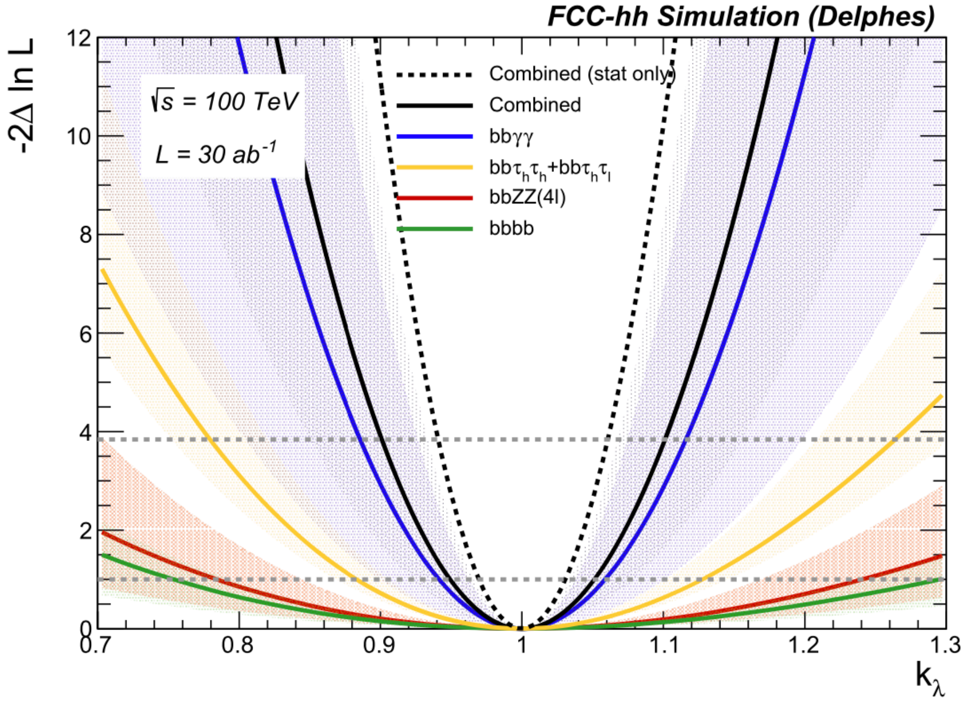


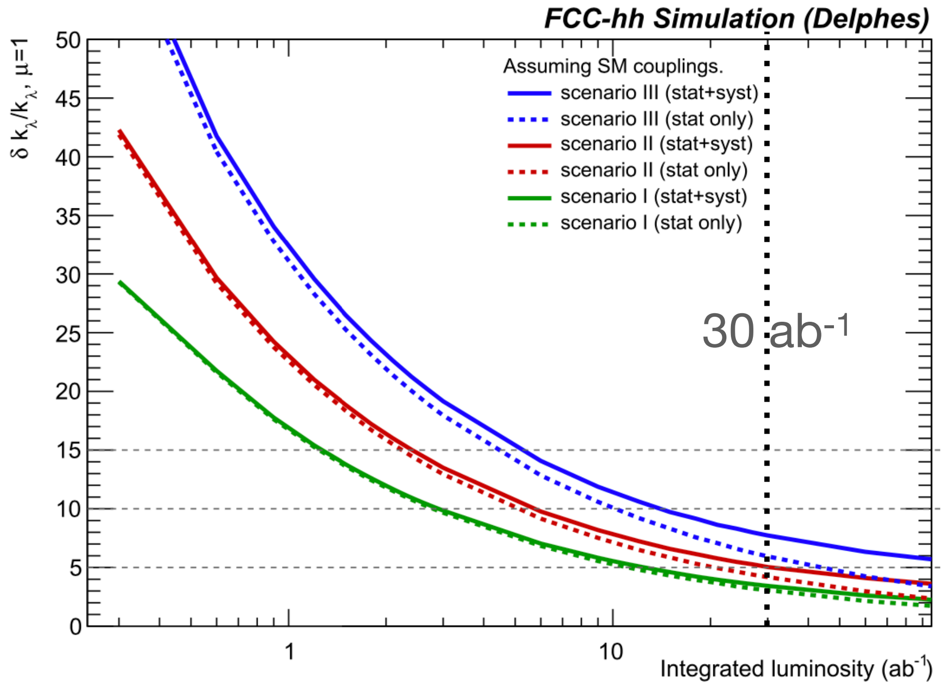
- Very large di-Higgs samples produced at FCC-hh
  - σ(100 TeV) / σ(14 TeV) ≅ 40
  - L(FCC-hh) / L(HL-LHC) ≅ 10
  - → Naively, factor 20 smaller statistical uncertainty

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



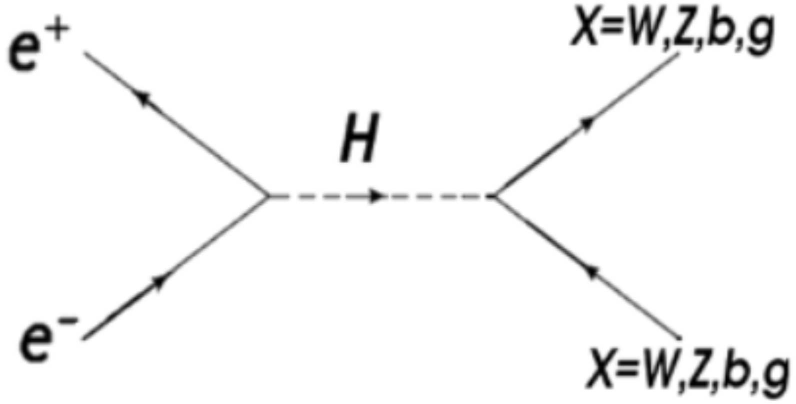


https://doi.org/10.1140/epjc/s10052-020-08595-3

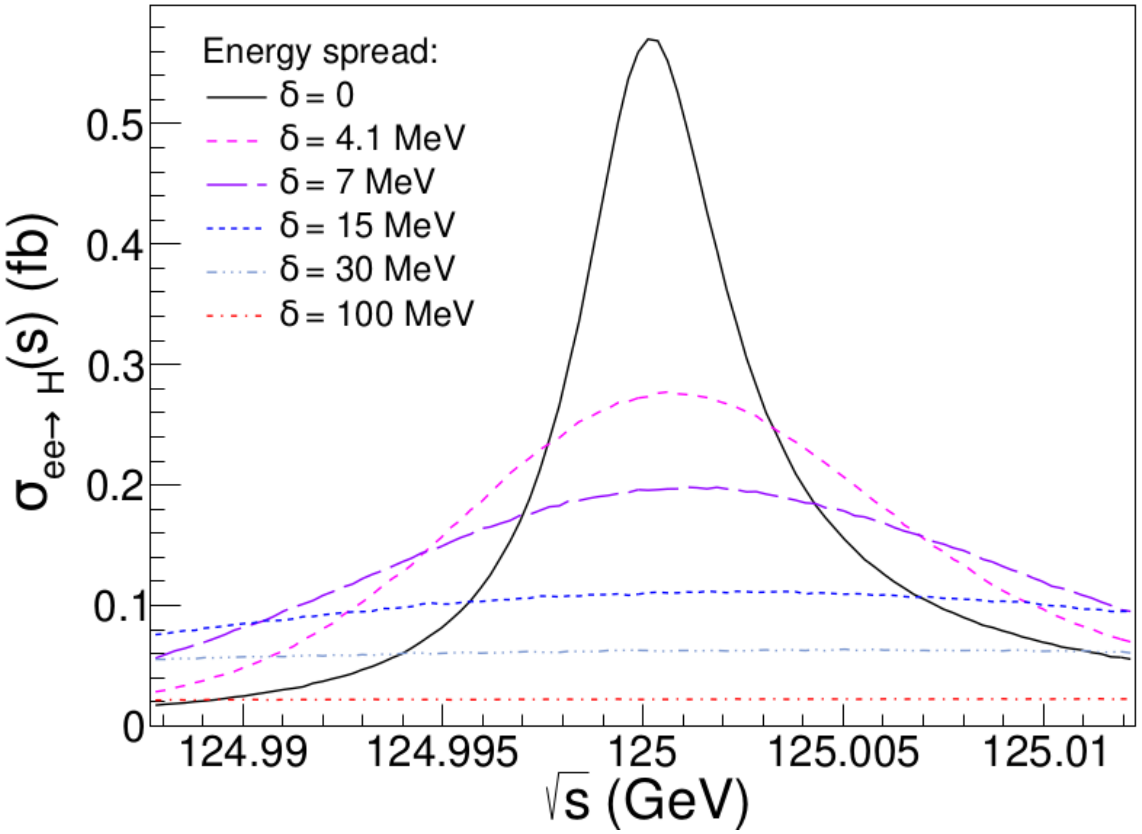
Higgs Yukawa Coupling to Electrons

@FCC-ee

- Unique opportunity for the measurement of the Higgs Yukawa coupling to electron
- Measurement through the resonant s-channel production
  $e^+e^- \rightarrow H$
- Highly challenging:
  - $\sigma(e^+e^- \rightarrow H) = 1.64$ fb tree level (Born)
  - reduced to 0.6 fb when **ISR** is included
  - reduced to 0.3 fb if **the centre-of-mass energy spread were equal to the Higgs boson width of 4.1 MeV**



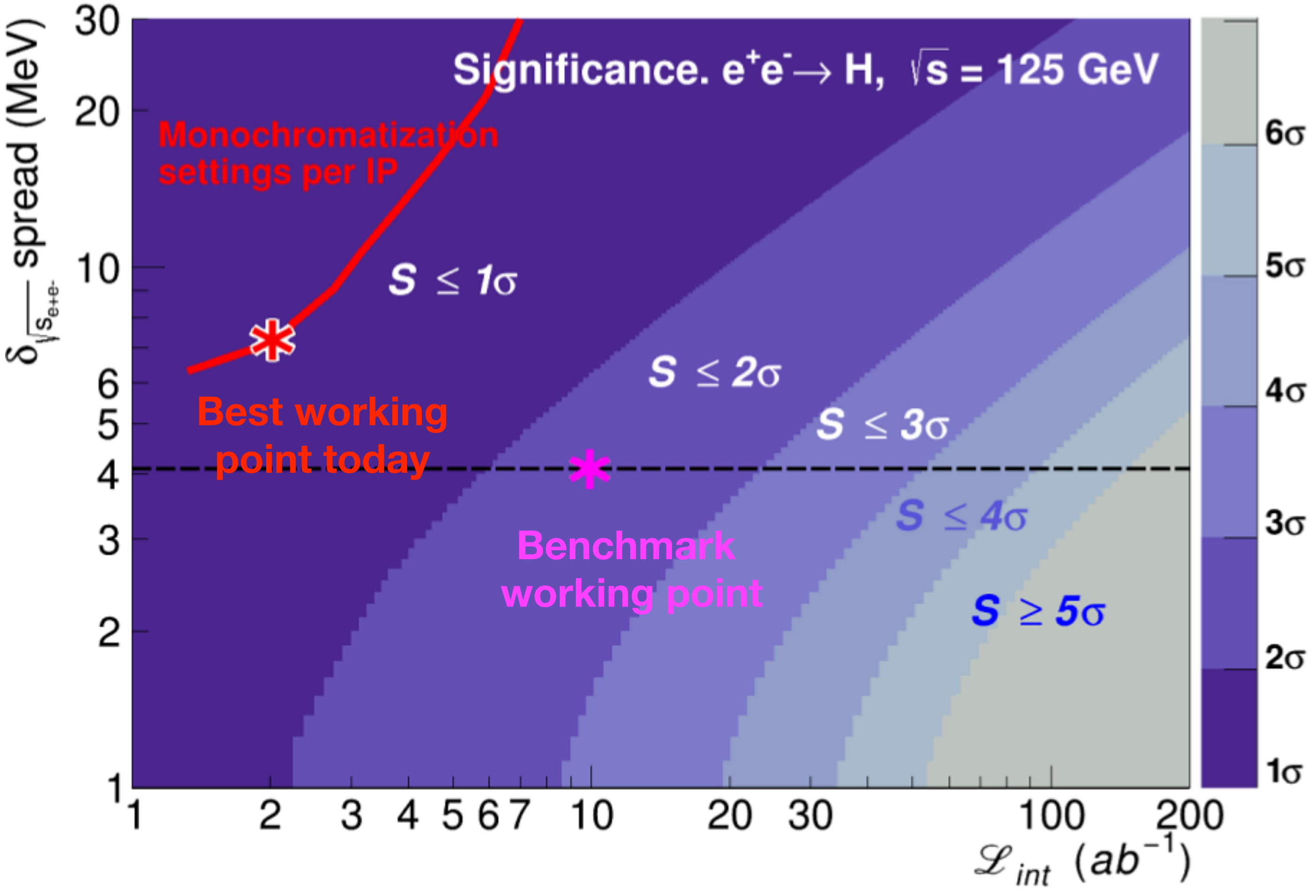
S.Jadach, R. KyciaPLB755 (2016) 58



Higgs Yukawa Coupling to Electrons

Electron Yukawa from s-channel resonant Higgs production at FCC-ee M. David d'Enterria

- Large energy spread, typically ~100 MeV → rendering the resonant Higgs production virtually invisible
- Beam monochromatisation studies to reduce the beam senergy spread
- Two monochromatisation working points in the plane [L_{int}/year, $\delta\sqrt{s}$]
  - best working point: $\delta\sqrt{s}$ = 7 MeV and L = 2 ab^{-1} → Significance of 0.4 σ
  - benchmark working point: $\delta\sqrt{s}$ = 4.1 MeV and L = 10 ab^{-1} → Significance of 1.3 σ



- → Few years at $\sqrt{s}$ = 125.09 GeV with high luminosity is an interesting addition providing a unique opportunity for measurement close to SM sensitivity

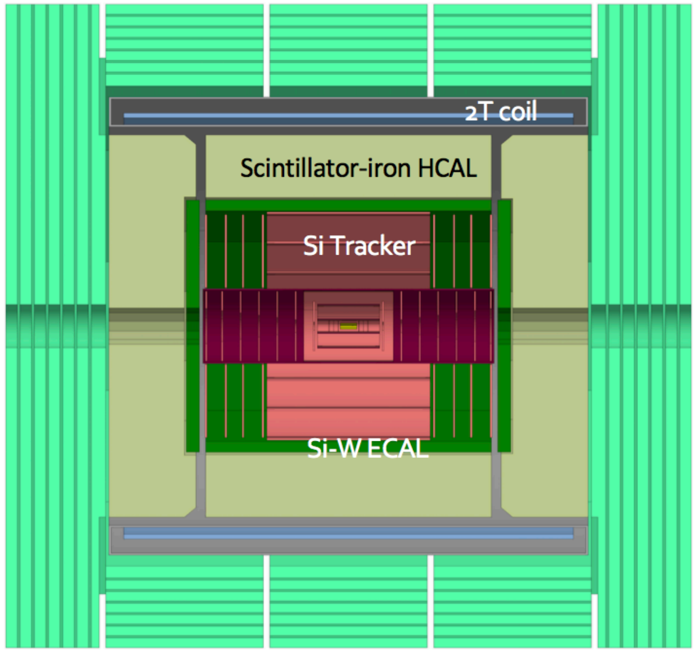
Conclusions

- 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
  - **Unique opportunity** for **Higgs-electron Yukawa** coupling measurement
- **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

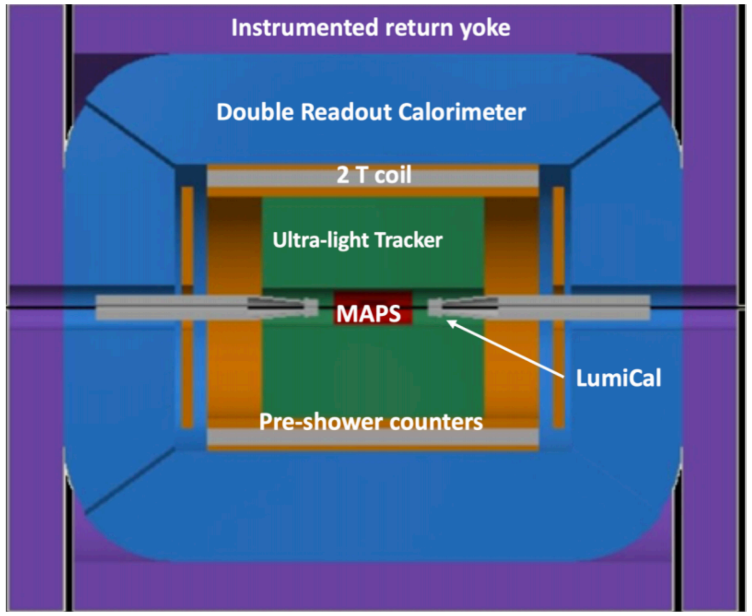
Detectors @FCC-ee

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

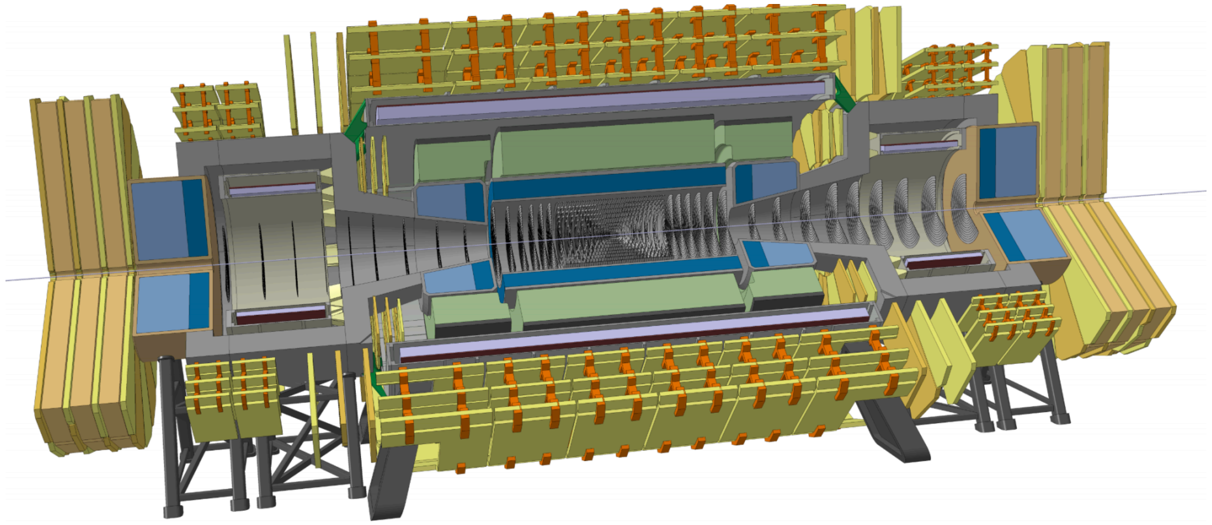
IDEA

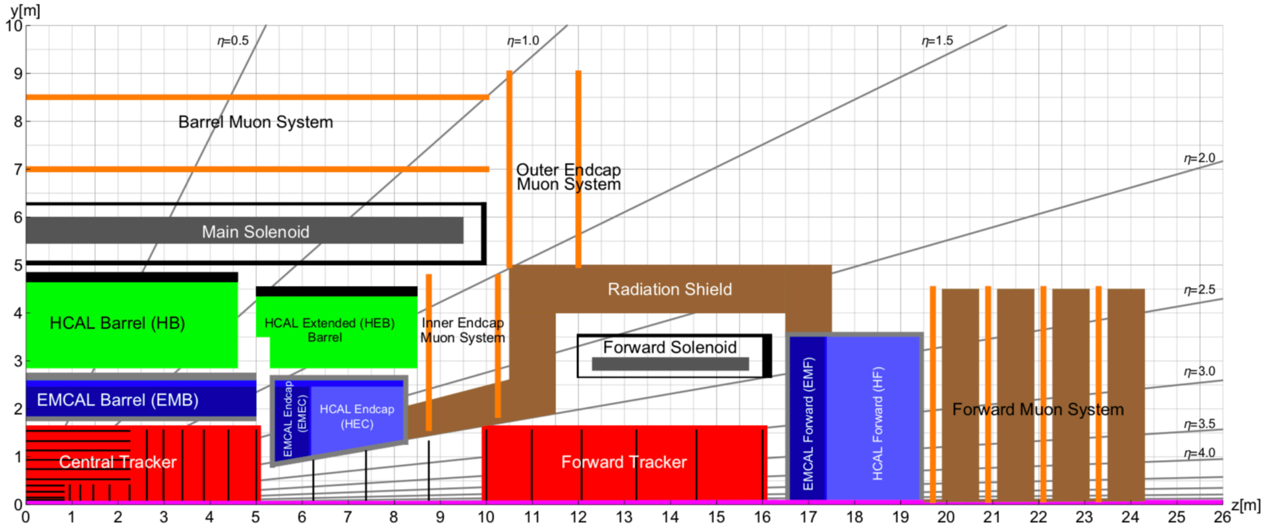


- New, innovative, probably more cost-effective design
- Thin and light 2 T solenoid coil inside calorimeter system
    - Silicon vertex detector
    - Short drift, ultra light wire chamber
    - Dual Readout calorimeter
    - MPGD-based muon detector

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**

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

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

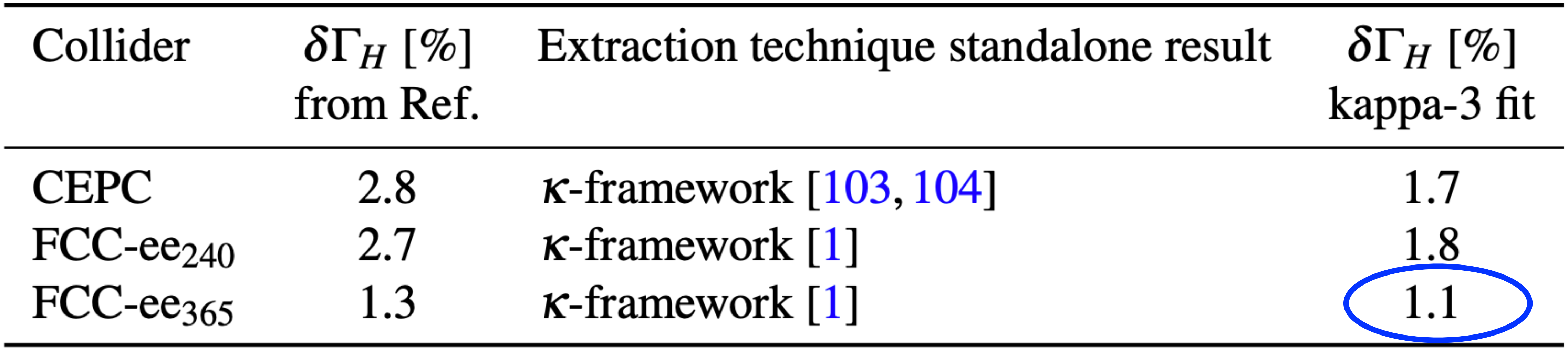
$\sqrt{s}$	240 GeV		365 GeV	
Integrated luminosity	$5\,\mathrm{ab}^{-1}$		$1.5\,\mathrm{ab}^{-1}$	
$\delta(\sigma\mathcal{B})/\sigma\mathcal{B}$ (%)	ZH	$\nu_e\bar{\nu}_e$ H	ZH	$\nu_e\bar{\nu}_e$ H
$H \rightarrow$ any	±0.5		±0.9	
$H \rightarrow b\bar{b}$	±0.3	±3.1	±0.5	±0.9
$H \rightarrow c\bar{c}$	±2.2		±6.5	±10
$H \rightarrow gg$	±1.9		±3.5	±4.5
$H \rightarrow W^+W^-$	±1.2		±2.6	±3.0
$H \rightarrow ZZ$	±4.4		±12	±10
$H \rightarrow \tau^+\tau^-$	±0.9		±1.8	±8
$H \rightarrow \gamma\gamma$	±9.0		±18	±22
$H \rightarrow \mu^+\mu^-$	±19		±40	
$H \rightarrow$ 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%**

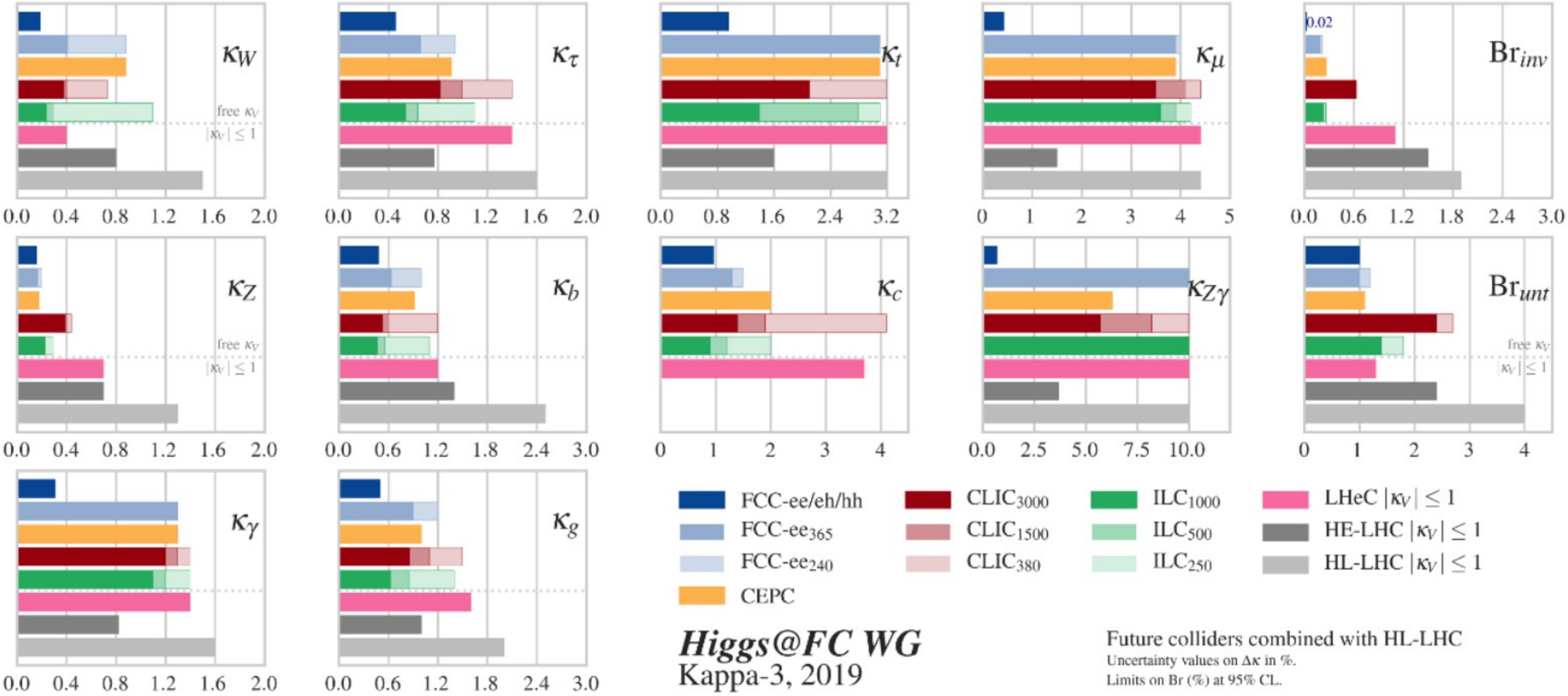
- Overview of expected precision



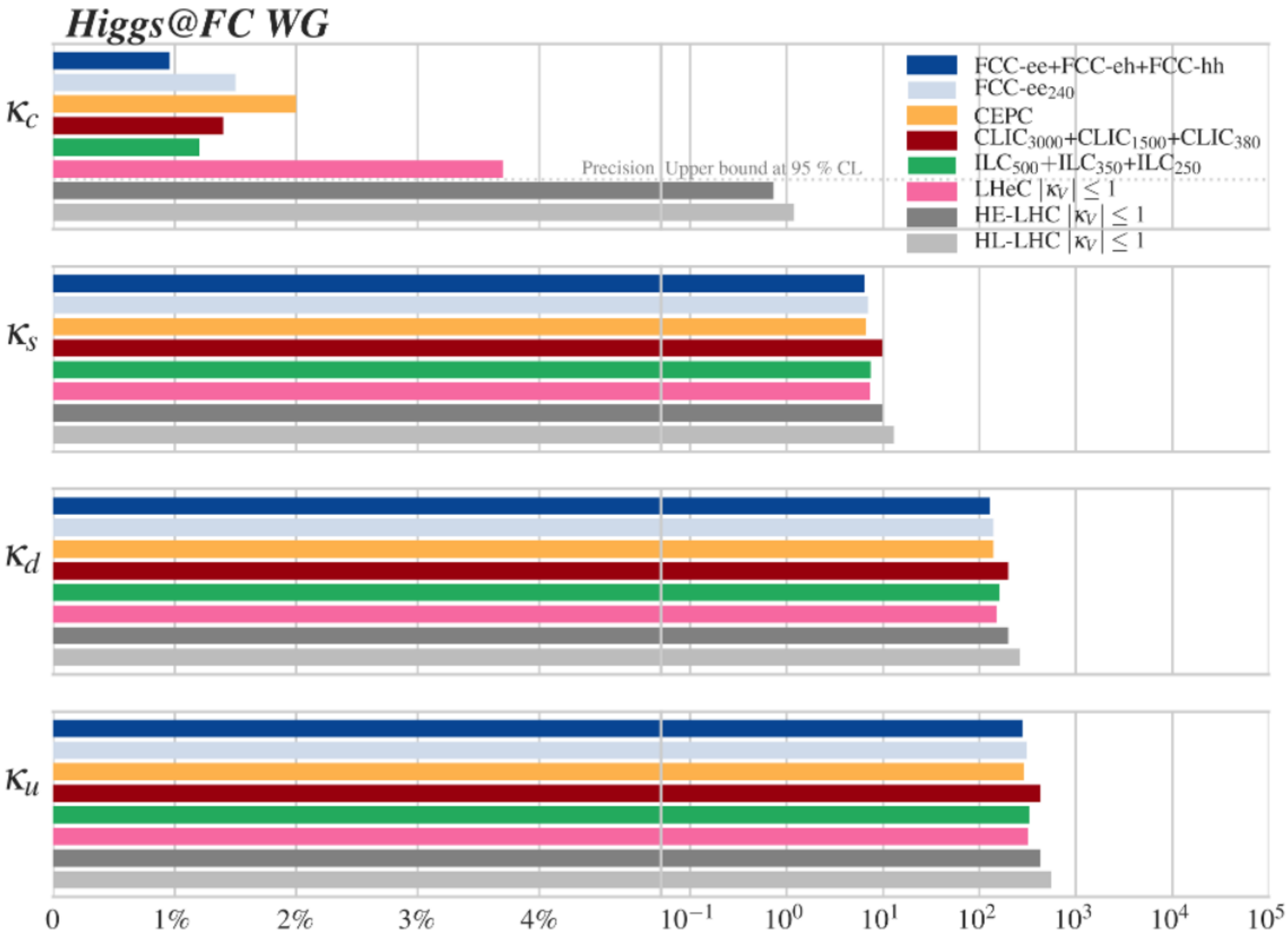
Collider	$\delta\Gamma_H$ [%] from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ [%] kappa-3 fit
CEPC	2.8	κ-framework [103, 104]	1.7
FCC-ee$_{240}$	2.7	κ-framework [1]	1.8
FCC-ee$_{365}$	1.3	κ-framework [1]	1.1

Higgs Couplings at Future Colliders

arXiv:1910.11775



Higgs Decays to Light Quarks

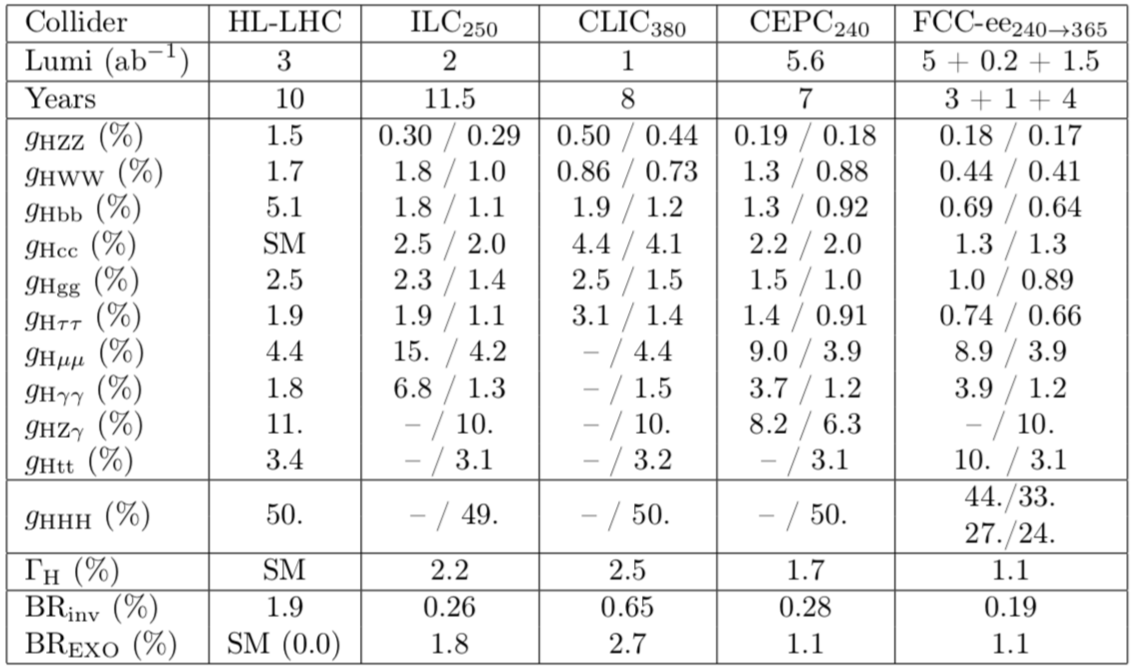


Higgs Boson Couplings

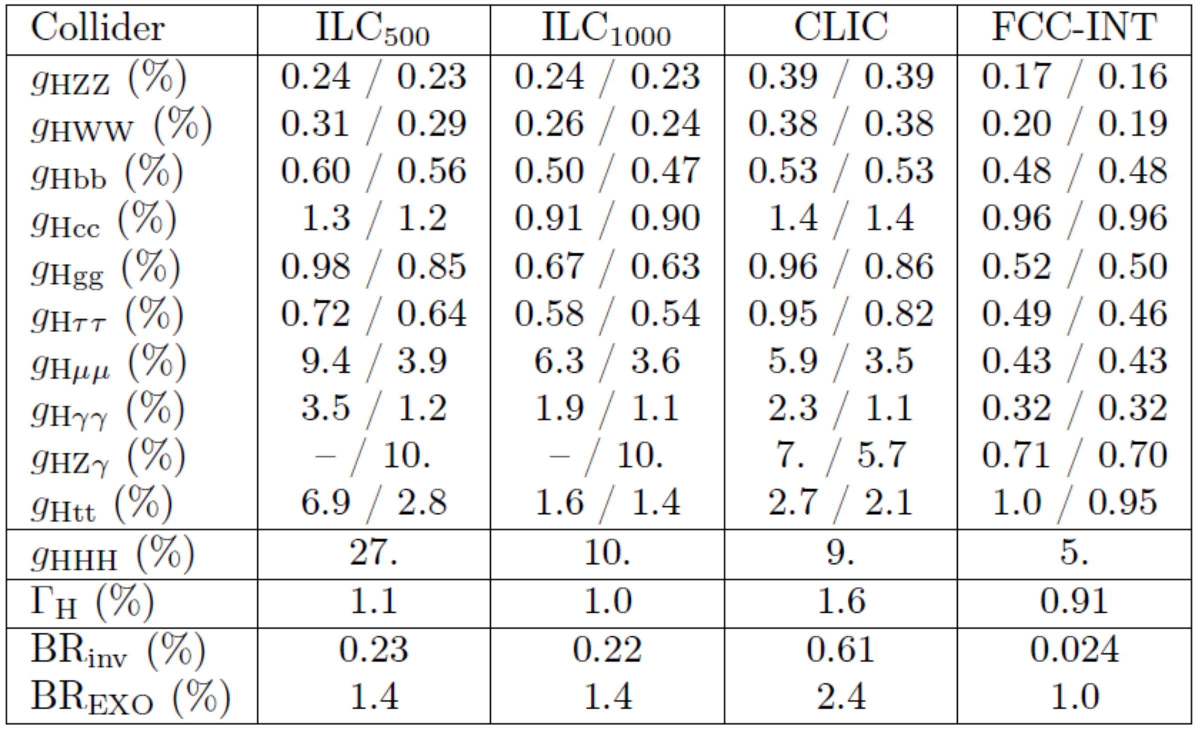
With/Without HL-LHC

- 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}	$\mathrm{FCC\text{-}ee}_{240\rightarrow365}$
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
$g_{\mathrm{H}\tau\tau}$ (%)	1.9	1.9 / 1.1	3.1 / 1.4	1.4 / 0.91	0.74 / 0.66
$g_{\mathrm{H}\mu\mu}$ (%)	4.4	15. / 4.2	– / 4.4	9.0 / 3.9	8.9 / 3.9
$g_{\mathrm{H}\gamma\gamma}$ (%)	1.8	6.8 / 1.3	– / 1.5	3.7 / 1.2	3.9 / 1.2
$g_{\mathrm{HZ}\gamma}$ (%)	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
$\mathrm{BR}_{\mathrm{inv}}$ (%)	1.9	0.26	0.65	0.28	0.19
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	SM (0.0)	1.8	2.7	1.1	1.1



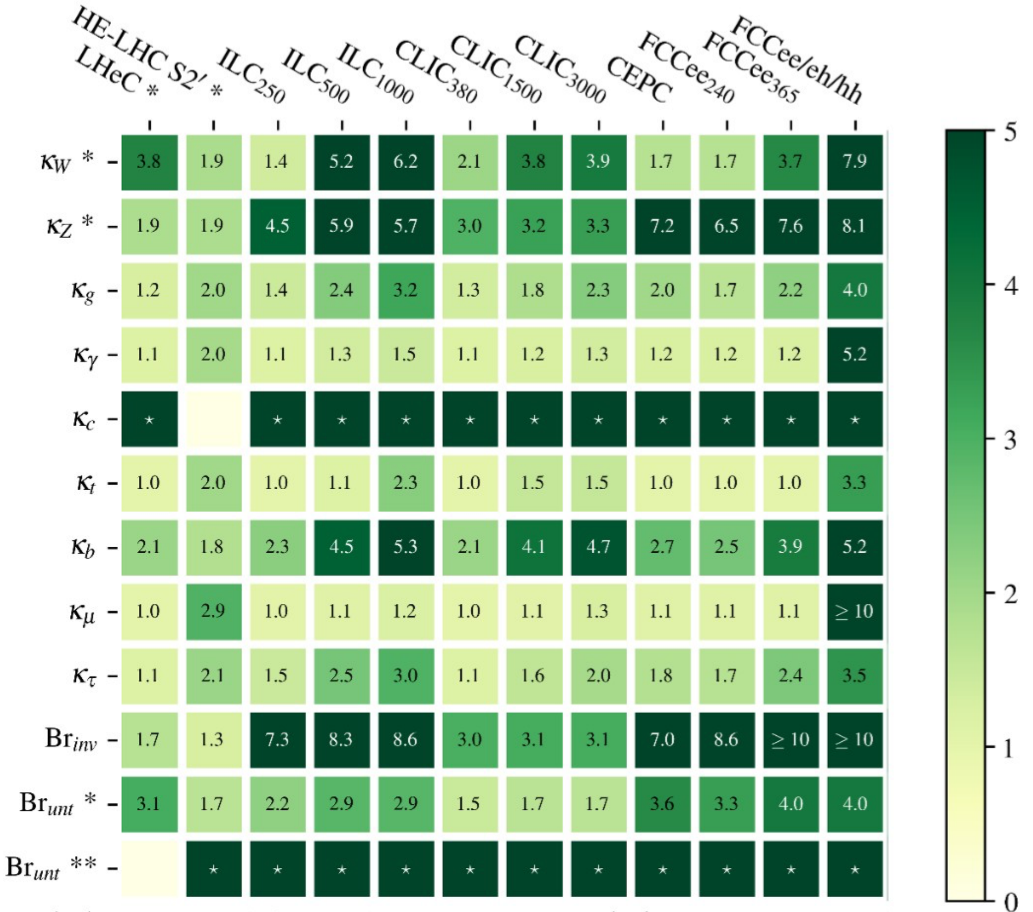
Collider	ILC_{500}	ILC_{1000}	CLIC	FCC-INT
g_{HZZ} (%)	0.24 / 0.23	0.24 / 0.23	0.39 / 0.39	0.17 / 0.16
g_{HWW} (%)	0.31 / 0.29	0.26 / 0.24	0.38 / 0.38	0.20 / 0.19
g_{Hbb} (%)	0.60 / 0.56	0.50 / 0.47	0.53 / 0.53	0.48 / 0.48
g_{Hcc} (%)	1.3 / 1.2	0.91 / 0.90	1.4 / 1.4	0.96 / 0.96
g_{Hgg} (%)	0.98 / 0.85	0.67 / 0.63	0.96 / 0.86	0.52 / 0.50
$g_{\mathrm{H}\tau\tau}$ (%)	0.72 / 0.64	0.58 / 0.54	0.95 / 0.82	0.49 / 0.46
$g_{\mathrm{H}\mu\mu}$ (%)	9.4 / 3.9	6.3 / 3.6	5.9 / 3.5	0.43 / 0.43
$g_{\mathrm{H}\gamma\gamma}$ (%)	3.5 / 1.2	1.9 / 1.1	2.3 / 1.1	0.32 / 0.32
$g_{\mathrm{HZ}\gamma}$ (%)	– / 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
$\mathrm{BR}_{\mathrm{inv}}$ (%)	0.23	0.22	0.61	0.024
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	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

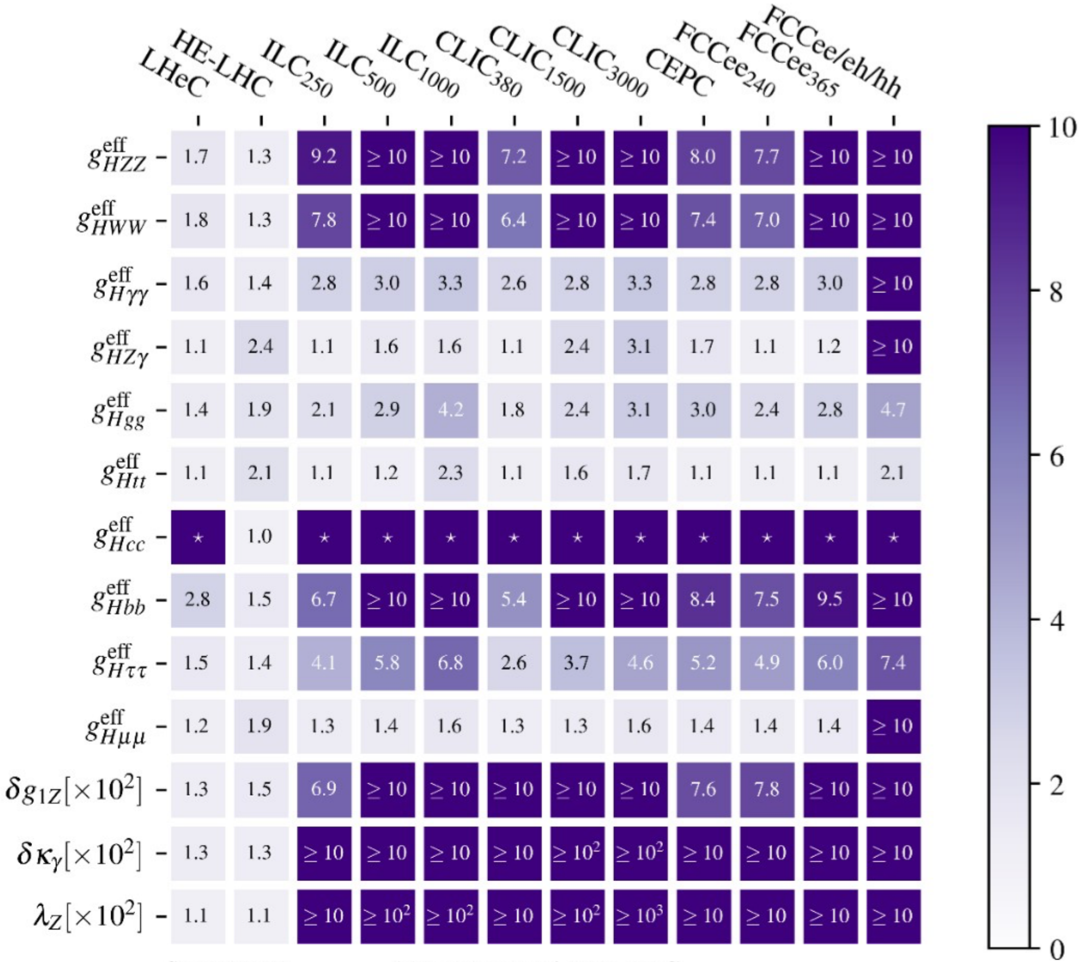
kappa framework



	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

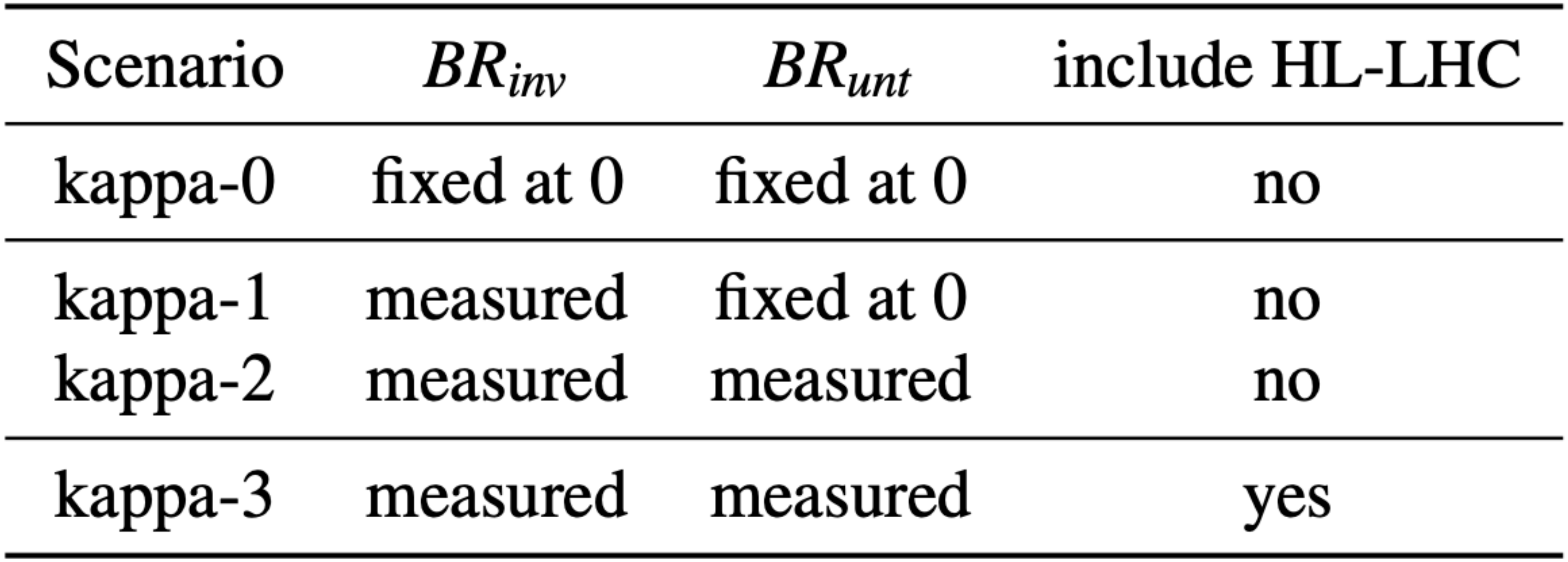
- Characterisation of Higgs couplings in terms of a series of Higgs coupling strength modifier parameters κ
  - defined as the ratios of the couplings of the Higgs bosons to particles *i* to their corresponding Standard Model values

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

- 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 → ZZ* mostly at √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^- → Hνν**
    mostly at $\sqrt{s}$ = 365 GeV

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

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

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

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

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

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

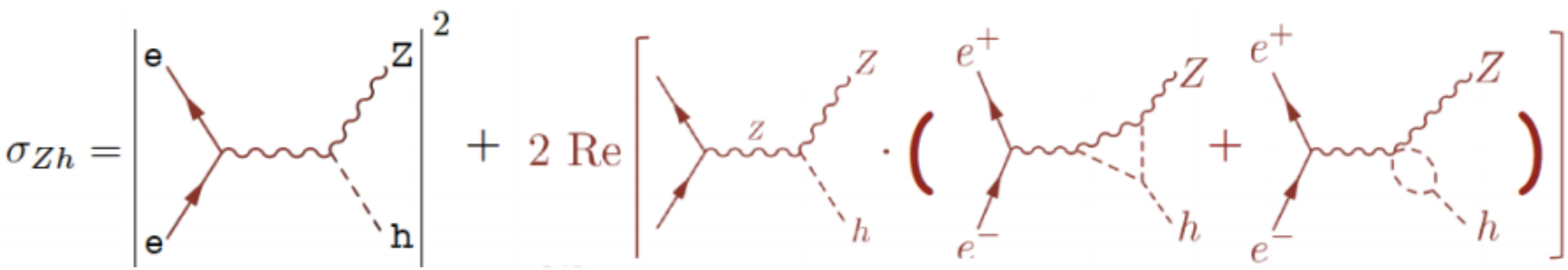
  where angle α parametrizes the departure from the CP-even case

- @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:

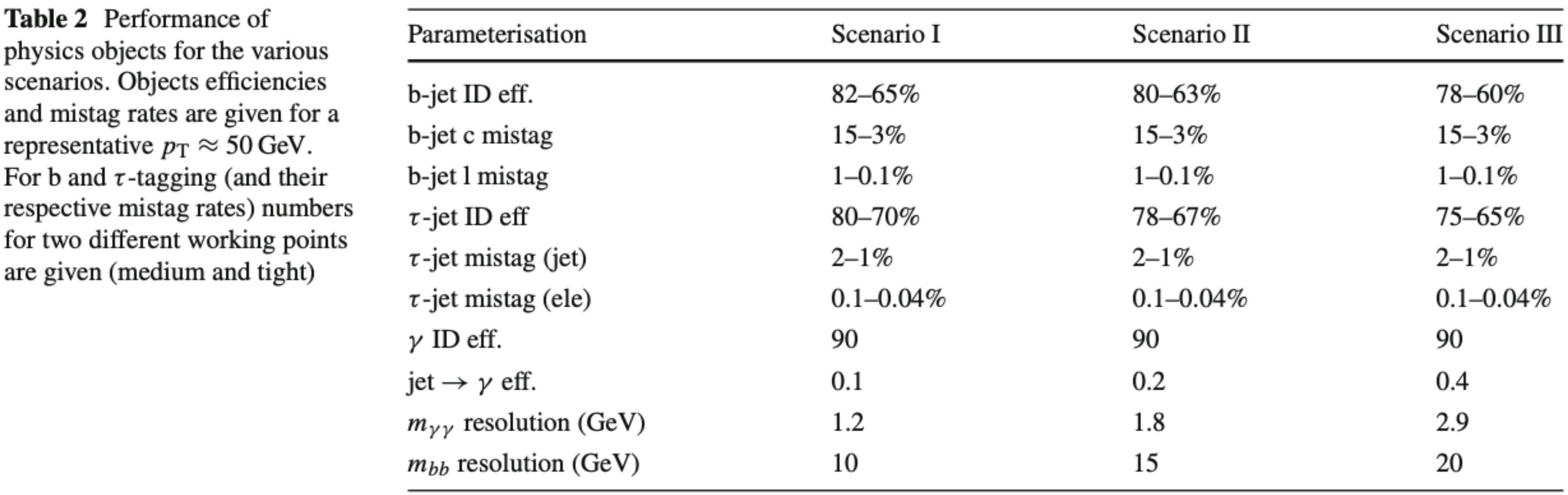


Table 2 Performance of physics objects for the various scenarios. Objects efficiencies and mistag rates are given for a representative $p_T \approx 50\,\text{GeV}$. For b and τ-tagging (and their respective mistag rates) numbers for two different working points are given (medium and tight)

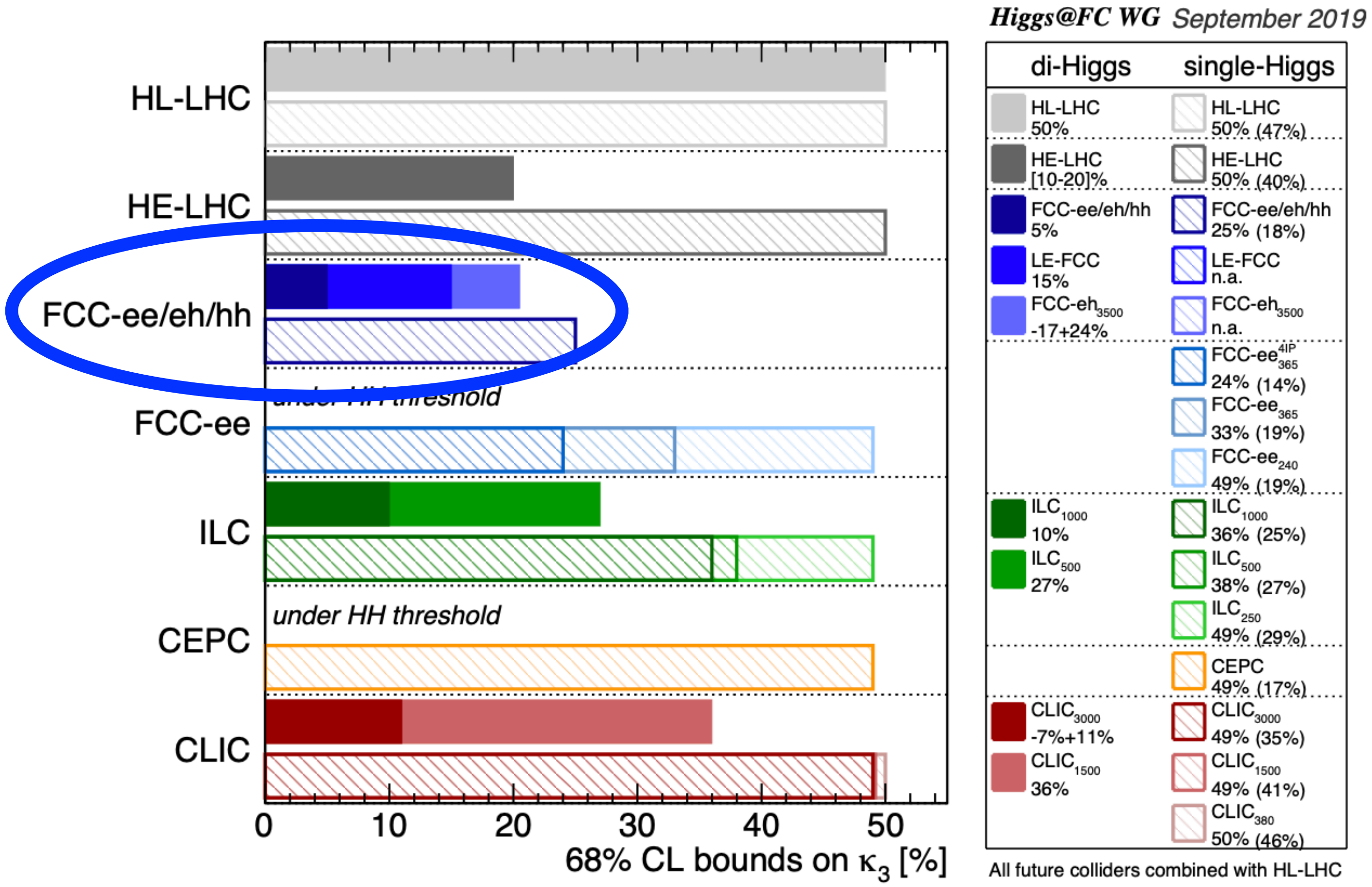
Parameterisation	Scenario I	Scenario II	Scenario III
b-jet ID eff.	82–65%	80–63%	78–60%
b-jet c mistag	15–3%	15–3%	15–3%
b-jet l mistag	1–0.1%	1–0.1%	1–0.1%
τ-jet ID eff	80–70%	78–67%	75–65%
τ-jet mistag (jet)	2–1%	2–1%	2–1%
τ-jet mistag (ele)	0.1–0.04%	0.1–0.04%	0.1–0.04%
γ ID eff.	90	90	90
jet → γ 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

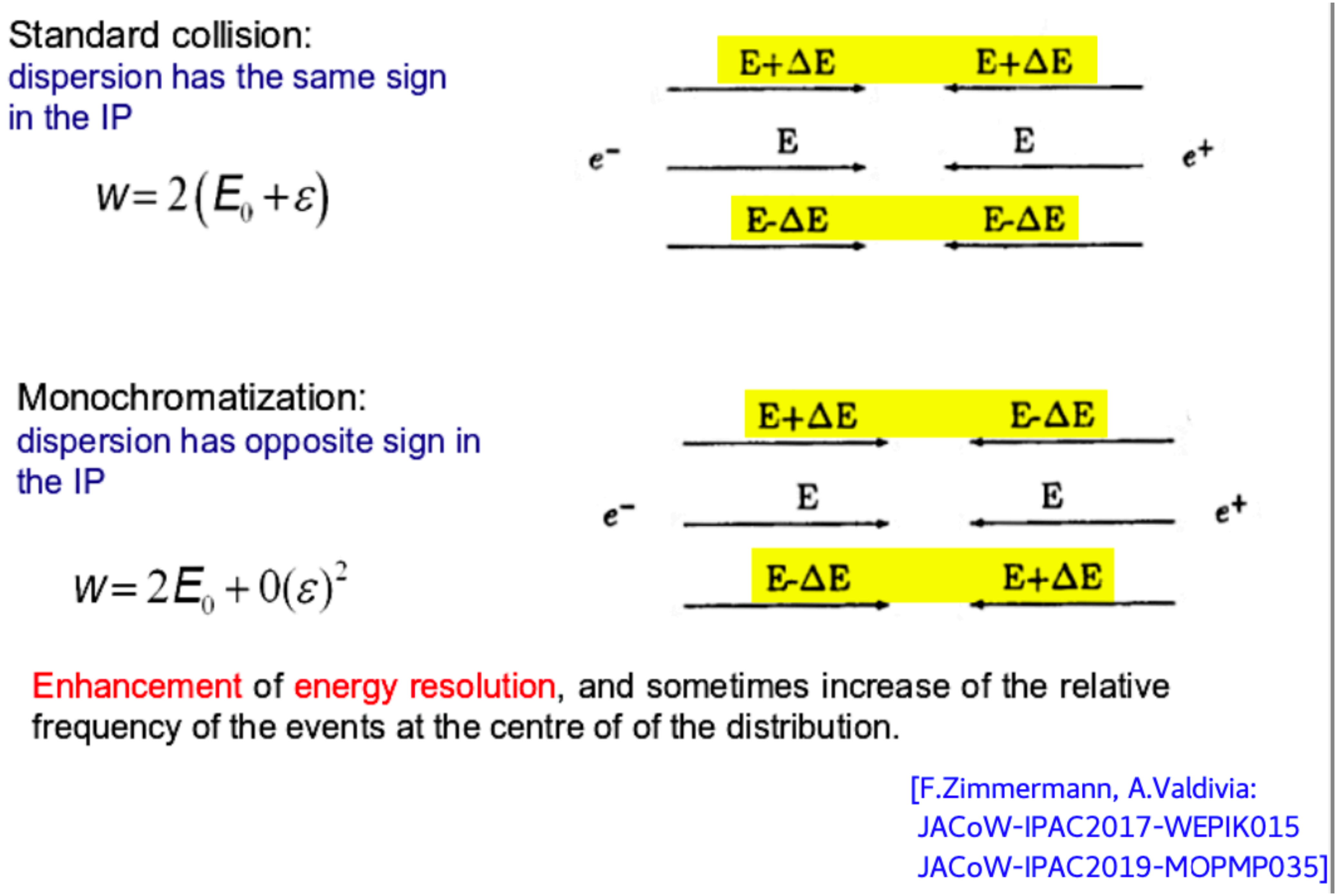
Higgs Boson Self-Coupling

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



Beam monochromatisation



Standard collision:
dispersion has the same sign in the IP

$$W = 2(E_0 + \varepsilon)$$

Monochromatization:
dispersion has opposite sign in the IP

$$W = 2E_0 + 0(\varepsilon)^2$$

Enhancement of energy resolution, and sometimes increase of the relative frequency of the events at the centre of of the distribution.

[F.Zimmermann, A.Valdivia:
JACoW-IPAC2017-WEPIK015
JACoW-IPAC2019-MOPMP035]