

Prospects for Higgs Precision at the LHC and FCC

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Contents:

- Framework
- LHC
- FCC-ee
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Framework

Higgs couplings: CPsuperH [JSL et al., CPC (hep-ph/0307377)]

Yongtae Heo, Dong-Won Jung, JSL, PRD [e-Print:2402.02822]

$$\mathcal{L}_{H\bar{f}f} = - \sum_{f=\{\ell,q\}} \frac{gm_f}{2M_W} \left[\bar{f} \left(g_{H\bar{f}f}^S + i g_{H\bar{f}f}^P \gamma_5 \right) f \right] H$$

$$\mathcal{L}_{HVV} = g M_W \left(g_{HWW} W_\mu^+ W^{-\mu} + g_{HZZ} \frac{1}{2c_W^2} Z_\mu Z^\mu \right) H$$

$$\mathcal{M}_{\gamma\gamma H} = - \frac{\alpha(0) M_H^2}{4\pi v} \left\{ S^\gamma(M_H) (\epsilon_{1\perp}^* \cdot \epsilon_{2\perp}^*) - P^\gamma(M_H) \frac{2}{M_H^2} \langle \epsilon_1^* \epsilon_2^* k_1 k_2 \rangle \right\}$$

$$S^\gamma(M_H) = 2 \sum_{f=b,t,\tau} N_C^f Q_f^2 g_{H\bar{f}f}^S F_{sf}(\tau_f) - g_{HWW} F_1(\tau_W) + \Delta S^\gamma;$$

$$P^\gamma(M_H) = 2 \sum_{f=b,t,\tau} N_C^f Q_f^2 g_{H\bar{f}f}^P F_{pf}(\tau_f) + \Delta P^\gamma,$$

$$\mathcal{M}_{ggH}^{ab} = - \frac{\alpha_s(M_H) M_H^2 \delta^{ab}}{4\pi v} \left\{ S^g(M_H) (\epsilon_{1\perp}^* \cdot \epsilon_{2\perp}^*) - P^g(M_H) \frac{2}{M_H^2} \langle \epsilon_1^* \epsilon_2^* k_1 k_2 \rangle \right\}$$

$$S^g(M_H) = \sum_{f=b,t,c} g_{H\bar{f}f}^S F_{sf}(\tau_f) + \Delta S^g; \quad P^g(M_H) = \sum_{f=b,t,c} g_{H\bar{f}f}^P F_{pf}(\tau_f) + \Delta P^g$$

$$\mathcal{M}_{Z\gamma H} = - \frac{\alpha}{2\pi v} \left\{ S^{Z\gamma}(M_H, M_Z) [k_1 \cdot k_2 \epsilon_1^* \cdot \epsilon_2^* - k_1 \cdot \epsilon_2^* k_2 \cdot \epsilon_1^*] - P^{Z\gamma}(M_H, M_Z) \langle \epsilon_1^* \epsilon_2^* k_1 k_2 \rangle \right\}$$

$$S^{Z\gamma}(M_H, M_Z) = 2 \sum_{f=t,b,\tau} N_C^f Q_f \frac{I_3^f - 2s_W^2 Q_f}{s_W c_W} g_{H\bar{f}f}^S G_{sf}(\tau_f, \lambda_f) - \frac{1}{s_W} g_{HWW} G_1(\tau_W, \lambda_W) + \Delta S^{Z\gamma}, \quad P^{Z\gamma}(M_H, M_Z) = 2 \sum_{f=t,b,\tau} N_C^f Q_f \frac{I_3^f - 2s_W^2 Q_f}{s_W c_W} g_{H\bar{f}f}^P G_{pf}(\tau_f, \lambda_f) + \Delta P^{Z\gamma},$$

Loop-induced Higgs couplings at LO : MH=125 GeV

$$S^\gamma = -8.324 g_{HWW} + 1.826 g_{H\bar{t}t}^S + (-0.020 + 0.025 i) g_{H\bar{b}b}^S + (-0.024 + 0.022 i) g_{H\tau\tau}^S + \Delta S^\gamma ;$$

$$P^\gamma = 2.771 g_{H\bar{t}t}^P + (-0.022 + 0.025 i) g_{H\bar{b}b}^P + (-0.025 + 0.022 i) g_{H\tau\tau}^P + \Delta P^\gamma ,$$

$$S_{\text{SM}}^\gamma = -6.542 + 0.046 i$$

$$S^g = 0.688 g_{H\bar{t}t}^S + (-0.043 + 0.063 i) g_{H\bar{b}b}^S + (-0.009 + 0.008 i) g_{H\bar{c}c}^S + \Delta S^g ;$$

$$P^g = 1.047 g_{H\bar{t}t}^P + (-0.050 + 0.063 i) g_{H\bar{b}b}^P + (-0.010 + 0.008 i) g_{H\bar{c}c}^P + \Delta P^g ,$$

$$S_{\text{SM}}^g = 0.636 + 0.071 i$$

$$S^{Z\gamma} = -12.3401 g_{HWW} + 0.6891 g_{H\bar{t}t}^S + (-0.0186 + 0.0111 i) g_{H\bar{b}b}^S + (-0.0005 + 0.0002 i) g_{H\tau\tau}^S + \Delta S^{Z\gamma}$$

$$P^{Z\gamma} = 1.0459 g_{H\bar{t}t}^P + (-0.0219 + 0.0112 i) g_{H\bar{b}b}^P + (-0.0006 + 0.0002 i) g_{H\tau\tau}^P + \Delta P^{Z\gamma} ,$$

$$S_{\text{SM}}^{Z\gamma} = -11.6701 + 0.0114 i$$

Signal strengths:

$$\mu(\mathcal{P}, \mathcal{D}) \simeq \hat{\mu}(\mathcal{P}) \hat{\mu}(\mathcal{D})$$

$$\hat{\mu}(\mathcal{P}) = \frac{\sigma_{\mathcal{P}}}{\sigma_{\mathcal{P}}^{\text{SM}}} \quad \hat{\mu}(\mathcal{D}) = \frac{B(H \rightarrow \mathcal{D})}{B(H_{\text{SM}} \rightarrow \mathcal{D})}$$

$$\begin{array}{ll} \mathcal{P} & \text{ggF, VBF, WH, ZH, ttH, and tH} \\ \mathcal{D} & \gamma\gamma, ZZ^*, WW^*, bb, \tau\tau, \text{ and } \mu\mu \end{array}$$

$$\hat{\mu}(\mathcal{D}) = \frac{B(H \rightarrow \mathcal{D})}{B(H_{\text{SM}} \rightarrow \mathcal{D})} = \frac{\Gamma(H \rightarrow \mathcal{D})}{\Gamma(H_{\text{SM}} \rightarrow \mathcal{D})} \times \frac{\Gamma_{\text{tot}}(H_{\text{SM}})}{\Gamma_{\text{tot}}(H) + \Delta\Gamma_{\text{tot}}}$$

Precisely, we calculate the total Higgs decay width by summing over the 9 partial widths of the Higgs decay modes into $b\bar{b}$, WW^* , gg , $\tau^+\tau^-$, $c\bar{c}$, ZZ^* , $\gamma\gamma$, $Z\gamma$, and $\mu^+\mu^-$. Therefore, $\Delta\Gamma_{\text{tot}}$ addresses either all the Higgs decays into particles other than these 9 final states **such as dark matter and light quarks or decays into gg , $c\bar{c}$, and $Z\gamma$ beyond the SM.**

Productions@LHC:

$$\hat{\mu}(\text{ggF})^{\text{LO}} = \frac{|S^g(M_H)|^2 + |P^g(M_H)|^2}{|S_{\text{SM}}^g(M_H)|^2}; \quad \hat{\mu}(\text{bbH}) = (g_{H\bar{b}b}^S)^2 + (g_{H\bar{b}b}^P)^2,$$

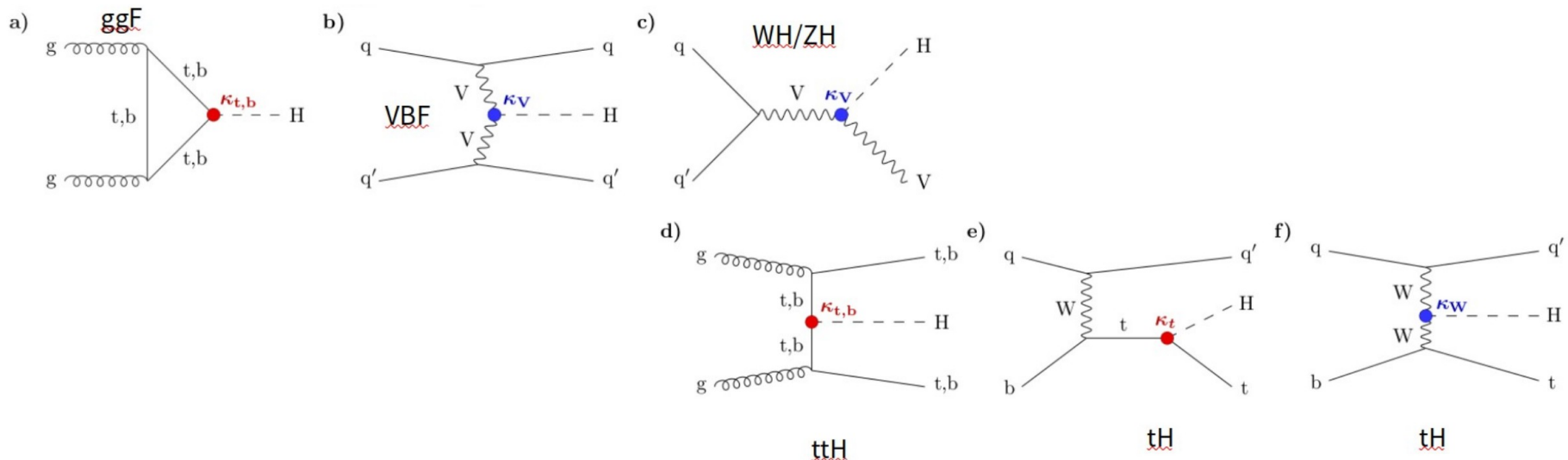
$$\hat{\mu}(\text{VBF}) = 0.73 g_{HWW}^2 + 0.27 g_{HZZ}^2,$$

$$\hat{\mu}(\text{WH}) = g_{HWW}^2,$$

$$\hat{\mu}(\text{ZH}) = g_{HZZ}^2,$$

$$\hat{\mu}(\text{ttH}) = (g_{H\bar{t}t}^S)^2 + (g_{H\bar{t}t}^P)^2,$$

$$\hat{\mu}(\text{tH}) = 2.99 [(g_{H\bar{t}t}^S)^2 + (g_{H\bar{t}t}^P)^2] + 3.38 g_{HWW}^2 - 5.37 g_{H\bar{t}t}^S g_{HWW},$$



Decays: Seong Youl Choi, JSL, Jubin Park, PPNP [2101.12435]

$$\Gamma(H \rightarrow f\bar{f}) = N_C^f \frac{m_f^2}{v^2} \frac{\beta_f M_H}{8\pi} \left[\beta_f^2 |g_{H\bar{f}f}^S|^2 \left(1 + \delta_{\text{QCD}} + \delta_t^{f:S} + \delta_{\text{mixed}}^f \right) \left(1 + \delta_{\text{elw}}^f \right) + |g_{H\bar{f}f}^P|^2 \left(1 + \delta_{\text{QCD}} + \delta_t^{f:P} \right) \right],$$

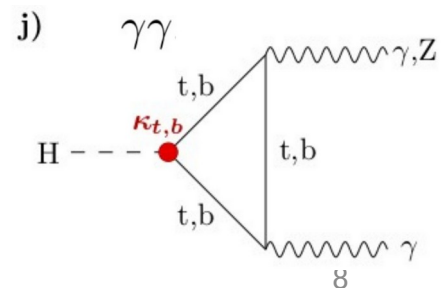
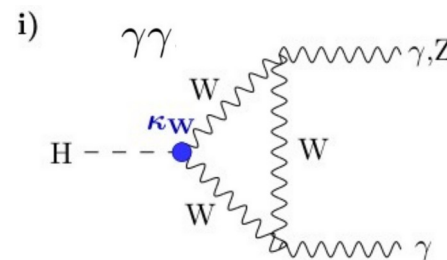
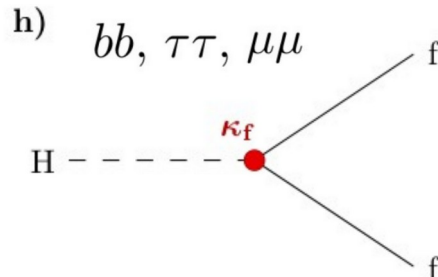
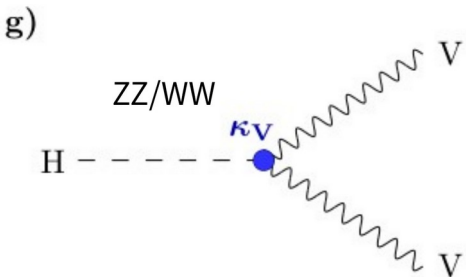
$$\Gamma(H \rightarrow VV \rightarrow 4f) = \Gamma^{\text{LO}}(H \rightarrow V^*V^*) \left(1 + \delta_{\text{elw}}^V \right)$$

$$\Gamma^{\text{LO}}(H \rightarrow V^*V^*) = \frac{1}{\pi^2} \int_0^{\omega_V} \frac{\epsilon_V dy}{(y-1)^2 + \epsilon_V^2} \int_0^{(\sqrt{\omega_V} - \sqrt{y})^2} \frac{\epsilon_V dx}{(x-1)^2 + \epsilon_V^2} \frac{\delta_V g_{HVV}^2 G_F M_H^3}{16\sqrt{2}\pi} \lambda^{1/2} \left(1, \frac{x}{\omega_V}, \frac{y}{\omega_V} \right) \left[\lambda \left(1, \frac{x}{\omega_V}, \frac{y}{\omega_V} \right) + 12 \frac{xy}{\omega_V^2} \right],$$

$$\Gamma(H \rightarrow gg) = \frac{M_H^3 \alpha_S^2}{32\pi^3 v^2} \left[|S^g(M_H)|^2 \left(1 + \delta_{\text{QCD}}^{g:S} \right) \left(1 + \delta_{\text{elw}}^{g:S} \right) + |P^g(M_H)|^2 \left(1 + \delta_{\text{QCD}}^{g:P} \right) \left(1 + \delta_{\text{elw}}^{g:P} \right) \right]$$

$$\Gamma(H \rightarrow \gamma\gamma) = \frac{M_H^3 \alpha^2}{256\pi^3 v^2} \left[|S^\gamma(M_H)|^2 \left(1 + \delta_{\text{QCD}}^{\gamma:S} \right) \left(1 + \delta_{\text{elw}}^{\gamma:S} \right) + |P^\gamma(M_H)|^2 \left(1 + \delta_{\text{QCD}}^{\gamma:P} \right) \left(1 + \delta_{\text{elw}}^{\gamma:P} \right) \right]$$

$$\Gamma^{\text{LO}}(H \rightarrow Z\gamma) = \frac{\alpha(0) G_F^2 M_W^2 s_W^2}{64\pi^4} M_H^3 \left(1 - \frac{M_Z^2}{M_H^2} \right)^3 \left(|S^{Z\gamma}(M_H, M_Z)|^2 + |P^{Z\gamma}(M_H, M_Z)|^2 \right)$$





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Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp



Review

Decays of Higgs bosons in the Standard Model and beyond

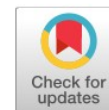
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Decay widths and Brs of the SM Higgs boson

Table 6

Partial and total decay widths of the SM Higgs in MeV taking $M_H = 125.5$ GeV. We compare our numerical estimates with those presented in Ref. [84] by introducing a quantity δ_Γ defined by $\delta_\Gamma \equiv (\Gamma_{\text{This Review}} - \Gamma_{\text{Ref. [84]}}) / \Gamma_{\text{Ref. [84]}}$. Also presented are theoretical uncertainties (THUs) of the partial and total decay widths from missing higher orders estimated around $M_H = 125$ GeV, see Tables 178 and 182 in Ref. [84].

	$\Gamma(H \rightarrow b\bar{b})$	$\Gamma(H \rightarrow WW)$	$\Gamma(H \rightarrow gg)$	$\Gamma(H \rightarrow \tau\tau)$	$\Gamma(H \rightarrow c\bar{c})$
This Review	2.367	9.185×10^{-1}	3.382×10^{-1}	2.572×10^{-1}	1.173×10^{-1}
Ref. [84]	2.387	9.222×10^{-1}	3.386×10^{-1}	2.573×10^{-1}	1.185×10^{-1}
δ_Γ [%]	-0.8	-0.4	-0.1	-0.05	-1.0
THU [%]	± 0.5	± 0.5	± 3.2	± 0.5	± 0.5
	$\Gamma(H \rightarrow ZZ)$	$\Gamma(H \rightarrow \gamma\gamma)$	$\Gamma(H \rightarrow Z\gamma)$	$\Gamma(H \rightarrow \mu\mu)$	Γ_{tot}
This Review	1.139×10^{-1}	9.405×10^{-3}	6.531×10^{-3}	8.913×10^{-4}	4.129
Ref. [84]	1.139×10^{-1}	9.438×10^{-3}	6.550×10^{-3}	8.927×10^{-4}	4.156
δ_Γ [%]	-0.03	-0.4	-0.3	-0.2	-0.65
THU [%]	± 0.5	± 1.0	± 5.0	± 0.5	± 0.73

Table 7

Branching ratios (BRs) of the SM Higgs taking $M_H = 125.5$ GeV. We compare our numerical estimates with those presented in Ref. [84]. Estimation of the total uncertainty THU+ PU has been done by adding linearly the THU and the total parametric uncertainty (PU) where the latter is obtained by adding the individual PUs in quadrature, see Tables 174, 175, 176, 177, and 178 in Ref. [84].

	$B(H \rightarrow b\bar{b})$	$B(H \rightarrow WW)$	$B(H \rightarrow gg)$	$B(H \rightarrow \tau\tau)$	$B(H \rightarrow c\bar{c})$
This Review	5.733×10^{-1}	2.225×10^{-1}	8.190×10^{-2}	6.230×10^{-2}	2.841×10^{-2}
Ref. [84]	5.744×10^{-1}	2.219×10^{-1}	8.147×10^{-2}	6.192×10^{-2}	2.852×10^{-2}
THU+ PU [%]	1.7	2.1	7.2	2.3	6.6
	$B(H \rightarrow ZZ)$	$B(H \rightarrow \gamma\gamma)$	$B(H \rightarrow Z\gamma)$	$B(H \rightarrow \mu\mu)$	Γ_{tot} [MeV]
This Review	2.758×10^{-2}	2.278×10^{-3}	1.582×10^{-3}	2.159×10^{-4}	4.129
Ref. [84]	2.741×10^{-2}	2.271×10^{-3}	1.576×10^{-3}	2.148×10^{-4}	4.156
THU+ PU [%]	2.1	2.9	6.9	2.4	1.9

our framework ~ kappa framework

$$C_W = g_{HWW}, \quad C_Z = g_{HZZ};$$

$$C_t^{S,P} = g_{H\bar{t}t}^{S,P}, \quad C_c^{S,P} = g_{H\bar{c}c}^{S,P},$$

$$C_b^{S,P} = g_{H\bar{b}b}^{S,P}, \quad C_\tau^{S,P} = g_{H\bar{\tau}\tau}^{S,P}, \quad C_\mu^{S,P} = g_{H\bar{\mu}\mu}^{S,P}$$

$$\left\{ \Delta\Gamma_{\text{tot}}, \Delta S^\gamma, \Delta S^g \right\}$$

More useful for the studies of
CPV, signs of Higgs couplings,
BSM particles in loops, etc

**** Comparison:** $\kappa_g^2(\kappa_b, \kappa_t, m_H)$

$$\sim \hat{\mu}(\text{ggF} + \text{bbH}) = \frac{\sigma_{\text{ggF}}^{\text{SM}} \hat{\mu}(\text{ggF}) + \sigma_{\text{bbH}}^{\text{SM}} \hat{\mu}(\text{bbH})}{\sigma_{\text{ggF}}^{\text{SM}} + \sigma_{\text{bbH}}^{\text{SM}}}$$

$$= \sum_{X=S,P} \left[c_{tt}^X (g_{H\bar{t}t}^X)^2 + c_{bb}^X (g_{H\bar{b}b}^X)^2 + c_{tb}^X (g_{H\bar{t}t}^X g_{H\bar{b}b}^X) + c_{tc}^X (g_{H\bar{t}t}^X g_{H\bar{c}c}^X) + c_{t\Delta}^X (g_{H\bar{t}t}^X \Delta X^g) + c_{\Delta\Delta}^X (\Delta X^g)^2 \right],$$

LHC HXSWG interim recommendations to explore the coupling structure of a
Higgs-like particle

LHC Higgs Cross Section Working Group • A. David (LIP, Lisbon) et al. (Sep, 2012)

e-Print: [1209.0040](#) [hep-ph]

[pdf](#) [cite](#) [claim](#)

Production modes

$$\frac{\sigma_{\text{ggH}}}{\sigma_{\text{ggH}}^{\text{SM}}} = \left\{ \kappa_g^2(\kappa_b, \kappa_t, m_H) \right\} \quad (3)$$

$$\frac{\sigma_{\text{VBF}}}{\sigma_{\text{VBF}}^{\text{SM}}} = \kappa_{\text{VBF}}^2(\kappa_W, \kappa_Z, m_H) \quad (4)$$

$$\frac{\sigma_{\text{WH}}}{\sigma_{\text{WH}}^{\text{SM}}} = \kappa_W^2 \quad (5)$$

$$\frac{\sigma_{\text{ZH}}}{\sigma_{\text{ZH}}^{\text{SM}}} = \kappa_Z^2 \quad (6)$$

$$\frac{\sigma_{\text{t}\bar{\text{t}}\text{H}}}{\sigma_{\text{t}\bar{\text{t}}\text{H}}^{\text{SM}}} = \kappa_t^2 \quad (7)$$

Detectable decay modes

$$\frac{\Gamma_{\text{WW}^{(*)}}}{\Gamma_{\text{WW}^{(*)}}^{\text{SM}}} = \kappa_W^2 \quad (8)$$

$$\frac{\Gamma_{\text{ZZ}^{(*)}}}{\Gamma_{\text{ZZ}^{(*)}}^{\text{SM}}} = \kappa_Z^2 \quad (9)$$

$$\frac{\Gamma_{\text{b}\bar{\text{b}}}}{\Gamma_{\text{b}\bar{\text{b}}}^{\text{SM}}} = \kappa_b^2 \quad (10)$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{\text{SM}}} = \kappa_\tau^2 \quad (11)$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\text{SM}}} = \left\{ \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \right\} \quad (12)$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{\text{SM}}} = \left\{ \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \right\} \quad (13)$$

Total width

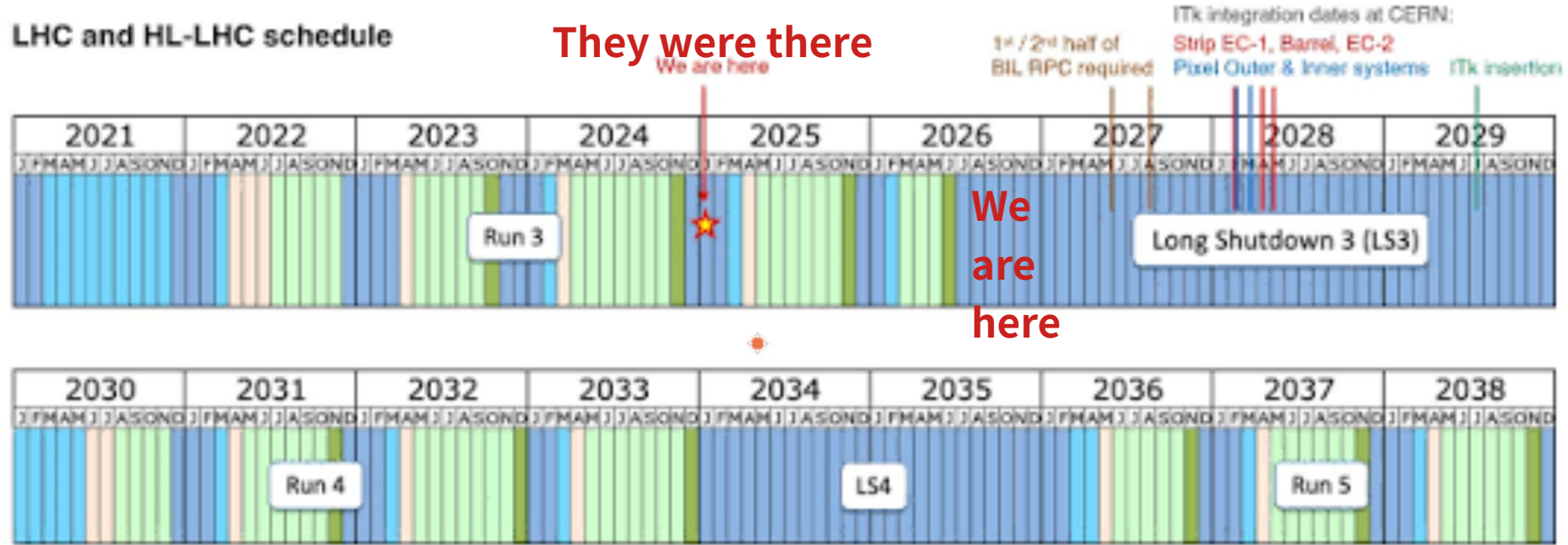
$$\frac{\Gamma_H}{\Gamma_H^{\text{SM}}} = \left\{ \kappa_H^2(\kappa_i, m_H) \right\}$$

#1

LHC

High-Luminosity LHC (HL-LHC)

LHC and HL-LHC schedule



Run 3 wrapped up in **June 2026** and the official start of Long Shutdown 3 (LS3) occurring on **August 31, 2026**

LS3 Duration: Ongoing through **late 2029**

Run 4 / High-Luminosity LHC (HL-LHC) Start: Scheduled to begin in **June 2030**

Higgs productions @ LHC (Run 1 & Run 2): MH=125GeV

$\sqrt{s}$ (TeV)	ggF (pb)	VBF (fb)	WH (fb)	ZH (fb)	ttH (fb)	tHq (fb)	tHW (fb)	bbH (fb)
7	16.85	1241.4	577.30	339.10	88.78	12.26	—	155.20
8	21.42	1601.2	702.50	420.70	133.0	18.69	—	202.10
13	48.57	3781.7	1373.00	883.70	507.2	74.25	15.2	488.00

$$N_H = \sigma \times \mathcal{L} \sim 60 \text{ pb} \times 150/\text{fb} = 9,000,000$$

Run 1 (2010 ~ 2013): 5/fb @ 7 TeV & 20/fb @ 8 TeV (each collaboration)

Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV #3

ATLAS and CMS Collaborations • Georges Aad (Marseille, CPPM) et al. (Jun 7, 2016)

Published in: *JHEP* 08 (2016) 045 • e-Print: [1606.02266](#) [hep-ex]

 pdf  DOI  cite  datasets  claim  reference search  2,028 citations

Run2 (2015 ~ 2018): ATLAS 139/fb @ 13 TeV & CMS 138/fb @ 13 TeV

A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery #1

ATLAS Collaboration • Georges Aad (Marseille, CPPM) et al. (Jun 30, 2022)

Published in: *Nature* 607 (2022) 7917, 52-59, *Nature* 612 (2022) 7941, E24 (erratum) • e-Print: [2207.00092](#) [hep-ex]

 pdf  links  DOI  cite  datasets  claim  reference search  1,015 citations

A portrait of the Higgs boson by the CMS experiment ten years after the discovery. #1

CMS Collaboration • Armen Tumasyan (Yerevan Phys. Inst.) et al. (Jun 30, 2022)

Published in: *Nature* 607 (2022) 7917, 60-68, *Nature* 623 (2023) 7985, E4 (erratum) • e-Print: [2207.00043](#) [hep-ex]

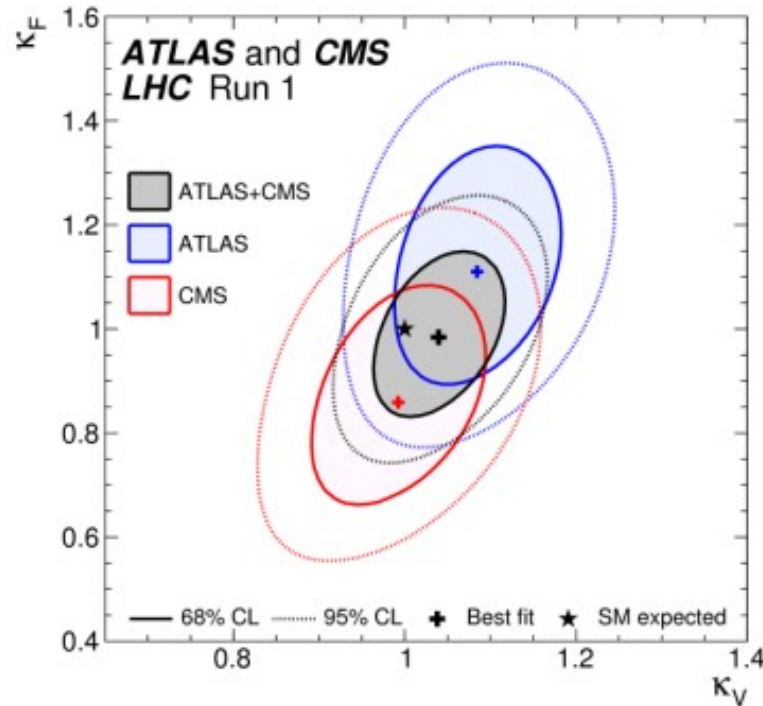
 pdf  links  DOI  cite  datasets  claim  reference search  1,063 citations

Run 1 ATLAS+CMS: 20 signal strengths $\mu_{\text{Run 1}}^{\text{Global}} = 1.09^{+0.11}_{-0.10}$

Production mode	Decay mode				
	$\gamma\gamma$	ZZ^*	WW^*	bb	$\tau\tau$
ggF	$1.10^{+0.23}_{-0.22}$	$1.13^{+0.34}_{-0.31}$	$0.84^{+0.17}_{-0.17}$	—	$1.0^{+0.6}_{-0.6}$
VBF	$1.3^{+0.5}_{-0.5}$	$0.1^{+1.1}_{-0.6}$	$1.2^{+0.4}_{-0.4}$	—	$1.3^{+0.4}_{-0.4}$
WH	$0.5^{+1.3}_{-1.2}$	—	$1.6^{+1.2}_{-1.0}$	$1.0^{+0.5}_{-0.5}$	$-1.4^{+1.4}_{-1.4}$
ZH	$0.5^{+3.0}_{-2.5}$	—	$5.9^{+2.6}_{-2.2}$	$0.4^{+0.4}_{-0.4}$	$2.2^{+2.2}_{-1.8}$
ttH	$2.2^{+1.6}_{-1.3}$	—	$5.0^{+1.8}_{-1.7}$	$1.1^{+1.0}_{-1.0}$	$-1.9^{+3.7}_{-3.3}$

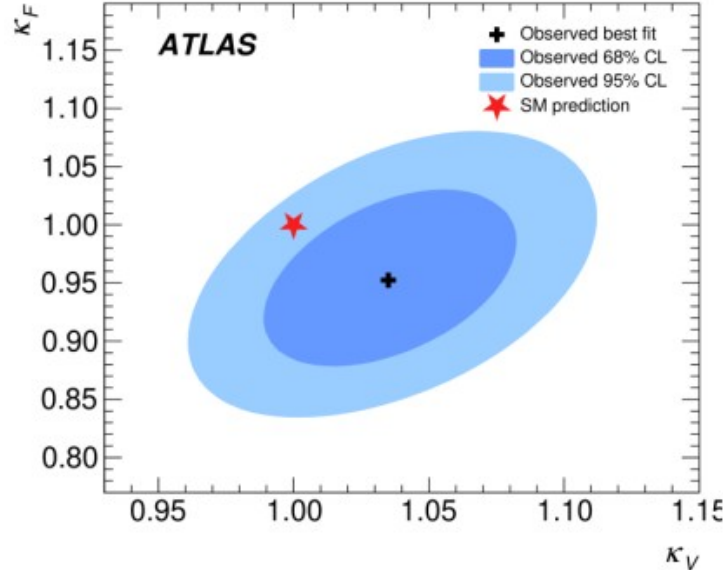
$$C_f^{S,P} = C_u^{S,P} = C_d^{S,P} = C_\ell^{S,P}$$

$$C_V = C_W = C_Z$$



Run2 ATLAS: 25 signal strengths

Production mode	Decay mode					
	$\gamma\gamma$	ZZ^*	WW^*	$b\bar{b}$	$\tau\tau$	$\mu\mu$
ggF+bbH	$1.04^{+0.10}_{-0.10}$	$0.95^{+0.11}_{-0.10}$	$1.14^{+0.13}_{-0.13}$	—	$0.90^{+0.29}_{-0.26}$	—
VBF	$1.36^{+0.30}_{-0.26}$	$1.33^{+0.52}_{-0.43}$	$1.13^{+0.19}_{-0.18}$	—	$1.00^{+0.21}_{-0.18}$	—
WH	$1.53^{+0.56}_{-0.51}$	—	$2.26^{+1.21}_{-1.02}$	$1.06^{+0.28}_{-0.26}$	—	—
ZH	$-0.22^{+0.61}_{-0.54}$	—	$2.86^{+1.84}_{-1.33}$	$1.00^{+0.25}_{-0.23}$	—	—
ttH	$0.90^{+0.33}_{-0.31}$	—	—	—	—	—
tH	$2.61^{+4.23}_{-3.38}$	—	—	—	—	—
ggF+bbH $\oplus$ VBF	—	—	—	$0.98^{+0.38}_{-0.36}$	—	—
WH $\oplus$ ZH	—	$1.50^{+1.17}_{-0.94}$	—	—	$1.00^{+0.62}_{-0.59}$	—
ttH $\oplus$ tH	—	$1.68^{+1.68}_{-1.11}$	$1.64^{+0.65}_{-0.61}$	$0.35^{+0.34}_{-0.33}$	$1.37^{+0.86}_{-0.75}$	—
ggF+bbH $\oplus$ ttH $\oplus$ tH	—	—	—	—	—	$0.54^{+0.89}_{-0.88}$
VBF $\oplus$ WH $\oplus$ ZH	—	—	—	—	—	$2.31^{+1.33}_{-1.26}$



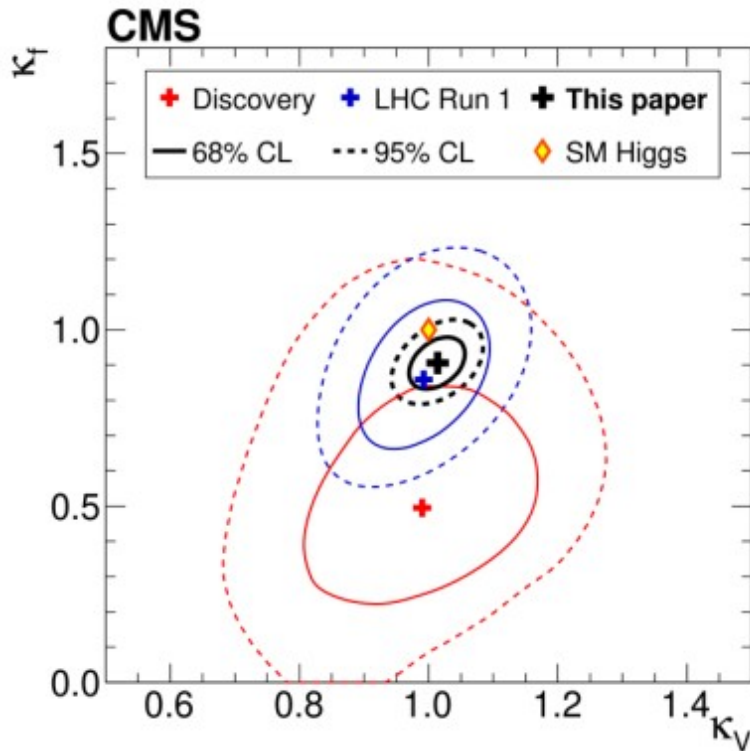
$$\mu_{\text{Run 2 ATLAS}}^{\text{Global}} = 1.05 \pm 0.06$$

$$\begin{aligned} \kappa_F &: 0.95 \pm 0.05 \\ \kappa_V &: 1.035 \pm 0.031 \end{aligned}$$

$$C_f^{S,P} = C_u^{S,P} = C_d^{S,P} = C_\ell^{S,P} \quad C_V = C_W = C_Z$$

Run2 CMS: 28 signal strengths

Production mode	Decay mode					
	$\gamma\gamma$	ZZ^*	WW^*	bb	$\tau\tau$	$\mu\mu$
ggF+bbH	$1.08^{+0.12}_{-0.11}$	$0.93^{+0.14}_{-0.13}$	$0.90^{+0.11}_{-0.10}$	$5.31^{+2.97}_{-2.54}$	$0.66^{+0.21}_{-0.21}$	$0.33^{+0.74}_{-0.70}$
VBF	$1.00^{+0.35}_{-0.32}$	$0.32^{+0.48}_{-0.32}$	$0.73^{+0.28}_{-0.24}$	—	$0.86^{+0.17}_{-0.16}$	$1.55^{+0.86}_{-0.73}$
WH	$1.43^{+0.54}_{-0.47}$	$0.00^{+1.55}$	$2.41^{+0.72}_{-0.70}$	$1.26^{+0.42}_{-0.41}$	$1.33^{+0.61}_{-0.57}$	—
ZH	$1.19^{+0.71}_{-0.62}$	$12.24^{+6.59}_{-5.69}$	$1.76^{+0.75}_{-0.67}$	$0.90^{+0.36}_{-0.34}$	$1.89^{+0.65}_{-0.56}$	—
$WH \oplus ZH$	—	—	—	—	—	$5.63^{+3.04}_{-3.36}$
$ttH \oplus tH$	$1.38^{+0.34}_{-0.29}$	$0.00^{+0.73}$	$1.44^{+0.32}_{-0.32}$	$0.90^{+0.46}_{-0.44}$	$0.35^{+0.44}_{-0.37}$	$3.07^{+2.63}_{-2.21}$

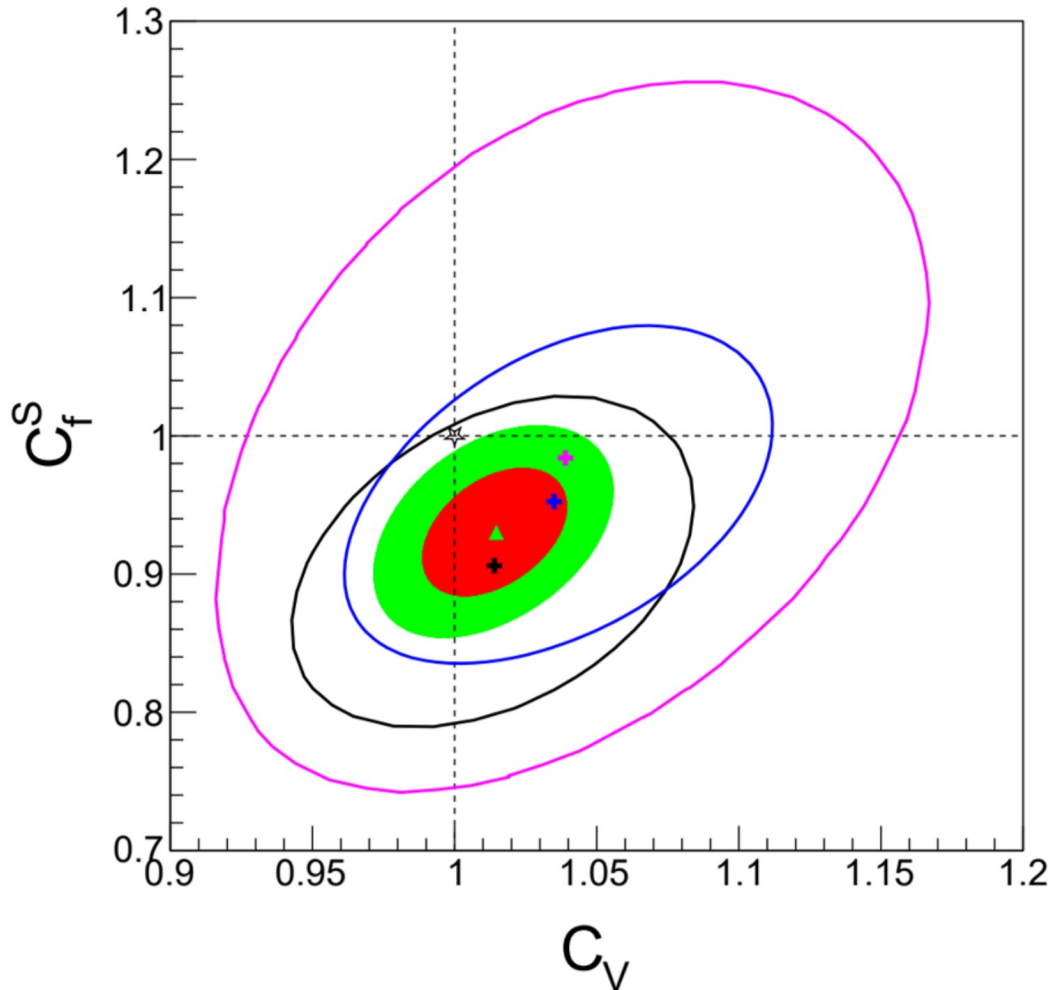


$$\mu_{\text{Run 2 CMS}}^{\text{Global}} = 1.002 \pm 0.057$$

$$C_f^{S,P} = C_u^{S,P} = C_d^{S,P} = C_\ell^{S,P} \quad C_V = C_W = C_Z$$

Combined: Run1 + Run2 ATLAS + Run2 CMS

Yongtae Heo, Dong-Won Jung, JSL, PRD [2402.02822]



magenta: Run1 (95%CL)

blue: Run2 ATLAS (95%CL)

black: Run2 CMS (95%CL)

shaded: Combined

(red,green)=(68%CL, 95%CL)

$$C_f^S = 0.930 \pm 0.031$$

$$C_V = 1.015 \pm 0.017$$

... driven by the data:

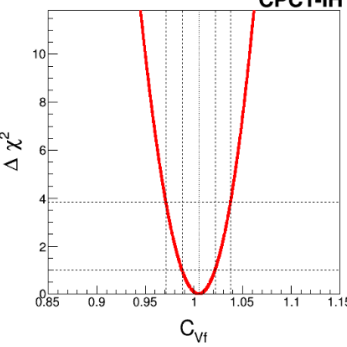
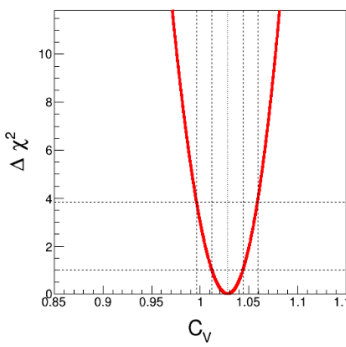
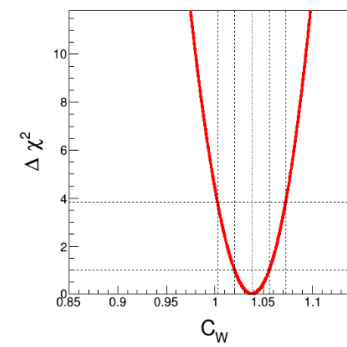
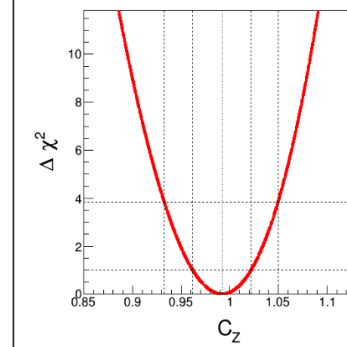
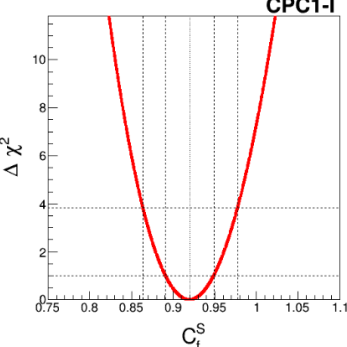
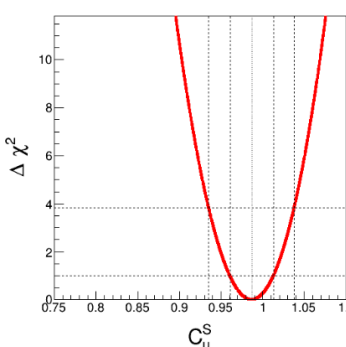
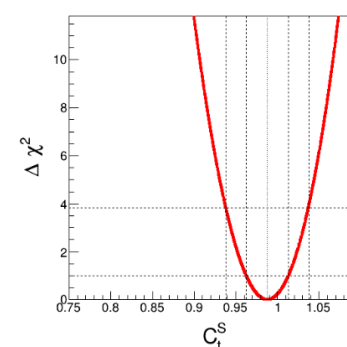
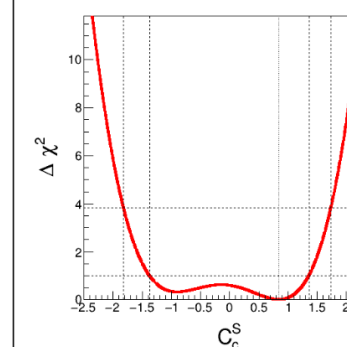
$$\mu(\gamma\gamma) > 1,$$

$$\mu(bb) < 1, \text{ and/or}$$

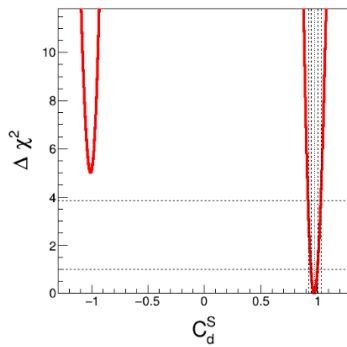
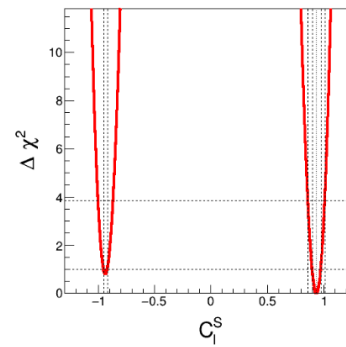
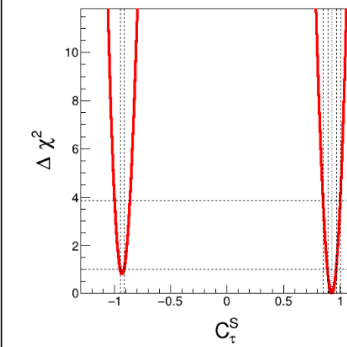
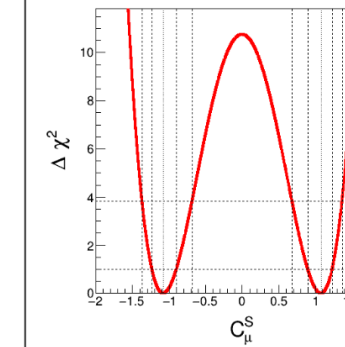
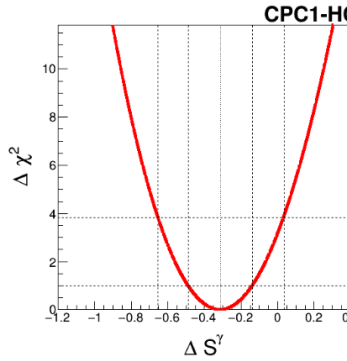
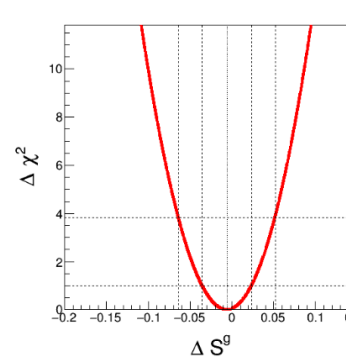
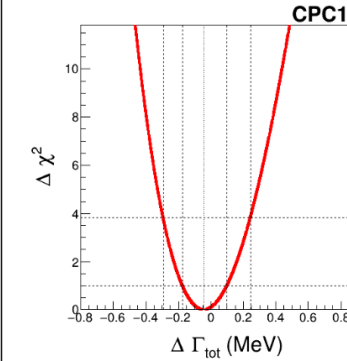
$$\mu(\tau\tau) < 1$$

$$C_f^{S,P} = C_u^{S,P} = C_d^{S,P} = C_\ell^{S,P} \quad C_V = C_W = C_Z$$

Single parameter varied

Varying Parameter	$C_{Vf} = 1.005^{+0.017}_{-0.017}$	$C_V = 1.028^{+0.016}_{-0.016}$	$C_W = 1.031^{+0.018}_{-0.018}$	$C_Z = 0.992^{+0.030}_{-0.030}$
gof	0.2649	0.3449	0.3867	0.2641
p-value	0.7590	0.0810	0.0349	0.8014
				
Varying Parameter	$C_f^S = 0.920^{+0.029}_{-0.029}$	$C_u^S = 0.987^{+0.026}_{-0.026}$	$C_t^S = 0.988^{+0.025}_{-0.025}$	$C_c^S = 0.847^{+0.513}_{-2.221}$
gof	0.4753	0.2687	0.2680	0.2643
p-value	0.0071	0.6209	0.6421	0.7948
				

Single parameter varied

Varying Parameter	$C_d^S = 0.978^{+0.029}_{-0.028}$	$C_\ell^S = 0.939^{+0.038}_{-0.039}$	$C_\tau^S = 0.933^{+0.038}_{-0.039}$	$C_\mu^S = +1.078^{+0.154}_{-0.180}, -1.078^{+0.180}_{-0.154}$
gof	0.2774	0.3330	0.3451	0.2678
p -value	0.4450	0.1048	0.0806	0.6473
				
Varying Parameter	$\Delta S^\gamma = -0.313^{+0.176}_{-0.176}$	$\Delta S^g = -0.006^{+0.029}_{-0.030}$	$\Delta \Gamma_{\text{tot}} = -0.042^{+0.142}_{-0.132} \text{ MeV}$	
gof	0.3474	0.2636	0.2649	
p -value	0.0769	0.8425	0.7590	
				

$$0.176/6.542 = 2.7 \%$$

$$0.030/0.636 = 4.7 \%$$

$$0.142/4.129 = 3.4 \%$$

Combining the LHC Run1 and Run2 Higgs: Summary of CPCn fits with $n = 2 \sim 6$ parameters varied:

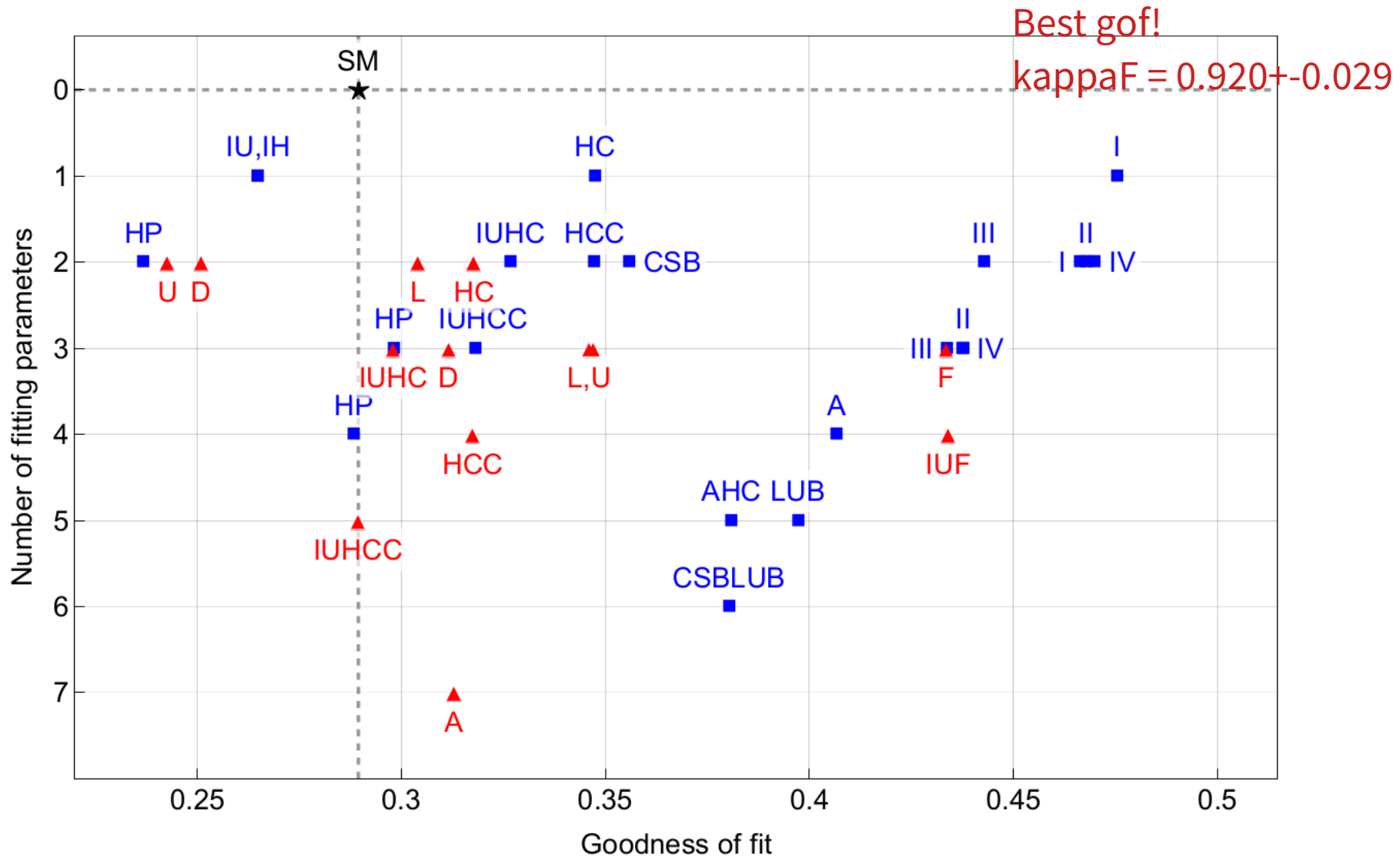
- C_V, C_W, C_Z : consistent with the SM with the 1σ error of 2%-3%
- $C_u^S, C_{ud}^S, C_{ul}^S$: about 2σ below the SM with the 1σ error of 3%-4%
- $C_{d\ell}^S, C_\ell^S, C_\tau^S$: about 2σ below the SM with the 1σ error of 4%-5%
- C_d^S : about 1σ below the SM with the 1σ error of 7%-8%
- $|C_\mu^S|$: consistent with the SM with the 1σ error of 12-15%

CPC1 fits with a single parameter varied:

- * kappa_g: 1sigma error of 5%
- * kappa_gamma: 1sigma error of 3%
- * Gamma_H: 1sigma error of 4%

Additionally,

- * Wrong sign of the top Yukawa is completely ruled out
- * Wrong signs of the bottom and tau Yukawa start to be excluded



*The Run1 + Run 2 LHC Higgs precision data are **NOT** best described by the SM Higgs boson !*

Higgs productions @ LHC (Run 3): MH=125 GeV

Run3 (2022 ~ 2026): ATLAS 332/fb @ 13.6 TeV & CMS 326/fb @ 13.6 TeV

arXiv:1610.07922 (CYR), 1607.05862 (13 TeV tHW), 2207.00092 (Run3)

$\sqrt{s}$ (TeV)	ggF (pb)	VBF (fb)	WH (fb)	ZH (fb)	ttH (fb)	tHq (fb)	tHW (fb)	bbH (fb)
7	16.85	1241.4	577.30	339.10	88.78	12.26	—	155.20
8	21.42	1601.2	702.50	420.70	133.0	18.69	—	202.10
13	48.57	3781.7	1373.00	883.70	507.2	74.25	15.2	488.00
13.6	52.23	4078	1457	943.9	570	86.7	17.2	527

$$N = \sigma \times \mathcal{L} \sim 60 \text{ pb} \times 300/\text{fb} \sim 2 \times 10^7$$

Run3 Higgs data are not included in this report...

we might need to wait...

One of the key points to watch: κ_F is smaller than 1 or not driven by $\mu(\gamma\gamma) > 1$, $\mu(bb) < 1$, and/or $\mu(\tau\tau) < 1$

FCC-ee

FCC-ee

Main Ref.: *FCC Physics Opportunities* Eur. Phys. J. C 79 (2019) 6,474
Future Circular Collider Conceptual Design Report Volume 1

FCC Physics Opportunities : Future Circular Collider Conceptual Design Report Volume 1

#3

FCC Collaboration • [A. Abada \(LPCE, Orleans\)](#) et al. (Dec 14, 2018)

Published in: *Eur.Phys.J.C* 79 (2019) 6, 474

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 reference search  1,222 citations 

FCC

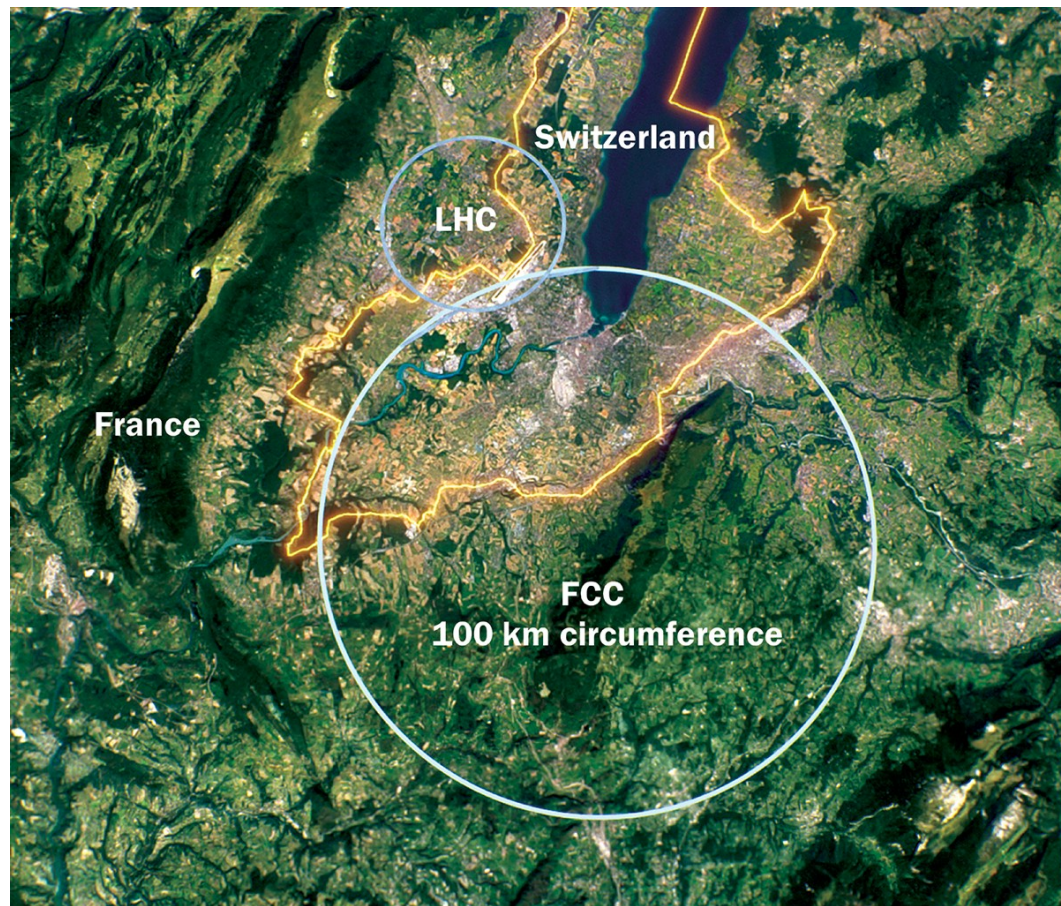


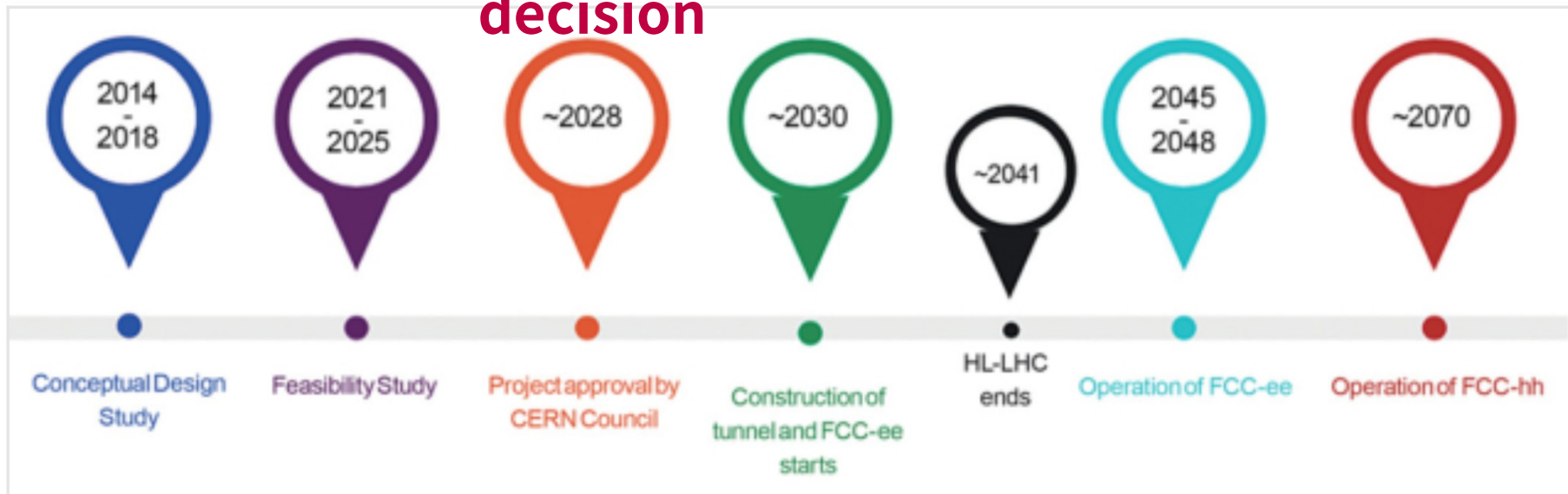
Table 2.1 Run plan for FCC-ee in its baseline configuration with two experiments. The number of WW events is given for the entirety of the FCC-ee running at and above the WW threshold

Phase	Run duration (years)	Centre-of-mass energies (GeV)	Integrated lumi- nosity (ab^{-1})	Event statistics
FCC-ee-Z	4	88–95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158–162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt(1)	1	340–350	0.2	$t\bar{t}$ threshold scan
FCC-ee-tt(2)	4	365	1.5	10^6 $t\bar{t}$ events

Towards a century of trailblazing physics

1 September 2023

**Final
decision**

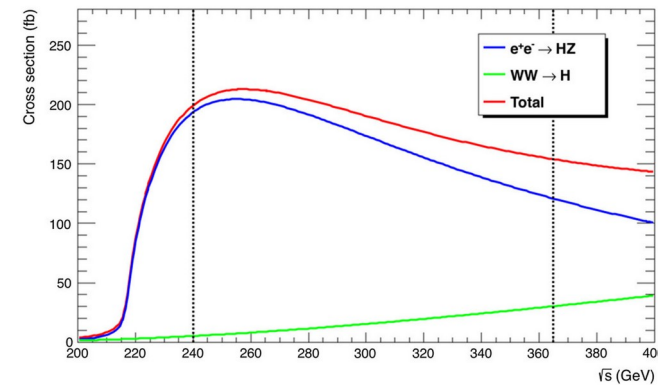


Real time Taking into account past experience with building colliders at CERN, the approval timeline, and assuming that the HL-LHC will run until 2041, FCC could begin operations in 2045–2048. From the perspective of the technical schedule alone, operation of FCC-ee could start in 2040 or earlier. Credit: E Bentall

FCC-ee could start in 2040 or earlier !

@240GeV:

200 fb * 5/ab (3 years) $\sim 10^6$ HZ



The key point is the **absolute** measurement of the Higgs coupling to ZZ and the total decay width !

1st: The total Higgs production cross section is determined by counting $e^+ e^- \rightarrow HZ$ events tagged with a leptonic Z decay, $Z \rightarrow l^+ l^-$, **independently of the Higgs boson decay** considering the recoil mass

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

2nd: The measurement of g_{HZZ} allows Γ_H to be extracted through $e^+ e^- \rightarrow HZ$; $H \rightarrow ZZ$ since

$$\sigma_{HZ} \times \text{BR}(H \rightarrow ZZ) \propto \frac{g_{HZZ}^4}{\Gamma_H}$$

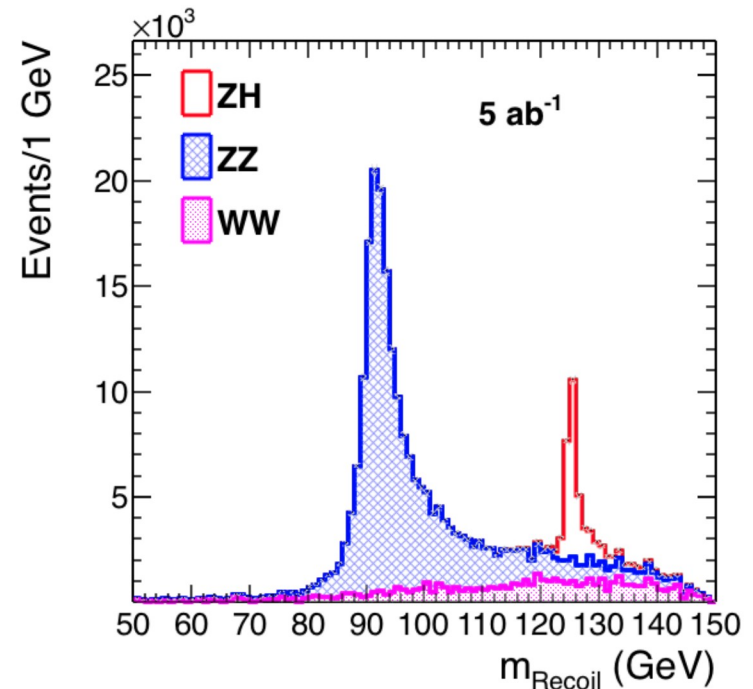
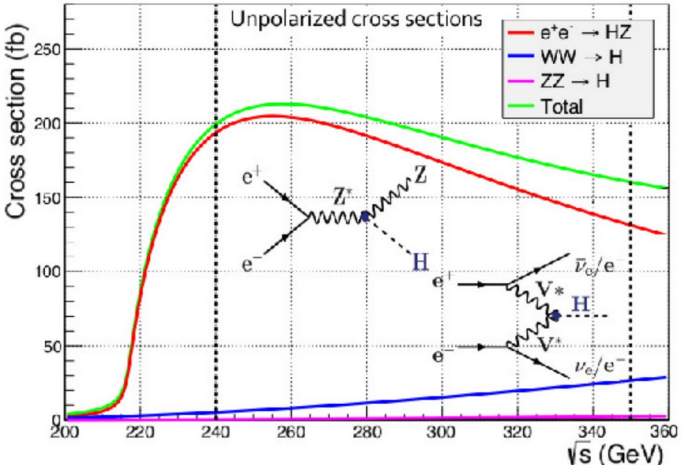


Table 4.2: Precision determined in the κ framework of the Higgs boson couplings and total decay width (results of global fits)

Collider	HL-LHC	ILC ₂₅₀	CLIC ₃₈₀	LEP3 ₂₄₀	CEPC ₂₅₀	FCC-ee ₂₄₀₊₃₆₅		
Lumi (ab ⁻¹)	3	2	1	3	5	5 ₂₄₀	+ 1.5 ₃₆₅	+ HL-LHC
Years	25	15	8	6	7	3	+ 4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	1.3	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	0.17	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	0.43	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	0.61	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	tagged c quarks & gluons 1.7	1.21	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	1.01	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	0.74	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	9.0	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	3.9	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	—	—	—	—	—	—	3.1
BR _{EXO} (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	< 1.0	< 1.0

Table 2.1 Run plan for FCC-ee in its baseline configuration with two experiments. The number of WW events is given for the entirety of the FCC-ee running at and above the WW threshold

Phase	Run duration (years)	Centre-of-mass energies (GeV)	Integrated lumi- nosity (ab ⁻¹)	Event statistics
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FCC-ee-tt(1)	1	340–350	0.2	t $\bar{t}$ threshold scan
FCC-ee-tt(2)	4	365	1.5	10 ⁶ t $\bar{t}$ events



Synergies

Synergies: with FCC-eh and FCC-hh

FCC-eh: Productions via $ep \rightarrow \nu HX$ (WW fusion: $\sigma = 1 \text{ pb}$) and $ep \rightarrow eH X$ (ZZ fusion: $\sigma = 0.15 \text{ pb}$) : $NH \sim 2.3 \cdot 10^6 \text{ events w/ } 2 \text{ ab-1}$

Fig. 4.12: Determination of the κ scaling parameter uncertainties from a joint SM fit of CC and NC signal strengths: **green=FCC-eh alone**

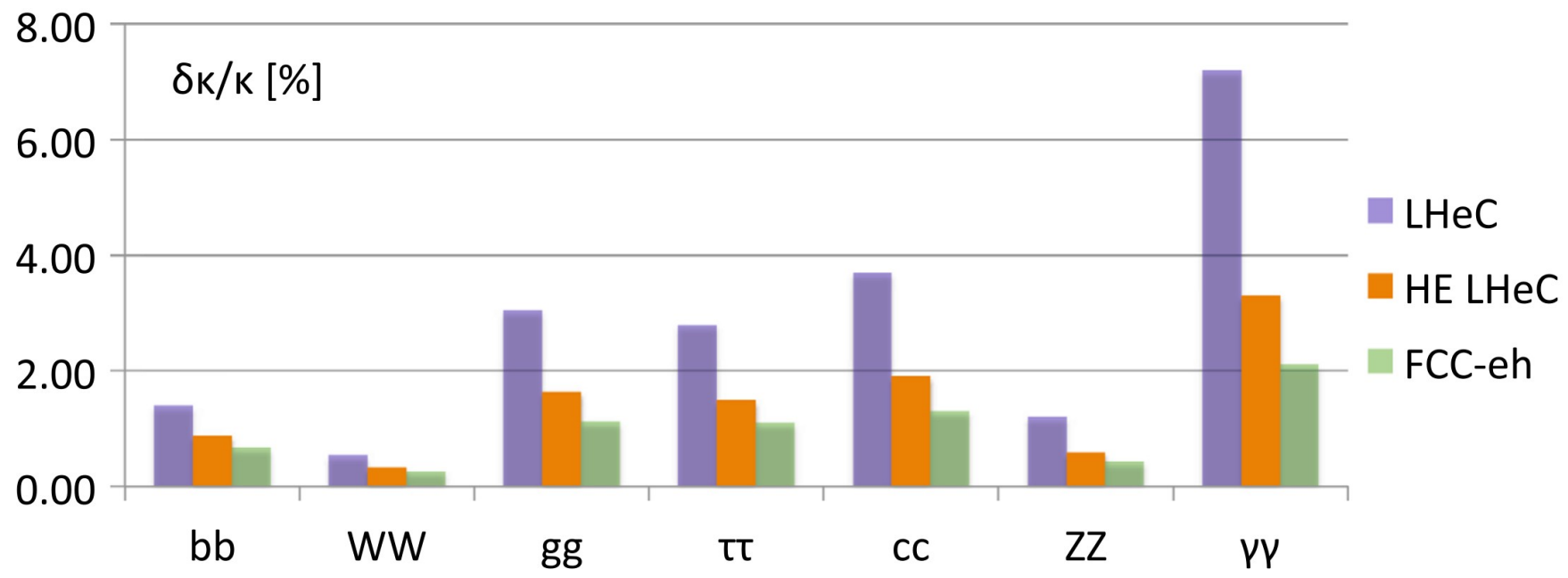
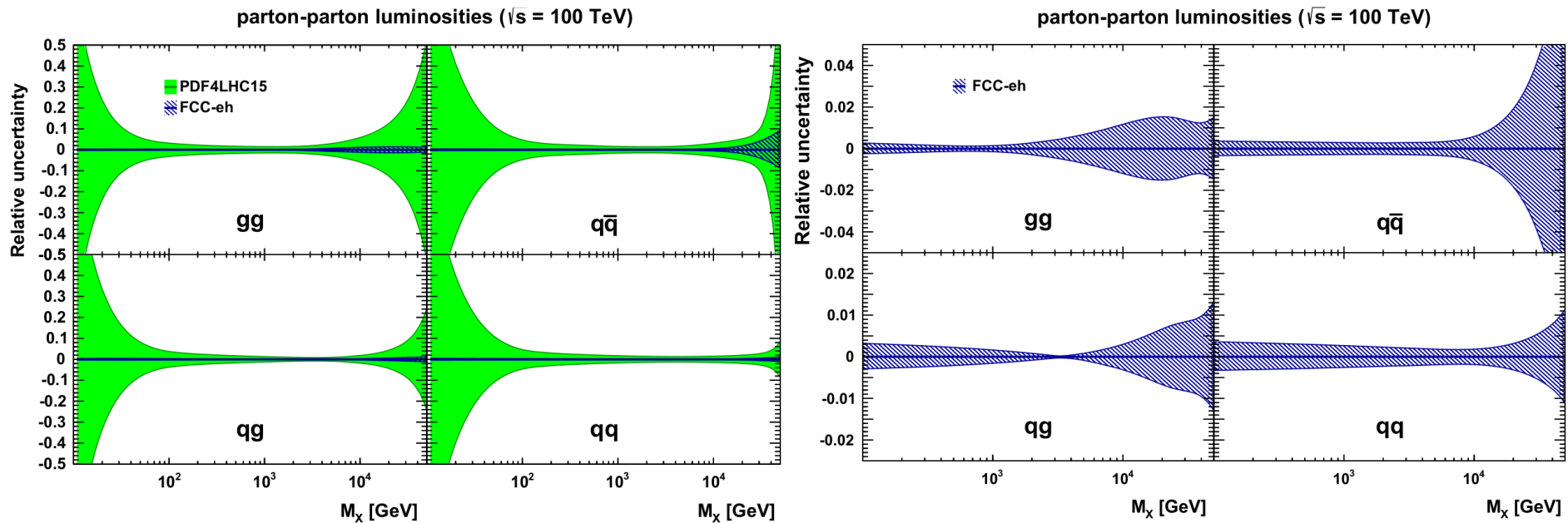


Table S.1	0.74%	0.26%	1.17%	1.10%	1.35%	0.43%	2.3%
							tt: 1.7%

The FCC-eh provides measurements the very precise PDF and α_s which will critically improve the systematics of Higgs measurements at FCC-hh:

Fig. 5.13 (left) and Fig. 5.14 (right)



For example, the gg PDF uncertainty at 100 TeV: subpercent between M_H and several TeV

Two characteristic elements of FCC-hh:

large statistics & large kinetic range

Large statistics: Table 4.3

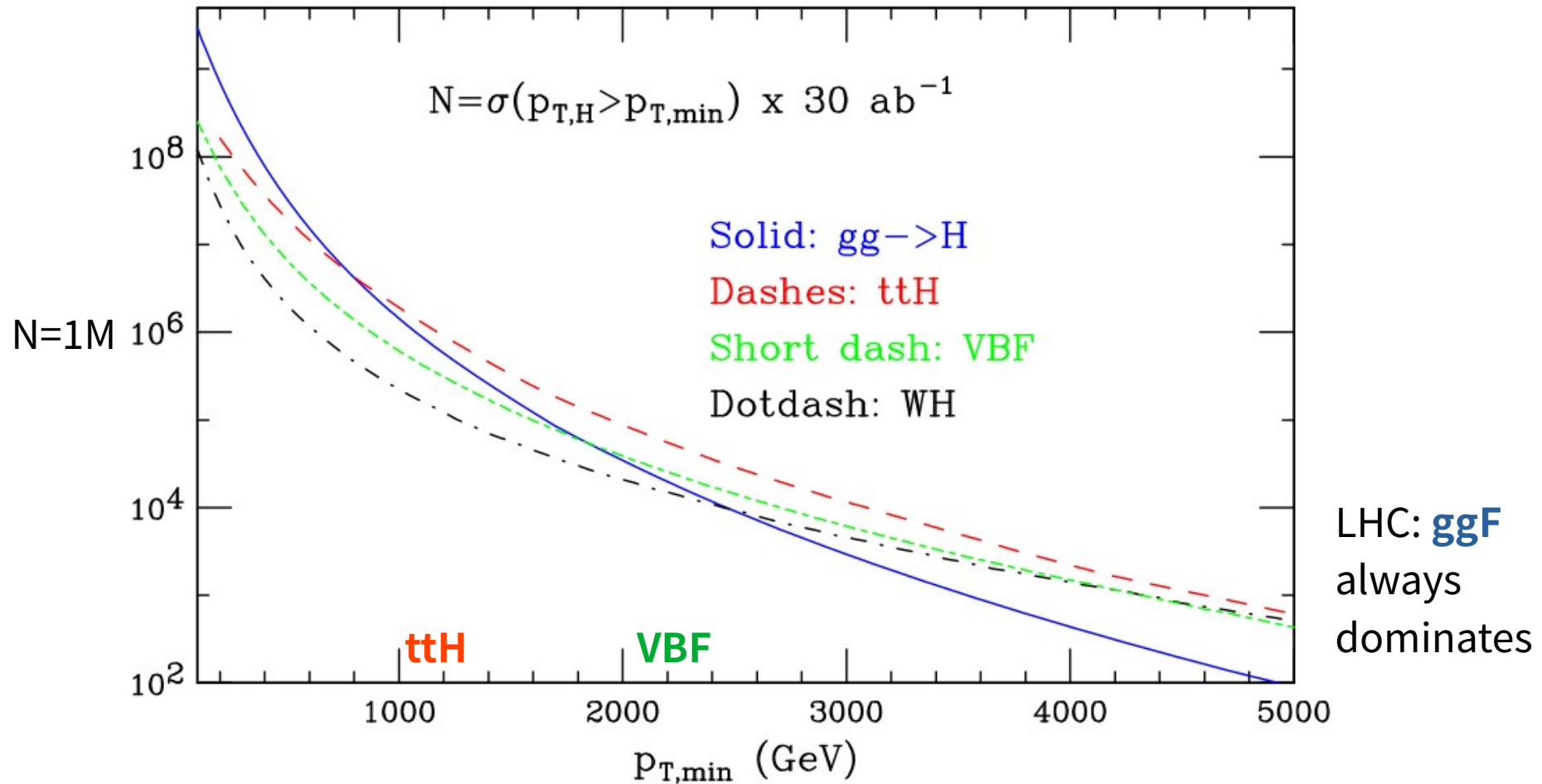
Table 4.3 Higgs production event rates for selected processes at 100 TeV (N_{100}) and 27 TeV (N_{27}), and statistical increase with respect to the statistics of the HL-LHC ($N_{100/27} = \sigma_{100/27 \text{ TeV}} \times 30/15 \text{ ab}^{-1}$, $N_{14} = \sigma_{14 \text{ TeV}} \times 3 \text{ ab}^{-1}$)

	$gg \rightarrow H$	VBF	WH	ZH	$t\bar{t}H$	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390
N_{27}	2.2×10^9	1.8×10^8	5.1×10^7	3.7×10^7	4.4×10^7	2.1×10^6
N_{27}/N_{14}	16	15	11	12	24	19

The large rates enable precise measurements of branching ratios for rare decay channels such as $\gamma\gamma$, $\mu\mu$, or $Z\gamma$.

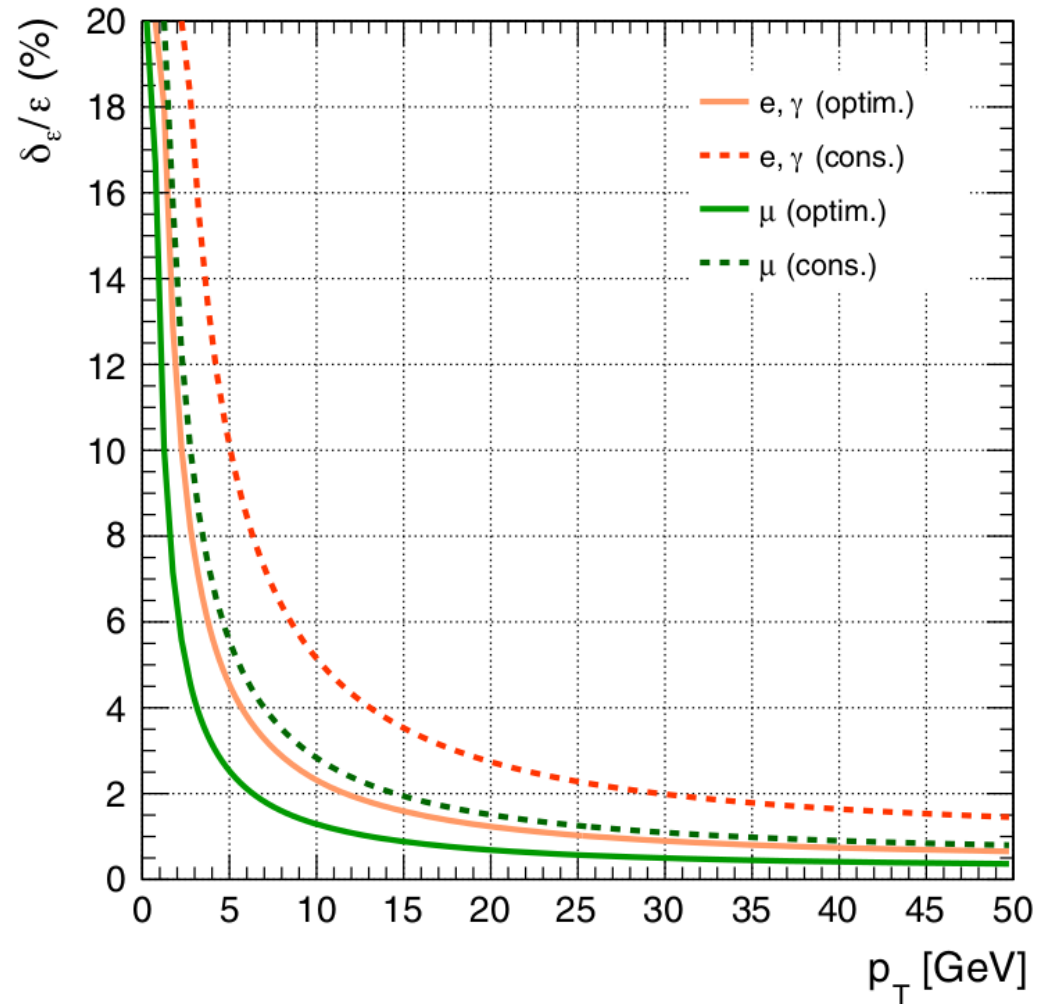
Large kinetic range: Fig. 4.3

Production rates of Higgs bosons above a given p_T threshold, for various production channels at 100 TeV and 30 ab^{-1}



The large kinematic range can be used to **improve** the S/B ratios, **suppress** the systematic uncertainties and **amplify** the presence of modified Higgs couplings due to higher-dimensional operators (SMEFT)

Fig. 4.4: The uncertainty on the reconstruction efficiency of electrons, photons and muons as a function of transverse momentum



The smaller uncertainties at large p_T improve the experimental systematics

Target precisions @FCC-hh(rare decays): FCC-ee,eh + precision EW

Table 4.4 Target precision for the parameters relative to the measurement of various Higgs decays, ratios thereof, and of the Higgs self-coupling λ . Notice that Lagrangian couplings have a precision that is typically half that of what is shown here, since all rates and branching ratios depend quadratically on the couplings

Observable	Parameter	Precision (stat)	Precision (stat+syst+lumi)
$\mu = \sigma(H) \times B(H \rightarrow \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.5%
$\mu = \sigma(H) \times B(H \rightarrow \mu\mu)$	$\delta\mu/\mu$	0.28%	1.2%
$\mu = \sigma(H) \times B(H \rightarrow 4\mu)$	$\delta\mu/\mu$	0.18%	1.9%
$\mu = \sigma(H) \times B(H \rightarrow \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.6%
$\mu = \sigma(HH) \times B(H \rightarrow \gamma\gamma)B(H \rightarrow b\bar{b})$	$\delta\lambda/\lambda$	5%	7.0%
$R = B(H \rightarrow \mu\mu)/B(H \rightarrow 4\mu)$ some	$\delta R/R$	0.33%	1.3%
$R = B(H \rightarrow \gamma\gamma)/B(H \rightarrow 2e2\mu)$ systematics	$\delta R/R$	0.17%	0.8%
$R = B(H \rightarrow \gamma\gamma)/B(H \rightarrow 2\mu)$ cancel in	$\delta R/R$	0.29%	1.4%
$R = B(H \rightarrow \mu\mu\gamma)/B(H \rightarrow \mu\mu)$ Ratios	$\delta R/R$	0.58%	1.8%
$R = \sigma(t\bar{t}H) \times B(H \rightarrow b\bar{b})/\sigma(t\bar{t}Z) \times B(Z \rightarrow b\bar{b})$	$\delta R/R$	1.05%	1.9%
$B(H \rightarrow \text{invisible})$	$B@95\%CL$	1×10^{-4}	2.5×10^{-4}

- * Considering the neglected experimental complexity such as pile-up, the most robust measurements will involve the ratios of branching ratios:
 $\mu\mu$ (0.7%), $\gamma\gamma$ (0.4%), $Z\gamma$ (0.9%), and $t\bar{t}$ (1%)
- * Higgs self-coupling: HH (7%)
- * $H>inv$: $BR(H>4\nu)\sim 1.1\times 10^{-3}$ (visible with 1/ab) ; sensitivity $\sim 2\times 10^{-4}$ with 30/ab

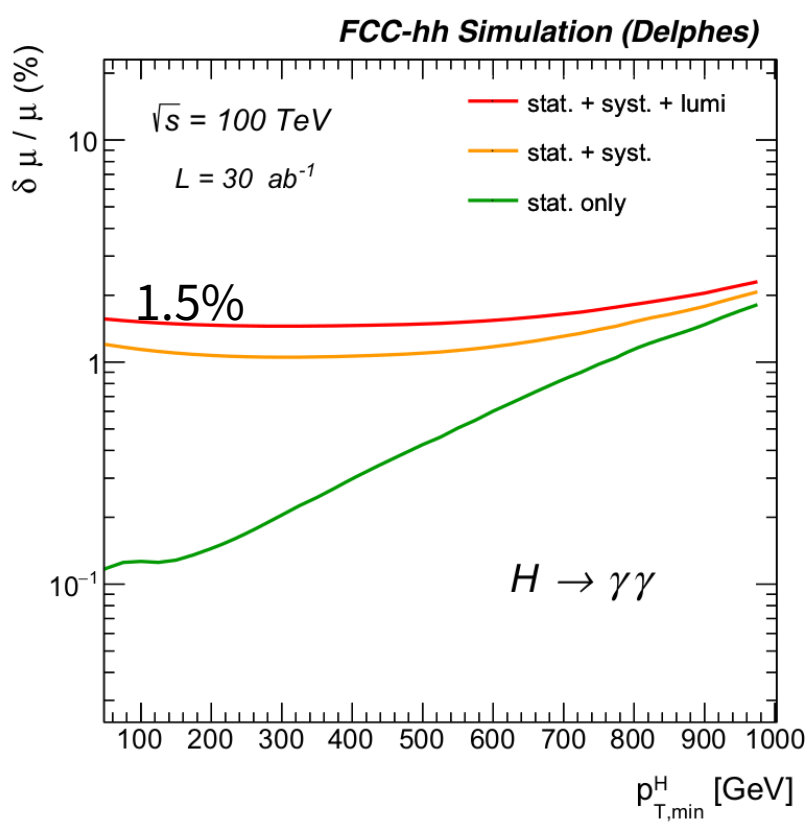


Fig. 4.5 Projected precision for the rate measurement of various Higgs final states, in the $gg \rightarrow H$ production channel (Taking, for example, $H \rightarrow \gamma\gamma$)

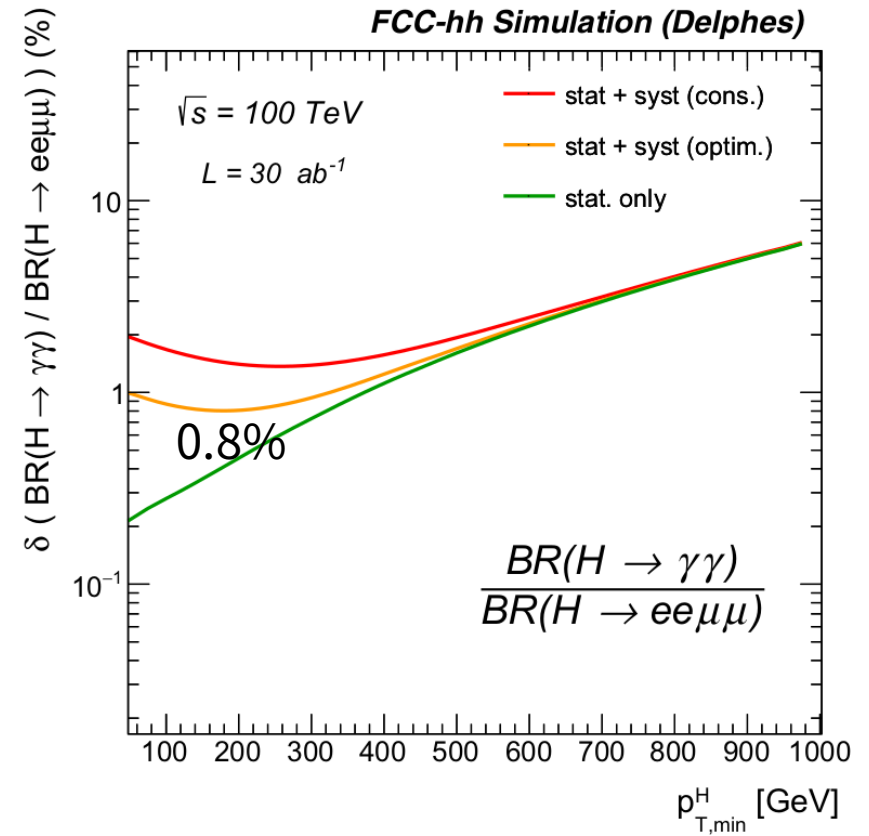


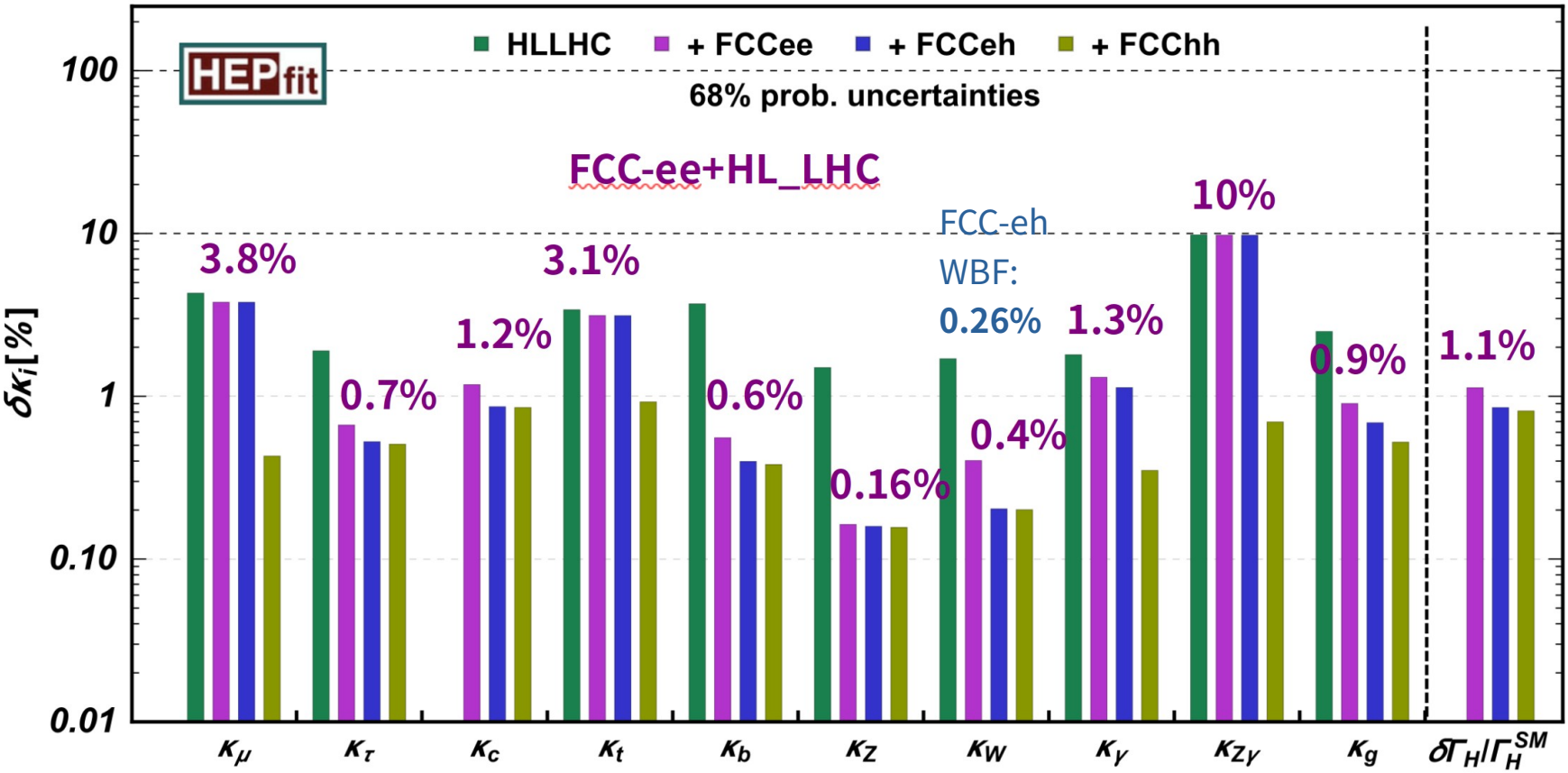
Fig. 4.6 Projected precision for the measurement of ratios of rates of different Higgs final states, in the $gg \rightarrow H$ production channel.

The uncertainties of the ratios of branching ratios of different decay modes become dominated by the statistics and the uncorrelated systematics as $p_{T,\min}(H)$ grows.

FCC-ee+HL_LHC: Table 4.2 →

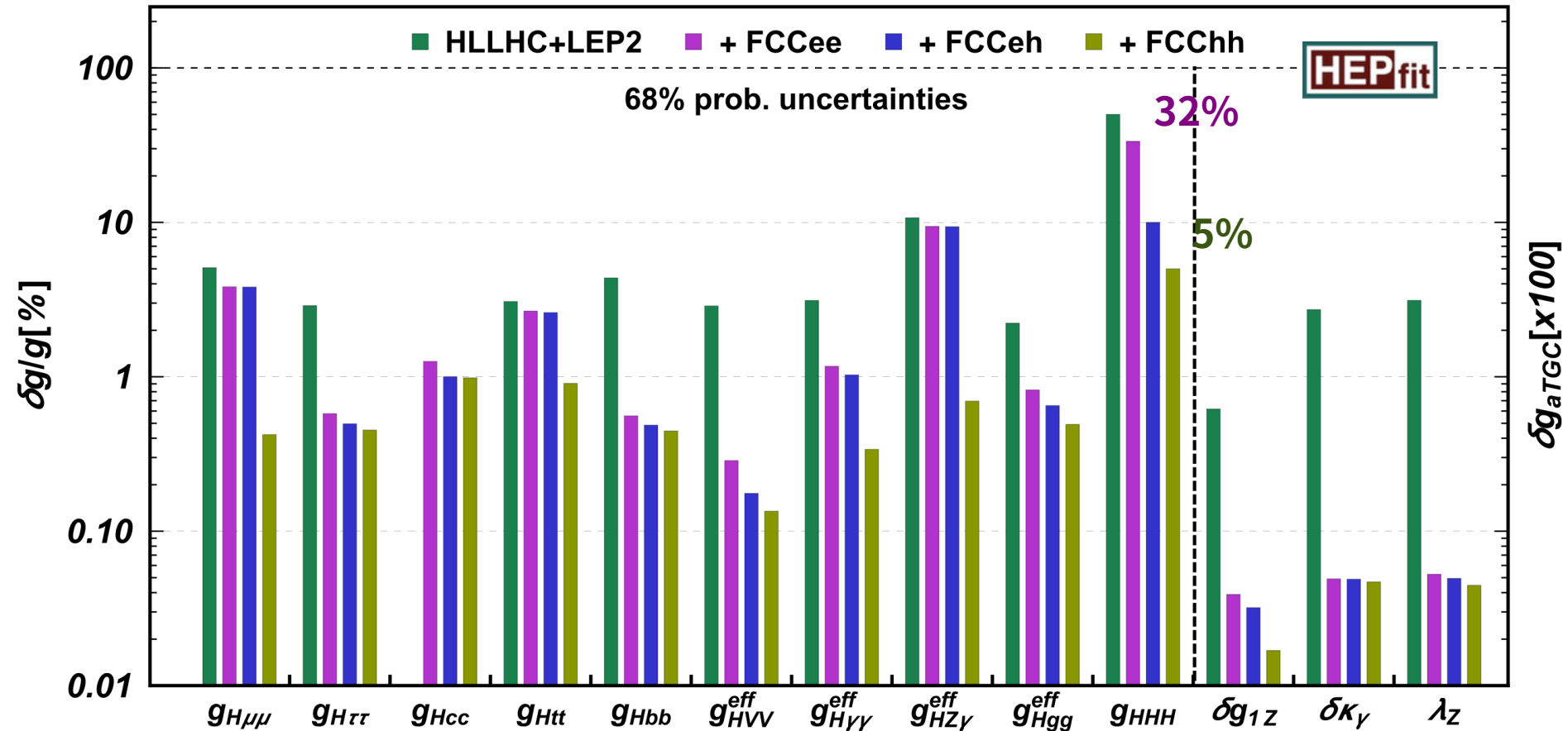
kappa framework: Fig. 8.5

Collider	HL-LHC	ILC ₂₅₀	CLIC ₃₈₀	LEP3 ₂₄₀	CEPC ₂₅₀	FCC-ee ₂₄₀₊₃₆₅	+ HL-LHC
Lumi (ab ⁻¹)	3	2	1	3	5	5 ₂₄₀	+1.5 ₃₆₅
Years	25	15	8	6	7	3	+4
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	1.3
$\delta g_{WZZ}/g_{WZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	0.17
$\delta g_{WWW}/g_{WWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	0.43
$\delta g_{WWb}/g_{WWb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	0.61
$\delta g_{Wcc}/g_{Wcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	1.21
$\delta g_{HZZ}/g_{HZZ}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	1.01
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	0.74
$\delta g_{Hbb}/g_{Hbb}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	9.0
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	3.9
$\delta g_{Hb}/g_{Hb}$ (%)	3.4	–	–	–	–	–	–
BR _{EXO} (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	< 1.0

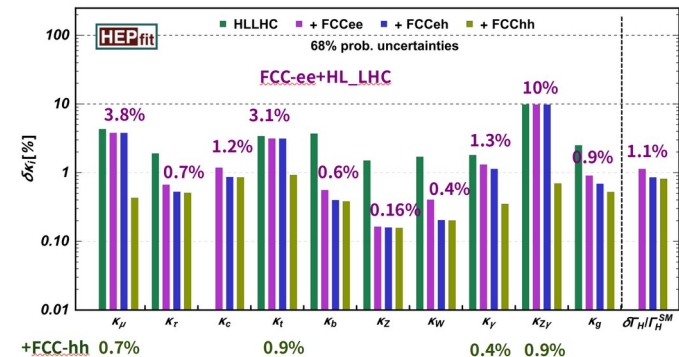


+FCC-hh 0.7%
 FCC-hh: $\mu\mu$ (0.7%) (absolute), tt (0.9%), and Higgs self-coupling (5%)
 $\gamma\gamma$ (0.4%), $Z\gamma$ (0.9%) (absolute);

EFT framework: Fig. 8.4



c.f. kappa framework



Updated analysis on the trilinear Higgs self-coupling (FCC-hh):

7.5%(2-6%) with 3(30)/ab

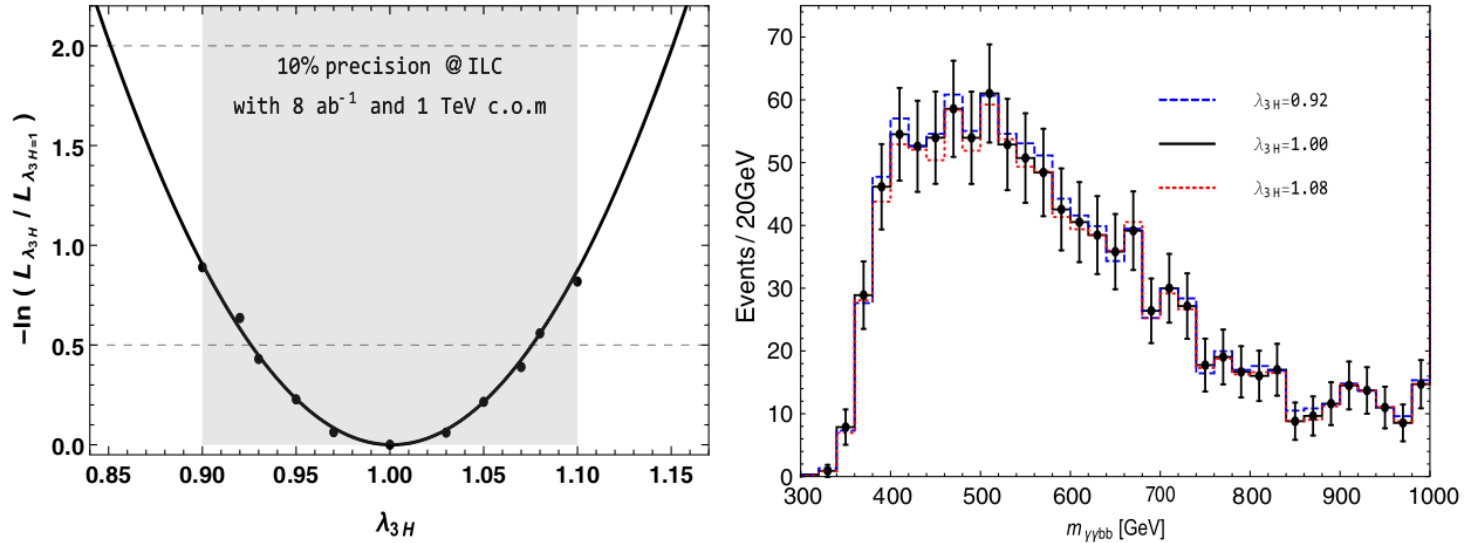


FIG. 3. Left: the relative log likelihood distribution for the nominal value of $\lambda_{3H} = 1$ at the 100 TeV hadron collider with 3 ab⁻¹. The black circles are the values obtained by a likelihood fitting of $M_{\gamma\gamma bb}$ distributions using BDT_{SM} with the BDT response cut of 0.216. The black solid line shows the result of a polynomial fitting and the thin dashed line at 0.5(2.0) indicates the value corresponding to a 1σ(2σ) CI. The shaded region shows the 1σ CI expected at the ILC at 1 TeV with 8 ab⁻¹. Right: the SM $M_{\gamma\gamma bb}$ distribution (solid line with dots with 1σ error bars) and those for $\lambda_{3H} = 0.92$ and 1.08 (dashed lines).

Jubin Park, Jung Chang, Kingman Cheung, JSL, PRD [2003.12281];
Mangano, Ortona, Selvaggi, EPJC [2004.03505];
Stapf et al., PoS EPS-HEP2023 [2312.03513]

Executive summary: The Higgs couplings to **all gauge bosons** and to **the charged fermions of the second and third generation** (except the strange quark) will be known with a precision ranging **from a few per mil to $\sim 1\%$**

Summary

- **LHC**: BSM with $\kappa_F < 1$?
- **FCC-ee**: Absolute measurements of g_{HZZ} and Γ_H
- **FCC-hh $\oplus$ FCC-eh $\oplus$ FCC-ee**: The Higgs couplings to γ , Z and W bosons, and gluons; t , b , c quarks; and τ , μ leptons with **a precision below 1%** ... theoretical and parametric uncertainties should be improved !

Backup

Individual Production and Decay signal strengths

from 76 Production $\times$ Decay signal strengths

TABLE VI. *LHC signal strengths for individual Higgs production processes and decay modes obtained from the signal strengths in Table II (Run 1), Table III (Run 2 ATLAS), and Table IV (Run 2 CMS). Note that, being different from the signal strengths in Table V, no assumptions have been imposed on the Higgs boson branching ratios and/or production cross-sections. The combined signal strengths are shown in the last line including all the 76 signal strengths available.*

LHC	Production process					Decay mode					
	ggF($\oplus$ bbH)	VBF	WH	ZH	ttH $\oplus$ tH	$\gamma\gamma$	ZZ^*	WW^*	bb	$\tau\tau$	$\mu\mu$
Run 1 (Table II)	$0.99^{+0.11}_{-0.11}$	$1.17^{+0.20}_{-0.20}$	$0.79^{+0.33}_{-0.33}$	$0.78^{+0.34}_{-0.34}$	$1.99^{+0.61}_{-0.63}$	$1.11^{+0.16}_{-0.17}$	$1.03^{+0.28}_{-0.29}$	$1.01^{+0.14}_{-0.14}$	$0.68^{+0.29}_{-0.29}$	$1.04^{+0.25}_{-0.25}$	—
Run 2 ATLAS (Table III)	$1.03^{+0.06}_{-0.06}$	$1.12^{+0.12}_{-0.12}$	$1.22^{+0.23}_{-0.23}$	$0.83^{+0.20}_{-0.20}$	$0.91^{+0.20}_{-0.21}$	$1.04^{+0.09}_{-0.09}$	$1.01^{+0.10}_{-0.10}$	$1.20^{+0.12}_{-0.12}$	$0.89^{+0.15}_{-0.15}$	$0.95^{+0.13}_{-0.15}$	$1.11^{+0.62}_{-0.62}$
Run 2 CMS (Table IV)	$0.93^{+0.07}_{-0.07}$	$0.81^{+0.11}_{-0.11}$	$1.40^{+0.24}_{-0.24}$	$1.50^{+0.26}_{-0.26}$	$1.06^{+0.17}_{-0.17}$	$1.20^{+0.12}_{-0.12}$	$0.90^{+0.13}_{-0.13}$	$0.95^{+0.10}_{-0.11}$	$1.06^{+0.23}_{-0.24}$	$0.79^{+0.11}_{-0.11}$	$1.14^{+0.49}_{-0.49}$
Combined (76 signal strengths)	$0.99^{+0.04}_{-0.04}$	$0.98^{+0.08}_{-0.08}$	$1.20^{+0.15}_{-0.15}$	$1.03^{+0.14}_{-0.14}$	$1.04^{+0.13}_{-0.13}$	$1.10^{+0.07}_{-0.07}$	$0.97^{+0.08}_{-0.08}$	$1.04^{+0.07}_{-0.07}$	$0.90^{+0.12}_{-0.12}$	$0.87^{+0.08}_{-0.08}$	$1.13^{+0.38}_{-0.38}$

TABLE V. *LHC signal strengths for individual Higgs production processes and decay modes. For the combined Run 1 signal strengths, see Tables 12 and 13 in Ref. [13]. For the ATLAS Run 2 signal strengths, see Fig. 2 in Ref. [3] together with detailed information on them provided in the website <https://doi.org/10.17182/hepdata.130266>. The CMS Run 2 signal strengths are from Fig. 2 in Ref. [4]. Note that the production signal strengths have been obtained assuming that the Higgs boson branching fractions are the same as in the SM and the decay signal strengths have been extracted assuming that the Higgs boson production cross-sections are the same as in the SM.*

LHC	Production process						Decay mode					
	ggF($\oplus$ bbH)	VBF	WH	ZH	ttH	tH	$\gamma\gamma$	ZZ^*	WW^*	bb	$\tau\tau$	$\mu\mu$
Run 1 [13]	$1.03^{+0.16}_{-0.14}$	$1.18^{+0.25}_{-0.23}$	$0.89^{+0.40}_{-0.38}$	$0.79^{+0.38}_{-0.36}$	$2.3^{+0.7}_{-0.6}$	—	$1.14^{+0.19}_{-0.18}$	$1.29^{+0.26}_{-0.23}$	$1.09^{+0.18}_{-0.16}$	$0.70^{+0.29}_{-0.27}$	$1.11^{+0.24}_{-0.22}$	—
Run 2 ATLAS [3]	$1.03^{+0.07}_{-0.07}$	$1.10^{+0.13}_{-0.12}$	$1.16^{+0.23}_{-0.22}$	$0.96^{+0.22}_{-0.21}$	$0.74^{+0.24}_{-0.24}$	$6.61^{+4.24}_{-3.76}$	$1.09^{+0.10}_{-0.09}$	$1.04^{+0.11}_{-0.10}$	$1.20^{+0.12}_{-0.11}$	$0.91^{+0.15}_{-0.14}$	$0.96^{+0.12}_{-0.11}$	$1.21^{+0.62}_{-0.60}$
Run 2 CMS [4]	$0.97^{+0.08}_{-0.08}$	$0.80^{+0.12}_{-0.12}$	$1.49^{+0.26}_{-0.25}$	$1.29^{+0.24}_{-0.23}$	$1.13^{+0.18}_{-0.17}$		$1.13^{+0.09}_{-0.09}$	$0.97^{+0.12}_{-0.11}$	$0.97^{+0.09}_{-0.09}$	$1.05^{+0.22}_{-0.21}$	$0.85^{+0.10}_{-0.10}$	$1.21^{+0.45}_{-0.42}$

Decay widths and Brs of the SM Higgs boson

Table 6

Partial and total decay widths of the SM Higgs in MeV taking $M_H = 125.5$ GeV. We compare our numerical estimates with those presented in Ref. [84] by introducing a quantity δ_Γ defined by $\delta_\Gamma \equiv (\Gamma_{\text{This Review}} - \Gamma_{\text{Ref. [84]}}) / \Gamma_{\text{Ref. [84]}}$. Also presented are theoretical uncertainties (THUs) of the partial and total decay widths from missing higher orders estimated around $M_H = 125$ GeV, see Tables 178 and 182 in Ref. [84].

	$\Gamma(H \rightarrow b\bar{b})$	$\Gamma(H \rightarrow WW)$	$\Gamma(H \rightarrow gg)$	$\Gamma(H \rightarrow \tau\tau)$	$\Gamma(H \rightarrow c\bar{c})$
This Review	2.367	9.185×10^{-1}	3.382×10^{-1}	2.572×10^{-1}	1.173×10^{-1}
Ref. [84]	2.387	9.222×10^{-1}	3.386×10^{-1}	2.573×10^{-1}	1.185×10^{-1}
δ_Γ [%]	-0.8	-0.4	-0.1	-0.05	-1.0
THU [%]	± 0.5	± 0.5	± 3.2	± 0.5	± 0.5
	$\Gamma(H \rightarrow ZZ)$	$\Gamma(H \rightarrow \gamma\gamma)$	$\Gamma(H \rightarrow Z\gamma)$	$\Gamma(H \rightarrow \mu\mu)$	Γ_{tot}
This Review	1.139×10^{-1}	9.405×10^{-3}	6.531×10^{-3}	8.913×10^{-4}	4.129
Ref. [84]	1.139×10^{-1}	9.438×10^{-3}	6.550×10^{-3}	8.927×10^{-4}	4.156
δ_Γ [%]	-0.03	-0.4	-0.3	-0.2	-0.65
THU [%]	± 0.5	± 1.0	± 5.0	± 0.5	± 0.73

Table 7

Branching ratios (BRs) of the SM Higgs taking $M_H = 125.5$ GeV. We compare our numerical estimates with those presented in Ref. [84]. Estimation of the total uncertainty THU+ PU has been done by adding linearly the THU and the total parametric uncertainty (PU) where the latter is obtained by adding the individual PUs in quadrature, see Tables 174, 175, 176, 177, and 178 in Ref. [84].

	$B(H \rightarrow b\bar{b})$	$B(H \rightarrow WW)$	$B(H \rightarrow gg)$	$B(H \rightarrow \tau\tau)$	$B(H \rightarrow c\bar{c})$
This Review	5.733×10^{-1}	2.225×10^{-1}	8.190×10^{-2}	6.230×10^{-2}	2.841×10^{-2}
Ref. [84]	5.744×10^{-1}	2.219×10^{-1}	8.147×10^{-2}	6.192×10^{-2}	2.852×10^{-2}
THU+ PU [%]	1.7	2.1	7.2	2.3	6.6
	$B(H \rightarrow ZZ)$	$B(H \rightarrow \gamma\gamma)$	$B(H \rightarrow Z\gamma)$	$B(H \rightarrow \mu\mu)$	Γ_{tot} [MeV]
This Review	2.758×10^{-2}	2.278×10^{-3}	1.582×10^{-3}	2.159×10^{-4}	4.129
Ref. [84]	2.741×10^{-2}	2.271×10^{-3}	1.576×10^{-3}	2.148×10^{-4}	4.156
THU+ PU [%]	2.1	2.9	6.9	2.4	1.9

- The electron Yukawa: H_run@FCC-ee with $\sqrt{s} \simeq 129.09$ GeV
 - resonant production: $1.64 \text{ fb} > 0.6 \text{ fb (+ISR)}$
 $> 0.3 \text{ fb (+com energy spread of 4.2 MeV)}$
 - maximum luminosity $> 100 \text{ MeV spread}$: the resonance is invisible
 - one year luminosity: 2 (7) /ab for the com energy spread of 6 (10) MeV
 - one year run: upper limit of 2.5 times the SM value
 - the SM sensitivity: 5 years needed

kappa framework

