Higgs at FCC-ee

ICHEP-2020

Virtual (Prague), 29th July 2020

David d'Enterria
(on behalf of FCC-ee collaboration)

CERN

Open questions in the SM (1)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$

[Gauge interactions: $U(1)_Y$, $SU(2)_L$, $SU(3)_c$]

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.})$$

[Lepton dynamics]

$$\boxed{-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi}\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T\begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right]}$$

[Lepton masses]

$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.})$$

[Quark dynamics]

$$\boxed{-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi}\begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T\begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right]}$$

[Quark masses]

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$

[Higgs dynamics & mass]

✘ Light masses: Higgs Yukawa mechanism for lightest fermions (q,e,ν's) unproven

Open questions in the SM (2)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$

[Gauge interactions: $U(1)_Y$, $SU(2)_L$, $SU(3)_c$]

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R \sigma^\mu iD_\mu e_R + \bar{\nu}_R \sigma^\mu iD_\mu \nu_R + (\mathrm{h.c.})$$

[Lepton dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right]$$

[Lepton masses]

$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R \sigma^\mu iD_\mu u_R + \bar{d}_R \sigma^\mu iD_\mu d_R + (\mathrm{h.c.})$$

[Quark dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right]$$

[Quark masses]

$$+\overline{(D_\mu\phi)}D^\mu\phi \boxed{- m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.}$$

[Higgs dynamics & mass]

- ✘ Light masses: Higgs Yukawa mechanism for lightest fermions (q,e,ν's) unproven
- ✘ Higgs potential: Higgs trilinear & quartic self-couplings unknown

Open questions in the SM (3)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$

[Gauge interactions: U(1)$_Y$, SU(2)$_L$, SU(3)$_c$]

$$+(\bar\nu_L,\bar e_L)\,\tilde\sigma^\mu iD_\mu \begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + \bar e_R\sigma^\mu iD_\mu e_R + \bar\nu_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.})$$

[Lepton dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar\nu_L,\bar e_L)\,\phi M^e e_R + \bar e_R \bar M^e \bar\phi \begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar e_L,\bar\nu_L)\,\phi^* M^\nu \nu_R + \bar\nu_R \bar M^\nu \phi^T \begin{pmatrix}-e_L\\ \nu_L\end{pmatrix}\right]$$

[Lepton masses]

$$+(\bar u_L,\bar d_L)\,\tilde\sigma^\mu iD_\mu \begin{pmatrix}u_L\\ d_L\end{pmatrix} + \bar u_R\sigma^\mu iD_\mu u_R + \bar d_R\sigma^\mu iD_\mu d_R + (\text{h.c.})$$

[Quark dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar u_L,\bar d_L)\,\phi M^d d_R + \bar d_R \bar M^d \bar\phi \begin{pmatrix}u_L\\ d_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar d_L,\bar u_L)\,\phi^* M^u u_R + \bar u_R \bar M^u \phi^T \begin{pmatrix}-d_L\\ u_L\end{pmatrix}\right]$$

[Quark masses]

$$+\overline{(D_\mu\phi)}D^\mu\phi \boxed{- m_h^2[\bar\phi\phi - v^2/2]^2/2v^2.}$$

[Higgs dyn. & mass]

+ new particles/symmetries ?

- ✘ Light masses: Higgs Yukawa mechanism for lightest fermions (q,e,ν's) unproven
- ✘ Higgs potential: Higgs trilinear & quartic self-couplings unknown
- ✘ Fine-tuning: Higgs mass virtual corrections «untamed» up to Planck scale

Open questions in the SM (4)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$

[Gauge interactions: U(1)$_Y$, SU(2)$_L$, SU(3)$_c$]

$$+(\bar{\nu}_L,\bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.})$$

[Lepton dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L,\bar{e}_L)\,\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi}\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{e}_L,\bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T\begin{pmatrix}-e_L\\ \nu_L\end{pmatrix}\right]$$

[Lepton masses]

$$+(\bar{u}_L,\bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}u_L\\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.})$$

[Quark dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L,\bar{d}_L)\,\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi}\begin{pmatrix}u_L\\ d_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{d}_L,\bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T\begin{pmatrix}-d_L\\ u_L\end{pmatrix}\right]$$

[Quark masses]

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$

[Higgs dyn. & mass]

+ new particles/symmetries ?

- ✘ Light masses: Higgs Yukawa mechanism for lightest fermions (q,e,ν's) unproven
- ✘ Higgs potential: Higgs trilinear & quartic self-couplings unknown
- ✘ Fine-tuning: Higgs mass virtual corrections «untamed» up to Planck scale
- ✘ Dark matter: SM describes only 4% of Universe (visible fermions+bosons): Higgs should couple to any massive dark world.

Open questions in the SM

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$

[Gauge interactions: U(1)$_Y$, SU(2)$_L$, SU(3)$_c$]

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu i D_\mu \begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu i D_\mu e_R + \bar{\nu}_R\sigma^\mu i D_\mu \nu_R + (\mathrm{h.c.})$$

[Lepton dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi}\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T\begin{pmatrix}-e_L\\ \nu_L\end{pmatrix}\right]$$

[Lepton masses]

$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu i D_\mu \begin{pmatrix}u_L\\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu i D_\mu u_R + \bar{d}_R\sigma^\mu i D_\mu d_R + (\mathrm{h.c.})$$

[Quark dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi}\begin{pmatrix}u_L\\ d_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T\begin{pmatrix}-d_L\\ u_L\end{pmatrix}\right]$$

[Quark masses]

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$

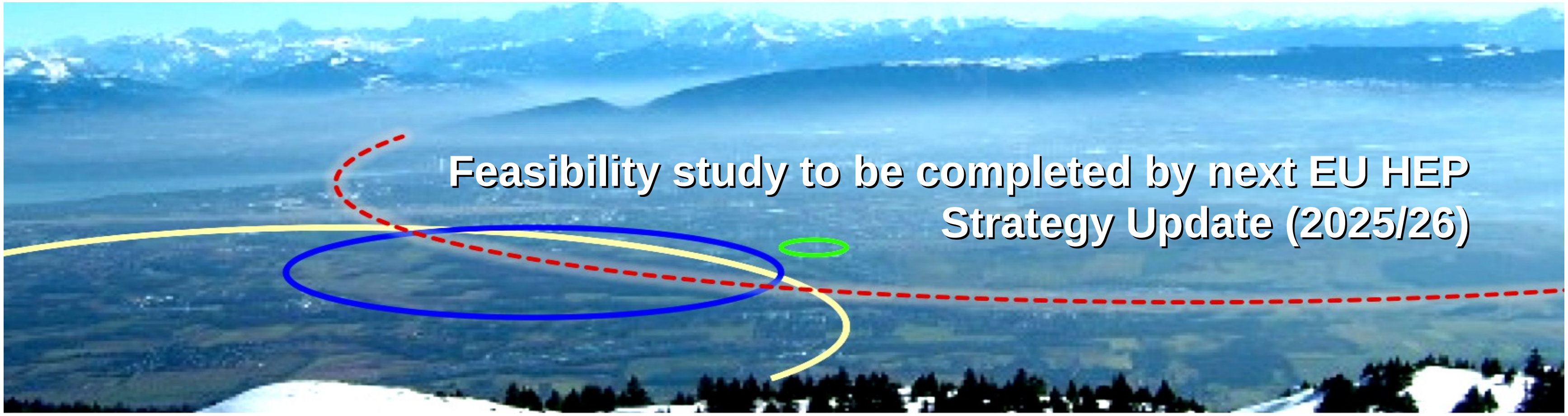
[Higgs dyn. & mass] **+ new particles/symmetries ?**

- ✘ Light masses: Higgs Yukawa mechanism for lightest fermions (q,e,ν's) unproven
- ✘ Higgs potential: Higgs trilinear & quartic self-couplings unknown
- ✘ Fine-tuning: Higgs mass virtual corrections «untamed» up to Planck scale
- ✘ Dark matter: SM describes only 4% of Universe (visible fermions+bosons) Higgs should couple to any massive dark world.

Some/Most(!?) of these questions will not be fully answered at the LHC!

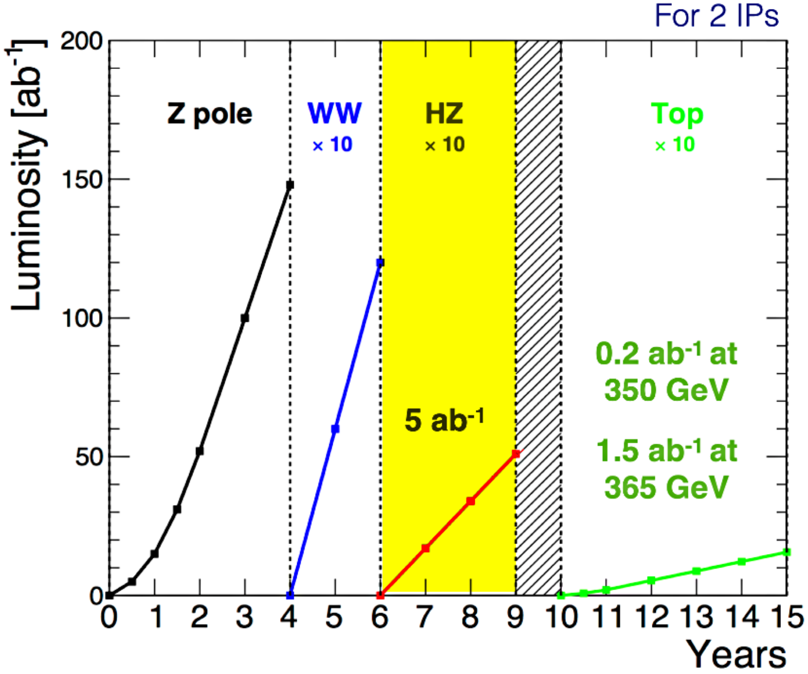
CERN Future Circular Collider (FCC) project

- Solving those+others HEP fundamental problems requires new e^+e^- & pp collider:



Feasibility study to be completed by next EU HEP Strategy Update (2025/26)

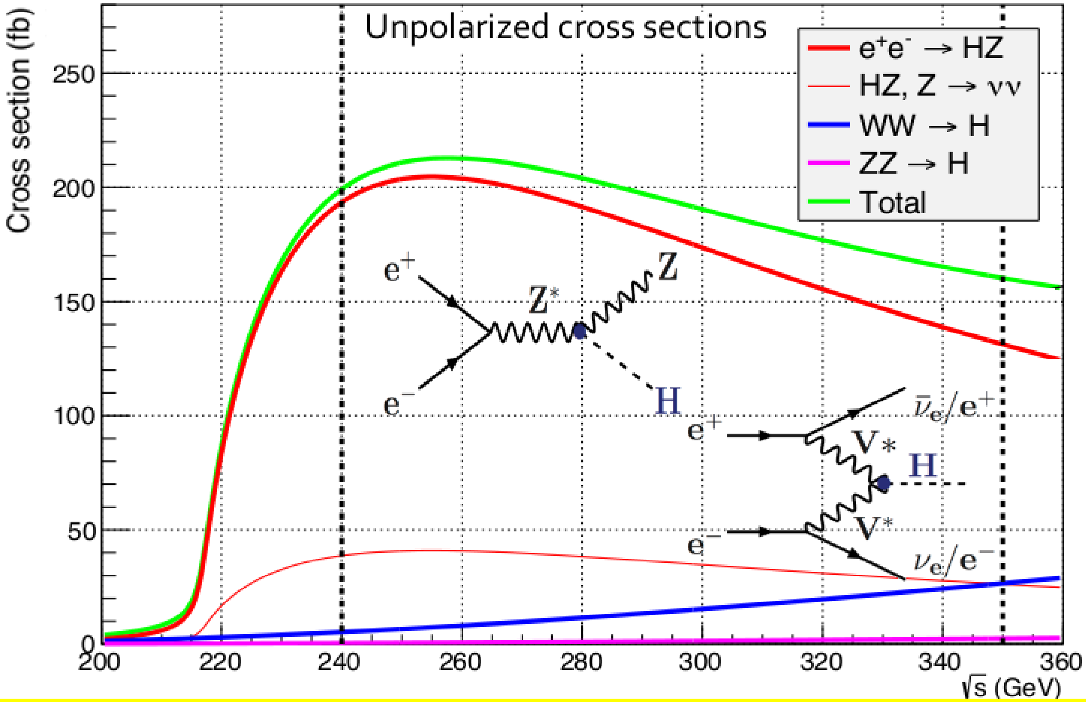
- FCC: 100 km ring, Nb_3Sn 16-T magnets, LHC used as injector:
  - pp at $\sqrt{s}$=100 TeV, L~2x10^{35}, L_{int}=2 ab^{-1}/yr (also pPb, PbPb at $\sqrt{s}$=39–63 TeV)
  - e^+e^- before pp at $\sqrt{s}$=90–350 GeV $L_{int} \approx$ 7 ab^{-1} Higgs factory ~1.3 million Higgs in 3+5 years. Plus 10^{12} Zs(!), 10^8 Ws(!), 0.5·10^6 tops



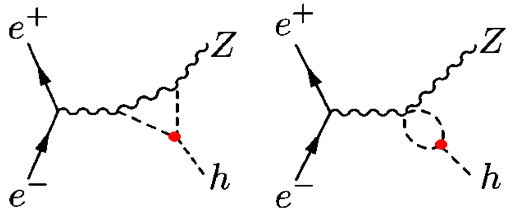
FCC-ee = Higgs boson factory

- Higgs cross sections: $\sigma(e^+e^- \to H+X) \approx 200$ (HZ)+ 50 (VBF) fb
- 1.3M Higgs bosons produced:
  - Small & very well controlled backgrounds (S/B~10^{-2}–10^{-3})
  - Extra-clean environment w/o pileup:

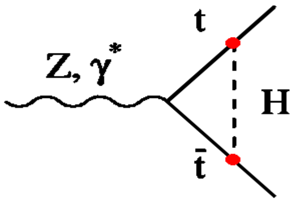
	5/ab @ 240 GeV	0.2/ab @ 350 GeV 1.5/ab @ 365 GeV
# Higgs from HZ	1,000,000	200,000
# Higgs from VBF	25,000	50,000



(sensitivity to self-coupling)



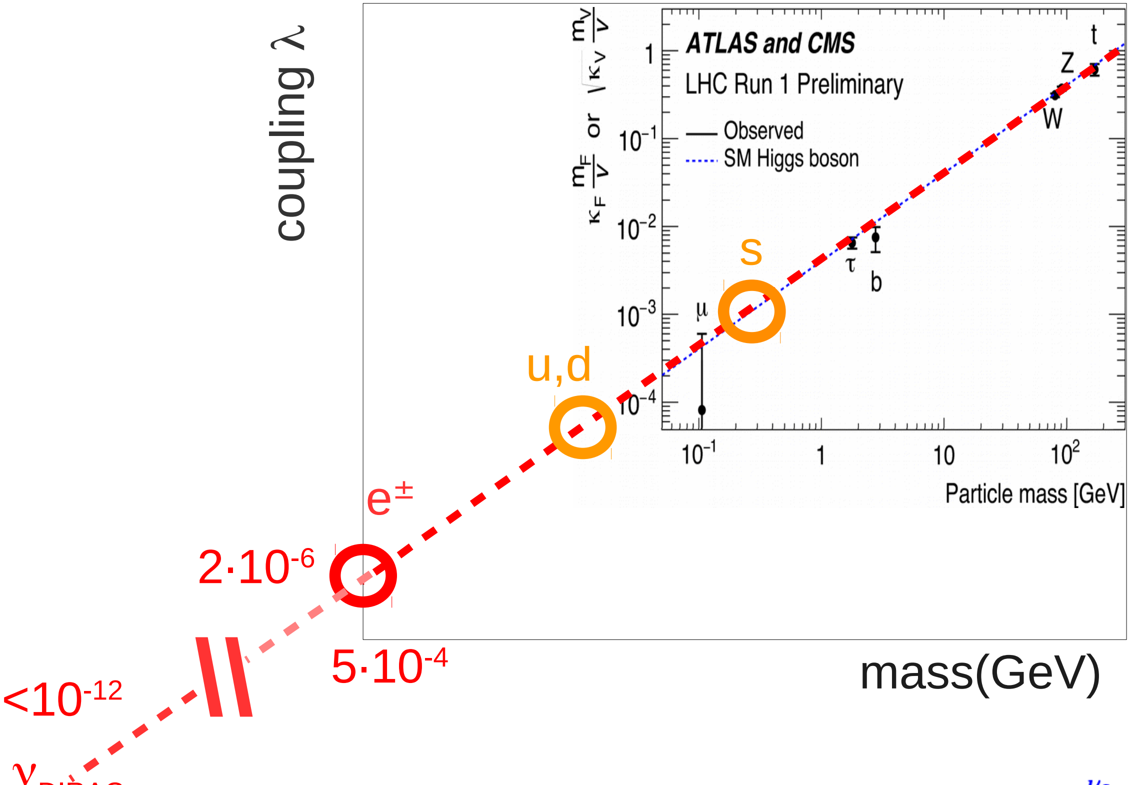
(sensitivity to top y_t)

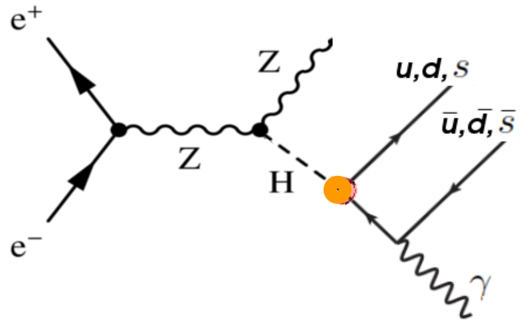


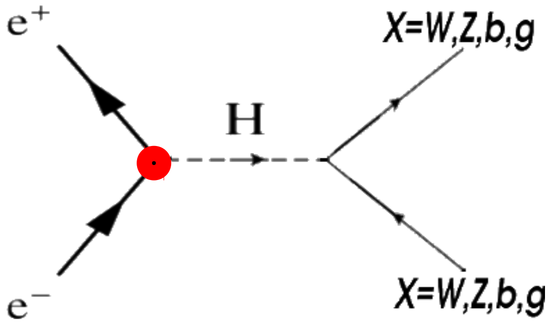
- Access to precise (down to 0.15%) Higgs couplings & rare & BSM decays

Open SM issue (1): Generation of lightest fermion ($e^\pm$, ν's) masses

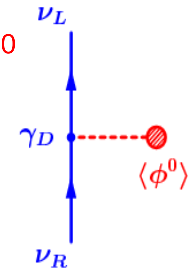
- LHC can only access 3rd (plus few 2nd) gen.Yukawas. What about the rest?

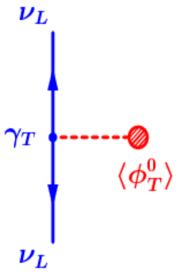


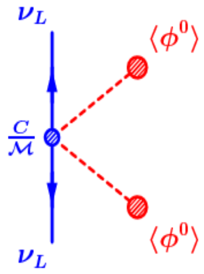


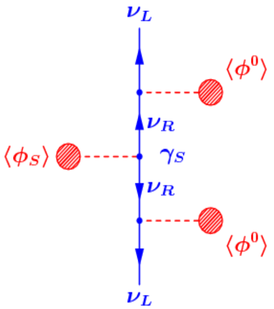


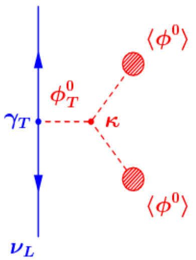
How do electron, neutrino(s) get their masses?







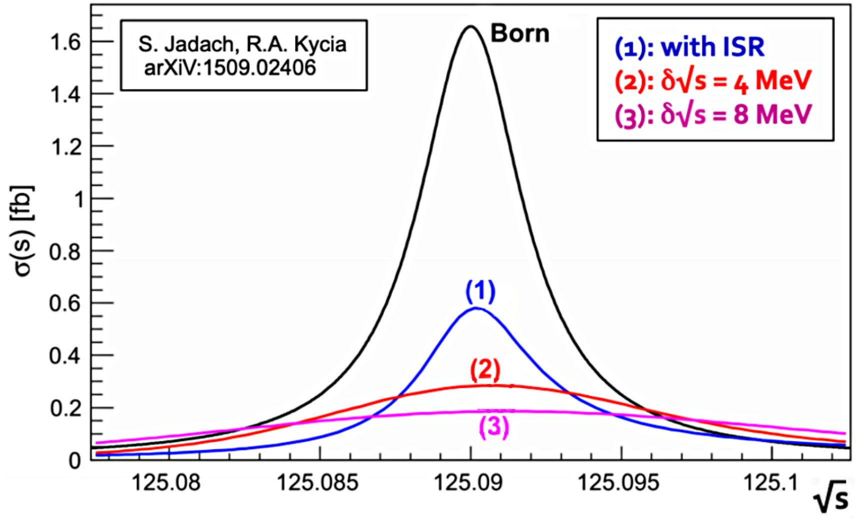




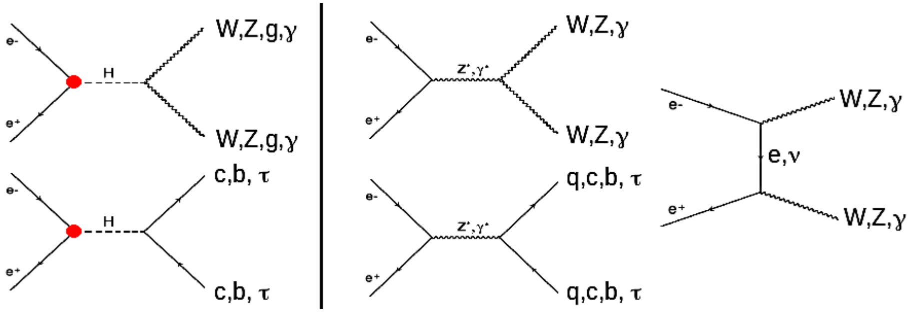
e Yukawa via s-channel $e^+e^- \to H$ production

- Higgs decay to e^+e^- is unobservable: BR($H\to e^+e^-$) $\approx 5\cdot10^{-9}$
- Resonant Higgs production considered so far only for muon collider: $\sigma(\mu\mu\to H) \approx 70$ pb. Tiny g_{eH} Yukawa coupling ⇒ Tiny $\sigma(ee\to H)$:

$$\sigma(e^+e^-\to H) = \frac{4\pi\Gamma_H^2 Br(H\to e^+e^-)}{(\hat{s}-M_H^2)^2+\Gamma_H^2 M_H^2} = 1.64\ \text{fb} \Rightarrow 290\ \text{ab}\ [\text{ISR}+\delta\sqrt{s}\approx\Gamma_H=4.2\ \text{MeV}]$$



- Preliminary study for 10 decay modes with huge Z^*/γ^* backgrounds ($\times10^2$–10^8 larger than signal, before cuts):



- Most significant channel $H\to WW^*\to l\nu jj$:

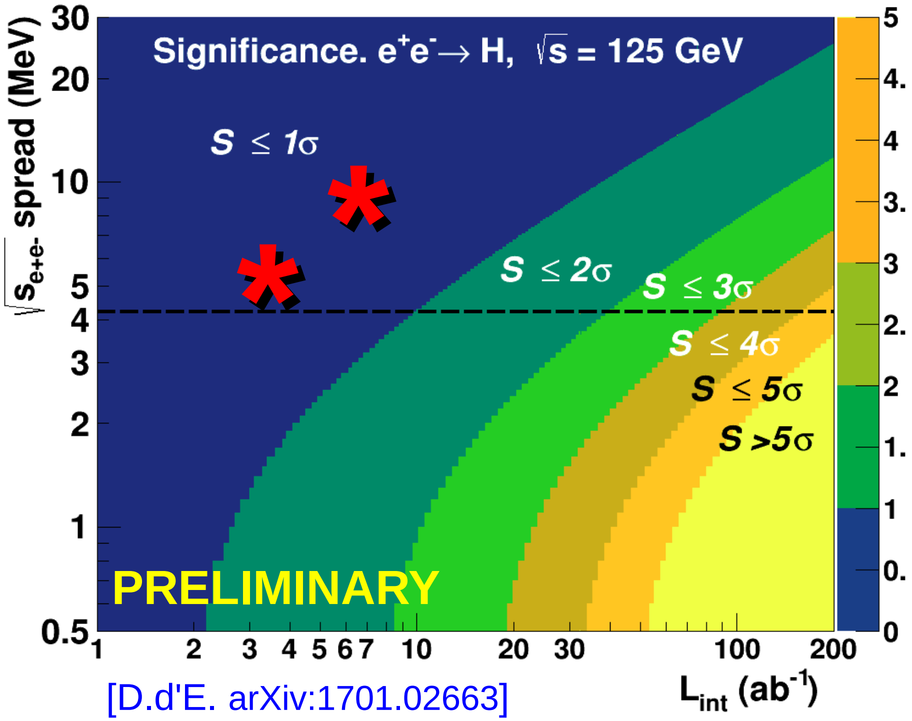
$E_{j1,j2} < 52,45$ GeV ← Kills $e^+e^-\to q\bar{q}$
$m_{w(l\nu)} > 12$ GeV/c^2 ← Kills $e^+e^-\to q\bar{q}$
$E_{lepton} > 10$ GeV ← Kills $e^+e^-\to q\bar{q}$
ME > 20 GeV ← Kills $e^+e^-\to q\bar{q}$
$m_{ME} < 3$ GeV/c^2 ← Kills $e^+e^-\to\tau\tau$
BDT MVA ← Kills $e^+e^-\to WW^*$ continuum
(exploits opposite $W^\pm$ polarizations in H decay)

$q\bar{q}$:	σ = 22 pb ⇒	σ(after) = 4 ab
τ τ:	σ = 1 pb ⇒	σ(after) = 2.6 ab
WW*:	σ = 16.3 fb ⇒	σ(after) = 2.7 fb
H(WW*):	σ = 23 ab ⇒	σ(after) = 8 ab

For L_{int}=10 ab^{-1}
S/√B =80/√27000 ≈ 0.5
Significance ≈ 0.5

$e^{\pm}$ Yukawa coupling at FCC-ee(125)

- Counting experiment combining signal+backgds in 10 Higgs decay channels:



[D.d'E. arXiv:1701.02663]

- Monochromatization working points:

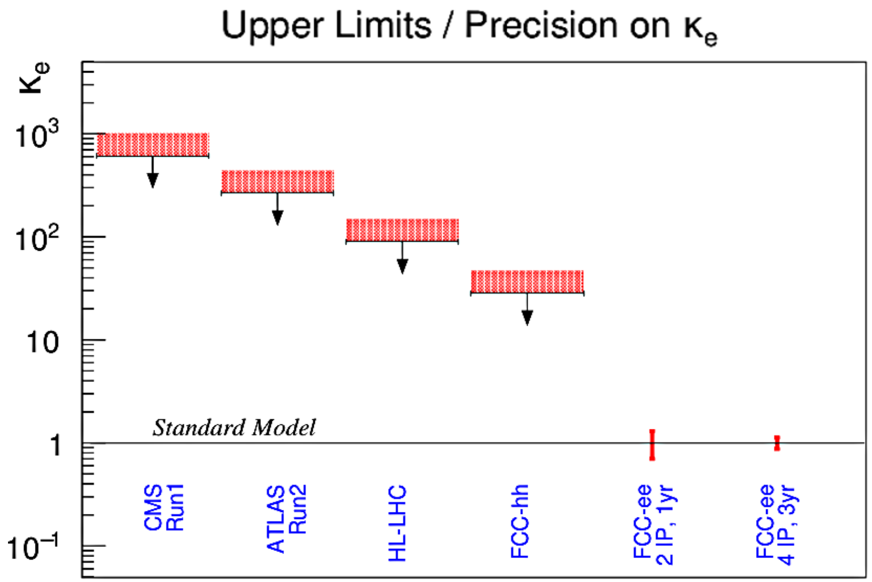
$\delta\sqrt{s}$ = 6 MeV, L_{int} = 3 ab^{-1} (baseline)
$\delta\sqrt{s}$ = 10 MeV, L_{int} = 7 ab^{-1} (optimized)

3σ evidence of ee → H would require 4 exps. running ~2 years at Higgs pole

(Ongoing analysis improvements: See poster by A.Poldaru, Fri 31st July)

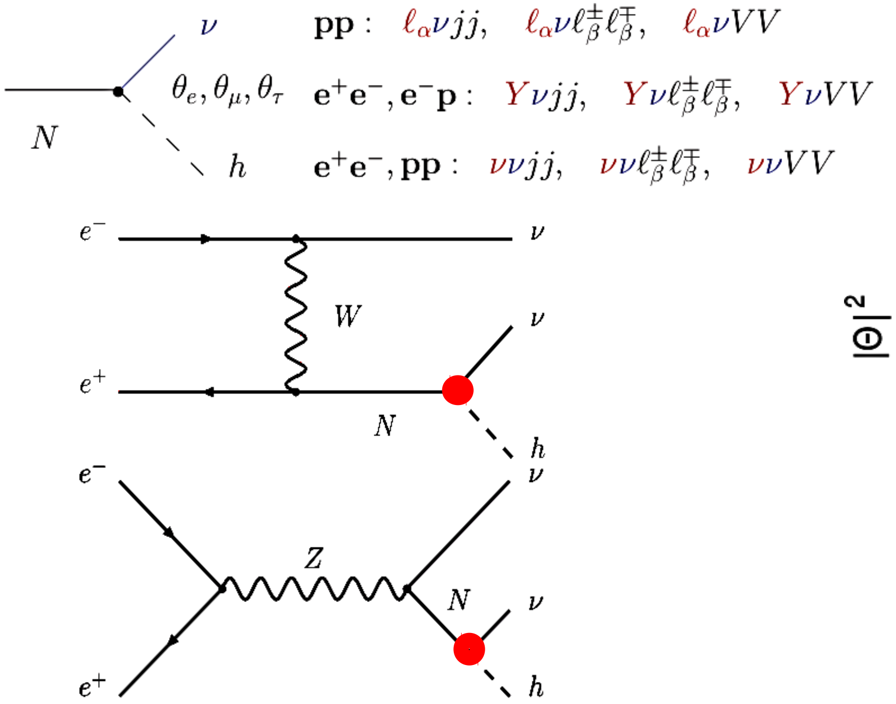
- Preliminary upper limits on e-Yukawa κ_e coupling at SM-level:

Limits on κ_e are ×100 (×30) better than at HL-LHC (FCC-hh).



Higgs coupling to neutrinos

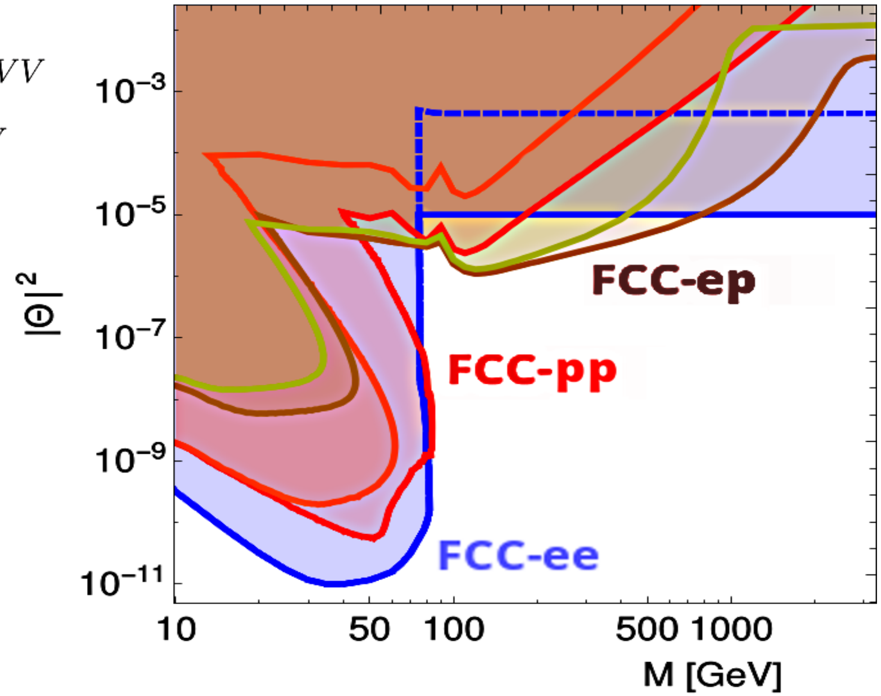
- Low-mass seesaw scenario with sterile ν (N_i) that mix with the SM ν with O(1) Yukawa couplings & EW-scale masses.
- N_i decay to Higgs+ν. Exp. signature: mono-Higgs(jj+ME).



$\mathbf{pp}$: $\ell_\alpha \nu jj$, $\ell_\alpha \nu \ell^\pm_\beta \ell^\mp_\beta$, $\ell_\alpha \nu VV$

$\mathbf{e^+e^-, e^-p}$: $Y \nu jj$, $Y \nu \ell^\pm_\beta \ell^\mp_\beta$, $Y \nu VV$

$\mathbf{e^+e^-, pp}$: $\nu \nu jj$, $\nu \nu \ell^\pm_\beta \ell^\mp_\beta$, $\nu \nu VV$



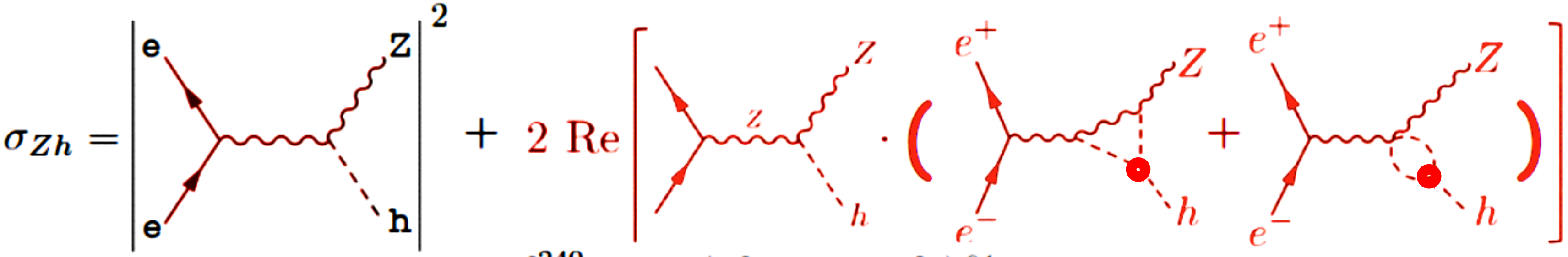
(Also via invisible $H \to N_i \nu$ decays for $m_N < m_H$)

[Antusch, Cazzato, Fischer, IJMPA 32 (2017)1750078]

- With Z (EWPO), sensitivity down to active-sterile mix $|\theta|^2 \sim 10^{-11}$ for $m_N > 10$ GeV

Open SM issue (2): Higgs self-coupling

- Higgs trilinear indirectly constrained through loop corrections to σ(H+Z):



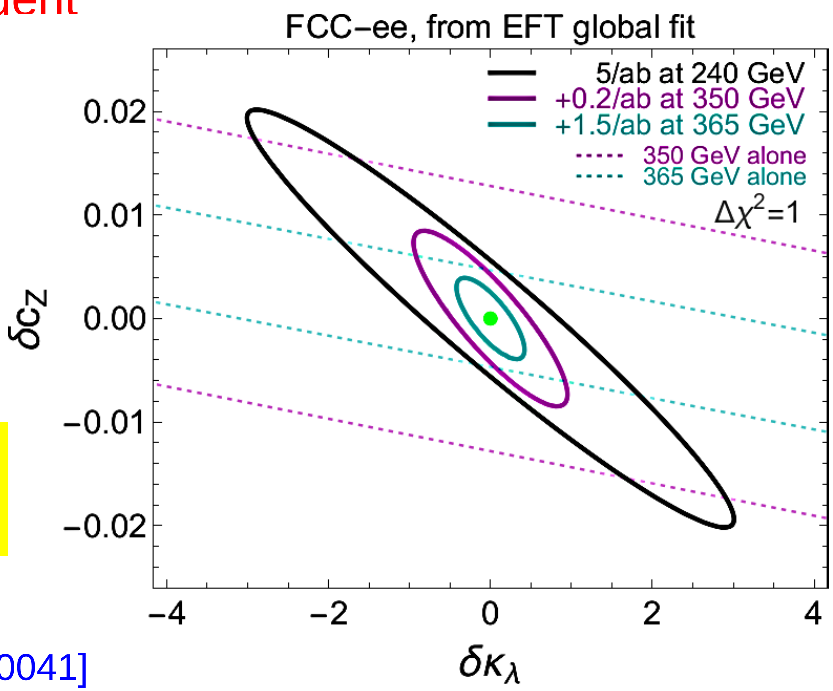
$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

[M. McCullough, 2014]

Self-coupling correction δ_h: energy-dependent
δ_Z: energy-independent (distinguishable).

- Small effect, but visible thanks to excellent (0.4%) precision on σ_{ZH} coupling reachable at FCC-ee.

- Indirect limits on trilinear λ coupling at ~20% level combining 240+350GeV



[Blondel & Janot, arXiv:1809.10041]

Open issue in the SM (3): Hierarchy/Naturalness (BSM scalar-coupled physics)

- Solved via many BSM realizations: SUSY, composite-H, little-H,...
- Parametrize (B)SM as an Effective Theory:

$$\mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d$$

- Indirect (loop) constraints on new physics coupled to Higgs:

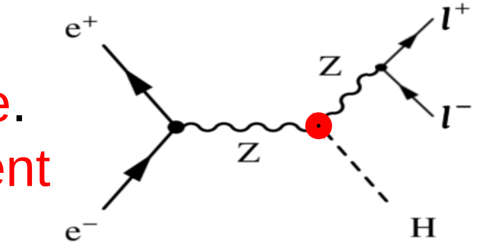
$$\Lambda \gtrsim (1\,\mathrm{TeV})/\sqrt{(\delta g_{\rm HXX}/g^{\rm SM}_{\rm HXX})/5\%}$$

~5% deviations of Higgs couplings w.r.t. SM ⇒ Λ >1 TeV

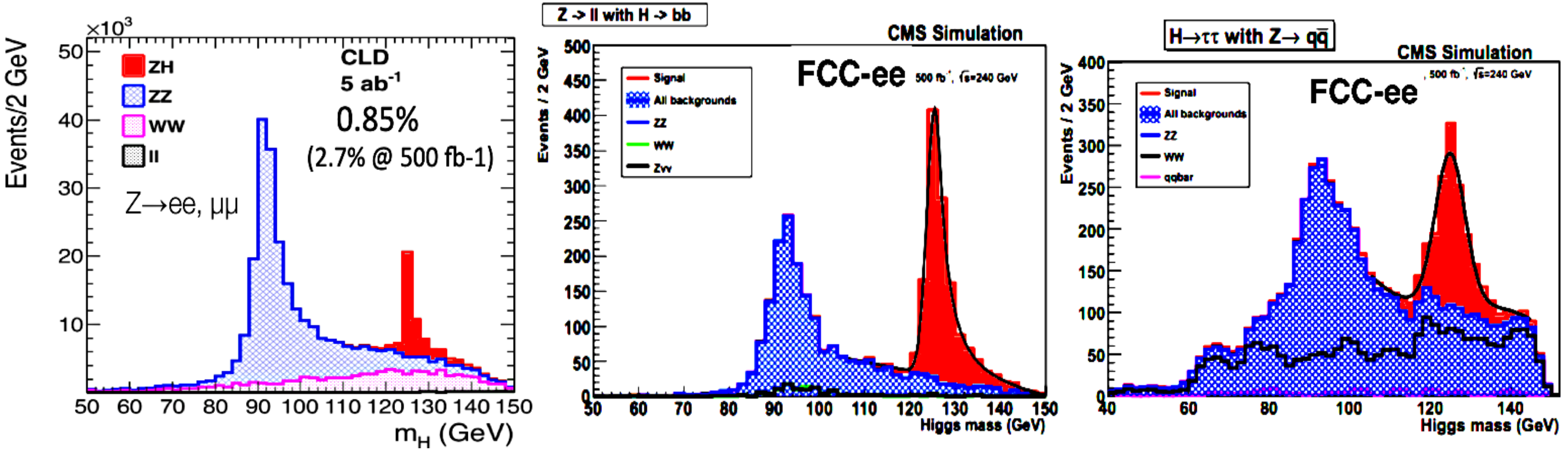
~0.1% Higgs couplings precision (~10^6 Higgs) ⇒ Λ>7 TeV

Precision H couplings, width, mass

- Recoil method in H-Z(ll) unique to lepton collider: reconstruct H 4-mom. independent of H decay mode.
- High-precision (0.4%) σ_{ZH} provides model-independent g_Z coupling: $\sigma(ee \to ZH) \propto g_Z^2$, with ±0.2% uncert.



$$m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{f\bar{f}})^2 - p^2_{f\bar{f}}$$



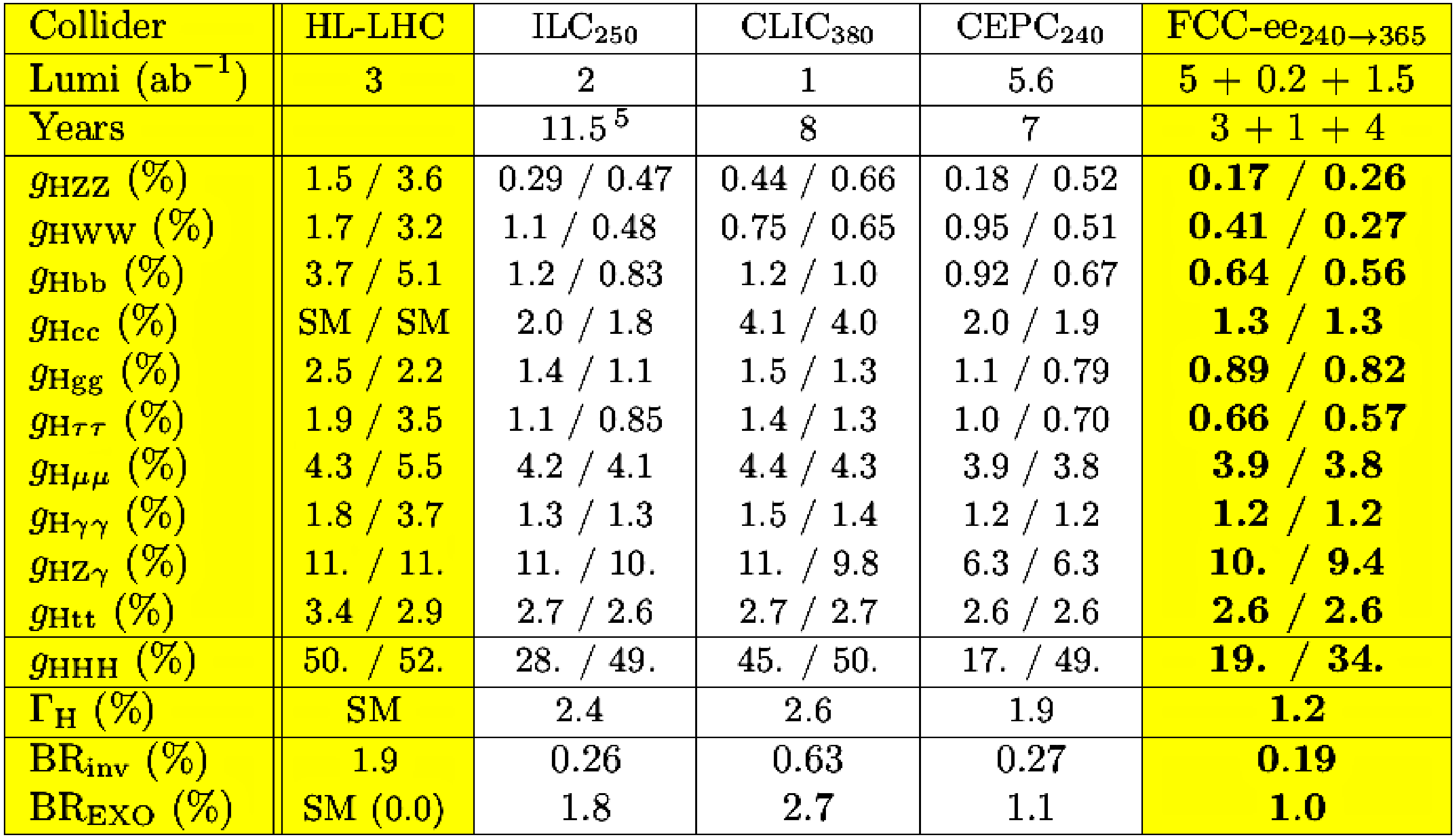
- Total width (Γ_H) with ~1% precision by combining σ(ZH) and BR(H→ZZ):

$$\sigma(ee \to ZH) BR(H \to ZZ) \propto \frac{g^4_{HZZ}}{\Gamma} \Rightarrow \Gamma$$

- Rest of Yukawa from other decays: $\sigma(ee \to ZH) BR(H \to XX) \propto \frac{g^2_{HZZ} g^2_{HXX}}{\Gamma} \Rightarrow g^2_{HXX}$
- Higgs mass (δm_H = 5–8 MeV) from recoil mass in Z→μμ,ee

Precision of Higgs couplings

- FCC-ee provides ×2–20 improvement in couplings uncertainties w.r.t. (model-dependent) HL-LHC expectations (2–5%):



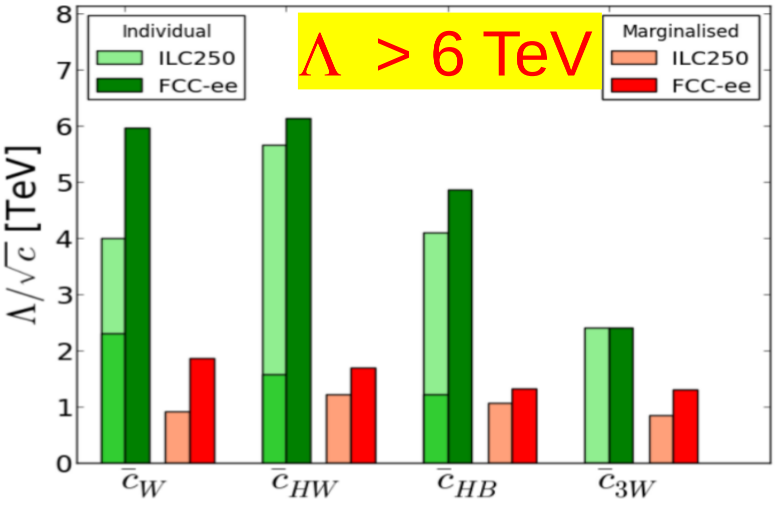
Collider	HL-LHC	ILC$_{250}$	CLIC$_{380}$	CEPC$_{240}$	FCC-ee$_{240\to365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years		11.5 ^{5}	8	7	3 + 1 + 4
g_{HZZ} (%)	1.5 / 3.6	0.29 / 0.47	0.44 / 0.66	0.18 / 0.52	**0.17 / 0.26**
g_{HWW} (%)	1.7 / 3.2	1.1 / 0.48	0.75 / 0.65	0.95 / 0.51	**0.41 / 0.27**
g_{Hbb} (%)	3.7 / 5.1	1.2 / 0.83	1.2 / 1.0	0.92 / 0.67	**0.64 / 0.56**
g_{Hcc} (%)	SM / SM	2.0 / 1.8	4.1 / 4.0	2.0 / 1.9	**1.3 / 1.3**
g_{Hgg} (%)	2.5 / 2.2	1.4 / 1.1	1.5 / 1.3	1.1 / 0.79	**0.89 / 0.82**
$g_{\mathrm{H}\tau\tau}$ (%)	1.9 / 3.5	1.1 / 0.85	1.4 / 1.3	1.0 / 0.70	**0.66 / 0.57**
$g_{\mathrm{H}\mu\mu}$ (%)	4.3 / 5.5	4.2 / 4.1	4.4 / 4.3	3.9 / 3.8	**3.9 / 3.8**
$g_{\mathrm{H}\gamma\gamma}$ (%)	1.8 / 3.7	1.3 / 1.3	1.5 / 1.4	1.2 / 1.2	**1.2 / 1.2**
$g_{\mathrm{HZ}\gamma}$ (%)	11. / 11.	11. / 10.	11. / 9.8	6.3 / 6.3	**10. / 9.4**
g_{Htt} (%)	3.4 / 2.9	2.7 / 2.6	2.7 / 2.7	2.6 / 2.6	**2.6 / 2.6**
g_{HHH} (%)	50. / 52.	28. / 49.	45. / 50.	17. / 49.	**19. / 34.**
Γ_{H} (%)	SM	2.4	2.6	1.9	**1.2**
BR$_{\mathrm{inv}}$ (%)	1.9	0.26	0.63	0.27	**0.19**
BR$_{\mathrm{EXO}}$ (%)	SM (0.0)	1.8	2.7	1.1	**1.0**

- Most precise g_{ZZ} ≈0.17% coupling sets limit on new scalar-coupled physics at: $\Lambda \gtrsim (1\,\mathrm{TeV})/\sqrt{(\delta g_{\mathrm{HXX}}/g^{\mathrm{SM}}_{\mathrm{HXX}})/5\%}$ > 6 TeV

Precision H properties: Generic BSM bounds

- FCC-ee Higgs measurements greatly improve scalar-coupled BSM reach.

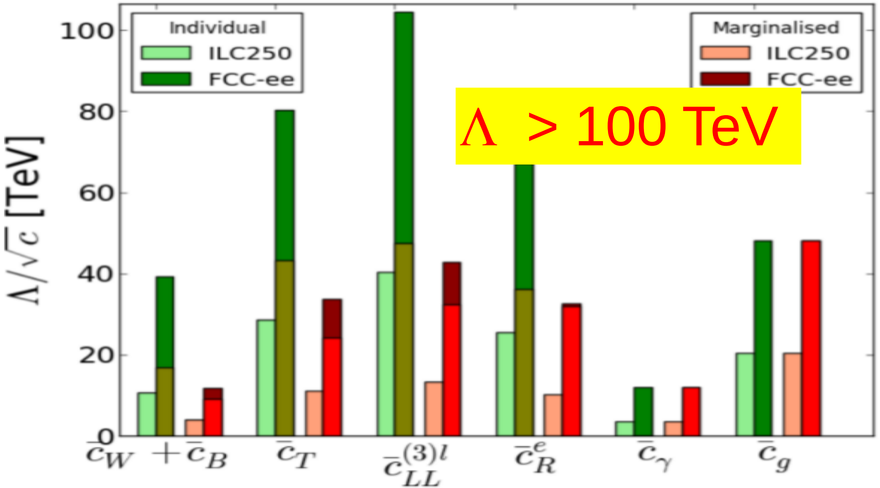
- NP bounds from FCC-ee Higgs:



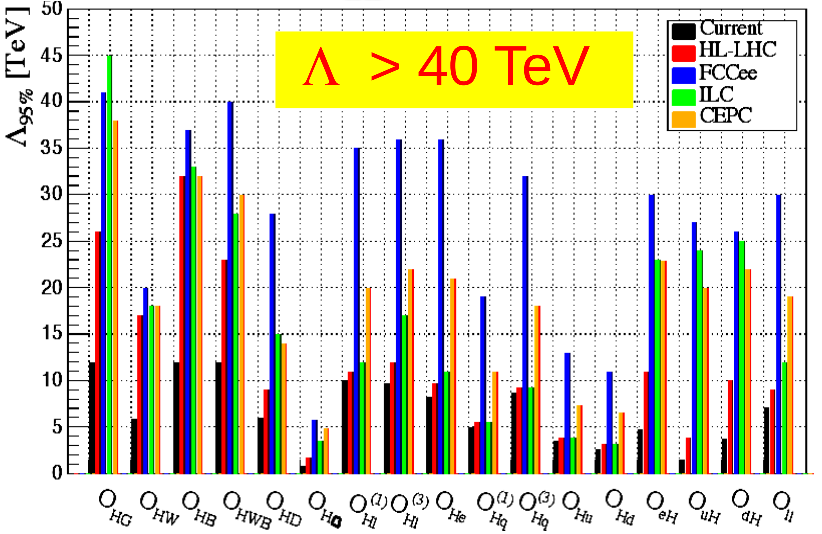
Λ > 6 TeV

[J.Ellis and T.You, arXiv:1510:04561]

- From H+EWPO combined:



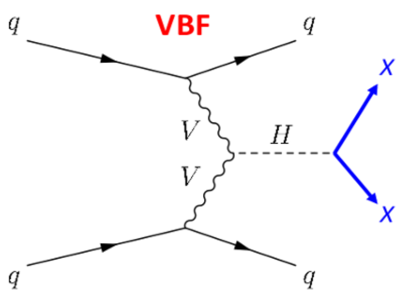
Λ > 100 TeV

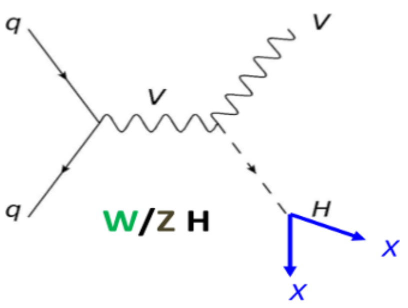


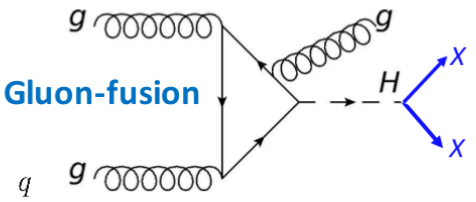
Λ > 40 TeV

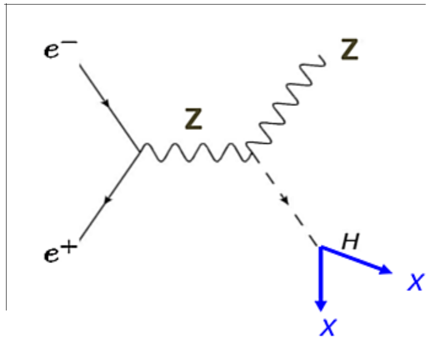
[DeBlas et al. arXiv:1608.01509]

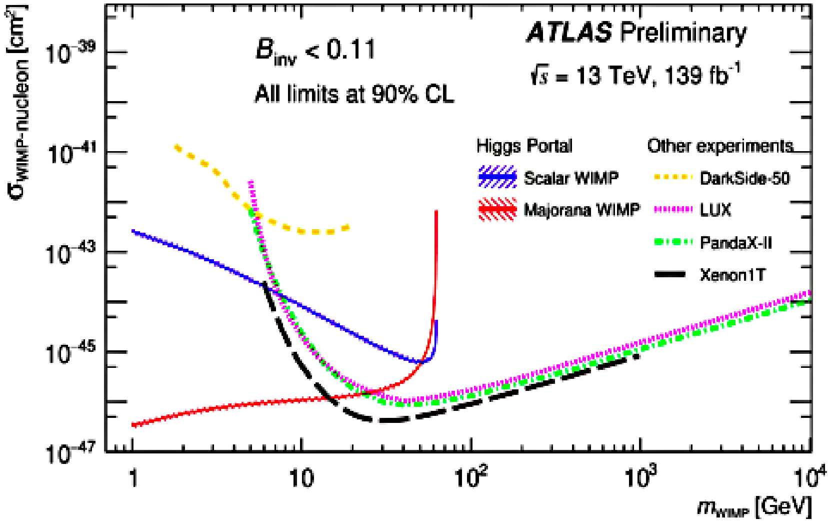
Open issue in the SM (4): Dark matter (Higgs-portal)









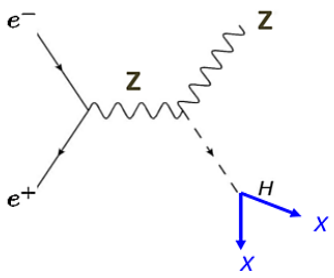


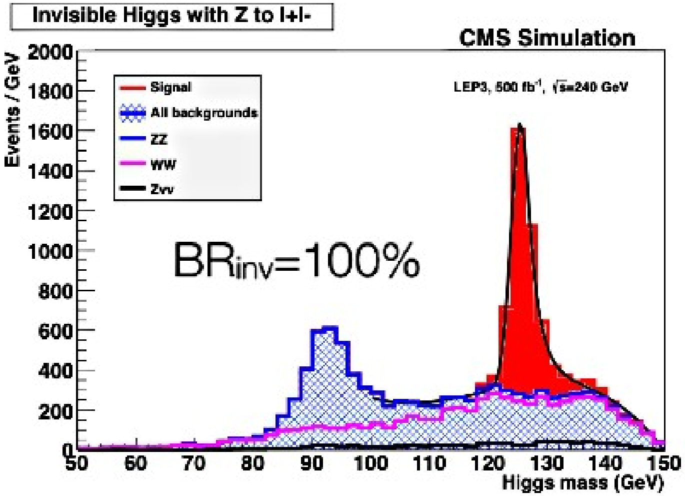
[B(H→inv) > 11% today]

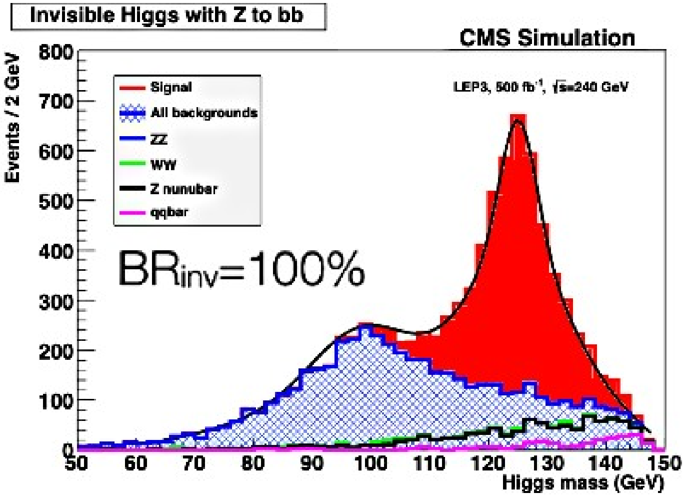
[B(H→inv) > 2% for HL-LHC]

Limits on invisible Higgs decays

- Invisible branching ratio: $e^+e^- \to ZH$, $Z \to \ell^+\ell^-/b\bar{b}$, $H \to$ invisible.
  Perform S+B fit to missing mass (m_{recoil}) distribution:





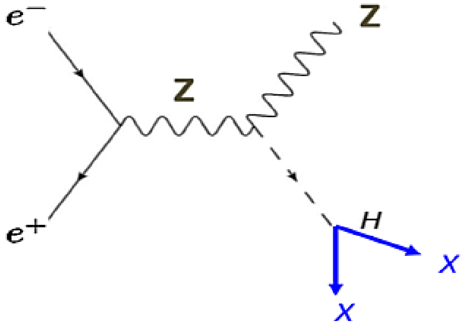


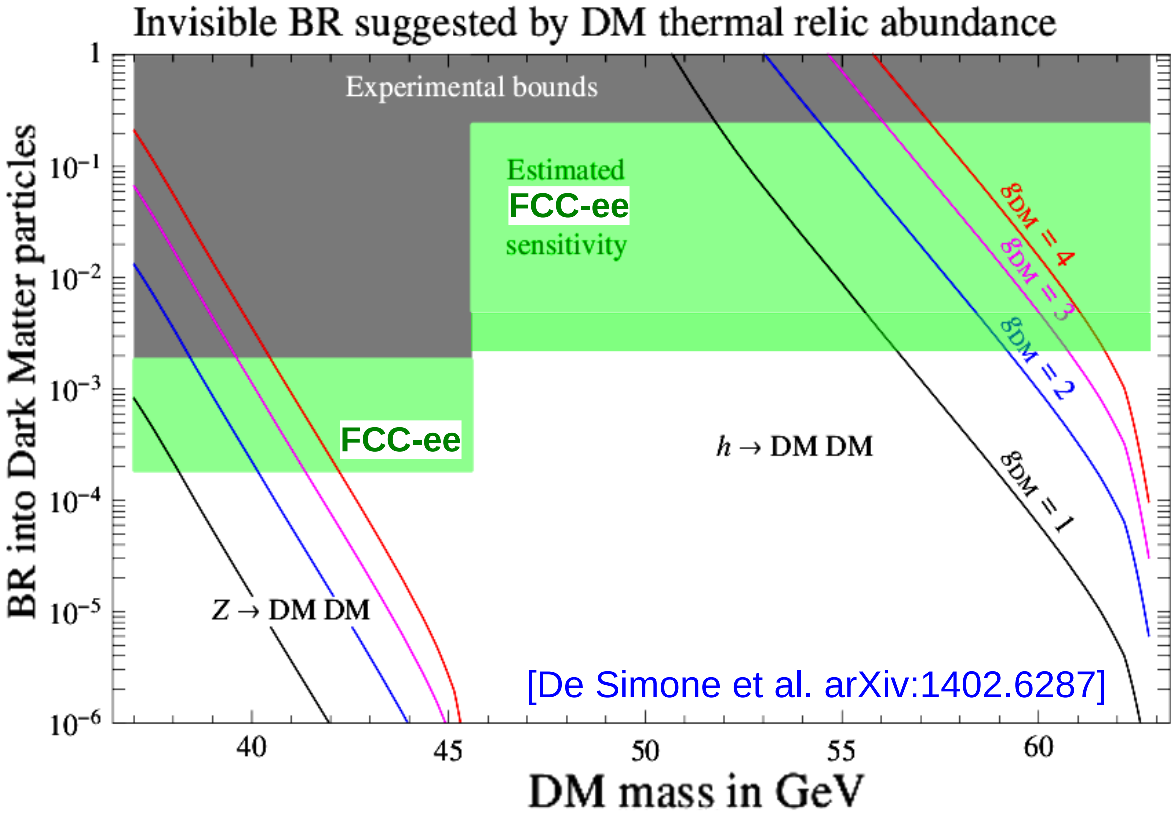
- Limits in branching ratio to invisible down to ~0.2% @ 95% CL.
  Also 1% limits on "exotic" BRs (final states that cannot be tagged as SM decays)

Collider	HL-LHC	ILC$_{250}$	CLIC$_{380}$	CEPC$_{240}$	FCC-ee$_{240\to365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years		11.5[5]	8	7	3 + 1 + 4
BR$_{\text{inv}}$ (%)	1.9	0.26	0.63	0.27	**0.19**
BR$_{\text{EXO}}$ (%)	SM (0.0)	1.8	2.7	1.1	**1.0**

Dark Matter ($m_{DM}<m_H/2$) via H decays

- DM freeze-out fixes $\sigma v \approx 3\cdot10^{-26}$cm^3/s. If m_{DM} is just below $m_{Z,H}/2$, DM freeze-out dominated by resonant Z,H exchange, fixing $\Gamma_{Z,H}$.





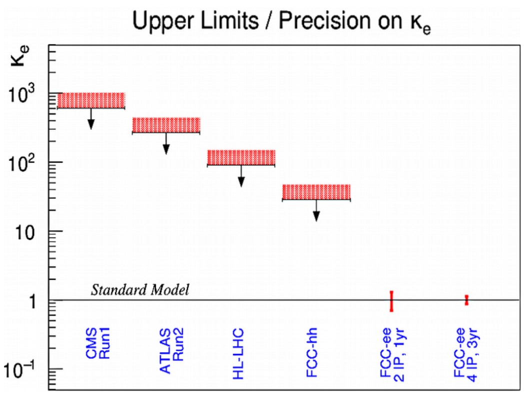
[De Simone et al. arXiv:1402.6287]

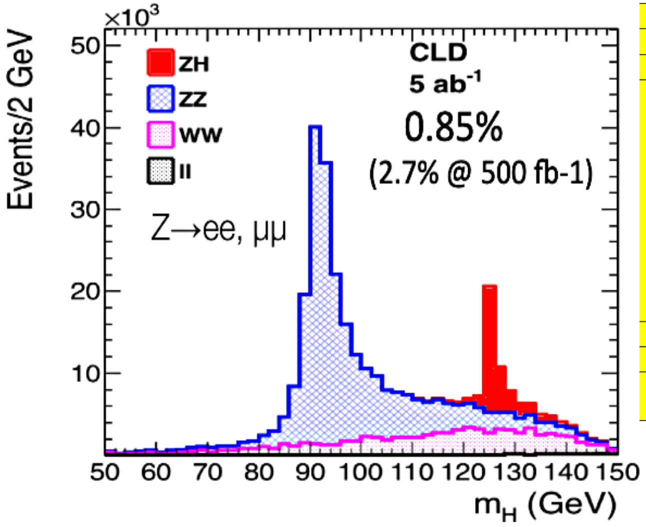
- Precision ($<10^{-3}$ and $<10^{-1}$) measurements of invisible Z & H widths are best collider option to test any $m_{DM}<m_{Z,H}/2$ that couples via SM mediators.

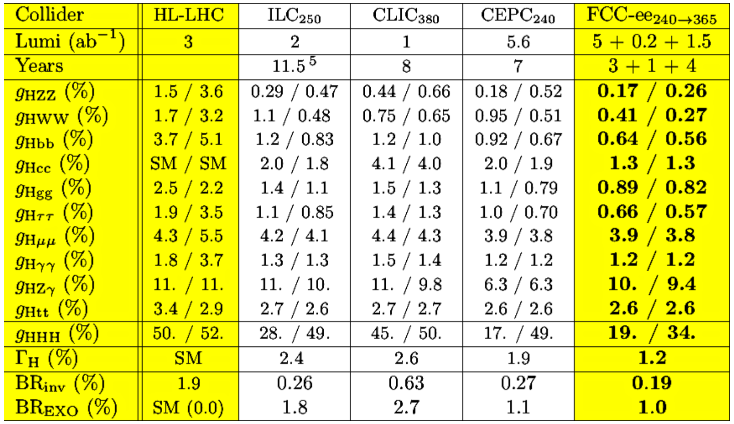
Summary

- FCC provides unparalleled luminosities (~10 ab^{-1}) in e^+e^- at c.m. energy 125–350 GeV for ultra-precise Higgs studies (down to ~0.15% uncert.):
- Testing SM ($g_{1st\text{-}gen}$,g_λ) & constraining scalar-coupled BSM up to multi-TeV:

e± Yukawa



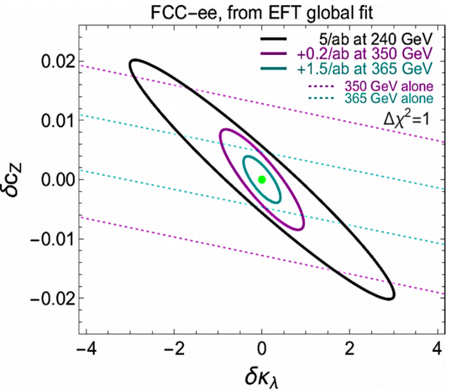




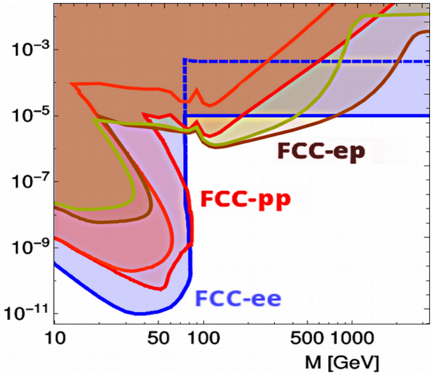
Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	$FCC\text{-}ee_{240\to365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years		11.5 [5]	8	7	3 + 1 + 4
g_{HZZ} (%)	1.5 / 3.6	0.29 / 0.47	0.44 / 0.66	0.18 / 0.52	**0.17 / 0.26**
g_{HWW} (%)	1.7 / 3.2	1.1 / 0.48	0.75 / 0.65	0.95 / 0.51	**0.41 / 0.27**
g_{Hbb} (%)	3.7 / 5.1	1.2 / 0.83	1.2 / 1.0	0.92 / 0.67	**0.64 / 0.56**
g_{Hcc} (%)	SM / SM	2.0 / 1.8	4.1 / 4.0	2.0 / 1.9	**1.3 / 1.3**
g_{Hgg} (%)	2.5 / 2.2	1.4 / 1.1	1.5 / 1.3	1.1 / 0.79	**0.89 / 0.82**
$g_{H\tau\tau}$ (%)	1.9 / 3.5	1.1 / 0.85	1.4 / 1.3	1.0 / 0.70	**0.66 / 0.57**
$g_{H\mu\mu}$ (%)	4.3 / 5.5	4.2 / 4.1	4.4 / 4.3	3.9 / 3.8	**3.9 / 3.8**
$g_{H\gamma\gamma}$ (%)	1.8 / 3.7	1.3 / 1.3	1.5 / 1.4	1.2 / 1.2	**1.2 / 1.2**
$g_{HZ\gamma}$ (%)	11. / 11.	11. / 10.	11. / 9.8	6.3 / 6.3	**10. / 9.4**
g_{Htt} (%)	3.4 / 2.9	2.7 / 2.6	2.7 / 2.7	2.6 / 2.6	**2.6 / 2.6**
g_{HHH} (%)	50. / 52.	28. / 49.	45. / 50.	17. / 49.	**19. / 34.**
Γ_H (%)	SM	2.4	2.6	1.9	**1.2**
BR_{inv} (%)	1.9	0.26	0.63	0.27	**0.19**
BR_{EXO} (%)	SM (0.0)	1.8	2.7	1.1	**1.0**

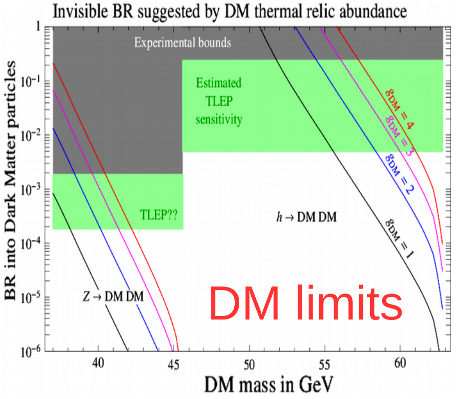
×2–20 more precise couplings than HL-LHC

Self-coupling

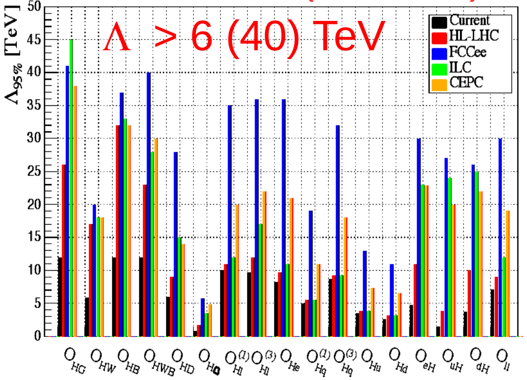


Sterile ν's



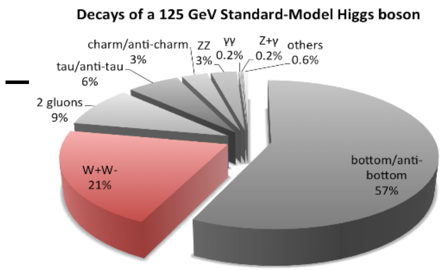


BSM limits (+EWPO)



Backup slides

Most significant channel: $e^+e^- \rightarrow H(WW^*) \rightarrow l\nu jj$

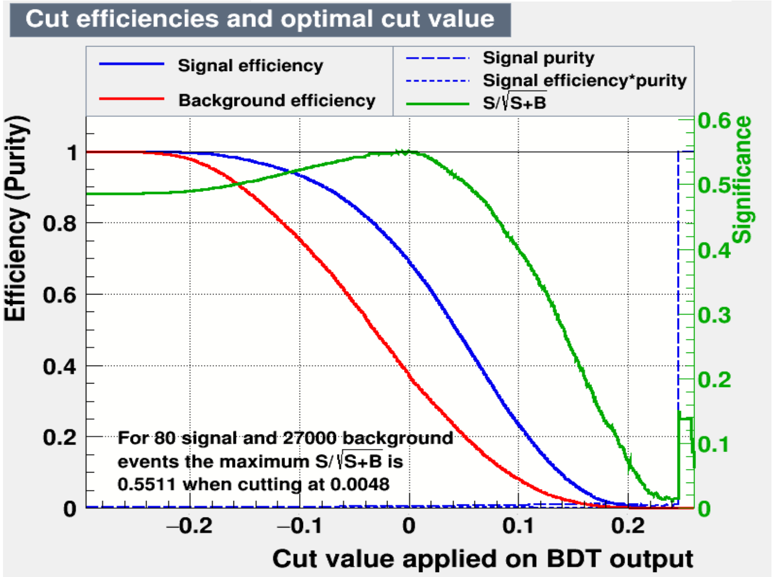


- Final state (retains 80% of $\sigma(WW^*(l\nu jj))$ = 28 ab):
  1 isolated $e,\mu,\tau(e),\tau(\mu)$ + ME>2 GeV + 2 jets (excl.)

- Analysis cuts:

✓ $E_{j1,j2}$ < 52,45 GeV ← Kills $e^+e^-\rightarrow q\bar{q}$
✓ $m_{w(l\nu)}$ > 12 GeV/c^2 ← Kills $e^+e^-\rightarrow q\bar{q}$
✓ E_{lepton} > 10 GeV ← Kills $e^+e^-\rightarrow q\bar{q}$
✓ ME > 20 GeV ← Kills $e^+e^-\rightarrow q\bar{q}$
✓ m_{ME} < 3 GeV/c^2 ← Kills $e^+e^-\rightarrow\tau\tau$
✓ BDT MVA ← Kills $e^+e^-\rightarrow WW^*$ continuum

(exploits opposite $W^\pm$ polarizations in H decay)



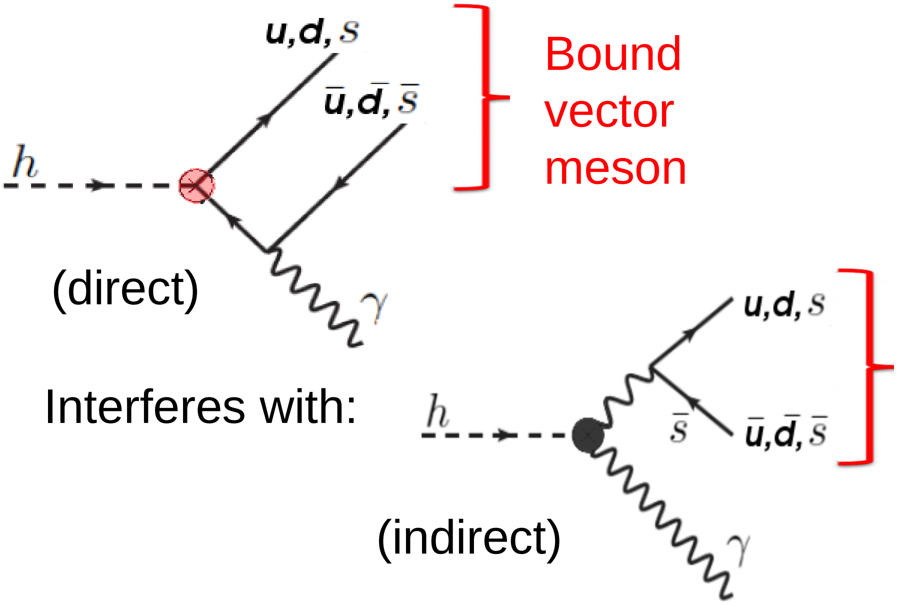
- Signal & backgrounds before/after cuts:

$q\bar{q}$: σ = 22 pb ⇒ σ(after) = 4 ab
τ τ: σ = 1 pb ⇒ σ(after) = 2.6 ab
WW*: σ = 16.3 fb ⇒ σ(after) = 2.7 fb
H(WW*): σ = 23 ab ⇒ σ(after) = 8 ab

For L_{int}=10 ab^{-1}
$S/\sqrt{B} = 80/\sqrt{27000} \approx 0.5$
Significance ≈ 0.5

1^{st}-generation quark Yukawa couplings

- 1^{st} & 2^{nd} gen. quark Yukawa accessible via exclusive H→Vγ , V=ρ,ω,ϕ



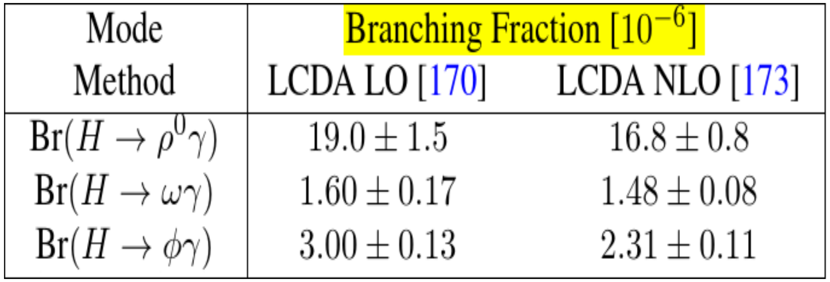
Bound vector meson

(direct)

Interferes with:

(indirect)

[G. Perez et al, arXiv:1505.06689]



Mode Method	Branching Fraction $[10^{-6}]$ LCDA LO [170]	 LCDA NLO [173]
$\mathrm{Br}(H \to \rho^0\gamma)$	19.0 ± 1.5	16.8 ± 0.8
$\mathrm{Br}(H \to \omega\gamma)$	1.60 ± 0.17	1.48 ± 0.08
$\mathrm{Br}(H \to \phi\gamma)$	3.00 ± 0.13	2.31 ± 0.11

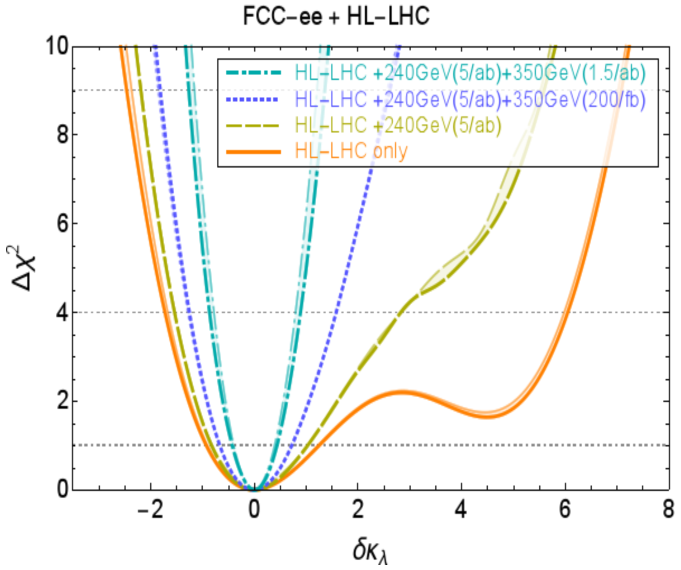
- H→ρ(ππ)γ channel most promising: N~40 counts expected, low backgds
- Sensitivity to u/d quark Yukawa couplings:

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]}{0.57\bar{\kappa}_b^2} \times 10^{-5}$$

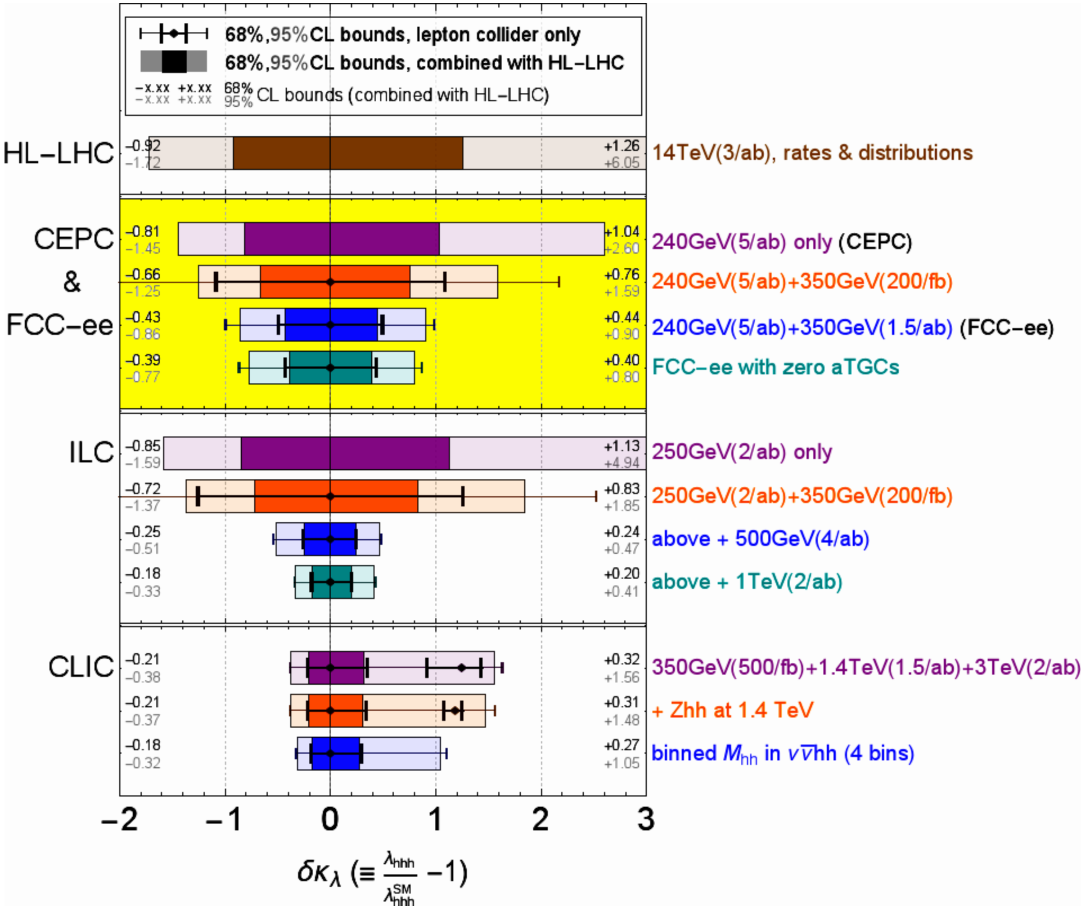
($k_q = y_q/y_b$)

- All channels also accessible with higher stats at FCC-pp, but much worse backgrounds (QCD and pileup).

Higgs self-coupling through σ(HZ)



- Addition of FCC-ee 240+350GeV Higgs cross section solves 2nd minimum on λ from HL-LHC data alone.



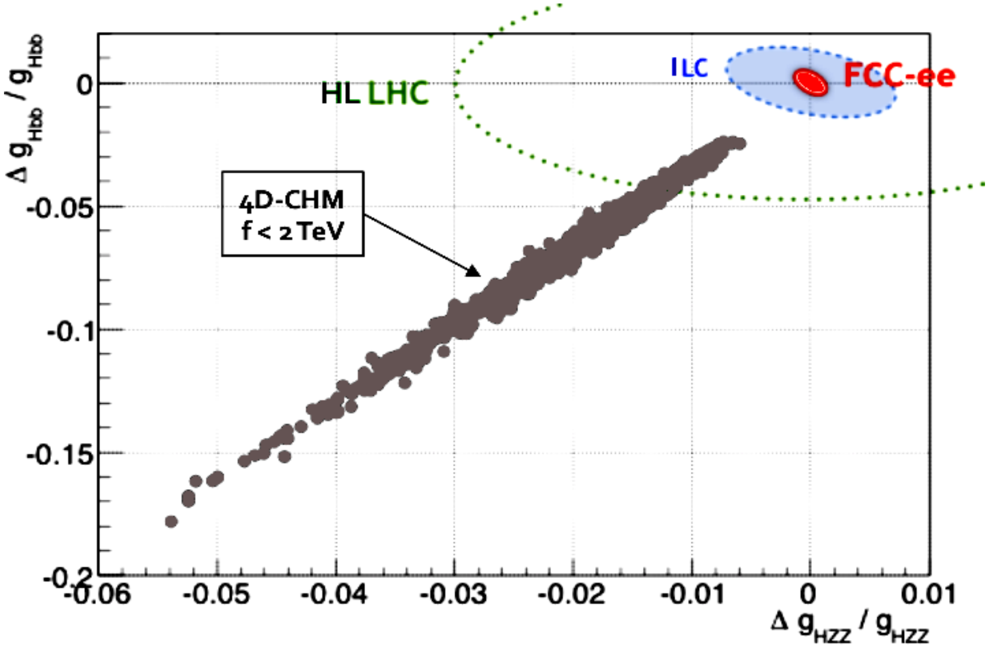
- Higgs self-coupling constrained to within ~40%. Higher-energy e^+e^- collisions required to reduce it to ~20%

Precision H properties: Concrete BSM bounds

- FCC-ee precision measurements greatly improve scalar-coupled BSM limits.

- 4D-Composite Higgs models:

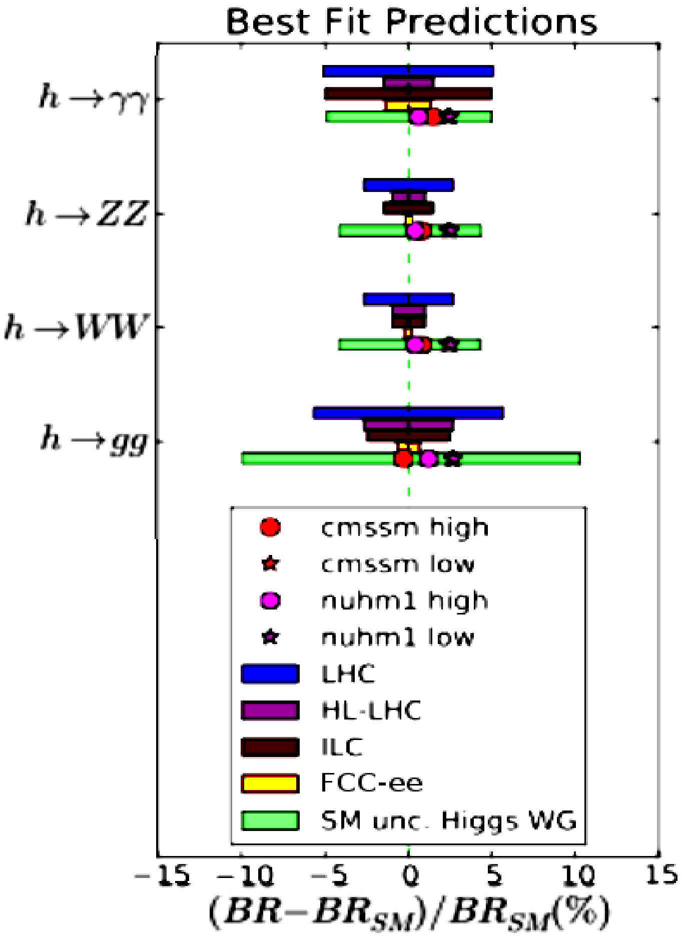
Correlated effect on g_{HZZ} & g_{Hbb}



(All other couplings affected in a similar manner)

FCC-ee sensitivity on composite-scale parameter: f > 4–5 TeV

- Benchmark SUSY models (CMSSM, NUHM1)



[arXiv:1308.6176]