Portuguese Discussion on the European Strategy for Particle Physics

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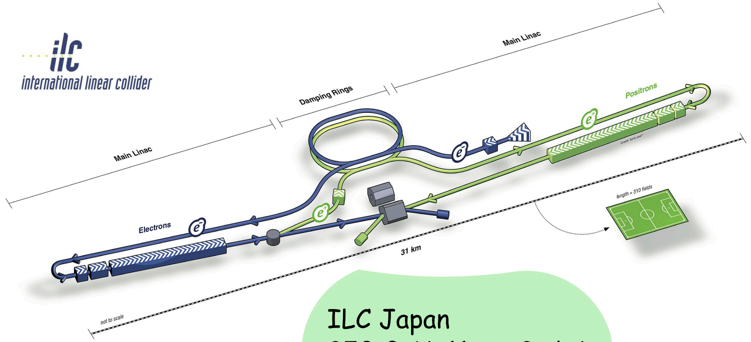
20 January 2025

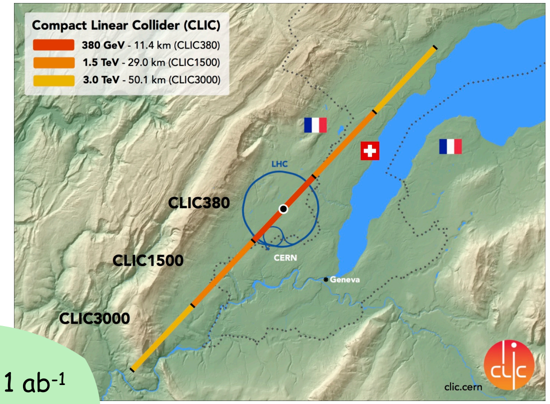
Funded by FCT - projects no. CFTC: UIDB/00618/2020 (https://doi.org/10.54499/UIDB/00618/2020), UIDP/00618/2020, (https://doi.org/10.54499/UIDP/00618/2020)., CERN/FIS-PAR/0025/2021, DOI: https://doi.org/10.54499/CERN/FIS-PAR/0025/2021, This work is funded by the Fundação para a Ciência e a Tecnologia, I.P., through the PRR (Recovery and Resilience Plan), within the scope of the investment "RE-C06-i06 - Science Plus Capacity Building", measure "RE-C06-i06.m02 - Reinforcement of financing for International Partnerships in Science, Technology and Innovation of the PRR", under the project with the reference 2024.03328.CERN

Future e^+e^- Collider Projects

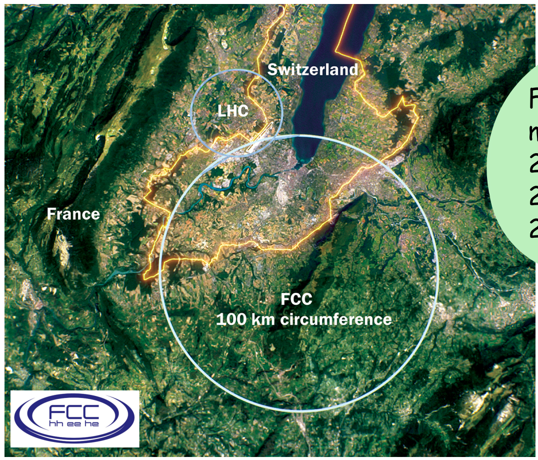


ILC Japan
250 GeV, 11y -> 2 ab^{-1}
500 GeV, 8.5y 4 ab^{-1}
1000 GeV, 8.5y 8 ab^{-1}

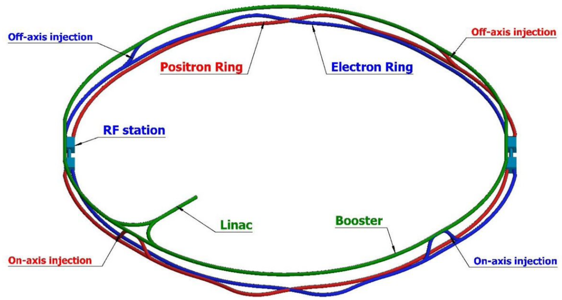
Cool Copper Collider
250 GeV -> $1.3\times10^{34}/cm^2s$
550 GeV -> $2.4\times10^{34}/cm^2s$



CLIC, CERN
380 GeV, 8y -> 1 ab^{-1}
1500 GeV, 7y 2.5 ab^{-1}
3000 GeV, 8.5y 5 ab^{-1}

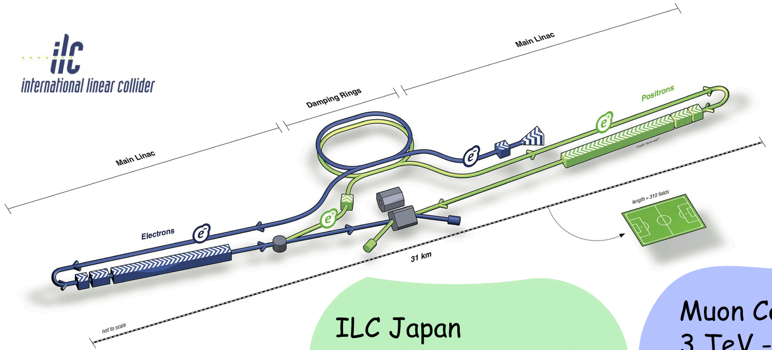


FCC-ee, CERN
m_Z, 4y -> 150 ab^{-1}
2 m_W, 1-2y 10 ab^{-1}
240 GeV, 3y 5 ab^{-1}
2 m_{top}, 5y 1.5 ab^{-1}



CEPC, China
m_Z, 2y -> 16 ab^{-1}
2 m_W, 1y 2.6 ab^{-1}
240 GeV, 7y 5.6 ab^{-1}

Future Collider Projects



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250 GeV -> 1.3x10^{34}/cm^{2}s
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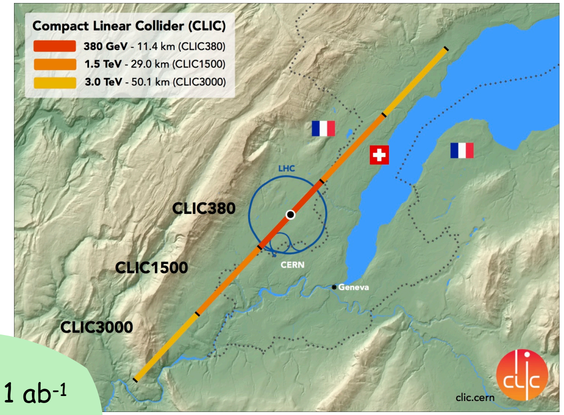


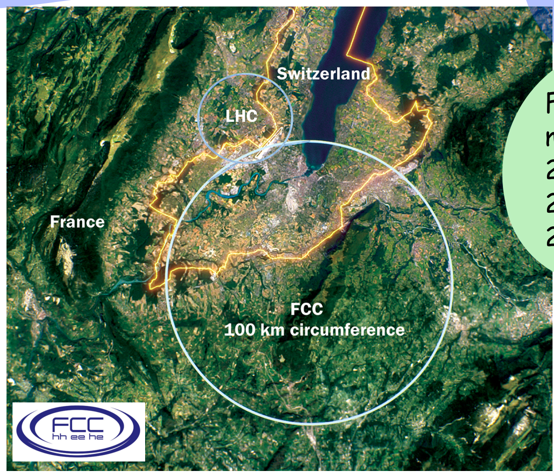
ILC Japan
250 GeV, 11y -> 2 ab^{-1}
500 GeV, 8.5y 4 ab^{-1}
1000 GeV, 8.5y 8 ab^{-1}

Muon Collider
3 TeV -> 1 ab^{-1}
10 TeV -> 10 ab^{-1}

CLIC, CERN
380 GeV, 8y -> 1 ab^{-1}
1500 GeV, 7y 2.5 ab^{-1}
3000 GeV, 8.5y 5 ab^{-1}

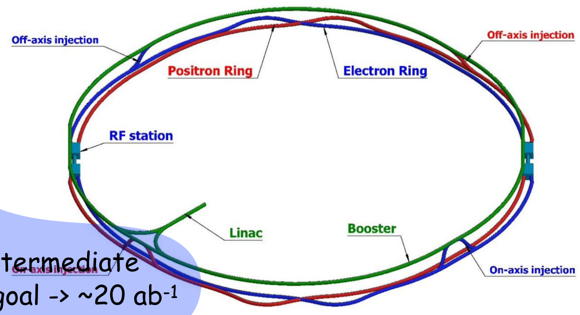
LHeC 0.2-1.3 TeV
run together w/ HL-LHC
($\gtrsim$ Run 5) -> 1 ab^{-1}

FCC-eh ($E_{e/p}$=60 GeV/50TeV)
3.5 TeV -> 2 ab^{-1}
run together w/ FCC-hh



FCC-ee, CERN
m_Z, 4y -> 150 ab^{-1}
2 m_W, 1-2y 10 ab^{-1}
240 GeV, 3y 5 ab^{-1}
2 m_{top}, 5y 1.5 ab^{-1}

FCC-hh
100 TeV -> ~20-25 ab^{-1}
during 20-25y runtime



SPPC
75 TeV intermediate
125 TeV goal -> ~20 ab^{-1}

CEPC, China
m_Z, 2y -> 16 ab^{-1}
2 m_W, 1y 2.6 ab^{-1}
240 GeV, 7y 5.6 ab^{-1}

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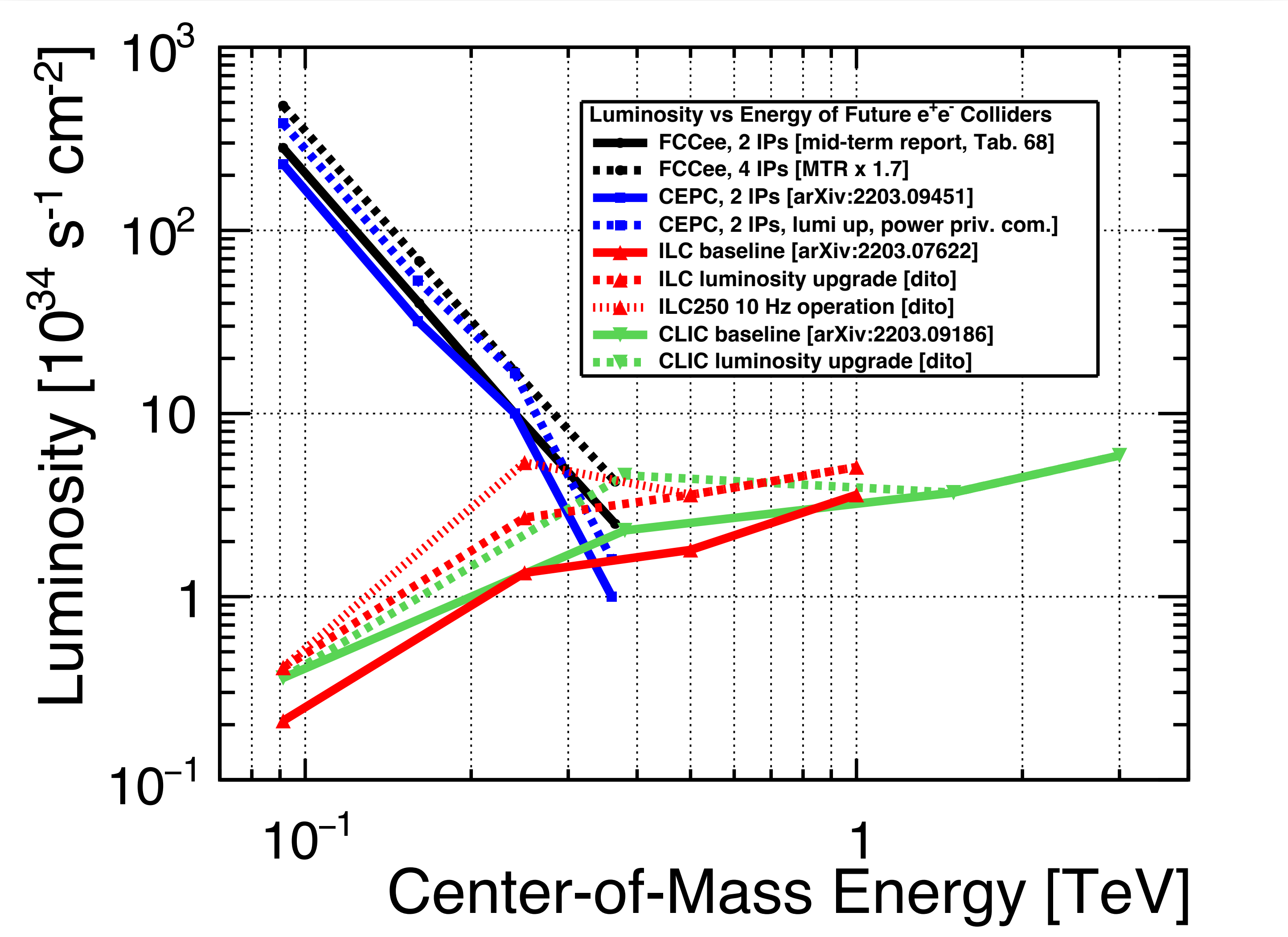
ee-Colliders Energy Range & Luminosity



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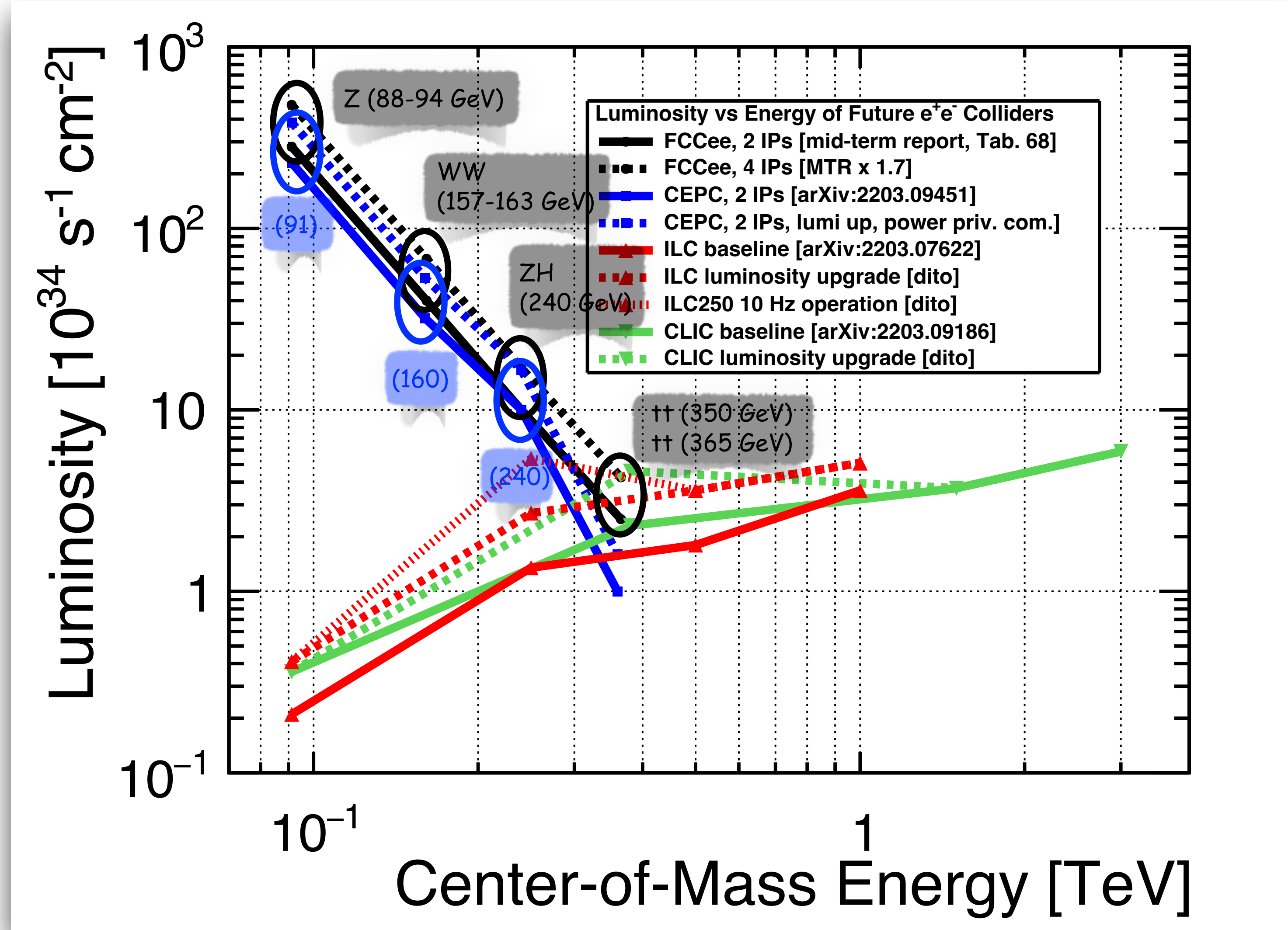
ee-Colliders Energy Range & Luminosity



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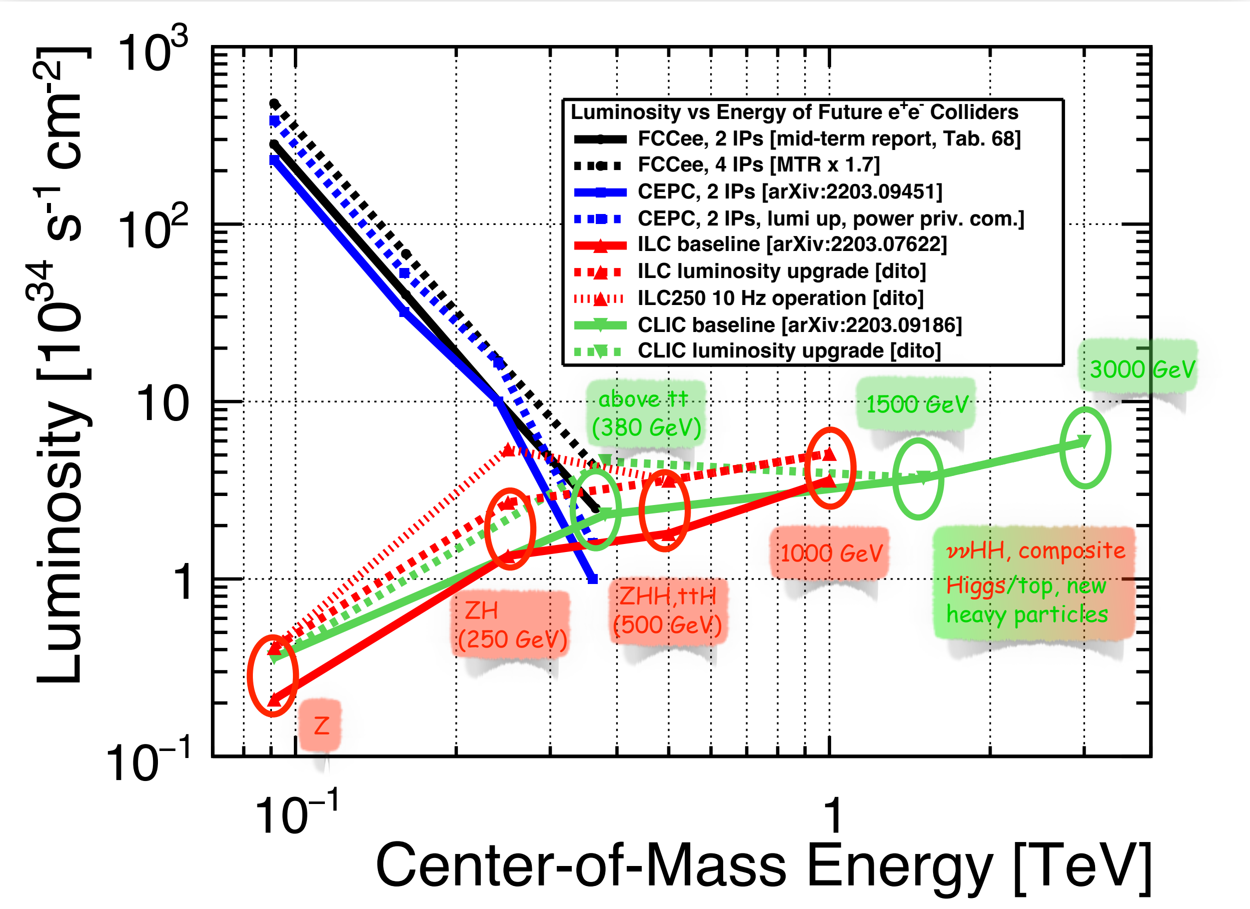
ee-Colliders Energy Range & Luminosity

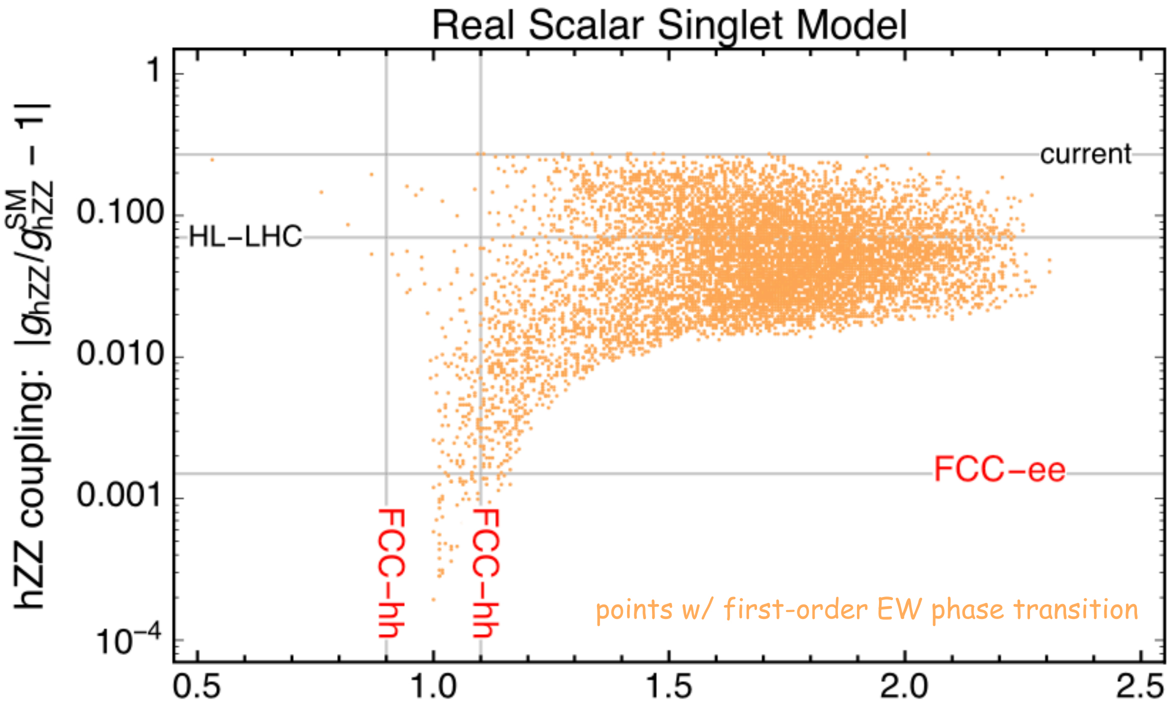


Accelerator	$\sqrt{s}$ (TeV)	Integrated luminosity (ab^{-1})
CLIC	1.5	2.5
CLIC	3	5
Muon Collider	3	1
Muon Collider	7	10
Muon Collider	14	20

Relation with Single Higgs Couplings

Real Scalar Singlet Model

[Huang eal,1608.06619]



Precise single Higgs coupling measurements at FCC-ee
constrain trilinear Higgs self-coupling values w/ FOPT

Summary Single Higgs

Higgs Factories
(e+e- circ/lin, μ+μ-)

◇ absolute coupling measur. ($\delta\Gamma_H = \mathcal{O}(1\%)$)

◇ perform similar ($\mathcal{L}$ vs. polarisation)

◇ precision: % to ‰ level

◇ running at 2 energies: precision ↑

◇ less sensitive to rare decays

FCC-ee

◇ $\delta m_H = 4$ MeV ◇ $|\delta y_t| \sim 10\,\%$

◇ unique: Hee-coupling measurement

mu-Collider

◇ lineshape: $\delta m_H = 0.21$ MeV, $\delta\Gamma_H = 1.1$-1.4%

◇ $|\delta y_t| \sim 3\,\%$ (<- high prec. Γ_H)

Linear e+e- Colliders

◇ $\delta m_H = 14$ MeV

◇ $|\delta y_t|_{dir} \sim 3/1.5\,\%$ CLIC,ILC500/ILC1000

(HE-)LHeC/FCC-eh

◇ precise measurement of pdf, α_S

◇ input for FCC-hh prec. measur.

◇ LHeC parallel to HL-LHC: synergy

FCC-hh

◇ optimal for rare decays & heavy states

◇ sub-percent on all major couplings

◇ precise measur. of diff. distributions

HE-LHC/FCC-hh<100TeV

◇ precise measurements possible

◇ discovery & precision alternative

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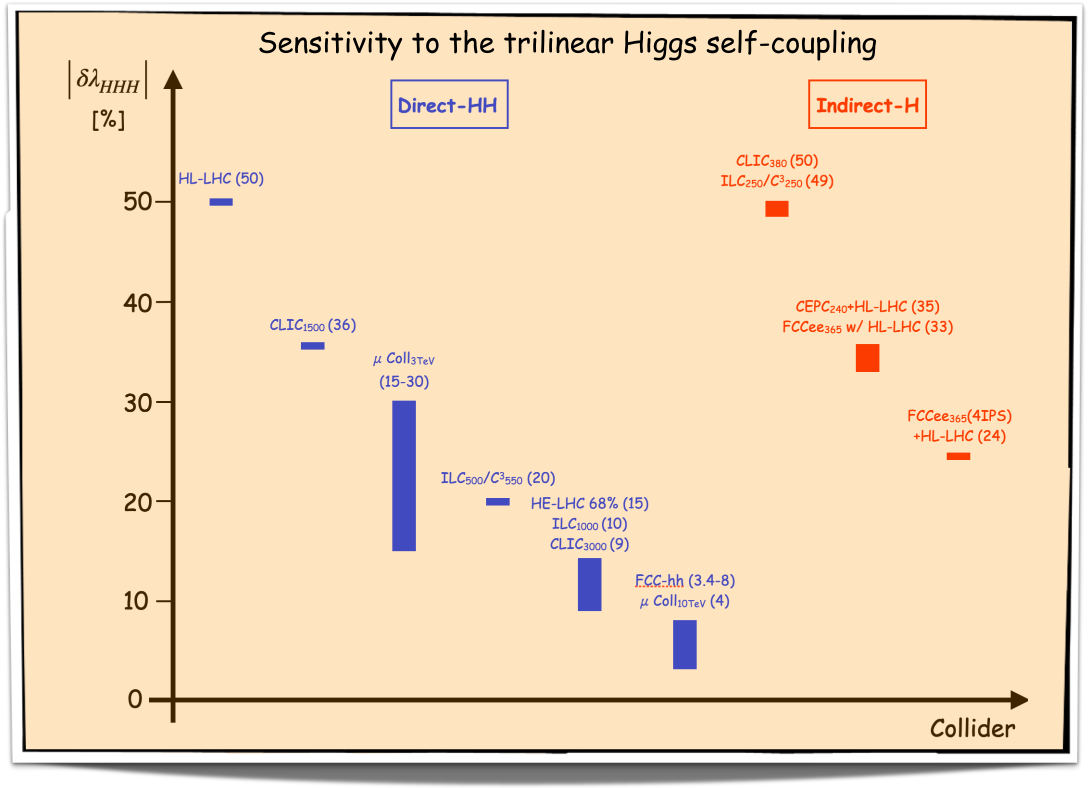
Summary Di-Higgs

Indirect Detection from Single Higgs **Direct Detection from Double Higgs**

- ◇ Single/Di-Higgs: Sensitivity depends on New Physics Scenario
- ◇ Single Higgs: EFT analysis taking into account LO and NLO operators crucial
- ◇ Single/Di-Higgs: Challenge ⇝ determination of all input parameters as precisely as possible, exploit different energies, polarization



Note on λ_{HHHH}: first studies show sensitivity @ HL-LHC, $LC_{>1TeV}$, FCC-hh

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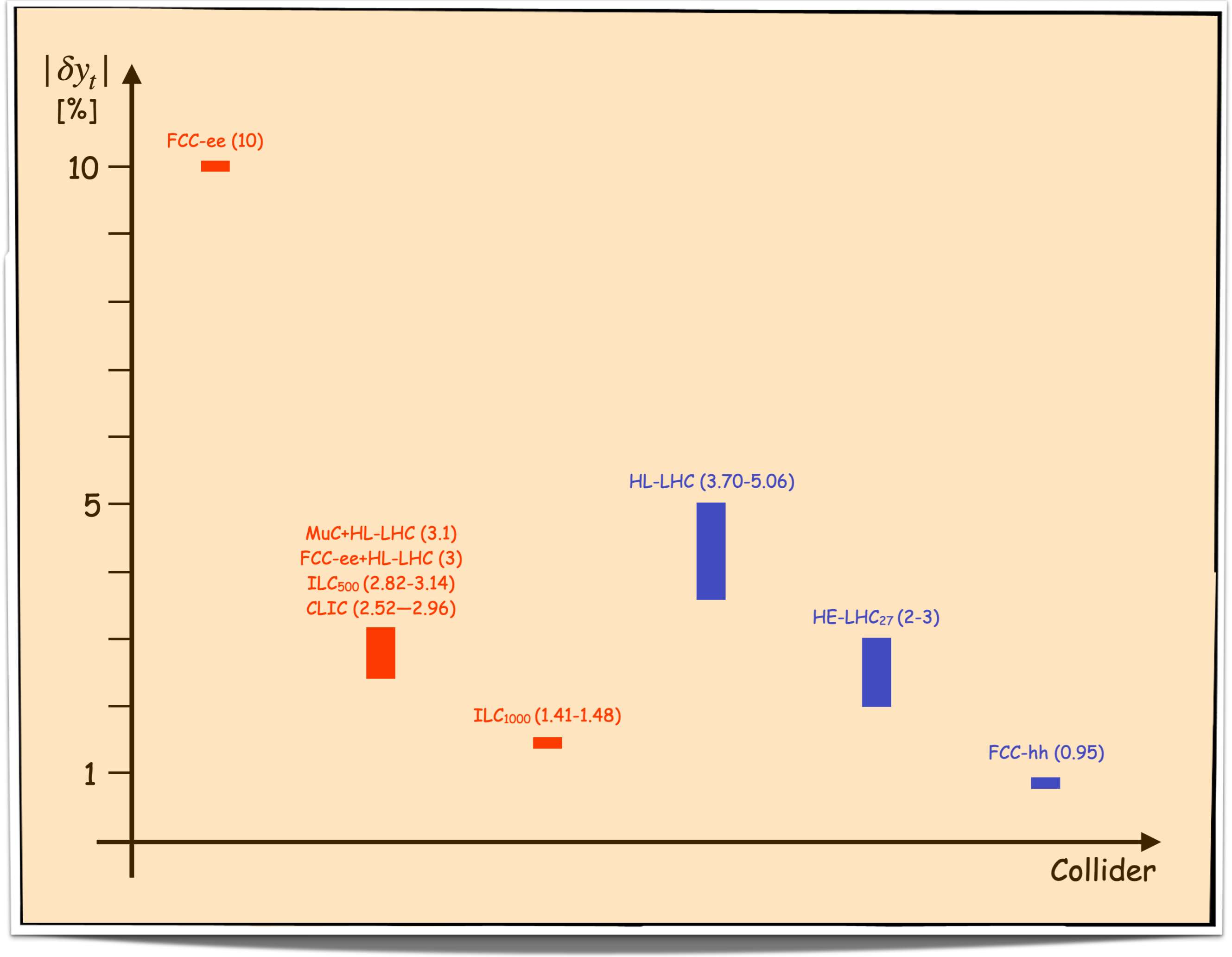
Comparison of Various Collider Options



Higgs Mass Measurement

Higgs mass: comparison w/ other colliders

Today	HL-LHC	ILC_{250}	FCC-ee	muColl
~ 150 MeV	~ 20 MeV	~ 14 MeV	~ 4 MeV	~ 0.21 MeV

[HL-LHC: CMS-PAS-FTR-21-007, CERN-2019-007]
[ILC250: Yan,Watanuki,Fujii,Ishikawa,Jeans,Strube eal,Phys.Rev.D94(2016)113002 [1604.07524]]
[FCC-ee: Bernardi,Dewyspelaere,Eysermans,Li, FCC-Coll, ICHEP2024]
[muC: J. de Blas et al., arXiv:2203.04324 [hep-ph] from lineshape 0.21 MeV]

Precision on Trilinear Higgs Self-Coupling

Taken from: S. Dawson et al., arXiv:2209.07510 [hep-ph]

collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
ILC_{250}/C^3-250 [51, 52]	49%	–	49%
ILC_{500}/C^3-550 [51, 52]	38%	20%	20%
$CLIC_{380}$ [54]	50%	–	50%
$CLIC_{1500}$ [54]	49%	36%	29%
$CLIC_{3000}$ [54]	49%	9%	9%
FCC-ee [55]	33%	–	33%
FCC-ee (4 IPs) [55]	24%	–	24%
FCC-hh [79]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [64]	-	15-30%	15-30%
μ(10 TeV) [64]	-	4%	4%

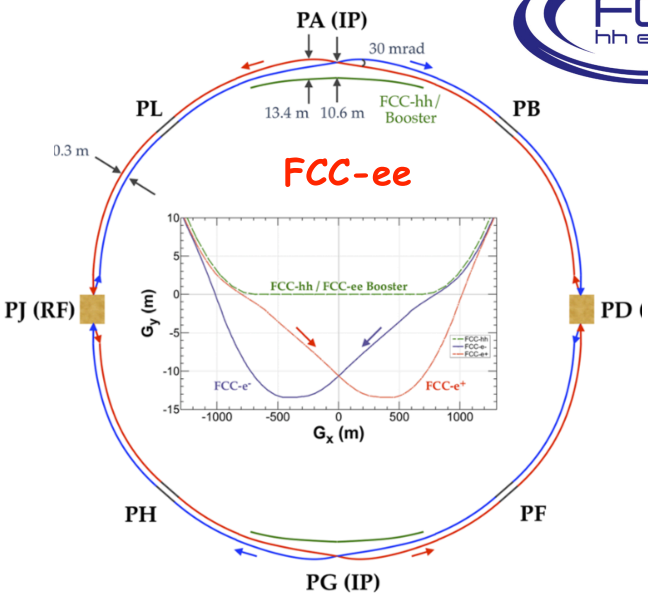
Sensitivity at 68% probability on λ_{hhh}. Values for indirect extraction from single Higgs below the first line are taken from [2]. The quoted values are combined with an independent determination of λ_{hhh} with 50% uncertainty from the HL-LHC. [2] J. de Blas et al., JHEP01 (2020) 139, arXiv:1905.03764 [hep-ph]

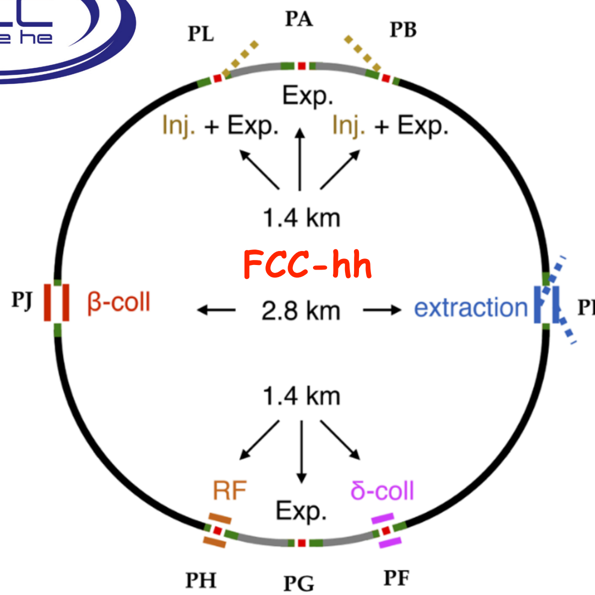
FCC Integrated Program

Stage1: Higgs,top,EW factory at highest luminosities (91->365 GeV)
Stage2: 100 TeV pp, energy frontier
(in addition eh and ion options)

Higgs, top, EW&QCD precision model independence; flavor factory; weakly coupled new physics; prepare for hh

Higgs self-coupling
Higgs-top Yukawa coupling
Heavy new physics





2029-2041	2048-2063	2074-

Colliders and luminosity

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Collider implications

Collider / Observable	LHC	HL-LHC	FCC-ee$_{365}$	CEPC	ILC	CLIC	Muon Collider	HE-LHC 27TeV, 15ab^{-1}	FCC-hh
Single Higgs $\lvert\delta_{VV}\rvert^{exp}$	≲ 7% [1,2]	1.5% [5]	+HL-LHC 0.17% [55]	240/360+ HL-LHC 0.074/ 0.072% [83]	250/500/1000+ HL-LHC 0.22/0.17/ 0.16% [80]	380/500/1000+ HL-LHC 0.44/0.40 /0.39% [7]	3/10TeV+ HL-LHC 0.89/ 0.33% [69]	1.3% [5]	+FCCee/eh 0.12% [80]
$\lvert\delta_{h^3}\rvert^{theor}$	x40	x9	100 %	40 %	130-100%	260-230%	530-200%	x8	72%
Single Higgs $\lvert\delta_{h^3}^{exp}\rvert$			FCC-ee w/HL-LHC **33%** [55] FCCee$_{4IP}$ w/HL-LHC **24%** [55]	CEPC$_{240}$ + HL-LHC **35%** [82]	ILC$_{250}$/ C^3$_{250}$ **49%** [51,52]	CLIC$_{380}$ **50%** [54]			
Di- Higgs $\lvert\delta_{h^3}^{exp}\rvert$	**-1.4-7.5** [3,4]	**50%** [5,6]			ILC$_{500}$/C^3$_{550}$ **20%** [10,51,52] ILC$_{1000}$ **10%** [7]	CLIC$_{1500}$ **36%** [54] CLIC$_{3000}$ **~9%** [9,54]	Muon$_{3TeV}$ **15-30%** [64] Muon$_{10TeV}$ **4%** [64]	95%CL **~30%** [11] 68%CL **~15%** [11]	30 ab^{-1} **3.4-7.8%** [79]

Do we actually have a saying?

- Is the FCC-ee decided? (If so we have a generation of precision physics waiting).

  What can we do to help to approve the FCC-ee?

- Will China build their circular collider? (Decision by end 2025/ beginning 2026).

  What is the alternative for CERN? Or others? (muon collider?)

- Build a physics case for a linear collider? (that compares the different possibilities).

  What motivates the different energies and luminosities?

CP-violation and a Model

CP-violation and a Model, the C2HDM

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.)$$
$$+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2) + h.c.\right]$$

and CP is explicitly and not spontaneously broken

$$<\Phi_1> = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix} \quad <\Phi_2> = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

- **m^2_{12} and λ_5 real** **2HDM**
- **m^2_{12} and λ_5 complex** **C2HDM**

➡ $\tan\beta = \frac{v_2}{v_1}$ ratio of vacuum expectation values

➡ 2 charged, $H^\pm$, and 3 neutral CP-conserving - h, H and A

CP-violating - h_1, h_2 and h_3

➡ rotation angles in the neutral sector CP-conserving – α

CP-violating - α_1, α_2 and α_3

➡ soft breaking parameter

CP-conserving – m^2_{12} CP-violating – $\mathrm{Re}(m^2_{12})$

$$g_{2HDM}^{hVV} = \sin(\beta - \alpha) g_{SM}^{hVV}$$

CP-violating 2HDM

"Pseudoscalar" component (doublet)

$$g_{C2HDM}^{hVV} = \cos\alpha_2 \, g_{2HDM}^{hVV}$$

$$|s_2| = 0 \;\Rightarrow\; h_1 \text{ is a pure scalar,}$$
$$|s_2| = 1 \;\Rightarrow\; h_1 \text{ is a pure pseudoscalar}$$

h_{125} couplings

Type I $\quad \kappa_U^I = \kappa_D^I = \kappa_L^I = \dfrac{\cos\alpha}{\sin\beta}$

Type II $\quad \kappa_U^{II} = \dfrac{\cos\alpha}{\sin\beta} \qquad \kappa_D^{II} = \kappa_L^{II} = -\dfrac{\sin\alpha}{\cos\beta}$

$$Y_{C2HDM} = \cos\alpha_2 Y_{2HDM} \pm i\gamma_5 \sin\alpha_2 \tan\beta (1/\tan\beta)$$

Type F(Y) $\quad \kappa_U^F = \kappa_L^F = \dfrac{\cos\alpha}{\sin\beta} \qquad \kappa_D^F = -\dfrac{\sin\alpha}{\cos\beta}$

Type LS(X) $\quad \kappa_U^{LS} = \kappa_D^{LS} = \dfrac{\cos\alpha}{\sin\beta} \qquad \kappa_L^{LS} = -\dfrac{\sin\alpha}{\cos\beta}$

Three neutral states mix

CP-violating 2HDM $\quad [h_i]_{mass} = [R_{ij}][h_j]_{gauge}$

$$[R_{ij}] = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$

There are many other combinations if one moves away from the alignment limit

$$h_1 \to ZZ(+)\ h_2 \to ZZ(+)\ h_2 \to h_1 Z$$

Combinations of three decays

Forbidden in the exact alignment limit

$$h_1 \to ZZ \Leftarrow CP(h_1) = 1 \qquad h_2 \to ZZ \quad CP(h_2) = 1 \qquad h_2 \to h_1 Z \quad CP(h_2) = -CP(h_1)$$

$$h_3 h_2 Z \quad CP(h_3) = -CP(h_2) \qquad h_3 h_1 Z \quad CP(h_3) = -CP(h_1) \qquad h_2 h_1 Z \quad CP(h_2) = -CP(h_1)$$

$$h_3 \to h_2 h_1 \Rightarrow CP(h_3) = CP(h_2)$$

FONTES, ROMÃO, RS, SILVA, PRD92 (2015) 5, 055014

If the world is too SM-like we need to go to the general C2HDM to find signs of CP-violation. And we need more energy.

Let us go the general 2HDM in the alignment limit (h_1 is SM like). In this case only if we find other particles a search for CP-violation makes sense.

In this limit the vertices that are CP-violating

$$h_3 h_3 h_3; \quad h_3 h_2 h_2; \quad h_3 H^+ H^-; \quad h_3 h_3 h_3 h_1; \quad h_3 h_2 h_2 h_1; \quad h_3 h_1 H^+ H^-;$$

A different choice of the parameters of the potential would interchange h_2 and h_3.

A combination of 3 decays signals CP-violation

$$h_2 H^+ H^-; \quad h_3 H^+ H^-; \quad Z h_2 h_3$$

$$h_2 h_k h_k; \quad h_3 H^+ H^-; \quad Z h_2 h_3; \quad (k = 2, 3) \quad (2 \leftrightarrow 3)$$

$$h_2 h_k h_k; \quad h_3 h_l h_l; ; \quad Z h_2 h_3; \quad (k, l = 2, 3)$$

Haber, Keus, RS, PRD 106 (2022) 9, 095038

CP-violation with a lot of energy

CP-violation with a lot of energy

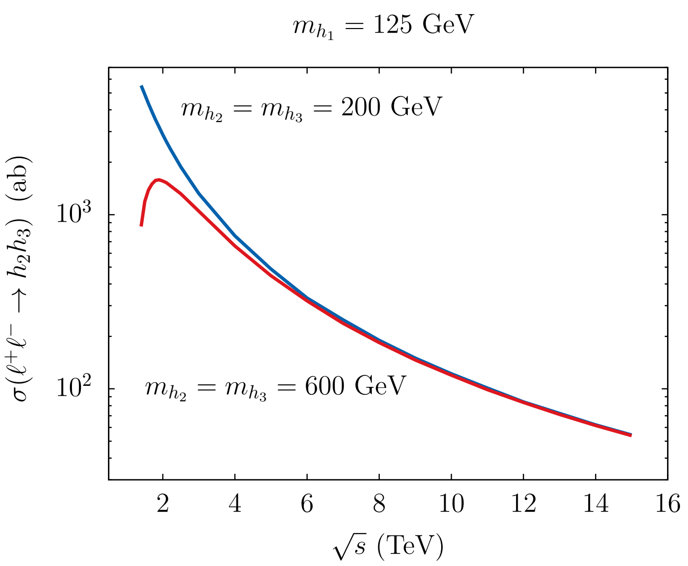
It could happen that at the end of the last LHC run we just move closer and closer to the alignment limit and to a very CP-even 125 GeV Higgs. Considering a few future lepton colliders

Accelerator	$\sqrt{s}$ (TeV)	Integrated luminosity (ab^{-1})
CLIC	1.5	2.5
CLIC	3	5
Muon Collider	3	1
Muon Collider	7	10
Muon Collider	14	20

$$h_2 H^+ H^-; \quad h_3 H^+ H^-; \quad Z h_2 h_3$$

$$h_2 h_k h_k; \quad h_3 H^+ H^-; \quad Z h_2 h_3; \quad (k = 2, 3) \quad (2 \leftrightarrow 3)$$

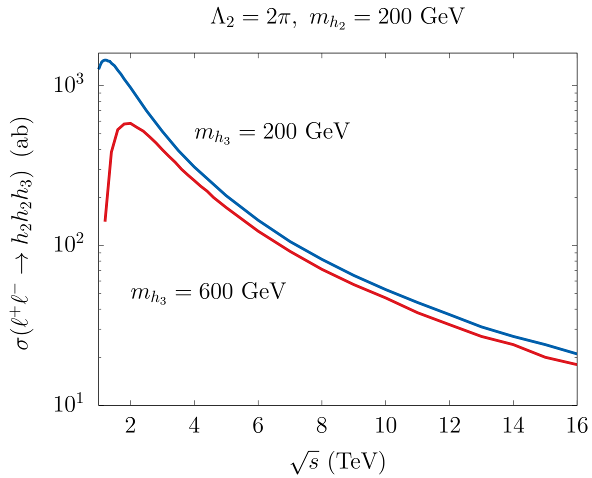
$$h_2 h_k h_k; \quad h_3 h_l h_l; ; \quad Z h_2 h_3; \quad (k, l = 2, 3)$$

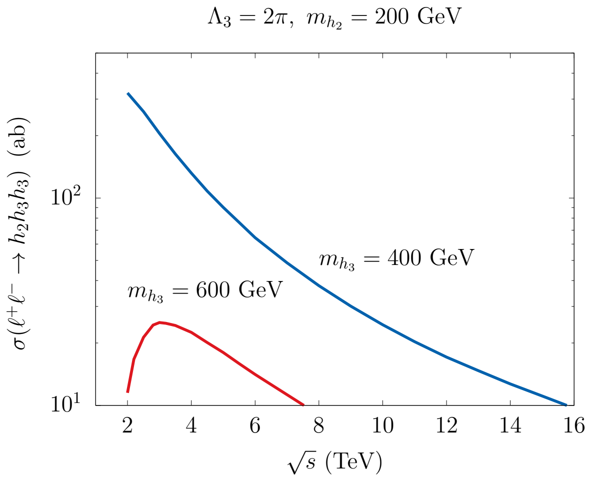


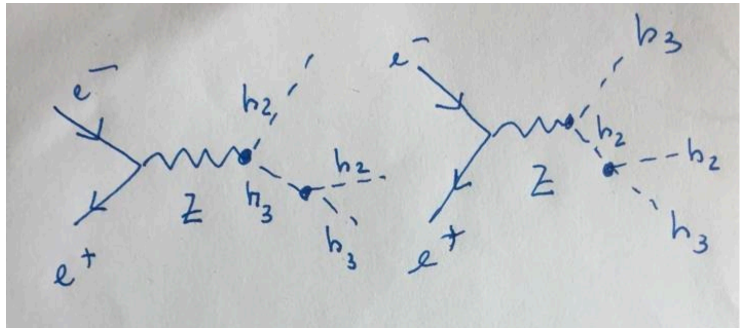
This is an s-channel process with a Z exchange and therefore a gauge coupling. We still need to detect the 2 scalars.

CP-violation with a lot of energy

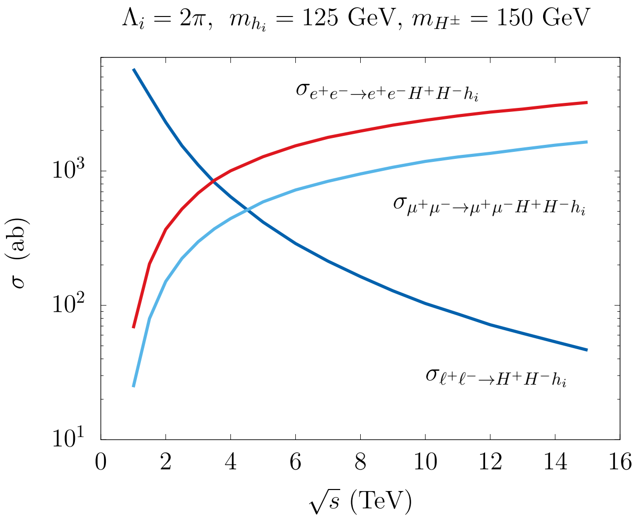
If the new particles are heavier we will need more energy. Still it will be a hard task.

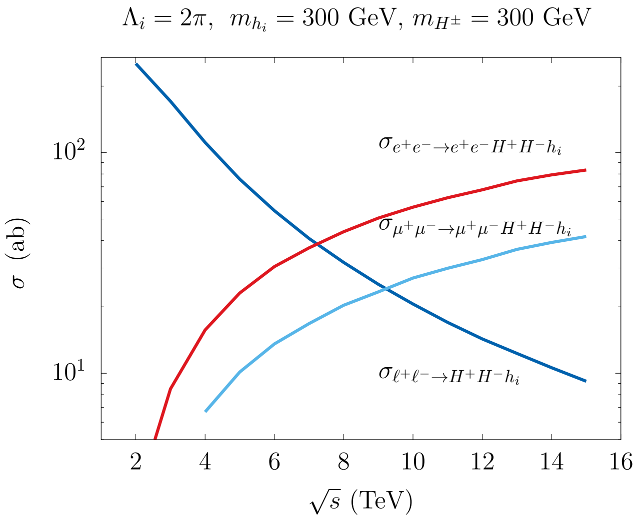


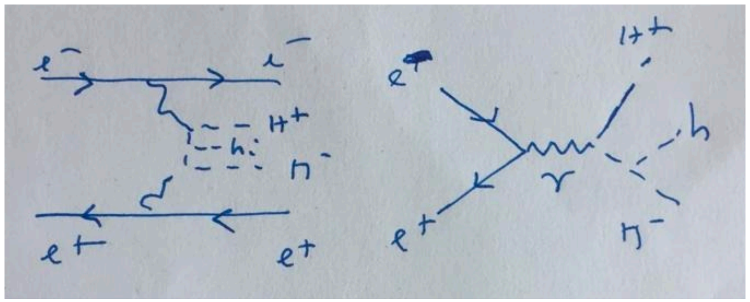




$h_2h_3h_3;\quad h_3h_2h_2;\quad Zh_2h_3$

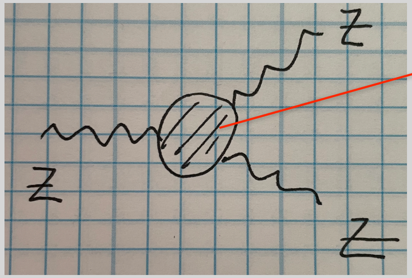






$h_2H^+H^-;\quad h_3H^+H^-;\quad Zh_2h_3$

CP-violation with not so much energy



CP-violation is hidden inside the blob!

Note that these are dimension six operators, They appear at one-loop in renormalisable models. They lead to a finite result with no need for renormalisation.

In the SM $f_4^V = 0$ at one-loop.

CP-violation with not so much energy (ZZZ)

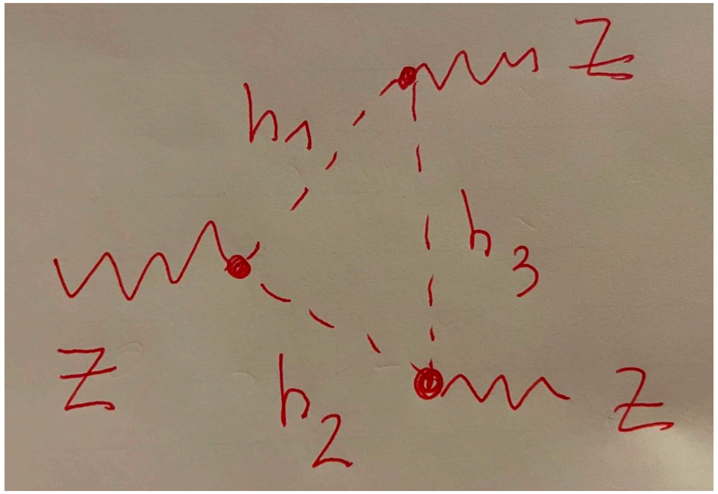
Low energy means to go quantum - look inside loops. Remember CP-violation could be seen via the combination:

$$h_2 \rightarrow h_1 Z \quad CP(h_2) = -\,CP(h_1)$$

$$h_3 \rightarrow h_1 Z \quad CP(h_3) = -\,CP(h_1)$$

$$h_3 \rightarrow h_2 Z \quad CP(h_3) = -\,CP(h_2)$$

If we don't have access to the decays we can build a nice Feynman diagram with the same vertices.



And see if it is possible to extract information from the measurement of the triple ZZZ anomalous coupling.

Can we build such a model? Dark versions in the 3HDM and 2HDM+singlet and also in the C2HDM

3HDM - Cordero-Cid, Hernández-Sánchez, Keus, King, Moretti, Rojas, Sokołowska, JHEP 12 (2016) 014

2HDM+singlet - Azevedo, Ferreira, Mühlleitner, Patel, RS, Wittbrodt, JHEP 1811 (2018) 091

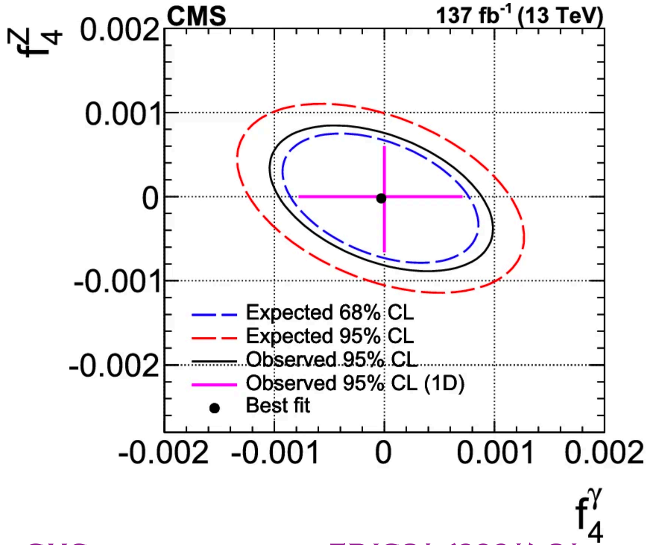
The most general form of the vertex includes a P-even CP-violating term of the form

$$i\Gamma_{\mu\alpha\beta} = -e\frac{p_1^2 - m_Z^2}{m_Z^2} f_4^Z (g_{\mu\alpha}p_{2,\beta} + g_{\mu\beta}p_{3,\alpha}) + \ldots$$

GAEMERS, GOUNARIS, ZPC1 (1979) 259; HAGIWARA, PECCEI, ZEPPENFELD, HIKASA, NPB282 (1987) 253; GRZADKOWSKI, OGREID, OSLAND, JHEP 05 (2016) 025

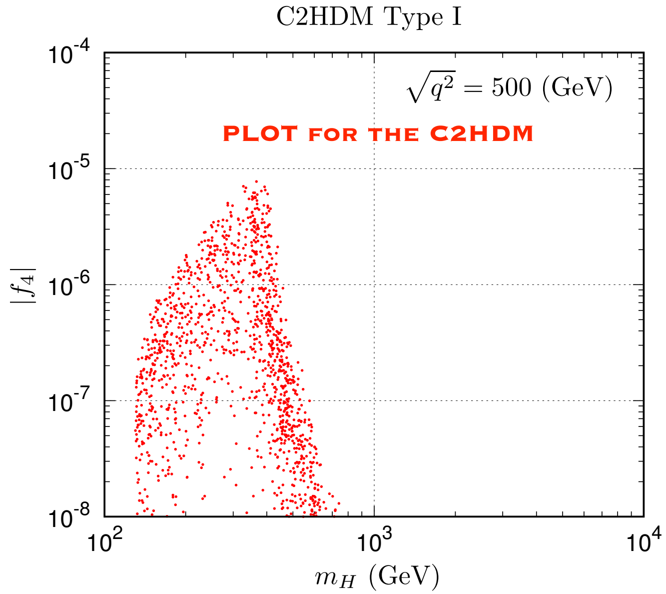
CMS COLLABORATION, EPJC78 (2018) 165. $-1.2 \times 10^{-3} < f_4^Z < 1.0 \times 10^{-3}$

ATLAS COLLABORATION, PRD97 (2018) 032005. $-1.5 \times 10^{-3} < f_4^Z < 1.5 \times 10^{-3}$

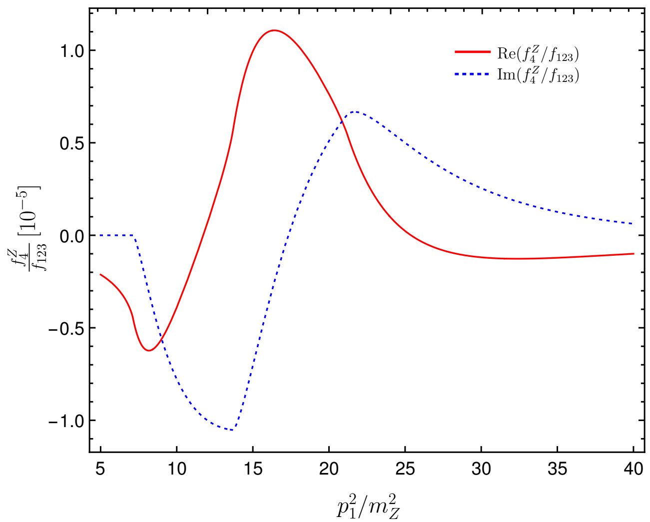


CMS COLLABORATION, EPJC81 (2021) 81.

BÉLUSCA-MAÏTO, FALKOWSKI, FONTES, ROMÃO, SILVA, JHEP 04 (2018) 002



PLOT FOR CP IN THE DARK



AZEVEDO, FERREIRA, MÜHLLEITNER, PATEL, RS, WITTBRODT, JHEP 1811 (2018) 091

The typical maximal value for f_4 seems to be below 10^{-4}.

No studies for future colliders

More CP-violation inside loops

$$\mathscr{L}_{hZZ} = \kappa \frac{m_Z^2}{v} h Z_\mu Z^\mu + \frac{\alpha}{v} h Z_\mu \partial_\alpha \partial^\alpha Z^\mu + \frac{\beta}{v} h Z_{\mu\nu} Z^{\mu\nu} + \frac{\gamma}{v} h Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

ONLY TERM IN THE C2HDM (AND SM) AT TREE-LEVEL

$$i\Gamma^{\mu\nu}_{hWW} = i(g_2 m_w)\left[g^{\mu\nu}\left(1 + a_W - \frac{b_{W1}}{m_W^2}(k_1 \,.\, k_2)\right) + \frac{b_{W2}}{m_W^2} k_1^\nu k_2^\mu + \frac{c_W}{m_W^2}\epsilon^{\mu\nu\rho\sigma} k_{1\rho} \,.\, k_{2\sigma})\right]$$

P-VIOLATING, CP VIOLATION

$$\mathscr{M}(hW^+W^-) \sim a_1^{W^+W^-} m_W^2 \epsilon^*_{W^+} \epsilon^*_{W^-} + a_3^{W^+W^-} f^{*+}_{\mu\nu} \tilde{f}^{*-\,\mu\nu}$$

CP-violation with not so much energy (hWW)

In this case we start with the most general WWh vertex

$$\mathcal{M}(hW^+W^-) \sim a_1^{W^+W^-} m_W^2 \epsilon^*_{W^+}\epsilon^*_{W^-} + a_3^{W^+W^-} f^{*+}_{\mu\nu}\tilde{f}^{*-\,\mu\nu}$$

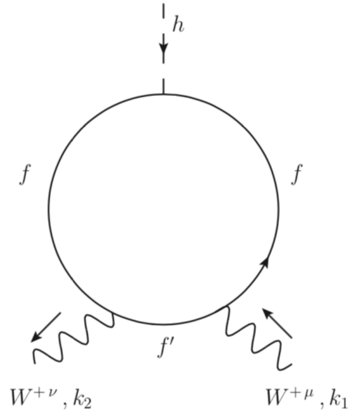
TERM COMING FROM A CPV OPERATOR.
- CONTRIBUTION FROM THE SM AT 2-LOOP
- CONTRIBUTION FROM C2HDM AT 1-LOOP

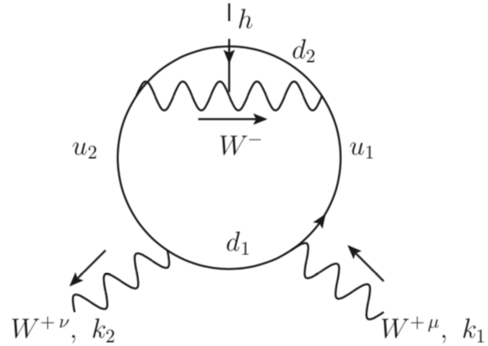
TERM IN THE SM AT TREE-LEVEL
BUT ALSO IN MODELS WITH CP-VIOLATION

$$c_{\rm CPV}^{\rm C2HDM} \simeq 6.6 \times 10^{-4} \sim \mathcal{O}(10^{-3})$$

$$c_{\rm CPV} = 2\frac{a_3^{W^+W^-}}{a_1^{W^+W^-}}$$

$$\frac{a_3^{W^+W^-}}{a_1^{W^+W^-}} \in [-0.81, 0.31]$$





HUANG, MORAIS, RS, JHEP 01 (2021) 168

EXPERIMENTAL BOUND FROM ATLAS AND CMS

CMS COLLABORATION, PRD100 (2019) 112002.

ATLAS COLLABORATION, EPJC 76 (2016) 658.

	Observed/(10^{-3})		Expected/(10^{-3})	
Parameter	68% C.L.	95% C.L.	68% C.L.	95% C.L.
$f_{a3}\cos(\phi_{a3})$	0.00 ± 0.27	[−92, 14]	0.00 ± 0.23	[−1.2, 1.2]

Parameter	Observed/(10^{-3})		Expected/(10^{-3})	
	68% CL	95% CL	68% CL	95% CL
f_{a3}	$0.20^{+0.26}_{-0.16}$	[−0.01, 0.88]	0.00 ± 0.05	[−0.21, 0.21]

CMS COLLABORATION, ARXIV:2205.05120V1.

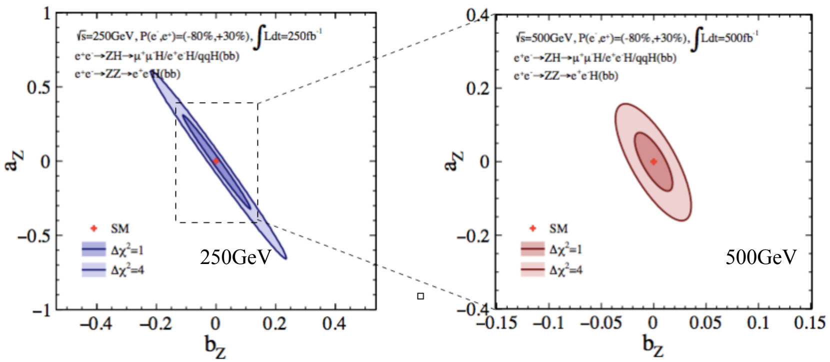
THE BOUND HAS IMPROVED AT LEAST TWO ORDERS OF MAGNITUDE

Anomalous ZZH/γZH couplings

3-parameter fit

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v}+\frac{a_Z}{\Lambda}\right)Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu}H$$

(Λ=1TeV)



SLIDE FROM KEISUKE FUJII'S PRESENTATION AT HIGGS COUPLINGS 2018, TOKYO

SITIVITY PROJECTIONS FOR FUTURE COLLIDERS

5-parameter fit

$ZH + ZZ$ at $250 + 500$ GeV with $H20$

https://arxiv.org/abs/1506.07830

1σ bounds including 500 GeV operation

$$\begin{cases} a_Z = \pm 0.0223 \\ \zeta_{ZZ} = \pm 0.0067 \\ \zeta_{AZ} = \pm 0.0024 \\ \tilde{\zeta}_{ZZ} = \pm 0.0109 \end{cases}, \quad \rho = \begin{pmatrix} 1 & -.837 & -.134 & -.009 & -.010 \\ - & 1 & .040 & .008 & .013 \\ - & - & 1 & .006 & -.0012 \\ - & - & - & 1 & .600 \\ - & - & - & - & 1 \end{pmatrix}$$

($\eta_Z = \pm 0.5\%$)

ZZH / γZH structures can be measured to ~0.5%

The most comprehensive study for futures colliders so far was performed for the ILC. The work presents results are for polarised beams P (e^-, e^+) = (−80%, 30%) and two COM energies 250 GeV (and an integrated luminosity of 250 fb^{-1}) and 500 GeV (and an integrated luminosity 500fb^{-1}). Limits obtained for an energy of 250 GeV were $c^W_{CPV} \in [-0.321, 0.323]$ and $c^Z_{CPV} \in [-0.016, 0.016]$. For 500 GeV we get $c^W_{CPV} \in [-0.063, 0.062]$ and $c^Z_{CPV} \in [-0.0057, 0.0057]$.

OGAWA, PHD THESIS (2018)

THEREFORE MODELS SUCH AS THE C2HDM MAY BE WITHIN THE REACH OF THESE MACHINES. CAN BE USED TO CONSTRAINT THE C2HDM AT LOOP-LEVEL

Thank you!

CP violation from C violation - still observable at the LHC

✦ Example C2HDM T1: H_1=SM-like Higgs CP-even, m_{H3} = 267 GeV

m_{H_1} [GeV]	m_{H_2} [GeV]	$m_{H^\pm}$ [GeV]	α_1	α_2	α_3	$\tan\beta$	Re(m_{12}^2) [GeV^2]
125.09	265	236	1.419	0.004	-0.731	5.474	9929

$\sigma^{\rm NLO}_{H_1H_1}$ [fb]	K-factor	$\Gamma^{\rm tot}_{H_1}$ [GeV]	$\Gamma^{\rm tot}_{H_2}$ [GeV]	$\Gamma^{\rm tot}_{H_3}$ [GeV]	$\Gamma^{\rm tot}_{H^\pm}$ [GeV]
387	2.06	4.106×10^{-3}	3.625×10^{-3}	4.880×10^{-3}	0.127
$\lambda_{3H_1}/\lambda_{3H}$	$y^e_{t,H_1}/y_{t,H}$	$\sigma^{\rm NNLO}_{H_1}$ [pb]	$\sigma^{\rm NNLO}_{H_2}$ [pb]	$\sigma^{\rm NNLO}_{H_3}$ [pb]	
0.995	1.005	49.75	0.76	0.84	

$$\sigma(H_2)\times{\rm BR}(H_2\to H_1H_1) = 191 \text{ fb}, \quad \sigma(H_2)\times{\rm BR}(H_2\to WW) = 254 \text{ fb}$$
$$\sigma(H_2)\times{\rm BR}(H_2\to ZZ) = 109 \text{ fb}, \quad \sigma(H_2)\times{\rm BR}(H_2\to ZH_1) = 122 \text{ fb}$$
$$\sigma(H_3)\times{\rm BR}(H_3\to H_1H_1) = 235 \text{ fb}, \quad \sigma(H_3)\times{\rm BR}(H_3\to WW) = 315 \text{ fb}$$
$$\sigma(H_3)\times{\rm BR}(H_3\to ZZ) = 136 \text{ fb}, \quad \sigma(H_3)\times{\rm BR}(H_3\to ZH_1) = 76 \text{ fb}.$$

CP-even

CP-odd

Abouabid, arhrib, Azevedo, El-falaki, Ferreira, Mühlleitner, RS, JHEP 09 (2022) 011

CP violation from C violation - still observable at the LHC

✦ Example C2HDM T1: H_1=SM-like Higgs CP-even, m_{H3} = 267 GeV

m_{H_1} [GeV]	m_{H_2} [GeV]	$m_{H^\pm}$ [GeV]	α_1	α_2	α_3	$\tan\beta$	$\mathrm{Re}(m_{12}^2)$ [GeV^2]
125.09	265	236	1.419	0.004	-0.731	5.474	9929

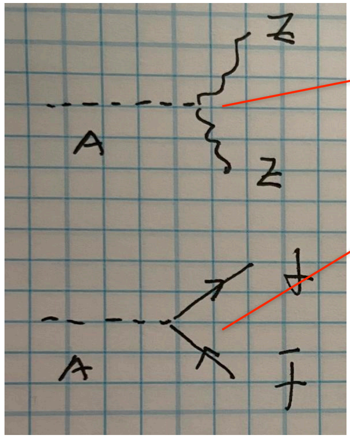
$\sigma^{\rm NLO}_{H_1H_1}$ [fb]	K-factor	$\Gamma^{\rm tot}_{H_1}$ [GeV]	$\Gamma^{\rm tot}_{H_2}$ [GeV]	$\Gamma^{\rm tot}_{H_3}$ [GeV]	$\Gamma^{\rm tot}_{H^\pm}$ [GeV]
387	2.06	4.106×10^{-3}	3.625×10^{-3}	4.880×10^{-3}	0.127
$\lambda_{3H_1}/\lambda_{3H}$	$y^e_{t,H_1}/y_{t,H}$	$\sigma^{\rm NNLO}_{H_1}$ [pb]	$\sigma^{\rm NNLO}_{H_2}$ [pb]	$\sigma^{\rm NNLO}_{H_3}$ [pb]	
0.995	1.005	49.75	0.76	0.84	

$$\sigma(H_2)\times \mathrm{BR}(H_2\to H_1H_1) = 191\ \mathrm{fb}\,,\quad \sigma(H_2)\times \mathrm{BR}(H_2\to WW) = 254\ \mathrm{fb}$$
$$\sigma(H_2)\times \mathrm{BR}(H_2\to ZZ) = 109\ \mathrm{fb}\,,\quad \sigma(H_2)\times \mathrm{BR}(H_2\to ZH_1) = 122\ \mathrm{fb}$$
$$\sigma(H_3)\times \mathrm{BR}(H_3\to H_1H_1) = 235\ \mathrm{fb}\,,\quad \sigma(H_3)\times \mathrm{BR}(H_3\to WW) = 315\ \mathrm{fb}$$
$$\sigma(H_3)\times \mathrm{BR}(H_3\to ZZ) = 136\ \mathrm{fb}\,,\quad \sigma(H_3)\times \mathrm{BR}(H_3\to ZH_1) = 76\ \mathrm{fb}\,.$$

CP-even   CP-odd

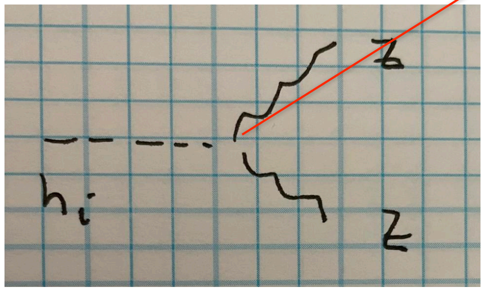
Abouabid, arhrib, Azevedo, El-falaki, Ferreira, Mühlleitner, RS, JHEP 09 (2022) 011

However…

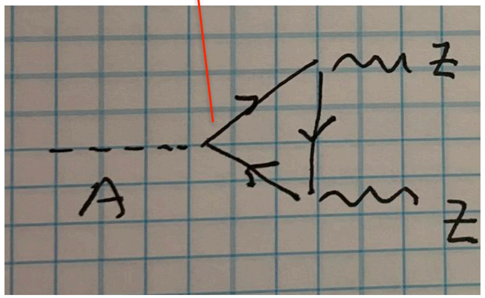


Disallowed in a CP conserving model. A is a pseudoscalar

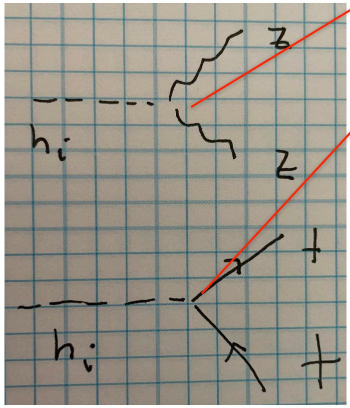
Allowed in a CP-conserving model.

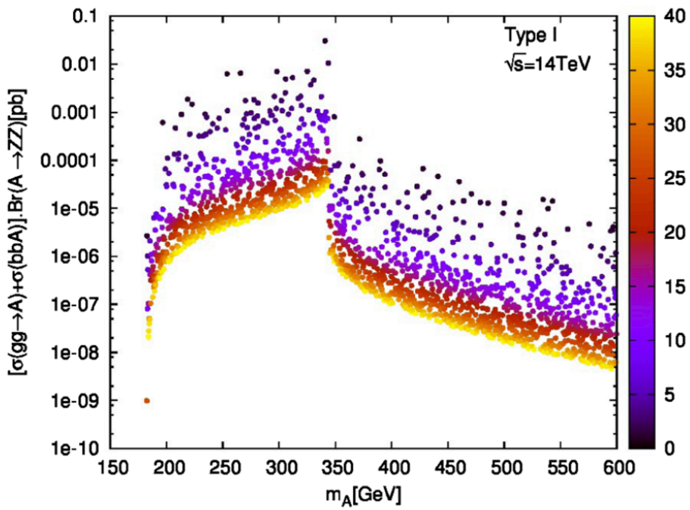


If this tree-level coupling is very small (of the order of the loop process below) it is not possible to distinguish the models.



Both allowed in a CP-violating model.





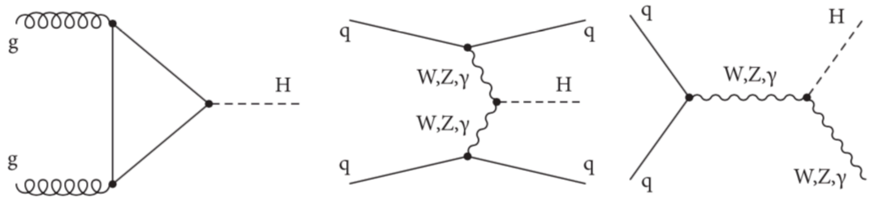
To unambiguously identify CP-violation combine as many CP-sensitive measurements as possible

Arhrib, Benbrik, El Falaki, Sampaio, RS, PRD 99 (2019) 3, 035043

CP-violation with not so much energy (hWW)

$$A(\text{HVV}) \sim \left[a_1^{\text{VV}} + \frac{\kappa_1^{\text{VV}} q_1^2 + \kappa_2^{\text{VV}} q_2^2}{\left(\Lambda_1^{\text{VV}}\right)^2}\right] m_{\text{V}1}^2 \epsilon_{\text{V}1}^* \epsilon_{\text{V}2}^* + a_2^{\text{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\text{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

EFFECTIVE LAGRANGIAN (CMS NOTATION)



CMS COLLABORATION, PRD100 (2019) 112002.

FIG. 1. Examples of leading-order Feynman diagrams for H boson production via the gluon fusion (left), vector boson fusion (middle), and associated production with a vector boson (right). The HWW and HZZ couplings may appear at tree level, as the SM predicts. Additionally, HWW, HZZ, $HZ\gamma$, $H\gamma\gamma$, and Hgg couplings may be generated by loops of SM or unknown particles, as indicated in the left diagram but not shown explicitly in the middle and right diagrams.

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \cdots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right),$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \cdots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right),$$

$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \cdots}, \qquad \phi_{\Lambda 1},$$

$$f_{\Lambda 1}^{Z\gamma} = \frac{\tilde{\sigma}_{\Lambda 1}^{Z\gamma}/(\Lambda_1^{Z\gamma})^4}{|a_1|^2\sigma_1 + \tilde{\sigma}_{\Lambda 1}^{Z\gamma}/(\Lambda_1^{Z\gamma})^4 + \cdots}, \qquad \phi_{\Lambda 1}^{Z\gamma},$$

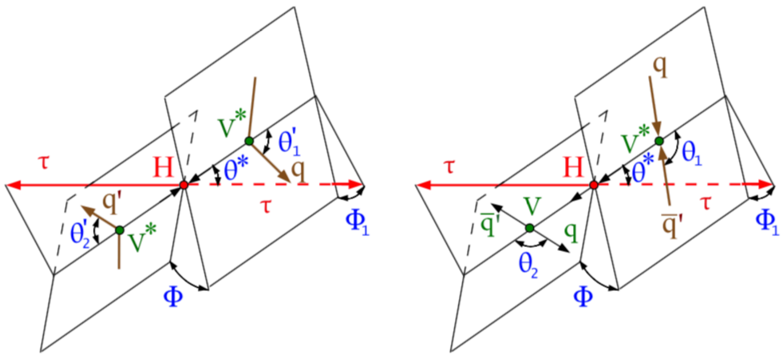
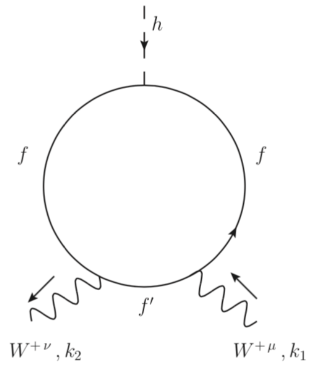


FIG. 2. Illustrations of H boson production in $qq' \to gg(qq') \to H(qq') \to \tau\tau(qq')$ or VBF $qq' \to V^*V^*(qq') \to H(qq') \to \tau\tau(qq')$ (left) and in associated production $q\bar{q}' \to V^* \to VH \to q\bar{q}'\tau\tau$ (right). The $H \to \tau\tau$ decay is shown without further illustrating the τ decay chain. Angles and invariant masses fully characterize the orientation of the production and two-body decay chain and are defined in suitable rest frames of the V and H bosons, except in the VBF case, where only the H boson rest frame is used [26,28].

CP-violation with not so much energy (hWW)

THE C2HDM



Starting with f=t and f'=b

Is it worth it?

$$i\mathcal{M}_{tb}^{\rm C2HDM} \sim \frac{ig^2 N_c c_t^o}{16\pi^2 v}\frac{m_t^2}{m_W^2}|V_{tb}|^2 \epsilon_{\mu\nu\rho\sigma} k_1^\rho k_2^\sigma \mathcal{I}_1\left(\frac{m_t^2}{m_W^2}, \frac{m_b^2}{m_W^2}\right)$$

$$\mathcal{I}_1(x,y) \equiv \int_0^1 d\alpha \frac{\alpha^2}{\alpha x + (1-\alpha)y - \alpha(1-\alpha)}$$

And because f=b and f'=t can also contribute, the final result is

$$c_{\rm CPV}^{\rm C2HDM} = \frac{N_c g^2}{32\pi^2}|V_{tb}|^2\left[\frac{c_t^o m_t^2}{m_W^2}\mathcal{I}_1\left(\frac{m_t^2}{m_W^2}, \frac{m_b^2}{m_W^2}\right) + \frac{c_b^o m_b^2}{m_W^2}\mathcal{I}_1\left(\frac{m_b^2}{m_W^2}, \frac{m_t^2}{m_W^2}\right)\right]$$

$$c_{\rm CPV} = 2\frac{a_3^{W^+W^-}}{a_1^{W^+W^-}}$$

$$c_{\rm CPV}^{\rm C2HDM} \simeq 6.6 \times 10^{-4} \sim \mathcal{O}(10^{-3})$$

USING ALL EXPERIMENTAL (AND THEORETICAL) BOUNDS

HUANG, MORAIS, RS, JHEP 01 (2021) 168