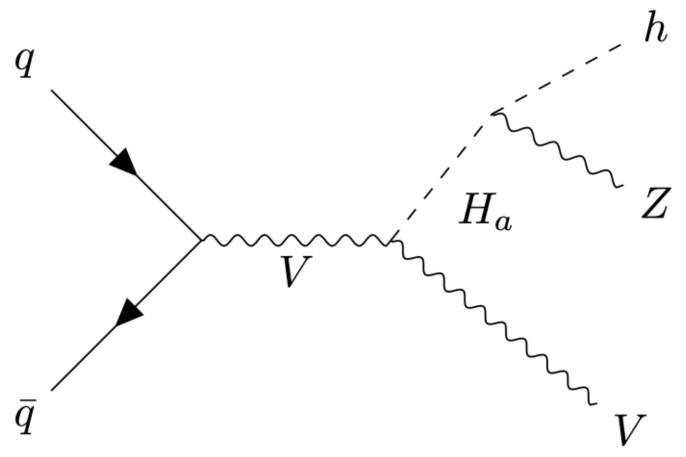
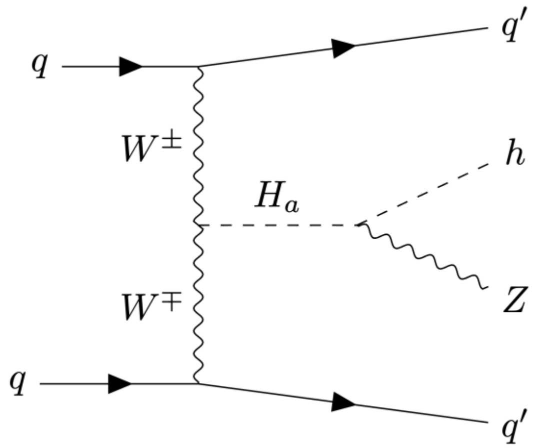




V-associated production & vector boson fusion as an LHC signature of *CP* violation

Álvaro Lozano Onrubia

with Rodrigo Capucha, Luca Merlo, José Miguel No, Rui Santos

June 26, 2026

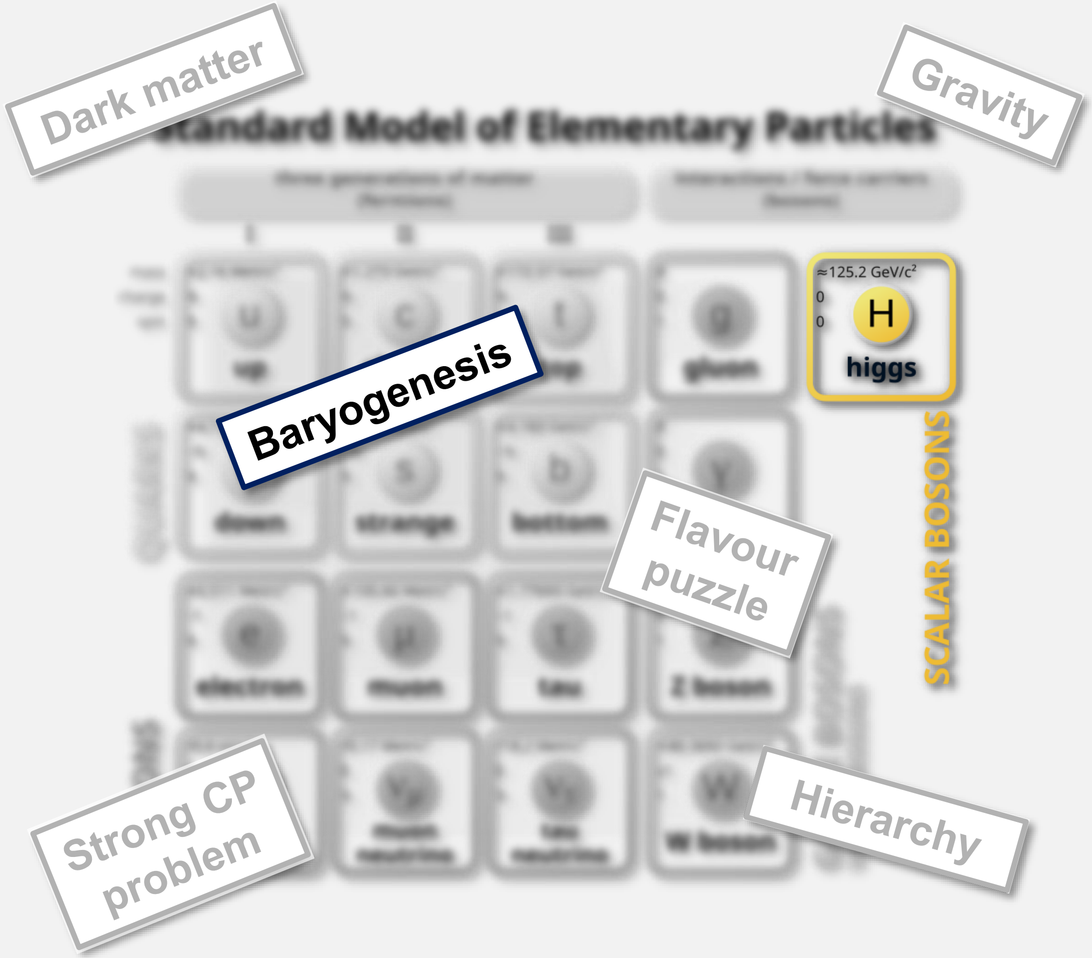
PASCOS 2026

Based on 2507.05942

PRD 112 (2025) 9, 095005

CP violation… in the Higgs sector?

A personal and non-exhaustive take

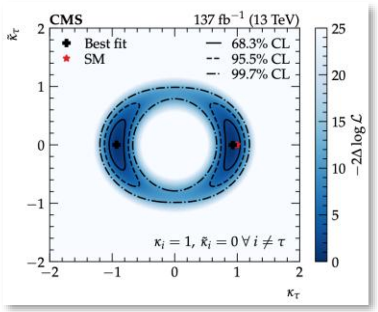


Matter-antimatter asymmetry

CP violation (CPV) **in SM insufficient!**

Gavela, M. B. et al. (1994). Nucl. Phys. B, 430(2), 345-381.
Gavela, M. B. et al. (1994). Nucl. Phys. B, 430(2), 382-426.

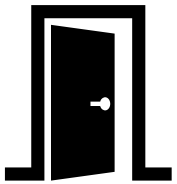
CP properties of SM Higgs



Yukawa & gauge couplings…

… SM-***like!***

CMS – 2110.04836

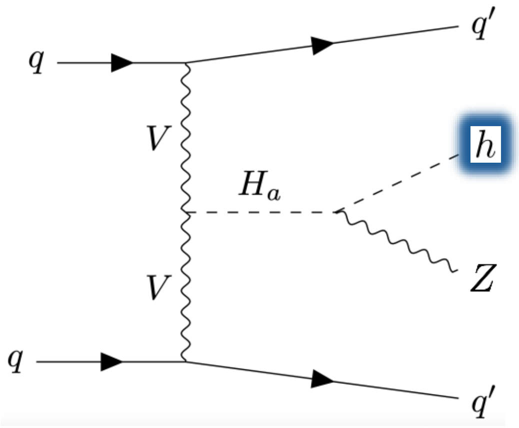


*CPV in **BSM** Higgs sector?*

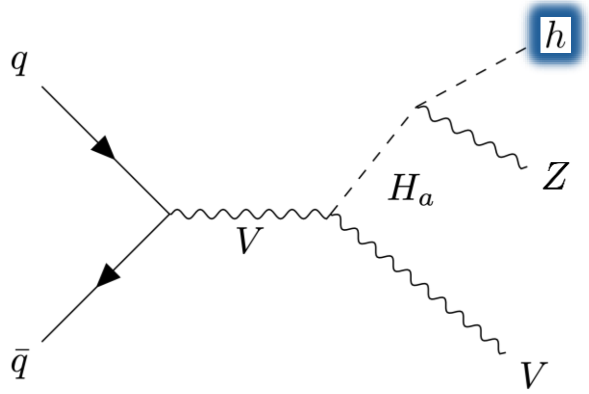
Unlocking the power of the LHC

Searches of *CPV* in extended scalar sectors

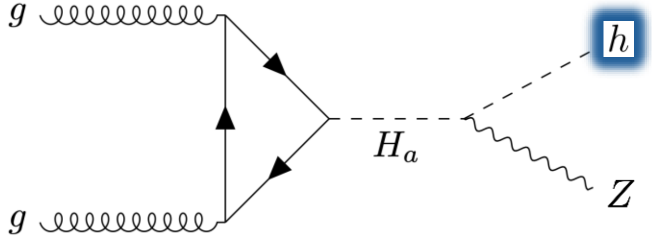
Vector boson fusion *(VBF)*



V-associated production *(V-AP)*



Gluon fusion assisted (*ggF*)

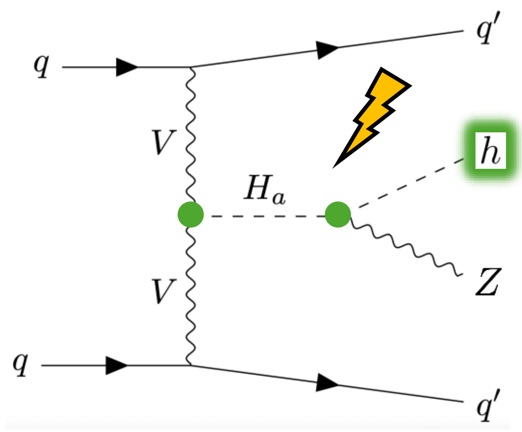


Throughout the talk:
h is the SM-like, a priori *CP*-even Higgs with $m_h = 125$ GeV

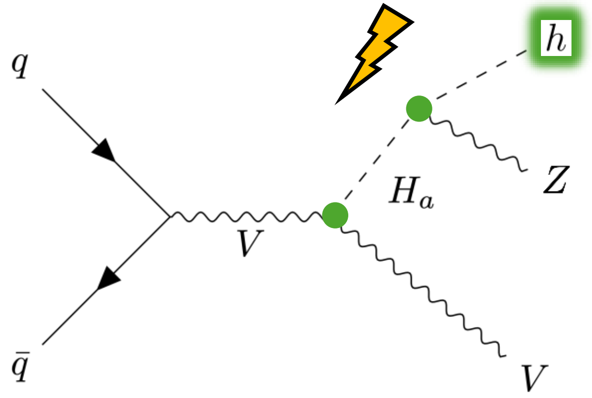
Unlocking the power of the LHC

Searches of *CPV* in extended scalar sectors

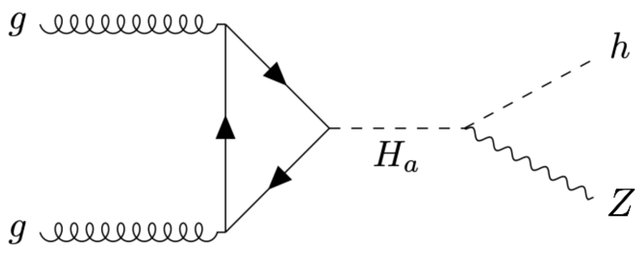
Vector boson fusion *(VBF)*



V-associated production *(V-AP)*



Gluon fusion assisted *(ggF)*



1) $H_a \to VV$: $\boldsymbol{H_a}$ **is CP-even!** *(provided loop-effects are small)*

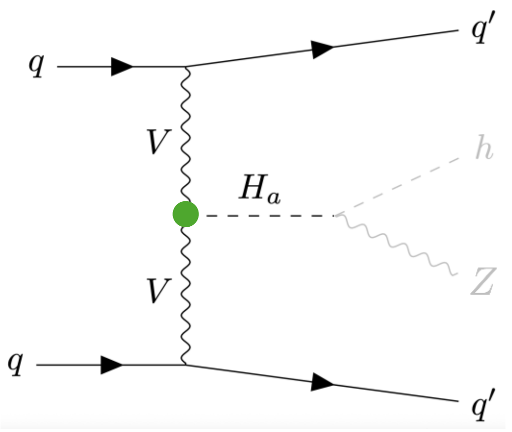
2) $H_a \to Zh$: ***opposite CP assignments*** *in renormalizable theory* ➡ **Signals of *CPV* !**

3) $\boldsymbol{h}$ *is a priori* ***CP-even***

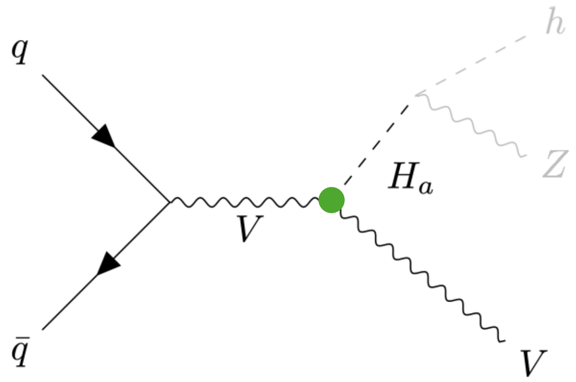
Unlocking the power of the LHC

Searches of *CPV* in extended scalar sectors

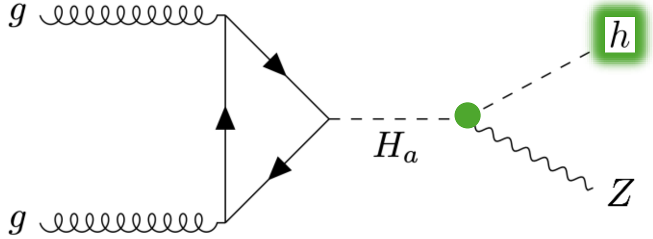
Vector boson fusion *(VBF)*



V-associated production *(V-AP)*



Gluon fusion assisted (*ggF*)



***ggF*-assisted *CPV* signal** ➡

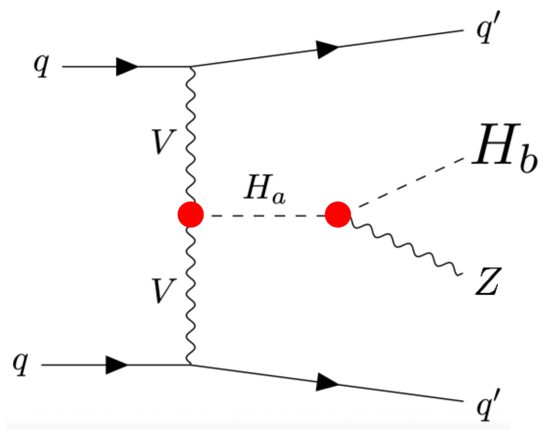
Benefit from **larger cross sections…**

… but need **concurrent pure *VBF*** or ***V-AP* of H_a** !

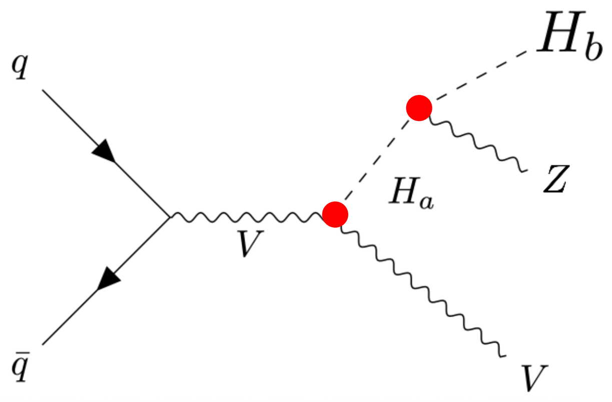
Unlocking the power of the LHC

Venturing beyond the 125 GeV Higgs

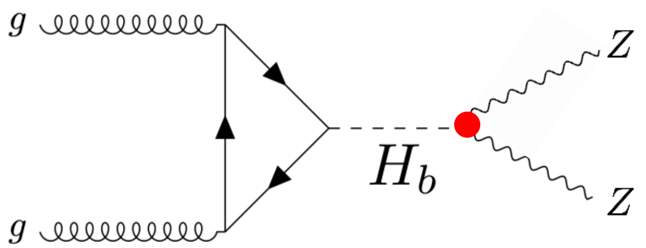
Vector boson fusion *(VBF)*



V-associated production *(V-AP)*



Gluon fusion assisted (*ggF*)



Same spiel with ***two BSM scalars BUT:***

trade CP knowledge of h for ***another process***

Unlocking the power of the LHC

LHC joint signatures of *CPV* featuring *V-AP* and/or *VBF*

Each set (i) – (vii) is a **self-sufficient joint signature** of CPV.

Is there any set where *all* processes are observable?

(i) $pp \to VH_a,\, H_a \to Zh$

(ii) *VBF* production of $H_a,\, H_a \to Zh$

(iii) $pp \to VH_a,\, H_a \to ZH_b$ as well as $pp \to VH_b$

(iv) *VBF* production of $H_a,\, H_a \to ZH_b$ as well as *VBF* of H_b

(v) *ggF* production of H_a decaying via $H_a \to ZH_b$, as well as $pp \to VH_{a,b}$ or *VBF* of both $H_{a,b}$

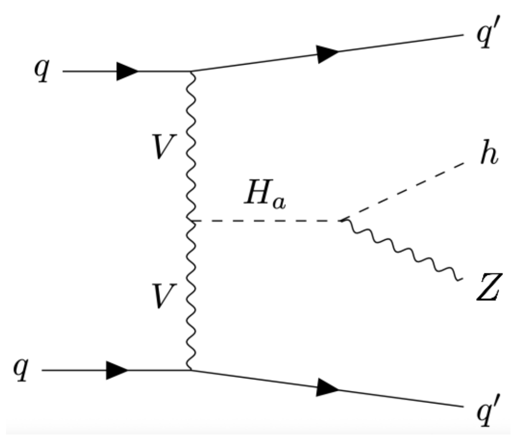
(vi) *ggF* production of H_a decaying both via $H_a \to ZH_b$ and $H_a \to VV$ (or $H_a \to H_bH_b$), as well as $pp \to VH_b$ (or *VBF* of H_b)

(vii) *ggF* production of H_a decaying via $H_a \to Zh$, as well as $pp \to VH_a$ (or *VBF* production of H_a)

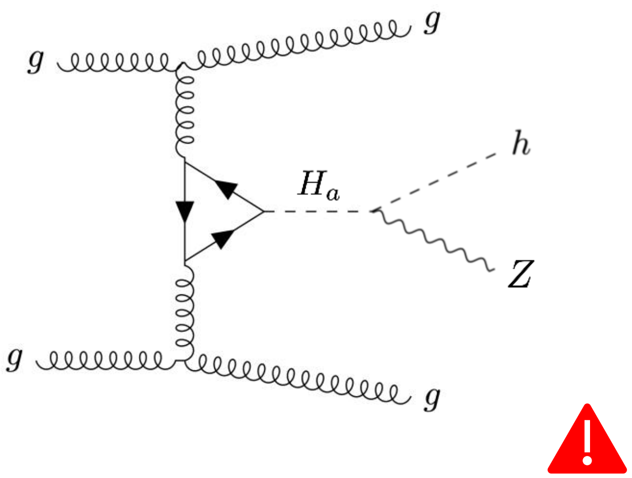
Unlocking the power of the LHC

A few words of caution for *VBF*

Vector boson fusion *(VBF)*



Gluon fusion + 2 gluon jets

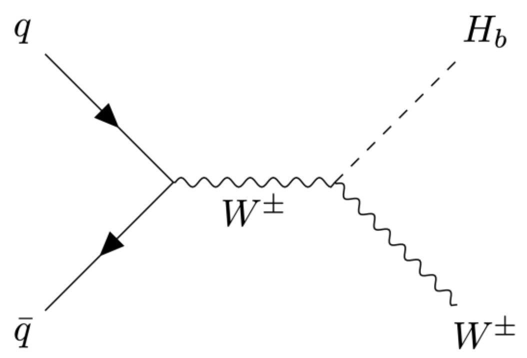


- Contamination from ***ggF+jj*** process which **does not fix *would-be* CP properties of H_a**
- Possible improvement through **cuts** as in SM… but ***ggF-to-VBF ratio*** unknown *a priori* (BSM)
- Optimized ***quark-gluon jet tagging*** might solve this

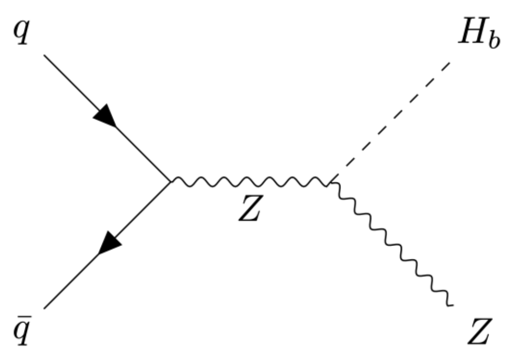
Unlocking the power of the LHC

A few words of caution for *V-AP*

V-associated production *(V-AP)*



V-associated production *(V-AP)*



Avoids background from *ggF* → intermediate **neutral scalars**

Only small background from qq → intermediate **charged scalars** (e.g. 2HDMs)

Benchmarking the LHC

Complex Two-Higgs-Doublet Model (C2HDM)

$$V = m_{11}^2|\Phi_1|^2+m_{22}^2|\Phi_2|^2-\left(\boxed{m_{12}^2}\Phi_1^\dagger\Phi_2 + \text{h.c.}\right)+\frac{\lambda_1}{2}|\Phi_1|^4+\frac{\lambda_2}{2}|\Phi_2|^4+\lambda_3|\Phi_1|^2|\Phi_2|^2+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)+\left[\frac{\boxed{\lambda_5}}{2}(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right]$$

Two *SU(2)* doublets

$$\Phi_j = \begin{pmatrix} \phi_j^+ \\ \frac{v_j+\rho_j+i\eta_j}{\sqrt{2}} \end{pmatrix}$$

with

$$\tan\beta \equiv \frac{v_2}{v_1}$$

CPV phases

1 independent phase

$$\delta \equiv \text{Arg}[(m_{12}^2)^2\lambda_5^*]$$

Scalar spectrum

3 neutral + <u>CP-indefinite</u>

$$H_1,\ H_2,\ H_3$$

$$m_{H_1} \le m_{H_2} \le m_{H_3}$$

2 charged

$$H^\pm \dashrightarrow m_{H^\pm}$$

+ 3 Goldstones

Mass basis

$$R = \begin{pmatrix} c_1c_2 & s_1c_2 & s_2 \\ -(c_1s_2s_3+s_1c_3) & c_1c_3-s_1s_2s_3 & c_2s_3 \\ -c_1s_2c_3+s_1s_3 & -(c_1s_3+s_1s_2c_3) & c_2c_3 \end{pmatrix}$$

$$s_i,\ c_i \equiv \sin\alpha_i,\ \cos\alpha_i$$

$$-\pi/2 < \alpha_{1,2,3} \le \pi/2$$

hep-ph/0211371, 1408.2534, 1502.01720, 1711.09419, 2403.02425

Benchmarking the LHC

Complex Two-Higgs-Doublet Model (C2HDM)

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - \left(\boxed{m_{12}^2}\Phi_1^\dagger\Phi_2 + \text{h.c.}\right) + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left[\frac{\boxed{\lambda_5}}{2}(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right]$$

Angular parameters

$$\tan\beta \equiv \frac{v_2}{v_1}$$

$$s_i,\, c_i \equiv \sin\alpha_i,\, \cos\alpha_i$$

Yukawa couplings

	u-type	d-type	leptons
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-Specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

	u-type	d-type	leptons
Type I	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$
Type II	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$
Lepton-Specific	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$
Flipped	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$

1711.09419

Mass basis

$$R = \begin{pmatrix} c_1c_2 & s_1c_2 & s_2 \\ -(c_1s_2s_3 + s_1c_3) & c_1c_3 - s_1s_2s_3 & c_2s_3 \\ -c_1s_2c_3 + s_1s_3 & -(c_1s_3 + s_1s_2c_3) & c_2c_3 \end{pmatrix}$$

hep-ph/0211371, 1408.2534, 1502.01720, 1711.09419, 2403.02425

Gauge couplings

$$[H_i, W_\mu^+, W_\nu^-] = i\, gM_W\, g_{\mu\nu}\, [R_{i1}\cos(\beta) + R_{i2}\sin(\beta)] \equiv i\, gM_W\, g_{\mu\nu}\, C_i$$

$$[H_i, Z_\mu, Z_\nu] = i\,\frac{gM_Z}{c_W}\, g_{\mu\nu}\, [R_{i1}\cos(\beta) + R_{i2}\sin(\beta)] \equiv i\,\frac{gM_Z}{c_W}\, g_{\mu\nu}\, C_i$$

1711.09419

Benchmarking the LHC

Setting up the scan

HDECAY
Djouadi et al. - 1801.09506
Branching ratios of scalars

SusHi
Harlander et al. - 1605.03190
ggF Higgs production

MadGraph
J. Alwall et al. - 1405.0301
V-AP cross sections

Scan parameters

$-\pi/2 \leq \alpha_i \leq \pi/2$ $\quad$ $70\,\mathrm{GeV} \leq m_{H^\pm} \leq 500\,\mathrm{GeV}$

$0.8 \leq \tan\beta \leq 35$ $\quad$ $0.1\,\mathrm{GeV}^2 \leq \Re(m_{12}^2) \leq 10^5\,\mathrm{GeV}^2$

1

$40\,\mathrm{GeV} \leq m_{H_1} \leq 120\,\mathrm{GeV}$

$m_{H_2} = 125\,\mathrm{GeV}$

2

$m_{H_1} = 125\,\mathrm{GeV}$

$130\,\mathrm{GeV} \leq m_{H_2} \leq 500\,\mathrm{GeV}$

ScannerS
Mühlleitner et al. - 2007.02985

Theoretical constraints
Perturbative unitarity
Vacuum stability
Boundedness from below

Flavor

EW precision

Higgs searches

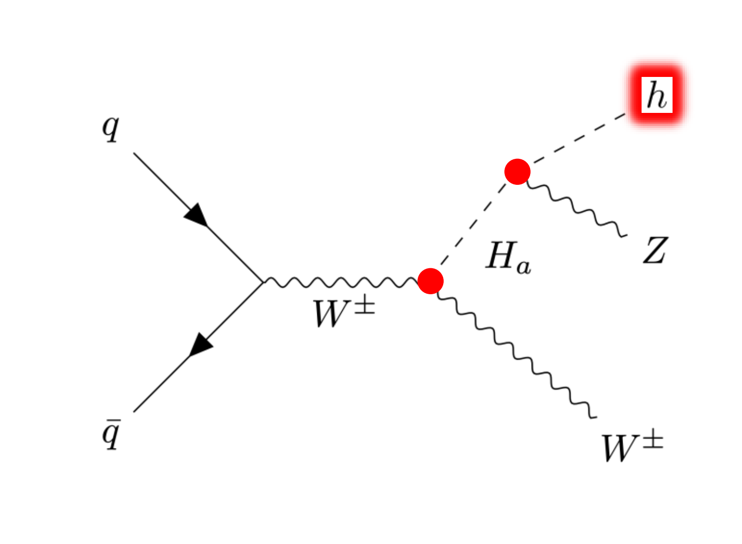
HiggsTools
Bahl et al. - 2210.09332

with & without electron EDMs
$d = 4.1 \times 10^{-30} e\ cm$
Roussy et al. – 2212.11841

Results

Set (i): Probing *CPV* with poster child *W-AP* ?

V-associated production (V-AP)

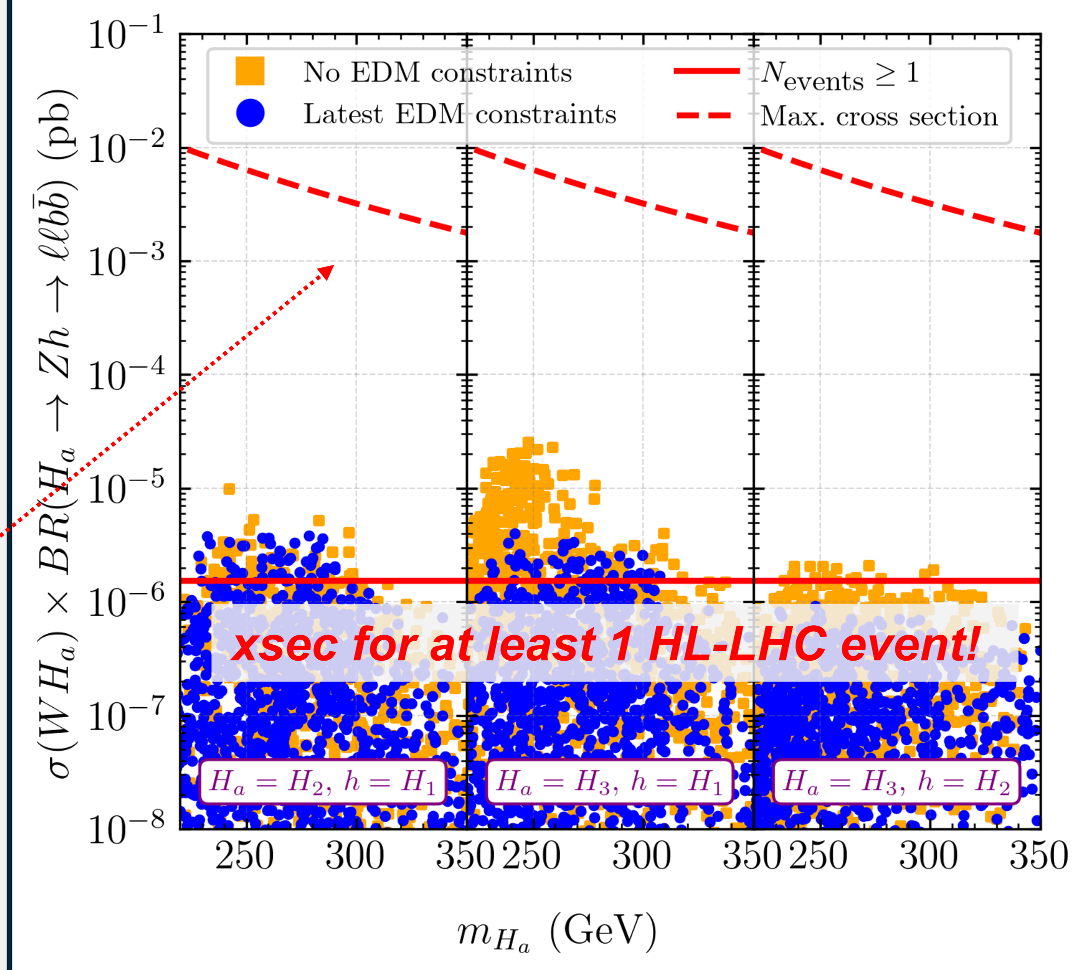


Theoretically maximal cross sections!

$L_{int} = 3\ ab^{-1}$

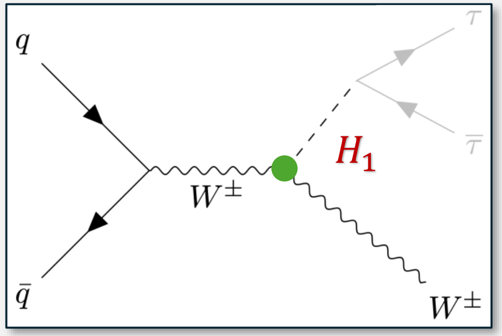
$W \to \ell\nu$

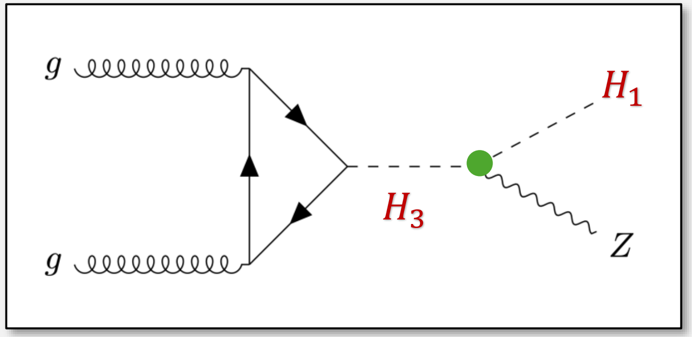
$\mathcal{O}(1)$ **events**

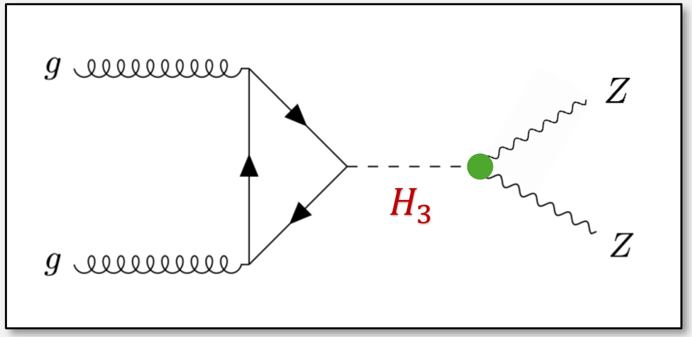


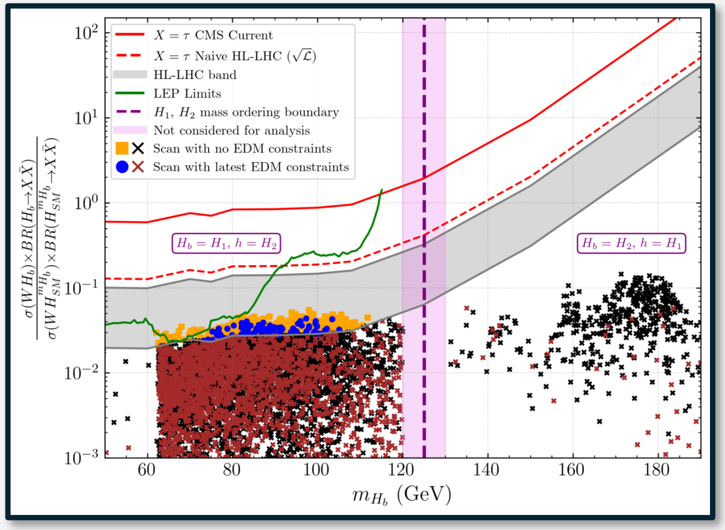
Results

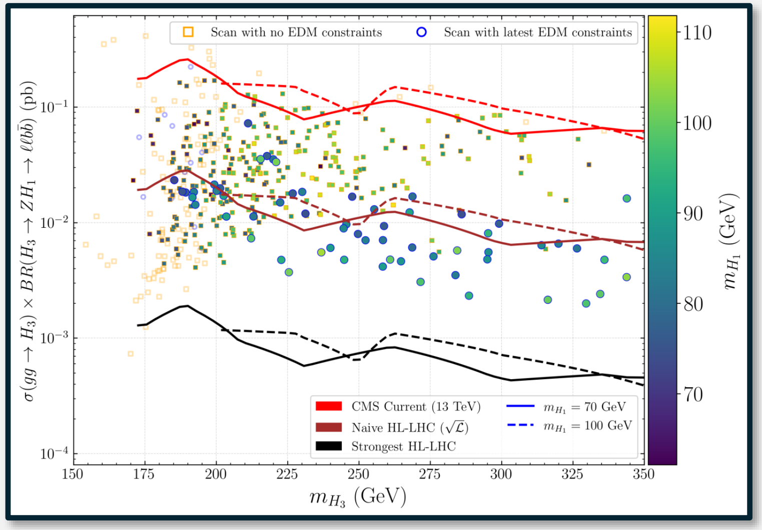
Set (vi): Example of a joint CPV signature

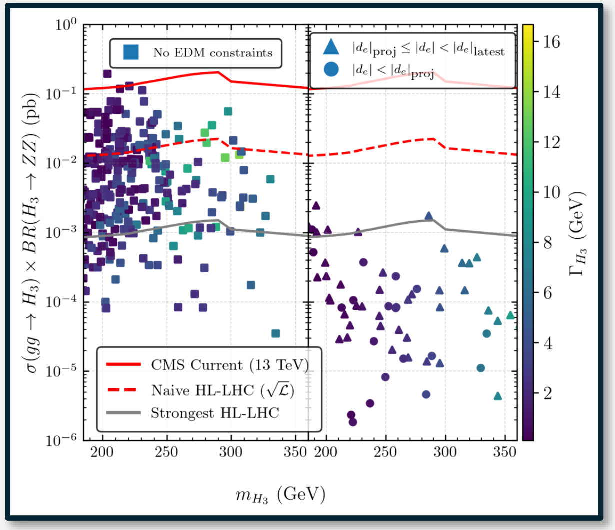








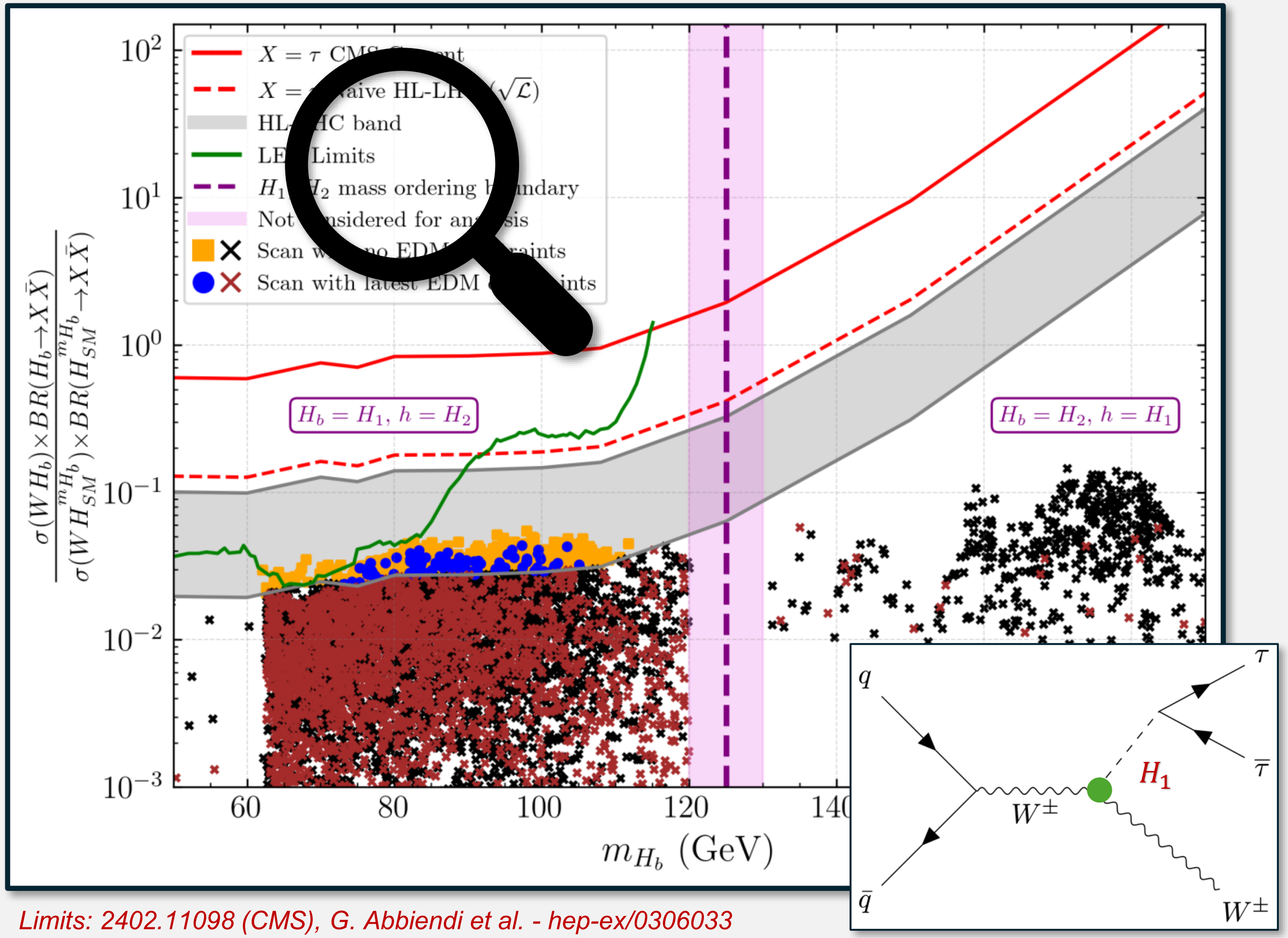


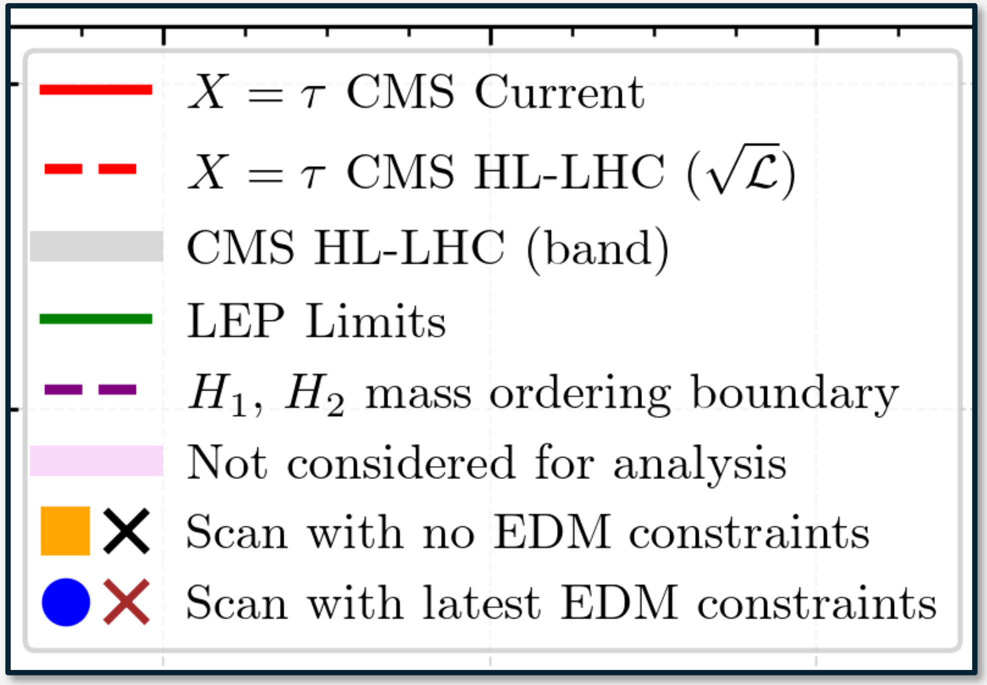


Results

Set (vi): W-AP of lightest non-SM Higgs in the C2HDM

W-AP in C2HDM normalized to *W-AP* of *same-mass* SM Higgs



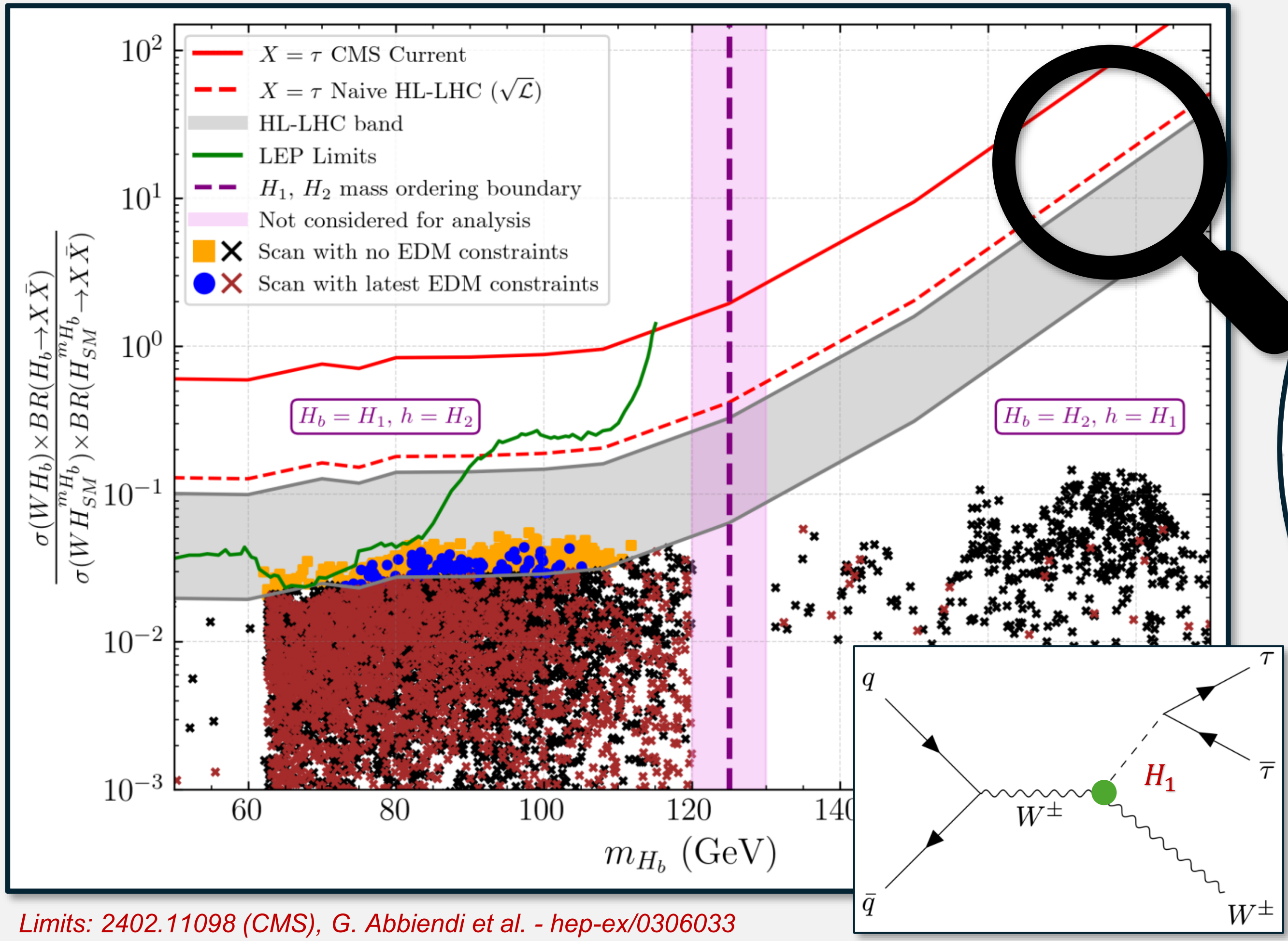


Limits: 2402.11098 (CMS), G. Abbiendi et al. - hep-ex/0306033

Results

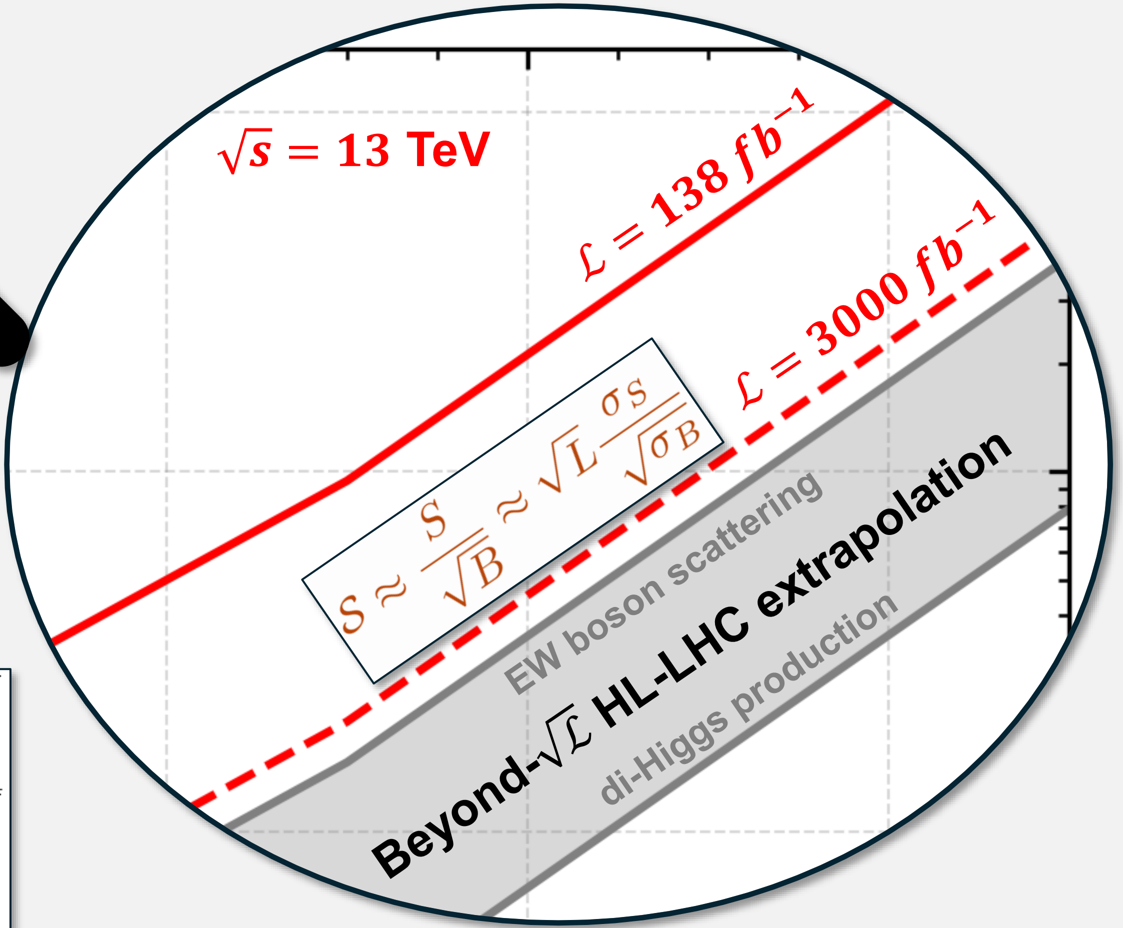
Set (vi): W-AP of lightest non-SM Higgs in the C2HDM

W-AP in C2HDM normalized to *W-AP* of *same-mass* SM Higgs



Limits: 2402.11098 (CMS), G. Abbiendi et al. - hep-ex/0306033

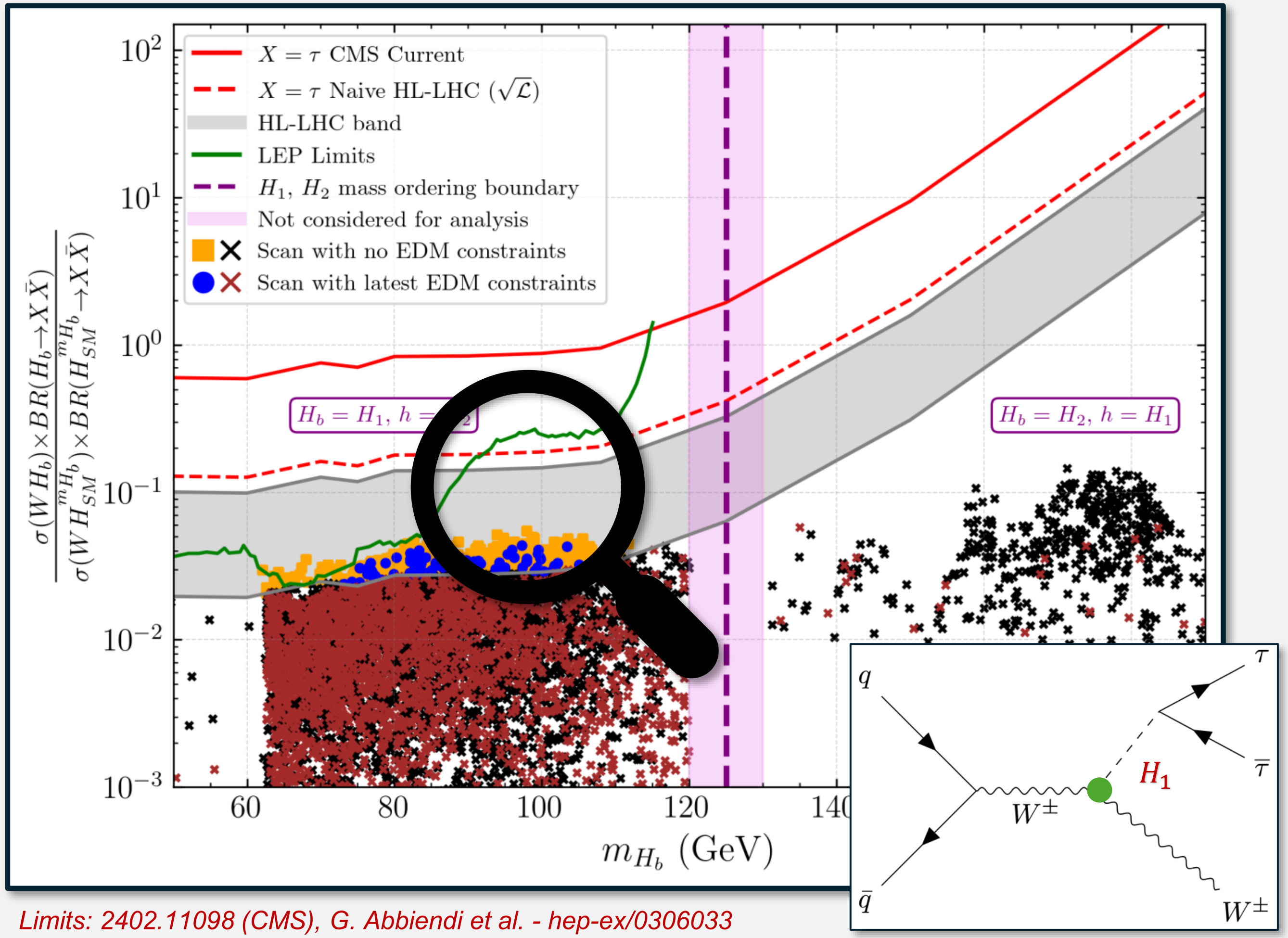
Statistics vs heuristics

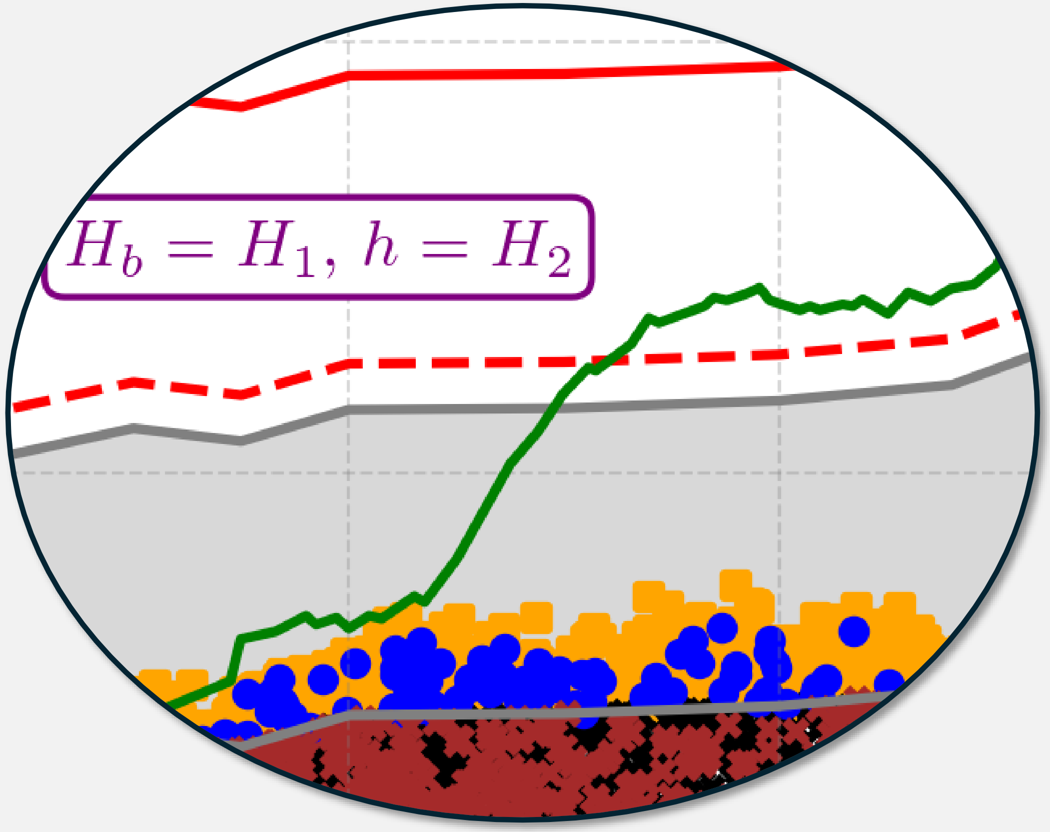


Results

Set (vi): W-AP of lightest non-SM Higgs in the C2HDM

_W-AP_ in C2HDM normalized to _W-AP_ of _same-mass_ SM Higgs





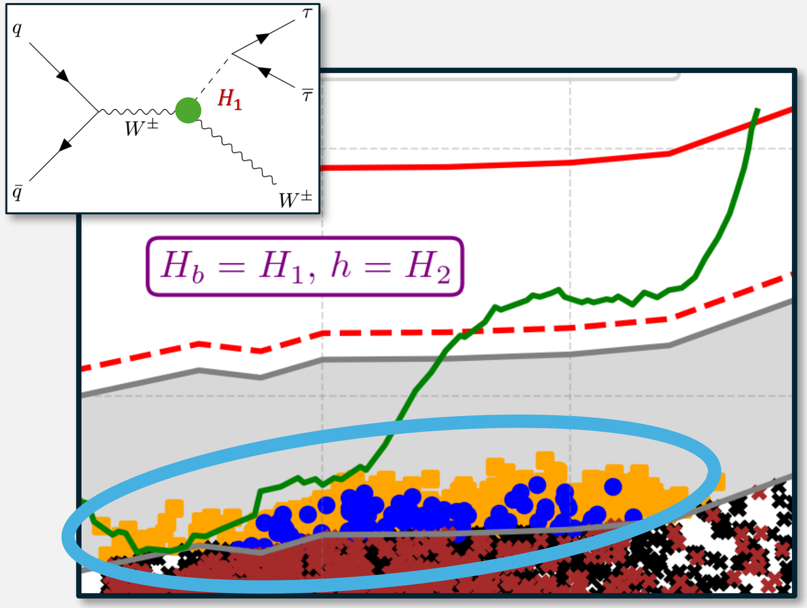
Limits: 2402.11098 (CMS), G. Abbiendi et al. - hep-ex/0306033

LEP limits: ***"Where does suppression come from?"***

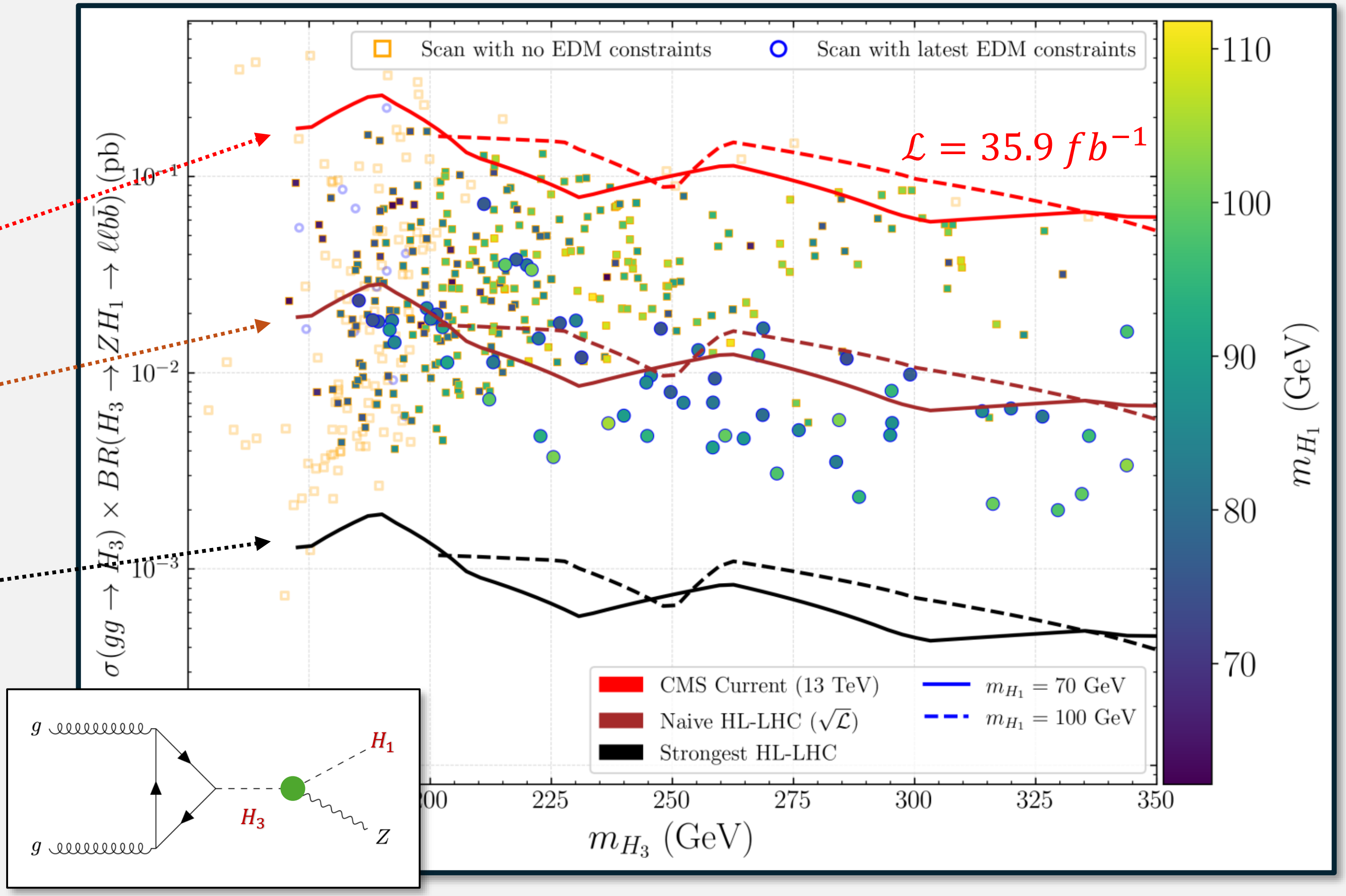
Results

Set (vi): reliance on $gg \to H_3 \to ZH_1$

W-AP in C2HDM normalized …



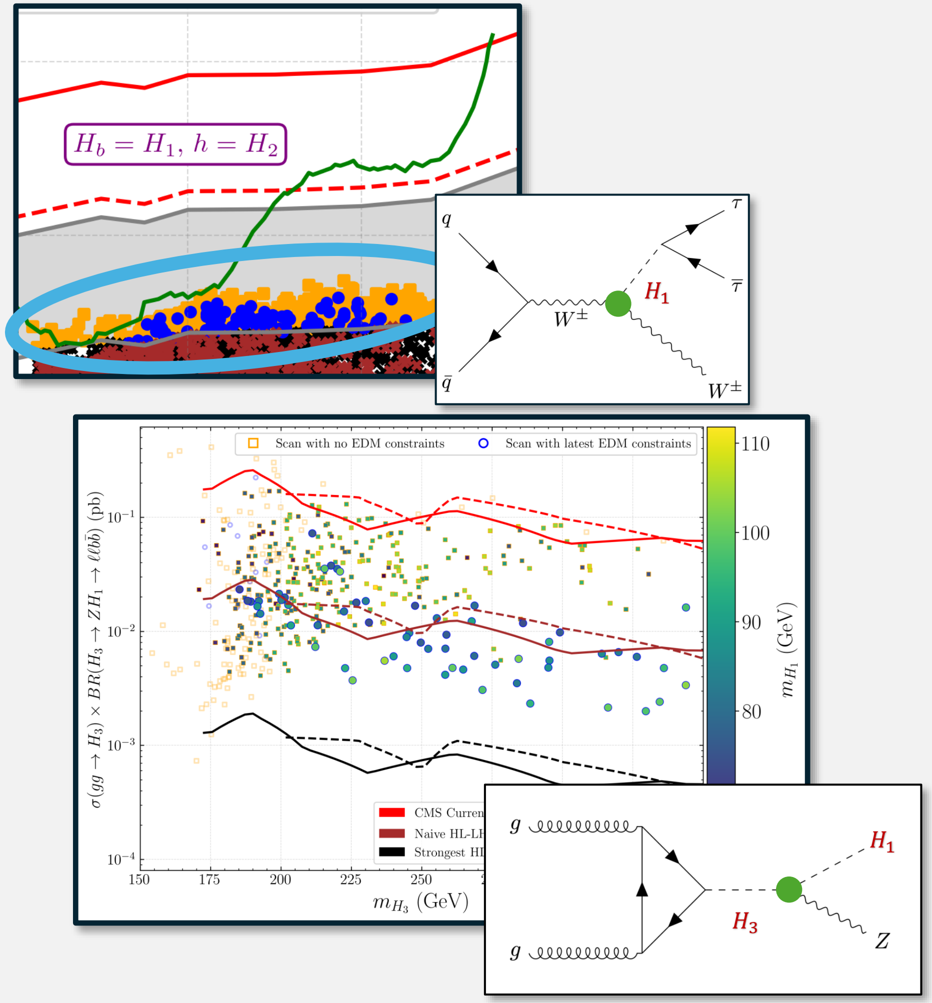
Sensitivity in $ZH_1 \to \ell\ell b\bar{b}$ depends on m_{H_1}



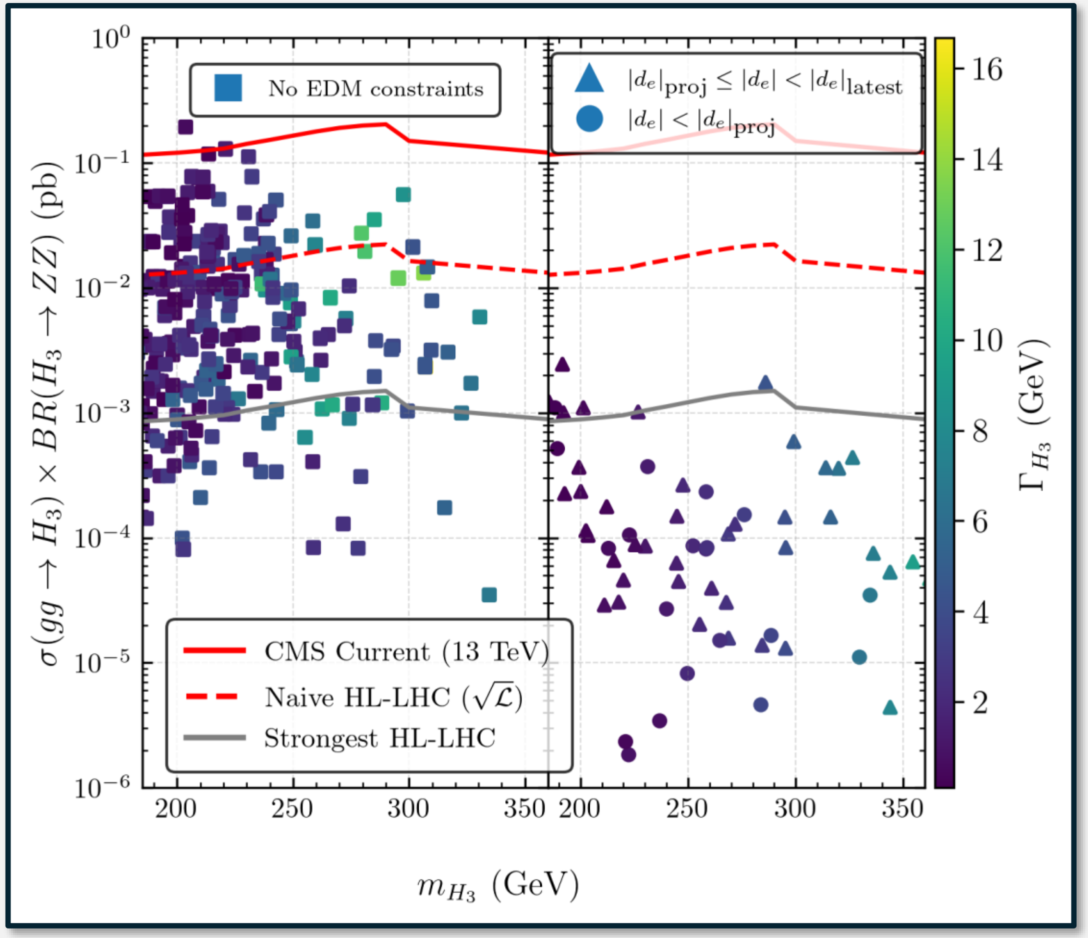
Limits: 1911.03781 (CMS)

Results

Set (vi): sensitivity to $pp \to H_3 \to ZZ$



Feasible in principle – up to Nature…



Limits: 1804.01939 (CMS)

Results

The (not so) dark clouds of eEDM

Present constraints: $|\boldsymbol{d_e}| \leq \mathbf{1.1} \times \mathbf{10^{-29}}\ \boldsymbol{e \cdot cm}$

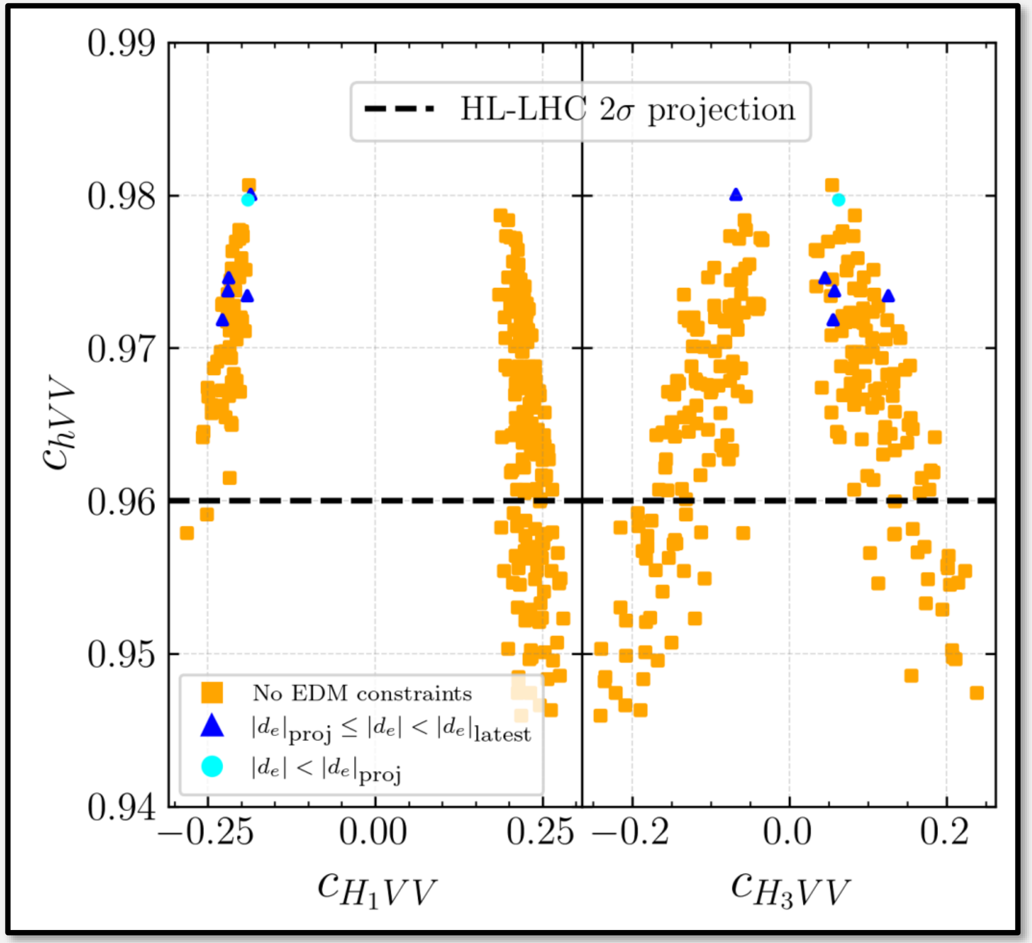
Future sensitivity projections: $|\boldsymbol{d_e}| \leq \mathbf{1.0} \times \mathbf{10^{-30}}\ \boldsymbol{e \cdot cm}$

Kill off significant amount of testable points at LHC…!

Nonetheless, points still allowed under projections:

very SM-like **Higgses** $\boldsymbol{h}$ even by HL-LHC prospects!

Results of this work and upcoming spin-off: ***remain relevant!***

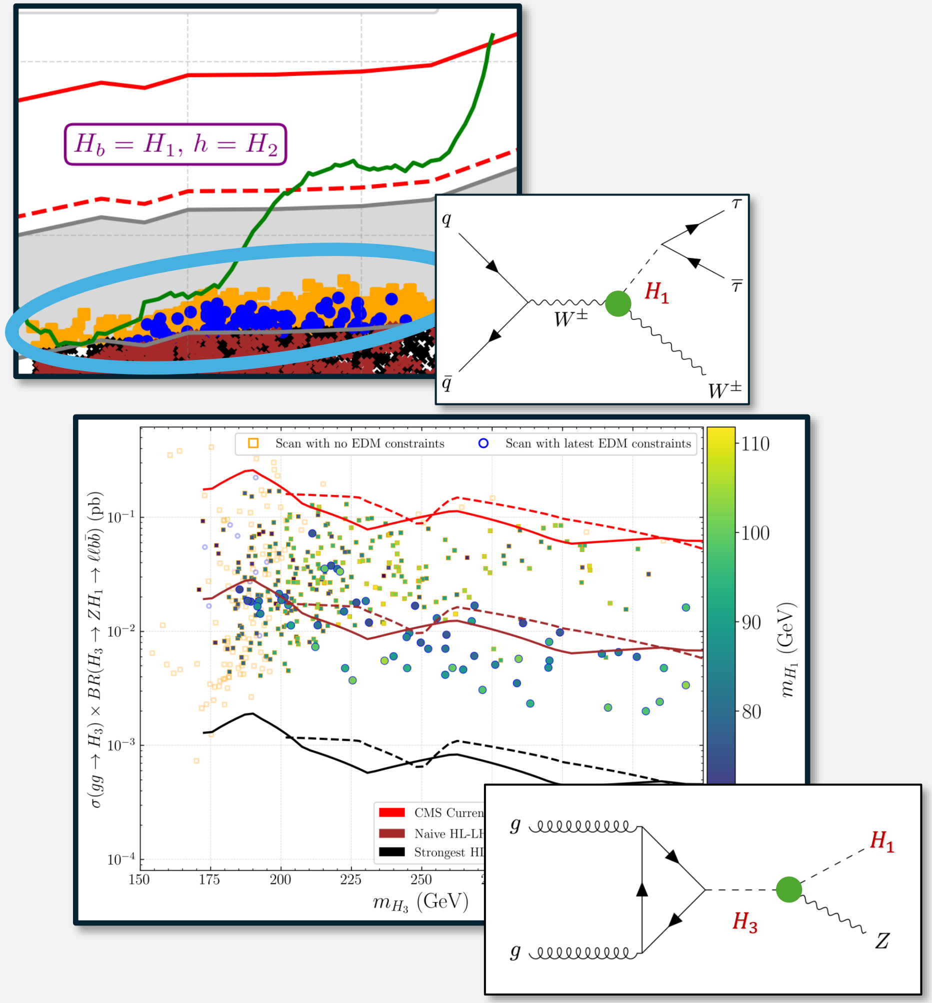


Gauge-Higgs couplings for points passing set *(vi)*

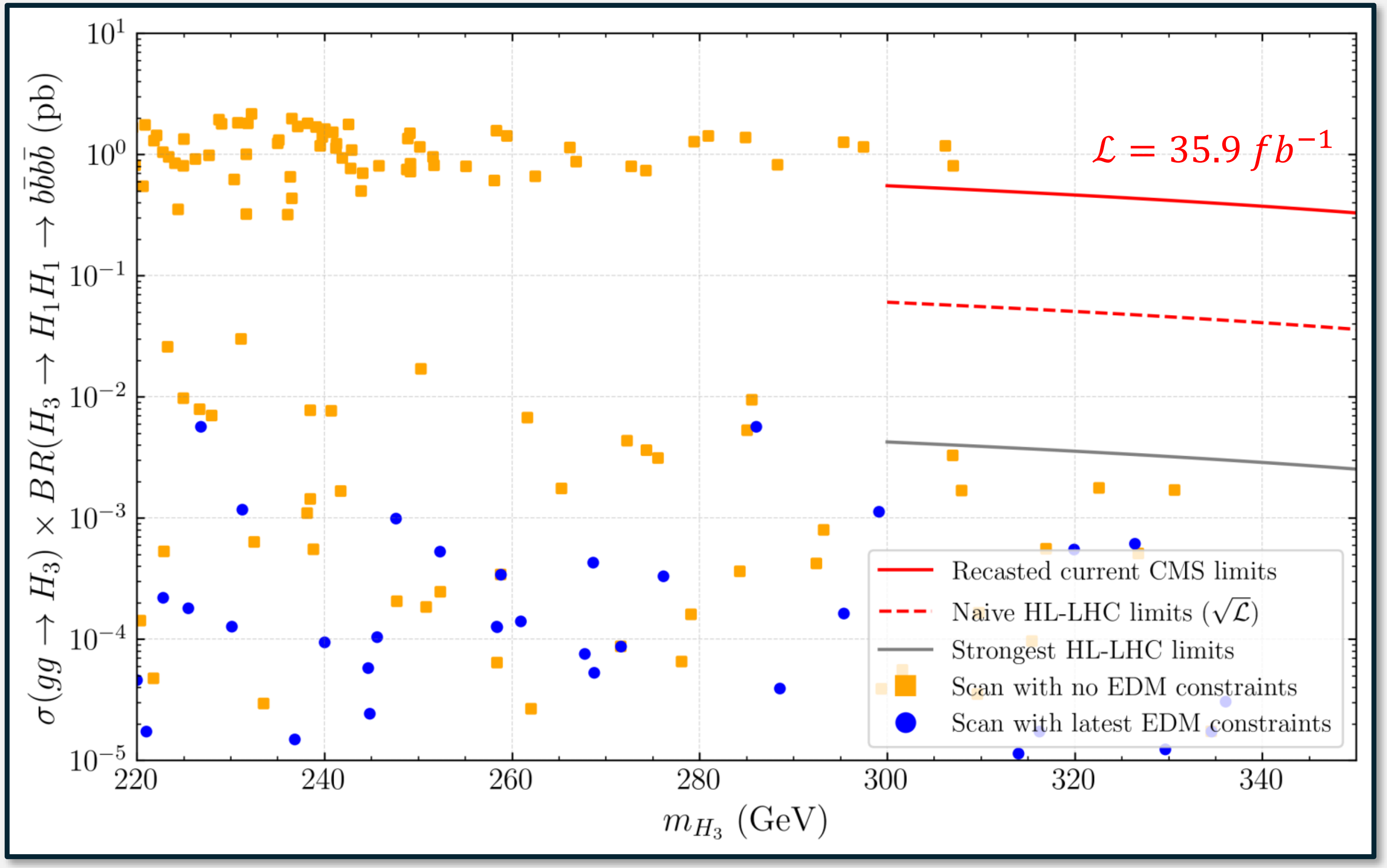
Limits: 2207.00043

Results

Set (vi): sensitivity to $pp \to H_3 \to H_1 H_1$



Limits need to be extended... but likely feasible



Limits: 1910.08574 (Barducci et al.)

Unlocking the power of the LHC

Outlook and open issues: what can the community do?

- No experimental limits on some processes…
- … or available in inconvenient formats!
- Address quark-gluon jet tagging for *VBF* signals!

(i) $pp \to VH_a,\, H_a \to Zh$

(ii) *VBF* production of $H_a,\, H_a \to Zh$

(iii) $pp \to VH_a,\, H_a \to ZH_b$ as well as $pp \to VH_b$

(iv) *VBF* production of $H_a,\, H_a \to ZH_b$ as well as *VBF* of H_b

(v) *ggF* production of H_a decaying via $H_a \to ZH_b$, as well as $pp \to VH_{a,b}$ or *VBF* of both $H_{a,b}$

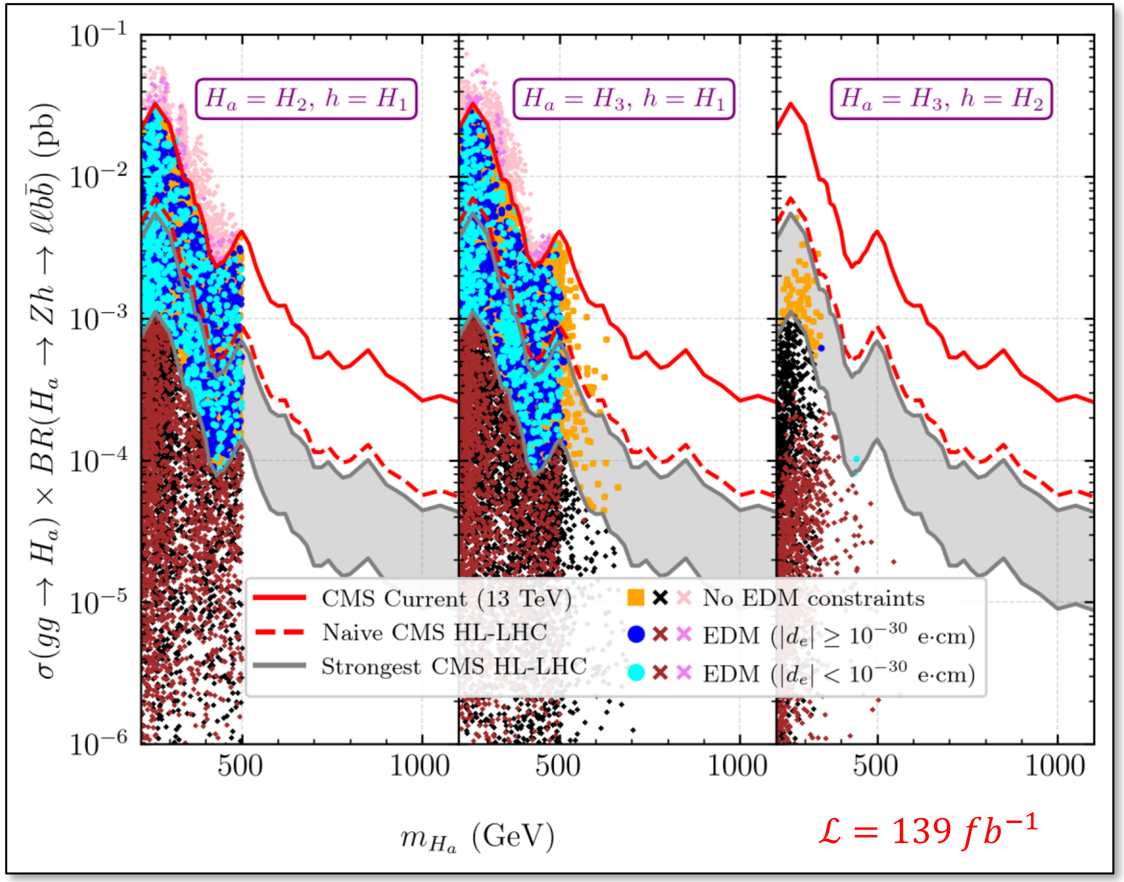
(vi) *ggF* production of H_a decaying both via $H_a \to ZH_b$ and $H_a \to VV$ (or $H_a \to H_bH_b$), as well as $pp \to VH_b$ (or *VBF* of H_b)

(vii) *ggF* production of H_a decaying via $H_a \to Zh$, as well as $pp \to VH_a$ (or *VBF* production of H_a)

For the skeptics out there…

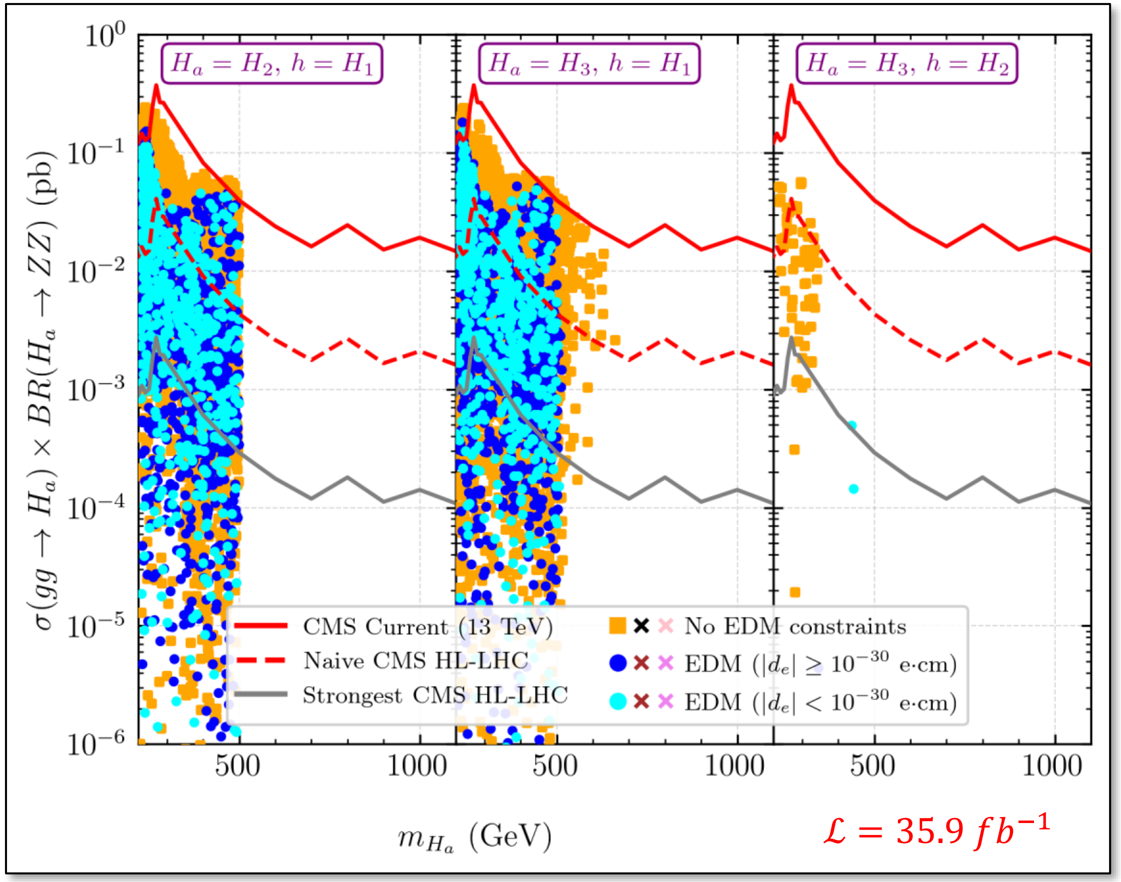
Preliminary results of the sequel, ggF-only work

$\sigma(gg \to H_a) \times BR(H_a \to Zh \to \ell\ell b\bar{b})$ (pb)



Limits from 2207.00230

$\sigma(gg \to H_a) \times BR(H_a \to ZZ)$ (pb)



Limits from 1804.01939

Concluding remarks

CPV may be hiding in a scalar sector beyond the SM…

… the LHC is a promising place to find out…

… but hard work lies ahead.

ggF-only sets:
upcoming spin-off!

Thank you!

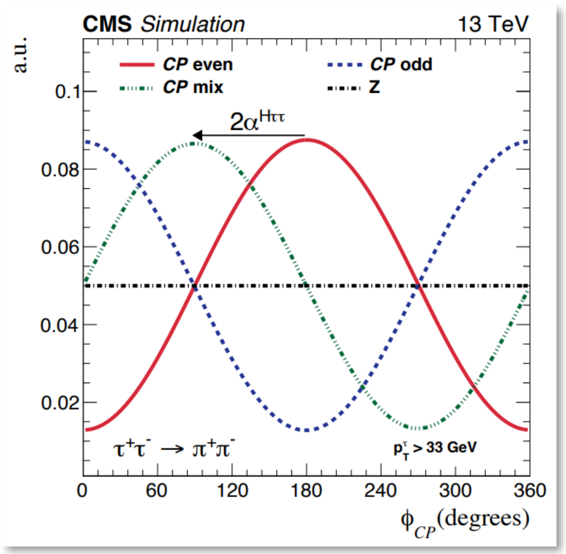
CP violation… in the Higgs sector?

A personal and non-exhaustive take

Fermion sector

$$-\frac{m_\tau}{v}\mathrm{H}\left(\boxed{\kappa_\tau}\bar{\tau}\tau+\boxed{\tilde{\kappa}_\tau}\bar{\tau}i\gamma_5\tau\right)$$

CP-even **CP-odd**



CMS – 2110.04836

Scalar sector

Bosonic field	J^{PC}	J^P
γ	1^{--}	
Z	1^{--}	
$H_{\text{CP-even}}$	0^{++}	
$H_{\text{CP-odd}}$, G^0	0^{+-}	
$W^\pm$		1^-
$H^\pm$, $G^\pm$		0^+

$H_3 \to ZH_2$ $H_2 \to ZH_1$ $H_3 \to ZH_1$	$H_2 \to Zh_1$ $H_1 \to ZZ$ $H_2 \to ZZ$	…

1506.06755, 2206.09643, …

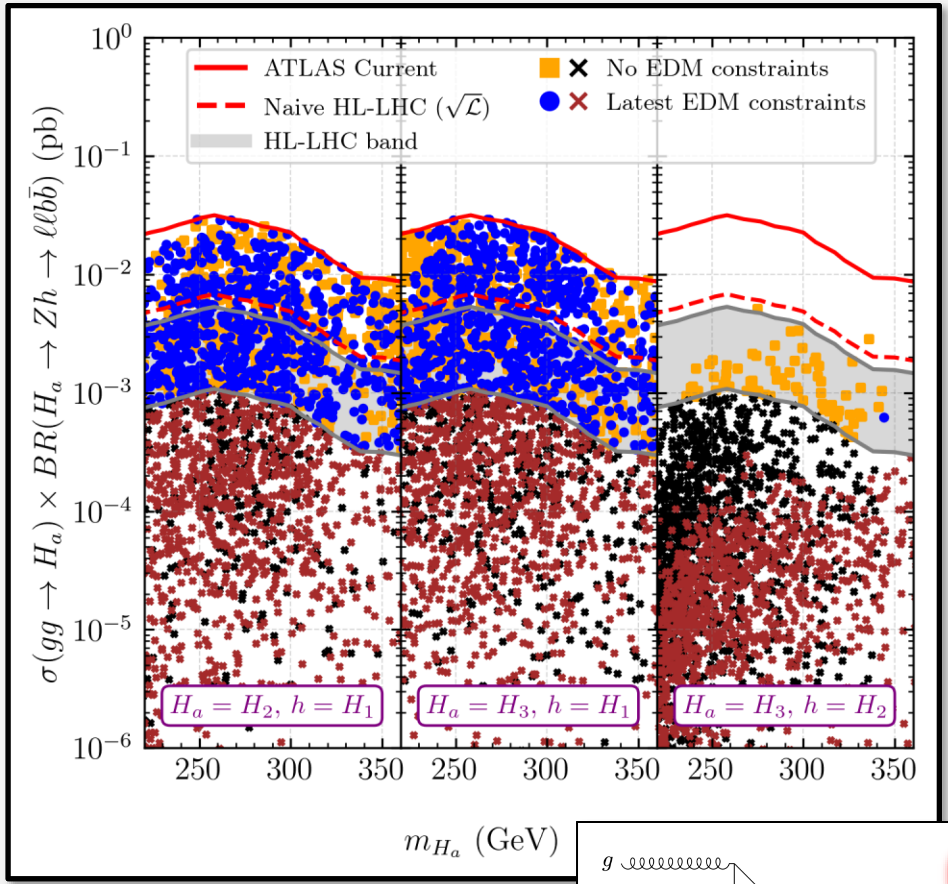
CP states *ad absurdum?*

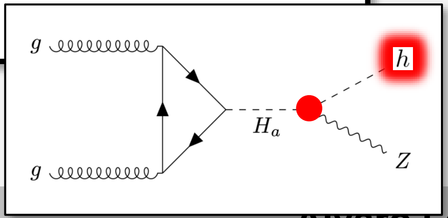
→ ***CPV***

Results

Set (vii): Example of a joint signature

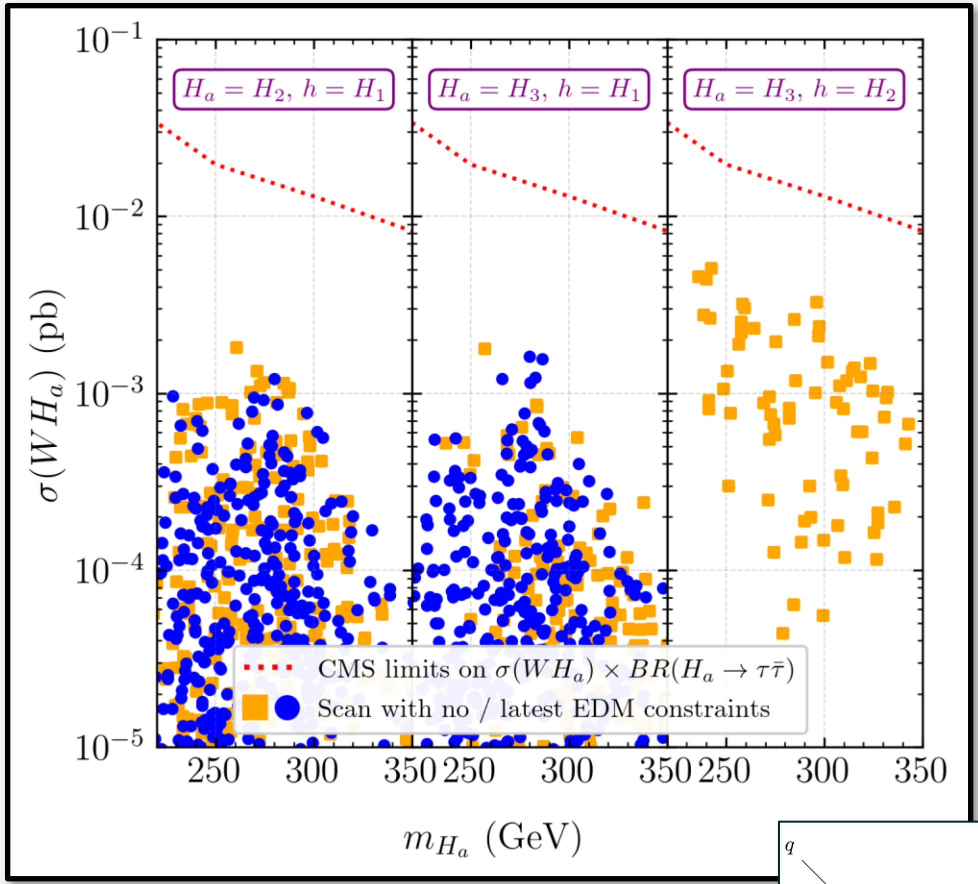
Sensitivity to $gg \to H_a,\ H_a \to Zh \to \ell\ell b\bar{b}$

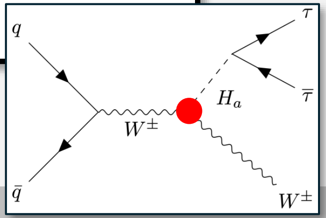




Limits: 2207.00230 (ATLAS)

Sensitivity to $pp \to WH_a$



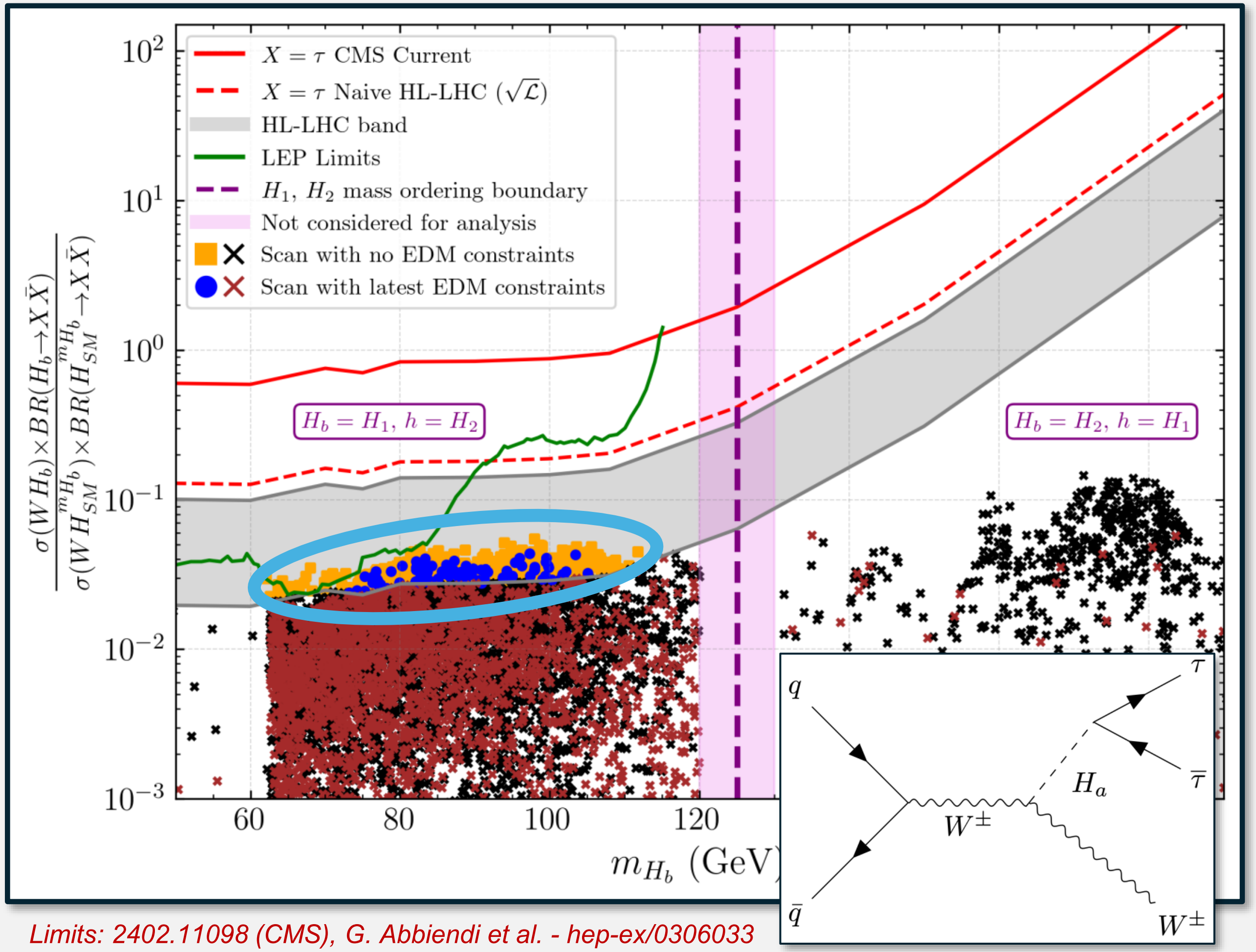


Limits: 2402.11098 (CMS), G. Abbiendi et al. - hep-ex/0306033

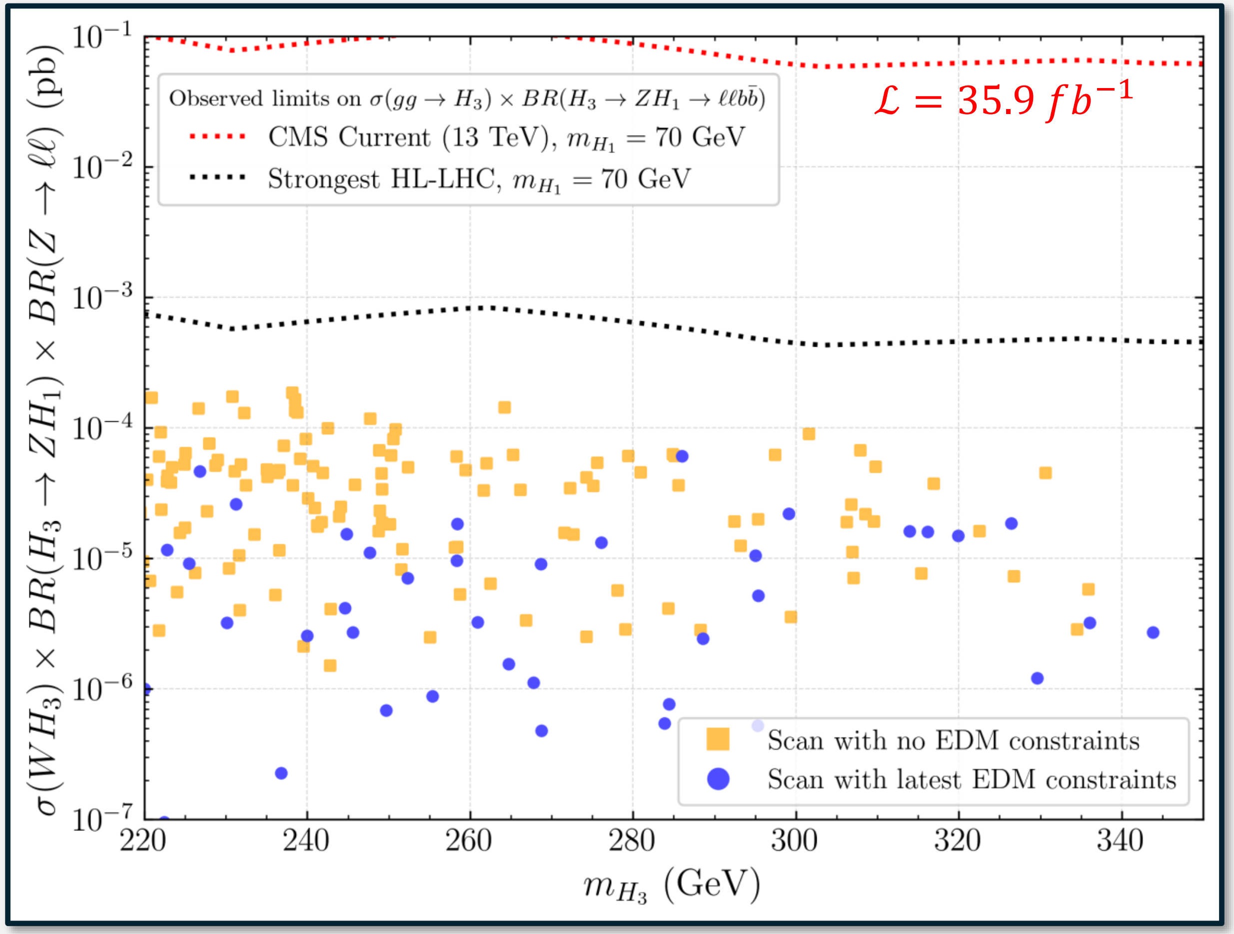
Results

Set (iii): $pp \to VH_a,\ H_a \to ZH_b$ and $pp \to VH_b$

W-AP in C2HDM normalized to *W-AP* of *same-mass* SM Higgs



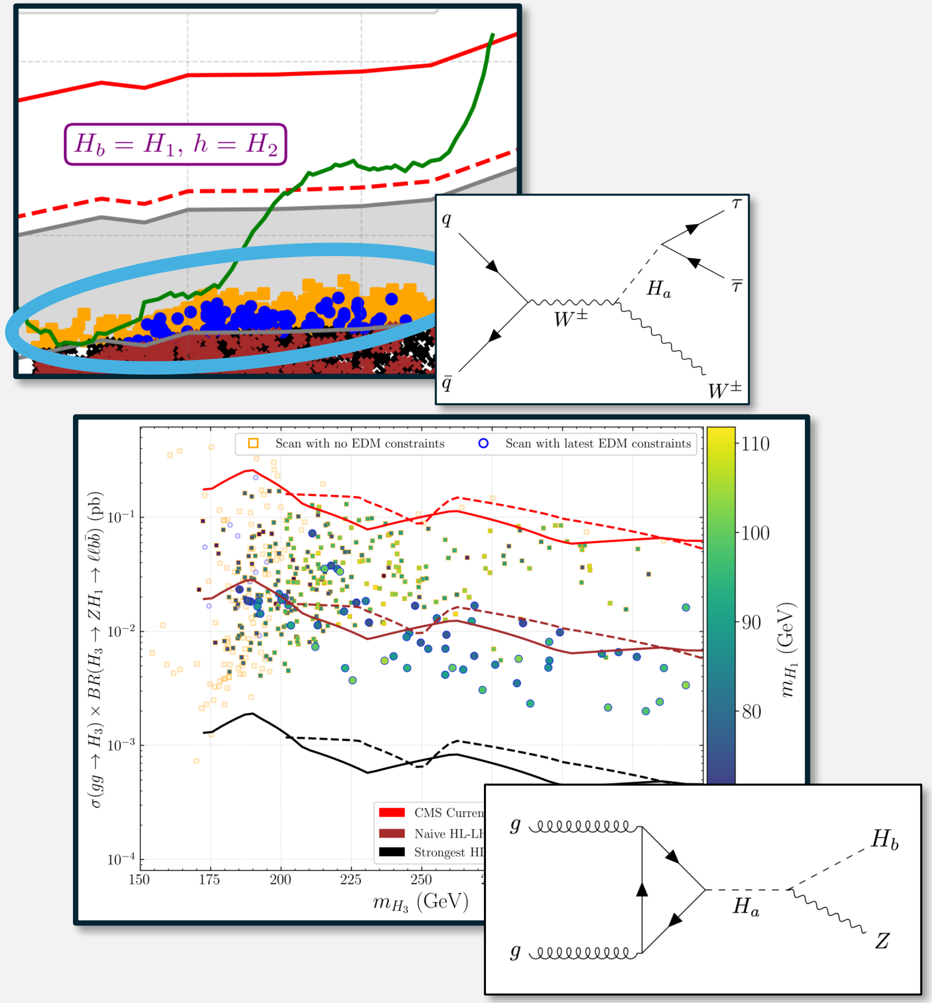
No existing limits on $pp \to VH_3,\ H_3 \to H_1(Z \to \ell\ell)$!



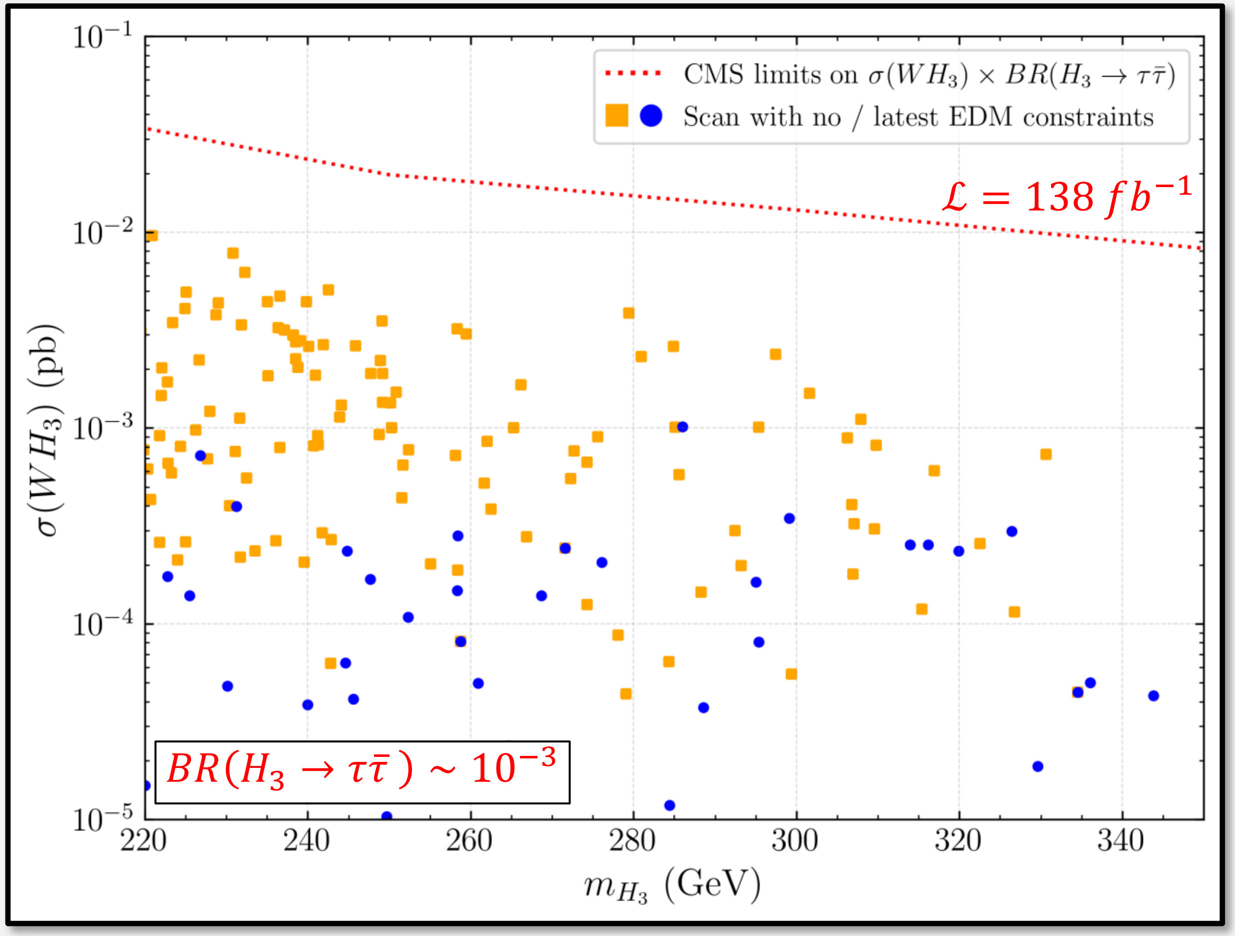
Limits: 2402.11098 (CMS), G. Abbiendi et al. - hep-ex/0306033

Results

Set (v): sensitivity to $pp \to W(H_3 \to \tau\bar{\tau})$



Full cross section well below sensitivity to $\tau\bar{\tau}$ final state

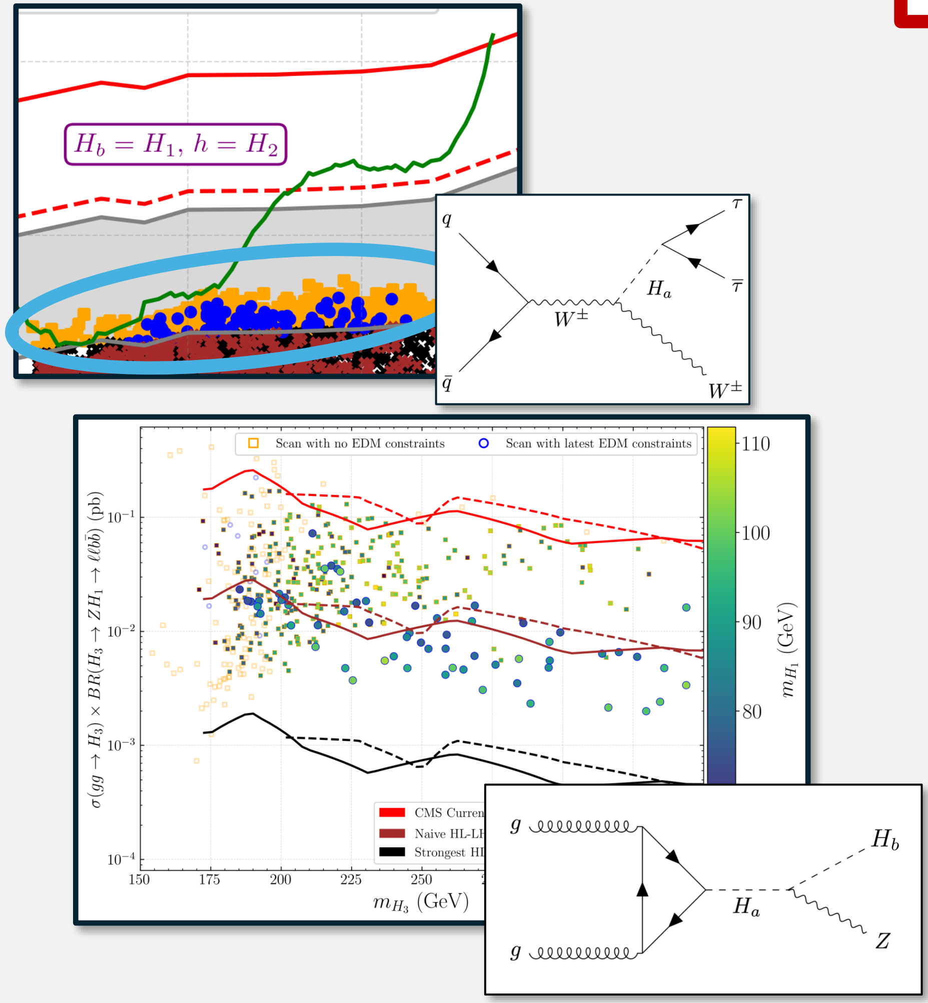


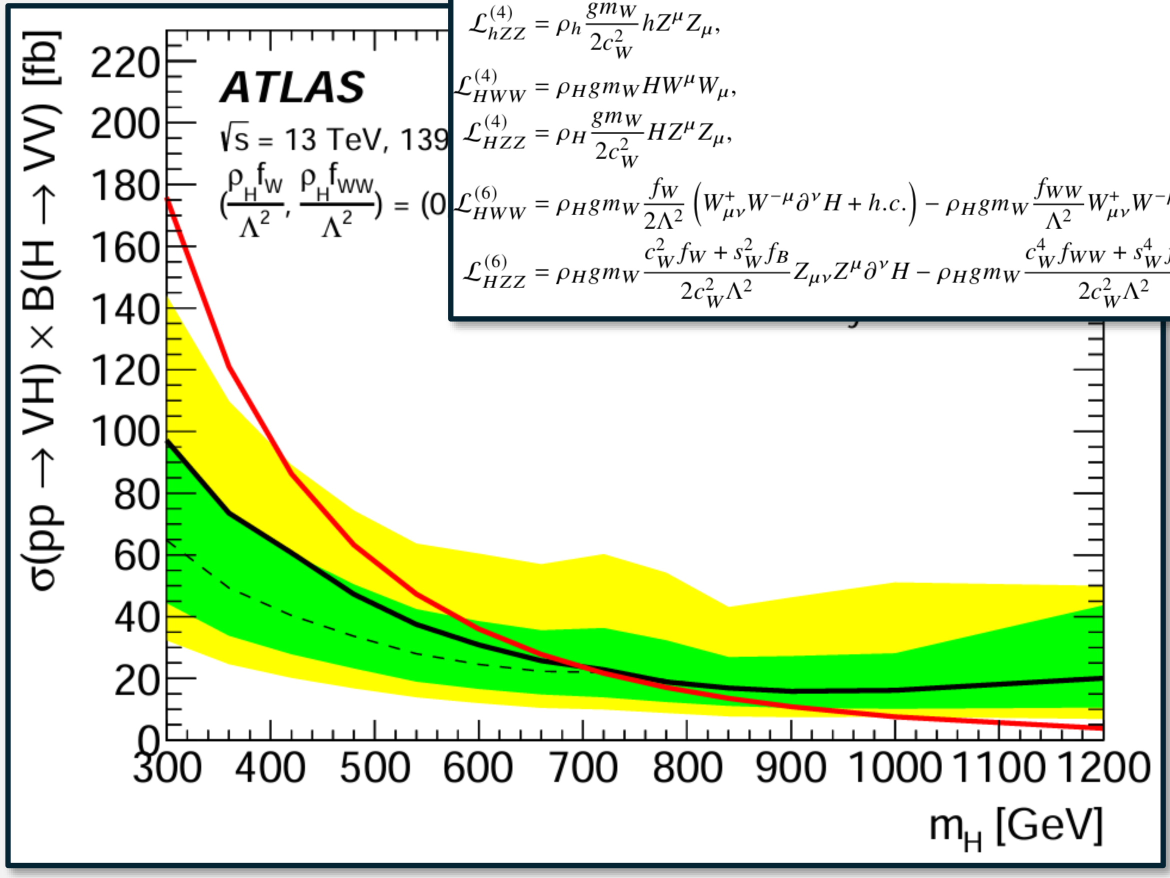
Limits: 2402.11098 (CMS), G. Abbiendi et al. - hep-ex/0306033

Results

Set (v): sensitivity to $pp \to W(H_3 \to WW \to 2\ell^{+/-} + 2\nu)$

Cannot use existing limits!





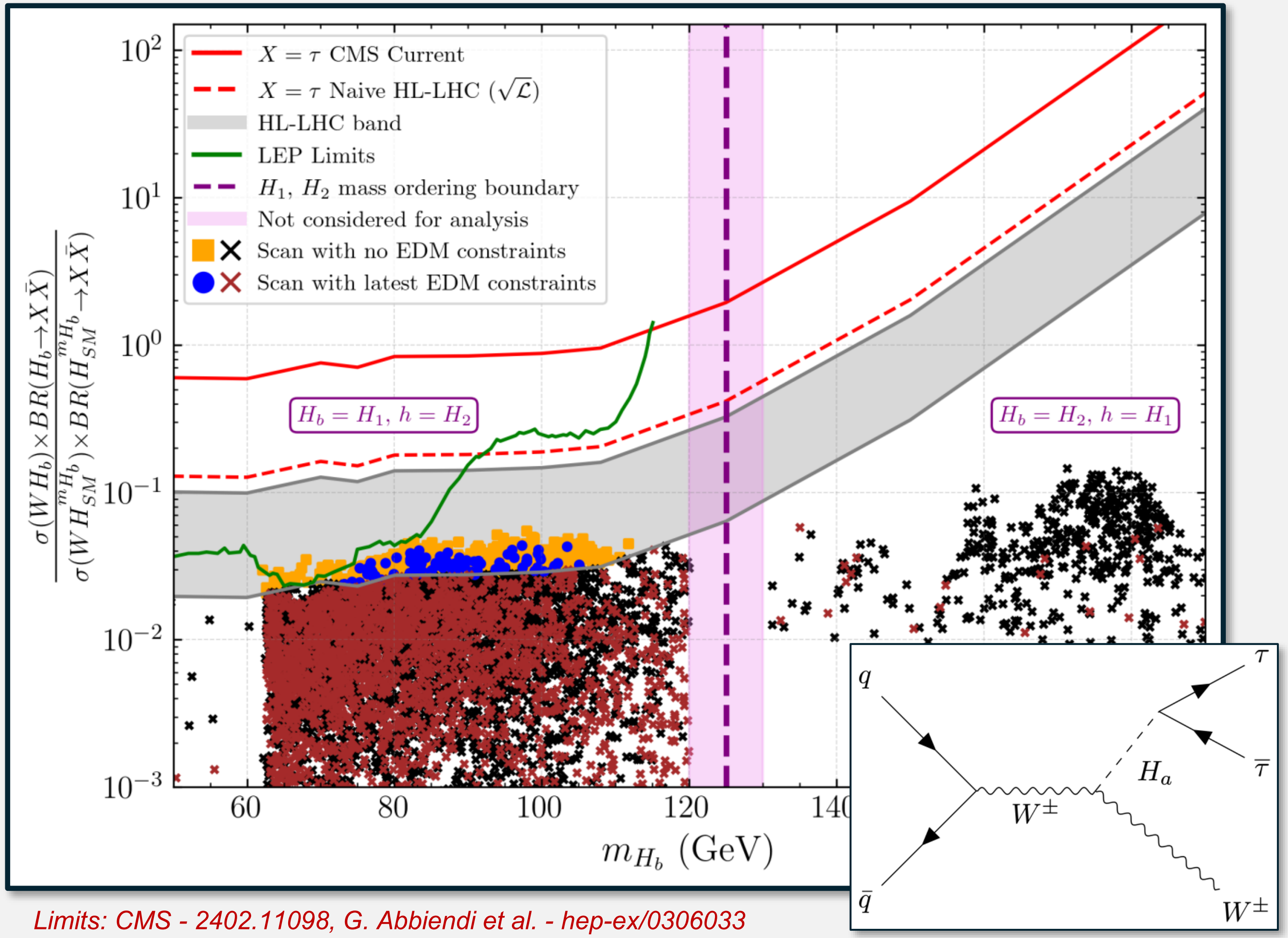
$$\mathcal{L}^{(4)}_{hWW} = \rho_h g m_W h W^\mu W_\mu,$$
$$\mathcal{L}^{(4)}_{hZZ} = \rho_h \frac{g m_W}{2c_W^2} h Z^\mu Z_\mu,$$
$$\mathcal{L}^{(4)}_{HWW} = \rho_H g m_W H W^\mu W_\mu,$$
$$\mathcal{L}^{(4)}_{HZZ} = \rho_H \frac{g m_W}{2c_W^2} H Z^\mu Z_\mu,$$
$$\mathcal{L}^{(6)}_{HWW} = \rho_H g m_W \frac{f_W}{2\Lambda^2}\left(W^+_{\mu\nu} W^{-\mu}\partial^\nu H + h.c.\right) - \rho_H g m_W \frac{f_{WW}}{\Lambda^2} W^+_{\mu\nu} W^{-\mu\nu} H,$$
$$\mathcal{L}^{(6)}_{HZZ} = \rho_H g m_W \frac{c_W^2 f_W + s_W^2 f_B}{2c_W^2\Lambda^2} Z_{\mu\nu} Z^\mu \partial^\nu H - \rho_H g m_W \frac{c_W^4 f_{WW} + s_W^4 f_{BB}}{2c_W^2\Lambda^2} Z_{\mu\nu} Z^{\mu\nu} H$$

Plot and formulae taken from 2211.02617 (ATLAS)

Exemplary results

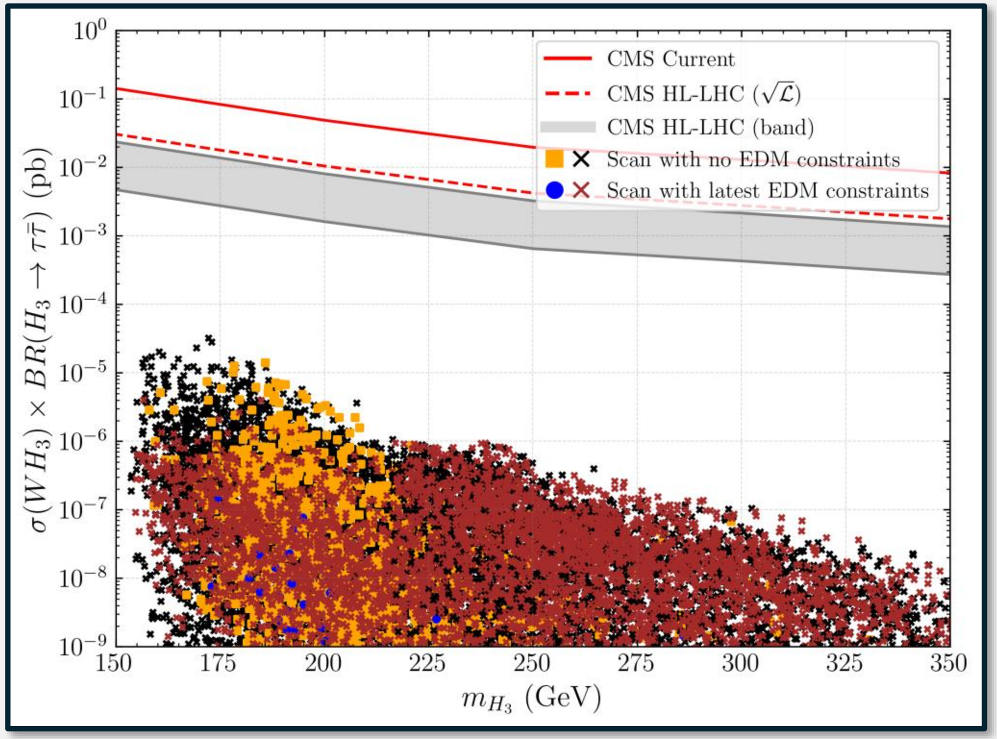
Sets (ii) – (vi): W-AP of lightest non-SM Higgs in the C2HDM

_W-AP_ in C2HDM normalized to _W-AP_ of _same-mass_ SM Higgs

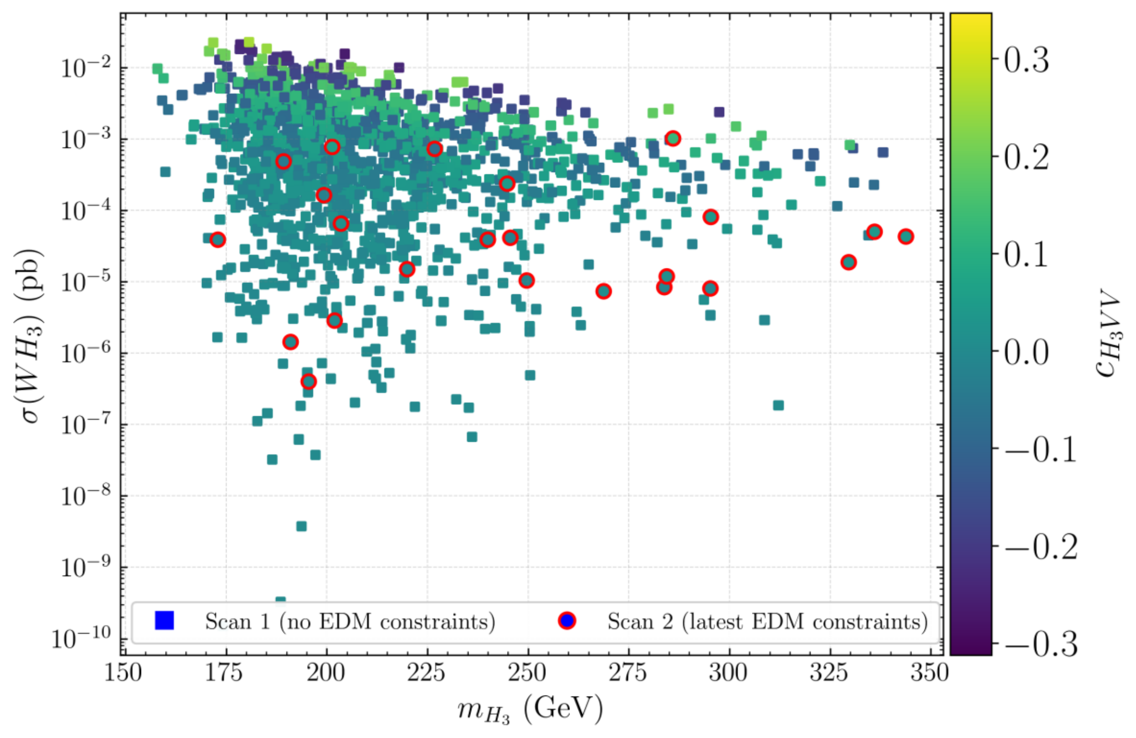


Limits: CMS - 2402.11098, G. Abbiendi et al. - hep-ex/0306033

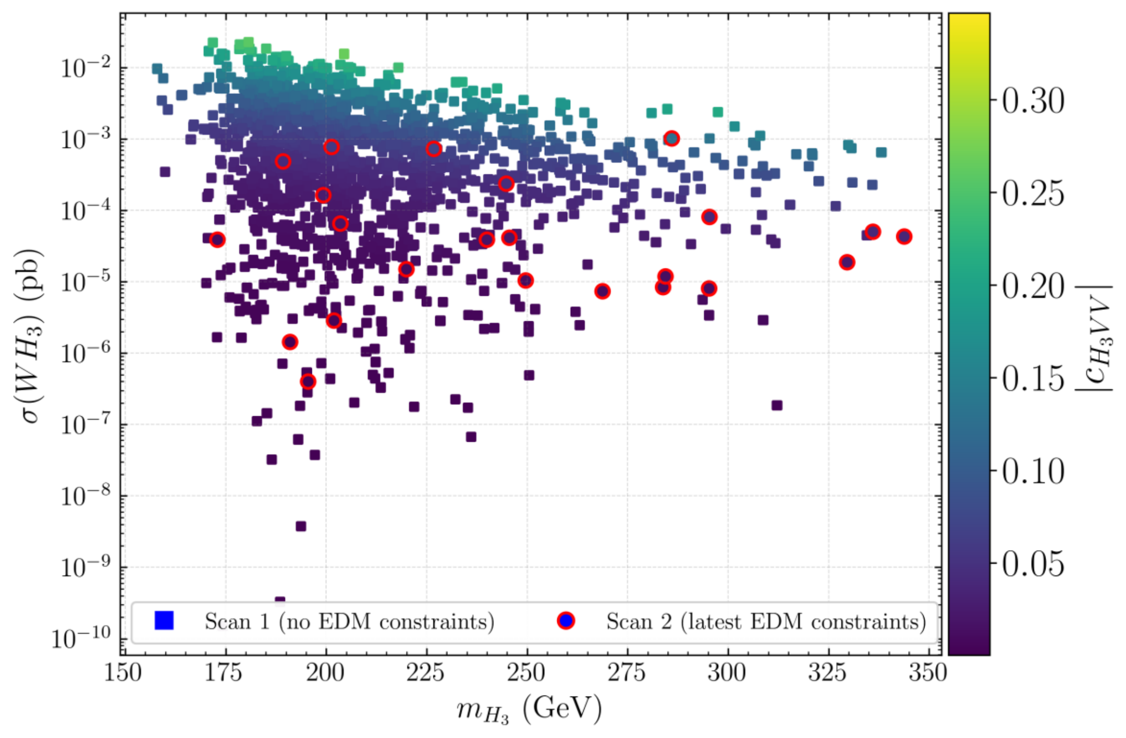
Compare to _W-AP_ of H_3…



Backup

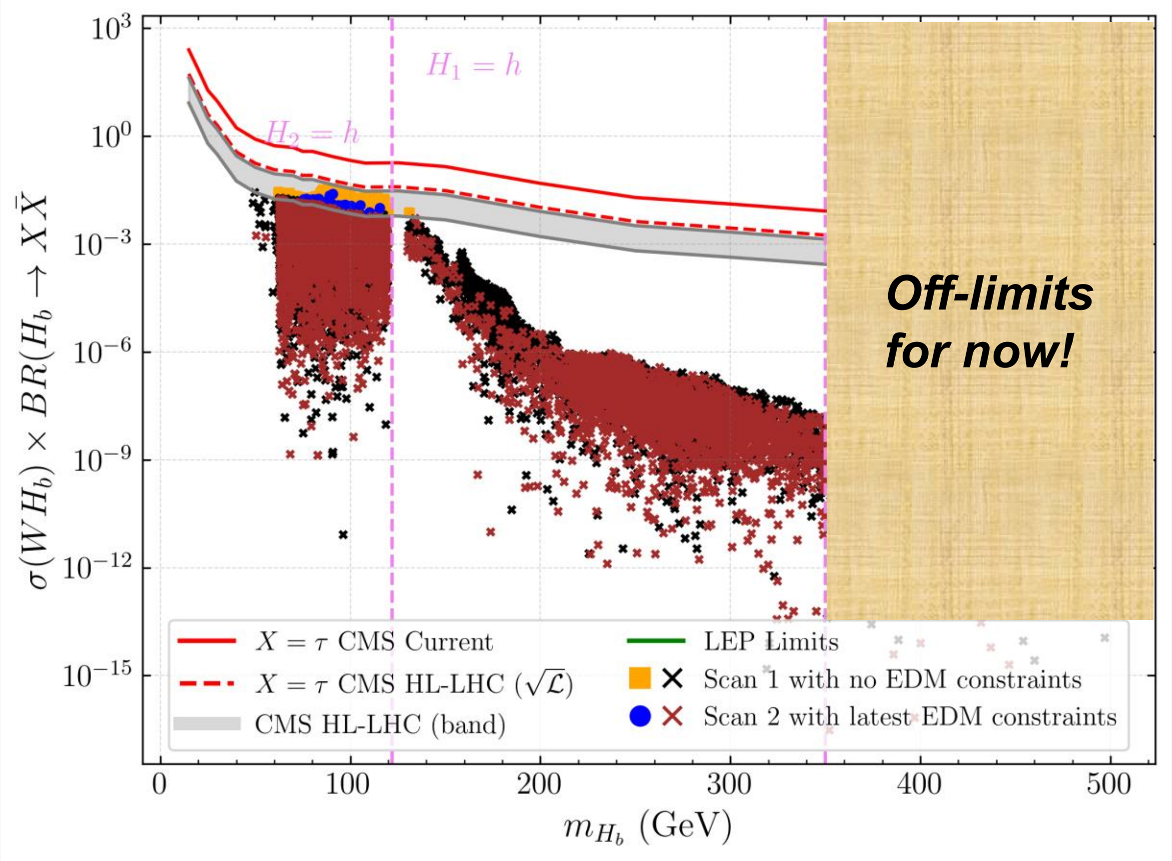


10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$\sigma(WH_3)$ (pb)
150 175 200 225 250 275 300 325 350
m_{H_3} (GeV)
Scan 1 (no EDM constraints)
Scan 2 (latest EDM constraints)
0.3 0.2 0.1 0.0 −0.1 −0.2 −0.3
c_{H_3VV}

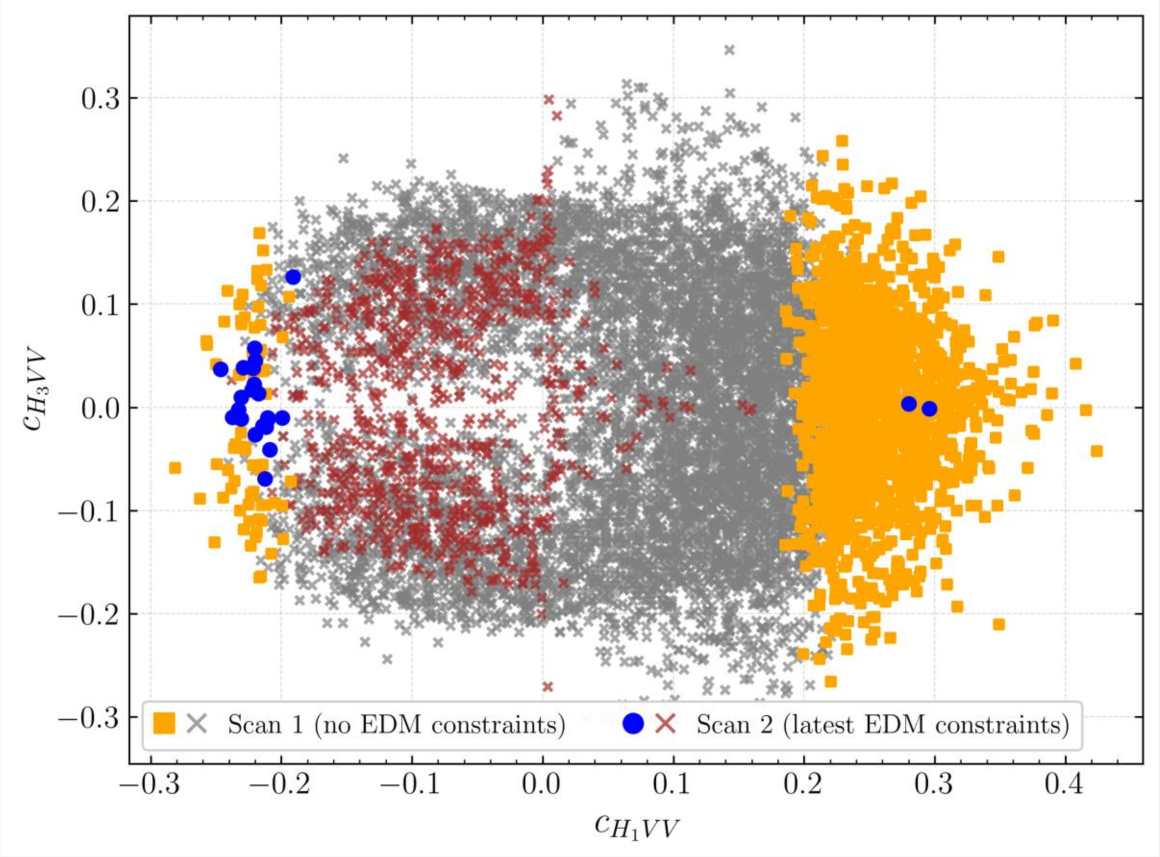


10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$\sigma(WH_3)$ (pb)
150 175 200 225 250 275 300 325 350
m_{H_3} (GeV)
Scan 1 (no EDM constraints)
Scan 2 (latest EDM constraints)
0.30 0.25 0.20 0.15 0.10 0.05
$|c_{H_3VV}|$

Backup

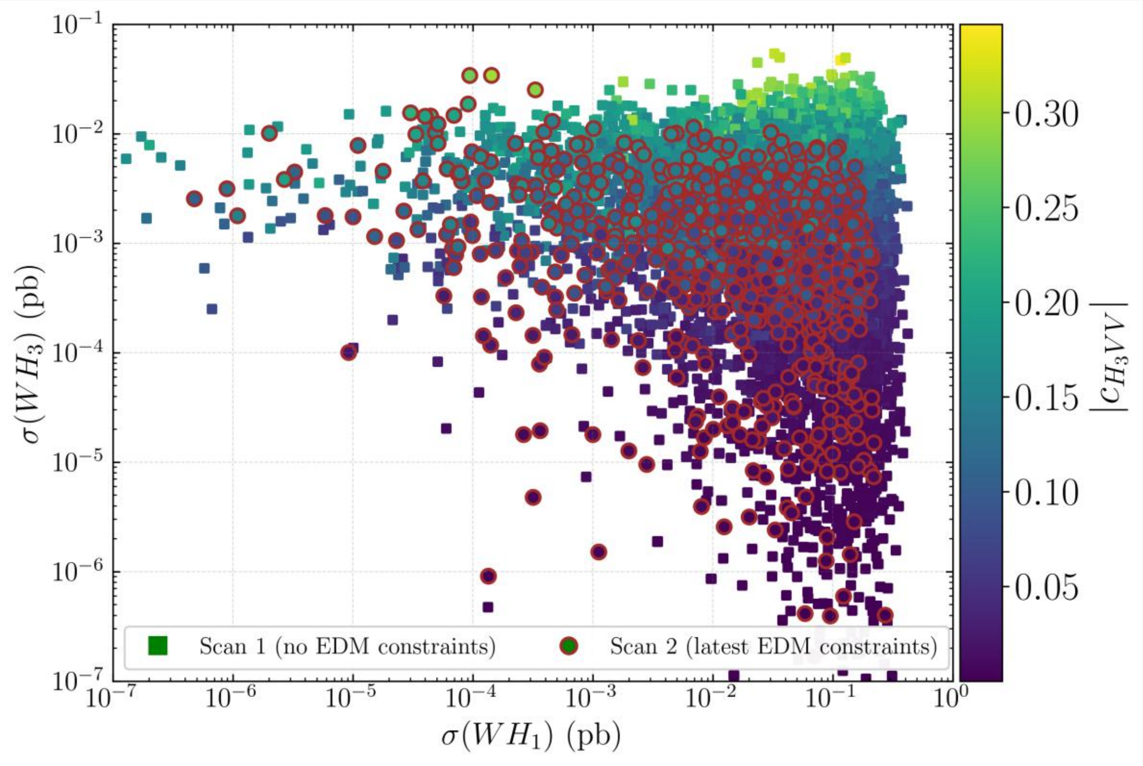


10^3
10^0
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
$\sigma(WH_b) \times BR(H_b \to X\bar{X})$
$H_1 = h$
$H_2 = h$
Off-limits for now!
$X = \tau$ CMS Current
$X = \tau$ CMS HL-LHC ($\sqrt{\mathcal{L}}$)
CMS HL-LHC (band)
LEP Limits
Scan 1 with no EDM constraints
Scan 2 with latest EDM constraints
0
100
200
300
400
500
m_{H_b} (GeV)

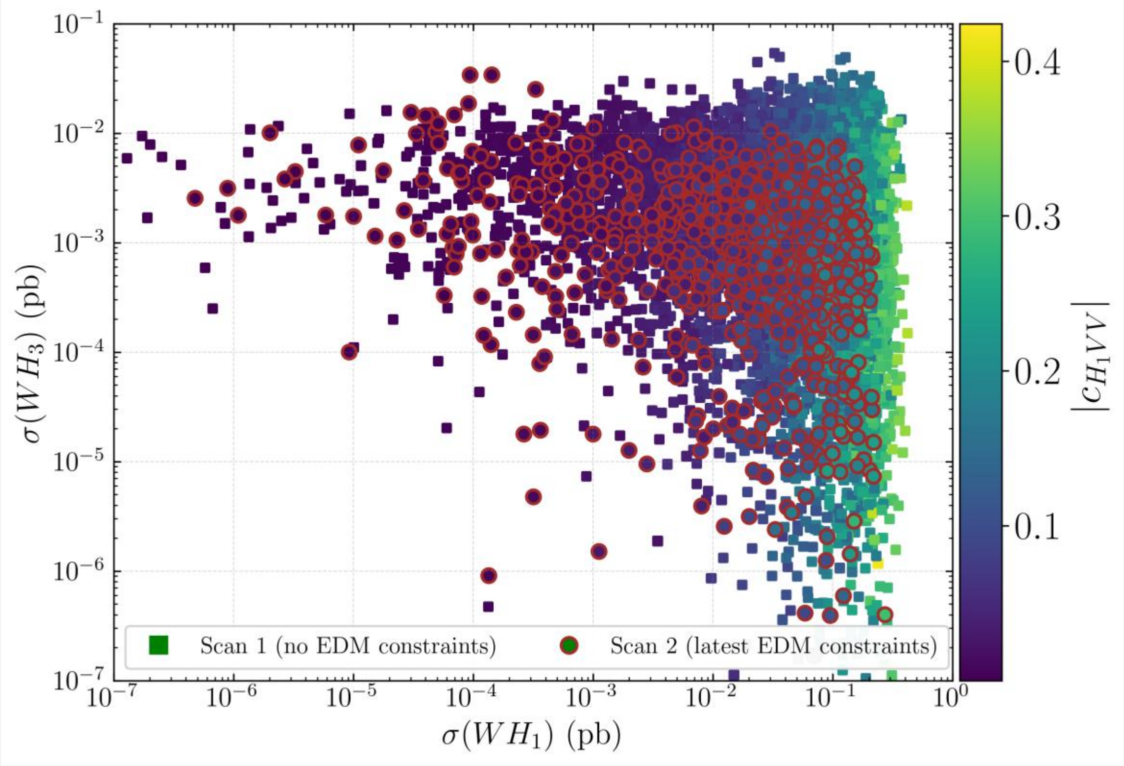


0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
c_{H_3VV}
Scan 1 (no EDM constraints)
Scan 2 (latest EDM constraints)
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
c_{H_1VV}

Backup



10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$\sigma(WH_3)$ (pb)
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
$\sigma(WH_1)$ (pb)
Scan 1 (no EDM constraints)
Scan 2 (latest EDM constraints)
0.30
0.25
0.20
0.15
0.10
0.05
$|c_{H_3VV}|$



10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$\sigma(WH_3)$ (pb)
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
$\sigma(WH_1)$ (pb)
Scan 1 (no EDM constraints)
Scan 2 (latest EDM constraints)
0.4
0.3
0.2
0.1
$|c_{H_1VV}|$