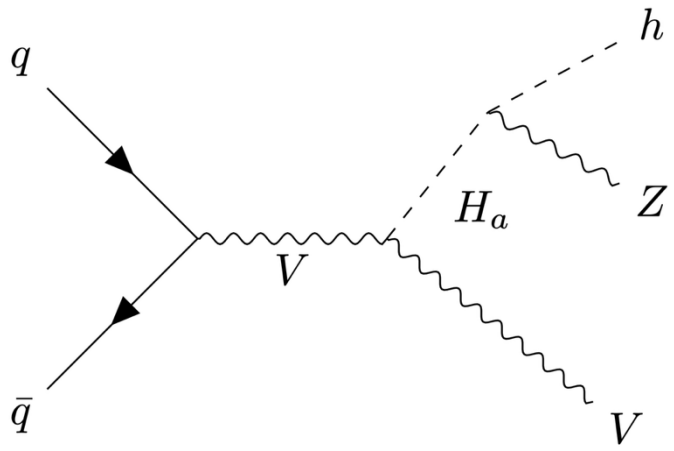
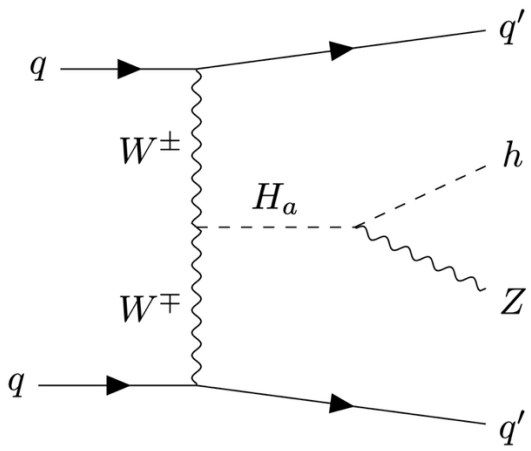




Vector boson fusion & associated production as an LHC signature of CP violation

Based on 2506.XXXXX

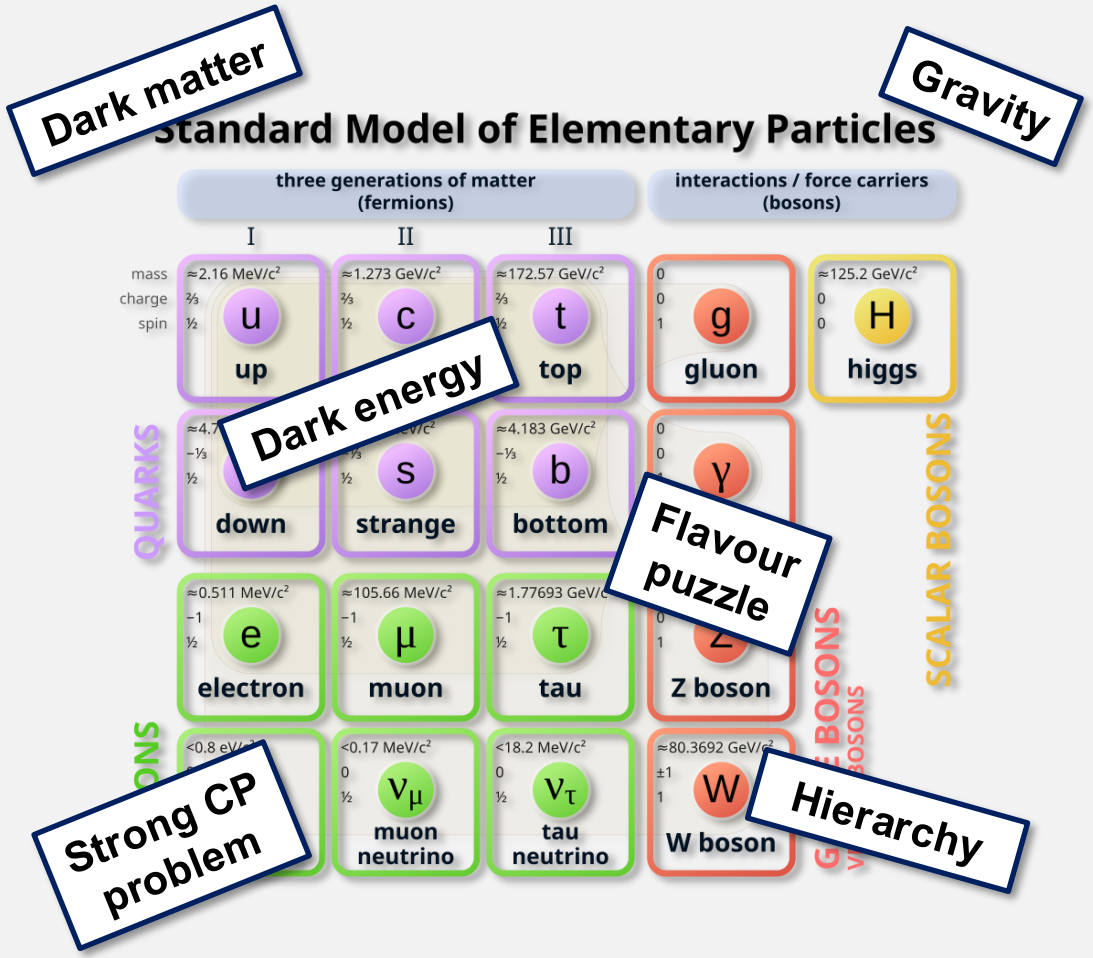
Álvaro Lozano Onrubia

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

Padova, May 27 – PLANCK2025

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.

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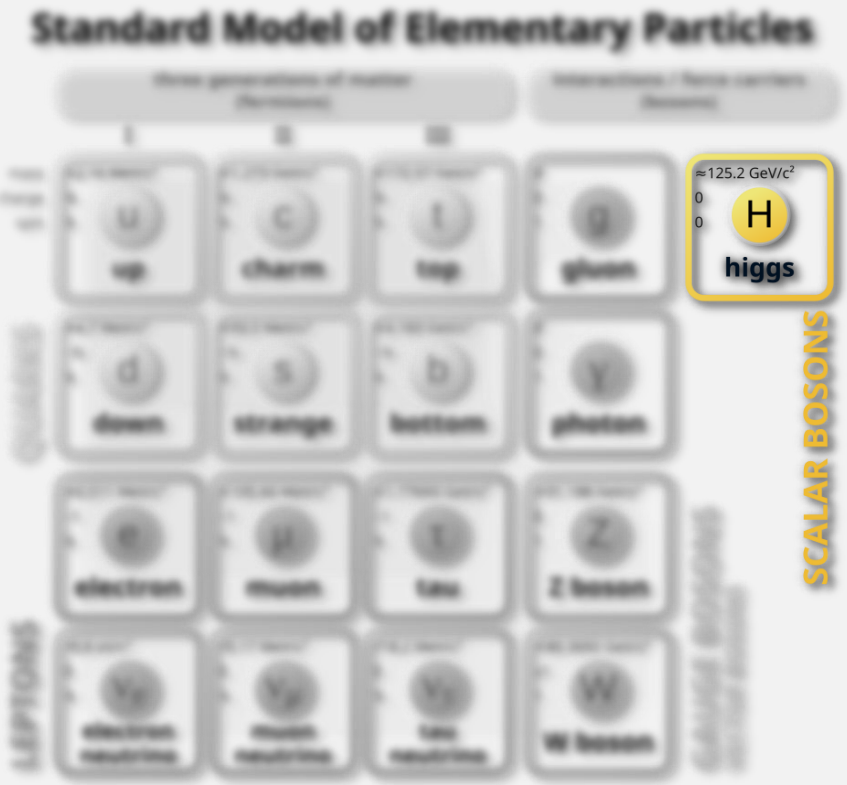

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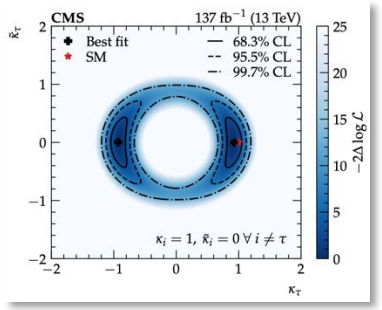
CP properties of SM Higgs



Yukawa & gauge *couplings*…

… SM-***like!***

CMS – 2110.04836

*CPV in **BSM** Higgs sector: well-motivated!*

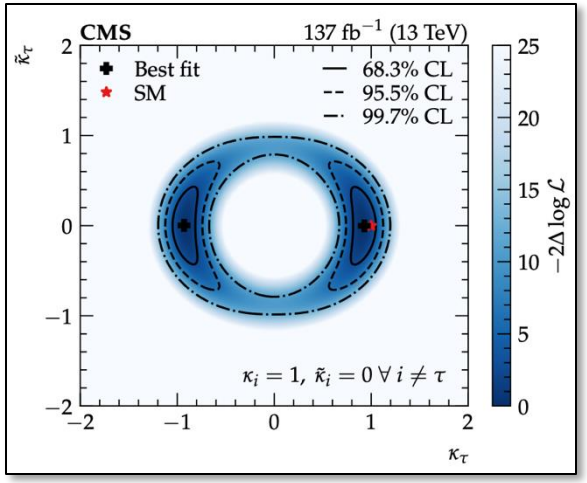
CP violation… in the Higgs sector?

A personal and non-exhaustive take

Fermion sector

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

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^+

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

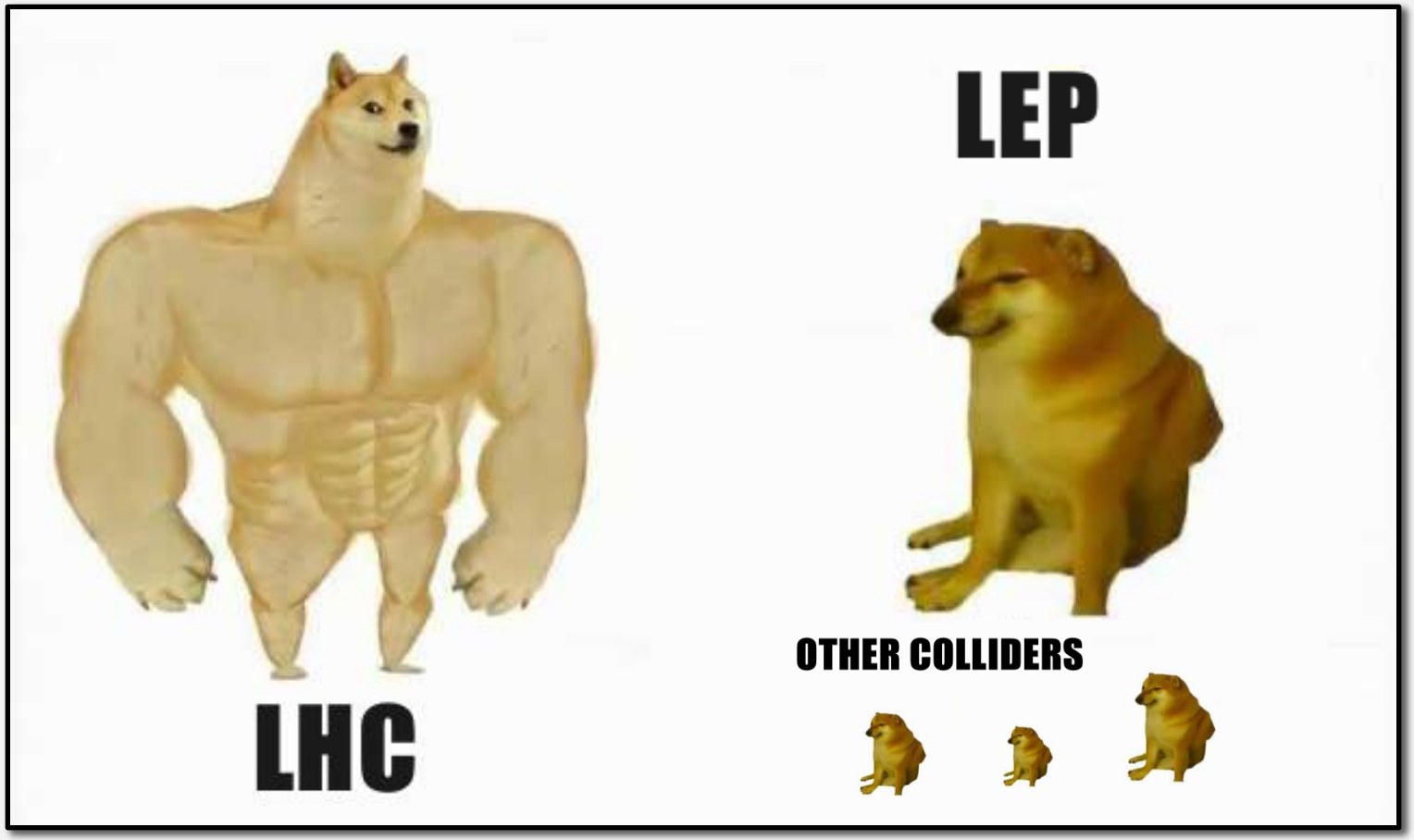
1506.06755, 2206.09643, …

CP states *ad absurdum?*

➡ ***CPV***

CP violation… in the Higgs sector?

A personal and non-exhaustive take



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$W^{\pm}$		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, …

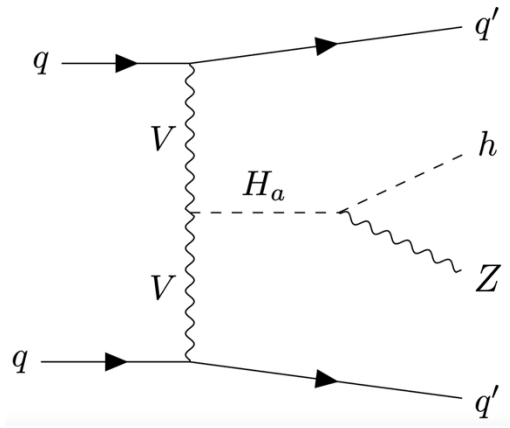
CP states *ad absurdum?*

➡ ***CPV***

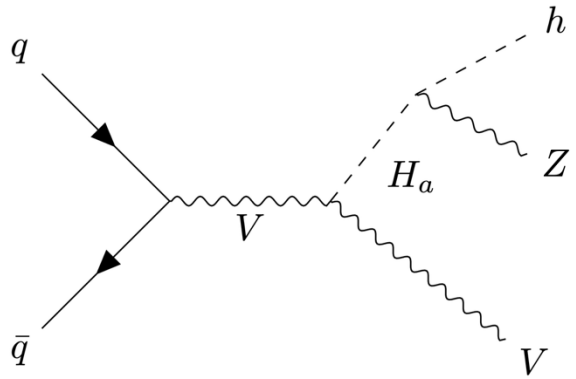
Unlocking the power of the LHC

A threefold way…

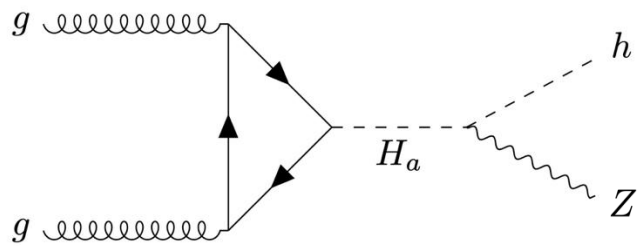
Vector boson fusion *(VBF)*



V-associated production *(V-AP)*



Gluon fusion assisted (*ggF*)

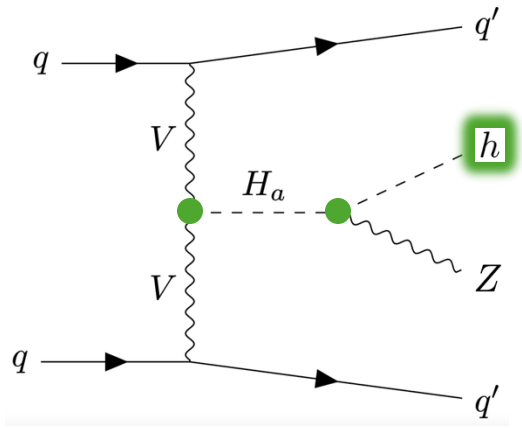


*** Throughout the talk: h is the SM Higgs with $m_h = 125\ \mathrm{GeV}$**

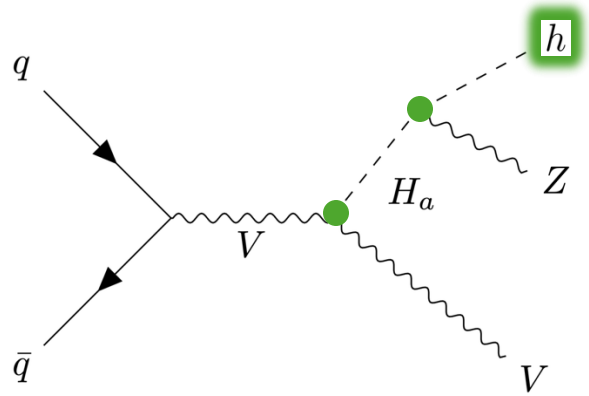
Unlocking the power of the LHC

A threefold way…

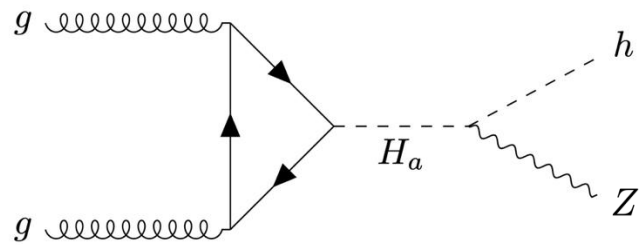
Vector boson fusion *(VBF)*



V-associated production *(V-AP)*



Gluon fusion assisted (*ggF*)

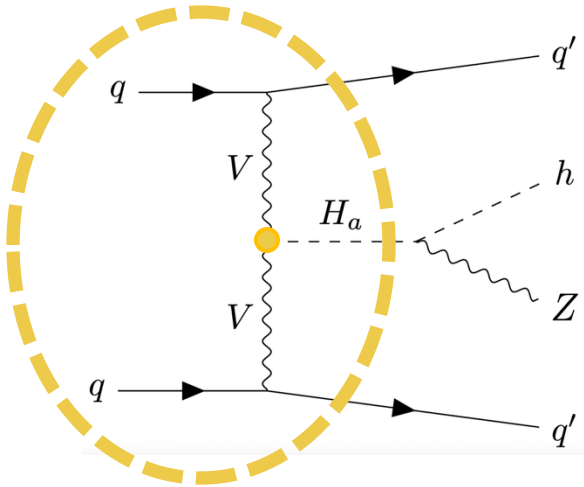


Unambiguous signals of CPV

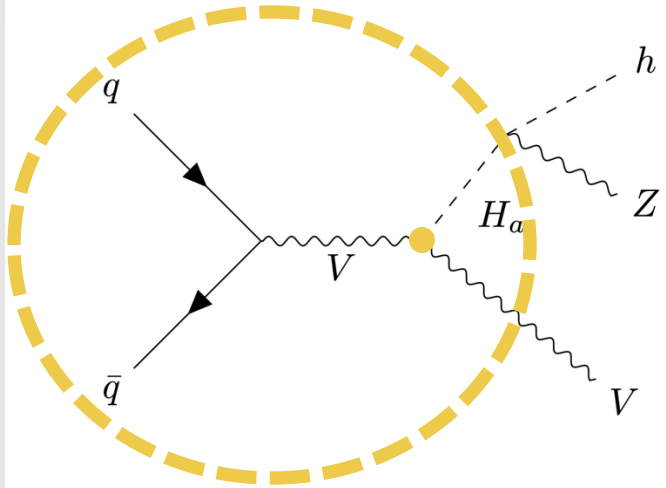
Unlocking the power of the LHC

A threefold way…

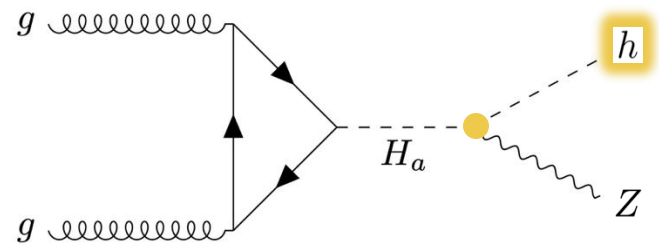
Vector boson fusion *(VBF)*



V-associated production *(V-AP)*



Gluon fusion assisted (*ggF*)

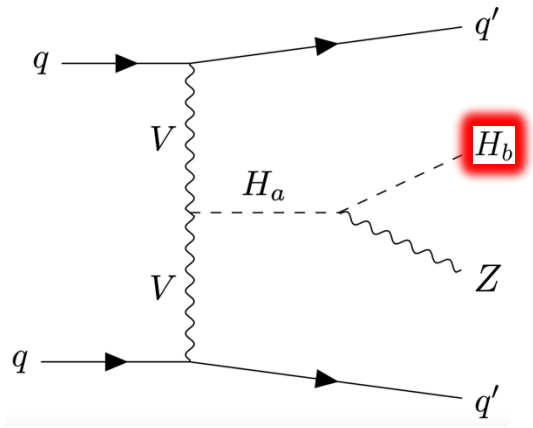


Needs *VBF* or *V-AP* of H_a

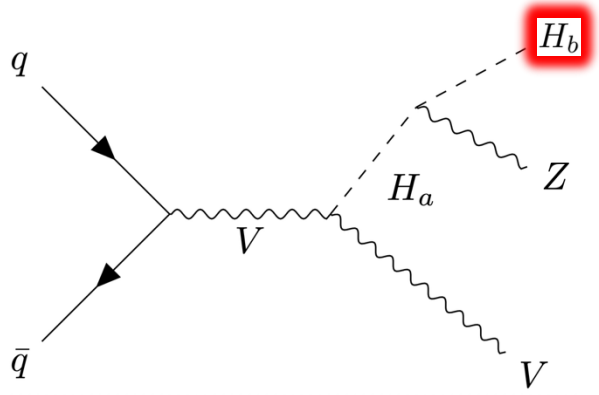
Unlocking the power of the LHC

A threefold way…?

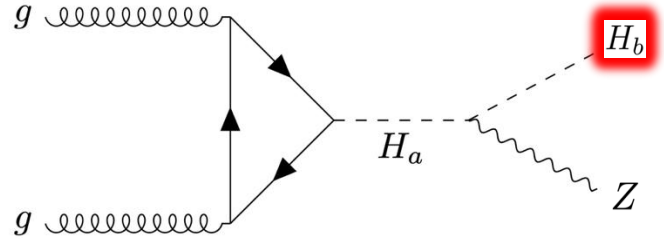
Vector boson fusion *(VBF)*



V-associated production *(V-AP)*



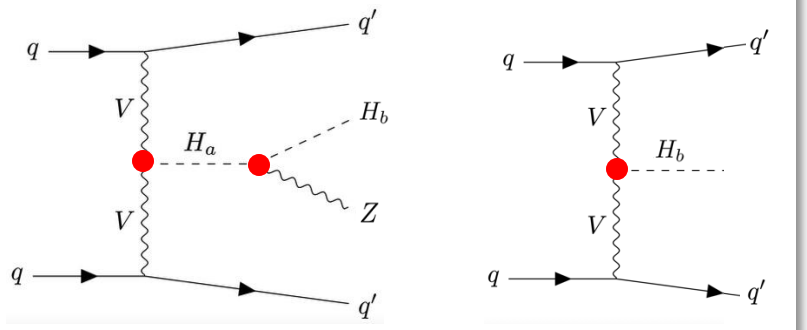
Gluon fusion assisted (*ggF*)



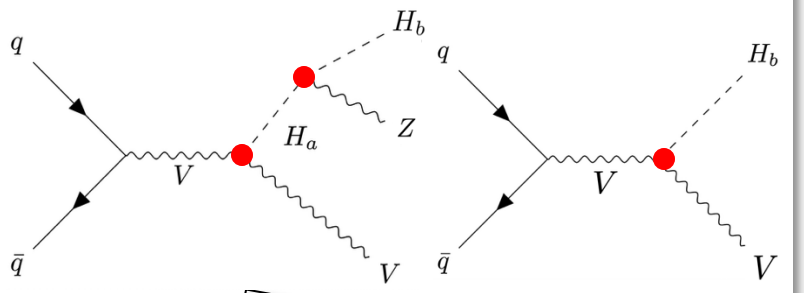
Unlocking the power of the LHC

A threefold way…?

Vector boson fusion *(VBF)*

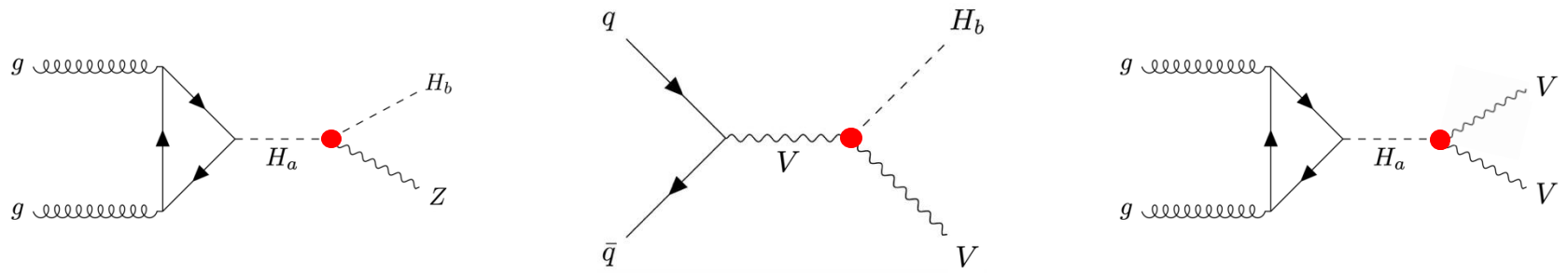


V-associated production *(V-AP)*



Mix & Match

Gluon fusion assisted (*ggF*)

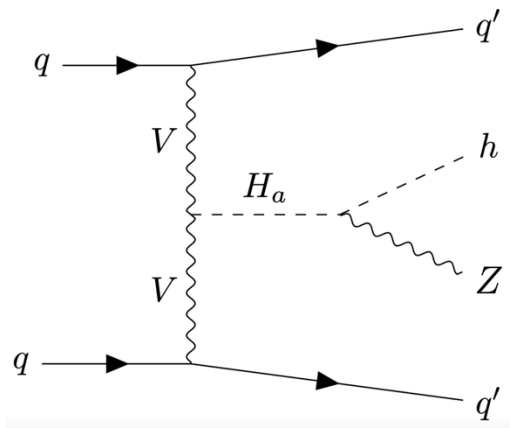


One of many – *see paper for more!*

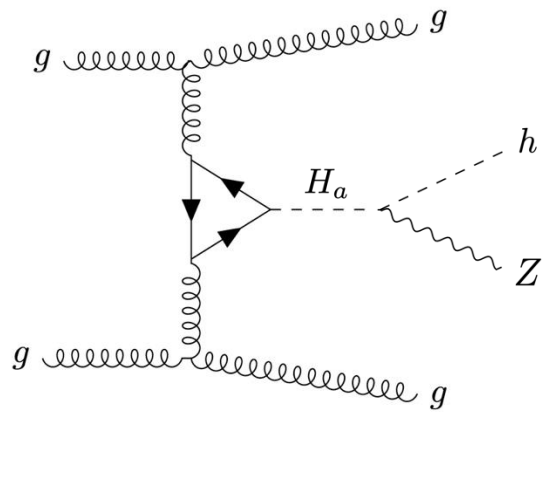
Unlocking the power of the LHC

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**

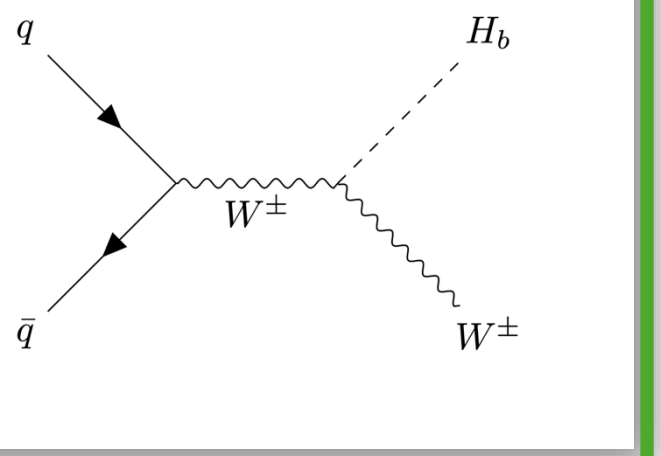
? Possible improvement through **cuts** as in SM… but ***ggF-to-VBF ratio*** unknown *a priori* (BSM)

✓ Optimized ***quark-gluon jet tagging*** might solve this

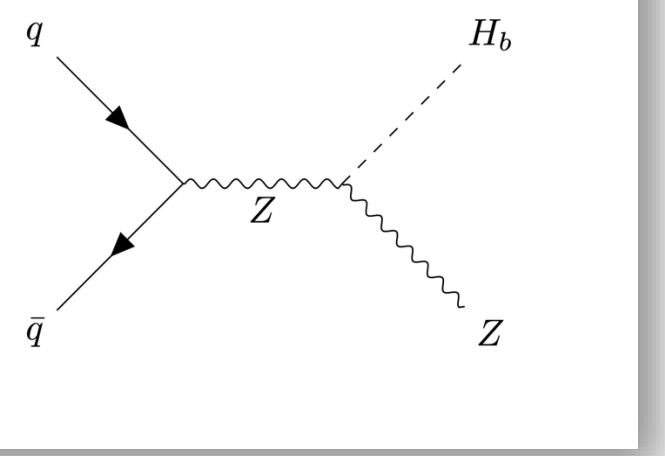
Unlocking the power of the LHC

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)

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

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 + CP-indefinite

$$H_1,\ H_2,\ H_3$$

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

2 charged

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

+ 3 Goldstones

Mass basis

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

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

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

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

Benchmarking the LHC

Complex Two-Higgs-Doublet Model (C2HDM)

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

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

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

Gauge couplings

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

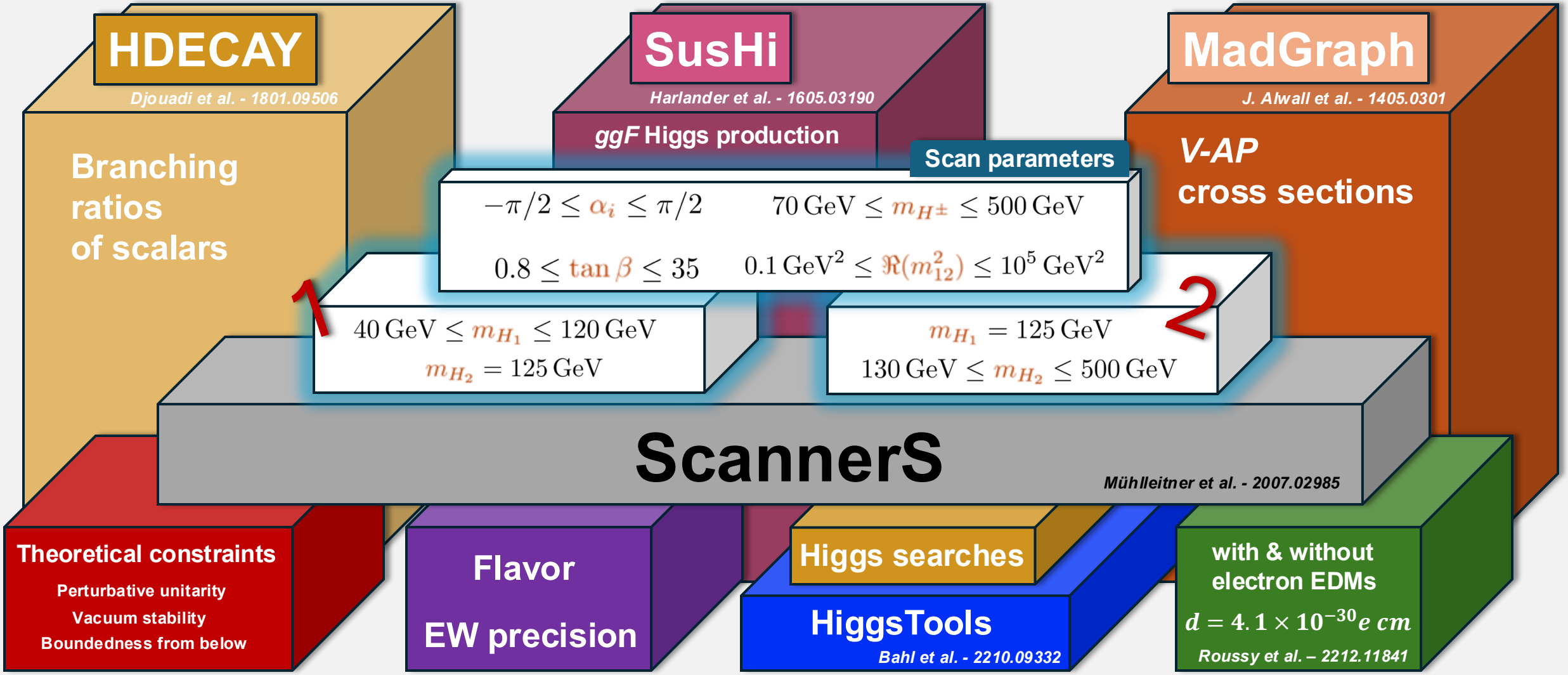
$$[H_i, Z_\mu, Z_\nu] = i\,\frac{gM_Z}{c_W}\,g_{\mu\nu}\,[R_{i1}\cos(\beta) + R_{i2}\sin(\beta)] \equiv i\,\frac{gM_Z}{c_W}\,g_{\mu\nu}\,C_i$$

1711.09419

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

Benchmarking the LHC

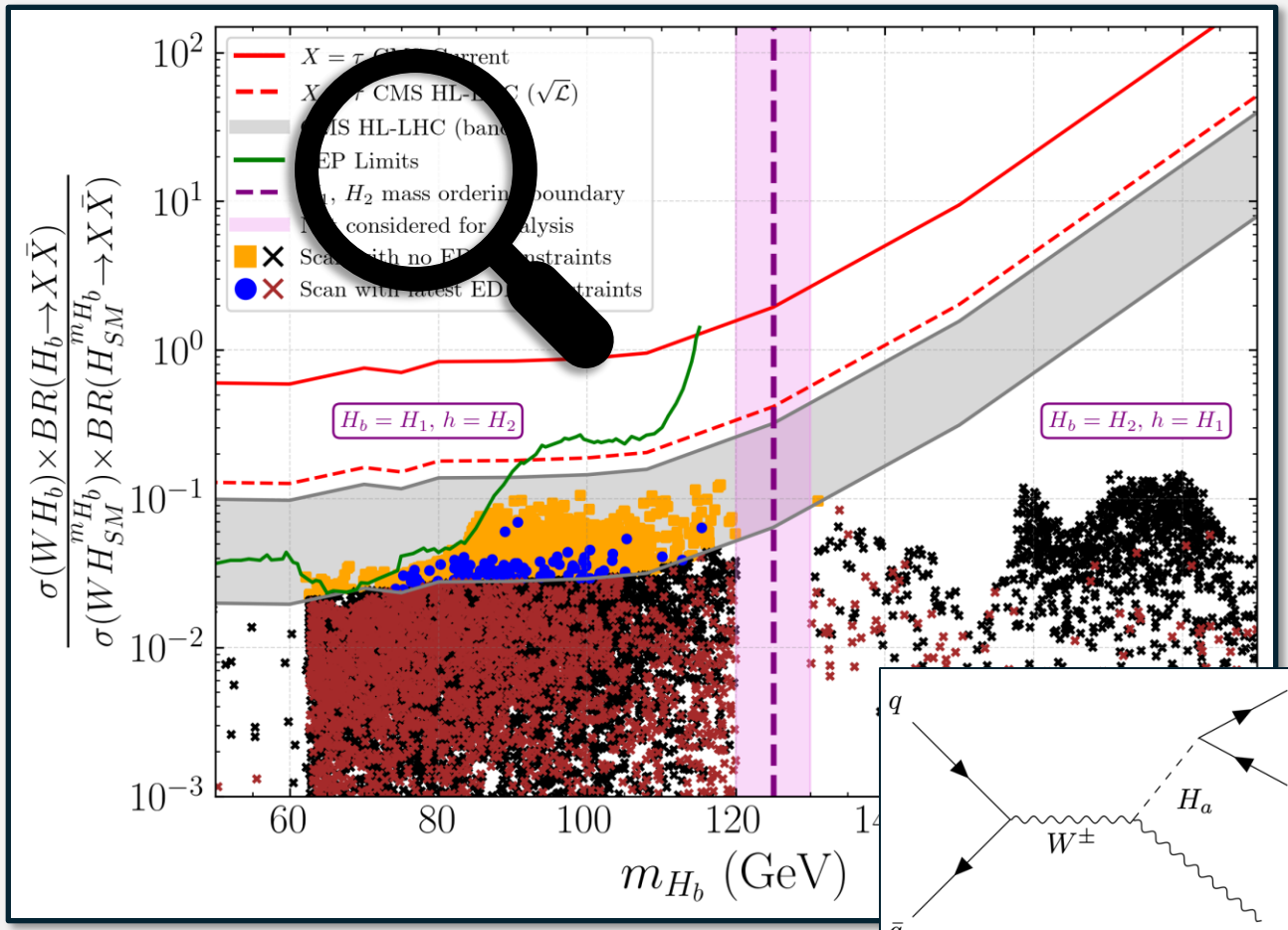
Setting up the scan

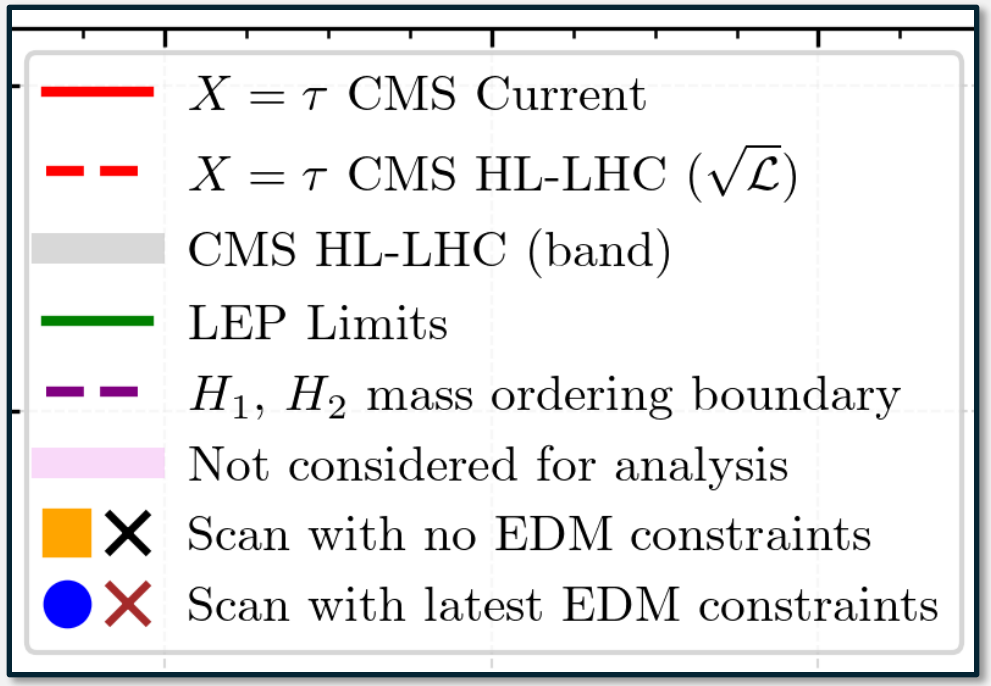


Exemplary results

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

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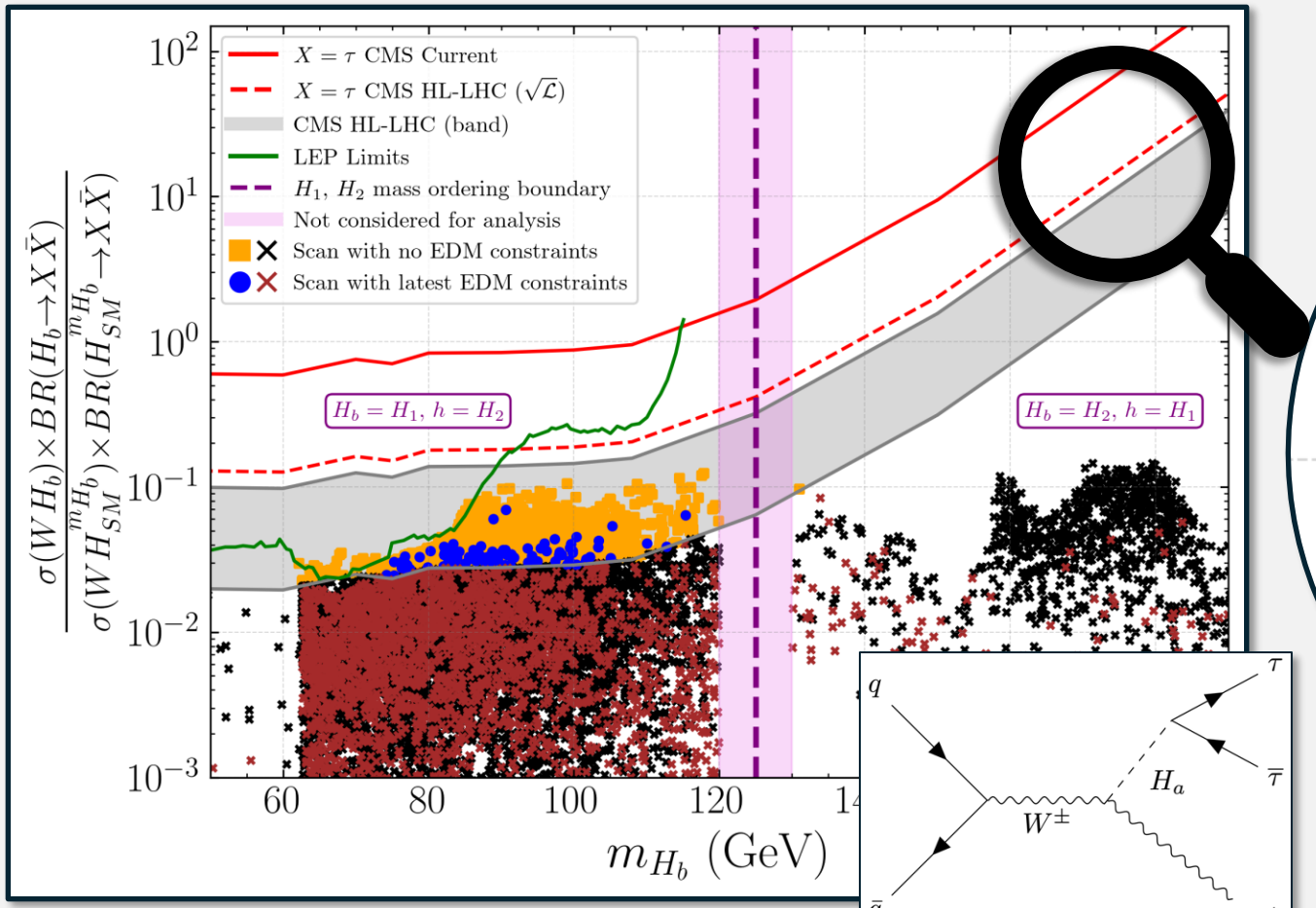
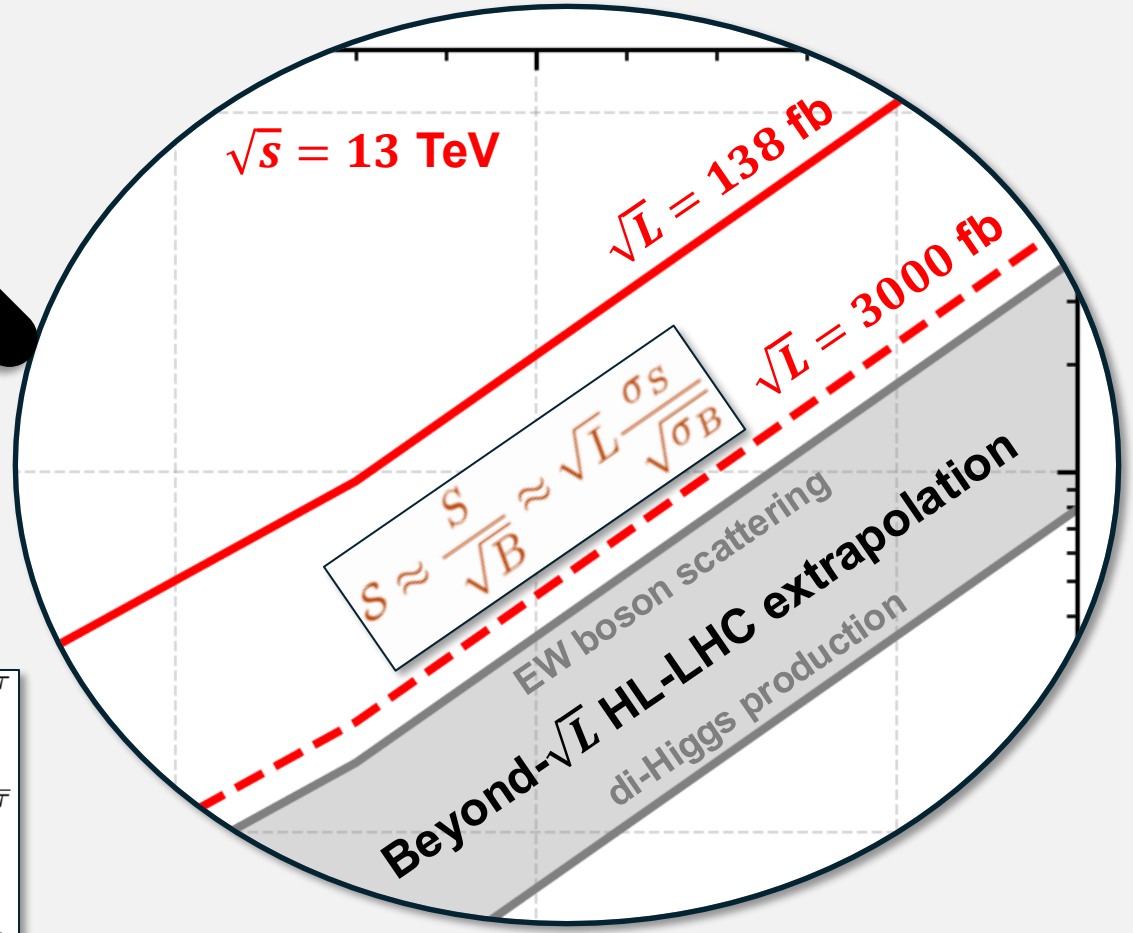


Limits: CMS - 2402.11098, G. Abbiendi et al. - hep-ex/0306033

Statistics vs heuristics



Exemplary results

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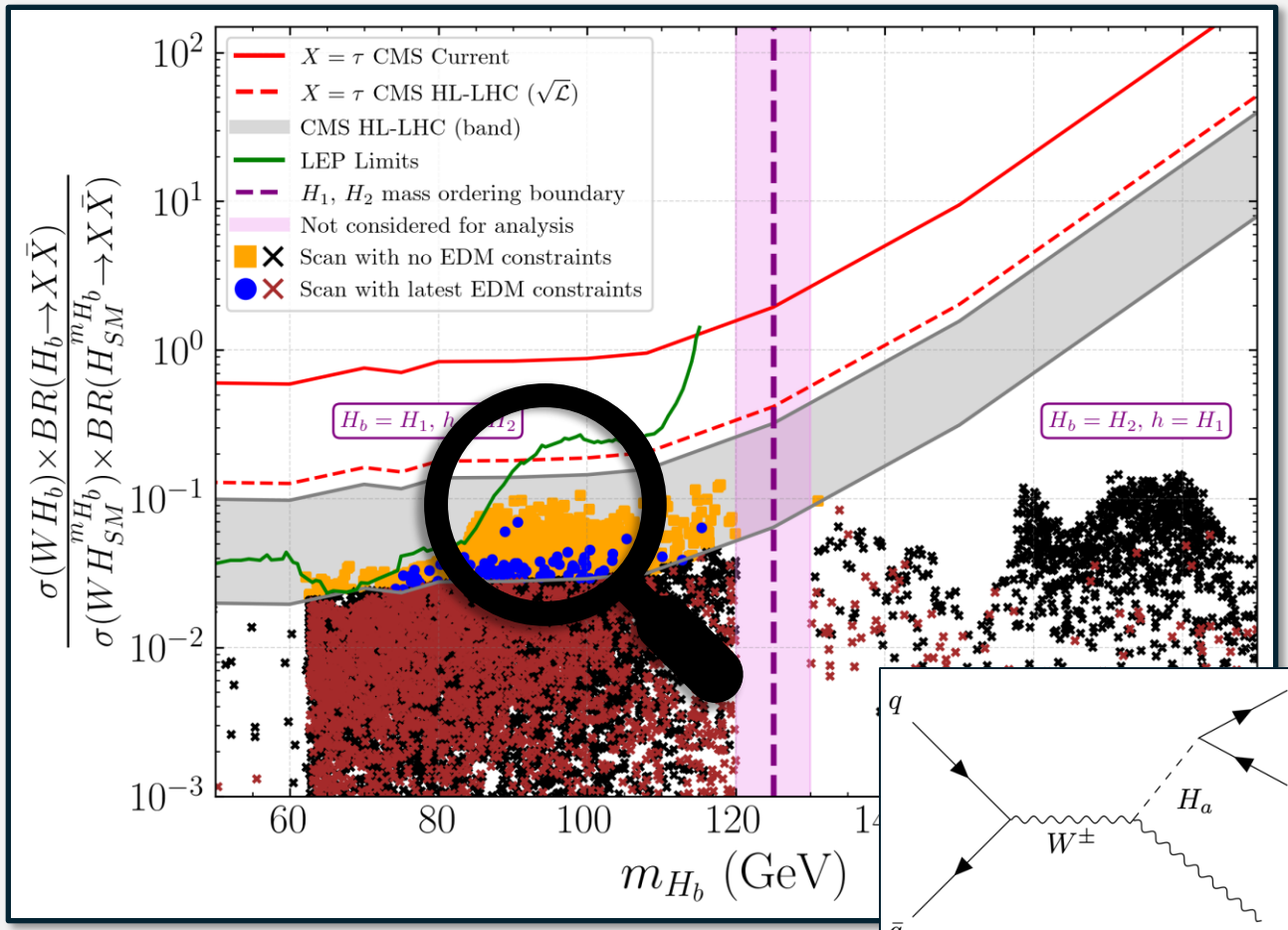
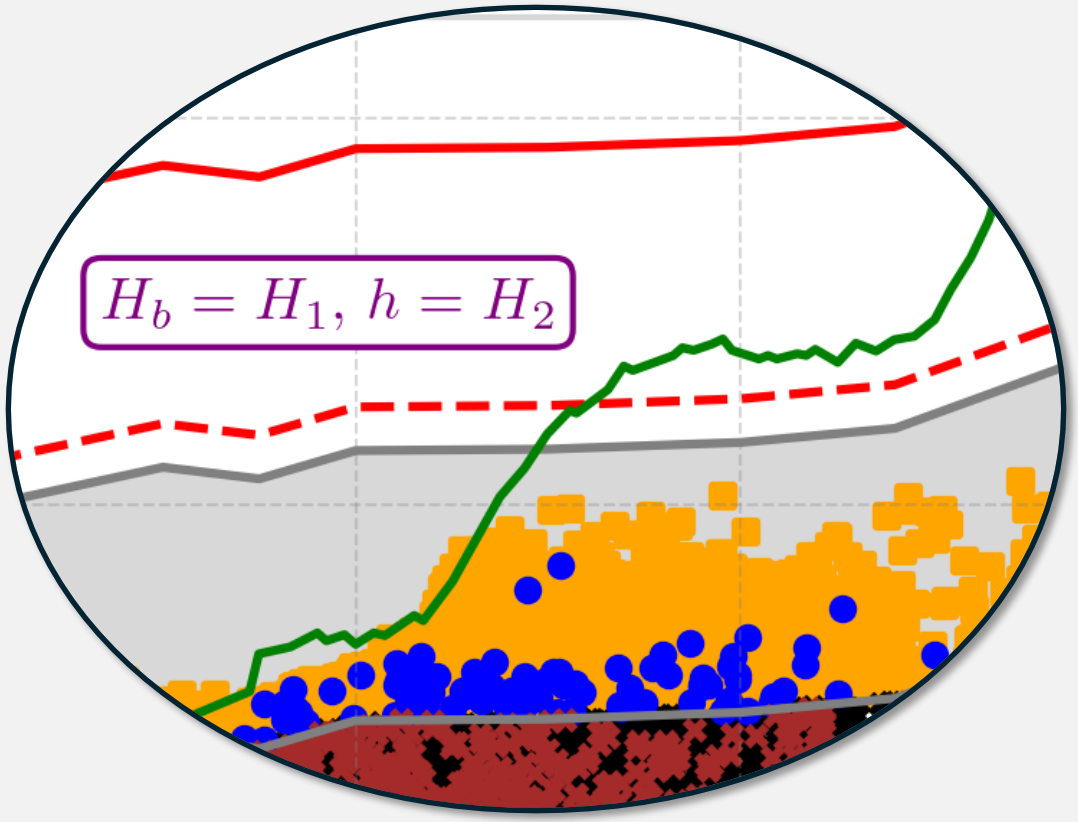


Limits: CMS - 2402.11098, G. Abbiendi et al. - hep-ex/0306033

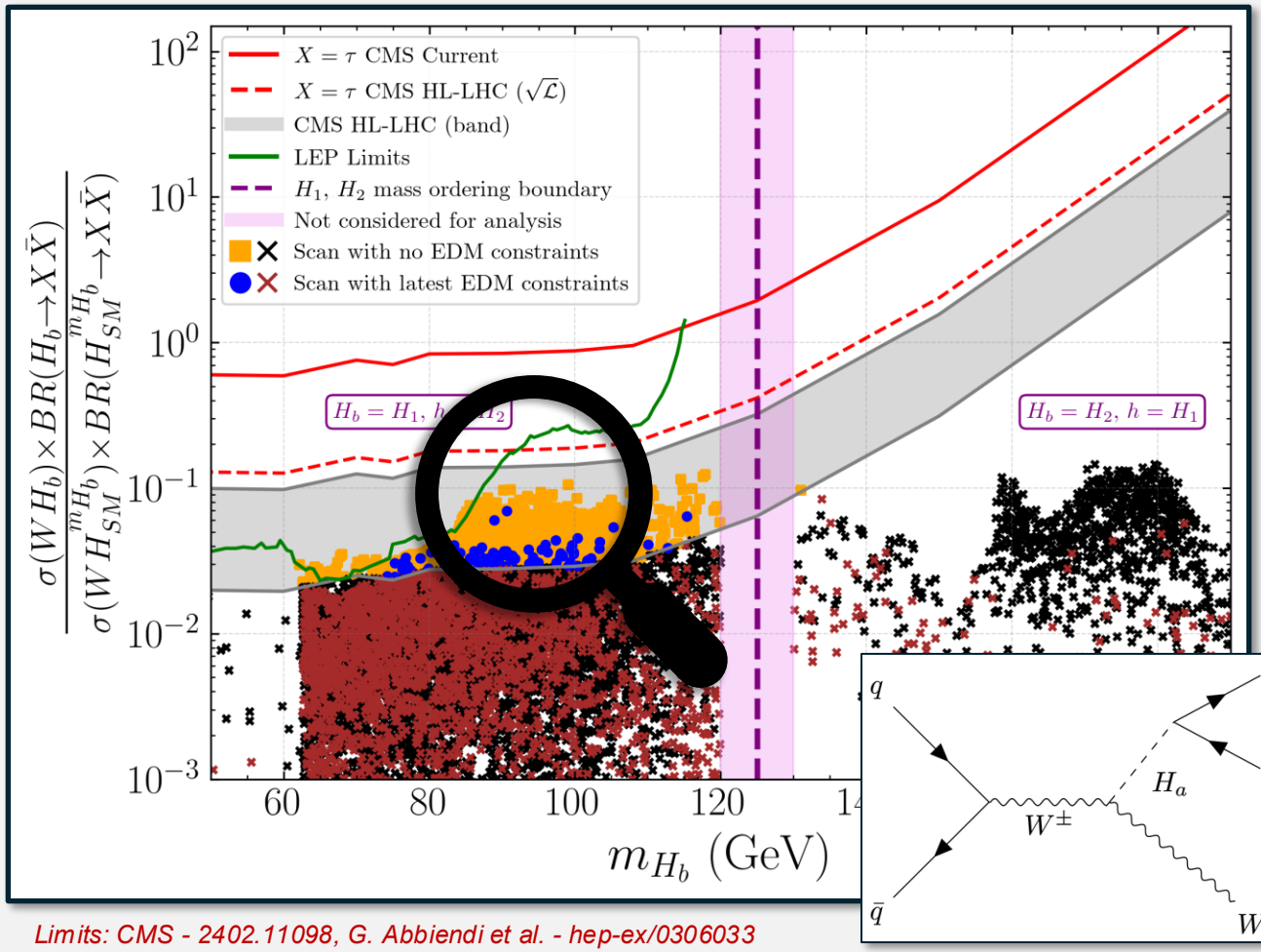


LEP limits: ***"Where does suppression come from?"***

Exemplary results

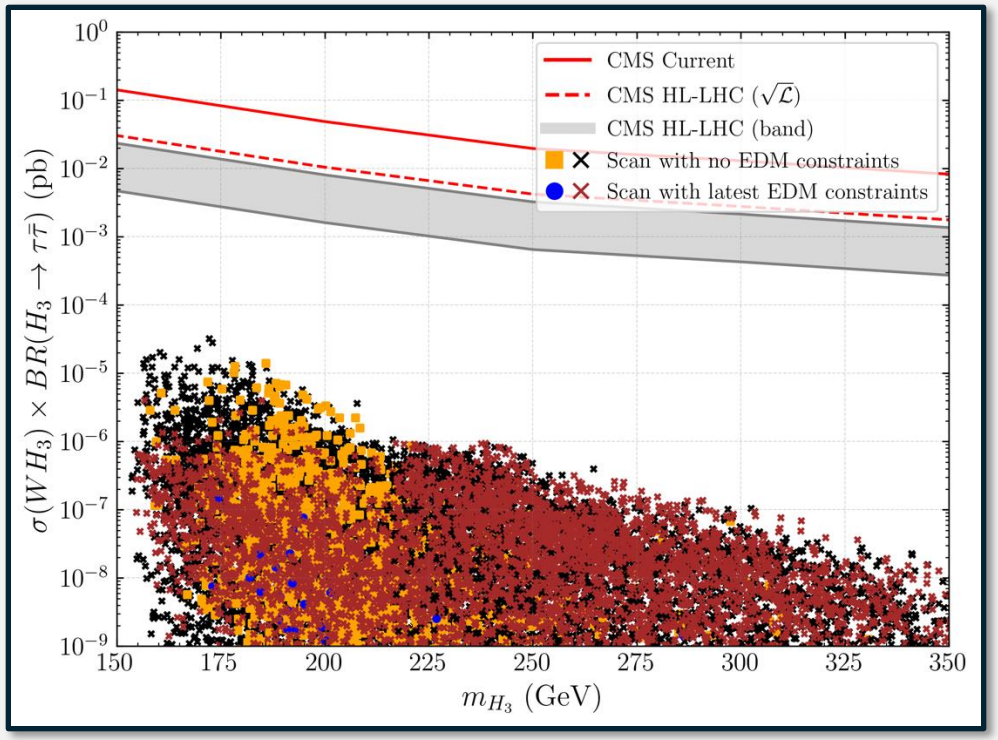
W-AP of lightest non-SM Higgs in the C2HDM

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



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

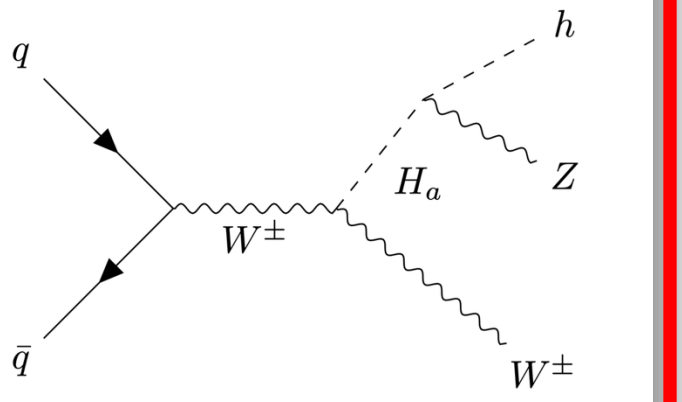
Compare to W-AP of H_3…



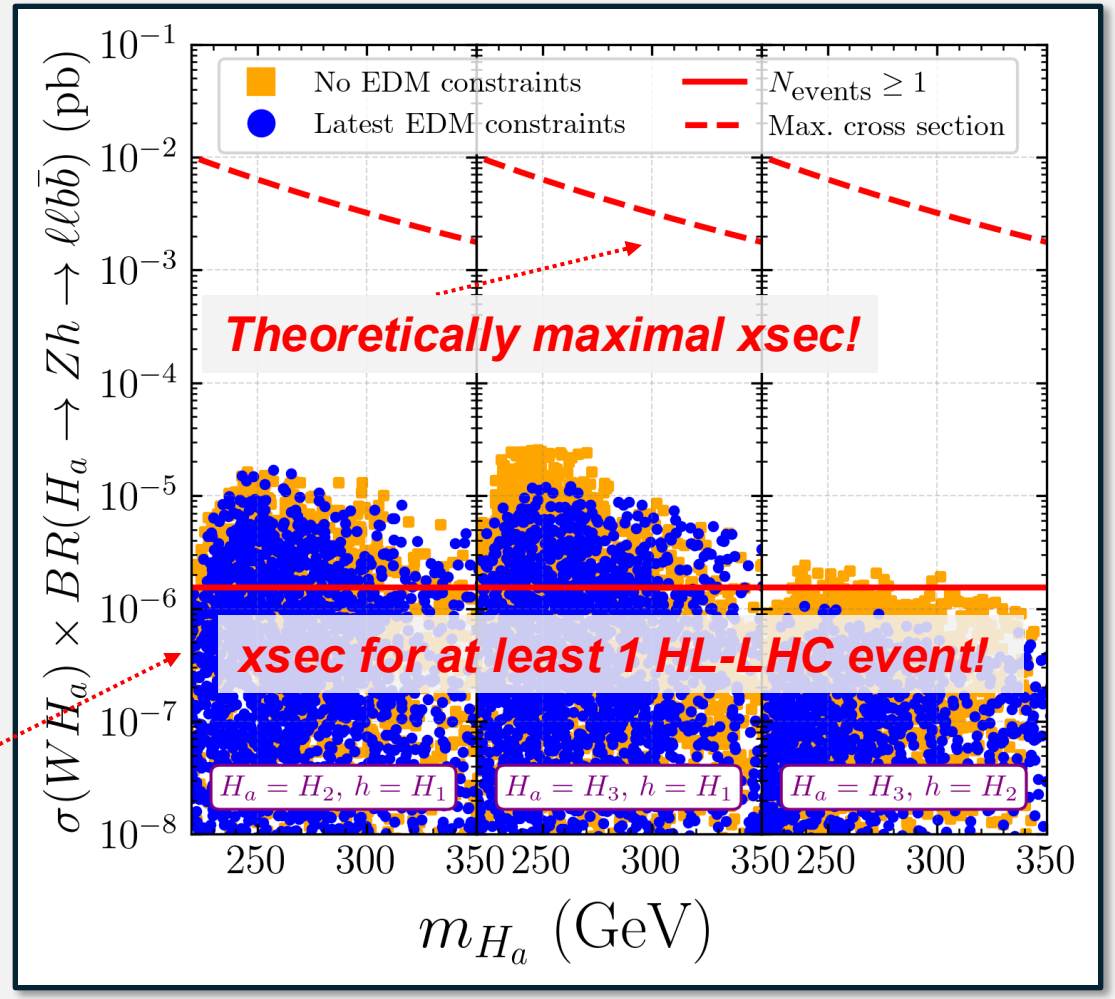
Exemplary results

Probing CPV with poster child *W-AP*?

V-associated production *(V-AP)*

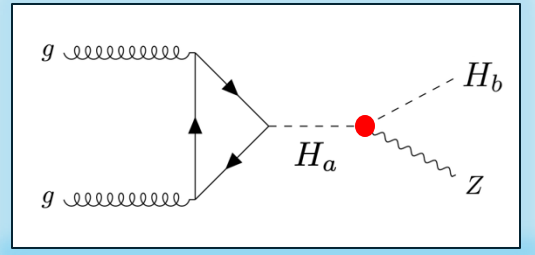


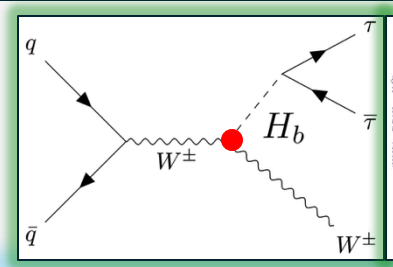
***Don't have limits*… but needle in a haystack!**

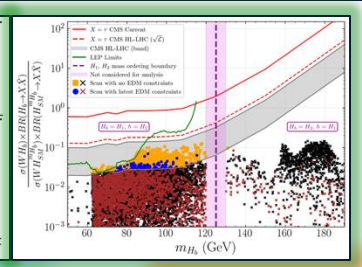


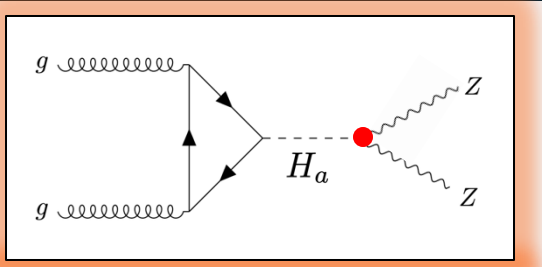
Exemplary results

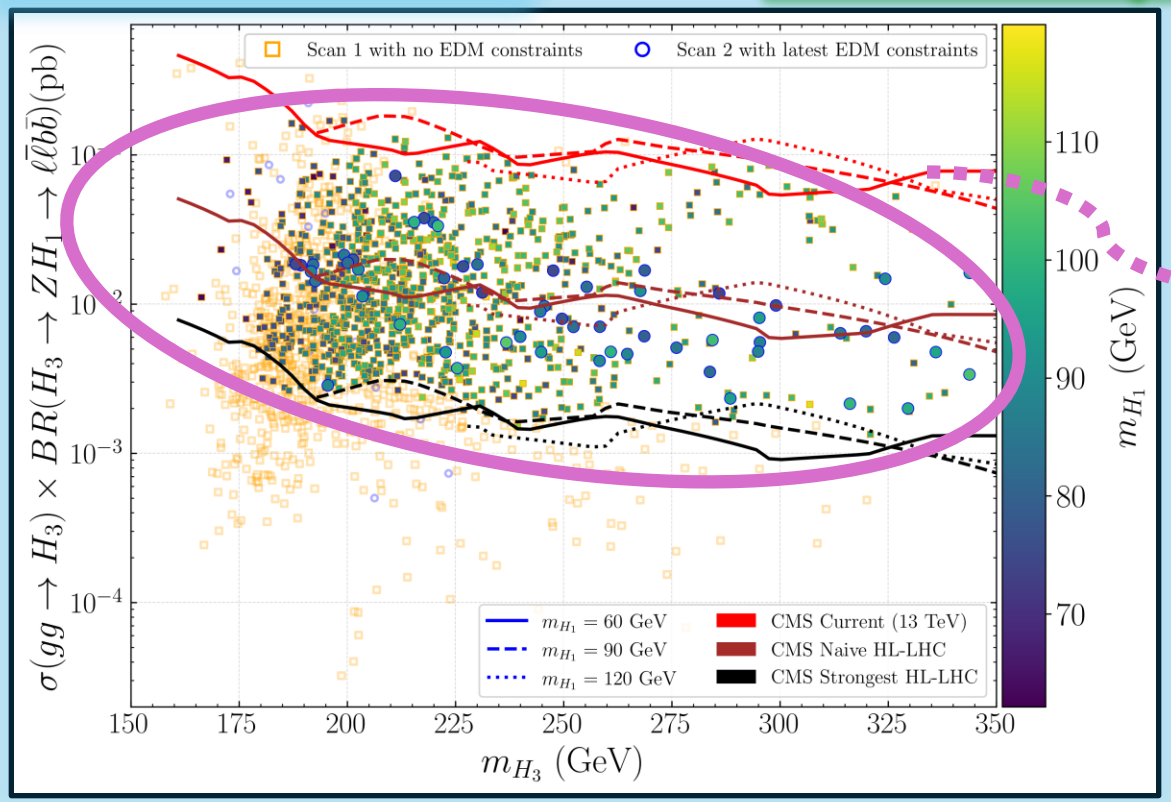
The *ggF* way – *good game, fellas!*

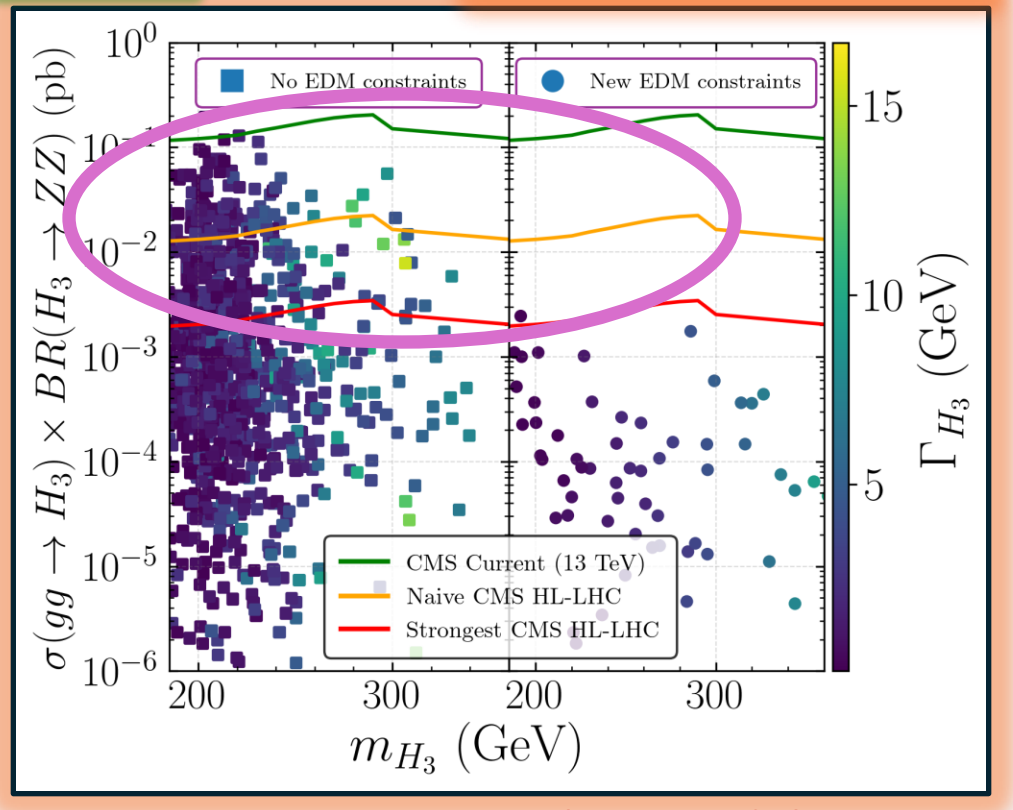












Limits: A. M. Sirunyan et al. (CMS) – 1911.03781

Limits: A. M. Sirunyan et al. (CMS) – 1804.01939

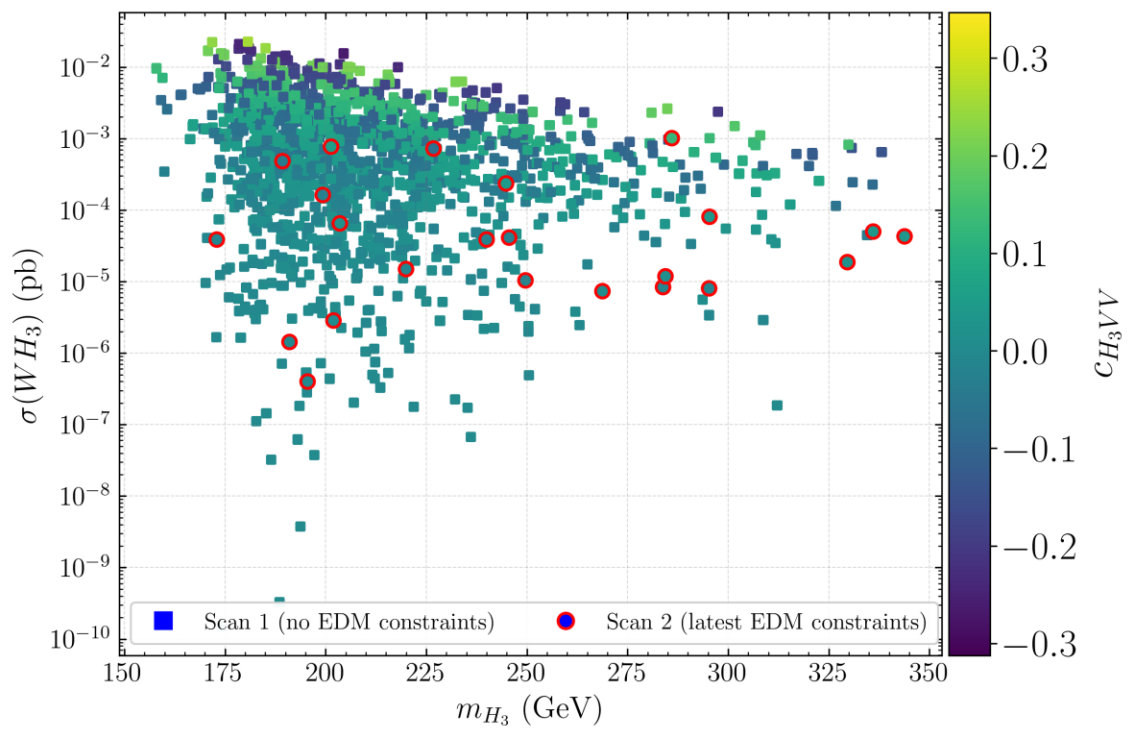
Concluding remarks

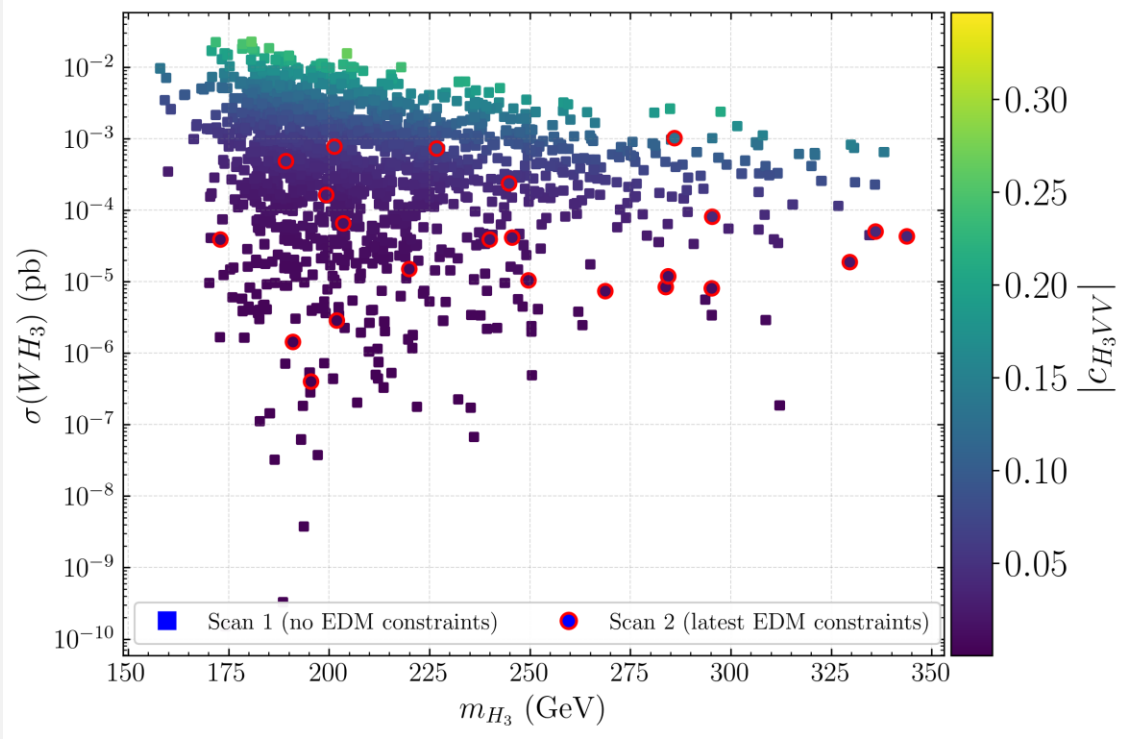
CPV may be hiding in the scalar sector beyond the SM…

… and the LHC may be a great place to find out.

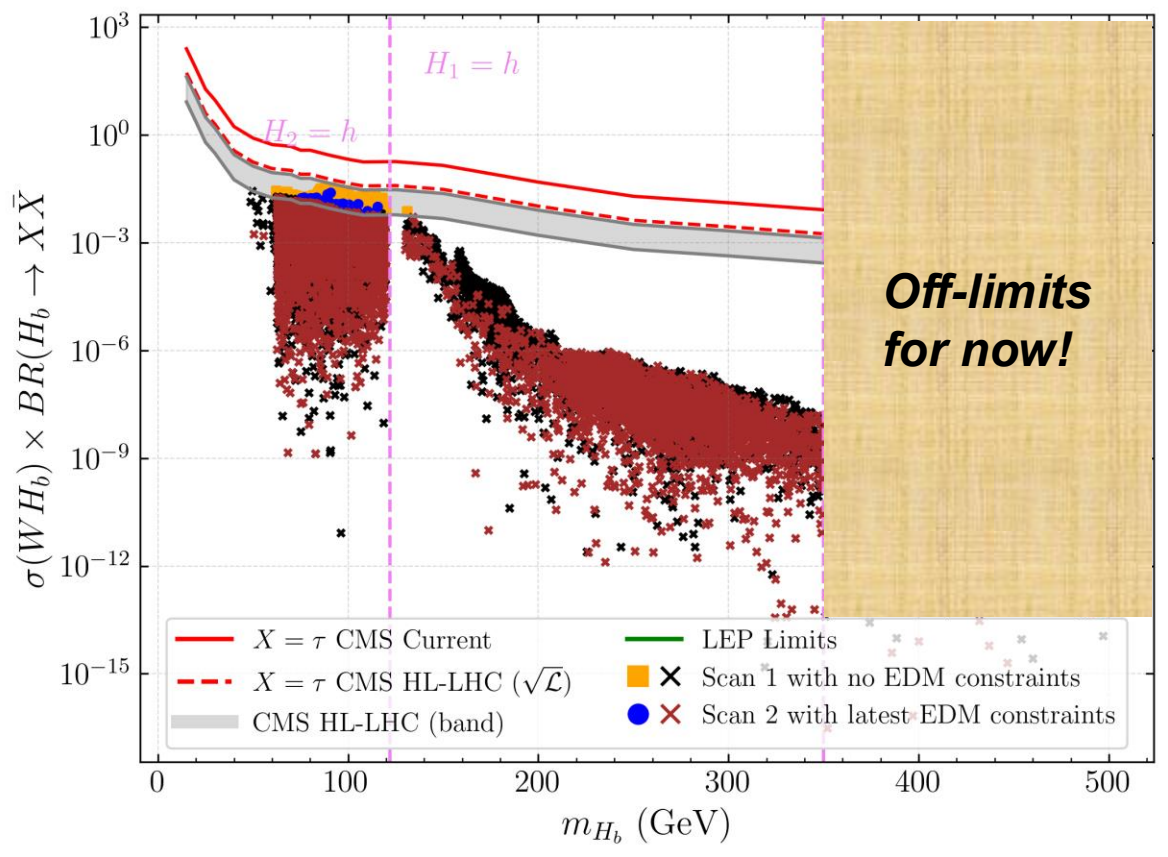
Thank you!

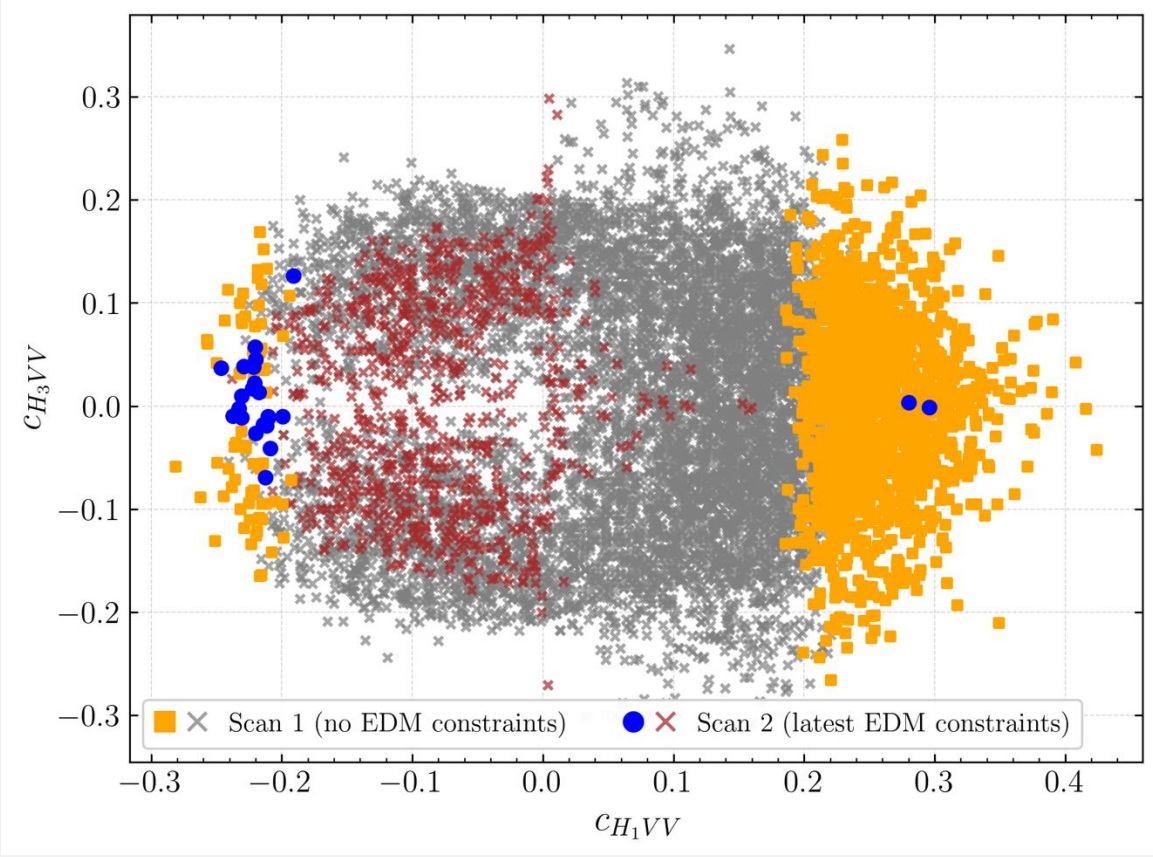
Backup


$\sigma(WH_3)$ (pb)
m_{H_3} (GeV)
Scan 1 (no EDM constraints)
Scan 2 (latest EDM constraints)
c_{H_3VV}

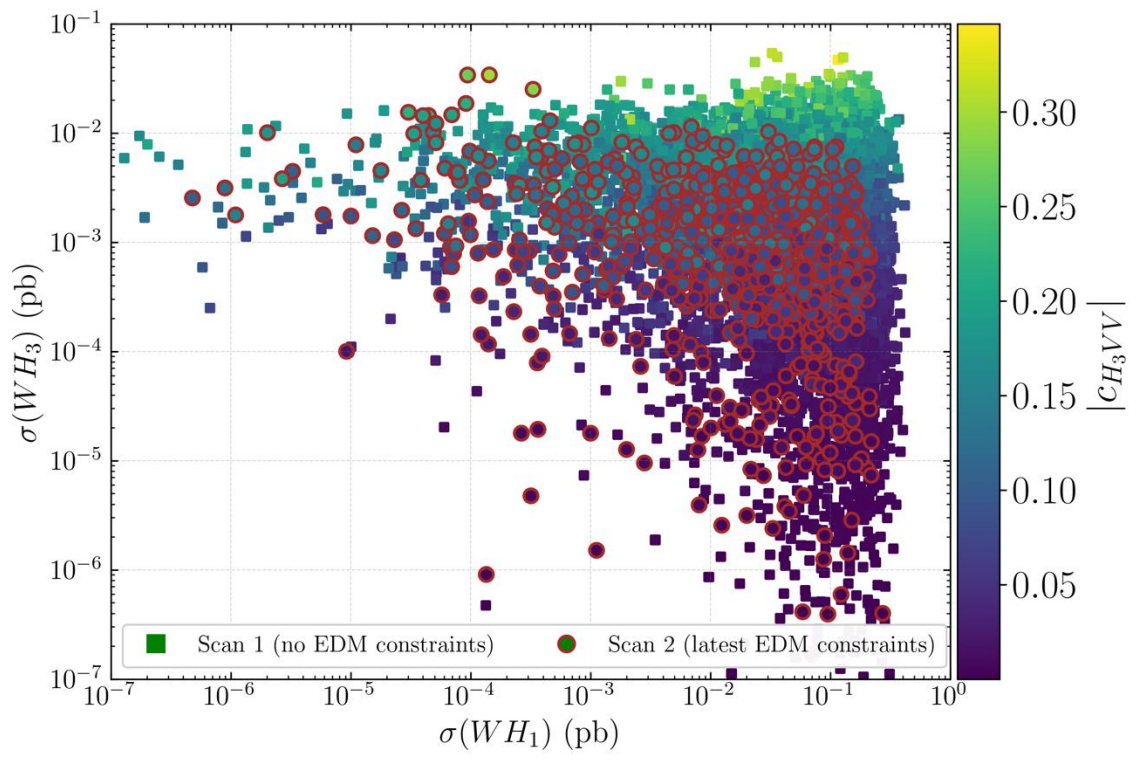

$\sigma(WH_3)$ (pb)
m_{H_3} (GeV)
Scan 1 (no EDM constraints)
Scan 2 (latest EDM constraints)
$|c_{H_3VV}|$

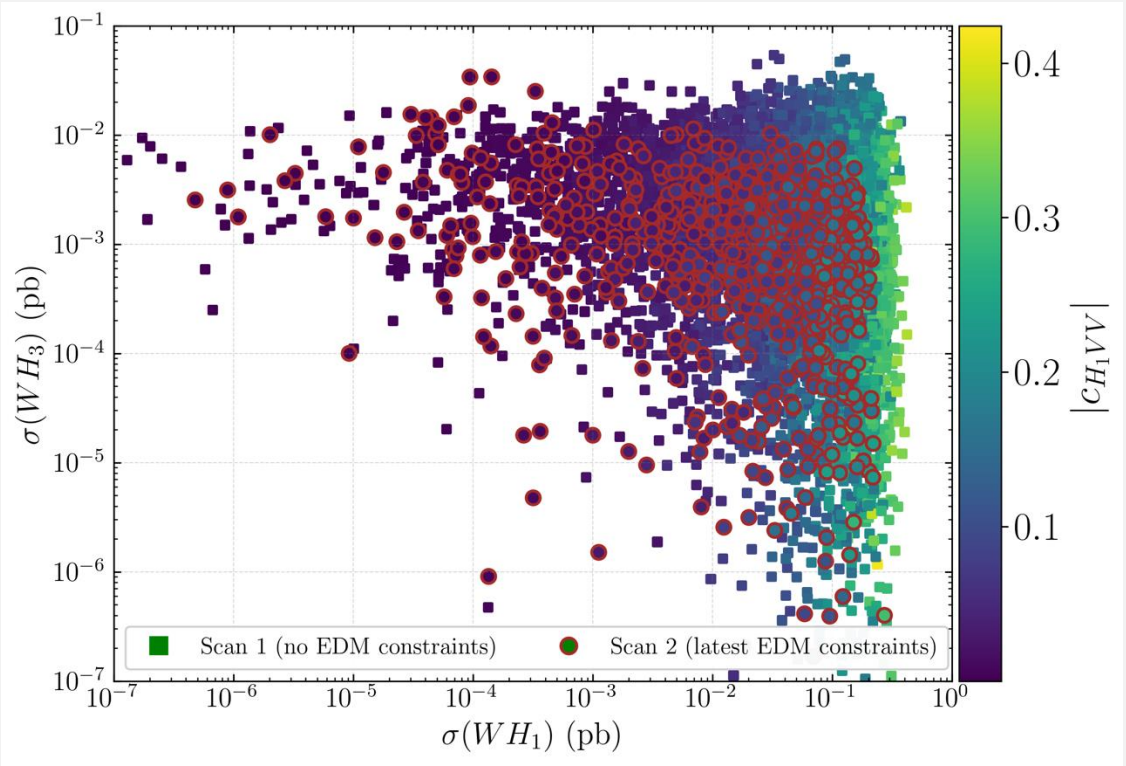
Backup


$H_1 = h$
$H_2 = h$
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
$\sigma(WH_b) \times BR(H_b \to X\bar{X})$
m_{H_b} (GeV)


Scan 1 (no EDM constraints)
Scan 2 (latest EDM constraints)
c_{H_3VV}
c_{H_1VV}

Backup


$\sigma(WH_3)$ (pb)
$\sigma(WH_1)$ (pb)
$|c_{H_3VV}|$
Scan 1 (no EDM constraints)
Scan 2 (latest EDM constraints)


$\sigma(WH_3)$ (pb)
$\sigma(WH_1)$ (pb)
$|c_{H_1VV}|$
Scan 1 (no EDM constraints)
Scan 2 (latest EDM constraints)