Trilinear Higgs Couplings in 2HDMS and N2HDM Type II at e^+e^- Colliders

Master Thesis Project: Mid-term Talk

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Two Higgs Doublet Models Plus Singlet

N2HDM (real singlet)

$$\phi_{1,2} = \begin{pmatrix} \chi_i^\pm \\ \frac{v_i+\rho_i+i\eta_i}{\sqrt{2}} \end{pmatrix}, \qquad S = v_S + \rho_S$$

$$\sqrt{v_1^2 + v_2^2} = 246.22\,\text{GeV}$$

symmetries:

- $\mathbb{Z}_2$ $\qquad \phi_2 \to -\phi_2$
- $\mathbb{Z}_2'$ $\qquad S \to -S$

2HDMS($\mathbb{Z}_3$) (complex singlet)

$$\phi_{1,2} = \begin{pmatrix} \chi_i^\pm \\ v_i + \frac{\rho_i+i\eta_i}{\sqrt{2}} \end{pmatrix}, \qquad S = v_S + \frac{\rho_S + i\eta_S}{\sqrt{2}}$$

$$\sqrt{v_1^2 + v_2^2} = 174\,\text{GeV} = \frac{v_{\text{SM}}}{\sqrt{2}}$$

symmetries:

- $\mathbb{Z}_2$ $\qquad \phi_2 \to -\phi_2$
- $\mathbb{Z}_3$ $\qquad \begin{pmatrix} \phi_2 \\ S \end{pmatrix} \to \begin{pmatrix} e^{i\frac{2\pi}{3}} & 0 \\ 0 & e^{-i\frac{2\pi}{3}} \end{pmatrix} \begin{pmatrix} \phi_2 \\ S \end{pmatrix}$

N2HDM

$$V = \underline{m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2} - m_{12}^2(\phi_2^\dagger\phi_1 + \phi_1^\dagger\phi_2)$$

$$+ \underline{\frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2)}$$

$$+ \underline{\lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1)} + \frac{\lambda_5}{2}((\phi_1^\dagger\phi_2)^2 + (\phi_2^\dagger\phi_1)^2)$$

$$+ \underline{\frac{m_S^2}{2}S^2 + \frac{\lambda_6}{8}S^4 + \frac{\lambda_7}{2}(\phi_1^\dagger\phi_1)S^2 + \frac{\lambda_8}{2}(\phi_2^\dagger\phi_2)S^2}$$

2HDMS

$$V = \underline{m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2} - m_{12}^2(\phi_2^\dagger\phi_1 + \phi_1^\dagger\phi_2)$$

$$+ \underline{\frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2)}$$

$$+ \underline{\lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1)} + \underline{m_S^2(S^\dagger S)} + \underline{\lambda_1'(S^\dagger S)(\phi_1^\dagger\phi_1)}$$

$$+ \underline{\lambda_2'(S^\dagger S)(\phi_2^\dagger\phi_2) + \lambda_3''(S^\dagger S)^2} + \frac{\mu_{S_1}}{6}(S^3 + S^{\dagger 3})$$

$$+ \mu_{12}(S\phi_1^\dagger\phi_2 + S^\dagger\phi_2^\dagger\phi_1)$$

same   same with h.c.   softly breaks $\mathbb{Z}_2$ breaks $\mathbb{Z}_3 \,|\, \mathbb{Z}_2'$

Physical Inputs and New Particles

N2HDM (11 dof)

- $\tan\beta = \frac{v_2}{v_1}$
- scalar: $m_{h_1}, m_{h_2}, m_{h_3}$
- pseudoscalar: m_A
- charged: $m_{h^\pm}$
- mixing: $\alpha_1, \alpha_2, \alpha_3$
- m_{12}
- v_S

$$\underbrace{\hphantom{xxxxxxxxxxxxxxxx}}_{\lambda_1,\lambda_2,\lambda_3,\lambda_4,\lambda_5,\lambda_6,\lambda_7,\lambda_8,\tan\beta,v_S,m_{12}}^{\text{basis change}}$$

2HDMS (12 dof)

- $\tan\beta = \frac{v_2}{v_1}$
- scalar: $m_{h_1}, m_{h_2}, m_{h_3}$
- pseudoscalar: m_{a_1}, m_{a_2}
- charged: $m_{h^\pm}$
- mixing: $\alpha_1, \alpha_2, \alpha_3, \alpha_4$
- $v_S = v_S^{\mathrm{N2HDM}}/\sqrt{2}$

$$\underbrace{\hphantom{xxxxxxxxxxxxxxxx}}_{\lambda_1,\lambda_2,\lambda_3,\lambda_4,\lambda'_1,\lambda'_2,\lambda''_3,\mu_{12},\mu_{s_1},\tan\beta,v_S,m_{12}}^{\text{basis change}}$$

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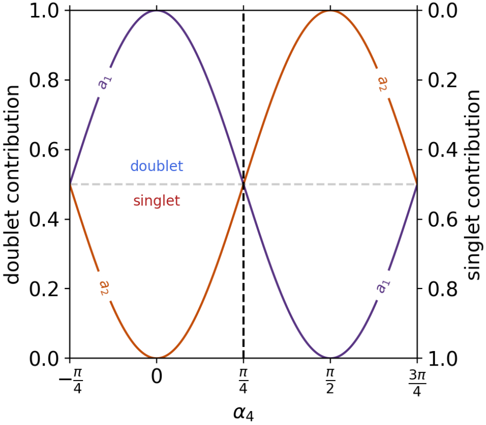
Pseudo Scalar Mass Hierarchy



$$\text{Doublet:} \begin{cases} \eta_1 = -a_1 \sin\beta \cos\alpha_4 + a_2 \ldots \\ \eta_2 = a_1 \cos\beta \cos\alpha_4 + a_2 \ldots \end{cases}$$

$$\text{Singlet:} \quad \eta_S = a_1 \sin\alpha_4 + a_2 \ldots$$

$$m_a^{\text{doublet}} = m_A^{N2HDM}$$

$\alpha_4 \leq \frac{\pi}{4}$:	$\alpha_4 \geq \frac{\pi}{4}$:
$m_{a_1} = m_a^{\text{doublet}}$	$m_{a_1} = m_a^{\text{singlet}}$
$m_{a_2} = m_a^{\text{singlet}}$	$m_{a_2} = m_a^{\text{doublet}}$

m_{12} Constraint

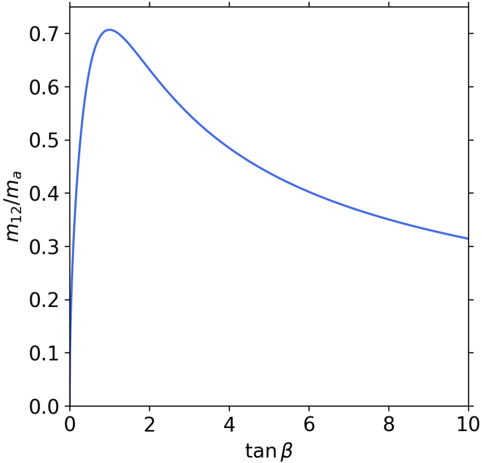
$$\left.\begin{aligned}\alpha_4 &\to 0\\ \alpha_4 &\to \frac{\pi}{2}\end{aligned}\right\}\text{2HDMS} \to \text{N2HDM}$$

$$\tilde{\mu}^2_{\text{2HDMS}} = m^2_{a_1}\cos^2\alpha_4 + m^2_{a_2}\sin^2\alpha_4$$

$$\to m^2_{a_i} = \hat{\mu}^2_{\text{N2HDM}} = \frac{m^2_{12}}{\sin\beta\cos\beta}$$

N2HDM constraint:

$$\Rightarrow m^2_{12} = m^2_A \sin\beta\cos\beta$$



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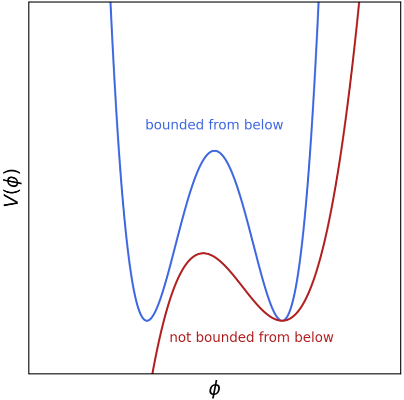
Theoretical Constraints

- Tree level perturbative unitarity
  - $|\mathcal{M}| \leq 8\pi$
- Boundedness from below
  - $\phi_i, S \to \pm\infty \Rightarrow V \to \infty$
- Conditions on $\lambda_1, \lambda_2, \lambda_3 \ldots$
  - N2HDM [1]
  - 2HDMS [2]



Experimental Constraints

- HiggsSignals[3]: h_2 agrees with measurements of 125 GeV Higgs boson (95 %CL)

$$\chi^2_{125;\mathrm{SM}} - \chi^2_{125;\mathrm{BSM}} \leq 5.99$$

- HiggsBounds[3]: exclusions on BSM searches (95 %CL)

- A hypothetical 95.4 GeV Higgs boson
- Fit experimental excesses (95 %CL):
  - ATLAS [4]

$$\mu^{\gamma\gamma}_{\mathrm{ATLAS}} = 0.21 \pm 0.12$$

  - CMS [1] [5]

$$\mu^{\gamma\gamma}_{\mathrm{CMS}} = 0.33^{+0.19}_{-0.12}$$

  - LEP[6]

$$\mu^{b\bar{b}}_{\mathrm{LEP}} = 0.117 \pm 0.057$$

[1] $\mu^{\tau\tau}_{\mathrm{CMS}}$ also exists but not compatible with Type II

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Vector Boson and Yukawa Couplings

- $R = \begin{pmatrix} c_{\alpha_1}c_{\alpha_2} & s_{\alpha_1}c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1}s_{\alpha_2}s_{\alpha_3}+s_{\alpha_1}c_{\alpha_3}) & -s_{\alpha_1}s_{\alpha_2}s_{\alpha_3}+c_{\alpha_1}c_{\alpha_3} & c_{\alpha_2}s_{\alpha_3} \\ -c_{\alpha_1}s_{\alpha_2}c_{\alpha_3}+s_{\alpha_1}s_{\alpha_3} & -(s_{\alpha_1}s_{\alpha_2}c_{\alpha_3}+c_{\alpha_1}s_{\alpha_3}) & c_{\alpha_2}c_{\alpha_3} \end{pmatrix}$
- coupling ratio: $c_{h_ipp} = \frac{g_{h_ipp}}{g_{h_{SM}pp}}$

Vector Boson Coupling

- $c_{h_iVV} = R_{i1}\cos\beta + R_{i2}\sin\beta$
- alignment limit to SM
  - $c_{h_2VV} \to 1$
  - $c_{h_{1,3}VV} \to 0$
  - $\beta - \alpha_1 - \mathrm{sg}(\alpha_2)\alpha_3 \to \frac{\pi}{2}$

Yukawa Coupling

Type II: $t\bar{t} \sim \phi_2 \quad b\bar{b} \sim \phi_1 \quad \tau\bar{\tau} \sim \phi_1$

- $c_{h_itt} = \frac{R_{i2}}{\sin\beta}$
- $c_{h_ibb} = \frac{R_{i1}}{\cos\beta}$
- $c_{h_i\tau\tau} = \frac{R_{i1}}{\cos\beta}$

Trilinear Higgs Couplings

4 Type II Couplings

- $g_{h_i h_j h_k} = \frac{\partial^3 V}{\partial_{h_i} \partial_{h_j} \partial_{h_k}}\Big|_{h_{i,j,k}=0}$
- $\Lambda(a,b,c) = \sum_{\sigma \in S_3} R_{i\sigma(a)} R_{j\sigma(b)} R_{k\sigma(c)}$

$$
\begin{aligned}
g_{h_i h_j h_k} = \; & \underline{\left(m_i^2 + m_j^2 + m_k^2\right)\left[\frac{R_{i1}R_{j1}R_{k1}}{v\cos\beta} + \frac{R_{i2}R_{j2}R_{k2}}{v\sin\beta} + \frac{R_{i3}R_{j3}R_{k3}}{v_S}\right]} \\
& + \frac{\tilde{\mu}^2}{v}\left[-\frac{3R_{i1}R_{j1}R_{k1}\sin^2\beta}{\cos\beta} - \frac{3R_{i2}R_{j2}R_{k2}\cos^2\beta}{\sin\beta} + \frac{1}{2}\cos\beta\Lambda(1,2,2) + \frac{1}{2}\sin\beta\Lambda(1,1,2)\right] \\
& + \left(\frac{m_{a_2}^2 - m_{a_1}^2}{v}\cos\alpha_4\sin\alpha_4\right)\left[\frac{5R_{i3}R_{j3}R_{k3}v^2\sin 2\beta}{3v_S^2} - \frac{1}{2}\tan\beta\Lambda(1,1,3) - \frac{v\sin\beta}{2v_S}\Lambda(1,3,3)\right. \\
& \left. - \frac{1}{2}\cot\beta\Lambda(2,2,3) - \frac{v\cos\beta}{2v_S}\Lambda(2,3,3) + \Lambda(1,2,3)\right] + \frac{R_{i3}R_{j3}R_{k3}}{3v_S}\left(m_{a_1}^2\sin^2\alpha_4 + m_{a_2}^2\cos^2\alpha_4\right)
\end{aligned}
$$

same part $\qquad \tilde{\mu}_{\mathrm{2HDMS}} \neq \hat{\mu}_{\mathrm{N2HDM}} \qquad$ only in 2HDMS

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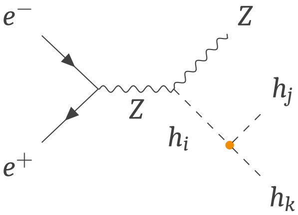
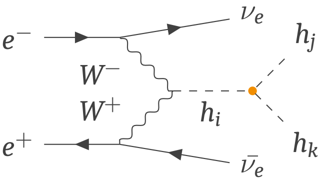
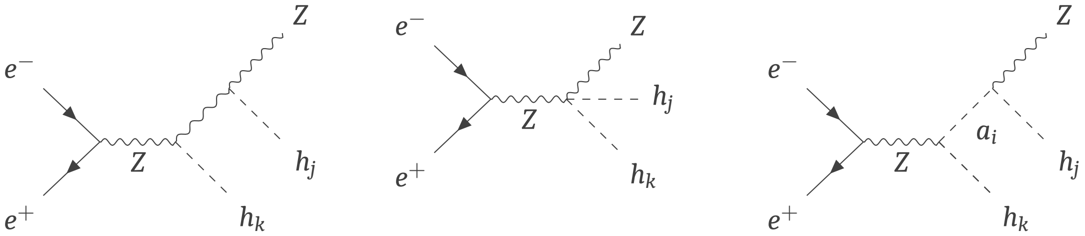
Higgs Strahlung



Vector Boson Fusion



Higgs Strahlung Background



- $\sqrt{s} = 500\,\text{GeV}$
- $\mathcal{L}_{\text{int}} = 4\,\text{ab}^{-1}$
- Pol. $e^{+} = +0.3$
- Pol. $e^{-} = -0.8$
- Expected $\sigma_{\text{SM}}(ZHH) = 0.232\,\text{fb}$

uncertainty estimation

- ILC$_{500}$ significance: 8σ at $2\,\text{ab}^{-1}$ [7]
- $\text{unc} = \frac{\sigma_{\text{SM}}}{8}\sqrt{\frac{2}{4}\frac{\sigma_{\text{SM}}}{\sigma(Zh_ih_j)}}$
- $\text{dev} = \frac{|\sigma_{\text{2HDMS}} - \sigma_{\text{N2HDM}}|}{unc_{\text{N2HDM}}}$

Cross-sections with `MadGraph5_aMC@NLO`[8]

Analysis

α_4 Limits

Strategy

6 Analysis

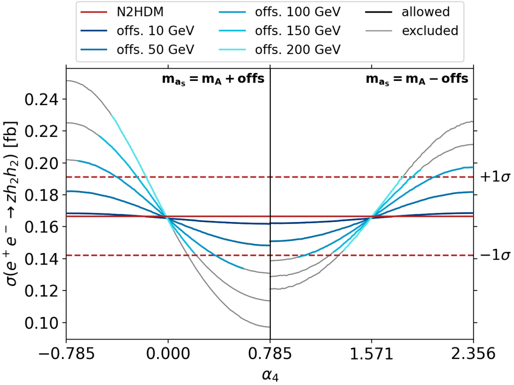
- differences only in α_4 and m_{A_s}
- hierarchy: $\alpha_4 \lessgtr \pi/4$
- angles by coupling:

$$c_{h_1VV}, \frac{c_{h_1bb}}{c_{h_1tt}}, \varepsilon \to \alpha_1, \alpha_2, \alpha_3$$

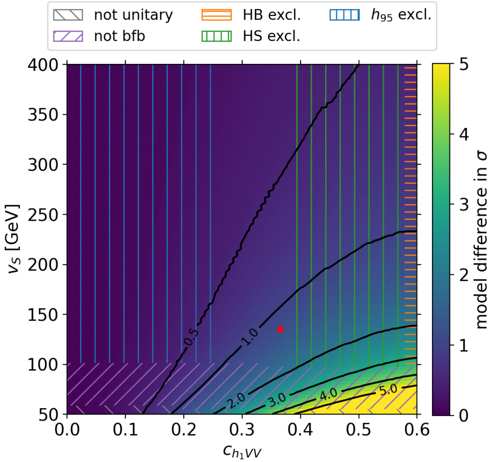
- alignment limit offset:

$$\beta - \alpha_1 - \mathrm{sg}(\alpha_2)\alpha_3 = \frac{\pi}{2} - \varepsilon$$

$\Rightarrow$ 1σ limits on α_4 for $\tan\beta$ vs m_A



Distinguishable Parameter Space



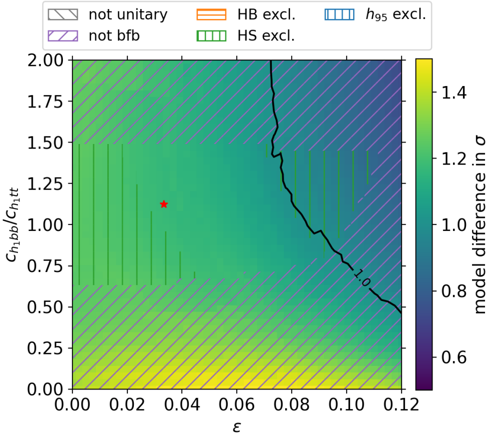
- set $\alpha_4 = 2.2$
- set $m_{a_1} = m_A - 120$ GeV

$\Downarrow$

- $v_S \leq 150$ GeV
- $c_{h_1VV} \in (0.23, 0.4)$
- $\star$ benchmark point

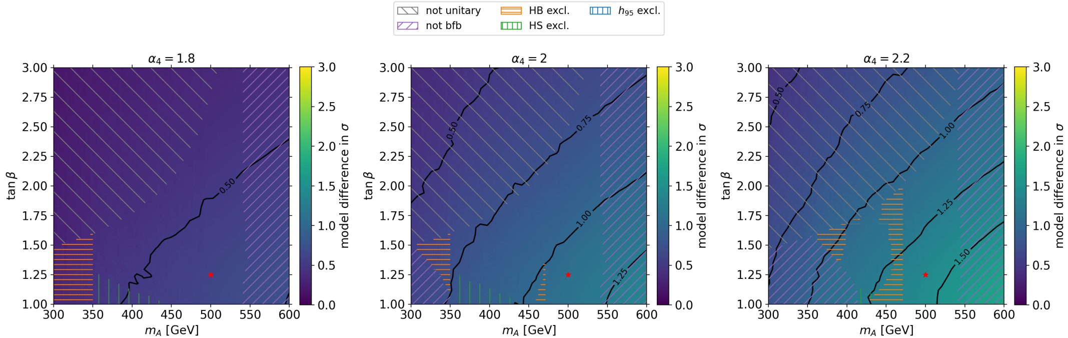
Distinguishable Parameter Space

- small impact
- $\varepsilon \approx 0.05$[1]
- $\frac{c_{h_1 bb}}{c_{h_1 tt}} \approx 1$



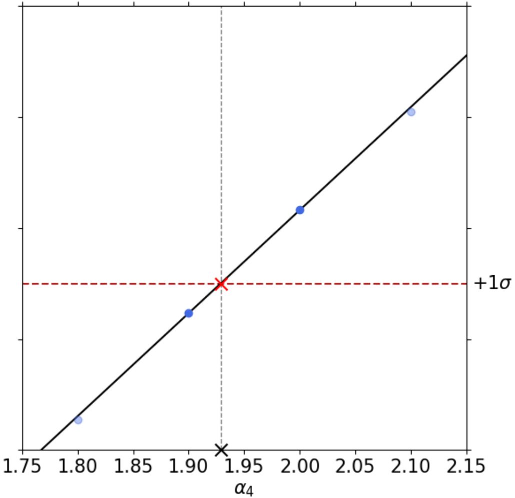
[1] further investigation needed!

α_4 Limit Estimation



α_4 Limit Calculation

- precision vs running time
- 50 α_4 steps
- linear interpolation in between



Benchmark Point

$$m_{h_1} = 95.4\,\text{GeV} \qquad m_{h^\pm} = 539.662\,\text{GeV} \qquad c_{h_1 VV} = 0.36$$

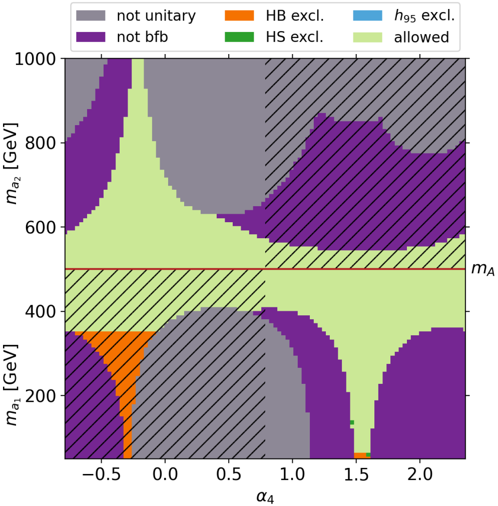
$$m_{h_2} = 125.09\,\text{GeV} \qquad v_S = 135.31\,\text{GeV} \qquad c_{h_1 bb}/c_{h_1 tt} = 1.124$$

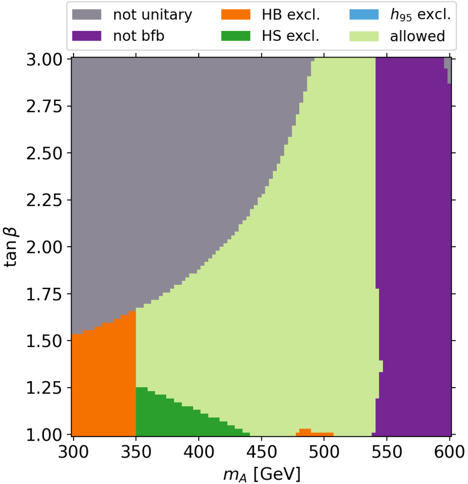
$$m_{h_3} = 539.662\,\text{GeV} \qquad m_{a_S} = m_{A_D} \pm 120\,\text{GeV} \qquad \varepsilon = 0.033$$

scan:
$$\tan\beta \in (1,3)$$
$$m_A \in (300,600)\,\text{GeV}$$

Limit Regions

6 Analysis





1σ Limits $\alpha_4 \geq \pi/4$ ($m_A \geq m_{a_s}$)

6 Analysis

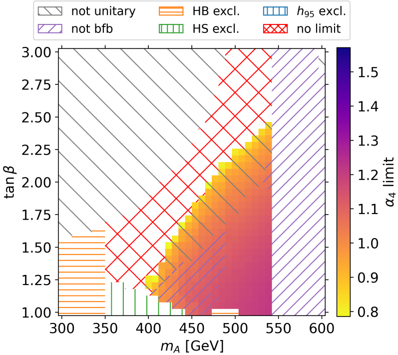


Figure: $\alpha_4 \in \left(\frac{\pi}{4}, \frac{\pi}{2}\right)$

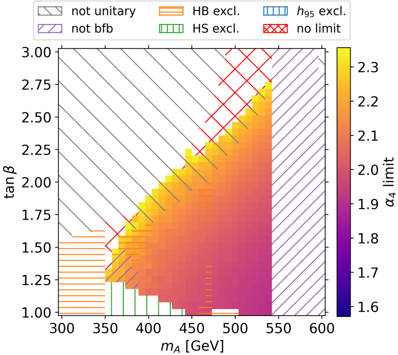


Figure: $\alpha_4 \in \left(\frac{\pi}{2}, \frac{3\pi}{4}\right)$

1σ Limits $\alpha_4 \leq \pi/4$ ($m_A \leq m_{a_s}$)

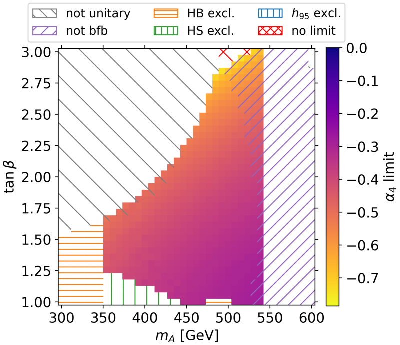


Figure: $\alpha_4 \in \left(-\frac{\pi}{4}, 0\right)$

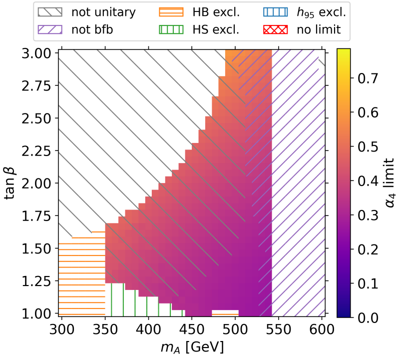


Figure: $\alpha_4 \in \left(0, \frac{\pi}{4}\right)$

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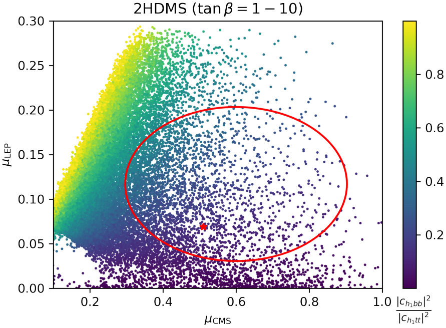
Outlook

- Better choice of c_{h_1bb}/c_{h_1tt}
- mass limits for fixed α_4
- ML Limit enhancement?
- different final states $(h_1h_2, h_1h_1 \dots)$
- cross-check with different processes $pp \to t\bar{t}t\bar{t}$ from Cheng Li
- TeV scale m_{A_S} in decoupling limit



Plot taken from [2]

Any Questions?

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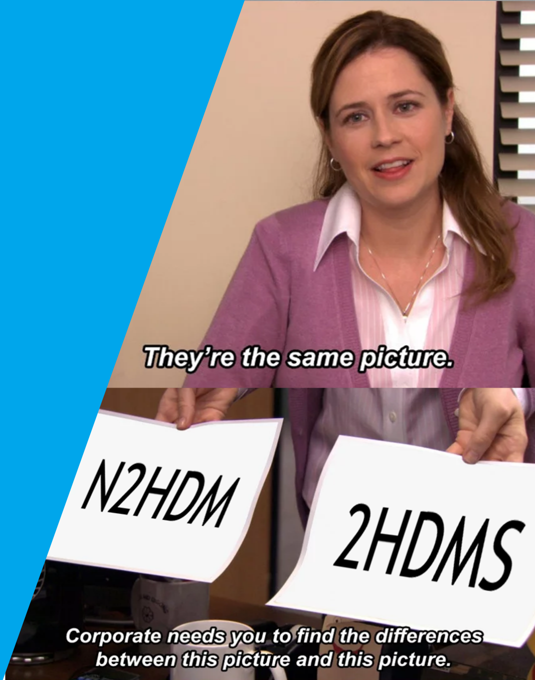

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Back up

Tree Level Perturbative Unitarity

scattering matrix unitary! Optical Theorem:

$$\mathbb{1} = S^\dagger S = (\mathbb{1} - iT^\dagger)(\mathbb{1} + iT) = \mathbb{1} + i(T - T^\dagger) + T^\dagger T \Rightarrow T^\dagger T = -i(T - T^\dagger) = \mathfrak{Im}(T)$$

Decompose matrix element $\mathcal{M}$ with partial wave expansion:

$$\mathcal{M}(s,\theta) = 16\pi \sum_J (2J+1) a_J P_J(\cos\theta) \text{ with } |a_J|^2 = \mathfrak{Im}(a_J) \Rightarrow \mathfrak{Re}(a_J) \leq \frac{1}{2}$$

In high energy limit leading contribution $\mathcal{M}_0$ to tree level matrix element

$$\Rightarrow |\mathcal{M}| \leq 8\pi$$

$\mathcal{M}$ from interaction basis all possible initial and final states: $\chi^\pm_{1,2}, \rho_{1,2,S}, \eta_{1,2,S}$
Eigenvalues smaller than 8π

$\alpha_1, \alpha_2, \alpha_3$ calculation

$$\alpha_1 = \arctan\left(\frac{\tan\beta}{c_{h_1 bb}/c_{h_1 tt}}\right) \tag{1}$$

$$\alpha_2 = \arccos\left(\frac{c_{h_1 VV}}{\cos\beta\cos\alpha_1 + \sin\beta\sin\alpha_1}\right) \tag{2}$$

$$\alpha_3 = \mathrm{sg}(\alpha_2)\left(\beta - \alpha_1 - \frac{\pi}{2} + \varepsilon\right) \tag{3}$$