Non-resonant Collider Signatures of a Singlet-Driven Electroweak Phase Transition

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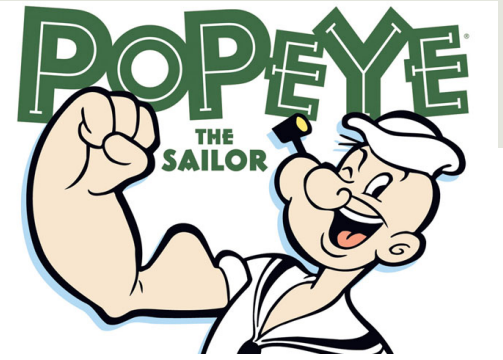
C.-Y. C, J. Kozaczuk and I. M. Lewis,
1704.0xxxx



ACFI Workshop: Making EWPT Strong
April 7, 2017

Holy grails

1. Where and what is dark matter?
2. How massive are neutrinos?
3. What are the implications of neutrino mass?
4. What are the origins of mass?
5. Why is there a spectrum of fermion masses?
6. Why is gravity so weak?
7. Is Nature supersymmetric?
8. Why is the Universe made of matter and not antimatter?
9. Where do ultrahigh-energy cosmic rays come from?
10. Did the Universe inflate at birth?

[Quigg lecture at the 2004 SLAC Summer Institute.]

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Strong indication of new physics

[Quigg lecture at the 2004 SLAC Summer Institute.]

Baryogenesis

- Evidence from cosmology:

$$\frac{n_B}{s} = (8.59 \pm 0.11) \times 10^{-11} \quad \text{(Planck)}$$

- Sakharov's 3 conditions (1967), for baryogenesis
  - Baryon number violation
  - Out of equilibrium
  - C and CP violation

- EW baryogenesis is one of the potential solutions
- Need new physics because in SM:
  1) EW phase transition is a crossover, instead of 1st order
  2) CP violation is too small

Testability

- LHC is running!

- What's the sensitivity of HL-LHC, 100 TeV pp colliders, and future e+ e- colliders to the region of parameter space where SFOPT is allowed?
- Gravitational waves: Bubble collisions

Model:
SM+singlet

SM + Singlet

- SM Higgs doublet H mixes with an additional singlet S. The singlet doesn't couple to SM fermions and gauge bosons.

$$V_0(H,S) = V_H + V_{HS} + V_S,$$

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$$V_S(S) = b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

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$$V_{HS}(H,S) = \frac{a_1}{2} H^\dagger H\, S + \frac{a_2}{2} H^\dagger H\, S^2$$

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$$V_0(H,S) = V_H + V_{HS} + V_S,$$

If apply Z_2 symmetry:
S-> -S

$$V_H(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

$$V_{HS}(H,S) = \frac{a_1}{2} H^\dagger H\, S + \frac{a_2}{2} H^\dagger H\, S^2$$

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- After spontaneous symmetry breaking:

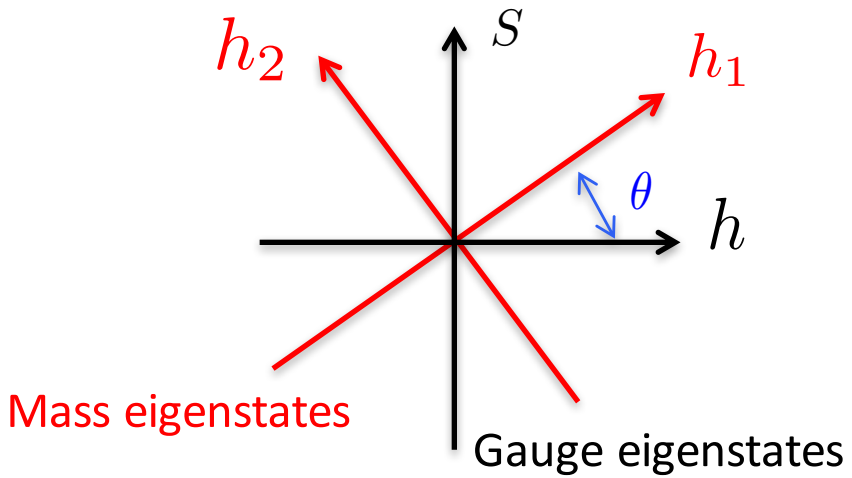
$$H \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ h+v \end{pmatrix}, \quad \text{in unitary gauge}$$

$$S \to S + x$$

SM + Singlet

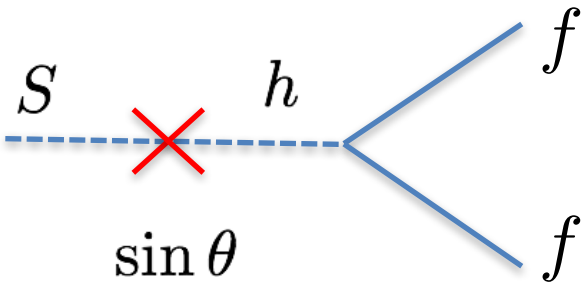
- Mass eigenstates and mixing angle:

$$h_1 = h\cos\theta + S\sin\theta$$
$$h_2 = -h\sin\theta + S\cos\theta$$



- h_1 : the Higgs we observed; its couplings to fermions and gauge bosons are **universally suppressed by a factor of** $\cos\theta$.

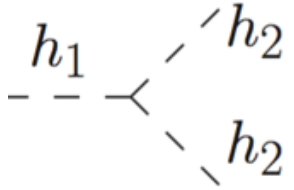
- h_2 : Heavy Higgs; its couplings to fermions and gauge bosons are **universally suppressed by a factor of** $\sin\theta$.



SM + Singlet

- Cubic terms:

$$V_{\text{cubic}} = \frac{1}{6}\lambda_{111}h_1^3 + \frac{1}{2}\lambda_{211}h_2h_1^2 + \frac{1}{2}\lambda_{221}h_2^2h_1 + \frac{1}{6}\lambda_{222}h_2^3, \qquad \lambda_{ijk} \equiv \frac{\partial^3 V(h_1,h_2)}{\partial h_i \partial h_j \partial h_k}$$



$\sim \lambda_{221}$

- Quartic terms are not very relevant for EWBG

Effective potential

$$V_{\rm eff}(\phi_h,\phi_s,T) = V_0(\phi_h,\phi_s) + V_1^{\rm CW}(\phi_h,\phi_s) + V_T(\phi_h,\phi_s,T) + V_T^{\rm ring}(\phi_h,\phi_s,T)$$

- breakdown

$$V_1^{\rm CW}(\phi_h,\phi_s) = \sum_j \frac{\pm n_j}{32\pi^2}\left\{\frac{1}{2}m_j^4(\phi_h,\phi_s)\left[\log\left(\frac{m_j^2(\phi_h,\phi_s)}{\Lambda^2}\right)-\frac{1}{2}\right]+m_j^2(\phi_h,\phi_s)\Lambda^2\right\}$$

$$V_T(\phi_h,\phi_s,T) = \frac{T^4}{2\pi^2}\left[\sum_i \pm n_i J_\pm\left(\frac{m_i^2(\phi_h,\phi_s)}{T^2}\right)\right]$$

$+$: bosons

$-$: fermions

$$J_\pm(x) = \int_0^\infty dy\, y^2 \log\left[1 \mp \exp(-\sqrt{x^2+y^2})\right]$$

$$V_T^{\rm ring}(\phi_h,\phi_s,T) = \sum_j \frac{n_j T}{12\pi}\left[m_j^3(\phi_h,\phi_s) - m_j^3(\phi_h,\phi_s,T)\right]$$

n_j: degrees of freedom

ϕ_i : background fields

$m_j^2(\phi_h,\phi_s)$: field dependent mass squared

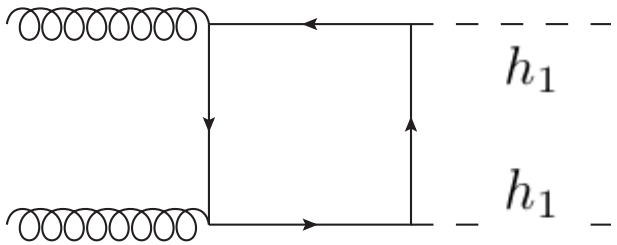
[Profumo, Ramsey-Musolf, Shaughnessy (2007)]
[Espinosa et al. NPB 854(2012)]

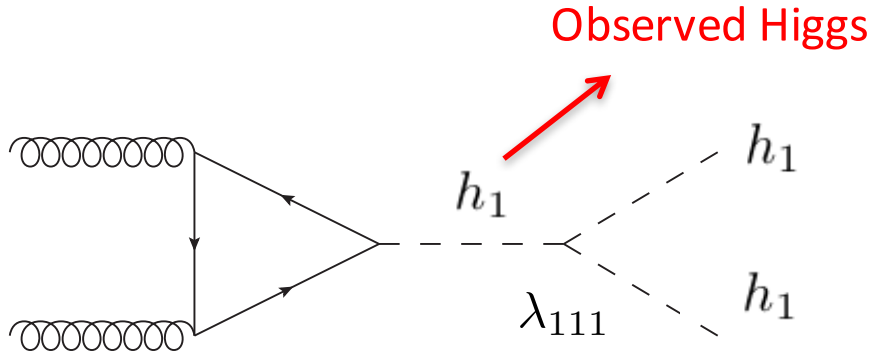
Double Higgs Production

Double Higgs Production through Gluon Fusion

- Important because it can be used to measure the Higgs self-couplings

In SM:





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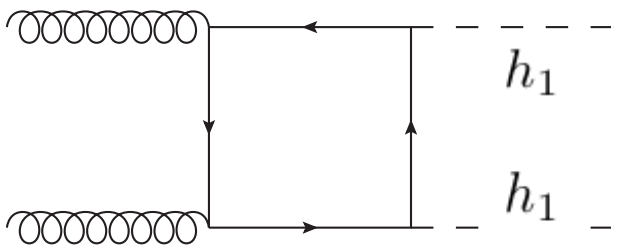
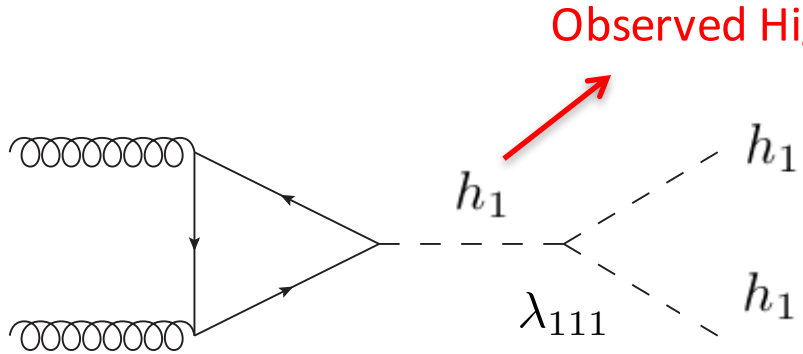
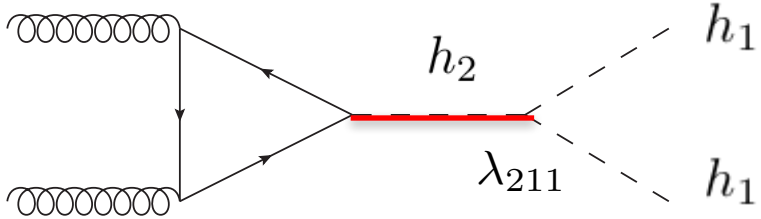




BSM:



- Production cross section of di-Higgs can be enhanced due to the decay of heavy resonances if $m_2 > 2m_1$

Double Higgs Production through Gluon Fusion

- Resonant production in the singlet model and its implication for EWBG

[1] J. M. No and M. Ramsey-Musolf, Phys. Rev. D 89, no. 9, 095031 (2014)
[2] K. Assamagan et al., arXiv:1604.05324 [hep-ph].
[3] A. V. Kotwal, M. J. Ramsey-Musolf, J. M. No and P. Winslow, arXiv:1605.06123 [hep-ph].
[4] T. Huang, J. M. No, L. Pernié, M. Ramsey-Musolf, A. Safonov, M. Spannowsky and P. Winslow, arXiv:1701.04442 [hep-ph].
[5] R. Contino et al., arXiv:1606.09408 [hep-ph].

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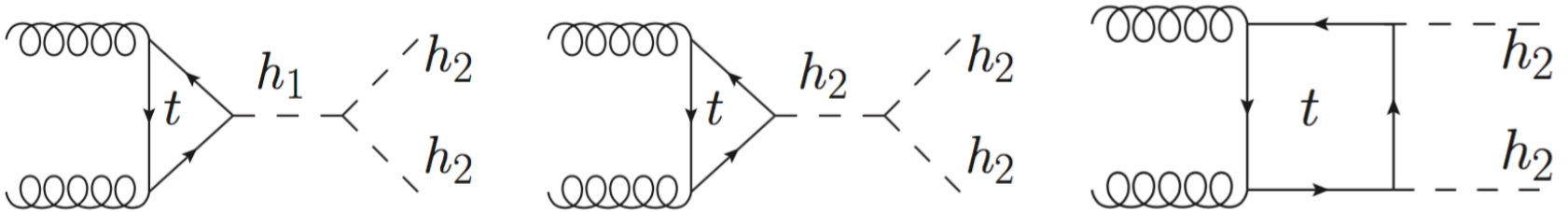
Double Higgs Production through Gluon Fusion

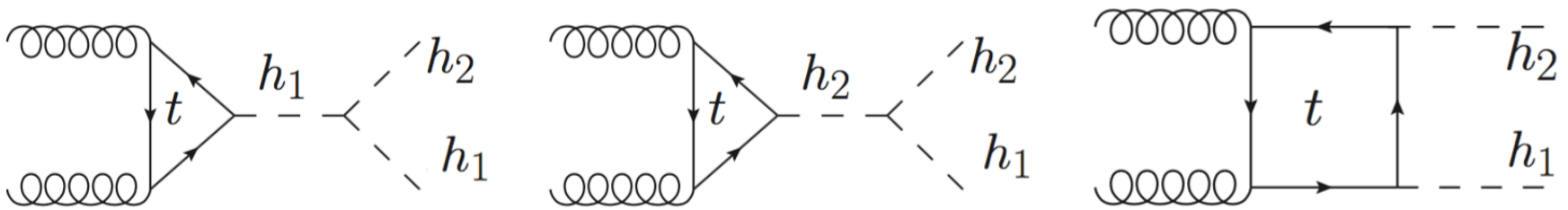
- What if $\sin\theta$ is small and $m_2 < 2m_1$?
- Non-resonant production dominates

BSM:



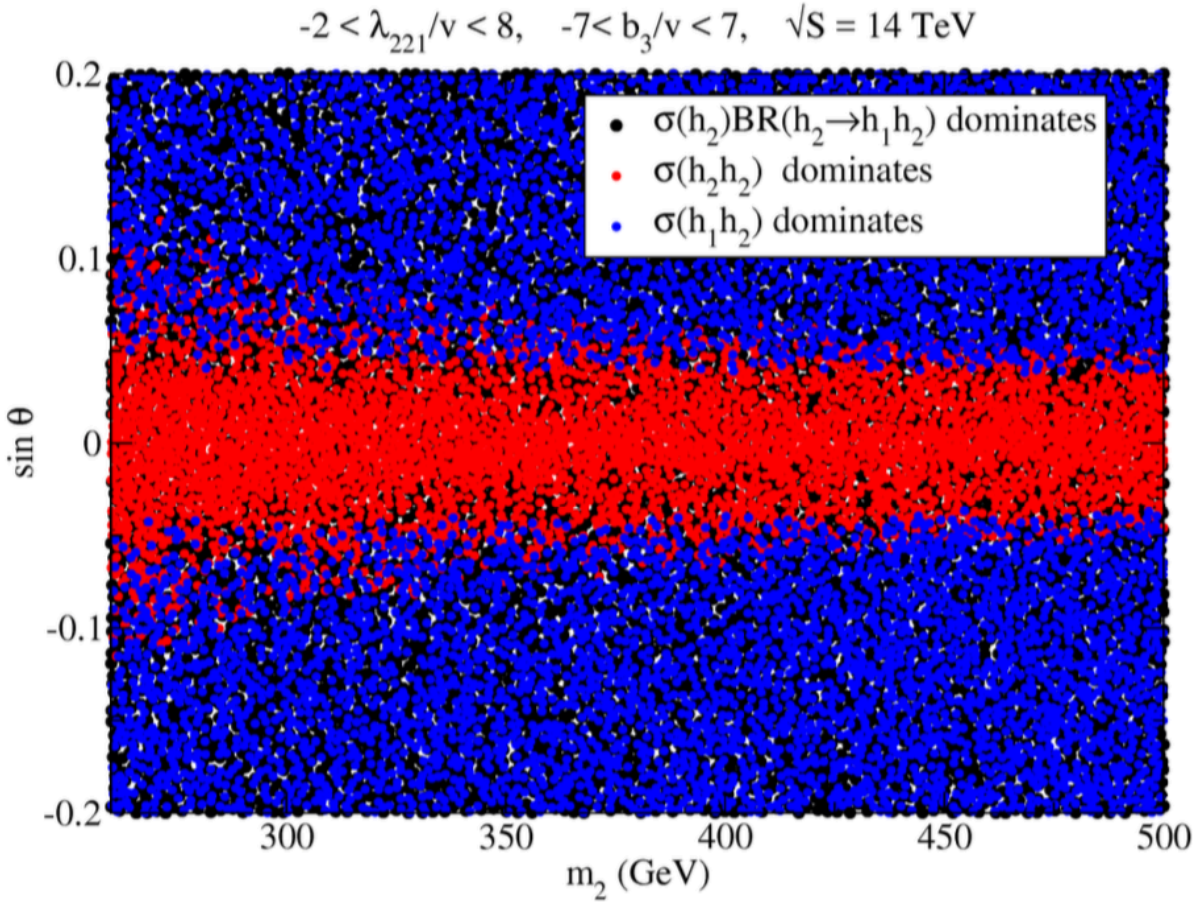
$\sigma(h_2 h_2)$

and



$\sigma(h_1 h_2)$

Parameter space



- Small angle regions are mostly dominated by $\sigma(h_2 h_2)$
- Plot for 100 TeV is similar

Constraints on scalar potential

- Vacuum stability: no vacuum exit at T=0 that is deeper than EW vaccum with v=246 GeV and v_s = 0 GeV

- Perturbativity: all dimensionless couplings < 4 pi at the EW scale

$$|b_3|/v < 4\pi$$

- Perturbative unitarity:

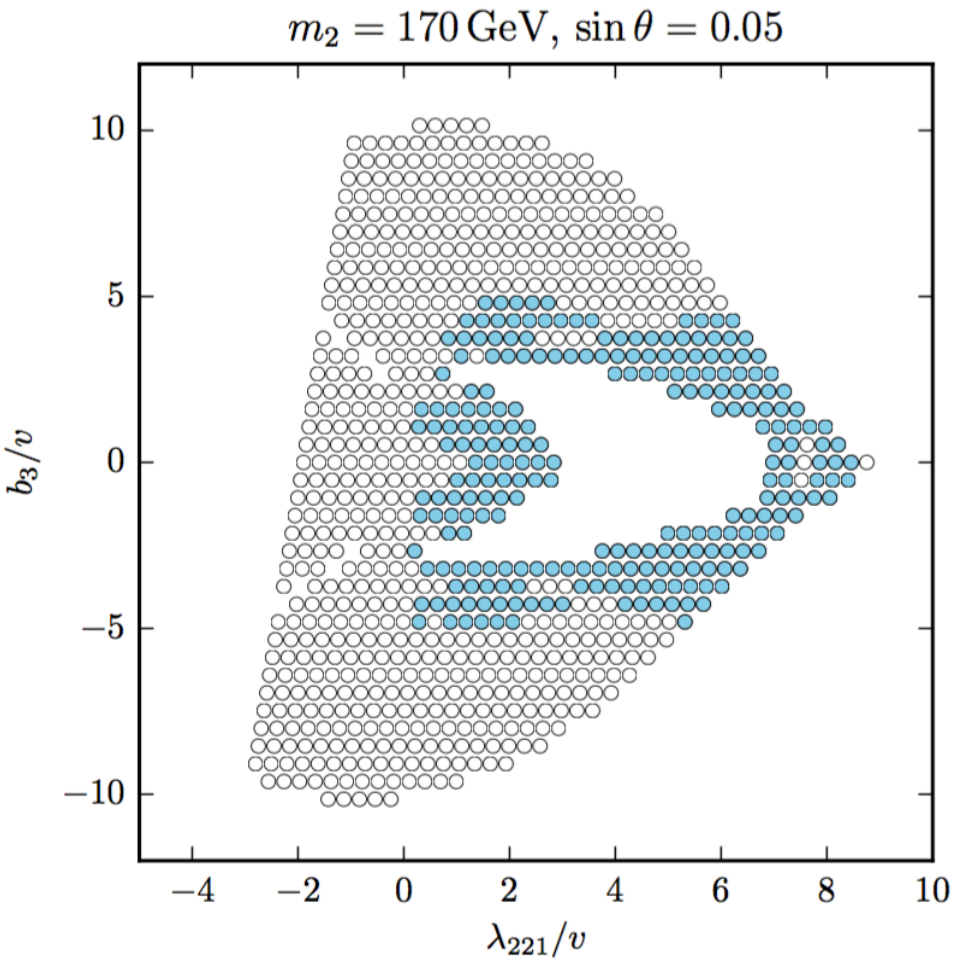
$$b_4 < 8\pi/3$$

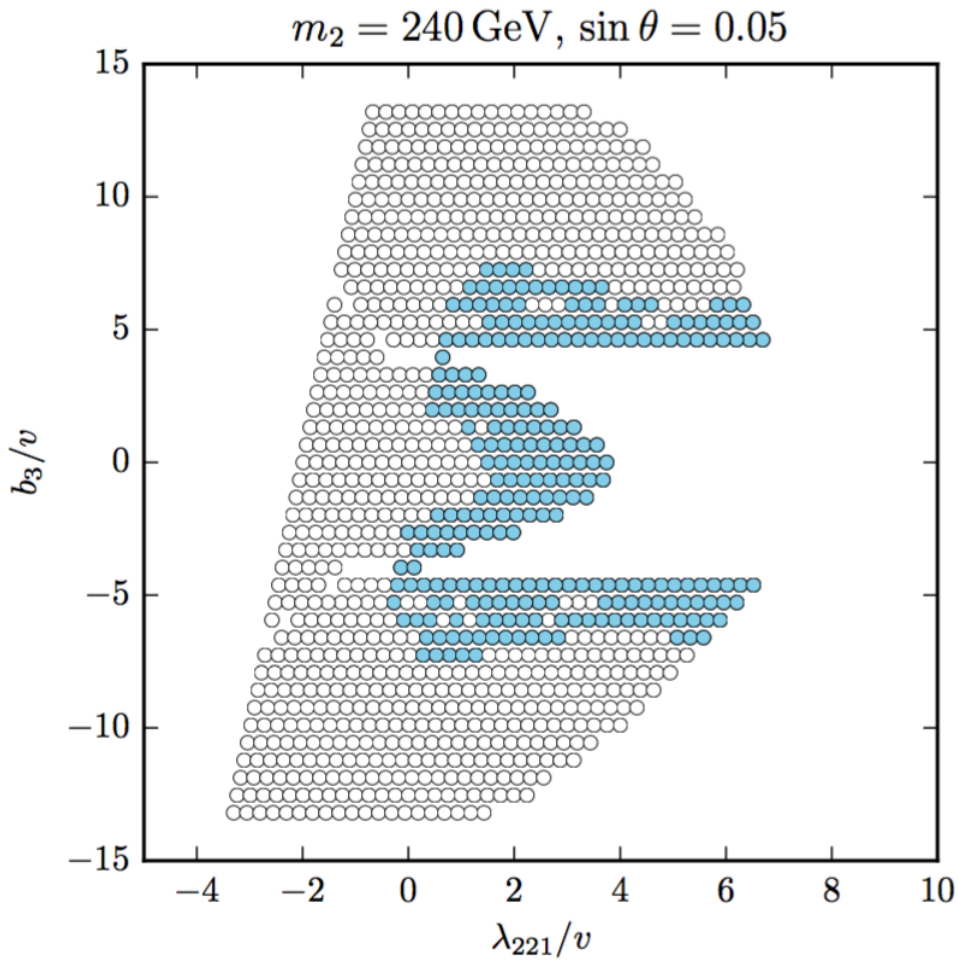
$$\lambda < 4\pi/3$$

[Lee et al. PRD 16(1977)]

- Number of free parameter (once fix $\sin\theta$ and m_2)
  - a_2, b_3 and b_4

Parameter space



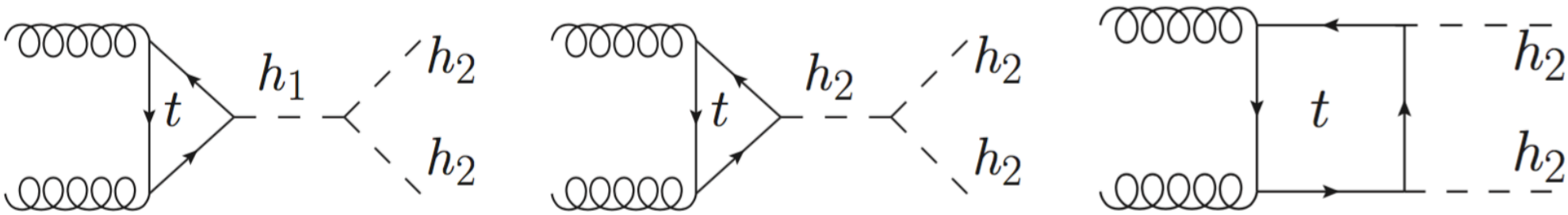


- Shaded region: satisfy all constraints
- Blue regions show strongly first-order phase transition (SFOPT) allowed region $\frac{\phi_h(T_c)}{T_c} \gtrsim 1$

Collider signatures: trilepton channel

- Signal:

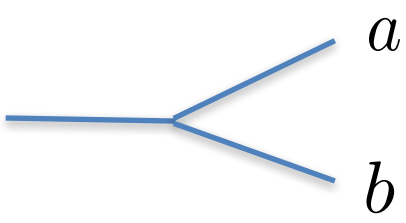
$$pp \to h_2 h_2 \to 4W \to 2j2\ell^{\pm}\ell'^{\mp}3\nu, \qquad \ell \neq \ell'$$



- Background:
  - Jets fakes leptons: dominant background, t tbar $\epsilon_{j\to\ell} \simeq 4\times 10^{-3}$
  - 3 prompt leptons:
    - WZ (W γ^*)
    - WWW
    - ttW
    - ttZ or tt γ^*
    - tt h_1

Collider signatures: variables

- Transverse mass : m_T



$$m_T(a,b) \equiv \sqrt{(E_T^a + E_T^b)^2 - (\vec{p}_T^{\,a} + \vec{p}_T^{\,b})^2}$$

$$(E_T^a)^2 = (p_T^a)^2 + m_a^2$$

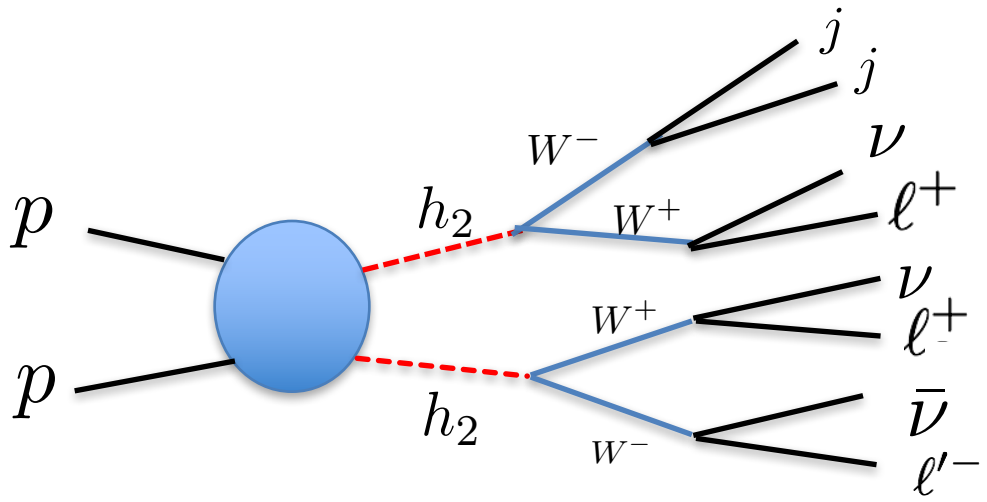
$a,\ b$: can be a particle or a group of particles

- $m_T^{\min}$: useful in rejecting backgrounds with non-prompt leptons.

$$m_T^{\min} \equiv \mathrm{Min}\left\{m_T(\ell_1, \not{E}_T), m_T(\ell_2, \not{E}_T), m_T(\ell_3, \not{E}_T)\right\}$$

V. Khachatryan et al. [CMS Collaboration], Eur. Phys. J. C 76, no. 8, 439 (2016)

Collider signatures: variables



$\ell \neq \ell'$

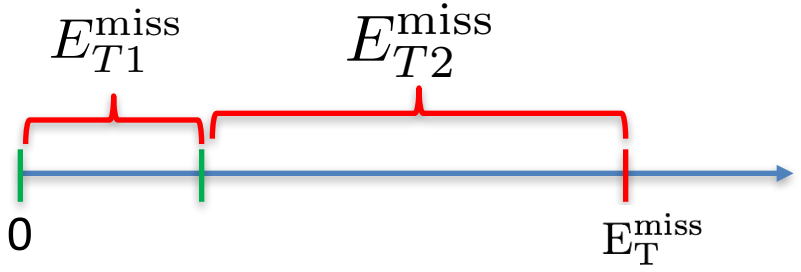
- m_{T2} : reconstruct mass of the mother particle (h_2) when final states involves missing energy.
- Two possibilities:

$$1) m_{T2}^1 = \text{Min}\left\{\text{Max}\left[m_T(jj\ell_1, E_{T1}^{\text{miss}}), m_T(\ell_2\ell', E_{T2}^{\text{miss}})\right]\right\}$$

$$E_{T1}^{\text{miss}} + E_{T2}^{\text{miss}} = E_T^{\text{miss}}$$

$$2) m_{T2}^2 = m_{T2}^1(\ell_1 \leftrightarrow \ell_2)$$

$$m_{T2} \equiv \text{Min}(m_{T2}^{1,2})$$



Collider signatures: variables

- Total invariant mass of visible particles:

$$m_{vis}^2 = \left[\sum_{i=\ell,\ell',\text{jets}} E_i\right]^2 - \left[\sum_{i=\ell,\ell',\text{jets}} \mathbf{p_i}\right]^2$$

Collider signatures: benchmark points

- LHC 14 TeV at 3/ab:
  - $m_2 = 170$ GeV: $50\ \text{GeV} < m_{jj} < 110\ \text{GeV}$.

$$p_T^{j_1,j_2} > 30\,\text{GeV}, \quad p_T^{\ell_1,\ell_2} > 25\,\text{GeV}, \quad m_{T2} < 150\,\text{GeV},$$

$$m_{\text{vis}} < 600\,\text{GeV}, \quad m_T^{\min} > 40\,\text{GeV}. \quad \not{E}_T > 30\ \text{GeV}$$

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$$m_{\text{vis}} < 600\,\text{GeV}, \quad m_T^{\min} > 40\,\text{GeV}. \quad \not{E}_T > 30\ \text{GeV}$$

- LHC 100 TeV at 30/ab:
  - $m_2 = 170$ GeV: $50\ \text{GeV} < m_{jj} < 110\ \text{GeV}$.

$$p_T^{j_1,j_2} > 30\,\text{GeV}, \quad p_T^{\ell_1,\ell_2} > 25\,\text{GeV}, \quad m_{T2} < 150\,\text{GeV},$$

$$m_{\text{vis}} < 600\,\text{GeV}, \quad m_T^{\min} > 60\,\text{GeV}, \quad \not{E}_T > 50\ \text{GeV}.$$

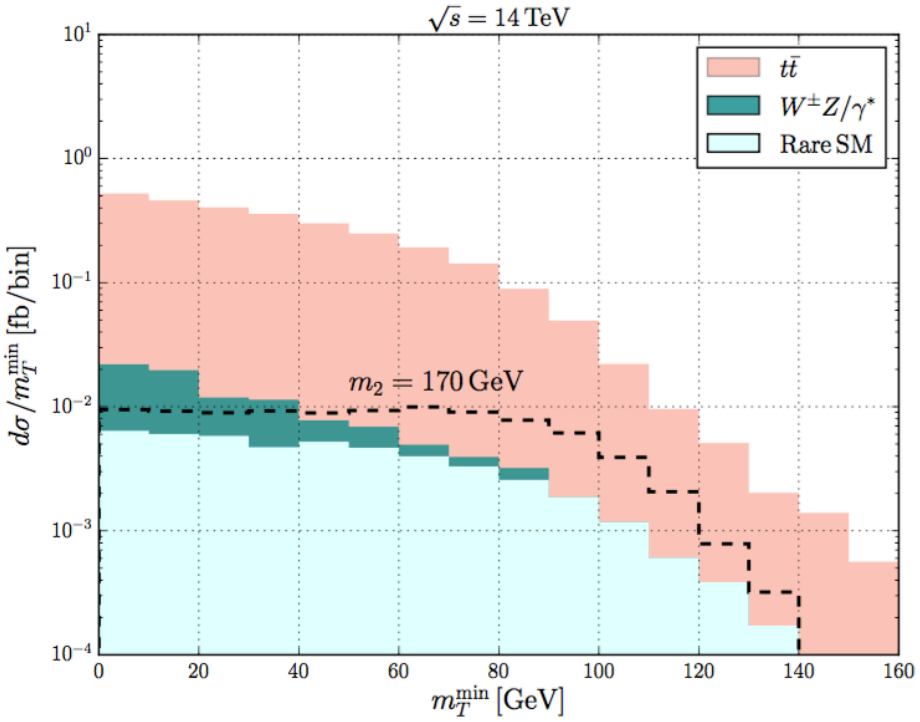
  - $m_2 = 240$ GeV: $50\ \text{GeV} < m_{jj} < 110\ \text{GeV}$.

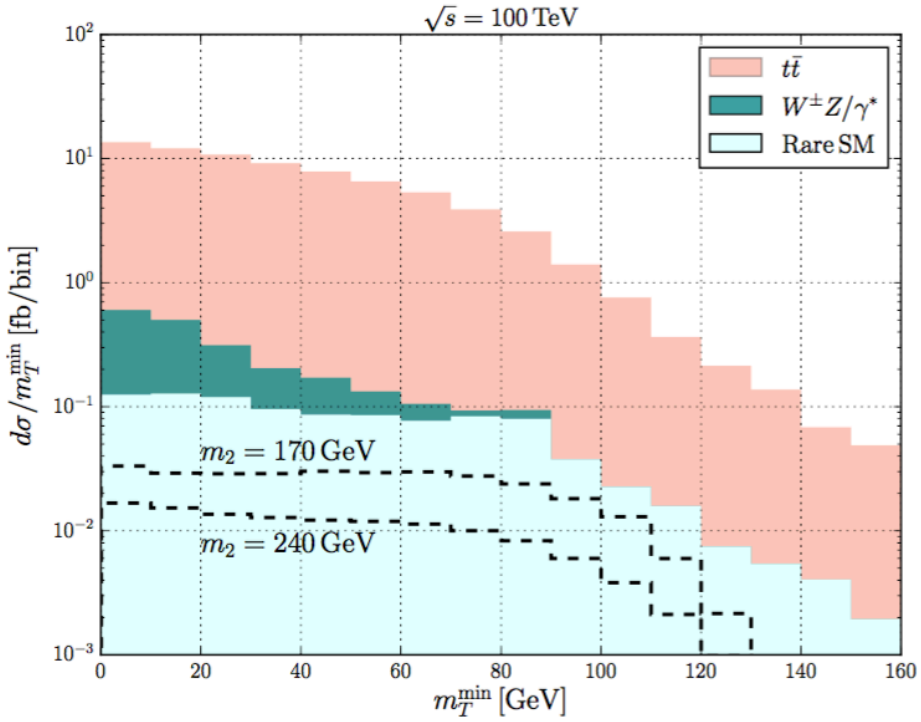
$$p_T^{j_1,j_2} > 50\,\text{GeV}, \quad p_T^{\ell_1,\ell_2} > 40\,\text{GeV}, \quad m_{T2} < 200\,\text{GeV},$$

$$m_{\text{vis}} < 400\,\text{GeV}, \quad m_T^{\min} > 80\,\text{GeV}, \quad \not{E}_T > 50\ \text{GeV}.$$

Collider signatures

- $m_T^{\min}$





Additional probes

CEPC and ILC

- Presence of an addition scalar, alters the Zh_1 production cross section due to contributions to the wave-function renormalization of h_1 [Craig et al. PRL 111(2013), Curtin et al. JHEP1411 (2014), Huang et al. PRD.94 (2016)]
- Sensitivity of lepton colliders: $\delta_{Zh_1} > 1\%$

[Dawson, et al. 1310.8361)]

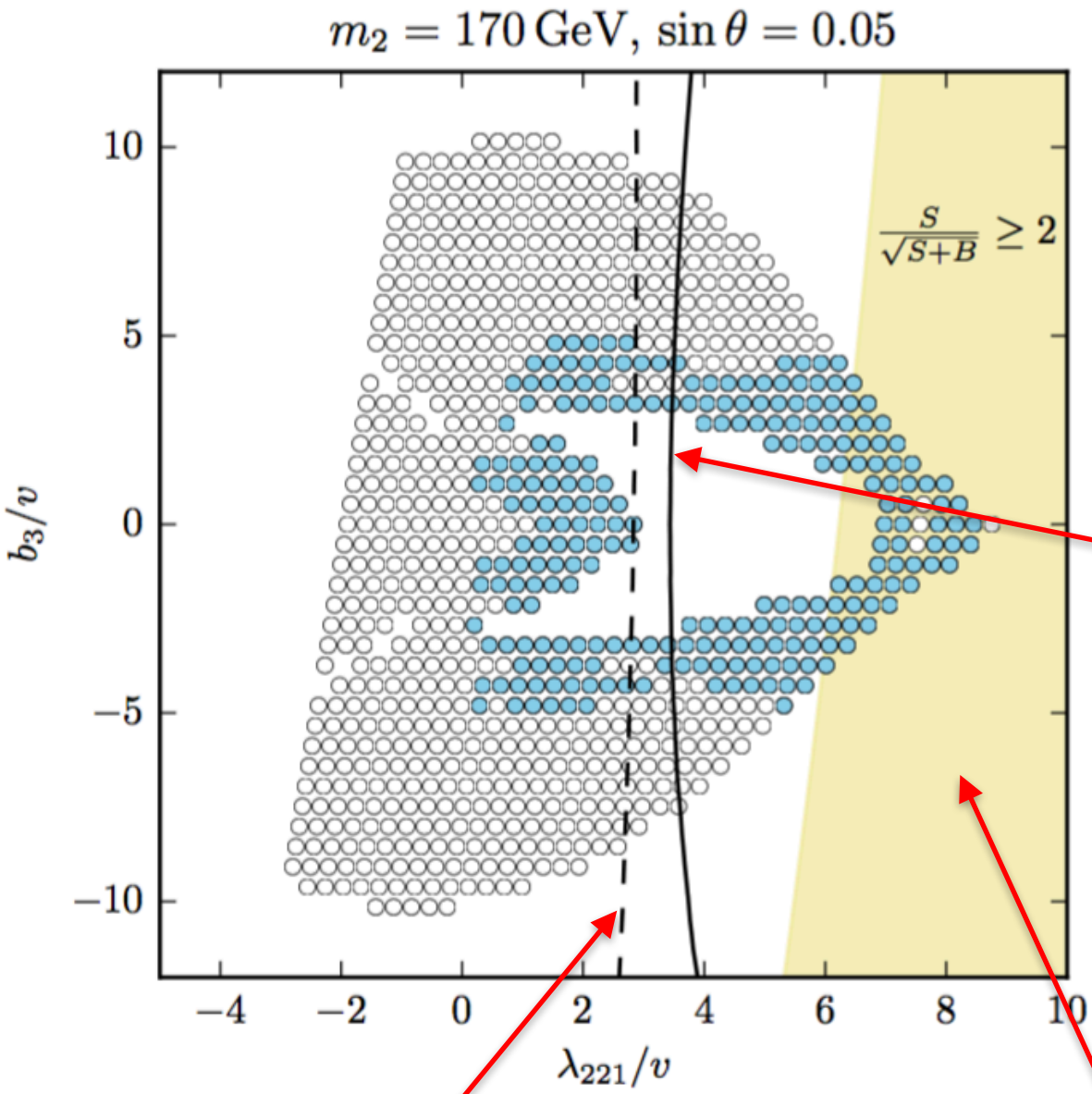
Higgs self-coupling measurement at pp collider

$$|\lambda_{111} - \lambda_{hhh}^{\rm SM}|/\lambda_{hhh}^{\rm SM} > 30\%$$ for HL-LHC

$$|\lambda_{111} - \lambda_{hhh}^{\rm SM}|/\lambda_{hhh}^{\rm SM} \sim 15\% \text{ with } 30 \text{ ab}^{-1}$$ for 100 TeV pp collider

[Dawson, et al. 1310.8361)]
[Curtin et al. JHEP 1411(2014)]

HL-LHC



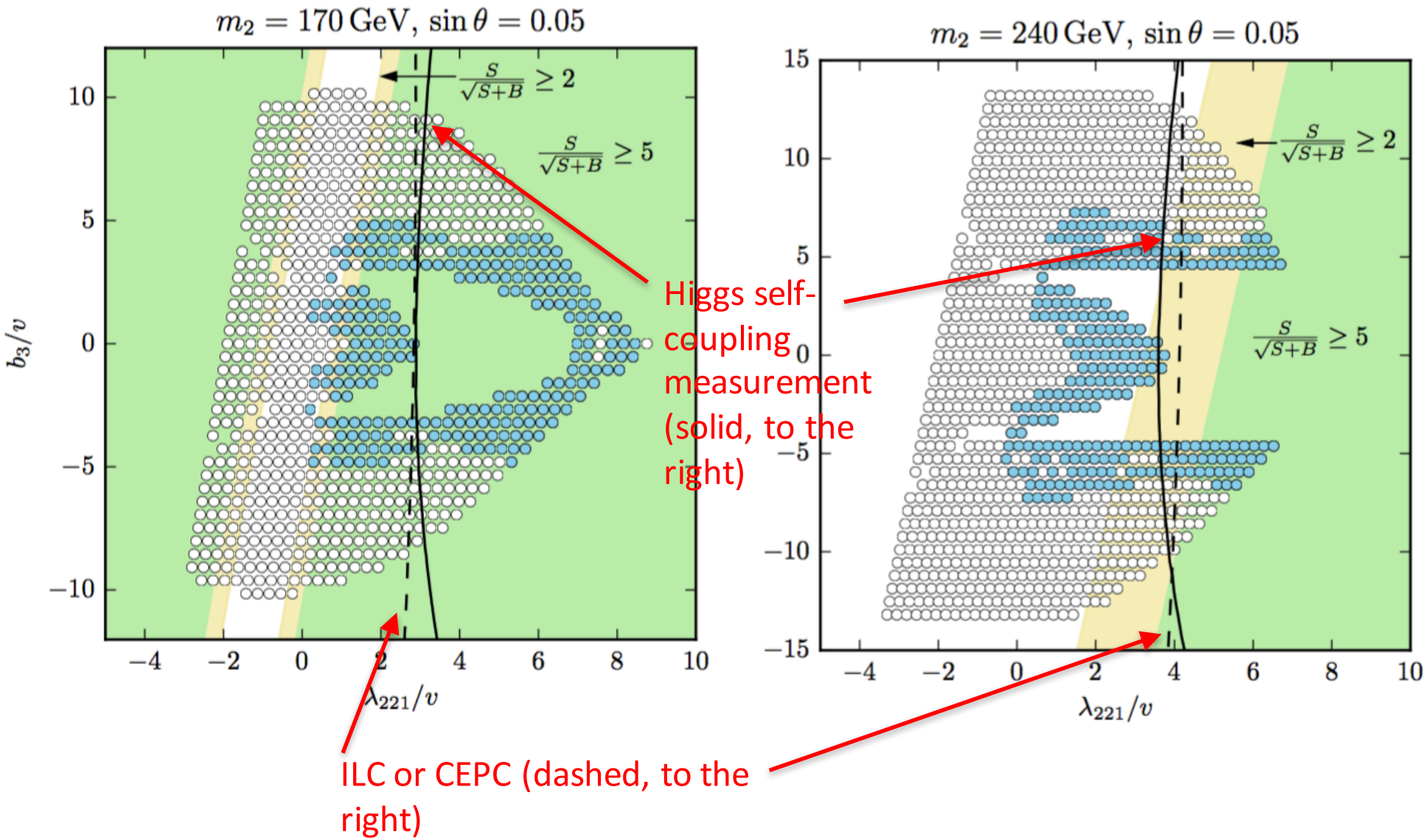
λ_{111}

Higgs self-coupling measurement (to the right)

ILC or CEPC (to the right)

Excluded by HL-LHC

100 TeV collider



Higgs self-coupling measurement (solid, to the right)

ILC or CEPC (dashed, to the right)

- Green region: 5 sigma discovery using trilepton channel at 100 TeV with 30/ab
- Yellow region: excluded by 2 sigma using trilepton channel at 100 TeV wth 30/ab

Take Home Message

- Direct probe of EWPT in non-resonant scalar pair production channels at both 14 TeV LHC and 100 TeV collider
- At 14 TeV LHC, measurement of the h_1 self-coupling as well as that from lepton colliders will provide better coverage
- At a 100 TeV collider, non-resonant production with m_2~170 GeV is sensitive to most of the parameter space with SFOPT.

Take Home Message

Prospect:

- $\sigma(h_1 h_2)$ channel
- $m_2 < m_1$: displaced decay of h_2

THANK YOU!

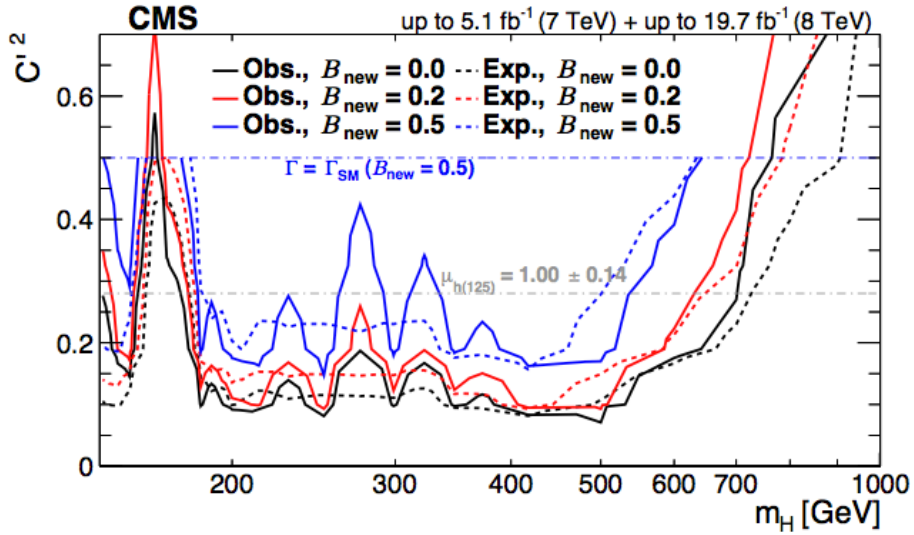
BACKUP

Constraints on Mixing Angle

- Light Higgs coupling measurements: $\sin^2\theta < 0.12$
  - combine $h \to \gamma\gamma, ZZ^*, WW^*, \tau\tau, b\bar{b}$
  - Independent of branching ratios of new decay channels
  - Independent of m_2

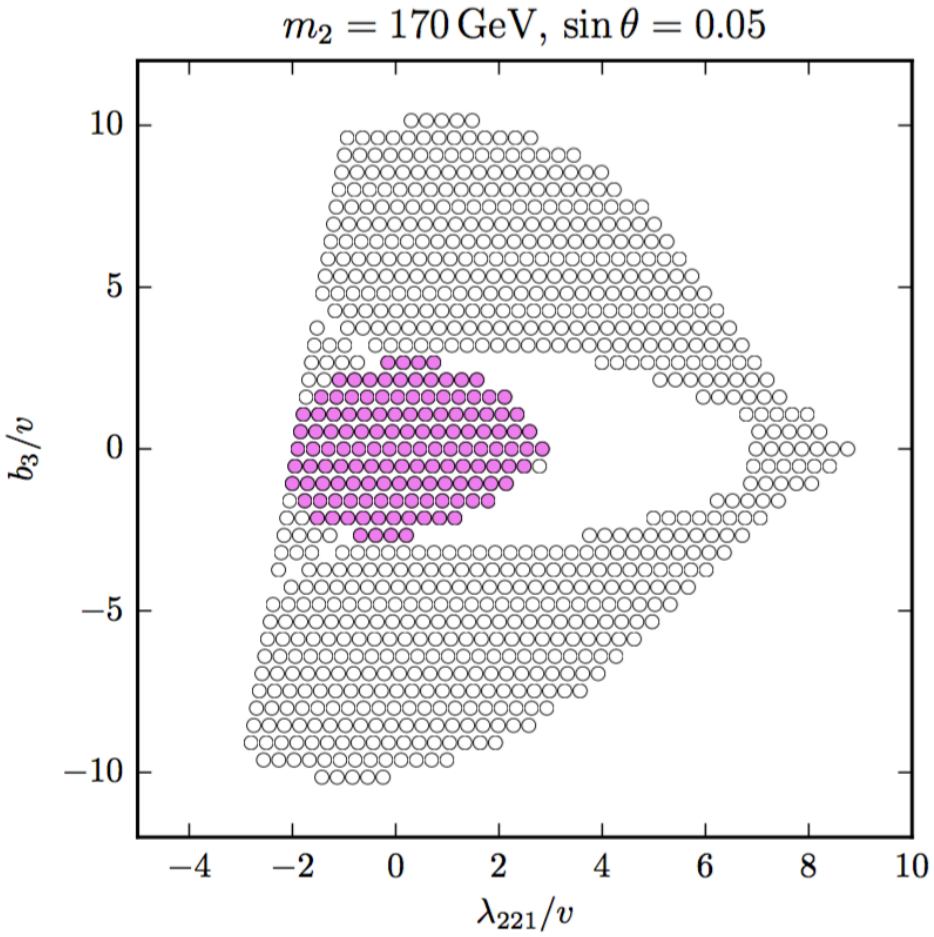
ATLAS-CONF-2014-010

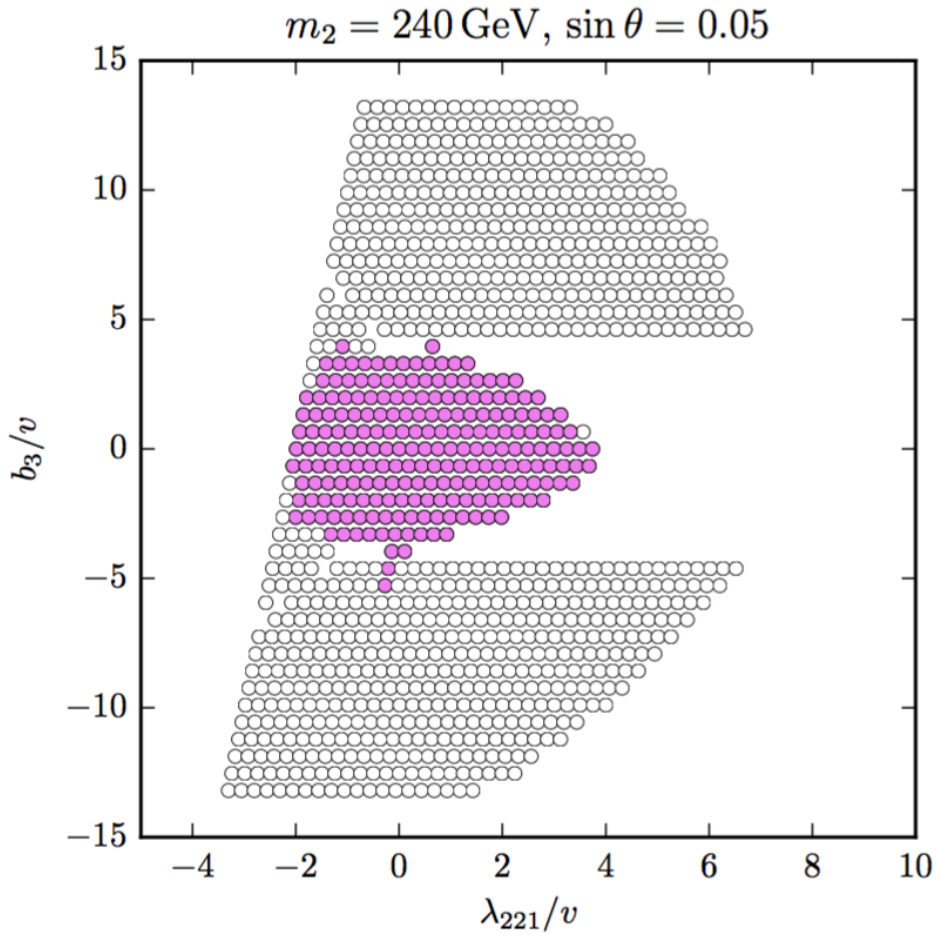
- Heavy Higgs searches:
  - Depend on branching ratios of new decay channels
  - E.g. take B_{new}=0, $\sin^2\theta < 0.2$ for $200 < m_2 < 600$ GeV



arXiv: 1504.00936, CMS

Parameter space





- Purple: satisfy all requirement at both tree and 1-loop level
- circled: satisfy all requirement when 1-loop correction is added

14 TeV

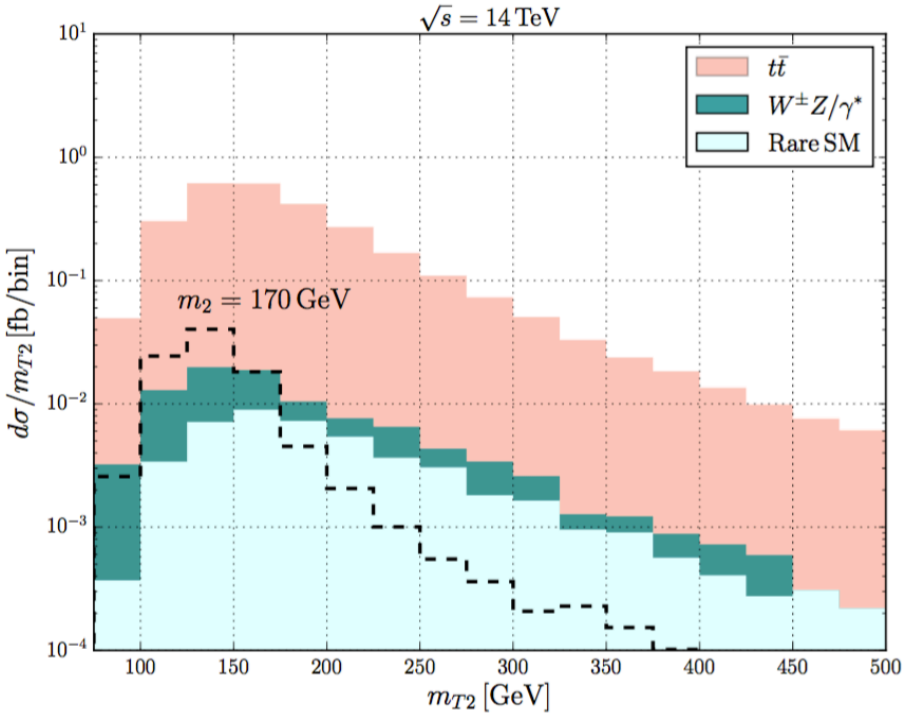
Process	Basic Selection	All cuts
$t\bar{t}$	8144	375
WZ/γ^*	147	4
Rare SM	141	6
Signal ($m_2 = 170$ GeV)	250	76

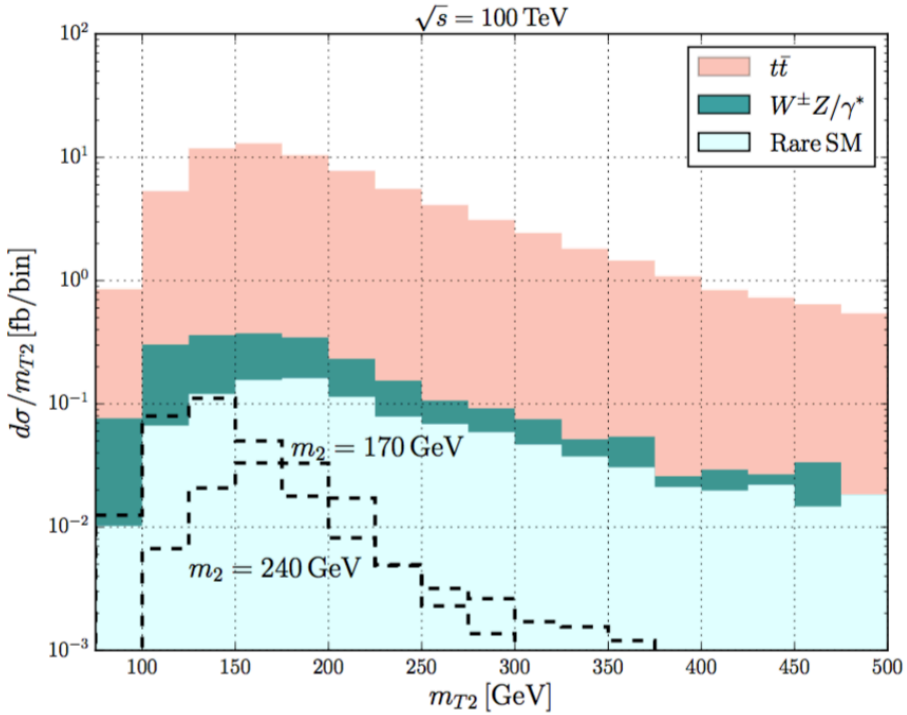
100 TeV

Process	Basic Selection	All cuts: $m_2 = 170$ GeV	$m_2 = 240$ GeV
$t\bar{t}$	498049	6486	1869
WZ/γ^*	40134	284	142
Rare SM	34288	332	306
$m_2 = 170$ GeV	7411	1311	-
$m_2 = 240$ GeV	1024	-	112

Collider signatures

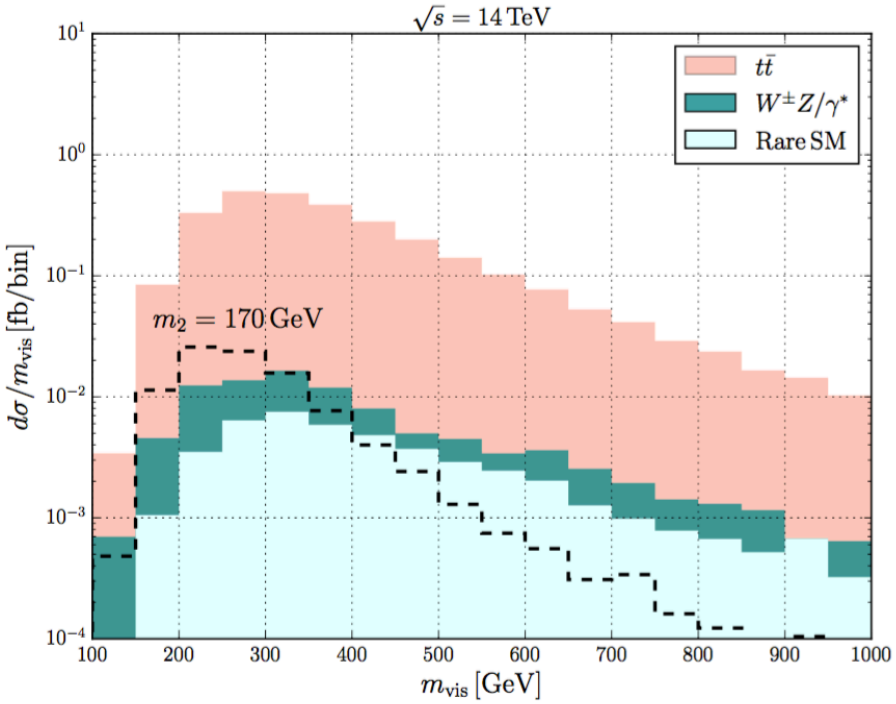
- m_{T2}

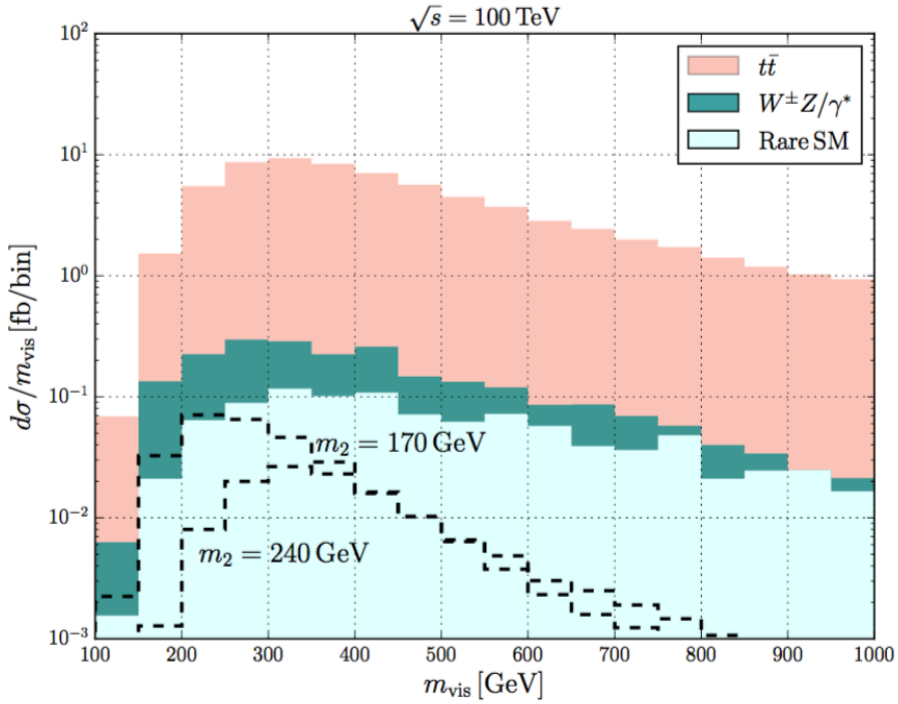




Collider signatures

- $m_{\rm vis}$





$$m_t^2(\phi_h) = \frac{1}{2}\phi_h^2, \qquad m_W^2(\phi_h) = \frac{1}{4}g^2\phi_h^2, \qquad m_Z^2(\phi_h) = \frac{g^2+g'^2}{4}\phi_h^2$$

$$m_G^2(\phi_h,\phi_s) = \lambda\phi_h^2 - \mu^2 + \frac{1}{2}\left(a_1 + a_2\phi_s\right)\phi_s.$$

$$\mathcal{M}^2(\phi_h,\phi_s) = \begin{pmatrix} -\mu^2 + 3\lambda\phi_h^2 + \frac{1}{2}\left(a_1+a_2\phi_s\right)\phi_s & \frac{1}{2}\left(a_1+2a_2\phi_s\right)\phi_h \\ \frac{1}{2}\left(a_1+2a_2\phi_s\right)\phi_h & b_2 + 3b_4\phi_s^2 + 2a_1\phi_s + \frac{1}{2}a_2\phi_h^2 \end{pmatrix}$$

$$m_i^2(\phi_h,\phi_s,T) \equiv m_i^2(\phi_h,\phi_s) + \Pi_i(\phi_h,\phi_s,T).$$

$$\Pi_G(T) = \left(\frac{3}{16}g^2 + \frac{1}{16}g'^2 + \frac{1}{4}y_t^2 + \frac{1}{2}\lambda + \frac{1}{24}a_2\right)T^2$$

$$\Delta\mathcal{M}^2(\phi_h,\phi_s,T) = \begin{pmatrix} \frac{3}{16}g^2 + \frac{1}{16}g'^2 + \frac{1}{4}y_t^2 + \frac{1}{2}\lambda + \frac{1}{24}a_2 & 0 \\ 0 & \frac{1}{6}a_2 + \frac{1}{4}b_4 \end{pmatrix}T^2$$

$$\left.\frac{\partial\left(\Delta V_1+\Delta V_{\rm ct}\right)}{\partial\phi_h}\right|_{\phi_h=v,\phi_s=0}=0, \qquad \left.\frac{\partial\left(\Delta V_1+\Delta V_{\rm ct}\right)}{\partial\phi_s}\right|_{\phi_h=v,\phi_s=0}=0,$$

$$\left.\frac{\partial^2\left(\Delta V_1+\Delta V_{\rm ct}\right)}{\partial\phi_i\partial\phi_j}\right|_{\phi_h=v,\phi_s=0}=0, \qquad \left.\frac{\partial^3\left(\Delta V_1+\Delta V_{\rm ct}\right)}{\partial\phi_s^3}\right|_{\phi_h=v,\phi_s=0}=0,$$

$$\left.\frac{\partial^3\left(\Delta V_1+\Delta V_{\rm ct}\right)}{\partial\phi_s^2\partial\phi_h}\right|_{\phi_h=v,\phi_s=0}=0, \qquad \left.\frac{\partial^4\left(\Delta V_1+\Delta V_{\rm ct}\right)}{\partial\phi_s^4}\right|_{\phi_h=v,\phi_s=0}=0.$$

Explicitly writing out $\Delta V_{\rm ct}$ as

$$\begin{aligned}\Delta V_{\rm ct} =&\delta\mu^2\left|H\right|^2+\delta\lambda\left|H\right|^4+\frac{\delta a_1}{2}\left|H\right|^2 S+\frac{\delta a_2}{2}\left|H\right|^2 S^2\\ &+\delta b_1 S+\frac{\delta b_2}{2}S^2+\frac{\delta b_3}{3}S^3+\frac{\delta b_4}{4}S^4,\end{aligned}$$