Non-resonant Higgs Production with a scalar Singlet at the LHC

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based on work in collaboration with
C. Chen, J. Kim, K. Kong,
J. Kozaczuk, and I. Lewis

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Motivation

1. Very simple extension to the Standard Model with rich phenomenology.

2. Provides a potential interaction channel with the Dark Sector.

3. Motivates a strong Electro-weak First Order Phase Transition, a mechanism for the Electro-weak Baryogenesis.

4. Studying scalar extended models, indirectly enhances our search for double Higgs production at the LHC or vice versa.

Non-resonant Higgs Production with a scalar Singlet at the LHC

The Model

Extend the SM by a real scalar particle, S

$$V(H) \quad \sum \longrightarrow \quad V(H, S)$$
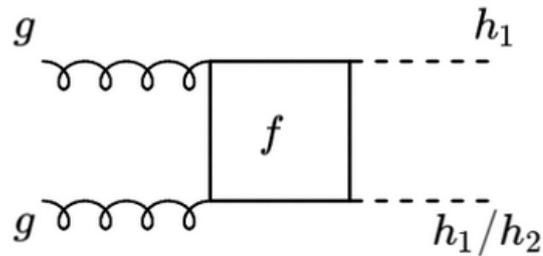
Study the trilinear interactions

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

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

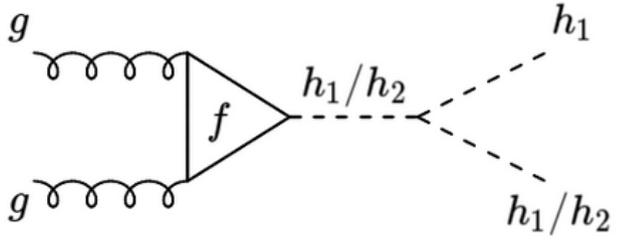$$V_S(S) = b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4.$$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix}$$

$$V_{\text{self}} \supset \frac{\lambda_{111}}{3!} h_1^3 + \frac{\lambda_{211}}{2!} h_2 h_1^2 + \frac{\lambda_{221}}{2!} h_2^2 h_1 + \frac{\lambda_{222}}{3!} h_2^3 +$$

$$\frac{\lambda_{1111}}{4!} h_1^4 + \frac{\lambda_{2111}}{3!} h_2 h_1^3 + \frac{\lambda_{2211}}{4} h_2^2 h_1^2 + \frac{\lambda_{2221}}{3!} h_2^3 h_1 + \frac{\lambda_{2222}}{4!} h_2^4.$$

Chen, Dawson, Lewis (arXiv:1410.5488) and many others

$+$

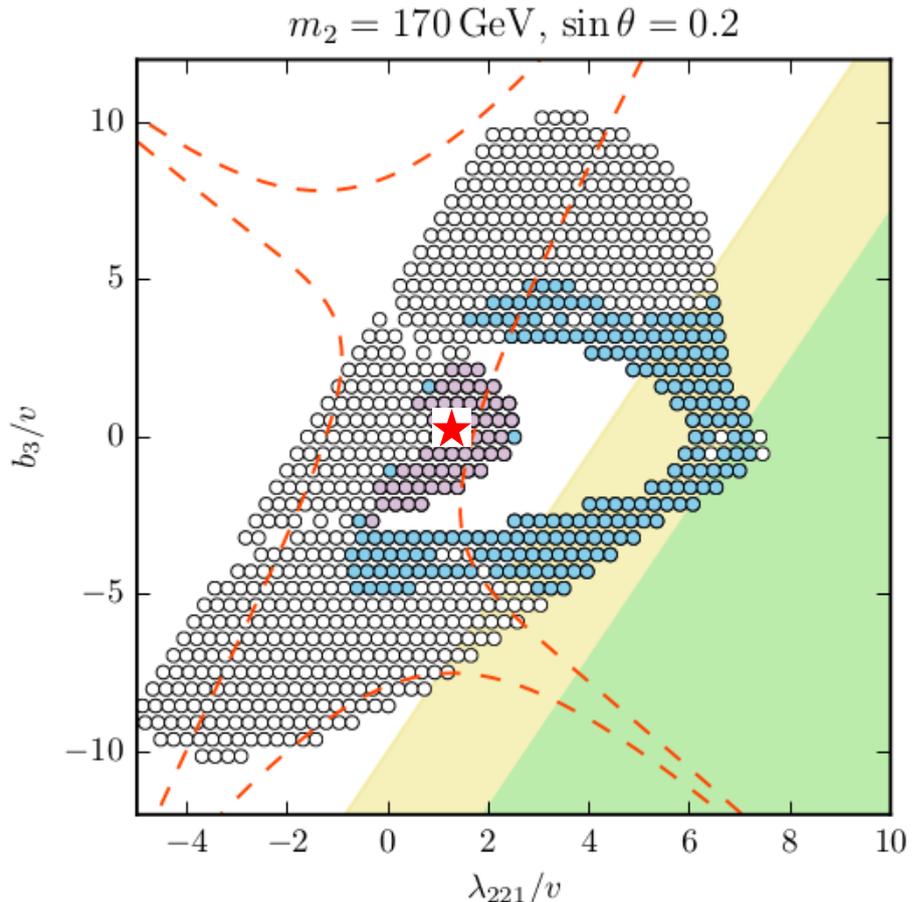Alhazmi, Chen, Kim, Kong, Kozaczuk, Lewis (arXiv:1905.XXXX)

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Non-resonant Higgs Production with a scalar Singlet at the LHC

Model Parameters: $m_{h_1} = 125\,\mathrm{GeV}, \ m_{h_2}, \ \theta, \ b_3, \ a_2$
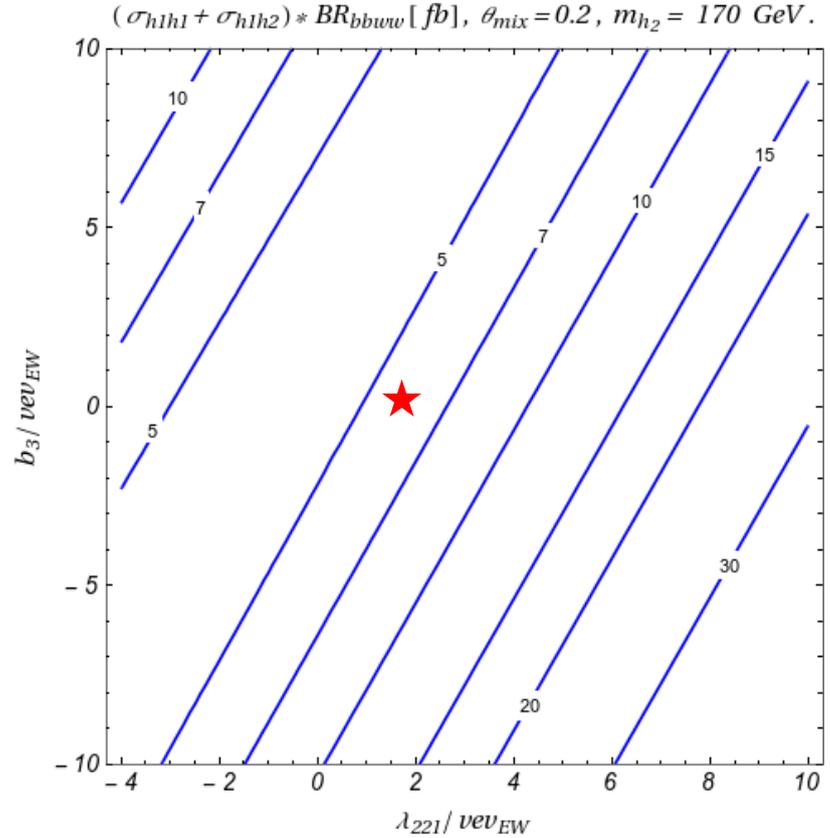
1. Existing Study

$$pp \to h_2 h_2 \to 4W \to 2j2\ell^{\pm}\ell'^{\mp}3\nu, \qquad \ell \neq \ell'.$$
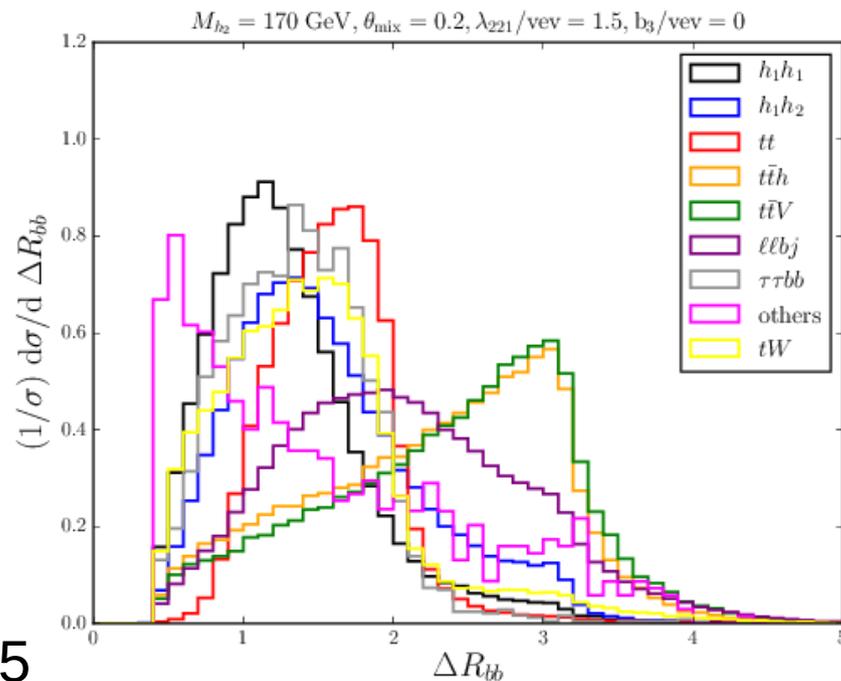
$m_2 = 170\,\mathrm{GeV}, \ \sin\theta = 0.2$
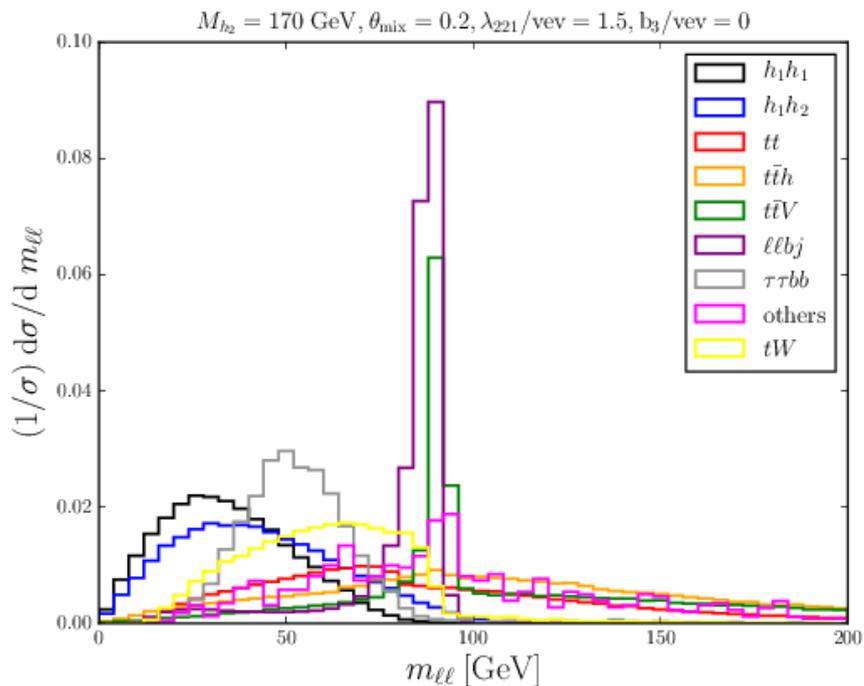
Chen, Kozaczuk, Lewis
(arXiv:1704:05844)

2. New Study

$$pp \to h_1 h_1 + h_1 h_2 \to b\bar{b}\,W^+W^- \to b\bar{b}\,\ell\,\bar{\ell}\,\nu_l\,\bar{\nu}_l$$

$(\sigma_{h1h1} + \sigma_{h1h2}) * BR_{bbww}\,[fb], \ \theta_{mix} = 0.2, \ m_{h_2} = 170\,\mathrm{GeV}.$

Alhazmi, Chen, Kim, Kong,
Kozaczuk, Lewis
(arXiv:1905.XXXX)

Challenging ?

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Generate Signal and Background, select two isolated leptons and two b-tagged jets.
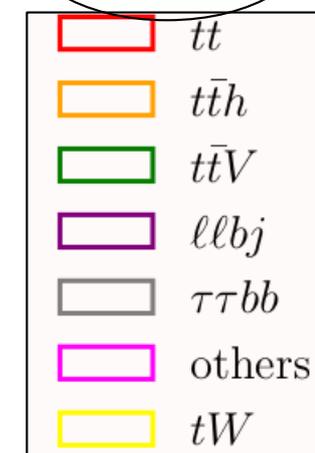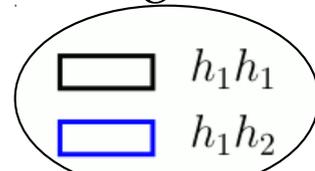

m

p_T

$E\!\!\!/_T$

ΔR

$\bullet \bullet \bullet$

Signal

$h_1 h_1$

$h_1 h_2$

tt

$t\bar{t}h$

$t\bar{t}V$

$\ell\ell bj$

$\tau\tau bb$

others

tW

Background

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Non-resonant Higgs Production with a scalar Singlet at the LHC

Why does bbww final state still very challenging?

After choosing events with some

selection cuts:

$$E\!\!\!/_T > 20 \, \text{GeV}, \ p_T^\ell > 20 \, \text{GeV}, \ \Delta R_{\ell\ell} < 1.1,$$

$$m_{\ell\ell} < 65 \, \text{GeV}, \ \Delta R_{bb} < 1.5,$$
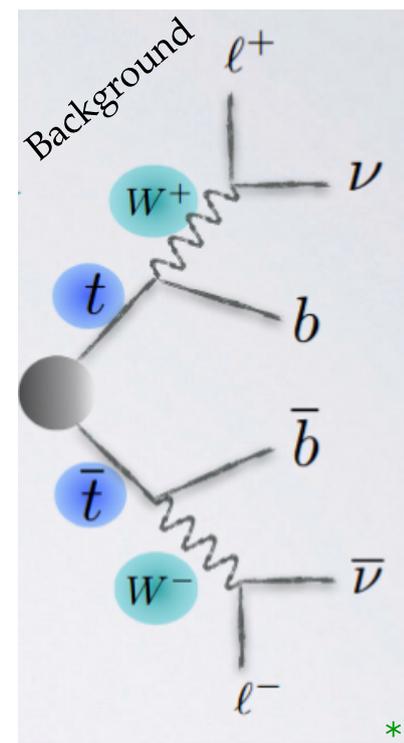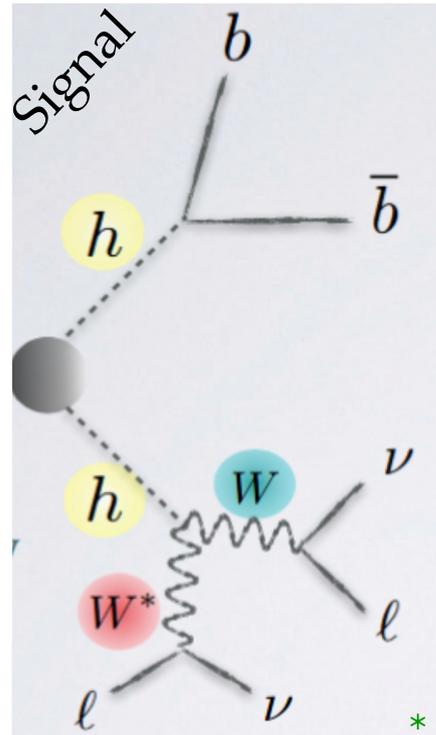
$$95 \, \text{GeV} < m_{\ell\ell} < 140 \, \text{GeV}$$

☐	$h_1 h_1$
☐	$h_1 h_2$
☐	tt
☐	$t\bar{t}h$
☐	$t\bar{t}V$
☐	$\ell\ell bj$
☐	$\tau\tau bb$
☐	others
☐	tW

⟹ Signl ~ 0.01 fb

Background ~ 6 fb

🛑

The ratio is very small!

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Topness vs Higgsness

Signal

Background

New variables, minimizing
over neutrino momentum
using mass constraints.
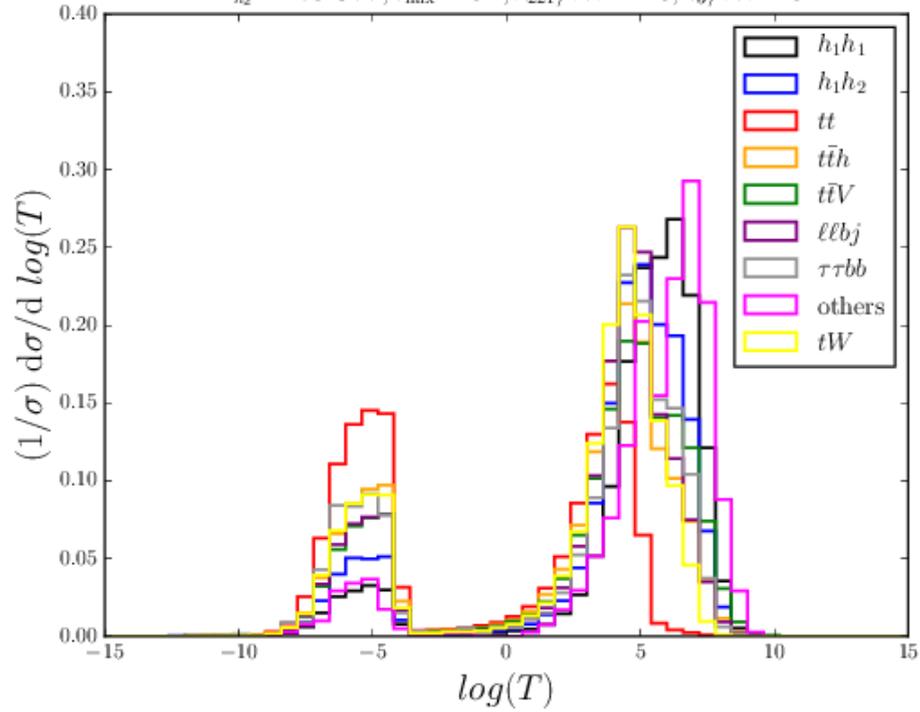
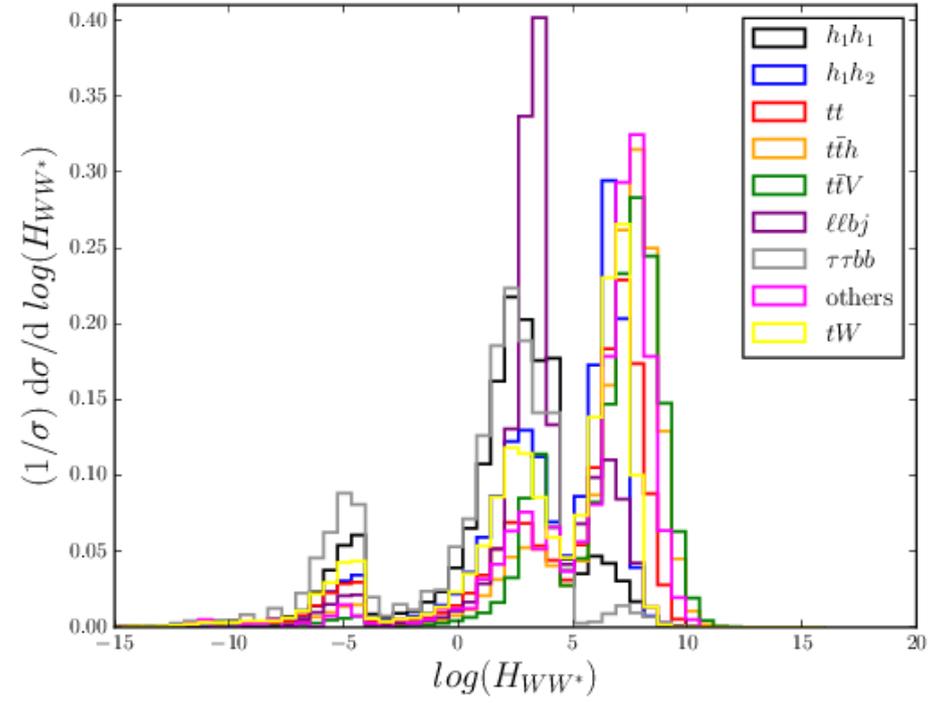$T, H, M_{T2}, ...$

Kim, Kong, Matchev,
Park arXiv:1807:11498

* Slide taken from Kim
(Double Higgs production
workshop, FNAL 2018)

Topness vs Higgsness

Alhazmi, Chen, Kim, Kong,
Kozaczuk, Lewis
(arXiv:1905.XXXX)

Non-resonant Higgs Production with a scalar Singlet at the LHC

Can we use Deep Neural Network? "event classification"

Prepare and feed kinematic variables

as an input layer to the DNN

$m, p_T, \not{E}_T, \Delta R, ...$

11 + 7 variables

$T, H, M_{T2}, ...$

"training data"

Hidden Layers

Output

Input Layer

x_1

x_N

y

Microsoft CNTK Library.

DeepLearning Score

"test data"

sig
bkg

signal

background

Non-resonant Higgs Production with a scalar Singlet at the LHC

Significance at High Luminosity

DeepLearning Score

2 Dense Layers, 45 Neurons

significance

11+7 variables

N_{sig}

Benchmark Point

$$m_{h_1} = 125\,\text{GeV},\ m_{h_2} = 170\,\text{GeV},$$

$$\theta = 0.2,\ b_3 = 0,\ \lambda_{221} = 1.5/vev_{\text{EW}}$$

Non-resonant Higgs Production with a scalar Singlet at the LHC

Discussion

1. Scan over parameter space

2. Study smaller mixing angle

$m_2 = 170\,\mathrm{GeV},\ \sin\theta = 0.2$

$(\sigma_{h1h1}+\sigma_{h1h2})*BR_{bbww}[fb],\ \theta_{mix}=0.1,\ m_{h_2}= 170\,GeV.$

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Non-resonant Higgs Production with a scalar Singlet at the LHC

Thank You

Non-resonant Higgs Production with a scalar Singlet at the LHC

Back Up

Non-resonant Higgs Production with a scalar Singlet at the LHC

"Left corner, not yet studied"

$(\sigma_{h1h1} + \sigma_{h1h2}) * BR_{bbww}[fb]$, $\theta_{mix} = 0.2$, $m_{h_2} = 170$ GeV.

under scanning

2-σ Exclusion

Non-resonant Higgs Production with a scalar Singlet at the LHC

$$a_1 = \frac{m_1^2 - m_2^2}{v_{EW}} \sin 2\theta,$$

$$b_2 + \frac{a_2}{2} v_{EW}^2 = m_1^2 \sin^2 \theta + m_2^2 \cos^2 \theta,$$

$$\lambda = \frac{m_1^2 \cos^2 \theta + m_2^2 \sin^2 \theta}{2 v_{EW}^2}.$$

$$\lambda_{111} = 2s^3 b_3 + \frac{3a_1}{2} sc^2 + 3a_2 s^2 cv + 6c^3 \lambda v,$$

$$\lambda_{211} = 2s^2 c b_3 + \frac{a_1}{2} c(c^2 - 2s^2) + (2c^2 - s^2) s v a_2 - 6\lambda s c^2 v$$

$$\lambda_{221} = 2c^2 s b_3 + \frac{a_1}{2} s(s^2 - 2c^2) - (2s^2 - c^2) c v a_2 + 6\lambda c s^2 v$$

$$\lambda_{222} = 2c^3 b_3 + \frac{3a_1}{2} cs^2 - 3a_2 c^2 sv - 6s^3 \lambda v,$$

Non-resonant Higgs Production with a scalar Singlet at the LHC

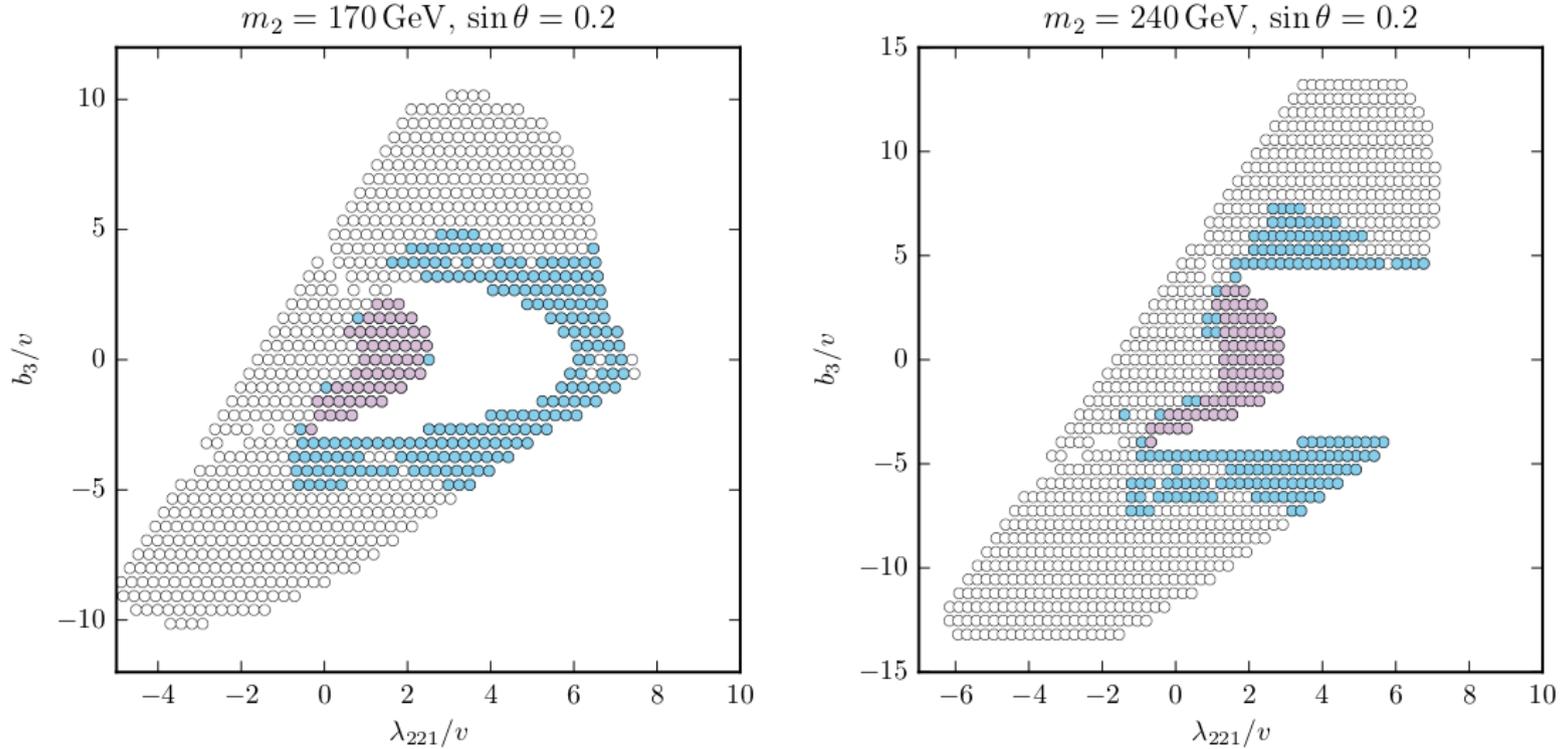**Figure 2.** The parameter space of the model consistent with our requirements for $m_2 = 170$, 240 GeV and $\sin\theta = 0.05$, 0.2 , now showing regions with a strong first-order electroweak phase transition. Results for both $\sin\theta = 0.05$ and 0.2 are shown. Blue points feature an EWPT with $\phi_h(T_c)/T_c \geq 1$ for some value of $b_4 > 0.01$ in our approach utilizing the one-loop daisy-resummed thermal effective potential. Purple points additionally feature a strong first-order electroweak phase transition as predicted by the gauge-invariant high-T approximation (which drops the Coleman-Weinberg potential and is thus only applied to regions with tree-level vacuum stability). Strong electroweak phase transitions are typically correlated with sizable values of λ_{221}.

Chen, Kozaczuk, Lewis
(arXiv:1704:05844)

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Non-resonant Higgs Production with a scalar Singlet at the LHC

Topness (T)

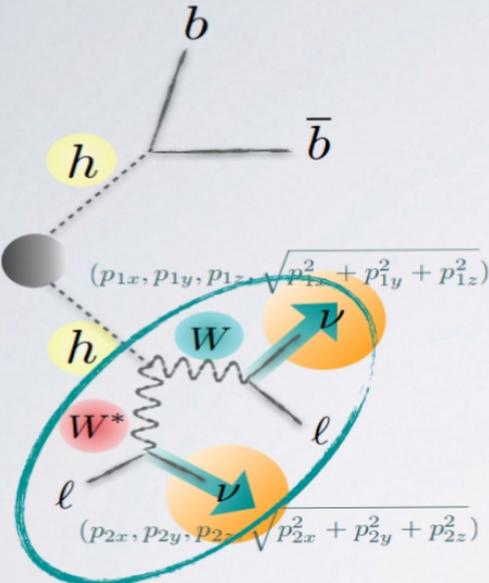$$\chi^2_{ij} \equiv \min_{\vec{p}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m^2_{b_i \ell^+ \nu} - m^2_t\right)^2}{\sigma^4_t} + \frac{\left(m^2_{\ell^+ \nu} - m^2_W\right)^2}{\sigma^4_W} \right.$$

$$\left. + \frac{\left(m^2_{b_j \ell^- \bar{\nu}} - m^2_t\right)^2}{\sigma^4_t} + \frac{\left(m^2_{\ell^- \bar{\nu}} - m^2_W\right)^2}{\sigma^4_W} \right]$$

$$T \equiv min\left(\chi^2_{12}, \chi^2_{21}\right)$$

two possible ways of paring b and ℓ

Higgsness (H)

$$H \equiv \min_{\vec{p}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m^2_{\ell^+ \ell^- \nu \bar{\nu}} - m^2_h\right)^2}{\sigma^4_{h_\ell}} + \frac{\left(m^2_{\nu \bar{\nu}} - m^2_{\nu \bar{\nu}, peak}\right)^2}{\sigma^4_\nu} \right.$$

$$+ \min \left(\frac{\left(m^2_{\ell^+ \nu} - m^2_W\right)^2}{\sigma^4_W} + \frac{\left(m^2_{\ell^- \bar{\nu}} - m^2_{W*, peak}\right)^2}{\sigma^4_{W*}}, \right.$$

$$\left. \left. \frac{\left(m^2_{\ell^- \bar{\nu}} - m^2_W\right)^2}{\sigma^4_W} + \frac{\left(m^2_{\ell^+ \nu} - m^2_{W*, peak}\right)^2}{\sigma^4_{W*}} \right) \right],$$

two possible ways of paring ν and ℓ

$\sim m_h - m_W$
off-shell

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Non-resonant Higgs Production with a scalar Singlet at the LHC

Cut-flow summary

	S(fb)	B(fb)	S/B
Reco & b-tag	0.027	369.3	7.20E-05
baseline	0.01	6.45	0.0016
H & T	0.007	0.258	0.029
2D with 45N	0.0033	0.012	0.28

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$M_{h_2} = 170 \text{ GeV}, \theta_\text{mix} = 0.2, \lambda_{221}/\text{vev} = 1.5, b_3/\text{vev} = 0$

$M_{h_2} = 170 \text{ GeV}, \theta_\text{mix} = 0.2, \lambda_{221}/\text{vev} = 1.5, b_3/\text{vev} = 0$

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Non-resonant Higgs Production with a scalar Singlet at the LHC

2D*45N & 64mb & 100n, no (ϕ_{llbb}, MET)

Legend:
- □ B|D|R|B|D|R|B
- □ D|R|B|D|R|B
- □ D|R|D|R|B
- ■ D|R|D|R
- ■ B|D|R|B|D|R|B with MET
- ■ B|D|R|B|D|R|B with MET & ϕ_{llbb}
- ▲ B|D|R|B|D|R|B Low var only
- ▲ B|D|R|B|D|R|B High var only
- ▲ B|D|R|B|D|R|B with MET no MT2B

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Non-resonant Higgs Production with a scalar Singlet at the LHC

```python
varselect = C.splice(met,l1pt,l2pt,drll,mbb,ptbb,drbb,mll,ptll,
                sminbbll,sminll,MT2sysA,MT2sysB,hnessonoff,hnessonon,tness, DRljmin, axis=1)
h2 = varselect
h2 = C.layers.BatchNormalization(map_rank=1)(h2)
h2 = C.layers.Dense(45)(h2)
h2 = C.relu(h2)
h2 = C.layers.BatchNormalization(map_rank=1)(h2)
h2 = C.layers.Dense(45)(h2)
h2 = C.relu(h2)
h2 = C.layers.BatchNormalization(map_rank=1)(h2)

r = C.layers.Dense(num_output_classes, activation=None, name='classify')(h2)
return r
```