Non-resonant Higgs Production in Scalar Extended Model at the LHC

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based on work in collaboration with

C. Chen, J. Kim, K. Kong,
J. Kozaczuk, and I. Lewis

October, 12th 2019

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.

Alhazmi, Chen, Kim, Kong, Kozaczuk, Lewis
(arXiv:19XX.XXXX)

The Model

$$V_H(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$
$$V_{HS}(H,S) = \frac{a_1}{2} H^\dagger H\, S + \frac{a_2}{2} H^\dagger H\, S^2$$
$$V_S(S) = b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4.$$

Extend the SM by a real scalar particle, S

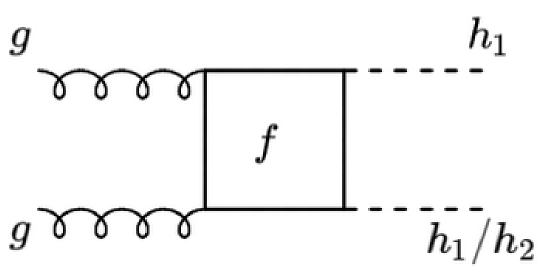
V(H) ⟶ V(H, S)

Study the trilinear interactions

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

$$V_{\rm self} \supset \frac{\lambda_{111}}{3!} h_1^3 + \frac{\lambda_{211}}{2!} h_2 h_1^2 + \frac{\lambda_{221}}{2!} h_2^2 h_1 + \frac{\lambda_{222}}{3!} h_2^3 + \frac{\lambda_{1111}}{4!} h_1^4 + \frac{\lambda_{2111}}{3!} h_2 h_1^3 + \frac{\lambda_{2211}}{4} h_2^2 h_1^2 + \frac{\lambda_{2221}}{3!} h_2^3 h_1 + \frac{\lambda_{2222}}{4!} h_2^4.$$

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



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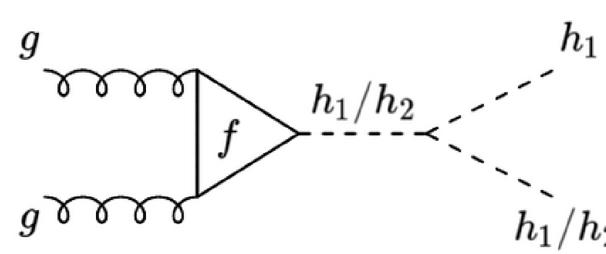


Alhazmi, Chen, Kim, Kong, Kozaczuk, Lewis (arXiv:19XX.XXXX)

Non-resonant Higgs Production in Scalar Extended Model at the LHC

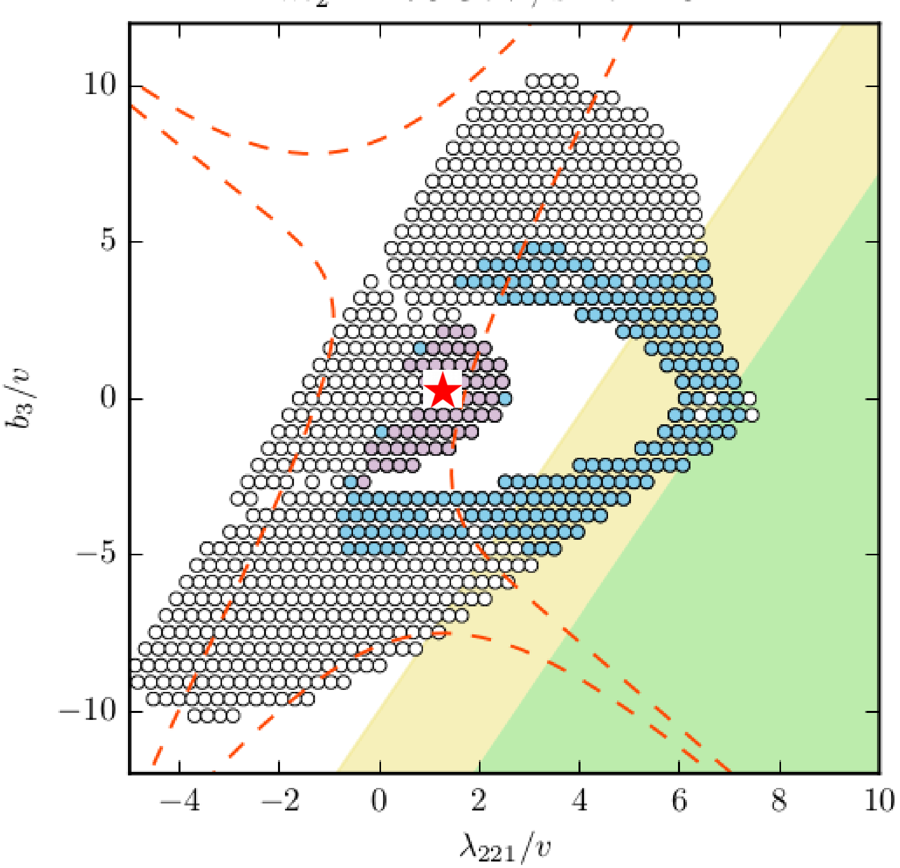
Model Parameters:

$$m_{h_1} = 125\,\text{GeV},\ m_{h_2},\ \theta,\ b_3,\ \lambda_{221}$$

1. Existing Study

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

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

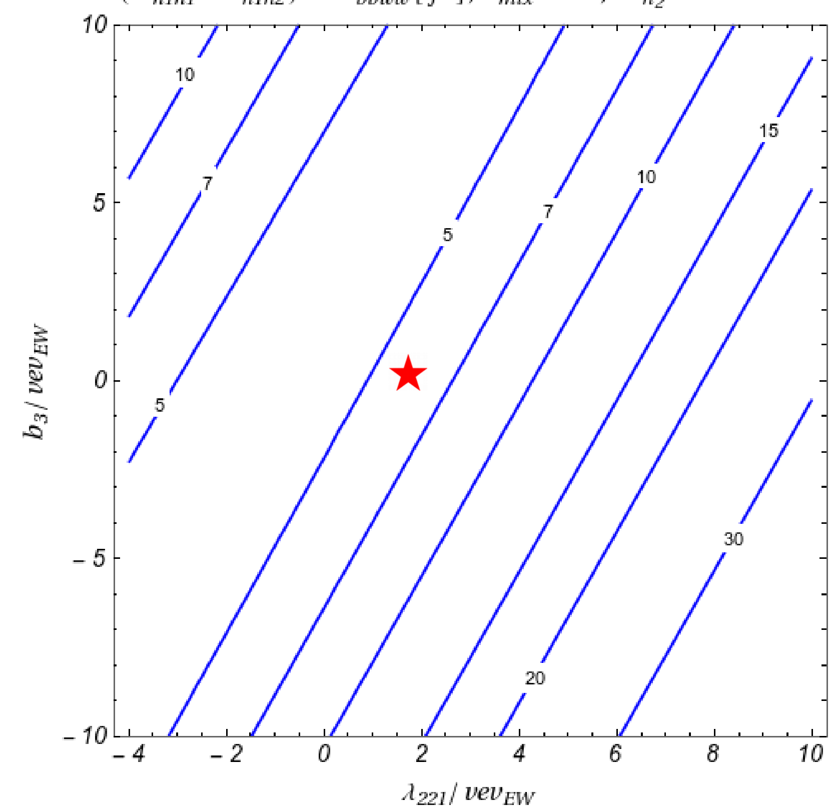


Chen, Kozaczuk, Lewis
(arXiv:1704:05844)

2. New Study

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

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



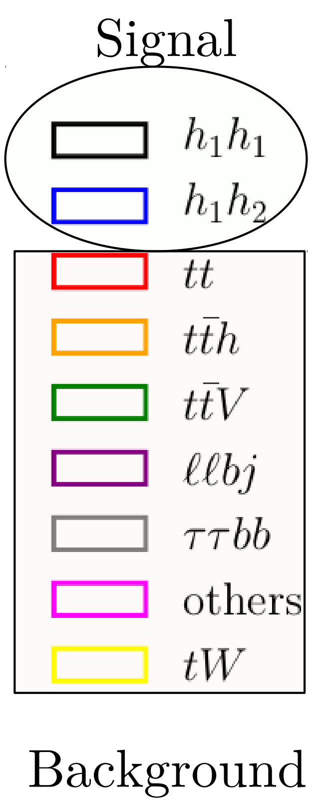
Alhazmi, Chen, Kim, Kong,
Kozaczuk, Lewis
(arXiv:19XX.XXXX)

Challenging ?

Generate Signal and Background.

Select events with:

1. missing transverse momentum
2. two isolated leptons
3. two b-tagged jets



Benchmark Point ★

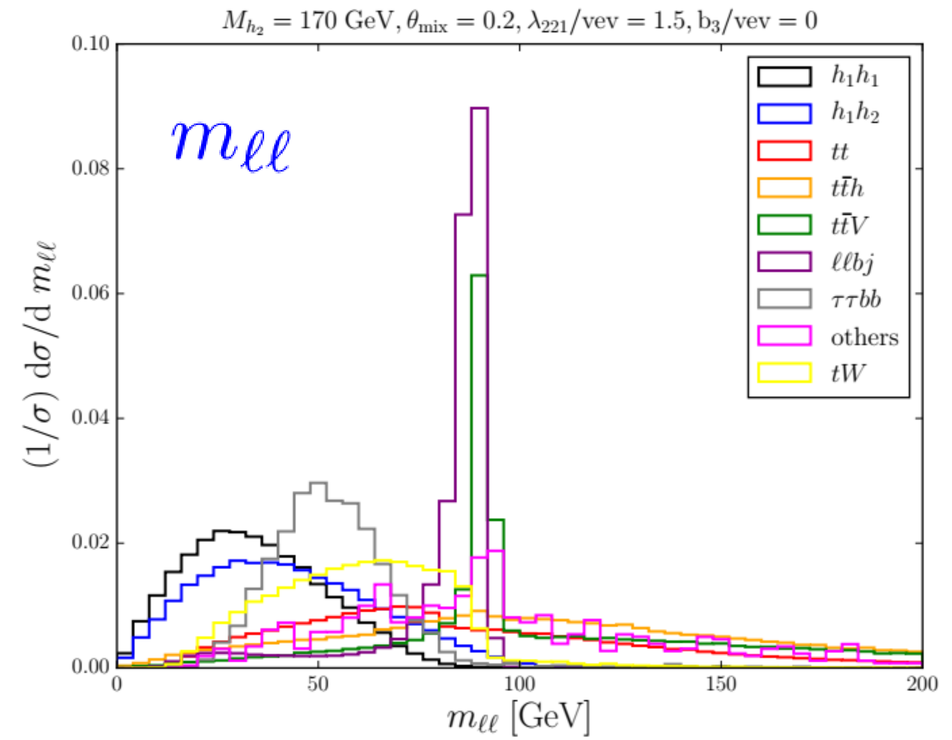
$$m_{h_1} = 125\,\text{GeV},\ m_{h_2} = 170\,\text{GeV},$$
$$\theta = 0.2,\ b_3 = 0,\ \lambda_{221} = 1.5\,vev$$

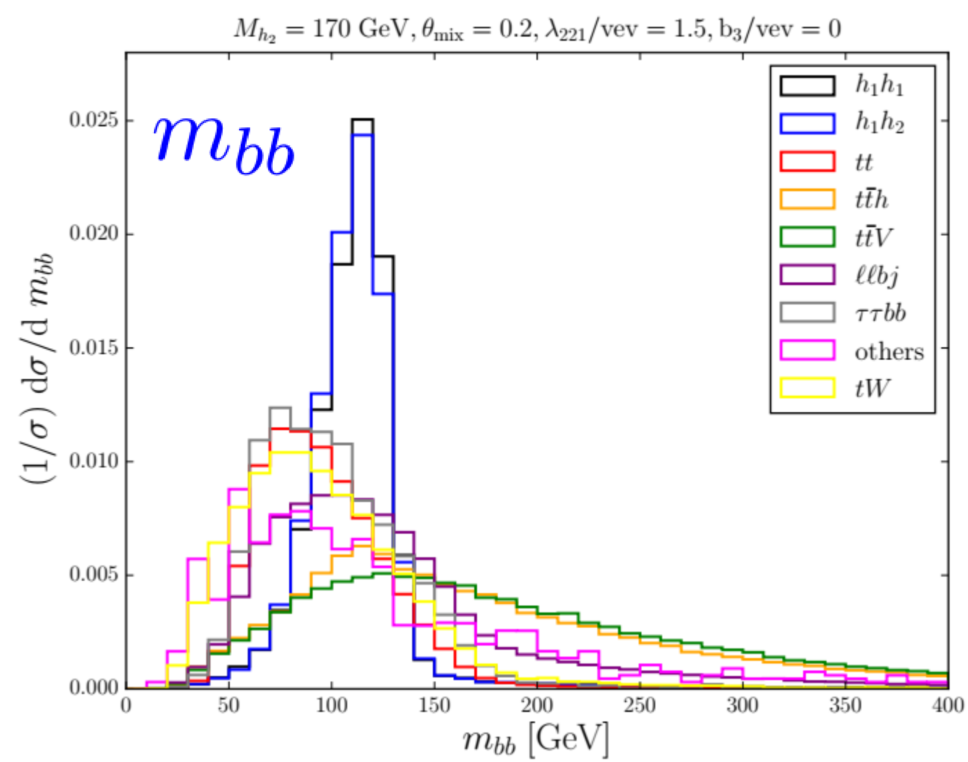
$\not{p}_T$ p_{T,ℓ_1} p_{T,ℓ_2}

$p_{T,bb}$ $p_{T,\ell\ell}$

$\Delta R_{\ell\ell}$ ΔR_{bb} $\Delta\phi_{bb,\ell\ell}$

$m_{\ell\ell}$ m_{bb}





Generate Signal and Background.

Select events with:

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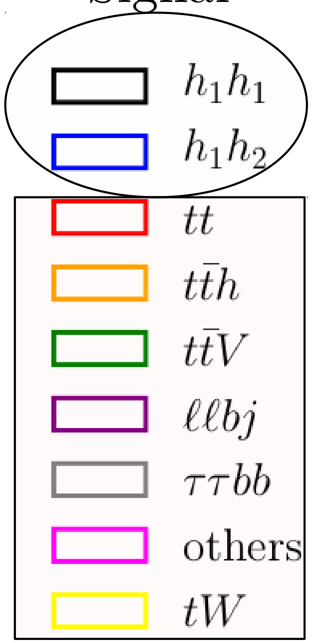
Signal



Background

Benchmark Point

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

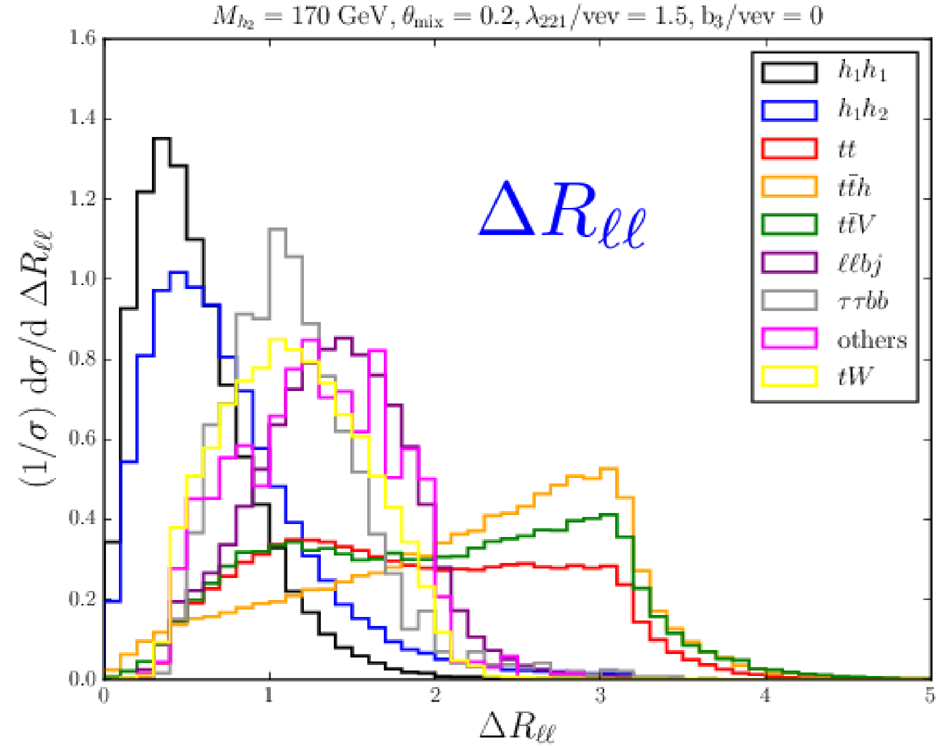
$\theta = 0.2,\ b_3 = 0,\ \lambda_{221} = 1.5\, vev$

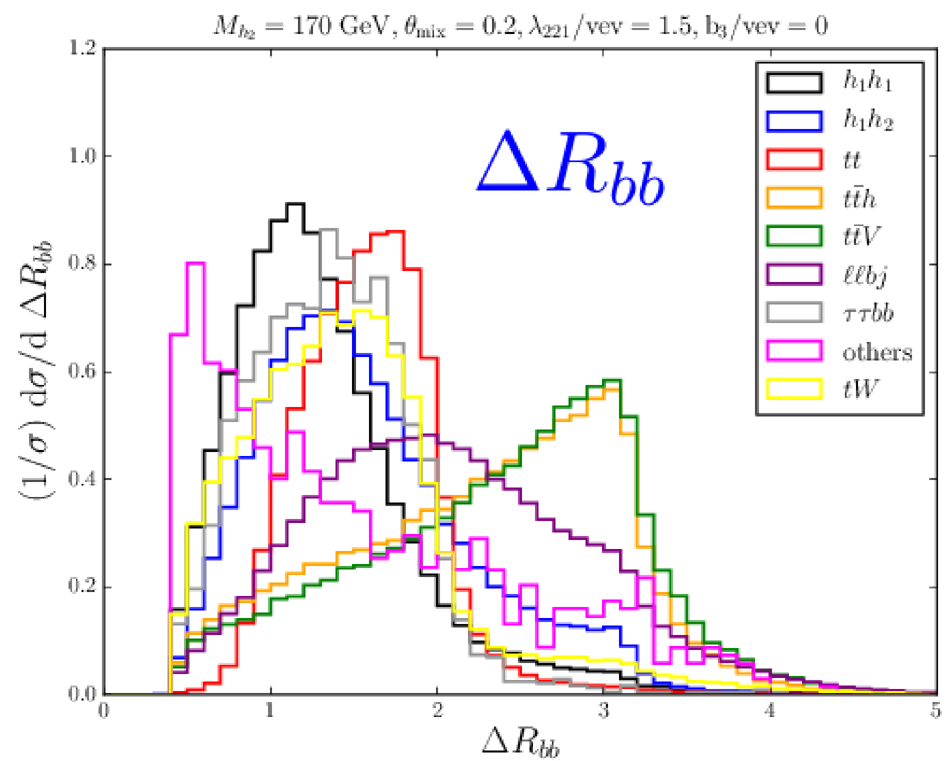
$\not{p}_T \quad p_{T,\ell_1} \quad p_{T,\ell_2}$

$p_{T,bb} \quad p_{T,\ell\ell}$

$\Delta R_{\ell\ell} \quad \Delta R_{bb} \quad \Delta\phi_{bb,\ell\ell}$

$m_{\ell\ell} \quad m_{bb}$





Why does bbww final state still very challenging?

After choosing events with some selection cuts:

$$\not{E}_T > 20\,\text{GeV},\ p_T^\ell > 20\,\text{GeV},\ \Delta R_{\ell\ell} < 1.1,$$

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

$$95\,\text{GeV} < m_{bb} < 140\,\text{GeV}$$

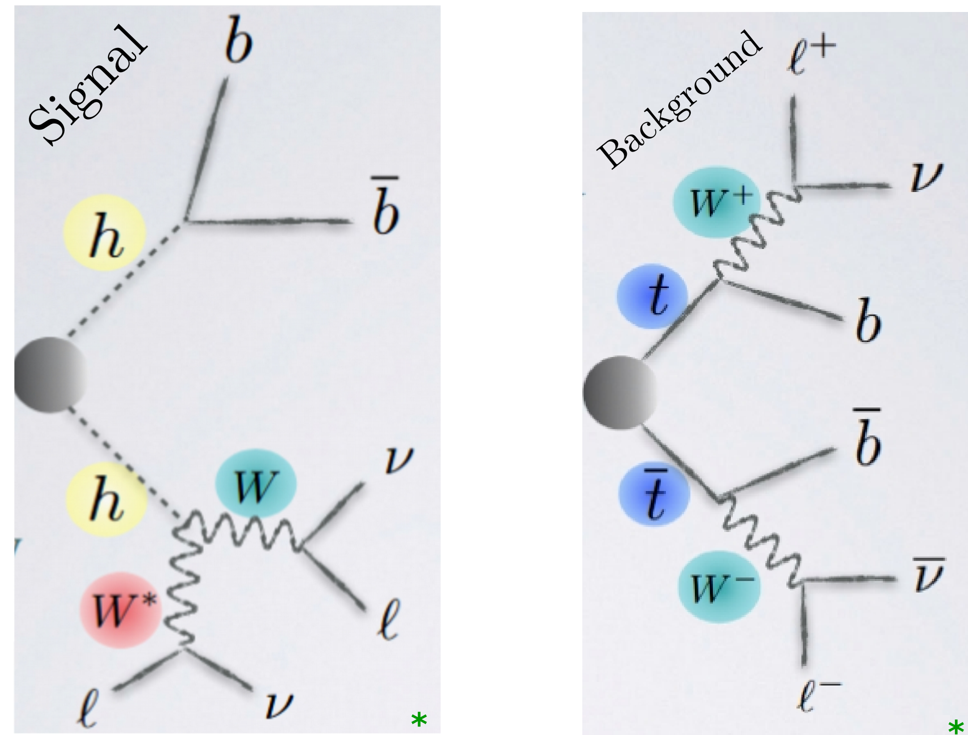
- $h_1 h_1$
- $h_1 h_2$
- tt
- $t\bar{t}h$
- $t\bar{t}V$
- $\ell\ell bj$
- $\tau\tau bb$
- others
- tW

Signl ~ 0.01 fb

Background ~ 6 fb

The ratio is very small!

Topness vs Higgsness



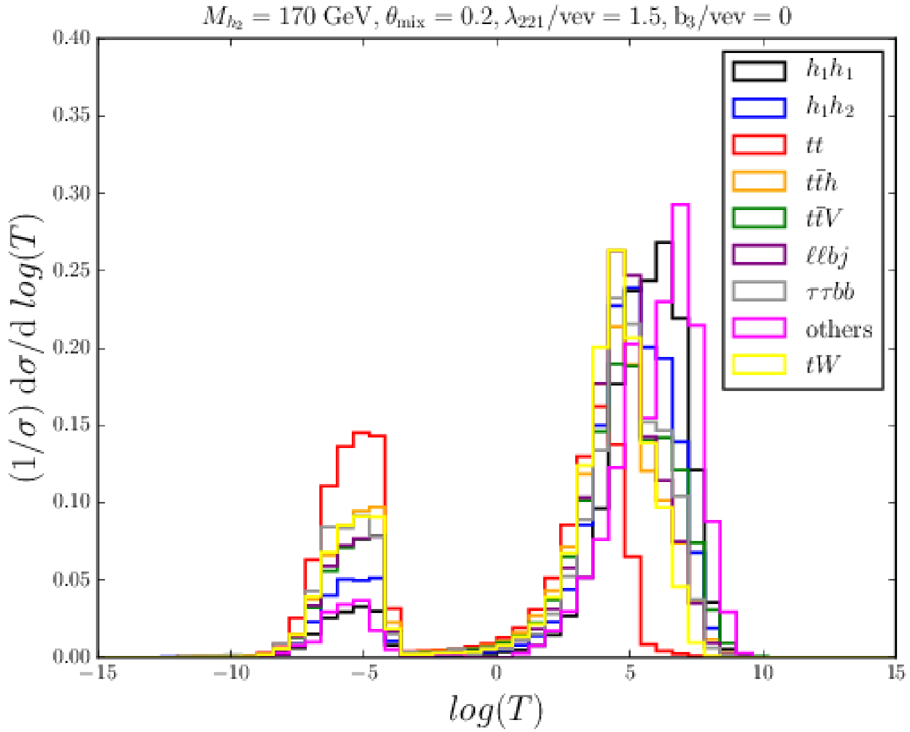
New variables, minimizing over neutrino momentum using mass constraints.

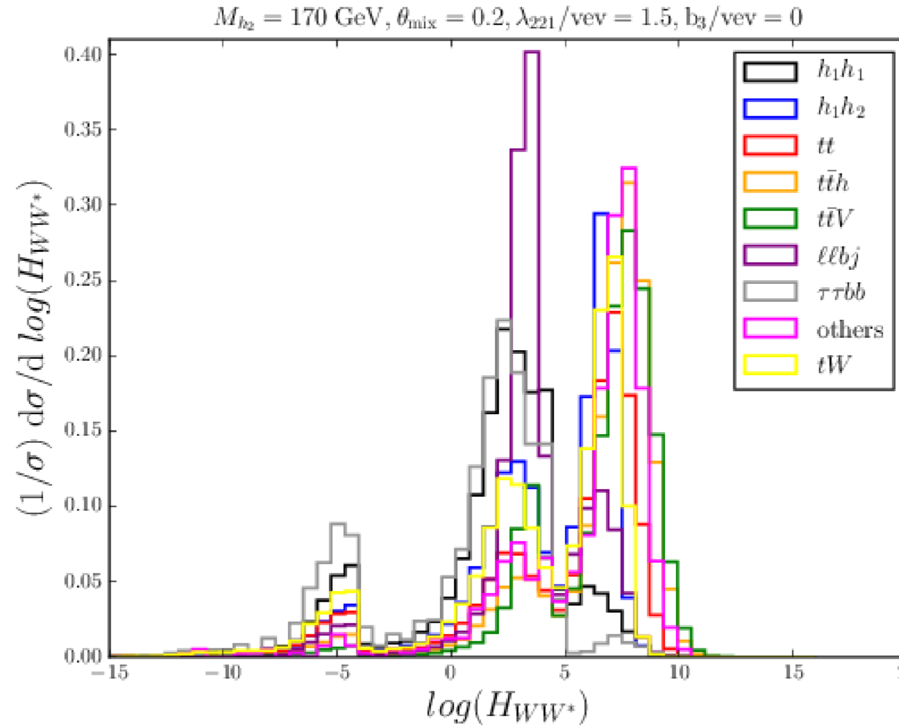
$T,\ H,\ M_{T2}, \ldots$

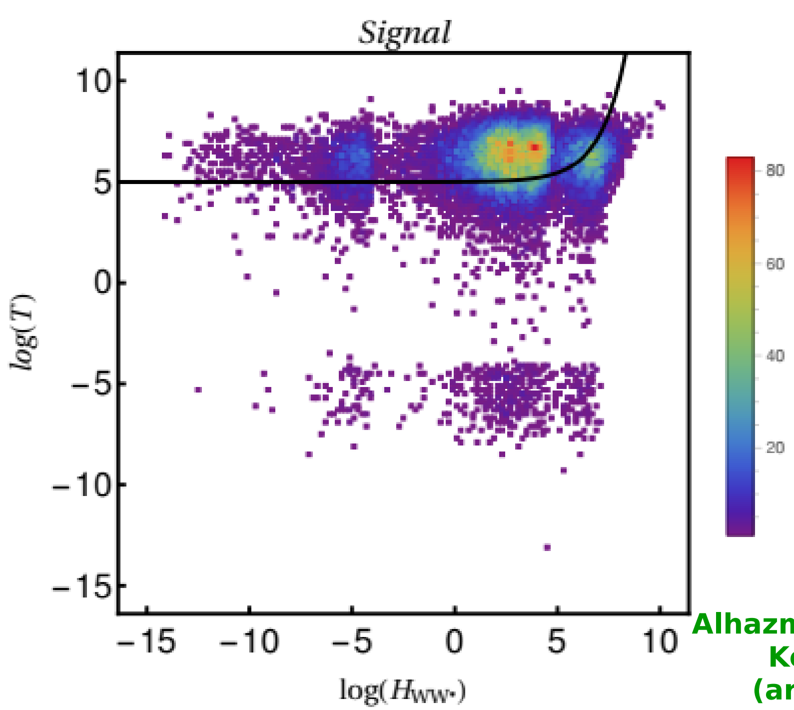
Kim, Kong, Matchev, Park arXiv:1807:11498

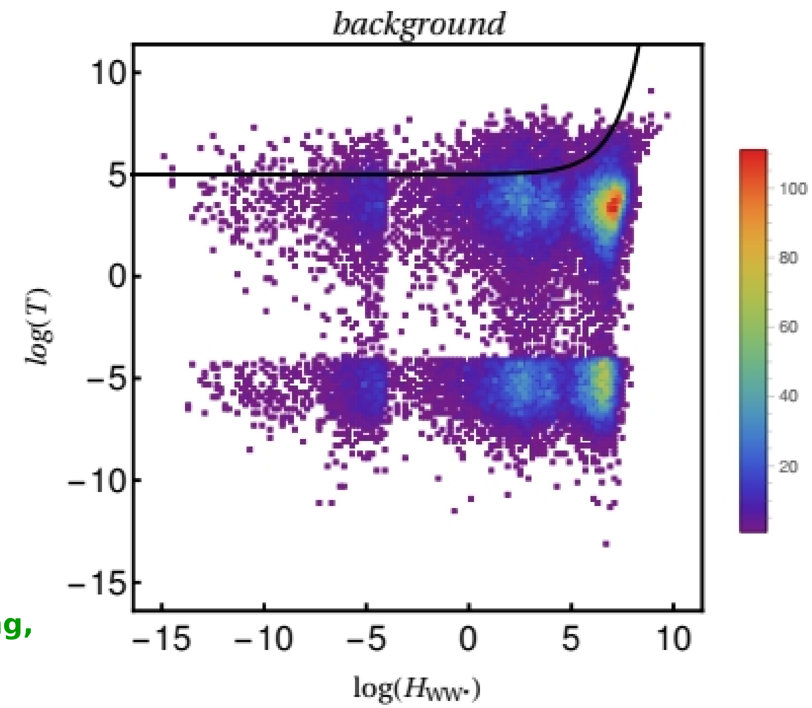
* Slide taken from Kim (Double Higgs production workshop, FNAL 2018)

Topness vs Higgsness









Alhazmi, Chen, Kim, Kong, Kozaczuk, Lewis (arXiv:19XX.XXXX)

Can we use Deep Neural Network?

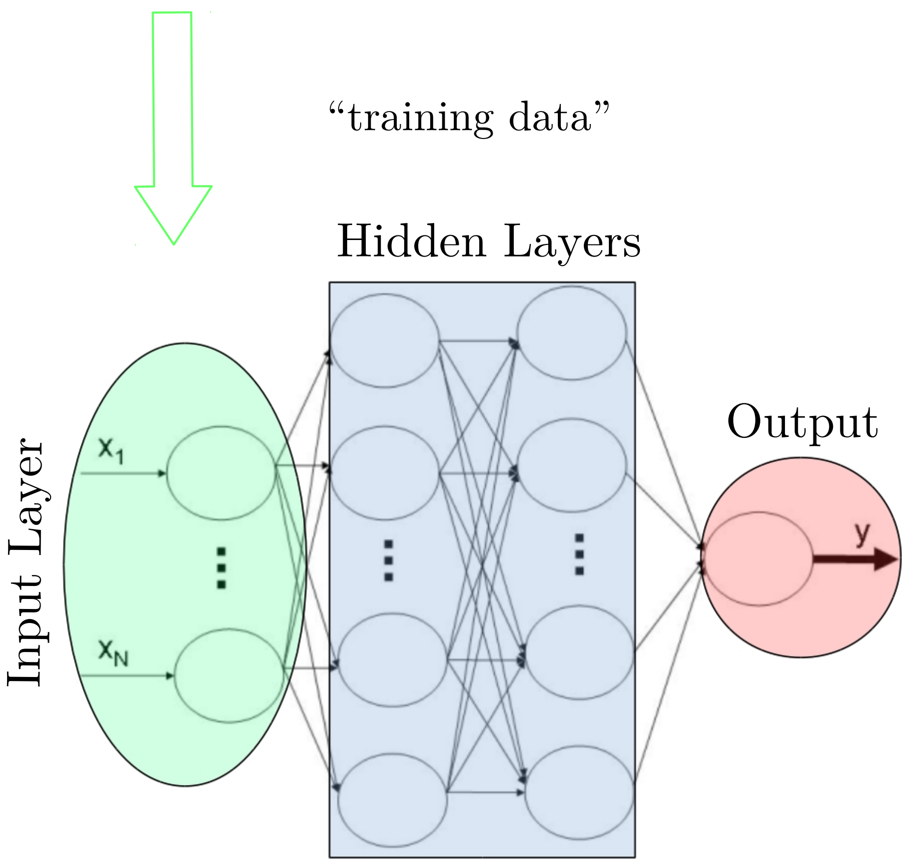
"event classification"

Prepare and feed kinematic variables as an input layer to the DNN

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

11 + 7 variables

$T,\ H,\ M_{T2}, \ldots$



Microsoft CNTK Library.

$$z_1 \rightarrow p_1 = \frac{e^{z_1}}{e^{z_1} + e^{z_2}}$$

$$z_2 \rightarrow p_2 = \frac{e^{z_2}}{e^{z_1} + e^{z_2}}$$

$$H = -y_1 \log(p_1) - y_2 \log(p_2)$$

$$\text{Signal}: \quad (y_1, y_2) = (1, 0)$$

$$\text{Backgrounds}: \quad (y_1, y_2) = (0, 1)$$

Can we use Deep Neural Network?

"event classification"

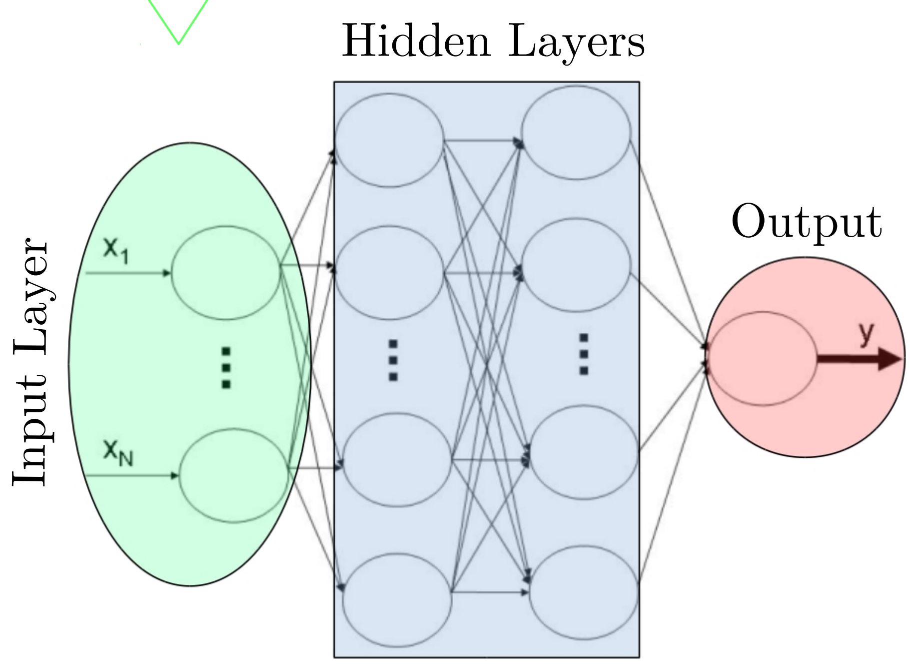
Prepare and feed kinematic variables
as an input layer to the DNN

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

11 + 7 variables

$T,\ H,\ M_{T2}, \ldots$

"training data"



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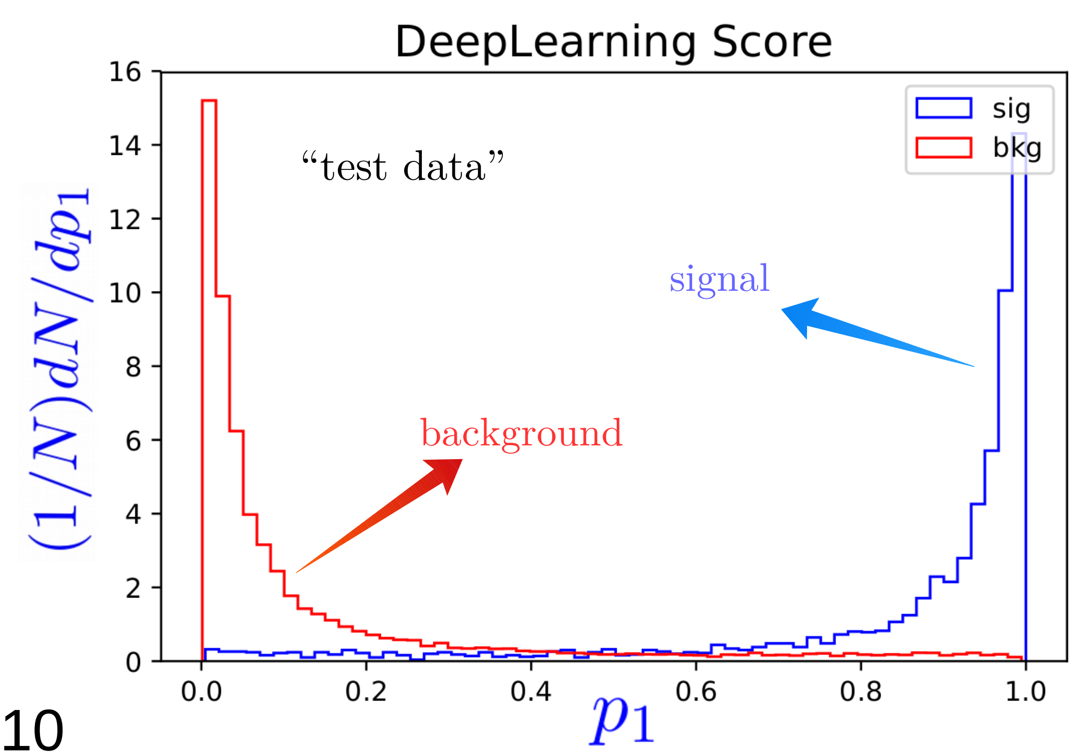

Can we use Deep Neural Network?

"event classification"

F ★ les

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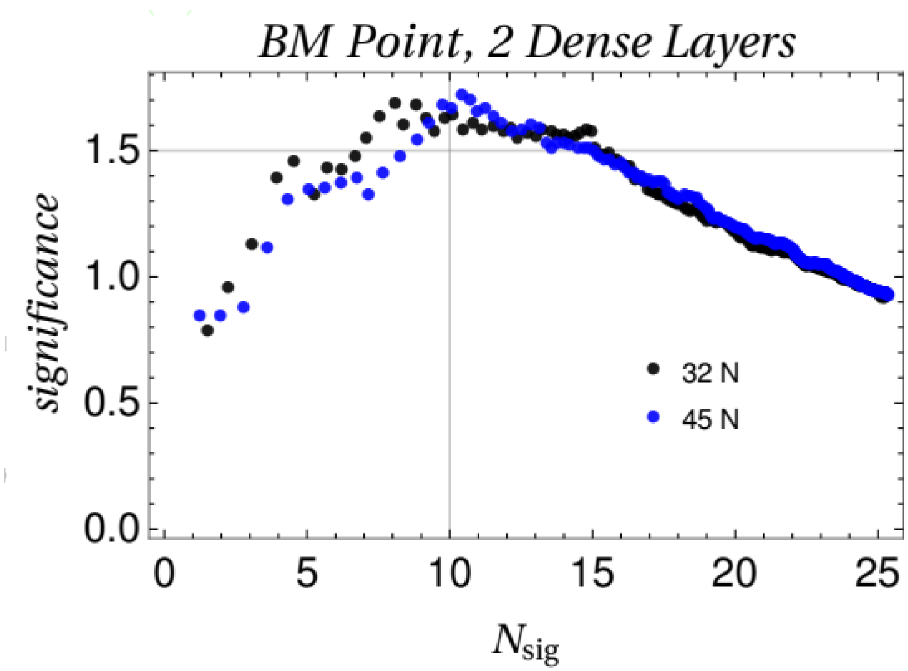
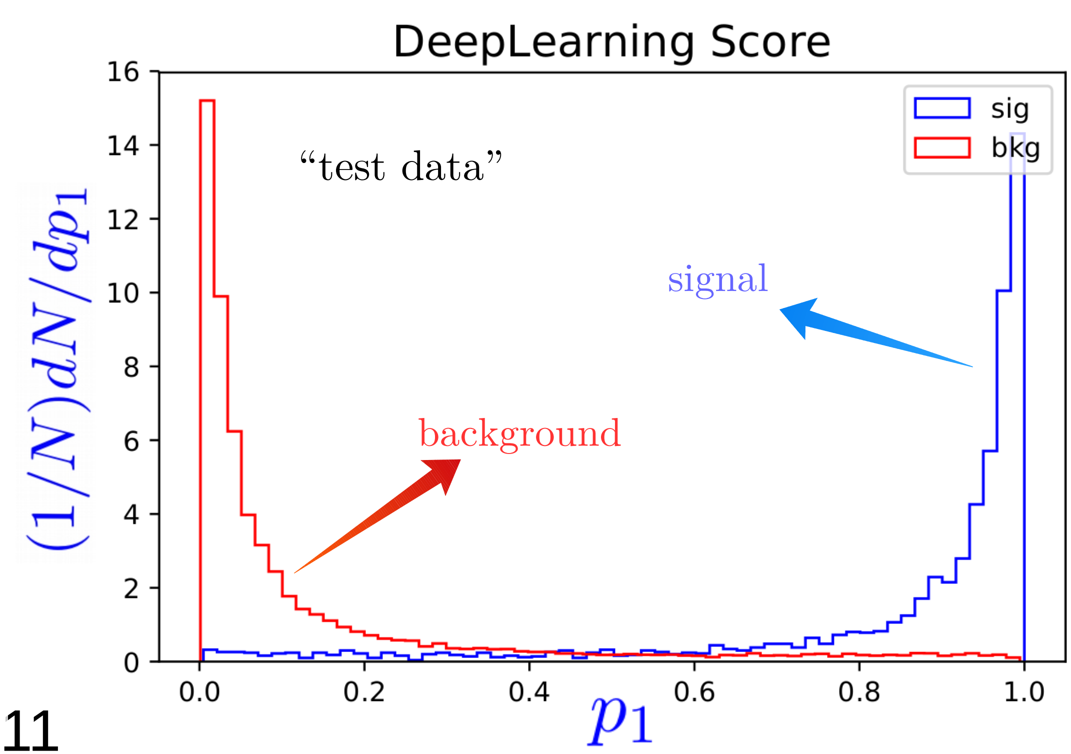
$m, p_T, \not{E}_T, \Delta R, \ldots$

11 + 7 variables

$T,\ H,\ M_{T2}, \ldots$





Alhazmi, Chen, Kim, Kong, Kozaczuk, Lewis (arXiv:19XX.XXXX)

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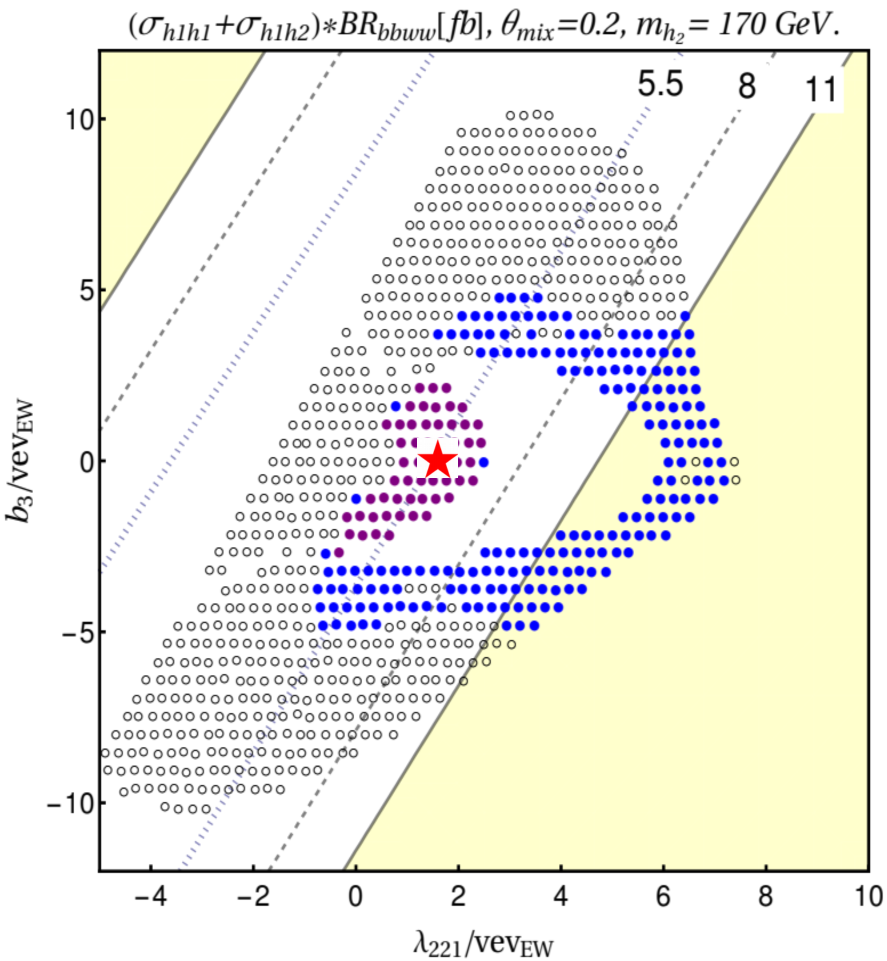
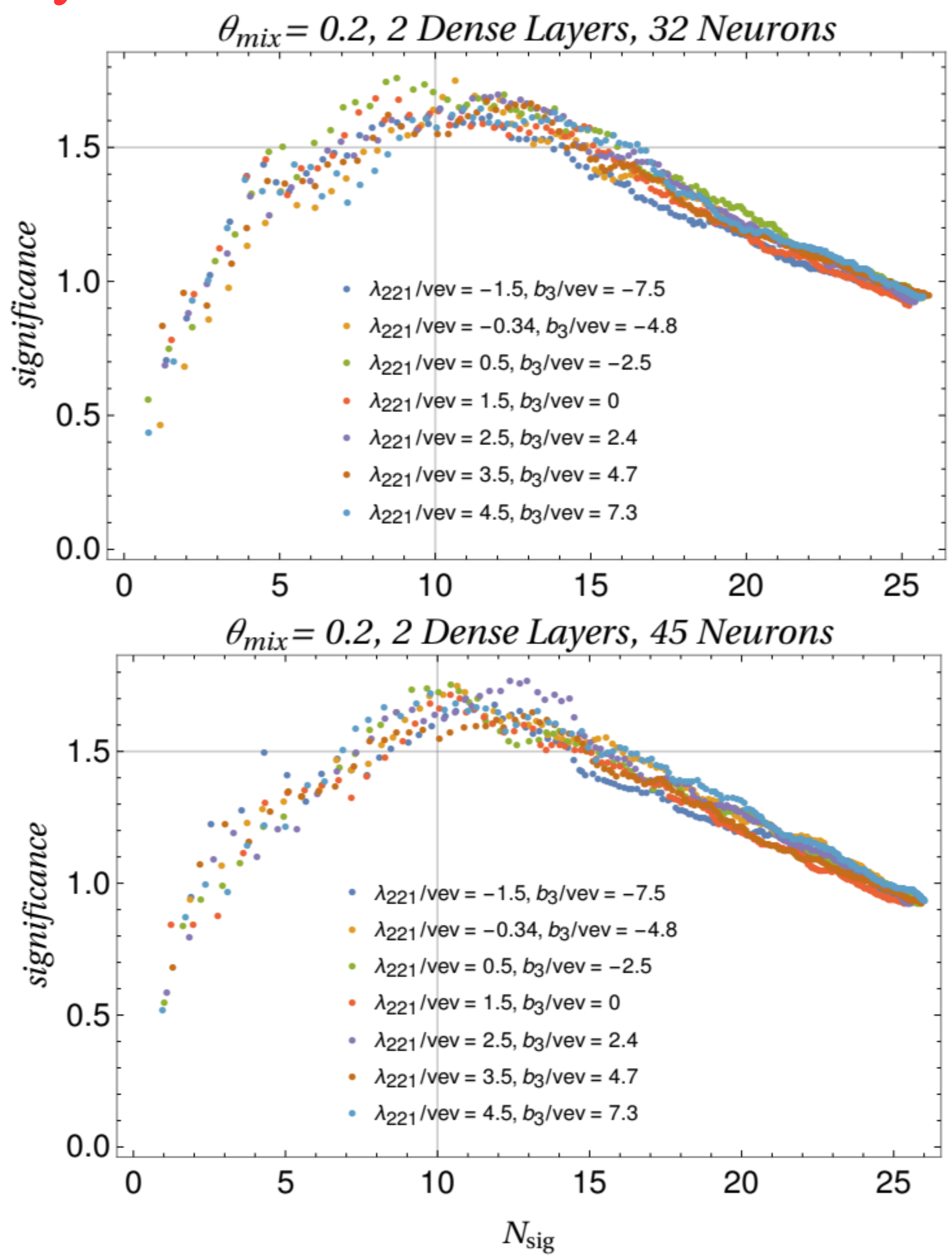
Non-resonant Higgs Production in Scalar Extended Model at the LHC

Significance at High Luminosity





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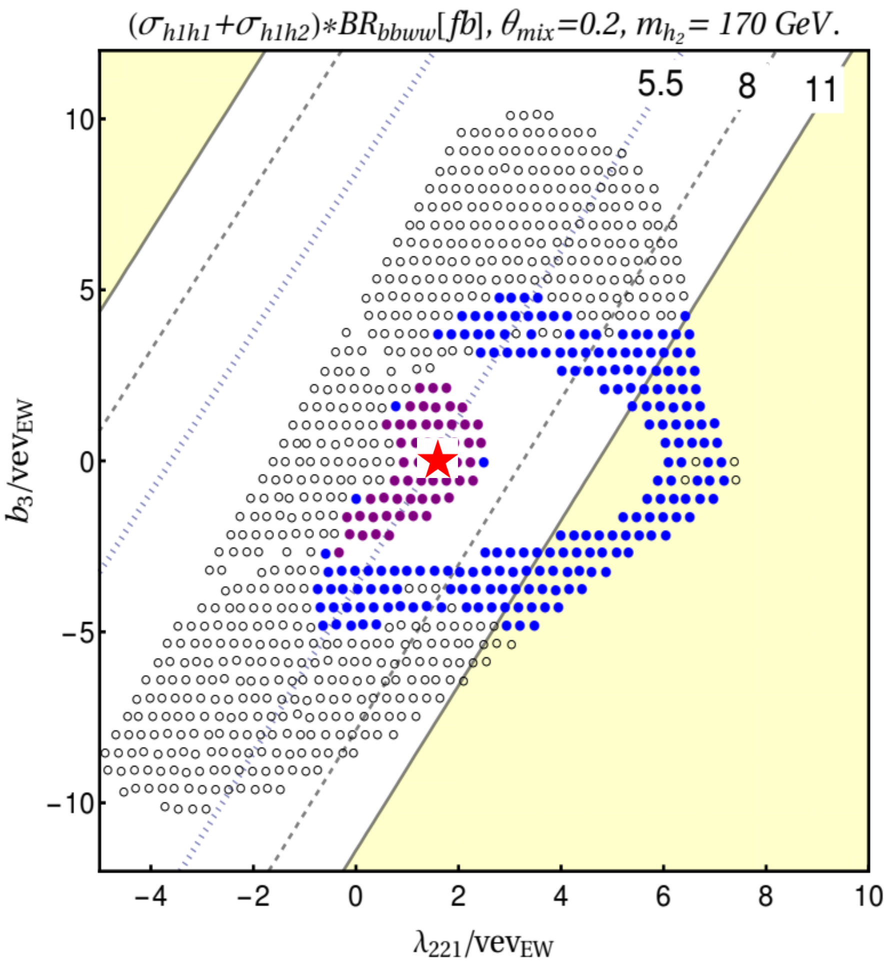

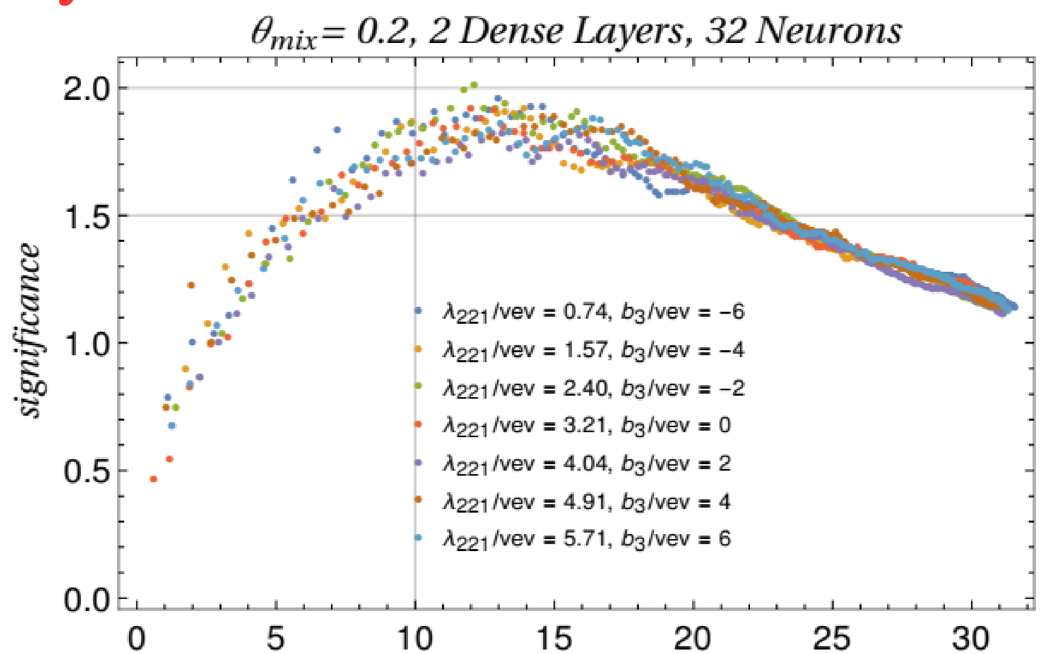

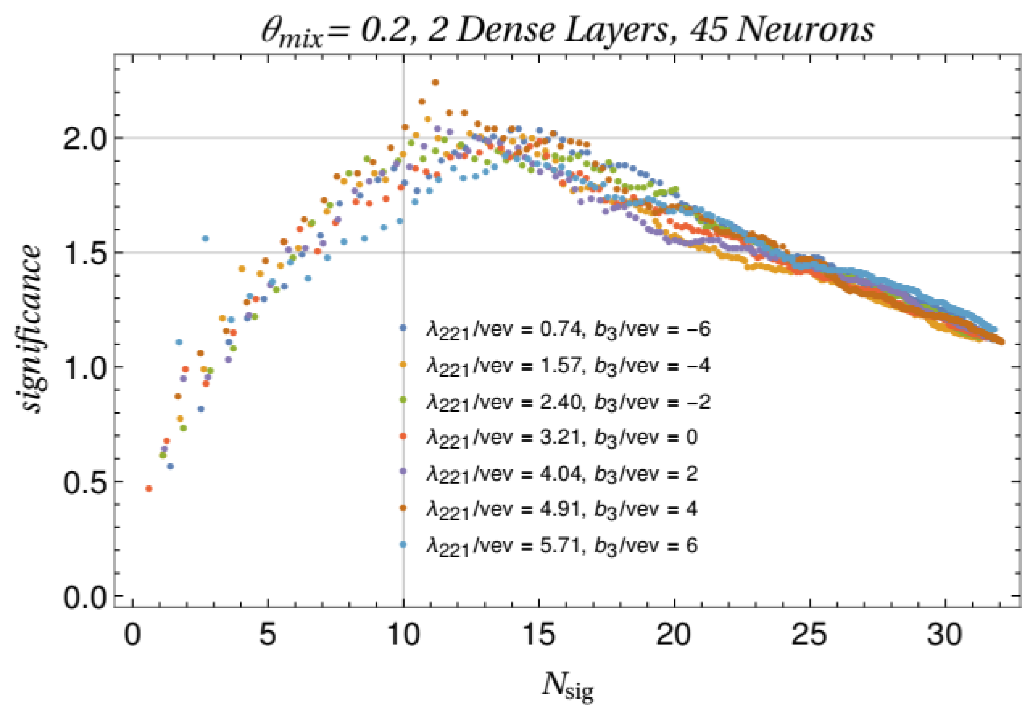

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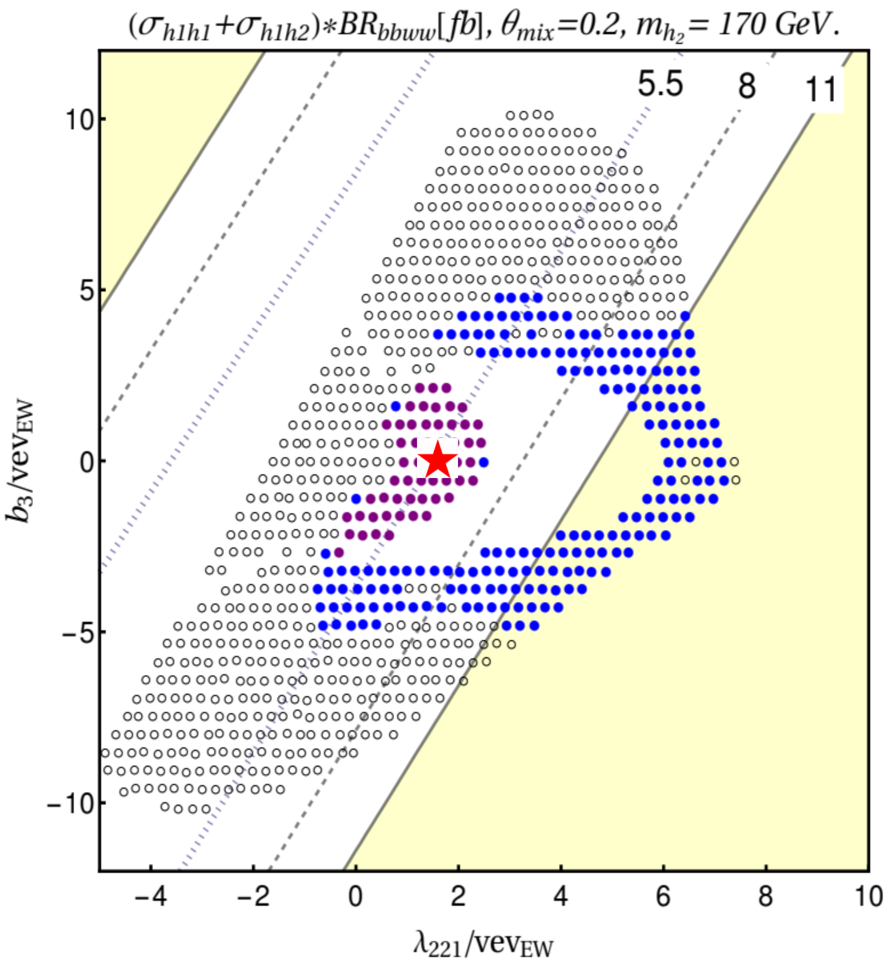
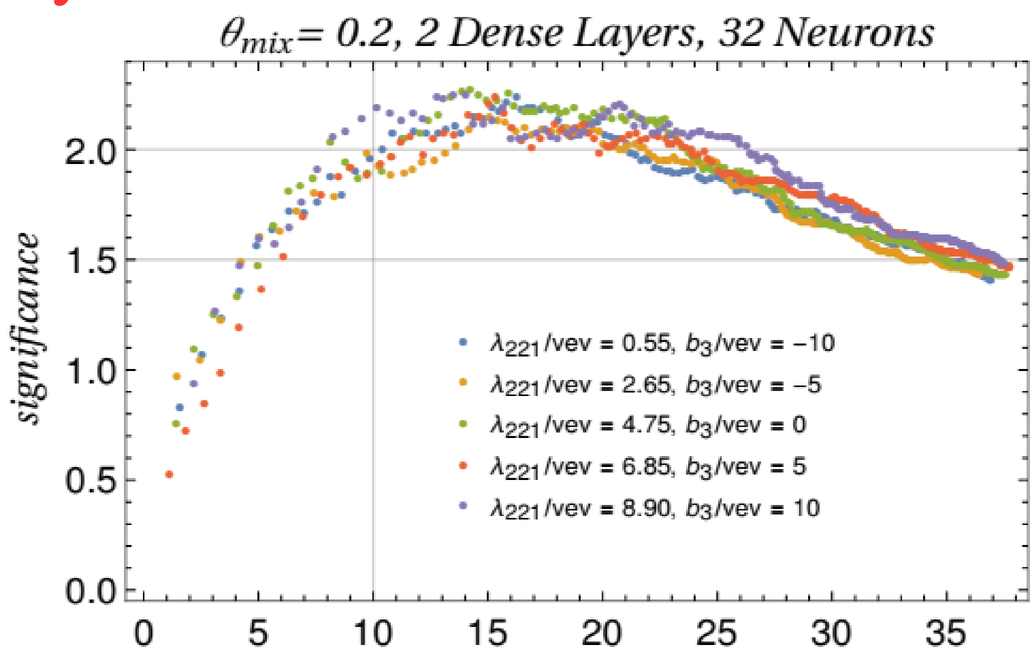
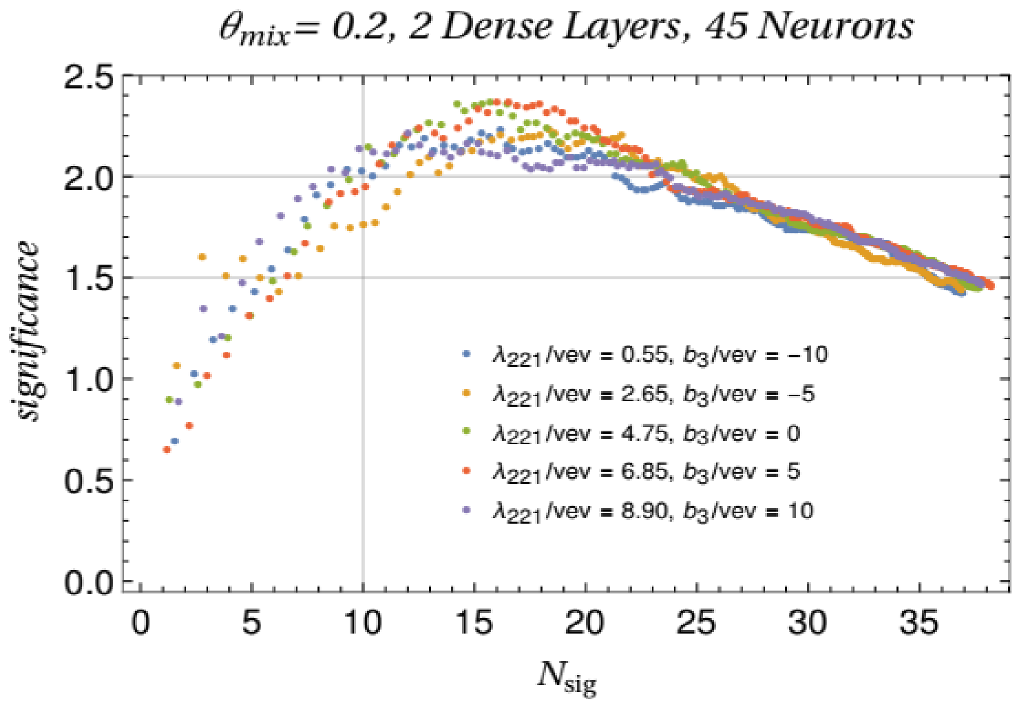


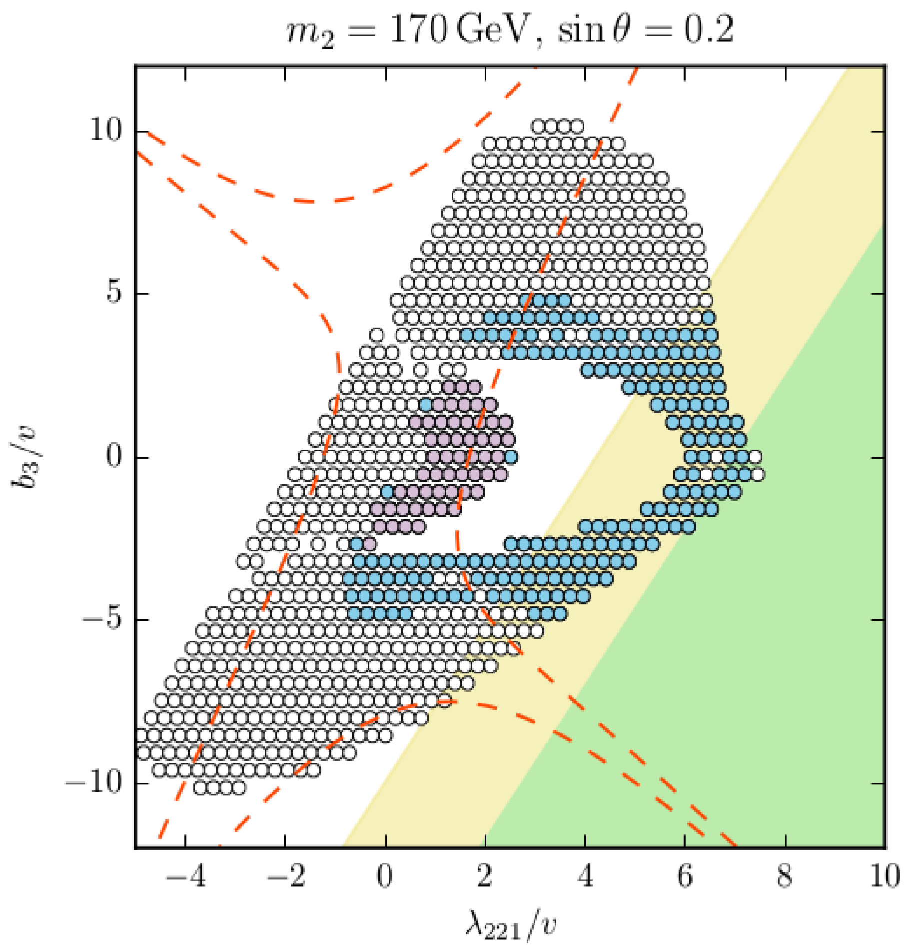




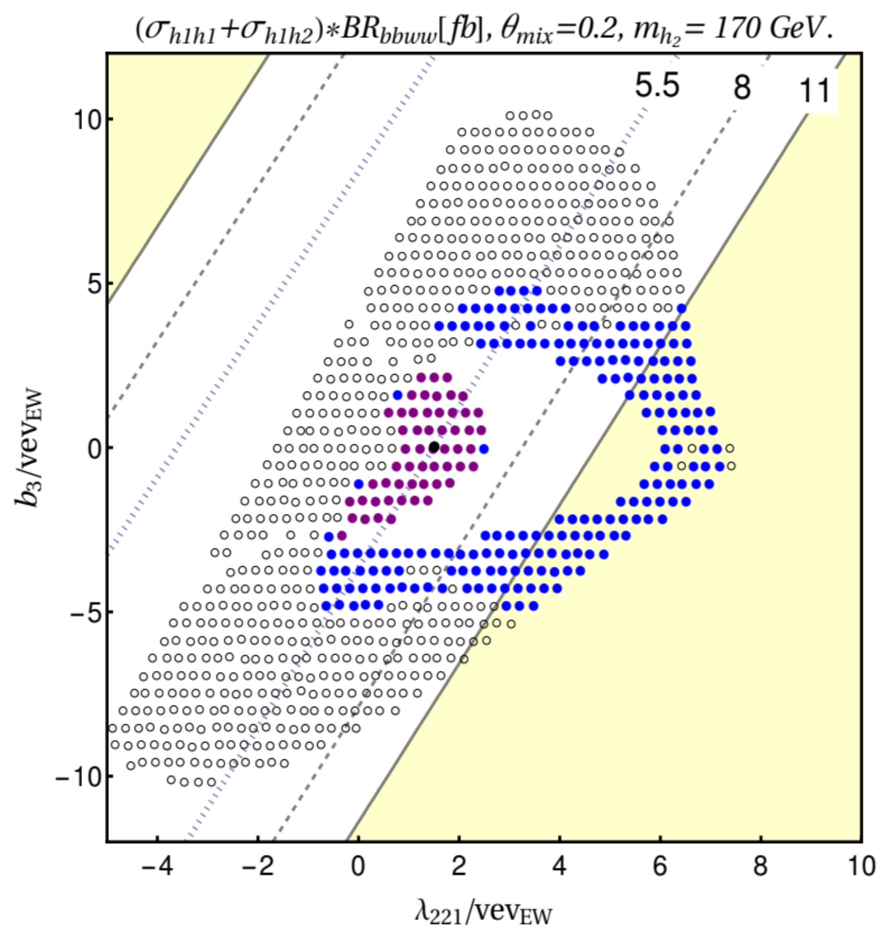
Alhazmi, Chen, Kim, Kong, Kozaczuk, Lewis (arXiv:19XX.XXXX)

Significance at High Luminosity

$$pp \to h_2 h_2 \to 4W \to 2j2\ell^{\pm}\ell'^{\mp}3\nu, \qquad \ell \neq \ell'. \qquad pp \to h_1 h_1 + h_1 h_2 \to b\,\bar{b}\,W^+W^- \to b\,\bar{b}\,\ell\,\bar{\ell}\,\nu_l\,\bar{\nu_l}$$



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



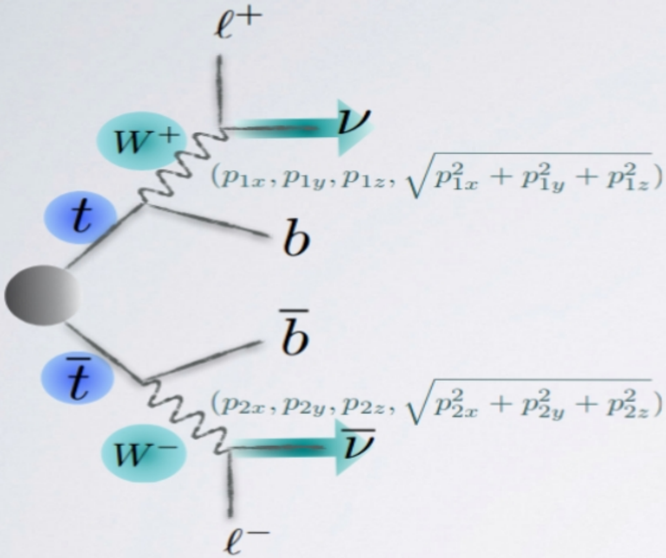
Alhazmi, Chen, Kim, Kong, Kozaczuk, Lewis (arXiv:19XX.XXXX)

Thank You

Alhazmi, Chen, Kim, Kong,
Kozaczuk, Lewis
(arXiv:19XX.XXXX)

Back Up

Topness (T)



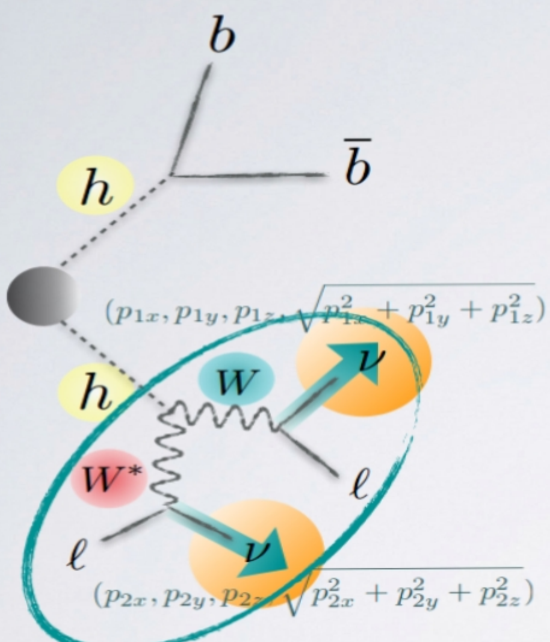
$$\chi_{ij}^2 \equiv \min_{\vec{p}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m_{b_i \ell^+ \nu}^2 - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m_{\ell^+\nu}^2 - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m_{b_j \ell^- \bar{\nu}}^2 - m_t^2\right)^2}{\sigma_t^4} + \frac{\left(m_{\ell^-\bar{\nu}}^2 - m_W^2\right)^2}{\sigma_W^4} \right]$$

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

two possible ways of paring b and ℓ

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

Higgsness (H)



$$H \equiv \min_{\vec{p}_T = \vec{p}_{\nu T} + \vec{p}_{\bar{\nu} T}} \left[\frac{\left(m_{\ell^+\ell^-\nu\bar{\nu}}^2 - m_h^2\right)^2}{\sigma_{h_\ell}^4} + \frac{\left(m_{\nu\bar{\nu}}^2 - m_{\nu\bar{\nu},peak}^2\right)^2}{\sigma_\nu^4} + min\left(\frac{\left(m_{\ell^+\nu}^2 - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m_{\ell^-\bar{\nu}}^2 - m_{W^*,peak}^2\right)^2}{\sigma_{W_*}^4}, \frac{\left(m_{\ell^-\bar{\nu}}^2 - m_W^2\right)^2}{\sigma_W^4} + \frac{\left(m_{\ell^+\nu}^2 - m_{W^*,peak}^2\right)^2}{\sigma_{W_*}^4} \right) \right],$$

two possible ways of paring ν and ℓ

$\sim m_h - m_W$
off-shell

Non-resonant Higgs Production in Scalar Extended Model at the LHC

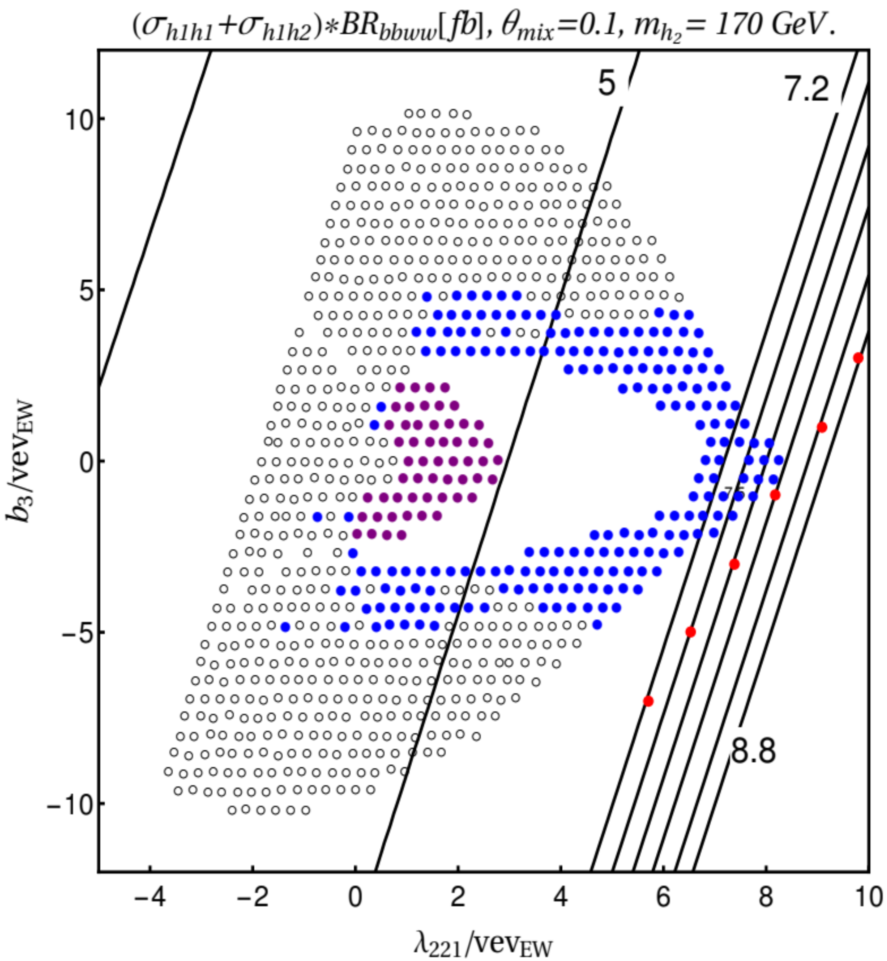
$$
\begin{aligned}
a_1 &= \frac{m_1^2 - m_2^2}{v_{EW}} \sin 2\theta, \\
b_2 + \frac{a_2}{2} v_{EW}^2 &= m_1^2 \sin^2\theta + m_2^2 \cos^2\theta, \\
\lambda &= \frac{m_1^2 \cos^2\theta + m_2^2 \sin^2\theta}{2 v_{EW}^2}.
\end{aligned}
$$

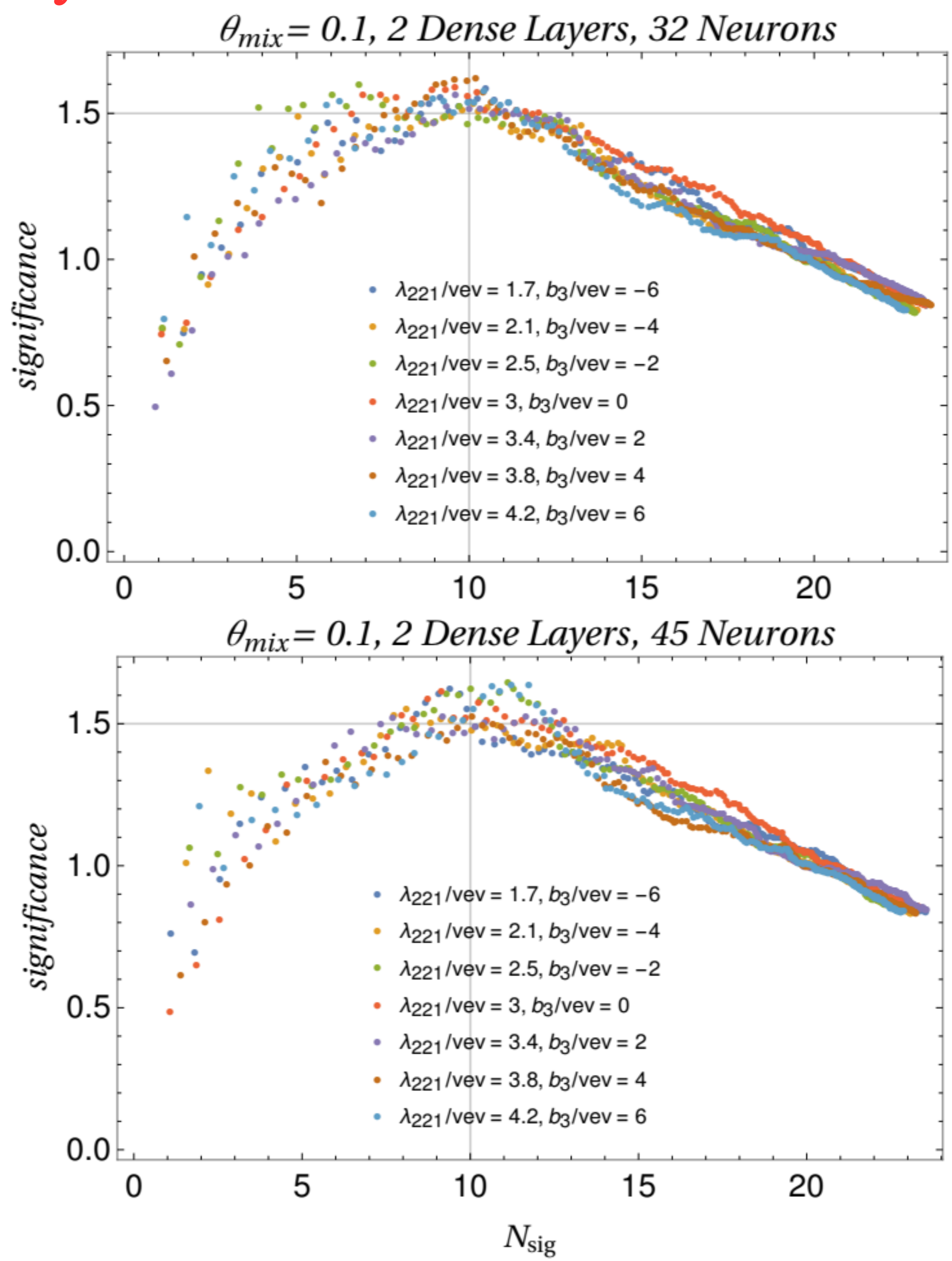
$$
\begin{aligned}
\lambda_{111} &= 2s^3 b_3 + \frac{3a_1}{2} sc^2 + 3a_2 s^2 cv + 6c^3 \lambda v, \\
\lambda_{211} &= 2s^2 c b_3 + \frac{a_1}{2} c(c^2 - 2s^2) + (2c^2 - s^2) sva_2 - 6\lambda sc^2 v \\
\lambda_{221} &= 2c^2 s b_3 + \frac{a_1}{2} s(s^2 - 2c^2) - (2s^2 - c^2) cva_2 + 6\lambda cs^2 v \\
\lambda_{222} &= 2c^3 b_3 + \frac{3a_1}{2} cs^2 - 3a_2 c^2 sv - 6s^3 \lambda v,
\end{aligned}
$$

Chen, Dawson, Lewis (arXiv:1410.5488)

Non-resonant Higgs Production in Scalar Extended Model at the LHC

Significance at High Luminosity





Alhazmi, Chen, Kim, Kong, Kozaczuk, Lewis (arXiv:19XX.XXXX)

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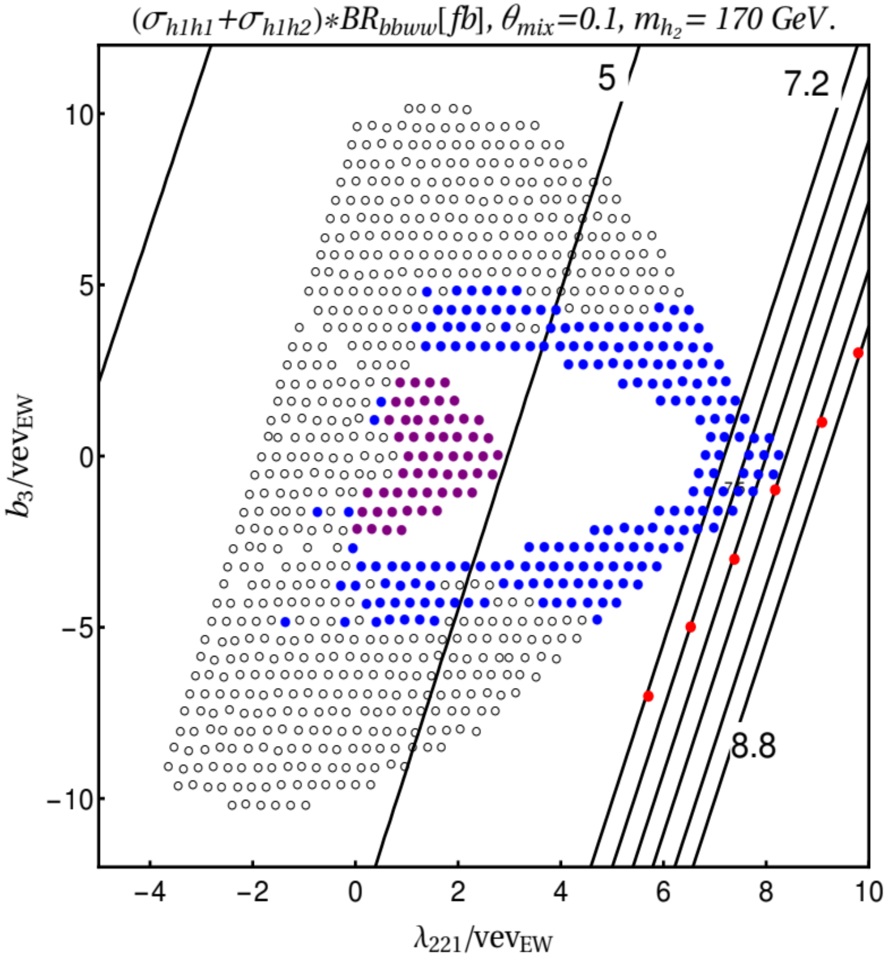

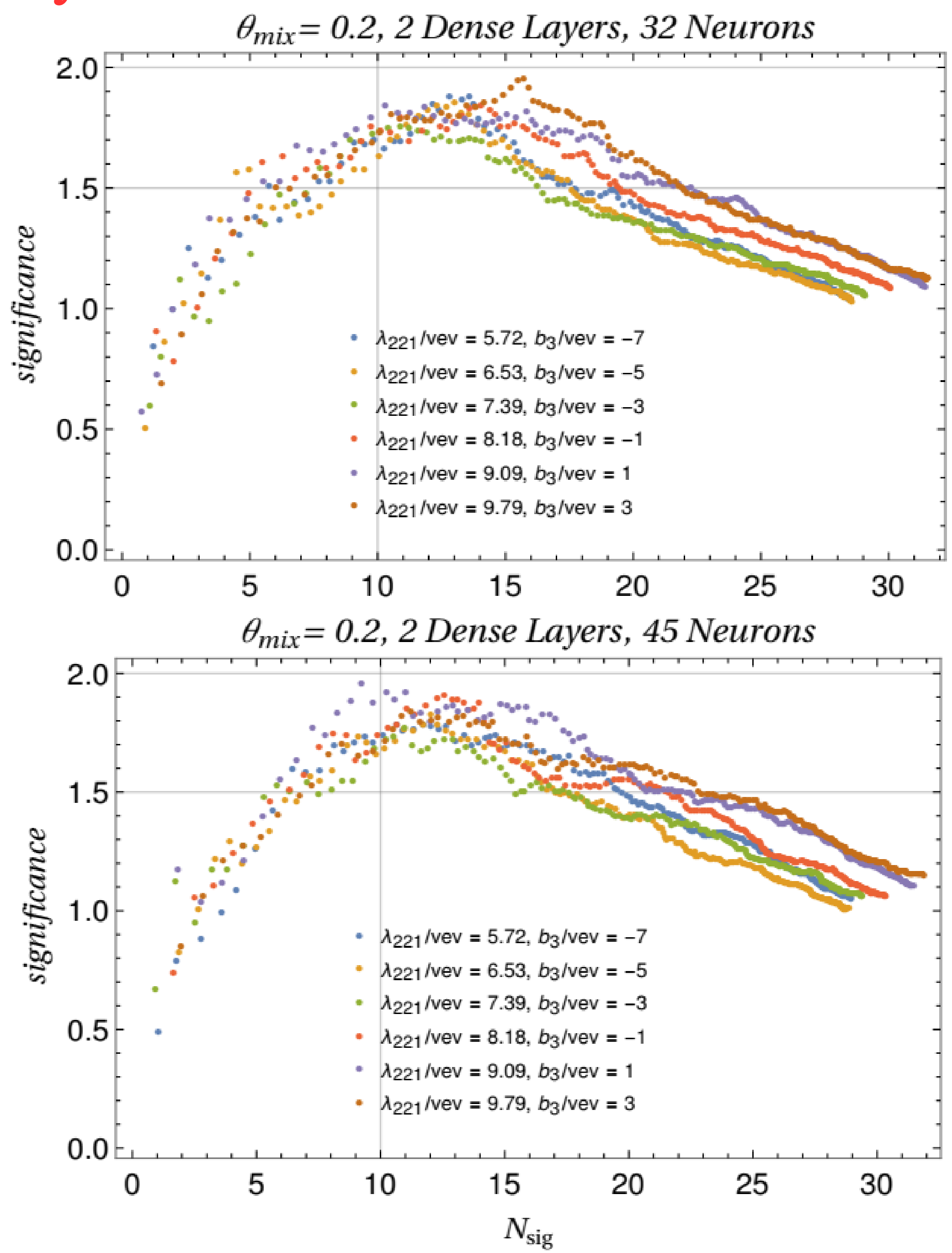

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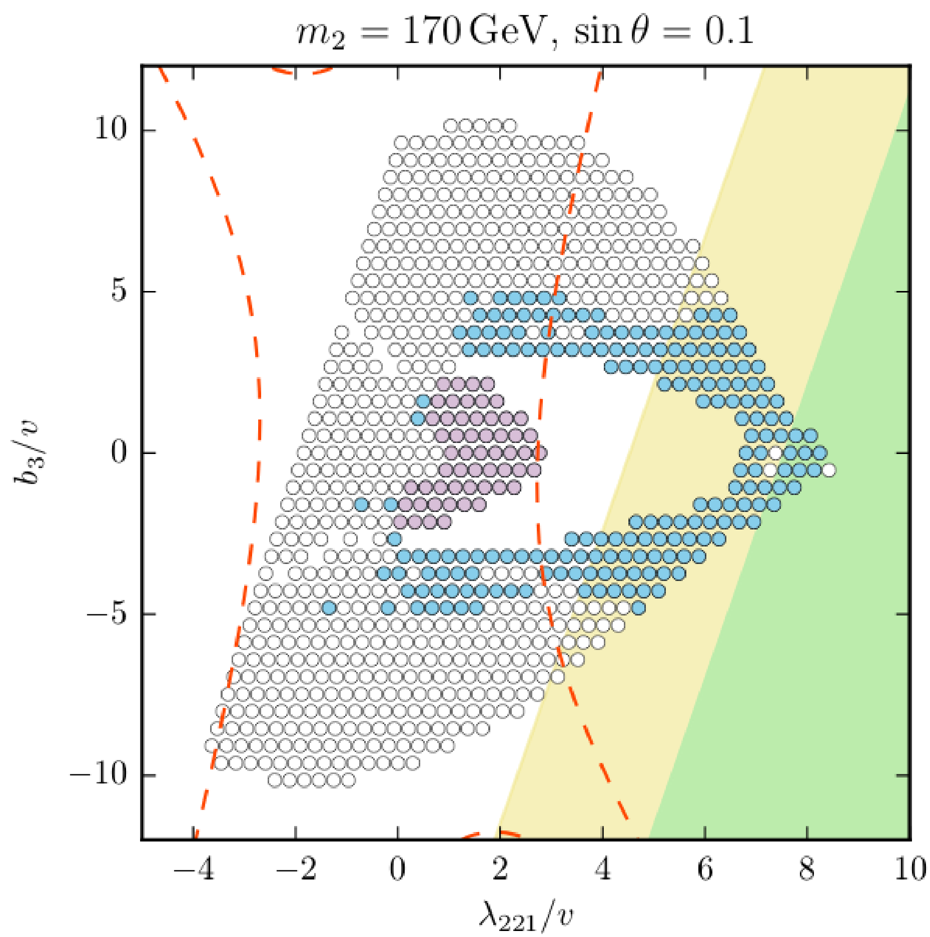
Significance at High Luminosity

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

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



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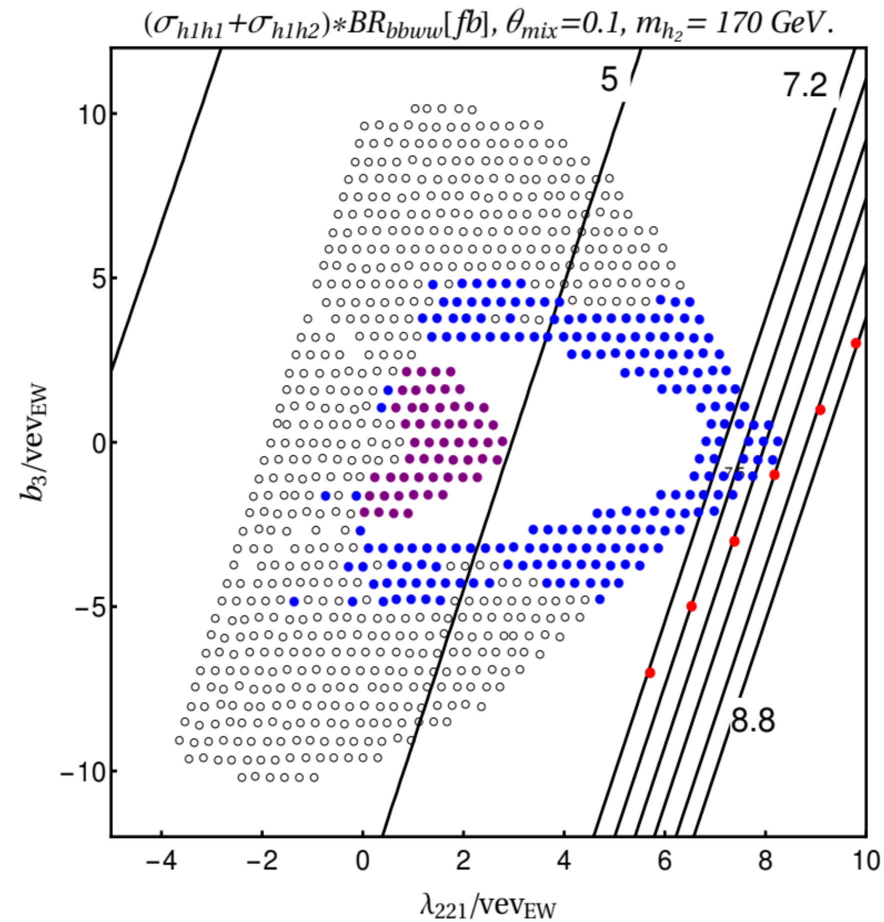

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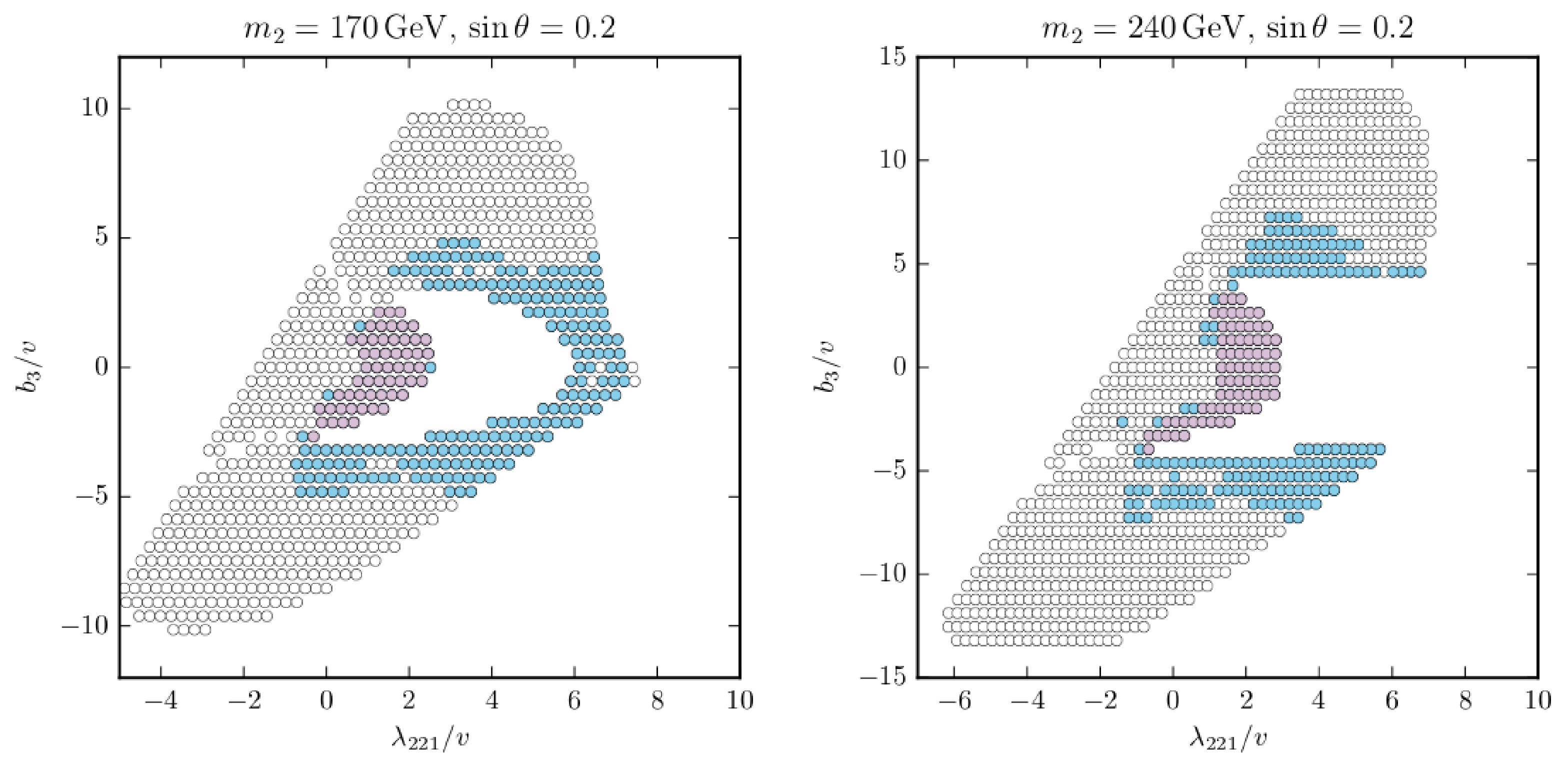


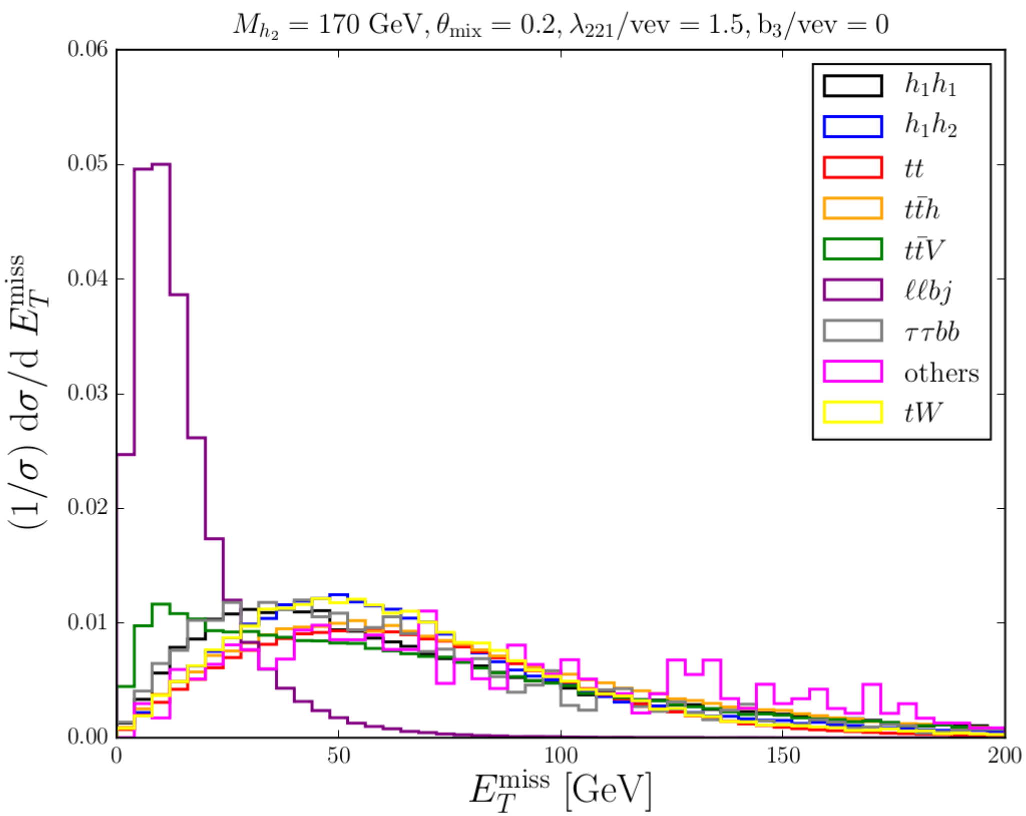
Figure 2. The parameter space of the model consistent with our requirements for $m_2 = 170$, 240 GeV and $\sin\theta = 0.05,\ 0.2$, now showing regions with a strong first-order electroweak phase transition. Results for both $\sin\theta = 0.05$ and 0.2 are shown. Blue points feature an EWPT with $\phi_h(T_c)/T_c \geq 1$ 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}.

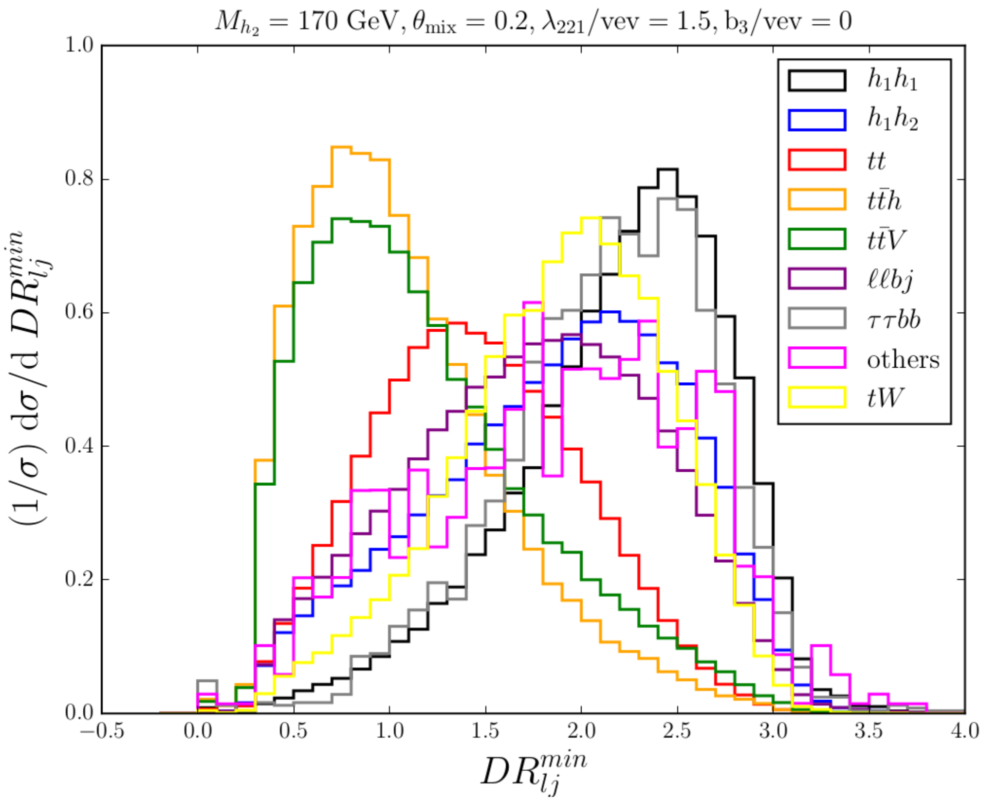
Chen, Kozaczuk, Lewis
(arXiv:1704:05844)

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

Non-resonant Higgs Production in Scalar Extended Model at the LHC





Alhazmi, Chen, Kim, Kong, Kozaczuk, Lewis (arXiv:19XX.XXXX)