

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

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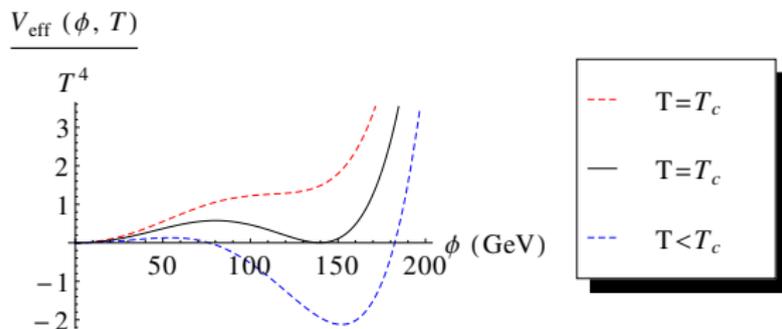
May 9, 2017
Phenomenology Symposium

Electroweak Baryogenesis



- Why is there more matter than anti-matter?
- Sakharov's three minimum requirements for baryogenesis:
 - 1 Baryon number violating process.
 - 2 C- and CP-violation.
 - 3 Out of equilibrium interactions.
 - Can be provided for by a strong first order EW phase transition (EWPT).

First Order EWPT



- In the SM the barrier between the two minima do not exist of $m_1 = 125$ GeV.
- New interactions at EW scale needed to generate barrier.
- For the constraint of a “strong” first order phase transition we use the criteria:

$$\phi_h(T_c)/T_c \gtrsim 1$$

where $\phi_h(T_c)$ is the non-zero Higgs vev at the critical temperature.

- Real singlet scalar can solve this problem.

Scalar Singlet

- Add a real scalar singlet S that is a SM gauge singlet.
- At the renormalizable level, only couplings to SM are through the Scalar potential:

$$V(\Phi, S) = V_\Phi(\Phi) + V_{\Phi S}(\Phi, S) + V_S(S)$$

$$V_\Phi(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

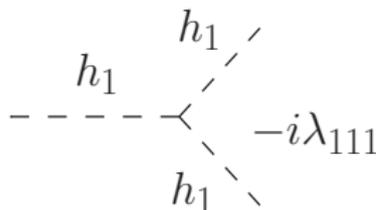
$$V_S(S) = b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

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

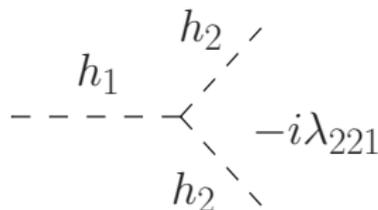
- Parameter counting:
 - 5 “physical” parameters:
 - Two mass eigenstates: $M_H > m_h = 125$ GeV.
 - Scalar mixing angle: $\sin \theta$
 - Two vevs: $\langle \Phi \rangle = v/\sqrt{2}$ $\langle S \rangle = x$.
- If $a_1 = b_1 = b_3 = 0$ potential has Z_2 symmetry: $S \rightarrow -S$

Relevant Feynman Rules For Production and Decay

- Trilinear couplings:

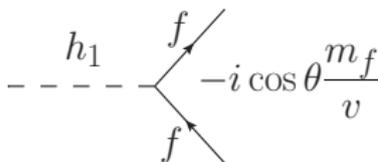


A Feynman diagram showing a dashed line labeled h_1 on the left entering a vertex. From this vertex, two dashed lines labeled h_1 exit to the right. The coupling constant is $-i\lambda_{111}$.

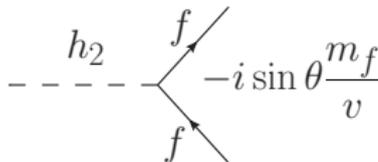


A Feynman diagram showing a dashed line labeled h_1 on the left entering a vertex. From this vertex, two dashed lines labeled h_2 exit to the right. The coupling constant is $-i\lambda_{221}$.

- Couplings to fermions:

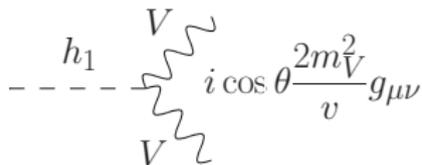


A Feynman diagram showing a dashed line labeled h_1 on the left entering a vertex. From this vertex, two solid lines labeled f exit to the right, one above and one below. The coupling constant is $-i \cos \theta \frac{m_f}{v}$.

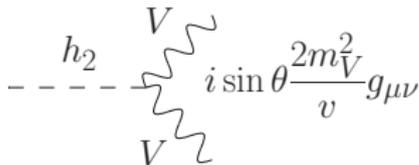


A Feynman diagram showing a dashed line labeled h_2 on the left entering a vertex. From this vertex, two solid lines labeled f exit to the right, one above and one below. The coupling constant is $-i \sin \theta \frac{m_f}{v}$.

- Couplings to gauge bosons:



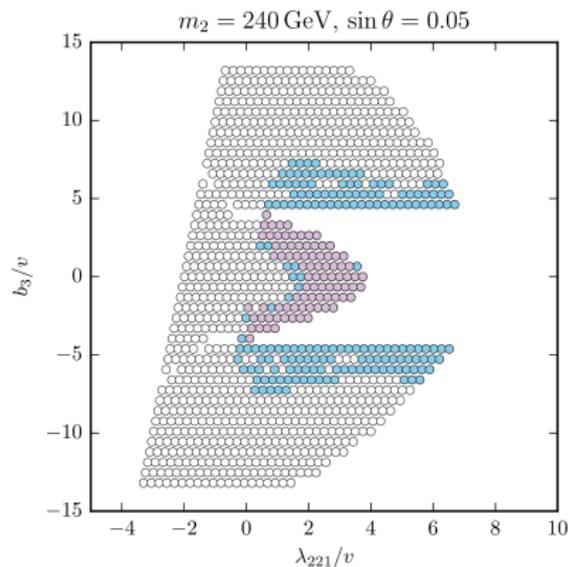
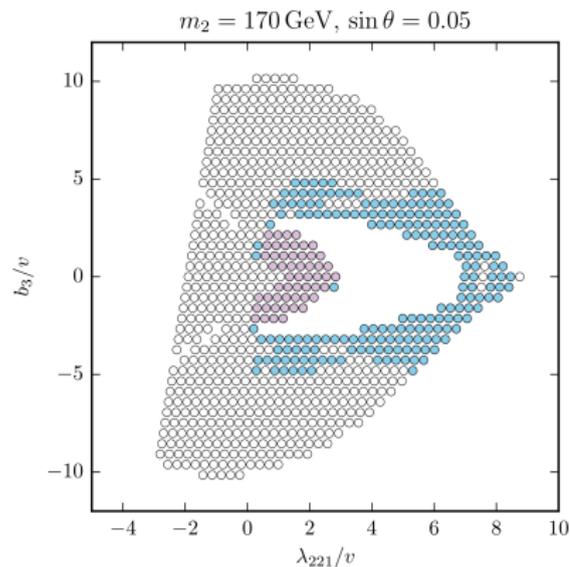
A Feynman diagram showing a dashed line labeled h_1 on the left entering a vertex. From this vertex, two wavy lines labeled V exit to the right, one above and one below. The coupling constant is $i \cos \theta \frac{2m_V^2}{v} g_{\mu\nu}$.



A Feynman diagram showing a dashed line labeled h_2 on the left entering a vertex. From this vertex, two wavy lines labeled V exit to the right, one above and one below. The coupling constant is $i \sin \theta \frac{2m_V^2}{v} g_{\mu\nu}$.

- Since h_2 couplings to fermions and gauge bosons proportional to SM coupling, it is produced through same mechanisms as SM Higgs boson.

Strong First Order EWPT



- White dots: Consistent with vacuum stability at tree level and the EWSB global minimum constraints at 1-loop.
- Blue and violet dots: Consistent with a strong first order EW phase transition.
- There is a correlation between the strength of the EW phase transition and λ_{221} .

λ_{221} and the phase transition

- Couplings between singlet and SM:

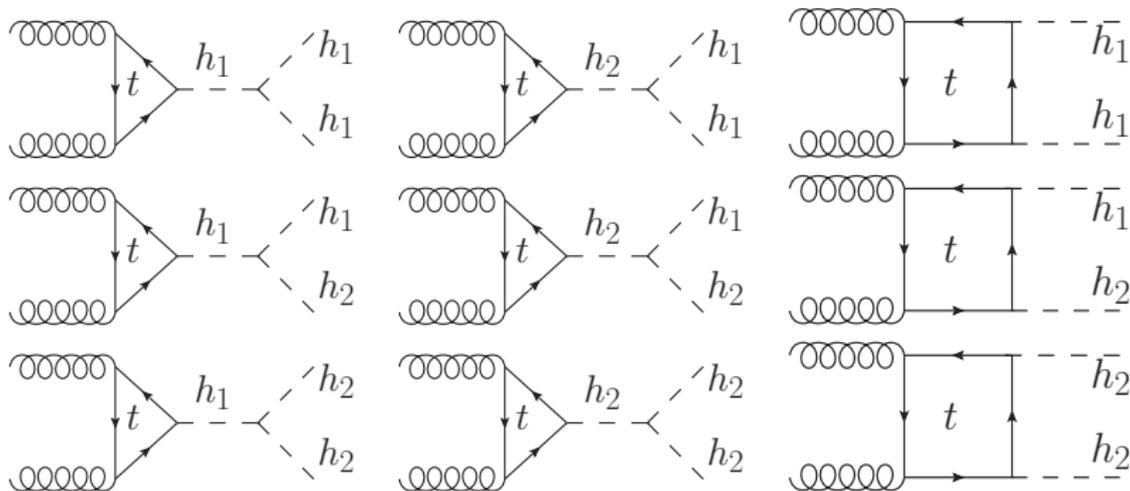
$$V_{\Phi S}(\Phi, S) = \frac{a_1}{2} \Phi^\dagger \Phi S + \frac{a_2}{2} \Phi^\dagger \Phi S^2 = \frac{a_1}{4} (h+v)^2 S + \frac{a_2}{4} (h+v)^2 S^2$$

- As $\theta \rightarrow 0$, only term that persists that couples SM to Singlet is a_2 .
 - This term drive the phase transition.
 - The trilinear coupling λ_{221} is directly proportional to a_2 .
- Trilinear scalar couplings as scalar mixing angle goes to zero:

$$\begin{aligned} h_1 - h_1 - h_1 & : \quad \lambda_{111} = \lambda_{111}^{SM} + O(\theta^2) \\ h_2 - h_1 - h_1 & : \quad \lambda_{211} = O(\theta) \\ h_2 - h_2 - h_1 & : \quad \lambda_{221} = a_2 v + O(\theta) \\ h_2 - h_2 - h_2 & : \quad \lambda_{222} = 2b_3 + O(\theta) \\ a_1 & = \quad O(\theta) \end{aligned}$$

- **BLUE: SM**, **RED: Singlet Only**, **VIOLET: Coupling between SM and Singlet**

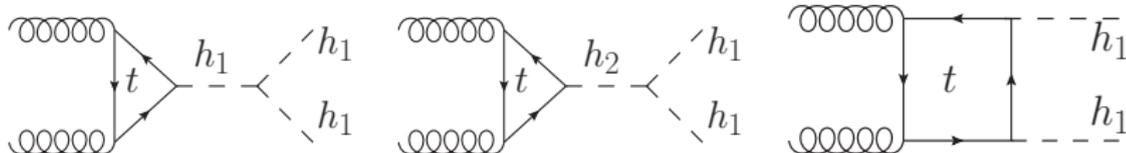
Double Scalar Production



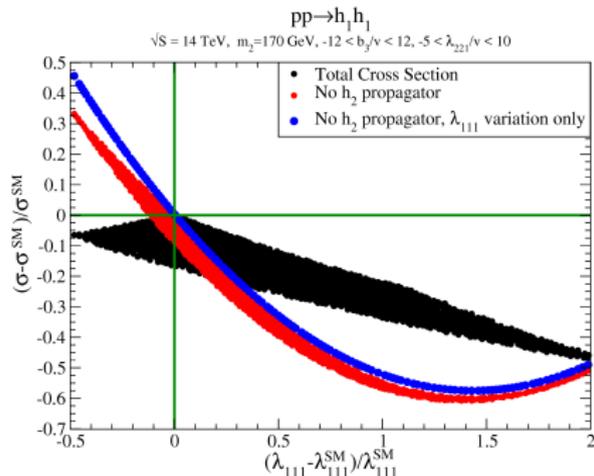
- $h_1 h_2$ and $h_2 h_2$ production are sensitive to λ_{221} .
 - However, h_2 -top coupling disappears as $\theta \rightarrow 0$.
 - Only h_1 s-channel production of $h_2 h_2$ survives.
 - $h_1 h_1$ production approaches SM limit as $\theta \rightarrow 0$.

Non-resonant $h_1 h_1$ production

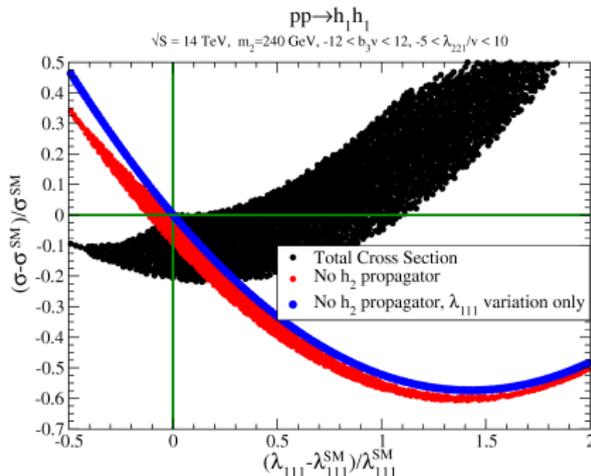
- The LHC is expected to limit the Higgs trilinear to within 30 – 50% the SM value at 1σ Curtin, Meade, Yu JHEP 1411 (2014) 127
 - Many theoretical studies with similar results Huang, Joglekar, Li, Wagner PRD93 (2016) 055049; Baglio *et al* JHEP 1304 (2013) 151; Barger, Everett, Jackson, Shaughnessy PLB728 (2014) 433; Barr, Dolan, Englert, Spannowsky PLB728 (2014) 308; Lu, Chang, Cheung, Lee JHEP 1508 (2015) 133
 - Projections from ATLAS and CMS make this seem optimistic ATLAS-PHYS-PUB-2014-019, CMS PAS FTR-15-002
 - Using distributions may help with sensitivity Huang, Joglekar, Li, Wagner PRD93 (2016) 055049; Kling, Plehn, Schichtel PRD95 (2017) 035026
- Many studies translate a total $h_1 h_1$ cross section measurement into a constraint on λ_{111} .
 - Assume that λ_{111} is the only parameter that varies.
 - In singlet model Yukawa couplings vary and there is an s -channel h_2 measurement.



$h_1 h_1$ non-resonant production



$m_2 = 170$ GeV



$m_2 = 240$ GeV

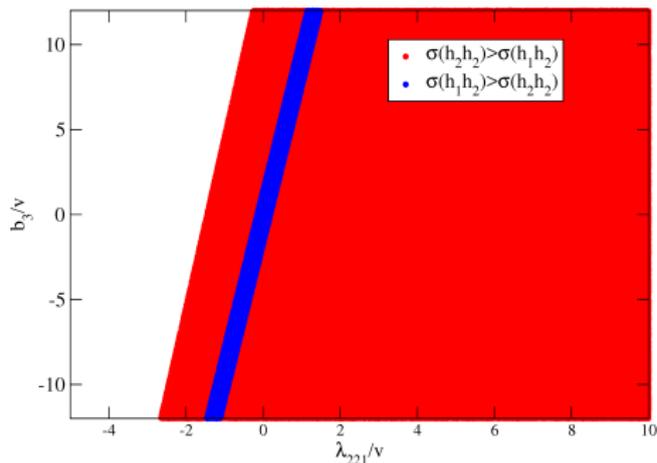
- With 300 fb^{-1} of data expect to limit $\sin\theta \lesssim 0.2$ [Buttazzo, Sala, Tesi JHEP 1511 \(2015\) 158](#); [Profumo, Ramsey-Musolf, Wainwright, Winslow PRD91 \(2015\) 035018](#); [Dawson et al arXiv:1310.8361](#)
- Scan over relevant parameter space for phase transition:

$$-5 < \lambda_{221}/v < 10 \quad -12 < b_3/v < 12 \quad |\sin\theta| < 0.2$$

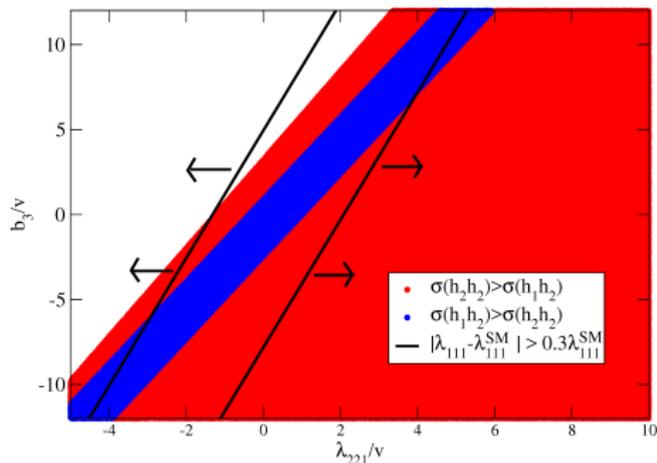
- Distributions can help [Huang, Joglekar, Li, Wagner PRD93 \(2016\) 055049](#); [Kling, Plehn, Schichtel PRD95 \(2017\) 035026](#).
- Never-the-less, will be optimistic and take $h_1 h_1$ limit to be $|\lambda_{111} - \lambda_{111}^{SM}| < 0.3 \lambda_{111}^{SM}$

Non-resonant $h_1 h_1$ production: $m_2 < 2m_1$

$m_2 = 170$ GeV, $\sin \theta = 0.05$, $\sqrt{S} = 14$ TeV



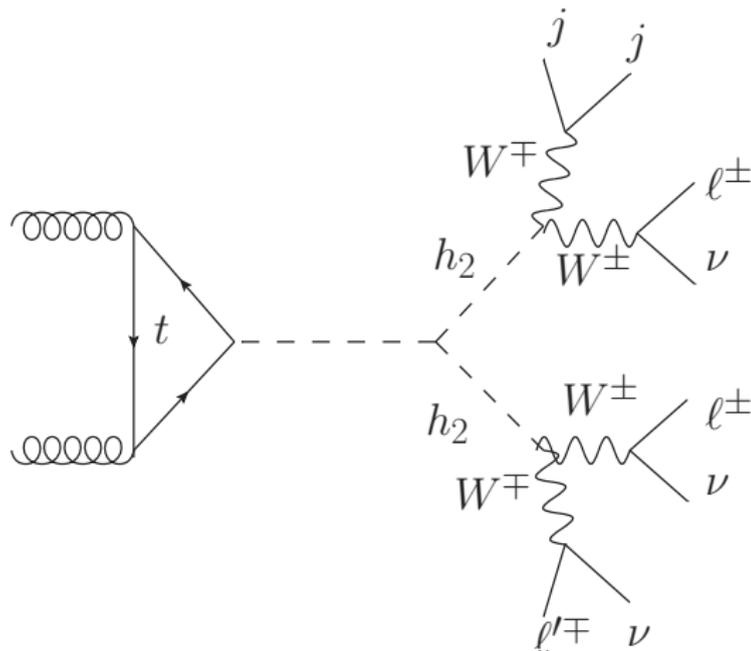
$m_2 = 170$ GeV, $\sin \theta = 0.2$, $\sqrt{S} = 14$ TeV



- $m_2 = 170$ GeV
- Use constraint on λ_{111} and then compare $h_1 h_2$ and $h_2 h_2$ production.
- As constraints on $\sin \theta$ get stronger, λ_{111} measurement become less sensitive to important regions of parameter space.

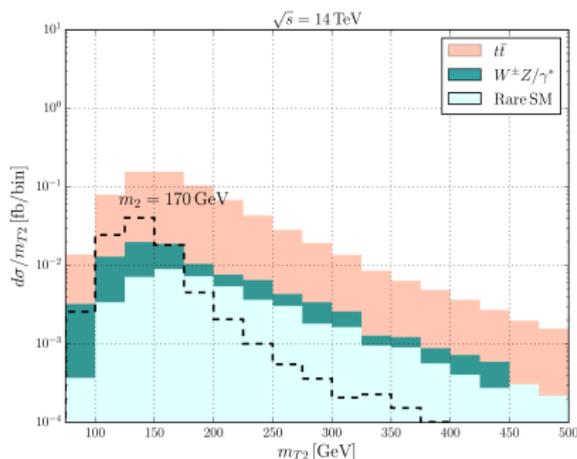
h_2h_2 production at LHC and future colliders

- Need a holistic approach to be sensitive to all of the parameter space.
- We focus on h_2h_2 production and decay into same-sign leptons [Baur, Plehn, Rainwater PRD67 \(2003\) 033003, PRL89 \(2002\) 151801](#):



Optimizing for signal

- $m_{T2} = \left(\min_{\vec{p}_1 + \vec{p}_2 = \vec{p}_T} \right) \left[\left(\max_{i=1,2} \right) \{ m_T^2(p_T, \vec{p}_i) \} \right]$
 - Using transverse mass: $m_T^2(p_T, \vec{p}_i) = (E_T + E_i)^2 - (\vec{p}_T + \vec{p}_i)^2$
 - Combinatorics:
 - Two opposite sign leptons, $\ell^\pm \ell'^\mp$ come from one $h_2 \rightarrow WW$
 - 2 jets and other lepton ℓ^\pm coming from other $h_2 \rightarrow WW$.
 - Have two ℓ^\pm , have two ways to group with jets.
 - Generalize and use $m_{T2} = \text{Min}(m_{T2}^{1,2})$

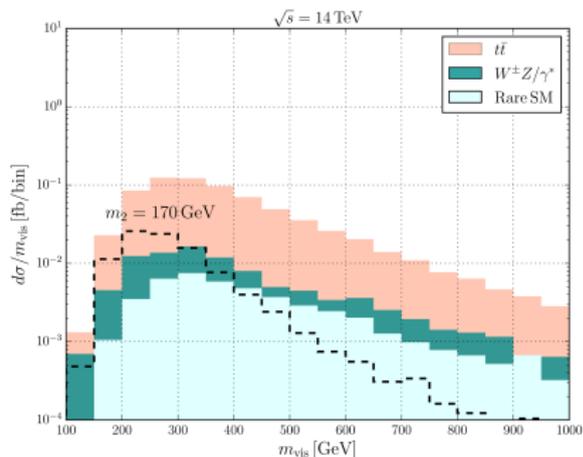
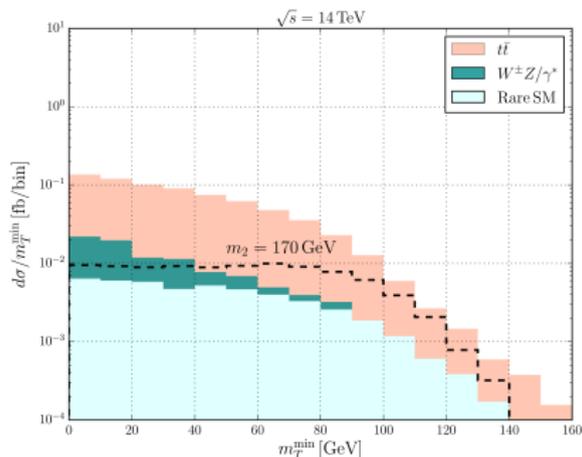


Signal vs. Background

- Also define [CMS EPJC76 \(2016\) 439](#)

$$m_T^{\min} = \text{Min}(m_T(\ell_1, \cancel{E}_T), m_T(\ell_2, \cancel{E}_T), m_T(\ell_3, \cancel{E}_T))$$

- Finally use [Baur, Plehn, Rainwater PRD67 \(2003\) 033003](#) $m_{\text{vis}}^2 = \left| \sum_i p_i^{\text{vis}} \right|^2$



Optimizing for Signal

- 14 TeV and $m_2 = 170$ GeV:

- $p_T^{j_1, j_2} > 30$ GeV, $p_T^{\ell_1, \ell_2} > 25$ GeV
- $p_T^{\ell_3} > 20$ GeV, $\cancel{E}_T > 30$ GeV
- $m_{T2} < 150$ GeV, $m_{vis} < 600$ GeV, $m_T^{min} > 40$ GeV

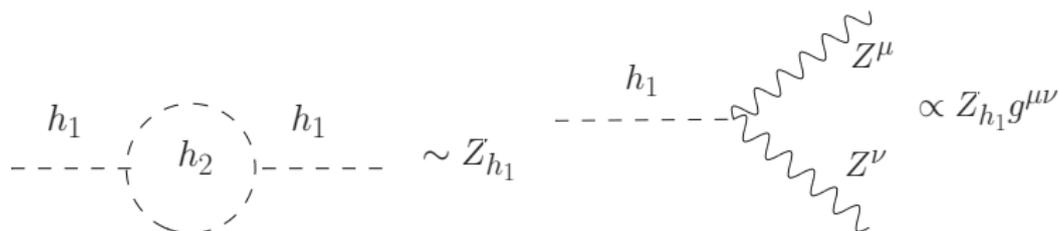
- 100 TeV and $m_2 = 170$ GeV:

- $p_T^{j_1, j_2} > 30$ GeV, $p_T^{\ell_1, \ell_2} > 25$ GeV
- $p_T^{\ell_3} > 20$ GeV, $\cancel{E}_T > 50$ GeV
- $m_{T2} < 150$ GeV, $m_{vis} < 600$ GeV, $m_T^{min} > 60$ GeV

- 100 TeV and $m_2 = 240$ GeV:

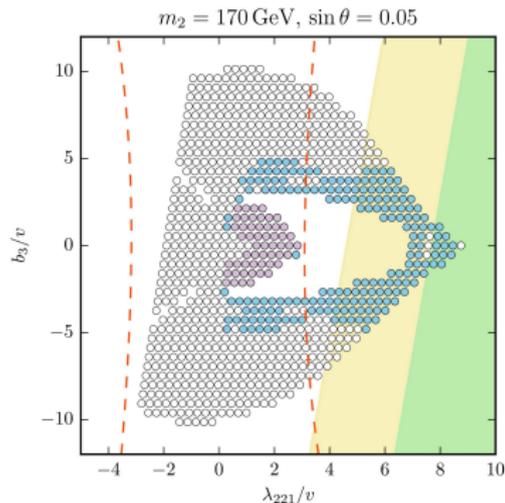
- $p_T^{j_1, j_2} > 50$ GeV, $p_T^{\ell_1, \ell_2} > 50$ GeV
- $p_T^{\ell_3} > 20$ GeV, $\cancel{E}_T > 50$ GeV
- $m_{T2} < 250$ GeV, $m_{vis} < 600$ GeV, $m_T^{min} > 0$ GeV (no requirement)

Additional probes

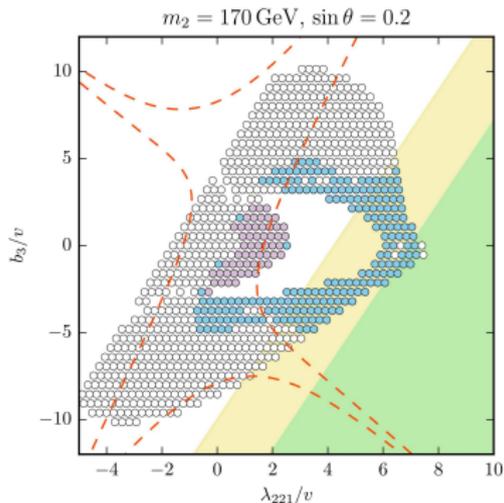


- Singlet model can also alter $Z - h$ coupling via wavefunction renormalization [Craig, Englert, McCullough PRL111 \(2013\) 121803](#).
 - Higgs wavefunction renormalization is multiplicative, so new physics effects will shift all of its couplings.
 - Take small angle limit up to $O(\theta^2)$ [Huang, Long, Wang PRD94 \(2016\) 075008](#); [Chen, Kozaczuk, IL arXiv:1704.05844](#)
 - Future lepton colliders are expected to measure the $Z - h$ coupling to within 0.5%.
- Higgs trilinear coupling with 30% of the SM value.

LHC Sensitivity at 3 ab^{-1}



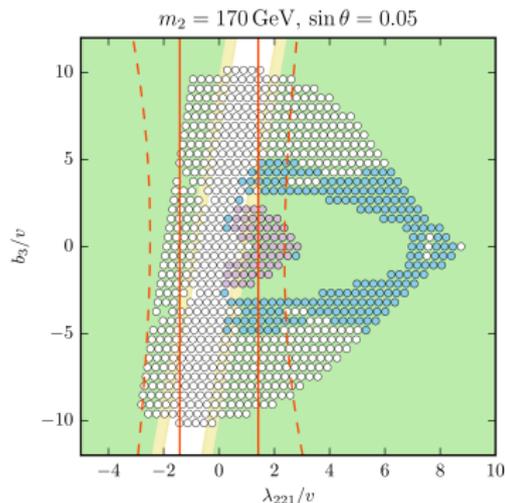
$\sin \theta = 0.05$



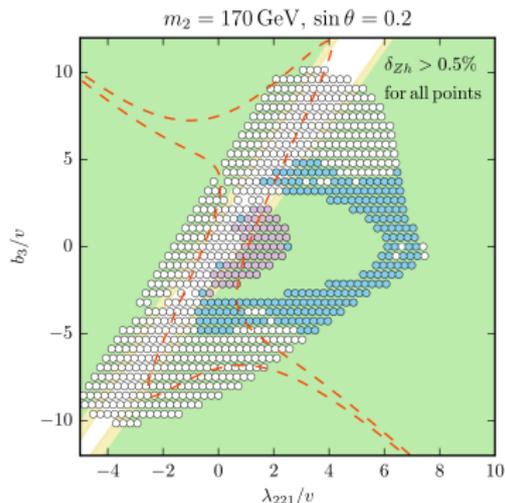
$\sin \theta = 0.2$

- Green: $S/\sqrt{S+B} > 5$ and $S/B > 0.1$.
- Yellow: $S/\sqrt{S+B} > 2$ and $S/B > 0.1$
- Outside of dashed lines: $h_1 - h_1 - h_1$ self-coupling measurement to 30%.

100 TeV Sensitivity at 30 ab^{-1} : $m_2 = 170 \text{ GeV}$



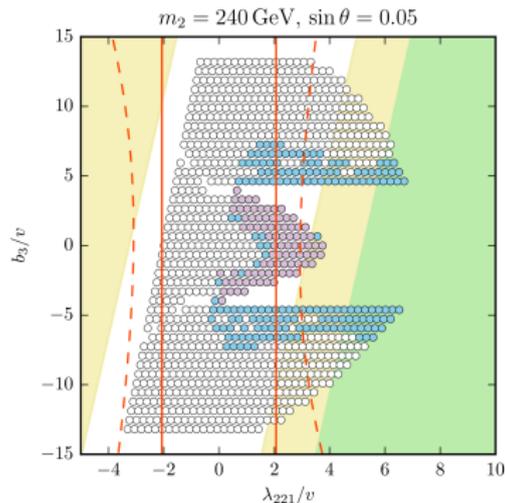
$\sin \theta = 0.05$



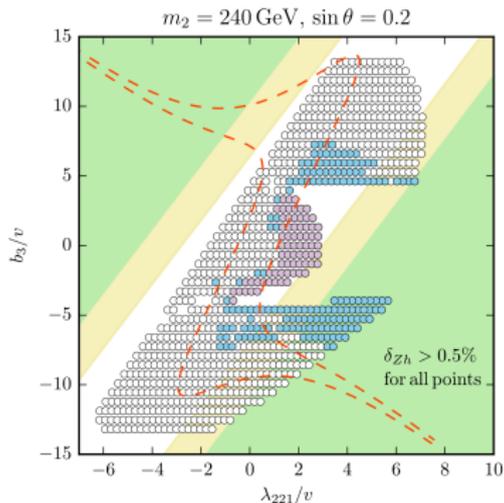
$\sin \theta = 0.2$

- Green: $S/\sqrt{S+B} > 5$ and $S/B > 0.05$.
- Yellow: $S/\sqrt{S+B} > 2$ and $S/B > 0.05$
- Outside dashed lines: $h_1 - h_1 - h_1$ self-coupling measurement to 30%.
- Outside solid line: $Z - h$ measurement at future electron colliders sensitive.

100 TeV Sensitivity at 30 ab^{-1} : $m_2 = 240 \text{ GeV}$



$\sin \theta = 0.05$



$\sin \theta = 0.2$

- Green: $S/\sqrt{S+B} > 5$ and $S/B > 0.05$.
- Yellow: $S/\sqrt{S+B} > 2$ and $S/B > 0.05$
- Outside dashed lines: $h_1 - h_1 - h_1$ self-coupling measurement to 30%.
- Outside solid line: $Z - h$ measurement at future electron colliders sensitive.

Conclusions

- Singlet model can provide a strong first order phase transition.
 - Important to consider all double scalar final states, h_1h_1 , h_1h_2 , and h_2h_2 , to fully cover relevant parameter space.
 - Performed collider study for in region in which resonant double Higgs production is not possible: $m_2 = 170$ GeV and $m_2 = 240$ GeV.
 - Found that while LHC has little sensitivity, a 100 TeV would be able to probe most of the parameter region relevant for a strong first order EW phase transition.