Non-resonant Collider Signatures of the Electroweak Phase Transition

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Overview

There are exceptions to the standard approach of "just measuring the Higgs self-coupling" to probe the electroweak phase transition (EWPT)

Case study: singlet models (typically the stealthiest scenarios predicting a strong first-order PT)

-New light degrees of freedom can impact the EWPT without significant deviations in the Higgs self-coupling (see e.g. Profumo et al, 2014)

-New diagrams impact the extraction of the *hhh* coupling from double Higgs production

-Instead, pair production of the new states can provide powerful **direct** probe of the EWPT at colliders

Singlet Models

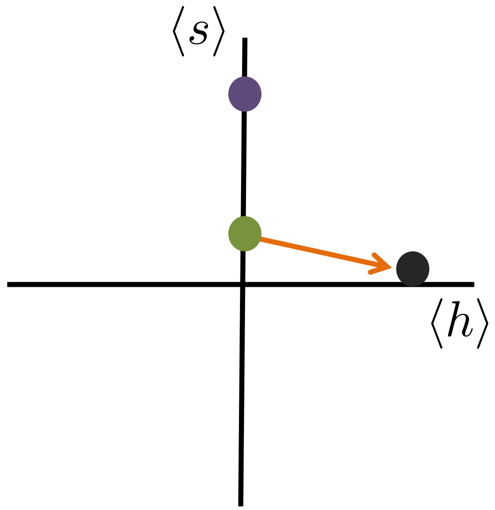
Consider real singlet scalar field coupling to the Higgs

$$V_0(H,S) = -\,\mu^2\left|H\right|^2 + \lambda\left|H\right|^4 + \frac{1}{2}a_1\left|H\right|^2 S + \frac{1}{2}a_2\left|H\right|^2 S^2$$
$$+\, b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4$$

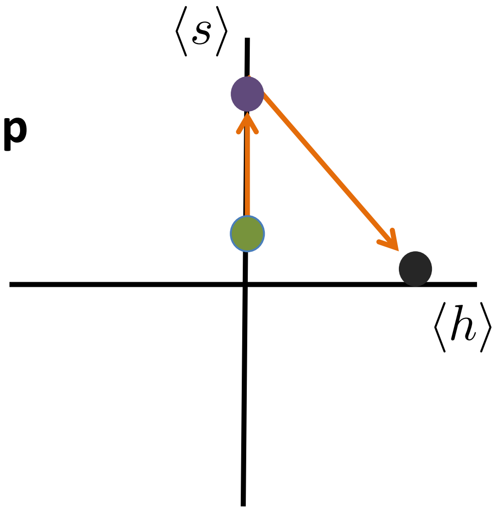
The EWPT can be strongly first order and proceed in one or two steps

See e.g. Profumo et al, 2007; Espinosa et al, 2011; Curtin et al, 2014, Profumo et al, 2014; Jiang et al, 2015; Xiao + Yu, 2016

1-step



2-step



Singlet Models

How might we test the EWPT in such scenarios? EWPT governed by scalar potential

$$V_0(H,S) = -\,\mu^2 \left|H\right|^2 + \lambda \left|H\right|^4 + \frac{1}{2}a_1 \left|H\right|^2 S + \frac{1}{2}a_2 \left|H\right|^2 S^2 + b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4$$

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\varphi^+ \\ \phi_h + h + i\varphi^0 \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}}\left(\phi_s + s\right) \xrightarrow{\text{EWSB}} \begin{aligned} h_1 &= h\cos\theta + s\sin\theta \\ h_2 &= -h\sin\theta + s\cos\theta \end{aligned}$$

At T=0, couplings dictate interactions between scalar mass eigenstates

$$V_{\text{cubic}} = \frac{1}{6}\lambda_{111}h_1^3 + \frac{1}{2}\lambda_{211}h_2h_1^2 + \frac{1}{2}\lambda_{221}h_2^2h_1 + \frac{1}{6}\lambda_{222}h_2^3$$

Pair production of combinations of the two scalars encode information about the couplings relevant for the EWPT. **How well can the FCC-hh do?**

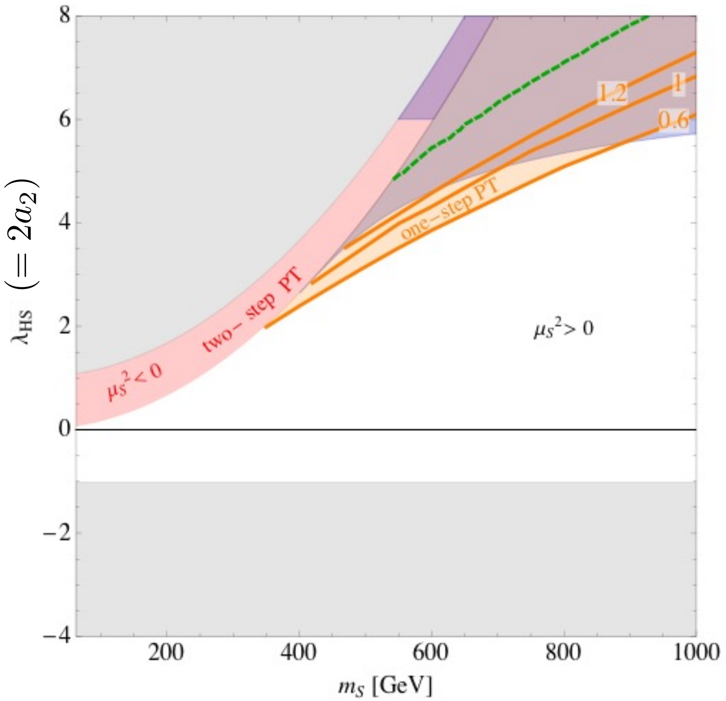
Z_2 Limit

First, consider the model with a Z_2 symmetry Curtin, Meade, Yu, 2014

See also Craig et al, 2014

$$V_0(H,S) = -\mu^2|H|^2 + \lambda|H|^4 + \cancel{\frac{1}{2}a_1|H|^2 S} + \boxed{\frac{1}{2}a_2|H|^2 S^2}$$
$$+ \cancel{b_1 S} + \frac{1}{2}b_2 S^2 + \cancel{\frac{1}{3}b_3 S^3} + \frac{1}{4}b_4 S^4$$

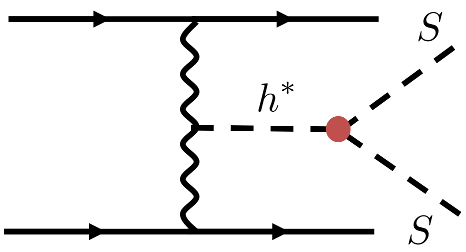
Coupling relevant for the EWPT



Strong first-order EWPT implies lower bound on h^2s^2 coupling. Both the *FCC-ee* and *FCC-hh* will be crucial in probing this coupling

FCC-ee: indirect probe via Zh production (see talk by Andrew Long)

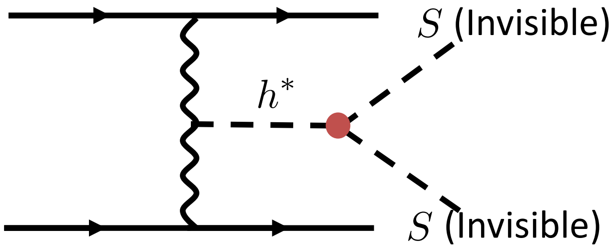
FCC-hh: direct probe via **p p → h* (+X) → s s (+X)**



Z_2 Limit

Non-resonant SS production at the FCC-hh

Curtin, Meade, Yu, 2014

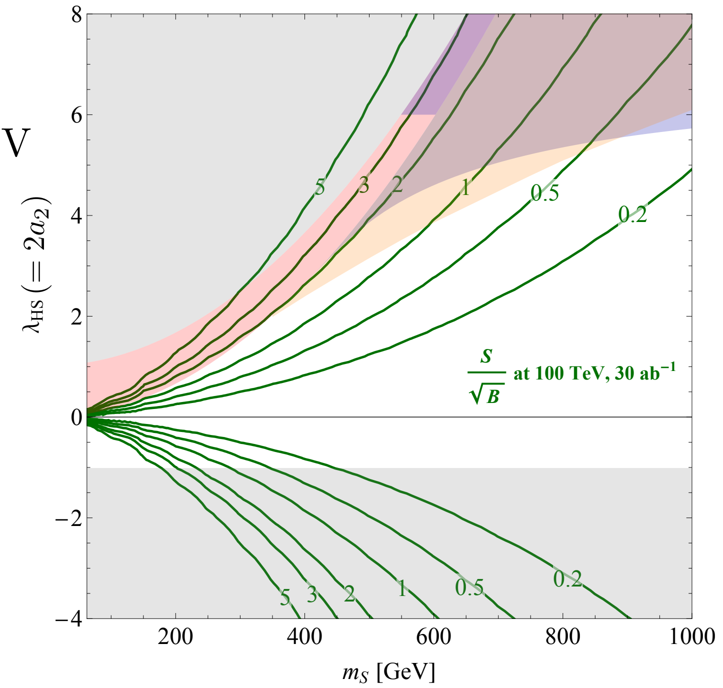


Search requirements:

- exactly two jets with $p^T_{j_{1,2}} > 40$ GeV, $|\eta_{j_{1,2}}| < 5$
- $\not{E}_T > 150$ GeV,
- $\Delta\eta_{jj} = |\eta_{j_1} - \eta_{j_2}| > 3.5$ and $|\eta_{j_{1,2}}| > 1.8$,
- $M_{jj} > 800$ GeV.
- reject events with leptons satisfying $|\eta| < 2.5$ and $p_T > 15$ GeV

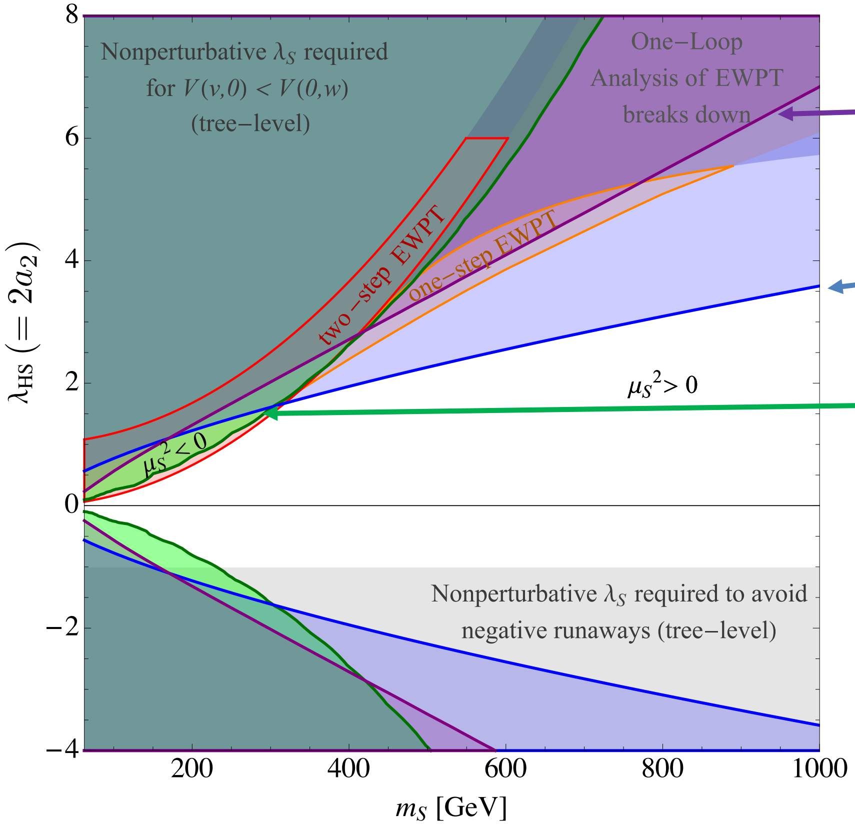
Main background: $(Z \to \nu\nu)+jj$ (Drell-Yan + VBF)

S/B typically very small; large sensitivity to systematics. Data-driven background estimation possible via $(Z \to \ell\ell)jj$ with $p^T_{\ell\ell} \to \not{E}_T$



Z_2 Limit

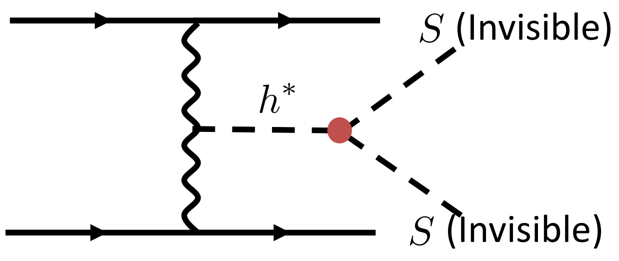
The FCC-hh can probe the EWPT in this “nightmare scenario” via non-resonant singlet pair production. Complementary to Higgs self-coupling and Zh measurements Curtin, Meade, Yu, 2014



$e^+e^- \rightarrow$ Zh cross-section deviation > 0.6%

Higgs self-coupling deviation > 10%

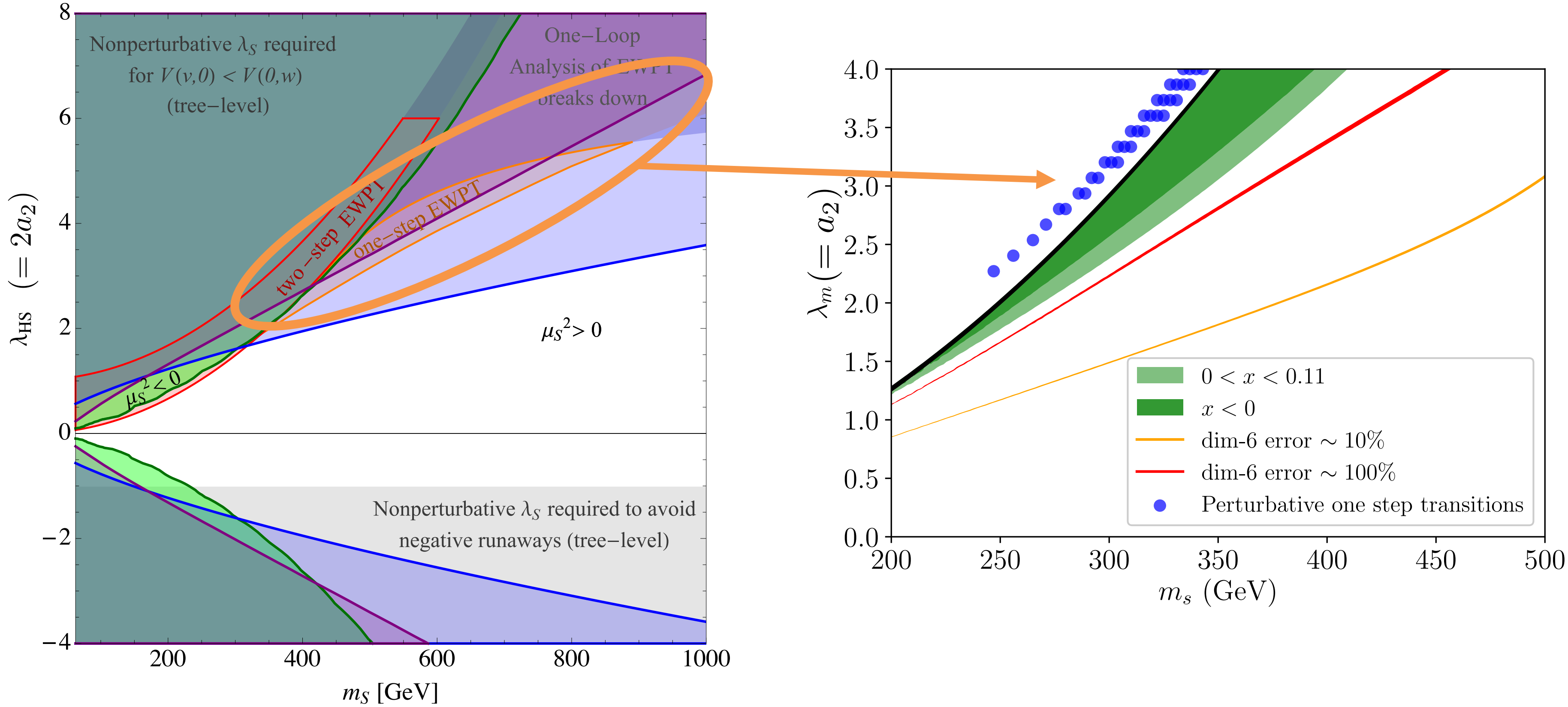
Non-res ss production (30 ab^{-1})



Z_2 Limit: Beyond Perturbation Theory

Important to cross-check against non-perturbative results

JK, Tenkanen, Weir, 1802.xxxx



Non-perturbative results agree qualitatively: lower bound on *ss* production from requiring first-order EWPT

More general singlets

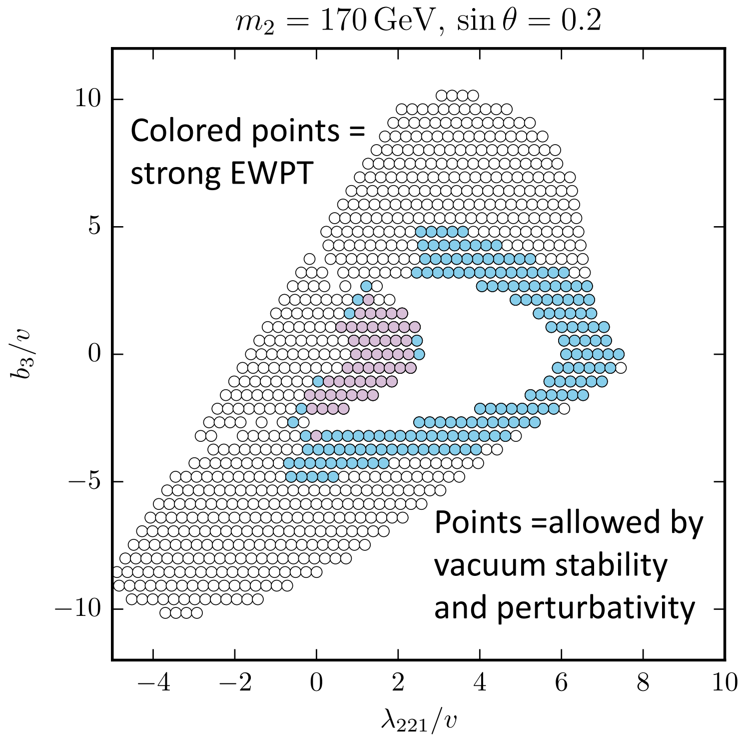
Similar considerations in the more general case Chen, JK, Lewis, 2017

$$V_0(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2}a_1 |H|^2 S + \frac{1}{2}a_2 |H|^2 S^2 + b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4$$

EWSB →

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

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



Colored points = strong EWPT

Points =allowed by vacuum stability and perturbativity

$$V_{\rm cubic} = \frac{1}{6}\lambda_{111}h_1^3 + \frac{1}{2}\lambda_{211}h_2 h_1^2 + \frac{1}{2}\lambda_{221}h_2^2 h_1 + \frac{1}{6}\lambda_{222}h_2^3$$

Strong EWPT correlated with size of Higgs coupling to two singlet-like scalars

Expected in small-mixing limit:

$h_1 \sim h$, $h_2 \sim s$ (assuming singlet heavier than Higgs)

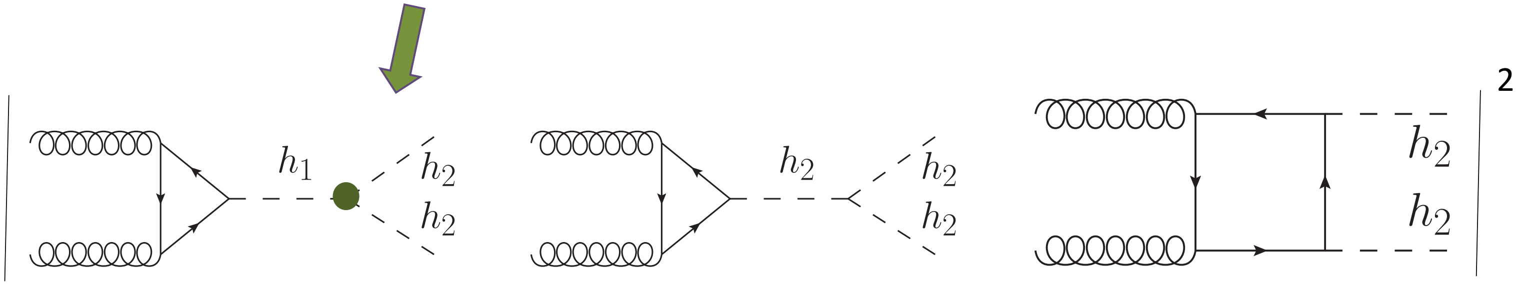
→ $\lambda_{221} \sim a_2/2v$ generally required to be non-negligible

More general singlets

Expect **singlet-like pair production** to be correlated with the strength of the EWPT (modulo interference effects) Chen, JK, Lewis, 2017

$$V_{\rm cubic} = \frac{\lambda_{111}}{3!}h_1^3 + \frac{\lambda_{211}}{2!}h_2 h_1^2 + \boxed{\frac{\lambda_{221}}{2!}h_2^2 h_1} + \frac{\lambda_{222}}{3!}h_2^3$$

$$\sigma_{h_2h_2} \propto$$



Now the singlet-like state decays visibly. Various final states, but consider trileptons

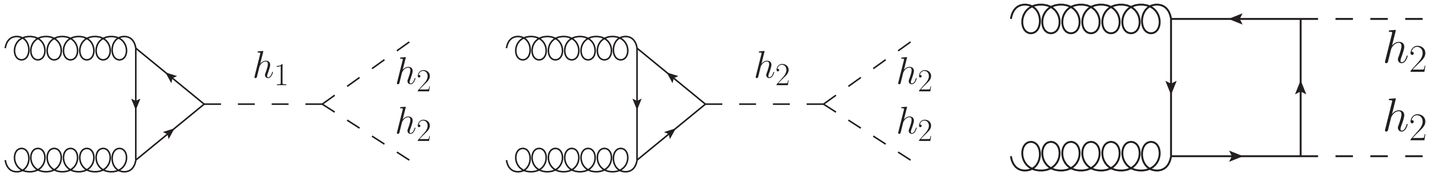
$$3\ell 3\nu 2j,\ {\rm BR}(h_2 \to WW \to \ell\nu 2j, h_2 \to WW \to 2\ell 2\nu) = 32.41 \times 10^{-4}$$

Familiar channel from pre-Higgs discovery papers

(e.g. Baur, Plehn, and Rainwater, 2002)

More general singlets

Non-resonant singlet-like pair production at the FCC-hh Chen, JK, Lewis, 2017



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

Dominant backgrounds: $t\bar{t},\ WZ,$ rare SM processes (assume fake rate $\epsilon_{j\to\ell} = 10^{-3}$)

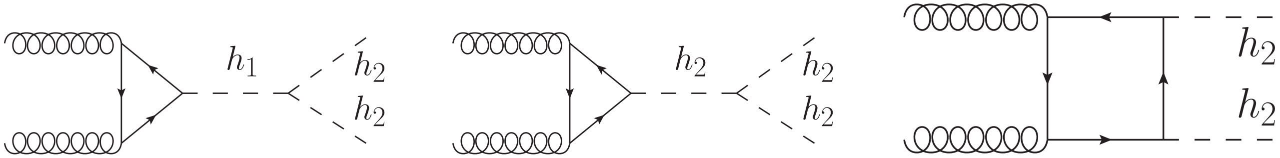
Baseline selection:

- -3 identified leptons with no OSSF pair
- -At least one jet pair reconstructing to the W mass
- -*MET*>30 GeV
- -b-jet, hadronic tau vetoes

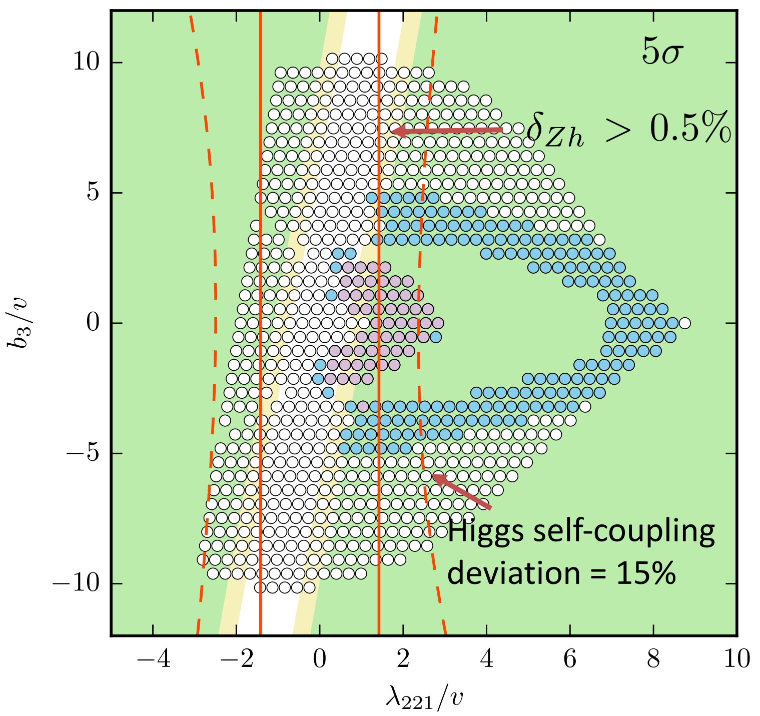
Additional cuts on m_{T2} , $m_T^{\rm min} \equiv {\rm Min}\{M_T(\ell_1, E_T), M_T(\ell_2, E_T), M_T(\ell_3, E_T)\}$ and total invariant mass

FCC-hh Projections (30 ab^{-1})

Non-resonant singlet-like pair production at the FCC-hh can probe much of the EWPT-favored region via trileptons. Complementarity with Zh, Higgs self-coupling measurements, and resonant di-Higgs Chen, JK, Lewis, 2017



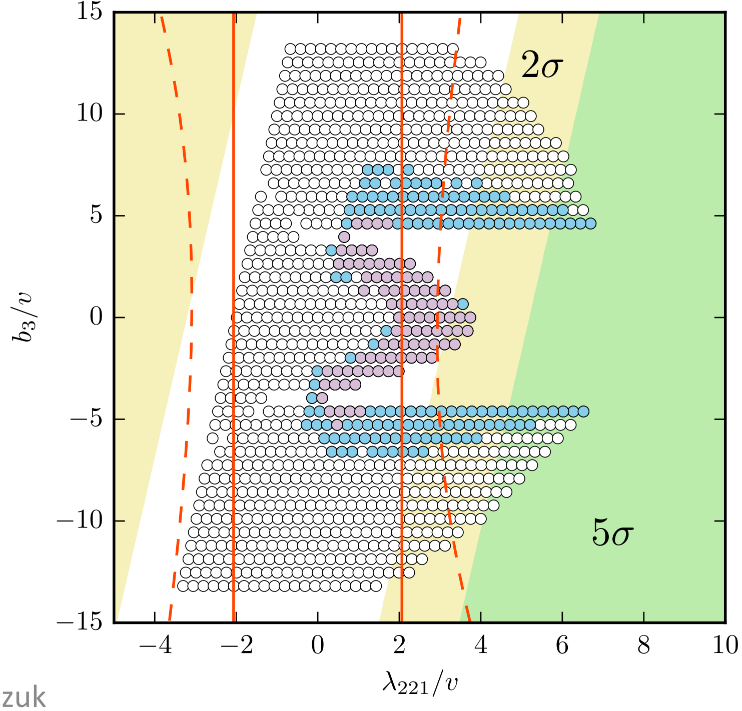
$m_2 = 170\,\mathrm{GeV},\ \sin\theta = 0.05$



$\delta_{Zh} > 0.5\%$

Higgs self-coupling deviation = 15%

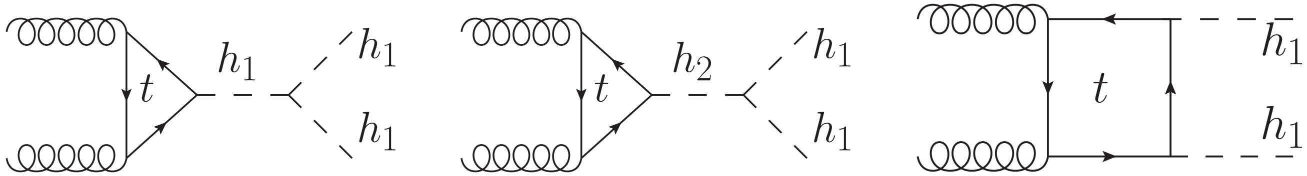
$m_2 = 240\,\mathrm{GeV},\ \sin\theta = 0.05$

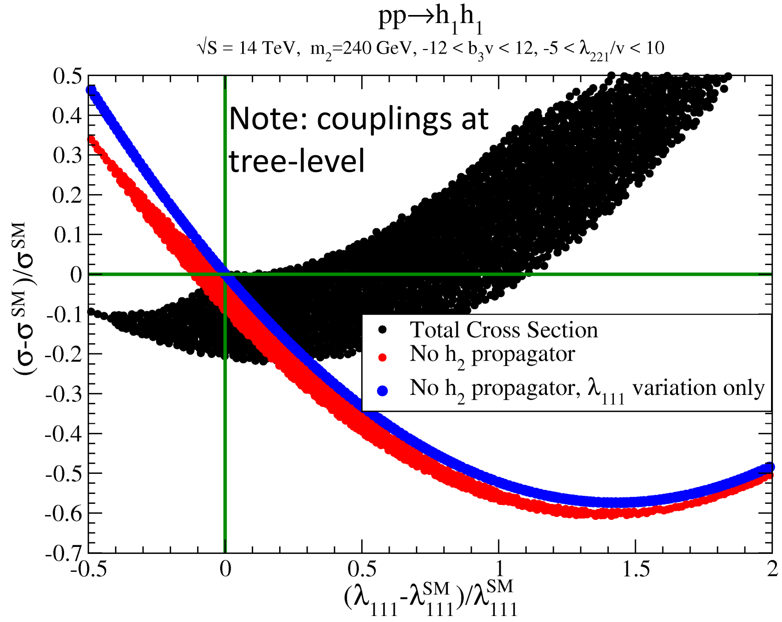


Higgs self-coupling revisited

Be careful… in models with additional light scalars, the usual correlation between σ_{hh} and the Higgs self-coupling can break down Chen, JK, Lewis, 2017

Higgs coupling to top quark altered New diagram! Higgs coupling to top quark altered



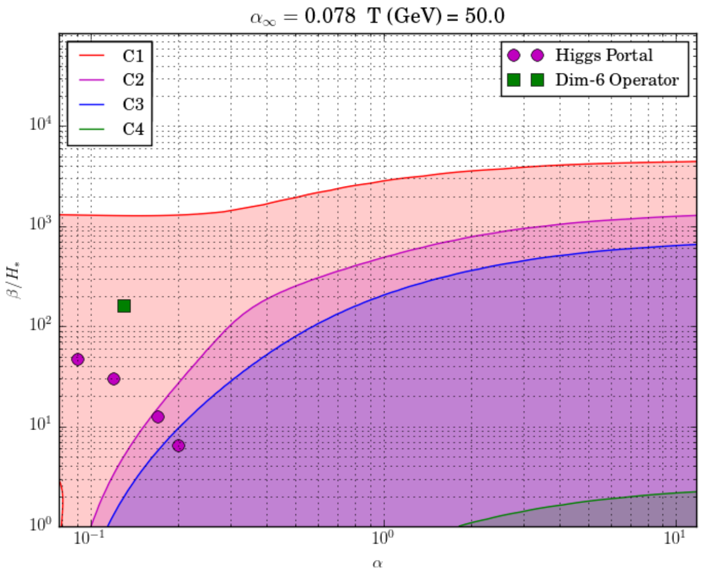


Note: couplings at tree-level

How well can the FCC actually determine the Higgs self-coupling in this case? Information about the *hhs* coupling? Can use information encoded in distributions… Study in progress with Ian Lewis

Complementarity with LISA

If a signal is observed, LISA could give direct evidence of a strong first-order phase transition (see also Andrew Long's talk)



Caprini et al, 2015

(see also Huang, Long, Wang, 2016)

Status of LISA: chosen by the ESA as the Cosmic Vision L3 experiment. Very active community moving forward with design and science studies. Launch in mid 2030's.

Configuration ~finalized. Stay tuned for update from Cosmology Working Group regarding sensitivity to phase transitions given recent developments

Future directions

-Other final states/larger mass range for double singlet production

-Constraints from Higgs decays in the low-mass region?

-Prospects for observing *sh* production and impact on EWPT-viable regions

-Impact of additional contributions to SM-like hh production on expected sensitivities to the Higgs self-coupling

-Improvement of theoretical uncertainties on phase transition calculation

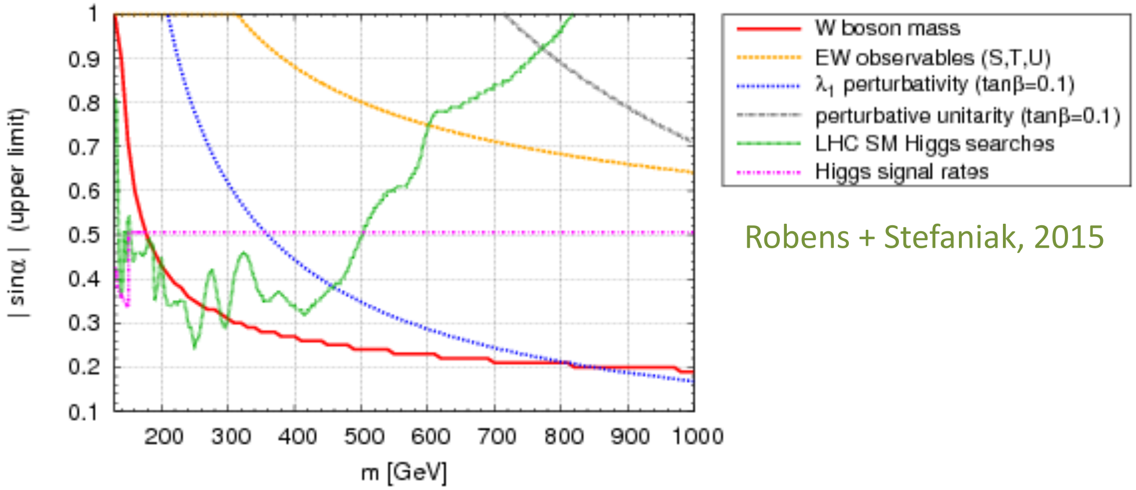
See also Michael Ramsey-Musolf's talk

-Other "stealthy"/"nightmare scenarios"?

Backup

Real Singlet Parameter Space

Lots of phenomenologically viable parameter space



Robens + Stefaniak, 2015

HL-LHC likely to probe down to $|\sin\theta|$ ~ 0.1 via direct production

Buttazzo, Sala and Tesi, 2015

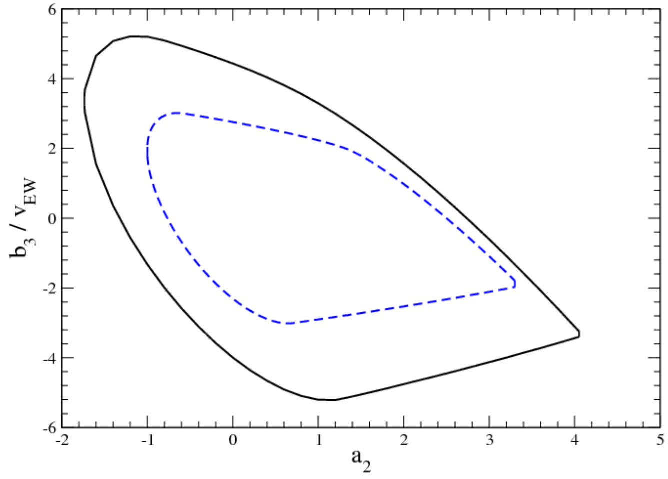
For $m_2 > 2m_1$, resonant di-Higgs will provide additional coverage (provided $|\sin\theta|$ is not too small) See e.g. No, Ramsey-Musolf, 2013; Chen, Dawson, Lewis, 2014

Small mixing will be difficult

Real Singlet Parameter Space

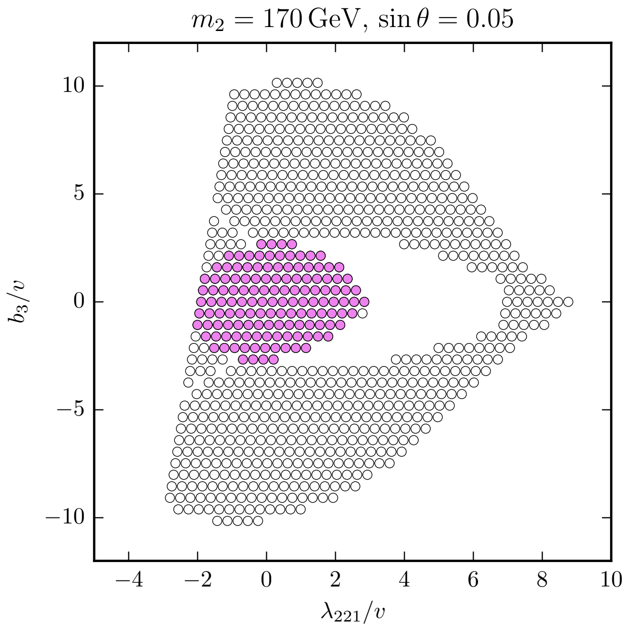
How can we comprehensively analyze the parameter space?

Choose mass, mixing angle and require correct Higgs mass and VEV. Then scan over all parameter space consistent with 1-loop vacuum stability, perturbativity, and perturbative unitarity → $|a_2|,\ |b_3|/v < 4\pi, \quad b_4 < 8\pi/3$



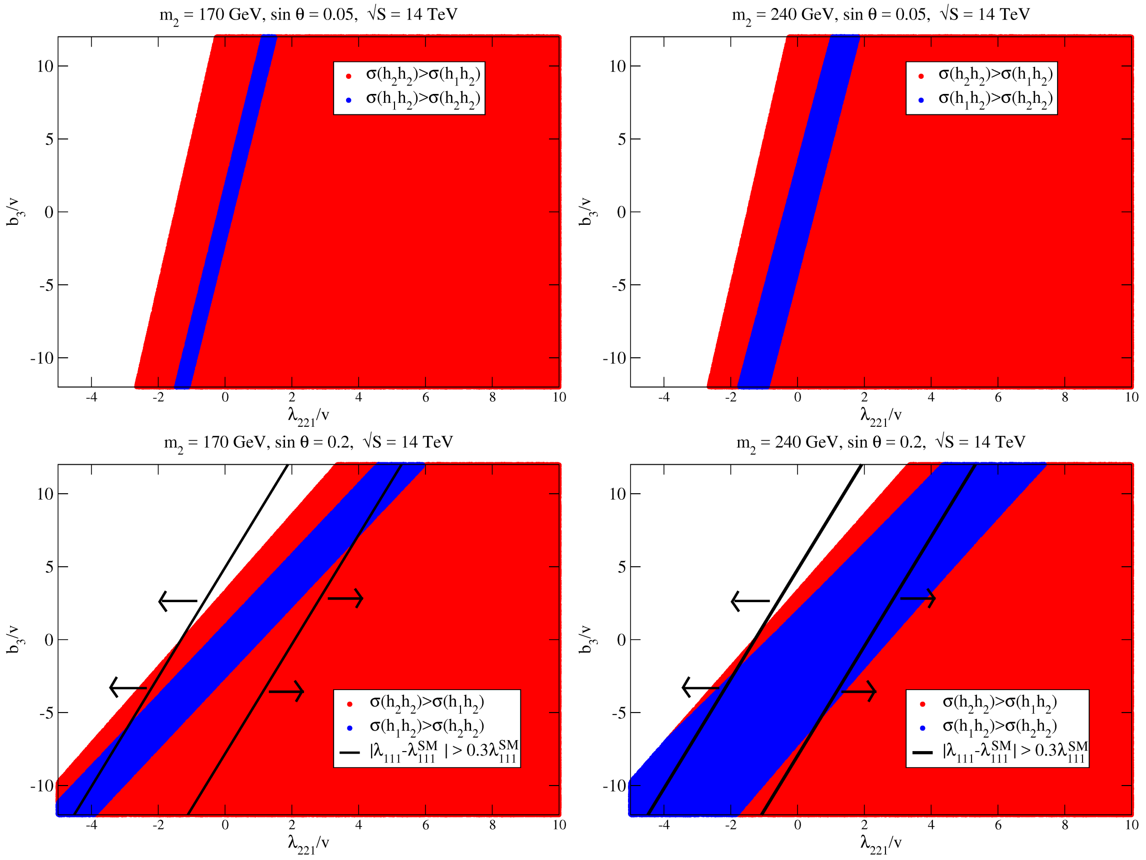
From Chen, Dawson, Lewis 2014

Marginalize over singlet quartic coupling; include 1-loop corrections



The EWPT and Double Scalar Production

Various scalar pair production modes (h_1h_1, h_1h_2, h_2h_2) cover different regions of parameter space

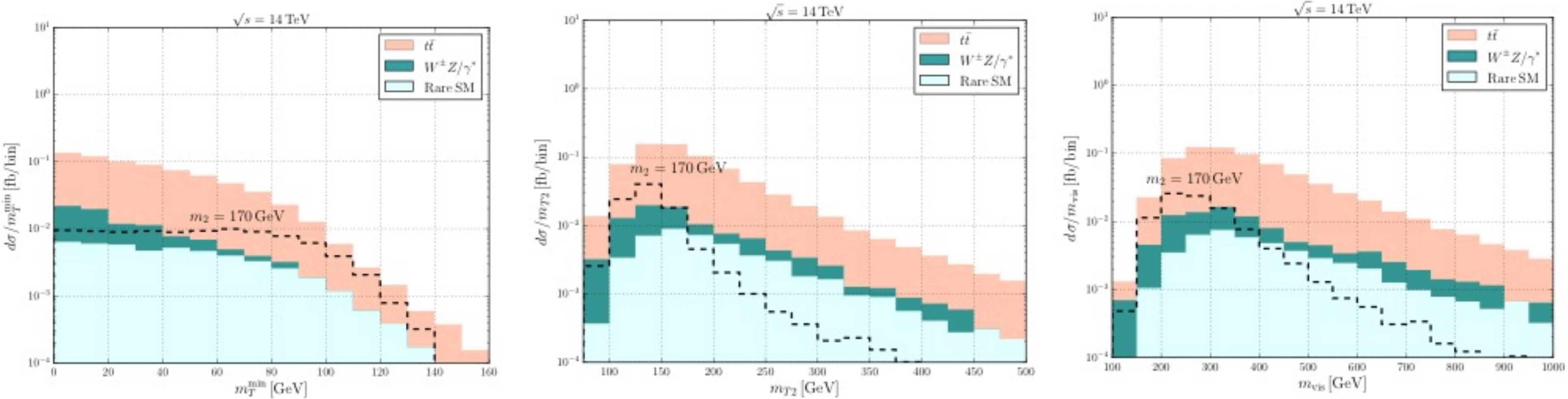


h_2h_2 most sensitive to the EWPT-favored regions at small mixing

Double Scalar Production and Trileptons

Dominant backgrounds: $t\bar{t},\ WZ,$ rare SM processes

Fake backgrounds normalized to CMS trilepton searches using the method outlined in Curtin, Galloway, Wacker, 2013



$$m_T^{\rm min} \equiv {\rm Min}\{M_T(\ell_1, \not{E}_T), M_T(\ell_2, \not{E}_T), M_T(\ell_3, \not{E}_T)\}$$

$$m_{\rm vis} \equiv \left(\sum_{\rm i} p_i^{\rm vis}\right)^2$$

Several kinematic handles to discriminate signal from background

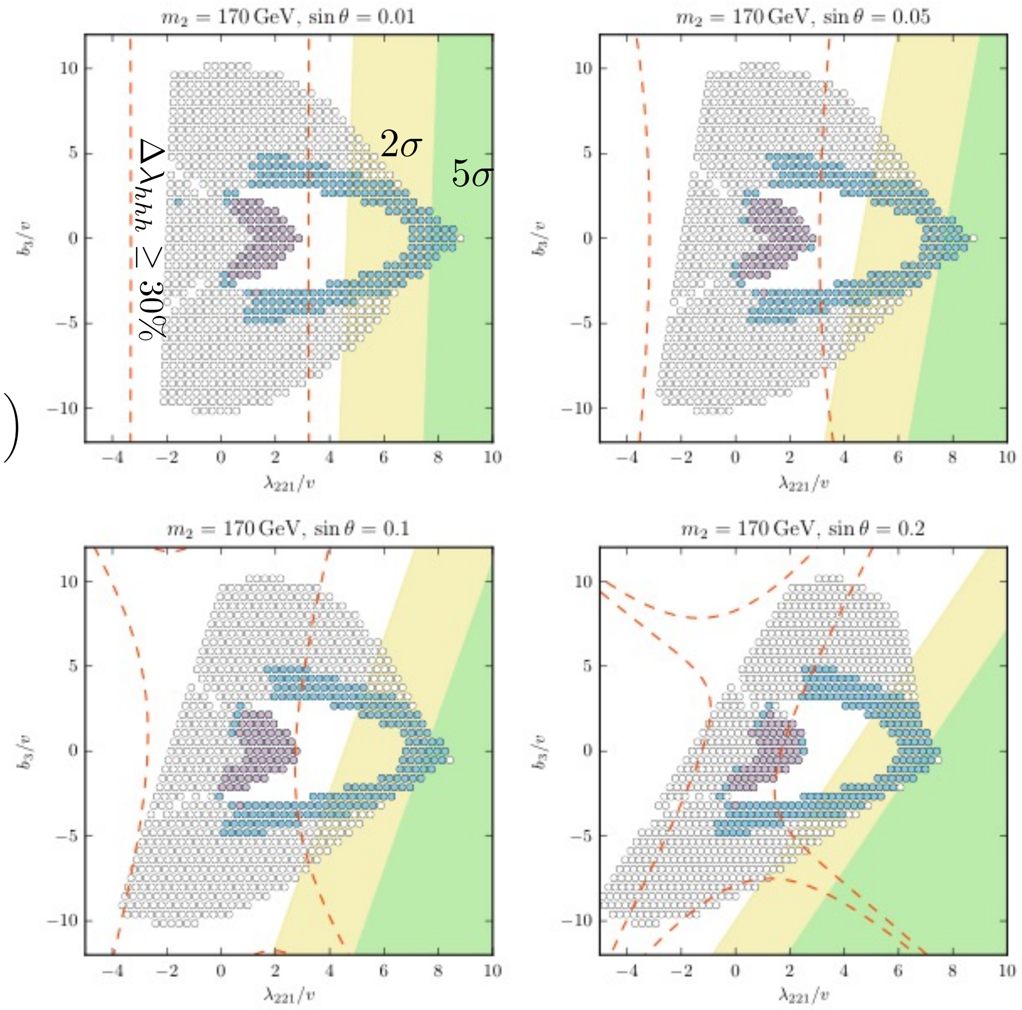
HL-LHC Projections (3000 fb^{-1})

Compare to estimated sensitivity to Higgs pair production at HL-LHC

$$\Delta\lambda_{111}^{1-\text{loop}} = \frac{1}{16\pi^2}\left(\frac{1}{2m_2^2}a_2^3 v^3 + 27\frac{m_1^4}{v^3} + \frac{3}{m_2^2}a_2^2 b_3 v^2 \sin\theta + \mathcal{O}(\sin^2\theta)\right)$$

Potentially sensitive to $\Delta\lambda_{hhh} \geq 30\%$ (neglecting interference from new diagrams!)

See e.g. Dolan et al, 2012



Trilepton channel will likely provide direct coverage to large couplings and intermediate masses