LHC New Physics Searches in the Future

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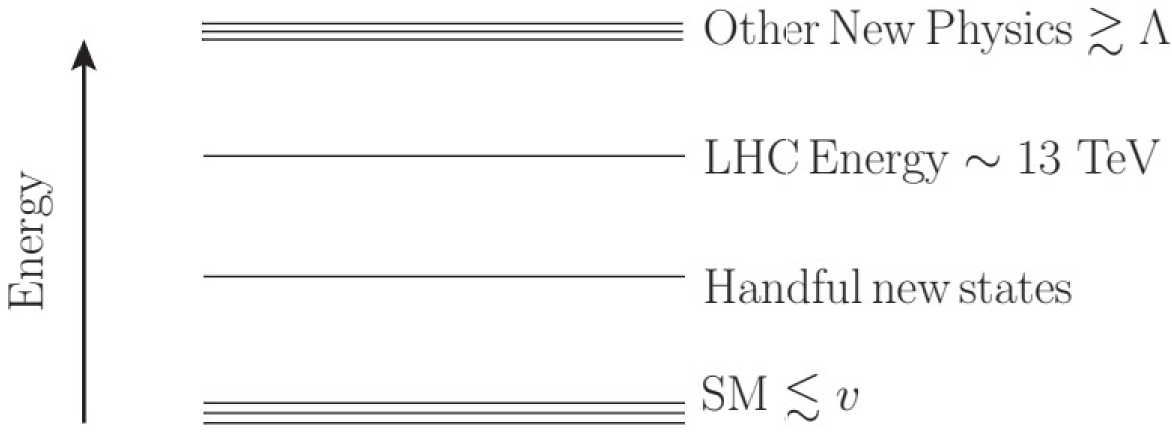
Approaches to New Physics

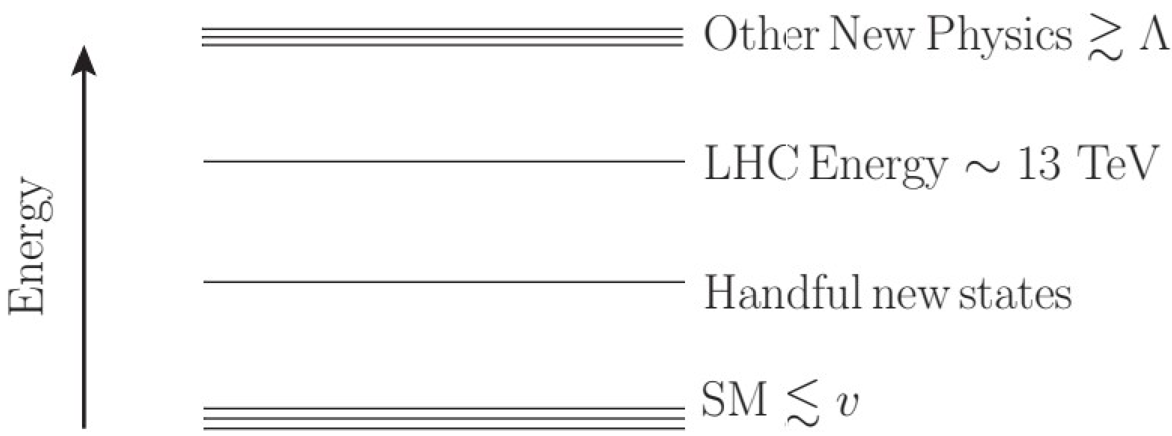
- Complete Models:
  - Supersymmetry, composite models, etc.
  - Many new particles in general.
  - The particle zoo has not been discovered yet.
- Simplified models:
  - Assume a few low lying states.
  - Postulate particles that are ubiquitous in BSM theories, and decouple the rest of the states to high energies.
  - Problem: still have not discovered these.



- Effective field theories (SMEFT/HEFT):
  - Assume all new particles are too heavy to be produced at the SM.
  - Can generically write down operators that consist of SM particle respect SM symmetries.
  - Powerful method to combine many measurements/experiments in one overarching theoretical framework and search for anomalies.
- Note: can also look at topologies of Feynman diagrams without worrying about the underlying model.

Approaches to New Physics

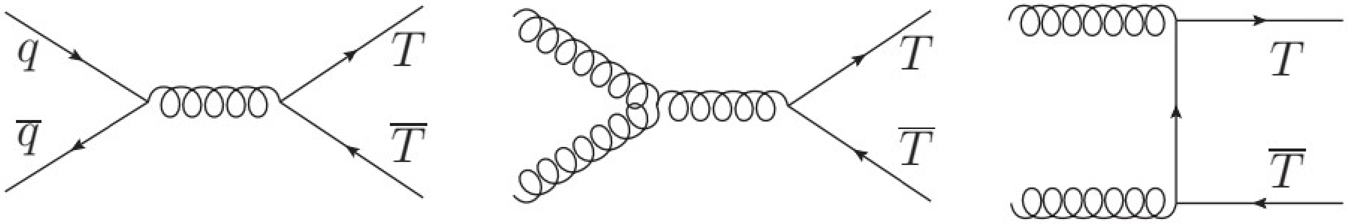
- Will focus on simplified models.
- We have not discovered anything yet.
  - Should we give up?
  - Are we missing anything?
- Consider two case studies:
  - Vector-like top partners:
    - Appear in composite Higgs models.
    - Are our simplified models too simple?
    - What if we perturb them a little? Does phenomenology change?
    - Do those higher states truly decouple?
  - Extended scalar sectors:
    - What more searches should we have for extended scalar sectors?
    - Again, for simplified models, do the higher states truly decouple?



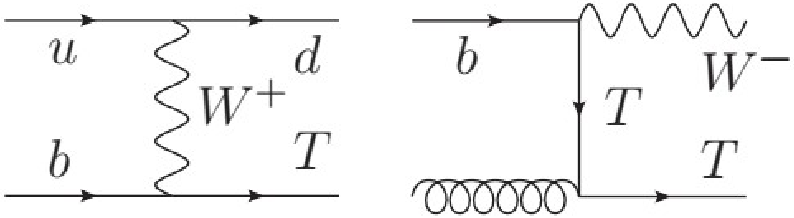
Vector Like Quarks

Traditional Fermionic Top-partner Searches

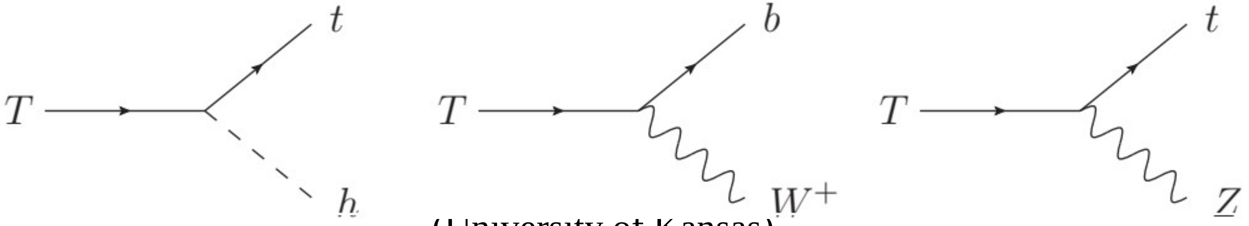
- When we say “top-partner” we mean vector-like up-type quarks.
- Traditional search methods:
  - Pair production:



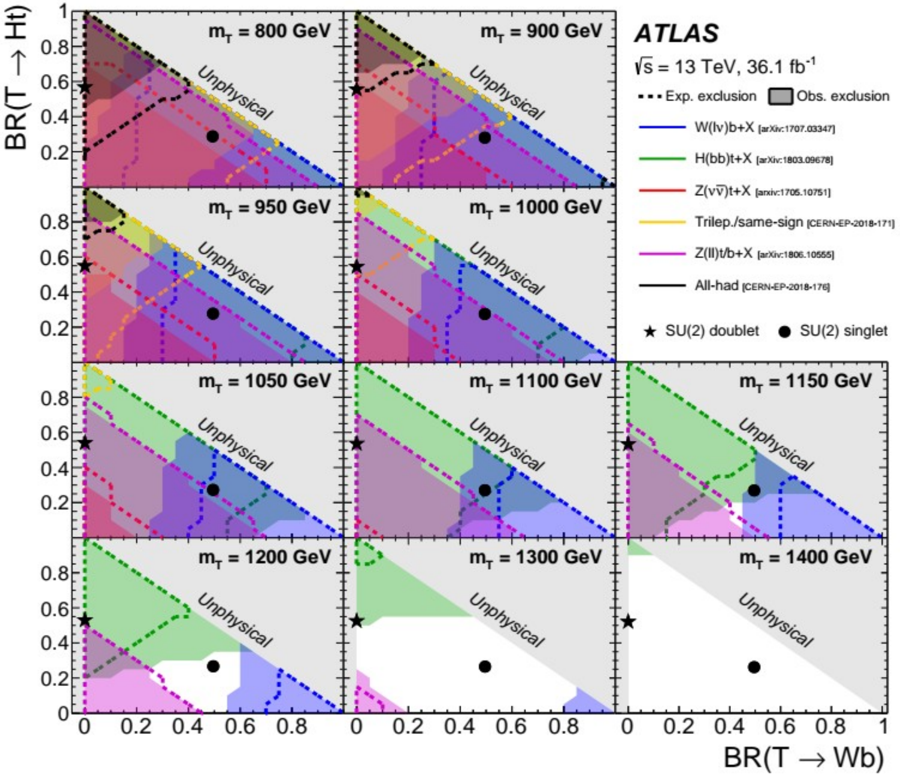
  - Single production:

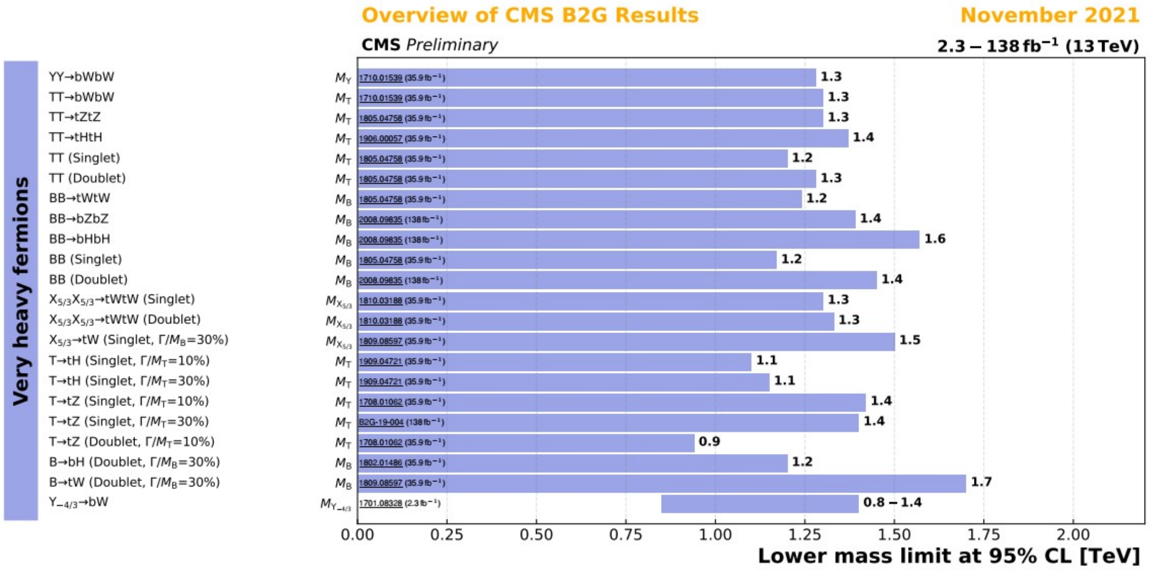


  - Decays:



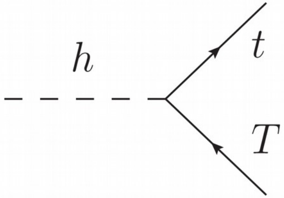
Top Partner Search Results



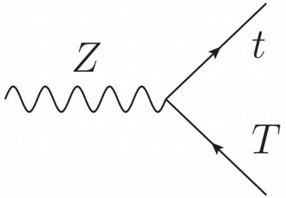


Singlet Top Partner

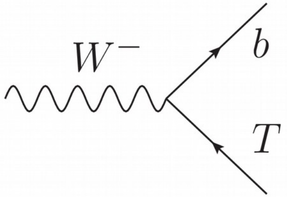
- A typical model:
  - As an SU(2) singlet to the SM:
  - $$-L \supset y_t \overline{Q}_L \widetilde{\Phi} t_{1R} + \lambda_t \overline{Q}_L \widetilde{\Phi} t_{2R} + M_2 \bar{t}_{2L} t_{2R} + h.c.$$
  - 3rd Generation SM quarks: $Q_L, \ t_{1R}$
  - Vector-like-quark: t_2
  - Higgs doublet: Φ
- The couplings that determine single production and decays are suppressed by the mixing angle between the top partner and top quark:



$$i\sqrt{2}\theta_L (m_t P_L - m_T P_R) + \mathcal{O}(\theta_L^2)$$



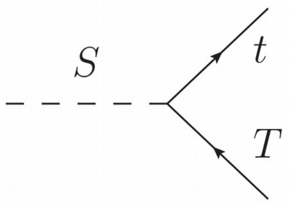
$$-i\frac{e}{2\cos\theta_W \sin\theta_W}\theta_L \gamma^\mu P_L + \mathcal{O}(\theta_L^2)$$



$$-i\frac{e}{\sin\theta_W}\sqrt{2}\theta_L \gamma^\mu P_L + \mathcal{O}(\theta_L^2)$$

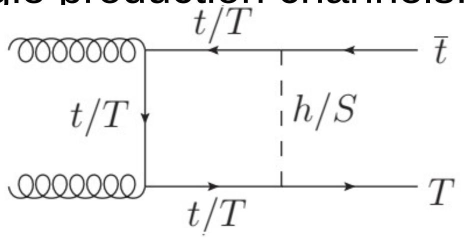
Top Partner+Scalar Singlet

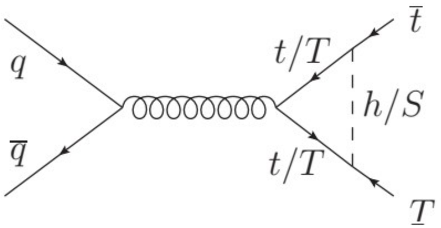
- Perturb in a very simple way: add a singlet scalar S.
- New interactions in the Yukawa sector: See also Dolan, Hewett, Krämer, Rizzo, JHEP 08 (2016) 039
- $$-L \supset \lambda_1 S \bar{t}_{2L} t_{1R} + \lambda_2 S \bar{t}_{2L} t_{2R} + h.c.$$
- l1 is an off-diagonal coupling independent of the mixing angle:



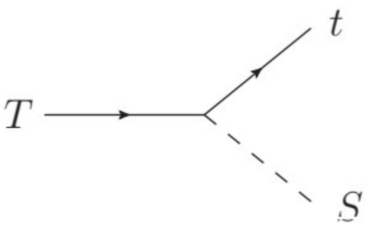
$$i\left(\lambda_1 P_L + \lambda_2 \theta_L \left(P_R - \frac{m_t}{m_T} P_L\right)\right) + \mathcal{O}(\theta_L^2)$$

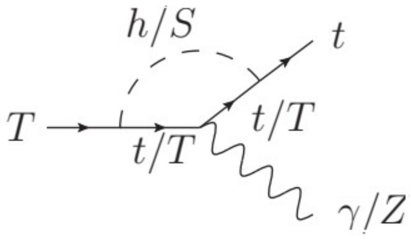
- Introduces new single production channels:

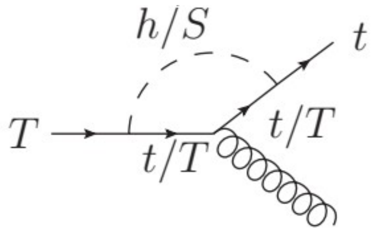




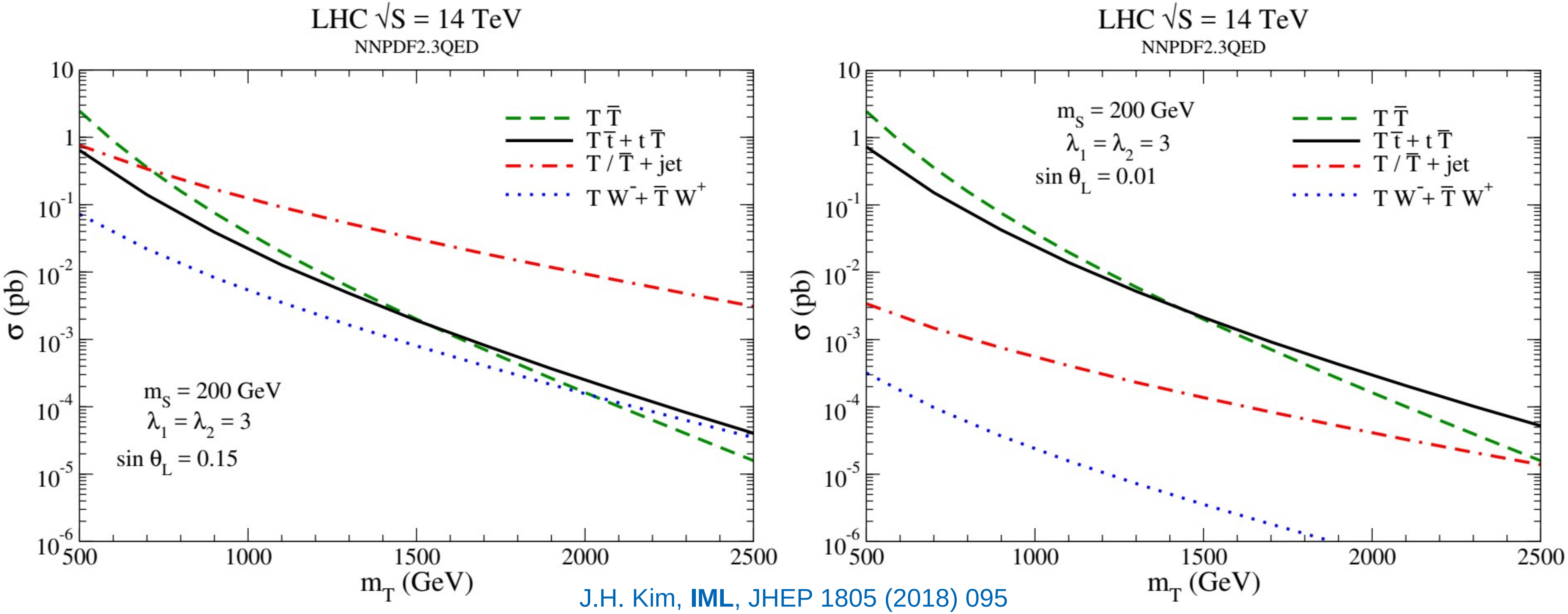
- New decay channels depending on kinematic regime





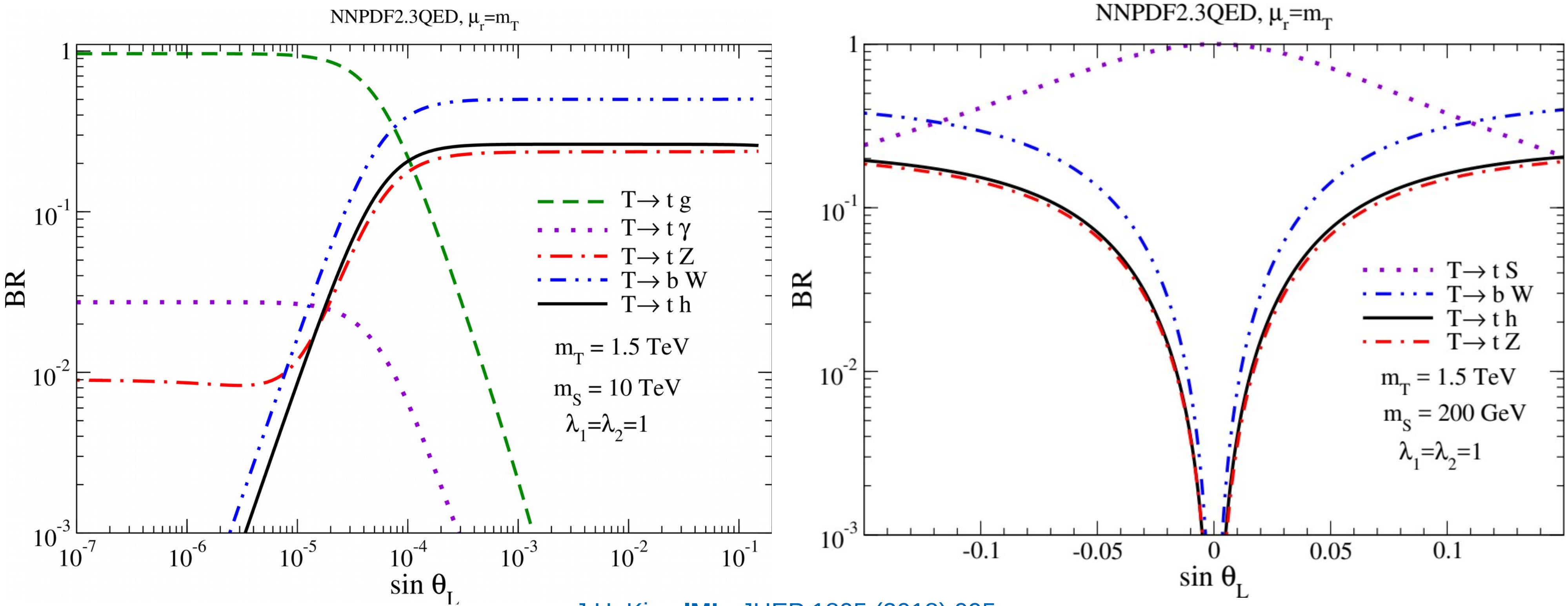


- New single production modes dominate at small angle:



J.H. Kim, **IML**, JHEP 1805 (2018) 095

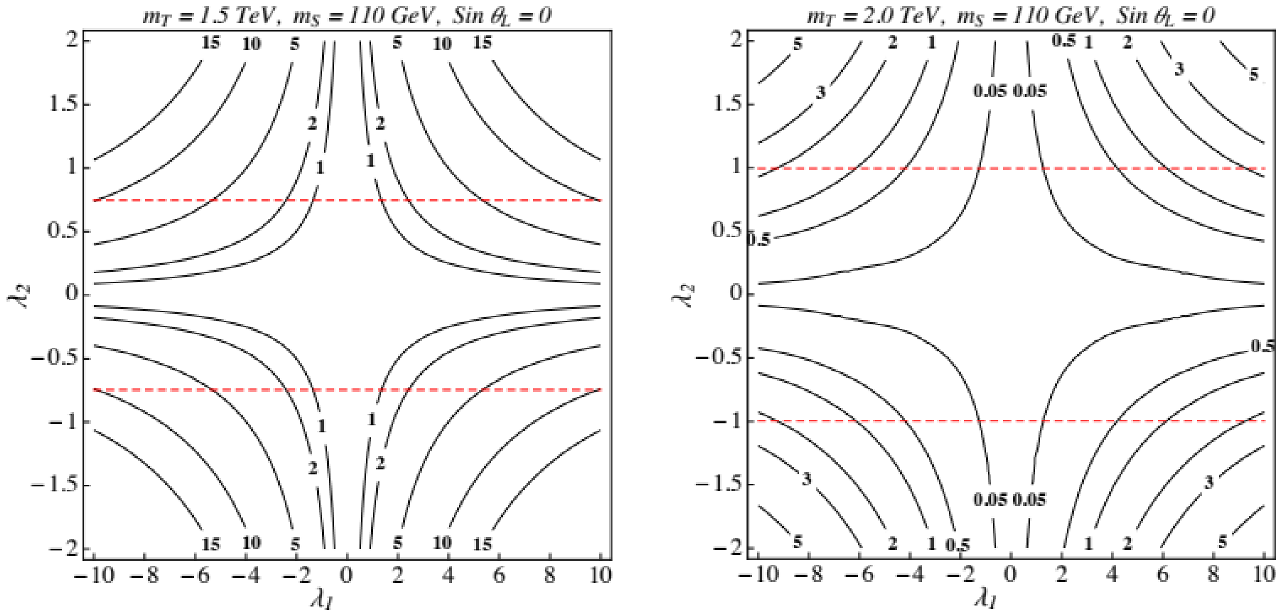
- New decay modes dominate as small angles:



J.H. Kim, **IML**, JHEP 1805 (2018) 095

Search For New Production Mode

- Collider search for $pp \to T\bar{t}+t\bar{T} \to t\bar{t}S \to l+2b+2q+gg+MET$
  - Zero mixing limit

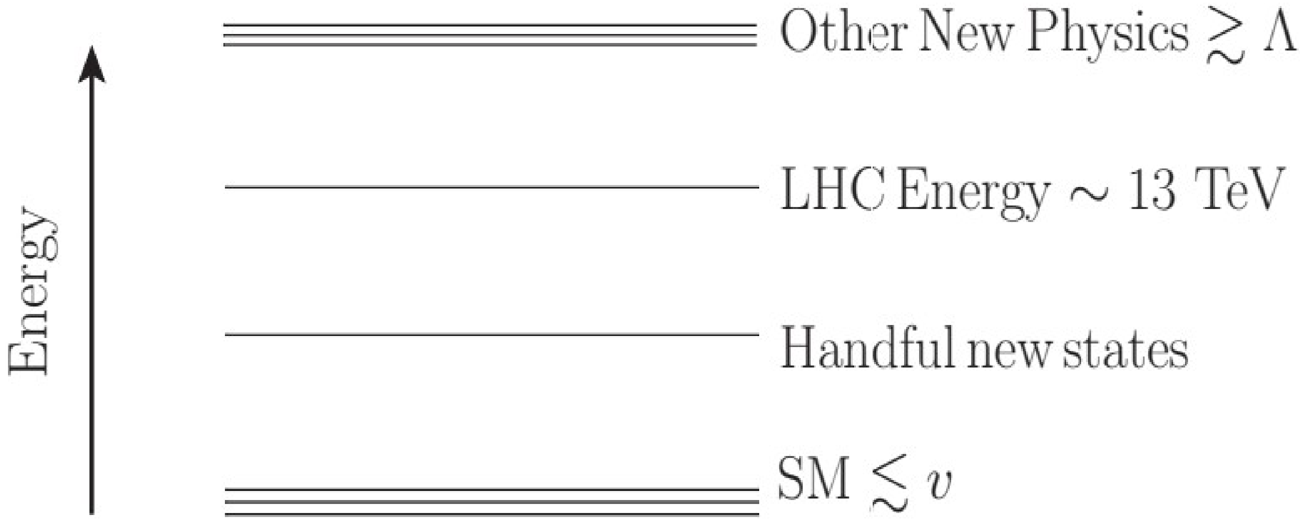


J.H. Kim, **IML**, JHEP 1805 (2018) 095

- Solid black lines for $T\bar{t}+t\bar{T}$ at the HL-LHC
- Dashed red lines: expected limits from $S \to \gamma\gamma$ through VLQ loops at the HL-LHC

Aside: Beyond the Standard Model EFTs:

- Previous results are from adding a few new particles to the SM in the TeV.
- Implied assumption to these simplified models is that all other new physics and heavy and decoupled.
- This can be tested via an effective field theory:
  - Often get new phenomena, or different interpretations of data.



$$L = L_{simplified} + \sum_k \frac{c_{1,k}}{\Lambda} O_{1,k} + \sum_k \frac{c_{2,k}}{\Lambda^2} O_{2,k} \cdots$$

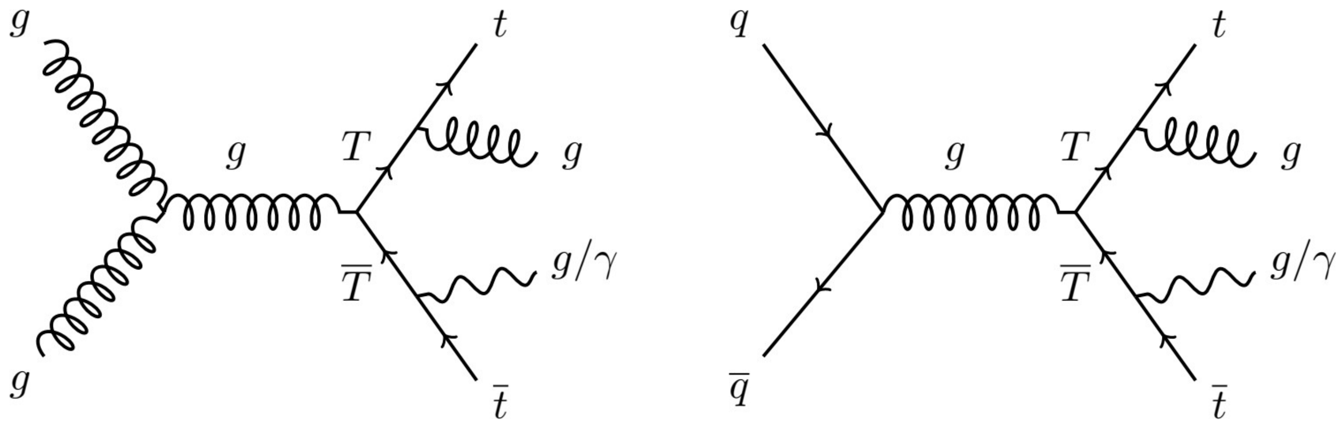
Adhikari, IML, Sullivan, PRD (2021) 075027; Alhazmi, Kim, Kong, IML JHEP 01 (2019) 139; JHEP 01 (2020) 057; Anisha, Das Bakshi, Chakrobortty, Prakash JHEP 09 (2019) 035; Banerjee, Chakrabortty, Prakash, Rahaman, Spannowsky JHEP 01 (2021) 028; etc.

Beyond the SM EFT

- For a heavy scalar boson, simplified model will induce operators:

$$\overline{T}_L \sigma^{\mu\nu} t_R B_{\mu\nu} \qquad \overline{T}_L \sigma^{\mu\nu} t^A t_R G^A_{\mu\nu}$$

- Can induce production of top quark+VLQ Criado, Perez-Victoria JHEP 01 (2020) 057
- Will look at pair production with decays through these operators.

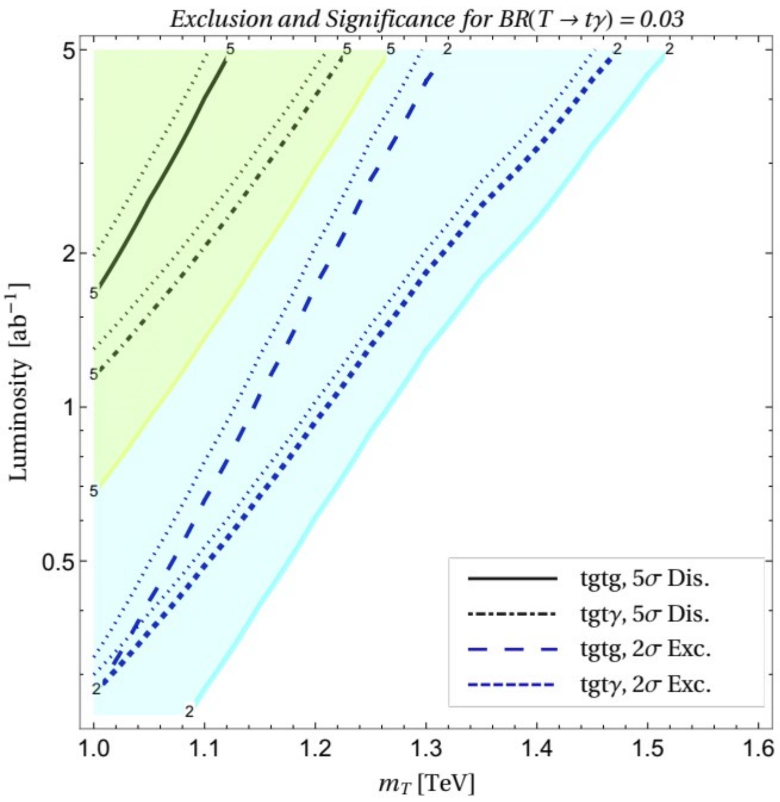


- CMS has a search for $T\overline{T} \rightarrow t\,\bar{t}\,g\,g$ for the spin 3/2 case PLB778(2018) 349

Results for Spin 1/2

- Blue: 2σ exclusion
- Black: 5σ discovery
- Dotted: varying background by 20%
- Blue shaded: combined 2σ exclusion
- Green shaded: combined 5σ discover

$$BR(T \to t\,g) = 0.97, \quad BR(T \to t\,\gamma) = 0.03$$



H. Alhazmi, J.H. Kim, KC Kong, **IML** JHEP 1901 (2019) 139

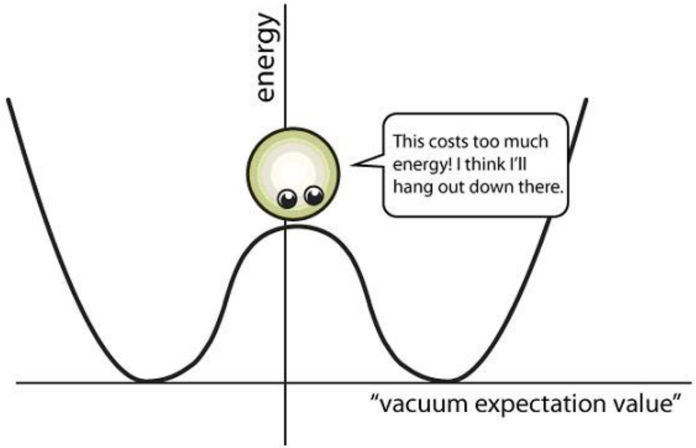
Higgs Physics: Scalar Extensions

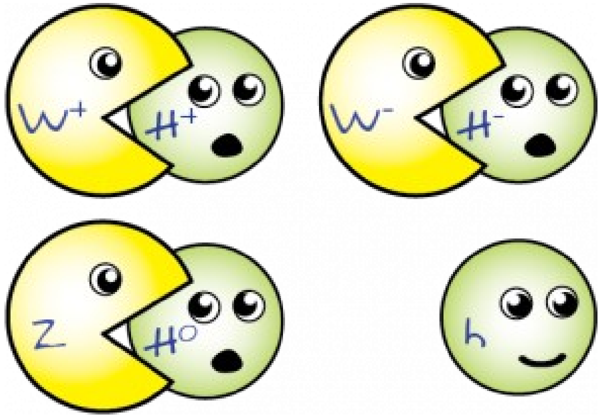
Motivation

- Scalar Extensions:
  - The Higgs is unique in the Standard Model in that you cannot forbid the Higgs portal:

$$|\Phi|^2|S|^2$$

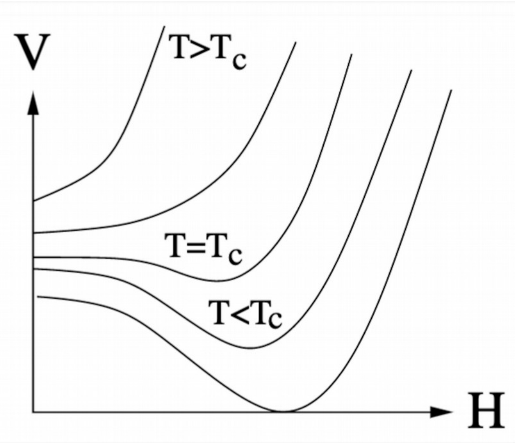
  - Scalar extensions are simple extensions of the SM that can provide a lot of interesting phenomenology.
  - They can also help solve many particle physics problems.
- This section: interpret BSM Higgs as (mostly) new scalars.
  - Discuss why they're interesting.
  - Interesting signatures to search for currently and in the future.
  - Mainly interested in collider physics.
  - Mostly focused on the importance of Di-Scalar production.
    - Di-Higgs, double production of new scalars, asymmetric production of Higgs and new scalar.

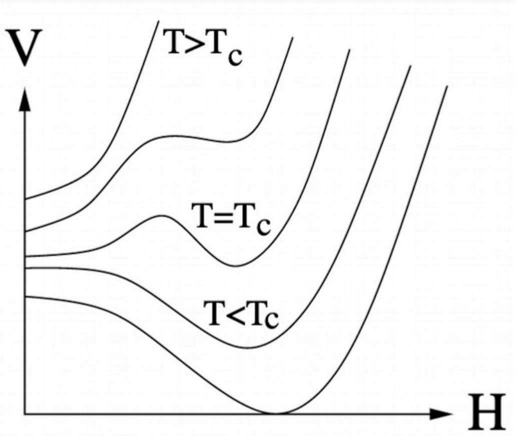




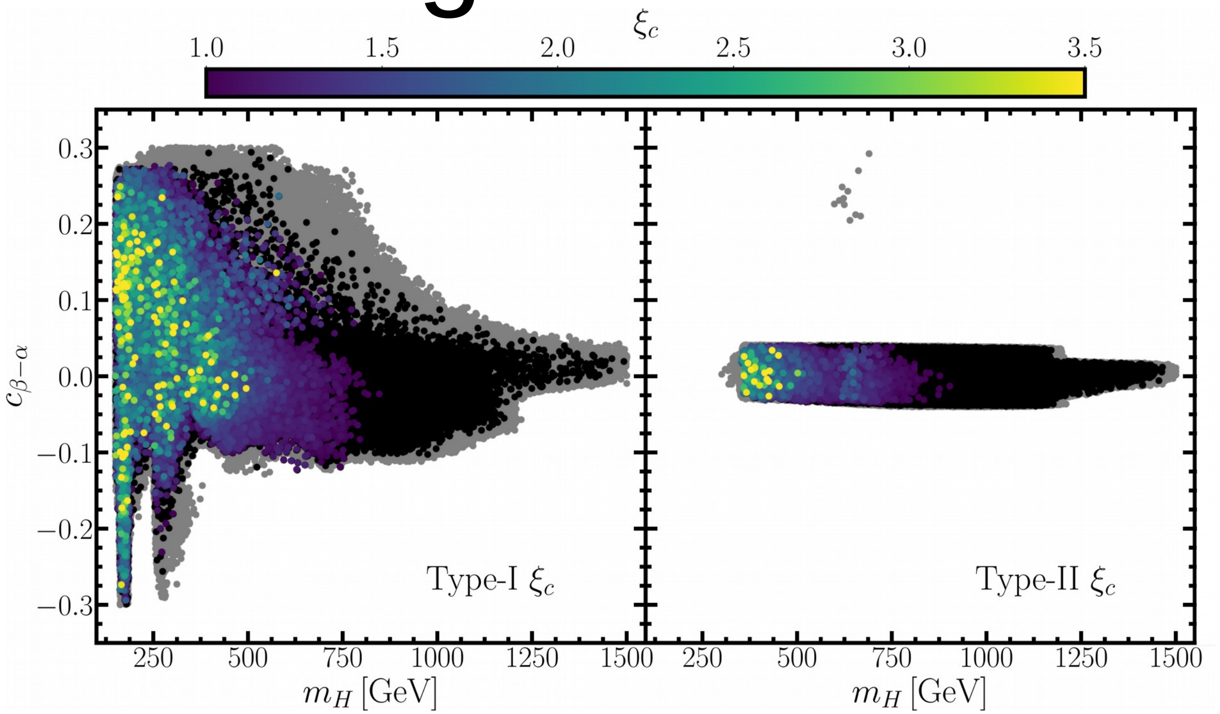
Thermal History of the Universe: Strong First Order EWPT

- Standard model only satisfies one of the three Sakharov conditions for baryon asymmetry of the Universe: Baryon number violation.
- Electroweak Baryogenesis is a mechanism to satisfy the other two conditions: out of equilibrium interactions, C and CP violation
  - To obtain out of equilibrium interactions, the electroweak phase transition (EWPT) is strong an first order.
  - In the SM it is second order.
- Need to alter the Higgs potential.
  - The simplest way is to add additional scalars to the SM.
  - Many scalar extensions can give a strong first order electroweak phase transitions.
    - Singlet scalar extensions: add new scalar with no SM quantum charges
    - 2HDMs: Add a second Higgs doublet.
  - In principle, need new physics at the EW scale to alter Higgs potential.
  - Good benchmark for collider physics.





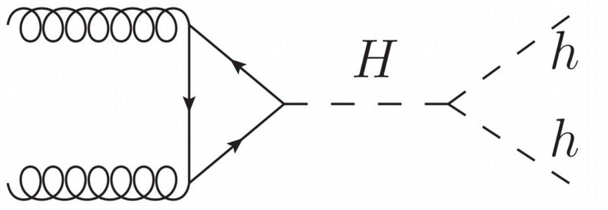
2HDM Strong First Order EWPT

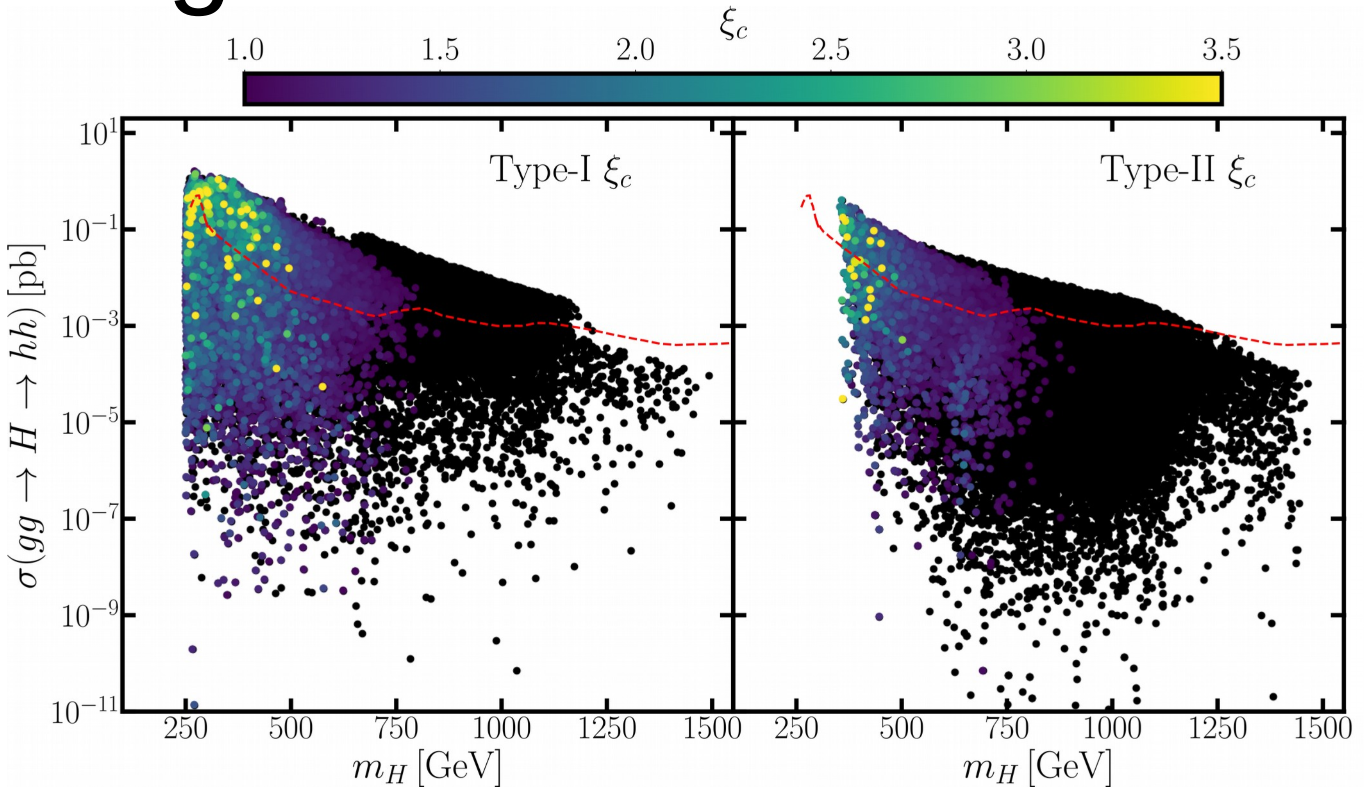


Gonçalves, Kaladharan, Wu PRD105 (2022) 095041

- Colored dots have a strong first order electroweak phase transition.
- Need new scalar masses below 750-1000 GeV.
- See also Dorsch, Huber, No, JHEP10 (2013) 029; Basler et al JHEP02 (2017) 121; Ramsey-Musolf JHEP09 (2020) 179, etc.

2HDM Strong First Order EWPT





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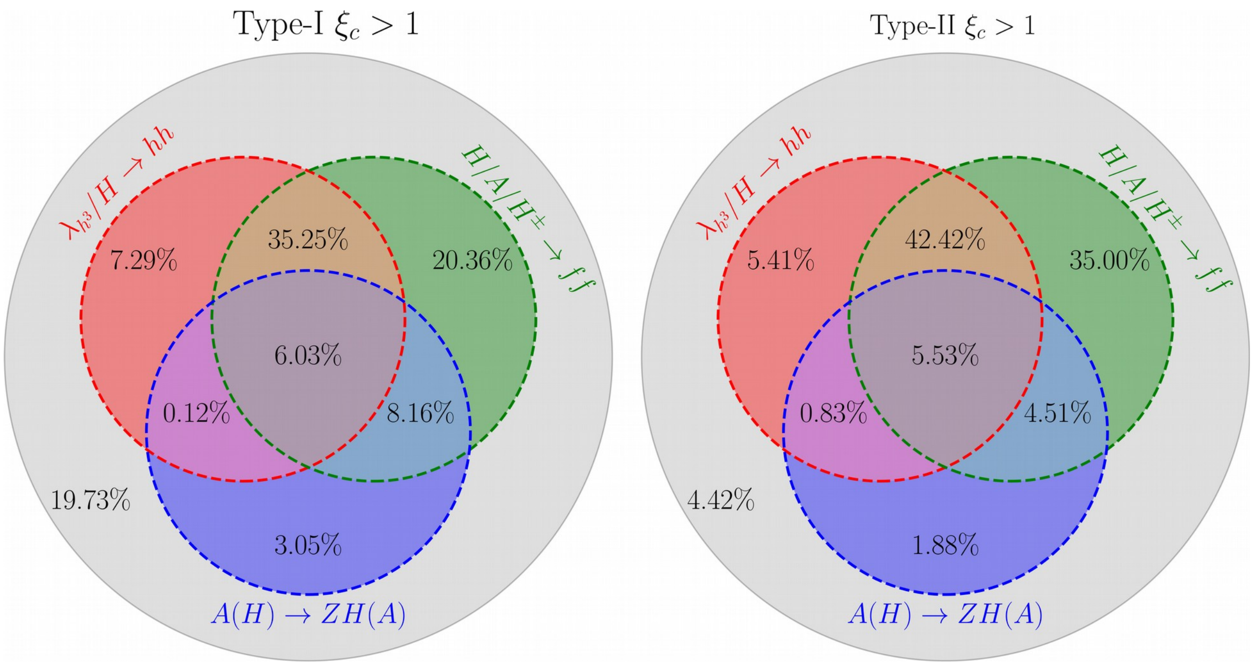
- Red dashed: extrapolated Di-Higgs bounds from ATLAS with 3 ab^{-1}

2HDM: Different Search Channels



Gonçalves, Kaladharan, Wu PRD105 (2022) 095041

- Percentage that different search channels cover regions of parameter space to give a strong first order electroweak phase transition.

Singlet Scalar Extension EWPT

- Simplest possible extension to the Standard Model: add a singlet scalar.
- At the renormalizable level, only couples to the SM Higgs:

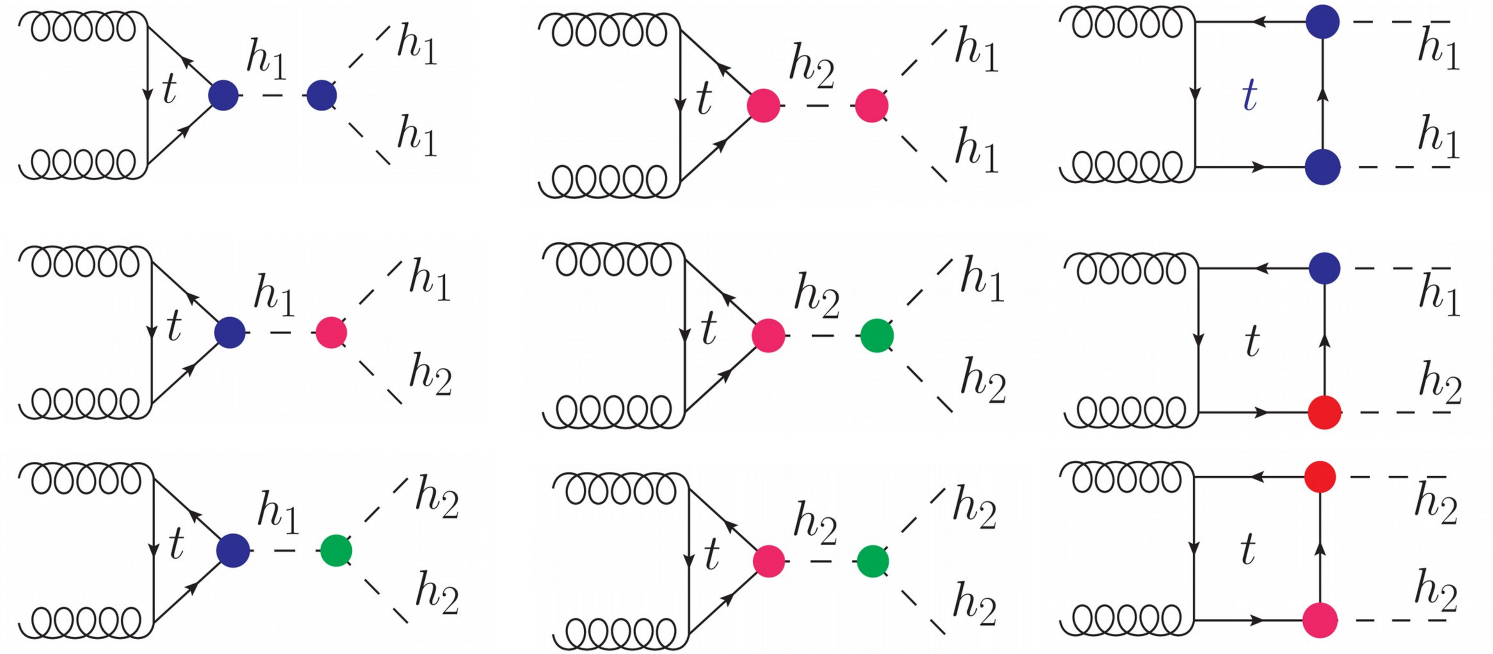
$$V \supset \frac{a_1}{2}|\Phi|^2 S + \frac{a_2}{2}|\Phi|^2 S^2 \supset \frac{a_1 v}{2} h S + \frac{a_1}{4} h^2 S + \frac{a_2 v}{2} h S^2$$

  - In the zero mixing limit, a_1 is zero.
  - Only a_2 survives and give a coupling between SM-like Higgs and two heavy scalars.
    - Hence, in the small mixing angle limit, a_2 drives the strong first order EWPT.
  - This effects the phenomenology for searching the parameter regions that can give a strong first order EWPT.
  - This process does not decouple in the small mixing angle limit:

$$h^{(*)} \rightarrow S\, S$$

Di-Scalar Production

$$V \supset \frac{a_1}{2}|\Phi|^2 S + \frac{a_2}{2}|\Phi|^2 S^2$$



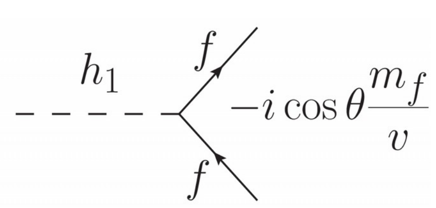
As mixing approaches zero:

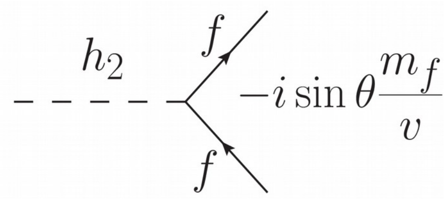
Blue: Approaches SM Value

Red: Goes to zero

Green: New physics coupling that survives

- In zero mixing limit, only $h_2 h_2$ production through s-channel h_1 give new physics contributions.
- Is sensitive to the coupling that drive the EWPT





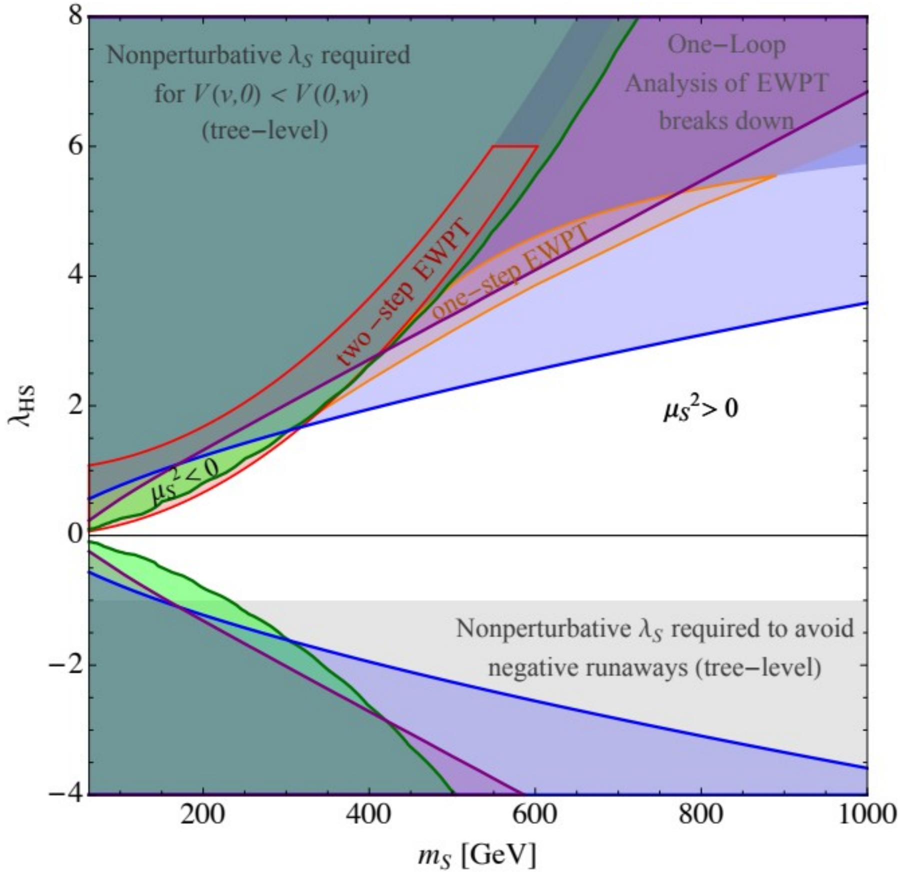
Curtin, Meade, Yu JHEP11 (2014) 127

Nightmare Scenario

- This is similar to the nightmare scenario from many years ago.
  - Nightmare scenario: exact Z_2, can only pair produce double scalar via off-shell Higgs. They do not decay:

$$h^{(*)} \rightarrow S\,S$$

  - Blue shaded: λ_{111} shifts by 10%
  - Green shaded: would be excluded by VBF double Scalar production at 100 TeV pp collider
  - Purple shaded: Z-h coupling shifted by 0.6%.
- If not exactly in the zero mixing, heavy scalars can still decay.
- New signals to look for at the LHC.

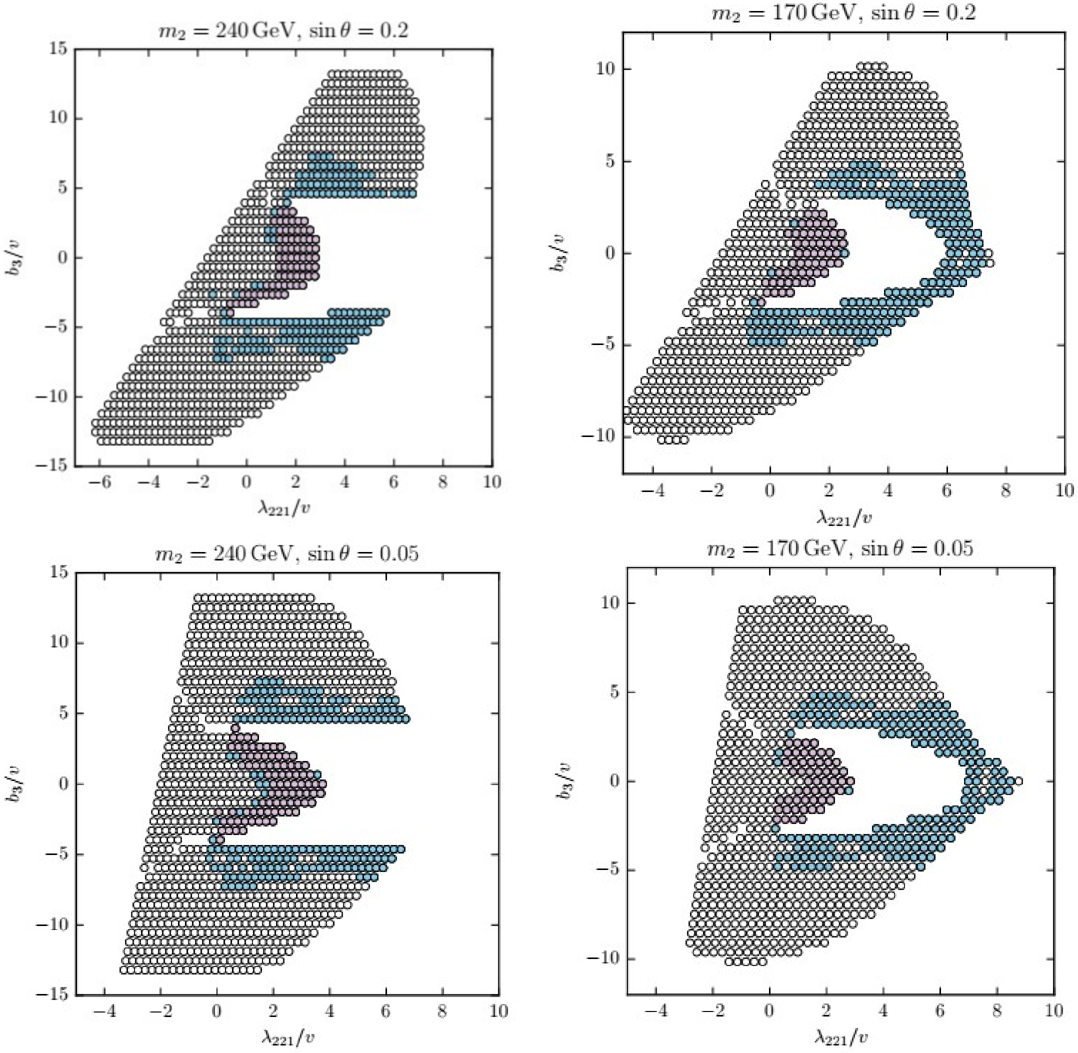


Di-Scalar Production and EWPT

- Colored regions give strong first order EWPT.
  - x-axis is h_1-h_2-h_2 coupling
- As mixing angle decreases, correlation between h_1-h_2-h_2 coupling and EWPT increases.
- Considering mass points of m_2=170 and 240 GeV.

sin θ = 0.2:

sin θ = 0.05:



Chen, Kozaczuk, **IML** JHEP 08 (2017) 096

Collider Searches at HL-LHC

- Considered the production and decay mechanism

$$pp \rightarrow h_2 h_2 \rightarrow 4W \rightarrow (2j)(2l^{\pm})l'^{\mp}(3\nu)$$
$$l \neq l'$$

- At HL-LHC, considered m_2=170 GeV.
- Yellow: 2 sigma.
- Green: 5 sigma
- Red dashed: Higgs trilinear with 30% of SM prediction.
- Direct searches for heavy scalars can be sensitive to interesting regions of parameter space.

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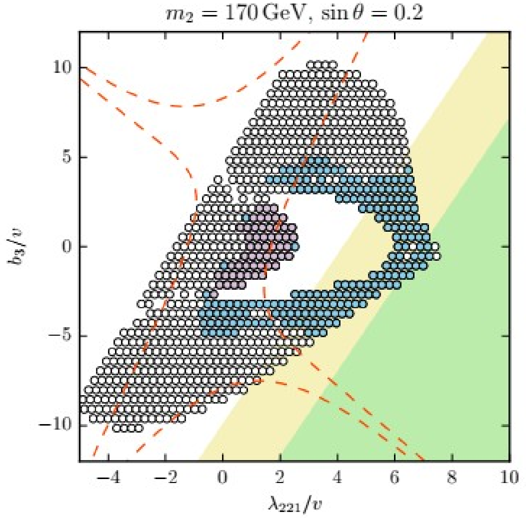
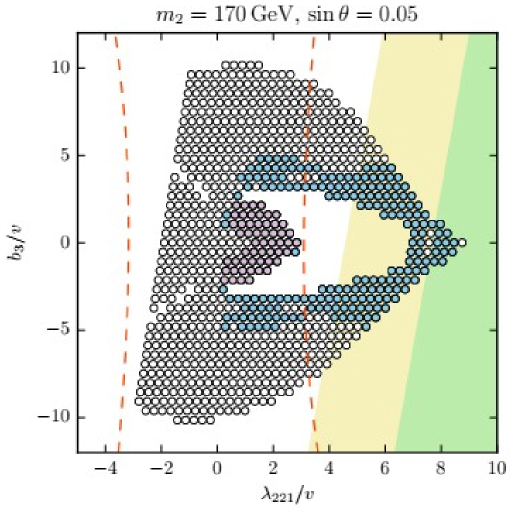
sin θ = 0.2:



sin θ = 0.05:



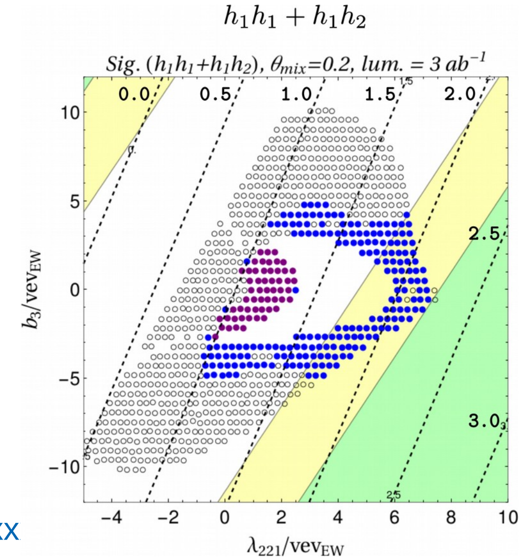
Collider Searches at HL-LHC

- For larger mixing angle, h_1h_1 and h_1h_2 pair production can add information:
  - 2W + 2b channel
  - m_2=170 GeV, θ = 0.2
- The point:
  - **It is important to search for all Di-Scalar channels, resonant and non-resonant.**
  - They contain complementary information that might shed light on the mechanism of electroweak symmetry breaking.
  - We need to measure all trilinears in the potential, not just the Higgs trilinear.
- Dashed lines are for constant deviations from SM trilinear Higgs coupling.
  - Can have sizable deviations.
  - Current LHC projections:

$$\frac{\delta\lambda_{111}}{\lambda_{111}}\sim 50\,\%$$

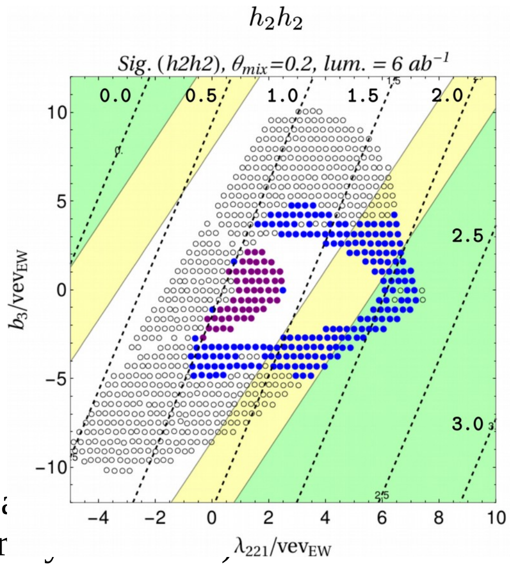
  - Likely to do better.
  - There's a caveat, though...

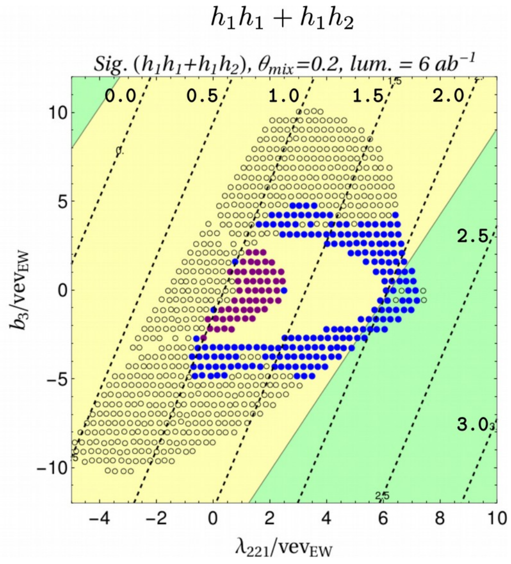
3 ab^{-1}:



Alhazmi, Kim, Kong, **IML** 22xx.xxx

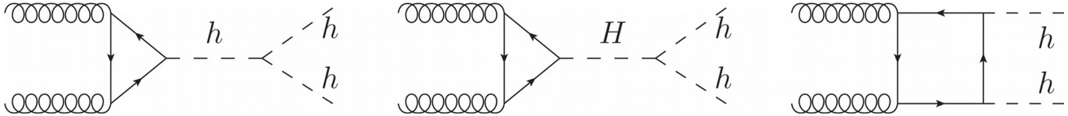
6 ab^{-1}



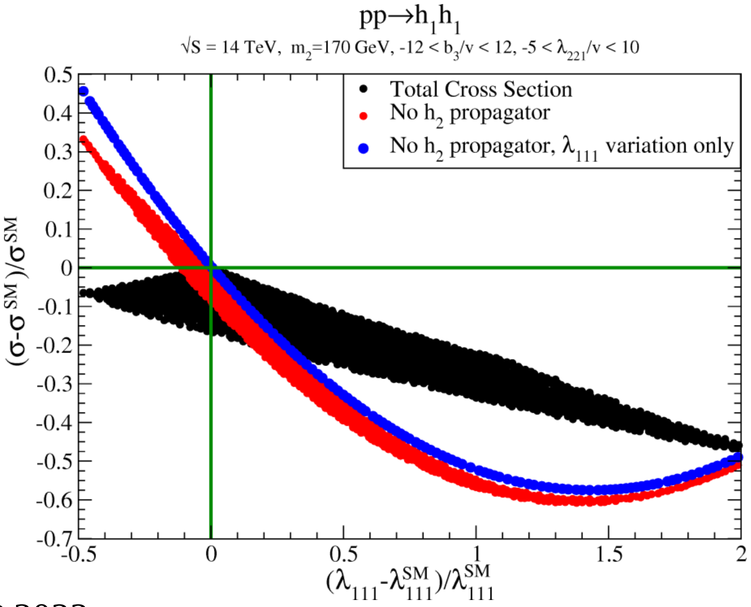


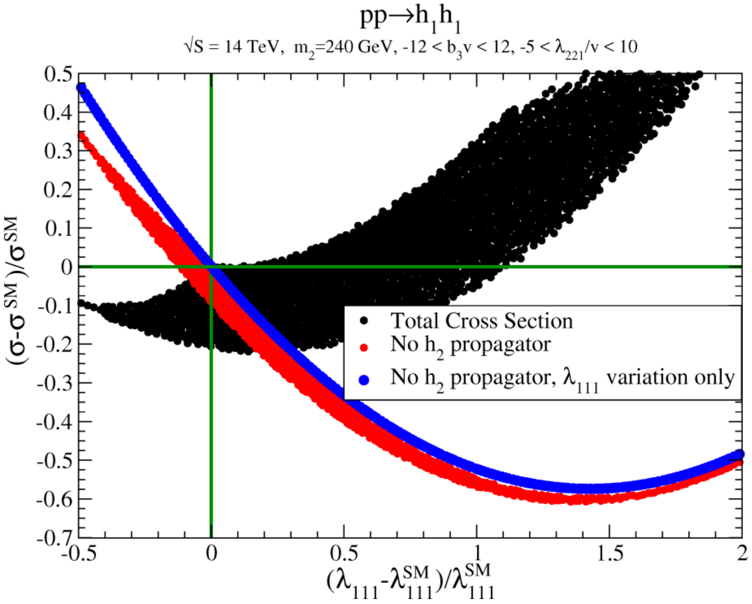
Cross Section vs. Higgs Trilinear: Non resonant production

- Variations within the model:
  - Blue: only SM-like Higgs trilinear
  - Red: SM-like Higgs trilinear and top Yukawa
  - Black: all contributions
- The new diagram weakens the correlation between cross section and Higgs trilinear.
  - Effect not account for by varying couplings.

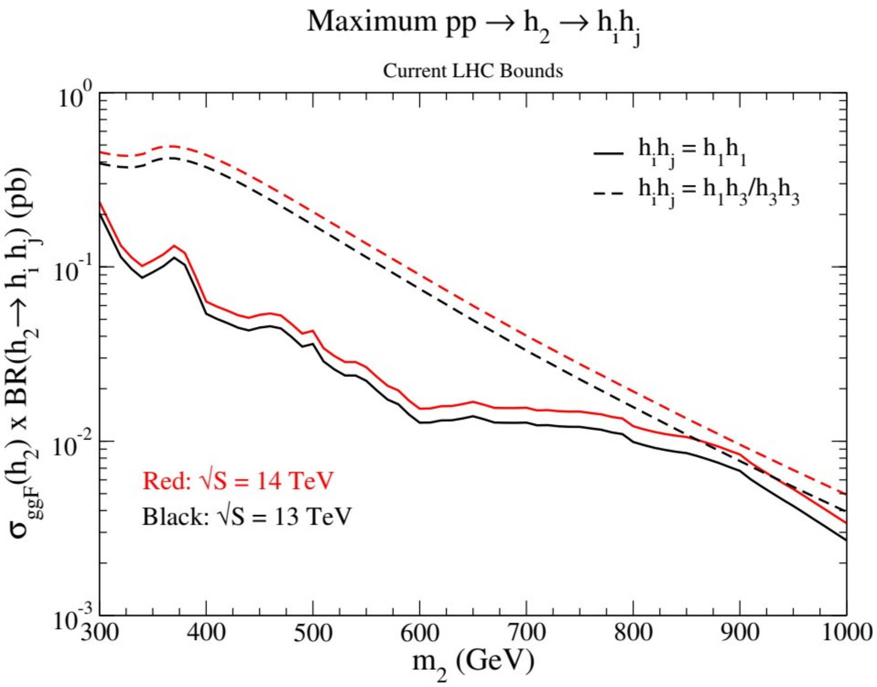


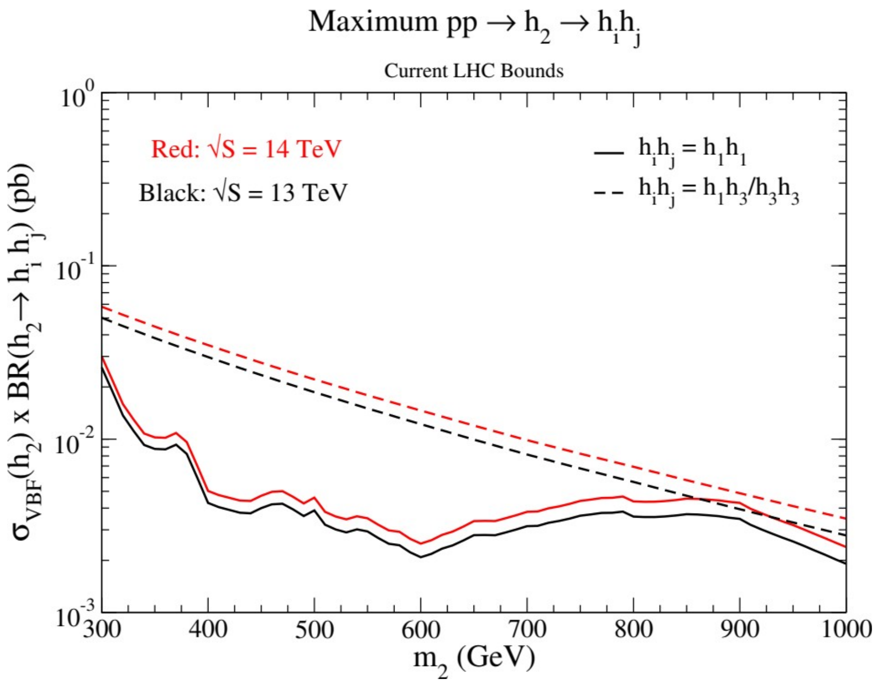
Chen, Kozaczuk, **IML** JHEP 08 (2017) 096





Resonant Production





Adhikari, Lane, **IML**, Sullivan, arXiv:2203.07455

- In models with more than one additional scalar, is possible to pair produce Di-Higgs, two new scalars, or asymmetrically with a new scalar+Higgs.

  Dawson, Sullivan, PRD97 (2018) 015022; Adhikari, Lane, **IML**, Sullivan, arXiv:2203.07455; Abouabid et al arXiv:2112.12515; Basler, Dawson, Englert, Mühlleitner, PRD101 (2020) 015019; Robens, Stefaniak, Wittbrodt, EPJC80 (2020) 151; etc.

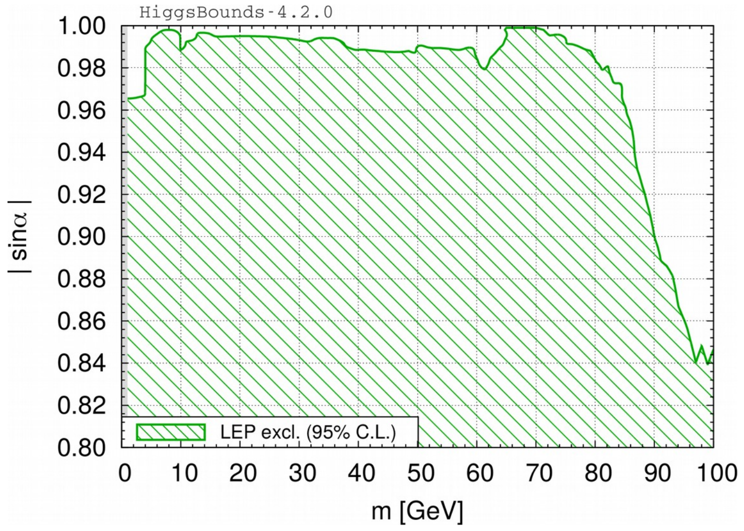
- Increasing interest among experimental community to search for these final states.

  CMS arXiv:2204.12413; CMS JHEP09 (2021) 57

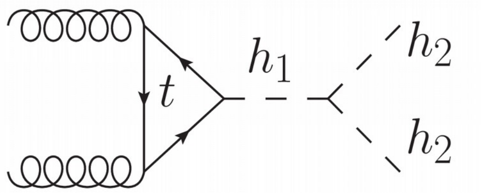
Exotic Higgs Decays

- What if the SM-like Higgs can decay to the new scalar?
  - LEP very strongly constrains the mixing angle for lighter scalar masses.
- a_1 is negligible because it creates a mixing.
- a_2 only surviving coupling between Higgs and new scalar.
  - To get a strong first order electroweak phase transition, it must persist.
  - Can give rise to exotic Higgs decays.

$$h_1 \rightarrow h_2 h_2$$

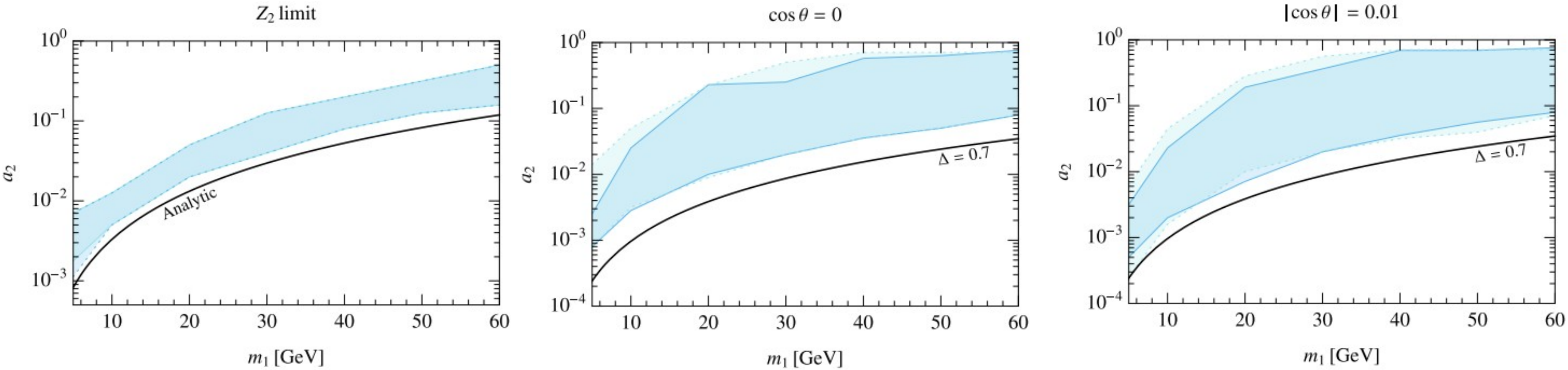


Robens, Stefaniak EPJC 75 (2015) 104



$$V \supset \frac{a_1}{2}|\Phi|^2 S + \frac{a_2}{2}|\Phi|^2 S^2 \supset \frac{a_1 v}{2} h S + \frac{a_1}{4} h^2 S + \frac{a_2 v}{2} h S^2$$

Exotic Higgs Decays+EWPT



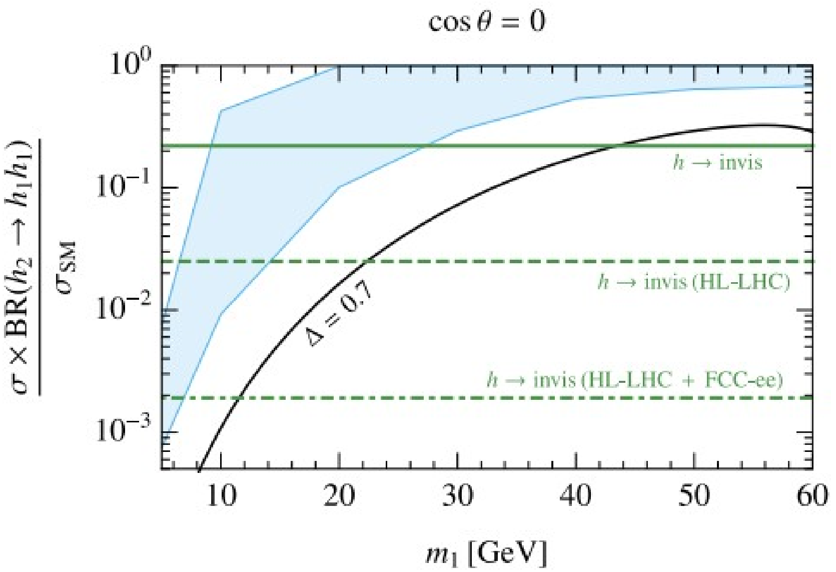
Kozaczuk, Ramsey-Musolf, Shelton, PRD101 (2020) 115035

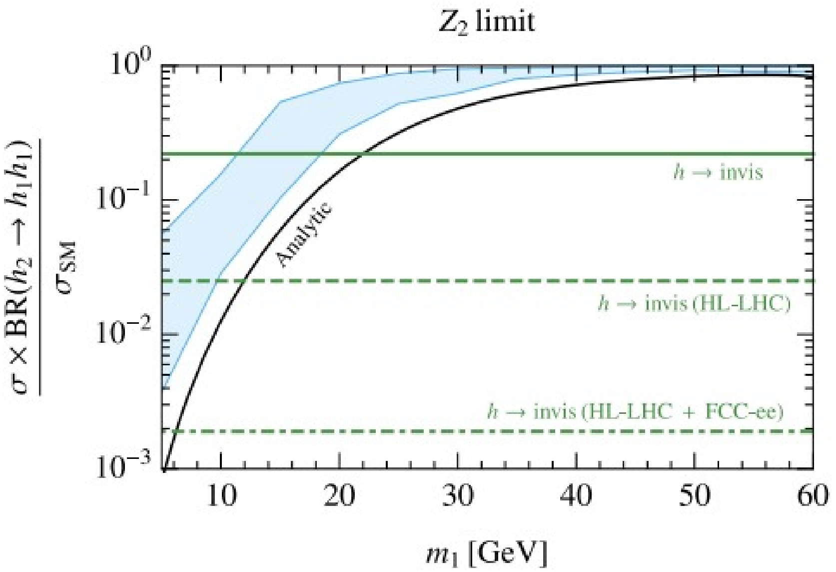
- Blue shaded regions: have a strong first order electroweak phase transition.
  - Need non-zero a2
  - Need non zero branching ratio for $h_1 \rightarrow h_2 h_2$
- a_2 (y-axis) can be quite small, hence Higgs coupling to two new scalars is small
  - In this parameter region have exotic Higgs decays.
  - Higgs couplings to all SM particle for mh=125 GeV are small.
  - Higgs has small width, so is sensitive to small coupling to new physics if it decays into it.

$$V \supset \frac{a_1}{2}|\Phi|^2 S + \frac{a_2}{2}|\Phi|^2 S^2$$

Kozaczuk, Ramsey-Musolf, Shelton, PRD101 (2020) 115035

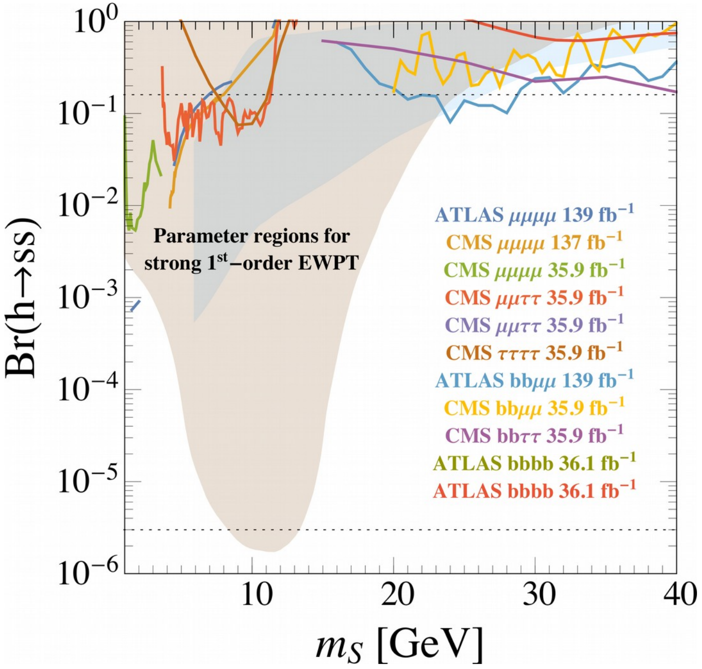
Invisible Higgs Decays+EWPT

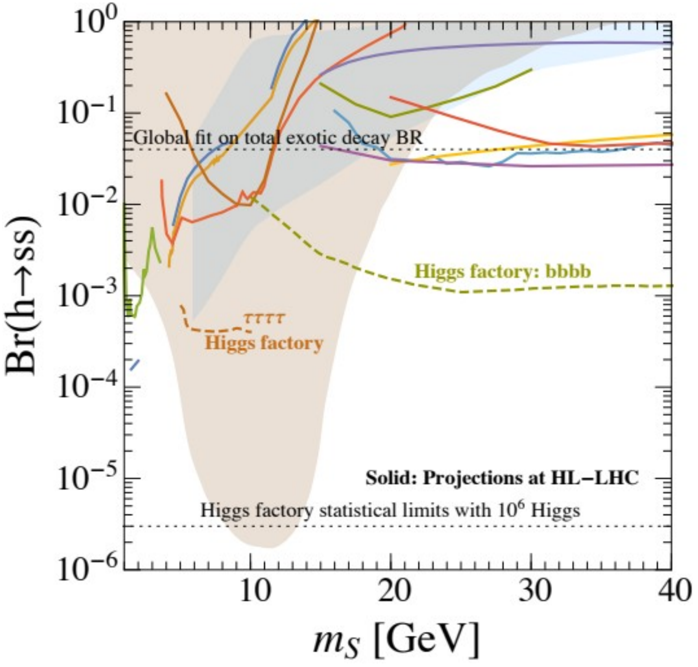




- Shaded region: strong first or EW phase transition.
- Need a non-zero resonant production in much of the parameter space.
- When there is no mixing with the SM Higgs, singlet doesn't couple to SM gauge bosons or fermions, so may not decay on collider time scales.
- Future searches can cover much of this parameter space.

Visible Higgs Decays+EWPT



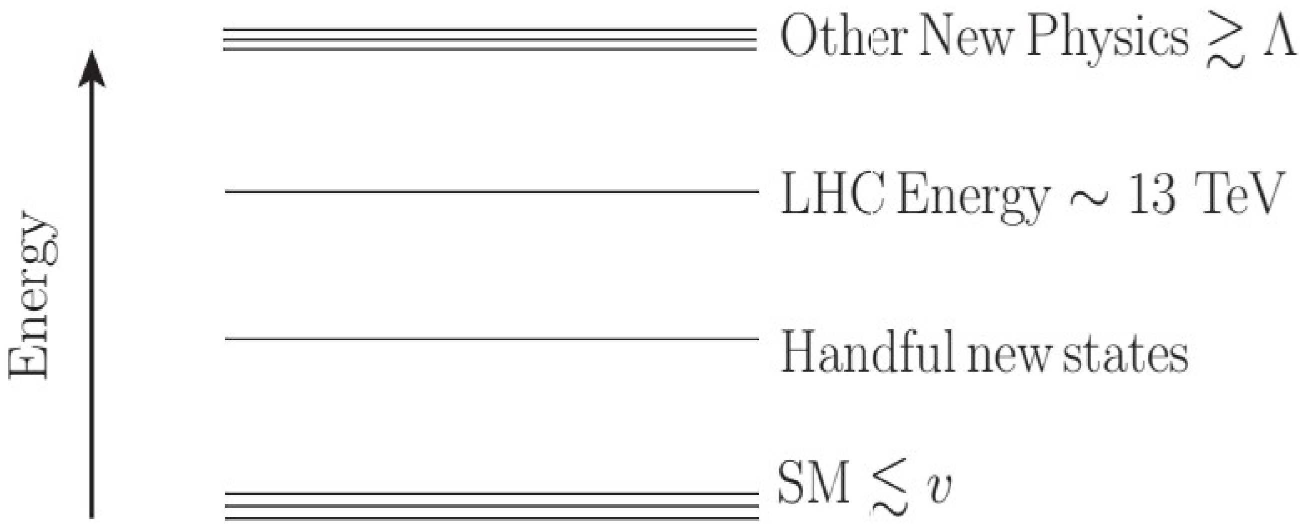


Carena et al, arXiv:2203.08206

- LHC current and future constraints.
- For more future Higgs factory searches see also Wang et al, arXiv:2203.10184

Word of Warning: Interpreting Results in Simplified Models

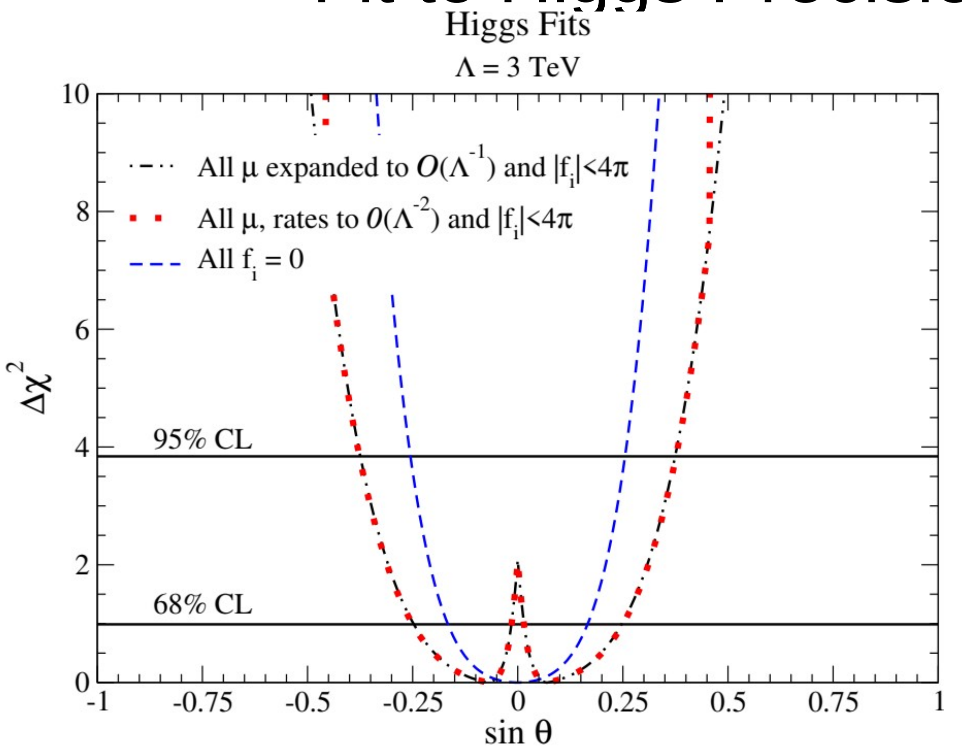
- Previous results are from adding a few new particles to the SM in the TeV.
- Implied assumption to these simplified models is that all other new physics and heavy and decoupled.
- This can be tested via an effective field theory:
  - Often get new phenomena, or different interpretations of data.

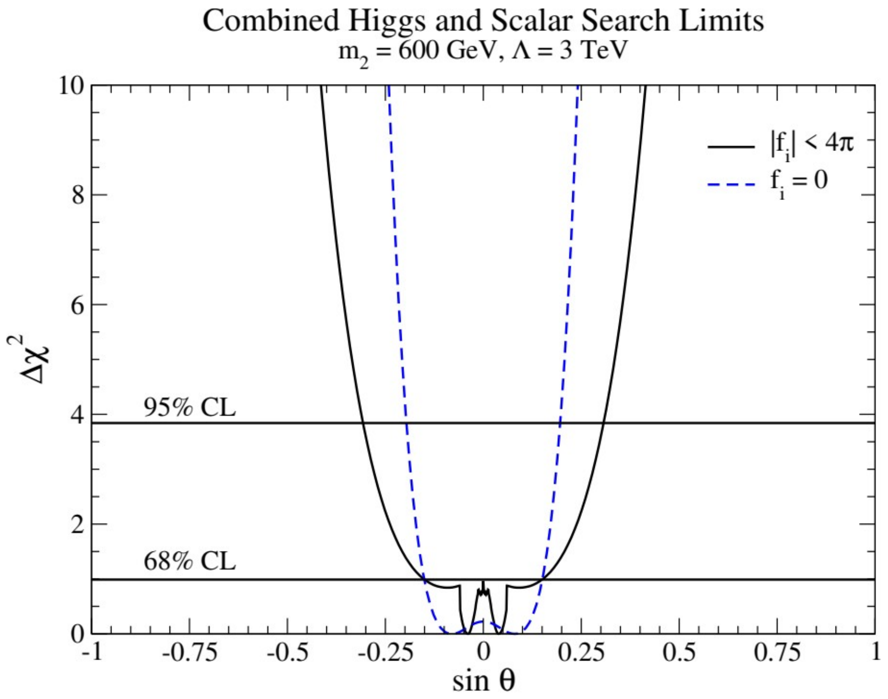


$$L = L_{simplified} + \sum_k \frac{c_{1,k}}{\Lambda} O_{1,k} + \sum_k \frac{c_{2,k}}{\Lambda^2} O_{2,k} \cdots$$

Adhikari, IML, Sullivan, PRD (2021) 075027; Alhazmi, Kim, Kong, IML JHEP 01 (2019) 139; JHEP 01 (2020) 057; Anisha, Das Bakshi, Chakrobortty, Prakash JHEP 09 (2019) 035; Banerjee, Chakrabortty, Prakash, Rahaman, Spannowsky JHEP 01 (2021) 028; etc.

Fit to Higgs Precision Data+Direct Searches





Adhikari, **IML**, Sullivan, PRD (2021) 075027

At dimension-5, singlet scalar has new effective interactions with SM gauge bosons and fermions.

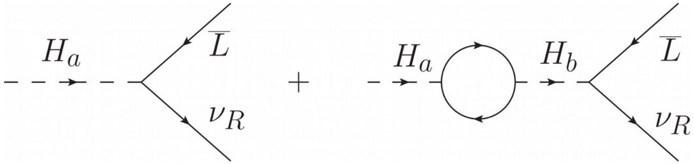
- Blue dashed: no effective interactions.
- Black/red: effective interactions profiled over.
- New physics pushed to 3 TeV makes a considerable difference.

Baryogenesis from Higgs Decays

Davoudiasl, **IML**, Sullivan,
PRD101 (2020) 055010,
PRD104 (2021) 015024

Baryogenesis From Higgs Decays

- Asymmetry decay of a heavy doublet into leptons can create a lepton asymmetry that becomes a baryon asymmetry:



- Asymmetry parameter that governs the magnitude of the baryon asymmetry generated:

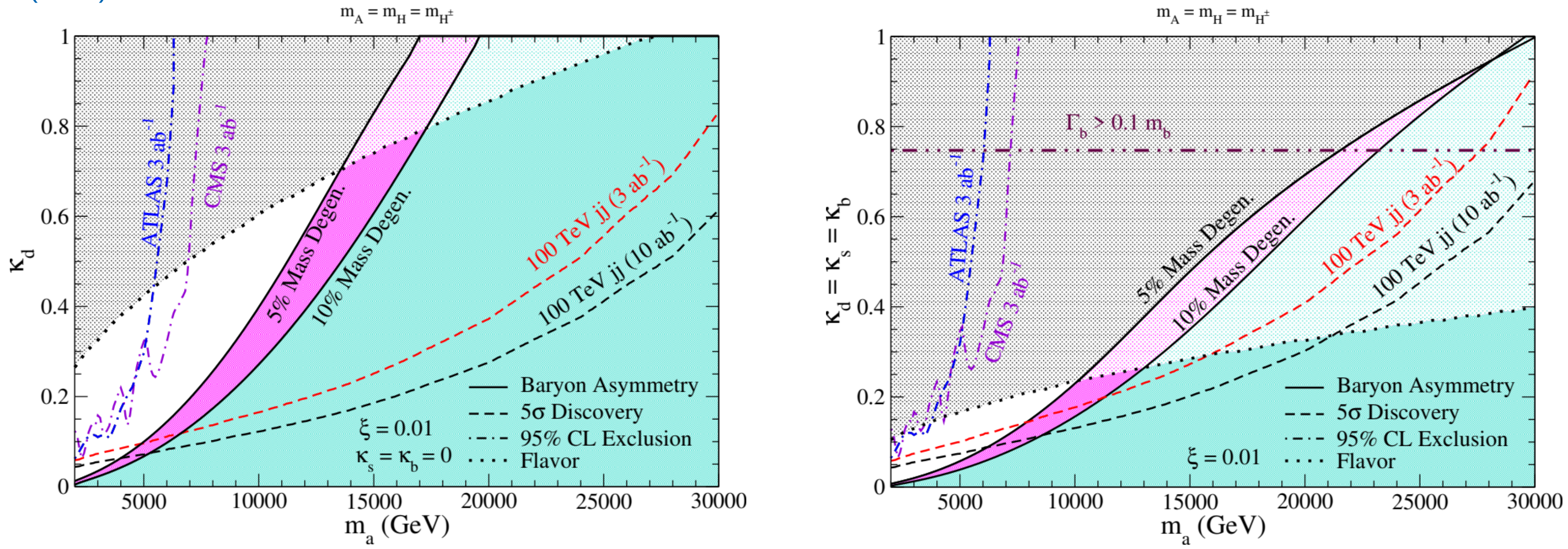
$$\varepsilon_a = \frac{1}{8\pi}\frac{(m_b^2 - m_a^2)m_a^2}{(m_b^2 - m_a^2)^2 + m_b^2\Gamma_b^2}\frac{\sum_{f=q} N_{c,f}\mathrm{Im}\left(\mathrm{Tr}_\nu^{ba}\mathrm{Tr}_f^{ba*}\right)}{\sum_{f=q} N_{c,f}\mathrm{Tr}_f^{aa}}$$

- Need two extra Higgs doublets in order to overcome small SM Yukawas.
  - The Higgs Troika.
  - (For a 2HDM that relies on highly degenerate neutrinos see Hambye, Teresi, PRL117 (2016) 091801, PRD96 (2017) 015031)
- This model can have large couplings between the extra Higgs doublets and SM light quarks.
  - Two flavor structures were studied.
  - One was spontaneous flavor violation where the Yukawas are diagonal or proportional to SM Yukawas.
- Hence, at colliders can have large rates via s-channel production through light quark/anti-quark annihilation:

$$q'\bar{q} \rightarrow H, A, H^{\pm}.$$

Davoudiasl, **IML**, Sullivan,
PRD101 (2020) 055010,
PRD104 (2021) 015024

Baryogenesis from Higgs Decays



- All else being equal, asymmetry prefers a degeneracy in masses. It is maximized when

$$\frac{m_a}{m_b} = \pm \frac{\Gamma_b}{2\, m_b}$$

- Depending on couplings can have TeV doublets that generate the baryon asymmetry.

Summary

- LHC has had successful runs, although no BSM discoveries so far.
- In this talk we studied several scenarios:
  - Well known simplified models whose phenomenology changes dramatically when slightly perturbed.
  - Models in which we have yet to get to the much of the “interesting” parameter region.
- Vector-like top partners:
  - Addition of a scalar singlet introduces new decay and production modes.
  - New channels to search for.
  - These additions are ubiquitous in composite models. Banerjee et al. 2203:07270 [hep-ph] and refs. therein
- Matter/anti-matter asymmetry:
  - Much of the parameter space in scalar extensions that give rise to a strong first order electroweak phase transition is yet to be explored.
  - Need resonant and non-resonant searches for production new scalars.
    - Scalars above and below the Higgs mass.
  - Can have interesting models with TeV scale Higgses that can generate the matter anti-matter/symmetry that can appear in surprising channels.

Summary

- It can be fruitful to study beyond the SM EFTs:
  - Just like SMEFT, they are inevitable in simplified models.
  - Can give rise to new phenomenology, and change our interpretations of current measurements.
- Many other scenarios not talked about here:
- New vector-like quarks could be charged under a new U(1).
  - Vector-like quarks could decay into new gauge bosons and Higgses:

    $$T \to t\,\gamma_d\,,\quad T \to t\,h_d$$

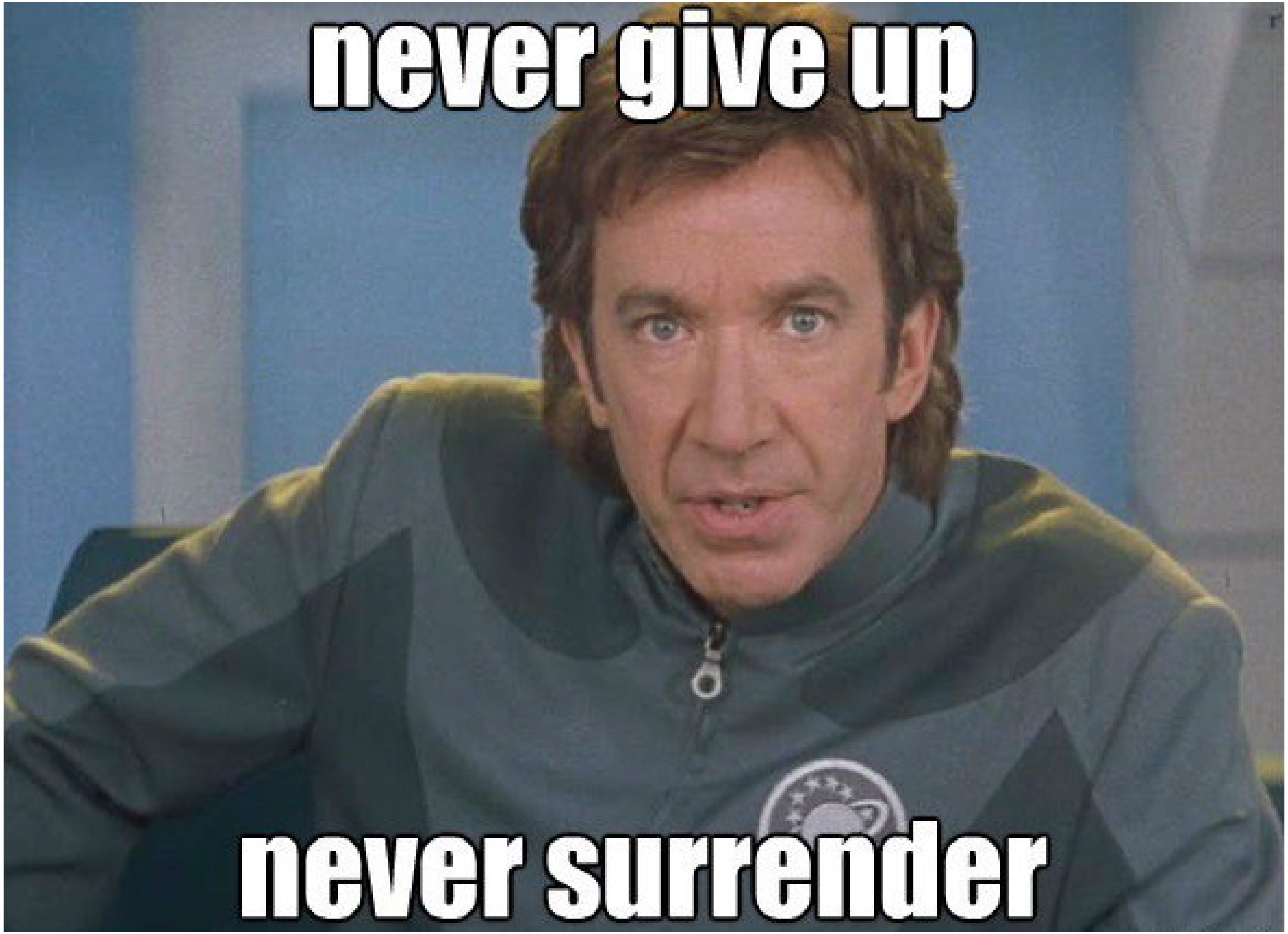
  - If the vev of the new Higgs is smaller than the EW vev, can easily be dominant branching ratio.
    - $\Gamma(T \to t\,h) \sim \Gamma(T \to t\,V) \sim M_T^3 / v^2$
  - Could discover a light dark photon through decays of a heavy VLQ.
    - If light enough, one of the dominant decays of a VLQ could be into lepton jets.

Rizzo, PRD99 (2019) 115024
Kim, **IML**, et al. PRD101 (2020 035041
Bhardway et al, 2204:09005 [hep-ph]

- Vector-like quarks + 2HDM:

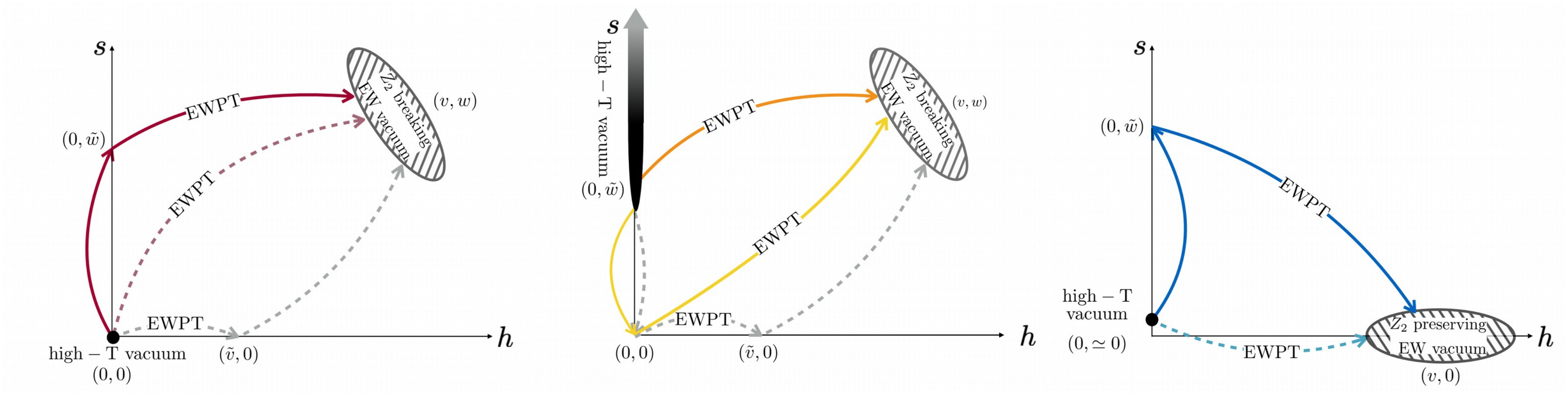
Dermisek et. al. 2203.03852 and references therein

  - VLQs can decay into the 2nd Higgs doublet leading to surprising signatures.
  - Could singly produce 2nd Higgs doublet that then decays int the VLQs
- There are many additional scenarios to search for new physics at the LHC.


never give up
never surrender

Extra Slides

Symmetry Non-Restoration

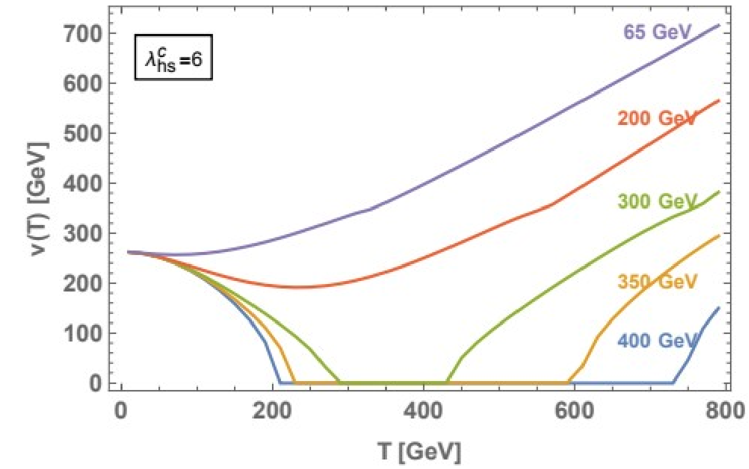


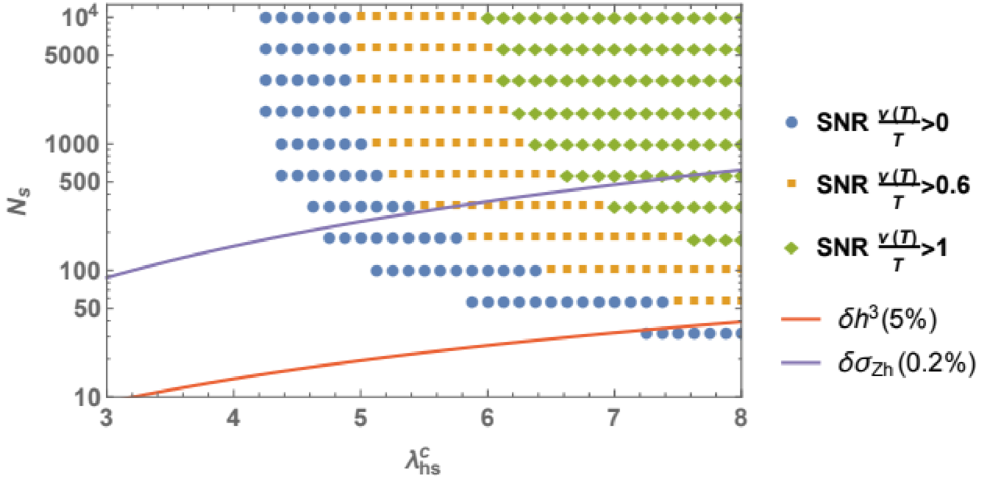
Carena et al, arXiv:2203.08206

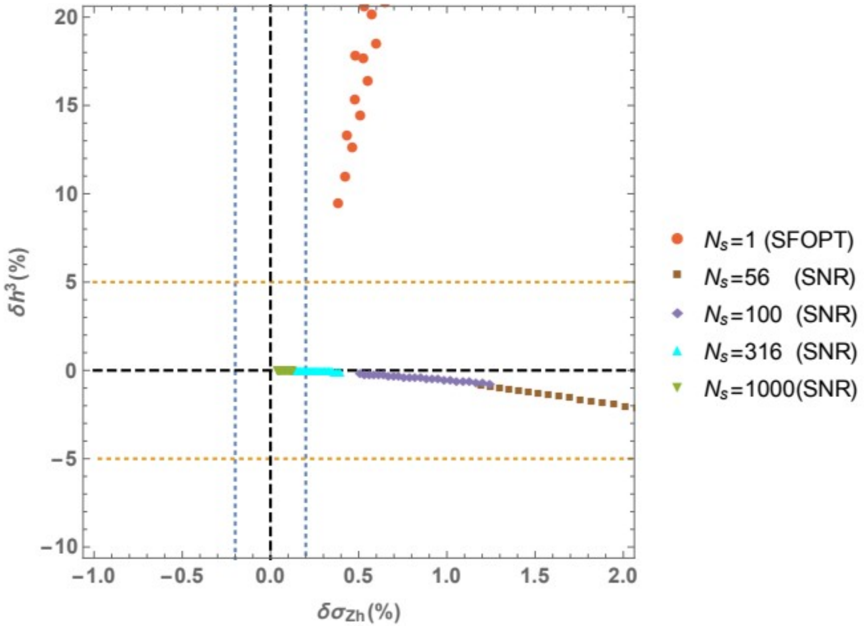
- Electroweak symmetry breaking may not be a simple pattern.
- There are scenarios in which the symmetries are not restored at low temperatures.
- Electroweak symmetry itself may not be restored at high energies.
- Weinberg PRD9 (1974) 3357; Mohapatra, Senjanovic,PRD20 (1979) 3390, etc.
- Can help avoid constraints from EDMs by moving EW symmetry breaking to much higher temperatures.

Meade, Ramani, PRL122 (2019) 4

EW Symmetry Non-Restoration







- Can be hard to probe at colliders
- Need many new degrees of freedom.

Baldes, Servant, JHEP10 (2018) 053; Glioti, Rattazzi, Vecchi, JHEP04 (2019) 027; Carena, Krause, Liu, Wang, PRD104 (2021) 5

Collider Searches at 100 TeV with 30 ab^{-1}

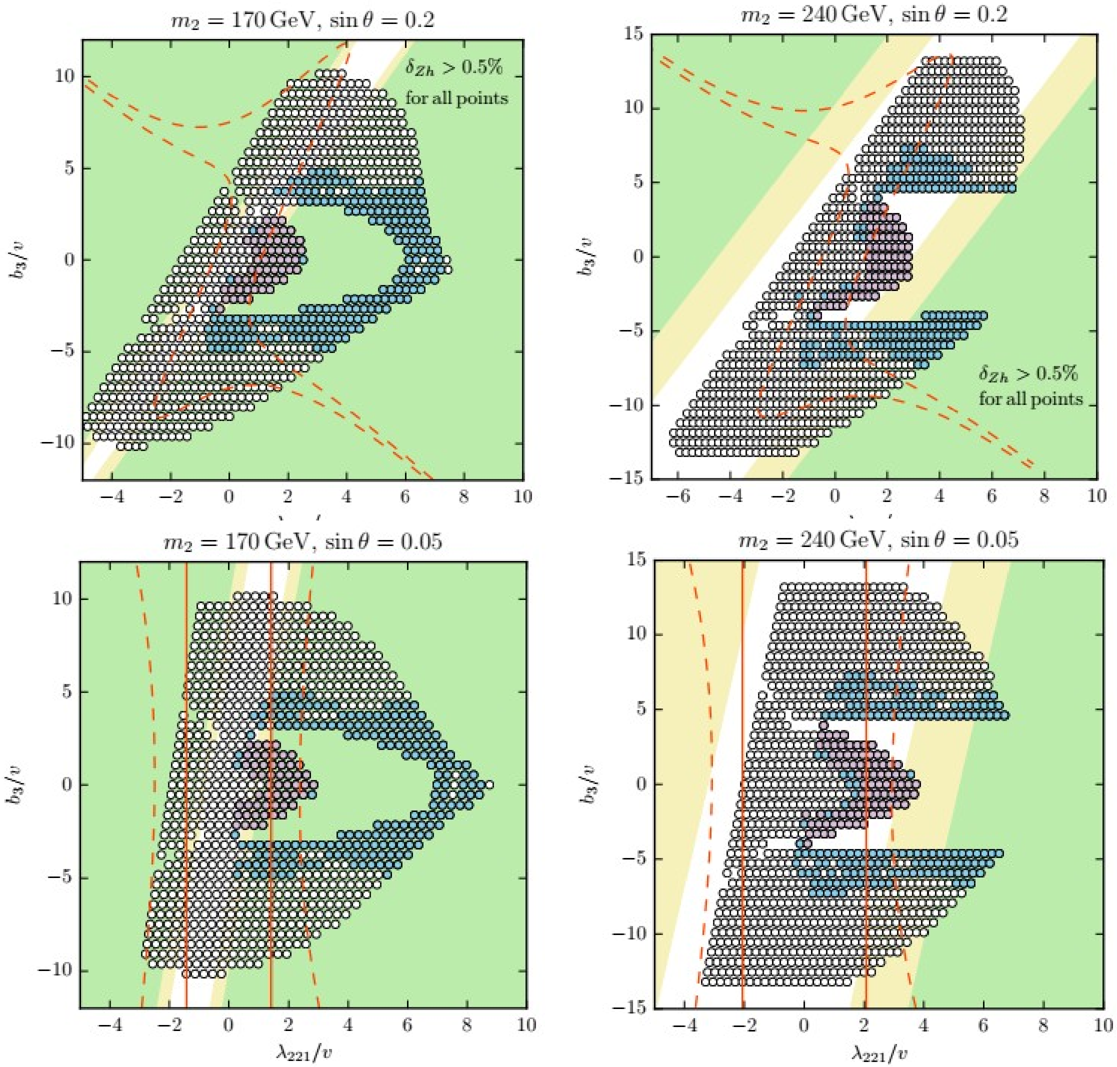
- Considered the production and decay mechanism

$$pp \to h_2 h_2 \to 4W$$
$$\to (2j)(2l^{\pm})l'^{\mp}(3\nu)$$
$$l \neq l'$$

- Yellow: 2 sigma exclusion.
- Green: 5 sigma discovery
- Red dashed: Higgs trilinear with 30% of SM prediction.
- Red Solid: Z-h coupling shift by 0.5%.
- Direct searches for heavy scalars can be sensitive to interesting regions of parameter space.

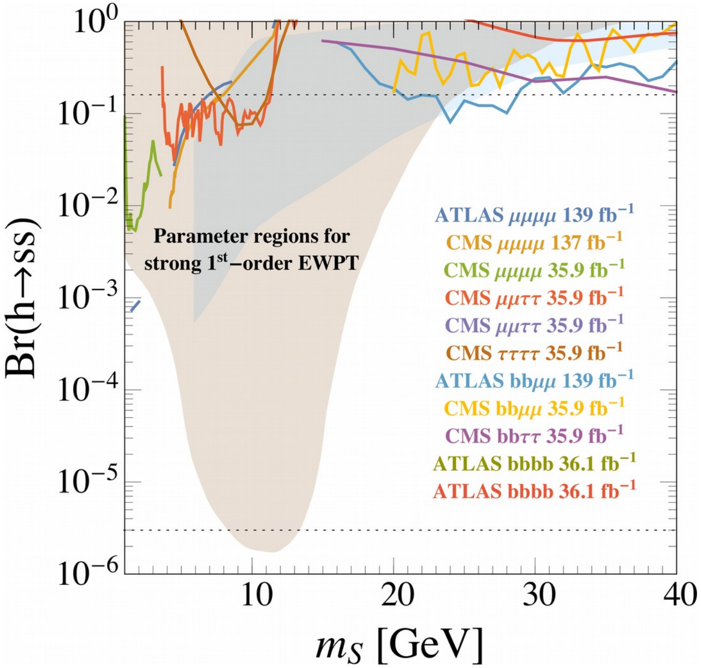
sin θ = 0.2:

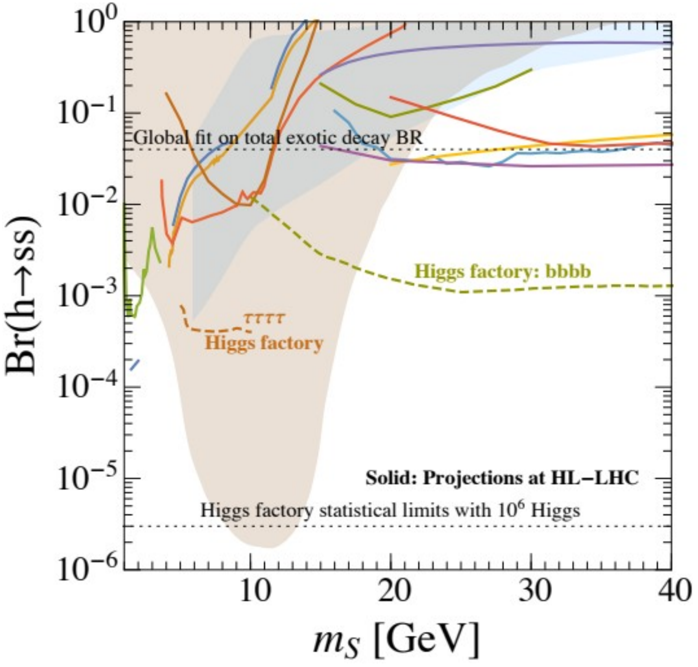
sin θ = 0.05:



Chen, Kozaczuk, **IML** JHEP 08 (2017) 096

Visible Higgs Decays+EWPT





Carena et al, arXiv:2203.08206

- LHC current and future constraints.
- For more future Higgs factory searches see also Wang et al, arXiv:2203.10184