BSM Higgs

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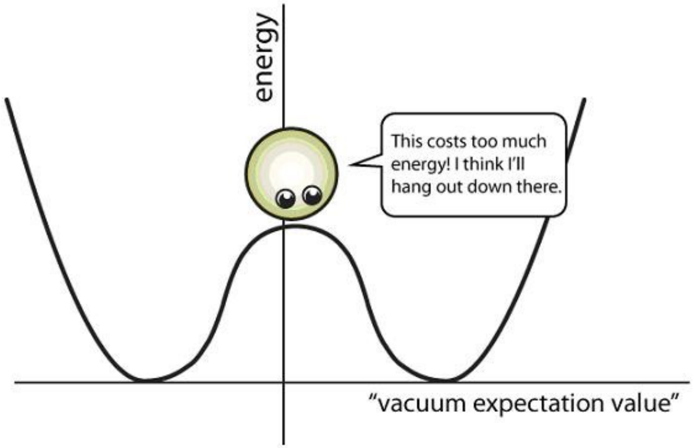
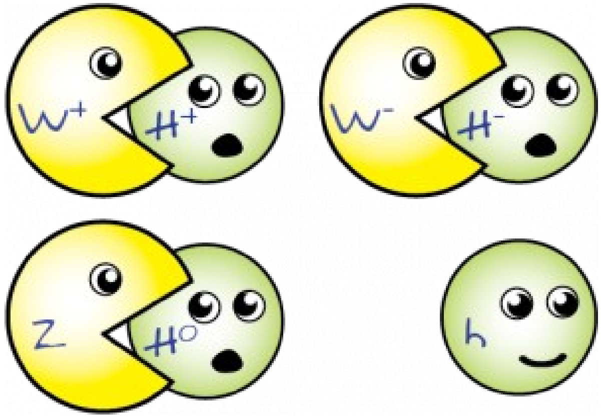
Motivation

- Why BSM Higgs?
  - Higgs very important, it is at the center of electroweak symmetry breaking.
  - All precision measurements look Standard Model like so far, but
  - Might expect deviations from the typical Standard Model electroweak symmetry breaking mechanism to appear in Higgs physics.
  - At the center of many BSM scenarios:
    - Electroweak baryogenesis.
      - Interesting because need new
    - Higgs Portals.
    - Connection to DM physics.



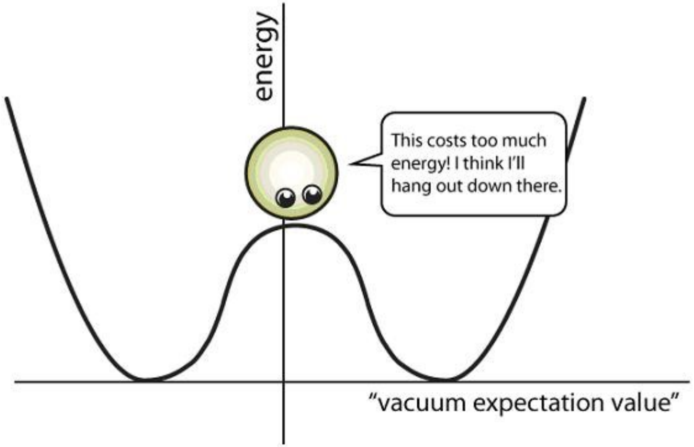


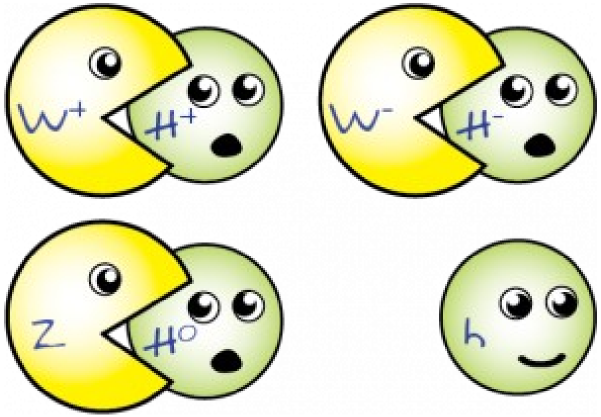
Motivation

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

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

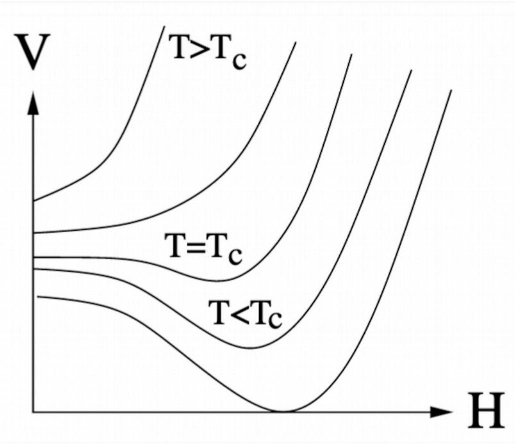
  - Scalar extensions are simple extensions of the SM that can provide a lot of interesting phenomenology.
  - They can also help solve many particle physics problems.
- This talk: interpret BSM Higgs as (mostly) new scalars.
  - Discuss why they're interesting.
  - Interesting signatures to search for.
  - 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.

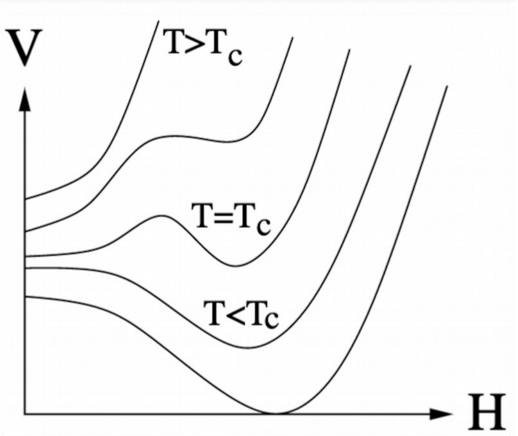




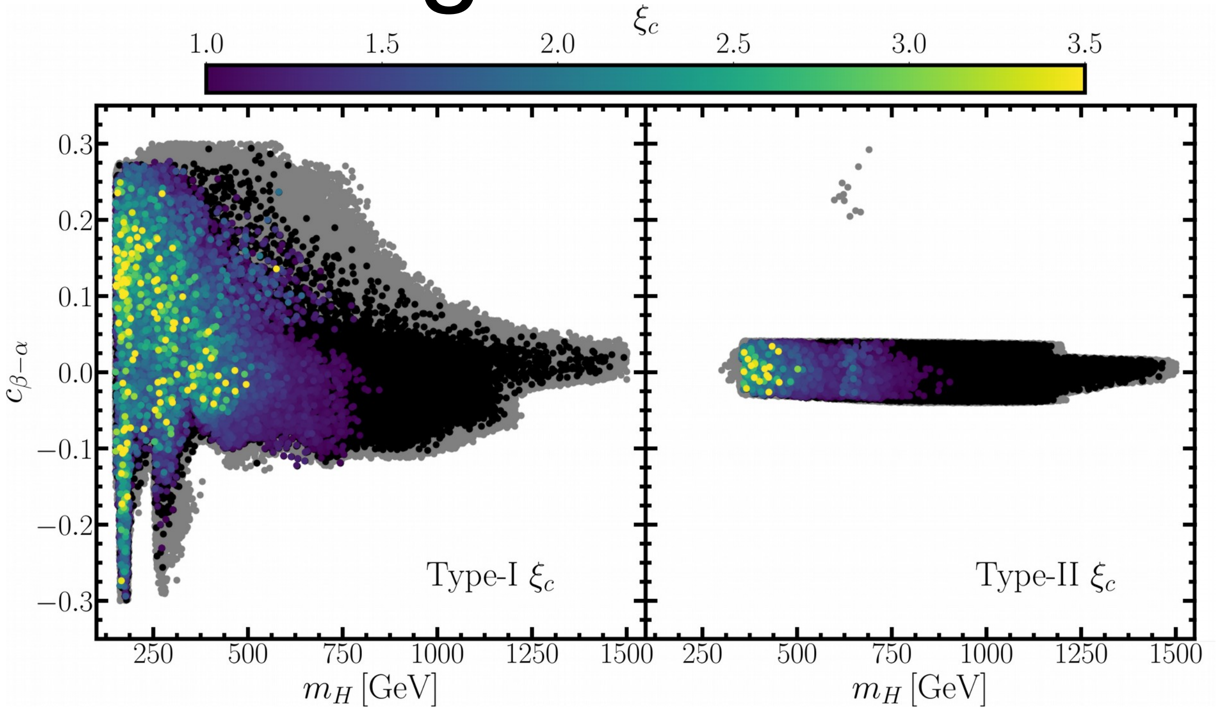
Thermal History of the Universe: Strong First Order EWPT

- 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.





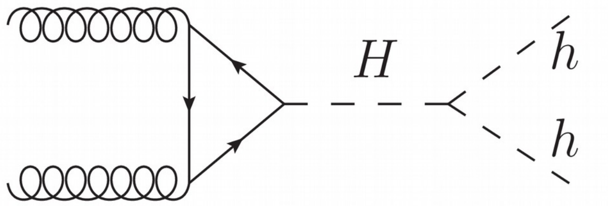
2HDM Strong First Order EWPT

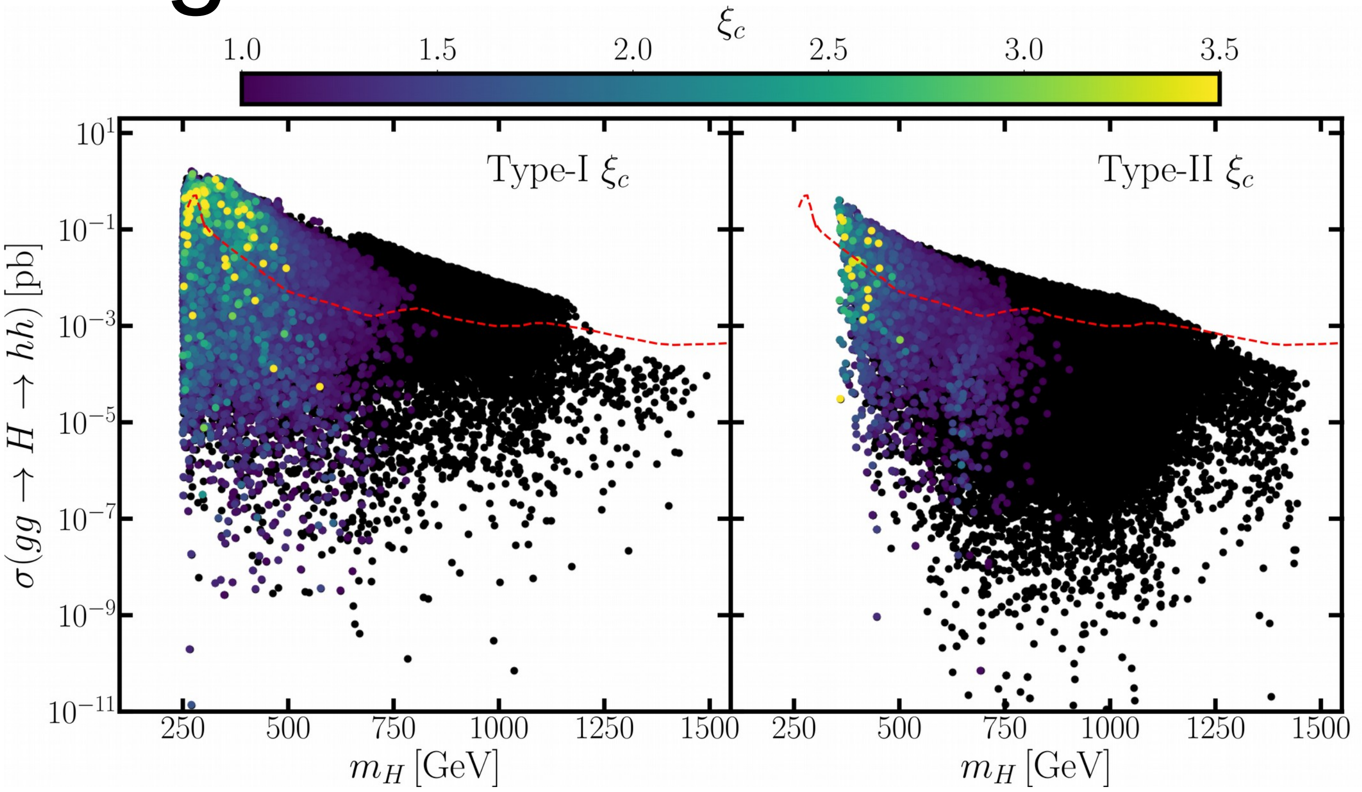


Gonçalves, Kaladharan, Wu PRD105 (2022) 095041

- 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

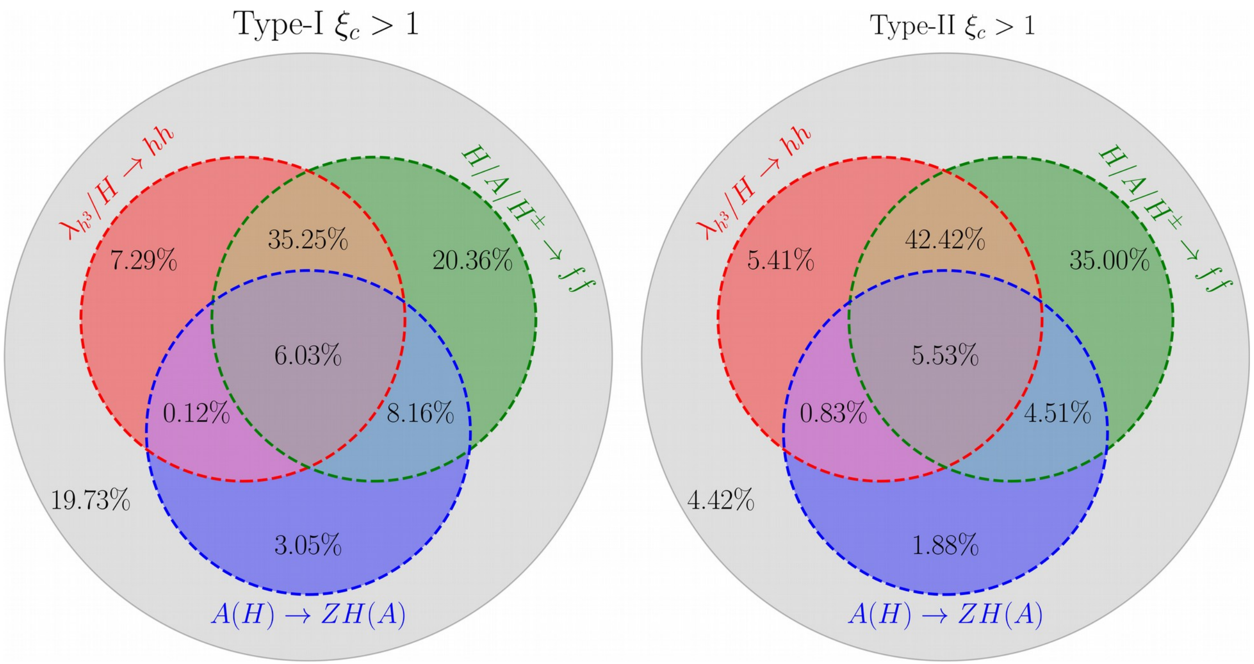




Gonçalves, Kaladharan, Wu PRD105 (2022) 095041

- 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:

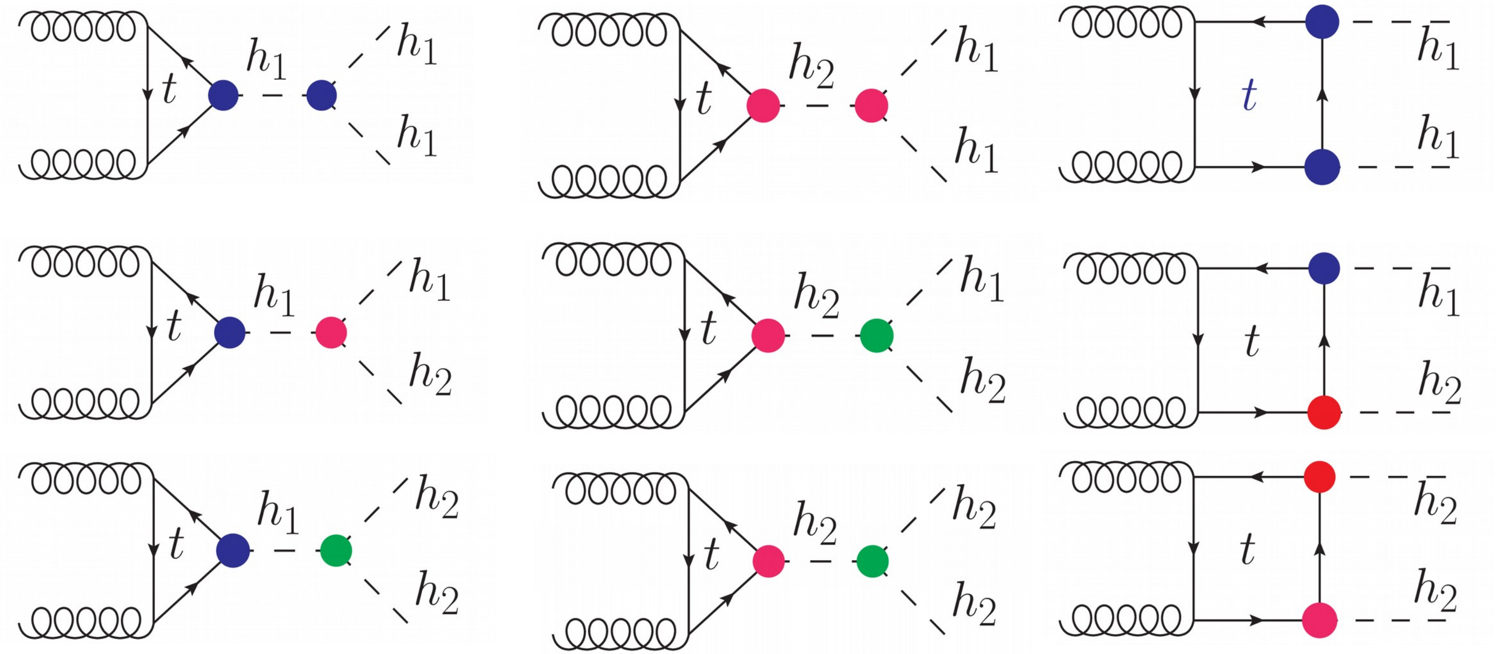
$$V \supset \frac{a_1}{2}|\Phi|^2 S + \frac{a_2}{2}|\Phi|^2 S^2 \supset \frac{a_1 v}{2} h S + \frac{a_1}{4} h^2 S + \frac{a_2 v}{2} h S^2$$

  - 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:

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

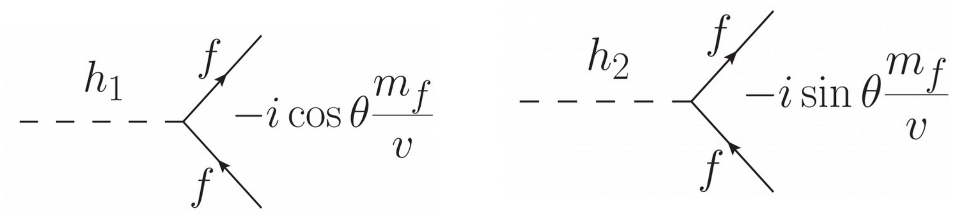
Di-Scalar Production

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



As mixing approaches zero:
Blue: Approaches SM Value
Red: Goes to zero
Green: New physics coupling that survives

- In zero mixing limit, only h_2h_2 production through s-channel h_1 give new physics contributions.
- Is sensitive to the coupling that drive the EWPT



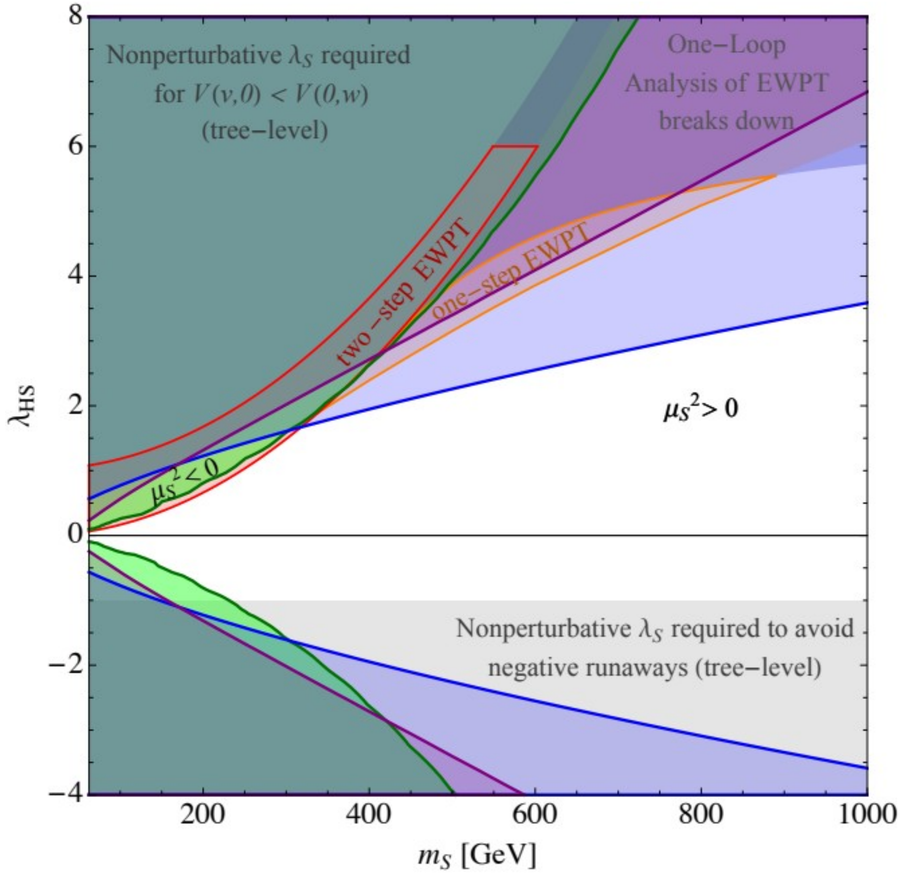
Curtin, Meade, Yu JHEP11 (2014) 127

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.

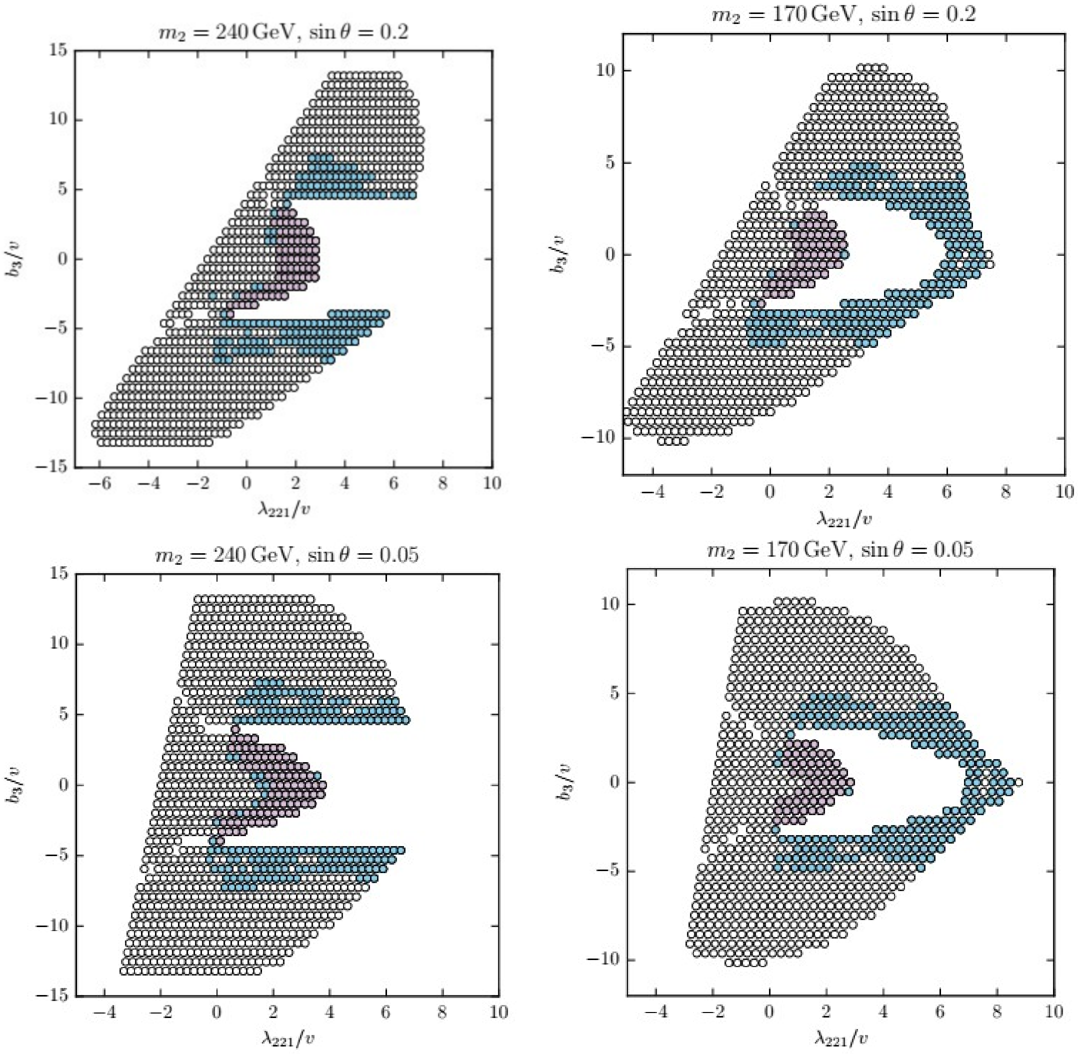


Di-Scalar Production and EWPT

- 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

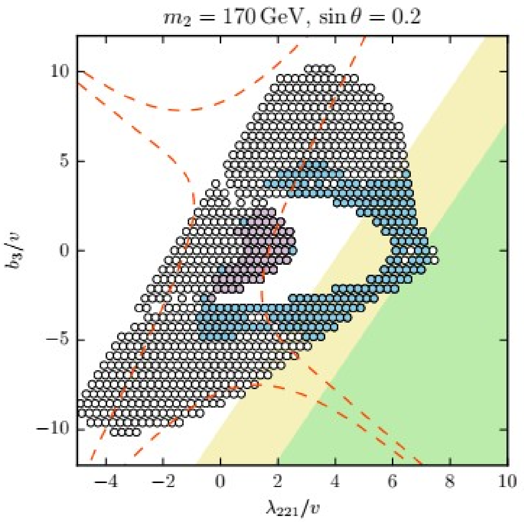
- Considered the production and decay mechanism

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

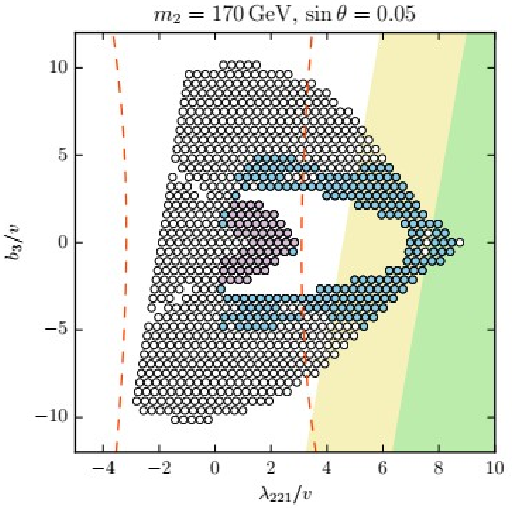
- At HL-LHC, considered m_2=170 GeV.
- Yellow: 2 sigma.
- Green: 5 sigma
- Red dashed: Higgs trilinear with 30% of SM prediction.
- Direct searches for heavy scalars can be sensitive to interesting regions of parameter space.

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

sin θ = 0.2:



sin θ = 0.05:



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

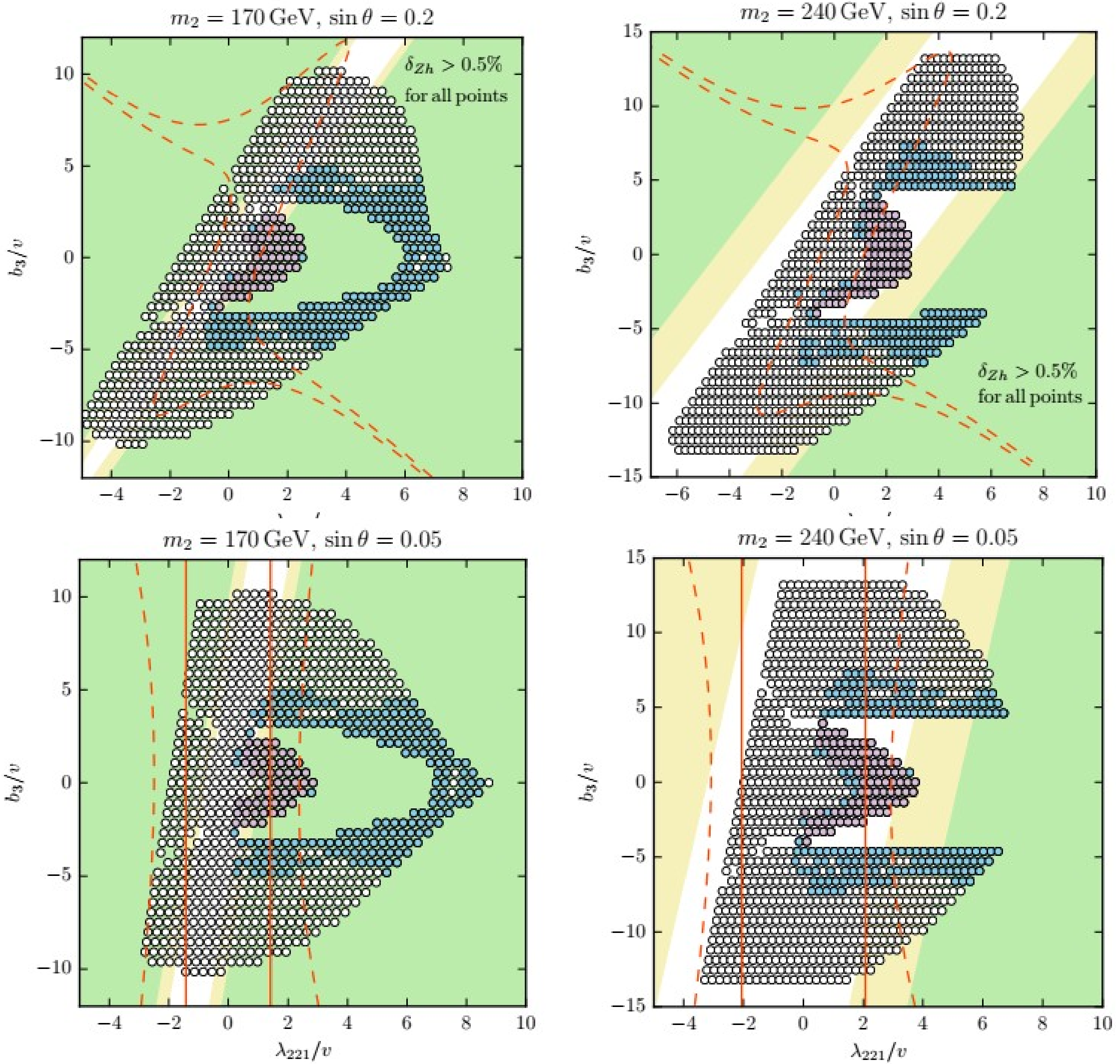
- Considered the production and decay mechanism

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

- 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

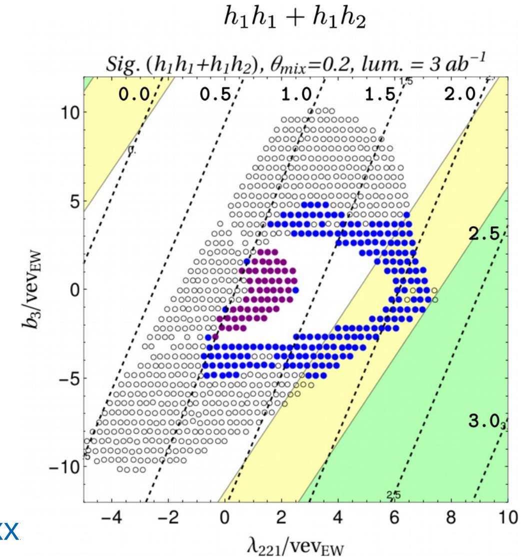
Collider Searches at HL-LHC

- 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.
  - 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:

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

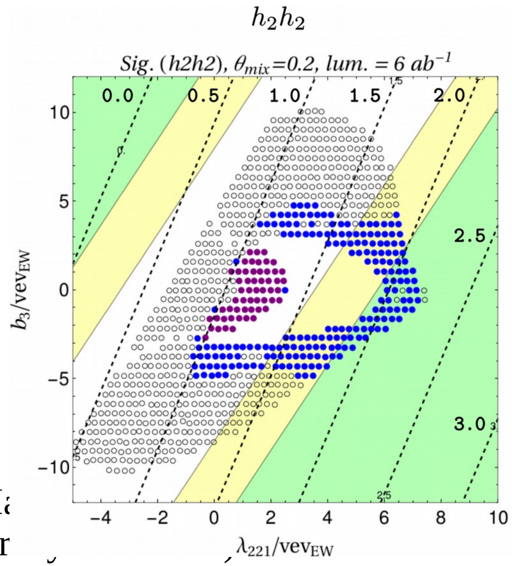
  - Likely to do better.
  - There's a caveat, though...

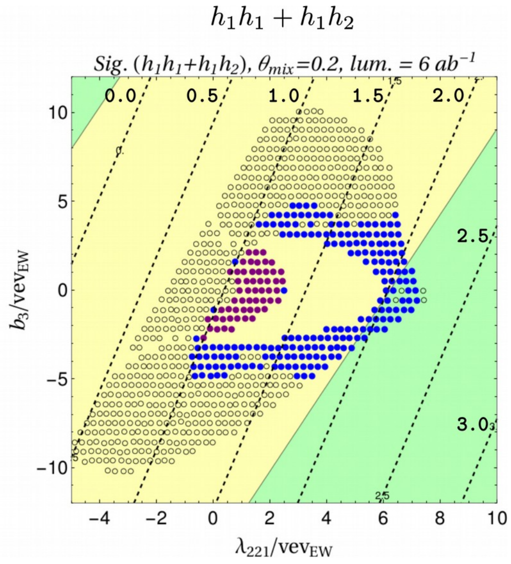
3 ab^{-1}:



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

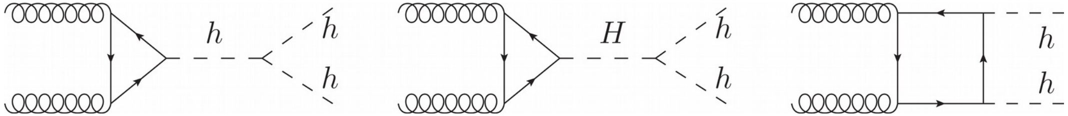
6 ab^{-1}



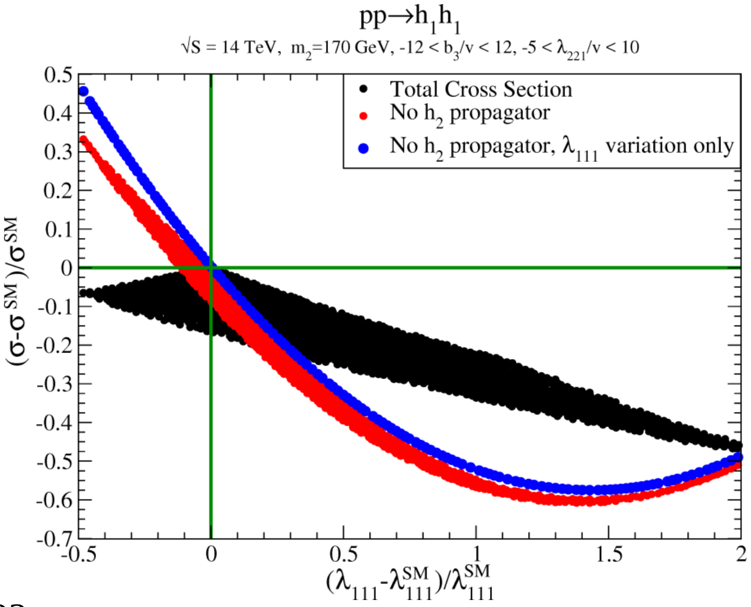


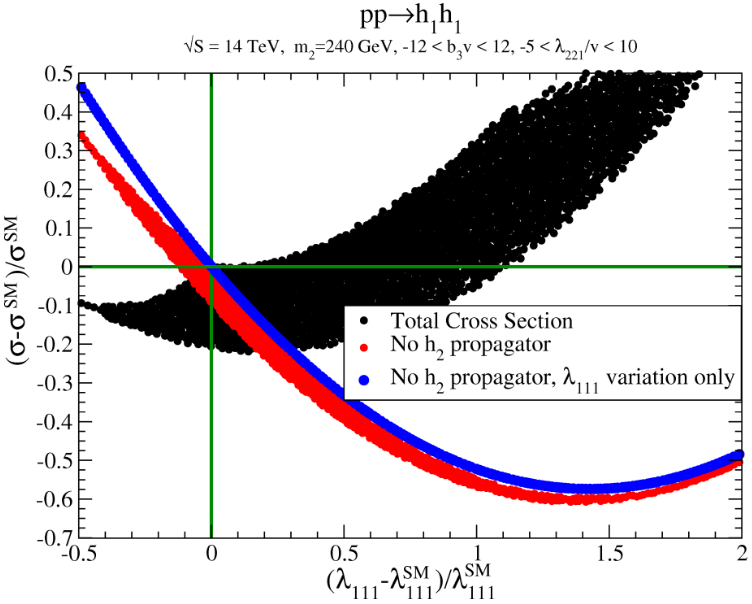
Cross Section vs. Higgs Trilinear: Non resonant production

- 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

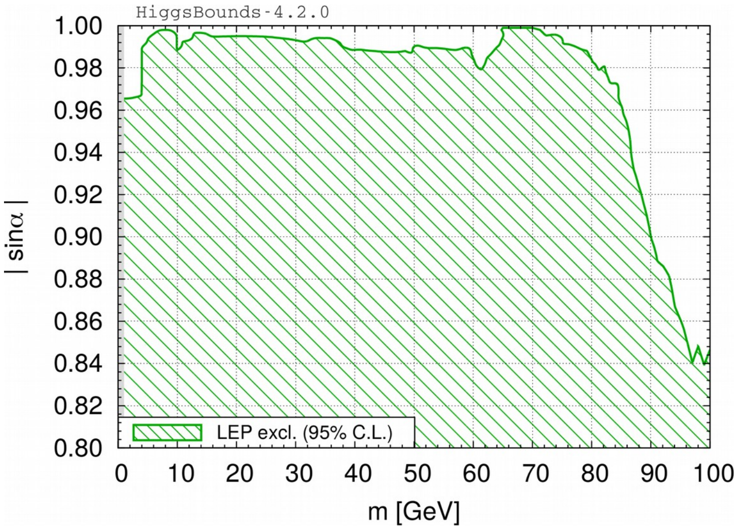




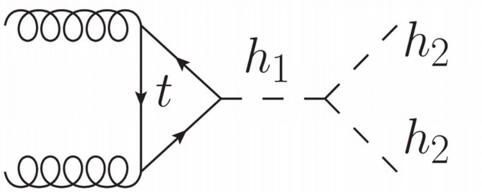
Exotic Higgs Decays

- 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.

$$h_1 \rightarrow h_2 h_2$$

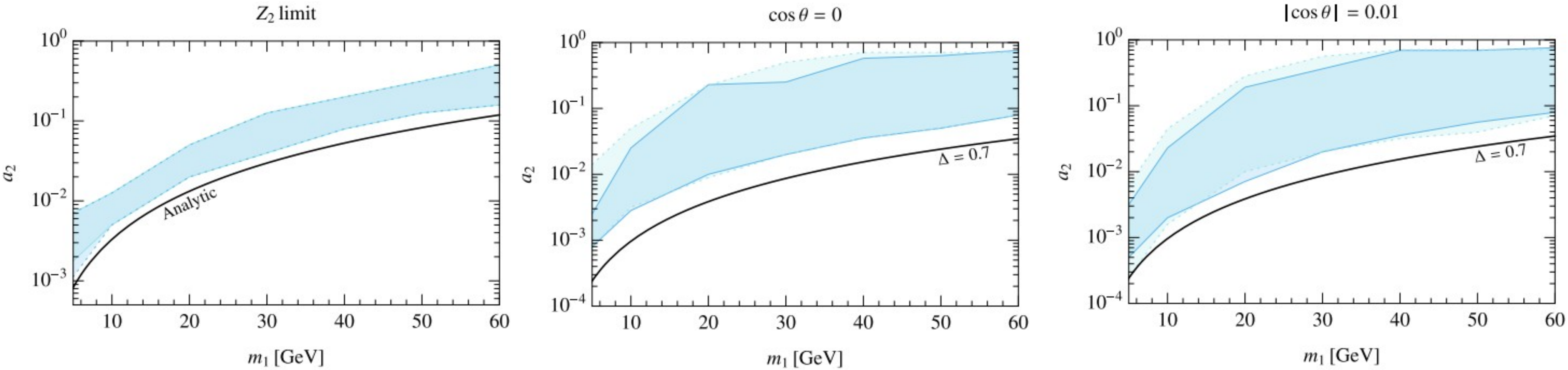


Robens, Stefaniak EPJC 75 (2015) 104



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

Exotic Higgs Decays+EWPT

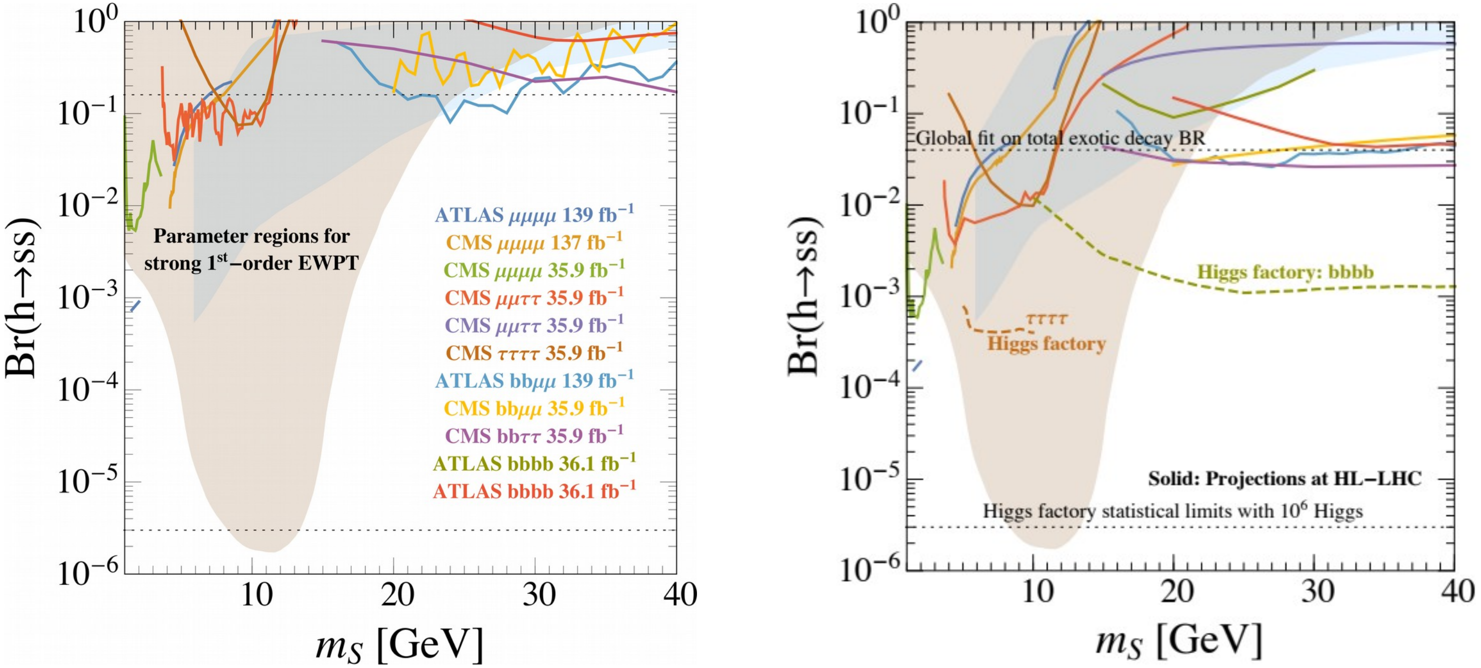


Kozaczuk, Ramsey-Musolf, Shelton, PRD101 (2020) 115035

- 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.

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

Visible Higgs Decays+EWPT

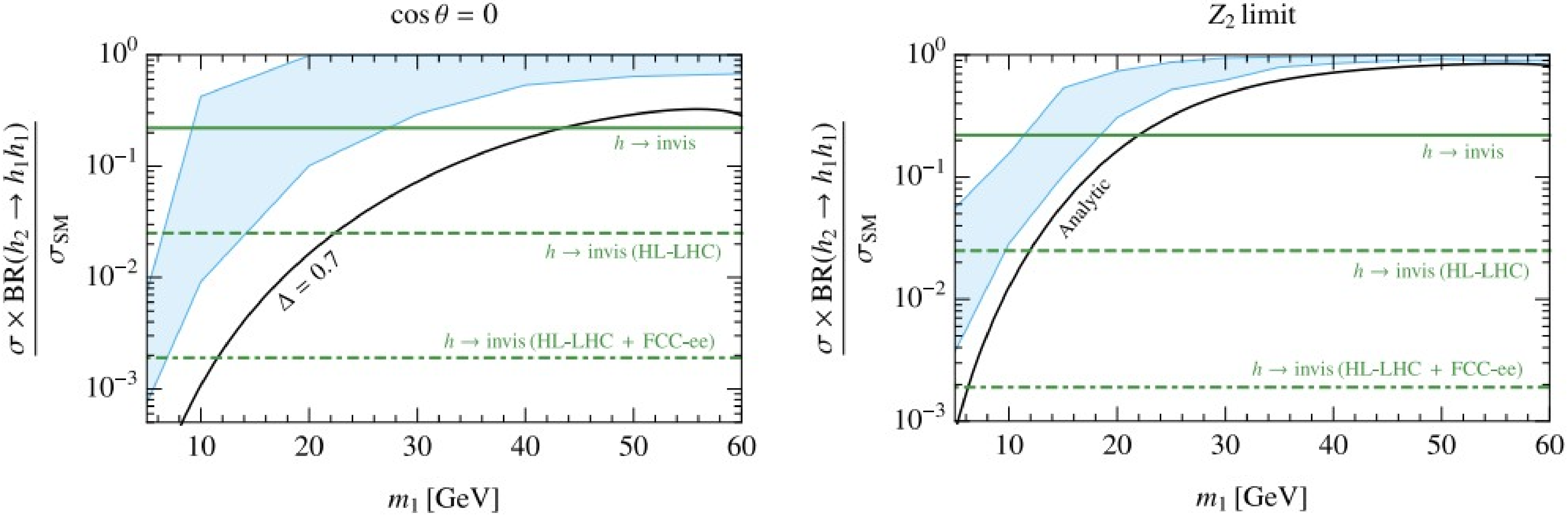


Carena et al, arXiv:2203.08206

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

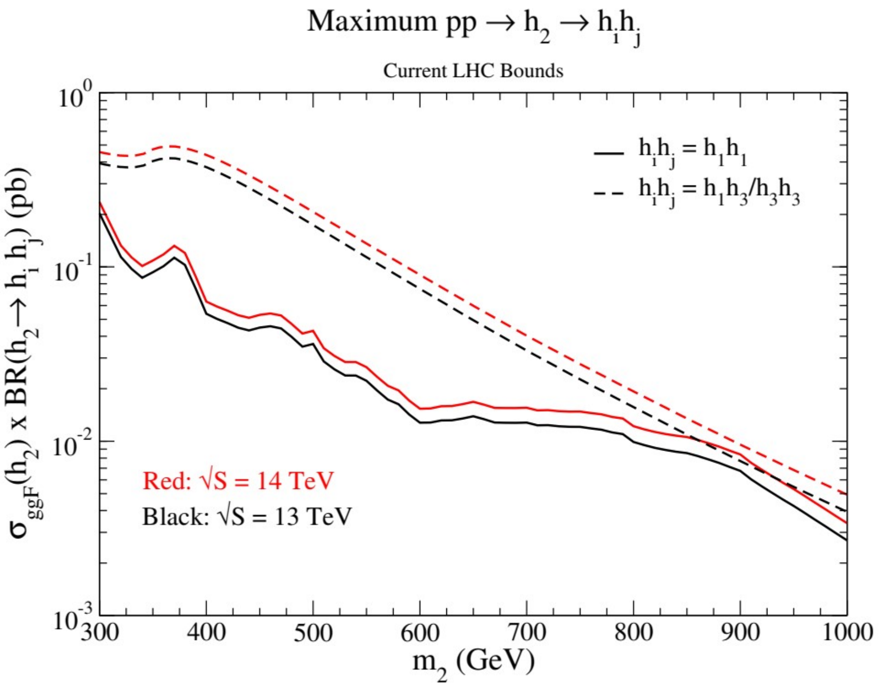
Invisible Higgs Decays+EWPT

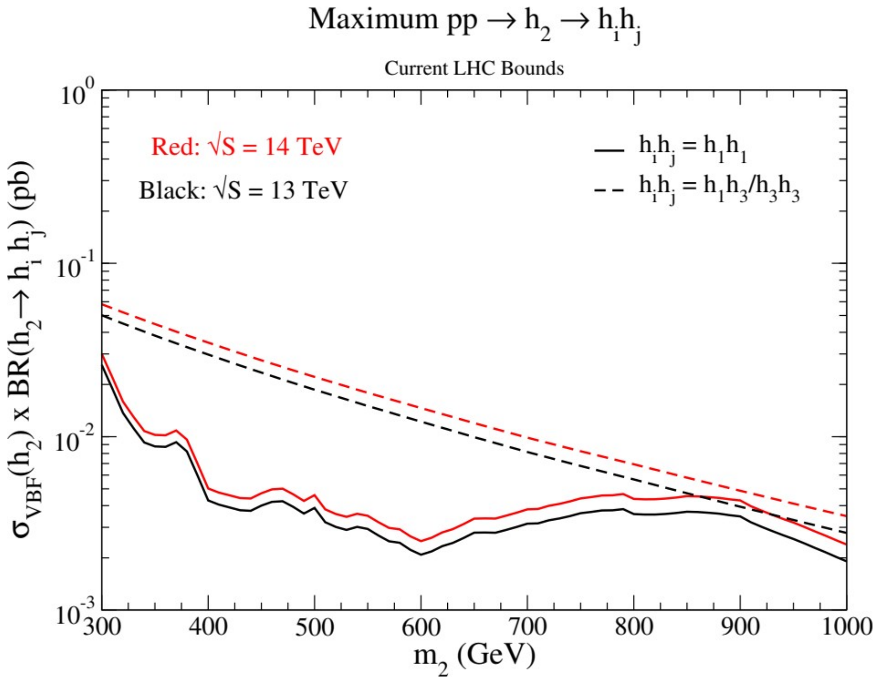
Kozaczuk, Ramsey-Musolf, Shelton, PRD101 (2020) 115035



- 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.

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.

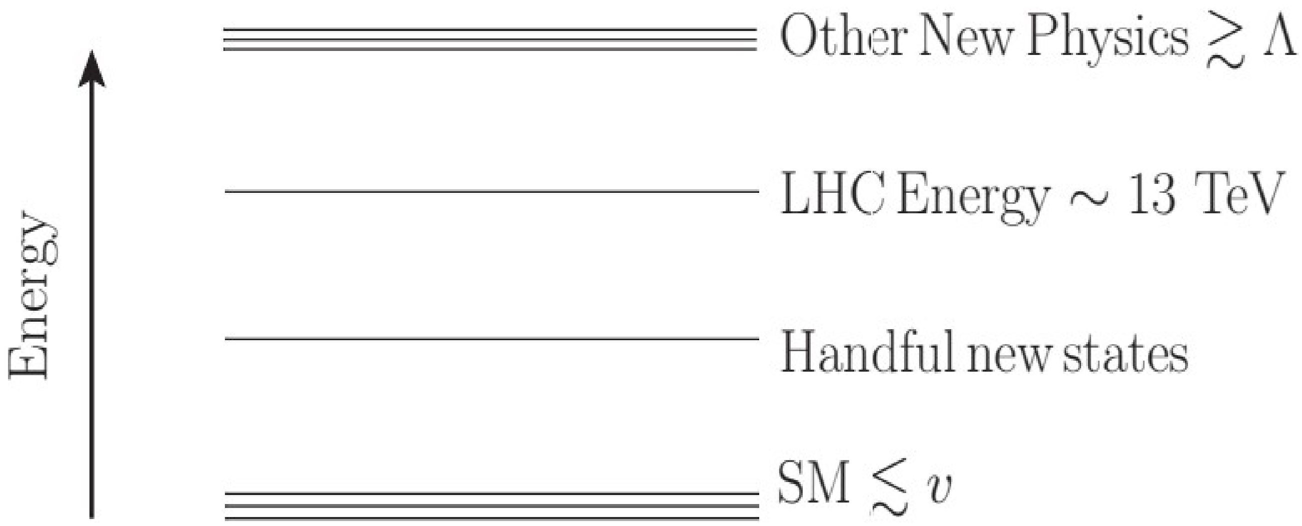
  Dawson, Sullivan, PRD97 (2018) 015022; Adhikari, Lane, **IML**, Sullivan, arXiv:2203.07455; Abouabid et al arXiv:2112.12515; Basler, Dawson, Englert, Mühlleitner, PRD101 (2020) 015019; Robens, Stefaniak, Wittbrodt, EPJC80 (2020) 151; etc.

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

  CMS arXiv:2204.12413; CMS JHEP09 (2021) 57

Word of Warning: Interpreting Results in Simplified Models

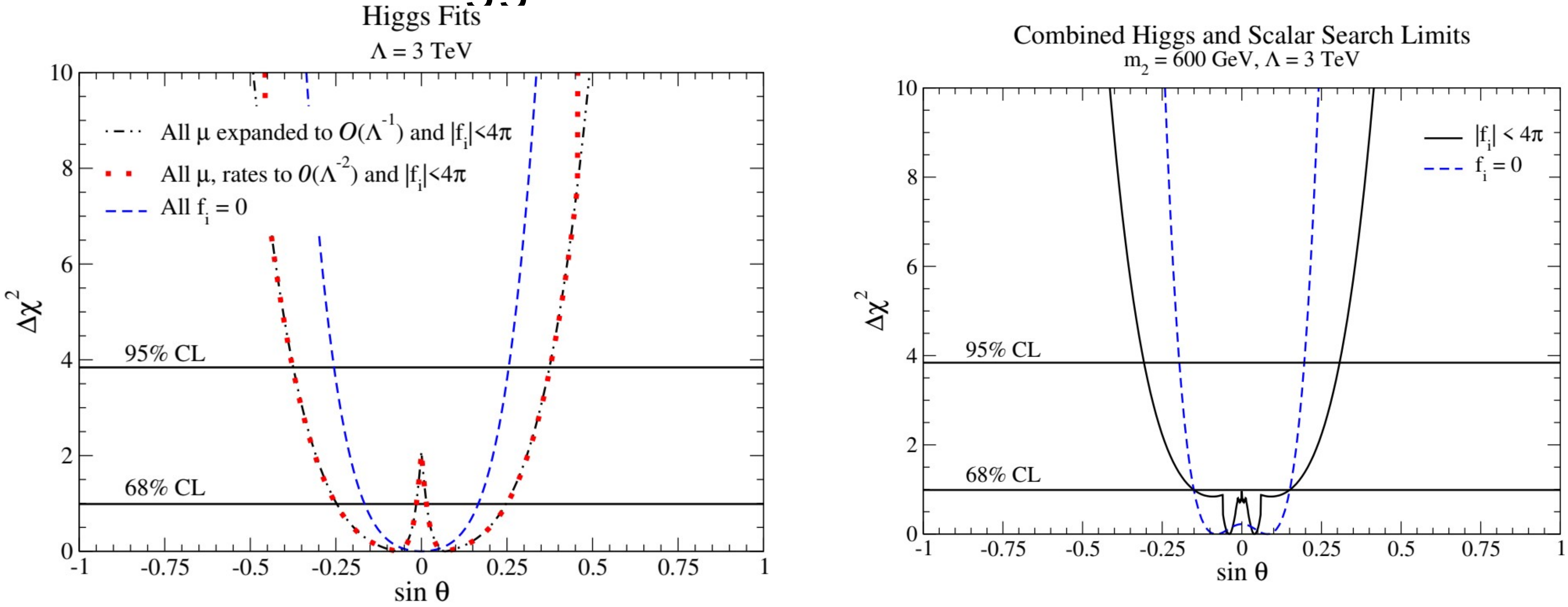
- Previous results are from adding a few new particles to the SM in the TeV.
- Implied assumption to these simplified models is that all other new physics and heavy and decoupled.
- This can be tested via an effective field theory:
  - Often get new phenomena, or different interpretations of data.



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

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**, Sulivan, PRD (2021) 075027

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

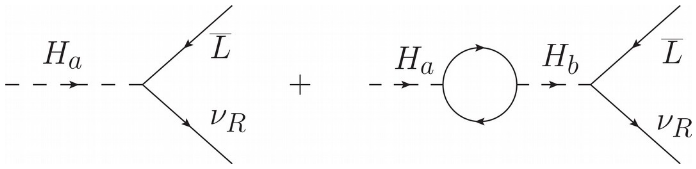
- Blue dashed: no effective interactions.
- Black/red: effective interactions profiled over.
- New physics pushed to 3 TeV makes a considerable difference.

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:

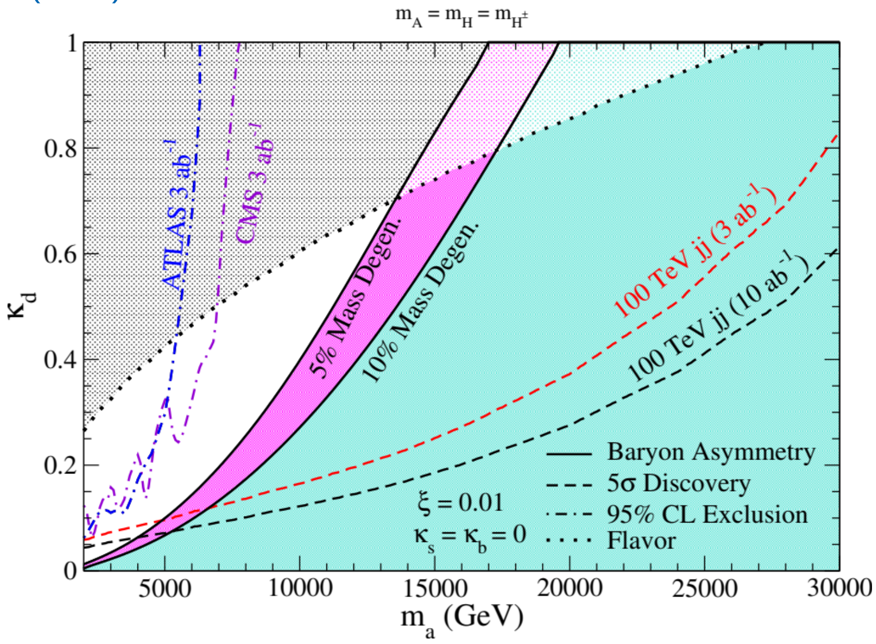
$$\varepsilon_a = \frac{1}{8\pi} \frac{(m_b^2 - m_a^2) m_a^2}{(m_b^2 - m_a^2)^2 + m_b^2 \Gamma_b^2} \frac{\sum_{f=q} N_{c,f} \mathrm{Im}\left(\mathrm{Tr}_\nu^{ba} \mathrm{Tr}_f^{ba*}\right)}{\sum_{f=q} N_{c,f} \mathrm{Tr}_f^{aa}}$$

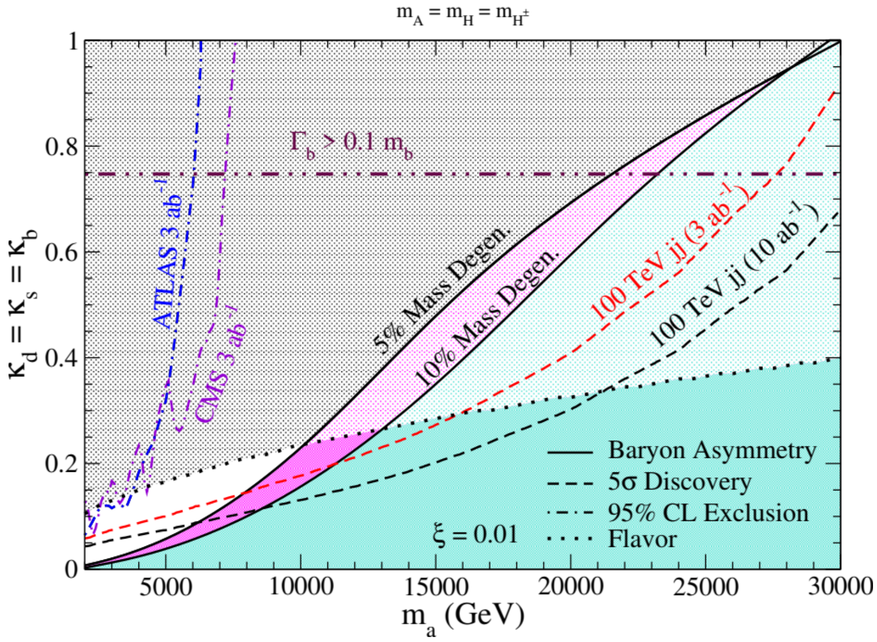
- Need two extra Higgs doublets in order to overcome small SM Yukawas.
  - The Higgs Troika.
  - (For a 2HDM that relies on highly degenerate neutrinos see Hambye, Teresi, PRL117 (2016) 091801, PRD96 (2017) 015031)
- This model can have large couplings between the extra Higgs doublets and SM light quarks.
  - 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.

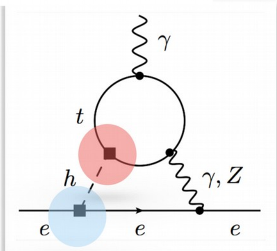
CP Violating Top Yukawa

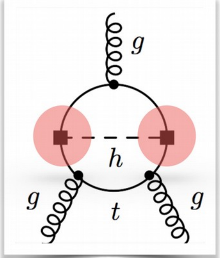
EDMs Strongly Constraining

- Slide from Dorival Gonçalves LHCP 2022 talk
- EDMs are indirect.
  - Depend on everything in the loop.
  - Turn off first generation Yukawas, relax constraints.
  - Need direct searches.

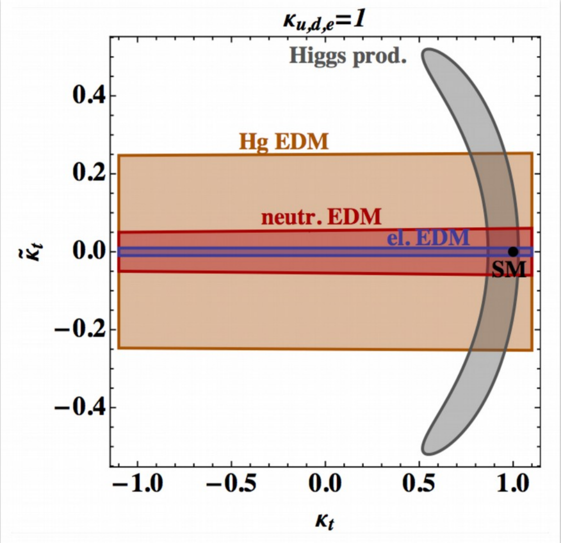
Indirect constraints from eEDM very strong

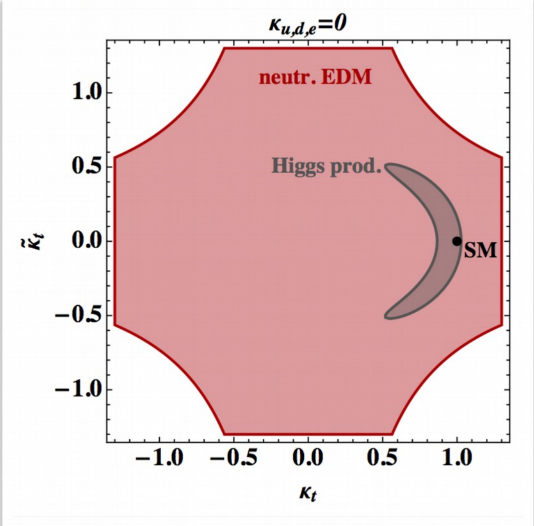
$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right) h$$





$$\frac{d_e}{e} = \frac{16}{3}\frac{\alpha}{(4\pi)^3}\sqrt{2}G_F m_e\left[\kappa_e\tilde{\kappa}_t\, f_1(x_{t/h}) + \tilde{\kappa}_e\kappa_t\, f_2(x_{t/h})\right]$$

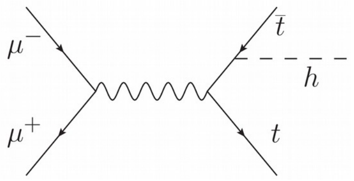




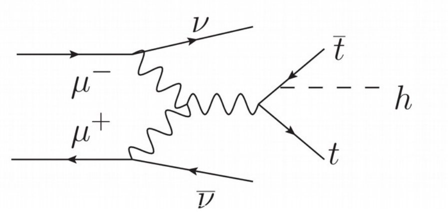
Brod, Haisch, Zupan (2013); Engel, Ramsey-Musolf, Kolck (2013); Cirigliano, Dekens, Vries, Mereghetti (2016)

Direct tests at Muon Colliders

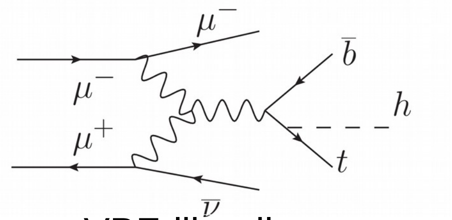
- Directly probe top Yukawa, need processes with a Higgs and top in final state.
- Representative diagrams:
  - tth:

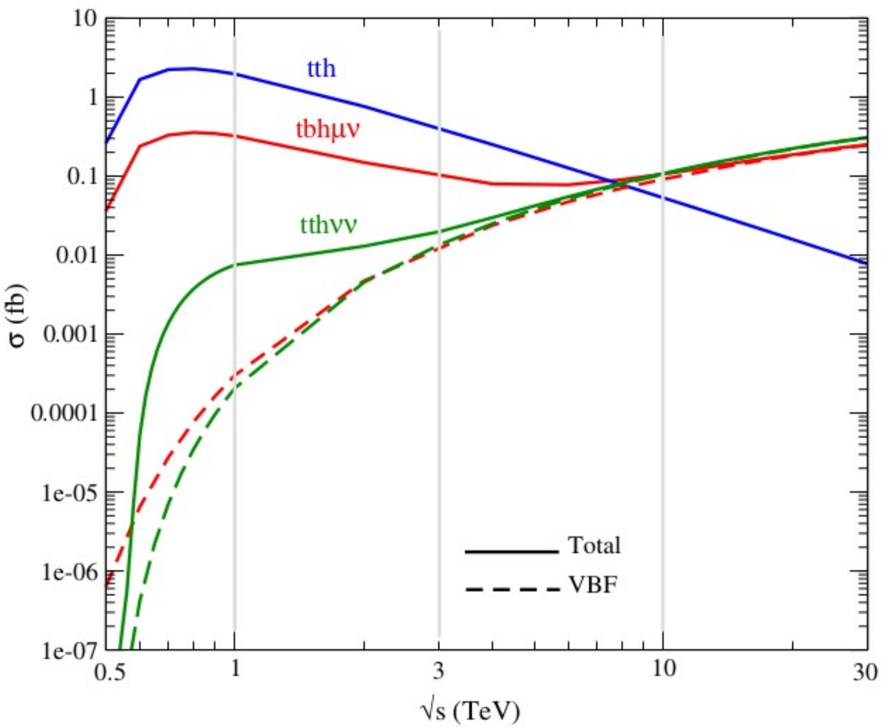


  - tthνν



  - tbhνμ



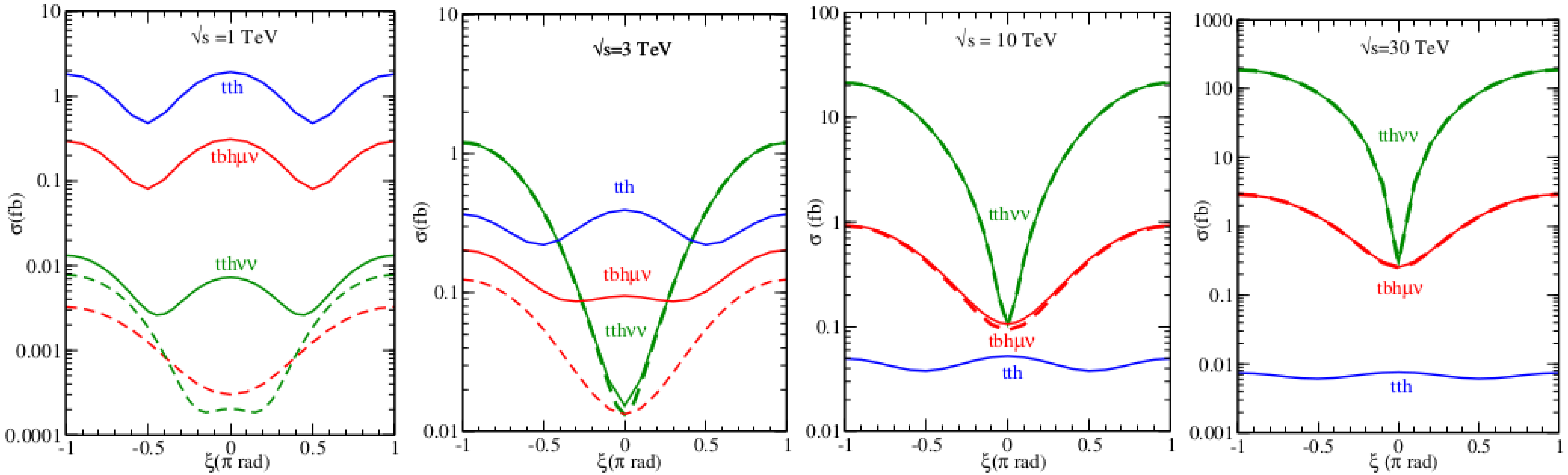


Cassidy, Dong, Kong, **IML**, Zhang, Zheng, 22xx.xxxxx

- Dotted lines are VBF-like diagrams.
  - Dominate at high energy due to collinear enhancement: $\log(E^2/M_W^2)$

Han, Liu, Low, Wang, PRD 103 (2021) 013002;
Costantini, et al. JHEP 09 (2020) 080; etc. etc.

Cross Section Dependence on Phase at Muon Collider



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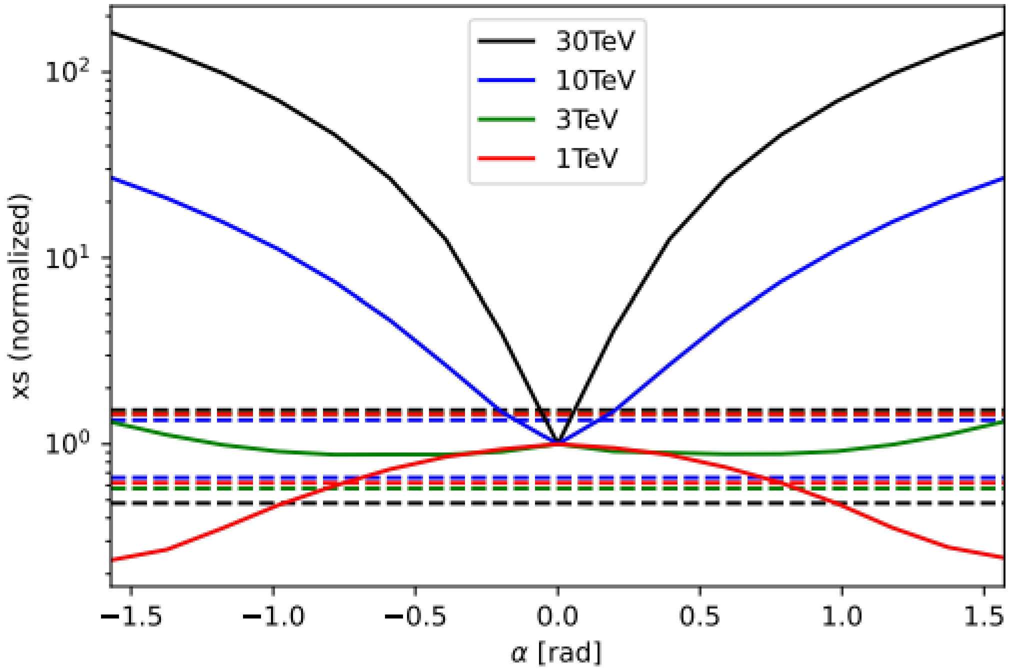
- Very different behavior at different energies and for different diagram types.
- Dashed: VBF-like diagrams.
- SM has a strong cancellation in the VBF channel, making cross section very sensitive to CP-violating phase at high energies.

Projected 2σ α bounds at Muon Collider

- Benchmark luminosities:
  - 1 TeV: 100 fb^{-1}
  - 3 TeV: 1 ab^{-1}
  - 10 TeV: 10 ab^{-1}
  - 30 TeV: 10 ab^{-1}
- Statistics dominated.
  - Adding 5% or 10% systematics makes little difference.
- Sharp dependence on α at 10 TeV and 30 TeV provides strong constraints.
- At 3 TeV, cross section relatively independent on α.
- Precision on top Yukawa in ttH comparable to previous results.
  - Can get stronger constraints on top Yukawa considering indirect contributions with top quark loops $h\to\gamma\gamma, h\to gg, h\to Z\gamma$
  - Direct measurements preferable.

Forslund, Meade, arXiv:2203.09425



Comparison to Other Colliders

Also see Morgan Cassidy's talk later this afternoon.

Bounds on α at 95% CL ($\kappa_t = 1$)	Channel	Collider	Luminosity
$\lvert\alpha\rvert \lesssim 36°$ [1]	dileptonic $t\bar{t}(h \to b\bar{b})$	HL-LHC	3 ab^{-1}
$\lvert\alpha\rvert \lesssim 25°$ [2]	$t\bar{t}(h \to \gamma\gamma)$ combination	HL-LHC	3 ab^{-1}
$\lvert\alpha\rvert \lesssim 3°$ [1]	dileptonic $t\bar{t}(h \to b\bar{b})$	100 TeV FCC	30 ab^{-1}
$\lvert\alpha\rvert \lesssim 9°$ [3]	semileptonic $t\bar{t}(h \to b\bar{b})$	10 TeV $\mu^+\mu^-$	10 ab^{-1}
$\lvert\alpha\rvert \lesssim 3°$ [3]	semileptonic $t\bar{t}(h \to b\bar{b})$	30 TeV $\mu^+\mu^-$	10 ab^{-1}

Barman, et al., arXiv:2203.0817

- [1] Gonçalves, Kim, Kong, Wu, JHEP 01 (2022) 158
- [2] Barman, Gonçalves, Kling, PRD105 (2022) 035023
- [3] Cassidy, Dong Kong, IML, Zheng, Zhang, arXiv:22xx.xxxxx

Three degrees is near CP violation needed for EWBG

Fuchs, Losada, Nir, Viernik, JHEP05 (2020) 056

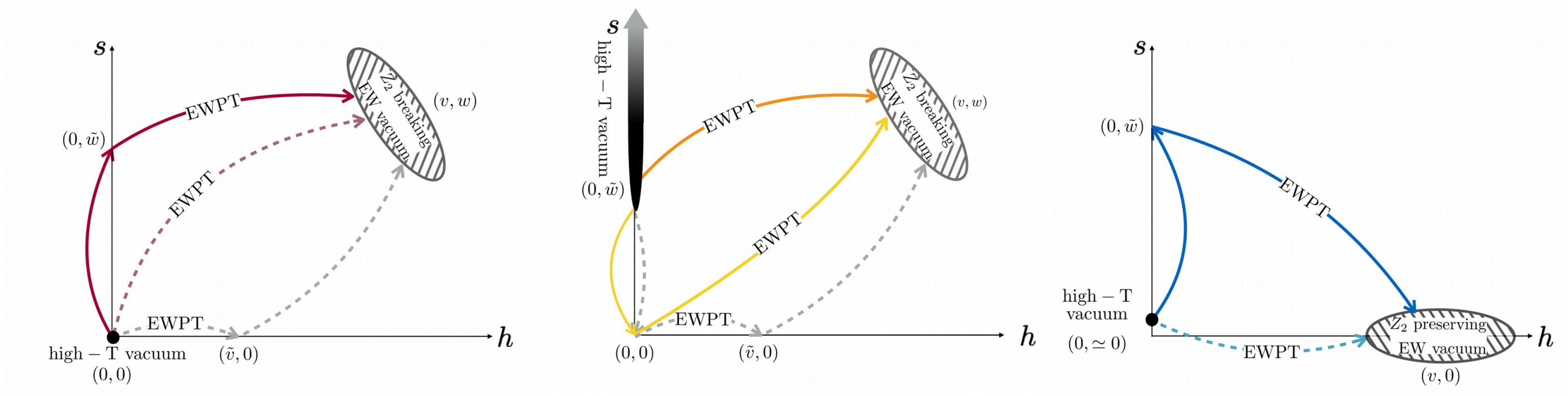
Summary

- BSM Higgs is interesting: many interesting scenarios not yet being robustly probed.
- Covered (nowhere near all) BSM Higgs scenarios and what we can search for at colliders.
- Many interesting searches for extended scalar searches.
  - Various di-Scalar production modes are sensitive to different trilinears.
  - Non-resonant Di-Scalar production can be important to close out important regions of parameter space.
  - Searches for many di-Scalar final states, resonant and not resonant, will be necessary to fully explore the possibility of a strong first order EW phase transition.
- Increasing interest in di-Scalar resonant production in general: hh, hS, SS.
- Beyond the Standard Model EFTs can be useful tools to test our base assumptions about our simplified models.
- We can generate the baryon asymmetry via decays of heavy Higgs doublet.
  - The Higgs doublet can be be TeV scale.
  - Possibly observable in di-jet final states at colliders.
- We need direct measurements of the CP angle of Higgs-top Yukawa to tie it down definitively
  - Indirect constraints depend strongly on couplings beyond the Higgs-top Yukawa.
  - Future colliders are promising to bound this angle tightly (or discover a non-zero angle)
  - See Morgan Cassidy’s talk later this afternoon.


Thank You

Extra Slides

Symmetry Non-Restoration

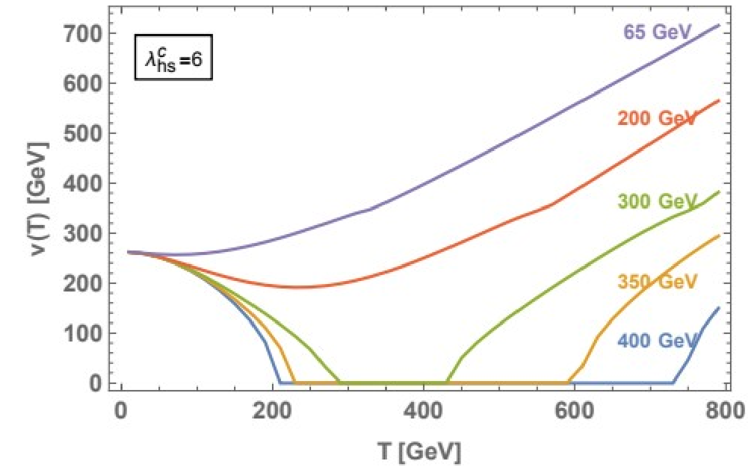


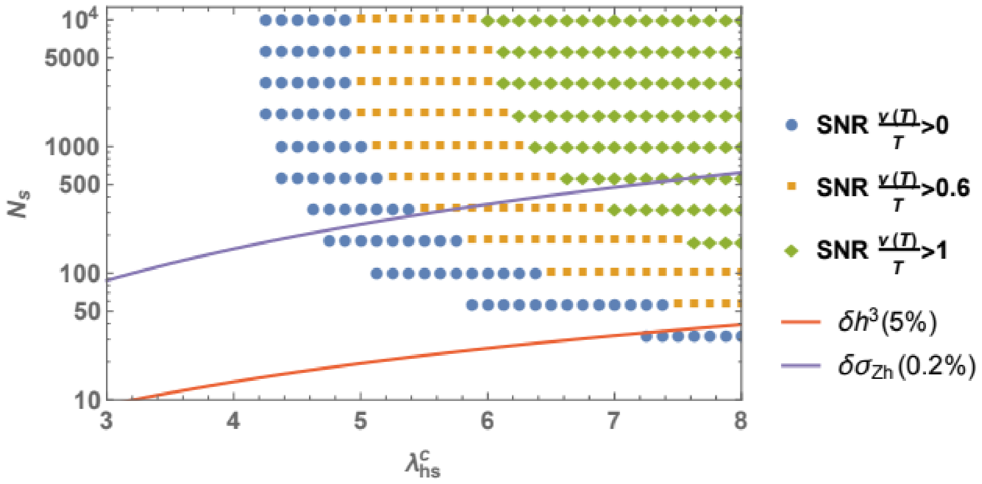
Carena et al, arXiv:2203.08206

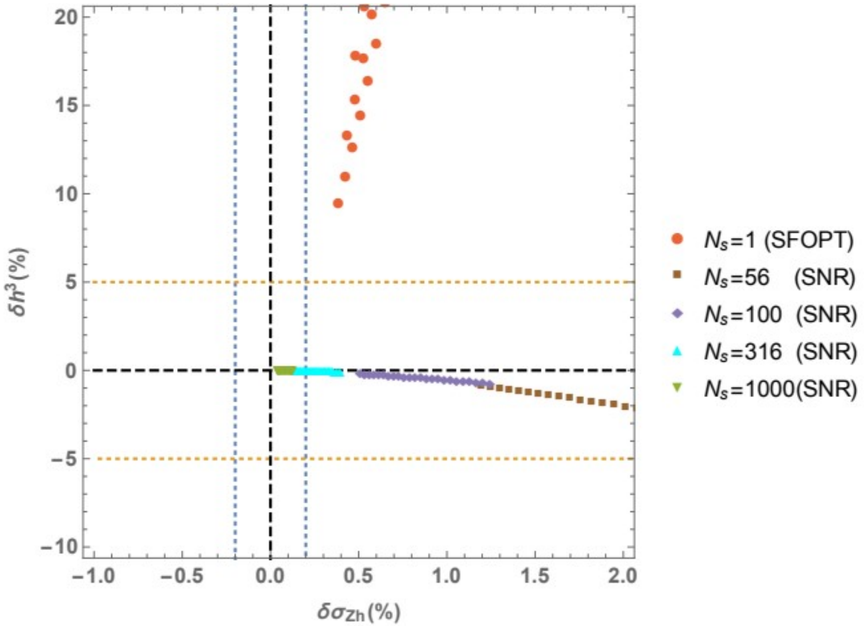
- Electroweak symmetry breaking may not be a simple pattern.
- There are scenarios in which the symmetries are not restored at low temperatures.
- Electroweak symmetry itself may not be restored at high energies.
- Weinberg PRD9 (1974) 3357; Mohapatra, Senjanovic,PRD20 (1979) 3390, etc.
- Can help avoid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