Higgs Boson Physics: An Update

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Outline

- Introduction.
- Precision Higgs measurements.
  - Current and future measurements
- Di-Scalar Production
  - Resonant and non-resonant.
- More exotic signatures:
  - Dijets from Higgs doublets
  - Multi-photon Higgs decays
- Conclude

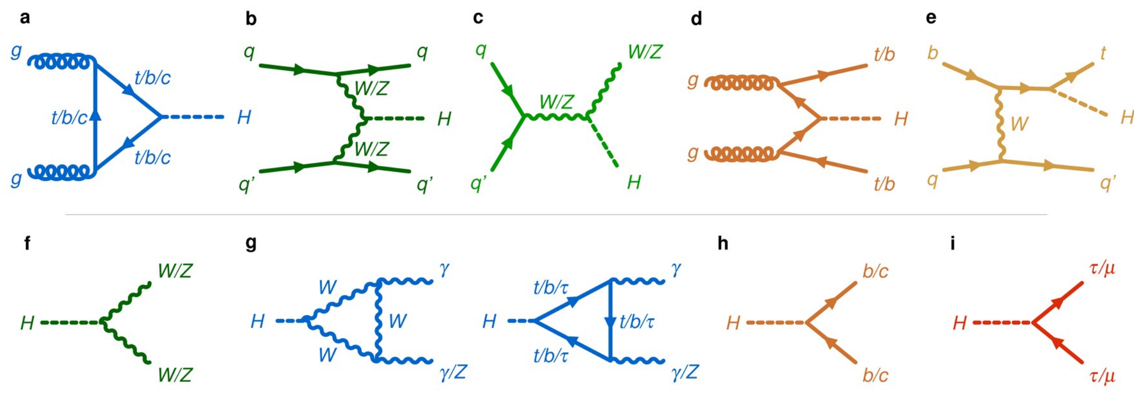
Introduction

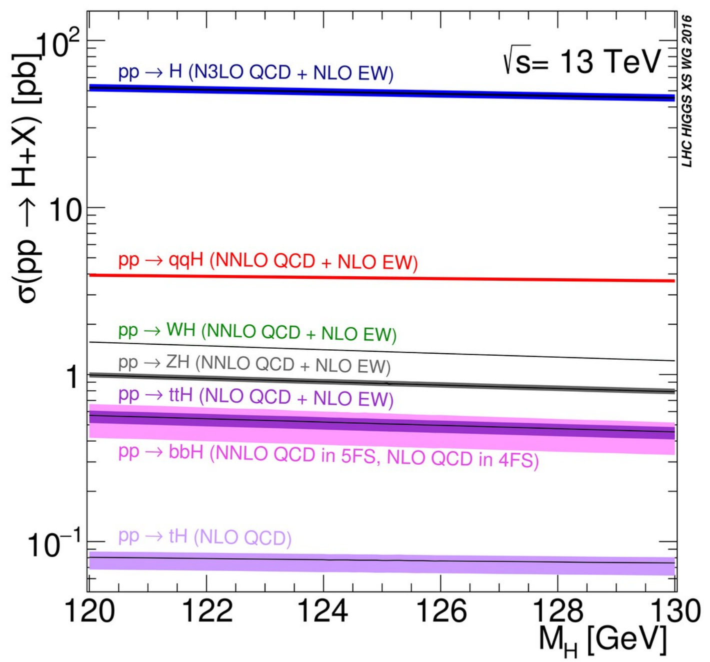
- Higgs nearly 11 years old now.
- Higgs is central to the Standard Model.
  - Source of electroweak symmetry breaking.
  - The source of mass for gauge boson and fermions.
- Last parameter needed in the Standard Model was the Higgs mass.
  - The SM is now completely predictive.
  - Opportunity to test structure of the Standard Model.
  - Opportunity to look for deviations from the Standard Model.
- Try to convince you that still many interesting things to search for in Higgs physics.
  - Understanding how electroweak symmetry is broken, i.e. measure the Higgs potential.
  - Connections to baryogenesis.

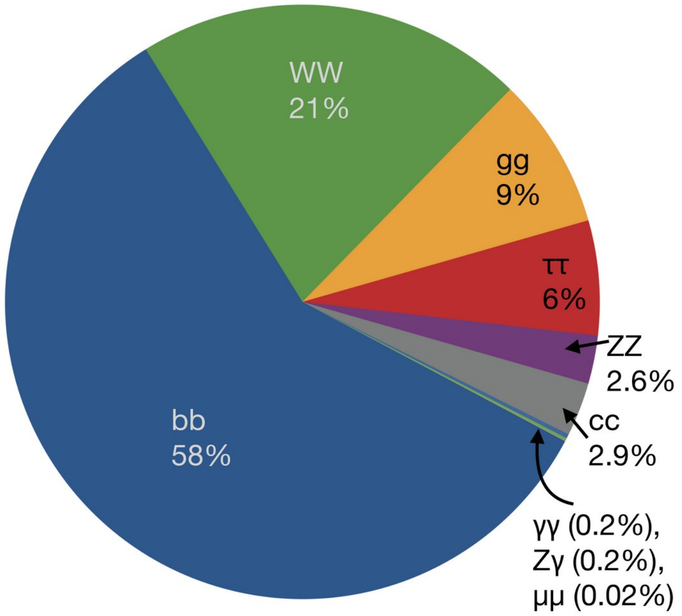
Feynman Diagrams from ATLAS, Nature, arXiv:2207.00092

Completely Predictive

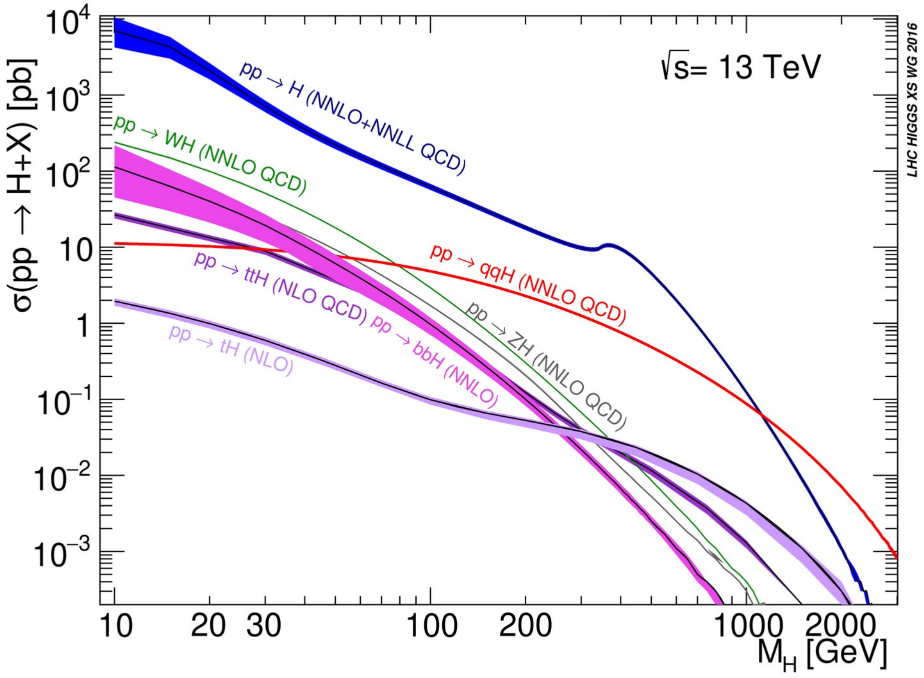
- Once we know Higgs mass, can calculate production and decay rates to high precision..

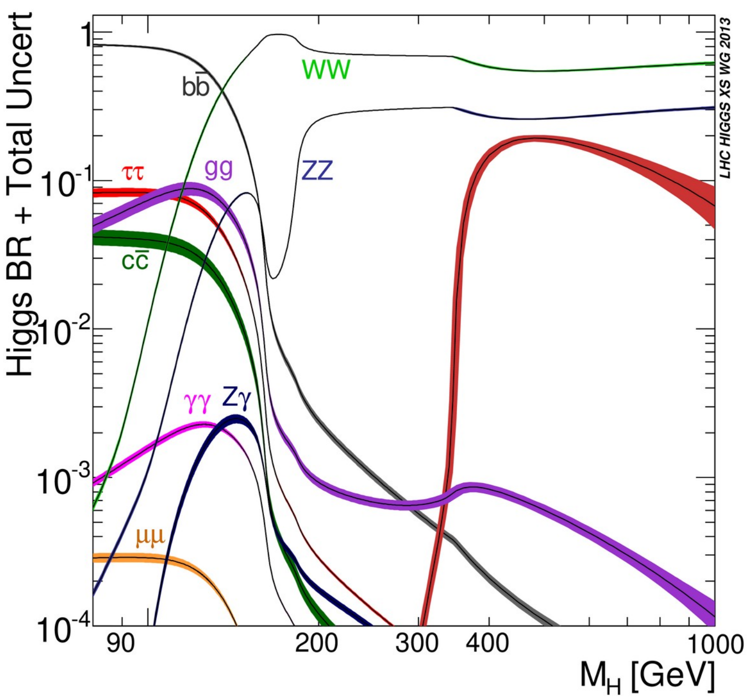






Lucky in mass



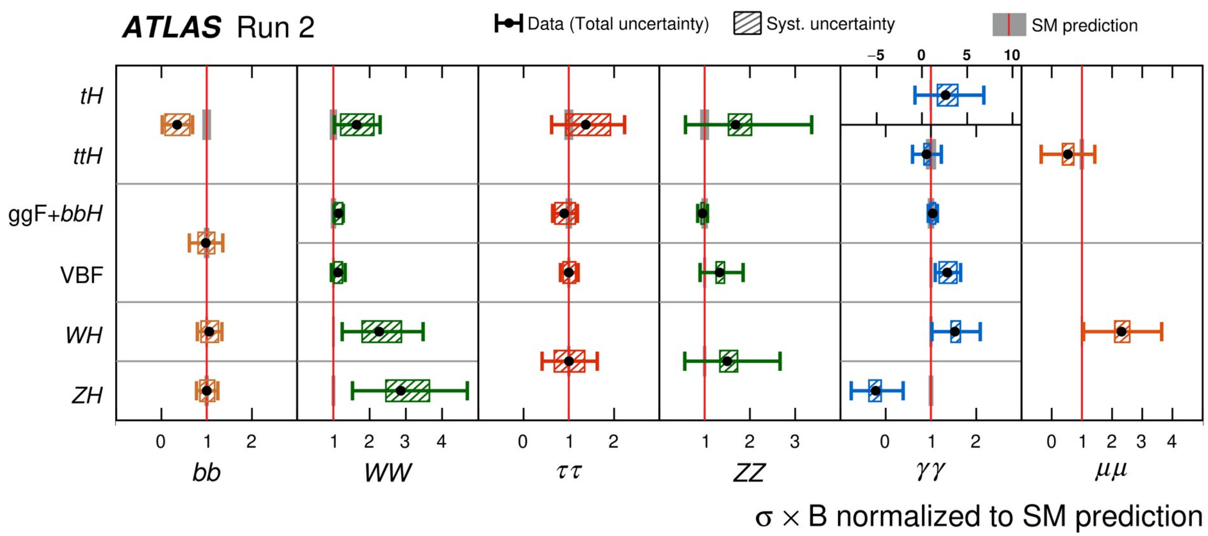


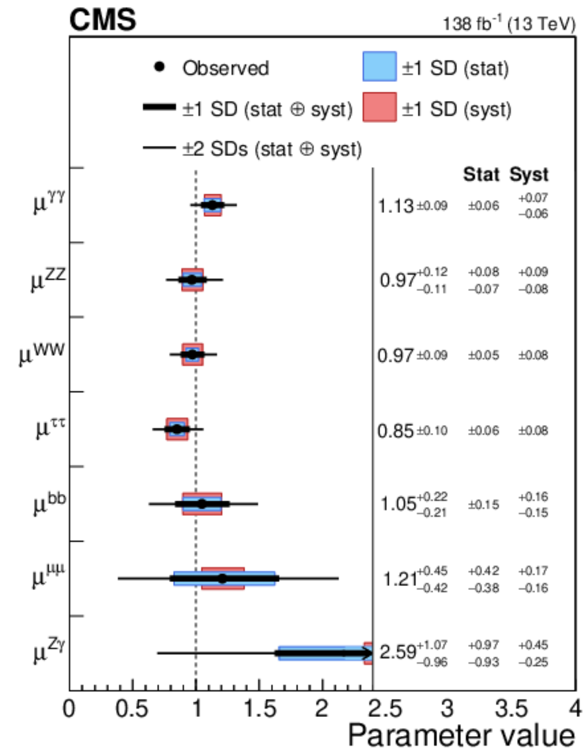
- At $m_h = 125\, GeV$, many decay channels are open.
  - At higher mass, harder to measure couplings to fermions
  - At lower mass, harder to measure couplings to gauge bosons.
  - Quite lucky that so many decay channels are open so that we can thoroughly probe the couplings of the Higgs with SM particles.

CMS, Nature, arXiv:2207.00043

ATLAS, Nature, arXiv:2207.00092

Where We're At

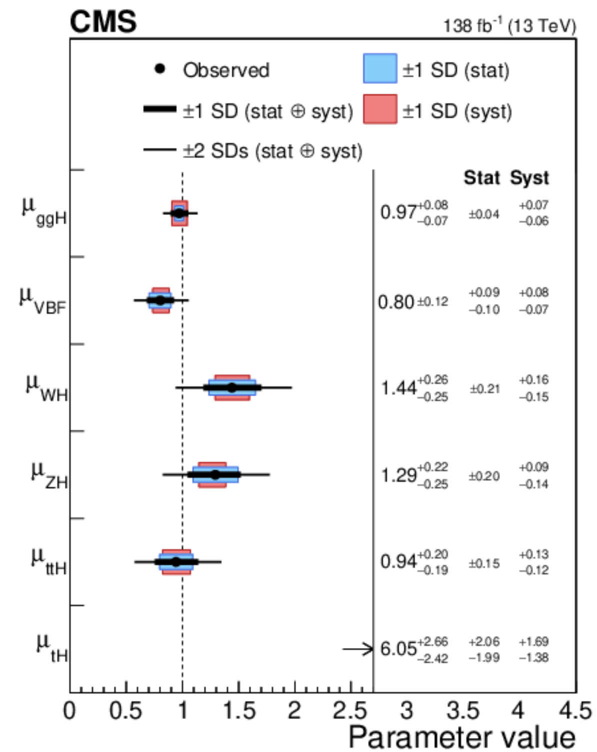




- Higgs precision shown in terms of signal strengths.

$$\mu_i^f = \frac{\sigma_{\exp}(i \to h \to f)}{\sigma_{SM}(i \to h \to f)}$$

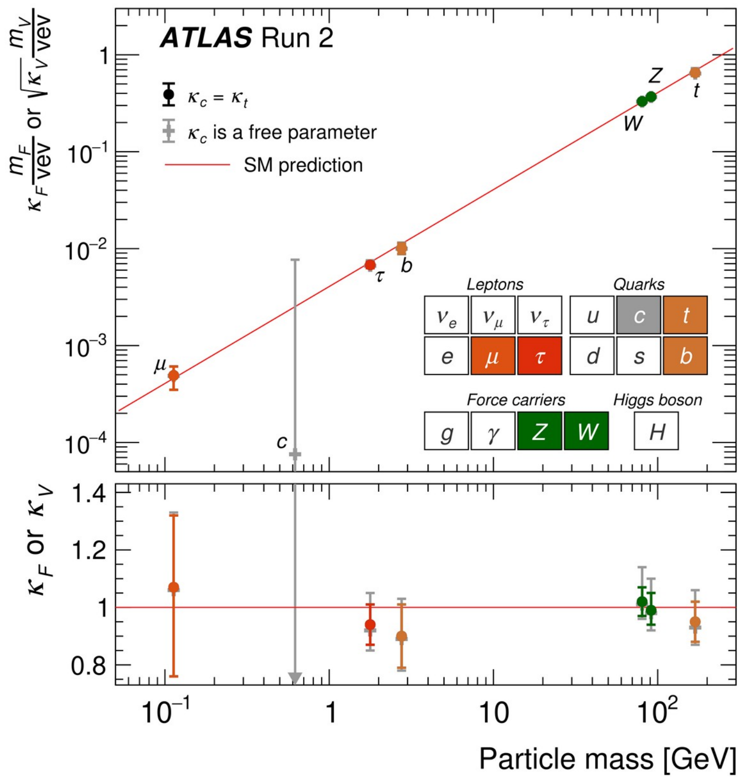
- Most measurements agree well with the SM.
- Already measuring many rates to order 10% accuracy.

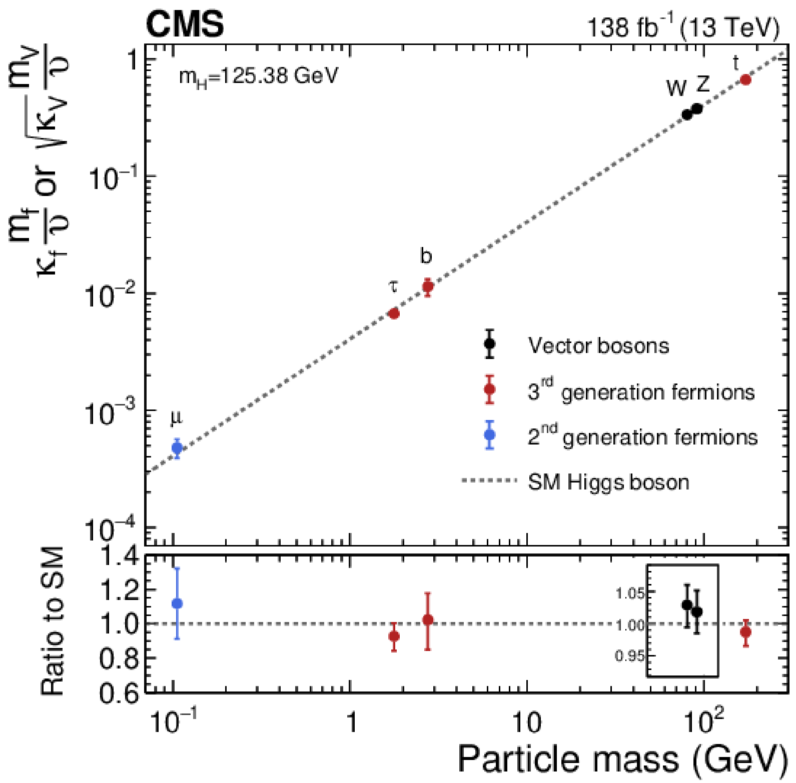


Where We're At

CMS, Nature, arXiv:2207.00043

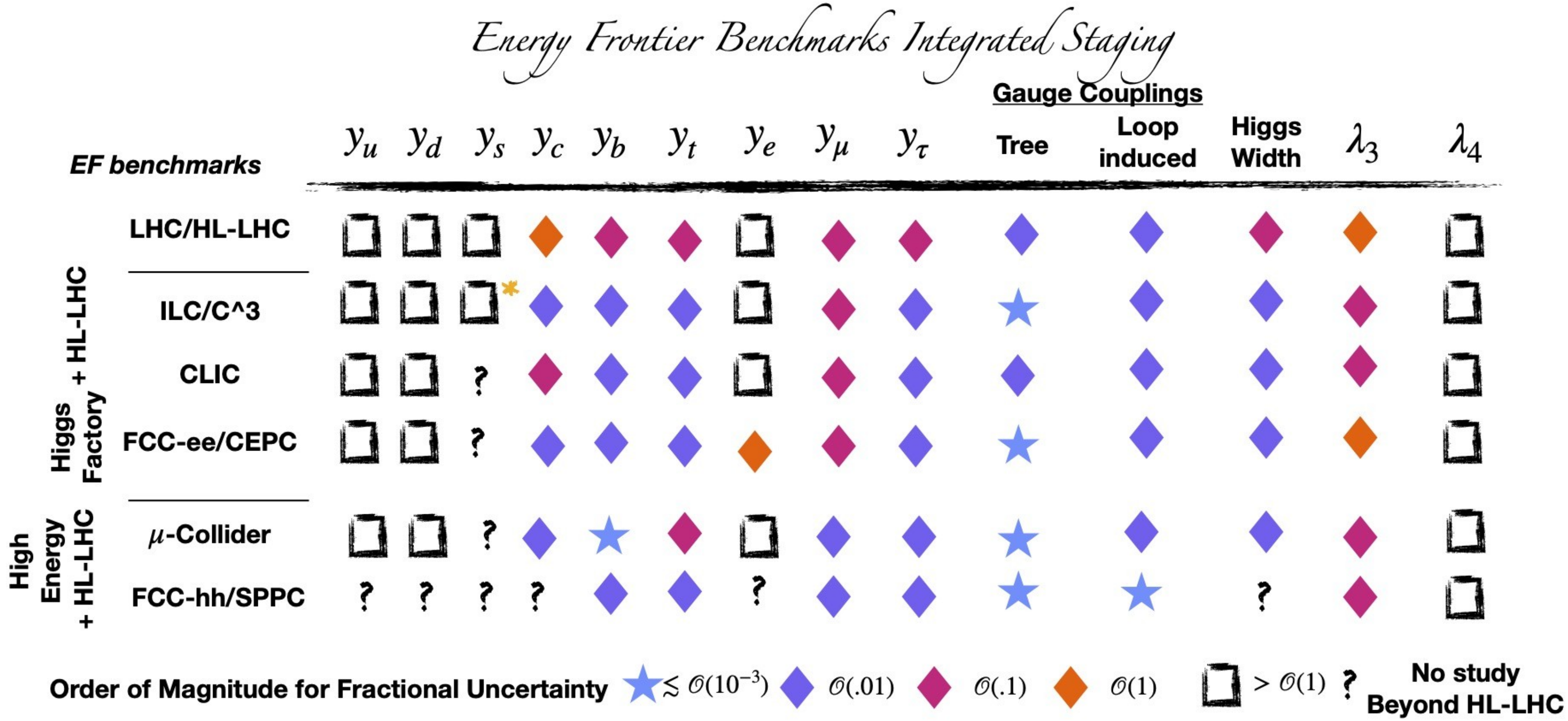
ATLAS, Nature, arXiv:2207.00092





- Higgs boson associated with the source of EW symmetry breaking.
  - Higgs couplings should be proportional to masses (or squared masses)
  - Have verified that over many orders of magnitude in coupllings and mass.

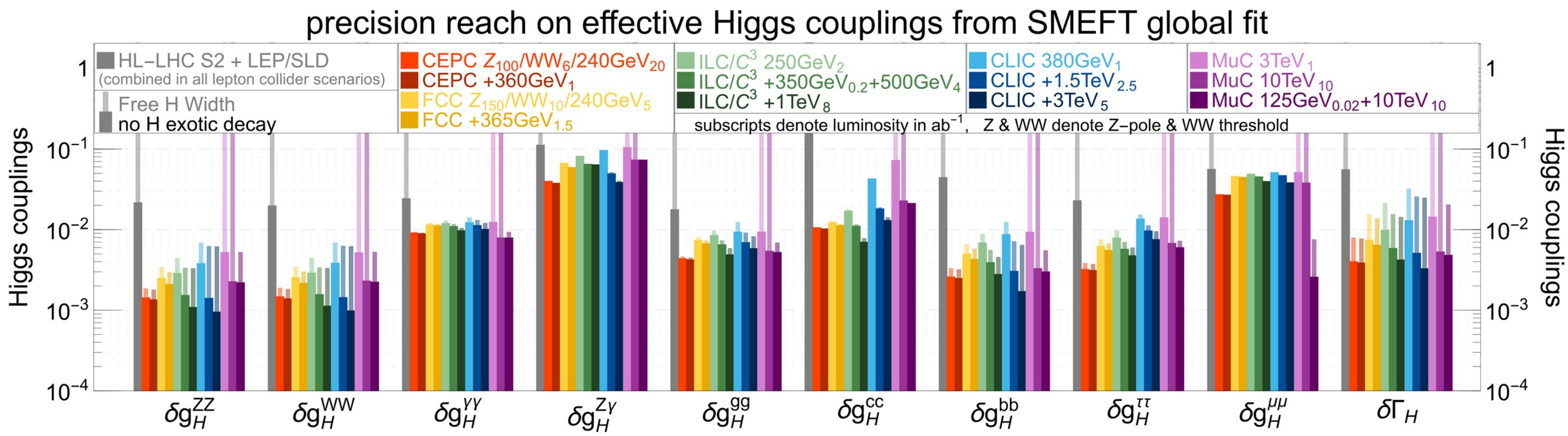
Where We’re Going



Snowmass EF01/EF02 Report

- Much of the future collider program is focused on measuring the Higgs to greater precision.
- Different colliders have different capabilities.

Where We're Going



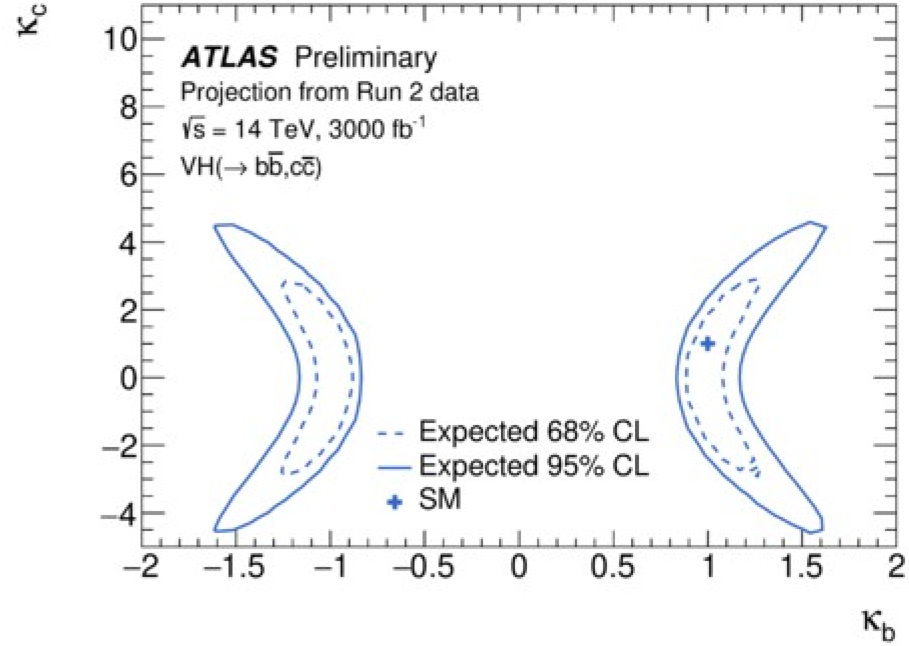
de Blas et al., 2206.08326

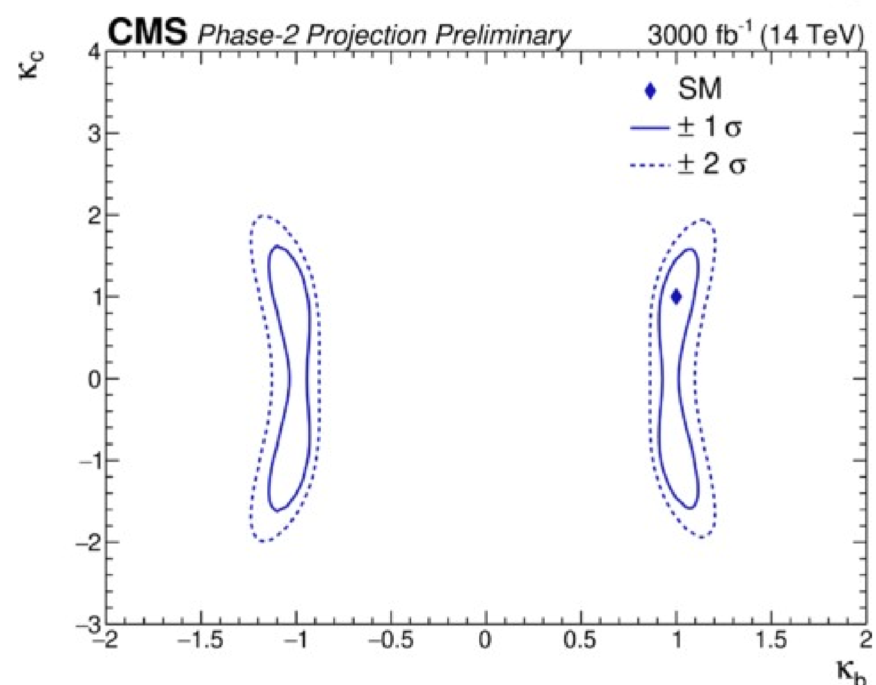
- Much of the future collider program is focused on measuring the Higgs to greater precision.
- Different colliders have different capabilities.

Couplings to Second Generation Fermions

$$\kappa_i = \frac{g_i}{g_{i,SM}}$$

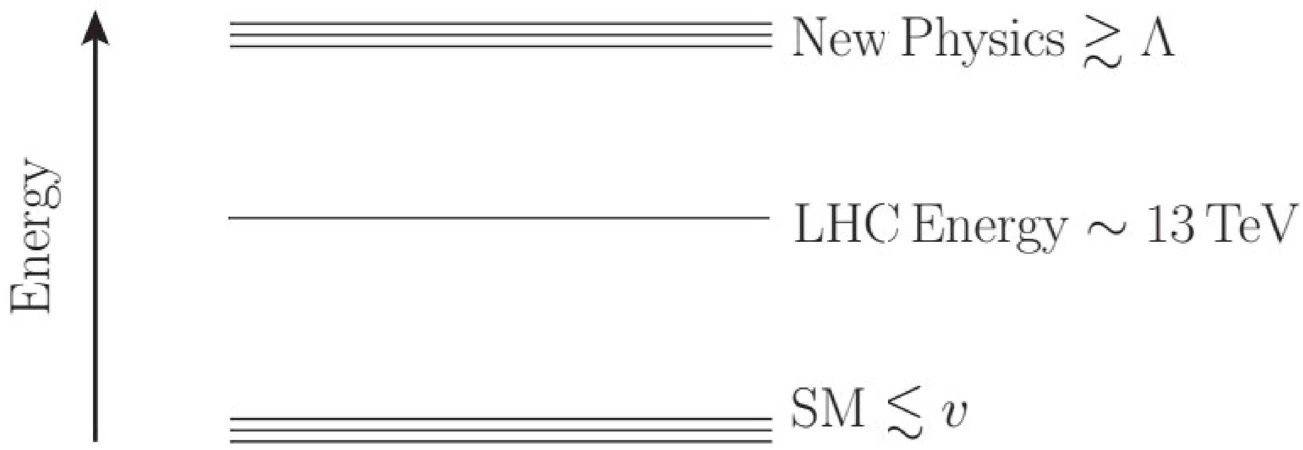
- Have measured couplings to third generation fermions and gauge bosons.
- Just beginning to be sensitive to couplings to second generation fermions:
  - ATLAS: $\mu = 1.2 \pm 0.6$ ATLAS, PLB 812 (2021) 135980
  - CMS: $\mu = 1.2 \pm 0.4$ CMS, JHEP 01 (2021) 148
- Bounds on charm quark Yukawa
  - Search for $Vh, h \to c\bar{c}$
  - ATLAS: $|\kappa_c| < 8.5$ ATLAS, EPJC 82 (2022) 717
  - CMS: $1.1 < |\kappa_c| < 5.5$ CMS, 2205.05550
- Recent new proposals to measure charm Yukawa:
  - $h \to c\bar{c} + J/\psi$ Han, Leibovich, Ma, Tan JHEP 08 (2022) 073
  - $h \to c\bar{c} + \eta_c$





Effective Field Theory Interpretation

- If we see a deviation, can we map it onto a model?
- Useful to have a generic theoretical framework to understand:
  Effective Field Theories
- Assume all new physics too heavy to be produced directly.



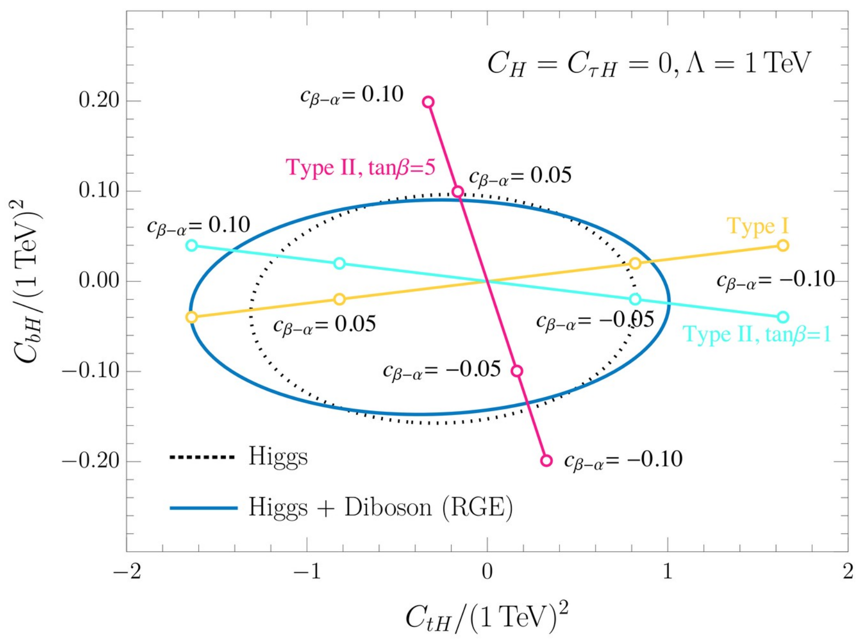
- Generically obtain a tower of operators:

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

- Standard Model Effective Field Theory parameterizes deviations away from SM predictions.
- Different UV models should have different predictions for relations among Wilson coefficients.
  - The hope would be to see an anomaly and measure the relationships between the Wilson coefficients.
  - Patterns of values of Wilson coefficients may give hints to underlying physics.

Interpreting Precision Higgs

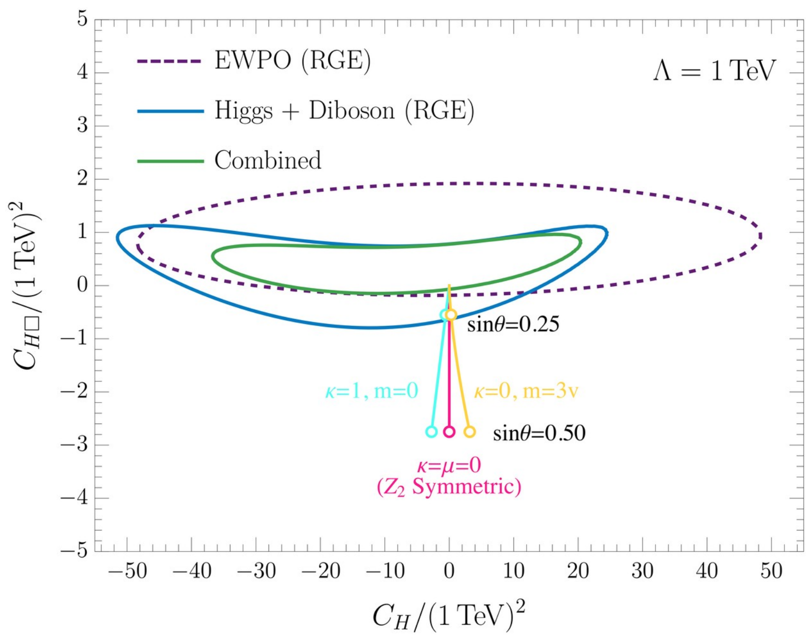
2HDM



$$O_{bh} = (\Phi^+ \Phi) \bar{Q}_L \Phi b_R$$

$$O_{th} = (\Phi^+ \Phi) \bar{Q}_L \tilde{\Phi} t_R$$

Singlet Model



$$O_H = (\Phi^+ \Phi)^3$$

$$O_{H\square} = (\Phi^+ \Phi) \square (\Phi^+ \Phi)$$

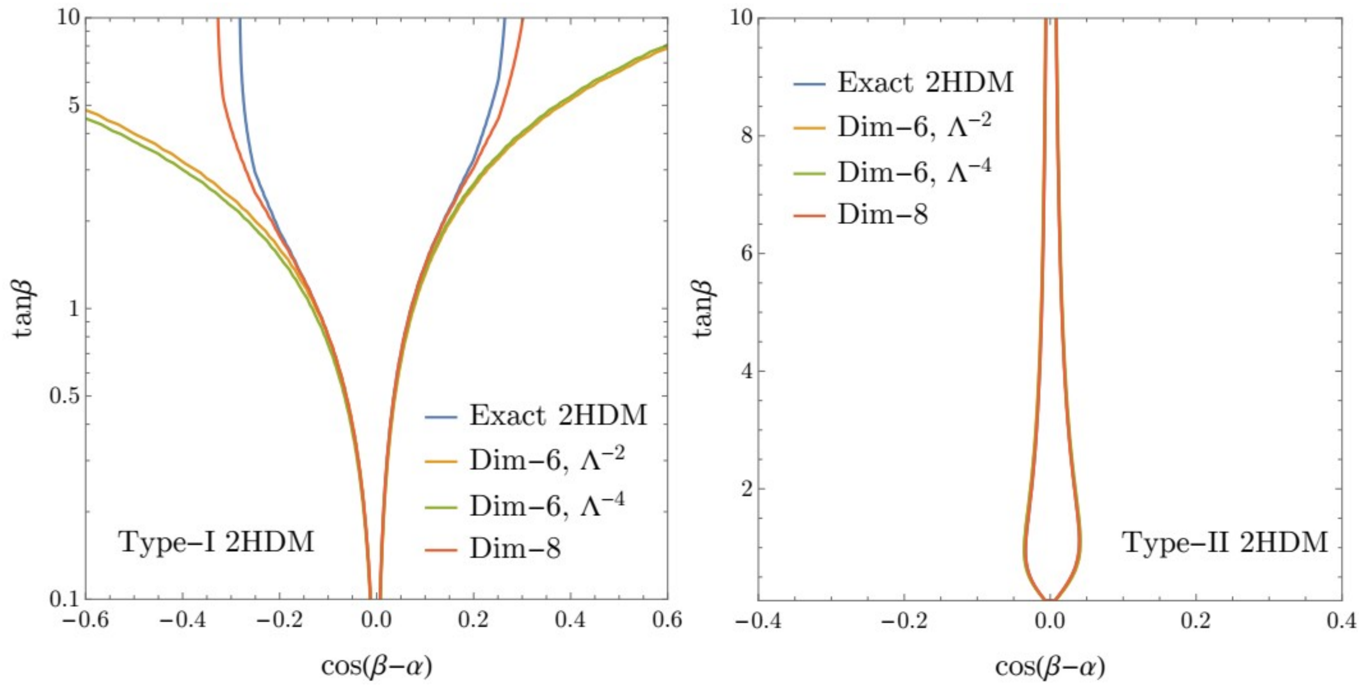
- Trajectories in Wilson coefficient space for specific UV completions.

Dawson, Homiller, Lane, PRD 102 (2020) 055012

EFTS and Underlying Models

- Comparison of exact 2HDM to 2HDM matched onto SMEFT.
- Precision Higgs fits.
- Dimension-6 terms come from fermion couplings.
  - For Type-I, Dimension-6 suppressed by $1/\tan\beta$

  Bélusca et al EPJC77 (2017) 176
- See Matt Sullivan's talk.



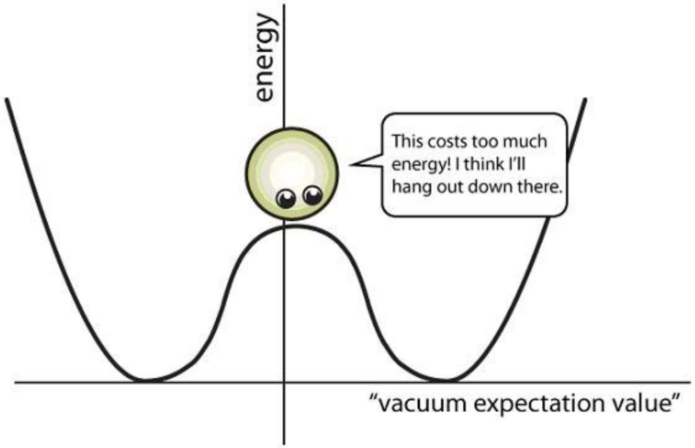
Dawson, Fontes, Homiller, Sullivan, PRD106 (2022) 055012

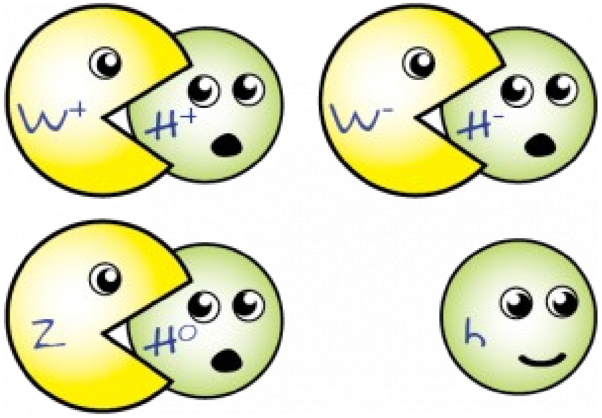
Beyond Single Higgs

- All precision measurements look Standard Model like so far.
- It appears like the observed scalar is related to the mass generating mechanism for the SM fermions and gauge bosons.
- We still have not determined precisely how the Higgs obtains a vacuum expectation value.
- The vev comes from the shape of the scalar potential:

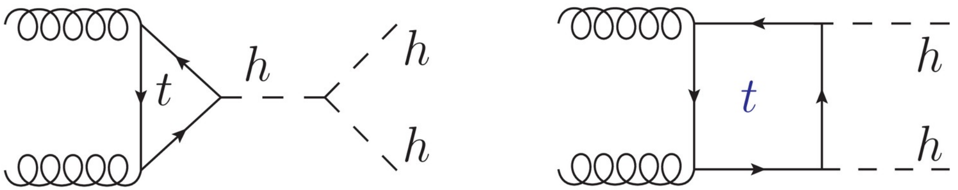
$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4 \supset \frac{1}{2} m_h^2 h^2 + \frac{\lambda_{hhh}}{3!} h^3 + \frac{\lambda_{hhhh}}{4!} h^4$$

- In the long run, need to measure Higgs trilinear (and maybe quartic?) couplings to get a handle on the mechanism that generates the vev.



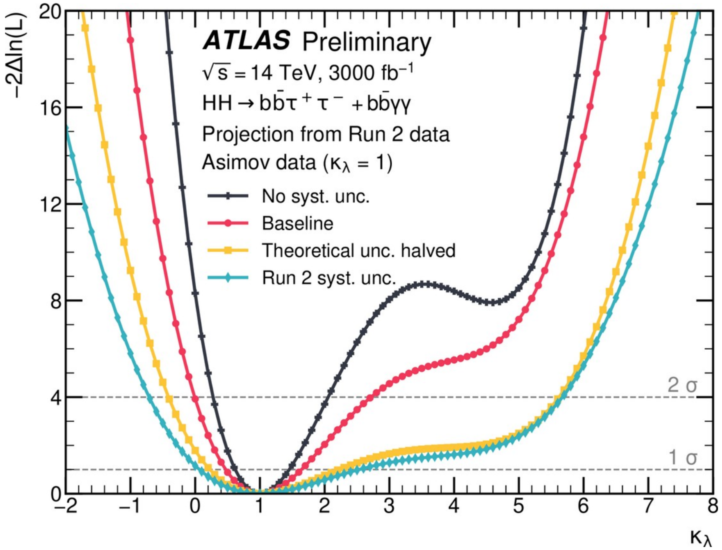


Double Higgs in the SM



$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4 \supset \frac{1}{2}m_h^2 h^2 + \frac{\lambda_{hhh}}{3!}h^3 + \frac{\lambda_{hhhh}}{4!}h^4$$

- SM scalar potential contains two parameters, completely determined by the mass and vev.
- Search for Higgs pair production to directly measure shape of potential:



collider	Indirect-h	hh	combined
HL-LHC [77]	100-200%	50%	50%
ILC$_{250}$/C^3-250 [50, 51]	49%	–	49%
ILC$_{500}$/C^3-550 [50, 51]	38%	20%	20%
CLIC$_{380}$ [53]	50%	–	50%
CLIC$_{1500}$ [53]	49%	36%	29%
CLIC$_{3000}$ [53]	49%	9%	9%
FCC-ee [54]	33%	–	33%
FCC-ee (4 IPs) [54]	24%	–	24%
FCC-hh [78]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [63]	-	15-30%	15-30%
μ(10 TeV) [63]	-	4%	4%

ATL-PHYS-PUB-2022-005

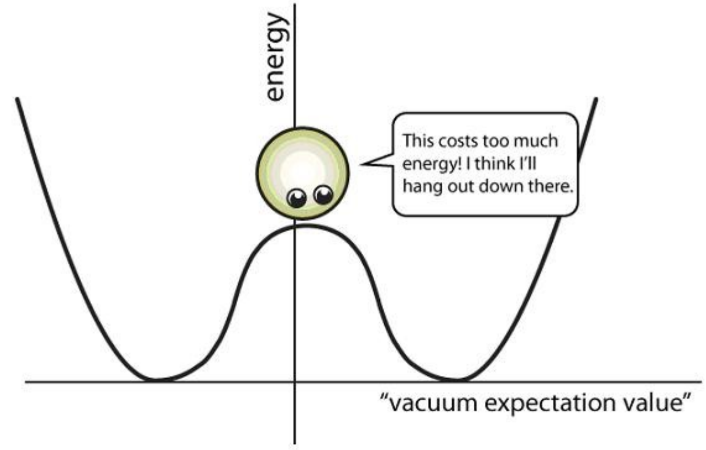
Snowmass Higgs Topical Group Report, arXiv:2209.07510

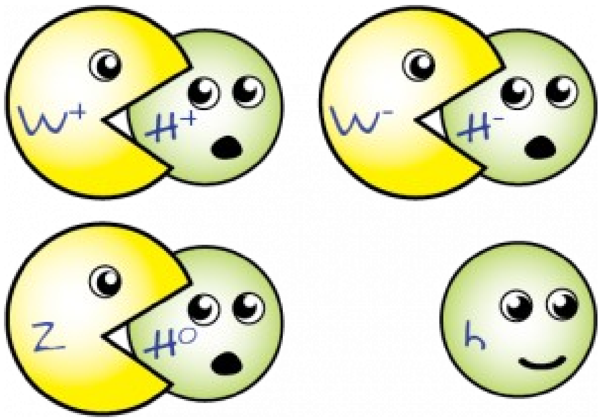
Scalar Extensions

- Scalar Extensions:
  - Adding new scalars will alter the Higgs potential.
  - 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.
- With new scalar, have more scalar trilinear and quartic couplings.
- New production modes of di-scalar final states.



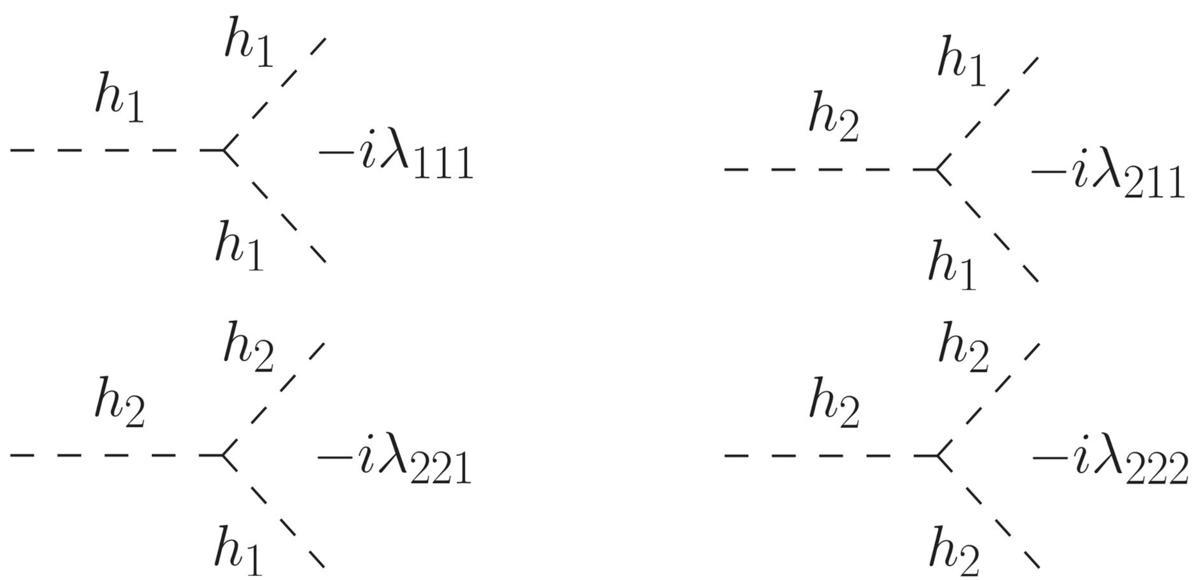


Additional trilinears

- Simplest extension: Real gauge singlet scalar

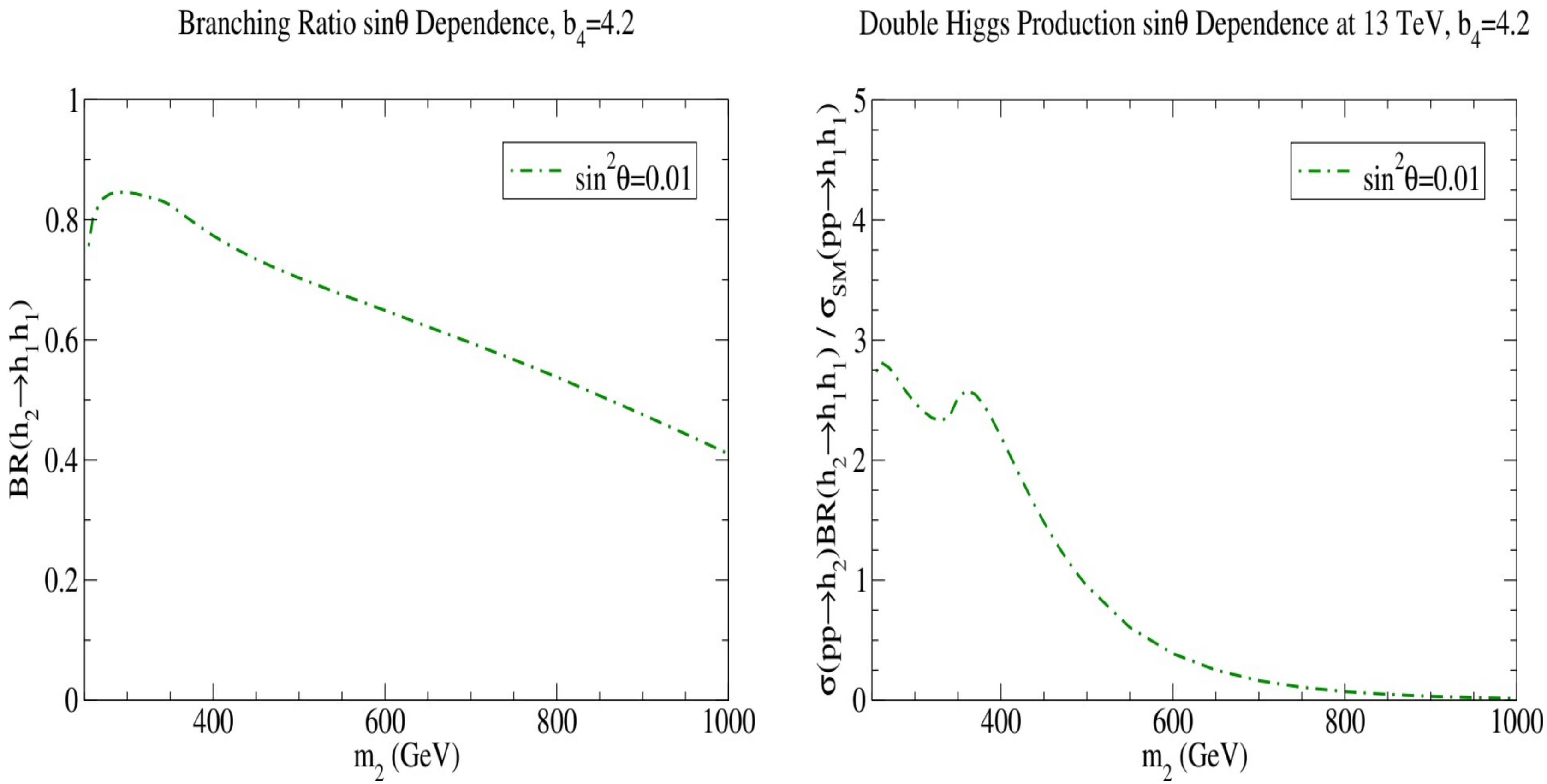
$$V(\Phi, S) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4 + \frac{1}{2}a_1|\Phi|^2 S + \frac{1}{2}a_2|\Phi|^2 S^2$$
$$+ b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4$$

- After EW symmetry breaking and mixing, these couplings will give rise to additional trilinear couplings between mass eigenstates:



- Need to search for more scalar production than just di-Higgs to map out the full potential.
- Can get interesting new resonant decays

Resonant Di-Higgs Production

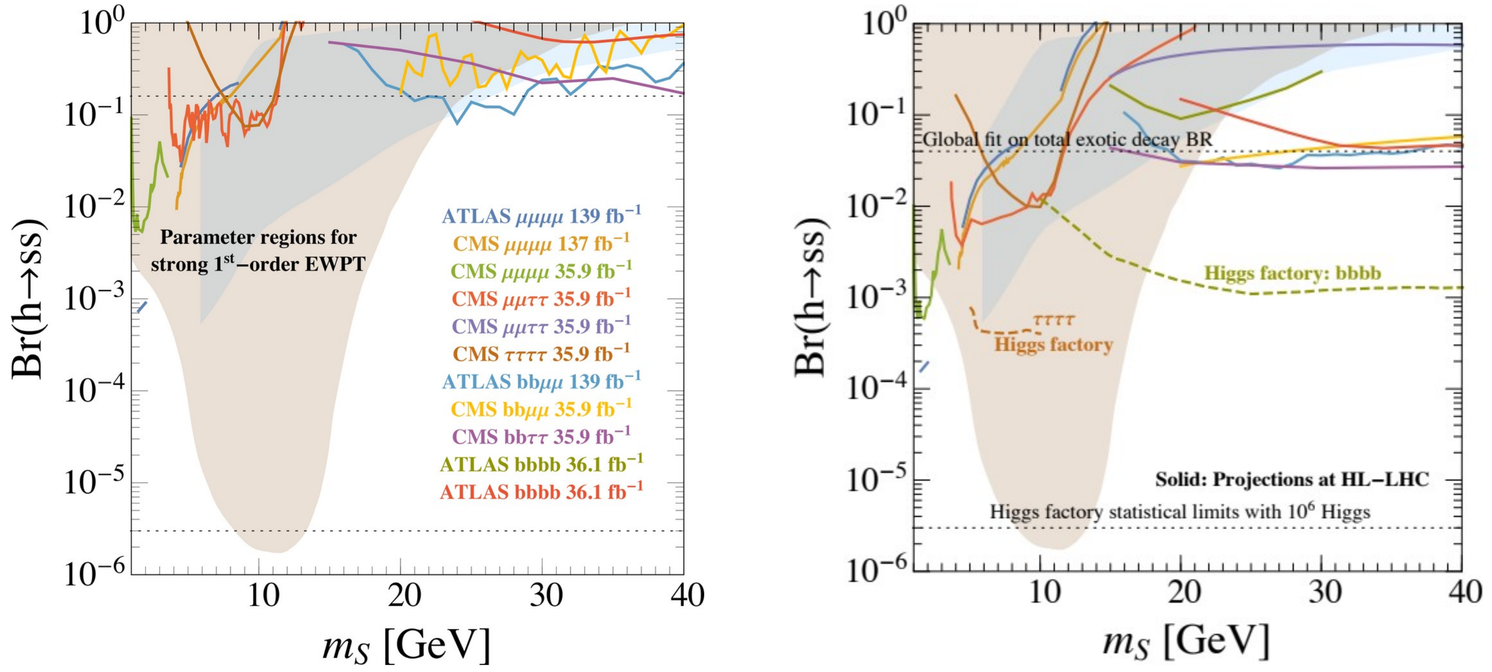


IML, Sullivan, PRD96 (2017) 035037

- Can still get a factor of a few enhancement for smaller resonant masses.
- For a Z_2 symmetric real singlet see also Robens, arXiv:2209.15544

Exotic Higgs Decays

Carena et al, arXiv:2203.08206



- If $m_1 > 2\, m_2$ can have decays $h_1 \rightarrow 2\, h_2$
- Shaded regions: have a strong first order electroweak phase transition.
  - LEP constrains mixing angle to be quite small.
  - a_1 gives mass mixing, so must be small.
  - Only parameter left to change potential is a_2
  - Need non-zero a_2 for a strong first order electroweak phase transition.
  - a_2 is also the coupling that gives $h_1 \rightarrow 2\, h_2$
  - Need a non-zero branching ratio.
  - Benchmark scenario to search for.
- See also Wang et al, arXiv:2203.10184

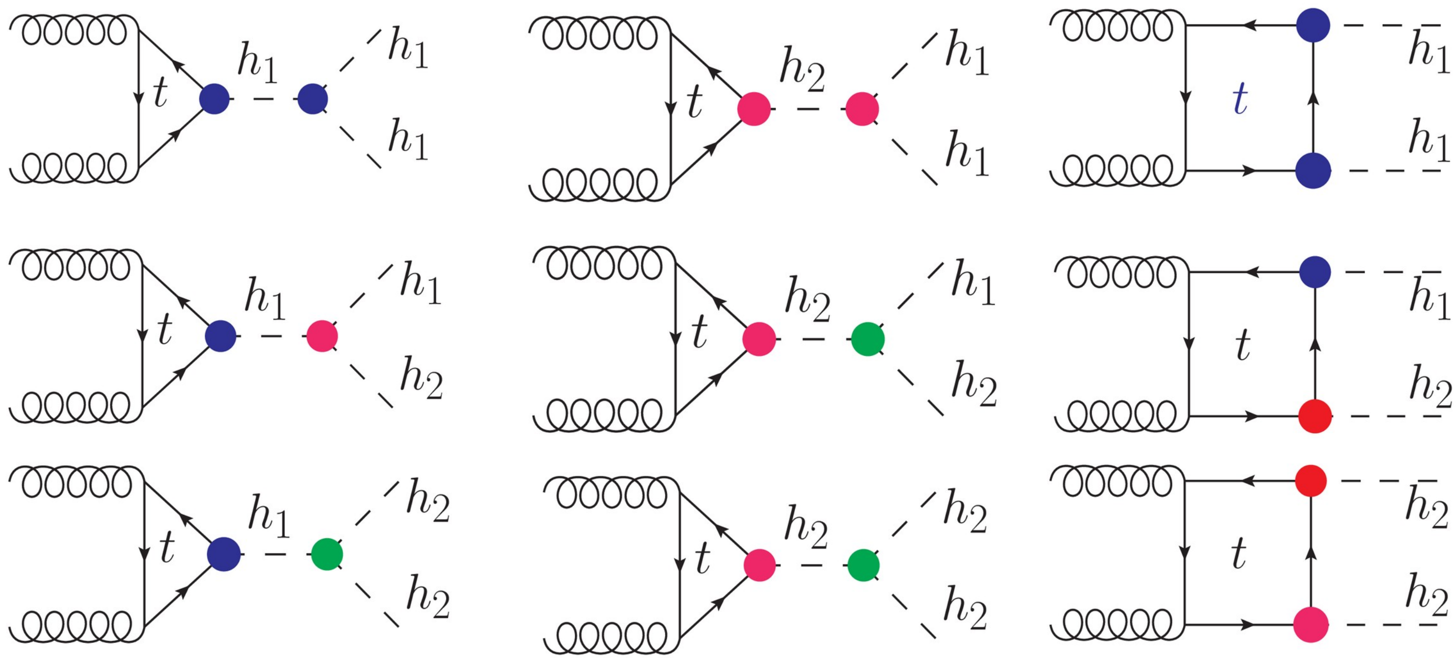
$$V \supset \frac{a_1}{2}|\Phi|^2 S + \frac{a_2}{2}|\Phi|^2 S^2$$

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

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

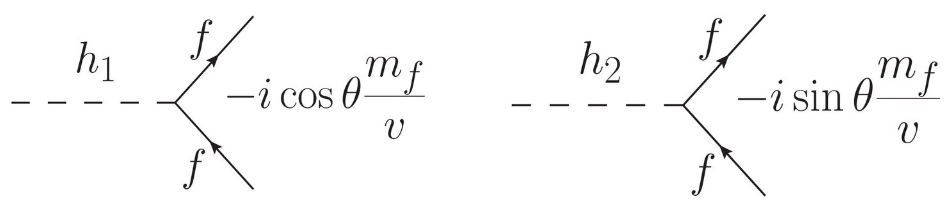
Non-Resonant Di-Scalar Production

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



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

- In general, different di-scalar production sensitive to different trilinear couplings, i.e. different terms in the scalar potential.
  - Should search for all
- In particular, in zero mixing limit, only h_2h_2 production through s-channel h_1 give new physics contributions.

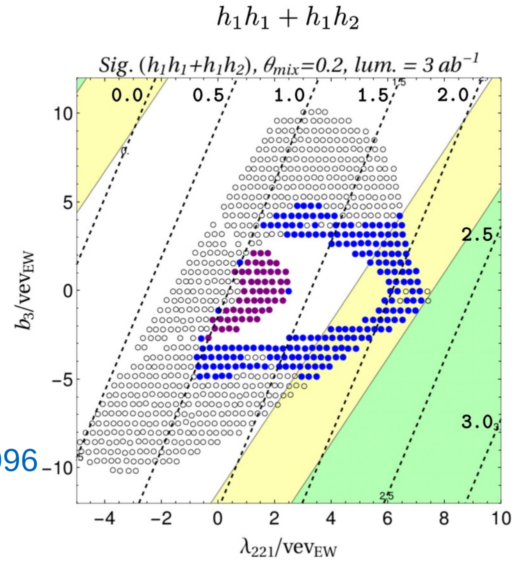


Collider Searches at HL-LHC

- For larger mixing angle, h_1h_1 and h_1h_2 pair production can add information:
  - $h_1h_1+h_1h_2 \rightarrow 2W+2b \rightarrow 2l\ \ 2\nu\ \ 2b$
  - m_2=170 GeV, sin θ = 0.2
- h_2h_2 also important:
  $h_2h_2 \rightarrow 4W \rightarrow (2j)(2l^{\pm})l'^{\mp}(3\nu) \quad l \neq l'$
- At smaller mixing angle, h_2h_2 is more important.
- The point:
  - It is important to search for all Di-Scalar channels.
  - They contain complementary information about the potential.
  - 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:

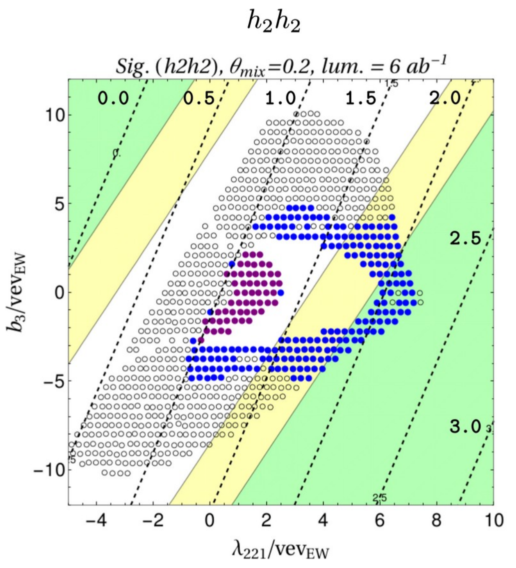
$$\frac{\delta\lambda_{111}}{\lambda_{111}} \sim 50\%$$

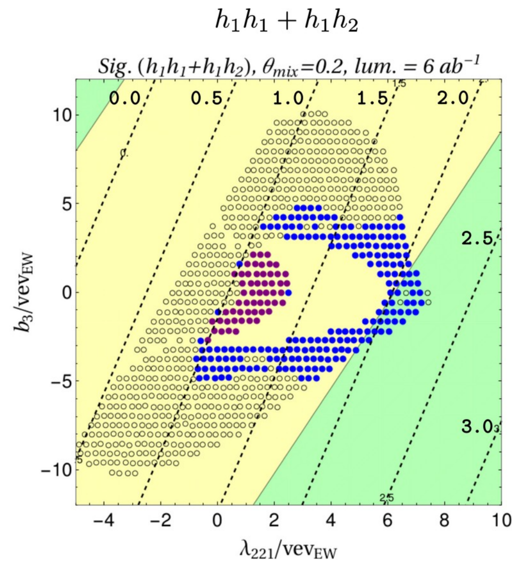
3 ab^{-1}:



Chen, Kozaczuk, **IML** JHEP 08 (2017) 096
Alhazmi, Kim, Kong, **IML** 2xxx.xxxxxx

6 ab^{-1}





Di-Scalar Resonant Production

- Advocated for searching for generic non-resonant di-scalar production:

$$h_1 h_1 \quad h_1 h_2 \quad h_2 h_2$$

- If you add more than one additional scalar, can have resonant production:

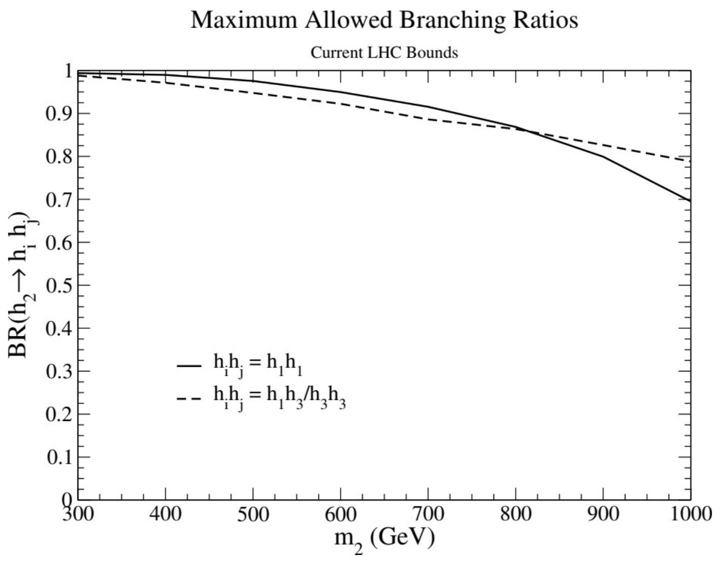
$$h_2 \to h_1 h_1 \quad h_2 \to h_1 h_3 \quad h_2 \to h_3 h_3$$

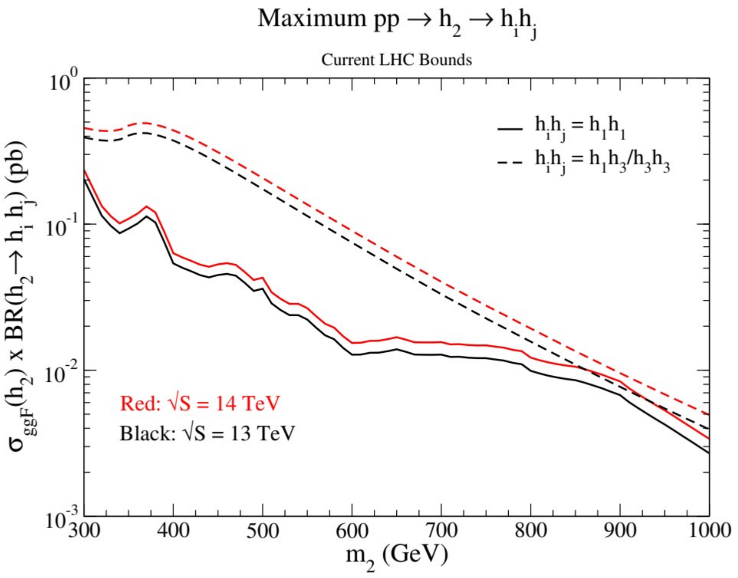
- Consider complex scalar extension with no additional symmetry (identical to two real scalar extension with no additional symmetry)
  - Have three real scalars: SM h, and two new scalars S_0 and A.
  - Again, new scalars only appears in the potential and inherit couplings from mixing with SM Higgs.
  - Generic mixing:

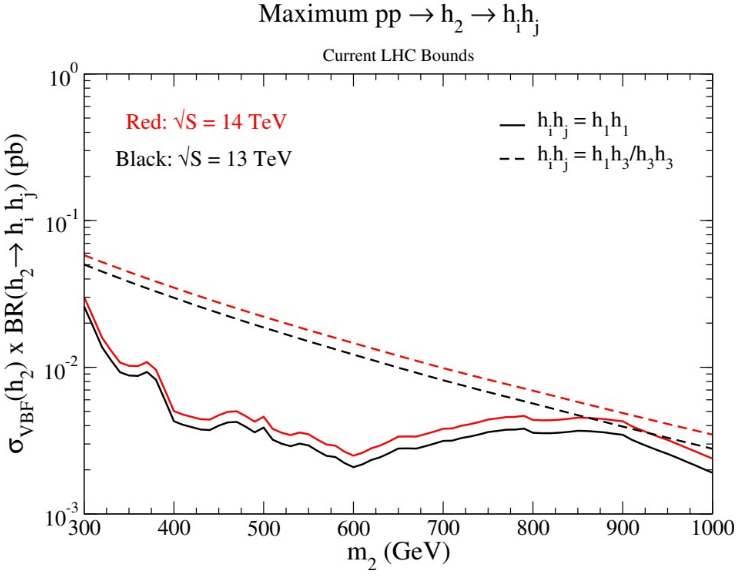
$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} \cos\theta_1 & -\sin\theta_1 & 0 \\ \sin\theta_1 & \cos\theta_1 & \sin\theta_2 \\ \sin\theta_1 \sin\theta_2 & \cos\theta_1 \sin\theta_2 & -1 \end{pmatrix} \begin{pmatrix} h \\ S_0 \\ A \end{pmatrix} + O\left(\sin^2\theta_2\right)$$

  - In limit $\theta_2 \to 0$, h_3 has very small couplings to SM fermions and gauge bosons.
  - The production of h_3 is mainly through decays of heavier scalar h_2: may be the only way to discover.
  - Could discover two scalars at once.

Di-Scalar Resonant Production





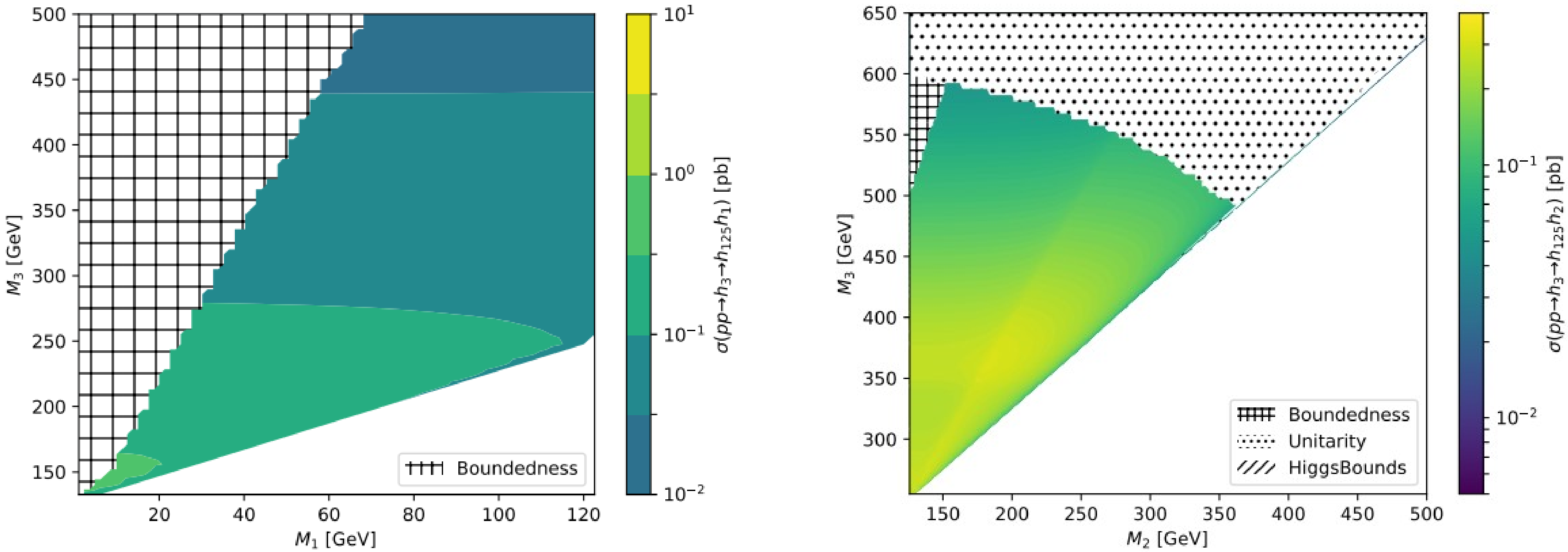


Adhikari, Lane, **IML**, Sullivan, arXiv:2203.07455

- We considered 130 GeV < m_3 < 270 GeV
- Interest to search for these final states.

CMS arXiv:2204.12413; CMS JHEP09 (2021) 57

Resonant Di-Scalar Production: Two Real Singlet Model



Robens, arXiv:2209.10996

- Two real singlet model with each model with two Z_2s: Robens, Stefaniak, Wittbrodt EPJC80 (2020) 151
  - $Z_2: S \to -S, X \to X, SM \to SM, \quad Z_2': S \to S, X \to -X, SM \to SM$
- Different mass ordering $m_1 < m_2 < m_3$
- 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: Complex 2HDM, Real 2HDM+Singlet, etc.

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; etc.

Two Higgs Doublet Models

Two Higgs Doublet Models

- Introduce a second Higgs doublet:
  - $\Phi_1, \quad \Phi_2$
- Typically make one Higgs doublet odd under a Z_2 parity: $\Phi_1 \rightarrow -\Phi_1$

Glashow, Weinberg PRD15 (1977) 1958; Paschos PRD15 (1977) 1966

  - Right handed fermions assigned a parity to forbid couplings to one type of Higgs doublet.
  - Mass and Yukawa matrices are proportional, so they are simultaneously diagonalizable and tree level FCNCs are avoided.
  - The types and their patterns of couplings:

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

Branco, Ferreira, Lavoura, Rebelo, Sher Phys. Rept. 516 (2012) 1

Beyond Typical 2HDM

- Usually assume Z_2 in 2HDM to avoid tree level flavor changing neutral currents., however, Yukawas can have different structures.
- For example Spontaneous Flavor Violation. Egana-Ugrinovic, Homiller, Meade PRL 123 (2019) 031802, PRD100 (2019) 115041, PRD 103(2021) 115005
- In the Higgs basis:

$$\langle H_1^+ H_1 \rangle = \frac{v^2}{2}, \langle H_2^+ H_2 \rangle = 0$$

  - H_1 couples according the SM Yukawas:

$$\lambda_1^u = V^T Y^u, \quad \lambda_1^d = Y^d, \quad \lambda_1^l = Y^l$$

    - Where Y are diagonal Yukawa matrices and V is the CKM matrix.
  - H_2 either couples according to SM Yukawas or diagonal:
    - Up type Spontaneous Flavor Violation:

$$\lambda_2^u = \xi V^T Y^u \qquad \lambda_2^d = K^d = \mathrm{diag}(\kappa_d, \ \kappa_s, \ \kappa_b) \qquad \lambda_2^l = \xi^l Y^l$$

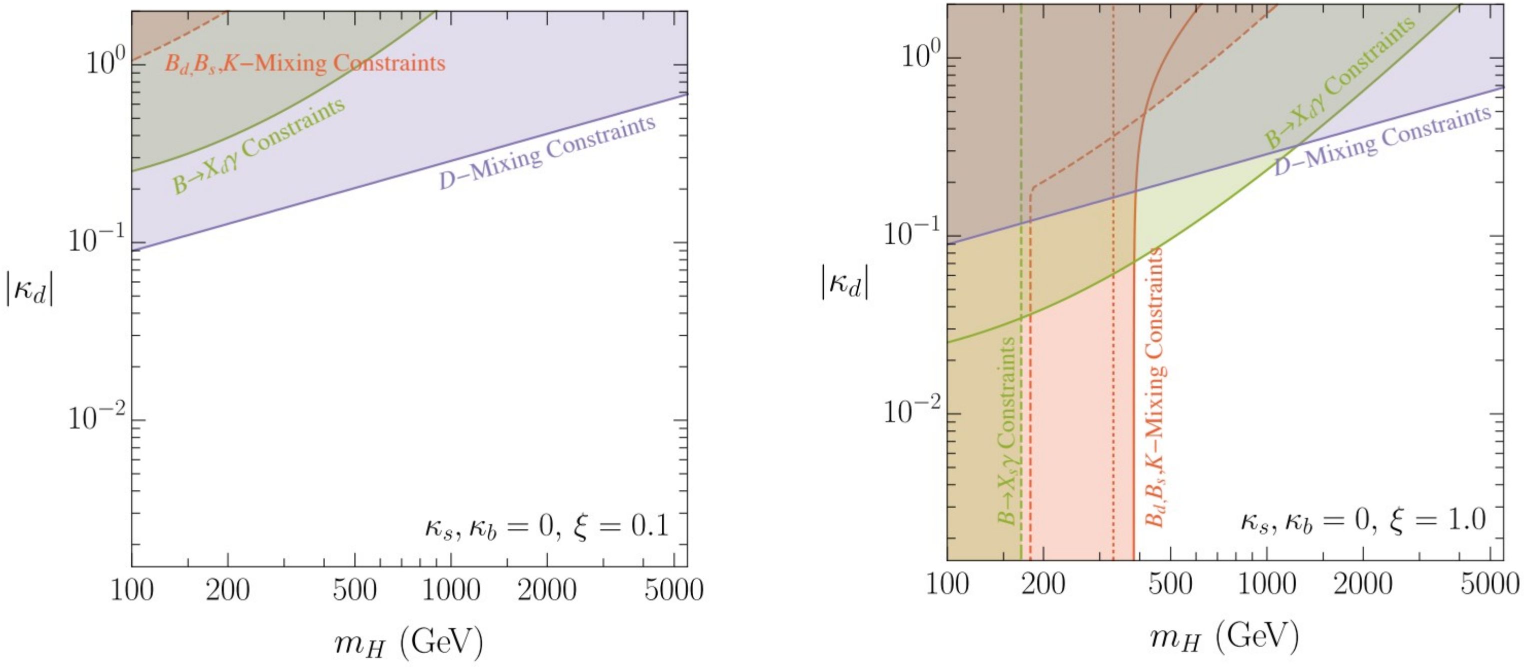
    - Down Type Spontaneous Flavor Violation:

$$\lambda_2^u = \xi K^u = \mathrm{diag}(\kappa_u, \ \kappa_c, \ \kappa_t) \qquad \lambda_2^d = Y^d \qquad \lambda_2^l = \xi^l Y^l$$

- Leads to new types of signatures: dijet resonance.
- Different ansatzes to avoid FCNCs without parity have been considered:

Cheng, Sher PRD35 (1987) 3484, Babu, Jana JHEP02 (2019) 193

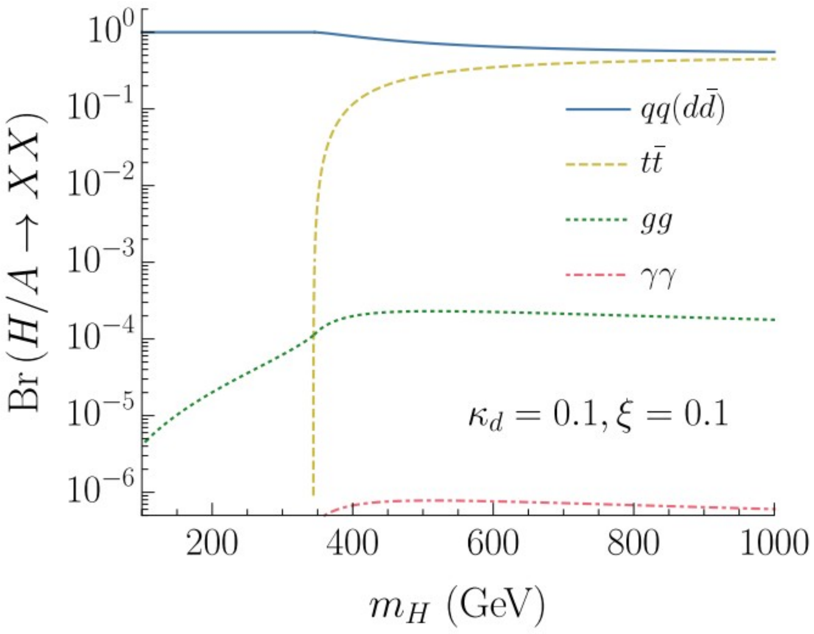
Flavor Constraints in SFV

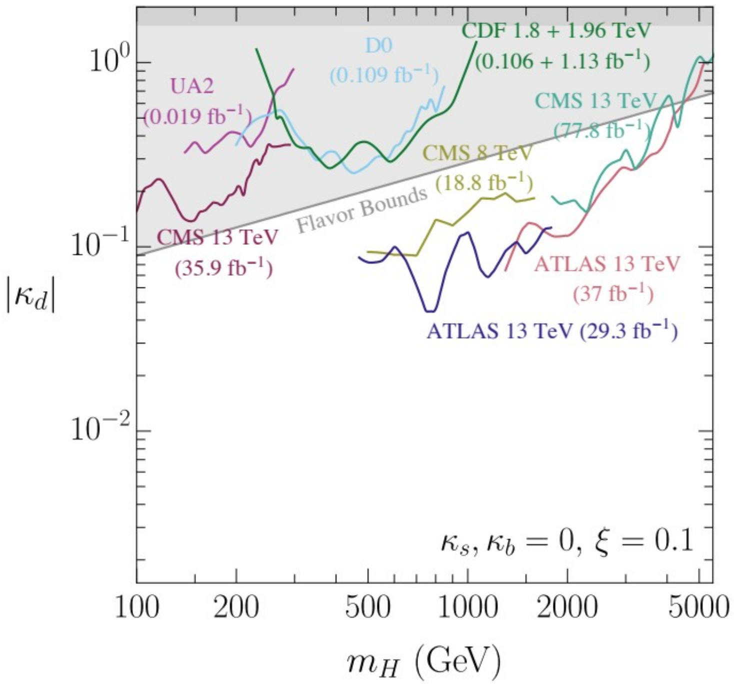


Egana-Ugrinovic, Homiller, Meade PRD 103 (2021) 115005

- Can avoid many flavor constraints with this ansatz.
- For flavor constraints at higher masses see Davoudiasl, **IML**, Sullivan, PRD104 (2021) 015024

Dijet Signal





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- New scalar can have be produced via quark anti-quark annihilation and decay into dijets:

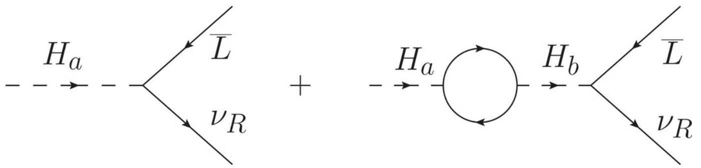
$$q^{(1)}\bar{q}^{(2)} \rightarrow H/A/H^{+-} \rightarrow q^{(3)}\bar{q}^{(4)}$$

- What can we do with this?

Baryogenesis From Three Higgs Doublets

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

- 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:

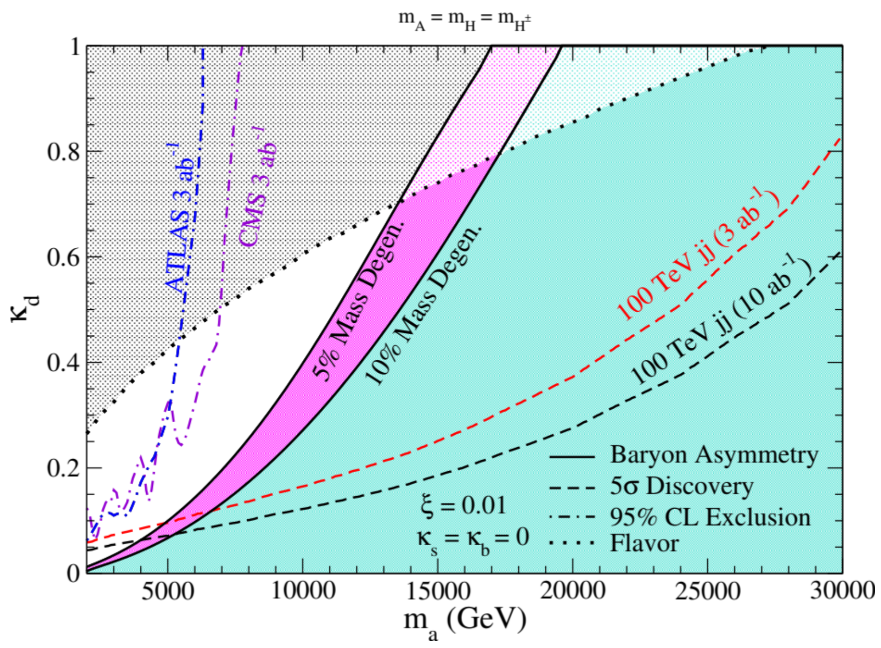
$$\varepsilon_a = \frac{1}{8\pi}\frac{(m_b^2 - m_a^2)m_a^2}{(m_b^2 - m_a^2)^2 + m_b^2\Gamma_b^2}\frac{\sum_{f=q} N_{c,f}\mathrm{Im}\left(\mathrm{Tr}_\nu^{ba}\mathrm{Tr}_f^{ba*}\right)}{\sum_{f=q} N_{c,f}\mathrm{Tr}_f^{aa}} \qquad \mathrm{Tr}_f^{ba} = \mathrm{Tr}[\lambda_f^{b\dagger}\lambda_f^a].$$

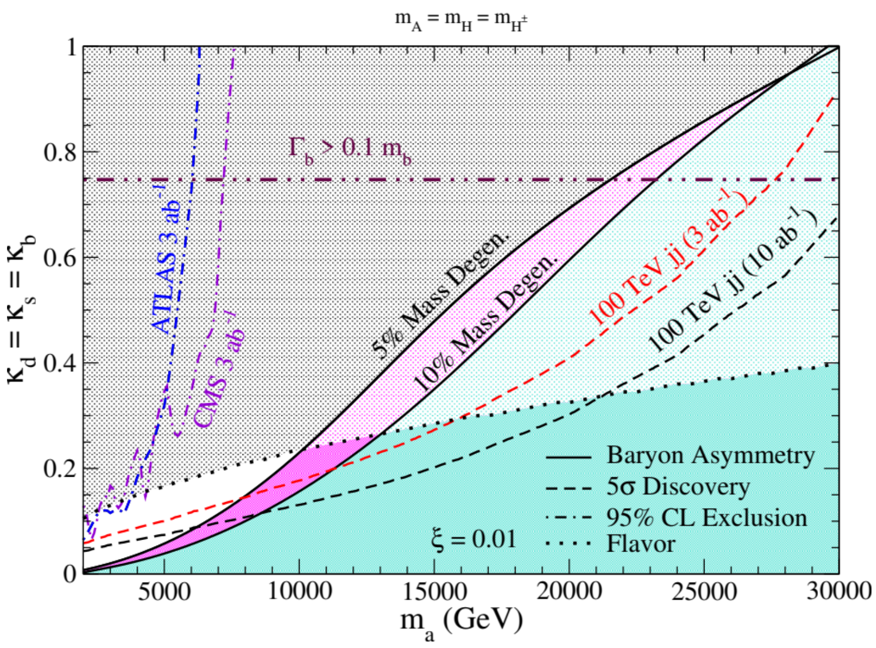
- Need two additional Higgs doublets in order to overcome small SM Yukawas Dirac neutrinos.
  - The Higgs Troika: three Higgs doublet model.
  - (For a 2HDM that relies on highly degenerate neutrinos see Hambye, Teresi, PRL117 (2016) 091801, PRD96 (2017) 015031)
- This model can have large couplings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

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

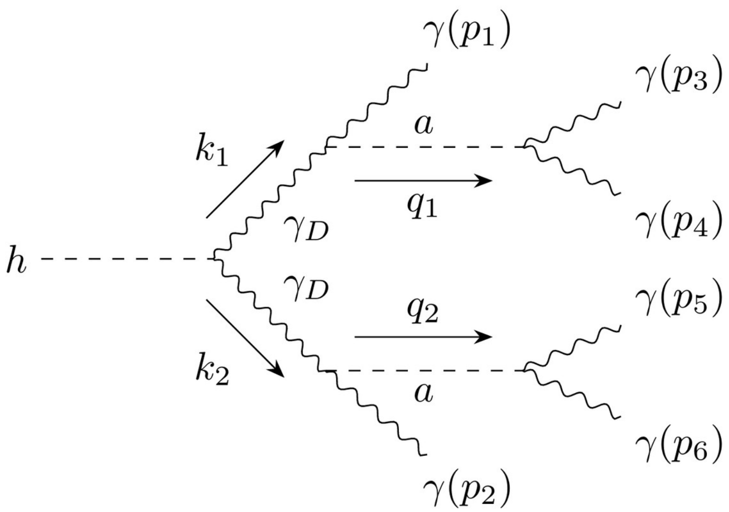
- Depending on couplings can have TeV doublets that generate the baryon asymmetry.
- Heavy Higgs up-quark couplings proportional to SM Yukawas with proportionality constant ξ
- $\kappa_d, \kappa_s, \kappa_b$ are the diagonal couplings between heavy Higgs and down-type quarks

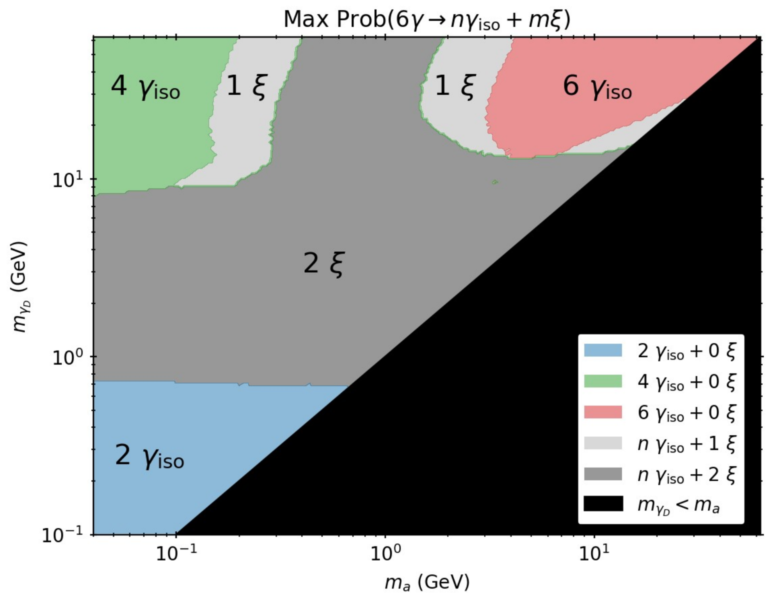
More Exotica:
Multi-Photon Higgs Decays

Multi-Photon Higgs Signals

- Higgs has very small width: $\Gamma = 4.1\,MeV$
  - Searches for exotic Higgs decays can be quite sensitive to new physics.
- Many works on di-photon and 4-photon resonances.
- Recently looked at a 6 photon signal.
  - Depending on masses and can get variety of signals.
  - Photon jets: $\Delta R < 0.04$
  - ξ -jets: $0.04 < \Delta R < 0.4$
  - Isolated: $0.4 < \Delta R$
- The 4-photon signal is an apparent Landau-Yang violation.
- ξ-jets and six photons particularly difficult.
  - Non-isolated photons not usually consider in analysis.
    - Isolated photons will not reconstruct Higgs mass
  - The six photons are soft and difficult to pass triggers.
  - Many of these events may have passed two and four photon triggers.
- See Sam Lane's talk/slides.

Lee, Lane, **IML**, arXiv:2305.00013



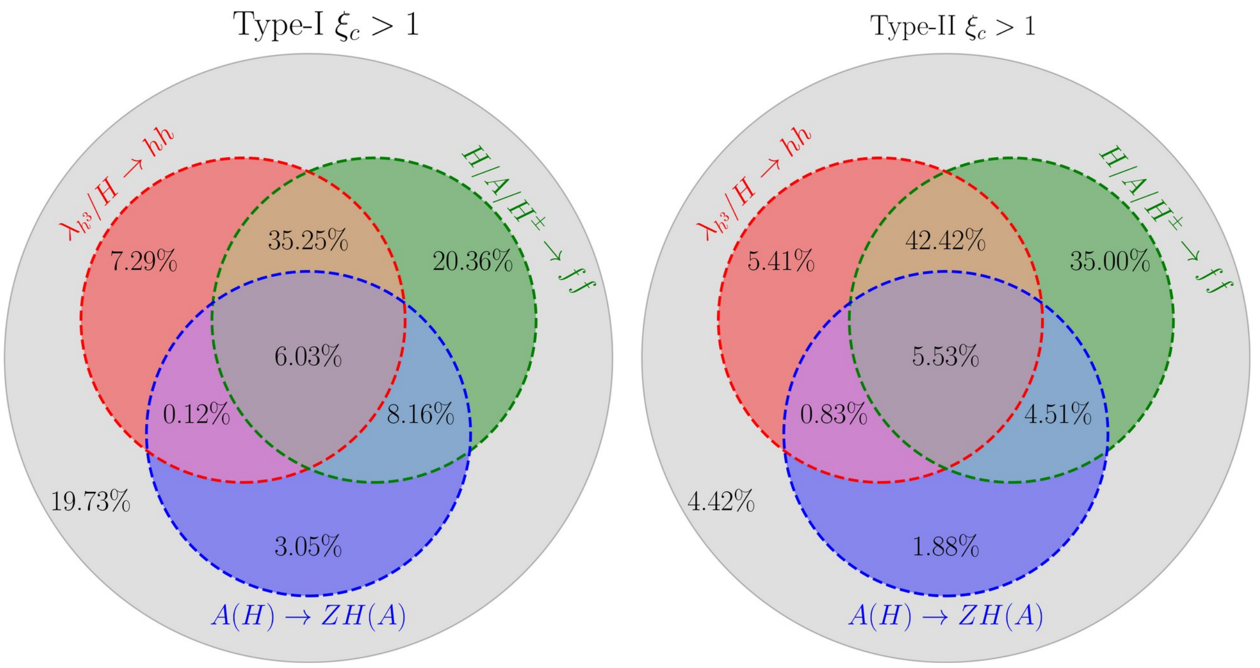


Conclusions

- The Higgs is central to the Standard Model.
  - Standard Model now completely predictive.
- Very robust experimental program measuring its properties (with many excellent talks at this conference.)
- Still much to learn, even in the SM
  - Probing the structure of the Higgs potential still an ongoing program.
- Higgs is special in that the Higgs portal is very difficult to forbid.
  - New di-scalar production modes can probe the different couplings in scalar extensions of the SM.
  - New scalar resonances.
- Still interesting signals and models to explore:
  - Higgs tied closely to flavor.
  - TeV scale Higgs decays could explain the matter/anti-matter asymmetry.
  - The theory space of exotic Higgs decays not fully explored: multi-photon Higgs decays.

Thank You

2HDM: Different Heavy Higgs Search Channels



Gonçalves, Kaladharan, Wu PRD105 (2022) 095041

- Color shaded regions are percentage that different search channels cover regions of parameter space that are allowed and provide a strong first order electroweak phase transition at HL-LHC.
- Important to look at many different possible channels.
- Including searches for pp → Z H (A) → Z t t increases overlap region in Type-I, but overall coverage is the same.

Gonçalves, Kaladharan, Wu arXiv:2206.08381