Higgs Physics at Colliders

Lecture 2: Beyond the Standard Model

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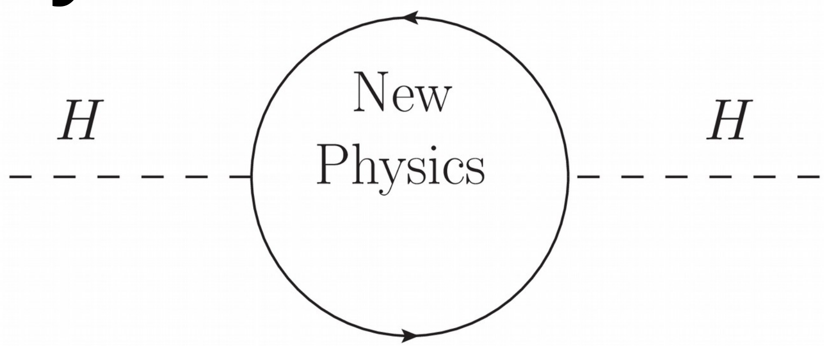
Lecture 2 Overview

- Review why the we expect new physics.
- New physics in Higgs sector (highly subjective):
  - SUSY
  - Extended Scalar Sectors.
  - Electroweak baryogenesis and strong first order electroweak phase transition.

Why the Discontent?



$$\delta m_H^2 \sim \frac{\lambda^2}{16\pi^2} m_{NP}^2$$

$$m_h^2 \sim \mu^2 + \delta m_h^2 \sim \mu^2 + \frac{\lambda^2}{16\pi^2} m_{NP}^2$$

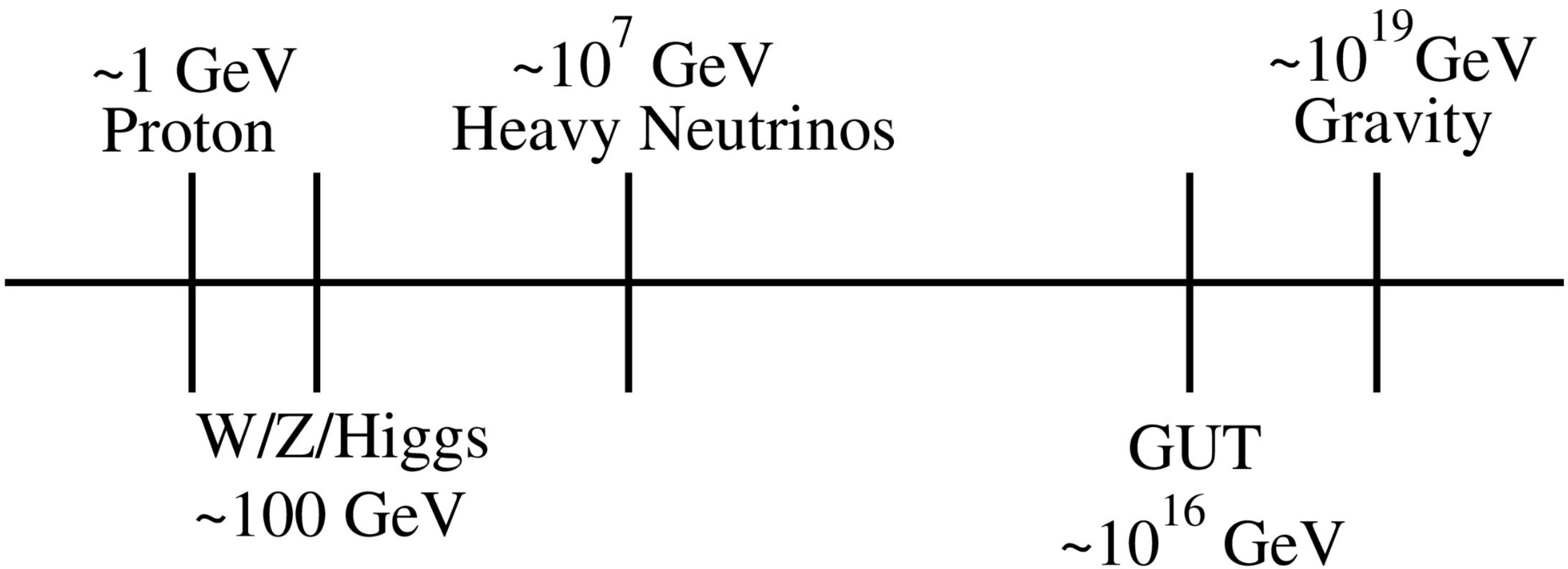
- Note: this is a physical mass of a new particle ***not*** a cutoff scale.
  - A cutoff scale is a mechanism for renormalization, cutting off the integrals of loops to parameterize infinities that we can then cancel
  - Could renormalize with dimensional regularization:

$$d^4 p \to d^{4-2\varepsilon} p$$

  - Then infinities appear as $1/\varepsilon$
  - Cancel infinities like normal and move on.
  - However, if there is a new particle going in the loop, the Higgs mass is quadratically dependent on the new scale independent of regularization scheme.

New Physics Scales

- Expect new physics scales:



Fermion Masses are protect Protected

- Look at a generic fermion kinetic term:

$$\mathcal{L} = \overline{\psi} i \not{D} \psi = \overline{\psi}_L i \not{D} \psi_L + \overline{\psi}_R i \not{D} \psi_R$$

  - Invariant under separate transformations of both the left- and right-handed fermions.

$$\psi_L \to e^{i\theta_L} \psi_L \qquad \psi_R \to e^{i\theta_R} \psi_R$$

- Add a mass term:

$$\mathcal{L} = \overline{\psi}_L i \not{D} \psi_L + \overline{\psi}_R i \not{D} \psi_R - m \left(\overline{\psi}_L \psi_R + \overline{\psi}_R \psi_L \right)$$

  - Now left- and right-handed transformations have to be equal: $\theta_L == \theta_R$
- Fermion masses are "technically natural"
  - As you send mass to zero the symmetries of the Lagrangian are expanded.
  - Hence quantum corrections are proportional to fermion masses.
  - If the fermion masses are small, they stay small and fermion masses are "protected."

Higgs mass not protected

- The problem is that the Higgs mass term is invariant under symmetries:

$$V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda\left(\Phi^\dagger\Phi\right)^2$$

- So sending the mass to zero does not enhance the symmetry of the Lagrangian, and it is not protected.
  - Everything invariant under any Unitary transformation:

$$\Phi \to U\Phi, \quad \Phi^\dagger \to \Phi^\dagger U^\dagger \Rightarrow \Phi^\dagger\Phi \to \Phi^\dagger\Phi$$

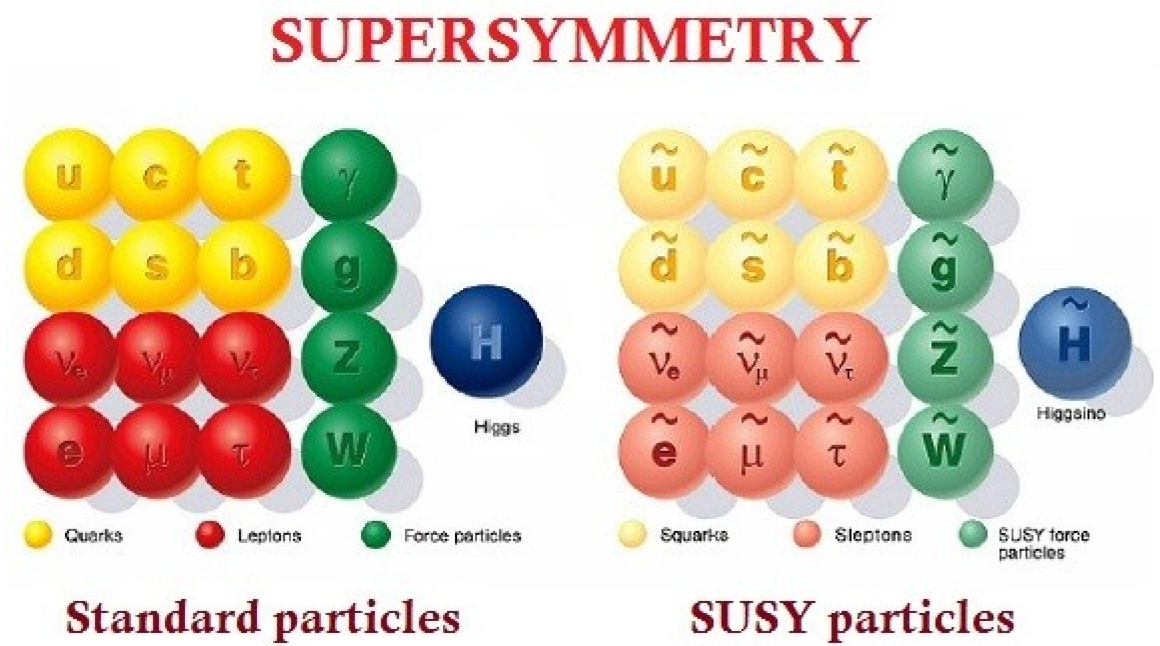
- Loop corrections (even after renormalization) are quadratically sensitive to the masses of new particles at high scales.

$$m_h^2 \sim \mu^2 + \delta m_h^2 \sim \mu^2 + \frac{\lambda^2}{16\pi^2} m_{NP}^2$$

- Distressing, because a “low energy” parameter like the Higgs mass parameter depends intimately upon the high scale new physics.
  - Generically expect to make predictions at low scale without have to know about the high scale physics.

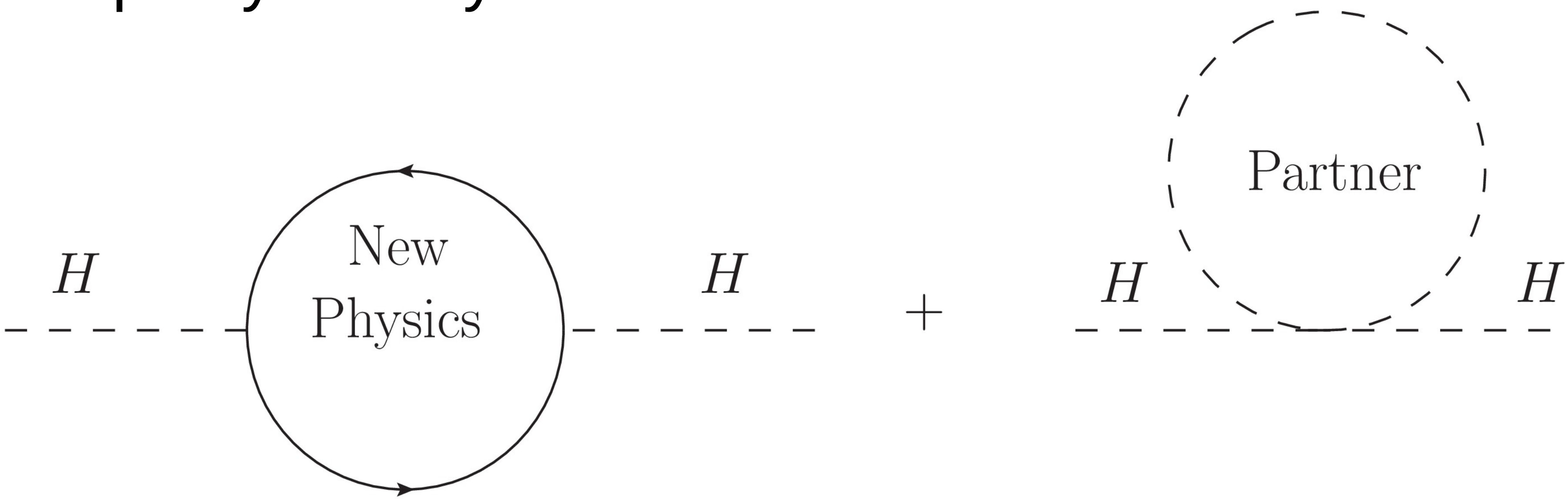
Weakly Interacting Solution
Supersymmetry

- Every boson has a fermionic partner.
- Every fermion has a bosonic partner.



Solutions to Hierarchy Problem

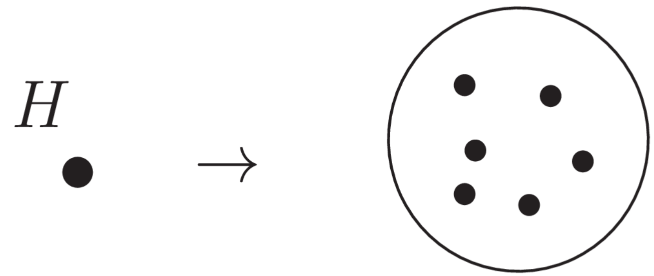
- Supersymmetry:



- Supersymmetry relates mass and couplings of fermion and scalar partners.
  - Loops have opposite signs and cancel.
  - SUSY must be broken, cancellation incomplete.

Strongly Interacting Solution Composite Models

- Observed Higgs boson is a composite particle:



- No fundamental scalars
  - Hierarchy problem unique to scalars.
    - Fermions and gauge bosons only have logarithmic dependence on mass of new physics.
  - If constituents are fermions, once you go above confinement scale fermions are relevant and they have no hierarchy problem.

Electroweak Symmetry Breaking Sector

- Many of these models contain extended or altered electroweak symmetry breaking sectors.

- Typically have additional new physics associated with this sector.
  - Top partners
    - Scalar tops in SUSY
    - Fermionic top partner in composite models.
  - New resonances
- Will focus on measuring single or multi-Higgs production.
- WARNING: This is a highly subjective selection of subjects/models.

Supersymmetry
(Weakly Interacting Solution to Hierarchy Problem)

SUSY

- Minimal Supersymmetric Standard Model (MSSM):
  - Two Higgs Doublets: H_u, H_d
    - $H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$ gives masses to up-type fermions.
    - $H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$ gives masses to down-type fermions.
  - So called Type-II Two Higgs Doublet Model (2HDM).

$$\mathcal{L} = -y_u \overline{u_R} H_u Q_L - y_d \overline{d_R} H_d Q_L - y_\ell \bar{e}_R H_d L_L + \text{h.c.}$$

Higgs Sector

- The two Higgses get vevs:

$$\langle H_u\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_u\end{pmatrix} \qquad \langle H_d\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}v_d\\ 0\end{pmatrix}$$

- When we try to calculate the W-mass (Using the covariant derivative. Note that H_u has the SM Higgs Hypercharge and H_d has the opposite hypercharge):

$$M_W = \frac{1}{2}g\sqrt{v_u{}^2 + v_d{}^2} = \frac{1}{2}gv$$

- Can define and angle $\tan\beta = v_u/v_d$ such that $v_d = v\cos\beta$ and $v_u = v\sin\beta$

- Now note $\widetilde{H}_d = -\varepsilon H_d^* = \begin{pmatrix}-H_d^+\\ H_d^{0*}\end{pmatrix}$ that also transforms as a doublet.
  - ε is the 2x2 Levi-Civitia matrix: $\varepsilon = \begin{pmatrix}0 & 1\\ -1 & 0\end{pmatrix}$

- Then $H_u, \widetilde{H}_d$ have the same quantum numbers and can mix.

Higgs Sector

- Now we perform the mixing:

$$H_1 = \cos\beta \widetilde{H}_d + \sin\beta H_u \qquad\qquad H_2 = -\sin\beta \widetilde{H}_d + \cos\beta H_u$$

- Note that the vevs of the new fields are:

$$\langle H_1 \rangle = \cos\beta \langle \widetilde{H}_d \rangle + \sin\beta \langle H_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \cos\beta v_d + \sin\beta v_u \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\langle H_2 \rangle = -\sin\beta \langle \widetilde{H}_d \rangle + \cos\beta \langle H_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ -\sin\beta v_d + \cos\beta v_u \end{pmatrix} = 0$$

  – Used $v_d = v\,\cos\beta$ and $v_u = v\,\sin\beta$

- Then H_1 is the SM Higgs doublet, and H_2 is a second Higgs doublet.
  – H_1 is the combination that gives Ws and Zs masses, hence the Goldstone bosons live here.
  – H_2 has no vev, does not give Ws and Zs masses, there are no Goldstones in H_2. The physical charged scalars and pseudoscalars live here.

Higgs Particles

- Goldstones:

$$G^{\pm} = -\cos\beta\, H_d^{\pm} + \sin\beta\, H_u^{\pm} \qquad G^0 = \sqrt{2}\left(-\cos\beta\,\mathrm{Im}(H_d^0) + \sin\beta\,\mathrm{Im}(H_u^0)\right)$$

- Charged and pseudoscalar Higgs:

$$H^{\pm} = \sin\beta\, H_d^{\pm} + \cos\beta\, H_u^{\pm} \qquad A = \sqrt{2}\left(\sin\beta\,\mathrm{Im}(H_d^0) + \cos\beta\,\mathrm{Im}(H_u^0)\right)$$

  - With masses: $M_{H^{\pm}}$ M_A
- We also have two scalar Higgs boson, which are superpositions of the neutral scalar components of H_u and H_d:

$$h = -(\sqrt{2}\,\mathrm{Re}\,H_d^0 - v_d)\sin\alpha + (\sqrt{2}\,\mathrm{Re}\,H_u^0 - v_u)\cos\alpha$$

$$H = (\sqrt{2}\,\mathrm{Re}\,H_d^0 - v_d)\cos\alpha + (\sqrt{2}\,\mathrm{Re}\,H_u^0 - v_u)\sin\alpha$$

- Where h has mass M_h and H has mass M_H
  - There is a new mixing angle α.
- Counting: originally 8 real scalar fields (4 for each doublet):
  - 3 eaten to give Ws and Z masses.
  - 5 left over physical Higgs bosons.

Scalar Higgs Boson Couplings

- H and h couplings to fermions:

	Top Quarks	Bottom Quarks	τ leptons
h	$\frac{\cos\alpha}{\sin\beta}\frac{m_t}{v}$	$-\frac{\sin\alpha}{\cos\beta}\frac{m_b}{v}$	$-\frac{\sin\alpha}{\cos\beta}\frac{m_\tau}{v}$
H	$\frac{\sin\alpha}{\sin\beta}\frac{m_t}{v}$	$\frac{\cos\alpha}{\cos\beta}\frac{m_b}{v}$	$\frac{\cos\alpha}{\cos\beta}\frac{m_\tau}{v}$

- H and h couplings to bosons.

	WW	ZZ
h	$2\frac{M_W^2}{v}\sin(\beta-\alpha)$	$2\frac{M_W^2}{v}\sin(\beta-\alpha)$
H	$2\frac{M_Z^2}{v}\cos(\beta-\alpha)$	$2\frac{M_Z^2}{v}\cos(\beta-\alpha)$

- Take h to be the observed Higgs boson ($m_h = 125$ GeV), then couplings are shifted from the SM. Precision measurement of SM Higgs constrains the new sector
- If $\beta-\alpha=\frac{\pi}{2}$ then H coupling to gauge bosons goes to zero, and h couplings to gauge bosons go to SM value.

MSSM Higgs

- Minimal Supersymmetric Standard Model (MSSM) Higgs potential:

$$V = m_1^2 H_d^\dagger H_d + m_2^2 H_u^\dagger H_u - m_{12}^2 \left(\varepsilon_{ab} H_d^a H_u^b + \mathrm{h.c.}\right)$$

$$+\frac{g'^2+g^2}{8}\left(H_d^\dagger H_d - H_u^\dagger H_u\right)^2 + \frac{g^2}{2}\left|H_u^\dagger H_d\right|^2$$

  - Quartic terms come from gauge couplings.
  - Only three free parameters in potential.
- Like normal two Higgs doublet model, there are 5 physical Higgs:
  - Two Scalars: h, H
  - Pseudoscalar: A
  - Two Charged Higgs Boson: $H^\pm$
- Three degrees of freedom:
  - SM Higgs mass of M_h=125 GeV
  - Ratio of vevs: $\tan\beta = v_u/v_d$
  - Mass of pseudoscalar: M_A

Everything Else Can Be Calculated

- Masses of scalar Higgs (tree level):

$$M_{h,H}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 4\,M_Z^2\,M_A^2 \cos^2 2\beta}\right]$$

- Mass of charged Higgs:

$$M_{H\pm}^2 = M_A^2 + M_W^2$$

- Mixing between neutral scalars (tree level):

$$\cos 2\alpha = -\cos 2\beta \left(\frac{M_A^2 - M_Z^2}{M_H^2 - M_h^2}\right)$$

MSSM Mass Predictions

- Upper limit on Higgs mass at tree level:

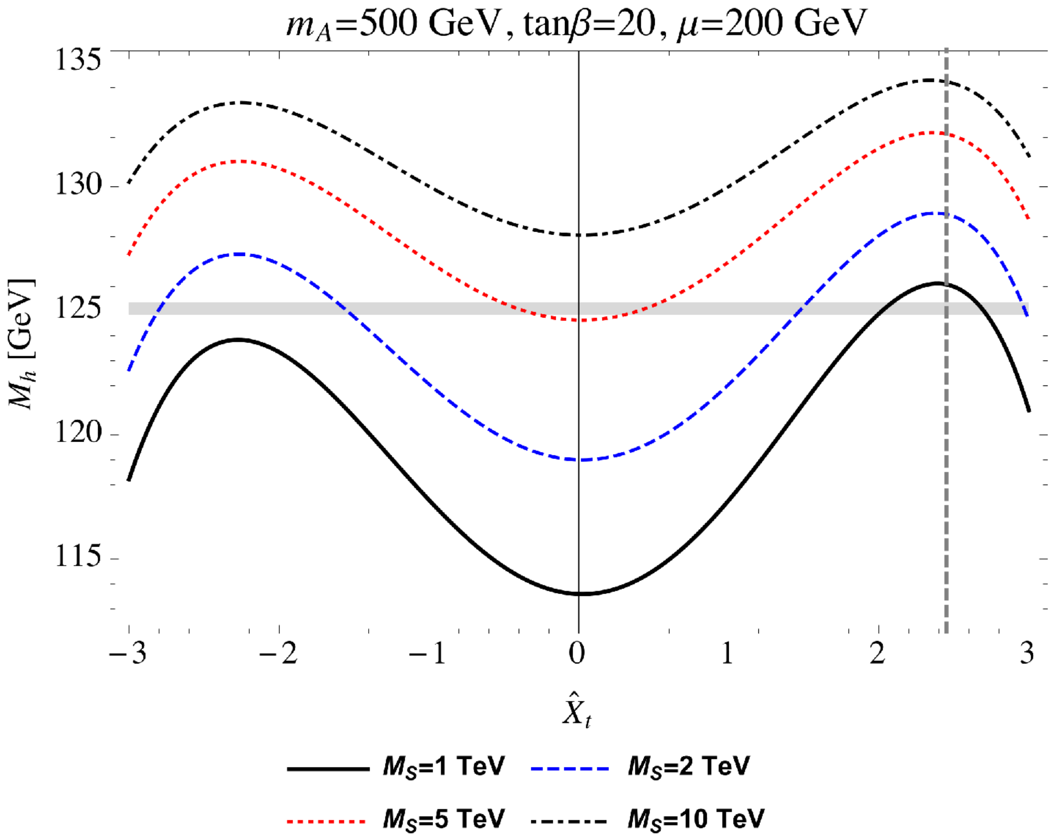
$$M_h < M_Z|\cos 2\,\beta| < M_Z$$

- Loop corrections predominantly from scalar top loops. (Largest couplings to Higgs)

$$M_h^2 \leq M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2 \sin^2\beta}\left(\ln\frac{\widetilde{m}_t^2}{m_t^2} + \frac{X_t^2}{\widetilde{m}_t^2}\left(1 - \frac{X_t^2}{12\widetilde{m}_t^2}\right)\right)$$

  - There are two scalar tops, 1 for left-handed top and 1 for right-handed top.
  - $\widetilde{m}_t^2$ is the average mass of the two scalar tops.
  - X_t is the mixing parameter of the two scalar tops.
  - m_t is the mass of the top quark.

Large Stop Masses



G. Lee, C.W. arXiv:1508.00576

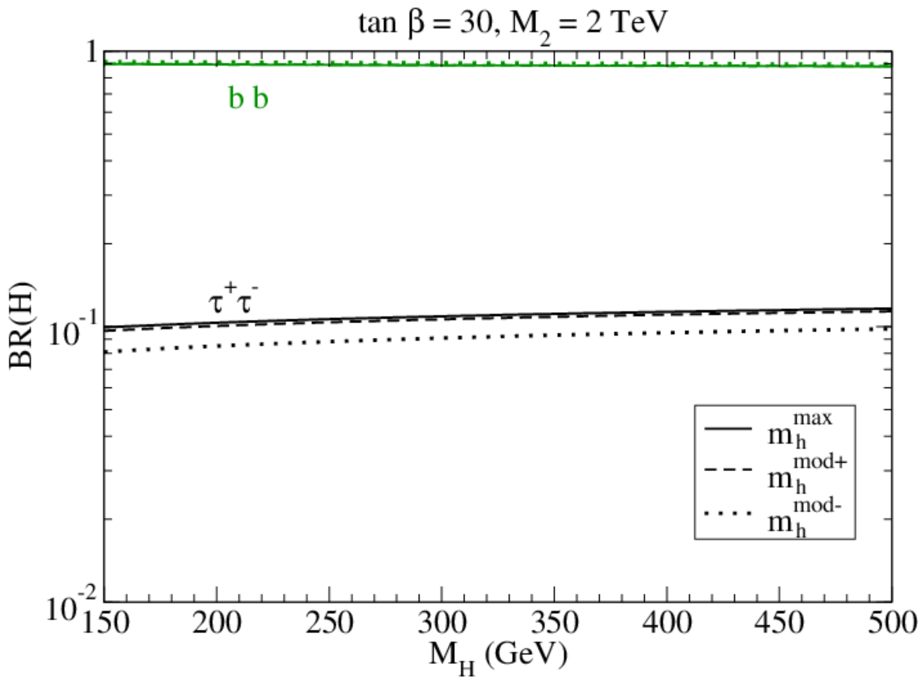
- Need stop masses around 1-2 TeV to get Higgs mass to 125 GeV.

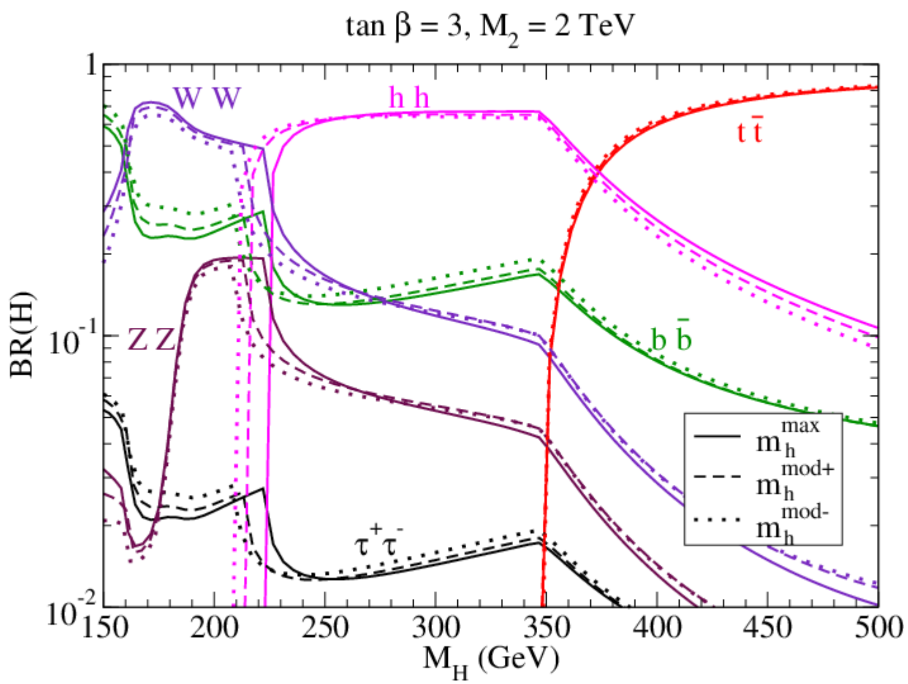
Decays of Heavy Scalar

- Branching ratio depends greatly on $\tan\beta$
- For large $\tan\beta = v_u/v_d$
  - Down type fermions get mass from v_d
  - Smaller v_d , larger Yukawa to down-type fermions to get masses:

$$y_d = \sqrt{2}\, m_d/v_d$$

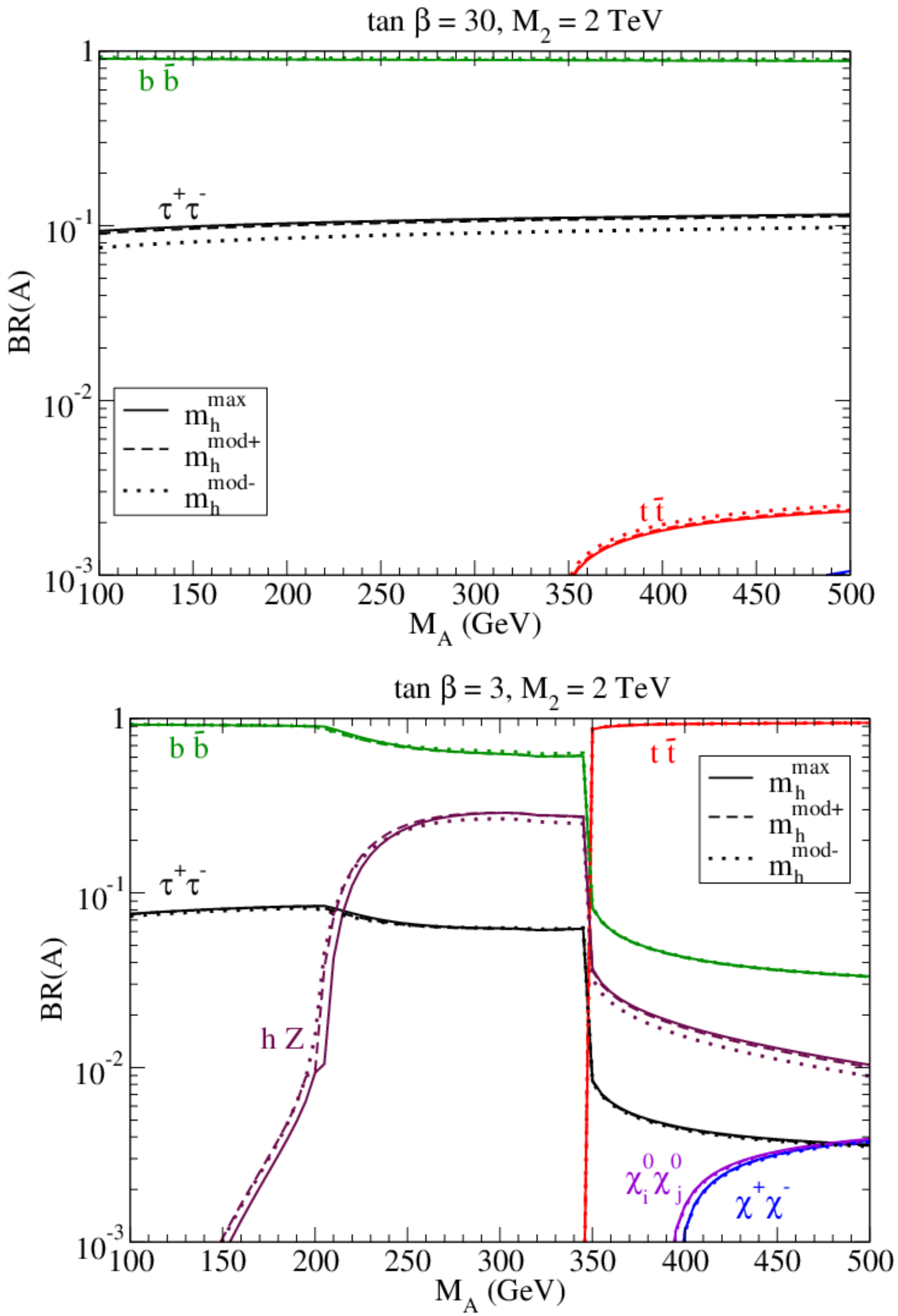
- For small $\tan\beta$
  - Many possible decay channels
  - Depends greatly on mass





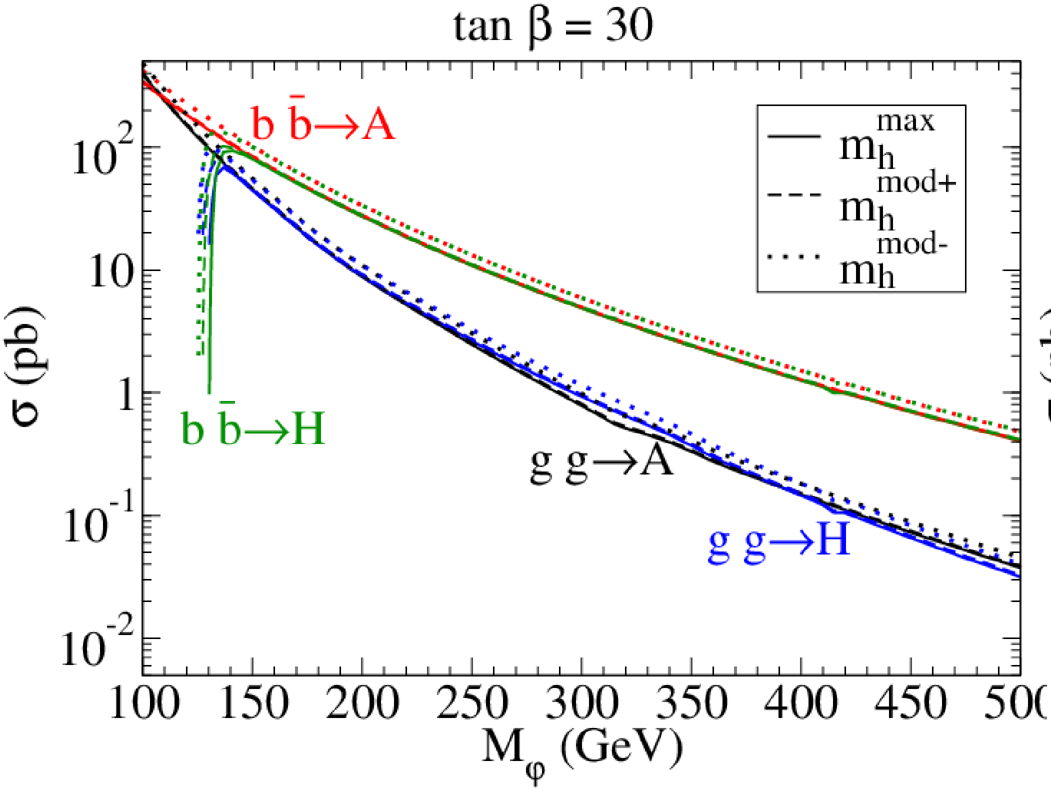
Decays of Pseudoscalar

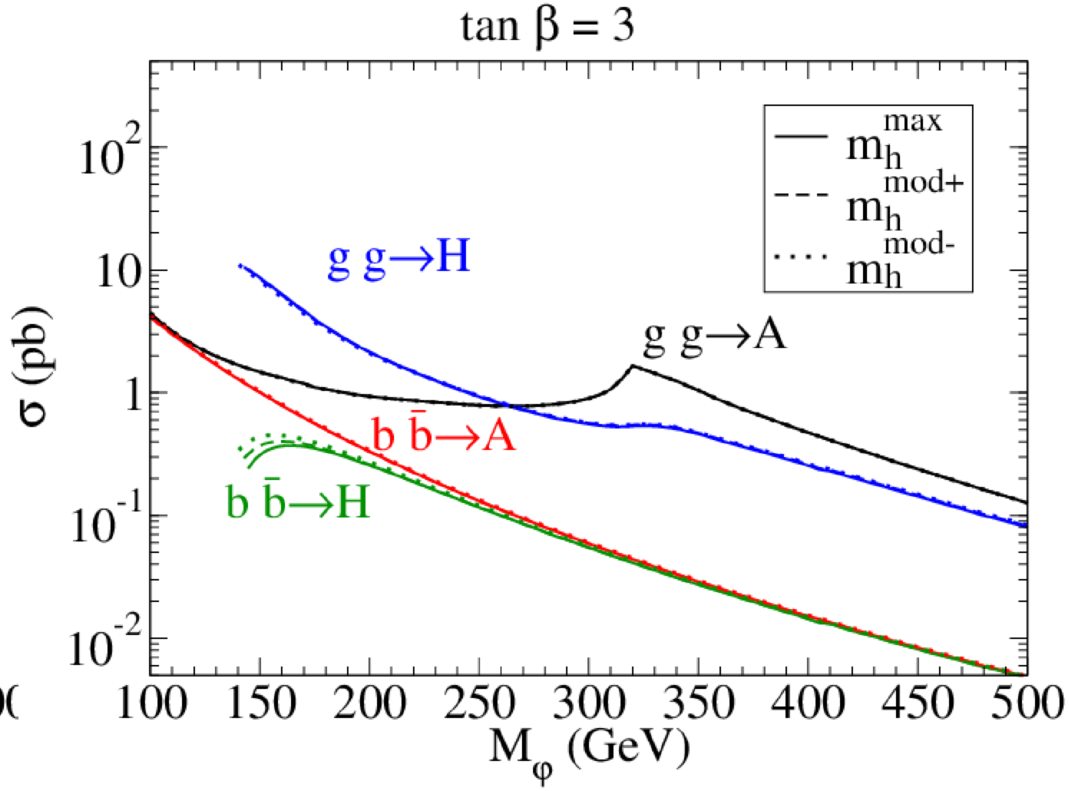
- Branching ratio depends greatly on $\tan\beta$
- For large $\tan\beta$
  - Decays to down-type fermions
- For small $\tan\beta$
  - Many possible decay channels
  - Exotic decay channels open up
  - Depends on thresholds

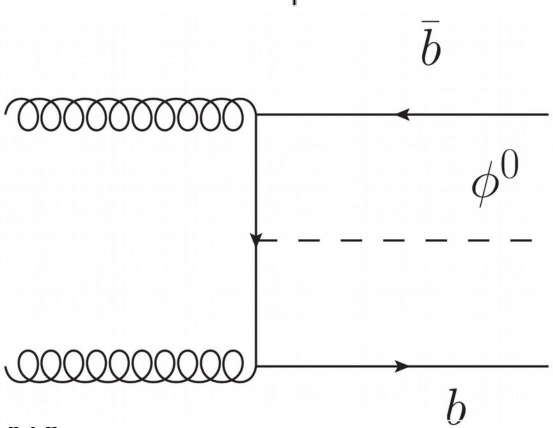


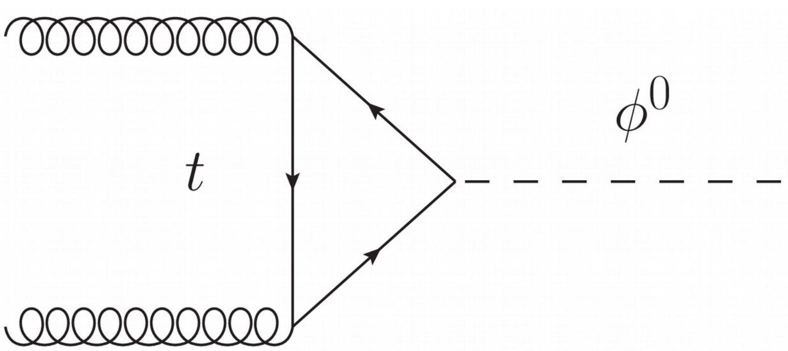
Production of Neutral Scalars

- Production mechanism depends on $\tan\beta$

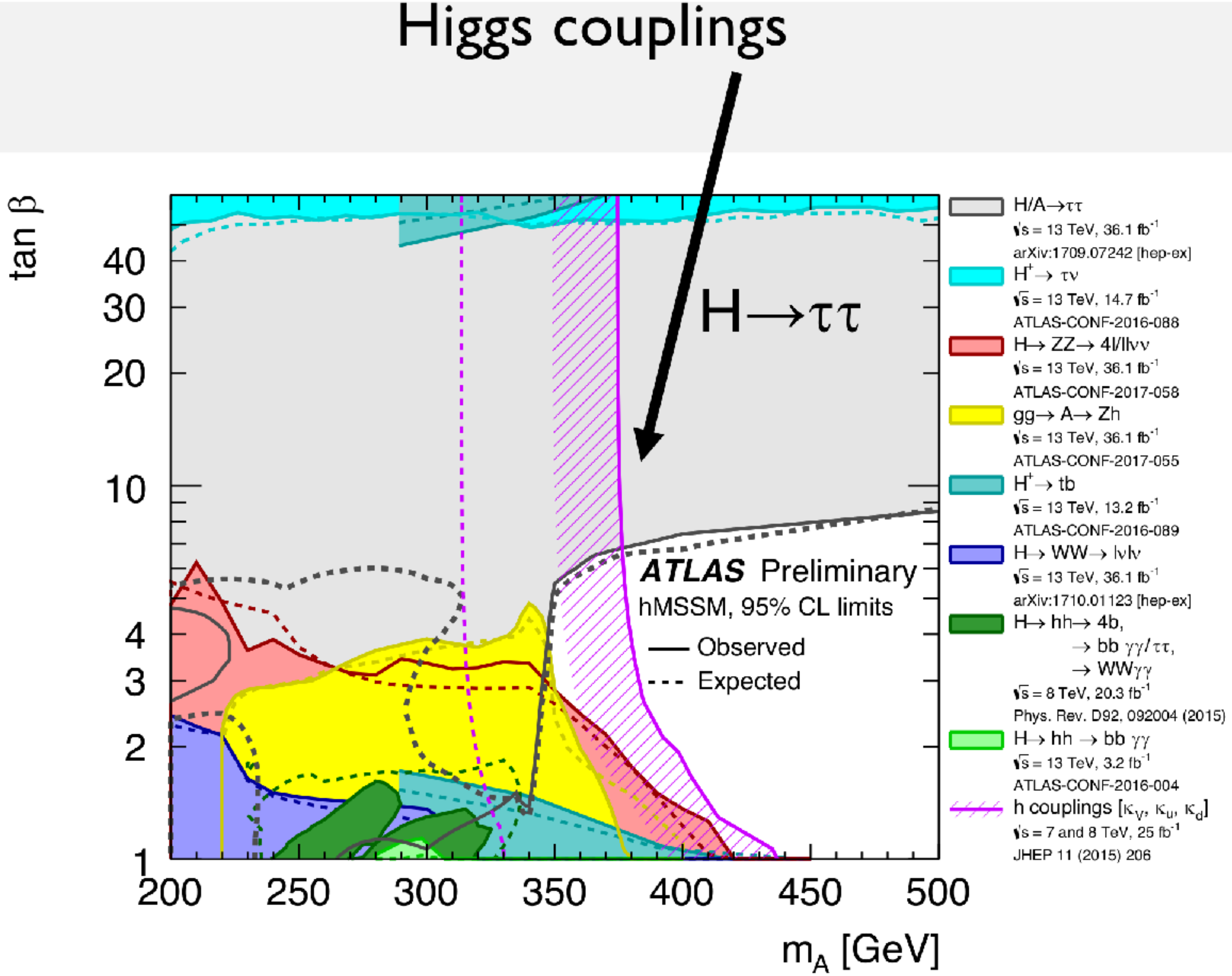








Current Constraints on SUSY Higgs



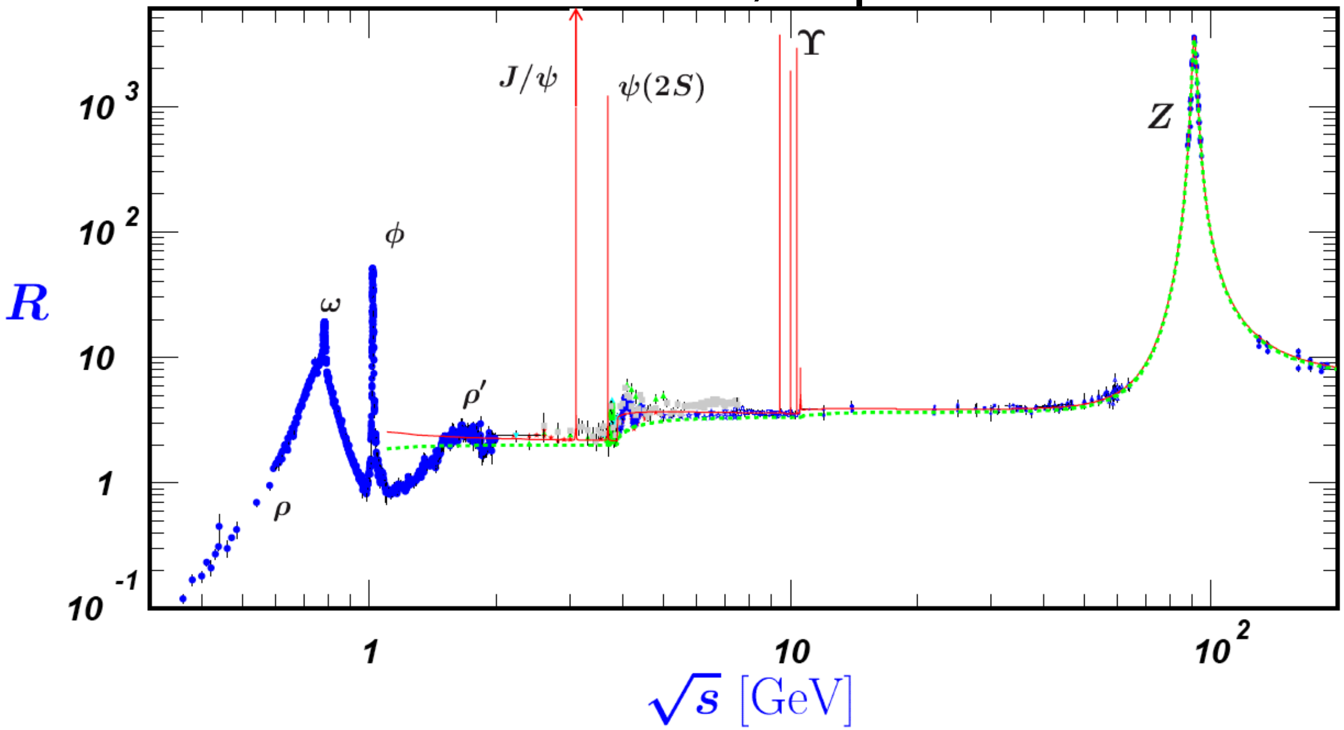
ATLAS arXiv:1610.07922, Sally Dawson lecture at Maria Laach 2018

- Complementarity between different direct searches and precision Higgs couplings.

Composite Models
(Strongly Interacting Solution)

Technicolor

- Most basically: scaled up QCD
  - Electroweak symmetry broken by strong interactions, similar to pions.
  - Strong scale is electroweak scale, expect resonances.



  - Separate strong interaction from electroweak scales.

Pseudo Nambu-Goldstone Boson Higgs

- Make Higgs a Nambu-Goldstone boson of some symmetry breaking.
  - Massless at tree level.
  - Natural to be much lighter than other resonances in the strongly interacting sector.
  - Use loops to give Higgs mass.

$$v_{EW} \quad \ll \quad m_\rho = g_\rho f \quad \ll \quad 4\pi f \to \text{UV completion}$$

Parameterize Via EFT

- Do not necessarily know dynamics of strongly interacting sector.

$$\mathcal{L}_{eff} = -c_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 + m_W^2 W_\mu^+ W^{-\mu}\left(1 + 2c_W \frac{h}{v} + \cdots\right) + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \left(1 + 2c_Z \frac{h}{v} + \cdots\right)$$

$$- \sum_{\psi=u,d,\ell} m_\psi \overline{\psi}\psi \left(1 + c_\psi \frac{h}{v} + \cdots\right) + \cdots$$

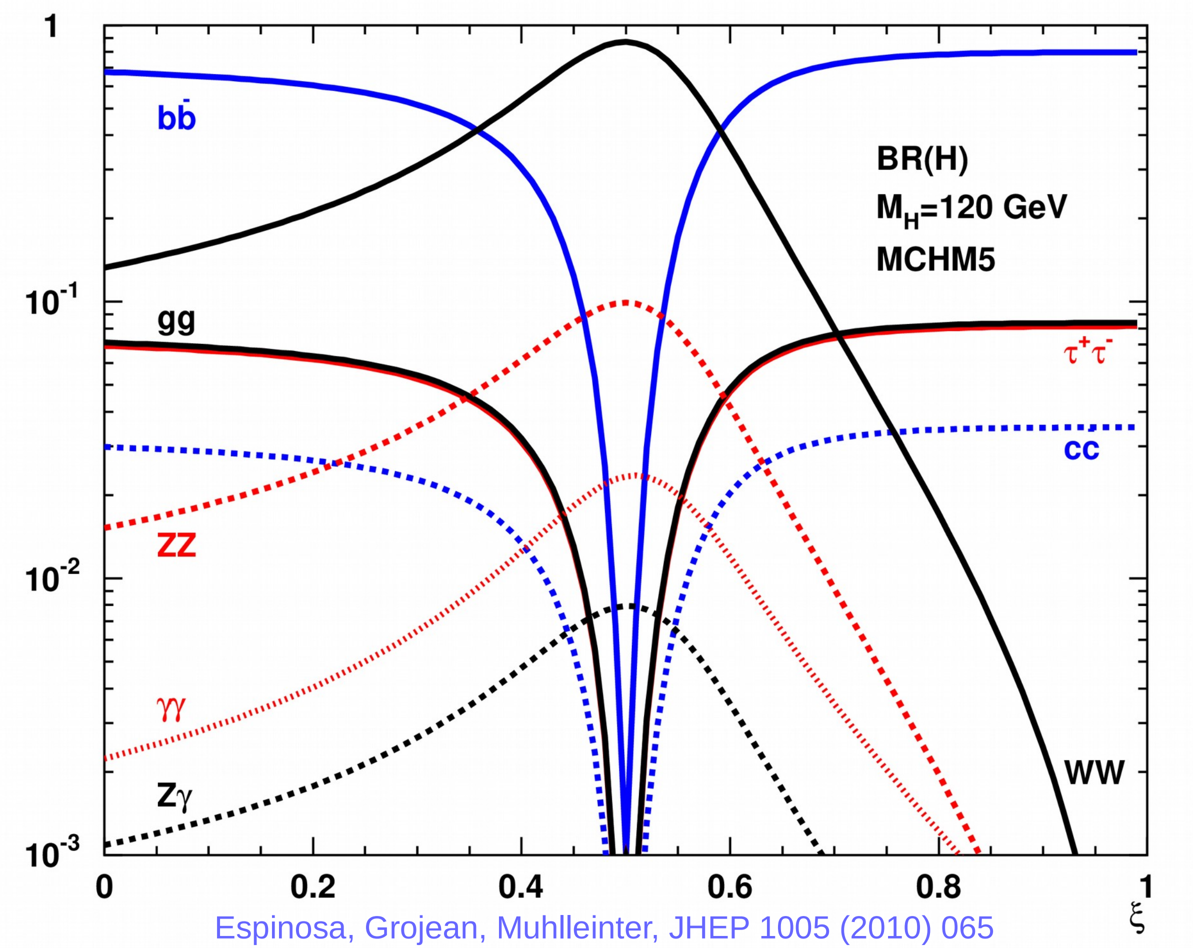
- Standard Model Limit: $c_W = c_Z = c_\psi = 1$
- Changes couplings from Standard Model, expect corrections of order

$$\xi = \frac{v^2}{f^2} \sim \frac{(\text{Electroweak scale})^2}{(\text{Strongly interacting scale})^2}$$

  - This parameter measures the fine-tuning, i.e. the separation between EW scale and strongly interacting scale.
  - The smaller the parameter, the more fine-tuned.

Minimal Composite Models

- Specific models $\Rightarrow$ specific predictions:
  - MCHM5: $c_W = c_Z = \sqrt{1-\xi}, \quad c_3 = c_\psi = \dfrac{1-2\xi}{\sqrt{1-\xi}}$ Agashe, Contino, Pomarol, Nucl.Phys. B719 (2005) 165-187



Espinosa, Grojean, Muhlleinter, JHEP 1005 (2010) 065

Precision Higgs Measurements

- Precise Higgs signal rates:

ξ	LHC	HL-LHC	LC	HL-LC	HL-LHC+HL-LC
universal	0.076	0.051	0.008	0.0052	0.0052
non-universal	0.068	0.015	0.0023	0.0019	0.0019
f [TeV]					
universal	0.89	1.09	2.82	3.41	3.41
non-universal	0.94	1.98	5.13	5.65	5.65

Englert et al J.Phys. G41 (2014) 113001

- For moderate fine tuning, generically expect top partners in TeV range.

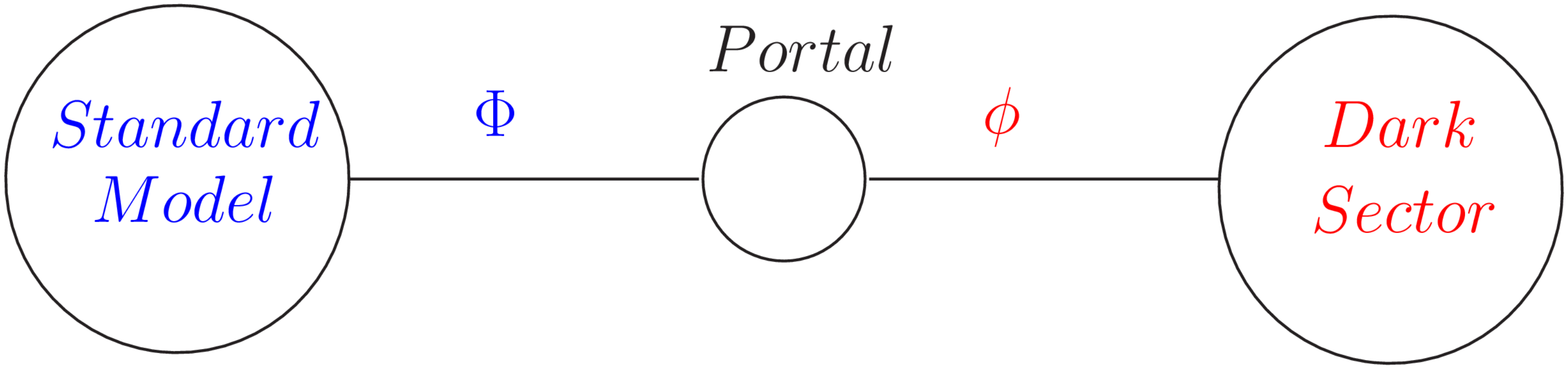
Matsedonskyi, Panico, Wulzer JHEP 1301 (2013) 164; Panico, Redi, Tesi, Wulzer JHEP 1303 (2013) 051

Extended Scalar Sector (Not 2HDM)

Why else new physics?

- The Standard Model is the most economical way to give masses to fermions and gauge bosons.
  - There is only one Higgs doublets to up-type quarks, down-type quark, leptons, and gauge bosons.
  - Relatively simple to expand the scalar sector.
  - So why not? Why do up-type and down-type quarks get mass from the same Higgs boson? They have different charges.
  - What about leptons?
  - In fact, in theories like supersymmetry, there must be two Higgs doublets.

Higgs as a Portal to New Sectors



- As mentioned earlier $\Phi^\dagger\Phi$ is invariant under any unitary transformation.
- Hence, if there is any sector out there with a new scalar ϕ, the interaction is possible:

$$\left(\Phi^\dagger\Phi\right)\left(\phi^\dagger\phi\right)$$

  - This is completely gauge invariant, renormalizable, and in general cannot be forbidden.
  - The so-call "Higgs portal."

Case study: Singlet Extended SM

- Focus on the simplest possibility for a new scalar, the addition of a real gauge singlet scalar S:
  - At the renormalizable level, only couples to the Higgs doublet (write down all possible terms)

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

- Singlet scalar is a gauge singlet (no charges), so S cannot couple to the gauge bosons.
  - The covariant derivative is $D_\mu S = \partial_\mu S$
- Cannot write down gauge invariant couplings to fermions because left and right double differently:
  - $\cancel{S\overline{Q}_L u_R}$ is not gauge invariant.

Case study: Singlet Extended SM

- After expanding about the vev $\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$ have two scalar fields
  - SM Higgs boson h
  - Scalar singlet S (free to set this vev to zero)
- Enforce the the minimum of the potential:

$$0 = \left.\frac{\partial V}{\partial h}\right|_{h=S=0} = \left.\frac{\partial V}{\partial S}\right|_{h=S=0}$$

- Then we have the mass terms:

$$V_{\rm mass} = \frac{1}{2}m_{hh}^2 h^2 + m_{hS}^2 h\,S + \frac{1}{2}m_{SS}^2 S^2$$

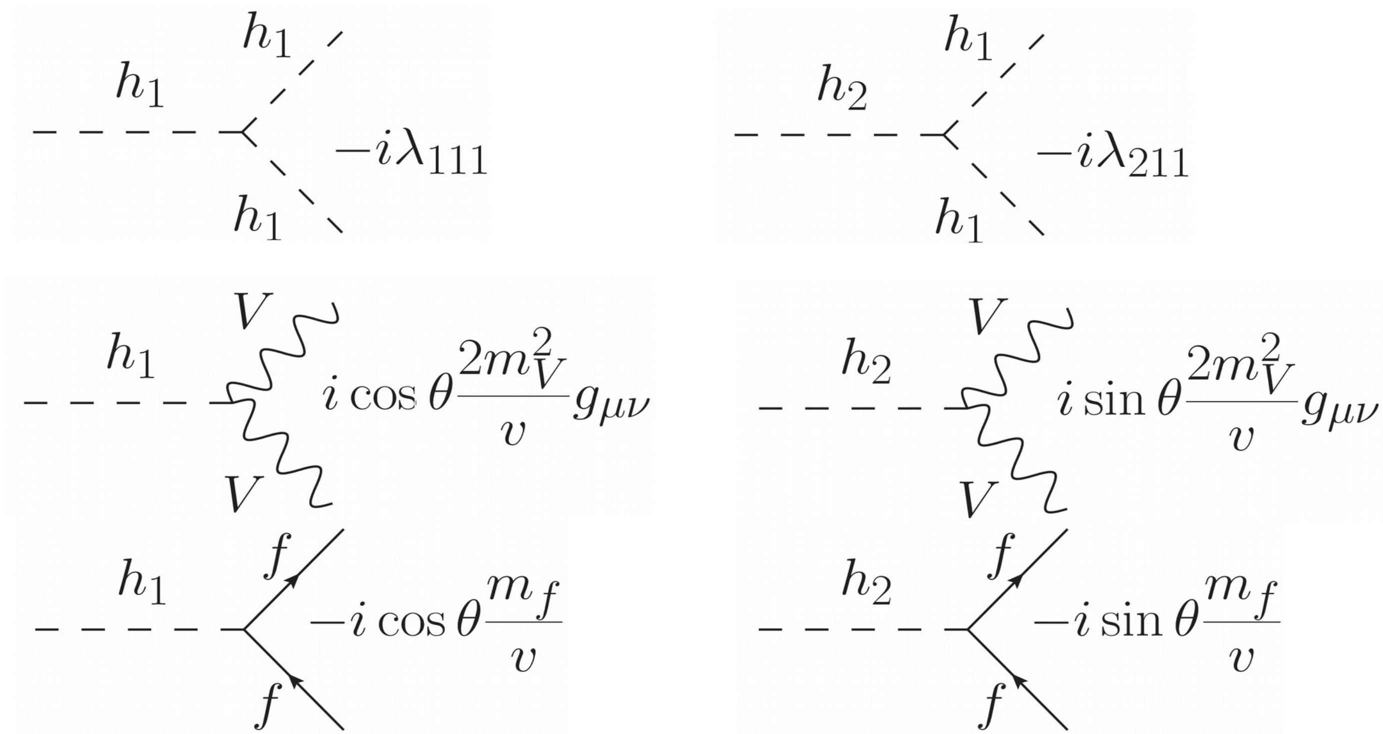
$$m_{hh}^2 = \left.\frac{\partial^2 V}{\partial h^2}\right|_{h=S=0}, \; m_{hS}^2 = \left.\frac{\partial^2 V}{\partial h \partial S}\right|_{h=S=0}, \; m_{SS}^2 = \left.\frac{\partial^2 V}{\partial S^2}\right|_{h=S=0}$$

- Need to diagonalize into the mass basis:

$$h_1 = \cos\theta\, h - \sin\theta\, S \qquad h_2 = \sin\theta\, h + \cos\theta\, S$$

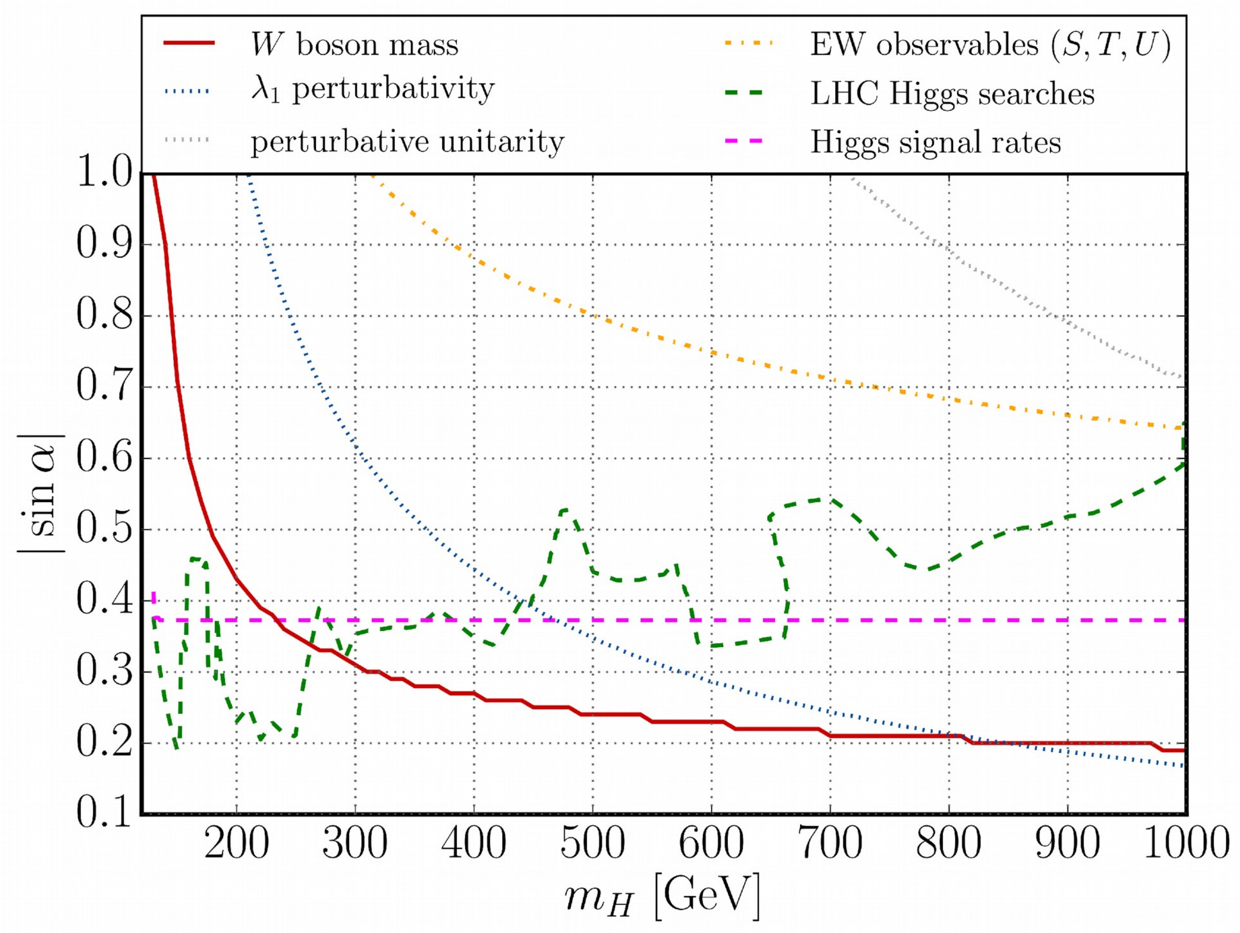
- Where h_1 has mass m_1, h_2 has mass m_2, and mass terms for h_1,h_2 are diagonal.
- Hence, h_1 obtains SM couplings from h suppressed by cosθ
- Hence, h_2 obtains SM couplings from h suppressed by sinθ

Couplings after Mixing With Higgs



- *Subscripts on triple scalar couplings indicate which scalars are coupling with each other.*
- If kinematically available, resonant double Higgs production possible.
- Production of h_2 same as SM Higgs suppressed by $\sin^2\theta$
- Decays of h_2 similar to SM Higgs with new channel $h_2 \rightarrow h_1\, h_1$
- Precision Higgs limits mixing of scalar singlet and Higgs boson.
  - Branching ratios unchanged.
  - Universal suppression of $\cos^2\theta$ for production of h_1

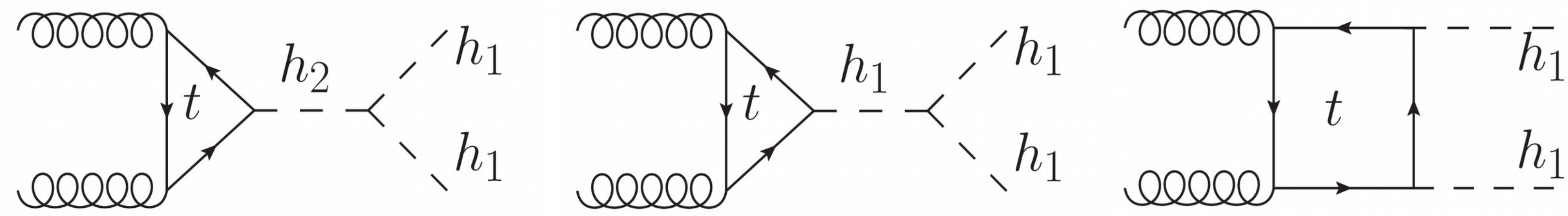
Current Constraints on Singlet

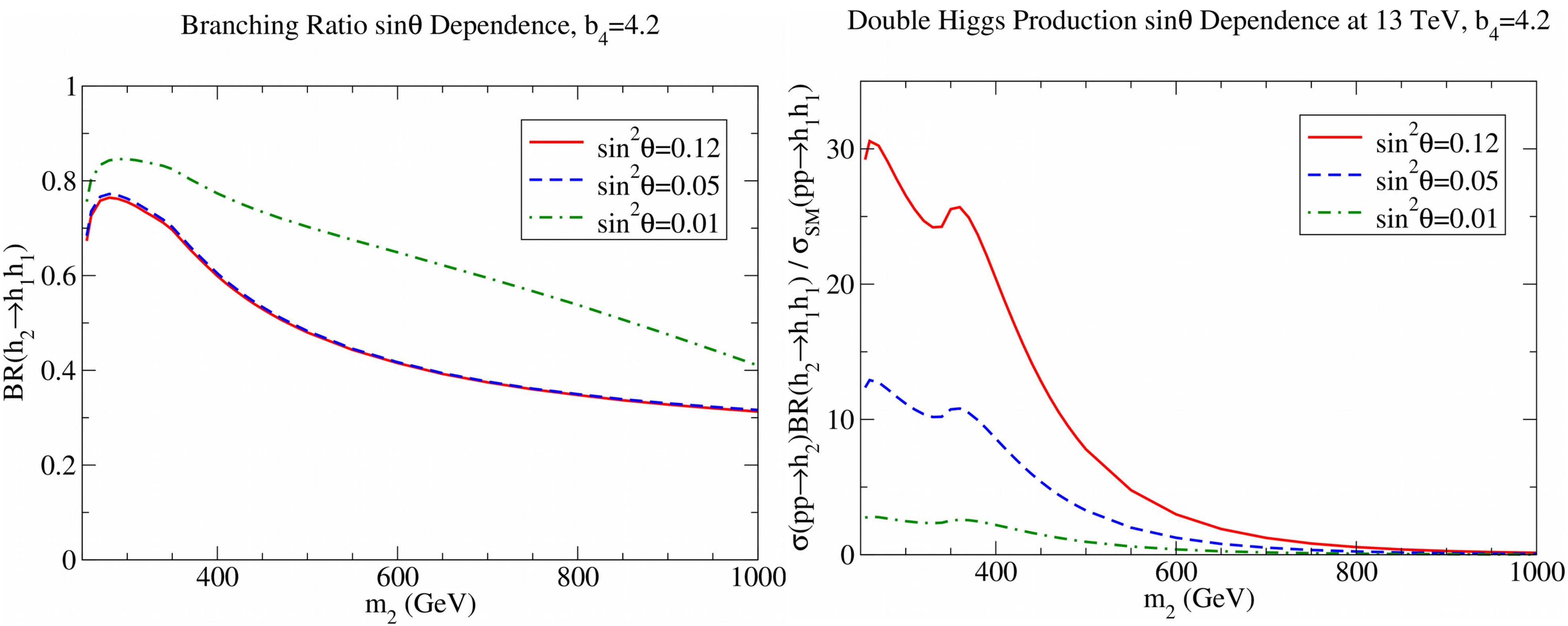


Ilnicka, Robens, Stefaniak, arXiv:1803.03594

- Precision Higgs are direct searches for new scalar are complementary.

Resonant Production

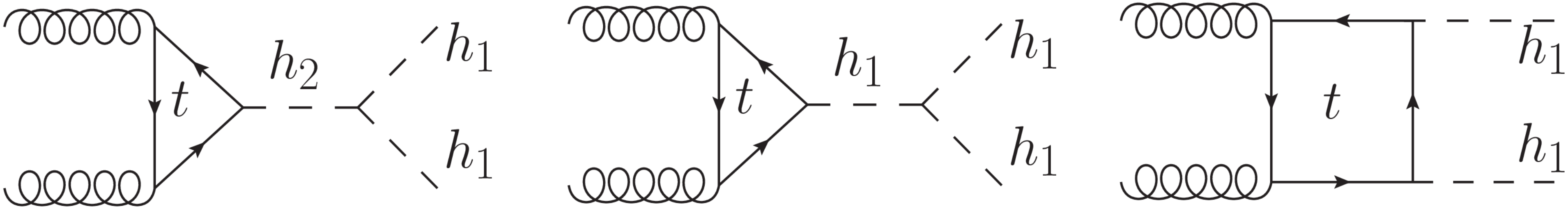




Ian Lewis, M. Sullivan PRD96 (2017) 035037

- If $m_2 > 2\, m_1$, can get resonant decay $h_2 \to h_1 h_1$
- Maximum rates possible.

Interference Effects

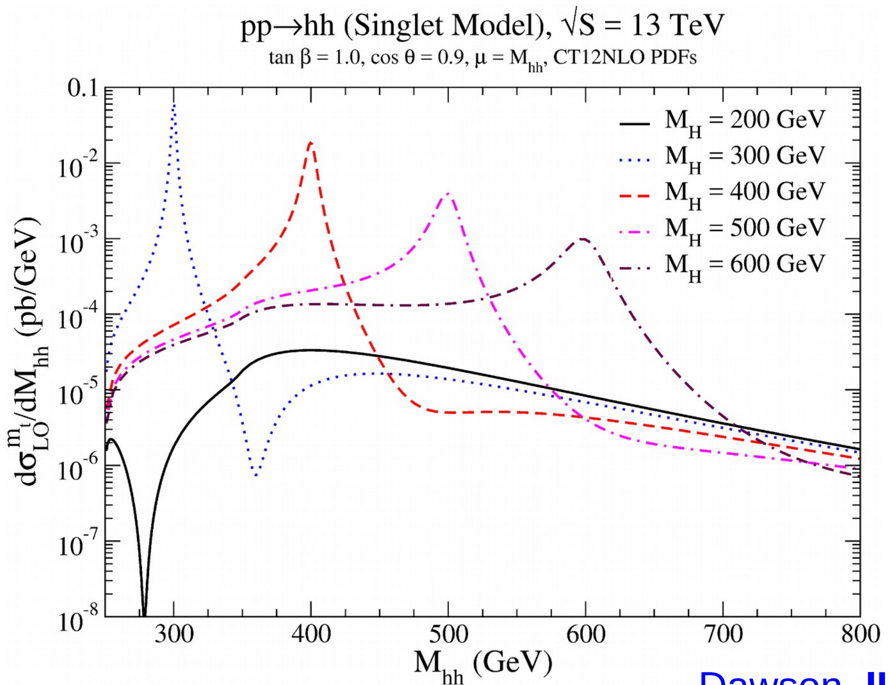


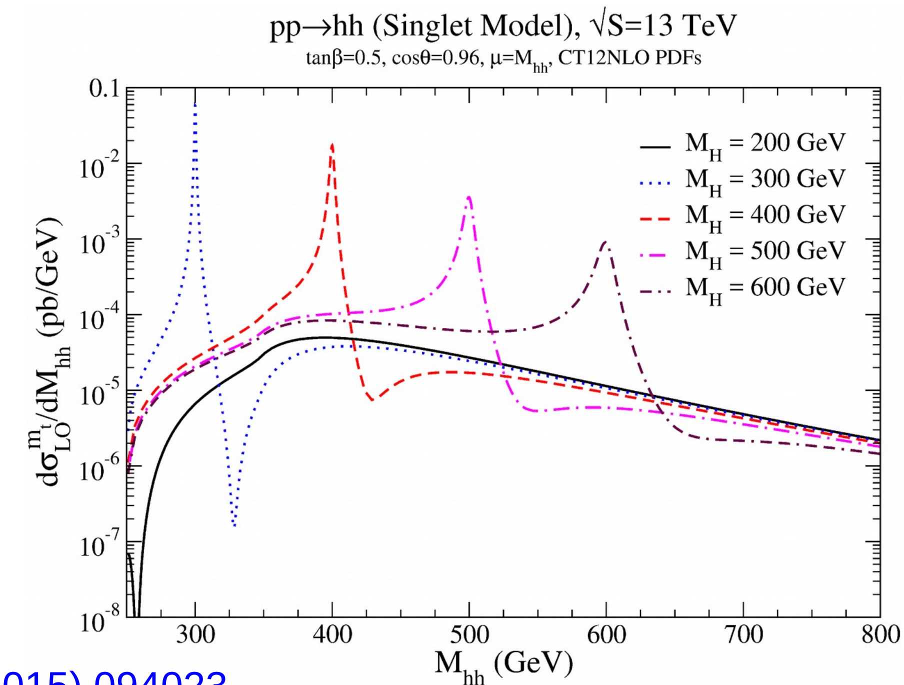
- Quantum mechanically need to add all diagrams simultaneously since they interfere.
- Typically assume narrow width approximation.

$$\frac{1}{(s-M^2)^2+\Gamma^2 M^2} \approx \frac{\pi}{\Gamma\, M}\delta(s-M^2), \quad \text{if} \quad \Gamma \ll M$$

  - Only take into consideration resonance.
- But Higgs couplings are proportional to mass, and we can get non-decoupling contributions:
-
- S-channel propagator: $$\frac{\cos\theta\,\lambda_{111} v}{s-m_1^2+i\Gamma_1 m_1} - \frac{\sin\theta\lambda_{112}\, v}{s-m_2^2+i\Gamma_2 m_2}$$
- Take limit $$s, m_1^2 \ll m_2^2 \Rightarrow \lambda_{112} \to \frac{m_2^2}{2\,v}\sin 2\theta\ (\cos\theta+\sin\theta\tan\beta)$$
- Propagator becomes $$\frac{\cos\theta\,\lambda_{111} v}{s-m_1^2+i\Gamma_1 m_1} + \frac{\sin\theta\sin 2\theta}{2}(\cos\theta+\sin\theta\tan\beta)$$
- No explicit dependence on m_2

Importance of Interference





Dawson, **IL** PRD92 (2015) 094023

- S-channel propagator: $$\frac{\cos\theta\,\lambda_{111} v}{s-m_1^2+i\Gamma_1 m_1} - \frac{\sin\theta\lambda_{112}\, v}{s-m_2^2+i\Gamma_2 m_2}$$
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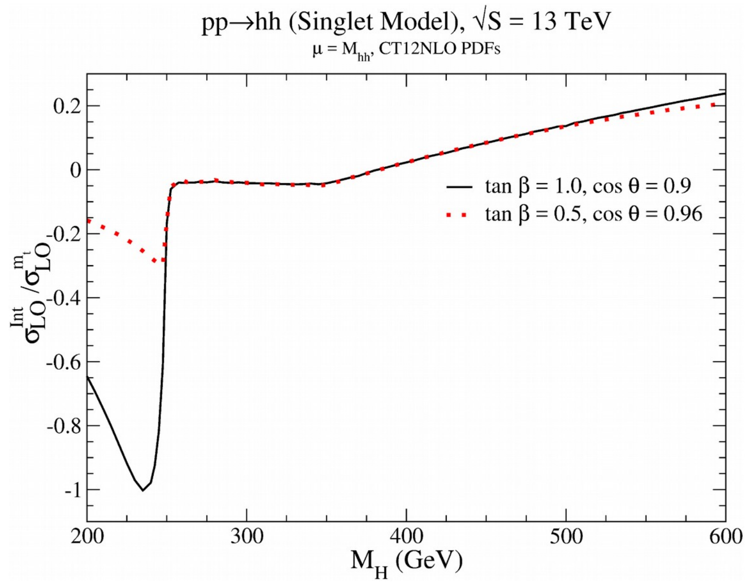
- No explicit dependence on m_2

Importance of Interference

- σ_{int} is the cross section of the interference of the h_2 resonance with the other diagrams.
- σ_{BW} is the cross section of the resonance by itself
- σ^{mt} is the total cross section with all diagram.
- Off-shell interference:
  - Higher mass resonance, more important

  Dawson, **Ian Lewis** PRD92 (2015) 094023



- On-shell interference:
  - Need phase between loops and imaginary part of propagator
  - Can get ~10% contributions from interference.

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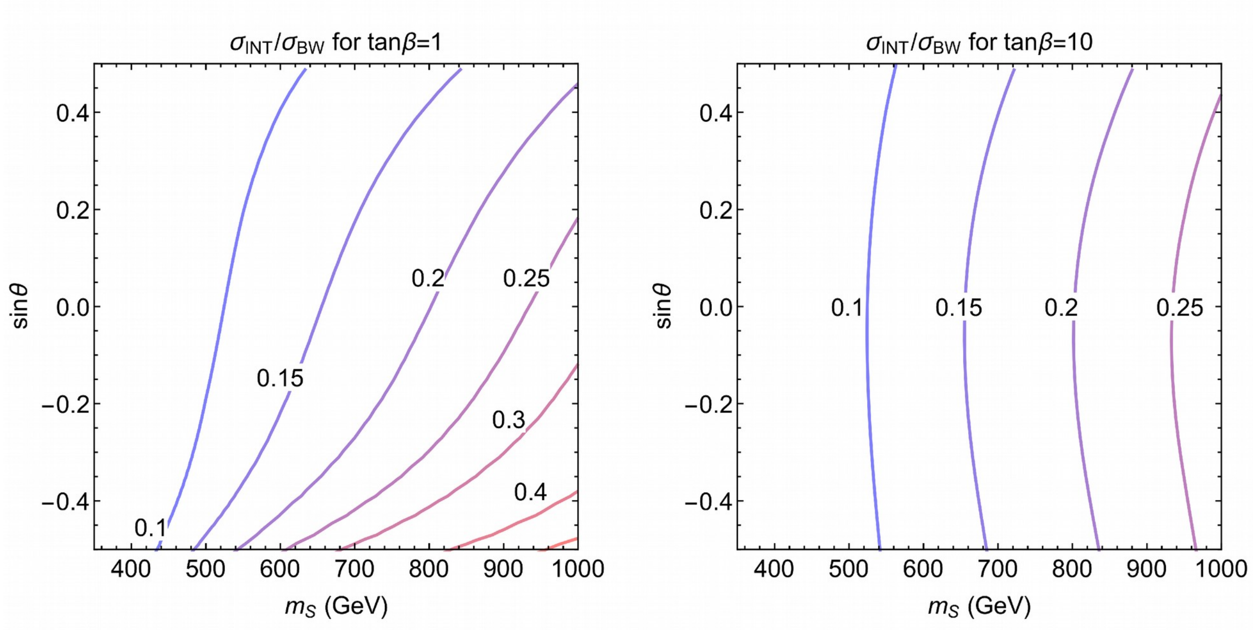


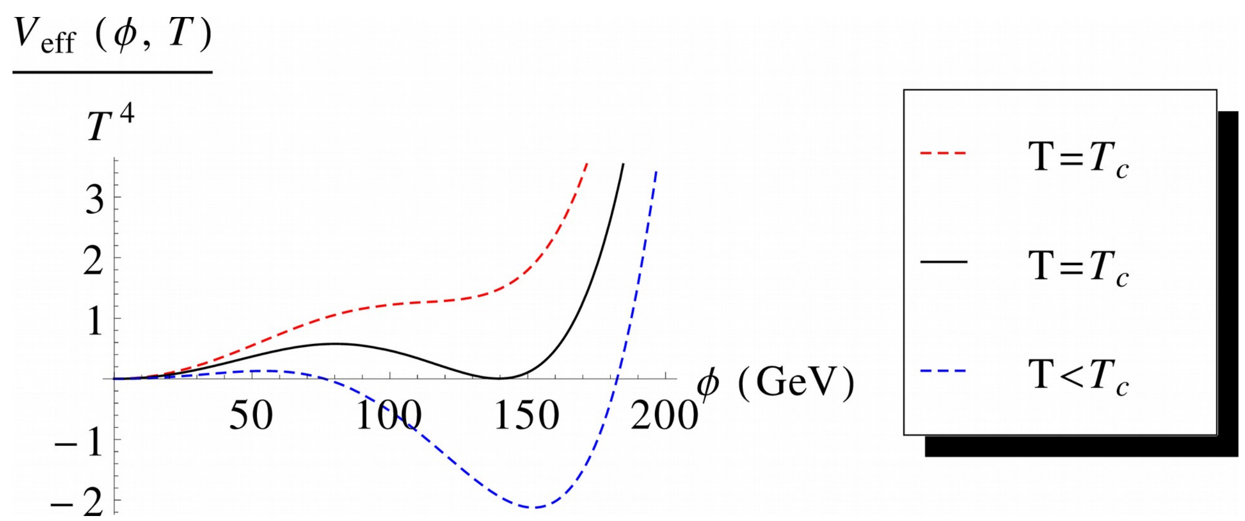
Electroweak Baryogenesis

Baryon Asymmetry of the Universe

- We know there is more matter than anti-matter.
- In 1967 Andrei Sakharov gave three conditions to generate a matter/anti-matter asymmetry:
  - Need Baryon number violating processes.
  - Need C and CP violation.
    - There can be processes that generate more matter than anti-matter
  - 3 need out of equilibrium interactions.
    - If baryon number violating processes in thermal equilibrium, they can be reversed and wash-out any asymmetry.
- Standard Model has baryon number violating processes, and C and CP violation (but not enough)
- Need out of equilibrium interactions.
  - Can be decays of heavy particles that are not in thermal equilibrium.
  - Can appear in Higgs physics.

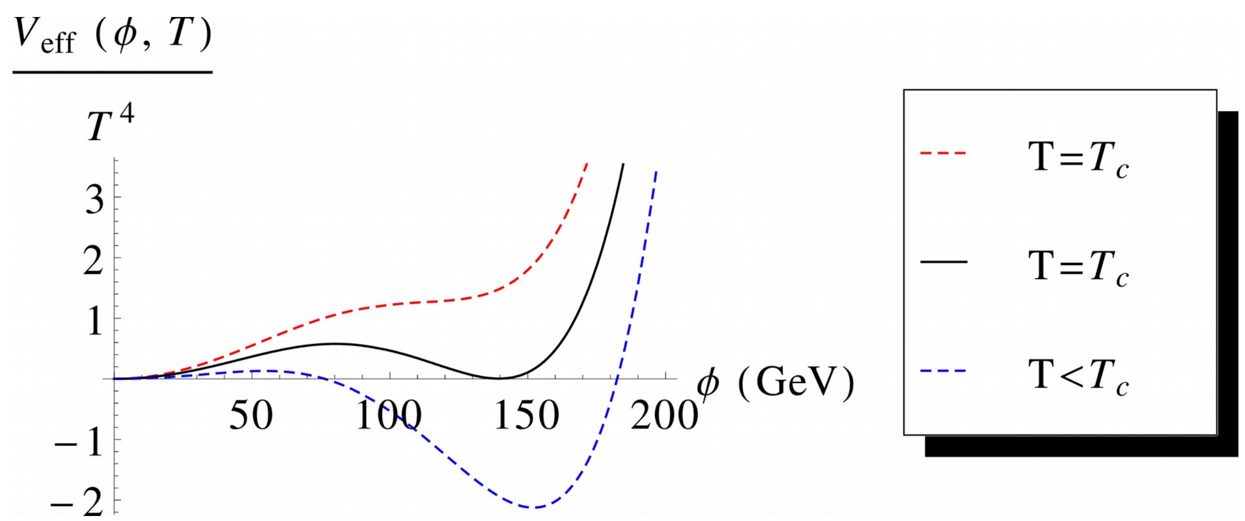
Strong First Order EW Phase Transition

- In early Universe, at high temperature, electroweak symmetry is restored.
- As temperature decreased, EW symmetry broke.
- If this breaking is first order, we have out of equilibrium interactions.
  - Tunnel from $\langle\phi\rangle = 0$ to $\langle\phi\rangle \neq 0$.
  - In second order phase transition, smoothly transition from $\langle\phi\rangle = 0$ to $\langle\phi\rangle \neq 0$.
  - The SM is a second order phase transition.
  - Need new physics.



Strong First Order EW Phase Transition

- EW symmetry breaking comes from the Higgs sector.
- To get strong first order EW phase transition, need to alter the Higgs potential.
- Measuring Higgs properties is vital to probing this scenario.
- Also, to change Higgs potential significantly, need new physics near the Higgs scale.
  - This scenario has a definite scale attached to it that cannot be arbitrarily increased.
- Simplest to add a new scalar singlet, and it does the job.
  - Nice simple, benchmark model to test the falsifiability of this scenario.



Zero Mixing Limit

- Couplings between scalar and Higgs:

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

- After symmetry breaking $\Phi = (0, (h+v)/\sqrt{2})^t$
  - Source of Higgs-scalar mixing is (assuming $\langle S \rangle = 0$)

$$V_{\Phi,S} \supset \frac{a_1\, v}{2} hS$$

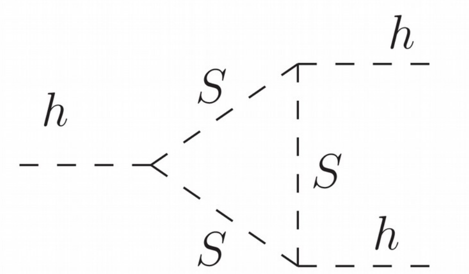
  - In the limit of zero mixing, $a_1 \rightarrow 0$ and only a_2 survives:

$$V_{\Phi,S} \rightarrow \frac{a_2}{2}\Phi^\dagger\Phi S^2$$

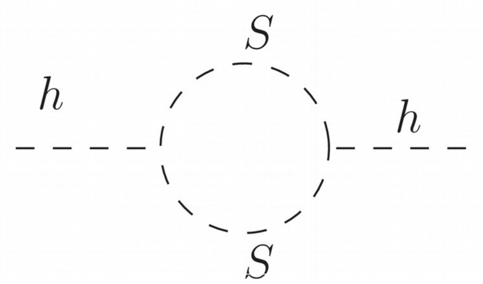
- If the scalar S does not mix with the SM Higgs, it does not couple to fermion/gauge boson. Very difficult to produce and can be stable.
- a_2 is the only term to drive the first order phase transition.
  - Lower limit on how large it can be.

Precision Higgs To the Rescue

- The scalar can still show up in loops:
  - Trilinear gauge boson:



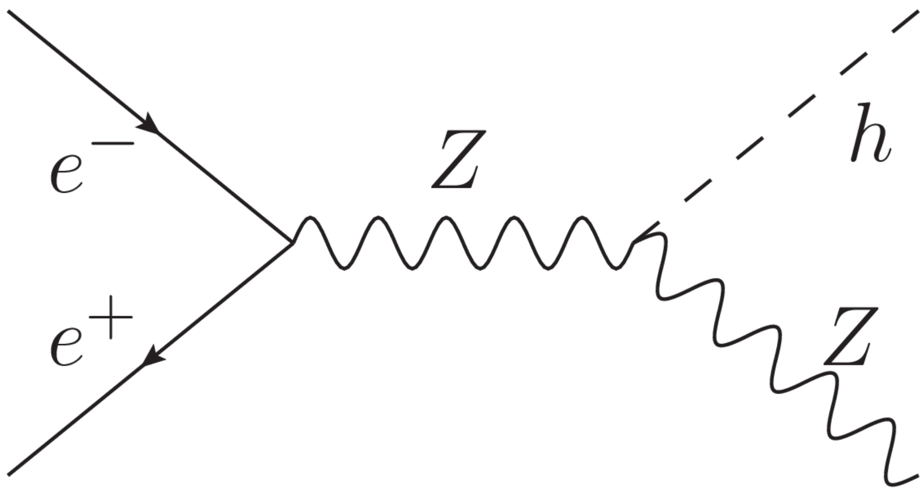
  - Wave function renormalization:



- Utility of wave function renormalization is that it shifts the Higgs field:
- $$h \to \sqrt{Z_h} h$$
- Hence it shifts ***all*** the Higgs couplings (Z coupling example here):

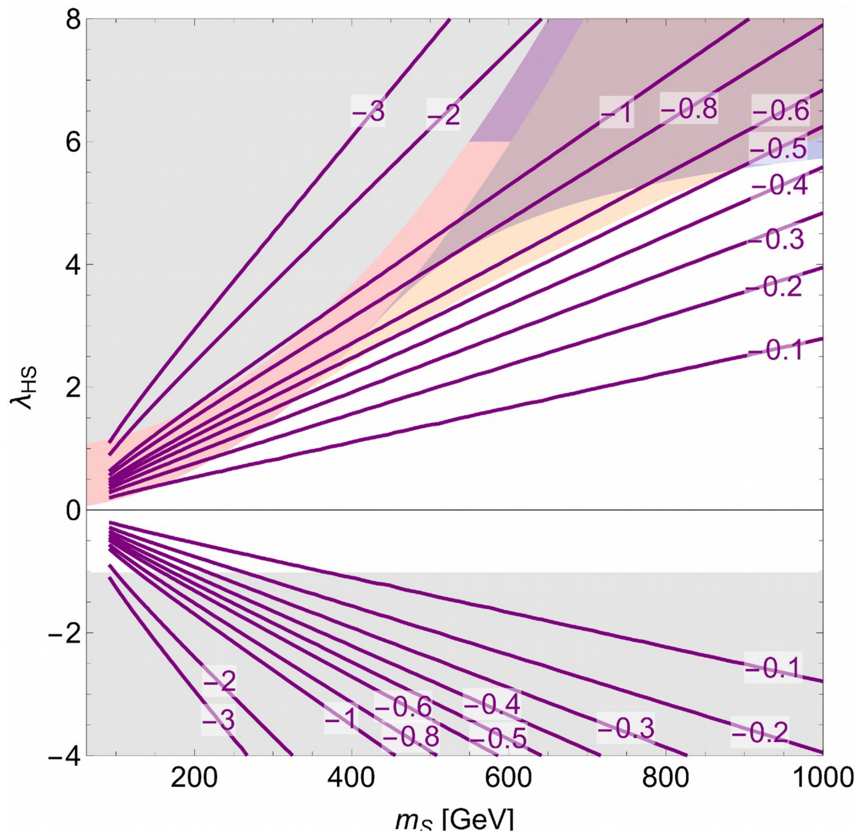
$$2\frac{M_Z^2}{v} h\, Z^\mu Z_\mu \to 2\frac{M_Z^2}{v}\sqrt{Z_h}\, h\, Z^\mu Z_\mu$$

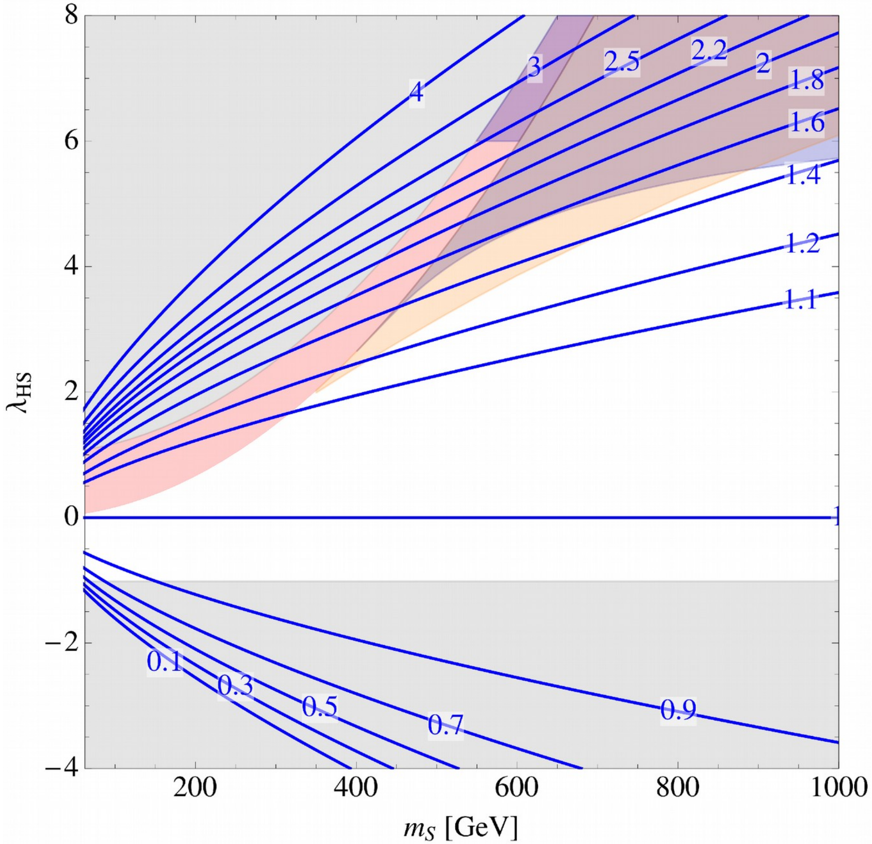
Z+Higgs Production



- Can measure h+Z production very well at future lepton colliders.
  - Expect percent to sub-percent level accuracy.
  - Can determine small deviation in h-Z-Z coupling.

Precision Measurements





Curtin, Meade, Yu JHEP 1411 (2014) 127, arXiv:1409.0005

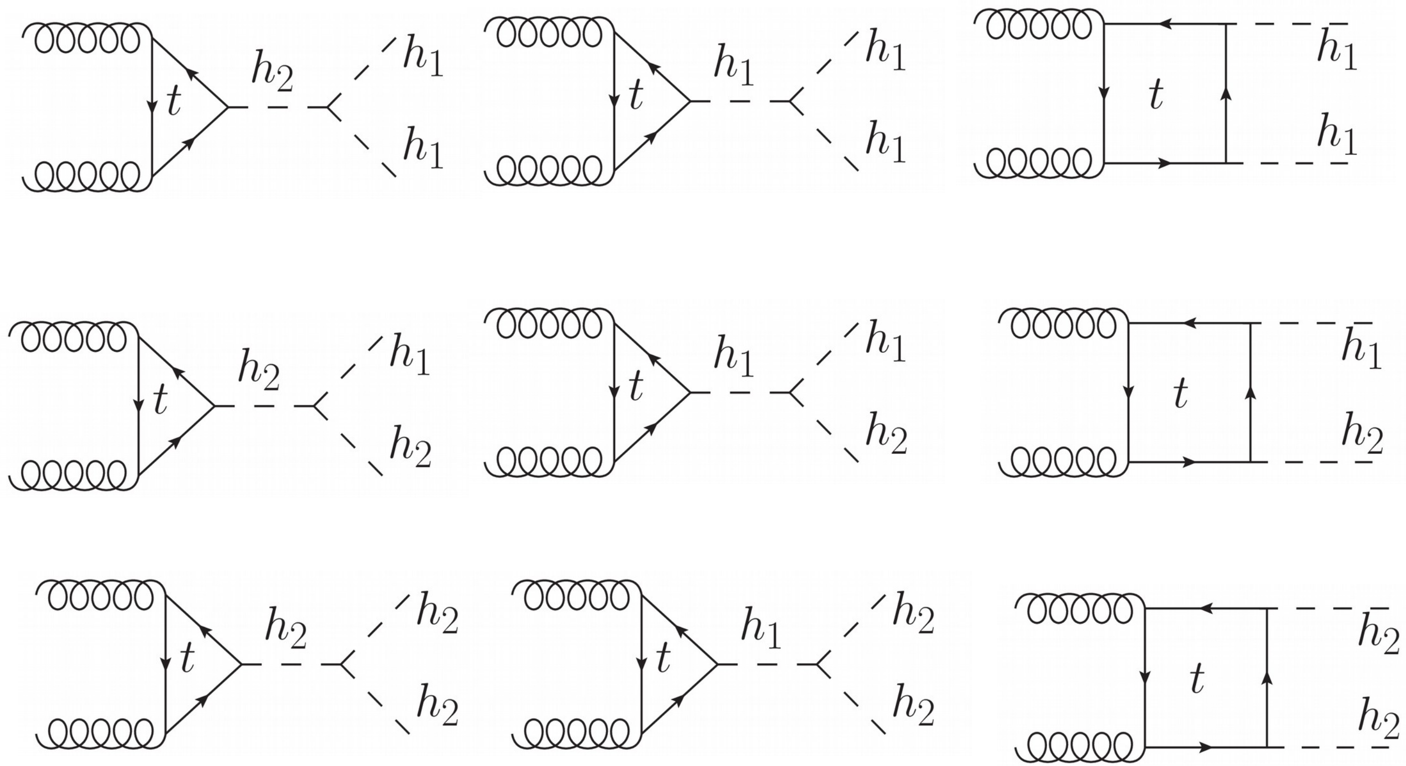
Percent change in Z+Higgs production at lepton colliders.

Fractional change in Higgs trilinear couplings.

Red, white, and orange regions give strong first order electroweak phase transition.

– Precision measurements constrain this scenario and can probe it in the long term.

Non-Zero Mixing

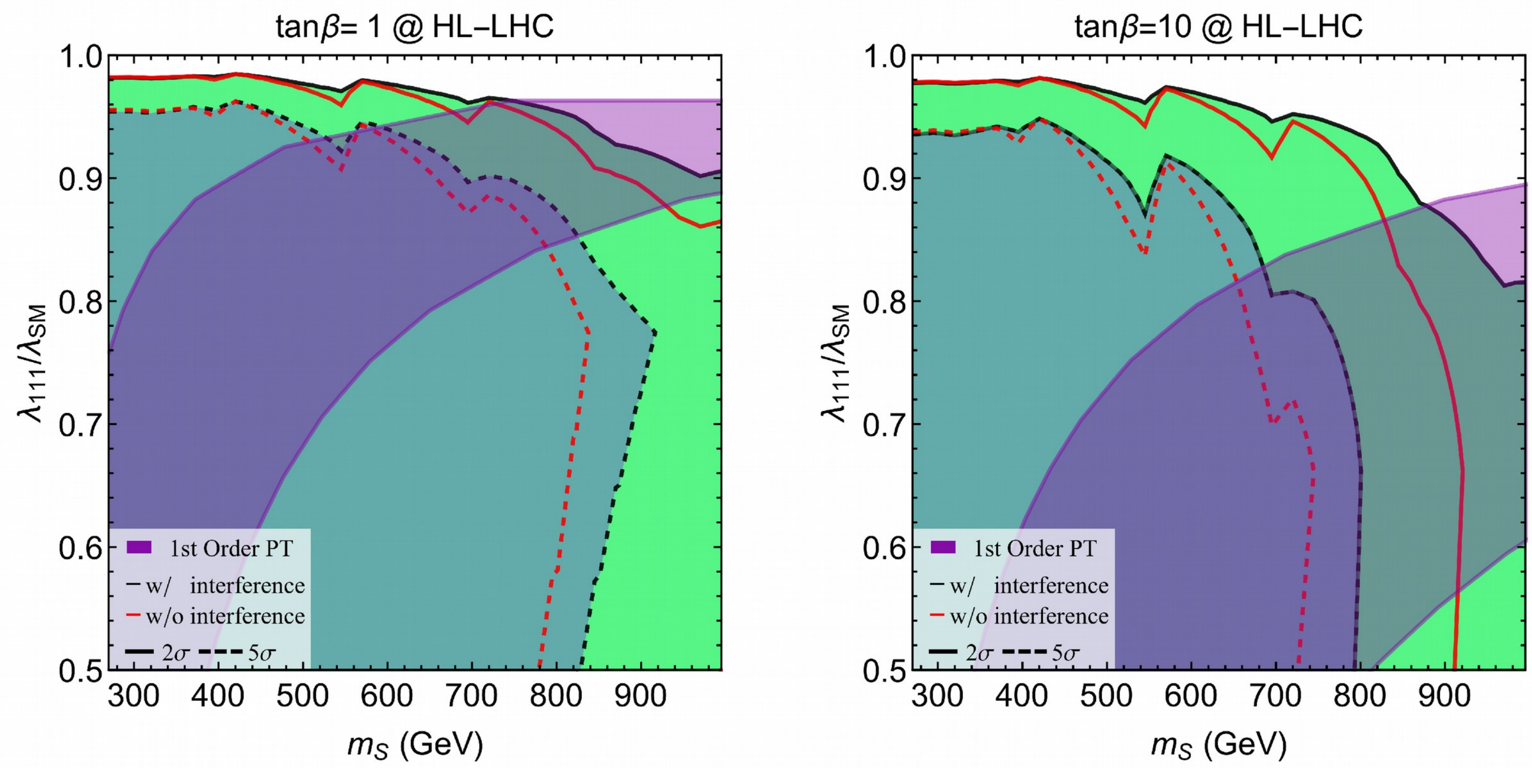


- Many di-boson production modes.
  - h_1 is observed Higgs, h_2 is a new heavier scalar.
  - Can have resonant double Higgs if kinematically allowed.
- Each final state sensitive to different trilinear couplings.
  - Need to try to observe all of them to see if we can verify this scenario.

Resonant Double Higgs Production

- Much focus on relationship between resonant double Higgs production and a strong electroweak phase transition in the singlet model

Huang, et. Al PRD96 (2017) 035007; Profumo et al PRD91 (2015) 035018; Alves, Ghosh, Guo, Sinha 1808.08974; etc.



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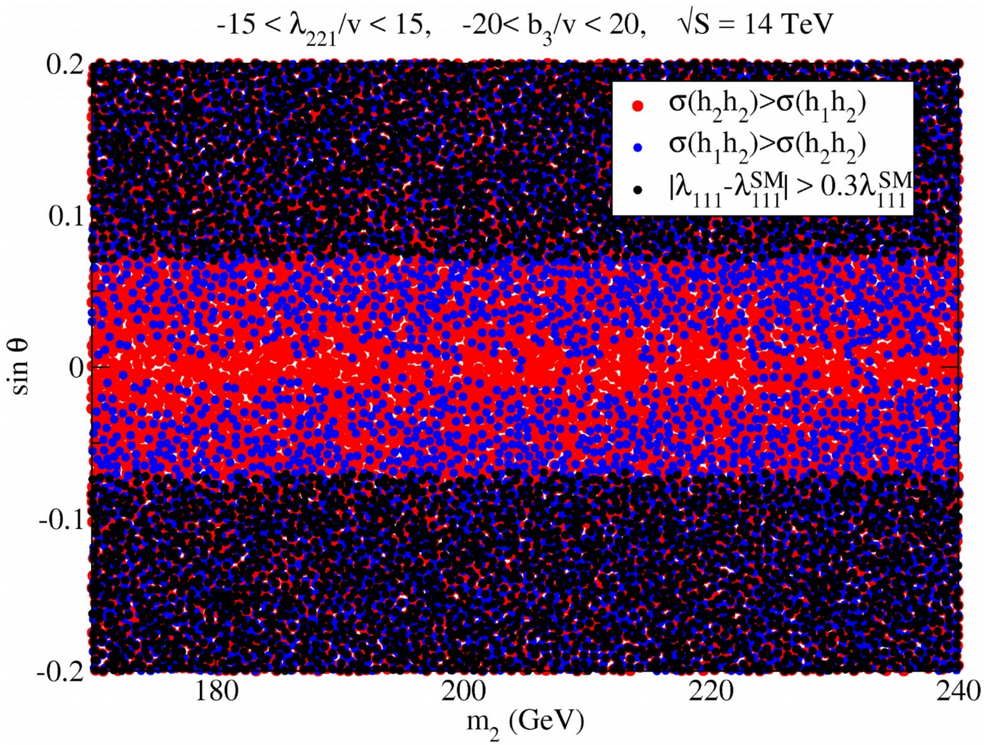
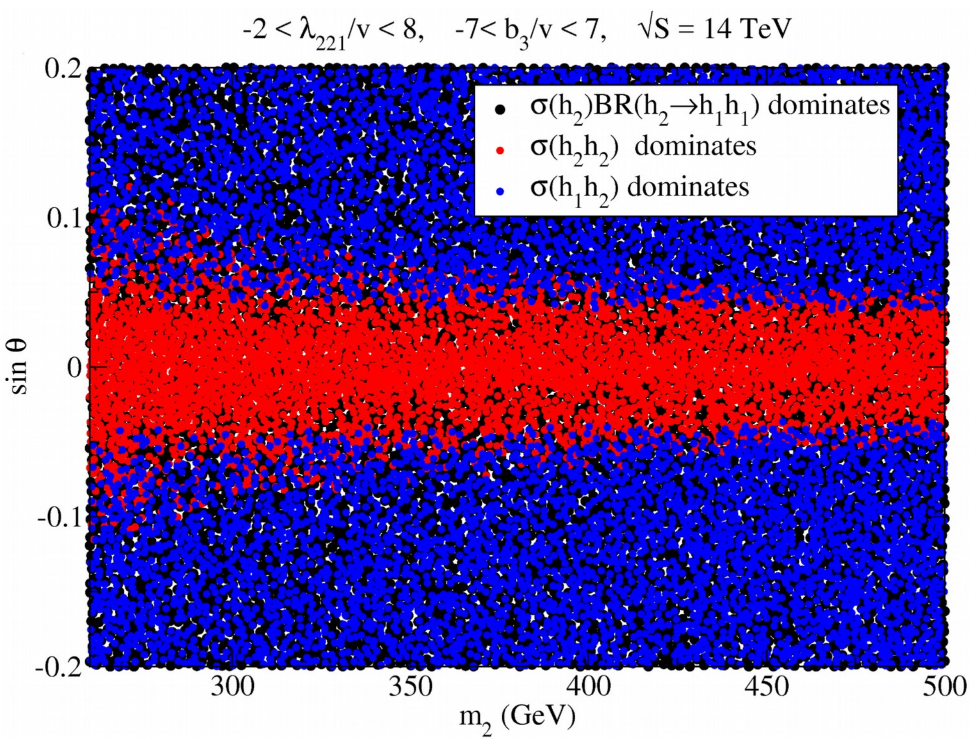
- Including interference effects important for determining viable parameter regions for strong first order electroweak phase transition.

Additional Non-Resonant Modes

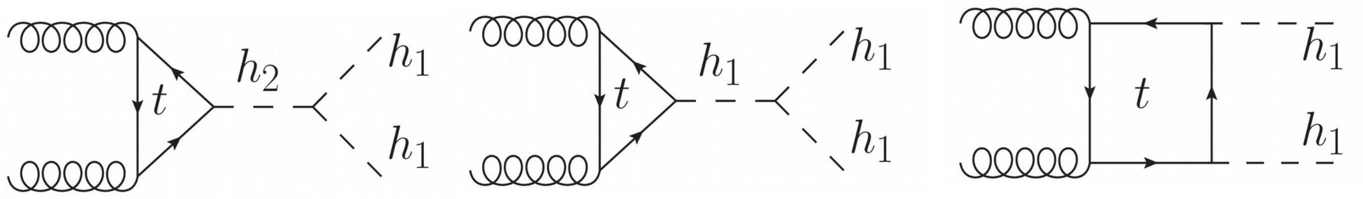


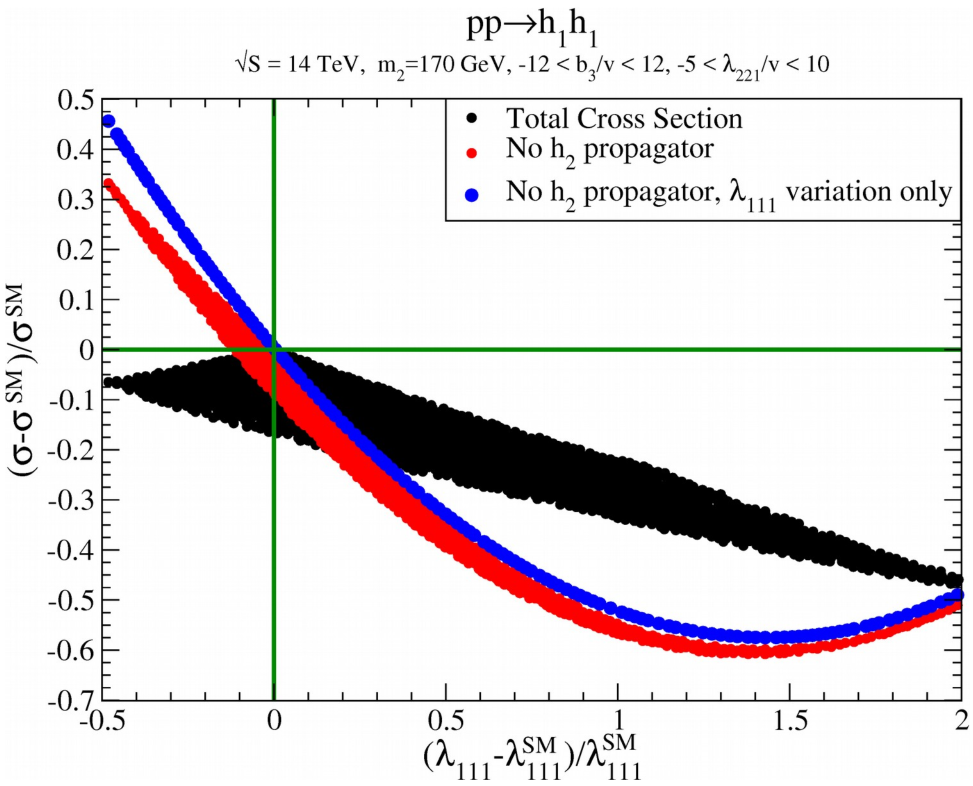


Chen, Kozaczuk, **Ian Lewis** JHEP 1708 (2017) 096

- New final states h_1h_2 and h_2h_2
- Different final state dominate in different parameter regimes.
- Measurement of Higgs trilinear important.
- Different production modes dominate in different regions.

Careful….





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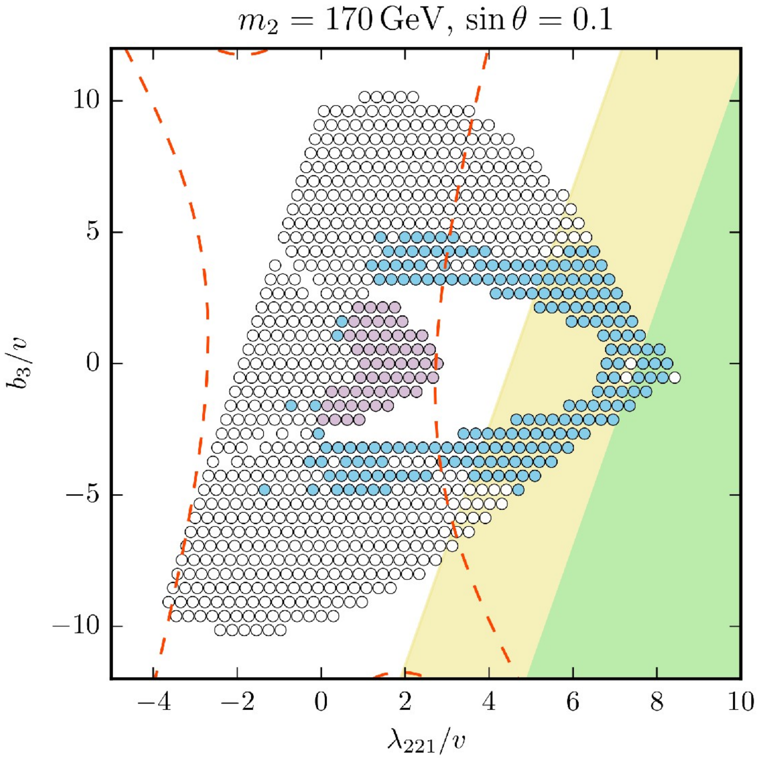
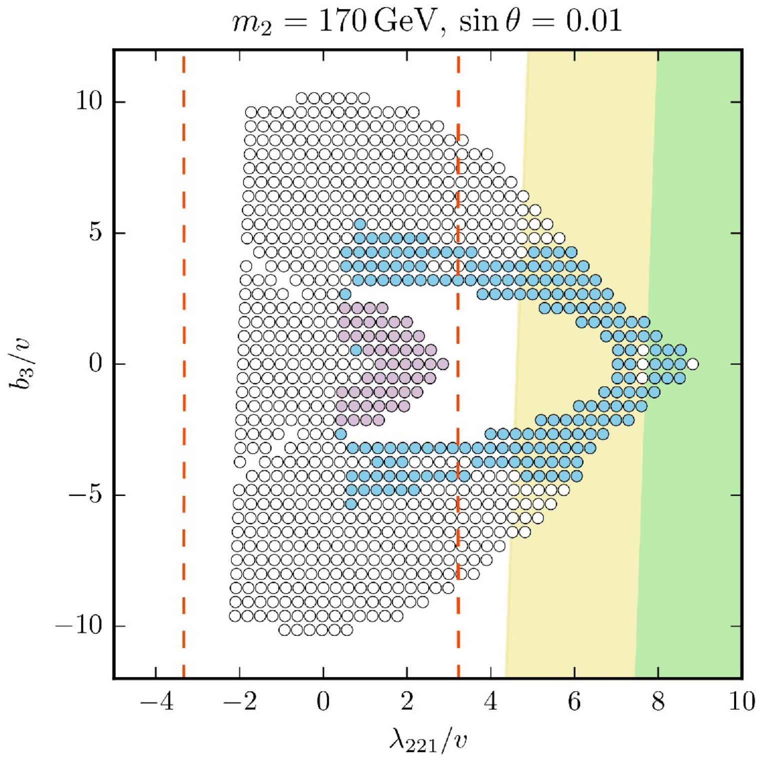
- Said before, we need to include all diagrams…
  - Simple correspondence between h_1h_1 production rate and h_1-h_1-h_1 coupling breaks down because of new h_2 propagator..

High Luminosity LHC





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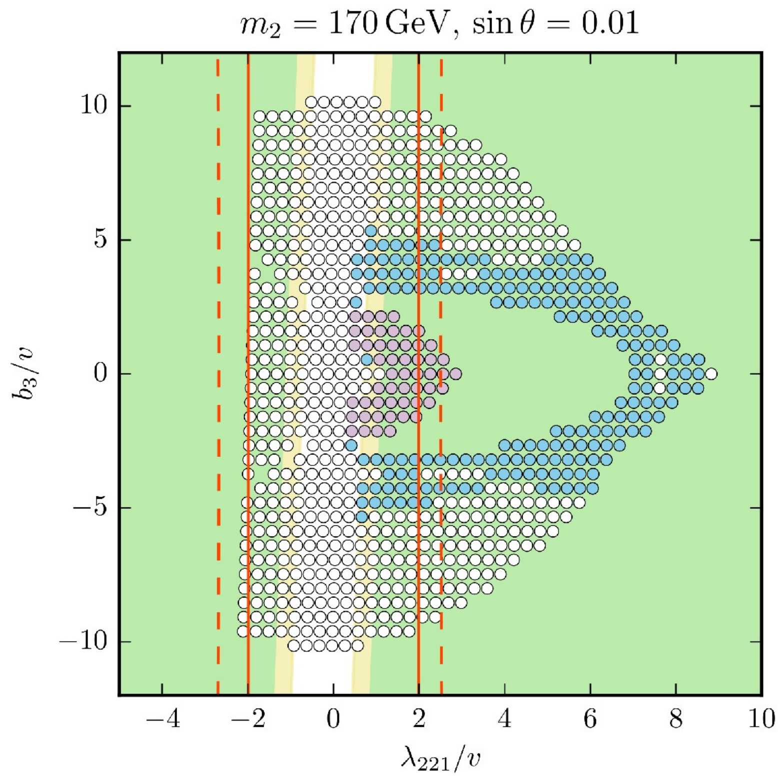
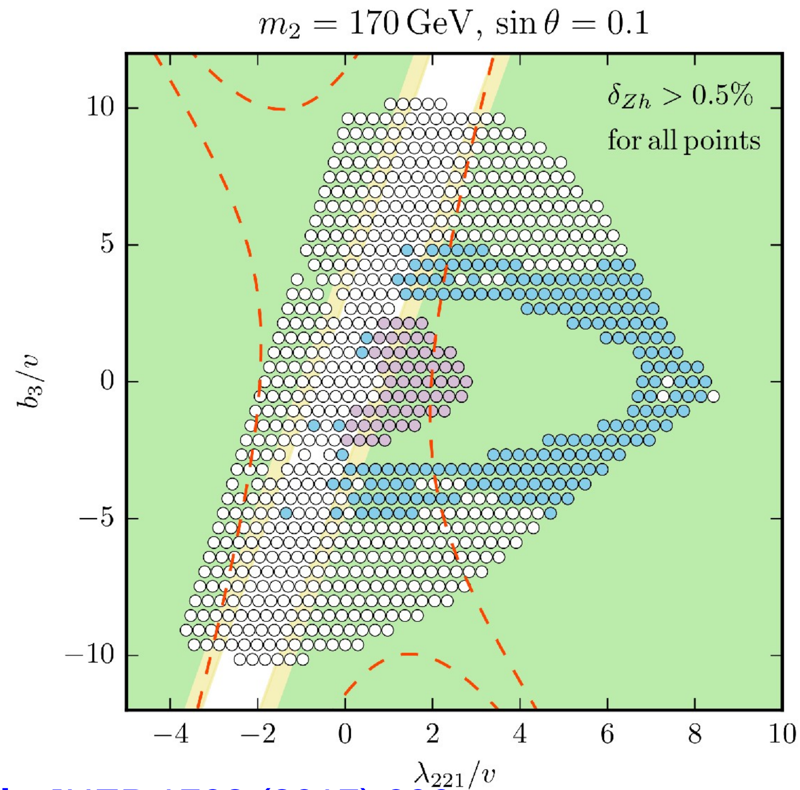
- 3 ab^{-1} at 14 TeV LHC.
- Comparison of different methods of searching.
- Colored Dots: Compatible with strong first order electroweak phase transition.
- Searches for h_2h_2 production: Yellow: Exclusion, Green: Discovery
- Red dashed curves: Higgs trilinear limits at 30%.

100 TeV





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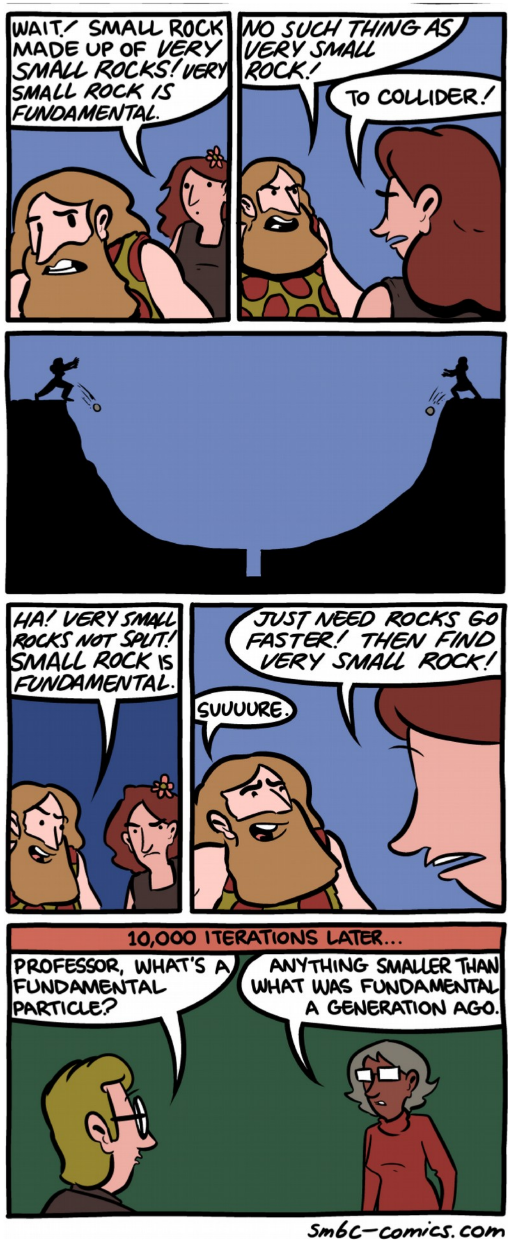
- 30 ab^{-1} at 100 TeV, can probe much of the parameter space.
- Colored Dots: Compatible with strong first order electroweak phase transition.
- Searches for h_2h_2 production: Yellow: Exclusion, Green: Discovery
- Red dashed curves: Higgs trilinear to 15%. Solid lines: Z-h limits to 0.5%

Conclusions

- Discovered a Higgs boson!
  - Not end of story, hierarchy problem still there.
  - Two major solutions:
    - Strong interactions: composite Higgs
    - Weak interactions: SUSY
  - Precision Higgs measurements and direct searches can shed light on situation.
- Higgs measurements sensitive to new physics that can appear at EW scale.
  - Important to measure all of its properties as well as we can.
  - Learn about many beyond the SM scenarios.
  - Direct searches for new physics and Higgs boson precision measurements provides complementary information.
- Still exciting new physics scenarios that are tied to EW scale.
  - Electroweak baryogenesis, must have new physics coupling to the Higgs and appear at the TeV scale.
  - May be falsifiable at the high luminosity LHC or future colliders.

Thank You


BIG ROCK IS MOST FUNDAMENTAL PARTICLE IN UNIVERSE!
NO! BIG ROCK IS MADE UP OF SMALL ROCKS.
TO COLLIDER!
LOOK! SMALL ROCK COME OUT OF BIG ROCK! SMALL ROCK FUNDAMENTAL!
...SMALL ROCK IS MAYBE STATISTICAL ARTIFACT.
OKAY. SMALL ROCK FUNDAMENTAL.
ME TOLD YOU SO!


WAIT! SMALL ROCK MADE UP OF VERY SMALL ROCKS! VERY SMALL ROCK IS FUNDAMENTAL.
NO SUCH THING AS VERY SMALL ROCK!
TO COLLIDER!
HA! VERY SMALL ROCKS NOT SPLIT! SMALL ROCK IS FUNDAMENTAL.
JUST NEED ROCKS GO FASTER! THEN FIND VERY SMALL ROCK!
SUUUURE.
10,000 ITERATIONS LATER...
PROFESSOR, WHAT'S A FUNDAMENTAL PARTICLE?
ANYTHING SMALLER THAN WHAT WAS FUNDAMENTAL A GENERATION AGO.
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