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Understanding recent collider excesses in light of light Higgs bosons

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Outline

- Introduction to two-Higgs-doublet models
- Existing collider excesses and hints at excesses
  - **Can new light Higgs bosons explain these?**
- Computing observables in a 2HDM
- Experimental and theoretical constraints on 2HDM parameter space
- Regions surviving existing constraints
- Connection with the electroweak phase transition

Two-Higgs-Doublet Models

- Extend the SM by one electroweak doublet of complex scalars, now have Φ_1 and Φ_2
  - Introduce a $\mathbb{Z}_2$ symmetry in which $\Phi_1 \to \Phi_1$ and $\Phi_2 \to -\Phi_2$
    - Ensures no tree level flavor changing neutral currents
  - Most general scalar potential can be written as:

$$V(\Phi_1\,,\,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) + \frac{1}{2}\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{1}{2}\lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+ \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{1}{2}\lambda_5\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \left(\Phi_2^\dagger\Phi_1\right)^2\right]$$

  - All λ's and mass scales are real. m_{12}^2 softly breaks the $\mathbb{Z}_2$ symmetry

- Parametrization of the doublets:

$$\Phi_1 = \begin{pmatrix} -H^+ s_\beta + G^+ c_\beta \\ \frac{1}{\sqrt{2}}\left(v c_\beta - h s_\alpha + H c_\alpha - i A^0 s_\beta + i G^0 c_\beta\right) \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} H^+ c_\beta + G^+ s_\beta \\ \frac{1}{\sqrt{2}}\left(v s_\beta + h c_\alpha + H s_\alpha + i A^0 c_\beta + i G^0 s_\beta\right) \end{pmatrix}$$

- Physical fields: two CP-even neutral scalars h and H, a CP-odd neutral pseudoscalar A^0, and two charged scalars $H^\pm$.
- Three Goldstones: G^0 and $G^\pm$ get eaten by the Z and $W^\pm$

Two-Higgs-Doublet Models: Scalar Sector

- Seven free parameters
  - Five mass scales: m_h , m_H , m_{A^0} , $m_{H^\pm}$, m_{12}
  - Two angles:
    - α mixes the CP-even neutral scalars h and H and diagonalizes their mass matrix
    - β mixes the VEVs of the doublets with $\tan\beta \equiv v_2/v_1$

- Extremizing the potential requires $\left.\frac{\partial V}{\partial h}\right|_{\varphi_i=0} = \left.\frac{\partial V}{\partial H}\right|_{\varphi_i=0} = 0$
- Define the mass-squared matrix:

$$\boldsymbol{\mathcal{M}}_{\text{sq.}} \equiv \begin{pmatrix} m_h^2 & 0 & 0 & 0 \\ 0 & m_H^2 & 0 & 0 \\ 0 & 0 & m_{A^0}^2 & 0 \\ 0 & 0 & 0 & m_{H^\pm}^2 \end{pmatrix} = \begin{pmatrix} \frac{\partial^2 V}{\partial h^2} & \frac{\partial^2 V}{\partial h \partial H} & 0 & 0 \\ \frac{\partial^2 V}{\partial H \partial h} & \frac{\partial^2 V}{\partial H^2} & 0 & 0 \\ 0 & 0 & \frac{\partial^2 V}{\partial A^{0\,2}} & 0 \\ 0 & 0 & 0 & \frac{\partial^2 V}{\partial H^+ \partial H^-} \end{pmatrix}$$

- Seven equations to allow for switching between the physical parameters and the parameters in the potential: $\{m_h\,, m_H\,, m_{A^0}\,, m_{H^\pm}\,, \alpha\,, \beta\} \leftrightarrow \{m_{11}\,, m_{22}\,, \lambda_{1-5}\}$

- Expand the scalar potential: induce triplet and quartic scalar couplings

Two-Higgs-Doublet Models: Gauge Sector

- Gauge interactions come from the kinetic term:

$$\mathcal{L}_{\text{Higgs-kinetic}} = \sum_{i=1}^{2} (\mathcal{D}_\mu \Phi_i)^\dagger (\mathcal{D}^\mu \Phi_i)$$

$$\mathcal{D}_\mu = \partial_\mu - i\frac{g}{\sqrt{2}}(W_\mu^+ T^+ + W_\mu^- T^-) - i\frac{e}{s_W c_W} Z_\mu (T^3 - s_W^2 Q) - ieA_\mu Q$$

- Higgs gauge interactions rescaled by trig factors:

$$\kappa_V^h = s_{\beta-\alpha} \quad , \quad \kappa_V^H = c_{\beta-\alpha}$$

  - κ: strength of coupling relative to SM
  - A^0 doesn't couple to gauge boson pairs at tree level since CP is not broken

- LHC favors α and β near the "alignment limit" where $\boldsymbol{\beta - \alpha = \pi/2}$
  - In alignment limit, h has SM couplings to gauge bosons and H is gauge-phobic

- Typically take h to be the observed Higgs at 125 GeV with H being heavier or lighter

Two-Higgs-Doublet Models: Yukawa Sector

- Tree level FCNCs can be avoided via *Natural Flavor Conservation*
  - Right-handed fermion fields also transform under the $\mathbb{Z}_2$ symmetry, couple to only one doublet
  - Leads to four 'types' of natural flavor conserving 2HDMs:

2HDM	e_R	d_R	u_R
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

- We focus on a **Type-I** 2HDM where all right-handed fermions couple to a single doublet, Φ_2:

$$\mathcal{L}_{\text{Yukawa}} = -y_{ij}^{\ell,2}\bar{e}_{R,i}\Phi_2^\dagger L_{L,j} - y_{ij}^{d,2}\bar{d}_{R,i}\Phi_2^\dagger Q_{L,j} - y_{ij}^{u,2}\bar{u}_{R,i}\tilde{\Phi}_2^\dagger Q_{L,j} + \text{h.c.}$$

- Find re-scalings of fermion couplings relative to the SM:

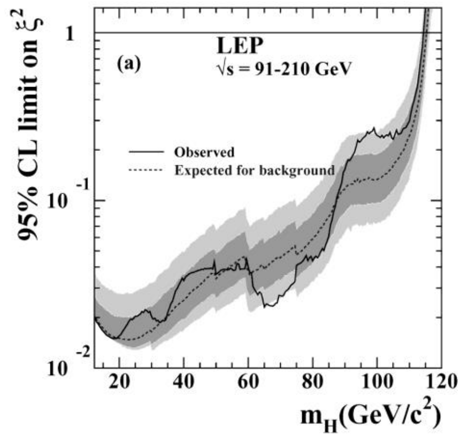
$$\kappa_f^H = \frac{s_\alpha}{s_\beta} = c_{\beta-\alpha} - s_{\beta-\alpha}/t_\beta, \quad , \quad \kappa_f^h = \frac{c_\alpha}{s_\beta} = s_{\beta-\alpha} + c_{\beta-\alpha}/t_\beta, \quad , \quad \kappa_u^{A^0} = -\kappa_{d,\ell}^{A^0} = 1/t_\beta,$$

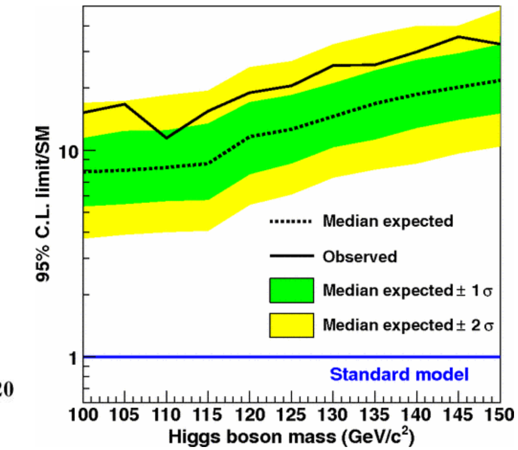
- In alignment limit, h also has SM couplings to fermions while H has couplings reduced by $1/t_\beta$
- In **Type-I**, all fermion masses and Yukawas have the same form:

$$m_f = \frac{y_f v}{\sqrt{2}}\sin\beta \leftrightarrow y_f = \frac{\sqrt{2}m_f}{v}\frac{1}{\sin\beta}$$

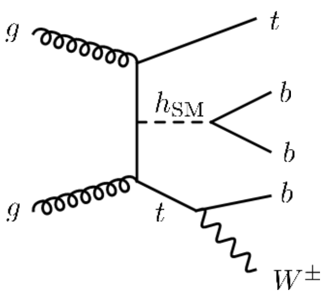
Collider Excesses in Higgs Searches

- Hint at excess seen at LEP
- $t\bar{t}h$ searches at the Tevatron sees an excess in inclusive cut-and-count vs exclusive BDT analyses with same final state

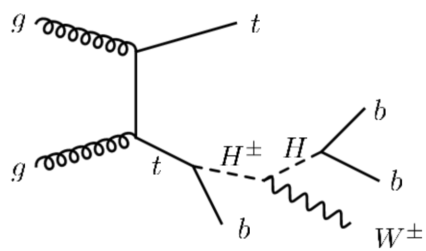


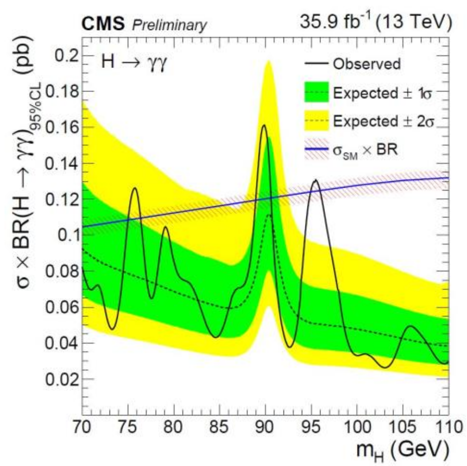


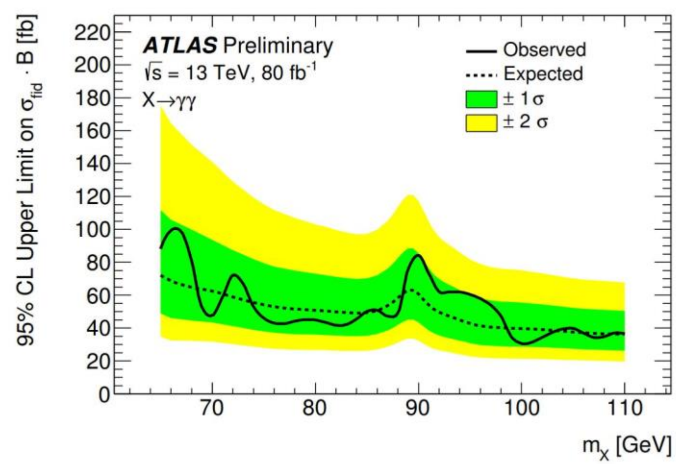
SM contribution



BSM contribution





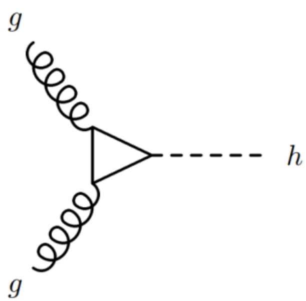


- CMS and ATLAS see excesses around 95 GeV (ATLAS puts limits on the fiducial cross section, must convert first)
- **Can H be responsible for these excesses?**

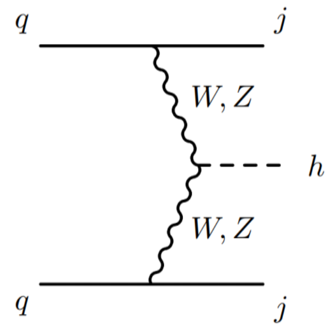
Higgs Signals

- Production mechanisms for neutral scalars:

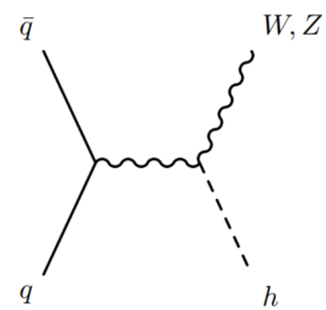
Gluon fusion (h, H, A^0)



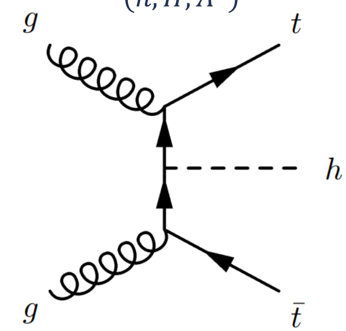
Vector boson fusion (h, H)



Vector boson associated production (h, H)



Top- (or bottom-) pair associated production (h, H, A^0)



  - Higgs working group has calculated BSM Higgs production rates for m_h in the range 10 GeV to few TeV
  - Production cross sections in the 2HDM are found by rescaling by the respective couplings to gauge bosons or fermions
    - For gluon fusion, must also rescale by appropriate form factors for the loop structure
- Charged Higgs bosons may be produced in association with a top and bottom quark, or via rare top decays
  - Rates are found in the 2HDM through a FeynRules implementation in MadGraph

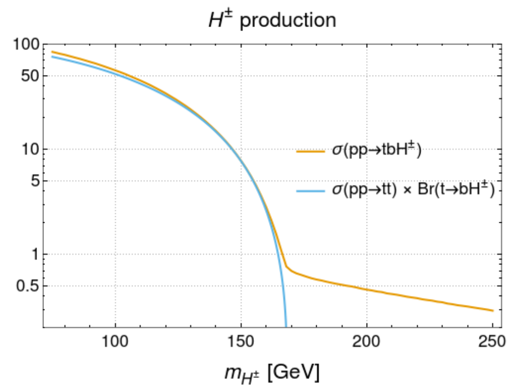
- Branching fractions:
  - Branching fractions are calculated using the HDECAY code developed by Michael Spira
  - Calculates branching fractions and widths of $h, H, A^0, H^{\pm}$ to SM and scalar final states (including off-shell decays)

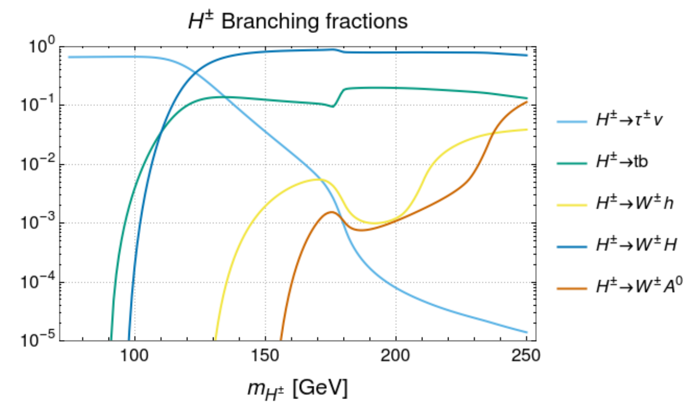
Higgs signals: Example

- Calculate $H \to \gamma\gamma$ through a charged $H^{\pm}$ decay
- Calculate production cross section and branching fractions for $m_{H^{\pm}} \in [75\,,\ 250]$ GeV

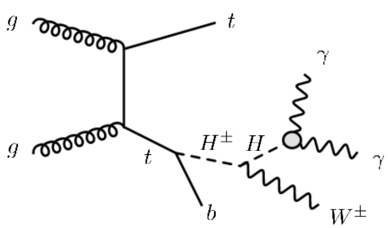
Parameter	m_H	m_h	m_A^0
Value	95 GeV	125 GeV	150 GeV
Parameter	m_{12}	t_β	$c_{\beta-\alpha}$
Value	30 GeV	4	$\sqrt{0.1}$

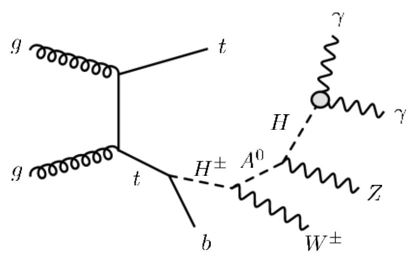
- Production cross section fraction and branching fractions:

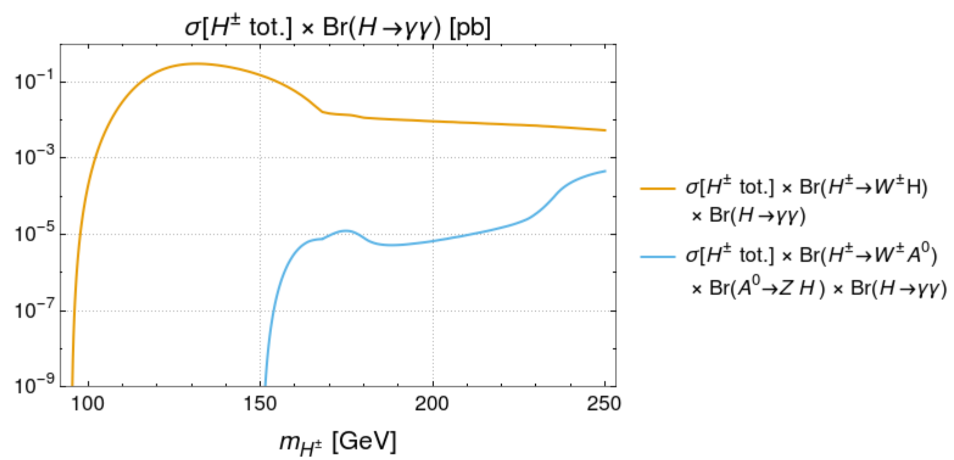




- $\sigma \times \mathrm{Br}(H \to \gamma\gamma)$ rate calculated by combining production cross sections with branching fractions





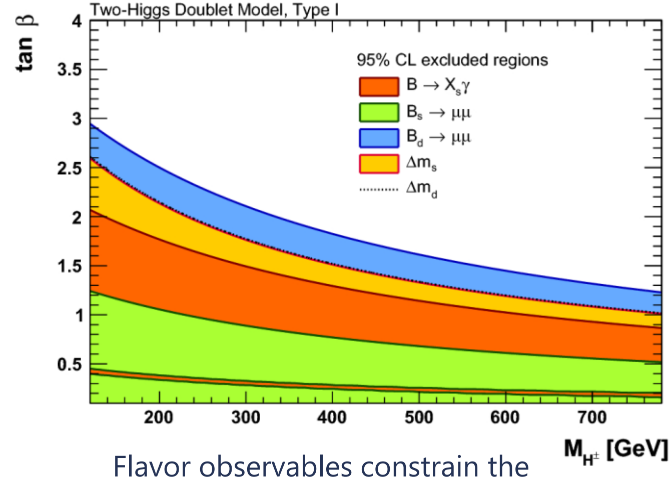


Constraints on 2HDM Parameter Space

- Many sources of constraints on the parameter space of two-Higgs-doublet Models
  - New scalars contribute to flavor observables like $B \to X_s \gamma$ and B mixing
  - Precision electroweak fits to the S and T parameters also constrain the parameter space

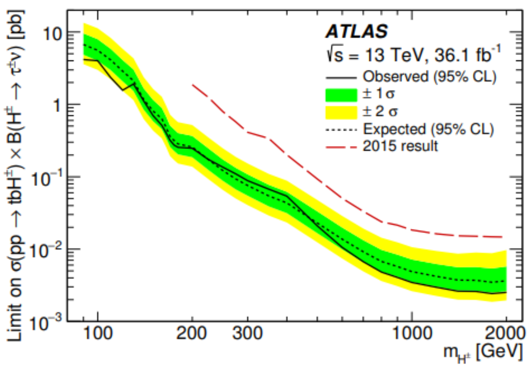
$$S = 0.04 \pm 0.11$$
$$T = 0.09 \pm 0.14$$

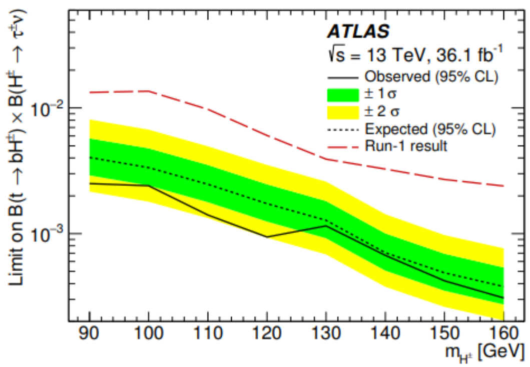
S and T fit by *Gfitter* (1803.01853)



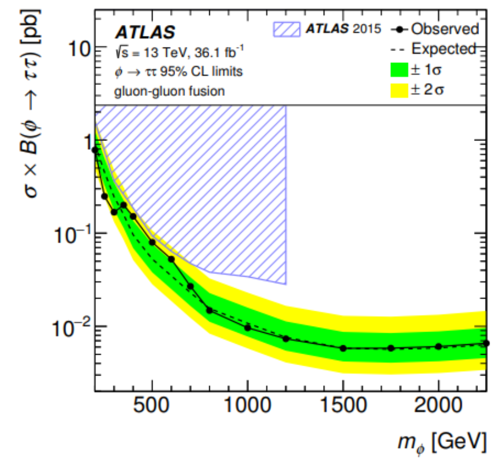
Flavor observables constrain the $m_{H^\pm} - \tan\beta$ plane (1803.01853)

  - Direct searches for light Higgs bosons give exclusions for quantities
    - Charged Higgs searches in the $\tau^\pm\nu$ channel





Limits on $H^\pm$ production via rare top decays (1807.07915)

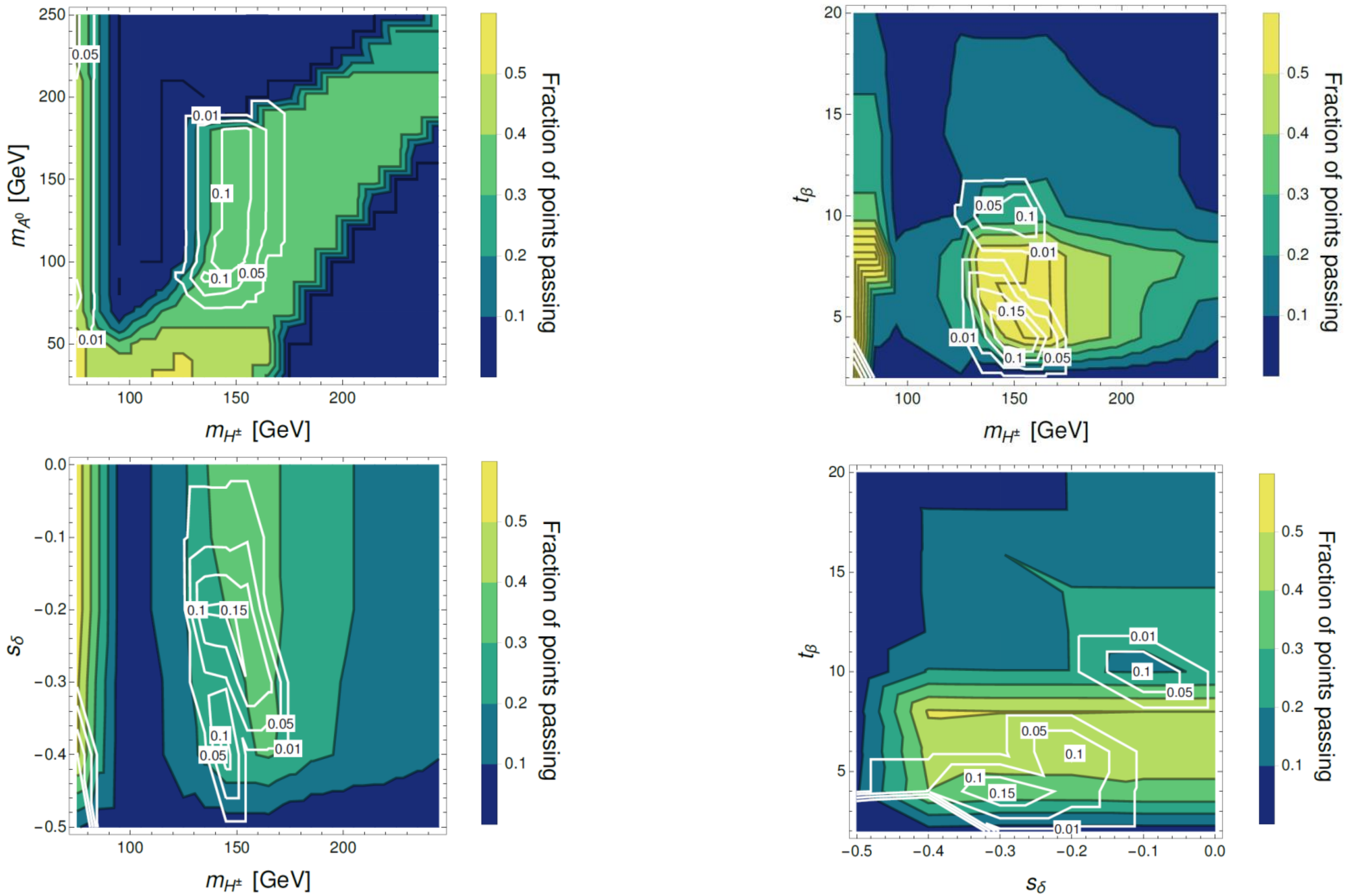


Limits on A^0 production via gluon fusion (1709.07242)

- Other constraints come from unitarity and tree-level perturbativity of the quartic couplings and stability of the electroweak vacuum

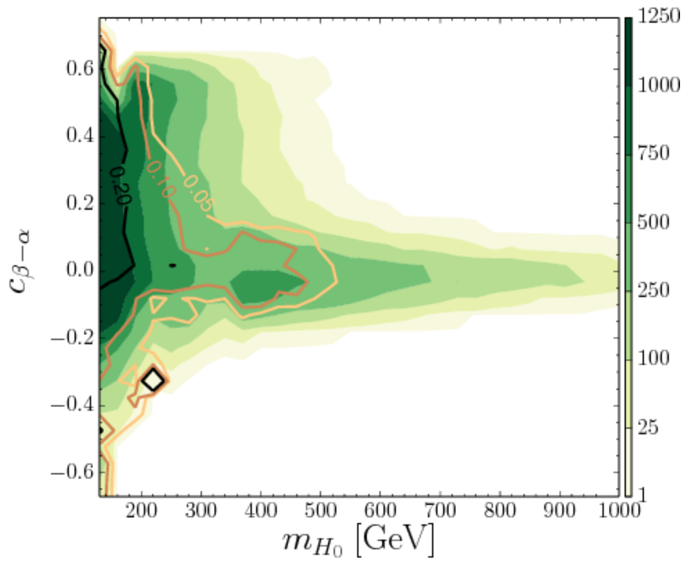
Regions That Survive and Can Explain Excess

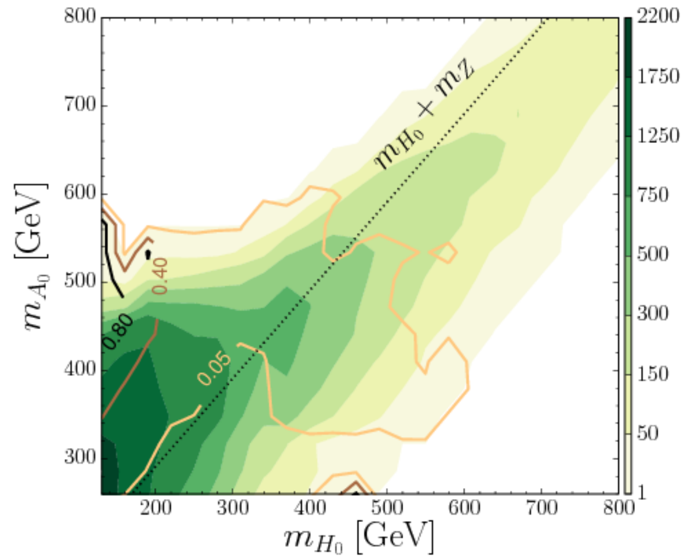
- Numerically scan over 2HDM parameter space, keeping $m_H = 95$ GeV and $m_h = 125$ GeV
  - Test each point against constraints, find points which pass and can also explain the CMS di-photon excess



Implications for the Electroweak Phase Transition

- For electroweak baryogenesis to occur in the early universe, a strong first-order electroweak phase transition (EWPT) is needed
  - The Standard Model does not allow for a first order EWPT with $m_h = 125$ GeV
- BSM scalar sector can lead to a modified phase transition – perhaps to a first order transition
- Recent analysis of the two-Higgs-doublet model parameter space has found point compatible with current constraints and a strong first order EWPT
  - Crucially, this analysis assumed $125\ \mathrm{GeV} = \boldsymbol{m_h} < \boldsymbol{m_H}$





- **Are there intersections between regions explaining collider excess and those providing a first order electroweak phase transition? Stay tuned!**

(1705.09186)

References and Resources

- Two-Higgs Doublet Model review material:
  - Theory and phenomenology of two-Higgs-doublet models, 1106.0034
  - The Anatomy of Electro-Weak Symmetry Breaking. II: The Higgs bosons in the Minimal Supersymmetric Model, hep-ph/0503173
- Collider excesses:
  - LEP: doi:10.1016/S0370-2693(03)00614-2
  - Tevatron: 1208.2662
  - ATLAS: ATLAS-CONF-2018-025
  - CMS: CMS-PAS-HIG-17-013
- Collider constraints:
  - See slide for individual citations
- LHC Higgs cross section working group twiki for BSM Higgs production rates
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG
- 2HDM FeynRules implementation
  - http://feynrules.irmp.ucl.ac.be/wiki/2HDM
- HDECAY Fortran code
  - http://tiger.web.psi.ch/proglist.html
- Electroweak phase transition in type-I 2HDM
  - The Higgs Vacuum Uplifted: Revisiting the Electroweak Phase Transition with a Second Higgs Doublet, 1705.09186