The 750 GeV Diphoton Excess: Models and Precision Tools

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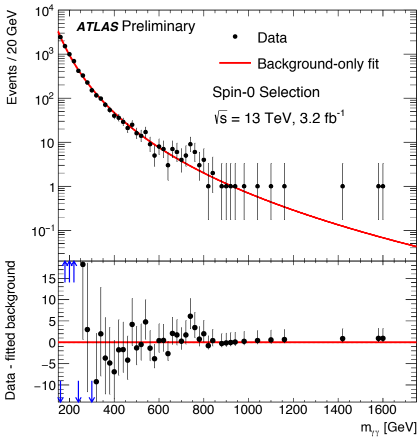
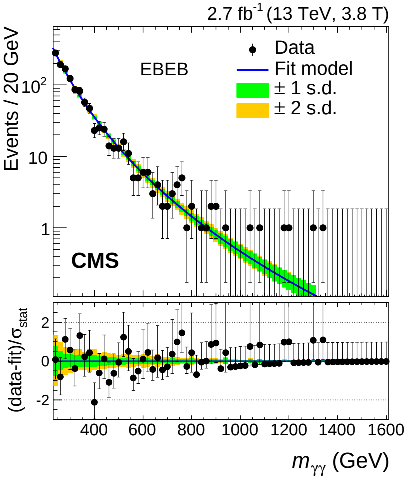


[ATLAS-CONF-2016-018]



[arXiv:1606.04093]

- ATLAS (spin-0): 3.9σ local, 2.0σ global for $\Gamma/M \approx 0.06$
- CMS: $\sim 3.4\sigma$ local, $\sim 1.6\sigma$ global, assuming $\Gamma/M = 1.4 \times 10^{-4}$

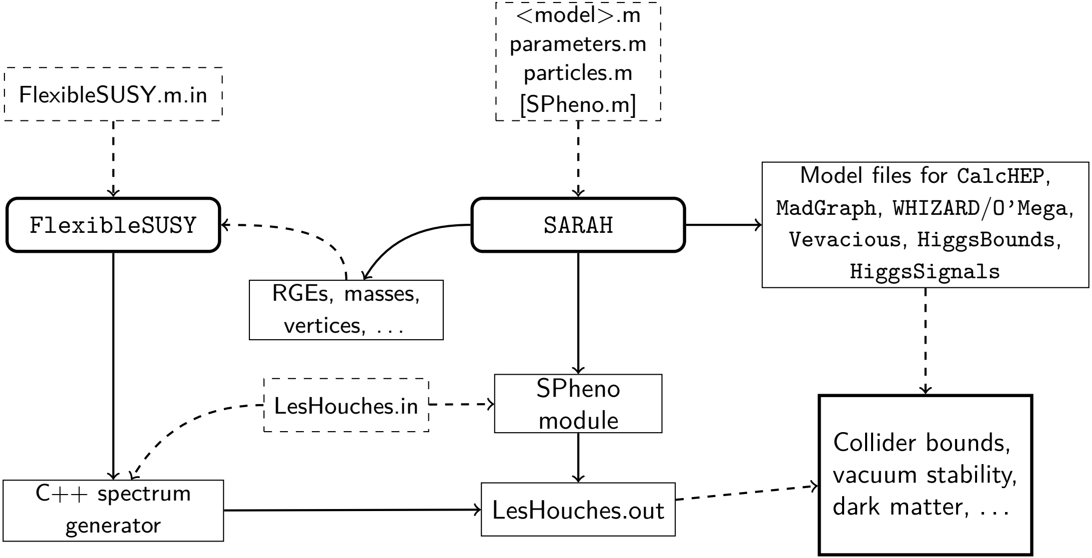
Why Precision Tools?

- Higher order corrections can be large ⇒ significant impacts on conclusions
- Analytic assumptions or calculational methods may not be satisfied (e.g. non-perturbative couplings)
- Models may contain many new parameters, mixings, VEVs, decay channels etc.; these can be missed, or neglecting them may not be justified
- Models must satisfy many constraints simultaneously

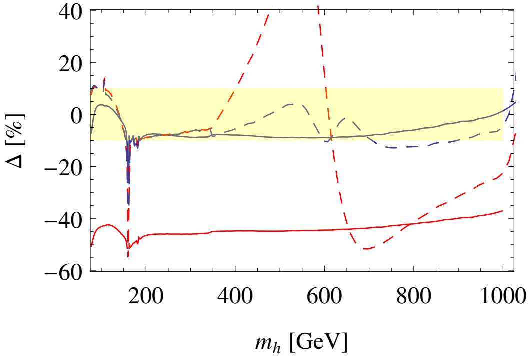
Advantages?
Fast to set-up ✓
Fast to run ✓
Completeness ✓
Precision ✓
Reliability ✓
Reproducible ✓
Many models already implemented ✓

https://sarah.hepforge.org/Diphoton_Models.tar.gz

Existing Capabilities



Calculation of Diphoton and Digluon Rates



Relative error compared to LHCHXSWG, red = LO, blue = including higher order corrections, solid = $BR(h \to g\,g)$, dashed = $BR(h \to \gamma\,\gamma)$

- Extend SPheno, FlexibleSUSY to calculate $\Gamma(S/A \to \gamma\,\gamma)$, $\Gamma(S/A \to g\,g)$ for scalar S or pseudoscalar A

- Standard results at LO, e.g.

$$\Gamma(S \to \gamma\,\gamma) = \frac{G_F \alpha^2(0) m_S^3}{128\sqrt{2}\pi^3} \left| \sum_i N_c^f Q_f^2 r_i^S A_i(\tau_i) \right|$$

$$\Gamma(S \to g\,g) = \frac{G_F \alpha_s^2(m_S) m_S^3}{36\sqrt{2}\pi^3} \left| \sum_i \frac{3}{2} D_2^i r_i^S A_i(\tau_i) \right|$$

- Include known QCD corrections where available (up to N^{3}LO) for colour triplets in loop

A $U(1)$ Extension of the MSSM

- Solve little hierarchy problem of MSSM:

$$m_{h_1}^2 = m_Z^2 \cos^2 2\beta + \Delta_D + \ldots$$

- Diphoton resonance: $\Rightarrow$ extra vector-like fields ($\hat{U}_i$, $\hat{\bar{U}}_i$, $\hat{E}_i$, $\hat{\bar{E}}_i$, $i = 1, 2, 3$)

- Anomaly cancellation $\Rightarrow$ include RH neutrinos charged under $U(1)_X$

- Don't neglect general mixings:

$$W = W_{\mathrm{MSSM}} + Y_\nu \hat{\nu}^c \hat{L} \hat{H}_u + Y_x \hat{\nu}^c \hat{\bar{\eta}} \hat{\nu}^c + \lambda \hat{S} \hat{H}_u \hat{H}_d + \hat{S}(\xi + \lambda_X \hat{\eta} \hat{\bar{\eta}}) + M_S \hat{S}^2 + \frac{\kappa}{3} \hat{S}^3 + \tilde{M}_E \hat{e}^c \hat{\bar{E}} + \tilde{M}_U \hat{u}^c \hat{\bar{U}} + \hat{S}(\lambda_e \hat{E} \hat{\bar{E}} + \lambda_u \hat{U} \hat{\bar{U}}) + M_e \hat{E} \hat{\bar{E}} + M_u \hat{U} \hat{\bar{U}} + Y_e' \hat{E} \hat{L} \hat{H}_d + Y_u' \hat{U} \hat{q} \hat{H}_u$$

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
$\hat{Q}_i$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	0
$\hat{L}_i$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	0
$\hat{d}_i^c$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	$\frac{1}{2}$
$\hat{u}_i^c$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	$-\frac{1}{2}$
$\hat{e}_i^c$	$\mathbf{1}$	$\mathbf{1}$	1	$\frac{1}{2}$
$\hat{\nu}_i^c$	$\mathbf{1}$	$\mathbf{1}$	0	$-\frac{1}{2}$
$\hat{U}_i$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	$-\frac{1}{2}$
$\hat{\bar{U}}_i$	$\mathbf{3}$	$\mathbf{1}$	$\frac{2}{3}$	$\frac{1}{2}$
$\hat{E}_i$	$\mathbf{1}$	$\mathbf{1}$	1	$\frac{1}{2}$
$\hat{\bar{E}}_i$	$\mathbf{1}$	$\mathbf{1}$	-1	$-\frac{1}{2}$
$\hat{H}_d$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$
$\hat{H}_u$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	$\frac{1}{2}$
$\hat{\eta}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
$\hat{\bar{\eta}}$	$\mathbf{1}$	$\mathbf{1}$	0	1
$\hat{S}$	$\mathbf{1}$	$\mathbf{1}$	0	0

EWSB and the Higgs Sector

- At physical minimum,

$$\langle H_d^0 \rangle = \frac{v_d}{\sqrt{2}}, \quad \langle H_u^0 \rangle = \frac{v_u}{\sqrt{2}}, \quad \langle \eta \rangle = \frac{v_\eta}{\sqrt{2}}, \quad \langle \overline{\eta} \rangle = \frac{v_{\overline{\eta}}}{\sqrt{2}}, \quad \langle S \rangle = \frac{v_S}{\sqrt{2}}$$

- Break $U(1)_X \Rightarrow$ massive Z', $m_{Z'}^2 \approx g_X^2 (v_d^2 + v_u^2 + v_\eta^2 + v_{\overline{\eta}}^2)/4$

- Extended Higgs sector: 3 physical pseudoscalars, 5 CP-even scalars

- In general, mixing between doublet and singlet components in CP-even and CP-odd states (e.g. due to λ)

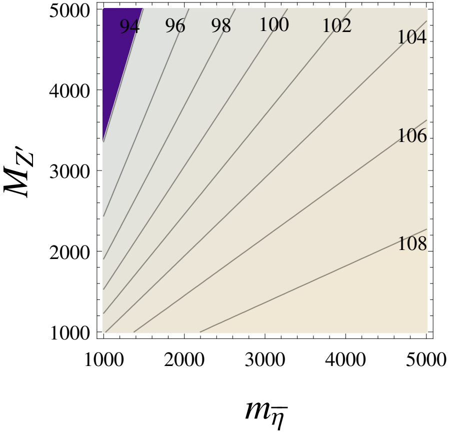
- Note $W \supset Y_x \hat{\nu} \hat{\overline{\eta}} \hat{\nu}$ $\Rightarrow$ decompose sneutrinos in CP-eigenstates

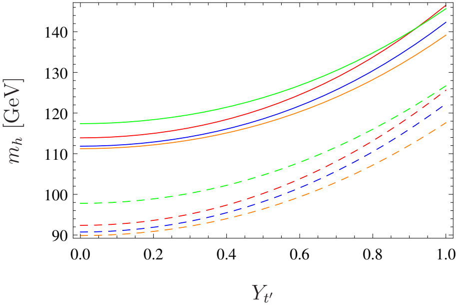
$$\tilde{\nu}_{L,i} \to \frac{1}{\sqrt{2}} \left(\phi_{L,i} + i \sigma_{L,i} \right), \quad \tilde{\nu}_{R,i} \to \frac{1}{\sqrt{2}} \left(\phi_{R,i} + i \sigma_{R,i} \right)$$

  i.e. extended sneutrino sector

Enhancing the Higgs Mass

$$m_{h_1}^2 \lesssim m_Z^2 \cos^2 2\beta + \frac{\lambda^2 v^2}{2} \sin^2 2\beta + \frac{g_X^2 v^2}{4}$$

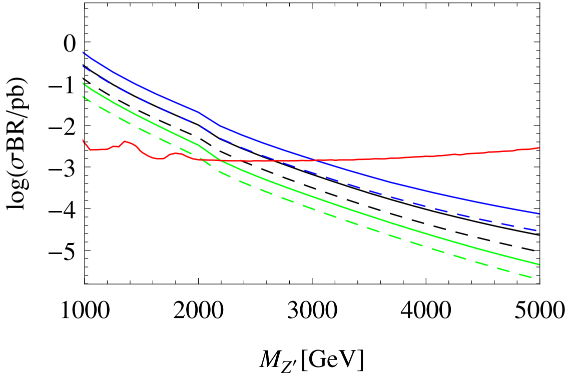




Red = 1-loop V_{eff}, orange = full 1-loop neglecting thresholds, blue = full 1-loop, green = dominant 2-loop (full: $\tan\beta = 10$, dashed: $\tan\beta = 2$)

- Corrections from exotic states in general not small (even at 1-loop)
- 2-loop corrections can contribute additional several GeV ⇒ simple using SPheno (for FlexibleSUSY, see talk by P. Athron, Tue 16:30)

Z' Collider Limits

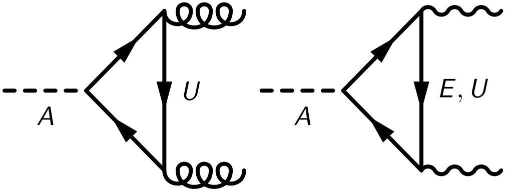


Green: $g_X = 0.3$, black: $g_X = 0.5$, blue: $g_X = 0.7$, red = ATLAS limit (dashed lines assume $g_{1X} = -g_X/5$)

- Large D-term enhancement $\Rightarrow$ large $U(1)_X$ gauge coupling
- Z' constraints relevant to setting allowed g_X, impacts possible mass spectrum
- Strong constraint on many $U(1)$ extensions
- Easily obtain specific model limits by linking SPheno/FlexibleSUSY to MadGraph
- $g_X \gtrsim 0.3 \Rightarrow$ require $m_{Z'} \gtrsim 2$ TeV
- Note: gauge kinetic mixing has non-negligible impact in general

750 GeV Candidate

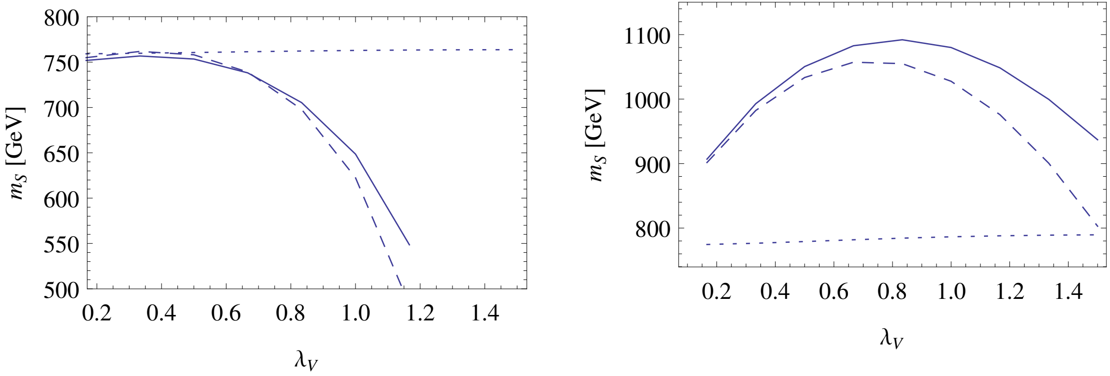
- CP-even scalars: mixing between all states $\Rightarrow$ tree-level WW, ZZ can be too large
- $\therefore$ assume pseudoscalar is 750 GeV resonance
- Vector-like $\hat{U}_i$, $\hat{\bar{U}}_i$, $\hat{E}_i$, $\hat{\bar{E}}_i$ $\Rightarrow$ additional states in loop (also extended scalar sector)
- Increase total width by requiring large BR($A \to$ invisible), e.g. via decays to sneutrinos



$$M_E = \begin{pmatrix} \frac{Y_e v_d}{\sqrt{2}} & -\frac{Y'_e v_d}{\sqrt{2}} \\ \tilde{M}_E & M_e + \frac{\lambda_e v_S}{\sqrt{2}} \end{pmatrix},$$

$$M_U = \begin{pmatrix} \frac{Y_u v_u}{\sqrt{2}} & \frac{Y'_u v_u}{\sqrt{2}} \\ \tilde{M}_U & M_u + \frac{\lambda_u v_S}{\sqrt{2}} \end{pmatrix}$$

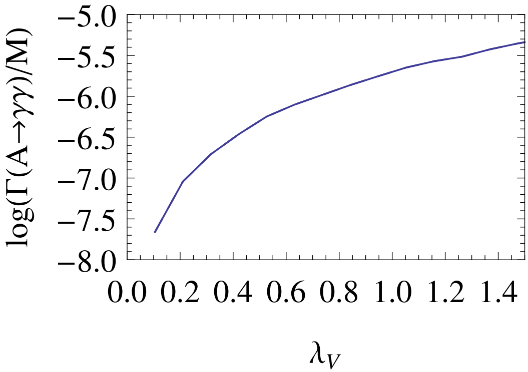
Pseudoscalar Mass

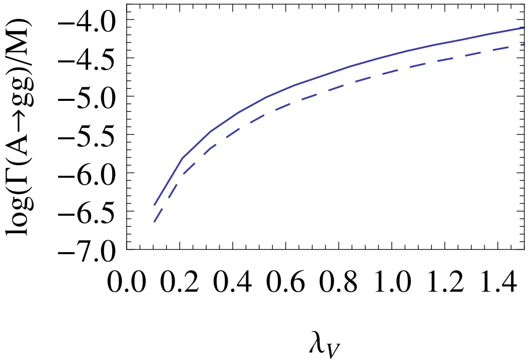


Dotted = tree-level, dashed = 1-loop, full = 2-loop (m_{SUSY} = 1.5 TeV left, m_{SUSY} = 2.5 TeV right)

- Loop corrections are significant (can be $O(100)$ GeV) ⇒ must be included for accurate understanding of parameter space
- Simple tree-level analysis is insufficient here ⇒ use of tools allows straightforward inclusion of loop corrections

Diphoton and Digluon Rates





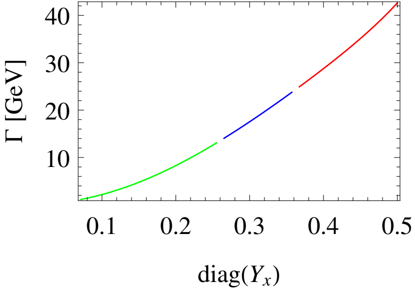
- Effective couplings grow quadratically with exotic Yukawas
- Required $\Gamma(A \to \gamma\,\gamma)/M \sim 10^{-6} \Rightarrow \lambda_e = \lambda_u \equiv \lambda_V \sim 1$, i.e. relatively large couplings required (loop corrections to pseudoscalar mass can be large)
- Note: include implemented QCD corrections $\Rightarrow \Gamma(A \to g\,g)$ increases by factor ~ 2

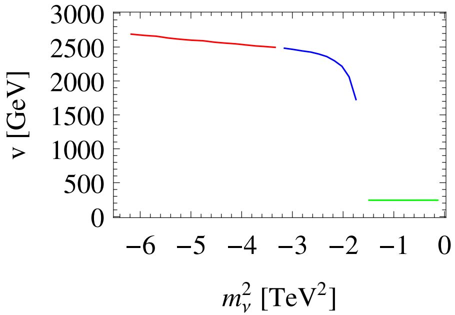
Vacuum Stability

- Large width via $A \to \tilde{\nu}^I \tilde{\nu}^R \Rightarrow$ sufficiently large Y_x, and require

$$m_\nu^2 = -\frac{Y_x^2}{4g_X^2}\left(4m_{Z'}^2 - g_X^2 v^2\right) < 0$$

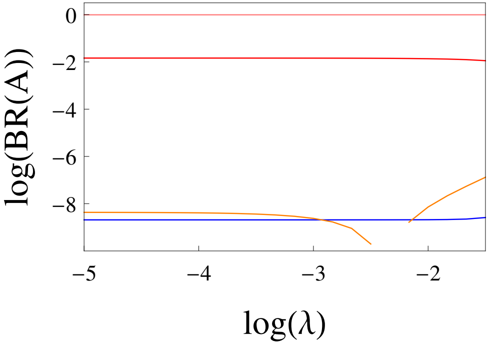
and $T_x = -\lambda_X v_S Y_x/\sqrt{2}$





- $\therefore$ danger of spontaneous *R*-parity violation and unstable EW vacuum
- Easy to check by linking `SPheno`/`FlexibleSUSY` to `Vevacious`
- Strong constraint on obtainable width, e.g. can be difficult to obtain $\Gamma \gtrsim 15$ GeV

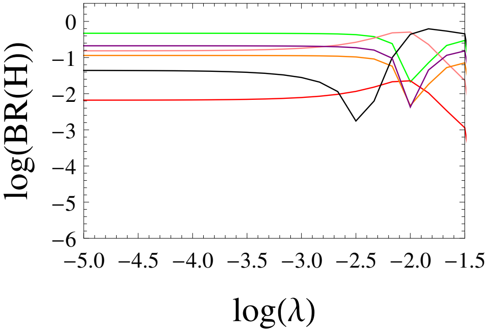
Impacts of Doublet-Singlet Mixing



Pink: $\gamma\,\gamma$, red: $g\,g$, blue: $h\,Z$, orange: $t\,\bar{t}$, black: $h\,h$, purple: $Z\,Z$, green: $W^+\,W^-$

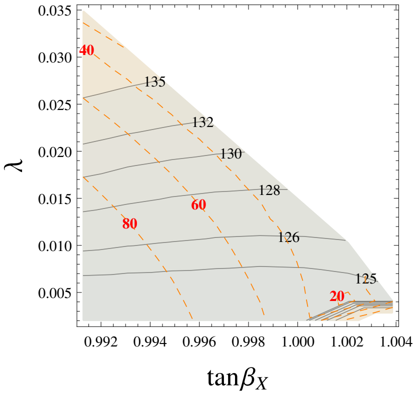
- Pseudoscalar branching ratios insensitive to λ

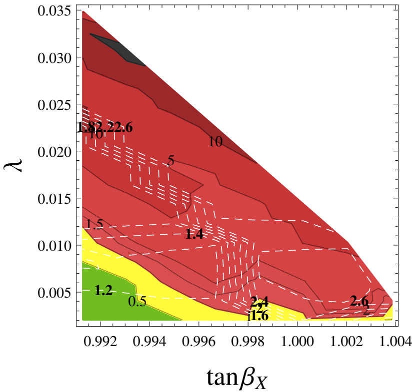
- Similar mass CP-even BRs also not strongly dependent on λ
- Note: significant difference in behaviour using tree-level mixing vs one-loop



Impacts of Doublet-Singlet Mixing

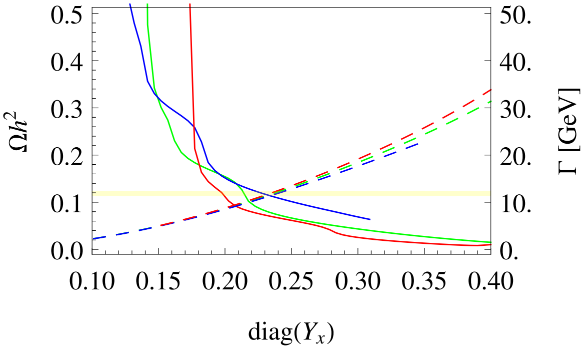
- Mixing in CP-even sector $\Rightarrow$ can obtain light CP-even scalar $m_{h_1} < 125$ GeV
- Compatible with existing limits? Link to HiggsBounds, HiggsSignals





- Masses highly sensitive to λ, $\tan\beta_X$ $\Rightarrow$ impact of mixing should be checked
- Best fit for SM-like Higgs being second lightest state, with light $m_{h_1} \approx 80$ GeV
- $m_{h_1} \sim 40$ GeV also allowed

Dark Matter Relic Density



Dashed = total width, full = relic density, green:
$$m_\nu^2 = -\frac{Y_x^2}{4g_X^2}\left(4m_{Z'}^2 - g_X^2 v^2\right)$$

- Light (RH) sneutrinos $\Rightarrow$ potential DM candidates
- Relic density very sensitive to m_ν^2, Y_x for sneutrino DM
- Mainly due to decrease in $m_{\tilde{\nu}}$ as Y_x increases
- Γ less sensitive $\Rightarrow$ Ωh^2 provides additional constraint that should be included
- Note: alternatives also possible, e.g. lightest neutralino as usual
- Investigated numerically using `CalcHEP`/ `micrOMEGAs` interface

Summary

- Explain diphoton excess (or any new physics signal) with new model: new parameters, mixings, higher-order corrections, many simultaneous constraints, ...
- $\Rightarrow$ challenging problem (and simplifying analytic assumptions not always justified)
- Generic automated tools (*toolchains*) exist for this purpose: `SARAH`/`SPheno`, `FlexibleSUSY`, ...
- $U(1)$ extended model with vector-like states can accommodate the excess
- Extra $U(1)$, exotic matter $\Rightarrow$ increase Higgs mass at tree-level
- Diphoton excess from loop induced decay of 750 GeV pseudoscalar with required $\Gamma(A \to \gamma\gamma)$ due to new vector-like states, but large width $\Rightarrow$ important constraints from vacuum stability
- Extended sneutrino, neutralino sectors $\Rightarrow$ additional DM candidates

Thank you for listening!

Additional Slides

Example: Impact of Higher Order Corrections

Relevant decays widths for CP-even/CP-odd scalars in the SM with a scalar singlet and vector-like fermions can change significantly (models as defined in Table III of arXiv:1512.04928)

Model		$Br(gg/\gamma\gamma)$	$\Gamma_{S\to gg}$ [MeV]	$\Gamma_{S\to\gamma\gamma}$ [MeV]
Ψ_{F_1}	SPheno LO	13.47/12.22	6.78/14.27	0.50/1.17
	SPheno NLO	23.27/20.27	11.04/23.71	0.47/1.17
Ψ_{F_2}	SPheno LO	28.32/25.70	15.26/32.12	0.54/1.25
	SPheno NLO	48.93/42.67	24.85/52.34	0.51/1.25
Ψ_{F_3}	SPheno LO	39.20/35.56	6.78/14.27	0.17/0.40
	SPheno NLO	67.72/59.06	11.04/23.71	0.16/0.40
Ψ_{F_4}	SPheno LO	57.80/52.44	15.26/32.12	0.26/0.61
	SPheno NLO	99.85/87.09	24.85/53.34	0.25/0.61
Ψ_{F_5}	SPheno LO	177.0/160.6	1.70/3.57	$9.58 \times 10^{-3}/22.22 \times 10^{-3}$
	SPheno NLO	305.8/266.7	2.76/5.93	$9.03 \times 10^{-3}/22.22 \times 10^{-3}$
Ψ_{F_6}	SPheno LO	453.2/411.1	6.78/14.27	$1.50 \times 10^{-2}/3.47 \times 10^{-2}$
	SPheno NLO	782.8/682.8	11.04/23.71	$1.41 \times 10^{-2}/3.47 \times 10^{-2}$

Pseudoscalar Mass Matrix

At tree-level, the symmetric 3×3 mass matrix in the basis $\{P_1,\ P_2,\ P_3\}$ has elements

$$(\tilde{M}^2)_{11} = \frac{2}{\sin 2\beta}\left(\sqrt{2}\lambda M_S v_S + \frac{\lambda\kappa v_S^2}{2} + B\mu + \lambda\xi + \frac{\lambda\lambda_X x^2}{4}\sin 2\beta_X + \frac{T_\lambda v_S}{\sqrt{2}}\right),$$

$$(\tilde{M}^2)_{22} = -\frac{2}{\sin 2\beta_X}\left(\sqrt{2}\lambda_X M_S v_S + \frac{\lambda_X\kappa v_S^2}{2} + \lambda_X\xi - \frac{\lambda\lambda_X v^2}{4}\sin 2\beta + \frac{T_{\lambda_X} v_S}{\sqrt{2}}\right),$$

$$(\tilde{M}^2)_{33} = -\sqrt{2}\kappa M_S v_S + \frac{\lambda M_S v^2}{\sqrt{2}v_S}\sin 2\beta + \lambda\kappa v^2\sin 2\beta - \frac{\lambda\mu v^2}{\sqrt{2}v_S} - \frac{2\sqrt{2}M_S\xi}{v_S} - 4\kappa\xi - 4B_S M_S$$
$$- \frac{\sqrt{2}L\xi}{v_S} - \frac{\lambda_X M_S x^2}{\sqrt{2}v_S}\sin 2\beta_X - \lambda_X\kappa x^2\sin 2\beta_X - \frac{3T_\kappa v_S}{\sqrt{2}} + \frac{T_\lambda v^2}{2\sqrt{2}v_S}\sin 2\beta - \frac{T_{\lambda_X} x^2}{2\sqrt{2}v_S}\sin 2\beta_X$$

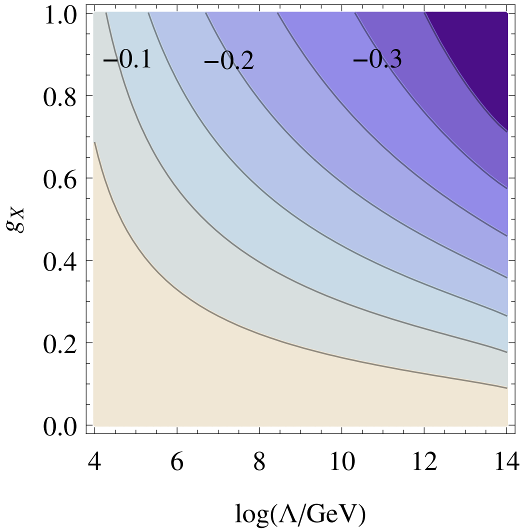
Pseudoscalar Mass Matrix (cont.)

$$(\tilde{M}^2)_{12} = -\frac{\lambda\lambda_X}{2}vx,$$
$$(\tilde{M}^2)_{13} = -\lambda v\left(\sqrt{2}M_S + \kappa v_S\right) + \frac{T_\lambda v}{\sqrt{2}},$$
$$(\tilde{M}^2)_{23} = \lambda_X x\left(\sqrt{2}M_S + \kappa v_S\right) - \frac{T_{\lambda_X} x}{\sqrt{2}}$$

where $x^2 = v_\eta^2 + v_{\overline{\eta}}^2$, $\tan\beta_X = v_\eta/v_{\overline{\eta}}$ and

$$P_1 = \mathrm{Im}\, H_d^0 \sin\beta + \mathrm{Im}\, H_u^0 \cos\beta,$$
$$P_2 = \mathrm{Im}\, \eta \cos\beta_X + \mathrm{Im}\, \overline{\eta} \sin\beta_X,$$
$$P_3 = \mathrm{Im}\, S$$

Gauge Kinetic Mixing



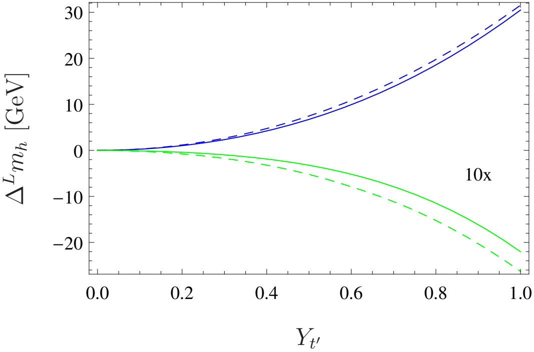
- Non-orthogonal $U(1)_Y$, $U(1)_X$:

$$\sum_{\Phi} \begin{pmatrix} Q_\Phi^Y \\ Q_\Phi^X \end{pmatrix} \begin{pmatrix} Q_\Phi^Y & Q_\Phi^X \end{pmatrix} \neq \text{diagonal}$$

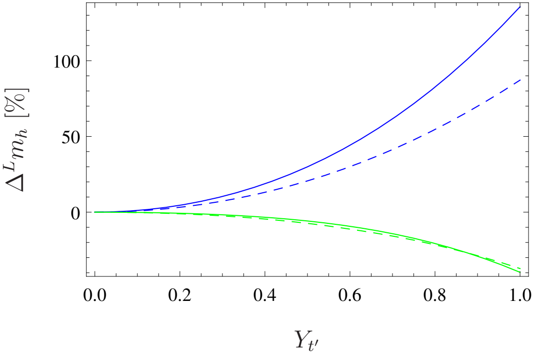
- $\Rightarrow$ off-diagonal gauge couplings induced
- Sometimes neglected analytically, but not small in general
- Potentially significant effect on m_{h_1}, collider limits
- Consistently handled by numerical tools

Size of Exotic Contributions

- Absolute contributions can amount to $\sim 1 - 2$ GeV

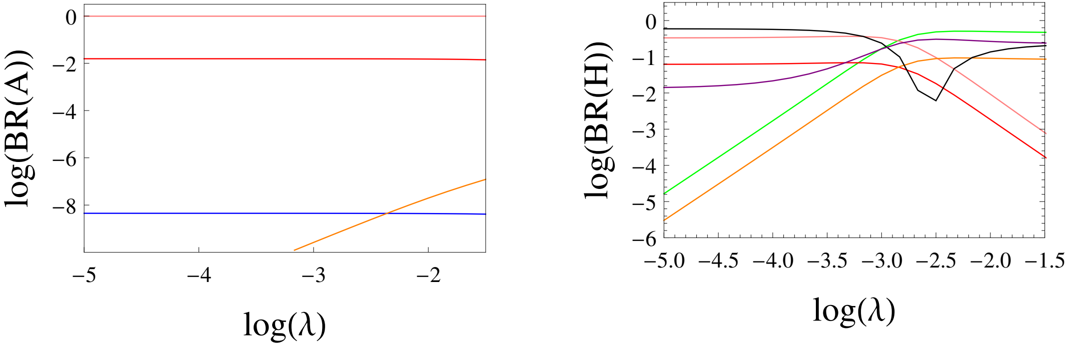


- Normalised to purely-MSSM corrections, can be of comparable size for large couplings



Blue = 1-loop, green = 2-loop (full: $\tan\beta = 10$, dashed: $\tan\beta = 2$)

Branching Ratios with Tree-Level Mixings



- Impact of mixing small for pseudoscalar
- BRs for CP-even state sensitive due to variation in doublet fraction