PRECISION TOOLS AND MODELS TO NARROW IN ON THE 750 GeV DIPHOTON RESONANCE

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Based on arXiv:1602.05581

in collaboration with
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universitätbonn

bctp Bethe Center for Theoretical Physics

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THE PURPOSE OF THIS TALK?

i) Emphasise a number of deficiencies in the diphoton literature

ii) Show how using `SARAH` framework can help to prevent these deficiencies

iii) Illustrate elements of a small complete example

Diphoton models

Composite Models

- $\mathcal{O}(20)$ papers
- Naturally broad resonance

Extra-dimensions

- $\mathcal{O}(10)$ papers

Exotic Models

- $\mathcal{O}(20)$ papers

Perturbative Models

- $\mathcal{O}(200)$ papers

[All references in 1602.05581]

Diphoton models

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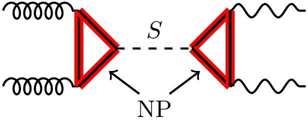
[All references in 1602.05581]

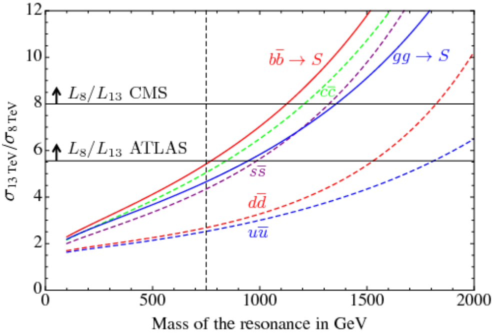
DECAY WIDTH

Generic explanation involves loop-induced couplings to both photons and gluons



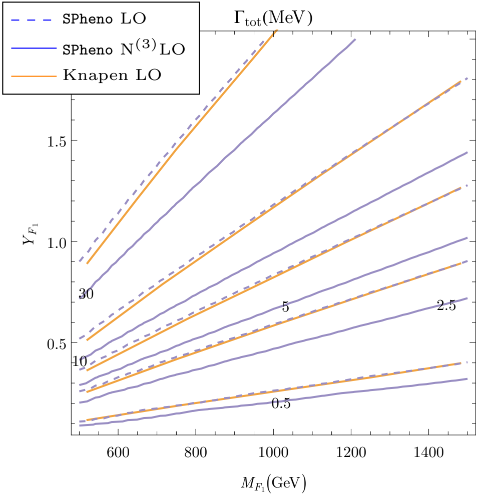
[S. Knapen et al. 1512.04928]

Important prediction of a model is the ratio $\mathrm{BR}(S \to gg)/\mathrm{BR}(S \to \gamma\gamma)$



[R. Franceschini et al 1512.04933]

DECAY WIDTH



Consider toy model containing:

Vector-like quarks	Ψ	$(\mathbf{3},\mathbf{2},7/6)$
Singlet	S	$(\mathbf{1},\mathbf{1},0)$

$$\mathcal{L}_Y \supset \left(M_{F_1} + Y_{F_1} S\right) \overline{\Psi_L} \Psi_R + \text{h.c.}$$

[S. Knapen et al. 1512.04928]

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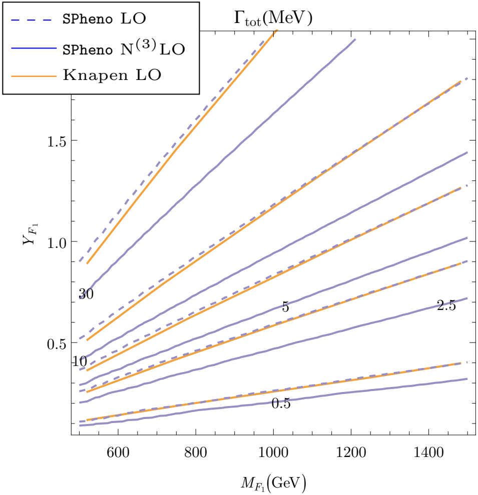

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CONCLUSION

- Small mismatch in LO result as $\alpha_{\rm em}(0) \neq \alpha_{\rm em}(M_S)$
- QCD corrections dominate over LO mismatch

CONSTRAINTS ON A LARGE DIPHOTON WIDTH

Necessary decay rate depends on signal width

- Narrow width: $\Gamma(S \to \gamma\gamma)/M_S \simeq 10^{-6}$
- Large width: $\Gamma(S \to \gamma\gamma)/M_S \simeq 10^{-4}$

[R. Franceschini et al 1512.04933]

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HOW TO INCREASE THE WIDTH:

1. Fermions with large Yukawa couplings
2. Fermions/scalars with large multiplicity and/or electric charge
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OPTION 1

Pert. calculation $\Rightarrow$ Yukawa must remain perturbative $\lesssim \sqrt{4\pi}$

(Not required in composite models)

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OPTION 2

Must check for Landau poles

Example:
SM + N_k generations of k^{++}

[Kanemura et al. 1512.09048

Nomura et al. 1601.00386]

N_k	μ_{Landau}
10	2×10^{13} TeV
100	1.2×10^{5} TeV
1000	3.8 TeV
6000	2.7 TeV
9000	2.6 TeV

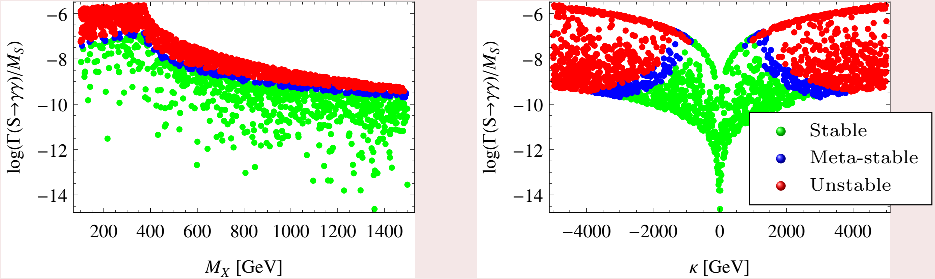
CONSTRAINTS ON A LARGE DIPHOTON WIDTH

OPTION 3

Alternative to fermions with large Yukawas ⟶ scalars with large κ

$$V \supset \kappa\, S|X|^2 + \frac{1}{2} M_S S^2 + M_X |X|^2 + \cdots$$

Stability of the EW vacuum:



MIXING WITH THE SM HIGGS

Toy model with CP-even singlet S and electrically charged scalars X

$$V = \frac{1}{2}M_S S^2 + M_X|X|^2 + \mu^2|H|^2 + \kappa S|X|^2 + \kappa_H S|H|^2 \\ + \lambda_S S^4 + \lambda_{SX} S^2 X^2 + \lambda_{HX}|H|^2|X|^2 + \lambda|H|^4$$

AT TREE-LEVEL

- Many studies choose $\kappa_H = 0 \implies$ no mixing
- Non-zero mixing:
  $\implies$ tree-level decays $\gg$ loop decays

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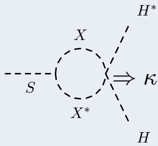
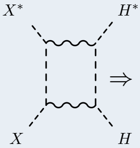
Loop-level



$\Rightarrow \kappa_H^{\text{loop}} \neq 0$



$\Rightarrow \lambda_{HX}^{\text{loop}} \neq 0$

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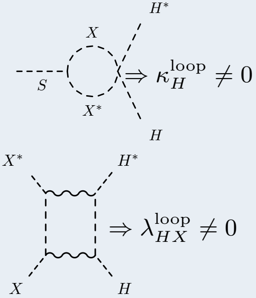
OTHER CONSIDERATIONS

- Similar arguments hold for vector-like fermions
- $\kappa_H \neq 0$ often required for pseudo-scalar masses
- **Good solution:** use CP to forbid unwanted tree-level decays (see later slide)

LOOP-LEVEL



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TO VEV OR NOT TO VEV

TYPICAL ASSUMPTION

$v_S = 0$ at all orders

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$v_S = 0$ at all orders

TADPOLE EQUATIONS

$$\frac{\partial V^{(1L)}}{\partial v_S} = T^{(1L)} = T^{(T)} + \delta T = 0$$

Assuming

$$T^{(T)} = c_1 v_S + c_2 v_S^2 + c_3 v_S^3 = 0$$

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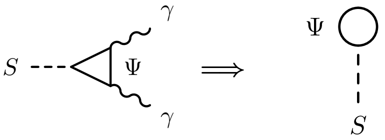
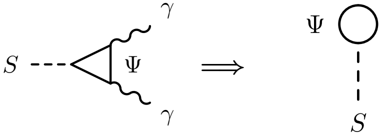


ONE-LOOP RESULTS

$$\delta T = \begin{cases} \kappa A(M_X^2) & \text{scalar loop} \\ 2Y M_\Psi A(M_\Psi^2) & \text{fermion loop} \end{cases}$$

$$A(x^2) = \frac{1}{16\pi^2} x^2 \left[1 + \log\left(\frac{\mu^2}{x^2}\right)\right]$$

TO VEV OR NOT TO VEV



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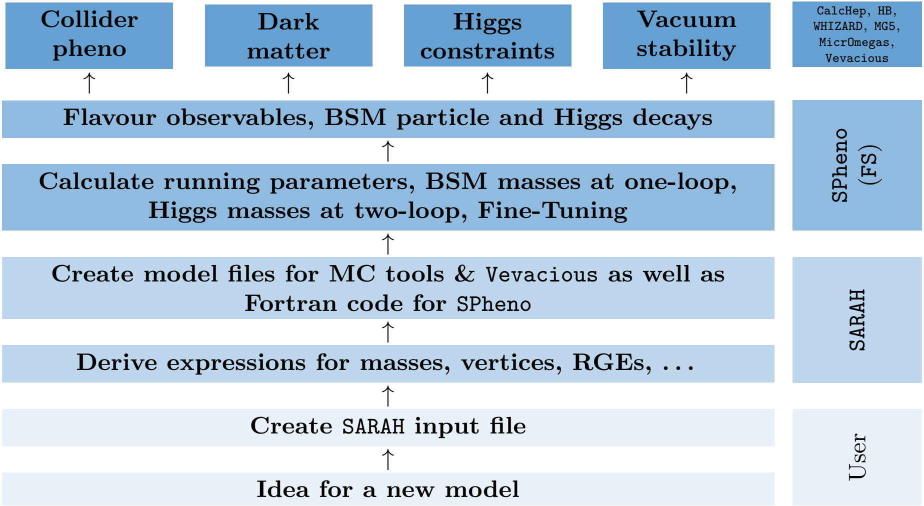
RESULT

If $M_\Psi \sim \kappa \sim M_X \sim \mathcal{O}(1\,\text{TeV})$ then $\delta T \simeq 1\,\text{TeV}^3/(16\pi^2 c_1)$

What is SARAH and how does it help?

WHAT IS `SARAH` AND HOW DOES IT HELP?



Collider pheno

Dark matter

Higgs constraints

Vacuum stability

`CalcHep`, `HB`, `WHIZARD`, `MG5`, `MicrOmegas`, `Vevacious`

Flavour observables, BSM particle and Higgs decays

Calculate running parameters, BSM masses at one-loop, Higgs masses at two-loop, Fine-Tuning

`SPheno` (FS)

Create model files for MC tools & `Vevacious` as well as Fortran code for `SPheno`

Derive expressions for masses, vertices, RGEs, ...

`SARAH`

Create `SARAH` input file

Idea for a new model

User

WHAT IS SARAH AND HOW DOES IT HELP?

Can consider a complete model **without (erroneous) simplifying assumptions**

What's new?

- diphoton and digluon effective vertices calulated
- `SPheno` then calculates decay width and production x-sec.
- Eff. vertices can be passed to `MadGraph` & `CalcHep`

Decay width Implementation

$\Phi \to \gamma\gamma$

LO expressions for decay width implemented using $\alpha_{\text{ew}}(\mu = 0)$

NLO SM corrections implemented for three limits:

- $m_\Phi < m_f$: corrections from heavy colour fermionic triplets
- $m_\Phi > 100 m_f$: analytic corrections in light quark limit

  [M. Spira et al. hep-ph/9504378]
- Intermediate range: numerical values from `HDECAY` used

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$\Phi \to gg$

LO expressions for decay width implemented

N^{3}LO SM corrections implemented

[Baglio et al. 1312.4788

Kramer et al. hep-ph/961127

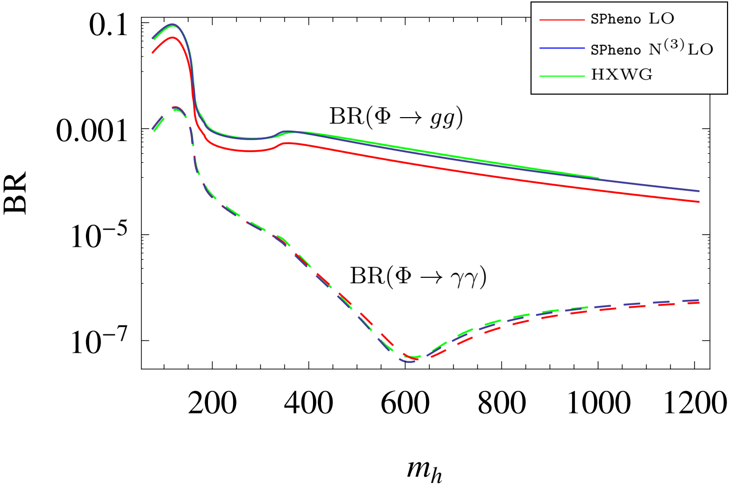
Chetyrkin et al. hep-ph/9705240, hep-ph/0512060

Schroder and Steinhauser hep-ph/0512058

Baikov and Chetyrkin hep-ph/0604194]

Only N^{2}LO corrections for pseudo-scalar Φ

Decay width implementation: SM comparison



[LHC Higgs Cross Section Working Group Collaboration, J. R. Andersen et al. 1307.1347]

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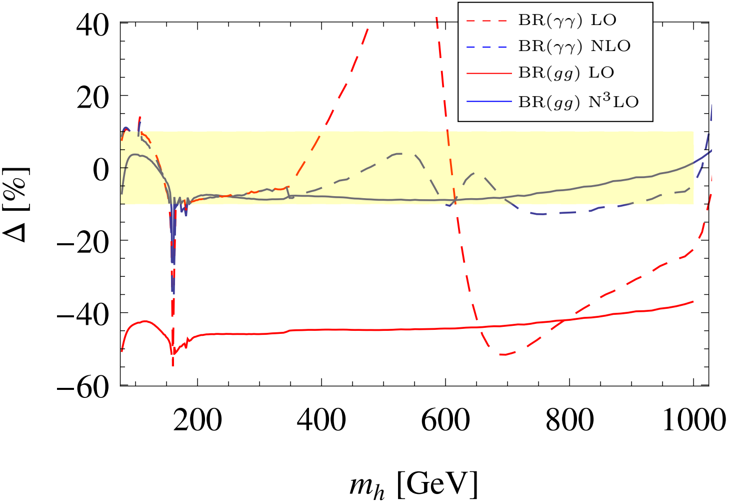

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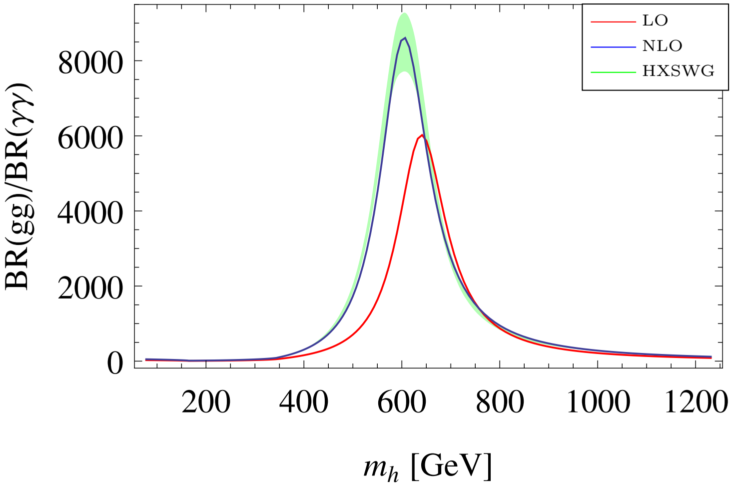

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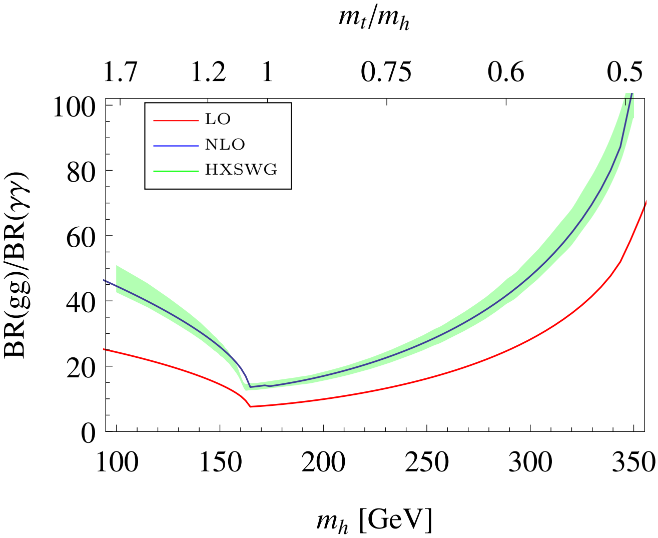

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Model	Name	
Toy models with vector-like fermions		
CP-even singlet	`SM+VL/CPevenS`	
CP-odd singlet	`SM+VL/CPoddS`	
Complex singlet	`SM+VL/complexS`	
Models based on the SM gauge-group		
Portal dark matter	`SM+VL/PortalDM`	
Scalar octet	`SM-S-Octet`	⚠(1)
$SU(2)$ triplet quark model	`SM+VL/TripletQuarks`	
Single scalar leptoquark	`LQ/ScalarLeptoquarks`	
Two scalar leptoquarks	`LQ/TwoScalarLeptoquarks`	⚠(3)
Georgi-Machacek model	`Georgi-Machacek`	
THDM w. colour triplet	`THDM+VL/min-3`	
THDM w. colour octet	`THDM+VL/min-8`	
THDM-I w. exotic fermions	`THDM+VL/Type-I-VL`	
THDM-II w. exotic fermions	`THDM+VL/Type-II-VL`	
THDM-I w. SM-like fermions	`THDM+VL/Type-I-SM-like-VL`	
THDM-II w. SM-like fermions	`THDM+VL/Type-II-SM-like-VL`	
THDM w. scalar septuplet	`THDM/ScalarSeptuplet`	

⚠(1) conflict with limits from $S \to jj$, ⚠(3) we disagree with their diphoton rate

Model	Name	
$U(1)$ **Extensions**		
Dark $U(1)'$	`U1Ex/darkU1`	
Hidden $U(1)$	`U1Ex/hiddenU1`	
Simple $U(1)$	`U1Ex/simpleU1`	
Scotogenic $U(1)$	`U1Ex/scotoU1`	⚠$^{(2)}$
Unconventional $U(1)_{B-L}$	`U1Ex/BL-VL`	
Sample of $U(1)'$	`U1Ex/VLsample`	
flavour-nonuniversal charges	`U1Ex/nonUniversalU1`	
Leptophobic $U(1)$	`U1Ex/U1Leptophobic`	⚠$^{(1)}$
Z' mimicking a scalar resonance	`U1Ex/trickingLY`	
Non-abelian gauge-group extensions of the SM		
LR without bidoublets	`LRmodels/LR-VL`	⚠$^{(2)}$
LR with $U(1)_L \times U(1)_R$	`LRmodels/LRLR`	⚠$^{(2)}$
LR with triplets	`LRmodels/tripletLR`	
Dark LR	`LRmodels/darkLR`	
331 model without exotic charges	`331/v1`	
331 model with exotic charges	`331/v2`	
Gauged THDM	`GTHDM`	

⚠$^{(1)}$ conflict with limits from $S \to jj$, ⚠$^{(2)}$ inconsistencies in charge assignments

Model	Name	
Supersymmetric models		
NMSSM with vectorlike top	`NMSSM+VL/VLtop`	⚠$^{(1)}$
NMSSM with **5**'s	`NMSSM+VL/5plets`	
NMSSM with **10**'s	`NMSSM+VL/10plets`	
NMSSM with **5**'s & **10**'s	`NMSSM+VL/10plets`	
NMSSM with **5**'s and RpV	`NMSSM+VL/5plets+RpV`	
Broken MRSSM	`brokenMRSSM`	
$U(1)'$-extended MSSM	`MSSM+U1prime-VL`	
E_6 with extra $U(1)$	`E6MSSMalt`	

⚠$^{(1)}$ conflict with limits from $S \rightarrow jj$

MODEL DETAILS

MODEL FEATURES

- Gauge sector extended by $U(1)_X$
- Tree-level Higgs mass enhancement (non-decoupling D-terms)
- CP-odd scalar acts as 750 GeV resonance
- Can potentially accommodate broad resonance

Model details

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SF	Gen.	$(\mathcal{G}_{\mathrm{SM}}, U(1)_X)$
$\hat{\nu}$	3	$(\mathbf{1}, \mathbf{1}, 0, -\frac{1}{2})$
$\hat{U}$	3	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}, -\frac{1}{2})$
$\hat{\hat{U}}$	3	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{2}{3}, \frac{1}{2})$
$\hat{E}$	3	$(\mathbf{1}, \mathbf{1}, 1, \frac{1}{2})$
$\hat{\hat{E}}$	3	$(\mathbf{1}, \mathbf{1}, -1, -\frac{1}{2})$
$\hat{\eta}$	1	$(\mathbf{1}, \mathbf{1}, 0, -1)$
$\hat{\hat{\eta}}$	1	$(\mathbf{1}, \mathbf{1}, 0, 1)$
$\hat{S}$	1	$(\mathbf{1}, \mathbf{1}, 0, 0)$

$$
\begin{aligned}
W = -W_{\mathrm{Yuk}} &+ Y_\nu\, \hat{\nu}\, \hat{l}\, \hat{H}_u + \hat{S}(\lambda_e\, \hat{E}\, \hat{\hat{E}} + \lambda_u\, \hat{U}\, \hat{\hat{U}}) \\
&+ Y_x\, \hat{\nu}\, \hat{\hat{\eta}}\, \hat{\nu} + (\mu + \lambda \hat{S})\, \hat{H}_u\, \hat{H}_d + \hat{S}(\xi + \lambda_X\, \hat{\eta}\, \hat{\hat{\eta}}) \\
&+ M_S\, \hat{S}\, \hat{S} + \frac{1}{3}\kappa\, \hat{S}\, \hat{S}\, \hat{S} + \tilde{M}_E \hat{e} \hat{\hat{E}} + \tilde{M}_U \hat{u} \hat{\hat{U}} \\
&+ M_e\, \hat{E}\, \hat{\hat{E}} + M_u\, \hat{U}\, \hat{\hat{U}} + Y'_e\, \hat{E}\, \hat{l}\, \hat{H}_d + Y'_u\, \hat{U}\, \hat{q}\, \hat{H}_u
\end{aligned}
$$

[R. M. Capdevilla, A. Delgado, and A. Martin 1509.02472]

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\end{aligned}
$$

[R. M. Capdevilla, A. Delgado, and A. Martin 1509.02472]

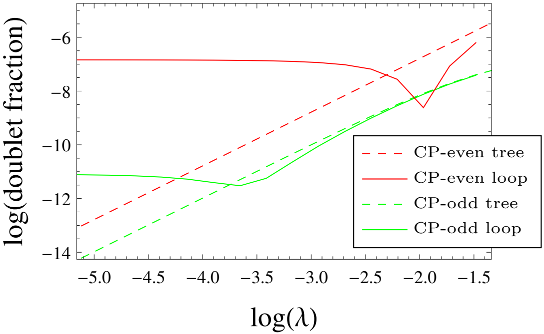
SHORT ANALYSIS INCLUDES:

- Full tree-level mass spectrum
- RGEs and gauge kinetic mixing
- Two-loop Higgs mass corrections
- Two-loop corrections to the 750 GeV scalar
- Diphoton and digluon rates
- Full scalar BRs and singlet-doublet mixing
- Compatibility with SM Higgs measurements
- Width constraints from vacuum stability
- DM relic abundance
- Constraints from rare lepton flavour processes
- Z' mass limits

Resonance decay modes

Illustrate effect of singlet-doublet mixing $\lambda \neq 0$:

- CP-even scalar mainly mixture η & $\bar{\eta}$ with small singlet component
- CP-odd almost purely singlet



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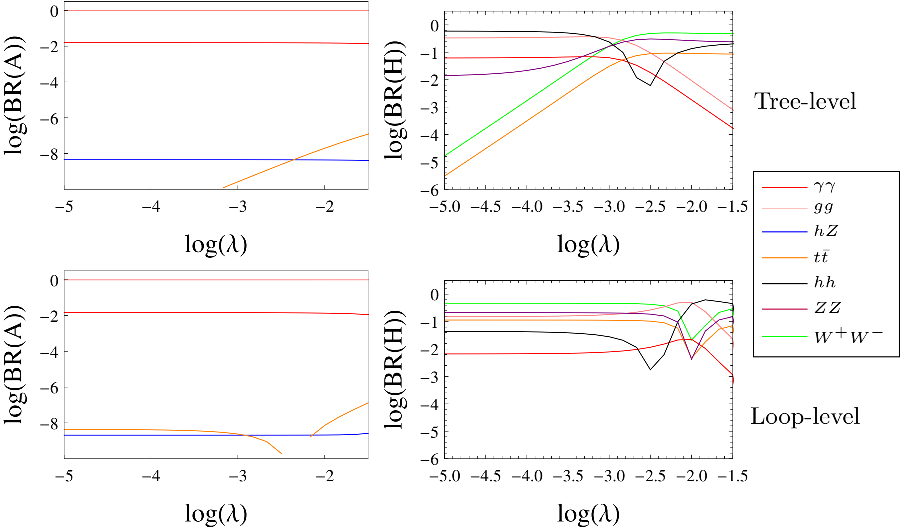

Tree-level

Loop-level

IS A LARGE WIDTH POSSIBLE?

ATLAS results slightly prefer a large width $\sim 40\,\mathrm{GeV}$

Explained with inv. decays to:

- Neutralinos
- Heavy neutrinos
- Sneutrinos

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BR to sneutrinos scales with Y_x

QUESTIONS?

1. How large can Γ_{tot} varying Y_x?
2. How large can Y_x be before the vacuum becomes unstable?

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- Sneutrinos

IN THIS MODEL

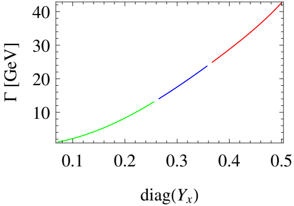
Small sneutrino masses and splitting between Re & Im can be achieved

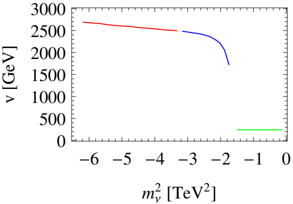
BR to sneutrinos scales with Y_x

QUESTIONS?

1. How large can Γ_{tot} varying Y_x?
2. How large can Y_x be before the vacuum becomes unstable?

Using `Vevacious`:





SUMMARY

`SARAH` framework allows easy analysis of complete models

Reduces necessity to make (extreme) simplifying assumptions

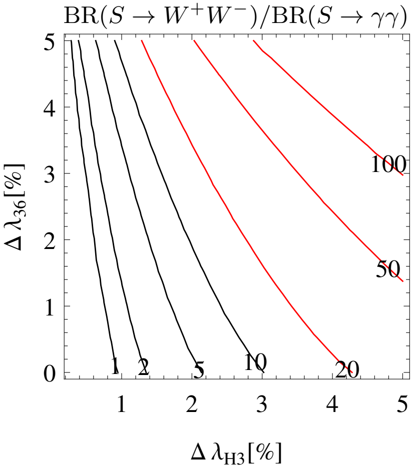
Introduced perturbative model where large width is feasible

Backup Slides

Tree-level vs. one-loop

Caution

Tree-level enforced relations (w/o symmetry arguments) **do not** hold at the loop-level



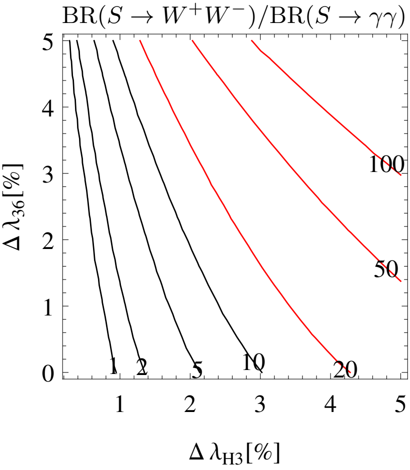
Tree-level vs. one-loop

Caution

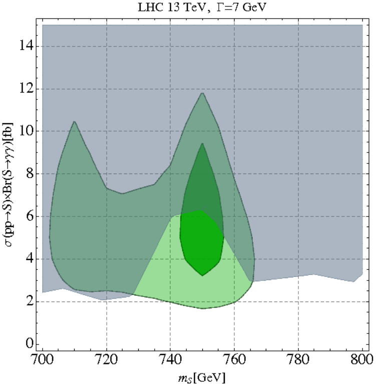
Tree-level enforced relations (w/o symmetry arguments) **do not** hold at the loop-level

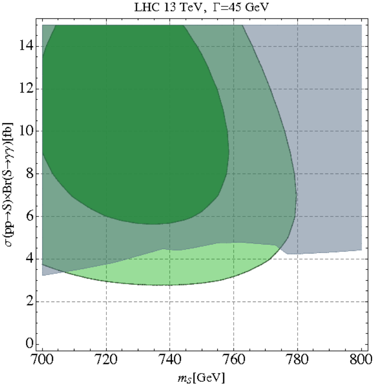
Decay mode	$\Gamma_{XX}/\Gamma_{\gamma\gamma}$
$e^+e^- + \mu^+\mu^-$	0.6
$\tau^+\tau^-$	6
$Z\gamma$	6
ZZ	6
Zh	10
hh	20
W^+W^-	20
$t\bar{t}$	300
$b\bar{b}$	500
jj	1300
inv.	400

[R. Franceschini et al 1512.04933]



Constraints from 8 TeV run





[Falkowski et al. 1512.05777]

PARAMETER VALUES

Mixing and decay width plots:

$$m_{\text{SUSY}} = 1.5 \text{ TeV}\,, M_\lambda = 1 \text{ TeV}\,, \tan\beta = 20\,, \tan\beta_x = 1\,, g_X = 0.5\,, M_{Z'} = 3 \text{ TeV},$$
$$\mu = 1 \text{ TeV}\,, B_\mu = (1 \text{ TeV})^2\,, v_S = 0.5 \text{ TeV}\,, M_S = -0.1 \text{ TeV}\,, B_S = 3.895 \text{ TeV}^2,$$
$$\lambda_X = -0.2\,, A_X = 1 \text{ TeV}\,, \lambda_E = \lambda_U = 1\,, M_E = 0.4 \text{ TeV}\,, M_U = 1 \text{ TeV}, m_{\bar\eta} = 2 \text{ TeV}\,.$$

For vacuum stability:

$$m_{\text{SUSY}} = 2.5 \text{ TeV}\,, \tan\beta = 10\,, \tan\beta_x = 1\,, g_X = 0.5\,, M_{Z'} = 2.5 \text{ TeV}, m_{\bar\eta} = 1 \text{ TeV},$$
$$v_S = 0.5 \text{ TeV}\,, B_S = 755000 \text{ GeV}^2\,, \lambda_X = -0.4\,, A_X = 0.4 \text{ TeV}.$$