The di-photon Excess in a Perturbative SUSY Model

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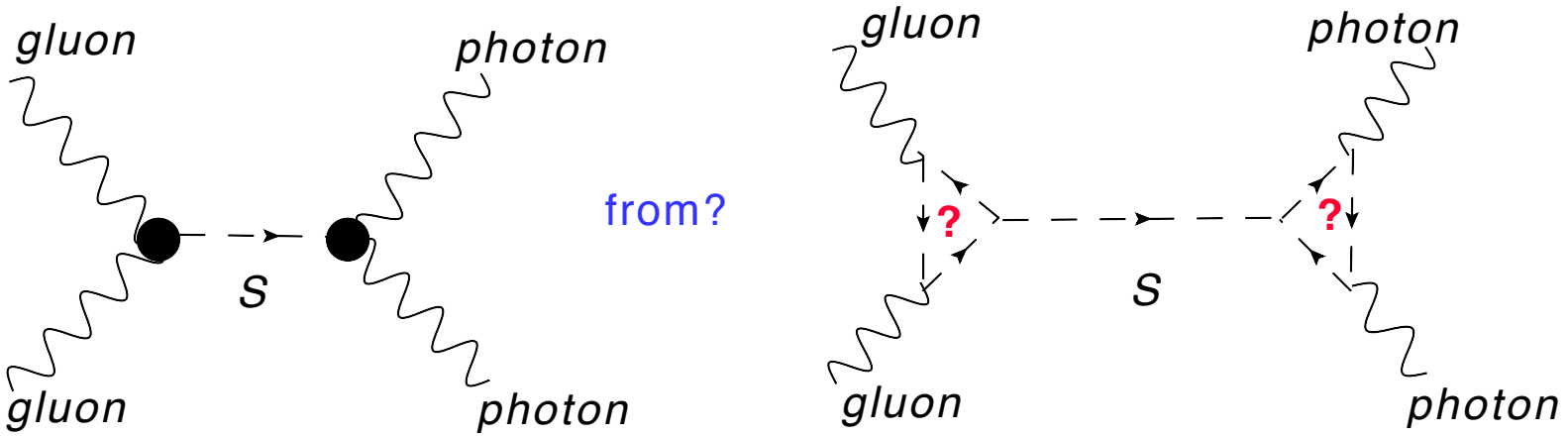
Introduction

The signal

- ATLAS and CMS reported in December 2015 a possible excess in the di-photon channel around 750 GeV.
- The simplest explanation: a statistical fluctuation
- The next to simplest is a spin-0 particle decaying to two photons
- A large width: two unresolved picks? scalar + pseudo-scalar give very close double peaks.
- We stick here with narrow width and a cross-section $\mathcal{O}(\text{few fb})$

How to generate such an excess?



1. Many states? large couplings?
2. light (at most in the TeV range): protection of their mass scale (other hierarchy problems? other μ-term problems?)
3. How do these states affect the gauge couplings running?

Our goal

We want to see if our model can fit the signal. We require that:

1. it satisfies all the experimental constraints
2. it is supersymmetric (required for addressing the hierarchy problem)
3. it remains perturbative up to the GUT scale
4. it does not contain ad-hoc fields motivated only by the excess

- A big part of this work is on models with Dirac gauginos independent from the 750 GeV signal.
- As long as it is a non-confirmed signal, it is of mainly developing models and tools for performing such studies.

SUSY breaking: Dirac vs Majorana gauginos

- SUSY is a symmetry of the UV theory. It is assumed to be softly broken.
- Visible sector: MSSM + additional states to give Dirac masses for the gauginos and to restore unification.
- Dirac gaugino masses preserve R-symmetry
- Dirac gauginos for di-photon excess also proposed by (Carpenter, Colburn, and Goodman) and (Cohen, Kribs, A.Nelson, Ostdiek)

MDGSSM

Dirac gauginos partners

- Dirac masses combine the gauginos $\tilde{B}$, $\tilde{W}$ and $\tilde{g}$ with fermions χ_S, χ_T, χ_O in adjoint representations.
- Fermions χ_S, χ_T, χ_O part of chiral supermultiplets $\mathbf{S}$, $\mathbf{T}^i$ and $\mathbf{O}^a$ in adjoint representations.
- Adjoint scalar S (sBino) in $\mathbf{S}$ provides candidates for the 750 GeV resonance.
- Dirac masses (ex: bino):

$$\mathcal{L} \supset \int d^2\theta \sqrt{2}\theta^\alpha m_{1D} \mathrm{tr}\, \mathbf{S} W_Y \ ,$$

- leads to new trilinears $\mathcal{L} \supset -\sqrt{2} g_Y m_{1D} (S + S^*) \sum_j Y_j \varphi_j^\dagger \varphi_j$

MDGSSM: Recovering unification

- "MSSM + gauginos Dirac partners+ unification fields = MDGSSM"
- Gluinos Dirac partners make $SU(3)$ coupling run stronger: no more color particles otherwise reach a Landau pole.
- Good perturbative gauge coupling unification at two-loop $\longrightarrow$ $(SU(3))^3$:

This requires new states

- $2 \times (\mathbf{1}, \mathbf{1}, \pm 1)$: two pairs of right-handed electron-like fields, $\hat{\mathbf{E}}'_{1,2}$ and $\hat{\mathbf{E}}_{1,2}$
- $(\mathbf{1}, \mathbf{2}, \pm 1/2)$: two Higgs-like doublets $\mathbf{R}_u$ and $\mathbf{R}_d$

MDGSSM

Names		Spin 0	Spin 1/2	Spin 1	$(SU(3), SU(2), U(1)_Y)$
Quarks	$\mathbf{Q}$	$\tilde{Q} = (\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)		$(\mathbf{3}, \mathbf{2}, 1/6)$
	$\mathbf{U^c}$	$\tilde{U}_L^c$	U_L^c		$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$
($\times$3 families)	$\mathbf{D^c}$	$\tilde{D}_L^c$	D_L^c		$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$
Leptons	$\mathbf{L}$	$(\tilde{\nu}_{eL}, \tilde{e}_L)$	(ν_{eL}, e_L)		$(\mathbf{1}, \mathbf{2}, -1/2)$
($\times$3 families)	$\mathbf{E^c}$	$\tilde{E}^c$	E^c		$(\mathbf{1}, \mathbf{1}, 1)$
Higgs	$\mathbf{H_u}$	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$		$(\mathbf{1}, \mathbf{2}, 1/2)$
	$\mathbf{H_d}$	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$		$(\mathbf{1}, \mathbf{2}, -1/2)$
Gluons	$\mathbf{W_{3ff}}$		$\lambda_{3\alpha}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
W	$\mathbf{W_{2ff}}$		$\lambda_{2\alpha}$	$W^{\pm}, W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
B	$\mathbf{W_{1ff}}$		$\lambda_{1\alpha}$	B	$(\mathbf{1}, \mathbf{1}, 0)$
DG-octet	$\mathbf{O}$	O	χ_g		$(\mathbf{8}, \mathbf{1}, 0)$
DG-triplet	$\mathbf{T}$	$\{T^0, T^{\pm}\}$	$\{\chi_T^0, \chi_T^{\pm}\}$		$(\mathbf{1}, \mathbf{3}, 0)$
DG-singlet	$\mathbf{S}$	S	χ_S		$(\mathbf{1}, \mathbf{1}, 0)$
Higgs-like Leptons	$\mathbf{R_u}$	R_u	$\tilde{R}_u$		$(\mathbf{1}, \mathbf{2}, -1/2)$
	$\mathbf{R_d}$	R_d	$\tilde{R}_d$		$(\mathbf{1}, \mathbf{2}, 1/2)$
Fake electrons	$\hat{\mathbf{E}}(\times 2)$	$\hat{E}$	$\hat{\tilde{E}}$		$(\mathbf{1}, \mathbf{1}, 1)$
	$\hat{\mathbf{E}}'(\times 2)$	$\hat{E}'$	$\hat{\tilde{E}}'$		$(\mathbf{1}, \mathbf{1}, -1)$

Chiral and gauge multiplet fields in the model.

MDGSSM - Lagrangian

- Adjoints-Higgs couplings (S- Higgs mixing/ ρ-parameter)

$$W \supset (\mu + \lambda_S \mathbf{S})\mathbf{H_d}\mathbf{H_u} + \sqrt{2}\lambda_T \mathbf{H_d}\mathbf{T}\mathbf{H_u}$$

- S-unification fields couplings (for S- di-photon decay)

$$W \supset (\mu_R + \lambda_{SR}\mathbf{S})\mathbf{R_u}\mathbf{R_d} + (\mu_{\hat{E}\,ij} + \lambda_{SE\,ij}\mathbf{S})\hat{\mathbf{E}}_i\hat{\mathbf{E}}'_j,$$

- Trilinears (for S- di-photon decay/ gluon-S production)

$$-\Delta\mathcal{L}^{\text{scalar soft}} \supset [T^{ij}_{SE} S \hat{E}_i \hat{E}'_j + T_{SR} S R_d R_u + T_{SO} S \mathrm{tr}(O^2) + h.c.] \ .$$

- R-symmetry forbids simultaneous existence of λ_{SE} and T_{SE} terms

MDGSSM - Lagrangian: R-symmetry violating terms

$$W \supset \frac{\hat{M}_1}{2}\mathbf{S}^2 + \hat{M}_2 \mathrm{tr}(\mathbf{TT}) + \hat{M}_3 \mathrm{tr}(\mathbf{OO}) + \lambda_{SO}\mathbf{S}\mathrm{tr}(\mathbf{OO})$$

$$\xrightarrow[\mathrm{R-symmetry}]{} 0$$

- For R-symmetry: these terms vanish.
- Allow this violation of R: λ_{SO} can help for 750 GeV signal.

We are assuming breaking R-symmetry in the Higgs sector ($B\mu$ in combination with the superpotential terms $\mu, \lambda_S, \lambda_T$).

MDGSSM - Lagrangian; soft-terms I

- Dirac gaugino masses:

$$\int d^2\theta\sqrt{2}\theta^\alpha \left[m_{D1}\mathbf{S}W_{Y\,\alpha} + 2m_{D2}\mathrm{tr}(\mathbf{T}W_{2\,\alpha}) + 2m_{D3}\mathrm{tr}(\mathbf{O}W_{3\,\alpha}) \right].$$

- soft terms associated with the adjoint scalars

$$m_S^2|S|^2 + \frac{1}{2}B_S(S^2 + h.c.) + 2m_T^2\mathrm{tr}(T^\dagger T) + (B_T\mathrm{tr}(TT) + h.c.)$$
$$+ 2m_O^2\mathrm{tr}(O^\dagger O) + (B_O\mathrm{tr}(OO) + h.c.)$$
$$+ \left[T_{SO}S\mathrm{tr}(O^2) + h.c. \right]$$

The term on the last line has generally been neglected, but will play an important role ihere.

MDGSSM - Lagrangian; soft-terms II

- soft terms involving the new vector-like leptons:

$$
\begin{aligned}
& m^2_{R_u}|R_u|^2 + m^2_{R_d}|R_d|^2 + [B_R R_d R_u + h.c.] \\
& + \hat{E}_i (m^2_{\hat{E}})^i_j \hat{E}^j + \hat{E}'^i (m^2_{\hat{E}'})^j_i \hat{E}'_j + [B^{ij}_{\hat{E}} \hat{E}_i \hat{E}'_j + h.c.] \\
& + [T^{ij}_{SE} S \hat{E}_i \hat{E}'_j + T_{SR} S R_d R_u + h.c.] \ .
\end{aligned}
$$

R-symmetry conserving model: No T_{SE} (respectively T_{SR}) with non-vanishing λ_{SE} (respectively λ_{SR}).

MDGSSM - Lagrangian: relevant parameters

Most relevant parameters:

1. **Higgs and singlet masses and mixing**: $m_{1D}, m_S, B_S, \tan\beta, \mu, \lambda_S$ and λ_T.
2. **Singlet decay/production amplitude to gg**: T_{SO}, m_O, B_O, $m_{\tilde{q}}$, where $m_{\tilde{q}}$ is the soft masses for right (or left)-handed squarks.
3. **Singlet decay amplitude to $\gamma\gamma$**: $T_{SE}, T_{SR}, \lambda_{SR}, \lambda_{SE}$ supplemented with soft masses and B terms for the fields $\hat{E}, \hat{E}', R_u$ and R_d.

- Landau poles $\rightarrow$ λ_{SE} and λ_{SR} constrained to be below 0.7.
- $\hat{E}, \hat{E}', R_u$ and R_d no charge-breaking vev $\rightarrow$ trilinears constrained.

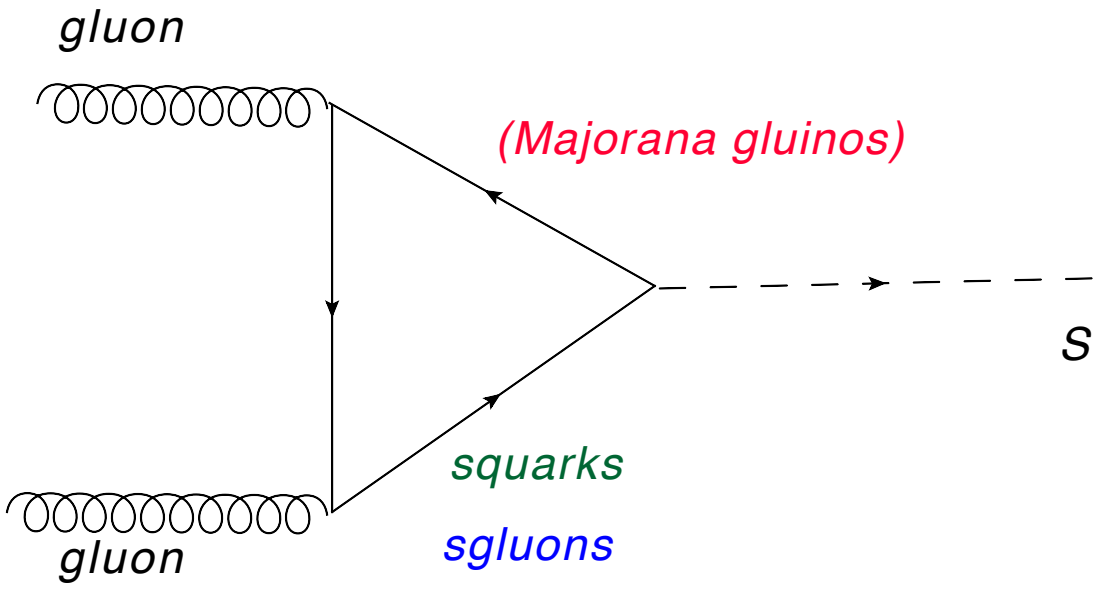
Production/Decay

MDGSSM for di-photon excess?

It contains all the necessary ingredients

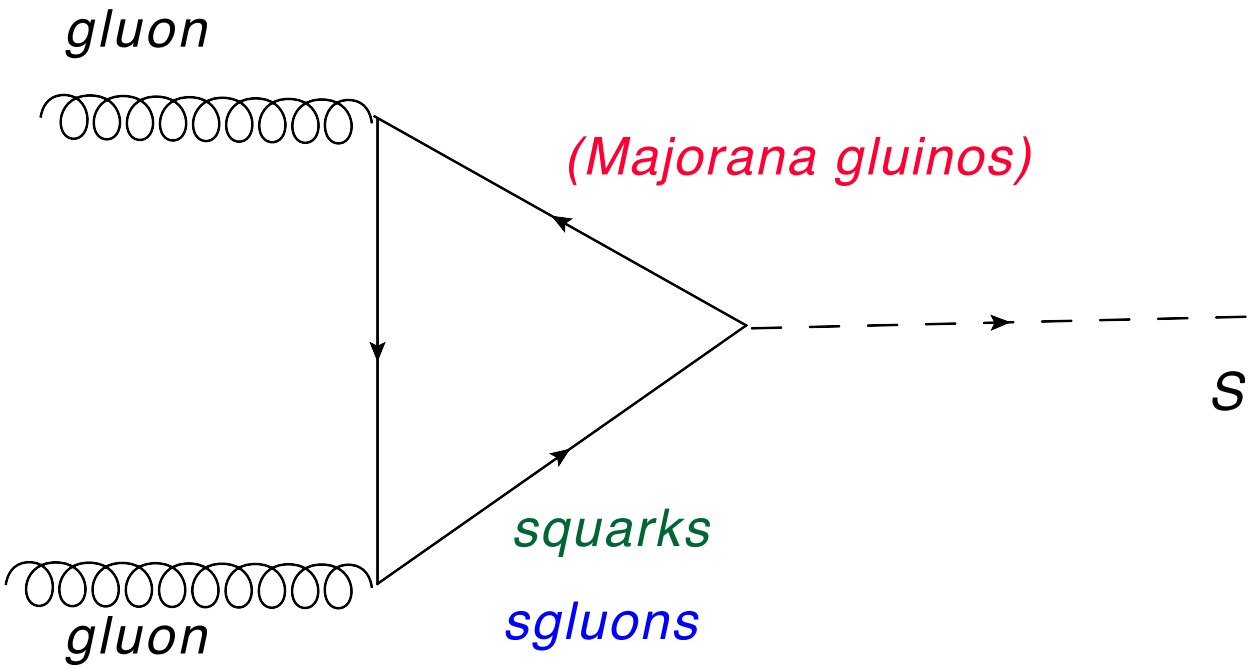
- The scalar/pseudo-scalar S in $\mathbf{S}$ candidates for a narrow 750 GeV resonance.
- The unification supermultiplets $\mathbf{R}_u, \mathbf{R}_d$ and $\hat{\mathbf{E}}_{1,2}$, $\hat{\mathbf{E}}'_{1,2}$ $\rightarrow$ loop decays of S in di-photons.
- Dirac masses provide additional trilinear couplings between S and any hypercharged scalars, proportional to m_{1D} (including squarks).
- The adjoint scalar octet O $\rightarrow$ increases the coupling of S to gluons.

Production



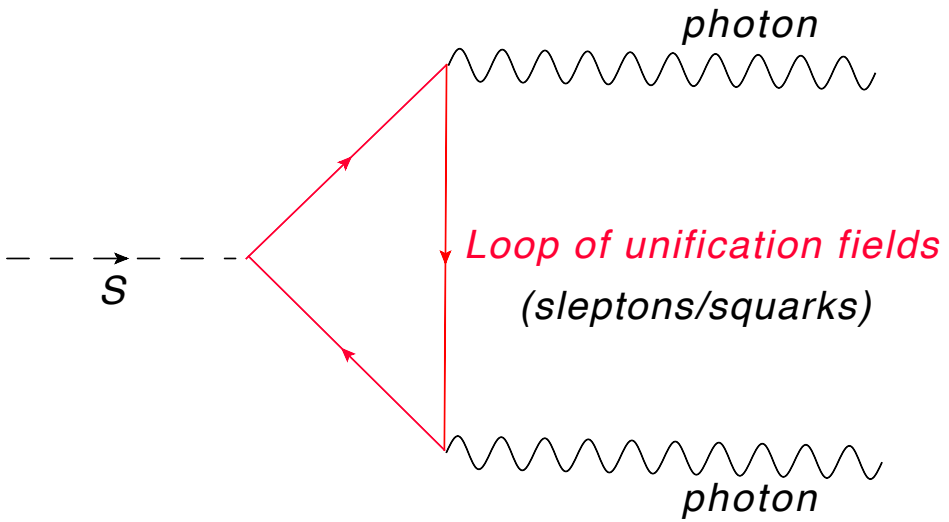
- sgluons participate if there is a coupling T_{SO}
- squarks from D-term: no left-right degeneracy
- gluinos need to be Majorana to contribute

Production



- for large m_{1D} (D-term large) squarks enhance the production.
- for small m_{1D}, scalar octets need to be light.
- R-symmetry violating $\lambda_{SO}\mathbf{S}\mathrm{tr}(\mathbf{OO}) \rightarrow$ enhanced production.

Decay to di-photons



- Simultaneous presence of T_{SE} and $\lambda_{SE} \rightarrow$ enhanced photons loop coupling

Production/Decay - summary

Production (R-violating couplings in blue)

- $\tilde{q}$ by $g_Y m_{1D}$
- octet scalar by T_{SO} and/or $v_s \lambda_{SO}^2$
- gluinos with Majorana masses and λ_{SO}

Decay

- D-term trilinears: squarks, leptons, Higgs, higgsinos, unification fields
- SUSY breaking trilinears: unification fields, triplets
- Superpotential Yukawas: unification fields, Higgsinos
- Majorana Winos

Constraints

Check list for reproducing di-photon

- A scalar singlet $\rightarrow$ dangerous mixing with SM Higgs
- Large $m_{1D} \rightarrow$ The 750 GeV scalar mass ($m_{SR}^2 \equiv m_S^2 + B_S + 4m_{1D}^2$)
- Large trilinears couplings $\rightarrow$ vacuum stability constraints
- Large $\lambda_{SE}, \ldots \rightarrow$ loss of perturbative behaviour.
- Particles participating in the loop have masses close to the resonant 750/2 GeV (especially for scalars) $\rightarrow$ Experimental searches

Mixing between SM Higgs and S

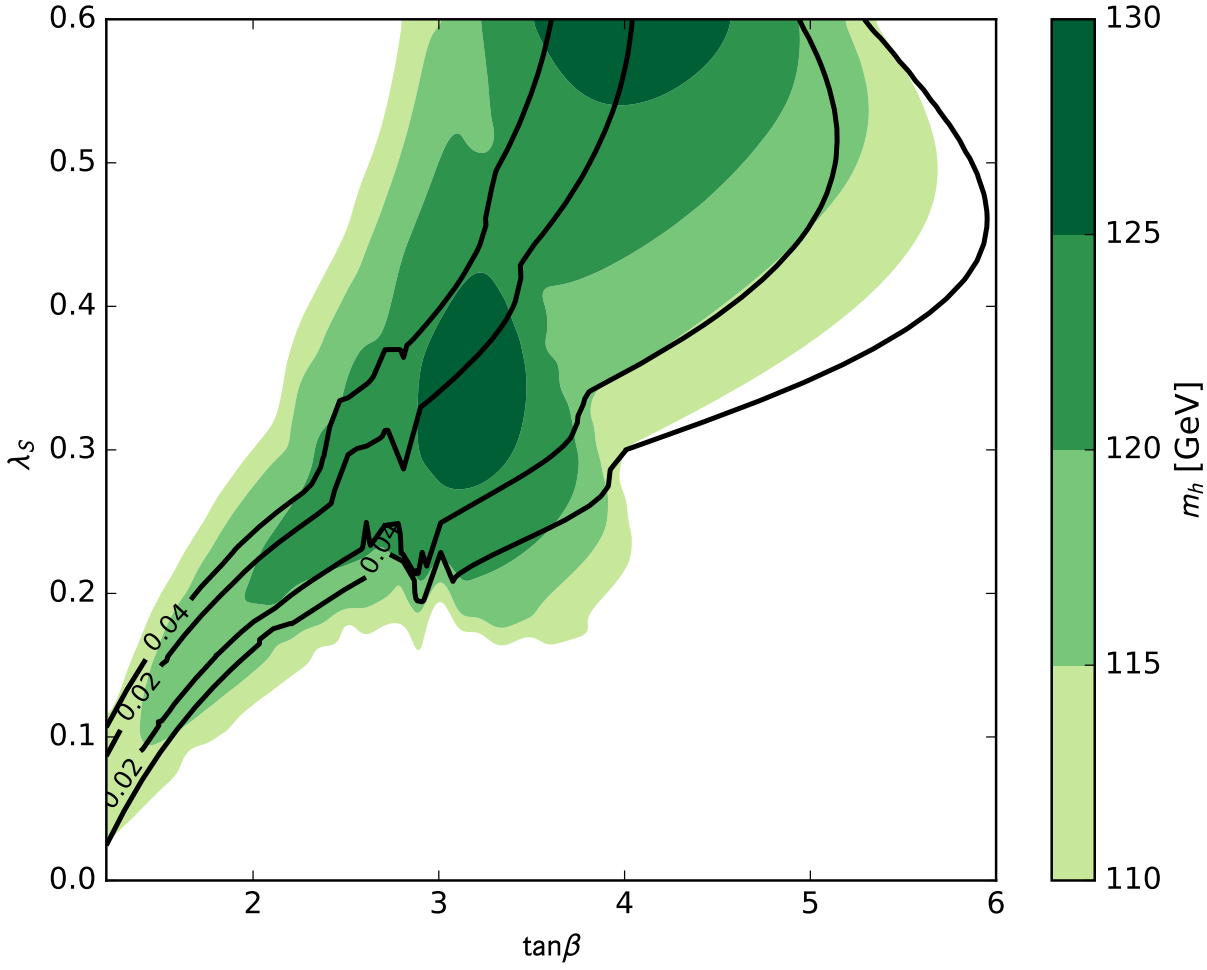
- Tree-level mixing of scalar S with SM Higgs

$$\Delta_{hS} = v[\sqrt{2}\lambda_S \tilde{\mu} - g' m_{1D} c_{2\beta}] \ ,$$

  Also computed at higher orders in perturbation theory.

- Mixing below the percent to avoid modification of the Higgs couplings and change of tree-level decays.
  These may lead to:
  1. Tension with constraints from LHC8
  2. Reduction of the cross-section of S to $\gamma\gamma$

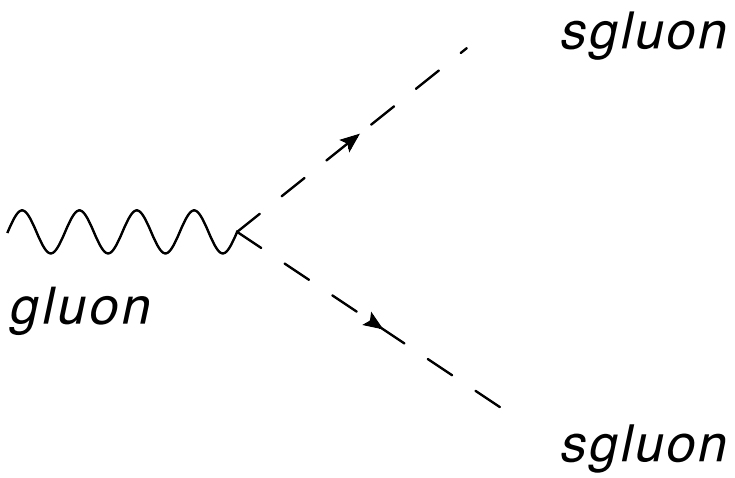
Mixing between S and SM Higgs



Higgs mass and mixing between h and S as a function of λ_S and $\tan\beta$. The black lines represent the 2% and 4% mixing contour lines.

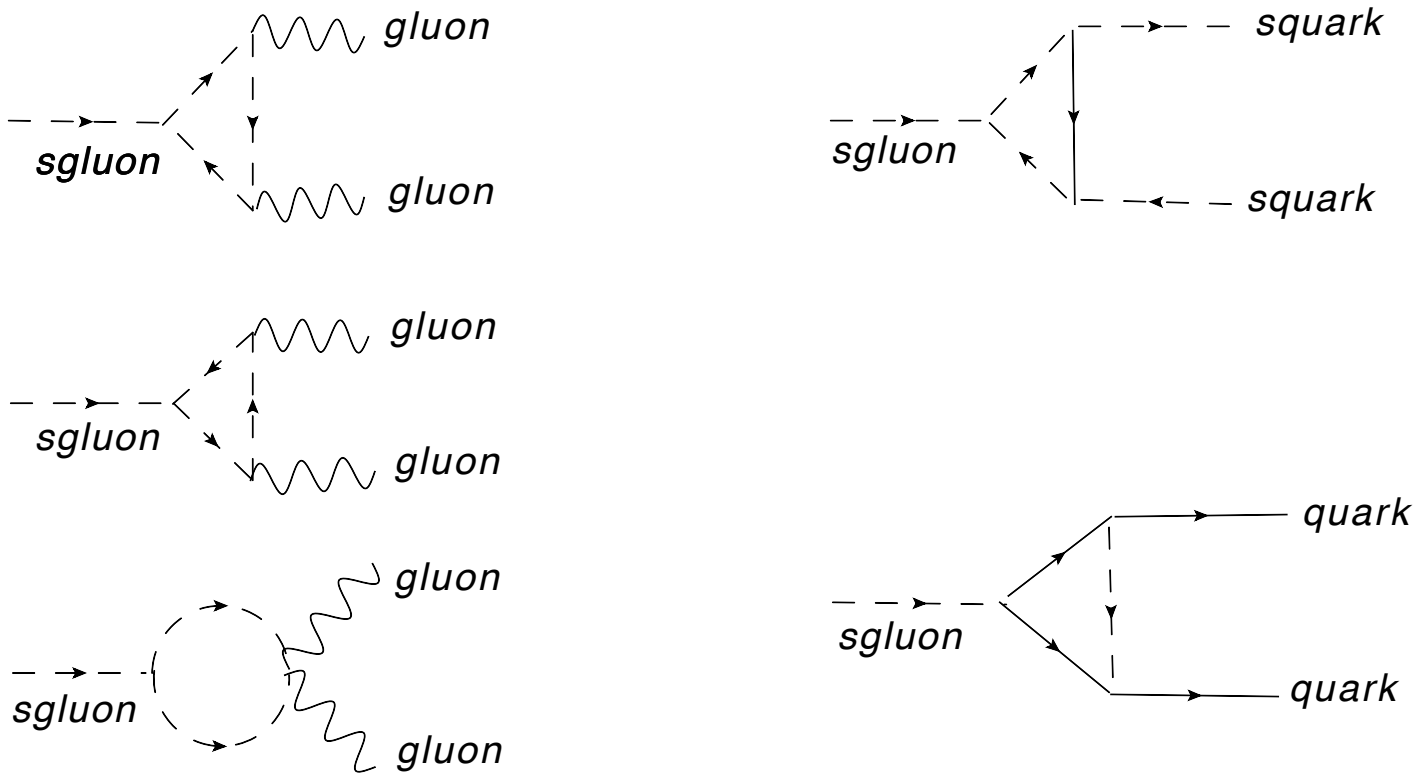
(Pseudo)-Scalar Octet

- **O** $\rightarrow$ scalar octet and pseudo-scalar octet.
- Pair-produced at LHC
- Octets decay to: gluons (squarks mediated) and tops (squarks and gluinos mediated)



Octet production

Octet decays



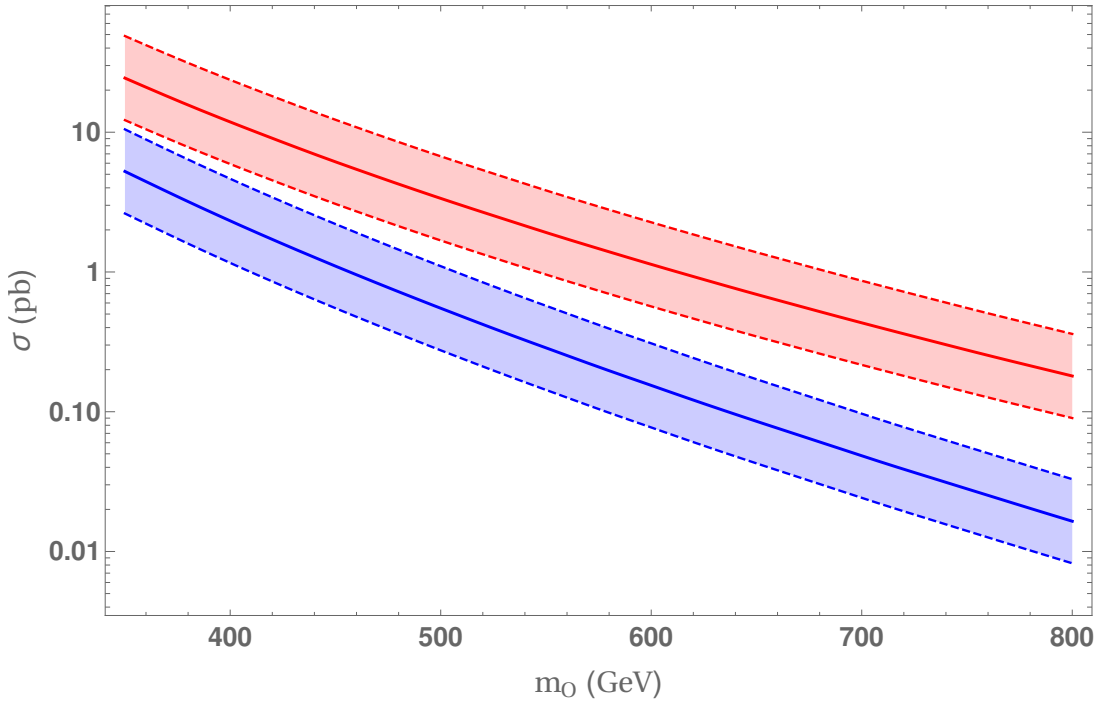
Octet decays at one-loop

(Pseudo)-Scalar Octet

- **O** $\rightarrow$ scalar octet and pseudo-scalar octet.
- Pair-produced at LHC
- They will decay to gluons (squarks mediated) and mainly tops (squarks and gluinos mediated)
- For the scalar, heavy gluinos and TeV squarks the dominant channel is to gluons
- Pseudo-scalar octet $\rightarrow$ no direct coupling to squarks (D-term trilinears only for scalar part): only decay to tops $\rightarrow$ stronger bound.

Four tops channels constraints

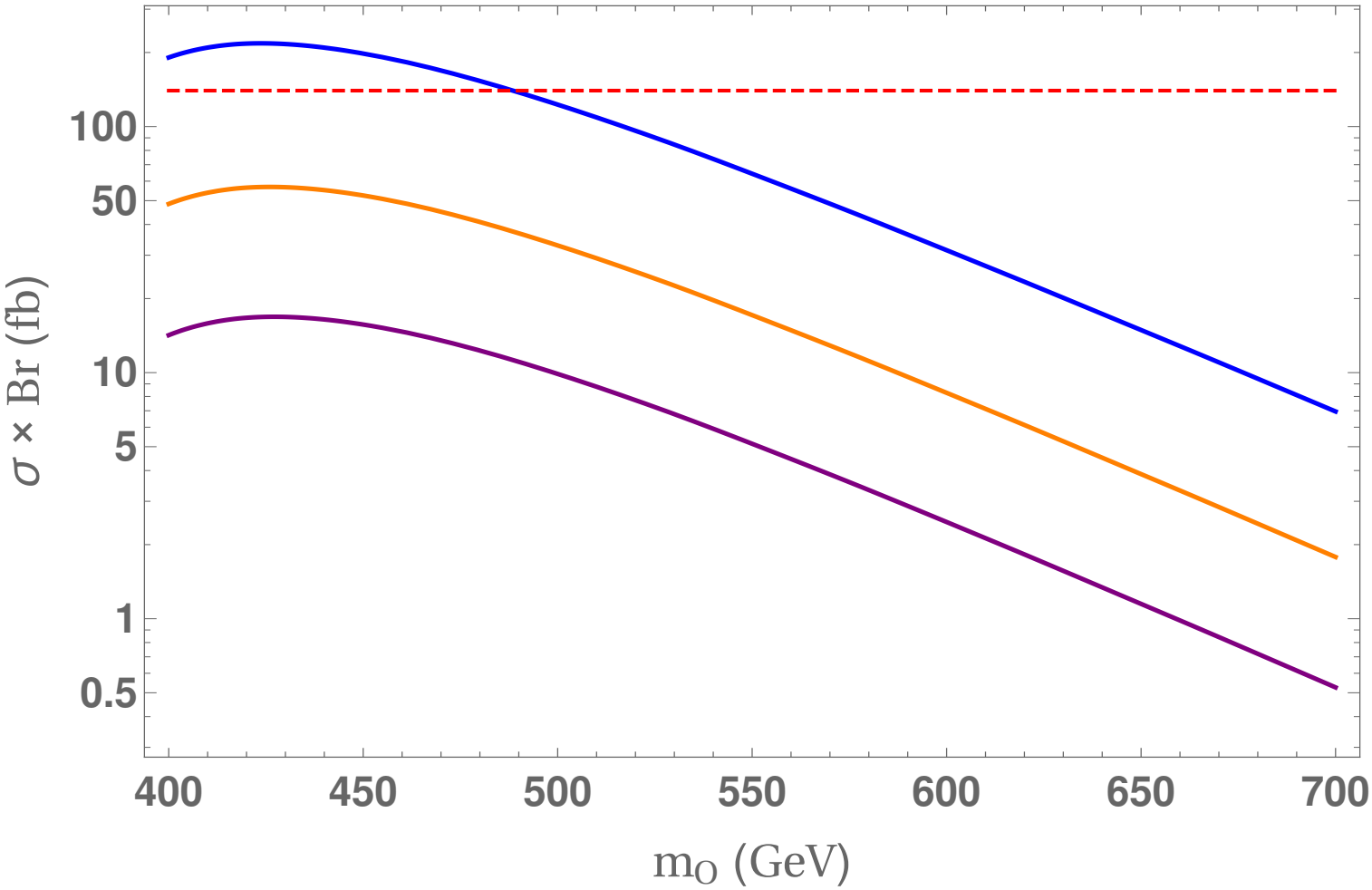
- Biggest constraints from 13 TeV four-tops searches (ATLAS-CONF-2016-013 $\rightarrow$ 140 fb)



Pair production cross-section of octets at tree-level, at 8 TeV (blue, lower curves) and 13 TeV (red, upper curves). The bands indicate a variation of a factor of 2 each way relative to the values obtained in `MadGraph`.

- For the pseudo-scalar octet which can only decay to tops (no CPV couplings) $\rightarrow$ heavier than 880 GeV

Constraints on scalar octet



Four-top production times branching ratio at 13 TeV from scalar colour octets as a function of the octet mass, for gluino masses of 2.5 TeV (upper curve, blue), 3 TeV (middle curve, orange) and 3.5 TeV (lower curve, purple).

Fine-tuning and triplets mass

- One new source is the adjoint triplet scalars T mass

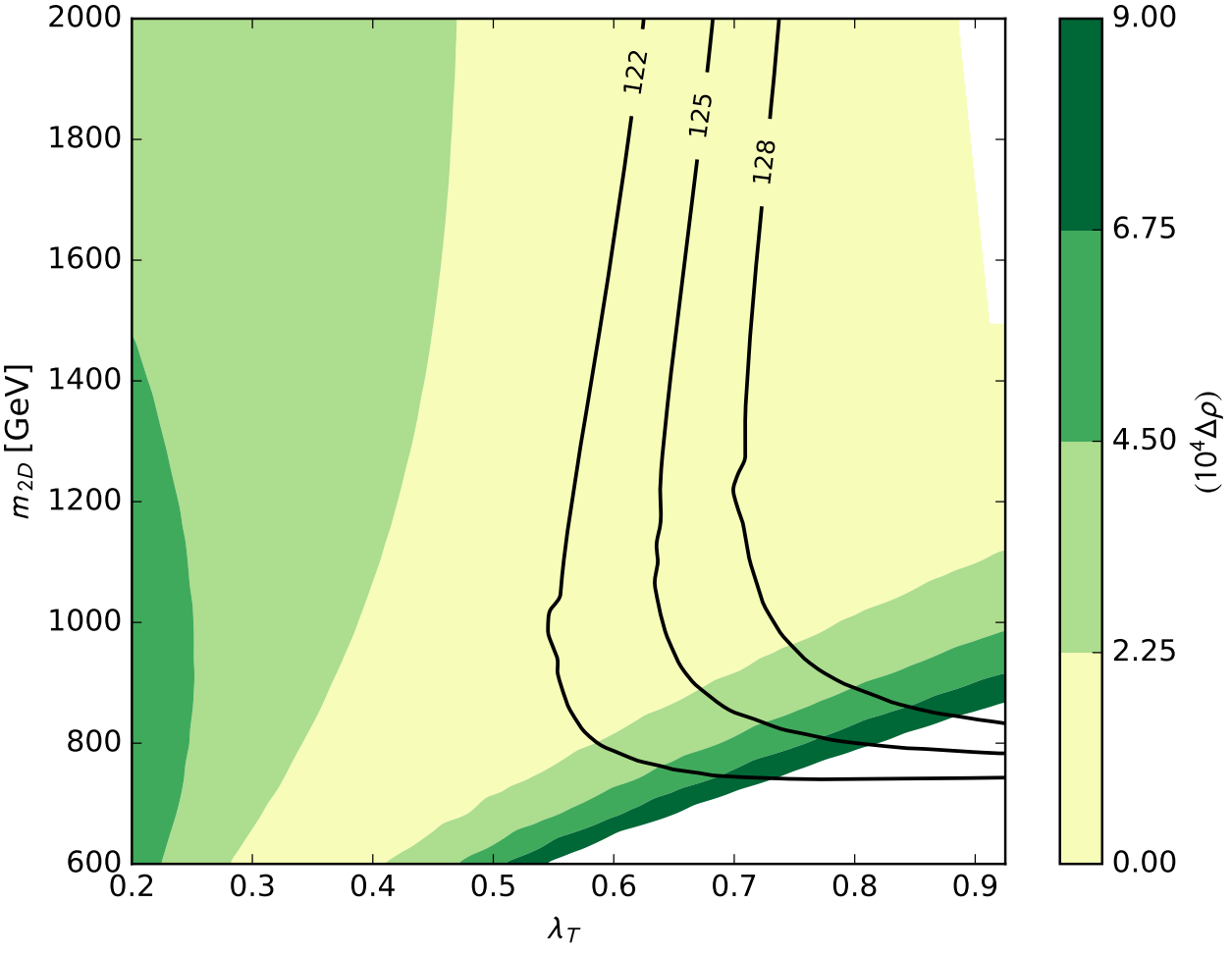
$$\delta m^2_{H_{u,d}} \supset -\frac{1}{16\pi^2}(2\lambda_T^2 m_T^2)\log\left\{\frac{\Lambda}{\mathrm{TeV}}\right\} \ ,$$

- For a 10% tuning

$$m_T \lesssim \frac{1}{\lambda_T} 450 \ \mathrm{GeV} \ .$$

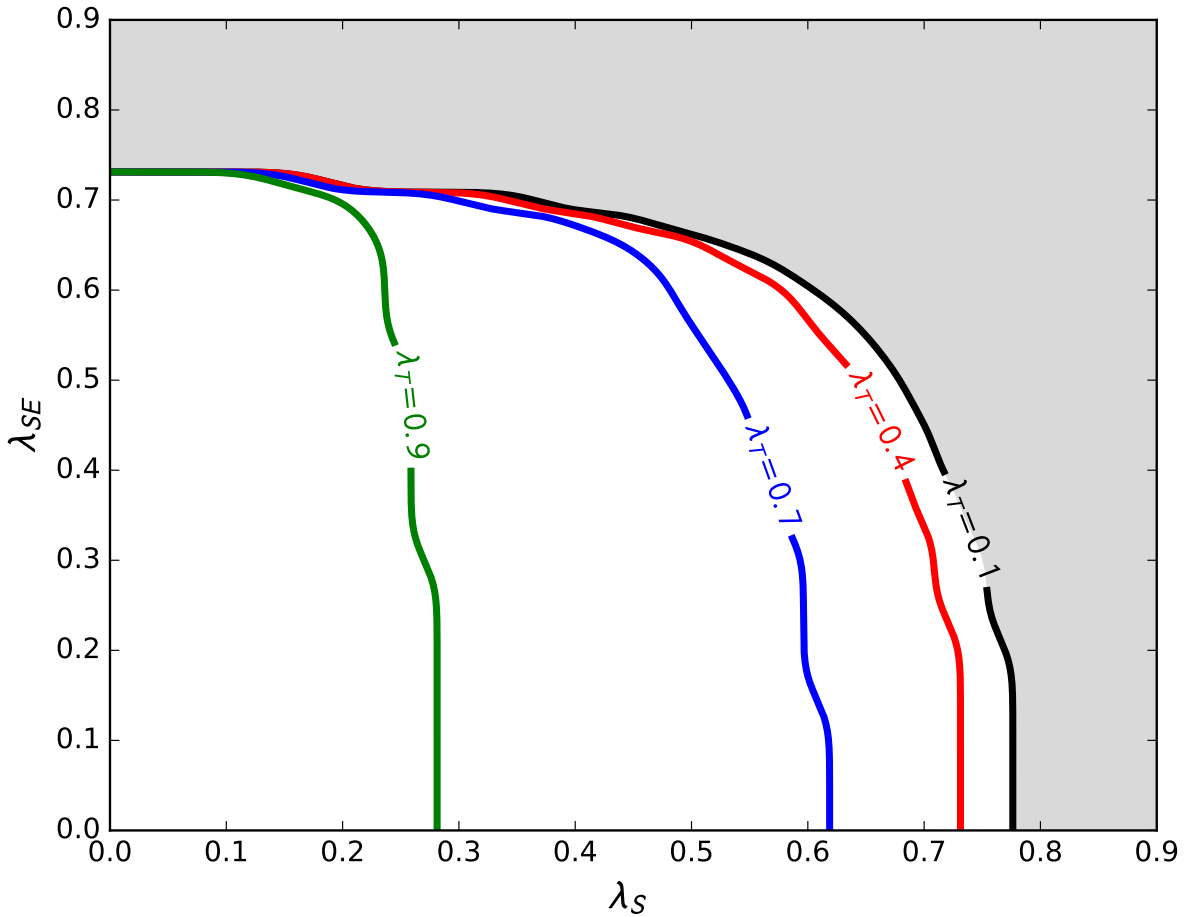
- Careful that light a triplet will contribute to ρ parameter $\Delta\rho_{(\mathrm{triplet})} \sim \frac{4v_T^2}{v^2}$

Electroweak constraint - result



One-loop $10^4(\Delta\rho)$ obtained by varying λ_T and m_{2D}. We have taken $m_T = 500$ GeV.

Constraining the Yukawas



Perturbativity bounds obtained from the requirement that no couplings overtake $\sqrt{4\pi}$ before the GUT scale. We consider $\lambda_{SR} = \lambda_{SE}$ at the SUSY scale. Bounds for (from left to right) $\lambda_T = 0.9, 0.7, 0.4, 0.1$ in the λ_S/λ_{SE} plane, all points above the curves are excluded.

Vaccum stability - Charge breaking vacua

Charge breaking vacua

- Destabilisiation by trilinears: $T_{SE}(S\hat{E}\hat{E}' + h.c.)$
- Stabilisation by quartics $\supset \lambda_{SE}^2|\hat{E}'\hat{E}|^2 + \frac{g'^2}{2}(|\hat{E}|^2 - |\hat{E}'|^2)^2$
- The D-flat direction $|\hat{E}| = |\hat{E}'|$, a lower charge-breaking vacuum exists if

$$\frac{T_{SE}^2}{\lambda_{SE}^2} > 4m_{ER}^2 + m_{SR}^2 + 2\sqrt{2}m_{ER}m_{SR}$$

with $m_{SR}^2 \equiv m_S^2 + B_S + 4m_{1D}^2$ and $m_{ER}^2 \equiv m_{\hat{E}}^2 + B_E + \mu_E^2$.

Vaccum stability - Color breaking vacua

Color breaking vacuua

- Destabilising trilinears $T_{SO}(S\mathrm{tr}(OO) + h.c.)$
- Stabilising quartics $\supset \frac{g_3^2}{2}\left[(O_b^\dagger(T^a)^{bc}O_c)(O_b^\dagger(T_a)^{bc}O_c)\right] + \sqrt{2}g_3 m_{3D}(O+O^\dagger)^a O_b^\dagger(T_a)^{bc}O_c + \ldots$
- This not enough, no quartic in a given $O^a = (O_R, 0, 0, \ldots)$ direction
- For $\tilde{\lambda}_{SO}, \tilde{\lambda}_O \sim \mathcal{O}(0.01) \rightarrow T_{SO} \lesssim 300$ GeV
- In R-violating scenario, $W \supset \lambda_{SO} S\ \mathrm{tr}\, OO$ can help stabilisation.

Summary of the constraints

- Detection scalar octet (sgluon): Pseudo-scalar close to TeV, scalar unconstrained for $m_{3D} \gtrsim 3$ TeV.
- Mixing and Higgs mass: Sub-percent mixing needed (mixing naturally at the percent level)
- Vacuum stability: $T_{SE} \lesssim 1$ TeV, small $T_{SO} \lesssim 300$ GeV (or R-symmetry violation).
- Perturbativity: $\lambda_{SE} \lesssim 0.7$, and large λ_{SE} implies $\lambda_T \lesssim 0.9, \lambda_S \lesssim 0.4$
- Naturalness and $\Delta\rho$: light m_T, relatively heavy m_{2D}

Results

Implementation: state of the art

We use the SPheno-generated code from SARAH (F. Staub), which includes

- full two-loop RGEs
- two-loop masses for H_u, H_d, S, T and one-loop masses for all particles,
- one-loop decay to gluons and photons - *Tree*-level for the rest

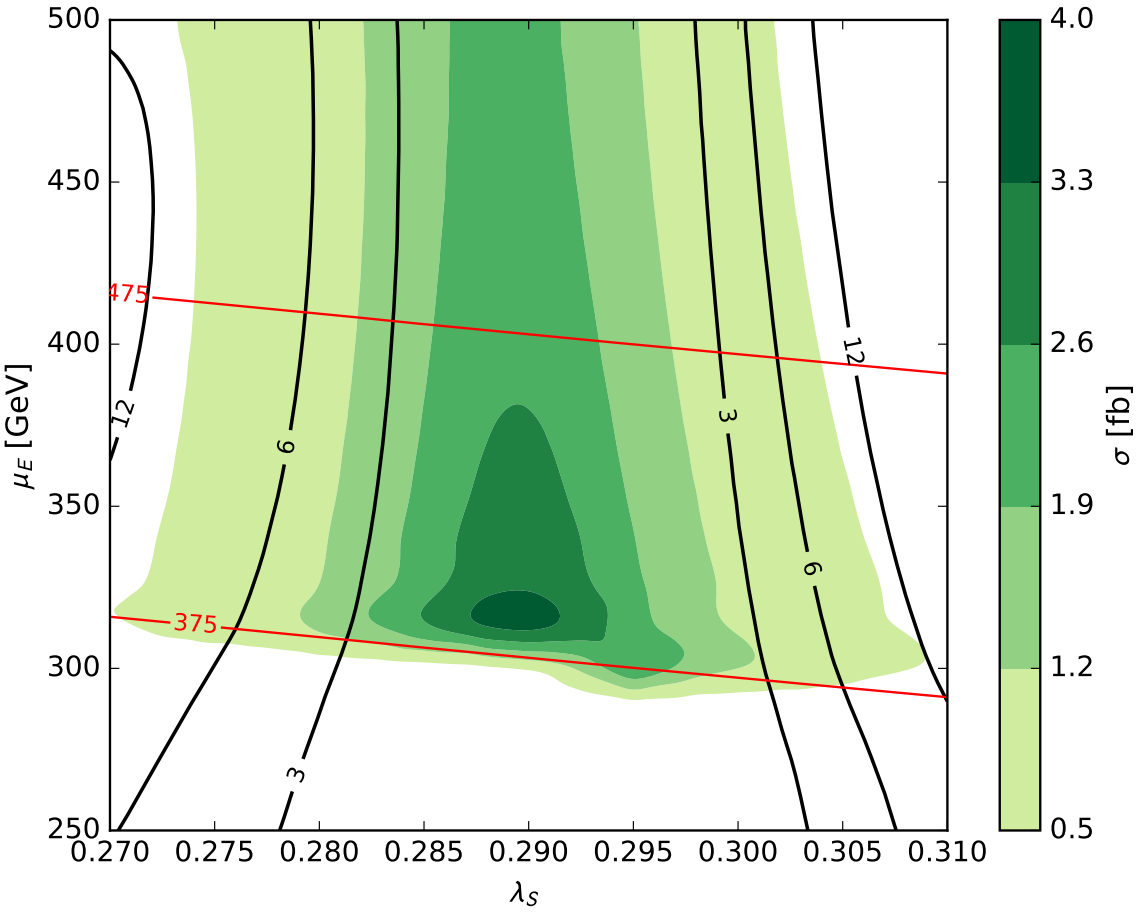
Model parameters

	Parameter	$\mathbf{R_a}$	$\mathbf{R_b}$
Higgs mass	μ	925 GeV	450 GeV
	$\tan\beta$	3	5
	λ_T	0.7	0.85
	$\sqrt{m_T^2}$	500 GeV	1000 GeV
Singlet masses and mixing	m_{1D}	1250 GeV	100 GeV
	$\sqrt{m_S^2}$	500 GeV	775 GeV
	B_S	-2.44^2 TeV^2	-200^2 GeV^2
	λ_S	0.29	0.05
Singlet decay /production amplitude to gg	T_{SO}	200 GeV	300 GeV
	$\sqrt{m_O^2}$	1300 GeV	1025 GeV
	$m_{\tilde{t}_R}$	500 GeV	1200 GeV
Singlet decay amplitude to $\gamma\gamma$	$\lambda_{SR} = \lambda_{SE}$	0.7	0.7
	$m_E^2 = m_{R_{u,d}}^2$	10^2 GeV^2	150^2 GeV^2
	$\mu_E = \mu_{R_{u,d}}/1.4$	325 GeV	65 GeV
	$m_{\tilde{l}R}$	250 GeV	500 GeV
Outputs	Pole mass Higgs	125.5 GeV	124.9 GeV
	Pole mass S_R	750.1 GeV	755.7 GeV
	Pole mass O_I/O_R ($\mathbf{R_a}$ /$\mathbf{R_b}$)	945.5 GeV	390.0 GeV
	Pole mass $\tilde{t}_R$	820.3 GeV	1165.0 GeV
	Pole mass $\tilde{l}_R$	418 GeV	513 GeV
	Pole mass $\tilde{\tilde{E}}$	397 GeV	382 GeV
	$\sigma(S \to \gamma\gamma)$	**3.20 fb**	**3.18 fb**
	$\Delta\rho$	0.97×10^{-4}	3.17×10^{-4}
	v_S	151.4 GeV	643.5 GeV

One example: scenario $\mathbf{R_a}$

- Production: gluon fusion through squark loops (large $m_{1D} \sim 1$ TeV).
- Decay: di-photons through loops of unification fields and sleptons.
- R-symmetry broken only in the Higgs sector (μ, $B\mu$)

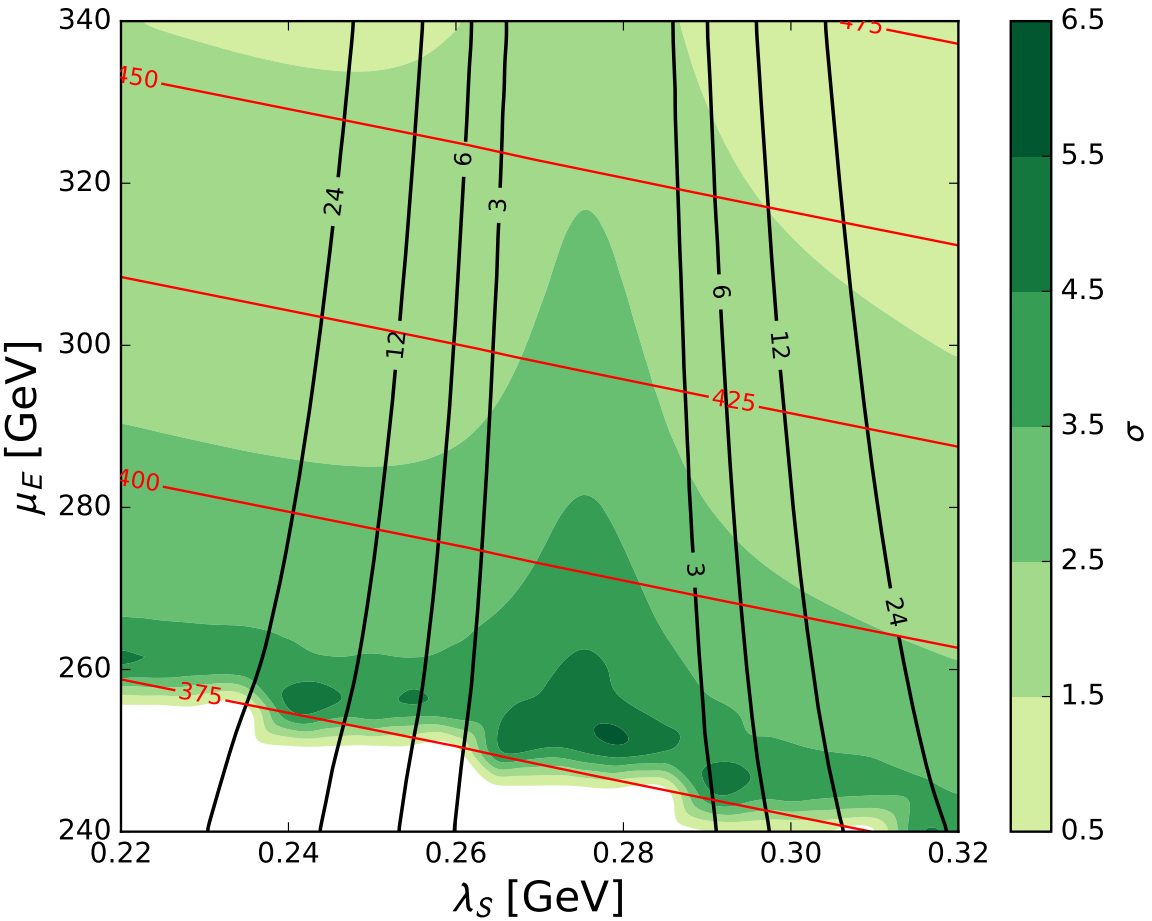
Cross-section



$S \to \gamma\gamma$ cross section in fb as a function of the μ_E and λ_S. The black contour shows the ratio $\frac{\Gamma(S \to ZZ)}{\Gamma(S \to \gamma\gamma)} \lesssim 6$ while the red contours shows the pole mass for the fake leptons.

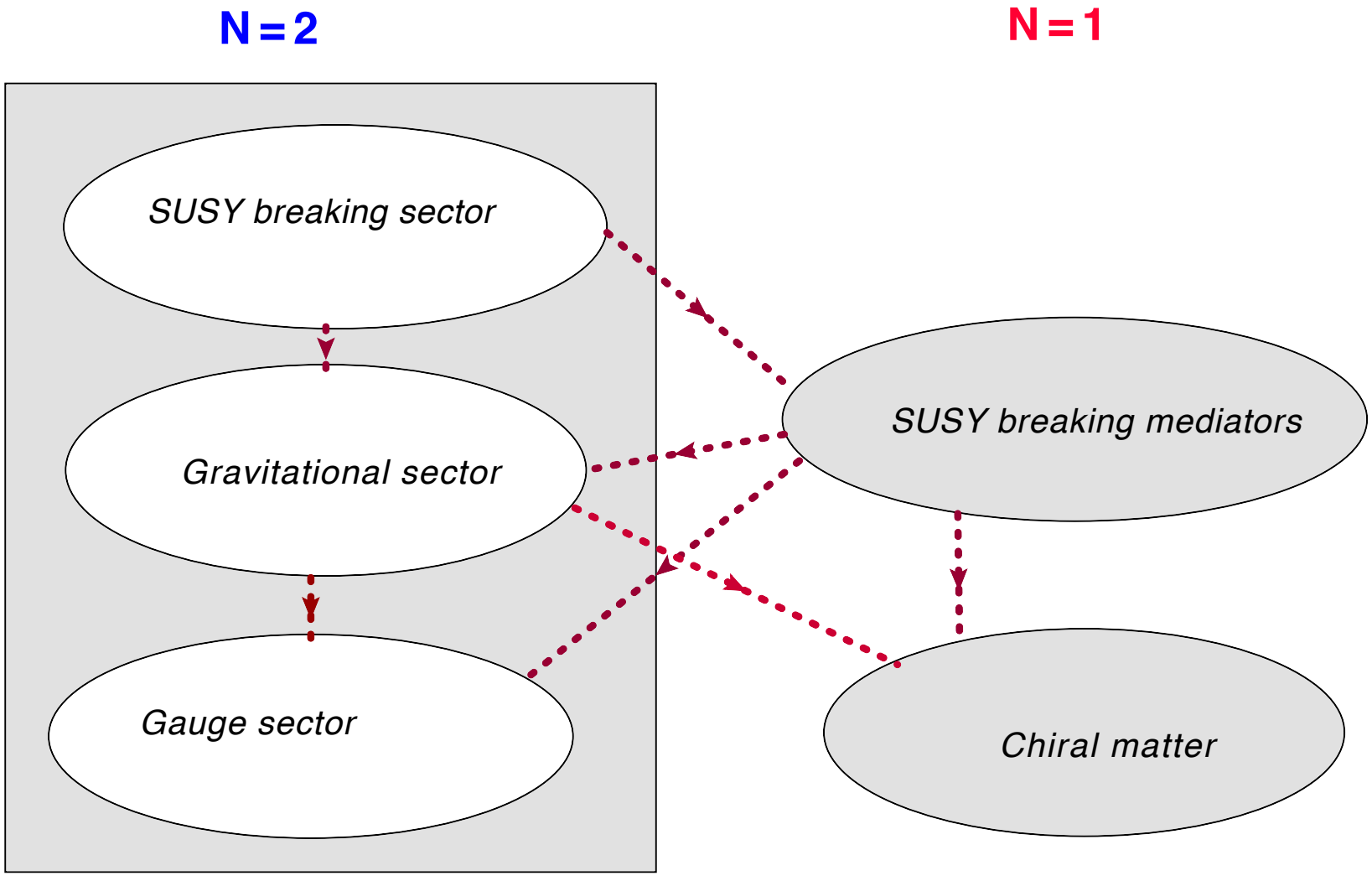
Another scenario - Double peaks

Adding also Majorana masses, both scalar and pseudo-scalar participate.



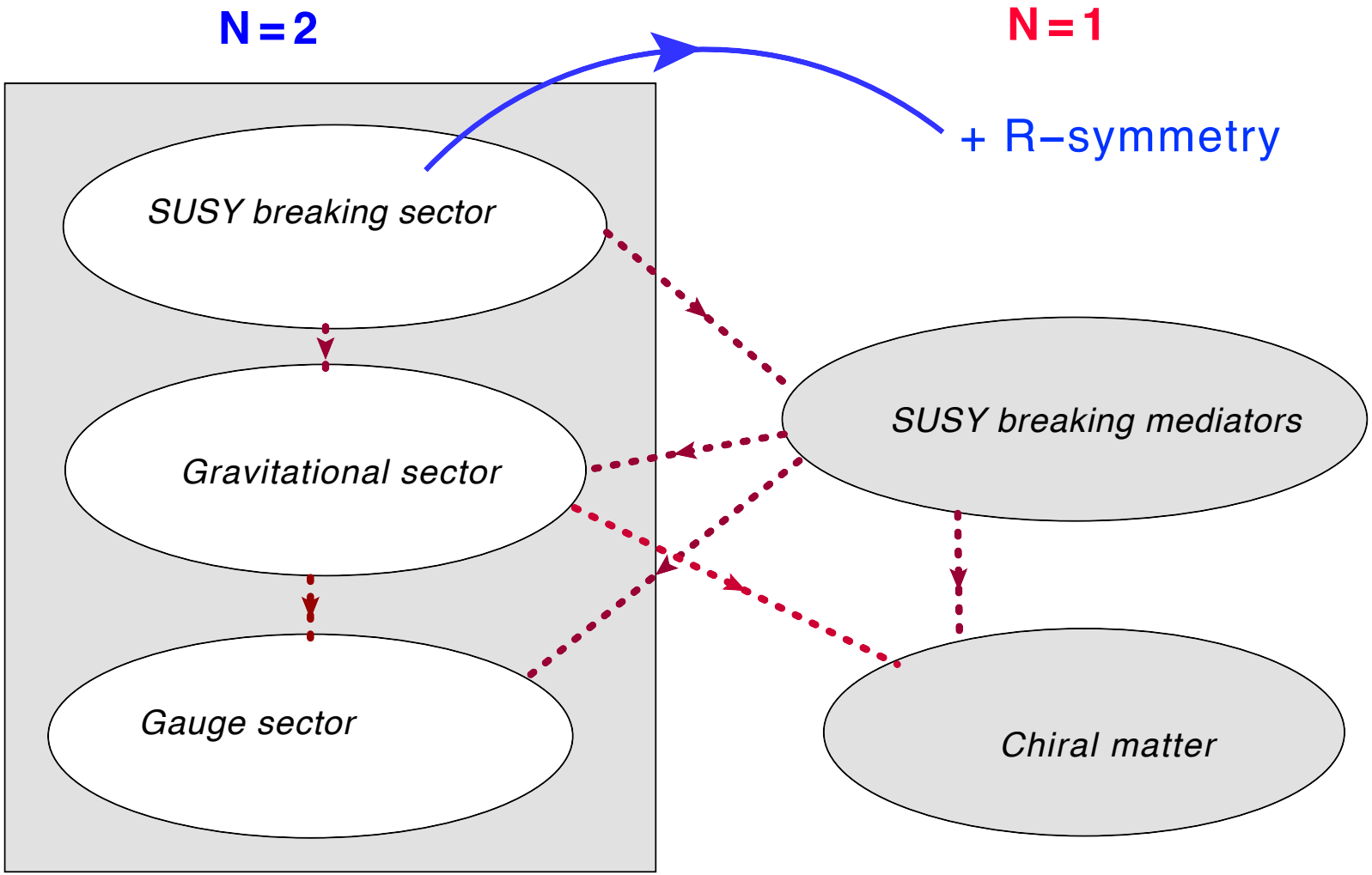
$S \to \gamma\gamma$ cross section in fb as a function of the μ_E and λ_S for R-violating scenario 2.

Schematics



N=2/N=1 sectors.

Schematics



N=2/N=1 sectors + R-symmetry.

MDGSSM from N=2

- R-symmetry broken only in the Higgs sector (μ, $B\mu$)
- Gravity in more than 4D: N=2.
- Gravitinos: two nearly degenerate states (pseudo-Dirac)(exemple: Scherk-Schwarz + very small correction).
- Gauginos: Dirac gauginos from N=2 sector of D-branes
- Matter fields chiral N=1
- In gauge mediation: mediators of SUSY breaking N=1 chiral fields
- Higgs choice N=1 or N=2 hypermultiplet
- S can be a modulus and λ_S takes its N=2 value (K.B., Goodsell, 2009)

Steps in this direction (Antoniadis, K.B., Delgado, Quiros, 2006)

Conclusion

Conclusion

- Construction and understanding of Dirac Gaugino Models approaching (N)MSSM state of the art
- Dirac Gauginos framework for approximatively R-symmetric and N=2/N=1 hybrid models alternatives
- String model building will become motivated if LHC gives hints
- Fitting the presumed 750 GeV di-photon excess is possible in the MDGSSM (it shows the parameter space is not that large as you can fit any thing easily)
- The MDGSSM signatures: extra fields (octets, unification fields, ...)

Conclusion

Thank you!