Automatized Matching of Scalar Couplings

Introduction to `SARAH` and applications

Martin Gabelmann

Thusrday's Meeting, 18.11.2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Outline

Motivation / Introduction

Matching and Running in `SARAH`

Live Demo

Results

Other Aspects of Matchings

SM Hierarchies

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Top quark

$$m_t \approx 173\,\mathrm{GeV}$$
$$\frac{m_b}{m_t} \approx 0.02$$

Weak bosons

$$m_W, m_Z \approx 80, 90\,\mathrm{GeV}$$
$$\frac{m_b}{m_W} \approx 0.05$$

light fermions

$$m_e \approx 500\,\mathrm{keV}$$
$$\frac{m_e}{m_\mu} \approx 0.0002$$

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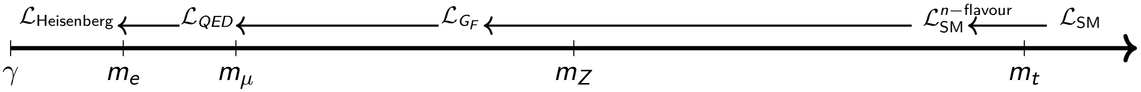

BSM Hierarchies: Experimental constraints on...

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Electroweakinos

(i.e. weak fermions)

$$m_{\chi_1^0} \gtrsim 50\text{-}200\,\mathrm{GeV}$$
$$m_{\chi_1^\pm} \gtrsim 94\,\mathrm{GeV}$$

Extended Higgs sectors

(e.g. MSSM inspired 2HDM)

$$m_A \gtrsim 500\text{-}600\,\mathrm{GeV}$$
$$\tan\beta \gtrsim 1-2$$ [Bahl et. al]

Coloured Scalars

(e.g. stops)

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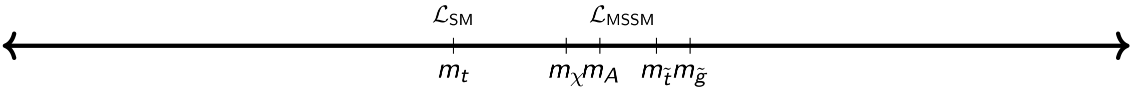

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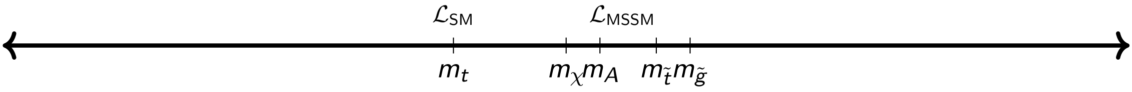
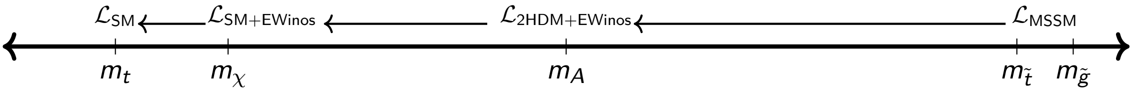
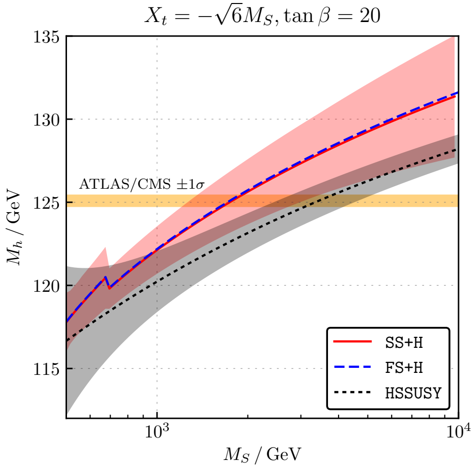


Split-SUSY: ✓



Example: Higgs Mass Uncertainty in the High-Scale MSSM

Assumption: all SUSY states heavy.



[Allanach, Voigt, '18]

- SS+H/FS+H: m_h fixed-order
- HSSUSY: m_h EFT (MSSM→SM matching)

Possible EFT Towers

Split-MSSM: $m_\chi < m_A$:

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$$\mathcal{L}_{\text{SM}} \longleftarrow \mathcal{L}_{\text{SM+EWinos}} \longleftarrow \mathcal{L}_{\text{2HDM+EWinos}} \longleftarrow \mathcal{L}_{\text{MSSM}}$$

$$m_t \quad m_\chi \quad m_A \quad m_{\tilde{t}} \quad m_{\tilde{g}}$$

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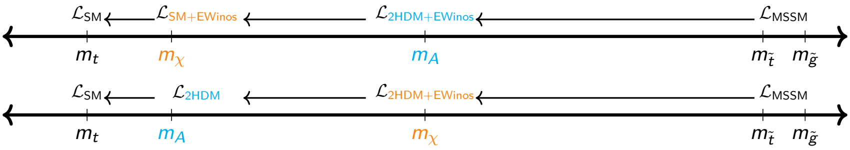

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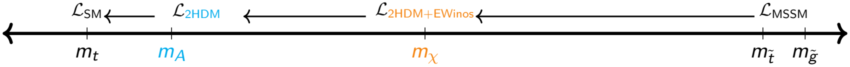

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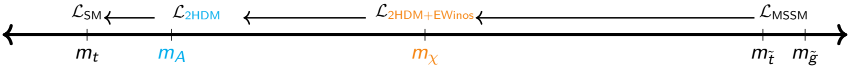

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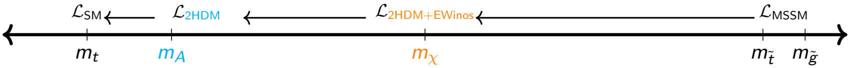

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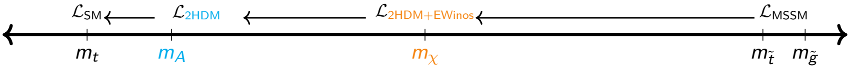

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- ...

$\rightarrow$ **Automation required!** ($\rightarrow$ 2nd part of talk)

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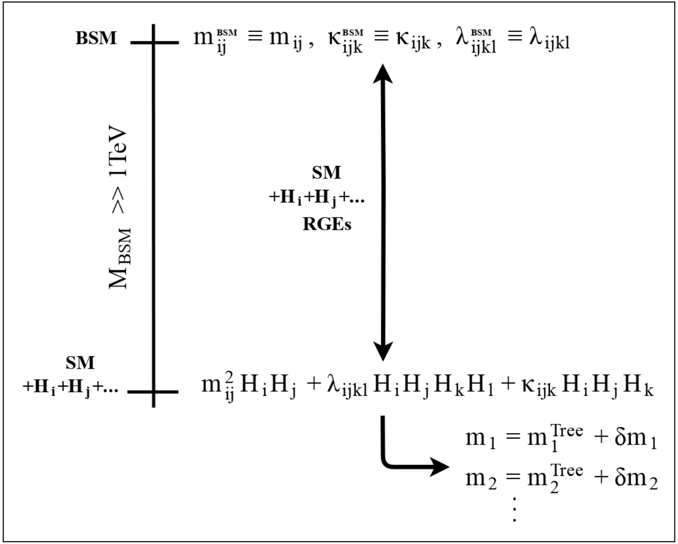
Which contributions are important?

For scalar sector and $v \ll \Lambda$: only renormalizable couplings!

Matching and Running - The Algorithm



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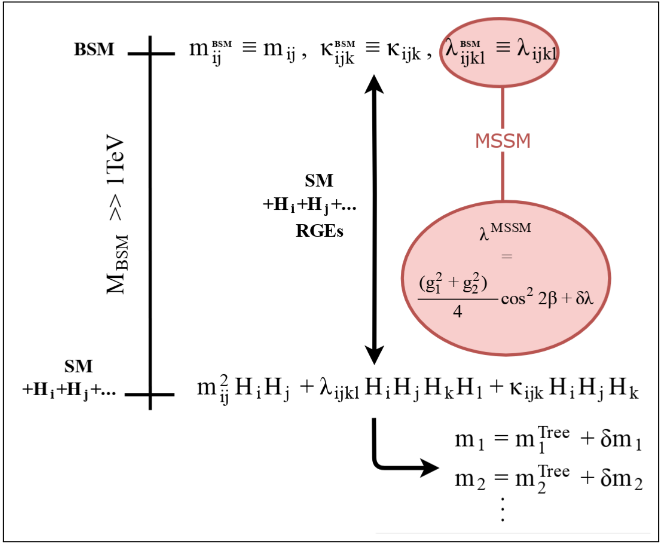

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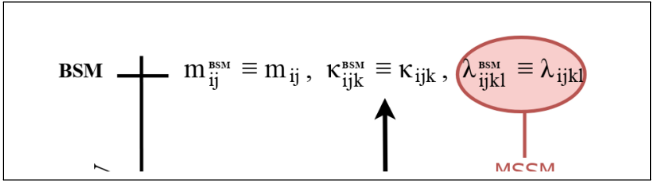

Matching condition: $\lambda^{\text{BSM}}(Q_{\text{match}}) = \lambda^{\text{EFT}}(Q_{\text{match}})$

- $\lambda_{i_1,\ldots,i_n} \to$ evaluate n-point function at $p^2_{\text{ext.}} = 0$ to m-loops in both models

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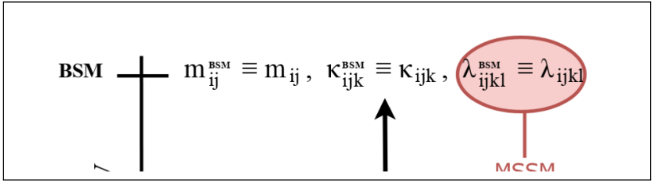

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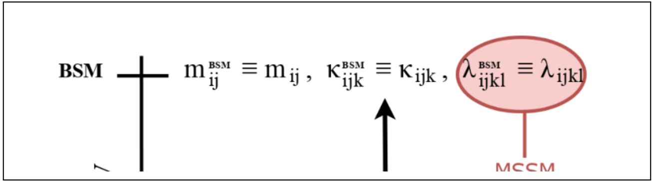

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More details for LO and NLO matchings:

- **1810.09388** [Braathen, Goodsell, Slavich]
- **1810.12326** [MG, Mühlleitner, Staub]
- **MG's** [Masterthesis]

Matching and Running - SARAH's Two-Fold Implementation

two independent implementations:

- numerical (Fortran)
- analytical (Mathematica)

SARAH Wiki

One-Loop Threshold Corrections in Scalar Sectors

Demo: MSSM $\to$ 2HDM Matching

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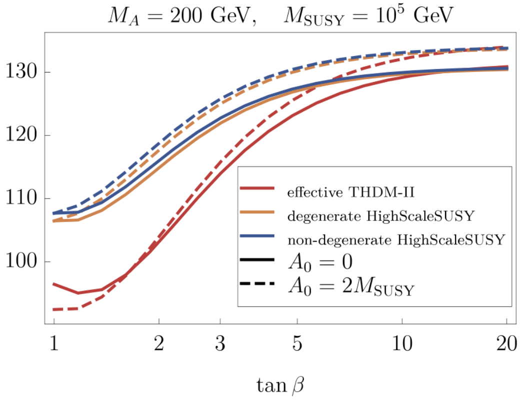
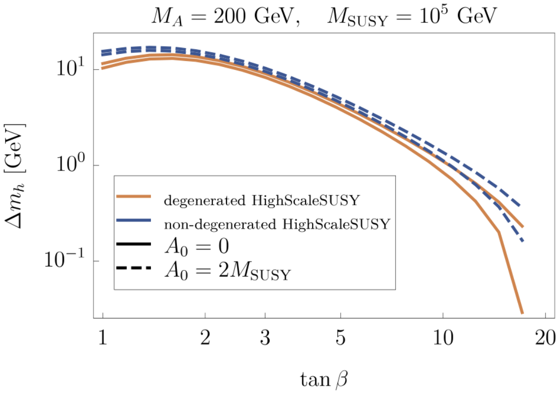
Results: MSSM $\to$ 2HDM Matching

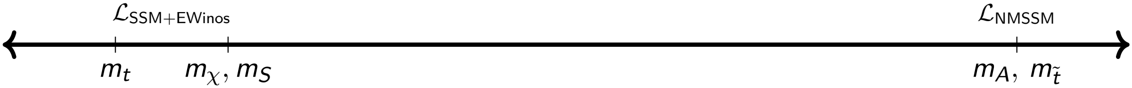
Comparison against MSSM $\to$ SM matching:





Matching the Split-NMSSM

Idea: NMSSM with a light singlet (+EWinos). Everything else decoupled.



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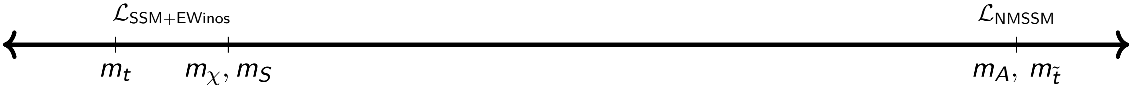
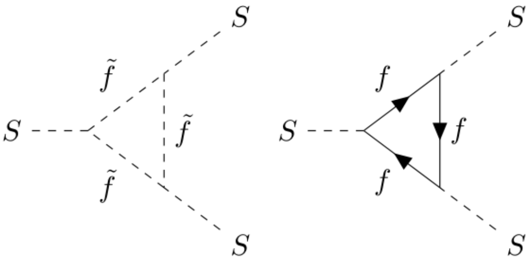


$$
\begin{aligned}
\mathcal{L}_{\text{SSM}} = &- m_H^2 HH^\dagger - \frac{\lambda_H}{2}|HH^\dagger|^2 - m_S^2 SS^* - \frac{\lambda_S}{2}|SS^*|^2 - \lambda_{SH} SS^* HH^\dagger \\
&+ \Big[\kappa_{SH} SHH^\dagger + \kappa_S S^3 \\
&- Y_d\, q\, H^\dagger\, d - Y_u\, q\, H - Y_e\, l\, H\, e - g_2^u \tilde{H}_u\, H^\dagger\, \tilde{W} - \frac{g_1^u}{\sqrt{2}}\, \tilde{H}_u\, H^\dagger\, \tilde{B} \\
&- g_2^d\, \tilde{H}_d\, H\, \tilde{W} - \frac{g_1^d}{\sqrt{2}}\, \tilde{H}_d\, H\, \tilde{B} - Y_S^u\, \tilde{S}\, \tilde{H}_u\, H^\dagger - Y_S^d\, \tilde{S}\, \tilde{H}_d\, H \\
&- Y_{\tilde{S}}\, \tilde{S}\, \tilde{S}\, S - \frac{Y_{ud}}{\sqrt{2}}\, S\, \tilde{H}_u \cdot \tilde{H}_d - \frac{M_{\tilde{g}}}{2} \tilde{g}\tilde{g} - \frac{M_{\tilde{B}}}{2} \tilde{B}\tilde{B} - \frac{M_{\tilde{W}}}{2} \tilde{W}\tilde{W} + \text{h.c.}\Big]
\end{aligned}
$$

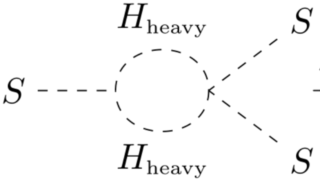
Why keep the EWinos light?

Decoupling them would destabilize the potential! **Example for $\kappa_S S^3$:**

$\delta^{(1)}\kappa_S \propto$ 

Non-Decoupling Effects

$\delta^{(1)}\kappa_S \supset$

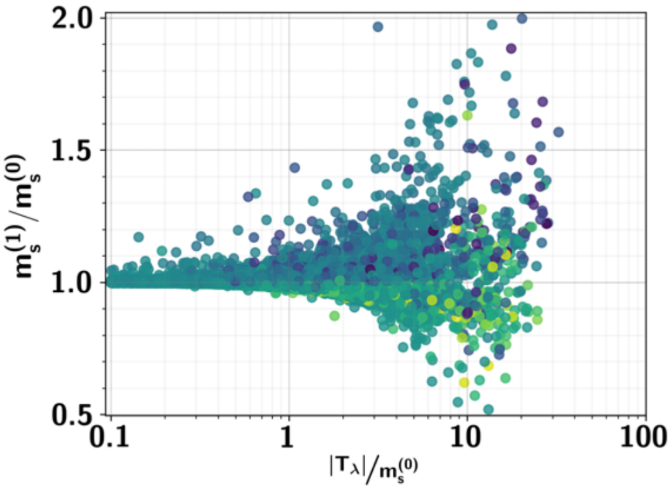


$$\xrightarrow[\to\infty]{m_{\text{heavy}}} -\frac{\kappa\,\lambda\,T_\lambda\cos^2 2\beta}{8\pi^2}$$

Thus:

$$\kappa_S^{\text{eff, one-loop}} \approx \frac{T_\kappa}{3} - \frac{\kappa\lambda T_\lambda \cos^2 2\beta}{8\pi^2}$$

Singlet Mass Prediction: LO vs. NLO



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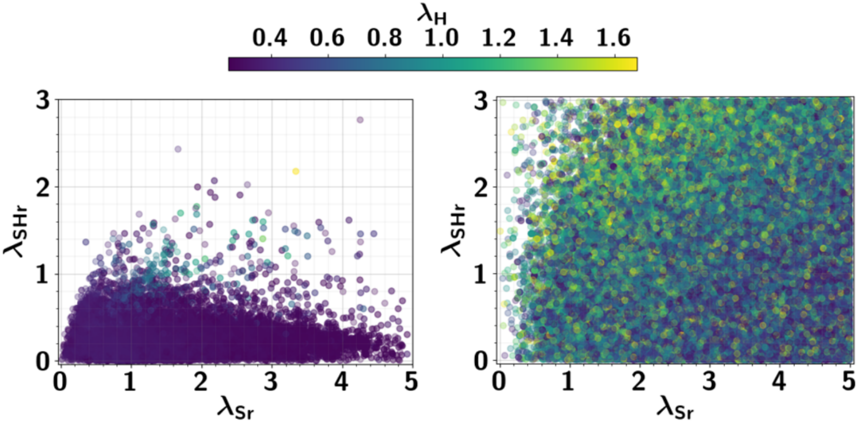
UV- vs. EFT-Model

parameter counting

		Σ
UV	$\lambda,\ \kappa,\ T_\lambda,\ T_\kappa,\ \tan\beta$	5
EFT	$\lambda_H,\ \lambda_S,\ \lambda_{SH},\ \kappa_S,\ \kappa_{SH}$	5

Matching important at all? Why not simply studying the EFT without connecting to any UV model?

UV- vs. EFT-model: Comparison of Parameter Scans



w/ matching w/o matching

Electroweak Phasetransistions (EWPTs)

Idea:

- use matching to simplify (SUSY) predictions other than m_h that also involve the Higgs sector.
- Starting point: **Strong first-order electroweak phasetransistions** (SFOEWPT).

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However:

- PTs are not only sensitive on scalar but also fermion sector (T-corrections).
- Q1: How do split-SUSY fermions influence the PT of a 2HDM?
- Q2: Which UV-completions of the $\text{2HDM}_{+\text{EWinos}}$ are compatible with a SFOEWPT?
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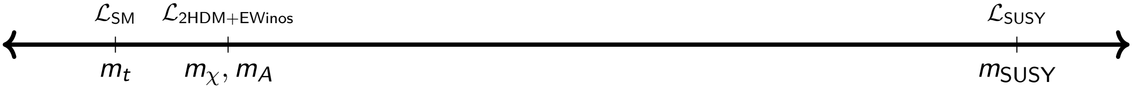

EWPT in the 2HDM+ EWinos

$$V(T) = V_{\text{2HDM}}^{(\text{tree})} + V_{CW}^{(1)} + V_T + V_{CT}$$

- tree-level potential $V_{\text{2HDM}}^{(\text{tree})}$ of the 2HDM

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- implemented in `BSMPT` [Basler et. al]

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- more details: [2107.09617]

Q1:

Can split-SUSY fermions relax tensions in the 2HDM?

Example Point: 2HDM

Idea: start with 2HDM (without EWinos) and then turn-on fermion contributions.

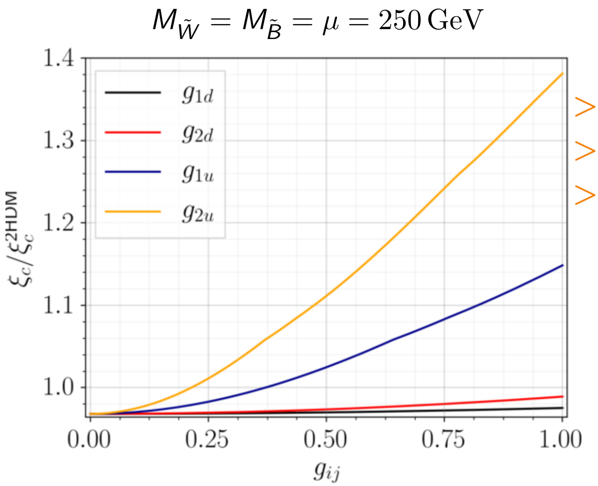
$$
\begin{aligned}
m_h &= 125.09\,\mathrm{GeV}, & m_H &= 637.37\,\mathrm{GeV}, \\
m_A &= 811.35\,\mathrm{GeV}, & m_{H^\pm} &= 839.90\,\mathrm{GeV}, \\
\tan\beta &= 6.15\ , & \alpha &= -0.1605\ ,
\end{aligned}
$$

leads to

$$\xi_c^{\text{2HDM}} = 0.82 < 1$$

when considering the pure 2HDM.

Example Point: 2HDM+EWinos



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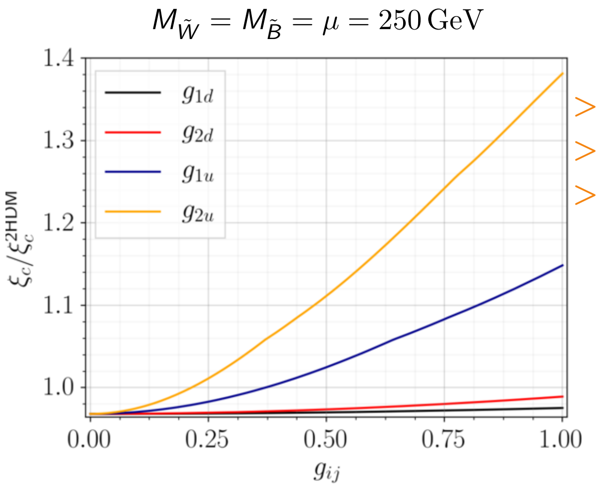

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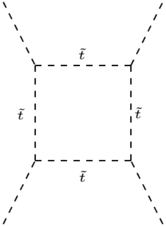
Backup-slides $\rightarrow$ general feature of EWinos!

Q2:

Can it emerge from split-SUSY?

Matching the 2HDM+EWinos to the MSSM

- MSSM:
  - $\lambda_{1,2,3,4} = \mathcal{O}(g_1^2, g_2^2) + \frac{1}{(4\pi)^2}\mathcal{O}(\frac{A_t}{m_{\tilde{t}}})$
  - $\lambda_{5,6,7} = 0 + \frac{1}{(4\pi)^2}\mathcal{O}(\frac{A_t}{m_{\tilde{t}}})$
  - A_t is a low-scale parameter
- our scan requires:
  $\lambda_5 > 0.1$ to reach $\xi_c > 1$ for $\lambda_{1,2,3,4} \approx \lambda_{1,2,3,4}^{\text{MSSM}}$



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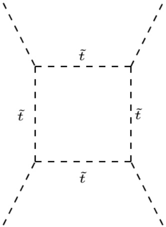

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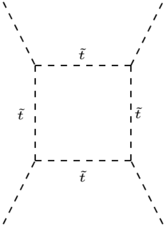

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- add light singlet (split-NMSSM) [Demidov et. al] [Athron et. al]
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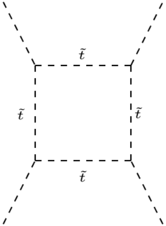

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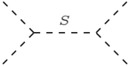
  NMSSM $\rightarrow$ MSSM $\rightarrow$ 2HDM+EWinos



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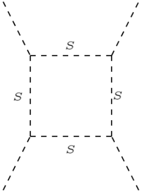

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Matching Dim>4 Operators

It is well established that dim>4 operators do not significantly contribute to m_h. Open question: how does this behave for e.g.

- Relic density? (4-fermion operators)
- EWPTs?
- Unitarity?
- ...

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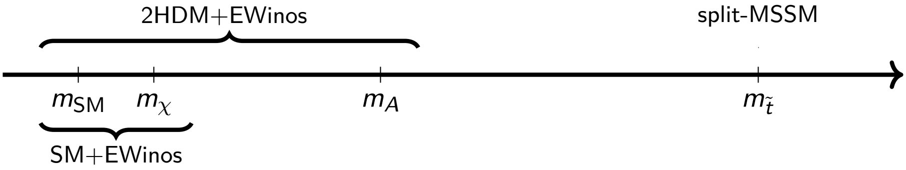

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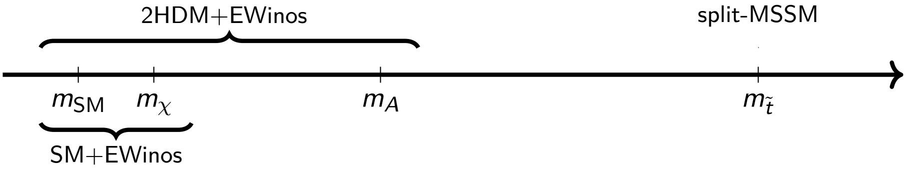

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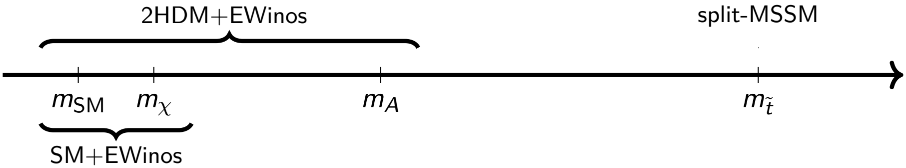

- precise Higgs masses for large $m_{\tilde{t}}$, m_A, ...
- also interesting: other predictions within SUSY-EFTs (e.g. Ωh^2 or $\frac{v_c}{T_c}$)

Thank you!

Backup

Global View: reopen parameter space with large masses

- random parameter scan using ScannerS [Coimbra et al.]
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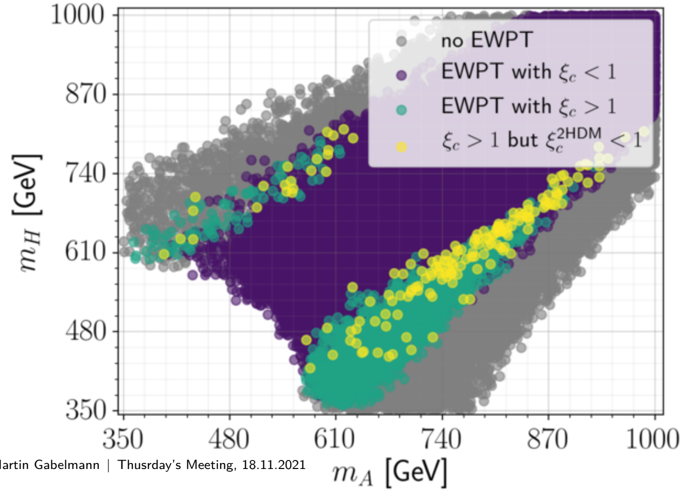
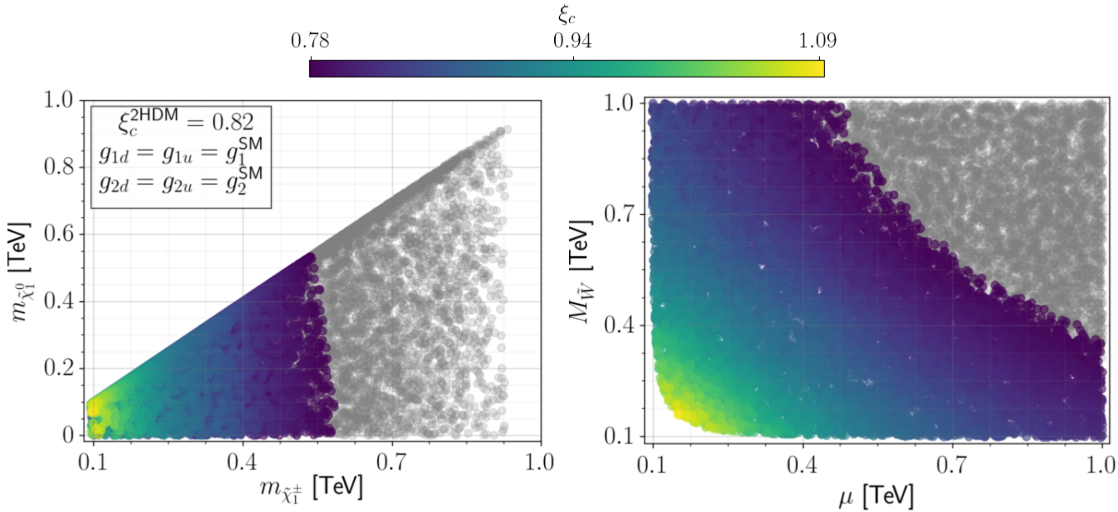


- large-mass points which were forbidden in the 2HDM are now allowed!

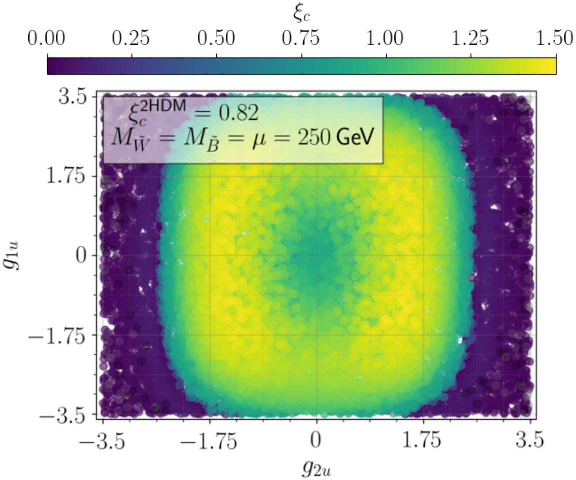
Global Mass Scan



$g_{1i} = g_1^{SM}$, $g_{2i} = g_2^{SM}$ fix

$\mu, m_{\tilde{B}}, m_{\tilde{W}}$ varied independently

Global Yukawa Scan



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- open source [phbasler.github.io/BSMPT]

Fixed-order VS. EFT

0	α^0				$\alpha \propto (4\pi)^{-1}$
1	$\alpha \log$	α			
2	$\alpha^2 \log^2$	$\alpha^2 \log$	α^2		
	$\vdots$	$\vdots$	$\vdots$		
n	$\alpha^n \log^n$	$\alpha^n \log^{n-1}$	$\alpha^n \log^{n-2}$	...	α^n
	LL	NLL	NNLL	...	N^{n}LL

fixed-order

EFT

Common lore: *n-loop matching requires $n+1$-loop running*

Not always appropriate: TODO ref to Johannes et. al.