Precision calculations in BSM theories

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M_h and $g-2$

Dominik Stöckinger (TU Dresden)

Loops & Legs, May 2018, St. Goar

Outline

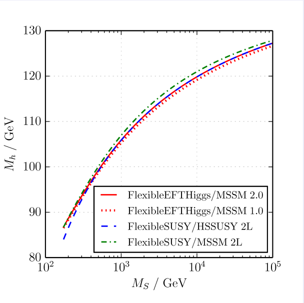
1. Higgs mass in MSSM and dimensional reduction [DS, Unger '18]

2. Muon $g-2$ in the THDM [Cherchiglia, DS, Stöckinger-Kim '17]

Motivation: Higgs mass and dimensional reduction

$m_h^{\text{Exp}} = 125$ GeV compatible with m_h^{SUSY}

$\Delta m_h^{\text{Exp}} = 0.2$ GeV $\ll \Delta m_h^{\text{SUSY}}$



$\Rightarrow$ should increase theory precision of m_h^{SUSY} !

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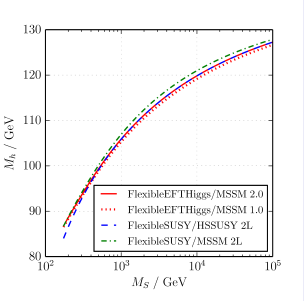

$\Rightarrow$ should increase theory precision of m_h^{SUSY} !

- current Δm_h^{SUSY} from FlexibleSUSY implementations:
  - fixed-order (2L), pure EFT, hybrid [Athron, Park, Steudtner, DS, Voigt '16]
  - fixed-order (3L), pure EFT [Allanach, Voigt '18]
  - scale variation not sufficient, dominant: $\propto m_t, \alpha_s$

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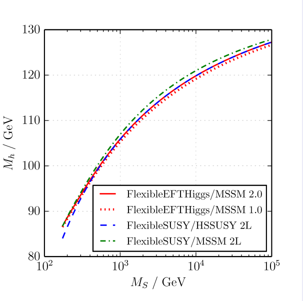


$\Rightarrow$ should increase theory precision of m_h^{SUSY} !

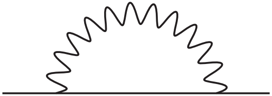
- existing 3-loop calculation $\mathcal{O}(\alpha_t \alpha_s^2)$: [Harlander, Kant, Mihaila, Steinhauser 08 + 10]

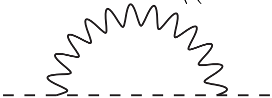
  further developments: [Kunz, Mihaila, Zerf '14; Harlander, Klappert, Voigt '17]
- future: full 3-loop calculation $\mathcal{O}(\alpha_t \alpha_s^2, \alpha_t^2 \alpha_s, \alpha_t^3)$: "gaugeless limit"
- But subtlety: regularization scheme!

Motivation: Regularization by dimensional reduction

Subtlety in such calculations: is DRED consistent with SUSY?

- E.g. in DREG: $m_e^{1L} \neq m_{\tilde{e}}^{1L}$ $\longleftrightarrow$ $\sim \left\langle \left(\delta_{\mathrm{SUSY}} \mathcal{L}^{(D)}\right) \phi\psi \right\rangle \neq 0$





- in DRED: better but no all-order proof

Question: Is DRED consistent with SUSY for 3-loop Higgs mass calculations in the gaugeless limit in the MSSM?

Previous related results:

- 2-loop SUSY-QCD: $\tilde{q}q\tilde{g}$, $qq\epsilon$, ... [Harlander, Jones, Kant, Mihaila, Steinhauser 06 + 09]
  - using higher-order β functions
- 2-loop 2-point functions, δm_h [DS 05][Hollik, DS 05]
  - using Slavnov-Taylor identities

Technical details

Tree-level:

$$m_h^2 = m_Z^2 \cos^2(2\beta) + \mathcal{O}(1/m_A^2)$$

after SUSY renormalization transformation:

$$\delta m_h^2 = \delta(m_Z^2 \cos^2(2\beta)) + \ldots$$

However, if SUSY is broken by DRED, we need:

$$\delta m_h^2 = \delta(m_Z^2 \cos^2(2\beta)) + \ldots + \delta m_h^2|_{\text{SUSY-restore}}$$

Technical details

Tree-level:

$$\mathcal{L}_{y_u} = y_u \Big(\quad H_2 \bar{u} q_L + \quad \tilde{u}_R^\dagger \overline{\tilde{H}_2^C} q_L + \ldots \Big)$$

after SUSY renormalization transformation:

$$\mathcal{L}_{y_u} \to y_u \Big(Z_{y_u} \sqrt{Z_{H_2} Z_{q_L} Z_{u_R}}\; H_2 \bar{u} q_L + Z_{y_u} \sqrt{Z_{\tilde{H}_2} Z_{q_L} Z_{\tilde{u}_R}}\; \tilde{u}_R^\dagger \overline{\tilde{H}_2^C} q_L + \ldots \Big) .$$

However, if SUSY is broken by DRED, we need:

$$\mathcal{L}_{y_u} \to y_u \Big(Z_{H_2 q u}\; H_2 \bar{u} q_L + Z_{\tilde{H}_2 q \tilde{u}}\; \tilde{u}_R^\dagger \overline{\tilde{H}_2^C} q_L + \ldots \Big) .$$

Technical details

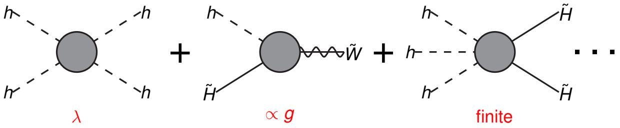
Technical goal: verify that/whether at 3-loop (2-loop)

$$\delta m_h^2|_{\text{SUSY-restore}} = 0, \quad (\text{and } Z_{y_u} \text{ etc sufficient})$$

Method:

1. find (set of) SUSY Slavnov-Taylor identities which determines CTs
2. verify that/whether STI is valid in DRED

Step 1: STI for Higgs mass/quartic Higgs coupling



$$0 = \frac{\delta^5 S(\Gamma)}{\delta\phi_a \delta\phi_b \delta\phi_c \delta\tilde{H} \delta\bar{\epsilon}} = \Gamma_{\tilde{H} Y_{\phi_i} \bar{\epsilon}} \Gamma_{\phi_a \phi_b \phi_c \phi_i} + \Gamma_{\phi_a \phi_b Y_\lambda \epsilon} \Gamma_{\phi_c \tilde{H} \lambda} + \ldots$$

Determines directly δm_h

Step 1: STIs for Yukawa couplings

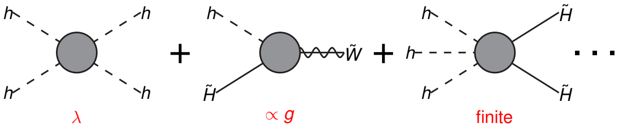
$$0 = -\Gamma_{\tilde{u}_R^\dagger \bar{\epsilon}\, y_{u_R}} \Gamma_{q_L^i\, H_2^j\, \bar{u}_R} - \Gamma_{H_2^j\, \bar{\epsilon}\, y_{\tilde{H}_l^m}{}^C} \Gamma_{q_L^i\, \tilde{u}_R^\dagger\, \overline{\tilde{H}_l^m}{}^C} + \ldots \quad \Rightarrow \text{Yukawa couplings}$$

$$0 = \Gamma_{\tilde{u}_R^\dagger \bar{\epsilon}\, y_{u_R}} \Gamma_{u_R\, \bar{\epsilon}\, Y_{\tilde{u}_R^\dagger}} + \text{known} \quad \Rightarrow \text{SUSY transf.}$$

$$0 = -\Gamma_{\tilde{u}_R^\dagger \bar{\epsilon}\, y_{u_R}} \Gamma_{u_R\, \bar{u}_R} - \Gamma_{u_R\, \bar{\epsilon}\, Y_{\tilde{u}_R^\dagger}} \Gamma_{\tilde{u}_R\, \tilde{u}_R^\dagger} \quad \Rightarrow \text{self energies}$$

Combination determines Yukawa counterterms
(up to field renormalization)

Step 2: Verify that STIs are valid in DRED



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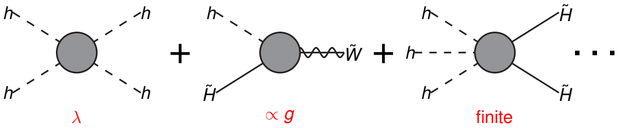

Strategy:

- Use quantum action principle in DRED [Breitenlohner, Maison '77][DS '05]

$$\text{violation of this STI in DRED} = \langle \Delta hhh\tilde{H} \rangle$$

where $\Delta = \delta_{\text{SUSY}} \int d^D x \mathcal{L}_{\text{bare}}$

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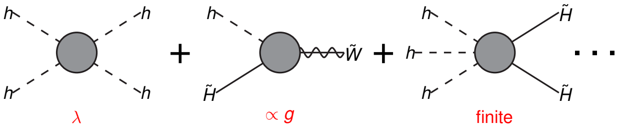

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- determine Δ from $\mathcal{L}_{\text{bare}}^{\leq 2L}$: [DS ’05]-result sufficient
- evaluate all diagrams for $\langle \Delta hhh\tilde{H} \rangle \Rightarrow$ they all vanish!

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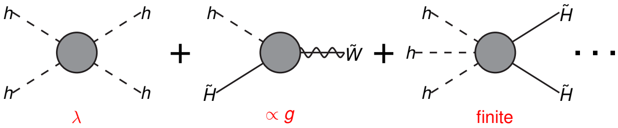

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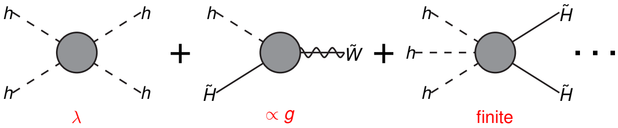
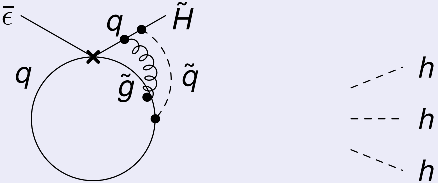


3-loop STI: sample diagrams at $\mathcal{O}(\alpha_t\alpha_s^2, \alpha_t^2\alpha_s, \alpha_t^3)$

$\langle \Delta hhh\tilde{H} \rangle = 0$?



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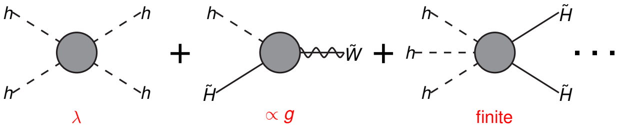

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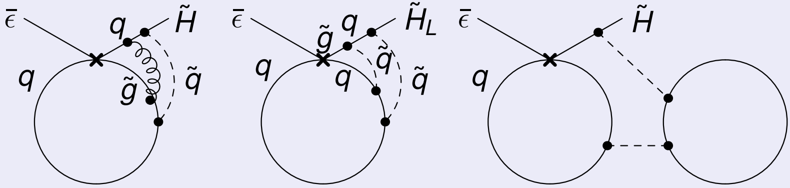

Is DRED consistent with SUSY for 3-loop Higgs mass calculations in the gaugeless limit in the MSSM?

Answer: Yes!

- all such diagrams vanish, for all relevant STIs
- no SUSY-restoring CTs needed at 3-loop or subrenormalization level
- concrete cases (all in gaugeless limit):
  - quartic Higgs coupling 3-loop
  - Yukawa interactions Higgs/Higgsino quark/squark 2-loop
  - quartic interactions Higgs–squarks 2-loop
  - quartic interactions Higgs–ϵ-scalars 2-loop
  - triple interactions gluon/gluino quark/squark [Harlander et al 06 + 09]

Outline

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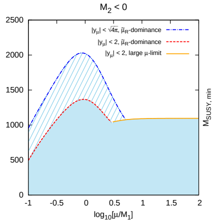
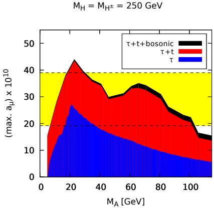
Motivation: Muon $g-2$ in the THDM

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (28.1 \pm (6.3^{\text{Exp}} \rightarrow 1.6^{\text{FUTURE}}) \pm 3.6^{\text{Th(KNT)}}) \times 10^{-10}$$

Keshavarzi,Nomura,Teubner'17;Jegerlehner'17:$\pm 4.4^{\text{Th}}$

New experiment (Fermilab)





$\Rightarrow$ should compare BSM scenarios

Largest SUSY

[Bach,Park,DS,Stöckinger-Kim '15]

Largest THDM

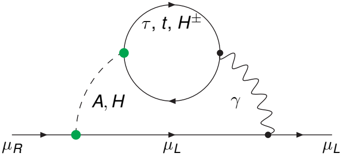
[Cherchiglia,DS,Stöckinger-Kim '17]

Motivation: Muon $g-2$ in the THDM

Extra Higgs bosons negligible at 1-loop $\rightsquigarrow$ 2-loop = leading

LHC constraints on extra Higgs bosons $\rightsquigarrow$ can 2HDM explain a_μ?

Recent calculations: all Barr-Zee [Ilisie '15], full 2-loop [Cherchiglia, Kneschke, DS, Stöckinger-Kim, 16]



Question: What is the largest a_μ possible in the THDM?

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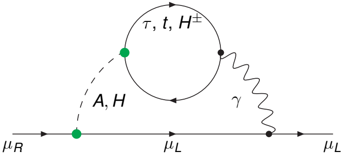
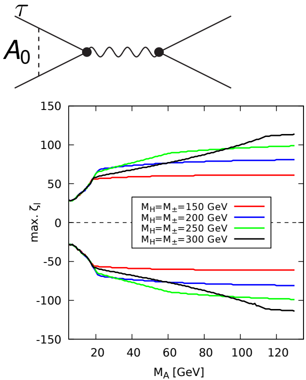


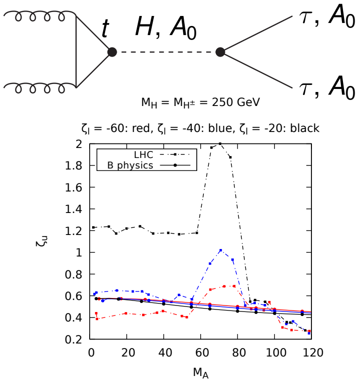
Question: What is the largest a_μ possible in the THDM?

- Need to study first: experimental constraints on parameters
  - non-Barr-Zee: small couplings to gauge bosons, $\Delta\rho$
  - Barr-Zee: $\propto$ new Yukawa couplings/triple Higgs couplings

What are the constraints on the 2HDM parameters ?

Most important: M_A, Yukawa parameters ζ_l and ζ_u





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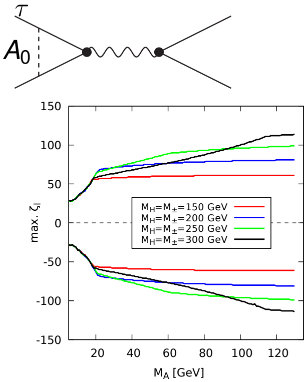
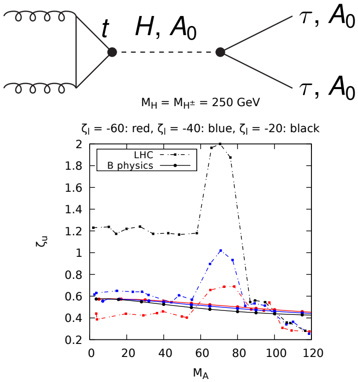
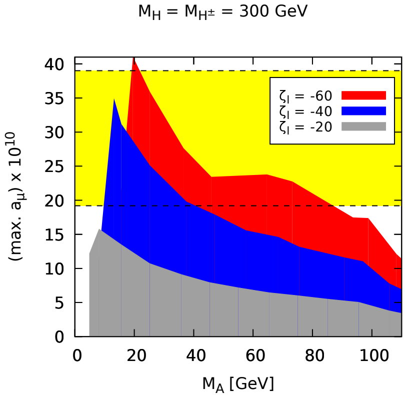


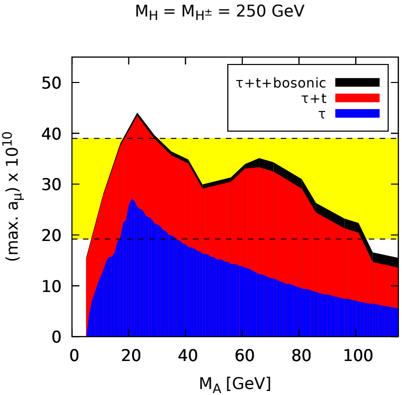


- lepton Yukawa $<\sim 100$ for $M_A > 20$ GeV
- quark Yukawas $<\sim 0.5$ for $M_A < 100$ GeV

What is the maximum possible a_μ in the 2HDM?

Answer:





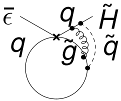
Small M_A and large ζ_l needed $\rightsquigarrow$ not in Type I or Type II (correlations!)

Type X ($\zeta_u \approx 0$): barely explains current deviation

Beyond Type I, II, X: top-loop, bosonic less suppressed for higher M_A; 1σ explanation possible between $M_A = 20 \ldots 100$.

Conclusions

- m_h in MSSM: DRED consistent with SUSY at 3-loop (gaugeless)?
  - Yes
  - SUSY renormalization transformation correct
  - holds for genuine 3-loop and sub-CTs
  - method: STI and quantum action principle



- Muon $g-2$: Largest a_μ in aligned Two-Higgs doublet model?
  - need light A_0 and large τ Yukawa
  - Type I, II excluded
  - also prefers large t Yukawa couplings
  - constraints: $|\zeta_l| <\sim 50$, $\zeta_u <\sim 0.5$
  - should be tested at LHC