Higgs Mass Predictions in the CP-Violating High-Scale NMSSM

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in preparation (2406.xxxxx), together with:

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Theory meets Experiment

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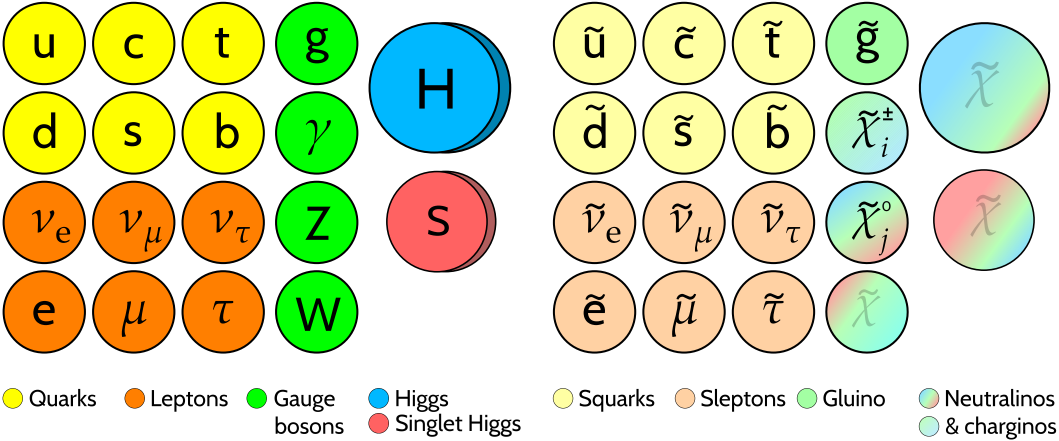
Outline

The Next-to-Minimal Supersymmetric Standard Model

Standard Model particles** / Supersymmetric partners



The Next-to-Minimal Supersymmetric Standard Model

Complex Next-to-Minimal Supersymmetric Standard Model

Superpotential of the $\mathbb{Z}_3$-symmetric NMSSM

$$\mathcal{W}_{\text{NMSSM}} = \left[y_e \hat{H}_d \cdot \hat{L}\hat{E}^c + y_d \hat{H}_d \cdot \hat{Q}\hat{D}^c - y_u \hat{H}_u \cdot \hat{Q}\hat{U}^c\right] - \lambda \hat{S}\hat{H}_d \cdot \hat{H}_u + \frac{1}{3}\kappa \hat{S}^3$$

- Complex scalar singlet extension of the MSSM (λ, κ complex, e.g. $\lambda = |\lambda| e^{i\varphi_\lambda}$)

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- μ parameter is generated dynamically:

$$\mu_{\text{eff}} = \frac{e^{i\varphi_S} v_S \lambda}{\sqrt{2}}$$

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Higgs sector

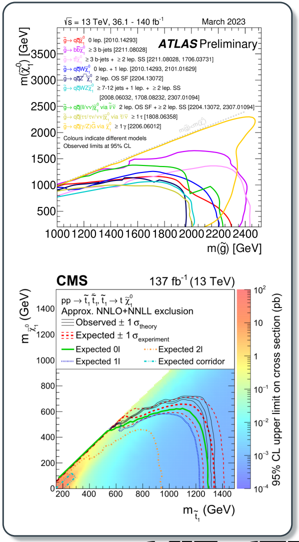
$$H_d = \begin{pmatrix} \frac{v_d + h_d + i a_d}{\sqrt{2}} \\ h_d^- \end{pmatrix}, \quad H_u = e^{i\varphi_u} \begin{pmatrix} h_u^+ \\ \frac{v_u + h_u + i a_u}{\sqrt{2}} \end{pmatrix}, \quad S = \frac{e^{i\varphi_S}}{\sqrt{2}}(v_S + h_S + i a_S)$$

$$\tan\beta = \frac{v_u}{v_d}$$

$$v = \sqrt{v_u^2 + v_d^2} = 246\,\text{GeV}$$

$h_d, h_u, h_S, a_d, a_u, a_S$ and $h_d^\pm, h_u^\pm$ mixing to $h_1, h_2, h_3, h_4, h_5, G^0$ and $h^\pm, G^\pm$

Supersymmetry – out of reach?



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Higgs mass calculations in the NMSSM

Constraining the NMSSM parameter space with the m_h^{SM} measurement

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Fixed-order status:

- Full 1L, 2L, in different renormalisation schemes ($\overline{\text{DR}}$, mixed OS-$\overline{\text{DR}}$)
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- Tools: `FlexibleSUSY` *[Athron et al.]*, `NMSSMCALC` *[Baglio et al.]*, `NMSSMTools` *[Ellwanger et al.]*, `SOFTSUSY` *[Allanach et al.]*, `SARAH/Spheno` *[Porod, Staub]*

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Status of effective field theory (EFT) approach:

- Pole-mass matching in `FlexibleEFTHiggs` *[Athron et al. '17]*, `SARAH/Spheno` *[Staub, Porod '17]*
- Automated full 1L EFT matching in SARAH *[Gabelmann et al. '18-'19]*
- Full 1L + (NMSSM-specific) 2L EFT matching in the real NMSSM *[Bagnaschi, Goodsell, Slavich '22]*

Higgs mass calculations at higher orders

Fixed-order calculations for the Higgs mass:

- Full perturbative series truncated at fixed order
- Reliable for not too high SUSY masses
- Dominant corrections from top/stop sector, e.g. at 1-loop: $\Delta M_h^2 \sim Y_t \ln \frac{m_{\tilde{t}}^2}{m_t^2}$

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If SUSY masses (e.g. stops) are heavy: large separation of scales

EW scale: $m_t \sim v \ll$ SUSY scale: $m_{\tilde{t}} \sim M_{\text{SUSY}} \Rightarrow \ln \frac{M_{\text{SUSY}}^2}{v^2} \gg 1$

Large logs $\ln \frac{M_{\text{SUSY}}^2}{v^2}$ from higher orders are relevant and **need to be resummed!**

Effective field theory approach to calculating M_h

Assuming **all** SUSY particles are heavy:

Consider the SM as a (renormalisable) effective field theory (EFT) valid at the EW scale ~ m_t ~ v, and the NMSSM as its UV completion at the high scale ~ M_{SUSY}

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$$\ln(M_{\text{SUSY}}^2/v^2) = \underbrace{\ln(\mu_R^2/v^2)}_{\text{resummed by RGEs}} + \underbrace{\ln(M_{\text{SUSY}}^2/\mu_R^2)}_{\substack{\text{part of matching conditions} \\ \text{at } \mu_R \sim Q_{\text{match}} \sim M_{\text{SUSY}}}}$$

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→ Non-log terms $\mathcal{O}(v/M_{\text{SUSY}})$ only included partially: **EFT valid for** $v/M_{\text{SUSY}} \ll 1$**!**

Matching the NMSSM parameters to the SM

Matching conditions relate the SM and NMSSM couplings such that both theories describe the same physics at the high scale $Q = Q_{\text{match}}$

$V^{\text{SM}} \supset \lambda^{\text{SM}} |H|^4$

$$\lambda^{\text{SM}}(Q) \overset{!}{=} \lambda^{\text{NMSSM}}(Q), \quad Y_i^{\text{SM}}(Q) \overset{!}{=} Y_i^{\text{NMSSM}}(Q), \quad g_j^{\text{SM}}(Q) \overset{!}{=} g_j^{\text{NMSSM}}(Q), \quad \ldots$$

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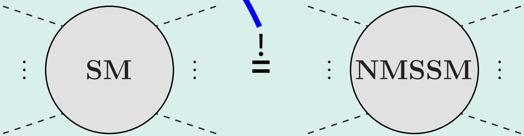

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"$\lambda^{\text{SM}} = \lambda^{\text{NMSSM}}$"

- Matching of 4-point functions
- Evaluate directly in $v \to 0$ limit

→ **Analytical expressions**

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⇒ Compare both approaches, estimate size of $\mathcal{O}(v/M_{\text{SUSY}})$ terms

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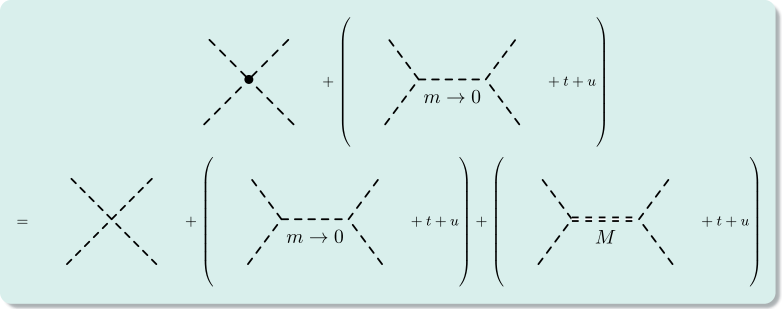
M heavy scale



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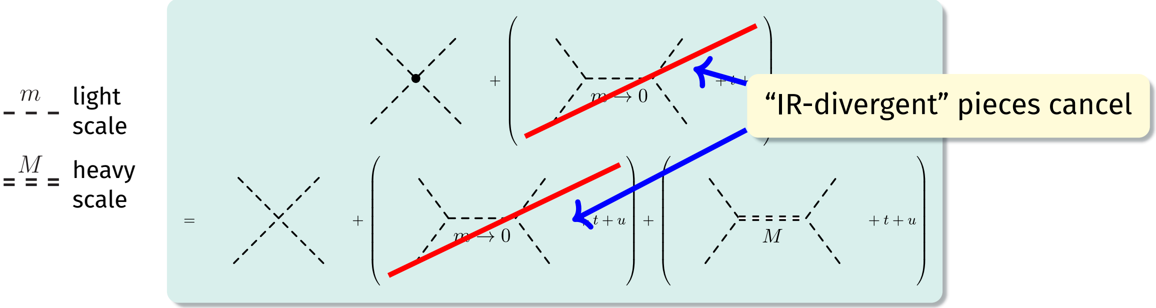

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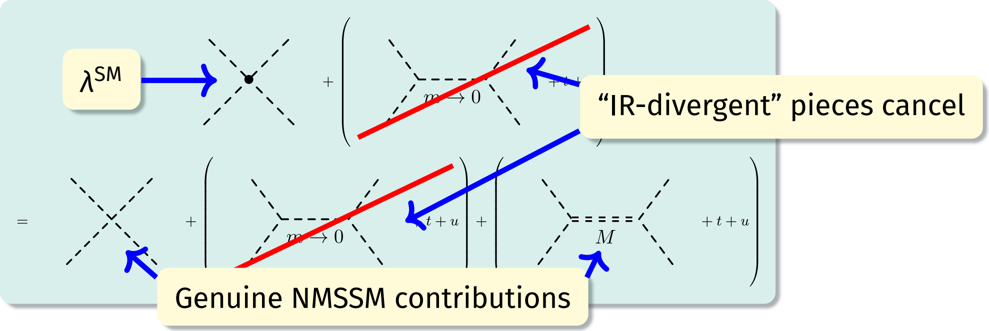

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1L amplitudes from SARAH with SM part already subtracted [Gabelmann et al. '18]

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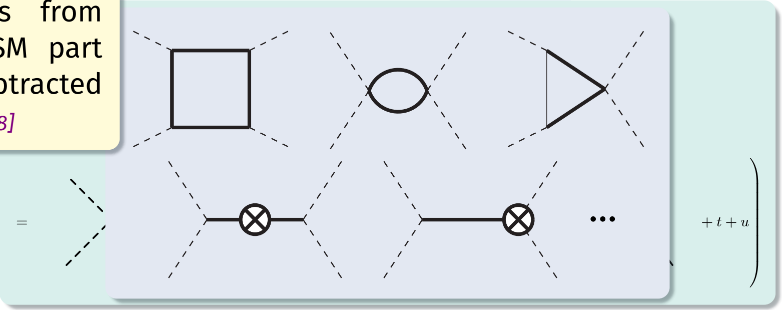

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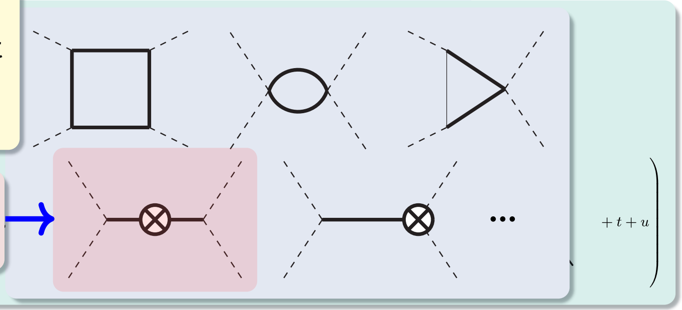
Contributions from singlet tadpoles



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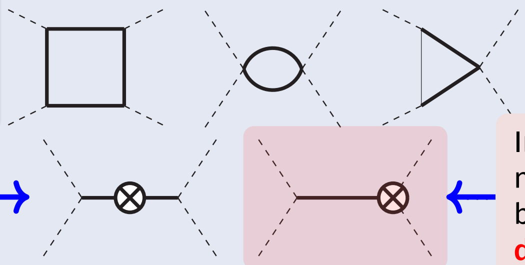

Contributions from singlet tadpoles

In CPV case: non-vanishing contribution from **CP-odd doublet tadpole!**

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Pole-mass matching

Demand that the pole masses of the SM-like Higgs states are the same:

$$(M_h^{\text{SM}})^2 = (M_h^{\text{NMSSM}})^2$$

e.g. [Athron et al. '16][Braathen et al. '18]

with $(M_h^X)^2 = (m_h^X)^2 - \hat{\Sigma}_h^{\text{SM}}\left((M_h^X)^2\right)$

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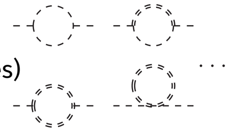

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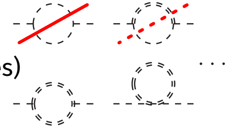

Use $\overline{\text{MS}}$ relation $(m_h^{\text{SM}})^2 = 2(v^{\text{SM}})^2\lambda_h^{\text{SM}}$ and solve for λ_h^{SM}:

$$\lambda_h^{\text{SM}} = \frac{1}{2(v^{\text{NMSSM}})^2}\left[(m_h^{\text{NMSSM}})^2\left(1 - 2\Delta\hat{\Sigma}_h'\right) - \Delta\hat{\Sigma}_h\right]$$

with
$\Delta\hat{\Sigma}_h^{(\prime)} \equiv \hat{\Sigma}_h^{\text{NMSSM}(\prime)}(0) - \hat{\Sigma}_h^{\text{SM}(\prime)}(0)$

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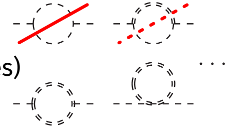

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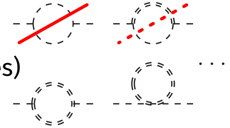
: renormalised self energies)



Numerical limit of $v \to 0$: excellent agreement with λ_h^{SM} from quartic-coupling matching!

for λ_h^{SM}:

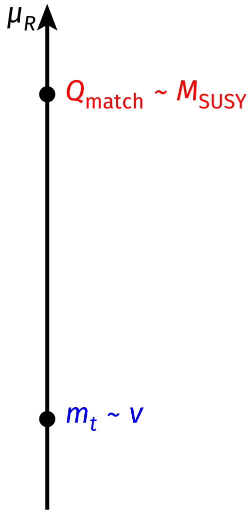
$$\lambda_h^{\text{SM}} = \frac{1}{2(v^{\text{NMSSM}})^2}\left[(m_h^{\text{NMSSM}})^2\left(1 - 2\Delta\hat{\Sigma}_h'\right) - \Delta\hat{\Sigma}_h\right]$$

with $\Delta\hat{\Sigma}_h^{(\prime)} \equiv \hat{\Sigma}_h^{\text{NMSSM}(\prime)}(0) - \hat{\Sigma}_h^{\text{SM}(\prime)}(0)$

$\Rightarrow$ Consistent expansion at 1L, captures leading terms when expanding in v/M_{SUSY}

$$(v^{\text{SM}})^2 = (v^{\text{NMSSM}})^2 + \delta v^2$$

Renormalisation-group running of λ^{SM}



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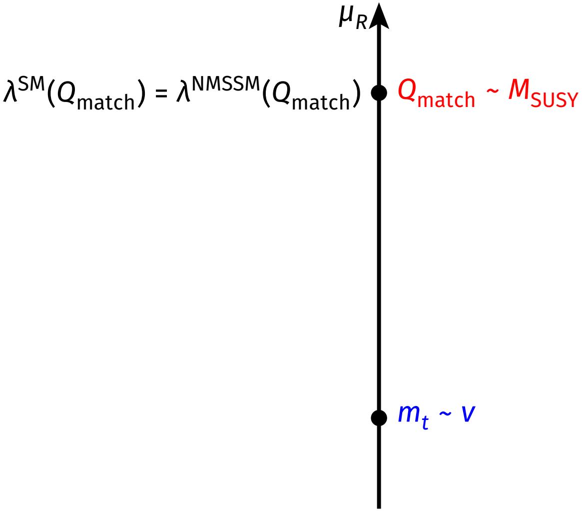

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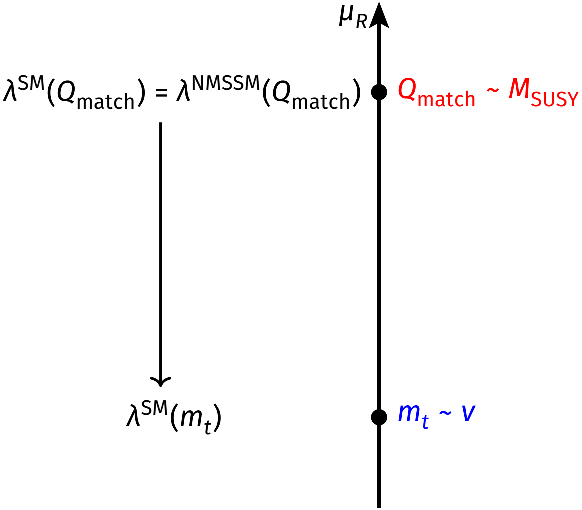

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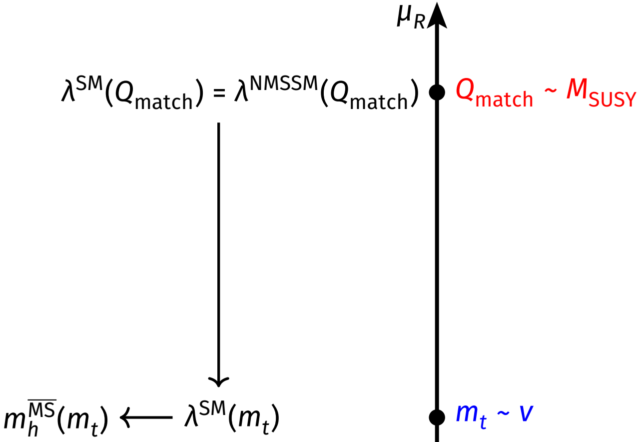


$$\left(m_h^{\overline{\text{MS}}}(m_t)\right)^2 = 2\left(v^{\text{SM}}(m_t)\right)^2 \lambda^{\text{SM}}(m_t)$$

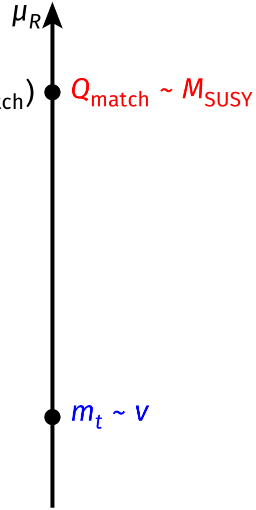
Renormalisation-group running of λ^{SM}

$$\lambda^{\text{SM}}(Q_{\text{match}}) = \lambda^{\text{NMSSM}}(Q_{\text{match}})$$

$$\downarrow$$

$$\boxed{M_h} \longleftarrow m_h^{\overline{\text{MS}}}(m_t) \longleftarrow \lambda^{\text{SM}}(m_t)$$

$$\left(m_h^{\overline{\text{MS}}}(m_t)\right)^2 = 2\left(v^{\text{SM}}(m_t)\right)^2 \lambda^{\text{SM}}(m_t)$$



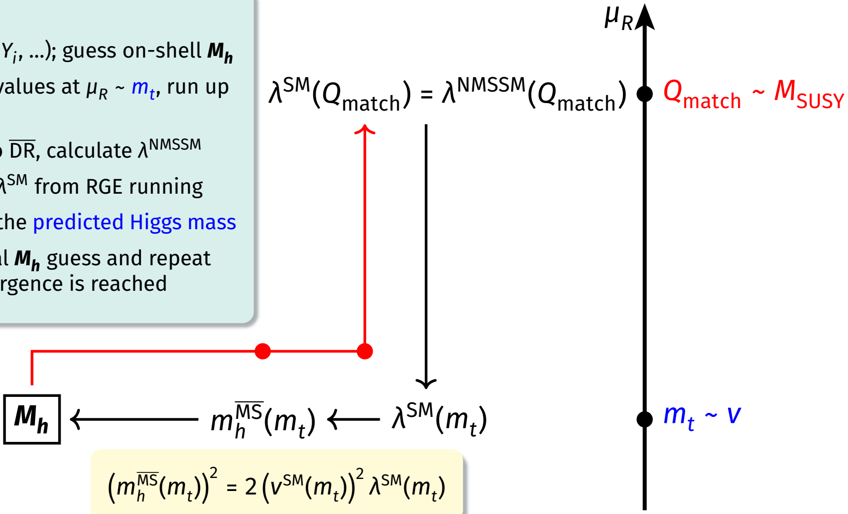
Renormalisation-group running of λ^{SM}

Iterative procedure

1. Choose SM inputs (g_i, Y_i, ...); guess on-shell $\boldsymbol{M_h}$
2. Convert inputs to $\overline{\text{MS}}$ values at $\mu_R \sim m_t$, run up to $\mu_R = Q_{\text{match}}$
3. Convert parameters to $\overline{\text{DR}}$, calculate λ^{NMSSM}
4. Compare λ^{NMSSM} with λ^{SM} from RGE running

5a. If same, chosen $\boldsymbol{M_h}$ is the predicted Higgs mass

5b. If not same, vary initial $\boldsymbol{M_h}$ guess and repeat procedure until convergence is reached



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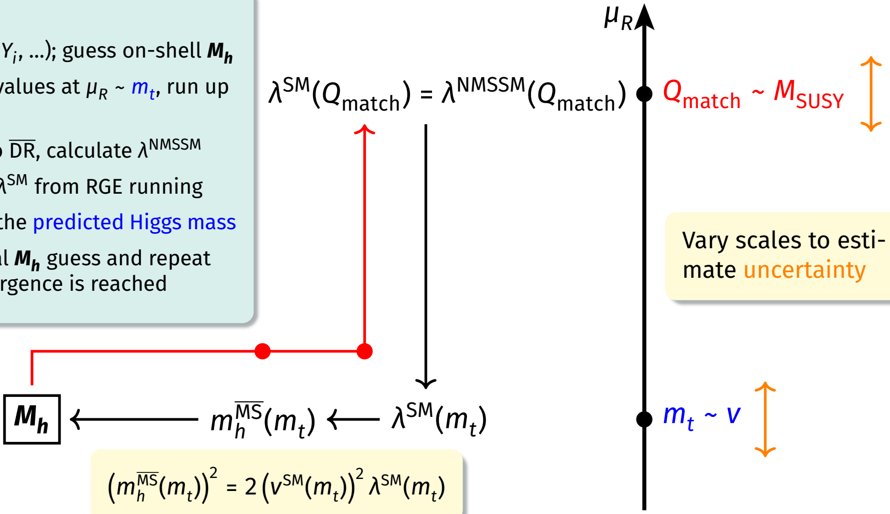
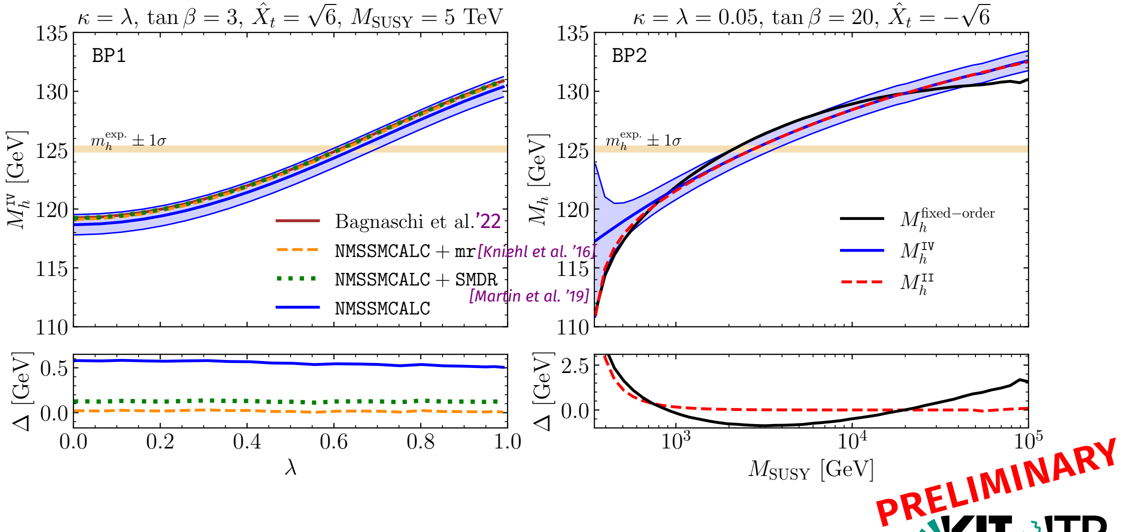


Vary scales to estimate uncertainty

$$\left(m_h^{\overline{\text{MS}}}(m_t)\right)^2 = 2\left(v^{\text{SM}}(m_t)\right)^2 \lambda^{\text{SM}}(m_t)$$

Comparison with previous works

[CB, Dao, Gabelmann, Mühlleitner, Rzehak; in preparation]



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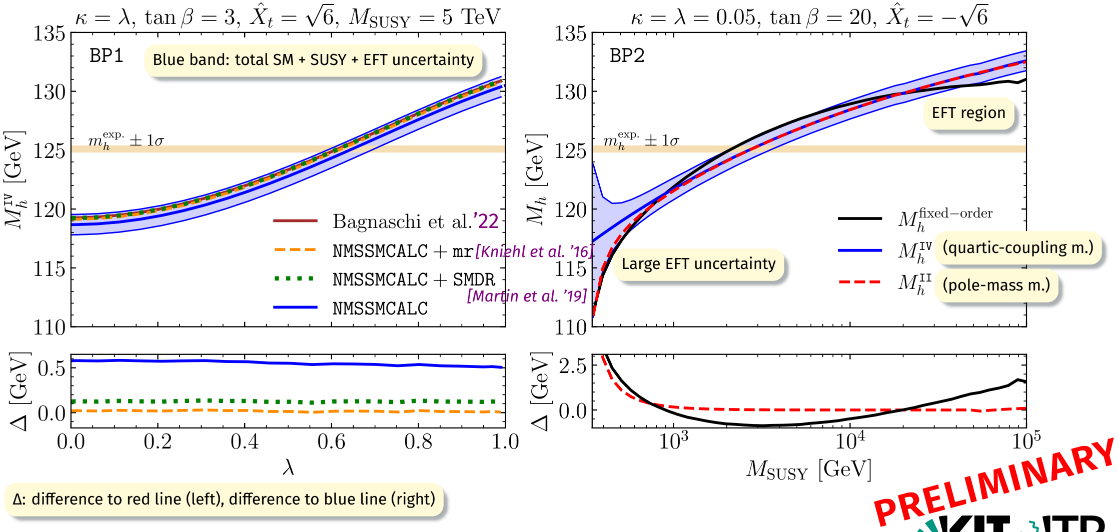
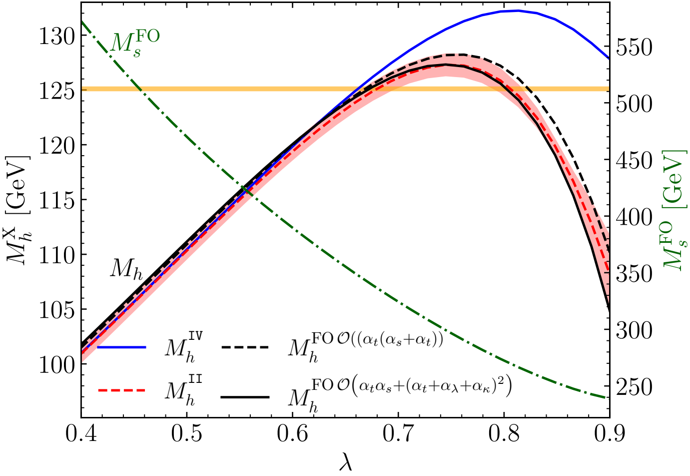


Δ: difference to red line (left), difference to blue line (right)

The case of a light singlet

[CB, Dao, Gabelmann, Mühlleitner, Rzehak; in preparation]

BP3 with $\kappa = \lambda \cdot \kappa^{\text{BP3}}/\lambda^{\text{BP3}}$, $A_\kappa = A_\kappa^{\text{BP3}} \cdot (3 - \lambda^{\text{BP3}}/\lambda)/2$

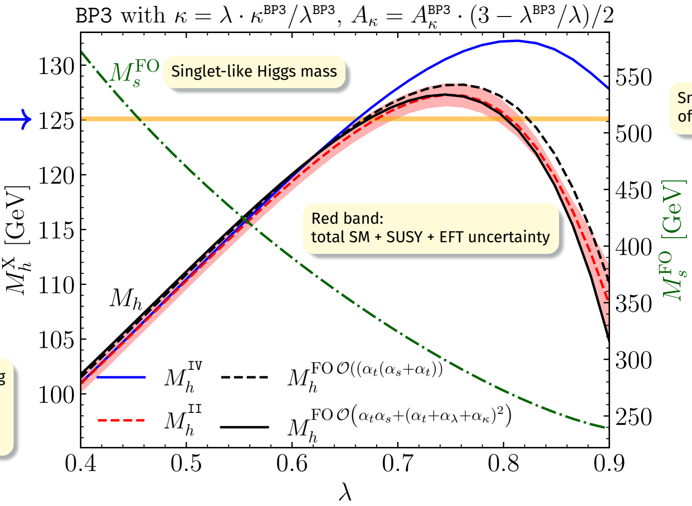


PRELIMINARY

The case of a light singlet

[CB, Dao, Gabelmann, Mühlleitner, Rzehak; in preparation]

Allowed region →



Small M_s: large impact of partial v/M_{SUSY} terms

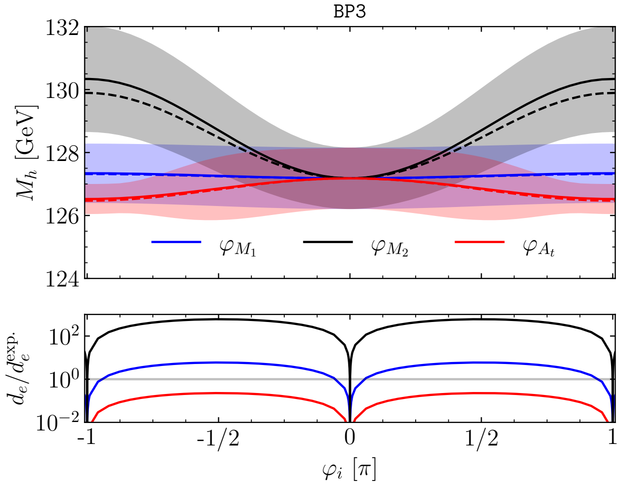
M_h^{IV}: quartic-coupling matching

M_h^{II}: pole-mass matching (contains v/M_{SUSY} terms)

PRELIMINARY

Effects of CP-violating phases

[CB, Dao, Gabelmann, Mühlleitner, Rzehak; in preparation]



PRELIMINARY

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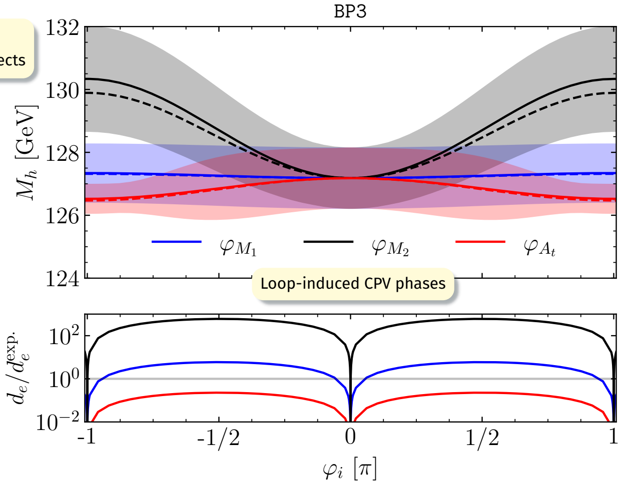
[CB, Dao, Gabelmann, Mühlleitner, Rzehak; in preparation]

Bands: total uncertainty
Solid vs. dashed: v/M_{SUSY} effects



$d_e/d_e^{\text{exp.}} > 1$:
excluded by electron EDMs

PRELIMINARY

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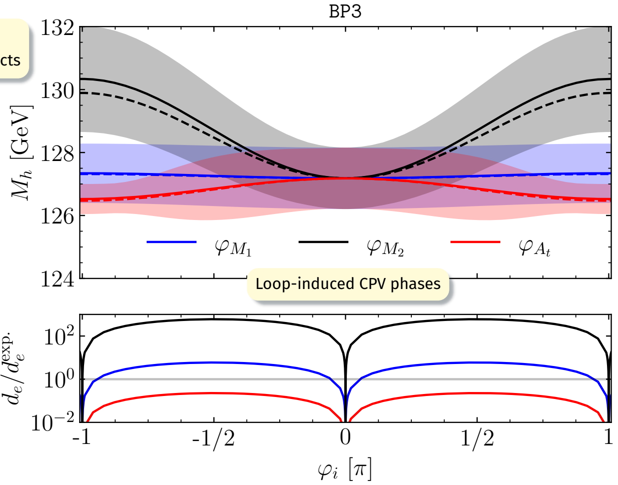

Loop-induced CPV phases

Tree-level CPV phases, e.g. φ_λ, more strongly constrained

$d_e/d_e^{\text{exp.}} > 1$: excluded by electron EDMs

PRELIMINARY

Summary

Calculation of the SM-like Higgs mass in the EFT approach for the CPV NMSSM

- Applicable for heavy SUSY masses ($v/M_{\text{SUSY}} \ll 1$), resums large logarithms
- Implementation at full 1L (+2L MSSM) via quartic-coupling & pole-mass matching
  - → Excellent agreement found for CPC and CPV case in $v \to 0$ limit ✓
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Implementation in our code **NMSSMCALC** (`https://itp.kit.edu/~maggie/NMSSMCALC`)

[Baglio, CB, Dao, Gabelmann, Gröber, Krause, Mühlleitner, Le, Rzehak, Spira, Streicher, Walz]

- Spectrum calculator of 1L & 2L Higgs masses, self couplings, decay widths
- For the CP-conserving and CP-violating NMSSM
- ...and more: electron eDMs, muon $g-2$, ρ parameter, W mass

EFT implementation to appear soon!

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THANK YOU FOR YOUR ATTENTION! ☺

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Backup

Quartic-coupling matching: tree-level contribution

$$\lambda_h^{\text{NMSSM,tree}} = \underbrace{\frac{1}{8}(g_1^2 + g_2^2)\cos^2 2\beta}_{\text{MSSM } D\text{-terms}} + \underbrace{\frac{1}{4}|\lambda|^2 \sin^2 2\beta}_{\text{NMSSM } F\text{-terms}}$$

$$- \underbrace{\frac{1}{48|\kappa|^2 M_S^2 (3M_S^2 + M_{A_s}^2)} \Big(3|\kappa|^2 M_{H^\pm}^2 (1 - \cos 4\beta) + (3M_S^2 + M_{A_s}^2)\big(|\kappa||\lambda| \cos\varphi_y \sin 2\beta - 2|\lambda|^2\big)\Big)^2}_{s/t/u\text{-channel } S}$$

$$- \underbrace{\frac{3}{16 M_{A_s}^2}|\lambda|^2 (3M_S^2 + M_{A_s}^2)\sin^2 2\beta \sin^2\varphi_y}_{s/t/u\text{-channel } A_s}$$

Benchmark points

BP1: *[Bagnaschi et al. '22]*
BP2: *[Slavich et al. '20]*

	$\tan\beta$	λ	κ	M_1	M_2	M_3	A_t	A_λ	A_κ	$\mu_{eff.}$	$m_{\tilde{Q}_{L_3}}$	$m_{\tilde{t}_{R_3}}$
BP1	3.0	0.6	0.6	1.0	2.0	2.5	12.75	0.3	-2.0	1.5	5.0	5.0
BP2	20.0	0.05	0.05	3.0	3.0	3.0	-7.20	-2.85	-1.0	3.0	3.0	3.0
BP3	1.27	0.73	0.62	0.24	1.18	2.3	-0.39	0.06	-1.44	0.49	1.79	1.51

	M_h^{II}	M_h^{IV}	m_{h_2}	m_{h_3}	m_{A_1}	m_{A_2}	m_{H^+}
BP1	124.29 (h_u)	124.31 (h_u)	2407.6 (h_s)	2971.8 (h_d)	2905.7 (a)	3000.2 (a_s)	2967.1
BP2	125.26 (h_u)	125.28 (h_u)	2996.4 (h_d)	5744.4 (h_s)	2985.3 (a_s)	3010.5 (a)	2997.8
BP3	127.18 (h_u)	129.47 (h_u)	305.5 (h_s)	659.5 (h_d)	663.8 (a)	1308.7 (a_s)	658.4