Effective Field Theories of the MSSM

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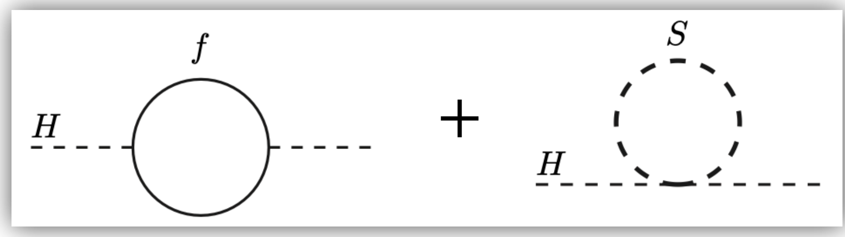
<u>Based on work in progress with:</u>

Sabine Kraml, Andre Lessa, Suraj Prakash, Lohan Sartore

Minimal Supersymmetric Standard Model (MSSM)

- **Hierarchy problem:** $\Delta m_H^2 \sim$ 

$\sim \frac{1}{16\pi^2}\left(\lambda_S M_S^2 - \lambda_f^2 M_f^2\right) \gg m_H^2$
- **Solutions:** technicolor/composite Higgs, supersymmetry, ...

For a SUSY/MSSM review see, e.g.: Martin [hep-ph/9709356]

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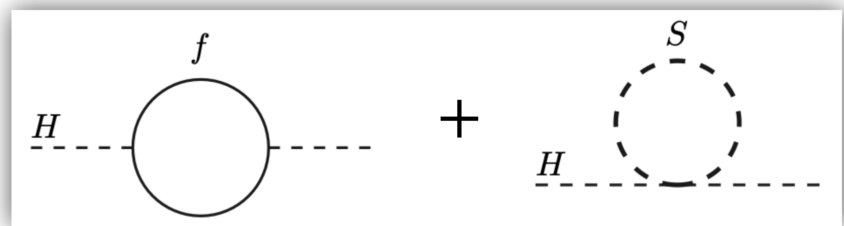
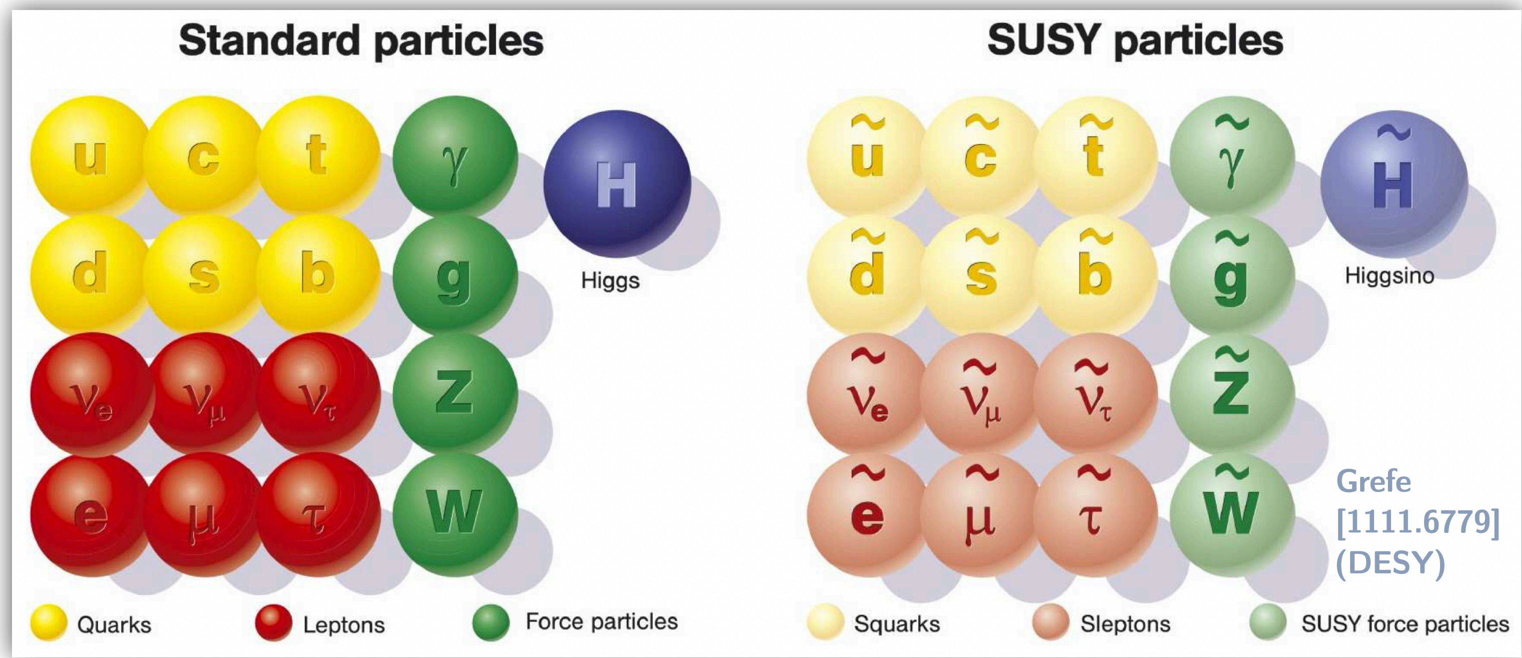
- **Hierarchy problem:** $\Delta m_H^2 \sim$  $\sim \frac{1}{16\pi^2} \underbrace{\left(\lambda_S M_S^2 - \lambda_f^2 M_f^2\right)}_{=0}$

for exact SUSY

- **Solutions:** technicolor/composite Higgs, supersymmetry, ...
- **Supersymmetry (SUSY):** space-time symmetry between scalars and fermions
- **M**inimal **S**upersymmetric **S**tandard **M**odel: every scalar/fermion has fermion/scalar partner



2nd Higgs doublet required to:

- Produce Yukawa couplings for both up- and down-type fermions with holomorphic super-potential
- Avoid gauge anomalies

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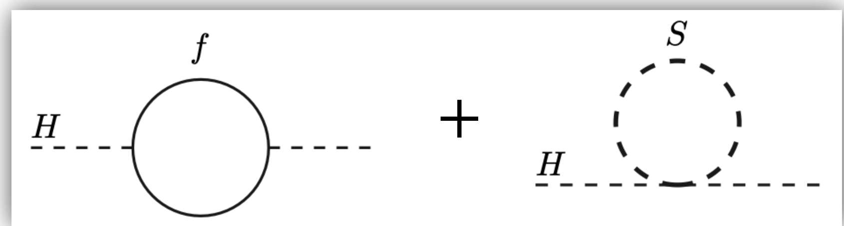
- **Hierarchy problem:** $\Delta m_H^2 \sim$ 

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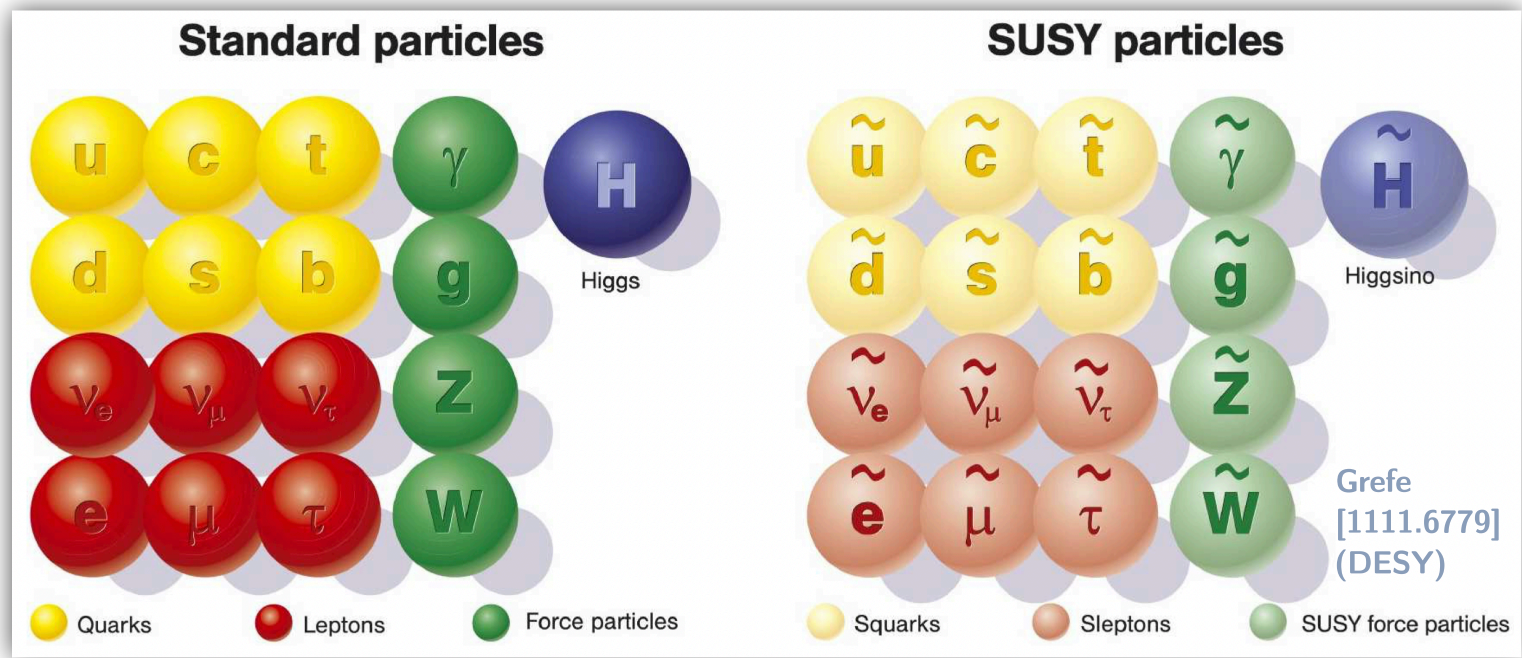

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- No observation of super-partners → **SUSY must be broken above electroweak scale**
- To solve Hierarchy problem SUSY breaking scale M_{SUSY} should not exceed a few TeV
- MSSM: best explored BSM theory (direct searches) → use also EFT methods ($M_{\text{SUSY}} \gg m_W$)

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Effective Field Theory scenarios for the MSSM

- So far: mostly model specific searches for MSSM superpartners
- Major developments in EFT community → exploit EFT toolbox for the MSSM analyses
- Consider R-parity conserving MSSM: even powers of superpartners in all interaction terms
  - **Leading MSSM-to-SMEFT matching contribution is at one loop** (except for 2nd Higgs)
- Automatic one-loop matching of full MSSM onto SMEFT using *MATCHETE* → see also Javi's talk

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- Possible scenarios:
  - Integrate out all superpartners at a single scale $m_W \ll M_{1,2,3}^{\text{SUSY}}$
  - Integrate out only 3rd gen. of sfermions $m_W \ll M_3^{\text{SUSY}} \ll M_{1,2}^{\text{SUSY}} \to \infty$
  - Retain 3rd gen. of sfermions in spectrum and integrate out 1st and 2nd gen. $m_W \lesssim M_3^{\text{SUSY}} \ll M_{1,2}^{\text{SUSY}}$

(last two scenarios) → $\text{U}(2)^5$ flavor symmetry

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  } → $\mathrm{U}(2)^5$ flavor symmetry
- Subtleties & challenges:
  - Many interactions in MSSM complicate matching (partially unknown EFT basis)
  - Lengthy matching conditions complicating mapping to Warsaw basis
  - Higgs sector: 2HDM → SM Higgs doublets needs to be identified

MSSM Lagrangian

- **Field content:** →
- **Gauge symmetry:** $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
- **Global symmetries:** Lorentz invariance, R-parity

Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\ \widetilde{e}_L)$	$(\nu\ \ e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H_u^+\ \ H_u^0)$	$(\widetilde{H}_u^+\ \ \widetilde{H}_u^0)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	H_d	$(H_d^0\ \ H_d^-)$	$(\widetilde{H}_d^0\ \ \widetilde{H}_d^-)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\,\mathbf{8},\ \mathbf{1}\,,\ 0)$
winos, W bosons	$\widetilde{W}^\pm\ \ \widetilde{W}^0$	$W^\pm\ \ W^0$	$(\,\mathbf{1},\ \mathbf{3}\,,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\,\mathbf{1},\ \mathbf{1}\,,\ 0)$

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- **Global symmetries:** Lorentz invariance, R-parity
- **Lagrangian:** Conventionally written in terms of supermultiplets (containing Weyl spinors)

$$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{chiral}} - \sqrt{2}g\left[(\phi^* T^a \psi)\,\lambda_a + \text{h.c.}\right] + g\,(\phi^* T^a \phi)\,D_a$$

$$\mathcal{L}_{\text{gauge}} = \mathcal{L}_{\text{gauge, kin}} + \frac{1}{2} D_a D^a$$

$$\mathcal{L}_{\text{chiral}} = \mathcal{L}_{\text{chiral, kin}} - \frac{1}{2}\left(W^{ij}\psi_i\psi_j + \text{h.c.}\right) - W_i^* W^i$$

$$D_a = -g\,(\phi^* T_a \phi) \qquad W_{\text{MSSM}} = \overline{u}\mathbf{y_u}QH_u - \overline{d}\mathbf{y_d}QH_d - \overline{e}\mathbf{y_e}LH_d + \mu H_u H_d$$

$$\begin{aligned}\mathcal{L}_{\text{soft}}^{\text{MSSM}} = & -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right) \\ & -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\ & -\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger \\ & - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + \text{c.c.})\,.\end{aligned}$$

- Express in terms of Dirac & Majorana spinors to match onto SMEFT

Two Higgs doublet model (2HDM) — type-II

- MSSM contains 2 Higgs doublets: $H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \sim (\mathbf{1},\mathbf{2})_{1/2}$ and $H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \sim (\mathbf{1},\mathbf{2})_{-1/2}$
- Higgs potential:

$$V_{\text{Higgs}}(H_1,H_2) = (|\mu|^2 + m_{H_u}^2)H_u^\dagger H_u + (|\mu|^2 + m_{H_d}^2)H_d^\dagger H_d + [bH_u^\intercal \varepsilon H_d + \text{H.c.}]$$
$$+ \frac{1}{8}(g_1^2 + g_2^2)\left(H_u^\dagger H_u - H_d^\dagger H_d\right)^2 + \frac{g_2^2}{2}(H_u^\dagger H_d)(H_d^\dagger H_u)\,.$$

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- **Physical Higgs bosons h^0:** superposition of CP-even components of H_u^0 and H_d^0
- Most general decomposition of Higgs doublets:

$$\begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix} = \frac{1}{\sqrt{2}}\left[R_\beta \begin{pmatrix} v \\ 0 \end{pmatrix} + R_\alpha \begin{pmatrix} h^0 \\ H^0 \end{pmatrix} + i\,R_{\beta_0}\begin{pmatrix} G^0 \\ A^0 \end{pmatrix}\right], \quad \begin{pmatrix} H_u^+ \\ H_d^+ \end{pmatrix} = R_{\beta_\pm}\begin{pmatrix} G^+ \\ H^+ \end{pmatrix}$$

$$R_\beta = \begin{pmatrix} s_\beta & -c_\beta \\ c_\beta & s_\beta \end{pmatrix}, \quad R_\alpha = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix}, \quad R_{\beta_0} = \begin{pmatrix} s_{\beta_0} & c_{\beta_0} \\ -c_{\beta_0} & s_{\beta_0} \end{pmatrix}, \quad R_{\beta_\pm} = \begin{pmatrix} s_{\beta_\pm} & c_{\beta_\pm} \\ -c_{\beta_\pm} & s_{\beta_\pm} \end{pmatrix}$$

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- EWSB conditions: $\beta = \beta_0 = \beta_\pm$ but $\alpha \neq \beta$, where $\tan\beta = v_u / v_d$ with $\langle H_{u,d}\rangle = v_{u,d}/\sqrt{2}$

$$\sin 2\beta = \frac{2b}{2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2} \qquad \frac{\tan 2\alpha}{\tan 2\beta} = \frac{m_{A^0}^2 + m_Z^2}{m_{A^0}^2 - m_Z^2}$$

β: rotation angle to Higgs basis,
where only one of the doublets acquires a VEV

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- In general we **cannot** write the SM doublet H as linear combination of $H_{u,d}$

$$\begin{pmatrix} H_u \\ H_d^c \end{pmatrix} = \begin{pmatrix} H_u \\ \varepsilon H_d^* \end{pmatrix} = \begin{pmatrix} \sin\gamma & \cos\gamma \\ -\cos\gamma & \sin\gamma \end{pmatrix} \begin{pmatrix} H \\ \Phi \end{pmatrix}$$

possible only in alignment limit: $\alpha = \beta - \frac{\pi}{2}$

MSSM matching onto SMEFT and/or HEFT

See also:
Dawson, Fontes, Homiller, Sullivan [2205.01561]
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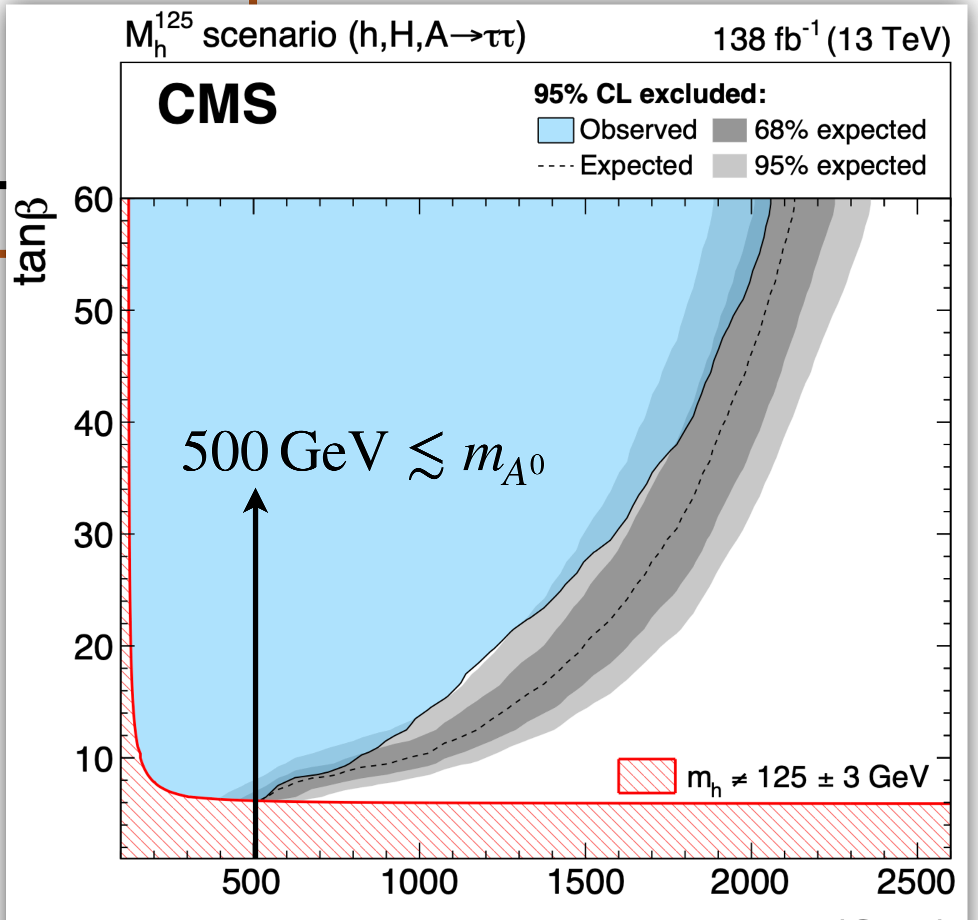
  - Natural alignment in decoupling limit $m_Z \ll m_{A^0}$
  - With bound $500\,\text{GeV} \lesssim m_{A^0}$ we find $\delta \lesssim 0.015$



CMS [2208.02717]

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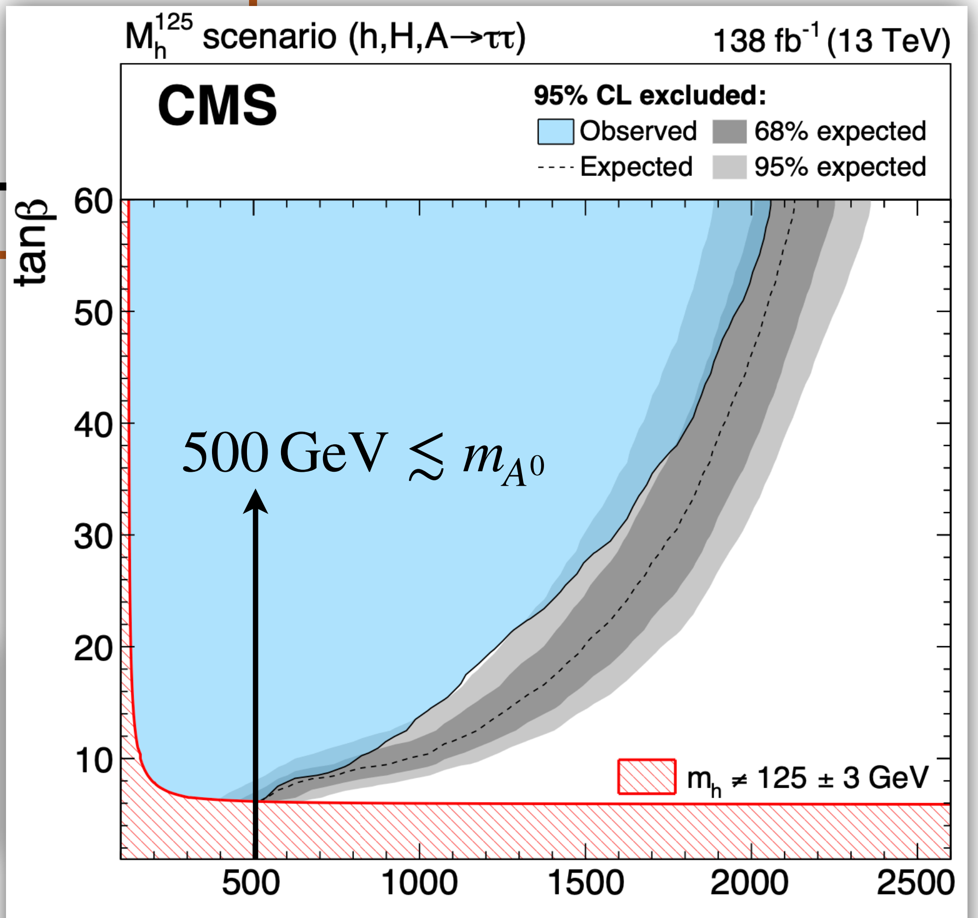
$$\mathcal{L}_{\text{Higgs}} = (D_\mu H)^\dagger (D^\mu H) + (D_\mu \Phi)^\dagger (D^\mu \Phi) - m_H^2 (H^\dagger H) - m_\Phi^2 (\Phi^\dagger \Phi) - \Delta (H^\dagger \Phi) - \Delta (\Phi^\dagger H) + \dots$$



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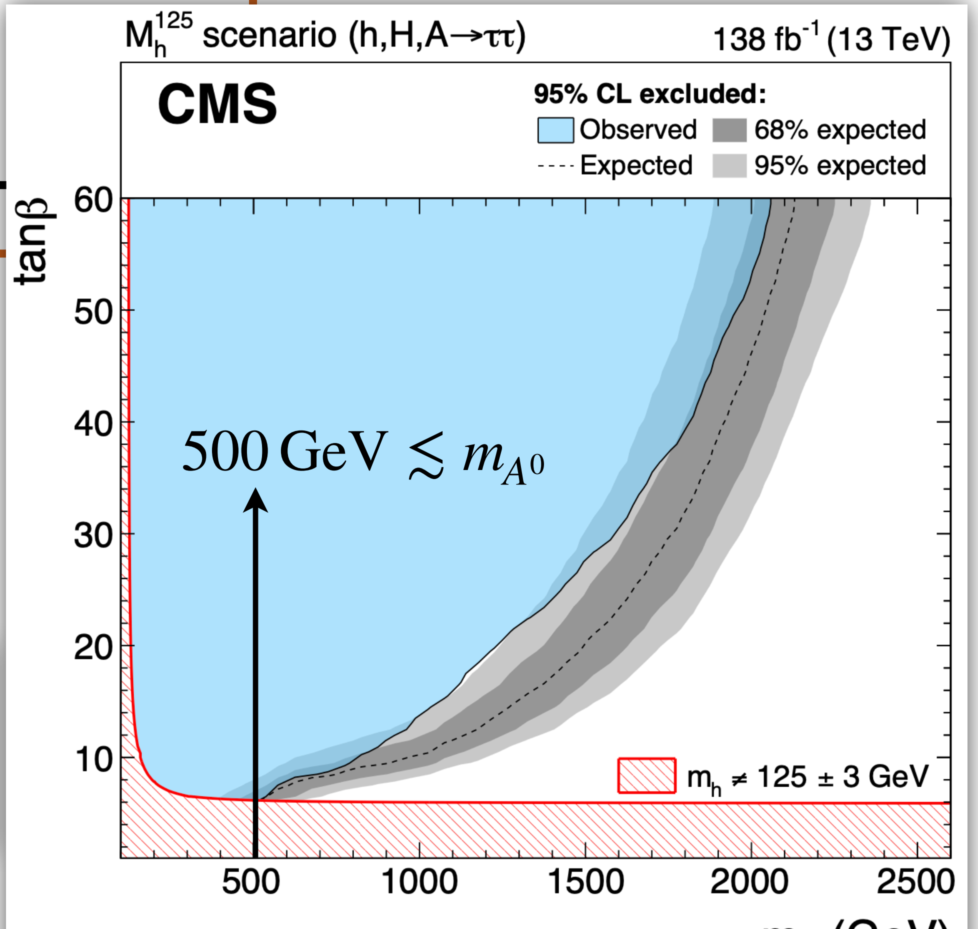

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$$\begin{aligned}\mathcal{L}_{\text{Higgs}} = \; & (D_\mu H)^\dagger (D^\mu H) + (D_\mu \Phi)^\dagger (D^\mu \Phi) \\ & - m_H^2 (H^\dagger H) - m_\Phi^2 (\Phi^\dagger \Phi) - \Delta (H^\dagger \Phi) - \Delta (\Phi^\dagger H) + \ldots\end{aligned}$$

- Mass mixing Δ between H and Φ

$$\Delta = (m_{H_u}^2 - m_{H_d}^2) s_\beta c_\beta + b(s_\beta^2 - c_\beta^2) = m_Z^2 \frac{\sin 4\beta}{4}$$

$\to \mathcal{O}(m_Z)$ mixing

$\Delta \sim m_H^2 \ll m_\Phi^2$
IR & UV d.o.f properly separated

Diagonalizing the Higgsino mass term

$\tilde{H}_u = \left(\tilde{H}_u^+,\, \tilde{H}_u^0\right)^\intercal \sim (\mathbf{1},\mathbf{2})_{1/2}$

$\tilde{H}_d = \left(\tilde{H}_d^0,\, \tilde{H}_d^-\right)^\intercal \sim (\mathbf{1},\mathbf{2})_{-1/2}$

chiral fermions chosen as left-handed

- Higgsinos $\tilde{H}_{u,d}$:
  - Heavy chiral fermions with mixed mass term:

$$\mathscr{L}_{\tilde{H}} \supset \overline{\tilde{H}}_u \gamma^\mu P_L D_\mu \tilde{H}_u + \overline{\tilde{H}}_d \gamma^\mu P_L D_\mu \tilde{H}_d + \left(\mu\, \overline{\tilde{H}}{}^c_d\, \varepsilon\, \tilde{H}_u + \text{H.c.}\right)$$

  - Mass term cannot be diagonalized (chiral fermions cannot be massive)

Diagonalizing the Higgsino mass term

$\tilde{H}_u = \left(\tilde{H}_u^+,\, \tilde{H}_u^0\right)^\intercal \sim (\mathbf{1},\mathbf{2})_{1/2}$

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  - Mass term cannot be diagonalized (chiral fermions cannot be massive)

- Combine both Higgsinos into a vectorlike fermion Σ
  - Use that $\varepsilon \tilde{H}_d^c \sim (\mathbf{1},\mathbf{2})_{1/2}$
  - Define vectorlike fermion by $\Sigma = P_L \tilde{H}_u + \varepsilon\, P_R \tilde{H}_d^c$
  - $\tilde{H}_u = P_L \Sigma$ and $\tilde{H}_d = -\,\varepsilon\, P_L \Sigma^c$

- Final Higgsino Lagrangian given by

$$\mathscr{L}_{\tilde{H}} \supset \overline{\Sigma} \gamma^\mu D_\mu \Sigma - \mu^2 \overline{\Sigma}\Sigma$$

Implementation in Matchete

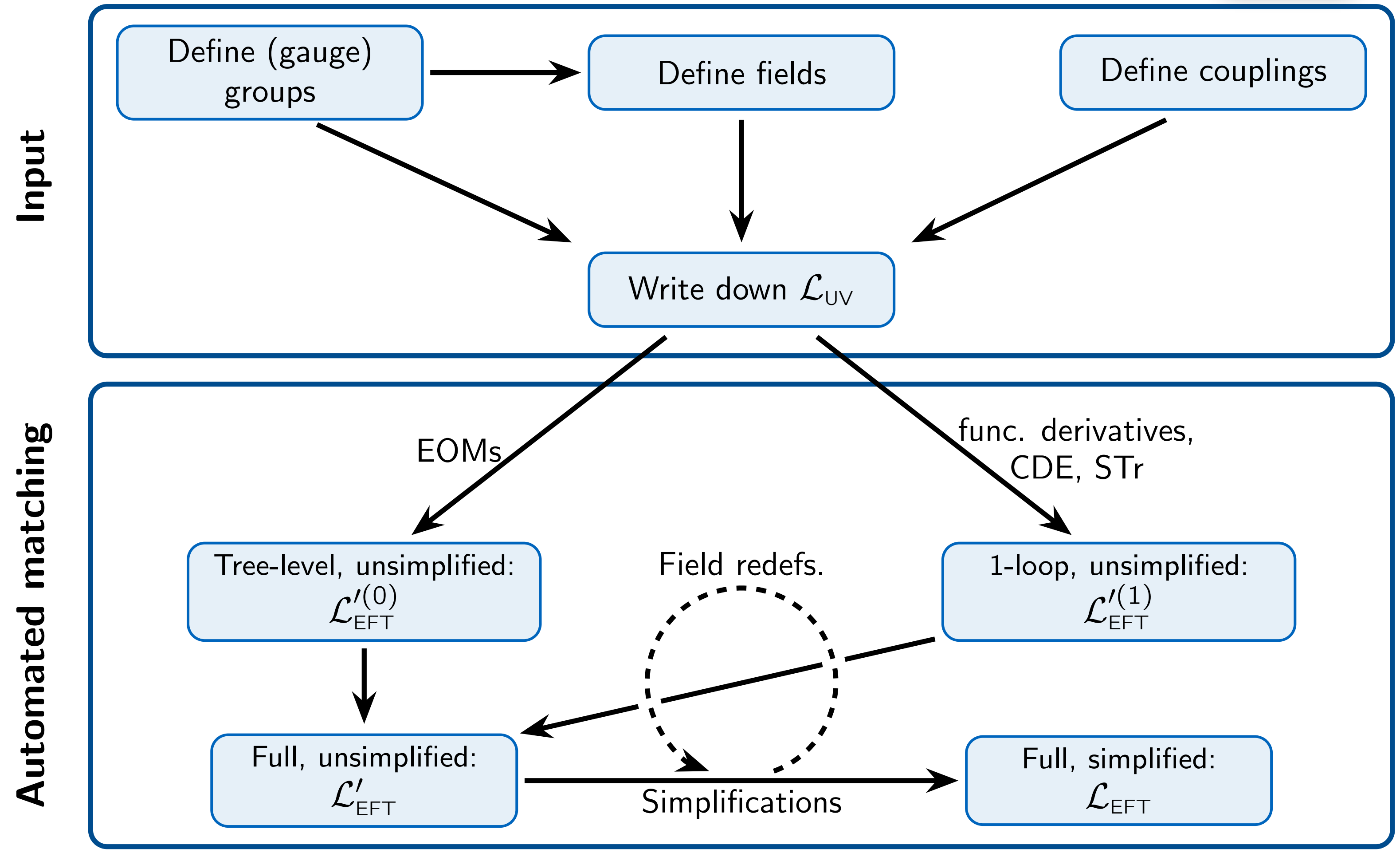
- Implement MSSM Lagrangian in an automatic matching tool

see also:
Carmona, Lazopoulos, Olgoso, Santiago [2112.10787]

→ see also Javi's talk

MATCHETE

- Lagrangian implemented using:
  - Dirac spinors for sfermions
  - Majorana spinors for gauginos
  - Vectorlike fermion for Higgsinos
  - Higgs basis for Higgs doublets



Fuentes-Martín, König, Pagès, Thomsen, FW [2212.04510]
https://gitlab.com/matchete/matchete

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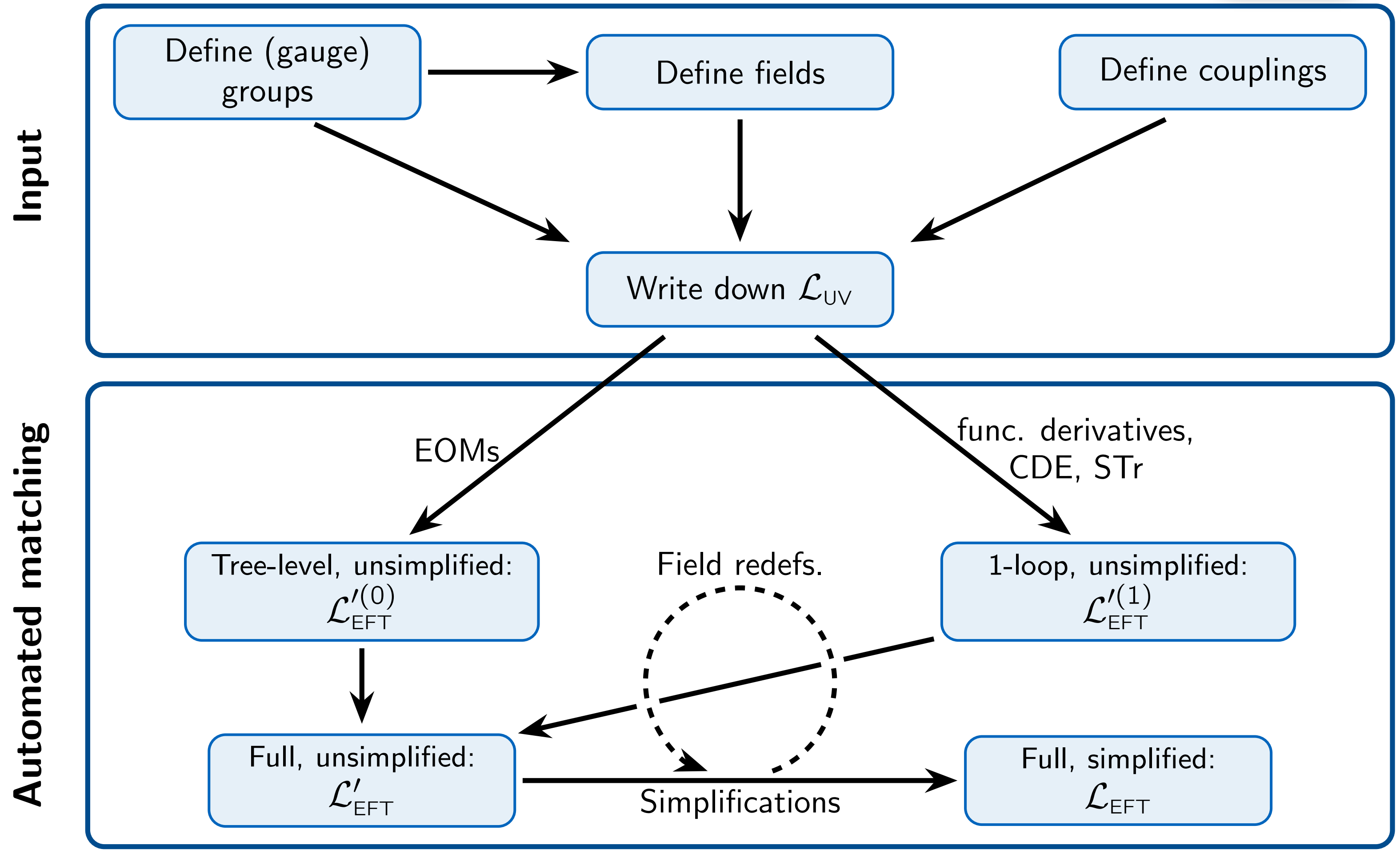

Fuentes-Martín, König, Pagès, Thomsen, FW [2212.04510]
https://gitlab.com/matchete/matchete

- Automatic tree-level and one-loop matching
- Automatic reduction of redundant EFT operators
  - Using off-shell (IbP, Fierz, ...) and on-shell (field redefinitions) identities
  - Proper treatment of evanescent operators — see Marco's talk & Fuentes-Martín, König, Pagès, Thomsen, FW [2211.09144]
  - Output: matching conditions in **Warsaw basis**

MSSM Lagrangian in Matchete (part 1)

$$-\frac{1}{4} B^{\mu\nu 2} - \frac{1}{4} G^{\mu\nu A 2} - \frac{1}{4} W^{\mu\nu I 2} + D_\mu \overline{dt}^r_a D_\mu dt^{ap}\delta^{pr} - Md^2 \overline{dt}^r_a dt^{ap}\delta^{pr} + D_\mu \overline{et}^r D_\mu et^p \delta^{pr} - Me^2 \overline{et}^r et^p \delta^{pr} + D_\mu \overline{lt}^r_i D_\mu lt^{ip}\delta^{pr} - Ml^2 \overline{lt}^r_i lt^{ip}\delta^{pr} +$$

$$D_\mu \overline{qt}^r_{ai} D_\mu qt^{aip}\delta^{pr} - Mq^2 \overline{qt}^r_{ai} qt^{aip}\delta^{pr} + D_\mu \overline{ut}^r_a D_\mu ut^{ap}\delta^{pr} - Mu^2 \overline{ut}^r_a ut^{ap}\delta^{pr} + D_\mu\bar\phi_i D_\mu \phi^i - m\phi^2 \bar\phi_i \phi^i + D_\mu \bar\Phi_i D_\mu \Phi^i - M\Phi^2 \bar\Phi_i \Phi^i + i\left(\bar d^r_a \cdot \gamma_\mu P_R \cdot D_\mu d^{ap}\right)\delta^{pr} +$$

$$i\left(\bar e^r \cdot \gamma_\mu P_R \cdot D_\mu e^p\right)\delta^{pr} + i\left(\bar l^r_i \cdot \gamma_\mu P_L \cdot D_\mu l^{ip}\right)\delta^{pr} + i\left(\bar q^r_{ai} \cdot \gamma_\mu P_L \cdot D_\mu q^{aip}\right)\delta^{pr} + i\left(\bar u^r_a \cdot \gamma_\mu P_R \cdot D_\mu u^{ap}\right)\delta^{pr} + i\left(\bar\Sigma_i \cdot \gamma_\mu \cdot D_\mu \Sigma^i\right) - \mu\left(\bar\Sigma_i \cdot \Sigma^i\right) +$$

$$\frac{i}{2}\left(Bt^T \cdot C\gamma_\mu \cdot D_\mu Bt\right) - \frac{1}{2} MB\left(Bt^T \cdot C \cdot Bt\right) + \frac{i}{2}\left(Gt^{AT} \cdot C\gamma_\mu \cdot D_\mu Gt^A\right) - \frac{1}{2} MG\left(Gt^{AT} \cdot C \cdot Gt^A\right) + \frac{i}{2}\left(Wt^{IT} \cdot C\gamma_\mu \cdot D_\mu Wt^I\right) - \frac{1}{2} MW\left(Wt^{IT} \cdot C \cdot Wt^I\right) -$$

$$\frac{1}{8} c2\beta^2 \left(g1^2 + g2^2\right)\bar\phi_i\bar\phi_j\phi^i\phi^j + \Big(-s2\beta\, m\phi^2\, \bar\Phi_i \phi^i - Yd^{rp} c\beta\, \bar\phi_i \left(\bar d^r_a \cdot P_L \cdot q^{aip}\right) - Ye^{rp} c\beta\, \bar\phi_i\left(\bar e^r \cdot P_L \cdot l^{ip}\right) - s\beta\, Yu^{rp}\phi^j\left(\bar u^r_a \cdot P_L \cdot q^{aip}\right)\varepsilon_{ij} +$$

$$\left(-ae^{rp} c\beta + s\beta\, Ye^{rp}\mu\right)\overline{et}^r lt^{ip}\bar\phi_i + \left(-ad^{rp} c\beta + s\beta\, Yd^{rp}\mu\right)\overline{dt}^r_a qt^{aip}\bar\phi_i + \left(-s\beta\, au^{rp} + Yu^{rp}\mu\, c\beta\right) qt^{aip}\overline{ut}^r_a \phi^j \varepsilon_{ij} + \frac{1}{8} s4\beta\left(g1^2+g2^2\right)\bar\Phi_j\bar\phi_i\phi^i\phi^j +$$

$$s\beta\, Yd^{rp}\bar\Phi_i\left(\bar d^r_a \cdot P_L \cdot q^{aip}\right) + Yd^{rp} qt^{aip}\left(\bar d^r_a \cdot C P_L \cdot \bar\Sigma_i{}^T\right) + s\beta\, Ye^{rp}\bar\Phi_i\left(\bar e^r \cdot P_L \cdot l^{ip}\right) + Ye^{rp} lt^{ip}\left(\bar e^r \cdot C P_L \cdot \bar\Sigma_i{}^T\right) - Yu^{rp} c\beta\, \Phi^j\left(\bar u^r_a \cdot P_L \cdot q^{aip}\right)\varepsilon_{ij} -$$

$$Yu^{rp} qt^{aip}\left(\bar u^r_a \cdot P_L \cdot \Sigma^j\right)\varepsilon_{ij} + Ye^{rp}\overline{et}^r\left(\bar\Sigma_i \cdot P_L \cdot l^{ip}\right) + Yd^{rp}\overline{dt}^r_a\left(\bar\Sigma_i \cdot P_L \cdot q^{aip}\right) - g1\, s\beta\, \bar\phi_i\left(Bt^T \cdot C P_L \cdot \Sigma^i\right)\frac{1}{\sqrt{2}} - g1\, c\beta\, \bar\phi_i\left(Bt^T \cdot C P_R \cdot \Sigma^i\right)\frac{1}{\sqrt{2}} -$$

$$Yu^{rp}\overline{ut}^r_a\left(q^{aipT} \cdot C P_L \cdot \Sigma^j\right)\varepsilon_{ij} - g2\, s\beta\, \bar\phi_i\left(Wt^{IT} \cdot C P_L \cdot \Sigma^j\right)\sqrt{2}\, T^{Ii}_j - g2\, c\beta\, \bar\phi_i\left(Wt^{IT} \cdot C P_R \cdot \Sigma^j\right)\sqrt{2}\, T^{Ii}_j + \left(s\beta\, ae^{rp} + Ye^{rp}\mu\, c\beta\right)\overline{et}^r lt^{ip}\bar\Phi_i +$$

$$\left(s\beta\, ad^{rp} + Yd^{rp}\mu\, c\beta\right)\overline{dt}^r_a qt^{aip}\bar\Phi_i - \frac{1}{8} s2\beta^2\left(g1^2+g2^2\right)\bar\Phi_i\bar\Phi_j\phi^i\phi^j + \left(-au^{rp} c\beta - s\beta\, Yu^{rp}\mu\right) qt^{aip}\overline{ut}^r_a\Phi^j\varepsilon_{ij} + g1\,\overline{lt}^r_i\left(Bt^T \cdot C P_L \cdot l^{ip}\right)\frac{1}{\sqrt{2}}\delta^{pr} -$$

$$\frac{1}{3} g1\,\overline{qt}^r_{ai}\left(Bt^T \cdot C P_L \cdot q^{aip}\right)\frac{1}{\sqrt{2}}\delta^{pr} - g1\, c\beta\, \bar\Phi_i\left(Bt^T \cdot C P_L \cdot \Sigma^i\right)\frac{1}{\sqrt{2}} - \frac{1}{3} g1\,\overline{dt}^r_a\left(Bt^T \cdot C P_R \cdot d^{ap}\right)\sqrt{2}\,\delta^{pr} - g1\,\overline{et}^r\left(Bt^T \cdot C P_R \cdot e^p\right)\sqrt{2}\,\delta^{pr} +$$

$$\frac{2}{3} g1\,\overline{ut}^r_a\left(Bt^T \cdot C P_R \cdot u^{ap}\right)\sqrt{2}\,\delta^{pr} + g1\, s\beta\, \bar\Phi_i\left(Bt^T \cdot C P_R \cdot \Sigma^i\right)\frac{1}{\sqrt{2}} - g3\,\overline{qt}^r_{ai}\left(Gt^{AT} \cdot C P_L \cdot q^{bip}\right)\sqrt{2}\, T^{Aa}_b\delta^{pr} + g3\,\overline{dt}^r_a\left(Gt^{AT} \cdot C P_R \cdot d^{bp}\right)\sqrt{2}\, T^{Aa}_b\delta^{pr} +$$

$$g3\,\overline{ut}^r_a\left(Gt^{AT} \cdot C P_R \cdot u^{bp}\right)\sqrt{2}\, T^{Aa}_b\delta^{pr} - g2\,\overline{lt}^r_i\left(Wt^{IT} \cdot C P_L \cdot l^{jp}\right)\sqrt{2}\, T^{Ii}_j\delta^{pr} - g2\,\overline{qt}^r_{ai}\left(Wt^{IT} \cdot C P_L \cdot q^{ajp}\right)\sqrt{2}\, T^{Ii}_j\delta^{pr} - g2\, c\beta\, \bar\Phi_i\left(Wt^{IT} \cdot C P_L \cdot \Sigma^j\right)\sqrt{2}\, T^{Ii}_j +$$

$$g2\, s\beta\, \bar\Phi_i\left(Wt^{IT} \cdot C P_R \cdot \Sigma^j\right)\sqrt{2}\, T^{Ii}_j + \frac{1}{6} s2\beta\left(3\,\overline{Yd}^{ps} Yd^{rs} - g1^2\delta^{pr}\right)\overline{dt}^r_a dt^{ap}\bar\Phi_i\phi^i + s\beta\, c\beta\left(\overline{Ye}^{ps} Ye^{rs} - g1^2\delta^{pr}\right)\overline{et}^r et^p\bar\Phi_i\phi^i +$$

$$s\beta\, c\beta\left(\overline{Ye}^{sr} Ye^{sp} - g2^2\delta^{pr}\right)\overline{lt}^r_i lt^{jp}\bar\Phi_j\phi^i + s\beta\, c\beta\left(\overline{Yd}^{sr} Yd^{sp} + \overline{Yu}^{sr} Yu^{sp} - g2^2\delta^{pr}\right)\overline{qt}^r_{ai} qt^{ajp}\bar\Phi_j\phi^i + \frac{1}{6} s2\beta\left(-3\,\overline{Yu}^{ps} Yu^{rs} + 2\, g1^2\delta^{pr}\right)\overline{ut}^r_a ut^{ap}\bar\Phi_i\phi^i +$$

$$\frac{1}{4}\left(2\,\overline{Ye}^{sr} Ye^{sp}\left(s2\beta - 2\, s\beta\, c\beta\right) + s2\beta\left(g1^2+g2^2\right)\delta^{pr}\right)\overline{lt}^r_i lt^{ip}\bar\Phi_j\phi^j + \frac{1}{12}\left(6\,\overline{Yd}^{sr} Yd^{sp}\left(s2\beta - 2\, s\beta\, c\beta\right) - s2\beta\left(6\,\overline{Yu}^{sr} Yu^{sp} + \left(g1^2 - 3\, g2^2\right)\delta^{pr}\right)\right)$$

$$\overline{qt}^r_{ai} qt^{aip}\bar\Phi_j\phi^j - \frac{1}{8} s4\beta\left(g1^2+g2^2\right)\bar\Phi_i\bar\Phi_j\Phi^j\phi^i - \overline{Yd}^{ps} Yu^{rs} dt^{ap}\overline{ut}^r_a\Phi^j\phi^i\varepsilon_{ij} - \overline{Yd}^{pt} Ye^{sr} dt^{ap}\overline{et}^s lt^{ir}\overline{qt}^t_{ai} + \text{H.c.}\Big) +$$

$$\left(-\overline{Yd}^{ps} Yd^{rs} c\beta^2 + \frac{1}{6} c2\beta\, g1^2\delta^{pr}\right)\overline{dt}^r_a dt^{ap}\bar\phi_i\phi^i + \left(-\overline{Ye}^{ps} Ye^{rs} c\beta^2 + \frac{1}{2} c2\beta\, g1^2\delta^{pr}\right)\overline{et}^r et^p\bar\phi_i\phi^i +$$

$$\left(-\overline{Ye}^{sr} Ye^{sp} c\beta^2 + \frac{1}{2} c2\beta\, g2^2\delta^{pr}\right)\overline{lt}^r_i lt^{jp}\bar\phi_j\phi^i +$$

$$\left(-\overline{Yd}^{sr} Yd^{sp} c\beta^2 + \overline{Yu}^{sr} Yu^{sp} s\beta^2 + \frac{1}{2} c2\beta\, g2^2\delta^{pr}\right)\overline{qt}^r_{ai} qt^{ajp}\bar\phi_j\phi^i +$$

MSSM Lagrangian in Matchete (part 2)

$$\left(-\overline{Yu}^{ps}\, Yu^{rs}\, s\beta^2 - \frac{1}{3}\, c2\beta\, g1^2\, \delta^{pr}\right) \overline{ut}^r_a\, ut^{ap}\, \bar{\phi}_i\, \phi^i -$$

$$\frac{1}{4}\, c2\beta\, \left(g1^2 + g2^2\right) \overline{lt}^r_i\, lt^{ip}\, \bar{\phi}_j\, \phi^j\, \delta^{pr} +$$

$$\left(-\overline{Yu}^{sr}\, Yu^{sp}\, s\beta^2 + \frac{1}{12}\, c2\beta\, \left(g1^2 - 3\, g2^2\right) \delta^{pr}\right) \overline{qt}^r_{ai}\, qt^{aip}\, \bar{\phi}_j\, \phi^j +$$

$$\frac{1}{8}\, \left(g1^2\, (-1 + c4\beta) + g2^2\, (3 + c4\beta)\right) \bar{\Phi}_j\, \Phi^i\, \bar{\phi}_i\, \phi^j +$$

$$\frac{1}{8}\, \left(g1^2\, (1 + c4\beta) + g2^2\, (-3 + c4\beta)\right) \bar{\Phi}_j\, \Phi^j\, \bar{\phi}_i\, \phi^i +$$

$$\frac{1}{36}\, \left(-2\, g1^2\, \delta^{pt}\, \delta^{rs} + 3\, g3^2\, \left(\delta^{pt}\, \delta^{rs} - 3\, \delta^{ps}\, \delta^{rt}\right)\right) \overline{dt}^s_a\, \overline{dt}^t_b\, dt^{ar}\, dt^{bp} -$$

$$\frac{1}{3}\, g1^2\, \overline{dt}^s_a\, dt^{ap}\, \overline{et}^t\, et^r\, \delta^{ps}\, \delta^{rt} - \frac{1}{2}\, g1^2\, \overline{et}^s\, \overline{et}^t\, et^p\, et^r\, \delta^{ps}\, \delta^{rt} +$$

$$\frac{1}{6}\, g1^2\, \overline{dt}^s_a\, dt^{ap}\, \overline{lt}^t_i\, lt^{ir}\, \delta^{ps}\, \delta^{rt} + \left(-\overline{Ye}^{pt}\, Ye^{sr} + \frac{1}{2}\, g1^2\, \delta^{ps}\, \delta^{rt}\right) \overline{et}^s\, et^p\, \overline{lt}^t_i\, lt^{ir} +$$

$$\frac{1}{8}\, \left(-g1^2\, \delta^{pt}\, \delta^{rs} + g2^2\, \left(\delta^{pt}\, \delta^{rs} - 2\, \delta^{ps}\, \delta^{rt}\right)\right) \overline{lt}^s_i\, \overline{lt}^t_j\, lt^{ir}\, lt^{jp} +$$

$$\left(-\overline{Yd}^{pt}\, Yd^{sr} + \frac{1}{2}\, g3^2\, \delta^{ps}\, \delta^{rt}\right) \overline{dt}^s_a\, dt^{bp}\, \overline{qt}^t_{bi}\, qt^{air} - \frac{1}{6}\, g1^2\, \overline{et}^s\, et^p\, \overline{qt}^t_{ai}\, qt^{air}\, \delta^{ps}\, \delta^{rt} -$$

$$\frac{1}{2}\, g2^2\, \overline{lt}^s_i\, lt^{jp}\, \overline{qt}^t_{aj}\, qt^{air}\, \delta^{ps}\, \delta^{rt} + \frac{1}{12}\, \left(g1^2 + 3\, g2^2\right) \overline{lt}^s_i\, lt^{ip}\, \overline{qt}^t_{aj}\, qt^{ajr}\, \delta^{ps}\, \delta^{rt} -$$

$$\frac{1}{18}\, \left(g1^2 + 3\, g3^2\right) \overline{dt}^s_a\, dt^{ap}\, \overline{qt}^t_{bi}\, qt^{bir}\, \delta^{ps}\, \delta^{rt} + \frac{1}{4}\, \left(-g3^2\, \delta^{pt}\, \delta^{rs} - g2^2\, \delta^{ps}\, \delta^{rt}\right) \overline{qt}^s_{ai}\, \overline{qt}^t_{bj}\, qt^{ajp}\, qt^{bir} -$$

$$\frac{1}{72}\, \left(g1^2 - 9\, g2^2 - 6\, g3^2\right) \overline{qt}^s_{ai}\, \overline{qt}^t_{bj}\, qt^{aip}\, qt^{bjr}\, \delta^{ps}\, \delta^{rt} - \frac{1}{2}\, g3^2\, \overline{dt}^s_a\, dt^{bp}\, \overline{ut}^t_b\, ut^{ar}\, \delta^{ps}\, \delta^{rt} +$$

$$\frac{2}{3}\, g1^2\, \overline{et}^s\, et^p\, \overline{ut}^t_a\, ut^{ar}\, \delta^{ps}\, \delta^{rt} - \frac{1}{3}\, g1^2\, \overline{lt}^s_i\, lt^{ip}\, \overline{ut}^t_a\, ut^{ar}\, \delta^{ps}\, \delta^{rt} +$$

$$\left(-\overline{Yu}^{rs}\, Yu^{tp} + \frac{1}{2}\, g3^2\, \delta^{ps}\, \delta^{rt}\right) \overline{qt}^s_{ai}\, qt^{bip}\, \overline{ut}^t_b\, ut^{ar} + \frac{1}{36}\, \left(-8\, g1^2\, \delta^{pt}\, \delta^{rs} + 3\, g3^2\, \left(\delta^{pt}\, \delta^{rs} - 3\, \delta^{ps}\, \delta^{rt}\right)\right) \overline{ut}^s_a\, \overline{ut}^t_b\, ut^{ar}\, ut^{bp} +$$

$$\frac{1}{18}\, \left(4\, g1^2 + 3\, g3^2\right) \overline{dt}^s_a\, dt^{ap}\, \overline{ut}^t_b\, ut^{br}\, \delta^{ps}\, \delta^{rt} + \frac{1}{18}\, \left(2\, g1^2 - 3\, g3^2\right) \overline{qt}^s_{ai}\, qt^{aip}\, \overline{ut}^t_b\, ut^{br}\, \delta^{ps}\, \delta^{rt} +$$

$$\left(-\overline{Yd}^{ps}\, Yd^{rs}\, s\beta^2 - \frac{1}{6}\, c2\beta\, g1^2\, \delta^{pr}\right) \overline{dt}^r_a\, dt^{ap}\, \bar{\Phi}_i\, \Phi^i + \left(-\overline{Ye}^{ps}\, Ye^{rs}\, s\beta^2 - \frac{1}{2}\, c2\beta\, g1^2\, \delta^{pr}\right) \overline{et}^r\, et^p\, \bar{\Phi}_i\, \Phi^i +$$

$$\left(-\overline{Ye}^{sr}\, Ye^{sp}\, s\beta^2 - \frac{1}{2}\, c2\beta\, g2^2\, \delta^{pr}\right) \overline{lt}^r_i\, lt^{jp}\, \bar{\Phi}_j\, \Phi^i + \left(-\overline{Yd}^{sr}\, Yd^{sp}\, s\beta^2 + \overline{Yu}^{sr}\, Yu^{sp}\, c\beta^2 - \frac{1}{2}\, c2\beta\, g2^2\, \delta^{pr}\right) \overline{qt}^r_{ai}\, qt^{ajp}\, \bar{\Phi}_j\, \Phi^i +$$

$$\left(-\overline{Yu}^{ps}\, Yu^{rs}\, c\beta^2 + \frac{1}{3}\, c2\beta\, g1^2\, \delta^{pr}\right) \overline{ut}^r_a\, ut^{ap}\, \bar{\Phi}_i\, \Phi^i + \frac{1}{4}\, c2\beta\, \left(g1^2 + g2^2\right) \overline{lt}^r_i\, lt^{ip}\, \bar{\Phi}_j\, \Phi^j\, \delta^{pr} +$$

$$\left(-\overline{Yu}^{sr}\, Yu^{sp}\, c\beta^2 - \frac{1}{12}\, c2\beta\, \left(g1^2 - 3\, g2^2\right) \delta^{pr}\right) \overline{qt}^r_{ai}\, qt^{aip}\, \bar{\Phi}_j\, \Phi^j - \frac{1}{8}\, c2\beta^2\, \left(g1^2 + g2^2\right) \bar{\Phi}_i\, \bar{\Phi}_j\, \Phi^i\, \Phi^j$$

MSSM Lagrangian:

117 different terms

(excluding Hermitian conjugates)

Tree-level matching

- Tree-level matching of $\mathscr{L}_{\text{MSSM}}$ to $\mathscr{L}_{\text{SMEFT}}$

```
ℒEFT0 = Match[ℒMSSM, EFTOrder → 6, LoopOrder → 0];
% // HcSimplify // NiceForm
```

$$
\begin{aligned}
&-\frac{1}{4} B^{\mu\nu 2} - \frac{1}{4} G^{\mu\nu A 2} - \frac{1}{4} W^{\mu\nu I 2} + D_\mu \bar{\phi}_i D_\mu \phi^i + \left(-m\phi^2 + m\phi^4\, s2\beta^2 \frac{1}{M\Phi^2}\right) \bar{\phi}_i \phi^i + \mathrm{i} \left(\bar{d}^r_a \cdot \gamma_\mu P_R \cdot D_\mu d^{ap}\right) \delta^{pr} + \\
&\mathrm{i} \left(\bar{e}^r \cdot \gamma_\mu P_R \cdot D_\mu e^p\right) \delta^{pr} + \mathrm{i} \left(\bar{l}^r_i \cdot \gamma_\mu P_L \cdot D_\mu l^{ip}\right) \delta^{pr} + \mathrm{i} \left(\bar{q}^r_{ai} \cdot \gamma_\mu P_L \cdot D_\mu q^{aip}\right) \delta^{pr} + \mathrm{i} \left(\bar{u}^r_a \cdot \gamma_\mu P_R \cdot D_\mu u^{ap}\right) \delta^{pr} + \\
&\left(-\frac{1}{8} c2\beta^2 \left(g1^2 + g2^2\right) - \frac{1}{4} s2\beta\, s4\beta\, m\phi^2 \frac{1}{M\Phi^2} \left(g1^2 + g2^2\right)\right) \bar{\phi}_i \bar{\phi}_j \phi^i \phi^j + \frac{1}{64} s4\beta^2 \frac{1}{M\Phi^2} \bar{\phi}_i \bar{\phi}_j \bar{\phi}_k \phi^i \phi^j \phi^k \left(g1^2 + g2^2\right)^2 + \\
&\Bigg(\left(-Yd^{rp} c\beta - s2\beta\, s\beta\, Yd^{rp} m\phi^2 \frac{1}{M\Phi^2}\right) \bar{\phi}_i \left(\bar{d}^r_a \cdot P_L \cdot q^{aip}\right) + \left(-Ye^{rp} c\beta - s2\beta\, s\beta\, Ye^{rp} m\phi^2 \frac{1}{M\Phi^2}\right) \bar{\phi}_i \left(\bar{e}^r \cdot P_L \cdot l^{ip}\right) + \left(s2\beta\, Yu^{rp} c\beta\, m\phi^2 \frac{1}{M\Phi^2} - s\beta\, Yu^{rp}\right) \\
&\quad \phi^j \left(\bar{u}^r_a \cdot P_L \cdot q^{aip}\right) \bar{\varepsilon}_{ij} + \frac{1}{8} s4\beta\, s\beta\, Yd^{rp} \frac{1}{M\Phi^2} \left(g1^2 + g2^2\right) \bar{\phi}_i \bar{\phi}_j \phi^i \left(\bar{d}^r_a \cdot P_L \cdot q^{ajp}\right) + \frac{1}{8} s4\beta\, s\beta\, Ye^{rp} \frac{1}{M\Phi^2} \left(g1^2 + g2^2\right) \bar{\phi}_i \bar{\phi}_j \phi^i \left(\bar{e}^r \cdot P_L \cdot l^{jp}\right) - \\
&\quad \frac{1}{8} s4\beta\, Yu^{rp} c\beta \frac{1}{M\Phi^2} \left(g1^2 + g2^2\right) \bar{\phi}_i \phi^i \phi^k \left(\bar{u}^r_a \cdot P_L \cdot q^{ajp}\right) \bar{\varepsilon}_{jk} + \overline{Yd}^{pt} Ye^{sr} s\beta^2 \frac{1}{M\Phi^2} \left(\bar{e}^s \cdot P_L \cdot l^{ir}\right) \left(\bar{q}^t_{ai} \cdot P_R \cdot d^{ap}\right) - \\
&\quad s\beta\, Ye^{sp} Yu^{tr} c\beta \frac{1}{M\Phi^2} \left(\bar{e}^s \cdot P_L \cdot l^{jp}\right) \left(\bar{u}^t_a \cdot P_L \cdot q^{air}\right) \bar{\varepsilon}_{ij} - s\beta\, Yd^{sp} Yu^{tr} c\beta \frac{1}{M\Phi^2} \left(\bar{d}^s_a \cdot P_L \cdot q^{ajp}\right) \left(\bar{u}^t_b \cdot P_L \cdot q^{bir}\right) \bar{\varepsilon}_{ij} + \mathrm{H.c.} \Bigg) + \\
&\overline{Ye}^{pt} Ye^{sr} s\beta^2 \frac{1}{M\Phi^2} \left(\bar{e}^s \cdot P_L \cdot l^{ir}\right) \left(\bar{l}^t_i \cdot P_R \cdot e^p\right) + \overline{Yd}^{pt} Yd^{sr} s\beta^2 \frac{1}{M\Phi^2} \left(\bar{d}^s_a \cdot P_L \cdot q^{air}\right) \left(\bar{q}^t_{bi} \cdot P_R \cdot d^{bp}\right) + \\
&\overline{Yu}^{rs} Yu^{tp} \frac{1}{M\Phi^2} c\beta^2 \left(\bar{q}^s_{ai} \cdot P_R \cdot u^{ar}\right) \left(\bar{u}^t_b \cdot P_L \cdot q^{bip}\right)
\end{aligned}
$$

- Contributions only by 2nd heavy Higgs Φ, superpartner contributions forbidden by R-parity

Tree-level matching

- Tree-level matching of $\mathscr{L}_{\text{MSSM}}$ to $\mathscr{L}_{\text{SMEFT}}$

```
ℒEFT0 = Match[ℒMSSM, EFTOrder → 6, LoopOrder → 0];
% // HcSimplify // NiceForm
```

$$
\begin{aligned}
&-\frac{1}{4}B^{\mu\nu 2}-\frac{1}{4}G^{\mu\nu A2}-\frac{1}{4}W^{\mu\nu I2}+D_\mu\bar\phi_i D_\mu\phi^i+\left(-m\phi^2+m\phi^4\, s2\beta^2\frac{1}{M\Phi^2}\right)\bar\phi_i\phi^i+i\left(\bar d^r_a\cdot\gamma_\mu P_R\cdot D_\mu d^{ap}\right)\delta^{pr}+\\
&i\left(\bar e^r\cdot\gamma_\mu P_R\cdot D_\mu e^p\right)\delta^{pr}+i\left(\bar l^r_i\cdot\gamma_\mu P_L\cdot D_\mu l^{ip}\right)\delta^{pr}+i\left(\bar q^r_{ai}\cdot\gamma_\mu P_L\cdot D_\mu q^{aip}\right)\delta^{pr}+i\left(\bar u^r_a\cdot\gamma_\mu P_R\cdot D_\mu u^{ap}\right)\delta^{pr}+\\
&\left(-\frac{1}{8}c2\beta^2\left(g1^2+g2^2\right)-\frac{1}{4}s2\beta\, s4\beta\, m\phi^2\frac{1}{M\Phi^2}\left(g1^2+g2^2\right)\right)\bar\phi_i\bar\phi_j\phi^i\phi^j+\frac{1}{64}s4\beta^2\frac{1}{M\Phi^2}\bar\phi_i\bar\phi_j\bar\phi_k\phi^i\phi^j\phi^k\left(g1^2+g2^2\right)^2+\\
&\Bigg(\left(-Yd^{rp}c\beta-s2\beta\, s\beta\, Yd^{rp}m\phi^2\frac{1}{M\Phi^2}\right)\bar\phi_i\left(\bar d^r_a\cdot P_L\cdot q^{aip}\right)+\left(-Ye^{rp}c\beta-s2\beta\, s\beta\, Ye^{rp}m\phi^2\frac{1}{M\Phi^2}\right)\bar\phi_i\left(\bar e^r\cdot P_L\cdot l^{ip}\right)+\left(s2\beta\, Yu^{rp}c\beta\, m\phi^2\frac{1}{M\Phi^2}-s\beta\, Yu^{rp}\right)\\
&\quad\phi^j\left(\bar u^r_a\cdot P_L\cdot q^{aip}\right)\bar\varepsilon_{ij}+\frac{1}{8}s4\beta\, s\beta\, Yd^{rp}\frac{1}{M\Phi^2}\left(g1^2+g2^2\right)\bar\phi_i\bar\phi_j\phi^i\left(\bar d^r_a\cdot P_L\cdot q^{ajp}\right)+\frac{1}{8}s4\beta\, s\beta\, Ye^{rp}\frac{1}{M\Phi^2}\left(g1^2+g2^2\right)\bar\phi_i\bar\phi_j\phi^i\left(\bar e^r\cdot P_L\cdot l^{jp}\right)-\\
&\quad\frac{1}{8}s4\beta\, Yu^{rp}c\beta\frac{1}{M\Phi^2}\left(g1^2+g2^2\right)\bar\phi_i\phi^i\phi^k\left(\bar u^r_a\cdot P_L\cdot q^{ajp}\right)\bar\varepsilon_{jk}+\overline{Yd}^{pt}Ye^{sr}s\beta^2\frac{1}{M\Phi^2}\left(\bar e^s\cdot P_L\cdot l^{ir}\right)\left(\bar q^t_{ai}\cdot P_R\cdot d^{ap}\right)-\\
&\quad s\beta\, Ye^{sp}Yu^{tr}c\beta\frac{1}{M\Phi^2}\left(\bar e^s\cdot P_L\cdot l^{jp}\right)\left(\bar u^t_a\cdot P_L\cdot q^{air}\right)\bar\varepsilon_{ij}-s\beta\, Yd^{sp}Yu^{tr}c\beta\frac{1}{M\Phi^2}\left(\bar d^s_a\cdot P_L\cdot q^{ajp}\right)\left(\bar u^t_b\cdot P_L\cdot q^{bir}\right)\bar\varepsilon_{ij}+\text{H.c.}\Bigg)+\\
&\overline{Ye}^{pt}Ye^{sr}s\beta^2\frac{1}{M\Phi^2}\left(\bar e^s\cdot P_L\cdot l^{ir}\right)\left(\bar l^t_i\cdot P_R\cdot e^p\right)+\overline{Yd}^{pt}Yd^{sr}s\beta^2\frac{1}{M\Phi^2}\left(\bar d^s_a\cdot P_L\cdot q^{air}\right)\left(\bar q^t_{bi}\cdot P_R\cdot d^{bp}\right)+\\
&\overline{Yu}^{rs}Yu^{tp}\frac{1}{M\Phi^2}c\beta^2\left(\bar q^s_{ai}\cdot P_R\cdot u^{ar}\right)\left(\bar u^t_b\cdot P_L\cdot q^{bip}\right)
\end{aligned}
$$

- Contributions only by 2nd heavy Higgs Φ, superpartner contributions forbidden by R-parity
- Only 3 operators not part of Warsaw basis
  - Fierz identity $(\bar\psi^1_L\psi^2_R)(\bar\psi^3_R\psi^4_L)=-(\bar\psi^1_L\gamma_\mu\psi^4_L)(\bar\psi^3_R\gamma^\mu\psi^2_R)/2$ (only valid in $D=4$)
  - Generates evanescent operators in $D=4-2\varepsilon$ — Buras, Weisz [Nucl. Phys. B 333 (1990) 66–99]; Herrlich, Nierste [hep-ph/9412375]

    → need to be absorbed by finite renormalization at one loop

Fuentes-Martín, König, Pagès, Thomsen, FW [2211.09144]

$$
\begin{aligned}
&-\frac{1}{6}O^{ptsr}_{qu1}-O^{ptsr}_{qu8}+\hbar\Bigg(\frac{3}{2}\overline{Y^{uv}_e}\,\overline{Y^{pr}_u}\,\overline{O^{uvts}_{lequ1}}-\frac{3}{2}\overline{Y^{uv}_d}\,\overline{Y^{pr}_u}\,\overline{O^{tsuv}_{quqd1}}+\left(-\frac{1}{2}\overline{O^{tsvu}_{quqd1}}+\frac{1}{12}\overline{O^{vstu}_{quqd1}}+\frac{1}{2}\overline{O^{vstu}_{quqd8}}\right)\overline{Y^{pu}_d}\,\overline{Y^{vr}_u}-\frac{3}{8}g_L\overline{Y^{pr}_u}\,\overline{O^{ts}_{uW}}-\frac{5}{8}g_Y\overline{Y^{pr}_u}\,\overline{O^{ts}_{uB}}-\frac{3}{2}\lambda\overline{Y^{pr}_u}\,\overline{O^{ts}_{uH}}-\frac{3}{2}\mu^2\overline{Y^{pr}_u}\,\overline{O^{ts}_{Yu}}+3Y^{vu}_u\overline{Y^{pu}_u}\,\overline{Y^{vr}_u}\,\overline{O^{ts}_{uH}}+\frac{3}{2}Y^{uv}_eY^{ts}_uO^{uvpr}_{lequ1}-\\
&\frac{1}{8}Y^{vs}_u\overline{Y^{ur}_u}O^{vtpu}_{qq1}-\frac{1}{8}Y^{vs}_u\overline{Y^{ur}_u}O^{vtpu}_{qq3}-\frac{1}{4}Y^{tv}_u\overline{Y^{ur}_u}O^{pusv}_{qu1}+\frac{1}{4}Y^{ts}_u\overline{Y^{uv}_u}O^{puvr}_{qu1}+\frac{1}{4}Y^{uv}_u\overline{Y^{pr}_u}O^{utsv}_{qu1}-\frac{1}{4}Y^{vs}_u\overline{Y^{pu}_u}O^{vtur}_{qu1}+\frac{3}{2}Y^{ts}_u\overline{Y^{uv}_u}O^{puvr}_{qu8}+\frac{3}{2}Y^{uv}_u\overline{Y^{pr}_u}O^{utsv}_{qu8}-\frac{3}{2}Y^{uv}_dY^{ts}_uO^{pruv}_{quqd1}-\frac{1}{2}Y^{tu}_dY^{vs}_uO^{prvu}_{quqd1}+\\
&\frac{1}{12}Y^{tu}_dY^{vs}_uO^{vrpu}_{quqd1}+\frac{1}{2}Y^{tu}_dY^{vs}_uO^{vrpu}_{quqd8}-\frac{5}{8}g_YY^{ts}_uO^{pr}_{uB}-\frac{1}{6}Y^{tv}_d\overline{Y^{pu}_d}O^{sruv}_{ud1}-Y^{tv}_d\overline{Y^{pu}_d}O^{sruv}_{ud8}+\left(-\frac{3}{2}Y^{ts}_u\lambda+3Y^{tv}_uY^{us}_u\overline{Y^{uv}_u}\right)O^{pr}_{uH}-\frac{1}{2}Y^{tv}_u\overline{Y^{pu}_u}O^{ursv}_{uu}-\frac{3}{8}g_LY^{ts}_uO^{pr}_{uW}-\frac{3}{2}Y^{ts}_u\mu^2O^{pr}_{Yu}\Bigg)\}
\end{aligned}
$$

Tree-level matching conditions for the Warsaw basis

```
MapEffectiveCouplings[
    GreensSimplify[ℒEFT0, TypeofIdentities → FourDimensional],
    LoadModel["SMEFT"]
] // NiceForm
```

preliminary (w.i.p)

$$\text{mH} \to \sqrt{-\text{m}\phi^2 + \text{m}\phi^4\,\text{s}2\beta^2\,\frac{1}{\text{M}\Phi^2}}$$
$$\text{Yd}^{\text{i1\_i2\_}} \to \overline{\text{Yd}}^{\text{i2i1}}\,\text{c}\beta + \text{s}2\beta\,\text{s}\beta\,\overline{\text{Yd}}^{\text{i2i1}}\,\text{m}\phi^2\,\frac{1}{\text{M}\Phi^2}$$
$$\text{Ye}^{\text{i1\_i2\_}} \to \overline{\text{Ye}}^{\text{i2i1}}\,\text{c}\beta + \text{s}2\beta\,\text{s}\beta\,\overline{\text{Ye}}^{\text{i2i1}}\,\text{m}\phi^2\,\frac{1}{\text{M}\Phi^2}$$
$$\text{Yu}^{\text{i1\_i2\_}} \to -\text{s}2\beta\,\overline{\text{Yu}}^{\text{i2i1}}\,\text{c}\beta\,\text{m}\phi^2\,\frac{1}{\text{M}\Phi^2} + \text{s}\beta\,\overline{\text{Yu}}^{\text{i2i1}}$$
$$\lambda \to -2\left(-\frac{1}{8}\,\text{g1}^2\,\text{c}2\beta^2 - \frac{1}{8}\,\text{g2}^2\,\text{c}2\beta^2 - \frac{1}{4}\,\text{s}2\beta\,\text{s}4\beta\,\text{g1}^2\,\text{m}\phi^2\,\frac{1}{\text{M}\Phi^2} - \frac{1}{4}\,\text{s}2\beta\,\text{s}4\beta\,\text{g2}^2\,\text{m}\phi^2\,\frac{1}{\text{M}\Phi^2}\right)$$

$$\text{cdH}^{\text{i1\_i2\_}} \to \frac{1}{8}\,\text{s}4\beta\,\text{s}\beta\,\overline{\text{Yd}}^{\text{i2i1}}\,\text{g1}^2\,\frac{1}{\text{M}\Phi^2} + \frac{1}{8}\,\text{s}4\beta\,\text{s}\beta\,\overline{\text{Yd}}^{\text{i2i1}}\,\text{g2}^2\,\frac{1}{\text{M}\Phi^2}$$
$$\text{ceH}^{\text{i1\_i2\_}} \to \frac{1}{8}\,\text{s}4\beta\,\text{s}\beta\,\overline{\text{Ye}}^{\text{i2i1}}\,\text{g1}^2\,\frac{1}{\text{M}\Phi^2} + \frac{1}{8}\,\text{s}4\beta\,\text{s}\beta\,\overline{\text{Ye}}^{\text{i2i1}}\,\text{g2}^2\,\frac{1}{\text{M}\Phi^2}$$
$$\text{cH} \to \frac{1}{64}\,\text{g1}^4\,\text{s}4\beta^2\,\frac{1}{\text{M}\Phi^2} + \frac{1}{32}\,\text{g1}^2\,\text{g2}^2\,\text{s}4\beta^2\,\frac{1}{\text{M}\Phi^2} + \frac{1}{64}\,\text{g2}^4\,\text{s}4\beta^2\,\frac{1}{\text{M}\Phi^2}$$
$$\text{cle}^{\text{i1\_i2\_i3\_i4\_}} \to -\frac{1}{2}\,\overline{\text{Ye}}^{\text{i4i1}}\,\text{Ye}^{\text{i3i2}}\,\text{s}\beta^2\,\frac{1}{\text{M}\Phi^2}$$
$$\text{cledq}^{\text{i1\_i2\_i3\_i4\_}} \to \text{Yd}^{\text{i3i4}}\,\overline{\text{Ye}}^{\text{i2i1}}\,\text{s}\beta^2\,\frac{1}{\text{M}\Phi^2}$$
$$\text{clequ1}^{\text{i1\_i2\_i3\_i4\_}} \to \text{s}\beta\,\overline{\text{Ye}}^{\text{i2i1}}\,\overline{\text{Yu}}^{\text{i4i3}}\,\text{c}\beta\,\frac{1}{\text{M}\Phi^2}$$
$$\text{cqd1}^{\text{i1\_i2\_i3\_i4\_}} \to -\frac{1}{6}\,\overline{\text{Yd}}^{\text{i4i1}}\,\text{Yd}^{\text{i3i2}}\,\text{s}\beta^2\,\frac{1}{\text{M}\Phi^2}$$
$$\text{cqd8}^{\text{i1\_i2\_i3\_i4\_}} \to -\overline{\text{Yd}}^{\text{i4i1}}\,\text{Yd}^{\text{i3i2}}\,\text{s}\beta^2\,\frac{1}{\text{M}\Phi^2}$$
$$\text{cqu1}^{\text{i1\_i2\_i3\_i4\_}} \to -\frac{1}{6}\,\overline{\text{Yu}}^{\text{i4i1}}\,\text{Yu}^{\text{i3i2}}\,\frac{1}{\text{M}\Phi^2}\,\text{c}\beta^2$$
$$\text{cqu8}^{\text{i1\_i2\_i3\_i4\_}} \to -\overline{\text{Yu}}^{\text{i4i1}}\,\text{Yu}^{\text{i3i2}}\,\frac{1}{\text{M}\Phi^2}\,\text{c}\beta^2$$
$$\text{cquqd1}^{\text{i1\_i2\_i3\_i4\_}} \to -\text{s}\beta\,\overline{\text{Yd}}^{\text{i4i3}}\,\overline{\text{Yu}}^{\text{i2i1}}\,\text{c}\beta\,\frac{1}{\text{M}\Phi^2}$$
$$\text{cuH}^{\text{i1\_i2\_}} \to -\frac{1}{8}\,\text{s}4\beta\,\overline{\text{Yu}}^{\text{i2i1}}\,\text{c}\beta\,\text{g1}^2\,\frac{1}{\text{M}\Phi^2} - \frac{1}{8}\,\text{s}4\beta\,\overline{\text{Yu}}^{\text{i2i1}}\,\text{c}\beta\,\text{g2}^2\,\frac{1}{\text{M}\Phi^2}$$

➡ Apply 4-dimensional Fierz identities at tree level to project onto Warsaw basis

Correction to SM parameters

Warsaw basis Wilson coefficients

without one-loop contribution from renormalizing evanescent operators

One-loop matching

- Automatic one-loop matching of $\mathscr{L}_{\text{MSSM}}$

```
ℒEFT1 = Match[ℒMSSM, EFTOrder → 6, LoopOrder → 1] /. ϵ^-1 → 0;
```

**approximate & preliminary values for the case of mass degenerate sfermions*

→ 10 min, 93 MB*

One-loop matching

**approximate & preliminary values for the case of mass degenerate sfermions*

- Automatic one-loop matching of $\mathscr{L}_{\text{MSSM}}$

```
ℒEFT1 = Match[ℒMSSM, EFTOrder → 6, LoopOrder → 1] /. ϵ^-1 → 0;
```

→ 10 min, 93 MB*

- Automatic off-shell simplifications (incl. evanescent operators) of $\mathscr{L}_{\text{SMEFT}}$

```
ℒEFT1 = GreensSimplify[ℒEFT1, TypeofIdentities → Evanescent];
```

→ 3 min, 12 MB*

One-loop matching

**approximate & preliminary values for the case of mass degenerate sfermions*

- Automatic one-loop matching of $\mathscr{L}_{\mathrm{MSSM}}$

```
ℒEFT1 = Match[ℒMSSM, EFTOrder → 6, LoopOrder → 1] /. ϵ^-1 → 0;
```

→ 10 min, 93 MB*

- Automatic off-shell simplifications (incl. evanescent operators) of $\mathscr{L}_{\mathrm{SMEFT}}$

```
ℒEFT1 = GreensSimplify[ℒEFT1, TypeofIdentities → Evanescent];
```

→ 3 min, 12 MB*

- Automatic on-shell simplifications (field redefinitions) of $\mathscr{L}_{\mathrm{SMEFT}}$

```
ℒEFT1 = EOMSimplify[ℒEFT1];
```

→ 35 min, 28 MB*

One-loop matching

**approximate & preliminary values for the case of mass degenerate sfermions*

- Automatic one-loop matching of $\mathscr{L}_{\mathrm{MSSM}}$

```
ℒEFT1 = Match[ℒMSSM, EFTOrder → 6, LoopOrder → 1] /. ϵ^-1 → 0;
```

$\to$ 10 min, 93 MB*

- Automatic off-shell simplifications (incl. evanescent operators) of $\mathscr{L}_{\mathrm{SMEFT}}$

```
ℒEFT1 = GreensSimplify[ℒEFT1, TypeofIdentities → Evanescent];
```

$\to$ 3 min, 12 MB*

- Automatic on-shell simplifications (field redefinitions) of $\mathscr{L}_{\mathrm{SMEFT}}$

```
ℒEFT1 = EOMSimplify[ℒEFT1];
```

$\to$ 35 min, 28 MB*

- Matching conditions in Warsaw basis

```
MatchingCondition = MapEffectiveCouplings[ℒEFT1, LoadModel["SMEFT"]];
```

$\to$ 35 min, 66 MB*

One-loop matching

**approximate & preliminary values for the case of mass degenerate sfermions*

- Automatic one-loop matching of $\mathscr{L}_{\text{MSSM}}$

```
ℒEFT1 = Match[ℒMSSM, EFTOrder → 6, LoopOrder → 1] /. ϵ^-1 → 0;
```

→ 10 min, 93 MB*

- Automatic off-shell simplifications (incl. evanescent operators) of $\mathscr{L}_{\text{SMEFT}}$

```
ℒEFT1 = GreensSimplify[ℒEFT1, TypeofIdentities → Evanescent];
```

→ 3 min, 12 MB*

- Automatic on-shell simplifications (field redefinitions) of $\mathscr{L}_{\text{SMEFT}}$

```
ℒEFT1 = EOMSimplify[ℒEFT1];
```

→ 35 min, 28 MB*

- Matching conditions in Warsaw basis

```
MatchingCondition = MapEffectiveCouplings[ℒEFT1, LoadModel["SMEFT"]];
```

→ 35 min, 66 MB*

- Example: $Q_{HG} = (H^\dagger H) G_{\mu\nu} G^{\mu\nu}$

```
cHG[] /. MatchingCondition // RelabelIndices // NiceForm
```

$$-\frac{1}{48}\hbar\, c2\beta\, g1^2\, g3^2 \frac{1}{Md^2} - \frac{1}{48}\hbar\, c2\beta\, g1^2\, g3^2 \frac{1}{Mq^2} - \frac{1}{24}\hbar\, \overline{ad}^{pr}\, ad^{pr}\, g3^2 \frac{1}{Md^2}\frac{1}{Mq^2} c\beta^2 + \frac{1}{24}\hbar\, c2\beta\, g1^2\, g3^2 \frac{1}{Mu^2} -$$
$$\frac{1}{24}\hbar\, \overline{au}^{pr}\, au^{pr}\, g3^2\, s\beta^2 \frac{1}{Mq^2}\frac{1}{Mu^2} + \frac{1}{24}\hbar\, \overline{Yd}^{pr}\, Yd^{pr}\, g3^2 \frac{1}{Md^2} c\beta^2 + \frac{1}{24}\hbar\, \overline{Yd}^{pr}\, Yd^{pr}\, g3^2 \frac{1}{Mq^2} c\beta^2 + \frac{1}{24}\hbar\, \overline{Yu}^{pr}\, Yu^{pr}\, g3^2\, s\beta^2 \frac{1}{Mq^2} +$$
$$\frac{1}{24}\hbar\, \overline{Yu}^{pr}\, Yu^{pr}\, g3^2\, s\beta^2 \frac{1}{Mu^2} + \frac{1}{24}\hbar\, s\beta\, \overline{Yd}^{pr}\, \mu\, ad^{pr}\, c\beta\, g3^2 \frac{1}{Md^2}\frac{1}{Mq^2} + \frac{1}{24}\hbar\, s\beta\, \overline{Yu}^{pr}\, \mu\, au^{pr}\, c\beta\, g3^2 \frac{1}{Mq^2}\frac{1}{Mu^2} + \frac{1}{24}\hbar\, s\beta\, Yd^{pr}\, \mu\, \overline{ad}^{pr}\, c\beta\, g3^2 \frac{1}{Md^2}\frac{1}{Mq^2} +$$
$$\frac{1}{24}\hbar\, s\beta\, Yu^{pr}\, \mu\, \overline{au}^{pr}\, c\beta\, g3^2 \frac{1}{Mq^2}\frac{1}{Mu^2} - \frac{1}{24}\hbar\, \overline{Yd}^{pr}\, Yd^{pr}\, g3^2\, s\beta^2 \frac{1}{Md^2}\frac{1}{Mq^2}\mu^2 - \frac{1}{24}\hbar\, \overline{Yu}^{pr}\, Yu^{pr}\, g3^2 \frac{1}{Mq^2}\frac{1}{Mu^2}\mu^2 c\beta^2$$

Leading terms cross checked with:
Drozd, Ellis, Quevillon, You [1504.02409]

preliminary (w.i.p)

- Example: $Q_H = (H^\dagger H)^3$ → ∼4500 terms and 16.5 MB

One-loop matching

**approximate & preliminary values for the case of mass degenerate sfermions*

- Automatic one-loop matching of $\mathscr{L}_{\text{MSSM}}$

```
ℒEFT1 = Match[ℒMSSM, EFTOrder → 6, LoopOrder → 1] /. ϵ^-1 → 0;
```

→ 10 min, 93 MB*

- Automatic off-shell simplifications (incl. evanescent operators) of $\mathscr{L}_{\text{SMEFT}}$

```
ℒEFT1 = GreensSimplify[ℒEFT1, TypeofIdentities → Evanescent];
```

→ 3 min, 12 MB*

- Automatic on-shell simplifications (field redefinitions) of $\mathscr{L}_{\text{SMEFT}}$

```
ℒEFT1 = EOMSimplify[ℒEFT1];
```

→ 35 min, 28 MB*

- Matching conditions in Warsaw basis

```
MatchingCondition = MapEffectiveCouplings[ℒEFT1, LoadModel["SMEFT"]];
```

→ 35 min, 66 MB*

- Example: $Q_{HG} = (H^\dagger H) G_{\mu\nu} G^{\mu\nu}$

```
cHG[] /. MatchingCondition // RelabelIndices // NiceForm
```

$$
\begin{aligned}
&-\frac{1}{48}\hbar\, c2\beta\, g1^2\, g3^2 \frac{1}{Md^2} - \frac{1}{48}\hbar\, c2\beta\, g1^2\, g3^2 \frac{1}{Mq^2} - \frac{1}{24}\hbar\, \overline{ad}^{pr}\, ad^{pr}\, g3^2 \frac{1}{Md^2}\frac{1}{Mq^2} c\beta^2 + \frac{1}{24}\hbar\, c2\beta\, g1^2\, g3^2 \frac{1}{Mu^2} - \\
&\frac{1}{24}\hbar\, \overline{au}^{pr}\, au^{pr}\, g3^2\, s\beta^2 \frac{1}{Mq^2}\frac{1}{Mu^2} + \frac{1}{24}\hbar\, \overline{Yd}^{pr}\, Yd^{pr}\, g3^2 \frac{1}{Md^2} c\beta^2 + \frac{1}{24}\hbar\, \overline{Yd}^{pr}\, Yd^{pr}\, g3^2 \frac{1}{Mq^2} c\beta^2 + \frac{1}{24}\hbar\, \overline{Yu}^{pr}\, Yu^{pr}\, g3^2\, s\beta^2 \frac{1}{Mq^2} + \\
&\frac{1}{24}\hbar\, \overline{Yu}^{pr}\, Yu^{pr}\, g3^2\, s\beta^2 \frac{1}{Mu^2} + \frac{1}{24}\hbar\, s\beta\, \overline{Yd}^{pr}\, \mu\, ad^{pr}\, c\beta\, g3^2 \frac{1}{Md^2}\frac{1}{Mq^2} + \frac{1}{24}\hbar\, s\beta\, \overline{Yu}^{pr}\, \mu\, au^{pr}\, c\beta\, g3^2 \frac{1}{Mq^2}\frac{1}{Mu^2} + \frac{1}{24}\hbar\, s\beta\, Yd^{pr}\, \mu\, \overline{ad}^{pr}\, c\beta\, g3^2 \frac{1}{Md^2}\frac{1}{Mq^2} + \\
&\frac{1}{24}\hbar\, s\beta\, Yu^{pr}\, \mu\, \overline{au}^{pr}\, c\beta\, g3^2 \frac{1}{Mq^2}\frac{1}{Mu^2} - \frac{1}{24}\hbar\, \overline{Yd}^{pr}\, Yd^{pr}\, g3^2\, s\beta^2 \frac{1}{Md^2}\frac{1}{Mq^2}\mu^2 - \frac{1}{24}\hbar\, \overline{Yu}^{pr}\, Yu^{pr}\, g3^2 \frac{1}{Mq^2}\frac{1}{Mu^2}\mu^2 c\beta^2
\end{aligned}
$$

Leading terms cross checked with:
Drozd, Ellis, Quevillon, You [1504.02409]

preliminary (w.i.p)

- Example: $Q_H = (H^\dagger H)^3$ → ~4500 terms and 16.5 MB

➡ **Generating all B- and L-conserving operators without dual field-strength tensors**

Conclusions & outlook: phenomenology

- **Full MSSM-to-SMEFT matching condition in Warsaw basis computed with**
  - Need to include flavor indices on sfermion masses, separating of 3rd gen. sfermions
- Need efficient way to isolate leading contributions / restrict matching conditions to subsets
- Make matching conditions available for analyses
- Link to codes for phenomenological analysis → e.g. `SMEFiT`
  - Export matching conditions to `C++` for faster evaluation
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- Compare different EFT scenarios → investigate EFT validity
- Longterm ideas/goals:
  - Combine with further phenomenological codes (e.g.: `flavio/smelli`, `SFitter`, ...)
  - Global MSSM fit using SMEFT

future work

Thank you for your attention!

Backup

Path integral methods for EFT matching

- **Lagrangian:** $\mathscr{L}_{\mathrm{UV}}(\eta)$ with fields $\eta = \left(\eta_H, \eta_L\right)^\intercal$ and hierarchy $m_H \gg m_L$

- **Background field method:** shift all fields $\eta \to \hat{\eta} + \eta$
  - $\hat{\eta}$: background fields (satisfy classical EOM)
  - η: pure quantum fluctuation

- **Path integral representation of effective quantum action:**

$$\exp\left(i\Gamma_{\mathrm{UV}}(\hat{\eta})\right) = \int \mathscr{D}\eta \, \exp\left(i\int \mathrm{d}^d x \, \mathscr{L}_{\mathrm{UV}}(\eta + \hat{\eta})\right)$$

  - Perform path integral over η_H (*"integrating out"* the heavy states)
  - Expand in powers of m_H^{-1}

➡ Γ_{EFT} containing all higher-dimensional operators and coefficients

Gaillard [*Nucl. Phys. B* 268 (1986) 669-692];

Cheyette [*Nucl. Phys. B* 297 (1988) 183-204];

Dittmaier, Grosse-Knetter [hep-ph/9501285] [hep-ph/9505266];

Henning, Lu, Murayama [1412.1837];

Drozd, Ellis, Quevillon, You [1512.03003];

del Aguila, Kunszt, Santiago [1602.00126];

Fuentes-Martin, Portoles, Ruiz-Femenia [1607.02142];

Henning, Lu, Murayama [1604.01019];

Zhang [1610.00710];

Krämer, Summ, Voigt [1908.04798];

Cohen, Lu, Zhang [2011.02484] [2012.07851];

Fuentes-Martín, König, Pagès, Thomsen, FW [2012.08506] [2212.04510];

& many more

Functional Matching at Tree Level & One Loop

- **Saddle point approximation of the action:**

$$S_{\mathrm{UV}}(\eta) \to S_{\mathrm{UV}}(\hat{\eta} + \eta) = S_{\mathrm{UV}}(\hat{\eta}) + \frac{1}{2}\bar{\eta}_i \left. \frac{\delta^2 S_{\mathrm{UV}}}{\delta\bar{\eta}_i \delta\eta_j} \right|_{\eta=\hat{\eta}} \eta_j + \mathcal{O}(\eta^3)$$

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- Method of regions
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higher loop orders

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$$\Gamma^{(1)}_{\rm UV} = -\,i\log\left({\rm SDet}\,\mathcal{Q}[\hat\eta]\right)^{1/2} = \frac{i}{2}{\rm STr}\left(\log\mathcal{Q}[\hat\eta]\right) \longrightarrow$$

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Evanescent Operators

Operator reduction to a 4-dimensional on-shell basis of the EFT

Evanescent Operators

- Some identities for the reduction of redundant operator structures are **intrinsically 4-dimensional** and do not hold in $D = 4 - 2\epsilon$ dimensions:
  - Projections onto 4-dimensional Dirac basis $\{\Gamma_N\} = \{P_L, P_R, \gamma^\mu P_L, \gamma^\mu P_R, \sigma^{\mu\nu}\}$
    - Dirac reduction $$X \otimes Y = \sum_n b_n(X, Y)\Gamma^n \otimes \tilde{\Gamma}_n$$
    - Fierz identities $$(X) \otimes [Y] = \frac{1}{4}\mathrm{tr}\{X\tilde{\Gamma}_n Y \tilde{\Gamma}_m\}\,(\Gamma^m] \otimes [\Gamma^n)$$
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$$R \xrightarrow{D=4 \text{ identities}} Q$$

redundant (R) **$D = 4$ basis** (Q)

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$$\underbrace{R}_{\text{redundant}} \xrightarrow{D=4 \text{ identities}} \underbrace{Q}_{D=4 \text{ basis}} \qquad \underbrace{E}_{\text{evanescent}} \equiv R - Q \sim \mathcal{O}(\epsilon)$$

Physical Contributions by Evanescent Operators

- Evanescent operators $E \equiv R - Q$ are formally of rank ϵ
- Only physical contributions when inserted into a UV-divergent one-loop diagram
  - No physical contributions at tree level
  - One-loop contributions stem from (local) UV poles of the diagrams
- Only finite contributions to one-loop matrix elements

Buras, Weisz [*Nucl.Phys.B* 333 (1990) 66-99]; Dugan and Grinstein [PLB 256 (1991) 239]; Herrlich, Nierste [hep-ph/9412375]

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Evanescent-Free Schemes

Fuentes-Martin, König, Pages, Thomsen, FW [2211.09144]

- Match EFT Lagrangian containing redundant operators (R) onto EFT Lagrangian containing only physical operators (Q), i.e., a 4-dimensional basis: $\Gamma_R[\eta] = \Gamma_Q[\eta]$
- For the one-loop EFT action $S^{(1)}$ we find ($\mathscr{P}$ projection $R \to Q$ using $D = 4$ identities)

$$\mathscr{P} S_Q^{(1)} = \mathscr{P} S_R^{(1)} + \Delta S^{(1)}, \qquad \text{where} \qquad \Delta S^{(1)} \equiv \mathscr{P}\left(\overline{\Gamma}_R^{(1)} - \overline{\Gamma}_Q^{(1)}\right)$$

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- Compute $\Delta S^{(1)}$ using functional methods

$$\Delta S^{(1)} = -\frac{i}{2}\sum_{n=1}^{\infty}\frac{1}{n}\mathscr{P}\,\mathrm{STr}\left[\left(\Delta X_R\right)^n - \left(\Delta X_Q\right)^n\right]\Big|_{\mathrm{hard}}$$

- Result: $S_Q^{(1)}$ action containing only operators in physical basis (free of evanescent operators), but reproducing the same physics as $S_R^{(1)}$ obtained from the matching

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- **Note: these tools also allow for extracting β functions**

Example: Evanescent Operators in the SMEFT

$$\mathscr{L} \supset C_{lqde}^{prst}(\bar{\ell}^p \gamma^\mu q^t)(\bar{d}^s \gamma_\mu e^r) \xrightarrow[D=4]{\textbf{Fierz identity}} \mathscr{L}' \supset -2C_{lqde}^{prst}(\bar{\ell}^p e^r)(\bar{d}^s q^t)$$

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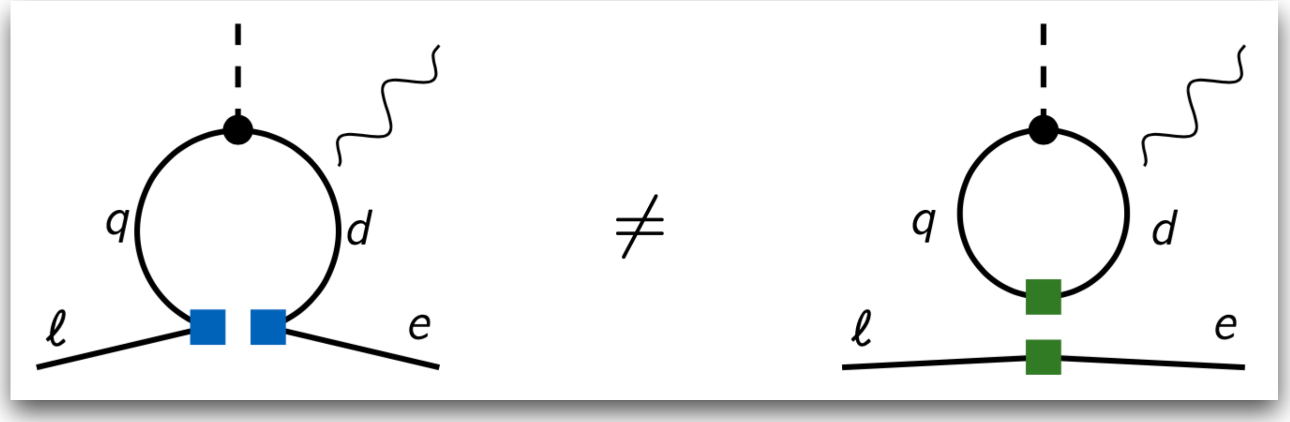

figure by A. Thomsen

The one-loop effective action built from $\mathscr{L}$ and $\mathscr{L}'$ do not agree:

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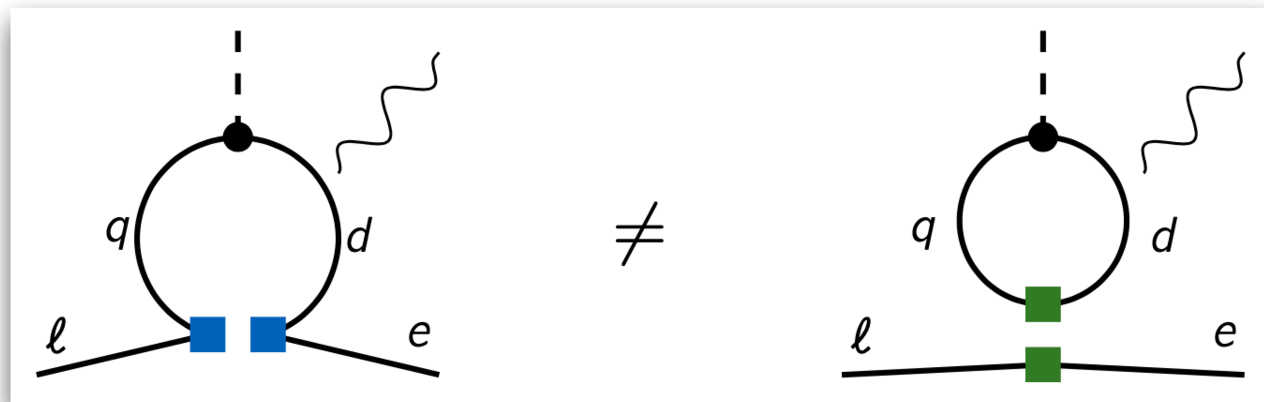

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  evanescent operator $\mathcal{O}(\epsilon)$
- Effective one-loop action: $\Gamma_{\text{EFT}}^{(1)} = \Gamma_{\text{EFT}}^{\prime(1)} + \Delta S_E$
- Absorb physical effect of evanescent operators by finite one-loop shift of action ΔS_E (depends on all UV poles ϵ_{UV} of SMEFT one-loop integrals)
- Computed for the SMEFT in Fuentes-Martin, König, Pages, Thomsen, FW [2211.09144]
- For LEFT: Aebischer, Buras, Kumar [2202.01225]; Aebischer, Pesut [2208.10513]; Aebischer, Pesut, Polonsky [2211.01379]