Funded by DFG Deutsche Forschungsgemeinschaft German Research Foundation

Collaborative Research Center TRR 257 P³H Particle Physics Phenomenology after the Higgs Discovery

TTK Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

From the MSSM to the SMEFT with MATCHETE

Felix Wilsch

Institute for Theoretical Particle Physics and Cosmology
RWTH Aachen University

<u>Based on w.i.p. in collaboration with:</u>

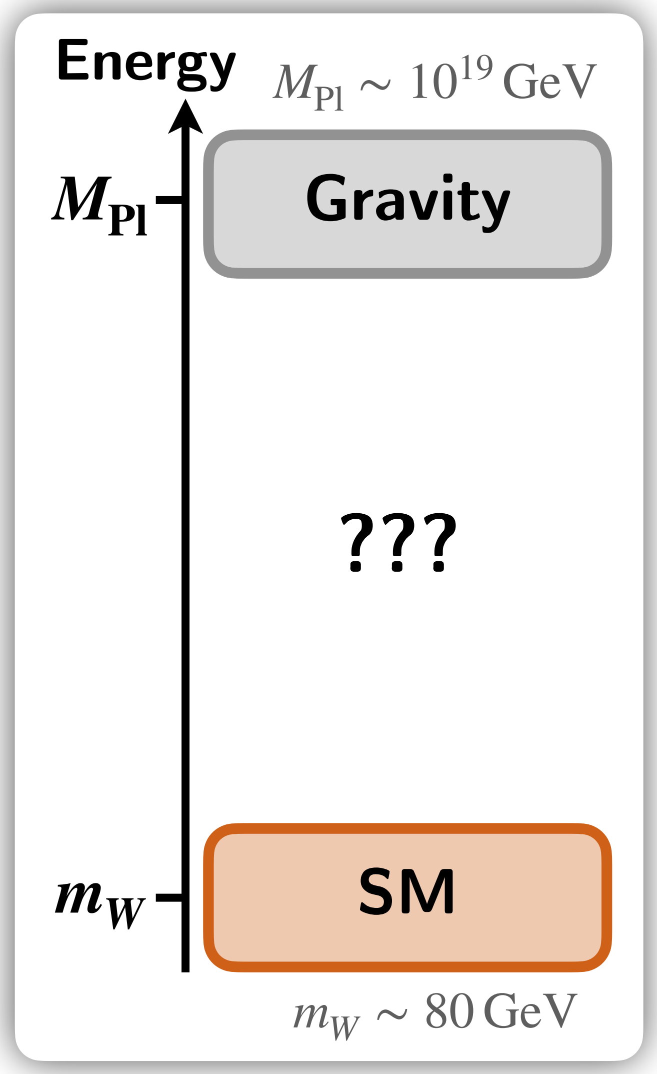
Sabine Kraml, Andre Lessa, Suraj Prakash [250X.XXXX]

SMEFT-Tools 2025 | Mainz Institute for Theoretical Physics | Johannes Gutenberg University

January 30, 2025

Physics Beyond the Standard Model

- **Deficits of the Standard Model:**
  - <u>Cosmological observations:</u>
    - dark matter
    - baryon asymmetry
    - dark energy
    - gravity
  - <u>Theoretical shortcomings:</u>
    - No protection of Higgs mass (*hierarchy problem*)
    - No explanation of neutrino masses
    - No explanation for flavor structure/hierarchies



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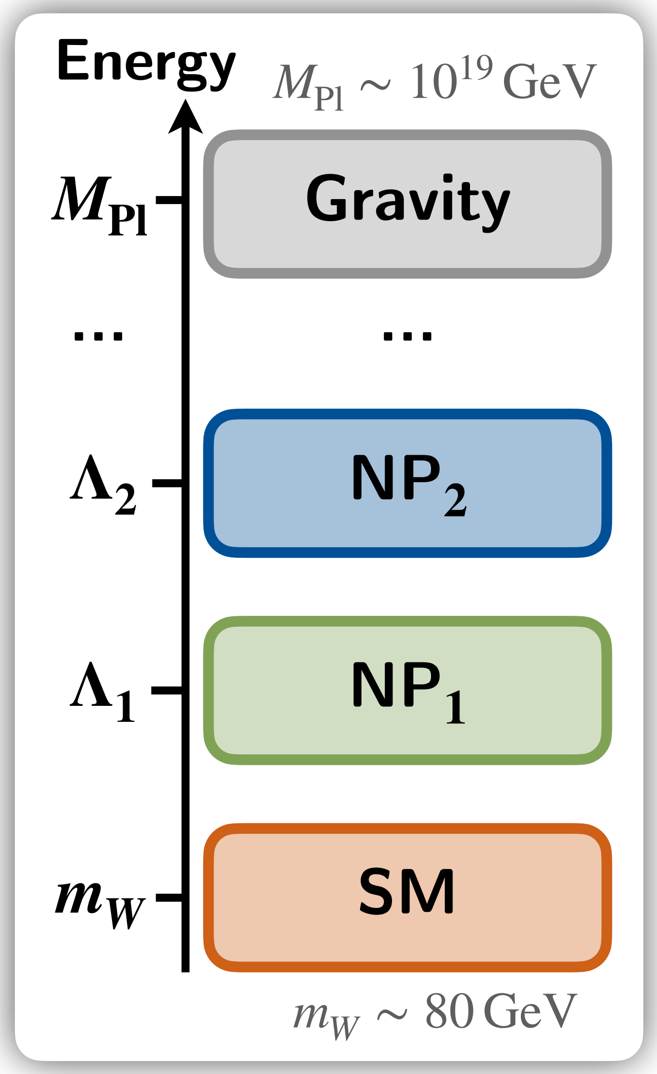

- Wide range of BSM theories (SUSY, composite Higgs, ...) proposed to address issues
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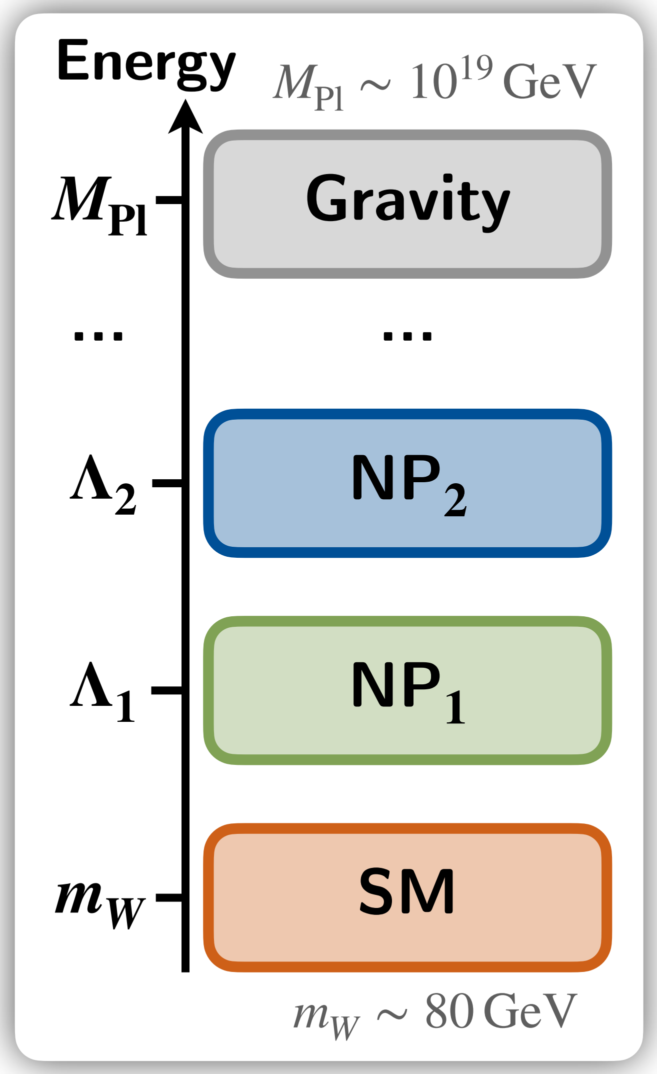

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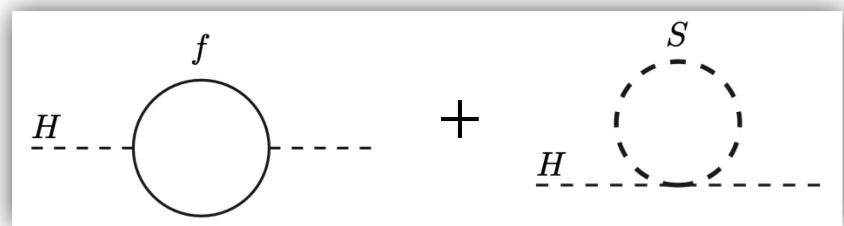
Hierarchy Problem and Supersymmetry (SUSY)

Hierarchy problem:

- Masses of fundamental scalars are radiatively unstable
- Radiative corrections to mass of fundamental scalar H
  - In presence of fermion f and scalar S with mass scale hierarchy $M_f \sim M_S \gg m_H$

$\Delta m_H^2 \sim$



$$\sim \frac{1}{16\pi^2}\left(\lambda_S M_S^2 - \lambda_f^2 M_f^2\right) \gg m_H^2$$

- *Solutions:* technicolor/composite Higgs, supersymmetry, ...

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

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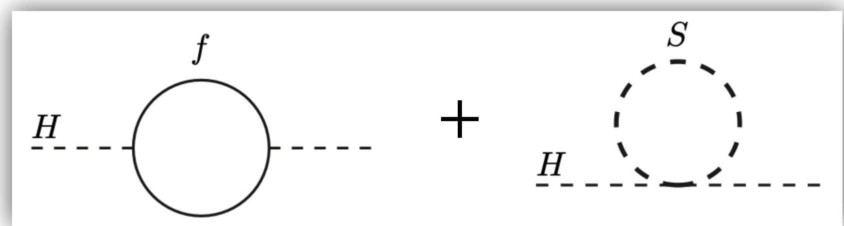

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- Space-time symmetry between bosons ϕ and fermions ψ
- SUSY transformations δ_ξ: (ξ: spinor)
  $\delta_\xi \phi = \xi\psi$ and $\delta_\xi \psi = -i\sigma^\mu \xi^\dagger(\partial_\mu \phi) + \xi F$
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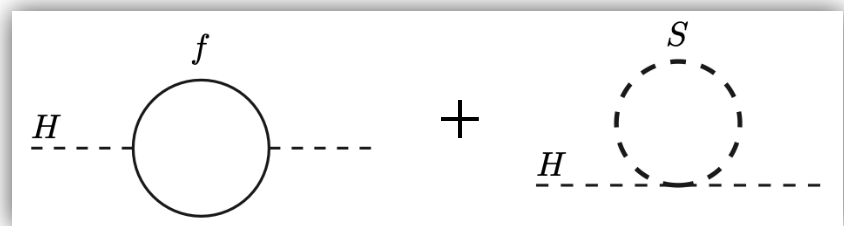

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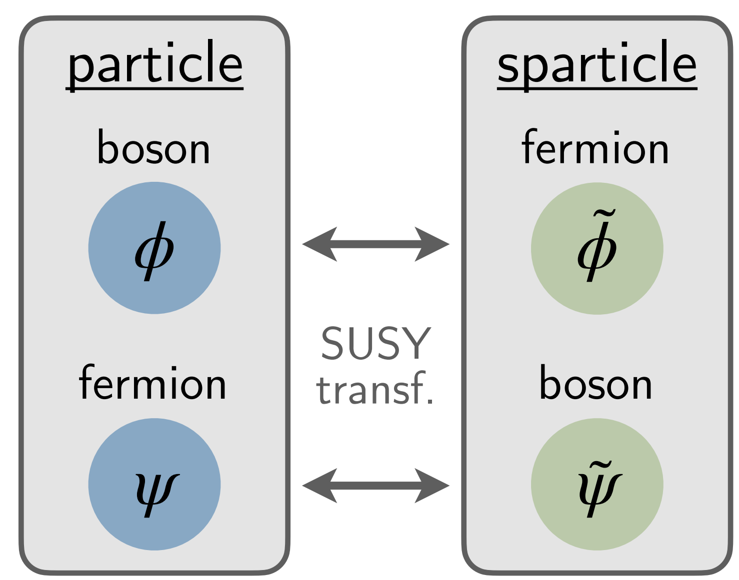

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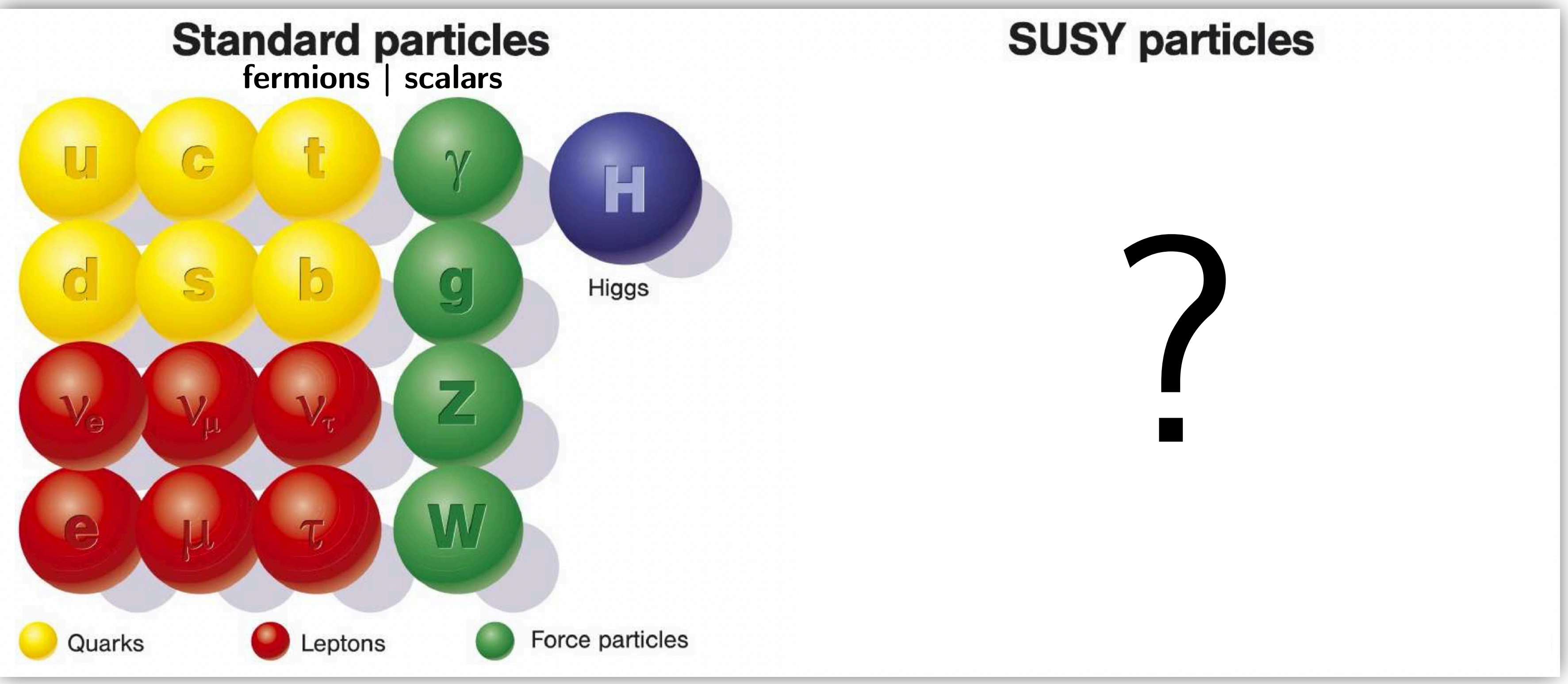

Figure from Grefe/DESY [1111.6779]

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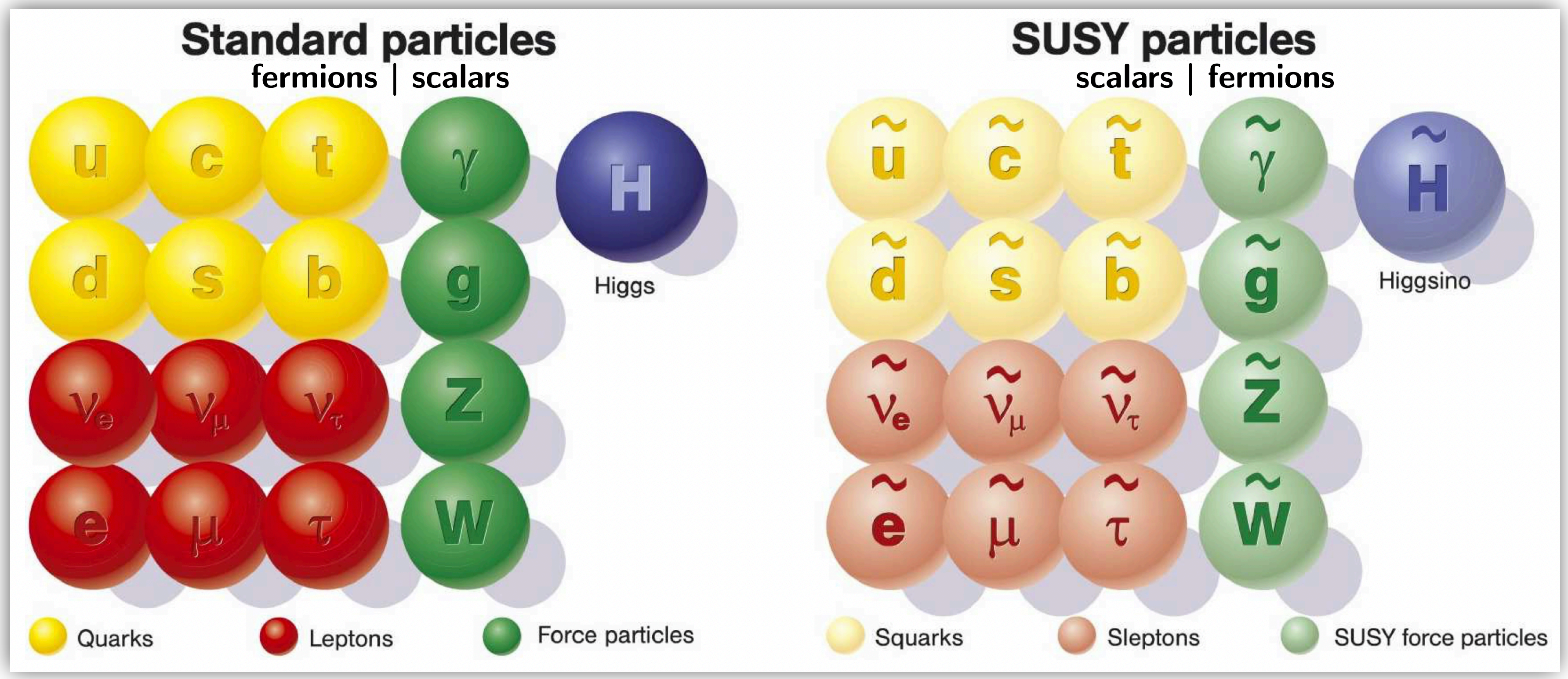

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- SUSY invariance: superpartners identical to particles except for spin
- SUSY breaking: allows for $m_{\mathrm{SM}} < m_{\mathrm{MSSM}}$ → but m_{MSSM} must be:
  - large enough to evade LHC detection
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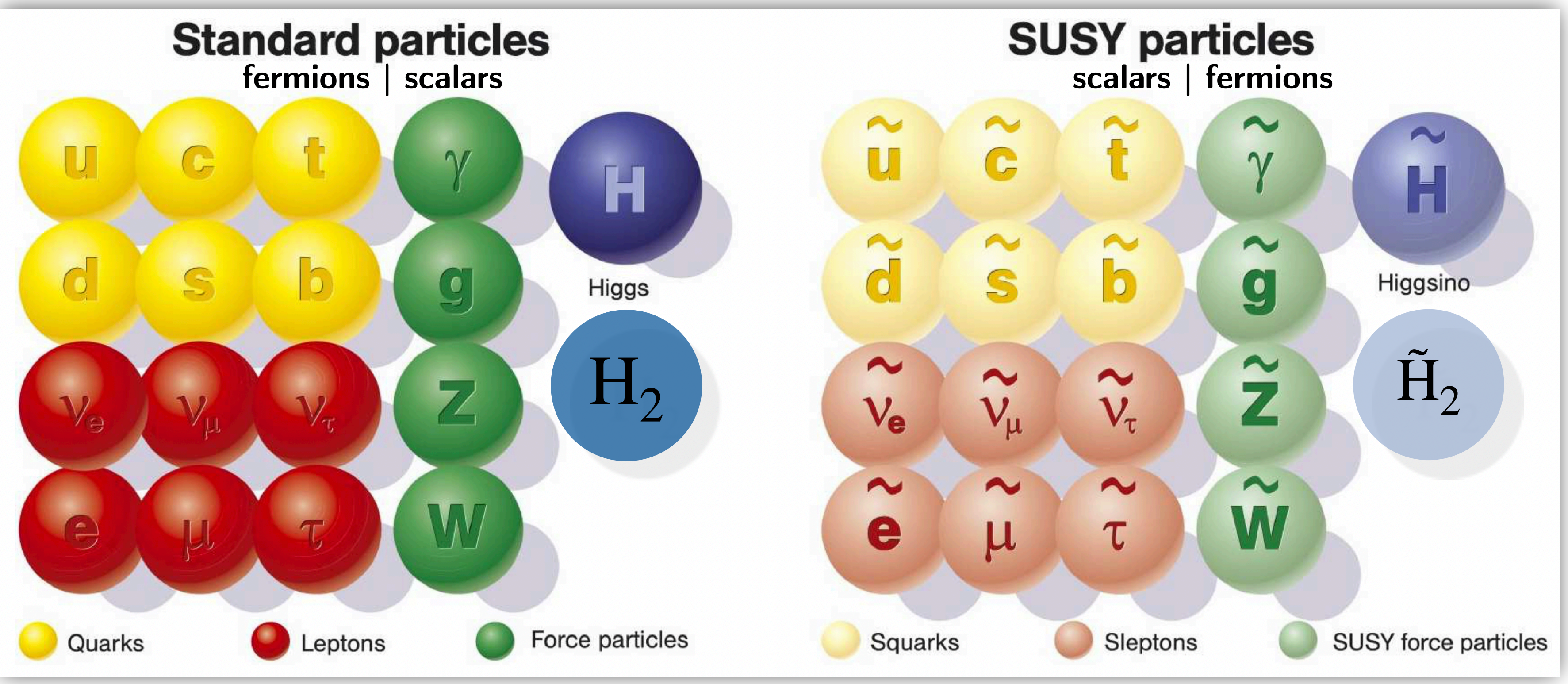

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2nd Higgs doublet needed:

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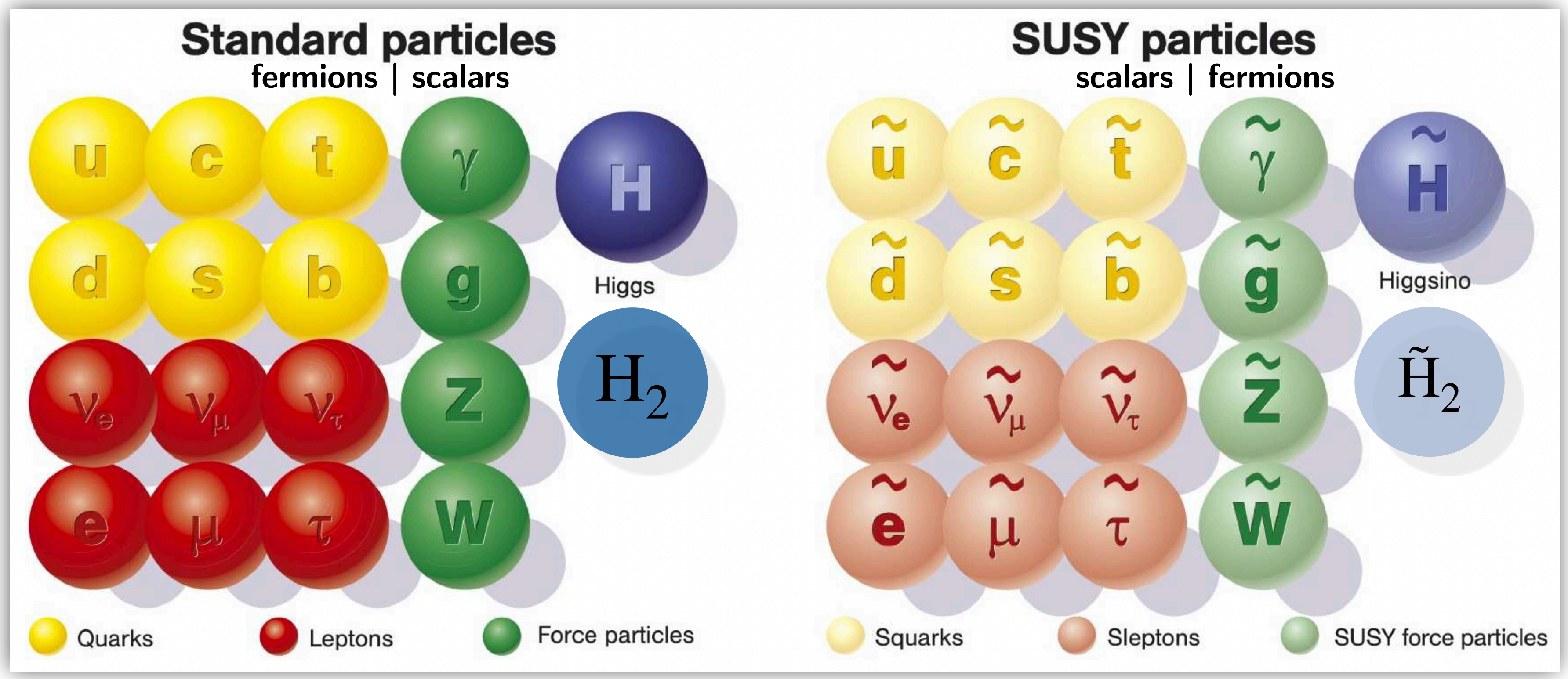

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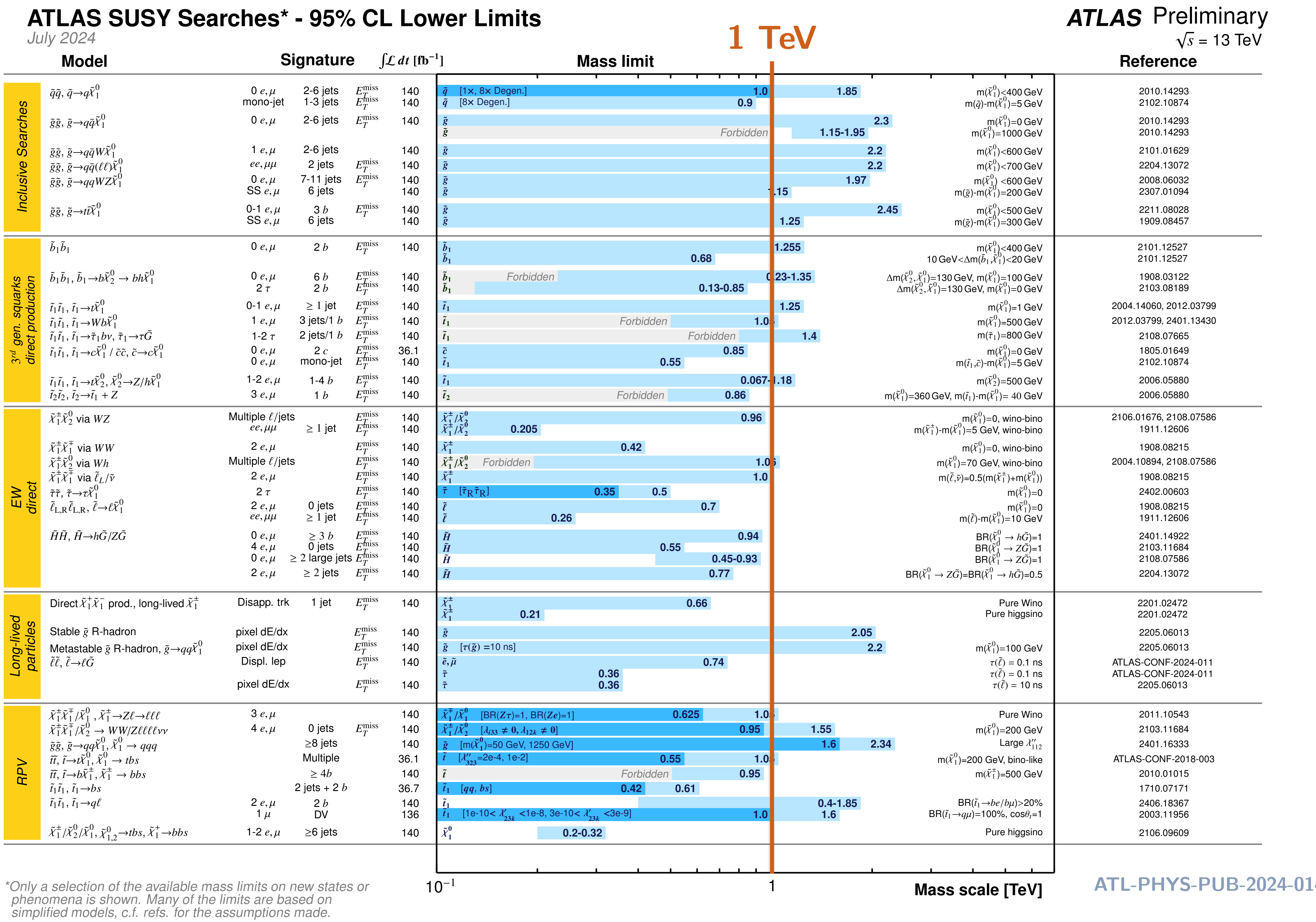
- Features: impose R-parity to avoid B and L violation (similar to $\mathbb{Z}_2$ where $\begin{matrix} \eta_{\text{SM}} \to +\eta_{\text{SM}} \\ \eta_{\text{SUSY}} \to -\eta_{\text{SUSY}} \end{matrix}$)
  - lightest superpartner stable (DM candidate) → missing energy signatures

LHC Constraints



High(er)-Scale SUSY with Effective Field Theory

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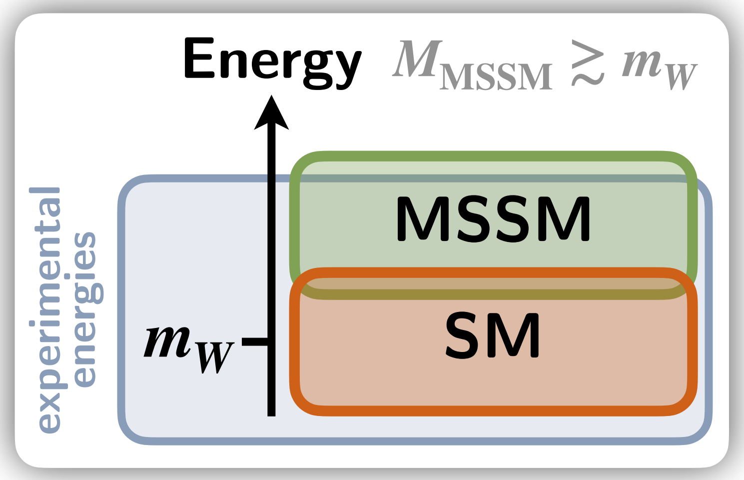

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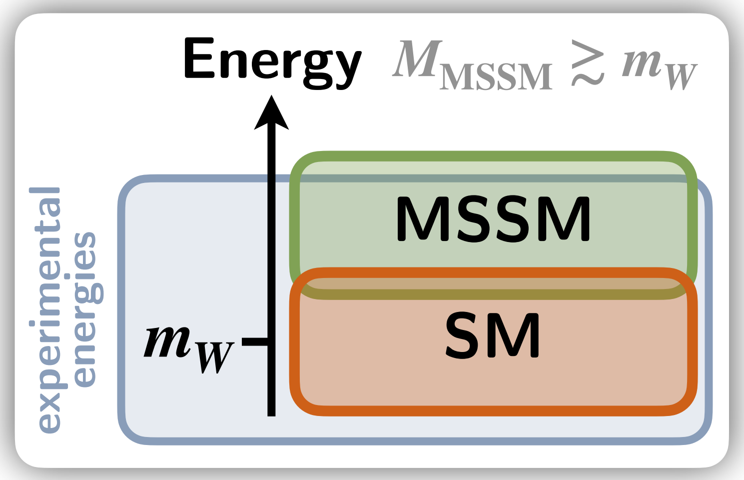

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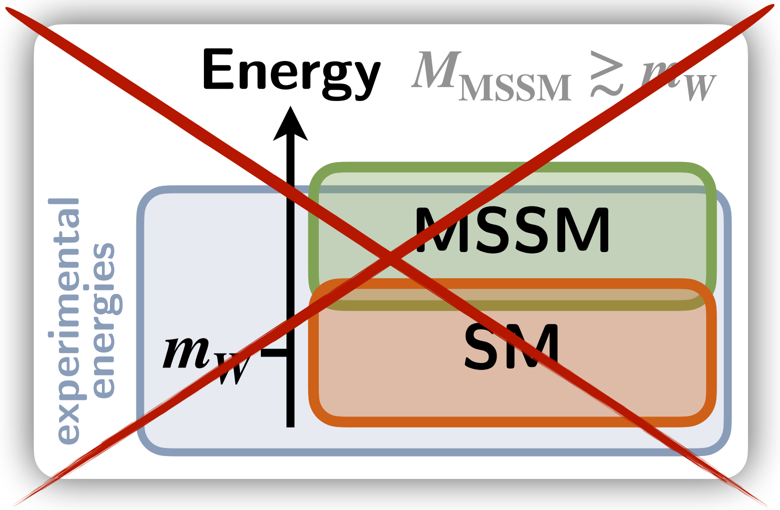

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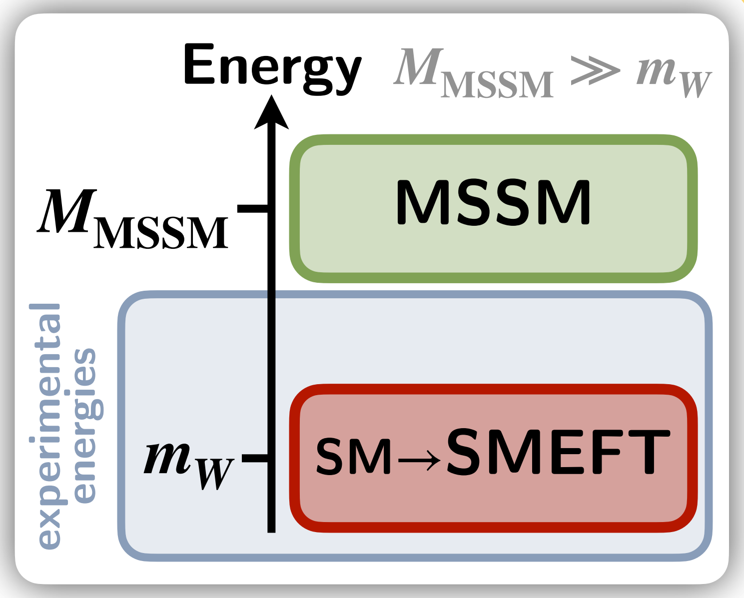

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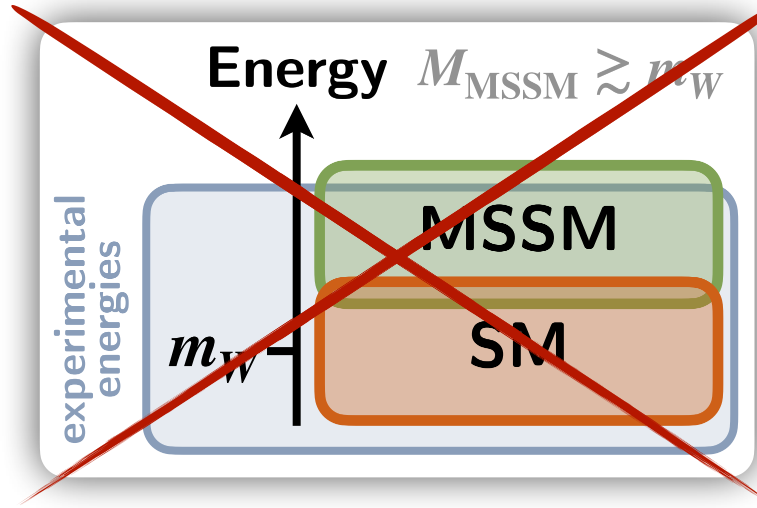

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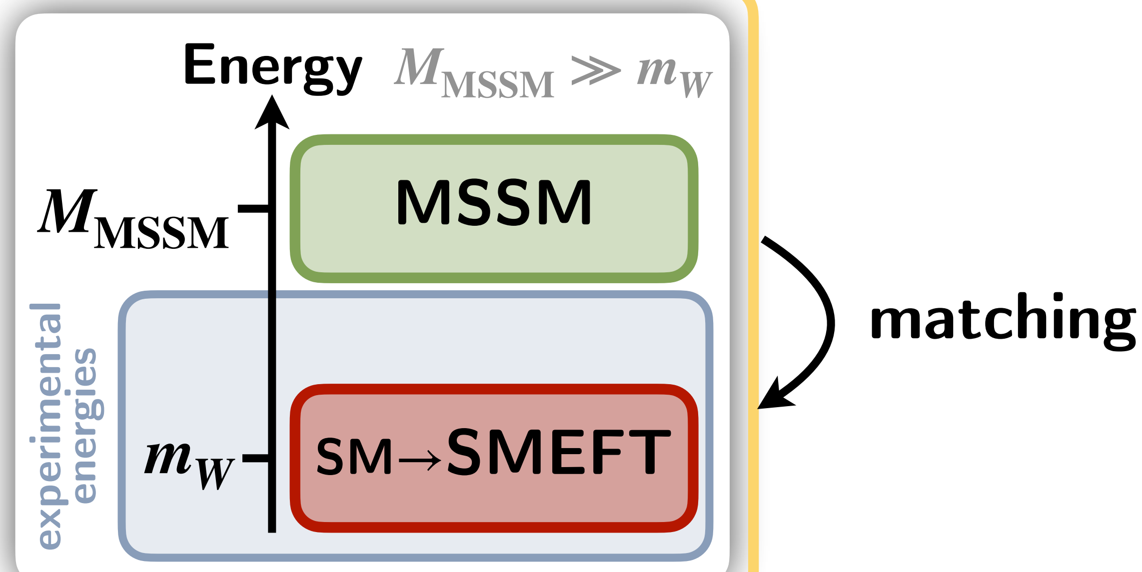

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Supersymmetric Lagrangians

- General supersymmetric Lagrangian: $\mathcal{L}_{\rm SUSY} = \mathcal{L}_{\rm chiral} + \mathcal{L}_{\rm gauge}$

$$\mathcal{L}_{\rm chiral} = (D_\mu\phi_i)^\dagger(D^\mu\phi_i) + i\psi^{\dagger i}\overline{\sigma}^\mu D_\mu\psi_i + F^{\dagger i}F_i + \left(W^i F_i - \frac{1}{2}W^{ij}\psi_i\cdot\psi_j + \text{H.c.}\right),$$

$$\mathcal{L}_{\rm gauge} = -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu a} + i\lambda^{\dagger a}\overline{\sigma}^\mu D_\mu\lambda^a - \sqrt{2}\,g\big[(\phi^\dagger T^a\psi)\cdot\lambda^a + \text{H.c.}\big] + g(\phi^\dagger T^a\phi)\mathcal{D}^a + \frac{1}{2}\mathcal{D}^a\mathcal{D}^a$$

- Fields: ϕ-ψ : scalar-fermion partners, $F^a_{\mu\nu}$-λ^a : gauge field-gaugino partners

- Auxiliary fields set to EoM: $\mathcal{D}^a = -g(\phi^\dagger T^a\phi)\,,\qquad F_i = -W_i^\dagger\,,\qquad F^{\dagger i} = -W^i$

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- Superpotential:

$$W(\phi) = \frac{1}{2}M^{ij}\phi_i\phi_j + \frac{1}{6}y^{ijk}\phi_i\phi_j\phi_k\,,$$

$$W^i = \frac{\partial W}{\partial\phi_i} = M^{ij}\phi_j + \frac{1}{2}y^{ijk}\phi_j\phi_k\,,\qquad W^{ij} = \frac{\partial^2 W}{\partial\phi_i\partial\phi_j} = M^{ij} + y^{ijk}\phi_k$$

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- Soft SUSY breaking: $\mathcal{L}_{\text{soft}} = -\left[\frac{1}{2} M\, \lambda^a \cdot \lambda^a + \frac{1}{6} a^{ijk}\, \phi_i \phi_j \phi_k + \frac{1}{2} b^{ij}\, \phi_i \phi_j + \text{H.c.} \right] - (m^2)^i_j\, \phi^{*j} \phi_i$

Field Content of the MSSM

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

- **Field content:**
  - SM
    → remain in EFT
  - Superpartners
    → integrated out
  - Higgs doublets
    → identification of SM doublet required

Chiral supermultiplets

Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
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sleptons, leptons	L	$(\widetilde{\nu}\ \ \widetilde{e}_L)$	$(\nu\ \ e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
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winos, W bosons	$\widetilde{W}^\pm\ \ \widetilde{W}^0$	$W^\pm\ \ W^0$	$(\,\mathbf{1},\ \mathbf{3}\,,\ 0)$
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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	$(H_d^0\ \ H_d^-)$	$(\widetilde{H}_d^0\ \ \widetilde{H}_d^-)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

Gauge supermultiplets

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	$(\,\mathbf{1},\ \mathbf{1}\,,\ 0)$

Symmetries and Lagrangian of the MSSM

- **Symmetries:**
  - **Gauge:** $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
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    - Lorentz invariance
    - R-parity (B and L conservation)
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$$\mathcal{W}_{\mathrm{MSSM}} = \int \mathrm{d}^2\theta \left[\mu_H \hat{H}_u \varepsilon \hat{H}_d + (\hat{\bar{u}} y_u \hat{q}) \varepsilon \hat{H}_u - (\hat{\bar{d}} y_d \hat{q}) \varepsilon \hat{H}_d - (\hat{\bar{e}} y_e \hat{\ell}) \varepsilon \hat{H}_d\right]$$

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- **Soft SUSY breaking:**

$$\begin{aligned}
\mathcal{L}^{\mathrm{Weyl}}_{\mathrm{break}} = &-\frac{1}{2}\left[m_3\, \widetilde{\mathsf{G}}^A \cdot \widetilde{\mathsf{G}}^A + m_2\, \widetilde{\mathsf{W}}^I \cdot \widetilde{\mathsf{W}}^I + m_1\, \widetilde{\mathsf{B}} \cdot \widetilde{\mathsf{B}} + \mathrm{H.c.}\right] \\
&- \left[(\widetilde{q}^\dagger a_u \widetilde{u}) \varepsilon H_u^* - (\widetilde{q}^\dagger a_d \widetilde{d}) \varepsilon H_d^* - (\widetilde{\ell}^\dagger a_e \widetilde{e}) \varepsilon H_d^* + \mathrm{H.c.}\right] \\
&- \left[\widetilde{q}^\dagger m_q^2 \widetilde{q} + \widetilde{\ell}^\dagger m_\ell^2 \widetilde{\ell} + \widetilde{u}^\dagger m_u^2 \widetilde{u} + \widetilde{d}^\dagger m_d^2 \widetilde{d} + \widetilde{e}^\dagger m_e^2 \widetilde{e}\right] \\
&- m_{H_u}^2 H_u^\dagger H_u - m_{H_d}^2 H_d^\dagger H_d - \left[b H_u^\intercal \varepsilon H_d + \mathrm{H.c.}\right] ,
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➡ Fully general R-parity conserving MSSM

➡ **Free parameters: 124**

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Two Higgs Doublet Model (2HDM) — Type-II

- **Higgs potential:**

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

- MSSM contains 2HDM:

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \sim (\mathbf{1}, \mathbf{2})_{1/2} \quad \text{and} \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \sim (\mathbf{1}, \mathbf{2})_{-1/2}$$

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

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- EWSB conditions: $\beta = \beta_0 = \beta_\pm$, but independent α (where $\tan\beta = v_u/v_d$)

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

⇒ α and β not aligned: $\alpha \neq \beta - \pi/2$

→ cannot write the SM doublet H as linear combination of $H_{u,d}$

MSSM Matching in Decoupling Limit

$H_d^c \sim (\mathbf{1}, \mathbf{2})_{1/2}$

- In alignment limit ($\alpha \simeq \beta - \pi/2$) we can write:

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

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Alignment/Decoupling limit:
Haber, Nir
[Nucl.Phys.B 335 (1990) 363-394]
Gunion, Haber [hep-ph/0207010]
Haber, O'Neil [hep-ph/0602242]

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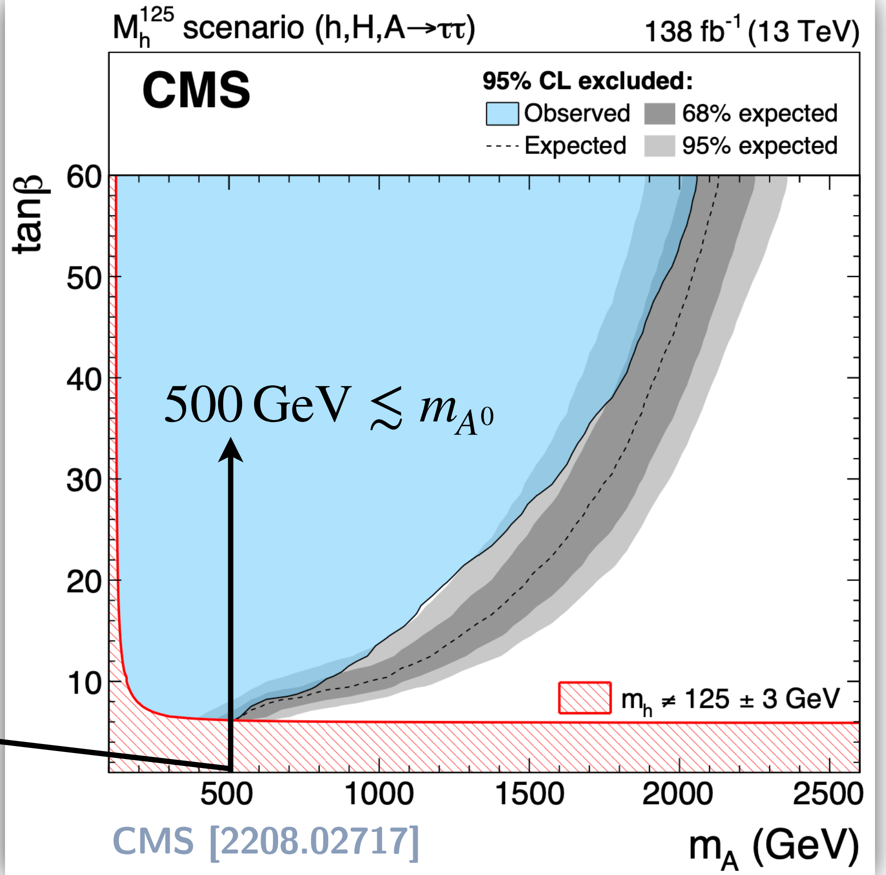

CMS [2208.02717]

➡ **general feature of type-II 2HDMs** Dawson, Fontes, Homiller, Sullivan [2205.01561] Dawson, Fontes, Quezada-Calonge, Sanz-Cillero [2305.07689]

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

- Free part of Higgsino Lagrangian can be written as

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

→ Integrating out chiral Higgsinos $\tilde{H}_{u,d}$ or vectorlike Σ is equivalent.

One-Loop Matching

Automatic One-Loop Matching

- Tools for automatic one-loop matching:
  - `CoDEx` *(UOLEA)* — Das Bakshi, Chakrabortty, Kumar Patra [1808.04403]
  - `MatchMakerEFT` *(diagrammatic)* — Carmona, Lazopoulos, Olgoso, Santiago [2112.10787]
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- MSSM ideal test case for automatic one-loop matching tools:
  - Only scalars (squarks & sleptons) and fermions (Higgsinos & gauginos)
  - R-parity acts as $\mathbb{Z}_2$ symmetry, which forbids tree-level matching contribution from all BSM states in MSSM, except for second Higgs doublet
    - Leading matching contributions mostly one-loop

Automatic One-Loop Matching with MATCHETE

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

https://gitlab.com/matchete/matchete

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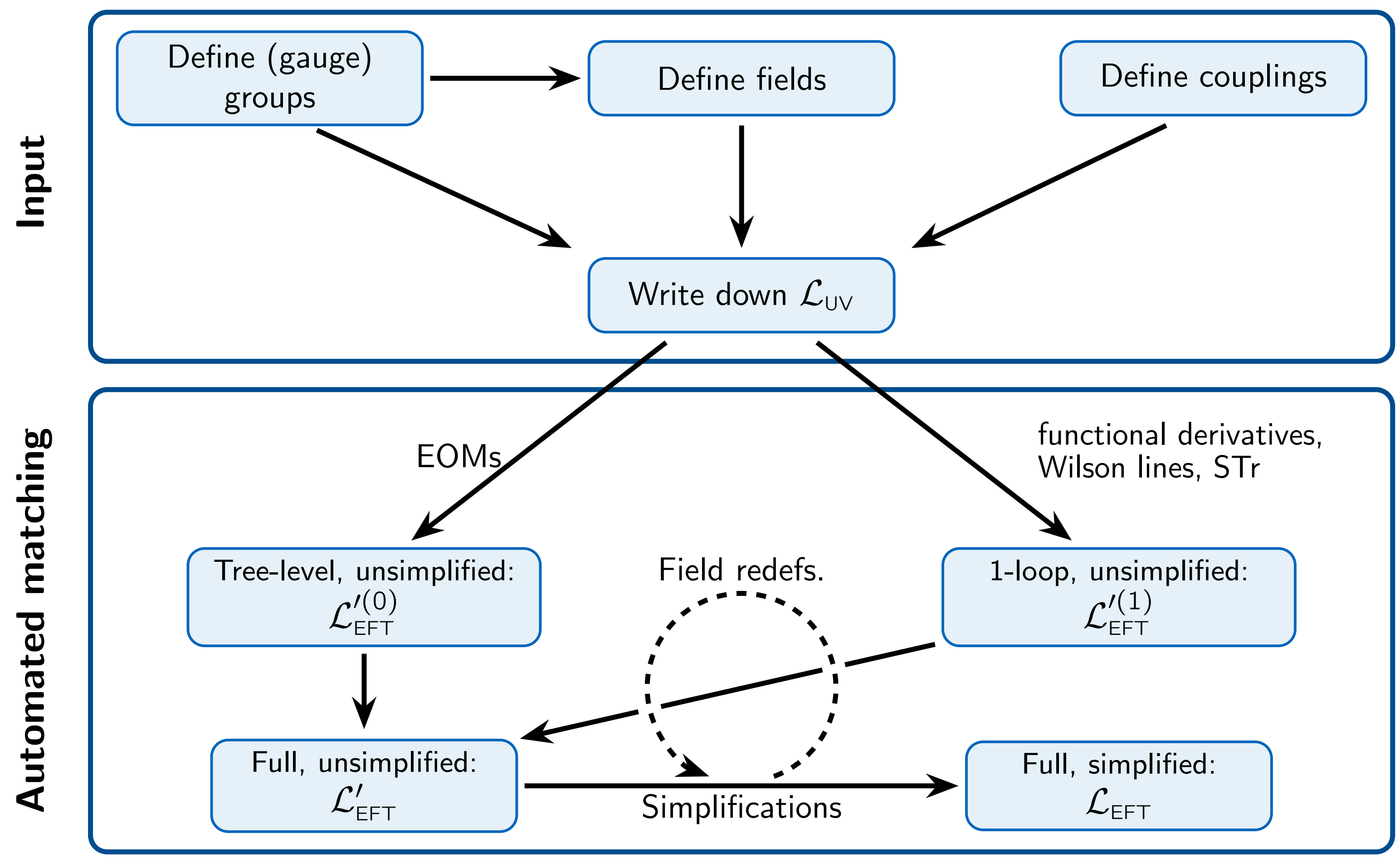

MATCHETE

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Model implementation input:

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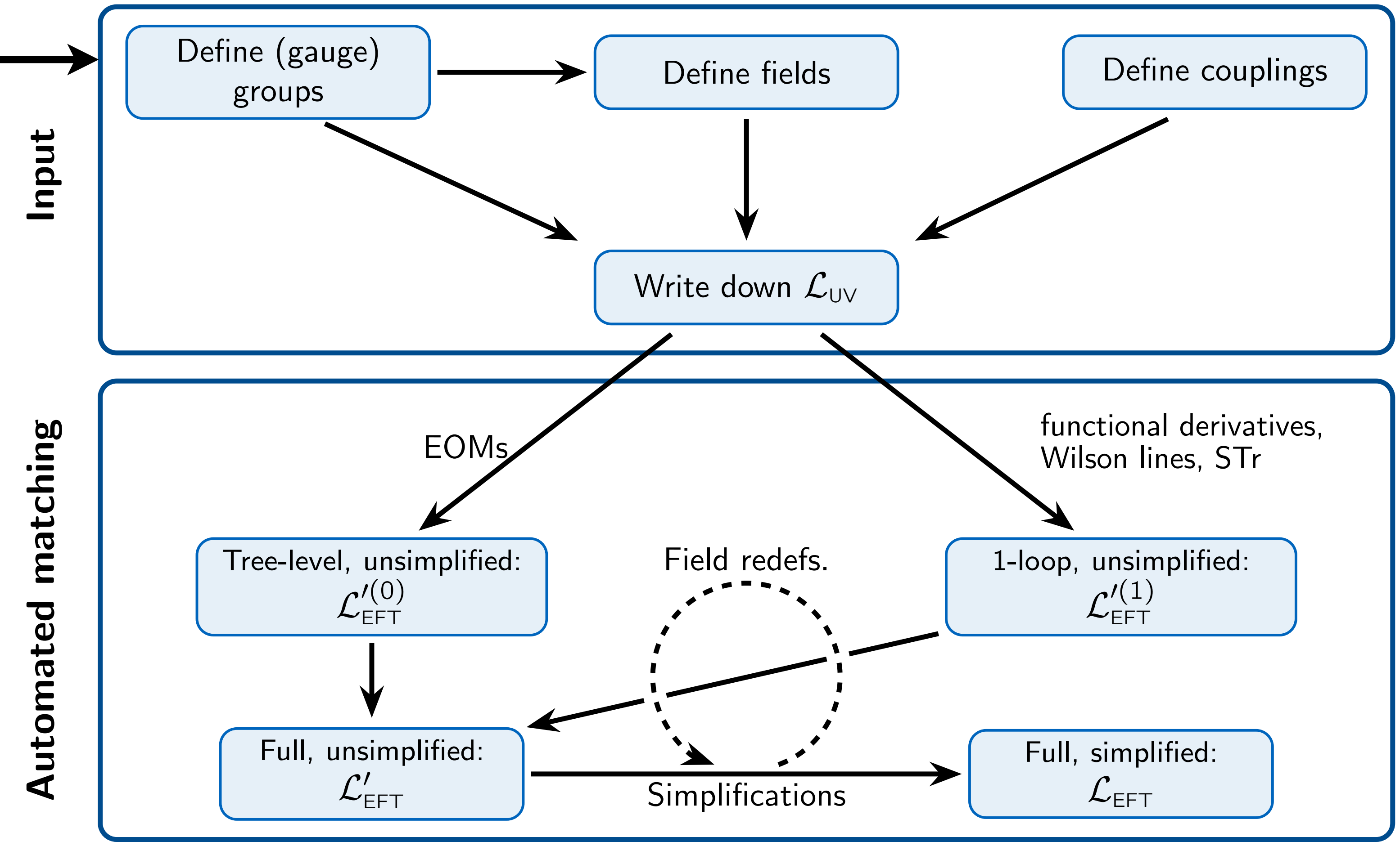

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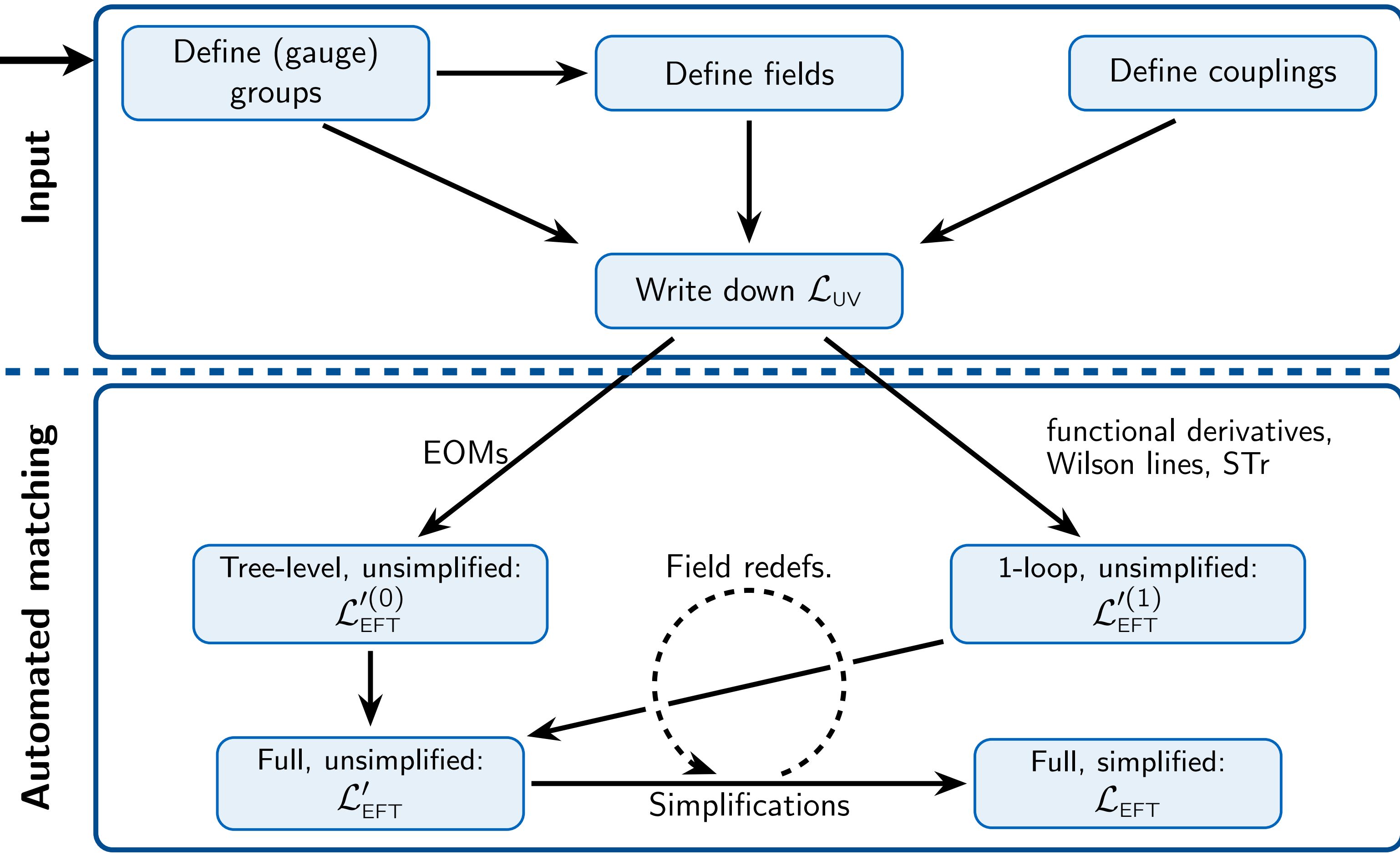

Automatic calculation:

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  - Off-shell (IbP, ...)
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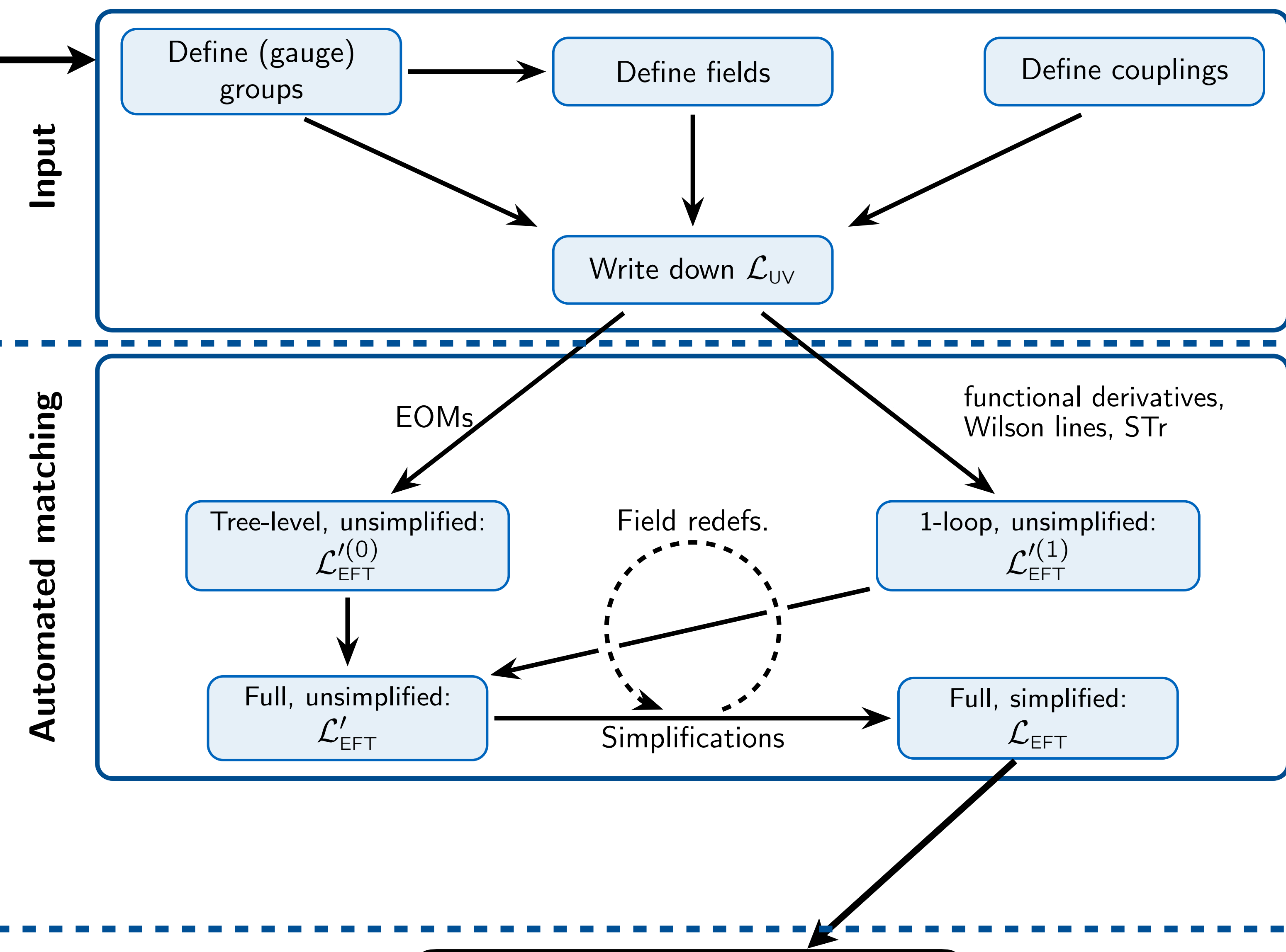

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Matching conditions in **Warsaw basis**

Redundant Operator Reduction

- Functional methods directly **provide full EFT Lagrangian (operators & coefficients)**, but $\mathscr{L}_{\text{EFT}}$ contains redundancies among the operators and is in a D-dimensional space

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Full reduction to Warsaw basis automated in *MATCHETE*

Evanescent Operators

- **Intrinsically 4-dimensional** identities do not hold in $D = 4 - 2\epsilon$ dimensions:
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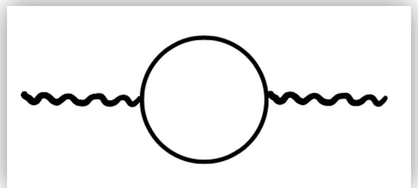
evanescent (E)

- Change to evanescent-free scheme:
  - Compute all one-loop insertions of evanescent operators
  - Shift physical coefficients accordingly to drop evanescent operators from EFT

Gauge Field and Coupling Redefinitions

- Matching contribution to gauge boson self-energy



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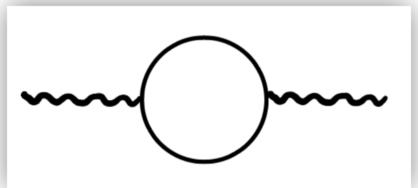

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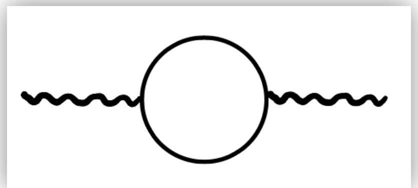

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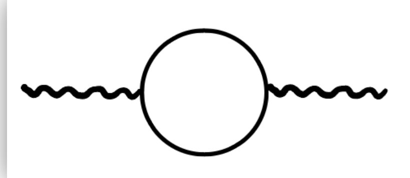

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$$g_Y^{\text{SMEFT}} = \mathrm{g}_Y^{\text{MSSM}} - \frac{\mathrm{g}_Y^3}{16\pi^2}\left[\frac{1}{36}\log\frac{\bar\mu^2}{M_q^{p2}} + \frac{2}{9}\log\frac{\bar\mu^2}{M_u^{p2}} + \frac{1}{18}\log\frac{\bar\mu^2}{M_d^{p2}} + \frac{1}{12}\log\frac{\bar\mu^2}{M_l^{p2}} + \frac{1}{6}\log\frac{\bar\mu^2}{M_e^{p2}} + \frac{1}{12}\log\frac{\bar\mu^2}{M_\Phi^2} + \frac{1}{3}\log\frac{\bar\mu^2}{\mu^2}\right]$$

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New *MATCHETE* Features for MSSM Matching

- **Improvements required in *MATCHETE* for MSSM matching:**
  - Performance:
    - Memory optimization for matching
    - Computation time of operator reduction (simplification routines applied to complicated operator coefficients)
  - Flavor indices:
    - Integrating out heavy flavored particles (squarks & sleptons)
    - Consistent treatment of different flavor tensors (e.g. $n_f \times n_f$ matrices Y_{pr} and diagonal matrices m_p)
    - Teaching a computer how to treat Einstein summation convention for:

$$\mathscr{L} \supset \overline{\psi}_p \gamma^\mu D_\mu \psi_p - m_p \overline{\psi}_p \psi_p - \left(Y_{pr} \overline{\psi}_p \psi_r \phi + \mathrm{H.c.} \right)$$

    - Loop functions with up to 6 flavor indices for MSSM

Improvements required for MSSM matching will be included in next Matchete version!

Further New MATCHETE Features Employed

- **<u>Further new MATCHETE features used for MSSM matching:</u>** → see Matthias' talk
  - More performance improvements in simplifications
  - Automatic treatment of evanescent operators
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- Matching corrections to renormalizable SM couplings
  - Higgs mass m_H^2, Higgs quartic λ, Yukawas $Y_{u,d,e}$, (gauge couplings $g_{1,2,3}$)
- Phenomenology in Warsaw basis:
  - Redefine the renormalizable couplings to absorb these threshold corrections
  - Shits these contributions to $d = 6$ matching conditions
- Redefinition automatically performed by Matchete

MSSM Implementation

Implementation of MSSM Lagrangian & Assumptions

- ***MATCHETE*** implementation of MSSM Lagrangian:
  - Based on 4-component spinors
    - Gauginos: Majorana fermions (3)
    - Higgsinos: vectorlike fermion (1)
  - Higgs doublets: mass basis (*before EWSB*) (1)
  - Sfermions: complex scalars (5 types in 3 generations)

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- All masses **non-degenerate**, but matching performed at a **single scale $\bar{\mu}$** (before EWSB)
  - Integrate out all superpartners at single scale: $m_W \ll M_3^{\mathrm{SUSY}} \sim M_2^{\mathrm{SUSY}} \sim M_1^{\mathrm{SUSY}}$
  - Other scale hierarchies possible

Matching Setup

MSSM

SUSY intact

(dimensional reduction)

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MSSM
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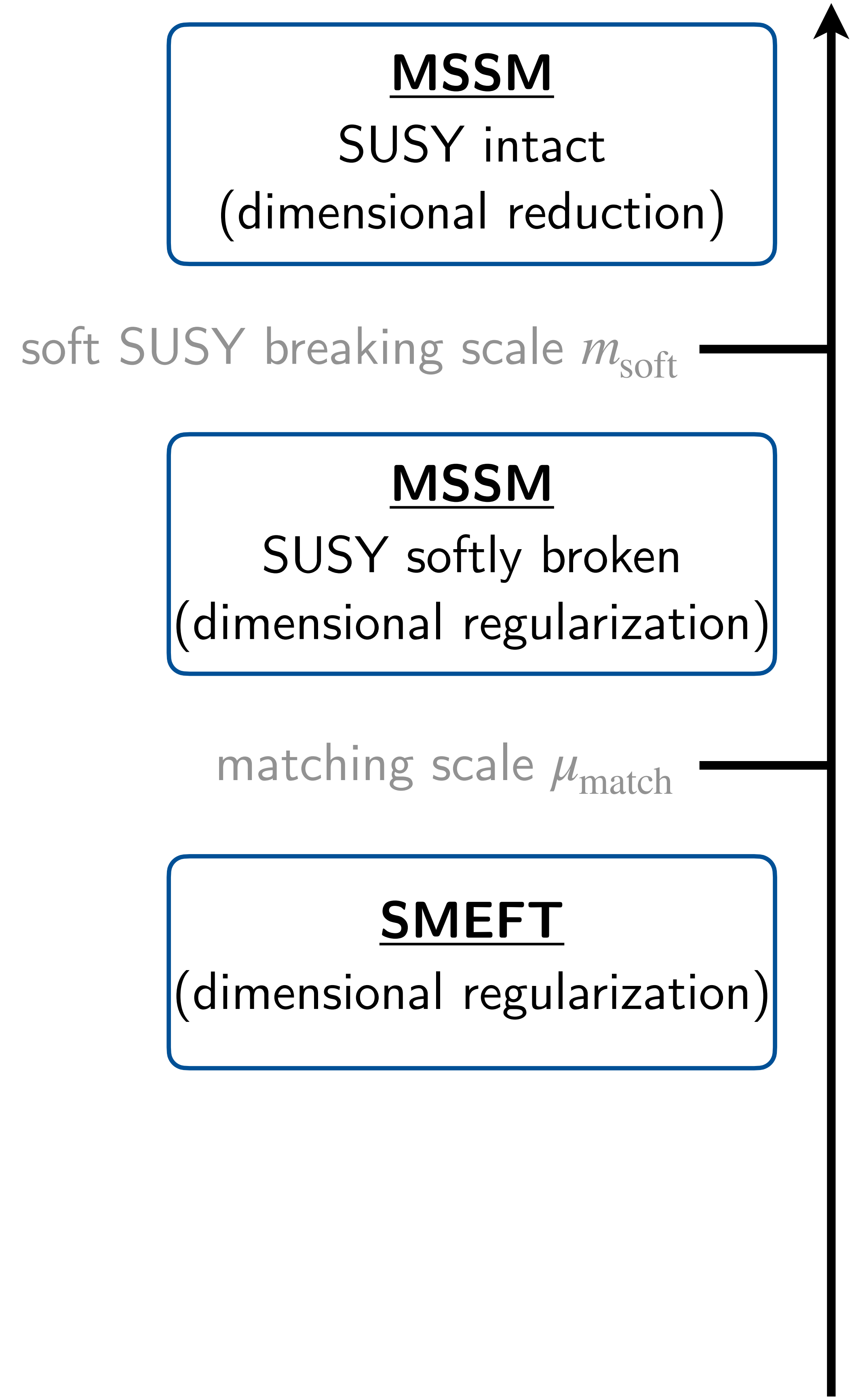
soft SUSY breaking scale m_{soft}

MSSM
SUSY softly broken
(dimensional regularization)

Matching Setup



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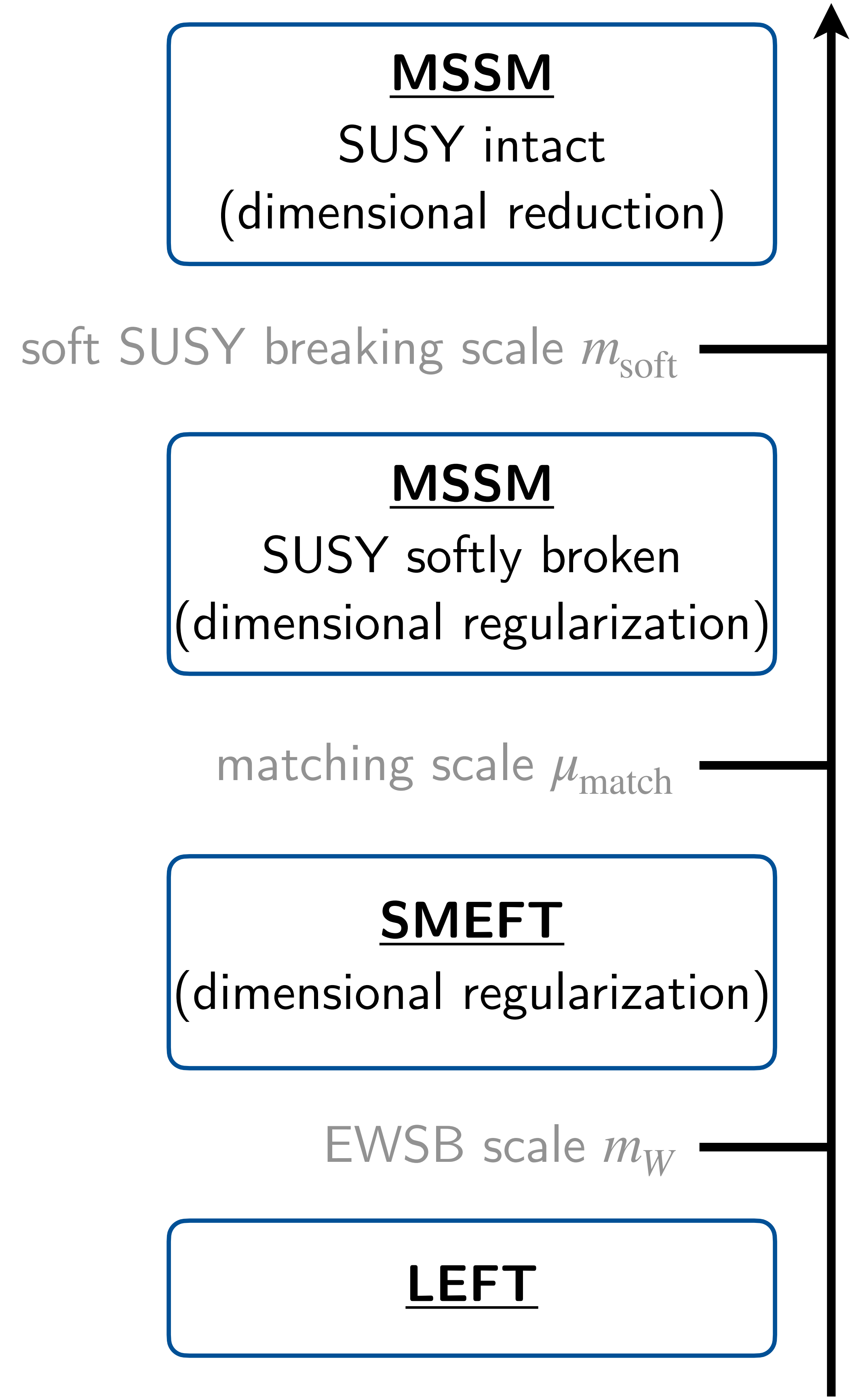

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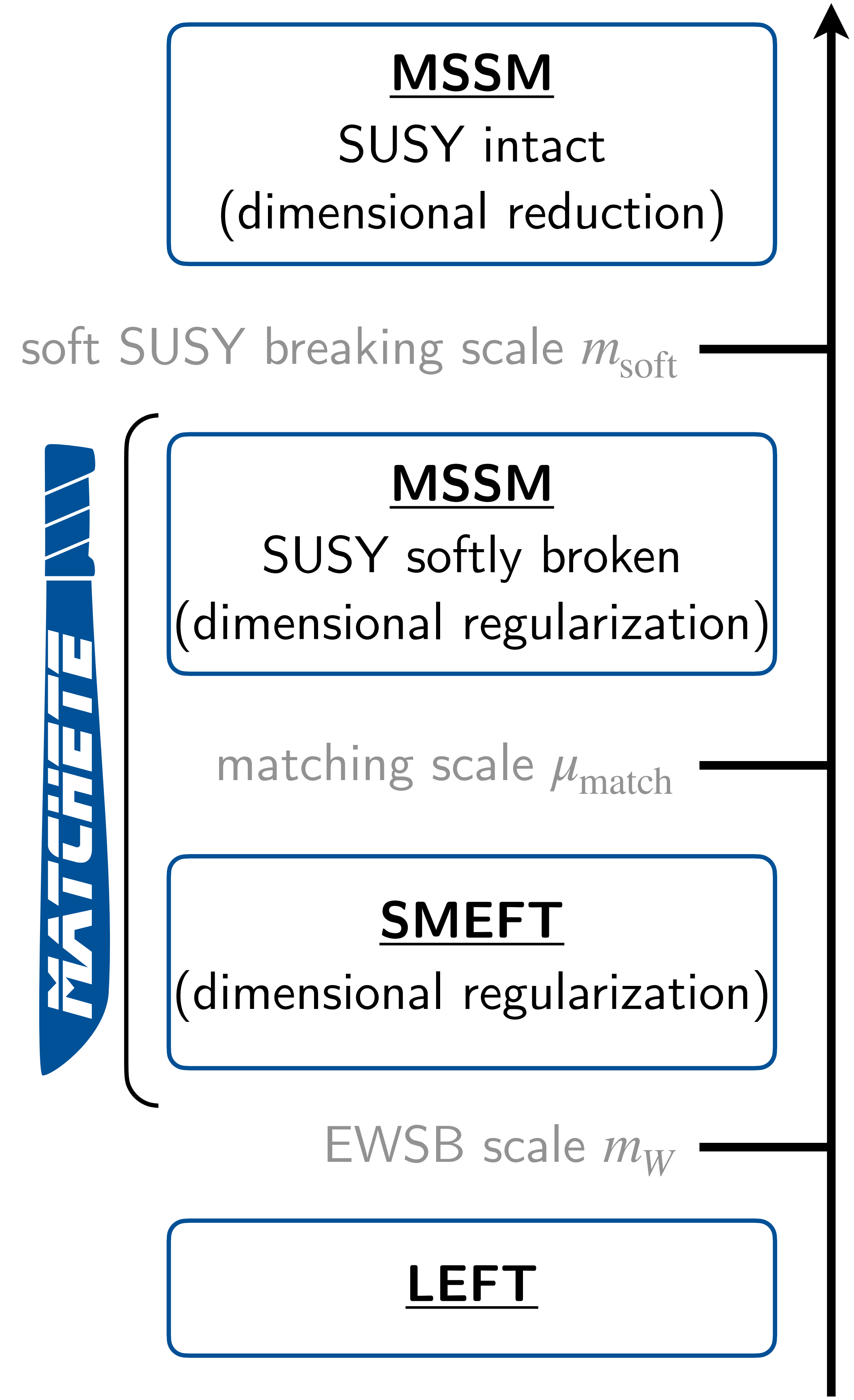
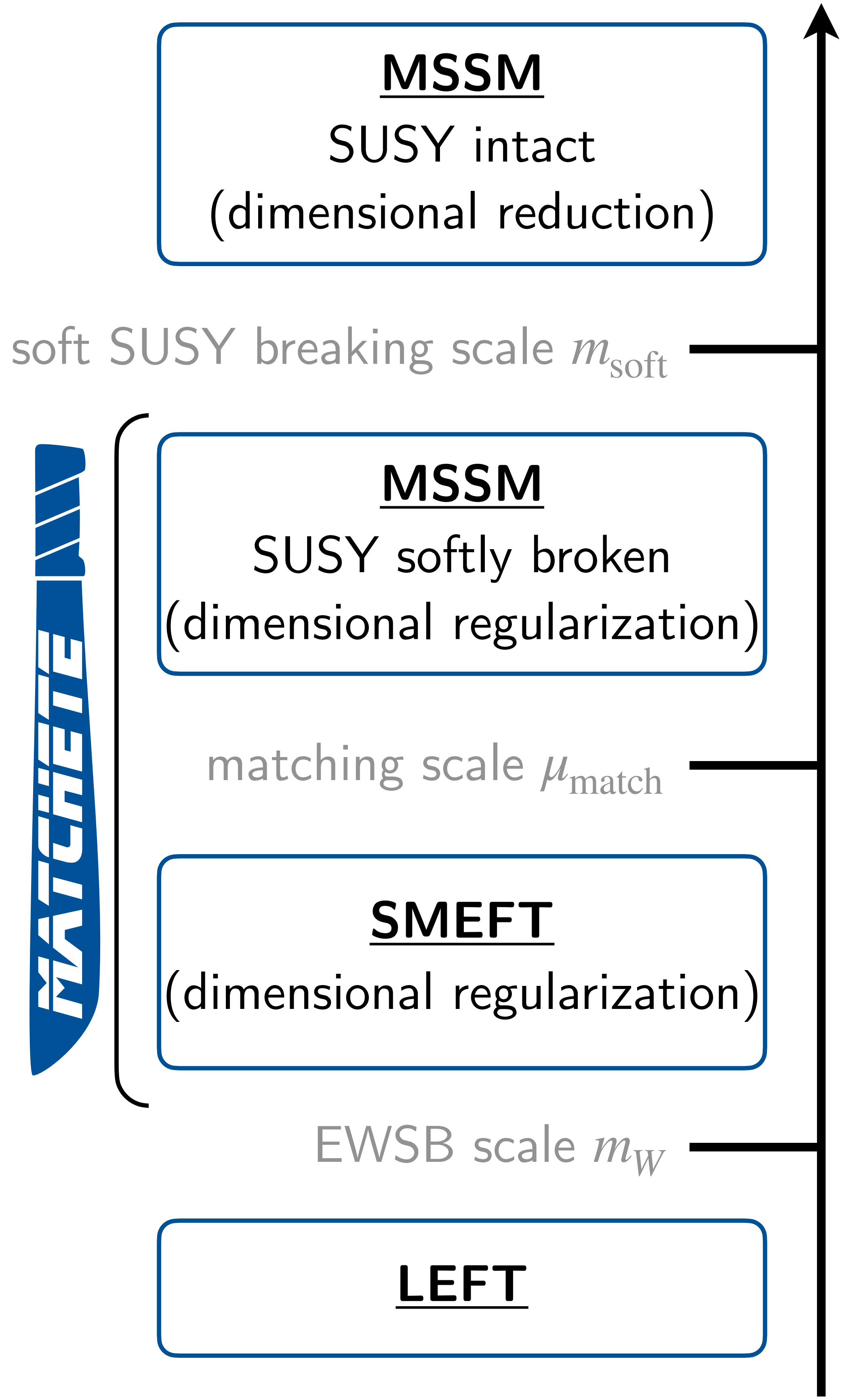


Matching Setup

Starting point: MSSM

- with soft breaking terms
- in dimensional regularization (DimReg)
  - DimReg does not preserve SUSY, would need dimensional reduction (DRED)
  - DRED not implemented, but we start after soft SUSY breaking
    - regulator not required to preserve SUSY
- in unbroken electroweak phase
  - matching onto SMEFT must be before EWSB
  - matching in mass basis
    - only soft but no EWSB mass terms



Effective Field Theory Scenarios for the MSSM

- **Possible scale hierarchy scenarios:**

  - Integrate out all superpartners at a single scale

    $$m_W \ll M_3^{\mathrm{SUSY}} \sim M_2^{\mathrm{SUSY}} \sim M_1^{\mathrm{SUSY}}$$ → **SMEFT**

  - Integrate out only 3rd generation of sfermions

    $$m_W \ll M_3^{\mathrm{SUSY}} \ll M_2^{\mathrm{SUSY}} \sim M_1^{\mathrm{SUSY}} \to \infty$$ → **SMEFT**

  - Retain 3rd gen. of sfermions in spectrum and integrate out 1st and 2nd gen.

    $$m_W \lesssim M_3^{\mathrm{SUSY}} \ll M_2^{\mathrm{SUSY}} \sim M_1^{\mathrm{SUSY}}$$ → **unknown EFT operator basis** (can be derived by `Matchete`)

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

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---

- Lightest superpartner stable due to R-parity / $\mathbb{Z}_2$-symmetry
  - Dark Matter (DM) candidate [*if neutral*] → bino only neutral state before EWSB
  - Keep bino in spectrum of EFT ⇒ SMEFT+bino (*basis obtainable with* `Matchete`)
  - Allows to better study missing energy signatures at colliders → future work

MSSM Lagrangian in MATCHETE

$\mathscr{L}_{\text{MSSM}} =$

$$-\frac{1}{4} B^{\mu\nu 2} - \frac{1}{4} G^{\mu\nu A 2} - \frac{1}{4} W^{\mu\nu I 2} + \delta^{pr} D_\mu \bar{\tilde{d}}^r_a D_\mu \tilde{d}^{ap} - m_d{}^{p2} \delta^{pr} \bar{\tilde{d}}^r_a \tilde{d}^{ap} + \delta^{pr} D_\mu \bar{\tilde{e}}^r D_\mu \tilde{e}^p - M_e{}^{p2} \delta^{pr} \bar{\tilde{e}}^r \tilde{e}^p + D_\mu \bar{H}_i D_\mu H^i - m_H^2 \bar{H}_i H^i + \delta^{pr} D_\mu \bar{\tilde{l}}^r_i D_\mu \tilde{l}^{ip} -$$

$$m_l{}^{p2} \delta^{pr} \bar{\tilde{l}}^r_i \tilde{l}^{ip} + \delta^{pr} D_\mu \bar{\tilde{q}}^r_{ai} D_\mu \tilde{q}^{aip} - m_q{}^{p2} \delta^{pr} \bar{\tilde{q}}^r_{ai} \tilde{q}^{aip} + \delta^{pr} D_\mu \bar{\tilde{u}}^r_a D_\mu \tilde{u}^{ap} - m_u{}^{p2} \delta^{pr} \bar{\tilde{u}}^r_a \tilde{u}^{ap} + D_\mu \bar{\Phi}_i D_\mu \Phi^i - m_\Phi{}^2 \bar{\Phi}_i \Phi^i + i\, \delta^{pr} \left(\bar{d}^r_a \cdot \gamma_\mu P_R \cdot D_\mu d^{ap}\right) +$$

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

$$\mu_H \left(\bar{\Sigma}_i \cdot \Sigma^i\right) + \frac{i}{2} \left(\tilde{B}^T \cdot C \gamma_\mu \cdot D_\mu \tilde{B}\right) - \frac{1}{2} m_B \left(\tilde{B}^T \cdot C \cdot \tilde{B}\right) + \frac{i}{2} \left(\tilde{G}^{AT} \cdot C \gamma_\mu \cdot D_\mu \tilde{G}^A\right) - \frac{1}{2} m_G \left(\tilde{G}^{AT} \cdot C \cdot \tilde{G}^A\right) + \frac{i}{2} \left(\tilde{W}^{IT} \cdot C \gamma_\mu \cdot D_\mu \tilde{W}^I\right) - \frac{1}{2} M_W \left(\tilde{W}^{IT} \cdot C \cdot \tilde{W}^I\right) -$$

$$\frac{1}{8} c_{2\beta}{}^2 \left(g_Y{}^2 + g_L{}^2\right) \bar{H}_i \bar{H}_j H^i H^j + \Big(-Y_e{}^{rp} c_\beta H^i \left(\bar{l}^r_i \cdot P_R \cdot e^p\right) - Y_d{}^{rp} c_\beta H^i \left(\bar{q}^r_{ai} \cdot P_R \cdot d^{ap}\right) - s_\beta Y_u{}^{rp} \bar{H}_i \left(\bar{q}^r_{aj} \cdot P_R \cdot u^{ap}\right) \varepsilon^{ji} + \left(-a_d{}^{rp} c_\beta + s_\beta Y_d{}^{rp} \mu_H\right) \tilde{d}^{ap} \bar{\tilde{q}}^r_{ai} H^i +$$

$$\left(-a_e{}^{rp} c_\beta + s_\beta Y_e{}^{rp} \mu_H\right) \tilde{e}^p \bar{\tilde{l}}^r_i H^i + \frac{1}{8} s_{4\beta} \left(g_Y{}^2 + g_L{}^2\right) \bar{H}_i H^i H^j \bar{\Phi}_j + \left(-s_\beta a_u{}^{rp} + Y_u{}^{rp} \mu_H c_\beta\right) \bar{\tilde{q}}^r_{aj} \tilde{u}^{ap} \bar{H}_i \varepsilon^{ji} + s_\beta Y_e{}^{rp} \Phi^i \left(\bar{l}^r_i \cdot P_R \cdot e^p\right) +$$

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$$\left(s_\beta a_d{}^{rp} + Y_d{}^{rp} \mu_H c_\beta\right) \tilde{d}^{ap} \bar{\tilde{q}}^r_{ai} \Phi^i + \left(s_\beta a_e{}^{rp} + Y_e{}^{rp} \mu_H c_\beta\right) \tilde{e}^p \bar{\tilde{l}}^r_i \Phi^i + Y_e{}^{rp} \tilde{e}^p \left(\bar{l}^r_i \cdot P_R \cdot \Sigma^i\right) + Y_d{}^{rp} \tilde{d}^{ap} \left(\bar{q}^r_{ai} \cdot P_R \cdot \Sigma^i\right) - Y_u{}^{rp} \tilde{u}^{ap} \left(\bar{q}^r_{ai} \cdot C P_R \cdot \bar{\Sigma}_j{}^T\right) \varepsilon^{ij} -$$

$$g_Y c_\beta H^i \left(\bar{\Sigma}_i \cdot P_L \cdot \tilde{B}\right) \frac{1}{\sqrt{2}} - g_L c_\beta H^j \left(\bar{\Sigma}_i \cdot P_L \cdot \tilde{W}^I\right) \sqrt{2}\, T^{Ii}_j - g_Y s_\beta H^i \left(\bar{\Sigma}_i \cdot P_R \cdot \tilde{B}\right) \frac{1}{\sqrt{2}} - g_L s_\beta H^j \left(\bar{\Sigma}_i \cdot P_R \cdot \tilde{W}^I\right) \sqrt{2}\, T^{Ii}_j - Y_u{}^{rp} \bar{\tilde{q}}^r_{ai} \left(\bar{\Sigma}_j \cdot P_R \cdot u^{ap}\right) \varepsilon^{ij} +$$

$$g_Y \delta^{pr} \bar{\tilde{l}}^r_i \left(\tilde{B}^T \cdot C P_L \cdot l^{ip}\right) \frac{1}{\sqrt{2}} - \frac{1}{3} g_Y \delta^{pr} \bar{\tilde{q}}^r_{ai} \left(\tilde{B}^T \cdot C P_L \cdot q^{aip}\right) \frac{1}{\sqrt{2}} - \frac{1}{3} g_Y \delta^{pr} \bar{\tilde{d}}^r_a \left(\tilde{B}^T \cdot C P_R \cdot d^{ap}\right) \sqrt{2} - g_Y \delta^{pr} \bar{\tilde{e}}^r \left(\tilde{B}^T \cdot C P_R \cdot e^p\right) \sqrt{2} +$$

$$\frac{2}{3} g_Y \delta^{pr} \bar{\tilde{u}}^r_a \left(\tilde{B}^T \cdot C P_R \cdot u^{ap}\right) \sqrt{2} + Y_d{}^{rp} \bar{\tilde{q}}^r_{ai} \left(d^{apT} \cdot C P_R \cdot \Sigma^i\right) + Y_e{}^{rp} \bar{\tilde{l}}^r_i \left(e^{pT} \cdot C P_R \cdot \Sigma^i\right) - g_s \delta^{pr} \bar{\tilde{q}}^r_{ai} \left(\tilde{G}^{AT} \cdot C P_L \cdot q^{bip}\right) \sqrt{2}\, T^{Aa}_b +$$

$$g_s \delta^{pr} \bar{\tilde{d}}^r_a \left(\tilde{G}^{AT} \cdot C P_R \cdot d^{bp}\right) \sqrt{2}\, T^{Aa}_b + g_s \delta^{pr} \bar{\tilde{u}}^r_a \left(\tilde{G}^{AT} \cdot C P_R \cdot u^{bp}\right) \sqrt{2}\, T^{Aa}_b - g_L \delta^{pr} \bar{\tilde{l}}^r_i \left(\tilde{W}^{IT} \cdot C P_L \cdot l^{jp}\right) \sqrt{2}\, T^{Ii}_j - g_L \delta^{pr} \bar{\tilde{q}}^r_{ai} \left(\tilde{W}^{IT} \cdot C P_L \cdot q^{ajp}\right) \sqrt{2}\, T^{Ii}_j +$$

$$\frac{1}{6} s_{2\beta} \left(3 \bar{Y}_d{}^{sr} Y_d{}^{sp} - g_Y{}^2 \delta^{pr}\right) \bar{\tilde{d}}^r_a \tilde{d}^{ap} H^i \bar{\Phi}_i + \frac{1}{2} s_{2\beta} \left(\bar{Y}_e{}^{sr} Y_e{}^{sp} - g_Y{}^2 \delta^{pr}\right) \bar{\tilde{e}}^r \tilde{e}^p H^i \bar{\Phi}_i + \frac{1}{4} s_{2\beta} \left(g_Y{}^2 + g_L{}^2\right) \delta^{pr} \bar{\tilde{l}}^r_i \tilde{l}^{ip} H^j \bar{\Phi}_j +$$

$$\frac{1}{2} s_{2\beta} \left(\bar{Y}_e{}^{ps} Y_e{}^{rs} - g_L{}^2 \delta^{pr}\right) \bar{\tilde{l}}^r_i \tilde{l}^{jp} H^i \bar{\Phi}_j - \frac{1}{12} s_{2\beta} \left(6 \bar{Y}_u{}^{ps} Y_u{}^{rs} + \left(g_Y{}^2 - 3 g_L{}^2\right) \delta^{pr}\right) \bar{\tilde{q}}^r_{ai} \tilde{q}^{aip} H^j \bar{\Phi}_j + \frac{1}{2} s_{2\beta} \left(\bar{Y}_d{}^{ps} Y_d{}^{rs} + \bar{Y}_u{}^{ps} Y_u{}^{rs} - g_L{}^2 \delta^{pr}\right) \bar{\tilde{q}}^r_{ai} \tilde{q}^{ajp} H^i \bar{\Phi}_j +$$

$$\frac{1}{6} s_{2\beta} \left(-3 \bar{Y}_u{}^{sr} Y_u{}^{sp} + 2 g_Y{}^2 \delta^{pr}\right) \bar{\tilde{u}}^r_a \tilde{u}^{ap} H^i \bar{\Phi}_i - \frac{1}{8} s_{4\beta} \left(g_Y{}^2 + g_L{}^2\right) H^j \bar{\Phi}_i \bar{\Phi}_j \Phi^i - Y_d{}^{sp} \bar{Y}_u{}^{sr} \tilde{d}^{ap} \bar{\tilde{u}}^r_a H^i \Phi^j \varepsilon_{ij} - g_Y c_\beta \bar{\Phi}_i \left(\tilde{B}^T \cdot C P_L \cdot \Sigma^i\right) \frac{1}{\sqrt{2}} +$$

$$g_Y s_\beta \bar{\Phi}_i \left(\tilde{B}^T \cdot C P_R \cdot \Sigma^i\right) \frac{1}{\sqrt{2}} - g_L c_\beta \bar{\Phi}_i \left(\tilde{W}^{IT} \cdot C P_L \cdot \Sigma^j\right) \sqrt{2}\, T^{Ii}_j + g_L s_\beta \bar{\Phi}_i \left(\tilde{W}^{IT} \cdot C P_R \cdot \Sigma^j\right) \sqrt{2}\, T^{Ii}_j - Y_d{}^{tp} \bar{Y}_e{}^{rs} \tilde{d}^{ap} \bar{\tilde{e}}^s \tilde{l}^{ir} \bar{\tilde{q}}^t_{ai} + \text{H.c.} \Big) +$$

$$\left(-\overline{Y_d}^{sr}\,Y_d^{sp}\,c_\beta^2+\frac{1}{6}\,c_{2\beta}\,g_Y^2\,\delta^{pr}\right)\overline{\tilde{d}}{}^r_a\,\tilde{d}^{ap}\,\bar{H}_i\,H^i+\left(-\overline{Y_e}^{sr}\,Y_e^{sp}\,c_\beta^2+\frac{1}{2}\,c_{2\beta}\,g_Y^2\,\delta^{pr}\right)\overline{\tilde{e}}{}^r\,\tilde{e}^p\,\bar{H}_i\,H^i+\left(-\overline{Y_e}^{ps}\,Y_e^{rs}\,c_\beta^2+\frac{1}{2}\,c_{2\beta}\,g_L^2\,\delta^{pr}\right)\overline{\tilde{l}}{}^r_j\,\tilde{l}^{ip}\,\bar{H}_i\,H^j-$$

$$\frac{1}{4}\,c_{2\beta}\,\left(g_Y^2+g_L^2\right)\delta^{pr}\,\overline{\tilde{l}}{}^r_j\,\tilde{l}^{jp}\,\bar{H}_i\,H^i+$$

$$\left(-\overline{Y_d}^{ps}\,Y_d^{rs}\,c_\beta^2+\overline{Y_u}^{ps}\,Y_u^{rs}\,s_\beta^2+\frac{1}{2}\,c_{2\beta}\,g_L^2\,\delta^{pr}\right)\overline{\tilde{q}}{}^r_{aj}\,\tilde{q}^{aip}\,\bar{H}_i\,H^j+$$

$$\left(-\overline{Y_u}^{ps}\,Y_u^{rs}\,s_\beta^2+\frac{1}{12}\,c_{2\beta}\,\left(g_Y^2-3\,g_L^2\right)\delta^{pr}\right)\overline{\tilde{q}}{}^r_{aj}\,\tilde{q}^{ajp}\,\bar{H}_i\,H^i+$$

$$\left(-\overline{Y_u}^{sr}\,Y_u^{sp}\,s_\beta^2-\frac{1}{3}\,c_{2\beta}\,g_Y^2\,\delta^{pr}\right)\overline{\tilde{u}}{}^r_a\,\tilde{u}^{ap}\,\bar{H}_i\,H^i+\frac{1}{8}\,\left(g_Y^2\,\left(-1+c_{4\beta}\right)+g_L^2\,\left(3+c_{4\beta}\right)\right)\bar{H}_i\,H^j\,\bar{\Phi}_j\,\Phi^i+$$

$$\frac{1}{8}\,\left(g_Y^2\,\left(1+c_{4\beta}\right)+g_L^2\,\left(-3+c_{4\beta}\right)\right)\bar{H}_i\,H^i\,\bar{\Phi}_j\,\Phi^j+$$

$$\frac{1}{36}\,\left(-2\,g_Y^2\,\delta^{pt}\,\delta^{rs}+3\,g_s^2\,\left(\delta^{pt}\,\delta^{rs}-3\,\delta^{ps}\,\delta^{rt}\right)\right)\overline{\tilde{d}}{}^s_a\,\overline{\tilde{d}}{}^t_b\,\tilde{d}^{ar}\,\tilde{d}^{bp}-\frac{1}{3}\,g_Y^2\,\delta^{ps}\,\delta^{rt}\,\overline{\tilde{d}}{}^s_a\,\tilde{d}^{ap}\,\overline{\tilde{e}}{}^t\,\tilde{e}^r-$$

$$\frac{1}{2}\,g_Y^2\,\delta^{ps}\,\delta^{rt}\,\overline{\tilde{e}}{}^s\,\overline{\tilde{e}}{}^t\,\tilde{e}^p\,\tilde{e}^r+\frac{1}{6}\,g_Y^2\,\delta^{ps}\,\delta^{rt}\,\overline{\tilde{d}}{}^s_a\,\tilde{d}^{ap}\,\overline{\tilde{l}}{}^t_i\,\tilde{l}^{ir}+\left(-\overline{Y_e}^{rs}\,Y_e^{tp}+\frac{1}{2}\,g_Y^2\,\delta^{ps}\,\delta^{rt}\right)\overline{\tilde{e}}{}^s\,\tilde{e}^p\,\overline{\tilde{l}}{}^t_i\,\tilde{l}^{ir}+$$

$$\frac{1}{8}\,\left(-g_Y^2\,\delta^{pt}\,\delta^{rs}+g_L^2\,\left(\delta^{pt}\,\delta^{rs}-2\,\delta^{ps}\,\delta^{rt}\right)\right)\overline{\tilde{l}}{}^s_i\,\overline{\tilde{l}}{}^t_j\,\tilde{l}^{ir}\,\tilde{l}^{jp}+\left(-\overline{Y_d}^{rs}\,Y_d^{tp}+\frac{1}{2}\,g_s^2\,\delta^{ps}\,\delta^{rt}\right)\overline{\tilde{d}}{}^s_a\,\tilde{d}^{bp}\,\overline{\tilde{q}}{}^t_{bi}\,\tilde{q}^{air}-$$

$$\frac{1}{6}\,g_Y^2\,\delta^{ps}\,\delta^{rt}\,\overline{\tilde{e}}{}^s\,\tilde{e}^p\,\overline{\tilde{q}}{}^t_{ai}\,\tilde{q}^{air}-\frac{1}{2}\,g_L^2\,\delta^{ps}\,\delta^{rt}\,\overline{\tilde{l}}{}^s_i\,\tilde{l}^{jp}\,\overline{\tilde{q}}{}^t_{aj}\,\tilde{q}^{air}+\frac{1}{12}\,\left(g_Y^2+3\,g_L^2\right)\delta^{ps}\,\delta^{rt}\,\overline{\tilde{l}}{}^s_i\,\tilde{l}^{ip}\,\overline{\tilde{q}}{}^t_{aj}\,\tilde{q}^{ajr}+$$

$$\frac{1}{4}\,\left(-g_L^2\,\delta^{pt}\,\delta^{rs}-g_s^2\,\delta^{ps}\,\delta^{rt}\right)\overline{\tilde{q}}{}^s_{ai}\,\overline{\tilde{q}}{}^t_{bj}\,\tilde{q}^{ajr}\,\tilde{q}^{bip}-\frac{1}{18}\,\left(g_Y^2+3\,g_s^2\right)\delta^{ps}\,\delta^{rt}\,\overline{\tilde{d}}{}^s_a\,\tilde{d}^{ap}\,\overline{\tilde{q}}{}^t_{bi}\,\tilde{q}^{bir}-$$

$$\frac{1}{72}\,\left(g_Y^2-9\,g_L^2-6\,g_s^2\right)\delta^{ps}\,\delta^{rt}\,\overline{\tilde{q}}{}^s_{ai}\,\overline{\tilde{q}}{}^t_{bj}\,\tilde{q}^{aip}\,\tilde{q}^{bjr}-\frac{1}{2}\,g_s^2\,\delta^{ps}\,\delta^{rt}\,\overline{\tilde{d}}{}^s_a\,\tilde{d}^{bp}\,\overline{\tilde{u}}{}^t_b\,\tilde{u}^{ar}+$$

$$\frac{2}{3}\,g_Y^2\,\delta^{ps}\,\delta^{rt}\,\overline{\tilde{e}}{}^s\,\tilde{e}^p\,\overline{\tilde{u}}{}^t_a\,\tilde{u}^{ar}-\frac{1}{3}\,g_Y^2\,\delta^{ps}\,\delta^{rt}\,\overline{\tilde{l}}{}^s_i\,\tilde{l}^{ip}\,\overline{\tilde{u}}{}^t_a\,\tilde{u}^{ar}+\left(-\overline{Y_u}^{pt}\,Y_u^{sr}+\frac{1}{2}\,g_s^2\,\delta^{ps}\,\delta^{rt}\right)\overline{\tilde{q}}{}^s_{ai}\,\tilde{q}^{bip}\,\overline{\tilde{u}}{}^t_b\,\tilde{u}^{ar}+$$

$$\frac{1}{36}\,\left(-8\,g_Y^2\,\delta^{pt}\,\delta^{rs}+3\,g_s^2\,\left(\delta^{pt}\,\delta^{rs}-3\,\delta^{ps}\,\delta^{rt}\right)\right)\overline{\tilde{u}}{}^s_a\,\overline{\tilde{u}}{}^t_b\,\tilde{u}^{ar}\,\tilde{u}^{bp}+\frac{1}{18}\,\left(4\,g_Y^2+3\,g_s^2\right)\delta^{ps}\,\delta^{rt}\,\overline{\tilde{d}}{}^s_a\,\tilde{d}^{ap}\,\overline{\tilde{u}}{}^t_b\,\tilde{u}^{br}+$$

$$\frac{1}{18}\,\left(2\,g_Y^2-3\,g_s^2\right)\delta^{ps}\,\delta^{rt}\,\overline{\tilde{q}}{}^s_{ai}\,\tilde{q}^{aip}\,\overline{\tilde{u}}{}^t_b\,\tilde{u}^{br}+\left(-\overline{Y_d}^{sr}\,Y_d^{sp}\,s_\beta^2-\frac{1}{6}\,c_{2\beta}\,g_Y^2\,\delta^{pr}\right)\overline{\tilde{d}}{}^r_a\,\tilde{d}^{ap}\,\bar{\Phi}_i\,\Phi^i+$$

$$\left(-\overline{Y_e}^{sr}\,Y_e^{sp}\,s_\beta^2-\frac{1}{2}\,c_{2\beta}\,g_Y^2\,\delta^{pr}\right)\overline{\tilde{e}}{}^r\,\tilde{e}^p\,\bar{\Phi}_i\,\Phi^i+\left(-\overline{Y_e}^{ps}\,Y_e^{rs}\,s_\beta^2-\frac{1}{2}\,c_{2\beta}\,g_L^2\,\delta^{pr}\right)\overline{\tilde{l}}{}^r_i\,\tilde{l}^{jp}\,\bar{\Phi}_j\,\Phi^i+$$

$$\left(-\overline{Y_d}^{ps}\,Y_d^{rs}\,s_\beta^2+\overline{Y_u}^{ps}\,Y_u^{rs}\,c_\beta^2-\frac{1}{2}\,c_{2\beta}\,g_L^2\,\delta^{pr}\right)\overline{\tilde{q}}{}^r_{ai}\,\tilde{q}^{ajp}\,\bar{\Phi}_j\,\Phi^i+\left(-\overline{Y_u}^{sr}\,Y_u^{sp}\,c_\beta^2+\frac{1}{3}\,c_{2\beta}\,g_Y^2\,\delta^{pr}\right)\overline{\tilde{u}}{}^r_a\,\tilde{u}^{ap}\,\bar{\Phi}_i\,\Phi^i+$$

$$\frac{1}{4}\,c_{2\beta}\,\left(g_Y^2+g_L^2\right)\delta^{pr}\,\overline{\tilde{l}}{}^r_i\,\tilde{l}^{ip}\,\bar{\Phi}_j\,\Phi^j+\left(-\overline{Y_u}^{ps}\,Y_u^{rs}\,c_\beta^2-\frac{1}{12}\,c_{2\beta}\,\left(g_Y^2-3\,g_L^2\right)\delta^{pr}\right)\overline{\tilde{q}}{}^r_{ai}\,\tilde{q}^{aip}\,\bar{\Phi}_j\,\Phi^j-\frac{1}{8}\,c_{2\beta}^2\,\left(g_Y^2+g_L^2\right)\bar{\Phi}_i\,\bar{\Phi}_j\,\Phi^i\,\Phi^j$$

117 different terms

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
```

$$-\frac{1}{4}B^{\mu\nu 2}-\frac{1}{4}G^{\mu\nu A2}-\frac{1}{4}W^{\mu\nu I2}+D_\mu\bar{H}_i D_\mu H^i-m_H^2\bar{H}_i H^i+i\,\delta^{pr}\left(\bar{d}^r_a\cdot\gamma_\mu P_R\cdot D_\mu d^{ap}\right)+$$
$$i\,\delta^{pr}\left(\bar{e}^r\cdot\gamma_\mu P_R\cdot D_\mu e^p\right)+i\,\delta^{pr}\left(\bar{l}^r_i\cdot\gamma_\mu P_L\cdot D_\mu l^{ip}\right)+i\,\delta^{pr}\left(\bar{q}^r_{ai}\cdot\gamma_\mu P_L\cdot D_\mu q^{aip}\right)+i\,\delta^{pr}\left(\bar{u}^r_a\cdot\gamma_\mu P_R\cdot D_\mu u^{ap}\right)-$$
$$\frac{1}{8}c_{2\beta}^2\left(g_Y^2+g_L^2\right)\bar{H}_i\bar{H}_j H^i H^j+\Big(-Y_e{}^{rp}c_\beta H^i\left(\bar{l}^r_i\cdot P_R\cdot e^p\right)-Y_d{}^{rp}c_\beta H^i\left(\bar{q}^r_{ai}\cdot P_R\cdot d^{ap}\right)-s_\beta Y_u{}^{rp}\bar{H}_i\left(\bar{q}^r_{aj}\cdot P_R\cdot u^{ap}\right)\varepsilon^{ji}+$$
$$\frac{1}{8}s_{4\beta}s_\beta Y_e{}^{rp}\frac{1}{m_\Phi{}^2}\left(g_Y^2+g_L^2\right)\bar{H}_i H^i H^j\left(\bar{l}^r_j\cdot P_R\cdot e^p\right)+\frac{1}{8}s_{4\beta}s_\beta Y_d{}^{rp}\frac{1}{m_\Phi{}^2}\left(g_Y^2+g_L^2\right)\bar{H}_i H^i H^j\left(\bar{q}^r_{aj}\cdot P_R\cdot d^{ap}\right)-$$
$$\frac{1}{8}s_{4\beta}Y_u{}^{rp}c_\beta\frac{1}{m_\Phi{}^2}\left(g_Y^2+g_L^2\right)\bar{H}_i\bar{H}_j H^j\left(\bar{q}^r_{ak}\cdot P_R\cdot u^{ap}\right)\varepsilon^{ki}+Y_d{}^{tp}\,\overline{Y_e}{}^{rs}\frac{1}{m_\Phi{}^2}s_\beta^2\left(\bar{e}^s\cdot P_L\cdot l^{ir}\right)\left(\bar{q}^t_{ai}\cdot P_R\cdot d^{ap}\right)-$$
$$s_\beta Y_e{}^{sp}Y_u{}^{tr}c_\beta\frac{1}{m_\Phi{}^2}\left(\bar{l}^s_j\cdot P_R\cdot e^p\right)\left(\bar{q}^t_{ai}\cdot P_R\cdot u^{ar}\right)\varepsilon^{ij}-s_\beta Y_d{}^{sp}Y_u{}^{tr}c_\beta\frac{1}{m_\Phi{}^2}\left(\bar{q}^t_{ai}\cdot P_R\cdot u^{ar}\right)\left(\bar{q}^s_{bj}\cdot P_R\cdot d^{bp}\right)\varepsilon^{ij}+\text{H.c.}\Big)+$$
$$\frac{1}{64}\frac{1}{m_\Phi{}^2}s_{4\beta}^2\bar{H}_i\bar{H}_j\bar{H}_k H^i H^j H^k\left(g_Y^2+g_L^2\right)^2+\overline{Y_e}{}^{rs}Y_e{}^{tp}\frac{1}{m_\Phi{}^2}s_\beta^2\left(\bar{e}^s\cdot P_L\cdot l^{ir}\right)\left(\bar{l}^t_i\cdot P_R\cdot e^p\right)+$$
$$\overline{Y_d}{}^{rs}Y_d{}^{tp}\frac{1}{m_\Phi{}^2}s_\beta^2\left(\bar{d}^s_a\cdot P_L\cdot q^{air}\right)\left(\bar{q}^t_{bi}\cdot P_R\cdot d^{bp}\right)+\overline{Y_u}{}^{pt}Y_u{}^{sr}\frac{1}{m_\Phi{}^2}c_\beta^2\left(\bar{q}^s_{ai}\cdot P_R\cdot u^{ar}\right)\left(\bar{u}^t_b\cdot P_L\cdot q^{bip}\right)$$

- 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 A 2} - \frac{1}{4} W^{\mu\nu I 2} + D_\mu \bar{H}_i D_\mu H^i - m_H^2 \bar{H}_i H^i + i\,\delta^{pr} (\bar{d}^r_a \cdot \gamma_\mu P_R \cdot D_\mu d^{ap}) + \\
&i\,\delta^{pr} (\bar{e}^r \cdot \gamma_\mu P_R \cdot D_\mu e^p) + i\,\delta^{pr} (\bar{l}^r_i \cdot \gamma_\mu P_L \cdot D_\mu l^{ip}) + i\,\delta^{pr} (\bar{q}^r_{ai} \cdot \gamma_\mu P_L \cdot D_\mu q^{aip}) + i\,\delta^{pr} (\bar{u}^r_a \cdot \gamma_\mu P_R \cdot D_\mu u^{ap}) - \\
&\frac{1}{8} c_{2\beta}^2 (g_Y^2 + g_L^2) \bar{H}_i \bar{H}_j H^i H^j + \Big(-Y_e^{rp} c_\beta H^i (\bar{l}^r_i \cdot P_R \cdot e^p) - Y_d^{rp} c_\beta H^i (\bar{q}^r_{ai} \cdot P_R \cdot d^{ap}) - s_\beta Y_u^{rp} \bar{H}_i (\bar{q}^r_{aj} \cdot P_R \cdot u^{ap}) \varepsilon^{ji} + \\
&\quad \frac{1}{8} s_{4\beta} s_\beta Y_e^{rp} \frac{1}{m_\Phi^2} (g_Y^2 + g_L^2) \bar{H}_i H^i H^j (\bar{l}^r_j \cdot P_R \cdot e^p) + \frac{1}{8} s_{4\beta} s_\beta Y_d^{rp} \frac{1}{m_\Phi^2} (g_Y^2 + g_L^2) \bar{H}_i H^i H^j (\bar{q}^r_{aj} \cdot P_R \cdot d^{ap}) - \\
&\quad \frac{1}{8} s_{4\beta} Y_u^{rp} c_\beta \frac{1}{m_\Phi^2} (g_Y^2 + g_L^2) \bar{H}_i \bar{H}_j H^j (\bar{q}^r_{ak} \cdot P_R \cdot u^{ap}) \varepsilon^{ki} + Y_d^{tp} \overline{Y_e}^{rs} \frac{1}{m_\Phi^2} s_\beta^2 (\bar{e}^s \cdot P_L \cdot l^{ir}) (\bar{q}^t_{ai} \cdot P_R \cdot d^{ap}) - \\
&\quad s_\beta Y_e^{sp} Y_u^{tr} c_\beta \frac{1}{m_\Phi^2} (\bar{l}^s_j \cdot P_R \cdot e^p) (\bar{q}^t_{ai} \cdot P_R \cdot u^{ar}) \varepsilon^{ij} - s_\beta Y_d^{sp} Y_u^{tr} c_\beta \frac{1}{m_\Phi^2} (\bar{q}^t_{ai} \cdot P_R \cdot u^{ar}) (\bar{q}^s_{bj} \cdot P_R \cdot d^{bp}) \varepsilon^{ij} + \text{H.c.} \Big) + \\
&\frac{1}{64} \frac{1}{m_\Phi^2} s_{4\beta}^2 \bar{H}_i \bar{H}_j \bar{H}_k H^i H^j H^k (g_Y^2 + g_L^2)^2 + \overline{Y_e}^{rs} Y_e^{tp} \frac{1}{m_\Phi^2} s_\beta^2 (\bar{e}^s \cdot P_L \cdot l^{ir}) (\bar{l}^t_i \cdot P_R \cdot e^p) + \\
&\overline{Y_d}^{rs} Y_d^{tp} \frac{1}{m_\Phi^2} s_\beta^2 (\bar{d}^s_a \cdot P_L \cdot q^{air}) (\bar{q}^t_{bi} \cdot P_R \cdot d^{bp}) + \overline{Y_u}^{pt} Y_u^{sr} \frac{1}{m_\Phi^2} c_\beta^2 (\bar{q}^s_{ai} \cdot P_R \cdot u^{ar}) (\bar{u}^t_b \cdot P_L \cdot q^{bip})
\end{aligned}
$$

- Contributions only by 2nd heavy Higgs Φ, superpartner contributions forbidden by R-parity
- Only 3 operators not part of Warsaw basis
  - Require 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]

    ➡ Relevant at loop level only → absorbed by finite renormalization

Tree-Level Matching Conditions for the Warsaw Basis

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

$Y_d{}^{i1\_i2\_} \to Y_d{}^{i1i2}\, c_\beta$

$Y_e{}^{i1\_i2\_} \to Y_e{}^{i1i2}\, c_\beta$

$Y_u{}^{i1\_i2\_} \to s_\beta\, Y_u{}^{i1i2}$

$\lambda \to \frac{1}{4} g_Y{}^2\, c_{2\beta}{}^2 + \frac{1}{4} g_L{}^2\, c_{2\beta}{}^2$

$\mu 2 \to -m_H^2$

$\mathcal{C}_{dH}{}^{i1\_i2\_} \to \frac{1}{8} s_{4\beta}\, s_\beta\, Y_d{}^{i1i2}\, g_Y{}^2 \frac{1}{m_\Phi{}^2} + \frac{1}{8} s_{4\beta}\, s_\beta\, Y_d{}^{i1i2}\, g_L{}^2 \frac{1}{m_\Phi{}^2}$

$\mathcal{C}_{eH}{}^{i1\_i2\_} \to \frac{1}{8} s_{4\beta}\, s_\beta\, Y_e{}^{i1i2}\, g_Y{}^2 \frac{1}{m_\Phi{}^2} + \frac{1}{8} s_{4\beta}\, s_\beta\, Y_e{}^{i1i2}\, g_L{}^2 \frac{1}{m_\Phi{}^2}$

$\mathcal{C}_{H} \to \frac{1}{64} g_Y{}^4 \frac{1}{m_\Phi{}^2} s_{4\beta}{}^2 + \frac{1}{32} g_Y{}^2\, g_L{}^2 \frac{1}{m_\Phi{}^2} s_{4\beta}{}^2 + \frac{1}{64} g_L{}^4 \frac{1}{m_\Phi{}^2} s_{4\beta}{}^2$

$\mathcal{C}_{le}{}^{i1\_i2\_i3\_i4\_} \to -\frac{1}{2} \overline{Y_e}{}^{i2i3}\, Y_e{}^{i1i4} \frac{1}{m_\Phi{}^2} s_\beta{}^2$

$\mathcal{C}_{ledq}{}^{i1\_i2\_i3\_i4\_} \to \overline{Y_d}{}^{i4i3}\, Y_e{}^{i1i2} \frac{1}{m_\Phi{}^2} s_\beta{}^2$

$\mathcal{C}^{(1)}_{lequ}{}^{i1\_i2\_i3\_i4\_} \to s_\beta\, Y_e{}^{i1i2}\, Y_u{}^{i3i4}\, c_\beta \frac{1}{m_\Phi{}^2}$

$\mathcal{C}^{(1)}_{qd}{}^{i1\_i2\_i3\_i4\_} \to -\frac{1}{6} \overline{Y_d}{}^{i2i3}\, Y_d{}^{i1i4} \frac{1}{m_\Phi{}^2} s_\beta{}^2$

$\mathcal{C}^{(8)}_{qd}{}^{i1\_i2\_i3\_i4\_} \to -\overline{Y_d}{}^{i2i3}\, Y_d{}^{i1i4} \frac{1}{m_\Phi{}^2} s_\beta{}^2$

$\mathcal{C}^{(1)}_{qu}{}^{i1\_i2\_i3\_i4\_} \to -\frac{1}{6} \overline{Y_u}{}^{i2i3}\, Y_u{}^{i1i4} \frac{1}{m_\Phi{}^2} c_\beta{}^2$

$\mathcal{C}^{(8)}_{qu}{}^{i1\_i2\_i3\_i4\_} \to -\overline{Y_u}{}^{i2i3}\, Y_u{}^{i1i4} \frac{1}{m_\Phi{}^2} c_\beta{}^2$

$\mathcal{C}^{(1)}_{quqd}{}^{i1\_i2\_i3\_i4\_} \to -s_\beta\, Y_d{}^{i3i4}\, Y_u{}^{i1i2}\, c_\beta \frac{1}{m_\Phi{}^2}$

$\mathcal{C}_{uH}{}^{i1\_i2\_} \to -\frac{1}{8} s_{4\beta}\, Y_u{}^{i1i2}\, c_\beta\, g_Y{}^2 \frac{1}{m_\Phi{}^2} - \frac{1}{8} s_{4\beta}\, Y_u{}^{i1i2}\, c_\beta\, g_L{}^2 \frac{1}{m_\Phi{}^2}$

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

Tree-Level Matching Conditions for the Warsaw Basis

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

$$Y_d{}^{i1\_i2\_} \to Y_d{}^{i1i2}\, c_\beta$$
$$Y_e{}^{i1\_i2\_} \to Y_e{}^{i1i2}\, c_\beta$$
$$Y_u{}^{i1\_i2\_} \to s_\beta\, Y_u{}^{i1i2}$$
$$\lambda \to \frac{1}{4} g_Y{}^2\, c_{2\beta}{}^2 + \frac{1}{4} g_L{}^2\, c_{2\beta}{}^2$$
$$\mu 2 \to -m_H^2$$

$$\mathcal{C}_{dH}{}^{i1\_i2\_} \to \frac{1}{8} s_{4\beta}\, s_\beta\, Y_d{}^{i1i2}\, g_Y{}^2 \frac{1}{m_\Phi{}^2} + \frac{1}{8} s_{4\beta}\, s_\beta\, Y_d{}^{i1i2}\, g_L{}^2 \frac{1}{m_\Phi{}^2}$$
$$\mathcal{C}_{eH}{}^{i1\_i2\_} \to \frac{1}{8} s_{4\beta}\, s_\beta\, Y_e{}^{i1i2}\, g_Y{}^2 \frac{1}{m_\Phi{}^2} + \frac{1}{8} s_{4\beta}\, s_\beta\, Y_e{}^{i1i2}\, g_L{}^2 \frac{1}{m_\Phi{}^2}$$
$$\mathcal{C}_{H} \to \frac{1}{64} g_Y{}^4 \frac{1}{m_\Phi{}^2} s_{4\beta}{}^2 + \frac{1}{32} g_Y{}^2\, g_L{}^2 \frac{1}{m_\Phi{}^2} s_{4\beta}{}^2 + \frac{1}{64} g_L{}^4 \frac{1}{m_\Phi{}^2} s_{4\beta}{}^2$$
$$\mathcal{C}_{le}{}^{i1\_i2\_i3\_i4\_} \to -\frac{1}{2} \overline{Y_e}{}^{i2i3}\, Y_e{}^{i1i4} \frac{1}{m_\Phi{}^2} s_\beta{}^2$$
$$\mathcal{C}_{ledq}{}^{i1\_i2\_i3\_i4\_} \to \overline{Y_d}{}^{i4i3}\, Y_e{}^{i1i2} \frac{1}{m_\Phi{}^2} s_\beta{}^2$$
$$\mathcal{C}^{(1)}_{lequ}{}^{i1\_i2\_i3\_i4\_} \to s_\beta\, Y_e{}^{i1i2}\, Y_u{}^{i3i4}\, c_\beta \frac{1}{m_\Phi{}^2}$$
$$\mathcal{C}^{(1)}_{qd}{}^{i1\_i2\_i3\_i4\_} \to -\frac{1}{6} \overline{Y_d}{}^{i2i3}\, Y_d{}^{i1i4} \frac{1}{m_\Phi{}^2} s_\beta{}^2$$
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$$\mathcal{C}^{(1)}_{qu}{}^{i1\_i2\_i3\_i4\_} \to -\frac{1}{6} \overline{Y_u}{}^{i2i3}\, Y_u{}^{i1i4} \frac{1}{m_\Phi{}^2} c_\beta{}^2$$
$$\mathcal{C}^{(8)}_{qu}{}^{i1\_i2\_i3\_i4\_} \to -\overline{Y_u}{}^{i2i3}\, Y_u{}^{i1i4} \frac{1}{m_\Phi{}^2} c_\beta{}^2$$
$$\mathcal{C}^{(1)}_{quqd}{}^{i1\_i2\_i3\_i4\_} \to -s_\beta\, Y_d{}^{i3i4}\, Y_u{}^{i1i2}\, c_\beta \frac{1}{m_\Phi{}^2}$$
$$\mathcal{C}_{uH}{}^{i1\_i2\_} \to -\frac{1}{8} s_{4\beta}\, Y_u{}^{i1i2}\, c_\beta\, g_Y{}^2 \frac{1}{m_\Phi{}^2} - \frac{1}{8} s_{4\beta}\, Y_u{}^{i1i2}\, c_\beta\, g_L{}^2 \frac{1}{m_\Phi{}^2}$$

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

Correction to SM parameters

Tree-Level Matching Conditions for the Warsaw Basis

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

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$$Y_d{}^{i1\_i2\_} \to Y_d{}^{i1i2}\, c_\beta$$
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$$Y_u{}^{i1\_i2\_} \to s_\beta\, Y_u{}^{i1i2}$$
$$\lambda \to \frac{1}{4} g_Y{}^2 c_{2\beta}{}^2 + \frac{1}{4} g_L{}^2 c_{2\beta}{}^2$$
$$\mu 2 \to -m_H^2$$

Warsaw basis Wilson coefficients

(without one-loop contribution from renormalizing evanescent operators)

$$C_{dH}{}^{i1\_i2\_} \to \frac{1}{8} s_{4\beta} s_\beta Y_d{}^{i1i2} g_Y{}^2 \frac{1}{m_\Phi{}^2} + \frac{1}{8} s_{4\beta} s_\beta Y_d{}^{i1i2} g_L{}^2 \frac{1}{m_\Phi{}^2}$$
$$C_{eH}{}^{i1\_i2\_} \to \frac{1}{8} s_{4\beta} s_\beta Y_e{}^{i1i2} g_Y{}^2 \frac{1}{m_\Phi{}^2} + \frac{1}{8} s_{4\beta} s_\beta Y_e{}^{i1i2} g_L{}^2 \frac{1}{m_\Phi{}^2}$$
$$C_H \to \frac{1}{64} g_Y{}^4 \frac{1}{m_\Phi{}^2} s_{4\beta}{}^2 + \frac{1}{32} g_Y{}^2 g_L{}^2 \frac{1}{m_\Phi{}^2} s_{4\beta}{}^2 + \frac{1}{64} g_L{}^4 \frac{1}{m_\Phi{}^2} s_{4\beta}{}^2$$
$$C_{le}{}^{i1\_i2\_i3\_i4\_} \to -\frac{1}{2} \overline{Y_e}{}^{i2i3} Y_e{}^{i1i4} \frac{1}{m_\Phi{}^2} s_\beta{}^2$$
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$$C^{(1)}_{quqd}{}^{i1\_i2\_i3\_i4\_} \to -s_\beta Y_d{}^{i3i4} Y_u{}^{i1i2} c_\beta \frac{1}{m_\Phi{}^2}$$
$$C_{uH}{}^{i1\_i2\_} \to -\frac{1}{8} s_{4\beta} Y_u{}^{i1i2} c_\beta g_Y{}^2 \frac{1}{m_\Phi{}^2} - \frac{1}{8} s_{4\beta} Y_u{}^{i1i2} c_\beta g_L{}^2 \frac{1}{m_\Phi{}^2}$$

Tree-Level Matching Conditions for the Warsaw Basis

```
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```

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

Correction to SM parameters

$Y_d{}^{i1\_i2\_} \to Y_d{}^{i1i2}\, c_\beta$

$Y_e{}^{i1\_i2\_} \to Y_e{}^{i1i2}\, c_\beta$

$Y_u{}^{i1\_i2\_} \to s_\beta\, Y_u{}^{i1i2}$

$\lambda \to \frac{1}{4} g_Y{}^2\, c_{2\beta}{}^2 + \frac{1}{4} g_L{}^2\, c_{2\beta}{}^2$

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$\mathcal{C}_{eH}{}^{i1\_i2\_} \to \frac{1}{8} s_{4\beta}\, s_\beta\, Y_e{}^{i1i2}\, g_Y{}^2 \frac{1}{m_\Phi{}^2} + \frac{1}{8} s_{4\beta}\, s_\beta\, Y_e{}^{i1i2}\, g_L{}^2 \frac{1}{m_\Phi{}^2}$

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$\mathcal{C}_{le}{}^{i1\_i2\_i3\_i4\_} \to -\frac{1}{2} \overline{Y_e}{}^{i2i3}\, Y_e{}^{i1i4} \frac{1}{m_\Phi{}^2} s_\beta{}^2$

$\mathcal{C}_{ledq}{}^{i1\_i2\_i3\_i4\_} \to \overline{Y_d}{}^{i4i3}\, Y_e{}^{i1i2} \frac{1}{m_\Phi{}^2} s_\beta{}^2$

$\mathcal{C}^{(1)}_{lequ}{}^{i1\_i2\_i3\_i4\_} \to s_\beta\, Y_e{}^{i1i2}\, Y_u{}^{i3i4}\, c_\beta \frac{1}{m_\Phi{}^2}$

$\mathcal{C}^{(1)}_{qd}{}^{i1\_i2\_i3\_i4\_} \to -\frac{1}{6} \overline{Y_d}{}^{i2i3}\, Y_d{}^{i1i4} \frac{1}{m_\Phi{}^2} s_\beta{}^2$

$\mathcal{C}^{(8)}_{qd}{}^{i1\_i2\_i3\_i4\_} \to -\overline{Y_d}{}^{i2i3}\, Y_d{}^{i1i4} \frac{1}{m_\Phi{}^2} s_\beta{}^2$

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$\mathcal{C}_{uH}{}^{i1\_i2\_} \to -\frac{1}{8} s_{4\beta}\, Y_u{}^{i1i2}\, c_\beta\, g_Y{}^2 \frac{1}{m_\Phi{}^2} - \frac{1}{8} s_{4\beta}\, Y_u{}^{i1i2}\, c_\beta\, g_L{}^2 \frac{1}{m_\Phi{}^2}$

- Only contributions from integrating out 2nd heavy Higgs doublet Φ
- R-parity acts like a $\mathbb{Z}_2$ symmetry for superpartners *(even powers required)* → No tree-level matching contributions

One-Loop Matching

**approximate & preliminary values for Apple M3*

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

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

→ 15 min*

  - Performs entire one-loop matching, integrating out all heavy fields at once
  - Resulting SMEFT Lagrangian contains many redundancies
  - Reduction to Warsaw basis required for phenomenological analyses

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  - Performs entire one-loop matching, integrating out all heavy fields at once
  - Resulting SMEFT Lagrangian contains many redundancies
  - Reduction to Warsaw basis required for phenomenological analyses

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

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

→ 1 min*

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

```
ℒEFT1 = EOMSimplify[ℒEFT1];
```

→ 8 min*

- Mapping resulting minimal SMEFT Lagrangian onto Warsaw basis

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

→ 10 min (50 MB)*

➡ Matching conditions in Warsaw basis

Results & Validation

- MSSM-to-SMEFT matching generates **all $\boldsymbol{B}$- and $\boldsymbol{L}$-conserving operators of the Warsaw basis** that do not contain dual field-strength tensors

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

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

$$\frac{1}{144}\hbar g_s^2 \frac{1}{m_q^{p2}} \Bigg(6\,\overline{Y_d}^{pr} Y_d^{pr} \frac{1}{m_d^{r2}} c_\beta^2 \left(m_d^{r2} + m_q^{p2}\right) + 6\,\overline{Y_u}^{pr} Y_u^{pr} \frac{1}{m_u^{r2}} s_\beta^2 \left(m_q^{p2} + m_u^{r2}\right) + \sum_p c_{2\beta}\, g_Y^2 \left(-1 + m_q^{p2}\left(-\frac{1}{m_d^{p2}} + 2\frac{1}{m_u^{p2}}\right)\right)\Bigg) -$$

$$\frac{1}{4}\hbar g_s^2 \left(\overline{a_d}^{pr} c_\beta - s_\beta \overline{Y_d}^{pr}\mu_H\right)\left(a_d^{pr} c_\beta - s_\beta Y_d^{pr}\mu_H\right) LF_{2,2,0}\left[m_d^r, m_q^p\right] -$$

$$\frac{1}{4}\hbar g_s^2 \left(\overline{a_d}^{pr} c_\beta - s_\beta \overline{Y_d}^{pr}\mu_H\right)\left(a_d^{pr} c_\beta - s_\beta Y_d^{pr}\mu_H\right) LF_{3,1,0}\left[m_d^r, m_q^p\right] +$$

$$\frac{1}{4}\hbar g_s^2 \left(\overline{a_d}^{pr} c_\beta - s_\beta \overline{Y_d}^{pr}\mu_H\right)\left(a_d^{pr} c_\beta - s_\beta Y_d^{pr}\mu_H\right) LF_{3,2,-1}\left[m_d^r, m_q^p\right] +$$

$$\frac{1}{4}\hbar g_s^2 \left(\overline{a_d}^{pr} c_\beta - s_\beta \overline{Y_d}^{pr}\mu_H\right)\left(a_d^{pr} c_\beta - s_\beta Y_d^{pr}\mu_H\right) LF_{4,1,-1}\left[m_d^r, m_q^p\right] -$$

$$\frac{1}{4}\hbar g_s^2 \left(\overline{a_d}^{pr} c_\beta - s_\beta \overline{Y_d}^{pr}\mu_H\right)\left(a_d^{pr} c_\beta - s_\beta Y_d^{pr}\mu_H\right) LF_{3,1,0}\left[m_q^p, m_d^r\right] +$$

$$\frac{1}{4}\hbar g_s^2 \left(\overline{a_d}^{pr} c_\beta - s_\beta \overline{Y_d}^{pr}\mu_H\right)\left(a_d^{pr} c_\beta - s_\beta Y_d^{pr}\mu_H\right) LF_{3,2,-1}\left[m_q^p, m_d^r\right] +$$

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$$\frac{1}{4}\hbar g_s^2 \left(s_\beta \overline{a_u}^{pr} - \overline{Y_u}^{pr}\mu_H c_\beta\right)\left(s_\beta a_u^{pr} - Y_u^{pr}\mu_H c_\beta\right) LF_{2,2,0}\left[m_q^p, m_u^r\right] -$$

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$$\frac{1}{4}\hbar g_s^2 \left(s_\beta \overline{a_u}^{pr} - \overline{Y_u}^{pr}\mu_H c_\beta\right)\left(s_\beta a_u^{pr} - Y_u^{pr}\mu_H c_\beta\right) LF_{3,2,-1}\left[m_q^p, m_u^r\right] +$$

$$\frac{1}{4}\hbar g_s^2 \left(s_\beta \overline{a_u}^{pr} - \overline{Y_u}^{pr}\mu_H c_\beta\right)\left(s_\beta a_u^{pr} - Y_u^{pr}\mu_H c_\beta\right) LF_{4,1,-1}\left[m_q^p, m_u^r\right] -$$

$$\frac{1}{4}\hbar g_s^2 \left(s_\beta \overline{a_u}^{pr} - \overline{Y_u}^{pr}\mu_H c_\beta\right)\left(s_\beta a_u^{pr} - Y_u^{pr}\mu_H c_\beta\right) LF_{3,1,0}\left[m_u^r, m_q^p\right] +$$

$$\frac{1}{4}\hbar g_s^2 \left(s_\beta \overline{a_u}^{pr} - \overline{Y_u}^{pr}\mu_H c_\beta\right)\left(s_\beta a_u^{pr} - Y_u^{pr}\mu_H c_\beta\right) LF_{3,2,-1}\left[m_u^r, m_q^p\right] +$$

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$$\begin{aligned}16\pi^2 C_{HG} = \frac{g_s^2}{144}\Bigg[& c_{2\beta}\, g_Y^2 \left(2\frac{1}{(M_u^p)^2} - \frac{1}{(M_d^p)^2} - \frac{1}{(M_q^p)^2}\right) \\ &+ 6c_\beta^2 [Y_d^*]^{pr}[Y_d]^{pr}\left(\frac{1}{(M_q^r)^2} + \frac{1}{(M_d^p)^2}\right) + 6s_\beta^2 [Y_u^*]^{pr}[Y_u]^{pr}\left(\frac{1}{(M_q^r)^2} + \frac{1}{(M_u^p)^2}\right)\Bigg] \\ &- \frac{g_s^2}{24}\left|c_\beta [a_d^*]^{pr} - s_\beta \mu [Y_d^*]^{pr}\right|^2 \frac{1}{(M_d^p)^2}\frac{1}{(M_q^r)^2} - \frac{g_s^2}{24}\left|s_\beta [a_u^*]^{pr} - c_\beta \mu [Y_u^*]^{pr}\right|^2 \frac{1}{(M_u^p)^2}\frac{1}{(M_q^r)^2}\end{aligned}$$

→ LF: loop function → *evaluate*

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

Results & Validation

- MSSM-to-SMEFT matching generates **all B- and L-conserving operators of the Warsaw basis** that do not contain dual field-strength tensors

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

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

$$
\begin{aligned}
&\frac{1}{144}\,\hbar\, g_s^2\, \frac{1}{m_q^{p\,2}} \left(6\, \overline{Y_d}^{pr}\, Y_d^{pr}\, \frac{1}{m_d^{r\,2}}\, c_\beta^2\, \left(m_d^{r\,2} + m_q^{p\,2}\right) + 6\, \overline{Y_u}^{pr}\, Y_u^{pr}\, \frac{1}{m_u^{r\,2}}\, s_\beta^2\, \left(m_q^{p\,2} + m_u^{r\,2}\right) + \sum_p c_{2\beta}\, g_Y^2 \left(-1 + m_q^{p\,2}\left(-\frac{1}{m_d^{p\,2}} + 2\,\frac{1}{m_u^{p\,2}}\right)\right)\right) - \\
&\frac{1}{4}\,\hbar\, g_s^2\, \left(\overline{a_d}^{pr}\, c_\beta - s_\beta\, \overline{Y_d}^{pr}\, \mu_H\right) \left(a_d^{pr}\, c_\beta - s_\beta\, Y_d^{pr}\, \mu_H\right) \mathrm{LF}_{2,2,0}\left[m_d^r,\, m_q^p\right] - \\
&\frac{1}{4}\,\hbar\, g_s^2\, \left(\overline{a_d}^{pr}\, c_\beta - s_\beta\, \overline{Y_d}^{pr}\, \mu_H\right) \left(a_d^{pr}\, c_\beta - s_\beta\, Y_d^{pr}\, \mu_H\right) \mathrm{LF}_{3,1,0}\left[m_d^r,\, m_q^p\right] + \\
&\frac{1}{4}\,\hbar\, g_s^2\, \left(\overline{a_d}^{pr}\, c_\beta - s_\beta\, \overline{Y_d}^{pr}\, \mu_H\right) \left(a_d^{pr}\, c_\beta - s_\beta\, Y_d^{pr}\, \mu_H\right) \mathrm{LF}_{3,2,-1}\left[m_d^r,\, m_q^p\right] + \\
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&\frac{1}{4}\,\hbar\, g_s^2\, \left(\overline{a_d}^{pr}\, c_\beta - s_\beta\, \overline{Y_d}^{pr}\, \mu_H\right) \left(a_d^{pr}\, c_\beta - s_\beta\, Y_d^{pr}\, \mu_H\right) \mathrm{LF}_{3,1,0}\left[m_q^p,\, m_d^r\right] + \\
&\frac{1}{4}\,\hbar\, g_s^2\, \left(\overline{a_d}^{pr}\, c_\beta - s_\beta\, \overline{Y_d}^{pr}\, \mu_H\right) \left(a_d^{pr}\, c_\beta - s_\beta\, Y_d^{pr}\, \mu_H\right) \mathrm{LF}_{3,2,-1}\left[m_q^p,\, m_d^r\right] + \\
&\frac{1}{4}\,\hbar\, g_s^2\, \left(\overline{a_d}^{pr}\, c_\beta - s_\beta\, \overline{Y_d}^{pr}\, \mu_H\right) \left(a_d^{pr}\, c_\beta - s_\beta\, Y_d^{pr}\, \mu_H\right) \mathrm{LF}_{4,1,-1}\left[m_q^p,\, m_d^r\right] - \\
&\frac{1}{4}\,\hbar\, g_s^2\, \left(s_\beta\, \overline{a_u}^{pr} - \overline{Y_u}^{pr}\, \mu_H\, c_\beta\right) \left(s_\beta\, a_u^{pr} - Y_u^{pr}\, \mu_H\, c_\beta\right) \mathrm{LF}_{2,2,0}\left[m_q^p,\, m_u^r\right] - \\
&\frac{1}{4}\,\hbar\, g_s^2\, \left(s_\beta\, \overline{a_u}^{pr} - \overline{Y_u}^{pr}\, \mu_H\, c_\beta\right) \left(s_\beta\, a_u^{pr} - Y_u^{pr}\, \mu_H\, c_\beta\right) \mathrm{LF}_{3,1,0}\left[m_q^p,\, m_u^r\right] + \\
&\frac{1}{4}\,\hbar\, g_s^2\, \left(s_\beta\, \overline{a_u}^{pr} - \overline{Y_u}^{pr}\, \mu_H\, c_\beta\right) \left(s_\beta\, a_u^{pr} - Y_u^{pr}\, \mu_H\, c_\beta\right) \mathrm{LF}_{3,2,-1}\left[m_q^p,\, m_u^r\right] + \\
&\frac{1}{4}\,\hbar\, g_s^2\, \left(s_\beta\, \overline{a_u}^{pr} - \overline{Y_u}^{pr}\, \mu_H\, c_\beta\right) \left(s_\beta\, a_u^{pr} - Y_u^{pr}\, \mu_H\, c_\beta\right) \mathrm{LF}_{4,1,-1}\left[m_q^p,\, m_u^r\right] - \\
&\frac{1}{4}\,\hbar\, g_s^2\, \left(s_\beta\, \overline{a_u}^{pr} - \overline{Y_u}^{pr}\, \mu_H\, c_\beta\right) \left(s_\beta\, a_u^{pr} - Y_u^{pr}\, \mu_H\, c_\beta\right) \mathrm{LF}_{3,1,0}\left[m_u^r,\, m_q^p\right] + \\
&\frac{1}{4}\,\hbar\, g_s^2\, \left(s_\beta\, \overline{a_u}^{pr} - \overline{Y_u}^{pr}\, \mu_H\, c_\beta\right) \left(s_\beta\, a_u^{pr} - Y_u^{pr}\, \mu_H\, c_\beta\right) \mathrm{LF}_{3,2,-1}\left[m_u^r,\, m_q^p\right] + \\
&\frac{1}{4}\,\hbar\, g_s^2\, \left(s_\beta\, \overline{a_u}^{pr} - \overline{Y_u}^{pr}\, \mu_H\, c_\beta\right) \left(s_\beta\, a_u^{pr} - Y_u^{pr}\, \mu_H\, c_\beta\right) \mathrm{LF}_{4,1,-1}\left[m_u^r,\, m_q^p\right]
\end{aligned}
$$

→ LF: loop function → evaluate

$$
\begin{aligned}
16\pi^2\, C_{HG} = \frac{g_s^2}{144} \Bigg[& c_{2\beta}\, g_Y^2 \left(2\frac{1}{(M_u^p)^2} - \frac{1}{(M_d^p)^2} - \frac{1}{(M_q^p)^2}\right) \\
& + 6 c_\beta^2 [Y_d^*]^{pr} [Y_d]^{pr} \left(\frac{1}{(M_q^r)^2} + \frac{1}{(M_d^p)^2}\right) + 6 s_\beta^2 [Y_u^*]^{pr} [Y_u]^{pr} \left(\frac{1}{(M_q^r)^2} + \frac{1}{(M_u^p)^2}\right)\Bigg] \\
& - \frac{g_s^2}{24} \left| c_\beta [a_d^*]^{pr} - s_\beta \mu [Y_d^*]^{pr} \right|^2 \frac{1}{(M_d^p)^2} \frac{1}{(M_q^r)^2} - \frac{g_s^2}{24} \left| s_\beta [a_u^*]^{pr} - c_\beta \mu [Y_u^*]^{pr} \right|^2 \frac{1}{(M_u^p)^2} \frac{1}{(M_q^r)^2}
\end{aligned}
$$

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

- Example: $Q_H = (H^\dagger H)^3$
  → ∼4700 terms and ∼12 MB

- Matching conditions will be released in printed and electronic form

- Further validated leading terms of: C_{uG}, $C_{qu}^{(8)}$, C_{uu} Lessa, Sanz [2312.00670]

Matching of Higgs Mass at One-Loop

$c_{H^2} \rightarrow$

$$
\begin{aligned}
& m_H^2 + \hbar \Bigg(\tfrac{1}{4} m_H^2 \left(g_Y^2 + 3 g_L^2\right) \left(c_\beta^2 + s_\beta^2\right) + \tfrac{1}{2} \textstyle\sum_p c_{2\beta} \, g_Y^2 \, \mathrm{LF}_{1,0}[m_d{}^p] - 3 \, \overline{Y_d}^{pr} Y_d{}^{pr} c_\beta^2 \, \mathrm{LF}_{1,0}[m_d{}^r] + \tfrac{1}{2} \textstyle\sum_p c_{2\beta} \\
& \quad g_Y^2 \, \mathrm{LF}_{1,0}[M_e{}^p] - \overline{Y_e}^{pr} Y_e{}^{pr} c_\beta^2 \, \mathrm{LF}_{1,0}[M_e{}^r] + \left(-\overline{Y_e}^{pr} Y_e{}^{pr} c_\beta^2 - \tfrac{1}{2} \textstyle\sum_p c_{2\beta} \, g_Y^2\right) \mathrm{LF}_{1,0}[m_l{}^p] + \\
& \quad \left(-3 \, \overline{Y_d}^{pr} Y_d{}^{pr} c_\beta^2 - 3 \, \overline{Y_u}^{pr} Y_u{}^{pr} s_\beta^2 + \tfrac{1}{2} \textstyle\sum_p c_{2\beta} \, g_Y^2\right) \mathrm{LF}_{1,0}[m_q{}^p] - \textstyle\sum_p c_{2\beta} \, g_Y^2 \, \mathrm{LF}_{1,0}[m_u{}^p] - \\
& \quad 3 \, \overline{Y_u}^{pr} Y_u{}^{pr} s_\beta^2 \, \mathrm{LF}_{1,0}[m_u{}^r] + \tfrac{1}{8} \left(g_Y^2 (1 + 3 c_{4\beta}) + 3 g_L^2 (-1 + c_{4\beta})\right) \mathrm{LF}_{1,0}[m_\Phi] + \\
& \quad g_Y^2 \left(c_\beta^2 + s_\beta^2\right) \mathrm{LF}_{1,1,-1}[m_B, \mu_H] + 2 m_B s_\beta \mu_H c_\beta g_Y^2 \, \mathrm{LF}_{1,1,0}[m_B, \mu_H] - \\
& \quad 3 \left(\overline{a_d}^{pr} c_\beta - s_\beta \overline{Y_d}^{pr} \mu_H\right) \left(a_d{}^{pr} c_\beta - s_\beta Y_d{}^{pr} \mu_H\right) \mathrm{LF}_{1,1,0}[m_d{}^r, m_q{}^p] - \\
& \quad \left(\overline{a_e}^{pr} c_\beta - s_\beta \overline{Y_e}^{pr} \mu_H\right) \left(a_e{}^{pr} c_\beta - s_\beta Y_e{}^{pr} \mu_H\right) \mathrm{LF}_{1,1,0}[M_e{}^r, m_l{}^p] + \\
& \quad m_H^2 \left(\overline{a_e}^{pr} c_\beta - s_\beta \overline{Y_e}^{pr} \mu_H\right) \left(a_e{}^{pr} c_\beta - s_\beta Y_e{}^{pr} \mu_H\right) \mathrm{LF}_{2,1,0}[m_l{}^p, M_e{}^r] - \\
& \quad m_H^2 \left(\overline{a_e}^{pr} c_\beta - s_\beta \overline{Y_e}^{pr} \mu_H\right) \left(a_e{}^{pr} c_\beta - s_\beta Y_e{}^{pr} \mu_H\right) \mathrm{LF}_{3,1,-1}[m_l{}^p, M_e{}^r] - \\
& \quad m_H^{2\,2} \left(\overline{a_e}^{pr} c_\beta - s_\beta \overline{Y_e}^{pr} \mu_H\right) \left(a_e{}^{pr} c_\beta - s_\beta Y_e{}^{pr} \mu_H\right) \mathrm{LF}_{3,1,0}[m_l{}^p, M_e{}^r] + \\
& \quad 3 m_H^{2\,2} \left(\overline{a_e}^{pr} c_\beta - s_\beta \overline{Y_e}^{pr} \mu_H\right) \left(a_e{}^{pr} c_\beta - s_\beta Y_e{}^{pr} \mu_H\right) \mathrm{LF}_{4,1,-1}[m_l{}^p, M_e{}^r] - \\
& \quad 2 m_H^{2\,2} \left(\overline{a_e}^{pr} c_\beta - s_\beta \overline{Y_e}^{pr} \mu_H\right) \left(a_e{}^{pr} c_\beta - s_\beta Y_e{}^{pr} \mu_H\right) \mathrm{LF}_{5,1,-2}[m_l{}^p, M_e{}^r] + \\
& \quad 3 m_H^2 \left(\overline{a_d}^{pr} c_\beta - s_\beta \overline{Y_d}^{pr} \mu_H\right) \left(a_d{}^{pr} c_\beta - s_\beta Y_d{}^{pr} \mu_H\right) \mathrm{LF}_{2,1,0}[m_q{}^p, m_d{}^r] - \\
& \quad 3 m_H^2 \left(\overline{a_d}^{pr} c_\beta - s_\beta \overline{Y_d}^{pr} \mu_H\right) \left(a_d{}^{pr} c_\beta - s_\beta Y_d{}^{pr} \mu_H\right) \mathrm{LF}_{3,1,-1}[m_q{}^p, m_d{}^r] - \\
& \quad 3 m_H^{2\,2} \left(\overline{a_d}^{pr} c_\beta - s_\beta \overline{Y_d}^{pr} \mu_H\right) \left(a_d{}^{pr} c_\beta - s_\beta Y_d{}^{pr} \mu_H\right) \mathrm{LF}_{3,1,0}[m_q{}^p, m_d{}^r] + \\
& \quad 9 m_H^{2\,2} \left(\overline{a_d}^{pr} c_\beta - s_\beta \overline{Y_d}^{pr} \mu_H\right) \left(a_d{}^{pr} c_\beta - s_\beta Y_d{}^{pr} \mu_H\right) \mathrm{LF}_{4,1,-1}[m_q{}^p, m_d{}^r] - \\
& \quad 6 m_H^{2\,2} \left(\overline{a_d}^{pr} c_\beta - s_\beta \overline{Y_d}^{pr} \mu_H\right) \left(a_d{}^{pr} c_\beta - s_\beta Y_d{}^{pr} \mu_H\right) \mathrm{LF}_{5,1,-2}[m_q{}^p, m_d{}^r] - \\
& \quad 3 \left(s_\beta \overline{a_u}^{pr} - \overline{Y_u}^{pr} \mu_H c_\beta\right) \left(s_\beta a_u{}^{pr} - Y_u{}^{pr} \mu_H c_\beta\right) \mathrm{LF}_{1,1,0}[m_q{}^p, m_u{}^r] + \\
& \quad 3 m_H^2 \left(s_\beta \overline{a_u}^{pr} - \overline{Y_u}^{pr} \mu_H c_\beta\right) \left(s_\beta a_u{}^{pr} - Y_u{}^{pr} \mu_H c_\beta\right) \mathrm{LF}_{2,1,0}[m_u{}^r, m_q{}^p] - \\
& \quad 3 m_H^2 \left(s_\beta \overline{a_u}^{pr} - \overline{Y_u}^{pr} \mu_H c_\beta\right) \left(s_\beta a_u{}^{pr} - Y_u{}^{pr} \mu_H c_\beta\right) \mathrm{LF}_{3,1,-1}[m_u{}^r, m_q{}^p] - \\
& \quad 3 m_H^{2\,2} \left(s_\beta \overline{a_u}^{pr} - \overline{Y_u}^{pr} \mu_H c_\beta\right) \left(s_\beta a_u{}^{pr} - Y_u{}^{pr} \mu_H c_\beta\right) \mathrm{LF}_{3,1,0}[m_u{}^r, m_q{}^p] + \\
& \quad 9 m_H^{2\,2} \left(s_\beta \overline{a_u}^{pr} - \overline{Y_u}^{pr} \mu_H c_\beta\right) \left(s_\beta a_u{}^{pr} - Y_u{}^{pr} \mu_H c_\beta\right) \mathrm{LF}_{4,1,-1}[m_u{}^r, m_q{}^p] - \\
& \quad 6 m_H^{2\,2} \left(s_\beta \overline{a_u}^{pr} - \overline{Y_u}^{pr} \mu_H c_\beta\right) \left(s_\beta a_u{}^{pr} - Y_u{}^{pr} \mu_H c_\beta\right) \mathrm{LF}_{5,1,-2}[m_u{}^r, m_q{}^p] + \\
& \quad 3 g_L^2 \left(c_\beta^2 + s_\beta^2\right) \mathrm{LF}_{1,1,-1}[M_W, \mu_H] + 6 M_W s_\beta \mu_H c_\beta g_L^2 \, \mathrm{LF}_{1,1,0}[M_W, \mu_H] - \\
& \quad \tfrac{3}{2} m_H^2 g_Y^2 \left(c_\beta^2 + s_\beta^2\right) \mathrm{LF}_{2,1,-1}[\mu_H, m_B] - 2 m_B m_H^2 s_\beta \mu_H c_\beta g_Y^2 \, \mathrm{LF}_{2,1,0}[\mu_H, m_B] + \\
& \quad m_H^2 g_Y^2 \left(c_\beta^2 + s_\beta^2\right) \mathrm{LF}_{3,1,-2}[\mu_H, m_B] + 2 m_H^2 g_Y^2 \left(m_H^2 \left(c_\beta^2 + s_\beta^2\right) + m_B s_\beta \mu_H c_\beta\right) \mathrm{LF}_{3,1,-1}[\mu_H, m_B] + \\
& \quad 2 m_B s_\beta \mu_H c_\beta g_Y^2 m_H^{2\,2} \, \mathrm{LF}_{3,1,0}[\mu_H, m_B] - 4 g_Y^2 m_H^{2\,2} \left(c_\beta^2 + s_\beta^2\right) \mathrm{LF}_{4,1,-2}[\mu_H, m_B] - \\
& \quad 6 m_B s_\beta \mu_H c_\beta g_Y^2 m_H^{2\,2} \, \mathrm{LF}_{4,1,-1}[\mu_H, m_B] + 2 g_Y^2 m_H^{2\,2} \left(c_\beta^2 + s_\beta^2\right) \mathrm{LF}_{5,1,-3}[\mu_H, m_B] + \\
& \quad 4 m_B s_\beta \mu_H c_\beta g_Y^2 m_H^{2\,2} \, \mathrm{LF}_{5,1,-2}[\mu_H, m_B] - \tfrac{9}{2} m_H^2 g_L^2 \left(c_\beta^2 + s_\beta^2\right) \mathrm{LF}_{2,1,-1}[\mu_H, M_W] - \\
& \quad 6 m_H^2 M_W s_\beta \mu_H c_\beta g_L^2 \, \mathrm{LF}_{2,1,0}[\mu_H, M_W] + 3 m_H^2 g_L^2 \left(c_\beta^2 + s_\beta^2\right) \mathrm{LF}_{3,1,-2}[\mu_H, M_W] + \\
& \quad 6 m_H^2 g_L^2 \left(m_H^2 \left(c_\beta^2 + s_\beta^2\right) + M_W s_\beta \mu_H c_\beta\right) \mathrm{LF}_{3,1,-1}[\mu_H, M_W] + 6 M_W s_\beta \mu_H c_\beta g_L^2 m_H^{2\,2} \, \mathrm{LF}_{3,1,0}[\mu_H, M_W] - \\
& \quad 12 g_L^2 m_H^{2\,2} \left(c_\beta^2 + s_\beta^2\right) \mathrm{LF}_{4,1,-2}[\mu_H, M_W] - 18 M_W s_\beta \mu_H c_\beta g_L^2 m_H^{2\,2} \, \mathrm{LF}_{4,1,-1}[\mu_H, M_W] + \\
& \quad 6 g_L^2 m_H^{2\,2} \left(c_\beta^2 + s_\beta^2\right) \mathrm{LF}_{5,1,-3}[\mu_H, M_W] + 12 M_W s_\beta \mu_H c_\beta g_L^2 m_H^{2\,2} \, \mathrm{LF}_{5,1,-2}[\mu_H, M_W] \Bigg)
\end{aligned}
$$

Matching of $d = 4$ Yukawa Couplings

SMEFT
up-type Yukawa:

$$c_{Hqu}{}^{i1\_i2\_} \to -s_\beta\, Y_u{}^{i2i1} +$$

$$\hbar \Big(\tfrac{1}{144}\, s_\beta \tfrac{1}{m_\Phi{}^2} \Big(18\, Y_u{}^{pi1} \Big(-\overline{Y_d}^{pr}\, Y_d{}^{i2r} \big(2 m_H^2 c_\beta{}^2 + m_\Phi{}^2 (1 + s_\beta{}^2)\big)\Big) - 3\, \overline{Y_u}^{pr}\, Y_u{}^{i2r}\, m_\Phi{}^2 \big(1 + c_\beta{}^2\big)\Big) -$$

$$Y_u{}^{i2i1} \Big(m_\Phi{}^2 \Big(96\, g_s{}^2 + 27\, g_L{}^2 \big(1 + 2 c_\beta{}^2 + 2 s_\beta{}^2\big) + g_Y{}^2 \big(17 + 18 c_\beta{}^2 + 18 s_\beta{}^2\big)\Big) +$$

$$216\, m_H^2\, \overline{Y_u}^{pr}\, Y_u{}^{pr}\, c_\beta{}^2\Big)\Big) - \tfrac{1}{2} \textstyle\sum_p s_{2\beta}\, Y_u{}^{i2i1}\, c_\beta\, g_Y{}^2 \tfrac{1}{m_\Phi{}^4} \big(m_H^2 + m_\Phi{}^2\big)\, \mathrm{LF}_{1,0}[m_d{}^p] +$$

$$\tfrac{3}{2}\, s_{2\beta}\, \overline{Y_d}^{pr}\, Y_d{}^{pr}\, Y_u{}^{i2i1}\, c_\beta \tfrac{1}{m_\Phi{}^4} \big(m_H^2 + m_\Phi{}^2\big)\, \mathrm{LF}_{1,0}[m_d{}^r] - \tfrac{1}{2} \textstyle\sum_p s_{2\beta}\, Y_u{}^{i2i1}\, c_\beta\, g_Y{}^2 \tfrac{1}{m_\Phi{}^4}$$

$$\big(m_H^2 + m_\Phi{}^2\big)\, \mathrm{LF}_{1,0}[M_e{}^p] + \tfrac{1}{2}\, s_{2\beta}\, \overline{Y_e}^{pr}\, Y_e{}^{pr}\, Y_u{}^{i2i1}\, c_\beta \tfrac{1}{m_\Phi{}^4} \big(m_H^2 + m_\Phi{}^2\big)\, \mathrm{LF}_{1,0}[M_e{}^r] +$$

$$\tfrac{1}{2}\, s_{2\beta}\, Y_u{}^{i2i1}\, c_\beta \tfrac{1}{m_\Phi{}^4} \big(m_H^2 + m_\Phi{}^2\big) \big(\overline{Y_e}^{pr}\, Y_e{}^{pr} + \textstyle\sum_p g_Y{}^2\big)\, \mathrm{LF}_{1,0}[m_l{}^p] -$$

$$\tfrac{1}{2}\, s_{2\beta}\, Y_u{}^{i2i1}\, c_\beta \tfrac{1}{m_\Phi{}^4} \big(m_H^2 + m_\Phi{}^2\big) \big(-3\, \overline{Y_d}^{pr}\, Y_d{}^{pr} + 3\, \overline{Y_u}^{pr}\, Y_u{}^{pr} + \textstyle\sum_p g_Y{}^2\big)\, \mathrm{LF}_{1,0}[m_q{}^p] +$$

$$\textstyle\sum_p s_{2\beta}\, Y_u{}^{i2i1}\, c_\beta\, g_Y{}^2 \tfrac{1}{m_\Phi{}^4} \big(m_H^2 + m_\Phi{}^2\big)\, \mathrm{LF}_{1,0}[m_u{}^p] -$$

$$\tfrac{3}{2}\, s_{2\beta}\, \overline{Y_u}^{pr}\, Y_u{}^{pr}\, Y_u{}^{i2i1}\, c_\beta \tfrac{1}{m_\Phi{}^4} \big(m_H^2 + m_\Phi{}^2\big)\, \mathrm{LF}_{1,0}[m_u{}^r] -$$

$$\tfrac{3}{8}\, s_{4\beta}\, Y_u{}^{i2i1}\, c_\beta \tfrac{1}{m_\Phi{}^4} \big(g_Y{}^2 + g_L{}^2\big) \big(m_H^2 + m_\Phi{}^2\big)\, \mathrm{LF}_{1,0}[m_\Phi] +$$

$$\tfrac{1}{4}\, s_\beta\, Y_u{}^{pi1} \big(\overline{Y_d}^{pr}\, Y_d{}^{i2r} \big(4 c_\beta{}^2 + s_\beta{}^2\big) + 3\, \overline{Y_u}^{pr}\, Y_u{}^{i2r}\, c_\beta{}^2\big)\, \mathrm{LF}_{1,1}[m_\Phi] -$$

$$\tfrac{1}{2}\, m_H^2\, s_\beta\, \overline{Y_d}^{pr}\, Y_d{}^{i2r}\, Y_u{}^{pi1}\, c_\beta{}^2\, \mathrm{LF}_{1,2}[m_\Phi] + \tfrac{1}{36}\, s_\beta\, Y_u{}^{i2i1}\, g_Y{}^2\, \mathrm{LF}_{1,1,0}[m_B, m_q{}^{i2}] -$$

$$\tfrac{1}{72}\, s_\beta\, Y_u{}^{i2i1}\, g_Y{}^2\, \mathrm{LF}_{2,1,-1}[m_B, m_q{}^{i2}] + \tfrac{4}{9}\, s_\beta\, Y_u{}^{i2i1}\, g_Y{}^2\, \mathrm{LF}_{1,1,0}[m_B, m_u{}^{i1}] -$$

$$\tfrac{2}{9}\, s_\beta\, Y_u{}^{i2i1}\, g_Y{}^2\, \mathrm{LF}_{2,1,-1}[m_B, m_u{}^{i1}] + m_B\, Y_u{}^{i2i1}\, \mu_H\, c_\beta\, g_Y{}^2 \tfrac{1}{m_\Phi{}^4} \big(m_H^2 + m_\Phi{}^2\big) \big(c_\beta{}^2 - s_\beta{}^2\big)\, \mathrm{LF}_{1,1,0}[m_B, \mu_H] +$$

$$3\, Y_u{}^{i2i1}\, c_\beta \tfrac{1}{m_\Phi{}^4} \big(m_H^2 + m_\Phi{}^2\big) \big(\overline{a_d}^{pr}\, c_\beta - s_\beta\, \overline{Y_d}^{pr}\, \mu_H\big) \big(s_\beta\, a_d{}^{pr} + Y_d{}^{pr}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{1,1,0}[m_d{}^r, m_q{}^p] +$$

$$\tfrac{1}{2}\, s_\beta\, \overline{Y_d}^{pr}\, Y_d{}^{i2r}\, Y_u{}^{pi1}\, \mathrm{LF}_{1,1,0}[m_d{}^r, \mu_H] +$$

$$Y_u{}^{i2i1}\, c_\beta \tfrac{1}{m_\Phi{}^4} \big(m_H^2 + m_\Phi{}^2\big) \big(\overline{a_e}^{pr}\, c_\beta - s_\beta\, \overline{Y_e}^{pr}\, \mu_H\big) \big(s_\beta\, a_e{}^{pr} + Y_e{}^{pr}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{1,1,0}[M_e{}^r, m_l{}^p] +$$

$$\tfrac{4}{3}\, s_\beta\, Y_u{}^{i2i1}\, g_s{}^2\, \mathrm{LF}_{1,1,0}[m_G, m_q{}^{i2}] - \tfrac{2}{3}\, s_\beta\, Y_u{}^{i2i1}\, g_s{}^2\, \mathrm{LF}_{2,1,-1}[m_G, m_q{}^{i2}] +$$

$$\tfrac{4}{3}\, s_\beta\, Y_u{}^{i2i1}\, g_s{}^2\, \mathrm{LF}_{1,1,0}[m_G, m_u{}^{i1}] - \tfrac{2}{3}\, s_\beta\, Y_u{}^{i2i1}\, g_s{}^2\, \mathrm{LF}_{2,1,-1}[m_G, m_u{}^{i1}] -$$

$$\tfrac{1}{2}\, Y_u{}^{i2i1} \tfrac{1}{m_\Phi{}^2} \big(\overline{a_e}^{pr}\, c_\beta - s_\beta\, \overline{Y_e}^{pr}\, \mu_H\big) \big(s_\beta\, a_e{}^{pr}\, c_\beta \big(2 m_H^2 + m_\Phi{}^2\big) + Y_e{}^{pr}\, \mu_H \big(2 m_H^2 c_\beta{}^2 - m_\Phi{}^2 s_\beta{}^2\big)\big)$$

$$\mathrm{LF}_{2,1,0}[m_l{}^p, M_e{}^r] + \tfrac{1}{2}\, Y_u{}^{i2i1} \tfrac{1}{m_\Phi{}^2} \big(\overline{a_e}^{pr}\, c_\beta - s_\beta\, \overline{Y_e}^{pr}\, \mu_H\big)$$

$$\big(s_\beta\, a_e{}^{pr}\, c_\beta \big(2 m_H^2 + m_\Phi{}^2\big) + Y_e{}^{pr}\, \mu_H \big(2 m_H^2 c_\beta{}^2 - m_\Phi{}^2 s_\beta{}^2\big)\big)\, \mathrm{LF}_{3,1,-1}[m_l{}^p, M_e{}^r] +$$

$$m_H^2\, s_\beta\, Y_u{}^{i2i1} \big(-\overline{a_e}^{pr}\, c_\beta + s_\beta\, \overline{Y_e}^{pr}\, \mu_H\big) \big(-a_e{}^{pr}\, c_\beta + s_\beta\, Y_e{}^{pr}\, \mu_H\big)\, \mathrm{LF}_{3,1,0}[m_l{}^p, M_e{}^r] -$$

$$3\, m_H^2\, s_\beta\, Y_u{}^{i2i1} \big(-\overline{a_e}^{pr}\, c_\beta + s_\beta\, \overline{Y_e}^{pr}\, \mu_H\big) \big(-a_e{}^{pr}\, c_\beta + s_\beta\, Y_e{}^{pr}\, \mu_H\big)\, \mathrm{LF}_{4,1,-1}[m_l{}^p, M_e{}^r] +$$

$$2\, m_H^2\, s_\beta\, Y_u{}^{i2i1} \big(-\overline{a_e}^{pr}\, c_\beta + s_\beta\, \overline{Y_e}^{pr}\, \mu_H\big) \big(-a_e{}^{pr}\, c_\beta + s_\beta\, Y_e{}^{pr}\, \mu_H\big)\, \mathrm{LF}_{5,1,-2}[m_l{}^p, M_e{}^r] -$$

$$\tfrac{3}{2}\, Y_u{}^{i2i1} \tfrac{1}{m_\Phi{}^2} \big(\overline{a_d}^{pr}\, c_\beta - s_\beta\, \overline{Y_d}^{pr}\, \mu_H\big) \big(s_\beta\, a_d{}^{pr}\, c_\beta \big(2 m_H^2 + m_\Phi{}^2\big) + Y_d{}^{pr}\, \mu_H \big(2 m_H^2 c_\beta{}^2 - m_\Phi{}^2 s_\beta{}^2\big)\big)$$

$$\mathrm{LF}_{2,1,0}[m_q{}^p, m_d{}^r] + \tfrac{3}{2}\, Y_u{}^{i2i1} \tfrac{1}{m_\Phi{}^2} \big(\overline{a_d}^{pr}\, c_\beta - s_\beta\, \overline{Y_d}^{pr}\, \mu_H\big)$$

$$\big(s_\beta\, a_d{}^{pr}\, c_\beta \big(2 m_H^2 + m_\Phi{}^2\big) + Y_d{}^{pr}\, \mu_H \big(2 m_H^2 c_\beta{}^2 - m_\Phi{}^2 s_\beta{}^2\big)\big)\, \mathrm{LF}_{3,1,-1}[m_q{}^p, m_d{}^r] +$$

$$3\, m_H^2\, s_\beta\, Y_u{}^{i2i1} \big(-\overline{a_d}^{pr}\, c_\beta + s_\beta\, \overline{Y_d}^{pr}\, \mu_H\big) \big(-a_d{}^{pr}\, c_\beta + s_\beta\, Y_d{}^{pr}\, \mu_H\big)\, \mathrm{LF}_{3,1,0}[m_q{}^p, m_d{}^r] -$$

$$9\, m_H^2\, s_\beta\, Y_u{}^{i2i1} \big(-\overline{a_d}^{pr}\, c_\beta + s_\beta\, \overline{Y_d}^{pr}\, \mu_H\big) \big(-a_d{}^{pr}\, c_\beta + s_\beta\, Y_d{}^{pr}\, \mu_H\big)\, \mathrm{LF}_{4,1,-1}[m_q{}^p, m_d{}^r] +$$

$$6\, m_H^2\, s_\beta\, Y_u{}^{i2i1} \big(-\overline{a_d}^{pr}\, c_\beta + s_\beta\, \overline{Y_d}^{pr}\, \mu_H\big) \big(-a_d{}^{pr}\, c_\beta + s_\beta\, Y_d{}^{pr}\, \mu_H\big)\, \mathrm{LF}_{5,1,-2}[m_q{}^p, m_d{}^r] +$$

$$3\, Y_u{}^{i2i1}\, c_\beta \tfrac{1}{m_\Phi{}^4} \big(m_H^2 + m_\Phi{}^2\big) \big(\overline{a_u}^{pr}\, c_\beta + s_\beta\, \overline{Y_u}^{pr}\, \mu_H\big) \big(-s_\beta\, a_u{}^{pr} + Y_u{}^{pr}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{1,1,0}[m_q{}^p, m_u{}^r] +$$

$$s_\beta\, \overline{Y_u}^{pr}\, Y_u{}^{pi1}\, Y_u{}^{i2r}\, \mathrm{LF}_{1,1,0}[m_q{}^p, \mu_H] + \tfrac{3}{4}\, s_\beta\, Y_u{}^{i2i1}\, g_L{}^2\, \mathrm{LF}_{1,1,0}[m_q{}^{i2}, M_W] +$$

$$\tfrac{3}{2}\, Y_u{}^{i2i1} \tfrac{1}{m_\Phi{}^2} \big(\overline{a_u}^{pr} \big(2 m_H^2 c_\beta{}^2 - m_\Phi{}^2 s_\beta{}^2\big) + s_\beta\, \overline{Y_u}^{pr}\, \mu_H\, c_\beta \big(2 m_H^2 + m_\Phi{}^2\big)\big) \big(s_\beta\, a_u{}^{pr} - Y_u{}^{pr}\, \mu_H\, c_\beta\big)$$

$$\mathrm{LF}_{2,1,0}[m_u{}^r, m_q{}^p] + \tfrac{3}{2}\, Y_u{}^{i2i1} \tfrac{1}{m_\Phi{}^2} \big(\overline{a_u}^{pr} \big(2 m_H^2 c_\beta{}^2 - m_\Phi{}^2 s_\beta{}^2\big) + s_\beta\, \overline{Y_u}^{pr}\, \mu_H\, c_\beta \big(2 m_H^2 + m_\Phi{}^2\big)\big)$$

$$\big(-s_\beta\, a_u{}^{pr} + Y_u{}^{pr}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{3,1,-1}[m_u{}^r, m_q{}^p] +$$

$$3\, m_H^2\, s_\beta\, Y_u{}^{i2i1} \big(s_\beta\, \overline{a_u}^{pr} - \overline{Y_u}^{pr}\, \mu_H\, c_\beta\big) \big(s_\beta\, a_u{}^{pr} - Y_u{}^{pr}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{3,1,0}[m_u{}^r, m_q{}^p] -$$

$$9\, m_H^2\, s_\beta\, Y_u{}^{i2i1} \big(s_\beta\, \overline{a_u}^{pr} - \overline{Y_u}^{pr}\, \mu_H\, c_\beta\big) \big(s_\beta\, a_u{}^{pr} - Y_u{}^{pr}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{4,1,-1}[m_u{}^r, m_q{}^p] +$$

$$6\, m_H^2\, s_\beta\, Y_u{}^{i2i1} \big(s_\beta\, \overline{a_u}^{pr} - \overline{Y_u}^{pr}\, \mu_H\, c_\beta\big) \big(s_\beta\, a_u{}^{pr} - Y_u{}^{pr}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{5,1,-2}[m_u{}^r, m_q{}^p] +$$

$$\tfrac{1}{2}\, s_\beta\, \overline{Y_u}^{pr}\, Y_u{}^{pi1}\, Y_u{}^{i2r}\, \mathrm{LF}_{1,1,0}[m_u{}^r, \mu_H] - \tfrac{3}{8}\, s_\beta\, Y_u{}^{i2i1}\, g_L{}^2\, \mathrm{LF}_{2,1,-1}[M_W, m_q{}^{i2}] +$$

$$3\, M_W\, Y_u{}^{i2i1}\, \mu_H\, c_\beta\, g_L{}^2 \tfrac{1}{m_\Phi{}^4} \big(m_H^2 + m_\Phi{}^2\big) \big(c_\beta{}^2 - s_\beta{}^2\big)\, \mathrm{LF}_{1,1,0}[M_W, \mu_H] +$$

$$\tfrac{3}{4}\, s_\beta\, Y_u{}^{i2i1}\, g_Y{}^2 \big(c_\beta{}^2 + s_\beta{}^2\big)\, \mathrm{LF}_{2,1,-1}[\mu_H, m_B] + m_B\, Y_u{}^{i2i1}\, \mu_H\, c_\beta\, g_Y{}^2 \tfrac{1}{m_\Phi{}^2}$$

$$\big(-m_H^2 c_\beta{}^2 + s_\beta{}^2 \big(m_H^2 + m_\Phi{}^2\big)\big)\, \mathrm{LF}_{2,1,0}[\mu_H, m_B] - \tfrac{1}{2}\, s_\beta\, Y_u{}^{i2i1}\, g_Y{}^2 \big(c_\beta{}^2 + s_\beta{}^2\big)\, \mathrm{LF}_{3,1,-2}[\mu_H, m_B] +$$

$$Y_u{}^{i2i1}\, g_Y{}^2 \tfrac{1}{m_\Phi{}^2} \big(-2 m_H^2\, s_\beta\, m_\Phi{}^2 \big(c_\beta{}^2 + s_\beta{}^2\big) + m_B\, \mu_H\, c_\beta \big(m_H^2 c_\beta{}^2 - s_\beta{}^2 \big(m_H^2 + m_\Phi{}^2\big)\big)\big)\, \mathrm{LF}_{3,1,-1}[\mu_H, m_B] -$$

$$2\, m_B\, m_H^2\, Y_u{}^{i2i1}\, \mu_H\, c_\beta\, g_Y{}^2\, s_\beta{}^2\, \mathrm{LF}_{3,1,0}[\mu_H, m_B] + 4\, m_H^2\, s_\beta\, Y_u{}^{i2i1}\, g_Y{}^2 \big(c_\beta{}^2 + s_\beta{}^2\big)\, \mathrm{LF}_{4,1,-2}[\mu_H, m_B] +$$

$$6\, m_B\, m_H^2\, Y_u{}^{i2i1}\, \mu_H\, c_\beta\, g_Y{}^2\, s_\beta{}^2\, \mathrm{LF}_{4,1,-1}[\mu_H, m_B] - 2\, m_H^2\, s_\beta\, Y_u{}^{i2i1}\, g_Y{}^2 \big(c_\beta{}^2 + s_\beta{}^2\big)\, \mathrm{LF}_{5,1,-3}[\mu_H, m_B] -$$

$$4\, m_B\, m_H^2\, Y_u{}^{i2i1}\, \mu_H\, c_\beta\, g_Y{}^2\, s_\beta{}^2\, \mathrm{LF}_{5,1,-2}[\mu_H, m_B] - \tfrac{1}{4}\, s_\beta\, \overline{Y_d}^{pr}\, Y_d{}^{i2r}\, Y_u{}^{pi1}\, \mathrm{LF}_{2,1,-1}[\mu_H, m_d{}^r] -$$

$$\tfrac{1}{2}\, s_\beta\, \overline{Y_u}^{pr}\, Y_u{}^{pi1}\, Y_u{}^{i2r}\, \mathrm{LF}_{2,1,-1}[\mu_H, m_q{}^p] - \tfrac{1}{4}\, s_\beta\, \overline{Y_u}^{pr}\, Y_u{}^{pi1}\, Y_u{}^{i2r}\, \mathrm{LF}_{2,1,-1}[\mu_H, m_u{}^r] +$$

$$\tfrac{9}{4}\, s_\beta\, Y_u{}^{i2i1}\, g_L{}^2 \big(c_\beta{}^2 + s_\beta{}^2\big)\, \mathrm{LF}_{2,1,-1}[\mu_H, M_W] + 3\, M_W\, Y_u{}^{i2i1}\, \mu_H\, c_\beta\, g_L{}^2 \tfrac{1}{m_\Phi{}^2}$$

$$\big(-m_H^2 c_\beta{}^2 + s_\beta{}^2 \big(m_H^2 + m_\Phi{}^2\big)\big)\, \mathrm{LF}_{2,1,0}[\mu_H, M_W] - \tfrac{3}{2}\, s_\beta\, Y_u{}^{i2i1}\, g_L{}^2 \big(c_\beta{}^2 + s_\beta{}^2\big)\, \mathrm{LF}_{3,1,-2}[\mu_H, M_W] +$$

$$3\, Y_u{}^{i2i1}\, g_L{}^2 \tfrac{1}{m_\Phi{}^2} \big(-2 m_H^2\, s_\beta\, m_\Phi{}^2 \big(c_\beta{}^2 + s_\beta{}^2\big) + M_W\, \mu_H\, c_\beta \big(m_H^2 c_\beta{}^2 - s_\beta{}^2 \big(m_H^2 + m_\Phi{}^2\big)\big)\big)\, \mathrm{LF}_{3,1,-1}[\mu_H, M_W] -$$

$$6\, m_H^2\, M_W\, Y_u{}^{i2i1}\, \mu_H\, c_\beta\, g_L{}^2\, s_\beta{}^2\, \mathrm{LF}_{3,1,0}[\mu_H, M_W] + 12\, m_H^2\, s_\beta\, Y_u{}^{i2i1}\, g_L{}^2 \big(c_\beta{}^2 + s_\beta{}^2\big)\, \mathrm{LF}_{4,1,-2}[\mu_H, M_W] +$$

$$18\, m_H^2\, M_W\, Y_u{}^{i2i1}\, \mu_H\, c_\beta\, g_L{}^2\, s_\beta{}^2\, \mathrm{LF}_{4,1,-1}[\mu_H, M_W] -$$

$$6\, m_H^2\, s_\beta\, Y_u{}^{i2i1}\, g_L{}^2 \big(c_\beta{}^2 + s_\beta{}^2\big)\, \mathrm{LF}_{5,1,-3}[\mu_H, M_W] - 12\, m_H^2\, M_W\, Y_u{}^{i2i1}\, \mu_H\, c_\beta\, g_L{}^2\, s_\beta{}^2\, \mathrm{LF}_{5,1,-2}[\mu_H, M_W] +$$

$$\tfrac{2}{9}\, m_B\, g_Y{}^2 \big(-s_\beta\, a_u{}^{i2i1} + Y_u{}^{i2i1}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{1,1,1,0}[m_B, m_q{}^{i2}, m_u{}^{i1}] +$$

$$\tfrac{1}{18}\, m_B\, m_H^2\, g_Y{}^2 \big(-s_\beta\, a_u{}^{i2i1} + Y_u{}^{i2i1}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{2,2,1,-1}[m_B, m_q{}^{i2}, m_u{}^{i1}] +$$

$$\tfrac{1}{6}\, s_\beta\, Y_u{}^{i2i1}\, g_Y{}^2\, \mathrm{LF}_{1,1,1,-1}[m_B, m_q{}^{i2}, \mu_H] + \tfrac{1}{6}\, m_B\, Y_u{}^{i2i1}\, \mu_H\, c_\beta\, g_Y{}^2\, \mathrm{LF}_{1,1,1,0}[m_B, m_q{}^{i2}, \mu_H] +$$

$$\tfrac{1}{18}\, m_B\, m_H^2\, g_Y{}^2 \big(-s_\beta\, a_u{}^{i2i1} + Y_u{}^{i2i1}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{2,2,1,-1}[m_B, m_u{}^{i1}, m_q{}^{i2}] -$$

$$\tfrac{2}{3}\, s_\beta\, Y_u{}^{i2i1}\, g_Y{}^2\, \mathrm{LF}_{1,1,1,-1}[m_B, m_u{}^{i1}, \mu_H] - \tfrac{2}{3}\, m_B\, Y_u{}^{i2i1}\, \mu_H\, c_\beta\, g_Y{}^2\, \mathrm{LF}_{1,1,1,0}[m_B, m_u{}^{i1}, \mu_H] -$$

$$\tfrac{1}{12}\, m_H^2\, s_\beta\, Y_u{}^{i2i1}\, g_Y{}^2\, \mathrm{LF}_{2,2,1,-2}[m_B, \mu_H, m_q{}^{i2}] - \tfrac{1}{12}\, m_B\, m_H^2\, Y_u{}^{i2i1}\, \mu_H\, c_\beta\, g_Y{}^2\, \mathrm{LF}_{2,2,1,-1}[m_B, \mu_H, m_q{}^{i2}] +$$

$$\tfrac{1}{3}\, m_H^2\, s_\beta\, Y_u{}^{i2i1}\, g_Y{}^2\, \mathrm{LF}_{2,2,1,-2}[m_B, \mu_H, m_u{}^{i1}] + \tfrac{1}{3}\, m_B\, m_H^2\, Y_u{}^{i2i1}\, \mu_H\, c_\beta\, g_Y{}^2\, \mathrm{LF}_{2,2,1,-1}[m_B, \mu_H, m_u{}^{i1}] +$$

$$Y_d{}^{i2r}\, Y_u{}^{pi1}\, \mu_H \big(\overline{a_d}^{pr}\, c_\beta - s_\beta\, \overline{Y_d}^{pr}\, \mu_H\big)\, \mathrm{LF}_{1,1,1,0}[m_d{}^r, m_q{}^p, \mu_H] +$$

$$\tfrac{1}{2}\, m_H^2\, Y_d{}^{i2r}\, Y_u{}^{pi1}\, \mu_H \big(-\overline{a_d}^{pr}\, c_\beta + s_\beta\, \overline{Y_d}^{pr}\, \mu_H\big)\, \mathrm{LF}_{2,1,1,0}[m_d{}^r, m_q{}^p, \mu_H] +$$

$$\tfrac{1}{2}\, m_H^2\, Y_d{}^{i2r}\, Y_u{}^{pi1}\, \mu_H \big(\overline{a_d}^{pr}\, c_\beta - s_\beta\, \overline{Y_d}^{pr}\, \mu_H\big)\, \mathrm{LF}_{3,1,1,-1}[m_d{}^r, m_q{}^p, \mu_H] +$$

$$\tfrac{1}{4}\, m_H^2\, Y_d{}^{i2r}\, Y_u{}^{pi1}\, \mu_H \big(\overline{a_d}^{pr}\, c_\beta - s_\beta\, \overline{Y_d}^{pr}\, \mu_H\big)\, \mathrm{LF}_{2,2,1,-1}[m_d{}^r, \mu_H, m_q{}^p] +$$

$$\tfrac{8}{3}\, m_G\, g_s{}^2 \big(-s_\beta\, a_u{}^{i2i1} + Y_u{}^{i2i1}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{1,1,1,0}[m_G, m_q{}^{i2}, m_u{}^{i1}] +$$

$$\tfrac{2}{3}\, m_G\, m_H^2\, g_s{}^2 \big(-s_\beta\, a_u{}^{i2i1} + Y_u{}^{i2i1}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{2,2,1,-1}[m_G, m_q{}^{i2}, m_u{}^{i1}] +$$

$$\tfrac{2}{3}\, m_G\, m_H^2\, g_s{}^2 \big(-s_\beta\, a_u{}^{i2i1} + Y_u{}^{i2i1}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{2,2,1,-1}[m_G, m_u{}^{i1}, m_q{}^{i2}] +$$

$$\tfrac{1}{2}\, m_H^2\, Y_d{}^{i2r}\, Y_u{}^{pi1}\, \mu_H \big(-\overline{a_d}^{pr}\, c_\beta + s_\beta\, \overline{Y_d}^{pr}\, \mu_H\big)\, \mathrm{LF}_{2,1,1,0}[m_q{}^p, m_d{}^r, \mu_H] +$$

$$\tfrac{1}{2}\, m_H^2\, Y_d{}^{i2r}\, Y_u{}^{pi1}\, \mu_H \big(\overline{a_d}^{pr}\, c_\beta - s_\beta\, \overline{Y_d}^{pr}\, \mu_H\big)\, \mathrm{LF}_{3,1,1,-1}[m_q{}^p, m_d{}^r, \mu_H] +$$

$$\tfrac{1}{4}\, m_H^2\, Y_d{}^{i2r}\, Y_u{}^{pi1}\, \mu_H \big(\overline{a_d}^{pr}\, c_\beta - s_\beta\, \overline{Y_d}^{pr}\, \mu_H\big)\, \mathrm{LF}_{2,2,1,-1}[m_q{}^p, \mu_H, m_d{}^r] +$$

$$\tfrac{1}{9}\, m_B\, m_H^2\, g_Y{}^2 \big(s_\beta\, a_u{}^{i2i1} - Y_u{}^{i2i1}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{2,1,1,0}[m_q{}^{i2}, m_B, m_u{}^{i1}] +$$

$$\tfrac{1}{9}\, m_B\, m_H^2\, g_Y{}^2 \big(-s_\beta\, a_u{}^{i2i1} + Y_u{}^{i2i1}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{3,1,1,-1}[m_q{}^{i2}, m_B, m_u{}^{i1}] +$$

$$\tfrac{4}{3}\, m_G\, m_H^2\, g_s{}^2 \big(s_\beta\, a_u{}^{i2i1} - Y_u{}^{i2i1}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{2,1,1,0}[m_q{}^{i2}, m_G, m_u{}^{i1}] +$$

$$\tfrac{4}{3}\, m_G\, m_H^2\, g_s{}^2 \big(-s_\beta\, a_u{}^{i2i1} + Y_u{}^{i2i1}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{3,1,1,-1}[m_q{}^{i2}, m_G, m_u{}^{i1}] -$$

$$\tfrac{3}{2}\, s_\beta\, Y_u{}^{i2i1}\, g_L{}^2\, \mathrm{LF}_{1,1,1,-1}[m_q{}^{i2}, M_W, \mu_H] - \tfrac{3}{2}\, M_W\, Y_u{}^{i2i1}\, \mu_H\, c_\beta\, g_L{}^2\, \mathrm{LF}_{1,1,1,0}[m_q{}^{i2}, M_W, \mu_H] +$$

$$\tfrac{1}{9}\, m_B\, m_H^2\, g_Y{}^2 \big(s_\beta\, a_u{}^{i2i1} - Y_u{}^{i2i1}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{2,1,1,0}[m_u{}^{i1}, m_B, m_q{}^{i2}] +$$

$$\tfrac{1}{9}\, m_B\, m_H^2\, g_Y{}^2 \big(-s_\beta\, a_u{}^{i2i1} + Y_u{}^{i2i1}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{3,1,1,-1}[m_u{}^{i1}, m_B, m_q{}^{i2}] +$$

$$\tfrac{4}{3}\, m_G\, m_H^2\, g_s{}^2 \big(s_\beta\, a_u{}^{i2i1} - Y_u{}^{i2i1}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{2,1,1,0}[m_u{}^{i1}, m_G, m_q{}^{i2}] +$$

$$\tfrac{4}{3}\, m_G\, m_H^2\, g_s{}^2 \big(-s_\beta\, a_u{}^{i2i1} + Y_u{}^{i2i1}\, \mu_H\, c_\beta\big)\, \mathrm{LF}_{3,1,1,-1}[m_u{}^{i1}, m_G, m_q{}^{i2}] +$$

$$\tfrac{3}{4}\, m_H^2\, s_\beta\, Y_u{}^{i2i1}\, g_L{}^2\, \mathrm{LF}_{2,2,1,-2}[M_W, \mu_H, m_q{}^{i2}] + \tfrac{3}{4}\, m_H^2\, M_W\, Y_u{}^{i2i1}\, \mu_H\, c_\beta\, g_L{}^2\, \mathrm{LF}_{2,2,1,-1}[M_W, \mu_H, m_q{}^{i2}] \Big)$$

Matching of $d = 6$ Yukawa Couplings

SMEFT $d = 6$ Yukawa C_{uH}:

$$
\begin{aligned}
& C_{uH}{}^{i1\_i2\_} \to \frac{1}{8}\, s_{4\beta}\, c_{Hqu}{}^{i2i1}\, c_\beta\, \frac{1}{m_\Phi{}^2}\, \frac{1}{s_\beta} \left(g_Y{}^2 + g_L{}^2\right) + \\
& \hbar \left(\frac{1}{192}\, \frac{1}{m_\Phi{}^4}\, \frac{1}{s_\beta{}^3}\, \frac{1}{c_\beta{}^2} \left(-6\, \overline{c_{Hqu}}{}^{pr} \left(6\, s_{4\beta}\, c_{Hqu}{}^{pr}\, c_{Hqu}{}^{i2i1}\, c_{H^2}\, c_\beta{}^5 \left(g_Y{}^2 + g_L{}^2\right) + \right.\right.\right. \\
& \qquad s_\beta\, m_\Phi{}^2\, c_\beta{}^3 \left(-8\, \overline{c_{Hqu}}{}^{st}\, c_{Hqu}{}^{pt}\, c_\beta \left(c_{Hqu}{}^{si1}\, c_{Hqu}{}^{i2r} - 12\, c_{Hqu}{}^{sr}\, c_{Hqu}{}^{i2i1} \right) - \right. \\
& \qquad\quad \left.\left. \left(g_Y{}^2 + g_L{}^2\right) \left(12\, c_{Hqu}{}^{pr}\, c_{Hqu}{}^{i2i1}\, c_\beta\, c_{2\beta}{}^2 - 5\, s_{4\beta}\, s_\beta\, c_{Hqu}{}^{pi1}\, c_{Hqu}{}^{i2r} \right)\right)\right) + \\
& \qquad s_\beta \left(s_{4\beta}\, s_\beta\, c_{Hqu}{}^{i2i1}\, m_\Phi{}^2\, c_\beta{}^2 \left(6\, c_\beta{}^3 \left(g_Y{}^2 + g_L{}^2\right) \left(g_Y{}^2 + 3\, g_L{}^2\right) - 3\, s_{4\beta}\, s_\beta \left(g_Y{}^2 + g_L{}^2\right)^2 + \right.\right. \\
& \qquad\quad \left.\left.\left. 2\, c_\beta \left(-38\, g_Y{}^4 - 14\, g_L{}^4 + 3\, s_\beta{}^2 \left(g_Y{}^2 + g_L{}^2\right) \left(g_Y{}^2 + 3\, g_L{}^2\right)\right)\right)\right) + \right. \\
& \qquad 2\, \overline{c_{Hqd}}{}^{pr} \left(3\, s_\beta\, c_{Hqd}{}^{pi1} \left(-s_{4\beta}\, c_{Hqu}{}^{i2r}\, c_{H^2}\, c_\beta{}^3 \left(g_Y{}^2 + g_L{}^2\right) + s_\beta\, m_\Phi{}^2 \left(2\, c_{Hqu}{}^{i2r}\, c_{2\beta}{}^2\, c_\beta{}^2 \right.\right.\right. \\
& \qquad\quad \left.\left. \left(g_Y{}^2 + g_L{}^2\right) + s_{4\beta}\, s_\beta\, c_{Hqu}{}^{i2r}\, c_\beta \left(g_Y{}^2 + g_L{}^2\right) + 8\, \overline{c_{Hqd}}{}^{st}\, c_{Hqd}{}^{sr}\, c_{Hqu}{}^{i2t}\, s_\beta{}^2 \right)\right) + \\
& \qquad\quad 8\, \overline{c_{Hqu}}{}^{st}\, m_\Phi{}^2 \left(-3\, c_{Hqd}{}^{pi1}\, c_{Hqu}{}^{sr}\, c_{Hqu}{}^{i2t}\, s_\beta{}^2\, c_\beta{}^2 + c_{Hqd}{}^{pt}\, c_{Hqu}{}^{si1}\, c_{Hqu}{}^{i2r} \right. \\
& \qquad\qquad \left.\left.\left.\left.\left. \left(3\, c_\beta{}^4 - 3\, s_\beta{}^2\, c_\beta{}^2 - s_\beta{}^4 \right)\right)\right)\right)\right)\right) + \\
& \quad \frac{1}{16}\, c_{Hqu}{}^{i2i1}\, \frac{1}{m_\Phi{}^6}\, \frac{1}{s_\beta{}^2}\, \frac{1}{c_\beta{}^2} \left(g_Y{}^2 + g_L{}^2\right) \left(3\, \overline{c_{Hqd}}{}^{pr}\, c_{Hqd}{}^{pr} \left(s_{2\beta}\, s_{4\beta}\, c_{H^2}\, c_\beta{}^2 + m_\Phi{}^2 \right.\right. \\
& \qquad \left.\left.\left(s_{2\beta}\, s_{4\beta}\, c_\beta{}^2 + s_{2\beta}\, s_{4\beta}\, s_\beta{}^2 + 2\, s_\beta\, c_\beta \left(-s_{2\beta} \left(c_{2\beta}{}^2 + c_{4\beta} \right) + s_{2\beta}{}^3 + s_{4\beta}\, s_\beta{}^2 \right)\right)\right) - \textstyle\sum_p g_Y{}^2\, c_\beta{}^2 \\
& \qquad \left.\left(s_{2\beta}\, s_{4\beta}\, c_\beta{}^2 \left(c_{H^2} + m_\Phi{}^2 \right) - s_\beta\, c_\beta\, m_\Phi{}^2 \left(2\, s_{2\beta} \left(c_{2\beta}{}^2 + c_{4\beta} - s_{2\beta}{}^2 \right) + s_{4\beta}\, c_{2\beta} \right) + s_{2\beta}\, s_{4\beta}\, m_\Phi{}^2\, s_\beta{}^2 \right)\right) \\
& \quad \mathrm{LF}_{1,0}[m_d{}^p] + \frac{1}{24}\, c_{Hqu}{}^{i2i1}\, \frac{1}{m_\Phi{}^2}\, \frac{1}{s_\beta}\, \frac{1}{c_\beta} \left(6\, s_{2\beta}\, \overline{c_{Hqd}}{}^{pr}\, c_{Hqd}{}^{pr}\, g_Y{}^2 \left(c_{2\beta} + 2\, c_\beta{}^2 \right) + \ \ldots \right.
\end{aligned}
$$

Matching of $d = 6$ Yukawa Couplings

SMEFT $d = 6$ Yukawa C_{uH}:

Matching of $d = 6$ Yukawa Couplings

SMEFT $d = 6$ Yukawa C_{uH}:

Can be further simplified?

Phenomenological Example

- Toy model with right-handed top partner $\tilde{t}$ and bino-like Dark Matter χ

$$\mathcal{L}_{BSM} = \bar{\chi}\left(i\partial\!\!\!/ - \frac{1}{2}M_1\right)\chi + |D_\mu \tilde{t}|^2 - m_{\tilde{t}}^2 \tilde{t}^\dagger \tilde{t} - \left(y_{\mathrm{DM}} \tilde{t}^\dagger \bar{\chi} t_R + h.c.\right)$$

- EFT obtained by integrating out $\tilde{t}$ and χ, where $x = M_1^2 / m_{\tilde{t}}^2$

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& + C_q^{LV}\left(\bar{t}_L T^A\gamma^\mu t_L\right)\left(\bar{u}T^A\gamma_\mu u + \bar{d}T^A\gamma_\mu d\right) \\
& + C_q^{RV}\left(\bar{t}_R T^A\gamma^\mu t_R\right)\left(\bar{u}T^A\gamma_\mu u + \bar{d}T^A\gamma_\mu d\right) \\
& + C_q^{RR}\left(\bar{t}_R\gamma^\mu t_R\right)\left(2\bar{u}_R\gamma_\mu u_R - \bar{d}_R\gamma_\mu d_R\right) \\
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\end{aligned}$$

$$\begin{aligned}
C_g &= -\frac{g_s y_{DM}^2}{384\pi^2}\frac{1}{m_{\tilde{t}}^2}\frac{1}{(1-x)^4}\left[1 - 6x + 3x^2 + 2x^3 - 6x^2\log(x)\right], \\
C_{G3} &= \frac{g_s^3}{5760\pi^2}\frac{1}{m_{\tilde{t}}^2}, \\
C_q^{LV} &= -\frac{g_s^4}{960\pi^2}\frac{1}{m_{\tilde{t}}^2}, \\
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C_q^{RR} &= \frac{y_{DM}^4}{2304\pi^2}\frac{1}{m_{\tilde{t}}^2}\frac{1}{(1-x)^4}\left[2 - 9x + 18x^2 - 11x^3 + 6x^3\log(x)\right], \\
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&\quad + \frac{y_{DM}^4}{1152\pi^2}\frac{1}{m_{\tilde{t}}^2}\frac{1}{(1-x)^4}\left[-7 - 36x + 99x^2 - 56x^3 + 6x\left(-6 + 3x + 4x^2\right)\log(x)\right], \\
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(can be mapped to Warsaw basis)

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Matching of toy model agrees with:

- full MSSM matching and taking appropriate limits
- partial results in Lessa, Sanz [2312.00670]

(can be mapped to Warsaw basis)

Conclusions & Outlook

- **Full MSSM-to-SMEFT one-loop matching condition in Warsaw basis computed**
  - No flavor assumptions, MSSM with 124 parameters,
  - Single-scale matching, integrating out all superpartners and 2nd Higgs at once
  - All Warsaw basis structures generated except operators with dual field-strength tenors
  - Proper elimination of redundant operators (incl. evanescent operators)

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- Longterm ideas/goals:
  - Combine with further phenomenological codes (e.g.: `smelli/flavio`, `SFitter`, ...)
  - Global MSSM fit using SMEFT framework

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Thank you for your attention!

Backup

Size of Wilson Coefficients

- Toy model with right-handed top partner $\tilde{t}$ and bino-like Dark Matter χ

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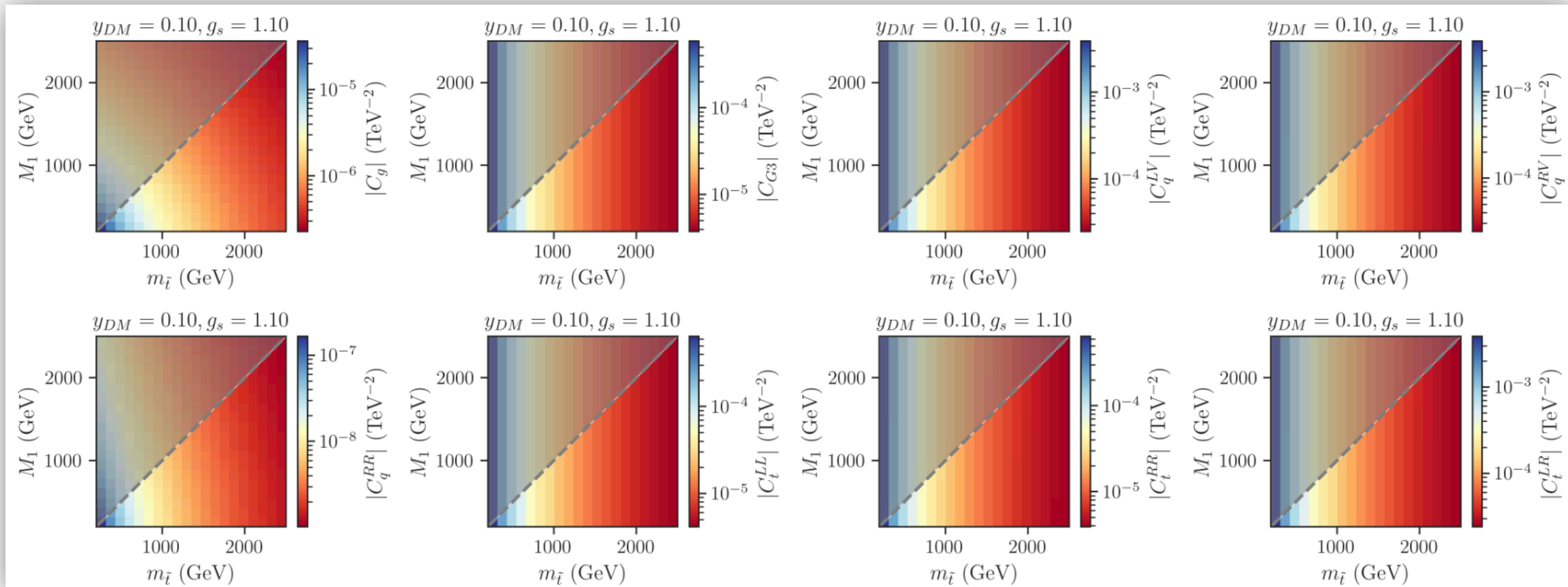
→ **check size of SMEFT Wilson coefficients**



Path Integral Methods for EFT Matching

- **Lagrangian:** $\mathscr{L}_{\text{UV}}(\eta)$ 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:**

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

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

- **Produces effective quantum action of EFT:**
  - 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:**

fluctuation operator $\mathcal{Q}_{ij}$

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

higher loop orders
Fuentes-Martín, Palavrić, Thomsen [2311.13630]

- **Tree-level matching:** $\mathcal{L}^{(0)}_{\rm EFT} = \mathcal{L}_{\rm UV}\left(\hat\eta_L, \hat\eta_H[\hat\eta_L]\right)$
  - Substitute $\hat\eta_H$ by its EOM and expand in m_H^{-1}

- **One-loop matching:** $\exp\left(i\Gamma^{(1)}_{\rm UV}\right) = \int \mathcal{D}\eta \exp\left(\int {\rm d}^d x\, \frac{1}{2}\bar\eta_i\, \mathcal{Q}_{ij}\, \eta_j\right)$

Evaluation using:
- Method of regions
- Wilson lines → covariance
  → see Anders' talk on Friday

  - Gaussian path integral:

$$\Gamma^{(1)}_{\rm UV} = -\,i \log\left({\rm SDet}\,\mathcal{Q}[\hat\eta]\right)^{1/2} = \frac{i}{2}{\rm STr}\left(\log \mathcal{Q}[\hat\eta]\right) = \pm\frac{i}{2}\int \frac{{\rm d}^D k}{(2\pi)^D}\langle k\,|\,{\rm tr}\left(\log\,\mathcal{Q}\right)|\,k\rangle$$

  - Expressed through a superdeterminant (SDet) or supertrace (STr)
  - Supertraces directly **provide EFT Lagrangian**: $\int {\rm d}^D x\, \mathcal{L}^{(1)}_{\rm EFT} = \Gamma^{(1)}_{\rm UV}\Big|_{\rm hard}$

Physical Contributions by Evanescent Operators

- Evanescent operators $E \equiv R - Q$ formally of rank ϵ

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

- Only physical contributions when inserted into UV-divergent one-loop diagrams
  - Tree level: no physical contributions
  - One loop: contributions from (local) UV poles ⇒ finite contribution to matrix elements
- Effect of evanescent operators can be absorbed by a **finite renormalization**
- We can **drop all evanescent operators** for the computation of one-loop matrix elements if:
  - **Projecting redundant operators** R onto the physical basis Q with $D = 4$ identities and
  - **Shifting coefficients** of Q by the appropriate finite renormalization constants
- For one-loop EFT action $S^{(1)}$ we find ($\mathscr{P}$ projection $R \to Q$ using $D = 4$ identities)

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

  - $\overline{\Gamma}_X^{(1)}$: sum of one-loop diagrams with vertices from X contributing to effective action
  - $\Delta S^{(1)}$: sum of one-loop diagrams with insertions of evanescent operators $E = R - Q$
- **Resulting renormalization scheme is an evanescent-free version of $\overline{\text{MS}}$**

Fuentes-Martin, König, Pages, Thomsen, FW [2211.09144]; Aebischer, Buras, Kumar [2202.01225]; Aebischer, Pesut [2208.10513]; Aebischer, Pesut, Polonsky [2211.01379]

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)

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- $\overline{\Gamma}_X^{(1)}$: sum of one-loop diagrams with vertices from X contributing to the effective action
- $\Delta S^{(1)}$: sum of all one-loop diagrams with the insertion of evanescent operators $E = R - Q$
- Compute $\Delta S^{(1)}$ using functional methods

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

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

Example: Evanescent Operators in the SMEFT

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

- Tree-level: $\mathscr{L}$ & $\mathscr{L}'$ lead to same physics
- One-loop: $\mathscr{L}$ & $\mathscr{L}'$ do not lead to same physics (in dimensional regularization $D = 4 - 2\epsilon$)

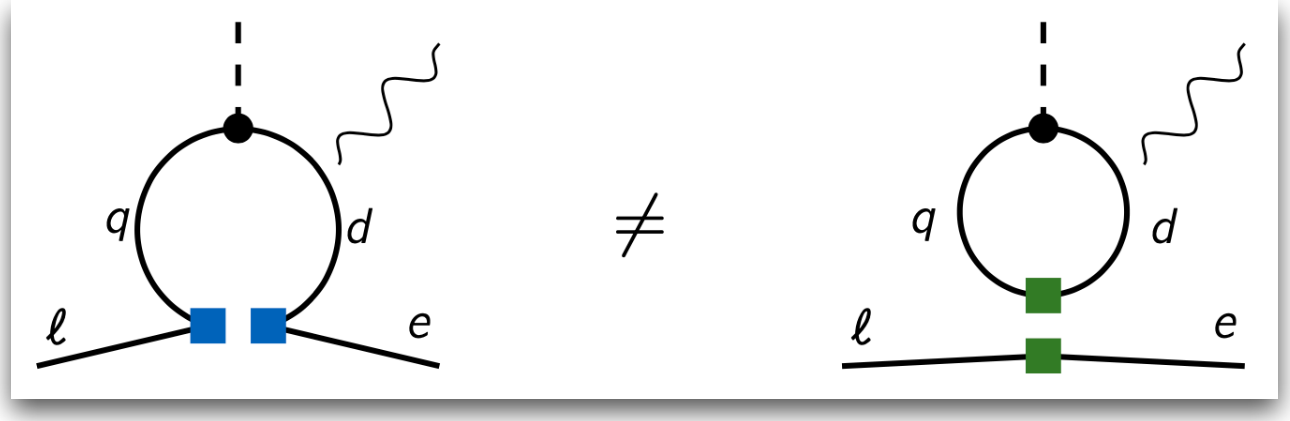


figure by A. Thomsen

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

$$\Gamma_{\text{EFT}}^{(1)} \neq \Gamma_{\text{EFT}}^{\prime(1)}$$

- In D dimensions we have: $C_{lqde}^{prst}(\bar{\ell}^p\gamma^\mu q^t)(\bar{d}^s\gamma_\mu e^r) = -2C_{lqde}^{prst}(\bar{\ell}^p e^r)(\bar{d}^s q^t) + C_{lqde}^{prst} E_{lqde}^{prst}$

  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]

Example

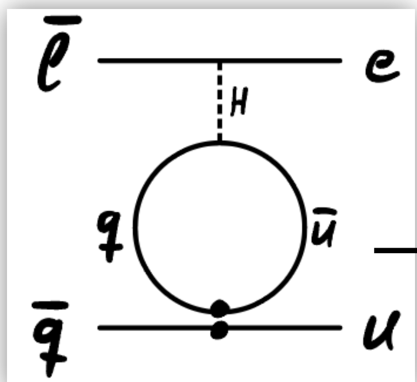
- Term from the tree-level EFT Lagrangian that requires Fierzing to map onto Warsaw basis

$$\overline{Y_u}^{rs}\, Y_u{}^{tp}\, \frac{1}{M_\Phi{}^2}\, c_\beta{}^2\, \left(\overline{q}^{s}_{ai}\cdot P_R\cdot u^{ar}\right)\left(\overline{u}^{t}_{b}\cdot P_L\cdot q^{bip}\right)$$

- Fierz identity: $(\bar{q}_p u_r)(\bar{u}_s q_t) = -\frac{1}{6}(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t) - (\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$

- Insert evanescent operator in all possible UV-divergent one-loop diagrams

$$(\bar{q}_p u_r)(\bar{u}_s q_t) \longrightarrow -\frac{1}{6}Q_{qu}^{(1)ptsr} - Q_{qu}^{(8)ptsr} + \frac{1}{16\pi^2}\Big(\frac{1}{12}y_d^{tu}y_u^{vs}Q_{quqd}^{(1)vrpu}$$
$$+\frac{1}{4}\overline{y_u^{uv}}\,y_u^{ts}Q_{qu}^{(1)puvr} + \frac{1}{4}\overline{y_u^{pr}}\,y_u^{uv}Q_{qu}^{(1)utsv} + \frac{1}{2}y_d^{tu}y_u^{vs}Q_{quqd}^{(8)vrpu}$$
$$+\overline{y_d^{pu}}\,\overline{y_u^{vr}}\left(\frac{1}{12}\overline{Q_{quqd}^{(1)vstu}} + \frac{1}{2}\overline{Q_{quqd}^{(8)vstu}} - \frac{1}{2}\overline{Q_{quqd}^{(1)tsvu}}\right)$$
$$+Q_{uH}^{pr}\left(3\overline{y_u^{uv}}\,y_u^{tv}y_u^{us} - \frac{3}{2}\lambda y_u^{ts}\right) + \frac{3}{2}\overline{y_e^{uv}}\,\overline{y_u^{pr}}\,\overline{Q_{\ell equ}^{(1)uvts}}$$
$$+\boxed{\frac{3}{2}y_e^{uv}y_u^{ts}Q_{\ell equ}^{(1)uvpr}} + \frac{3}{2}\overline{y_u^{uv}}\,y_u^{ts}Q_{qu}^{(8)puvr} + \frac{3}{2}\overline{y_u^{pr}}\,y_u^{uv}Q_{qu}^{(8)utsv}$$
$$+3\overline{y_u^{pu}}\,\overline{y_u^{vr}}\,y_u^{vu}\overline{Q_{uH}^{ts}} - \frac{1}{8}\overline{y_u^{ur}}\,y_u^{vs}Q_{qq}^{(1)vtpu} - \frac{1}{8}\overline{y_u^{ur}}\,y_u^{vs}Q_{qq}^{(3)vtpu}$$
$$-\frac{1}{6}\overline{y_d^{pu}}\,y_d^{tv}Q_{ud}^{(1)sruv} - \frac{1}{4}\overline{y_u^{ur}}\,y_u^{tv}Q_{qu}^{(1)pusv} - \frac{1}{4}\overline{y_u^{pu}}\,y_u^{vs}Q_{qu}^{(1)vtur}$$
$$-\frac{3}{8}g_L\overline{y_u^{pr}}\,\overline{Q_{uW}^{ts}} - \frac{3}{8}g_L y_u^{ts}Q_{uW}^{pr} - \frac{1}{2}y_d^{tu}y_u^{vs}Q_{quqd}^{(1)prvu}$$
$$-\frac{1}{2}\overline{y_u^{pu}}\,y_u^{tv}Q_{uu}^{ursv} - \frac{5}{8}g_Y\overline{y_u^{pr}}\,\overline{Q_{uB}^{ts}} - \frac{5}{8}g_Y y_u^{ts}Q_{uB}^{pr}$$
$$-\overline{y_d^{pu}}\,y_d^{tv}Q_{ud}^{(8)sruv} - \frac{3}{2}\overline{y_d^{uv}}\,\overline{y_u^{pr}}\,\overline{Q_{quqd}^{(1)tsuv}} - \frac{3}{2}\lambda\overline{y_u^{pr}}\,\overline{Q_{uH}^{ts}}$$
$$-\frac{3}{2}\mu^2\overline{y_u^{pr}}\,\overline{Q_{yu}^{ts}} - \frac{3}{2}y_d^{uv}y_u^{ts}Q_{quqd}^{(1)pruv} - \frac{3}{2}\mu^2 y_u^{ts}Q_{yu}^{pr}\Big)$$



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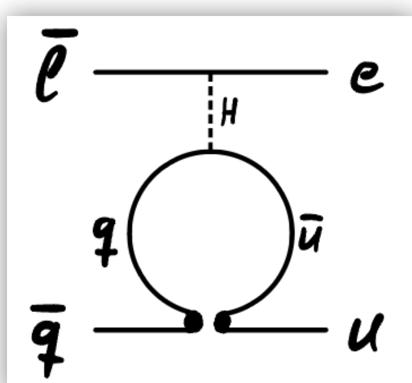

- Finite renormalization to compensate for evanescent operator
  (loop suppressed → only relevant for tree-level EFT Lagrangian)

- Renormalization scheme:
  evanescent-free version of $\overline{\text{MS}}$

- All finite renormalization constants required for SMEFT computed in
  Fuentes-Martín, König, Pagès, Thomsen, FW [2211.09144]