# From the MSSM to the SMEFT

André Lessa

UFABC, São Paulo, Brazil

IRN Terascale

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*In collaboration with Sabine Kraml, Suraj Prakash and Felix Wilsch*

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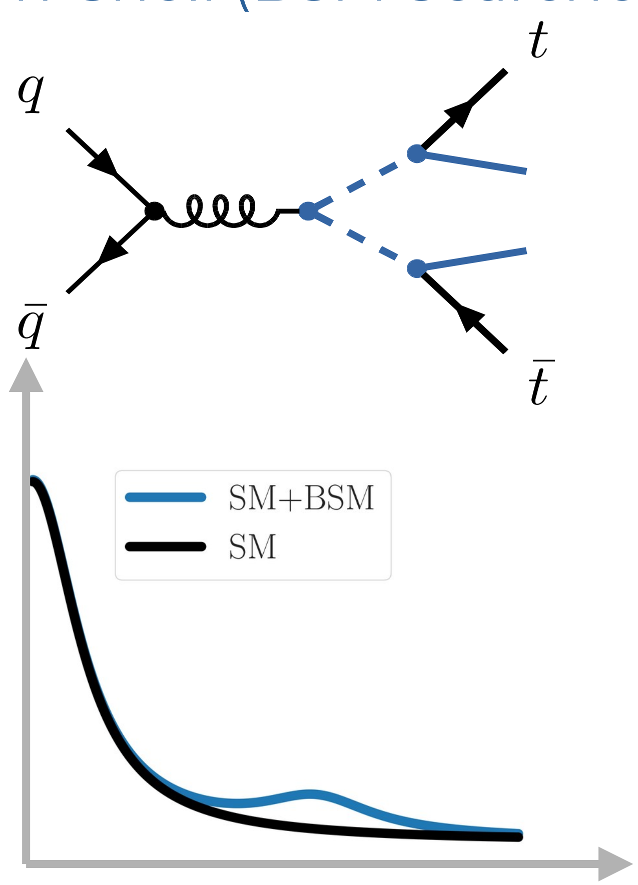

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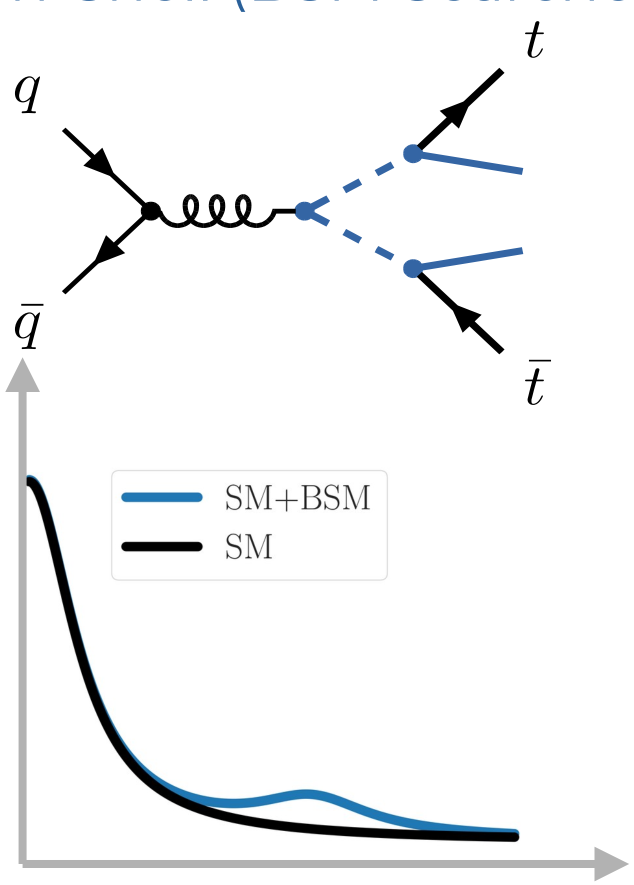


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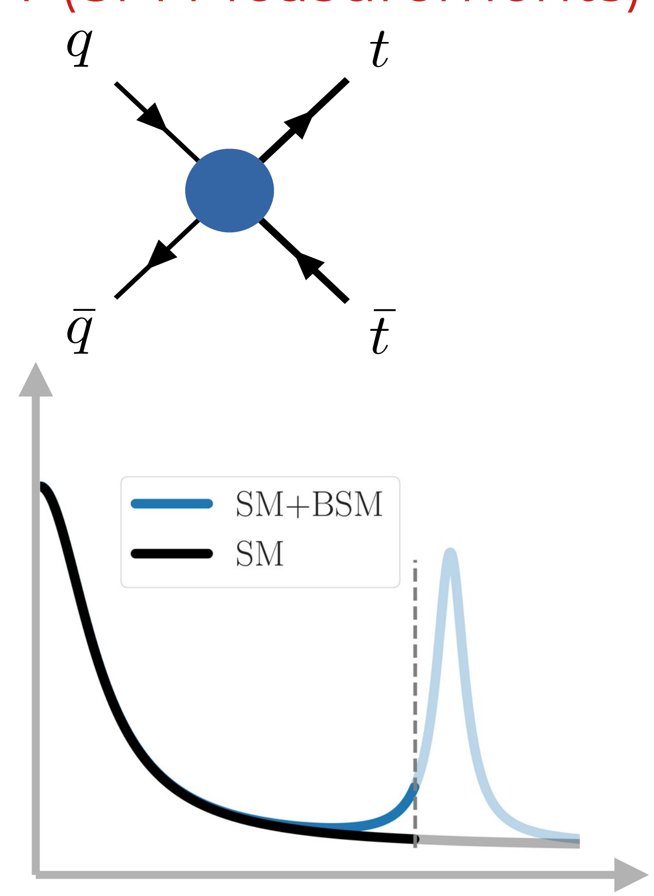

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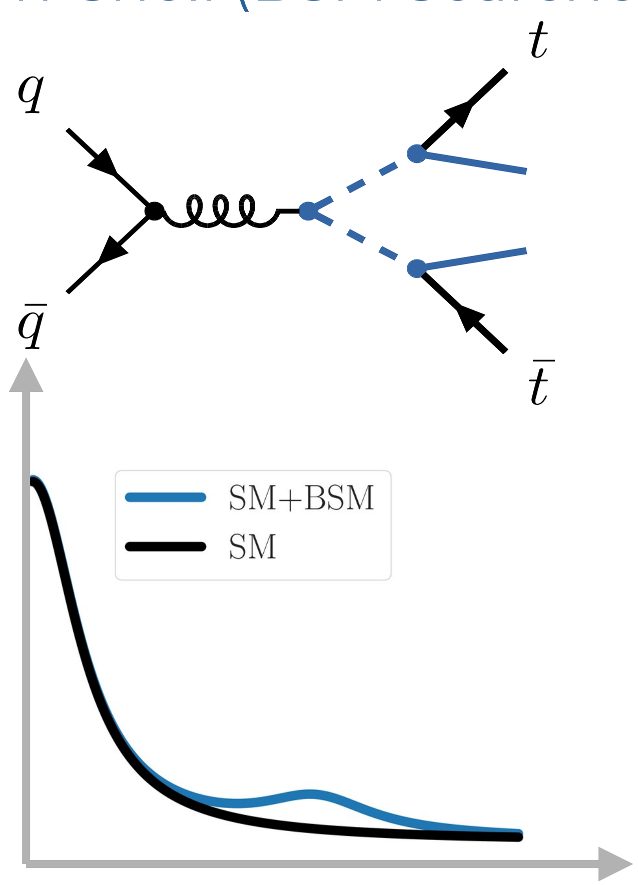


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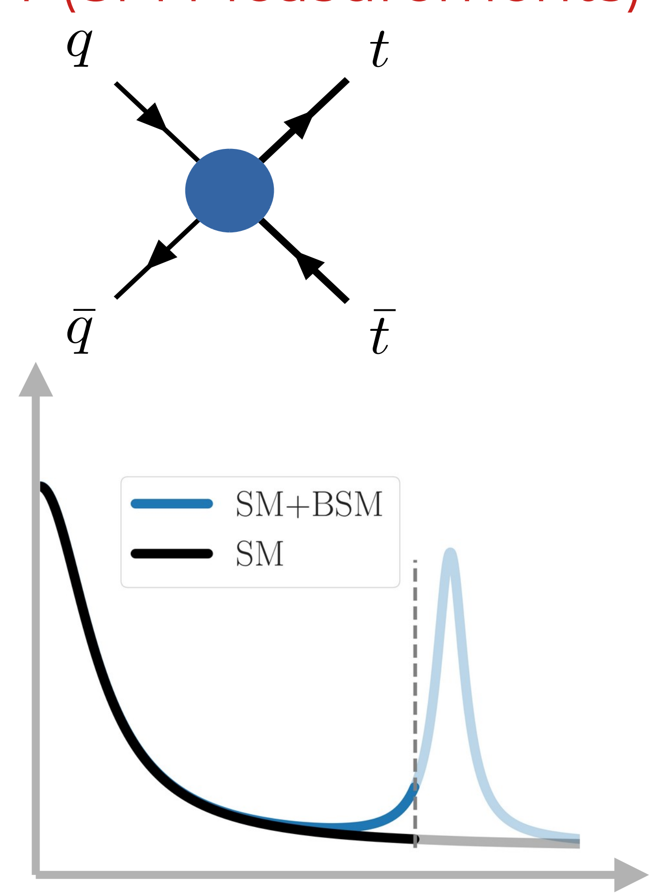

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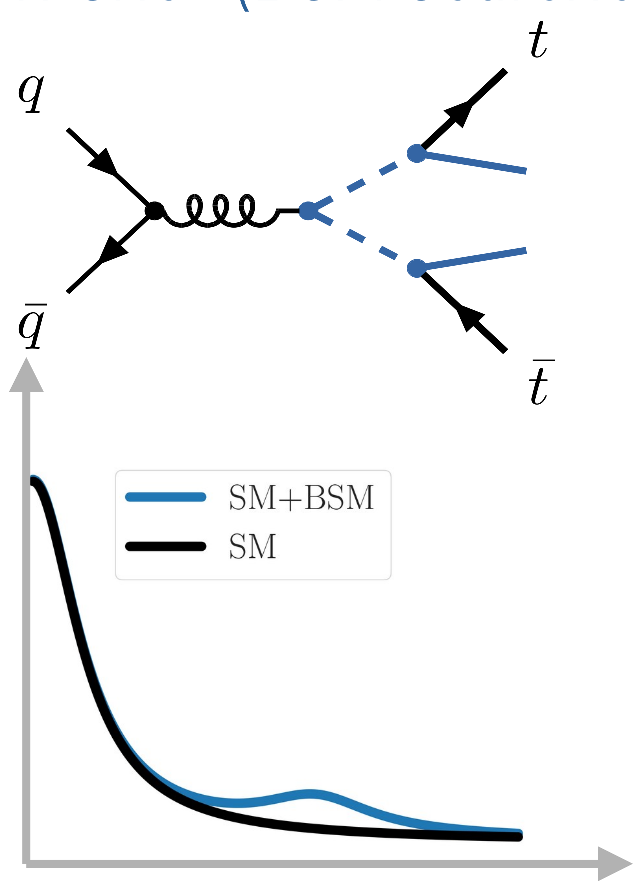


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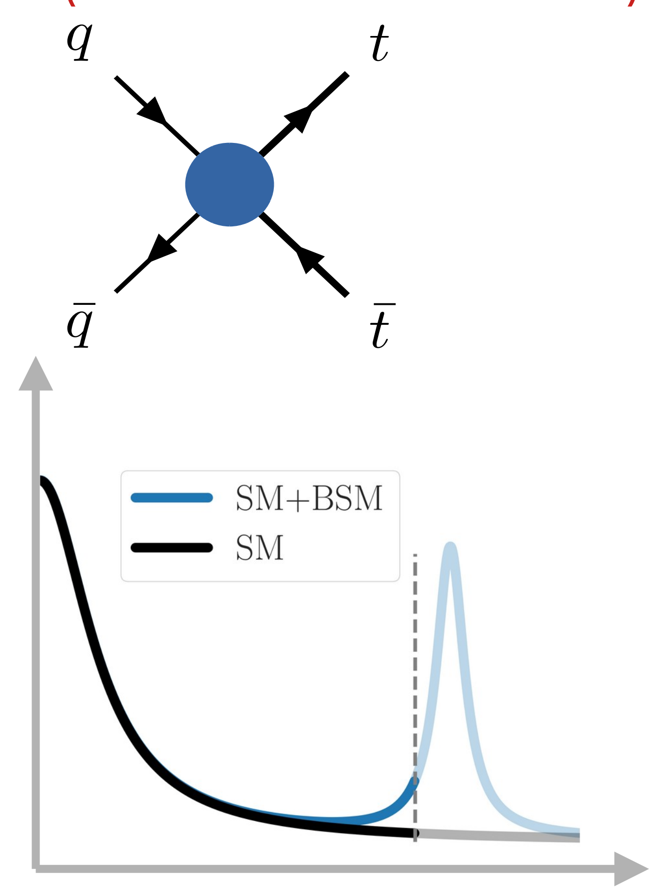

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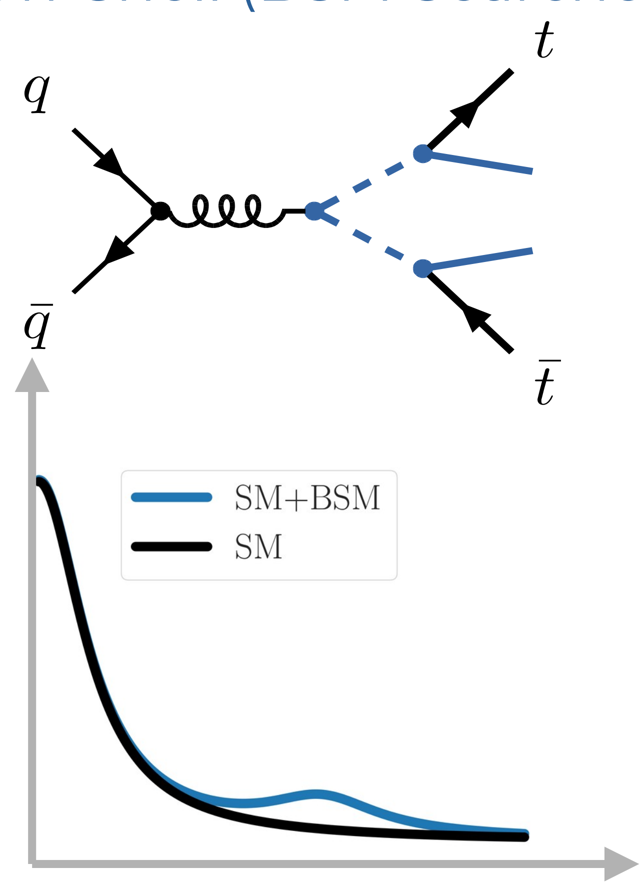


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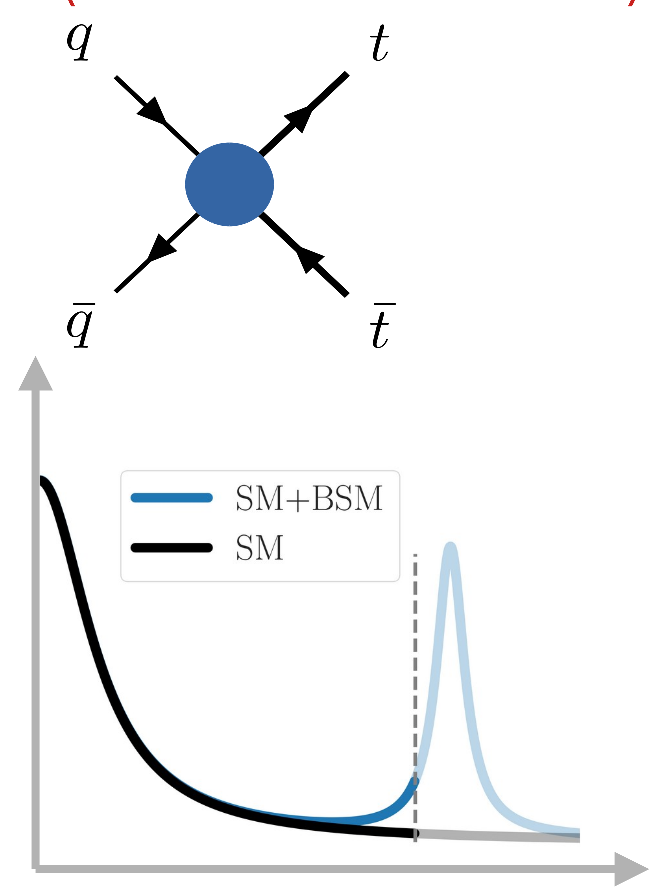

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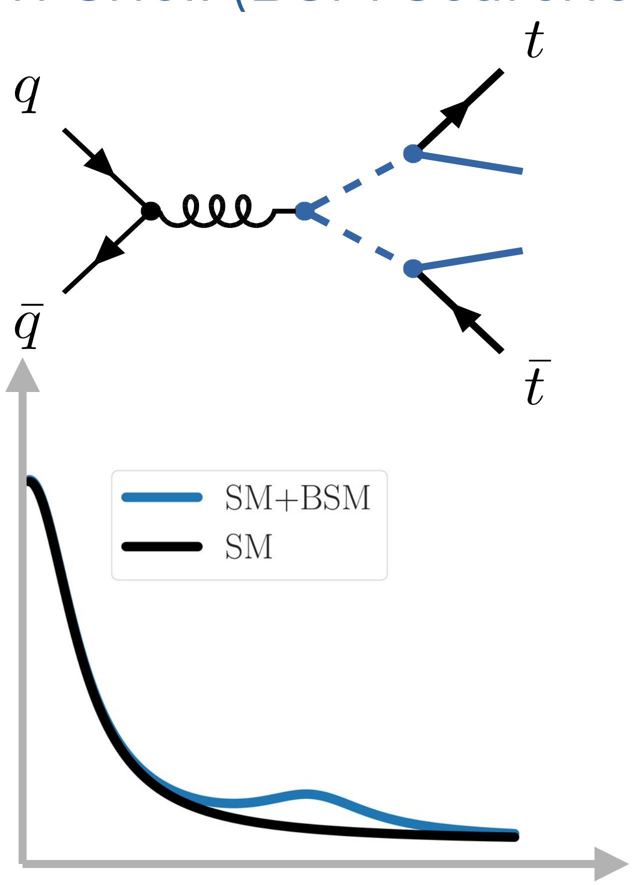


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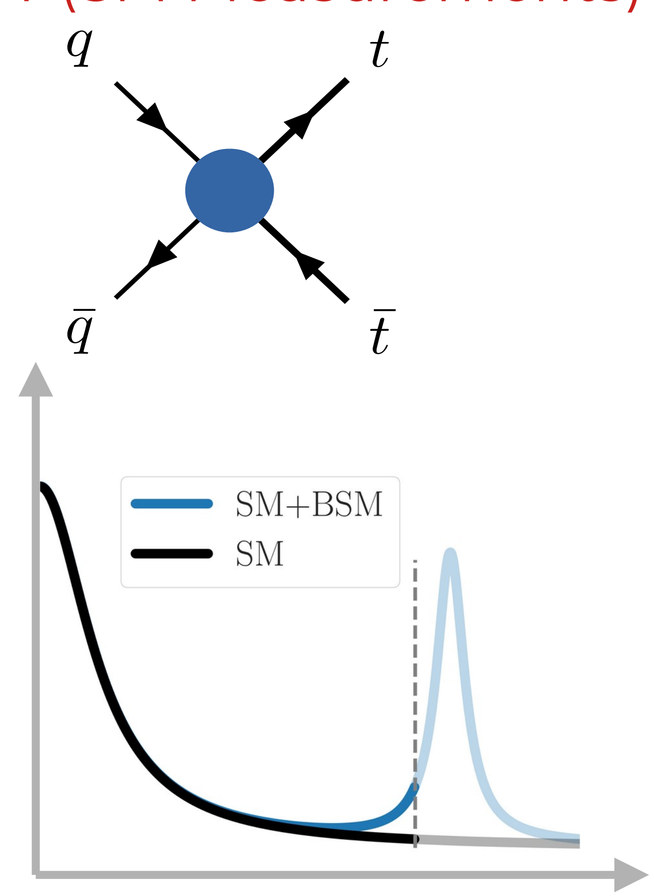

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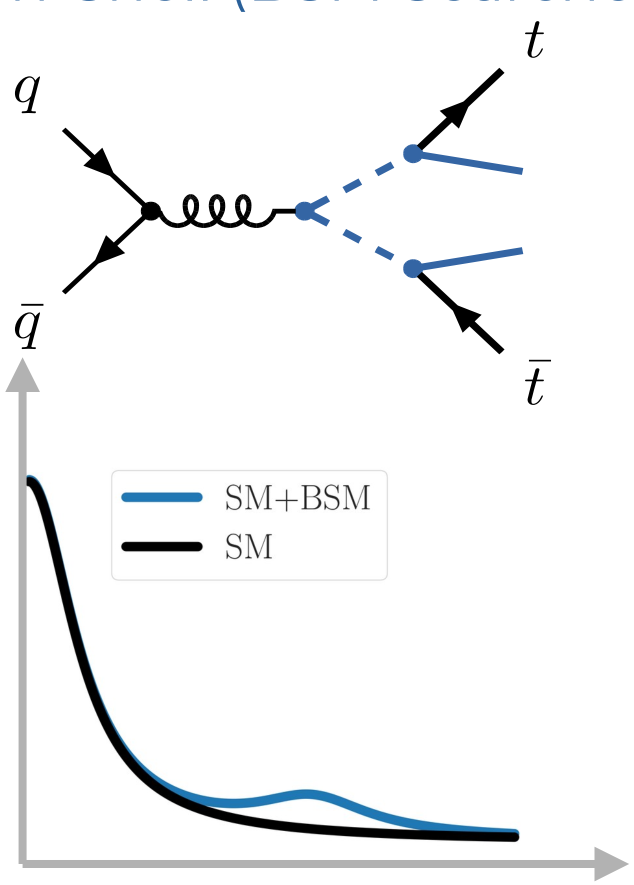


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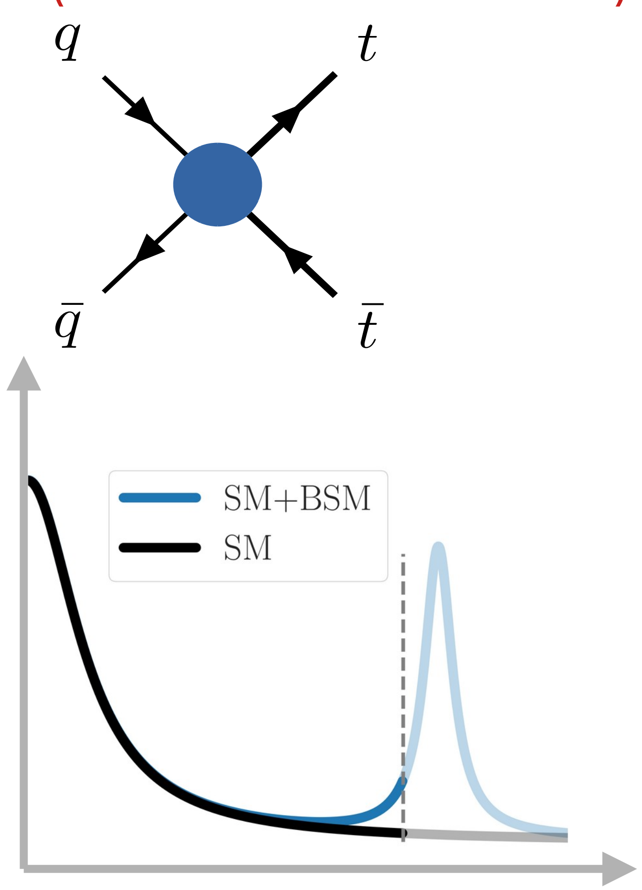

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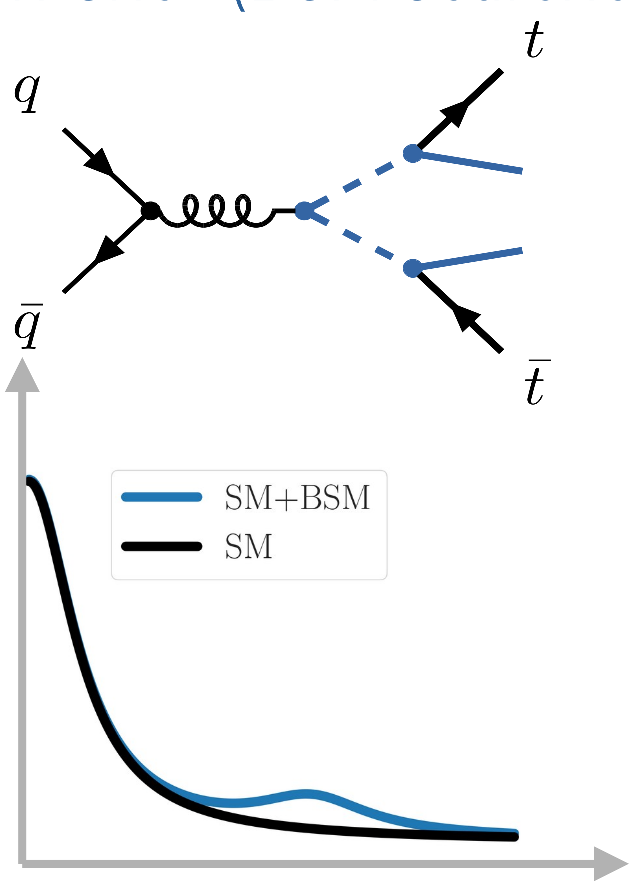


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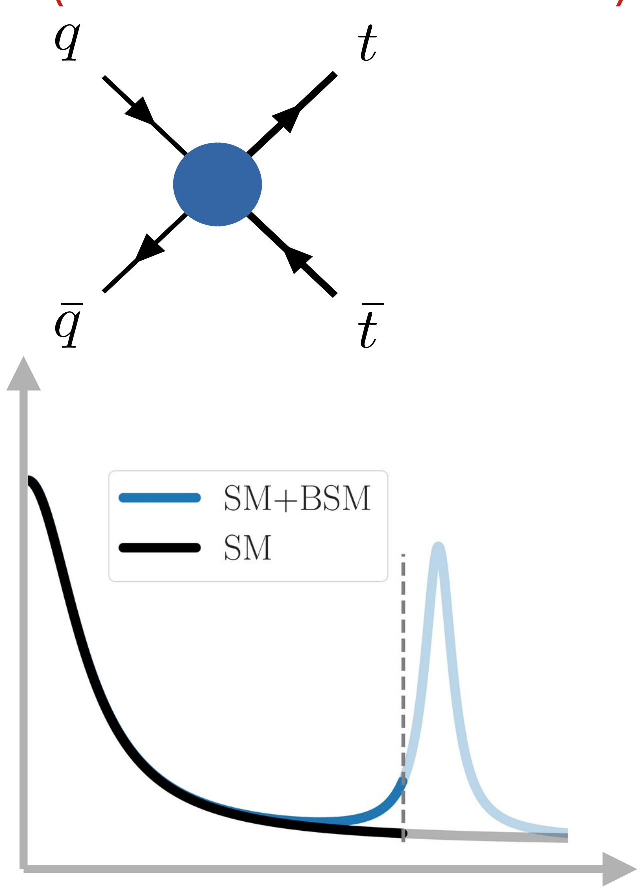


- To answer these questions we need a concrete UV model→ **MSSM**

From the MSSM

to the SMEFT

# MSSM

- The Minimal Supersymmetric SM (MSSM) has many interesting properties:
  - Stabilizes the EW scale
  - Dark Matter candidate
  - Predicts the Higgs mass
  - Almost all the interactions are fixed by the SM gauge and Yukawa couplings, ...

| spin 0 | spin 1/2 |
|---|---|
| $\tilde{q} = (\tilde{u}_L, \tilde{d}_L)$<br>$\tilde{u}^\dagger$<br>$\tilde{d}^\dagger$ | $q = (u_L, d_L)$<br>$u^c$<br>$d^c$ |
| $\tilde{\ell} = (\tilde{\nu}_L, \tilde{e}_L)$<br>$\tilde{e}^\dagger$ | $\ell = (\nu_L, e_L)$<br>$e^c$ |
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- **R-odd** and **R-even** fields
- **Higgs Sector**: Type-II 2HDM

# MSSM to SMEFT

- If the BSM fields are sufficiently heavy, their impact at low energies can be parametrized by the SM Effective Field Theory (SMEFT):

$$\mathcal{L}_{\text{MSSM}}(m_{\tilde{q}}, ...) \Rightarrow \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)}(m_{\tilde{q}}, ...)}{\Lambda^2} O_i^{(6)} + \mathcal{O}\left(\Lambda^{-4}\right)$$

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- Mapping Assumptions:

  I. all BSM fields are heavy (but not degenerate) → 31 fields !

  II. we consider up to dim-6 operators

  III. we do not include running between intermediate BSM scales

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$$\mathcal{L}_{\text{MSSM}}(m_{\tilde{q}}, ...) = y_u \bar{u}_R Q_L H_u + y_d \bar{d}_R Q_L H_d + ... \neq Y_u \bar{u}_R Q_L H + Y_d \bar{d}_R Q_L H^c$$

where both doublets acquire VEVs:

$$\langle H_u^0 \rangle \equiv \frac{v_u}{\sqrt{2}} \qquad \langle H_d^0 \rangle \equiv \frac{v_d}{\sqrt{2}} \qquad \tan\beta = \frac{v_u}{v_d} \qquad v^2 \equiv v_u^2 + v_d^2 = (246 \text{ GeV})^2$$

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- How to integrate out the heavy degrees of freedom in this case?

# MSSM to SMEFT

- The decoupling limit ($m_\Phi \gg m_H$) leads to alignment, thus making the SM-like Higgs doublet a linear combination of $H_u$ and $H_d$:

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- In this basis it is possible to integrate out the BSM fields:

**MSSM**
(4-component spinors, diagonal Higgs basis)

MATCHETE*
Functional methods (CDE)
→

**SMEFT**
(Warsaw basis)

* a modified version of Matchete was used, which will become public

# From the MSSM to the SMEFT

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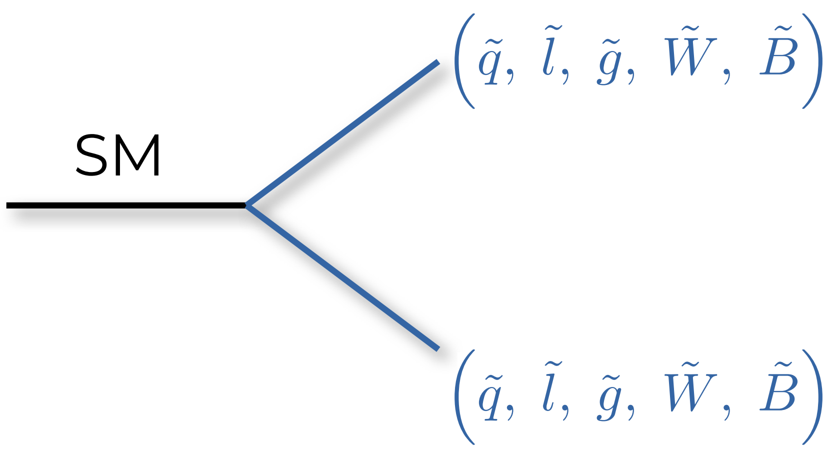

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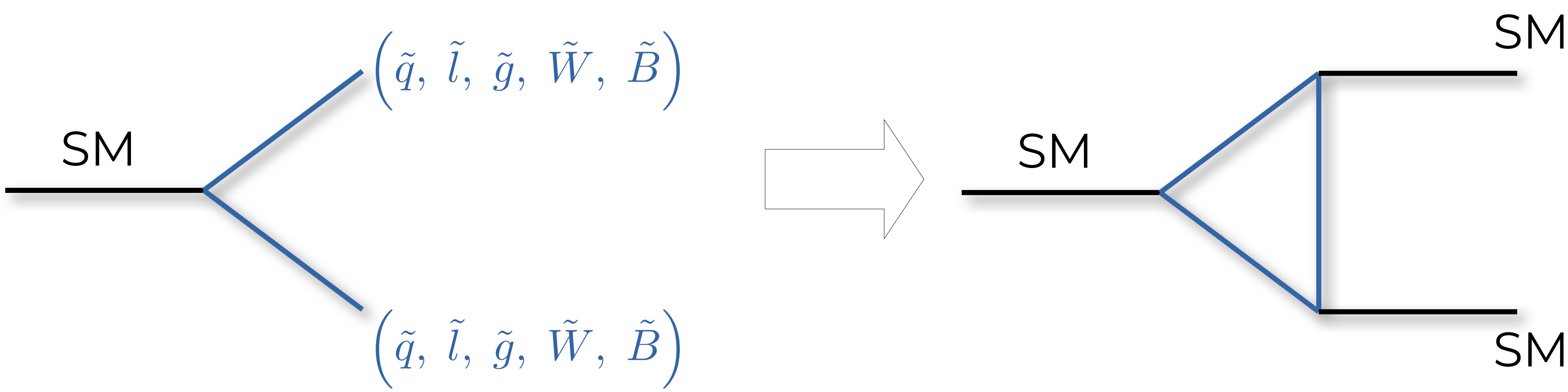


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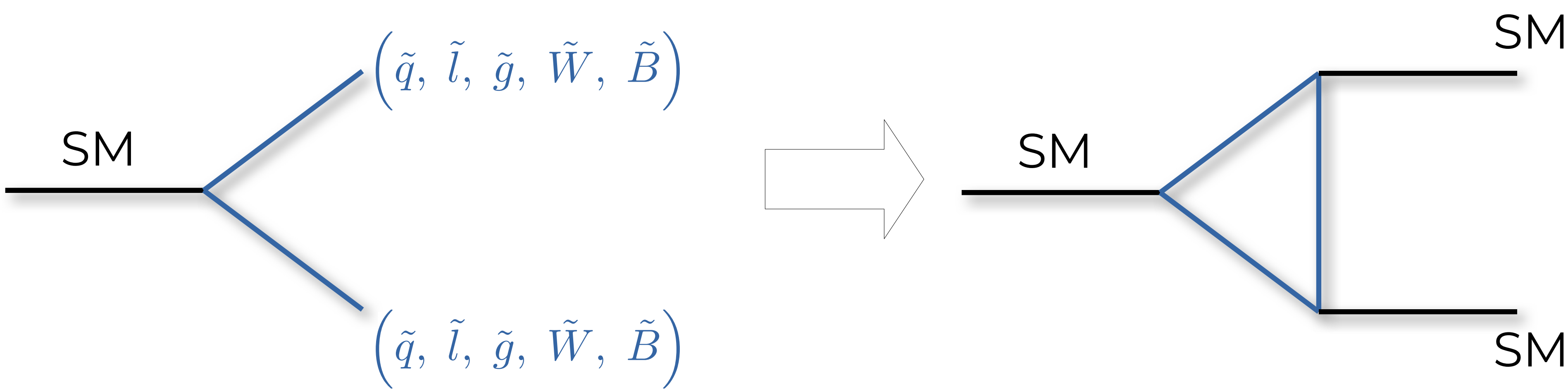


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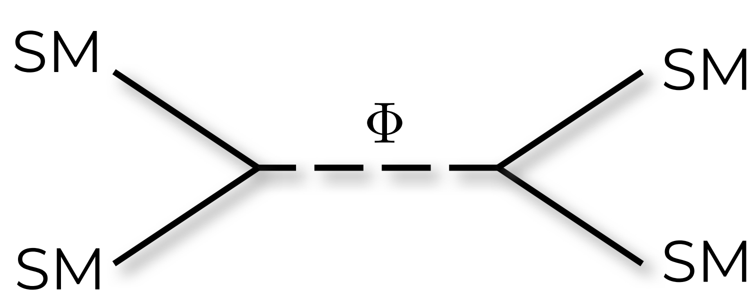

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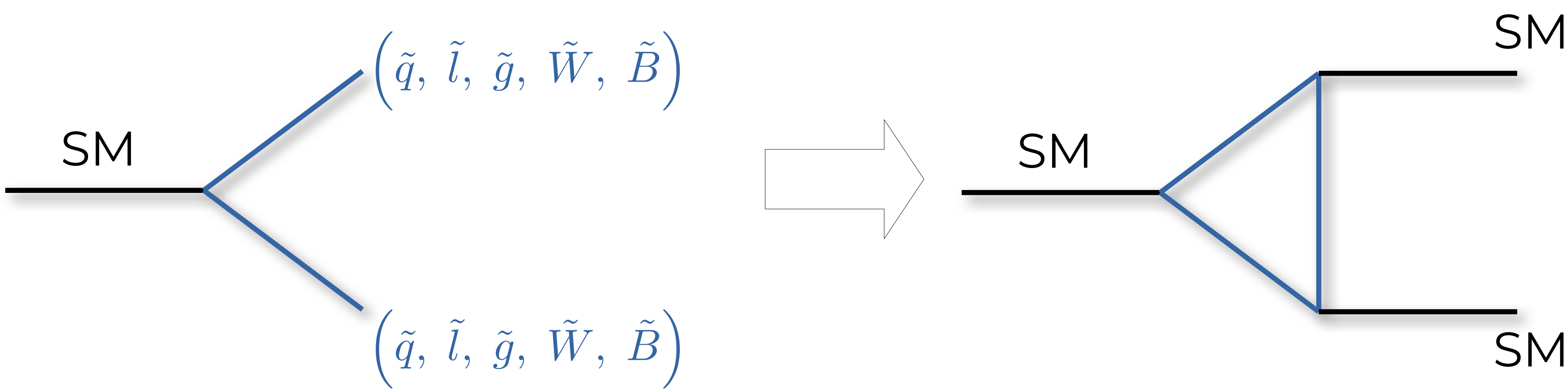


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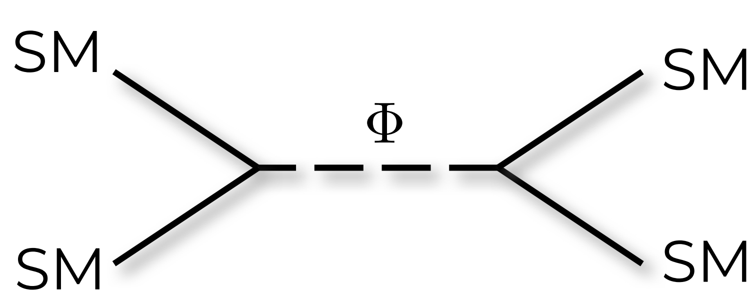


$$C_H = \frac{\sin^2(4\beta)}{m_\Phi^2} \frac{\left(g_1^2 + g_2^2\right)^2}{64} \,,$$

$$C_{qu}^{(1)prst} = \frac{1}{6} C_{qu}^{(8)prst} = -\frac{\cot^2\beta}{6m_\Phi^2} Y_u^{*rs} Y_u^{pt} \,,$$

$$\ldots$$

Fully correlated

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$$C_{HB} \to \hbar \Big( \tfrac{1}{36} \sum_p c_{2\beta} g_1^4 \mathrm{LF}_{3,0}[m_{\tilde{d}}{}^p] - \tfrac{1}{36} \sum_p c_{2\beta} g_1^4 \mathrm{LF}_{4,-1}[m_{\tilde{d}}{}^p] -$$
$$\tfrac{1}{6} g_1^2 c_\beta^2 \overline{y_d}^{pr} y_d^{pr} \mathrm{LF}_{3,0}[m_{\tilde{d}}{}^r] + \tfrac{1}{6} g_1^2 c_\beta^2 \overline{y_d}^{pr} y_d^{pr} \mathrm{LF}_{4,-1}[m_{\tilde{d}}{}^r] +$$
$$\tfrac{1}{4} \sum_p c_{2\beta} g_1^4 \mathrm{LF}_{3,0}[m_{\tilde{e}}{}^p] - \tfrac{1}{4} \sum_p c_{2\beta} g_1^4 \mathrm{LF}_{4,-1}[m_{\tilde{e}}{}^p] - \tfrac{1}{2} g_1^2 c_\beta^2 \overline{y_e}^{pr} y_e^{pr} \mathrm{LF}_{3,0}[m_{\tilde{e}}{}^r] +$$
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$$\tfrac{1}{16} \left(2 g_1^2 c_\beta^2 \overline{y_e}^{pr} y_e^{pr} + \sum_p c_{2\beta} g_1^4\right) \mathrm{LF}_{4,-1}[m_{\tilde{l}}{}^p] +$$
$$\tfrac{1}{144} g_1^2 \left(-6 c_\beta^2 \overline{y_d}^{pr} y_d^{pr} - 6 s_\beta^2 \overline{y_u}^{pr} y_u^{pr} + \sum_p c_{2\beta} g_1^2\right) \mathrm{LF}_{3,0}[m_{\tilde{q}}{}^p] +$$
$$\tfrac{1}{144} g_1^2 \left(6 c_\beta^2 \overline{y_d}^{pr} y_d^{pr} + 6 s_\beta^2 \overline{y_u}^{pr} y_u^{pr} - \sum_p c_{2\beta} g_1^2\right) \mathrm{LF}_{4,-1}[m_{\tilde{q}}{}^p] -$$
$$\tfrac{2}{9} \sum_p c_{2\beta} g_1^4 \mathrm{LF}_{3,0}[m_{\tilde{u}}{}^p] + \tfrac{2}{9} \sum_p c_{2\beta} g_1^4 \mathrm{LF}_{4,-1}[m_{\tilde{u}}{}^p] - \tfrac{2}{3} g_1^2 s_\beta^2 \overline{y_u}^{pr} y_u^{pr} \mathrm{LF}_{3,0}[m_{\tilde{u}}{}^r] +$$
$$\tfrac{2}{3} g_1^2 s_\beta^2 \overline{y_u}^{pr} y_u^{pr} \mathrm{LF}_{4,-1}[m_{\tilde{u}}{}^r] + \tfrac{1}{64} \left(g_1^4 (1 + 3 c_{4\beta}) + 3 g_1^2 g_2^2 (-1 + c_{4\beta})\right) \mathrm{LF}_{3,0}[m_\Phi] -$$
$$\tfrac{1}{64} g_1^2 \left(g_1^2 (1 + 3 c_{4\beta}) + 3 g_2^2 (-1 + c_{4\beta})\right) \mathrm{LF}_{4,-1}[m_\Phi] -$$
$$\tfrac{1}{6} g_1^2 \left(c_\beta \overline{a_d}^{pr} - s_\beta \tilde{\mu} \overline{y_d}^{pr}\right) \left(c_\beta a_d^{pr} - s_\beta \tilde{\mu} y_d^{pr}\right) \mathrm{LF}_{2,2,0}[m_{\tilde{d}}{}^r, m_{\tilde{q}}{}^p] -$$
$$\tfrac{1}{6} g_1^2 \left(c_\beta \overline{a_d}^{pr} - s_\beta \tilde{\mu} \overline{y_d}^{pr}\right) \left(c_\beta a_d^{pr} - s_\beta \tilde{\mu} y_d^{pr}\right) \mathrm{LF}_{3,1,0}[m_{\tilde{d}}{}^r, m_{\tilde{q}}{}^p] +$$
$$\tfrac{1}{6} g_1^2 \left(c_\beta \overline{a_d}^{pr} - s_\beta \tilde{\mu} \overline{y_d}^{pr}\right) \left(c_\beta a_d^{pr} - s_\beta \tilde{\mu} y_d^{pr}\right) \mathrm{LF}_{3,2,-1}[m_{\tilde{d}}{}^r, m_{\tilde{q}}{}^p] +$$
$$\tfrac{1}{6} g_1^2 \left(c_\beta \overline{a_d}^{pr} - s_\beta \tilde{\mu} \overline{y_d}^{pr}\right) \left(c_\beta a_d^{pr} - s_\beta \tilde{\mu} y_d^{pr}\right) \mathrm{LF}_{4,1,-1}[m_{\tilde{d}}{}^r, m_{\tilde{q}}{}^p] -$$
$$\tfrac{1}{2} g_1^2 \left(c_\beta \overline{a_e}^{pr} - s_\beta \tilde{\mu} \overline{y_e}^{pr}\right) \left(c_\beta a_e^{pr} - s_\beta \tilde{\mu} y_e^{pr}\right) \mathrm{LF}_{2,2,0}[m_{\tilde{e}}{}^r, m_{\tilde{l}}{}^p] -$$
$$\tfrac{1}{2} g_1^2 \left(c_\beta \overline{a_e}^{pr} - s_\beta \tilde{\mu} \overline{y_e}^{pr}\right) \left(c_\beta a_e^{pr} - s_\beta \tilde{\mu} y_e^{pr}\right) \mathrm{LF}_{3,1,0}[m_{\tilde{e}}{}^r, m_{\tilde{l}}{}^p] +$$
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$$\tfrac{1}{2} g_1^2 \left(c_\beta \overline{a_e}^{pr} - s_\beta \tilde{\mu} \overline{y_e}^{pr}\right) \left(c_\beta a_e^{pr} - s_\beta \tilde{\mu} y_e^{pr}\right) \mathrm{LF}_{3,2,-1}[m_{\tilde{l}}{}^p, m_{\tilde{e}}{}^r] -$$
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$$\tfrac{1}{4} g_1^2 \left(c_\beta \overline{a_e}^{pr} - s_\beta \tilde{\mu} \overline{y_e}^{pr}\right) \left(c_\beta a_e^{pr} - s_\beta \tilde{\mu} y_e^{pr}\right) \mathrm{LF}_{5,1,-2}[m_{\tilde{l}}{}^p, m_{\tilde{e}}{}^r] +$$
$$\tfrac{1}{3} g_1^2 \left(c_\beta \overline{a_d}^{pr} - s_\beta \tilde{\mu} \overline{y_d}^{pr}\right) \left(c_\beta a_d^{pr} - s_\beta \tilde{\mu} y_d^{pr}\right) \mathrm{LF}_{3,1,0}[m_{\tilde{q}}{}^p, m_{\tilde{d}}{}^r] +$$
$$\tfrac{1}{6} g_1^2 \left(c_\beta \overline{a_d}^{pr} - s_\beta \tilde{\mu} \overline{y_d}^{pr}\right) \left(c_\beta a_d^{pr} - s_\beta \tilde{\mu} y_d^{pr}\right) \mathrm{LF}_{3,2,-1}[m_{\tilde{q}}{}^p, m_{\tilde{d}}{}^r] -$$
$$\tfrac{13}{12} g_1^2 \left(c_\beta \overline{a_d}^{pr} - s_\beta \tilde{\mu} \overline{y_d}^{pr}\right) \left(c_\beta a_d^{pr} - s_\beta \tilde{\mu} y_d^{pr}\right) \mathrm{LF}_{4,1,-1}[m_{\tilde{q}}{}^p, m_{\tilde{d}}{}^r] +$$
$$\tfrac{3}{4} g_1^2 \left(c_\beta \overline{a_d}^{pr} - s_\beta \tilde{\mu} \overline{y_d}^{pr}\right) \left(c_\beta a_d^{pr} - s_\beta \tilde{\mu} y_d^{pr}\right) \mathrm{LF}_{5,1,-2}[m_{\tilde{q}}{}^p, m_{\tilde{d}}{}^r] -$$
$$\tfrac{1}{24} g_1^2 \left(s_\beta \overline{a_u}^{pr} - \tilde{\mu} c_\beta \overline{y_u}^{pr}\right) \left(s_\beta a_u^{pr} - \tilde{\mu} c_\beta y_u^{pr}\right) \mathrm{LF}_{2,2,0}[m_{\tilde{q}}{}^p, m_{\tilde{u}}{}^r] -$$
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$$\tfrac{7}{24} g_1^2 \left(s_\beta \overline{a_u}^{pr} - \tilde{\mu} c_\beta \overline{y_u}^{pr}\right) \left(s_\beta a_u^{pr} - \tilde{\mu} c_\beta y_u^{pr}\right) \mathrm{LF}_{3,1,0}[m_{\tilde{u}}{}^r, m_{\tilde{q}}{}^p] +$$
$$\tfrac{1}{24} g_1^2 \left(s_\beta \overline{a_u}^{pr} - \tilde{\mu} c_\beta \overline{y_u}^{pr}\right) \left(s_\beta a_u^{pr} - \tilde{\mu} c_\beta y_u^{pr}\right) \mathrm{LF}_{3,2,-1}[m_{\tilde{u}}{}^r, m_{\tilde{q}}{}^p] -$$
$$\tfrac{11}{24} g_1^2 \left(s_\beta \overline{a_u}^{pr} - \tilde{\mu} c_\beta \overline{y_u}^{pr}\right) \left(s_\beta a_u^{pr} - \tilde{\mu} c_\beta y_u^{pr}\right) \mathrm{LF}_{4,1,-1}[m_{\tilde{u}}{}^r, m_{\tilde{q}}{}^p] +$$
$$\tfrac{3}{4} g_1^2 \left(s_\beta \overline{a_u}^{pr} - \tilde{\mu} c_\beta \overline{y_u}^{pr}\right) \left(s_\beta a_u^{pr} - \tilde{\mu} c_\beta y_u^{pr}\right) \mathrm{LF}_{5,1,-2}[m_{\tilde{u}}{}^r, m_{\tilde{q}}{}^p] -$$
$$\tfrac{1}{8} g_1^4 \left(c_\beta^2 + s_\beta^2\right) \mathrm{LF}_{3,1,-1}[\tilde{\mu}, m_1] - \tfrac{1}{4} m_1 s_\beta \tilde{\mu} c_\beta g_1^4 \mathrm{LF}_{3,1,0}[\tilde{\mu}, m_1] +$$
$$\tfrac{3}{8} g_1^4 \left(c_\beta^2 + s_\beta^2\right) \mathrm{LF}_{4,1,-2}[\tilde{\mu}, m_1] + \tfrac{1}{2} m_1 s_\beta \tilde{\mu} c_\beta g_1^4 \mathrm{LF}_{4,1,-1}[\tilde{\mu}, m_1] -$$
$$\tfrac{1}{4} g_1^4 \left(c_\beta^2 + s_\beta^2\right) \mathrm{LF}_{5,1,-3}[\tilde{\mu}, m_1] - \tfrac{1}{2} m_1 s_\beta \tilde{\mu} c_\beta g_1^4 \mathrm{LF}_{5,1,-2}[\tilde{\mu}, m_1] -$$
$$\tfrac{3}{8} g_1^2 g_2^2 \left(c_\beta^2 + s_\beta^2\right) \mathrm{LF}_{3,1,-1}[\tilde{\mu}, m_2] - \tfrac{3}{4} m_2 s_\beta \tilde{\mu} c_\beta g_1^2 g_2^2 \mathrm{LF}_{3,1,0}[\tilde{\mu}, m_2] +$$
$$\tfrac{9}{8} g_1^2 g_2^2 \left(c_\beta^2 + s_\beta^2\right) \mathrm{LF}_{4,1,-2}[\tilde{\mu}, m_2] + \tfrac{3}{2} m_2 s_\beta \tilde{\mu} c_\beta g_1^2 g_2^2 \mathrm{LF}_{4,1,-1}[\tilde{\mu}, m_2] -$$
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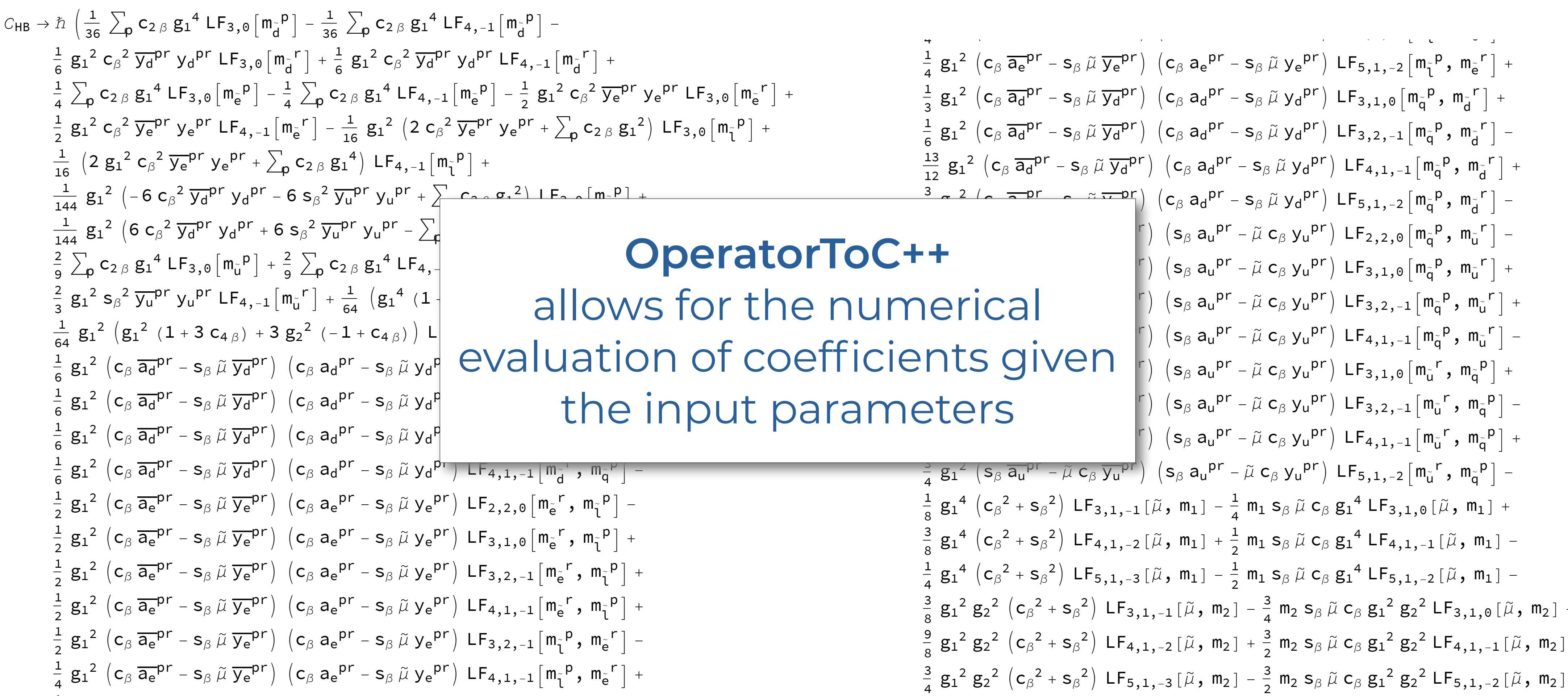
# Matching Results

- Wilson coefficients: $C_W W^{\mu\nu} W^{\nu\rho} W^{\rho\mu} + C_{HB} |H|^2 B_{\mu\nu} B^{\mu\nu} + \ldots$

$$C_W \to \hbar \Big( -\frac{1}{9} g_2^3 \, LF_{3,0}[m_2] + \frac{4}{15} g_2^3 \, LF_{5,-2}[m_2] - \frac{1}{18} \sum_p g_2^3 \, LF_{3,0}[m_{\tilde{l}}{}^p] + \frac{1}{8} \sum_p g_2^3 \, LF_{4,-1}[m_{\tilde{l}}{}^p] - \frac{1}{15} \sum_p g_2^3 \, LF_{5,-2}[m_{\tilde{l}}{}^p] - \frac{1}{6} \sum_p g_2^3 \, LF_{3,0}[m_{\tilde{q}}{}^p] + \frac{3}{8} \sum_p g_2^3 \, LF_{4,-1}[m_{\tilde{q}}{}^p] - \frac{1}{5} \sum_p g_2^3 \, LF_{5,-2}[m_{\tilde{q}}{}^p] - \frac{1}{18} g_2^3 \, LF_{3,0}[m_\Phi] + \frac{1}{8} g_2^3 \, LF_{4,-1}[m_\Phi] - \frac{1}{15} g_2^3 \, LF_{5,-2}[m_\Phi] - \frac{1}{18} g_2^3 \, LF_{3,0}[\tilde{\mu}] + \frac{2}{15} g_2^3 \, LF_{5,-2}[\tilde{\mu}] \Big)$$



**OperatorToC++**
allows for the numerical evaluation of coefficients given the input parameters

# Stop-Bino case

- "Light" Stop-Bino case: $v \ll m_{\tilde{t}_R},\ m_1 \ll m_{\rm SUSY}$

$$\mathcal{L}_{BSM} \to \frac{1}{2}\bar{\tilde{B}}\left(i\gamma^\mu\partial_\mu - m_1\right)\tilde{B} + |D_\mu\tilde{t}|^2 - m^2_{\tilde{t}_R}|\tilde{t}|^2 - \left(\frac{2\sqrt{2}}{3}g_1\tilde{t}^\dagger\bar{\tilde{B}}t_R + h.c.\right)$$

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- SMEFT Lagrangian: only 8 (out of 22) WCs are LI!

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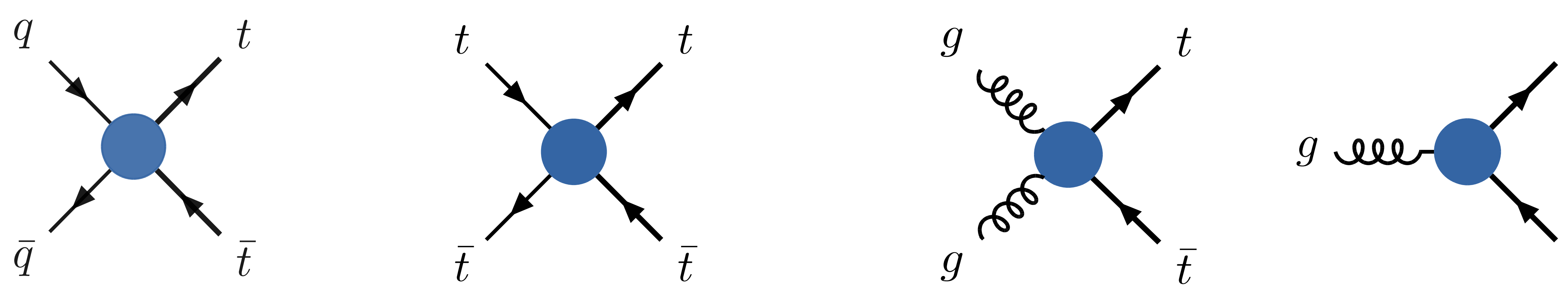
$$\begin{aligned}\mathcal{L}_{\rm SMEFT} = {} & C^{33}_{uG}\left(\bar{t}\sigma^{\mu\nu}T^At\right)\left(\epsilon\varphi^* G^A_{\mu\nu}\right) + C_G f^{ABC}G^{A\nu}_\mu\, G^{B\rho}_\nu\, G^{C\mu}_\rho \\ & + C^{(8)3311}_{qu}(\bar{t}_L\gamma^\mu T^A t_L)\left(\bar{Q}\gamma_\mu T^A Q\right) + C^{(8)1133}_{qu}(\bar{t}_R\gamma_\mu T^A t_R)\left(\bar{Q}\gamma_\mu T^A Q + \bar{t}_L\gamma_\mu T^A t_L\right) \\ & + 4C^{(1)3333}_{qq}(\bar{t}_L\gamma_\mu t_L)(\bar{t}_L\gamma_\mu t_L) + C^{3333}_{uu}(\bar{t}_R\gamma_\mu t_R)(\bar{t}_R\gamma_\mu t_R) \\ & + \frac{1}{4}C^{(1)3311}_{qd}(\bar{t}_L\gamma^\mu t_L)\left(4\bar{d}_R\gamma_\mu d_R - 2\bar{Q}_L\gamma_\mu Q_L + 3\bar{t}_L\gamma_\mu t_L\right) \\ & + C^{(1)1133}_{qu}(\bar{t}_R\gamma^\mu t_R)\left(4\bar{u}_R\gamma_\mu u_R - 2\bar{d}_R\gamma_\mu d_R + \bar{Q}_L\gamma_\mu Q_L\right) + \ldots\end{aligned}$$



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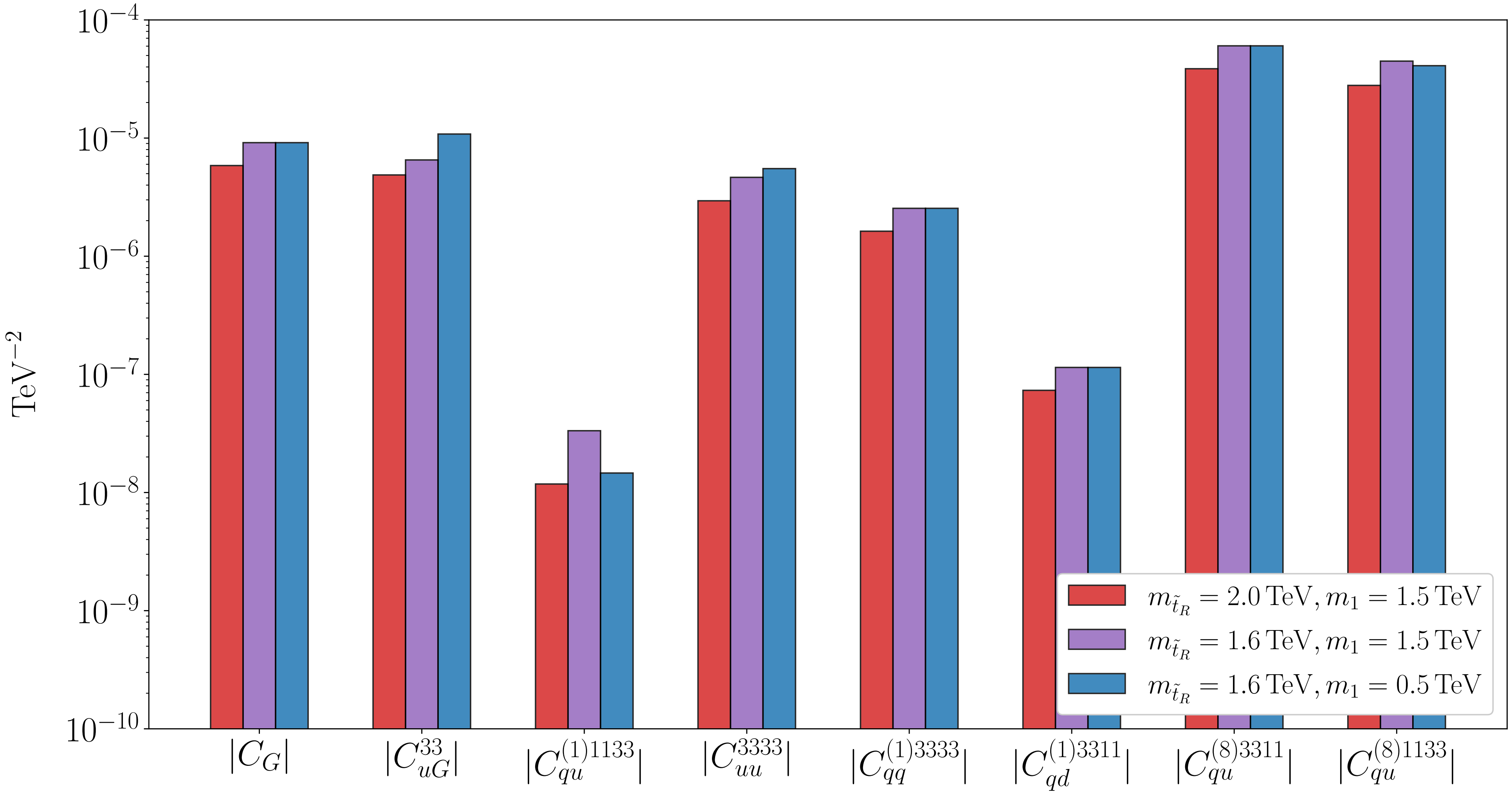
- Preliminary results:



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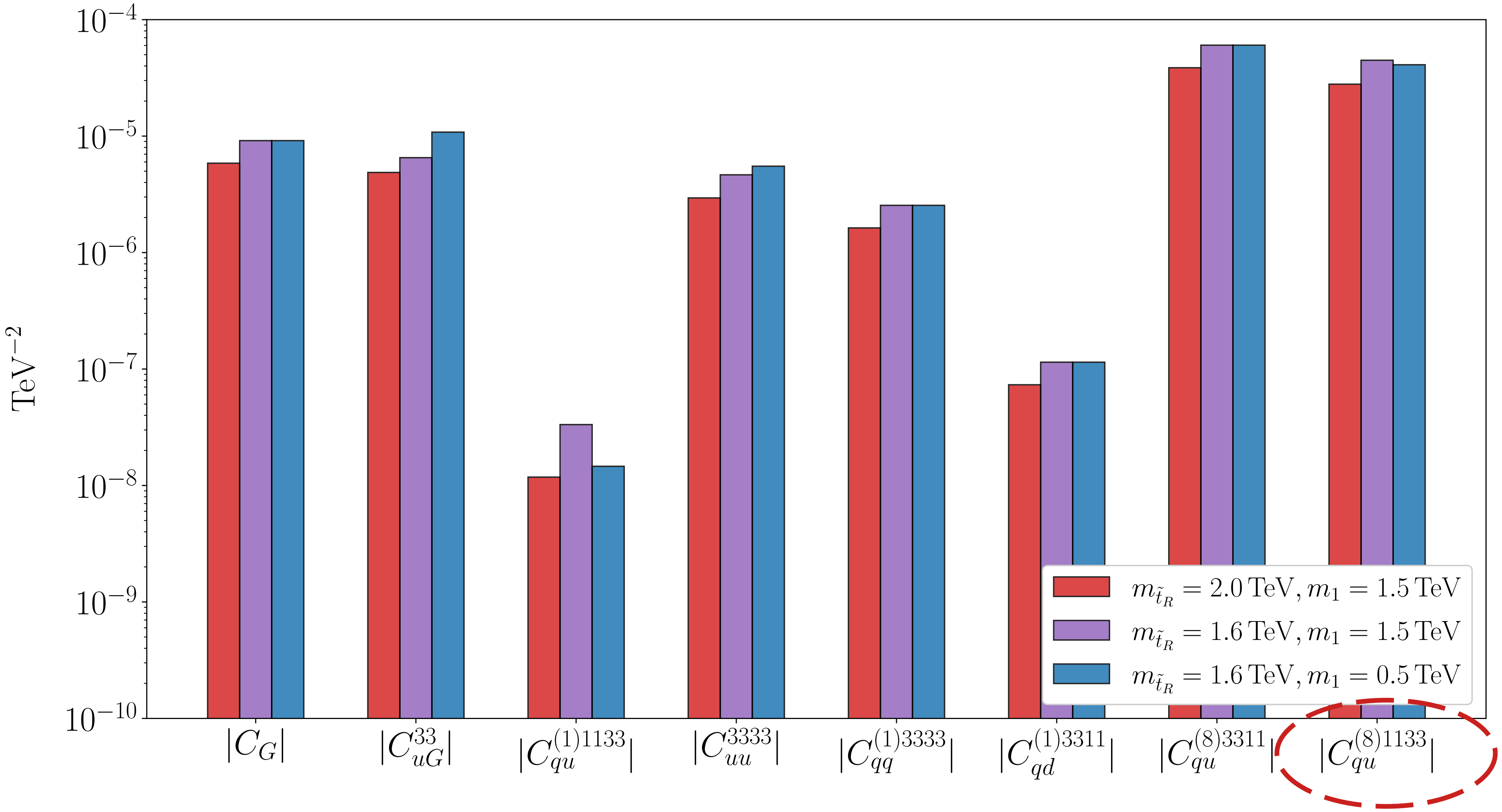

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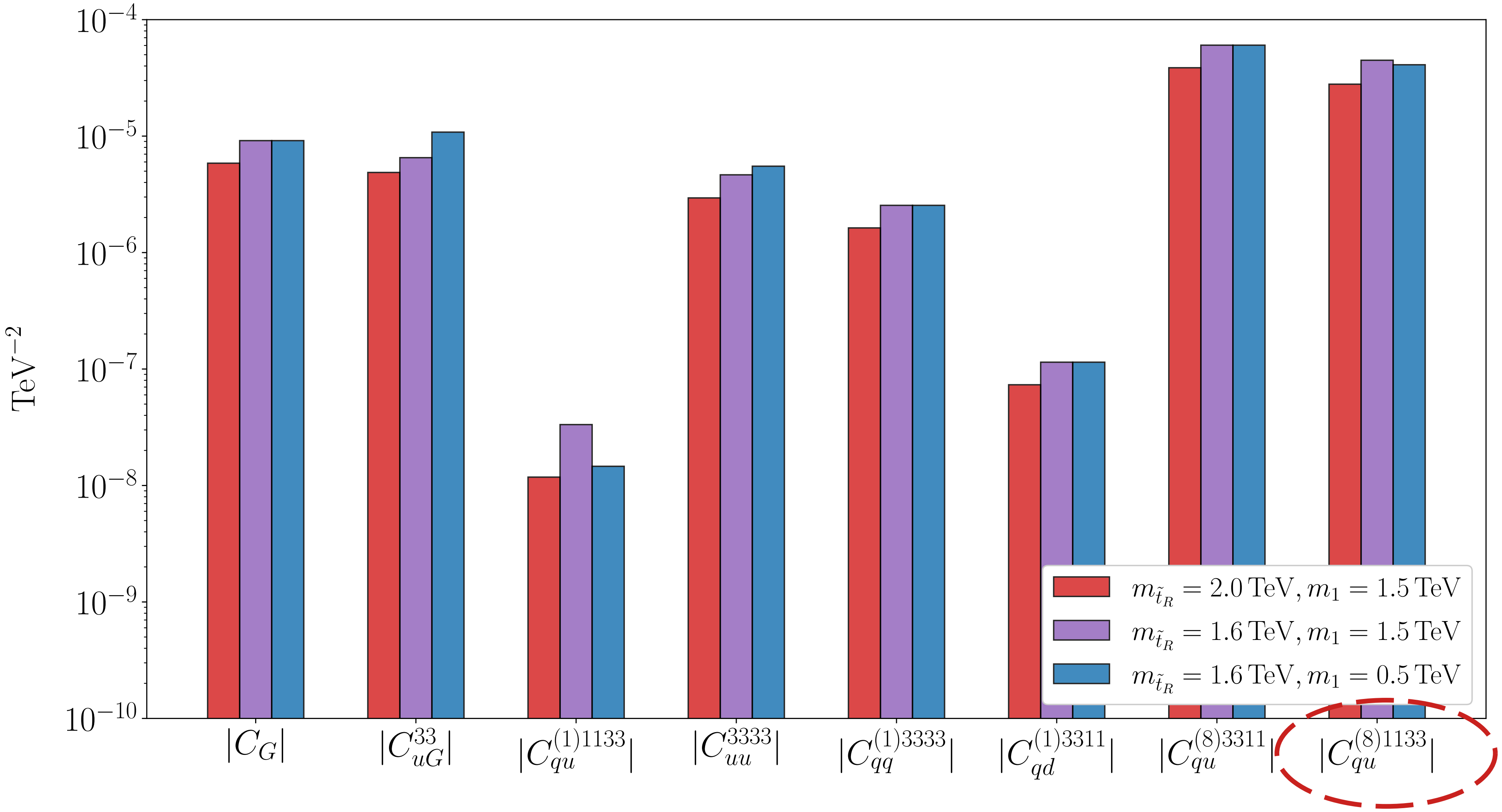


$$C_{qu}^{(8)1133} = -\frac{g_s^4}{960\pi^2}\frac{1}{m_{\tilde{t}_R}^2} + \frac{g_s^2}{576\pi^2}\frac{8g_1^2}{9}\frac{1}{m_{\tilde{t}_R}^2}\frac{1}{(1-x)^4}\left[2 - 9x + 18x^2 - 11x^3 + 6x^3\log(x)\right]$$

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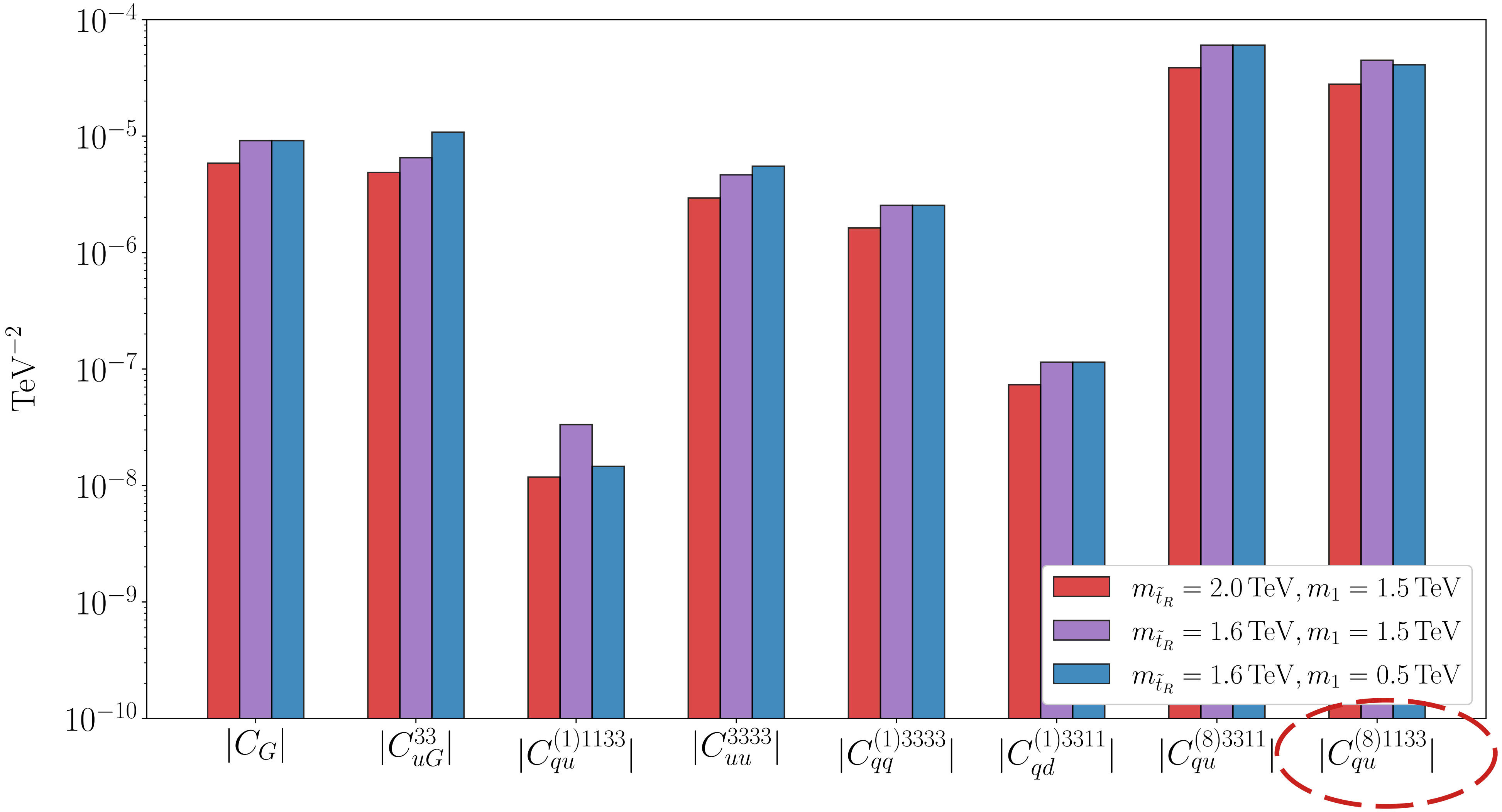


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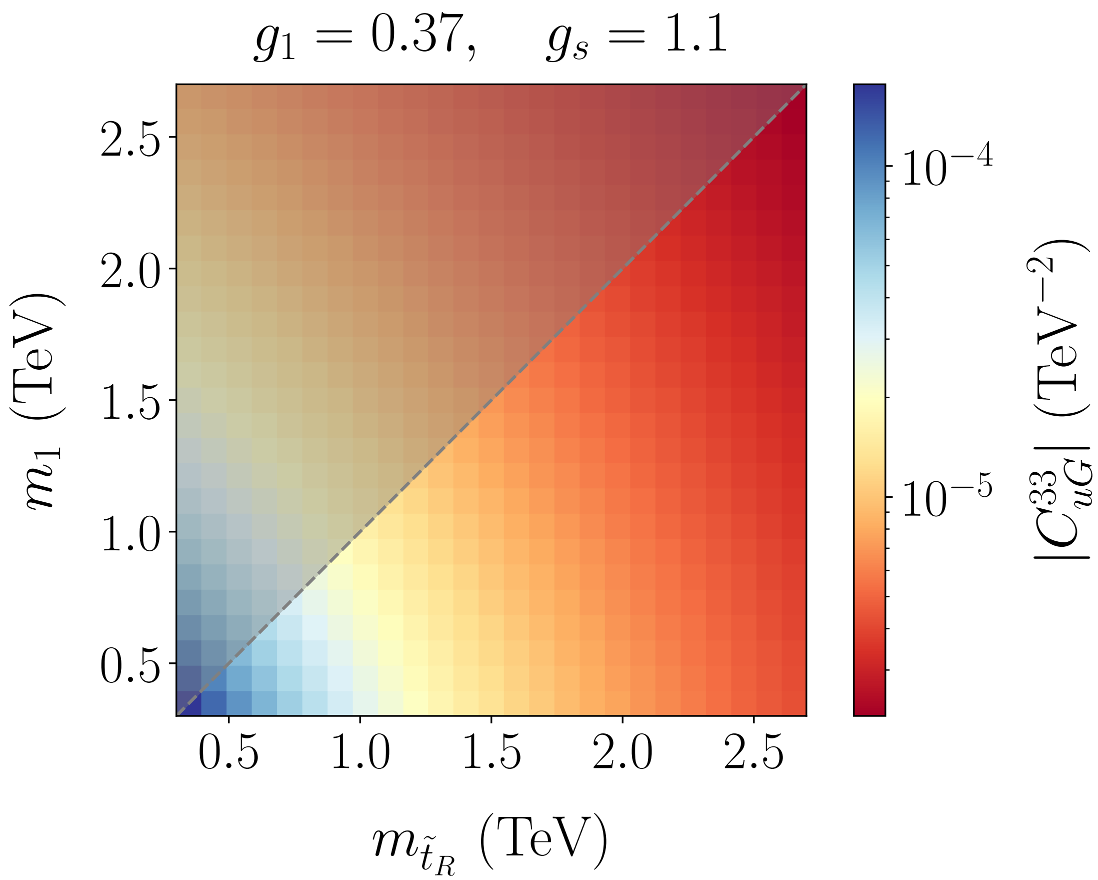

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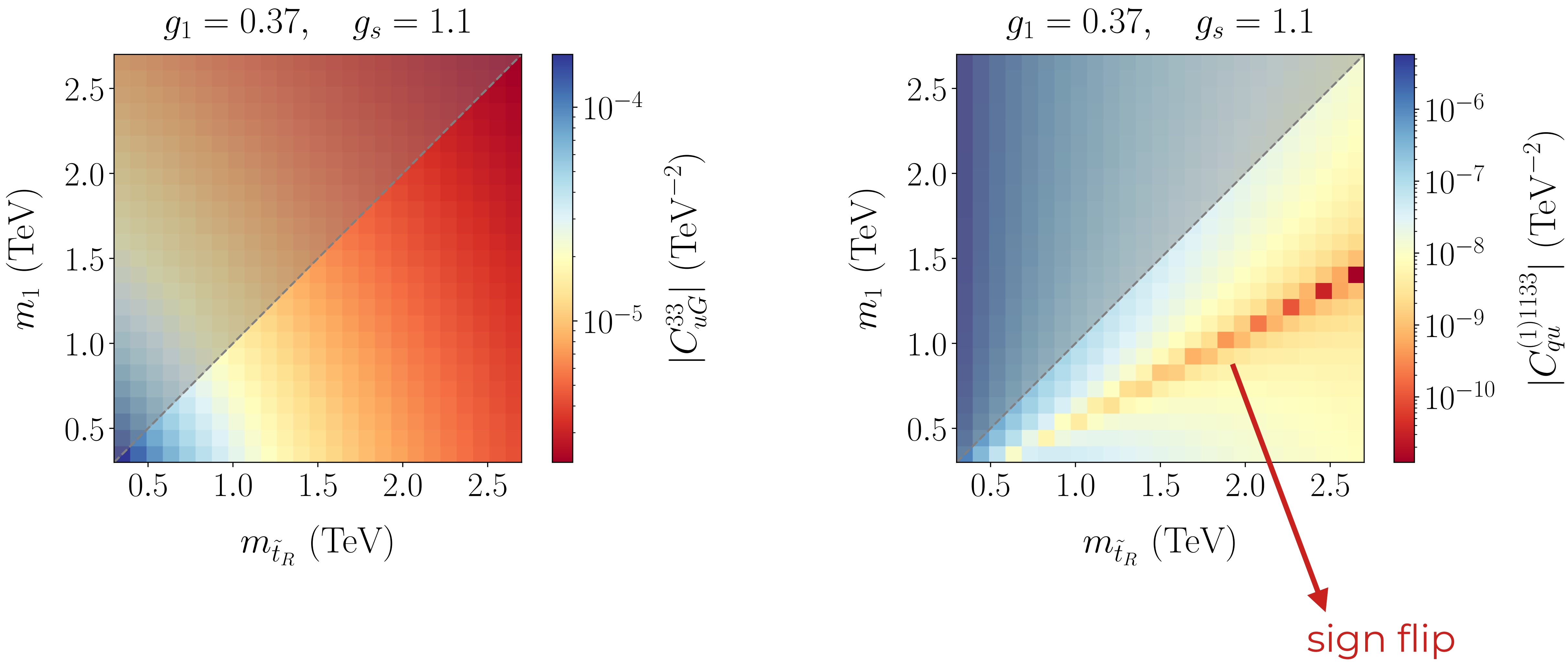

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**Thanks!**

# Backup

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matching scale

$$g_1^{\text{SMEFT}} = g_1^{\text{MSSM}} - \frac{g_1^3}{16\pi^2}\left\{\sum_p\left[\frac{1}{36}\log\frac{\bar{\mu}^2}{(m^p_{\tilde{q}})^2} + \frac{2}{9}\log\frac{\bar{\mu}^2}{(m^p_{\tilde{u}})^2} + \frac{1}{18}\log\frac{\bar{\mu}^2}{(m^p_{\tilde{d}})^2} + \frac{1}{12}\log\frac{\bar{\mu}^2}{(m^p_{\tilde{\ell}})^2} + \frac{1}{6}\log\frac{\bar{\mu}^2}{(m^p_{\tilde{e}})^2}\right] + \frac{1}{12}\log\frac{\bar{\mu}^2}{m^2_\Phi} + \frac{1}{3}\log\frac{\bar{\mu}^2}{\tilde{\mu}^2}\right\}$$

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  - Higgs quartic:

$$\lambda(\bar{\mu}) = c_{2\gamma}^2\,\frac{g_1^2(\bar{\mu}) + g_2^2(\bar{\mu})}{4} + \frac{1}{16\pi^2}\Delta_\lambda(\bar{\mu})$$

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Large logs if there is a large hierarchy in the BSM sector (requires RGE running)

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$$\lambda(\bar\mu) = c_{2\gamma}^2\,\frac{g_1^2(\bar\mu)+g_2^2(\bar\mu)}{4} + \frac{1}{16\pi^2}\,\Delta_\lambda(\bar\mu)$$

  - Yukawa couplings:

$$Y_u^{pr}(\bar\mu) = s_\gamma\, {y_u}^{pr}(\bar\mu) + \frac{1}{16\pi^2}\,\Delta_{Y_u}(\bar\mu)$$

$$Y_{d,e}^{pr}(\bar\mu) = c_\gamma\, y_{d,e}^{pr}(\bar\mu) + \frac{1}{16\pi^2}\,\Delta_{Y_{d,e}}(\bar\mu)$$

# Matching Results

- Dim-4 matching conditions (threshold corrections)
  - Gauge couplings:

matching scale

$$g_1^{\mathrm{SMEFT}} = g_1^{\mathrm{MSSM}} - \frac{g_1^3}{16\pi^2}\left\{\sum_p \left[\frac{1}{36}\log\frac{\bar{\mu}^2}{(m_{\tilde{q}}^p)^2} + \frac{2}{9}\log\frac{\bar{\mu}^2}{(m_{\tilde{u}}^p)^2} + \frac{1}{18}\log\frac{\bar{\mu}^2}{(m_{\tilde{d}}^p)^2} + \frac{1}{12}\log\frac{\bar{\mu}^2}{(m_{\tilde{\ell}}^p)^2} + \frac{1}{6}\log\frac{\bar{\mu}^2}{(m_{\tilde{e}}^p)^2}\right] + \frac{1}{12}\log\frac{\bar{\mu}^2}{m_\Phi^2} + \frac{1}{3}\log\frac{\bar{\mu}^2}{\tilde{\mu}^2}\right\}$$

$$g_2^{\mathrm{SMEFT}} = g_2^{\mathrm{MSSM}} + \ldots,\ g_3^{\mathrm{SMEFT}} = g_3^{\mathrm{MSSM}} + \ldots$$

Large logs if there is a large hierarchy in the BSM sector (requires RGE running)

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$$Y_{d,e}^{pr}(\bar{\mu}) = c_\gamma\, y_{d,e}^{pr}(\bar{\mu}) + \frac{1}{16\pi^2}\Delta_{Y_{d,e}}(\bar{\mu})$$

Input variables:

$v,\ Y_u,\ Y_d,\ g_i^{\mathrm{SMEFT}}$ (EW scale)

+ MSSM parameters (UV scale)

# Matching Results

- Higgs mass:

$$\mathrm{m}_{h^0}^2 = \lambda v^2 \left(1 - \frac{3v^2}{\lambda} C_H\right)$$
$$= \cos^2(2\gamma)\mathrm{m}_Z^2 \left[1 - 3\sin^2(2\gamma)\frac{\mathrm{m}_Z^2}{m_\Phi^2} \; + \; \text{loop corrections}\right]$$

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$$

  - This is the well-known result that at tree level the Higgs mass is smaller than $m_Z$
  - Large loop corrections are needed to achieve $m_h$ = 125 GeV

# Warsaw Basis

1–4: Bosonic Operators

| 1: $X^3$ | | 2: $H^6$ | | 4: $X^2H^2$ | | | |
|---|---|---|---|---|---|---|---|
| $Q_G$ | $\frac{1}{g_3^3} f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_H$ | $(H^\dagger H)^3$ | $Q_{HG}$ | $\frac{1}{g_3^2}(H^\dagger H) G^A_{\mu\nu} G^{A\mu\nu}$ | $Q_{HB}$ | $\frac{1}{g_1^2}(H^\dagger H) B_{\mu\nu} B^{\mu\nu}$ |
| $Q_{\tilde{G}}$ | $\frac{1}{g_3^3} f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | 3: $H^4D^2$ | | $Q_{H\tilde{G}}$ | $\frac{1}{g_3^2}(H^\dagger H) \tilde{G}^A_{\mu\nu} G^{A\mu\nu}$ | $Q_{H\tilde{B}}$ | $\frac{1}{g_1^2}(H^\dagger H) \tilde{B}_{\mu\nu} B^{\mu\nu}$ |
| $Q_W$ | $\frac{1}{g_2^3} \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{H\Box}$ | $(H^\dagger H)\Box(H^\dagger H)$ | $Q_{HW}$ | $\frac{1}{g_2^2}(H^\dagger H) W^I_{\mu\nu} W^{I\mu\nu}$ | $Q_{HWB}$ | $\frac{1}{g_2 g_1}(H^\dagger \tau^I H) W^I_{\mu\nu} B^{\mu\nu}$ |
| $Q_{\tilde{W}}$ | $\frac{1}{g_2^3} \varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{HD}$ | $(H^\dagger D_\mu H)^* (H^\dagger D^\mu H)$ | $Q_{H\tilde{W}}$ | $\frac{1}{g_2^2}(H^\dagger H) \tilde{W}^I_{\mu\nu} W^{I\mu\nu}$ | $Q_{H\tilde{W}B}$ | $\frac{1}{g_2 g_1}(H^\dagger \tau^I H) \tilde{W}^I_{\mu\nu} B^{\mu\nu}$ |

5–7: Fermion Bilinears ($\psi^2$)

| non-Hermitian ($\bar{L}R$) | | | | | | | |
|---|---|---|---|---|---|---|---|
| 5: $\psi^2 H^3$ + H.c. | | 6: $\psi^2 XH$ + H.c. | | | | | |
| $Q_{eH}$ | $(H^\dagger H)(\bar{\ell}_p e_r H)$ | $Q_{eW}$ | $\frac{1}{g_2}(\bar{\ell}_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$ | $Q_{uG}$ | $\frac{1}{g_3}(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\tilde{H} G^A_{\mu\nu}$ | $Q_{dG}$ | $\frac{1}{g_3}(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H G^A_{\mu\nu}$ |
| $Q_{uH}$ | $(H^\dagger H)(\bar{q}_p u_r \tilde{H})$ | $Q_{eB}$ | $\frac{1}{g_1}(\bar{\ell}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$ | $Q_{uW}$ | $\frac{1}{g_2}(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \tilde{H} W^I_{\mu\nu}$ | $Q_{dW}$ | $\frac{1}{g_2}(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H W^I_{\mu\nu}$ |
| $Q_{dH}$ | $(H^\dagger H)(\bar{q}_p d_r H)$ | | | $Q_{uB}$ | $\frac{1}{g_1}(\bar{q}_p \sigma^{\mu\nu} u_r)\tilde{H} B_{\mu\nu}$ | $Q_{dB}$ | $\frac{1}{g_1}(\bar{q}_p \sigma^{\mu\nu} d_r) H B_{\mu\nu}$ |

7: $\psi^2 H^2 D$ – Hermitian + $Q_{Hud}$

| $(\bar{L}L)$ | | $(\bar{R}R)$ | | $(\bar{R}R')$ + H.c. | |
|---|---|---|---|---|---|
| $Q_{Hl}^{(1)}$ | $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\ell}_p \gamma^\mu \ell_r)$ | $Q_{He}$ | $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$ | $Q_{Hud}$ | $i(\tilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$ |
| $Q_{Hl}^{(3)}$ | $(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{\ell}_p \tau^I \gamma^\mu \ell_r)$ | $Q_{Hu}$ | $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$ | | |
| $Q_{Hq}^{(1)}$ | $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$ | $Q_{Hd}$ | $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$ | | |
| $Q_{Hq}^{(3)}$ | $(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$ | | | | |

8: Fermion Quadrilinears ($\psi^4$)

| Hermitian | | | | | | non-Hermitian | |
|---|---|---|---|---|---|---|---|
| $(\bar{L}L)(\bar{L}L)$ | | $(\bar{R}R)(\bar{R}R)$ | | $(\bar{L}L)(\bar{R}R)$ | | $(\bar{L}R)(\bar{L}R)$ + H.c. | |
| $Q_{ll}$ | $(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{\ell}_s \gamma^\mu \ell_t)$ | $Q_{ee}$ | $(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$ | $Q_{le}$ | $(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{e}_s \gamma^\mu e_t)$ | $Q_{quqd}^{(1)}$ | $(\bar{q}_p^i u_r)\varepsilon_{ij}(\bar{q}_s^j d_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{u}_s \gamma^\mu u_t)$ | $Q_{quqd}^{(8)}$ | $(\bar{q}_p^i T^A u_r)\varepsilon_{ij}(\bar{q}_s^j T^A d_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$ | $Q_{dd}$ | $(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{d}_s \gamma^\mu d_t)$ | $Q_{lequ}^{(1)}$ | $(\bar{\ell}_p^i e_r)\varepsilon_{ij}(\bar{q}_s^j u_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{q}_s \gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$ | $Q_{lequ}^{(3)}$ | $(\bar{\ell}_p^i \sigma_{\mu\nu} e_r)\varepsilon_{ij}(\bar{q}_s^j \sigma^{\mu\nu} u_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar{\ell}_p \gamma_\mu \tau^I \ell_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$ | $Q_{ed}$ | $(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$ | | |
| | | $Q_{ud}^{(1)}$ | $(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$ | | |
| | | $Q_{ud}^{(8)}$ | $(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$ | $(\bar{L}R)(\bar{R}L)$ + H.c. | |
| | | | | $Q_{qd}^{(8)}$ | $(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$ | $Q_{ledq}$ | $(\bar{\ell}_p^i e_r)(\bar{d}_s q_{ti})$ |

# MSSM to SMEFT

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- Why not simply consider the general (model-independent) SMEFT framework?

# MSSM to SMEFT

- Why not simply consider the general (model-independent) SMEFT framework?
  - Many free parameters! (~2,500 @ dim-6)
  - The coefficients induced by a full BSM model can be strongly correlated
  - The BSM effects can be enhanced or suppressed with respect to single parameter fits
  - It allows for a direct comparison with on-shell searches

# MSSM to SMEFT

- Two approaches:

1) Consider the full MSSM, compute the physical masses *after* EWSB and only then integrate the fields → mapping to HEFT

$$V_{h^0}^{\mathrm{HEFT}} = \left(h^0\right)^2 \cos^2(2\beta)\,\frac{g_1^2+g_2^2}{8}\,v^2\left[1-\sin^2(2\beta)\,\frac{g_1^2+g_2^2}{4}\,\frac{v^2}{m_\Phi^2}\right]$$
$$+\left(h^0\right)^3 \cos^2(2\beta)\,\frac{g_1^2+g_2^2}{8}\,v\left[1-3\sin^2(2\beta)\,\frac{g_1^2+g_2^2}{4}\,\frac{v^2}{m_\Phi^2}\right]$$
$$+\left(h^0\right)^4 \cos^2(2\beta)\,\frac{g_1^2+g_2^2}{32}\left[1-13\sin^2(2\beta)\,\frac{g_1^2+g_2^2}{4}\,\frac{v^2}{m_\Phi^2}\right]$$
$$-\left(h^0\right)^5\, 3\sin^2(4\beta)\,\frac{\left(g_1^2+g_2^2\right)^2}{256}\,\frac{v}{m_\Phi^2}$$
$$-\left(h^0\right)^6 \sin^2(4\beta)\,\frac{\left(g_1^2+g_2^2\right)^2}{512}\,\frac{1}{m_\Phi^2}\,,$$

2) Integrate out the heavy scalars *before* EWSB → mapping to SMEFT

$$V_{\mathrm{Higgs}}^{\mathrm{SMEFT}} = M_H^2|H|^2 + \frac{\lambda}{2}|H|^4 - C_H|H|^6$$

$$\lambda = \cos^2(2\gamma)\,\frac{g_1^2+g_2^2}{4}$$

$$C_H = \frac{\sin^2(4\gamma)}{m_\Phi^2}\,\frac{\left(g_1^2+g_2^2\right)^2}{64}$$

- Both approaches give the same results up to leading order in the EFT expansion:

$$V_{\mathrm{Higgs}}^{\mathrm{SMEFT}} = V_{h^0}^{\mathrm{HEFT}} + \mathcal{O}(v^4/\Lambda^4)$$

# Stop-Bino case

- "Light" Stop-Bino case: $v \ll m_{\tilde{t}_R},\ m_1 \ll m_{\text{SUSY}}$

$$\mathcal{L}_{BSM} \to \frac{1}{2}\bar{\tilde{B}}\left(i\gamma^{\mu}\partial_{\mu} - m_1\right)\tilde{B} + |D_{\mu}\tilde{t}|^2 - m_{\tilde{t}_R}^2|\tilde{t}|^2 - \left(\frac{2\sqrt{2}}{3}g_1\tilde{t}^{\dagger}\bar{\tilde{B}}t_R + h.c.\right)$$

$m_{\tilde{t}_R},\ m_1$ → Free parameters

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- At the LHC:

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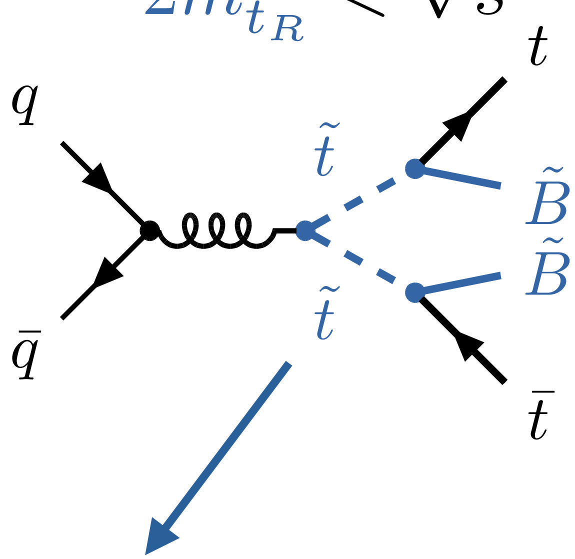
$m_{\tilde{t}_R},\ m_1$ → Free parameters

- At the LHC:

$2m_{\tilde{t}_R} < \sqrt{\hat{s}}$




Direct Searches

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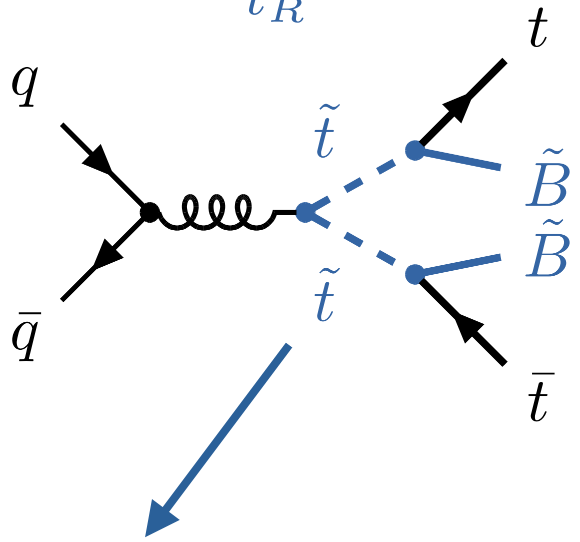
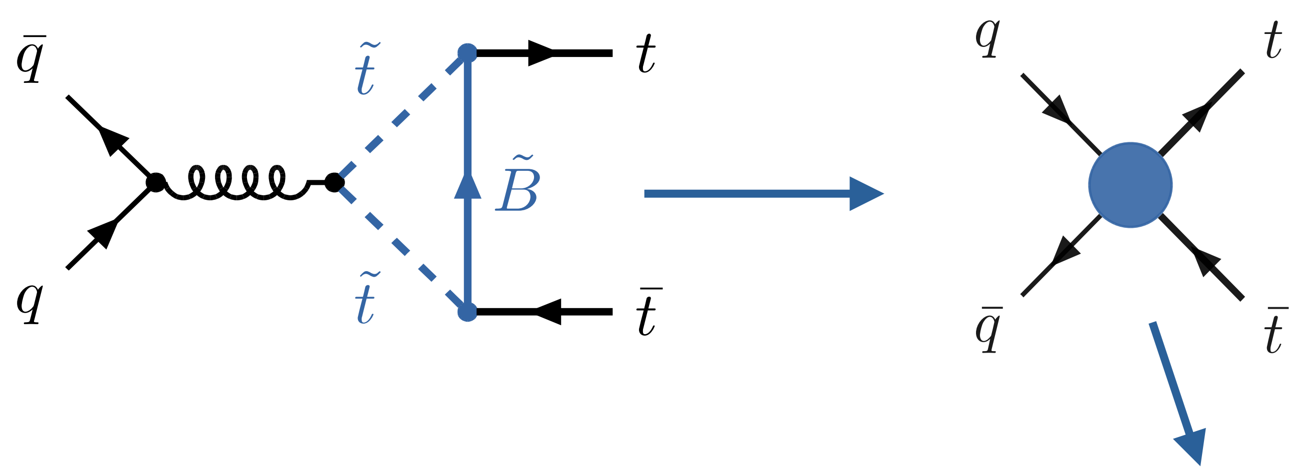



Direct Searches

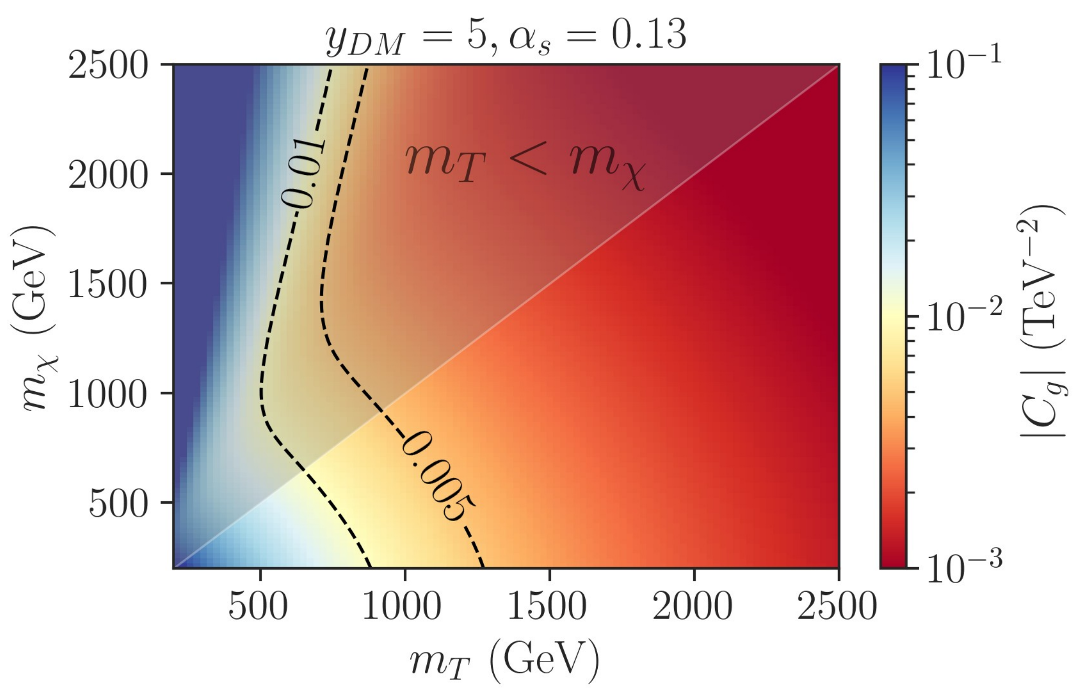
$m_{\tilde{t}_R},\, m_1 \gg \sqrt{\hat{s}}$

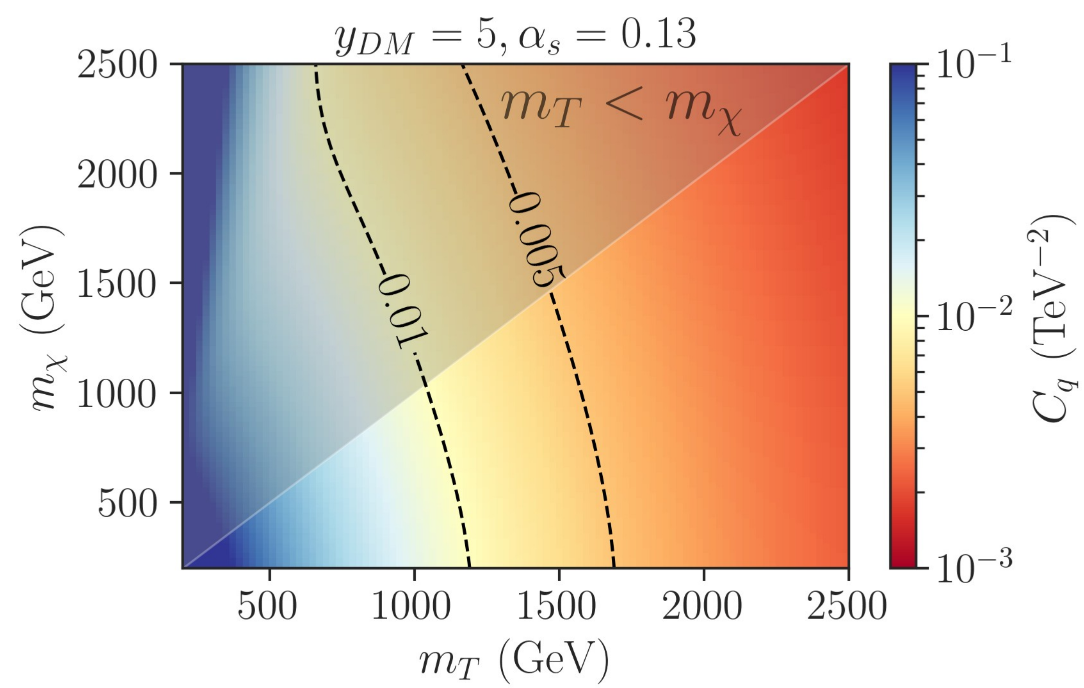



Indirect Searches (EFT)

# EFT Coefficients

- Toy Model:



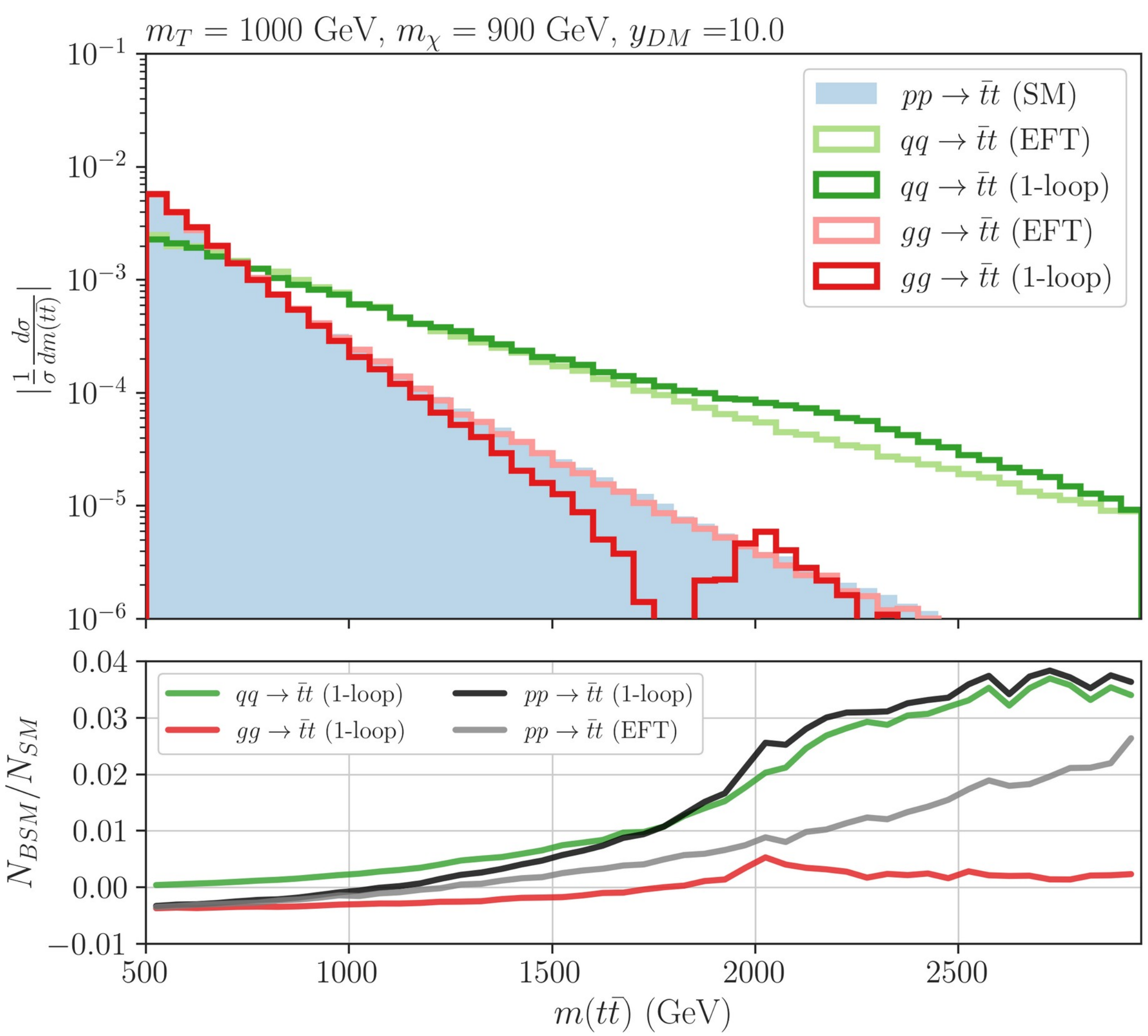

- Constraints:

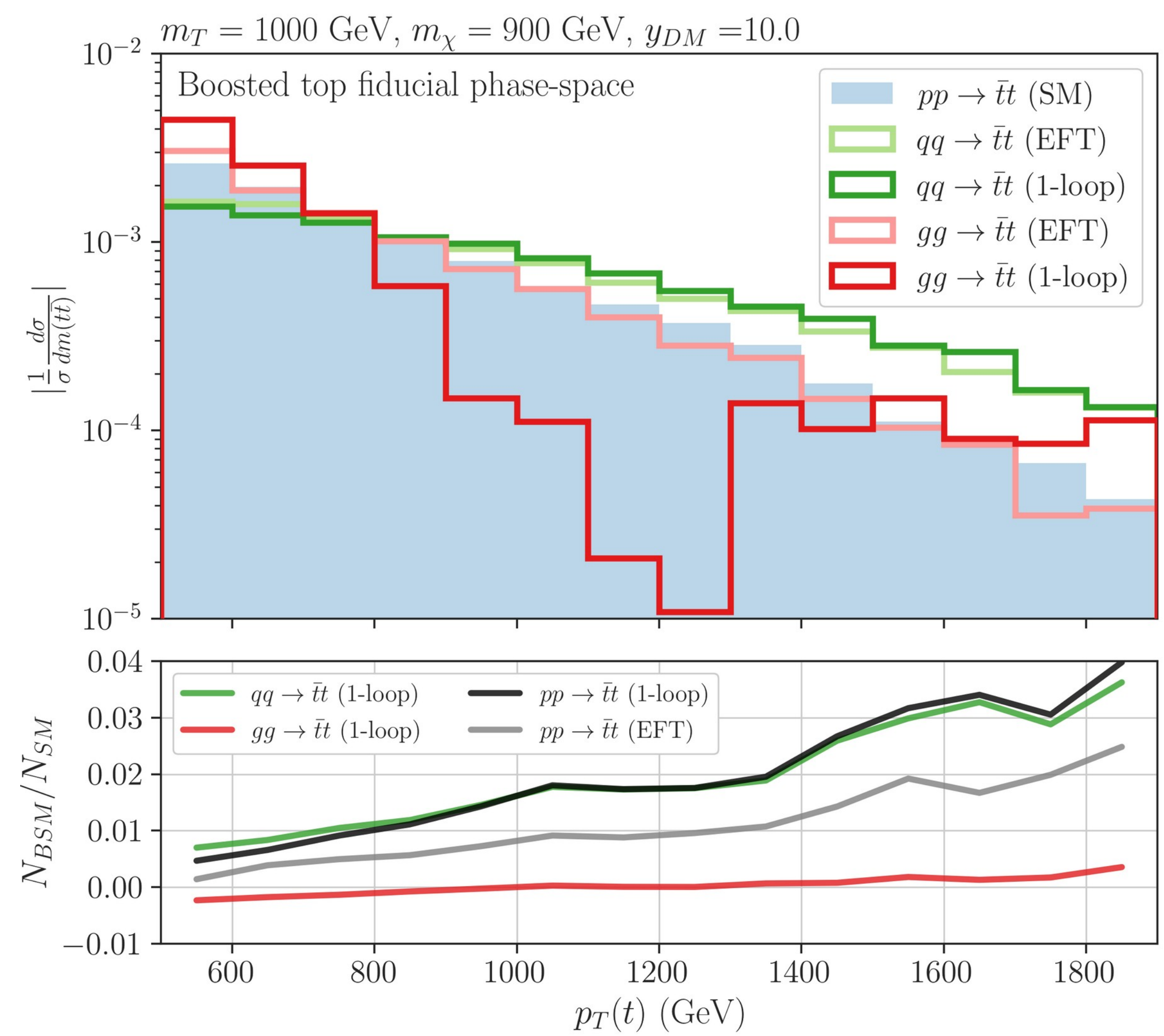
| Operator | Individual fit (TeV$^{-2}$) | Marginalised fit (TeV$^{-2}$) |
|---|---|---|
| $\mathcal{O}_{tG}$ | $-0.01^{+0.086}_{-0.1}$ | $0.36^{+0.12}_{-0.6}$ |
| $\mathcal{O}^{(8)}_{tq}$ | $-0.4^{+0.06}_{-0.85}$ | $5.^{+2.2}_{-13}$ |
| $\mathcal{O}^{(8)}_{tu}$ | $-0.45^{+0.23}_{-1.1}$ | $4.0\ ^{+19}_{-11}$ |
| $\mathcal{O}^{(8)}_{td}$ | $-1.0^{+0.38}_{-2.5}$ | $-0.42^{+11}_{-12}$ |

J. Ellis, M. Madigan, K. Mimasu, V. Sanz and T. You (2012.02779)

# More Results

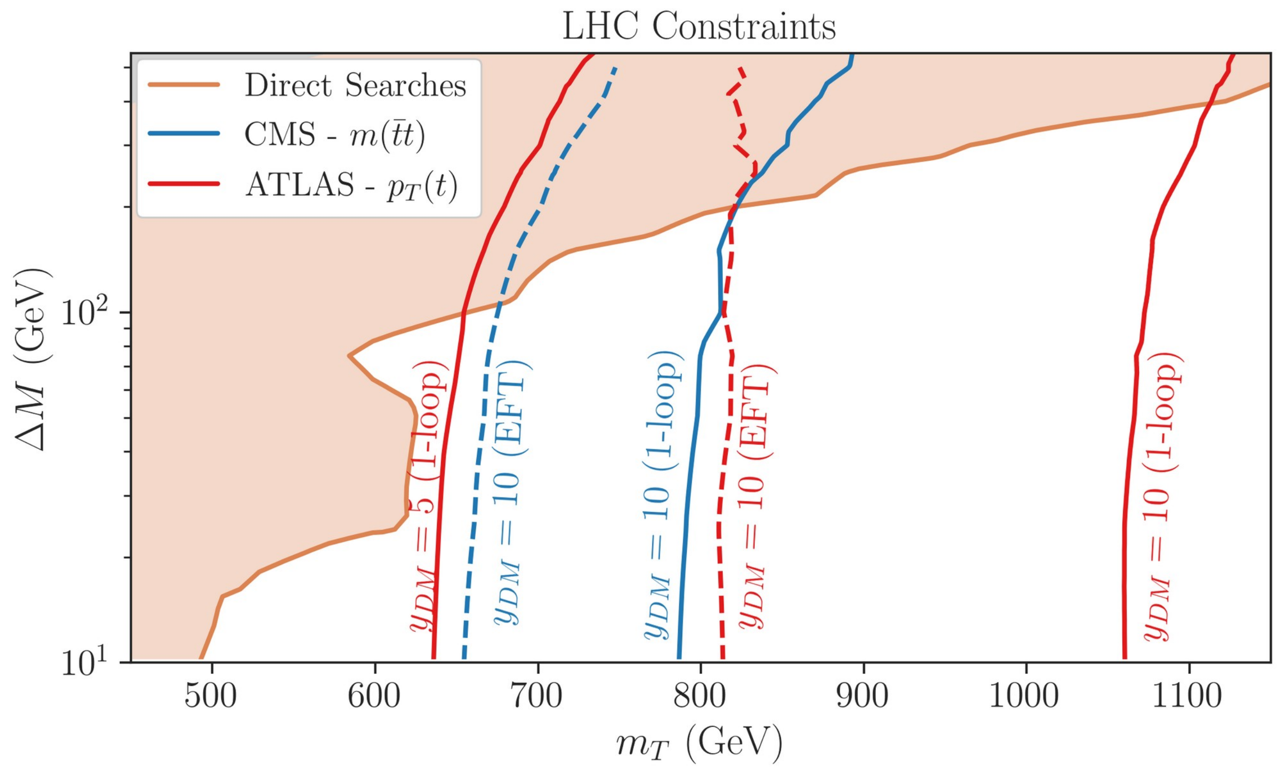
- Distributions for heavy masses:



# More Results

## Observed Limits:




## Expected Limits: