SMEFT at the LHC?

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Contents

Motivation

- LHC experiments did not find BSM physics
- Challenges pre-LHC notions of naturalness: is Nature technically natural?
- Still have compelling arguments for BSM physics: ν masses, baryon asymmetry, dark matter, ...
- $SU(3) \times SU(2) \times U(1)_Y$ gauge symmetry well established, as is existence of one SM-like Higgs boson h with $m_h \simeq 125$ GeV.
- LHC searches: new particles with couplings to SM $\gtrsim 0.2$ must be heavy, $M \gtrsim (\mathrm{few})\ \mathrm{TeV}$

Parameterize our Ignorance!

In absence of compelling guidance from theory, allow everything which:

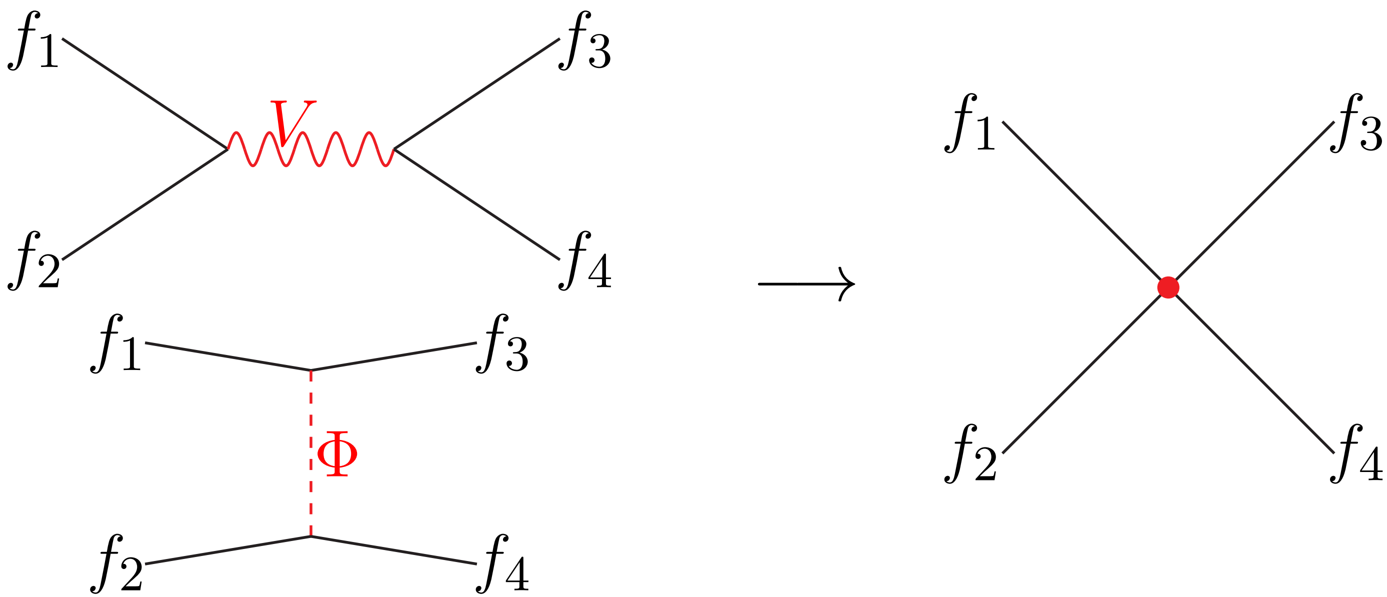
- Respects full SM gauge theory
- Contains *only* SM particle content, including $h(125)$
- Contains all such terms in $\mathcal{L}$ up to a given mass dimension
  - dim-4: Gives $\mathcal{L}_{\mathrm{SM}}$.
  - dim-5: Gives Weinberg operator, $\mathcal{L}_5 = \frac{C_{ij}}{\Lambda} L_i \cdot H L_j \cdot H$.
  - dim-6: Gives 59 operators for one generation, $2,499$ operators for three generations ("Warsaw basis")

Supposed Advantages of the SMEFT

- Is (almost) model–independent! Not really.
- In absence of BSM signal: constraining SMEFT coefficients from LHC (and other) data offers easy way to read off bounds on parameters of UV complete models! Not really.

SMEFT vs UV-Complete Theories

Idea: BSM particles with coupling $g \gtrsim 0.2$ must be heavy $\Longrightarrow$ can be integrated out!



Requires $M_V^2,\ M_\Phi^2 \gg \hat{s}$! Essentially, $1/(q^2 - M^2) \to -1/M^2$.

$$\frac{C_{\mathcal{O}}}{\Lambda^2} = \frac{g_{\rm BSM}^2}{M^2}\kappa_{\mathcal{O}} \qquad \kappa_{\mathcal{O}} : \text{order 1 coefficient}$$

Combinatorics

One advertized use of the SMEFT: “read off” bounds on parameters of UV complete models from SMEFT fits!

- Can *only* constrain ratio $g^2_{\rm BSM}/M^2$! (At dim-6.)
- Most BSM models generate several SMEFT operators!
  - Single operator fit: need $2,499$ separate fits.
  - Two operator fits: need $3,121,251$ separate fits
  - Actual situation often worse: models predict specific relations between SMEFT coefficients!
  - Is generic problem, not LHC specific.
- SMEFT fits with 20 (or more) free parameters have been performed: *useless* for deriving accurate bounds on models with (far) fewer free parameters!

Models Not Described by the SMEFT

Focus on LHC applications!

SMEFT does *not* describe BSM scenarios where new particles can only be produced in pairs!

E.g. $4-$quark operators: $\left|\frac{C}{\Lambda^2}\right| \leq \left(\frac{1}{10 \text{ TeV}}\right)^2$ (PDG).

For one–loop $(\tilde{q}, \tilde{g})$ contribution: $\frac{C}{\Lambda^2} \simeq \frac{g_S^4}{16\pi^2 M^2} \simeq \left(\frac{\alpha_S}{M}\right)^2$.

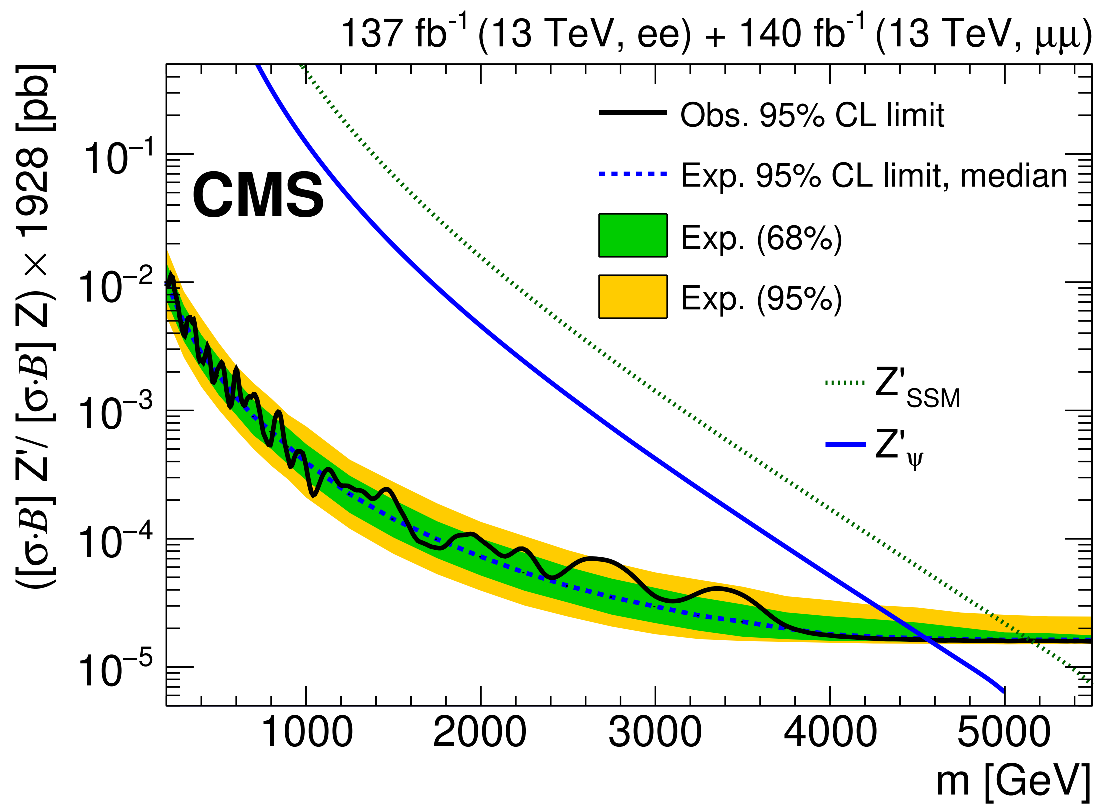
From $4-$quark operators: would imply $M \gtrsim 1$ TeV.
Bound comes from di-jet data with $M_{jj} \lesssim 5$ TeV: SMEFT approximation certainly not valid for $M \sim 1$ TeV!

Bounds from pair production of new particles are often stronger.

Examples

- $R-$parity conserving SUSY
- Large extra dimension with KK parity
- Anything else with a Z_N charged sector

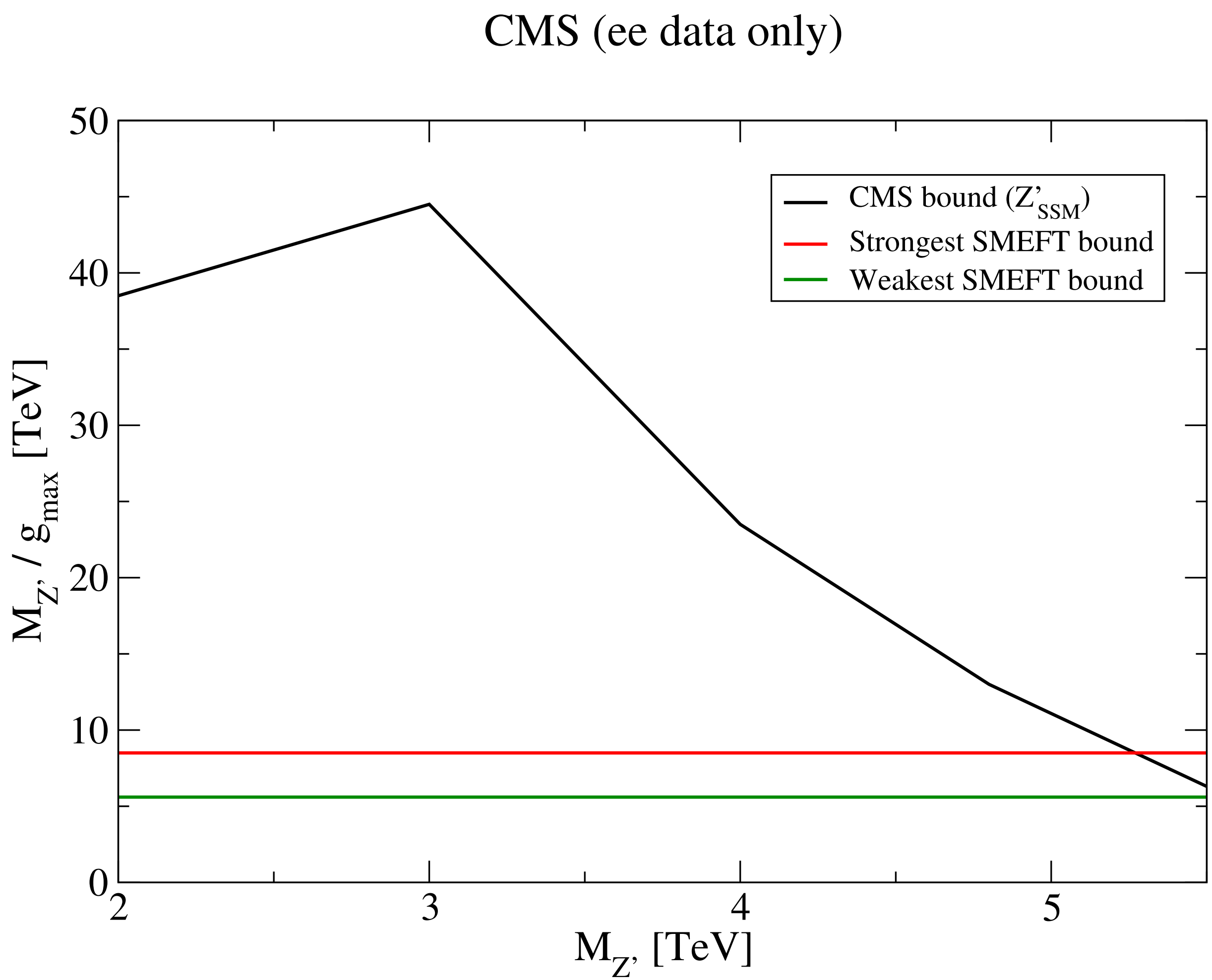
Z' Searches



For Z'_{SSM}: coupling $\simeq \frac{g_2}{2\cos\theta_W} \simeq 0.37$

$$\Longrightarrow g_{\max} \simeq 0.37\sqrt{\frac{\sigma_{\rm bound}}{\sigma_{Z'}}}$$

Z' and the SMEFT



Evidently, the SMEFT does *not* describe the CMS Z' bound!
Reason: No resonance peak in the SMEFT, instead $\hat{\sigma} \to$ const. [$\propto \hat{s}$] at $\mathcal{O}(\Lambda^{-2})$ [$\mathcal{O}(\Lambda^{-4})$].

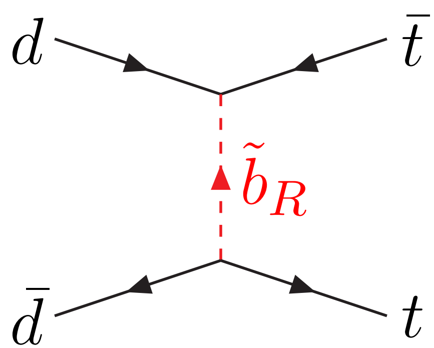
A SMEFT-Friendly Model

MD, Cong Zhang, `arXiv:2506.13500`

$R-$parity violating (RPV), baryon number violating SUSY involving only one first generation (s)quark:

$$W \supset \lambda''_{313} U_3 D_1 D_3$$

Generates $d\bar{d} \to t\bar{t}$ via $t-$channel $\tilde{b}_R$ exchange:



Assumptions

- All other RPV-couplings $\ll |\lambda''_{313}|$
- All other sparticles sufficiently heavier than $\tilde{b}_R$ (in particular, $\tilde{t}_R$, $\tilde{d}_R$)

Single $\tilde{b}_R$ production as $s-$channel resonance requires $t-$quark in initial state: strongly suppressed!

Matching: Get two $4-$quark operators at tree level:

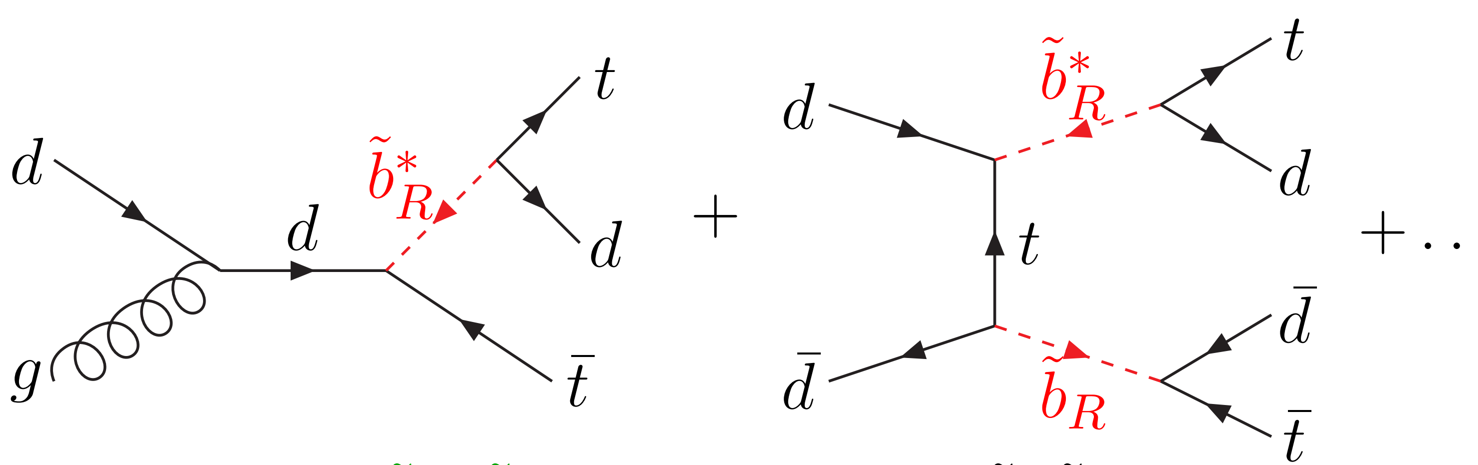
$$\mathcal{O}_{td}^{(1)} = (\bar{t}\gamma^\mu t)\left(\bar{d}\gamma_\mu d\right) , \quad C_{td}^{(1)} = \frac{|\lambda''_{313}|^2}{3M^2_{\tilde{b}_R}};$$

$$\mathcal{O}_{td}^{(8)} = (\bar{t}\gamma^\mu T^a t)\left(\bar{d}\gamma_\mu T^a d\right) , \quad C_{td}^{(8)} = -\frac{|\lambda''_{313}|^2}{M^2_{\tilde{b}_R}}.$$

$C_{td}^{(1)} = -C_{td}^{(8)}/3$, but $\mathcal{O}_{td}^{(1)}$ does not interfere with LO QCD $d\bar{d} \to t\bar{t}$: no $\mathcal{O}(\Lambda^{-2})$ contribution $\propto C_{td}^{(1)}$ in LO QCD.

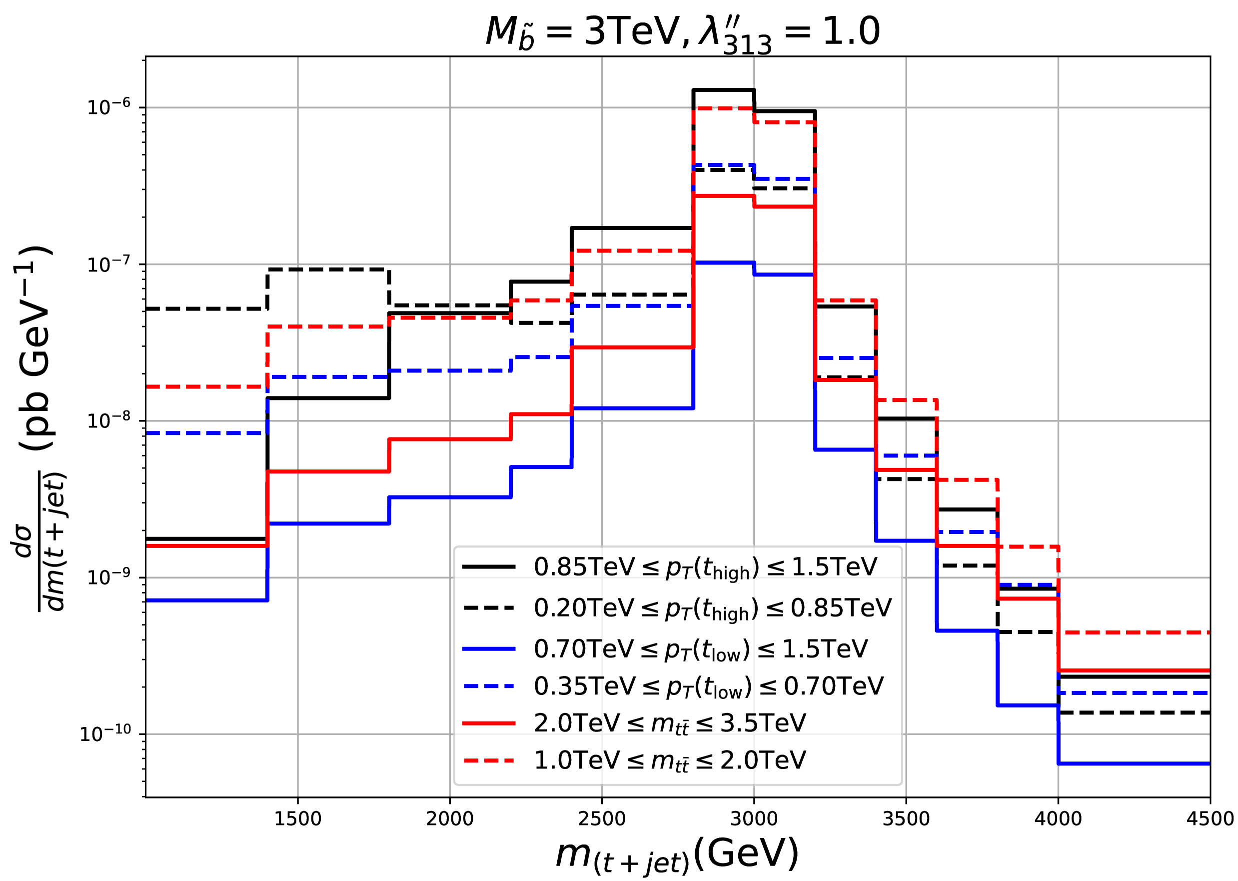
Issues

- Does the SMEFT describe $d\bar{d} \to t\bar{t}$ correctly, for parameters of interest to LHC experiments? No
- Experiments analyse *inclusive* $t\bar{t}$ production: should include:



Contribue at LO iff $\tilde{b}_R, \tilde{b}_R^*$ are on–shell! $\tilde{b}_R \tilde{b}_R^*$ pair production is unimportant, but single $\tilde{b}_R^{(*)}$ production is very important in inclusive $t\bar{t}$ production! Not described by SMEFT!

Single $\tilde{b}_R$ Diagrams Only



Only includes diagrams with single potentially on-shell $\tilde{b}_R^{(*)}$, using Breit-Wigner propagator for $\tilde{b}_R$.
On-shell production dominates even for $M_{\tilde{b}_R} = 3$ TeV!

Comparison with CMS Data

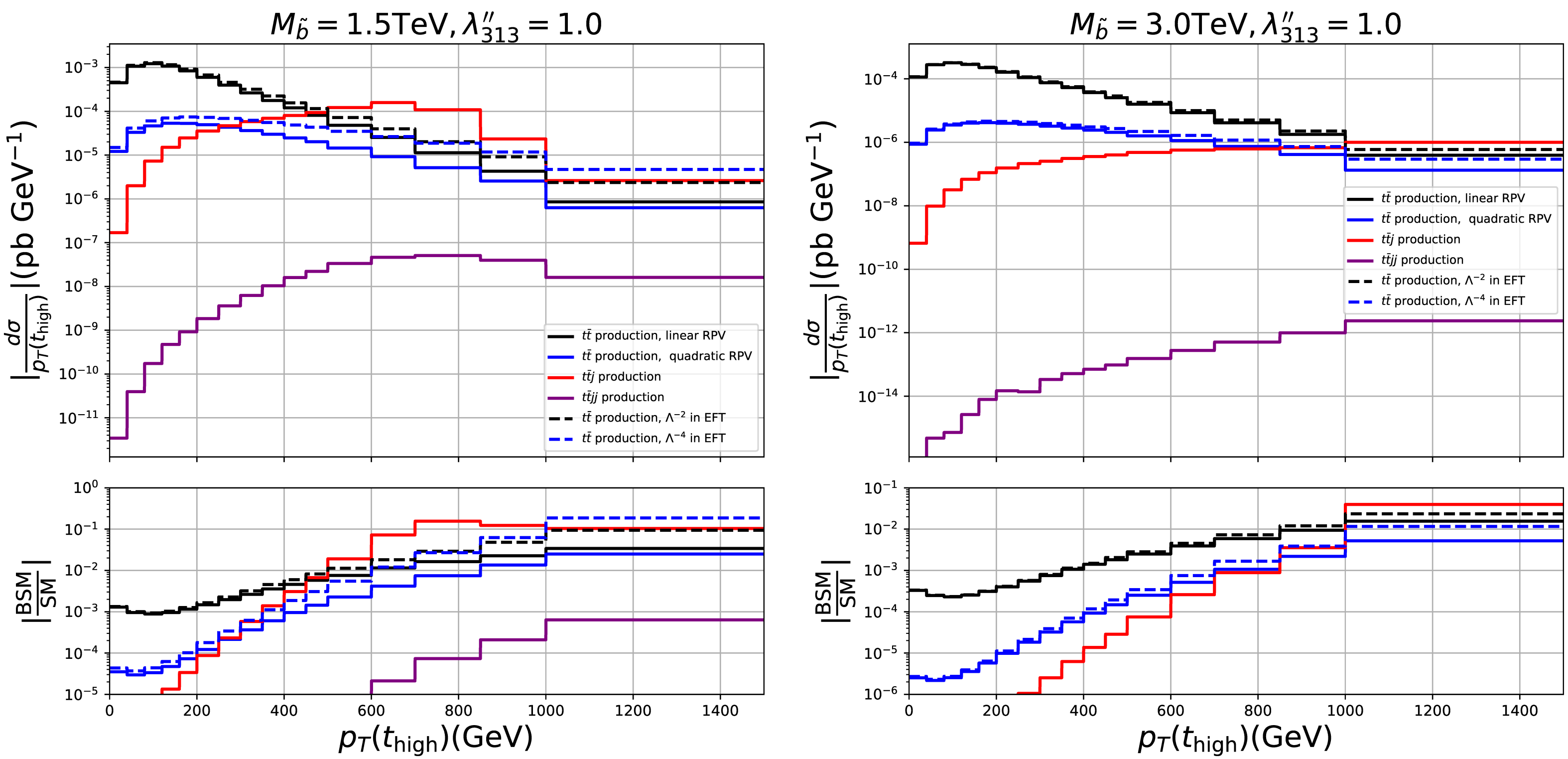
CMS provides (`arXiv:2108.02803`) data on inclusive $t\bar{t}$ production in the single-lepton mode, corrected to the parton level, and with full information on covariant matrix: Allows χ^2 fits of RPV model and its SMEFT implementation using MadGraph results only!

Notation:

$p_T(t_{\rm high})$: $\max(p_T(t),\, p_T(\bar{t}))$;
$p_T(t_{\rm low})$: $\min(p_T(t),\, p_T(\bar{t}))$;
$p_{T,h}$: p_T of hadronically decaying (anti-)top

Linear RPV/SMEFT: Only interference term included; is negative!
Quadratic RPV/SMEFT: Squared BSM contribution

$p_T(t_{\rm high})$ Distribution



- At large $p_T(t_{\rm high})$: SMEFT is off
- Single $\tilde{b}_R^{(*)}$ production is important

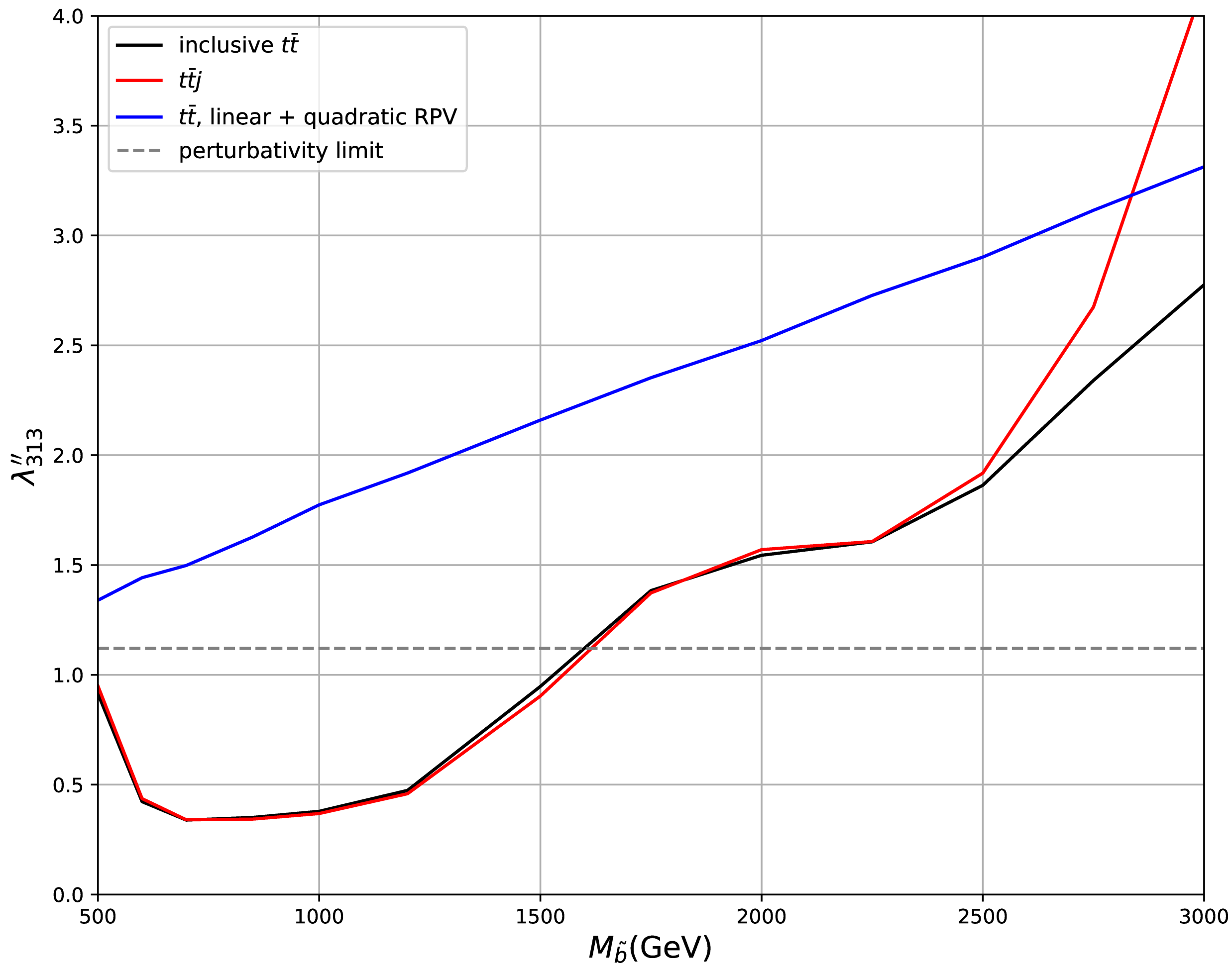
True even for $M_{\tilde{b}_R} = 3$ TeV!

Comparison RPV Model vs its SMEFT Implementation

Ratio σ(SMEFT)/σ(RPV)

$M_{\tilde{b}}$(GeV)	$p_T(t_{\text{high}})$ [GeV]	$t\bar{t}$ (linear)	$t\bar{t}$ (quadratic)	$t\bar{t}$ (linear+quadratic)	total
1500	500-600	1.50	2.42	1.10	-0.42
	1000-1500	2.77	7.46	-10.3	0.97
3000	500-600	1.13	1.37	1.10	1.14
	1000-1500	1.50	2.23	1.14	-0.41

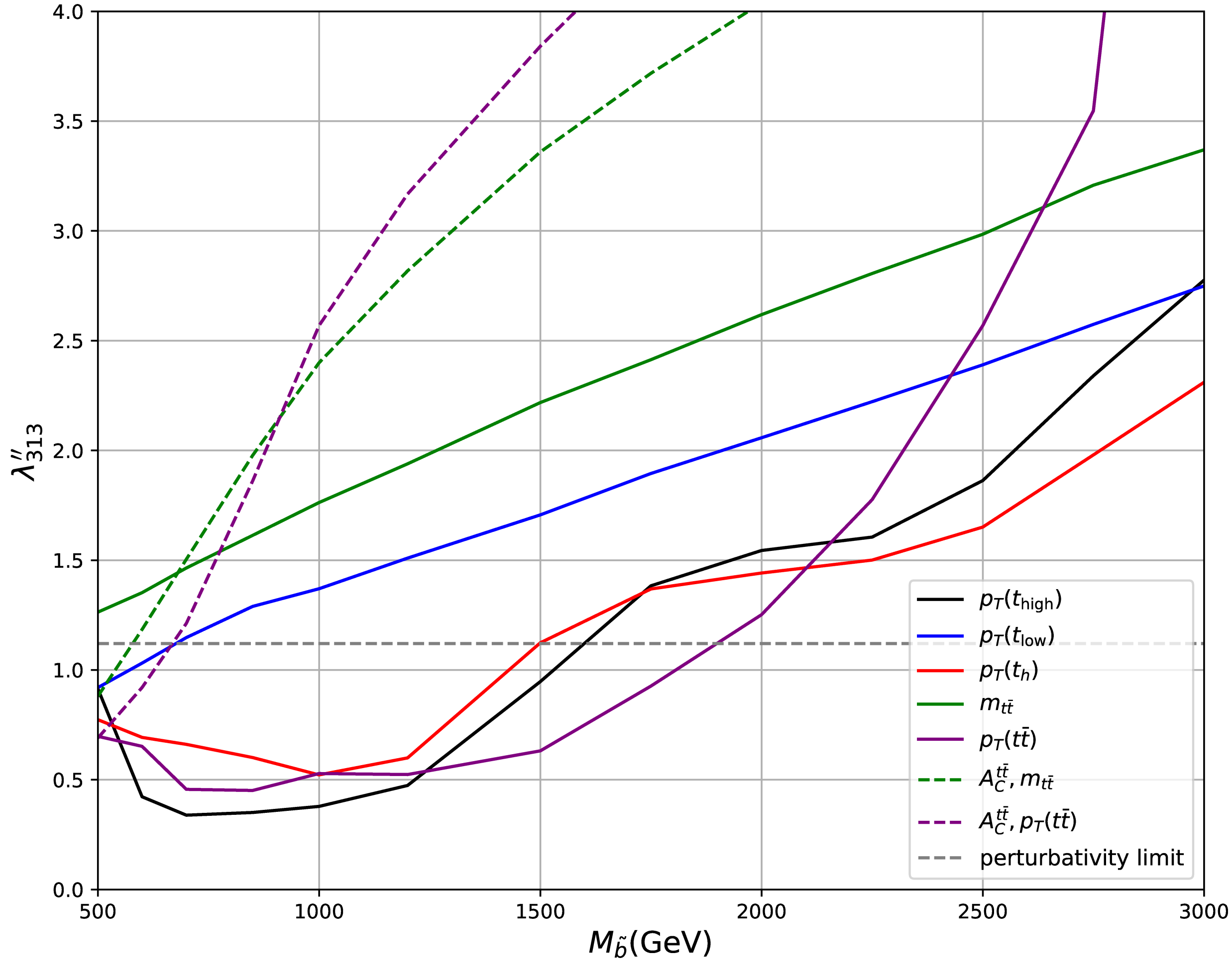
Bounds from $p_T(t_{\rm high})$ Distribution



Need $\lambda'' < 1.12$ in order to avoid Landau pole below 10^{16} GeV (Allanach, Dedes, Dreiner 1999)

Fit slightly prefers non-zero RPV contribution

Complete Set of Bounds



Note: Single $\tilde{b}_R^{(*)}$ production leads to $p_T(t\bar{t}) \neq 0$ even at LO without showering!

Summary

- Combinatorics: difficult to "read off" bounds on parameters of UV-complete model even if the SMEFT is applicable
- Don't use the SMEFT for LHC physics! Is "model independent" only in the sense that it doesn't describe *any* (weakly coupled) UV complete model (for parameter values of interest).
- Trying to "save the SMEFT" by discarding bins with high p_T or high invariant mass makes no sense: throws away most important data!