Dimension 8 SMEFT operators induced by extra-dimensional gravity

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Models with extra spatial dimensions

(4+δ)-dimensional action

$$S \sim M_*^{2+\delta} \int d^{4+\delta}x\sqrt{-g}R + \int d^4x\sqrt{-\tilde{g}}\mathcal{L}_{SM} + \ldots, \tag{1}$$

Example realizations

- Large flat compact extra dimensions (ADD) (hep-ph/9803315)
- Warped compact (hep-ph/9905221) or infinite (hep-th/9906064) extra dimensions (Randall–Sundrum)
- Universal extra dimensions (UED) (hep-ph/0012100)

Experimentally, no direct evidence for gravitons, radions, or related excitations has been observed so far in current collider and precision datasets

Stabilized RS1 model[1]

Randall-Sundrum 1 - stabilized brane world model with two branes and massive radion.

- The fifth dimension composed of the orbifold S^1/Z_2
- $-L \leq y \leq L$ - the corresponding coordinate
- The metric g^{MN} and the scalar field ϕ satisfy the corresponding orbifold symmetry conditions
- The branes are located at the fixed points of the orbifold, $y = 0$ and $y = L$

The action of the stabilized brane world model

$$S = -2M^3 \int d^4x \int_{-L}^{L} dyR\sqrt{-g} + \int d^4x \int_{-L}^{L} dy(\frac{1}{2}g^{MN}\partial_M\phi\partial_N\phi - V(\phi))\sqrt{-g}$$
$$- \int_{y=0} d^4x\lambda_1(\phi)\sqrt{-\tilde{g}} + \int_{y=L} d^4x(-\lambda_2(\phi) + \mathcal{L}_{SM})\sqrt{-\tilde{g}}, \quad (2)$$

where $V(\phi)$ is a bulk scalar field potential, $\lambda_{1,2}(\phi)$ are quadratic brane scalar field potentials, $\tilde{g}_{\mu\nu}$ - the metric induced on the branes

[1] arXiv:0710.3100

Low-energy "integrated-out" description

The passage from a UV model to a phenomenologically usable EFT often involves Kaluza–Klein (KK) reduction and several distinct expansions / truncations:

- Choice of operator content in the gravitational sector (e.g. $\mathcal{L}_{int} \sim \int d^4x\sqrt{-\tilde{g}}\mathcal{L}_{matter}$)
- Weak-field expansion around a background: $g_{\mu\nu} \approx \eta_{\mu\nu} + \kappa h_{\mu\nu} + \ldots$
- Low-momentum expansion of heavy propagators: $(\Box + M^2)^{-1} \approx M^{-2} + \ldots$

Retaining leading terms in the above expansions, the tree level dominant local contribution can be parameterized by dimension-8 operators:

$$\mathcal{L}_{int} \simeq c_T T_{\mu\nu} T^{\mu\nu} + c_S T^{\mu}_{\mu} T^{\nu}_{\nu}, \tag{3}$$

where $T_{\mu\nu} = 2\frac{\delta\mathcal{L}_{SM}}{\delta\eta^{\mu\nu}} - \eta_{\mu\nu}\mathcal{L}_{SM}$, c_T and c_S are theory dependent constants, governing contributions of tensor (graviton) and scalar (radion) modes.

SMEFT

SMEFT is constructed by extending the SM Lagrangian with gauge-invariant operators of higher dimension:

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum \frac{c_i^{\{6\}}}{\Lambda^2} O_i^{d=6} + \sum \frac{c_i^{\{8\}}}{\Lambda^4} O_i^{d=8} + \ldots, \tag{4}$$

where $\mathcal{L}_{SM}$ is the SM Lagrangian, Λ - hypothetical scale of the BSM physics, $O_i^{d=n}$ - local composite SMEFT operators of dimension n, c_i - dimensionless Wilson coefficients.

In the SMEFT framework, any observable, in particular the cross-section, can be parametrized in the following form:

$$\sigma = \sigma_{SM} + \sum_k \frac{c_i}{\Lambda^2} \sigma_k^{(1)} + \sum_{j<=k} \frac{c_i c_k}{\Lambda^4} \sigma_{k,j}^{(2)} + \ldots, \tag{5}$$

$\sigma^{(1)}$ and $\sigma^{(2)}$ - coefficients, representing linear and quadratic (in terms of EFT coupling) contributions of the SMEFT operators

Introduction summary

Goals

- Perform matching of gravity induced effective operators to dimension 8 SMEFT
- Obtain experimental constraints on Wilson Coefficients of relevant dimension 8 SMEFT operators
- Project WC constraints to limits on physical parameters of particular implementations of extra-dimensional models

Numerical Setup

Numerical toolchain

- FeynRules (1310.1921) - Generation of model files
- MadGraph (1405.0301) / CompHEP (hep-ph/0403113) - MC events generators
- Pythia8 (2203.11601) - hadronization / parton shower
- Rivet (2404.15984) - analysis reproduction
- Statistical software; good examples of dedicated packages are SMEFiT (arXiv:2302.06660) and EFTfitter (arXiv:1605.05585)

Obtaining statistical limits for WC

The cross-section with inclusion of dimension 8 SMEFT operators is parametrized as follows:

$$\sigma = \sigma_{SM} + \sum_{k} \frac{c_i}{\Lambda^4} \sigma_k^{(1)} + \sum_{j<=k} \frac{c_i c_k}{\Lambda^8} \sigma_{k,j}^{(2)}, \qquad (6)$$

- The value for σ is taken from CMS the measurement
- The SM cross-section σ_{SM} is taken at next-to-leading logarithmic accuracy (NLL$'$)
- Values for coefficients $\sigma^{(1)}$ and $\sigma^{(2)}$ are obtained using the previously mentioned toolchain
- **All variables are modeled by normal distribution with their errors corresponding to a Gaussian 1σ interval**

Given above, limits are obtained using MC sampling technique

Matching

Example

Fermion part of the energy-momentum tensor has the following form:

$$T_F^{\mu\nu} = \frac{i}{2}\bar{\psi}\gamma^{\mu}D^{\nu}\psi + \frac{i}{2}\bar{\psi}\gamma^{\nu}D^{\mu}\psi - \frac{i}{4}\partial^{\mu}(\bar{\psi}\gamma^{\nu}\psi) - \frac{i}{4}\partial^{\nu}(\bar{\psi}\gamma^{\mu}\psi) + ig^{\mu\nu}(\frac{1}{2}\partial_{\rho}(\bar{\psi}\gamma^{\rho}\psi) - \bar{\psi}\gamma^{\rho}D_{\rho}\psi), \quad (7)$$

Its contractions can be simplified using the following techniques

- All EOMs should be eliminated in a physical basis, e.g.

$$(\dots)(\bar{q}\gamma^{\mu}D_{\mu}q) \longrightarrow (\dots)(Y_u u\tilde{H} + Y_d dH)$$

- Mixed contractions are resolved using corresponding Fierz identities, e.g.

$$(\bar{u}^{\alpha}\gamma^{\mu}u^{\beta})(\bar{u}^{\beta}\gamma_{\mu}u^{\alpha}) \longrightarrow 2(\bar{u}^{\alpha}\gamma^{\mu}T^{A}u^{\alpha})(\bar{u}^{\beta}\gamma_{\mu}T^{A}u^{\beta}) + \frac{1}{3}(\bar{u}^{\alpha}\gamma^{\mu}u^{\alpha})(\bar{u}^{\beta}\gamma_{\mu}u^{\beta}) \quad (8)$$

- The ordering of the derivatives can be changed using integration-by-part, e.g.

$$(\dots)^{\nu}D_{\mu}D_{\nu}(\bar{u}\gamma^{\mu}u) \longrightarrow D_{\nu}(\dots)^{\nu}D_{\mu}(\bar{u}\gamma^{\mu}u) + (\text{total derivative}) \quad (9)$$

Matching

Example

Contractions of the Fermion part lead to operators of the following classes:

$$
\begin{aligned}
Fermion - Fermion &: \psi^4 D^2 \text{(with different Lorentz structure)},\\
Fermion - Higgs &: \psi^2\phi^5, \psi^2\phi^4 D, \psi^2\phi^3 D^2, \psi^2\phi^2 D^3, \psi^2 X\phi^2 D, \psi^4\phi D, \psi^4\phi^2\\
Fermion - Yukawa &: X^3\phi^2, X^2\phi^4, X^2\phi^2 D^2, \psi^2 X^2\phi, \psi^2 X\phi^2 D
\end{aligned}
$$

In the current work, matching is performed with the help of Matchete[a] package.

[a] arXiv:2212.04510

Matching results

H^8, H^6D^2 and H^4D^4

Name	Definition	Matching to C_T	Matching to C_S
	H^8		
Q_{H^8}	$(HH^\dagger)^4$	$3\lambda^2 - \frac{\lambda}{4}g_L^2 - \frac{\lambda}{4}g_Y^2$	$16\lambda^2$
	H^6D^2		
$Q_{H^6}^{(1)}$	$(HH^\dagger)^2(D_\mu H^\dagger D^\mu H)$	$\frac{5}{4}g_L^2 + \frac{5}{4}g_Y + 5\lambda$	16λ
$Q_{H^6}^{(2)}$	$(HH^\dagger)(H\tau^I H^\dagger)(D_\mu H^\dagger \tau^I D^\mu H)$	$\frac{1}{2}g_Y^2$	0
	H^4D^4		
$Q_{H^4}^{(2)}$	$(D_\mu H^\dagger D^\nu H)(D_\mu H^\dagger D^\nu H)$	2	0
$Q_{H^4}^{(3)}$	$(D_\mu H^\dagger D^\mu H)(D_\nu H^\dagger D^\nu H)$	0	4

Matching results

X^4

Name	Definition	Matching to C_T	Matching to C_S
		X^4	
$Q^{(1)}_{B^4}$	$(B_{\mu\nu}B^{\mu\nu})(B_{\rho\sigma}B^{\rho\sigma})$	$\frac{1}{4}$	0
$Q^{(2)}_{B^4}$	$(B_{\mu\nu}\widetilde{B}^{\mu\nu})(B_{\rho\sigma}\widetilde{B}^{\rho\sigma})$	$\frac{1}{4}$	0
$Q^{(1)}_{G^4}$	$(G_{\mu\nu}G^{\mu\nu})(G_{\rho\sigma}G^{\rho\sigma})$	$\frac{1}{4}$	0
$Q^{(2)}_{G^4}$	$(G_{\mu\nu}\widetilde{G}^{\mu\nu})(G_{\rho\sigma}\widetilde{G}^{\rho\sigma})$	$\frac{1}{4}$	0
$Q^{(1)}_{W^4}$	$(W_{\mu\nu}W^{\mu\nu})(W_{\rho\sigma}W^{\rho\sigma})$	$\frac{1}{4}$	0
$Q^{(2)}_{W^4}$	$(W_{\mu\nu}\widetilde{W}^{\mu\nu})(W_{\rho\sigma}\widetilde{W}^{\rho\sigma})$	$\frac{1}{4}$	0
$Q^{(1)}_{G^2B^2}$	$(B_{\mu\nu}B^{\mu\nu})(G_{\rho\sigma}G^{\rho\sigma})$	$-\frac{3}{2}$	0
$Q^{(2)}_{G^2B^2}$	$(B_{\mu\nu}\widetilde{B}^{\mu\nu})(G_{\rho\sigma}\widetilde{G}^{\rho\sigma})$	$-\frac{1}{2}$	0
$Q^{(1)}_{G^2W^2}$	$(W_{\mu\nu}W^{\mu\nu})(G_{\rho\sigma}G^{\rho\sigma})$	$-\frac{3}{2}$	0

Matching results

$X^2H^2D^2$ and XH^4D^2

Name	Definition	Matching to C_T	Matching to C_S
	$X^2H^2D^2$		
$Q^{(1)}_{G^2H^2D^2}$	$(D^\mu H^\dagger D^\nu H) G_{\mu\rho} G^\rho_\nu$	-4	0
$Q^{(1)}_{W^2H^2D^2}$	$(D^\mu H^\dagger D^\nu H) W_{\mu\rho} W^\rho_\nu$	-4	0
$Q^{(1)}_{B^2H^2D^2}$	$(D^\mu H^\dagger D^\nu H) B_{\mu\rho} B^\rho_\nu$	-4	0
$Q^{(2)}_{G^2H^2D^2}$	$(H^\dagger H)(D_\rho G^{A\mu\nu})(D_\rho G^A_{\mu\nu})$	1	0
$Q^{(2)}_{W^2H^2D^2}$	$(H^\dagger H)(D_\rho G^{A\mu\nu})(D_\rho G^A_{\mu\nu})$	1	0
$Q^{(2)}_{B^2H^2D^2}$	$(H^\dagger H)(D_\rho G^{A\mu\nu})(D_\rho G^A_{\mu\nu})$	1	0
	XH^4D^2		
$Q^{(1)}_{W^2H^4D^2}$	$(H^\dagger H)(D^\mu H^\dagger \tau^I D^\nu H) B^I_{\mu\nu}$	$-6g_L$	0
$Q^{(1)}_{B^2H^4D^2}$	$(H^\dagger H)(D^\mu H^\dagger D^\nu H) B_{\mu\nu}$	$-4g_Y$	0

Observables

- Drell-Yan double-differential $p_{T,ll}$ (CMS arXiv:2205.04897,HEPData ins2079374)
- $Z\gamma \to \nu\bar{\nu}\gamma$ differential σ/dp_T^{γ} (ATLAS arXiv:1810.04995, HEPData ins1698006)
- Inclusive $pp \to 4l$ differential spectra (ATLAS arXiv:2103.01918, HEPData ins1849535)
- Four top-quark production total cross-section (CMS arXiv:2305.13439, ATLAS arXiv:2303.15061)

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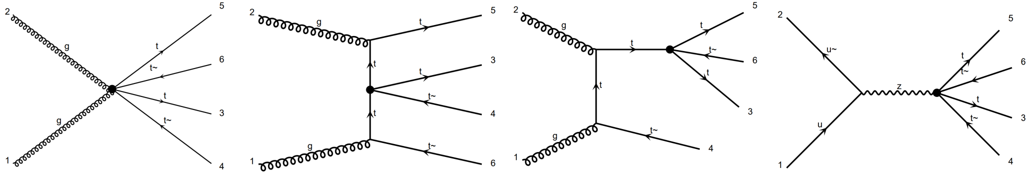
Four top-quark production

Setup

- Operators of the following classes are directly contribute to the process: $\psi^4 X$, $\psi^4\phi^2$, $\psi^4\phi D$, and $\psi^4 D^2$
- Simulation parameters follow CMS analysis (arXiv:2305.13439)

Examples of diagrams with inclusion of effective vertices:



Summary tables

$\psi^4\phi D$

Name	Definition	Matching coefficient	Limits on WC $C_k/\Lambda^4[\mathrm{TeV}^{-4}]$
$Q^{(1)}_{q^3uHD}$ + h.c.	$i(\bar{q}\gamma^\mu q)[(\bar{q}^j u)D_\mu H^{\dagger k}\epsilon_{jk}]$ + h.c.	$C_T Y_t$	[-8.637, 8.637]
$Q^{(1)}_{qu^3HD}$ + h.c.	$i(\bar{u}\gamma^\mu u)[(\bar{q}^j u)D_\mu H^{\dagger k}\epsilon_{jk}]$ + h.c.	$C_T Y_t$	[-, -]
$Q^{(1)}_{qud^2HD}$ + h.c.	$i(\bar{d}\gamma^\mu d)[(\bar{q}^j u)D_\mu H^{\dagger k}\epsilon_{jk}]$ + h.c.	$C_T Y_t$	[-, -]
$Q^{(1)}_{q^3dHD}$ + h.c.	$i(\bar{q}\gamma^\mu q)[(\bar{q}^j d)D_\mu H]$ + h.c.	$C_T(-Y_b)$	[-, -]
$Q^{(1)}_{qu^2dHD}$ + h.c.	$i(\bar{u}\gamma^\mu u)[(\bar{q}^j d)D_\mu H]$ + h.c.	$C_T(-Y_b)$	[-, -]
$Q^{(1)}_{qd^3HD}$ + h.c.	$i(\bar{d}\gamma^\mu d)[(\bar{q}^j d)D_\mu H]$ + h.c.	$C_T(-Y_b)$	[-, -]

Table 1: Definitions, matching coefficients and 1D statistical limits for corresponding WC of operators of the $\psi^4\phi D$ class, obtained from matching of stabilized RS1 model to dimension 8 SMEFT

Summary tables

$\psi^4\phi^2$: $(\bar{L}L)(\bar{L}L)$, $(\bar{R}R)(\bar{R}R)$ and $(\bar{L}R)(\bar{L}R)$

Name	Definition	Matching coefficient	Limits on WC $C_k/\Lambda^4[\mathrm{TeV}^{-4}]$
		$(\bar{L}L)(\bar{L}L)$	
$Q^{(1)}_{q^4H^2}$	$(\bar{q}\gamma^\mu q)(\bar{q}\gamma_\mu q)(H^\dagger H)$	$C_T(\frac{1}{6}g_S^2 - \frac{5}{36}g_Y^2)$	[-, -]
$Q^{(3)}_{q^4H^2}$	$(\bar{q}\gamma^\mu\tau^I q)(\bar{q}\gamma_\mu\tau^I q)(H^\dagger H)$	$C_T\frac{1}{2}(g_S^2 + g_L^2)$	[-, -]
		$(\bar{R}R)(\bar{R}R)$	
$Q_{u^4H^2}$	$(\bar{u}\gamma^\mu u)(\bar{u}\gamma_\mu u)(H^\dagger H)$	$C_T(\frac{2}{3}g_S^2 + \frac{11}{9}g_Y^2)$	[-, -]
$Q_{q^4H^2}$	$(\bar{d}\gamma^\mu d)(\bar{d}\gamma_\mu d)(H^\dagger H)$	$C_T(\frac{2}{3}g_S^2 + \frac{1}{18}g_Y^2)$	[-, -]
$Q^{(1)}_{u^2d^2H^2}$	$(\bar{u}\gamma^\mu u)(\bar{d}\gamma_\mu d)(H^\dagger H)$	$C_T(-\frac{13}{18}g_Y^2)$	[-, -]
$Q^{(2)}_{u^2d^2H^2}$	$(\bar{u}\gamma^\mu T^A u)(\bar{d}\gamma_\mu T^A d)(H^\dagger H)$	$C_T 4 g_S^2$	[-, -]
		$(\bar{L}R)(\bar{L}R)$	
$Q^{(1)}_{q^2udH^2}$ + h.c.	$(\bar{q}^j u)\epsilon_{jk}(\bar{q}^k d)(H^\dagger H)$ + h.c.	$C_T Y_t Y_b(-\frac{5}{2} + 2C_S)$	[-, -]
$Q^{(2)}_{q^2udH^2}$ + h.c.	$(\bar{q}^j u)(\tau^I\epsilon)_{jk}(\bar{q}^k d)(H^\dagger\tau^I H)$ + h.c.	$C_T(-\frac{3}{2}Y_t Y_b)$	[-, -]

Table 2: Definitions, matching coefficients and 1D statistical limits for corresponding WC of operators of the $\psi^4\phi^2$ class, obtained from matching of stabilized RS1 model to dimension 8 SMEFT

Summary tables

$\psi^4\phi^2$: $(\bar{L}L)(\bar{R}R)$

Name	Definition	Matching coefficient $(\bar{L}L)(\bar{R}R)$	Limits on WC $C_k/\Lambda^4[\mathrm{TeV}^{-4}]$
$Q^{(1)}_{q^2u^2H^2}$	$(\bar{q}\gamma^\mu q)(\bar{u}\gamma_\mu u)(H^\dagger H)$	$C_T(\frac{31}{36}g_Y^2 + Y_t^2(\frac{5}{12} - \frac{1}{3}C_S))$	[-, -]
$Q^{(2)}_{q^2u^2H^2}$	$(\bar{q}\gamma^\mu \tau^I q)(\bar{u}\gamma_\mu u)(H^\dagger \tau^I H)$	$C_T(-\frac{1}{4}Y_t^2)$	[-, -]
$Q^{(3)}_{q^2u^2H^2}$	$(\bar{q}\gamma^\mu T^A q)(\bar{u}\gamma_\mu T^A u)(H^\dagger H)$	$C_T(4g_S^2 + Y_t^2(\frac{5}{2} - 2C_S))$	[-, -]
$Q^{(4)}_{q^2u^2H^2}$	$(\bar{q}\gamma^\mu T^A \tau^I q)(\bar{u}\gamma_\mu T^A u)(H^\dagger \tau^I H)$	$C_T(-\frac{3}{2}Y_t^2)$	[-, -]
$Q^{(1)}_{q^2d^2H^2}$	$(\bar{q}\gamma^\mu q)(\bar{d}\gamma_\mu d)(H^\dagger H)$	$C_T(-\frac{11}{36}g_Y^2 + Y_t^2(\frac{5}{12} - \frac{1}{3}C_S))$	[-, -]
$Q^{(2)}_{q^2d^2H^2}$	$(\bar{q}\gamma^\mu \tau^I q)(\bar{d}\gamma_\mu d)(H^\dagger \tau^I H)$	$C_T(\frac{1}{4}Y_t^2)$	[-, -]
$Q^{(3)}_{q^2d^2H^2}$	$(\bar{q}\gamma^\mu T^A q)(\bar{d}\gamma_\mu T^A d)(H^\dagger H)$	$C_T(4g_S^2 + Y_t^2(\frac{5}{2} - 2C_S))$	[-, -]
$Q^{(4)}_{q^2d^2H^2}$	$(\bar{q}\gamma^\mu T^A \tau^I q)(\bar{d}\gamma_\mu T^A d)(H^\dagger \tau^I H)$	$C_T(\frac{3}{2}Y_t^2)$	[-, -]

Table 3: Definitions, matching coefficients and 1D statistical limits for corresponding WC of operators of the $\psi^4\phi^2$ class, obtained from matching of stabilized RS1 model to dimension 8 SMEFT

Summary tables

$\psi^4 D^2$

Name	Definition	Matching coefficient	Limits on WC $C_k/\Lambda^4[\mathrm{TeV}^{-4}]$
$Q^{(1)}_{q^4 D^2}$	$(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q)(\bar{q}\gamma_\mu \overleftrightarrow{D}_\nu q)$	$C_T\frac{1}{8}$	[-0.30, 0.31]
$Q^{(1)}_{u^4 D^2}$	$(\bar{u}\gamma^\mu \overleftrightarrow{D}^\nu u)(\bar{u}\gamma_\mu \overleftrightarrow{D}_\nu u)$	$C_T\frac{1}{8}$	[-0.55, 0.52]
$Q^{(1)}_{d^4 D^2}$	$(\bar{d}\gamma^\mu \overleftrightarrow{D}^\nu d)(\bar{d}\gamma_\mu \overleftrightarrow{D}_\nu d)$	$C_T\frac{1}{8}$	[-, -]
$Q^{(1)}_{q^2 u^2 D^2}$	$(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q)(\bar{u}\gamma_\mu \overleftrightarrow{D}_\nu u)$	$C_T\frac{1}{4}$	[-0.58, 0.55]
$Q^{(1)}_{q^2 d^2 D^2}$	$(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q)(\bar{d}\gamma_\mu \overleftrightarrow{D}_\nu d)$	$C_T\frac{1}{4}$	[-, -]
$Q^{(1)}_{u^4 D^2}$	$(\bar{u}\gamma^\mu \overleftrightarrow{D}^\nu u)(\bar{d}\gamma_\mu \overleftrightarrow{D}_\nu d)$	$C_T\frac{1}{4}$	[-, -]

Table 4: Definitions, matching coefficients and 1D statistical limits for corresponding WC of operators of the $\psi^4 D^2$ class, obtained from matching of stabilized RS1 model to dimension 8 SMEFT

Projection of the WC bounds on physical parameters

Result for effective parameters c_T and c_S

$$-2.31[\text{TeV}^{-4}] < c_T < 2.28[\text{TeV}^{-4}],$$

$$c_S - \text{N.A.}$$

Stabilized RS1 model (arXiv:0710.3100)

- Limit from four top-quark production:

$$\frac{1}{\Lambda_\pi^2 m_1^2} < 1.25[\text{TeV}^{-4}]$$

- Literature reference (arXiv:0710.3100):

$$\frac{1}{\Lambda_\pi^2 m_1^2} < 0.238 \cdot 10^{-2}[\text{TeV}^{-4}]$$

classic ADD (arXiv:hep-ph/9811291)

- Limit from four top-quark production:

$$\Lambda_{GRW} > 1.5\text{TeV}$$

- Literature reference (arXiv:1803.08030)

$$\Lambda_{GRW} > 10.1\text{TeV}$$

Summary

- Matching of extra-dimensional gravity induced effective opertators to dimension 8 SMEFT was performed
- Experimental limits for WC of corresponding SMEFT operators were obtained (for now, only from four-top production observation)
- WC limits were projected to constraints on physical parameters of several particular scenarios (for now, only for Stabilized RS1 model and classic ADD)