General constraints on Extra Dimensional gravity in SMEFT approach

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Aleshko A.M., Boos E.E.

SINP MSU

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SMEFT

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

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum \frac{c_i^{\{6\}}}{\Lambda^2} O_i^{d=6} + \sum \frac{c_i^{\{8\}}}{\Lambda^4} O_i^{d=8} + \dots, \quad (1)$$

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:

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

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

Models with extra spatial dimensions

(4+δ)-dimensional action

$$S \sim M_*^{2+\delta} \int d^{4+\delta}x\sqrt{-g}R + \int d^4x\sqrt{-\tilde{g}}\mathcal{L}_{SM} + \dots, \tag{3}$$

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

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

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:

$$\mathcal{L}_{int} \simeq c_T T_{\mu\nu} T^{\mu\nu} + c_S T^{\mu}_{\mu} T^{\nu}_{\nu}, \tag{5}$$

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.

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

Matching

Example

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

$$T_F^{\mu\nu} = \frac{i}{2}\bar{\psi}\gamma^\mu D^\nu \psi + \frac{i}{2}\bar{\psi}\gamma^\nu D^\mu \psi - \frac{i}{4}\partial^\mu(\bar{\psi}\gamma^\nu\psi) - \frac{i}{4}\partial^\nu(\bar{\psi}\gamma^\mu\psi) + ig^{\mu\nu}(\frac{1}{2}\partial_\rho(\bar{\psi}\gamma^\rho\psi) - \bar{\psi}\gamma^\rho D_\rho\psi), \tag{6}$$

Its contractions can be simplified using the following techniques

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

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

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

$$(\bar{u}^\alpha\gamma^\mu u^\beta)(\bar{u}^\beta\gamma_\mu u^\alpha) \longrightarrow 2(\bar{u}^\alpha\gamma^\mu T^A u^\alpha)(\bar{u}^\beta\gamma_\mu T^A u^\beta) + \frac{1}{3}(\bar{u}^\alpha\gamma^\mu u^\alpha)(\bar{u}^\beta\gamma_\mu u^\beta) \tag{7}$$

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

$$(\ldots)^\nu D_\mu D_\nu(\bar{u}\gamma^\mu u) \longrightarrow D_\nu(\ldots)^\nu D_\mu(\bar{u}\gamma^\mu u) + (\text{total derivative}) \tag{8}$$

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	
$Q_{B^4}^{(1)}$	$(B_{\mu\nu}B^{\mu\nu})(B_{\rho\sigma}B^{\rho\sigma})$	$\frac{1}{4}$	0
$Q_{B^4}^{(2)}$	$(B_{\mu\nu}\widetilde{B}^{\mu\nu})(B_{\rho\sigma}\widetilde{B}^{\rho\sigma})$	$\frac{1}{4}$	0
$Q_{G^4}^{(1)}$	$(G_{\mu\nu}G^{\mu\nu})(G_{\rho\sigma}G^{\rho\sigma})$	$\frac{1}{4}$	0
$Q_{G^4}^{(2)}$	$(G_{\mu\nu}\widetilde{G}^{\mu\nu})(G_{\rho\sigma}\widetilde{G}^{\rho\sigma})$	$\frac{1}{4}$	0
$Q_{W^4}^{(1)}$	$(W_{\mu\nu}W^{\mu\nu})(W_{\rho\sigma}W^{\rho\sigma})$	$\frac{1}{4}$	0
$Q_{W^4}^{(2)}$	$(W_{\mu\nu}\widetilde{W}^{\mu\nu})(W_{\rho\sigma}\widetilde{W}^{\rho\sigma})$	$\frac{1}{4}$	0
$Q_{G^2B^2}^{(1)}$	$(B_{\mu\nu}B^{\mu\nu})(G_{\rho\sigma}G^{\rho\sigma})$	$-\frac{3}{2}$	0
$Q_{G^2B^2}^{(2)}$	$(B_{\mu\nu}\widetilde{B}^{\mu\nu})(G_{\rho\sigma}\widetilde{G}^{\rho\sigma})$	$-\frac{1}{2}$	0
$Q_{G^2W^2}^{(1)}$	$(W_{\mu\nu}W^{\mu\nu})(G_{\rho\sigma}G^{\rho\sigma})$	$-\frac{3}{2}$	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

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:

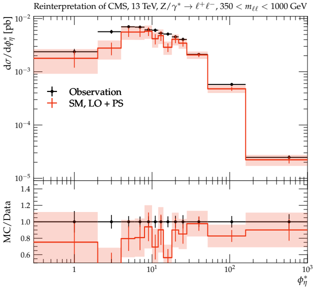
$$\sigma = \sigma_{SM} + \sum_k \frac{C_i}{\Lambda^4}\sigma_k^{(1)} + \sum_{j<=k} \frac{C_i C_k}{\Lambda^8}\sigma_{k,j}^{(2)}, \quad (9)$$

- 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**

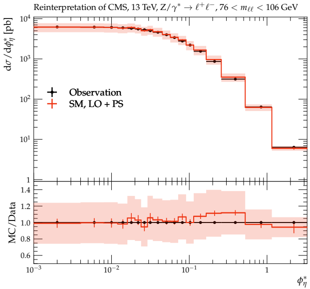
Given above, limits are obtained using MC sampling technique

Observables: Drell-Yan double-differential (CMS arXiv:2205.04897)

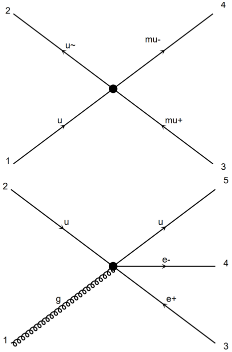
m_{ll} slices vs $p_{T,ll}$



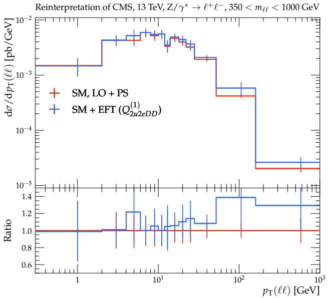
m_{ll} slices vs $\phi^\star_\eta$

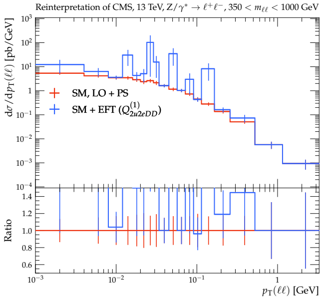


Examples of diagrams with inclusion of effective vertices:



Following spectra slices contribute to the fit:





Following operators are restricted in the analysis:

$$Q^{(1)}_{l^2 q^2 D^2} = (\bar{l}\gamma^\mu \overleftrightarrow{D}^\nu l)(\bar{q}\gamma_\mu \overleftrightarrow{D}_\nu q),$$
$$Q^{(1)}_{q^2 e^2 D^2} = (\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q)(\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e),$$
$$Q^{(1)}_{l^2 d^2 D^2} = (\bar{l}\gamma^\mu \overleftrightarrow{D}^\nu l)(\bar{d}\gamma_\mu \overleftrightarrow{D}_\nu d),$$
$$Q^{(1)}_{e^2 d^2 D^2} = (\bar{e}\gamma^\mu \overleftrightarrow{D}^\nu e)(\bar{d}\gamma_\mu \overleftrightarrow{D}_\nu d),$$
$$Q^{(1)}_{l^2 u^2 D^2} = (\bar{l}\gamma^\mu \overleftrightarrow{D}^\nu l)(\bar{u}\gamma_\mu \overleftrightarrow{D}_\nu u),$$
$$Q^{(1)}_{e^2 u^2 D^2} = (\bar{e}\gamma^\mu \overleftrightarrow{D}^\nu e)(\bar{u}\gamma_\mu \overleftrightarrow{D}_\nu u),$$

Fit result

$\psi^4 D^2$

Name	Definition	Matching coefficient	Limits on WC $C_k/\Lambda^4[\mathrm{TeV}^{-4}]$
$Q^{(1)}_{l^2 q^2 D^2}$	$(\bar{l}\gamma^\mu \overleftrightarrow{D}^\nu l)(\bar{q}\gamma_\mu \overleftrightarrow{D}_\nu q)$	$C_T\frac{1}{4}$	[-0.045, 0.257]
$Q^{(1)}_{q^2 e^2 D^2}$	$(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q)(\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)$	$C_T\frac{1}{4}$	[-0.448, 0.335]
$Q^{(1)}_{l^2 d^2 D^2}$	$(\bar{l}\gamma^\mu \overleftrightarrow{D}^\nu l)(\bar{d}\gamma_\mu \overleftrightarrow{D}_\nu d)$	$C_T\frac{1}{4}$	[-0.401, 0.481]
$Q^{(1)}_{e^2 d^2 D^2}$	$(\bar{e}\gamma^\mu \overleftrightarrow{D}^\nu e)(\bar{d}\gamma_\mu \overleftrightarrow{D}_\nu d)$	$C_T\frac{1}{4}$	[-0.129, 0.238]
$Q^{(1)}_{l^2 u^2 D^2}$	$(\bar{l}\gamma^\mu \overleftrightarrow{D}^\nu l)(\bar{u}\gamma_\mu \overleftrightarrow{D}_\nu u)$	$C_T\frac{1}{4}$	[-0.405, 0.421]
$Q^{(1)}_{e^2 u^2 D^2}$	$(\bar{e}\gamma^\mu \overleftrightarrow{D}^\nu e)(\bar{u}\gamma_\mu \overleftrightarrow{D}_\nu u)$	$C_T\frac{1}{4}$	[-0.251, 0.105]

Table 1: Definitions, matching coefficients and statistical limits for corresponding WC of operators of the $\psi^4 D^2$ class, constrained from data of CMS 2205.04897 analysis.

Projection of the WC bounds on physical parameters

Result for effective parameters c_T and c_S

$$-0.18[\text{TeV}^{-4}] < c_T < 0.41[\text{TeV}^{-4}],$$

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

Stabilized RS1 model (arXiv:0710.3100)

- Limit from four top-quark production:

$$\frac{1}{\Lambda_\pi^2 m_1^2} < 0.23[\text{TeV}^{-4}]$$

- 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:

$$\Lambda_{GRW} > 2.28\text{TeV}$$

- 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 from Drell-Yan double-differential measurement
- WC limits were projected to constraints on physical parameters of some particular scenarios (Stabilized RS1 model and classic ADD)