On the Phenomenology of the GRSMEFT

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Outline

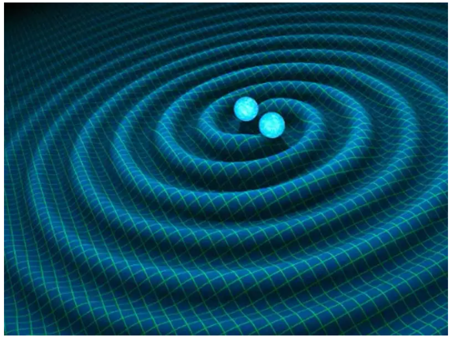
- Motivation
- The GRSMEFT
- Matching to toy UV model
- Testing GRSMEFT at LHC
- Bounds from jet + MET searches

Motivation

- Gravity is related to many fundamental problems in physics
  - Dark Matter
  - Quantum Gravity
  - Cosmological constant problem $(\Lambda_{cc} \ll M_{\rm Pl}^4)$
  - Electroweak hierarchy problem $(v^2 \ll M_{\rm Pl}^2)$

➢ We should test gravity by all means possible!

Motivation



- Experiments will be sensitive to low Λ
  - Gravitational waves: BH mergers

[Endlich, Gorbenko, Huang, Senatore 1704.01590]

$$\frac{1}{\Lambda^4}(C_{\mu\nu\rho\sigma}C^{\mu\nu\rho\sigma})^2\,,\;\Lambda \gtrsim \frac{1}{R_s} \sim \frac{1}{100\text{ km}} \sim 10^{-12}\text{ eV}$$

  - Torsion-balance detector

[Lee, Adelberger, Cook, Fleischer, Heckel 2002.11761]

$$\Lambda \gtrsim \frac{1}{d} \sim \frac{1}{50\ \mu\text{m}} \sim 10^{-3}\text{ eV}$$

The GRSMEFT

- The most general EFT of gravity coupled to the SM

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[-\frac{M_{Pl}^2}{2} R + \mathcal{L}_{\text{matter}} + \sum_n \frac{c_n}{\Lambda^{n-4}} \mathcal{L}_n \right]$$

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{2}{M_{Pl}} h_{\mu\nu}$$

$$-\frac{1}{M_{Pl}} h_{\mu\nu} T^{\mu\nu}$$

$$\Lambda \ll M_{Pl}$$

$$M_{Pl} = 2.435 \cdot 10^{18} \text{ GeV}$$

[Ruhdorfer, Serra, Weiler 1908.08050]

The GRSMEFT

- Gravitational degrees of freedom in Riemann tensor

$$R_{\mu\nu\rho\sigma} \sim (\mathbf{0},\mathbf{0}) \oplus (\mathbf{1},\mathbf{1}) \oplus (\mathbf{2},\mathbf{0}) \oplus (\mathbf{0},\mathbf{2})$$

$$\tilde{C}_{\mu\nu\rho\sigma} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}C^{\alpha\beta}{}_{\rho\sigma}$$

R $\qquad R_{\mu\nu} - \frac{1}{4}Rg_{\mu\nu}$ $\qquad C^{L,R}_{\mu\nu\rho\sigma} = \frac{1}{2}(C_{\mu\nu\rho\sigma} \pm i\tilde{C}_{\mu\nu\rho\sigma})$

$$C_{\mu\nu\rho\sigma} = R_{\mu\nu\rho\sigma} - (g_{\mu[\rho}R_{\sigma]\nu} - g_{\nu[\rho}R_{\sigma]\mu}) + \frac{1}{3}g_{\mu[\rho}g_{\sigma]\nu}R$$

- Einstein equations (EOM)

$$R_{\mu\nu} = \frac{1}{M_{Pl}^2}\left(T_{\mu\nu} - \frac{1}{2}Tg_{\mu\nu}\right), \qquad R = g^{\mu\nu}R_{\mu\nu} = -\frac{1}{M_{Pl}^2}T$$

➢ Operators with Ricci tensor and Ricci scalar can be redefined as pure matter operators

The GRSMEFT

- Operator terms of dimension 6

$$\begin{aligned}
\mathcal{L}_6 = {} & \frac{c_1}{\Lambda^2} C_{\mu\nu}{}^{\rho\sigma} C^{\mu\nu\alpha\beta} C_{\alpha\beta\rho\sigma} + \frac{\tilde{c}_1}{\Lambda^2} C_{\mu\nu}{}^{\rho\sigma} C^{\mu\nu\alpha\beta} \tilde{C}_{\alpha\beta\rho\sigma} \\
& + \frac{c_2}{\Lambda^2} \mathcal{H}^\dagger \mathcal{H} C_{\mu\nu\rho\sigma} C^{\mu\nu\rho\sigma} + \frac{\tilde{c}_2}{\Lambda^2} \mathcal{H}^\dagger \mathcal{H} C_{\mu\nu\rho\sigma} \tilde{C}^{\mu\nu\rho\sigma} \\
& + \frac{c_3}{\Lambda^2} B^{\mu\nu} B^{\rho\sigma} C_{\mu\nu\rho\sigma} + \frac{\tilde{c}_3}{\Lambda^2} B^{\mu\nu} B^{\rho\sigma} \tilde{C}_{\mu\nu\rho\sigma} \\
& + \frac{c_4}{\Lambda^2} G^{\mu\nu} G^{\rho\sigma} C_{\mu\nu\rho\sigma} + \frac{\tilde{c}_4}{\Lambda^2} G^{\mu\nu} G^{\rho\sigma} \tilde{C}_{\mu\nu\rho\sigma} \\
& + \frac{c_5}{\Lambda^2} W^{\mu\nu} W^{\rho\sigma} C_{\mu\nu\rho\sigma} + \frac{\tilde{c}_5}{\Lambda^2} W^{\mu\nu} W^{\rho\sigma} \tilde{C}_{\mu\nu\rho\sigma}
\end{aligned}$$

Pure Gravity

Matter couplings
beyond the SM

Matching to toy UV completion

- Heavy fermion and heavy scalar charged under $SU(3)_c$

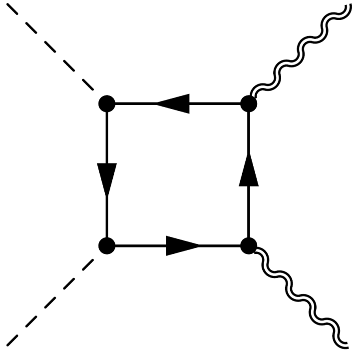
$$\mathcal{L}_{UV} = \mathcal{L}_f + \mathcal{L}_{sc} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm QCD}$$

$$\mathcal{L}_f = \bar{\psi} i \not{D} \psi - \frac{\sqrt{2} m}{v} \bar{\psi}_L \mathcal{H} \psi_R + \text{h.c.}$$

$$\mathcal{L}_{sc} = (D_\mu \phi)^\dagger D^\mu \phi - \frac{2m^2}{v^2} (\mathcal{H}^\dagger \mathcal{H})(\phi^\dagger \phi)$$

- After integrating out heavy d.o.f.s, GRSMEFT is an expansion in m and M_{Pl}

Matching to $\mathcal{H}^\dagger\mathcal{H}C_{\mu\nu\rho\sigma}C^{\mu\nu\rho\sigma}$



$\times\dfrac{1}{5760\pi^2\ v^2}$	fermion	scalar
$\mathcal{H}^\dagger\mathcal{H}C_{\mu\nu\rho\sigma}C^{\mu\nu\rho\sigma}$	7	4
$\mathcal{H}^\dagger\mathcal{H}R_{\mu\nu}R^{\mu\nu}$	22	4
$\mathcal{H}^\dagger\mathcal{H}RR$	$-\frac{22}{3}$	$\frac{26}{3}$
$(D^\mu\mathcal{H})^\dagger(D^\nu\mathcal{H})R_{\mu\nu}$	-88	-16
$(D^\mu\mathcal{H})^\dagger(D_\mu\mathcal{H})R$	20	-40
$\mathcal{H}^\dagger\mathcal{H}(\nabla^\mu\nabla_\mu R)$	12	24
$(D^\mu D_\mu\mathcal{H})^\dagger(D^\nu D_\nu\mathcal{H})$	72	24

$\longrightarrow \mathcal{L}_6$ (GRSMEFT)

$\dfrac{1}{M_{\rm Pl}^\alpha}$SMEFT

$\longrightarrow$ SMEFT

Matching to $C^{\mu\nu\rho\sigma}G_{\mu\nu}G_{\rho\sigma}$

$\times \dfrac{T_F \cdot \alpha_s}{720\pi\, m^2}$	fermion	scalar	
$g_s f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	-2	1	$\longrightarrow$ SMEFT
$C^{\mu\nu\rho\sigma}G_{\mu\nu}G_{\rho\sigma}$	-2	1	$\longrightarrow \mathcal{L}_6$ (GRSMEFT)
$R^{\mu\nu}g^{\rho\sigma}G_{\mu\rho}G_{\nu\sigma}$	22	4	$\longrightarrow$ $\dfrac{1}{M_{\mathrm{Pl}}^{\alpha}}$SMEFT
$Rg^{\mu\nu}g^{\rho\sigma}G_{\mu\rho}G_{\nu\sigma}$	$-\frac{13}{3}$	$\frac{13}{6}$	$\longrightarrow$ $\dfrac{1}{M_{\mathrm{Pl}}^{\alpha}}$SMEFT
$(\nabla^\mu G_{\mu\lambda})^2$	-24	-3	$\longrightarrow$ SMEFT

Matching to toy UV completion

- N copies of the heavy fermion / scalar with mass m

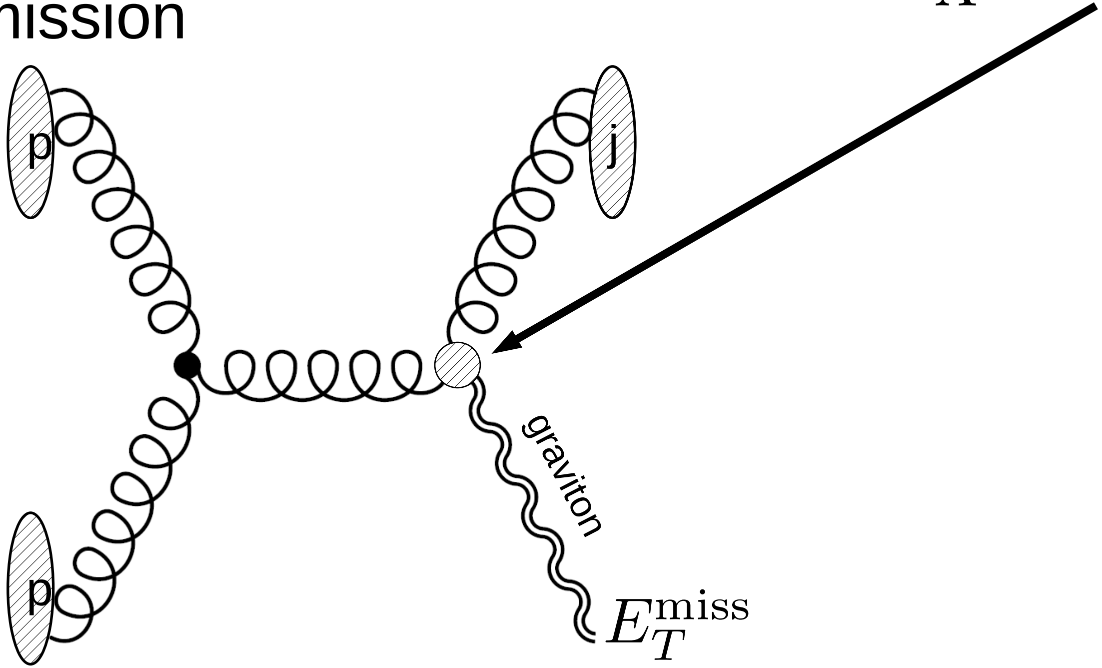
$$\frac{c_i}{\Lambda^2} \sim \frac{N}{m^2} \longrightarrow \text{Large coefficient / small } \Lambda$$

- In general we would like to be agnostic about the UV completion!
- We assume that GRSMEFT operators are the only generated operators

Testing GRSMEFT at the LHC

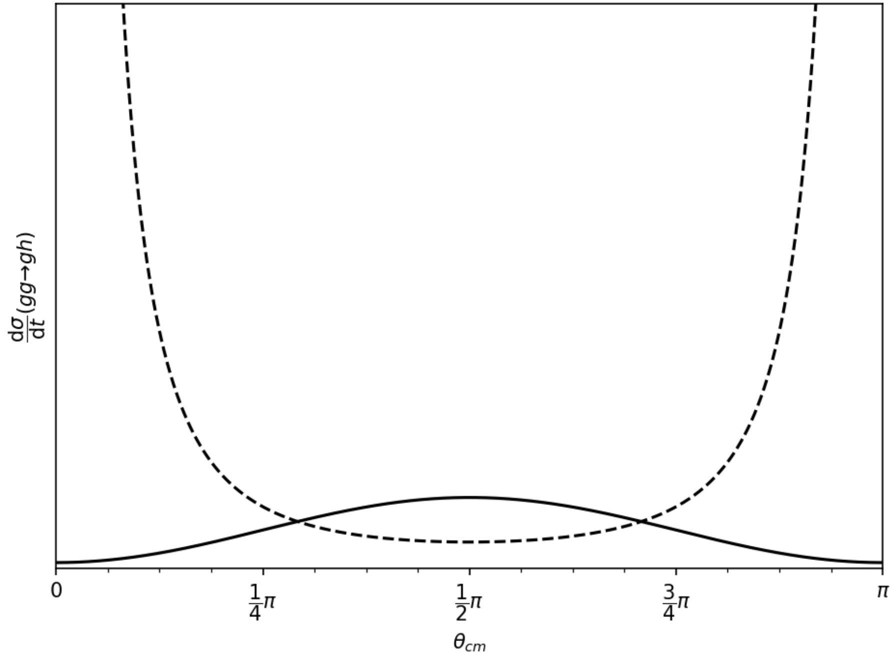
$$\mathcal{L}_6 = \frac{c_4}{\Lambda^2} G^{\mu\nu} G^{\rho\sigma} C_{\mu\nu\rho\sigma} + \frac{\tilde{c}_4}{\Lambda^2} G^{\mu\nu} G^{\rho\sigma} \tilde{C}_{\mu\nu\rho\sigma}$$

- Want to explore simple observable
- M_{Pl} is large! $C_{\mu\nu\rho\sigma} \sim \frac{1}{M_{\rm Pl}} \partial_* \partial_* h_{**}$
- Real graviton emission

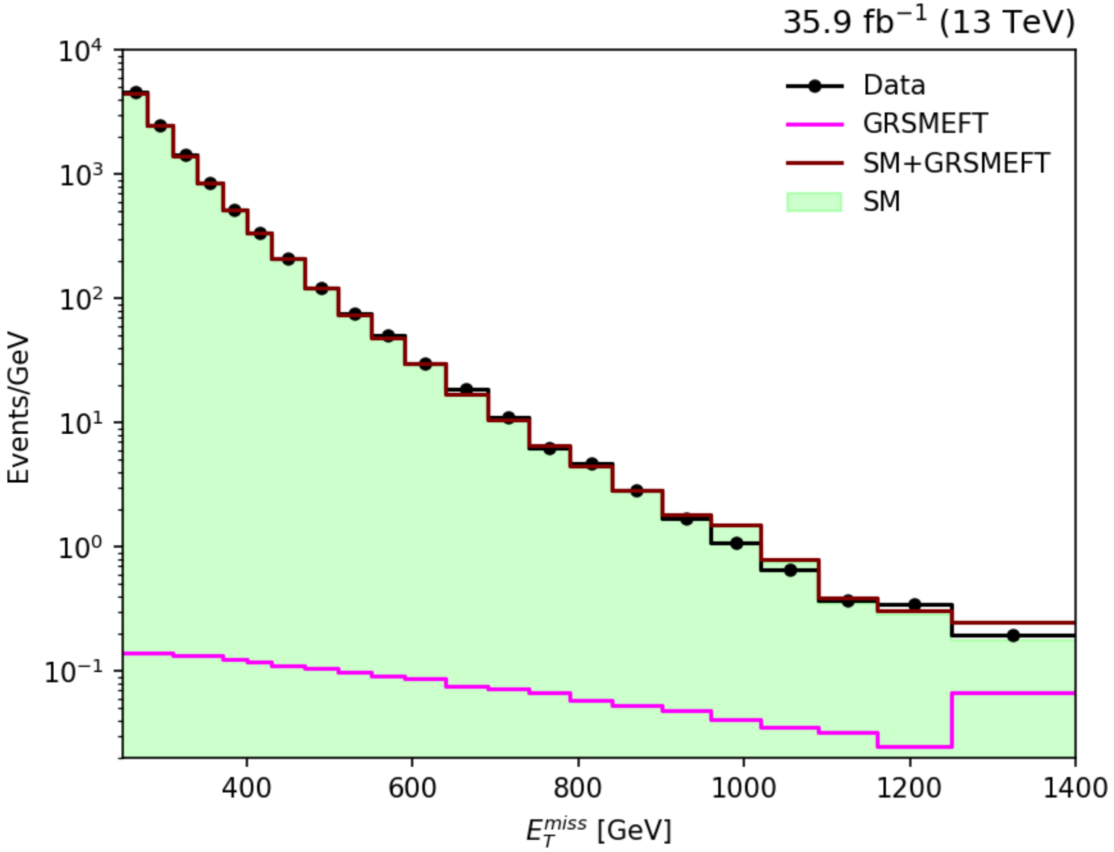


Parton Level Amplitude

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(gg \to gh) = \frac{3\alpha_s}{32}\frac{1}{s^2}\frac{1}{M_{\mathrm{Pl}}^2}\left[\boxed{\frac{s^4+t^4+u^4}{stu}} + \boxed{\frac{2(c_4^2+\tilde{c}_4^2)}{\Lambda^4}\; stu}\right]$$



CMS Search for jet + MET



Bounds from CMS

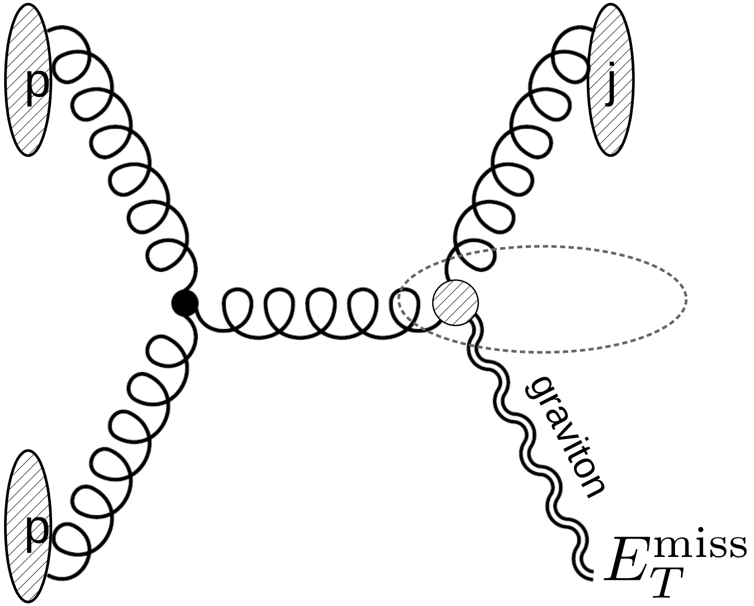
- $\mathcal{L}_6 = \frac{c_4}{\Lambda^2} G^{\mu\nu} G^{\rho\sigma} C_{\mu\nu\rho\sigma} + \frac{\tilde{c}_4}{\Lambda^2} G^{\mu\nu} G^{\rho\sigma} \tilde{C}_{\mu\nu\rho\sigma}$
- $c_4^2 + \tilde{c}_4^2 = 1$

➢ $\Lambda \gtrsim 340 \text{ keV} \sim \frac{1}{1 \text{ pm}}$ $(m_* \geq 5 \text{ TeV})$

- Gravitational waves: $\Lambda \gtrsim \frac{1}{R_s} \sim \frac{1}{100 \text{ km}} \sim 10^{-12} \text{ eV}$
- Torsion: $\Lambda \gtrsim \frac{1}{d} \sim \frac{1}{50\ \mu\text{m}} \sim 10^{-3} \text{ eV}$

EFT Validity

- Discard all events with $\sqrt{\hat{s}} \geq m_*$



$$\hat{s} = (p_g + p_h)^2 \geq (p_{T,\min,j} + p_{T,\min,h})^2 = (2E_{T,\min}^{\mathrm{miss}})^2$$

Summary

- Test gravity in all possible ways
- Gravity coupled to the SM is parameterized in the GRSMEFT
- GRSMEFT is testable at the LHC
- Bound on Λ of $\mathcal{O}(100\ \mathrm{keV})$ from jet + MET searches for gravitational couplings to gluons

Outlook

- Other observables
- Indirect tests

Backup

Bounds for $G^{\mu\nu}G^{\rho\sigma}C_{\mu\nu\rho\sigma}$-type operators