Probing New Physics through Entanglement in Diboson Production

Rafael Aoude, E.M., Fabio Maltoni, Luca Mantani – arXiv:2307.09675 [hep-ph]

Eric Madge

GGI – November 8, 2023

Introduction

so far in the workshop ...

top pairs

- Standard Model ✔
  see talks by J.R.M. de Nova, J.W. Howarth and D. Gonçalves

$h \to ZZ^*,\ WW^*$

- Standard Model ✔
  see talks by A. Barr, T. Maurin and J. Moreno

$WW,\ ZZ,\ WZ$

- Standard Model ✔
  see talk by A. Barr (also R.A. Morales)

Introduction

so far in the workshop ...

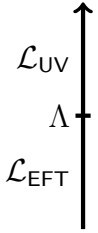
top pairs	$h \to ZZ^*,\ WW^*$	$WW,\ ZZ,\ WZ$
◌ Standard Model ✔ see talks by J.R.M. de Nova, J.W. Howarth and D. Gonçalves	◌ Standard Model ✔ see talks by A. Barr, T. Maurin and J. Moreno	◌ Standard Model ✔ see talk by A. Barr (also R.A. Morales)
◌ BSM ✔ see talks by L. Mantani and C. Severi	◌ BSM ✔ see talks by A. Bernal and L. Marzola	◌ BSM ✘ $\Longrightarrow$ this talk!

also: beyond QM (M. Eckstein)

Standard Model Effective Field Theory

- new physics at high scale Λ

  $\longrightarrow$ at low energies: EFT with SM fields only



$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d\geq 5} \sum_{n} \frac{C_n \, \mathcal{O}_n^{(d)}}{\Lambda^{d-4}}$$

$\Longrightarrow$ model independent

Standard Model Effective Field Theory

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dim-d operator composed of SM fields (respecting SM symmetries)

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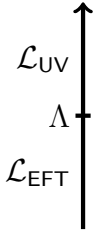

Standard Model Effective Field Theory

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Wilson coefficient

dim-d operator composed of SM fields (respecting SM symmetries)

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d\geq 5} \sum_{n} \frac{C_n \mathcal{O}_n^{(d)}}{\Lambda^{d-4}}$$

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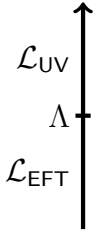

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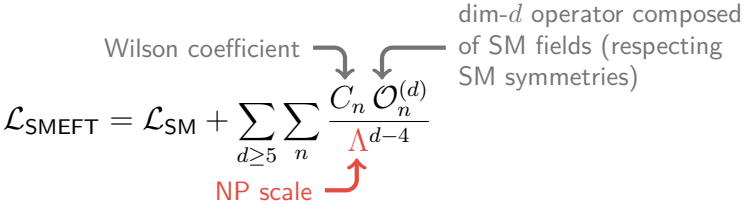

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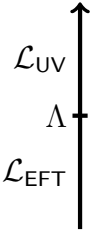

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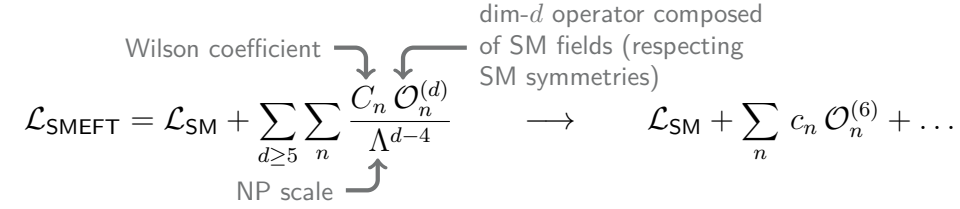

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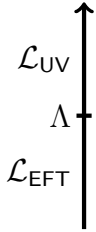

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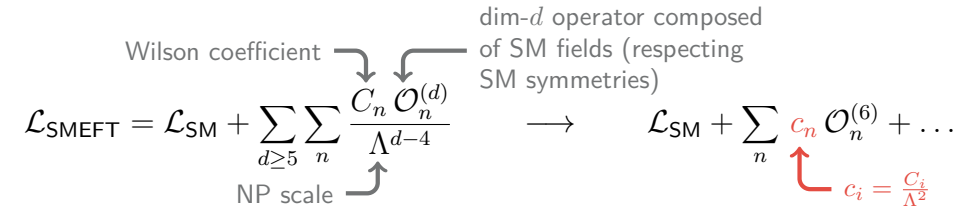

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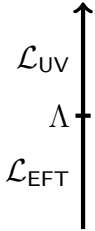

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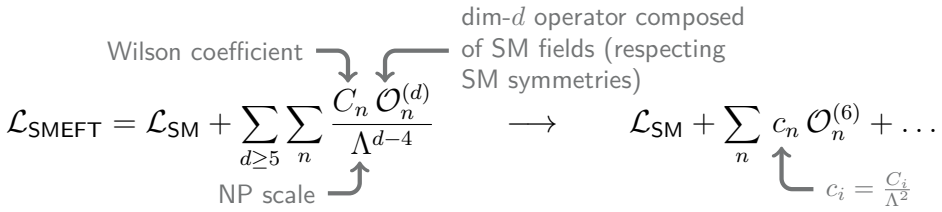

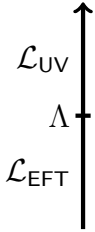

  $\Longrightarrow$ model independent

- Warsaw basis: (flavor universal) [Grzadkowski, Iskrzyński, Misiak, Rosiek (JHEP 2010)]
  - 1 dim-5 operator
  - 59 (non-$\not{B}$) + 4 ($\not{B}$) dim-6 operators

- here: 13 relevant CP-even dim-6 flavor-universal operators

Dimension-6 Operators

	Definition	95 % CL
two-fermion operators		
$c_{\varphi u}$	$i(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi)(\bar{u}\gamma^\mu u)$	$[-0.17, 0.14]$
$c_{\varphi d}$	$i(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi)(\bar{d}\gamma^\mu d)$	$[-0.07, 0.09]$
$c_{\varphi q}^{(1)}$	$i(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi)(\bar{q}\,\gamma^\mu\, q)$	$[-0.06, 0.22]$
$c_{\varphi q}^{(3)}$	$i(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \tau_I \varphi)(\bar{q}\,\gamma^\mu\,\tau^I q)$	$[-0.21, 0.05]$
$c_{\varphi e}$	$i(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi)(\bar{e}\gamma^\mu e)$	$[-0.21, 0.26]$
$c_{\varphi l}^{(1)}$	$i(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi)(\bar{l}\gamma^\mu l)$	$[-0.11, 0.13]$
$c_{\varphi l}^{(3)}$	$i(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \tau_I \varphi)(\bar{l}\gamma^\mu \tau^I l)$	$[-0.21, 0.05]$

	Definition	95 % CL
bosonic operators		
c_W	$\varepsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$	$[-0.18, 0.22]$
$c_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W^I_{\mu\nu}$	$[-0.15, 0.30]$
$c_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B_{\mu\nu} B^{\mu\nu}$	$[-0.11, 0.11]$
$c_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi) B^{\mu\nu} W^I_{\mu\nu}$	$[-0.17, 0.27]$
$c_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$	$[-0.52, 0.43]$
four-fermion operator		
c_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	$[-0.16, 0.02]$

95 % CL bounds in TeV^{-2} from [SMEFIT (JHEP 2021)]

Coupling Modification

- universal shifts in G_f, $\sin\theta_W$ and g_Z

$c_{\varphi u}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{u}\gamma^\mu u\right)$
$c_{\varphi d}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{d}\gamma^\mu d\right)$
$c_{\varphi q}^{(1)}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{q}\,\gamma^\mu\, q\right)$
$c_{\varphi q}^{(3)}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \tau_I \varphi\right)\left(\bar{q}\,\gamma^\mu\,\tau^I q\right)$
$c_{\varphi e}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{e}\gamma^\mu e\right)$
$c_{\varphi l}^{(1)}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{l}\gamma^\mu l\right)$
$c_{\varphi l}^{(3)}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \tau_I \varphi\right)\left(\bar{l}\gamma^\mu \tau^I l\right)$
c_W	$\varepsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$
$c_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B_{\mu\nu} B^{\mu\nu}$
$c_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi) B^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$
c_{ll}	$\left(\bar{l}\gamma_\mu l\right)\left(\bar{l}\gamma^\mu l\right)$

Coupling Modification

- universal shifts in G_f, $\sin\theta_W$ and g_Z

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c_W	$\varepsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$
$c_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B_{\mu\nu} B^{\mu\nu}$
$c_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi) B^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$
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Coupling Modification

- universal shifts in G_f, $\sin\theta_W$ and g_Z

$c_{\varphi u}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{u}\gamma^\mu u\right)$
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c_W	$\varepsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$
$c_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W^{\mu\nu}_I W^I_{\mu\nu}$
$c_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B_{\mu\nu} B^{\mu\nu}$
$c_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi) B^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$
c_{ll}	$\left(\bar{l}\gamma_\mu l\right)\left(\bar{l}\gamma^\mu l\right)$

Coupling Modification

- universal shifts in G_f, $\sin\theta_W$ and g_Z
- direct modification of quark couplings to Z

$c_{\varphi u}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{u}\gamma^\mu u\right)$
$c_{\varphi d}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{d}\gamma^\mu d\right)$
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$c_{\varphi l}^{(3)}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi\right)\left(\bar{l}\gamma^\mu \tau^I l\right)$
c_W	$\varepsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$
$c_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B_{\mu\nu} B^{\mu\nu}$
$c_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi) B^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$
c_{ll}	$\left(\bar{l}\gamma_\mu l\right)\left(\bar{l}\gamma^\mu l\right)$

Coupling Modification

- universal shifts in G_f, $\sin\theta_W$ and g_Z
- direct modification of quark couplings to Z
- direct modification of (LH) quark couplings to W

$c_{\varphi u}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{u}\gamma^\mu u\right)$
$c_{\varphi d}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{d}\gamma^\mu d\right)$
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$c_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B_{\mu\nu} B^{\mu\nu}$
$c_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi) B^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$
c_{ll}	$\left(\bar{l}\gamma_\mu l\right)\left(\bar{l}\gamma^\mu l\right)$

Coupling Modification

- universal shifts in G_f, $\sin\theta_W$ and g_Z
- direct modification of quark couplings to Z
- direct modification of (LH) quark couplings to W
- direct modification of electron couplings to Z

$c_{\varphi u}$	$i\left(\varphi^\dagger \overleftrightarrow{D_\mu} \varphi\right)\left(\bar{u}\gamma^\mu u\right)$
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c_{ll}	$\left(\bar{l}\gamma_\mu l\right)\left(\bar{l}\gamma^\mu l\right)$

Coupling Modification

- universal shifts in G_f, $\sin\theta_W$ and g_Z
- direct modification of quark couplings to Z
- direct modification of (LH) quark couplings to W
- direct modification of electron couplings to Z
- direct modification of (LH) electron couplings to W

$c_{\varphi u}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{u}\gamma^\mu u\right)$
$c_{\varphi d}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{d}\gamma^\mu d\right)$
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$c_{\varphi l}^{(3)}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi\right)\left(\bar{l}\gamma^\mu \tau^I l\right)$
c_W	$\varepsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$
$c_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B_{\mu\nu} B^{\mu\nu}$
$c_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi) B^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$
c_{ll}	$\left(\bar{l}\gamma_\mu l\right)\left(\bar{l}\gamma^\mu l\right)$

Coupling Modification

- universal shifts in G_f, $\sin\theta_W$ and g_Z
- direct modification of quark couplings to Z
- direct modification of (LH) quark couplings to W
- direct modification of electron couplings to Z
- direct modification of (LH) electron couplings to W
- direct modification of triple gauge couplings

$c_{\varphi u}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{u}\gamma^\mu u\right)$
$c_{\varphi d}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{d}\gamma^\mu d\right)$
$c_{\varphi q}^{(1)}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{q}\,\gamma^\mu\, q\right)$
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$c_{\varphi e}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{e}\gamma^\mu e\right)$
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$c_{\varphi l}^{(3)}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi\right)\left(\bar{l}\gamma^\mu \tau^I l\right)$
c_W	$\varepsilon_{IJK} W^{I}_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$
$c_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B_{\mu\nu} B^{\mu\nu}$
$c_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi) B^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$
c_{ll}	$\left(\bar{l}\gamma_\mu l\right)\left(\bar{l}\gamma^\mu l\right)$

Coupling Modification

- universal shifts in G_f, $\sin\theta_W$ and g_Z
- direct modification of quark couplings to Z
- direct modification of (LH) quark couplings to W
- direct modification of electron couplings to Z
- direct modification of (LH) electron couplings to W
- direct modification of triple gauge couplings (including new Lorentz structures)

$c_{\varphi u}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{u}\gamma^\mu u\right)$
$c_{\varphi d}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{d}\gamma^\mu d\right)$
$c_{\varphi q}^{(1)}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{q}\,\gamma^\mu\, q\right)$
$c_{\varphi q}^{(3)}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \tau_I \varphi\right)\left(\bar{q}\,\gamma^\mu\,\tau^I q\right)$
$c_{\varphi e}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{e}\gamma^\mu e\right)$
$c_{\varphi l}^{(1)}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{l}\gamma^\mu l\right)$
$c_{\varphi l}^{(3)}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \tau_I \varphi\right)\left(\bar{l}\gamma^\mu \tau^I l\right)$
c_W	$\varepsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$
$c_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B_{\mu\nu} B^{\mu\nu}$
$c_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi) B^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$
c_{ll}	$\left(\bar{l}\gamma_\mu l\right)\left(\bar{l}\gamma^\mu l\right)$

Coupling Modification

- universal shifts in G_f, $\sin\theta_W$ and g_Z
- direct modification of quark couplings to Z
- direct modification of (LH) quark couplings to W
- direct modification of electron couplings to Z
- direct modification of (LH) electron couplings to W
- direct modification of triple gauge couplings (including new Lorentz structures)
- direct modification of Higgs couplings

$c_{\varphi u}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{u}\gamma^\mu u\right)$
$c_{\varphi d}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{d}\gamma^\mu d\right)$
$c_{\varphi q}^{(1)}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{q}\,\gamma^\mu\, q\right)$
$c_{\varphi q}^{(3)}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \tau_I \varphi\right)\left(\bar{q}\,\gamma^\mu\,\tau^I q\right)$
$c_{\varphi e}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{e}\gamma^\mu e\right)$
$c_{\varphi l}^{(1)}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \varphi\right)\left(\bar{l}\gamma^\mu l\right)$
$c_{\varphi l}^{(3)}$	$i\left(\varphi^\dagger \overset{\leftrightarrow}{D}_\mu \tau_I \varphi\right)\left(\bar{l}\gamma^\mu \tau^I l\right)$
c_W	$\varepsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$
$c_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B_{\mu\nu} B^{\mu\nu}$
$c_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi) B^{\mu\nu} W^I_{\mu\nu}$
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$c_{\varphi u}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{u}\gamma^\mu u)$
$c_{\varphi d}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{d}\gamma^\mu d)$
$c_{\varphi q}^{(1)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}\,\gamma^\mu\, q)$
$c_{\varphi q}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{q}\,\gamma^\mu\,\tau^I q)$
$c_{\varphi e}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{e}\gamma^\mu e)$
$c_{\varphi l}^{(1)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{l}\gamma^\mu l)$
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c_W	$\varepsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$
$c_{\varphi W}$	$(\varphi^\dagger\varphi - \frac{v^2}{2}) W^{\mu\nu}_I W^I_{\mu\nu}$
$c_{\varphi B}$	$(\varphi^\dagger\varphi - \frac{v^2}{2}) B_{\mu\nu} B^{\mu\nu}$
$c_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi) B^{\mu\nu} W^I_{\mu\nu}$
$c_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$
c_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$

SMEFT corrections

- Calculation at LO, including dim-6 and (dim-6)^2 SMEFT corrections

$$R = \sum_{\text{IS}} L_{\text{IS}}(\hat{s}) \overline{\sum_{\substack{\text{DOFs (excl.} \\ \text{FS spin)}}}} \mathcal{M}^* \mathcal{M}$$

SMEFT corrections

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$$\mathcal{M} = \mathcal{M}_{\mathsf{SM}} + \textstyle\sum_n \frac{C_n}{\Lambda^2} \mathcal{M}_n^{(\text{dim-6})}$$

$$R = \sum_{\mathsf{IS}} L_{\mathsf{IS}}(\hat{s}) \overline{\sum_{\substack{\text{DOFs (excl.} \\ \text{FS spin)}}}} \mathcal{M}^* \mathcal{M}$$

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$\mathcal{M} = \mathcal{M}_{\text{SM}} + \sum_n \frac{C_n}{\Lambda^2} \mathcal{M}_n^{(\text{dim-6})}$

- expand R-matrix to order $\mathcal{O}(\Lambda^{-4})$

$$\rho = \frac{R}{\operatorname{tr} R} = \frac{1}{9}\left\{ \frac{R_{\text{SM}}}{\tilde{A}_{\text{SM}}} + \sum_n \frac{C_n}{\Lambda^2}\left[\frac{R_n}{\tilde{A}_{\text{SM}}} - \frac{\tilde{A}_n R_{\text{SM}}}{\tilde{A}_{\text{SM}}^2}\right] + \sum_{n,m} \frac{C_n C_m}{\Lambda^4}\left[\frac{R_{nm}}{\tilde{A}_{\text{SM}}} - \frac{\tilde{A}_n R_m + \tilde{A}_{nm} R_{\text{SM}}}{\tilde{A}_{\text{SM}}^2} + \frac{\tilde{A}_n \tilde{A}_m R_{\text{SM}}}{\tilde{A}_{\text{SM}}^3}\right]\right\}$$

- similar: concurrence, purity, Bell violation, ...

Reminder: Concurrence

[Horodecki, Horodecki, Horodecki, Horodeck, RMP 2009]
[Ashby-Pickering, Barr, Wierzchucka, JHEP 2022]

$$\mathcal{C}(\rho) = \inf_{\{|\Psi\rangle\}} \left[\sum_i p_i \, \mathcal{C}(|\Psi_i\rangle) \right], \quad \mathcal{C}(|\Psi\rangle) = \sqrt{2\left(1 - \mathrm{tr}_A\left[\left(\mathrm{tr}_B\, |\Psi\rangle\langle\Psi|\right)^2\right]\right)}$$

- $0 \leq \mathcal{C}(\rho) \leq \dfrac{2}{\sqrt{3}}, \quad \mathcal{C}(\rho) > 0 \Longrightarrow$ entangled

Reminder: Concurrence

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- $0 \leq \mathcal{C}(\rho) \leq \dfrac{2}{\sqrt{3}}, \quad \mathcal{C}(\rho) > 0 \implies$ entangled
- for qutrits: analytically calculable only for pure states

  $\implies$ provide lower and upper bound:

$\rho_{A/B} = \mathrm{tr}_{B/A}\, \rho$

$$\left(\mathcal{C}(\rho)\right)^2 \geq \left(\mathcal{C}_{\mathsf{LB}}(\rho)\right)^2 = 2 \, \max\left[\mathrm{tr}\, \rho^2 - \mathrm{tr}\, \rho_A^2, \; \mathrm{tr}\, \rho^2 - \mathrm{tr}\, \rho_B^2\right]$$

$$\left(\mathcal{C}(\rho)\right)^2 \leq \left(\mathcal{C}_{\mathsf{UB}}(\rho)\right)^2 = 2 \, \min\left[1 - \mathrm{tr}\, \rho_A^2, \; 1 - \mathrm{tr}\, \rho_B^2\right]$$

Reminder: Concurrence

[Horodecki, Horodecki, Horodecki, Horodeck, RMP 2009]
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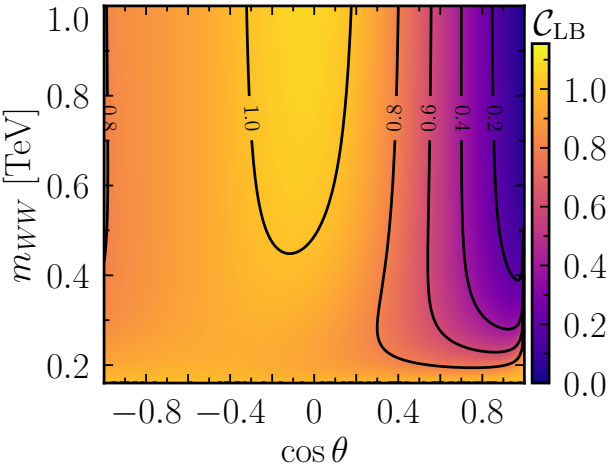
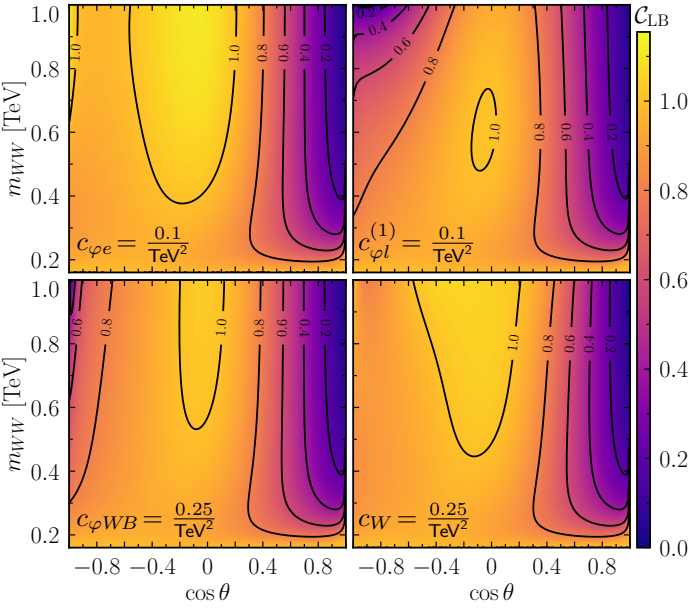
$$(\mathcal{C}(\rho))^2 \leq (\mathcal{C}_{\mathsf{UB}}(\rho))^2 = 2 \, \min\left[1 - \mathrm{tr}\, \rho_A^2, \; 1 - \mathrm{tr}\, \rho_B^2\right]$$

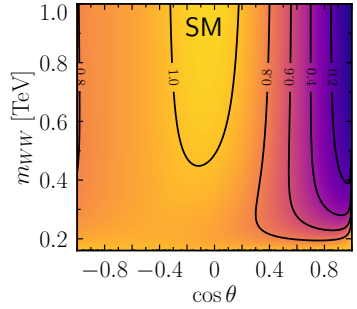
- for pure state: $P(\rho) = \mathrm{tr}\, \rho^2 = 1 \quad \implies \quad \mathcal{C}_{\mathsf{LB}}(\rho) = \mathcal{C}(\rho) = \mathcal{C}_{\mathsf{UB}}(\rho)$

SMEFT effects in $e^+e^- \to W^+W^-$

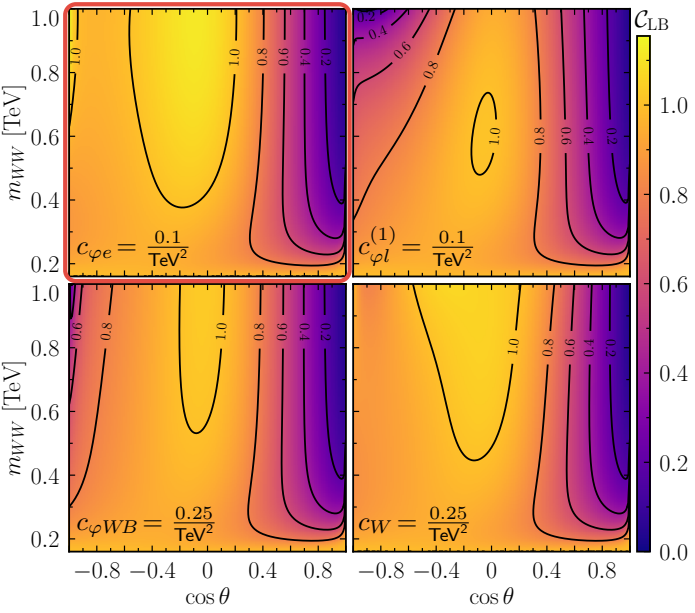


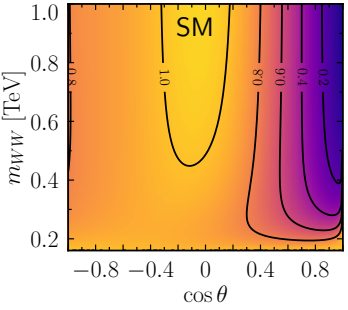
SMEFT effects in $e^+e^- \to W^+W^-$





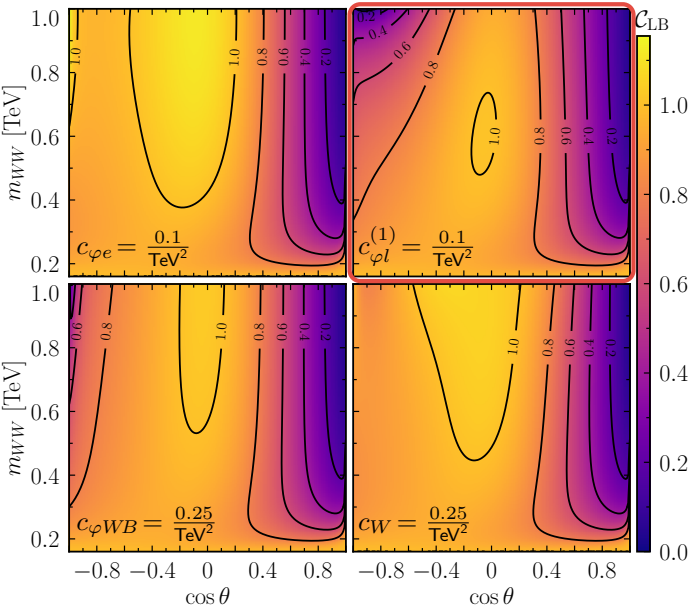
SMEFT effects in $e^+e^- \to W^+W^-$

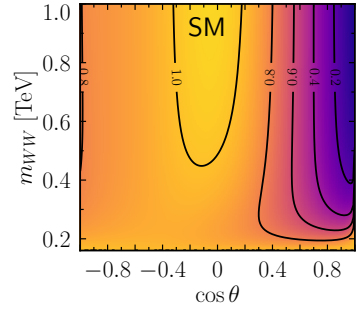




- $\mathcal{O}_{\varphi e}$: modifies $Ze^+_Re^-_R$ vertex
  $\Longrightarrow$ more entanglement in central and backward HE region

SMEFT effects in $e^+e^- \to W^+W^-$





- $\mathcal{O}_{\varphi e}$: modifies $Ze^+_Re^-_R$ vertex
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- $\mathcal{O}^{(1)}_{\varphi l}$: modifies $Ze^+_Le^-_L$ vertex
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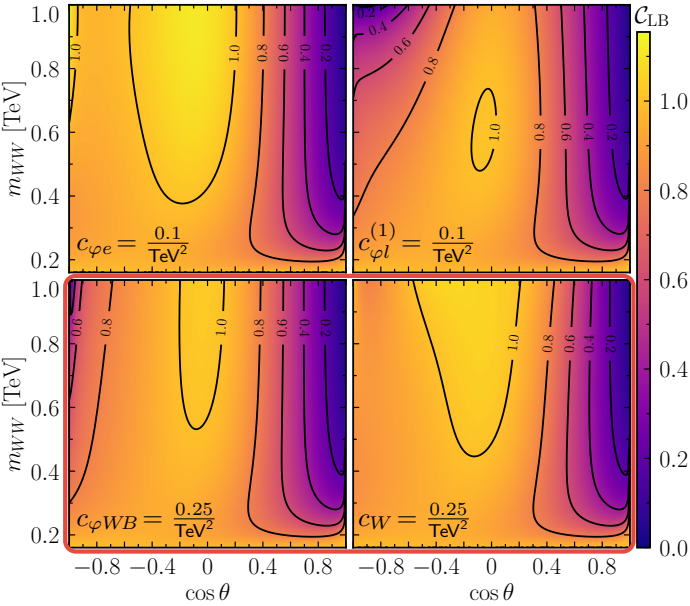
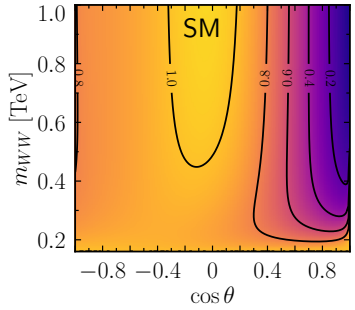
SMEFT effects in $e^+e^- \to W^+W^-$





- $\mathcal{O}_{\varphi e}$: modifies $Ze^+_Re^-_R$ vertex
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- $\mathcal{O}^{(1)}_{\varphi l}$: modifies $Ze^+_Le^-_L$ vertex
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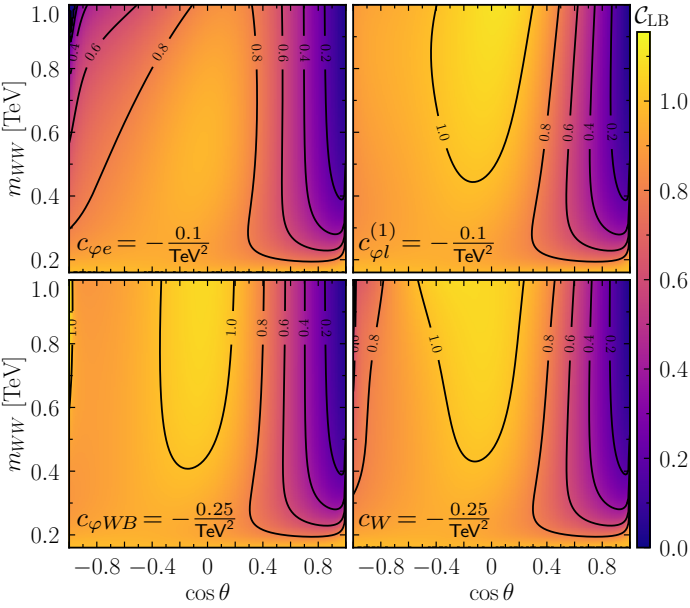
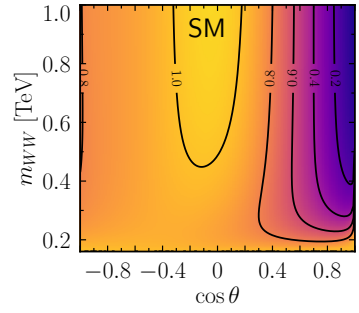
- $\mathcal{O}_{\varphi WB}$: modifies triple gauge coupling
  $\mathcal{O}_W$: non-SM Lorentz structure in TGC
  $\Longrightarrow$ small effect

SMEFT effects in $e^+e^- \to W^+W^-$





- $\mathcal{O}_{\varphi e}$: modifies $Ze^+_Re^-_R$ vertex
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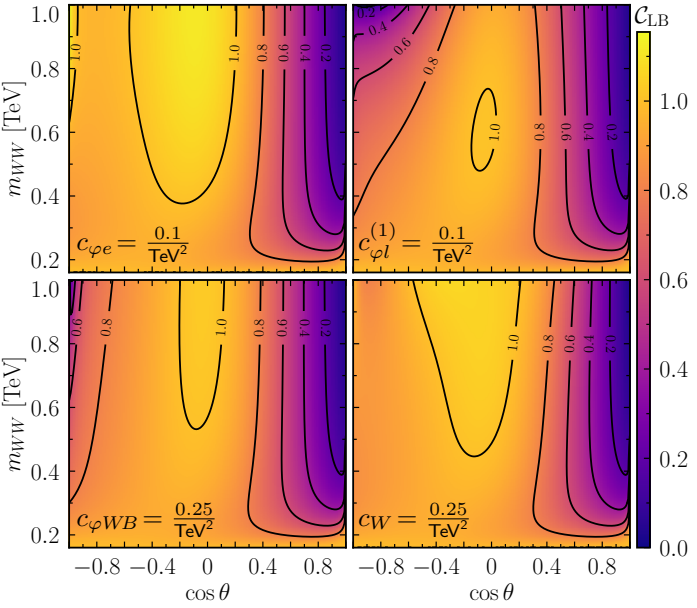
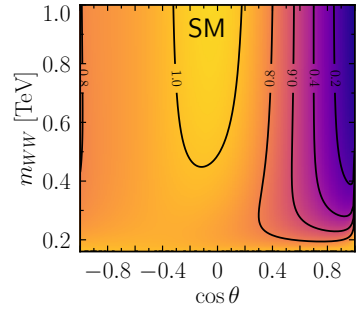
- $\mathcal{O}^{(1)}_{\varphi l}$: modifies $Ze^+_Le^-_L$ vertex
  $\Longrightarrow$ less entanglement in central and backward HE region
- $\mathcal{O}_{WWW}$, $\mathcal{O}_W$: modifies triple gauge coupling
  non-SM Lorentz structure in TGC
  $\Longrightarrow$ small effect

opposite effect for opposite sign

SMEFT effects in $e^+e^- \to W^+W^-$





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  $\mathcal{O}_W$: non-SM Lorentz structure in TGC
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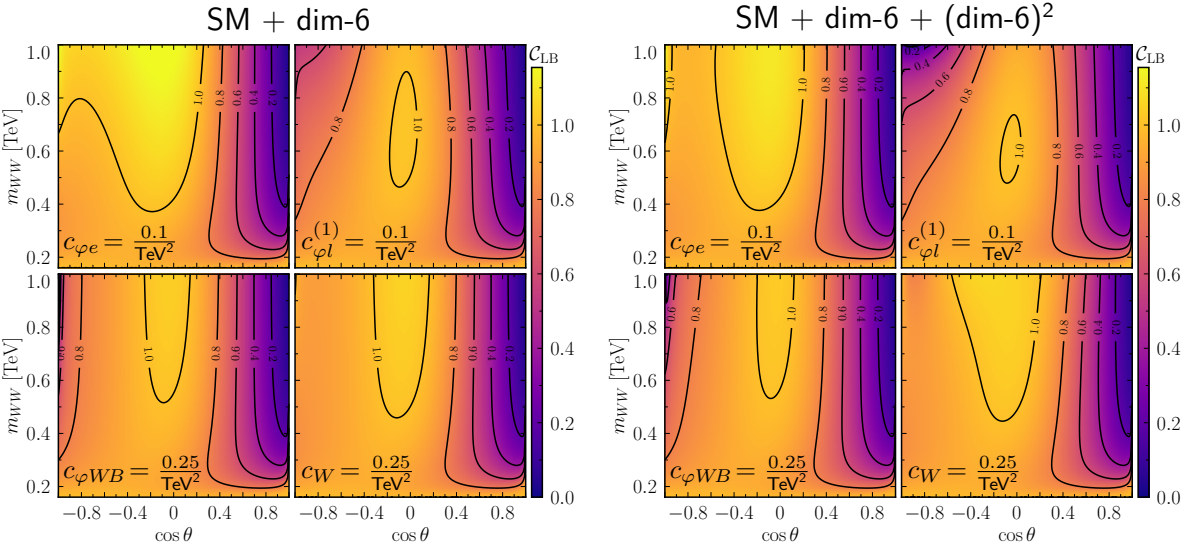
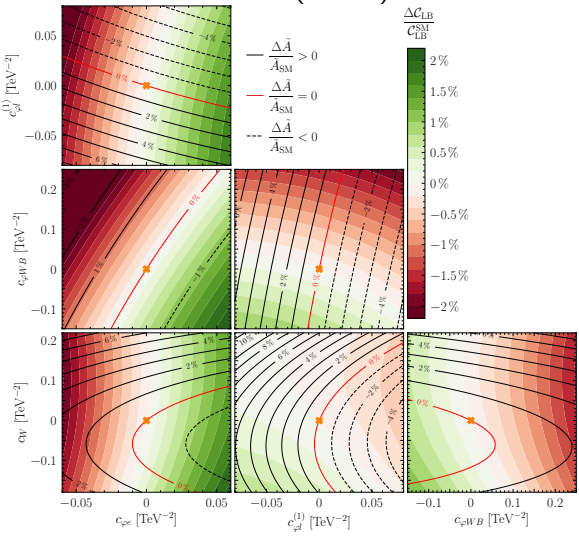
SMEFT effects in $e^+e^- \to W^+W^-$ at linear order



Central High-Energy Region ($e^+e^- \to W^+W^-$)

$$m_{WW} = 500\,\text{GeV},\ \cos\theta = 0$$

dim-6 + (dim-6)^2



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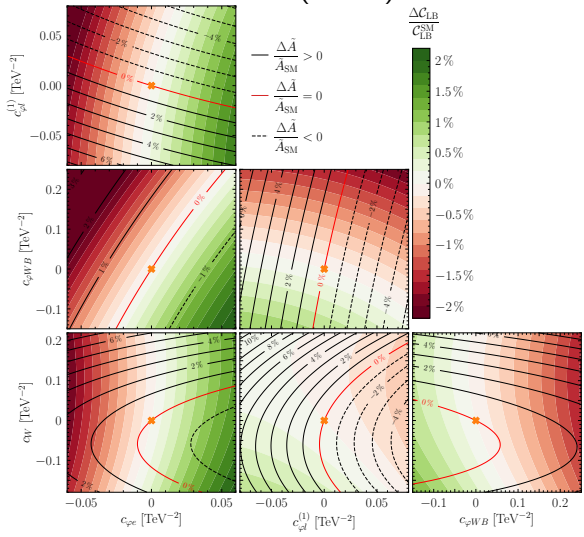
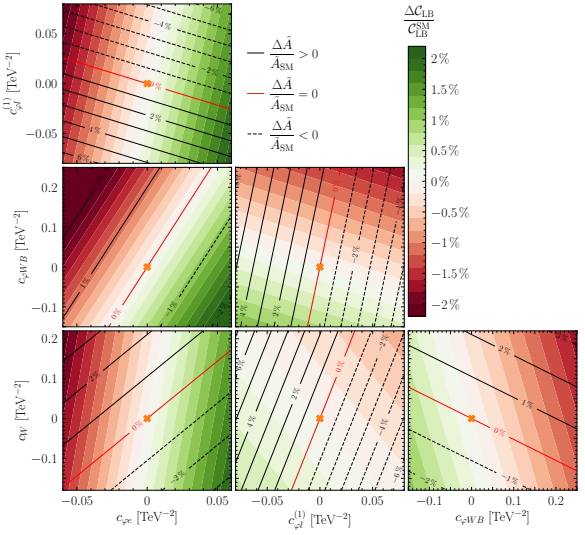
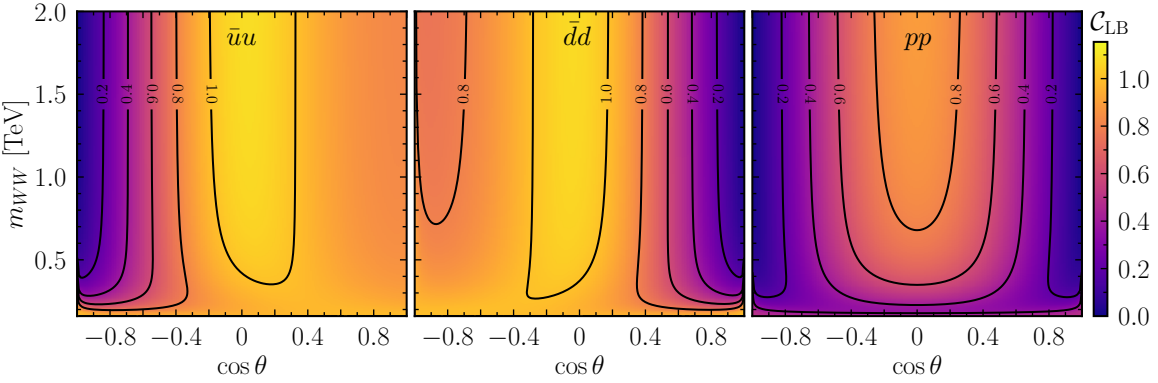


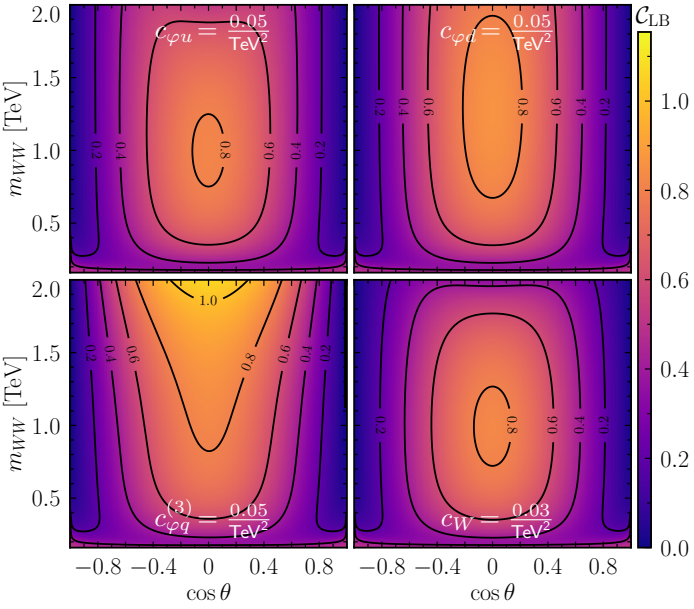
dim-6

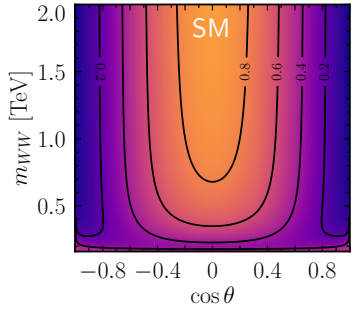


SMEFT effects in $pp \to W^+W^-$

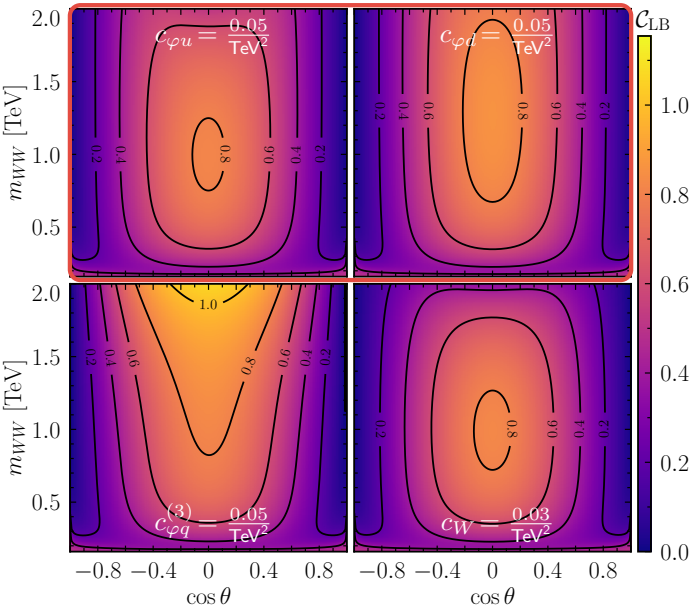


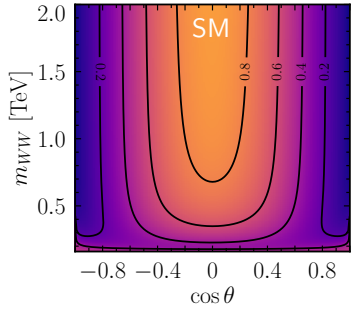
SMEFT effects in $pp \to W^+W^-$





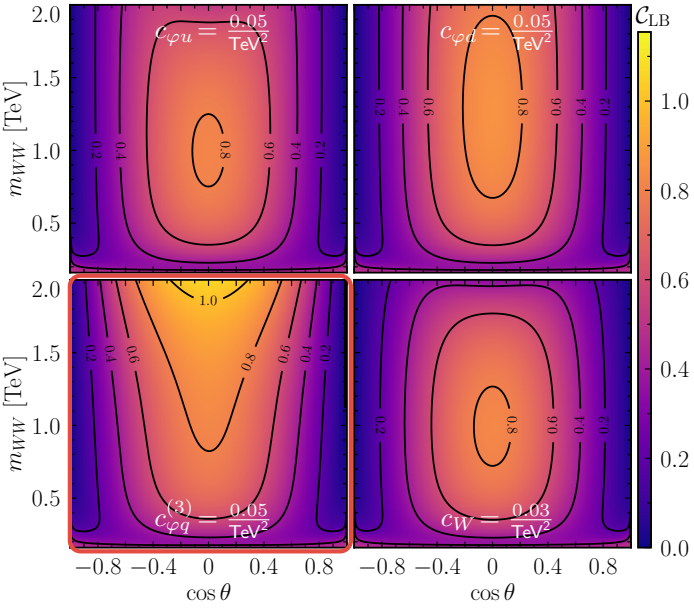
SMEFT effects in $pp \to W^+W^-$

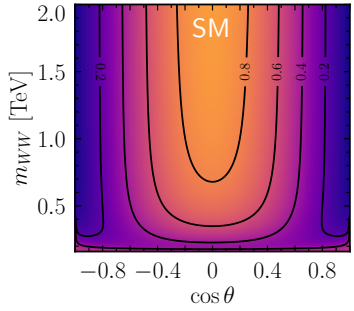




- $\mathcal{O}_{\varphi u}/\mathcal{O}_{\varphi d}$: modify $Z\bar{q}_R q_R$ vertex
  $\Longrightarrow$ less entanglement at high energy

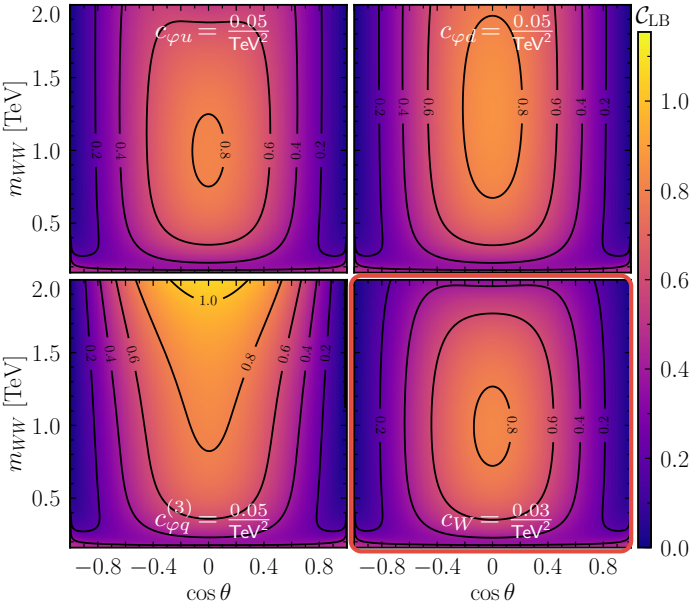
SMEFT effects in $pp \to W^+W^-$

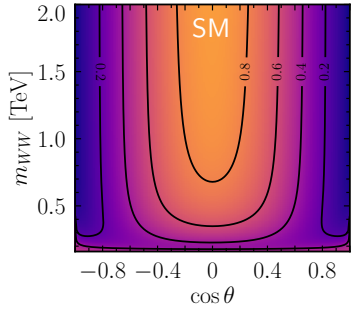




- $\mathcal{O}_{\varphi u}/\mathcal{O}_{\varphi d}$: modify $Z\bar{q}_R q_R$ vertex
  $\Longrightarrow$ less entanglement at high energy
- $\mathcal{O}_{\varphi q}^{(3)}$: modifies $W\bar{q}_L q'_L$ vertex
  $\Longrightarrow$ more entanglement at high energy

SMEFT effects in $pp \to W^+W^-$





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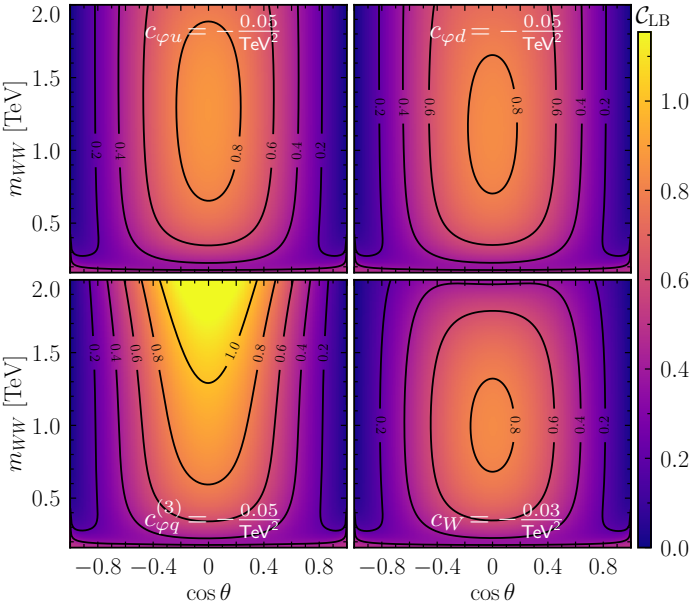
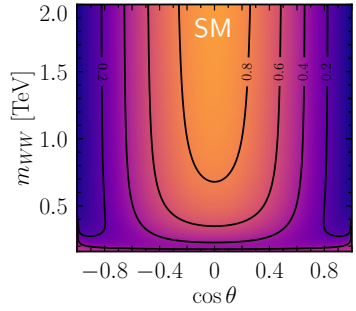
  $\Longrightarrow$ less entanglement at high energy
- $\mathcal{O}_{\varphi q}^{(3)}$: modifies $W\bar{q}_L q'_L$ vertex
  $\Longrightarrow$ more entanglement at high energy
- $\mathcal{O}_{\varphi W}$: additional Lorentz structures in triple gauge coupling

SMEFT effects in $pp \to W^+W^-$





- $\mathcal{O}_{\varphi u}/\mathcal{O}_{\varphi d}$: modify $Z\bar{q}_R q_R$ vertex
  $\Longrightarrow$ less entanglement at high energy
- $\mathcal{O}_{\varphi q}^{(3)}$: modifies $W\bar{q}_L q'_L$ vertex
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- $\mathcal{O}_{\varphi W}$: additional Lorentz structures in triple gauge coupling
- high-energy dominated by (dim-6)^2

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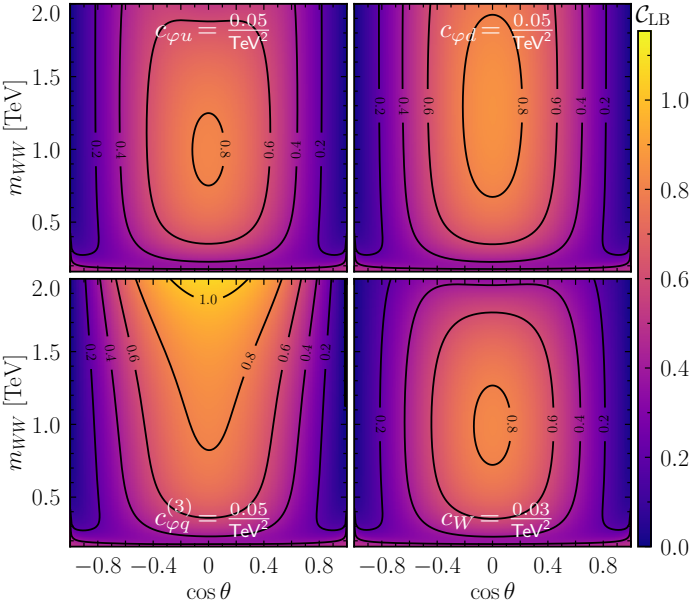

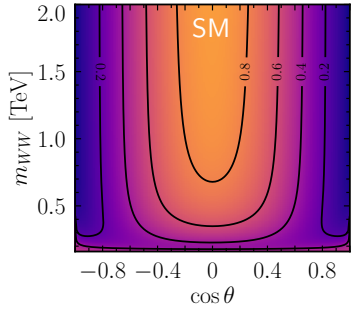

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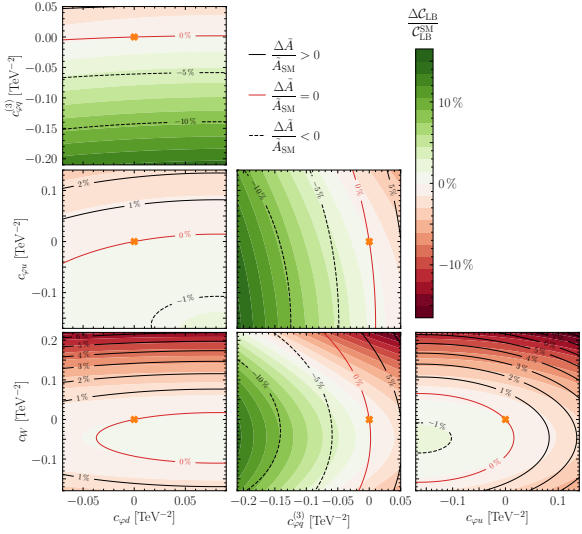
Central High-Energy Region ($pp \to W^+W^-$)

$$m_{WW} = 500\,\text{GeV},\ \cos\theta = 0$$

dim-6 + (dim-6)^2



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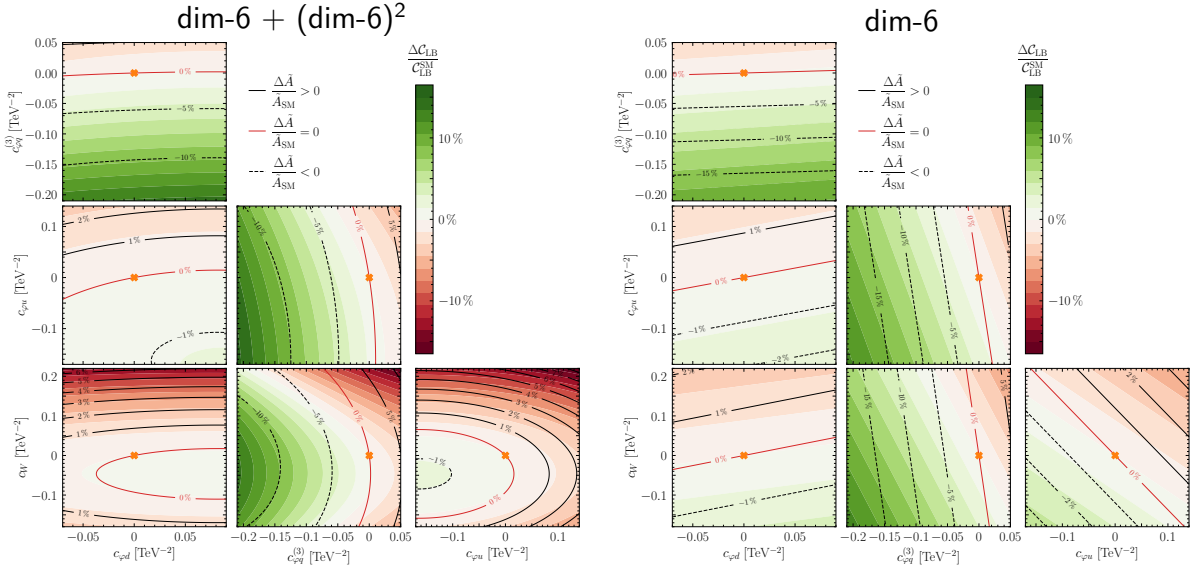
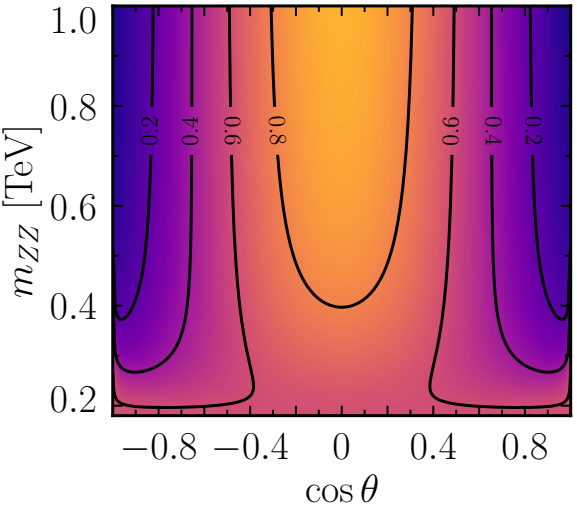


$e^+e^- \to ZZ$



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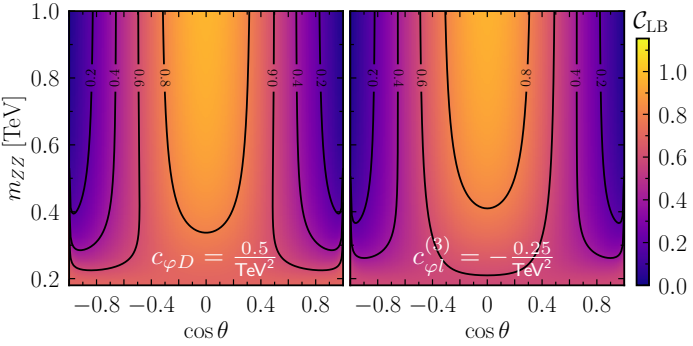
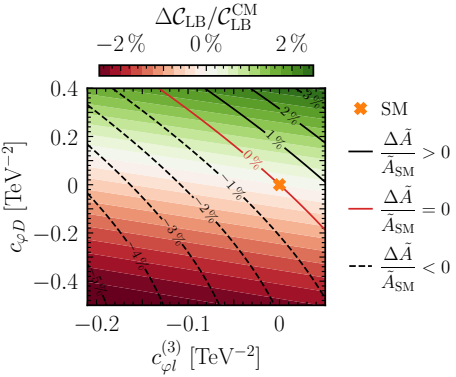

$\mathcal{C}_{\mathrm{LB}}$
m_{ZZ} [TeV]
$\cos\theta$
$c_{\varphi D} = \frac{0.5}{\mathrm{TeV}^2}$
$c^{(3)}_{\varphi l} = -\frac{0.25}{\mathrm{TeV}^2}$


$\Delta\mathcal{C}_{\mathrm{LB}}/\mathcal{C}_{\mathrm{LB}}^{\mathrm{CM}}$
$c_{\varphi D}$ [TeV^{-2}]
$c^{(3)}_{\varphi l}$ [TeV^{-2}]
SM
$\frac{\Delta\tilde{A}}{\tilde{A}_{\mathrm{SM}}} > 0$
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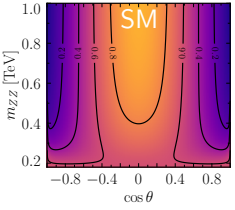
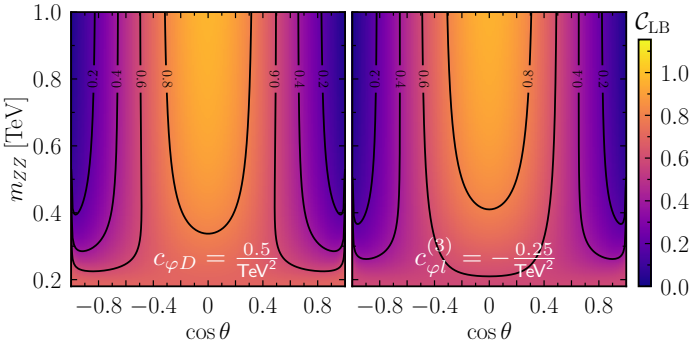

SM
m_{ZZ} [TeV]
$\cos\theta$

$e^+e^- \to ZZ$


$\mathcal{C}_{\mathrm{LB}}$
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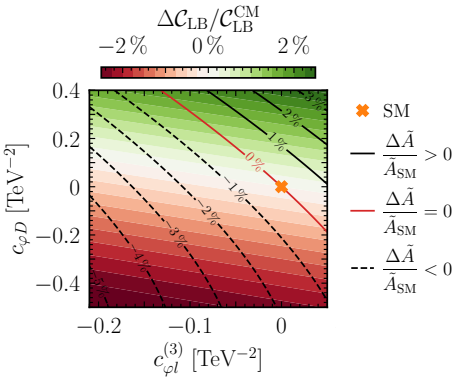
$\Delta\mathcal{C}_{\mathrm{LB}}/\mathcal{C}^{\mathrm{CM}}_{\mathrm{LB}}$
SM
$\frac{\Delta\tilde{A}}{\tilde{A}_{\mathrm{SM}}} > 0$
$\frac{\Delta\tilde{A}}{\tilde{A}_{\mathrm{SM}}} = 0$
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$c_{\varphi D}$ [TeV^{-2}]
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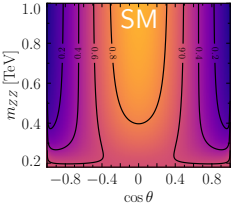
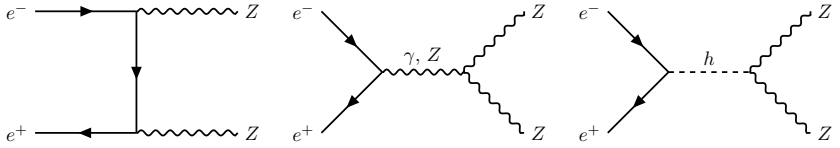
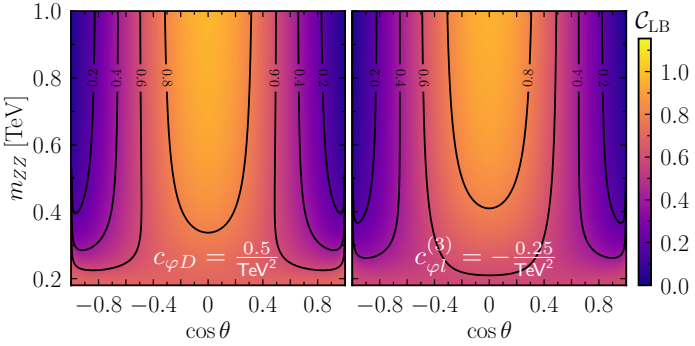

SM
m_{ZZ} [TeV]
$\cos\theta$


e^-
e^+
Z
γ, Z
h

$e^+e^- \to ZZ$


$\mathcal{C}_{\rm LB}$
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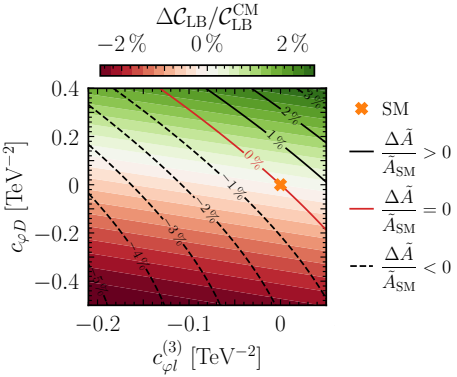
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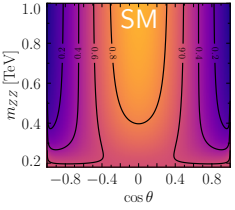
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m_{ZZ} [TeV]
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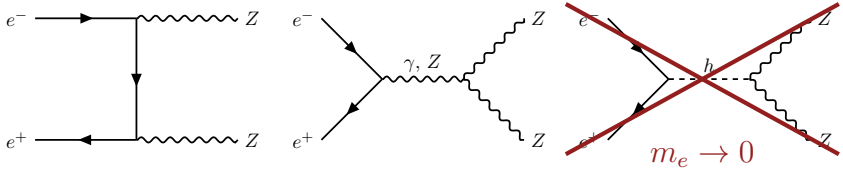
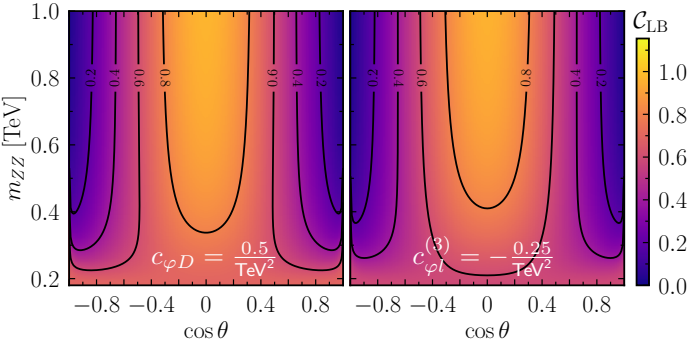

e^-
e^+
Z
γ, Z
h
$m_e \to 0$

$e^+e^- \to ZZ$


$\mathcal{C}_{\mathrm{LB}}$
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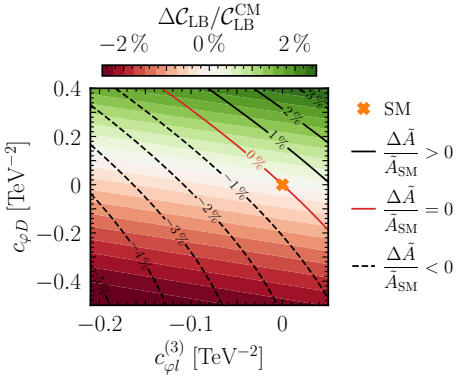
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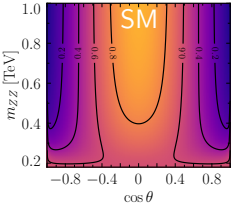
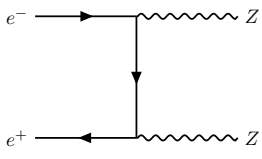
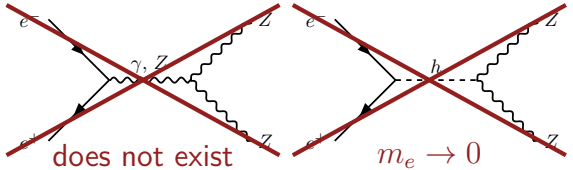
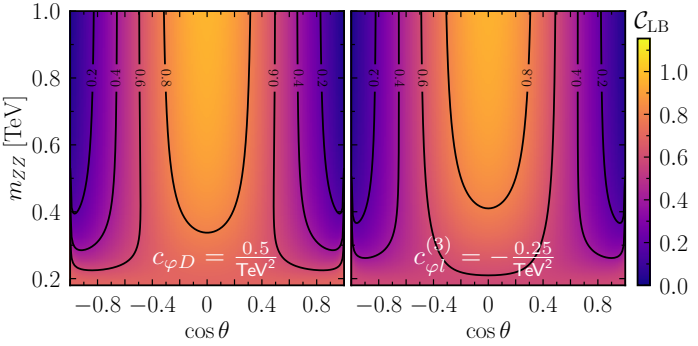
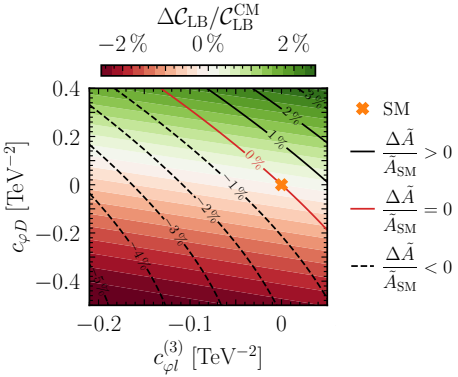

SM
m_{ZZ} [TeV]
$\cos\theta$

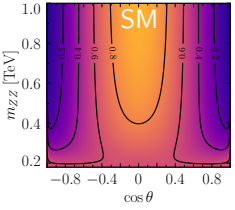

e^-
e^+
Z
Z

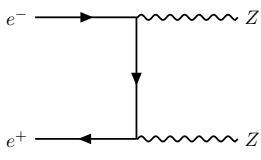

γ, Z
does not exist
h
$m_e \to 0$

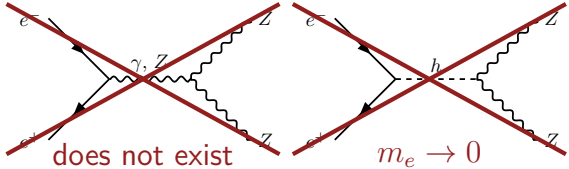
$e^+e^- \to ZZ$









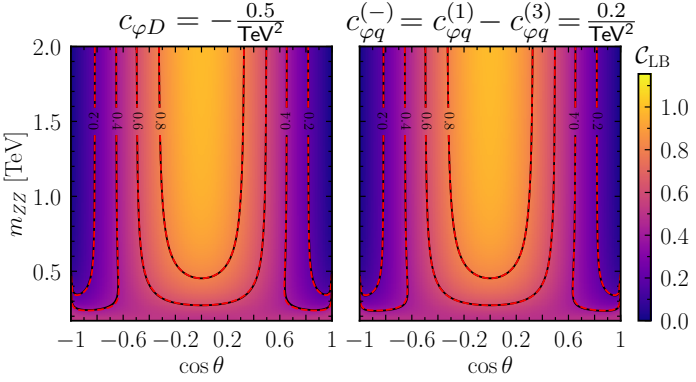


$\Longrightarrow$ SMEFT effects only through balance of RH and LH couplings

- additional effect:

  summation of $\bar{u}u$ and $\bar{d}d$ initial states

  $\Longrightarrow$ entanglement reduced (compared to partonic channels)



- additional effect:

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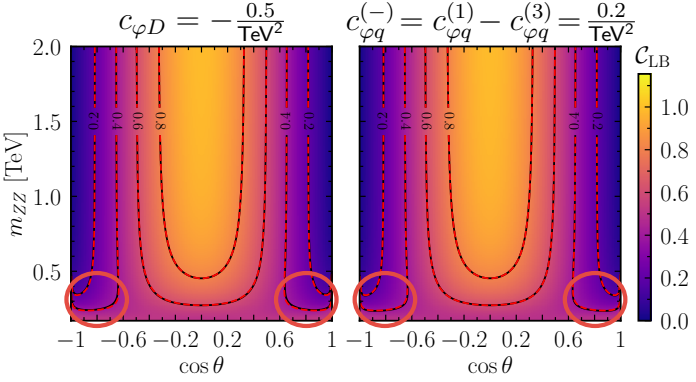
- only small effects in low-energy collinear region



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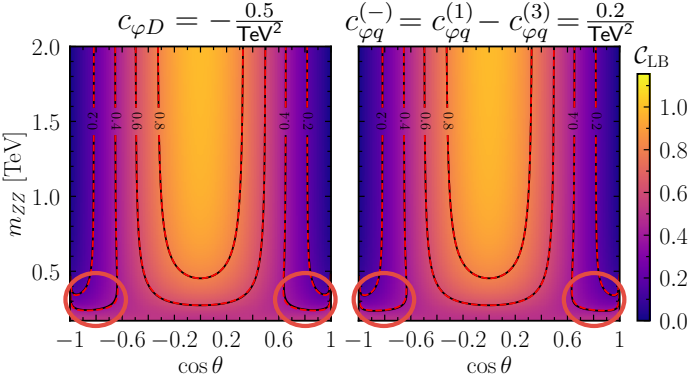

$\Longrightarrow$ entanglement in $pp \to ZZ$ not very sensitive to dim-6 effects

$pp \to W^{\pm}Z$

- only one partonic channel ($u\bar{d} \to W^+Z$); pure state

$pp \to W^{\pm}Z$

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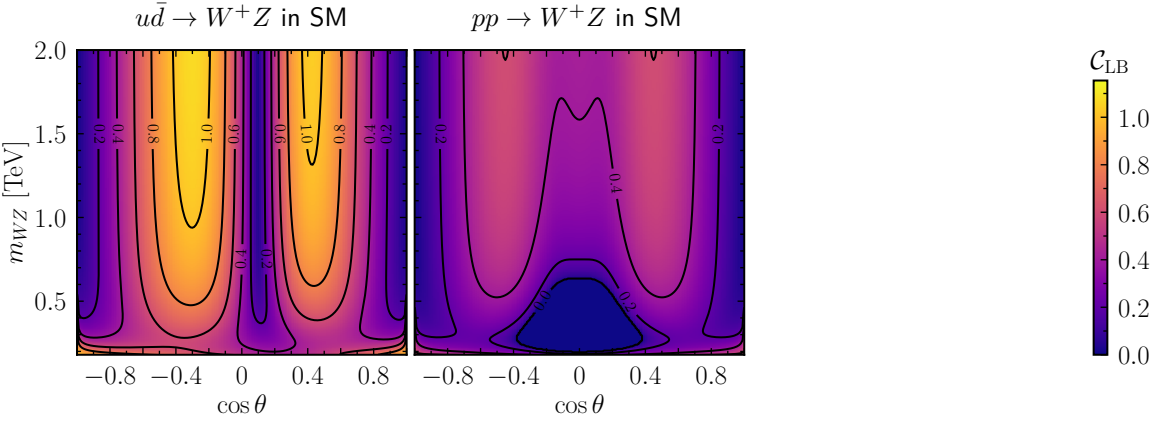
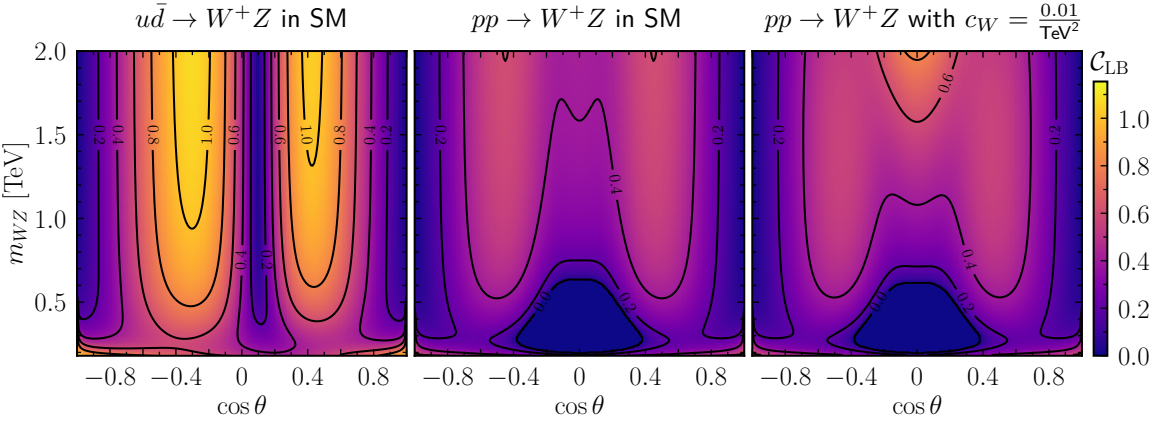
- at pp collider: $\bar{d}u$ and $u\bar{d}$ $\Longrightarrow$ mixed state



$pp \to W^{\pm}Z$

- only one partonic channel ($u\bar{d} \to W^+Z$); pure state
- at pp collider: $\bar{d}u$ and $u\bar{d}$ $\implies$ mixed state
- quite sensitive to $\mathcal{O}_W$ (and also $\mathcal{O}^{(3)}_{\varphi q}$)



Summary

- EFT effects can modify the SM entanglement patterns

  $\Longrightarrow$ entanglement-related observables can be used to probe new physics

- $e^+e^- \to W^+W^-$, $pp \to W^+W^-$ and $pp \to WZ$ are sensitive to dim-6 modifications

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  (but potentially to dim-8 operators)

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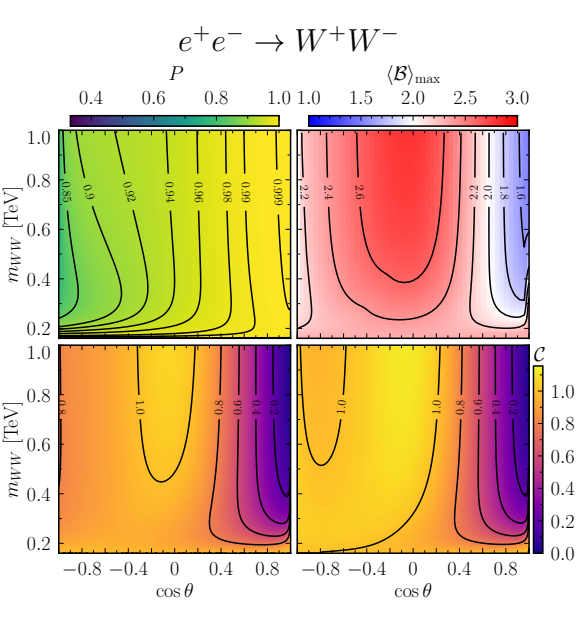
Thank you for your attention!

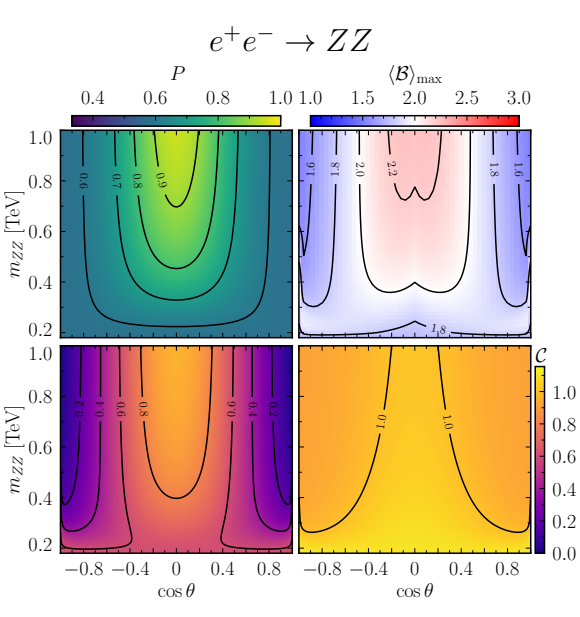
Probing New Physics through Entanglement in Diboson Production

Rafael Aoude, E.M., Fabio Maltoni, Luca Mantani – arXiv:2307.09675 [hep-ph]

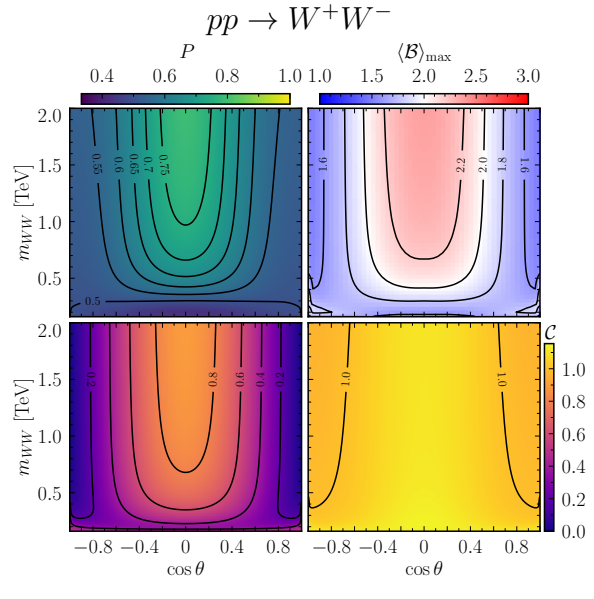
backup slides

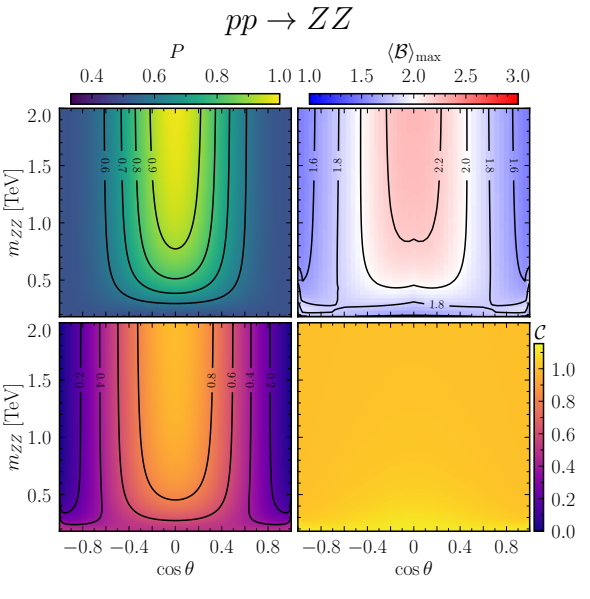
Weak boson production at electron colliders in the SM





Weak boson production at proton colliders in the SM I





Weak boson production at proton colliders in the SM II