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Difference between Warsaw, HISZ, SILH basis

----in the light of unitary constraint

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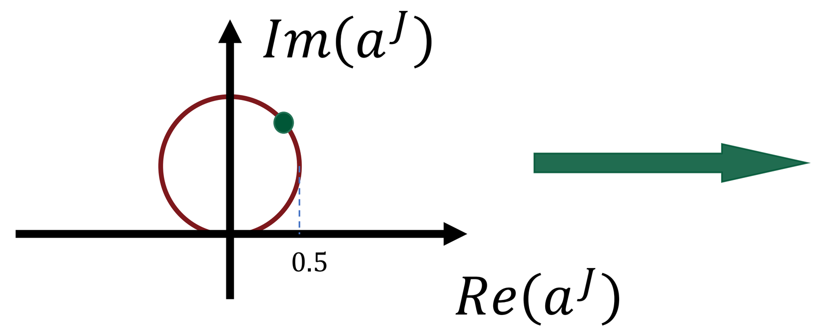
- The unitary constraint for **three basis** of SM Effective Field Theory (SMEFT) are reached;
- The **quartic derivative bilinear terms** are avoided by the Equation of Motion (EoM);
- The **cancellation between operators** is relatively severer for SILH and HISZ basis than Warsaw basis.

Framework 1

---Partial Wave Unitarity



$|Re(a^J)| \le 1/2$

a^J: partial wave $|M|$
J: angular momentum

---SMEFT

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \Sigma_{n=5}^{\infty}\Sigma_i \frac{C_i}{\Lambda^n}\mathcal{O}_i$$

C_i: Wilson coefficient
Λ: Cutoff scale

---Constrain Operators

- $a^J \propto s\frac{c_i}{\Lambda^2}\mathcal{O}_i + o(s^{1/2}) \Rightarrow \left|s\frac{c_i}{\Lambda^2}\mathcal{O}_i\right| \le f_i$

s: scattering energy
f_i: operators dependent constant

Operator basis of SMEFT 2

Warsaw basis

$\mathcal{O}_W$	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^*(\varphi^\dagger D_\mu\varphi)$	$\mathcal{O}_{\varphi W}$	$\varphi^\dagger\varphi W_{\mu\nu}^I W^{I\mu\nu}$
$\mathcal{O}_{\varphi B}$	$\varphi^\dagger\varphi B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi W_{\mu\nu}^I B^{\mu\nu}$
$\mathcal{O}_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$	$\mathcal{O}_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$	$\mathcal{O}_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$\mathcal{O}_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$	$\mathcal{O}_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$\mathcal{O}_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$	$\mathcal{O}_{\varphi ud}$	$(\widetilde\varphi^\dagger iD_\mu\varphi)(\bar u_p\gamma^\mu d_r)$
$\mathcal{O}_{eW}$	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$\mathcal{O}_{eB}$	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$
$\mathcal{O}_{uW}$	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi W_{\mu\nu}^I$	$\mathcal{O}_{uB}$	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi B_{\mu\nu}$
$\mathcal{O}_{dW}$	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi W_{\mu\nu}^I$	$\mathcal{O}_{dB}$	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi B_{\mu\nu}$

HISZ basis: $\mathcal{O}_W^{HISZ}$, $\mathcal{O}_B^{HISZ}$, Warsaw Basis, $\mathcal{O}_{\varphi l}^{(1)}$, $\mathcal{O}_{\varphi l}^{(3)}$

SILH basis: $\mathcal{O}_W^{HISZ}$, $\mathcal{O}_W^{HISZ}$, $\mathcal{O}_{2W}$, $\mathcal{O}_{2B}$, $\mathcal{O}_W^{SILH}$, $\mathcal{O}_W^{SILH}$, Warsaw Basis, $\mathcal{O}_{\varphi W}$, $\mathcal{O}_{\varphi WB}$, $\mathcal{O}_{\varphi\Box}$, $\mathcal{O}_{\varphi D}$, $\mathcal{O}_{\varphi l}^{(1)}$, $\mathcal{O}_{\varphi l}^{(3)}$

$$\mathcal{O}_W^{HISZ} = (D^\mu\varphi)^\dagger\left(ig\frac{\sigma^a}{2}W_{\mu\nu}^a\right)(D^\nu\varphi)$$
$$\mathcal{O}_B^{HISZ} = (D^\mu\varphi)^\dagger(i\frac{g_1}{2}B_{\mu\nu})(D^\nu\varphi)$$
$$\mathcal{O}_{2W} = -\frac{1}{2}\left(D^\mu W_{\mu\nu}^a\right)^2$$
$$\mathcal{O}_{2B} = -\frac{1}{2}\left(\partial^\mu B_{\mu\nu}\right)^2$$
$$\mathcal{O}_W^{SILH} = \frac{ig}{2}\left(\varphi^\dagger\sigma^a\overleftrightarrow{D^\mu}\varphi\right)\left(D^\nu W_{\mu\nu}^a\right)$$
$$\mathcal{O}_B^{HISZ} = \frac{ig_1}{2}\left(\varphi^\dagger\overleftrightarrow{D^\mu}\varphi\right)\left(\partial^\nu B_{\mu\nu}\right)$$

Annoying bilinear terms 3

$$\mathcal{O}_{\varphi W} = (\varphi^\dagger\varphi)W_{\mu\nu}^a W^{a,\mu\nu} \overset{\varphi\to\varphi+\langle v\rangle}{\Longrightarrow} \frac{v^2}{2}W_{\mu\nu}^a W^{a,\mu\nu}$$

$$W_\mu^a \to \left(1-\frac{v^2}{\Lambda^2}\mathcal{O}_{\varphi W}\right)\widehat W_\mu^a,\ g\to\left(1+\frac{v^2}{\Lambda^2}\mathcal{O}_{\varphi W}\right)\hat g,\ M_W\to\frac{1}{2}\hat g v$$

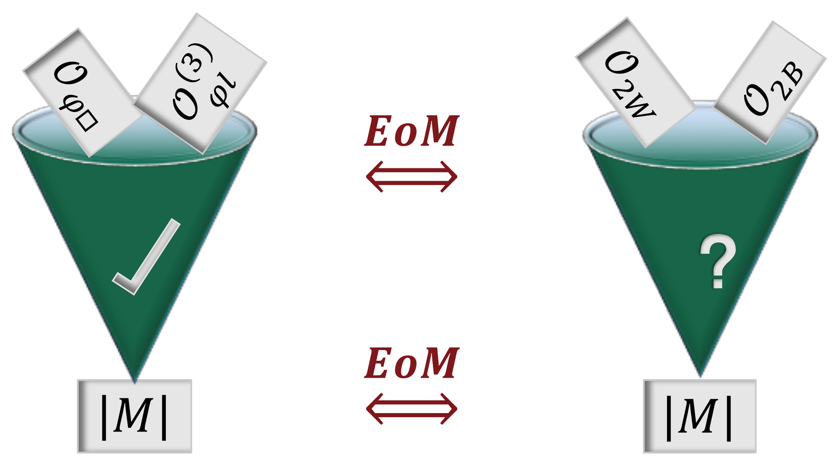
Good!

$$\mathcal{O}_{2W} \Rightarrow \left(\partial^\mu W_{\mu\nu}^a\right)^2$$

$$W_\mu^a \to \left(1-\frac{p^2}{\Lambda^2}\mathcal{O}_{2W}\right)W_\mu^a\ \ ???$$

Not good!

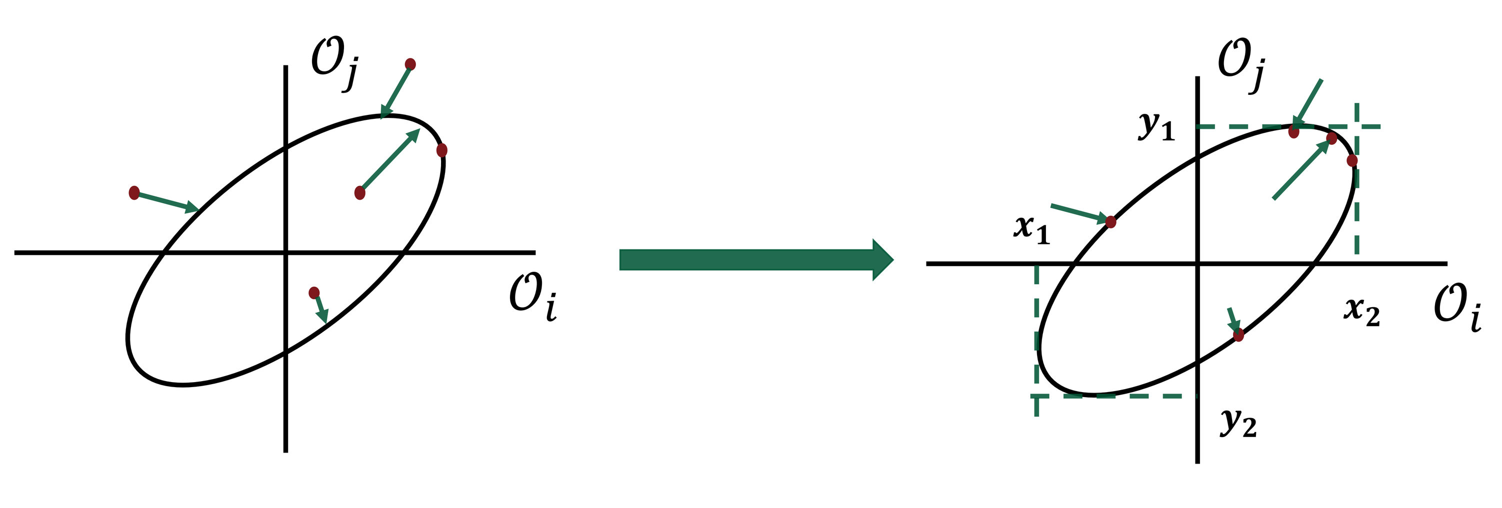
(One of) Solution



Use EoM to get scattering amplitudes $|M|$ directly!

Numerical Method 5

- MultiNest program: random points $\Rightarrow$ low efficiency
- $|M|$: only interference terms survived, $\propto \frac{s}{\Lambda^2}f(C_i)$
- $f(C_i)$:homogeneous functions $\Rightarrow$ **rescale** C_i to make all random points just sit on the unitary boundary.



$|\mathcal{O}_i| \le \max|x_1|, |x_2|$
$|\mathcal{O}_j| \le \max|y_1|, |y_2|$

EoMs 4

$$2\mathcal{O}_W^{HISZ} - \frac{1}{4}g^2\mathcal{O}_{\varphi W} - \frac{1}{4}g_1 g\mathcal{O}_{\varphi WB} + \frac{3}{4}g^2\mathcal{O}_{\varphi\Box} = -\frac{g^2}{4}\left[\mathcal{O}_{\varphi l}^{(3)} + \mathcal{O}_{\varphi q}^{(3)}\right] + \boxed{E},$$
$$2\mathcal{O}_B^{HISZ} - \frac{1}{4}g_1^2\mathcal{O}_{\varphi B} - \frac{1}{4}g_1 g\mathcal{O}_{\varphi WB} + g_1^2\left[\mathcal{O}_{\varphi D} + \frac{1}{4}\mathcal{O}_{\varphi\Box}\right] = -\frac{g_1^2}{2}\left[-\frac{1}{2}\mathcal{O}_{\varphi l}^{(1)} + \frac{1}{6}\mathcal{O}_{\varphi q}^{(1)} - \mathcal{O}_{\varphi e} + \frac{2}{3}\mathcal{O}_{\varphi u} - \frac{1}{3}\mathcal{O}_{\varphi d}\right] + \boxed{E},$$
$$\mathcal{O}_{2W} + \frac{3g^2}{8}\mathcal{O}_{\varphi\Box} = -\frac{g^2}{4}\left[\mathcal{O}_{\varphi l}^{(3)} + \mathcal{O}_{\varphi q}^{(3)}\right] + \boxed{E},$$
$$\mathcal{O}_{2B} + \frac{g_1^2}{2}\left[\frac{1}{4}\mathcal{O}_{\varphi\Box} + \mathcal{O}_{\varphi D}\right] = -\frac{g_1^2}{2}\left[-\frac{1}{2}\mathcal{O}_{\varphi l}^{(1)} + \frac{1}{6}\mathcal{O}_{\varphi q}^{(1)} - \mathcal{O}_{\varphi e} + \frac{2}{3}\mathcal{O}_{\varphi u} - \frac{1}{3}\mathcal{O}_{\varphi d}\right] + \boxed{E},$$
$$\mathcal{O}_W^{SILH} + \frac{3g^2}{4}\mathcal{O}_{\varphi\Box} = -\frac{g^2}{4}\left[\mathcal{O}_{\varphi l}^{(3)} + \mathcal{O}_{\varphi q}^{(3)}\right] + \boxed{E},$$
$$\mathcal{O}_B^{SILH} + g_1^2\left[\frac{1}{4}\mathcal{O}_{\varphi\Box} + \mathcal{O}_{\varphi D}\right] = -\frac{g_1^2}{2}\left[-\frac{1}{2}\mathcal{O}_{\varphi l}^{(1)} + \frac{1}{6}\mathcal{O}_{\varphi q}^{(1)} - \mathcal{O}_{\varphi e} + \frac{2}{3}\mathcal{O}_{\varphi u} - \frac{1}{3}\mathcal{O}_{\varphi d}\right] + \boxed{E}.$$

|M|

$$\underbrace{\sum_i a_i\mathcal{O}_i = 0}_{\text{EoM}} \Rightarrow 0 = \langle in|\textstyle\sum_i a_i\mathcal{O}_i|fi\rangle = \displaystyle\sum_i a_i\underbrace{\langle in|\mathcal{O}_i|fi\rangle}_{|M|} = \sum_i a_i m_i$$

e.g.

$$a = \begin{pmatrix} 2 & 0 & -\frac{g^2}{4} & 0 & -\frac{gg_1}{4} & 0 & \frac{3g^2}{4} \\ 0 & 2 & 2 & -\frac{g_1^2}{4} & -\frac{gg_1}{4} & g_1^2 & \frac{g_1^2}{4}\end{pmatrix},\quad \mathcal{O} = \left(\mathcal{O}_W^{HISZ},\mathcal{O}_B^{HISZ},\mathcal{O}_{\varphi W},\mathcal{O}_{\varphi B},\mathcal{O}_{\varphi WB},\mathcal{O}_{\varphi D},\mathcal{O}_{\varphi\Box}\right)^T$$

$W^+Z \to W^+\gamma$: $(L,-,L,+)$ Warsaw basis

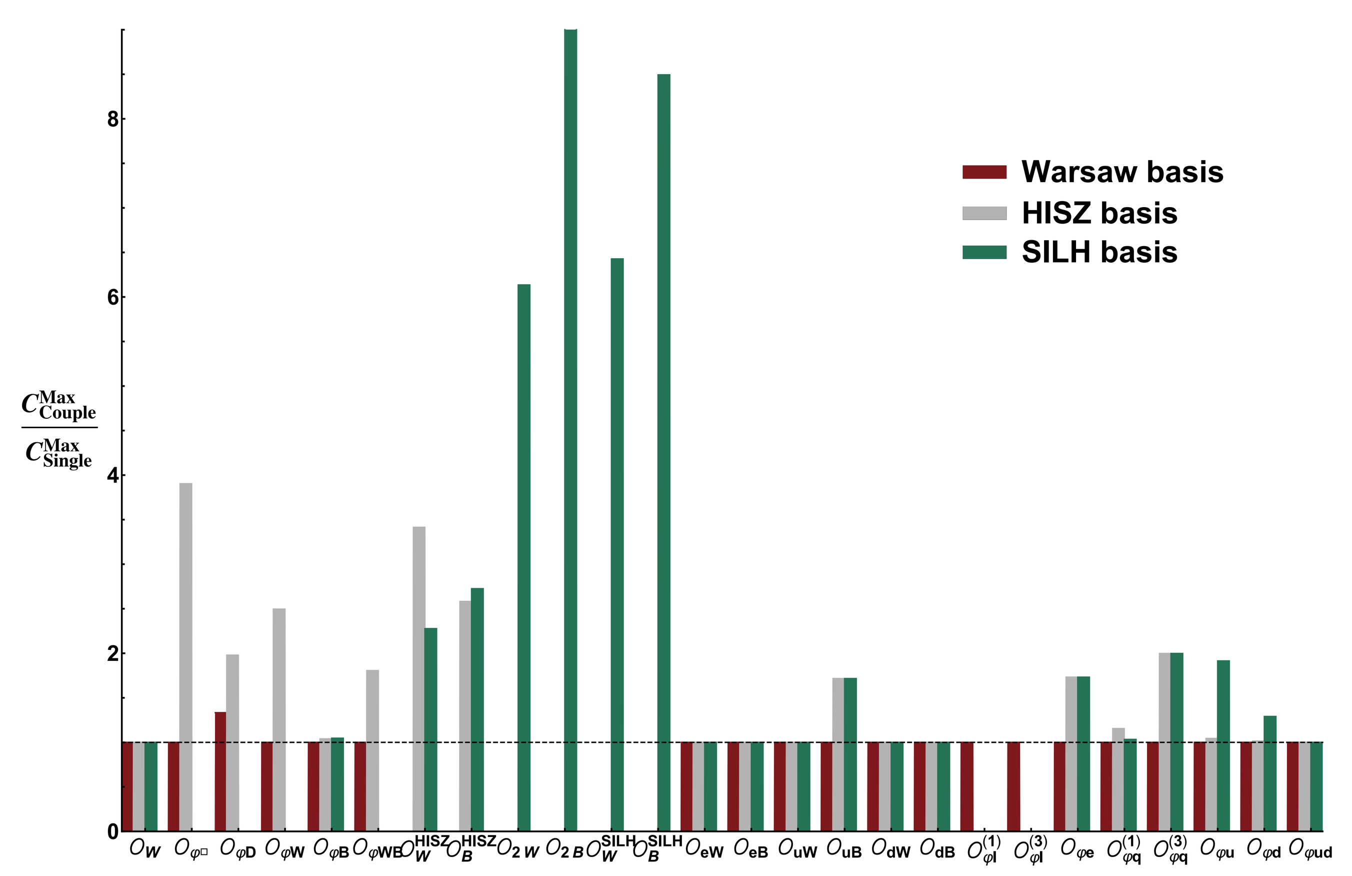
$$\frac{\sin^2(\frac{\theta}{2})}{g^2+g_1^2}\left[g^2C_{\varphi WB} + 2g_1g(C_{\varphi B}-C_{\varphi W}) + g_1^2C_{\varphi WB}\right]$$

$$= \frac{\sin^2\left(\frac{\theta}{2}\right)}{8(g^2+g_1^2)}\left(x,y,-16gg_1,16gg_1,8(g_1^2-g^2),0,0\right).\mathcal{O}$$

$$= 0 \quad \Rightarrow x = gg_1(g_1^2-3g^2), y = gg_1(3g_1^2-g^2),$$

Results for HISZ basis

Results & Conclusion 6



- Single operator v.s. all operators: big difference for SILH and HISZ basis

Severe cancellation!
Better not just use one operator in phenomenology analysis