Positivity bounds on HEFT operators: Towards the HEFT-hedron

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Trends in Astroparticle and Particle Physics

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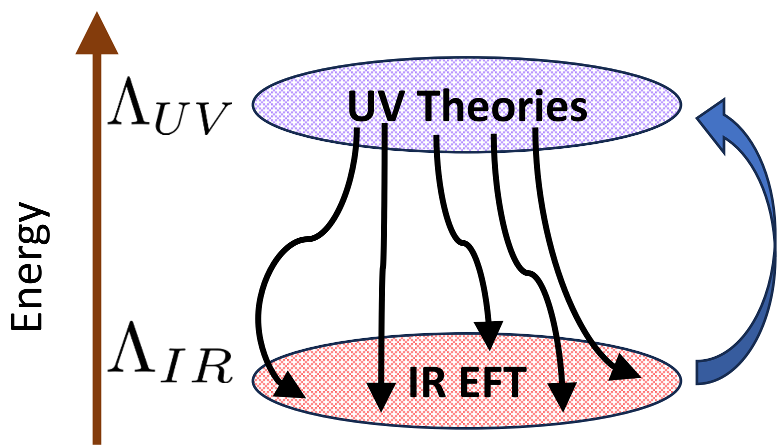
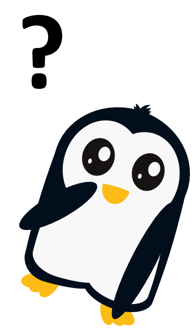
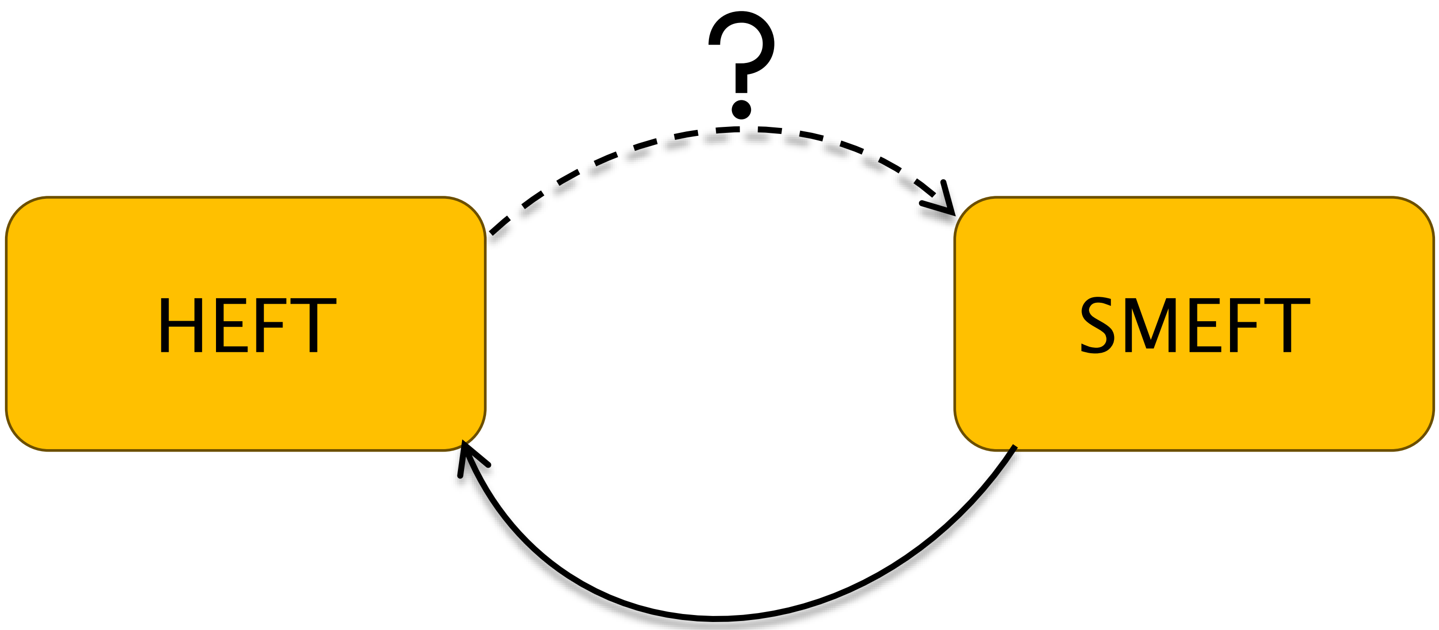




HEFT v/s SMEFT

	HEFT	**SMEFT**
Realization of Higgs dofs.	Non-linear $U \equiv Exp\left(\frac{i\vec{\phi}.\vec{\sigma}}{v}\right)$ $\mathbf{V}_\mu = iUD_\mu U^\dagger$ $\mathbf{T} = U\frac{\sigma_3}{2}U^\dagger$ h	Linear $H \equiv (v+h)\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix}$
Power Counting	$v^2\Lambda^2\left(\frac{D}{\Lambda}\right)^{n_D}\left(\frac{h}{v}\right)^{n_h}$	$\frac{\Lambda^4}{g_H^2}\left(\frac{D}{\Lambda}\right)^{n_D}\left(\frac{g_H H}{\Lambda}\right)^{n_H}$

HEFT ↔ SMEFT ?



A toy example: $\left(1+\frac{h}{v}\right)^{2/3}$

$$= \sum_{n=0}^{\infty} \binom{2/3}{n} \left(\frac{h}{v}\right)^{n} \rightarrow$$ A perfectly valid **HEFT** expansion

$$\sim \left(H^\dagger H\right)^{1/3} \rightarrow$$ **NOT** SMEFT

Correlations in SMEFT

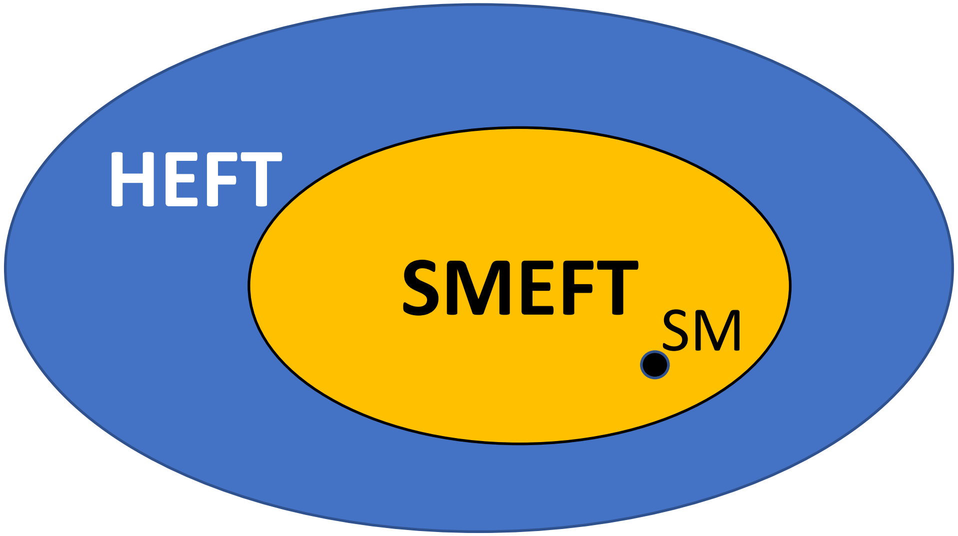
Example: V$\ell\ell$ couplings: (In unitary gauge)

$$SM + \delta g^{Z}_{e_L} Z_\mu \overline{e_L} \gamma^\mu e_L + \delta g^{Z}_{e_R} Z_\mu \overline{e_R} \gamma^\mu e_R$$
$$+ \delta g^{Z}_{\nu_L} Z_\mu \overline{\nu_L} \gamma^\mu \nu_L + \delta g^{W}_{L} \left(W^+_\mu \overline{\nu_L} \gamma^\mu e_L + h.c.\right)$$

SMEFT: $\delta g^{W}_{L} = \frac{\cos(\theta_W)}{\sqrt{2}} \left(\delta g^{Z}_{\nu_L} - \delta g^{Z}_{e_L}\right) + \mathcal{O}\left(\frac{v^4}{\Lambda^4}\right)$

$\Longrightarrow$ Only 3 WCs independent,

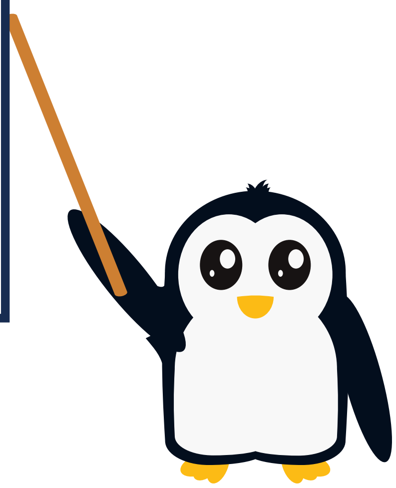
HEFT: all the 4 WCs appear independently at $\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$



Ref: Falkowski, Rattazzi ‘19;
Alonso, Jenkins, Manohar ‘15, ‘16;
Cohen, Craig, Lu, Sutherland ‘20

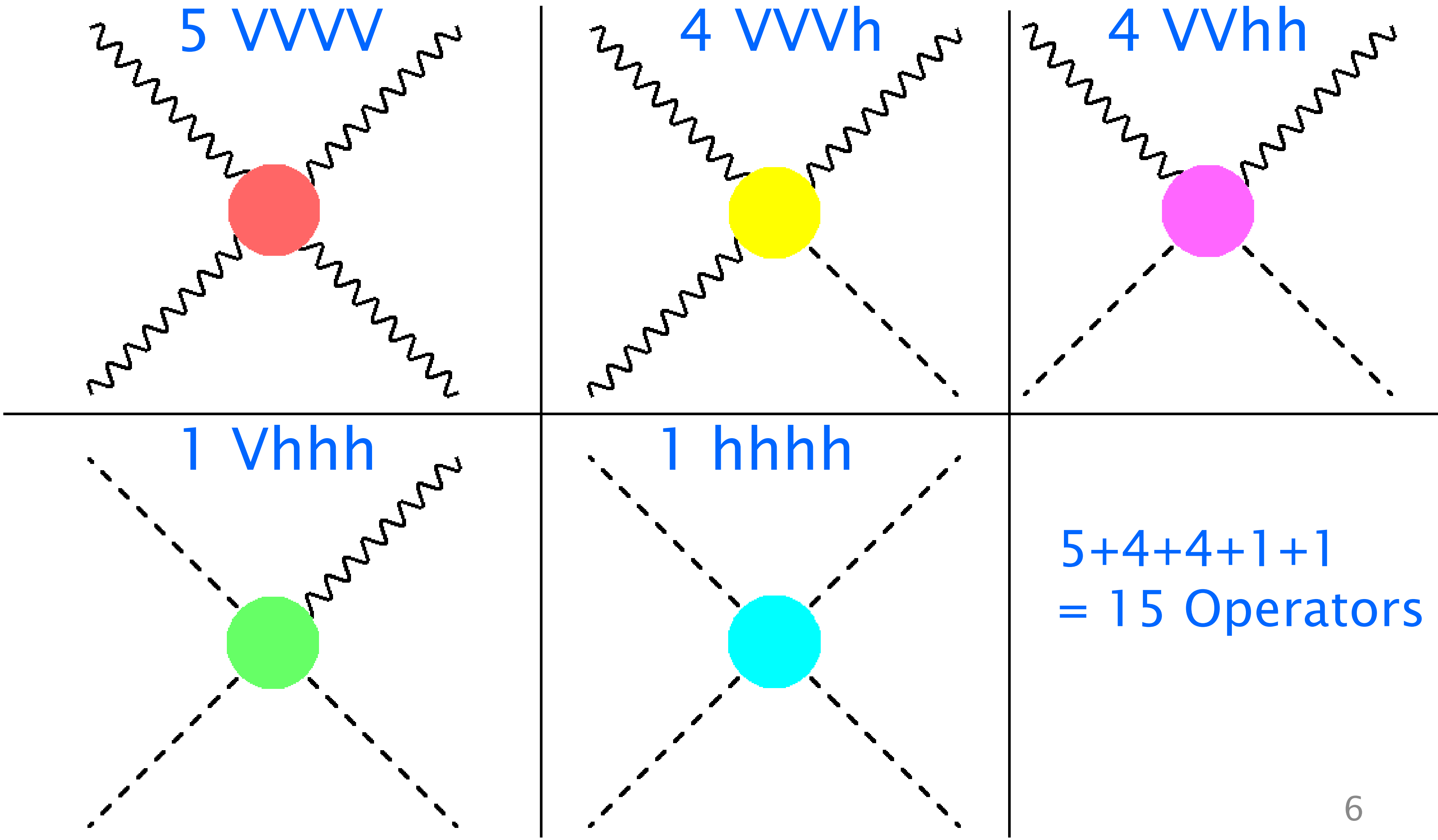
$$SMEFT \subset HEFT$$

Correlations exist between HEFT operators when written as SMEFT.



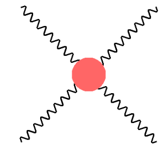
HEFT Operators @$\mathcal{O}(p^4)$

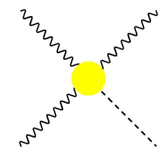
(Long.) Gauge-Higgs Couplings: $\mathrm{V} \equiv \mathrm{W}^{\pm}, \mathrm{Z}$

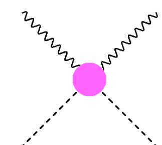


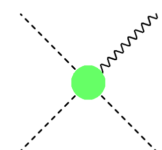
HEFT Operators @$\mathcal{O}(p^4)$

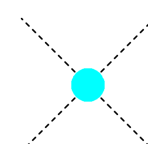
Type	$\mathcal{O}^{\mathbf{UhD^4}}$
$VVVV$	$\langle \mathbf{V}_\mu \mathbf{V}^\mu \rangle^2 \mathcal{F}_1^{UhD^4}(h)$
	$\langle \mathbf{V}_\mu \mathbf{V}_\nu \rangle \langle \mathbf{V}^\mu \mathbf{V}^\nu \rangle \mathcal{F}_2^{UhD^4}(h)$
	$\langle \mathbf{T}\mathbf{V}_\mu \rangle \langle \mathbf{T}\mathbf{V}_\nu \rangle \langle \mathbf{V}^\mu \mathbf{V}^\nu \rangle \mathcal{F}_3^{UhD^4}(h)$
	$\langle \mathbf{T}\mathbf{V}_\mu \rangle \langle \mathbf{T}\mathbf{V}^\mu \rangle \langle \mathbf{V}^\nu \mathbf{V}_\nu \rangle \mathcal{F}_4^{UhD^4}(h)$
	$(\langle \mathbf{T}\mathbf{V}_\mu \rangle \langle \mathbf{T}\mathbf{V}^\mu \rangle)^2 \mathcal{F}_5^{UhD^4}(h)$
$VVVh$	$\langle \mathbf{V}_\mu \mathbf{V}^\mu \rangle \langle \mathbf{T}\mathbf{V}_\nu \rangle \frac{D^\nu h}{v} \mathcal{F}_6^{UhD^4}(h)$
	$\langle \mathbf{V}_\mu \mathbf{V}_\nu \rangle \langle \mathbf{T}\mathbf{V}^\mu \rangle \frac{D^\nu h}{v} \mathcal{F}_7^{UhD^4}(h)$
	$\langle \mathbf{T}\mathbf{V}_\mu \mathbf{V}_\nu \rangle \langle \mathbf{T}\mathbf{V}^\mu \rangle \frac{D^\nu h}{v} \mathcal{F}_8^{UhD^4}(h)$
	$\langle \mathbf{T}\mathbf{V}_\mu \rangle \langle \mathbf{T}\mathbf{V}^\mu \rangle \langle \mathbf{T}\mathbf{V}_\nu \rangle \frac{D^\nu h}{v} \mathcal{F}_9^{UhD^4}(h)$
$VVhh$	$\langle \mathbf{V}_\mu \mathbf{V}^\mu \rangle \frac{h D^\mu D^\nu h}{v^2} \mathcal{F}_{10}^{UhD^4}(h)$
	$\langle \mathbf{V}_\mu \mathbf{V}^\mu \rangle \frac{D_\nu h D^\nu h}{v^2} \mathcal{F}_{11}^{UhD^4}(h)$
	$\langle \mathbf{T}\mathbf{V}_\mu \rangle \langle \mathbf{T}\mathbf{V}_\nu \rangle \frac{h D^\mu D^\nu h}{v^2} \mathcal{F}_{12}^{UhD^4}(h)$
	$\langle \mathbf{T}\mathbf{V}_\mu \rangle \langle \mathbf{T}\mathbf{V}^\mu \rangle \frac{D_\nu h D^\nu h}{v^2} \mathcal{F}_{13}^{UhD^4}(h)$
$Vhhh$	$\langle \mathbf{T}\mathbf{V}_\mu \rangle \frac{h D^\nu h D_\nu D^\mu h}{v^3} \mathcal{F}_{14}^{UhD^4}(h)$
$hhhh$	$\frac{1}{v^4} h^2 (D_\mu D_\nu h)(D^\mu D^\nu h) \mathcal{F}_{15}^{UhD^4}(h)$











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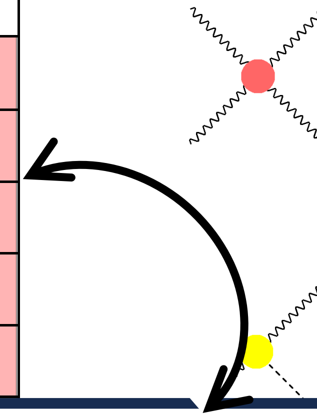
	$(\langle \mathbf{T}\mathbf{V}_\mu \rangle \langle \mathbf{T}\mathbf{V}^\mu \rangle)^2 \mathcal{F}_5^{UhD^4}(h)$



Anomalous Quartic Gauge Couplings (aQGCs)

$$\Delta\mathcal{L}_{QGC} = g^2 c_{\theta_W}^2 \left[\delta g_{ZZ1}^Q Z^\mu Z^\nu W_\mu^- W_\nu^+ - \delta g_{ZZ2}^Q Z^\mu Z_\mu W^{-\nu} W_\nu^+\right]$$
$$+ \frac{g^2}{2}\left[\delta g_{WW1}^Q W^{-\mu} W^{+\nu} W_\mu^- W_\nu^+ - \delta g_{WW2}^Q \left(W^{-\mu} W_\mu^+\right)^2\right] + \frac{g^2}{4c_{\theta_W}^4} h_{ZZ}^Q (Z^\mu Z_\mu)^2$$

$$\delta g_{ZZ1}^Q = \frac{g^2}{c_{\theta_w}^4}(c_2 + c_3), \quad \delta g_{ZZ2}^Q = -\frac{g^2}{c_{\theta_w}^4}(c_1 + c_4), \quad \delta g_{WW1}^Q = g^2 c_2$$
$$\delta g_{WW2}^Q = -g^2(2c_1 + c_2) \qquad h_{ZZ}^Q = g^2 c_{\theta_w}^2 (c_1 + c_2 + 2c_3 + 2c_4 + 4c_5)$$

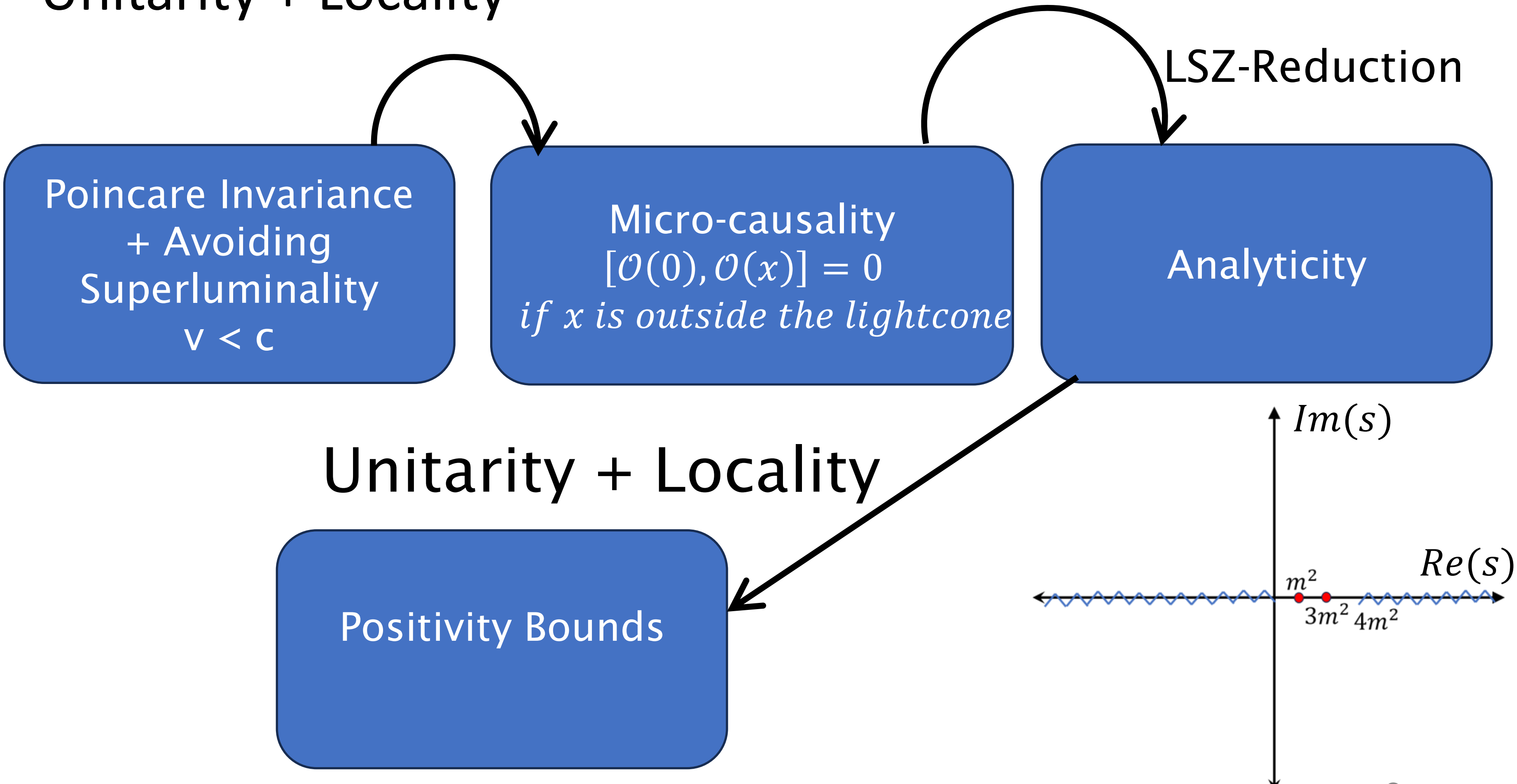
BUT, unlike HEFT, in SMEFT dim-8, there are only 3 independent operators for aQGCs.

Deriving Positivity

Ref: Adams et al. '06

For "**reasonable**" UV-completions:

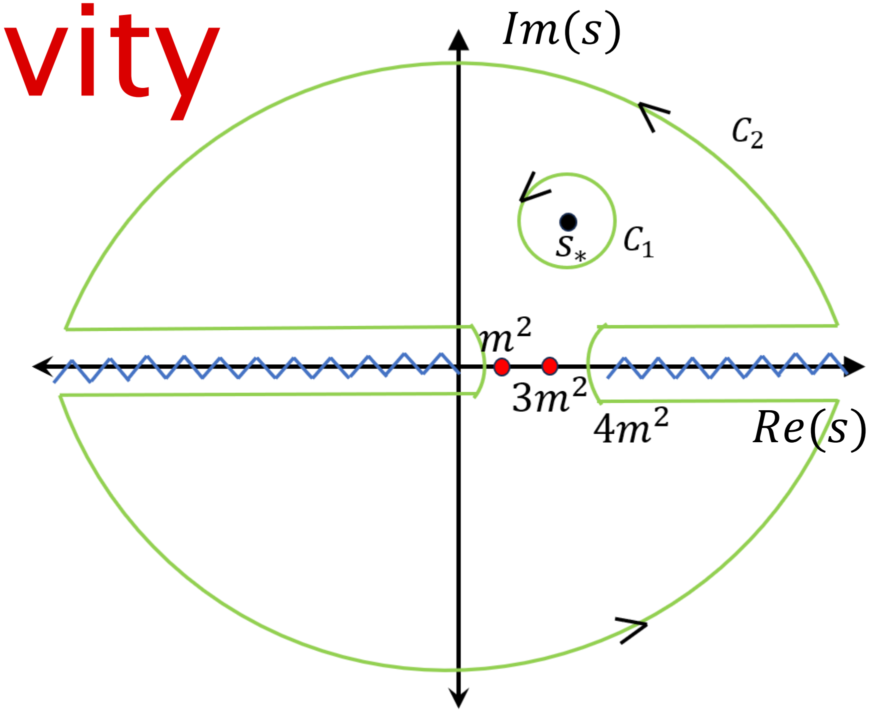
"**reasonable**" = Poincare Invariance + Causality + Unitarity + Locality



Deriving Positivity

$$\chi_i + \chi_j \to \chi_i + \chi_j,$$

$$\mathcal{M}_{ij}(s_\star, t) = \frac{1}{2\pi i} \oint_{C_1} \frac{ds' \mathcal{M}_{ij}(s', t)}{(s' - s_\star)}$$



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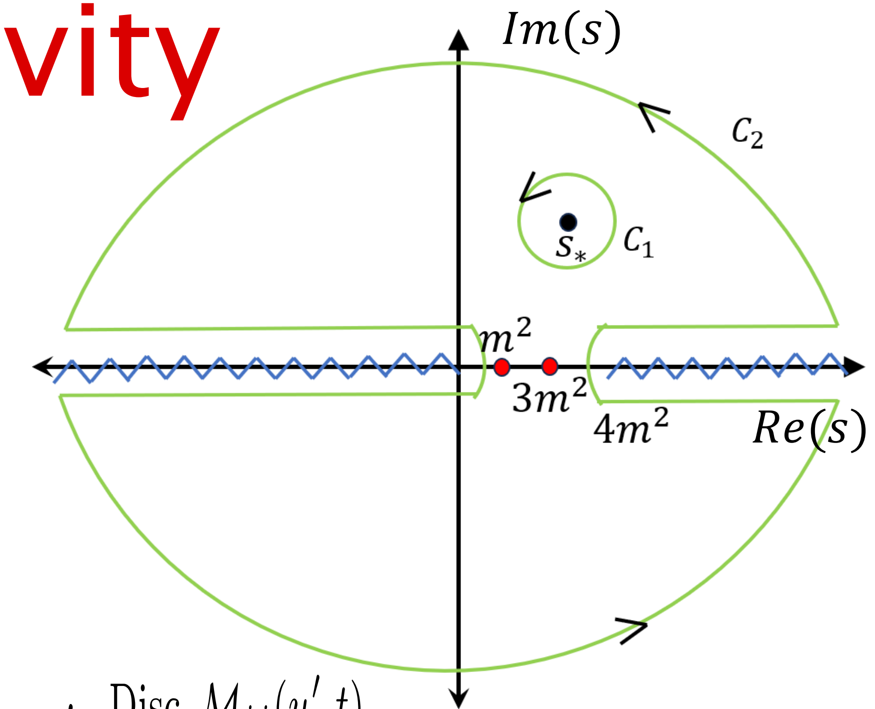
Froissart-Martin Bound:

$$\boldsymbol{Lim_{|s|\to\infty} \frac{\mathcal{M}(s,t)}{s^2} = 0}$$



$$\frac{1}{2}\frac{\partial^2 \mathcal{M}_{ij}(s,t)}{\partial s^2} = \frac{1}{2\pi i}\int_{4m^2}^{\infty} ds' \frac{\text{Disc } \mathcal{M}_{ij}(s',t)}{(s'-s)^3} + \frac{1}{2\pi i}\int_{4m^2-t}^{\infty} du' \frac{\text{Disc } \mathcal{M}_{ij}(u',t)}{(u'-(4m^2-s-t))^3}$$

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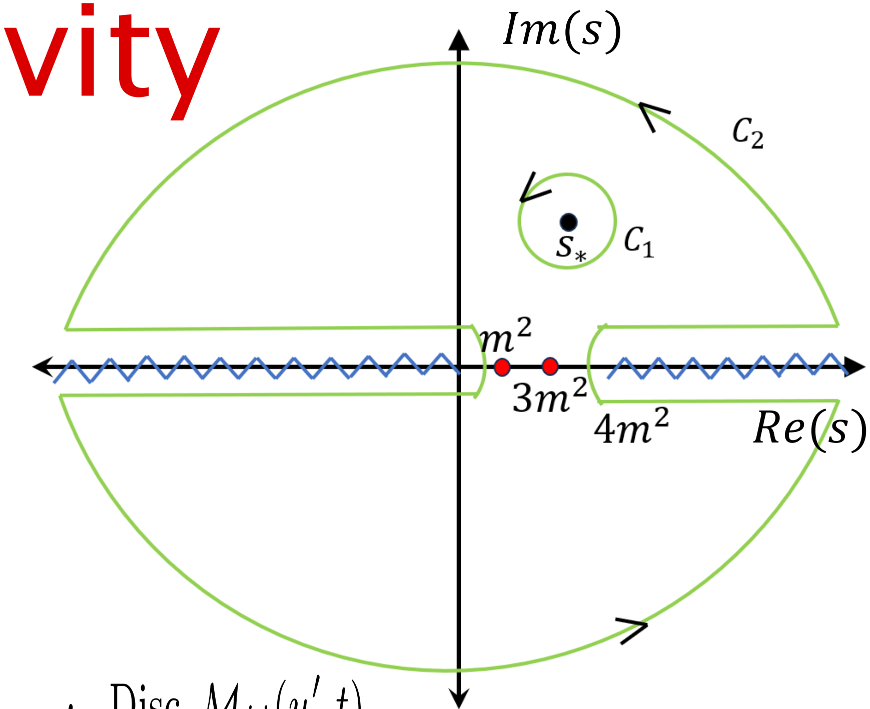

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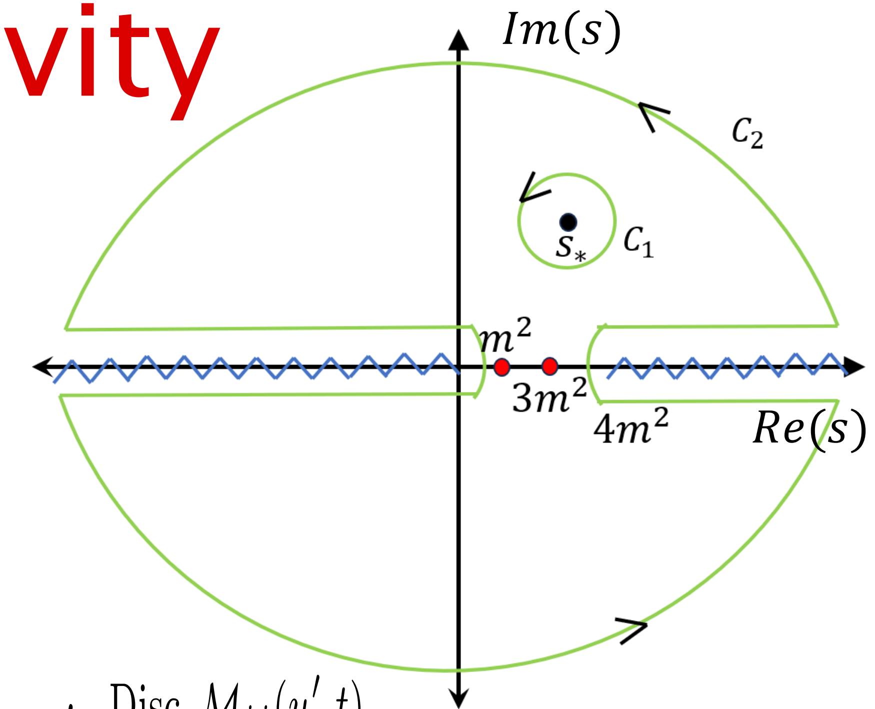
Optical Theorem

$$\frac{1}{2}\frac{\partial^2}{\partial s^2}\mathcal{M}_{ij}(s,t\to 0) = \frac{1}{\pi}\int_{4m^2}^{\infty} ds' \sqrt{s'(s'-m_{ij}^2)}\,\sigma_T(s')\left[\frac{1}{(s'-s)^3} + \frac{1}{(s'-4m^2+s)^3}\right]$$

Deriving Positivity



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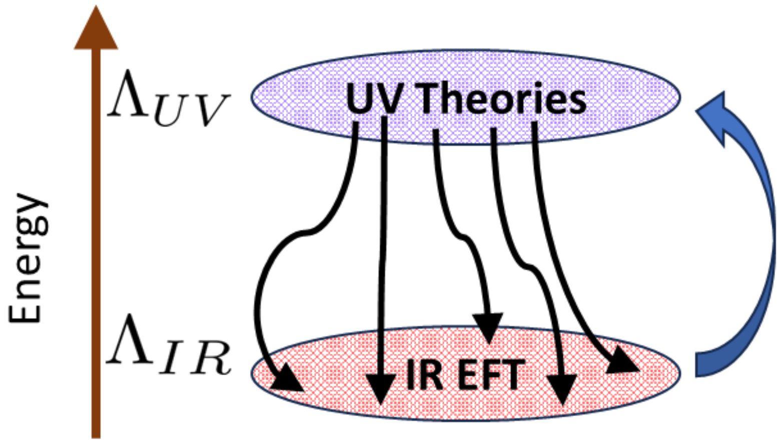
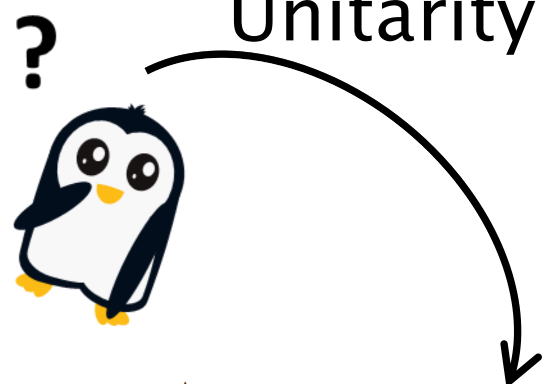
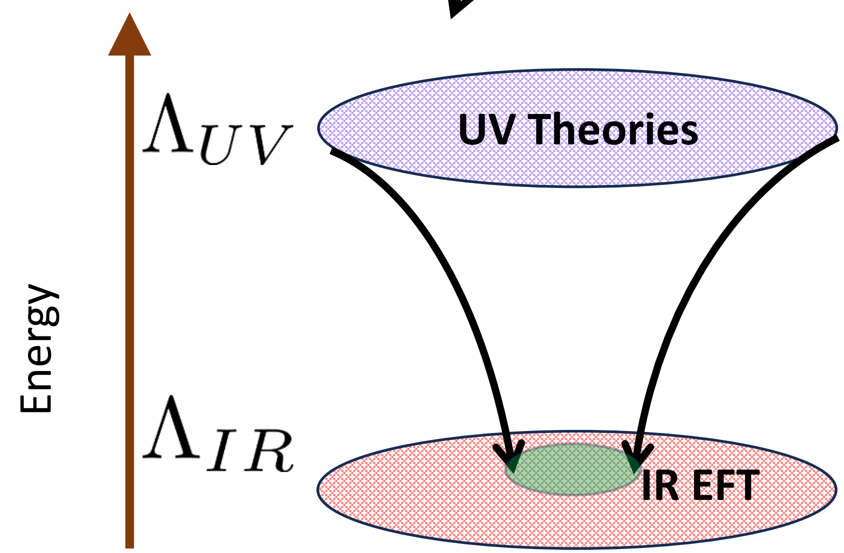
$$\left.\frac{\partial^2 M(s,t,u=4m^2-s-t)}{\partial s^2}\right|_{t\to 0} \geq 0$$





Poincare Invariance + Causality + Unitarity + Locality



$$M(s,t,u) = \sum_i \mathbf{c_i} \; f_i(s,t,u)$$

$$\left.\frac{\partial^2 M(s,t,u=4m^2-s-t)}{\partial s^2}\right|_{t\to 0} \geq 0$$

Positivity Bounds

$|\chi_a\rangle + |\chi_b\rangle \to |\chi_a\rangle + |\chi_b\rangle$, where

$$|\chi_a\rangle \equiv \sum_I \alpha_I |\phi_I\rangle + \alpha_4 |h\rangle$$

$$|\chi_b\rangle \equiv \sum_I \beta_I |\phi_I\rangle + \beta_4 |h\rangle$$

Superpositions give stronger constraints:

$$\left.\frac{\partial^2 M_{IJ\to KL}(s,t,u{=}4m^2-s-t)}{\partial s^2}\right|_{t\to 0} \succcurlyeq 0$$

Positivity Bounds

D.Chakraborty, SC, R.S.Gupta (in prep.)

$$\frac{v^4}{2}\frac{\partial^2 M(s,t,u{=}4m^2-s-t)}{\partial s^2}\Bigg|_{t\to 0} =$$

	$\phi_1\phi_1$	$\phi_1\phi_2$	$\phi_1\phi_3$	$\phi_2\phi_1$	$\phi_2\phi_2$	$\phi_2\phi_3$	$\phi_3\phi_1$	$\phi_3\phi_2$	$\phi_3\phi_3$	$\phi_1 h$	$\phi_2 h$	$\phi_3 h$	$h\phi_1$	$h\phi_2$	$h\phi_3$	hh
$\phi_1\phi_1$	a	0	0	0	b	0	0	0	c	0	0	$c6+\frac{c7}{2}$	0	0	$c6+\frac{c7}{2}$	2c11
$\phi_1\phi_2$	0	d	0	b	0	0	0	0	0	0	0	$-ic8$	0	0	$ic8$	0
$\phi_1\phi_3$	0	0	f	0	0	0	c	0	0	c7	0	0	$c6+\frac{c7}{2}$	$ic8$	0	0
$\phi_2\phi_1$	0	b	0	d	0	0	0	0	0	0	0	$ic8$	0	0	$-ic8$	0
$\phi_2\phi_2$	b	0	0	0	a	0	0	0	c	0	0	$c6+\frac{c7}{2}$	0	0	$c6+\frac{c7}{2}$	2c11
$\phi_2\phi_3$	0	0	0	0	0	f	0	c	0	0	c7	0	$-ic8$	$c6+\frac{c7}{2}$	0	0
$\phi_3\phi_1$	0	0	c	0	0	0	f	0	0	$c6+\frac{c7}{2}$	$ic8$	0	c7	0	0	0
$\phi_3\phi_2$	0	0	0	0	0	c	0	f	0	$-ic8$	$c6+\frac{c7}{2}$	0	0	c7	0	0
$\phi_3\phi_3$	c	0	0	0	c	0	0	0	e	0	0	g	0	0	g	h
$\phi_1 h$	0	0	c7	0	0	0	$c6+\frac{c7}{2}$	$-ic8$	0	$-2c10$	0	0	2c11	0	0	0
$\phi_2 h$	0	0	0	0	0	c7	$ic8$	$c6+\frac{c7}{2}$	0	0	$-2c10$	0	0	2c11	0	0
$\phi_3 h$	$c6+\frac{c7}{2}$	$-ic8$	0	$ic8$	$c6+\frac{c7}{2}$	0	0	0	g	0	0	$-2c10-c12$	0	0	$2c11+c13$	$-\frac{c14}{2}$
$h\phi_1$	0	0	$c6+\frac{c7}{2}$	0	0	$-ic8$	c7	0	0	2c11	0	0	$-2c10$	0	0	0
$h\phi_2$	0	0	$ic8$	0	0	$c6+\frac{c7}{2}$	0	c7	0	0	2c11	0	0	$-2c10$	0	0
$h\phi_3$	$c6+\frac{c7}{2}$	$ic8$	0	$-ic8$	$c6+\frac{c7}{2}$	0	0	0	g	0	0	$2c11+c13$	0	0	$-2c10-c12$	$-\frac{c14}{2}$
hh	2c11	0	0	0	2c11	0	0	0	h	0	0	$-\frac{c14}{2}$	0	0	$-\frac{c14}{2}$	2c15

VVVV (aQGC)

VVVh

VVhh

Vhhh

hhhh

Positivity Bounds

$$\frac{v^4}{2}\frac{\partial^2 M(s,t,u=4m^2-s-t)}{\partial s^2}\Bigg|_{t\to 0} =$$

	$\phi_1\phi_1$	$\phi_1\phi_2$	$\phi_1\phi_3$	$\phi_2\phi_1$	$\phi_2\phi_2$	$\phi_2\phi_3$	$\phi_3\phi_1$	$\phi_3\phi_2$	$\phi_3\phi_3$	$\phi_1 h$	$\phi_2 h$	$\phi_3 h$	$h\phi_1$	$h\phi_2$	$h\phi_3$	hh
$\phi_1\phi_1$	a	0	0	0	b	0	0	0	c	0	0	$c6+\frac{c7}{2}$	0	0	$c6+\frac{c7}{2}$	$2c11$
$\phi_1\phi_2$	0	d	0	b	0	0	0	0	0	0	0	$-ic8$	0	0	$ic8$	0
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$\phi_2\phi_1$	0	b	0	d	0	0	0	0	0	0	0	$ic8$	0	0	$-ic8$	0
$\phi_2\phi_2$	b	0	0	0	a	0	0	0	c	0	0	$c6+\frac{c7}{2}$	0	0	$c6+\frac{c7}{2}$	$2c11$
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$\phi_3\phi_1$	0	0	c	0	0	0	f	0	0	$c6+\frac{c7}{2}$	$ic8$	0	$c7$	0	0	0
$\phi_3\phi_2$	0	0	0	0	0	c	0	f	0	$-ic8$	$c6+\frac{c7}{2}$	0	0	$c7$	0	0
$\phi_3\phi_3$	c	0	0	0	c	0	0	0	e	0	0	g	0	0	g	h
$\phi_1 h$	0	0	$c7$	0	0	0	$c6+\frac{c7}{2}$	$-ic8$	0	$-2c10$	0	0	$2c11$	0	0	0
$\phi_2 h$	0	0	0	0	0	$c7$	$ic8$	$c6+\frac{c7}{2}$	0	0	$-2c10$	0	0	$2c11$	0	0
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$h\phi_1$	0	0	$c6+\frac{c7}{2}$	0	0	$-ic8$	$c7$	0	0	$2c11$	0	0	$-2c10$	0	0	0
$h\phi_2$	0	0	$ic8$	0	0	$c6+\frac{c7}{2}$	0	$c7$	0	0	$2c11$	0	0	$-2c10$	0	0
$h\phi_3$	$c6+\frac{c7}{2}$	$ic8$	0	$-ic8$	$c6+\frac{c7}{2}$	0	0	0	g	0	0	$2c11+c13$	0	0	$-2c10-c12$	$-\frac{c14}{2}$
hh	$2c11$	0	0	0	$2c11$	0	0	0	h	0	0	$-\frac{c14}{2}$	0	0	$-\frac{c14}{2}$	$2c15$

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Positivity Bounds

$$\left.\frac{\partial^2 M(s,t,u=4m^2-s-t)}{\partial s^2}\right|_{t\to 0} \succcurlyeq 0$$

$$a-b \geq 0$$

$$b+d \geq 0$$

$$\frac{1}{4}\left(\sqrt{4\left(8c\ c_{10}-8c\ c_{11}+8c_{10}\ f-8c_{11}\ f+4c_6^2+12c_6\ c_7+9c_7^2-4c_8^2\right)+\left(2c-4c_{10}+4c_{11}+2f\right)^2}\right.$$
$$\left.+2c-4c_{10}+4c_{11}+2f\right) \geq 0$$

$$\frac{1}{4}\left(-\sqrt{4\left(8c\ c_{10}-8c\ c_{11}+8c_{10}\ f-8c_{11}\ f+4c_6^2+12c_6\ c_7+9c_7^2-4c_8^2\right)+\left(2c-4c_{10}+4c_{11}+2f\right)^2}\right.$$
$$\left.+2c-4c_{10}+4c_{11}+2f\right) \geq 0$$

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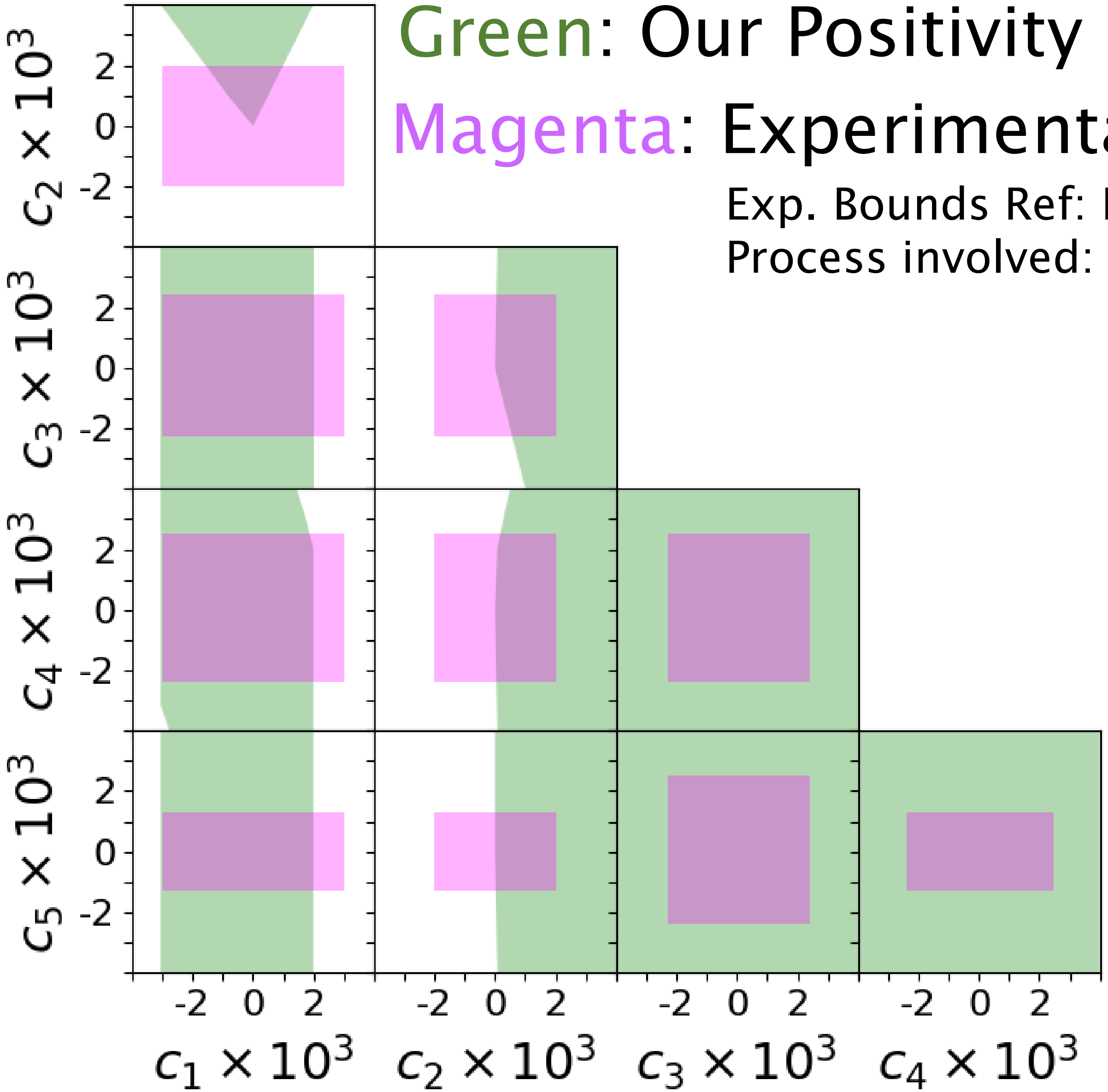
D.Chakraborty, SC, R.S.Gupta (in prep.)

Bounds on VVVV (aQGCs)

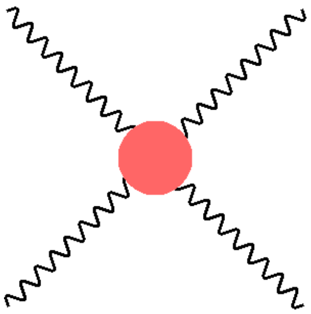


Green: Our Positivity Bounds

Magenta: Experimental Bounds

Exp. Bounds Ref: Eboli et al. '24

Process involved: $pp \to VVjj$ (VBS)



D.Chakraborty, SC, R.S.Gupta (in prep.)

For SMEFT Bounds see: Remmen, Rodd '19

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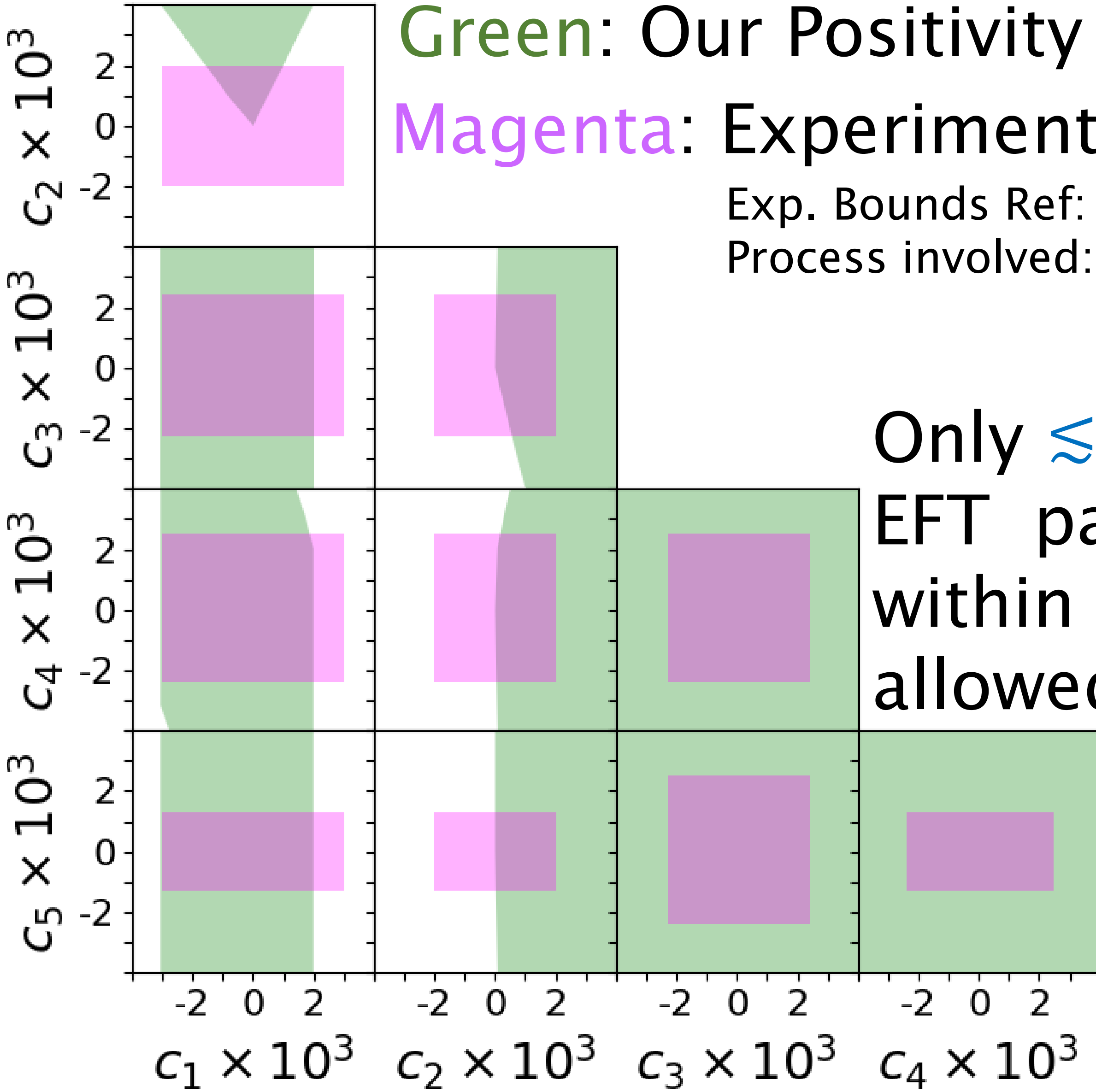

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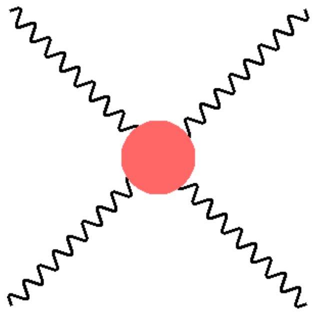
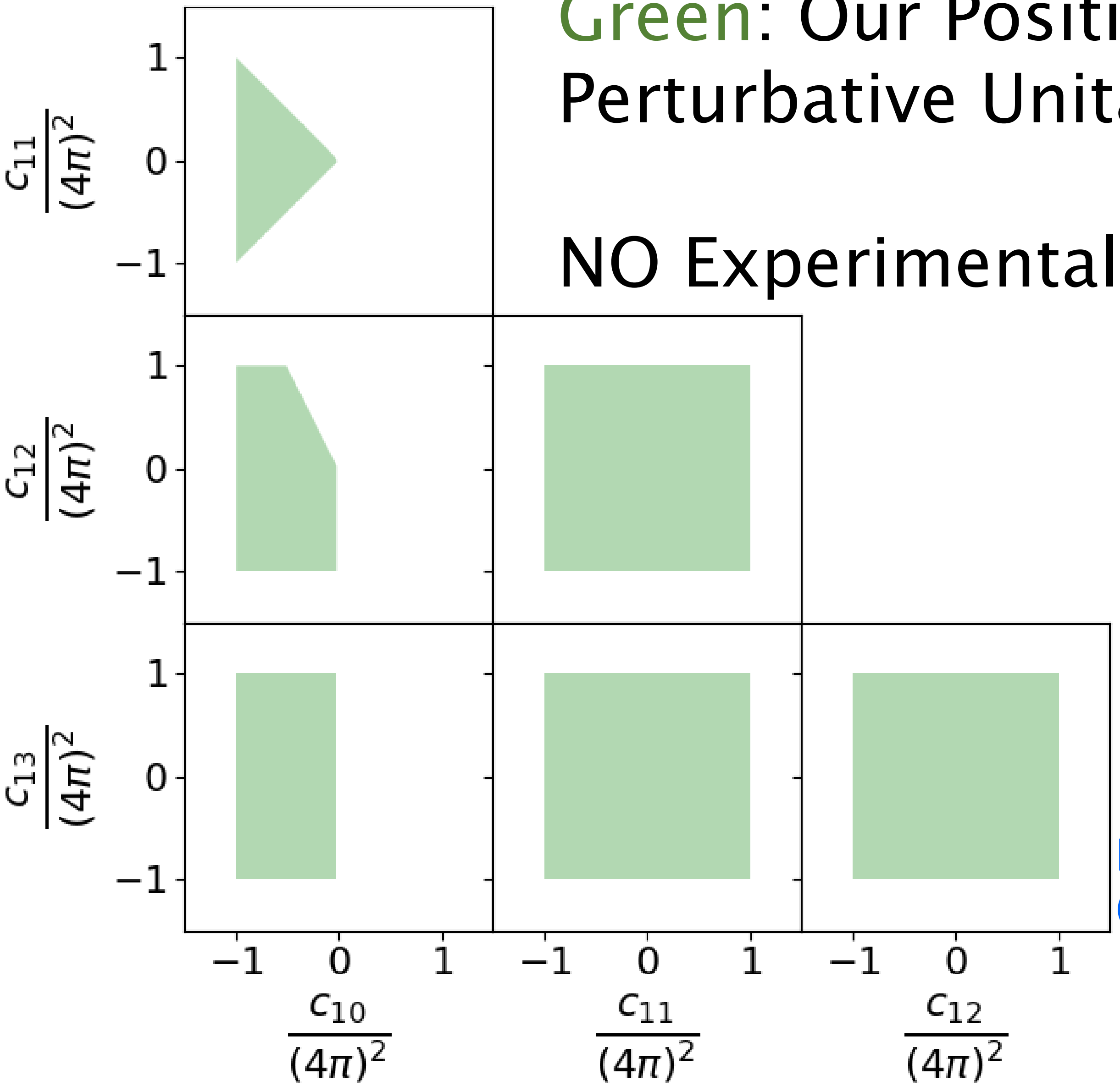


Only $\lesssim$ **8%** of the (5-Dim.) EFT parameter space within the Exp. bounds is allowed by positivity. 😇

D.Chakraborty, SC, R.S.Gupta (in prep.)

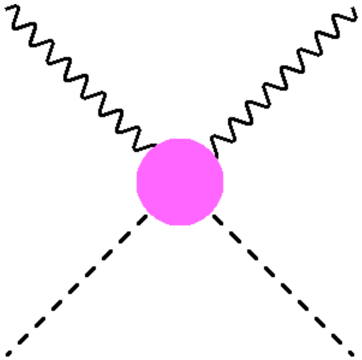
For SMEFT Bounds see: Remmen, Rodd '19

Bounds on VVhh



Green: Our Positivity Bounds + Perturbative Unitarity bounds

NO Experimental Bounds yet.

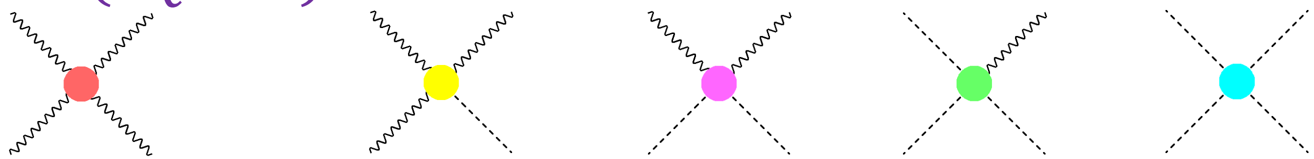


D.Chakraborty, SC, R.S.Gupta (in prep.)

Key Takeaways

- $SMEFT \subset HEFT$
- HEFT @ $\mathcal{O}(p^4)$ (Long.) Gauge-Higgs couplings:

$$5\, V^4(aQGCs) + 4\, V^3 h + 4\, V^2 h^2 + 1\, V h^3 + 1\, h^4$$



- Poincare Invariance + Causality + Unitarity + Locality → Positivity Bounds → significantly reduce the allowed IR parameter space. Eg:
  - **V^4 (aQGCs)** couplings: $\lesssim 8\%$ of (5-dim) EFT parameter space within the exp. bounds is allowed by positivity.
  - **V^2h^2** couplings: **No Exp. Bounds** yet. We obtain **positivity bounds** for these.

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- $SMEFT \subset HEFT$
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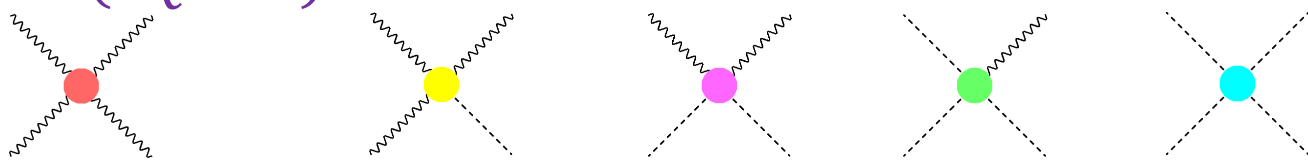

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Thank You !!!

BACKUP SLIDES

Dim-8 SMEFT Operators for VVVV

$$\begin{aligned}
\mathcal{O}_{s,1} &= \left[(D_\mu\Phi)^\dagger(D_\nu\Phi)\right]\left[(D^\mu\Phi)^\dagger(D^\nu\Phi)\right], \\
\mathcal{O}_{s,2} &= \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right]^2, \\
\mathcal{O}_{s,3} &= \left[(D_\mu\Phi)^\dagger(D_\nu\Phi)\right]\left[(D^\nu\Phi)^\dagger(D^\mu\Phi)\right].
\end{aligned}$$

HEFT in terms of SMEFT:

3 independent + 2 correlations

$$c_1 = \frac{1}{16}(a_3 + a_2 - a_1)\zeta; \qquad c_4 = -c_3;$$

$$c_2 = \zeta\frac{a_1}{8}; \qquad c_5 = 0$$

$$\zeta = \left(\frac{\Lambda}{v}\right)^4$$

$$c_3 = \zeta\frac{a_3 - a_1}{4}$$

BACKUP SLIDES

Definitions of some Elements of the matrix $\frac{\partial^2 M}{\partial s^2}$:

$$a = 16\left(c_1 + c_2\right)$$
$$b = 4\left(2c_1 + c_2\right)$$
$$c = 8c_1 + 4c_2 + c_3 + 2c_4$$
$$d = 8c_2$$
$$e = 16\left(c_1 + c_2\right) + 8\left(c_3 + c_4\right) + 4c_5$$
$$f = 2\left(4c_2 + c_3\right)$$
$$g = 2c_6 + 2c_7 + c_9$$
$$h = 2c_{11} + c_{13}$$