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Unitarity Bounds and Sum Rules in the SMEFT

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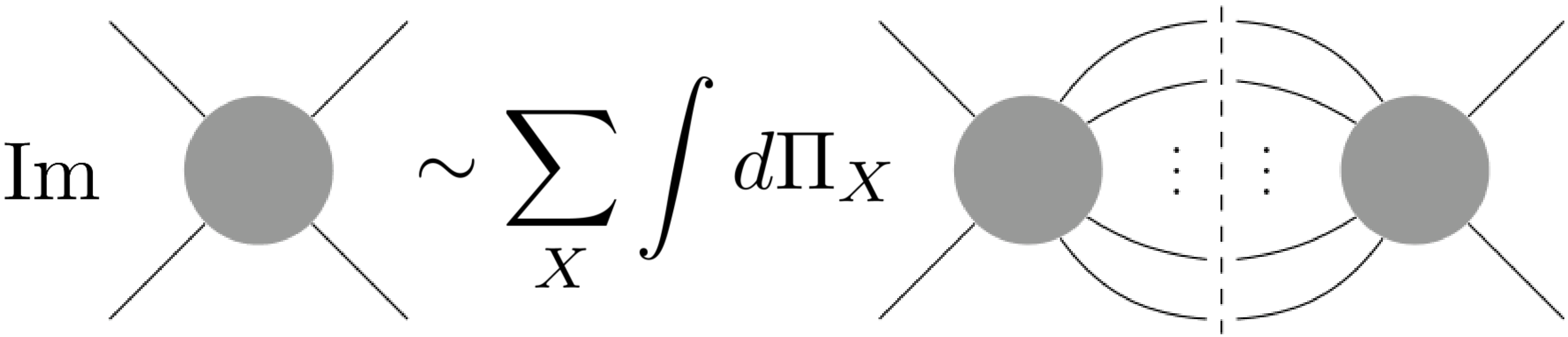
Based on [2603.03423] in collaboration with Luigi C. Bresciani and Paride Paradisi

LA THUILE 2025 - Les Rencontres de Physique de la Vallée d'Aoste

Unitarity Bounds

The unitarity of the S-matrix implies an upper bound on the modulus of scattering amplitudes, which is called (perturbative) unitarity bound



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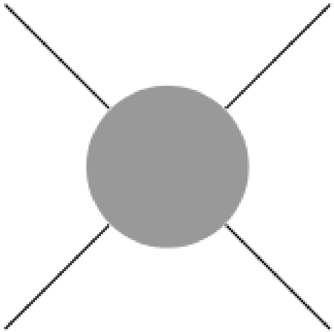
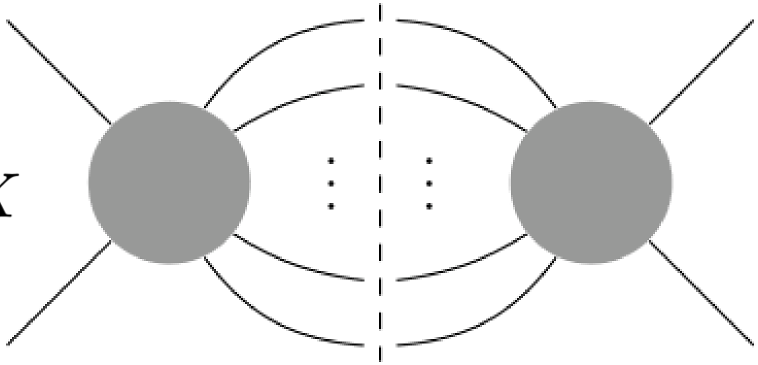
Im  $\sim \sum_X \int d\Pi_X$ 

In the past they have been used to set an upper bound on the UV cutoff of a Effective Field Theory (EFT)

Historical example: no-lose Higgs theorem

[Lee, Quigg, Thacker, '77]

$$m_H \lesssim 1\,\mathrm{TeV}$$

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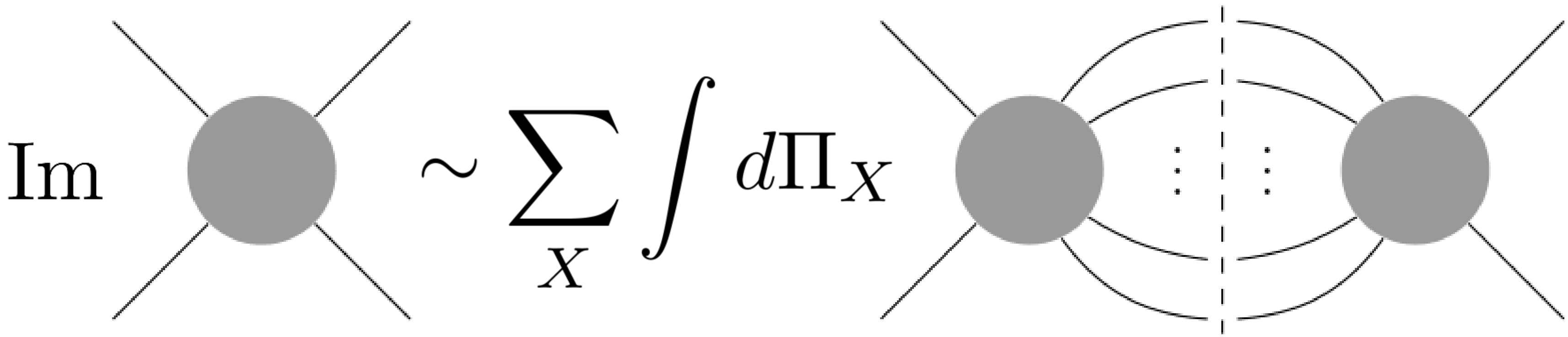

Standard approach to unitarity bounds: [Jacob, Wick, '59]

$$\mathcal{A}_{h_1,h_2\to h_3,h_4}(s,\theta) = 8\pi \sum_J (2J+1) a^J_{h_1,h_2\to h_3,h_4}(s)\, d^J_{h_1-h_2,h_3-h_4}(\theta)$$

$a^J_{h_1,h_2\to h_3,h_4}(s)$: Partial-wave coefficient

$d^J_{h_1-h_2,h_3-h_4}(\theta)$: Wigner-d matrix

The biggest limitation is that it works only for $2\to 2$ scattering processes

New approach to Unitarity Bounds

Recently [Bresciani et al, '25] developed a new formalism that allows to compute unitarity bounds of generic $N \to M \; (N, M \geq 2)$ scattering processes

We can project a generic amplitude onto a kinematic basis of a generic process $i \to f$ with definite angular momentum J

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$$|\mathcal{A}_{i\to f}\rangle = \sum_J a^J_{i\to f} \, |\mathcal{B}^J_{i\to f}\rangle$$

$a^J_{i\to f}$: Partial-wave coefficient

$|\mathcal{B}^J_{i\to f}\rangle$: Kinematic basis elements which are monomials in spinor-helicity variables

$$|\mathcal{A}_{i\to f}\rangle \, , \, |\mathcal{B}^J_{i\to f}\rangle \in V_{i\to f}$$

Vector space

New approach to Unitarity Bounds

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$$\left|\mathcal{A}_{i\to f}\right\rangle = \sum_J a^J_{i\to f} \left|\mathcal{B}^J_{i\to f}\right\rangle$$

We can derive the unitarity bounds on the partial-wave coefficients

$$\left|\mathrm{Re}\, a^J_{i\to i}\right| \leq 1 \qquad 0 \leq \mathrm{Im}\, a^J_{i\to i} \leq 2 \qquad \left|a^J_{i\to f}\right| \leq 1$$

Unitarity Bounds in SMEFT

We computed the unitarity bounds of the dimension-six SMEFT Wilson coefficients

Example:

$$\mathcal{O}_{\ell q}^{(1)} = (\bar{\ell}_p \gamma_\mu \ell_r)(\bar{q}_s \gamma^\mu q_t)$$
$$\mathcal{O}_{\ell q}^{(3)} = (\bar{\ell}_p \gamma_\mu \sigma^I \ell_r)(\bar{q}_s \gamma^\mu \sigma^I q_t)$$

Multiple DOFs coming from the quantum numbers of the fields

$i, j, k, \ell :$ $\mathrm{SU}(2)$

$\alpha, \beta :$ $\mathrm{SU}(3)$

$p, r, s, t :$ Flavor indices

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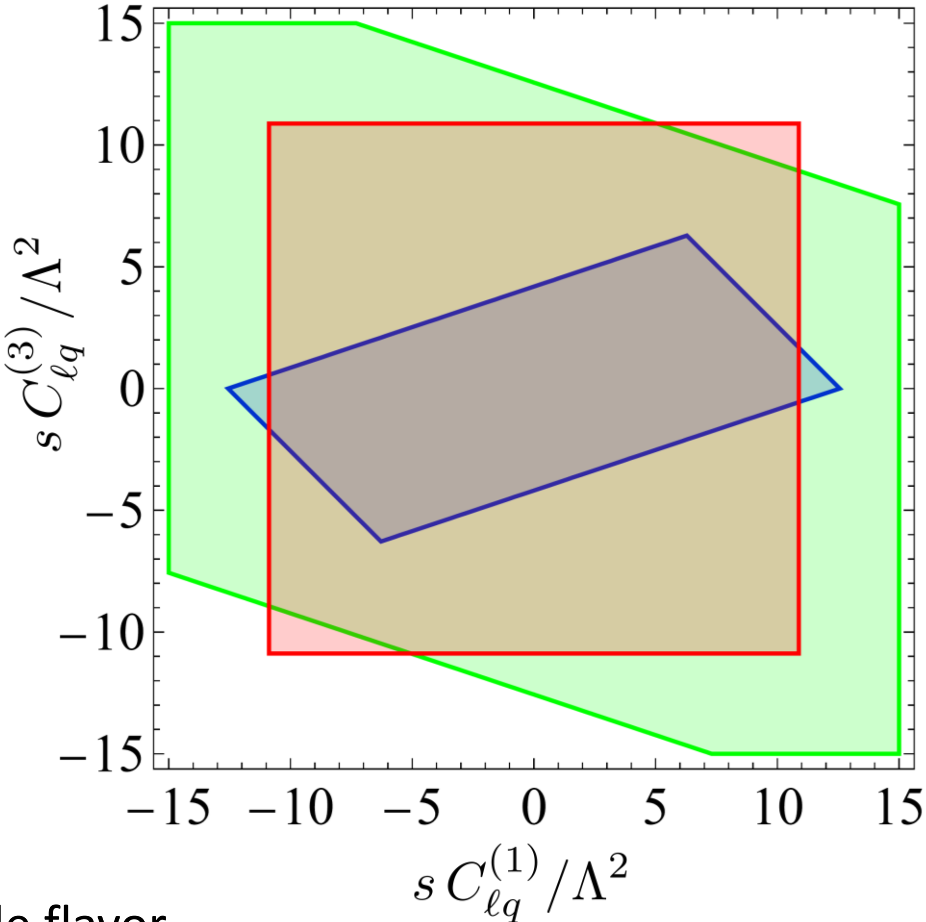
Multiple channels

- (blue) $\ell_p^i q_r^{j\alpha} \to \ell_s^k q_t^{\ell\beta}$ $\quad J = 0$
- (green) $\ell_p^i \bar{q}_r^{j\alpha} \to \ell_s^k \bar{q}_t^{\ell\beta}$ $\quad J = 1$
- (red) $\ell_p^i \bar{\ell}_r^j \to q_s^{k\alpha} \bar{q}_t^{\ell\beta}$ $\quad J = 1$



For practical purposes we limited to single flavor

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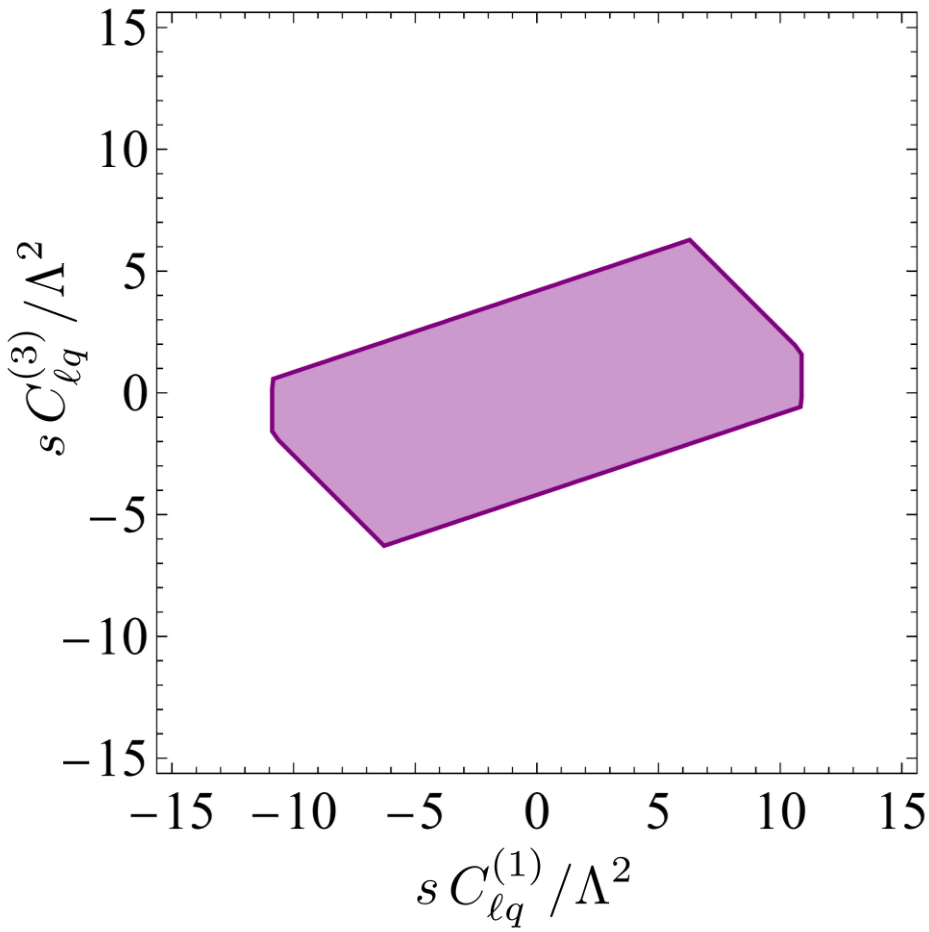
The fully coupled-channel analysis allow to constrain as much as possible the bounds



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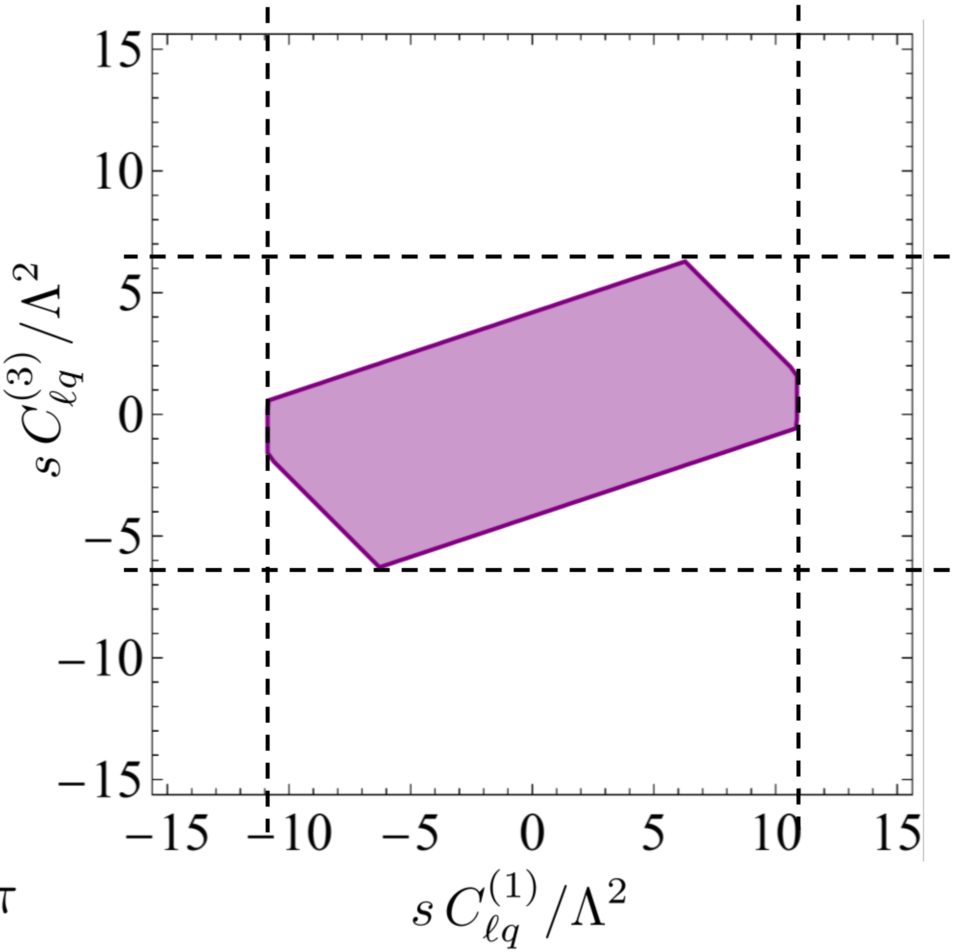
The fully coupled-channel analysis allow to constrain as much as possible the bounds

We marginalize over all the other SMEFT coefficients

$$\frac{s}{\Lambda^2}|C_{q\ell}^{(1)}| \leq 2\pi\sqrt{3} \qquad \frac{s}{\Lambda^2}|C_{q\ell}^{(3)}| \leq 2\pi$$



Unitarity Bounds in SMEFT

Unitarity bounds marginalized over all the other Wilson coefficients

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$		$(\bar{L}L)(\bar{L}L)$		$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
C_G	$4\pi/(9g_s)$	C_φ	$32\pi^3/3$	$C_{e\varphi}$	$32\pi^2/\sqrt{3}$	$C_{\ell\ell}$	2π	$C_{\ell edq}$	$8\pi/\sqrt{3}$
$C_{\widetilde{G}}$	$4\pi/(9g_s)$	$C_{\varphi\Box}$	$8\pi/3$	$C_{u\varphi}$	$32\pi^2/3$	$C_{qq}^{(1)}$	$6\pi/5$	$C_{quqd}^{(1)}$	$16\pi(1+\sqrt{2})/9$
C_W	$2\pi/(3g)$	$C_{\varphi D}$	$32\pi/3$	$C_{d\varphi}$	$32\pi^2/3$	$C_{qq}^{(3)}$	$4\pi/3$	$C_{quqd}^{(8)}$	$4\pi(2+7\sqrt{2})/3$
$C_{\widetilde{W}}$	$2\pi/(3g)$					$C_{\ell q}^{(1)}$	$2\pi\sqrt{3}$	$C_{\ell equ}^{(1)}$	$8\pi/\sqrt{3}$
						$C_{\ell q}^{(3)}$	2π	$C_{\ell equ}^{(3)}$	$(2+\sqrt{2})\pi/3$

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$C_{\varphi G}$	π	C_{uG}	$2\pi\sqrt{3}$	$C_{\varphi\ell}^{(1)}$	8π	C_{ee}	2π	$C_{\ell e}$	4π
$C_{\varphi\widetilde{G}}$	π	C_{dG}	$2\pi\sqrt{3}$	$C_{\varphi\ell}^{(3)}$	$8\pi/3$	C_{uu}	$3\pi/2$	$C_{\ell u}$	4π
$C_{\varphi W}$	$2\pi\sqrt{2/3}$	C_{eW}	$4\pi\sqrt{2/3}$	$C_{\varphi e}$	8π	C_{dd}	$3\pi/2$	$C_{\ell d}$	4π
$C_{\varphi\widetilde{W}}$	$2\pi\sqrt{2/3}$	C_{uW}	$4\pi\sqrt{2/3}$	$C_{\varphi q}^{(1)}$	$2\pi\sqrt{6}$	C_{eu}	4π	C_{qe}	4π
$C_{\varphi B}$	$2\pi\sqrt{2}$	C_{uB}	4π	$C_{\varphi q}^{(3)}$	$8\pi/3$	C_{ed}	4π	$C_{qu}^{(1)}$	$2\pi\sqrt{2}$
$C_{\varphi\widetilde{B}}$	$2\pi\sqrt{2}$	C_{eB}	4π	$C_{\varphi u}$	$4\pi\sqrt{3}$	$C_{ud}^{(1)}$	4π	$C_{qu}^{(8)}$	$3\pi(1+1/\sqrt{2})$
$C_{\varphi WB}$	4π	C_{dW}	$4\pi\sqrt{2/3}$	$C_{\varphi d}$	$4\pi\sqrt{3}$	$C_{ud}^{(8)}$	8π	$C_{qd}^{(1)}$	$2\pi\sqrt{2}$
$C_{\varphi\widetilde{W}B}$	4π	C_{dB}	4π	$C_{\varphi ud}$	8π			$C_{qd}^{(8)}$	$3\pi(1+1/\sqrt{2})$

Unitarity Bounds in SMEFT

Verified

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$		$(\bar{L}L)(\bar{L}L)$		$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
C_G	$4\pi/(9g_s)$	C_φ	$32\pi^3/3$	$C_{e\varphi}$	$32\pi^2/\sqrt{3}$	$C_{\ell\ell}$	2π	$C_{\ell edq}$	$8\pi/\sqrt{3}$
$C_{\widetilde{G}}$	$4\pi/(9g_s)$	$C_{\varphi\Box}$	$8\pi/3$	$C_{u\varphi}$	$32\pi^2/3$	$C_{qq}^{(1)}$	$6\pi/5$	$C_{quqd}^{(1)}$	$16\pi(1+\sqrt{2})/9$
C_W	$2\pi/(3g)$	$C_{\varphi D}$	$32\pi/3$	$C_{d\varphi}$	$32\pi^2/3$	$C_{qq}^{(3)}$	$4\pi/3$	$C_{quqd}^{(8)}$	$4\pi(2+7\sqrt{2})/3$
$C_{\widetilde{W}}$	$2\pi/(3g)$					$C_{\ell q}^{(1)}$	$2\pi\sqrt{3}$	$C_{\ell equ}^{(1)}$	$8\pi/\sqrt{3}$
						$C_{\ell q}^{(3)}$	2π	$C_{\ell equ}^{(3)}$	$(2+\sqrt{2})\pi/3$

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$C_{\varphi G}$	π	C_{uG}	$2\pi\sqrt{3}$	$C_{\varphi\ell}^{(1)}$	8π	C_{ee}	2π	$C_{\ell e}$	4π
$C_{\varphi\widetilde{G}}$	π	C_{dG}	$2\pi\sqrt{3}$	$C_{\varphi\ell}^{(3)}$	$8\pi/3$	C_{uu}	$3\pi/2$	$C_{\ell u}$	4π
$C_{\varphi W}$	$2\pi\sqrt{2/3}$	C_{eW}	$4\pi\sqrt{2/3}$	$C_{\varphi e}$	8π	C_{dd}	$3\pi/2$	$C_{\ell d}$	4π
$C_{\varphi\widetilde{W}}$	$2\pi\sqrt{2/3}$	C_{uW}	$4\pi\sqrt{2/3}$	$C_{\varphi q}^{(1)}$	$2\pi\sqrt{6}$	C_{eu}	4π	C_{qe}	4π
$C_{\varphi B}$	$2\pi\sqrt{2}$	C_{uB}	4π	$C_{\varphi q}^{(3)}$	$8\pi/3$	C_{ed}	4π	$C_{qu}^{(1)}$	$2\pi\sqrt{2}$
$C_{\varphi\widetilde{B}}$	$2\pi\sqrt{2}$	C_{eB}	4π	$C_{\varphi u}$	$4\pi\sqrt{3}$	$C_{ud}^{(1)}$	4π	$C_{qu}^{(8)}$	$3\pi(1+1/\sqrt{2})$
$C_{\varphi WB}$	4π	C_{dW}	$4\pi\sqrt{2/3}$	$C_{\varphi d}$	$4\pi\sqrt{3}$	$C_{ud}^{(8)}$	8π	$C_{qd}^{(1)}$	$2\pi\sqrt{2}$
$C_{\varphi\widetilde{W}B}$	4π	C_{dB}	4π	$C_{\varphi ud}$	8π			$C_{qd}^{(8)}$	$3\pi(1+1/\sqrt{2})$

Unitarity Bounds in SMEFT

Verified **Improved**

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$		$(\bar{L}L)(\bar{L}L)$		$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
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$C_{\widetilde{W}}$	$2\pi/(3g)$					$C_{\ell q}^{(1)}$	$2\pi\sqrt{3}$	$C_{\ell equ}^{(1)}$	$8\pi/\sqrt{3}$
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$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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$C_{\varphi\widetilde{B}}$	$2\pi\sqrt{2}$	C_{eB}	4π	$C_{\varphi u}$	$4\pi\sqrt{3}$	$C_{ud}^{(1)}$	4π	$C_{qu}^{(8)}$	$3\pi(1+1/\sqrt{2})$
$C_{\varphi WB}$	4π	C_{dW}	$4\pi\sqrt{2/3}$	$C_{\varphi d}$	$4\pi\sqrt{3}$	$C_{ud}^{(8)}$	8π	$C_{qd}^{(1)}$	$2\pi\sqrt{2}$
$C_{\varphi\widetilde{W}B}$	4π	C_{dB}	4π	$C_{\varphi ud}$	8π			$C_{qd}^{(8)}$	$3\pi(1+1/\sqrt{2})$

Unitarity Bounds in SMEFT

Verified **Improved** **New**

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$		$(\bar{L}L)(\bar{L}L)$		$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
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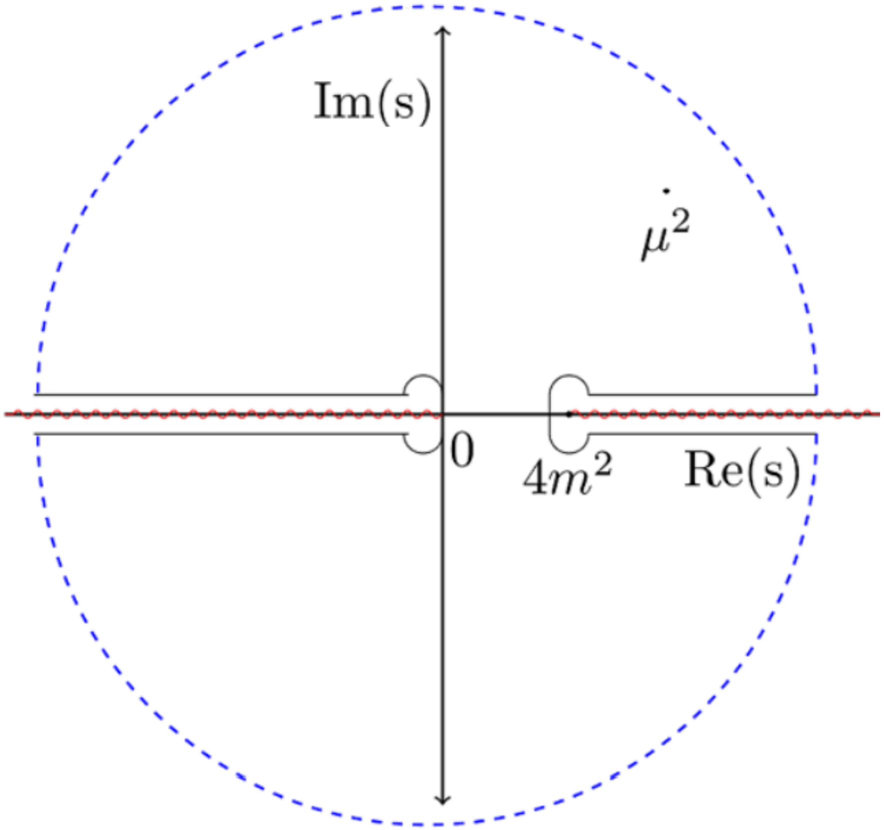
Sum Rules

Unitarity, locality and analiticity of scattering amplitudes are violated by some values of the Wilson coefficients in a given EFT

For dimension-eight operators they are called positivity bounds



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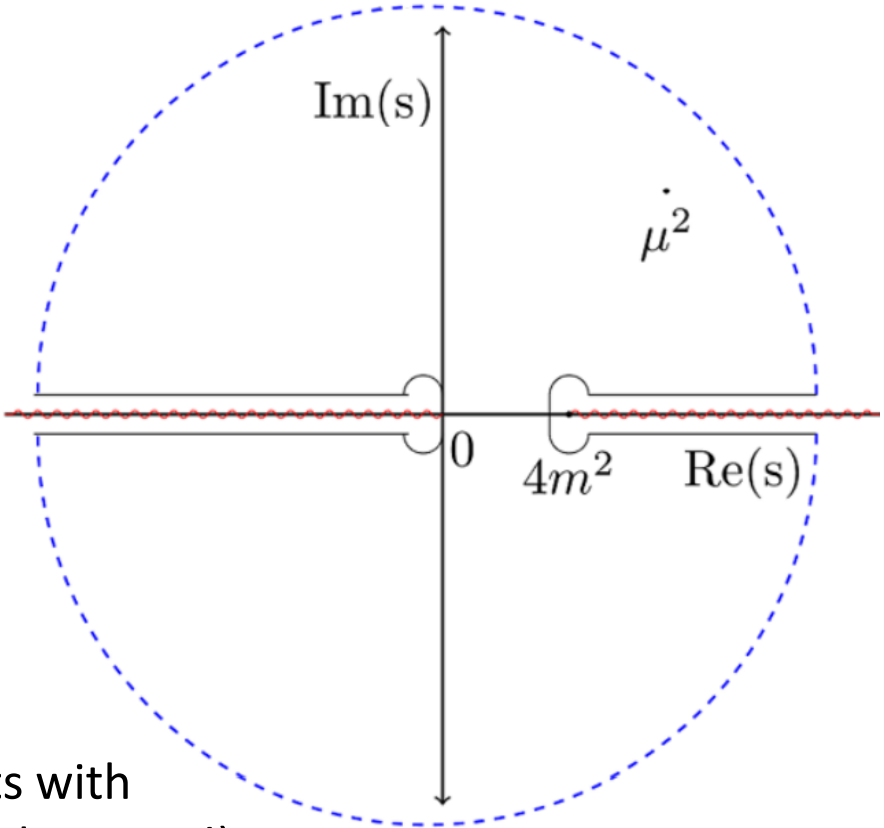
(Spinning) Sum Rules are positivity-like bounds for dimension-six operators [Remmen, Rodd, '22]

Caveat: the boundary term at infinity is not guaranteed to vanish!



They provide complementarity constraints with respect to unitarity bounds (they are not the same!)

Sum Rules in SMEFT

Sum Rules are useful in constraining 4-fermion operators in the SMEFT

Example:

$$\mathcal{O}_{\ell q}^{(1)} = (\bar{\ell}_p \gamma_\mu \ell_r)(\bar{q}_s \gamma^\mu q_t)$$

$$\mathcal{O}_{\ell q}^{(3)} = (\bar{\ell}_p \gamma_\mu \sigma^I \ell_r)(\bar{q}_s \gamma^\mu \sigma^I q_t)$$

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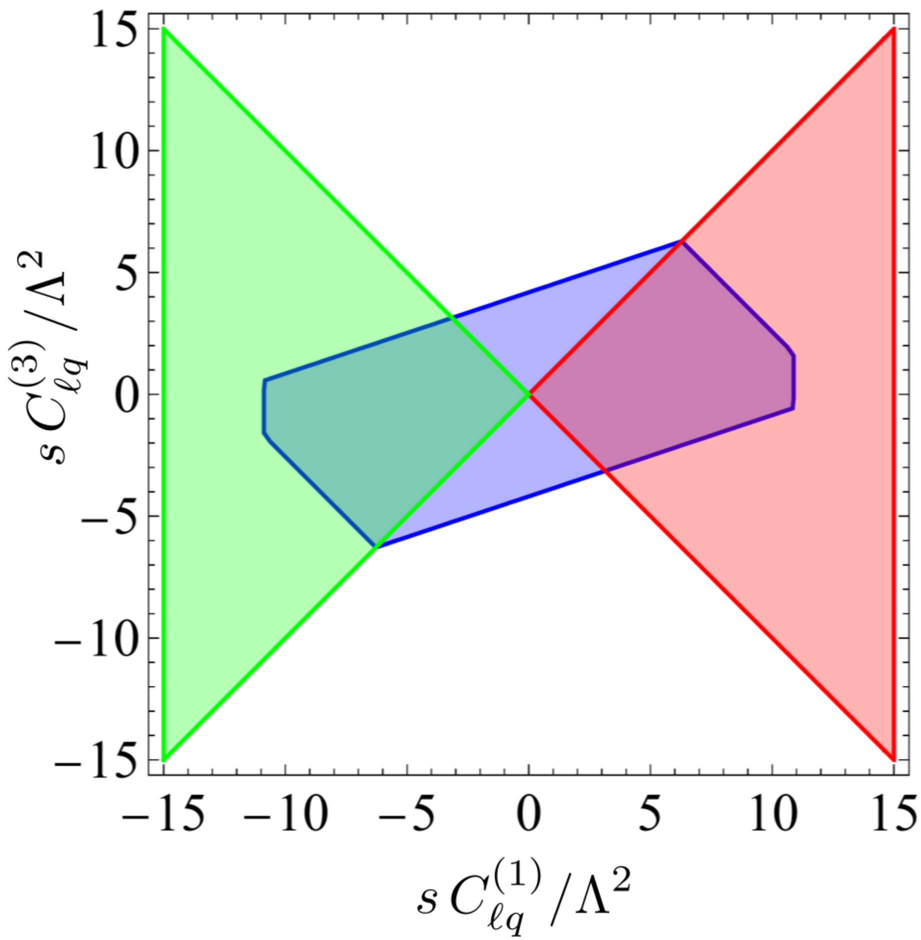
- Unitarity bounds (blue)
- Vector dominance in the UV (green)
- Scalar dominance in the UV (red)

For practical purposes we limited to single flavor



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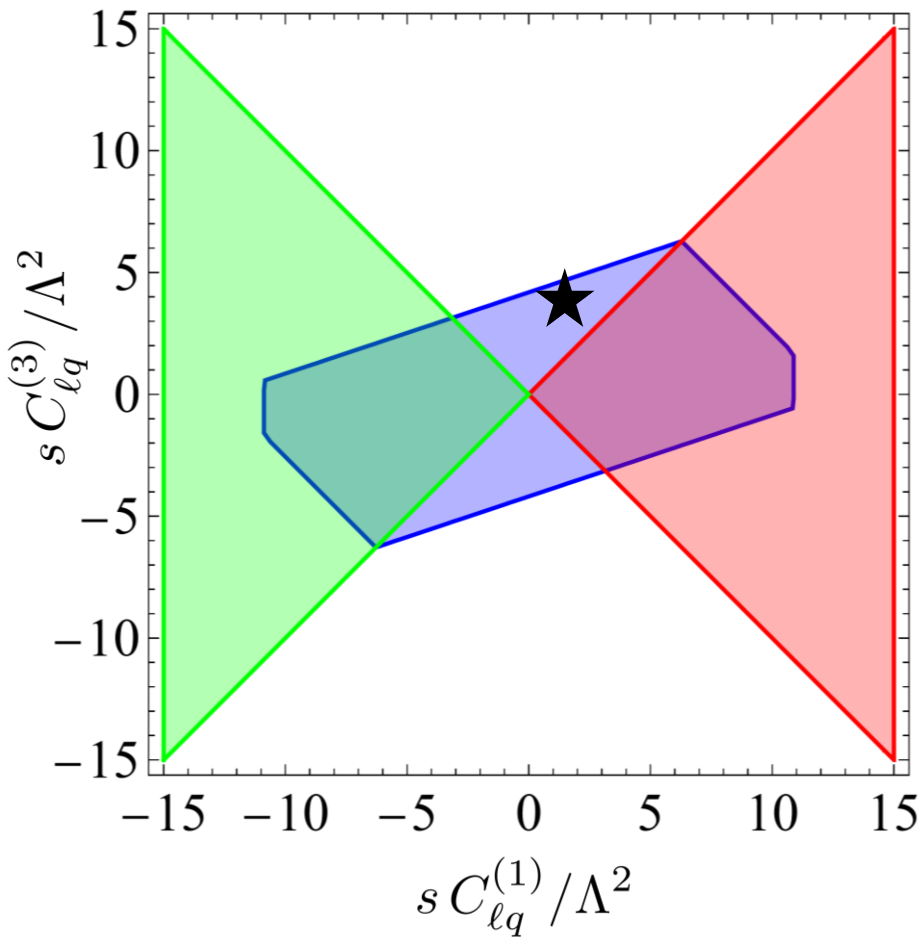


- Unitarity bounds
- Vector dominance in the UV
- Scalar dominance in the UV

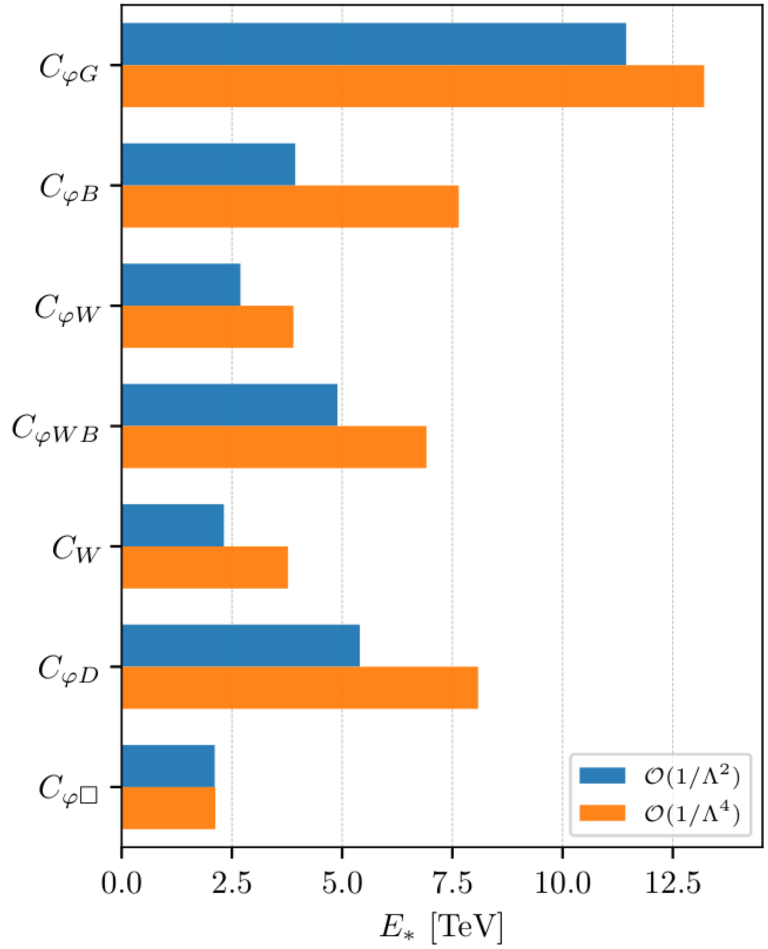
★ Even if the sum rules are violated, we can still infer something about the UV (t-channel domination…)

Phenomenology

The theoretical bounds can be used to provide complementary constraints to the experimental ones on the SMEFT Wilson coefficients

Unitarity Bounds for purely bosonic operators on the energy scale at which they are violated

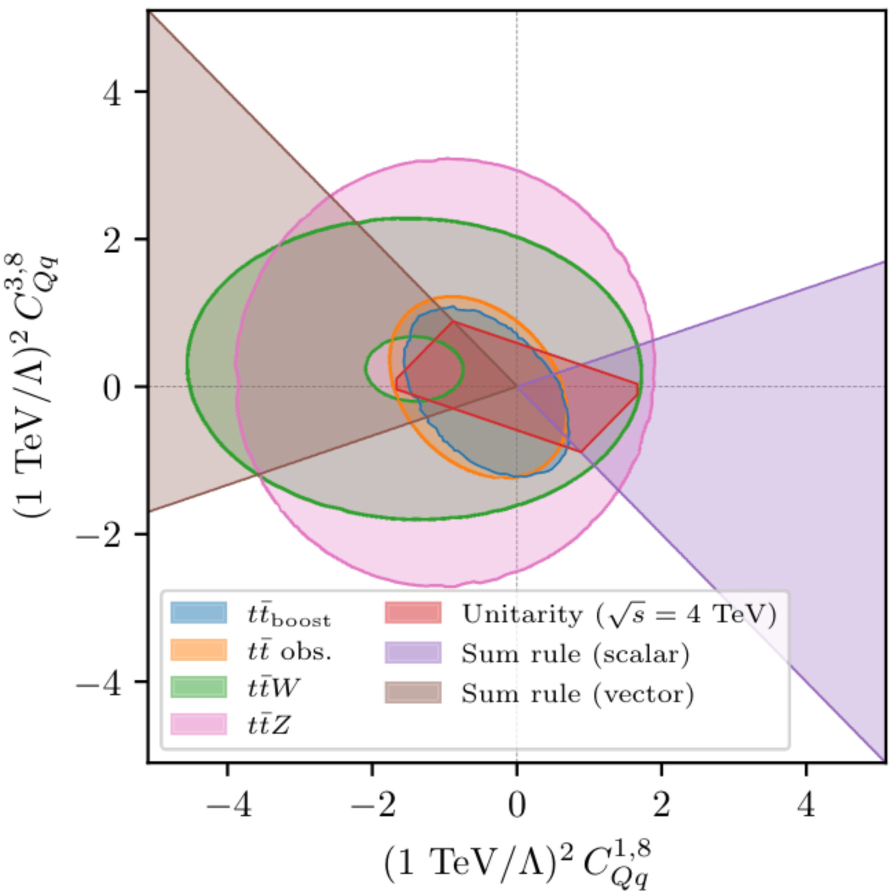
the value of each Wilson coefficient is assumed to be the current experimental sensitivity at 95% CL [Celada et al, ‘24]



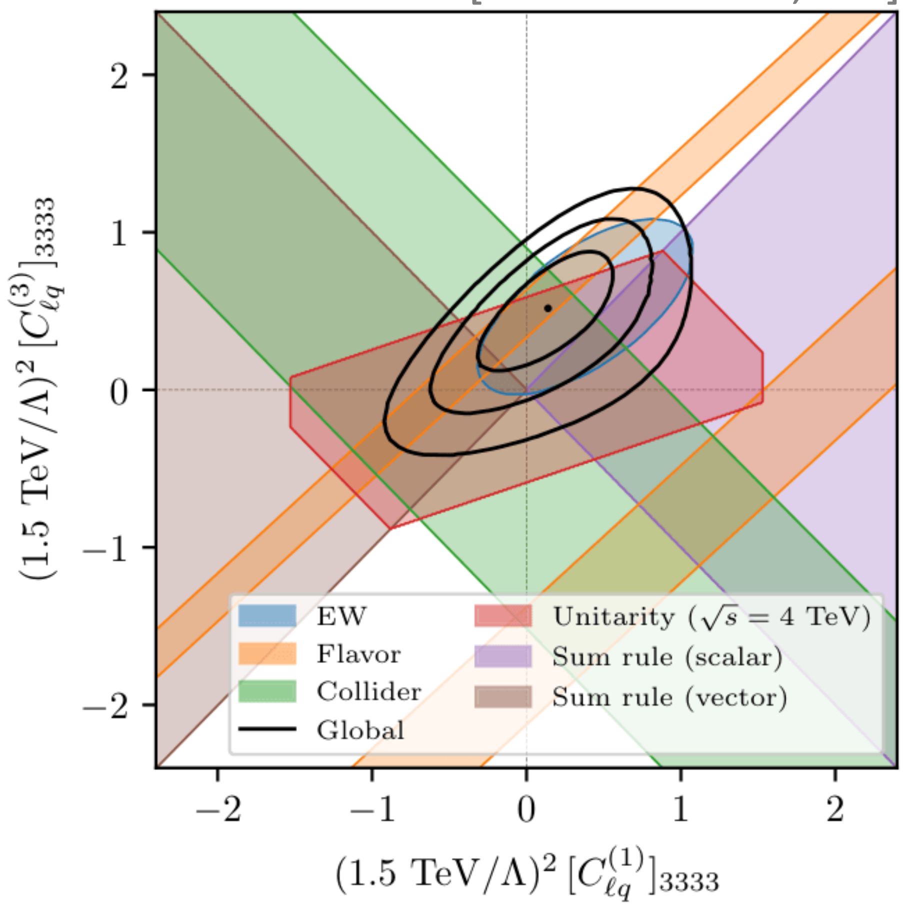
Phenomenology

The theoretical bounds can be used to provide complementary constraints to the experimental ones on the SMEFT Wilson coefficients

[Brivio et al, ‘19]



[Allwicher et al, ‘23]



Conclusions

In this work we presented for the first time the complete set of Unitarity Bounds for all the dimension-six SMEFT coefficients

For 4-fermion operators such bounds can be further strengthened by incorporating additional and complementary Sum Rules

We highlighted the synergy and interplay between theoretical bounds and experimental limits in the quest for new physics