POSITIVITY BOUNDS ON HIGGS-PORTAL DARK MATTER

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arXiv: 2302.02879 [hep-ph]

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View from
1st floor@310

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Effective Field Theory (EFT)

- EFT

  heavy degrees of freedom decouple

  for large-distance phenomena
  or small momentum scale

- EFT interaction terms:

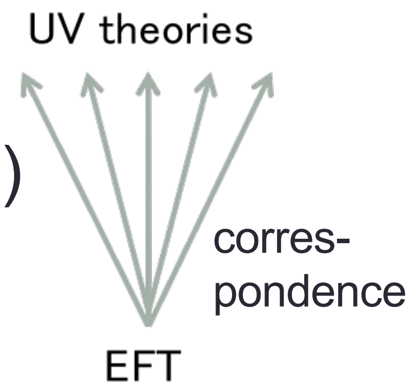
$$\mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \mathcal{L}^{(8)} + \cdots$$

Wilson coefficients

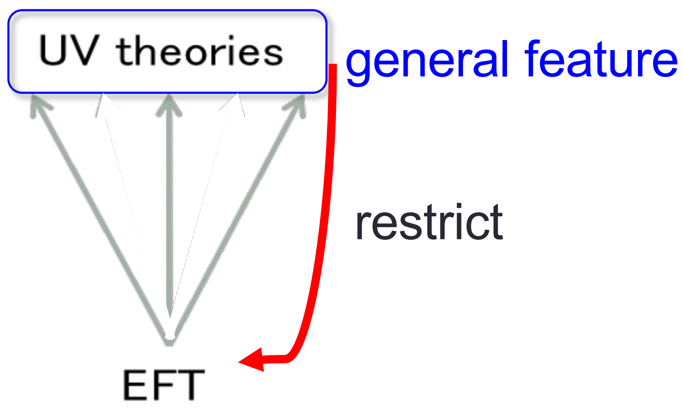
$$\mathcal{L} = \sum_{i=1}^{n_d} \frac{c_i^5}{\Lambda} \mathcal{O}_i^{(5)} + \frac{c_i^6}{\Lambda^2} \mathcal{O}_i^{(6)} + \frac{c_i^7}{\Lambda^3} \mathcal{O}_i^{(7)} + \frac{c_i^8}{\Lambda^4} \mathcal{O}_i^{(8)} + \cdots$$

Positivity Bounds

- EFT is for the energy scale of
  E << Λ (typical energy scale of the UV physics)
- Many UV models correspond with EFT



- From the general feature of UV theory,
  can we bound on Wilson coefficients of EFT?



If we base on the local Quantum Field Theory(QFT) for the general feature of UV theory,

1. Special relativity ⟶ Lorentz invariance
2. Conservation of probability ⟶ Unitarity
3. Causality - - - → Analyticity

Positivity Bounds

A. Adams, N. Arkani-Hamed, S. Dubovsky, A. Nicolis, R.Rattazzi, JHEP **0610**, 014(2006)

- One of the way to do this is Positivity bounds
- Positivity bounds: the signs of certain combinations of Wilson coefficients in EFT have to be positive, e.g. W^4 operators:

$$\frac{F_{T,0}}{\Lambda^4}\mathrm{Tr}[\hat{\mathrm{W}}_{\mu\nu}\hat{\mathrm{W}}^{\mu\nu}]\mathrm{Tr}[\hat{\mathrm{W}}_{\alpha\beta}\hat{\mathrm{W}}^{\alpha\beta}] \qquad \frac{F_{T,1}}{\Lambda^4}\mathrm{Tr}[\hat{\mathrm{W}}_{\alpha\nu}\hat{\mathrm{W}}^{\mu\beta}]\mathrm{Tr}[\hat{\mathrm{W}}_{\mu\beta}\hat{\mathrm{W}}^{\alpha\nu}]$$

$$\frac{F_{T,2}}{\Lambda^4}\mathrm{Tr}[\hat{\mathrm{W}}_{\alpha\mu}\hat{\mathrm{W}}^{\mu\beta}]\mathrm{Tr}[\hat{\mathrm{W}}_{\beta\nu}\hat{\mathrm{W}}^{\nu\alpha}] \qquad \frac{F_{T,10}}{\Lambda^4}\mathrm{Tr}[\hat{\mathrm{W}}_{\mu\nu}\tilde{\mathrm{W}}^{\mu\nu}]\mathrm{Tr}[\hat{\mathrm{W}}_{\alpha\beta}\tilde{\mathrm{W}}^{\alpha\beta}]$$

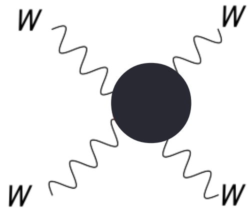
$$\hat{W}^{\mu\nu} \equiv ig\frac{\sigma^I}{2}W^{I,\mu\nu} \qquad \tilde{W}^{\mu\nu} \equiv ig\frac{\sigma^I}{2}\left(\frac{1}{2}\epsilon_{\mu\nu\rho\sigma}W^{I,\rho\sigma}\right)$$

One of the positivity bounds:

$$2F_{T,0} + 2F_{T,1} + F_{T,2} \geq 0$$

KY, C. Zhang, S. Y. Zhou, JHEP **01**, 095 (2021)

Positivity Bounds

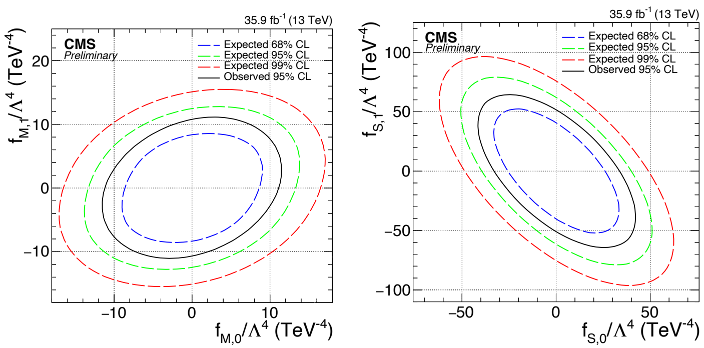


[FFFF]=Dim 8

- Positivity bounds can apply for dim-8 operators in tree-level ← Froissart Bound (⇦Analyticity)

- Dim-8 operators are more suppressed by Λ than lower dimensional ones, however, for dim-8 aQGC operators, LHC experimentalists have been and currently working on constraining them

CMS-PAS-SMP-18-001



- In the future, more dim-8 effects may become accessible

(e.g. new observable proposed for DY process:
Alioli, Boughezal, Mereghetti, Petriello, Phys. Lett. B **809**, 135703 (2020),
X. Li, K. Mimasu, KY, C. Yang, C. Zhang, S. Y. Zhou, JHEP**10**(2022)107)

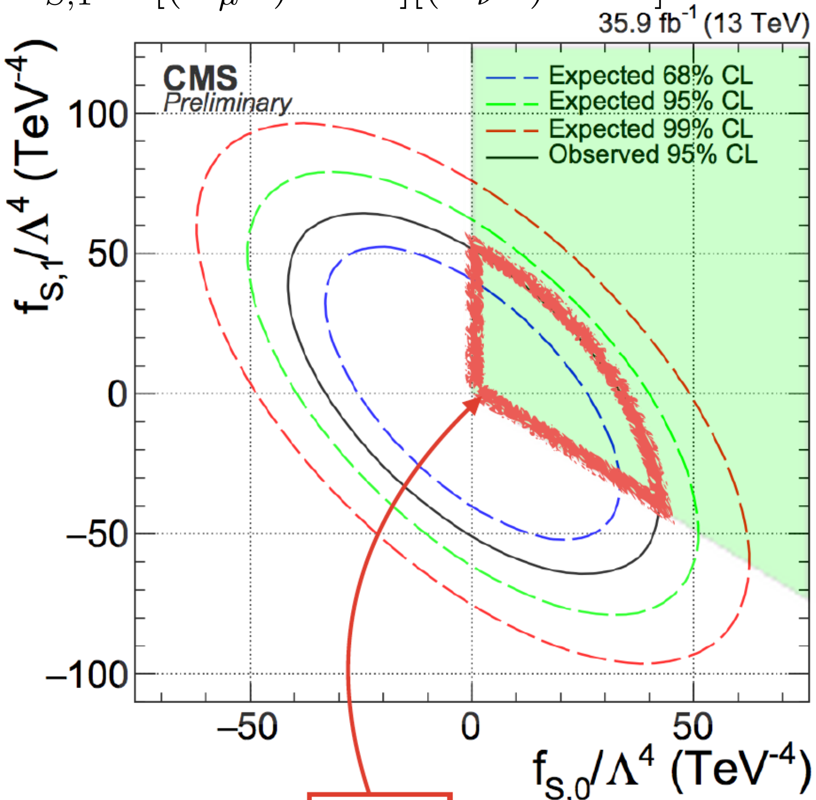
Positivity Bounds

Positivity bounds are important as they offer complementary bounds to the experiments

Q. Bi, C. Zhang, S.-Y. Zhou JHEP **1906** (2019) 137

E.g. WZjj (CMS-PAS-SMP-18-001)

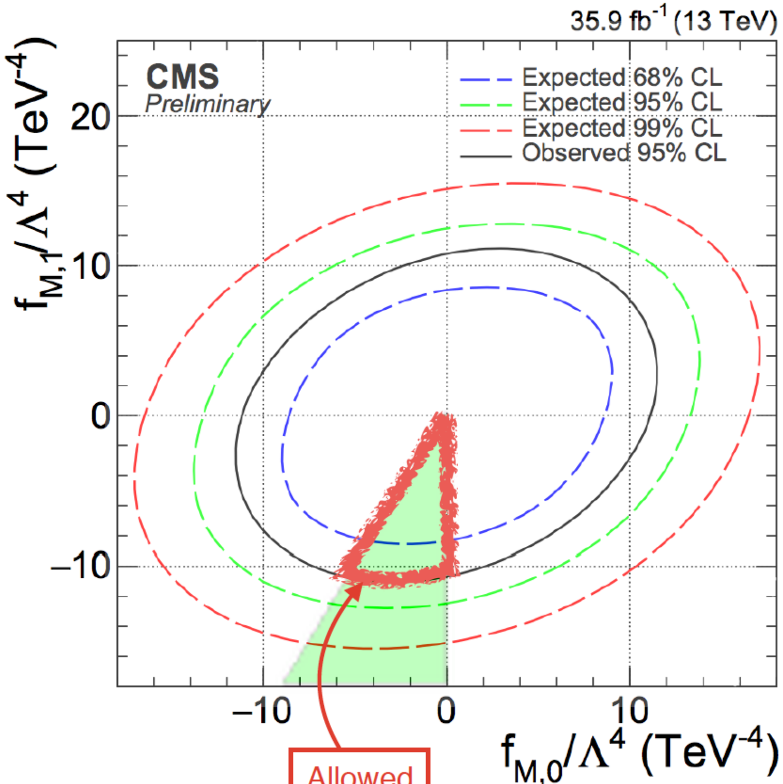
$O_{S,1} = [(D_\mu \Phi)^\dagger D^\mu \Phi][(D_\nu \Phi)^\dagger D^\nu \Phi]$



Allowed

$O_{S,0} = [(D_\mu \Phi)^\dagger D_\nu \Phi][(D^\mu \Phi)^\dagger D^\nu \Phi]$

$O_{M,1} = \mathrm{Tr}[\hat{W}_{\mu\nu} \hat{W}^{\nu\beta}][(D_\beta \Phi)^\dagger D^\mu \Phi]$



Allowed

$O_{M,0} = \mathrm{Tr}[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}][(D_\beta \Phi)^\dagger D^\beta \Phi]$

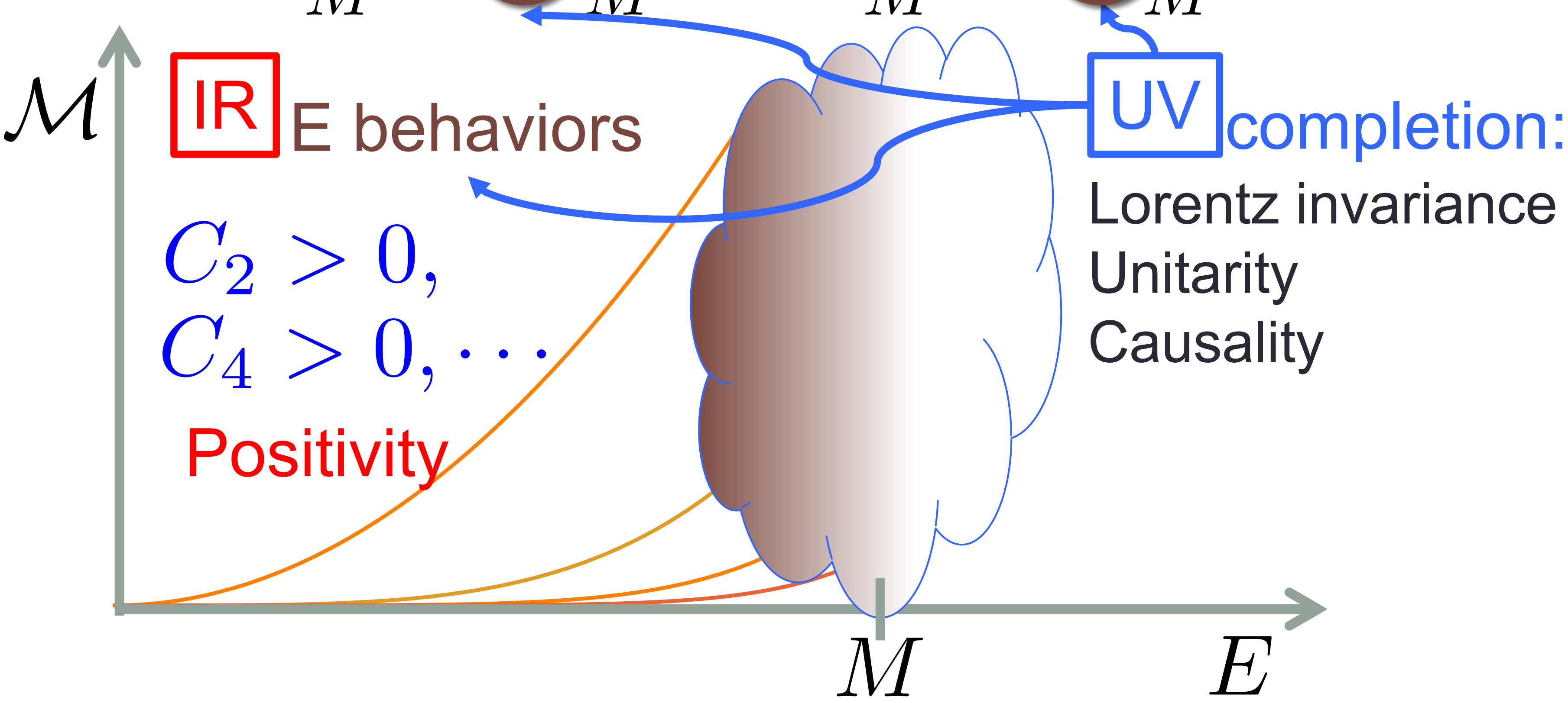
Positivity restricts the directions in which SM deviation is possible

Positivity Bounds

Ref: Slides by Francesco Riva
https://indico.ph.tum.de/event/4408/contributions/3825/attachments/3292/3974/Berlin-2.pdf

- Effective Theory Forward Amplitude (IR):

$$\mathcal{M} = C_0 + C_1 \frac{s}{M^2} + C_2 \frac{s^2}{M^4} + C_3 \frac{s^3}{M^6} + C_4 \frac{s^4}{M^8} + \cdots$$



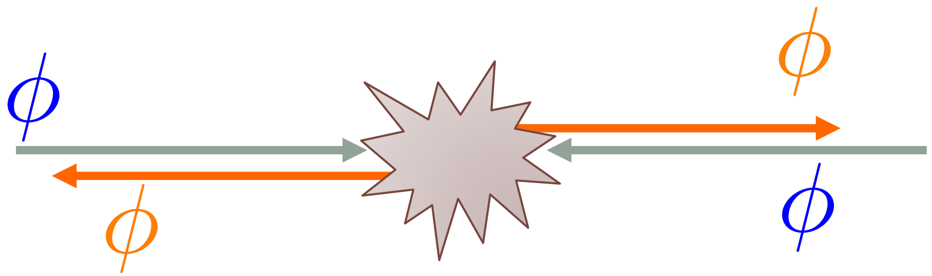
Positivity Bounds

$$\mathcal{M} = C_0 + C_1 \frac{s}{M^2} + C_2 \frac{s^2}{M^4} + C_3 \frac{s^3}{M^6} + C_4 \frac{s^4}{M^8} + \cdots$$

C_2 >0

massless scalar 2-2 forward elastic scattering:

forward: t=0



|+|| →|+||

elastic

Let us consider the amplitude of this: $\dfrac{\mathcal{M}(s,0)}{s^3}$

Positivity Bounds

Forward limit positivity bounds are from:

1. Lorentz Invariance

2. Unitarity ⇨ Optical theorem:
   e.g., elastic case,

$$\mathrm{Im}\mathcal{M}(k_1, k_2 \to k_1, k_2) = \underline{\underline{s\sigma_{\mathrm{tot}}(k_1, k_2 \to \mathrm{anything})}}$$

Positive

1. Analyticity* ⇨ Froissart Bound:

$$|\mathcal{M}(s, \underline{\underline{\cos\theta = 1}})| < \mathrm{Const.}\ s(\ln s)^2$$

forward

Froissart, Martin 1960's

(for real s→∞)

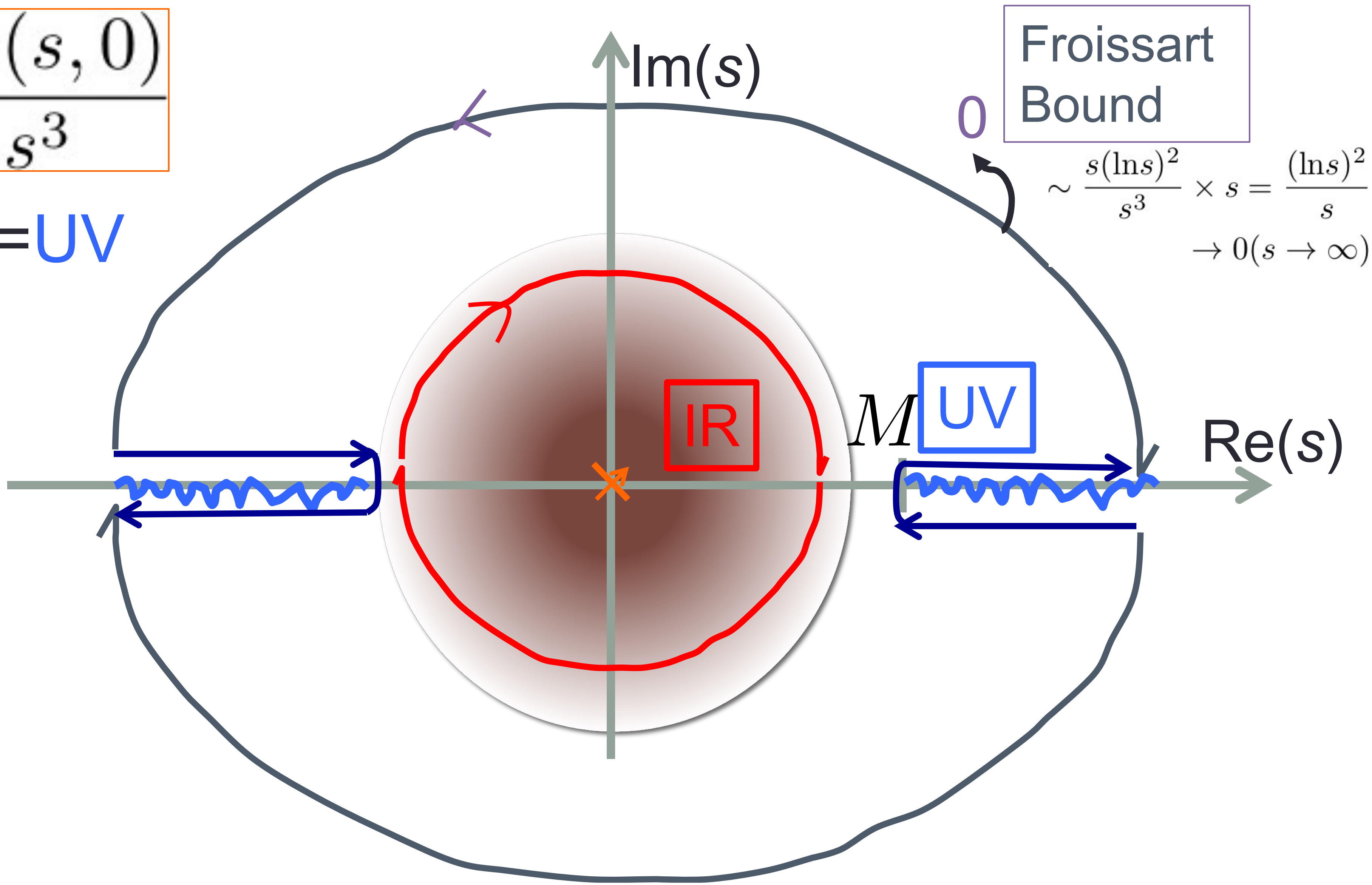
*Analyticity of the amplitude besides poles and branch cuts on real axis

Positivity Bounds

massless scalar 2-2 forward elastic scattering amplitude:

$$\frac{\mathcal{M}(s,0)}{s^3}$$

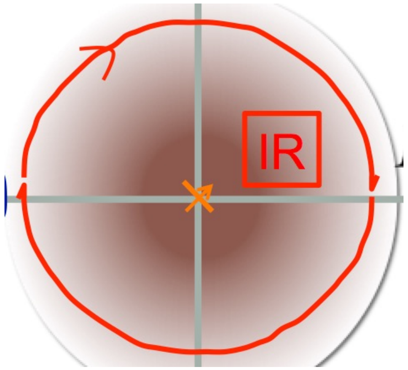
IR=UV



Positivity Bounds

IR

$$\frac{1}{2\pi i}\oint ds \frac{\mathcal{M}(s,0)}{s^3} = \frac{C_2}{M^4}$$



$$\mathcal{M} = C_0 + C_1\frac{s}{M^2} + C_2\frac{s^2}{M^4} + C_3\frac{s^3}{M^6} + C_4\frac{s^4}{M^8} + \cdots$$

Positivity Bounds

UV

$$\frac{1}{2\pi i}\int_M^\infty ds\,\left(M(s+i\epsilon,0)-M(s-i\epsilon,0)\right)/s^3$$

2)&3)
= (2i)Im M(s,0)
= (2i)s $\sigma_{tot}(s)$

II 1)

$$\frac{1}{2\pi i}\int_{-\infty}^{-M} ds\,\left(M(-s-i\epsilon,0)-M(-s+i\epsilon,0)\right)/s^3$$

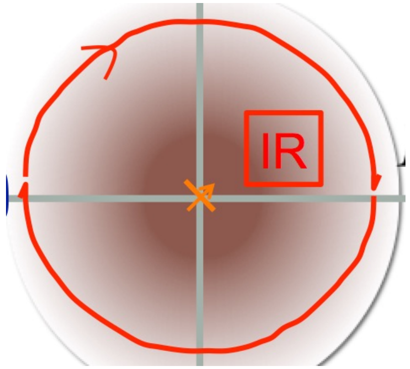
1. Crossing Symmetry: M(s,0)=M(-u,0),
2. Schwarz reflection principle: M(s*,0)=M(s,0)*
3. Optical theorem: Im M(s,0) = s σ_{tot}(s)

$$=\frac{2}{\pi}\int_M^\infty ds\,\frac{s\sigma_{tot}(s)}{s^3}>0$$

Positivity Bounds

IR

$$\frac{1}{2\pi i}\oint ds \frac{\mathcal{M}(s,0)}{s^3} = C_2$$

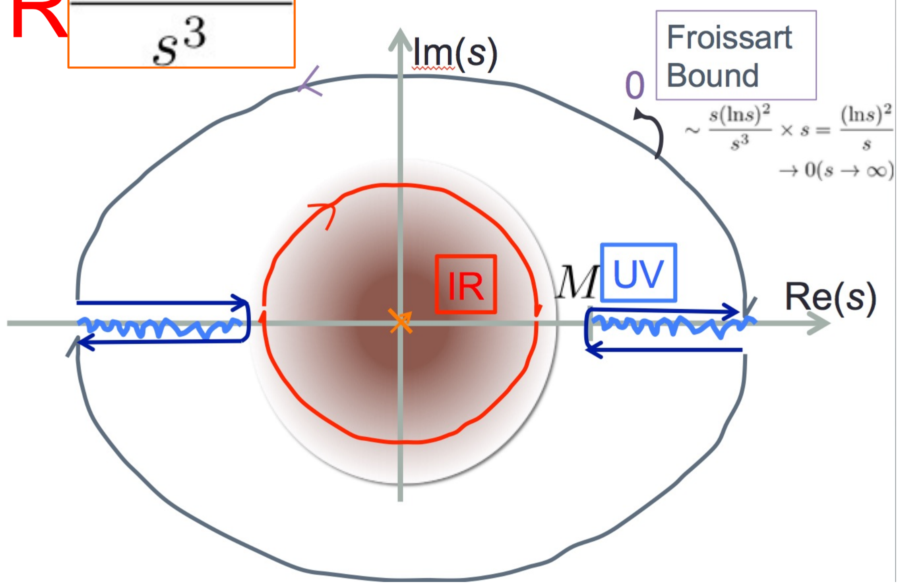


$$\mathcal{M} = C_0 + C_1\frac{s}{M^2} + C_2\frac{s^2}{M^4} + C_3\frac{s^3}{M^6} + C_4\frac{s^4}{M^8} + \cdots$$

$1/(2\pi i)\int M_{IR}/s^3$ $(=C_2/M^4)$…IR $\frac{\mathcal{M}(s,0)}{s^3}$

$=1/(2\pi i)\int M_{UV}/s^3 > 0$ …UV

→ $C_2>0$ …IR



Positivity Bounds

Example of Positivity

W. Heisenberg, H. Euler, Z. Phys. **98**, 714 (1936)

Heisenberg-Euler Lagrangian:

$$\mathfrak{L} = -\mathfrak{F} - \frac{1}{8\pi^2}\int_0^\infty ds\, s^{-3}\exp(-m^2 s) \times \left[(es)^2 \mathfrak{G}\frac{\mathrm{Re}\ \cosh esX}{\mathrm{Im}\ \cosh esX} - 1 - \tfrac{2}{3}(es)^2\mathfrak{F}\right]$$

$$X = \sqrt{2(\mathcal{F} + i\mathcal{G})},$$

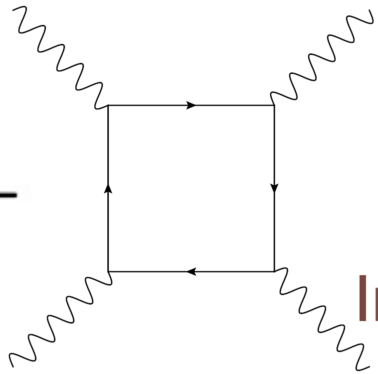
$$\mathcal{F} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} = \frac{1}{2}\left(\vec{H}^2 - \vec{E}^2\right)$$

$$\mathcal{G} = \frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu} = \vec{E}\cdot\vec{H}$$

$$= \tfrac{1}{2}(\mathbf{E}^2 - \mathbf{H}^2) + \underbrace{\frac{2\alpha^2}{45}\frac{(\hbar/mc)^3}{mc^2}}_{>0} \times [(\mathbf{E}^2-\mathbf{H}^2)^2 + 7(\mathbf{E}\cdot\mathbf{H})^2] + \cdots$$

from J. Schwinger, Phys. Rev. **82**, 664 (1951)

$$\mathcal{L}_{\mathrm{eff}} = -\frac{1}{4}F_{\mu\nu}^2 +$$



$$+ \quad \cdots$$

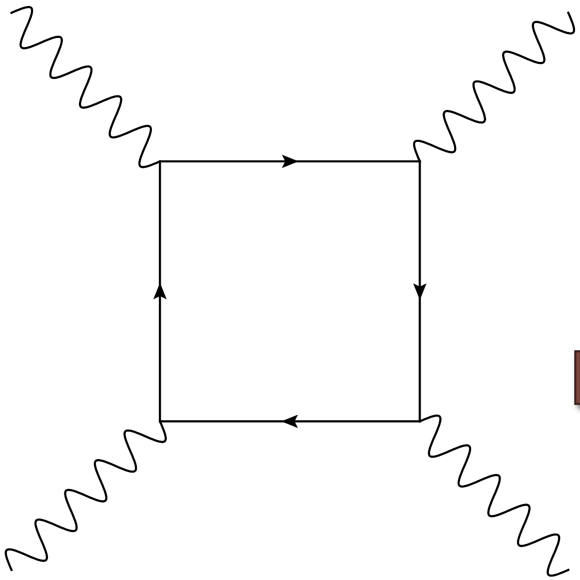
Including this

Positivity Bounds

Example of Positivity

$$\mathcal{F} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} = \frac{1}{2}\left(\vec{B}^2 - \vec{E}^2\right) \qquad \tilde{F}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\lambda\rho}F^{\lambda\rho}$$

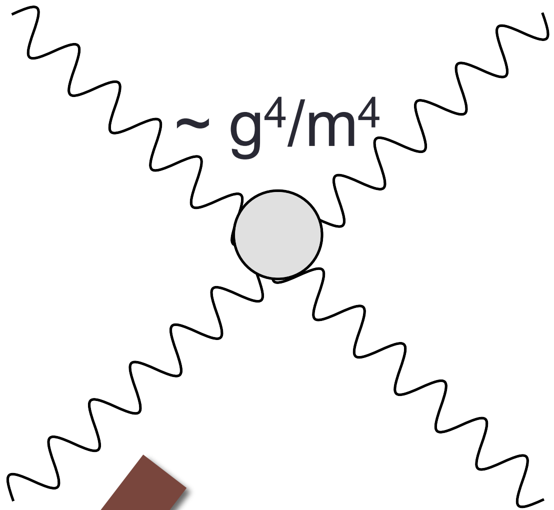
$$\mathcal{G} = \frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu} = \vec{E}\cdot\vec{B}$$



Photon Energy

^^

Fermion Mass



$$\mathcal{L}_{\text{eff}} = -\mathcal{F} + \boxed{a\mathcal{F}^2 + b\mathcal{G}^2}$$

CP even case

Consistent with QED

Positivity bounds: a>0, b>0

Dispersion Relation (for Positivity Bounds)

Forward scattering amp, at low energy (EFT)

(Amp by Dim.8) $\propto (F/\Lambda^4)\, s^2$

$$M^2 = m_i^2 + m_j^2 + m_k^2 + m_l^2$$

$$M_{ijkl} = \frac{1}{2}\frac{d^2}{ds^2} M_{ij\to kl}\left(s = \frac{1}{2}M^2, t = 0\right) + c.c.$$

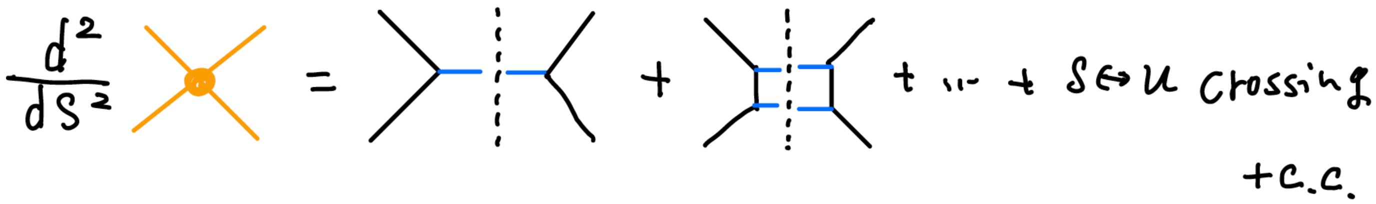
$$= \sum_X \int_{(\epsilon\Lambda)^2}^{\infty} \frac{ds\, M_{ij\to X} M^*_{kl\to X}}{2\pi s^3} + (j \leftrightarrow l) + c.c$$

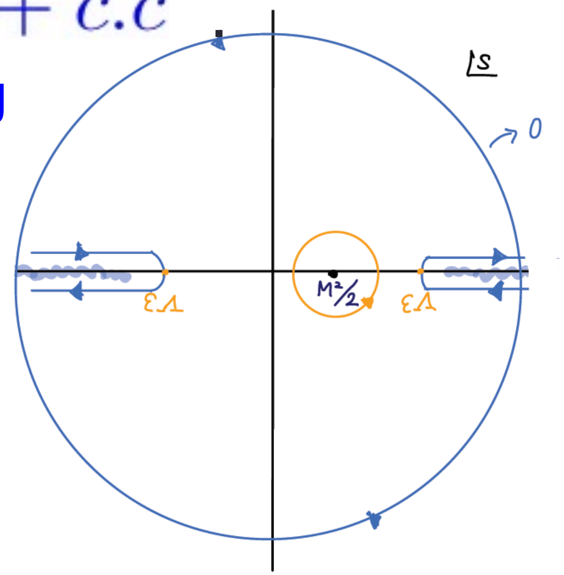
$\epsilon \lesssim 1$

Amplitude of SM →X

Σ_X: BSM states, X summation& LIPS integration

s⇆u crossing





Dispersion Relation (for Positivity Bounds)

- Useful to rewrite Dispersion Relation for Positivity Bounds

(Amp by Dim.8)
∝ $(F/\Lambda^4)\, s^2$

$$M_{ijkl} = \frac{F_\alpha M_\alpha^{ijkl}}{\Lambda^4}$$

$$M^{ijkl} = \int_{(\epsilon\Lambda)^2}^{\infty} \sum_X{}' \sum_{K=R,I} \frac{d\mu\, m_{K\,X}^{\;ij} m_{K\,X}^{\;kl}}{\pi\mu^3} + (j \leftrightarrow l)$$

where $M(ij \to X) \equiv m_{R_X}^{ij} + i m_{I_X}^{ij}$

- When i=k, j=l, RHS complete squares >=0

$M^{ijij} \geq 0$ because $m_{K\,X}^{\;ij} m_{K\,X}^{\;ij} \geq 0$

- More generally,
  Elastic Forward Scattering between Superposed States :

$M(ab \to ab)$ with $|a\rangle = u^i |i\rangle$, $|b\rangle = v^i |i\rangle$

||

$$u^i v^j u^{*k} v^{*l} M^{ijkl} = \int_{(\epsilon\Lambda)^2}^{\infty} \sum_X{}' \sum_{K=R,I} \frac{d\mu}{\pi\mu^3} \left[|u \cdot m_{K_X} \cdot v|^2 + |u \cdot m_{K_X} \cdot v^*|^2 \right] \geq 0$$

(generalized) Elastic Positivity Bounds

Higgs Portal DM operators -positivity side-

- Derivative Coupling for Higgs and Dark Matter Fields

$$O^{(1)}_{H^2\varphi^2} = (D_\mu H^\dagger D_\nu H)(\partial^\mu \varphi \partial^\nu \varphi)$$

$$O^{(2)}_{H^2\varphi^2} = (D_\mu H^\dagger D^\mu H)(\partial_\nu \varphi \partial^\nu \varphi)$$

- Sensitive to high-energy prosses
- Subject to satisfying positivity bounds
- Spin-2 massive graviton and spin-0 radion mediated DM model is a candidate of this scenario as the partial UV completion

Higgs Portal DM operators -positivity side-

- Positivity bounds from the superposed states:

$$O^{(1)}_{H^2\varphi^2} = (D_\mu H^\dagger D_\nu H)(\partial^\mu \varphi \partial^\nu \varphi)$$

$$O^{(2)}_{H^2\varphi^2} = (D_\mu H^\dagger D^\mu H)(\partial_\nu \varphi \partial^\nu \varphi)$$

$$O_{\varphi^4} = \partial_\mu \varphi \partial^\mu \varphi \partial_\nu \varphi \partial^\nu \varphi$$

$$O^{(1)}_{H^4} = (D_\mu H^\dagger D_\nu H)(D^\nu H^\dagger D^\mu H)$$

$$O^{(2)}_{H^4} = (D_\mu H^\dagger D_\nu H)(D^\mu H^\dagger D^\nu H)$$

$$O^{(3)}_{H^4} = (D_\mu H^\dagger D^\mu H)(D_\nu H^\dagger D^\nu H)$$

Higgs Portal DM operators -positivity side-

- Results:

Bounds	Channels $(\|1\rangle + \|2\rangle \to \|1\rangle + \|2\rangle)$
$C^{(1)}_{H^4} + C^{(2)}_{H^4} \geq 0$	$\|1\rangle = \|\phi_1\rangle\,,\ \|2\rangle = \|\phi_3\rangle$
$C^{(1)}_{H^4} + C^{(2)}_{H^4} + C^{(3)}_{H^4} \geq 0$	$\|1\rangle = \|\phi_1\rangle\,,\ \|2\rangle = \|\phi_1\rangle$
$C^{(2)}_{H^4} \geq 0$	$\|1\rangle = \|\phi_1\rangle\,,\ \|2\rangle = \|\phi_2\rangle$
$C^{(1)}_{H^2\varphi^2} \geq 0$	$\|1\rangle = \|\phi_1\rangle\,,\ \|2\rangle = \|\varphi\rangle$
$C_{\varphi^4} \geq 0$	$\|1\rangle = \|\varphi\rangle\,,\ \|2\rangle = \|\varphi\rangle$
$2\sqrt{(C^{(1)}_{H^4} + C^{(2)}_{H^4} + C^{(3)}_{H^4})C_{\varphi^4}} \geq -\left(C^{(1)}_{H^2\varphi^2} + C^{(2)}_{H^2\varphi^2}\right)$	$\|1\rangle = 2\sqrt{C_{\varphi^4}}\,\|\phi_1\rangle + \sqrt{-(C^{(1)}_{H^2\varphi^2} + C^{(2)}_{H^2\varphi^2})}\,\|\varphi\rangle,$ $\|2\rangle = \|1\rangle$ Superposition
$2\sqrt{(C^{(1)}_{H^4} + C^{(2)}_{H^4} + C^{(3)}_{H^4})C_{\varphi^4}} \geq C^{(2)}_{H^2\varphi^2}$	$\|1\rangle = 2\sqrt{C_{\varphi^4}}\,\|\phi_1\rangle + \sqrt{C^{(2)}_{H^2\varphi^2}}\,\|\varphi\rangle,$ $\|2\rangle = -2\sqrt{C_{\varphi^4}}\,\|\phi_1\rangle + \sqrt{C^{(2)}_{H^2\varphi^2}}\,\|\varphi\rangle$

Superposition

Higgs portal DM

$$O^{(1)}_{H^2\varphi^2} = (D_\mu H^\dagger D_\nu H)(\partial^\mu \varphi \partial^\nu \varphi)$$
$$O^{(2)}_{H^2\varphi^2} = (D_\mu H^\dagger D^\mu H)(\partial_\nu \varphi \partial^\nu \varphi)$$

Higgs Portal DM operators - dim4 and dim6 -

- Dim-4 and Dim-6 Higgs Portal DM operators relevant to the phenomenology (relic density, direct and indirect detections):

$$-\frac{1}{6\Lambda^4}\left(c_1 m_\varphi^4 \varphi^4 + 4c_2 m_H^4 |H|^4 + 8c_2' \lambda_H m_H^2 |H|^6 + 4c_2'' \lambda_H^2 |H|^8 \right.$$
$$\left. + 4c_3 m_\varphi^2 m_H^2 \varphi^2 |H|^2 + 4c_3' \lambda_H m_\varphi^2 \varphi^2 |H|^4 \right)$$
$$+\frac{1}{6\Lambda^4}\left(d_1 m_\varphi^2 \varphi^2 (\partial_\mu \varphi)^2 + 4d_2 m_H^2 |H|^2 |D_\mu H|^2 + 4d_2' \lambda_H |H|^4 |D_\mu H|^2 \right.$$
$$\left. + 2d_3 m_\varphi^2 \varphi^2 |D_\mu H|^2 + 2d_4 m_H^2 |H|^2 (\partial_\mu \varphi)^2 + 2d_4' \lambda_H |H|^4 (\partial_\mu \varphi)^2 \right)$$

Higgs Portal DM operators - Massive Graviton and Radion case-

- Higgs/DM and Graviton Interaction:

$$-\frac{c_H}{M} G^{\mu\nu} T^H_{\mu\nu} - \frac{c_\varphi}{M} G^{\mu\nu} T^\varphi_{\mu\nu}$$

- Higgs/DM and Radion Interaction:

$$\mathcal{L}_r = \frac{c^r_H}{\sqrt{6}M} r\, T^H + \frac{c^r_\varphi}{\sqrt{6}M} r\, T^\varphi$$

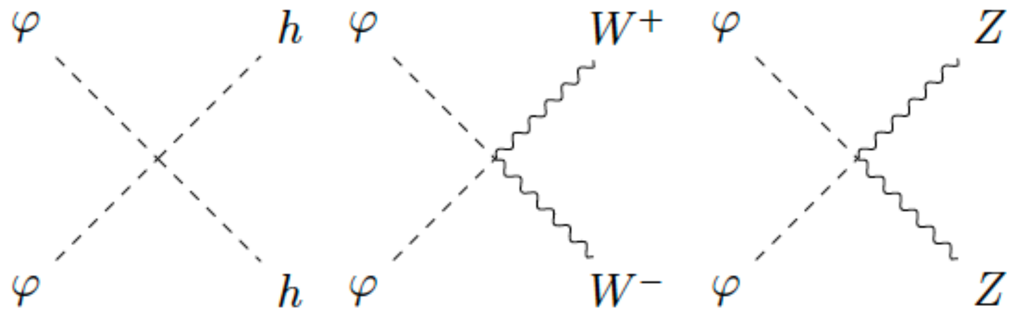
- After Integrating out Massive Graviton/Radion, we can identify coefficients of dim-4, 6, and 8 operators as an example
- We found that they satisfied the positivity conditions as far as $c_H c_\varphi \geq 0$ (attractive force for the graviton)

Relic Density

- Higgs-portal interactions linear in the Higgs boson *h*

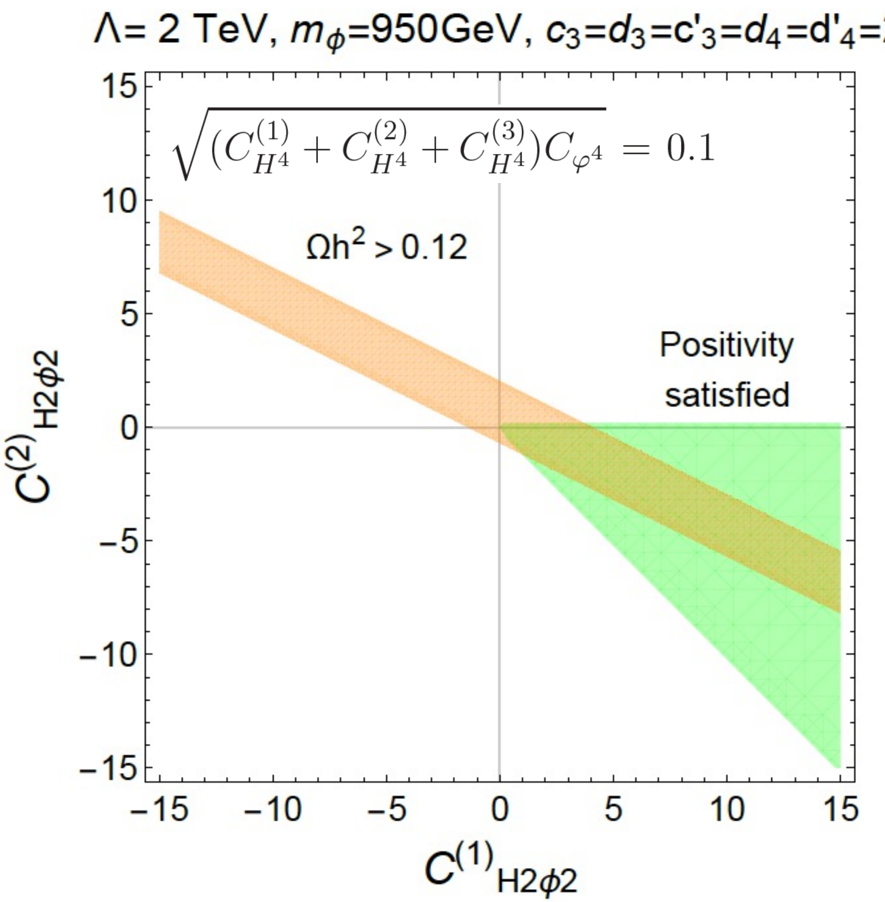
$$\mathcal{L}_{h,\text{linear}} = \frac{1}{3\Lambda^4} h \left[2(c_3 - c_3')\lambda_H v^3 m_\varphi^2 \varphi^2 - (d_4 - d_4')\lambda_H v^3 (\partial_\mu \varphi)^2 \right]$$

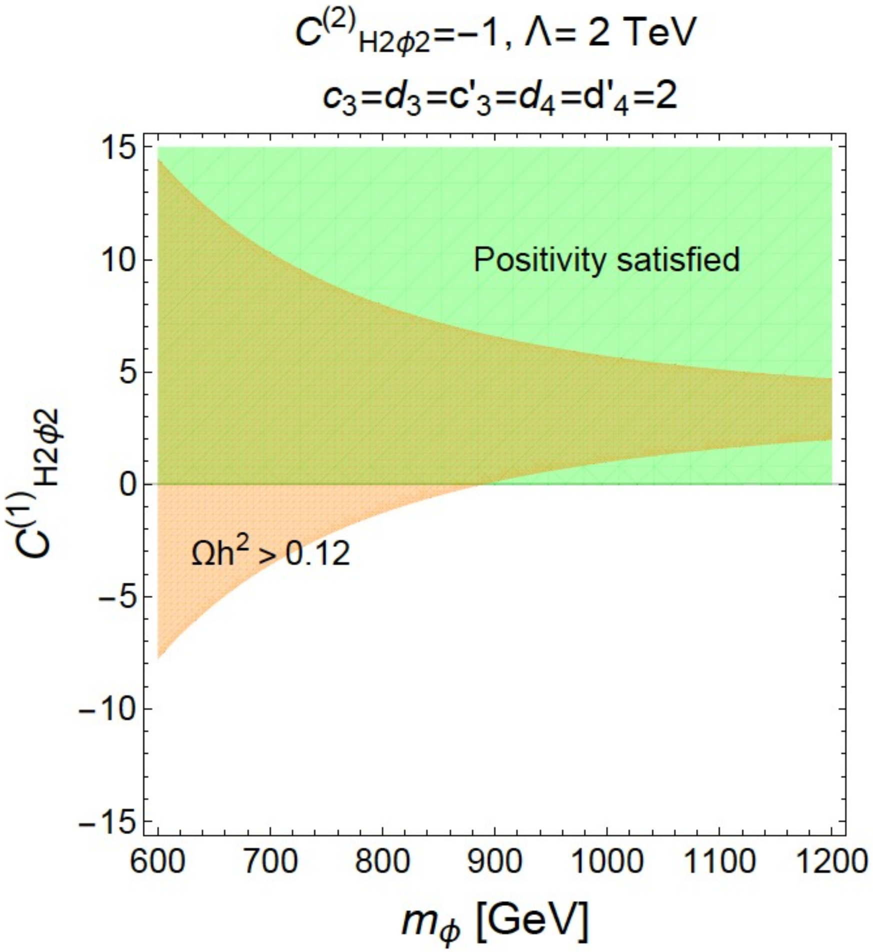
- Feynman diagrams for DM annihilation processes when $c'_3 = c_3$ and $c'_4 = c_4$ ($\varphi\varphi \rightarrow h \rightarrow ff$ are absent):



Note that the tree-level direct detection bounds are absent in this case

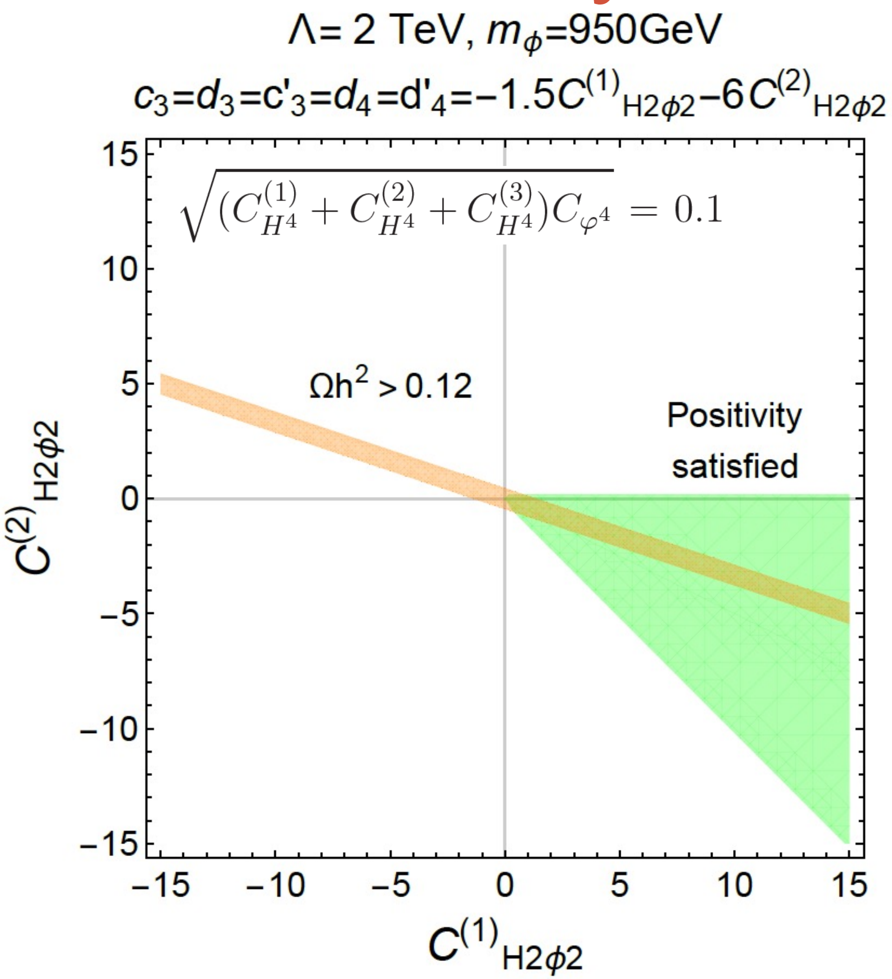
Relic Density

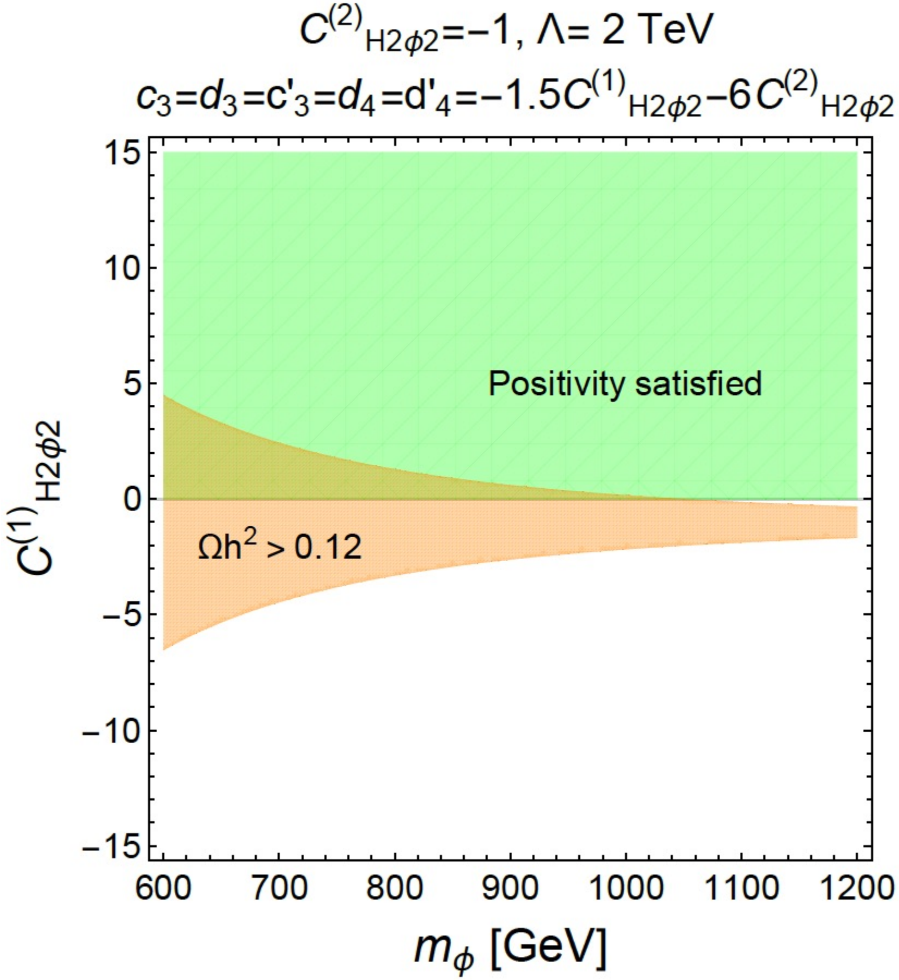




$$O^{(1)}_{H^2\varphi^2} = (D_\mu H^\dagger D_\nu H)(\partial^\mu\varphi\partial^\nu\varphi) \quad O^{(2)}_{H^2\varphi^2} = (D_\mu H^\dagger D^\mu H)(\partial_\nu\varphi\partial^\nu\varphi)$$

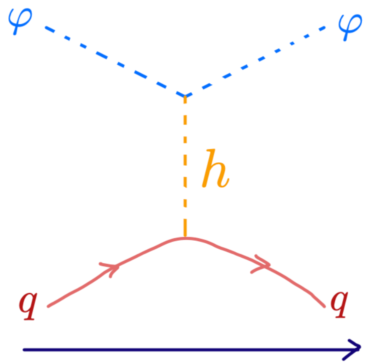
Relic Density -Graviton and Radion case-



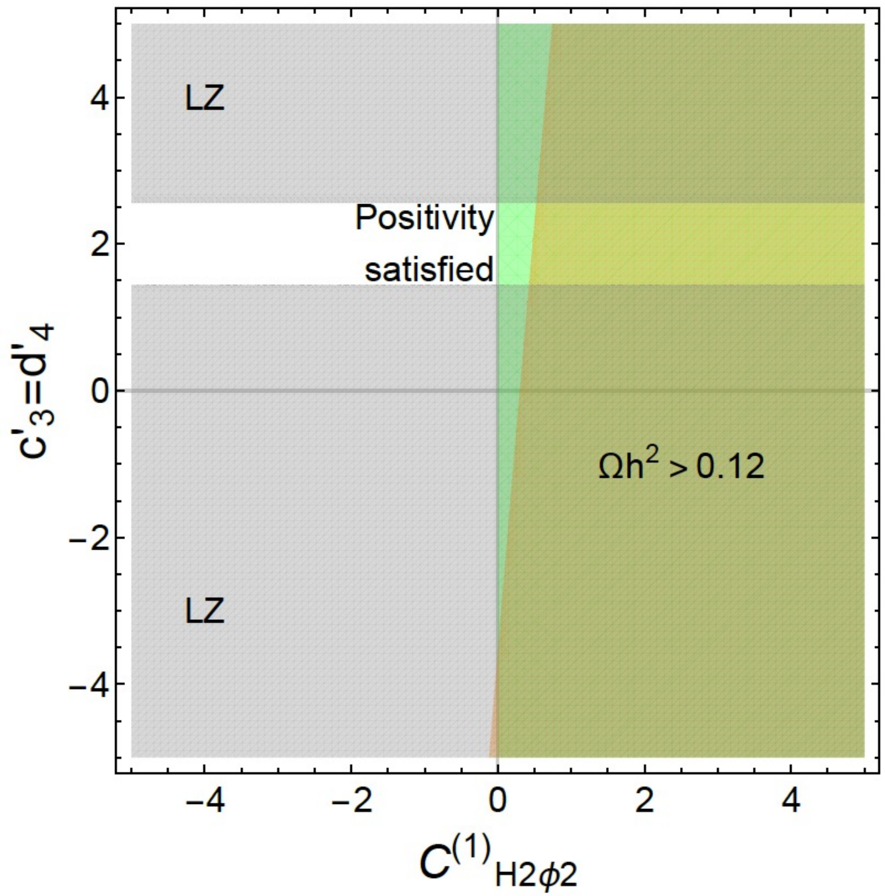


$$O^{(1)}_{H^2\varphi^2} = (D_\mu H^\dagger D_\nu H)(\partial^\mu\varphi\partial^\nu\varphi) \quad O^{(2)}_{H^2\varphi^2} = (D_\mu H^\dagger D^\mu H)(\partial_\nu\varphi\partial^\nu\varphi)$$

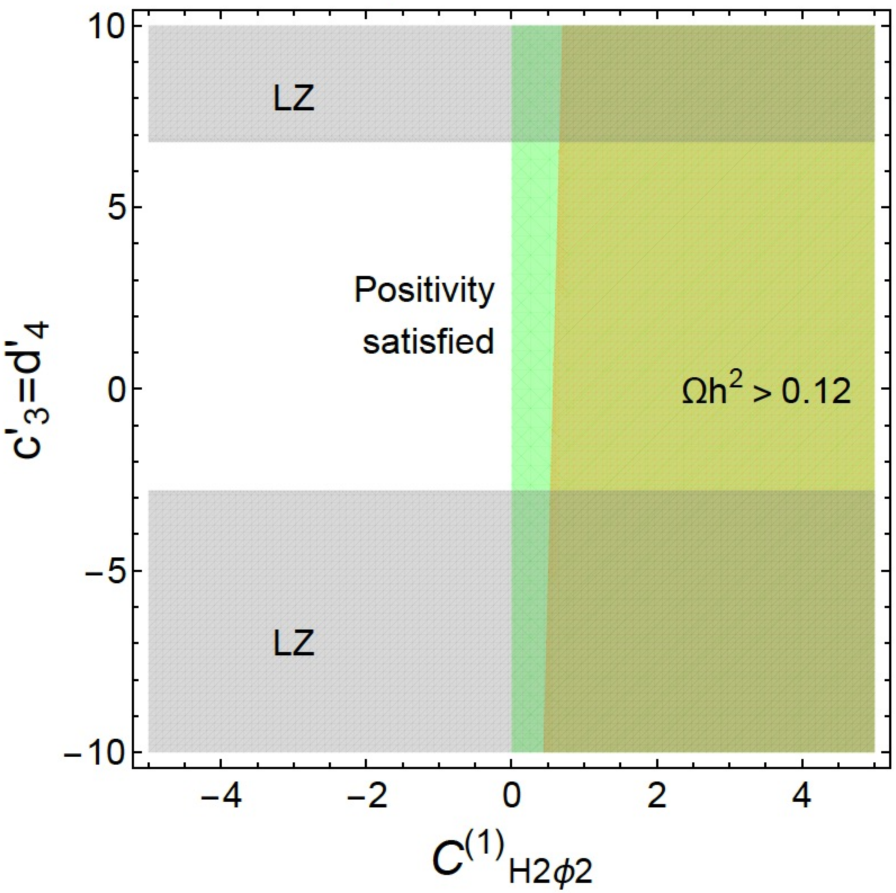
Direct Detection



Λ= 1 TeV, m_ϕ=3m_h
$C^{(2)}{}_{H2\phi2}$=−1, c_3=d_3=d_4=2



Λ= 2 TeV, m_ϕ=950GeV
$C^{(2)}{}_{H2\phi2}$=−1, c_3=d_3=d_4=2



Indirect Detection

Note on some cases:

- When c'$_3$=c$_3$ and c'$_4$=c$_4$, *φφ→h→ff* are absent:

$$\mathcal{L}_{h,\text{linear}} = \frac{1}{3\Lambda^4} h \left[2(c_3 - c_3')\lambda_H v^3 m_\varphi^2 \varphi^2 - (d_4 - d_4')\lambda_H v^3 (\partial_\mu \varphi)^2 \right]$$

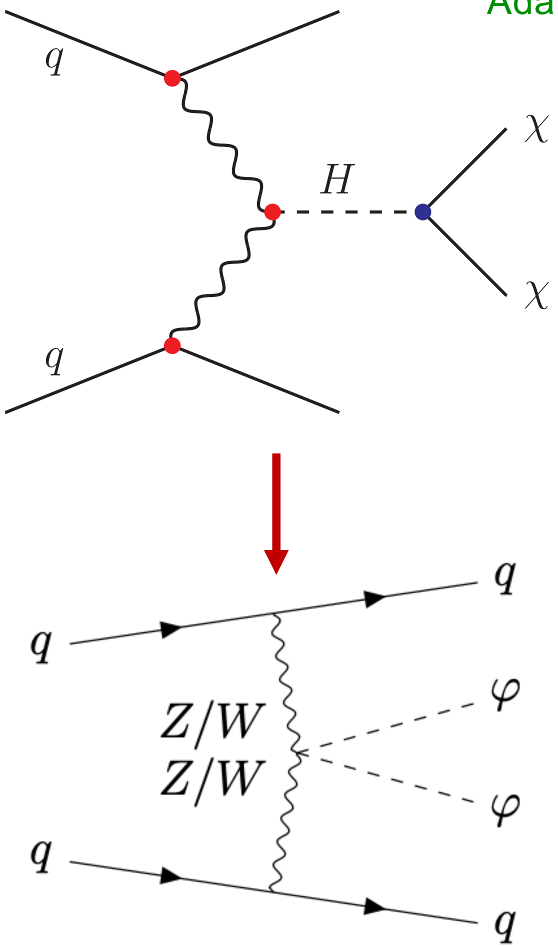
- In this case *φφ→hh, WW, and ZZ* can be constrained by indirect detection

- If we assume that only massive graviton is involved, *φφ→hh* also vahish at *s*-wave, but *φφ→WW/ZZ* are *s*-wave dominant

LHC Search

- ATLAS measurement with 139/fb at the 13 TeV LHC

Adapted from Fig. 1 in G. Aad *et al.* [ATLAS], JHEP **08**, 104 (2022)



- For our dim-8 operators, H in Fig. is integrated out
- $\chi \to \varphi$
- Higgs takes vev
- Covariant Derivative contains vector bosons

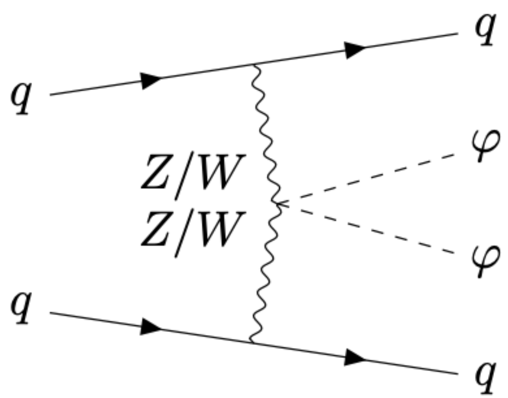
$$O^{(1)}_{H^2\varphi^2} = (D_\mu H^\dagger D_\nu H)(\partial^\mu \varphi \partial^\nu \varphi)$$

$$O^{(2)}_{H^2\varphi^2} = (D_\mu H^\dagger D^\mu H)(\partial_\nu \varphi \partial^\nu \varphi)$$

LHC Search

- 95% upper limits: 0.11 pb G. Aad *et al.* [ATLAS], JHEP **08**, 104 (2022)

$\sqrt{s} = 13$ TeV LHC, $L_{\rm int} = 139\ {\rm fb}^{-1}$	$\sigma^{\rm VBF} \times B_{\rm inv} = 0.11$ pb ($m_H = 1$ TeV)	
$\Lambda = 1$ TeV, $m_\varphi = 375$ GeV	cross section from EFT operators	
$(C^{(1)}_{H^2\varphi^2}, C^{(2)}_{H^2\varphi^2}) = (40, 40)$	0.28 pb	Excluded
$(C^{(1)}_{H^2\varphi^2}, C^{(2)}_{H^2\varphi^2}) = (32, 32)$	0.11 pb	Excluded
$(C^{(1)}_{H^2\varphi^2}, C^{(2)}_{H^2\varphi^2}) = (40, 0)$	0.012 pb	
$(C^{(1)}_{H^2\varphi^2}, C^{(2)}_{H^2\varphi^2}) = (0, 40)$	0.097 pb	

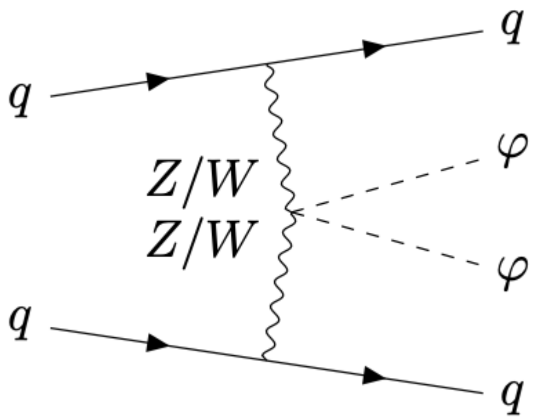


$$O^{(1)}_{H^2\varphi^2} = (D_\mu H^\dagger D_\nu H)(\partial^\mu \varphi \partial^\nu \varphi)$$

$$O^{(2)}_{H^2\varphi^2} = (D_\mu H^\dagger D^\mu H)(\partial_\nu \varphi \partial^\nu \varphi)$$

LHC Search

- High Luminocity LHC (HL-LHC) Search



Amplitude for $W^+W^-/ZZ \to \varphi\varphi$

- $O^{(2)}_{H^2\varphi^2}$ shows only Mondelstam *s* and mass dependencies
- $O^{(1)}_{H^2\varphi^2}$ causes *t* dependency also

Checking angular distributions may help to distinguish between $O^{(1)}_{H^2\varphi^2}$ and $O^{(2)}_{H^2\varphi^2}$

$$O^{(1)}_{H^2\varphi^2} = (D_\mu H^\dagger D_\nu H)(\partial^\mu \varphi \partial^\nu \varphi)$$

$$O^{(2)}_{H^2\varphi^2} = (D_\mu H^\dagger D^\mu H)(\partial_\nu \varphi \partial^\nu \varphi)$$

X. Li, K. Mimasu, KY, C. Yang,
C. Zhang, S. Y. Zhou, JHEP**10**(2022)107

Summary and Outlook

- We consider Higgs portal dark matter derivative coupled dim-8 interactions and apply the positivity conditions to them
- We also included dim-4 and dim-6 Higgs portal interactions
- We see constraints from positivity and relic density, direct and indirect detections, and the relation to the massive graviton&radion case as an example of the partial UV completion
- For HL-LHC search, utilizing the kinematical distributions may be useful