WW resonances as a window to Higgs physics

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Based on: ***I. Asiáin, D .Espriu and F .Mescia. arXiv:2301.13030***
I. Asiáin, D .Espriu and F .Mescia. arXiv:2305.03622
I. Asiáin, D. Espriu and F. Mescia. arXiv:2109.02673

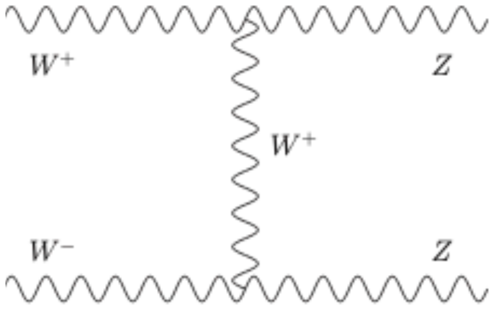
Motivation

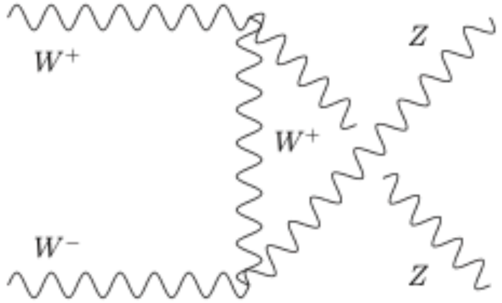
What is the origin of the Electroweak Symmetry Breaking Sector (EWSBS)?

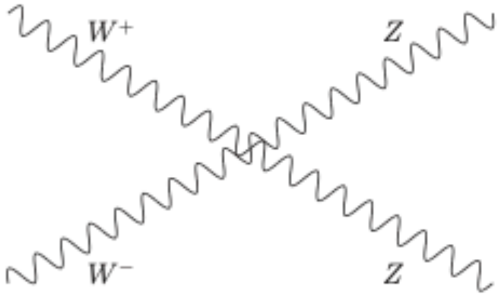
- **Open question**
  - **Dynamical** origin?
  - **Strongly interacting** UV theory? → **resonances** typically emerge

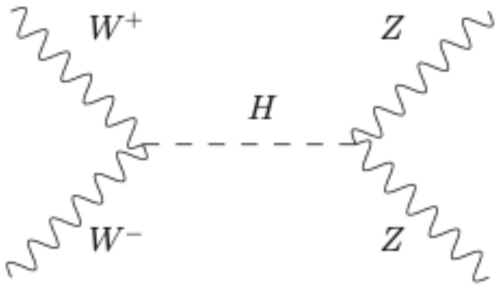
Vector Boson Scattering (VBS)

- Within SM, Higgs **unitarizes** $V_L V_L \to V_L V_L$, $V = \{W, Z\}$









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Vector Boson Scattering (VBS)

- Within SM, Higgs **unitarizes** $V_L V_L \to V_L V_L$, $V = \{W, Z\}$
- **HEFT modifies SM interactions** and breaks unitarity

Anomalous couplings in EW sector → Spoiled unitarity in BSM longitudinally polarized scattering → Restoration by the appearance of resonances

Effective Framework

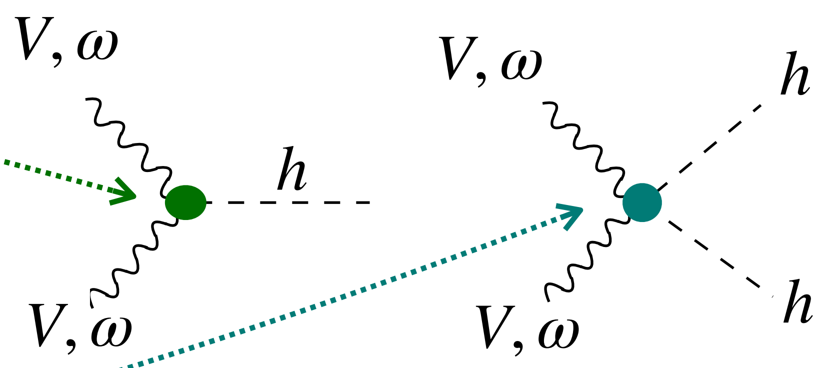
HEFT - Electroweak Chiral Lagrangian (EChL)

- Expansion in powers of the **momentum (derivatives):** $\mathscr{L}_{EChL} = \mathscr{L}_2 + \mathscr{L}_4 + \ldots$
- **Chiral order d**: counts derivatives and/or soft mass scales $\left(g \sim M, \sqrt{\lambda} \sim M_h\right)$
- **Building blocks**

$$U = e^{\frac{i\omega^a\tau^a}{v}} \qquad \mathscr{F}\left(\frac{h}{v}\right) = 1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2 + \ldots \qquad \mathscr{V}_\mu = \left(D_\mu U\right) U^\dagger \qquad \hat{W}_{\mu\nu}, \hat{B}_{\mu\nu}$$

- $\mathscr{L}_2$ **: chiral order 2**

$$\mathscr{L}_2 \supset \frac{v^2}{4}\left[1 + 2a\left(\frac{h}{v}\right) + b\left(\frac{h}{v}\right)^2\right] Tr\left[D^\mu U^\dagger D_\mu U\right]$$



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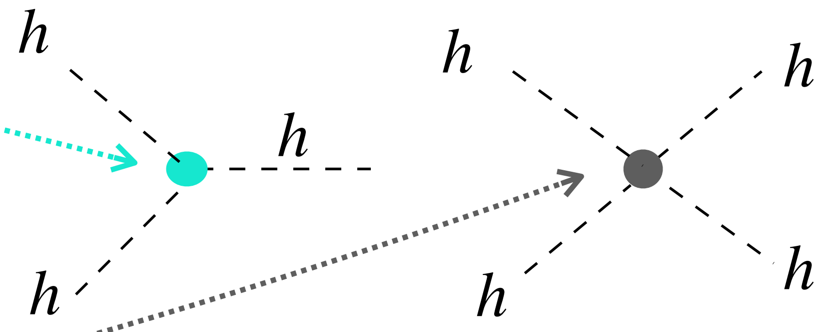
$$\mathscr{L}_2 \supset -d_3\lambda_{SM}\, vh^3 - \frac{1}{4}d_4\lambda_{SM}h^4$$



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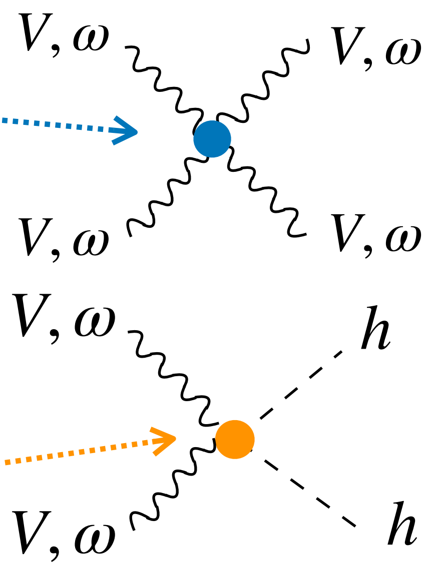
- $\mathscr{L}_4$ **: chiral order 4**

$$\mathscr{L}_4 \supset a_4 \left(Tr\left[\mathscr{V}_\mu \mathscr{V}_\nu\right] Tr\left[\mathscr{V}^\mu \mathscr{V}^\nu\right]\right) + a_5 \left(Tr\left[\mathscr{V}_\mu \mathscr{V}^\mu\right] Tr\left[\mathscr{V}_\nu \mathscr{V}^\nu\right]\right)$$

$$+ \frac{\delta}{v^2} \partial_\mu h \partial h^\mu \left(Tr\left[D_\nu U^\dagger D^\nu U\right]\right) + \frac{\eta}{v^2} \partial_\mu h \partial h_\nu \left(Tr\left[D^\mu U^\dagger D^\nu U\right]\right)$$



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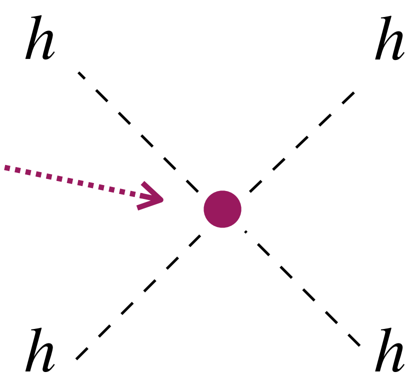
$$\mathscr{L}_4 \subset \frac{\gamma}{v^4}\left(\partial_\mu h \partial^\mu h\right)\left(\partial_\nu h \partial^\nu h\right)$$



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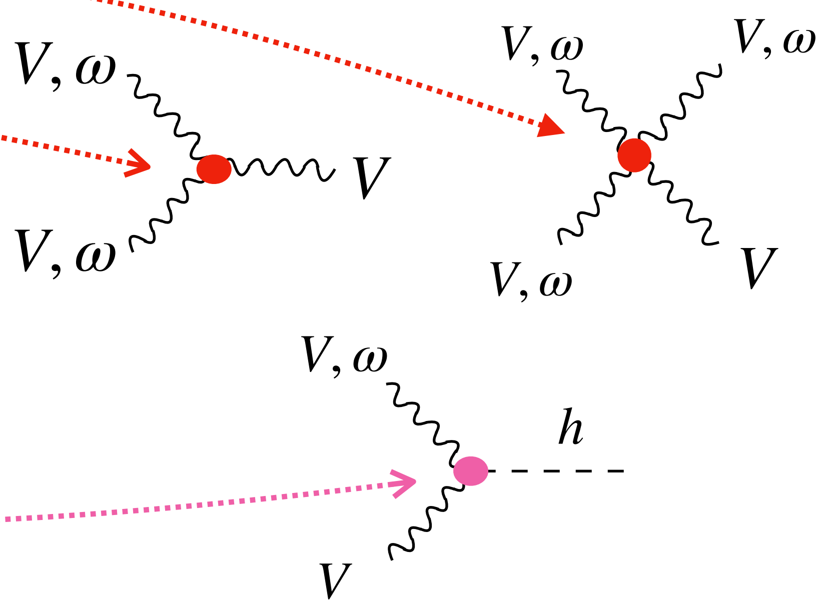
$$\mathscr{L}_4 \subset -i a_3\, Tr\left(\hat{W}_{\mu\nu}[\mathscr{V}^\mu, \mathscr{V}^\nu]\right) + i\frac{\zeta}{v} Tr\left(\hat{W}_{\mu\nu}\mathscr{V}^\mu\right)\partial^\nu h$$



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- **Our Complete Lagrangian:**

$$\mathscr{L}_2 = -\frac{1}{2g^2}Tr\left(\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right) - \frac{1}{2g'^2}Tr\left(\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\right) + \frac{v^2}{4}\mathscr{F}(h)Tr\left(D^\mu U^\dagger D_\mu U\right)$$
$$+\frac{1}{2}\partial_\mu h \partial^\mu h - V(h)$$

$$\mathscr{L}_4 = -ia_3 Tr\left(\hat{W}_{\mu\nu}\left[V^\mu, V^\nu\right]\right) + a_4\left(Tr\left(V_\mu V_\nu\right)\right)^2 + a_5\left(Tr\left(V_\mu V^\mu\right)\right)^2 + \frac{\gamma}{v^4}\left(\partial_\mu h \partial^\mu h\right)^2$$
$$+\frac{\delta}{v^2}\left(\partial_\mu h \partial^\mu h\right)Tr\left(D_\mu U^\dagger D^\mu U\right) + \frac{\eta}{v^2}\left(\partial_\mu h \partial_\nu h\right)Tr\left(D^\mu U^\dagger D^\nu U\right) + i\frac{\zeta}{v}Tr\left(\hat{W}_{\mu\nu}V^\mu\right)\partial^\nu h$$

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- **From HEFT we can recover SM:**
  - $\mathscr{L}_2 \to \mathscr{L}_{SM}: \; a = 1, \, b = 1, \, d_3 = 1, \, d_4 = 1 \quad \left(\alpha_{p^2}\right)$
  - $\mathscr{L}_4 \to 0: \; a_4 = 0, \, a_5 = 0, \, \delta = 0\, , \eta = 0, \, \gamma = 0, \, a_3 = 0, \, \zeta = 0 \quad \left(\alpha_{p^4}\right)$
- **Valid HEFT** $\to \{\alpha_{p^2}\} + \{\alpha_{p^4}\}$ **but** $\{\alpha_{p^2}\} + \{\alpha_{p^4}\} \nrightarrow$ **Valid HEFT**

Effective Framework

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  - $\mathscr{L}_4 \to 0: \; a_4 = 0, \; a_5 = 0, \; \delta = 0 \;, \eta = 0, \; \gamma = 0, \; a_3 = 0, \; \zeta = 0 \quad \left(\alpha_{p^4}\right)$
- **Valid HEFT ???**

Need criteria to discriminate among different HEFTs!

Our approach

- **Valid HEFT:** good low energy description of a strongly interacting UV theory
- Look for **resonant states in unitarized WW scattering**
- Properties of predicted resonances **constrain on HEFT coefficients**
    - **Phenomenology**: appearance (or absence) of these resonances at the LHC

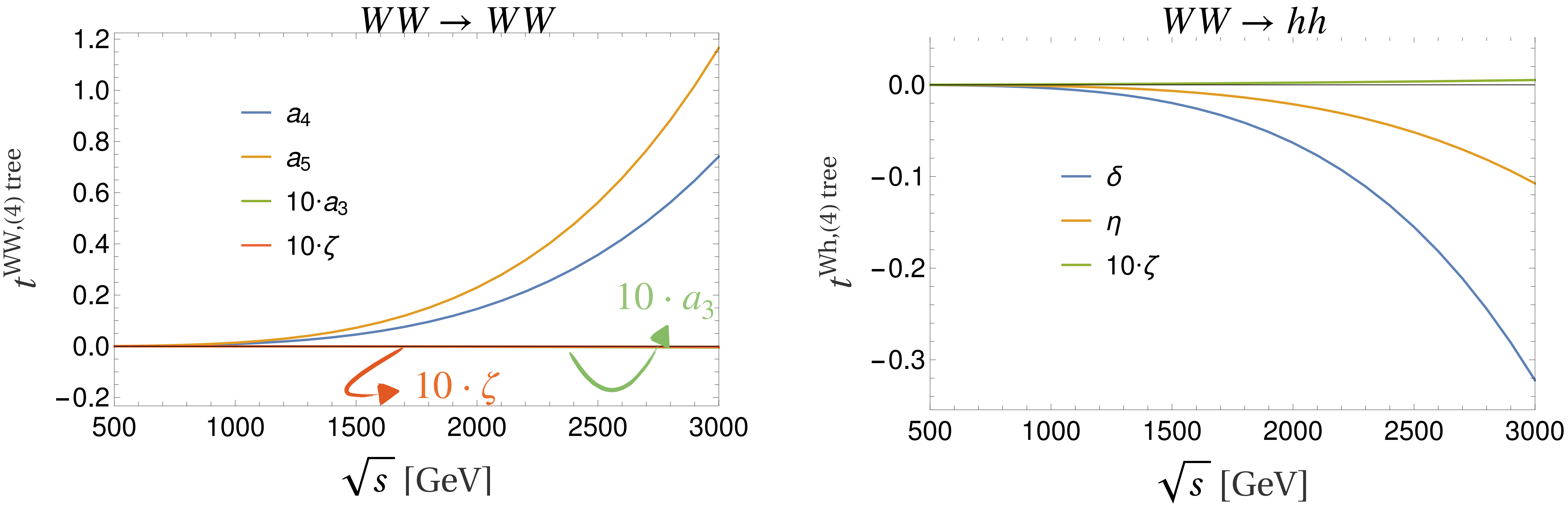
      minimum mass
    - **Theoretical**: no spurious (acausal) states appear
- **Up to now** from experiment at 95% C.L.

$$\overset{\text{CMS}}{a \in (0.94,\ 1.10)}, \qquad \overset{\text{ATLAS}}{b \in (0.55,\ 1.49)}, \qquad \overset{\text{ATLAS}}{d_3 \in (-1.4,\ 6.1)},$$

$$\underset{\text{CMS}}{a_4 \in (-0.0061,\ 0.0063)}, \quad \underset{\text{CMS}}{a_5 \in (-0.0094,\ 0.0098)}$$

- **The rest** remain experimentally unconstrained

Our approach



- The relevant ones are those surviving in the **$g = 0$** limit $\left(\mathbf{a_4}, \mathbf{a_5}, \delta, \eta, \gamma\right)$

- Quick **violation of unitarity** with fastly growing amplitudes

- **Unitarization methods required** for predictions

Unitarization

- **Unitarization methods required**: IAM

- Scalar resonances through **coupled channels**

$$t_{00}^{IAM} = t_{00}^{(2)} \underbrace{\left(t_{00}^{(2)} - t_{00}^{(4)}\right)^{-1}}_{\text{resonances}} t_{00}^{(2)} \qquad t_{00}^{(4)} = \begin{pmatrix} WW^{(4)}\left(a_4, a_5\right) & WH^{(4)}\left(\delta, \eta\right) \\ WH^{(4)}\left(\delta, \eta\right) & HH^{(4)}\left(\gamma\right) \end{pmatrix}$$

$WW : W_L W_L \to W_L W_L$
$WH : W_L W_L \to HH$
$HH : HH \to HH$

- In total **4 (LO) + 5 (NLO)** dimensional parameter space after neglecting $\mathcal{O}(p^4)$ $g \neq 0$ operators

- a **full NLO** $V_L V_L \to V_L V_L$ is available in the literature. Too complicated for for our purposes.

Maria J. Herrero and Roberto A. Morales
Phys. Rev. D104, 075013
Published 12 October 2021

- **Shortcut:** $t_{IJ}^{(4)} = Re\, t_{IJ}^{(4)} + iIm\, t_{IJ}^{(4)}$

  Tree level **One loop**

  - $Re\, t_{IJ}^{(4)} : \{\alpha_{p^4}\} - terms + NLO - ET$ amplitude

    Equivalence theorem: $\left[W_L \to \omega + o\left(M_V/\sqrt{s}\right)\right]$

  - $Im\, t_{IJ}^{(4)}$: **exact** calculation through perturbative **Optical Theorem**

Our work

- $V_LV_L \to V_LV_L$ at **NLO** with transverse W propagating inside the loops: $g \neq 0$

- **EFT + unitarization techniques** predict resonances in various channels

    - Isovector - vector (IJ = 11)

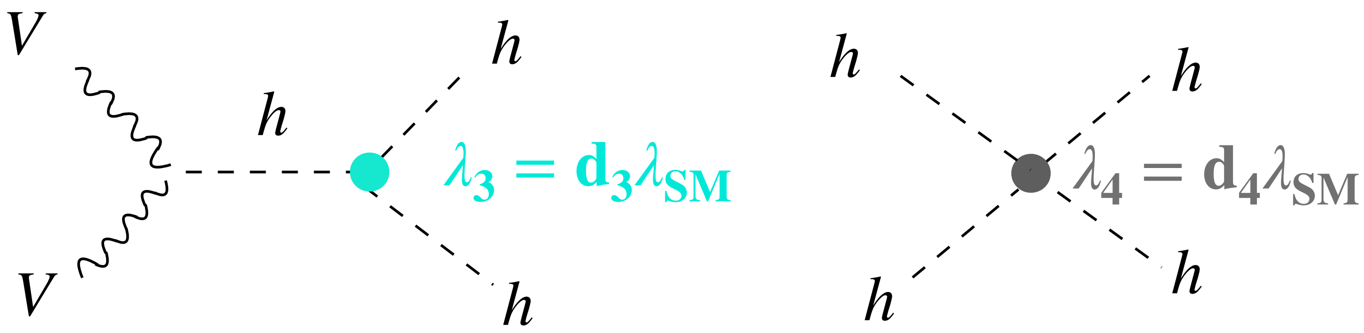
      I. Asiáin, D .Espriu and F .Mescia.
      Phys. Rev. D 105, 015009

    - Isotensor - tensor (IJ = 20)

      Excludes $2a_4 + a5 < 0$
      with acausal resonances

    - Isocalar - scalar (IJ = 00)

      $5a_4 + 8a_5$ combination



Now accessible at tree-level along unitarization of WW!

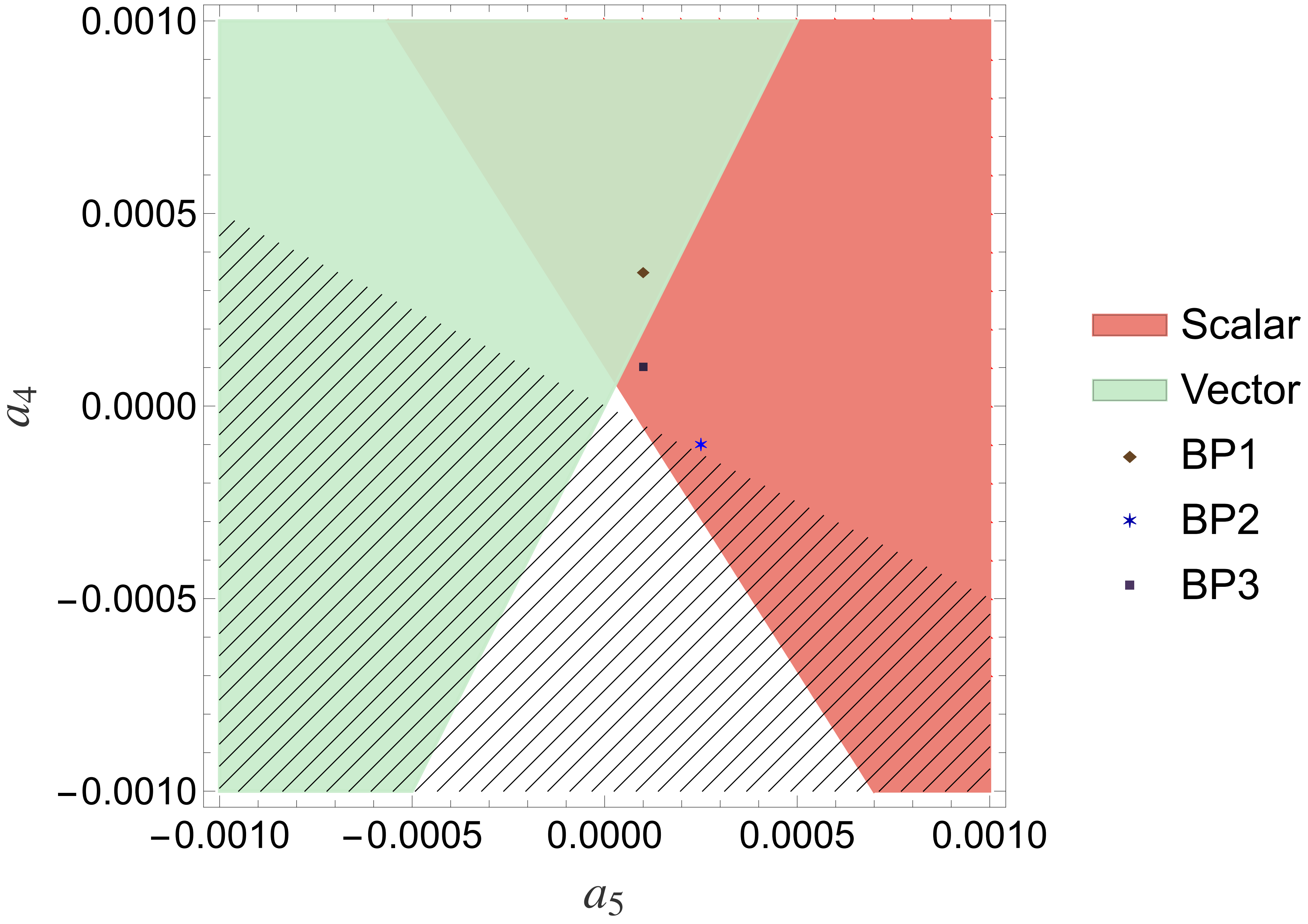
I. Rosell, A. Pich and J.J. Sanz-Cillero
PoS ICHEP2020, 077 (2021), 2010.08271.

- We **require** physical scalar resonances with $M_S > 1.8$ TeV

- Physical by **phase-shift criteria**: shift in the phase from $\pi/2$ to $-\pi/2$

scalar-isoscalar

- Start with $\mathscr{L}_{SM} + \{\alpha_{p^4}\}$ and see the effect of δ, η **and** γ



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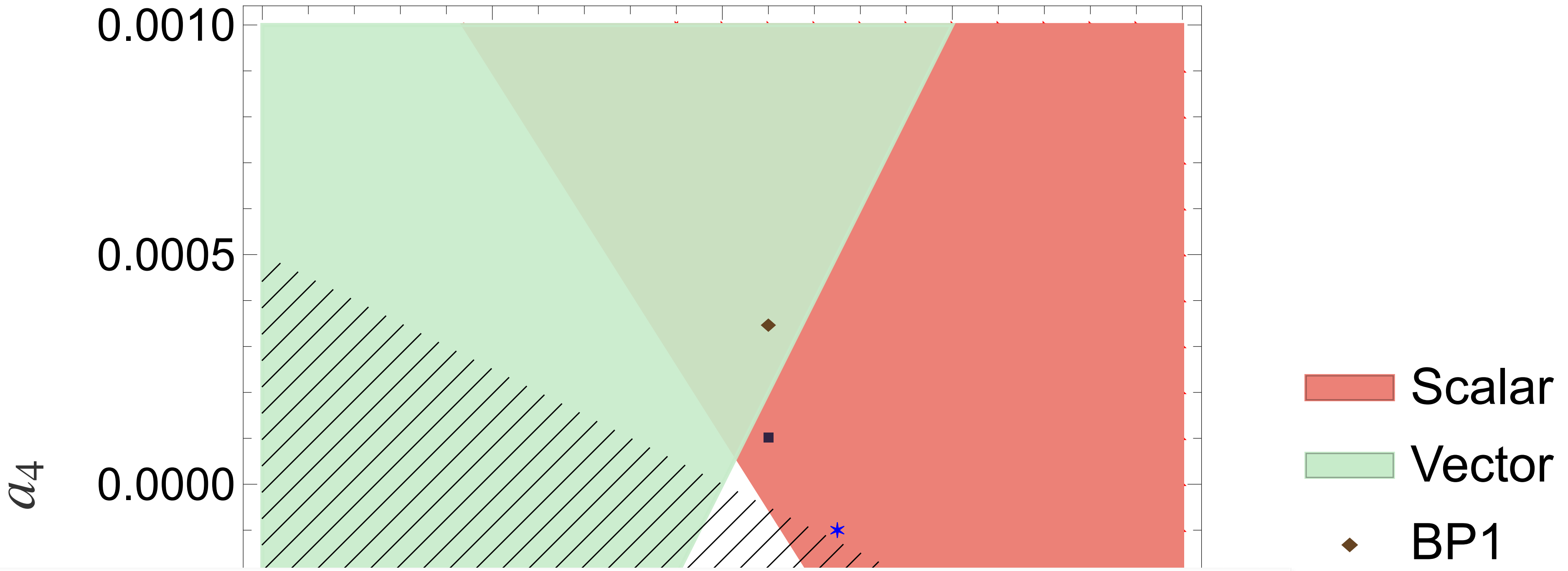

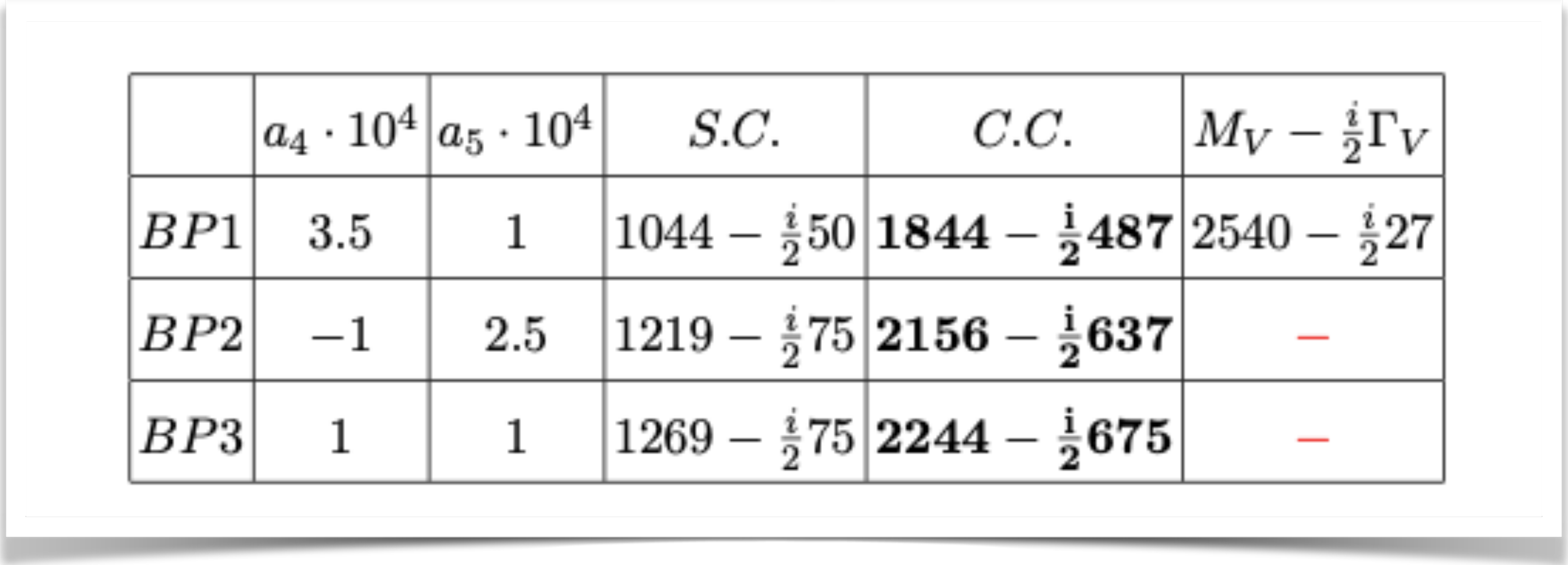

	$a_4 \cdot 10^4$	$a_5 \cdot 10^4$	$S.C.$	$C.C.$	$M_V - \frac{i}{2}\Gamma_V$
$BP1$	3.5	1	$1044 - \frac{i}{2}50$	$\mathbf{1844 - \frac{i}{2}487}$	$2540 - \frac{i}{2}27$
$BP2$	-1	2.5	$1219 - \frac{i}{2}75$	$\mathbf{2156 - \frac{i}{2}637}$	—
$BP3$	1	1	$1269 - \frac{i}{2}75$	$\mathbf{2244 - \frac{i}{2}675}$	—

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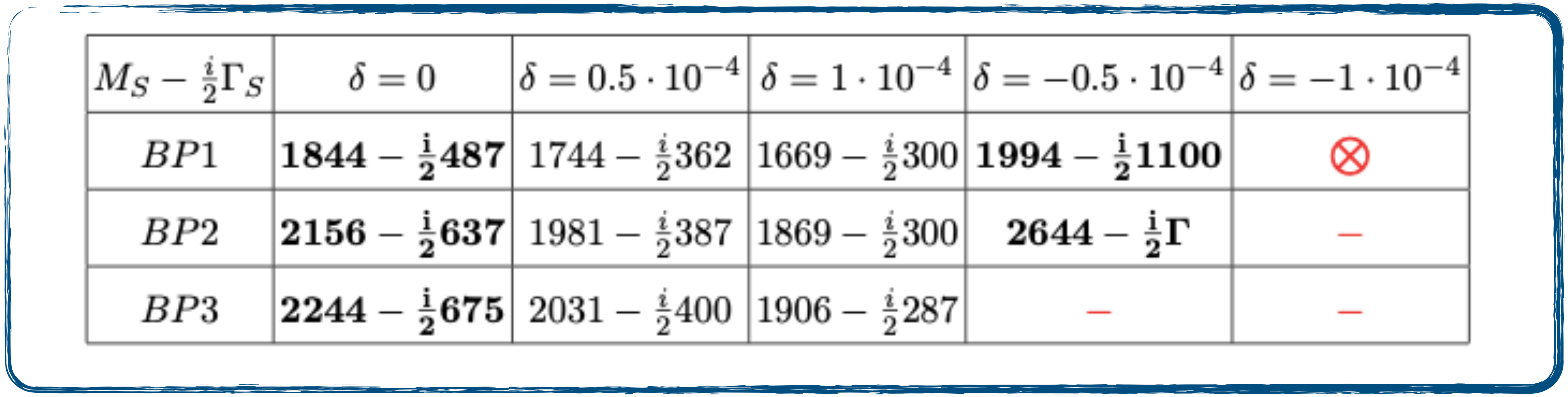
- Start with $\mathscr{L}_{SM} + \{\alpha_{p^4}\}$ and see the effect of $\boxed{\delta}$, η **and** γ



$M_S - \frac{i}{2}\Gamma_S$	$\delta = 0$	$\delta = 0.5 \cdot 10^{-4}$	$\delta = 1 \cdot 10^{-4}$	$\delta = -0.5 \cdot 10^{-4}$	$\delta = -1 \cdot 10^{-4}$
$BP1$	$\mathbf{1844 - \frac{i}{2}487}$	$1744 - \frac{i}{2}362$	$1669 - \frac{i}{2}300$	$\mathbf{1994 - \frac{i}{2}1100}$	$\otimes$
$BP2$	$\mathbf{2156 - \frac{i}{2}637}$	$1981 - \frac{i}{2}387$	$1869 - \frac{i}{2}300$	$\mathbf{2644 - \frac{i}{2}\Gamma}$	–
$BP3$	$\mathbf{2244 - \frac{i}{2}675}$	$2031 - \frac{i}{2}400$	$1906 - \frac{i}{2}287$	–	–

$\mathbf{\Gamma}$ means one of half maxima out of validity range

- **Variations** up to $\sim 10\,\%$ for natural values

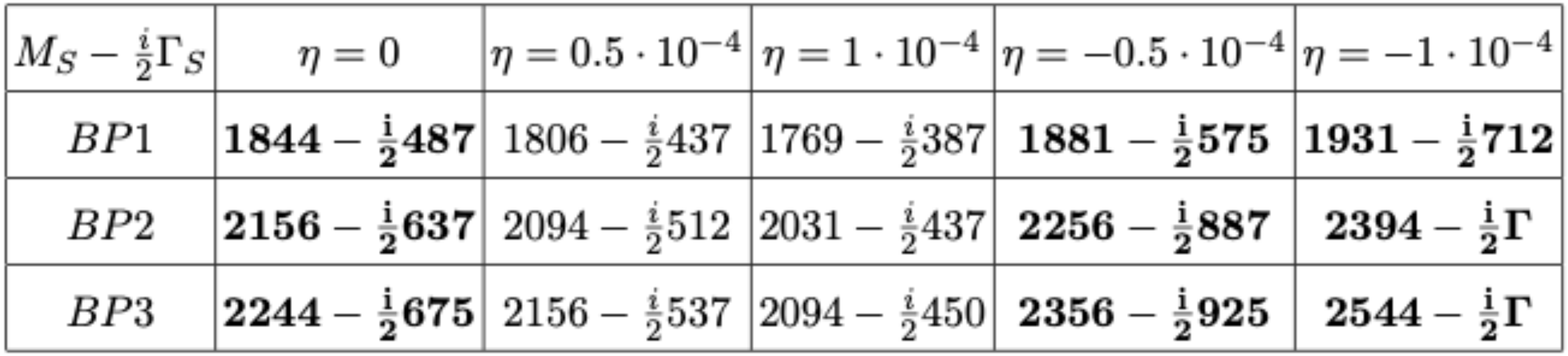
- **Positive values** favored for production of scalar resonances

- **Negative values** produce nonresonant enhancements or no poles

- $\otimes$ **excluded parameter** space with acausal resonances

scalar-isoscalar

- Start with $\mathscr{L}_{SM} + \{\alpha_{p^4}\}$ and see the effect of δ, $\boxed{\eta}$ **and** γ



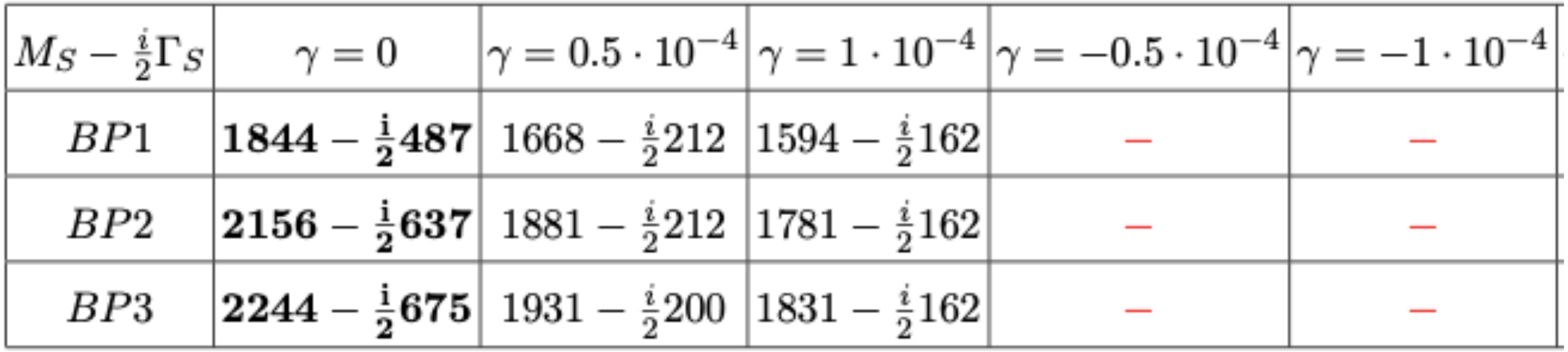
$M_S - \frac{i}{2}\Gamma_S$	$\eta = 0$	$\eta = 0.5 \cdot 10^{-4}$	$\eta = 1 \cdot 10^{-4}$	$\eta = -0.5 \cdot 10^{-4}$	$\eta = -1 \cdot 10^{-4}$
$BP1$	$\mathbf{1844 - \frac{i}{2}487}$	$1806 - \frac{i}{2}437$	$1769 - \frac{i}{2}387$	$\mathbf{1881 - \frac{i}{2}575}$	$\mathbf{1931 - \frac{i}{2}712}$
$BP2$	$\mathbf{2156 - \frac{i}{2}637}$	$2094 - \frac{i}{2}512$	$2031 - \frac{i}{2}437$	$\mathbf{2256 - \frac{i}{2}887}$	$\mathbf{2394 - \frac{i}{2}\Gamma}$
$BP3$	$\mathbf{2244 - \frac{i}{2}675}$	$2156 - \frac{i}{2}537$	$2094 - \frac{i}{2}450$	$\mathbf{2356 - \frac{i}{2}925}$	$\mathbf{2544 - \frac{i}{2}\Gamma}$

$\boldsymbol{\Gamma}$ means one of half maxima out of validity range

- **Variations** up to $\sim\ 4\,\%$ for natural values
- **Positive values** favored for production of scalar resonances
- **Negative values** produce nonresonant enhancements or no poles

scalar-isoscalar

- Start with $\mathscr{L}_{SM} + \{\alpha_{p^4}\}$ and see the effect of δ, η **and** $\boxed{\gamma}$



$M_S - \frac{i}{2}\Gamma_S$	$\gamma = 0$	$\gamma = 0.5 \cdot 10^{-4}$	$\gamma = 1 \cdot 10^{-4}$	$\gamma = -0.5 \cdot 10^{-4}$	$\gamma = -1 \cdot 10^{-4}$
$BP1$	$\mathbf{1844 - \frac{i}{2}487}$	$1668 - \frac{i}{2}212$	$1594 - \frac{i}{2}162$	–	–
$BP2$	$\mathbf{2156 - \frac{i}{2}637}$	$1881 - \frac{i}{2}212$	$1781 - \frac{i}{2}162$	–	–
$BP3$	$\mathbf{2244 - \frac{i}{2}675}$	$1931 - \frac{i}{2}200$	$1831 - \frac{i}{2}162$	–	–

- **Variations** up to $\sim 15\ \%$ for natural values

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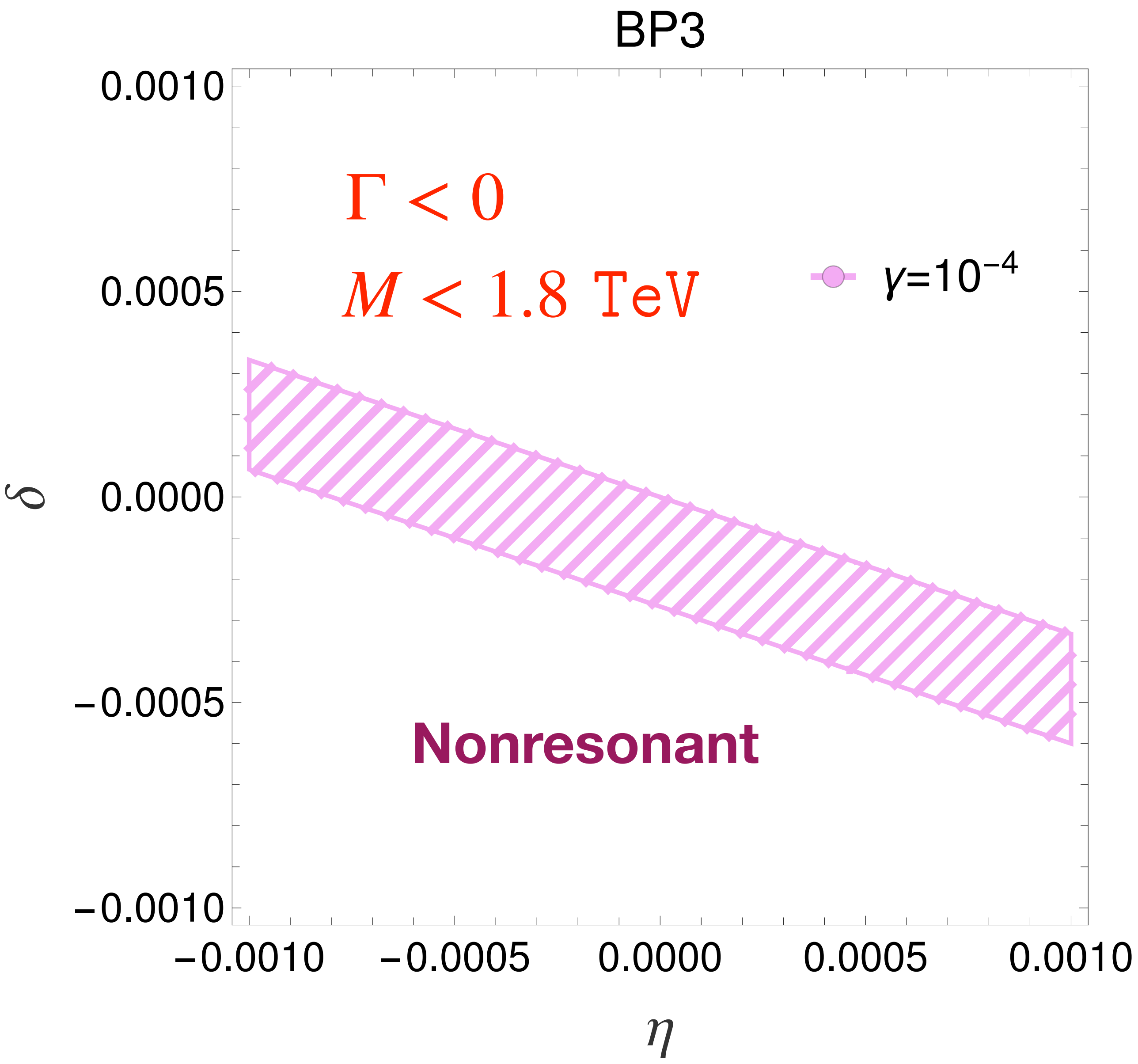

- a_4 and a_5 pretty much determines the position of the scalar pole
- sweeping natural values of the rest of NLO coefficients
  - **Nonresonant** below the color bands
  - **Excluded** above the color bands

    acausal states $\Gamma < 0$

    too light mass

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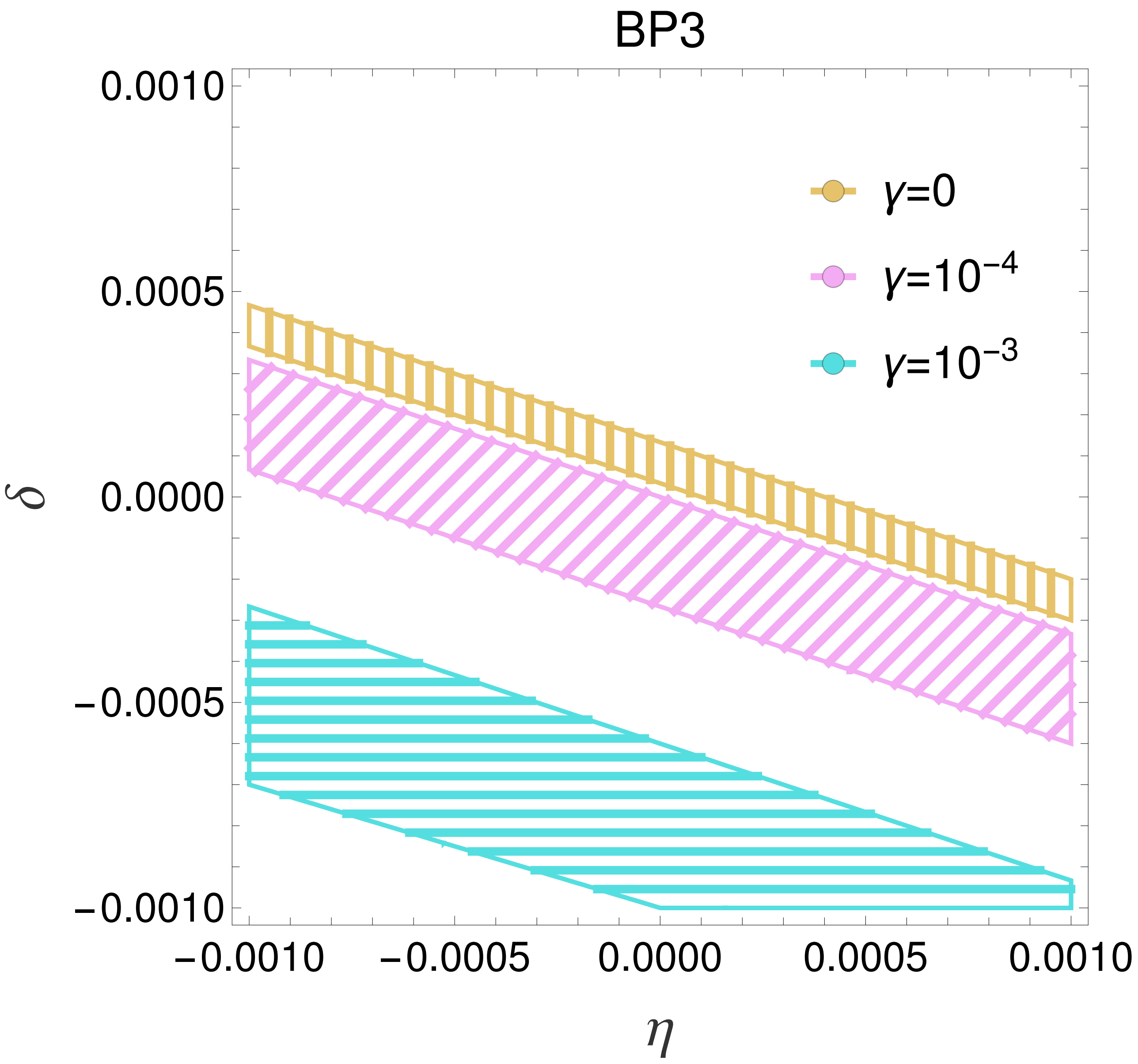

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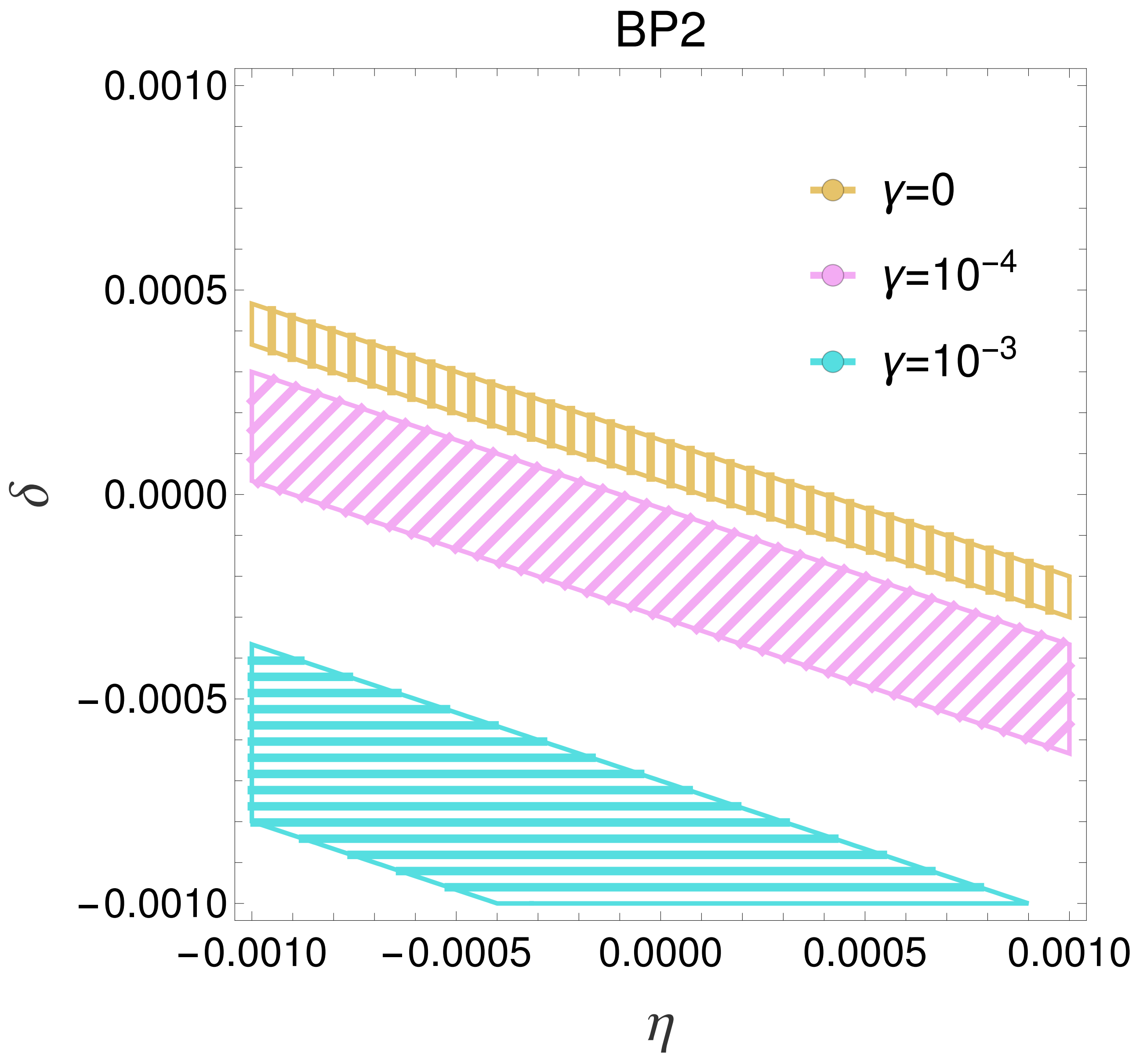

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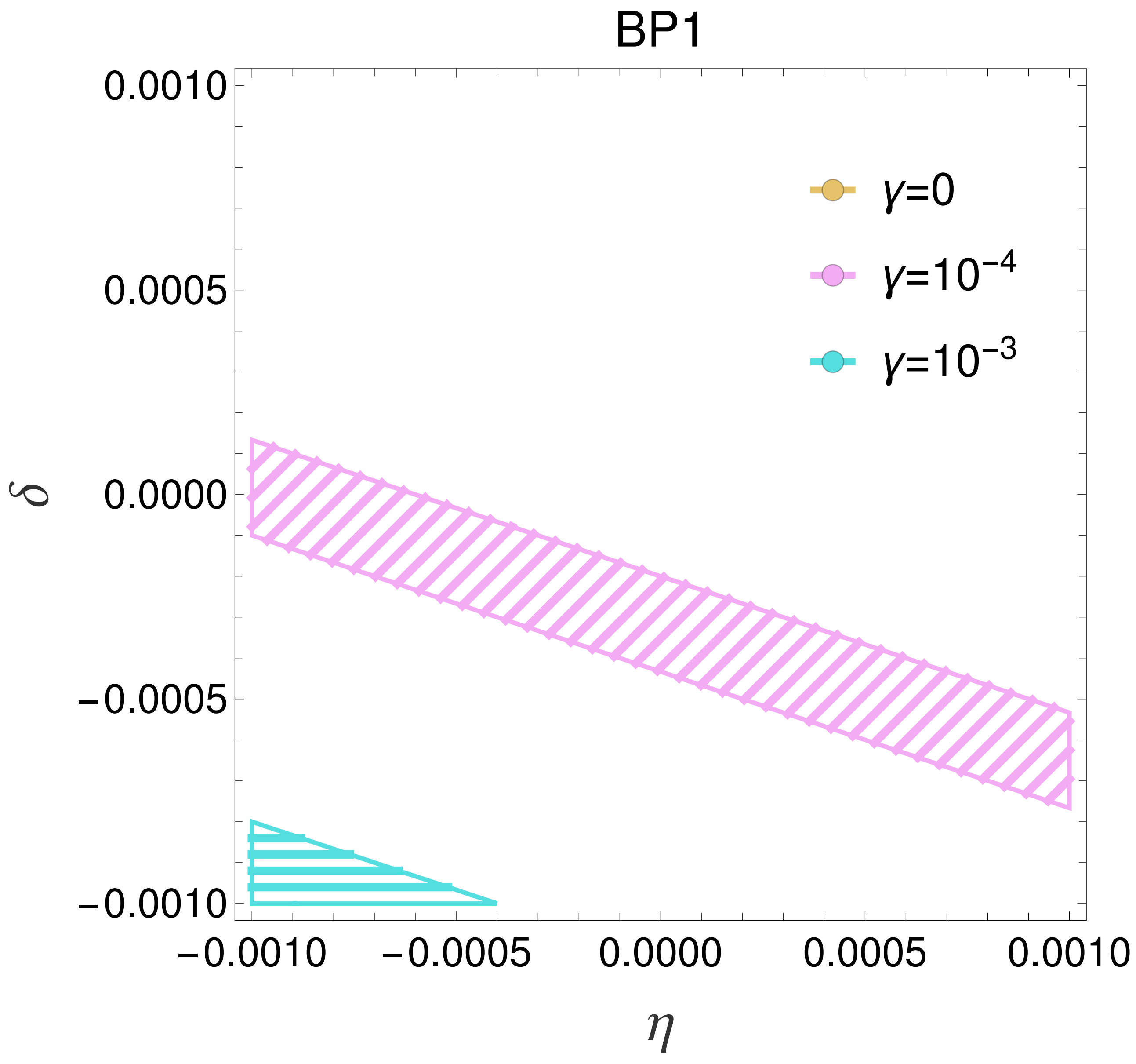
scalar-isoscalar



- a_4 and a_5 pretty much determines the position of the scalar pole
- sweeping natural values of the rest of NLO coefficients
  - **Nonresonant** below the color bands
  - **Excluded** above the color bands

    acausal states $\Gamma < 0$

    too light mass

scalar-isoscalar

- Can resonant states say something about **Higgs potential**?

- Start with $\{a = 1,\ b = 1,\ d_4 = 1\} + \{\alpha_{p^4}\}$ and repeat the exercise varying d_3

$M_S - \frac{i}{2}\Gamma_S$	$d_3 = 0.5$	$d_3 = 1$	$d_3 = 2$	$d_3 = 3$	$d_3 = 4$	$d_3 = 5$
$BP1$	$\mathbf{2006 - \frac{i}{2}\Gamma}$	$\mathbf{1884 - \frac{i}{2}487}$	$1681 - \frac{i}{2}187$	$994 - \frac{i}{2}25$ $1756 - \frac{i}{2}65$	$1044 - \frac{i}{2}38$ $2069 - \frac{i}{2}26$	$993 - \frac{i}{2}23$ $2444 - \frac{i}{2}25$
$BP2$	$\mathbf{2369 - \frac{i}{2}\Gamma}$	$\mathbf{2156 - \frac{i}{2}637}$	$1906 - \frac{i}{2}237$	$1119 - \frac{i}{2}27$ $1869 - \frac{i}{2}75$	$1219 - \frac{i}{2}37$ $2094 - \frac{i}{2}31$	$1181 - \frac{i}{2}21$ $2444 - \frac{i}{2}25$
$BP3$	$\mathbf{2468 - \frac{i}{2}\Gamma}$	$\mathbf{2244 - \frac{i}{2}675}$	$1969 - \frac{i}{2}250$	$1131 - \frac{i}{2}19$ $1894 - \frac{i}{2}75$	$1269 - \frac{i}{2}37$ $2094 - \frac{i}{2}20$	$1231 - \frac{i}{2}23$ $2444 - \frac{i}{2}25$

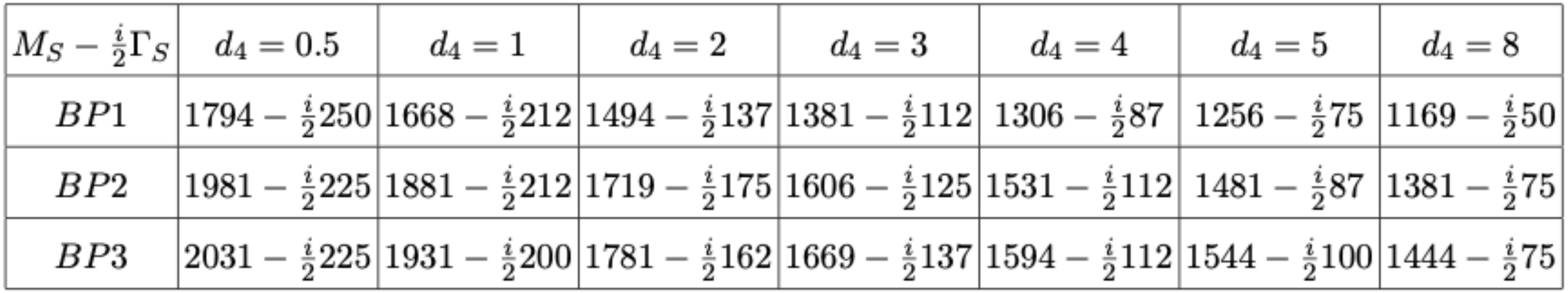
- **Two** physical poles

- **light pole** (< 1.8 TeV) appears for $d_3 \gtrsim 2.5$

scalar-isoscalar

- Can resonant states say something about **Higgs potential**?

- Start with $\{a = 1,\ b = 1,\ d_3 = 1\} + \{\alpha_{p^4}\}$ and repeat the exercise varying d_4



$M_S - \frac{i}{2}\Gamma_S$	$d_4 = 0.5$	$d_4 = 1$	$d_4 = 2$	$d_4 = 3$	$d_4 = 4$	$d_4 = 5$	$d_4 = 8$
$BP1$	$1794 - \frac{i}{2}250$	$1668 - \frac{i}{2}212$	$1494 - \frac{i}{2}137$	$1381 - \frac{i}{2}112$	$1306 - \frac{i}{2}87$	$1256 - \frac{i}{2}75$	$1169 - \frac{i}{2}50$
$BP2$	$1981 - \frac{i}{2}225$	$1881 - \frac{i}{2}212$	$1719 - \frac{i}{2}175$	$1606 - \frac{i}{2}125$	$1531 - \frac{i}{2}112$	$1481 - \frac{i}{2}87$	$1381 - \frac{i}{2}75$
$BP3$	$2031 - \frac{i}{2}225$	$1931 - \frac{i}{2}200$	$1781 - \frac{i}{2}162$	$1669 - \frac{i}{2}137$	$1594 - \frac{i}{2}112$	$1544 - \frac{i}{2}100$	$1444 - \frac{i}{2}75$

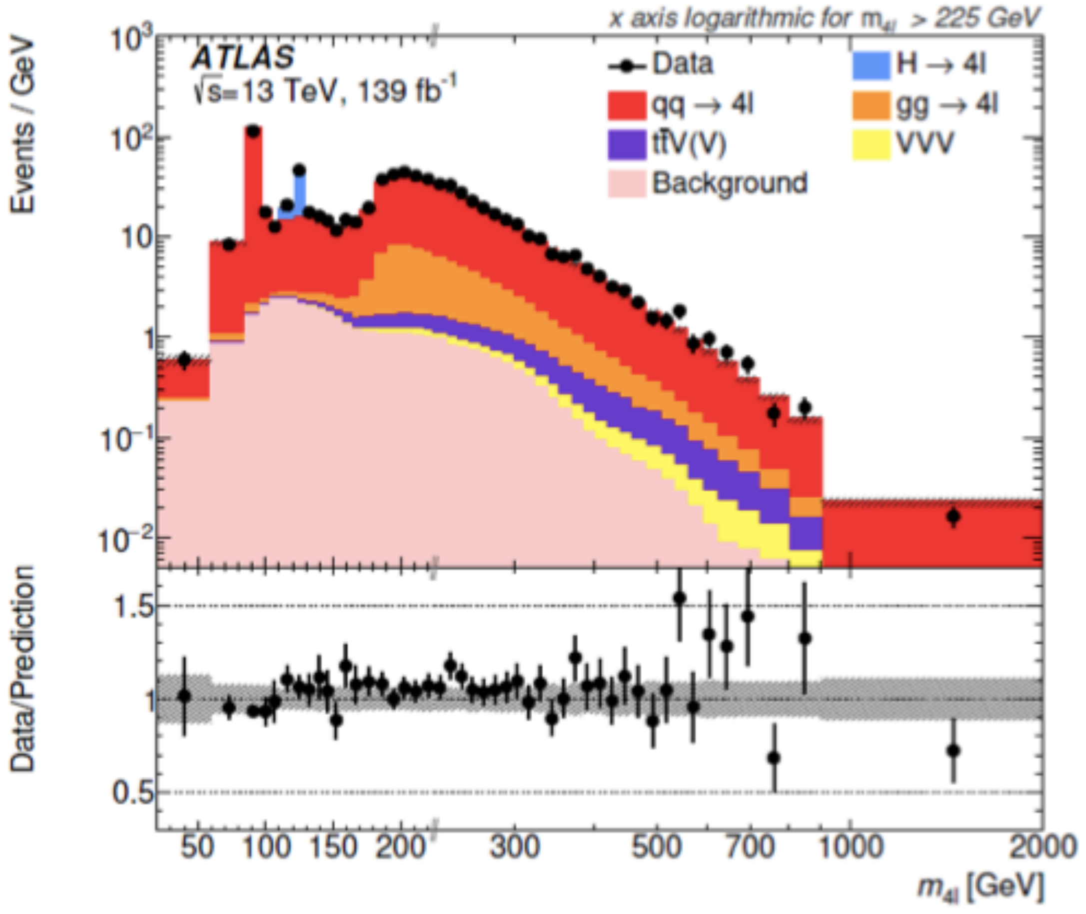
- **One pole** scenario. Makes sense since the effect of $\sim d_4 h^4$ should be similar to $\sim \gamma\left(\partial_\mu h \partial^\mu h\right)^2$

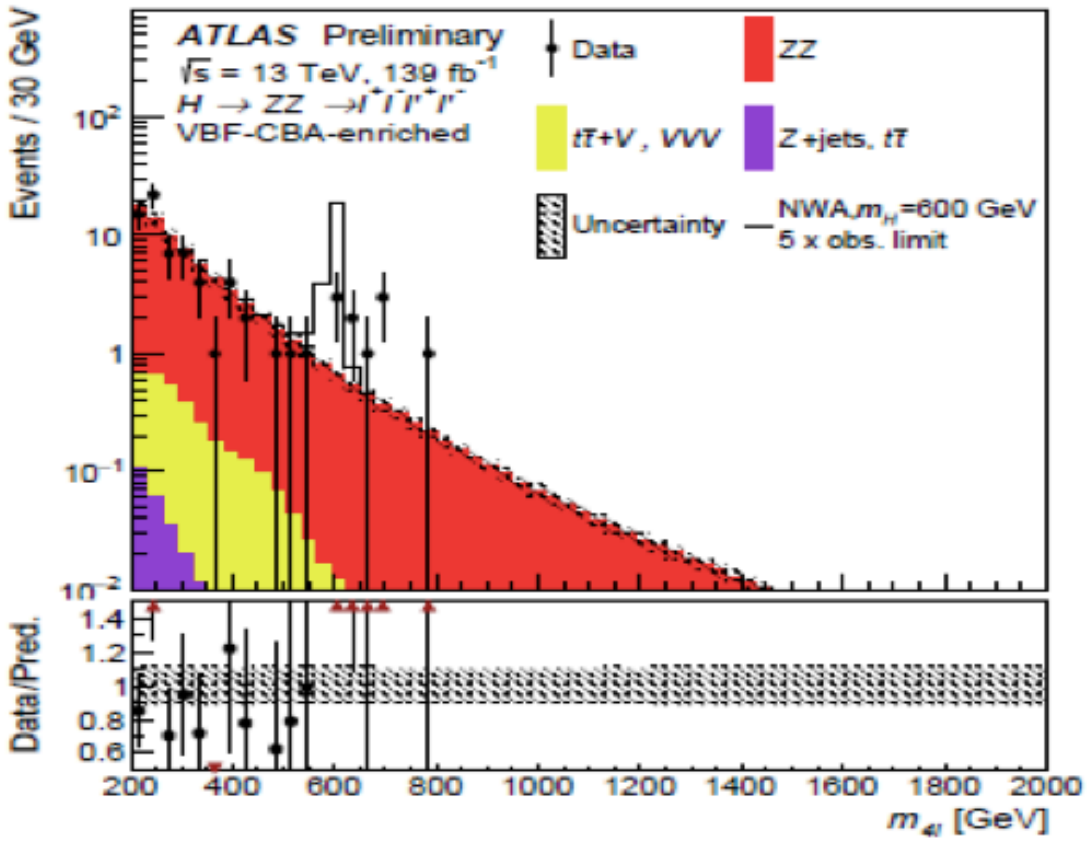
- **light pole** (< 1.8 TeV) appears for $d_4 \gtrsim 2$

What if…

- What if **there is** a light resonance (< 1.8 TeV) but not confirmed yet?

- **ATLAS + CMS: some evidence** H$(650) \to WW$ in 4 leptonic final state





arXiv:2103.01918

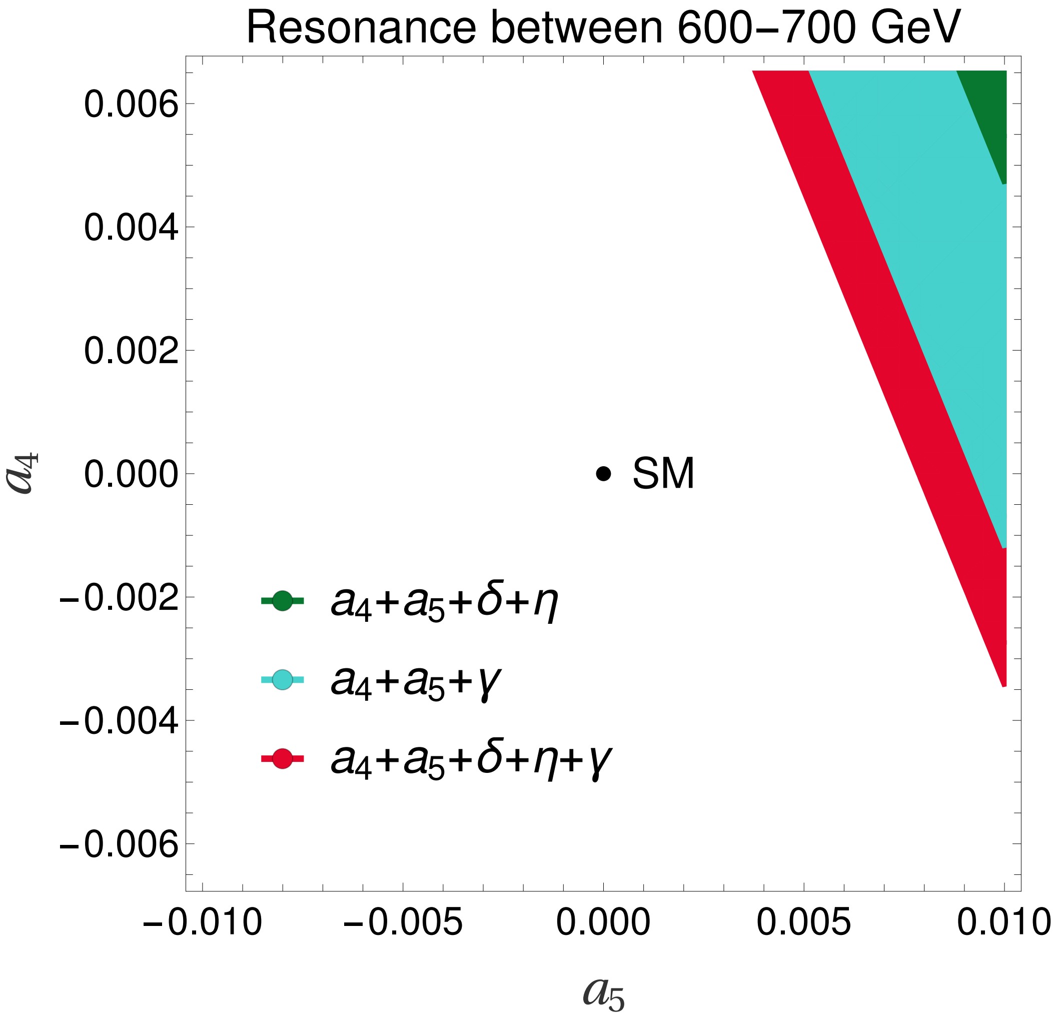
ATLAS collaboration

Scalar H(650)

- What if **there is** a light resonance (< 1.8 TeV) but not confirmed yet?

- **ATLAS + CMS: some evidence** $\mathrm{H}(650) \to WW$ in 4 leptonic final state

- Can we **accommodate this resonance** in the HEFT?



- $\mathscr{L} = \mathscr{L}_{SM}\ \left(a = 1,\ b = 1,\ d_3 = 1,\ d_4 = 1\right) + \mathscr{L}_4$

- We can in a **nontrivial way**

- Map shows if this light resonance **can be** produced for certain values of NLO coeffs.

- $a_4,\ a_5$ and γ are the more important ones

- Scalar resonances appear in combination $5a_4 + 8a_5 = k$

Scalar H(650)

- Are the properties of this resonance **compatible with experiment?**

- **Combined ATLAS + CMS analysis:**

P. Cea, Mod. Phys. Lett. A 34, 1950137 (2019), 1806.04529

Kundu, A. Le Yaouanc, P. Mondal, and F. Richard in 2022 ECFA Workshop

  - $\sigma(H(650) \rightarrow WW) = 160 \pm 50$ fb
    $\sigma(H(650) \rightarrow ZZ) = 30 \pm 15$ fb
  - $\Gamma = 90 \pm 28$ GeV

- We **assume** H$\left(650\right)$ decays purely **into gauge bosons**

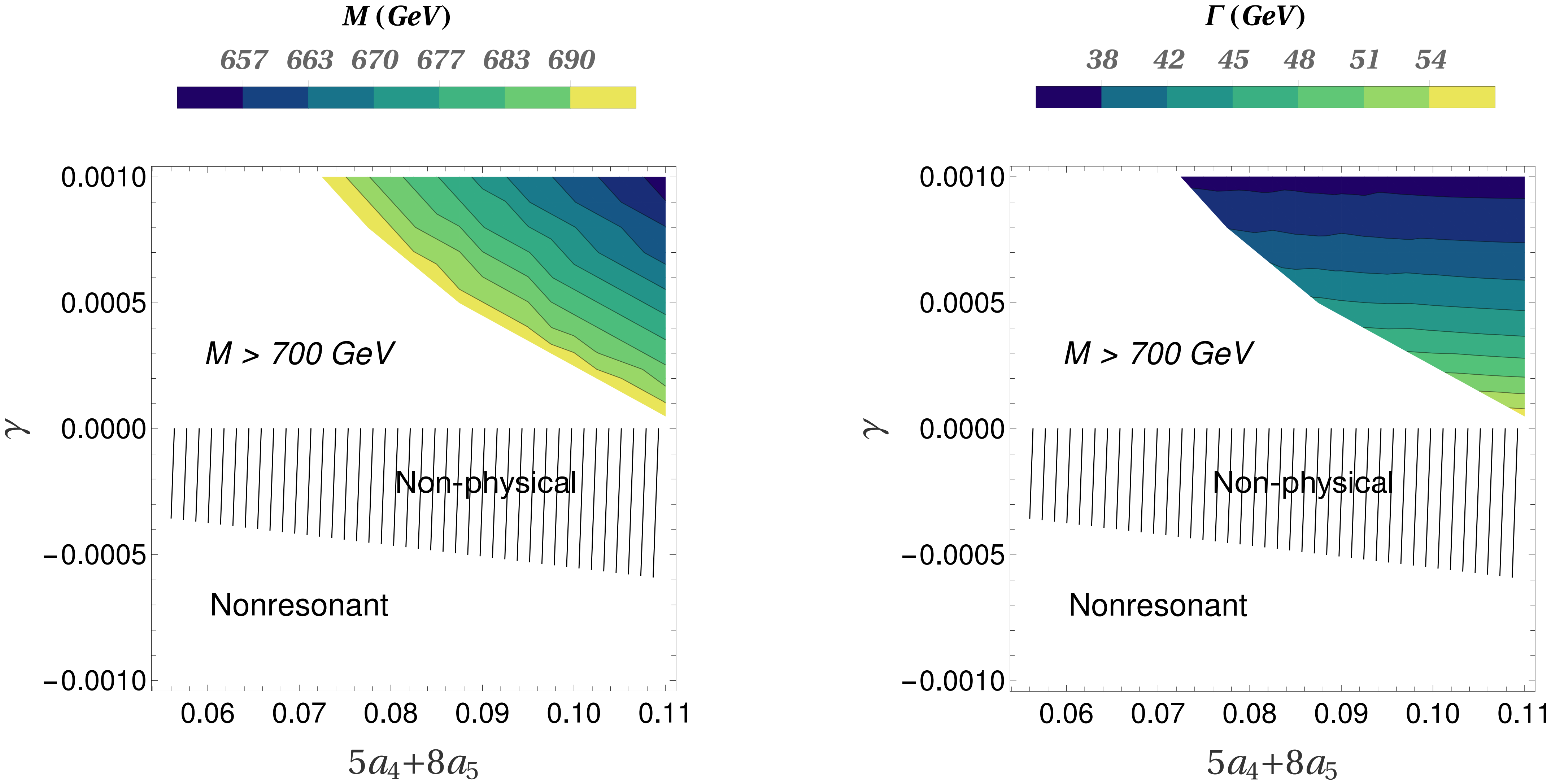
- **EWA**: gauge bosons as partons inside the proton

- Bidimensional space $\left[\gamma \times k = 5a4 + 8a_5\right]$

Scalar H(650)

- Bidimensional space $[\gamma \times k] = [(-0.001, 0.001) \times (0.055, 0.11)]$

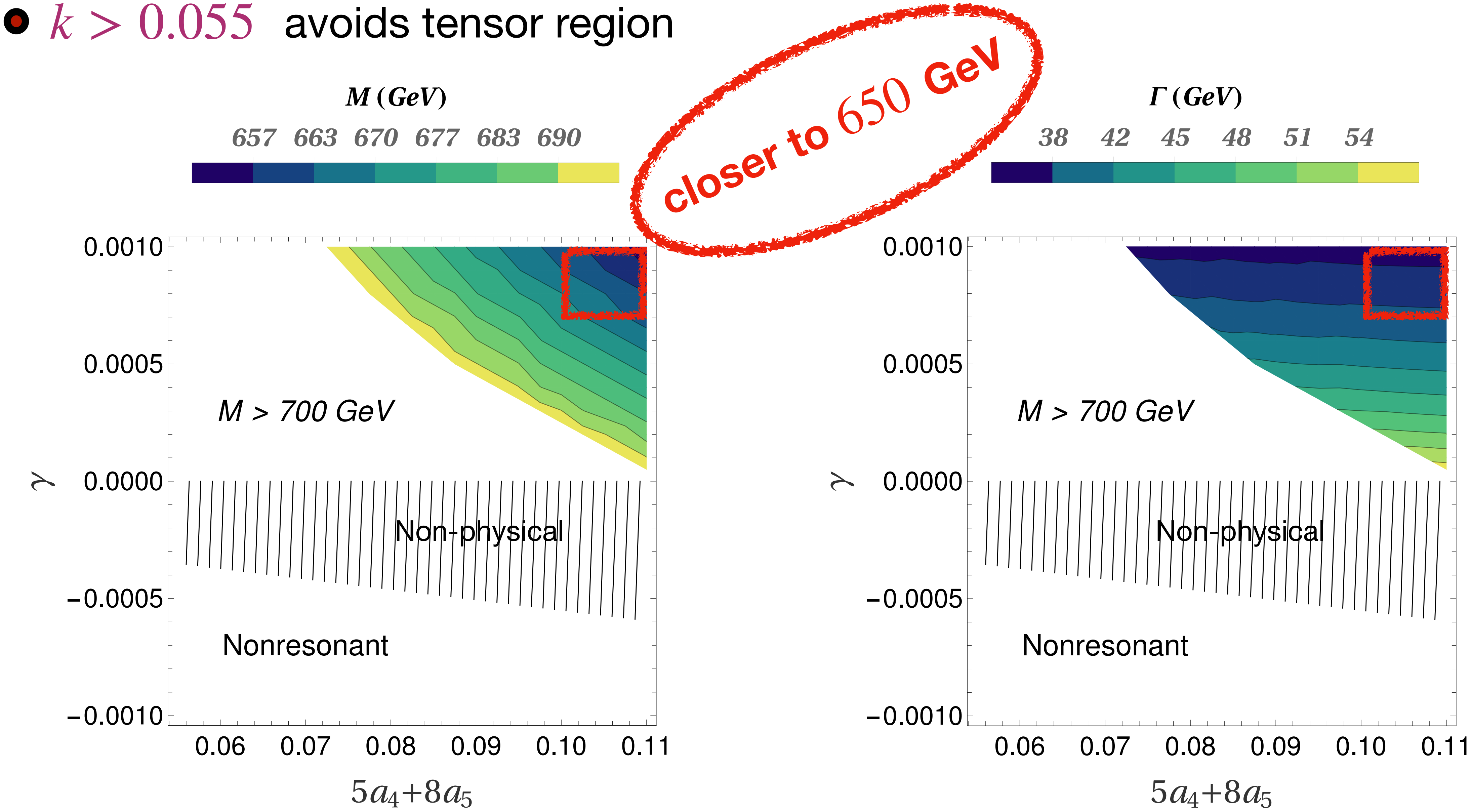
- $k > 0.055$ avoids tensor region



- **Widths** are **similar** to the experimental result 90 ± 28 GeV

Scalar H(650)

- Bidimensional space $[\gamma \times k] = [(-0.001, 0.001) \times (0.055, 0.11)]$
- $k > 0.055$ avoids tensor region



- **Widths** are **similar** to the experimental result 90 ± 28 GeV

Conclusions

- Effective field theories are **powerful tools** to explore High Energy Physics in a model-independent way

- Unitary amplitudes can help to **constrain anomalous couplings** by studying resonant (or non-resonant) scenarios

- An extended EWSBS typically **have such resonances**

- While studying scalar resonances the parameter space explodes

- The study of possible resonances in WW places restrictions in **Higgs potential**

- This line of analysis deserves further more systematic studies

- **H$\left(650\right)$-like** state can be reproduced in the HEFT with similar properties

Conclusions

- Effective field theories are **powerful tools** to explore High Energy Physics in a model-independent way
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- This line of analysis deserves further more systematic studies
- **H(650)-like** state can be reproduced in the HEFT with similar properties

THANK YOU!! :)

BACK UP SLIDES

The Lagrangian

- Our **complete Lagrangian**

$$\mathcal{L}_2 = -\frac{1}{2g^2}\mathrm{Tr}\left(\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right) - \frac{1}{2g'^2}\mathrm{Tr}\left(\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\right) + \frac{v^2}{4}\mathcal{F}(h)\mathrm{Tr}\left(D^\mu U^\dagger D_\mu U\right) + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h)$$

$$\mathcal{L}_4 = -ia_3\mathrm{Tr}\left(\hat{W}_{\mu\nu}\left[V^\mu, V^\nu\right]\right) + a_4\left(\mathrm{Tr}\left(V_\mu V_\nu\right)\right)^2 + a_5\left(\mathrm{Tr}\left(V_\mu V^\mu\right)\right)^2 + \frac{\gamma}{v^4}\left(\partial_\mu h \partial^\mu h\right)^2 + \frac{\delta}{v^2}\left(\partial_\mu h \partial^\mu h\right)\mathrm{Tr}\left(D_\mu U^\dagger D^\mu U\right) + \frac{\eta}{v^2}\left(\partial_\mu h \partial_\nu h\right)\mathrm{Tr}\left(D^\mu U^\dagger D^\nu U\right) + i\chi\,\mathrm{Tr}\left(\hat{W}_{\mu\nu}V^\mu\right)\partial^\nu \mathcal{G}(h)$$

- **Building blocks**

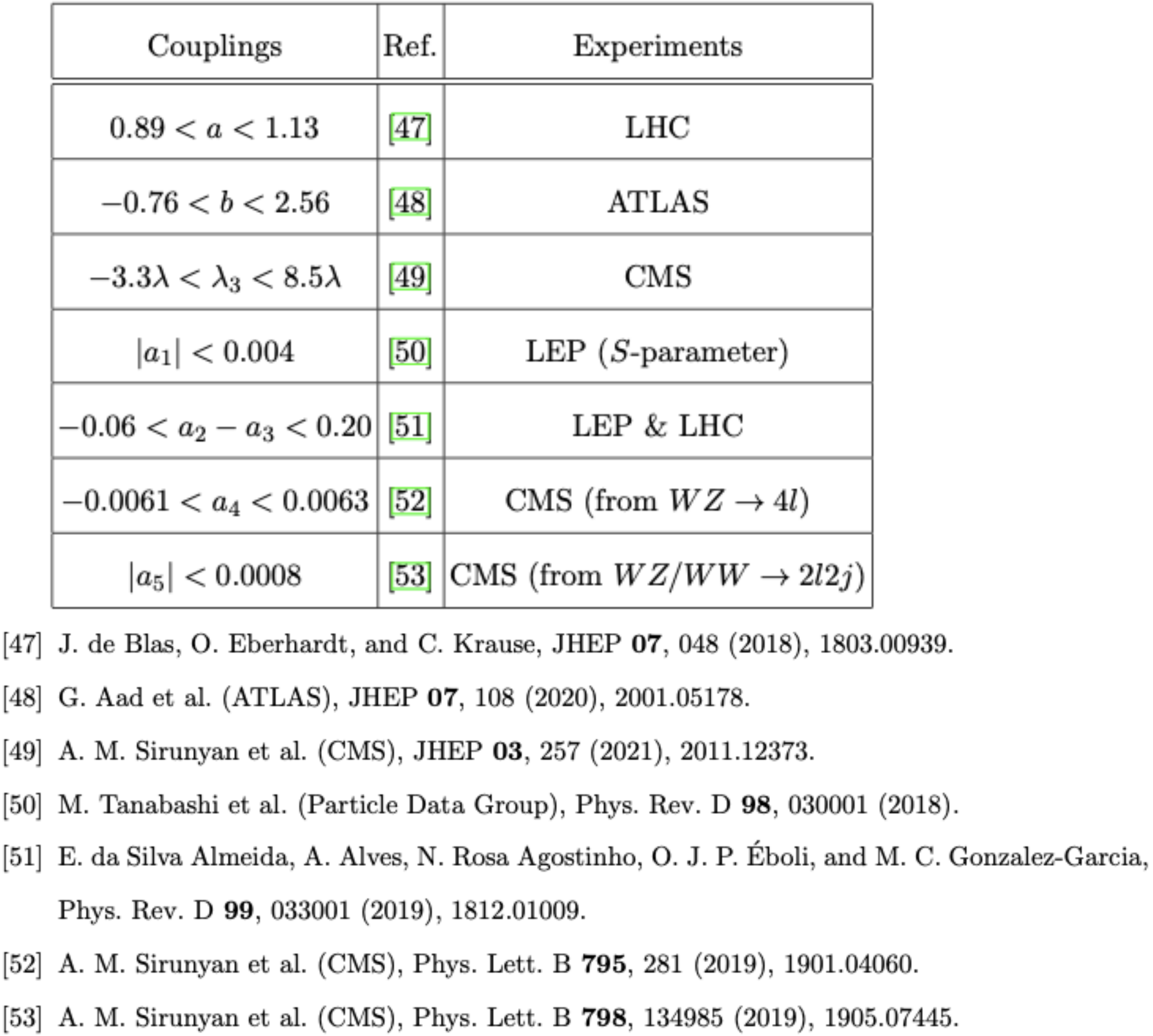
$$U = \exp\left(\frac{i\omega^a\sigma^a}{v}\right) \in SU(2)_V, \quad V_\mu = D_\mu U^\dagger U, \quad \mathcal{F}(h) = 1 + 2a\left(\frac{h}{v}\right) + b\left(\frac{h}{v}\right)^2 + \ldots,$$

$$D_\mu U = \partial_\mu U + i\hat{W}_\mu U, \quad \hat{W}_\mu = g\frac{\vec{W}_\mu \cdot \vec{\sigma}}{2}, \quad \hat{W}_{\mu\nu} = \partial_\mu \hat{W}_\nu - \partial_\nu \hat{W}_\mu + i\left[\hat{W}_\mu, \hat{W}_\nu\right],$$

$$V(h) = \frac{1}{2}M_h^2 h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4}h^4 + \ldots, \quad \mathcal{G}(h) = 1 + b_1\left(\frac{h}{v}\right) + b_2\left(\frac{h}{v}\right)^2 + \ldots$$

$$\boxed{\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_4 + \mathscr{L}_{GF} + \mathscr{L}_{FP}}$$

Experimental bounds on chiral couplings



Couplings	Ref.	Experiments
$0.89 < a < 1.13$	[47]	LHC
$-0.76 < b < 2.56$	[48]	ATLAS
$-3.3\lambda < \lambda_3 < 8.5\lambda$	[49]	CMS
$\lvert a_1 \rvert < 0.004$	[50]	LEP (S-parameter)
$-0.06 < a_2 - a_3 < 0.20$	[51]	LEP & LHC
$-0.0061 < a_4 < 0.0063$	[52]	CMS (from $WZ \to 4l$)
$\lvert a_5 \rvert < 0.0008$	[53]	CMS (from $WZ/WW \to 2l2j$)

[47] J. de Blas, O. Eberhardt, and C. Krause, JHEP **07**, 048 (2018), 1803.00939.

[48] G. Aad et al. (ATLAS), JHEP **07**, 108 (2020), 2001.05178.

[49] A. M. Sirunyan et al. (CMS), JHEP **03**, 257 (2021), 2011.12373.

[50] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D **98**, 030001 (2018).

[51] E. da Silva Almeida, A. Alves, N. Rosa Agostinho, O. J. P. Éboli, and M. C. Gonzalez-Garcia, Phys. Rev. D **99**, 033001 (2019), 1812.01009.

[52] A. M. Sirunyan et al. (CMS), Phys. Lett. B **795**, 281 (2019), 1901.04060.

[53] A. M. Sirunyan et al. (CMS), Phys. Lett. B **798**, 134985 (2019), 1905.07445.

The couterterms

- **The counterterms for:** $\omega\omega \to \omega\omega,\ \omega\omega \to hh\ and\ hh \to hh$

$$\delta v^2_{div} = \frac{\Delta}{16\pi^2}\left((b-a^2)M_h^2 + 3(a^2+2)M_W^2\right), \quad \delta T_{div} = -\frac{\Delta}{32\pi^2 v}3\left(d_3 M_h^4 + 6aM_W^4\right),$$

$$\delta a = \frac{\Delta}{32\pi^2 v^2}\left(6\,a\left(-2a^2+b+1\right)M_W^2 + (5a^3 - a(2+3b) - 3d_3(a^2-b))M_h^2\right),$$

$$\delta b = \frac{\Delta}{32\pi^2 v^2}\left(6\left(3a^4 - 6a^2 b + b(b+2)\right)M_W^2\right.$$
$$\left. - \left(21a^4 - a^2(8+19b) + b(4+2b) + 6ad_3(1+2b-3a^2) - 3d_4(b-a^2)\right)M_h^2\right),$$

$$\delta\lambda_{div} = \frac{\Delta}{64\pi^2 v^4}\left(\left(5a^2 - 2b + 3\left(d_3(3d_3-1)+d_4\right)\right)M_h^4 - 12\left(2a^2+1\right)M_W^2 M_h^2\right.$$
$$\left.+18(a(2a-1)+b)M_W^4\right),$$

$$\delta\lambda_3 = \frac{\Delta}{64\pi^2 v^4}\left(36abM_W^4 + 6(3a^3 - 3ab - d_3(5a^2+1))M_W^2 M_h^2\right.$$
$$\left.+(-9a^3 + 3ab + d_3(10a^2-b) + 9d_3 d_4)M_h^4\right),$$

$$\delta\lambda_4 = \frac{\Delta}{64\pi^2 v^4}\left(36b^2 M_W^4 - 12(a^2-b)(8a^2-2b-9ad_3)M_W^2 M_h^2\right.$$
$$\left.+(96a^4 + 4b^2 - d_3(114a^3 - 42ab) + 9d_4^2 + a^2(-64b + 27d_3^2 + 12d_4))M_h^4\right),$$

$$\delta a_3 = -\frac{\Delta}{384\pi^2}\left(1-a^2\right), \quad \delta a_4 = -\frac{\Delta}{192\pi^2}\left(1-a^2\right)^2,$$

$$\delta a_5 = -\frac{\Delta}{768\pi^2}\left(5a^4 - 2a^2(3b+2) + 3b^2 + 2\right),$$

$$\delta\gamma = -\frac{\Delta}{64\pi^2}3(b-a^2)^2, \quad \delta\delta = -\frac{\Delta}{192\pi^2}(b-a^2)(7a^2-b-6), \quad \delta\eta = -\frac{\Delta}{48\pi^2}(b-a^2)^2,$$

$$\delta\zeta = \frac{\Delta}{96\pi^2}a(b-a^2).$$

The couterterms

- **The counterterms for:** $\omega\omega \to \omega\omega,\ \omega\omega \to hh\ and\ hh \to hh$

$$\delta M^2_{h,div} = \frac{\Delta}{32\pi^2 v^2}\left(3\left[6\left(2a^2+b\right)M_W^4 - 6a^2 M_W^2 M_h^2 + \left(3d_3^2 + d_4 + a^2\right)M_h^4\right]\right),$$

$$\delta M^2_{W,div} = \frac{\Delta}{48\pi^2 v^2}\left(M_W^2\left[3\left(b-a^2\right)M_h^2 + \left(-69+10a^2\right)M_W^2\right]\right),$$

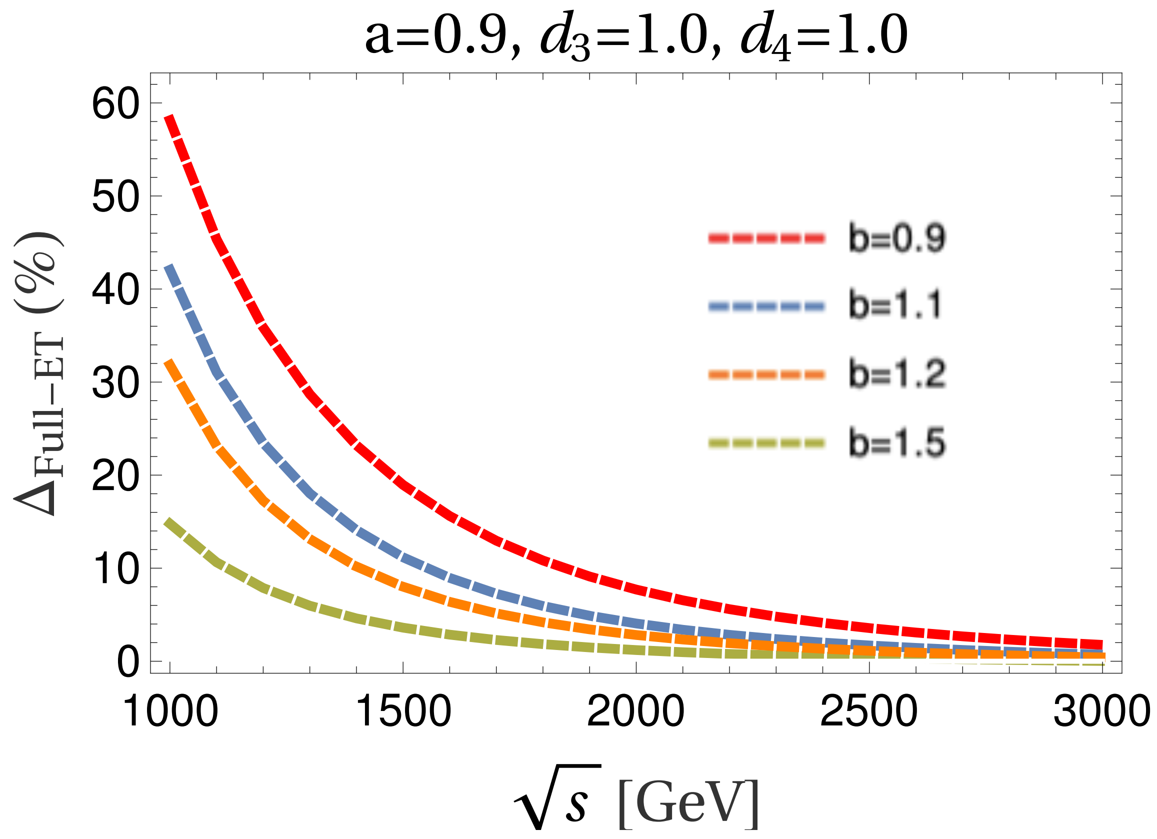
$$\delta Z_{h,div} = \frac{\Delta}{16\pi^2 v^2}\left(3a^2\left(3M_W^2 - M_h^2\right)\right),$$

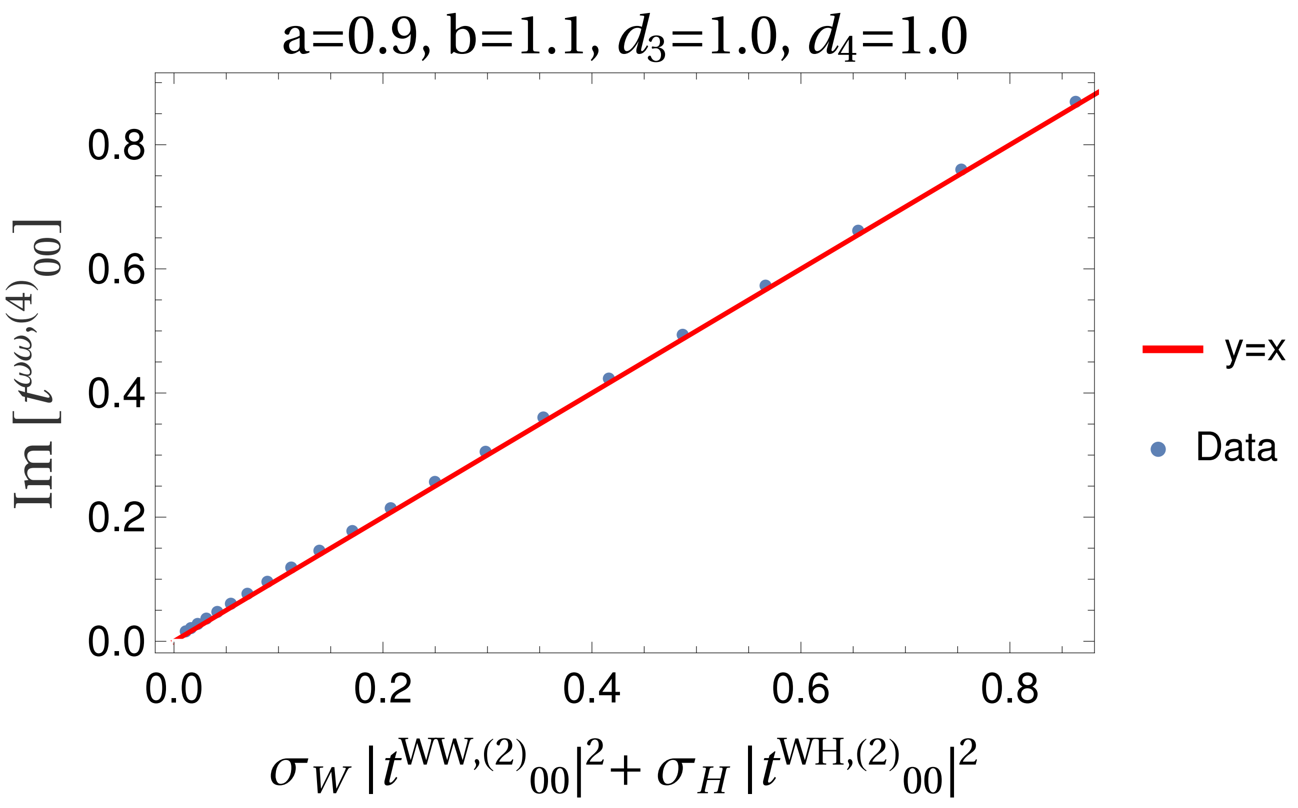
$$\delta Z_{\omega,div} = \frac{\Delta}{16\pi^2 v^2}\left(\left(b-a^2\right)M_h^2 + 3\left(a^2+2\right)M_W^2\right)$$

- In total: **17 counterterms + 1 tadpole**

ET validity

- Is it **safe** for us to use the ET?
  - We are only making use of the ET in the **one-loop calculation**
  - **Small** compared to $\mathcal{O}(p^4)$ **exact** contributions at TeV scale
  - Numerical check using **perturbative unitarity**

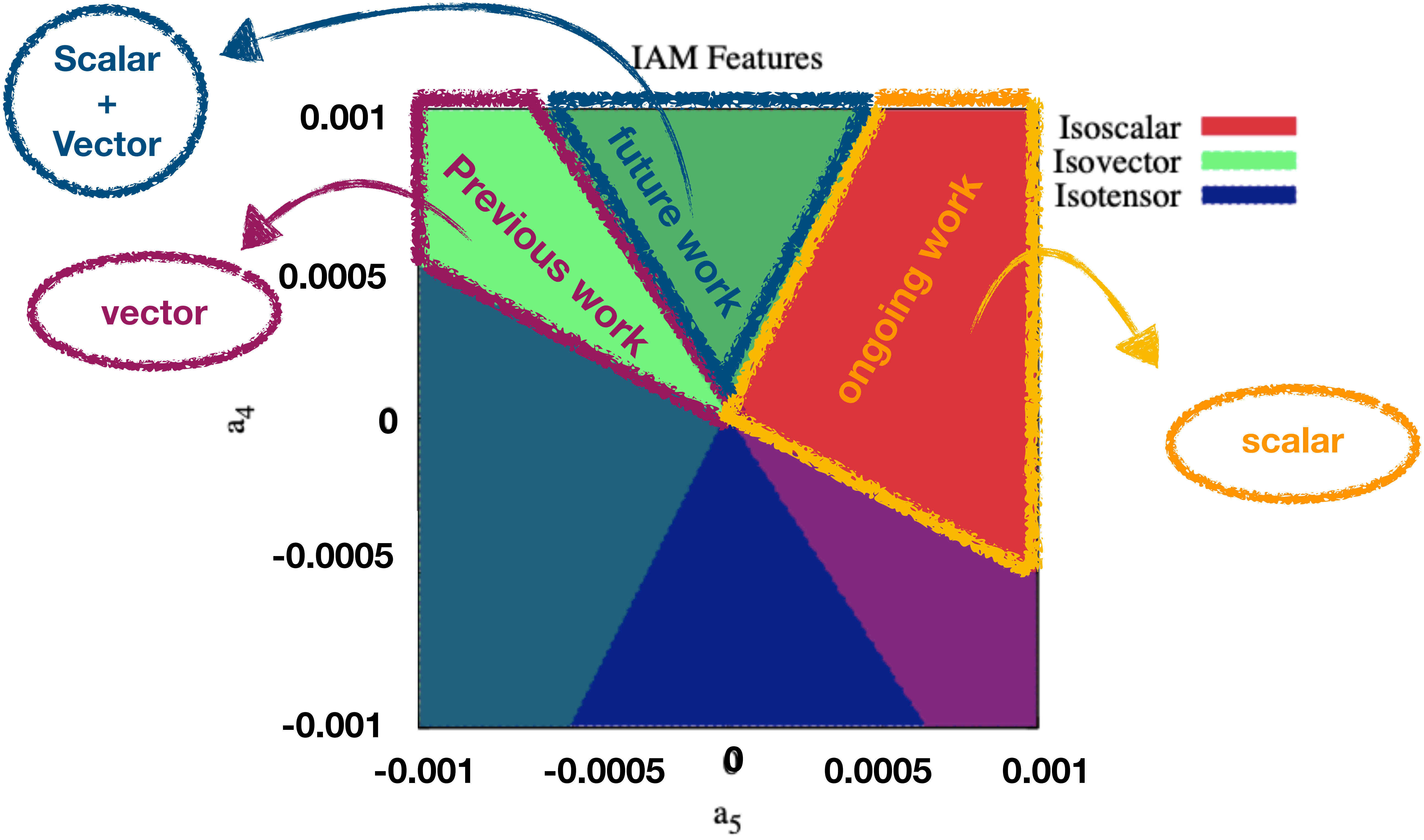




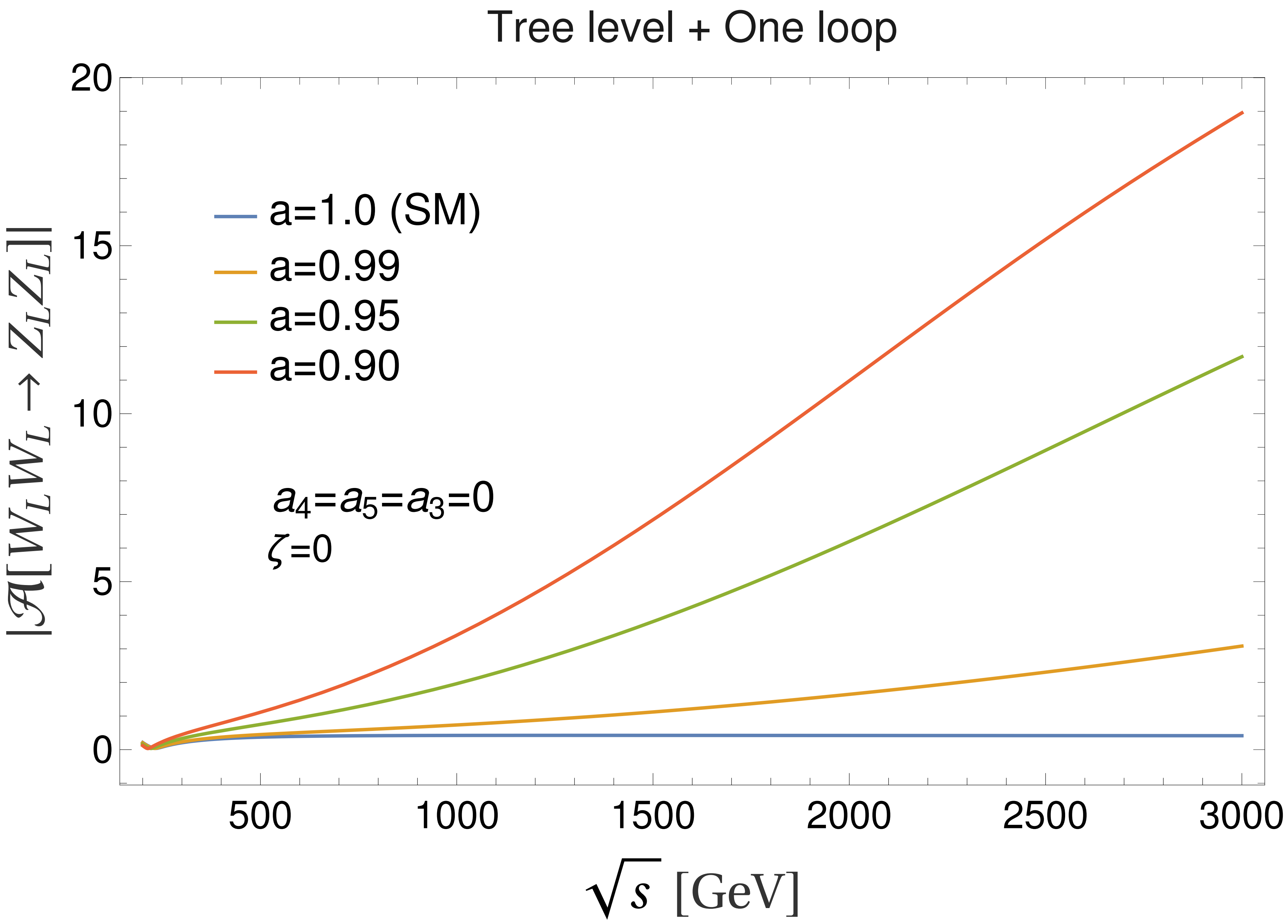
$(WW : WW \to WW)$

$\big(WH : WW \to hh\big)$

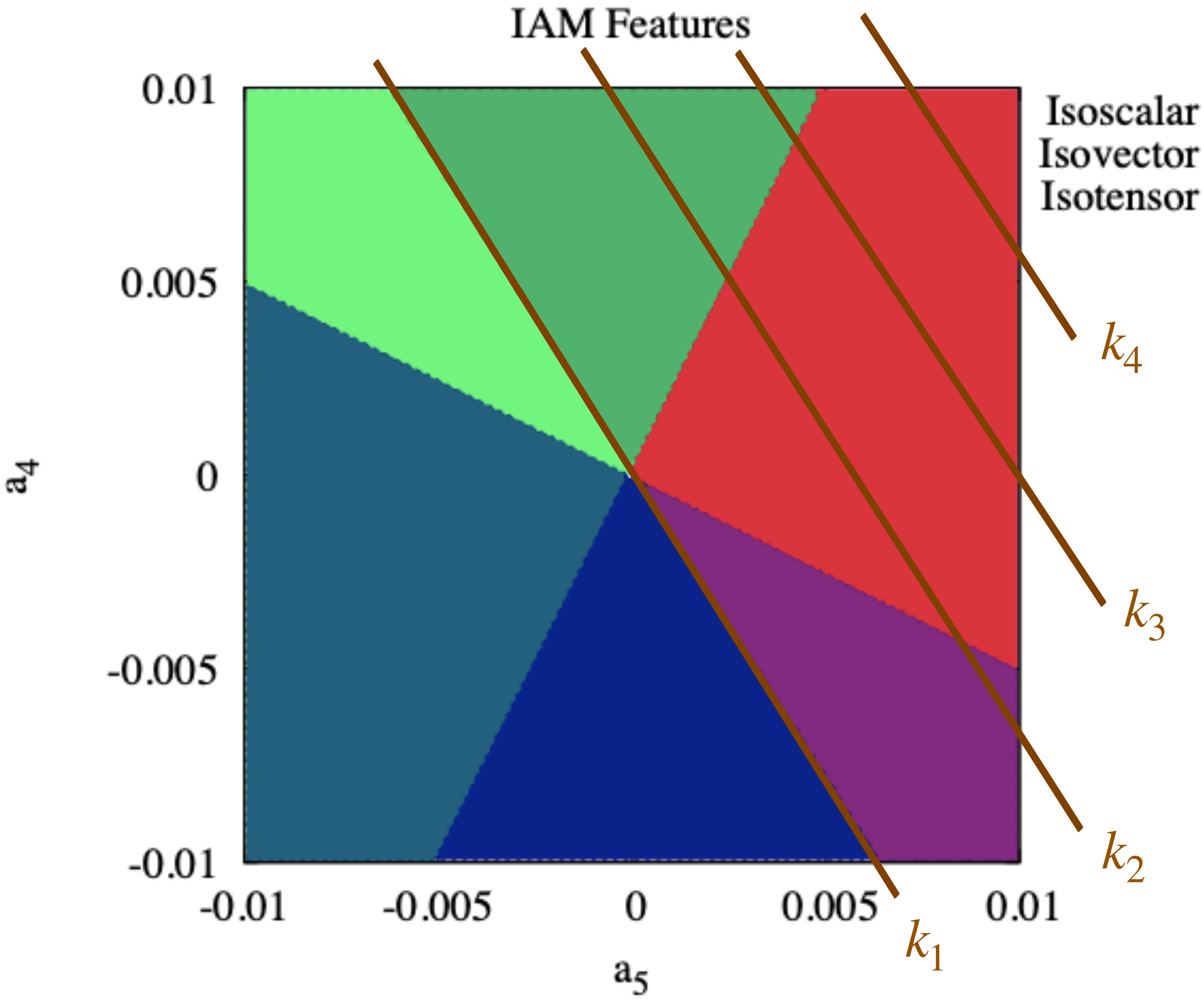
Relevant chiral parameter space



Violation of unitarity

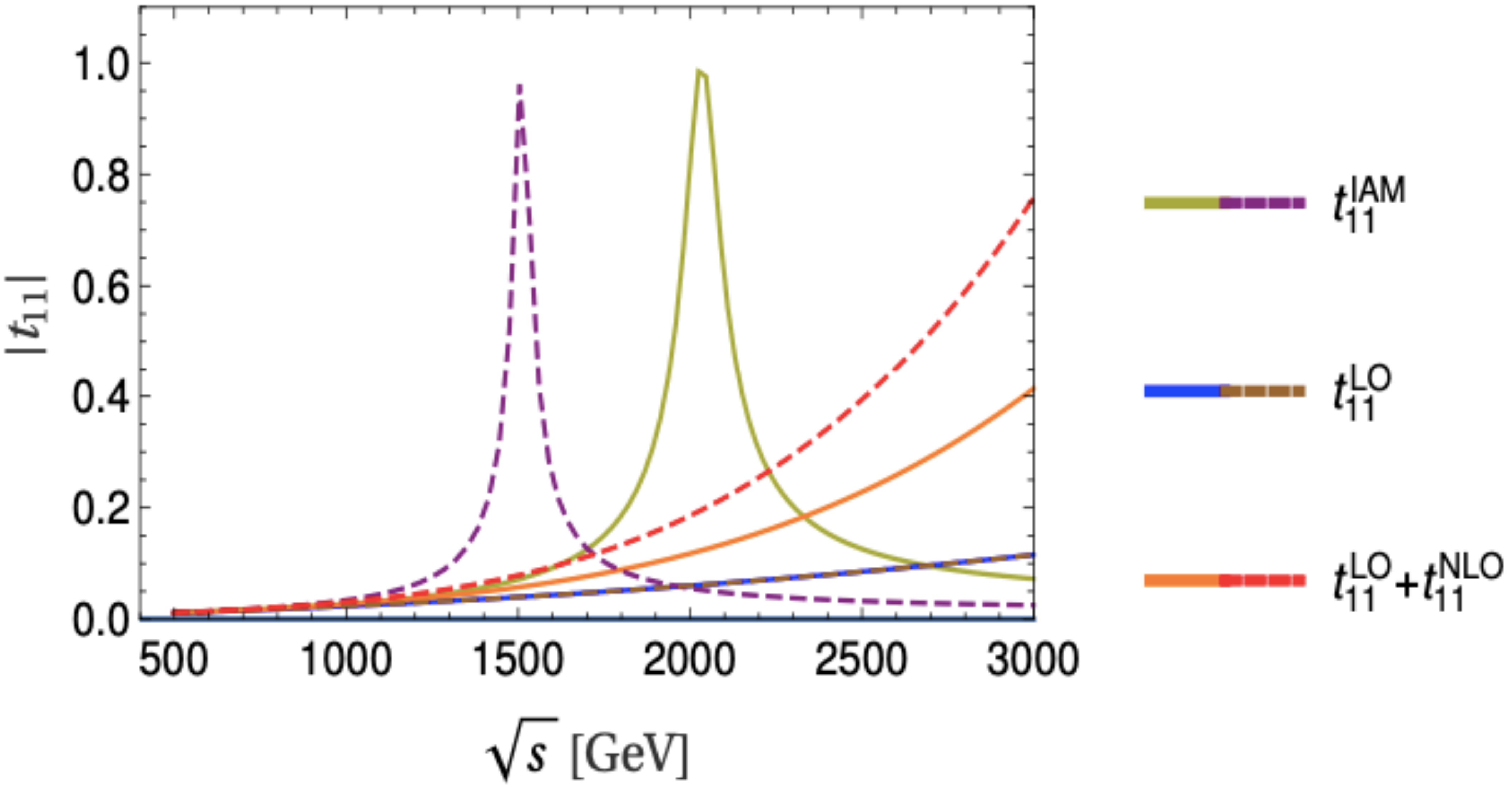


scalar-isoscalar



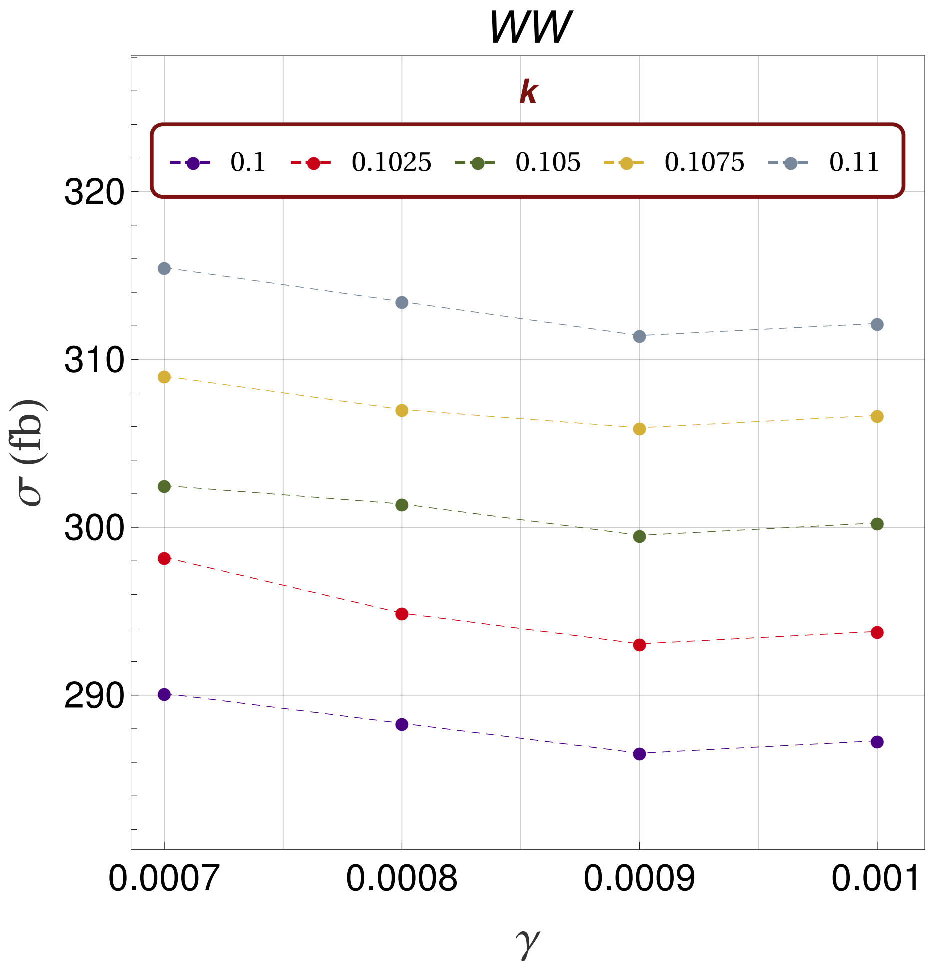
- $5a_4 + 8a_5 = k$
- Not significantly affected by δ, η and γ

Unitarized amplitudes: vector-isovector



Scalar H(650): cross section in EWA

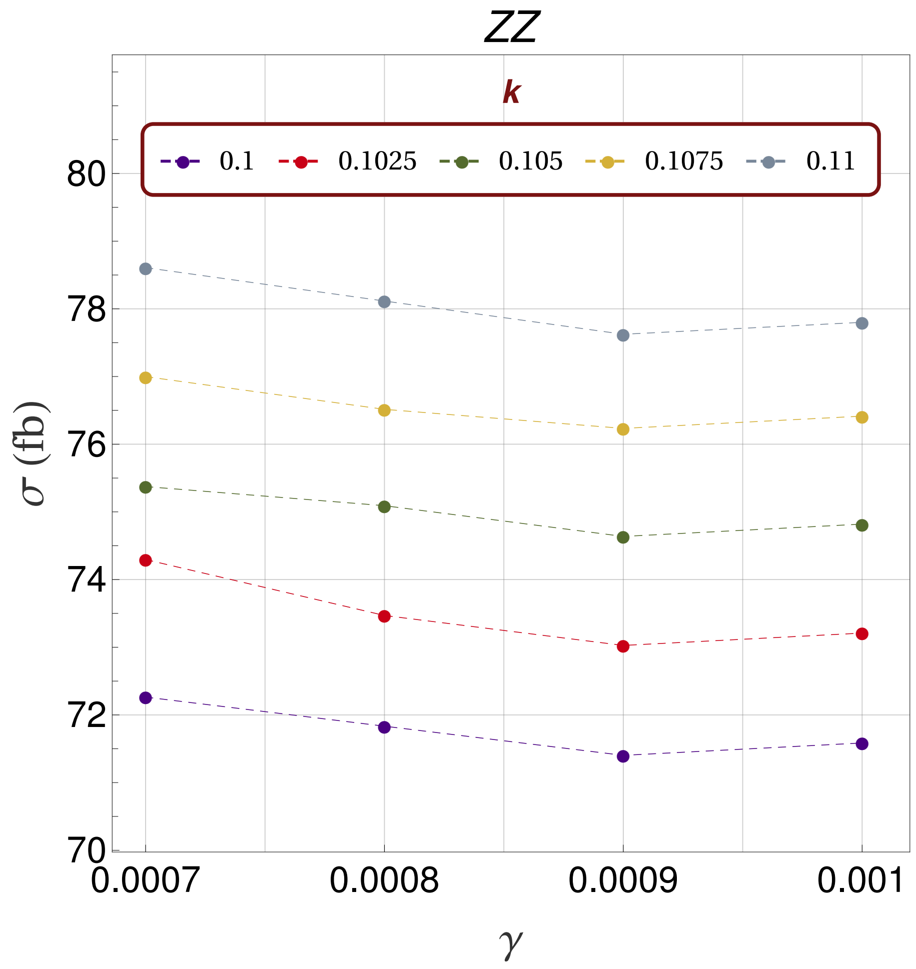
- $$\frac{d\sigma}{dM^2_{WW}} = \sum_{i,j}\int_{M^2_{WW}/s}^{1}\int_{M^2_{WW}/(x_1 s)}^{1}\frac{dx_1 dx_2}{x_1 x_2 s}\underbrace{f_i(x_1,\mu_F)f_j(x_2,\mu_F)}_{\text{p.d.f.}}\underbrace{\frac{dL_{WW}}{d\tau}}_{\text{effective luminosity}}\underbrace{\int_{-1}^{1}\frac{d\sigma_{WW}}{d\cos\theta}d\cos\theta}_{\text{partonic cross section}}$$
- $$\sigma = \int_{M-2\Gamma}^{M+2\Gamma}\frac{d\sigma}{dM^2_{WW}}dM^2_{WW}$$



- Cross sections for WW **final state** ~ 300 fb for all scenarios
- No **kinematical cuts**
- **Experimental result:** 160 ± 50 fb

Scalar H(650): cross section in EWA

- $$\frac{d\sigma}{dM_{WW}^2} = \sum_{i,j}\int_{M_{WW}^2/s}^{1}\int_{M_{WW}^2/(x_1 s)}^{1} \frac{dx_1 dx_2}{x_1 x_2 s}\underbrace{f_i(x_1,\mu_F)f_j(x_2,\mu_F)}_{\text{p.d.f.}}\underbrace{\frac{dL_{WW}}{d\tau}}_{\text{effective luminosity}}\underbrace{\int_{-1}^{1}\frac{d\sigma_{WW}}{d\cos\theta}d\cos\theta}_{\text{partonic cross section}}$$
- $$\sigma = \int_{M-2\Gamma}^{M+2\Gamma}\frac{d\sigma}{dM_{WW}^2}dM_{WW}^2$$



- Cross sections for ZZ **final state** ~ 75 fb for all scenarios
- No **kinematical cuts**
- **Experimental result:** 30 ± 15 fb