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# Characterizing LHC-Resonances in Extended HEFT

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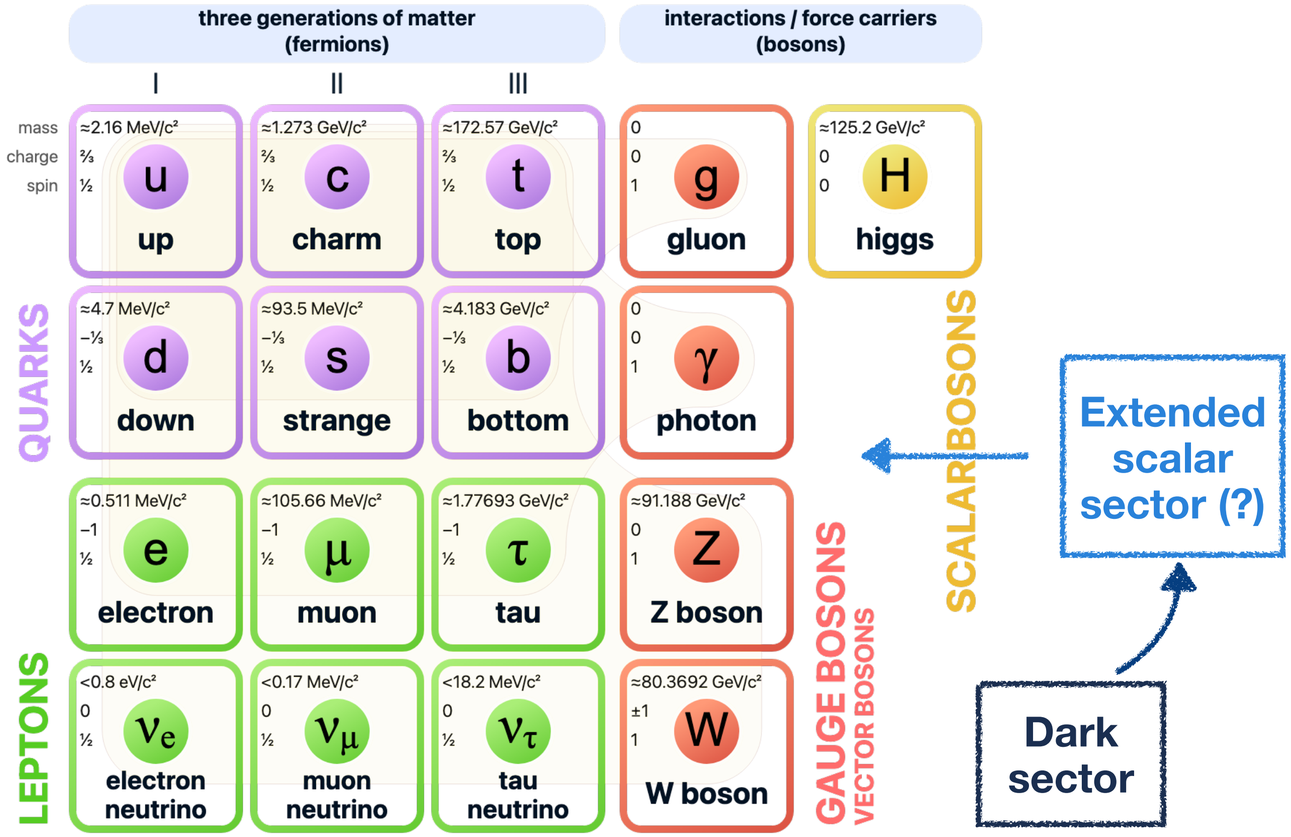
Based on arXiv: 2512.11764

In collaboration with:
Giorgio Arcadi, Florian Goertz and Maya Hager

# Content

- How can we extend the scalar sector in a model independent way?
- What information can we get from it?
- Example with the 95 GeV excess




Connection with DM see Arcadi, DCA, Fabian, Goertz 2208.02717

# HEFT

**HEFT:** The Higgs does not need to belong to an exact $SU(2)_L$ doublet

$$H = \frac{v+h}{\sqrt{2}}\Sigma(x)\begin{pmatrix}0\\1\end{pmatrix}$$

$h$

**Treated as a singlet with arbitrary couplings**

$$F(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots$$

$$\Sigma(x) = \exp\left(i\sigma^a G^a(x)/v\right)$$

**Derivative expansion**

**Chiral dimension:**

$$D_c(F) \equiv [F]$$
$$D_c = 2L + 2$$

F. Feruglio, arXiv:hep-ph/9301281

R. Alonso, M. B. Gavela, L. Merlo, S. Rigolin, J. Yepes, arXiv:1212.3305

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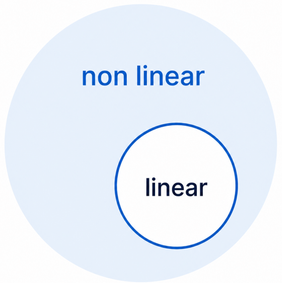


- A **very general** EFT

$h \neq$ **necessarily part of an** $SU(2)_L$ **doublet**

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# extended HEFT

$h \longrightarrow h, S$ A new (pseudo-)scalar field

**What if Higgs is not alone?**

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$\phi_j\phi_i Z$ interaction

$$\mathscr{L}_{\mathrm{eHEFT}} \supset \frac{1}{2}\sum_{\phi=\mathcal{S},h}\partial_\mu\phi\partial^\mu\phi - \mathscr{F}_{c_s} + i\frac{v^2}{4}\mathrm{Tr}\left[\Sigma^\dagger\left(D^\mu\Sigma\right)\sigma^3\right]\left(c^h_{1,0}h\partial_\mu h + c^h_{2,0}h\,h\,\partial_\mu h + \partial_\mu\mathcal{S}\,\mathscr{F}_S\right)$$

$$-\frac{v}{\sqrt{2}}\left(\left(\overline{u_{i,L}}\,\overline{d_{i,L}}\right)\Sigma\begin{pmatrix}Y^u_{ij}u_{j,R}\\ Y^d_{ij}d_{j,R}\end{pmatrix}\mathscr{F}_{c_q} + \left(\overline{\nu_{i,L}}\,\overline{\ell_{i,L}}\right)\Sigma\frac{1-\sigma_3}{2}Y^\ell_{ij}\begin{pmatrix}\nu_{j,R}\\ \ell_{j,R}\end{pmatrix}\mathscr{F}_{c_\ell} + \mathrm{h.c.}\right)$$

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Leading order and phenomenologically relevant operators

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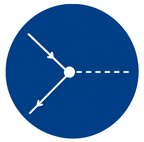

**Fermions** $\sum_f c'_f$

$$+\frac{v^2}{4}\mathrm{Tr}\left[\Sigma^\dagger\left(D^\mu\Sigma\right)\sigma^3\right]\mathrm{Tr}\left[\Sigma^\dagger\left(D_\mu\Sigma\right)\sigma^3\right]\mathscr{F}_{c_T} + \frac{v^2}{4}\mathrm{Tr}\left[\left(D_\mu\Sigma\right)^\dagger\left(D^\mu\Sigma\right)\right]\mathscr{F}_\kappa$$

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$$+\ldots$$ $\longrightarrow$ Leading order and phenomenologically relevant operators

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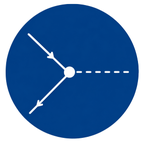
Leading order and phenomenologically relevant operators



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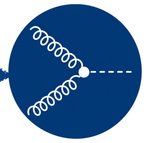
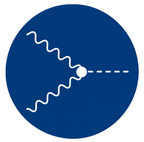


**Gluon** $c_G$



**Gauge vector** $\kappa,\ c_T,\ c_V,\ c_{WB}$

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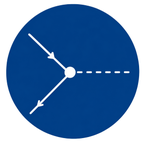

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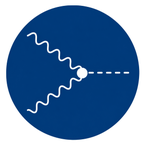
$$\frac{v^2}{4}\mathrm{Tr}\left[\left(D_\mu\Sigma\right)^\dagger\left(D^\mu\Sigma\right)\right]\mathcal{F}_\kappa \longrightarrow m_W^2 W_\mu^+ W^{-\mu}\mathcal{F}_\kappa + \frac{1}{2}m_Z^2 Z_\mu Z^\mu \mathcal{F}_\kappa$$



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$$gg' B_{\mu\nu}\mathrm{Tr}\left[\Sigma\sigma^3\Sigma^\dagger W^{\mu\nu}\right]\mathcal{F}_{c_{WB}} \longrightarrow gg' B_{\mu\nu}W^{3\mu\nu}\mathcal{F}_{c_{WB}} \qquad D_c = 4$$

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# Step-by-step idea

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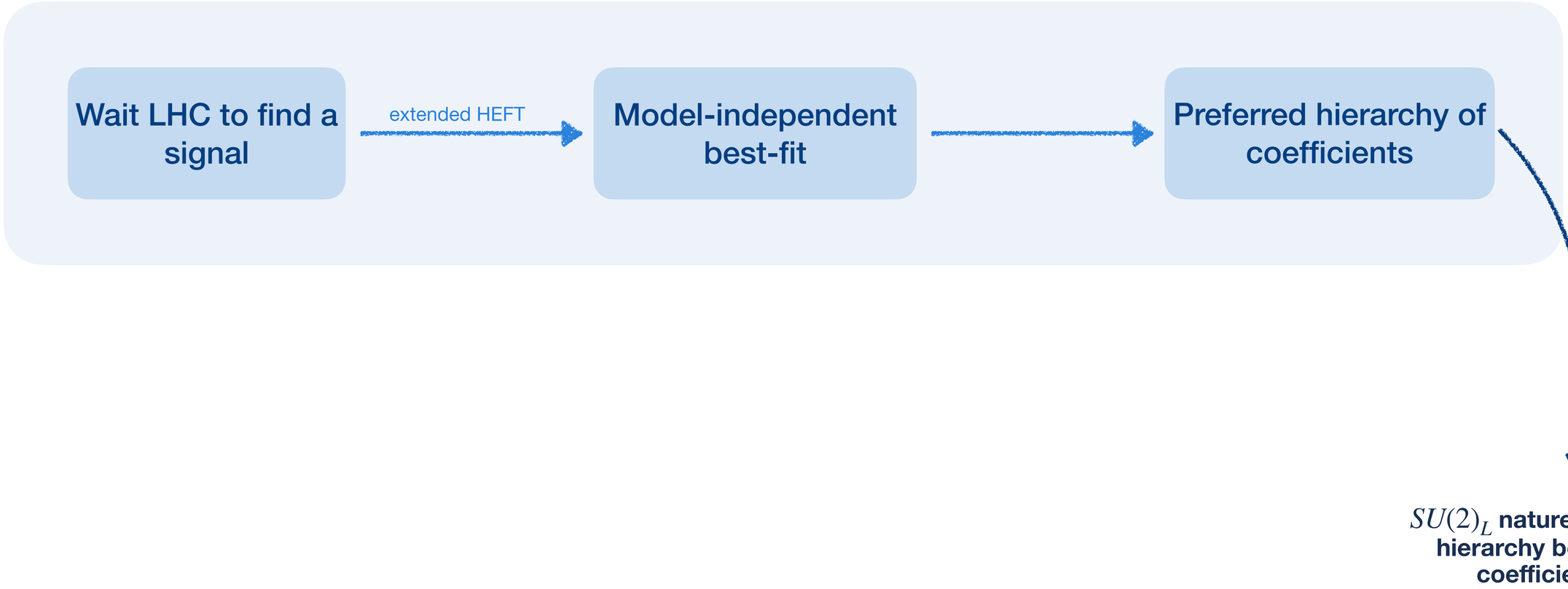

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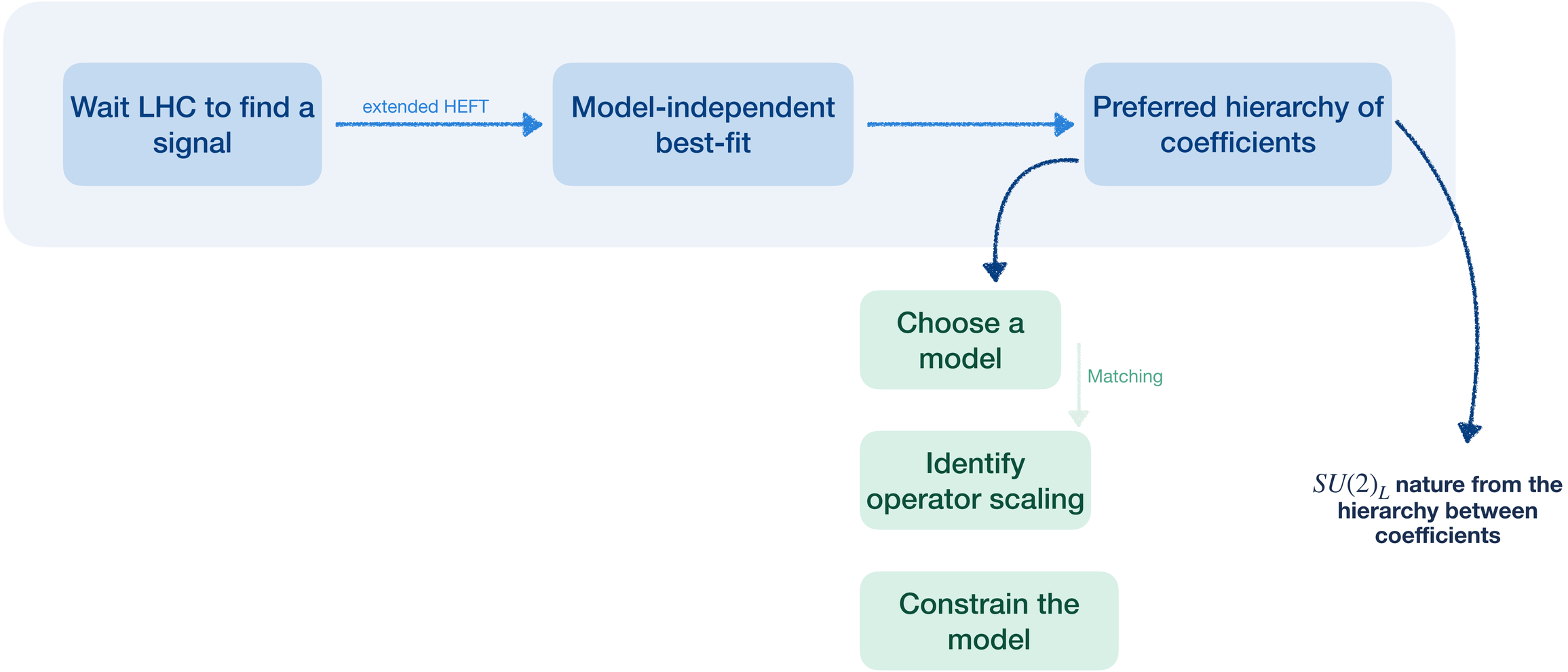


# Step-by-step idea

Wait LHC to find a signal

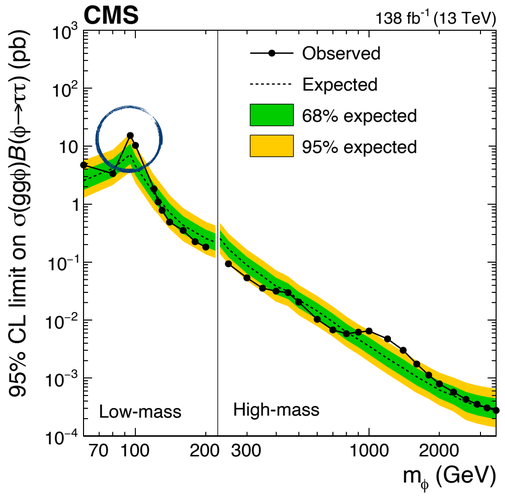
extended HEFT

Model-independent best-fit

Preferred hierarchy of coefficients

What can we do in the meantime?

95 GeV excess




Choose a model

Matching

Identify operator scaling

Constrain the model

$SU(2)_L$ nature from the hierarchy between coefficients

# 95 GeV as Example

- **di-tau** $\mu_{\tau\tau} = 1.22^{+0.62}_{-0.48}$

  2208.02717

- **di-bottom** $\mu_{bb} = 0.117 \pm 0.06$

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- **di-photon** $\mu_{\gamma\gamma} = 0.24^{+0.09}_{-0.08}$

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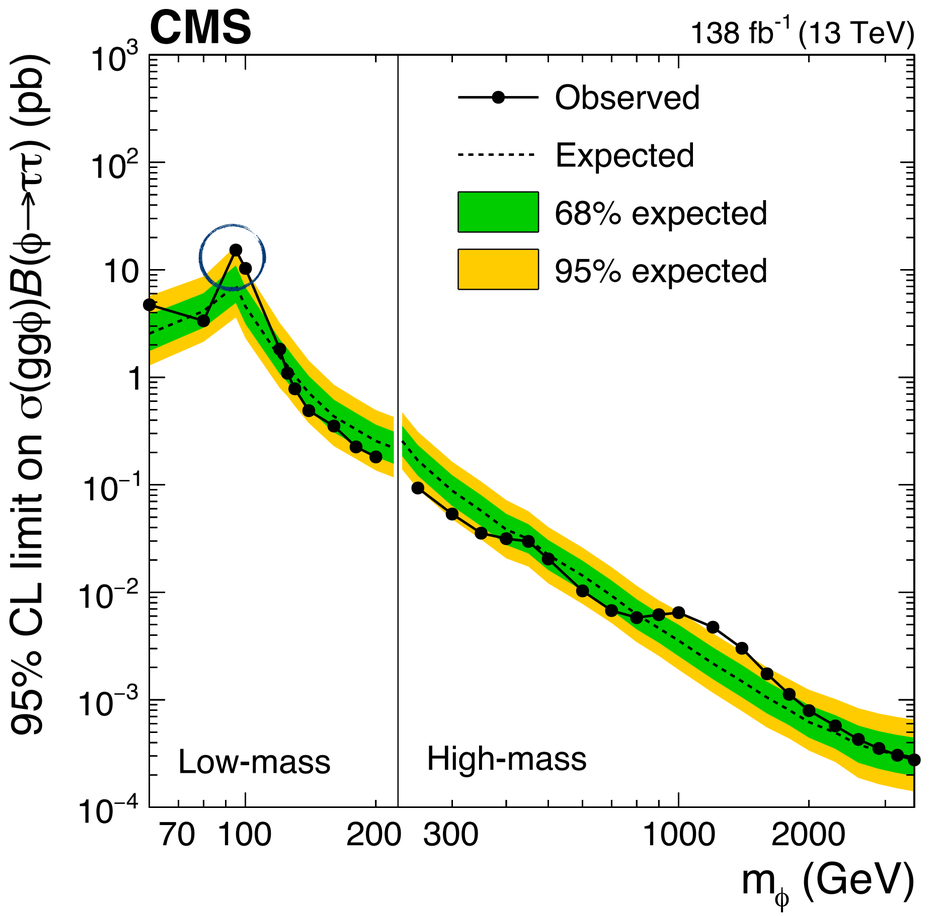

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- Tree-level processes
- Loop-decay into $W, Z, g, \gamma$
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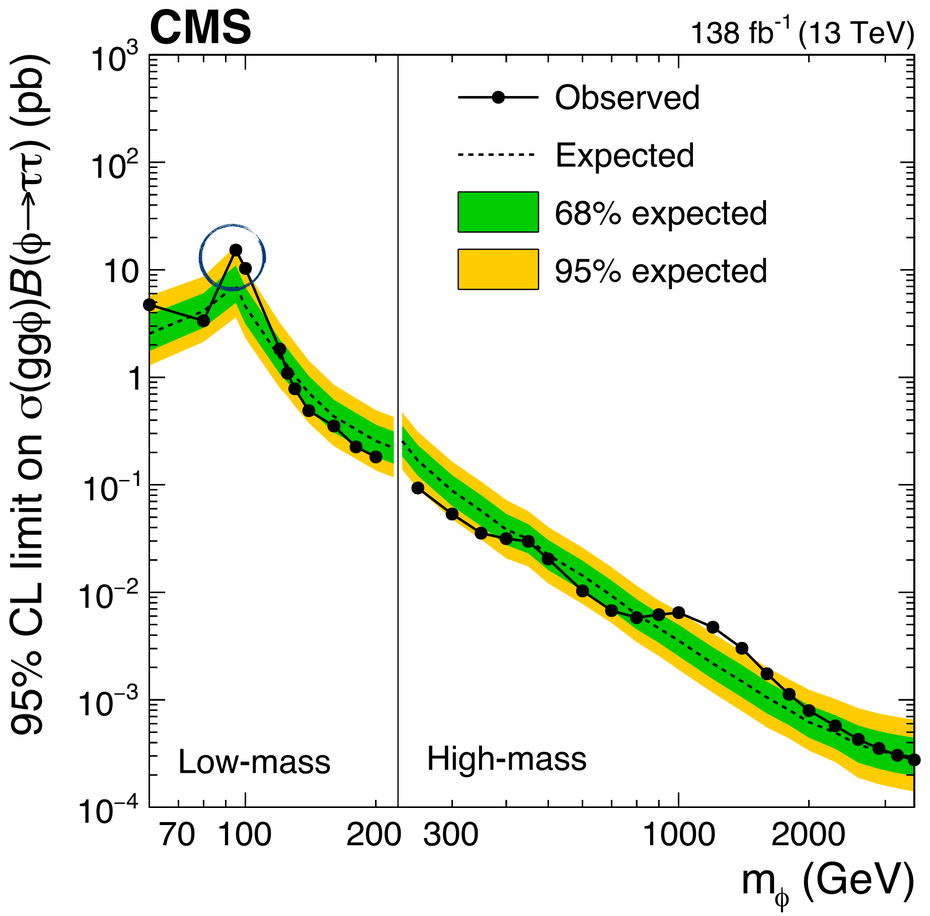
Production dominated by gluon fusion



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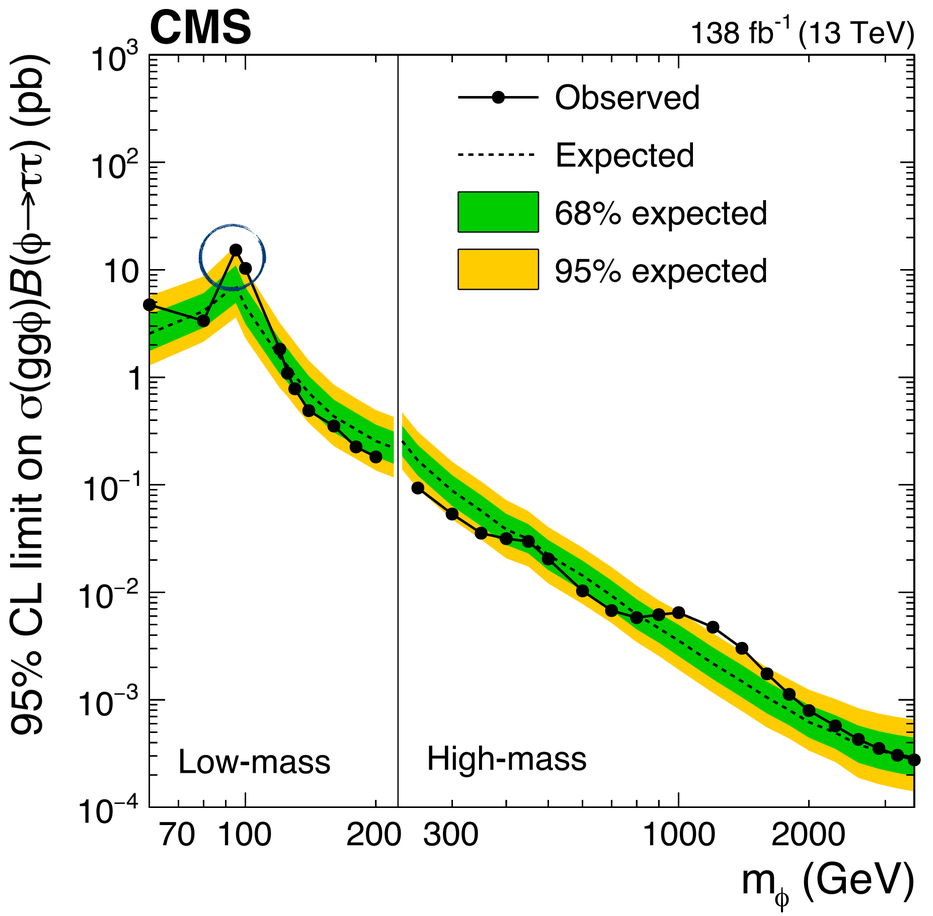


**Relevant couplings from eHEFT:** $\kappa'$, $c'_f$, $c_G$, $c'_T$, $c_V$, $c_{WB}$

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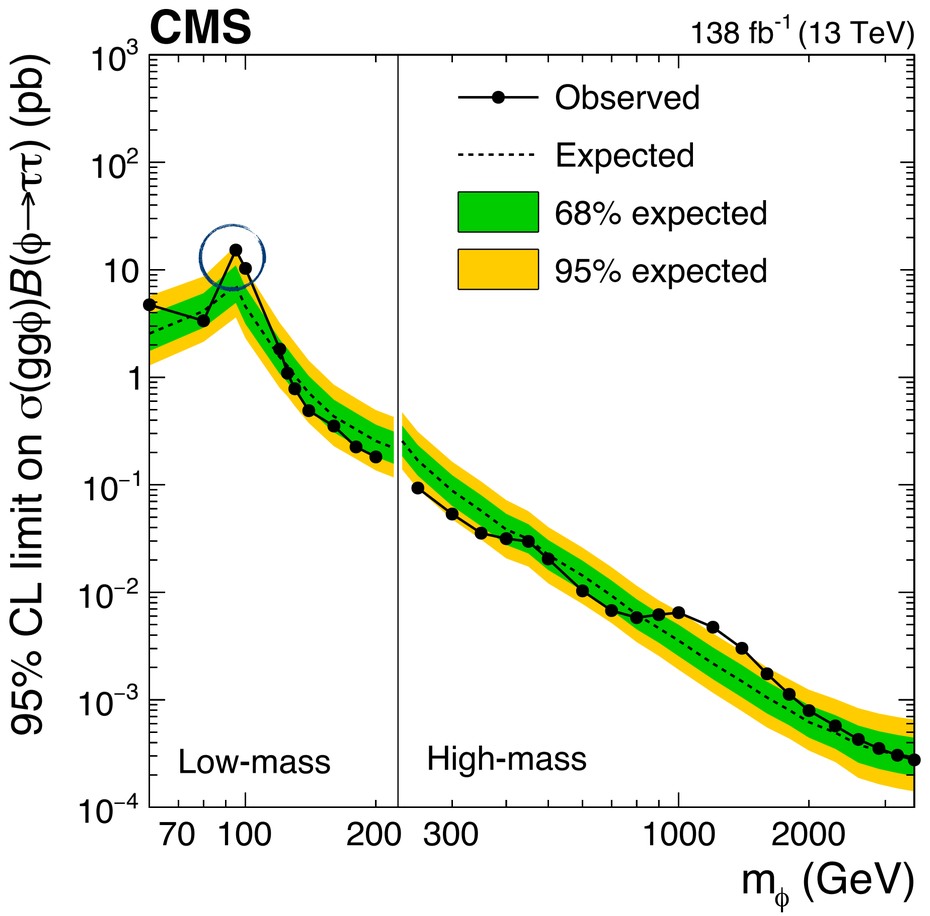
Subdominant



# Best fit

**Three simple coupling structures**

| Universal fermion coupling | Independent quark and lepton couplings | |
|---|---|---|
| | $c'_q, \quad c'_\ell$ | Marginalised |
| $\kappa', \quad c'_f$ | $\kappa' = 0$ | $\kappa' \neq 0$ |

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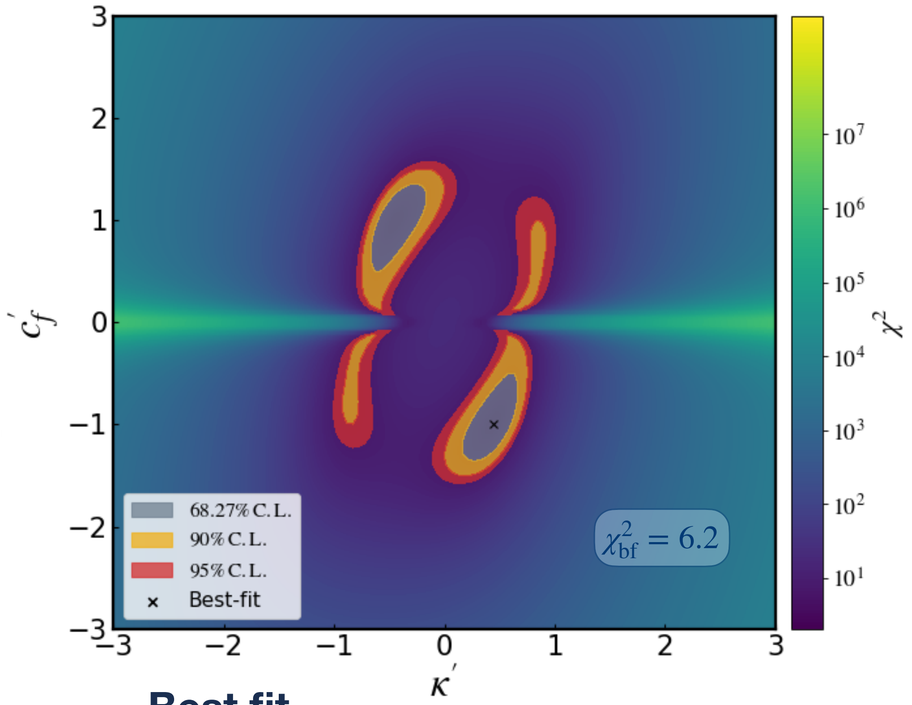
## We performed a $\chi^2$ at different C.L.

$$\chi^2_{\gamma\gamma,\tau\tau,b\bar{b}} = \frac{\left(\mu_{\gamma\gamma,\tau\tau,b\bar{b}} - \mu^{\text{exp}}_{\gamma\gamma,\tau\tau,b\bar{b}}\right)^2}{\left(\Delta\mu^{\text{exp}}_{\gamma\gamma,\tau\tau,b\bar{b}}\right)^2}$$

## Universal fermion coupling

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$$\kappa' = 0.44, \quad c'_f = -0.99$$

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## Three simple coupling structures

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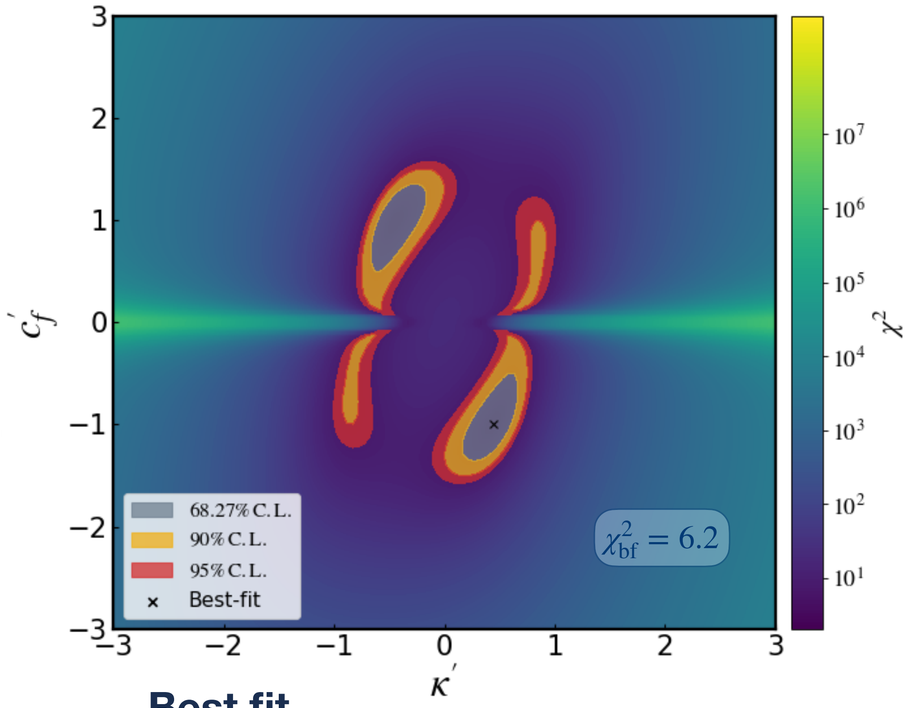
## Universal fermion coupling

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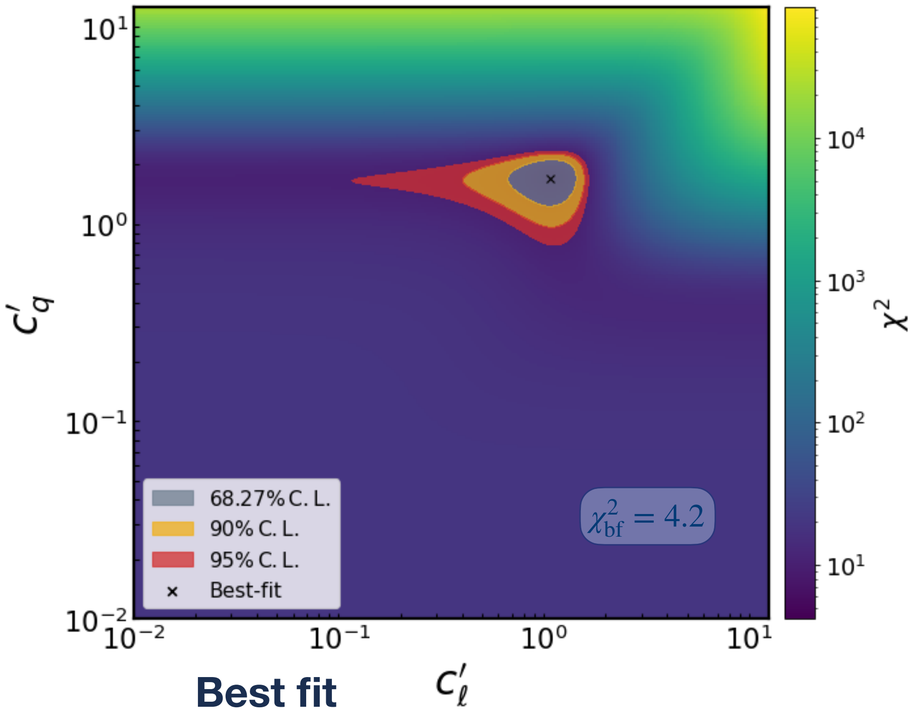
## Quark, lepton and $\kappa' = 0$



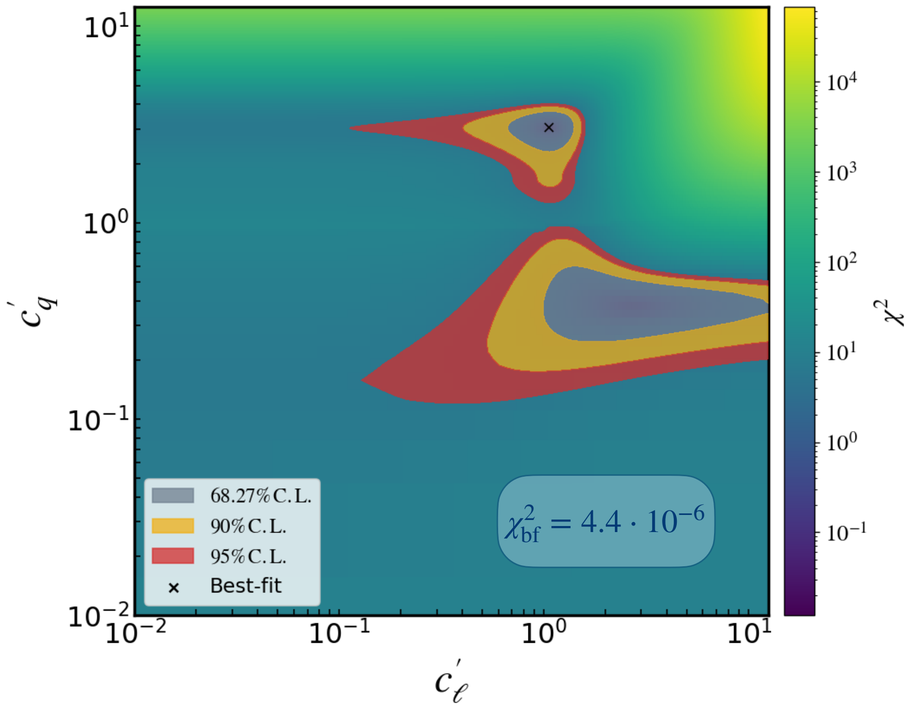

**Best fit**

$c'_q = 1.7, \quad c'_\ell = 1.1$

**The fit prefers a non fully universal fermion coupling**

# Best fit

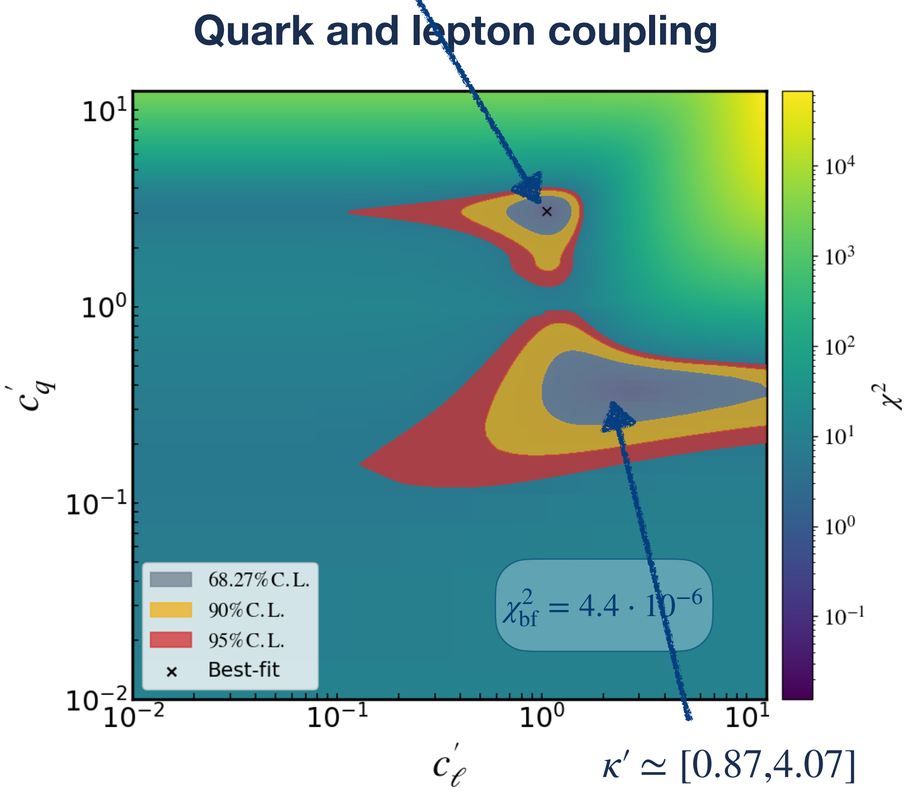
**Quark and lepton coupling**




$$\kappa' = 0.65, \quad c_q' = 3.1, \quad c_\ell' = 1.1$$

# Best fit

$\kappa' \simeq [0.0012, 0.86]$




$\kappa' \simeq [0.87, 4.07]$

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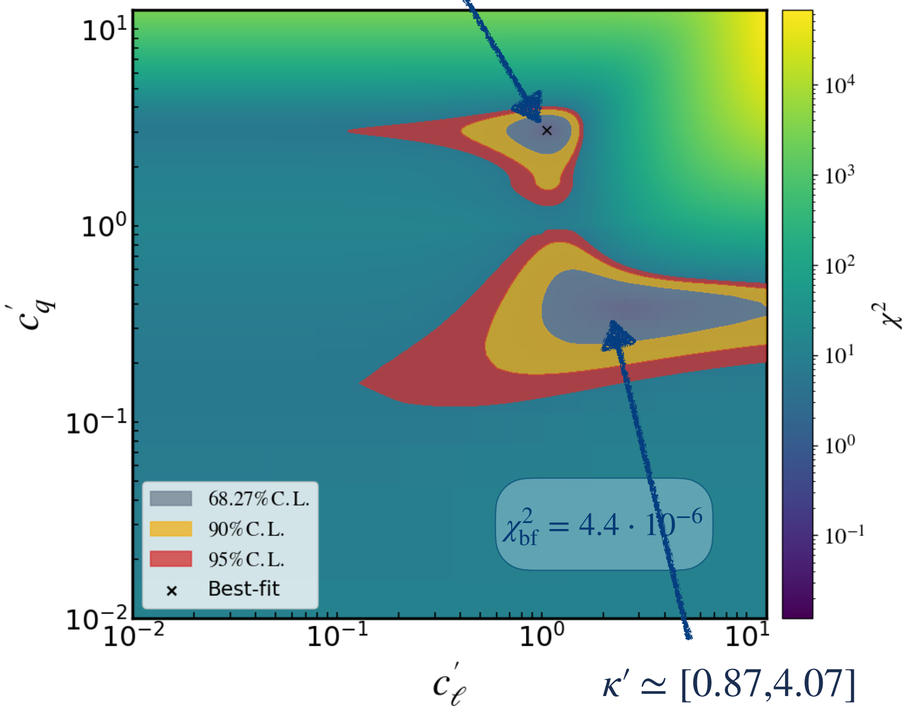
# Best fit

$\kappa' \simeq [0.0012, 0.86]$

**Quark and lepton coupling**

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**Some extra assumptions**

Higher $\kappa'$ leads to less suppressed EFT

At least Dim-5

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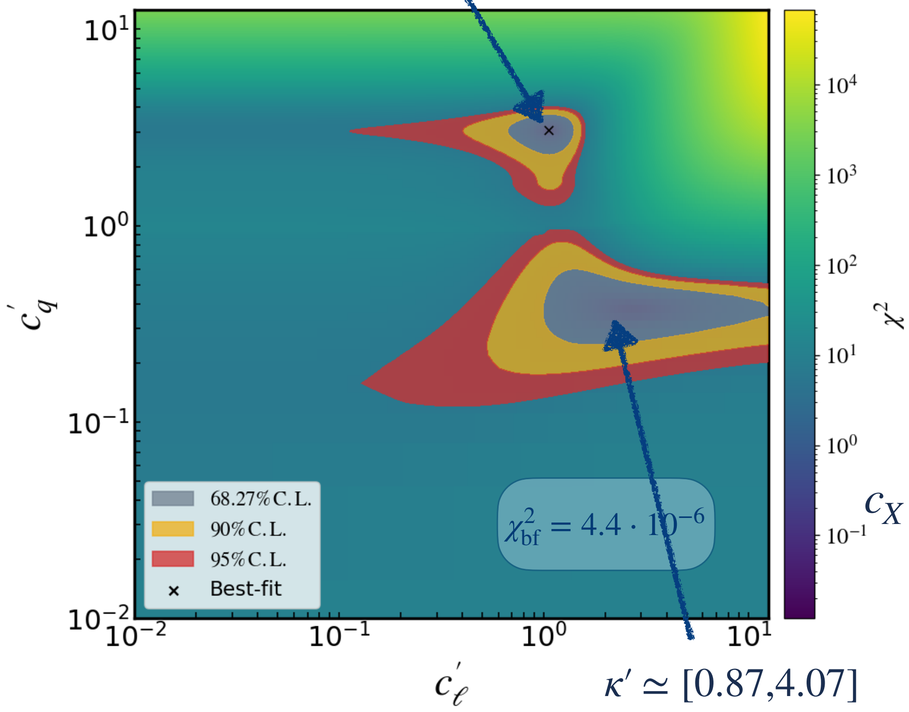


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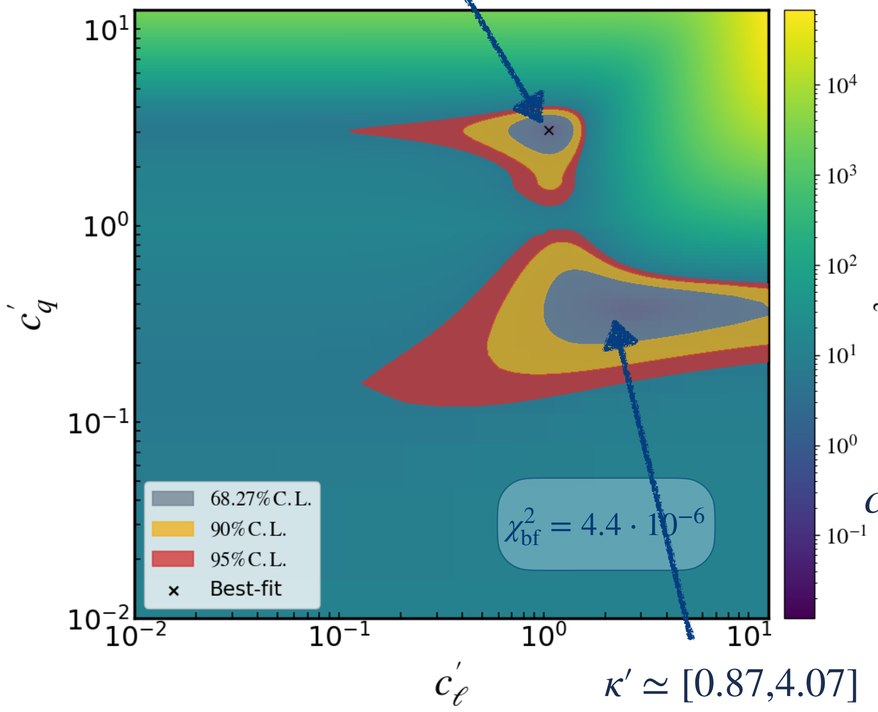


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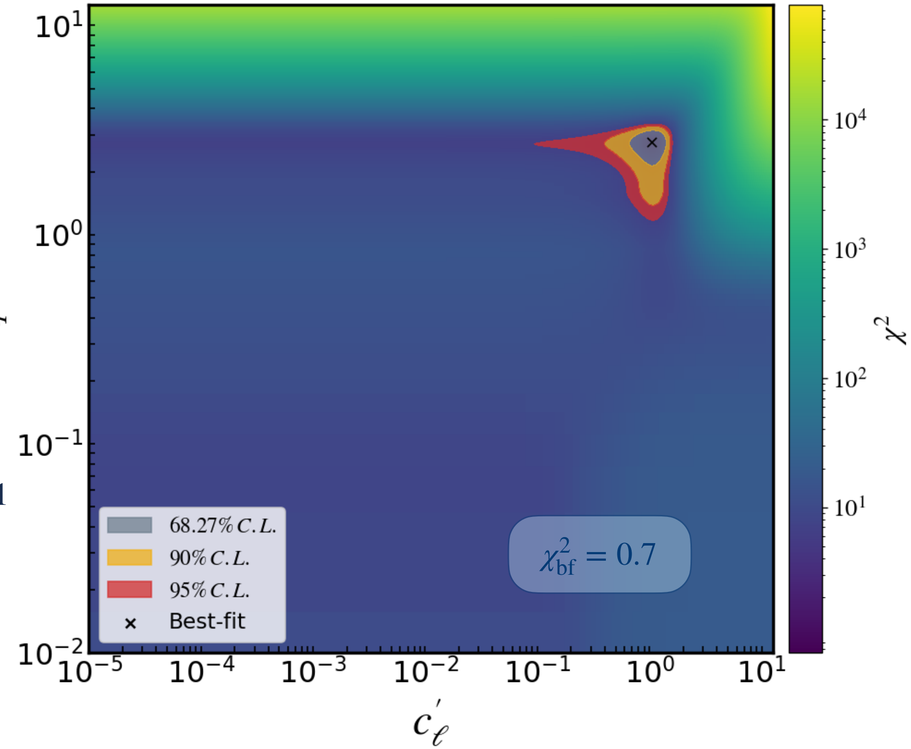
$0 < \kappa' \leq 0.5$ **and** $c_X = 0.24\,\text{TeV}^{-1}$




$\kappa' = 0.5, \quad c_q' = 2.75, \quad c_\ell' = 1.05$

**Preferred sizeable $\kappa'$**

**No relevant effect from $c_X$**

# Specific Model

**The previous fit can give us information about $UV$ models**

For simplicity and clarity we consider:

- Vanishing new $vev$
- No mixing terms $h - \mathcal{S}$
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**Model I**
**Singlet**

$$\lambda \frac{S}{\Lambda} \left( \mathscr{L}^{\text{SM}}_{\text{yuk}} + \mathscr{L}^{\text{SM}}_{\text{gauge}} \right)$$ **Dim-5**

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$$\lambda_\kappa (D_\mu \phi)^\dagger D^\mu \phi \quad \lambda_f \, y_{\text{SM}} \bar{f}_L \phi f_R$$ Dim-4

Due to not $vev$ there is only $\mathcal{S} - \mathcal{S} - V - V$ interaction

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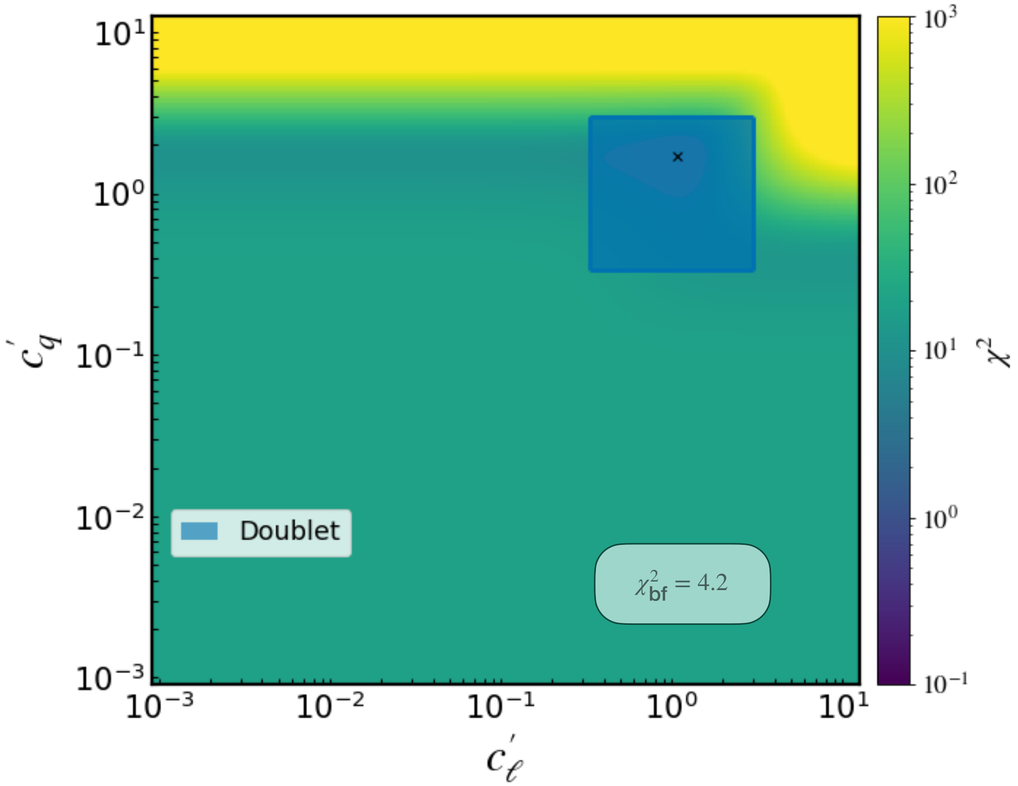
Singlet and triplet lead to a non-zero $\kappa'$ coupling, this give information about the $SU(2)_L$ nature!

# Naturalness region

**Considering a naturalness region for the $UV$ coupling** → $\lambda_i \in \pm [1/3,3]$

**Focusing on the 90% C.L.**

**Doublet like $\kappa' = 0$**

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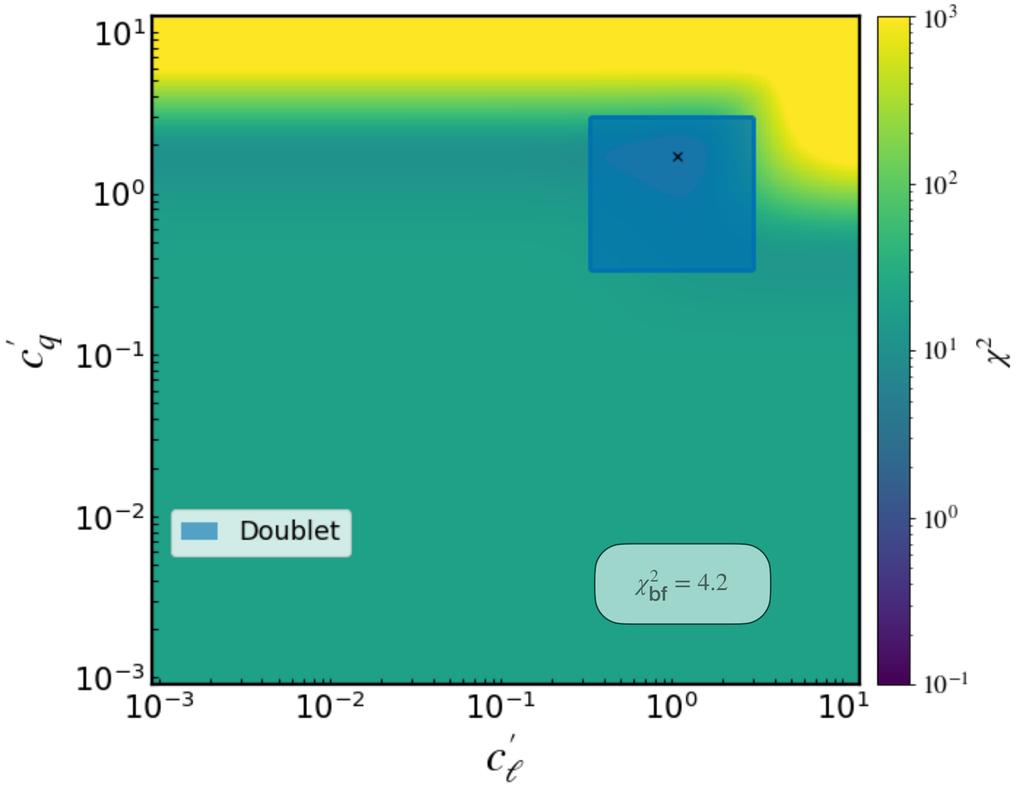
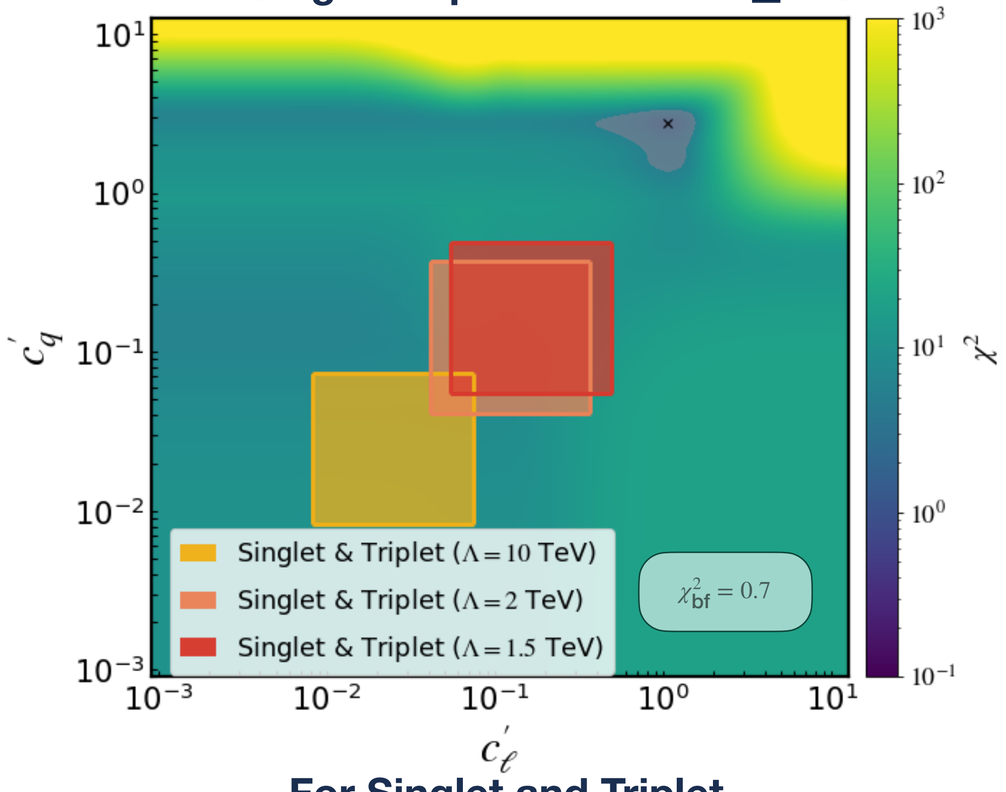



**Doublet can fit the excess but with a higher $\chi^2$**

**Singlet/Triplet like $0 < \kappa' \leq 0.5$**




**For Singlet and Triplet higher coupling or lower scale is preferred**

# Towards new models

**A fairly large value of $\kappa' \sim 0.6$ is preferred to match the 95 GeV excess.**

For a **singlet/triplet** toy models with $\langle S \rangle = 0 \longrightarrow \kappa' = \mathcal{O}(1)\frac{v}{\Lambda} \longrightarrow$ either $\lambda > \mathcal{O}(1)$ or low $\Lambda$

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For a **doublet** one can obtain $\kappa' \sim 0.6$ keeping $\Lambda$ low by generating it by a marginal operator and a new vev

$$\kappa' \propto \frac{v_{\text{new}}}{v}$$

Leading to different scaling for different multiplets:

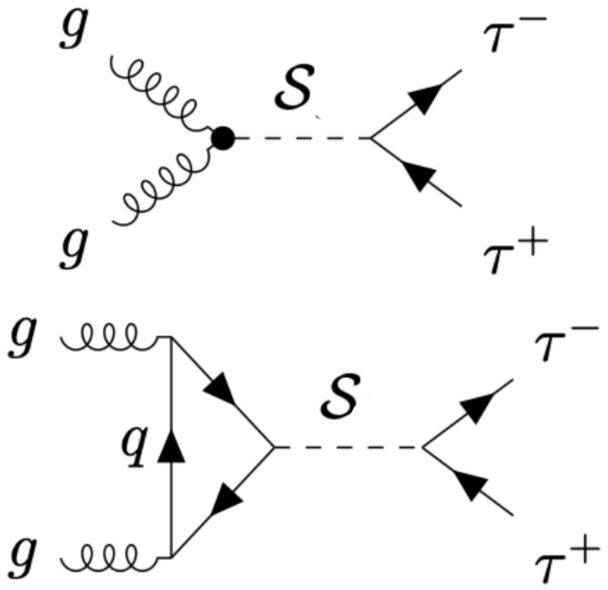
$$(\kappa')^{\text{doublet}} \sim \frac{2v_{\text{new}}}{v}, \quad (\kappa')^{\text{trip}} \sim \frac{4v_{\text{new}}}{v}, \quad \ldots \xrightarrow{\kappa' \sim 0.6} (v_{\text{new}})^{\text{doublet}} \simeq 0.3v, \quad (v_{\text{new}})^{\text{doublet}} \simeq 0.15v$$

However, one must be careful with EWPO effects from $c_T$

**Sizeable $\kappa'$ points to either an electroweak charged scalar with a new vev, or a singlet with low $\Lambda$ or large $\lambda_i$**

# Other mass range

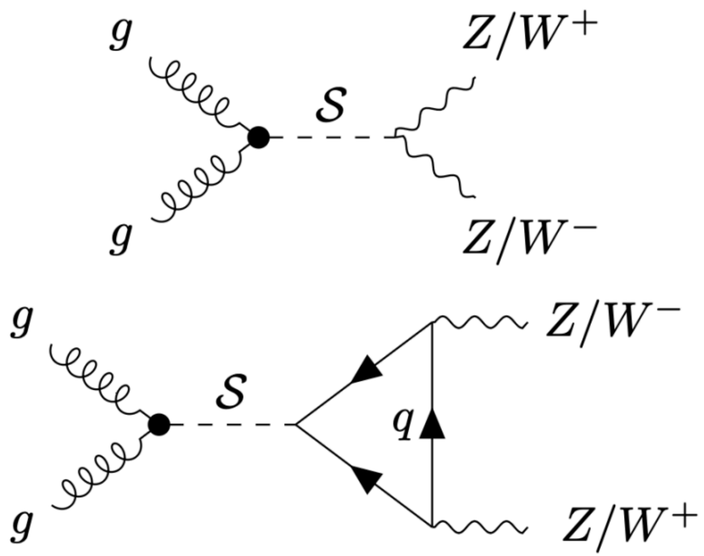
**Potentially interesting collider signals**




**$\tau$-pair production**

Probes coupling to fermions, fairly clear signal

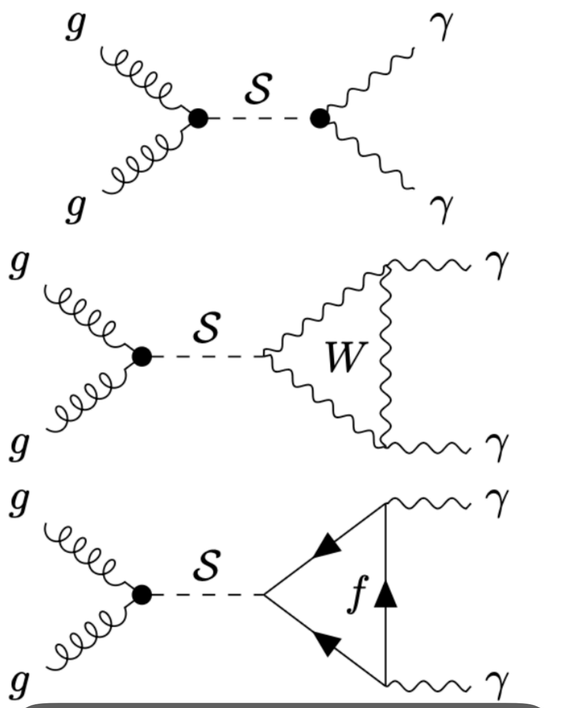
+ $q$-loop production




**Di-boson resonance**

Probes coupling to gauge bosons

+ $q$-loop production




**Decay into photons**

Probes interplay of coupling to fermions and gauge bosons

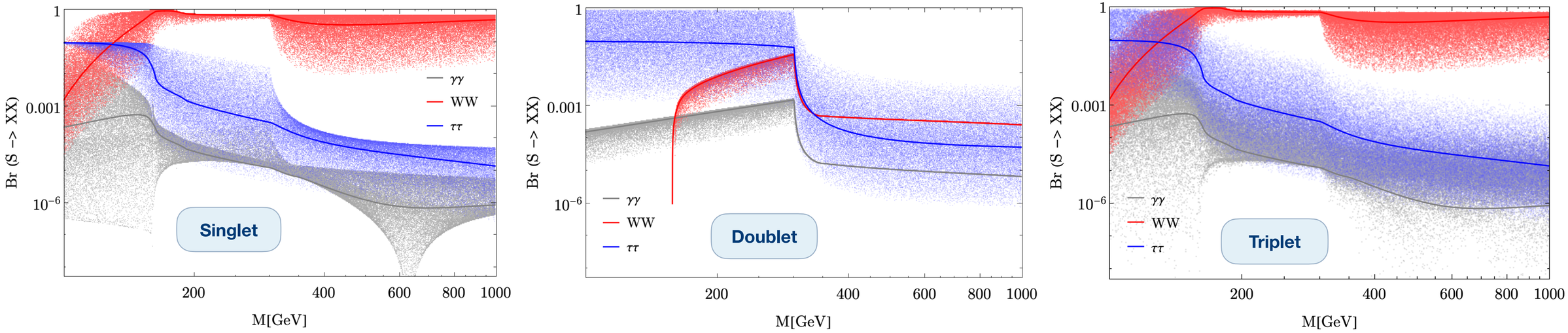
# Other mass range

**What can we expect for other resonances at higher masses?**

Line indicates $\lambda_i = 1$

$M \in [100,1000]\,\mathrm{GeV}, \quad \lambda_i \in \pm\,[1/3,3]$

100000 points




**Low-masses:** scalar with decays into gauge bosons dominating over $\tau$ is not well described unlikely to be a doublet

**High-masses:** scalar with gauge-boson decays subdominant to $\tau$ is disfavoured in Singlet and Triplet

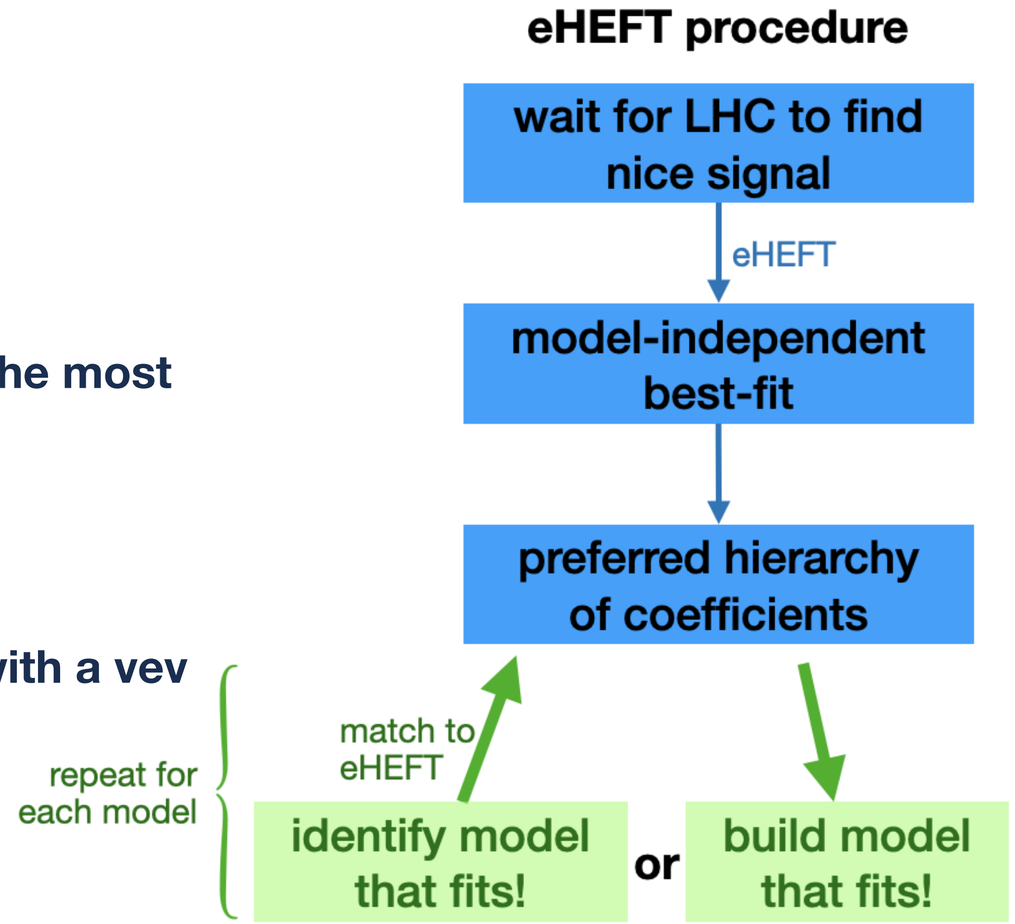
# Conclusions

**The framework**

- Consistent and LHC friendly
- Model independent and economic
- With symmetries and power counting helps to understand the most promising $SU(2)_L$ structure

**Applicability**

- The 95 GeV excess prefer an electroweak charged scalar with a vev
- Beyond the 95 GeV example, ratios $\gamma\gamma$, $WW$, $\tau\tau$ can help distinguish singlet/doublet/triplet



# Thank you!

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GÖTTINGEN IN PUBLICA COMMODA SEIT 1737

# Characterizing LHC-Resonances in Extended HEFT

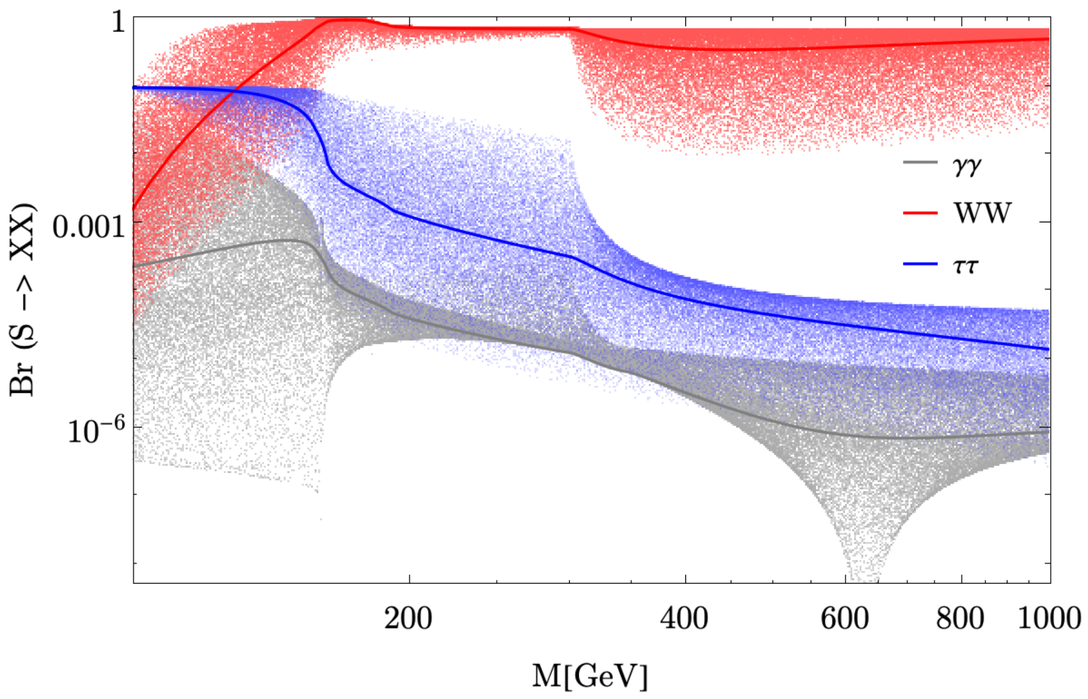
David Cabo-Almeida

Based on arXiv: 2512.11764

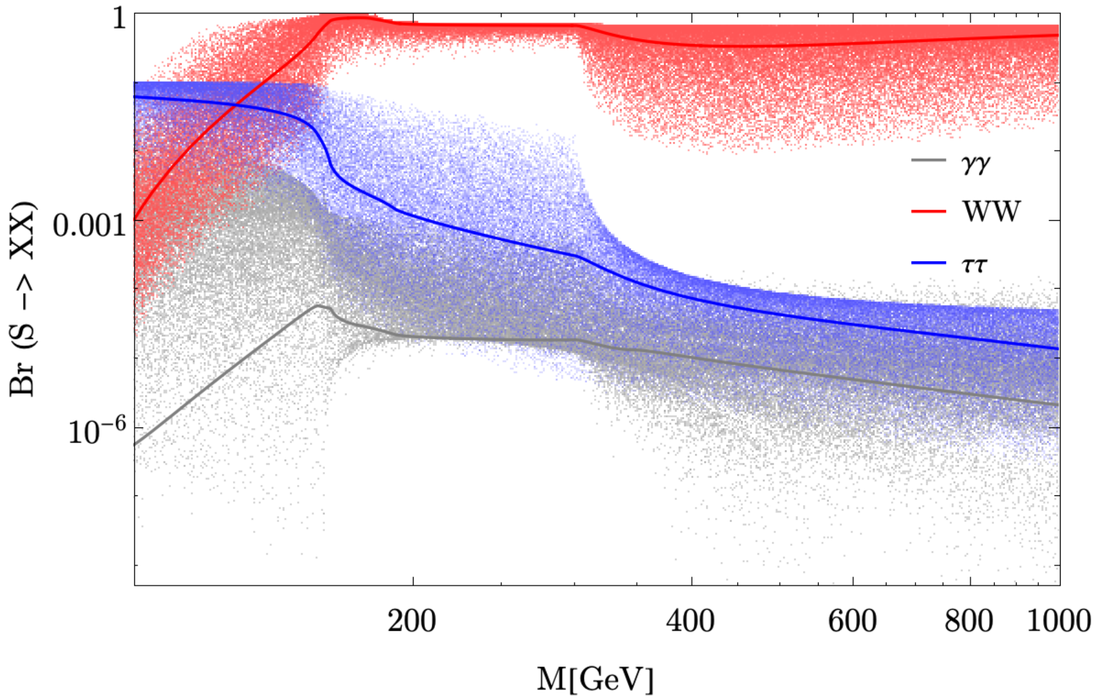
In collaboration with:
Giorgio Arcadi, Florian Goertz and Maya Hager

# Back-up

# Branching ratio cancellation




$\lambda_X, \lambda_{c_T} = 0$




$\lambda_X, \lambda_{c_T} = \mathcal{O}(1)$

- Coupling to FST ⟶ lifts destructive interference between top and W loop for decay into photons
- Expect decay into gauge bosons to dominate if new scalar has large mass

# Expected CP-odd

**Model I Singlet**

$$\kappa'_{(\mathrm{I})_{\mathrm{ps}}} = 0, \quad \left(c'_{q,\ell}\right)_{(\mathrm{I})_{\mathrm{ps}}} = \lambda_{q,\ell}\frac{v}{\Lambda}, \quad \left(\tilde{c}_X\right)_{(\mathrm{I})_{\mathrm{ps}}} = \lambda_X\frac{1}{\Lambda}, \quad \left(c'_T\right)_{(\mathrm{I})_{\mathrm{ps}}} = 0,$$

**Model II Doublet**

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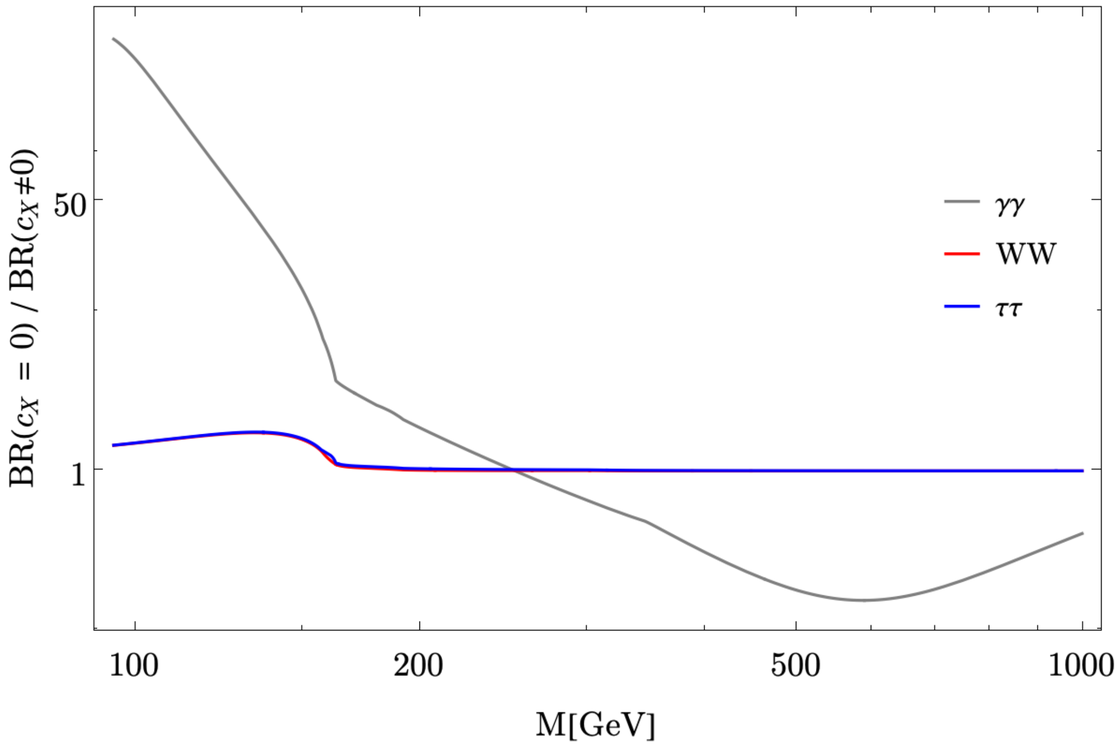
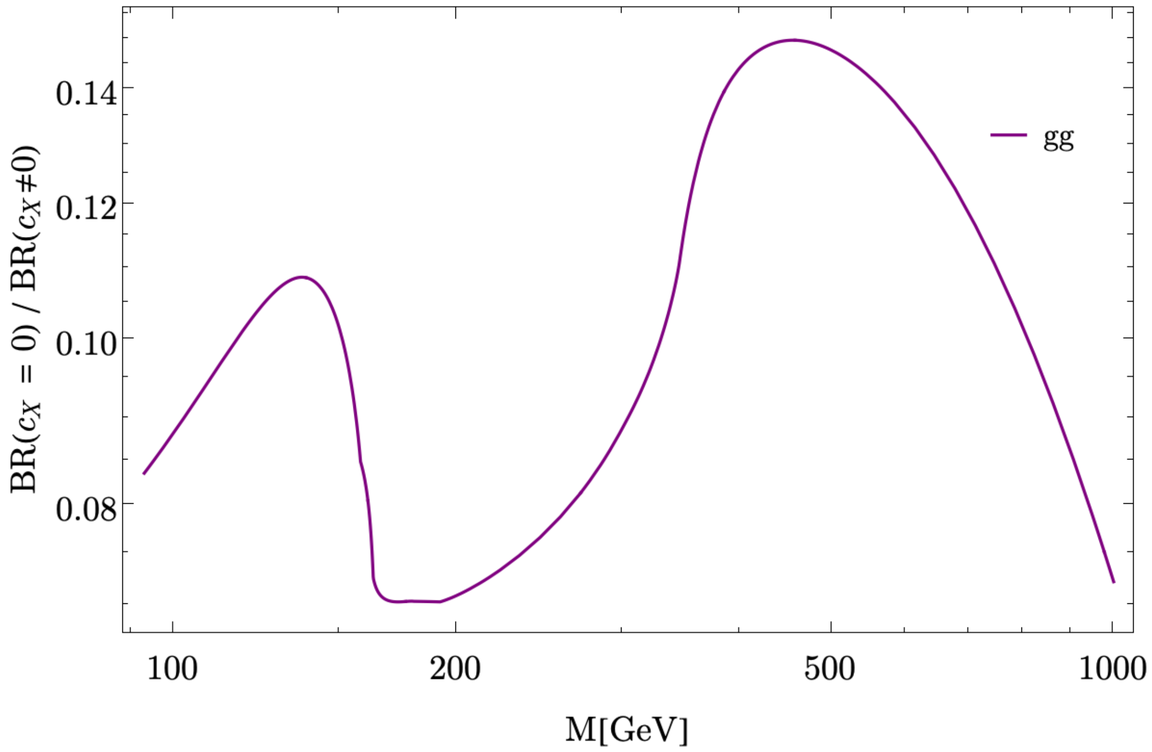
**Model III Triplet**

$$\kappa'_{(\mathrm{III})'_{\mathrm{ps}}} = 0, \quad \left(c'_{q,\ell}\right)_{(\mathrm{III})_{\mathrm{ps}}} = \lambda_{q,\ell}\frac{v}{\Lambda}, \quad \left(\tilde{c}_{WB}\right)_{(\mathrm{III})_{\mathrm{ps}}} = \frac{\lambda_{WB}}{\Lambda}, \quad \left(\tilde{c}_X^{\mathrm{rest}}\right)_{(\mathrm{III})_{\mathrm{ps}}} = 0, \quad \left(c'_T\right)_{(\mathrm{III})_{\mathrm{ps}}} = 0.$$

# Chiral dimension 4 operators

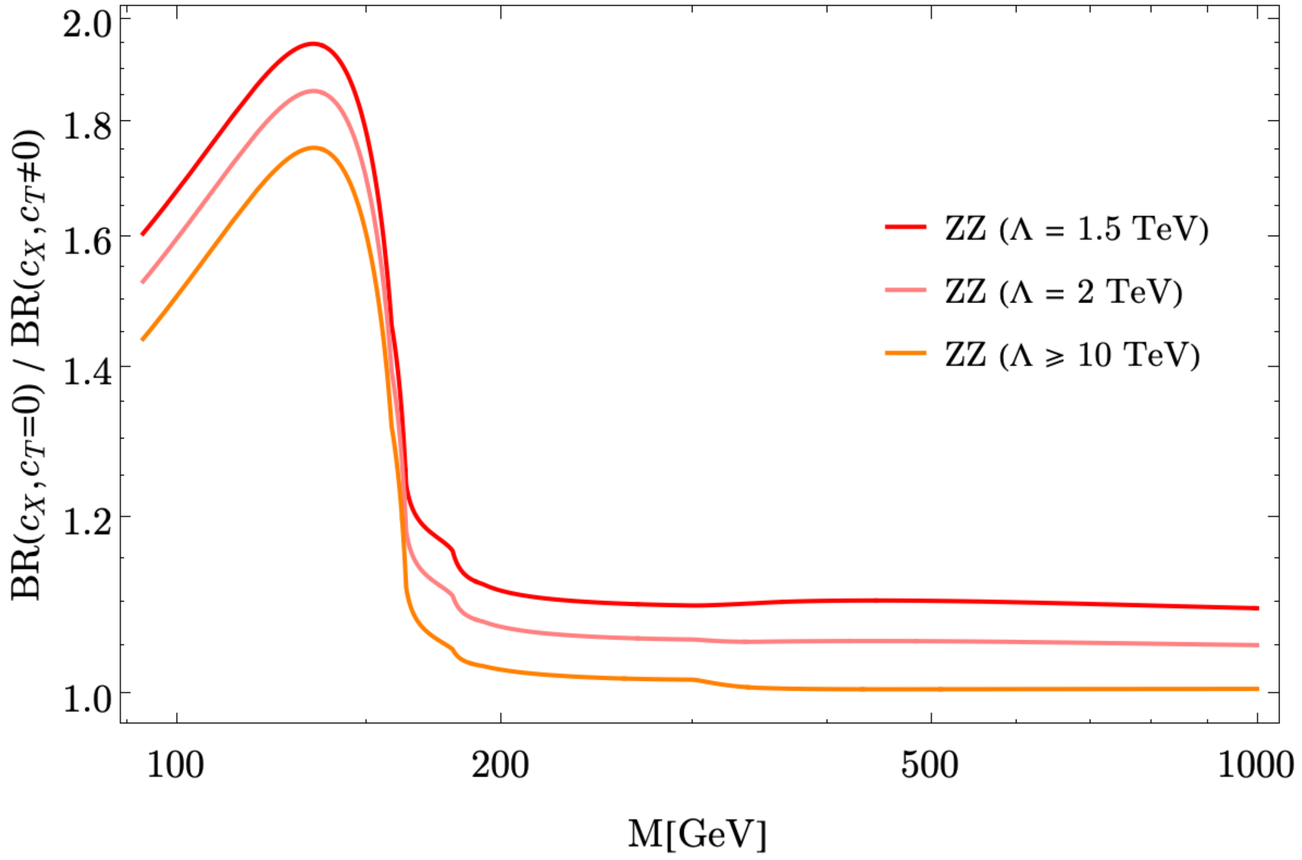



**Important for decay**

**Important for production**

# ZZ effect


2.0
1.8
1.6
1.4
1.2
1.0
BR($c_X$, $c_T$=0) / BR($c_X$, $c_T$≠0)
100
200
500
1000
M[GeV]
ZZ (Λ = 1.5 TeV)
ZZ (Λ = 2 TeV)
ZZ (Λ ⩾ 10 TeV)