MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

# CHARACTERISING NEW RESONANCES AT THE LHC IN EFT

## Hints about SU(2) nature in extended scalar sectors


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**based on 2510.XXXX**

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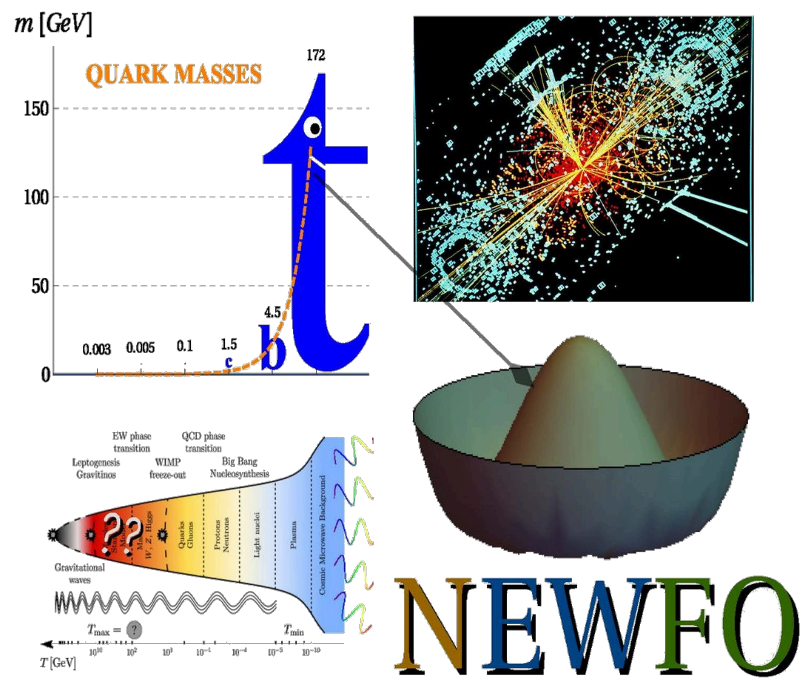
**DESY Workshop**

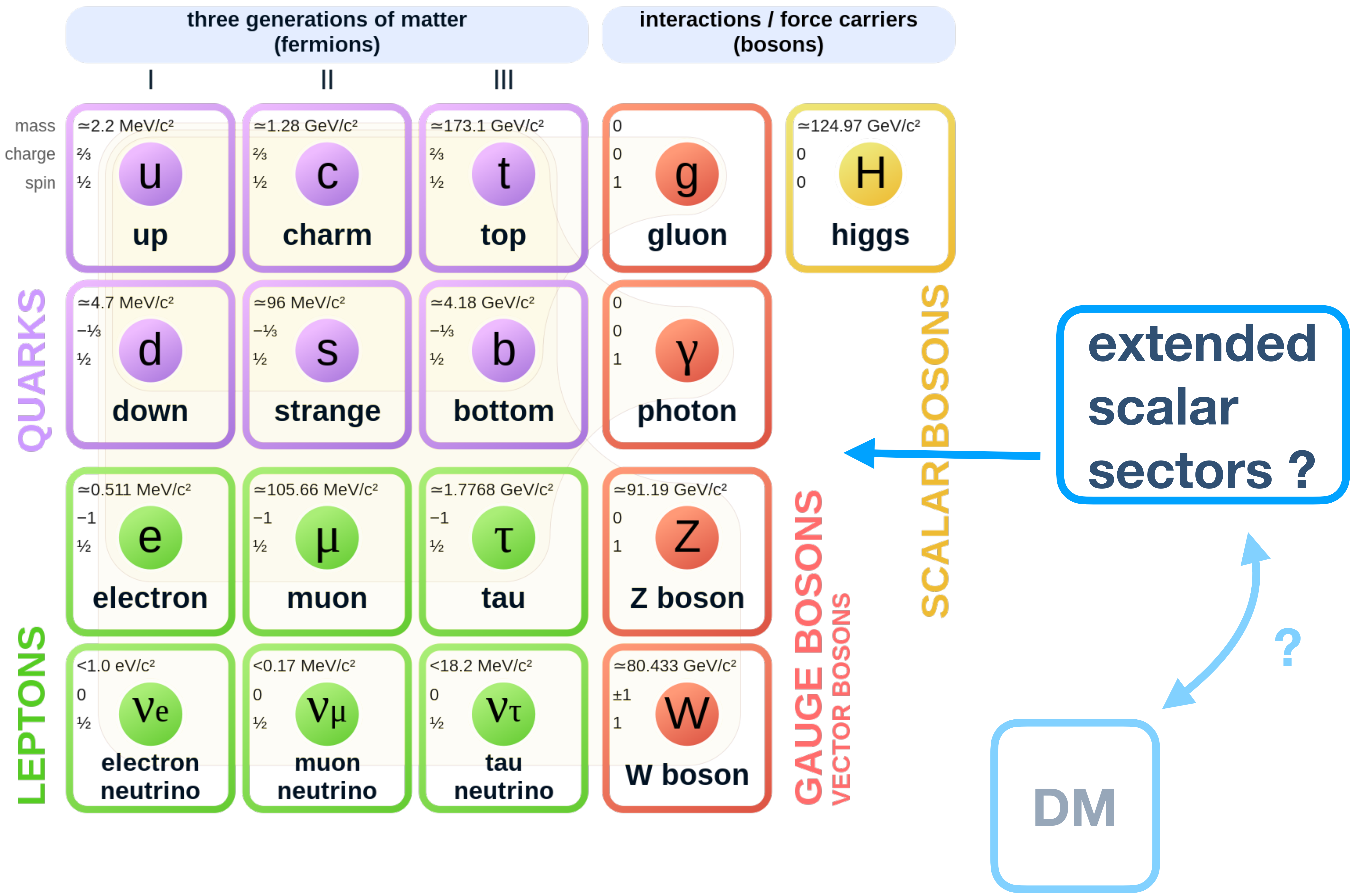


# Content…

## …of my talk:

- Framework
- Step-By-Step Guide
- Example: 95 GeV Resonance
- Outlook to Other Masses
- Conclusion

## …of the Standard Model:



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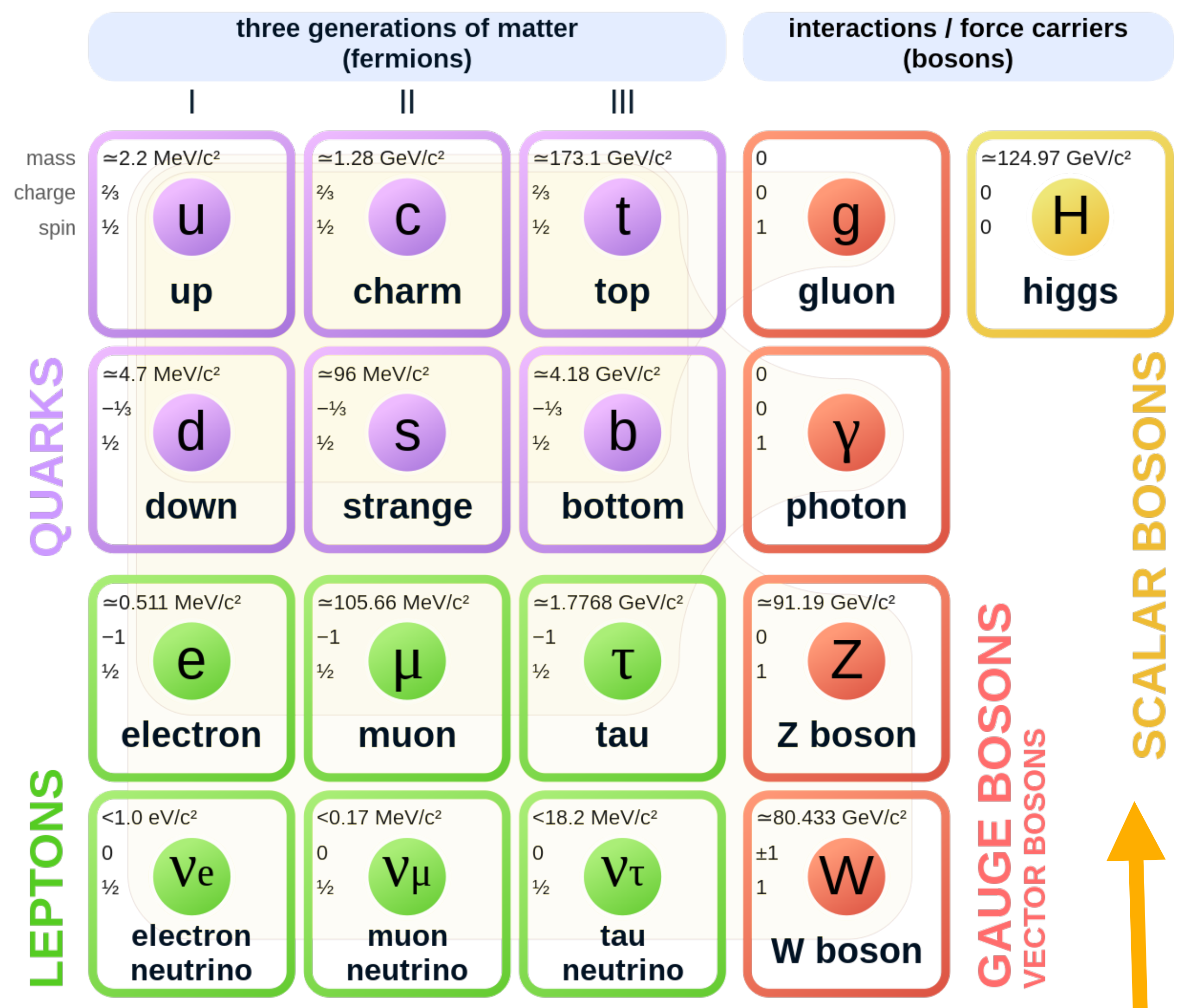
Framework:

# Generalised HEFT

non-linearly realised EW symmetry

HEFT ⊃ SMEFT

### Standard Model of Elementary Particles




**extended scalar sectors ?**

for connection to DM, see

2411.05914 Arcadi, Cabo-Almeida, Fabian, Goertz

leading operators:

$$\mathcal{L} \supset \frac{1}{2}\sum_{\phi=\mathcal{S},h} \partial_\mu\phi\,\partial^\mu\phi - \mathcal{O}_5^\lambda + \frac{v^2}{4}\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger (D^\mu\Sigma)\right]\mathcal{O}_3^\kappa$$

W, Z

$$- \frac{v}{\sqrt{2}}\left( \left(\overline{u_{i,L}}\ \overline{d_{i,L}}\right)\Sigma \begin{pmatrix} Y^u_{ij}u_{j,R}\\ Y^d_{ij}d_{j,R}\end{pmatrix}\mathcal{O}_2^{c_q} + \left(\overline{\nu_{i,L}}\ \overline{\ell_{i,L}}\right)\Sigma\,\frac{1-\sigma_3}{2}Y^\ell_{ij}\begin{pmatrix}\nu_{j,R}\\ \ell_{j,R}\end{pmatrix}\mathcal{O}_2^{c_\ell} + \text{h.c.}\right)$$

quarks

leptons

$$-\sum_{\phi=\mathcal{S},h}\frac{\phi}{16\pi^2}\left[g'^2 c_B^\phi B^{\mu\nu}B_{\mu\nu} + g^2 c_W^\phi W^{I\mu\nu}W^I_{\mu\nu} + g_s^2 c_G^\phi G^{a\mu\nu}G^a_{\mu\nu}\right]$$

W, Z, $\gamma$, g

$$+ \dots$$

$$\mathcal{O}_d^C \equiv \mathcal{O}_d^C(h,\mathcal{S}) \equiv \sum_{i=0}^{d}\sum_{j=0}^{i-j} C^{(i)}_{i-j}\, h^i \mathcal{S}^{i-j}$$

Higgs, new (light) scalar

EW Goldstone bosons in Goldstone matrix

$$\Sigma(x) = e^{i\sigma^j G^j(x)/v}$$

$$D_\mu\Sigma \equiv \partial_\mu\Sigma - i\frac{g}{2}\sigma^a W^a_\mu\Sigma + i\frac{g'}{2}B_\mu\Sigma\sigma^3$$



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# Step-By-Step Guide

let LHC find signal → (generalised HEFT) → model-independent best-fit → preferred hierarchy of coefficients

→ hints about at which order operators should arise

↔ SU(2) nature

# Step-By-Step Guide

let LHC find signal → (generalised HEFT) → model-independent best-fit → preferred hierarchy of coefficients

your favourite models

generalised HEFT ↓

identify operator scaling

$\Lambda_{NP}$ ↓

„naturalness region“

**constrain models!**

hints about at which order operators should arise

↔

**SU(2) nature**

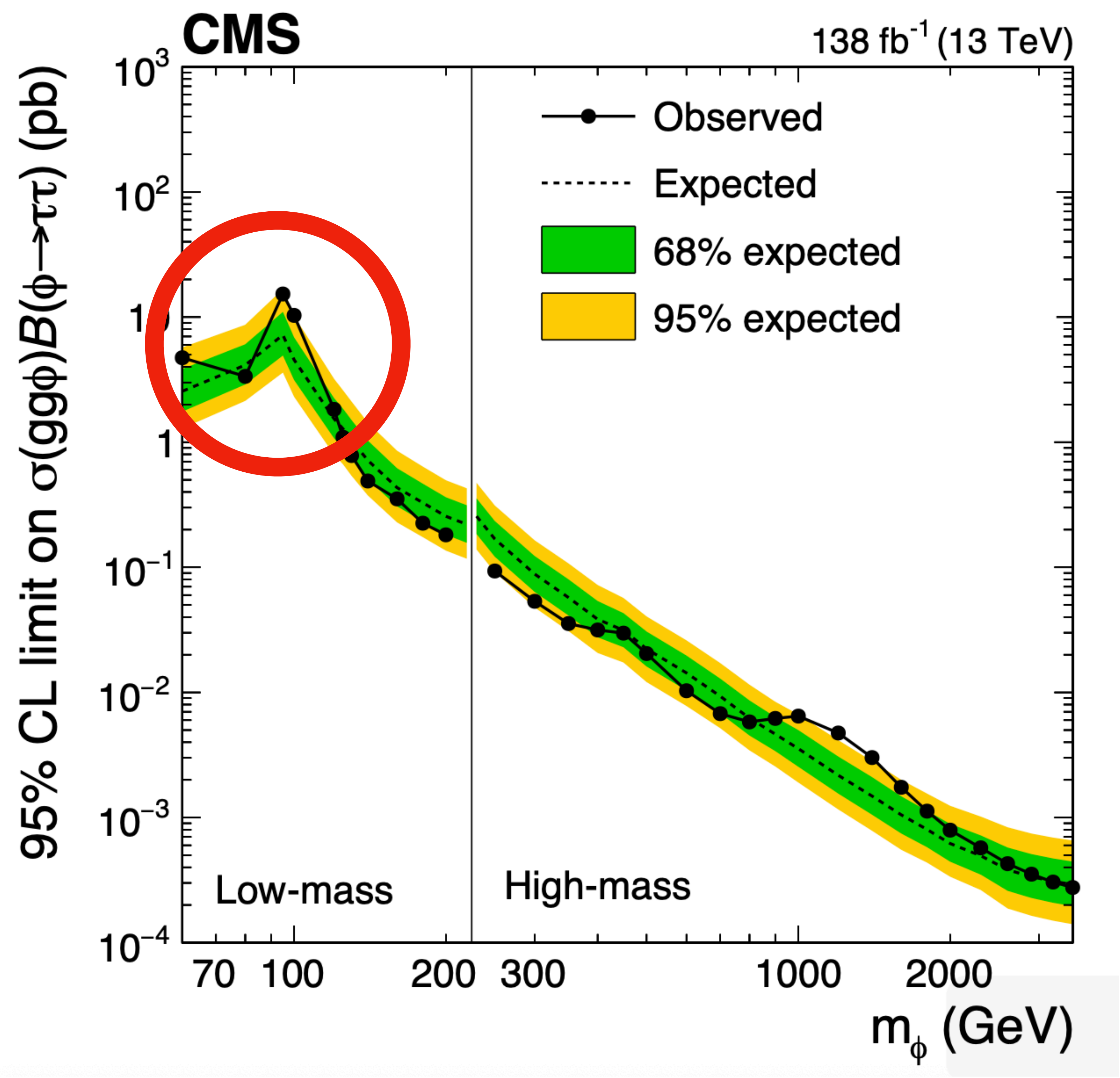
Toy Example:

# 95 GeV Resonance

signal strength
$$\mu = \frac{\sigma_{\text{new}}}{\sigma_{\text{SM}}} \times \frac{BR_{\text{new}}}{BR_{\text{SM}}}$$

- di-tau $\mu_{\tau\tau} = 1.22^{+0.62}_{-0.48}$ 2208.02717 →
- di-bottom $\mu_{bb} = 0.117 \pm 0.06$ 1612.08522
- di-photon $\mu_{\gamma\gamma} = 0.24^{+0.09}_{-0.08}$ 1811.08459

in analysis:
consider **90% C.L. (1.64 $\sigma$)** to avoid compatibility with 0



we consider:

FeynRules + Djouabi (2005)

- ✓ tree-level processes
- ✓ loop-decay into $W, Z, g, \gamma$
- ✓ off-shell decay into $WW^*, ZZ^*$

production dominated by gluon fusion

di-photon channel: VBF, VH included

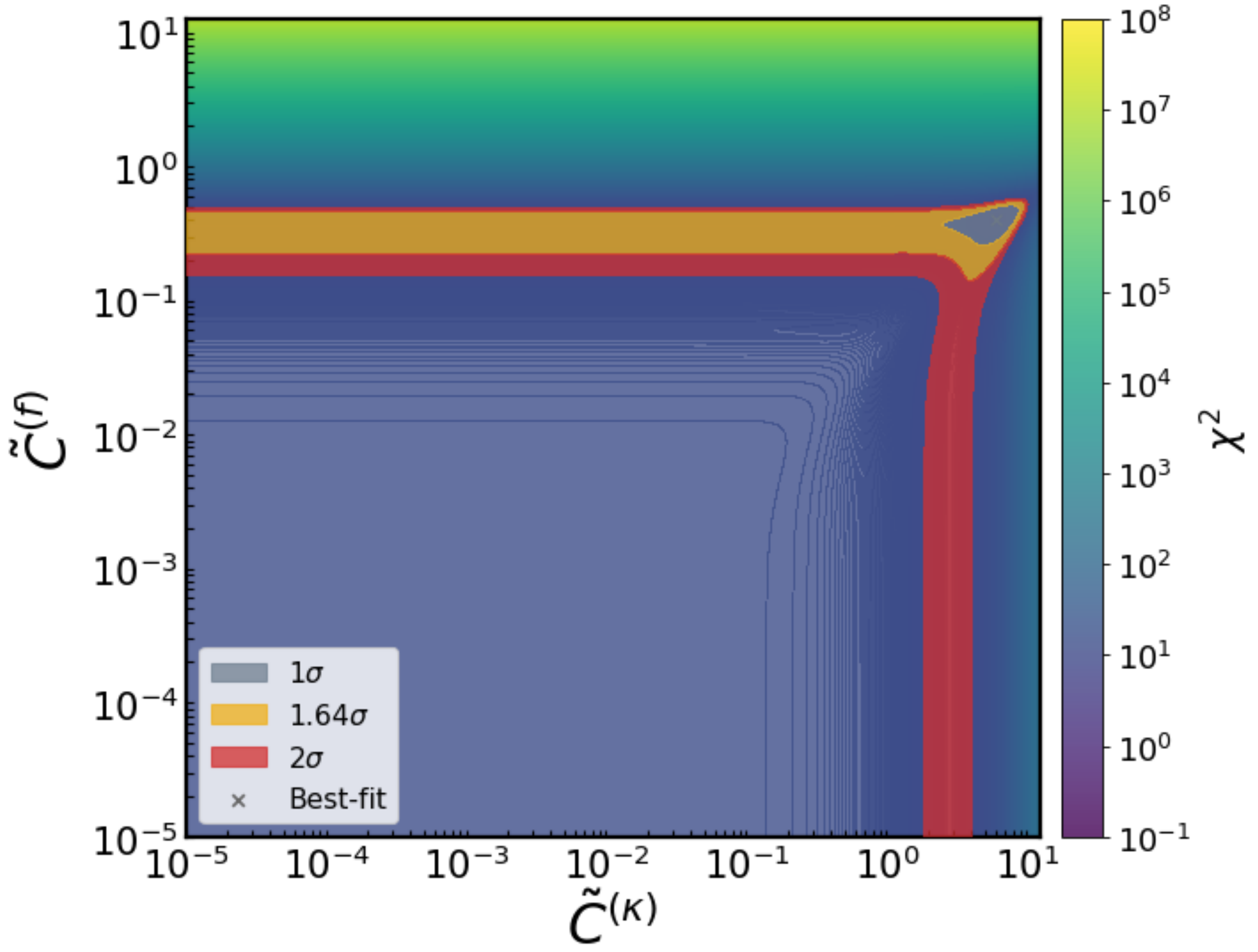
# Best Fit

preliminary

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

- scale-dependence absorbed into coefficients → no assumptions during analysis!
- universal fermion coupling $\tilde{c}_f$ vs gauge boson coupling $\tilde{c}_\kappa$
- best fit for $\tilde{c}_f \sim 0.4$ and $\tilde{c}_\kappa \sim 6.1$ (but at 90% C.L. compatible with $\tilde{c}_\kappa \to 0$)

$\chi^2 = 5.1$



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$\lambda \sim \mathcal{O}(1)$ parameter
$\Lambda$: NP scale

(absorption of factors of v into coefficients to make them dimensionless)

# Scaling Examples

**for simplicity & clarity: no vevs, no mixings**

## Singlet

dim-5

$$\lambda \frac{S}{\Lambda} \times \left( \mathcal{L}^{\text{SM}}_{\text{yuk}} + \mathcal{L}^{\text{SM}}_{\text{gauge}} \right)$$

+ loops

$W, Z$ $\quad \tilde{c}_\kappa \sim \lambda \frac{v}{\Lambda}$

quarks, leptons $\quad \tilde{c}_f \sim \lambda \frac{v}{\Lambda}$

$W, Z, \gamma, g$ $\quad \tilde{c}_X \sim \frac{\lambda}{16\pi^2} \frac{1}{\Lambda}$

(for now $\to 0$)

## Doublet

dim-4

Yukawa $\lambda \times y_{SM} \overline{f_L} S f_R$

+ loops

processes with **one** S decaying

$$\tilde{c}_\kappa = 0$$
$$\tilde{c}_f \sim \lambda$$
$$\tilde{c}_X = 0$$

## Triplet

$\overset{H}{2} \otimes \overset{f_L}{2} = 3 \oplus 1$

dim-5

Yukawa $\lambda \frac{v}{\Lambda} \times y_{SM} \overline{f_L} S f_R$

+ loops

processes with **one** S decaying

$$\tilde{c}_\kappa = 0$$
$$\tilde{c}_f \sim \lambda \frac{v}{\Lambda}$$
$$\tilde{c}_X = 0$$



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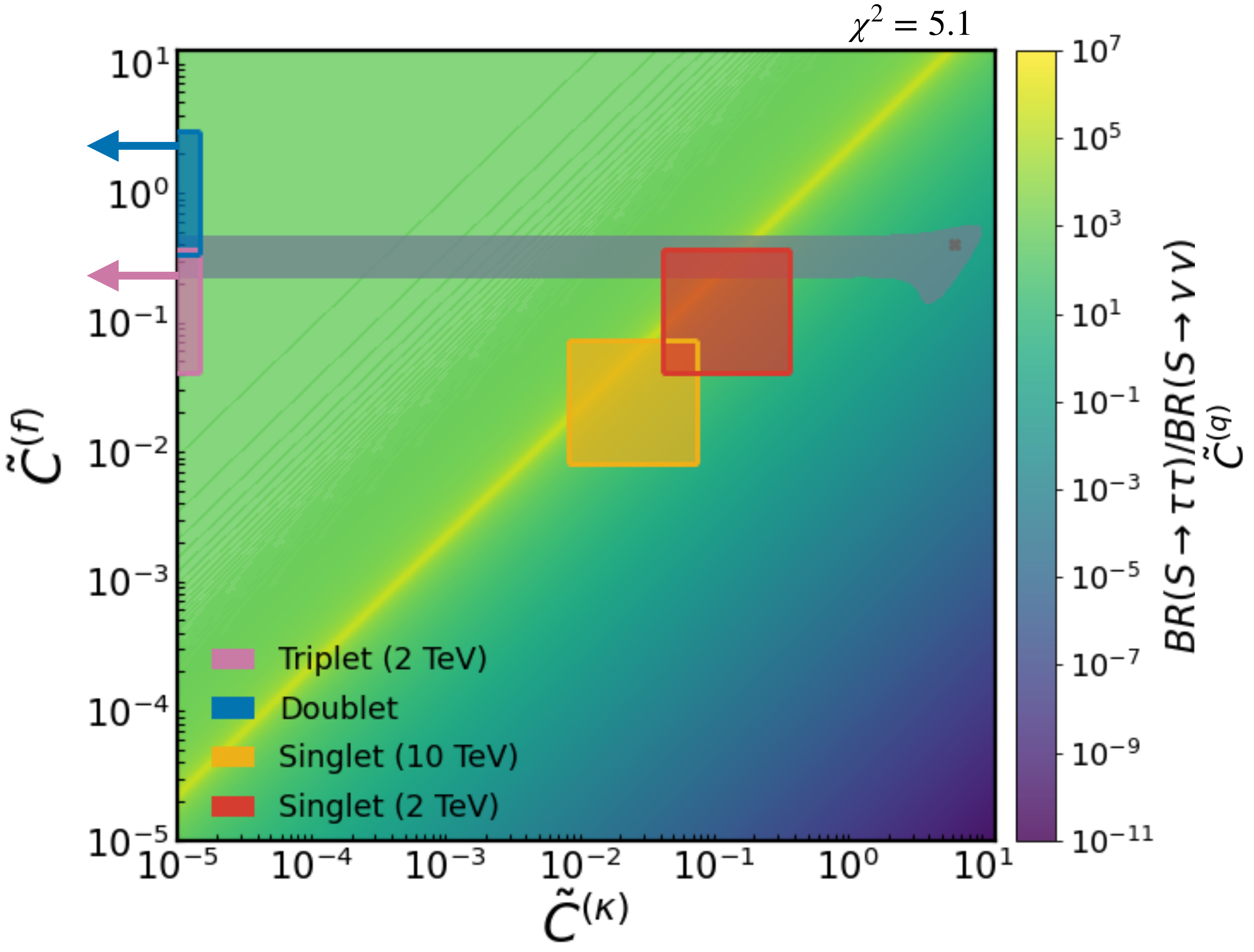
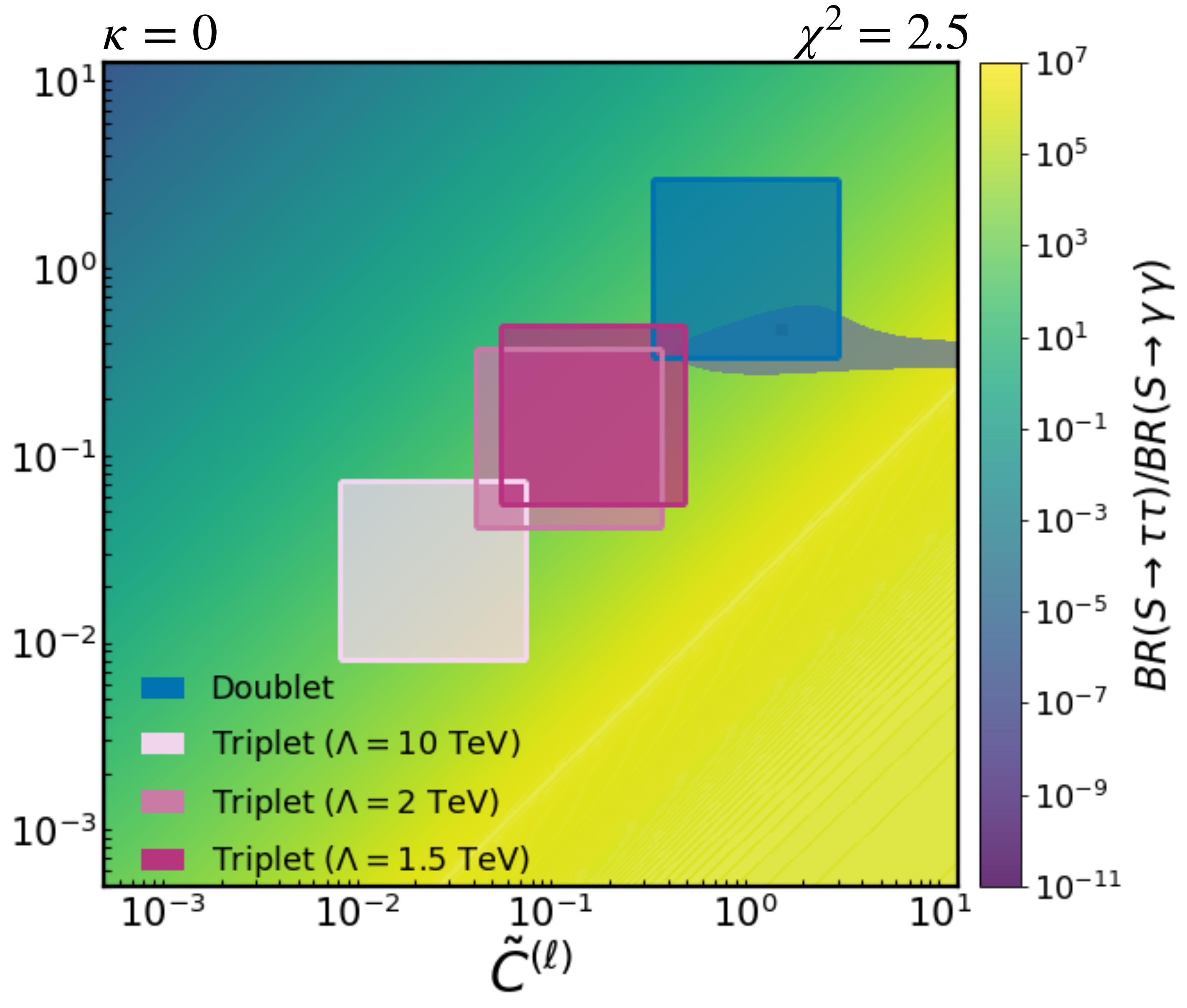
$\lambda \in [1/3,3]$
$\Lambda$: NP scale

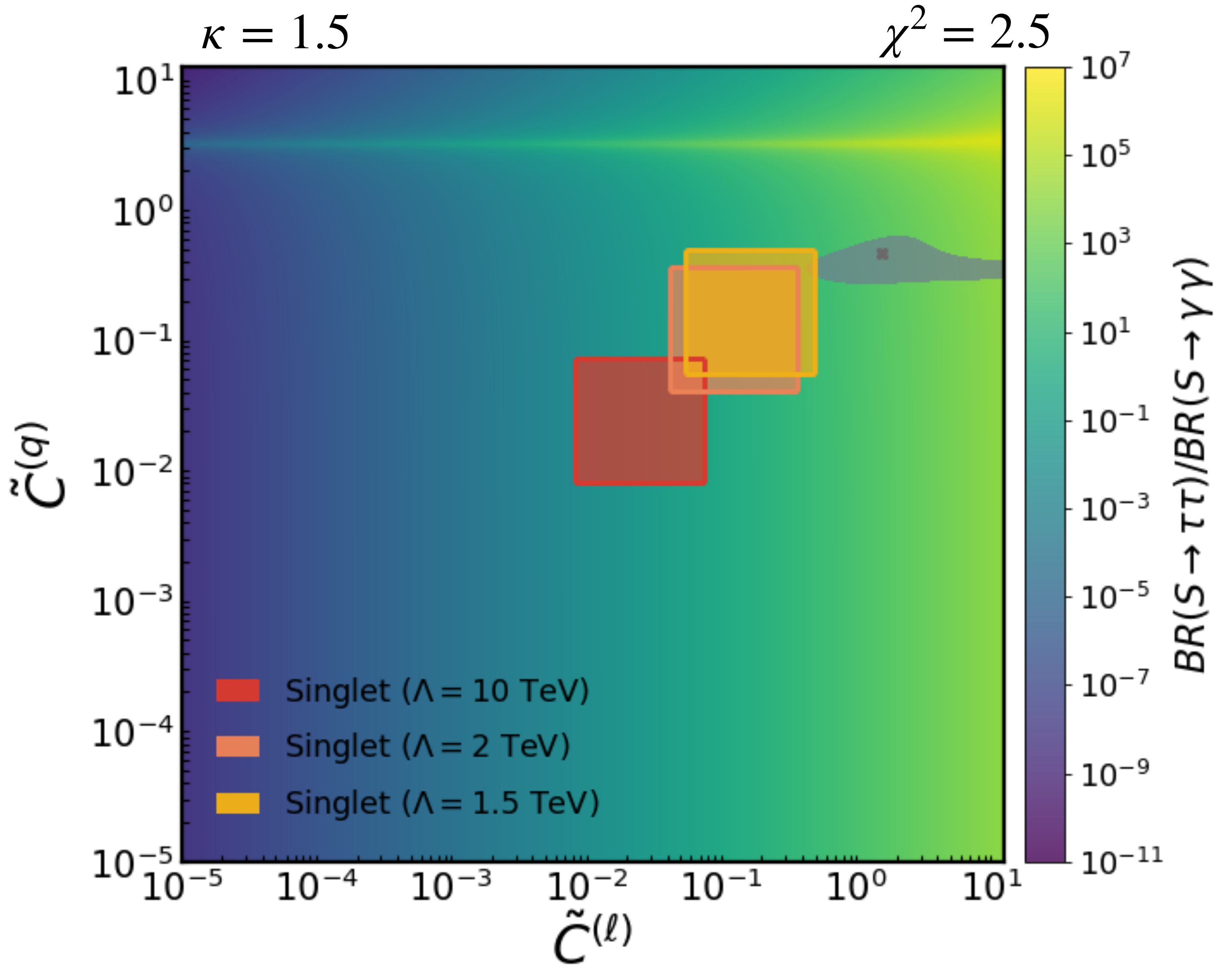
90% C.L. (1.64 $\sigma$)

# „Naturalness Regions“

preliminary



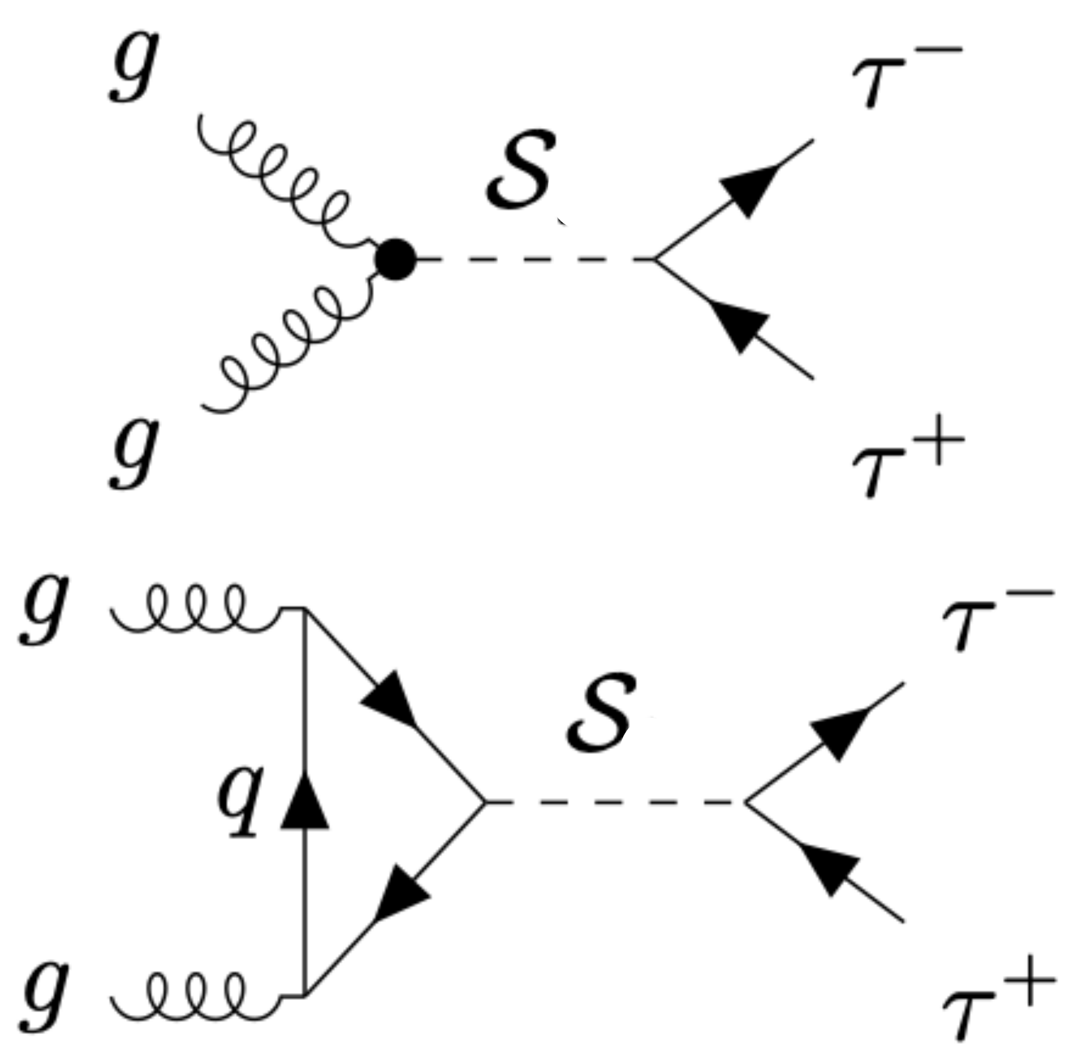




- if singlet or triplet: low $\Lambda_{NP}$ preferred
- non-universal fermion coupling preferred

- doublet better fit than triplet
- no need to redo best fit for each model variation!

# Outlook to Other Masses

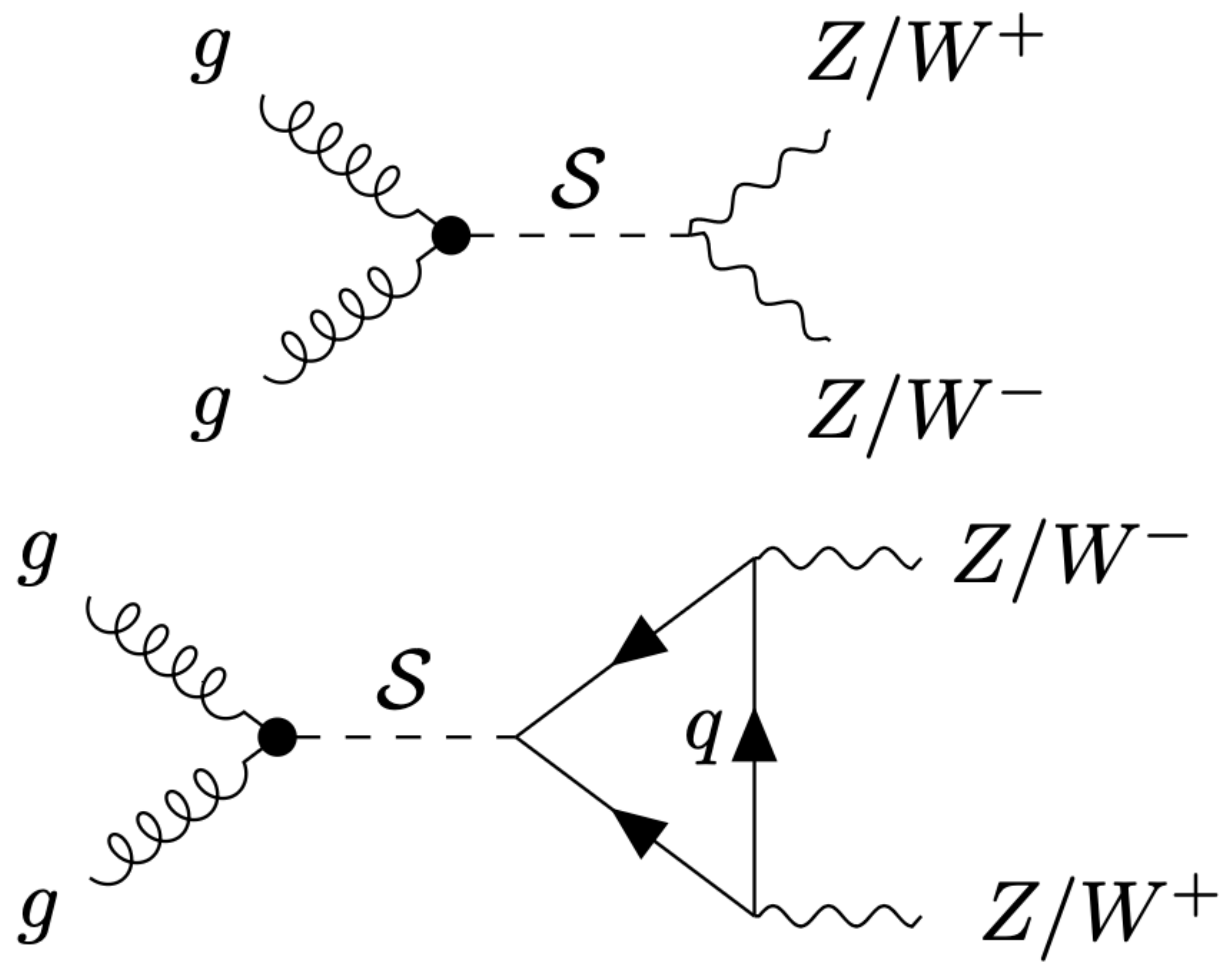
## Potentially Interesting Collider Signals




$\tau$-pair production

probes couplings to fermions
& fairly clean signal

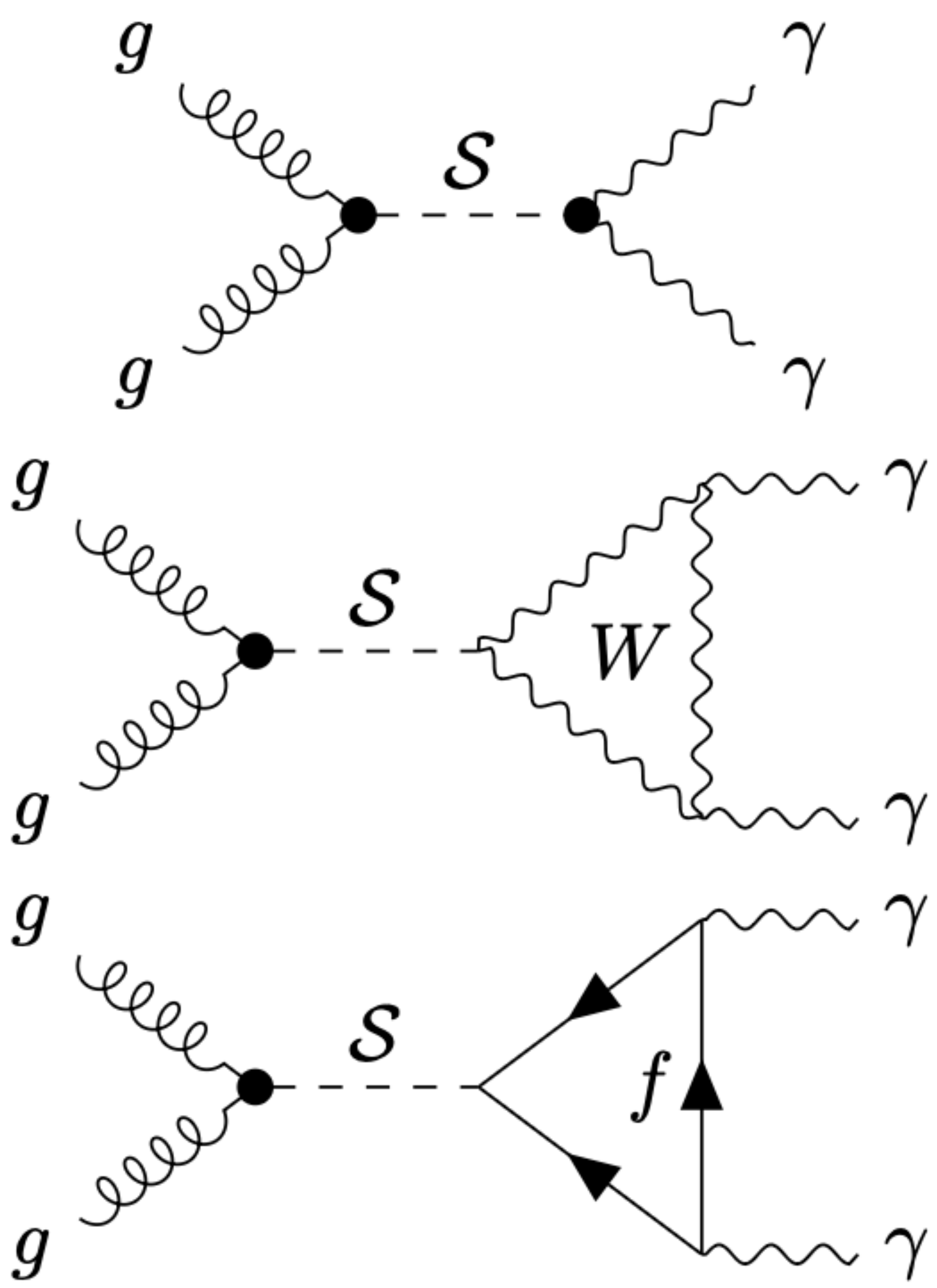
+ $q$-loop production




di-boson resonance

probes couplings to gauge bosons

+ $q$-loop production




decay into photons

probes interplay of coupling
to fermions and gauge bosons

$\tau$-pair production

di-boson resonance

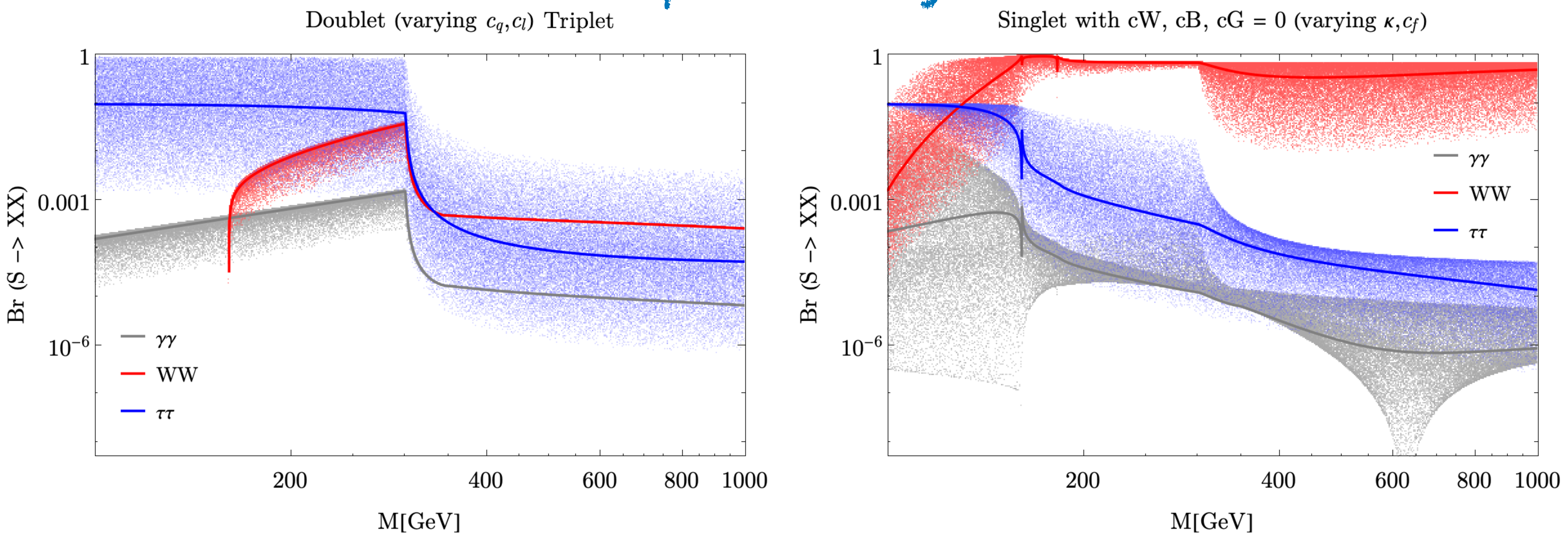
decay into photons

# Outlook: other masses

random scan:
$\lambda_i \in [1/3, 3]$
$M \in [100, 1000]$ GeV
10 000 parameter pts

lines $\hat{=}\ \lambda_i = 1$

preliminary




- for low masses: if $S \to WW$ dominates over $S \to \tau\tau$ : field unlikely to be a doublet / triplet
- for high masses: if $S \to \tau\tau$ or $S \to \gamma\gamma$ dominate over $S \to WW$ : field unlikely to be singlet



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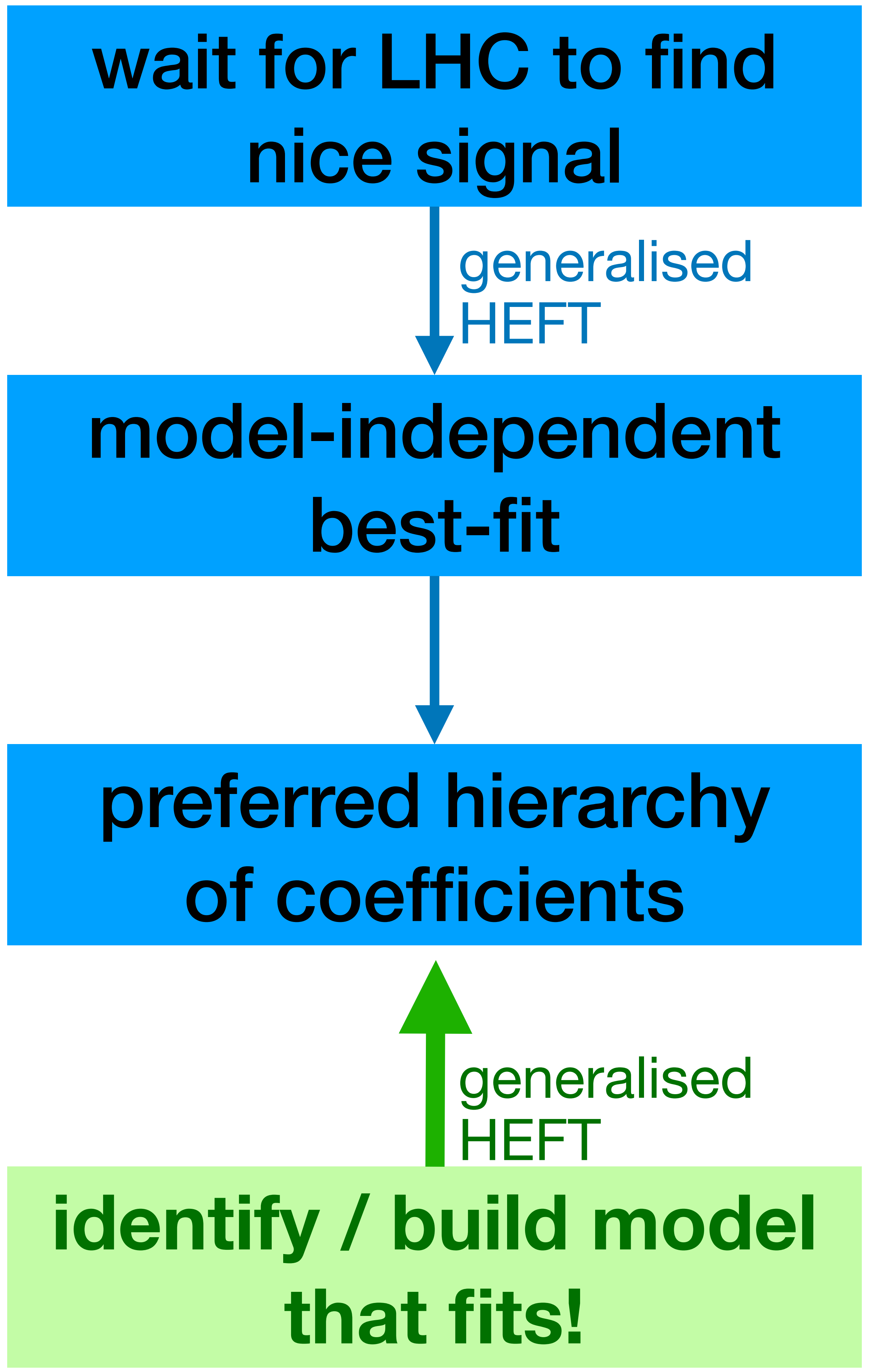
Questions?

# Conclusion & Outlook

- consistent + LHC-friendly
- **model-independent** analysis possible
- can **constrain** possible models
- employ **symmetries** + power counting to understand SU(2) nature of new scalar
- next: check effect of higher dimensional operators



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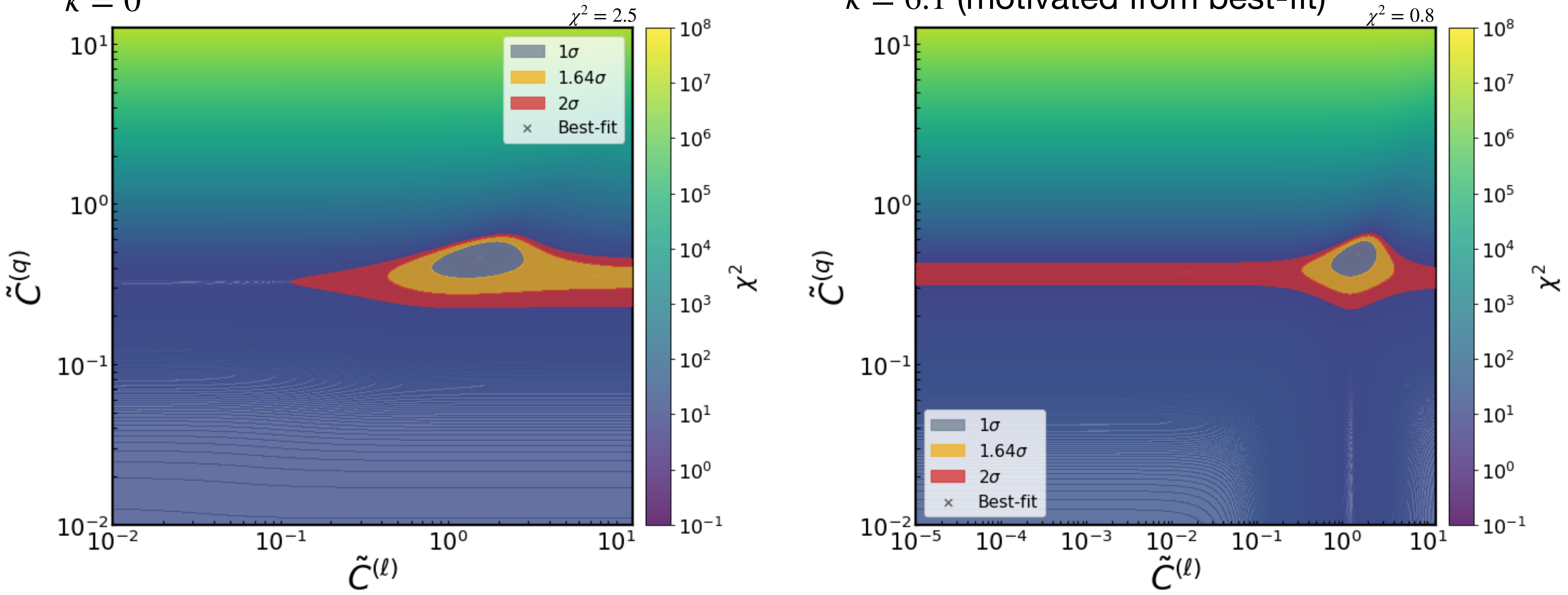
# Back-Up Slides

# $\chi^2$ for non-universal fermion coupling

$\kappa = 0$ | $\kappa = 6.1$ (motivated from best-fit)



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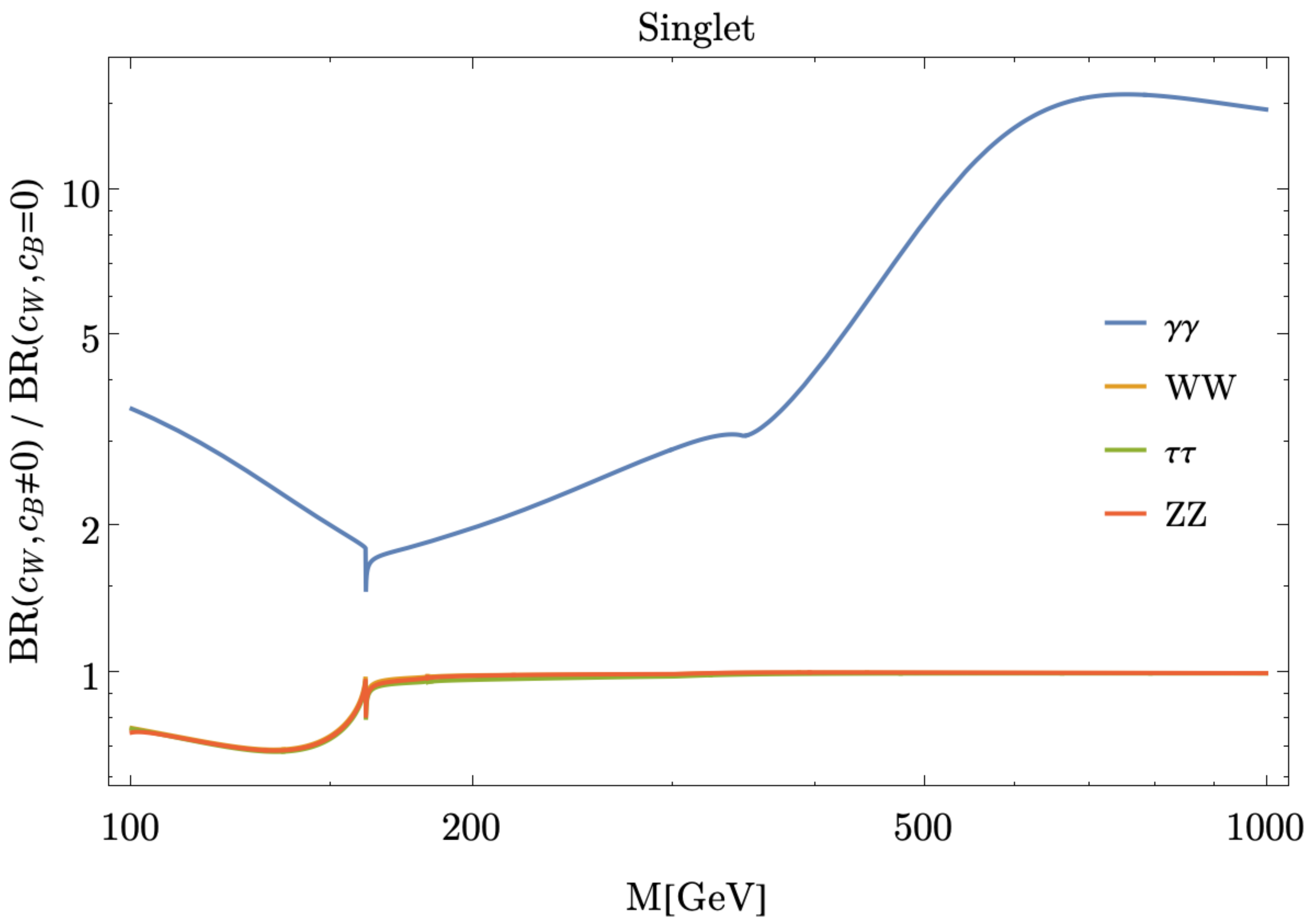
$\lambda = 1$
$\Lambda = 2$ TeV

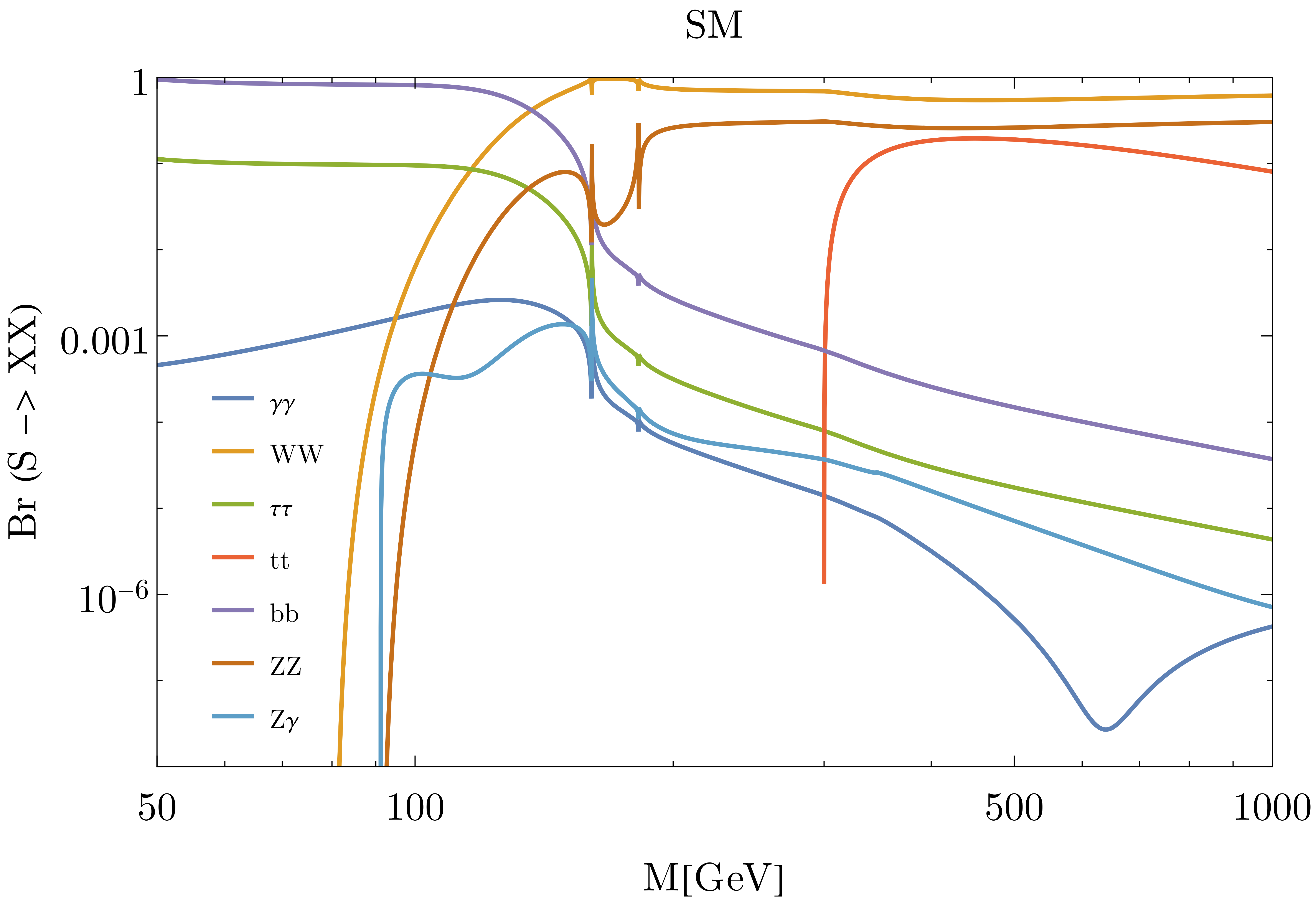
# Effect of FST term




$$-\sum \frac{\phi}{16\pi^2}\left[g'^2 c_B^\phi B^{\mu\nu}B_{\mu\nu} + g^2 c_W^\phi W^{I\mu\nu}W^I_{\mu\nu} + g_s^2 c_G^\phi G^{a\mu\nu}G^a_{\mu\nu}\right]$$

→ mainly relevant for decay into two photons

# SM Comparison




around $m_H \sim 650$ GeV:

**destructive interference** between top and W loop for $H \to \gamma\gamma$

$\tau$-pair production

di-boson resonance

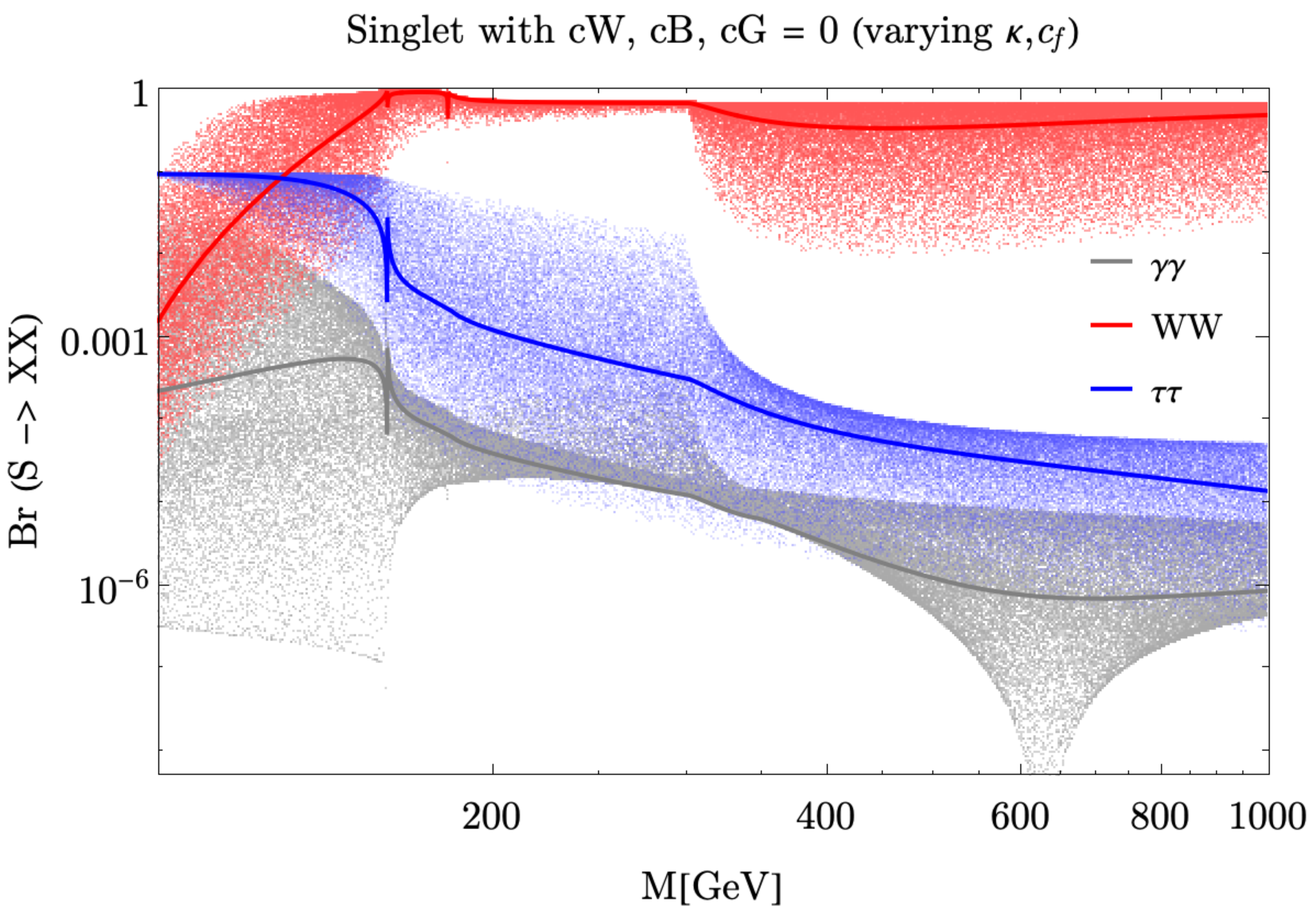
decay into photons

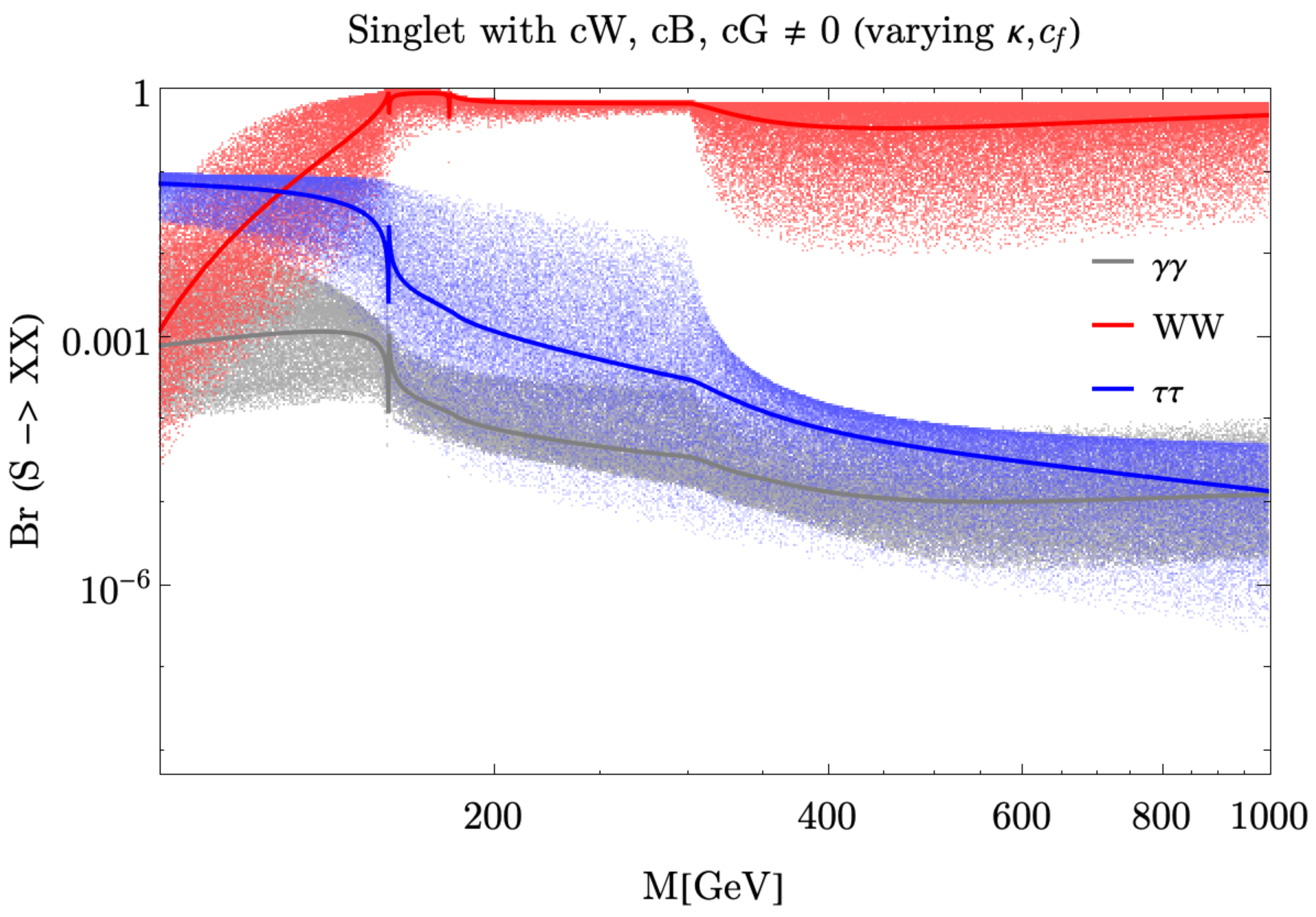
# Branching Ratios

preliminary

random scan:
$\lambda_i \in [1/3,3]$
$M \in [100,1000]$ GeV
10 000 parameter pts

lines $\hat{=}\ \lambda_i = 1$




- 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

$\tau$-pair production

di-boson resonance

decay into photons

# Contributions to decays

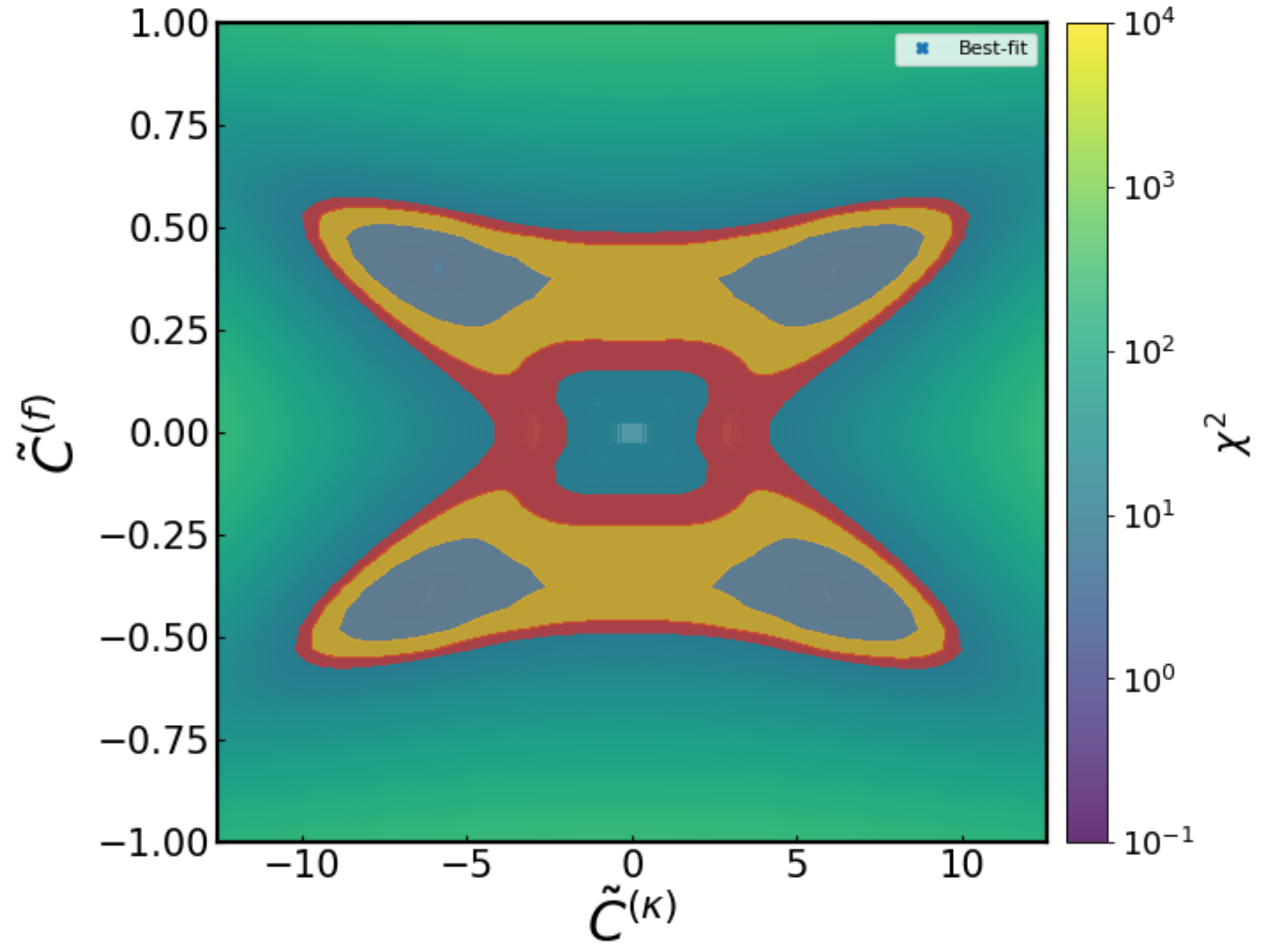
| decay $S \to \gamma\gamma$ | FST | loop $t$ | loop $b$ | loop $\tau$ | loop $W$ |
|---|---|---|---|---|---|
| singlet | ✓(5 + loop) | ✓(5 + SM loop) | ✓(5 + SM loop) | ✓(5 + SM loop) | ✓(5 + SM loop) |
| doublet | ✗ | ✓(4 + SM loop) | ✓(4 + SM loop) | ✓(4 + SM loop) | ✗ |
| triplet | ✗ | ✓(5 + SM loop) | ✓(5 + SM loop) | ✓(5 + SM loop) | ✗ |

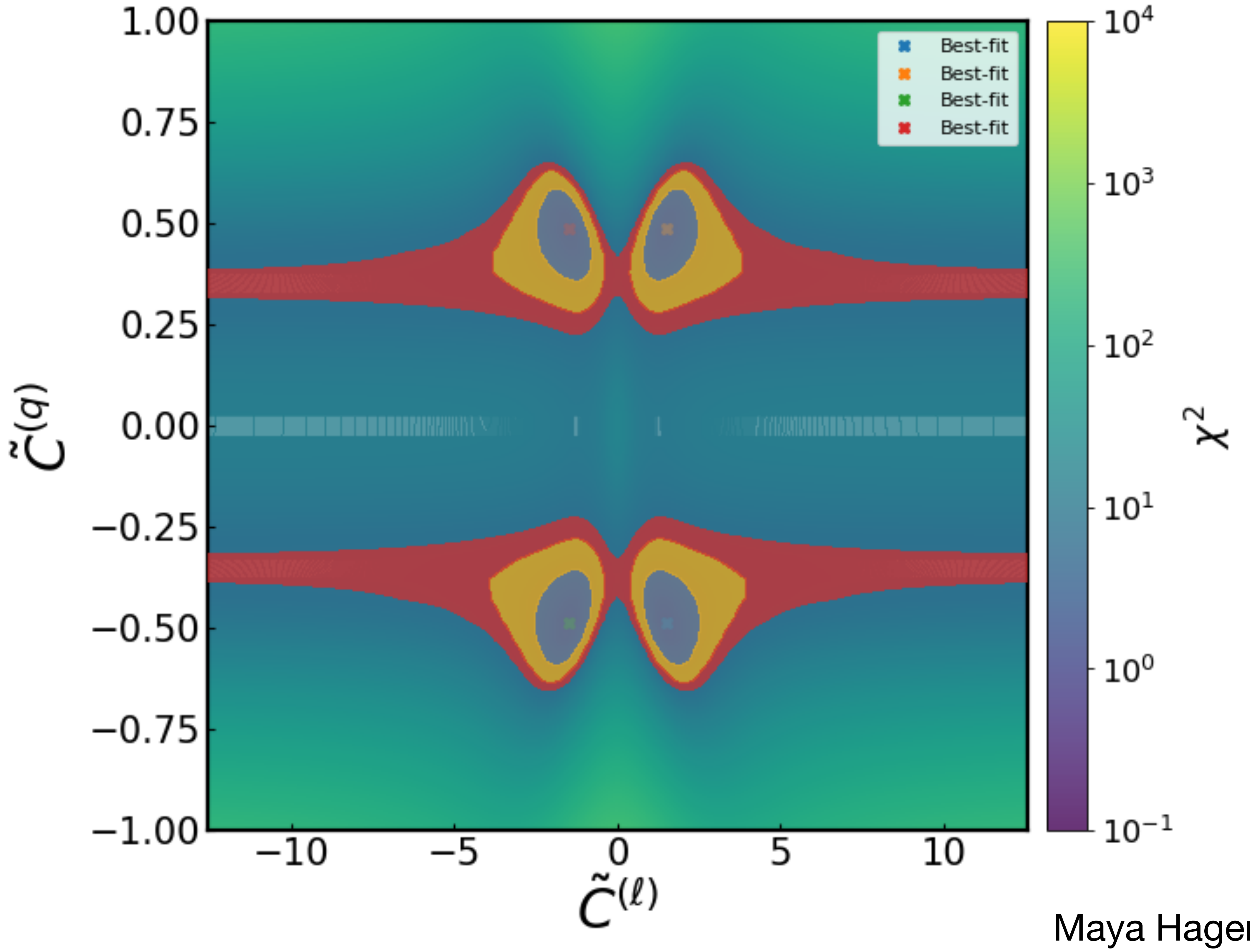
| decay $S \to \tau\tau$ | Yuk |
|---|---|
| singlet | ✓(5) |
| doublet | ✓(4) |
| triplet | ✓(5) |

| decay $S \to WW$ | FST | loop $t$ | loop $b$ | $\kappa$ |
|---|---|---|---|---|
| singlet | ✓(5 + loop) | ✓(5 + SM loop) | ✓(5 + SM loop) | ✓(5) |
| doublet | ✗ | ✓(4 + SM loop) | ✓(4 + SM loop) | ✗ |
| triplet | ✗ | ✓(5 + SM loop) | ✓(5 + SM loop) | ✗ |

# Coupling Range

- couplings can be a priori positive or negative
- but: signal strength symmetric up to negligible effects
- $\rightarrow$ focus on absolute value for couplings
- largest coupling for analysis: $4\pi$
  smallest coupling: 0
  (in log-scale $10^{-5}$,
  if dim 5 $\Rightarrow \Lambda_{\text{UV}} = 10^4$ TeV)



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