Composite scalar searches @ FCC

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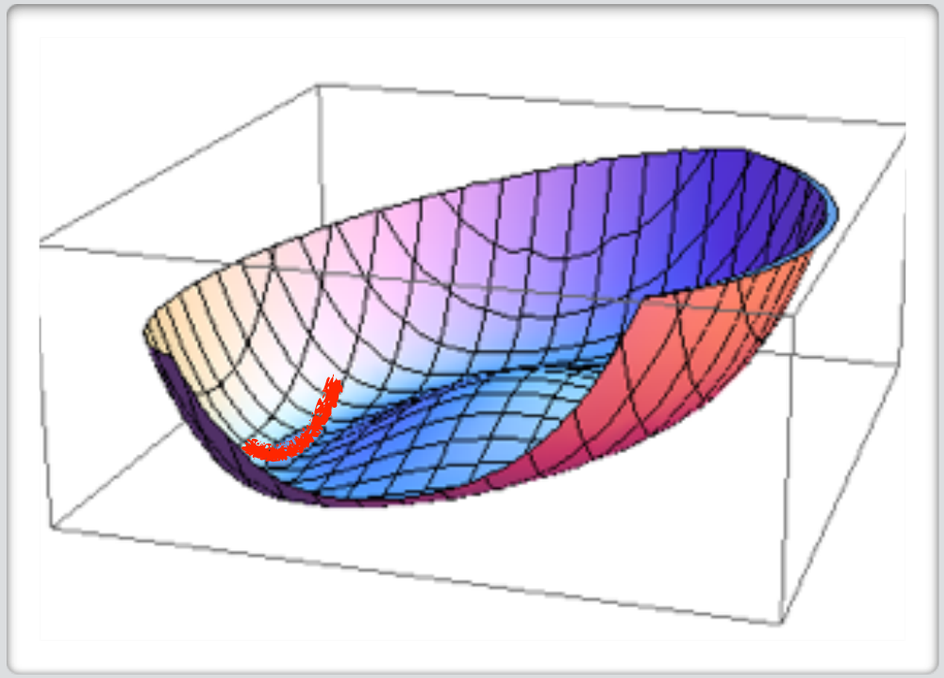
Based mainly on work in collaboration with:
G.Cacciapaglia, A.Cornell, T.Flacke, B.Fuks, A.Iyer, L.Mason

Strong dynamics in the EW sector

Global symmetry:

$$G \rightarrow H$$

$$SU(2)xU(1) \rightarrow U(1)_{em}$$

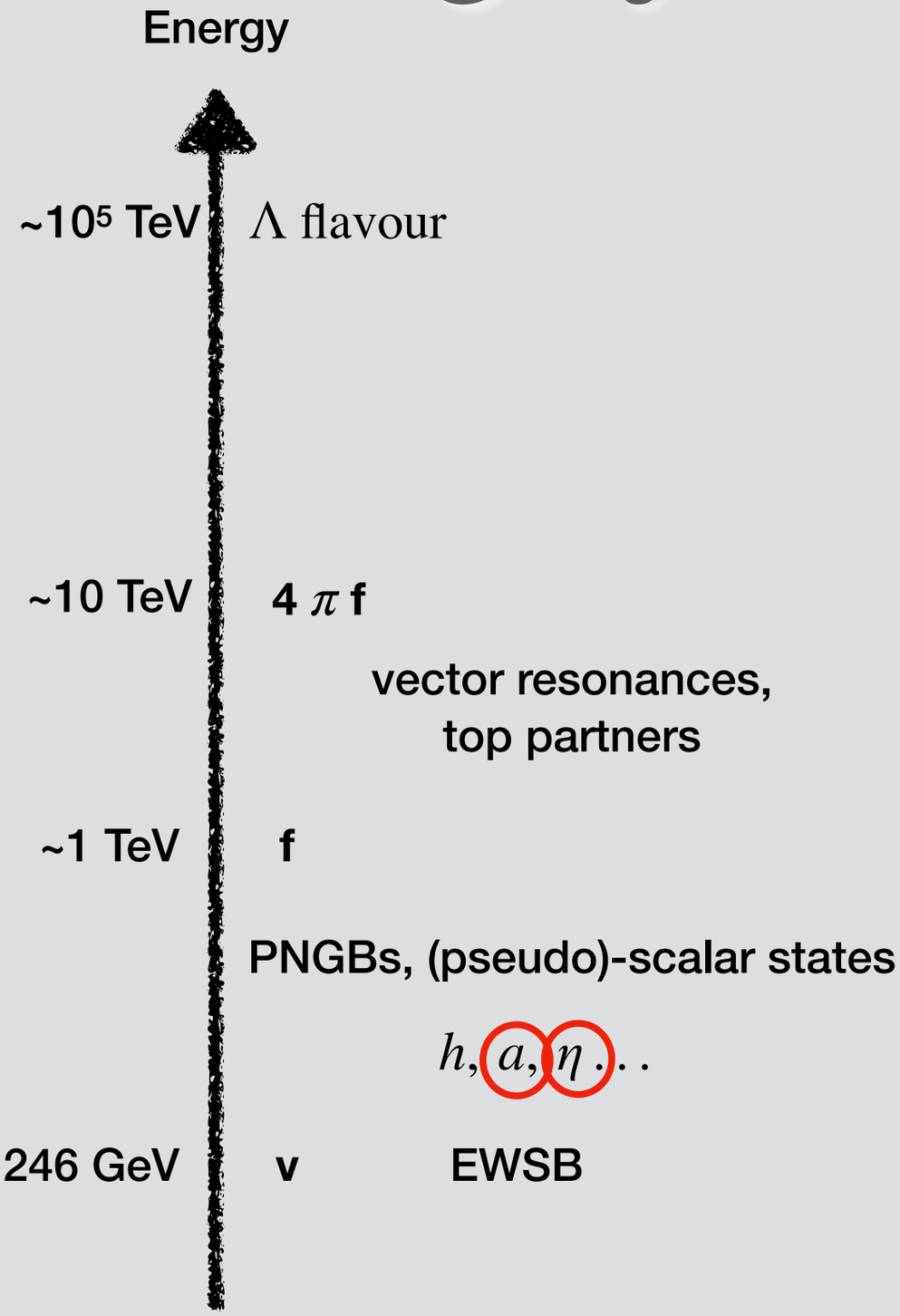


SM gauge symmetry

"pions" h, WL, ZL

Higgs boson light as pNGB of the broken symmetry of the strong sector, parameterisation with an effective chiral Lagrangian, detailed computations possible in terms of the fundamental fermionic states

Strong dynamics: energy scales



- Simple models based on fundamental gauge-fermion underlying theory can be built.
- The Higgs field is made of these new fermions, and other new bound states can/must be present.
- Symmetries can be broken dynamically without hierarchy problems.

Fundamental composite dynamics

- Strong dynamics from a confining gauge group G_{TC}:
  - define N fundamental fermions charged under G_{TC}
  - assign SM quantum number to fundamental fermions
  - couple to SM fermions
- The EFT for bound states Lagrangian must respect the symmetries (NOT a generic EFT !)
- Lattice results (if available) determine the spectra and couplings

Which models?

	rep R	rep R'	
G_{TC} :	ψ	χ	$T'=\psi\psi\chi$
SM :	EW	color and hypercharge	
global:	$\langle\psi\psi\rangle$	$\langle\chi\chi\rangle$	
	↓	↓	
	h pNGB, DM...	coloured pNGBs	

An attractive possibility is to separate the underlying fermions that generate the Higgs as a pNGB, ψ, from the ones that carry QCD colour χ (necessary to generate partial compositeness for the top quark), which give QCD colour to the spin-1/2 bound states that mix with the top.

Symmetries and zoology

$SU(N_Q) \times SU(N_\chi) \times U(1)_Q \times U(1)_\chi$

Anomalous U(1) : a new singlet state η

Orthogonal U(1) : a new pNGB singlet a

Neutral colour octet

Ferretti 1604.06467

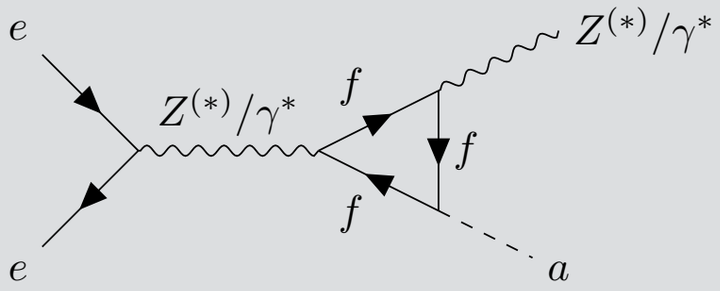
Cacciapaglia et al 1902.06890

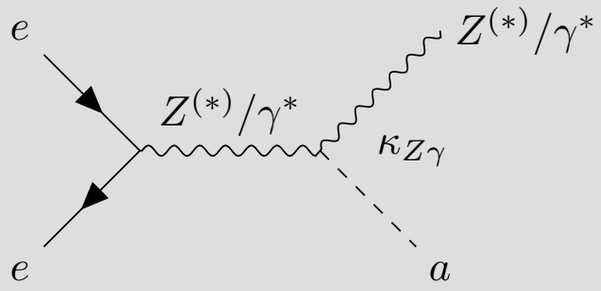
Model	EW coset					QCD coset					a	η'
	$\mathbf{2}_{\pm 1/2}$	$\mathbf{3}_0$	$\mathbf{3}_{\pm 1}$	$\mathbf{1}_0$	$\mathbf{1}_{\pm 1}$	$\mathbf{8}_0$	$\bar{\mathbf{3}}_{2/3}$	$\bar{\mathbf{3}}_{4/3}$	$\mathbf{6}_{2/3}$	$\mathbf{6}_{4/3}$		
M1	1	1	1	1	-	1	-	-	1	-	1	1
M2	1	1	1	1	-	1	-	-	1	-	1	1
M3	1	1	1	1	-	1	-	-	-	1	1	1
M4	1	1	1	1	-	1	-	-	-	1	1	1
M5	1	1	1	1	-	1	1	-	-	-	1	1
M6	1	1	1	1	-	1	-	-	-	-	1	1
M7	1	1	1	1	-	1	-	-	-	-	1	1
M8	1	-	-	1	-	1	-	-	-	1	1	1
M9	1	-	-	1	-	1	-	-	-	1	1	1
M10	2	1	-	2	1	1	-	-	-	1	1	1
M11	2	1	-	2	1	1	-	-	-	1	1	1
M12	2	1	-	2	1	1	-	-	-	-	1	1

$U(1)$ pseudo-scalars

Effective Lagrangian similar to ALPs but couplings dictated by the dynamics: WZW term, underlying gauge quantum numbers.

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{1}{2}m_a^2 a^2 - \Sigma_f \frac{iC_f m_f}{f_a} a\bar{\Psi}_f \gamma^5 \Psi_f +$$
$$\frac{g_s^2 K_g}{16\pi^2 f_a} a G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{g^2 K_W}{16\pi^2 f_a} a W^i_{\mu\nu}\tilde{W}^{i\mu\nu} + \frac{g'^2 K_B}{16\pi^2 f_a} a B_{\mu\nu}\tilde{B}^{\mu\nu},$$





see 1710.11142, 1902.06890, 2004.09825

Coupling = SM component (loop of SM fermions) + BSM component (effective vertex)

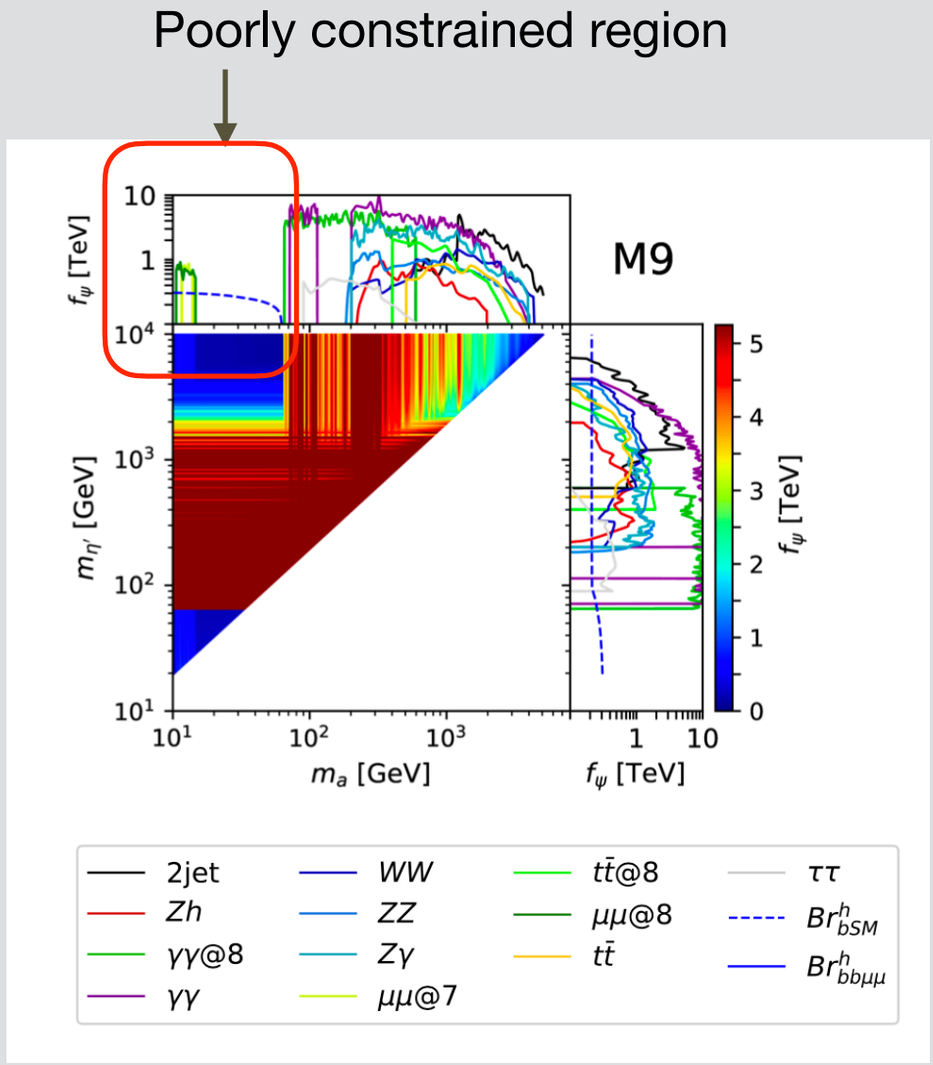
Inclusion of bottom quarks (non-negligible impact on phenomenology)

$U(1)$ pseudo-scalars

How has it evaded detection so far?

- weakly coupled - no strong or electric charge
- Small couplings
- Low mass

- Previous searches (di-j/di-μ/di-γ/di-τ) yield poor constraints in low pseudo-scalar mass region
- QCD backgrounds play a role in low mass searches at hadron colliders

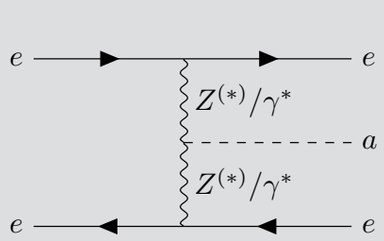


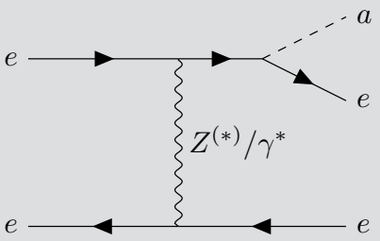
G. Cacciapaglia, G. Ferretti, T. Flacke, and H. Serôdio *Front.in Phys.*, vol. 7, p. 22, 2019.

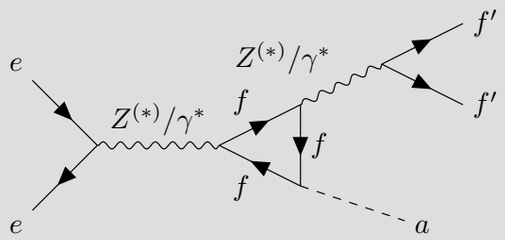
(Top band: bounds from a. Side band: bounds from η .
Bounds on f_ψ computed individually and then most stringent bound chosen)

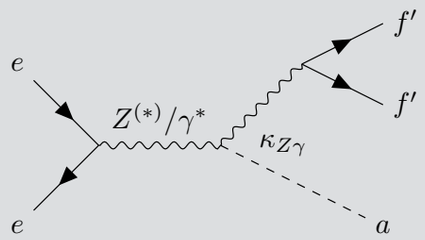
Production at FCC-ee

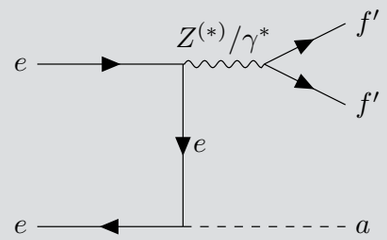
production in association with a (virtual or real) boson: $e^+e^- \to \ell^+\ell^- a$, $e^+e^- \to jja$

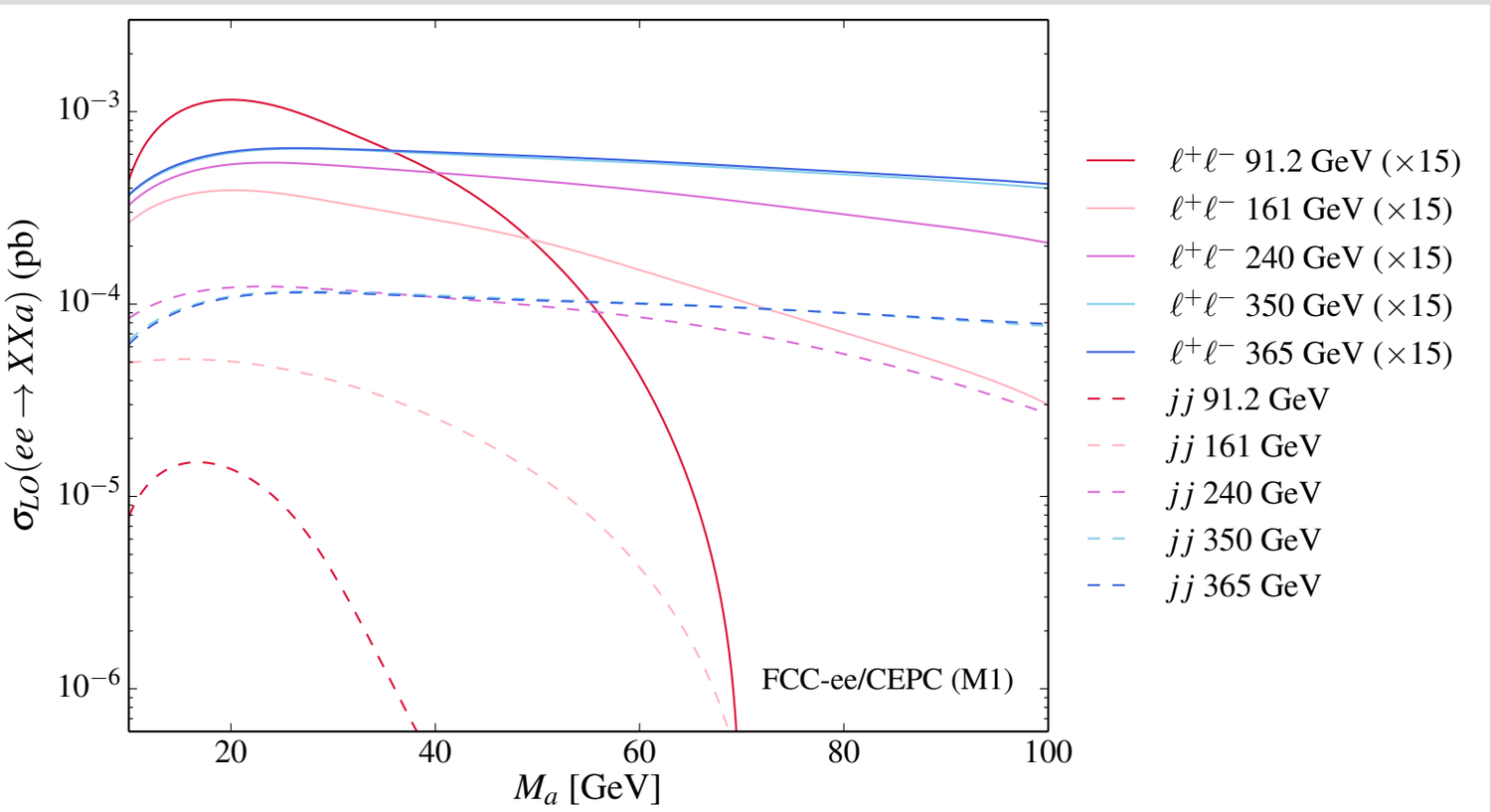












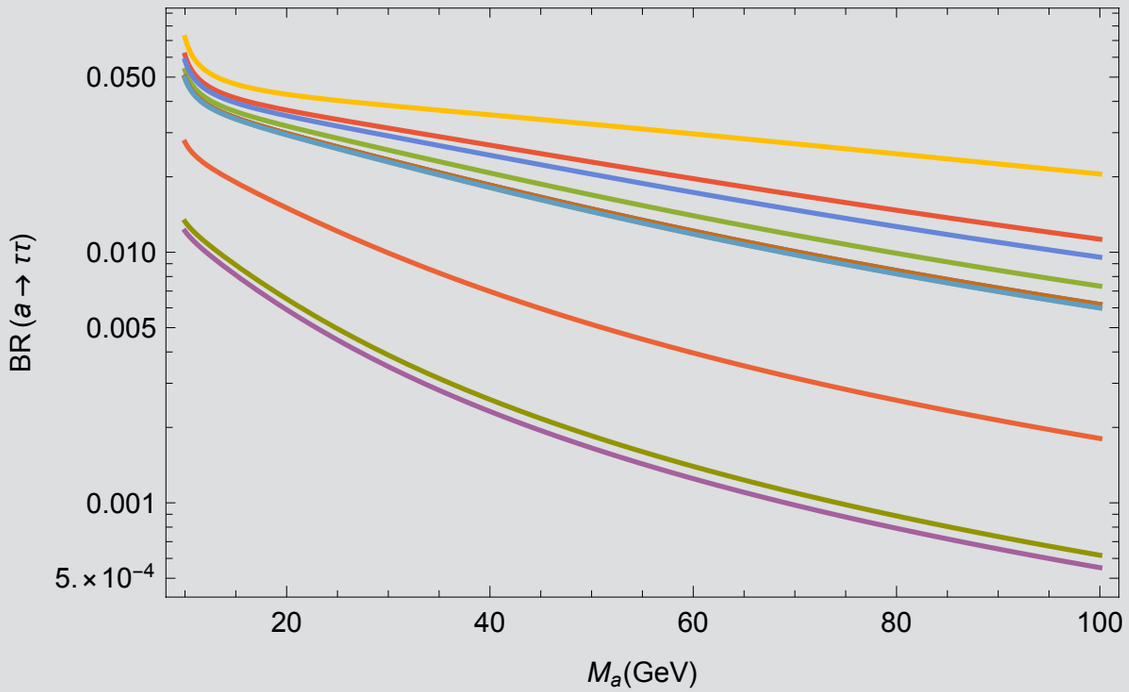
Mass range of interest is well covered, even at the Z pole

$$p_T(j) > 20 \text{ GeV} , \quad |\eta(j)| < 5$$

$$p_T(\ell) > 5 \text{ GeV} , \quad |\eta(\ell)| < 2.5$$

$$\Delta R(\ell, \ell') > 0.4 , \qquad \Delta R(j, j') > 0.4 .$$

FCC-ee: $\tau\tau$ decay

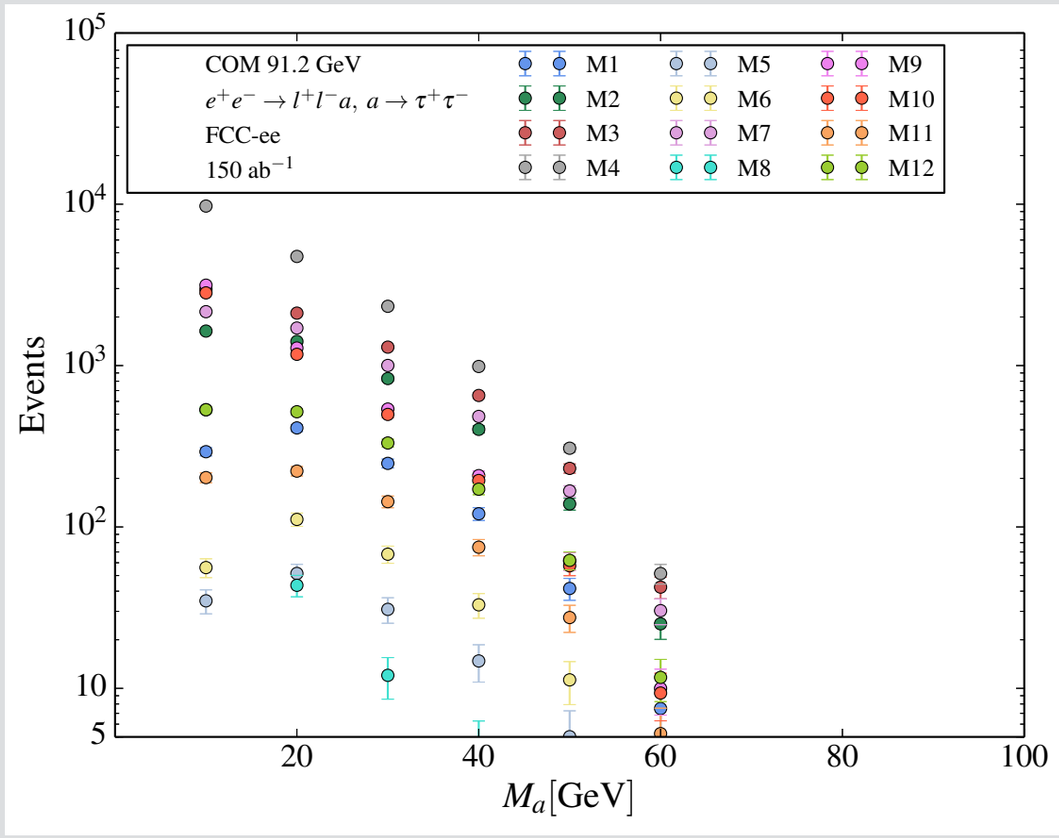


M1 M9
M2 M10
M3 M11
M4 M12
M5
M6
M7
M8

Branching to taus and b-quarks highest

(coupling proportional to fermion mass)

- Consider a produced in conjunction with a pair of OS leptons (avoid multi jet background)
- Signal events expected for subsequent decay to hadronic tau pair
- Sensitivity of machine depends on specifics of model



Sample analysis

- Signal: $e^+e^- \to a\ \ell^+\ell^-,\ a \to \tau^+\tau^-$ (hadronic taus)
- Z pole: low c.m energy means fewer background processes
- FCC-ee IDEA detector concept
- Background resulting from (virtual) Z/γ events

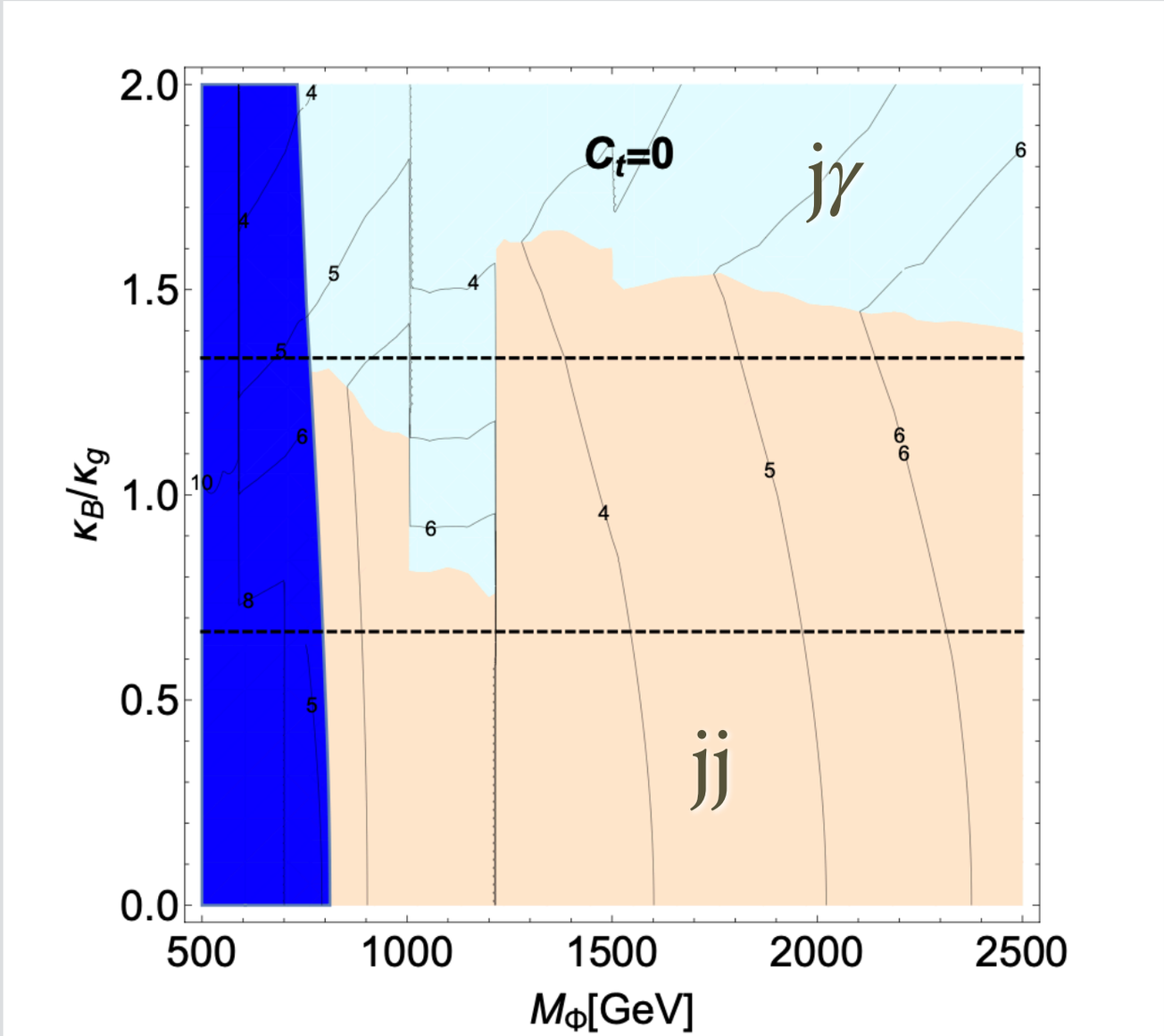
Preselection

$N_\ell \geq 2$ with $p_T(\ell) > 10$ GeV; $N_\tau \geq 2$ with $p_T(\tau) > 5$ GeV; $M_{\ell\ell} > 12$ GeV; $M_{\tau\tau} > 10$ GeV .

- Following preselection, we expect about 50,000 background events and up to 40 signal events (maximal production at $M_a = 20/30$ GeV)
- Signal tiny wrt background, but relatively clean
- Analysis with Machine Learning techniques and comparison with simple cut and count, 20-40 GeV mass range testable (see 2004.09825).

Color octect Φ

- Production (single and pair) via QCD interactions
- Decays Φ → gg, gγ, gZ, (t tbar) in particular decays with photons are relevant



Color octect Φ @ FCC-hh

- Simplified strategy: as di-jet pair search, replacing one or 2 jets with photons (fake rate $\epsilon_{j\to\gamma} = 10^{-4}$)

- HL-LHC can probe up to 1.2 TeV, FCC-hh more than 3 TeV

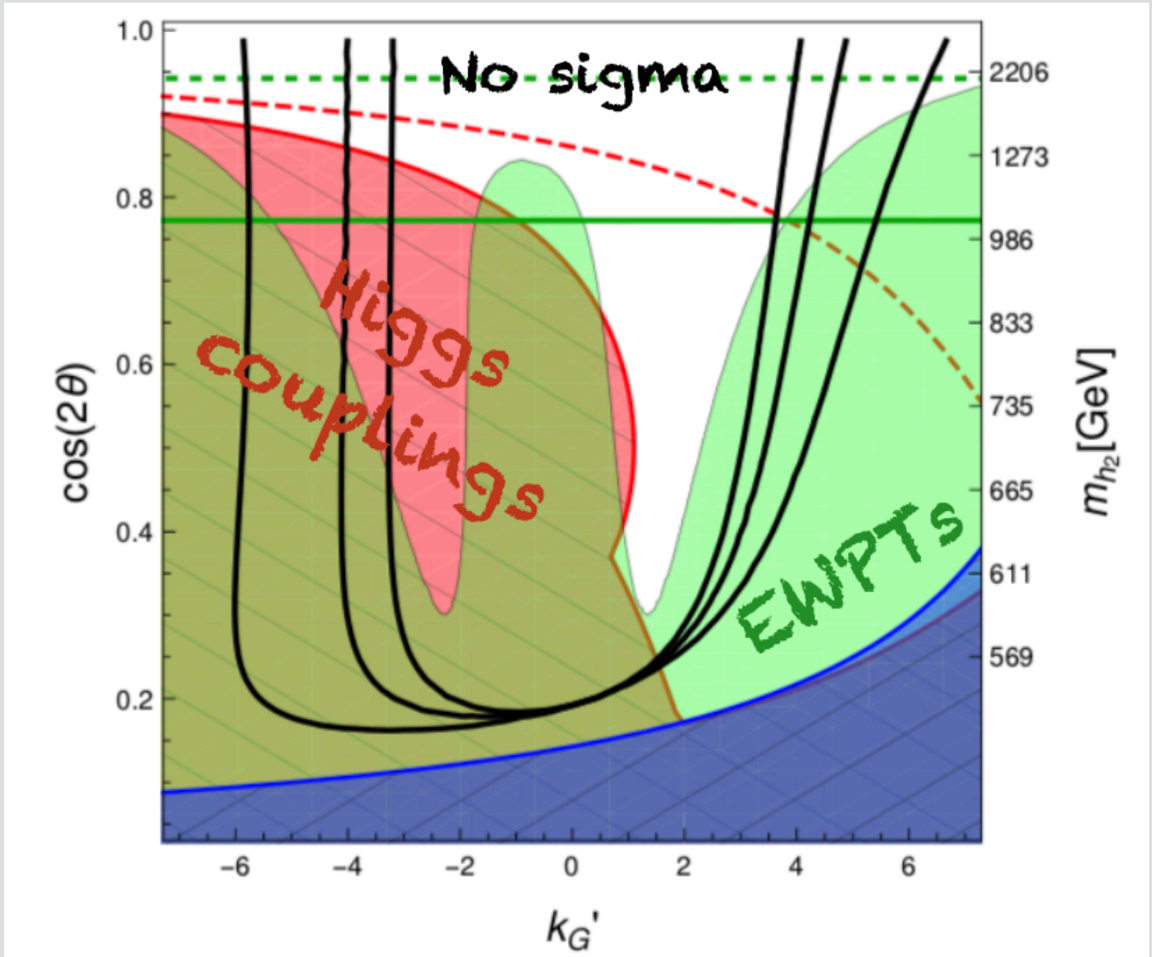
BP1 (2.5,270)			BP2 (3,100)		
	$Y_\chi = 1/3$	$Y_\chi = 2/3$		$Y_\chi = 1/3$	$Y_\chi = 2/3$
$Z_{ggg\gamma}$	11.7	30.8	$Z_{ggg\gamma}$	4.98	13.6
$Z_{gg\gamma\gamma}$	5.47	58.2	$Z_{gg\gamma\gamma}$	2.87	31.1

L = 3 ab^{-1}

$$Z = \frac{S}{\sqrt{B}}$$

see 2002.01474

Higgs and σ in EW strong dynamics



a scalar 0++ σ may be light if the theory has walking strong dynamics and can mix with the Higgs, modifying the couplings.

D. Buarque Franzosi et al. 1809.09146

Modifications to the Higgs couplings

$$\xi = \frac{v^2}{f^2}$$

$$\mathcal{L} = m_W^2 W_\mu^+ W^{-,\mu} \left(1 + c_V \frac{h}{v} + \frac{c_{2V}}{2}\frac{h^2}{v^2} + \dots\right),$$

$$c_V = \sin\theta = \sqrt{1-\xi}\,, \qquad c_{2V} = \cos 2\theta = 1 - 2\xi\,;$$

gauge couplings universal in all models:

$$m_W^2(\theta) = \frac{g^2 f^2}{4}\sin^2\theta \equiv \frac{g^2 v^2}{4}$$

$$\begin{aligned} g_{WWh} &= \frac{1}{f}\frac{\partial m_W^2(\theta)}{\partial\theta} = \frac{2m_W^2}{v}\cos\theta\,; \\ g_{WWhh} &= \frac{1}{f^2}\frac{\partial^2 m_W^2(\theta)}{\partial\theta^2} = \frac{2m_W^2}{v^2}\cos 2\theta\,; \end{aligned}$$

Modifications to the Higgs couplings

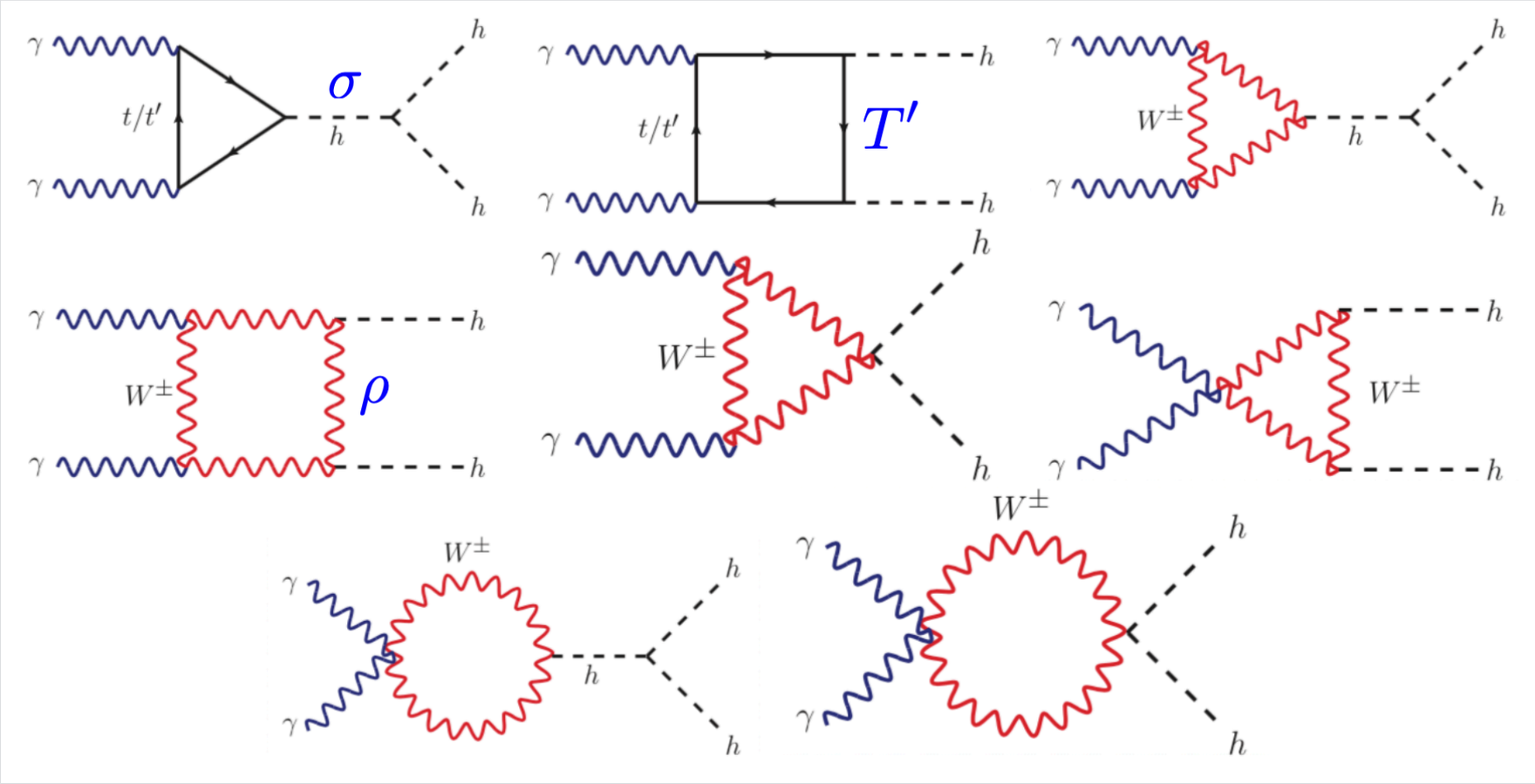
$$\mathcal{L} = \frac{v}{\sqrt{2}}\lambda_{ij}\left(\bar{\psi}^i \Sigma \psi^j\right)\left(1 + c_f\frac{h}{v} + \frac{\mathbf{1}}{\mathbf{2}}c_{2f}\frac{h^2}{v^2}\right) + h.c.$$

Fermion couplings model dependent, but 2 cases typically apply:

$$m_t(\theta) = \frac{\lambda f}{\sqrt{2}}\sin\theta \quad \Rightarrow \quad \begin{cases} g_{ffh} = \dfrac{m_t}{v}\cos\theta\,, \\ g_{ffhh} = -\dfrac{m_t}{v^2}\sin^2\theta\,. \end{cases}$$

$$m_t(\theta) = \frac{\lambda f}{\sqrt{2}}\sin 2\theta \quad \Rightarrow \quad \begin{cases} g_{ffh} = \dfrac{m_t}{v}\dfrac{\cos 2\theta}{2\cos\theta}\,, \\ g_{ffhh} = -\dfrac{m_t}{v^2}4\sin^2\theta\,. \end{cases}$$

Photon fusion @ FCC-ee

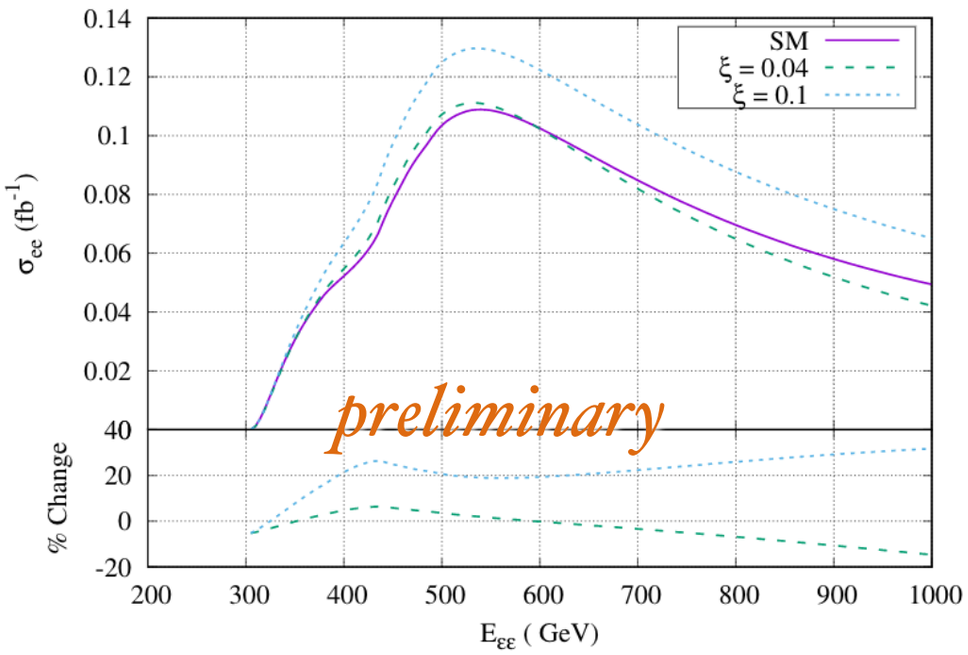


Loops sensitive to couplings and resonances

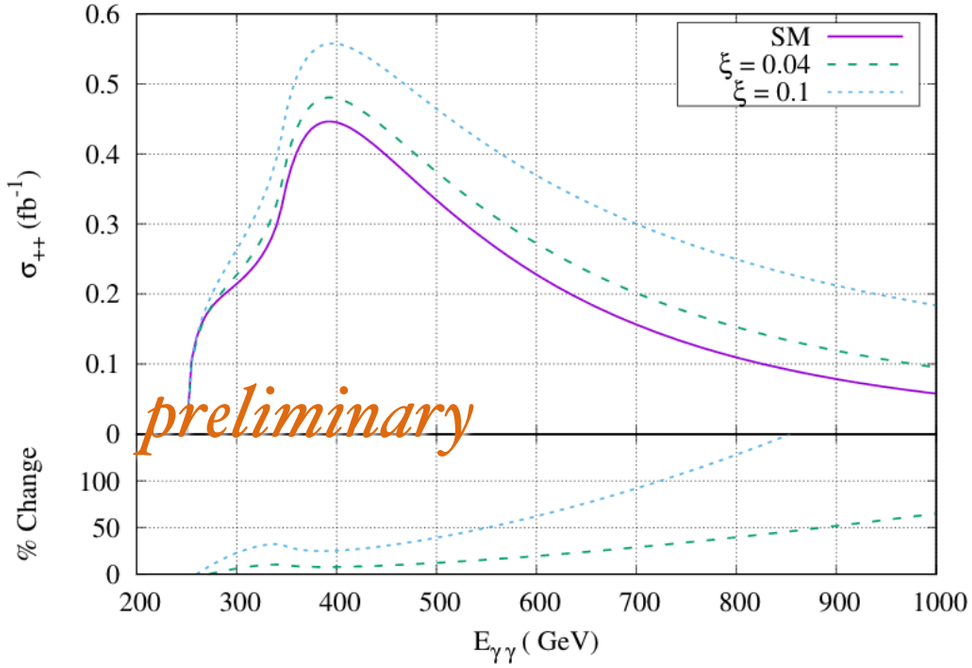
$\gamma\gamma \to hh$ @ FCC-ee

Model	$hf\bar{f}(c_f)$	$hhf\bar{f}(c_{2f})$	$hW^+W^-(c_V)$	$hhW^+W^-(c_{2V})$	c_{3h}
MCHM4 [2]	$\sqrt{1-\xi}$	$-\xi$	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$
MCHM5 [3]	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-\xi}{\sqrt{1-\xi}}$

MCHM5



MCHM5



A. Bharucha, G. Cacciapaglia, A. Deandrea, N. Gaur, D. Harada, F. Mahmoudi, K. Sridhar work in progress

Perspectives and outlook

- Light pseudo-scalars are ubiquitous: singlets + color octet
- U(1) pNGB (di-bosons), coloured pNGBs (gluon photon), EW pNGBs (W photon, ...)
- σ-type resonance in EW strong dynamics can be light
- hh channel can be a sensitive probe of couplings and resonances in loops
- FCC-ee and FCC-hh give complementary handles on composite scalar searches