BSM and Theory developments for FCC-ee : a composite perspective

Aldo Deandrea
IP2I, Université Lyon 1

4th FCC/DRD France Workshop

IPHC, November 22nd 2023

BSM at FCC-ee

Precision measurements:

deviations from SM expectations

precision electroweak parameters

Higgs, top, flavour

Direct detection of signals for new particles:

low mass (region where LHC has reduced sensitivity)

low couplings (as very high statistics)

long lived particles

among the BSM scenarios

Axion-like particles

Light composite states

Heavy Neutral Leptons

Exotic Higgs boson decays

Scenarios with other light scalars

Z', dark photons

....

in the following we focus on composite models

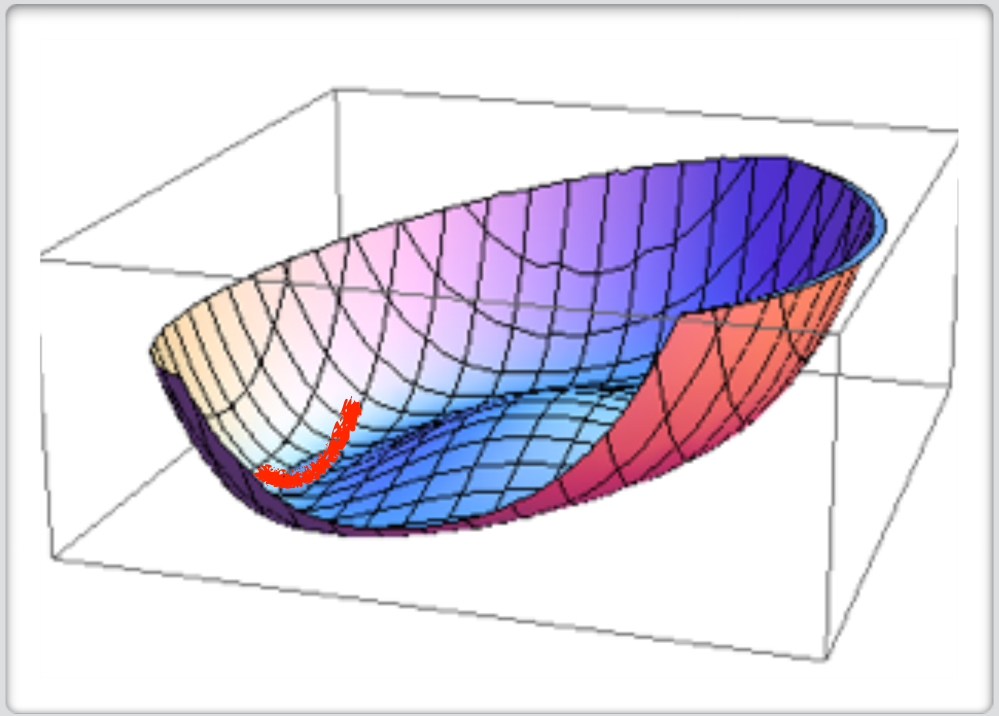
Strong dynamics in the EW sector

Global symmetry:

G → H

SU(2)xU(1) → $U(1)_{em}$

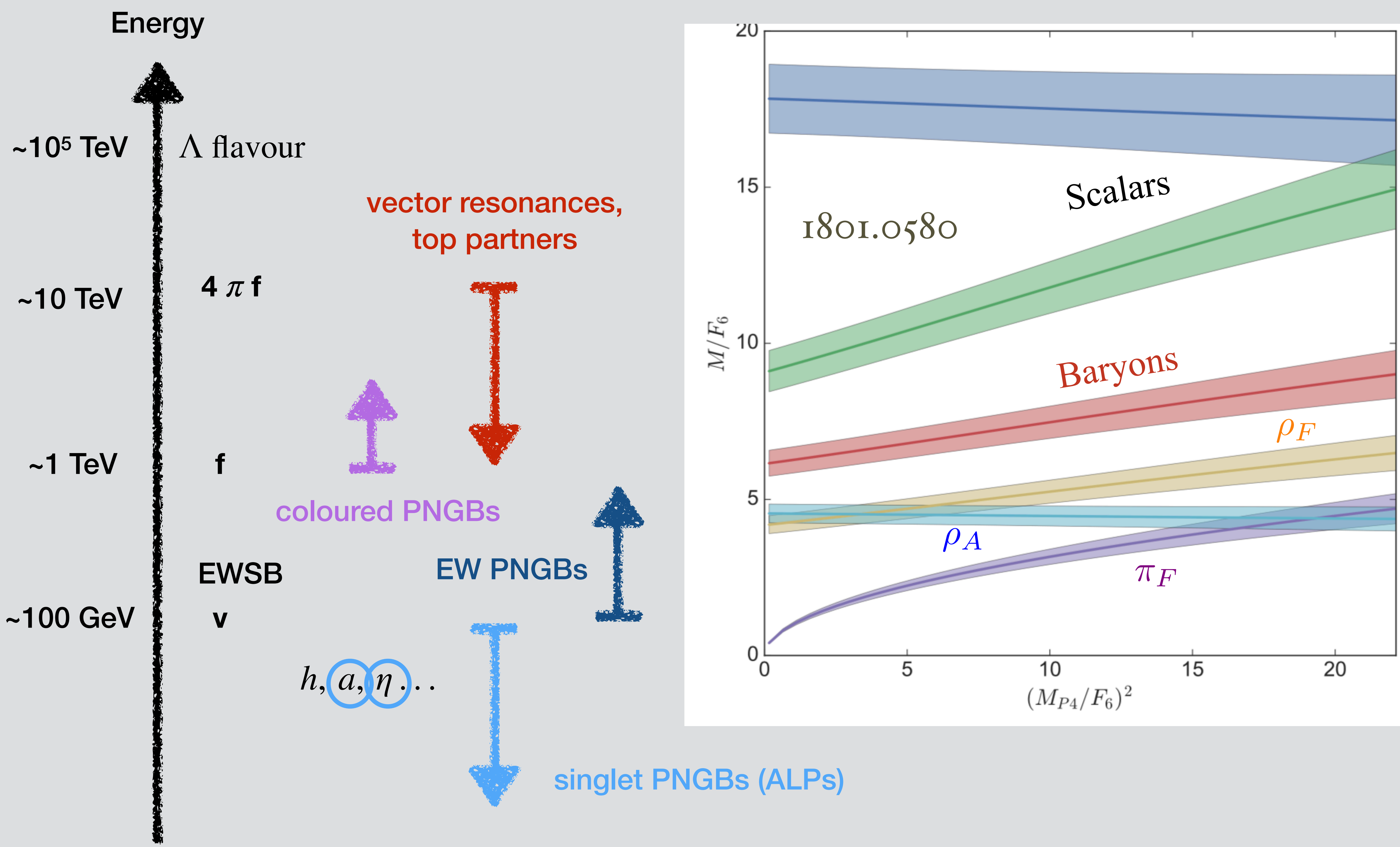
SM gauge symmetry



"pions"   h, W_L, Z_L

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

Strong dynamics: energy scales



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

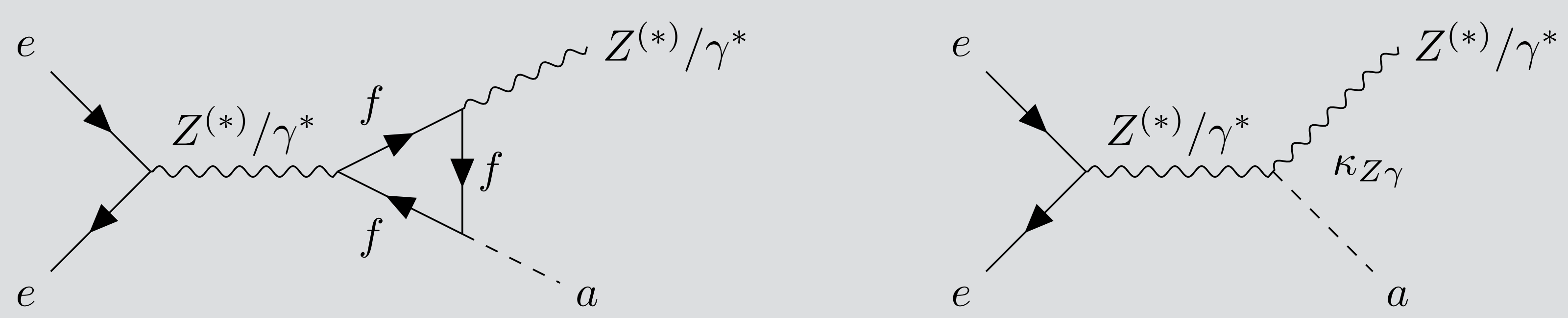
Cacciapaglia et al 1902.06890

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.

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



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

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

see 1710.11142, 1902.06890, 2004.09825

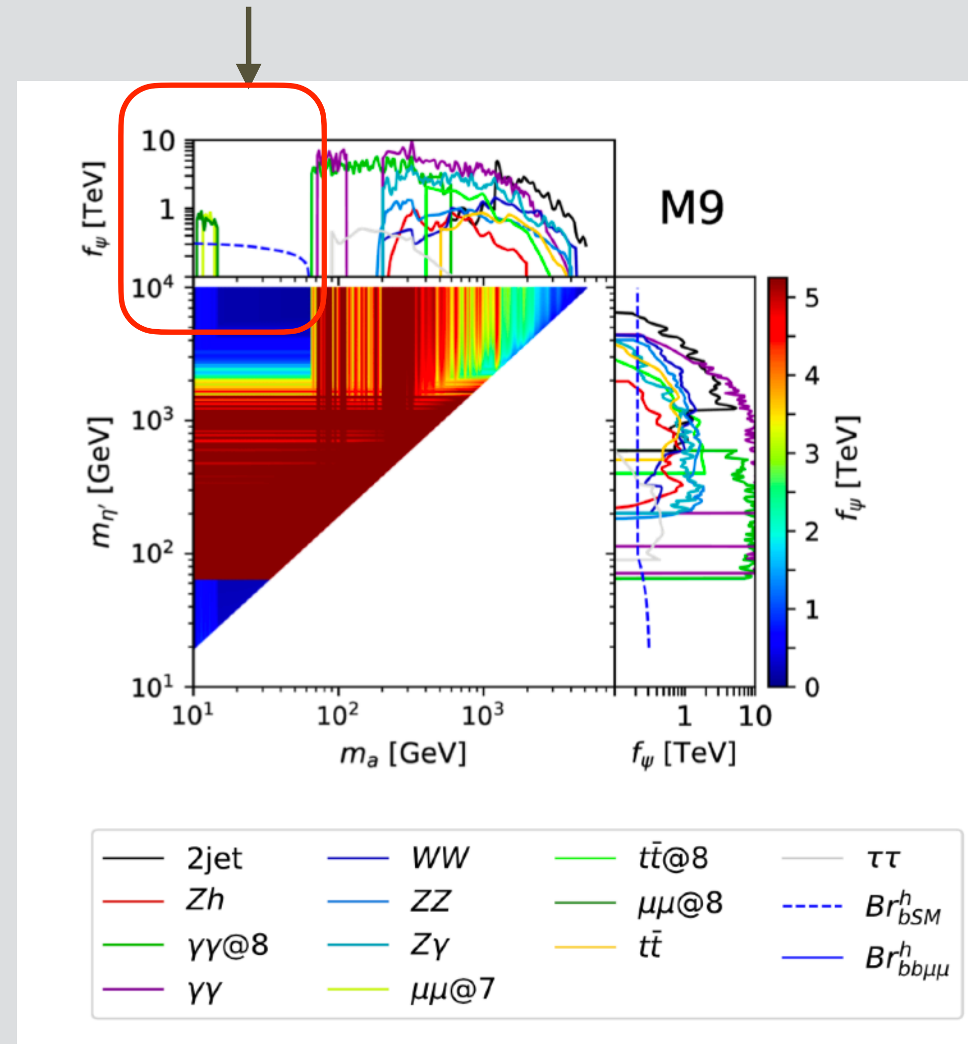
$U(1)$ pseudo-scalars

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

Poorly constrained region

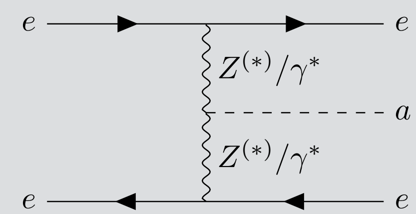


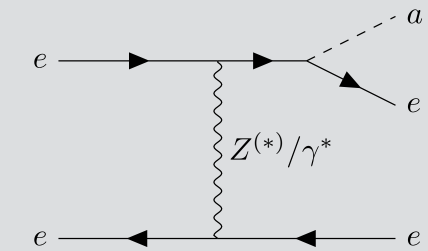
G. Cacciapaglia, G. Ferretti, T. Flacke, and H. Serôdio *Front.in Phys.*, vol. 7, p. 22, 2019.

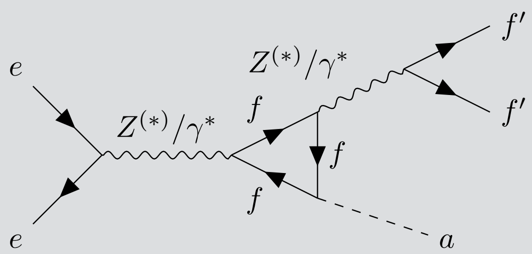
(Top band: bounds from a. Side band: bounds from η .
Bounds on f_ψ computed individually and then most stringent bound chosen)

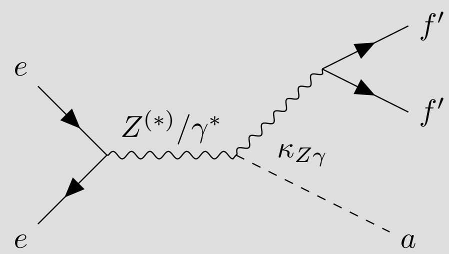
Production at FCC-ee

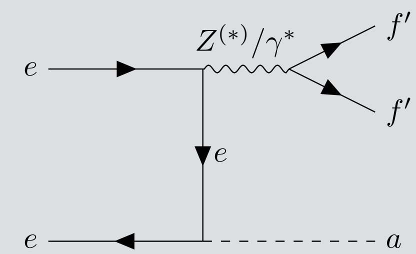
production in association with a (virtual or real) boson: $e^+e^- \to \ell^+\ell^- a$, $\quad e^+e^- \to jja$

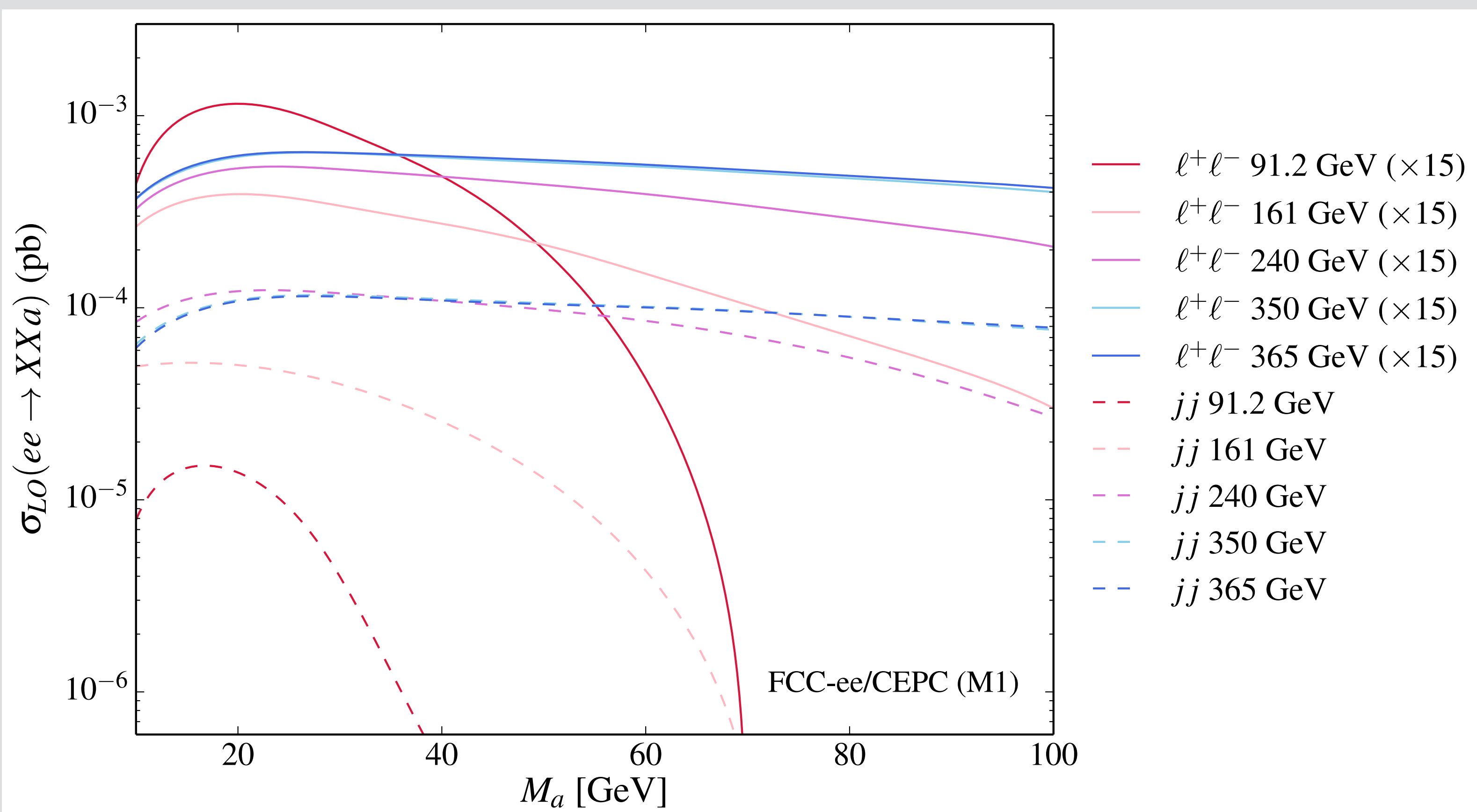












Mass range of interest is well covered, even at the Z pole

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

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

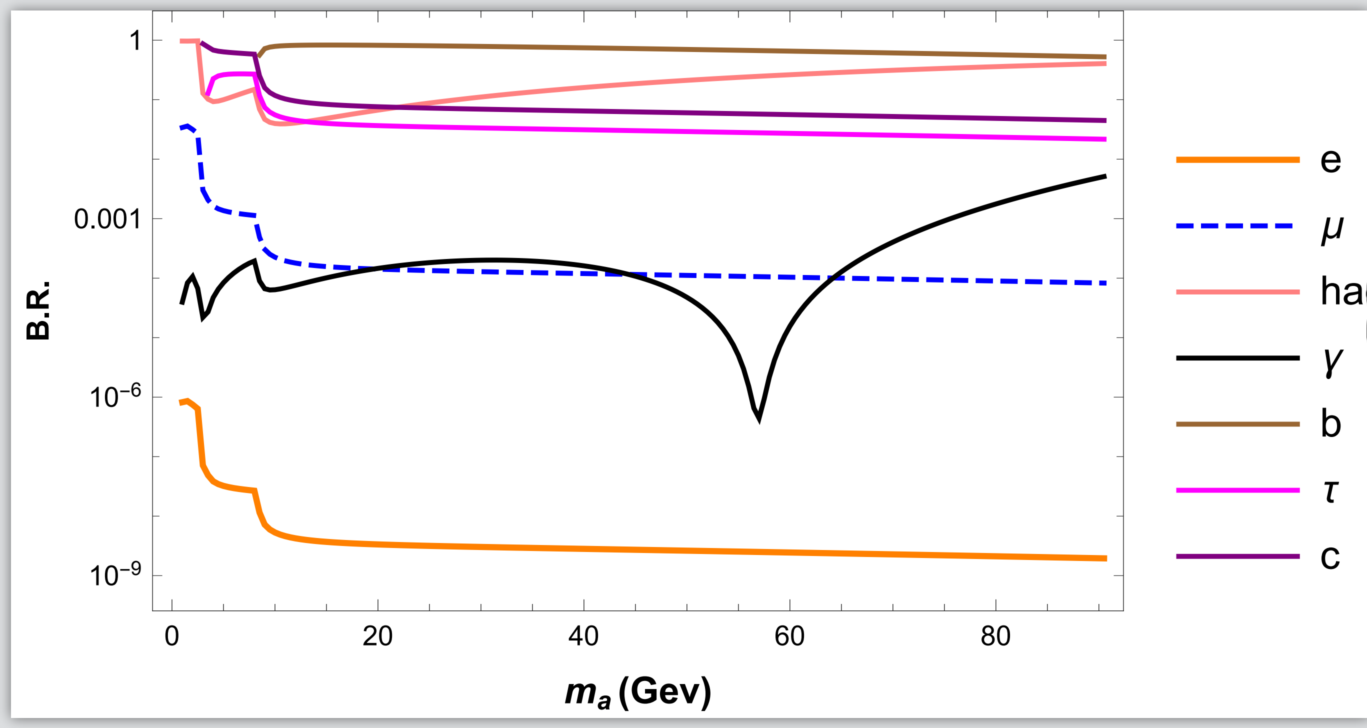
$$\Delta R(\ell, \ell') > 0.4 , \qquad \Delta R(j, j') > 0.4 .$$

Decays

Via coupling to fermions, ex. a $\rightarrow \tau\tau$ or WZW terms a $\rightarrow \gamma\gamma$

see 2104.11064

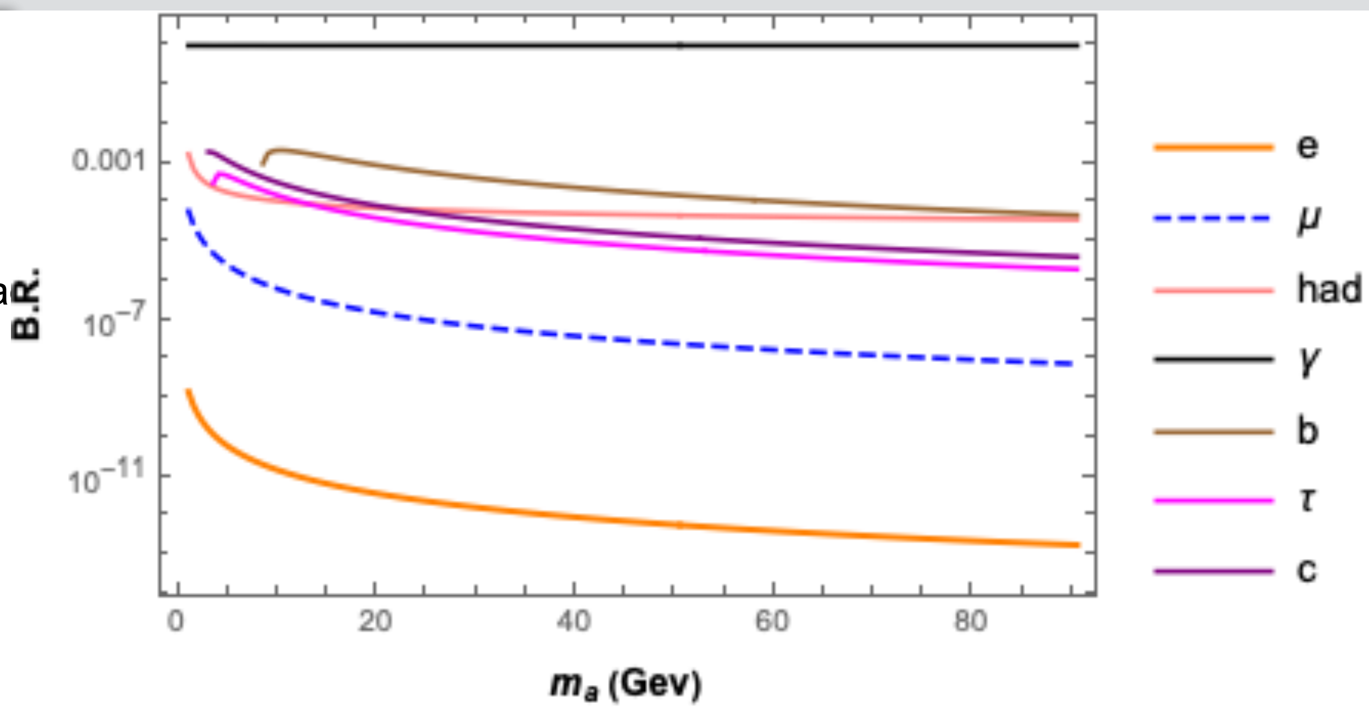
Photophobic



No leading order coupling to photons (WZW interaction is Zero)

eg. SU(4)/SP(4), SU(4)xSU(4)/SU(4)

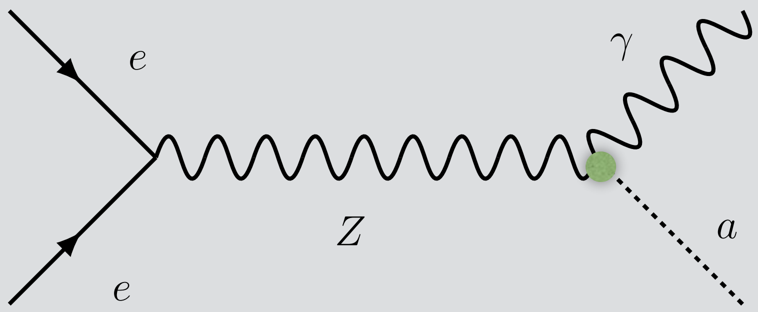
Photophilic



WZW interaction to photons (like the pion)

eg. SU(5)/SO(5), SU(6)/SO(6)

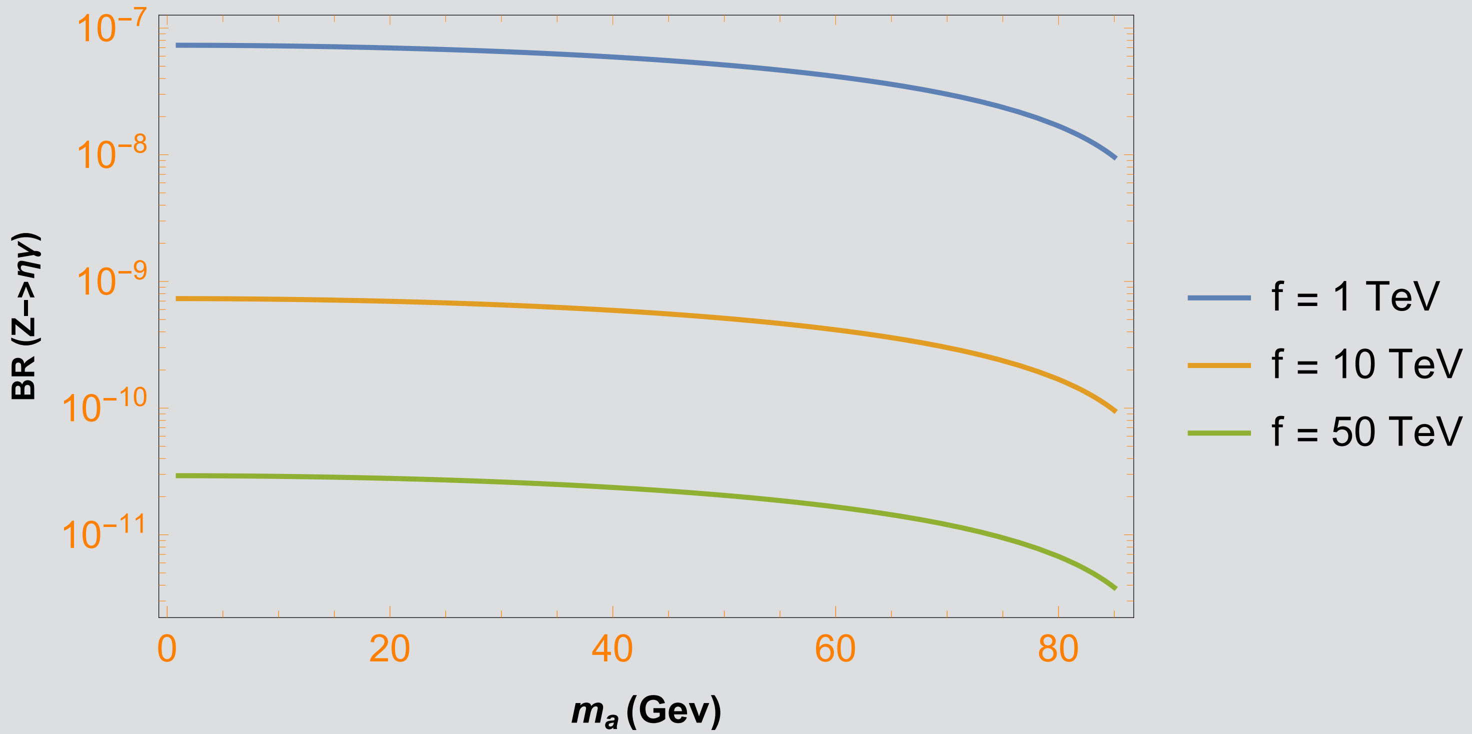
A portal to compositeness

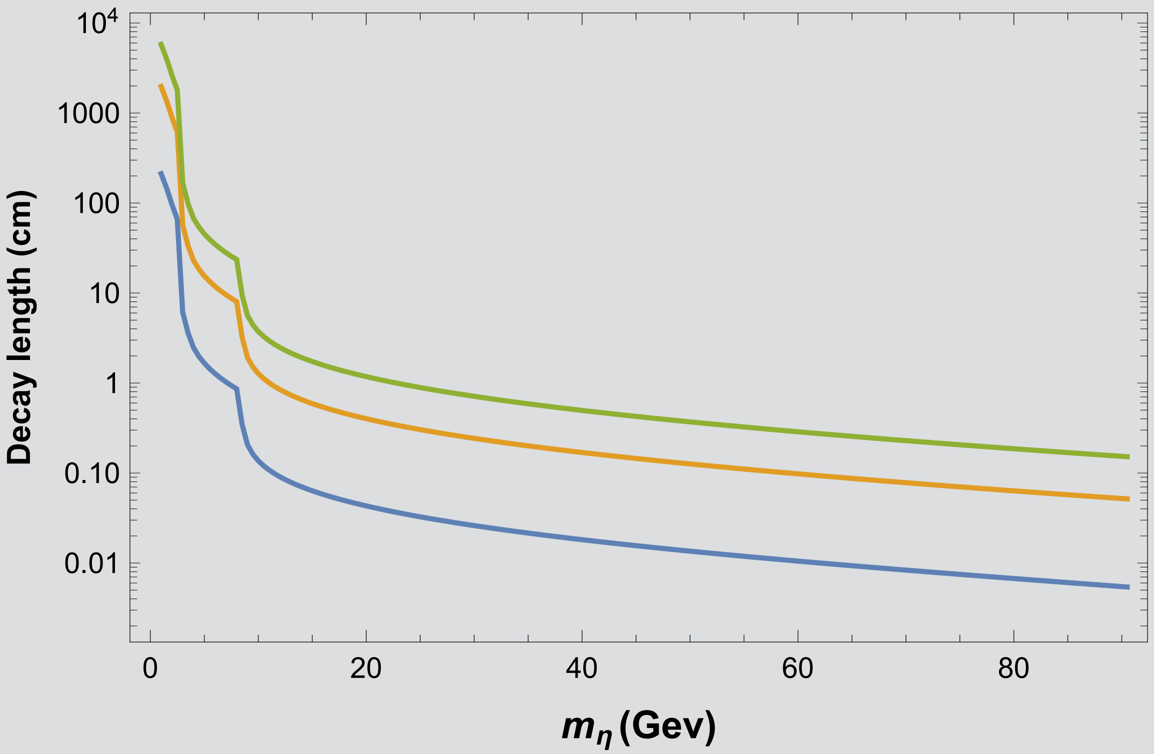


This process is always associated with a monochromatic photon.

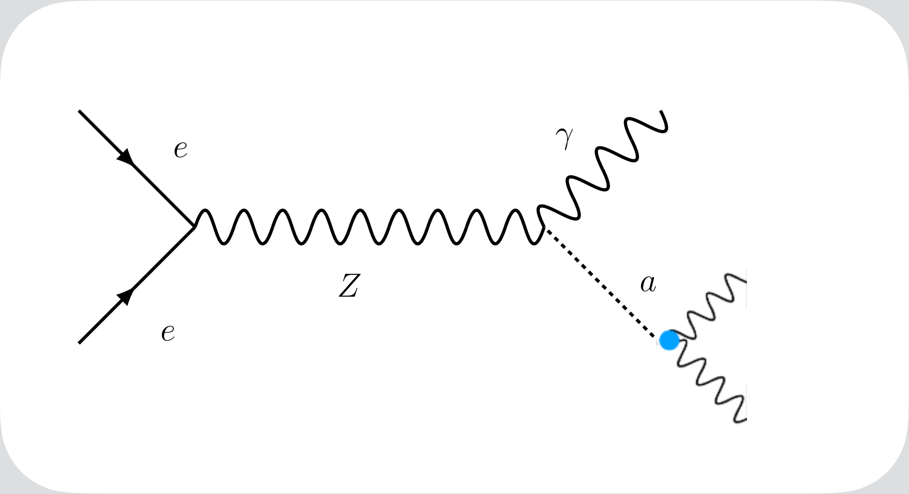
Tera Z phase of FCC-ee will lead to 5-6 10^{12} Z bosons at the end of the run.

Ideal test for rare Z decays!!





Prompt decays

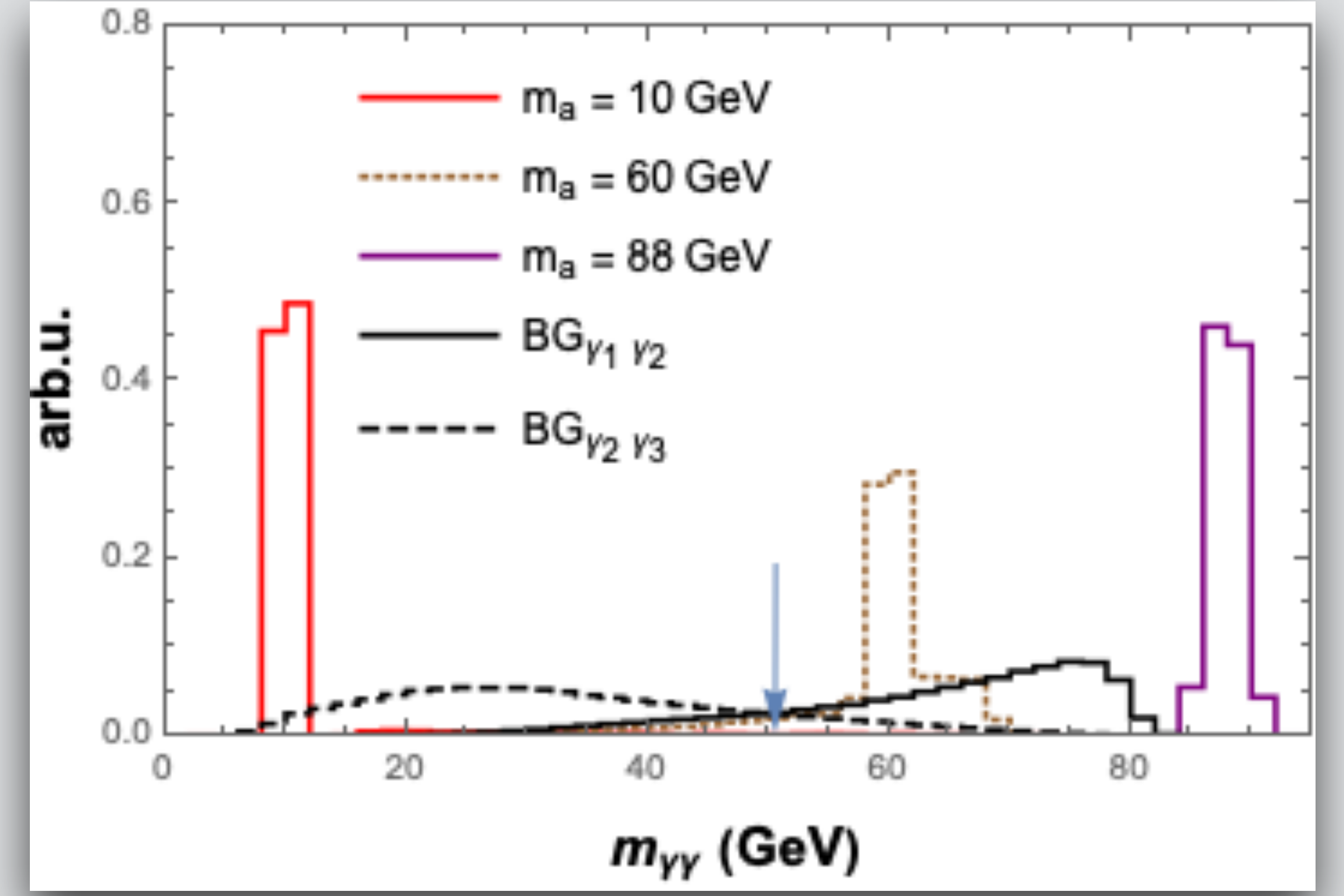


Three isolated photons
$BR(Z \to 3\gamma)_{LEP} < 2.2 \cdot 10^{-6}$

Discriminating variable: invariant mass

Photon ordering changes at inv. mass 50 GeV

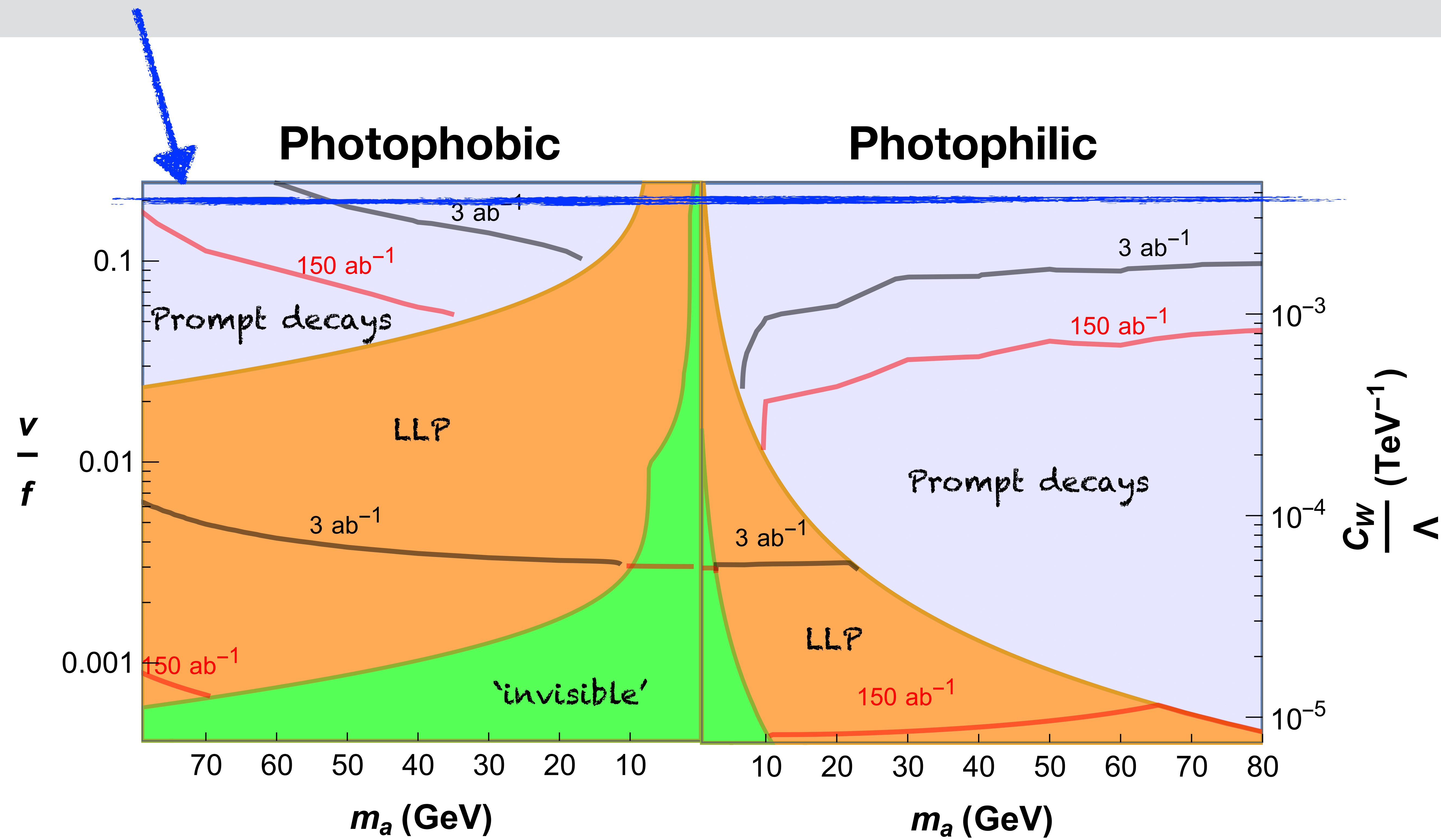
Bins above 80 GeV populated by fakes: hard to estimate



Photophobic vs photophilic

Typical EWPT bound

see 2104.11064

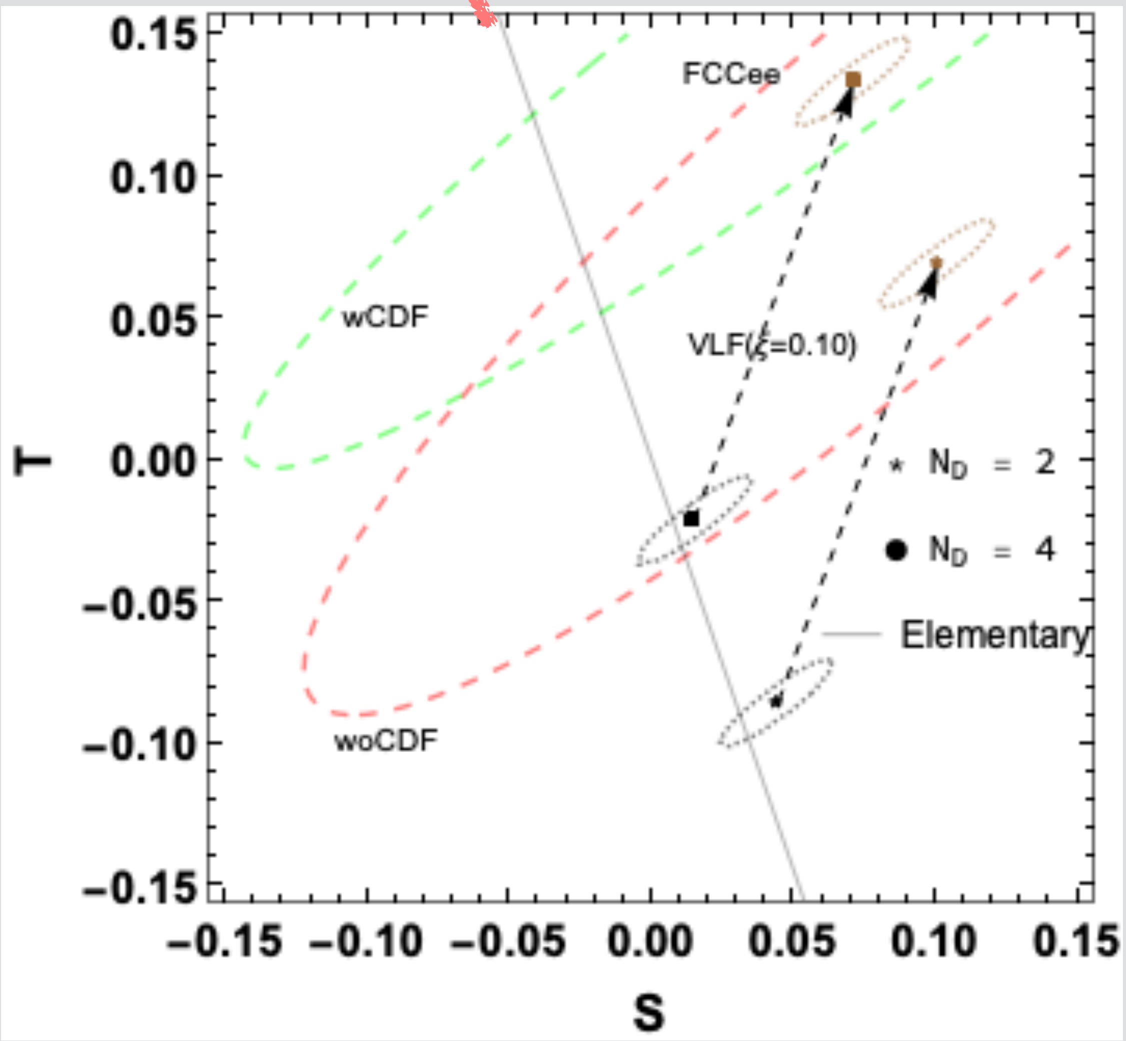


Elementary vs composite

see 2211.0091

EWPT only depend on H loops in the elementary case

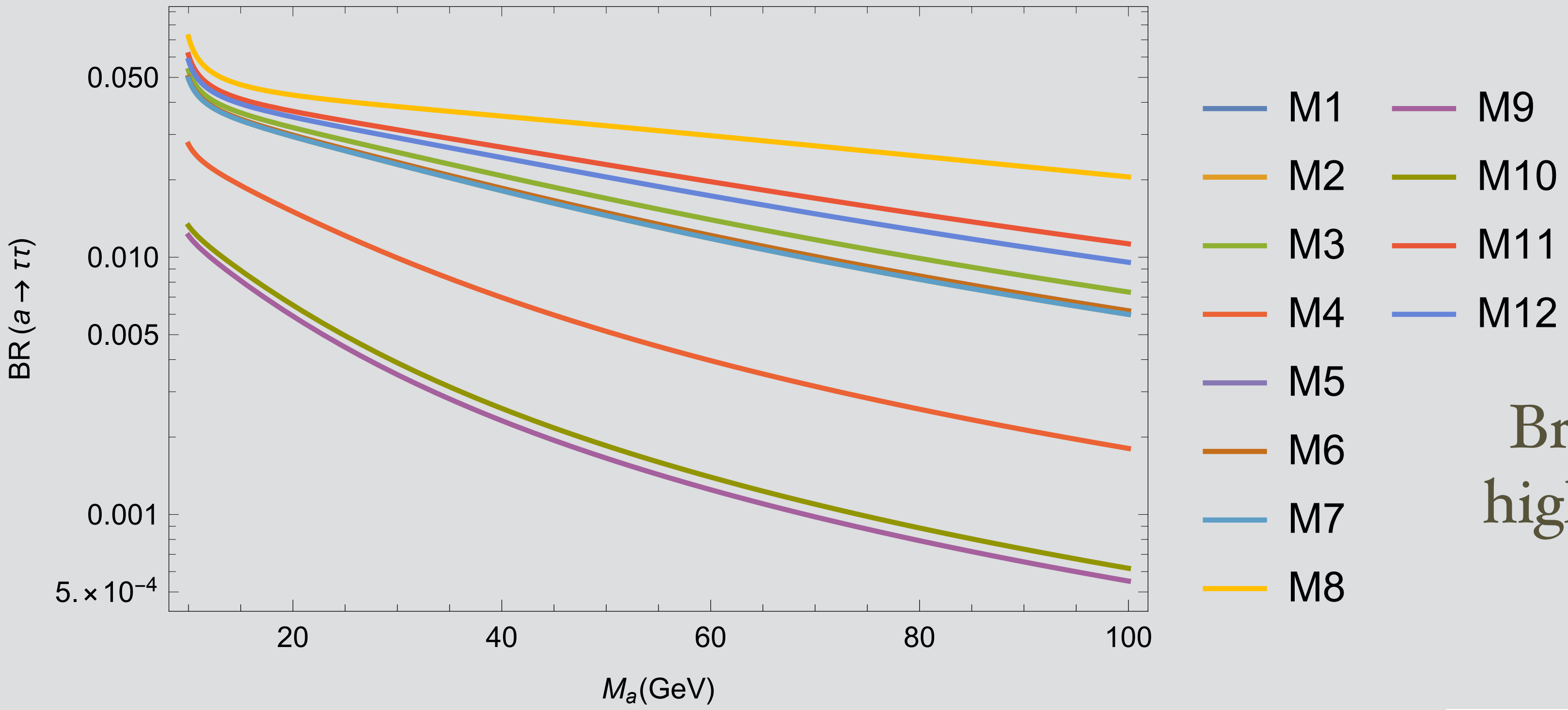
composite case: see 1502.04718



For fixed BR = 10^{-8}, i.e. discovery.

Arrows: “naive” contribution of top partner loops.

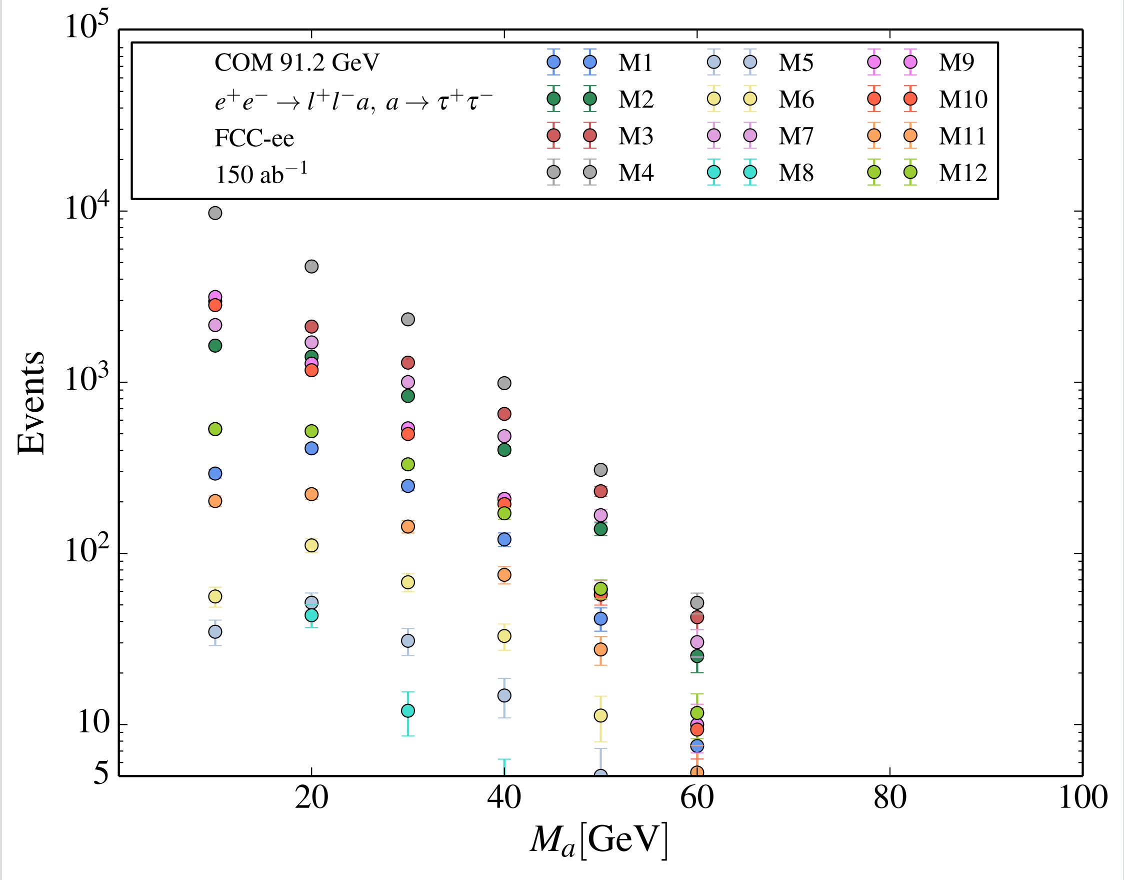
$\tau\tau$ decay



see 2004.09825

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

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

- Following preselection, we expect about 50,000 background events and up to 40 signal events (maximal production at $M_a = 20/30\ \text{GeV}$)
- 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.

Perspectives and outlook

- Light pseudo-scalars are ubiquitous (in CH and elsewhere)
- U(1) pNGB (di-bosons), coloured pNGBs (gluon photon), EW pNGBs (W photon, ...)
- A Tera-Z run will fully test the presence of a light composite ALP beyond ~ 10 TeV
- results will strongly constraint the model building and guide the following high energy pp phase.