Search for light pNGB with taus:

The promising mass window of 15 to 65 GeV

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based on:

A. Belyaev, G. Cacciapaglia, H. Cai, T. Flacke, **HS**, A. Parolini [PRD 94 (2016) no 1, 015004]
A. Belyaev, G. Cacciapaglia, H. Cai, G. Ferretti, T. Flacke, **HS**, A. Parolini [JHEP 1701 (2017) 094]
G. Cacciapaglia, G. Ferretti, T. Flacke, **HS**, [arXiv: 1710.11142]

Workshop on the physics of HL-LHC, and perspectives at HE-LHC
June 18, 2018

Outline

Composite Higgs and Underlying Dynamics

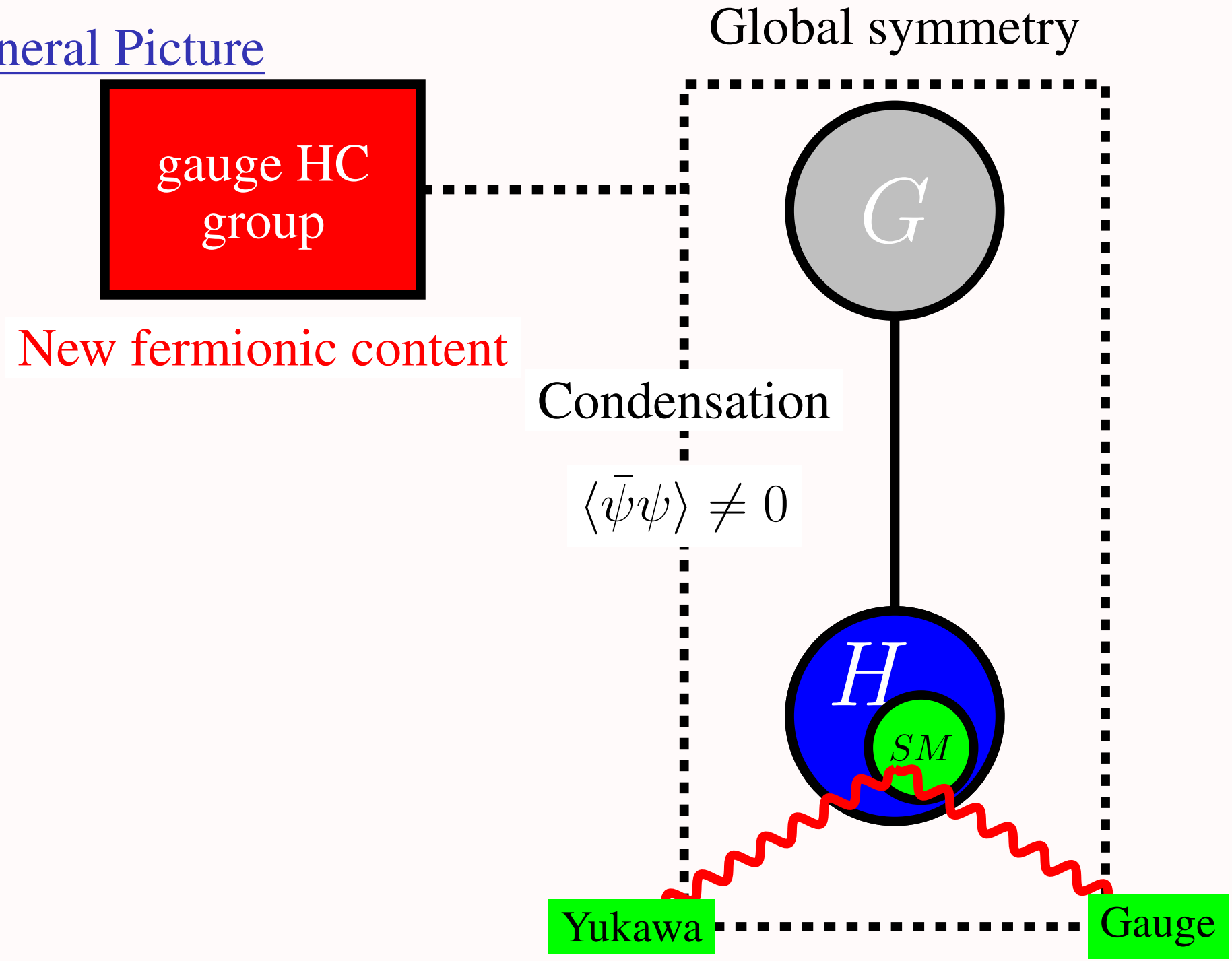
Timid composite pseudo-scalar (TCP)

Search for light pseudo-scalar with taus

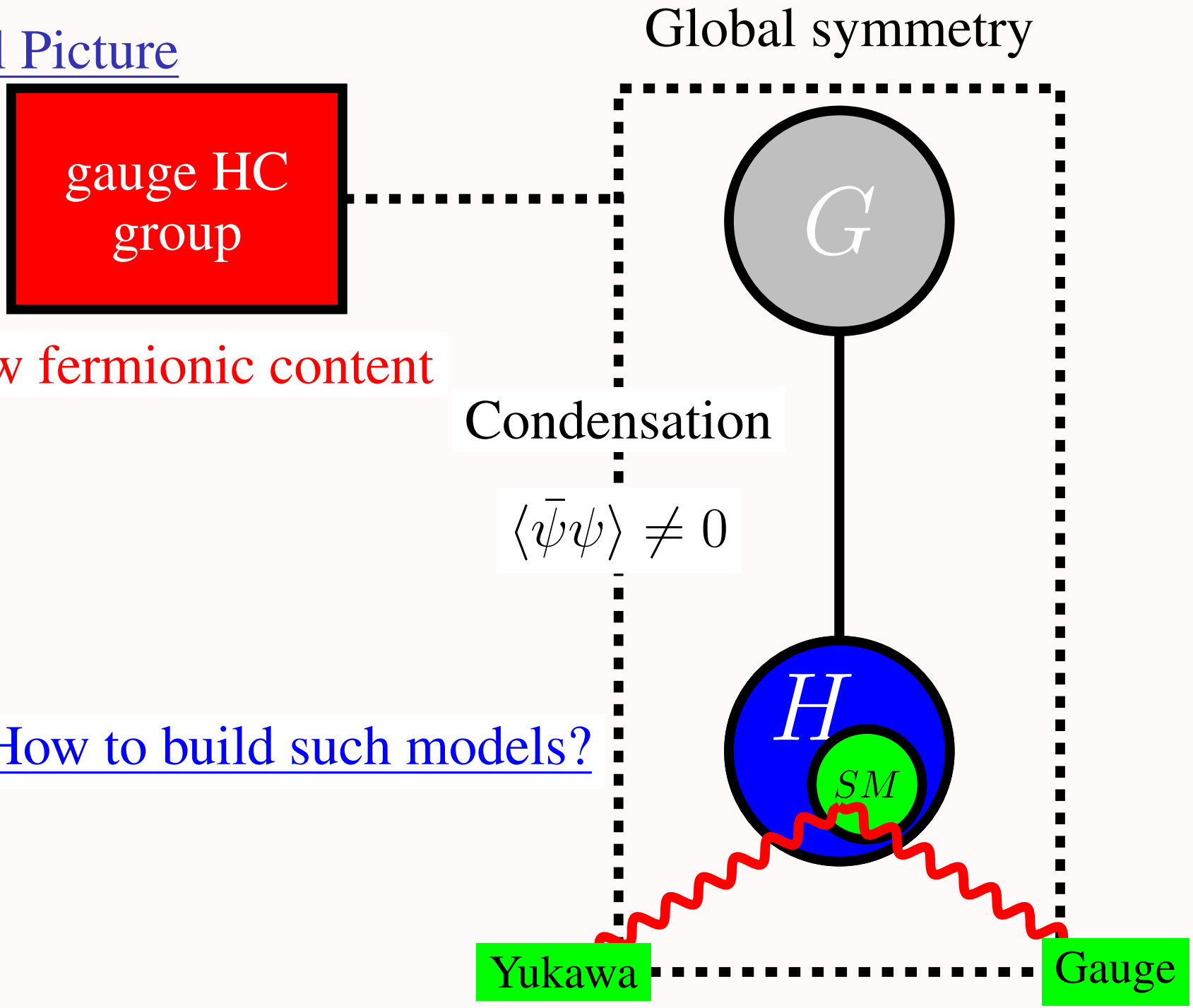
Conclusions/Outlook

Composite Higgs and Underlying Dynamics

General Picture



General Picture



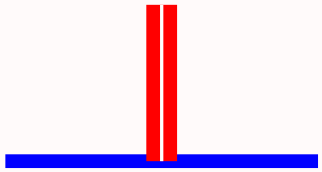
How to build such models?

Fermion masses

The bilinear approach.

(as in Technicolor)

[Dimopoulos, Susskind], [Eichten, Lane]

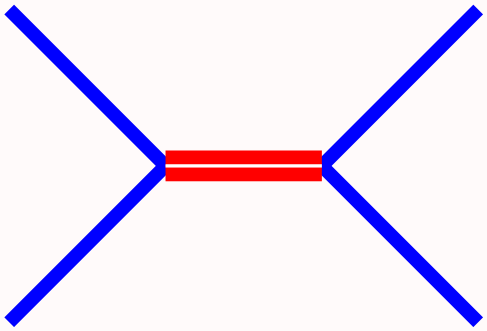


$$\frac{\lambda_t}{\Lambda_{UV}^{d-1}} \overline{q}_L \mathcal{O} t_R + \text{h.c.}$$

$\mathcal{O}$ carries Higgs quantum numbers.

Alert: dangerous 4-fermion operators

[Dimopoulus, Ellis]



The linear approach

(Partial Compositeness)

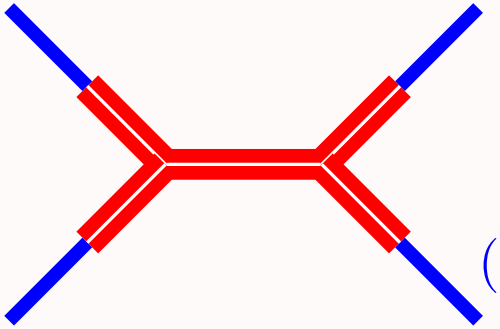
[Kaplan]

$$\frac{\lambda_{q_L}}{\Lambda_{UV}^{dL-5/2}} \overline{\mathcal{O}_R} q_L + \frac{\lambda_{t_R}}{\Lambda_{UV}^{dL-5/2}} \overline{\mathcal{O}_L} t_R + \text{h.c.}$$

$\mathcal{O}_{L,R}$ fermionic operators carrying quarks quantum numbers.

$$|\text{SM}\rangle = \cos\varphi\, |\text{elem}\rangle + \sin\varphi\, |\text{comp}\rangle$$

Better: 4-fermion operators



GIM-like:

$$(\bar{q}q)^2 \frac{\sin^4\varphi}{M_*^2}$$

Underline theories

Building an underlying theory that contains both a composite Higgs and composite top partners is not an easy task, as many conditions need to be satisfied: [Ferretti, Karateev]

- Simple hypercolor group (G_{HC})
- Asymptotically free theories
- Absence of gauge anomalies and Witten's global anomalies
- Symmetry breaking pattern: $G_F \to H_F \supset C_{cus} \supset G_{SM}$
- The most attractive channel (MAC) should not break neither G_{HC} nor G_{cus}
- $G/H \ni (\mathbf{1}, \mathbf{2}, \mathbf{2})_0$ of G_{cus}. (the Higgs boson)
- Fermionic hypercolor singlets $\in (\mathbf{3}, \mathbf{2})_{1/6}$ and $(\mathbf{3}, \mathbf{1})_{2/3}$ of G_{SM} (at least 3rd family) (Top-partners)
- B and L symmetry

We shall consider models with two chiral fermion species, each with n_i flavours:

Global symmetry: $U(n_\psi) \times U(n_\chi)$

- Colourless ψ, which produce the Higgs as a pNGB, after condensation occurs;
- Colourfull χ, since we want to obtain the top partners.

EW coset

- Complex: $\dfrac{SU(4) \times SU(4)'}{SU(4)_D}$
- Pseudoreal: $\dfrac{SU(4)}{Sp(4)}$
- Real: $\dfrac{SU(5)}{SO(5)}$

Colour coset

- Complex: $\dfrac{SU(3) \times SU(3)'}{SU(3)_D}$
- Pseudoreal: $\dfrac{SU(6)}{Sp(6)}$
- Real: $\dfrac{SU(6)}{SO(6)}$

Coset	HC	ψ	χ	$-q_\chi/q_\psi$	Y_χ	Model
$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{SO(6)}$	$SO(7)$ $SO(9)$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$5/6$ $5/12$	1/3	M1 M2
	$SO(7)$ $SO(9)$	$5 \times \mathbf{Spin}$	$6 \times \mathrm{F}$	$5/6$ $5/3$	2/3	M3 M4
$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{Sp(6)}$	$Sp(4)$	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	$5/3$	1/3	M5
$\frac{SU(5)}{SO(5)} \times \frac{SU(3)^2}{SU(3)}$	$SU(4)$ $SO(10)$	$5 \times \mathbf{A}_2$ $5 \times \mathbf{F}$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$ $3 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$5/3$ $5/12$	1/3	M6 M7
$\frac{SU(4)}{Sp(4)} \times \frac{SU(6)}{SO(6)}$	$Sp(4)$ $SO(11)$	$4 \times \mathbf{F}$ $4 \times \mathbf{Spin}$	$6 \times \mathbf{A}_2$ $6 \times \mathbf{F}$	$1/3$ $8/3$	2/3	M8 M9
$\frac{SU(4)^2}{SU(4)} \times \frac{SU(6)}{SO(6)}$	$SO(10)$ $SU(4)$	$4 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$ $4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{F}$ $6 \times \mathbf{A}_2$	$8/3$ $2/3$	2/3	M10 M11
$\frac{SU(4)^2}{SU(4)} \times \frac{SU(3)^2}{SU(3)}$	$SU(5)$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}_2})$	$4/9$	2/3	M12

Always 2 $U(1)$s that are spontaneously broken: $U(1)_\psi$, $U(1)_\chi$.
One combination of the two has an anomaly with the G_{HC}

$$U(1)_{\psi,\chi} G_{HC}^2 \neq 0 \quad \Rightarrow \quad [U(1)_\psi + U(1)_\chi]\, G_{HC}^2 \neq 0$$

For the anomaly free light pNGB, we have $q_\psi N_\psi T(\psi) + q_\chi N_\chi T(\chi) = 0$

Timid composite pseudo-scalar

A timid composite pseudo-scalar (TCP)

The pNGBs $\phi = \{a,\, \eta'\}$ can be both described by the effective Lagrangian.

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu\phi\partial^\mu\phi - M_\phi^2\phi^2\right) - \sum_f i\, C_f \frac{m_f}{f_\phi}\phi\, \overline{\Psi}_f\gamma_5\Psi_f$$

$$+ \frac{\phi}{f_\phi}\left(\frac{g_s^2 K_g}{16\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{g^2 K_W}{16\pi^2}W^i_{\mu\nu}\tilde{W}^{i\mu\nu} + \frac{g'^2 K_B}{16\pi^2}B_{\mu\nu}B^{\mu\nu}\right)$$

- spurion mass term $-m_t(h)e^{iC_t a/f_a}\bar{\Psi}_{tL}\Psi_{tR}$
- WZW coefficients K_i are fully determined by ψ, χ quant. num.;
- C_f is also fixed for each individual model;
- $K_g^{\text{eff}} \simeq K_g - C_t/2$ (top loop)

Decoupling limit: $m_{\eta'} \gg m_a$

	K_g	K_W	K_B	C_f	f_a/f_ψ
M1	-7.2	7.6	2.8	2.2	2.1
M2	-8.7	12.	5.9	2.6	2.4
M3	-6.3	8.7	-8.2	2.2	2.8
M4	-11.	12.	-17.	1.5	2.0
M5	-4.9	3.6	0.40	1.5	1.4
M6	-4.9	4.4	1.1	1.5	1.4
M7	-8.7	13.	7.3	2.6	2.4
M8	-1.6	1.9	-2.3	1.9	2.8
M9	-10.	5.6	-22.	0.70	1.2
M10	-9.4	5.6	-19.	0.70	1.5
M11	-3.3	3.3	-5.5	1.7	3.1
M12	-4.1	4.6	-6.3	1.8	2.6

- Free parameters: M_a, $M_{\eta'}$ and f;
- Note: in general we have 4 independent scales $f_{a_\psi}, f_{a_\chi}, f_{a_\psi}, f_{a_\chi}$. Under resonable assumptions we can reduce it to a single scale $f(\equiv f_\psi)$. $m_w = (g/2)f\sin\theta$ ($\theta \to \pi/2$ Technicolor limit)

TCP Phenomenology: M6 and M8

We shall pick 2 models:

M6

$$SU(4)_{HC}: \quad \begin{cases} \psi \sim 5 \times \mathbf{A}_2 & \chi \sim 3 \times (\mathbf{F}, \overline{\mathbf{F}}) \\ \dfrac{SU(5)}{SO(5)} \quad \times & \dfrac{SU(3)^2}{SU(3)} \end{cases}$$

[Ferretti JHEP1406,142]

Lattice: [Ayyar,et al. arXiv:1801.05809]

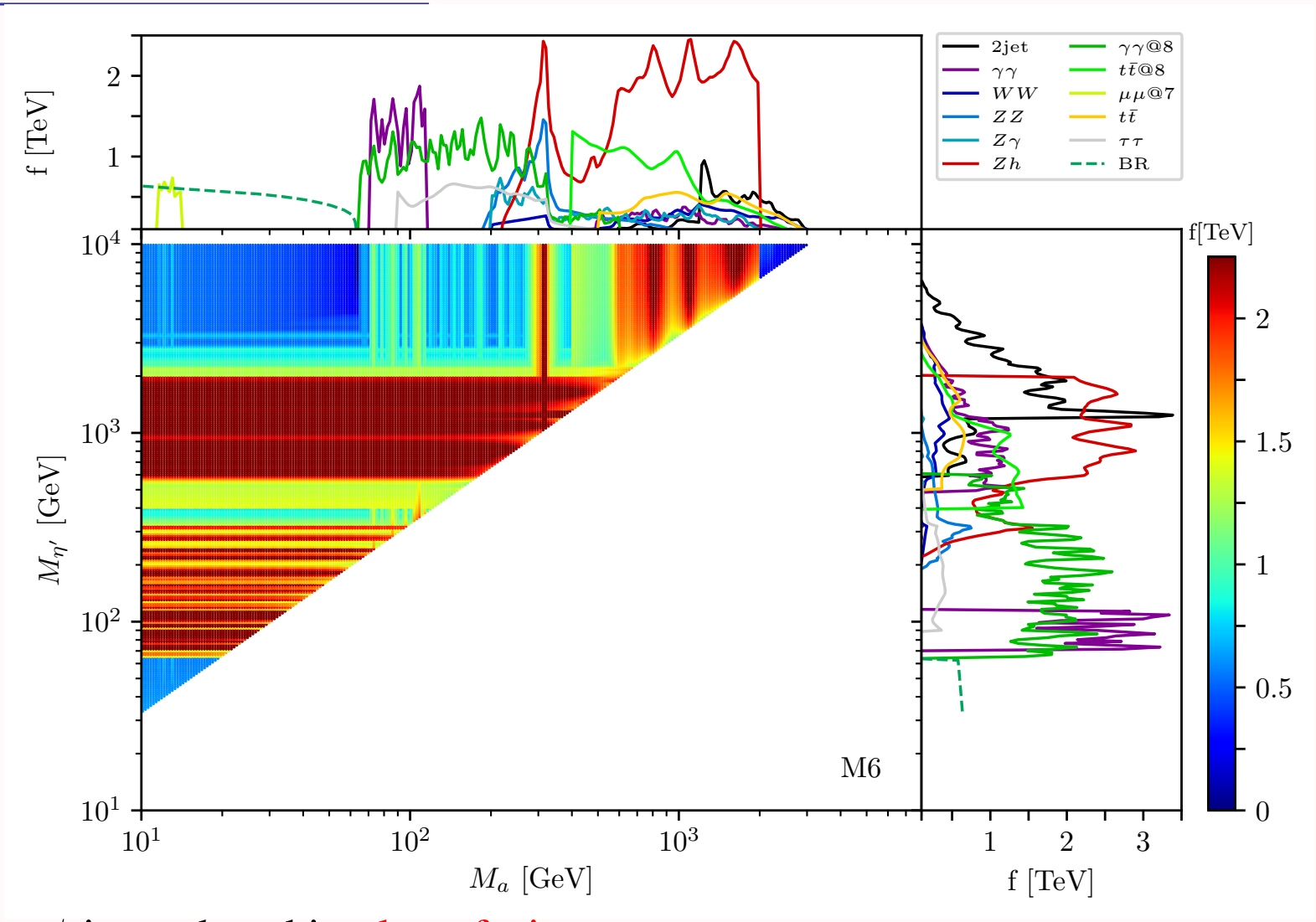
M8

$$Sp(4)_{HC}: \quad \begin{cases} \psi \sim 4 \times \mathbf{F} & \chi \sim 6 \times \mathbf{A}_2 \\ \dfrac{SU(4)}{Sp(4)} \quad \times & \dfrac{SU(6)}{SO(6)} \end{cases}$$

[Barnard,et al. JHEP1402,002]

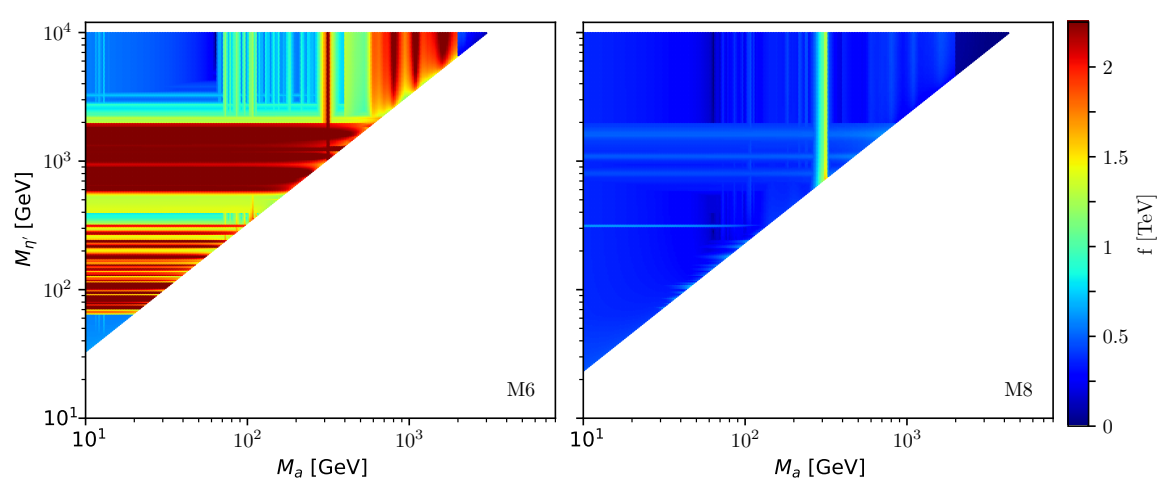
Lattice: [Bennett,et al. JHEP1803,185]

TCP Phenomenology



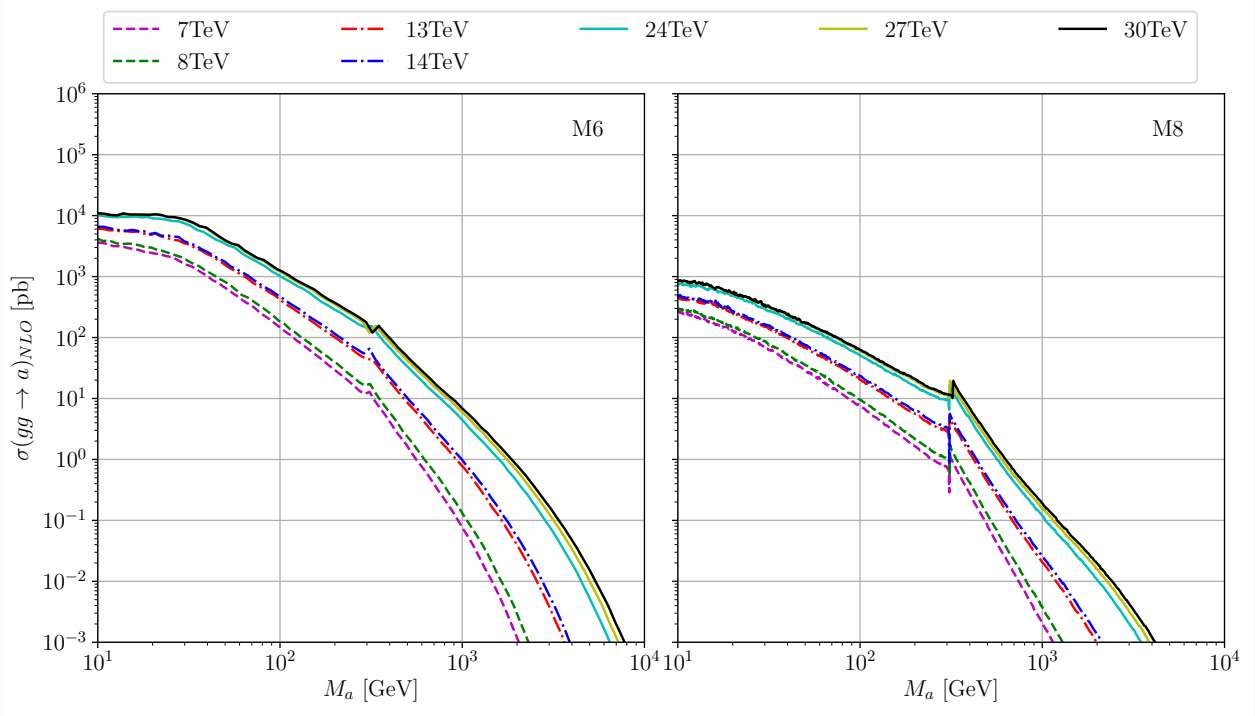
- ϕ is produced in gluon fusion;
- Small couplings to W and Z; Assc. production with a Z is tiny; No bounds from LEP;
- Weak indirect bounds from $h \to aa$ (BSM).

TCP Phenomenology: M6 and M8



- M8 weakly constrained;
- Decoupling limit and light a: needs exploration;

Large production XS for low masses (gluon fusion)

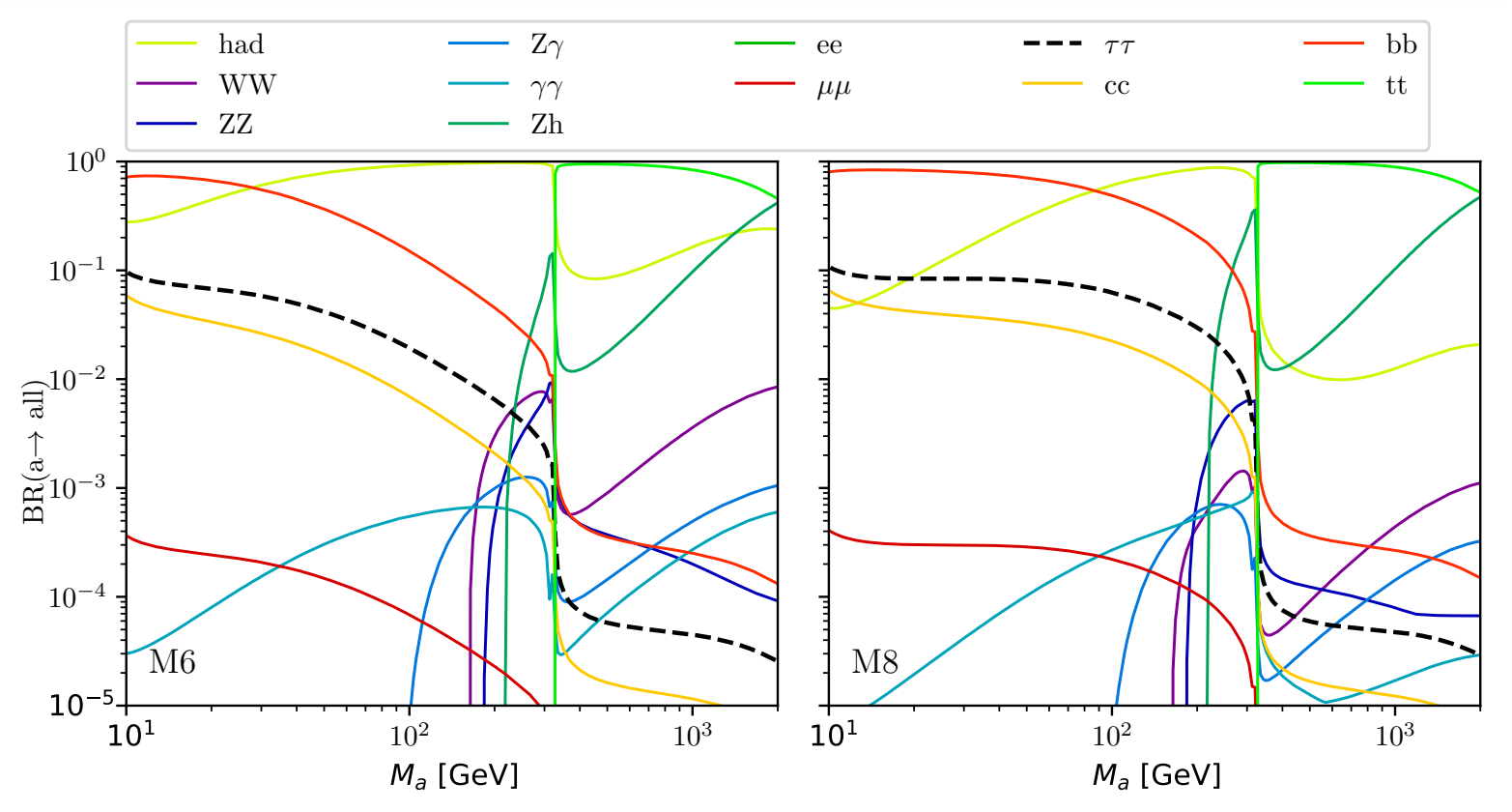


[HIGLU]

Search for light pseudo-scalar with taus

How to explore the mass gap 15 to 65 GeV?

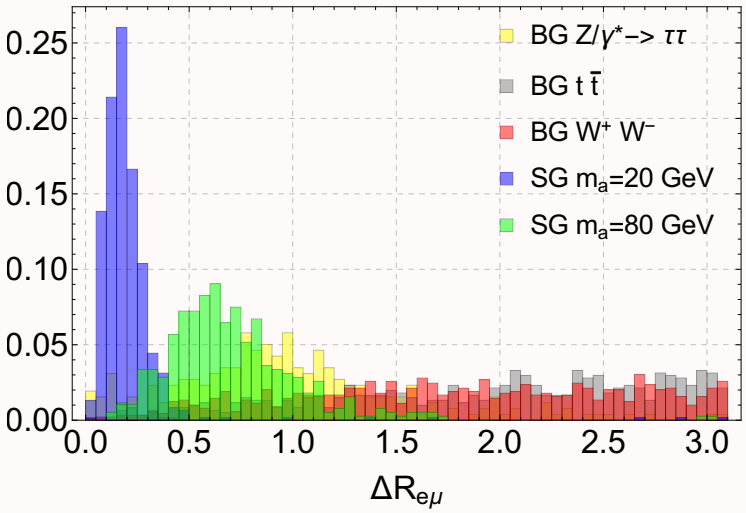
- $h \to aa$ (BSM) will not dramatically increase $f_a \sim BR(h \to aa)^{1/4}$
- Extending $\mu\mu$ resonance searches to higher mass?
- Extending $\gamma\gamma$ resonance searches to even lower mass?
- ...or looking for other decay channels: $\tau\tau$!



- Soft τ_{lep} of τ_{had} can not be used to trigger. But ISR can boost $gg \to a \to \tau\tau$ system;
- Prod. XS for a gets reduced. Not a big problem.

How to explore the mass gap 15 to 65 GeV?

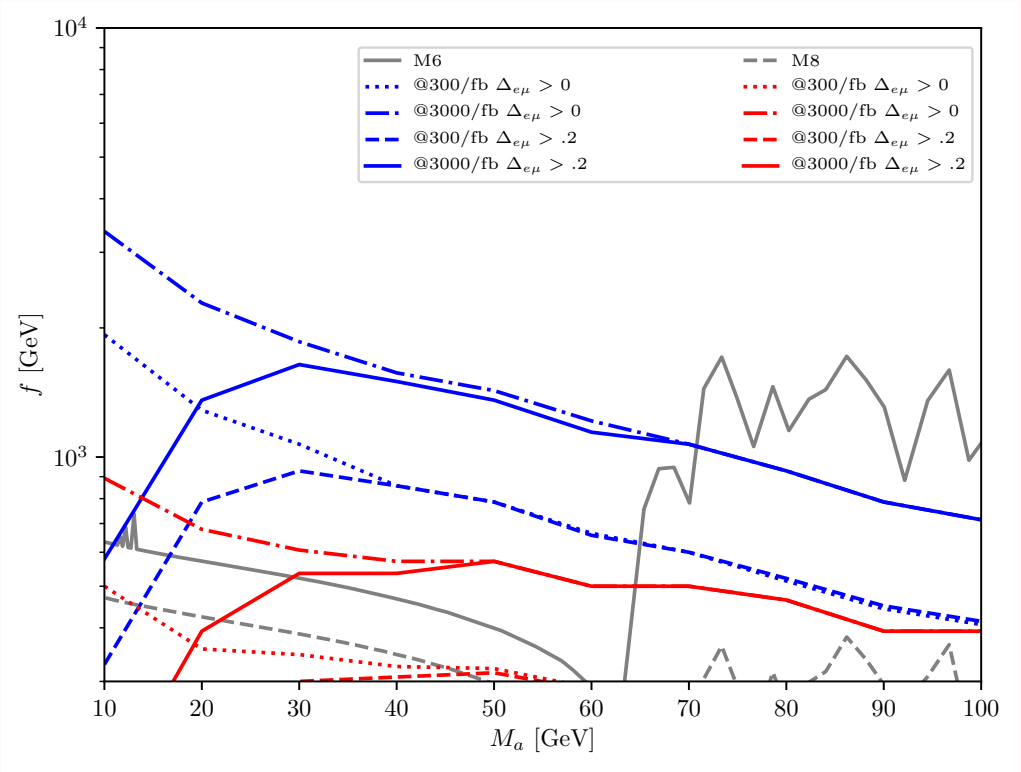
- Proof of principle analysis: $j\tau_\mu\tau_e$
- Cuts: $p_{T\mu} > 52$ GeV; $p_{T\mu} > 10$ GeV; $p_{T\mu} > 10$ GeV; $p_{Tj} > 150$ GeV; $m_{\mu e} < 100$ GeV; $\Delta R_{\mu j} > 0.5$; $\Delta R_{ej} > 0.5$; $\Delta R_{\mu e} < 1$;



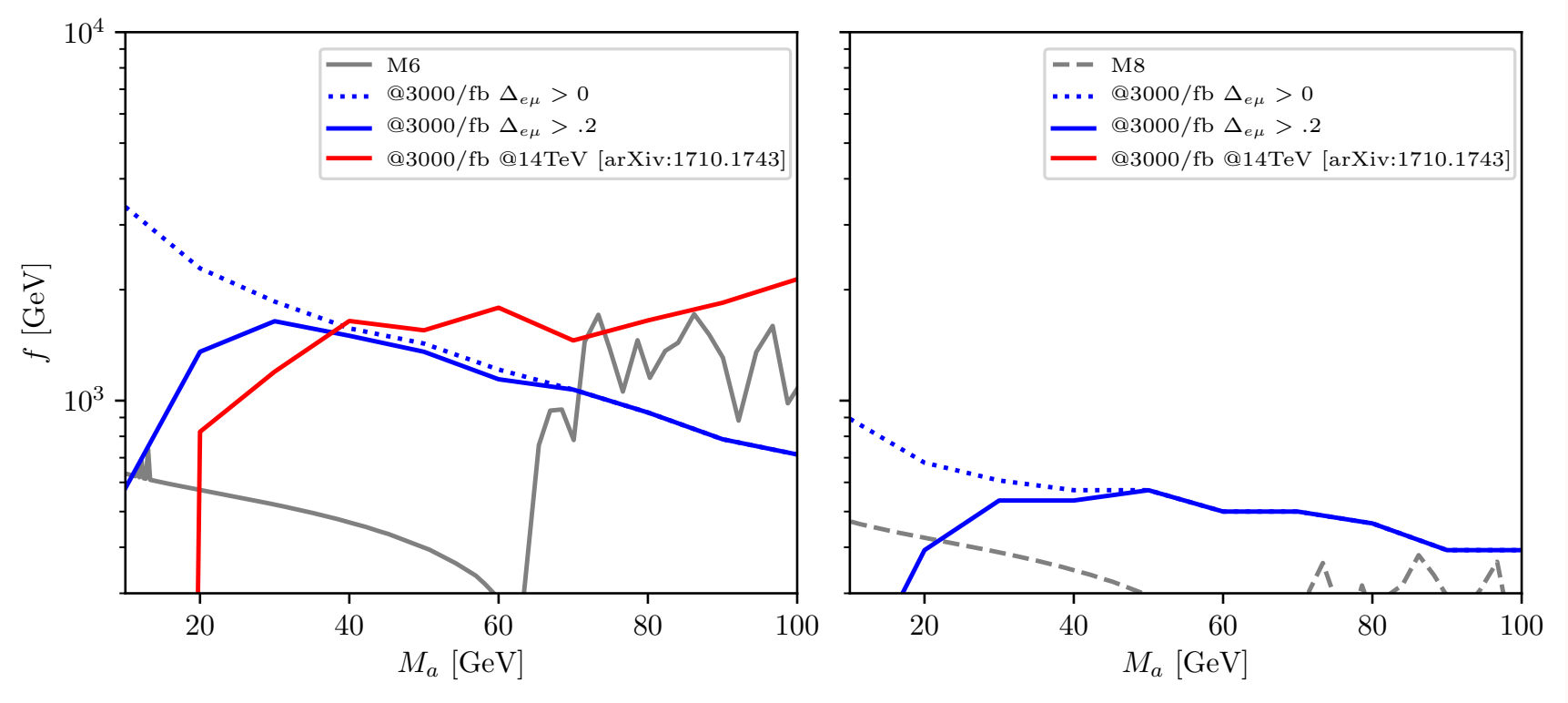
Crucial discriminating variable:

- $\Delta R_{\mu e} > 0$ or $\Delta R_{\mu e} > 0.2$

- Generate signal sample $pp \to a \to \tau^+\tau^-$.
- Projected reach after an integrated Luminosity of 300 fb^{-1} and 3000 fb^{-1} @13TeV



How to explore the mass gap 15 to 65 GeV?



- Low-mass $\gamma\gamma$ resonances projections in red; [Mariotti,et al. 1710.01743]
- In some cases can be competitive with boosted $\tau\tau$.

Conclusions/Outlook

Conclusions/Outlook

- CHM provide a viable solution to the hierarchy problem with still many challenges and room for exploration;
- EFT descriptions of CHM are only a part of the story. UV embeddings need to be studied in detail, and they will lead to novel BSM signatures;
- UV descriptions generally contain a SM singlet pNGB which couples to the SM gauge bosons through the WZW term; Fully determined by the quantum numbers of the underlying fermions;
- In a mass range of 15 - 65 GeV, to our knowledge, none of the existing LEP, Tevatron, and LHC searches are sensitive to this pseudo-scalar. (*timid* composite pseudo-scalar (TCP))
- Searching for the TCP in the di-tau channel with ISR against which the di-tau system recoils looks promising. Initial study shows very good sensitivity in this mass window.
- Room for improvement in the analysis:
  - No use any τ ID or triggers.
  - More careful background analysis.
  - Systematic uncertainties.