# Composite Higgs
# and
# Timid Composite Pseudo-scalars

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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]

Partikeldagarna, Stockholm, November 7, 2017

# Outline

Composite Higgs and Underlying Dynamics

Timid composite pseudo-scalar (TCP)

Final remarks

# Composite Higgs
# and
# Underlying Dynamics

# Composite Higgs Models

The general idea:

- Extend the SM with a sector which via running of the couplings become strongly coupled at $\Lambda \ll M_{PL}$ with a global symmetry which gets broken by a condensate.
- Build the model such that the Goldstone sector includes the whole Higgs multiplet with quantum numbers of the SM Higgs.

Higgs is a Goldstone

$$V(H) = 0$$

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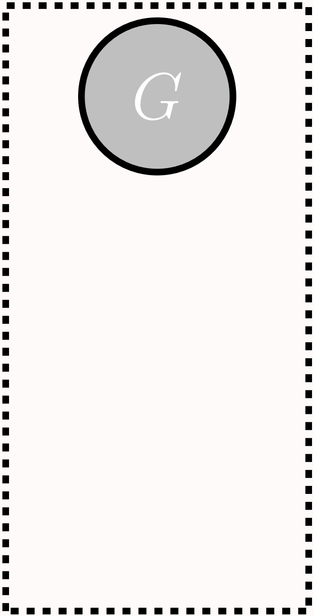
$$V(H) = 0$$

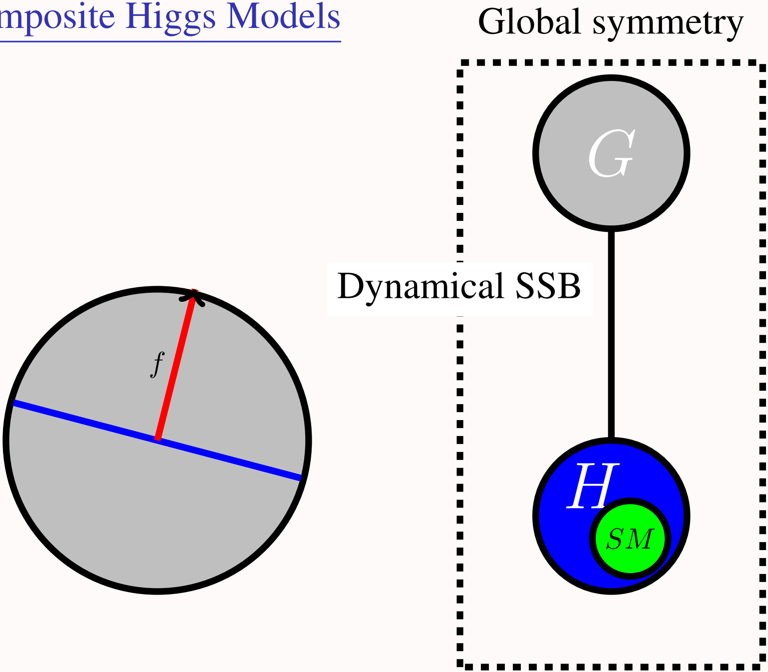
How to generate the scalar potential?

# Composite Higgs Models

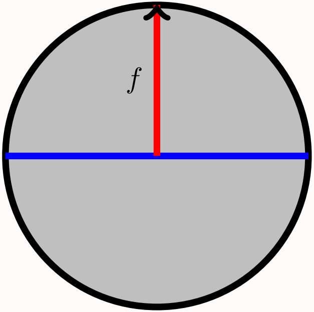
Global symmetry

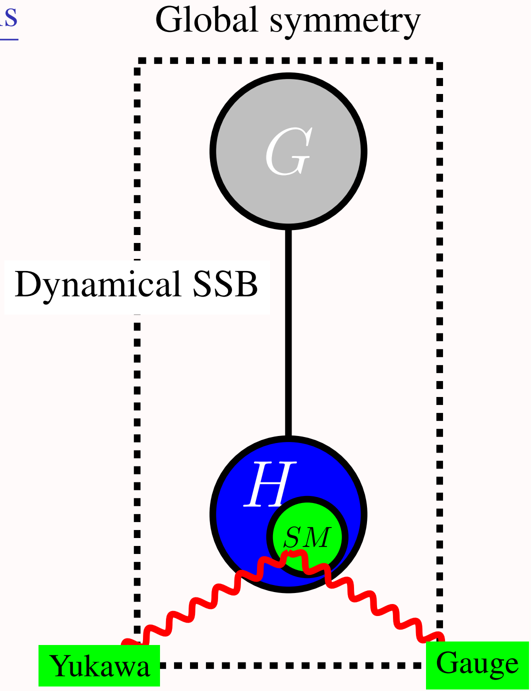


# Composite Higgs Models

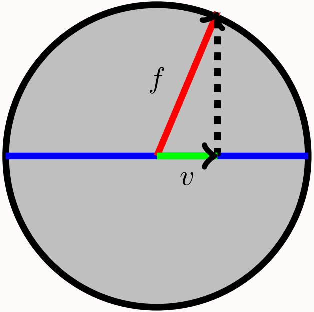


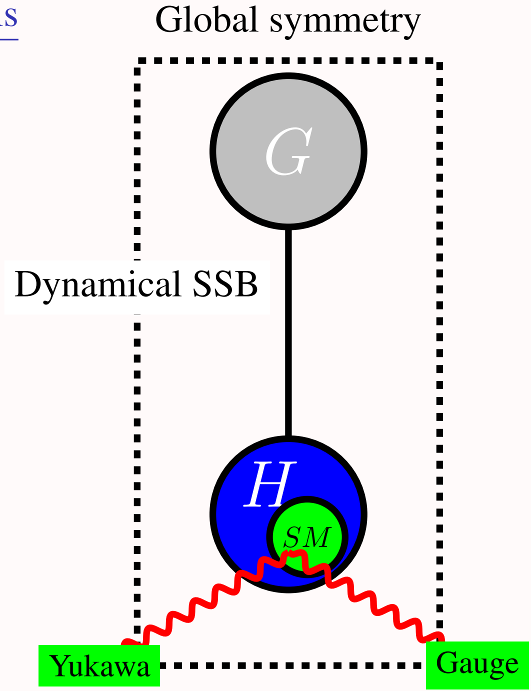
# Composite Higgs Models



# Composite Higgs Models

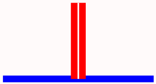


# Fermion masses: two approaches

**The bilinear approach**. (as in Technicolor)
[Dimopoulos, Susskind], [Eichten, Lane]

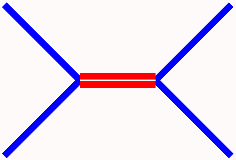
at the UV: $\frac{\lambda_t}{\Lambda_{UV}^{d-1}} \overline{q}_L \mathcal{O} t_R + \text{h.c.}$



$[\mathcal{O}] = d$ and carries the Higgs quantum numbers. Running down to $\Lambda$ (where the dynamics of SSB kicks in)

$$m_t \simeq \lambda_t v \left( \frac{\Lambda}{\Lambda_{UV}} \right)^{d-1}$$

**Alert:** dangerous 4-fermion operators [Dimopoulus, Ellis]



## **The linear approach** (Partial Compositeness) [Kaplan]

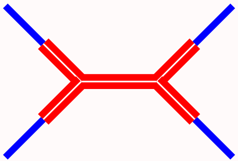
at the UV: $\frac{\lambda_{q_L}}{\Lambda_{UV}^{dL-5/2}}\overline{\mathcal{O}_R}q_L+\frac{\lambda_{t_R}}{\Lambda_{UV}^{dL-5/2}}\overline{\mathcal{O}_L}t_R+\text{h.c.}$

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

$$m_t \simeq \lambda_{q_L}\lambda_{t_R} v \left(\frac{\Lambda}{\Lambda_{UV}}\right)^{d_L+d_R-5}$$

$$|\text{SM}\rangle = \cos\varphi\,|\text{elementary}\rangle + \sin\varphi\,|\text{composite}\rangle$$

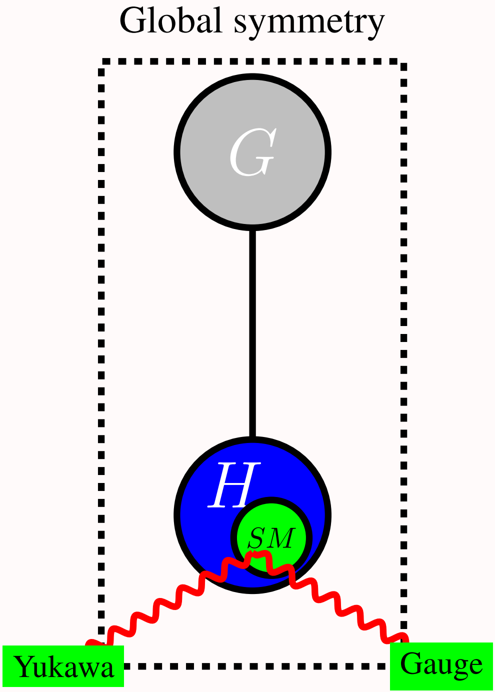
**Better:** alleviates the 4-fermion operators



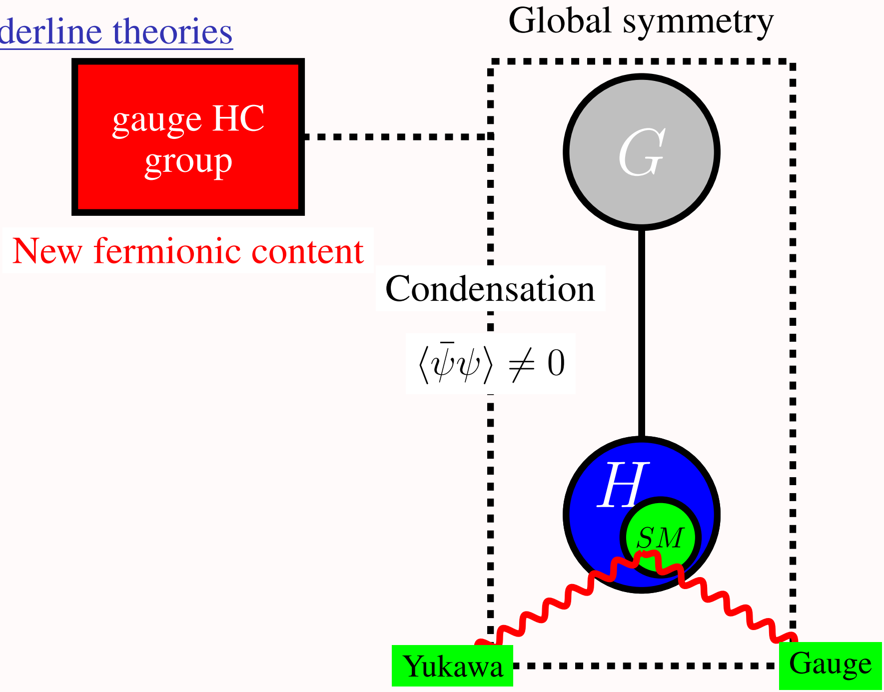
Sort of GIM protection

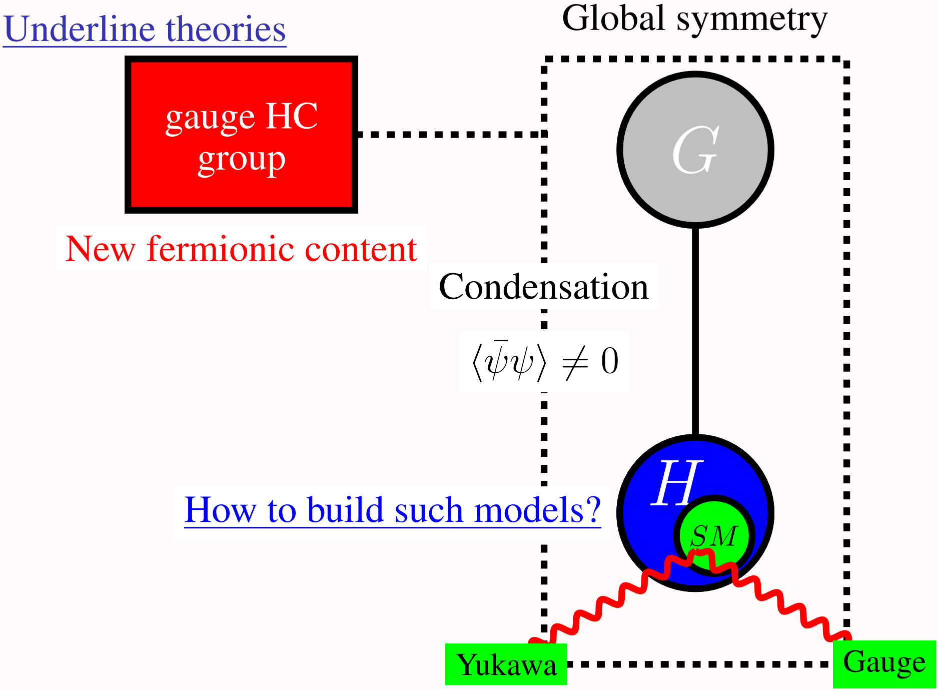
$(\bar{q}q)^2\frac{\sin^4\varphi}{M_*^2}$

# Underline theories



## Underline theories




Underline theories
Global symmetry
gauge HC group
G
New fermionic content
Condensation
$\langle\bar{\psi}\psi\rangle \neq 0$
H
SM
How to build such models?
Yukawa
Gauge

# 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 $3^{rd}$ family)
- $B$ 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 $\psi$, which produce the Higgs as a pNGB, after condensation occurs;
- Colourfull $\chi$, since we want to obtain the top partners.

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**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**

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- Pseudoreal: $\dfrac{SU(6)}{Sp(6)}$
- Real: $\dfrac{SU(6)}{SO(6)}$

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

| Coset | HC | $\psi$ | $\chi$ | $-q_\chi/q_\psi$ | $Y_\chi$ | Model |
|---|---|---|---|---|---|---|
| $\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{SO(6)}$ | $SO(7)$<br>$SO(9)$ | $5 \times \mathbf{F}$ | $6 \times \mathbf{Spin}$ | $5/6$<br>$5/12$ | 1/3 | M1<br>M2 |
| | $SO(7)$<br>$SO(9)$ | $5 \times \mathbf{Spin}$ | $6 \times \mathrm{F}$ | $5/6$<br>$5/3$ | 2/3 | M3<br>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 |
| $\frac{SU(5)}{SO(5)} \times \frac{SU(3)^2}{SU(3)}$ | $SU(4)$<br>$SO(10)$ | $5 \times \mathbf{A}_2$<br>$5 \times \mathbf{F}$ | $3 \times (\mathbf{F}, \overline{\mathbf{F}})$<br>$3 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$ | $5/3$<br>$5/12$ | 1/3 | M6<br>M7 |
| $\frac{SU(4)}{Sp(4)} \times \frac{SU(6)}{SO(6)}$ | $Sp(4)$<br>$SO(11)$ | $4 \times \mathbf{F}$<br>$4 \times \mathbf{Spin}$ | $6 \times \mathbf{A}_2$<br>$6 \times \mathbf{F}$ | $1/3$<br>$8/3$ | 2/3 | M8<br>M9 |
| $\frac{SU(4)^2}{SU(4)} \times \frac{SU(6)}{SO(6)}$ | $SO(10)$<br>$SU(4)$ | $4 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$<br>$4 \times (\mathbf{F}, \overline{\mathbf{F}})$ | $6 \times \mathbf{F}$<br>$6 \times \mathbf{A}_2$ | $8/3$<br>$2/3$ | 2/3 | M10<br>M11 |
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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 $U(1)$, associated to the 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 $a$ and $\eta'$ can be both described by the effective Lagrangian. We look at the decoupling limit $m_{\eta'} \gg m_a$.

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

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

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- WZW coefficients $K_i$ are fully determined by $\psi, \chi$ quant. num.;
- $C_f$ is also fixed for each individual model;
- $K_g^{\text{eff}} \simeq K_g - C_t/2$ (top loop)
- $K_{\gamma\gamma} = K_W + K_B$

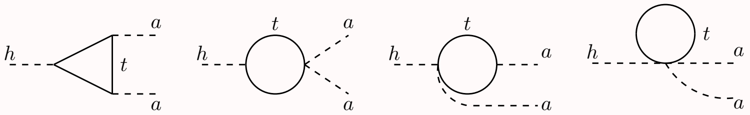
| | $K_g$ | $K_W$ | $K_B$ | $C_f$ | $f_a/f_\psi$ |
|---|---|---|---|---|---|
| M1 | -7.2 | 7.6 | 2.8 | 2.2 | 2.1 |
| M2 | -8.7 | 12. | 5.9 | 2.6 | 2.4 |
| M3 | -6.3 | 8.7 | -8.2 | 2.2 | 2.8 |
| M4 | -11. | 12. | -17. | 1.5 | 2.0 |
| M5 | -4.9 | 3.6 | 0.40 | 1.5 | 1.4 |
| M6 | -4.9 | 4.4 | 1.1 | 1.5 | 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 |

# A timid composite pseudo-scalar (TCP)

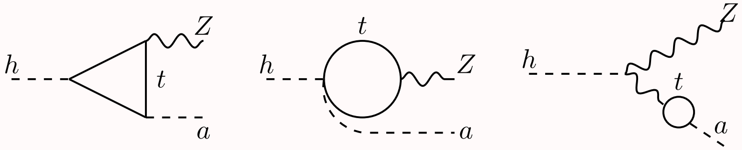
Effective coupling of $a$ to the Higgs are induced at loop level.

Relevant vertices present in the spurion term $-m_t(h)e^{iC_t a/f_a}\bar{\Psi}_{tL}\Psi_{tR}$

$\kappa_{t/V} \sim 1 + \mathcal{O}(v^2/f_a^2)$




$$\mathcal{L}_{haa} = \frac{3C_t^2 m_t^2 \kappa_t}{8\pi^2 f_a^2 v} \log \frac{\Lambda^2}{m_t^2} h(\partial_\mu a)(\partial^\mu a)$$

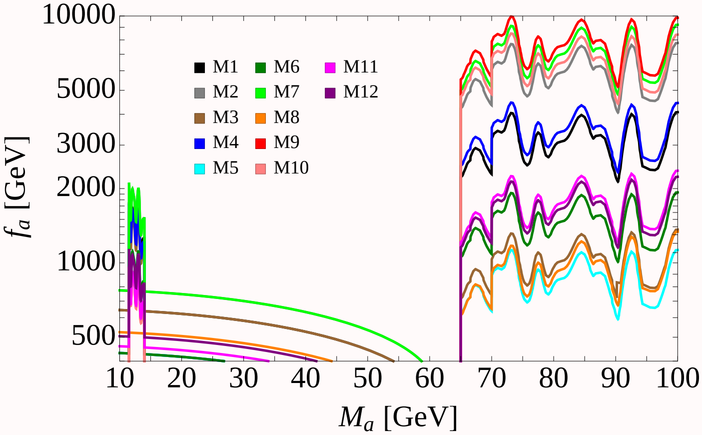



$$\mathcal{L}_{hZa} = \frac{3C_t m_t^2 g_A}{2\pi^2 f_a v}(\kappa_t - \kappa_V) \log \frac{\Lambda^2}{m_t^2} h(\partial_\mu a)Z^\mu$$

# TCP Phenomenology

- $a$ is produced in gluon fusion;
- $a$ decays to $gg$, $WW$, $ZZ$, $Z\gamma$, $\gamma\gamma$, $\Psi_f\bar{\Psi}_f$ (fully determined BR)
- Assc. production with a $Z$ is tiny; No bounds from LEP;
- For heavier $a$, LHC di-boson searches apply [JHEP 1701, 094]
- Weak indirect bounds from $h \to aa$ (BSM).
- $h \to aa \to 4\gamma$, $bb\mu\mu$, $bb\tau\tau$, $\ldots$ have very low signal rate due to small $haa$ coupling and small $BR(a \to \gamma\gamma, ff)$. The same for $h \to Za$
- $b$-associated production is small
- $t$-associated production could yield bounds in future searches

# TCP Phenomenology

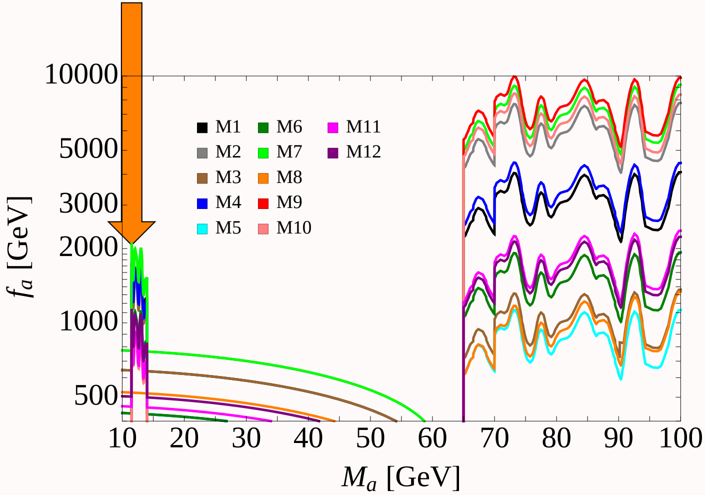


# TCP Phenomenology

$\mu\mu$

[PRL109, 121801] (CMS)

[ATLAS-CONF-2011-020]



# TCP Phenomenology

$\mu\mu$

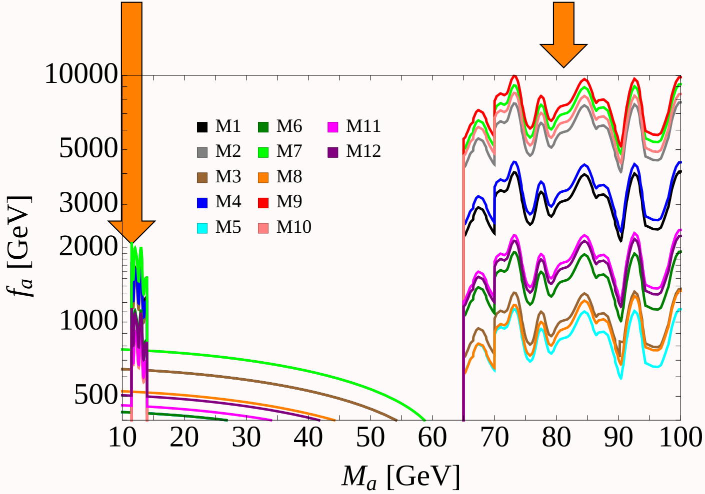
[PRL109,  121801]  (CMS)

[ATLAS-CONF-2011-020]

$\gamma\gamma$

[PRL113,17801]   (ATLAS)

[CMS-PAS-HIG-17-013]



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[ATLAS-CONF-2011-020]

BR$(h \to bSM) \leq .34$

[JHEP1608, 045]

(ATLAS+CMS)

$\gamma\gamma$

[PRL113,17801] (ATLAS)

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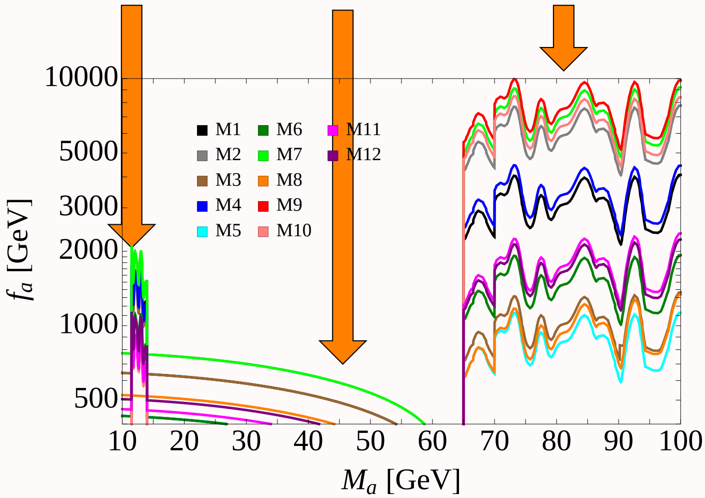

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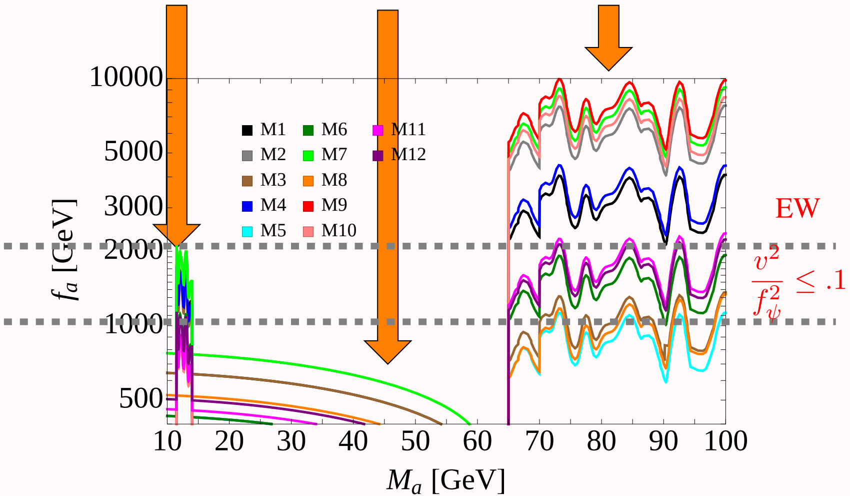

# How to explore the mass gap 15 to 65 GeV?

- $h \to aa$ (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?

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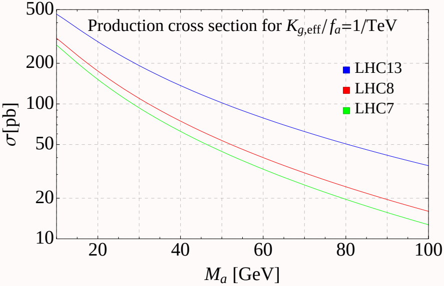
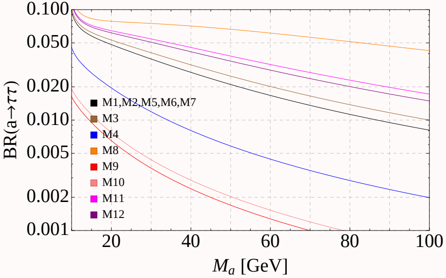
- …or looking for other decay channels: $\tau\tau$!



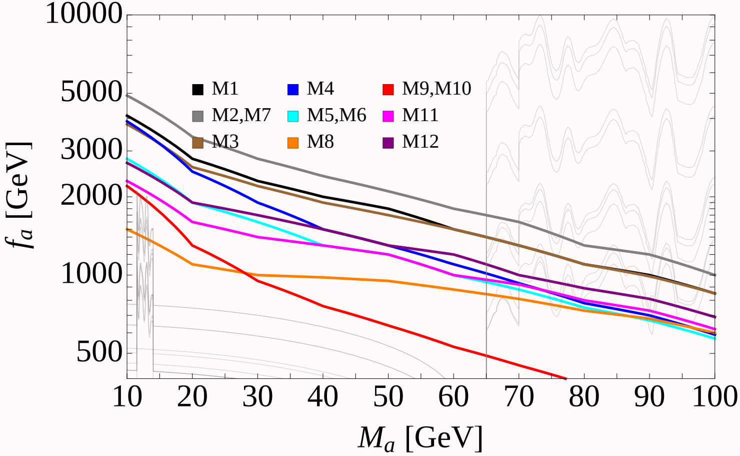

Large gluon-fusion production XS




$\tau\tau$ BRs are not small in many models

# How to explore the mass gap 15 to 65 GeV?

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




Boosted di-tau resonances, produced via gluon fusion, that can effectively cover this open window!

# Final remarks

# Conclusions

- 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.

**Thanks for the time!**

**Questions?**