Light ALPs from Partial Compositeness

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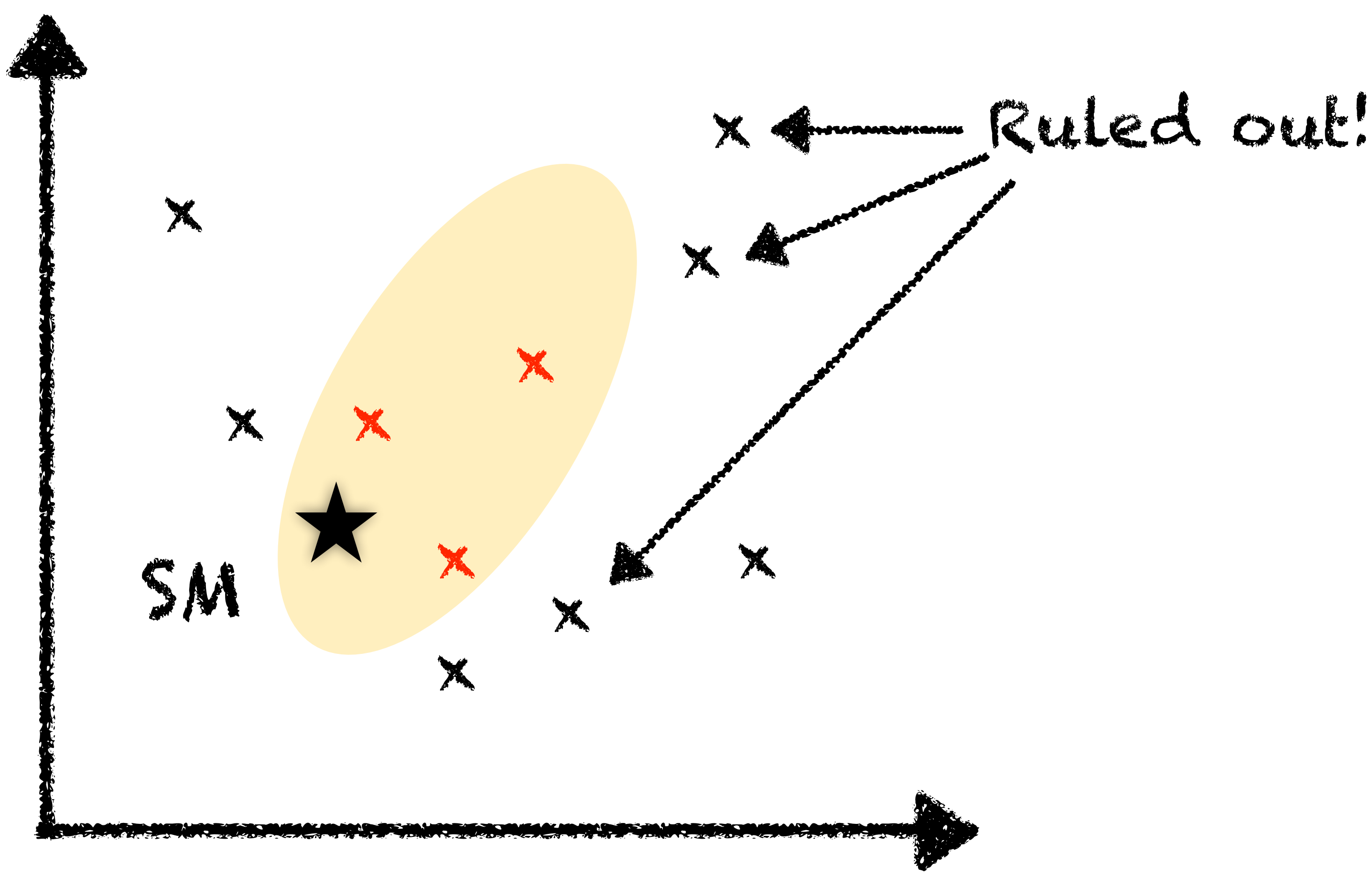
What is our job?

- Models can be ruled out, but cannot be proven right!



Even "disliked" possibilities need to be tested and ruled out!

What is our job?

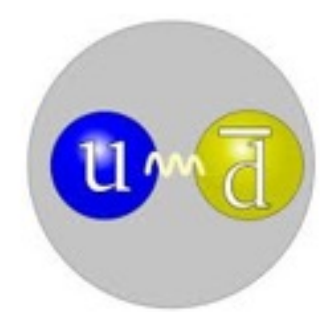
- The nature of the 125 GeV Higgs is not yet fully established!

We have a pretty good idea of the mechanism

But, we dont know how to protect it.

The possibility that it may be composite needs to be fully explored!

H →



The hot potato: flavour!

100,000 TeV	Λ_{flavour}	Scale of fermion mass generation	$$\mathcal{L}_{\text{fermions}} = \frac{1}{\Lambda_{\text{fl.}}^2}(\psi\psi)(q_L^c q_R) + \frac{1}{\Lambda_{\text{fl.}}^2}(q_L^c q_R)(q_L^c q_R) + \frac{1}{\Lambda_{\text{fl.}}^2}(\psi\psi)^2$$
		How can this hierarchy be generated?	Higgs; FCNCs; Higgs mass
10 TeV	$\Lambda \sim 4\pi f$	Vector resonances, ...	
1 TeV	f	Condensation scale (extra pions)	$$m_{\text{top}} \sim \frac{(4\pi f)^3}{\Lambda_{\text{fl.}}^2}\sin\theta$$
100 GeV	$v_{\text{SM}} \sim f \sin\theta$	EWSB	Too small!

The hot potato: flavour!

100,000 TeV Λ_{flavour} Scale of fermion mass generation

Intermediate conformal region

10 TeV $\Lambda \sim 4\pi f$ Vector resonances, ...

1 TeV f Condensation scale (extra pions)

100 GeV $v_{\text{SM}} \sim f \sin\theta$ EWSB

$$(\psi\psi) \to \mathcal{O}_H$$

$$\dim[\mathcal{O}_H] = d_H$$

effective Yukawa:

$$\frac{1}{\Lambda_{\text{fl.}}^{d_H - 1}} \mathcal{O}_H \; q_L^c q_R$$

$$m_{\text{top}} \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d_H - 1} 4\pi f \sin\theta$$

$$d_H \sim 1$$

$$d_{HH} \sim ???$$

The hot potato: flavour!

100,000 TeV — Λ_{flavour} — Light fermions

Conformal region

Λ_{top}

10 TeV — $\Lambda \sim 4\pi f$ — Vector resonances, …

1 TeV — f — Condensation scale (extra pions)

100 GeV — $v_{\text{SM}} \sim f \sin\theta$ — EWSB

Multi-scale model

$$m_c \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d_H - 1} 4\pi f \sin\theta$$

$$\Downarrow$$

$$\sim 0.01 \Rightarrow d_H \sim 1.5$$

Still, for the top, one would need:

$$\Lambda_{\text{top}} \sim 4\pi f$$

The partial compositeness paradigm

Kaplan Nucl.Phys. B365 (1991) 259

$$\frac{1}{\Lambda_{\text{fl.}}^{d_H-1}}\,\mathcal{O}_H\; q_L^c q_R \qquad \Delta m_H^2 \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d_{HH}-4} (4\pi f)^2$$ Both irrelevant if

we assume: $d_H > 1$ $\qquad d_{HH} > 4$

Let's postulate the existence of fermionic operators:

$$\frac{1}{\Lambda_{\text{fl.}}^{d_F-5/2}}(\tilde{y}_L\; q_L \mathcal{F}_L + \tilde{y}_R\; q_R \mathcal{F}_R)$$

This dimension is not related to the Higgs!

$$f(y_L\; q_L Q_L + y_R\; q_R Q_R)$$ with $$f\; y_{L/R} \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d_F-5/2} 4\pi f$$

Caveat: it's a wishful thinking scenario!

- Is it there an underlying theory that can actually do it?

- <u>New information may come from the UV!</u>

Image from Wikipedia

Towards a UV theory

$\mathcal{G}_{\rm TC}$: rep R $\quad$ rep R'

G.Ferretti, D.Karateev
1312.5330, 1604.06467

$\psi \qquad \chi \qquad Q = \psi\psi\chi$ or $\psi\chi\chi$

SM : EW $\quad$ colour + hypercharge

$global$: $\langle\psi\psi\rangle \neq 0$ $\quad$ $a)\ \ \langle\chi\chi\rangle \neq 0$

$\downarrow$

pNGB Higgs
DM?

coloured pNGBs
di-boson

$b)\ \ \langle\chi\chi\rangle = 0$

unlikely
('t Hooft anomaly matching)

Exception: 1506.00623

Predicting di-boson resonances

More precisely, the global symmetries are:

$$SU(N_\psi) \times SU(N_\chi) \times U(1)_\psi \times U(1)_\chi$$

WZW term:

$$\mathcal{L} \supset \frac{g_i^2}{32\pi^2}\frac{\kappa_i}{f_a}\, a\, \epsilon^{\mu\nu\alpha\beta} G^i_{\mu\nu} G^i_{\alpha\beta}\,,$$

Coefficients depend
on the underlying dynamics!

G = A, W, Z, g !!!

Cai, Flacke, Lespinasse 1512.04508

Anomalous U(1) -> heavy η'

Orthogonal U(1) -> pNGB a

Decays and production
only via WZW anomaly.

Predicting di-boson resonances

Belyaev, G.C., Cai, Ferretti, Flacke, Parolini, Serodio 1610.06591

- The two singlets mix!

$$-\mathcal{L}_{\text{mass}} = \underbrace{\frac{1}{2}m^2_{a_\chi}a^2_\chi + \frac{1}{2}m^2_{a_\psi}a^2_\psi}_{\text{fermion masses}} + \underbrace{\frac{1}{2}M^2_A(\overbrace{\cos\zeta a_\chi - \sin\zeta a_\psi}^{\eta'})^2}_{\text{anomaly}}$$

$$\left.\frac{m_a}{m_{\eta'}}\right|_{\text{max}} = \sqrt{\frac{1-\cos\zeta}{1+\cos\zeta}} = \left|\tan\frac{\zeta}{2}\right| .$$

Minimum mass splitting!

- Couplings to tops are inevitable!

$$ic_5 \frac{m_{\text{top}}}{\sqrt{q^2_\psi f^2_{a_\psi} + q^2_\chi f^2_{a_\chi}}}\left((n_\psi q_\psi + n_\chi q_\chi)\,\tilde{a} + \left(n_\chi q_\psi \frac{f_{a_\psi}}{f_{a_\chi}} - n_\psi q_\chi \frac{f_{a_\chi}}{f_{a_\psi}}\right)\tilde{\eta}'\right)\bar{t}\gamma^5 t\,,$$

Model zoology

$G_{\rm HC}$	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
	Real	Real	SU(5)/SO(5) $\times$ SU(6)/SO(6)				
$SO(N_{\rm HC})$	$5\times\mathbf{S}_2$	$6\times\mathbf{F}$	$N_{\rm HC}\geq 55$	$\frac{5(N_{\rm HC}+2)}{6}$	1/3	/	
$SO(N_{\rm HC})$	$5\times\mathbf{Ad}$	$6\times\mathbf{F}$	$N_{\rm HC}\geq 15$	$\frac{5(N_{\rm HC}-2)}{6}$	1/3	/	
$SO(N_{\rm HC})$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$N_{\rm HC}=7,9$	$\frac{5}{6},\frac{5}{12}$	1/3	$N_{\rm HC}=7,9$	M1, M2
$SO(N_{\rm HC})$	$5\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{\rm HC}=7,9$	$\frac{5}{6},\frac{5}{3}$	2/3	$N_{\rm HC}=7,9$	M3, M4
	Real	Pseudo-Real	SU(5)/SO(5) $\times$ SU(6)/Sp(6)				
$Sp(2N_{\rm HC})$	$5\times\mathbf{Ad}$	$6\times\mathbf{F}$	$2N_{\rm HC}\geq 12$	$\frac{5(N_{\rm HC}+1)}{3}$	1/3	/	
$Sp(2N_{\rm HC})$	$5\times\mathbf{A}_2$	$6\times\mathbf{F}$	$2N_{\rm HC}\geq 4$	$\frac{5(N_{\rm HC}-1)}{3}$	1/3	$2N_{\rm HC}=4$	M5
$SO(N_{\rm HC})$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$N_{\rm HC}=11,13$	$\frac{5}{24},\frac{5}{48}$	1/3	/	
	Real	Complex	SU(5)/SO(5) $\times$ SU(3)^2/SU(3)				
$SU(N_{\rm HC})$	$5\times\mathbf{A}_2$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$N_{\rm HC}=4$	$\frac{5}{3}$	1/3	$N_{\rm HC}=4$	M6
$SO(N_{\rm HC})$	$5\times\mathbf{F}$	$3\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$N_{\rm HC}=10,14$	$\frac{5}{12},\frac{5}{48}$	1/3	$N_{\rm HC}=10$	M7
	Pseudo-Real	Real	SU(4)/Sp(4) $\times$ SU(6)/SO(6)				
$Sp(2N_{\rm HC})$	$4\times\mathbf{F}$	$6\times\mathbf{A}_2$	$2N_{\rm HC}\leq 36$	$\frac{1}{3(N_{\rm HC}-1)}$	2/3	$2N_{\rm HC}=4$	M8
$SO(N_{\rm HC})$	$4\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{\rm HC}=11,13$	$\frac{8}{3},\frac{16}{3}$	2/3	$N_{\rm HC}=11$	M9
	Complex	Real	SU(4)^2/SU(4) $\times$ SU(6)/SO(6)				
$SO(N_{\rm HC})$	$4\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$6\times\mathbf{F}$	$N_{\rm HC}=10$	$\frac{8}{3}$	2/3	$N_{\rm HC}=10$	M10
$SU(N_{\rm HC})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$6\times\mathbf{A}_2$	$N_{\rm HC}=4$	$\frac{2}{3}$	2/3	$N_{\rm HC}=4$	M11
	Complex	Complex	SU(4)^2/SU(4) $\times$ SU(3)^2/SU(3)				
$SU(N_{\rm HC})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$N_{\rm HC}\geq 5$	$\frac{4}{3(N_{\rm HC}-2)}$	2/3	$N_{\rm HC}=5$	M12
$SU(N_{\rm HC})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{S}_2,\overline{\mathbf{S}}_2)$	$N_{\rm HC}\geq 5$	$\frac{4}{3(N_{\rm HC}+2)}$	2/3	/	
$SU(N_{\rm HC})$	$4\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$N_{\rm HC}=5$	4	2/3	/	

Ferretti
1604.06467

Model zoology

$G_{\rm HC}$	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
	Pseudo-Real	Real	SU(4)/Sp(4) $\times$ SU(6)/SO(6)				
$Sp(2N_{\rm HC})$	$4\times\mathbf{F}$	$6\times\mathbf{A}_2$	$2N_{\rm HC}\le 36$	$\frac{1}{3(N_{\rm HC}-1)}$	$2/3$	$2N_{\rm HC}=4$	M8
$SO(N_{\rm HC})$	$4\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{\rm HC}=11,13$	$\frac{8}{3}$, $\frac{16}{3}$	$2/3$	$N_{\rm HC}=11$	M9

Defines $\tan\zeta$

$Q=\psi\psi\chi$

Theory confines!

All couplings can be predicted!

Model-dependent results

	Pseudo-Real	Real	SU(4)/Sp(4) $\times$ SU(6)/SO(6)				
$Sp(2N_{\rm HC})$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$2N_{\rm HC} \leq 36$	$\frac{1}{3(N_{\rm HC}-1)}$	$2/3$	$2N_{\rm HC} = 4$	M8
$SO(N_{\rm HC})$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{\rm HC} = 11, 13$	$\frac{8}{3}$, $\frac{16}{3}$	$2/3$	$N_{\rm HC} = 11$	M9

The EFT is the same!

Numerical value of couplings:

Model		κ_g	$\frac{\kappa_W}{\kappa_g}$	$\frac{\kappa_B}{\kappa_g}$	$\frac{C_t}{\kappa_g}$ $(2,0)$	$\frac{C_t}{\kappa_g}$ $(0,2)$	$\tan\zeta$
M8	a	$-0.77(-0.39)$	$-1.2(-2.5)$	$1.5(0.17)$	$-1.2(-2.5)$	$0.40(0.40)$	
	η'	$1.9(2.0)$	$0.20(0.096)$	$2.9(2.8)$	$0.20(0.0.96)$	$0.40(0.40)$	-0.41
	π_8	7.1	0	1.3	0	0.40	
M9	a	$-4.3(-2.7)$	$-0.55(-2.4)$	$2.1(0.26)$	$-0.068(-0.30)$	$0.18(0.18)$	
	η'	$1.3(3.6)$	$5.8(1.3)$	$8.5(4.0)$	$0.73(0.16)$	$0.18(0.18)$	-3.26
	π_8	$16.$	0	1.3	0	0.18	

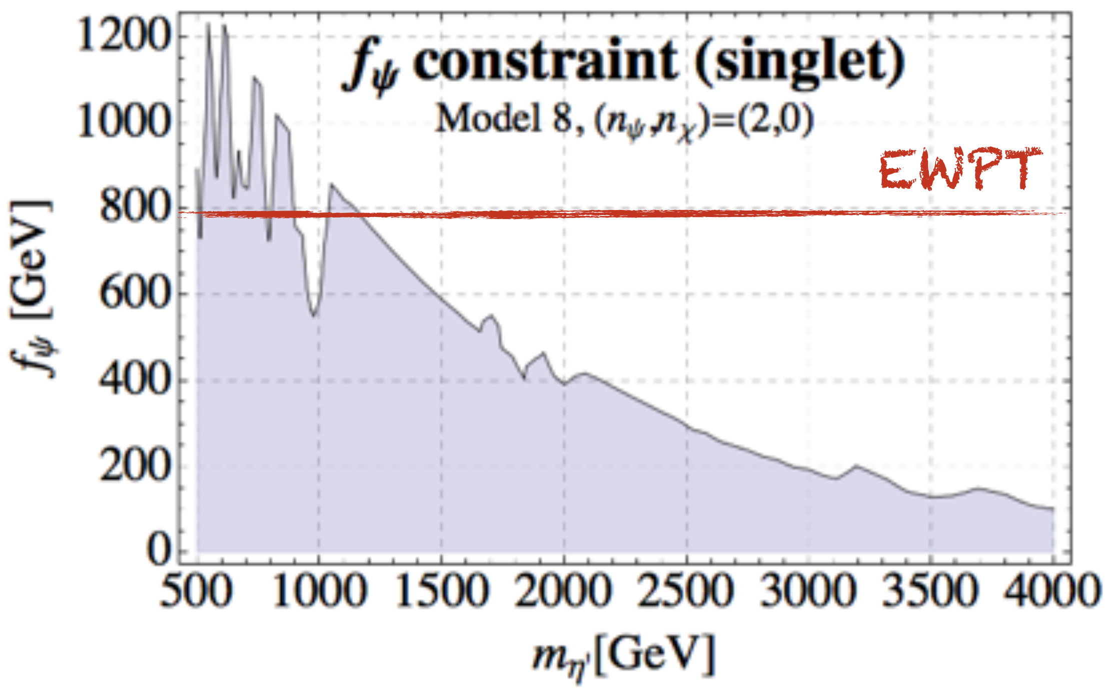
Assuming $f_a = f_\psi = f_\chi$

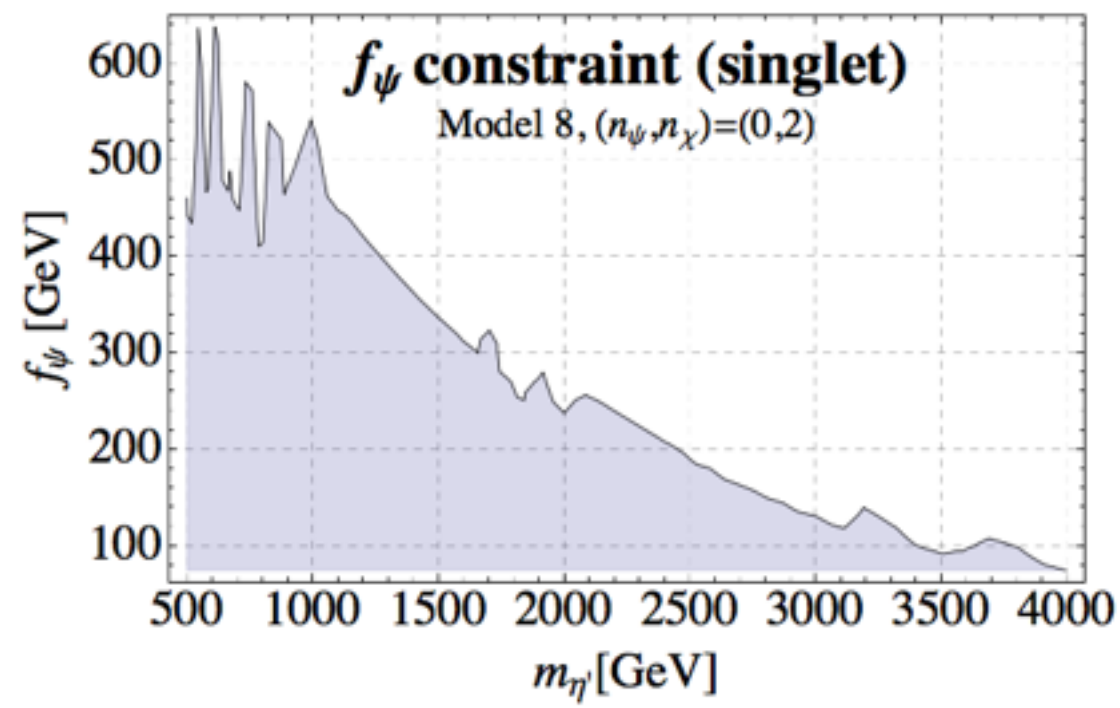
Model M8

Belyaev, G.C., Cai, Ferretti, Flacke, Parolini, Serodio 1610.06591

"a" too light for the LHC!

$$\left.\frac{m_a}{m_{\eta'}}\right|_{\max} = 0.20$$





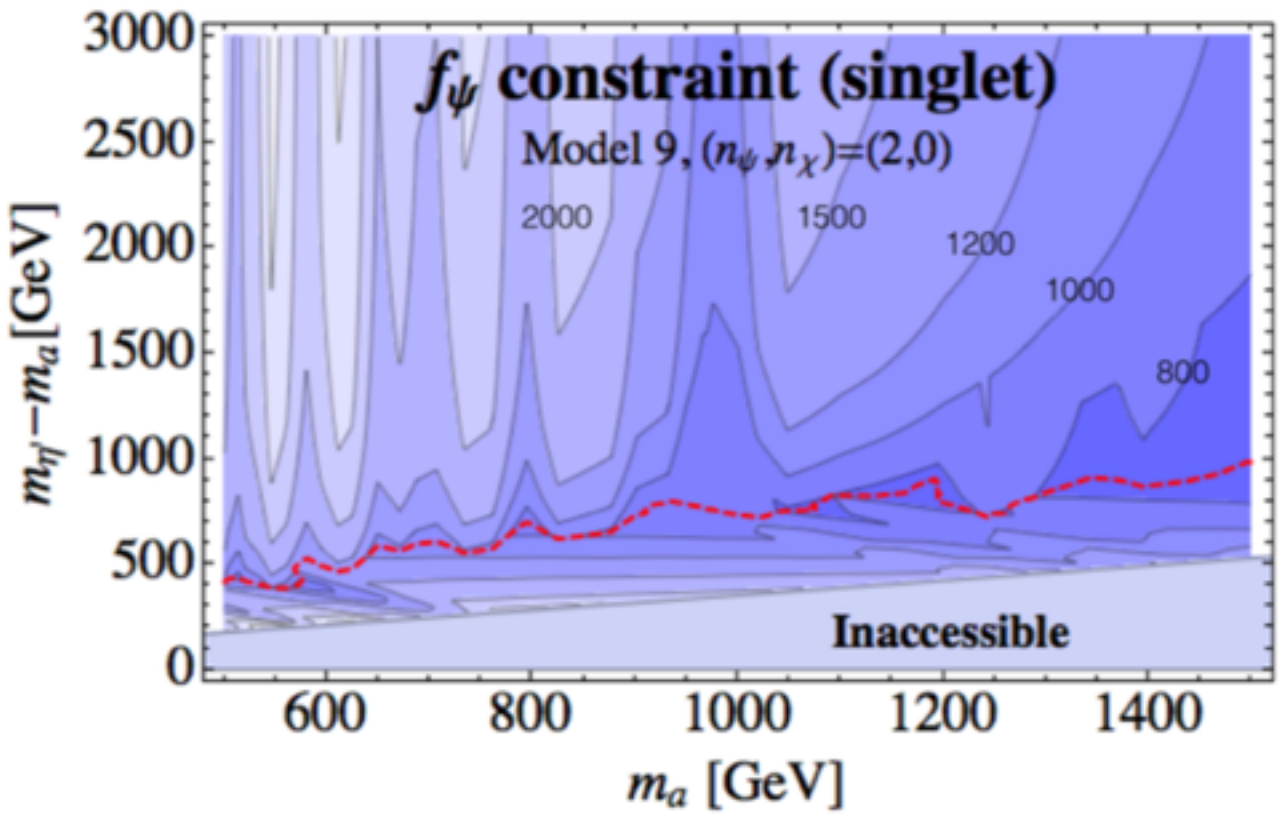
For light masses: bounds competitive with EW precision!

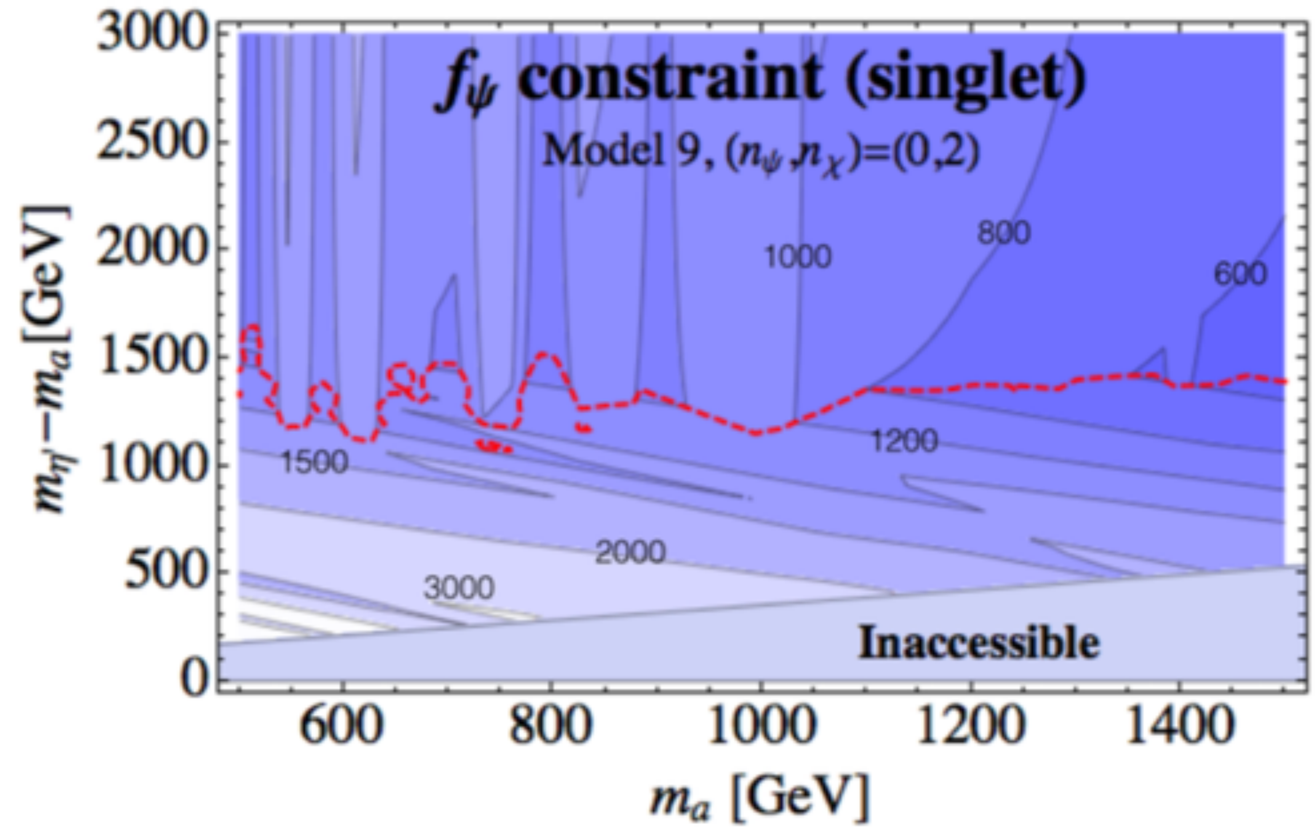
Larger top couplings: reduced di-boson rates due to tt BR.

Model M9

Belyaev, G.C., Cai, Ferretti, Flacke, Parolini, Serodio 1610.06591

$$\left.\frac{m_a}{m_{\eta'}}\right|_{\max} = 0.74$$





Above red line, bound driven by "a"!

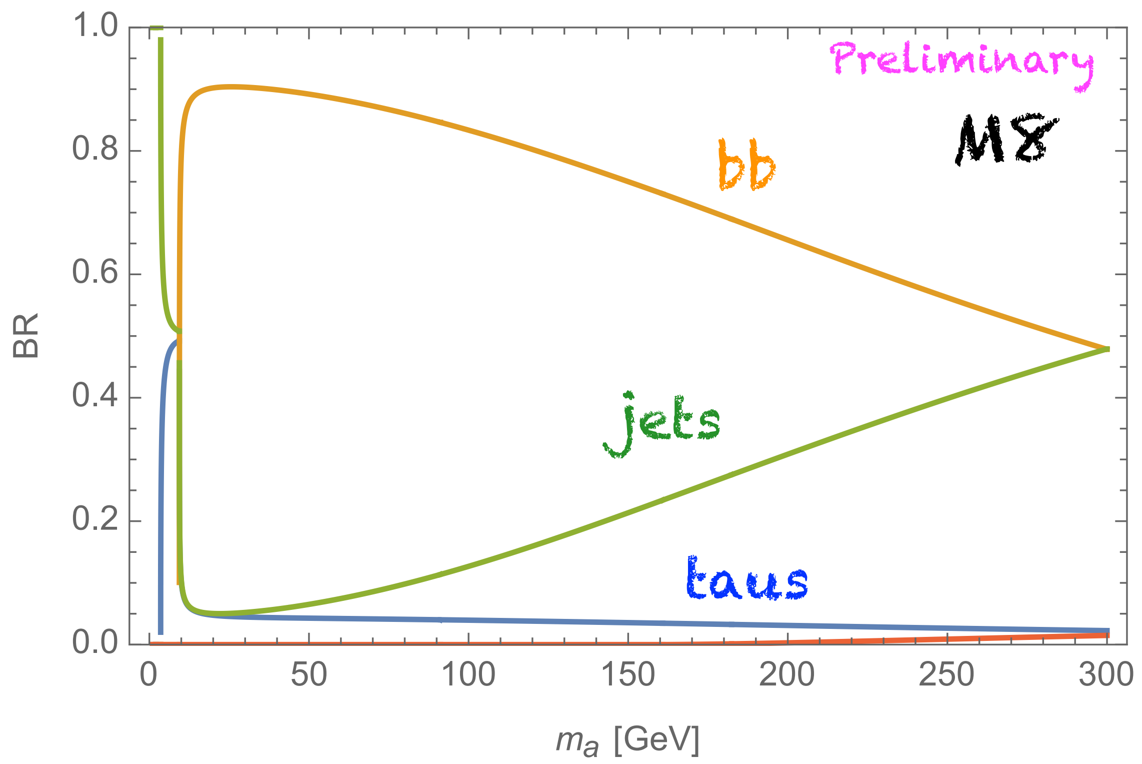
Bounds stronger than EW precision in most of the parameter space!

How light can "a" be?

Work in progress with
T.Flacke, G.Ferretti & H.Serôdio

$$-\mathcal{L}_{\text{mass}} = \frac{1}{2}m^2_{a_\chi}a^2_\chi + \frac{1}{2}m^2_{a_\psi}a^2_\psi + \frac{1}{2}M^2_A(\cos\zeta a_\chi - \sin\zeta a_\psi)^2$$

Mass driven by fermion masses: it may be as light as massless!

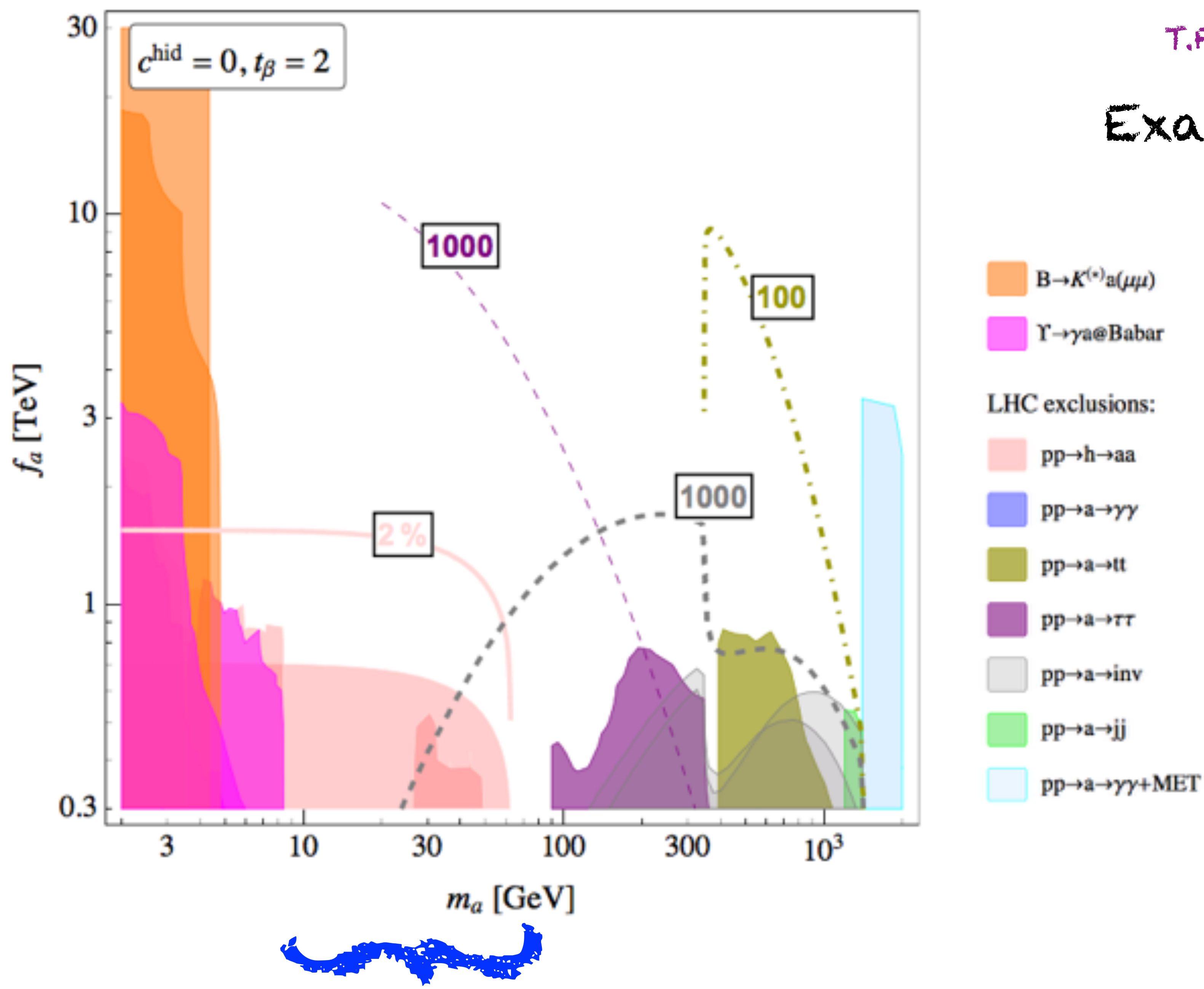


Di-photon very suppressed!

Main decay into b's & jets.

Taus?

How light can "a" be?



Work in progress with
T.Flacke, G.Ferretti & H.Serôdio

Example of bounds from 1702.02152

No LEP bounds, as couplings to GBs are suppressed.

Also: h -> aa does not apply to our models!

Mass range with no bounds!

How light can "a" be?

Work in progress with
T.Flacke, G.Ferretti & H.Serôdio

How can the mass range few to 100 GeV tested at the LHC?

Can the di-tau searches extend below the Z pole?