Common exotic LHC signatures from underlying models with a composite Higgs

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based on:

G. Cacciapaglia, H. Cai, A. Deandrea, TF, S.J. Lee, A. Parolini [JHEP 1511 (2015) 201]

A. Belyaev, G. Cacciapaglia, H. Cai, G. Ferretti, TF, H. Serodio, A. Parolini [JHEP 1701 (2017) 094]

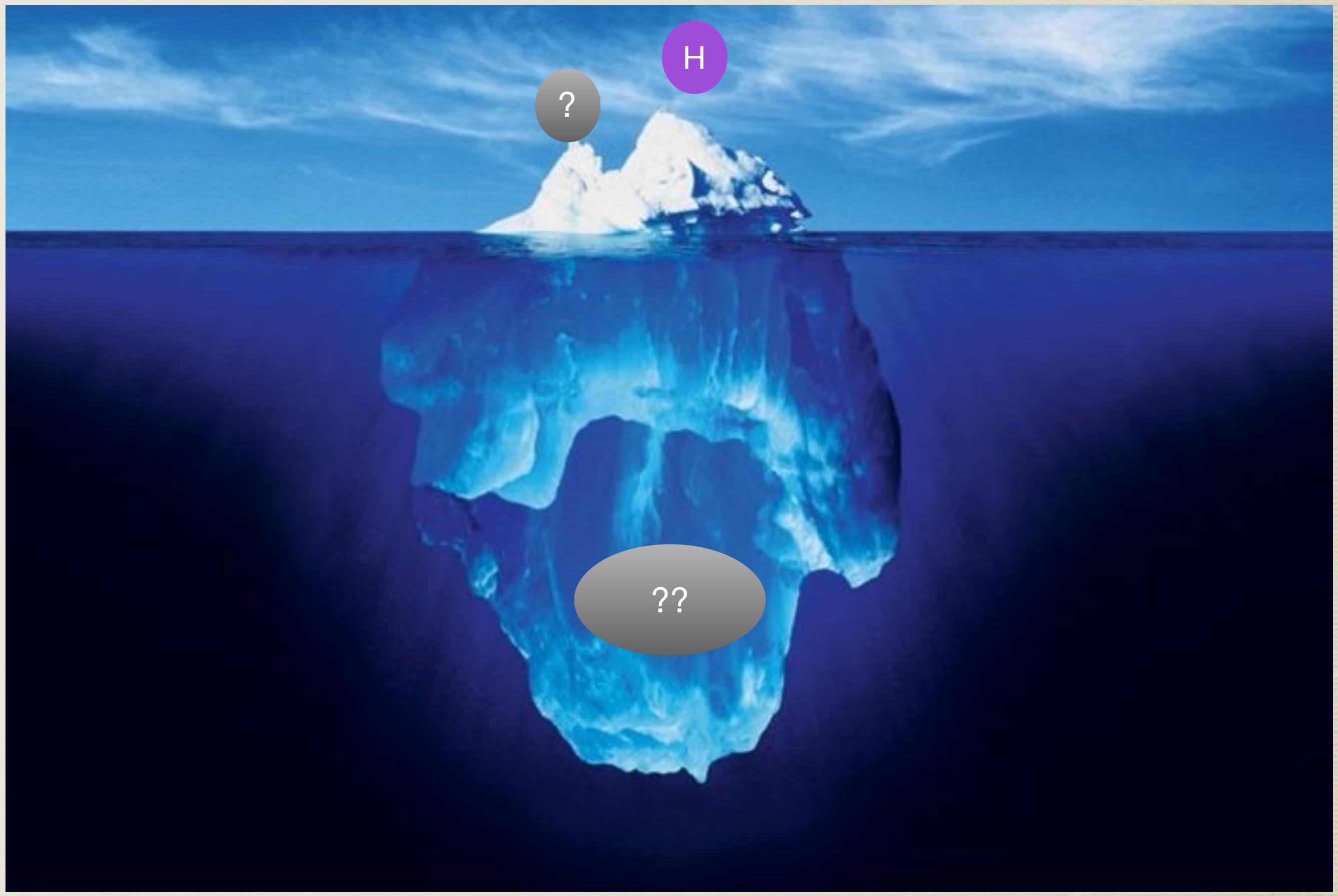
G. Cacciapaglia, G. Ferretti,TF, H. Serodio [arXiv:1710.11142]

N. Bizot, G. Cacciapaglia, TF [arXiv:1803.00021]

HL/HE LHC Meeting, April 4th, 2018

Outline

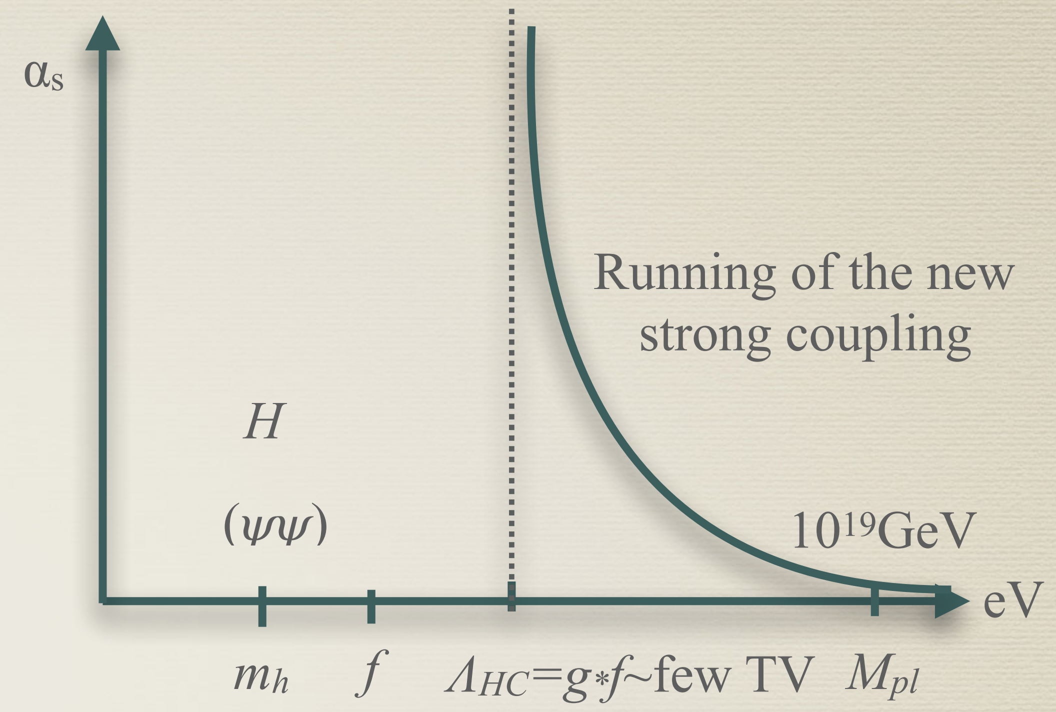
- Motivation & Overview
- Towards UV embeddings of a composite Higgs: Models
- New light pseudo-Nambu Goldstone bosons and their phenomenology
- Top-partners and common exotic decays / new signatures
- Conclusions



Motivation for a composite Higgs

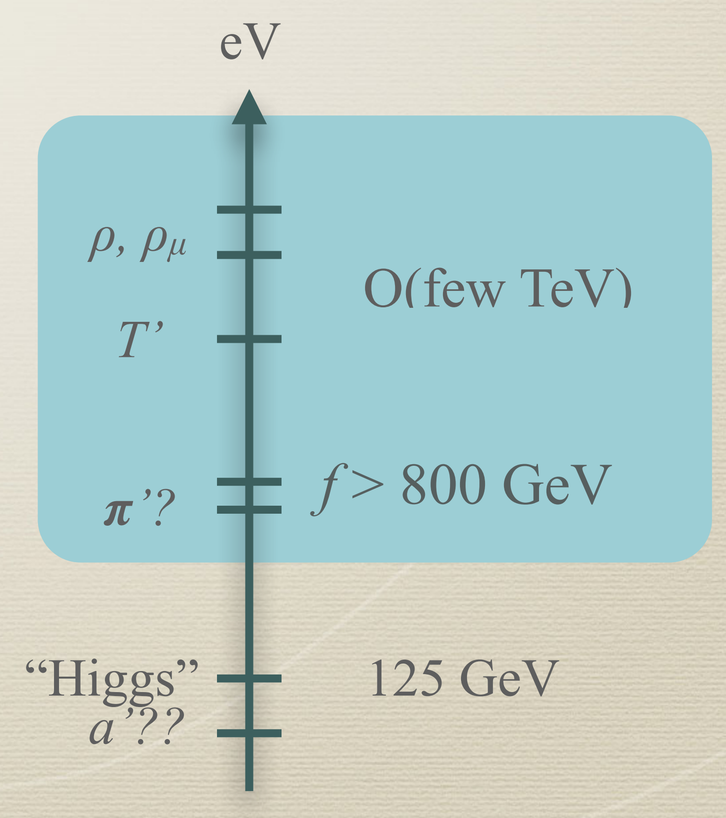
An alternative solution to the hierarchy problem:

- Generate a scale $\Lambda_{HC} << M_{pl}$ through a new confining gauge group.
- Interpret the Higgs as a pseudo-Nambu-Goldstone boson (pNGB) of a spontaneously broken global symmetry of the new strong sector.
  Kaplan, Georgi [1984]



The price to pay:

- From the generic setup, one expects additional resonances (vectors, vector-like fermions, scalars) around Λ_{HC} (and additional light pNGBs?).
- The non-linear realization of the Higgs yields deviations of the Higgs couplings from their SM values.
- … many model-building questions …
- … and potentially new signatures for LHC …



Composite Higgs Models: Towards an underlying model and its low-energy phenomenology

Ferretti etal. [JHEP 1403, 077] classified candidate models which:
c.f. also Gherghetta etal (2014), Vecchi (2015), Ferretti (2016) for related works on individual models

- contain no elementary scalars (to not re-introduce a hierarchy problem),
- have a simple hyper-color group,
- have a Higgs candidate amongst the pNGBs of the bound states,
- have a top-partner amongst its bound states (for top mass via partial compositeness),
- satisfy further “standard” consistency conditions (asymptotic freedom, no anomalies)

Example: SU(4)/Sp(4) coset based on GHC = Sp(2Nc) and colored pNGBs

Field content of the microscopic fundamental theory and its charges w.r.t. the gauge group $Sp(2N)\times SU(3)\times SU(2)\times U(1)$, and the global symmetries $SU(4)\times SU(6)\times U(1)$:

	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(4)$	$SU(6)$	$U(1)$
ψ_1 ψ_2	$\square$	**1**	**2**	0	**4**	**1**	$-3(N_c-1)q_\chi$
ψ_3	$\square$	**1**	**1**	$1/2$			
ψ_4	$\square$	**1**	**1**	$-1/2$			
χ_1 χ_2 χ_3	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	**3**	**1**	$2/3$	**1**	**6**	q_χ
χ_4 χ_5 χ_6	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{\bar{3}}$	**1**	$-2/3$			

[JHEP1511,201]

Bound states of the model:

	spin	SU(4)×SU(6)	Sp(4)×SO(6)	names
$\psi\psi$	0	$(\mathbf{6},\mathbf{1})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{5},\mathbf{1})$	σ π
$\chi\chi$	0	$(\mathbf{1},\mathbf{21})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{1},\mathbf{20})$	σ_c π_c
$\chi\psi\psi$	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_1^1 ψ_1^5
$\chi\overline{\psi}\overline{\psi}$	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_2^1 ψ_2^5
$\psi\overline{\chi}\overline{\psi}$	1/2	$(\mathbf{1},\overline{\mathbf{6}})$	$(\mathbf{1},\mathbf{6})$	ψ_3
$\psi\overline{\chi}\overline{\psi}$	1/2	$(\mathbf{15},\overline{\mathbf{6}})$	$(\mathbf{5},\mathbf{6})$ $(\mathbf{10},\mathbf{6})$	ψ_4^5 ψ_4^{10}
$\overline{\psi}\sigma^\mu\psi$	1	$(\mathbf{15},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$ $(\mathbf{10},\mathbf{1})$	a ρ
$\overline{\chi}\sigma^\mu\chi$ [JHEP1511,201]	1	$(\mathbf{1},\mathbf{35})$	$(\mathbf{1},\mathbf{20})$ $(\mathbf{1},\mathbf{15})$	a_c ρ_c

contains $SU(2)_L \times SU(2)_R$ bidoublet *"H"*

form a and η'; SM singlets

20 colored pNGB:
$(8,1,1)_0 \oplus (6,1,1)_{4/3} \oplus (\overline{6},1,1)_{-4/3}$

contain $(3,2,2)_{2/3}$ fermions: t_L-partners

contain $(3,1,X)_{2/3}$ fermions: t_R-partners

This is the BSM + Higgs sector which interacts with SM gauge bosons and matter through: SM gauge interactions, (global) anomaly couplings, and mixing of the top with top partners,

Full list of "minimal" CHM UV embeddings

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

[JHEP1701,094]

New PNGBs and their phenomenology

Additional model-dependent pNGBs (colored, EW charged, and neutral):

Electro-weak coset	$SU(2)_L \times U(1)_Y$
$SU(5)/SO(5)$	$\mathbf{3}_{\pm 1} + \mathbf{3}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{1}_0$
$SU(4)/Sp(4)$	$\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$
$SU(4) \times SU(4)'/SU(4)_D$	$\mathbf{3}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{2}'_{\pm 1/2} + \mathbf{1}_{\pm 1} + \mathbf{1}_0 + \mathbf{1}'_0$

Color coset	$SU(3)_c \times U(1)_Y$
$SU(6)/SO(6)$	$\mathbf{8}_0 + \mathbf{6}_{(-2/3 \text{ or } 4/3)} + \bar{\mathbf{6}}_{(2/3 \text{ or } -4/3)}$
$SU(6)/Sp(6)$	$\mathbf{8}_0 + \mathbf{3}_{2/3} + \bar{\mathbf{3}}_{-2/3}$
$SU(3) \times SU(3)'/SU(3)_D$	$\mathbf{8}_0$

[JHEP1701,094]

Additional two pseudo scalars associated to SSB of $U(1)_\chi \times U(1)_\psi$

In ALL models:

- One linear combination has a G_{HC} anomaly (η', no pNGB)
- One linear combination is G_{HC} anomaly free (a, remaining pNGB)

The timid pNGB summary and phenomenology

a and η': Arise from the SSB of U(1)$_\chi$ × U(1)$_\psi$. One linear combination has a G$_{HC}$ anomaly (η') and is expected heavier. The orthogonal linear combination (a) is a pNGB.

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_a^2 a^2 - \sum_f \frac{iC_f m_f}{f_a} a\bar{\psi}_f \gamma^5 \psi_f \qquad (1)$$

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

- The mass m_a must result from *explicit* breaking of the U(1) symmetries → treated as free parameter in the effective theory.
- f_a results from chiral symmetry breaking.   .
- The WZW coefficients κ_i are fully determined by the quantum numbers of χ, ψ.
- Effective couplings of a to the Higgs are induced at loop level :

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

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

Coefficients of *a* for sample models M1 - M12

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
K_g	-7.2	-8.7	-6.3	-11.	-4.9	-4.9	-8.7	-1.6	-10.	-9.4	-3.3	-4.1
K_W	7.6	12.	8.7	12.	3.6	4.4	13.	1.9	5.6	5.6	3.3	4.6
K_B	2.8	5.9	-8.2	-17.	.40	1.1	7.3	-2.3	-22.	-19.	-5.5	-6.3
C_f	2.2	2.6	2.2	1.5	1.5	1.5	2.6	1.9	.70	.70	1.7	1.8
$\frac{f_a}{f_\psi}$	2.1	2.4	2.8	2.0	1.4	1.4	2.4	2.8	1.2	1.5	3.1	2.6

C_t:

[arXiv:1710.11142]

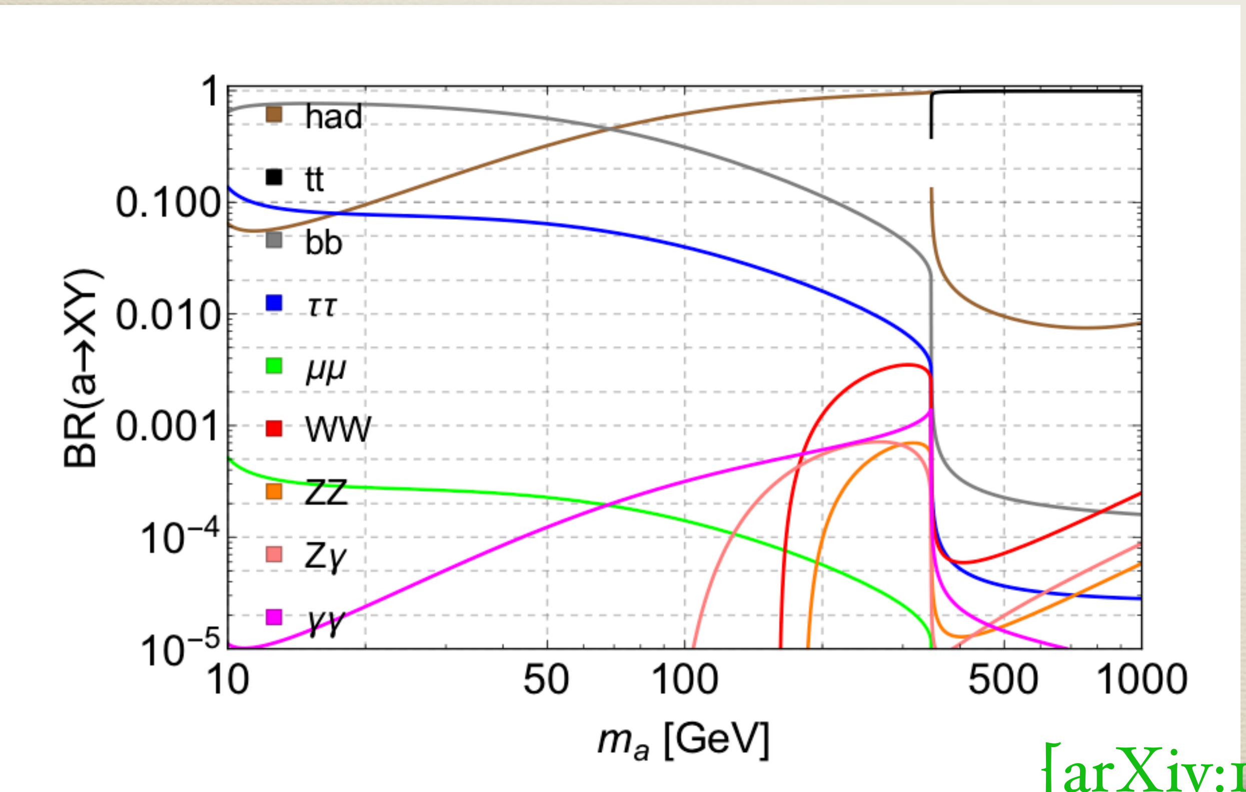
(n_ψ, n_χ)	$(\pm 2, 0)$	$(0, \pm 2)$	$(4,2)$ or $(2,4)$	$(-4,2)$ or $(2,-4)$
M1	± 2.2	∓ 1.8	-1.4	5.8
M2	± 2.6	∓ 1.1	0.44	4.8
M3	± 2.2	∓ 1.8	2.5	-6.2
M4	± 1.5	∓ 2.4	0.49	-5.3
M5	± 1.5	∓ 2.4	-3.4	6.3
M6	± 1.5	∓ 2.4	-3.4	6.3
M7	± 2.6	∓ 1.1	0.44	4.8
M8	± 1.9	∓ 0.63	3.2	-4.4
M9	± 0.70	∓ 1.9	-0.47	-3.3
M10	± 0.70	∓ 1.9	-0.47	-3.3
M11	± 1.7	∓ 1.1	2.2	-4.4
M12	± 1.8	∓ 0.81	2.8	-4.5

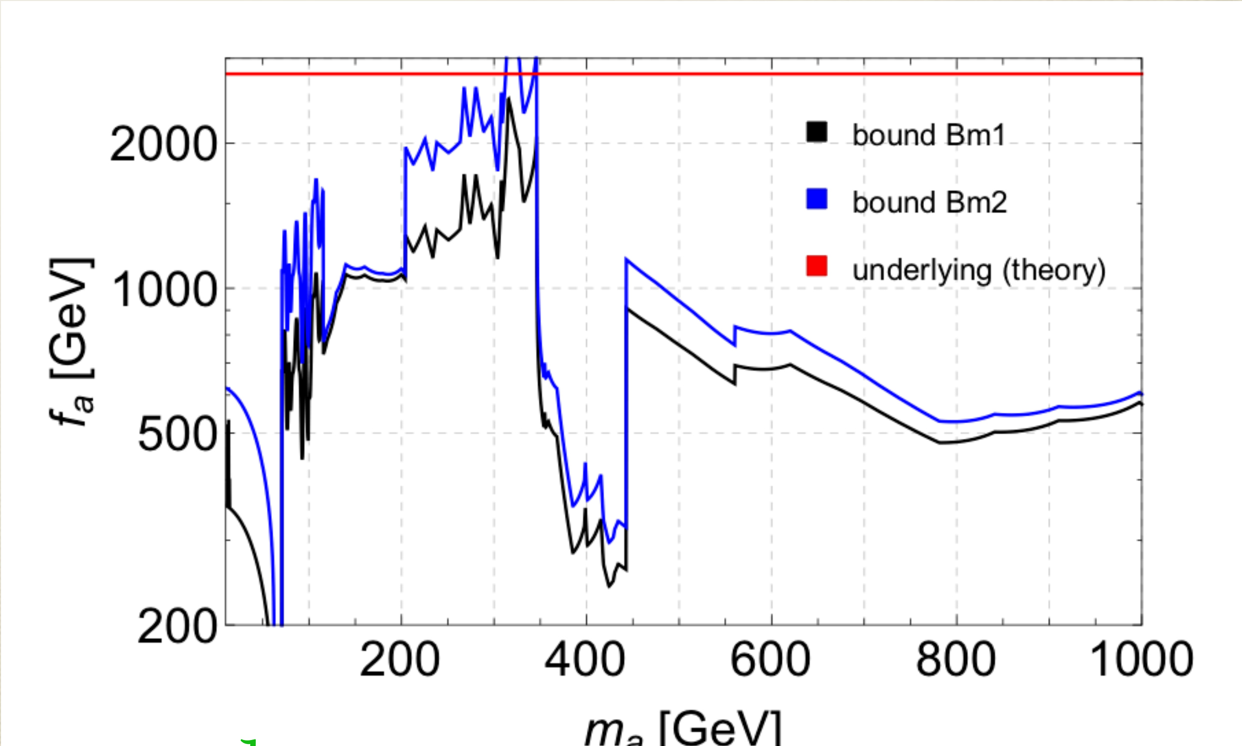
[arXiv:1710.11142]

TCP Phenomenology

- *a* is produced in gluon fusion (controlled by K_g/f_a).
- Assoc. production with a Z is tiny → No bounds from LEP Higgs searches.
- *a* decays to *gg, WW, ZZ, Zγ, γγ, ff* with fully determined branching ratios.
- For heavier *a,* LHC di-boson searches apply [JHEP 1701, 094].
- For light *a* (translating existing bounds and searches):

For a given model, we can combine bounds on all channels to get a bound on f_a .
E.g.: M8.

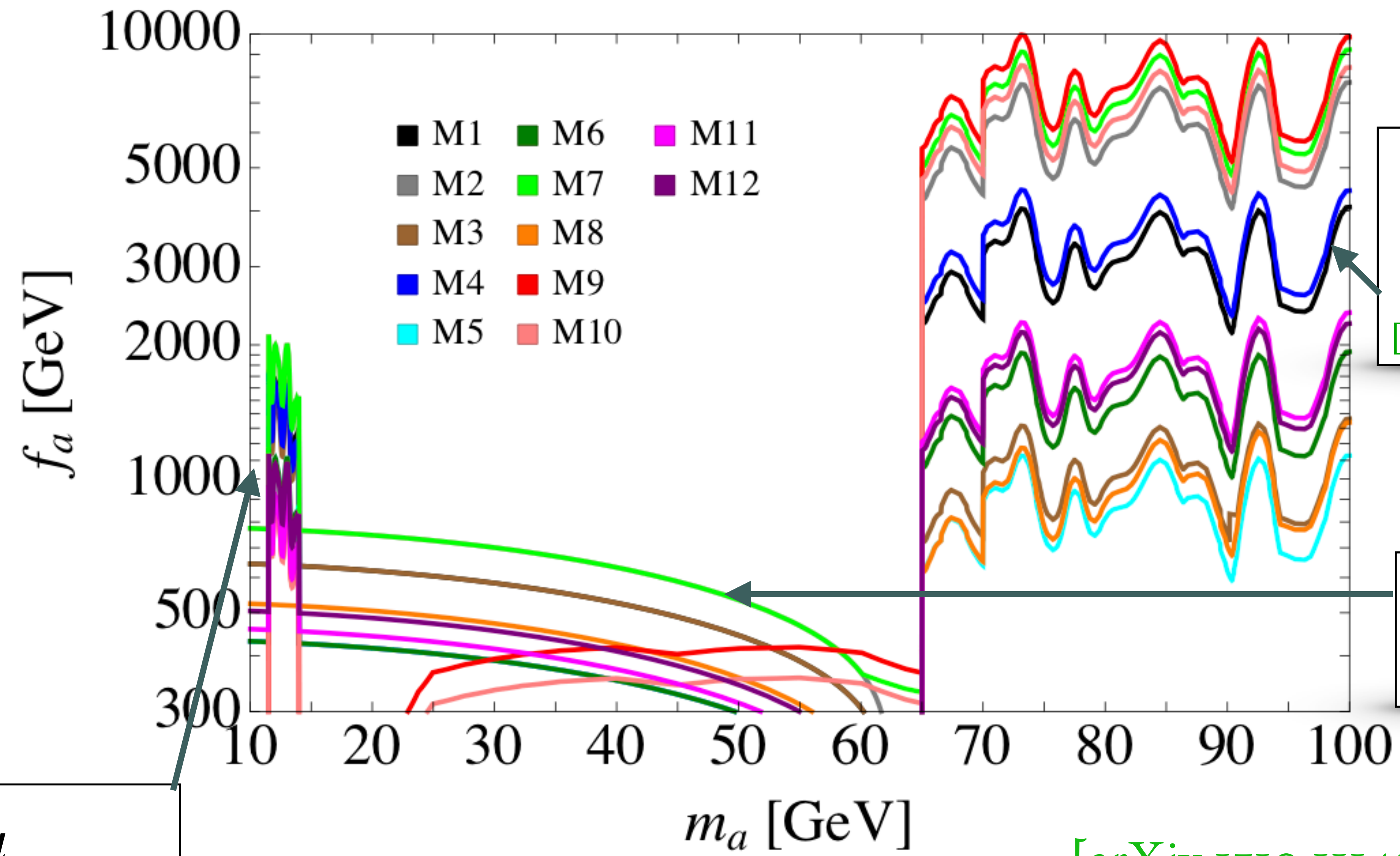




[arXiv:1803.00021]

TCP Phenomenology

NOTE: Low mass region has a “gap” between 15 - 65 GeV.



[arXiv:1710.11142]

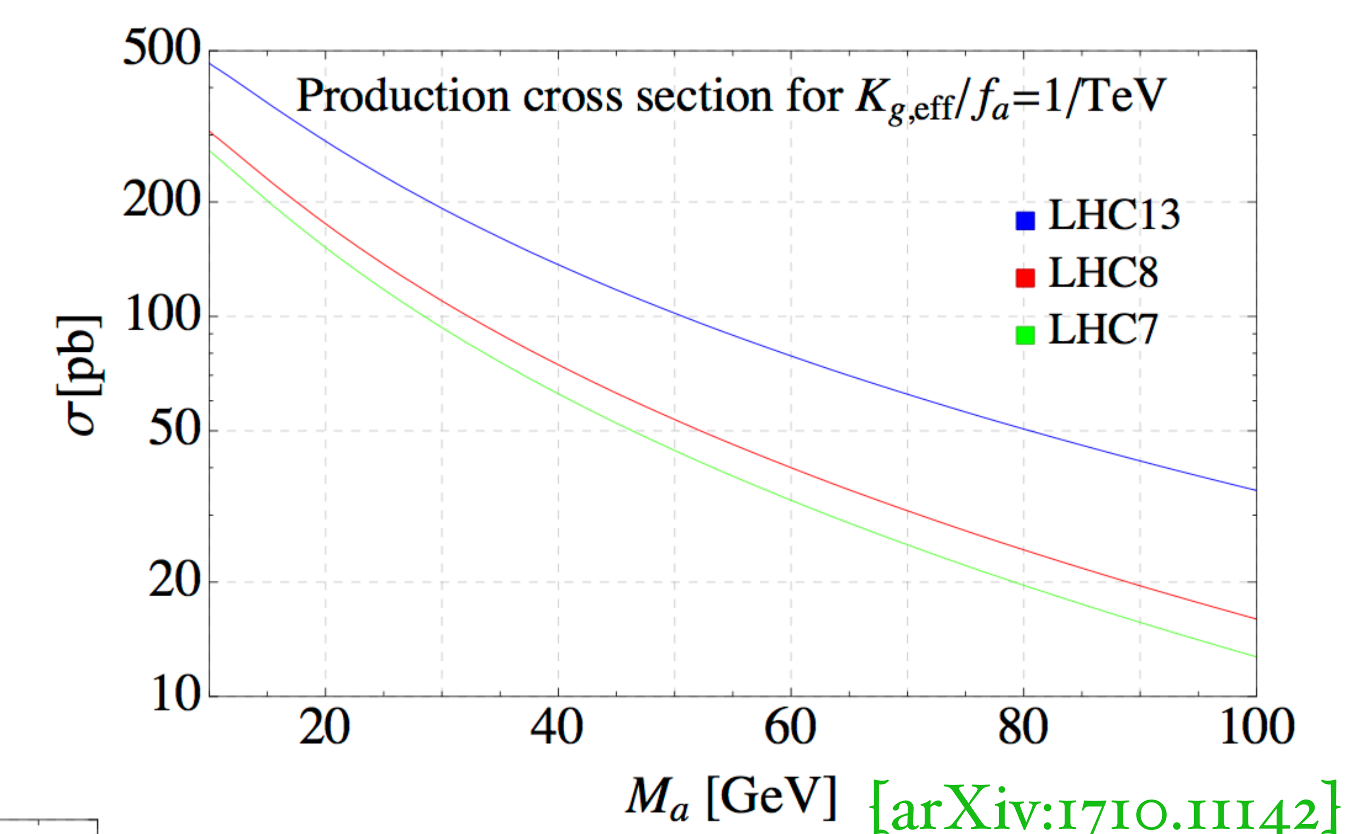
$\gamma\gamma$
[PRL113, 17801]
(ATLAS)
[CMS-PAS-HIG-17-013]

BR(h→BSM)<.34
[JHEP1608, 045]
(ATLAS+CMS)

$\mu\mu$
[PRL109, 121801]
(CMS)
[ATLAS-CONF-2011-020]

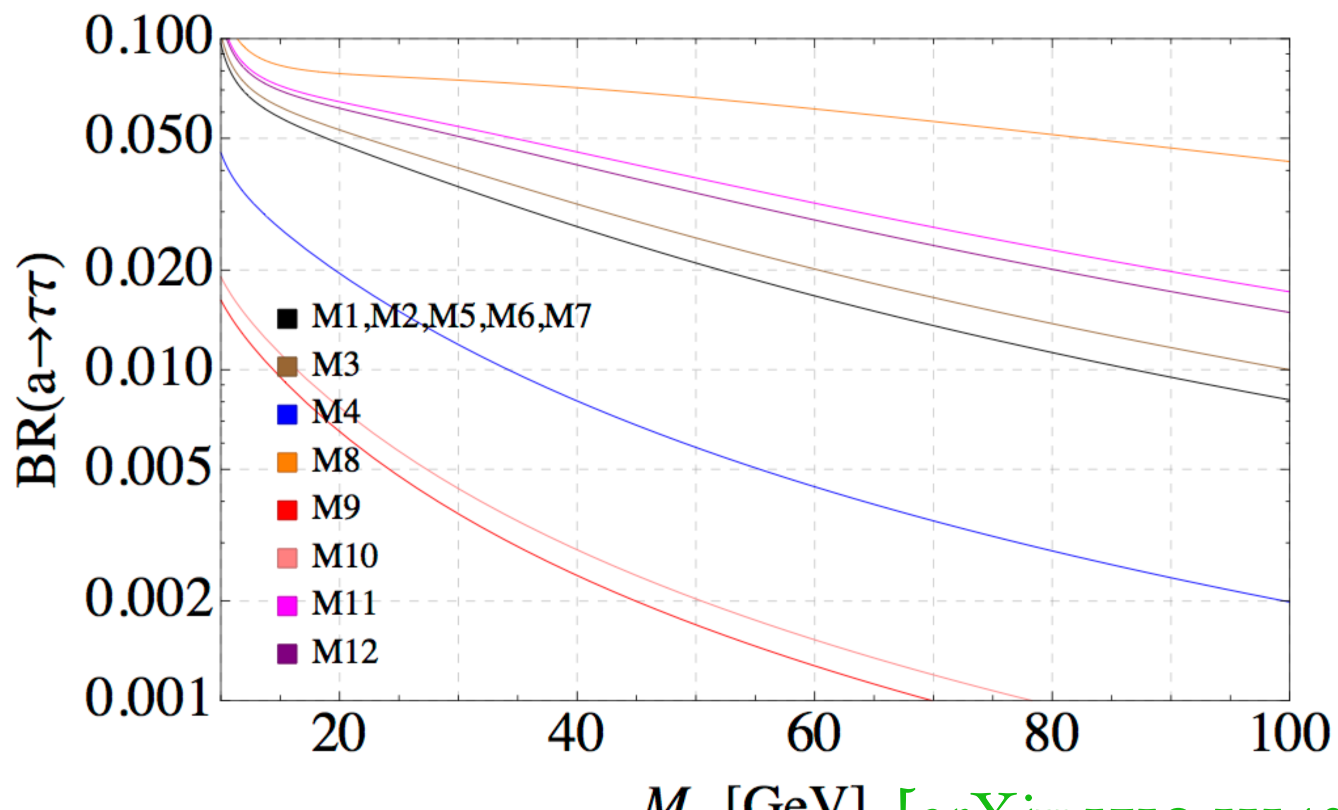
How can we search the gap at low mass? $\tau\tau$!

The gluon-fusion production cross section for light a is large…



[arXiv:1710.11142]

… and the $\tau\tau$ branching ratio is (for most models) not small.



[arXiv:1710.11142]

Soft $\tau_{\rm lep}$ or $\tau_{\rm had}$ cannot be used to trigger, but ISR can boost the $gg \to a \to \tau\tau$ system (at the cost of production cross section, but we have enough).

How can we search the gap at low mass? $\tau\tau$!

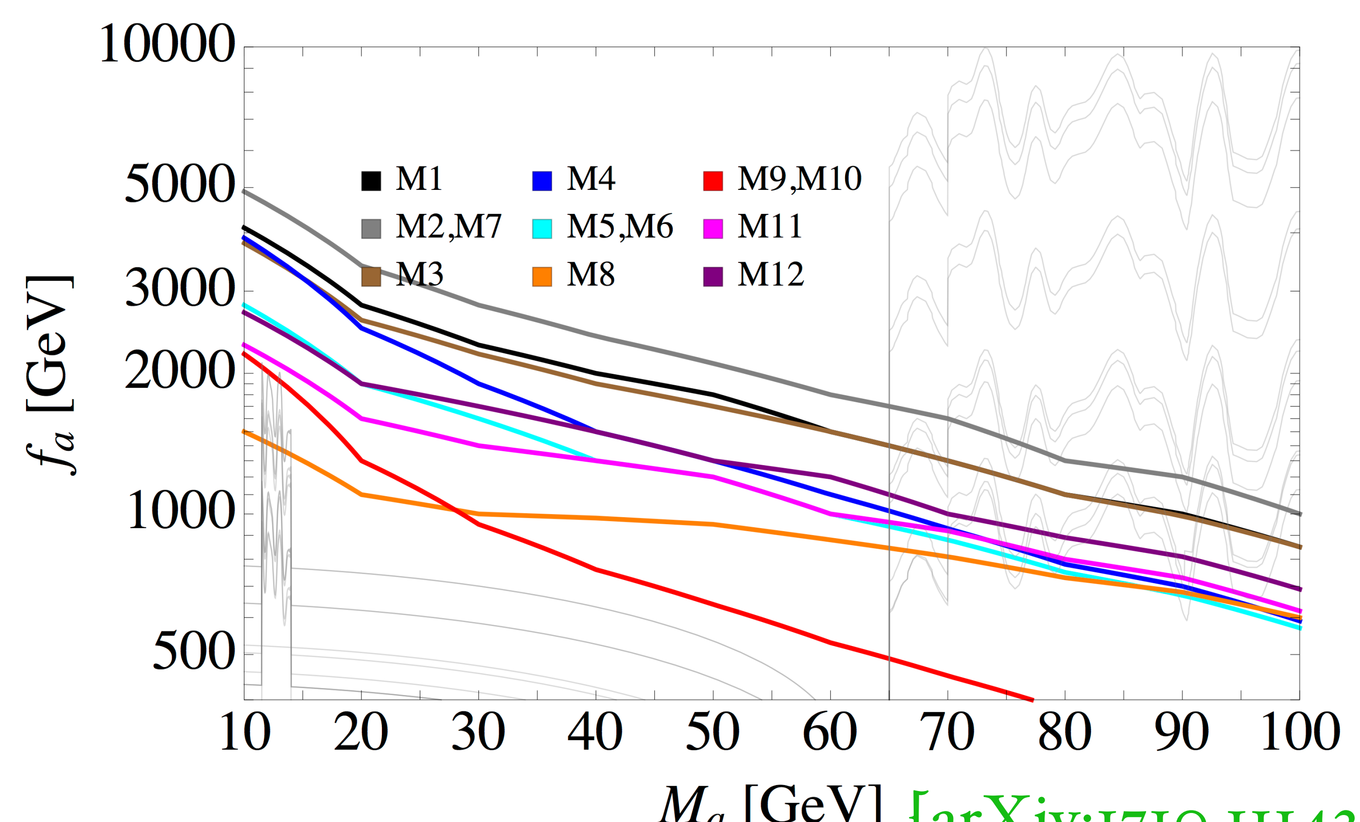
As a very naive proof of principle analysis we look for a $j\ \tau_\mu\ \tau_e$ final state (jet + opposite sign, opposite flavor leptons) with cuts:

- $p_{T\mu} > 42$ GeV (for triggering)
- $p_{Te} > 10$ GeV
- $m_{\mu e} < 100$ GeV
- $\Delta R_{\mu j} > 0.5$, $\Delta R_{ej} > 0.5$,
- $\Delta R_{\mu e} < 1.0$

m_a	M1	M2 M7	M3	M4	M5 M6	M8	M9 M10	M11	M12	$t\bar{t}+Wt$	γ^*/Z	VV
20	18.	26.	15.	14.	8.0	2.7	3.9	5.9	8.1	77.	35.	13.
40	8.8	13.	8.2	5.1	3.9	2.1	1.3	3.7	4.8			
60	5.0	7.3	4.8	2.6	2.3	1.7	.63	2.4	3.0			
80	2.7	3.9	2.7	1.3	1.2	1.2	.32	1.4	1.8			

TABLE II: The values of $\sigma_{\text{prod.}} \times BR_{\tau\tau} \times \epsilon$ in fb for $f_a = 1$ TeV and $m_a = 20,\ 40,\ 60,\ 80$ GeV for each of the models defined in Table I. The last three columns contain cross sections for the main backgrounds.

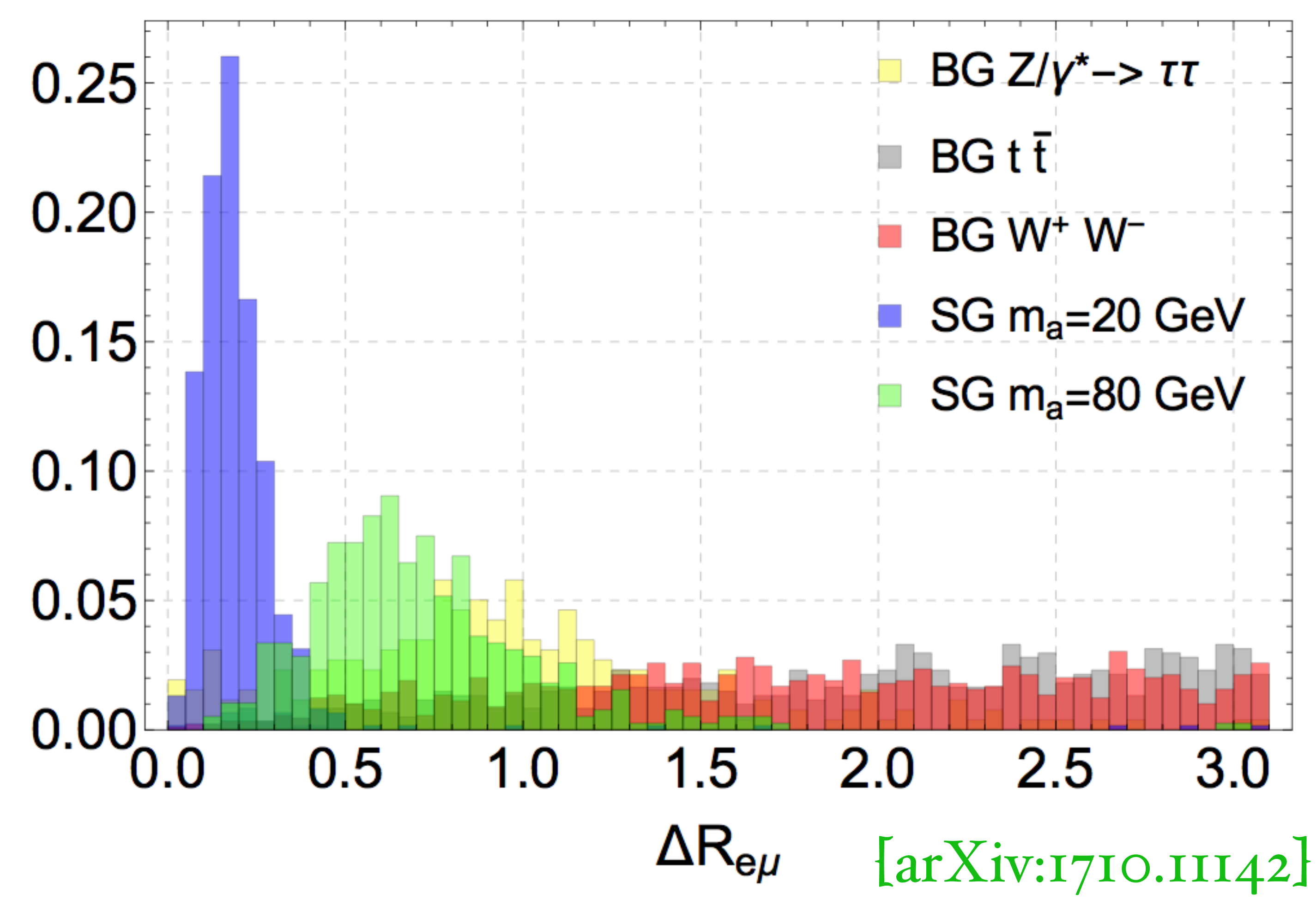
[arXiv:1710.11142]



[arXiv:1710.11142]

13 TeV, 300 fb expected bounds (S/√B = 3)

How can we search the gap at low mass? $\tau\tau$!



[arXiv:1710.11142]

This first proof of principle study is not optimized.

- Cutting harder on $\Delta R_{\mu e}$ can substantially increase background suppression for the lighter mass range.
- We did not use any τ ID or triggers.
- We only used the OSOF lepton channel. $\tau_\mu\tau_\mu$, $\tau_\mu\tau_{had}$, $\tau_{had}\tau_{had}$ have larger branching ratios but require a more careful background analysis.
  [And needs tagging efficiencies for boosted $\tau_\mu\tau_{had}$, $\tau_{had}\tau_{had}$ systems which are beyond our capabilities, but possible for experimentalists.]

Implications for VLQ searches

Current VLQ searches focus on charge 5/3, 2/3, -1/3, -4/3 top partners which are pair (or single) produced and decay into t/b and h/W/Z.

If pNGBs beyond the Higgs are present in the model they are conceivably lighter than top partners.

How large are top partner decay rates into pNGBs other than the Higgs?

The top obtains its mass through mixing with a top partner. But the top partners come a full multiplets of the global symmetry groups and the Higgs comes in the Goldstone-boson matrix which includes ALL pNGBs of the model. Thus, we can relate the coupling of a top partner to the Higgs to its couplings to other pNGBs in underlying models.

Scanning through the different underlying models we looked for "common exotic" top partner decays and found:

Common exotic VLQ decays

Candidate 1: decays to the singlet pseudo-scalar *a*

Effective Lagrangian(s):

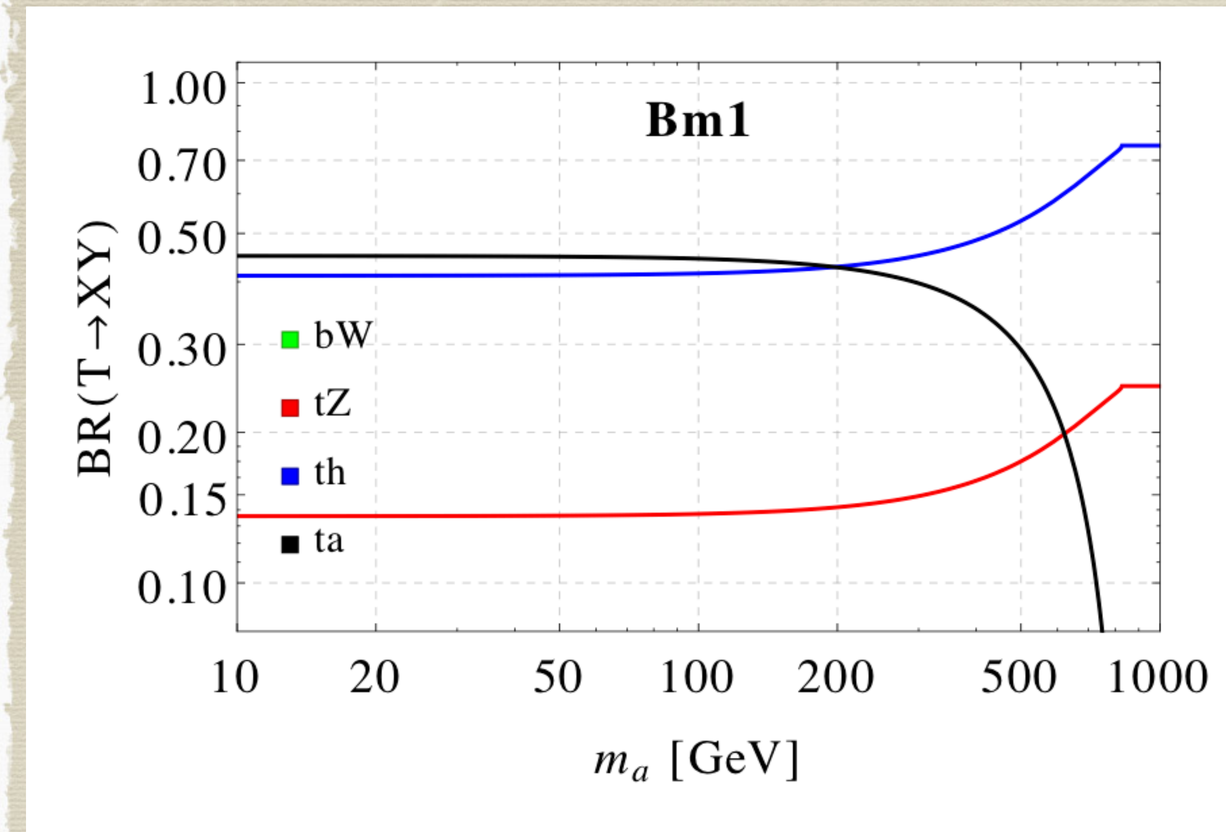
$$\mathcal{L}_T = \overline{T}\left(i\not{D} - M_T\right)T + \Bigg(\kappa^T_{W,L}\frac{g}{\sqrt{2}}\overline{T}\not{W}^+ P_L b + \kappa^T_{Z,L}\frac{g}{2c_W}\overline{T}\not{Z}P_L t$$
$$-\kappa^T_{h,L}\frac{M_T}{v}\overline{T}hP_L t + i\kappa^T_{a,L}\overline{T}aP_L t + L \leftrightarrow R + \text{ h.c. }\Bigg),$$

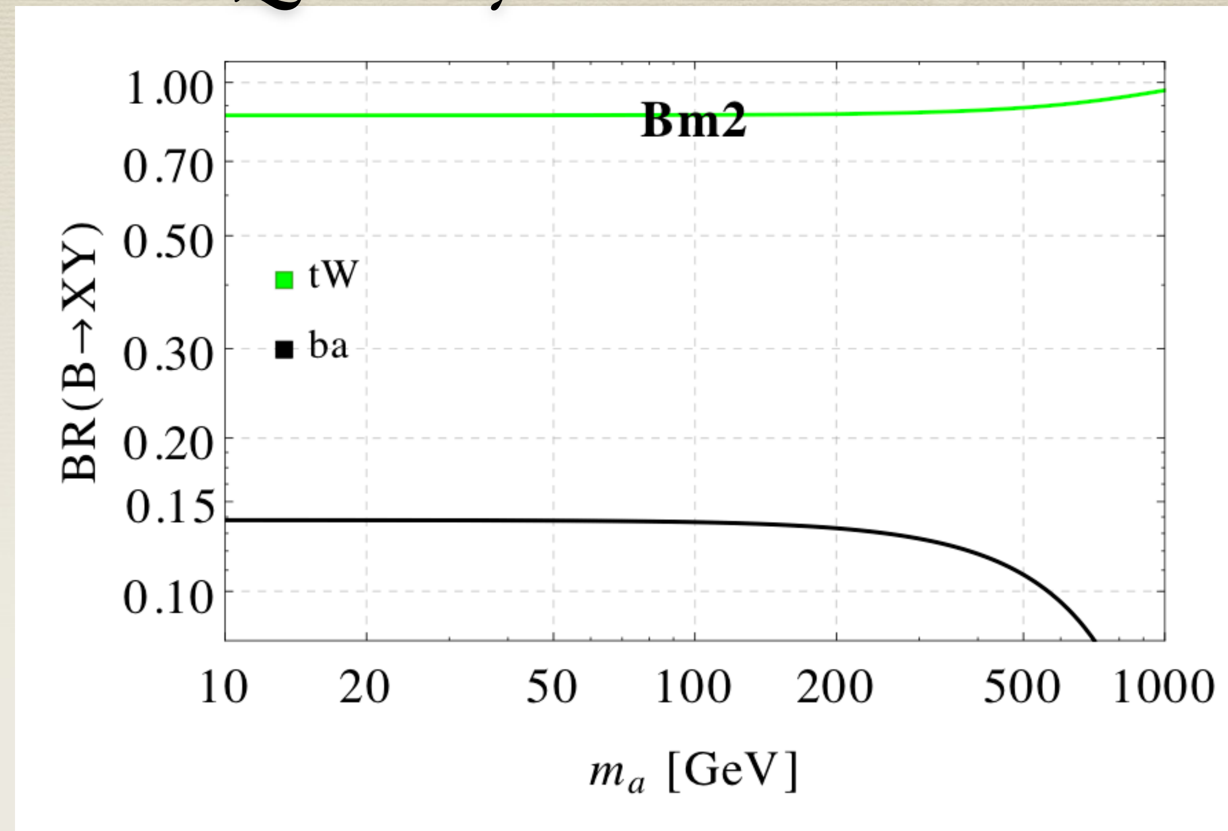
$$\mathcal{L}_B = \overline{B}\left(i\not{D} - M_B\right)B + \Bigg(\kappa^B_{W,L}\frac{g}{\sqrt{2}}\overline{B}\not{W}^- P_L t + \kappa^B_{Z,L}\frac{g}{2c_W}\overline{B}\not{Z}^+ P_L b$$
$$-\kappa^B_{h,L}\frac{M_B}{v}\overline{B}hP_L b + i\kappa^B_{a,L}\overline{B}aP_L b + L \leftrightarrow R + \text{ h.c. }\Bigg).$$

Benchmark parameters (obtained as eff. parameters from UV model):

$$\text{Bm1}: \quad M_T = 1 \text{ TeV}, \quad \kappa^{\rm T}_{\rm Z,R} = -0.03, \quad \kappa^{\rm T}_{\rm h,R} = 0.06, \quad \kappa^{\rm T}_{\rm a,R} = -0.24, \quad \kappa^{\rm T}_{\rm a,L} = -0.07;$$
$$\text{Bm2}: \quad M_B = 1.38 \text{ TeV}, \quad \kappa^{\rm B}_{\rm W,L} = 0.02, \quad \kappa^{\rm B}_{\rm W,R} = -0.08, \quad \kappa^{\rm B}_{\rm a,L} = -0.25, \qquad (2.3)$$

Common exotic VLQ decays



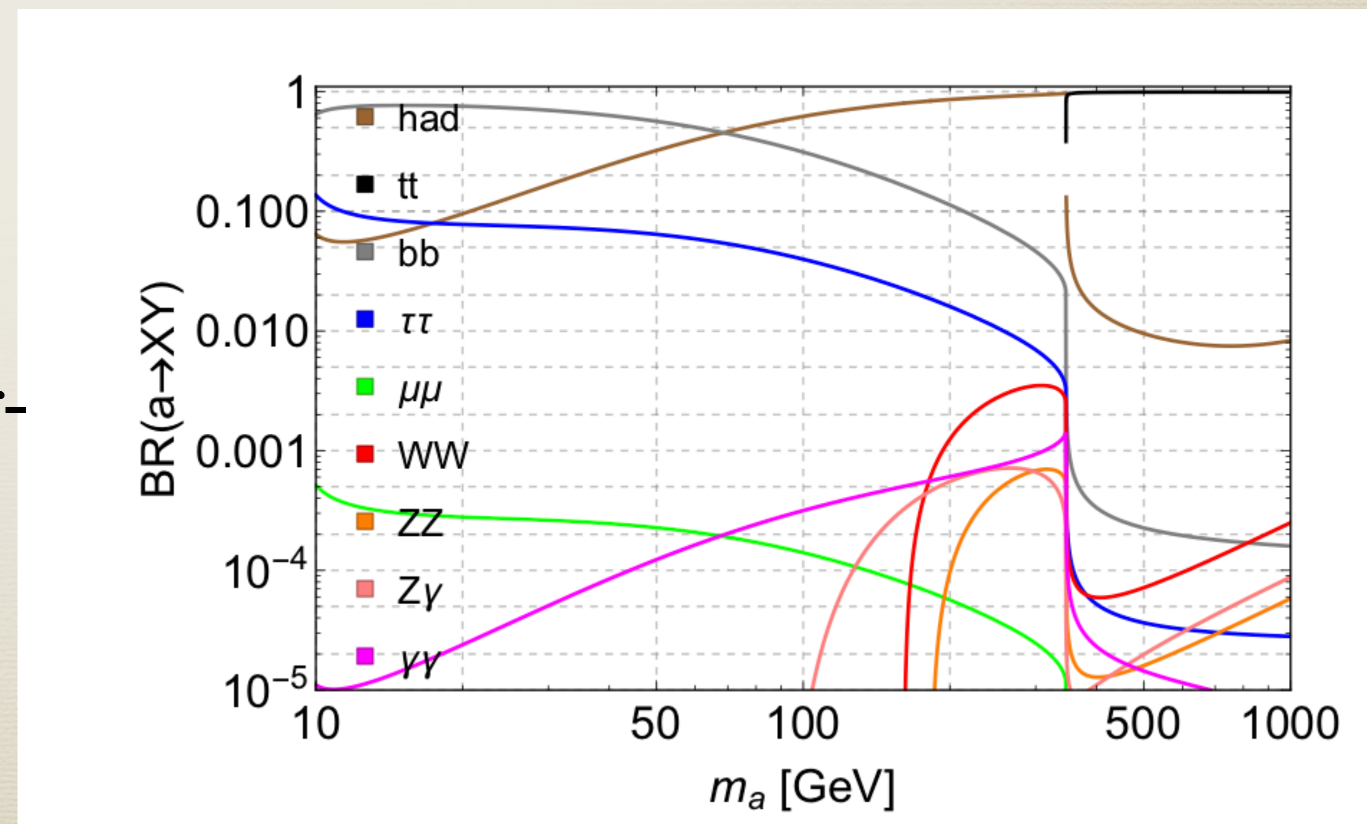


- T and B can be produced like "standard" top partners: QCD pair production or single production.
- New final states: MANY, depending on m_a and single- or pair-production

(E.g. heavy a and pair production:

"p p > T T~, T > t a, a > t t~";

that's a 6 top final state)



[arXiv:1803.00021]

Common exotic VLQ decays

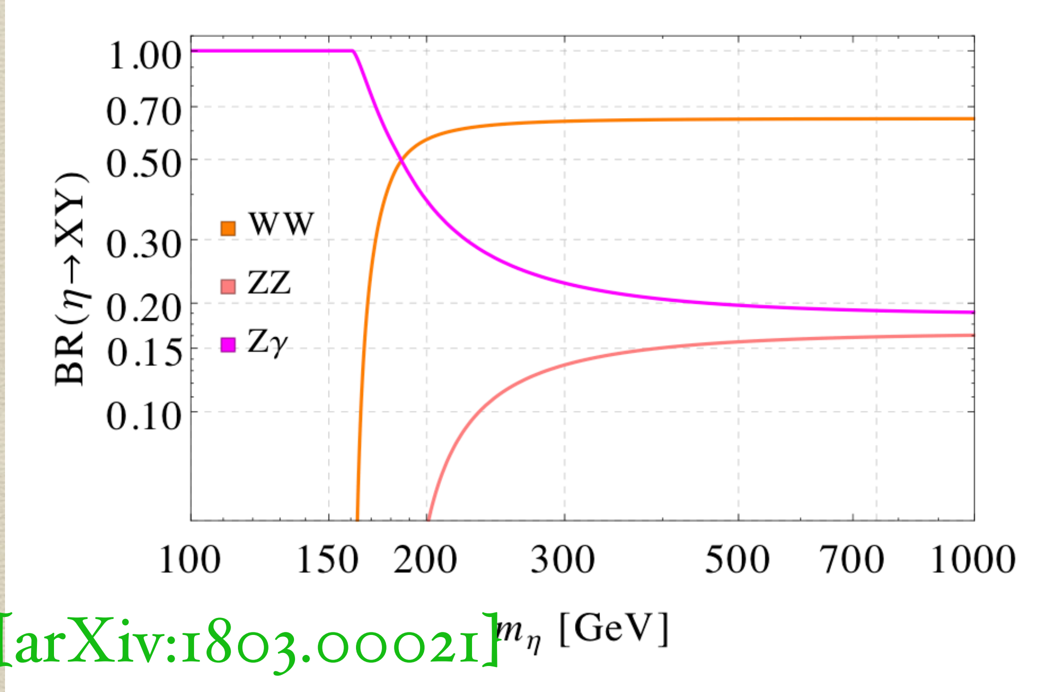
Candidate 2: Decays of a top partner to the "exclusive pseudo-scalar" η.

In models with SU(4)/Sp(4) breaking, one specific top partner couples only to the CP-odd SM singlet pNGB η. Both are odd under η-parity. η-parity is broken by EW anomaly couplings, and η decays to WW, ZZ, Zγ.

Effective Lagrangian:

$$\mathcal{L}_{\widetilde{T}} = \overline{\widetilde{T}}\left(i\not{D} - M_{\widetilde{T}}\right)\widetilde{T} - \left(i\kappa^{\widetilde{T}}_{\eta,L}\,\overline{\widetilde{T}}\eta P_L t + L \leftrightarrow R + \text{ h.c. }\right)$$

$$\mathcal{L}_\eta = \frac{1}{2}(\partial_\mu\eta)(\partial^\mu\eta) - \frac{1}{2}m_\eta^2\eta^2 + \frac{g_s^2 K_g^\eta}{16\pi^2 f_\eta}\eta G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{g^2 K_W^a}{8\pi^2 f_\eta}\eta W^+_{\mu\nu}\tilde{W}^{-,\mu\nu}$$
$$+ \frac{e^2 K_\gamma^\eta}{16\pi^2 f_\eta}\eta A_{\mu\nu}\tilde{A}^{\mu\nu} + \frac{g^2 c_W^2 K_Z^\eta}{16\pi^2 f_\eta}\eta Z_{\mu\nu}\tilde{Z}^{\mu\nu} + \frac{egc_W K^\eta_{Z\gamma}}{8\pi^2 f_\eta}\eta A_{\mu\nu}\tilde{Z}^{\mu\nu}$$



[arXiv:1803.00021]

The η-parity top partner is only QCD-pair produced.

Final states: |tWW + tZZ + tZγ| ^{2}

Common exotic VLQ decays

Candidate 3: $X_{5/3} \to \bar{b}\,\pi_6$ (with subsequent $\boldsymbol{\pi}_6 \to$ t t)

In models with SU(6)/SO(6) breaking in the color sector.

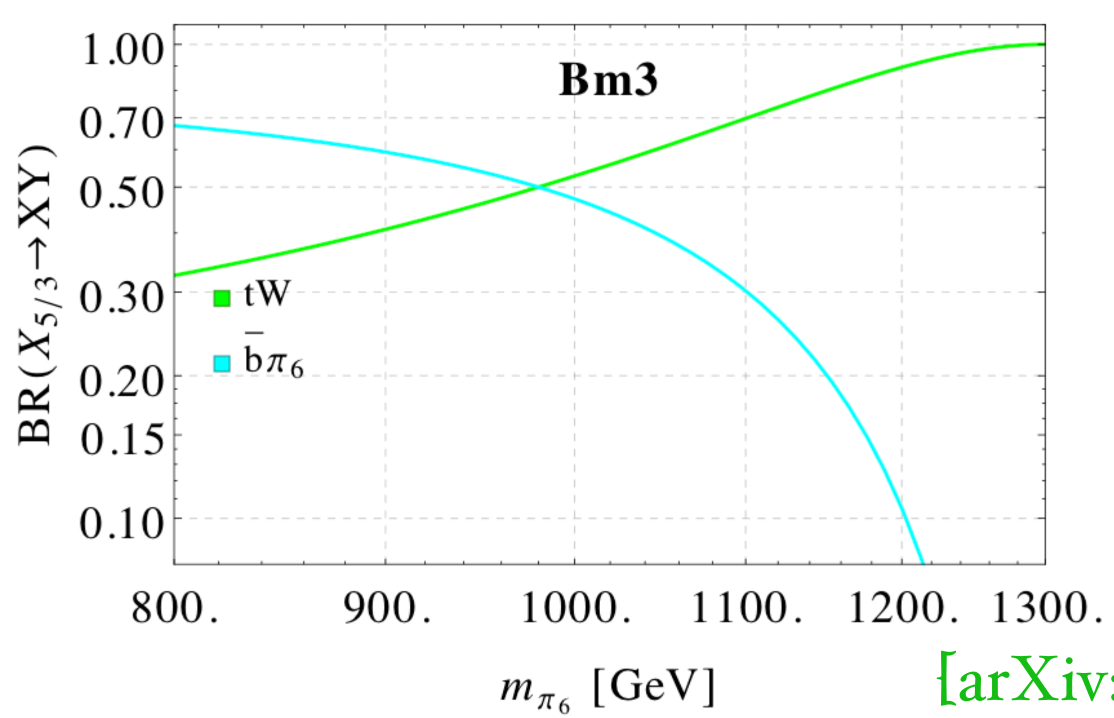
Effective Lagrangian:

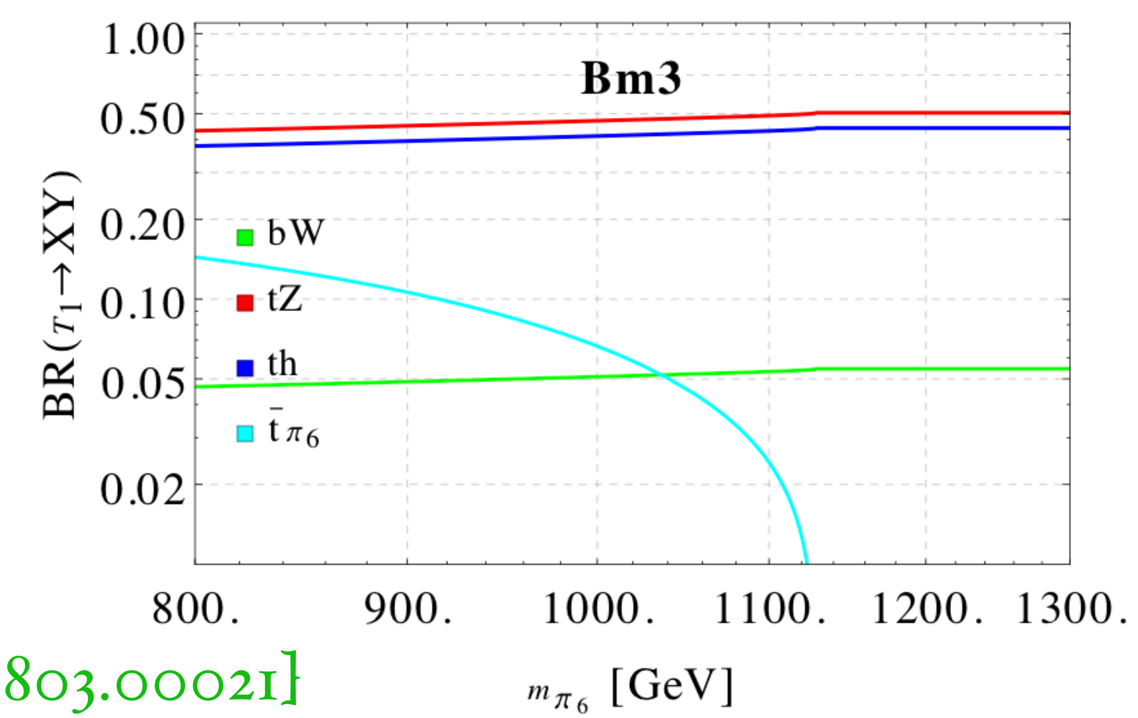
$$\mathcal{L}^{\pi_6}_{X_{5/3}} = \overline{X}_{5/3}\left(i\not{D} - M_{X_{5/3}}\right)X_{5/3} + \left(\kappa^{X}_{W,L}\frac{g}{\sqrt{2}}\,\overline{X}_{5/3}\not{W}^{+}P_L t + i\kappa^{X}_{\pi_6,L}\,\overline{X}_{5/3}\pi_6 P_L b^c + L \leftrightarrow R + \text{ h.c.}\right)$$

$$\mathcal{L}_{\pi_6} = |D_\mu \pi_6|^2 - m^2_{\pi_6}|\pi_6|^2 + \left(i\kappa^{\pi_6}_{tt,R}\,\bar{t}\pi_6(P_R t)^c + L \leftrightarrow R + \text{ h.c.}\right)$$

Benchmark parameters (obtained as eff. parameters from UV model):

$$\text{Bm3}: \quad M_{X_{5/3}} = 1.3\text{ TeV}, \quad \kappa^{\text{X}}_{\text{W,L}} = 0.03, \quad \kappa^{\text{X}}_{\text{W,R}} = -0.11, \quad \kappa^{\text{X}}_{\pi_6,\text{L}} = 1.95, \quad \kappa^{\pi_6}_{\text{tt,R}} = -0.56$$





[arXiv:1803.00021]

Common exotic VLQ decays

Candidate 4: $X_{5/3} \to t\ \phi^+$ and $X_{5/3} \to b\ \phi^{++}$

In models with SU(5)/SO(5) breaking in the EW sector, we have charged (and doubly charged) pNGBs.

Effective Lagrangian:

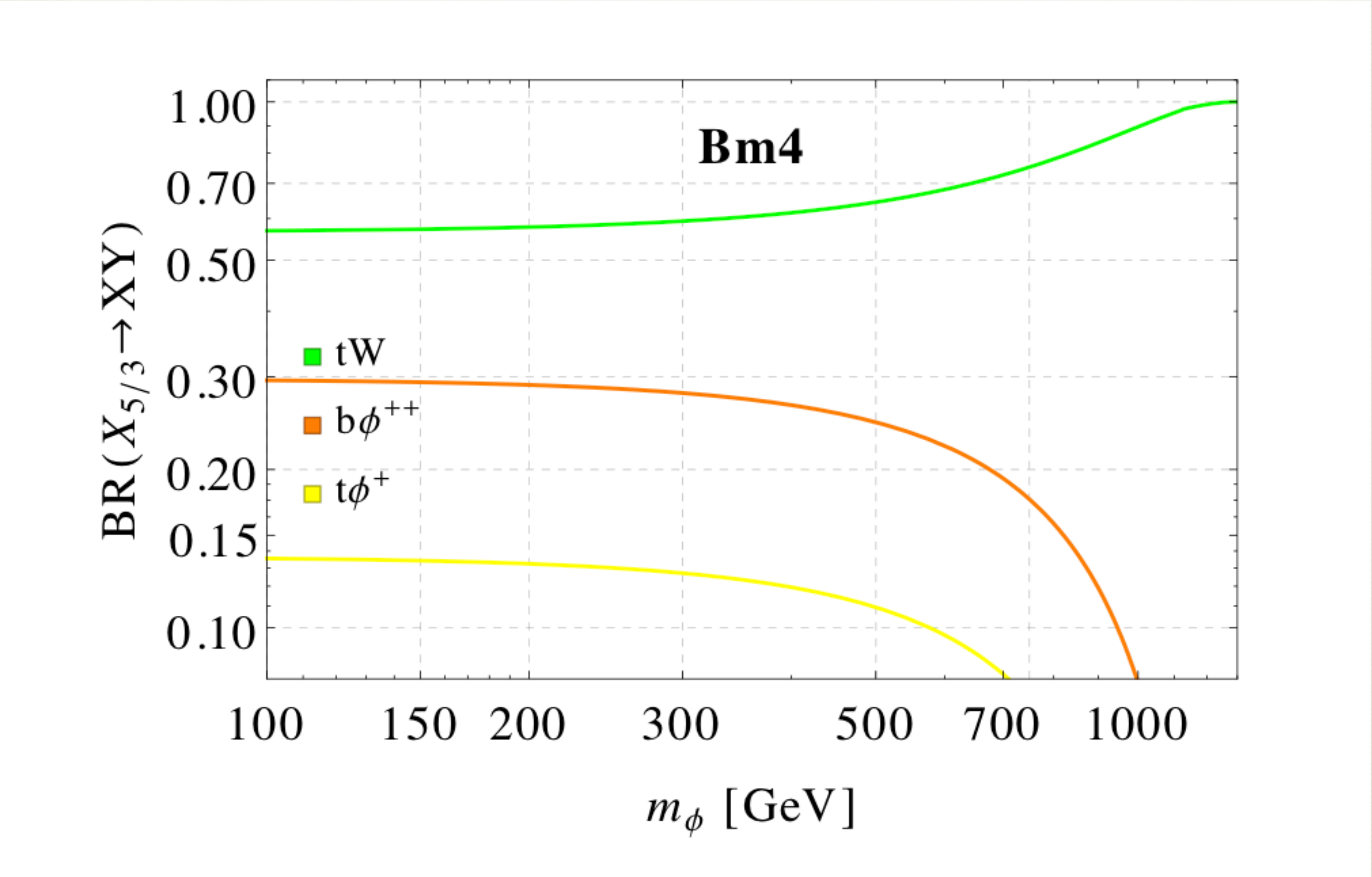
$$\mathcal{L}^{\phi}_{X_{5/3}} = \overline{X}_{5/3}\left(i\not{D} - M_{X_{5/3}}\right)X_{5/3} + \left(\kappa^X_{W,L}\frac{g}{\sqrt{2}}\overline{X}_{5/3}\not{W}^+P_Lt \right.$$
$$\left. + i\kappa^X_{\phi^+,L}\overline{X}_{5/3}\phi^+P_Lt + i\kappa^X_{\phi^{++},L}\overline{X}_{5/3}\phi^{++}P_Lb + L\leftrightarrow R + \text{h.c.}\right)$$

$$\mathcal{L}_\phi = \sum_{\phi=\phi^+,\phi^{++}}\left(|D_\mu\phi|^2 - m^2_\phi\,|\phi|^2\right) + \left(\frac{egK^\phi_{W\gamma}}{8\pi^2 f_\phi}\phi^+W^-_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{g^2c_wK^\phi_{WZ}}{8\pi^2 f_\phi}\phi^+W^-_{\mu\nu}\tilde{B}^{\mu\nu}\right.$$
$$\left. + \frac{g^2K^\phi_W}{8\pi^2 f_\phi}\phi^{++}W^-_{\mu\nu}\tilde{W}^{\mu\nu,-} + i\kappa^\phi_{tb,L}\frac{m_t}{f_\phi}\bar{t}\phi^+P_Lb + L\leftrightarrow R + \text{h.c.}\right)\,. \quad (2.13)$$

Common exotic VLQ decays

Benchmark parameters (obtained as eff. parameters from UV model):

$$\text{Bm4}: \quad M_{X_{5/3}} = 1.3 \text{ TeV}\,, \quad \kappa^{\text{X}}_{\text{W,L}} = 0.03\,, \quad \kappa^{\text{X}}_{\text{W,R}} = 0.13\,, \quad \kappa^{\text{X}}_{\phi^+,\text{L}} = 0.49\,, \quad \kappa^{\text{X}}_{\phi^+,\text{R}} = 0.12\,,$$
$$\kappa^{X}_{\phi^{++},L} = -0.69\,, \quad \kappa^{\phi}_{tb,L} = 0.53\,, \tag{2.14}$$



Production of $X_{5/3}$:

Single- or pair-production.

Decays of the pNGBs:

$\phi^{++} \rightarrow W^+ W^+$

$\phi^{+} \rightarrow tb,\ W^+ Z,\ W^+ \gamma$

Conclusions & Outlook

- EFT descriptions of composite Higgs models are only part of the story. UV embeddings need to be studied in more detail. They lead to novel (as well as already well-known) BSM LHC signatures.
- We showed that additional pNGBs are present in CH UV embeddings (colored as well as uncolored ones). We presented constraints for the SM singlet and propose to search for the light singlet in the boosted di-tau channel.
- Decays of top partners to t/b + pNGBs rather than to t/b + W/Z/h occur commonly in CH UV embeddings.
  - Obtained from underlying descriptions we presented 4 "common exotic decays" of top partners with effective Lagrangians and benchmark values.
  - The final states resulting from these decays are not targeted in current LHC searches. Many are partially covered by existing searches and recasts can provide some bounds.

There is a lot to explore!

Backup

Chiral Lagrangian for the pNGBs

The pseudo-Goldstones are parameterized by the Goldstone boson matrices

$$\Sigma_r = e^{i2\sqrt{2}c_5\pi_r^a T_r^a/f_r} \cdot \Sigma_{0,r} \,, \quad \Phi_r = e^{ic_5 a_r/f_{a_r}} \,,$$

where r = ψ,χ , $\boldsymbol{\pi}^a$ are the non-abelian Goldstones, T^a are the corresponding broken generators, $\boldsymbol{\Sigma}_{0,r}$ is the EW preserving vacuum, and *a* are the U(1) Goldstones parameterized via the Goldstone boson matrices. (c_5 is $\sqrt{2}$ for real reps and 1 otherwise).

The lowest order chiral Lagrangian is

$$\mathcal{L}_{\chi pt} = \sum_{r=\psi,\chi} \frac{f_r^2}{8c_5^2}\,\mathrm{Tr}[(D_\mu\Sigma_r)^\dagger(D^\mu\Sigma_r)] + \frac{f_{a_r}^2}{2c_5^2}\,(\partial_\mu\Phi_r)^\dagger(\partial^\mu\Phi_r)\,.$$

where we chose the normalization such that $m_W = \frac{g}{2} f_\psi \sin\theta$ where θ is the vacuum misalignment angle.

In the large N limit, expect $f_{a_r} \;=\; \sqrt{N_r} f_r$.

Upshot: - The pNGBs are described in a non-linear sigma model.
- The different pNGBs can have different decay constants (ratios can be estimated, but in the end only calculated on the Lattice. **.**

TH

Sources of masses and couplings of the pseudo Goldstone bosons:

1. The SM gauge group is weakly gauged, which explicitly breaks the global symmetry. This yields mass contributions for SM charged pNGBs. As the underlying fermions are SM charged, it also yields anomaly couplings of pNGBs to SM gauge bosons.
2. The elementary quarks (in particular tops) need to obtain masses. This can be achieved through linear mixing with composite fermionic operators ("top partners"), which explicitly break the global symmetries.
3. Mass terms for the underlying fermions explicitly break the global symmetries and give (correlated) mass contributions to all pseudo Goldstones.

Weak gauging and partial compositeness is commonly used in composite Higgs models to explain the generation of a potential for the Higgs (aka EW pNGBs). On the level of the underlying fermions, such mixing requires 4-fermion operators.

What are the implications of the above points for the SM singlet, and the color-octet pNGB?

TH

Couplings of pNGBs to SM gauge bosons:

The underlying fermions are charged under the SM gauge fields, and thus ABJ anomalies induce couplings of the Goldstone bosons to the SM fields which are fully determined by the underlying quantum numbers.

Singlets: $$\mathcal{L}_{\text{WZW}} \supset \frac{\alpha_A}{8\pi} c_5 \frac{C_A^r}{f_{a_r}} \delta^{ab} \, a_r \, \varepsilon^{\mu\nu\alpha\beta} A^a_{\mu\nu} A^b_{\alpha\beta} \, ,$$

where

r	coset ψ	C_W^ψ	C_B^ψ	coset χ	C_G^χ	C_B^χ
complex	$\mathrm{SU}(4)\times\mathrm{SU}(4)/\mathrm{SU}(4)$	d_ψ	d_ψ	$\mathrm{SU}(3)\times\mathrm{SU}(3)/\mathrm{SU}(3)$	d_χ	$6Y_\chi^2 d_\chi$
real	$\mathrm{SU}(5)/\mathrm{SO}(5)$	d_ψ	d_ψ	$\mathrm{SU}(6)/\mathrm{SO}(6)$	d_χ	$6Y_\chi^2 d_\chi$
pseudo-real	$\mathrm{SU}(4)/\mathrm{Sp}(4)$	$d_\psi/2$	$d_\psi/2$	$\mathrm{SU}(6)/\mathrm{Sp}(6)$	d_χ	$6Y_\chi^2 d_\chi$

Non-abelian pNGBs: $$\mathcal{L}_{\text{WZW}} \supset \frac{\sqrt{\alpha_A \alpha_{A'}}}{4\sqrt{2}\pi} c_5 \frac{C^r_{AA'}}{f_r} c^{abc} \, \pi_r^a \, \varepsilon^{\mu\nu\alpha\beta} A^a_{\mu\nu} A'^b_{\alpha\beta} \, ,$$

where $$C^r_{AA'} c^{abc} = d_r \mathrm{Tr}[T^a_\pi \{S^b, S^c\}]$$

Upshot: - The couplings $C^r{}_A$ of pNGBs to gauge bosons are fully fixed by the quantum numbers of χ and ψ.

- One model ⇔ one set of Branching ratios.

- Only unknown parameters are decay constants f_r.

TH

Couplings to tops and top mass:

We want to realize top masses through partial compositeness, i.e.

$$\mathcal{L}_{mix} \supseteq y_L \; \bar{q}_L \Psi_{q_L} + y_R \; \bar{\Psi}_{t_R} t_R + h.c.$$

where $\boldsymbol{\psi}$ are the composite top partners, depending on the model either $\psi\psi\chi$ or $\psi\chi\chi$ bound states. The spurions $y_{L,R}$ thus carry charges under the U(1)$_{\chi,\psi}$.
The top mass in partial compositeness is proportional to $y_{L^*}\, y_R$ fand thus also has definite U(1)$_{\chi,\psi}$ charges $n_{\psi,\chi}$. For $\psi\psi\chi$:

$$y_L \,,\; y_R \sim (\pm 2, 1) \,,\; (0, -1) \,, \quad \Rightarrow m_{\rm top} \sim (\pm 4, 2) \,, \;\; (0, \pm 2) \,, \;\; (\pm 2, 0) \,,$$

The singlet-to-top coupling Lagrangian can be written as

$$\mathcal{L}_{top} = m_{\rm top} \Phi_{\psi}^{n_\psi} \Phi_{\chi}^{n_\chi} \; \bar{t}_L t_R + h.c. = m_{\rm top} \; \bar{t}t + i c_5 \left(n_\psi \frac{a_\psi}{f_{a_\psi}} + n_\chi \frac{a_\chi}{f_{a_\chi}} \right) m_{\rm top} \; \bar{t}\gamma^5 t + \ldots$$

NOTE:

- The term that generates the top mass also generates couplings of the pNGBs to tops.
- The possible top couplings depend on the model and top partner embedding, with a discrete set of choices.
- For the singlet pNGBs, the coupling never vanishes as in no case $n_\psi = 0 = n_\chi$.
- The analogous argument yields zero coupling of $\boldsymbol{\pi}_8$ to tops if $n_\chi = 0$.

Upshot: - pNGBs couple to top-pairs.
- there is a discrete set of possible couplings per model.

TH

Underlying fermion mass terms:

The SM singlet pNGBs cannot obtain mass through the weak gauging. To make them massive, we add mass terms for χ (and in principle ψ) which break the chiral symmetry. They yield mass terms

$$\mathcal{L}_m = \sum_{r=\psi,\chi} \frac{f_r^2}{8c_5^2} \Phi_r^2 \mathrm{Tr}[X_r^\dagger \Sigma_r] + h.c. = \sum_{r=\psi,\chi} \frac{f_r^2}{4c_5^2} \left[\cos\left(2c_5 \frac{a_r}{f_{a_r}}\right) \mathrm{ReTr}[X_r^\dagger \Sigma_r] - \sin\left(2c_5 \frac{a_r}{f_{a_r}}\right) \mathrm{ImTr}[X_r^\dagger \Sigma_r] \right] .$$

The spurions X_r are related to the the fermion masses linearly

$$X_r = 2B_r m_r \qquad r = \psi, \chi \,,$$

If m_r is a common mass for all underlying fermions of species r, we get

$$m_{\pi_r}^2 = 2B_r \mu_r \,, \quad m_{a_r}^2 = 2N_r \frac{f_r^2}{f_{a_r}^2} B_r \mu_r = \xi_r \, m_{\pi_r}^2$$

Upshot: - masses of singlet and non-abelian pNGBs are related.
- ratios can be estimated, but calculating them needs the Lattice

TH

Singlets: masses and mixing

The states $a_{\psi,\chi}$ mix due to an anomaly w.r.t. the hyper color group which breaks $U(1)_\psi$ x $U(1)_\chi$ to $U(1)_a$.
The anomaly free and anomalous combinations are

$$\tilde{a} = \frac{q_\psi f_{a_\psi} a_\psi + q_\chi f_{a_\chi} a_\chi}{\sqrt{q_\psi^2 f_{a_\psi}^2 + q_\chi^2 f_{a_\chi}^2}}\,, \quad \tilde{\eta}' = \frac{q_\psi f_{a_\psi} a_\chi - q_\chi f_{a_\chi} a_\psi}{\sqrt{q_\psi^2 f_{a_\psi}^2 + q_\chi^2 f_{a_\chi}^2}}\,.$$

The singlet mass terms (including contributions from underlying fermion masses) is thus

$$\mathcal{L}_{\rm mass} = \frac{1}{2} m_{a_\chi}^2 a_\chi^2 + \frac{1}{2} m_{a_\psi}^2 a_\psi^2 + \frac{1}{2} M_A^2 (\cos\zeta a_\chi - \sin\zeta a_\psi)^2$$

where $\tan\zeta = \dfrac{q_\chi f_{a_\chi}}{q_\psi f_{a_\psi}}$, and M_A is a mass contribution generated by instanton effects.

The masses of the pNGBs are

$$m_{a/\eta'}^2 = \frac{1}{2}\left(M_A^2 + m_{a_\chi}^2 + m_{a_\psi}^2 \mp \sqrt{M_A^4 + \Delta m_{a_\chi}^4 + 2 M_A^2\ \Delta m_{a_\chi}^2 \cos 2\zeta} \right)$$

and the interactions in the mass eigenbasis are obtained by rotating from the $a_{\psi,\chi}$ basis into the a,η' basis with

$$\tan\alpha = \tan\zeta \left(1 - \frac{\Delta m_{\eta'}^2 + \Delta m_a^2 - \sqrt{(\Delta m_{\eta'}^2 - \Delta m_a^2)^2 - 4\Delta m_{\eta'}^2\ \Delta m_a^2 \tan^{-2}\zeta}}{2\Delta m_{\eta'}^2} \right)$$

Upshot: - The $\langle\chi\chi\rangle$ and $\langle\psi\psi\rangle$ pNGBs mix through an anomaly term and through their mass terms.

TH

Colored PNGBs (the color octet $\boldsymbol{\pi}_8$)

Effective Lagrangian:

$$\mathcal{L}_{\pi_8} = \frac{1}{2}(D_\mu \pi_8^a)^2 - \frac{1}{2} m_{\pi_8}^2 (\pi_8^a)^2 + i\, C_{t8} \frac{m_t}{f_{\pi_8}} \pi_8^a\, \bar{t}\gamma_5 \frac{\lambda^a}{2} t$$
$$+ \frac{\alpha_s \kappa_{g8}}{8\pi f_{\pi_8}} \pi_8^a\, \epsilon^{\mu\nu\rho\sigma} \left[\frac{1}{2} d^{abc}\, G_{\mu\nu}^b G_{\rho\sigma}^c + \frac{g' \kappa_{B8}}{g_s \kappa_{g8}}\, G_{\mu\nu}^a B_{\rho\sigma} \right],$$

where in the CH UV embeddings:

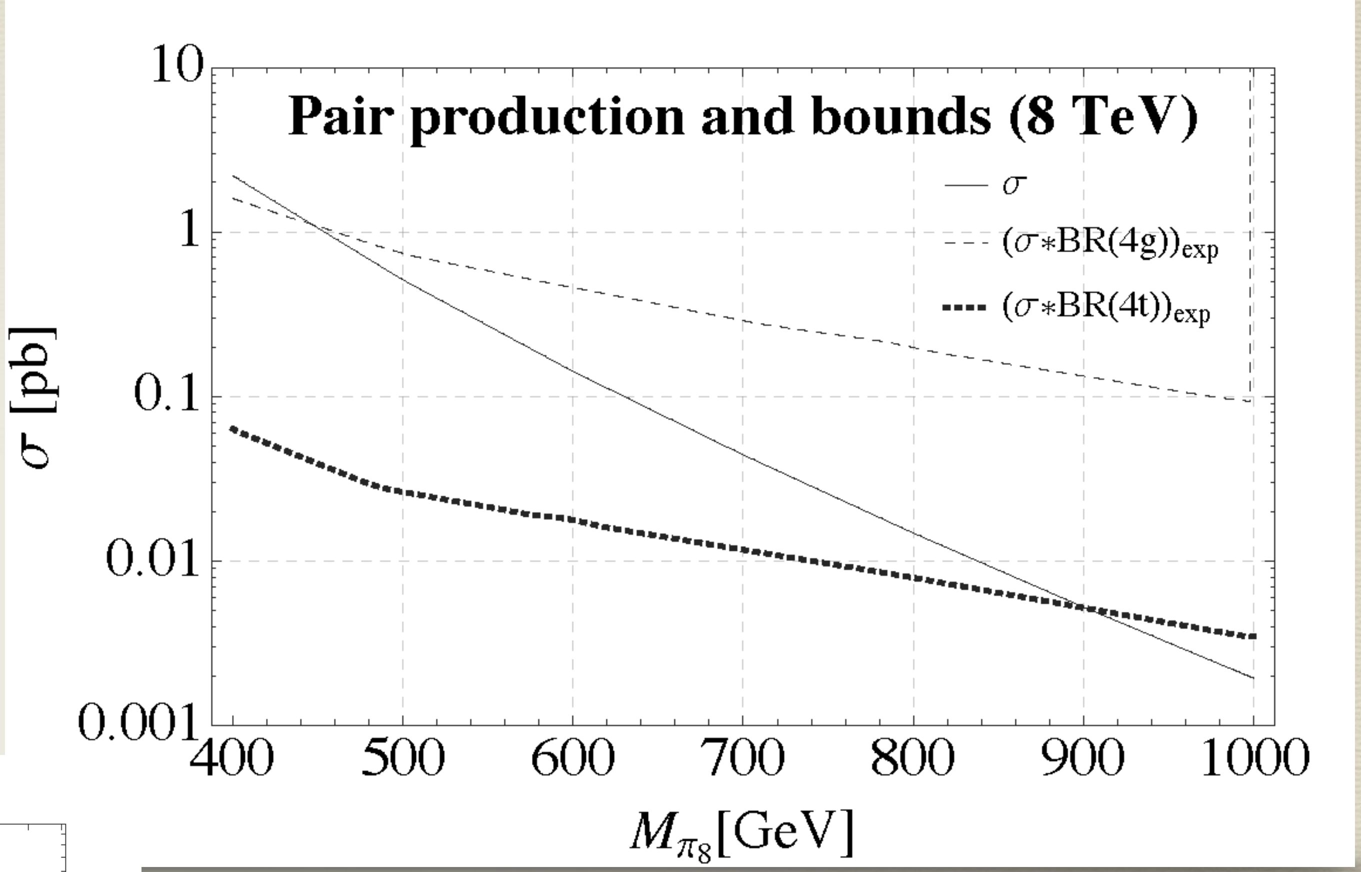
$$\kappa_{g8} = \sqrt{2} c_5\, d_\chi\,, \quad \kappa_{B8} = \sqrt{2} c_5\, 2Y_\chi\, d_\chi, \quad C_{t8} = n_\chi \sqrt{2} c_5 \quad , \quad m_{\pi_8}^2 \sim \frac{m_a^2}{\xi_\chi \sin^2\zeta} + C_g \frac{3}{4} g_s^2\, f_\chi^2$$

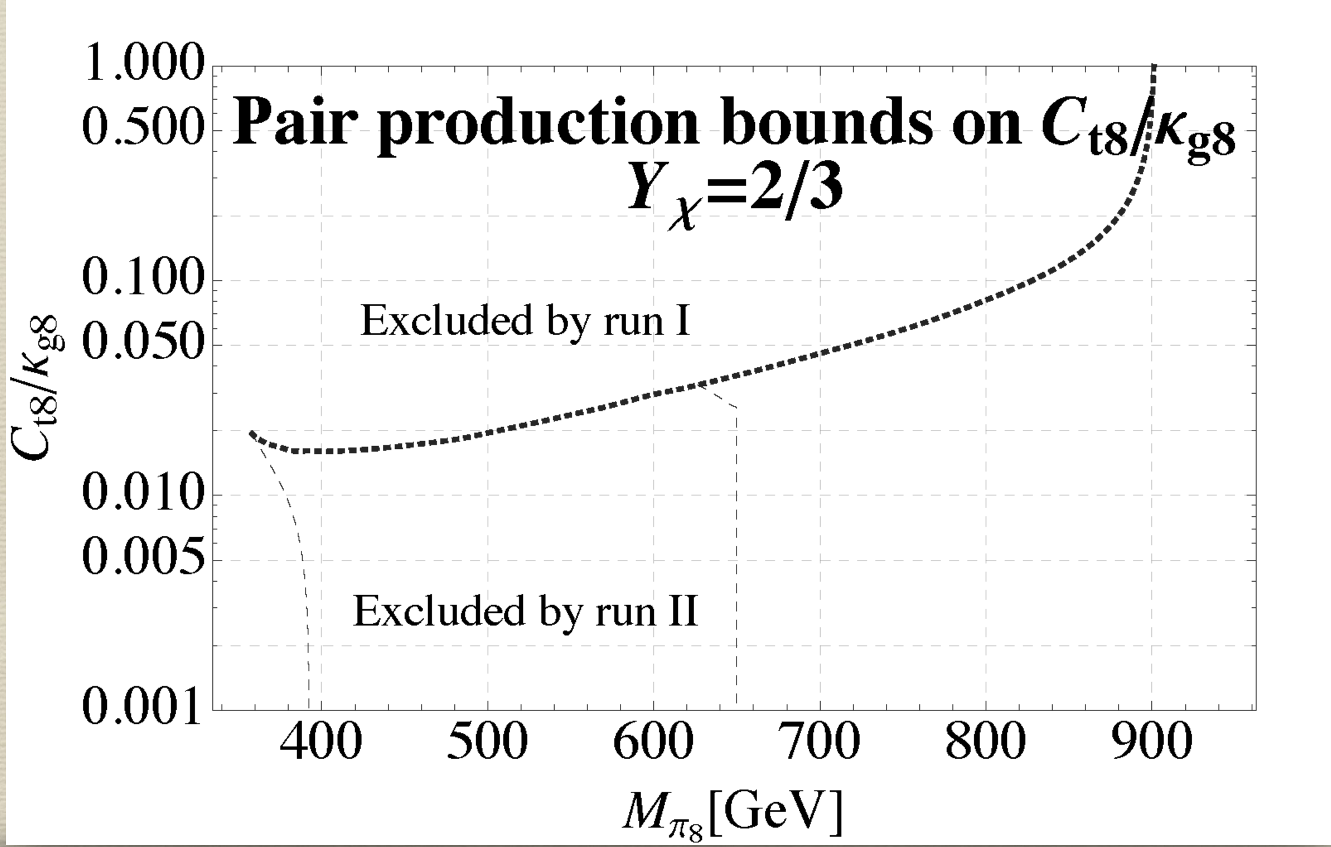
Phenomenology

- $\boldsymbol{\pi}_8$ is single-produced in gluon fusion or pair-produced through QCD.
- $\boldsymbol{\pi}_8$ decays to *gg, gγ, gZ,* $t\bar{t}$ with fully determined branching fractions into dibosons:
- For Y_χ =1/3: *gg/gγ/gZ* = 1 / .05 / .015, Y_χ =2/3: gg/gγ/gZ = 1 / .19 / .06.
- The resonance is narrow.

Colored PNGBs
Constraints from pair production: [JHEP1701,094]

Right: Pair production cross section and bounds from pair produced di-jet searches [CMS, PLB747, 98] and 4t searches [ATLAS, JHEP 08 (2015),105 and JHEP10 (2015), 150]. All data from LHC @ 8 TeV, still.



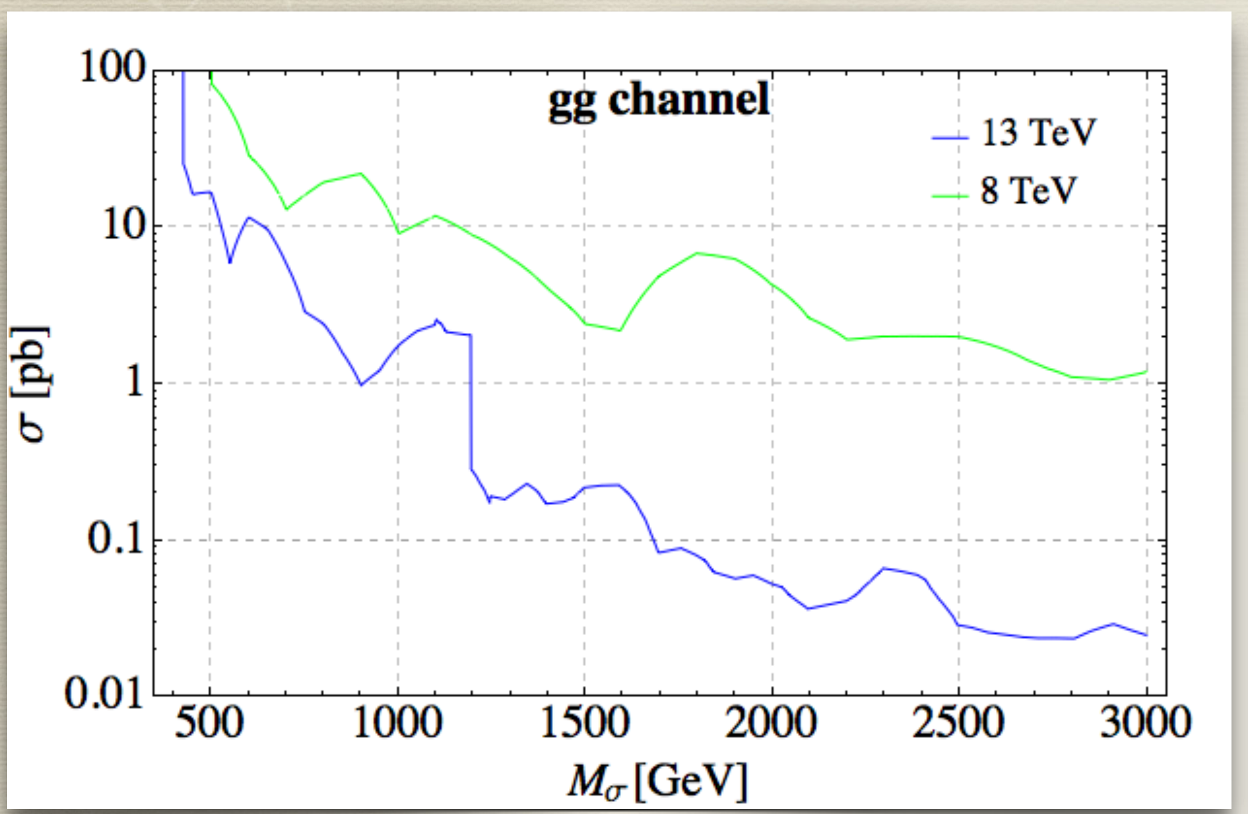


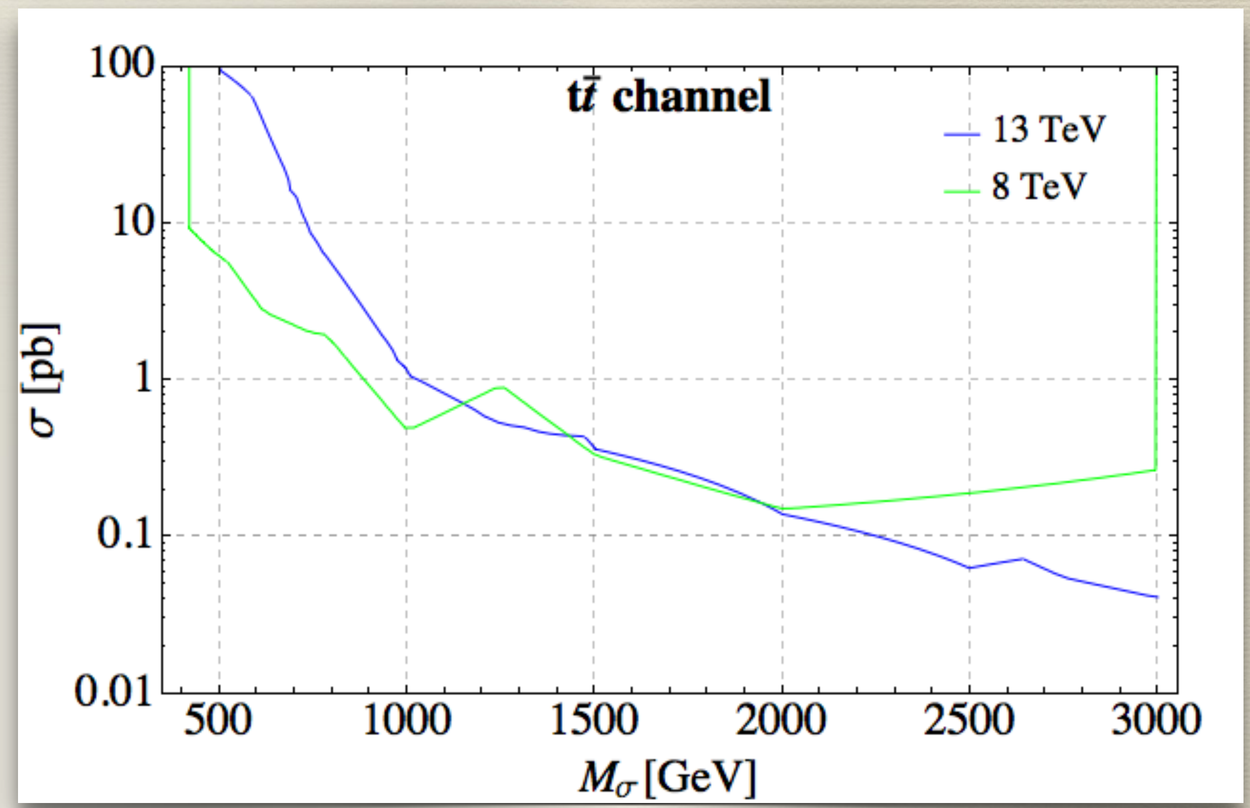
Left: Implied bounds on the C_{t8}/κ_g vs. M_{π_8} parameter space.

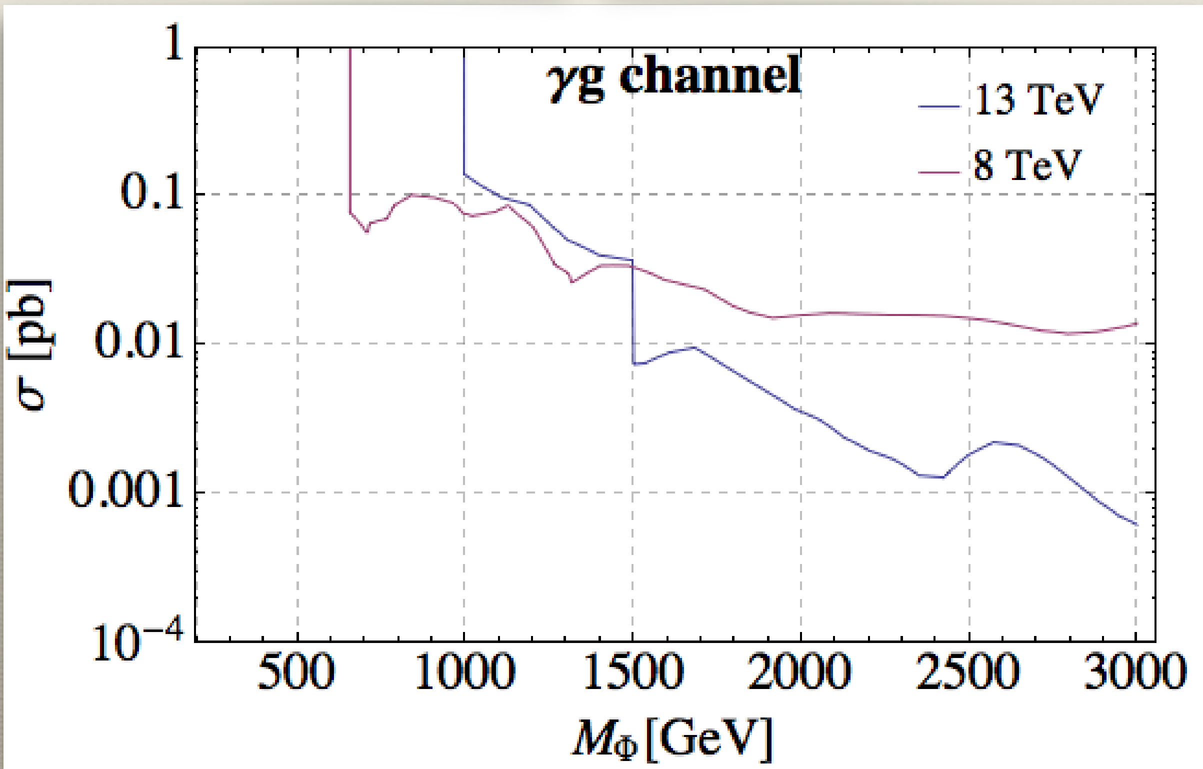
13 TeV bound from ICHEP on di-jet pairs [ATLAS-CONF-2016-084]

Colored PNGBs Constraints from single production:

(see JHEP 1701 (2017) 094 for studies included; pre-Moriond 2017)





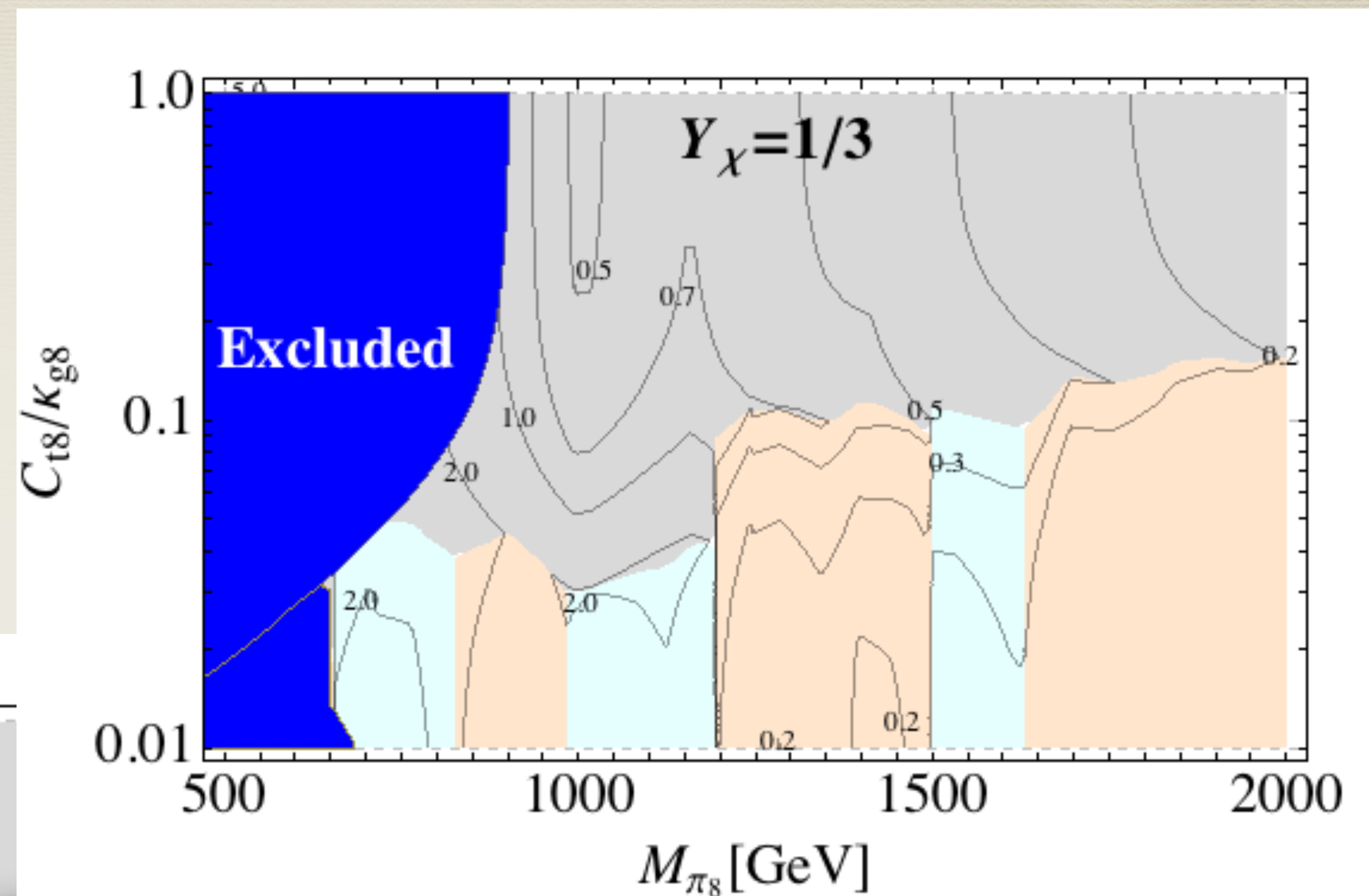


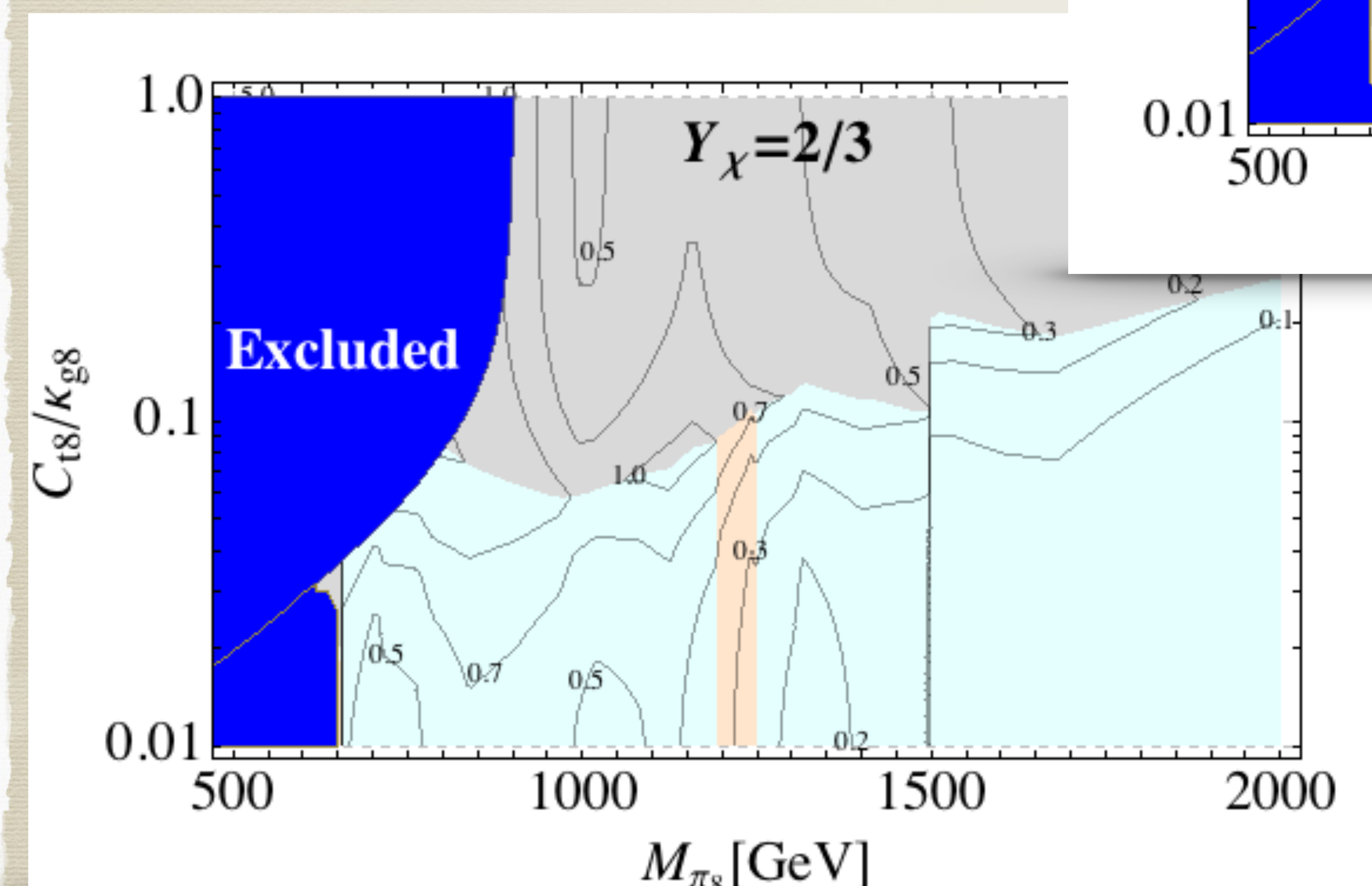
CPNGB

Colored PNGBs
Constraints from single and pair production:

Channels with the strongest bound: *gg* (red), *gγ* (cyan), *tt* (gray).

Contours give bounds on the $\boldsymbol{\pi}_8$ production cross section in pb.





Disclaimer: These plots do not include experimental bounds after Oct 2016.

CPNGB

Top partner mass mixing and couplings to pNGBs

Example:

For models with EW breaking pattern SU(4)/Sp(4), top-partners come in Sp(4) representations, e.g. **5** (for the t_L partner) and **1** (for the t_R partner).

$$\text{5-plet} \to \quad \begin{pmatrix} X_{5/3} \\ X_{2/3} \end{pmatrix}, \quad \begin{pmatrix} T \\ B \end{pmatrix}, \quad \widetilde{T}_5\ ; \qquad\qquad \text{singlet} \to \quad \widetilde{T}_1$$

The "mass matrix" (pNGB interactions, expanded to leading order in s_θ=v/f) reads in the basis $\psi_t = \{t, T, X_{2/3}, \widetilde{T}_1, \widetilde{T}_5\}$

$$\bar{\psi}_{tR} \begin{pmatrix} 0 & -\frac{y_{5R}}{\sqrt{2}} e^{i\xi_5 \frac{a}{f_a}} f s_\theta & -\frac{y_{5R}}{\sqrt{2}} e^{i\xi_5 \frac{a}{f_a}} f s_\theta & y_{1R} e^{i\xi_1 \frac{a}{f_a}} f c_\theta & i y_{5R} c_\theta \eta \\ y_{5L} e^{i\xi_5 \frac{a}{f_a}} f c^2_{\theta/2} & M_5 & 0 & 0 & 0 \\ -y_{5L} e^{i\xi_5 \frac{a}{f_a}} f s^2_{\theta/2} & 0 & M_5 & 0 & 0 \\ -\frac{y_{1L}}{\sqrt{2}} e^{i\xi_1 \frac{a}{f_a}} f s_\theta & 0 & 0 & M_1 & 0 \\ -i \frac{y_{5L}}{\sqrt{2}} s_\theta \eta & 0 & 0 & 0 & M_5 \end{pmatrix} \psi_{tL}$$

Diagonalizing the mass matrix (and expanding in a and η) yields couplings of top and top partners to the pNGB in terms of the underlying breaking parameters $y_{1,5}$ (pre-Yukawas) and strong-sector dynamics (M_1 , M_5 , f , f_a).