

# Exotic top partner decays: search gaps and opportunities

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Belyaev, G. Cacciapaglia, H. Cai, G. Ferretti, T. Flacke, H. Serodio, A. Parolini [[JHEP 1701, 094](#)]

G. Cacciapaglia, G. Ferretti, T. Flacke, H. Serodio [[EPJC 78 \(2018\) no.9, 724](#)]

G. Cacciapaglia, G. Ferretti, T. Flacke, H. Serodio [[arXiv:1902.06890](#)]

N. Bizot, G. Cacciapaglia, T. Flacke [[JHEP 1806, 065](#)]

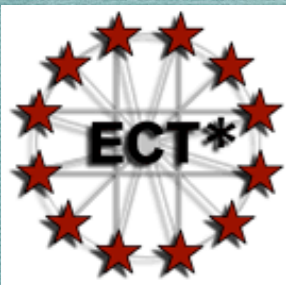
Ke-Pan Xi, G. Cacciapaglia, T. Flacke [[arXiv:1907.05894](#)]

G. Cacciapaglia, T. Flacke, Myeonghun Park, Mengchao Zhang [[arXiv:1908.07524](#)]

**LFC19: Strong dynamics for physics within and beyond the  
Standard Model at LHC and Future Colliders**

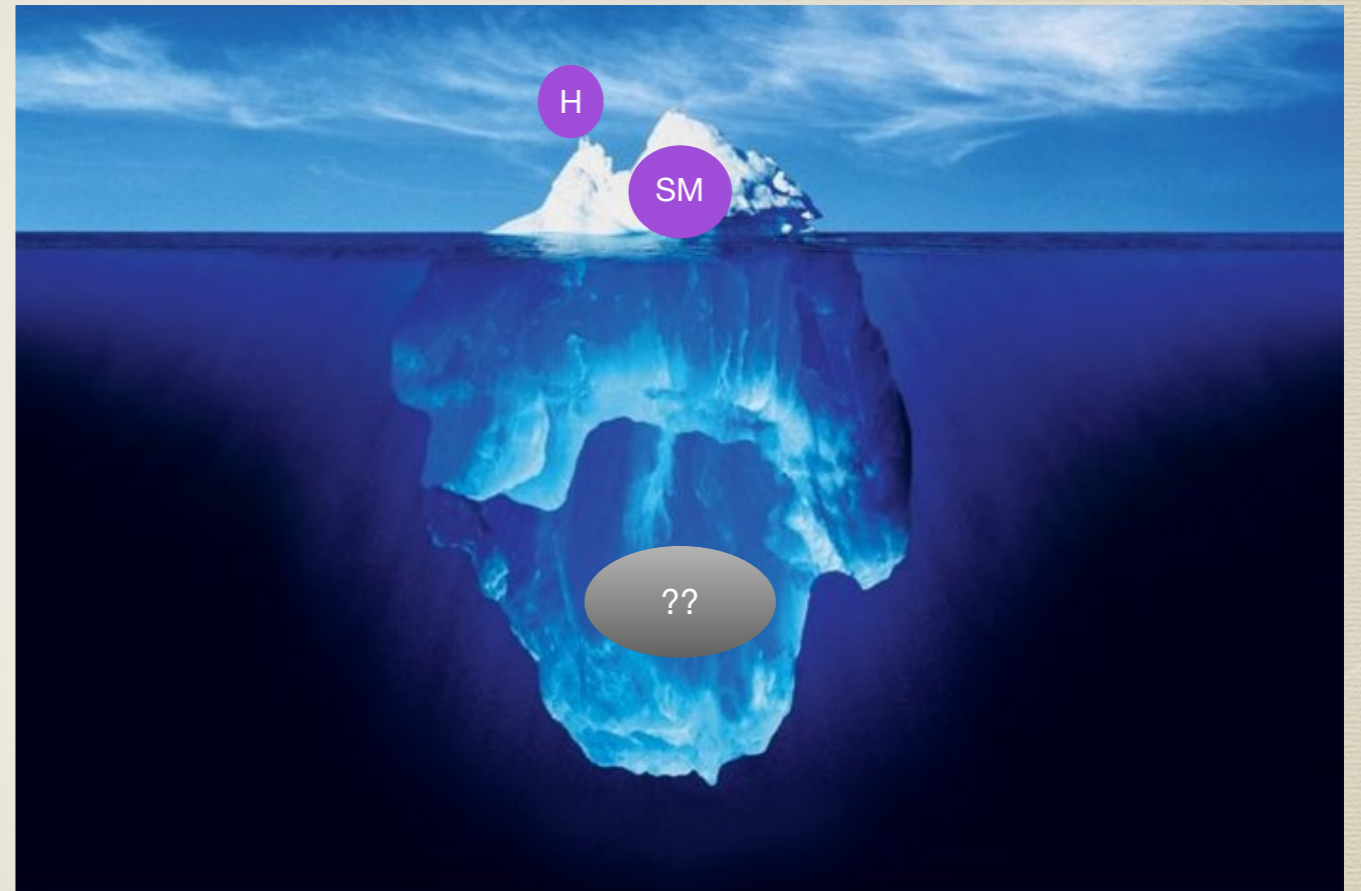
**ECT - Villa Tambosi, Trieste**

**Sep. 12th, 2019**



# Outline

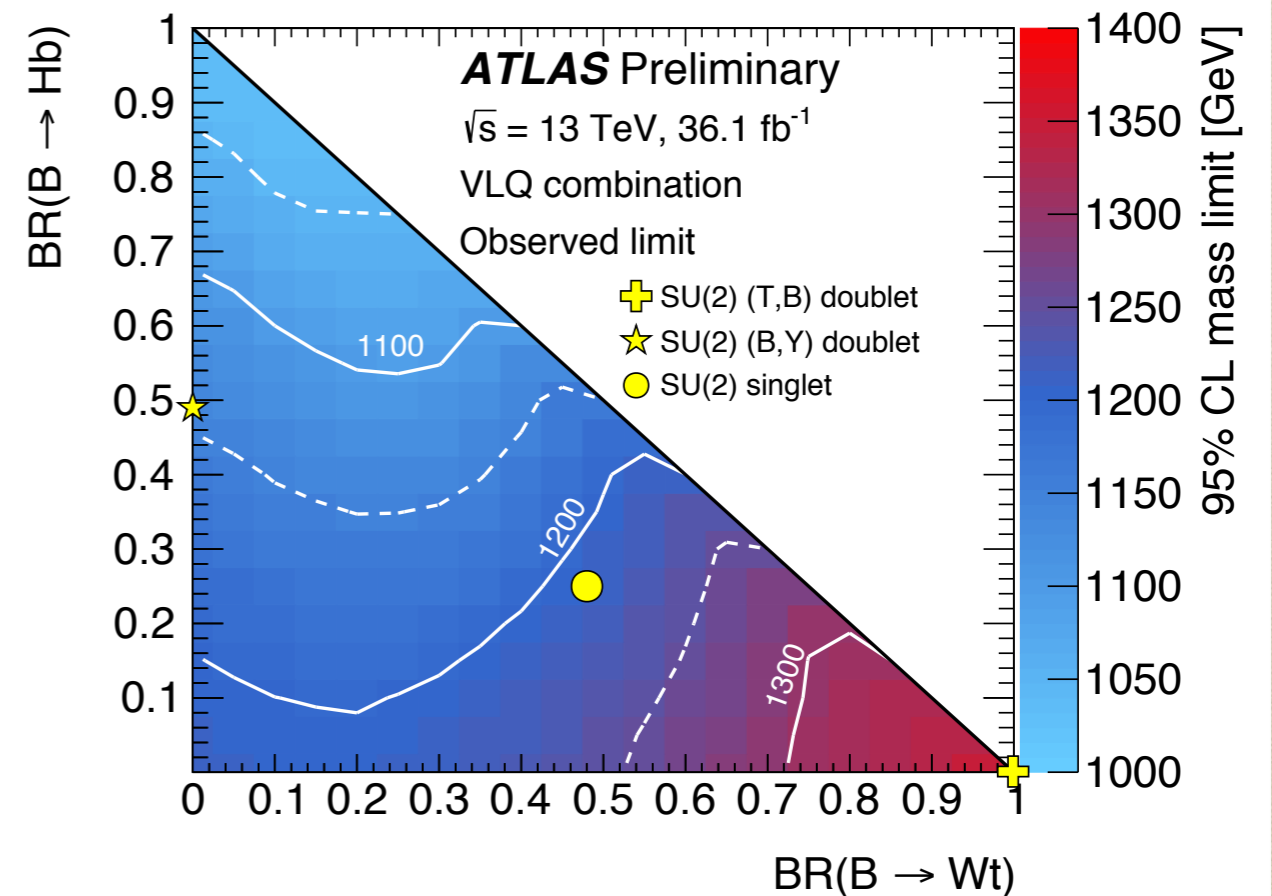
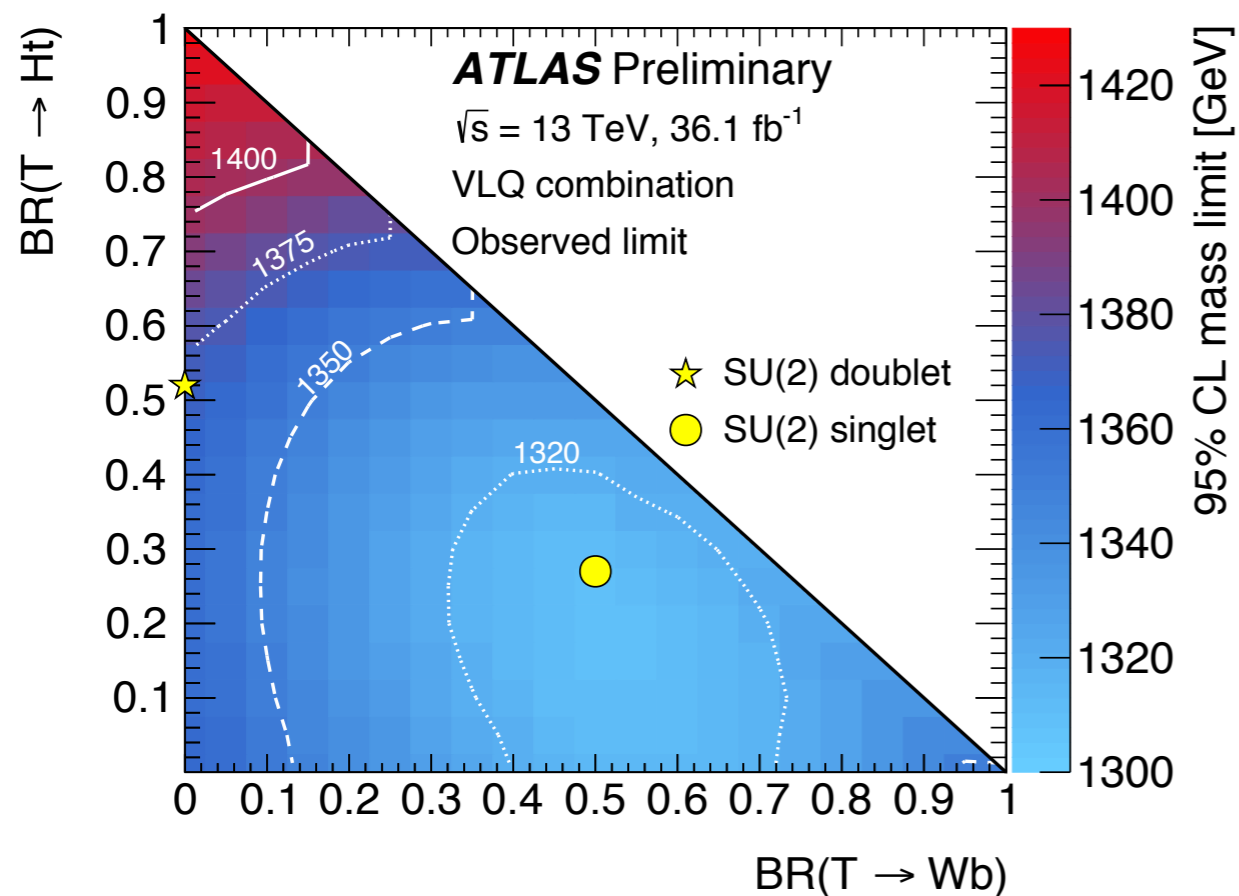
- Vector-like quarks (VLQs):  
current experimental status
- A theory motivation for VLQs:  
(Underlying models of) a composite Higgs
  - models contain light BSM scalars,
  - VLQ decays into BSM scalars are common
- Exotic charge 2/3 VLQ decays:  
 $T \rightarrow t a$ ,  $a \rightarrow gg$  or  $bb$   
(substantially) reduced bounds from existing searches.
- Exotic charge 5/3 VLQ decays:  
 $X_{5/3} \rightarrow \bar{b} \pi_6$ ,  $X_{5/3} \rightarrow t \phi^+$ ,  $X_{5/3} \rightarrow b \phi^{++}$   
bounds from reinterpreting SSL searches and possible improvements.
- Conclusions



# Vector-like quarks (top- partners or quark partners) with charge $5/3, 2/3, -1/3, -4/3$

$X_{5/3}$  (with  $X_{5/3} \rightarrow tW^+$ ):  $M_X \gtrsim 1.3$  TeV, [[CMS PAS B2G-16-019](#), [ATLAS: 1806.01762](#)]

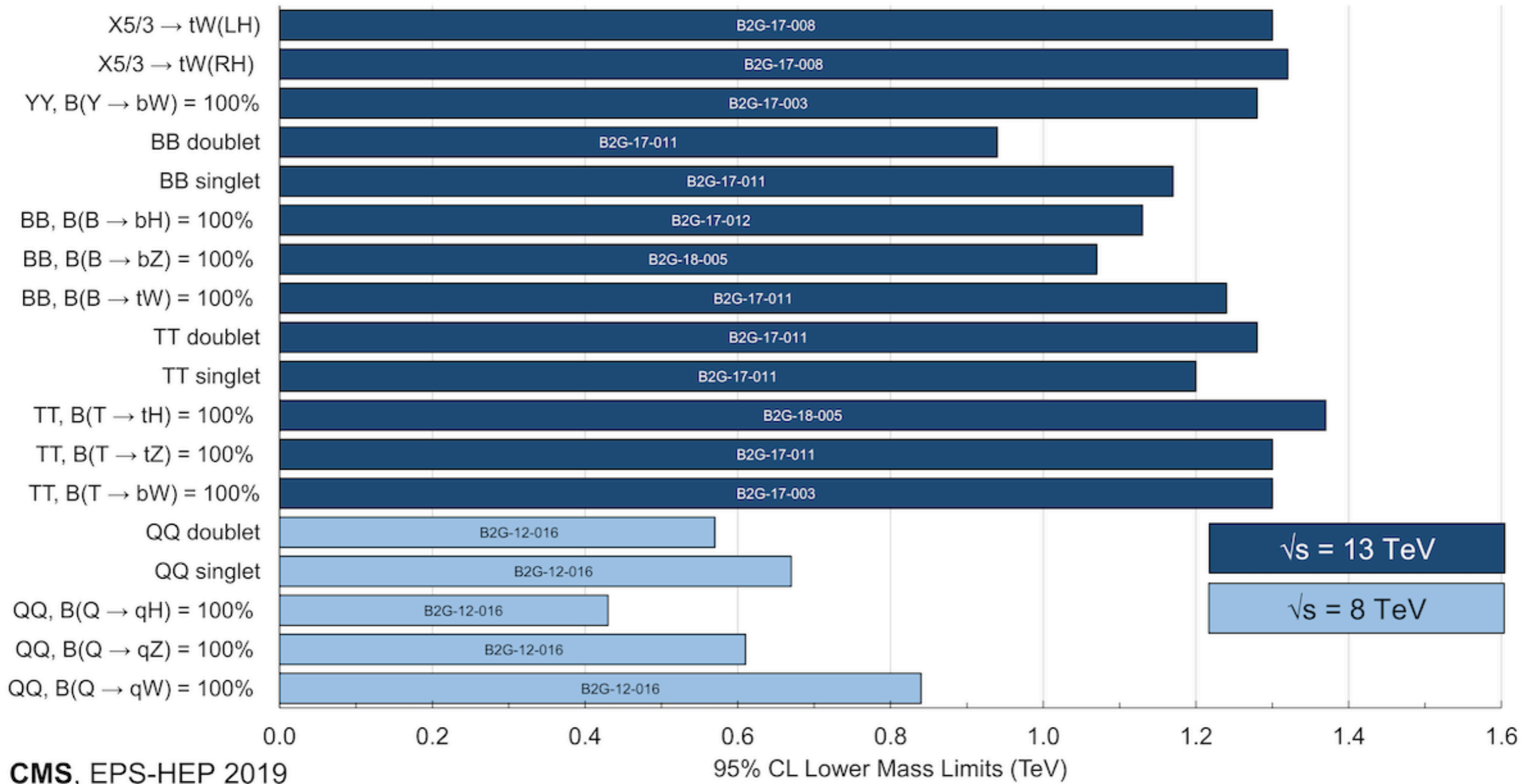
$T$  &  $B$ : Combined bounds on pair-produced top partners



[[ATLAS-CONF-2018-032](#)]

# CMS bounds on pair production

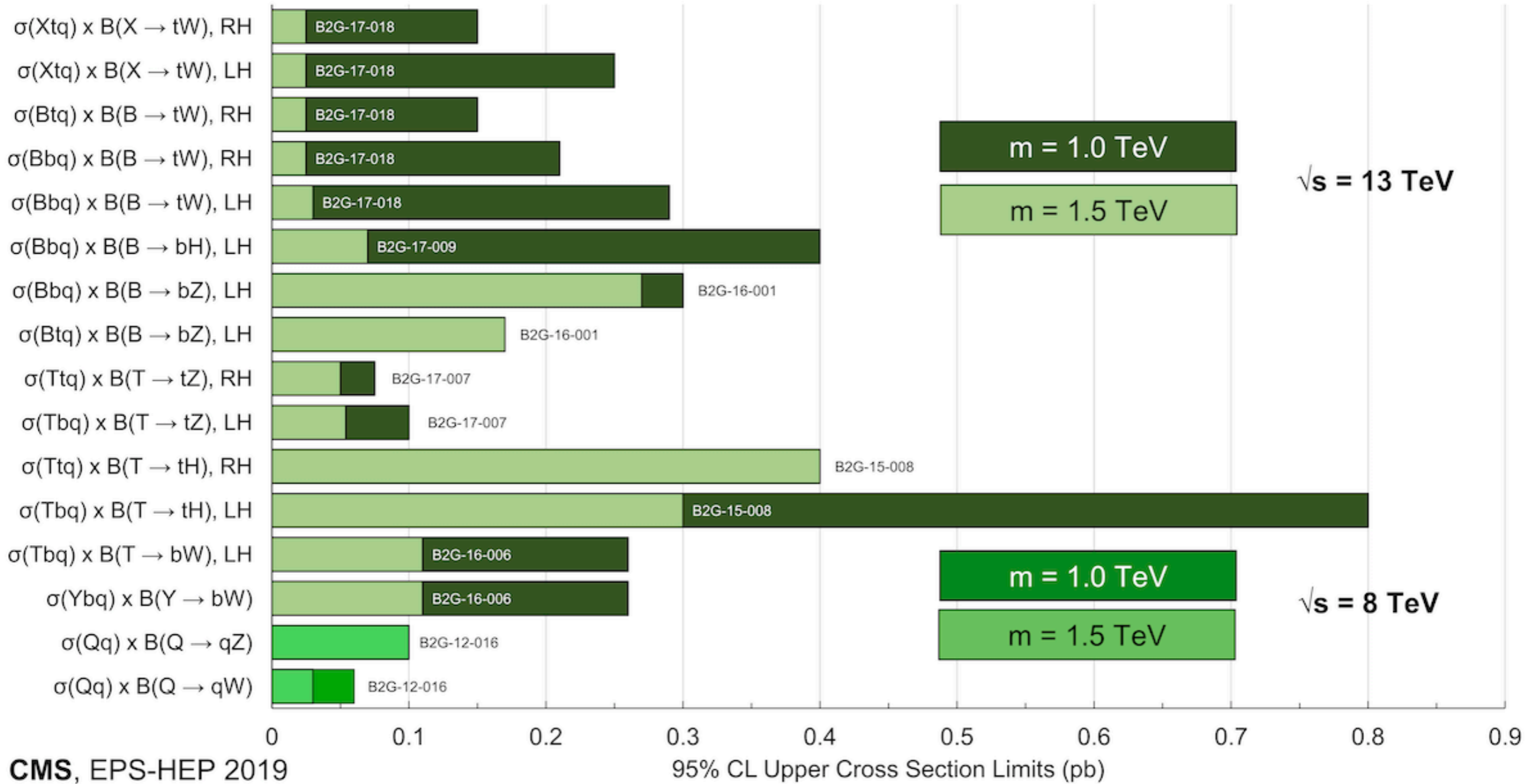
## Vector-like quark pair production



[CMS B2G Summary Plots]

# CMS bounds on single production

## Vector-like quark single production



CMS, EPS-HEP 2019

[CMS B2G Summary Plots]

# Composite Higgs Models: Towards underlying models

A wish list to construct and classify candidate models:  
Underlying models of a composite Higgs should

[Gherghetta etal \(2015\)](#), [Ferretti etal \(2014\)](#), [PRD 94 \(2016\) no 1, 015004](#), [JHEP 1701, 094](#)

- 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 gauge anomalies).

The resulting models all have:

- two species of underlying fermions:  $\psi$  for EW embedding,  $\chi$  for SU(3) embedding,
- several top partner multiplets  $\psi \psi \chi$  or  $\psi \chi \chi$  bound states,
- Several pNGBs beyond the Higgs multiplet,  $\psi \psi$  and  $\chi \chi$  bound states.

# Example: $SU(4)/Sp(4)$ coset based on $GHC = Sp(2N_c)$

	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(4)$	$SU(6)$	$U(1)$
$\psi_1$	$\square$	<b>1</b>	<b>2</b>	0	<b>4</b>	<b>1</b>	$-3(N_c - 1)q_x$
$\psi_2$	$\square$	<b>1</b>	<b>1</b>	$1/2$			
$\psi_3$	$\square$	<b>1</b>	<b>1</b>	$-1/2$			
$\psi_4$	$\square$	<b>1</b>	<b>1</b>	$-1/2$	<b>1</b>	<b>6</b>	$q_x$
$\chi_1$	$\begin{smallmatrix} \square \\ \square \end{smallmatrix}$	<b>3</b>	<b>1</b>	$2/3$			
$\chi_2$	$\begin{smallmatrix} \square \\ \square \end{smallmatrix}$						
$\chi_3$	$\begin{smallmatrix} \square \\ \square \end{smallmatrix}$						
$\chi_4$	$\begin{smallmatrix} \square \\ \square \end{smallmatrix}$	$\bar{\mathbf{3}}$	<b>1</b>	$-2/3$			
$\chi_5$	$\begin{smallmatrix} \square \\ \square \end{smallmatrix}$						
$\chi_6$	$\begin{smallmatrix} \square \\ \square \end{smallmatrix}$						

Underlying field content

[JHEP1511,201]

Bound states of the model

	spin	$SU(4) \times SU(6)$	$Sp(4) \times SO(6)$	names
$\psi\psi$	0	<b>(6, 1)</b>	<b>(1, 1)</b> <b>(5, 1)</b>	$\sigma$ $\pi$
$\chi\chi$	0	<b>(1, 21)</b>	<b>(1, 1)</b> <b>(1, 20)</b>	$\sigma_c$ $\pi_c$
$\chi\psi\psi$	1/2	<b>(6, 6)</b>	<b>(1, 6)</b> <b>(5, 6)</b>	$\psi_1$ $\psi_1^5$
$\chi\psi\bar{\psi}$	1/2	<b>(6, 6)</b>	<b>(1, 6)</b> <b>(5, 6)</b>	$\psi_2$ $\psi_2^5$
$\psi\bar{\chi}\bar{\psi}$	1/2	<b>(1, 6)</b>	<b>(1, 6)</b>	$\psi_3$
$\psi\bar{\chi}\bar{\psi}$	1/2	<b>(15, 6)</b>	<b>(5, 6)</b> <b>(10, 6)</b>	$\psi_4^5$ $\psi_4^{10}$
$\bar{\psi}\sigma^\mu\psi$	1	<b>(15, 1)</b>	<b>(5, 1)</b> <b>(10, 1)</b>	$a$ $\rho$
$\bar{\chi}\sigma^\mu\chi$	1	<b>(1, 35)</b>	<b>(1, 20)</b> <b>(1, 15)</b>	$a_c$ $\rho_c$

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

form a and  $\eta'$ ; SM singlets

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

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

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

[JHEP1511,201]

# List of "minimal" CHM UV embeddings

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

[JHEP1701,094]



# New PNGBs in composite Higgs models from underlying gauge-fermion theories

1. ALL models:

weak direct bounds  $a$  and  $\eta'$ : (one HC anomaly free, one anomalous pseudo-scalar) which couple to SM gauge bosons through WZW couplings and to fermions with  $m_f/f$ .

[PRD 94 (2016) no 1, 015004, JHEP1701,094, EPJC 78 (2018) no.9, 724, arXiv:1902.06890]

2. ALL models:

$\gtrsim 1$  TeV  $\pi_8$ : Color octet pseudo-scalar pNGB which couples to  $gg, g\gamma, gZ, tt$  [JHEP1701,094]

3. Depending on the embedding model: Additional colored and uncolored pNGBs

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

[Agugliaro etal]

[JHEP1511,201]

$\gtrsim O(200)$  GeV

$\gtrsim 1$  TeV

# Singlet pNGB summary and phenomenology

[arXiv:1902.06890]

$a$  and  $\eta'$ : Arise from the SSB of  $U(1)_\chi \times U(1)_\psi$ . One linear combination has a  $G_{HC}$  anomaly ( $\eta'$ ) and is expected heavier. The orthogonal linear combination ( $a$ ) is a pNGB.  $\phi = \{a, \eta'\}$

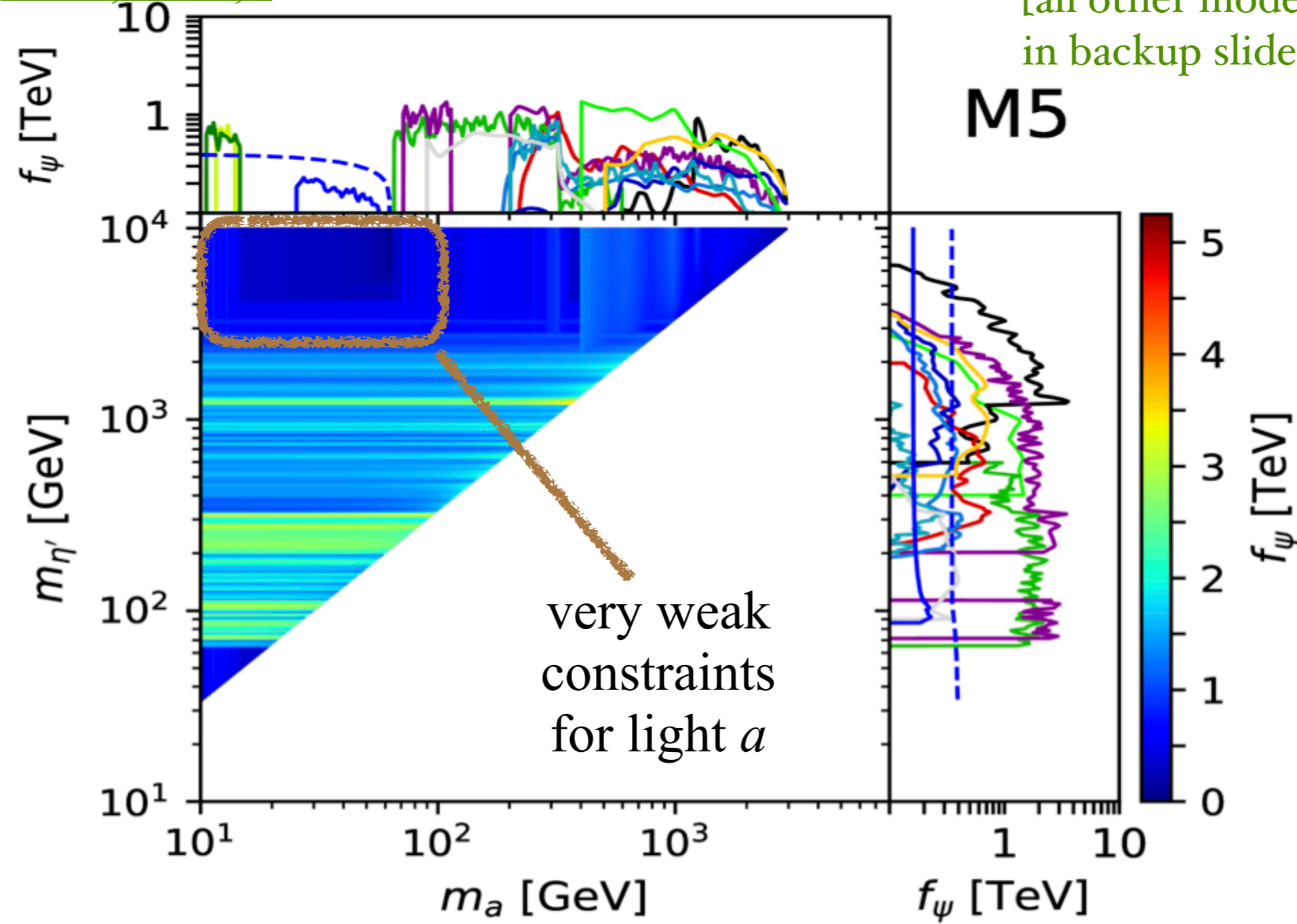
$$\begin{aligned} \mathcal{L}_{\text{eff}} \supset & \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}m_\phi^2 \phi^2 \\ & + \frac{\phi}{16\pi^2 f_\psi} \left( g_s^2 K_g^\phi G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + g^2 K_W^\phi W_{\mu\nu}^i \tilde{W}^{i\mu\nu} + g'^2 K_B^\phi B_{\mu\nu} \tilde{B}^{\mu\nu} \right) \\ & - i \sum_f \frac{C_f^\phi m_f}{f_\psi} \phi \bar{\psi}_f \gamma^5 \psi_f \\ & + \frac{2v}{f_\psi^2} K_{\phi h}^{\text{eff}} (\partial_\mu \phi) (\partial^\mu \phi) h + \frac{2m_Z}{f_\psi} K_{hZ}^{\text{eff}} (\partial_\mu \phi) Z^\mu h \end{aligned}$$

- $m_a$  must result from *explicit* breaking of the  $U(1)$ s.  $m_\eta$  also obtains mass from instantons.
- $f_\psi$  (decay constant of the EW sector) results from chiral symmetry breaking.
- The WZW coefficients  $K^\phi$  are determined by the quantum numbers of  $\chi, \psi$  (and  $(m_a, m_\eta)$ ).
- The coefficients  $C^\phi_f$  are also fixed (depending on dominantly mixing top-partner).
- $h\phi\phi$  and  $h\phi Z$  couplings are induced at 1-loop order.
- $a$  and  $\eta'$  are produced in gluon fusion.
- The resonances are narrow.

$a$  and  $\eta'$ : For a given model, we can combine bounds and sensitivities from resonance searches to get a bound on the compositeness scale  $f$ .

[arXiv:1902.06890]

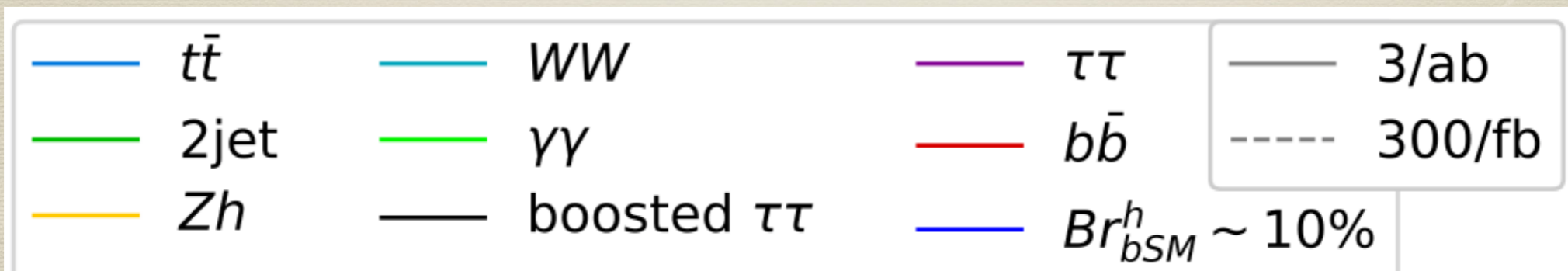
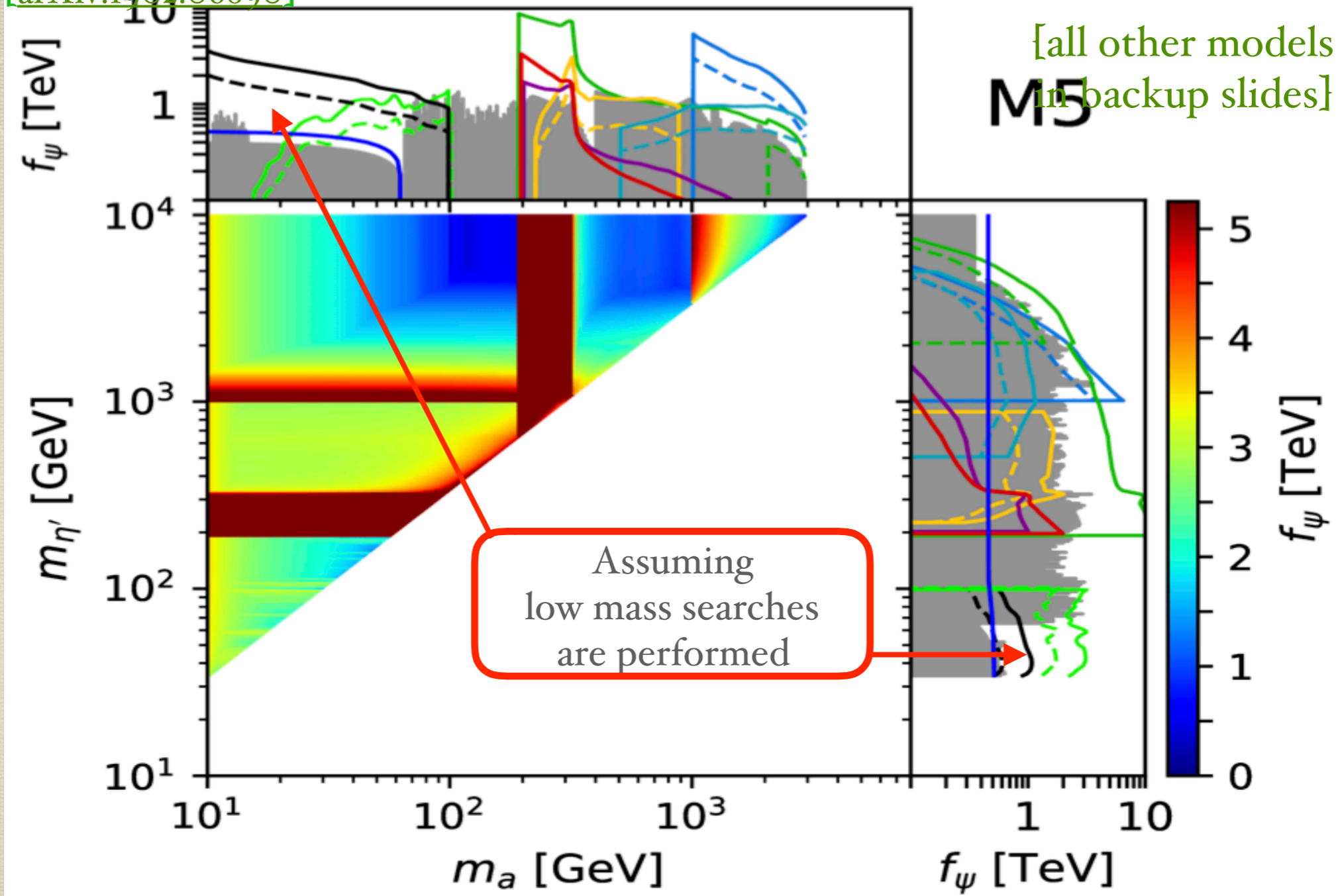
[all other models in backup slides]



—	2jet	—	$WW$	—	$t\bar{t}@8$	—	$\tau\tau$
—	$Zh$	—	$ZZ$	—	$\mu\mu@8$	- - -	$Br_{BSM}^h$
—	$\gamma\gamma@8$	—	$Z\gamma$	—	$t\bar{t}$	—	$Br_{bb\mu\mu}^h$
—	$\gamma\gamma$	—	$\mu\mu@7$				

# Projected reach at HL-LHC

[arXiv:1902.06890]



# Top partners in CH UV embeddings

[JHEP 1806, 065]

- UV embeddings of composite Higgs models come with additional pNGBs, which are naturally lighter than the top-partners, so decays of top partners to top / bottom and a pNGB are kinematically possible.
- With an underlying model specified, relations for branching ratios of top partners to h/W/Z vs new pNGBs can be determined.
- Scanning through the different underlying models we looked for “common exotic” top partner decays and found several scenarios:
  1. decays of  $T$  (and  $B$ ) to the singlet pseudo-scalar singlet  $a$ ,
  2. decays of  $T$  to the “exclusive pseudo-scalar”  $\eta$ ,
  3.  $X_{5/3} \rightarrow \bar{b} \pi_6$  (with subsequent  $\pi_6 \rightarrow t t$ ),
  4.  $X_{5/3} \rightarrow t \phi^+$ ,  $X_{5/3} \rightarrow b \phi^{++}$ .
- Decays of the pNGBs yield manifold novel multi-body decay modes and LHC signatures.

# Common exotic VLQ decays: $T \rightarrow t a$

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

Effective Lagrangian(s): [\[JHEP 1806, 065\]](#)

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

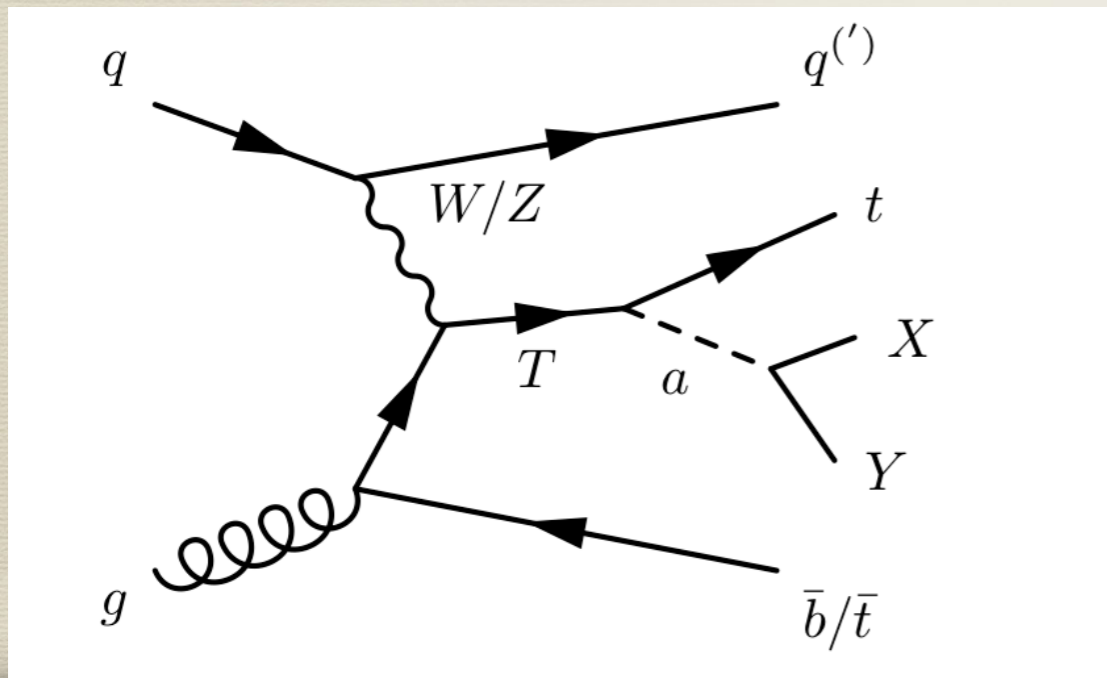
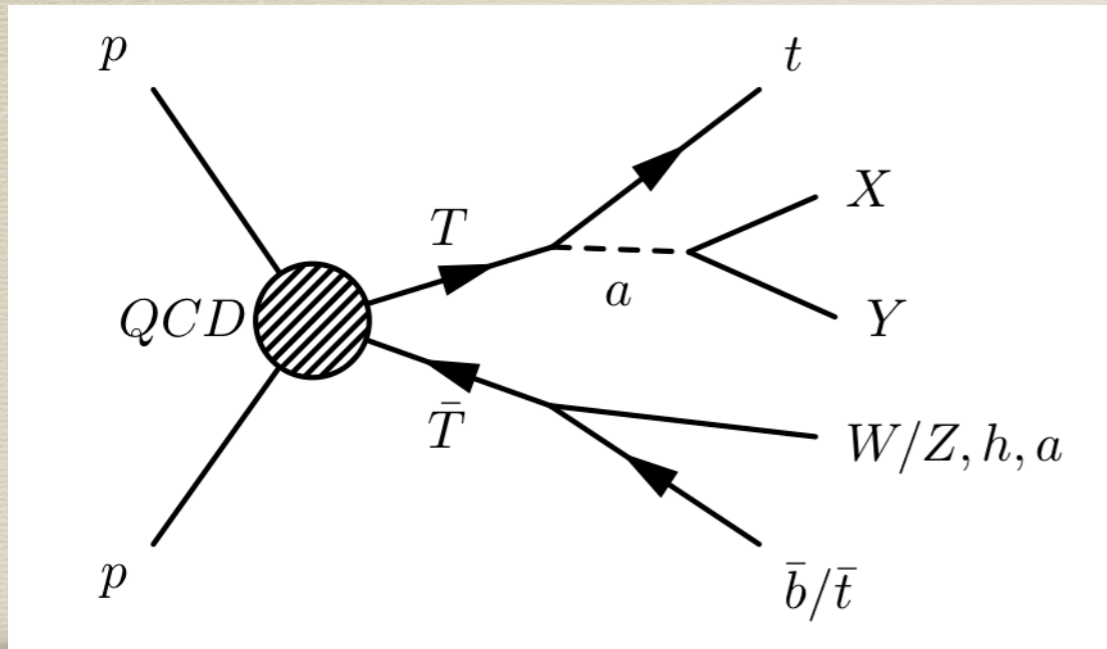
$$\mathcal{L}_B = \bar{B} (i\not{D} - M_B) B + \left( \kappa_{W,L}^B \frac{g}{\sqrt{2}} \bar{B} W^- P_L t + \kappa_{Z,L}^B \frac{g}{2c_W} \bar{B} Z^+ P_L b - \kappa_{h,L}^B \frac{M_B}{v} \bar{B} h P_L b + i\kappa_{a,L}^B \bar{B} a P_L b + L \leftrightarrow R + \text{h.c.} \right).$$

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

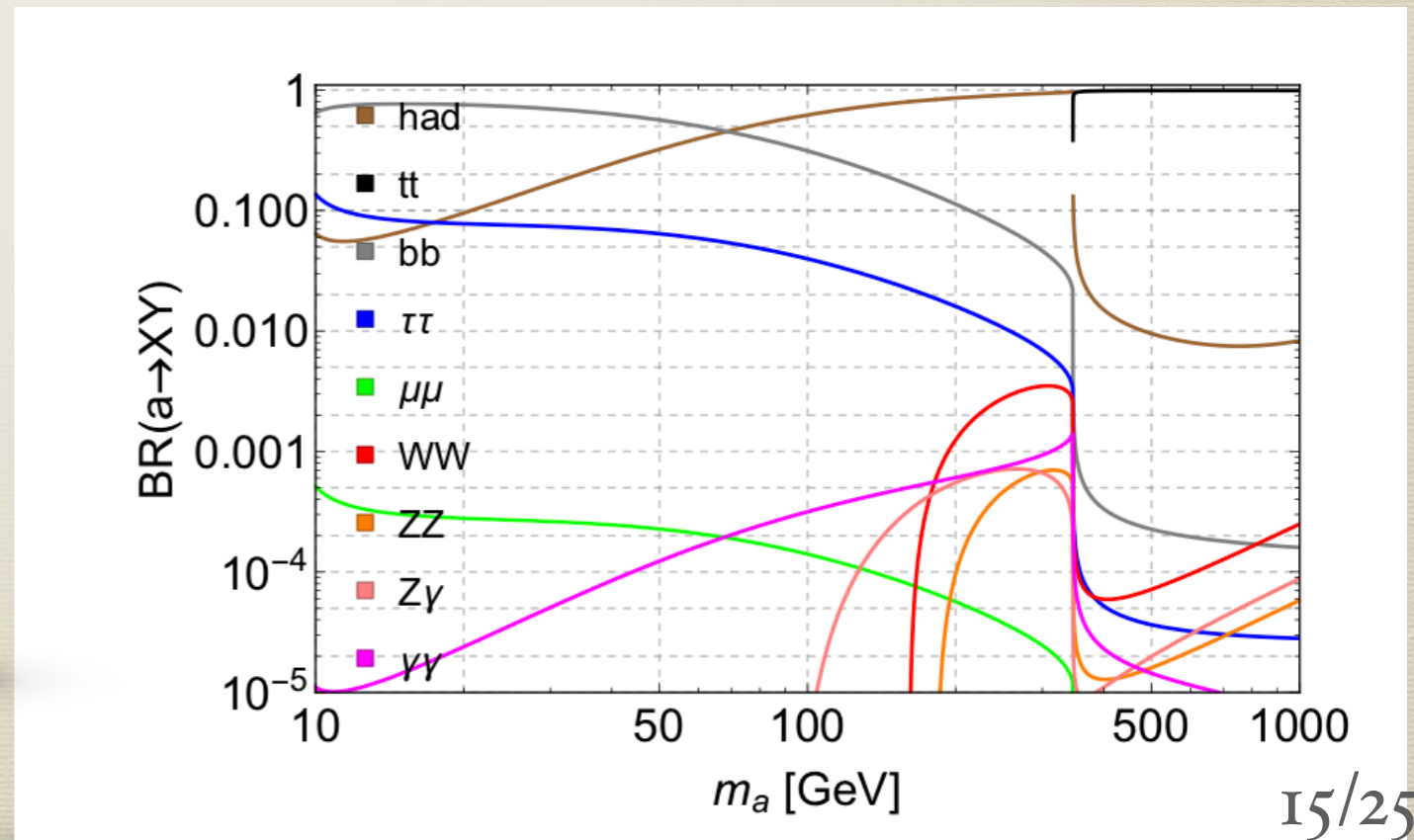
$$+ \frac{g_s^2 K_g a}{16\pi^2 f_a} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \frac{g^2 K_W a}{16\pi^2 f_a} W_{\mu\nu}^i \tilde{W}^{i\mu\nu} + \frac{g'^2 K_B a}{16\pi^2 f_a} B_{\mu\nu} \tilde{B}^{\mu\nu}$$

# Common exotic VLQ decays: $T \rightarrow t a$

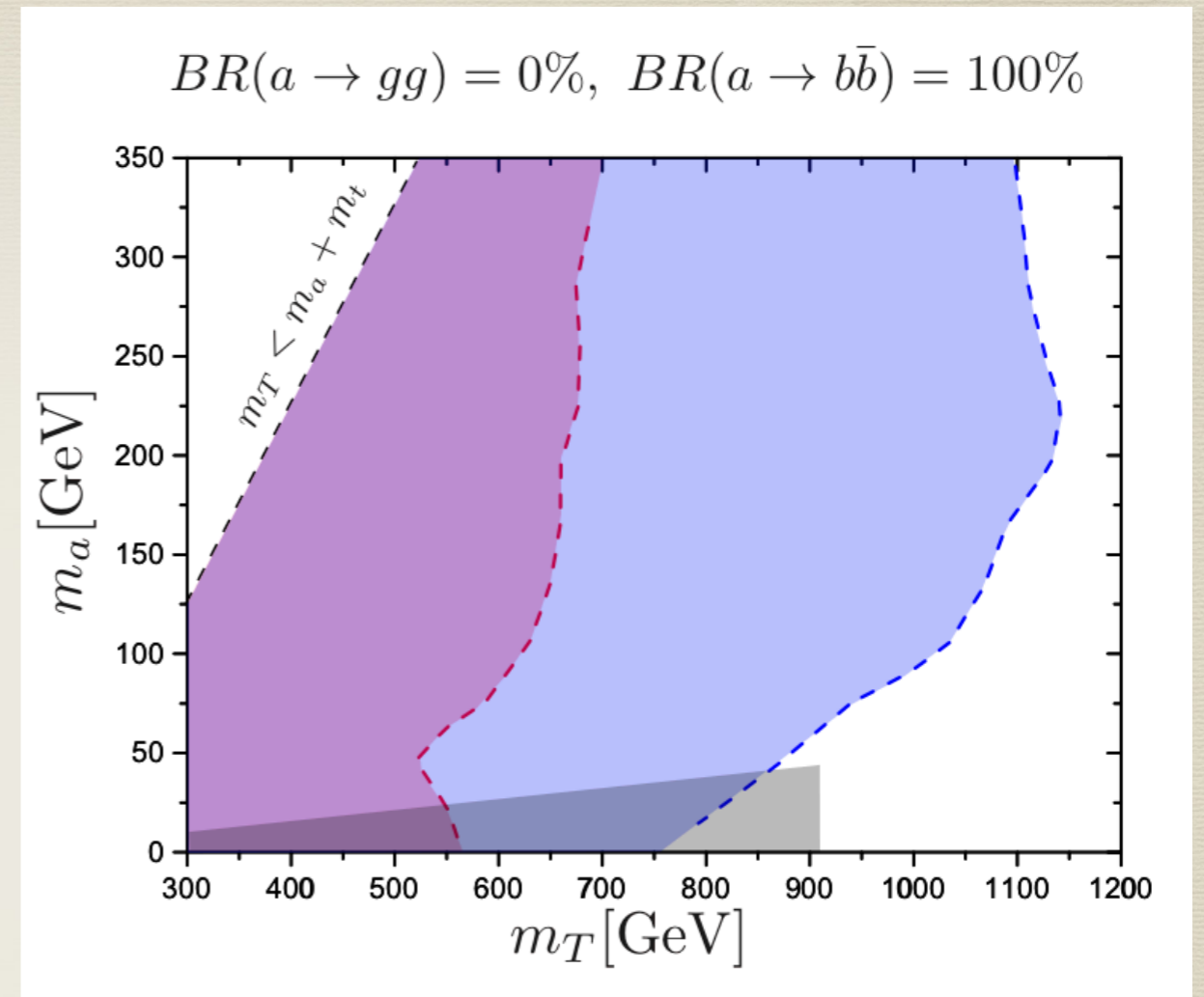
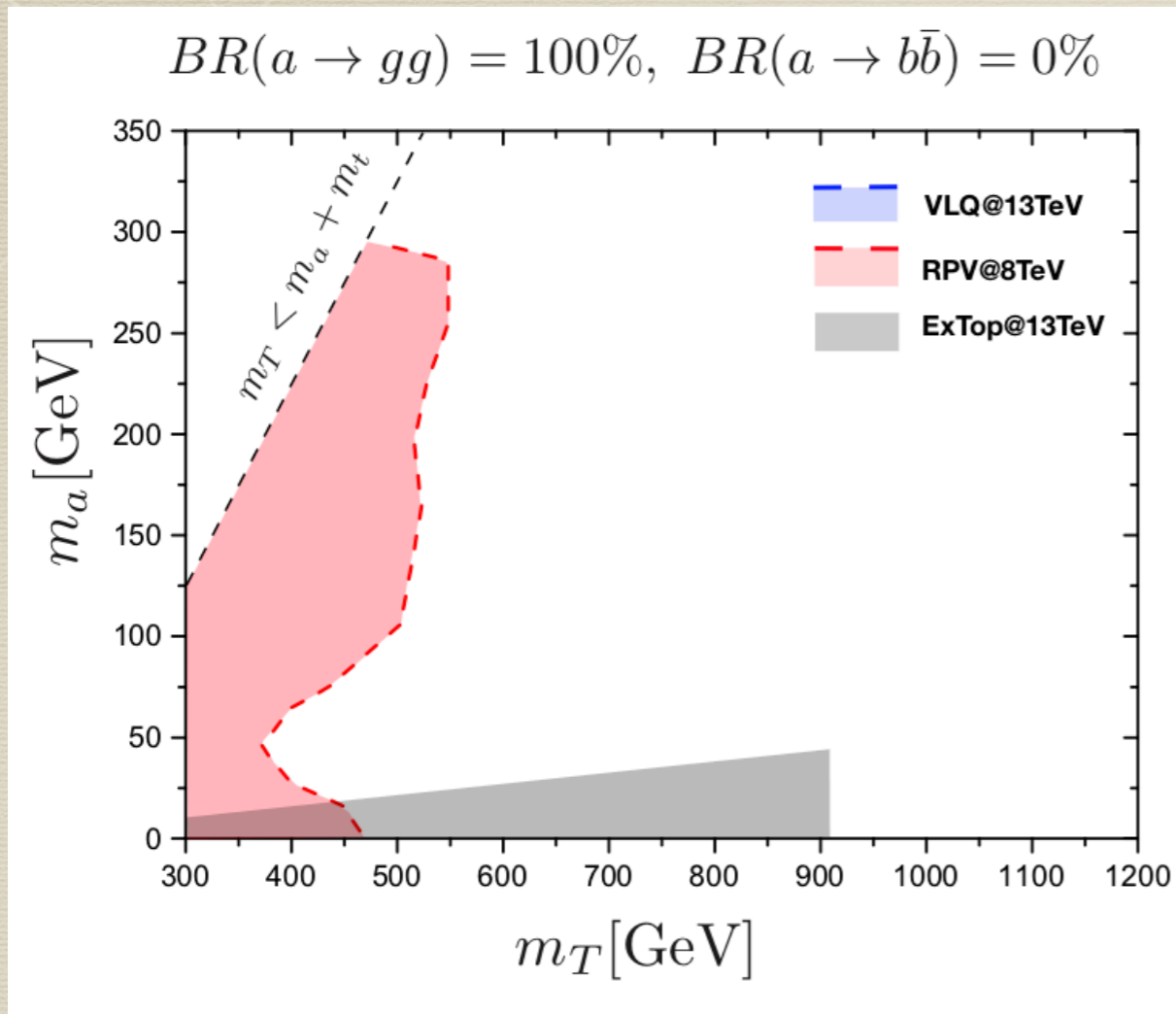
Examples of diagrams:



- $T$  (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.
- For light  $m_a < m_t$ ,  $gg$  and  $bb$  decays dominate.



For light  $a$ : Bounds on  $pp \rightarrow TT \rightarrow t a t a$ , with  $a \rightarrow gg$  or  $a \rightarrow b\bar{b}$



Recast searches

Red:

RPV-SUSY (hadronic)

[CERN-EP-2015-020 \(ATLAS\)](#)

[CERN-EP-2017-298 \(ATLAS\)](#)

Blue:

VLQ search

[CERN-EP-2018-031 \(ATLAS\)](#)

Gray:

Excited top search

[CERN-EP-2017-272 \(CMS\)](#)

The bounds on VLQ top partner masses are substantially lower when  $T$  decays into  $t a$  dominate. In particular  $T \rightarrow t a \rightarrow t g g$  is weakly constrained.

[1908.07524]



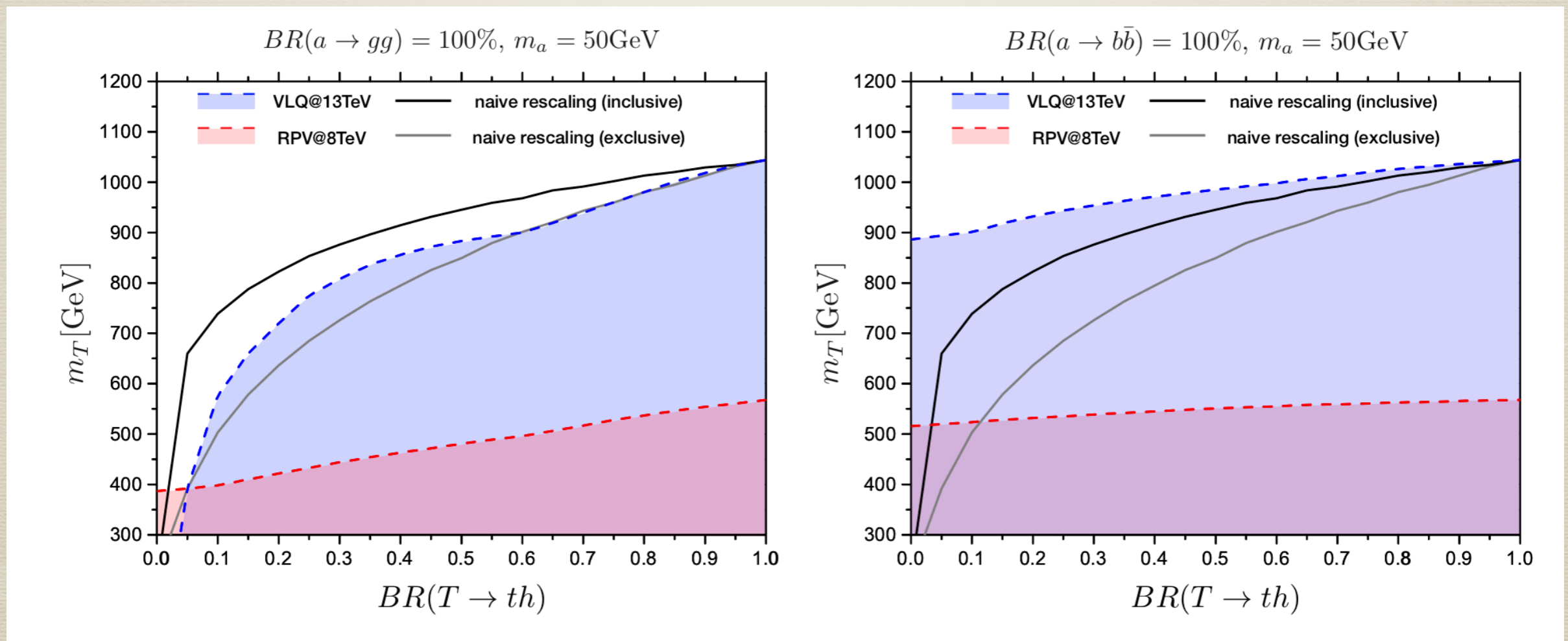
# For light $a$ : Bounds on $pp \rightarrow TT \rightarrow t a t h$ , with $a \rightarrow gg$ or $a \rightarrow bb$

If decays into both standard and exotic channels occur, and searches are not explicitly sensitive to  $T \rightarrow ta$ , naive bounds can be estimated.

Inclusive pair production search bounds on  $\sigma_{TT}$  are reduced by  $\sim (1 - BR_a)$ ,

Exclusive pair production search bounds on  $\sigma_{TT}$  are reduced by  $(1 - BR_a)^2$ .

$T \rightarrow t h$  searches potentially have explicit  $T \rightarrow t a$  sensitivity, so an explicit recast is required



[1908.07524]

## Common exotic VLQ decays: $X_{5/3}$

**Candidate 3:**  $X_{5/3} \rightarrow \bar{b} \pi_6$  (with subsequent  $\pi_6 \rightarrow t t$ )

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

Effective Lagrangian:

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

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

## Common exotic VLQ decays: $X_{5/3}$

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

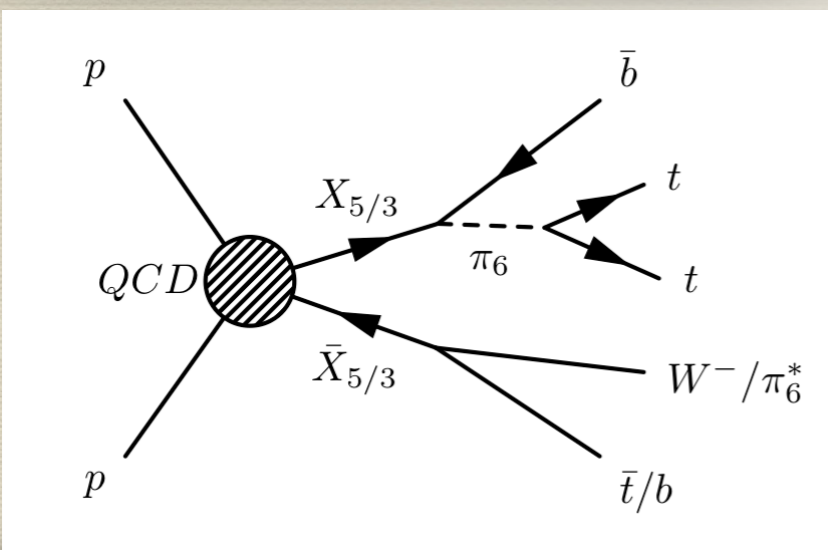
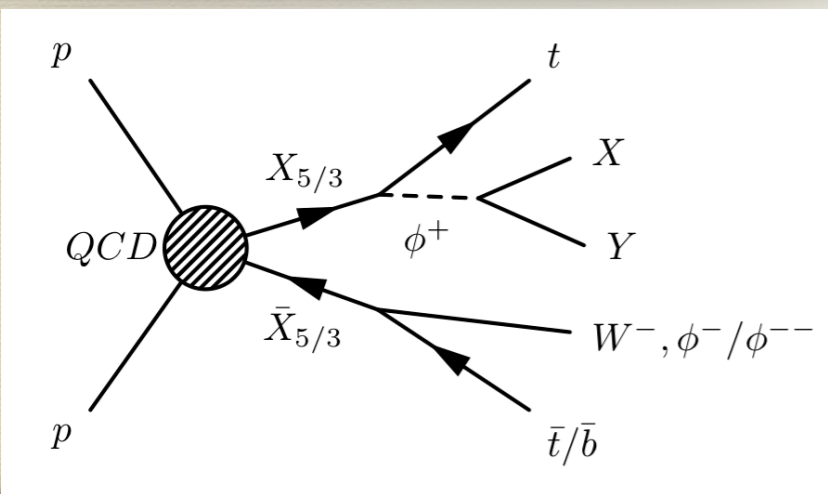
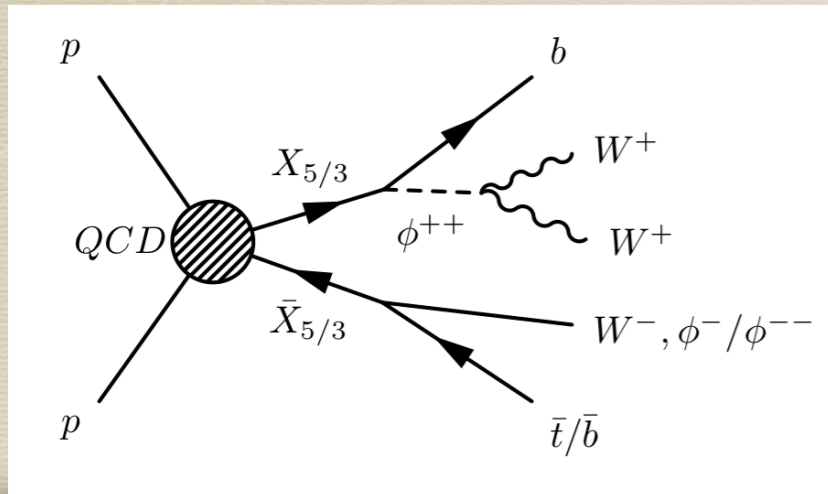
In models with SU(5)/SO(5) breaking in the EW sector, we have charged (and doubly charged) pNGBs.

Effective Lagrangian:

$$\begin{aligned}
 \mathcal{L}_{X_{5/3}}^\phi &= \bar{X}_{5/3} \left( i\not{D} - M_{X_{5/3}} \right) X_{5/3} + \left( \kappa_{W,L}^X \frac{g}{\sqrt{2}} \bar{X}_{5/3} W^+ P_L t \right. \\
 &\quad \left. + i\kappa_{\phi^+,L}^X \bar{X}_{5/3} \phi^+ P_L t + i\kappa_{\phi^{++},L}^X \bar{X}_{5/3} \phi^{++} P_L b + L \leftrightarrow R + \text{h.c.} \right) \\
 \mathcal{L}_\phi &= \sum_{\phi=\phi^+, \phi^{++}} \left( |D_\mu \phi|^2 - m_\phi^2 |\phi|^2 \right) + \left( \frac{egK_W^\phi}{8\pi^2 f_\phi} \phi^+ W_{\mu\nu}^- \tilde{B}^{\mu\nu} + \frac{g^2 c_w K_{WZ}^\phi}{8\pi^2 f_\phi} \phi^+ W_{\mu\nu}^- \tilde{B}^{\mu\nu} \right. \\
 &\quad \left. + \frac{g^2 K_W^\phi}{8\pi^2 f_\phi} \phi^{++} W_{\mu\nu}^- \tilde{W}^{\mu\nu,-} + i\kappa_{tb,L}^\phi \frac{m_t}{f_\phi} \bar{t} \phi^+ P_L b + L \leftrightarrow R + \text{h.c.} \right). \quad (2.13)
 \end{aligned}$$

# Common exotic VLQ decays: $X_{5/3}$

Examples of processes:



Full list of final states from  $X_{5/3}$  pair-production:

	Cascade decays		after $t$ and $\tau$ decay
$X_{5/3}$	$tW^+$	—	$(bW^+)W^+$
	$\bar{b}\pi_6$	$\bar{b}tt$	$\bar{b}(bW^+)(bW^+)$
	$t\phi^+$	$tW^+\gamma, tW^+Z$	$(bW^+)W^+\gamma, (bW^+)W^+Z$
		$t\bar{b}$	$(bW^+)(bW^+)\bar{b}$
		$t\tau^+\nu$	$(bW^+)(W^{+*}\bar{\nu})\nu$
	$b\phi^{++}$	$bW^+W^+$	$bW^+W^+$
		$bW^{+(*)}\phi^+$	$bW^{+(*)}W^{+(*)} + X$
		$b\tau^+\tau^+$	$b(W^{+(*)}\bar{\nu})(W^{+(*)}\bar{\nu})$

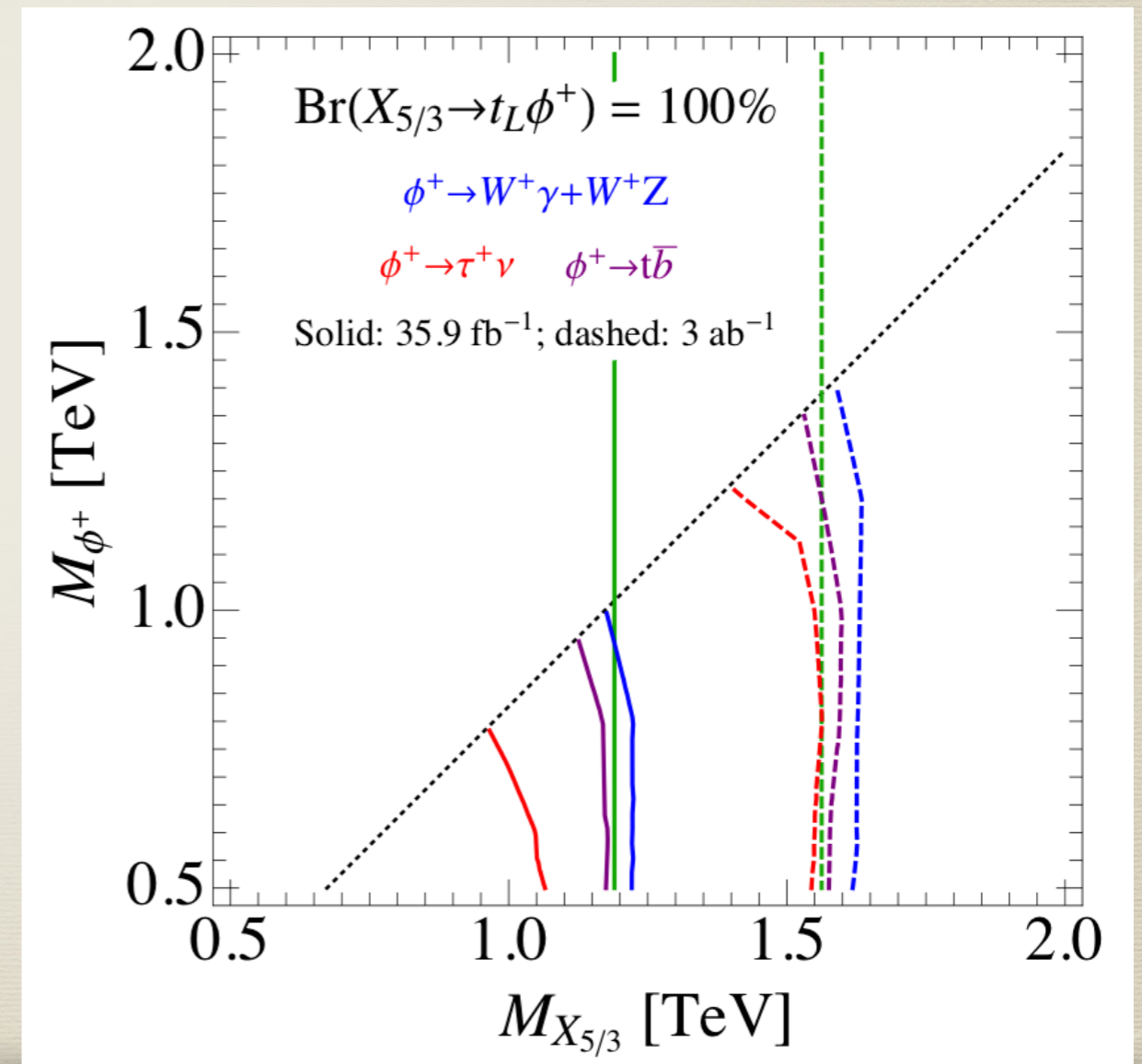
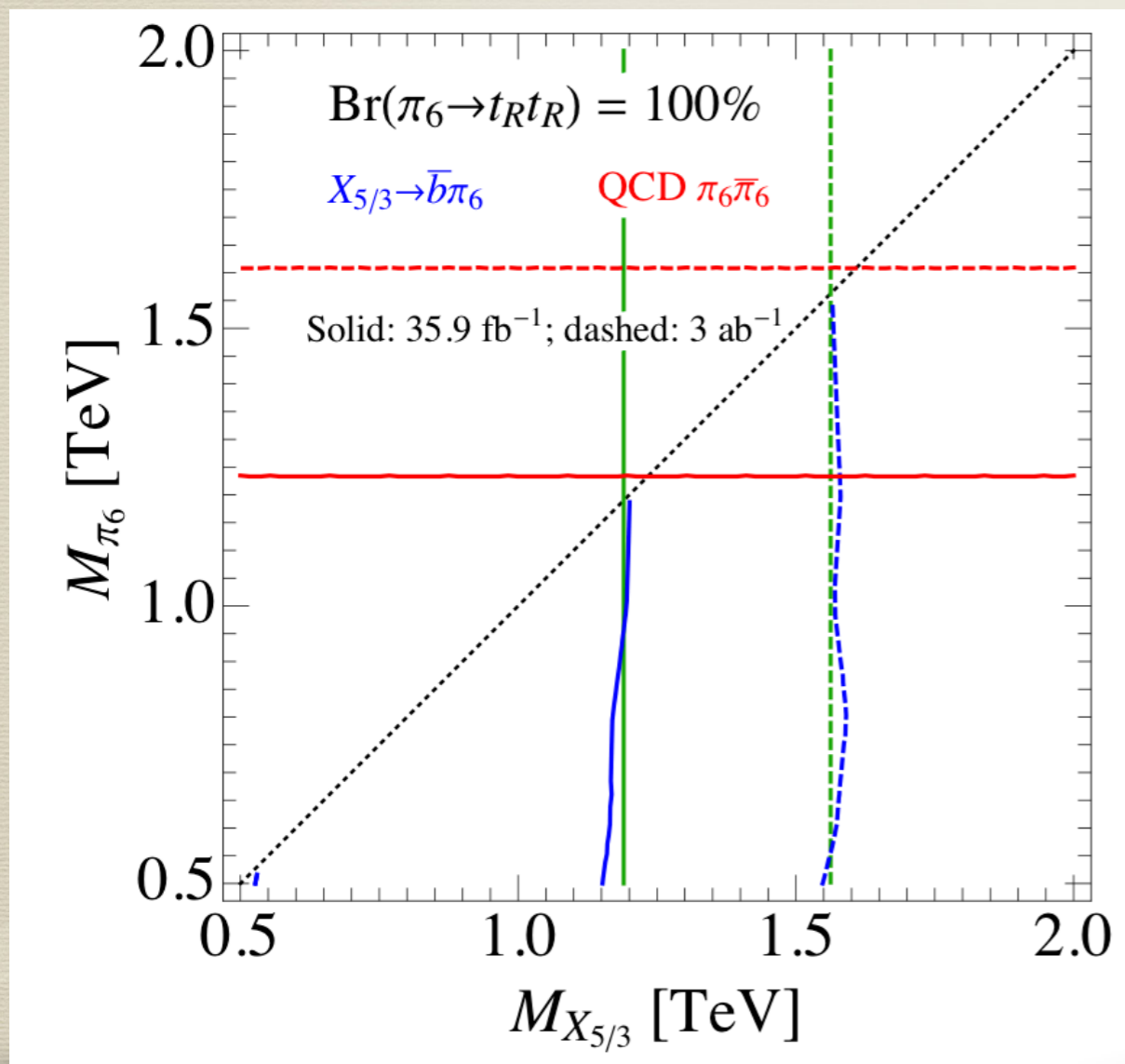
2

# Common exotic VLQ decays: $X_{5/3}$

Recasting the most recent CMS  $X_{5/3}$  same-sign lepton search [JHEP 1903, 082](#) we obtain bounds on  $X_{5/3}$  pair-production with exotic  $X_{5/3}$  decays:

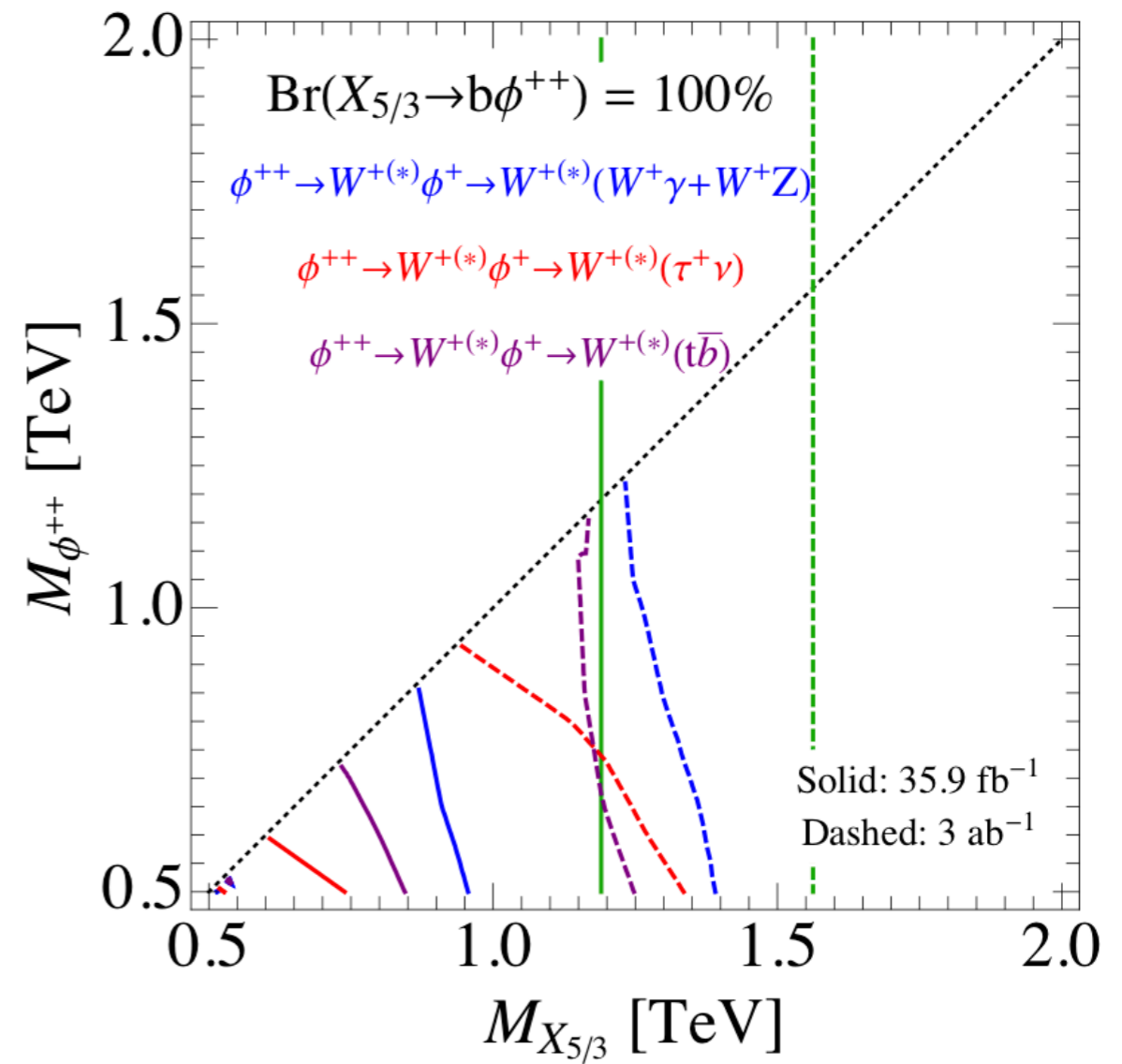
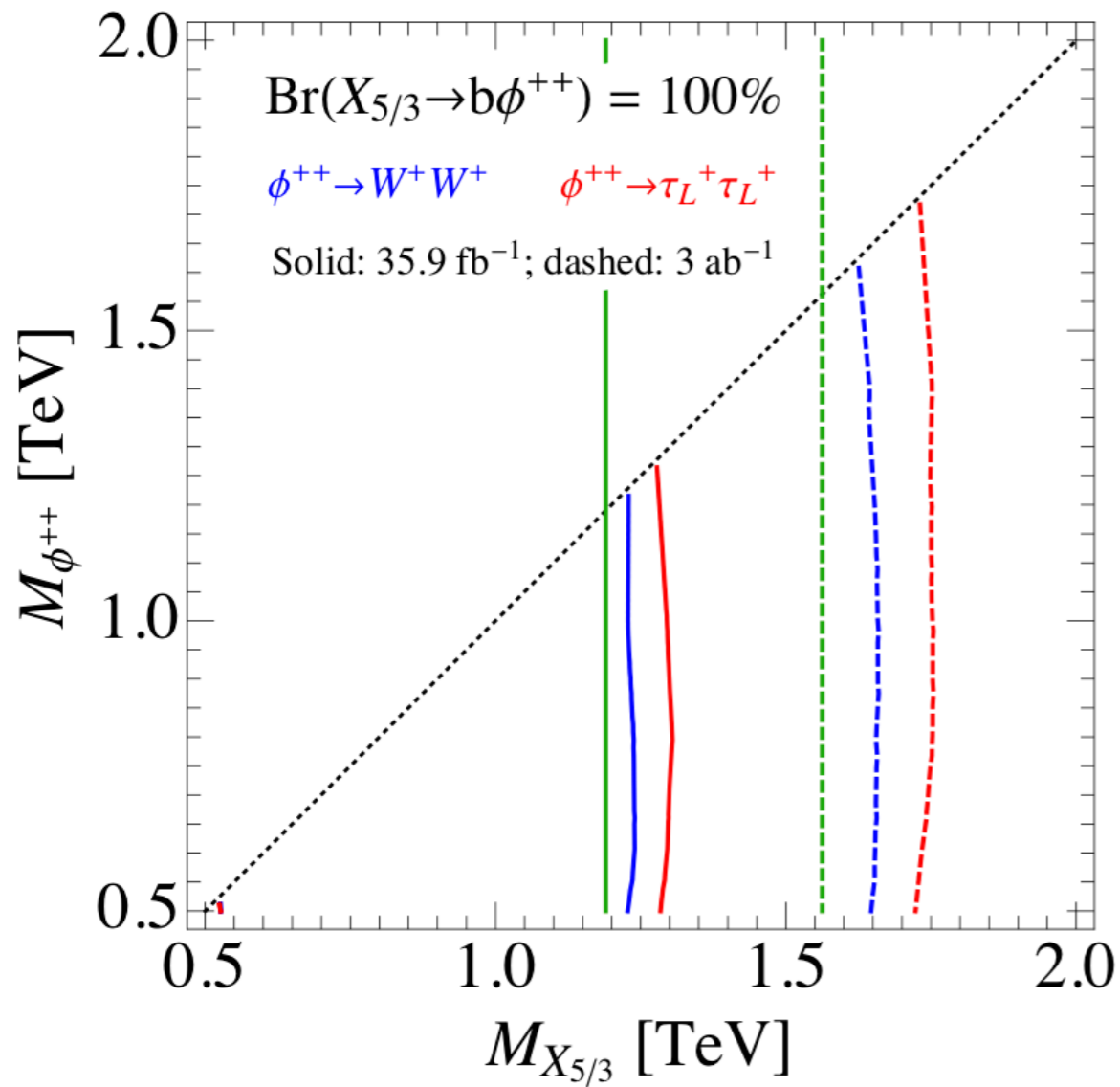
$\pi_6$ :

$\phi^+$ :



# Common exotic VLQ decays: $X_{5/3}$

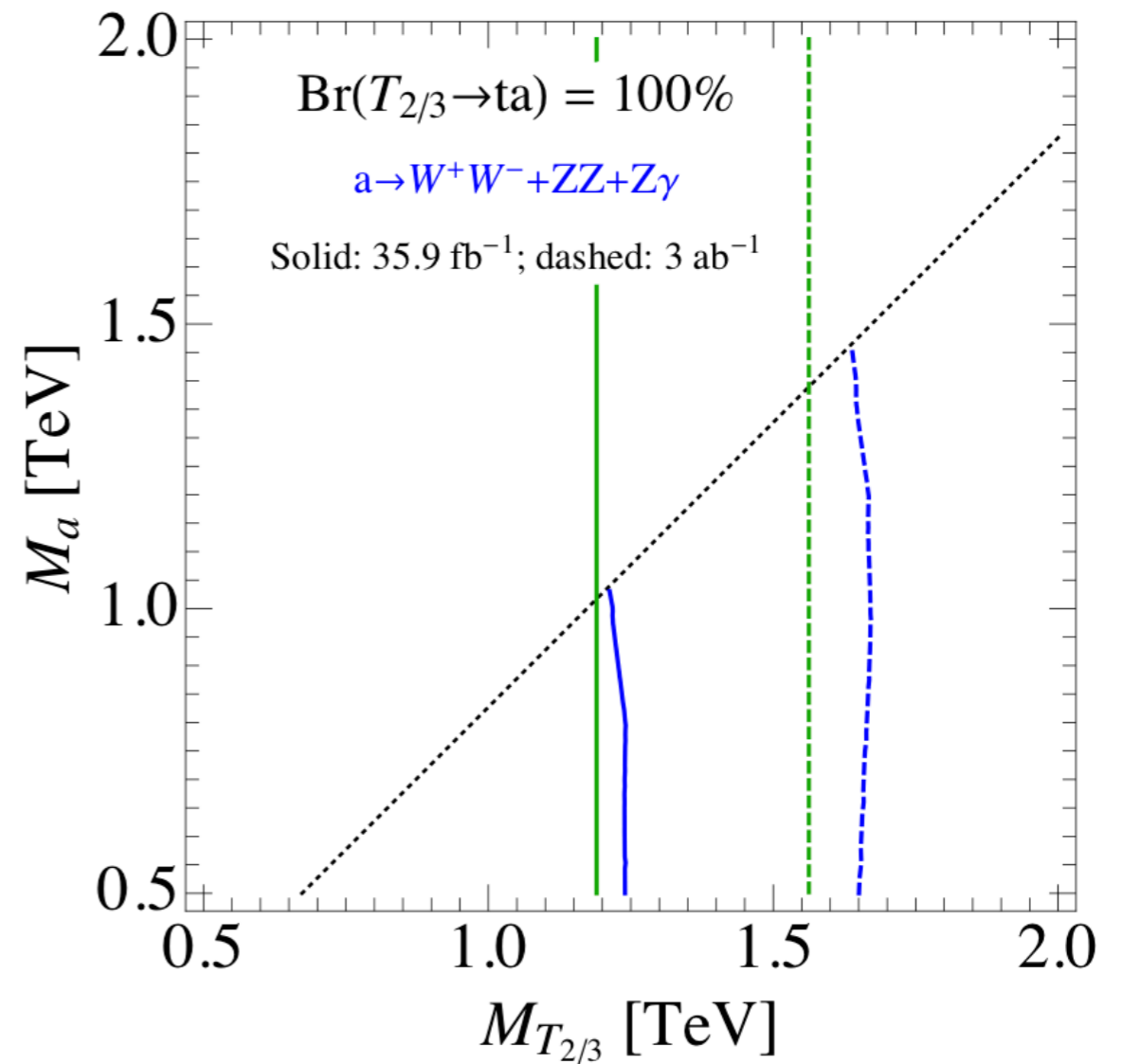
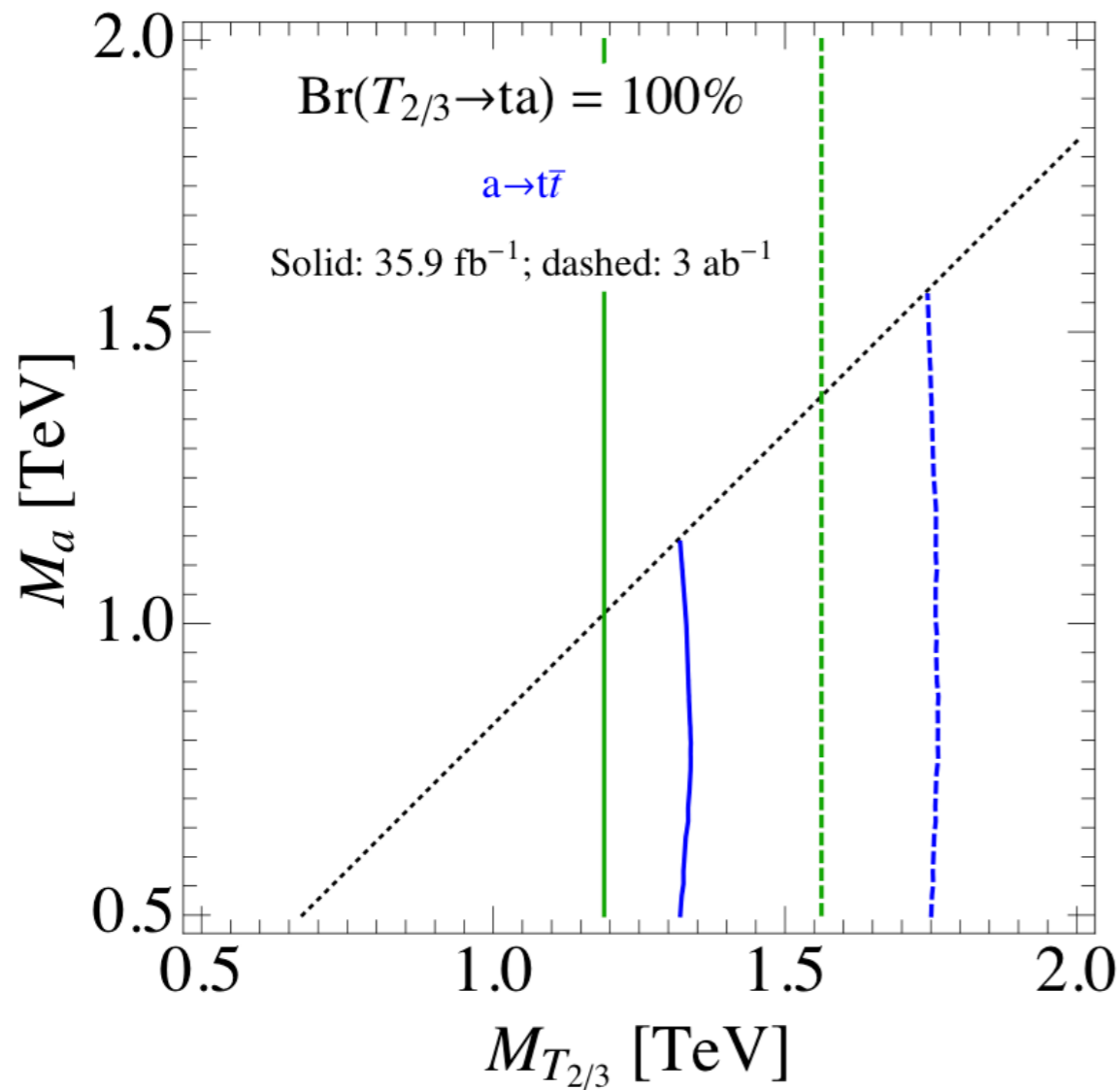
$\phi^{++}$ :



# Common exotic VLQ decays: $X_{5/3}$

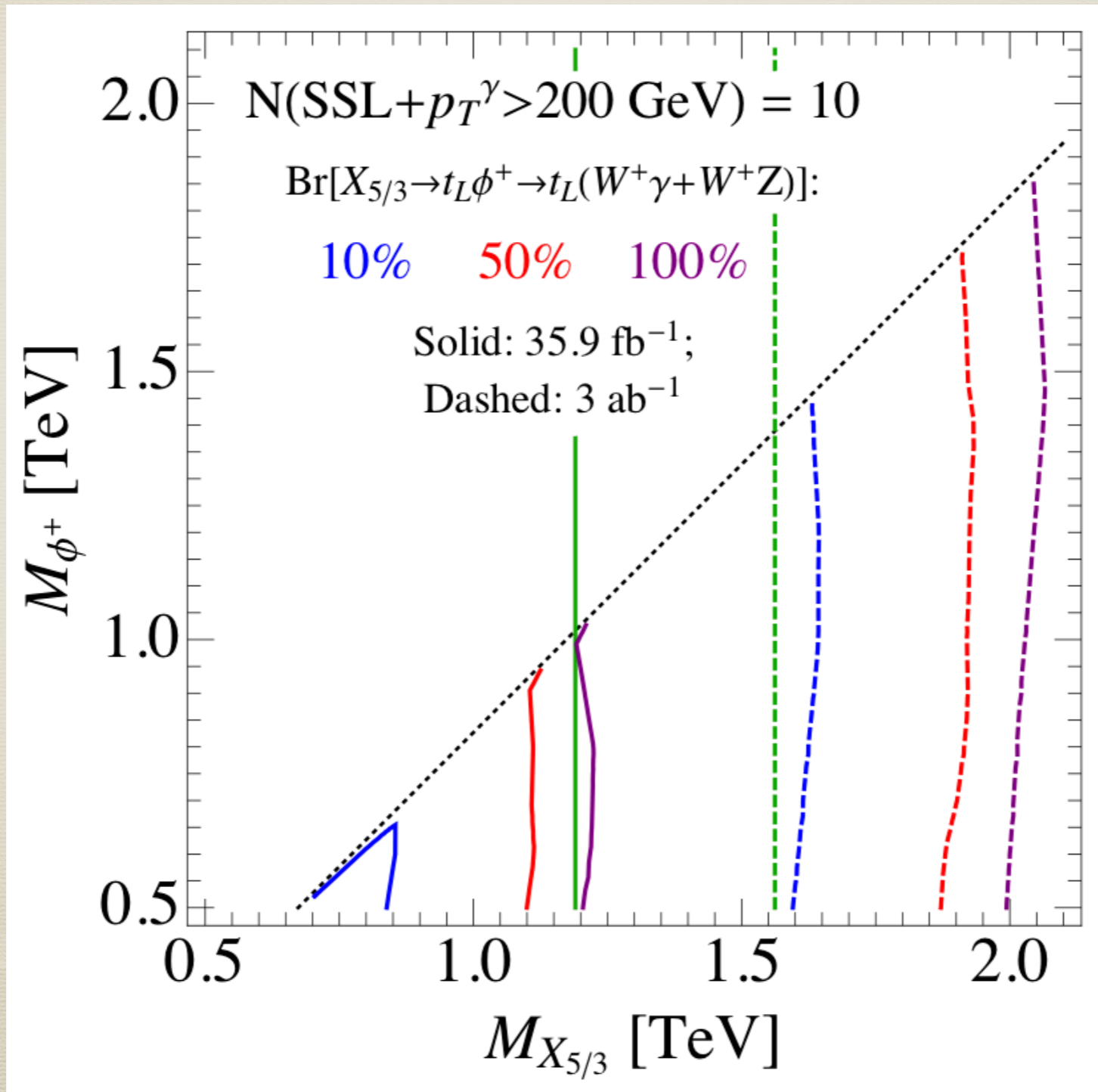
## Bonus Plots

The recast can also be used to constrain several exotic  $T_{2/3}$  decays.  
(c.f. [Shu etal \(2018\)](#), [Benbrik etal \(2019\)](#) for studies of other exotic channels)



# Common exotic VLQ decays: $X_{5/3}$

Some exotic decay channels provide opportunities to substantially increase sensitivity. E.g.:  $X_{5/3} \rightarrow t\phi^+ \rightarrow tW^+\gamma$  with a hard photon in the FS.





# Conclusions

- ‘Exotic’ decays of top partners to  $t/b + p\text{NGBs}$  rather than to  $t/b + W/Z/h$  occur commonly, for example, in CH UV embeddings. These decays lead to many final states which are not explicitly targeted by current LHC searches.
- Charge  $5/3$  resonances:  $X_{5/3}$  same-sign dilepton searches can be reinterpreted to obtain constraints on exotic  $X_{5/3}$  decays. Signal efficiencies of existing searches for exotic decays are modified, but of the same order. For some of the exotic channels, substantial improvements are possible.
- Charge  $2/3$  resonances: We investigate the decays  $T \rightarrow t a$  with  $a \rightarrow gg$  or  $a \rightarrow bb$ . For these decays (especially for  $T \rightarrow t a \rightarrow t g g$ ), bounds from existing searches on  $m_T$  are substantially weaker than for standard VLQ decays.

There is a lot to do!

Backup

# Motivation for Vector-like quarks: a composite Higgs

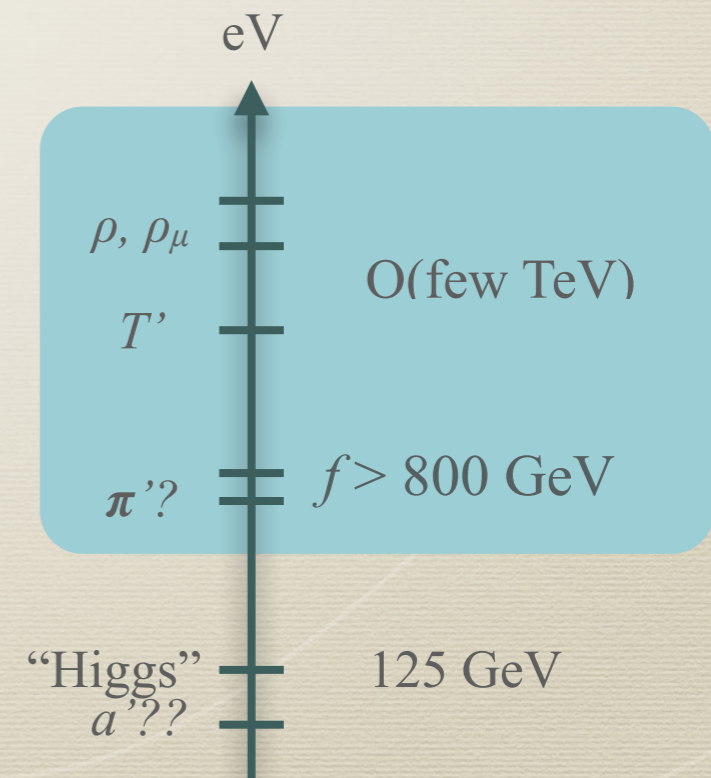
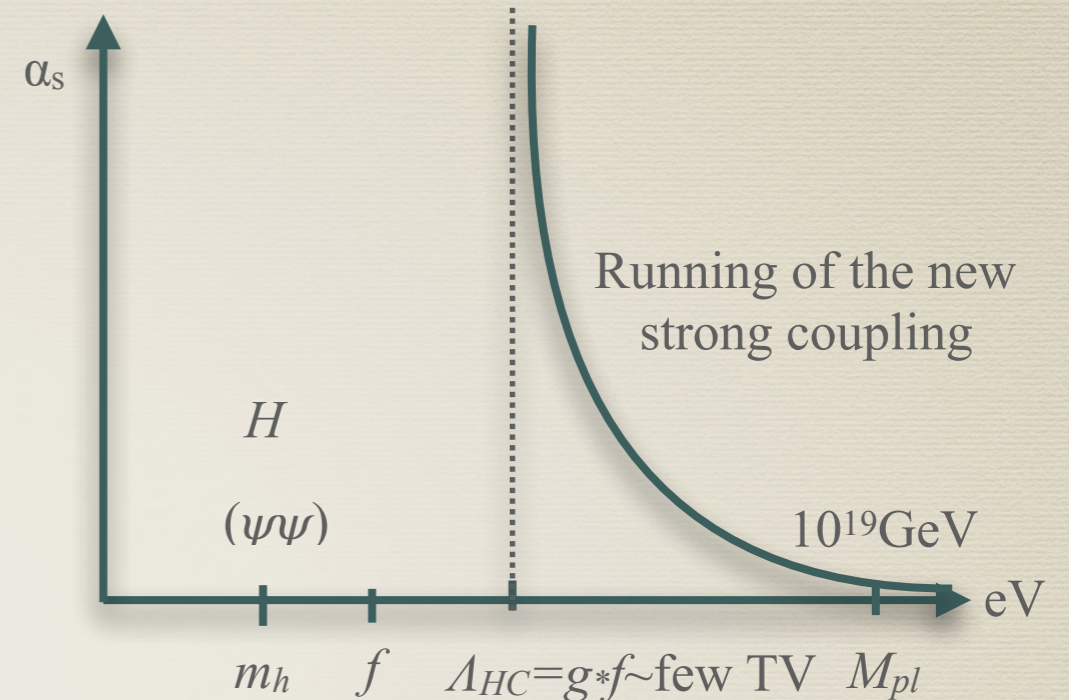
An alternative solution to the hierarchy problem:

- Generate a scale  $\Lambda_{HC} \ll M_{pl}$  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.

[Georgi, Kaplan (1984)]

The price to pay:

- additional resonances around  $\Lambda_{HC}$  (vectors, **vector-like fermions**, scalars),
- **additional light pNGBs** in an extended sector (?).
- deviations of the Higgs couplings from their SM values of  $O(v/f)$ .



# Chiral Lagrangian for the pNGBs

[JHEP1701,094]

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  $r = \psi, \chi$ ,  $\pi^a$  are the non-abelian Goldstones,  $T^a$  are the corresponding broken generators,  $\Sigma_{0,r}$  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

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

where we chose the normalization such that  $m_W = \frac{g}{2} f_\psi \sin \theta$  where  $\theta$  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).

# Sources of masses and couplings of the pseudo Goldstone bosons:

[[JHEP1701,094](#)]

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?

# 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. [\[JHEP1701,094\]](#)

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

where

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

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

where

$$C_{AA'}^r c^{abc} = d_r \text{Tr}[T_\pi^a \{S^b, S^c\}]$$

**Upshot:** - The couplings  $C_A^r$  of pNGBs to gauge bosons are fully fixed by the quantum numbers of  $\chi$  and  $\psi$ .

- One model  $\Leftrightarrow$  one set of Branching ratios.

- Only unknown parameters are decay constants  $f_r$ .

# Couplings to tops and top mass: [\[JHEP1701,094\]](#)

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

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

where  $\Psi$  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  $y_L y_R$  and thus also has definite  $U(1)_{\chi,\psi}$  charges  $n_{\psi,\chi}$ . For  $\psi\psi\chi$ :

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

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

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

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  $\pi_8$  to tops if  $n_{\chi} = 0$ .

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

# Underlying fermion mass terms: [\[JHEP1701,094\]](#)

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

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

The spurions  $X_r$  are related to the the fermion masses linearly

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

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**



# Singlets: masses and mixing

[JHEP1701,094]

The states  $a_{\psi, \chi}$  mix due to an anomaly w.r.t. the hyper color group which breaks  $U(1)_{\psi} \times U(1)_{\chi}$  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

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

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

The masses of the pNGBs are

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

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

# Singlet pNGB summary and phenomenology

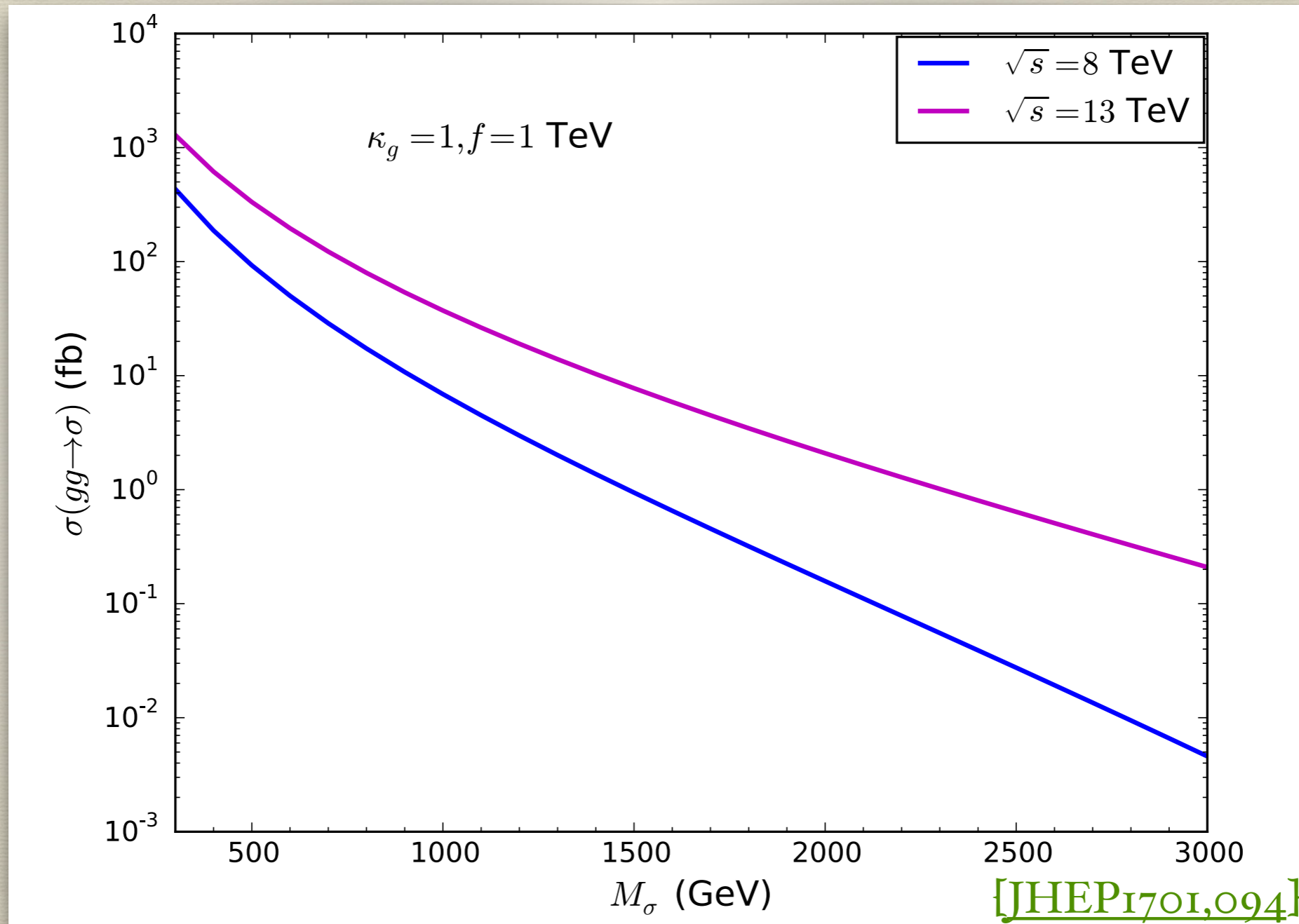
[arXiv:1902.06890]

$a$  and  $\eta'$ : Arise from the SSB of  $U(1)_\chi \times U(1)_\psi$ . One linear combination has a  $G_{HC}$  anomaly ( $\eta'$ ) and is expected heavier. The orthogonal linear combination ( $a$ ) is a pNGB.  $\phi = \{a, \eta'\}$

$$\begin{aligned} \mathcal{L}_{\text{eff}} \supset & \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}m_\phi^2 \phi^2 \\ & + \frac{\phi}{16\pi^2 f_\psi} \left( g_s^2 K_g^\phi G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + g^2 K_W^\phi W_{\mu\nu}^i \tilde{W}^{i\mu\nu} + g'^2 K_B^\phi B_{\mu\nu} \tilde{B}^{\mu\nu} \right) \\ & - i \sum_f \frac{C_f^\phi m_f}{f_\psi} \phi \bar{\psi}_f \gamma^5 \psi_f \\ & + \frac{2v}{f_\psi^2} K_{\phi h}^{\text{eff}} (\partial_\mu \phi) (\partial^\mu \phi) h + \frac{2m_Z}{f_\psi} K_{hZ}^{\text{eff}} (\partial_\mu \phi) Z^\mu h \end{aligned}$$

- $m_a$  must result from *explicit* breaking of the U(1)s.  $m_\eta$  also obtains mass from instantons.
- $f_\psi$  (decay constant of the EW sector) results from chiral symmetry breaking.
- The WZW coefficients  $K^\phi$  are determined by the quantum numbers of  $\chi, \psi$  (and  $(m_a, m_\eta)$ ).
- The coefficients  $C^\phi_f$  are also fixed (depending on dominantly mixing top-partner).
- $h\phi\phi$  and  $h\phi Z$  couplings are induced at 1-loop order.
- $a$  and  $\eta'$  are produced in gluon fusion.
- The resonances are narrow.

# Production cross section for a pseudo-scalar



	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
$K_g^a$	-3.5	-3.6	-2.3	-5.5	-3.5	-3.5	-3.7	-0.6	-8.4	-6.2	-1.1	-1.6
	-1.8	-1.9	-1.3	-3.1	-1.8	-1.8	-1.9	-.31	-4.8	-3.6	-.61	-.85
$K_W^a$	3.7	4.9	3.2	5.9	2.6	3.1	5.5	.68	4.6	3.7	1.1	1.8
	4.2	5.5	4.6	9.0	3.0	3.6	6.1	.92	7.1	6.8	1.7	2.3
$K_B^a$	1.3	2.5	-3.0	-8.8	.29	.81	3.1	-.83	-18.	-13.	-1.8	-2.4
	3.0	4.2	1.1	.74	1.8	2.4	4.8	.09	-5.6	-2.8	.12	.05
$K_g^{\eta'}$	5.4	5.9	1.8	3.9	5.4	5.1	6.6	.53	5.9	3.2	.68	1.5
	6.2	6.7	2.7	6.0	6.2	5.9	7.3	.71	9.2	5.9	1.1	2.0
$K_W^{\eta'}$	2.4	3.0	3.9	8.2	1.7	2.1	3.1	.73	6.5	7.1	1.7	1.8
	1.3	1.5	2.2	4.6	.90	1.1	1.6	.40	3.7	4.1	.96	.96
$K_B^{\eta'}$	6.0	6.9	8.9	19.	5.3	5.5	7.5	2.1	22.	16.	3.5	5.9
	5.4	6.0	9.3	21.	5.0	5.1	6.5	2.3	28.	20.	3.9	6.4
$f_\psi/f_\chi$	1.4	.75	.73	1.3	2.8	1.9	.58	.38	2.3	1.7	.52	.38
$f_a/f_\psi$	2.1	2.4	2.8	2.0	1.4	1.4	2.4	2.8	1.2	1.5	3.1	2.6

TABLE III. Couplings of  $a$  and  $\eta'$  to gauge bosons for all models. Each cell contains two values corresponding to decoupling limit (top) and maximal mixing (bottom). The last two rows shows the numerical value of the decay constant ratios used in this work

$C_t^a$	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
$(\pm 2, 0)$	$\pm 1.1$	$\pm 1.1$	$\pm .79$	$\pm .73$	$\pm 1.1$	$\pm 1.0$	$\pm 1.1$	$\pm .68$	$\pm .58$	$\pm .46$	$\pm .54$	$\pm .70$
	$\pm 1.2$	$\pm 1.2$	$\pm 1.1$	$\pm 1.1$	$\pm 1.2$	$\pm 1.2$	$\pm 1.2$	$\pm .92$	$\pm .89$	$\pm .85$	$\pm .88$	$\pm .92$
$(0, \pm 2)$	$\mp .88$	$\mp .45$	$\mp .66$	$\mp 1.2$	$\mp 1.8$	$\mp 1.7$	$\mp .46$	$\mp .23$	$\mp 1.5$	$\mp 1.2$	$\mp .36$	$\mp .31$
	$\mp .46$	$\mp .23$	$\mp .37$	$\mp .69$	$\mp .92$	$\mp .91$	$\mp .24$	$\mp .12$	$\mp .86$	$\mp .72$	$\mp .20$	$\mp .17$
$(4, 2)$	$-.71$	$.18$	$.92$	$.24$	$-2.5$	$-2.4$	$.18$	$1.1$	$-.38$	$-.31$	$.72$	$1.1$
	$.29$	$.75$	$1.9$	$1.6$	$-.63$	$-.62$	$.75$	$1.7$	$.91$	$.99$	$1.5$	$1.7$
$(-4, 2)$	$2.8$	$2.0$	$-2.2$	$-2.7$	$4.6$	$4.5$	$2.0$	$-1.6$	$-2.7$	$-2.2$	$-1.4$	$-1.7$
	$2.1$	$1.7$	$-2.6$	$-2.9$	$3.1$	$3.0$	$1.7$	$-2.0$	$-2.6$	$-2.4$	$-2.0$	$-2.0$
$C_t^{\eta'}$	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
$(\pm 2, 0)$	$\pm .69$	$\pm .66$	$\pm .99$	$\pm 1.0$	$\pm .69$	$\pm .71$	$\pm .62$	$\pm .73$	$\pm .82$	$\pm .89$	$\pm .84$	$\pm .71$
	$\pm .36$	$\pm .34$	$\pm .55$	$\pm .58$	$\pm .36$	$\pm .37$	$\pm .32$	$\pm .40$	$\pm .46$	$\pm .52$	$\pm .48$	$\pm .39$
$(0, \pm 2)$	$\pm 1.4$	$\pm .74$	$\pm .53$	$\pm .87$	$\pm 2.7$	$\pm 2.6$	$\pm .83$	$\pm .21$	$\pm 1.1$	$\pm .64$	$\pm .23$	$\pm .31$
	$\pm 1.5$	$\pm .83$	$\pm .76$	$\pm 1.3$	$\pm 3.1$	$\pm 3.0$	$\pm .92$	$\pm .28$	$\pm 1.7$	$\pm 1.2$	$\pm .37$	$\pm .40$
$(4, 2)$	$3.4$	$2.1$	$2.5$	$2.9$	$6.1$	$5.8$	$2.3$	$1.7$	$2.7$	$2.4$	$1.9$	$1.7$
	$3.5$	$2.0$	$1.9$	$2.5$	$6.6$	$6.3$	$2.2$	$1.1$	$2.6$	$2.2$	$1.3$	$1.2$
$(-4, 2)$	$-2.0$	$-.82$	$-1.5$	$-1.2$	$-4.7$	$-4.4$	$-1.0$	$-1.3$	$-.55$	$-1.1$	$-1.5$	$-1.1$
	$-2.7$	$-1.3$	$-.33$	$.17$	$-5.8$	$-5.6$	$-1.5$	$-.51$	$.75$	$.15$	$-.59$	$-.37$

TABLE IV. Coupling of  $a$  and  $\eta'$  to the top,  $C_t$ , for all models. Each cell contains two values corresponding to decoupling limit (top) and maximal mixing (bottom). For models with top partners in the form  $\psi\chi\chi$  (see Table I), the two last rows should be intended  $(2, 4)$  and  $(2, -4)$ .

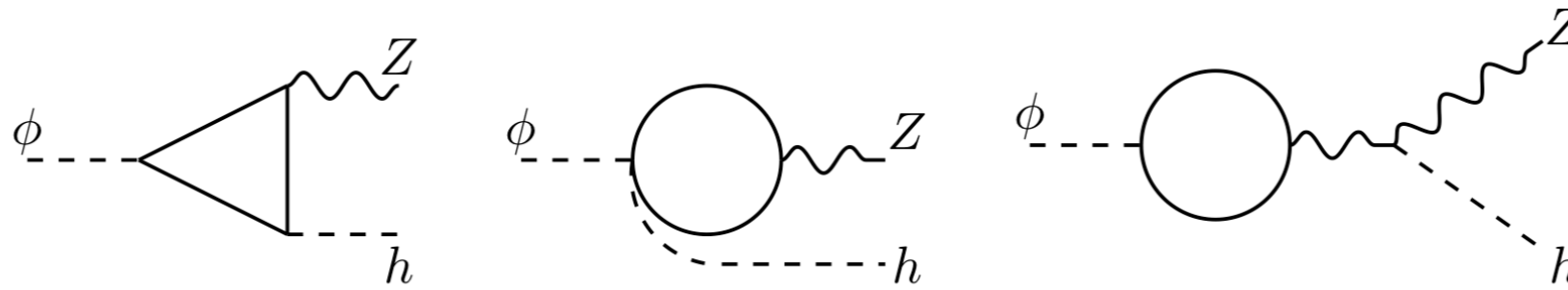
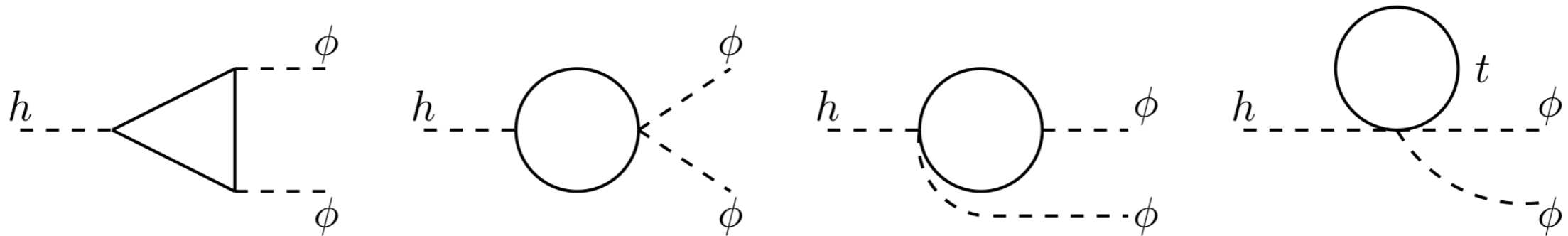


FIG. 1. Leading contributions to the decay  $\phi \rightarrow Zh$ .

$$K_{hZ}^{\phi \text{ eff}} = \frac{3m_t^2}{32\pi^2 v m_Z} C_t^\phi \left[ 2(\kappa_t - \kappa_Z) \mathcal{B}_0(\tau_{\phi/t}) - \kappa_t (\mathcal{B}_0(\tau_{h/t}) - \mathcal{B}_0(\tau_{\phi/t})) \right. \\ \left. + (4 - \tau_{Z/t}) \mathcal{C}_0(\tau_{\phi/t}, \tau_{h/t}, \tau_{Z/t}; 1) + (\tau_{\phi/t} + \tau_{h/t} - \tau_{Z/t}) \mathcal{C}_1(\tau_{\phi/t}, \tau_{h/t}, \tau_{Z/t}; 1) \right]$$



$$K_{\phi h}^{\text{eff}} = \frac{3\kappa_t}{8\pi^2} \left( \frac{C_t^\phi m_t}{v} \right)^2 \left[ \mathcal{B}_0(\tau_{\phi/t}) + 2\mathcal{C}_0(\tau_{\phi/t}, \tau_{h/t}, \tau_{\phi/t}; 1) + \frac{1}{1 - 2\tau_{a/h}} (\mathcal{B}_0(\tau_{h/t}) - \mathcal{B}_0(\tau_{a/t})) \right]$$

## SM singlet branching ratios

$$\Gamma(\phi \rightarrow \text{had}) = \frac{\alpha_s^2(m_\phi) m_\phi^3}{8\pi^3 f_\psi^2} \left[ 1 + \frac{83}{4} \alpha_s(m_\phi) \right] \left| K_{gg}^\phi + C_t^\phi \mathcal{C}_0(0, \tau_{\phi/t}, 0; 1) \right|^2$$

$$\Gamma(\phi \rightarrow \gamma\gamma) = \frac{\alpha^2 m_\phi^3}{64\pi^3 f_\psi^2} \left| K_{\gamma\gamma}^\phi + \frac{8}{3} C_t^\phi \mathcal{C}_0(0, \tau_{\phi/t}, 0; 1) \right|^2$$

$$\Gamma(\phi \rightarrow WW) = \frac{\alpha^2 m_\phi^3 (1 - 4\tau_{W/\phi})^{3/2}}{32\pi^3 f_\psi^2 s_W^4} \left| K_{WW}^\phi - \frac{3}{2} C_t^\phi \mathcal{C}_{1+2}(\tau_{W/t}, \tau_{\phi/t}, \tau_{W/t}; \sqrt{\tau_{b/t}}) \right|^2$$

$$\Gamma(\phi \rightarrow Z\gamma) = \frac{\alpha^2 m_\phi^3 (1 - \tau_{Z/\phi})^3}{32\pi^3 f_\psi^2 s_W^2 c_W^2} \left| K_{Z\gamma}^\phi + C_t^\phi \left( 1 - \frac{8}{3} s_W^2 \right) \mathcal{C}_0(\tau_{Z/f}, \tau_{\phi/t}, 0; 1) \right|^2$$

$$\Gamma(\phi \rightarrow ZZ) = \frac{\alpha^2 m_\phi^3 (1 - 4\tau_{Z/\phi})^{3/2}}{64\pi^3 f_\psi^2 s_W^4 c_W^4} \left| K_{ZZ}^\phi + C_t^\phi \left[ s_W^2 \left( \frac{8}{3} s_W^2 - 2 \right) \mathcal{C}_0(\tau_{Z/t}, \tau_{\phi/t}, \tau_{Z/t}; 1) - \frac{3}{4} \mathcal{C}_{1+2}(\tau_{Z/t}, \tau_{\phi/t}, \tau_{Z/t}; 1) \right] \right|^2$$

$$\Gamma(\phi \rightarrow hZ) = \frac{m_\phi^3}{16\pi f_\psi^2} \left| K_{hZ}^{\phi \text{ eff}} \right|^2 \lambda(1, \tau_{Z/\phi}, \tau_{h/\phi})^{3/2}$$

$$\Gamma(h \rightarrow \phi\phi) = \frac{v^2 m_h^3}{32\pi f_\psi^4} \left| K_{\phi h}^{\text{eff}} \right|^2 (1 - 2\tau_{\phi/h})^2 \sqrt{1 - 4\tau_{\phi/h}}.$$

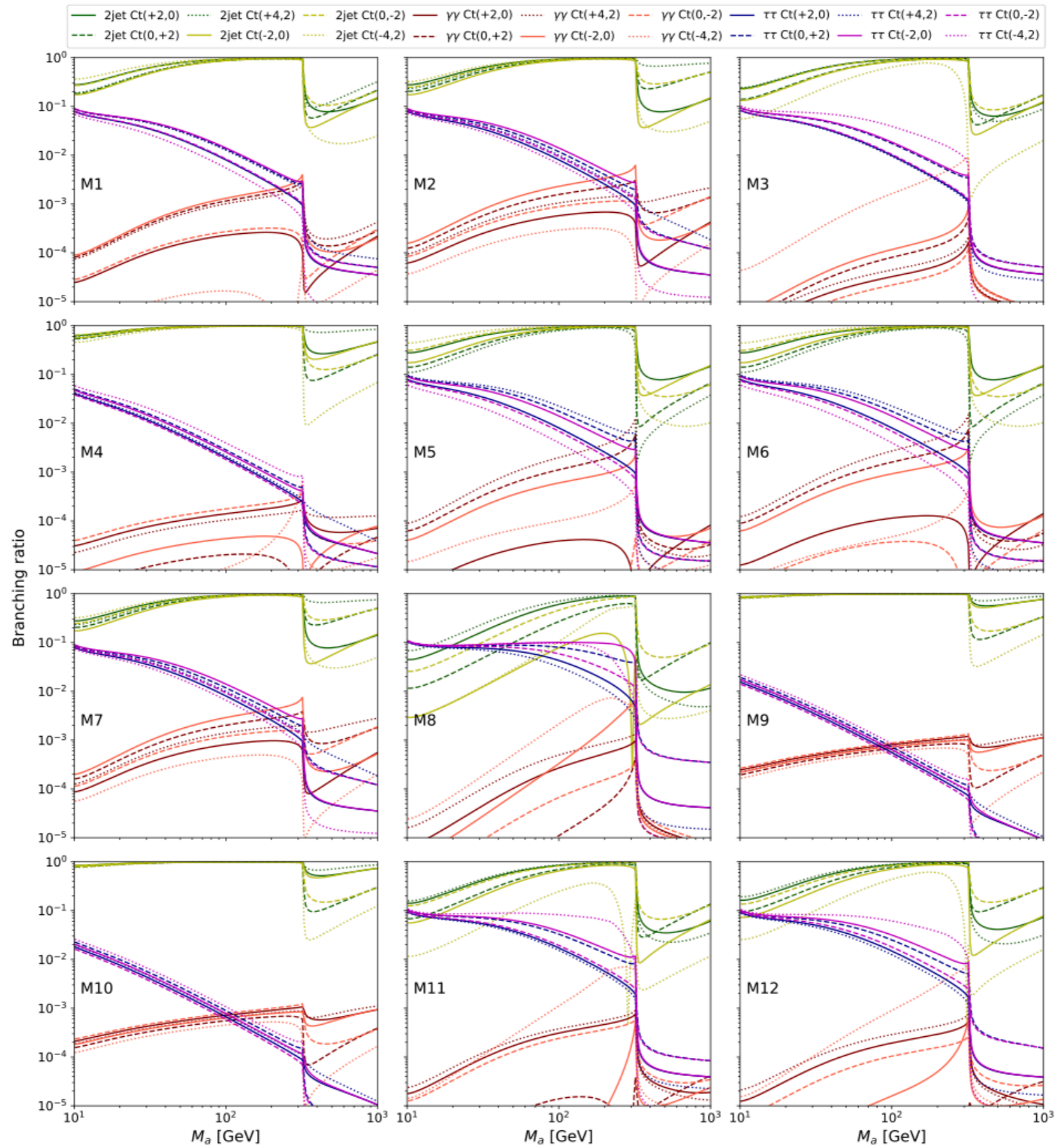
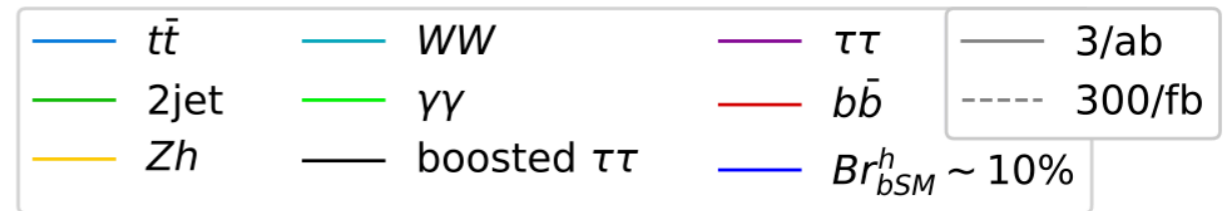
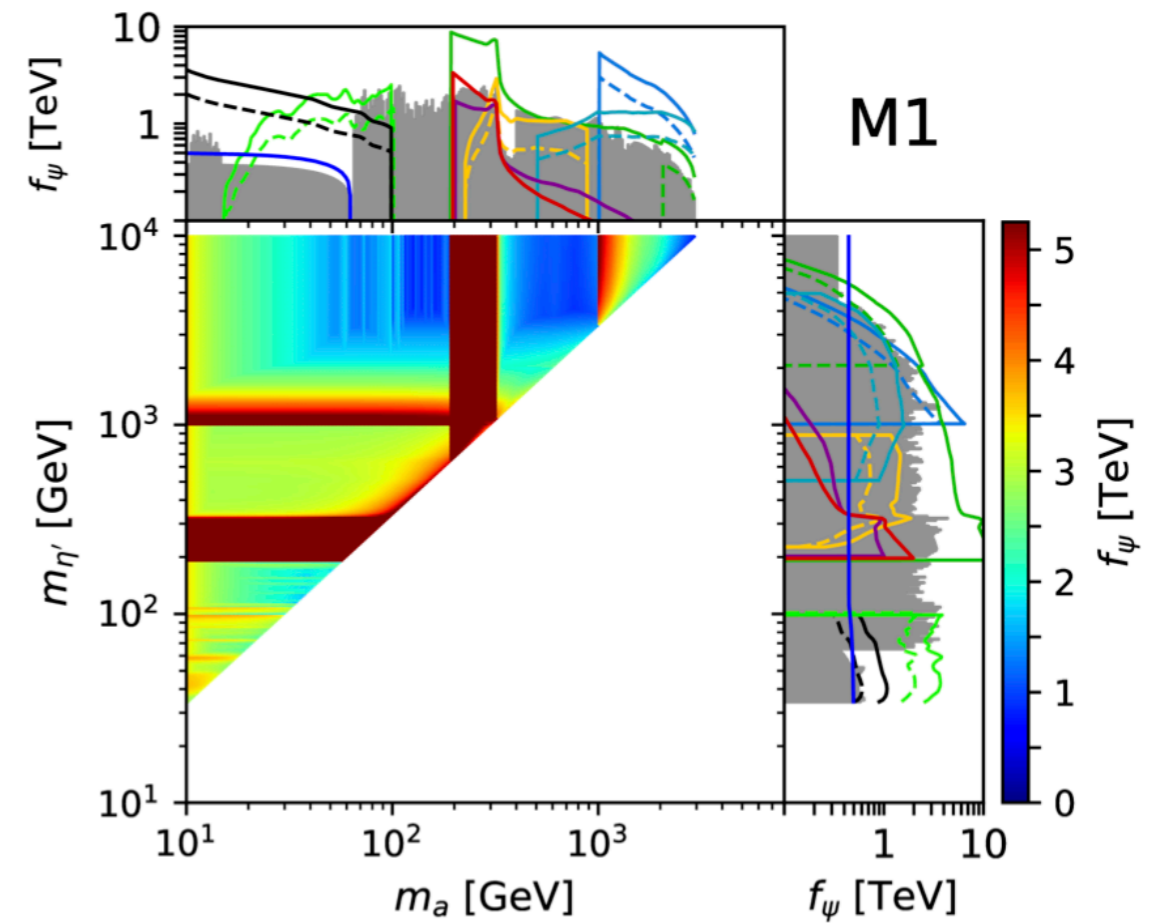
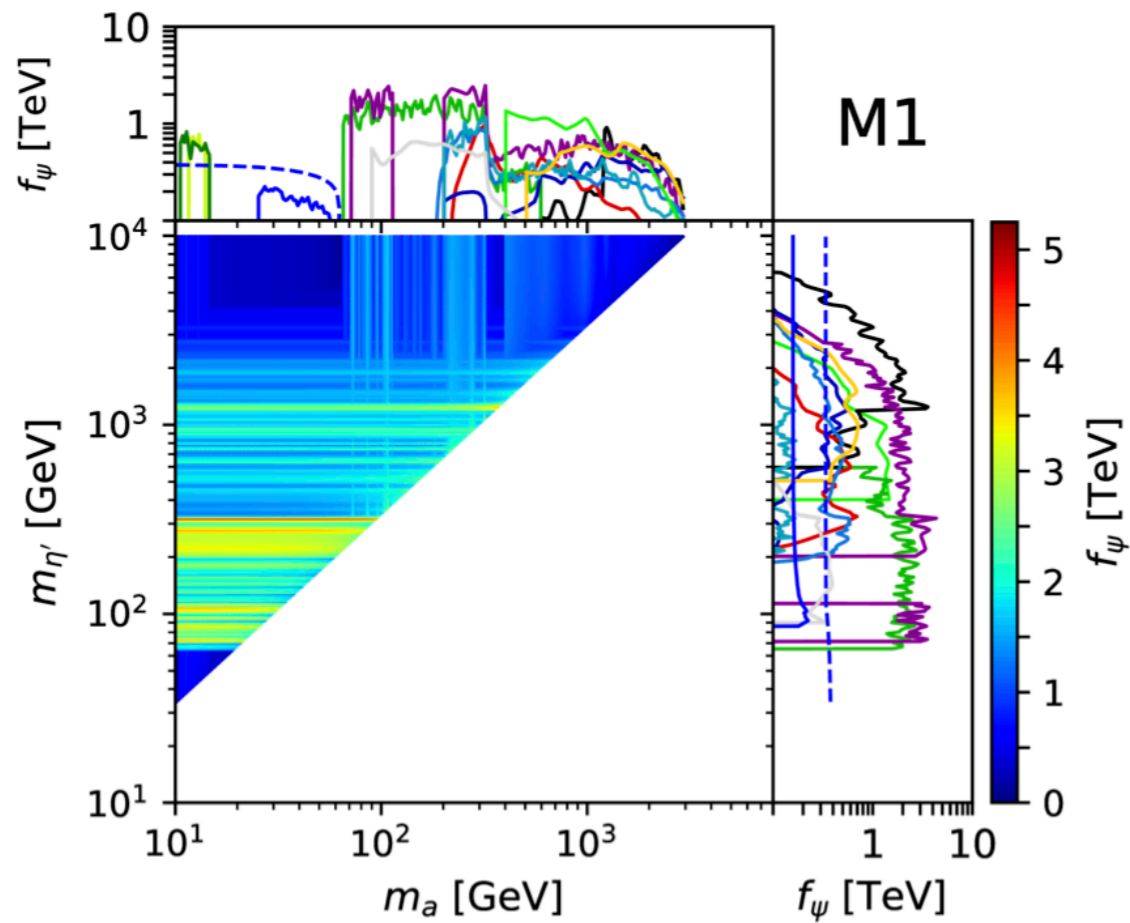
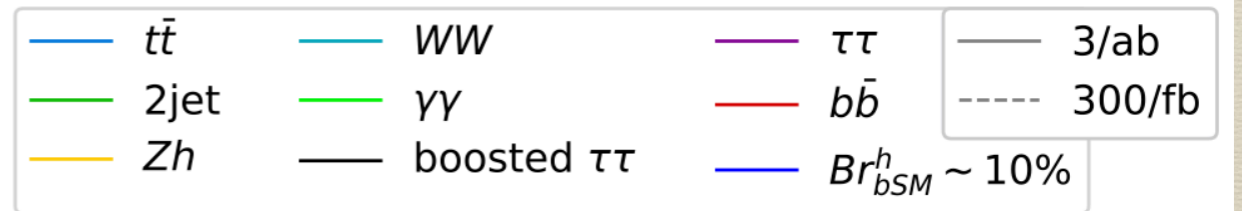
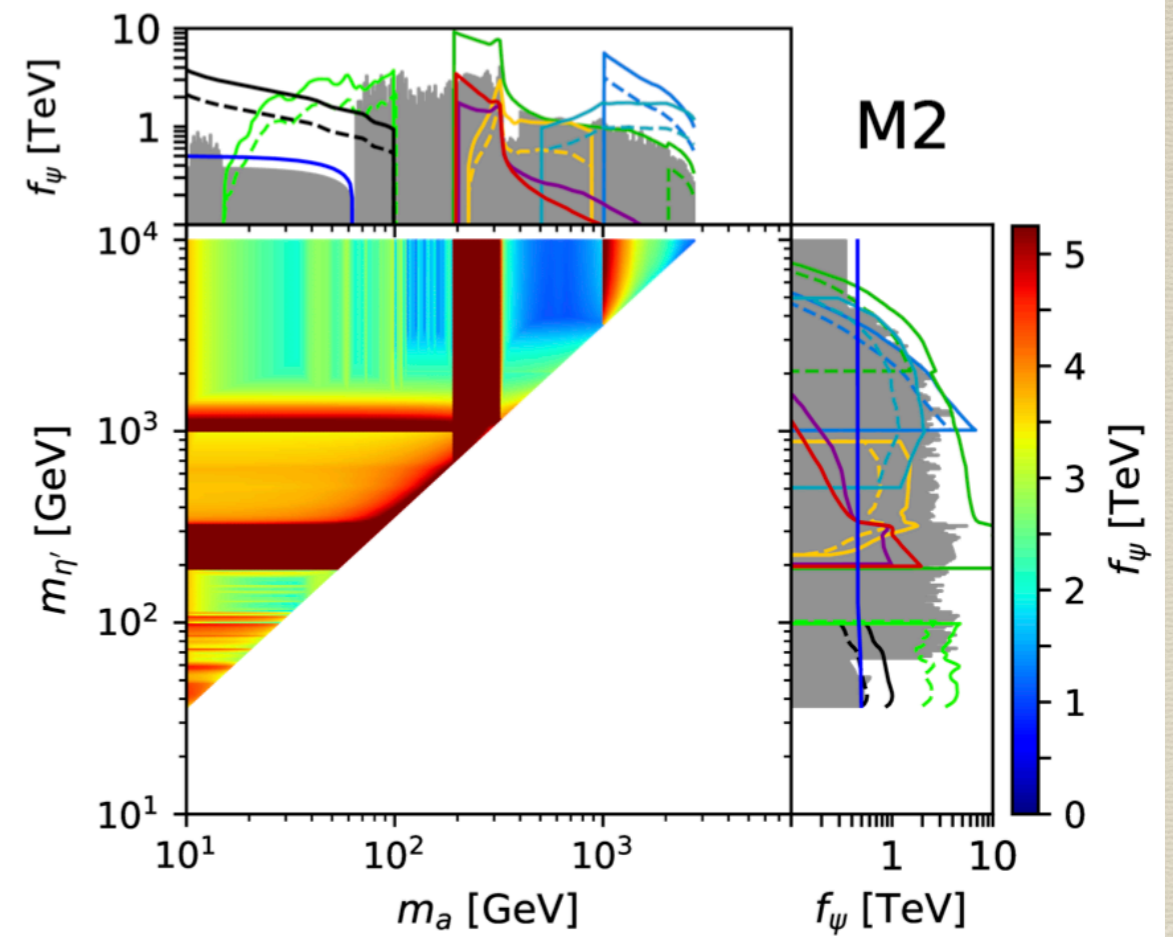
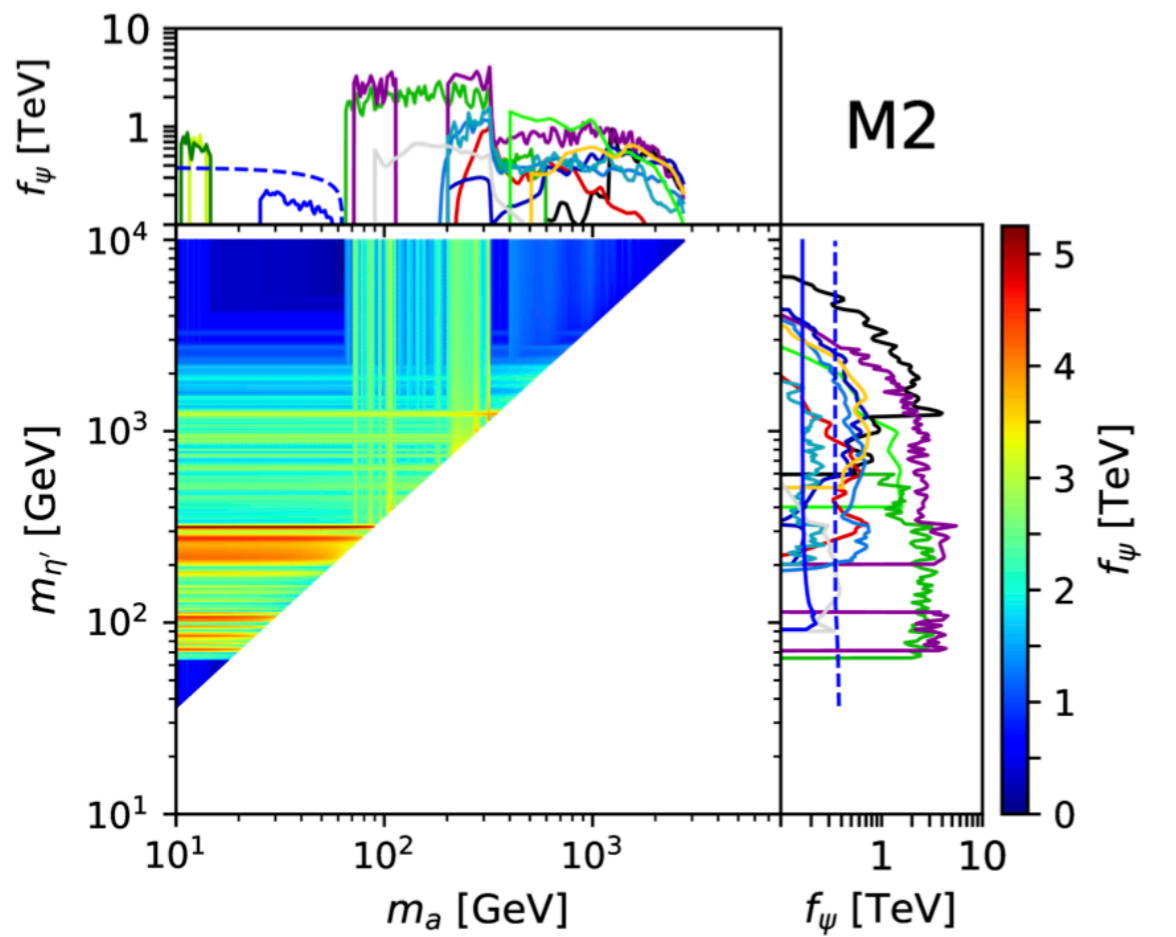
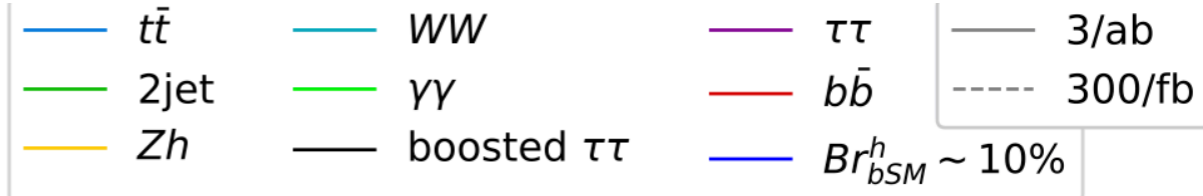
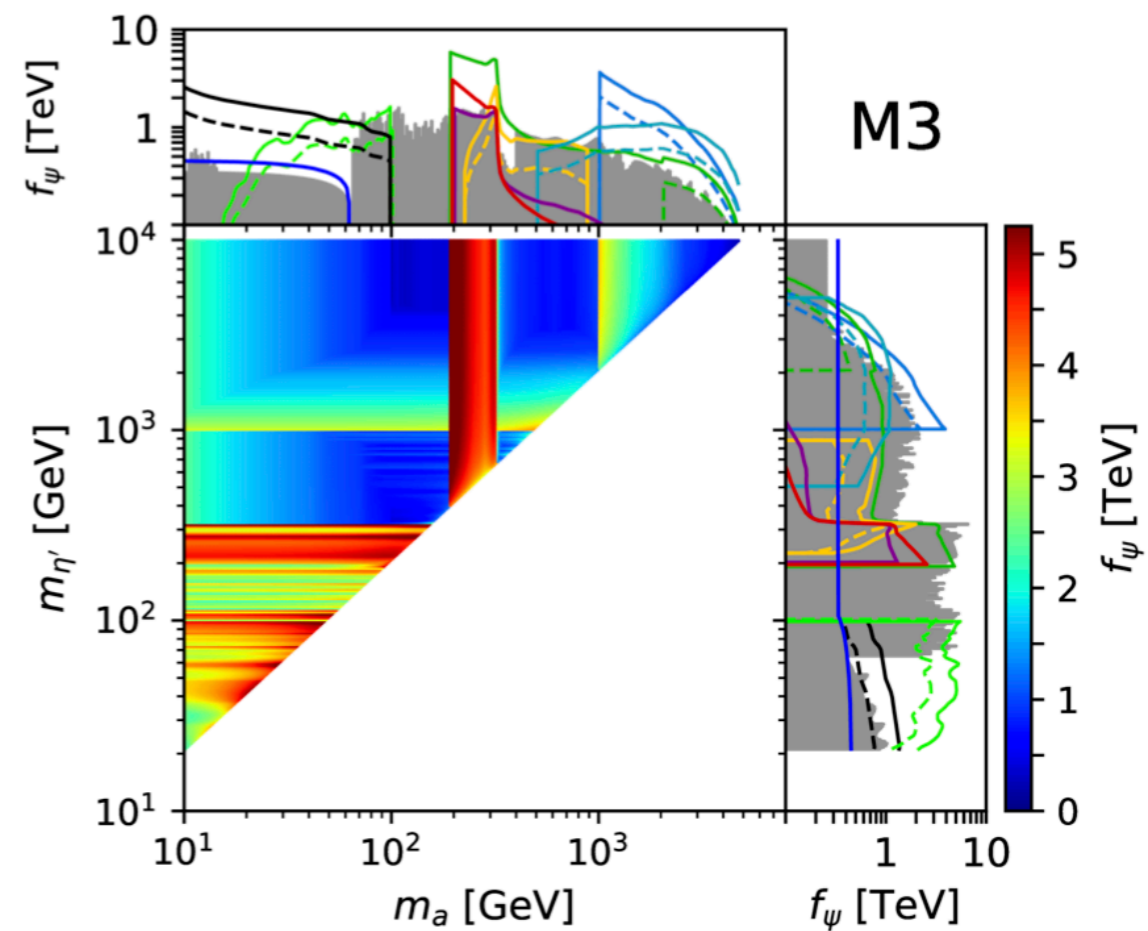
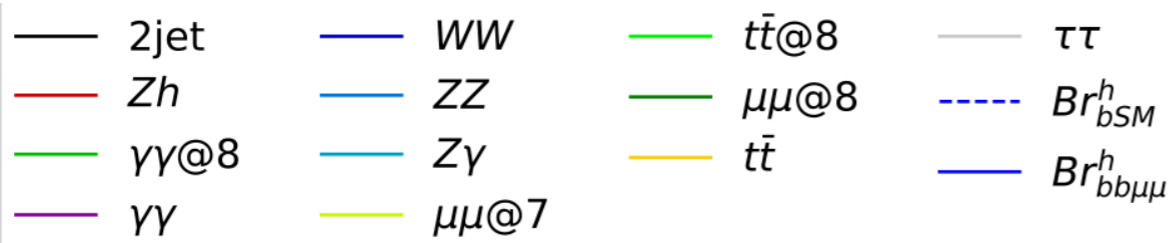
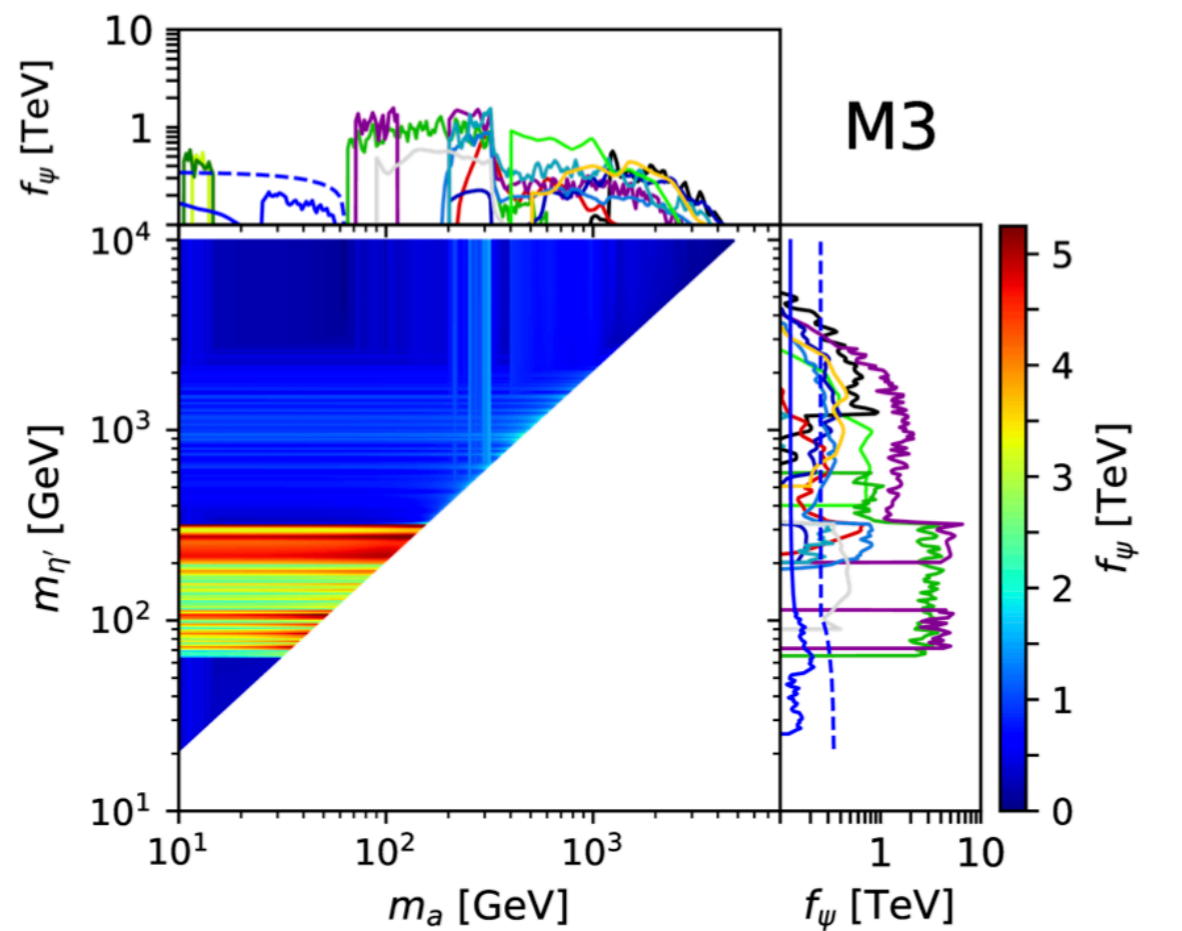


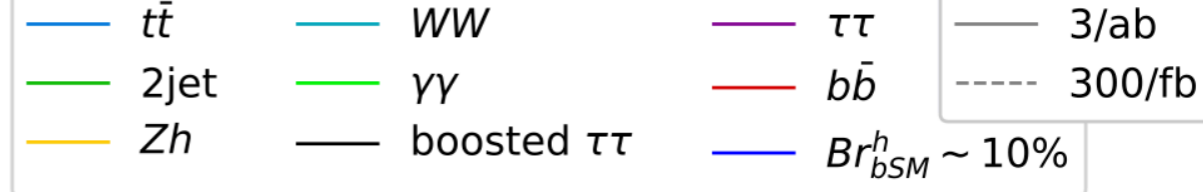
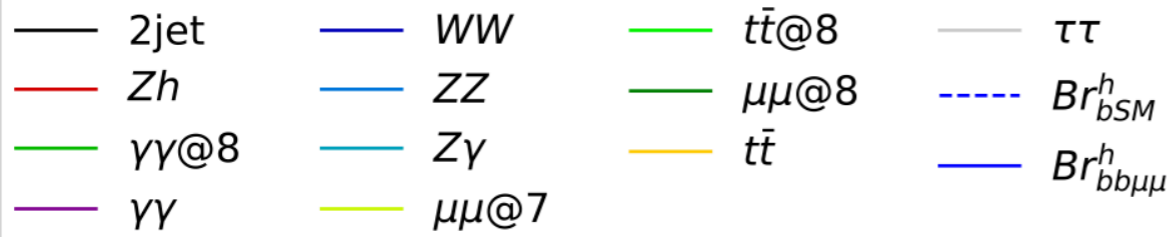
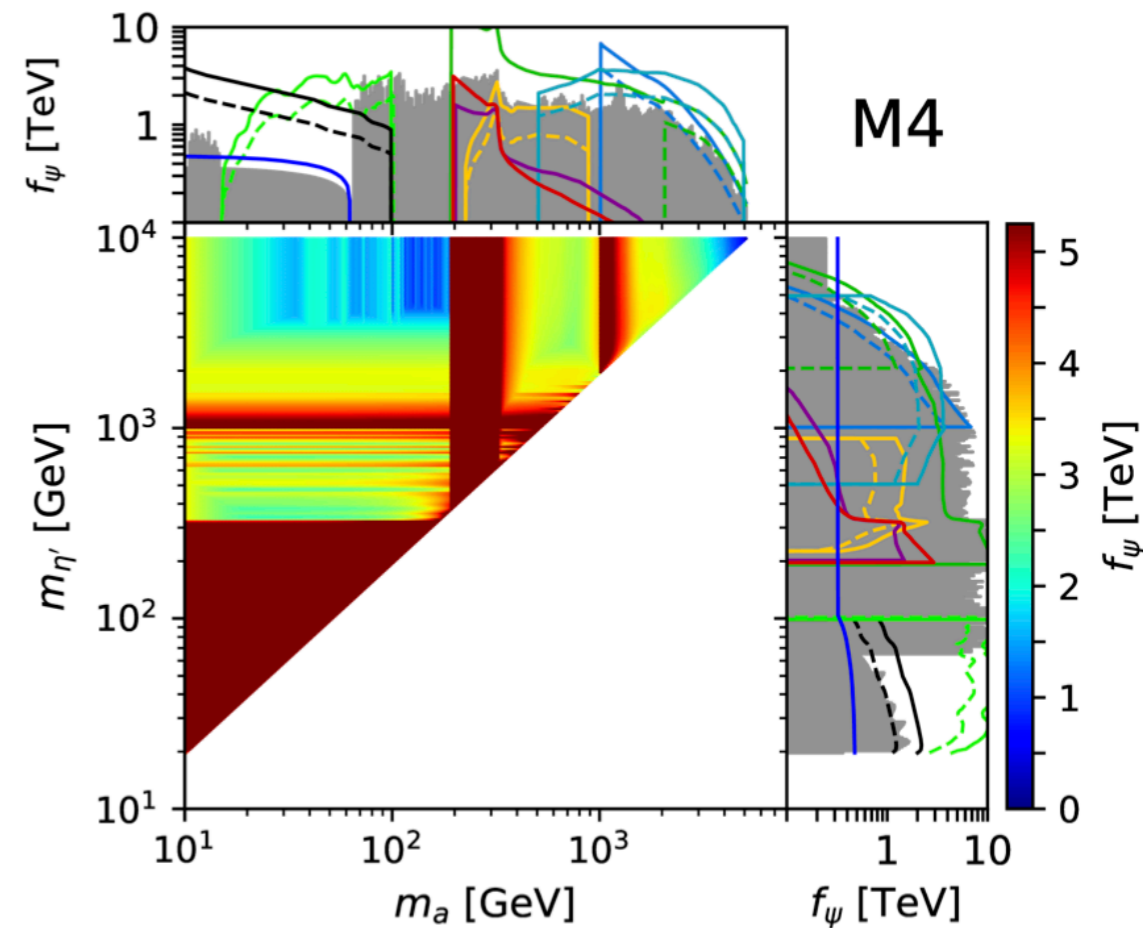
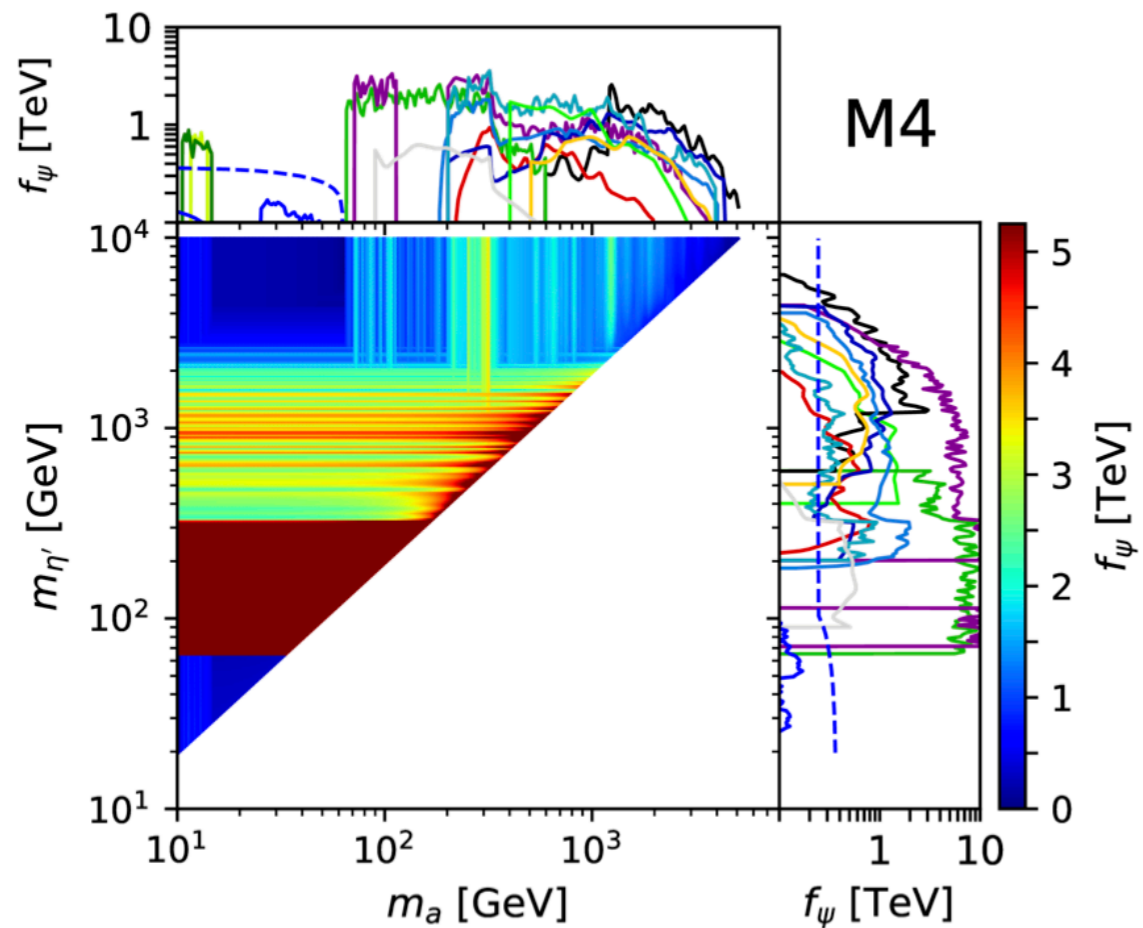
FIG. 7. Representative Branching Ratios of  $a$  in the decoupling limit for all models and for the six choices of top partner charges. We only show  $gg$  (light and dark green),  $\gamma\gamma$  (brown and red) and  $\tau\tau$  (purple and lilac).

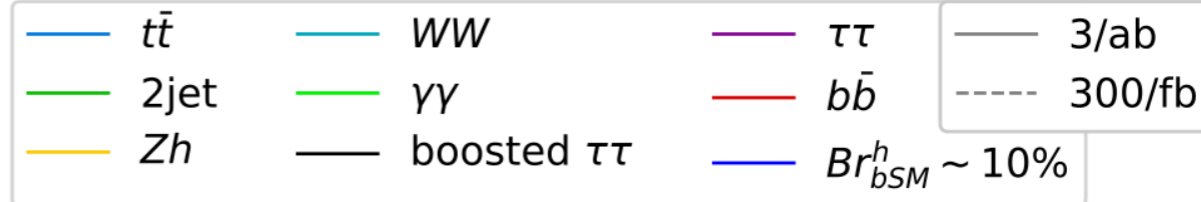
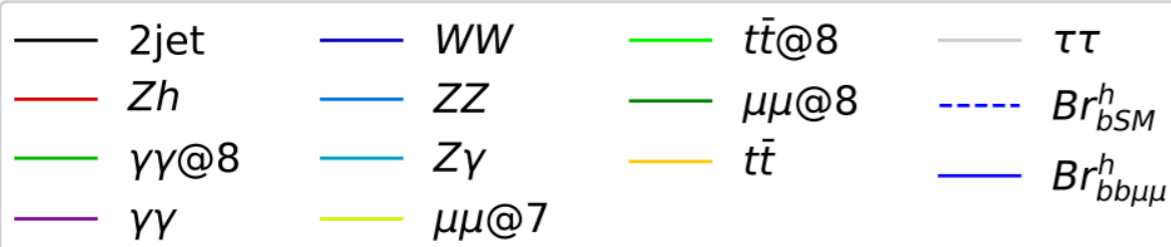
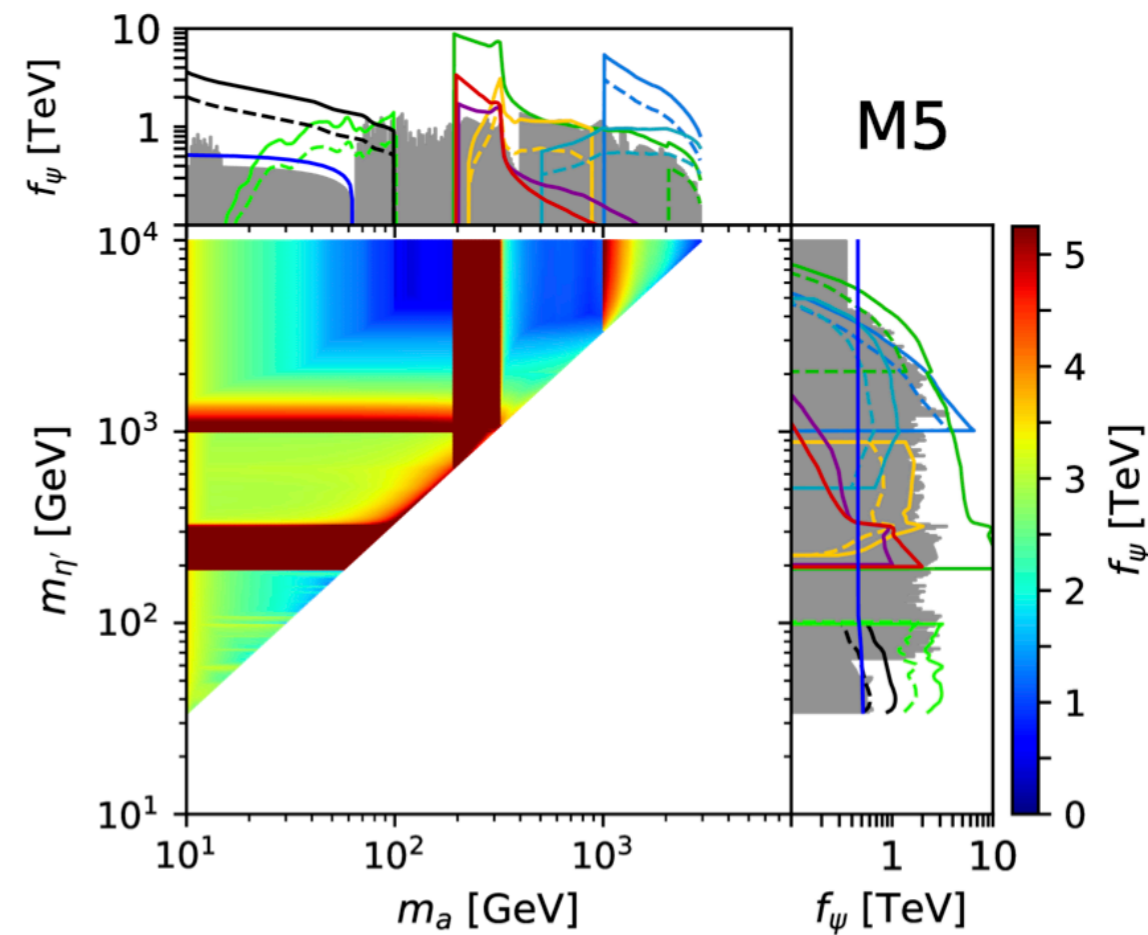
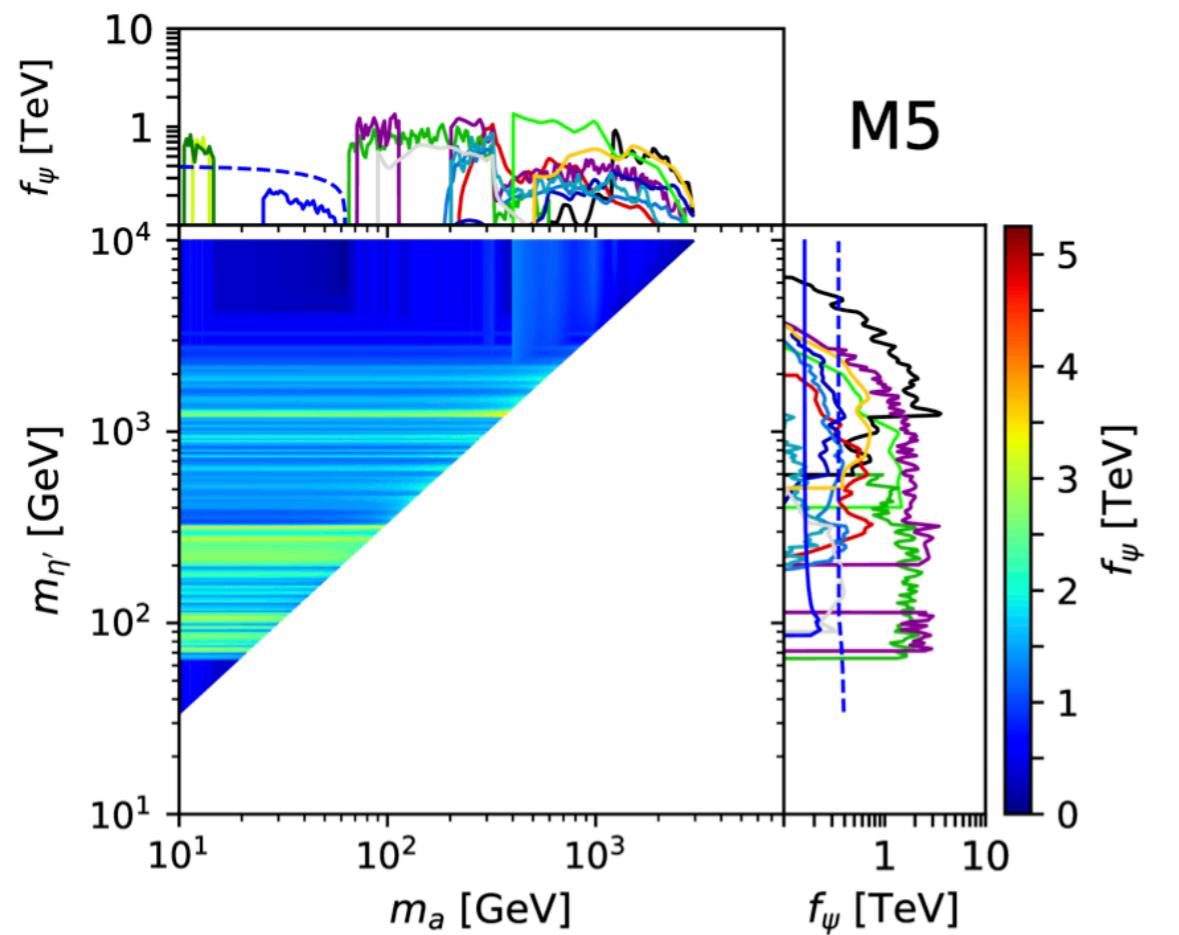


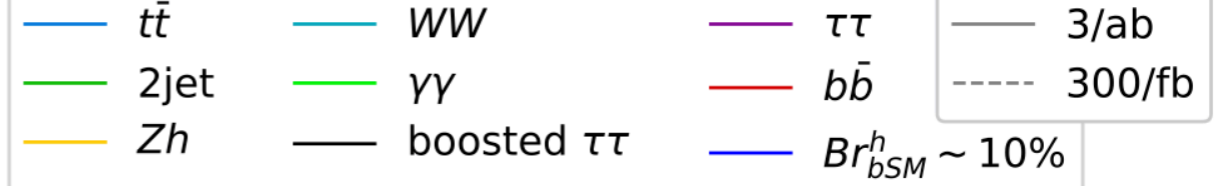
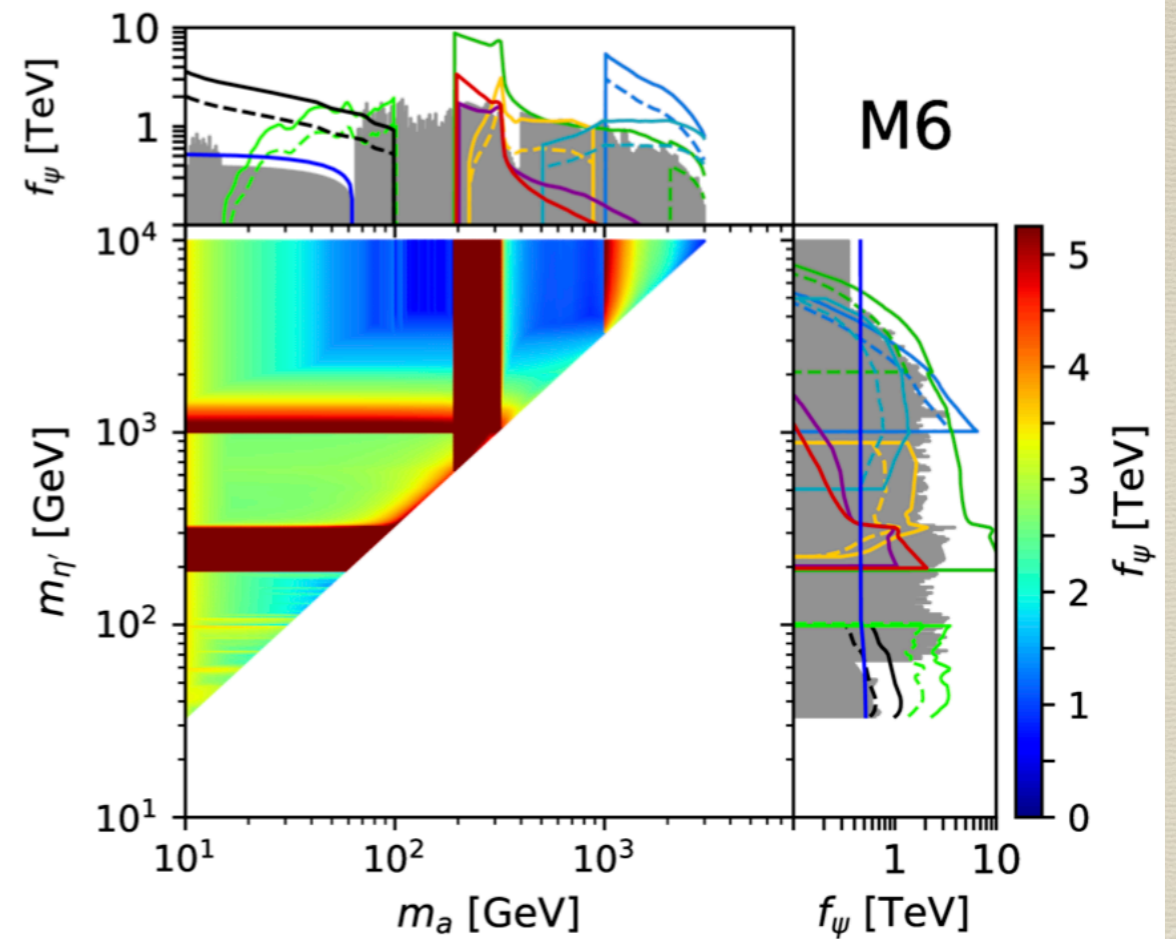
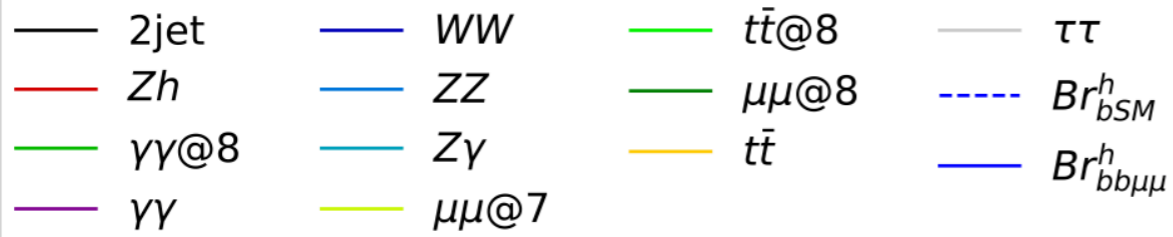
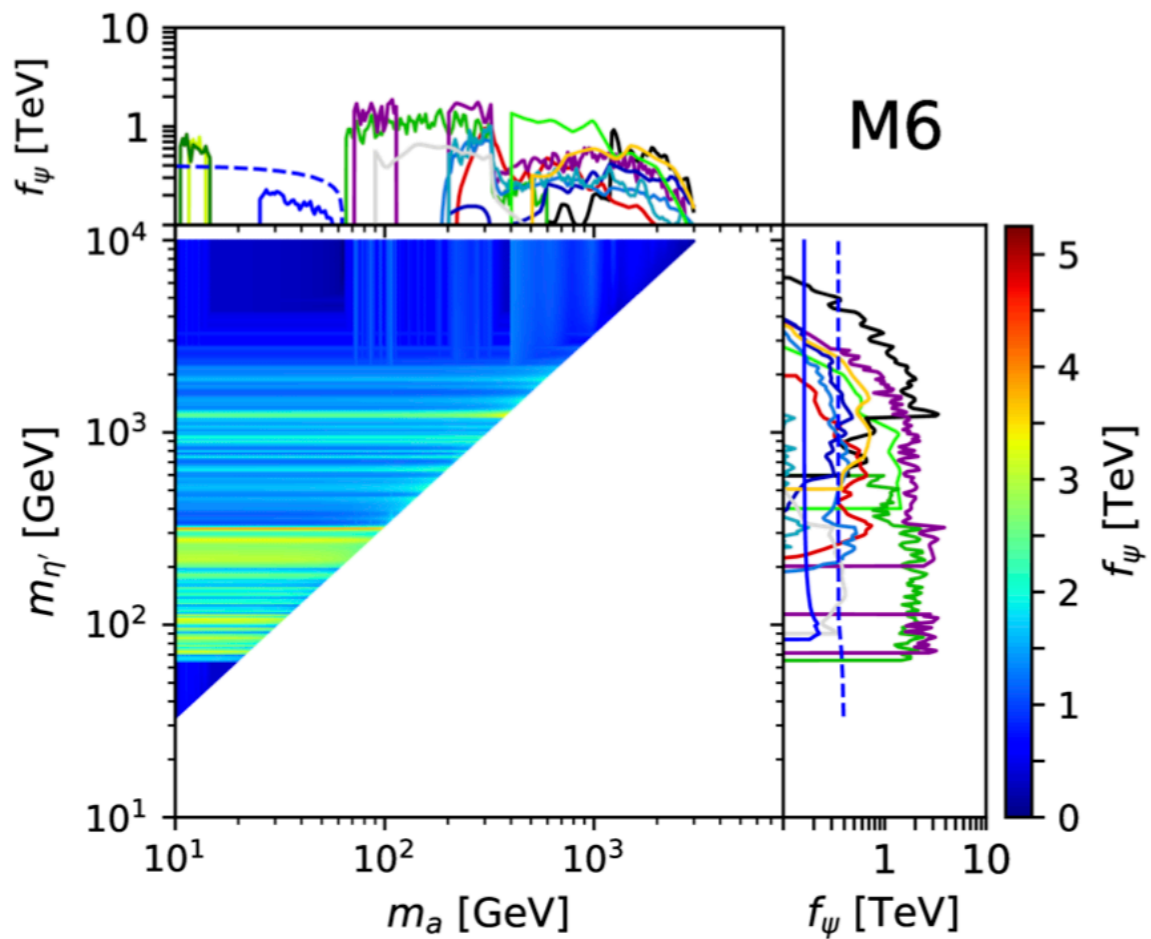


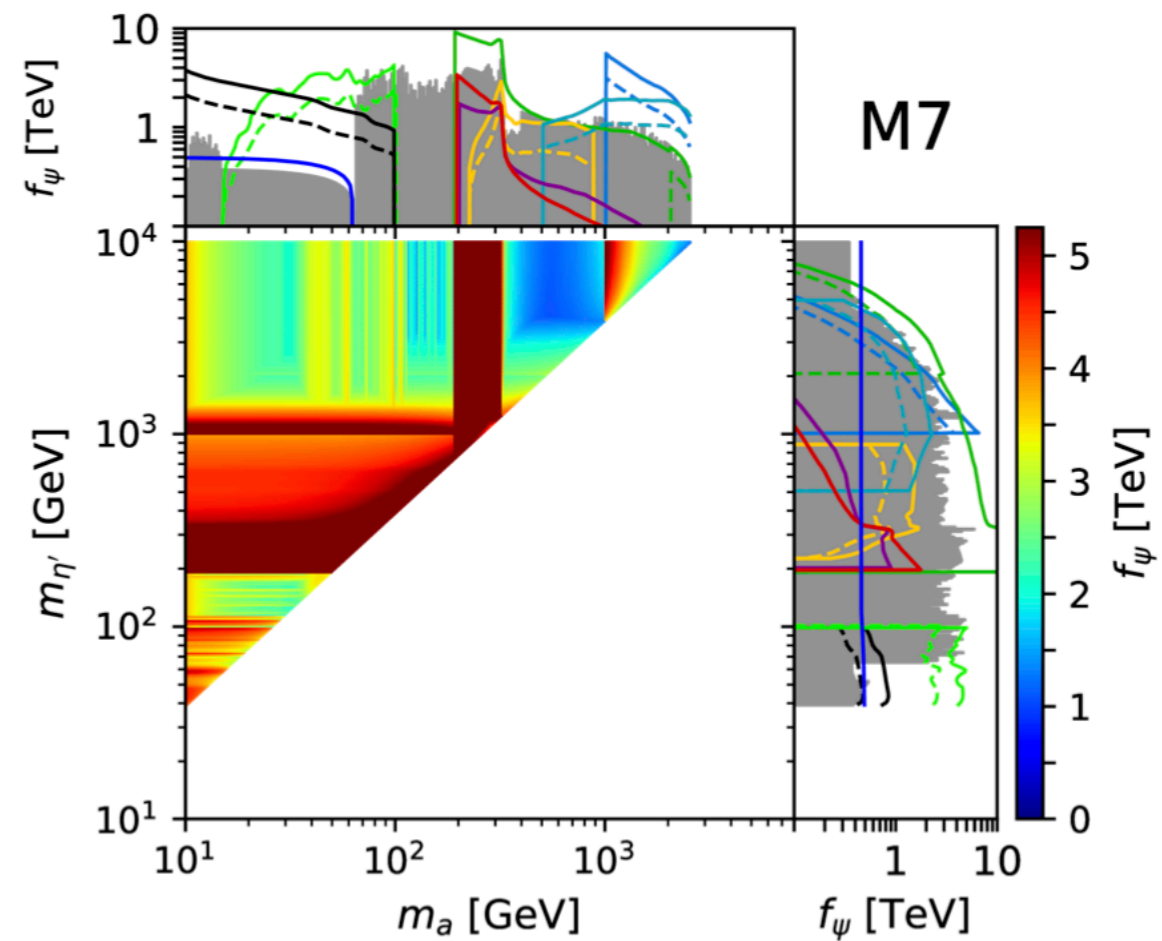
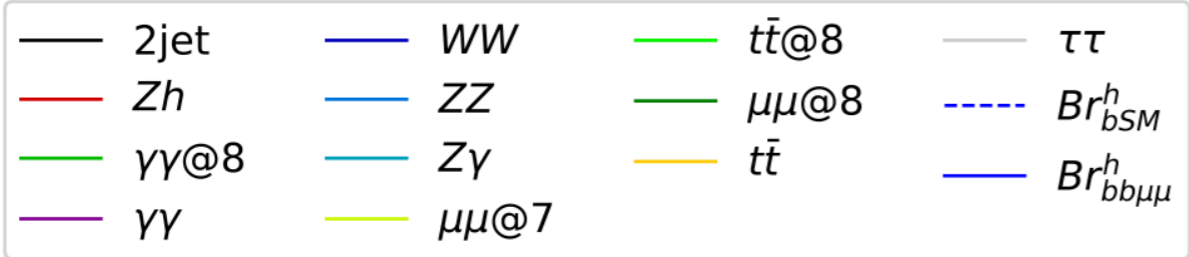
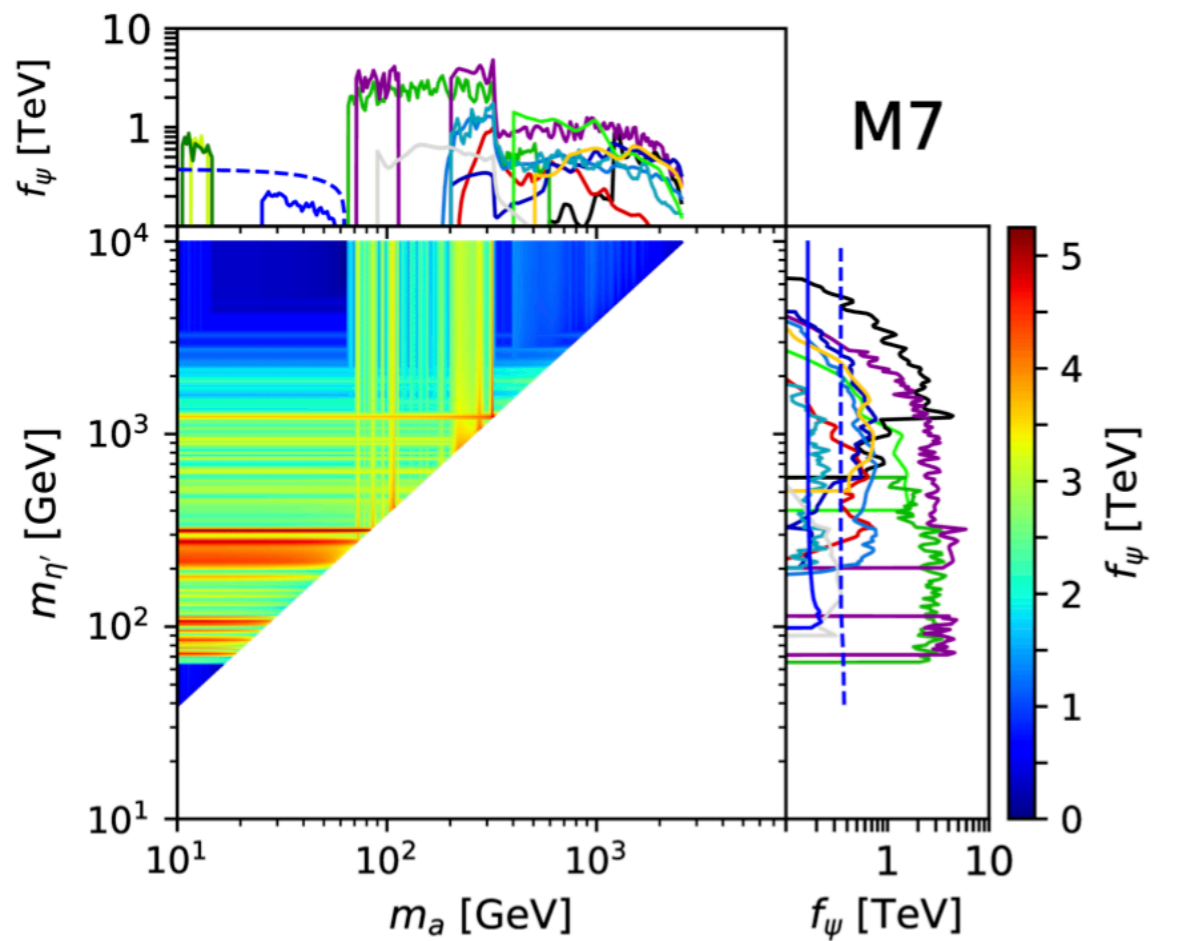


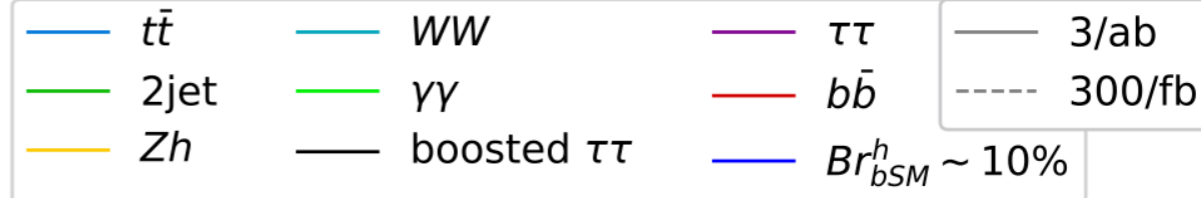
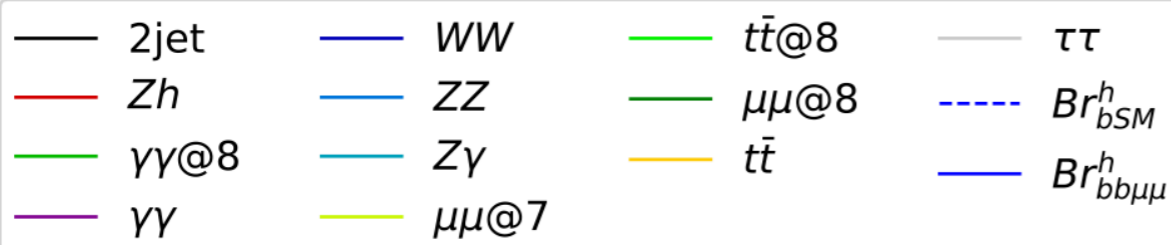
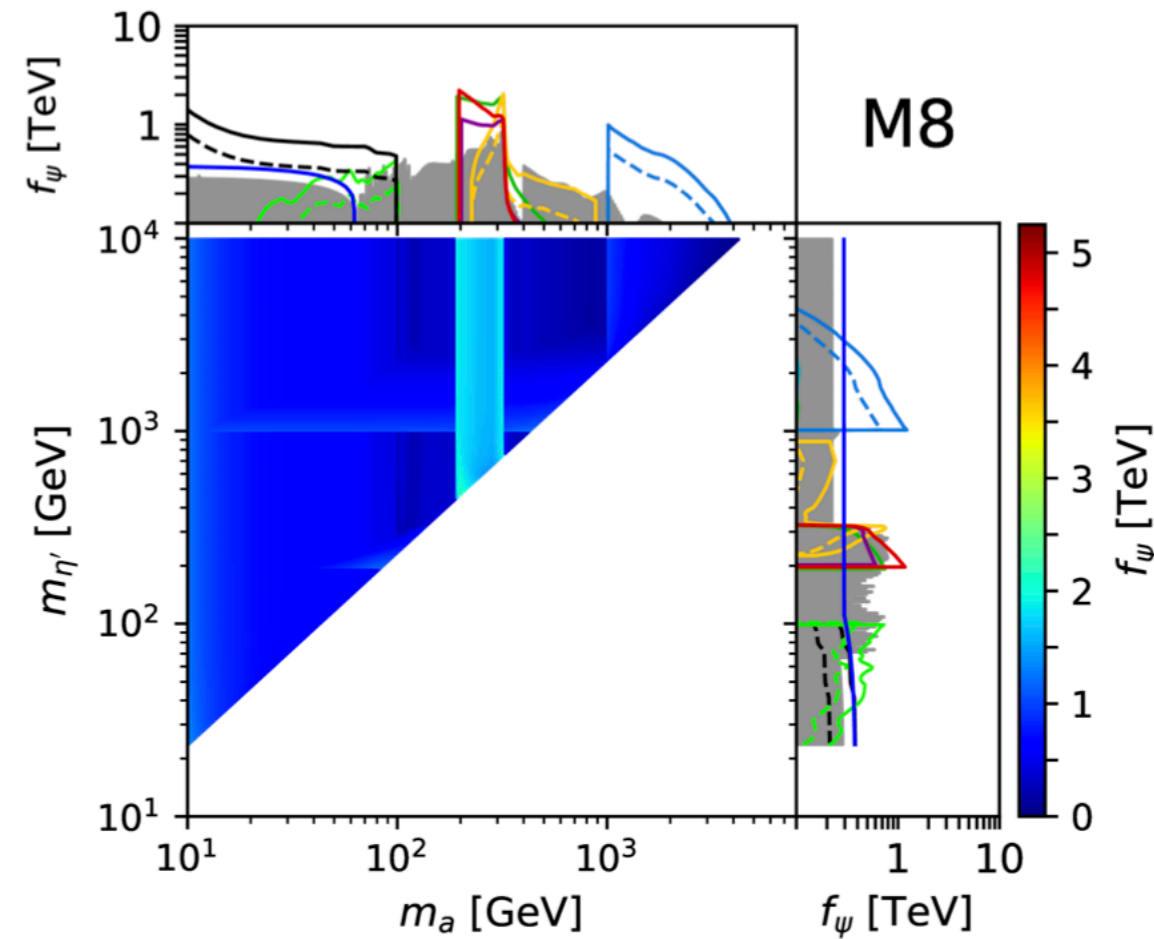
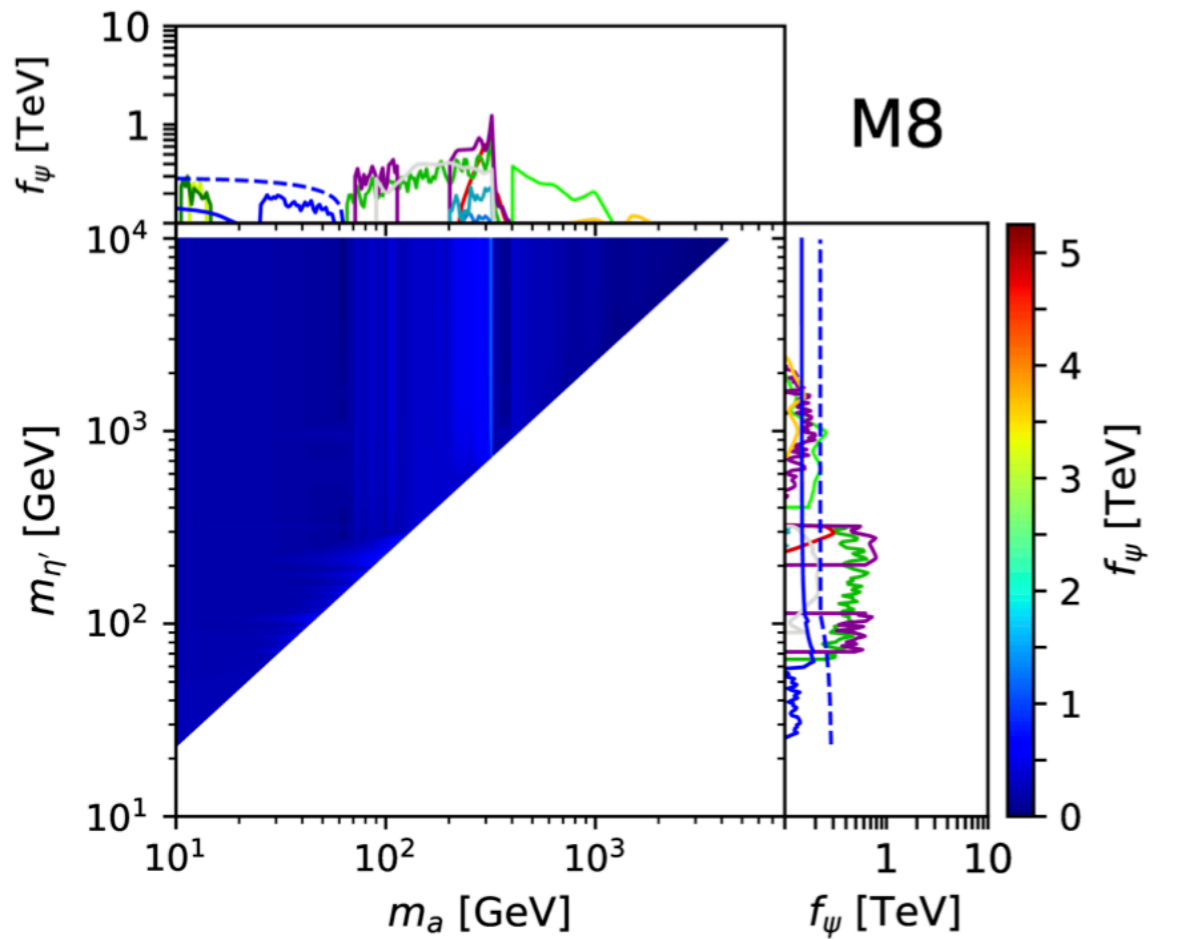




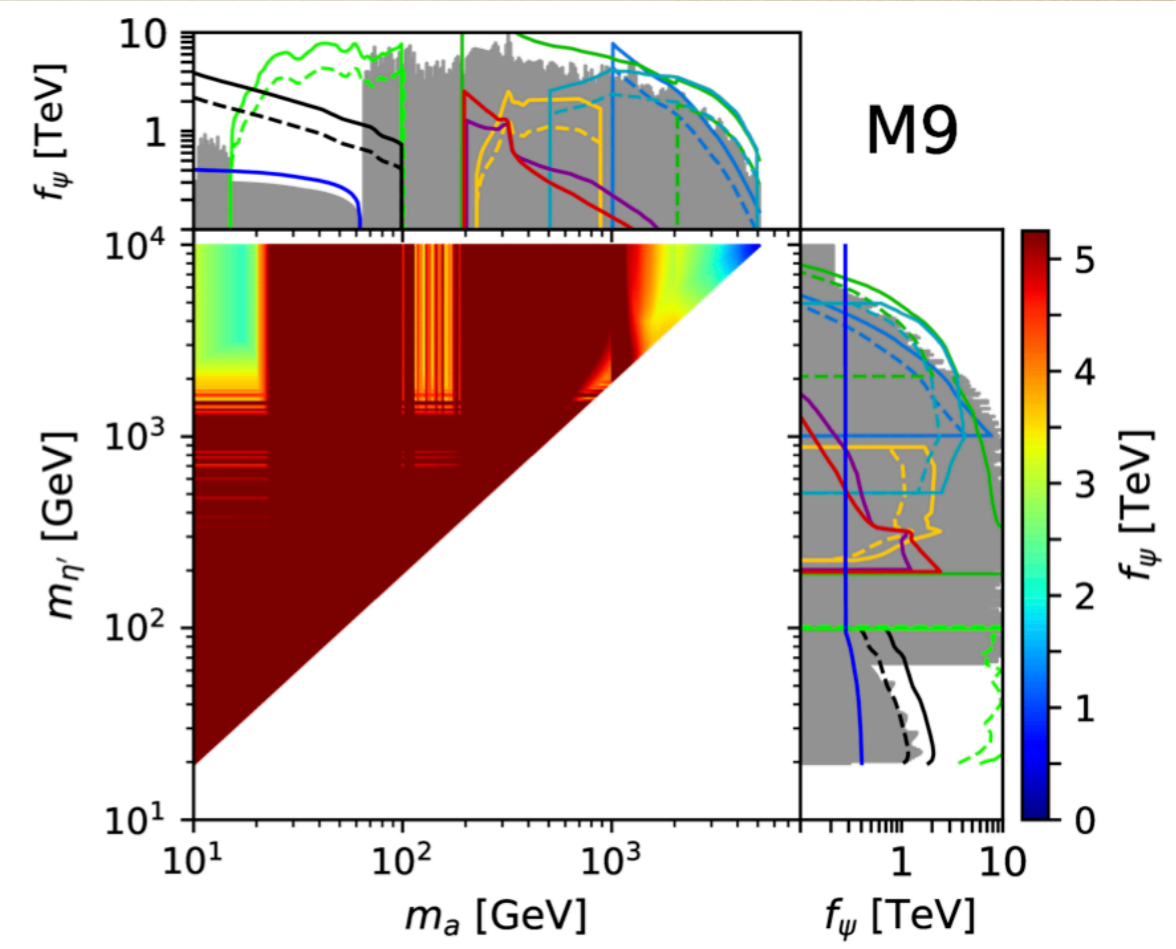
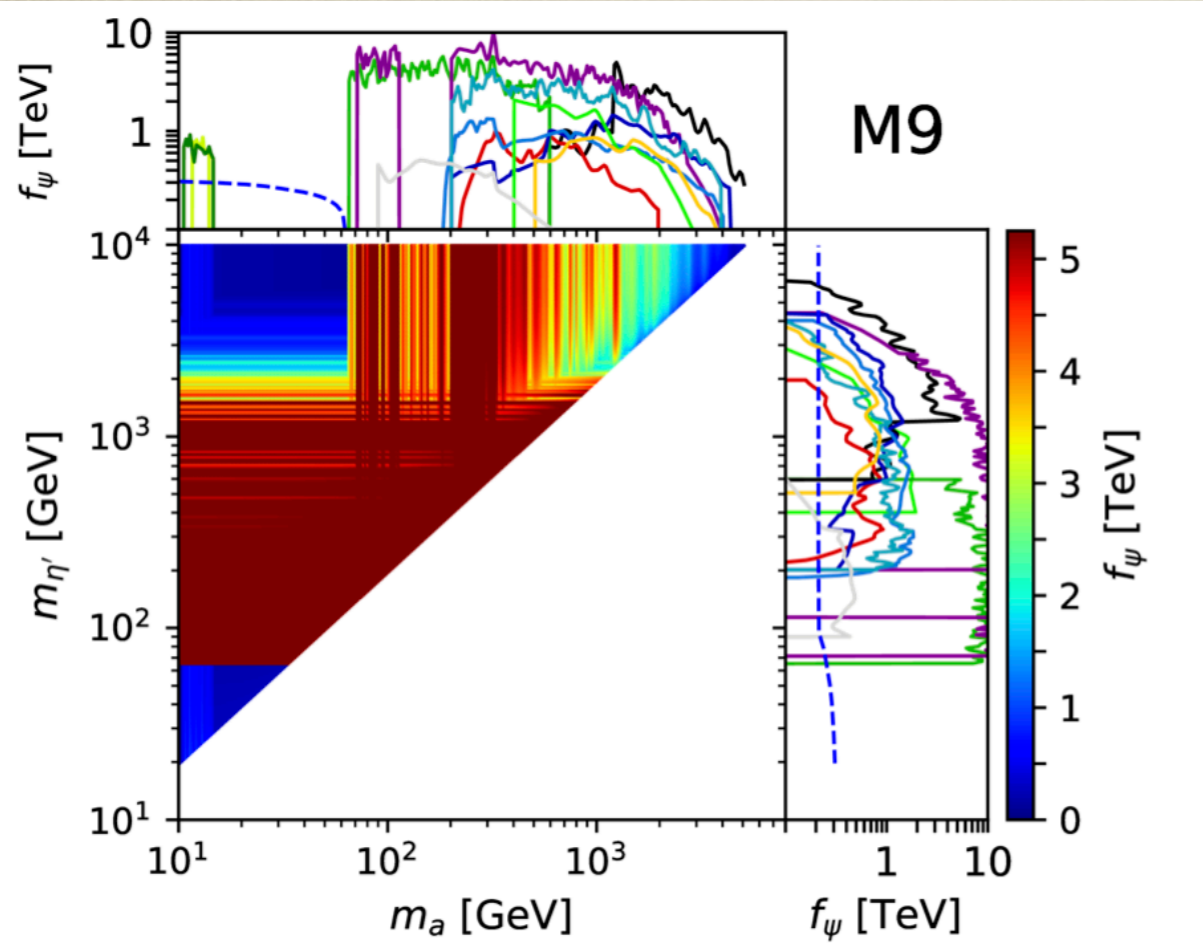






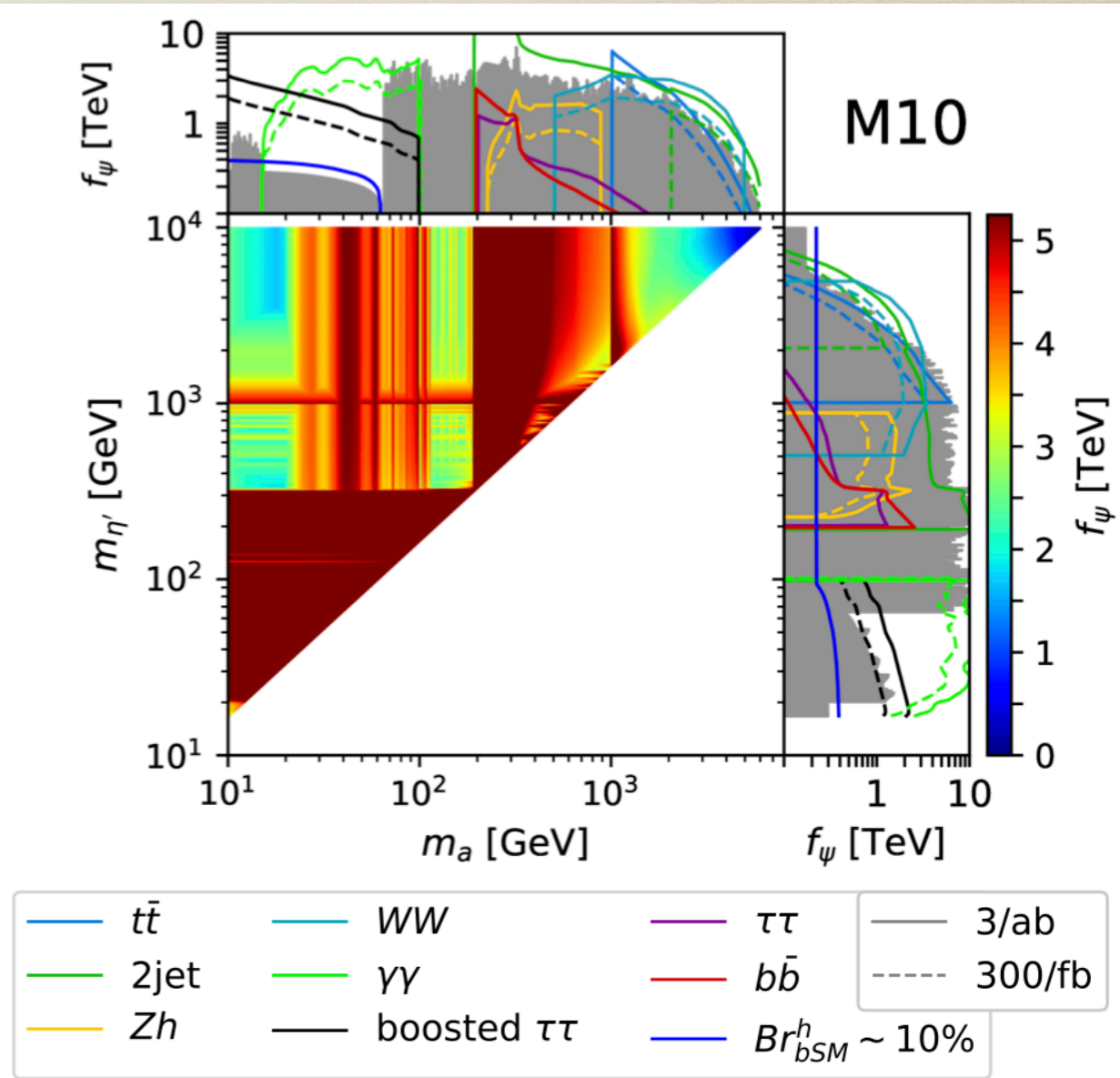
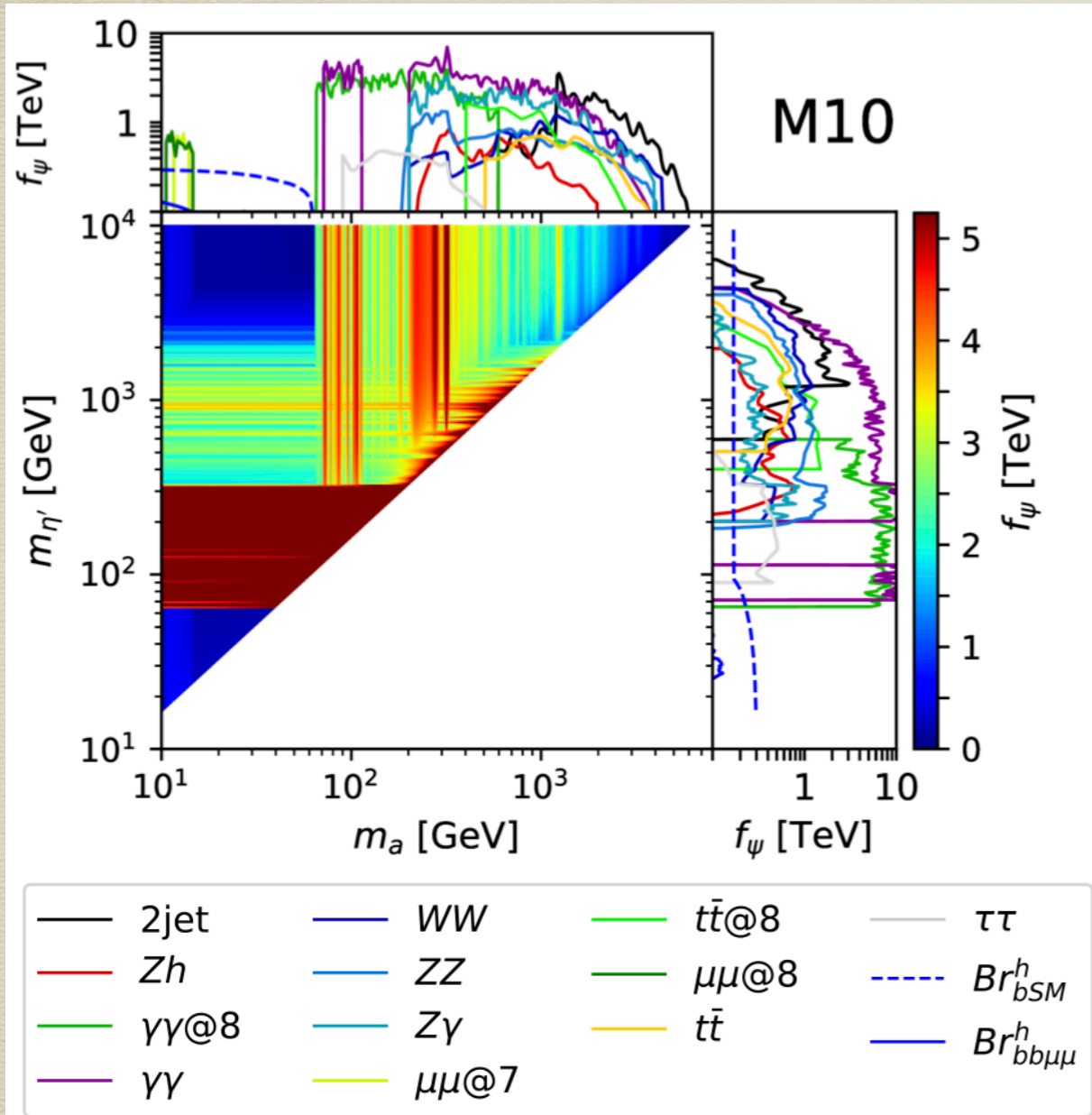


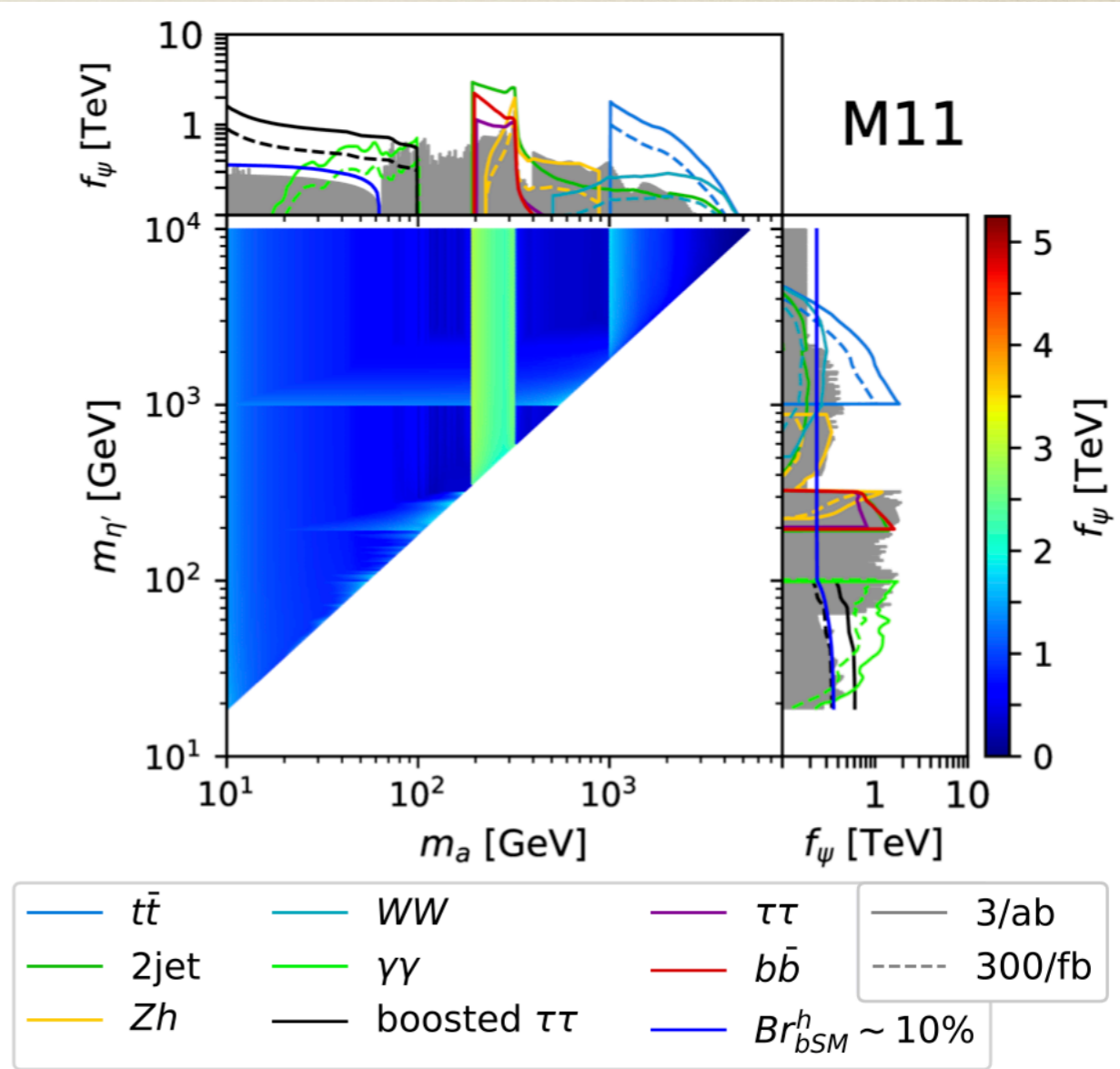
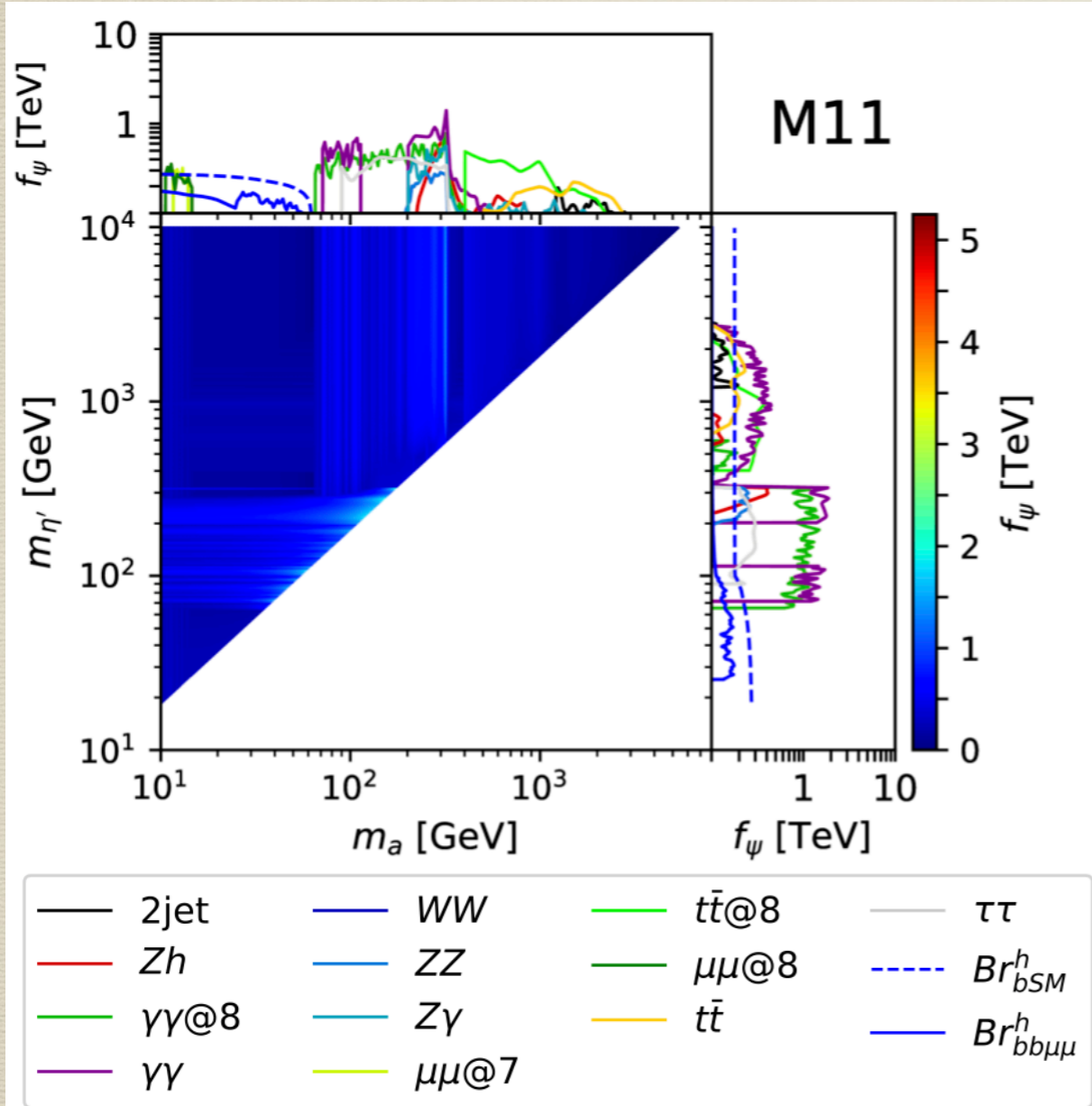


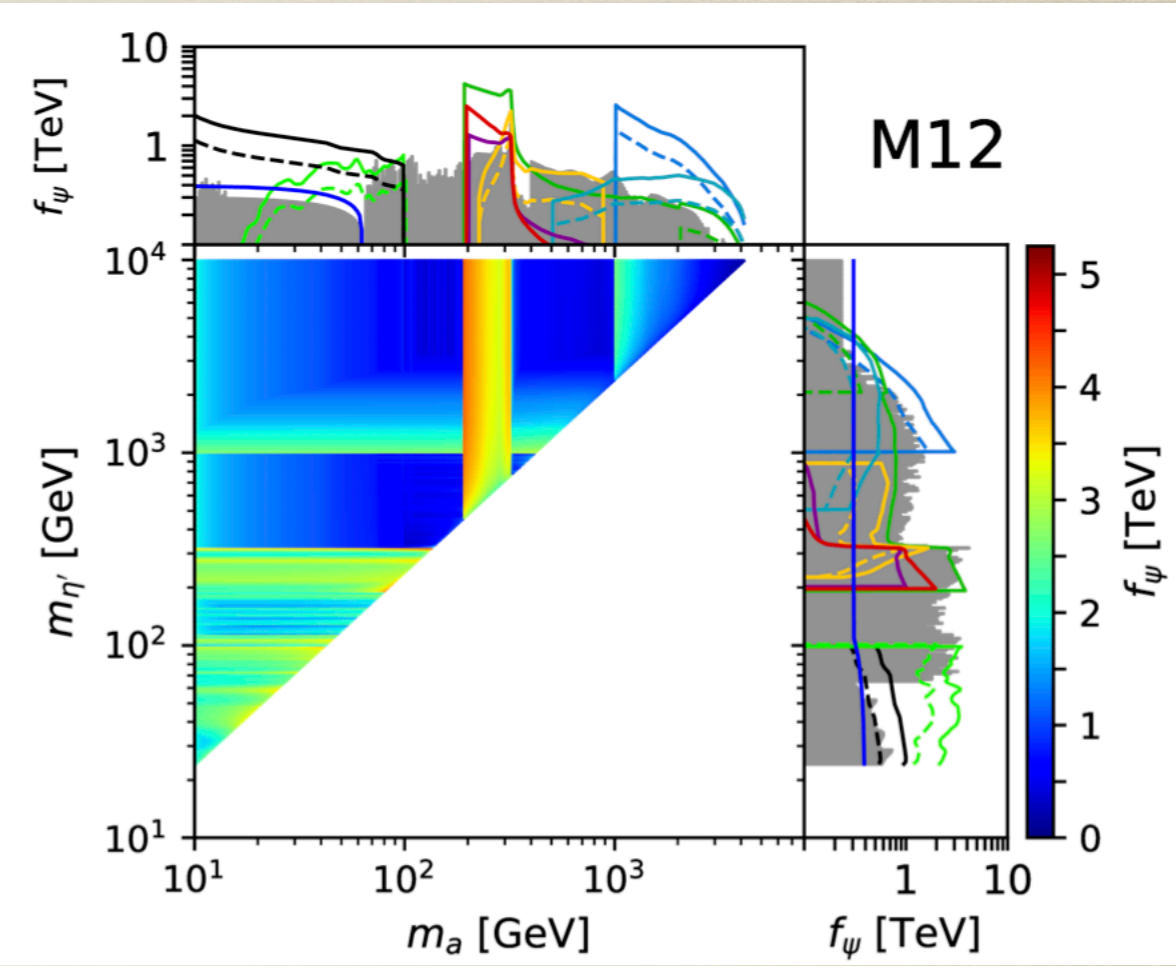
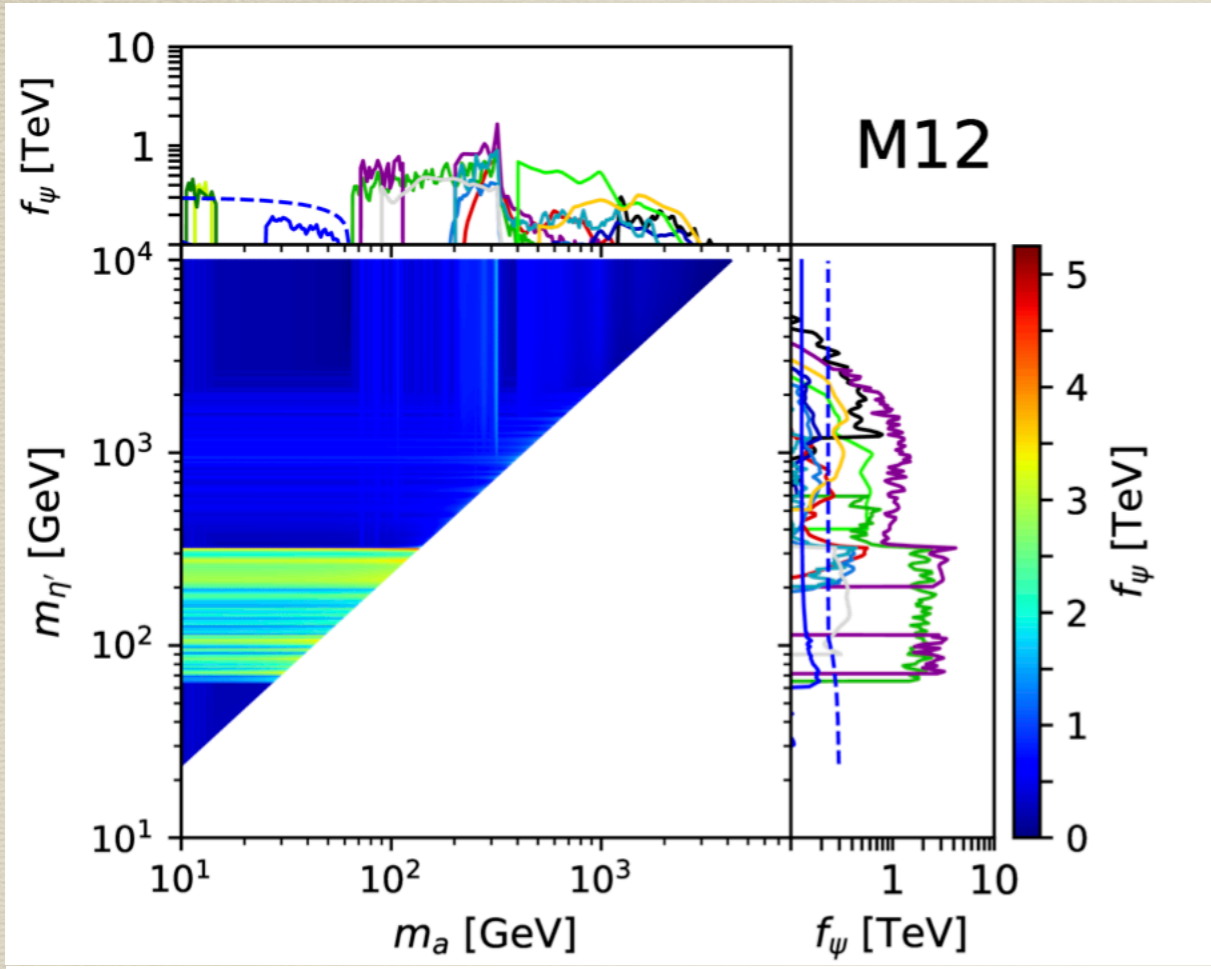


- |                    |              |                |                     |
|--------------------|--------------|----------------|---------------------|
| — 2jet             | — WW         | — $t\bar{t}@8$ | — $\tau\tau$        |
| — Zh               | — ZZ         | — $\mu\mu@8$   | - - - $Br_{bSM}^h$  |
| — $\gamma\gamma@8$ | — $Z\gamma$  | — $t\bar{t}$   | — $Br_{bb\mu\mu}^h$ |
| — $\gamma\gamma$   | — $\mu\mu@7$ |                |                     |

- |              |                      |                          |              |
|--------------|----------------------|--------------------------|--------------|
| — $t\bar{t}$ | — WW                 | — $\tau\tau$             | — 3/ab       |
| — 2jet       | — $\gamma\gamma$     | — $b\bar{b}$             | - - - 300/fb |
| — Zh         | — boosted $\tau\tau$ | — $Br_{bSM}^h \sim 10\%$ |              |



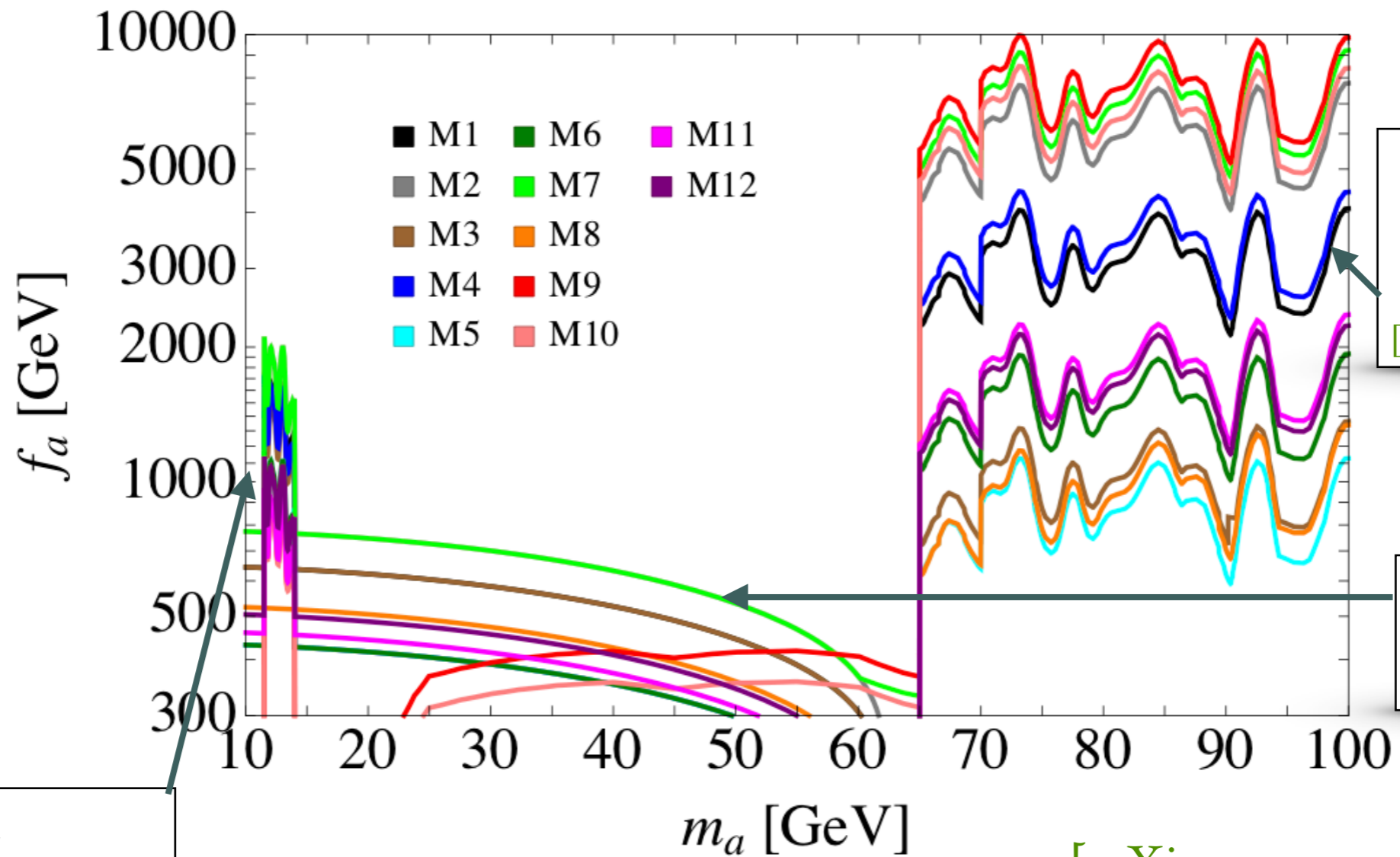




- |                    |              |                |                     |
|--------------------|--------------|----------------|---------------------|
| — 2jet             | — WW         | — $t\bar{t}@8$ | — $\tau\tau$        |
| — Zh               | — ZZ         | — $\mu\mu@8$   | - - - $Br_{bSM}^h$  |
| — $\gamma\gamma@8$ | — Z $\gamma$ | — $t\bar{t}$   | — $Br_{bb\mu\mu}^h$ |
| — $\gamma\gamma$   | — $\mu\mu@7$ |                |                     |

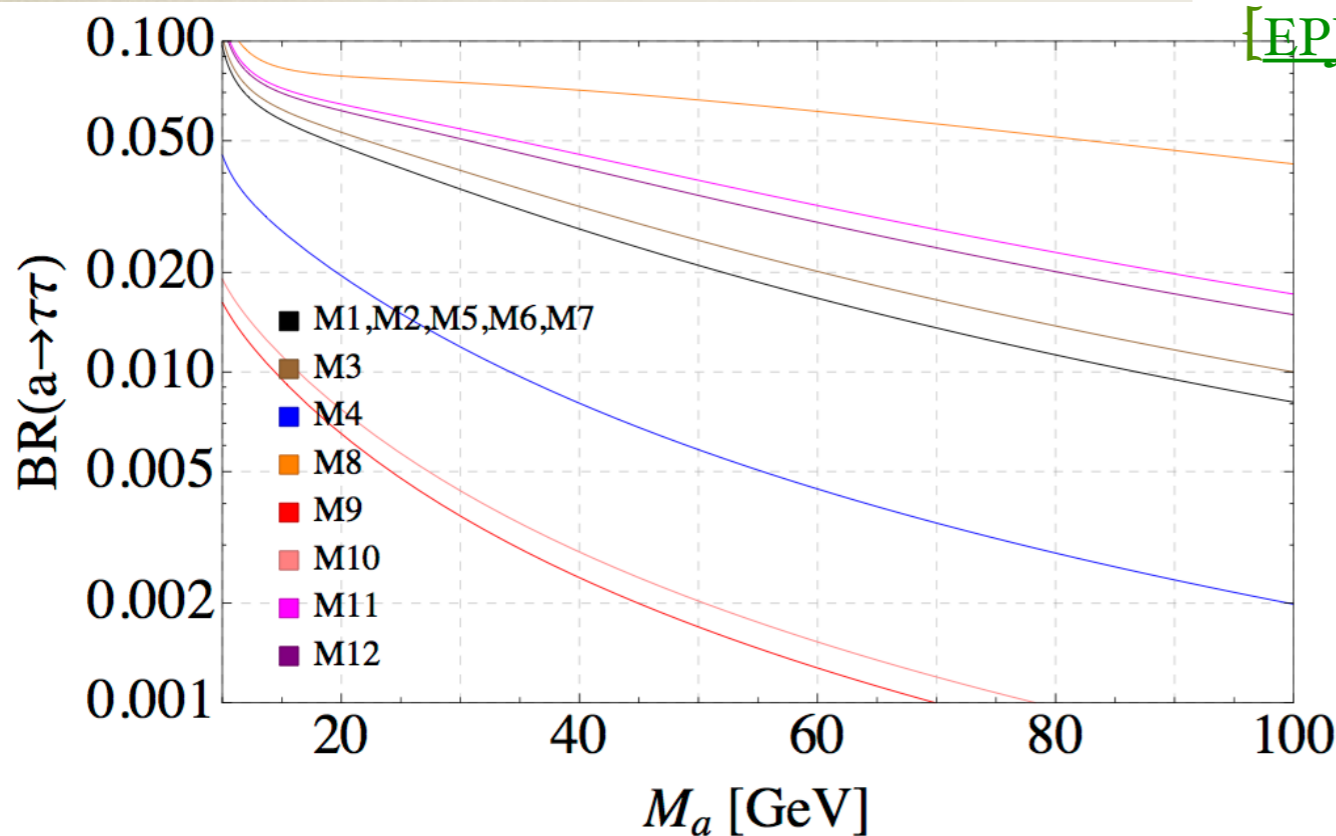
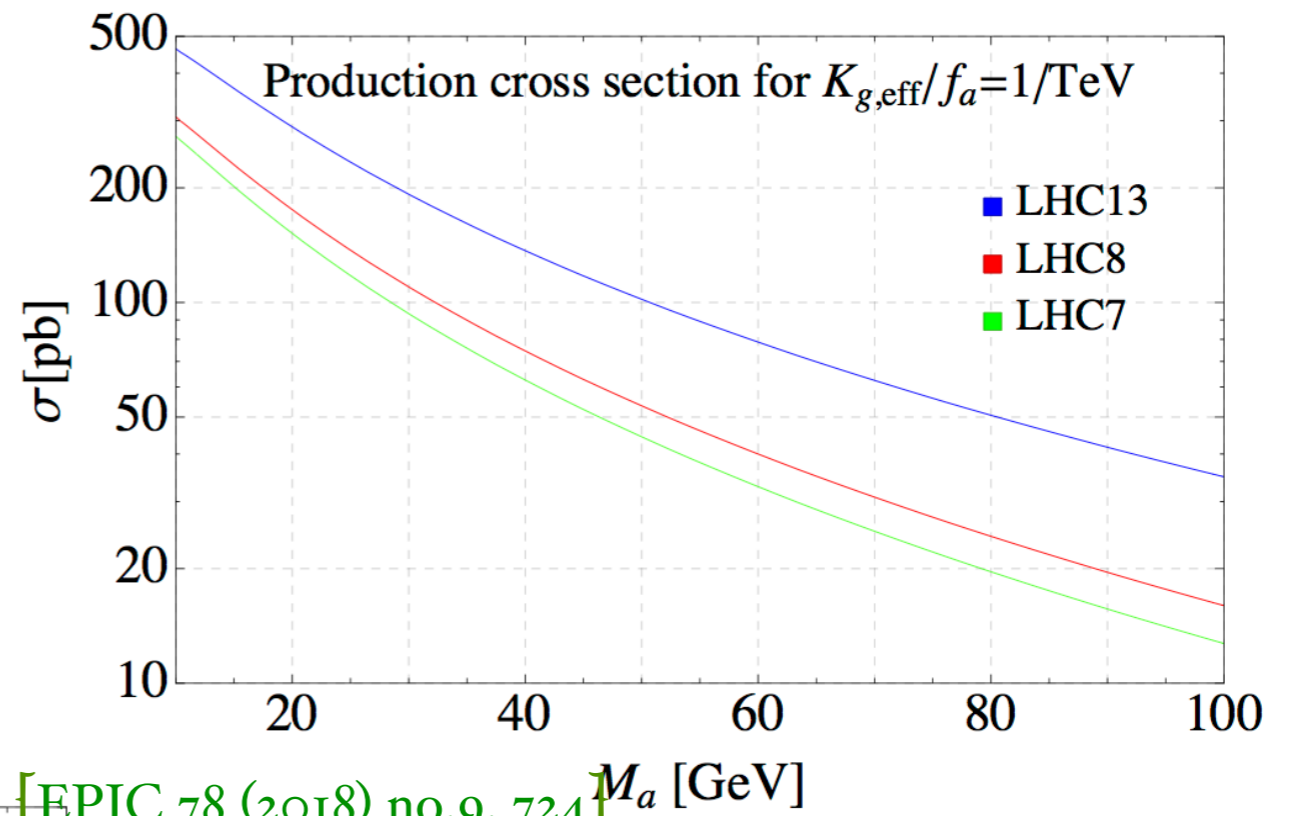
- |              |                      |                          |              |
|--------------|----------------------|--------------------------|--------------|
| — $t\bar{t}$ | — WW                 | — $\tau\tau$             | — 3/ab       |
| — 2jet       | — $\gamma\gamma$     | — $b\bar{b}$             | - - - 300/fb |
| — Zh         | — boosted $\tau\tau$ | — $Br_{bSM}^h \sim 10\%$ |              |

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



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

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



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

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

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

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
- $\Delta R_{\mu j} > 0.5, \Delta R_{ej} > 0.5,$
- $\Delta R_{\mu e} < 1.0$
- no lower cut on  $\Delta R_{\mu e}$  !
- $m_{\mu e} > 100$  GeV

Main background:

$Z/\gamma^* + \text{jets}$ : 35 fb,

$t\bar{t} + \text{jets}$ : 70 fb,  $Wt + \text{jets}$ :

7.4 fb,  $VV + \text{jets}$ : 13 fb.

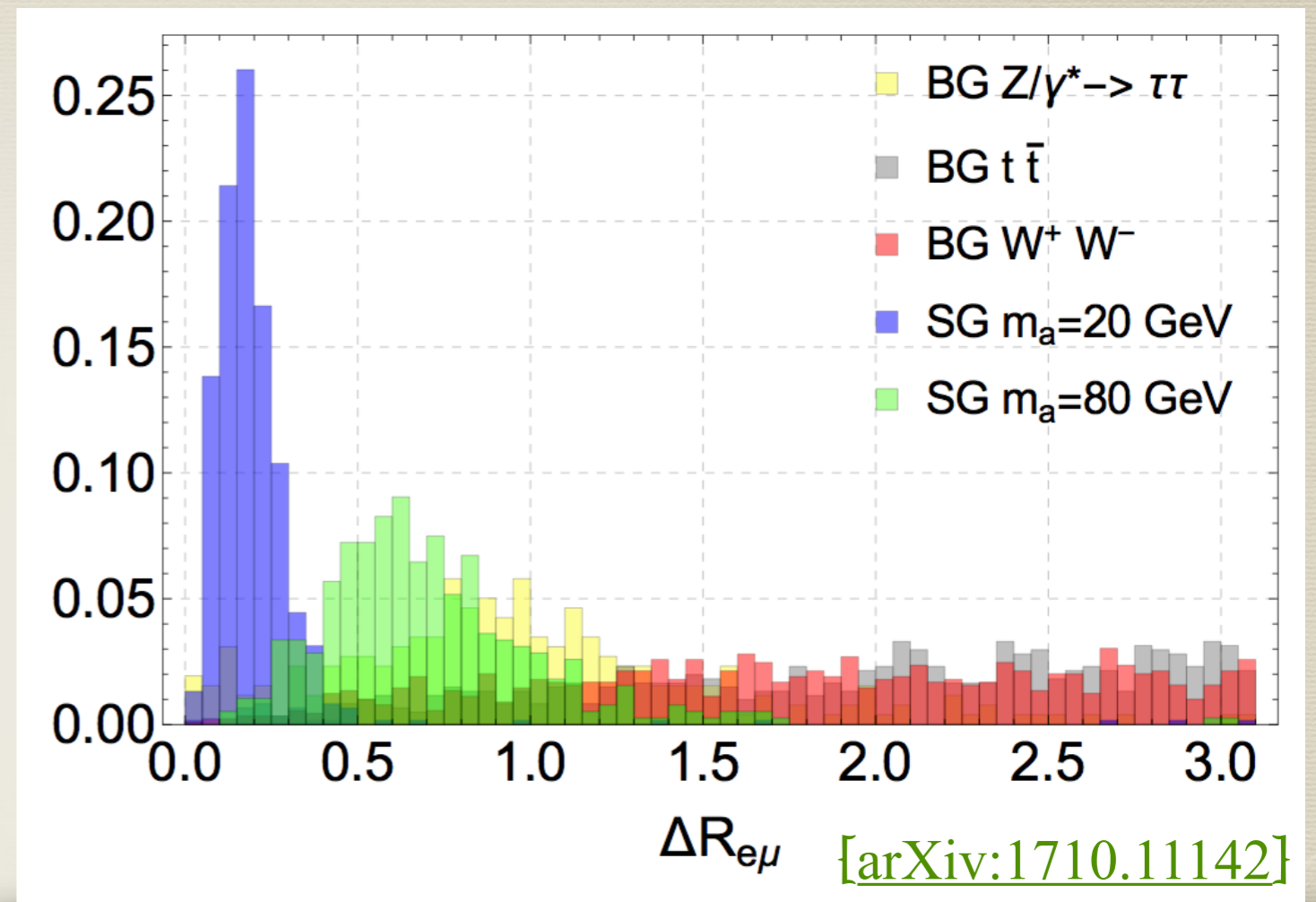
$m_a$	10	20	30	40	50	60	70	80	90	100
M1	30.	14.	9.3	6.6	5.3	3.7	3.0	2.3	1.7	1.4
M2	44.	20.	13.	9.5	7.7	5.4	4.4	3.2	2.4	2.0
M3	26.	12.	8.4	6.1	5.0	3.6	2.9	2.2	1.6	1.4
M4	28.	11.	6.1	3.8	2.9	1.9	1.5	1.1	0.80	0.67
M5	14.	6.3	4.2	3.0	2.4	1.7	1.4	1.0	0.74	0.63
M6	14.	6.3	4.2	3.0	2.4	1.7	1.4	1.0	0.74	0.63
M7	44.	20.	13.	9.5	7.7	5.4	4.4	3.2	2.4	2.0
M8	4.0	2.1	1.8	1.6	1.6	1.3	1.2	0.96	0.76	0.69
M9	8.3	3.1	1.6	0.95	0.70	0.47	0.36	0.26	0.19	0.16
M10	8.1	3.0	1.6	0.95	0.70	0.46	0.36	0.26	0.19	0.16
M11	9.4	4.7	3.5	2.8	2.4	1.8	1.5	1.2	0.87	0.74
M12	13.	6.4	4.7	3.6	3.1	2.3	1.9	1.4	1.1	0.92

TABLE II: The values of  $\sigma_{\text{prod.}} \times BR_{\tau\tau} \times \epsilon$  in fb for  $f_a = 1$  TeV and  $m_a = 10 \dots 100$  GeV for each of the models defined in Table I.

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

Note: This first proof of principle study is highly non-optimized.

- Cutting harder on  $\Delta R_{\mu e}$  can substantially increase background suppression for the lighter mass range.
- We did not use any  $\tau$  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.]





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

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

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:

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- $\Delta R_{\mu j} > 0.5, \Delta R_{ej} > 0.5,$
- $\Delta R_{\mu e} < 1.0$
- no lower cut on  $\Delta R_{\mu e}$  !
- $m_{\mu e} > 100$  GeV

Main background:

$Z/\gamma^* + \text{jets}$ : 35 fb,

$t\bar{t} + \text{jets}$ : 70 fb,  $Wt + \text{jets}$ :

7.4 fb,  $VV + \text{jets}$ : 13 fb.

$m_a$	10	20	30	40	50	60	70	80	90	100
M1	30.	14.	9.3	6.6	5.3	3.7	3.0	2.3	1.7	1.4
M2	44.	20.	13.	9.5	7.7	5.4	4.4	3.2	2.4	2.0
M3	26.	12.	8.4	6.1	5.0	3.6	2.9	2.2	1.6	1.4
M4	28.	11.	6.1	3.8	2.9	1.9	1.5	1.1	0.80	0.67
M5	14.	6.3	4.2	3.0	2.4	1.7	1.4	1.0	0.74	0.63
M6	14.	6.3	4.2	3.0	2.4	1.7	1.4	1.0	0.74	0.63
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M8	4.0	2.1	1.8	1.6	1.6	1.3	1.2	0.96	0.76	0.69
M9	8.3	3.1	1.6	0.95	0.70	0.47	0.36	0.26	0.19	0.16
M10	8.1	3.0	1.6	0.95	0.70	0.46	0.36	0.26	0.19	0.16
M11	9.4	4.7	3.5	2.8	2.4	1.8	1.5	1.2	0.87	0.74
M12	13.	6.4	4.7	3.6	3.1	2.3	1.9	1.4	1.1	0.92

TABLE II: The values of  $\sigma_{\text{prod.}} \times BR_{\tau\tau} \times \epsilon$  in fb for  $f_a = 1$  TeV and  $m_a = 10 \dots 100$  GeV for each of the models defined in Table I.

[EPJC 78 (2018) no.9, 724]

...are there other “common” top partner decays?

[JHEP 1806, 065]

- UV embeddings of composite Higgs models come with additional pNGBs, which are naturally lighter than the top-partners, so decays of top partners to top / bottom and a pNGB are kinematically possible.
- With an underlying model specified, we can relate top partner branching ratios to  $h/W/Z$  vs new pNGBs, as all relevant couplings arise from the Goldstone boson matrix.
- Scanning through the different underlying models we looked for “common exotic” top partner decays and found several scenarios.

# Relating top partner couplings to Higgs and other pNGBs

Example: [\[JHEP 1806, 065\]](#)

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).

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

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

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

Diagonalizing the mass matrix (and expanding in  $a$  and  $\eta$ ) yields couplings of top and top partners to the pNGB in terms of the pre-Yukawas  $y_{1,5}$ .

# Common exotic VLQ decays

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

Effective Lagrangian(s): [\[JHEP 1806, 065\]](#)

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

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

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

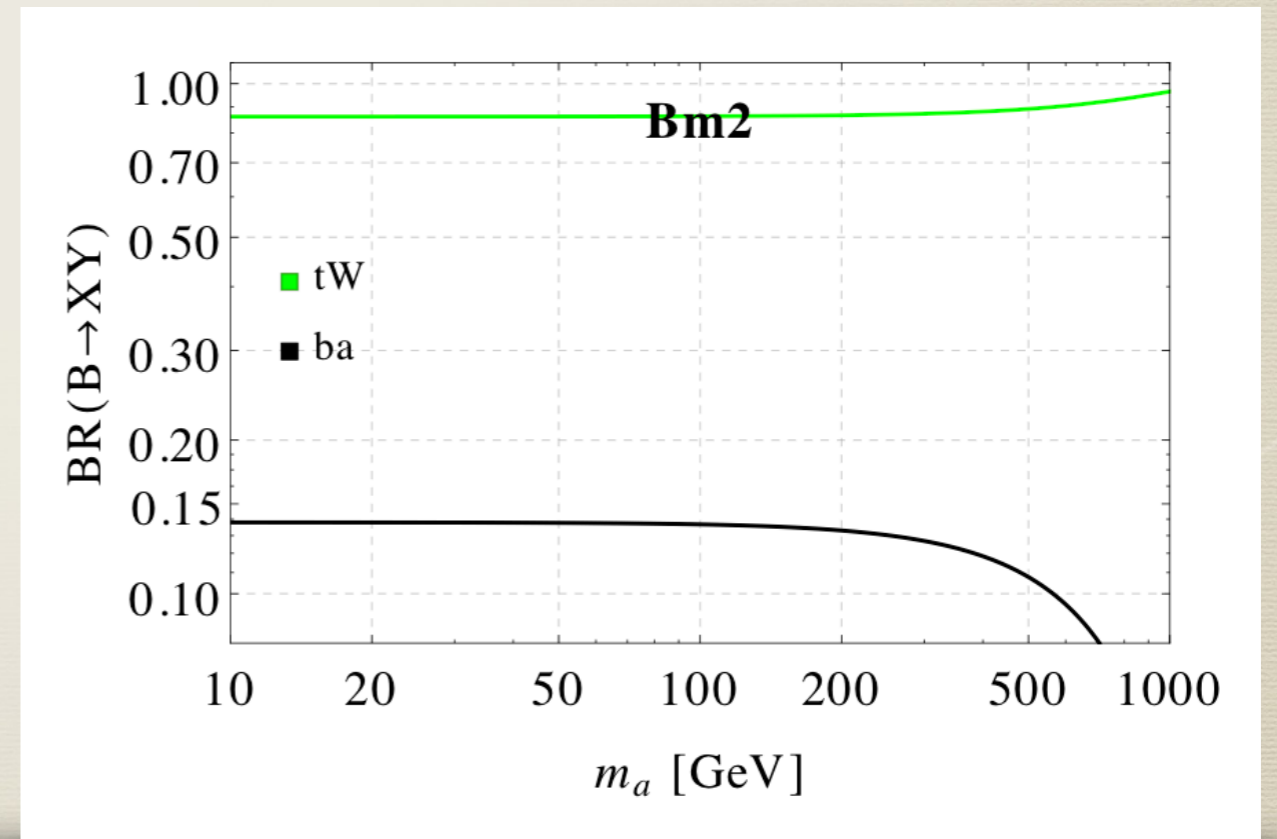
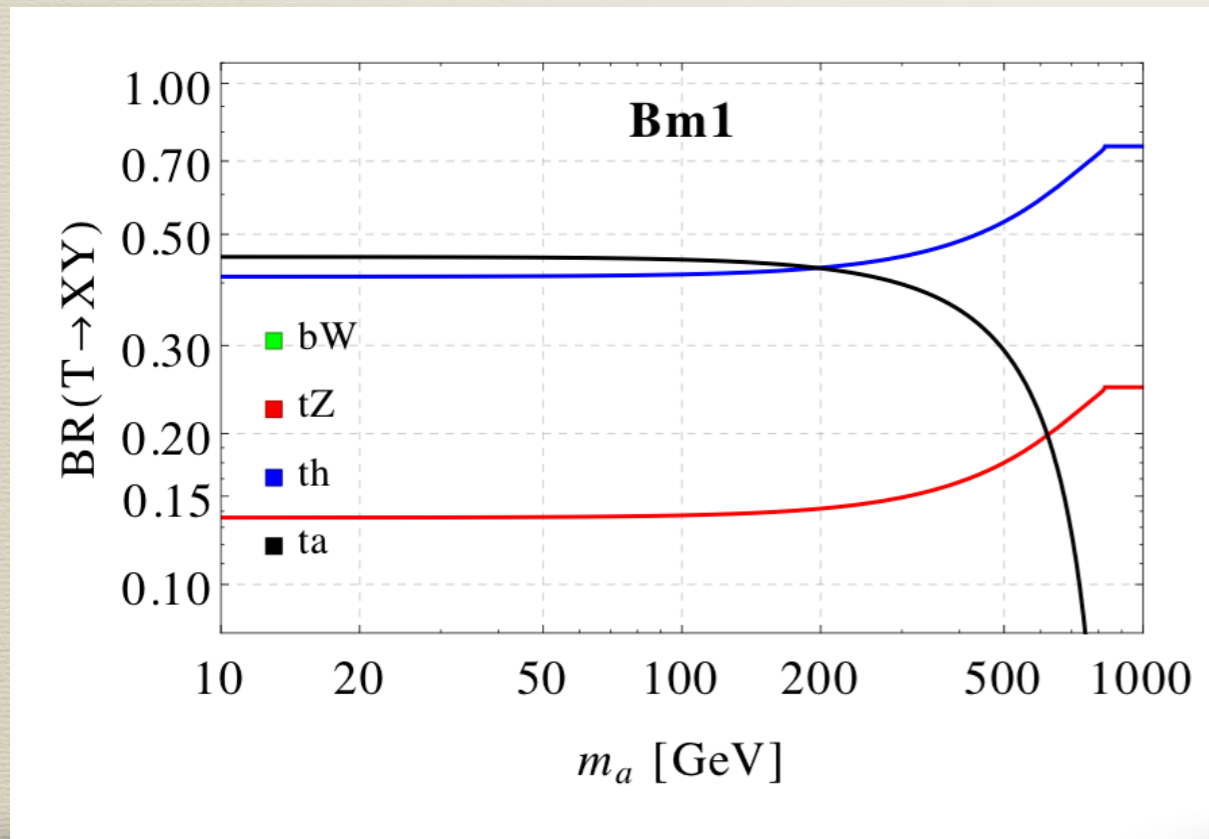
$$+ \frac{g_s^2 K_g a}{16\pi^2 f_a} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \frac{g^2 K_W a}{16\pi^2 f_a} W_{\mu\nu}^i \tilde{W}^{i\mu\nu} + \frac{g'^2 K_B a}{16\pi^2 f_a} B_{\mu\nu} \tilde{B}^{\mu\nu}$$

# Common exotic VLQ decays

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

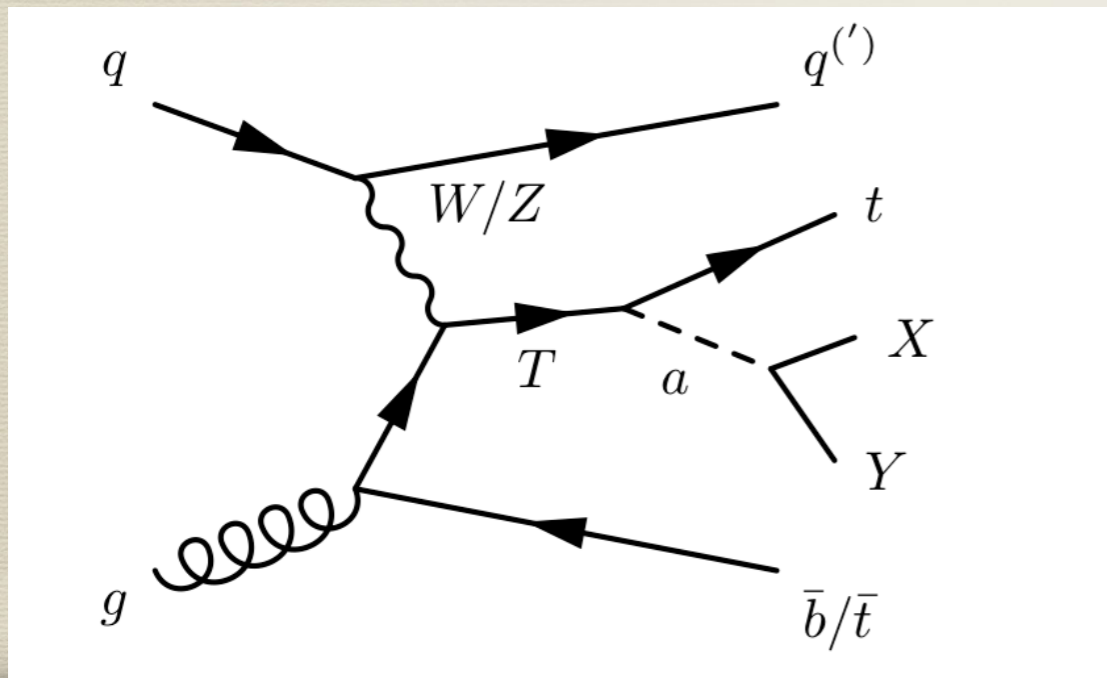
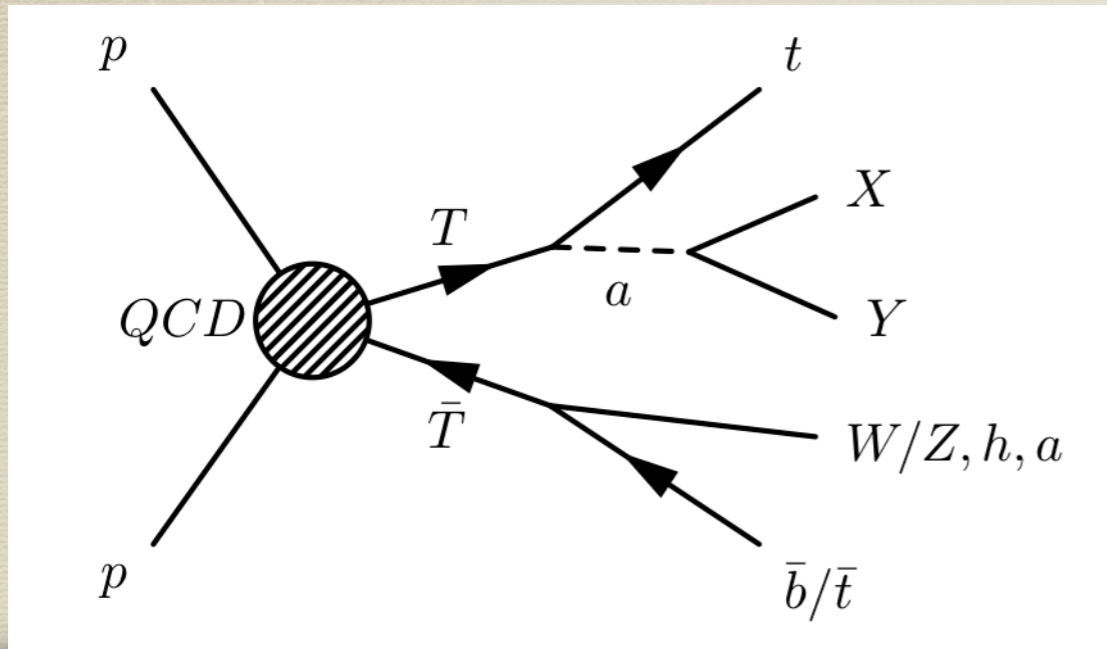
$$\begin{aligned} \text{Bm1 : } & M_T = 1 \text{ TeV , } \kappa_{Z,R}^T = -0.03 , \kappa_{h,R}^T = 0.06 , \kappa_{a,R}^T = -0.24 , \kappa_{a,L}^T = -0.07 ; \\ \text{Bm2 : } & M_B = 1.38 \text{ TeV , } \kappa_{W,L}^B = 0.02 , \kappa_{W,R}^B = -0.08 , \kappa_{a,L}^B = -0.25 , \end{aligned} \quad (2.3)$$

Branching ratios of quark partners to  $a$  in these benchmarks:

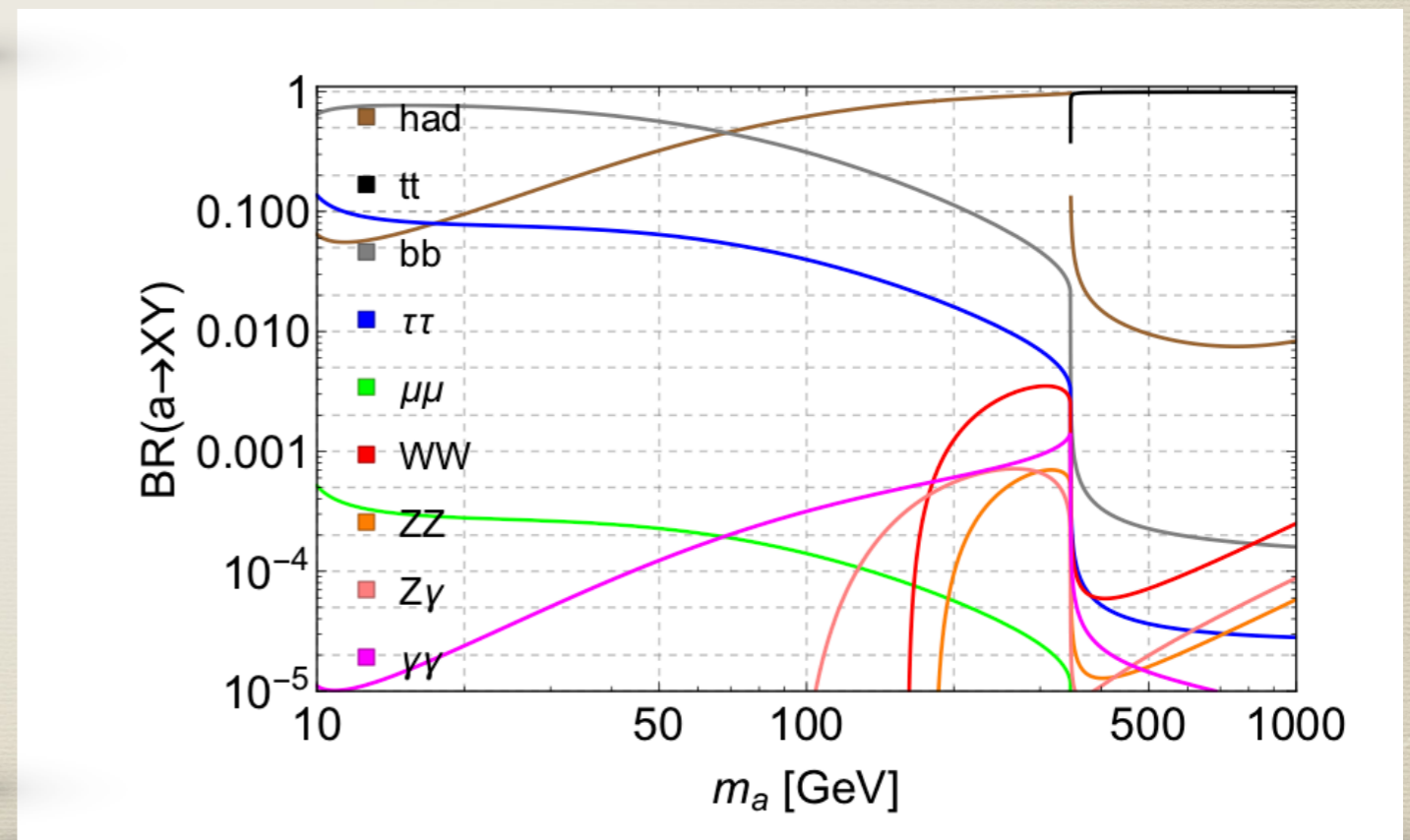


# Common exotic VLQ decays

Examples of diagrams:

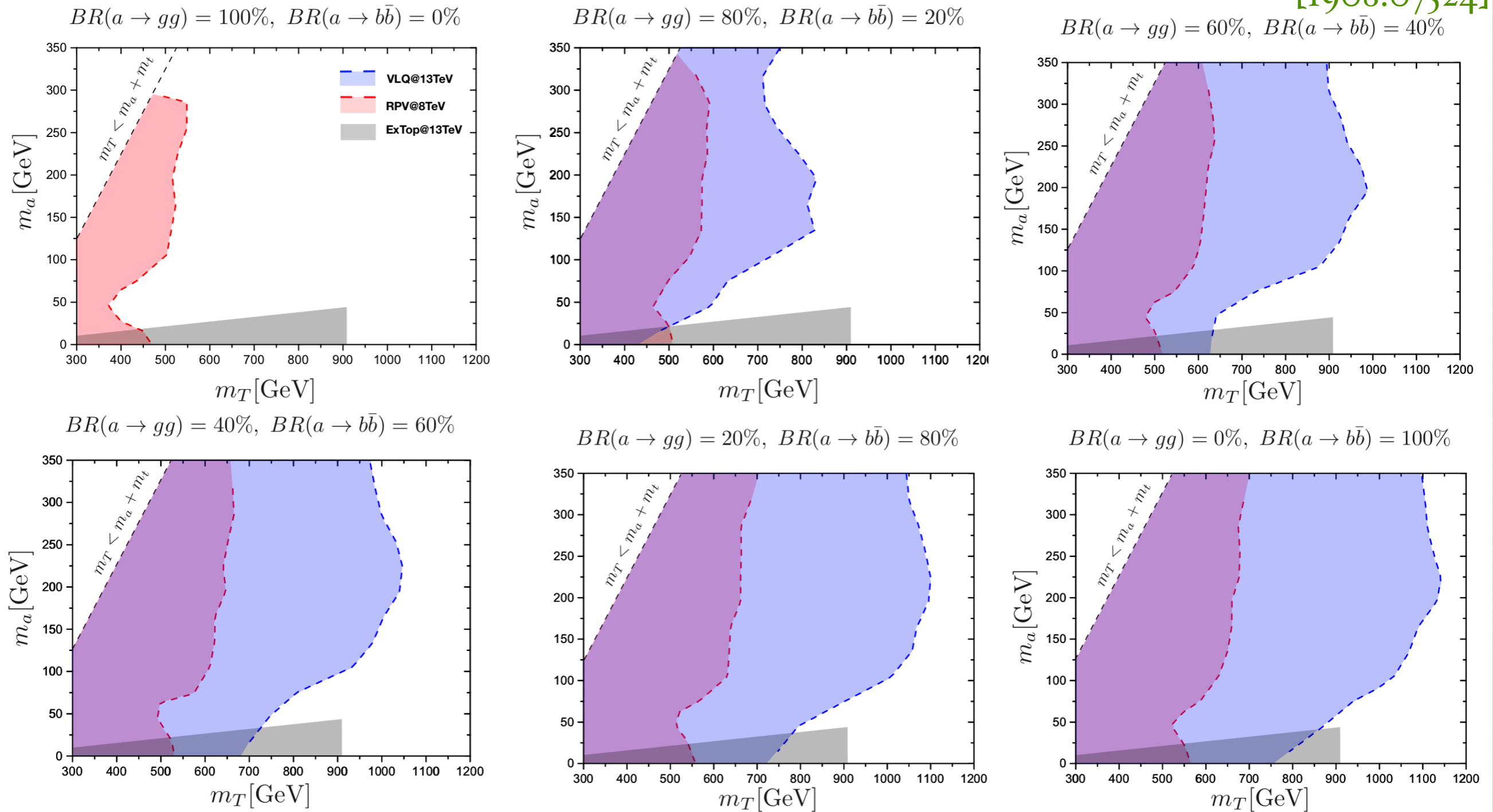


- $T$  and  $B$  can be produced like “standard” top partners: QCD pair production or single production.
- New final states: MANY, depending on  $m_a$  and single- or pair-production



# For light $a$ : Bounds on $pp \rightarrow TT \rightarrow t a t a$ , with $a \rightarrow gg$ or $a \rightarrow b\bar{b}$

[1908.07524]



Red: RPV-SUSY (hadronic) Blue: VLQ search

Gray: Excited top search

[CERN-EP-2015-020 \(ATLAS\)](#)

[CERN-EP-2018-031](#)

[CERN-EP-2017-272 \(CMS\)](#)

[CERN-EP-2017-298 \(ATLAS\)](#)

(ATLAS)

EVLQ

# Common exotic VLQ decays

**Candidate 2:** Decays of a top partner to the “exclusive pseudo-scalar”  $\eta$ .

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

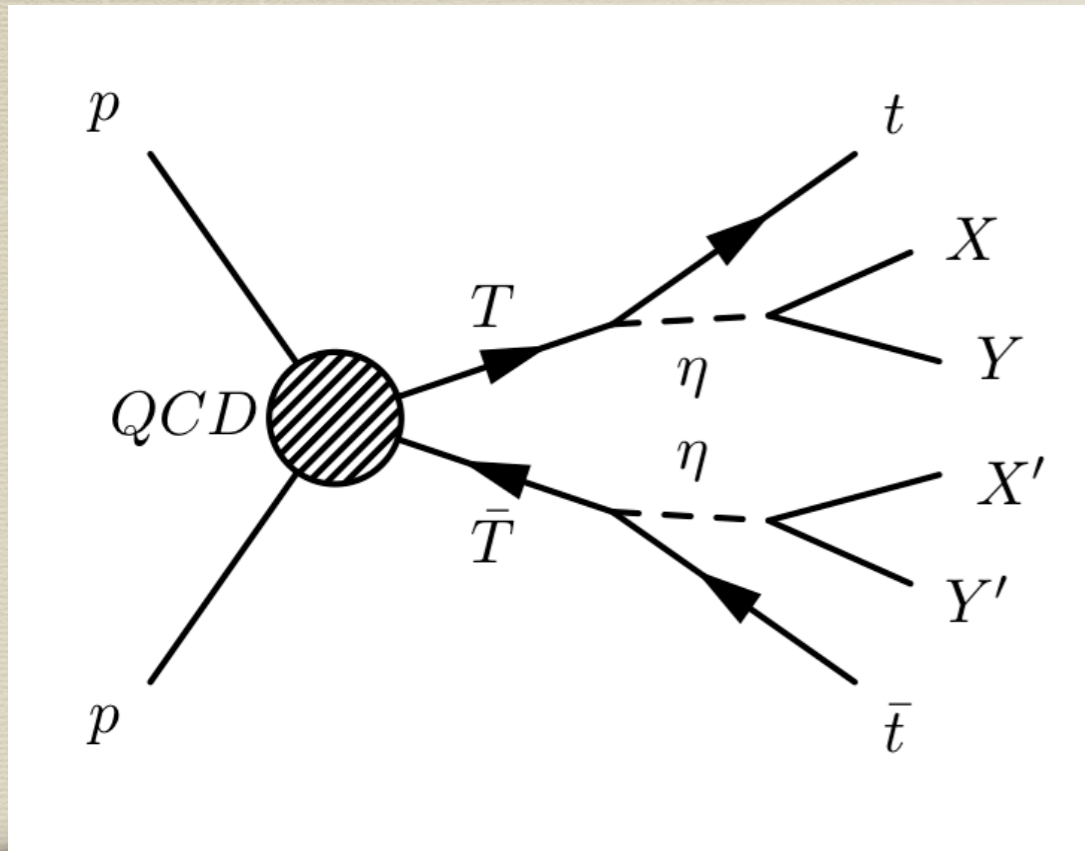
Effective Lagrangian:

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

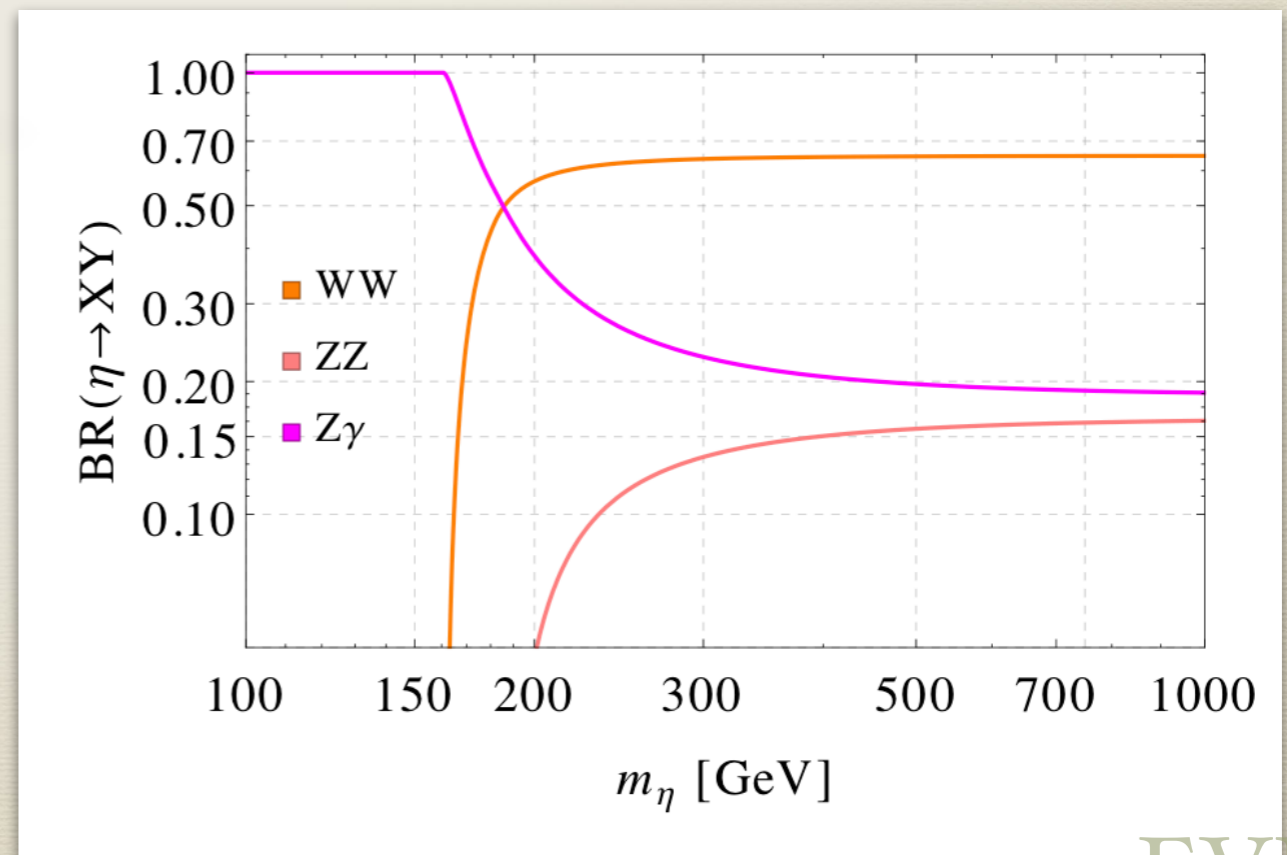
$$\begin{aligned} \mathcal{L}_{\eta} = & \frac{1}{2} (\partial_{\mu} \eta) (\partial^{\mu} \eta) - \frac{1}{2} m_{\eta}^2 \eta^2 + \frac{g_s^2 K_g^{\eta}}{16\pi^2 f_{\eta}} \eta G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \frac{g^2 K_W^a}{8\pi^2 f_{\eta}} \eta W_{\mu\nu}^+ \tilde{W}^{-,\mu\nu} \\ & + \frac{e^2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



# Common exotic VLQ decays



- The  $\eta$ -parity top partner is only QCD-pair produced.
- It decays 100% to  $t\eta$ .
- $\eta$  dominantly decays to  $W^+ W^-$  or  $Z\gamma$  (depending on its mass).



# Common exotic VLQ decays

**Candidate 3:**  $X_{5/3} \rightarrow \bar{b} \pi_6$  (with subsequent  $\pi_6 \rightarrow t t$ )

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

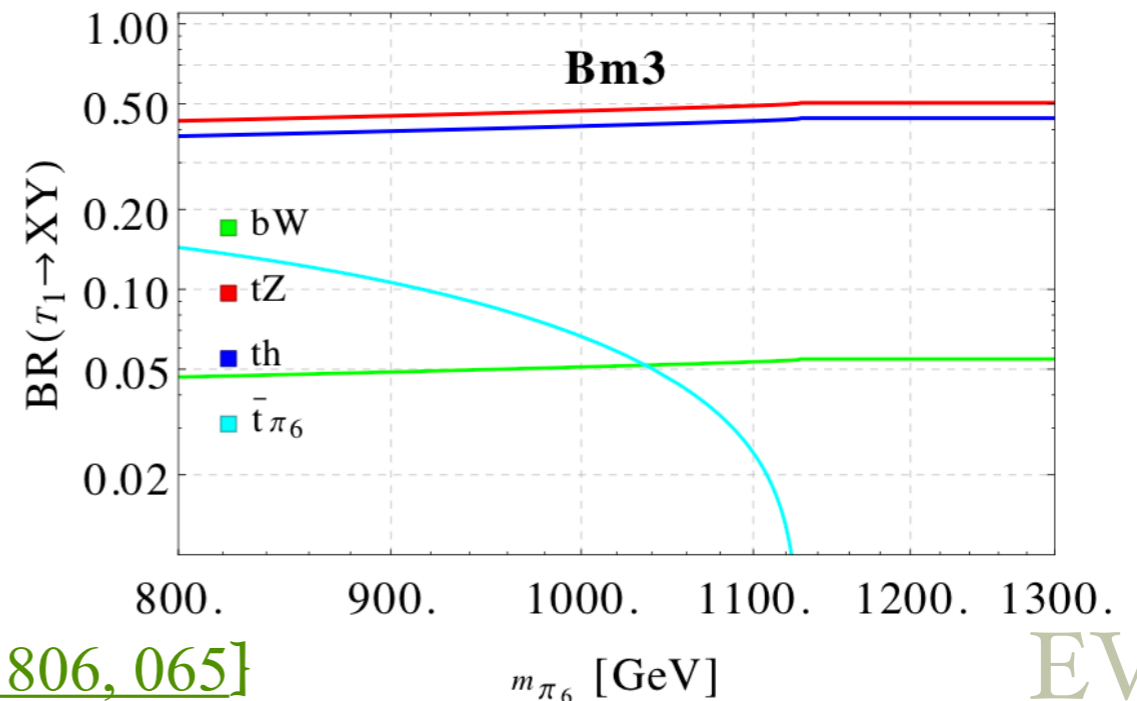
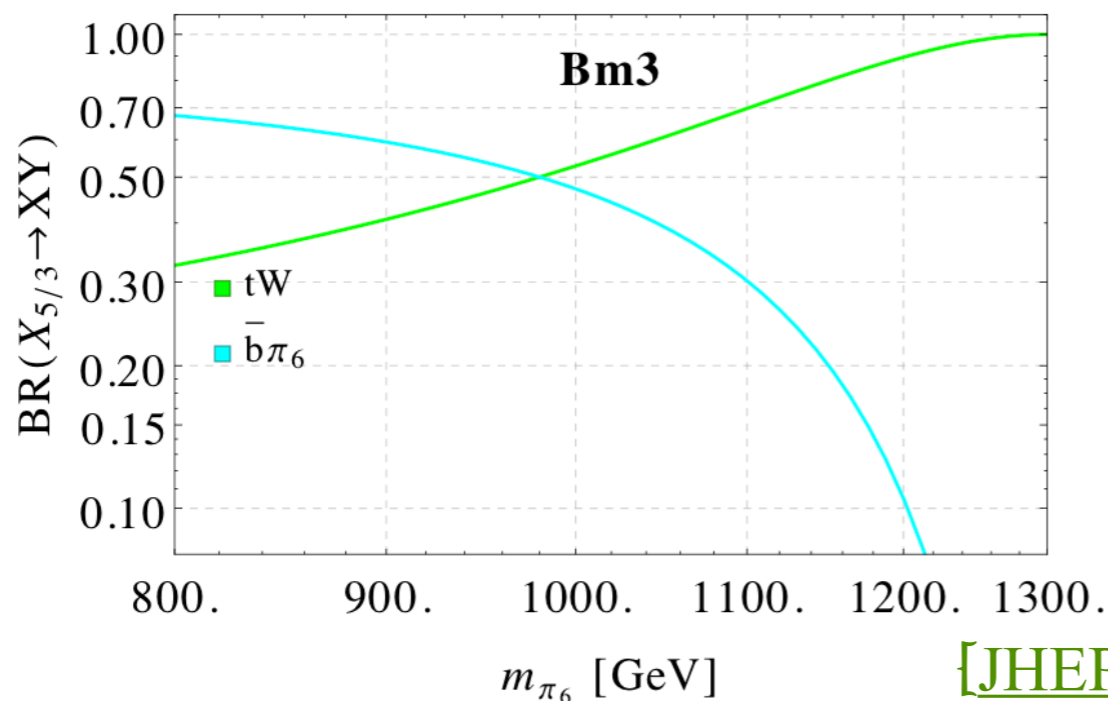
Effective Lagrangian:

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

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

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

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

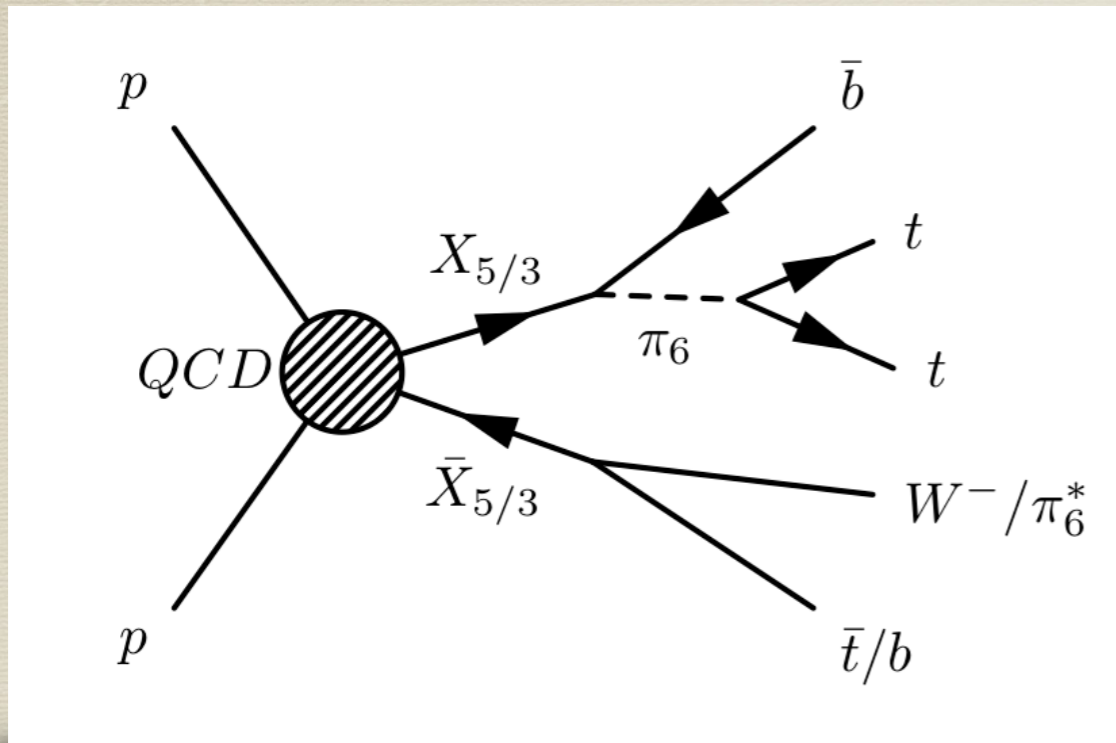


[JHEP 1806, 065]

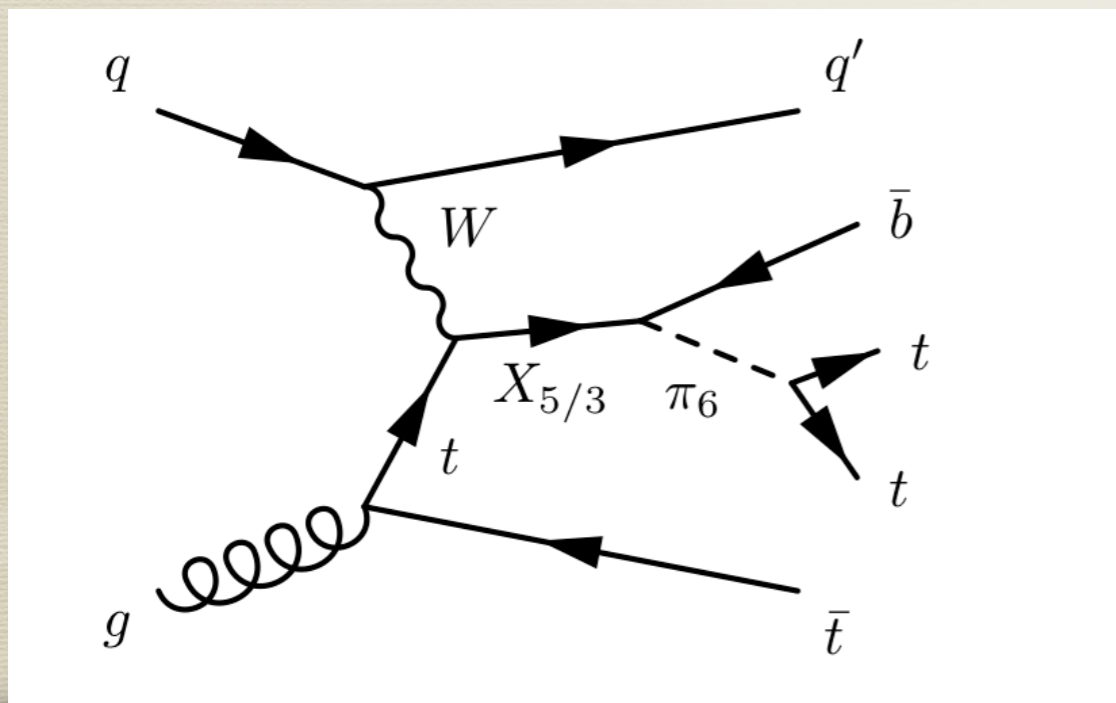
EV LQ

# Common exotic VLQ decays

Examples of diagrams:



- $X_{5/3}$  and  $B$  can be produced in QCD pair production or single production.
- $\pi_6$  decays to  $t t$ .



# Common exotic VLQ decays

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

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

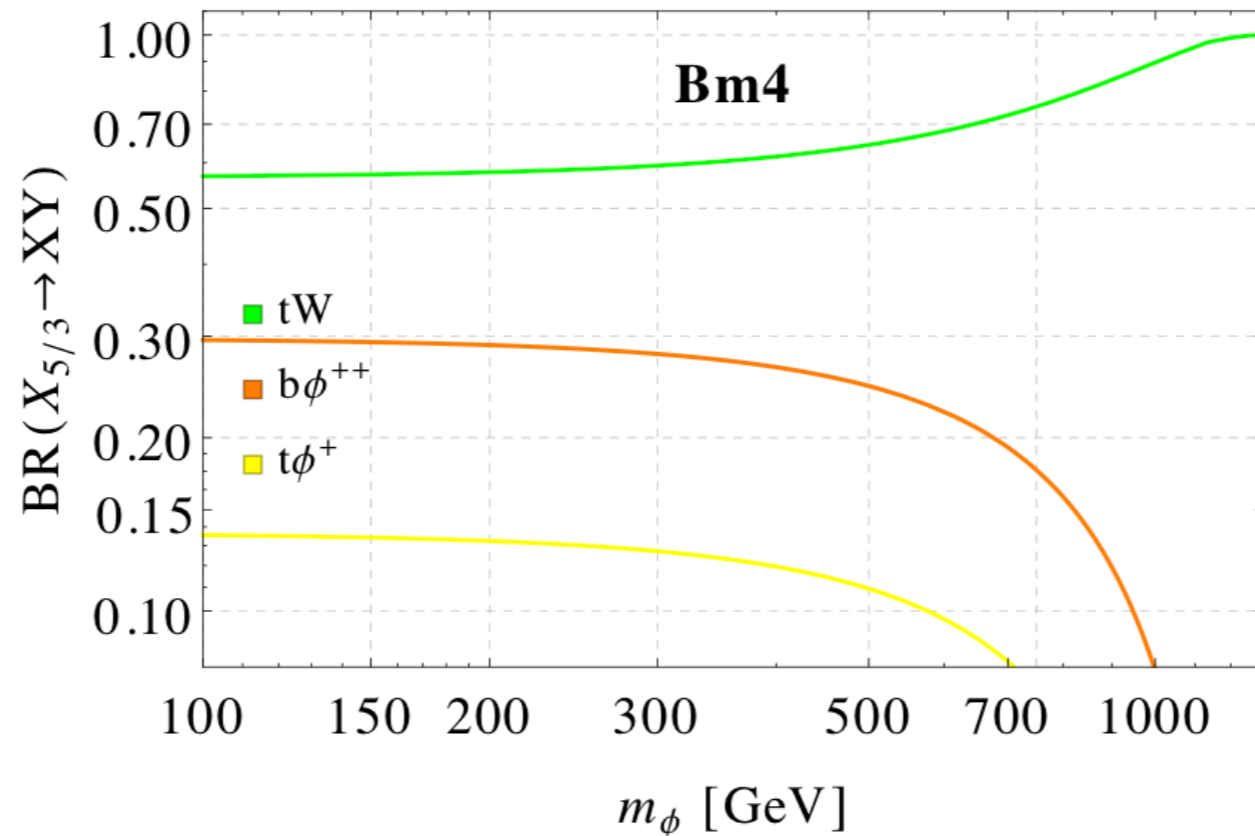
Effective Lagrangian:

$$\begin{aligned}
 \mathcal{L}_{X_{5/3}}^\phi &= \bar{X}_{5/3} \left( i\not{D} - M_{X_{5/3}} \right) X_{5/3} + \left( \kappa_{W,L}^X \frac{g}{\sqrt{2}} \bar{X}_{5/3} W^+ P_L t \right. \\
 &\quad \left. + i\kappa_{\phi^+,L}^X \bar{X}_{5/3} \phi^+ P_L t + i\kappa_{\phi^{++},L}^X \bar{X}_{5/3} \phi^{++} P_L b + L \leftrightarrow R + \text{h.c.} \right) \\
 \mathcal{L}_\phi &= \sum_{\phi=\phi^+, \phi^{++}} \left( |D_\mu \phi|^2 - m_\phi^2 |\phi|^2 \right) + \left( \frac{egK_W^\phi}{8\pi^2 f_\phi} \phi^+ W_{\mu\nu}^- \tilde{B}^{\mu\nu} + \frac{g^2 c_w K_{WZ}^\phi}{8\pi^2 f_\phi} \phi^+ W_{\mu\nu}^- \tilde{B}^{\mu\nu} \right. \\
 &\quad \left. + \frac{g^2 K_W^\phi}{8\pi^2 f_\phi} \phi^{++} W_{\mu\nu}^- \tilde{W}^{\mu\nu,-} + i\kappa_{tb,L}^\phi \frac{m_t}{f_\phi} \bar{t} \phi^+ P_L b + L \leftrightarrow R + \text{h.c.} \right). \quad (2.13)
 \end{aligned}$$

# Common exotic VLQ decays

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

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



Production of  $X_{5/3}$ :  
Single- or pair-production.

Decays of the pNGBs:

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

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

# Common exotic VLQ decays

Examples of processes:

