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]

Summer Institute 2019, SANDPINE, Gangneung, Korea, Aug. 22nd, 2019

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Outline

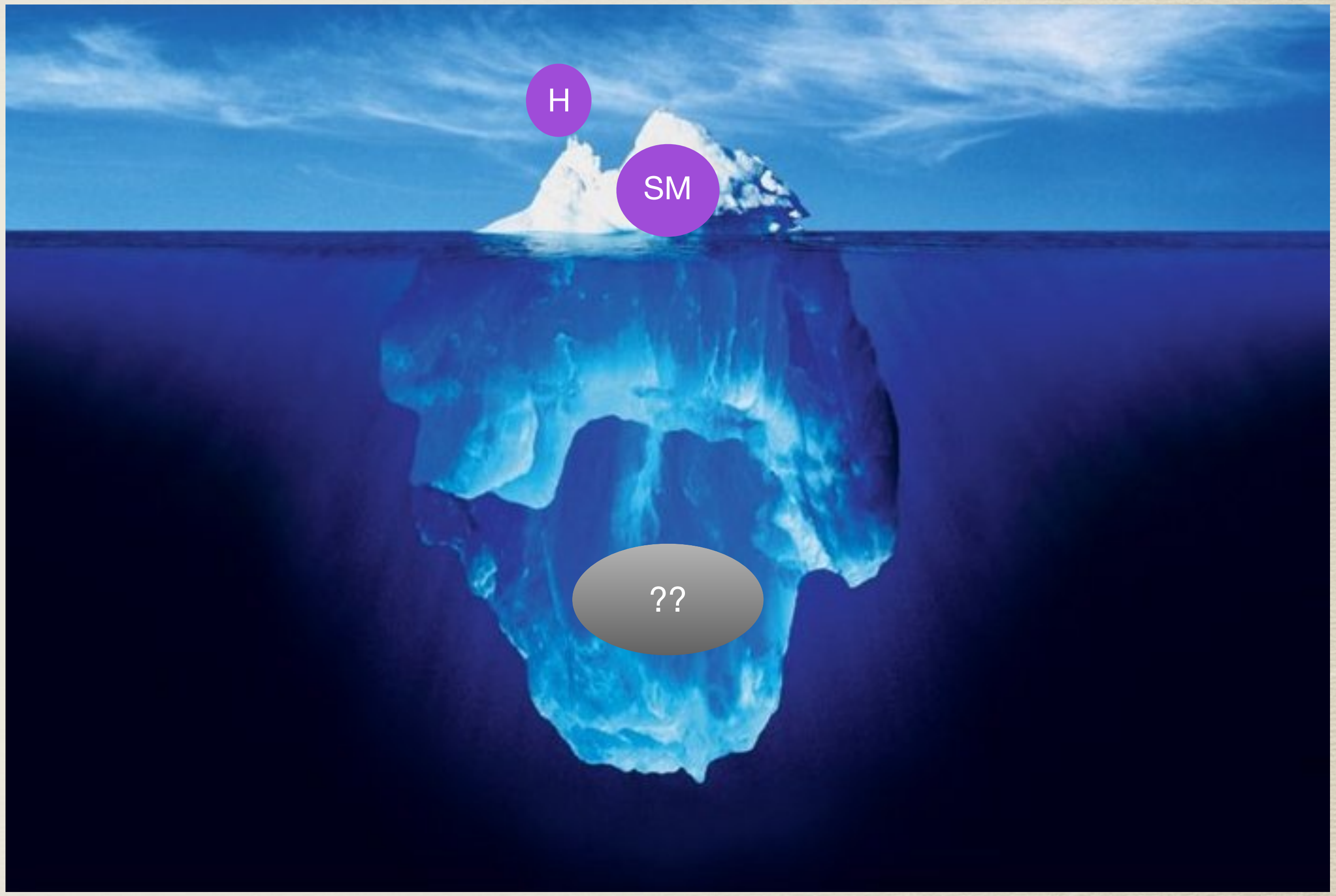
- Vector-like quarks (VLQs):
  current experimental status

- 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:
  $T \to t\, a,\ a \to gg$ or bb
  (substantially) reduced bounds from existing searches.

- Exotic charge 5/3 VLQ decays:
  $X_{5/3} \to \bar{b}\ \pi_6\,,\ X_{5/3} \to t\ \phi^+, X_{5/3} \to b\ \phi^{++}$
  bounds from reinterpreting SSL searches and possible improvements.

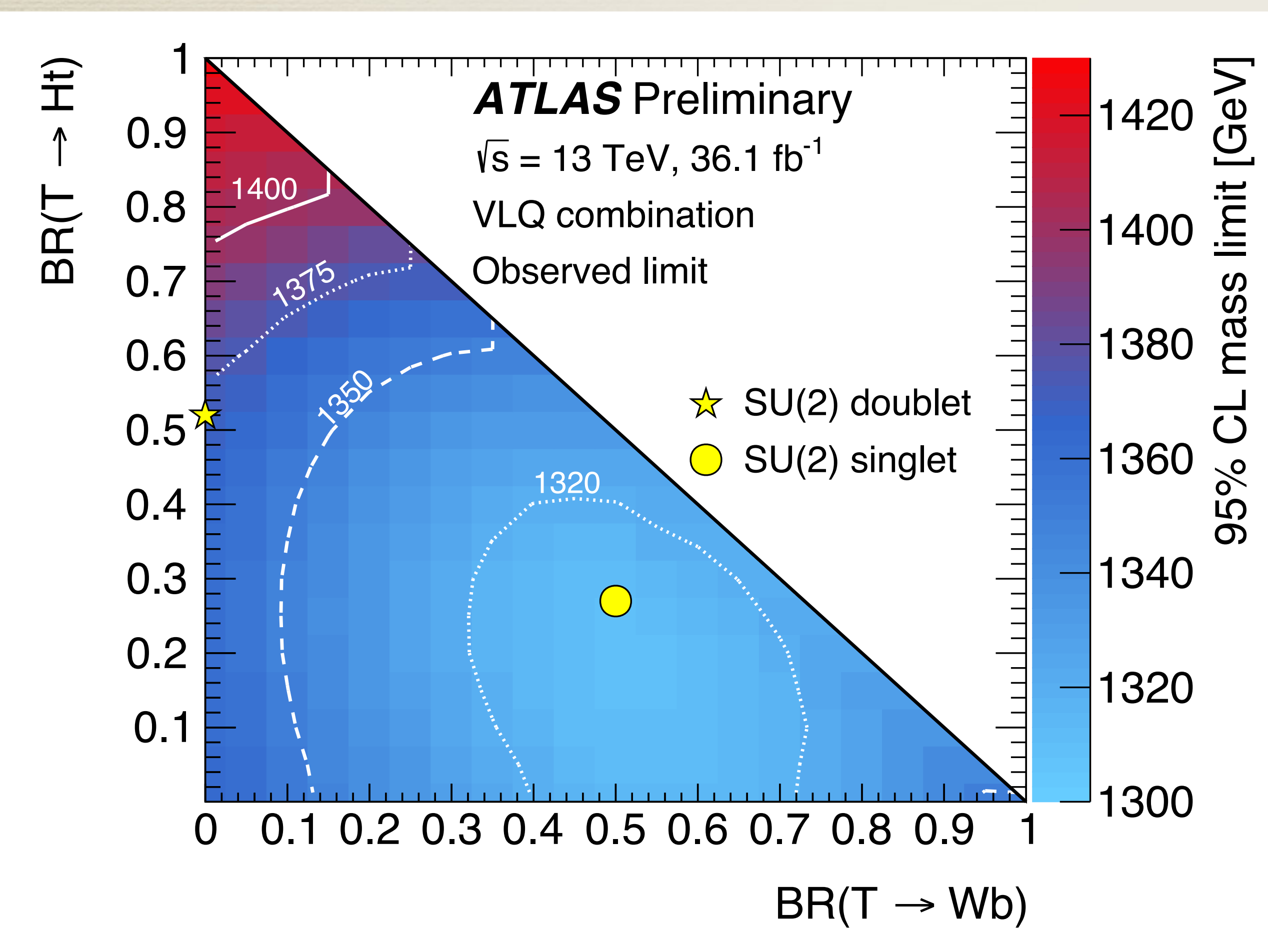
- Conclusions

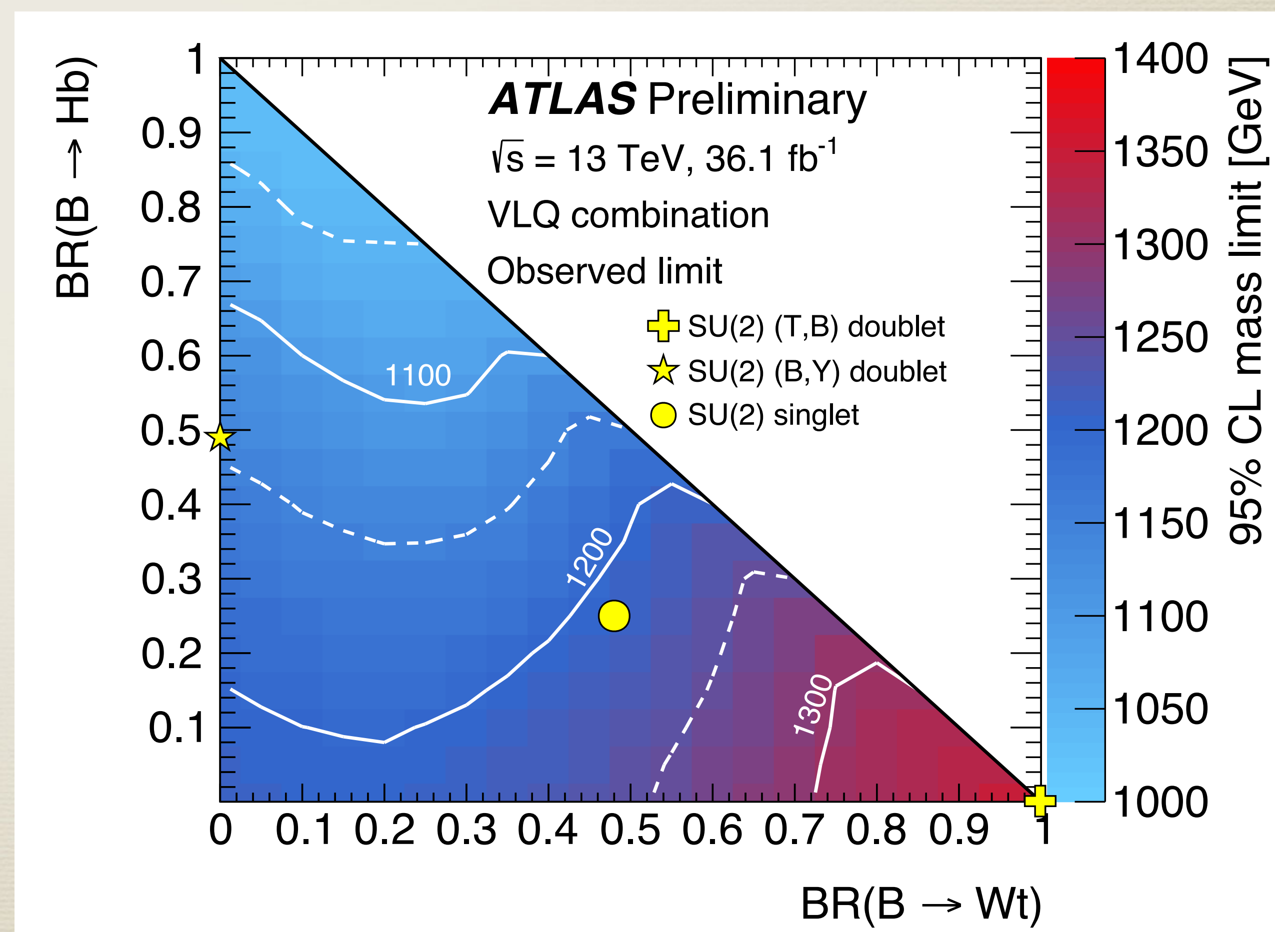


Vector-like quarks (top- partners or quark partners) with charge 5/3, 2/3, -1/3, -4/3

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

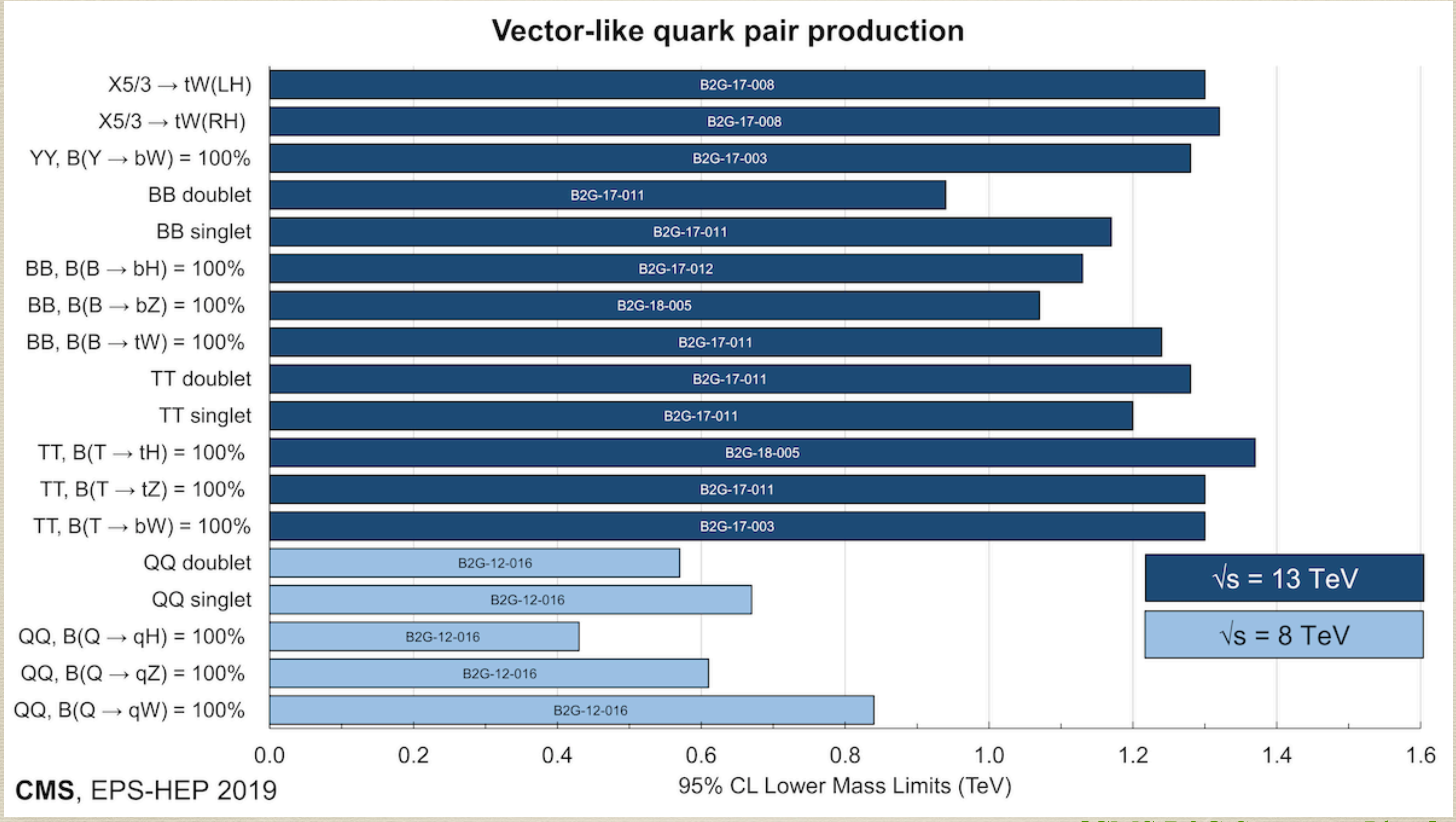
T & B: Combined bounds on pair-produced top partners





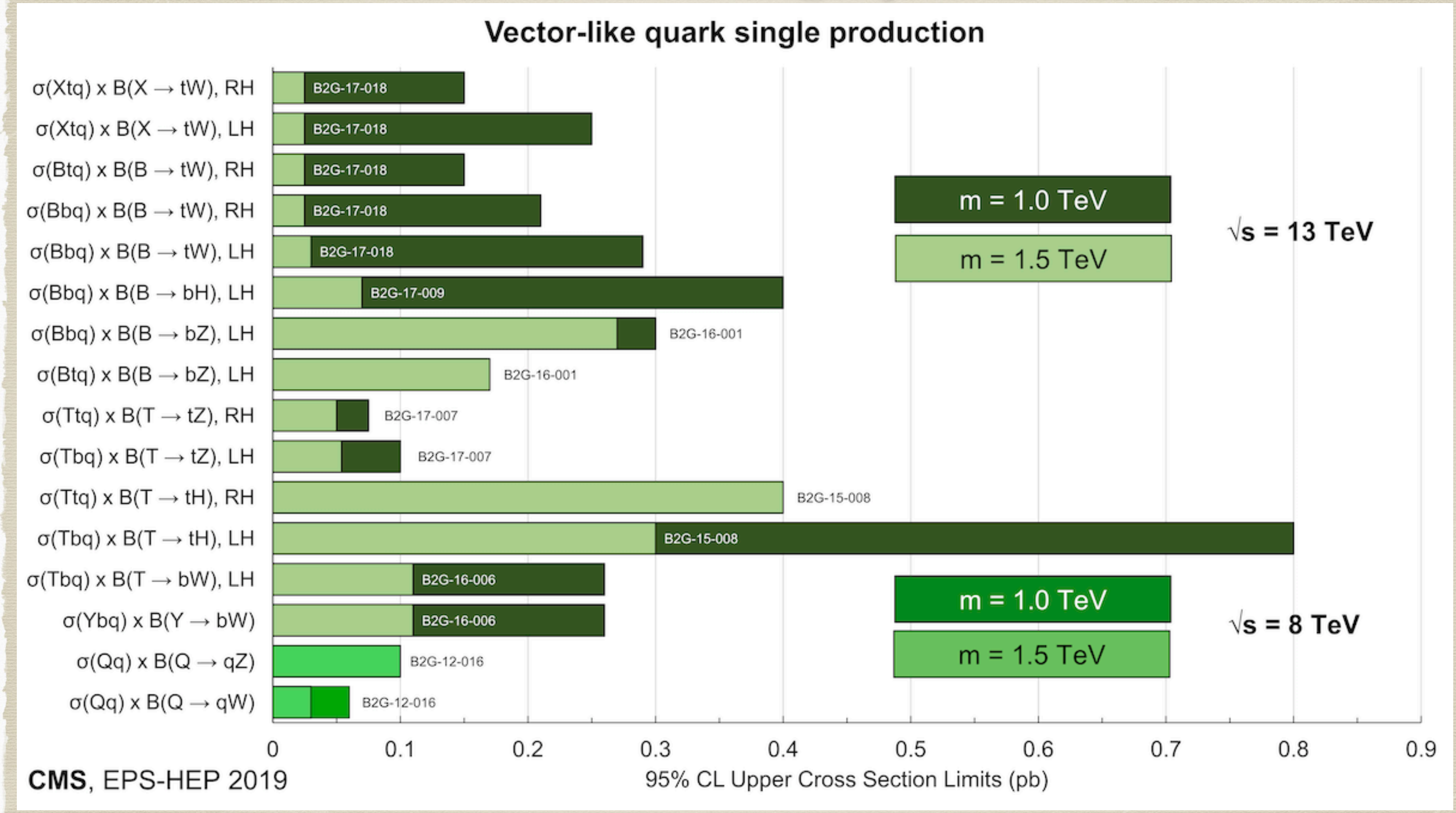
[ATLAS-CONF-2018-032]

CMS bounds on pair production



[CMS B2G Summary Plots]

CMS bounds on single production



[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: ψ for EW embedding , χ 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.

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

weak direct bounds

1. ALL models:
   a and *η'*:(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]

$\gtrsim$ 1 TeV

2. ALL models:
   π_8 : Color octet pseudo-scalar pNGB which couples to *gg, gγ, gZ, tt* [JHEP1701,094]

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

$\gtrsim$ O(200) GeV [Agugliaro etal]

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

$\gtrsim$ 1 TeV [JHEP1511,201]

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

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" *η*,
3. $X_{5/3} \to \bar{b}\, \pi_6$ (with subsequent $\boldsymbol{\pi}_6 \to t\, t$),
4. $X_{5/3} \to t\ \phi^{+}$, $X_{5/3} \to b\ \phi^{++}$.

- Decays of the pNGBs yield manifold novel multi-body decay modes and LHC signatures.

Common exotic VLQ decays: $T \to t\, a$

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

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

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

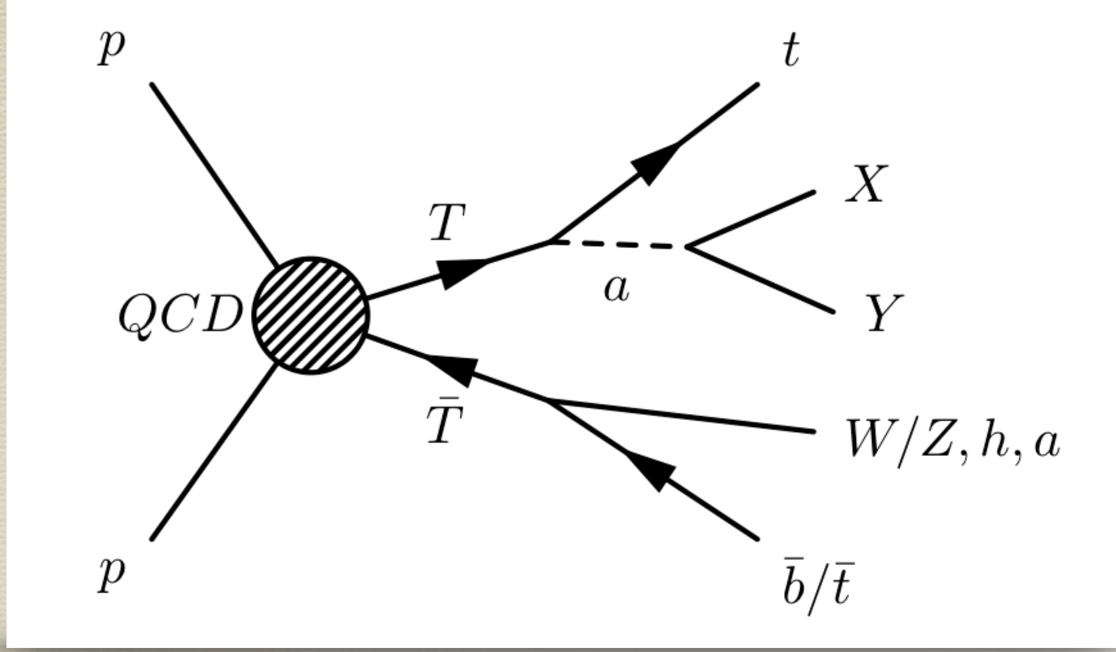
$$\mathcal{L}_B = \overline{B}\left(i\not{D} - M_B\right)B + \left(\kappa^B_{W,L}\frac{g}{\sqrt{2}}\,\overline{B}\not{W}^- P_L t + \kappa^B_{Z,L}\frac{g}{2c_W}\,\overline{B}\not{Z}^+ P_L b - \kappa^B_{h,L}\frac{M_B}{v}\,\overline{B}hP_L b + i\kappa^B_{a,L}\,\overline{B}aP_L b + L \leftrightarrow R +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

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

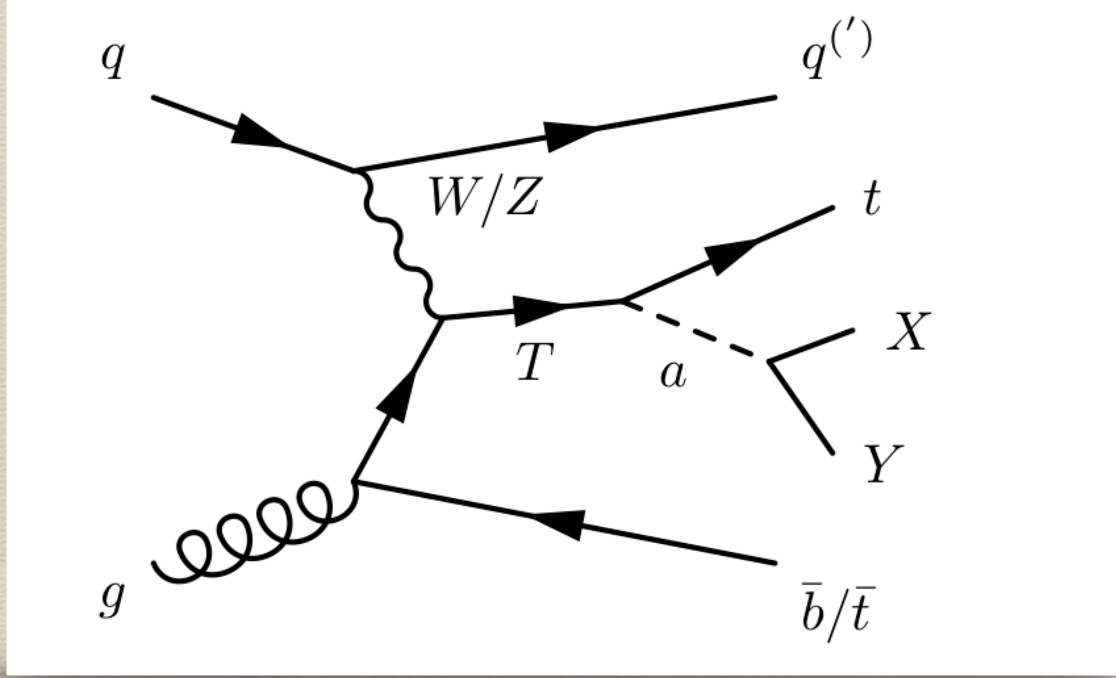
$$+ \frac{g_s^2 K_g a}{16\pi^2 f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{g^2 K_W a}{16\pi^2 f_a} W^i_{\mu\nu}\tilde{W}^{i\mu\nu} + \frac{g'^2 K_B a}{16\pi^2 f_a} B_{\mu\nu}\tilde{B}^{\mu\nu}$$

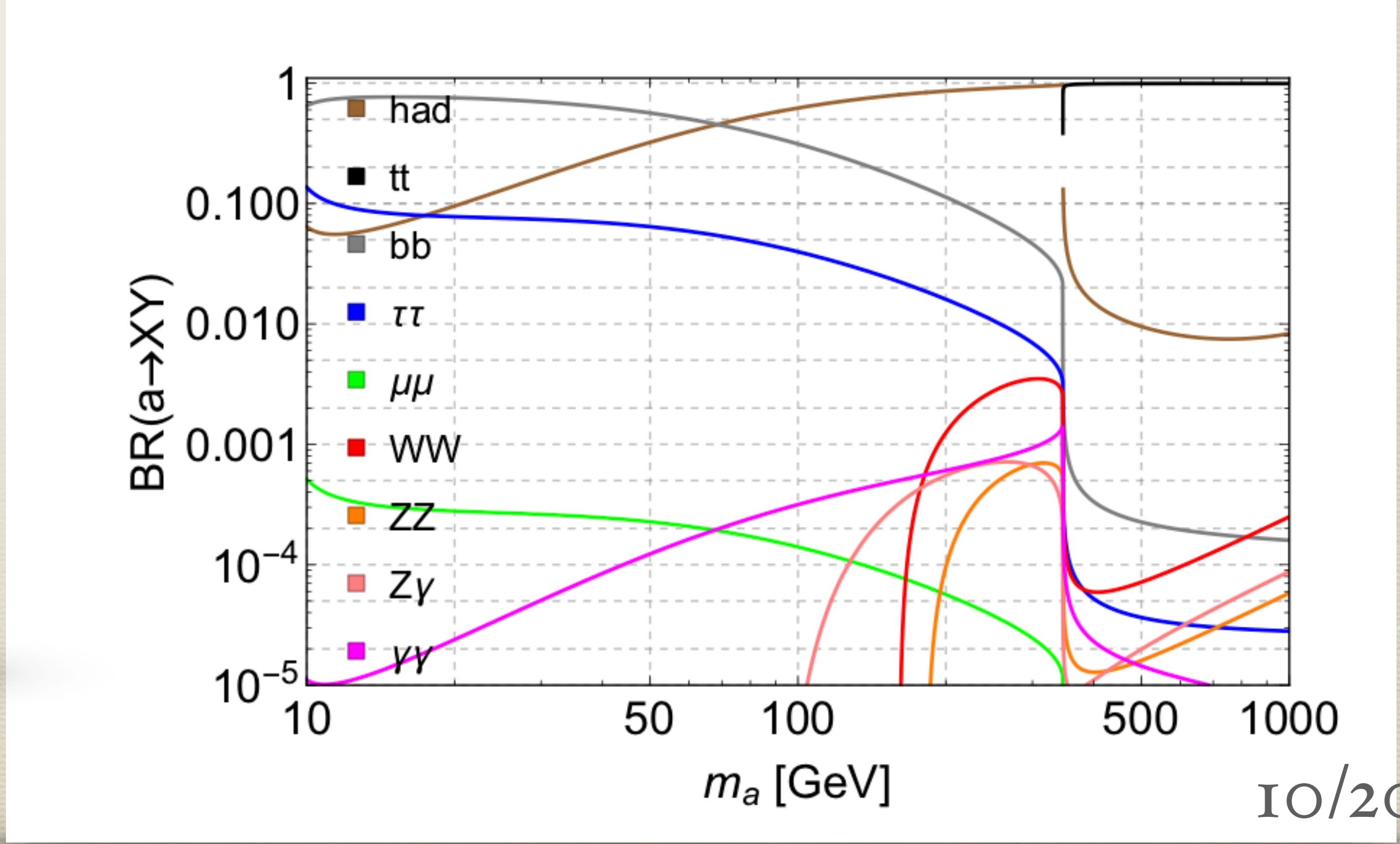
Common exotic VLQ decays: $T \to t\, a$

Examples of diagrams:

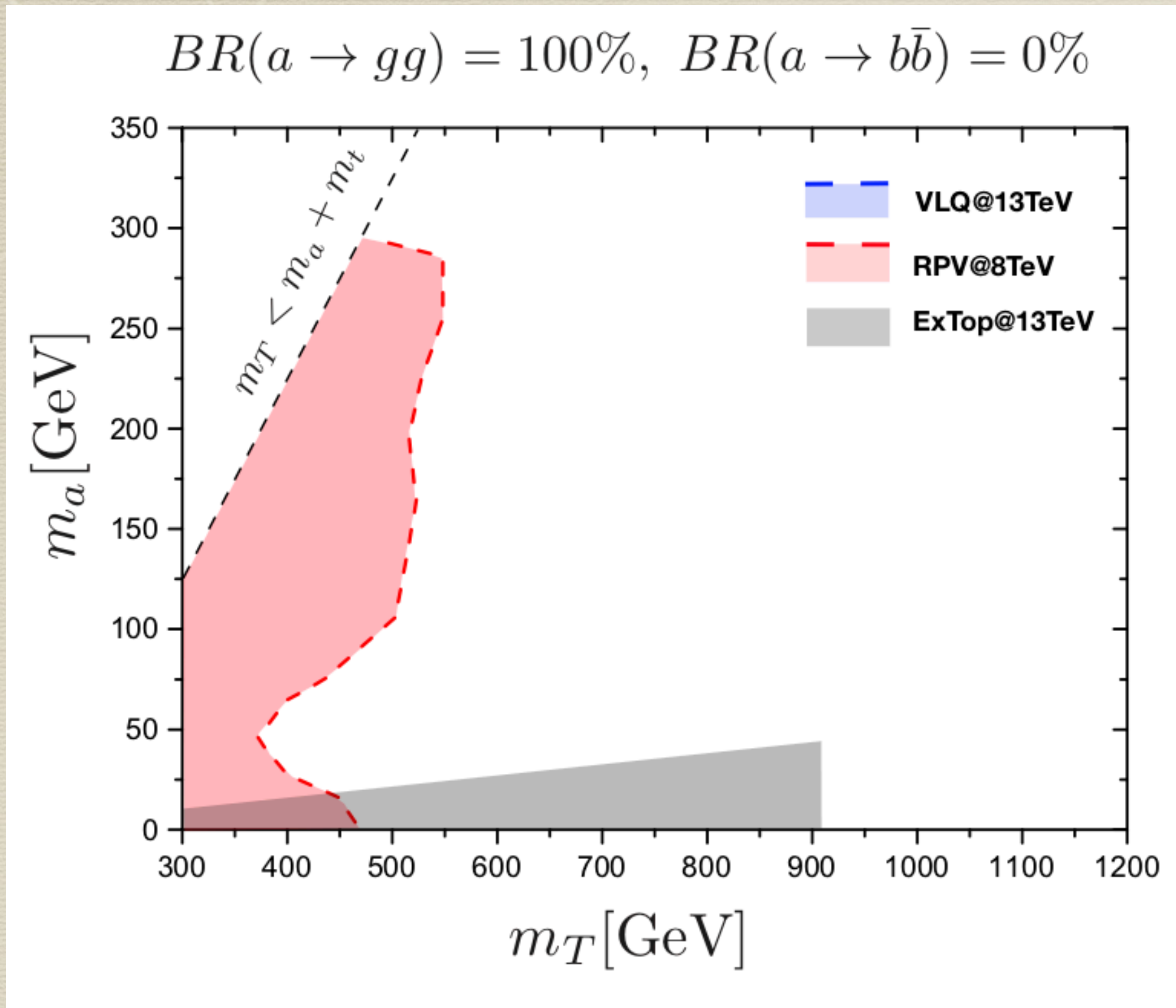


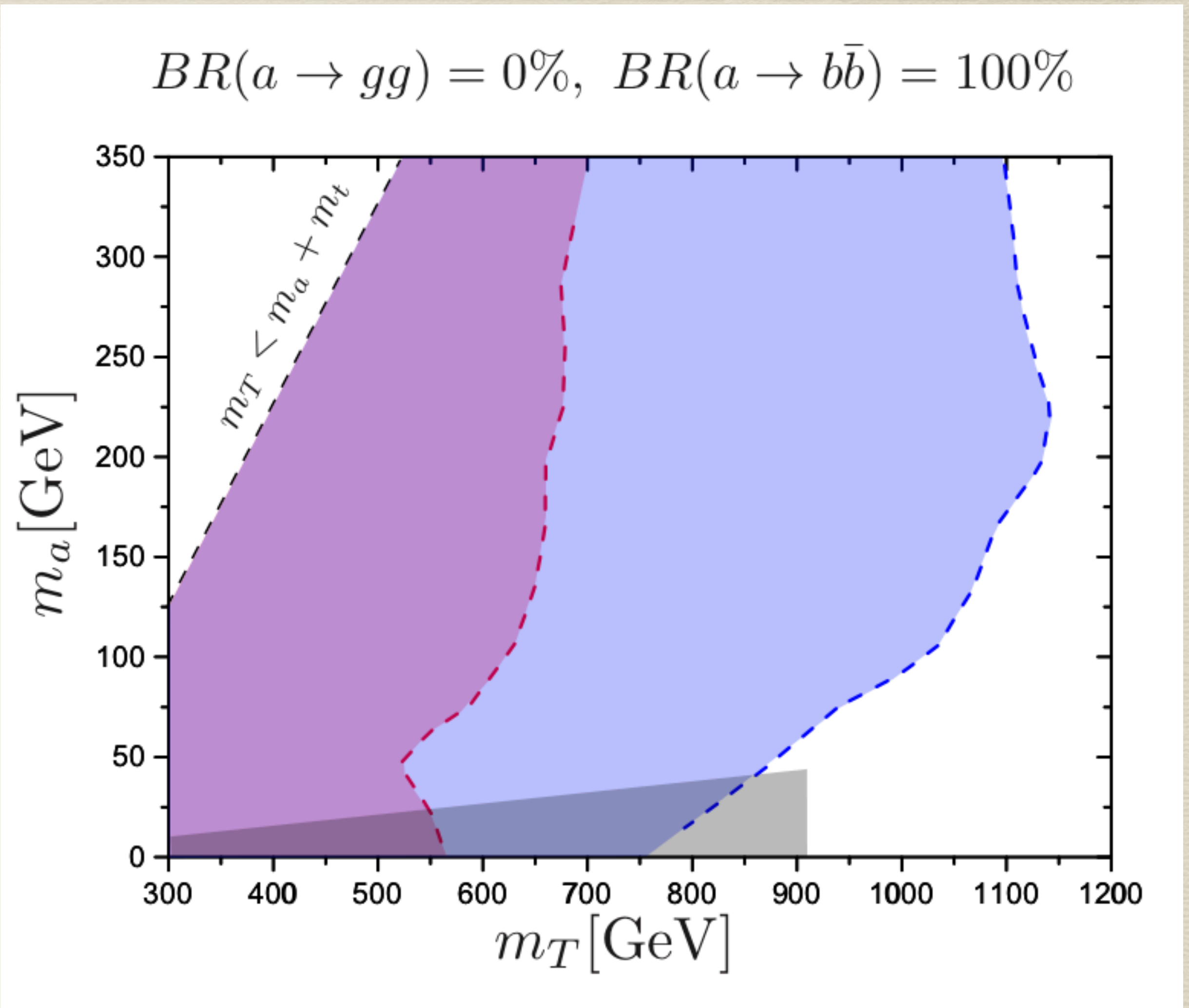
- T (and B) can be produced like "standard" top partners: QCD pair production or single production.
- New final states: MANY, depending on m_a and single- or pair-production.
- For light $m_a < m_t$, gg and bb decays dominate.





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





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 $T \to t\,a \to t\,g\,g$ is weakly constrained.

[1908.07524]

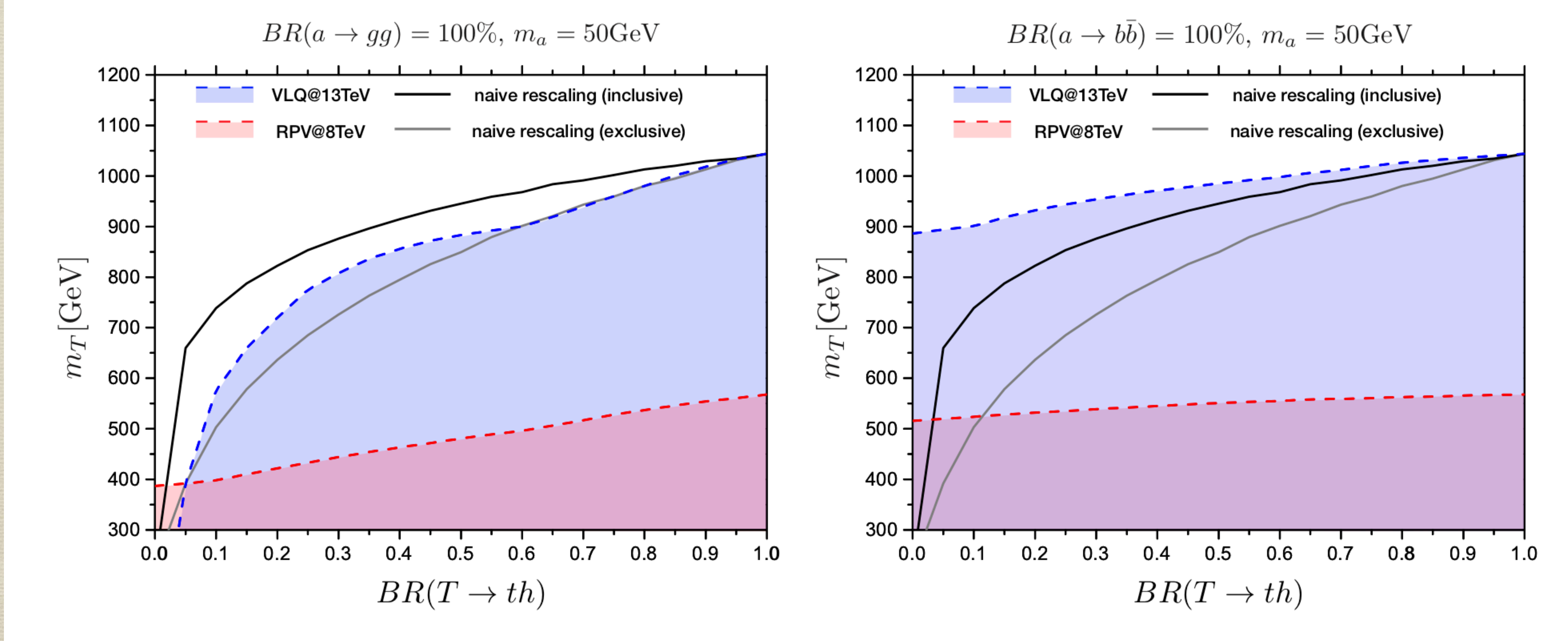
For light a: Bounds on $pp \to TT \to t\ a\ t\ h$, with $a \to gg$ or $a \to bb$

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

Inclusive pair production search bounds on σ_{TT} are reduced by ~ $(1 - BR_a)$,

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

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



[1908.07524]

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

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

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

Effective Lagrangian:

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

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

[JHEP 1806, 065]

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

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:

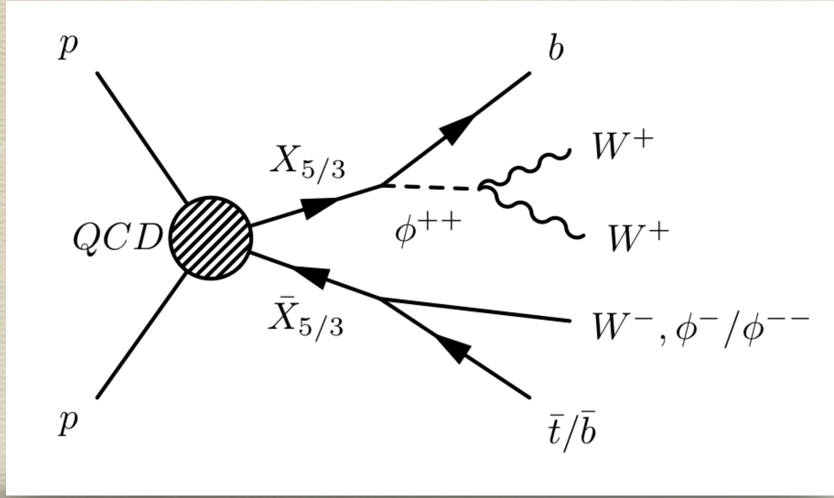
$$\mathcal{L}^{\phi}_{X_{5/3}} = \overline{X}_{5/3}\left(i\not{D} - M_{X_{5/3}}\right)X_{5/3} + \left(\kappa^{X}_{W,L}\frac{g}{\sqrt{2}}\,\overline{X}_{5/3}\not{W}^{+}P_L t + i\kappa^{X}_{\phi^+,L}\,\overline{X}_{5/3}\phi^{+}P_L t + i\kappa^{X}_{\phi^{++},L}\,\overline{X}_{5/3}\phi^{++}P_L b + L \leftrightarrow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

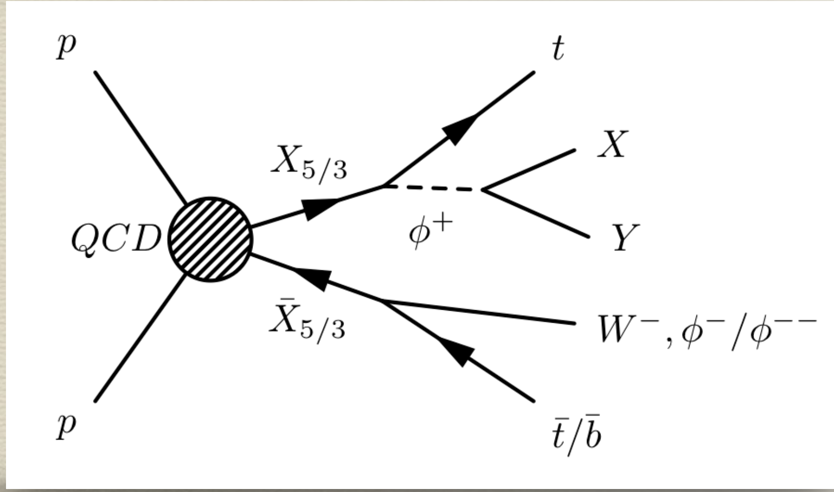
$$\mathcal{L}_{\phi} = \sum_{\phi=\phi^+,\phi^{++}}\left(|D_\mu\phi|^2 - m^2_\phi\,|\phi|^2\right) + \left(\frac{egK^{\phi}_{W\gamma}}{8\pi^2 f_\phi}\phi^{+}W^{-}_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{g^2 c_w K^{\phi}_{WZ}}{8\pi^2 f_\phi}\phi^{+}W^{-}_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{g^2K^{\phi}_{W}}{8\pi^2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

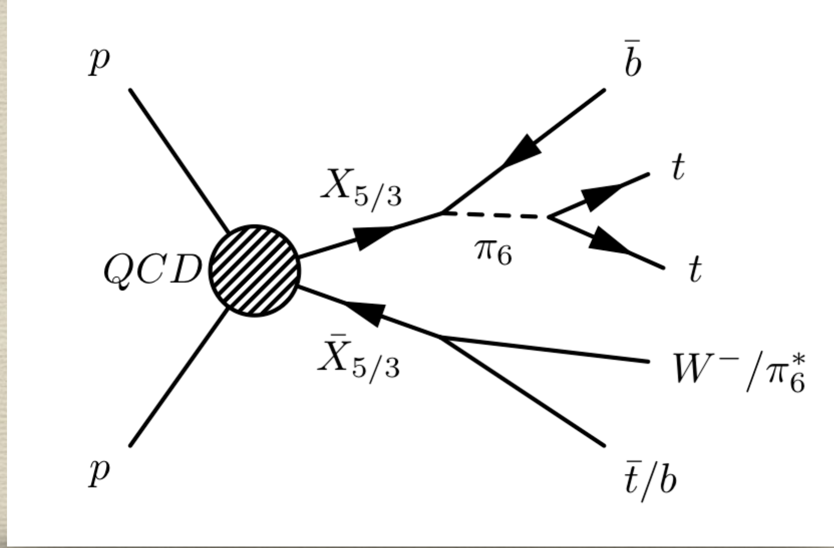
[JHEP 1806, 065]

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

Examples of processes:







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

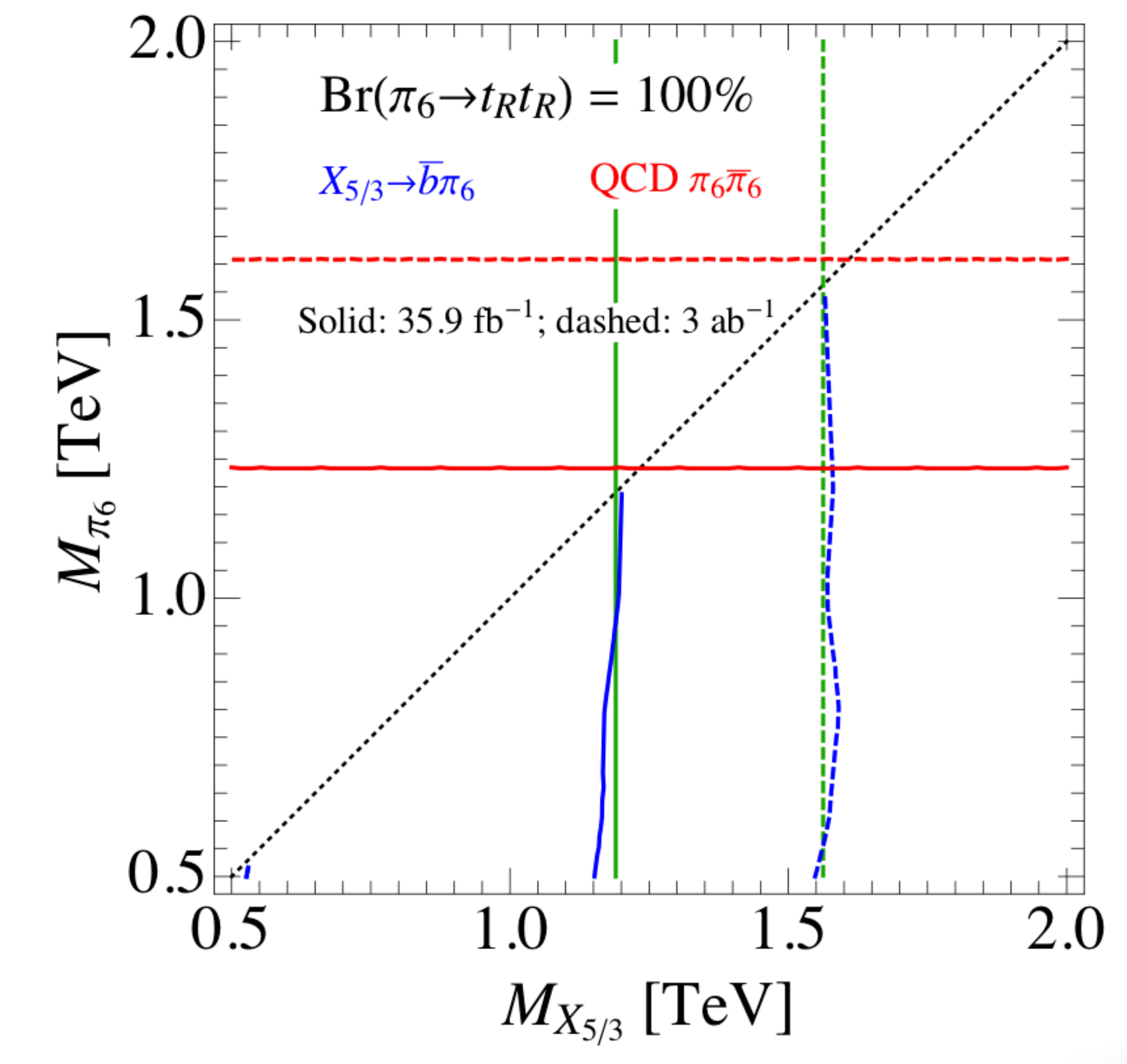
Cascade decays			after t and τ decay
$X_{5/3}$	tW^+	$-$	$(bW^+)W^+$
	$\bar{b}\pi_6$	$\bar{b}tt$	$\bar{b}(bW^+)(bW^+)$
	$t\phi^+$	$tW^+\gamma$, tW^+Z	$(bW^+)W^+\gamma$, $(bW^+)W^+Z$
		$tt\bar{b}$	$(bW^+)(bW^+)\bar{b}$
		$t\tau^+\nu$	$(bW^+)(W^{+*}\bar{\nu})\nu$
	$b\phi^{++}$	bW^+W^+	bW^+W^+
		$bW^{+(*)}\phi^+$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

$|\ldots|^2$

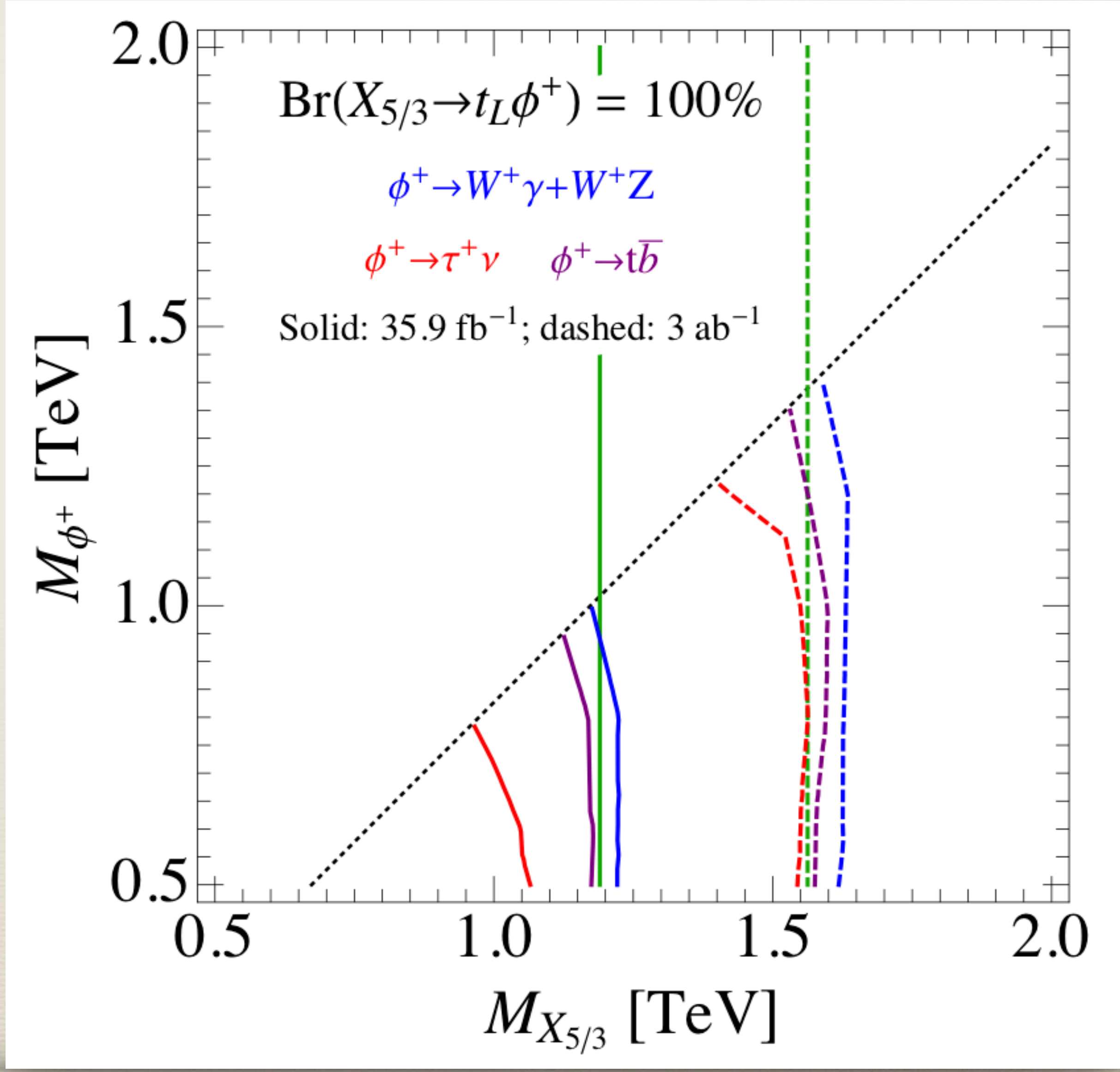
Common exotic VLQ decays: $X_{5/3}$

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:

π_6:



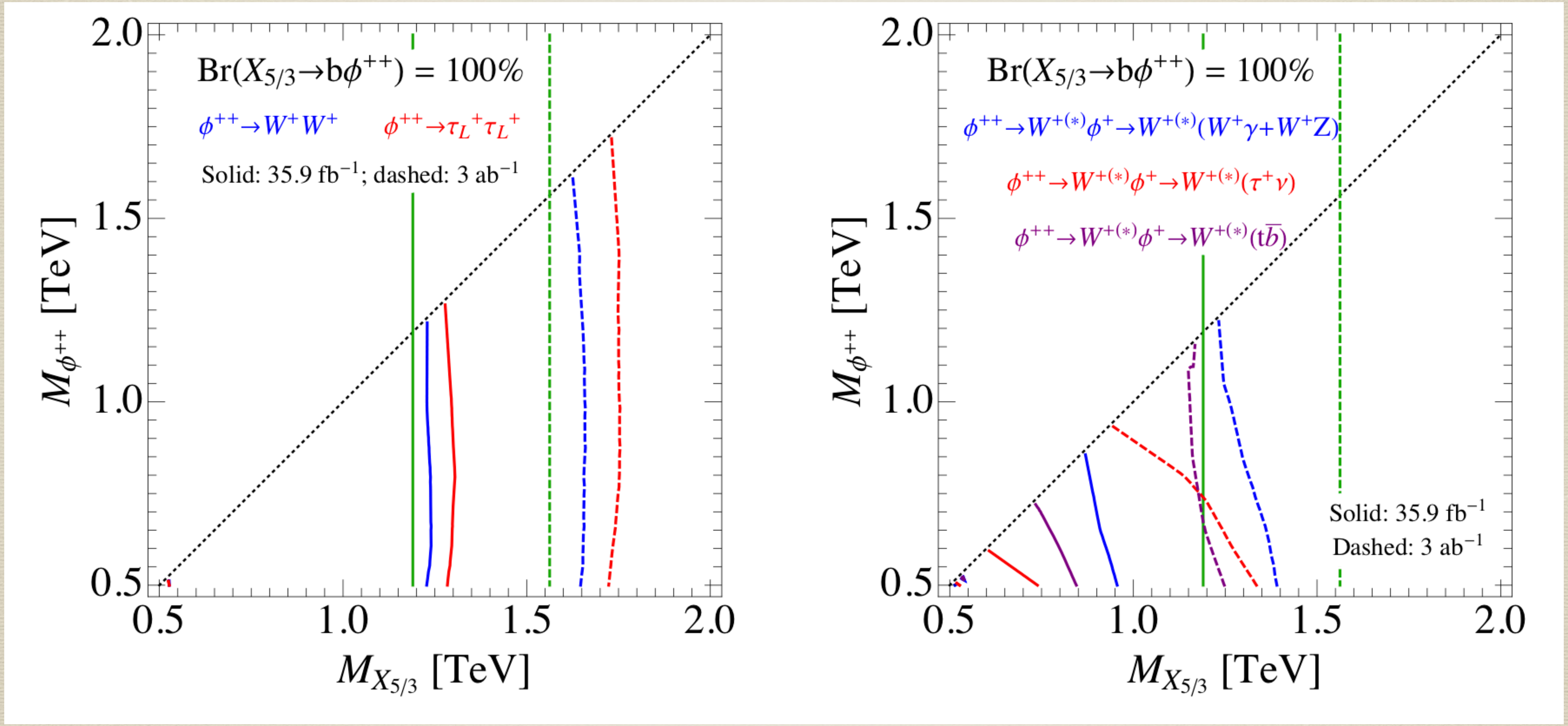
ϕ^+:



[1907.05894]

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

$\boldsymbol{\phi}^{++}$:



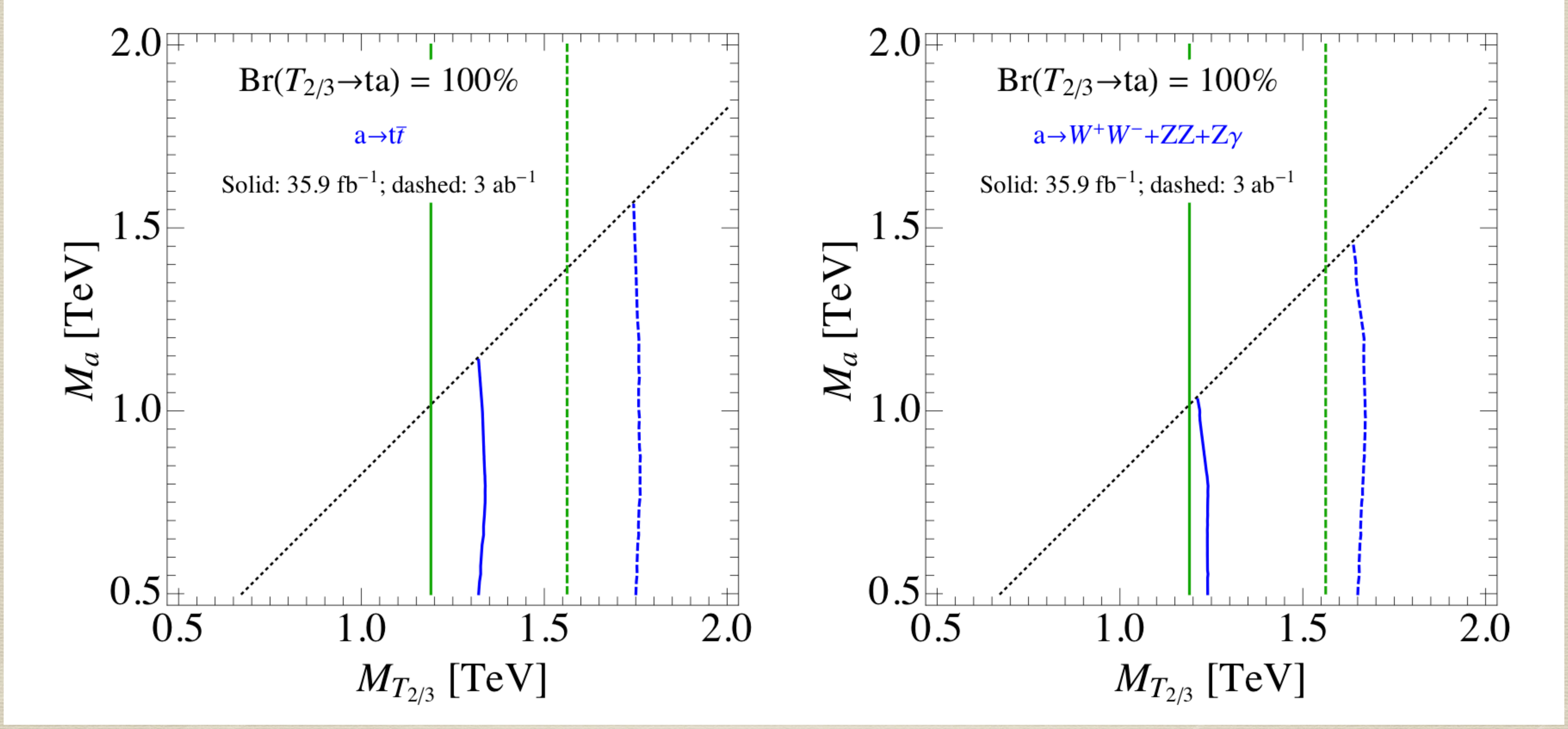
[1907.05894]

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

Bonus Plots

The recast can also be used to constrain several exotic $T_{2/3}$ decays.

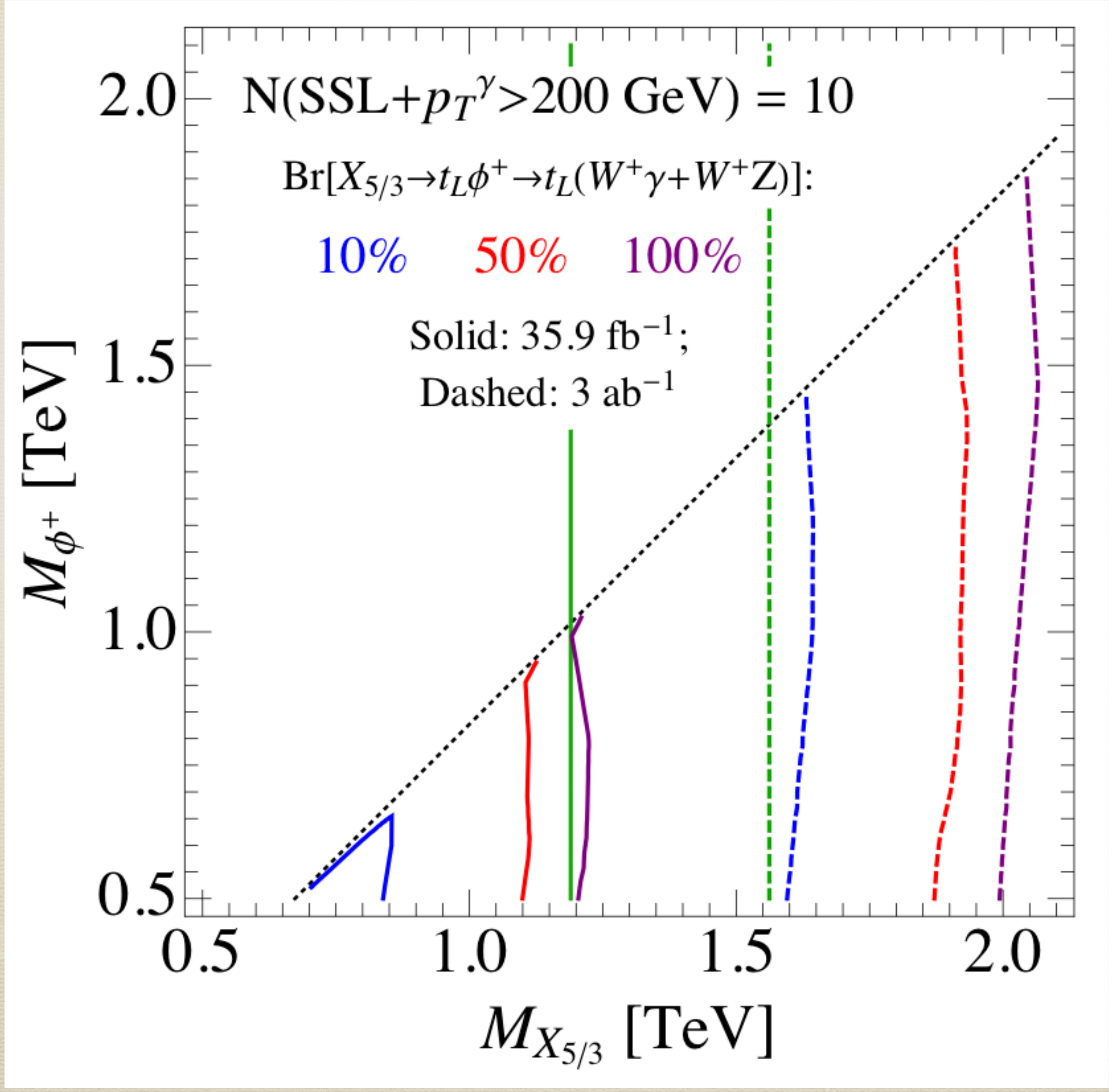
(c.f. Shu etal (2018), Benbrik etal (2019) for studies of other exotic channels)



[1907.05894]

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

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



[1907.05894]

Conclusions

- `Exotic'' decays of top partners to t/b + pNGBs 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 $T \to t\ a$ with $a \to gg$ or $a \to bb$. For these decays (especially for $T \to t\ a \to t\ g\ g$), bounds from existing searches on m_T are substantially weaker than for standard VLQ decays.

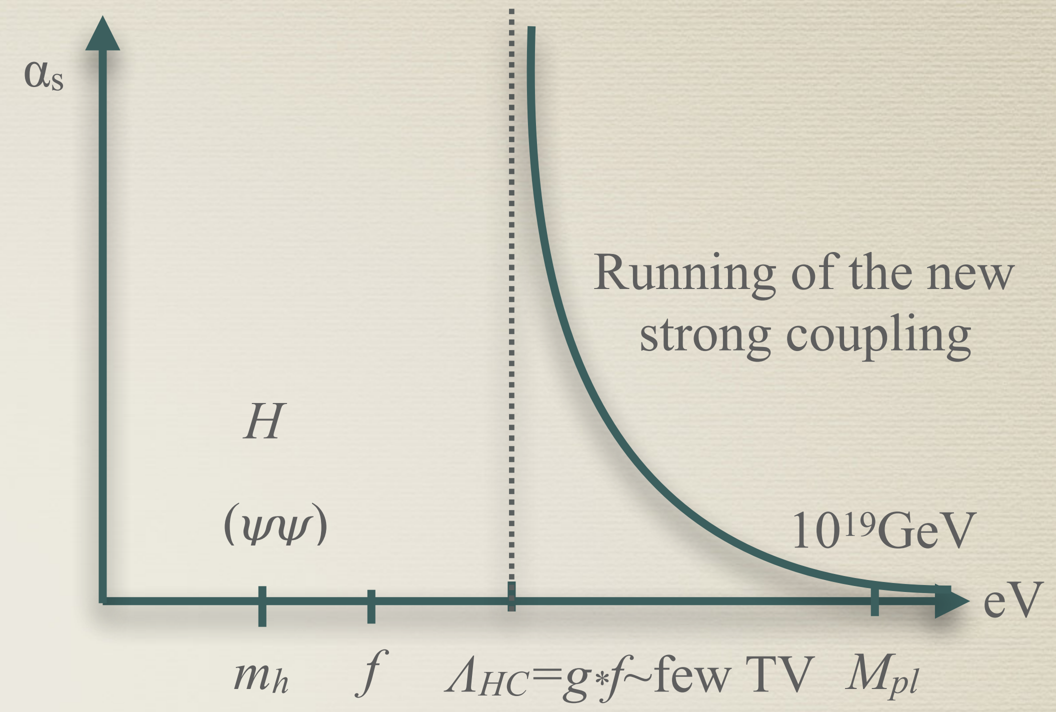
There is a lot to do!

Backup

Motivation for Vector-like quarks: a composite Higgs

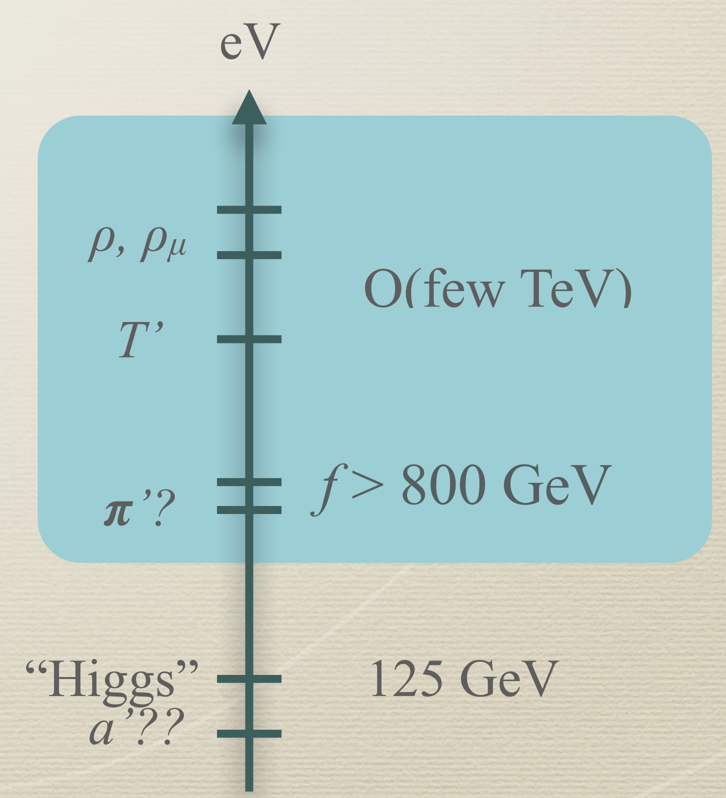
An alternative solution to the hierarchy problem:

- Generate a scale $\Lambda_{HC} << M_{pl}$ 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 Λ_{HC} (vectors, vector-like fermions, scalars),
- additional light pNGBs / an extended sector (?) .
- deviations of the Higgs couplings from their SM values of O(v/f).



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

	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(4)$	$SU(6)$	$U(1)$
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	$\begin{array}{c}\square\\[-4pt]\square\end{array}$	**3**	**1**	$2/3$	**1**	**6**	q_χ
χ_4 χ_5 χ_6	$\begin{array}{c}\square\\[-4pt]\square\end{array}$	$\bar{\mathbf{3}}$	**1**	$-2/3$			

[JHEP1511,201]

Underlying field content

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	$(\mathbf{1},\bar{\mathbf{6}})$	$(\mathbf{1},\mathbf{6})$	ψ_3
$\psi\overline{\chi}\overline{\psi}$	1/2	$(\mathbf{15},\bar{\mathbf{6}})$	$(\mathbf{5},\mathbf{6})$ $(\mathbf{10},\mathbf{6})$	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
$\overline{\chi}\sigma^\mu\chi$	1	$(\mathbf{1},\mathbf{35})$	$(\mathbf{1},\mathbf{20})$ $(\mathbf{1},\mathbf{15})$	a_c ρ_c

[JHEP1511,201]

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

form a and η'; SM singlets

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

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

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

List of "minimal" CHM UV embeddings

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

[JHEP1701,094]

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 = 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:

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

where

r	coset ψ	C_W^ψ	C_B^ψ	coset χ	C_G^χ	C_B^χ
complex	SU(4)×SU(4)/SU(4)	d_ψ	d_ψ	SU(3)×SU(3)/SU(3)	d_χ	$6Y_\chi^2 d_\chi$
real	SU(5)/SO(5)	d_ψ	d_ψ	SU(6)/SO(6)	d_χ	$6Y_\chi^2 d_\chi$
pseudo-real	SU(4)/Sp(4)	$d_\psi/2$	$d_\psi/2$	SU(6)/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 $C^r_{AA'} c^{abc} = d_r \,\text{Tr}[T^a_\pi \{S^b, S^c\}]$

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: [JHEP1701,094]

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:

[JHEP1701,094]

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

[JHEP1701,094]

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

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

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

The masses of the pNGBs are

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

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

Singlet pNGB summary and phenomenology

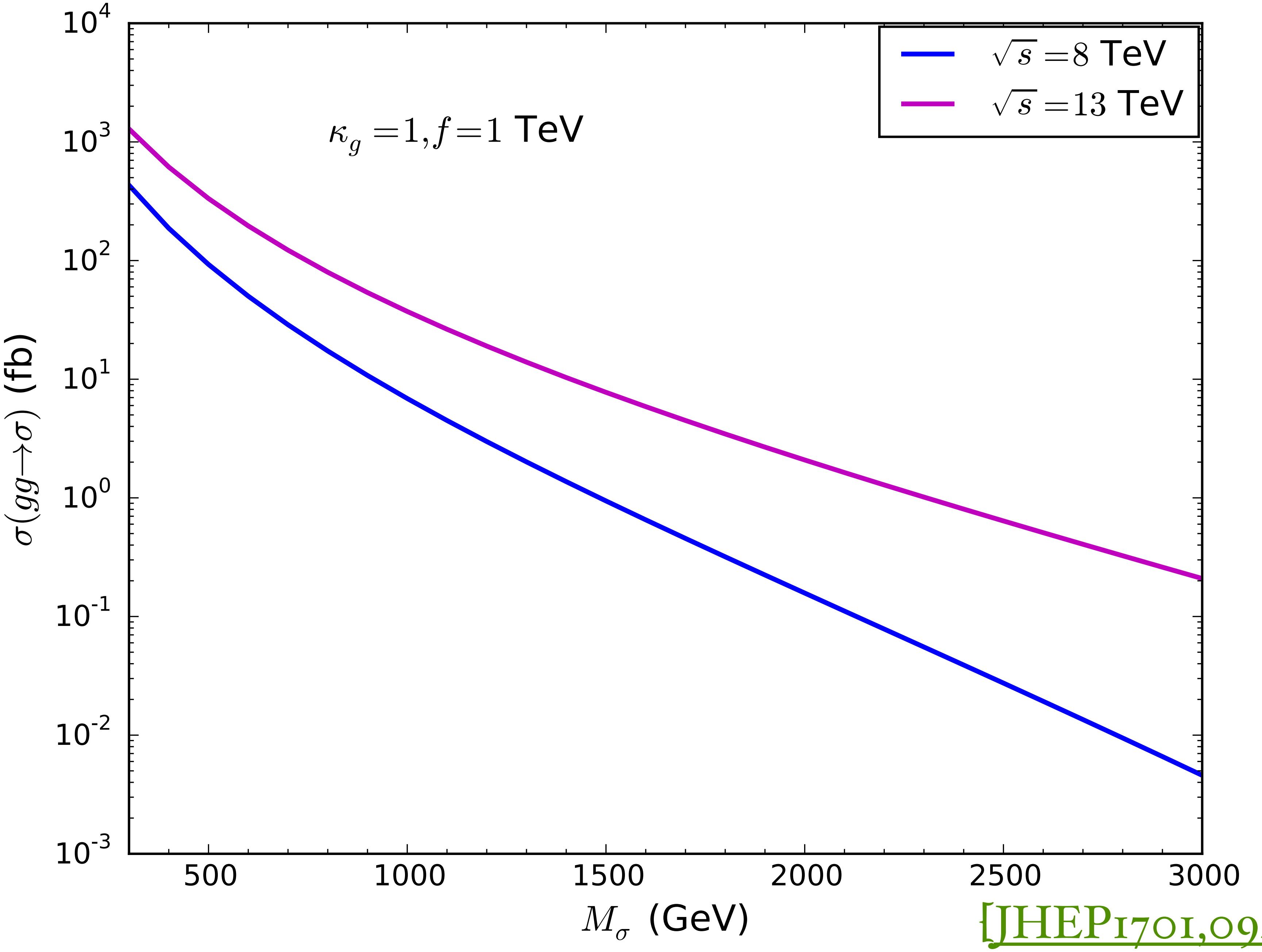
[arXiv:1902.06890]

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

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

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

Production cross section for a pseudo-scalar



[JHEP1701,094]

TCP

	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_ψ/f_χ	1.4	.75	.73	1.3	2.8	1.9	.58	.38	2.3	1.7	.52	.38
f_a/f_ψ	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 η' 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
$(\pm2, 0)$	±1.1 ±1.2	±1.1 ±1.2	±.79 ±1.1	±.73 ±1.1	±1.1 ±1.2	±1.0 ±1.2	±1.1 ±1.2	±.68 ±.92	±.58 ±.89	±.46 ±.85	±.54 ±.88	±.70 ±.92
$(0, \pm2)$	∓.88 ∓.46	∓.45 ∓.23	∓.66 ∓.37	∓1.2 ∓.69	∓1.8 ∓.92	∓1.7 ∓.91	∓.46 ∓.24	∓.23 ∓.12	∓1.5 ∓.86	∓1.2 ∓.72	∓.36 ∓.20	∓.31 ∓.17
$(4, 2)$	−.71 .29	.18 .75	.92 1.9	.24 1.6	−2.5 −.63	−2.4 −.62	.18 .75	1.1 1.7	−.38 .91	−.31 .99	.72 1.5	1.1 1.7
$(-4, 2)$	2.8 2.1	2.0 1.7	−2.2 −2.6	−2.7 −2.9	4.6 3.1	4.5 3.0	2.0 1.7	−1.6 −2.0	−2.7 −2.6	−2.2 −2.4	−1.4 −2.0	−1.7 −2.0

$C_t^{\eta'}$	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
$(\pm2, 0)$	±.69 ±.36	±.66 ±.34	±.99 ±.55	±1.0 ±.58	±.69 ±.36	±.71 ±.37	±.62 ±.32	±.73 ±.40	±.82 ±.46	±.89 ±.52	±.84 ±.48	±.71 ±.39
$(0, \pm2)$	±1.4 ±1.5	±.74 ±.83	±.53 ±.76	±.87 ±1.3	±2.7 ±3.1	±2.6 ±3.0	±.83 ±.92	±.21 ±.28	±1.1 ±1.7	±.64 ±1.2	±.23 ±.37	±.31 ±.40
$(4, 2)$	3.4 3.5	2.1 2.0	2.5 1.9	2.9 2.5	6.1 6.6	5.8 6.3	2.3 2.2	1.7 1.1	2.7 2.6	2.4 2.2	1.9 1.3	1.7 1.2
$(-4, 2)$	−2.0 −2.7	−.82 −1.3	−1.5 −.33	−1.2 .17	−4.7 −5.8	−4.4 −5.6	−1.0 −1.5	−1.3 −.51	−.55 .75	−1.1 .15	−1.5 −.59	−1.1 −.37

TABLE IV. Coupling of a and η' 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 $(2, -4)$.

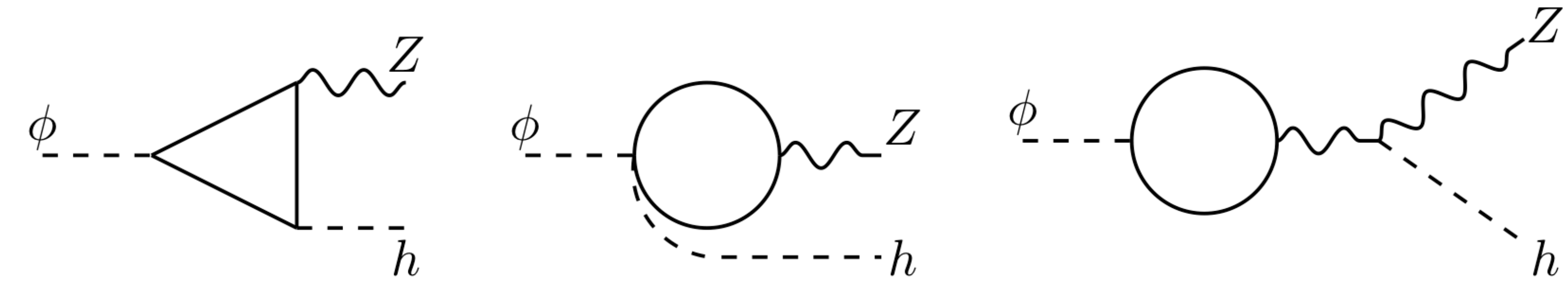
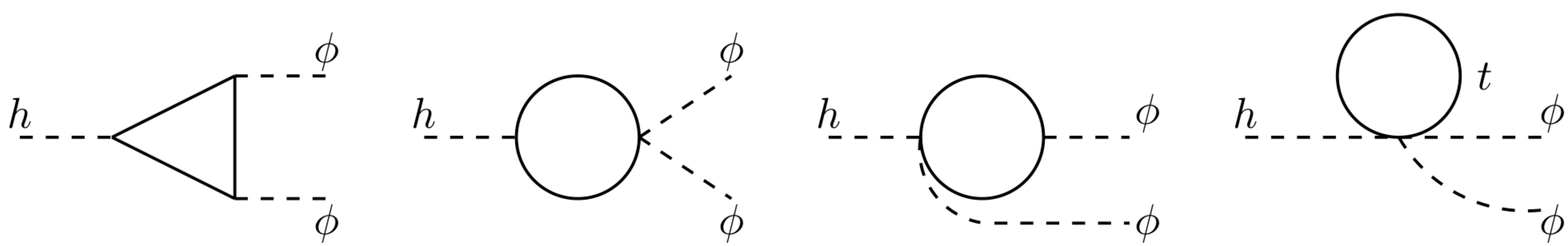


FIG. 1. Leading contributions to the decay $\phi \to Zh$.

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



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

TCP

SM singlet branching ratios

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

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

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

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

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

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

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

TCP

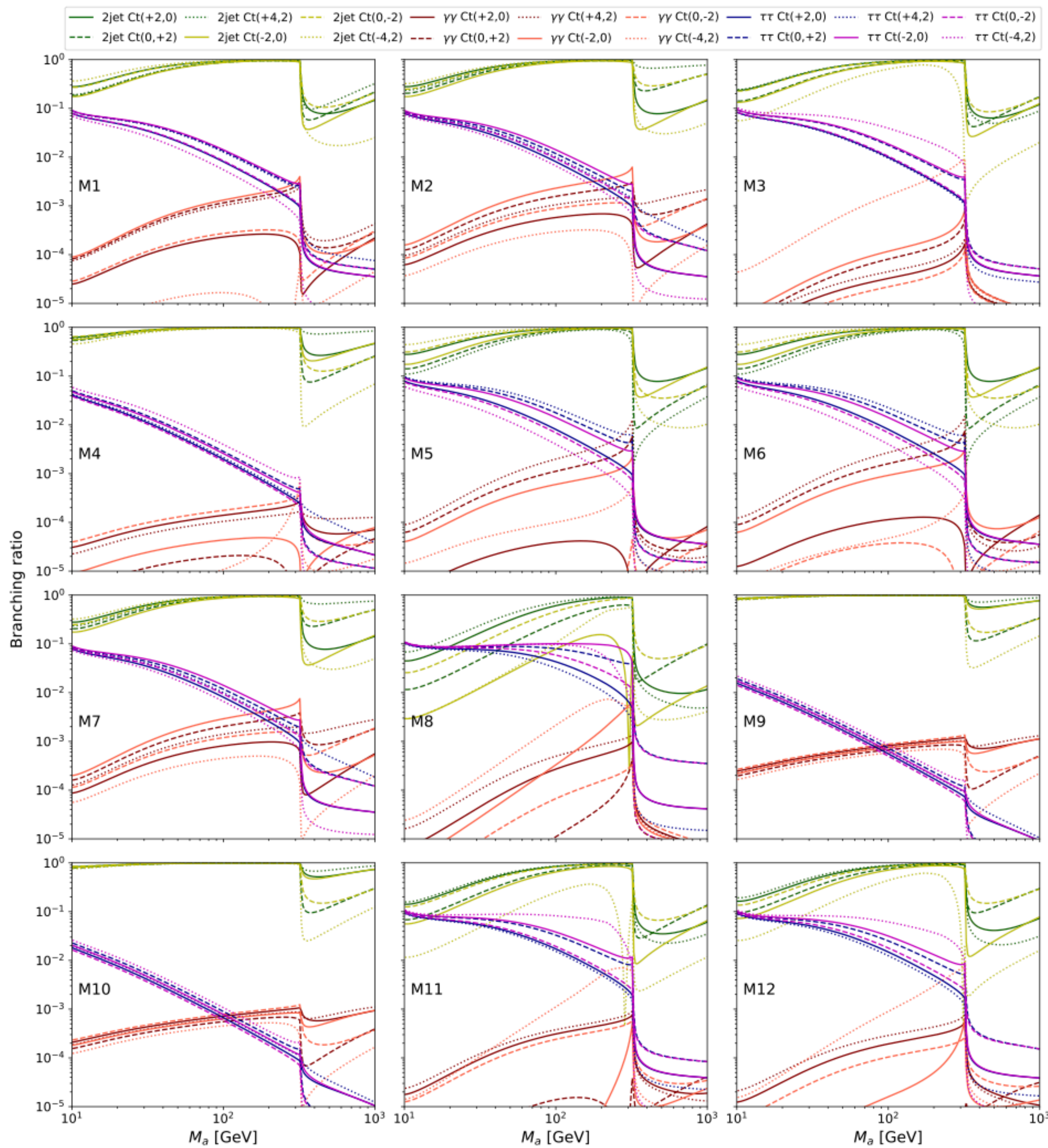
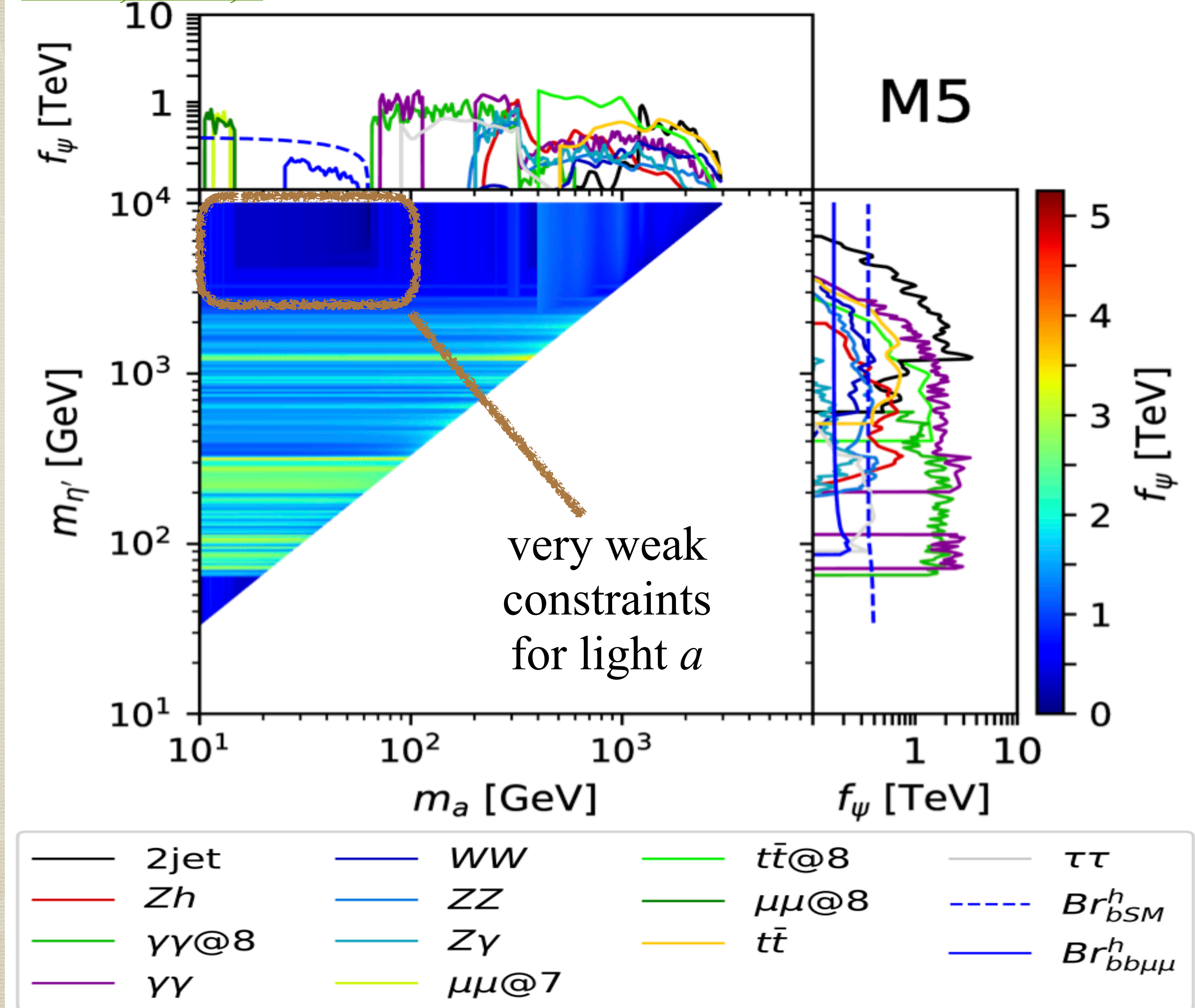


FIG. 7. Representative Branching Ratios of a in the decoupling limit for all models and for the six choices of top partner charges. We only show gg (light and dark green), $\gamma\gamma$ (brown and red) and $\tau\tau$ (purple and lilac).

a and *η'*: 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]



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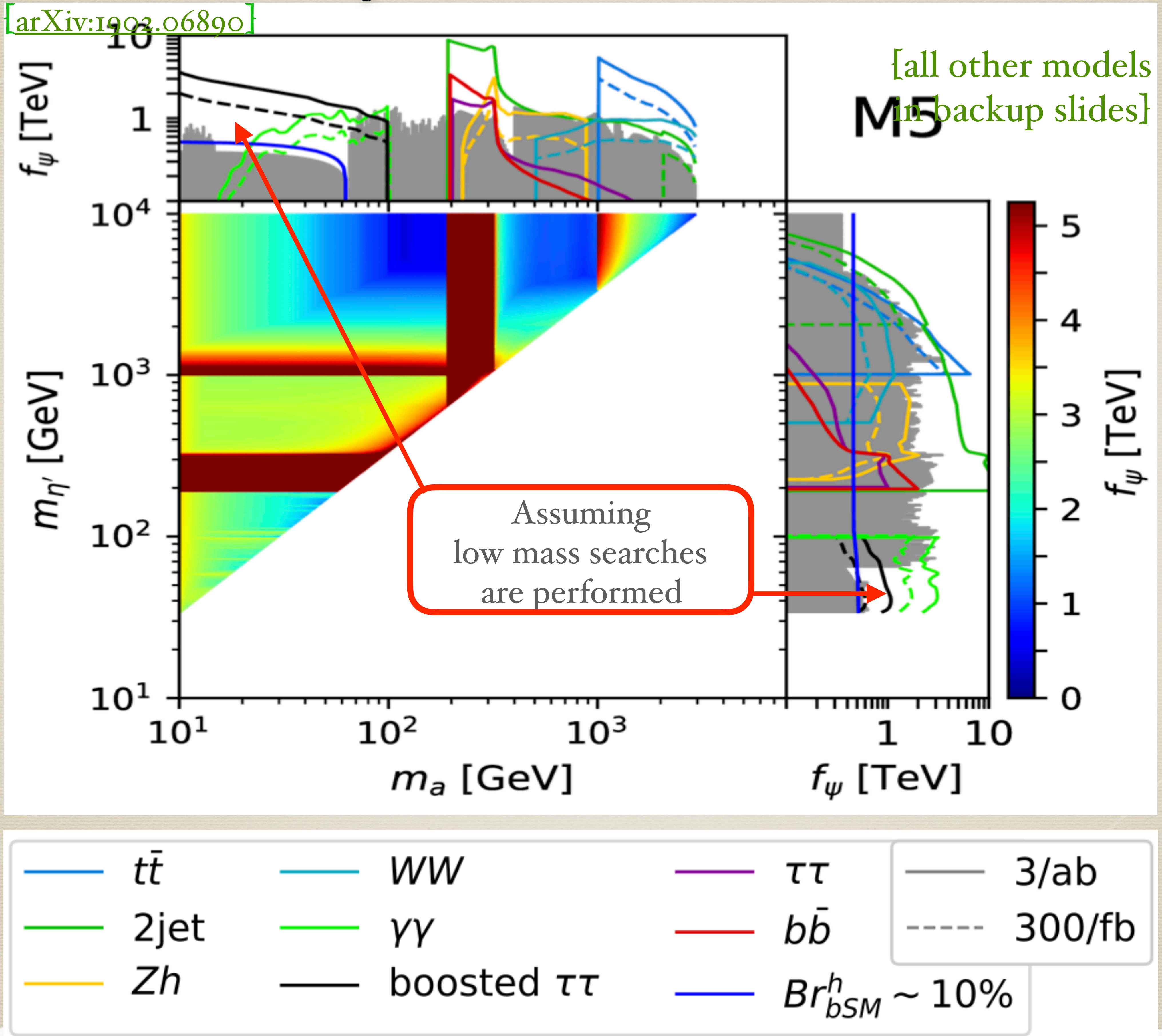
Projected reach at HL-LHC

[arXiv:1902.06890]

[all other models in backup slides]



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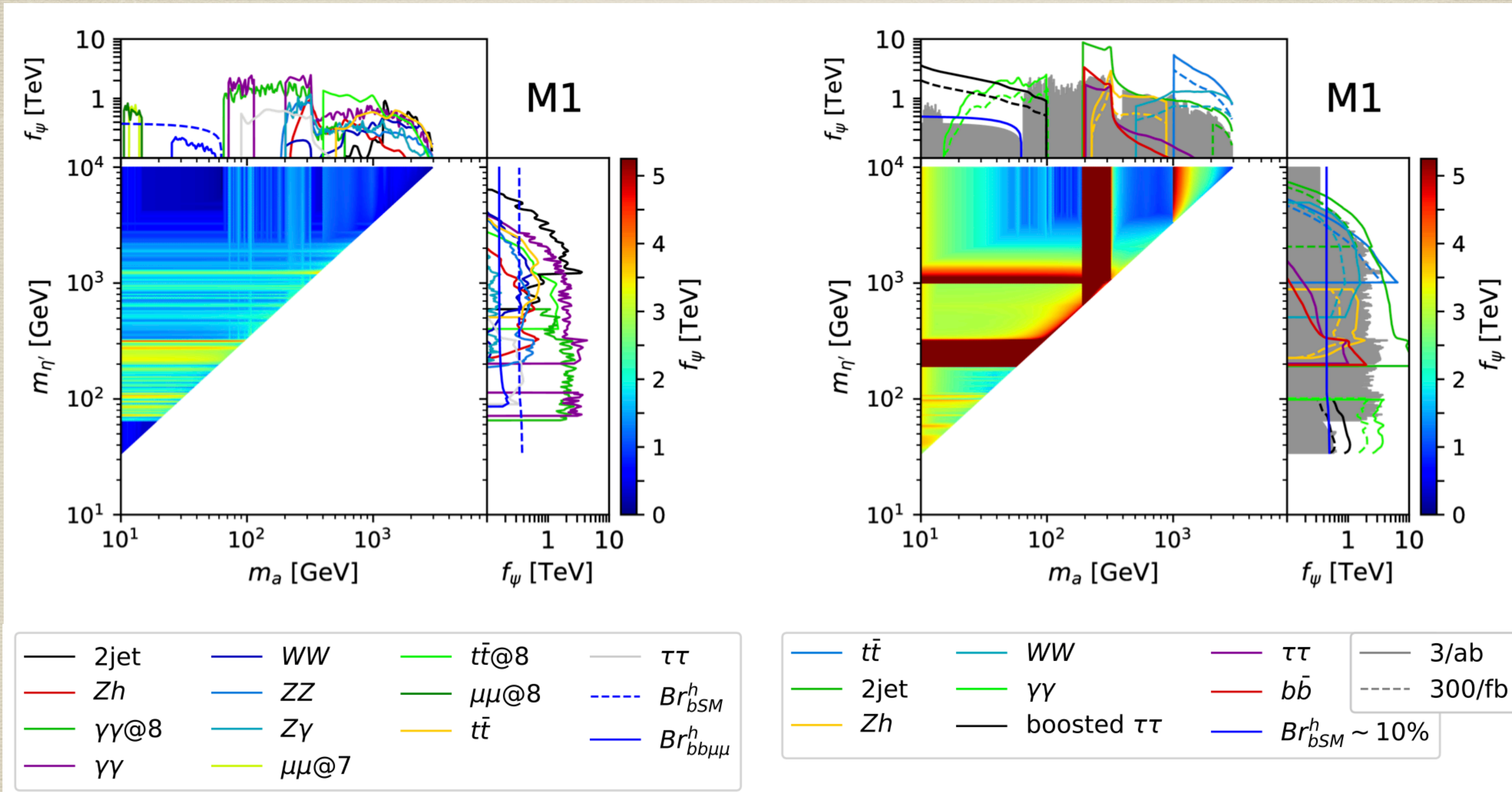
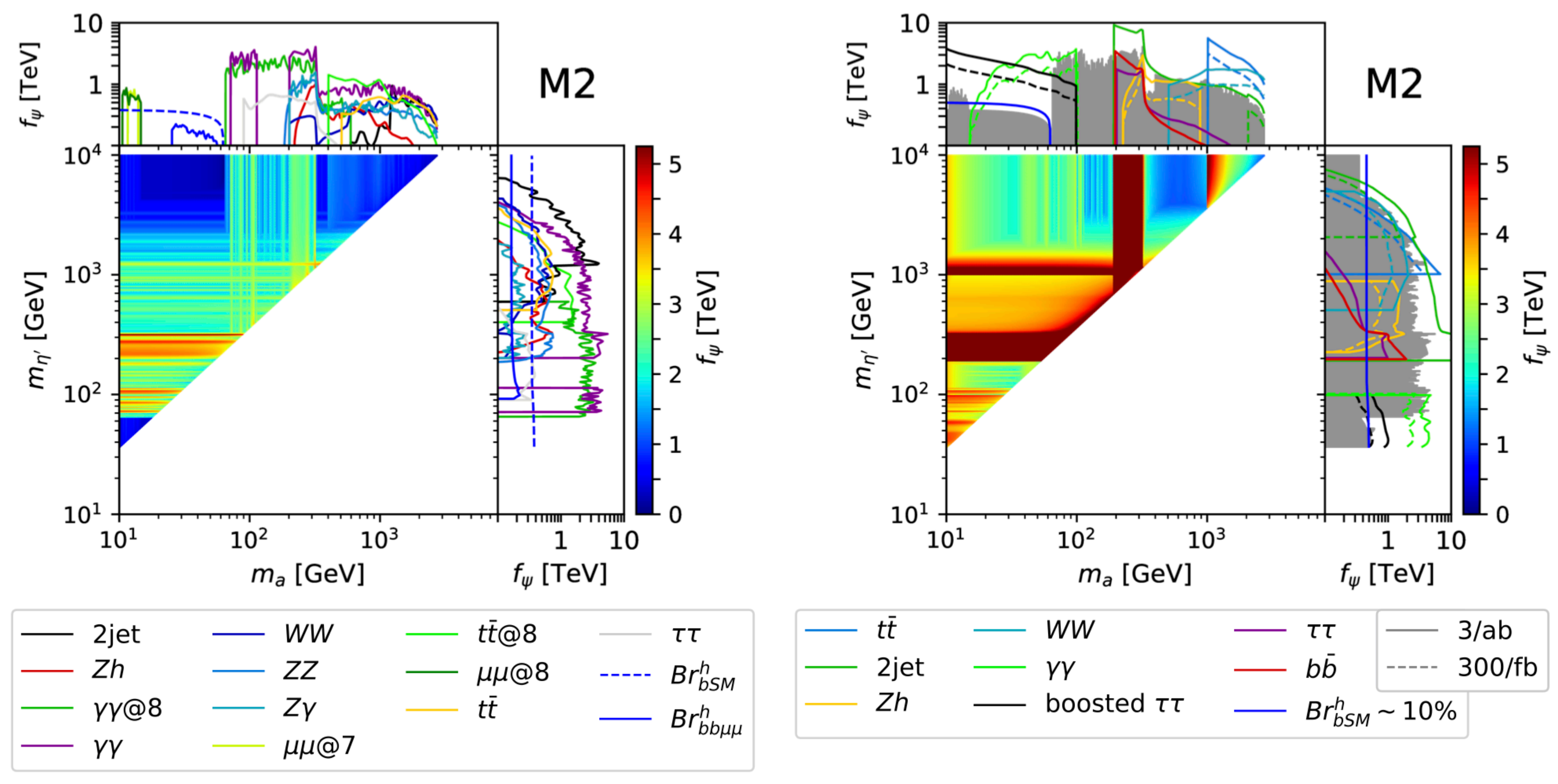
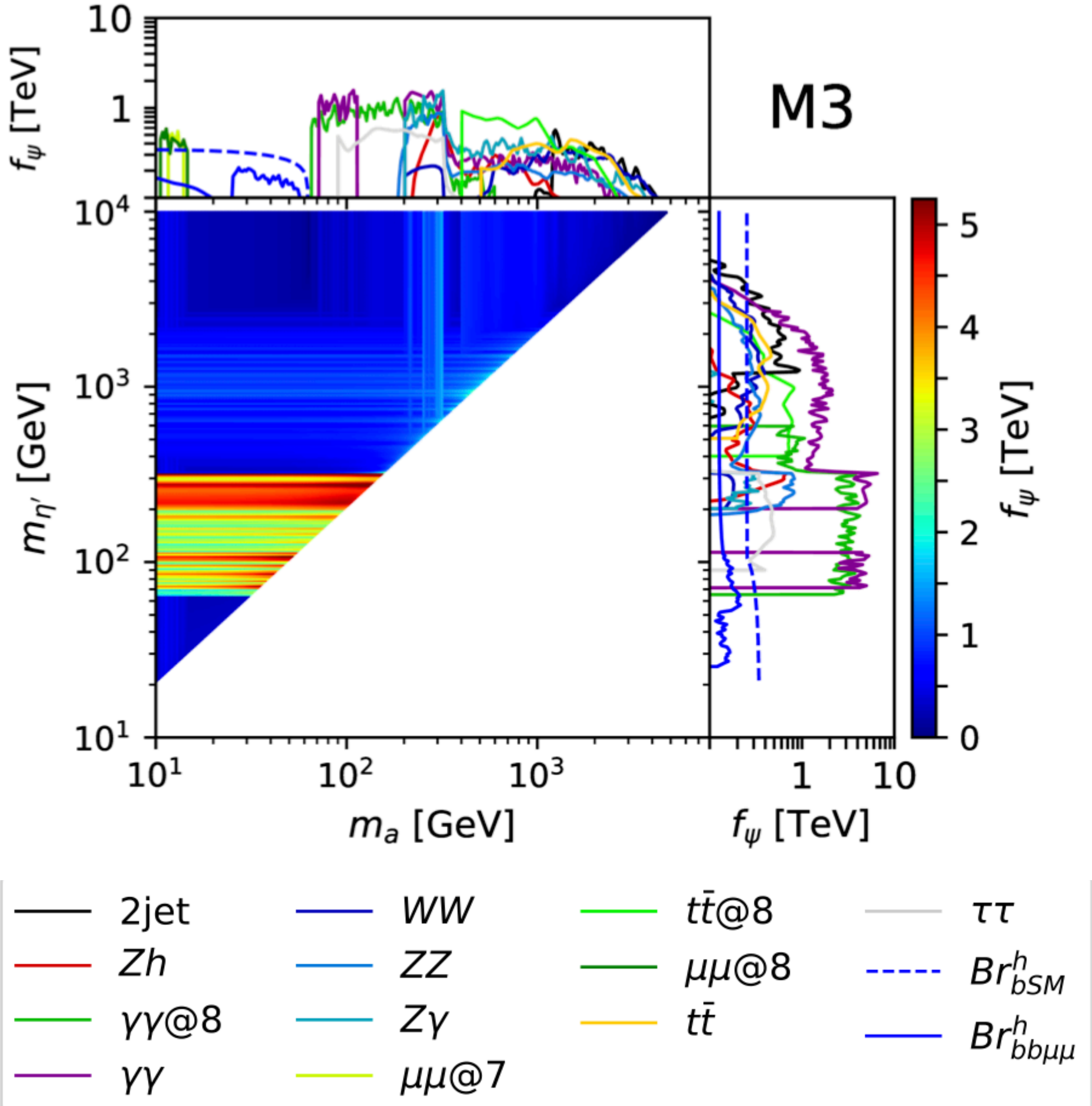
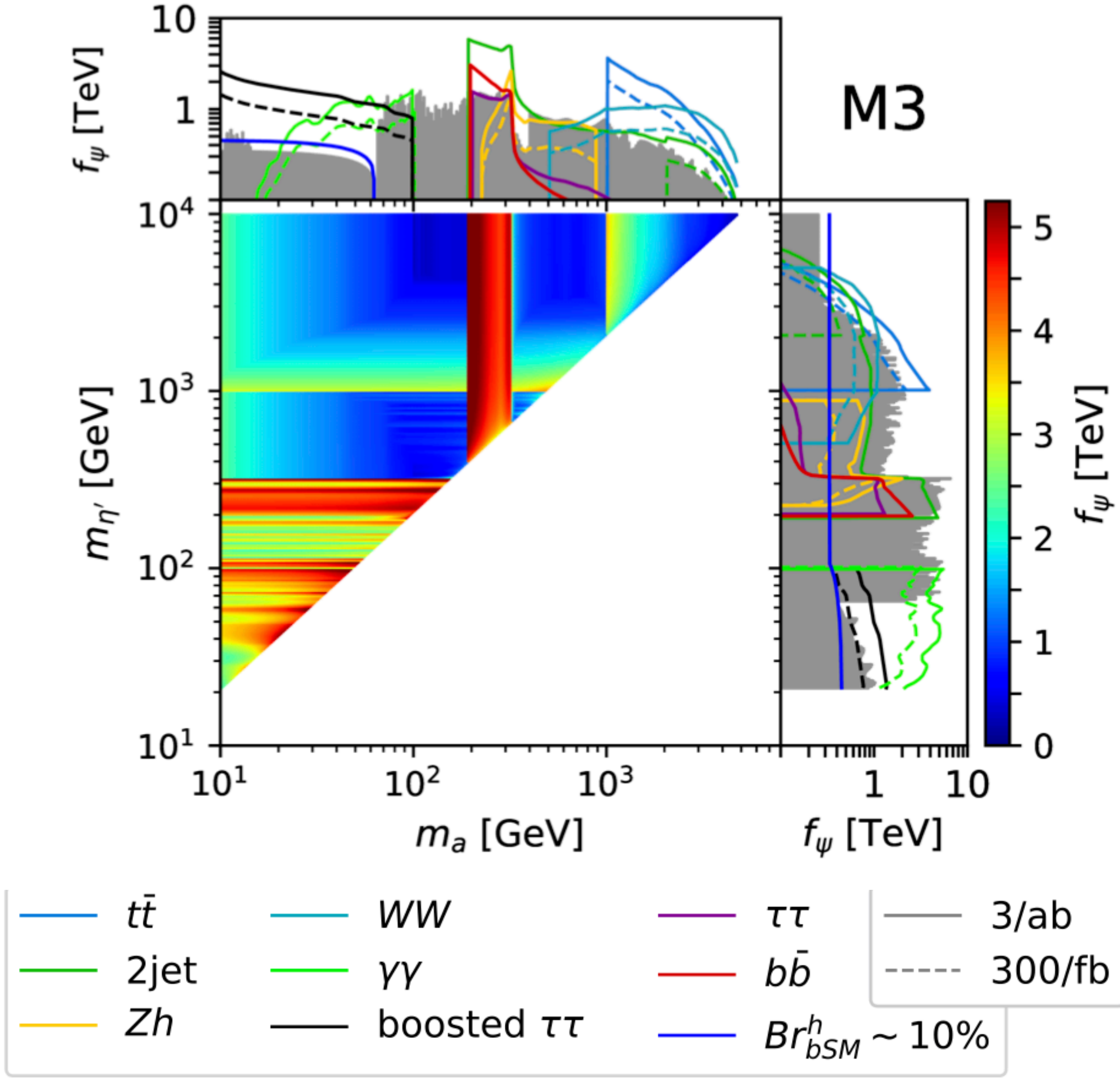


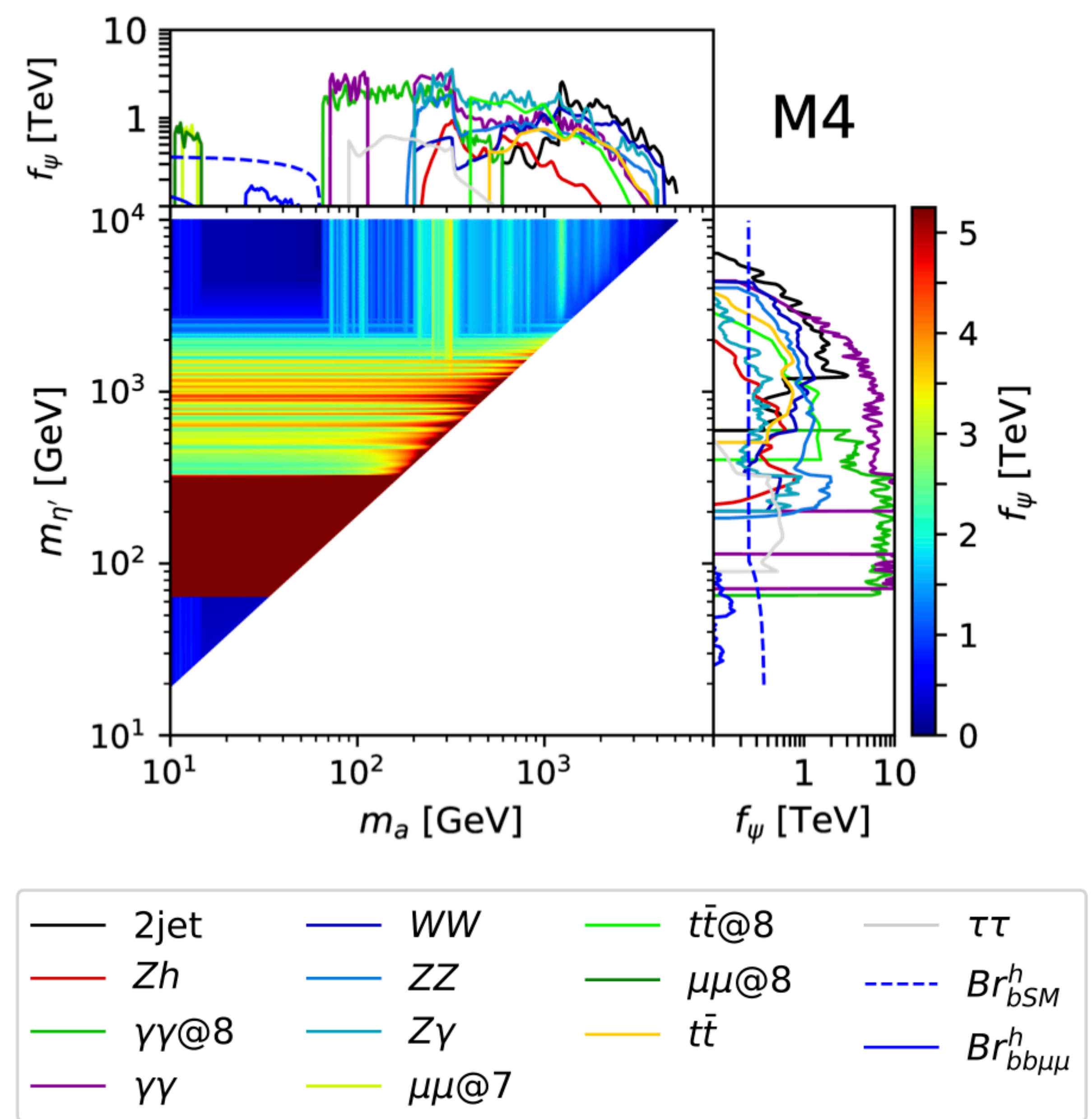
M1
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
f_ψ [TeV]
2jet
Zh
$\gamma\gamma$@8
$\gamma\gamma$
WW
ZZ
$Z\gamma$
$\mu\mu$@7
$t\bar{t}$@8
$\mu\mu$@8
$t\bar{t}$
$\tau\tau$
Br^h_{bSM}
$Br^h_{bb\mu\mu}$
M1
$t\bar{t}$
2jet
Zh
WW
$\gamma\gamma$
boosted $\tau\tau$
$\tau\tau$
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb

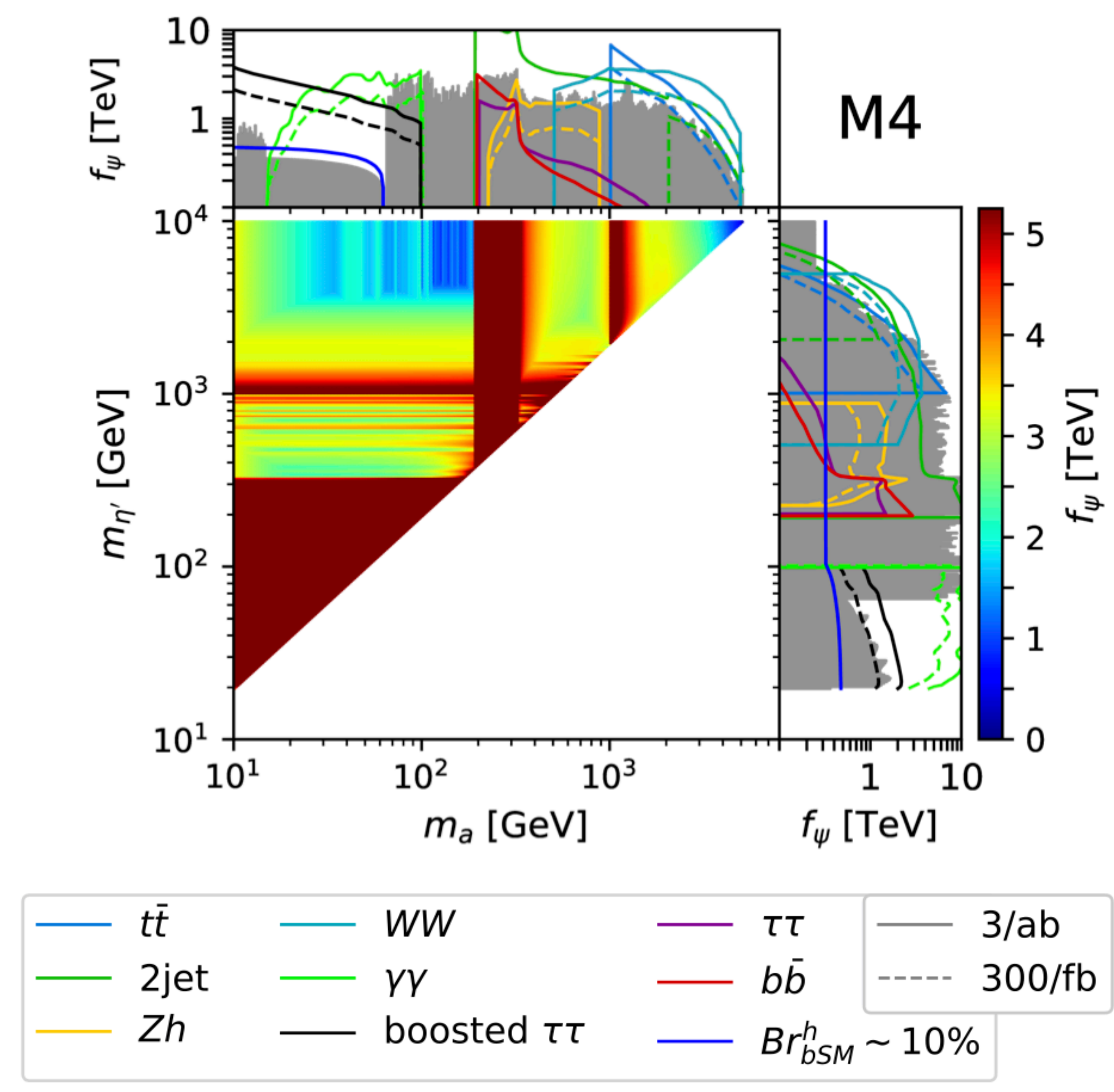
TCP

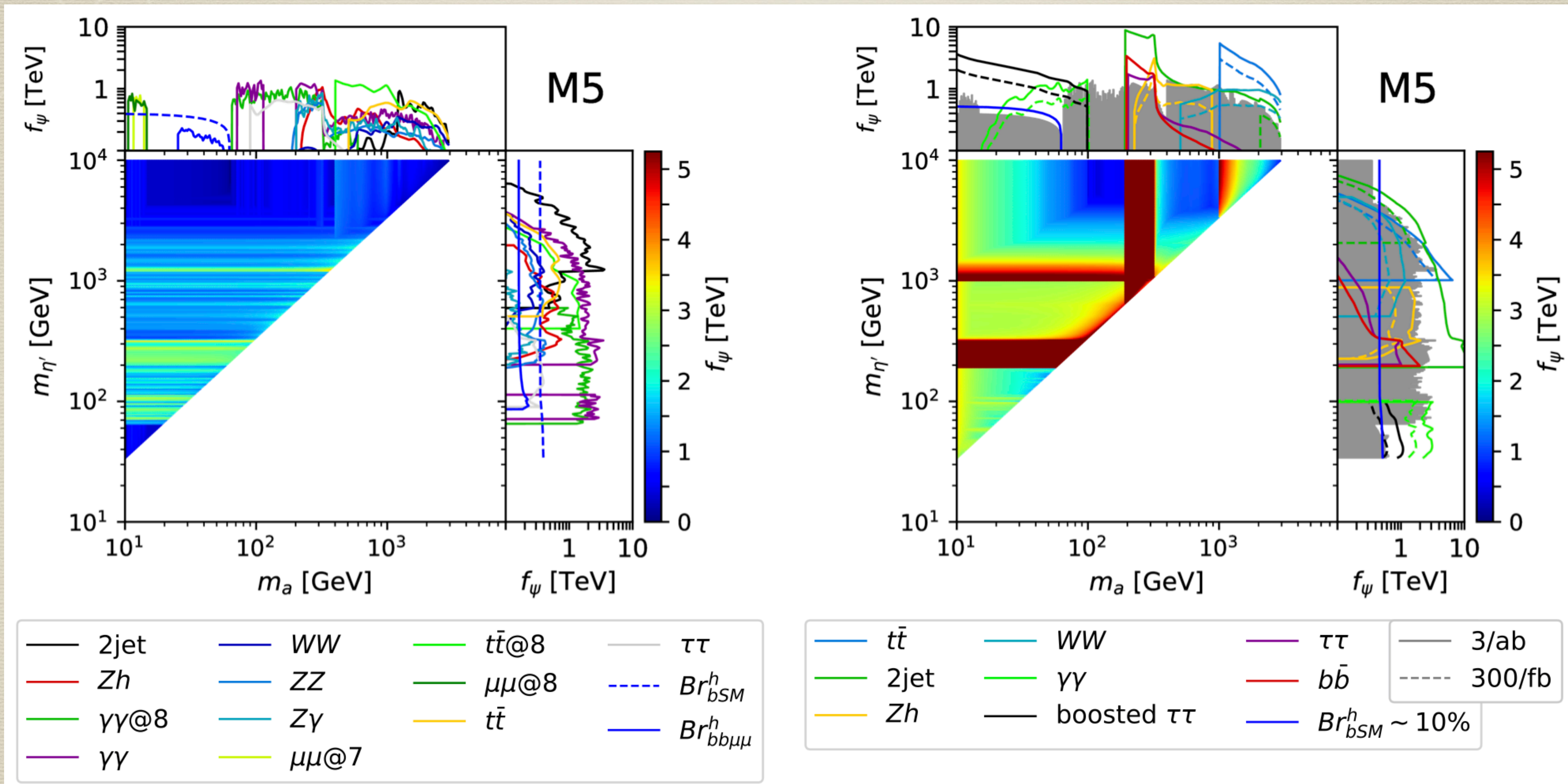

M2
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
2jet
Zh
$\gamma\gamma$@8
$\gamma\gamma$
WW
ZZ
$Z\gamma$
$\mu\mu$@7
$t\bar{t}$@8
$\mu\mu$@8
$t\bar{t}$
$\tau\tau$
Br^h_{bSM}
$Br^h_{bb\mu\mu}$
M2
$t\bar{t}$
2jet
Zh
WW
$\gamma\gamma$
boosted $\tau\tau$
$\tau\tau$
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb

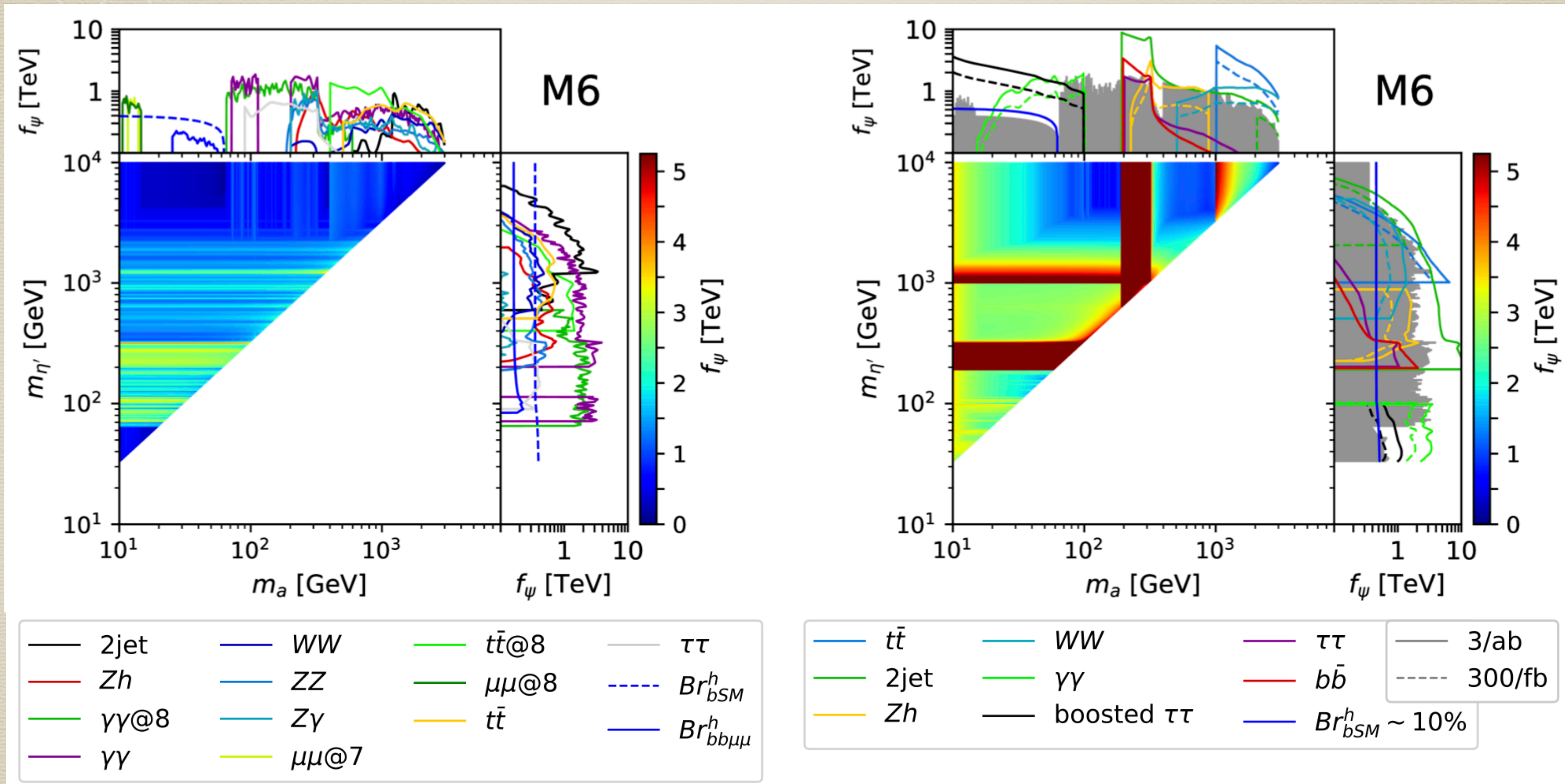

M3
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
2jet
Zh
$\gamma\gamma$@8
$\gamma\gamma$
WW
ZZ
$Z\gamma$
$\mu\mu$@7
$t\bar{t}$@8
$\mu\mu$@8
$t\bar{t}$
$\tau\tau$
Br^h_{bSM}
$Br^h_{bb\mu\mu}$


M3
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
$t\bar{t}$
2jet
Zh
WW
$\gamma\gamma$
boosted $\tau\tau$
$\tau\tau$
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb


M4
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
f_ψ [TeV]
f_ψ [TeV]
2jet
Zh
$\gamma\gamma$@8
$\gamma\gamma$
WW
ZZ
$Z\gamma$
$\mu\mu$@7
$t\bar{t}$@8
$\mu\mu$@8
$t\bar{t}$
$\tau\tau$
Br^h_{bSM}
$Br^h_{bb\mu\mu}$

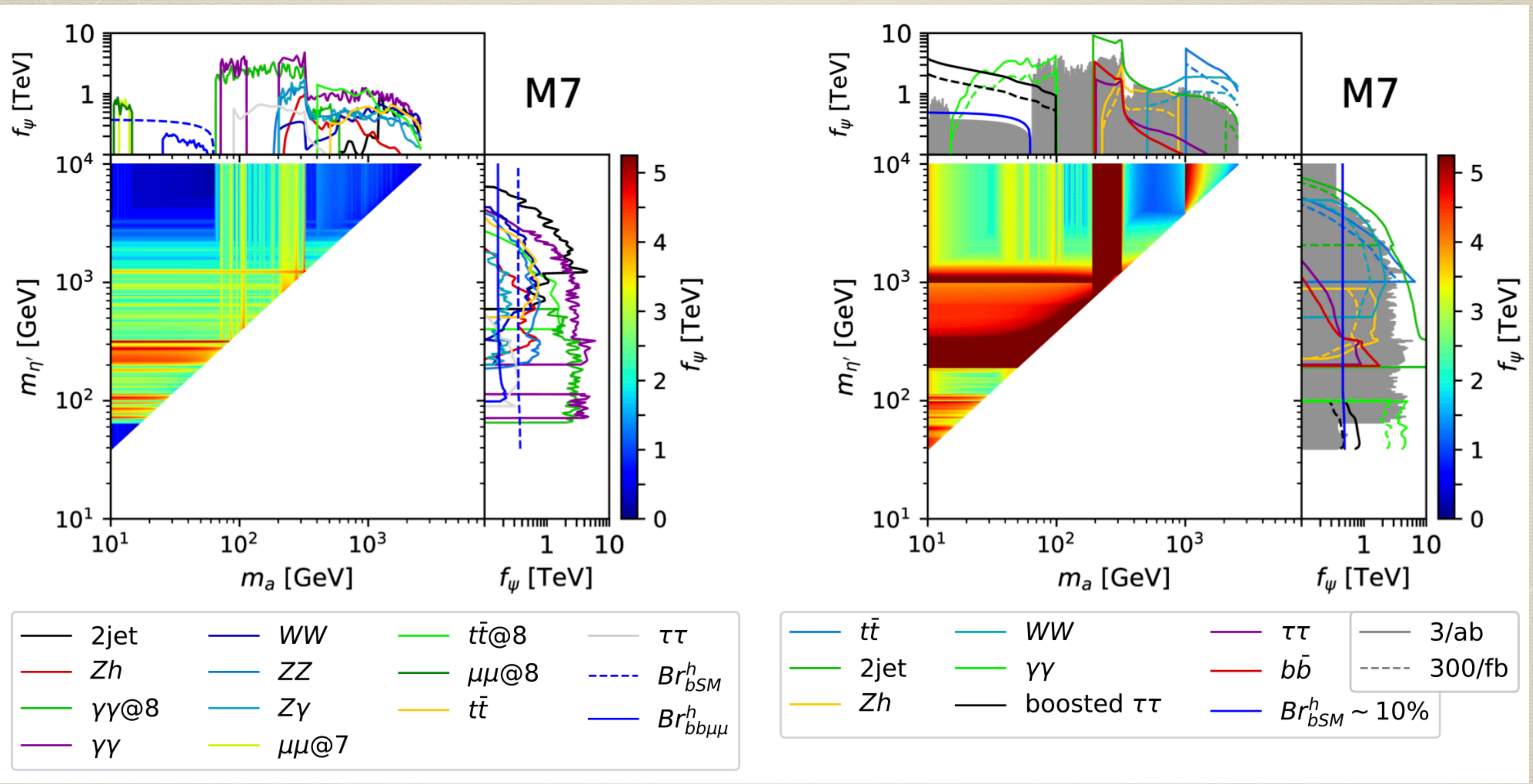

M4
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
f_ψ [TeV]
f_ψ [TeV]
$t\bar{t}$
2jet
Zh
WW
$\gamma\gamma$
boosted $\tau\tau$
$\tau\tau$
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb

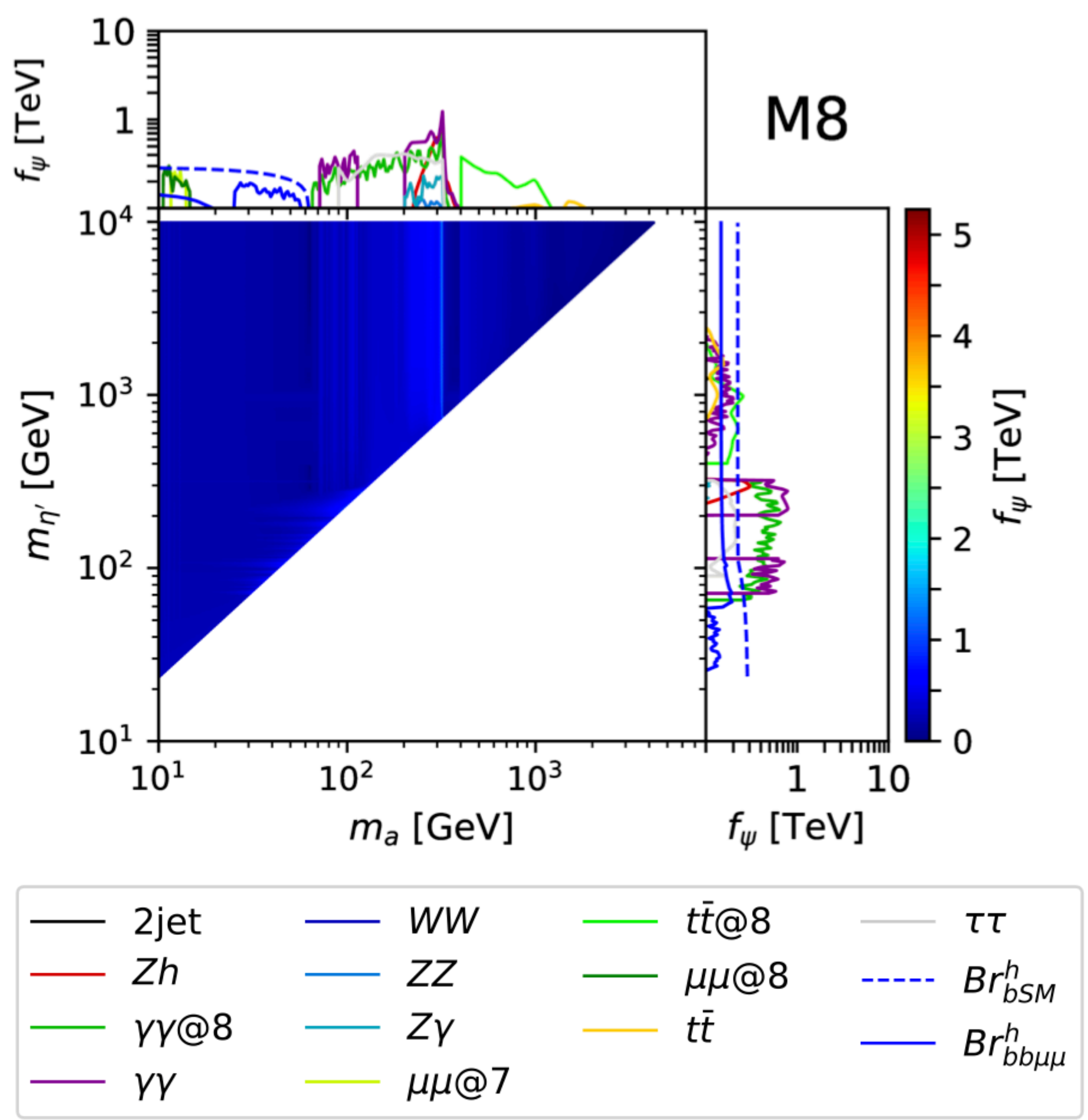

M5
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
2jet
Zh
$\gamma\gamma$@8
$\gamma\gamma$
WW
ZZ
$Z\gamma$
$\mu\mu$@7
$t\bar{t}$@8
$\mu\mu$@8
$t\bar{t}$
$\tau\tau$
Br^h_{bSM}
$Br^h_{bb\mu\mu}$
M5
$t\bar{t}$
2jet
Zh
WW
$\gamma\gamma$
boosted $\tau\tau$
$\tau\tau$
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb

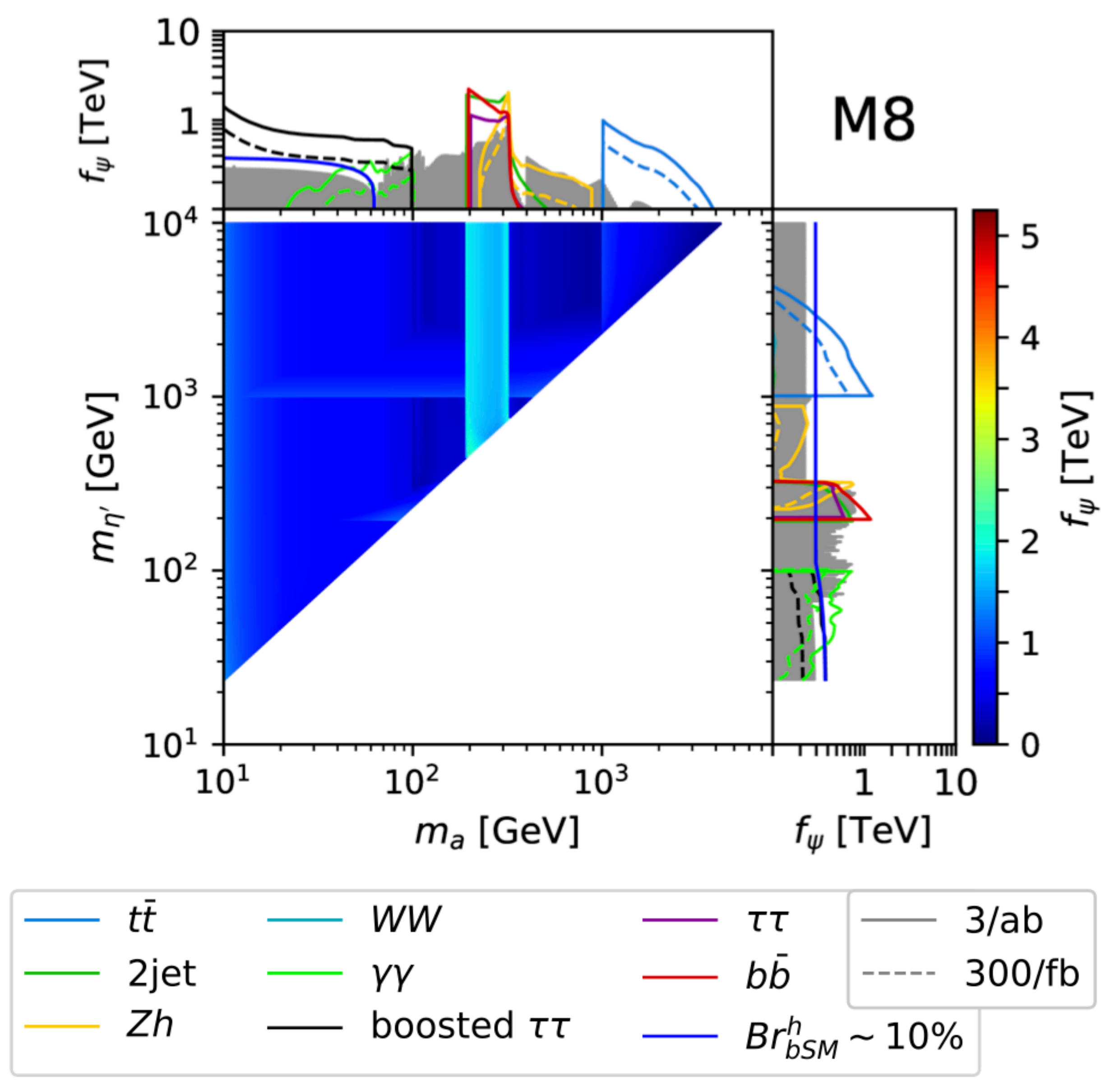


M6
M6
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
f_ψ [TeV]
2jet
Zh
$\gamma\gamma$@8
$\gamma\gamma$
WW
ZZ
$Z\gamma$
$\mu\mu$@7
$t\bar{t}$@8
$\mu\mu$@8
$t\bar{t}$
$\tau\tau$
Br^h_{bSM}
$Br^h_{bb\mu\mu}$
$t\bar{t}$
2jet
Zh
WW
$\gamma\gamma$
boosted $\tau\tau$
$\tau\tau$
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb

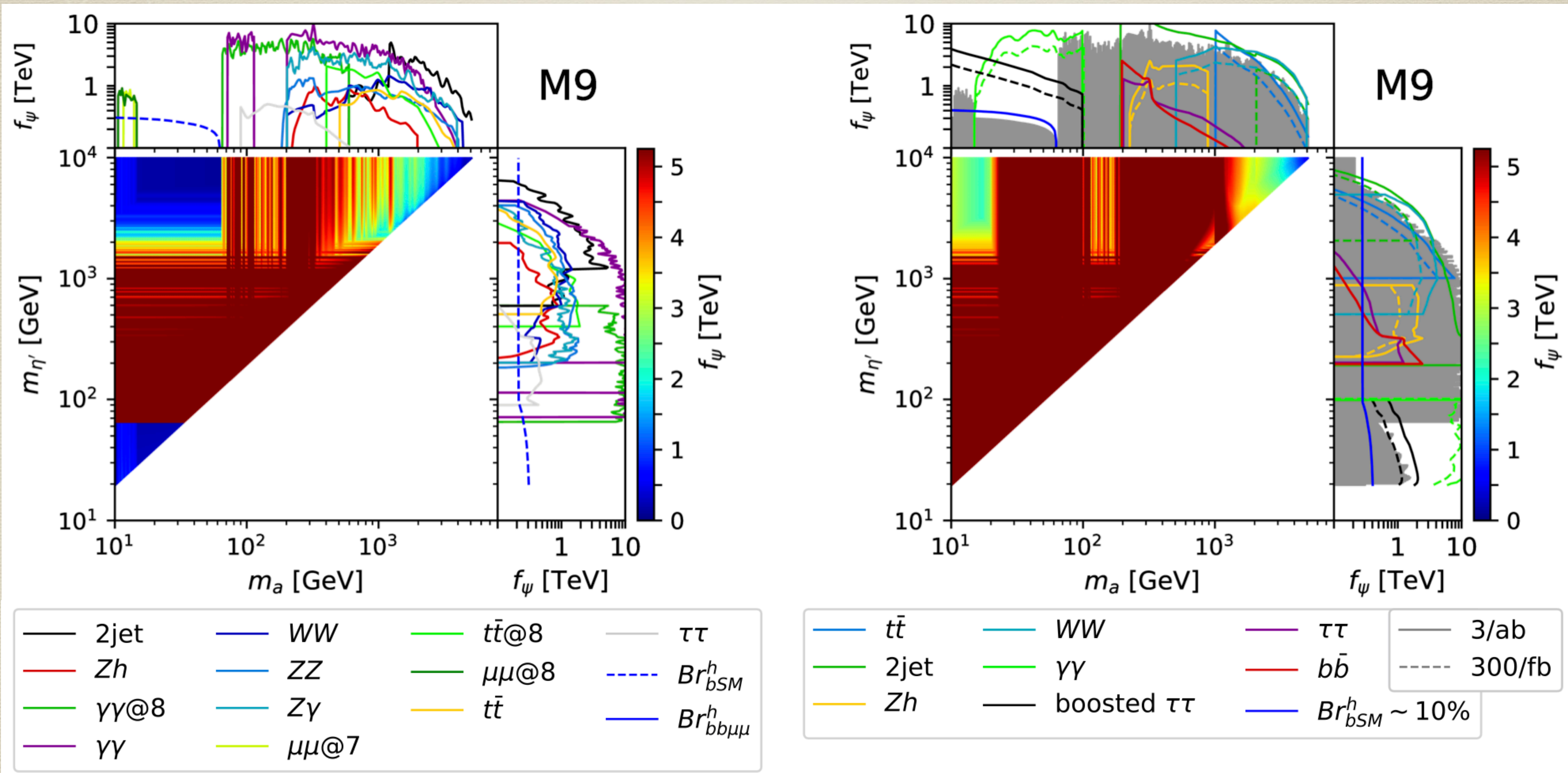
TCP

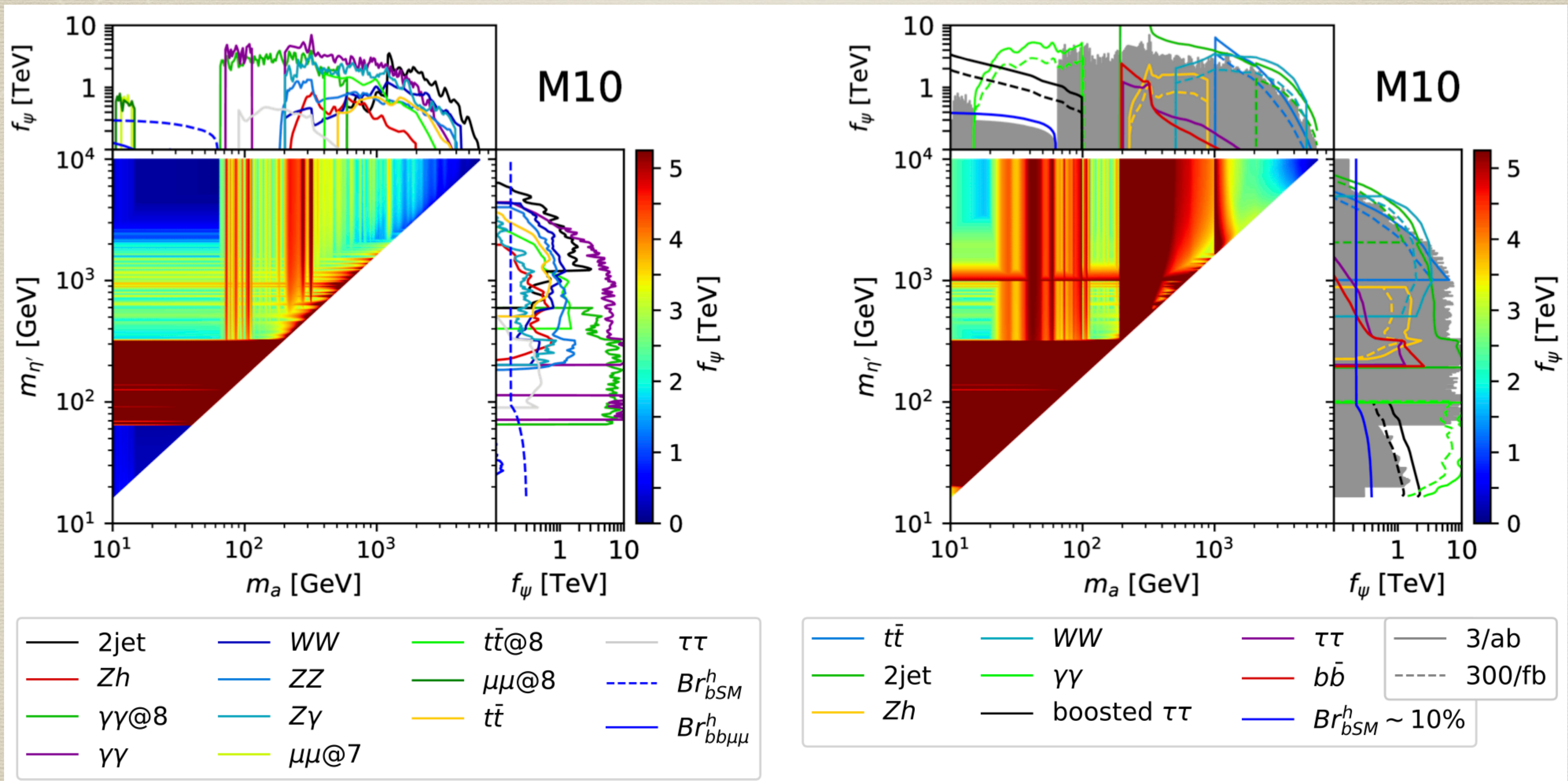

M7
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
2jet
Zh
γγ@8
γγ
WW
ZZ
Zγ
μμ@7
$t\bar{t}$@8
μμ@8
$t\bar{t}$
ττ
Br^h_{bSM}
$Br^h_{bb\mu\mu}$
M7
$t\bar{t}$
2jet
Zh
WW
γγ
boosted ττ
ττ
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb

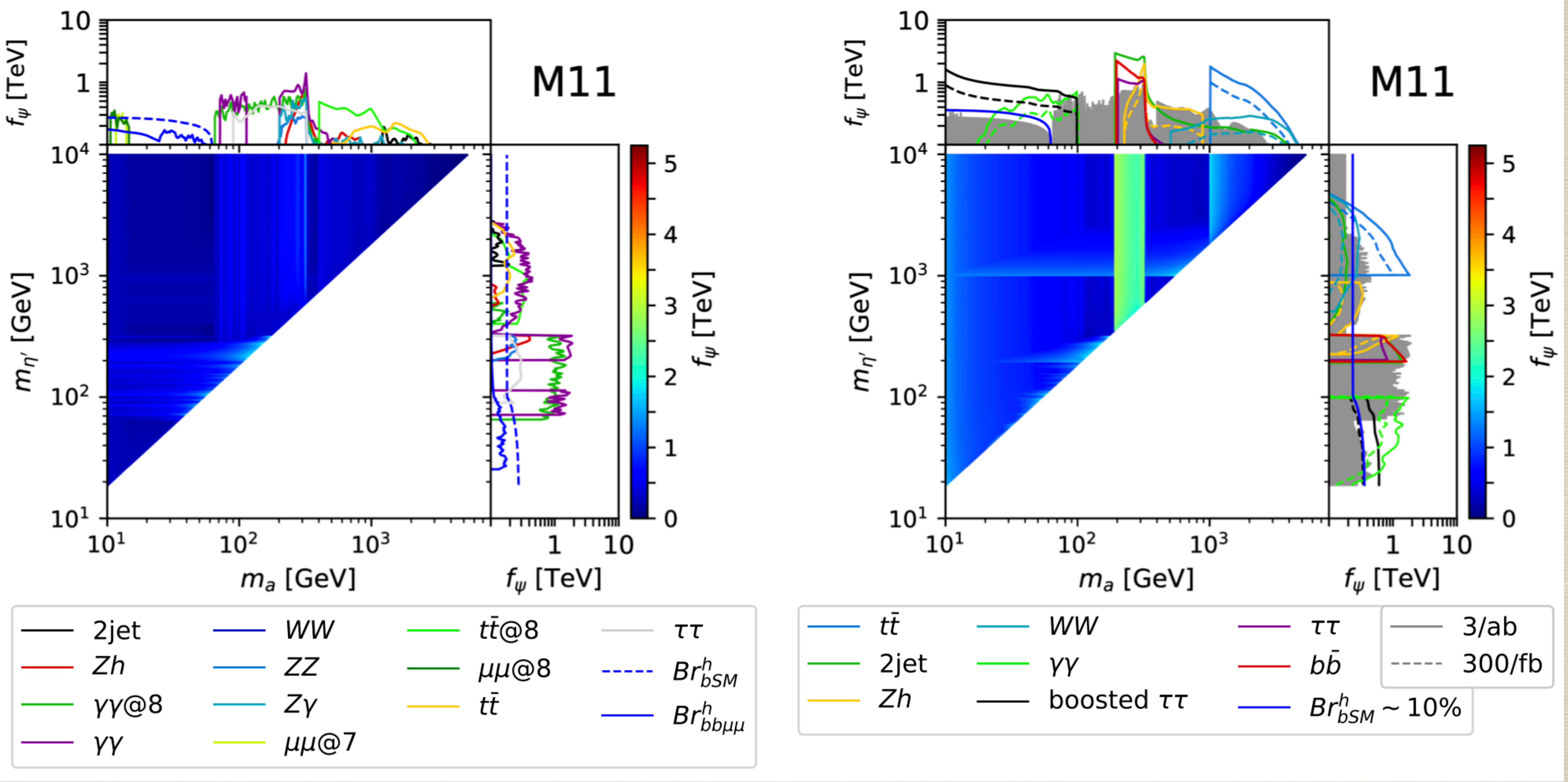

M8
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
2jet
Zh
$\gamma\gamma$@8
$\gamma\gamma$
WW
ZZ
$Z\gamma$
$\mu\mu$@7
$t\bar{t}$@8
$\mu\mu$@8
$t\bar{t}$
$\tau\tau$
Br^h_{bSM}
$Br^h_{bb\mu\mu}$


M8
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
$t\bar{t}$
2jet
Zh
WW
$\gamma\gamma$
boosted $\tau\tau$
$\tau\tau$
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb

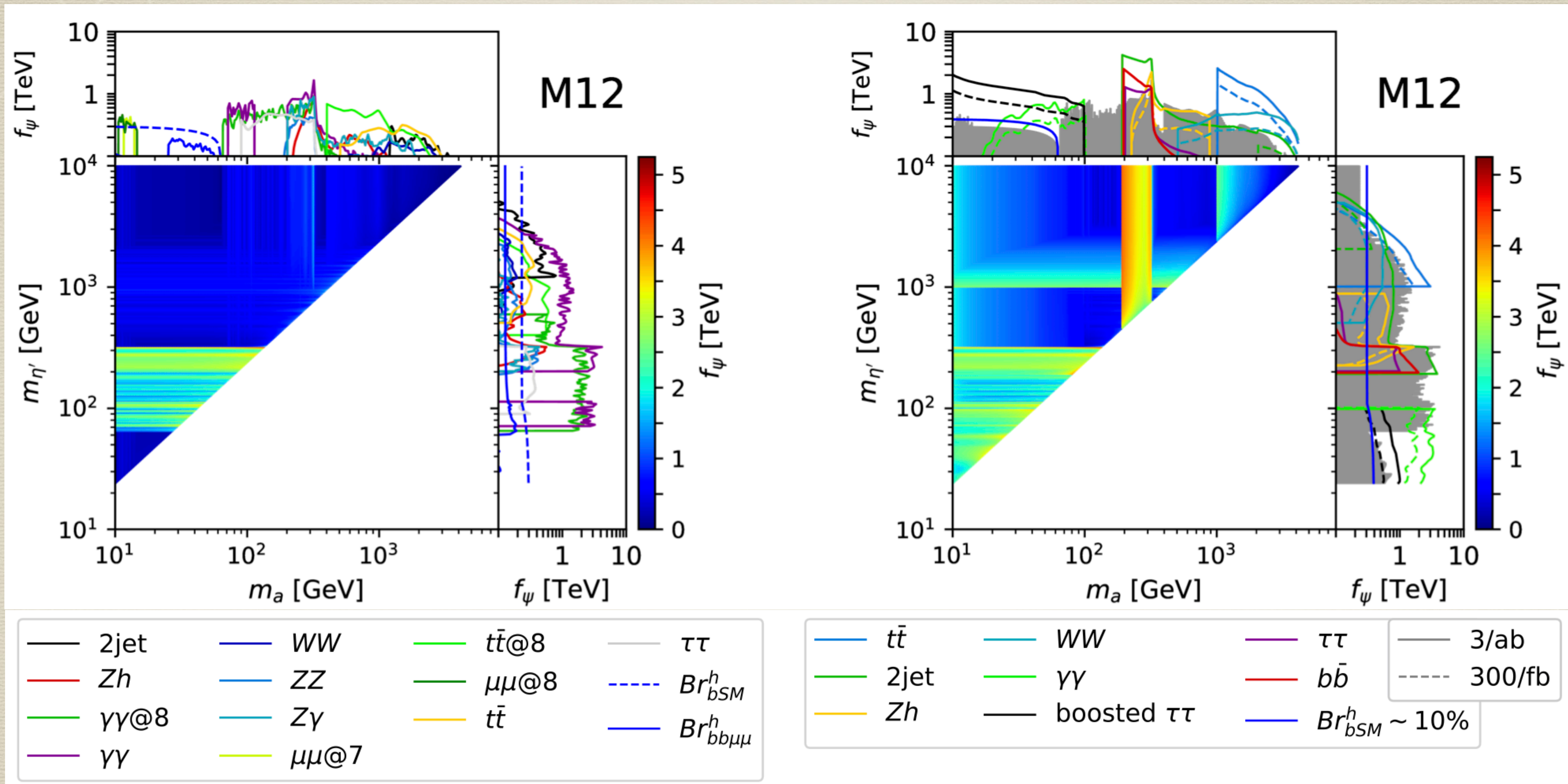
TCP


M9
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
2jet
Zh
$\gamma\gamma$@8
$\gamma\gamma$
WW
ZZ
$Z\gamma$
$\mu\mu$@7
$t\bar{t}$@8
$\mu\mu$@8
$t\bar{t}$
$\tau\tau$
Br^h_{bSM}
$Br^h_{bb\mu\mu}$
M9
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
$t\bar{t}$
2jet
Zh
WW
$\gamma\gamma$
boosted $\tau\tau$
$\tau\tau$
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb

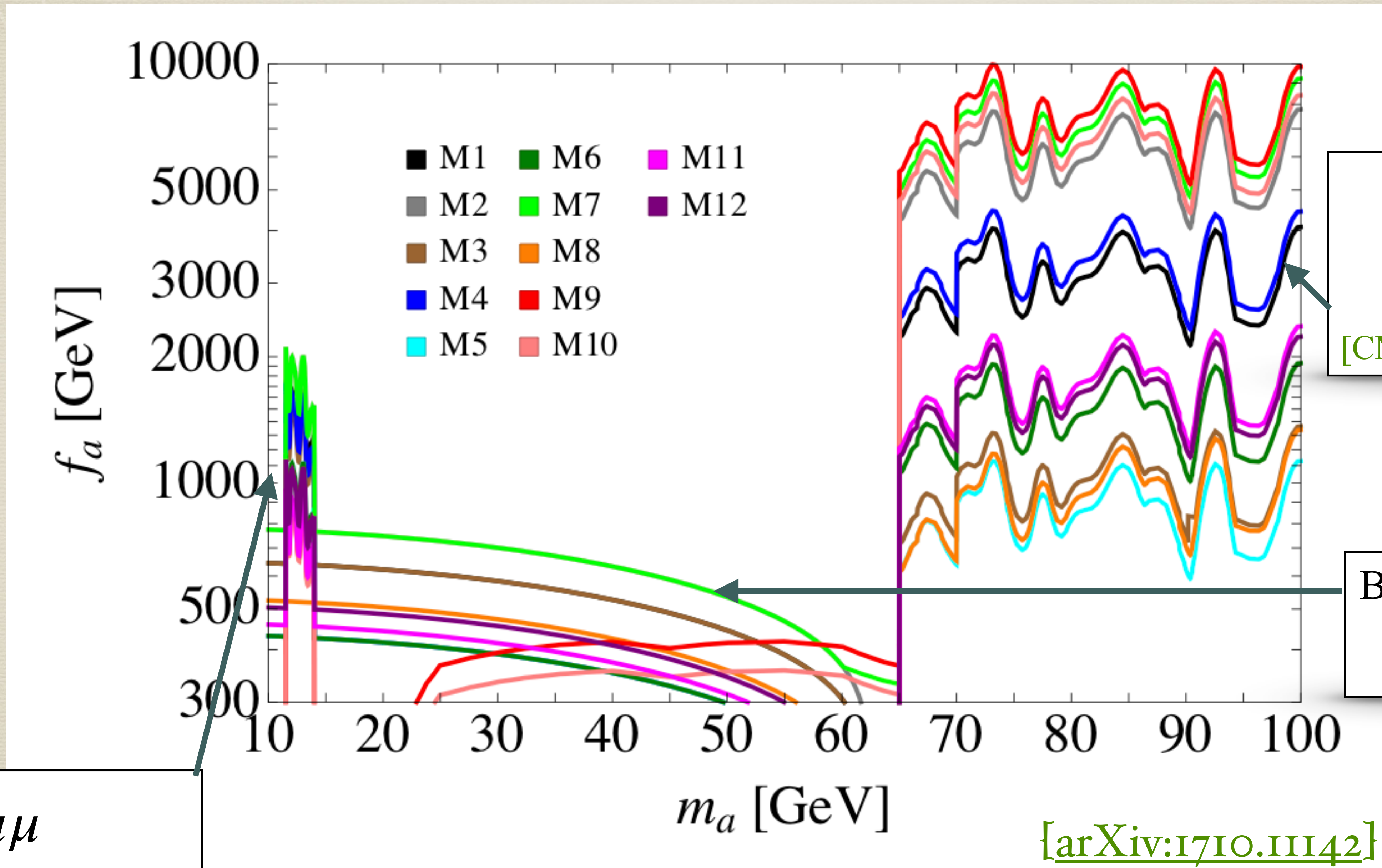

M10
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
f_ψ [TeV]
2jet
Zh
$\gamma\gamma$@8
$\gamma\gamma$
WW
ZZ
$Z\gamma$
$\mu\mu$@7
$t\bar{t}$@8
$\mu\mu$@8
$t\bar{t}$
$\tau\tau$
Br^h_{bSM}
$Br^h_{bb\mu\mu}$
M10
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
f_ψ [TeV]
$t\bar{t}$
2jet
Zh
WW
$\gamma\gamma$
boosted $\tau\tau$
$\tau\tau$
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb



M11
M11
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
2jet
Zh
$\gamma\gamma$@8
$\gamma\gamma$
WW
ZZ
$Z\gamma$
$\mu\mu$@7
$t\bar{t}$@8
$\mu\mu$@8
$t\bar{t}$
$\tau\tau$
Br^h_{bSM}
$Br^h_{bb\mu\mu}$
$t\bar{t}$
2jet
Zh
WW
$\gamma\gamma$
boosted $\tau\tau$
$\tau\tau$
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb


M12
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
2jet
Zh
$\gamma\gamma$@8
$\gamma\gamma$
WW
ZZ
$Z\gamma$
$\mu\mu$@7
$t\bar{t}$@8
$\mu\mu$@8
$t\bar{t}$
$\tau\tau$
Br^h_{bSM}
$Br^h_{bb\mu\mu}$
M12
$t\bar{t}$
2jet
Zh
WW
$\gamma\gamma$
boosted $\tau\tau$
$\tau\tau$
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb

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



$\gamma\gamma$

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

BR(h→BSM)<.34

[JHEP1608, 045]
(ATLAS+CMS)

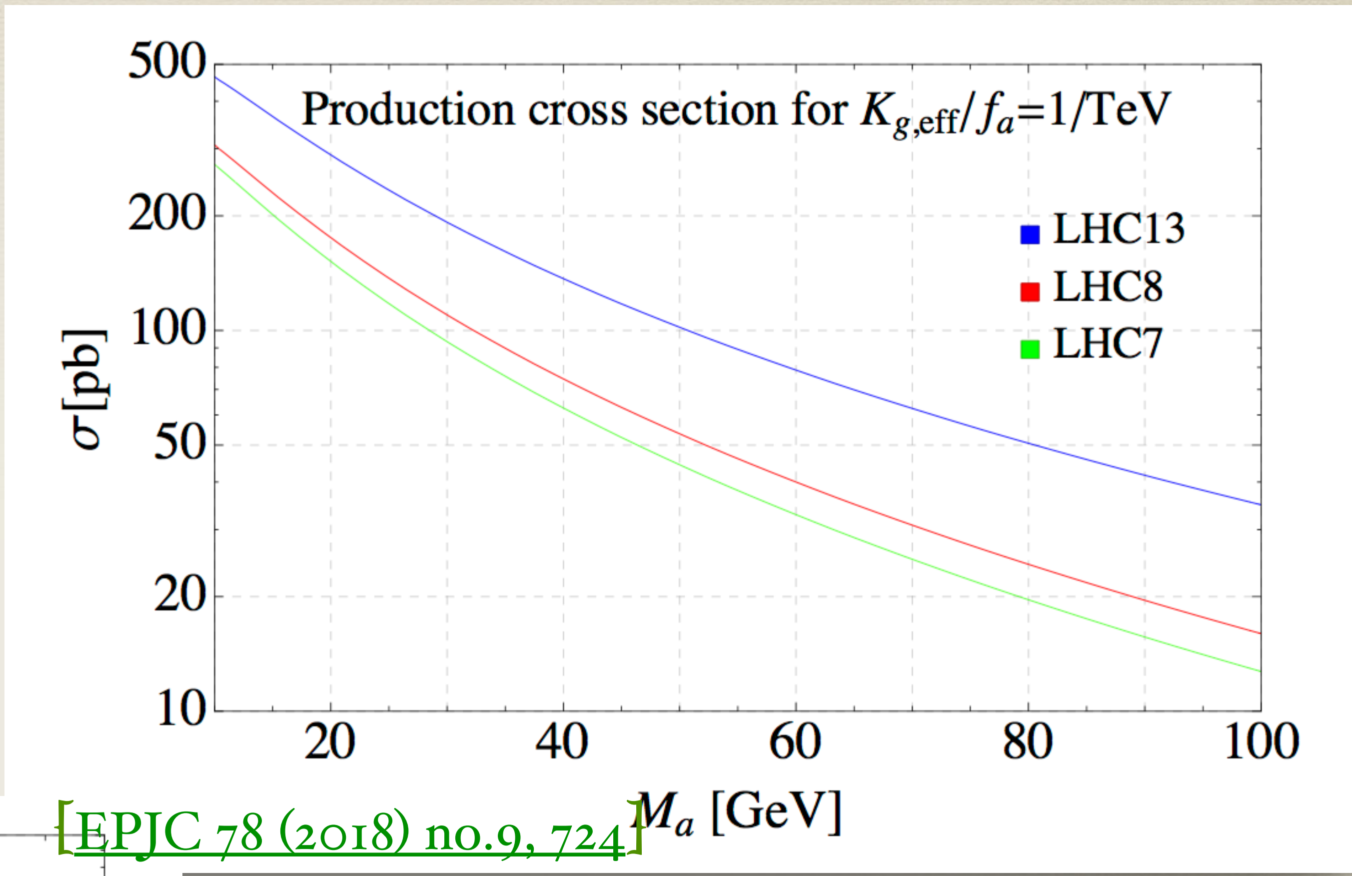
$\mu\mu$

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

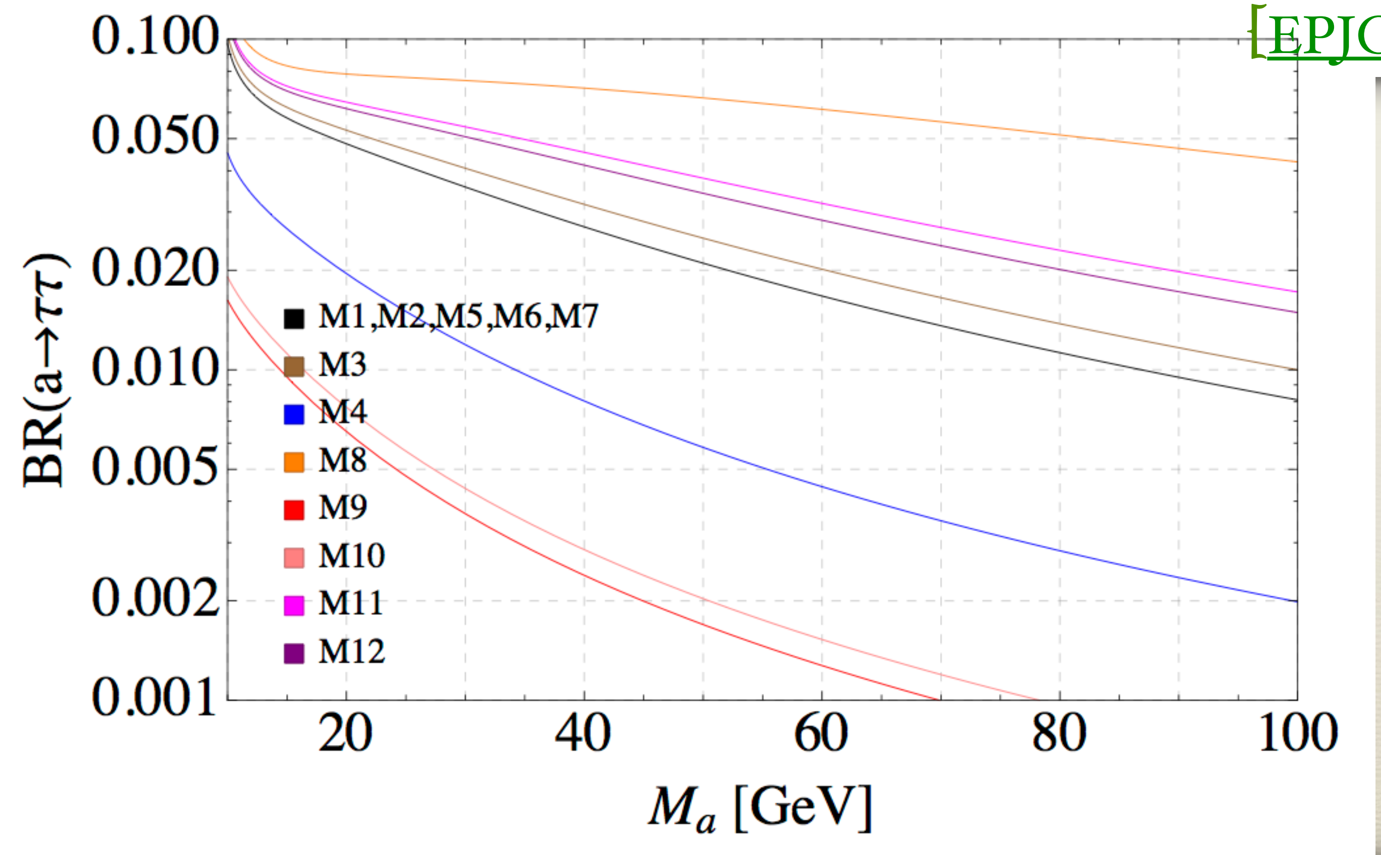
TCP

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

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



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



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

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

Soft τ_{lep} or τ_{had} cannot be used to trigger on, but initial state radiation can boost the gg → a → $\tau\tau$ 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/γ^*+jets: 35 fb,

tt+jets: 70 fb, Wt+jets:

7.4 fb, VV+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

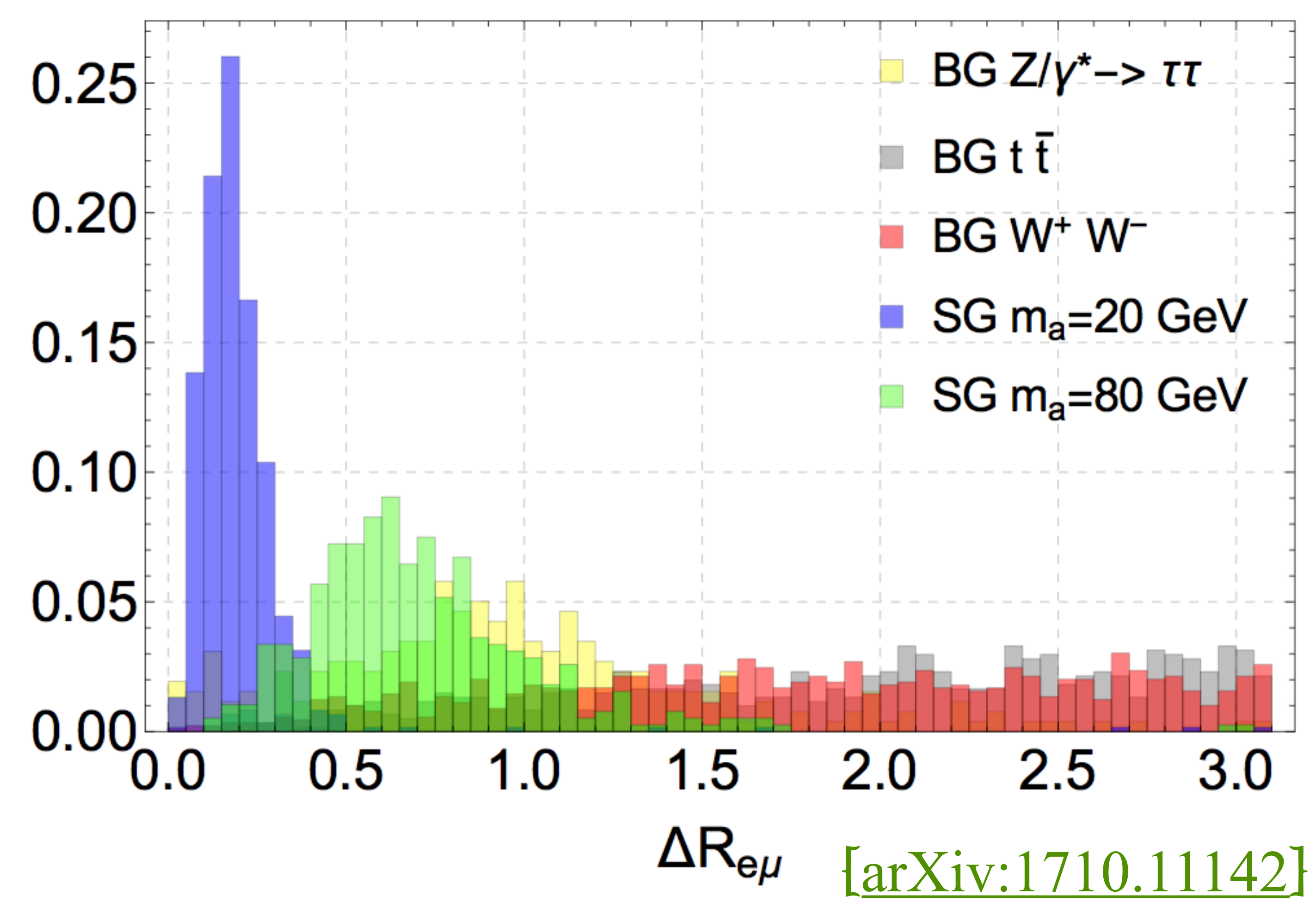
TABLE II: The values of $\sigma_{\text{prod.}} \times BR_{\tau\tau} \times \epsilon$ in fb for $f_a = 1$ TeV and $m_a = 10 \cdots 100$ GeV for each of the models defined in Table I.

TCP

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 τ ID or triggers.



[arXiv:1710.11142]

- 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.]

TCP

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

Soft τ_{lep} or τ_{had} cannot be used to trigger on, but initial state radiation can boost the gg → a → $\tau\tau$ 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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- 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/γ^*+jets: 35 fb,

tt+jets: 70 fb, Wt+jets: 7.4 fb, VV+jets: 13 fb.

m_a	10	20	30	40	50	60	70	80	90	100
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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 $\sigma_{\rm prod.} \times BR_{\tau\tau} \times \epsilon$ in fb for $f_a = 1$ TeV and $m_a = 10 \cdots 100$ GeV for each of the models defined in Table I.

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

TCP

…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).

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

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

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

Diagonalizing the mass matrix (and expanding in *a* and *η*) yields couplings of top and top partners to the pNGB in terms of the 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]

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

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

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

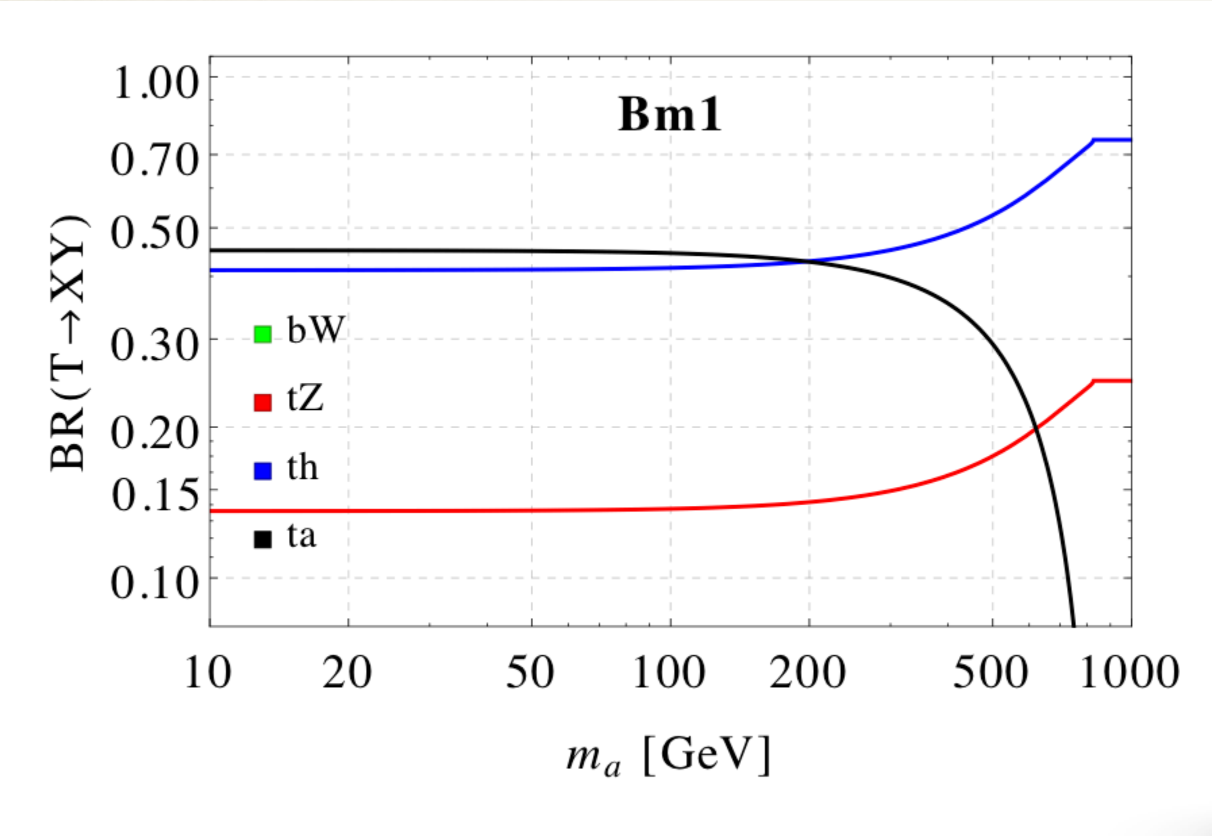
$$+\frac{g_s^2 K_g a}{16\pi^2 f_a}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{g^2 K_W a}{16\pi^2 f_a}W^i_{\mu\nu}\tilde{W}^{i\mu\nu} + \frac{g'^2 K_B a}{16\pi^2 f_a}B_{\mu\nu}\tilde{B}^{\mu\nu}$$

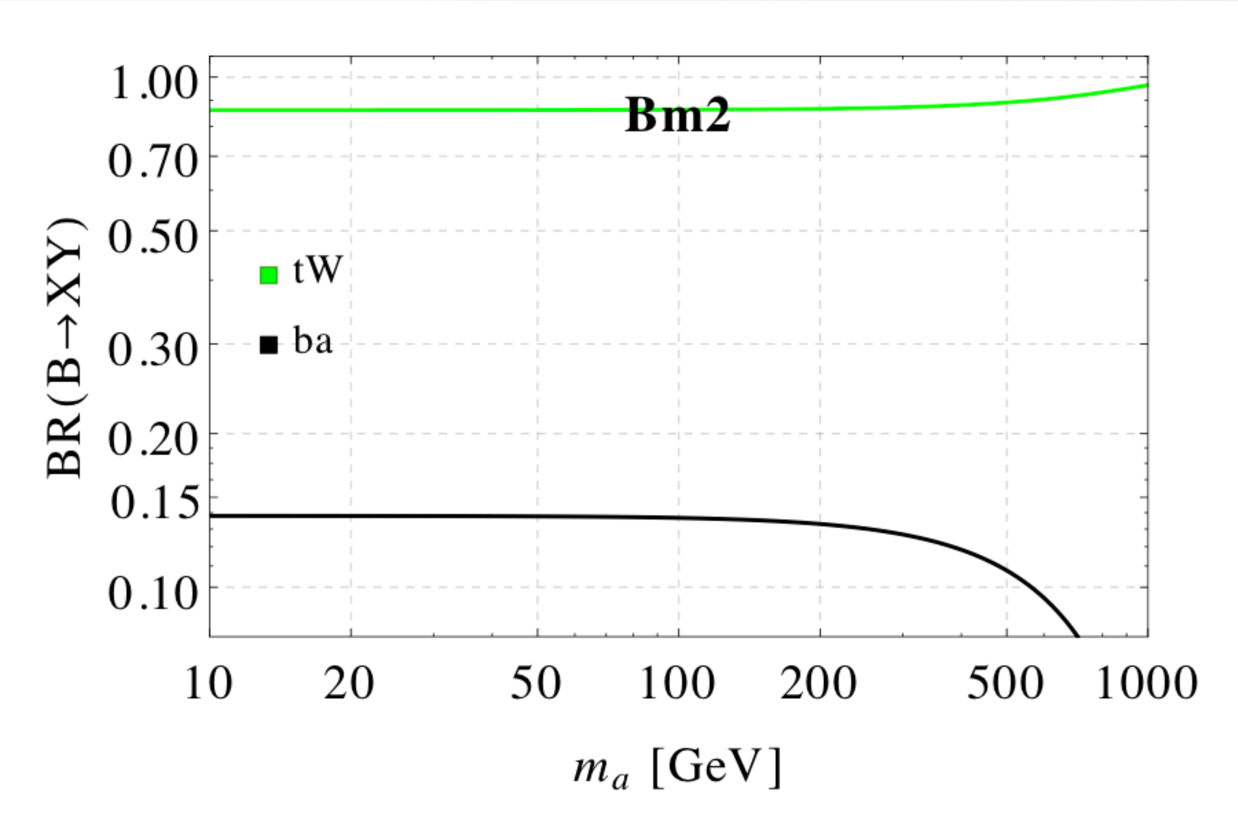
Common exotic VLQ decays

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

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

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





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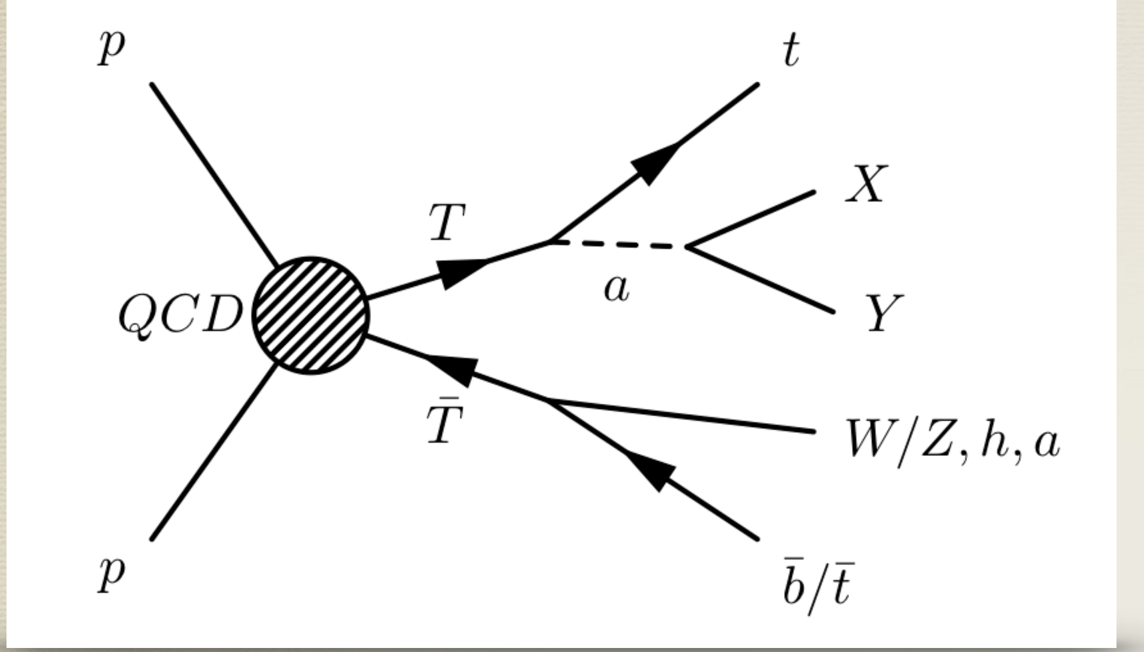
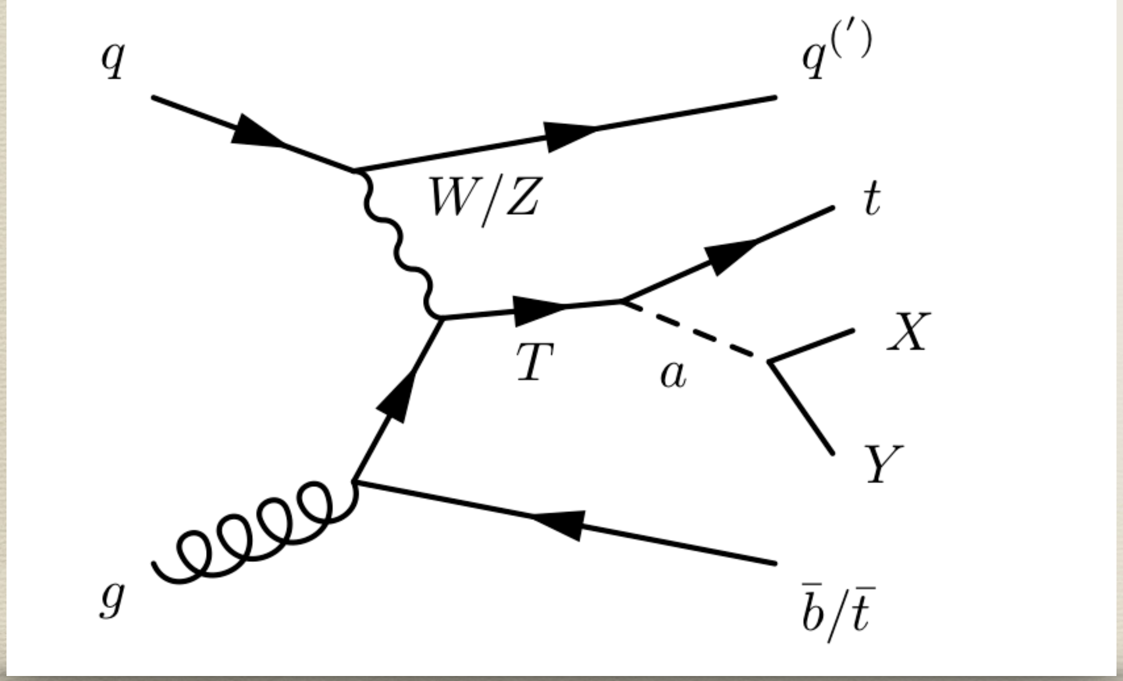
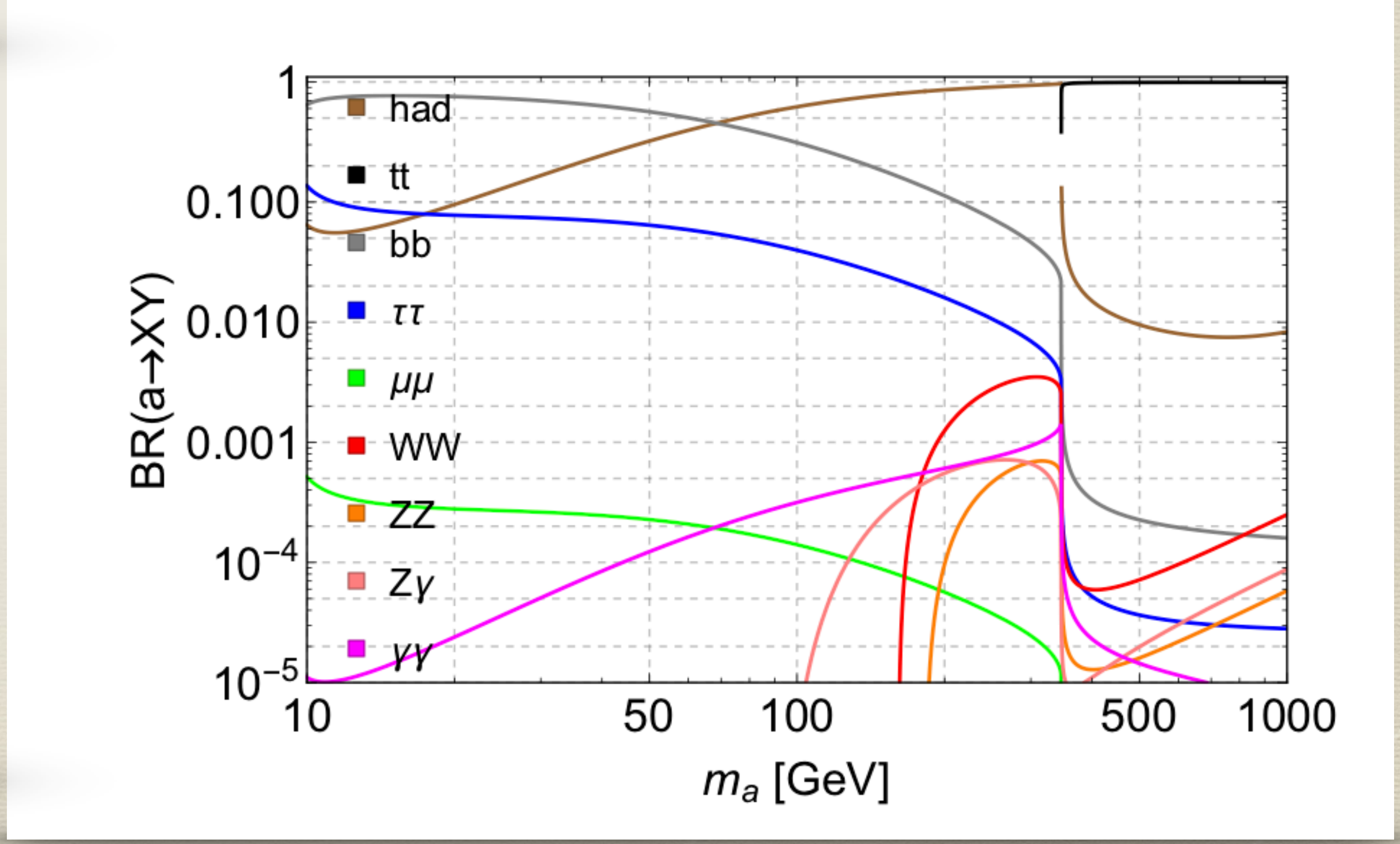
Common exotic VLQ decays

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



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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.

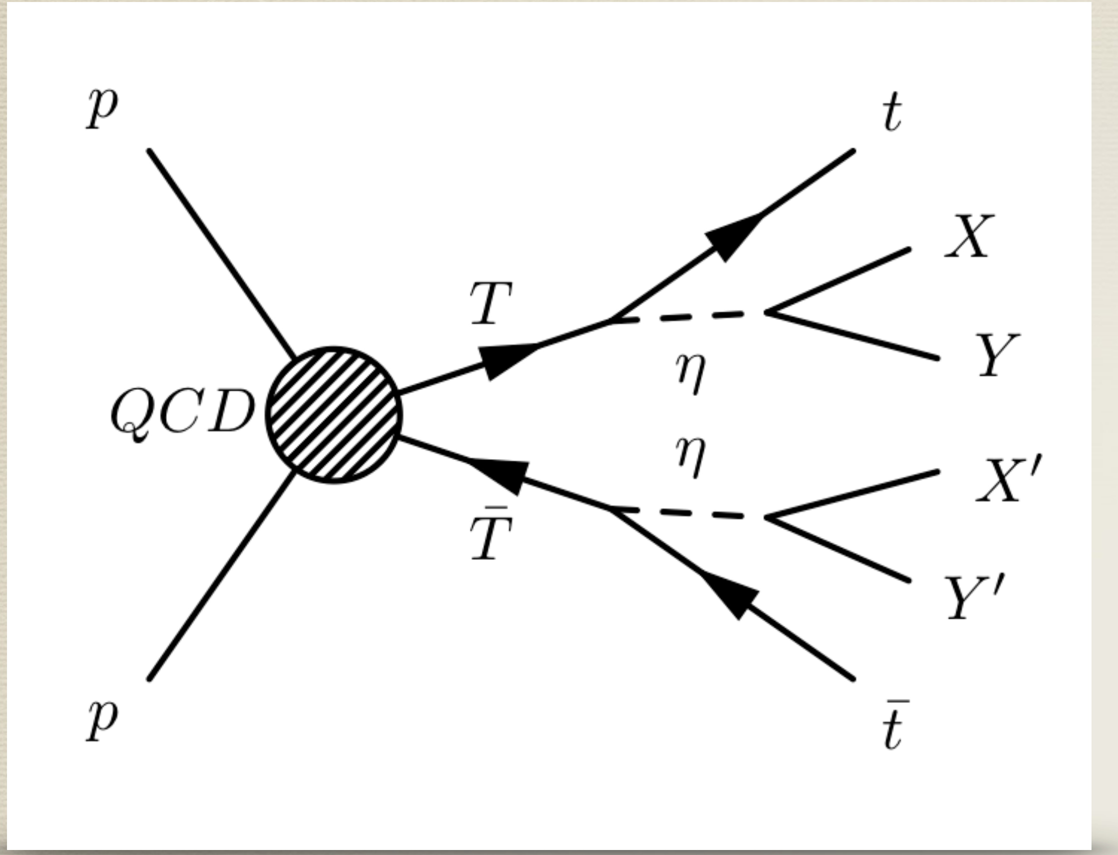
Effective Lagrangian:

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

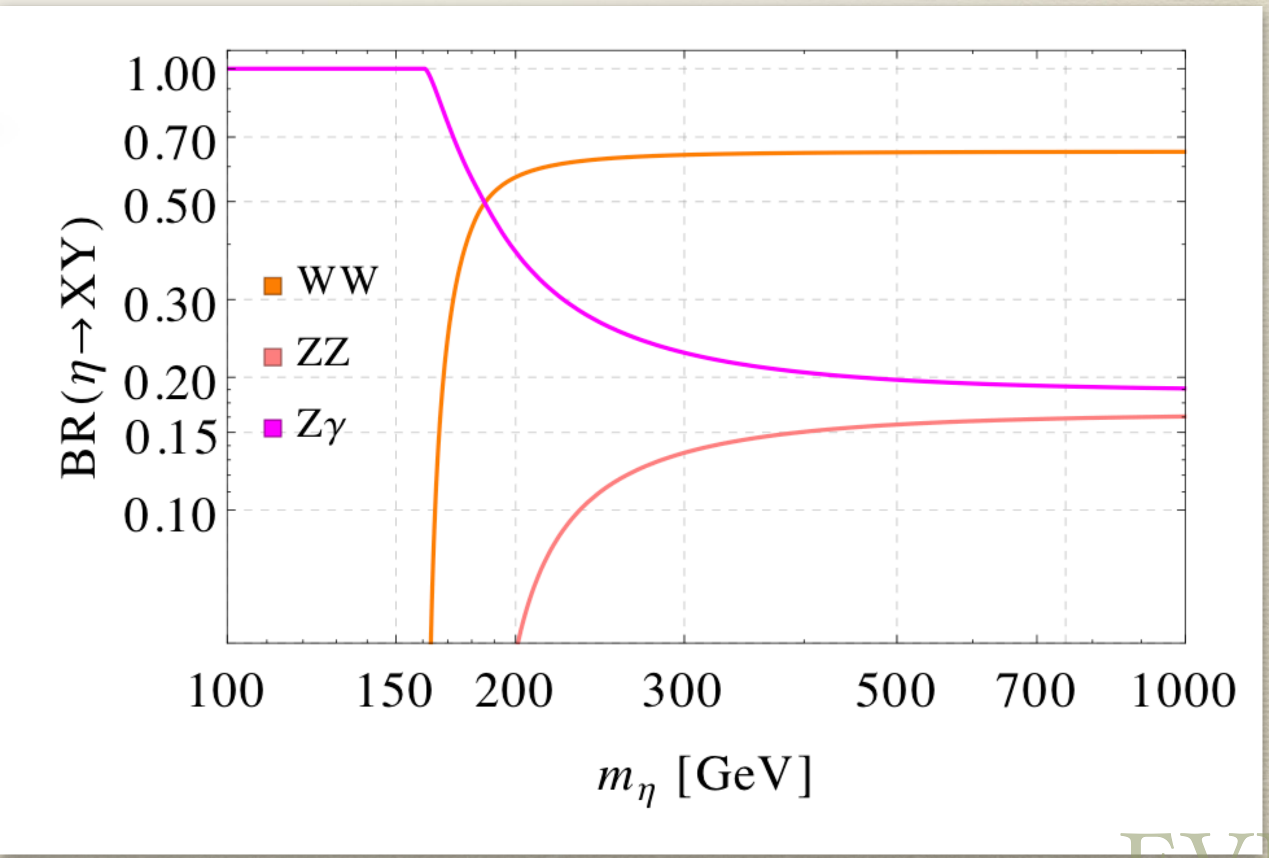
$$\mathcal{L}_\eta = \frac{1}{2}(\partial_\mu\eta)(\partial^\mu\eta) - \frac{1}{2}m_\eta^2\eta^2 + \frac{g_s^2 K_g^\eta}{16\pi^2 f_\eta}\eta G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{g^2 K_W^a}{8\pi^2 f_\eta}\eta W^+_{\mu\nu}\tilde{W}^{-,\mu\nu}$$
$$+ \frac{e^2 K_\gamma^\eta}{16\pi^2 f_\eta}\eta A_{\mu\nu}\tilde{A}^{\mu\nu}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

[JHEP 1806, 065]

Common exotic VLQ decays



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



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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.

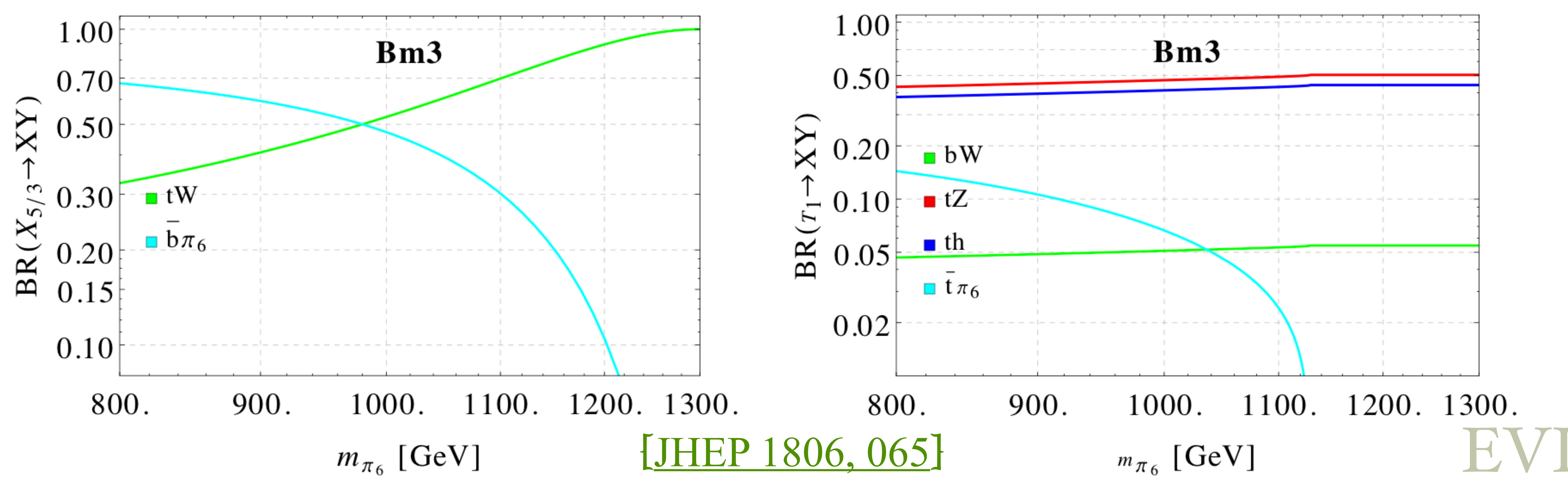
Effective Lagrangian:

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

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

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

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



[JHEP 1806, 065]

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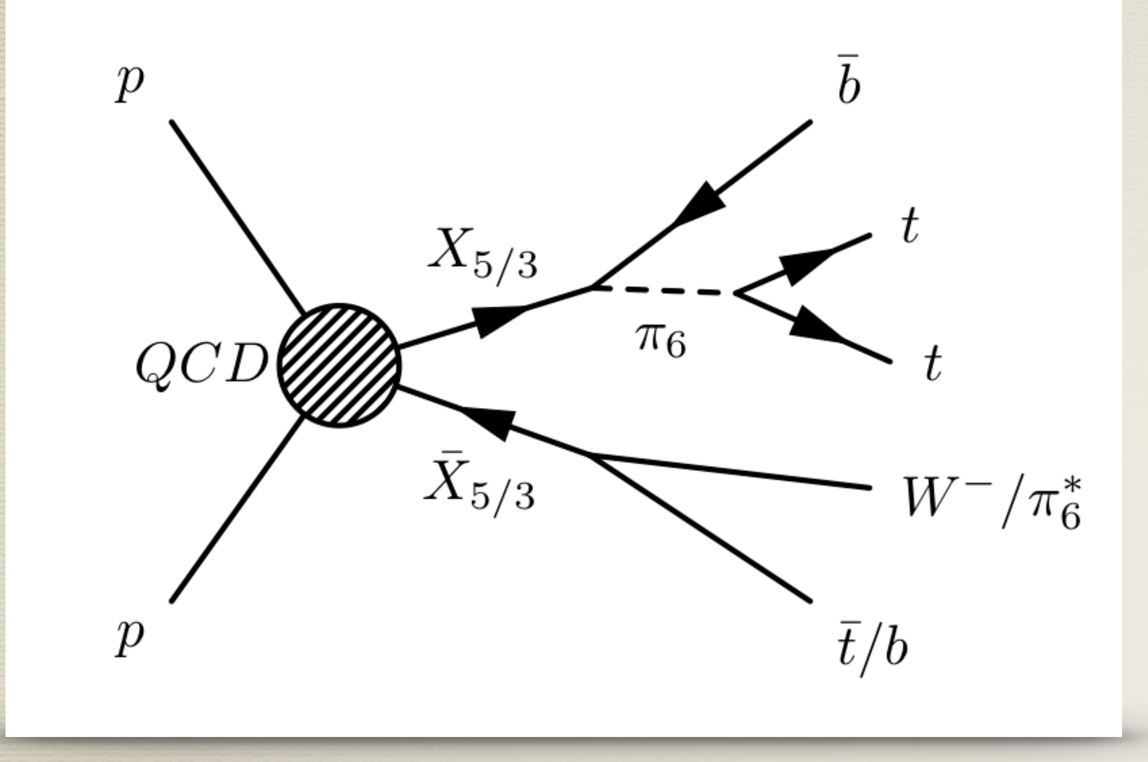
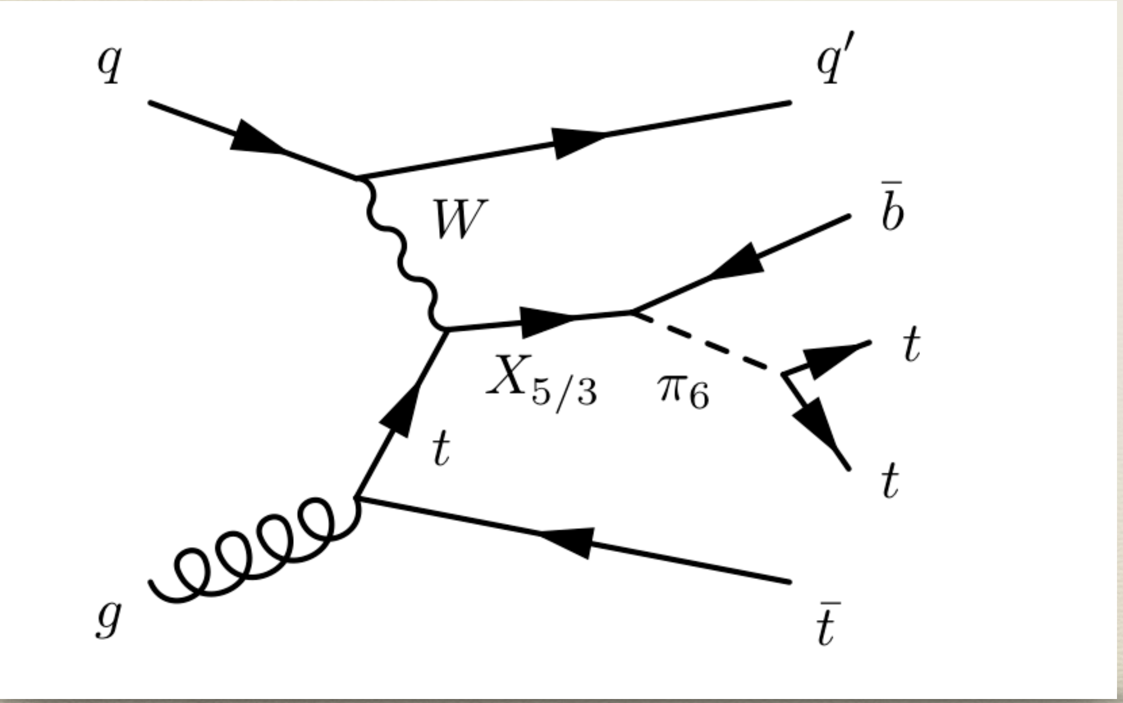
Common exotic VLQ decays

Examples of diagrams:





- $X_{5/3}$ and B can be produced in QCD pair production or single production.
- $\boldsymbol{\pi}_6$ decays to t t.

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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:

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

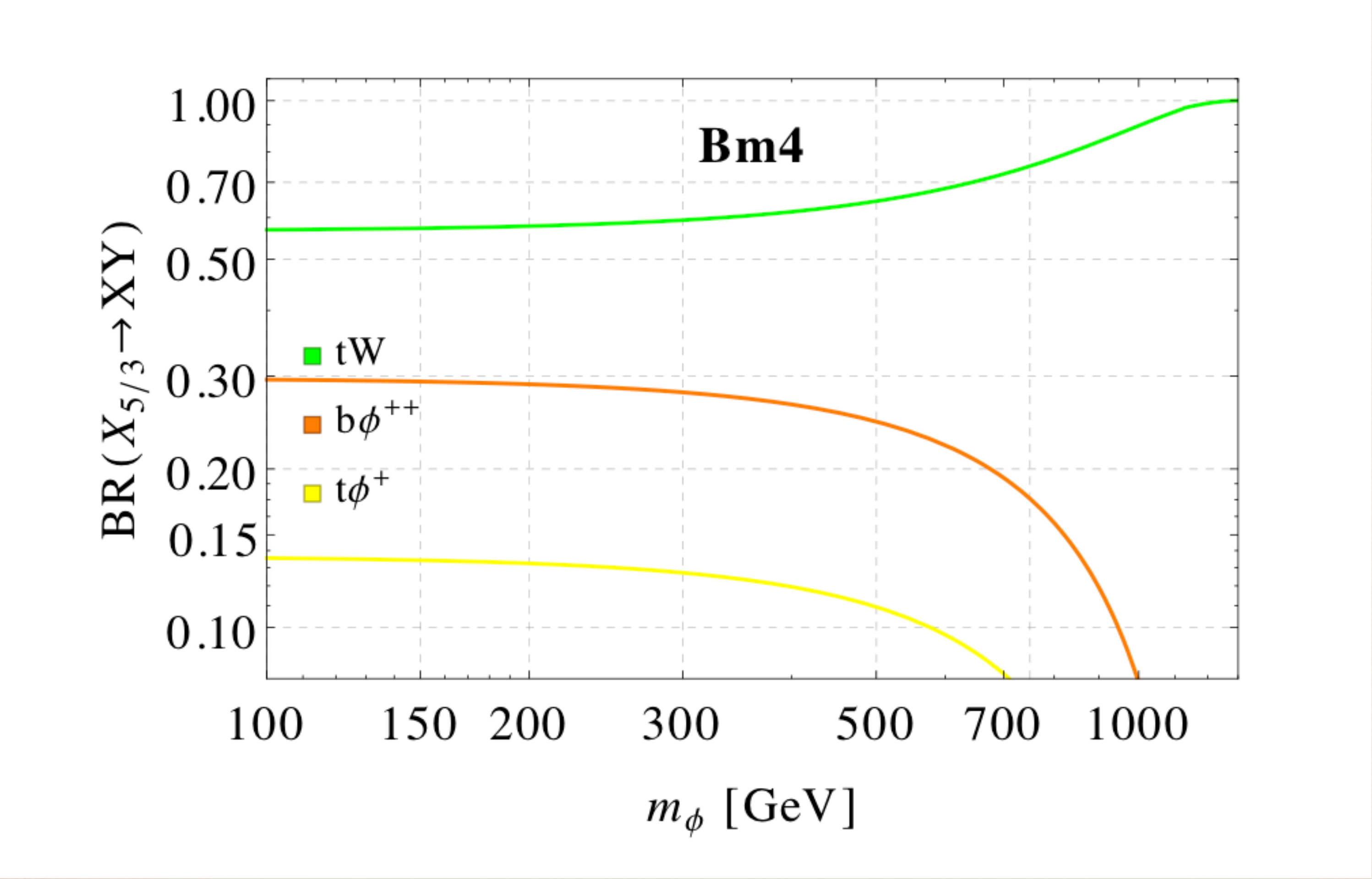
$$\mathcal{L}_{\phi} = \sum_{\phi=\phi^+,\phi^{++}}\left(|D_\mu\phi|^2 - m^2_{\phi}\,|\phi|^2\right) + \left(\frac{egK^{\phi}_{W\gamma}}{8\pi^2 f_{\phi}}\phi^{+}W^{-}_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{g^2 c_w K^{\phi}_{WZ}}{8\pi^2 f_{\phi}}\phi^{+}W^{-}_{\mu\nu}\tilde{B}^{\mu\nu}\right.$$
$$\left. +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

[JHEP 1806, 065]

Common exotic VLQ decays

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

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



Production of $X_{5/3}$:

Single- or pair-production.

Decays of the pNGBs:

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

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

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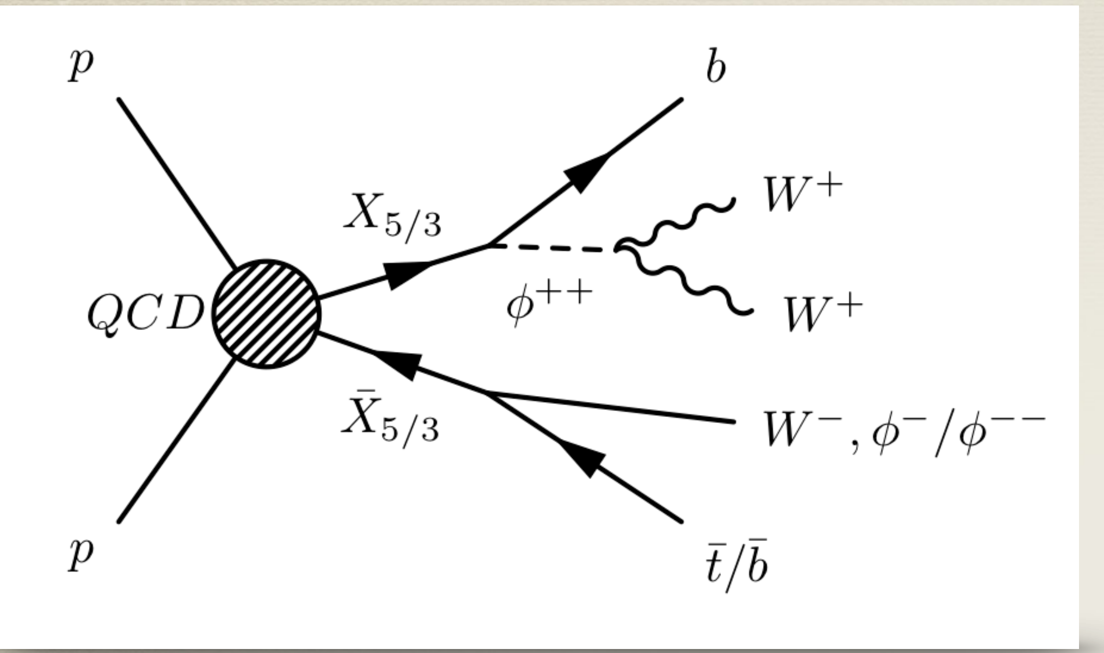
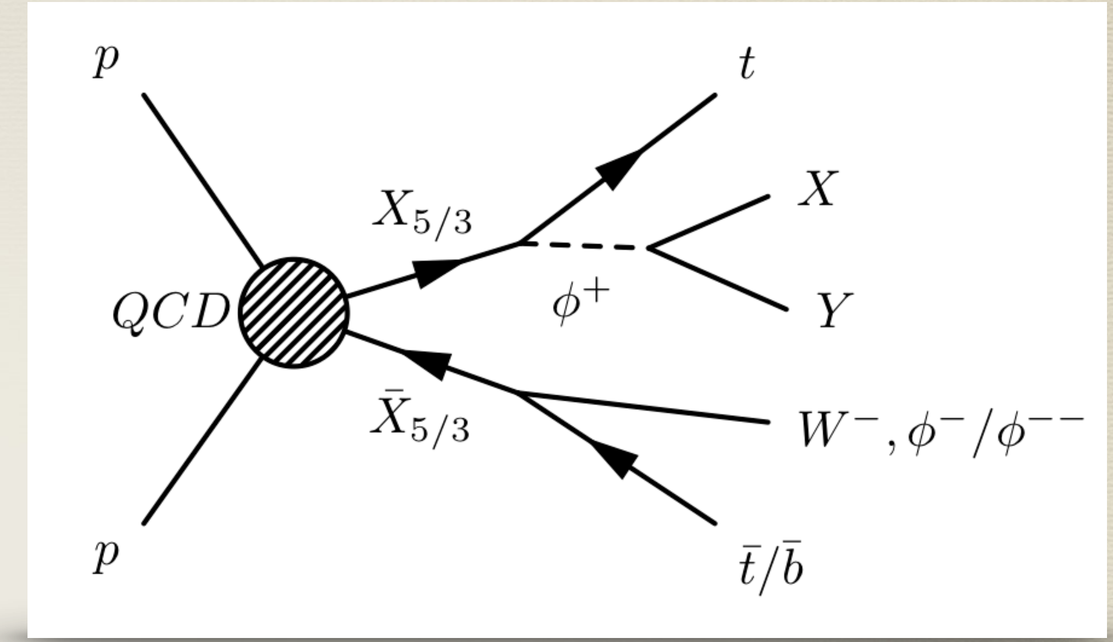
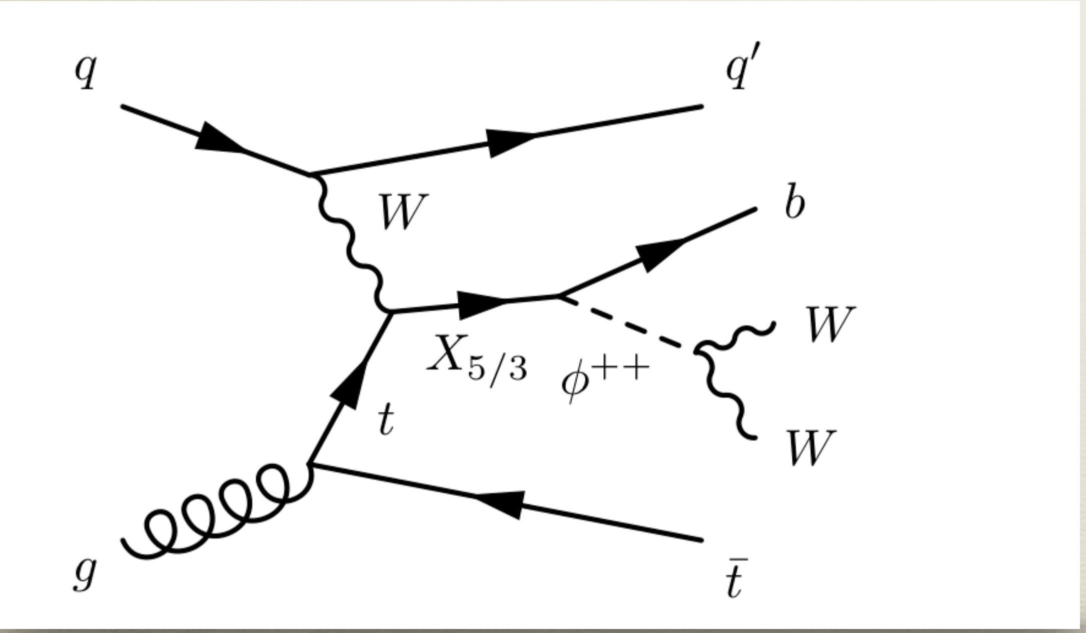
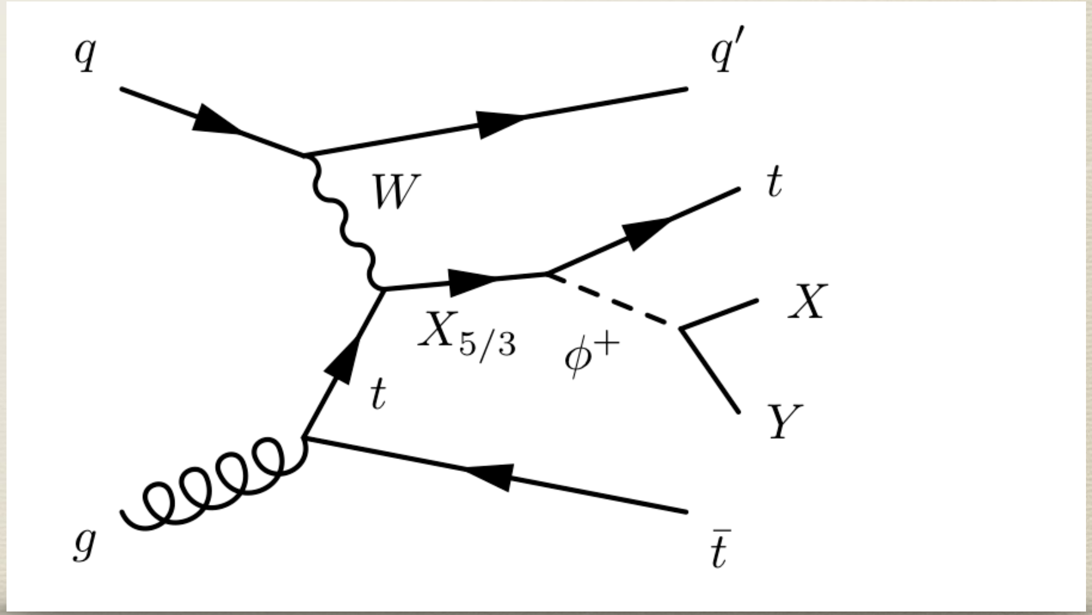
Common exotic VLQ decays

Examples of processes:









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