Common exotic decays of vector-like top partners: Motivation, challenges, and opportunities for collider searches

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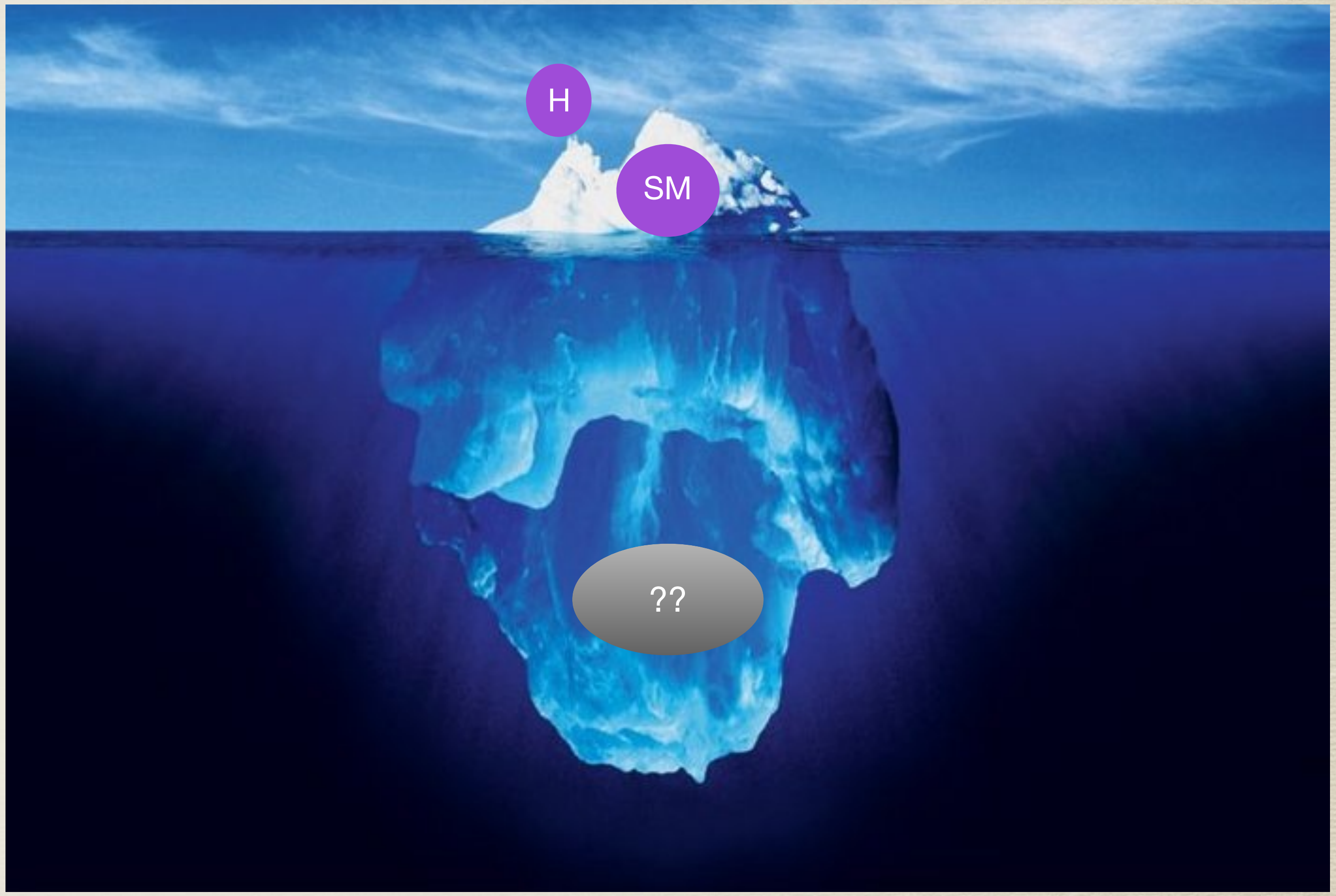
Belyaev, G. Cacciapaglia, H. Cai, G. Ferretti, T. Flacke, H. Serodio, A. Parolini [JHEP 1701, 094]
G. Cacciapaglia, G. Ferretti,T. Flacke, H. Serodio [EPJC 78 (2018) no.9, 724]
G. Cacciapaglia, G. Ferretti,T. Flacke, H. Serodio [Front.in Phys. 7 (2019) 22]
N. Bizot, G. Cacciapaglia, T. Flacke [JHEP 1806, 065]
G. Cacciapaglia, T. Flacke, Ke-Pan Xi [JHEP 1910, 134]
G. Cacciapaglia, T. Flacke, Myeonghun Park, Mengchao Zhang [PLB798, 135015 (2019)]
G. Cacciapaglia, A. Deandrea, T. Flacke, A. Iyer [appearing soon]

STAR French-Korean workshop "Higgs and Dark Matter Connections", IP2I Lyon, Dec. 17th 2019

Outline

- Motivation for composite Higgs models & VLQs
- Underlying models:
  - wishlist and model classification
  * light pNGBs are ubiquitous
  * "exotic" VLQ decays are common
- Bounds and search opportunities for pNGBs
  - SM neutral pNGB
  - color octet pNGB
- Bounds and search opportunities for exotic VLQ decays
  - Example 1: $T \to t\, a$, $a \to gg$ or $a \to bb$
  - Example 2: Exotic charge 5/3 VLQ decays
- Conclusions

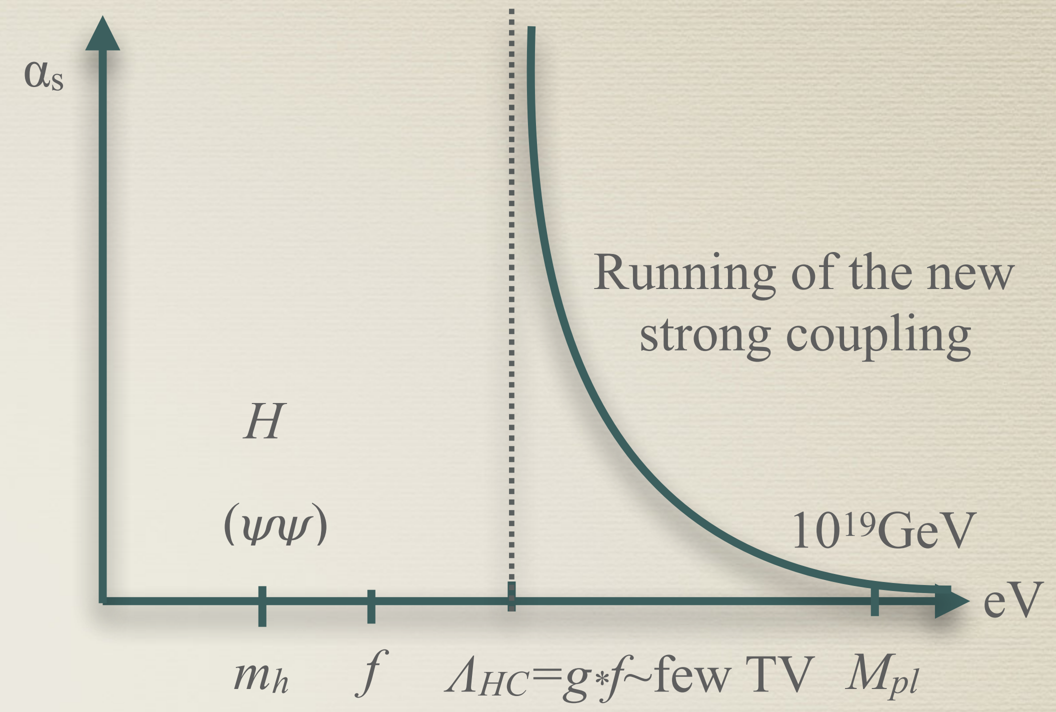


Motivation for Vector-like quarks: a composite Higgs

An alternative solution to the hierarchy problem:

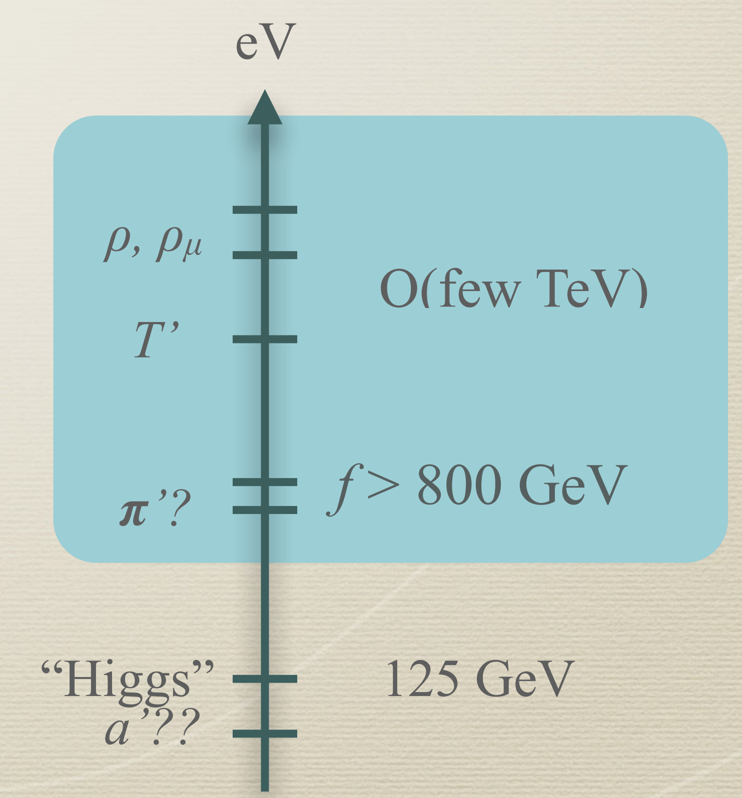
- Generate a scale $\Lambda_{HC} << M_{pl}$ through a new confining gauge group.
- Interpret the Higgs as a pseudo-Nambu-Goldstone boson (pNGB) of a spontaneously broken global symmetry of the new strong sector.

  [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).



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 have several common features:

- All models contain several top partner multiplets.
- All models predict pNGBs beyond the Higgs multiplet.

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	□	**1**	**2**	0	**4**	**1**	$-3(N_c-1)q_\chi$
ψ_3	□	**1**	**1**	1/2			
ψ_4	□	**1**	**1**	−1/2			
χ_1 χ_2 χ_3	⊟	**3**	**1**	2/3	**1**	**6**	q_χ
χ_4 χ_5 χ_6	⊟	$\bar{\mathbf{3}}$	**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	(**6**, **1**)	(**1**, **1**) (**5**, **1**)	σ π
$\chi\chi$	0	(**1**, **21**)	(**1**, **1**) (**1**, **20**)	σ_c π_c
$\chi\psi\psi$	1/2	(**6**, **6**)	(**1**, **6**) (**5**, **6**)	ψ_1^1 ψ_1^5
$\chi\bar{\psi}\bar{\psi}$	1/2	(**6**, **6**)	(**1**, **6**) (**5**, **6**)	ψ_2^1 ψ_2^5
$\psi\bar{\chi}\bar{\psi}$	1/2	(**1**, $\bar{\mathbf{6}}$)	(**1**, **6**)	ψ_3
$\psi\bar{\chi}\bar{\psi}$	1/2	(**15**, $\bar{\mathbf{6}}$)	(**5**, **6**) (**10**, **6**)	ψ_4^5 ψ_4^{10}
$\bar{\psi}\sigma^\mu\psi$	1	(**15**, **1**)	(**5**, **1**) (**10**, **1**)	a ρ
$\bar{\chi}\sigma^\mu\chi$	1	(**1**, **35**)	(**1**, **20**) (**1**, **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_{HC}	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
	Real	Real	SU(5)/SO(5) × SU(6)/SO(6)				
$SO(N_{HC})$	$5 \times \mathbf{S}_2$	$6 \times \mathbf{F}$	$N_{HC} \geq 55$	$\frac{5(N_{HC}+2)}{6}$	1/3	/	
$SO(N_{HC})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$N_{HC} \geq 15$	$\frac{5(N_{HC}-2)}{6}$	1/3	/	
$SO(N_{HC})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{HC} = 7, 9$	$\frac{5}{6}, \frac{5}{12}$	1/3	$N_{HC} = 7, 9$	M1, M2
$SO(N_{HC})$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{HC} = 7, 9$	$\frac{5}{6}, \frac{5}{3}$	2/3	$N_{HC} = 7, 9$	M3, M4
	Real	Pseudo-Real	SU(5)/SO(5) × SU(6)/Sp(6)				
$Sp(2N_{HC})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$2N_{HC} \geq 12$	$\frac{5(N_{HC}+1)}{3}$	1/3	/	
$Sp(2N_{HC})$	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	$2N_{HC} \geq 4$	$\frac{5(N_{HC}-1)}{3}$	1/3	$2N_{HC} = 4$	M5
$SO(N_{HC})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{HC} = 11, 13$	$\frac{5}{24}, \frac{5}{48}$	1/3	/	
	Real	Complex	SU(5)/SO(5) × SU(3)^2/SU(3)				
$SU(N_{HC})$	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$N_{HC} = 4$	$\frac{5}{3}$	1/3	$N_{HC} = 4$	M6
$SO(N_{HC})$	$5 \times \mathbf{F}$	$3 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$N_{HC} = 10, 14$	$\frac{5}{12}, \frac{5}{48}$	1/3	$N_{HC} = 10$	M7
	Pseudo-Real	Real	SU(4)/Sp(4) × SU(6)/SO(6)				
$Sp(2N_{HC})$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$2N_{HC} \leq 36$	$\frac{1}{3(N_{HC}-1)}$	2/3	$2N_{HC} = 4$	M8
$SO(N_{HC})$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{HC} = 11, 13$	$\frac{8}{3}, \frac{16}{3}$	2/3	$N_{HC} = 11$	M9
	Complex	Real	SU(4)^2/SU(4) × SU(6)/SO(6)				
$SO(N_{HC})$	$4 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$6 \times \mathbf{F}$	$N_{HC} = 10$	$\frac{8}{3}$	2/3	$N_{HC} = 10$	M10
$SU(N_{HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	$N_{HC} = 4$	$\frac{2}{3}$	2/3	$N_{HC} = 4$	M11
	Complex	Complex	SU(4)^2/SU(4) × SU(3)^2/SU(3)				
$SU(N_{HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}}_2)$	$N_{HC} \geq 5$	$\frac{4}{3(N_{HC}-2)}$	2/3	$N_{HC} = 5$	M12
$SU(N_{HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{S}_2, \overline{\mathbf{S}}_2)$	$N_{HC} \geq 5$	$\frac{4}{3(N_{HC}+2)}$	2/3	/	

[JHEP1701,094]

Top partners decays in Composite Higgs UV embeddings

[JHEP 1806, 065]

UV embeddings of composite Higgs models come with additional pseudo-Nambu-Goldstone-bosons (naturally light scalars).

weak bounds

1. a and η': SM singlets with WZW couplings to gauge bosons and couplings $\propto m_f$ to fermions. JHEP1701,094, EPJC 78 (2018) no.9, 724, FiP 7 (2019), 22]

$\gtrsim$ 1 TeV

2. π_8 : Color octet pseudo-scalar pNGB which couples to gg, $g\gamma$, gZ, tt [JHEP1701,094, CDFI]

3. Additional colored and uncolored pNGBs (model dependent)

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

$\gtrsim$ 1 TeV [JHEP1511,201]

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

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. $\boldsymbol{\phi} = \{a, \eta'\}$

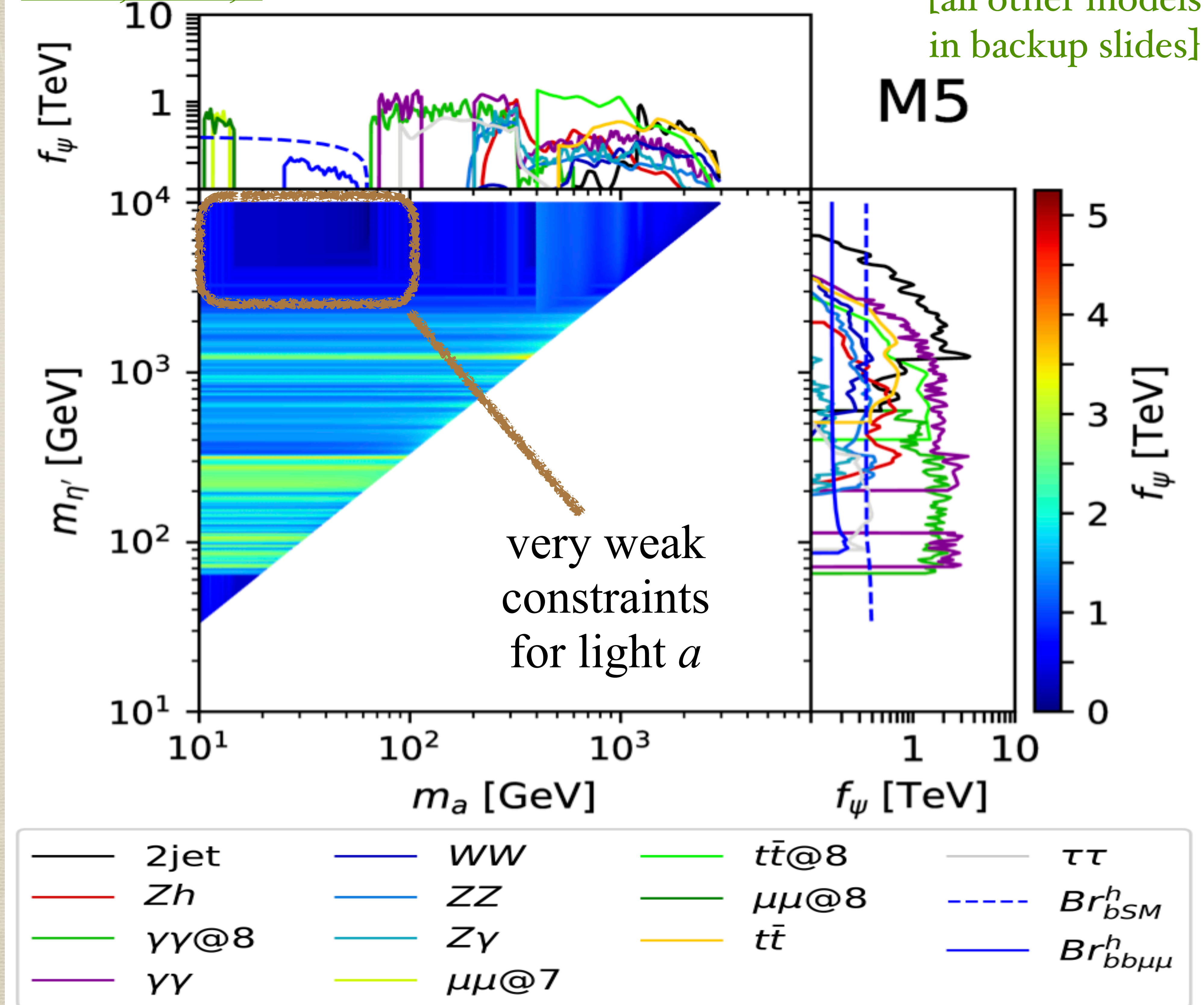
$$
\begin{aligned}
\mathcal{L}_{\text{eff}} \supset \; & \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2} m_\phi^2 \phi^2 \\
& + \frac{\phi}{16\pi^2 f_\psi}\left(g_s^2 K_g^\phi G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + g^2 K_W^\phi W^i_{\mu\nu}\tilde{W}^{i\mu\nu} + g'^2 K_B^\phi B_{\mu\nu}\tilde{B}^{\mu\nu}\right)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

- 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).
- $h\phi\phi$ and $h\phi Z$ couplings are induced at 1-loop order.
- *a* and *η'* are produced in gluon fusion.
- The resonances are narrow.

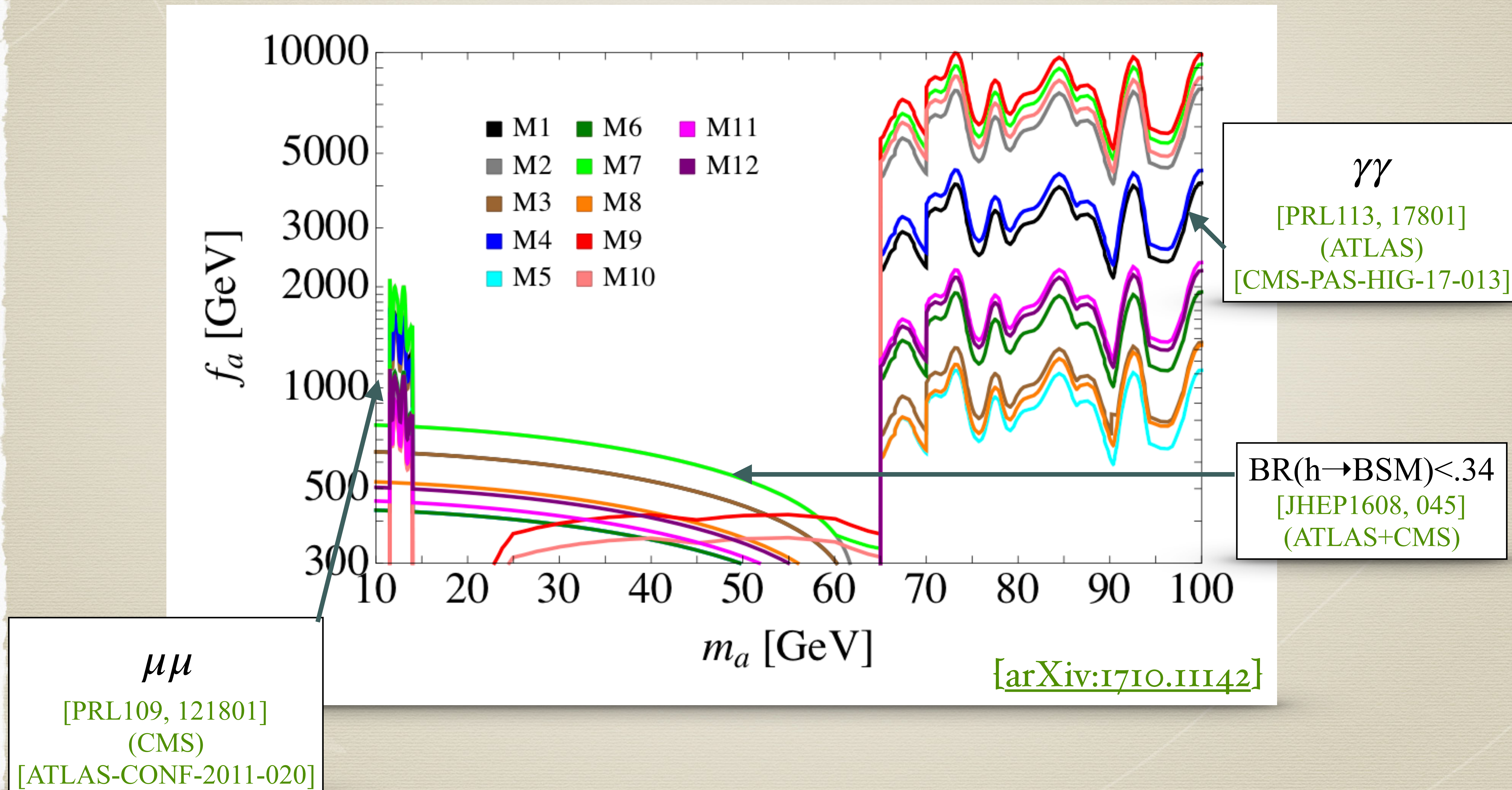
a and *η'*: For a given model, we can combine bounds and sensitivities from resonance searches to get a bound on the compositeness scale f .

[arXiv:1902.06890]

[all other models in backup slides]



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

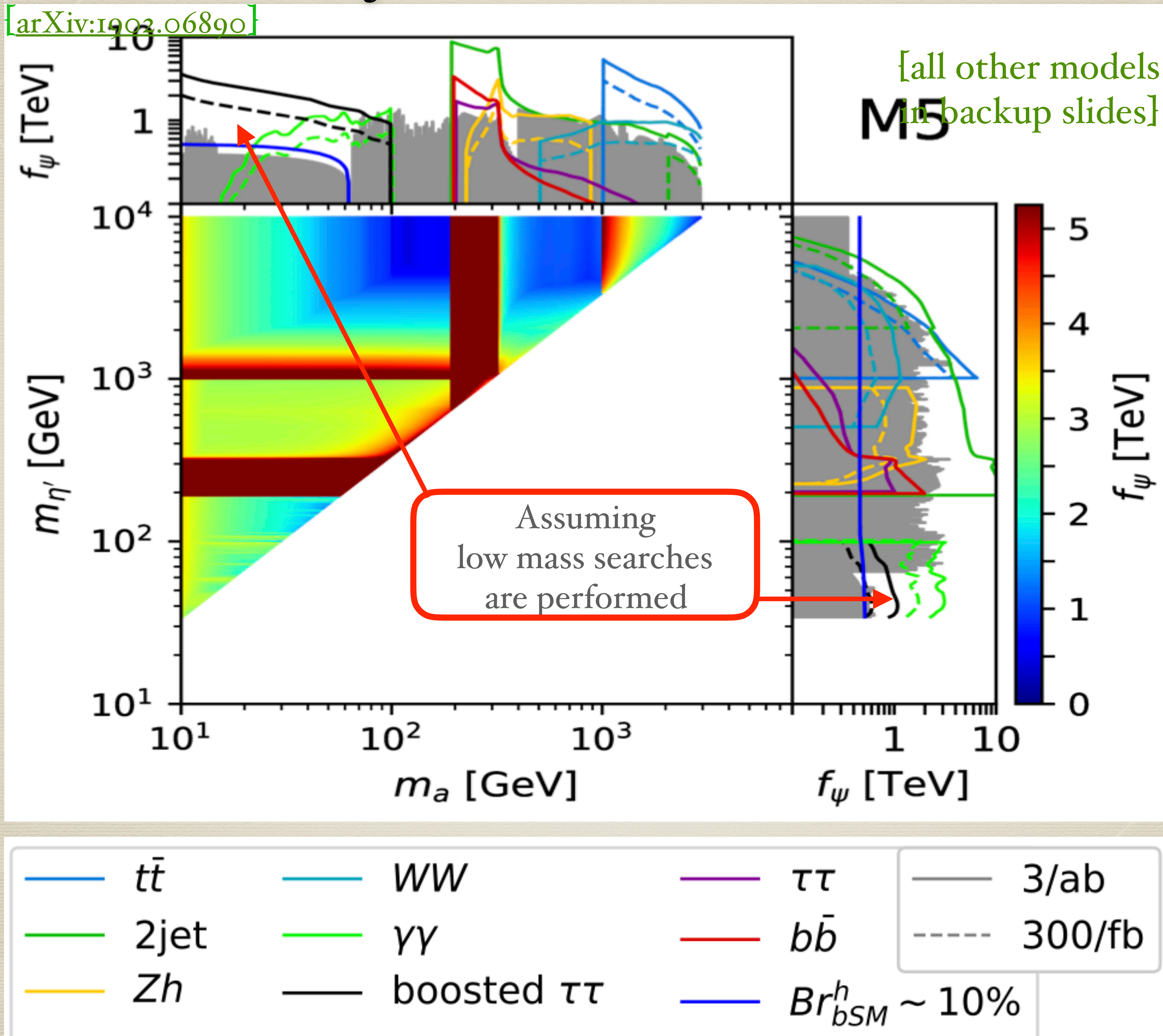


[arXiv:1710.11142]

Projected reach at HL-LHC

[arXiv:1902.06890]

[all other models in backup slides]



Colored PNGBs (the color octet $\mathbf{\Phi}$)

Effective Lagrangian:

$$\mathcal{L}_\Phi = \frac{1}{2}(D_\mu \Phi^a)^2 - \frac{1}{2} M_\Phi^2 (\Phi^a)^2 + i\ C_t \frac{m_t}{f_\Phi} \Phi^a\ \bar{t}\gamma_5 \frac{\lambda^a}{2} t$$

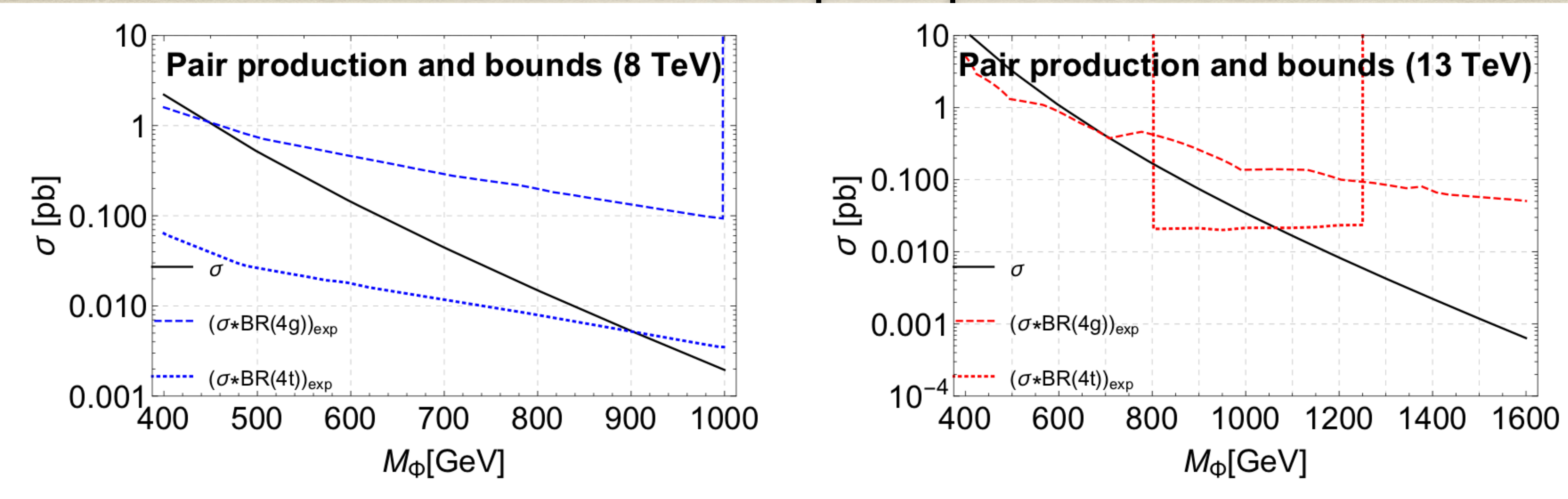
$$+ \frac{\alpha_s \kappa_g}{8\pi f_\Phi} \Phi^a\ \epsilon^{\mu\nu\rho\sigma} \left[\frac{1}{2} d^{abc}\ G^b_{\mu\nu} G^c_{\rho\sigma} + \frac{g' \kappa_B}{g_s \kappa_g}\ G^a_{\mu\nu} B_{\rho\sigma} \right]$$

where in CH UV embeddings: $\kappa_g = 2Y_\chi,\ \ M_\Phi \sim C_g \frac{3}{4} g_s^2 f_\Phi^2$

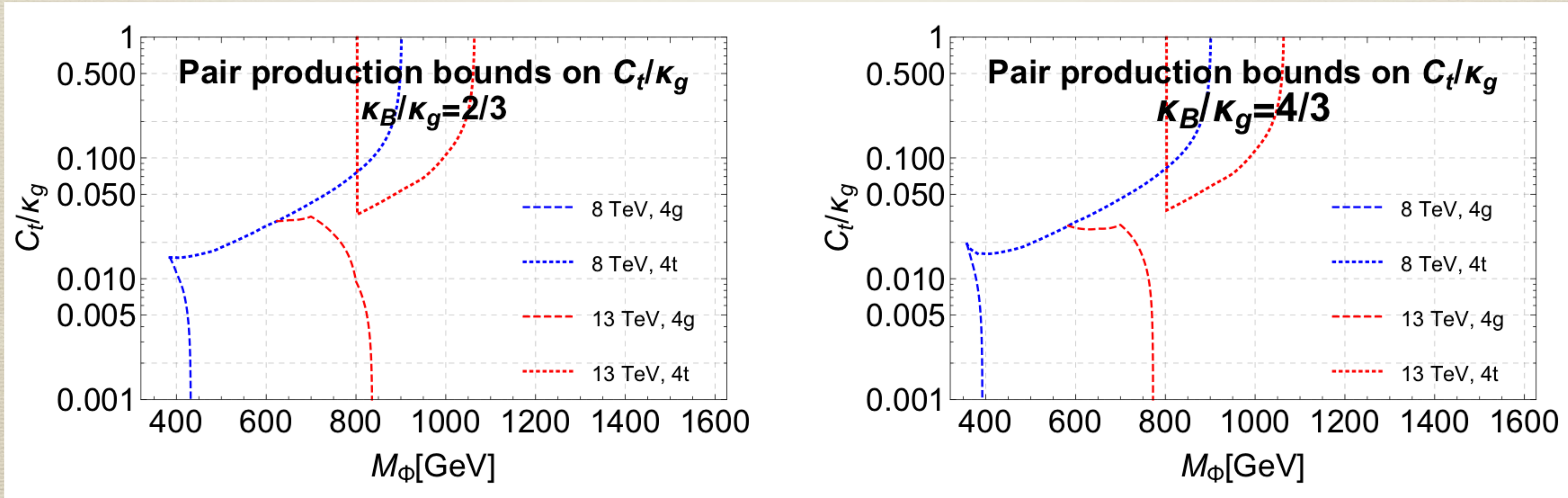
Phenomenology

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

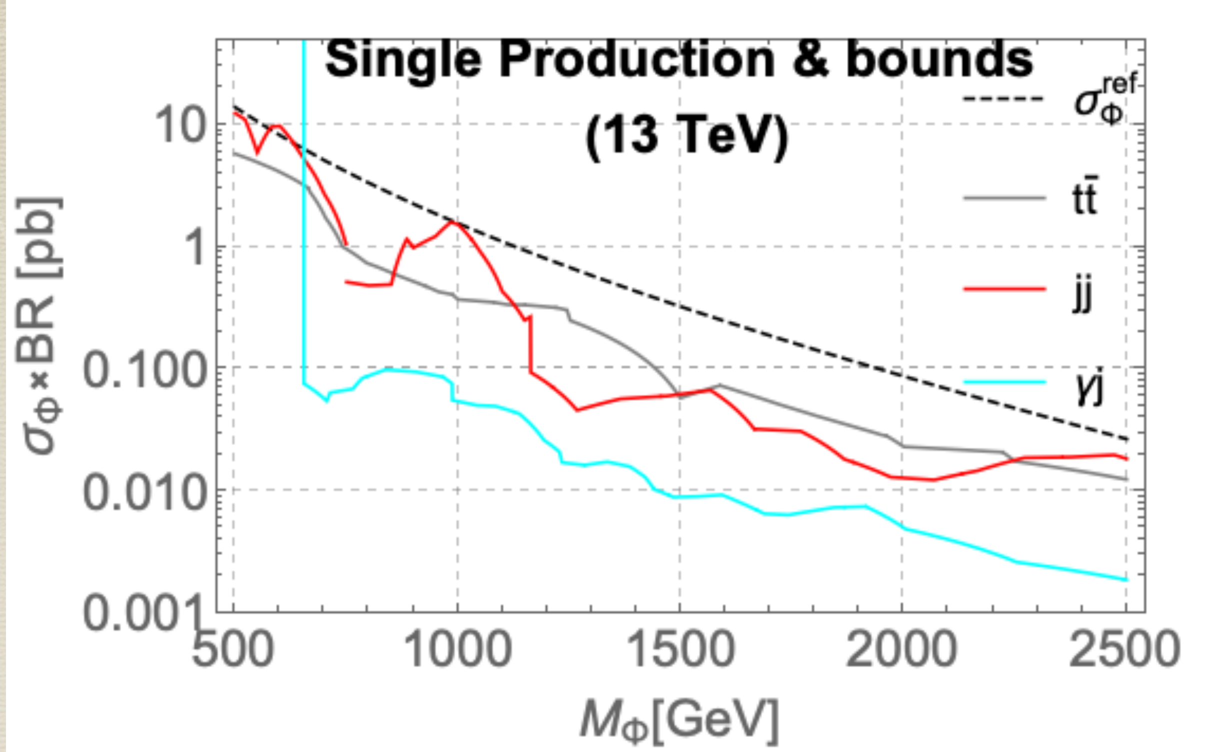
Colored PNGBs
Constraints from pair production:



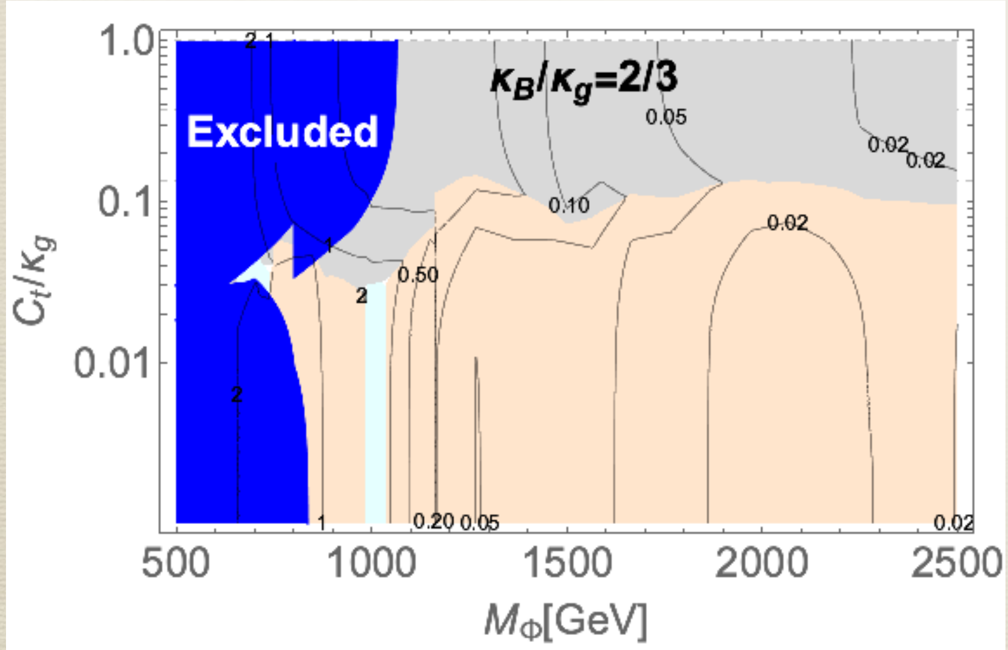
(Using ATLAS & CMS searches for dijet-pairs, 4-top searches, and the 4t-sgluon recast Fuks etal (2018))

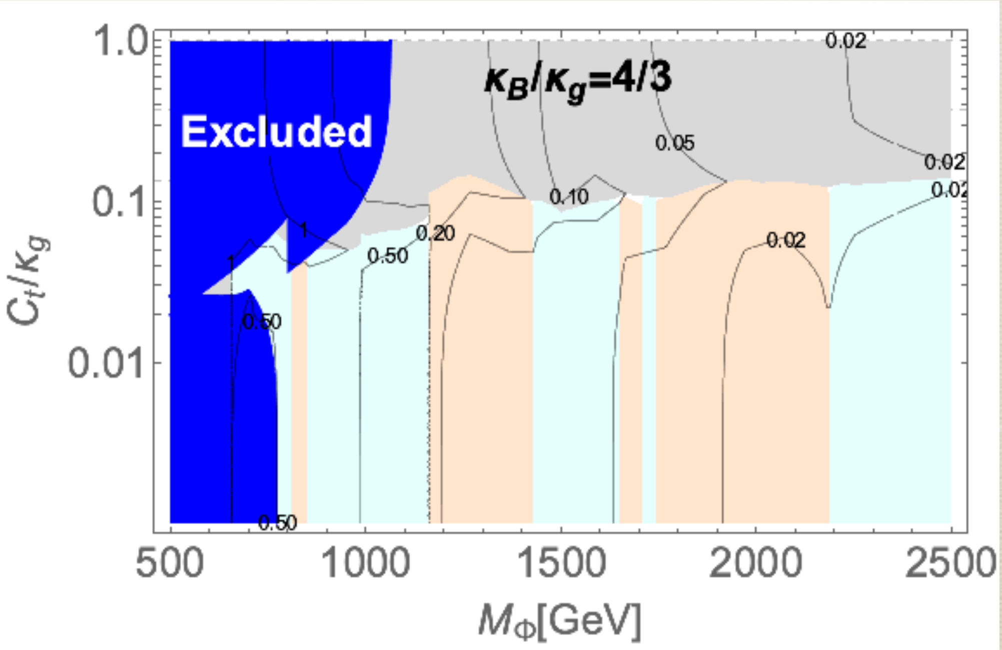


Colored PNGBs, constraints from single production:



(Using ATLAS & CMS searches for dijets, ditops, and excited quarks). σ_Φ^{ref} has $\frac{\kappa_g}{f_\Phi} = 10\ \text{TeV}^{-1}$





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

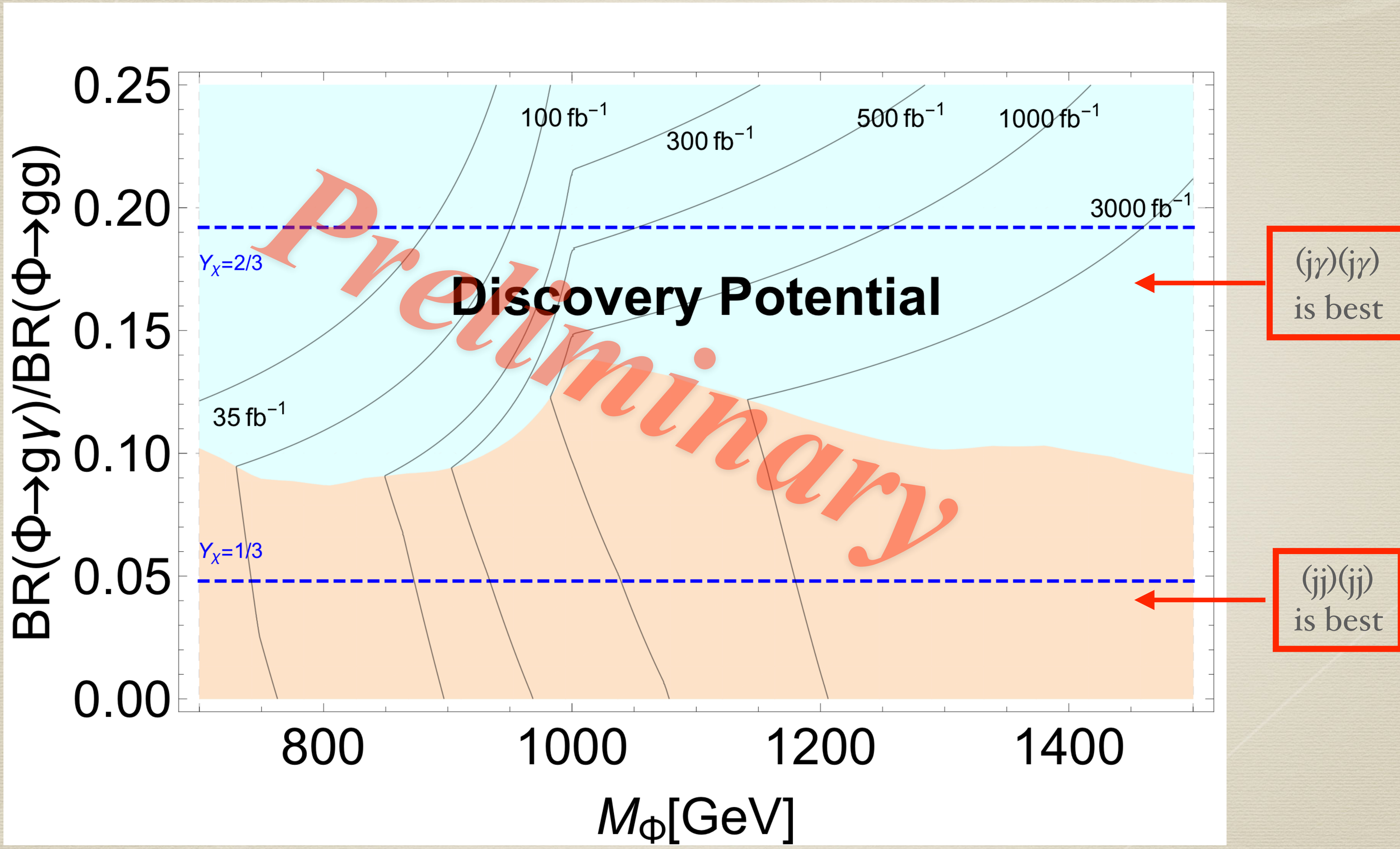
Contours give bounds on the **Φ** production cross section in pb.

Colored PNGBs, constraints from single production:

Note:

- From underlying models, we expect ~TeV scale mass.
  We only now start to scratch at the interesting parameter space.
- For pair-production, only the (jj)(jj) final state is directly covered by searches.
  For (tt)(tt), recasts are required for the latest ATLAS and CMS searches (see Fuks etal (2018)).
  Pair-production channels involving $\mathbf{\Phi} \rightarrow g\gamma$ decays are not searched for and have good discovery potential (to appear, soon).

Colored PNGBs, prospects for $\Phi \to g\gamma$

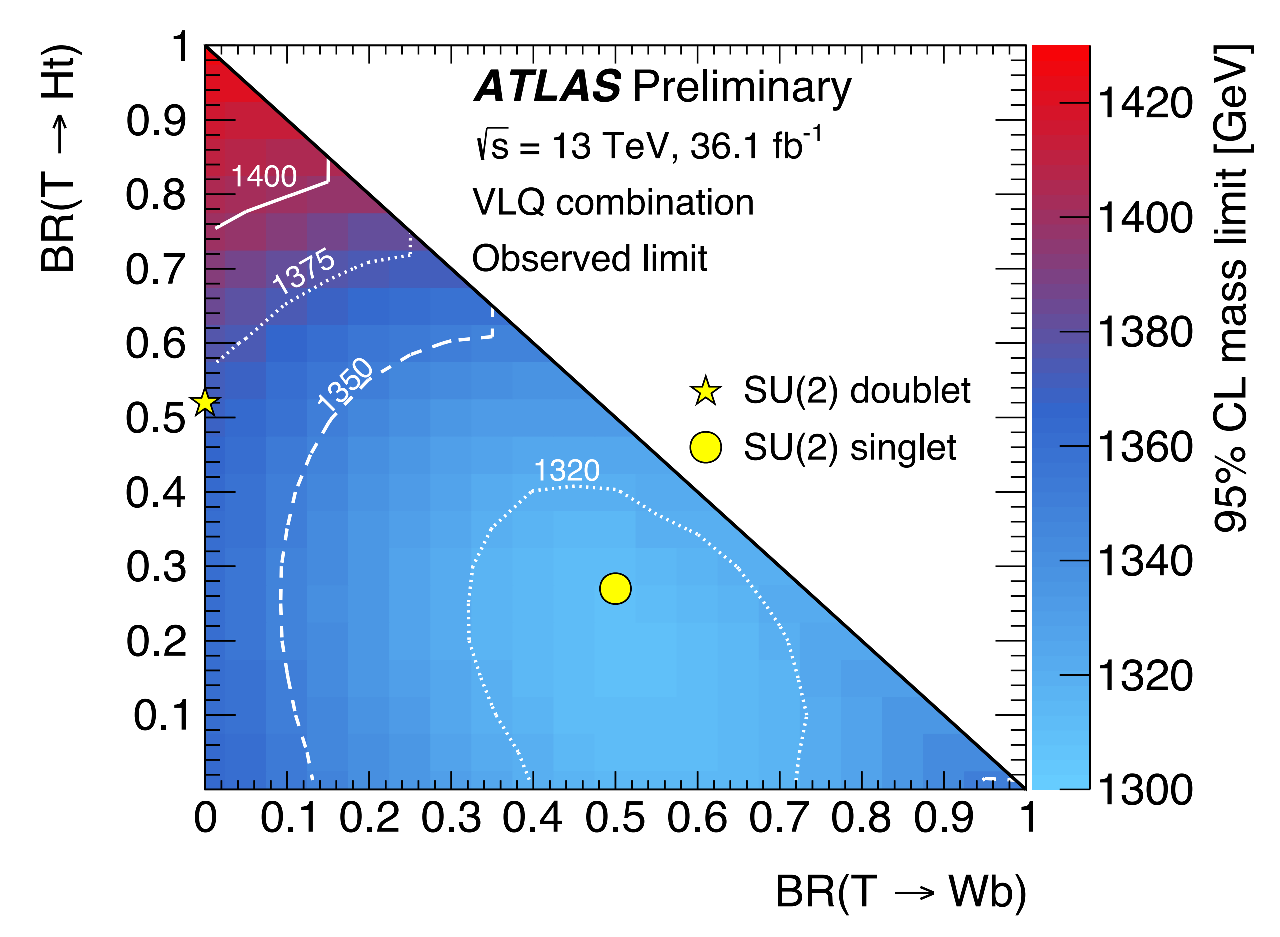


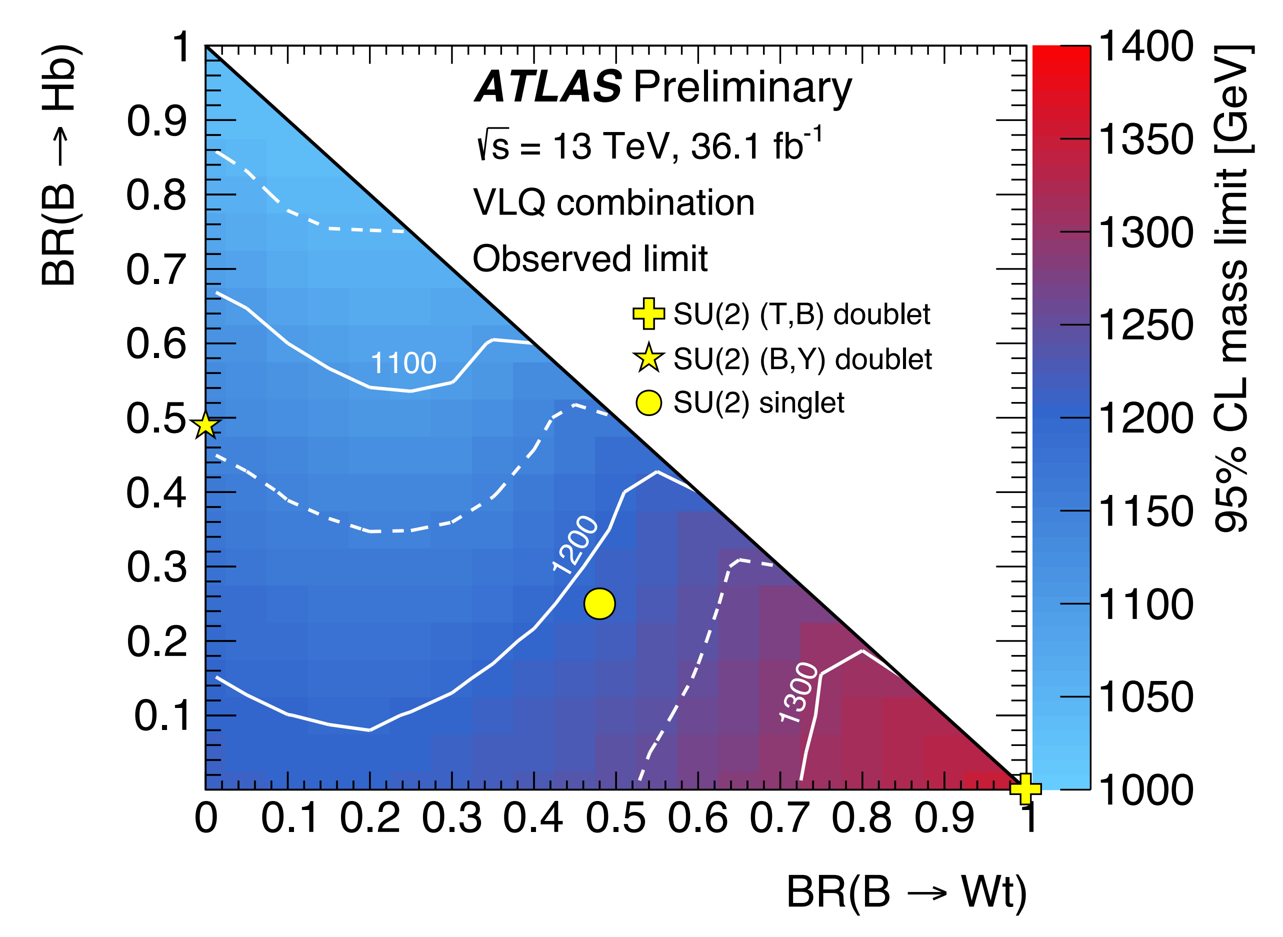
(Naive cut scheme, closely following the two di-jet search CMS-EXO-17-021).

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]

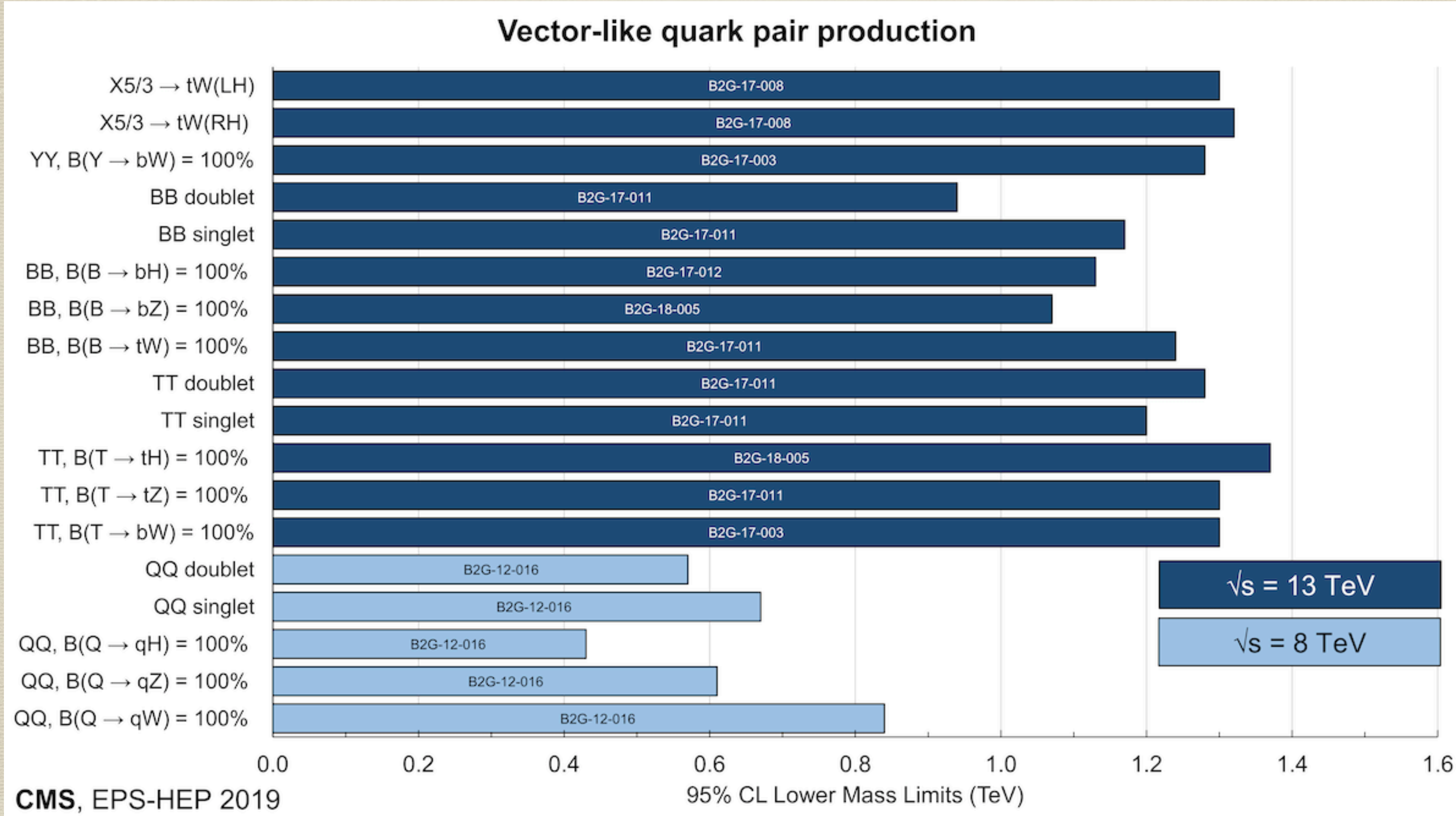
T & *B*: Combined bounds on pair-produced top partners





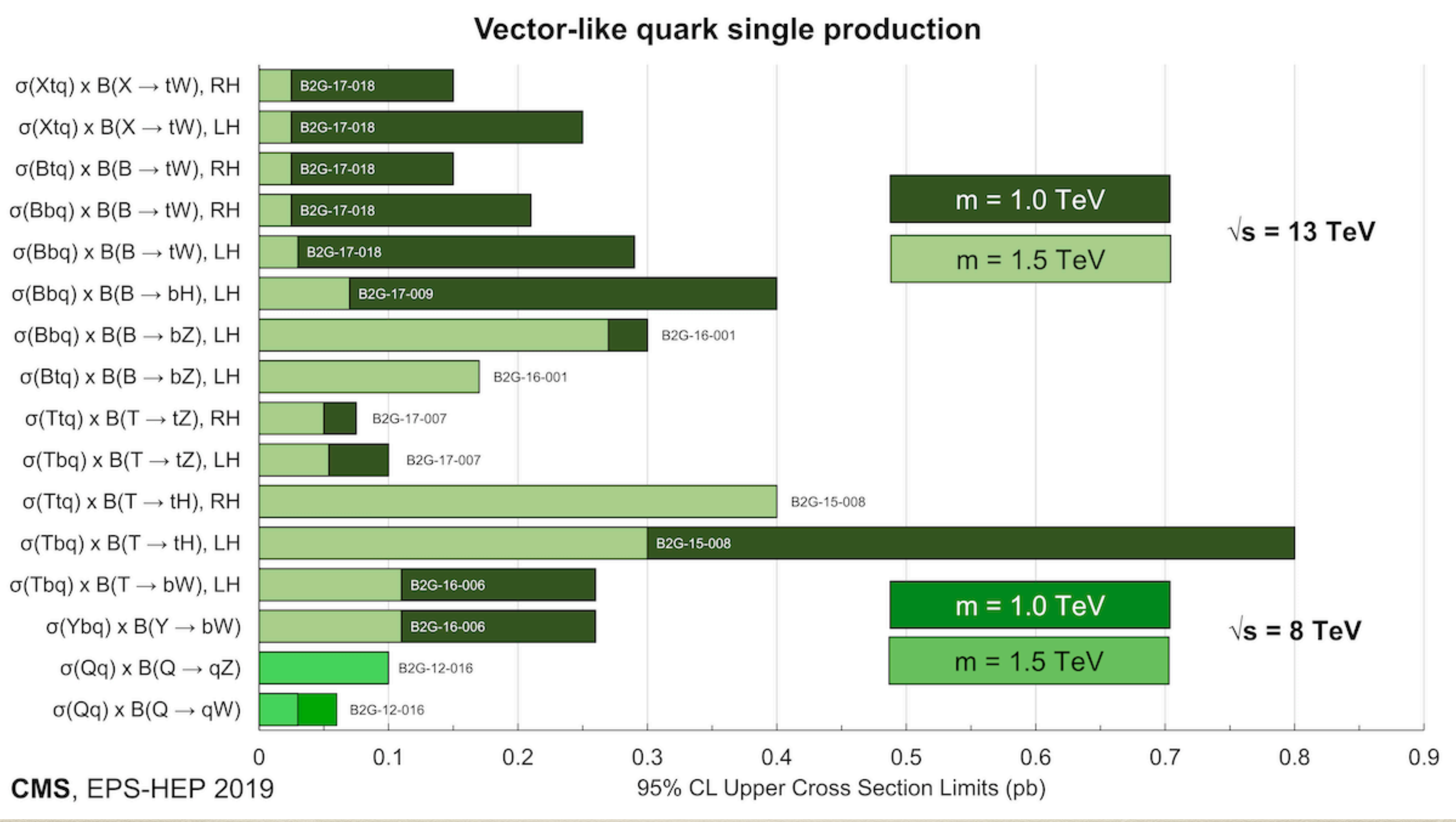
[ATLAS-CONF-2018-032]

CMS bounds on pair production



[CMS B2G Summary Plots]

CMS bounds on single production



[CMS B2G Summary Plots]

…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.

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, we showed how branching ratios of top partners to h/W/Z vs new pNGBs are related.
- 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]

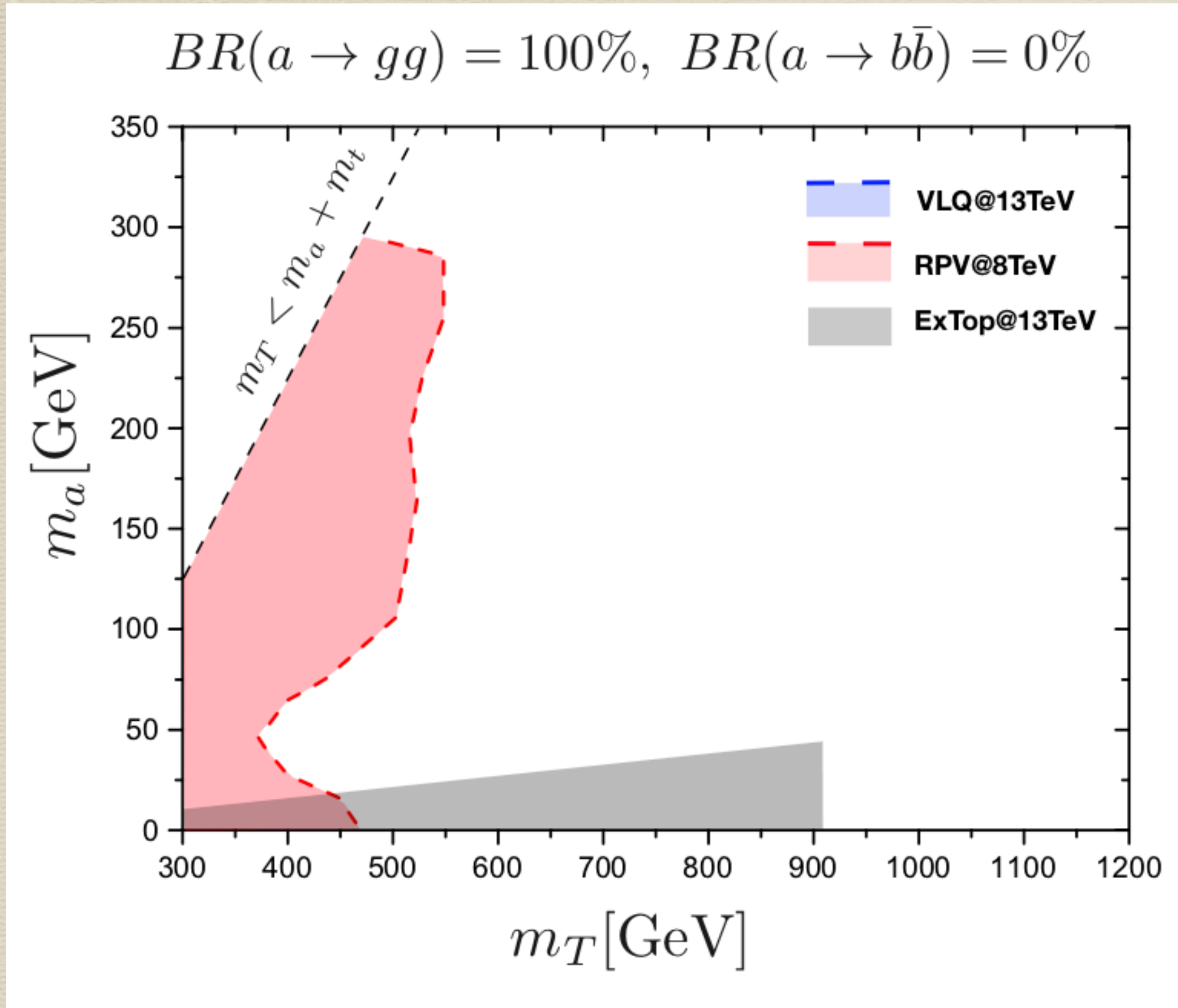
$$\mathcal{L}_T = \overline{T}\left(i\not{D} - M_T\right)T + \left(\kappa^T_{W,L}\frac{g}{\sqrt{2}}\,\overline{T}\not{W}^+ P_L b + \kappa^T_{Z,L}\frac{g}{2c_W}\,\overline{T}\not{Z}P_L t - \kappa^T_{h,L}\frac{M_T}{v}\,\overline{T}hP_L t + i\kappa^T_{a,L}\,\overline{T}aP_L t + L \leftrightarrow R + \text{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

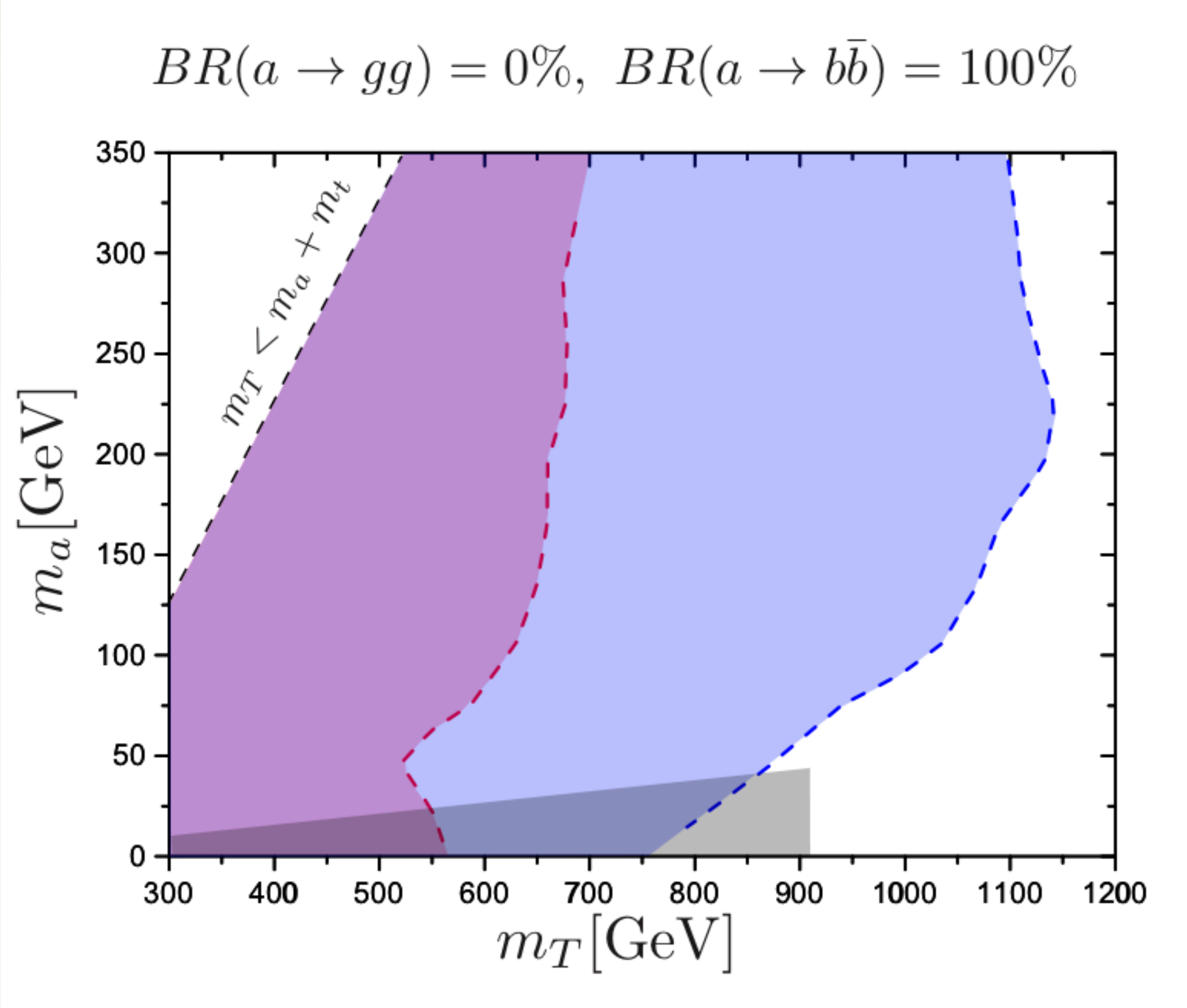
$$\mathcal{L}_B = \overline{B}\left(i\not{D} - M_B\right)B + \left(\kappa^B_{W,L}\frac{g}{\sqrt{2}}\,\overline{B}\not{W}^- P_L t + \kappa^B_{Z,L}\frac{g}{2c_W}\,\overline{B}\not{Z}^+ P_L b - \kappa^B_{h,L}\frac{M_B}{v}\,\overline{B}hP_L b + i\kappa^B_{a,L}\,\overline{B}aP_L b + L \leftrightarrow R +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

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

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

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.

[PLB798, 135015 (2019)]

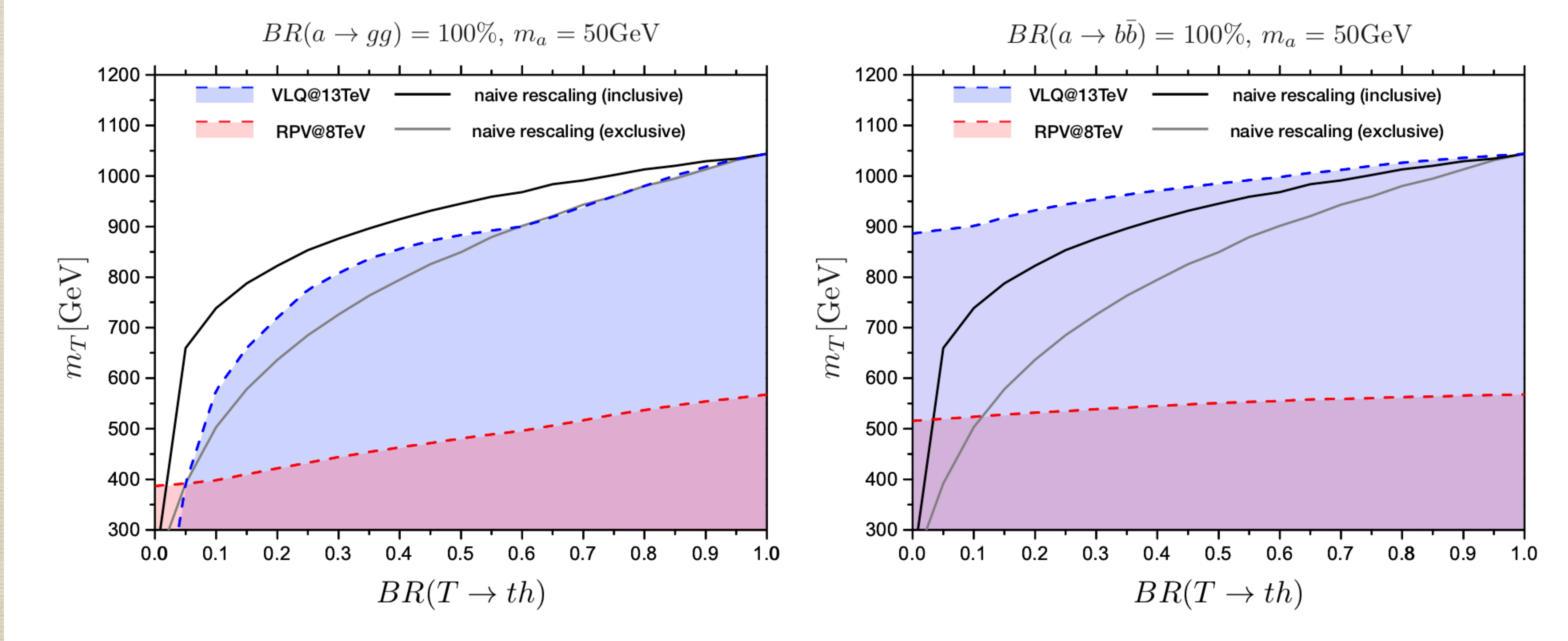
For light a: Bounds on $pp \to TT \to t\, a\, t\, h$, with $a \to gg$ or $a \to bb$

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:



[PLB798, 135015 (2019)]

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

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:

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

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

[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:

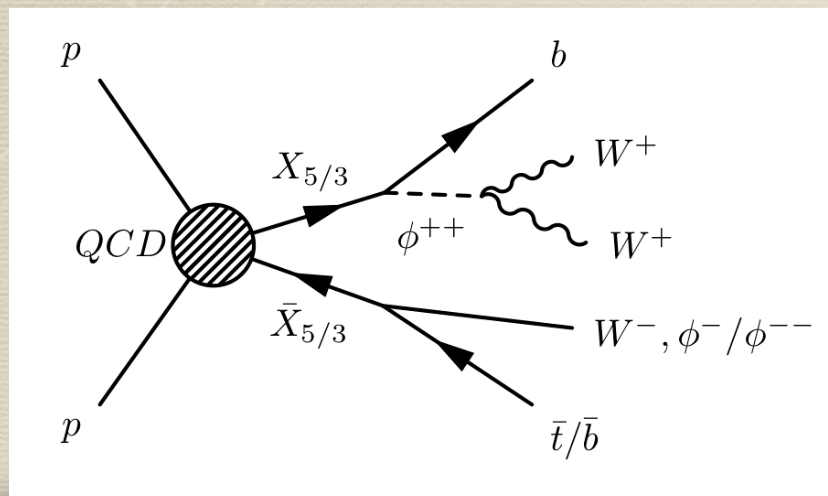
$$\mathcal{L}^{\phi}_{X_{5/3}} = \overline{X}_{5/3}\left(i\not{D} - M_{X_{5/3}}\right)X_{5/3} + \left(\kappa^X_{W,L}\frac{g}{\sqrt{2}}\overline{X}_{5/3}\not{W}^+ P_L t \right.$$
$$\left. + i\kappa^X_{\phi^+,L}\overline{X}_{5/3}\phi^+ P_L t + i\kappa^X_{\phi^{++},L}\overline{X}_{5/3}\phi^{++} P_L b +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

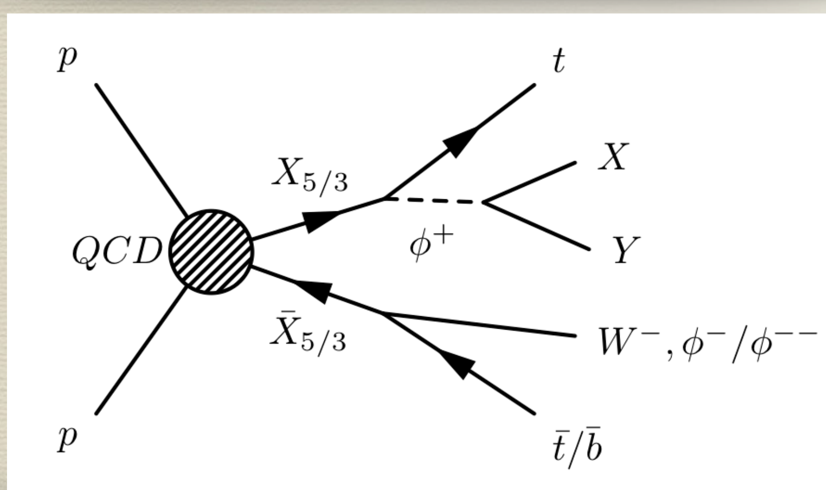
$$\mathcal{L}_\phi = \sum_{\phi=\phi^+,\phi^{++}} \left(|D_\mu\phi|^2 - m^2_\phi\,|\phi|^2\right) + \left(\frac{egK^\phi_{W\gamma}}{8\pi^2 f_\phi}\phi^+ W^-_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{g^2 c_w K^\phi_{WZ}}{8\pi^2 f_\phi}\phi^+ W^-_{\mu\nu}\tilde{B}^{\mu\nu}\right.$$
$$\left. + \frac{g^2 K^\phi_W}{8\pi^2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

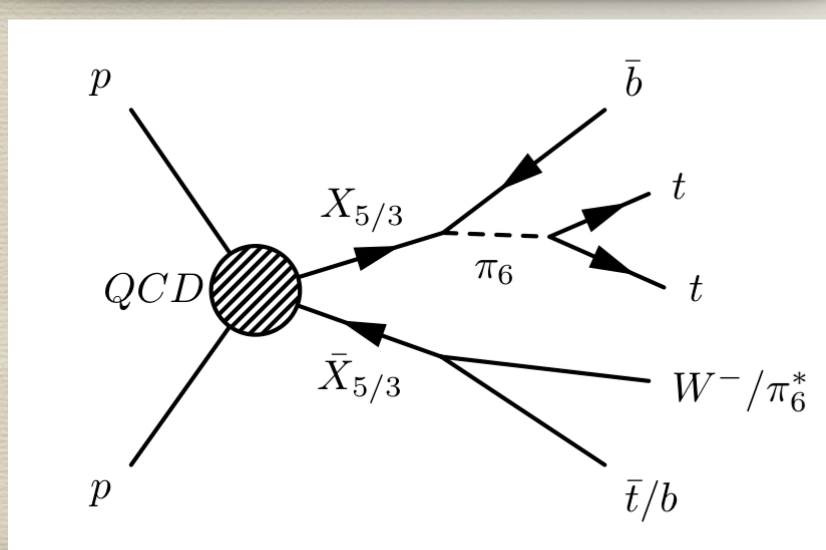
[JHEP 1806, 065]

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

Examples of processes:







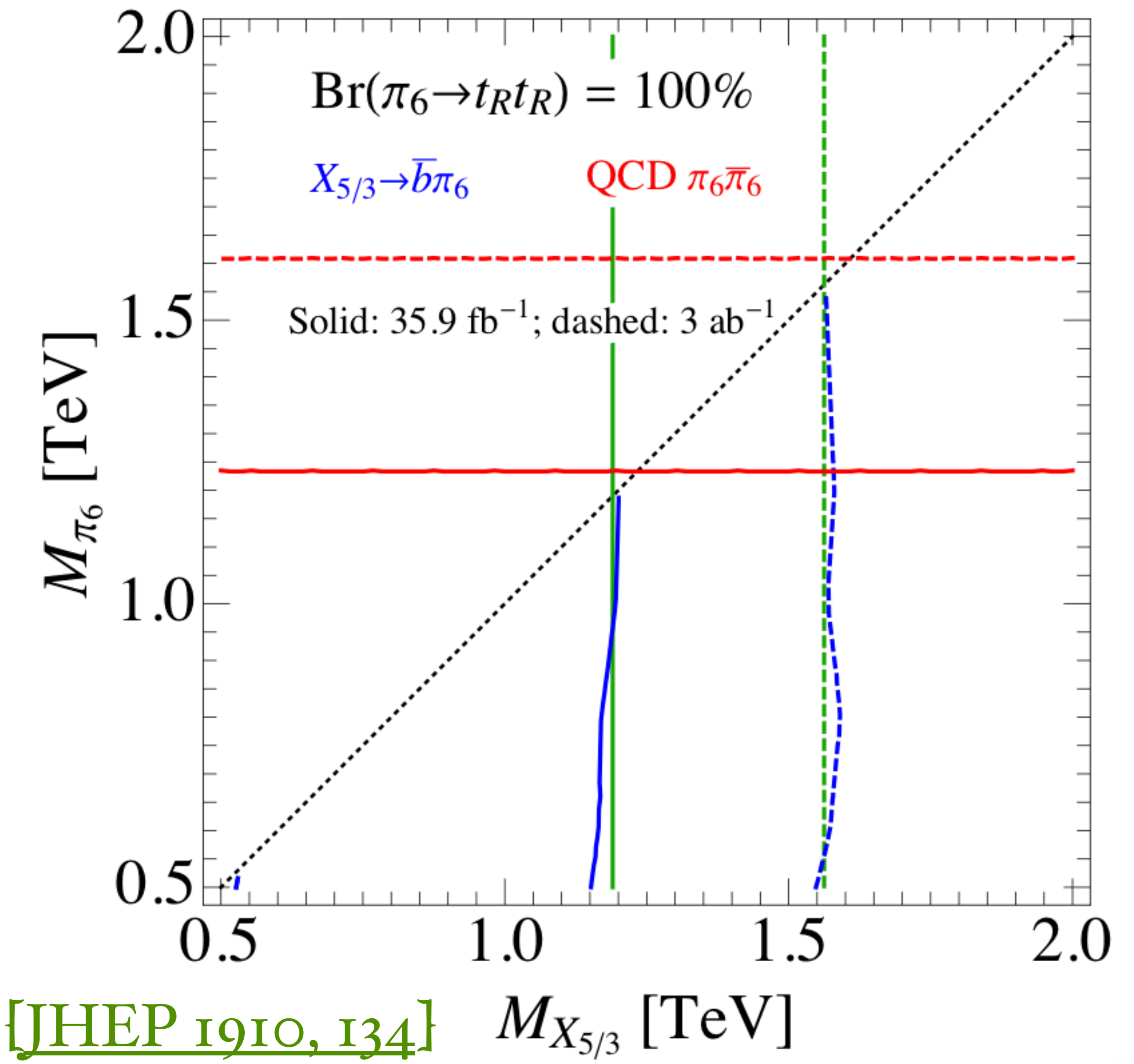
Full list of final states from $X_{5/3}$ pair-production:

2

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	$(bW^+)W^+\gamma$, $(bW^+)W^+Z$
		$t\tau^+\nu$	$(bW^+)(W^{+*}\bar{\nu})\nu$
		$tt\bar{b}$	$(bW^+)(bW^+)\bar{b}$
	$b\phi^{++}$	bW^+W^+	bW^+W^+
		$b\tau^+\tau^+$	$b(W^{+*}\bar{\nu})(W^{+*}\bar{\nu})$
		$bW^{+(*)}\phi^+$	$bW^{+(*)}W^{+(*)} + X$

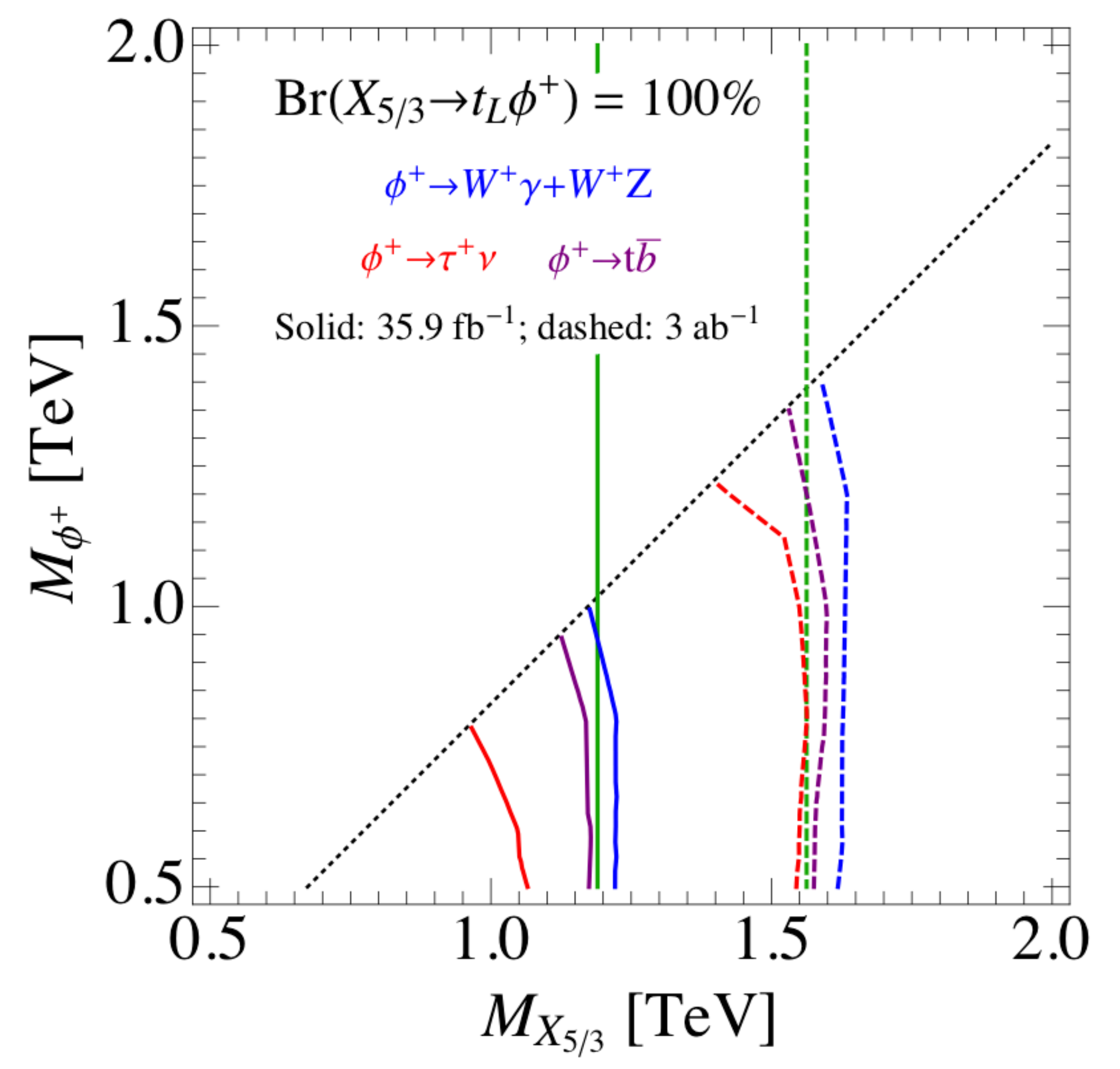
Recasting the most recent CMS $X_{5/3}$ same-sign lepton search JHEP 1903, 082 we obtain bounds on $X_{5/3}$ pair-production with exotic $X_{5/3}$ decays:

$\boldsymbol{\pi}_6$:



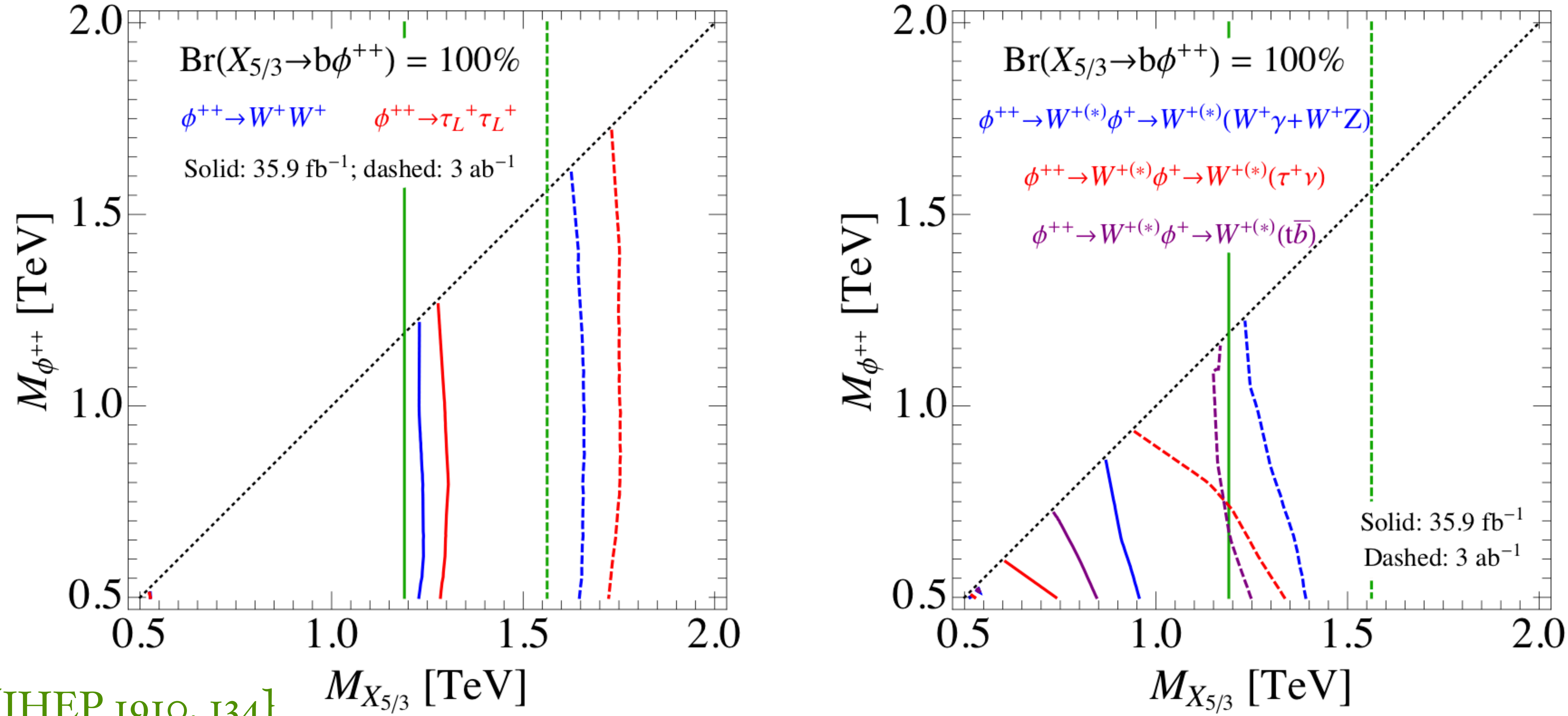
[JHEP 1910, 134]

$\boldsymbol{\phi}^+$:



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

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

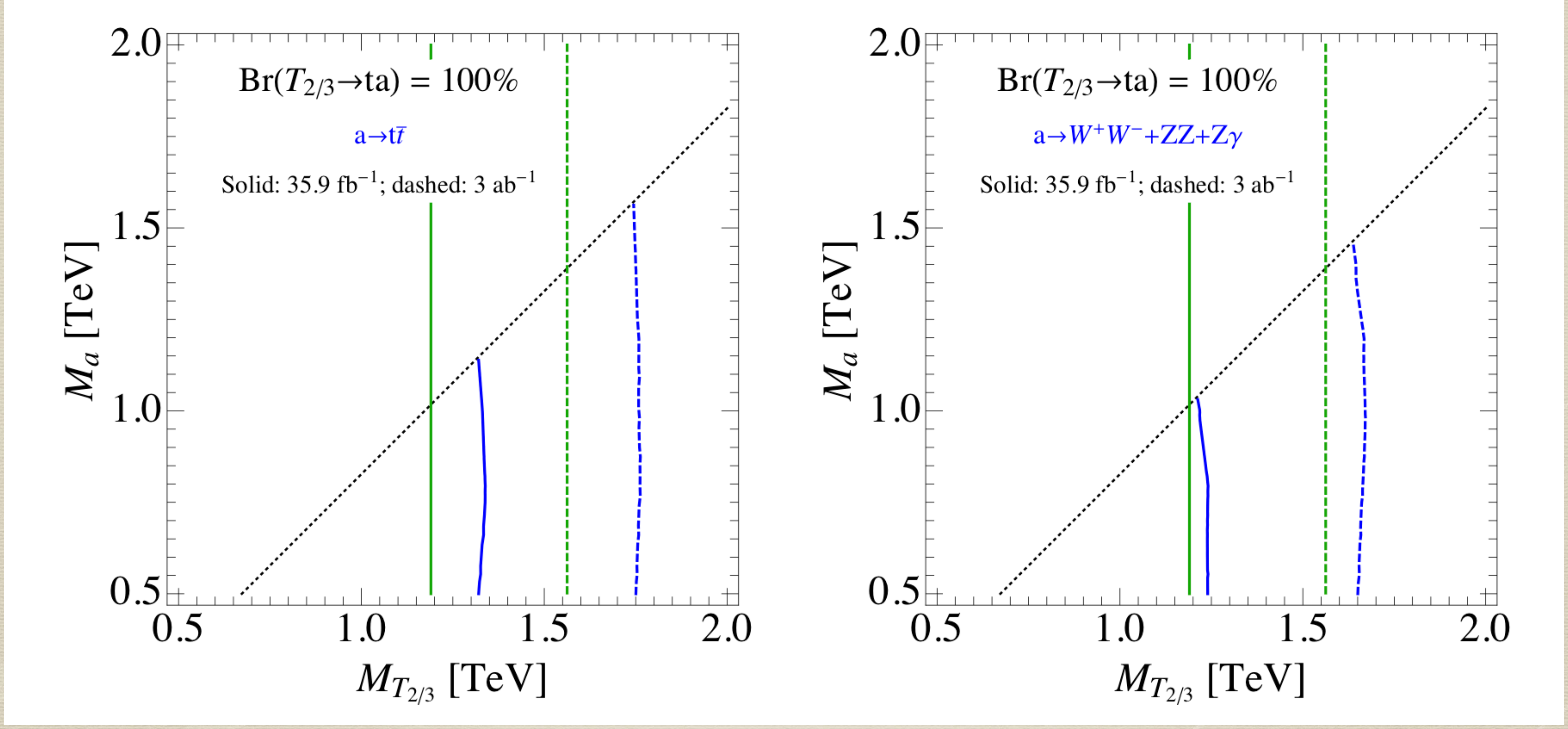


[JHEP 1910, 134]

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

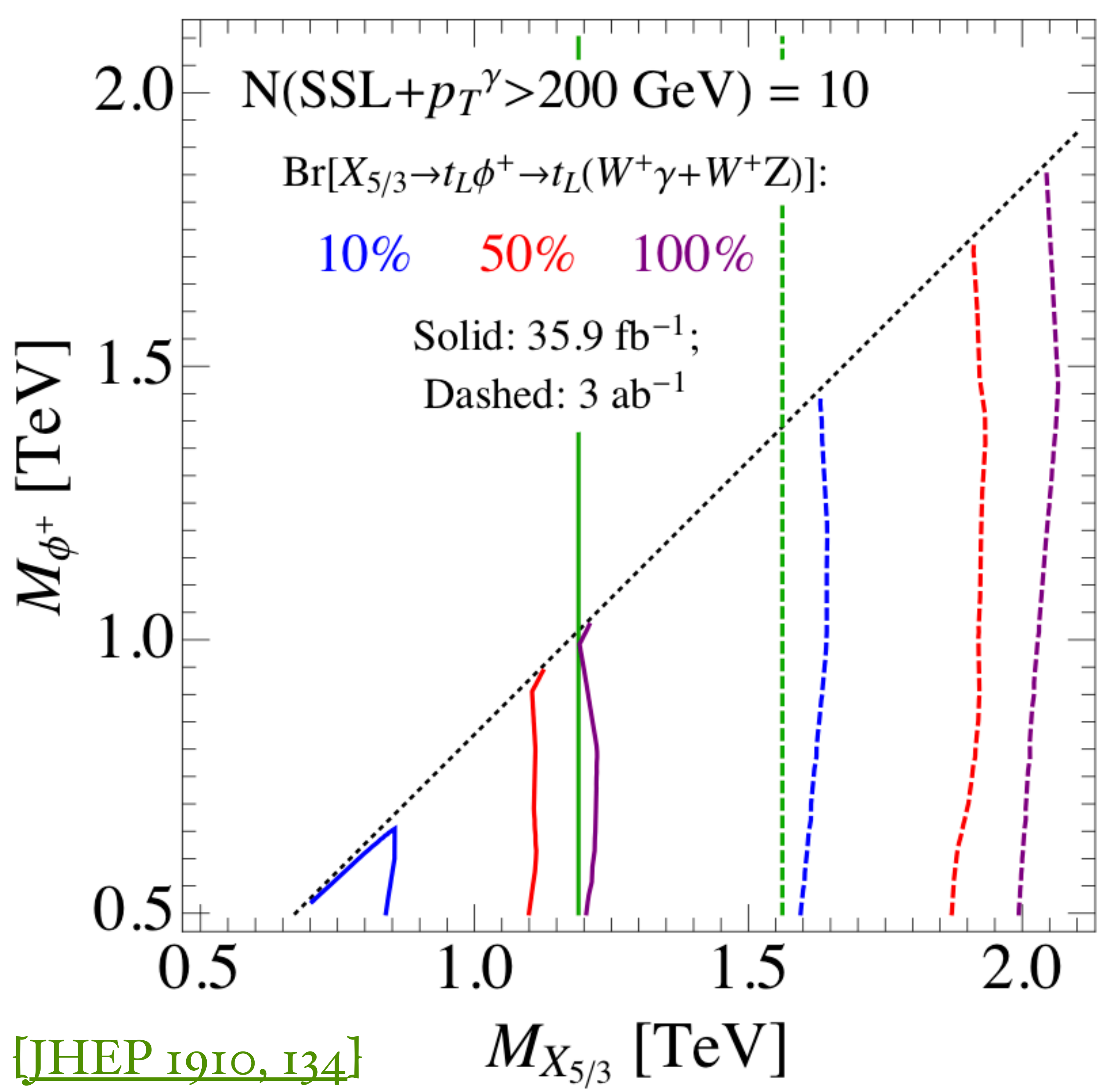
Bonus Plots

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



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.

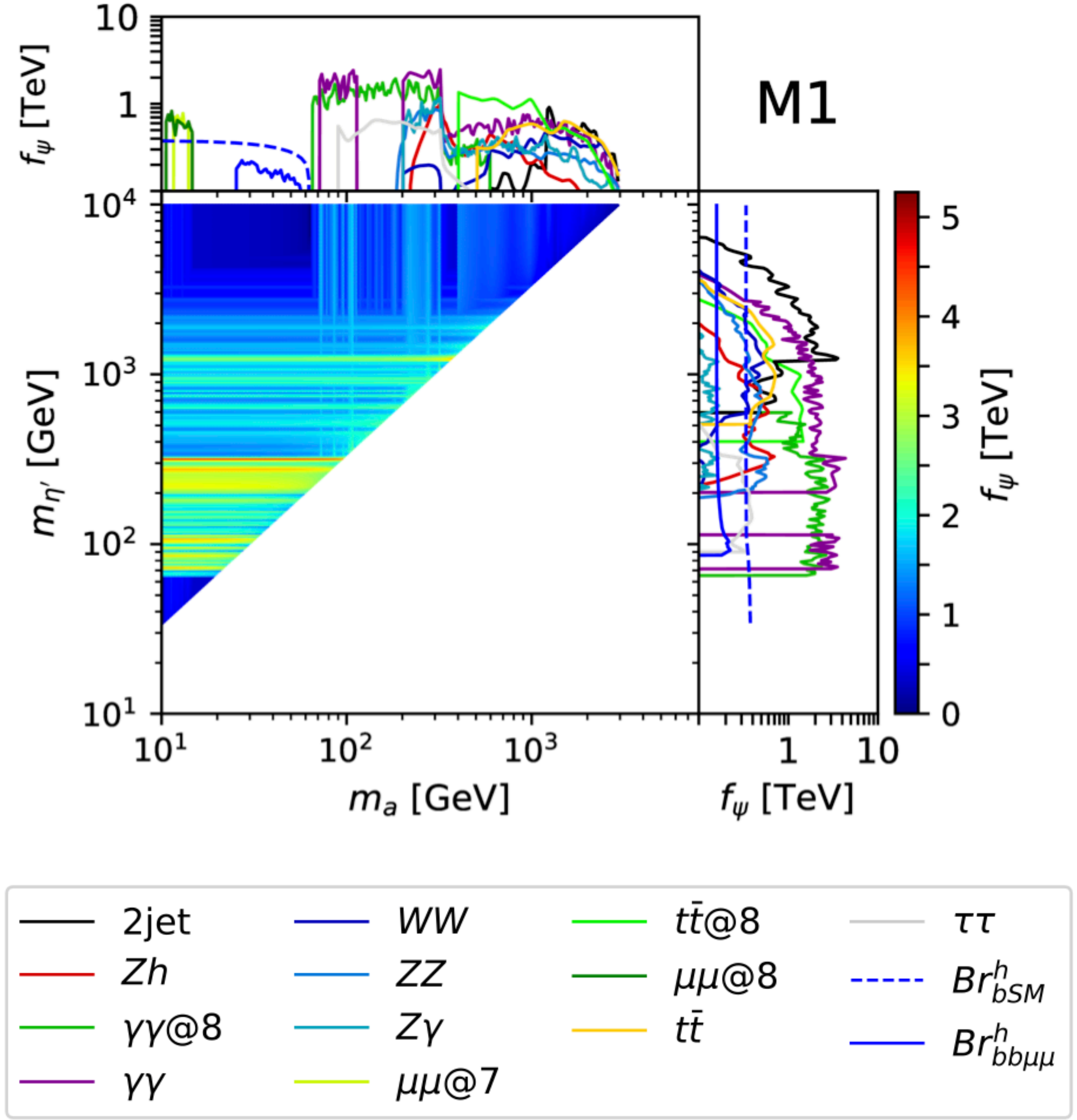


[JHEP 1910, 134]

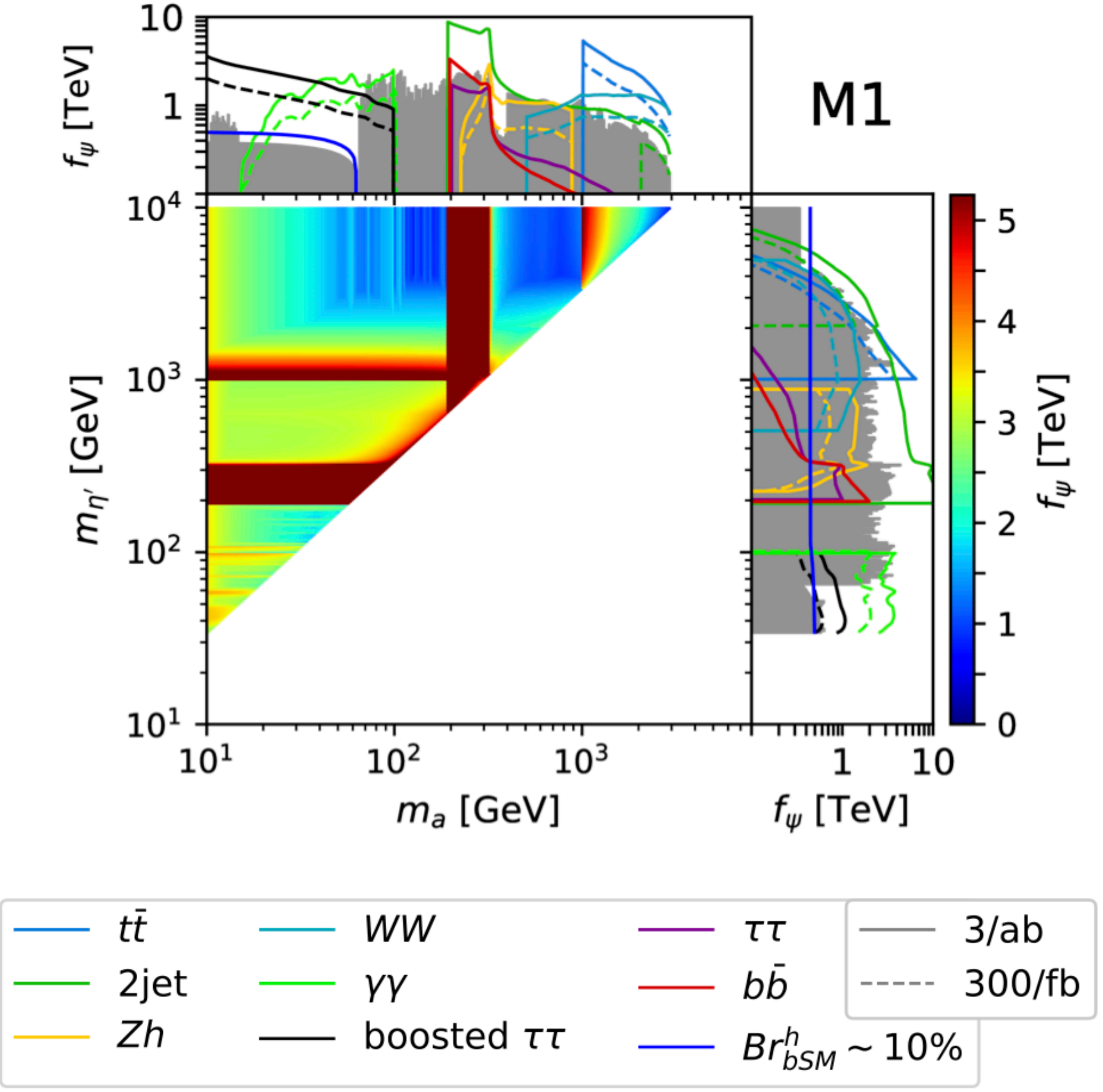
Conclusions

- Composite Higgs models provide a viable solution to the hierarchy problem but they still provide many challenges and room for exploration in theory and model-building.
- Light pNGBs as motivated from CH UV embeddings (neutral, charged and colored) are being tested by the LHC, but not in all relevant channels, are they are far from being ruled out. We only start to explore the interesting parameter space.
- `Exotic'' decays of top partners to t/b + pNGBs rather than to t/b + W/Z/h occur commonly 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.

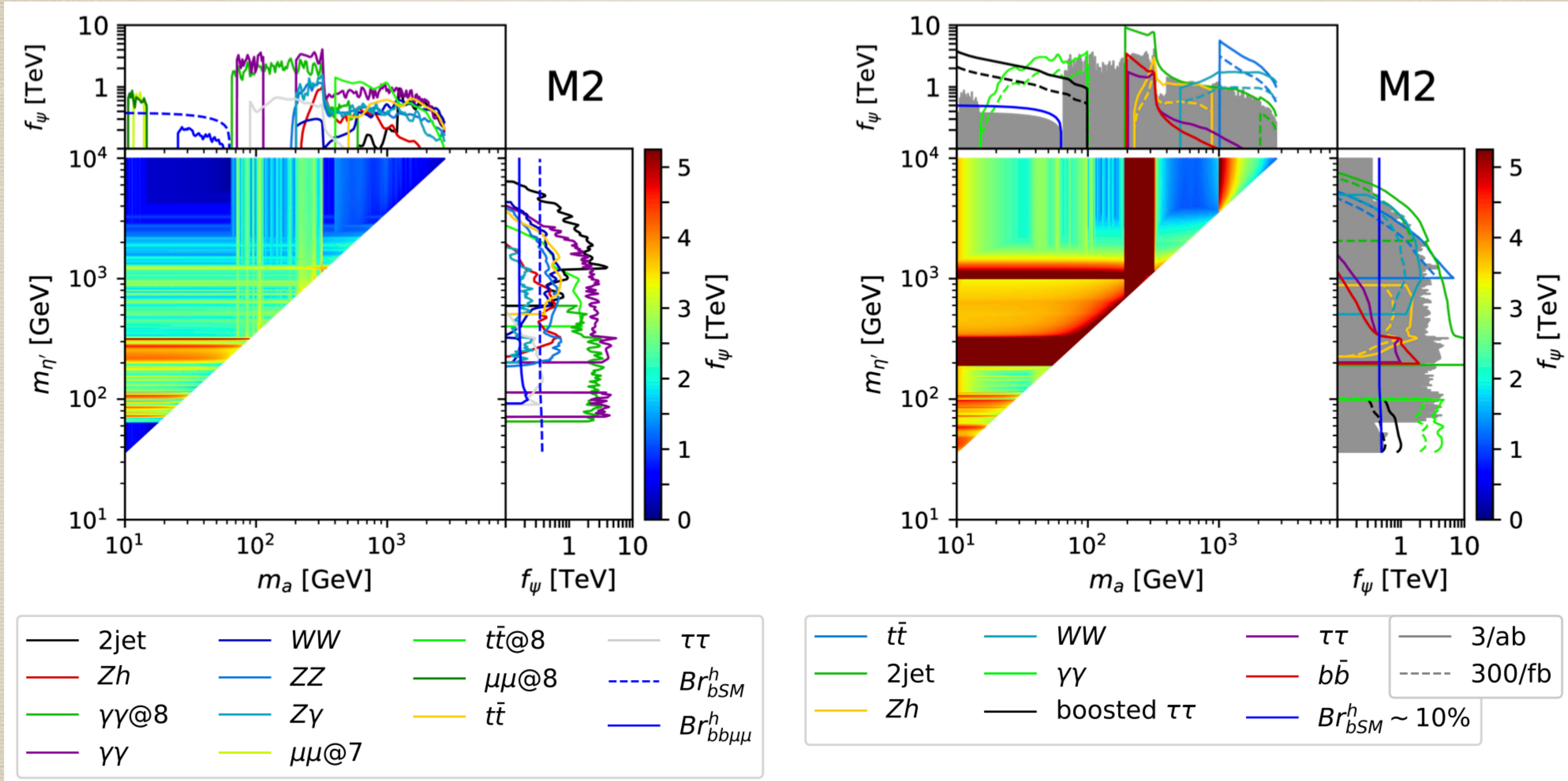
Backup



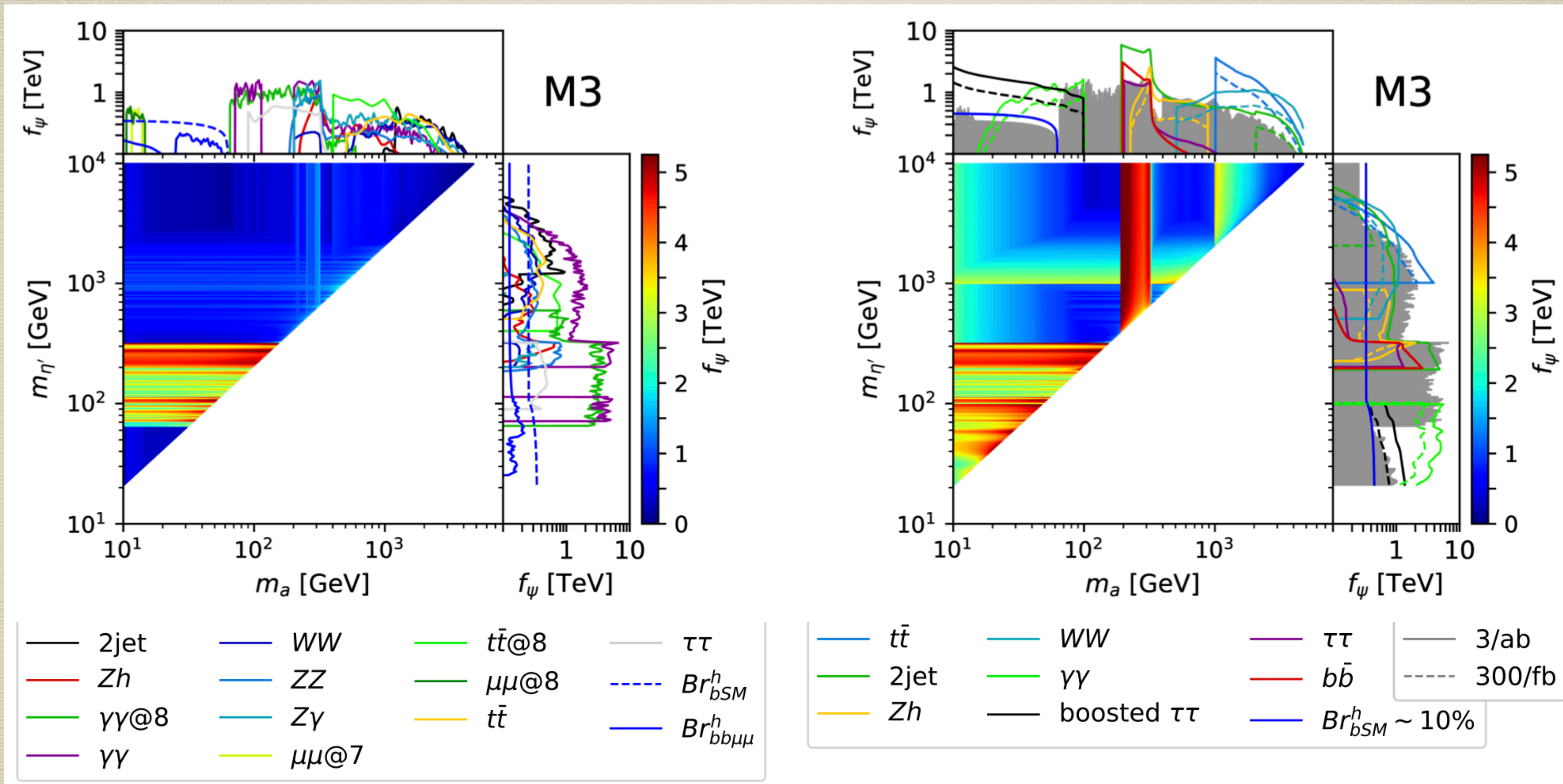
M1
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
2jet
Zh
γγ@8
γγ
WW
ZZ
Zγ
μμ@7
$t\bar{t}$@8
μμ@8
$t\bar{t}$
ττ
Br^h_{bSM}
$Br^h_{bb\mu\mu}$



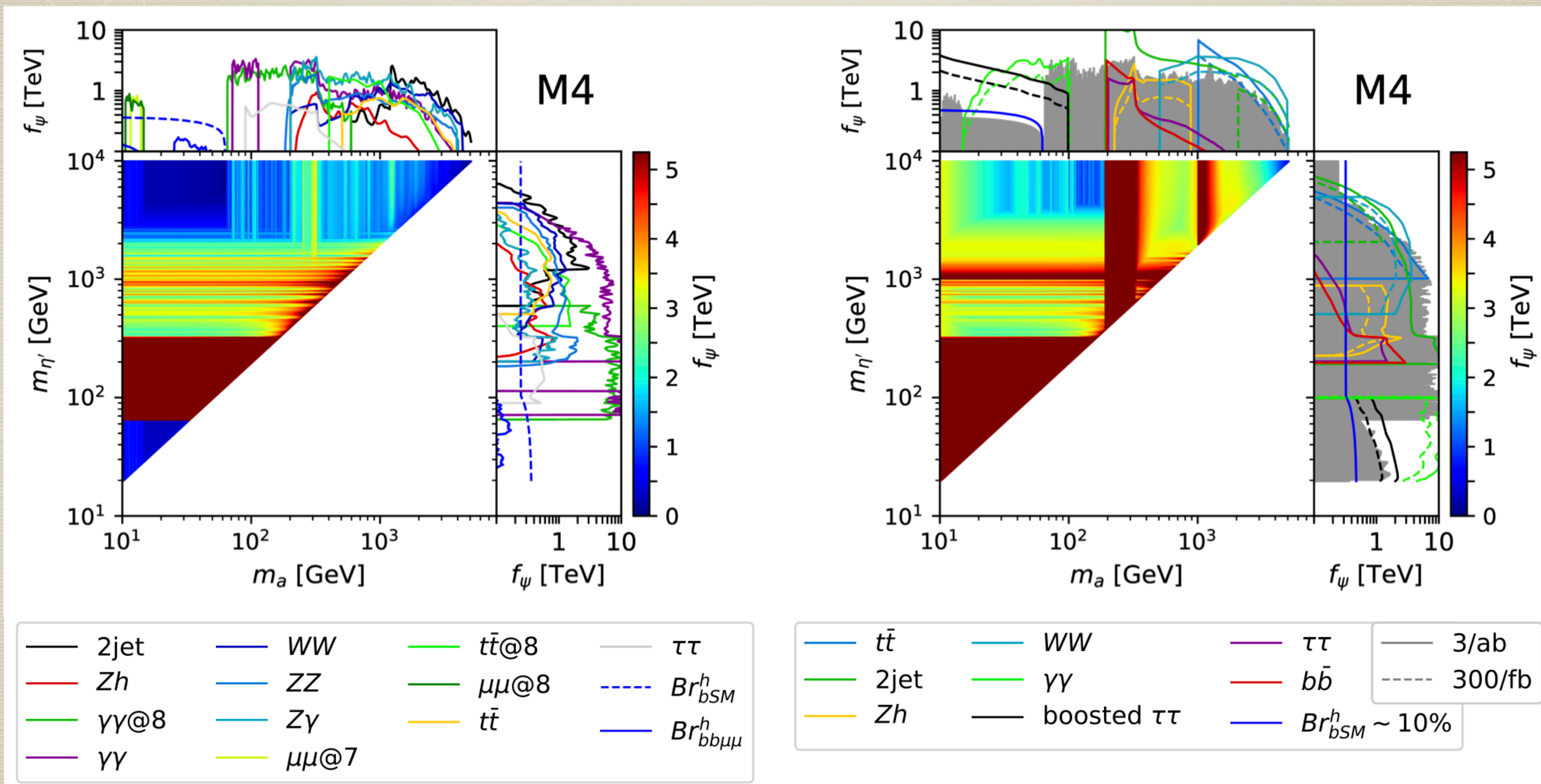
M1
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
$t\bar{t}$
2jet
Zh
WW
γγ
boosted ττ
ττ
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb



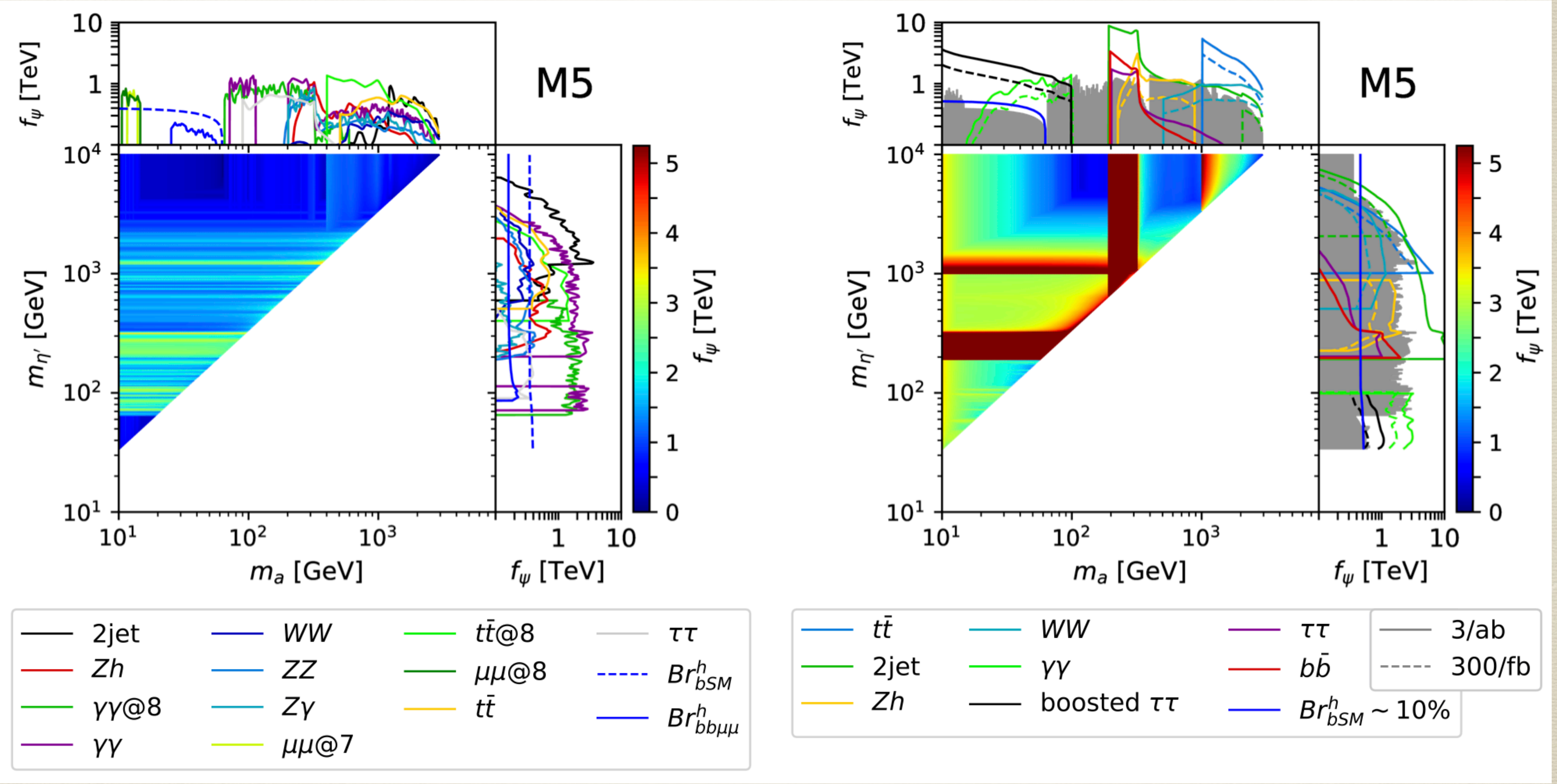
M2
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
2jet
Zh
γγ@8
γγ
WW
ZZ
Zγ
μμ@7
$t\bar{t}$@8
μμ@8
$t\bar{t}$
ττ
Br^h_{bSM}
$Br^h_{bb\mu\mu}$
M2
$t\bar{t}$
2jet
Zh
WW
γγ
boosted ττ
ττ
$b\bar{b}$
Br^h_{bSM} ~ 10%
3/ab
300/fb


M3
M3
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

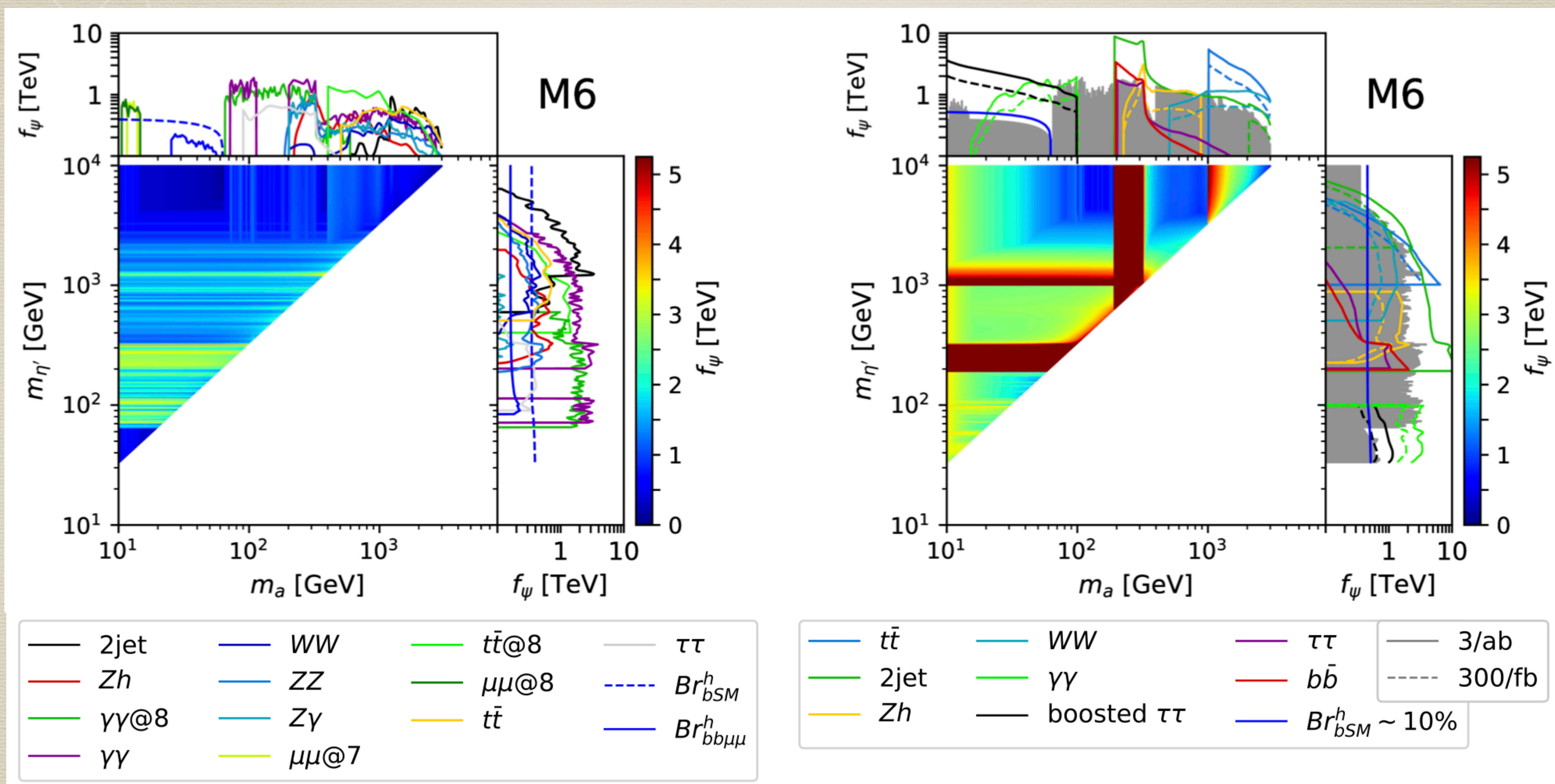
TCP


M4
fψ [TeV]
mη′ [GeV]
ma [GeV]
2jet
Zh
γγ@8
γγ
WW
ZZ
Zγ
μμ@7
tt̄@8
μμ@8
tt̄
ττ
Br^h_bSM
Br^h_bbμμ
M4
tt̄
2jet
Zh
WW
γγ
boosted ττ
ττ
bb̄
Br^h_bSM ~ 10%
3/ab
300/fb

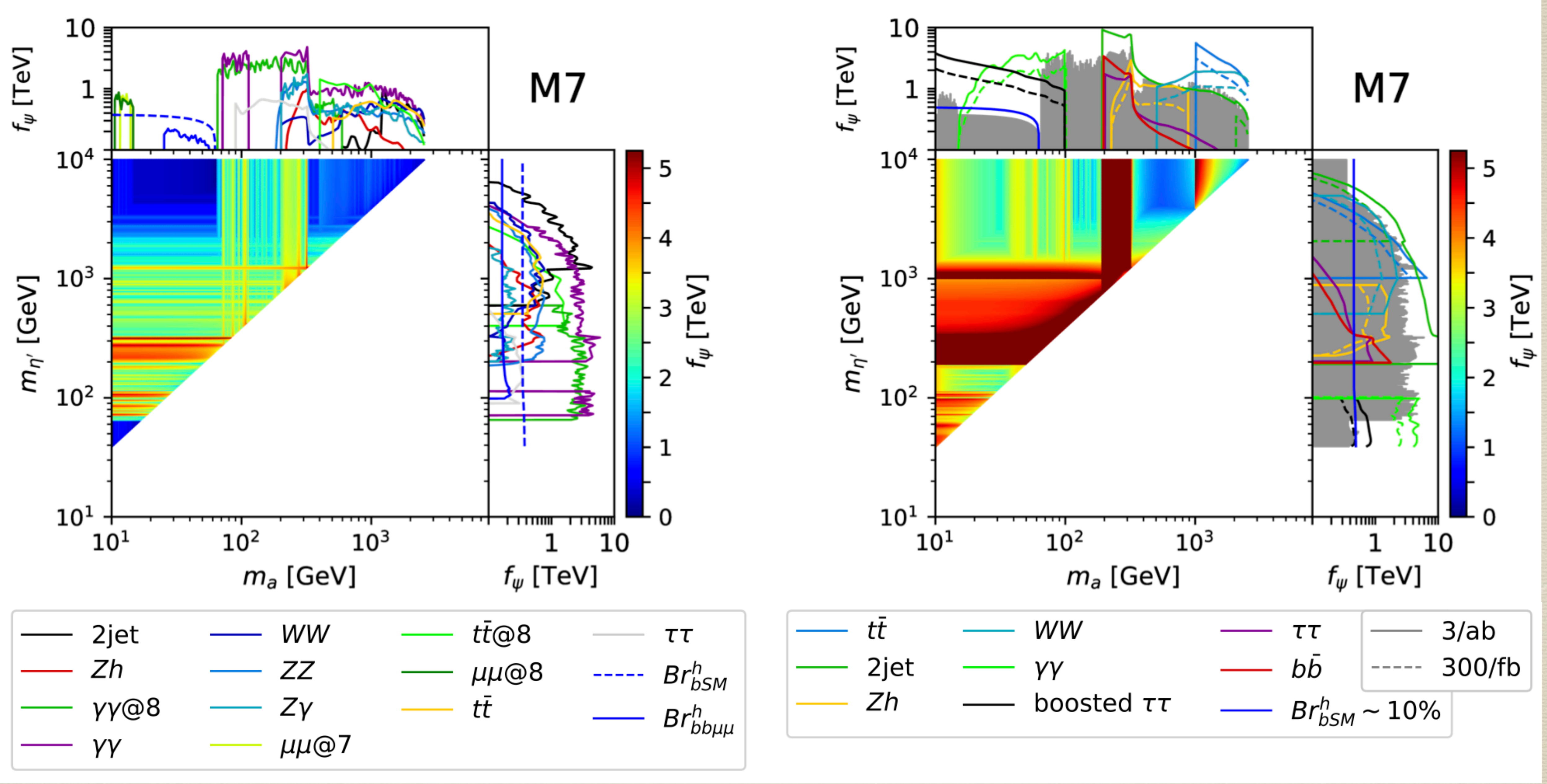
TCP



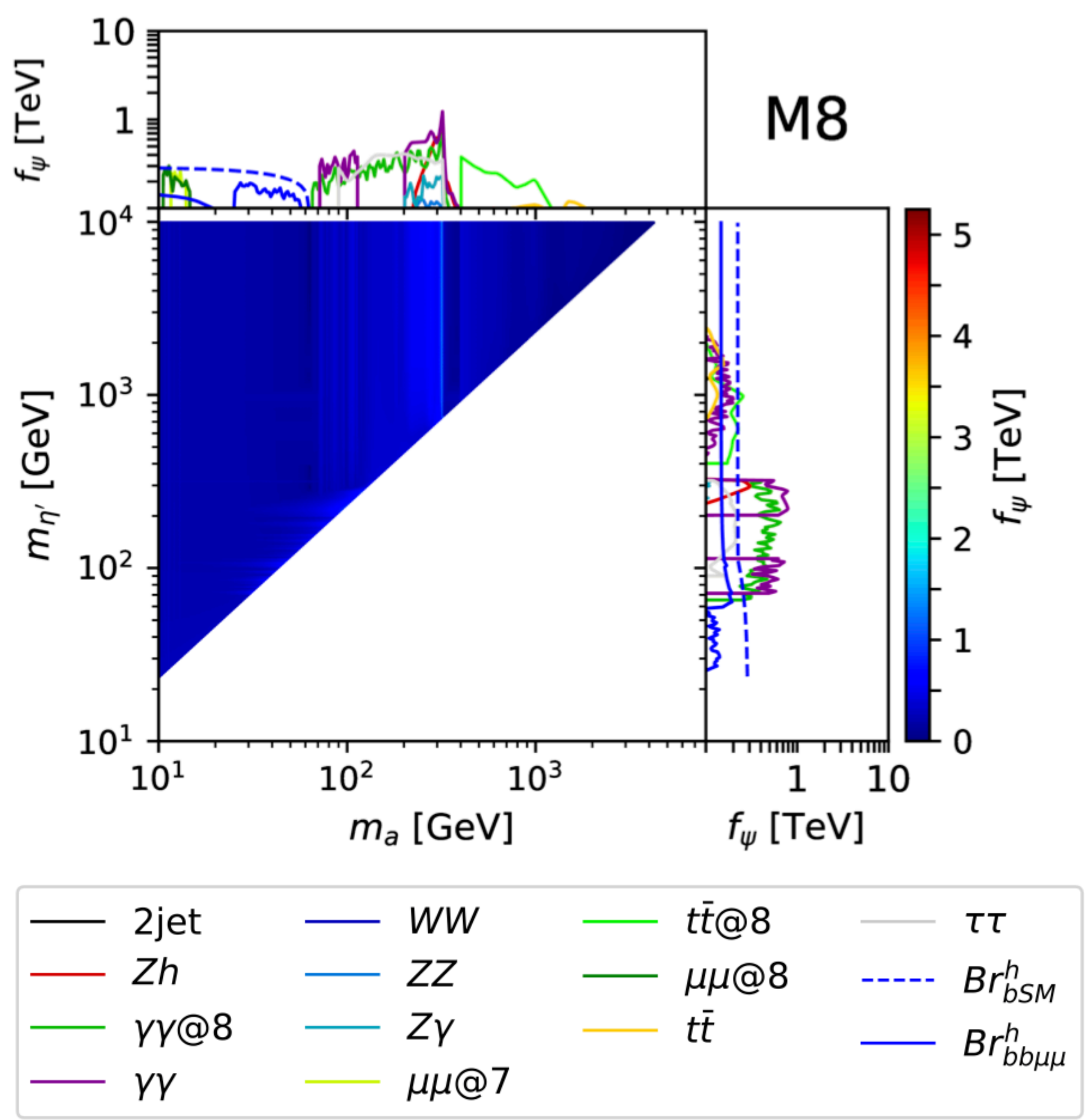
M5
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
2jet
Zh
$\gamma\gamma$@8
$\gamma\gamma$
WW
ZZ
$Z\gamma$
$\mu\mu$@7
$t\bar{t}$@8
$\mu\mu$@8
$t\bar{t}$
$\tau\tau$
Br^h_{bSM}
$Br^h_{bb\mu\mu}$
M5
$t\bar{t}$
2jet
Zh
WW
$\gamma\gamma$
boosted $\tau\tau$
$\tau\tau$
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb

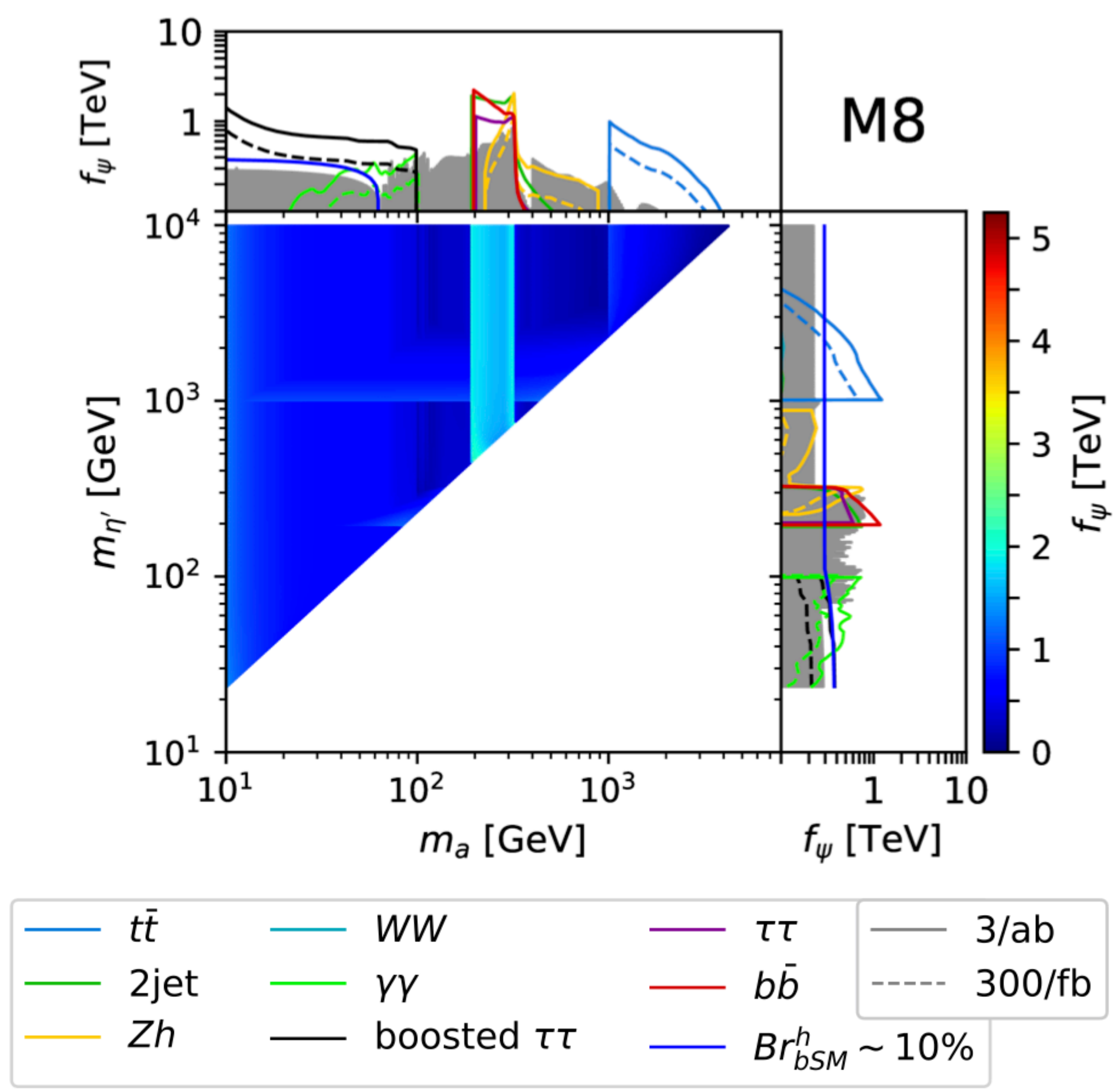

M6
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
f_ψ [TeV]
2jet
Zh
$\gamma\gamma$@8
$\gamma\gamma$
WW
ZZ
$Z\gamma$
$\mu\mu$@7
$t\bar{t}$@8
$\mu\mu$@8
$t\bar{t}$
$\tau\tau$
Br^h_{bSM}
$Br^h_{bb\mu\mu}$
M6
$t\bar{t}$
2jet
Zh
WW
$\gamma\gamma$
boosted $\tau\tau$
$\tau\tau$
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab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

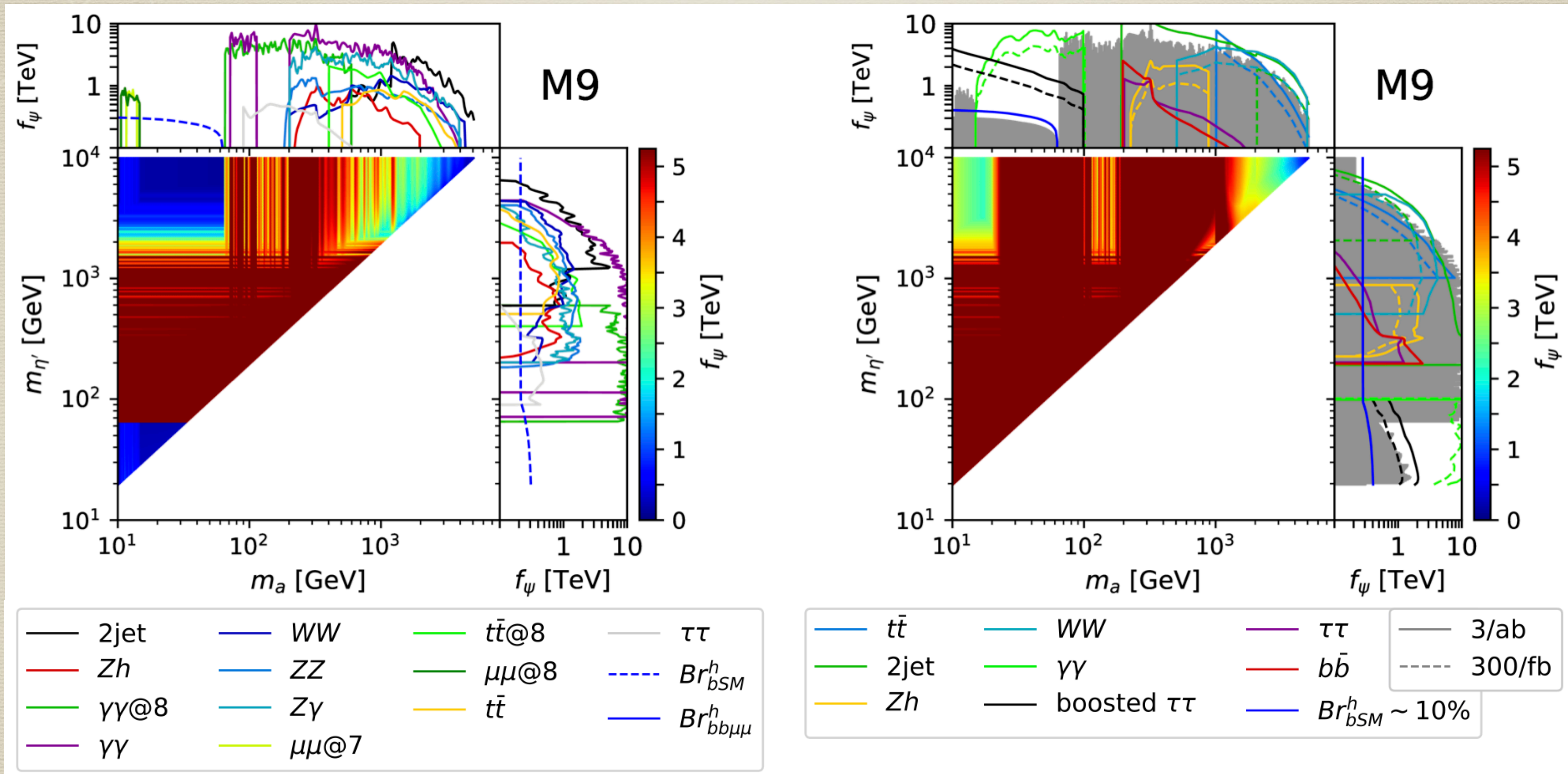
TCP



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

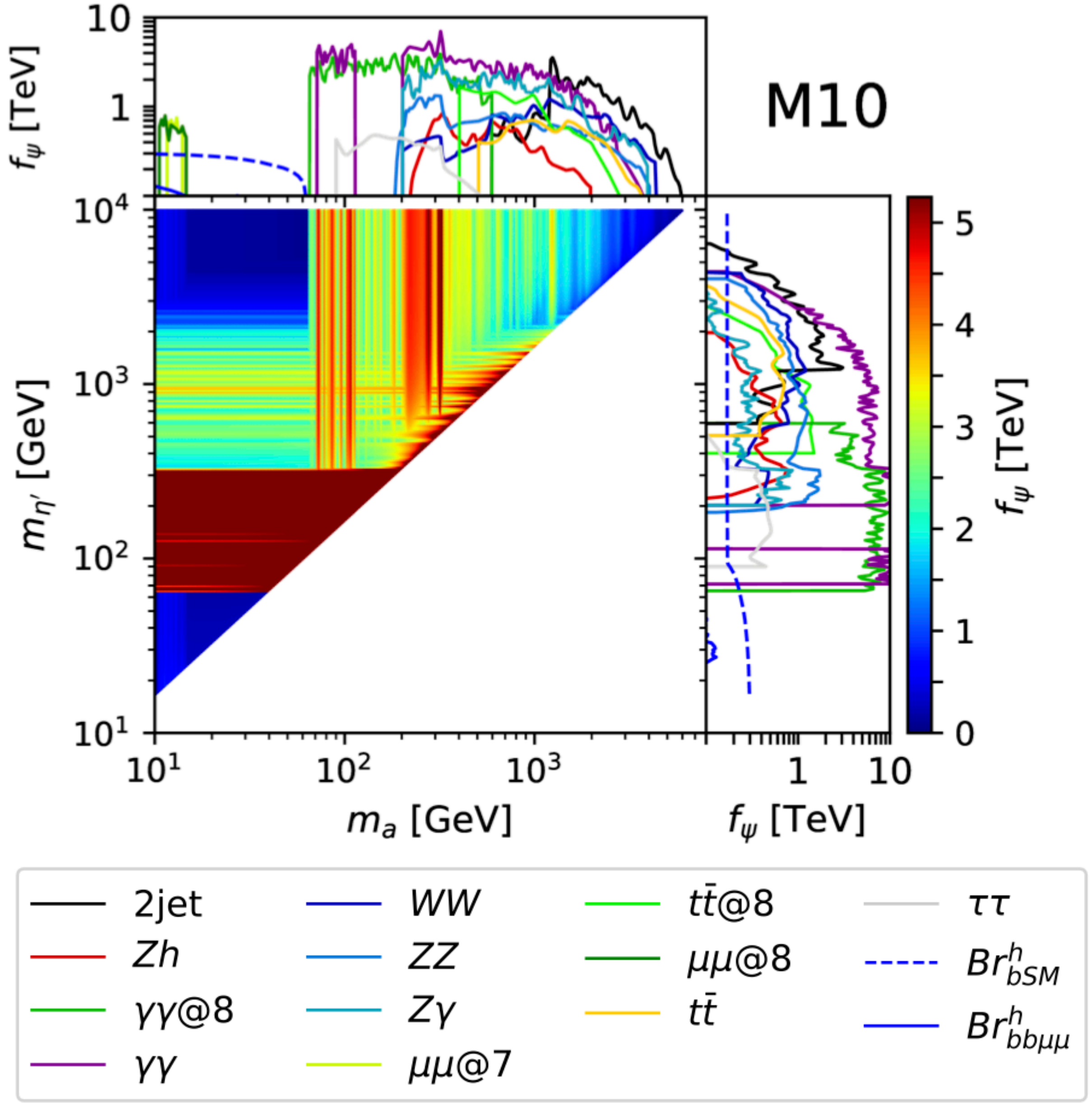

M8
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
f_ψ [TeV]
2jet
Zh
$\gamma\gamma$@8
$\gamma\gamma$
WW
ZZ
$Z\gamma$
$\mu\mu$@7
$t\bar{t}$@8
$\mu\mu$@8
$t\bar{t}$
$\tau\tau$
Br^h_{bSM}
$Br^h_{bb\mu\mu}$


M8
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

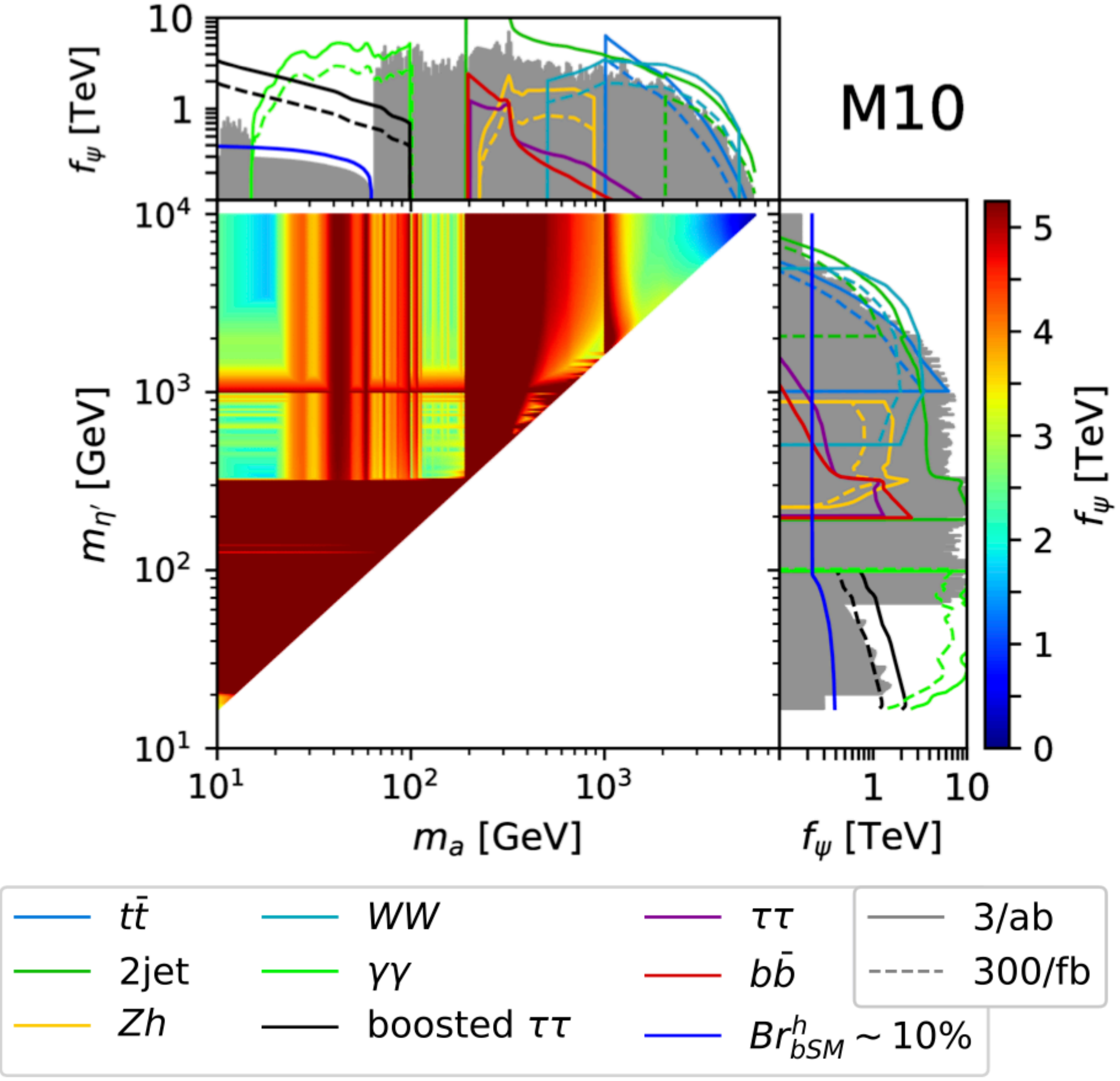


M9
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
2jet
Zh
$\gamma\gamma$@8
$\gamma\gamma$
WW
ZZ
$Z\gamma$
$\mu\mu$@7
$t\bar{t}$@8
$\mu\mu$@8
$t\bar{t}$
$\tau\tau$
Br^h_{bSM}
$Br^h_{bb\mu\mu}$
M9
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
$t\bar{t}$
2jet
Zh
WW
$\gamma\gamma$
boosted $\tau\tau$
$\tau\tau$
$b\bar{b}$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

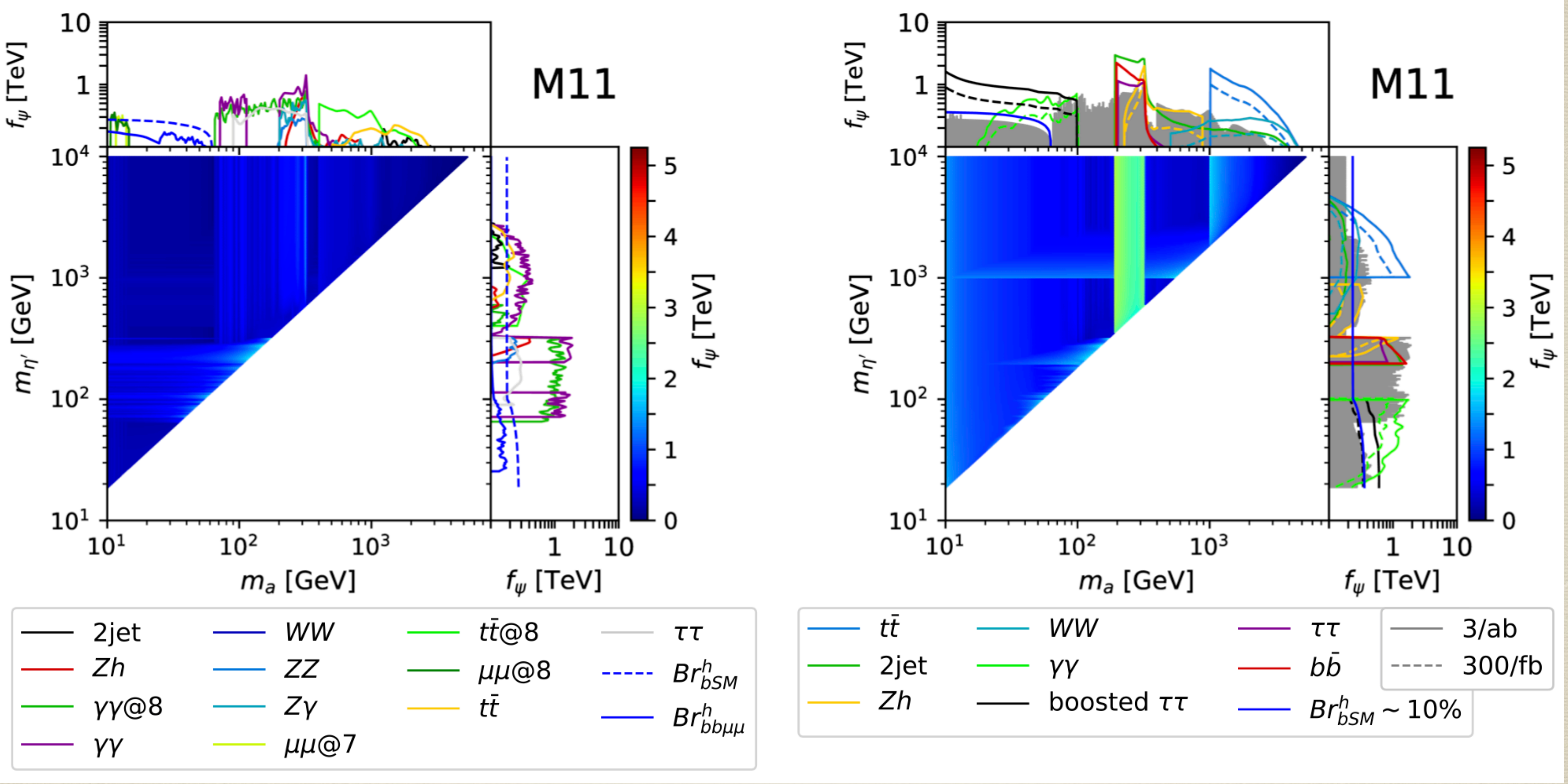
TCP



M10
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}
$Br^h_{bb\mu\mu}$

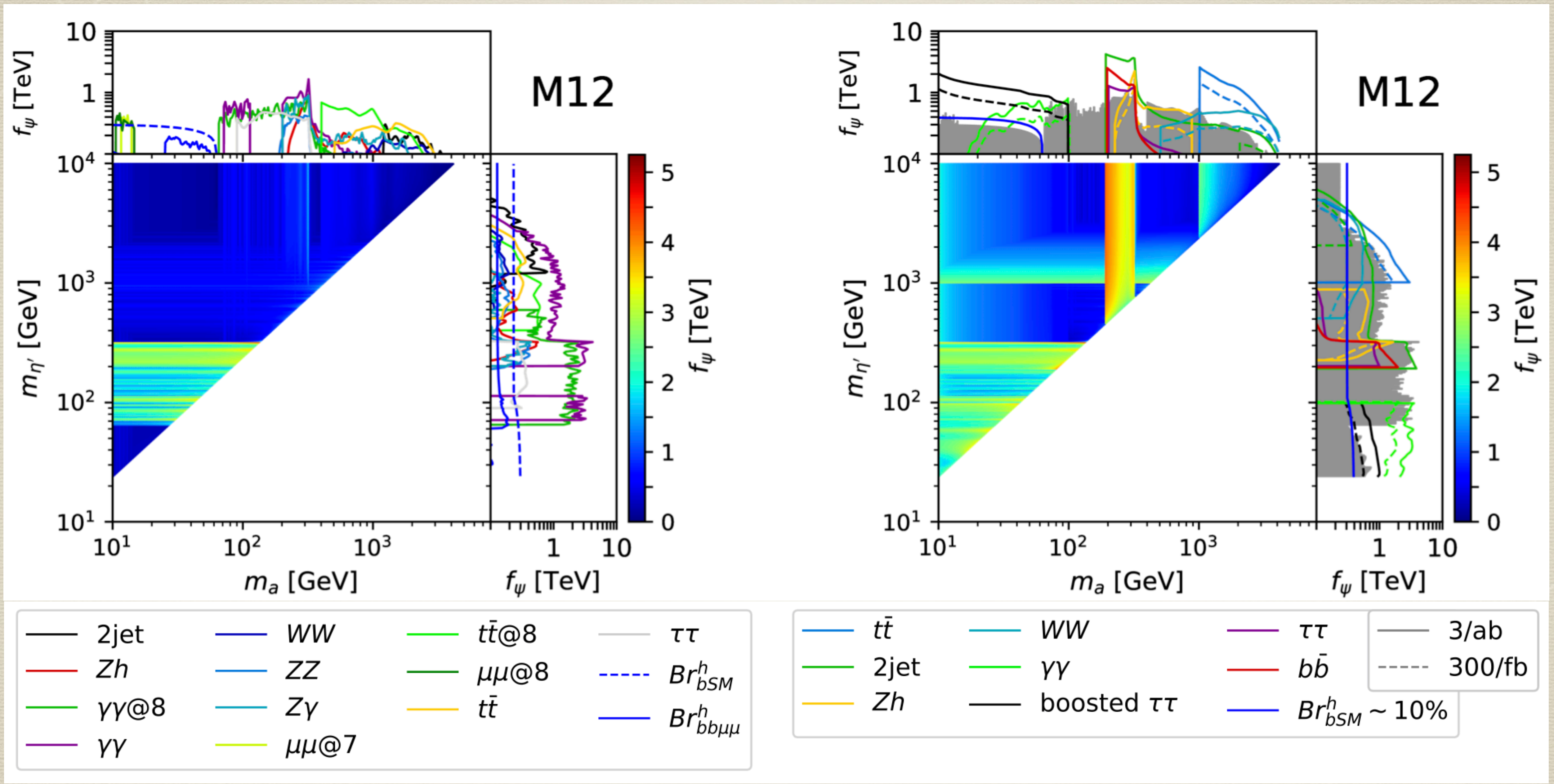


M10
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
f_ψ [TeV]
f_ψ [TeV]
$t\bar{t}$
2jet
Zh
WW
$\gamma\gamma$
boosted $\tau\tau$
$\tau\tau$
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb



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}
$Br^h_{bb\mu\mu}$
M11
$t\bar{t}$
2jet
Zh
WW
$\gamma\gamma$
boosted $\tau\tau$
$\tau\tau$
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb

TCP



M12
m_a [GeV]
$m_{\eta'}$ [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}
$Br^h_{bb\mu\mu}$
M12
m_a [GeV]
$m_{\eta'}$ [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

TCP

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

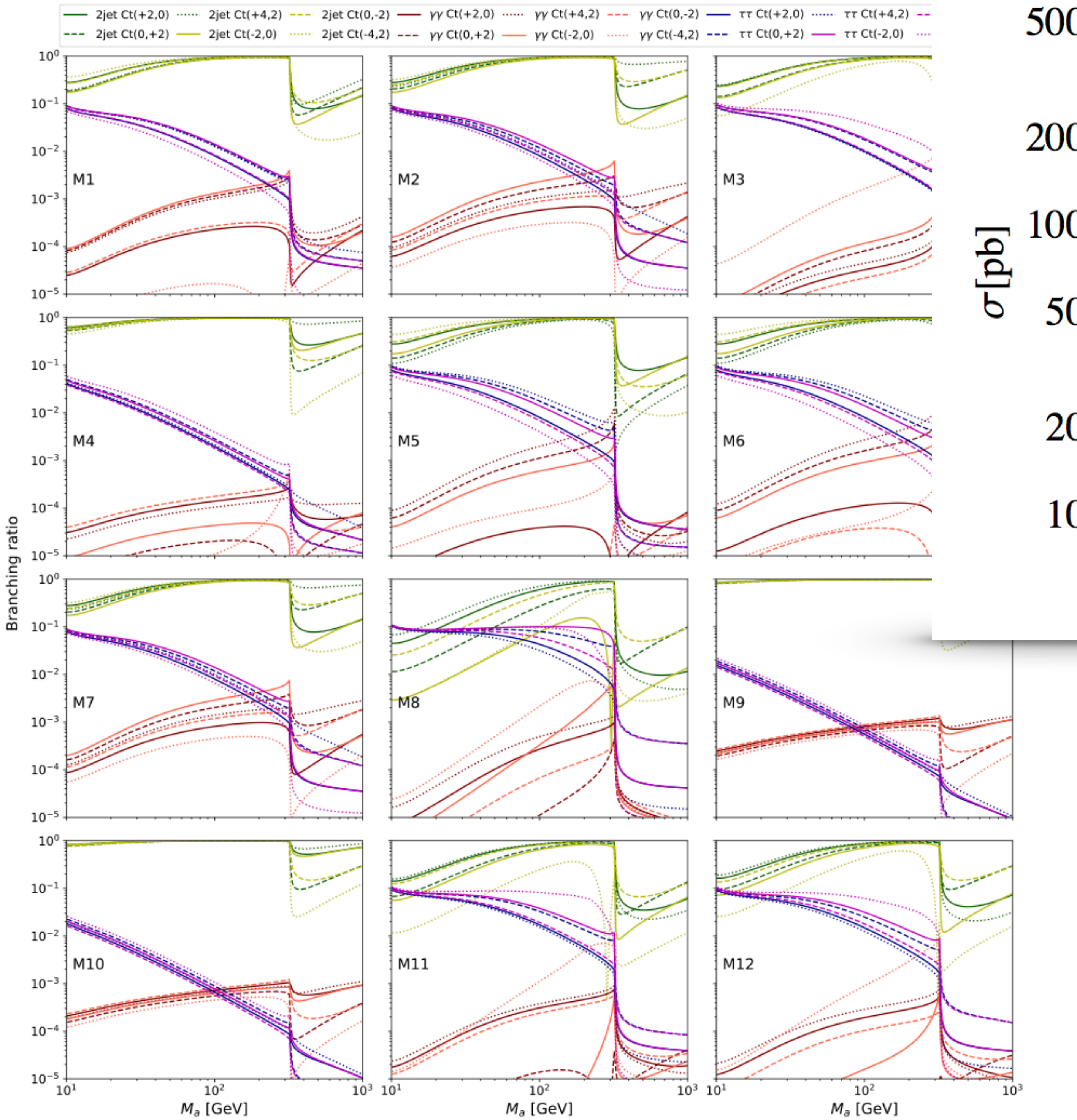
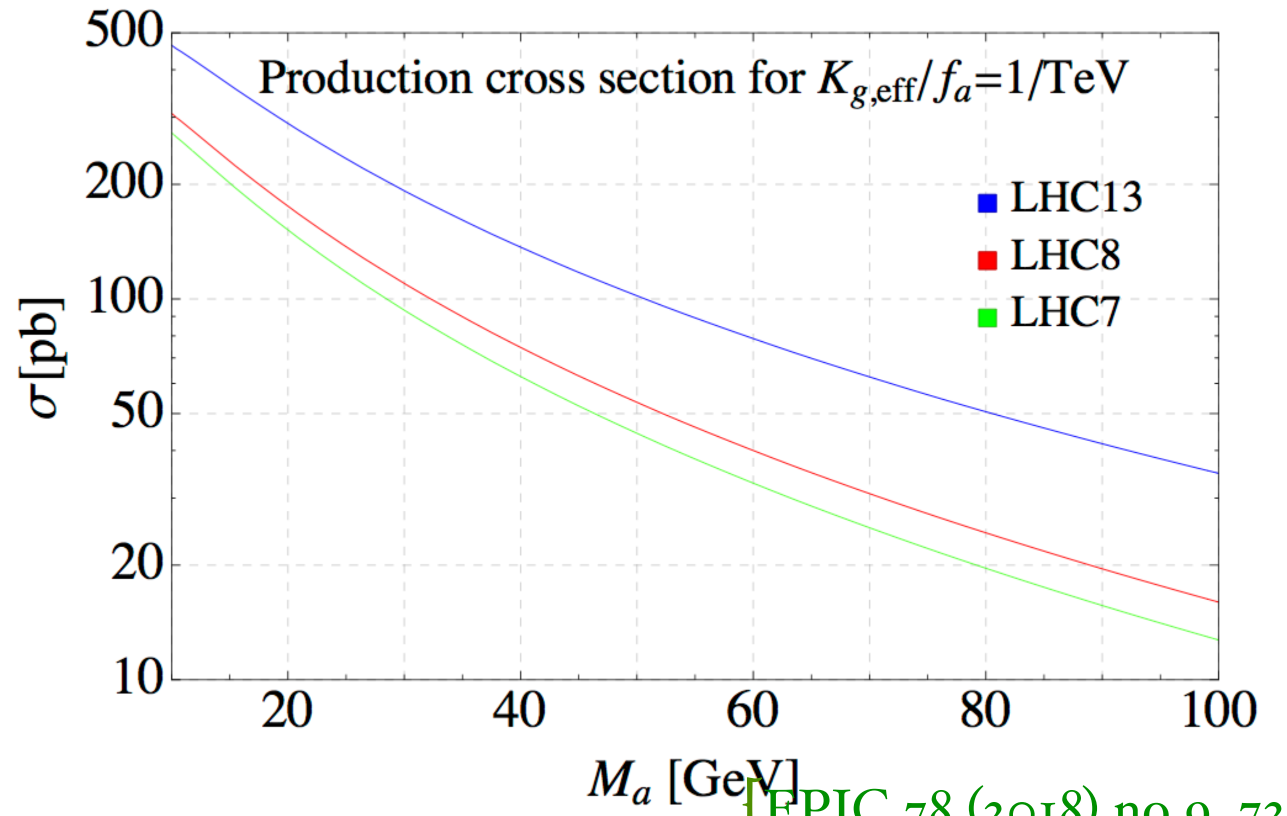


FIG. 7. Representative Branching Ratios of a in the decoupling limit for all models and for the six choices of top partner charges. We only show gg (light and dark green), $\gamma\gamma$ (brown and red) and $\tau\tau$ (purple and lilac).



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

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 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:

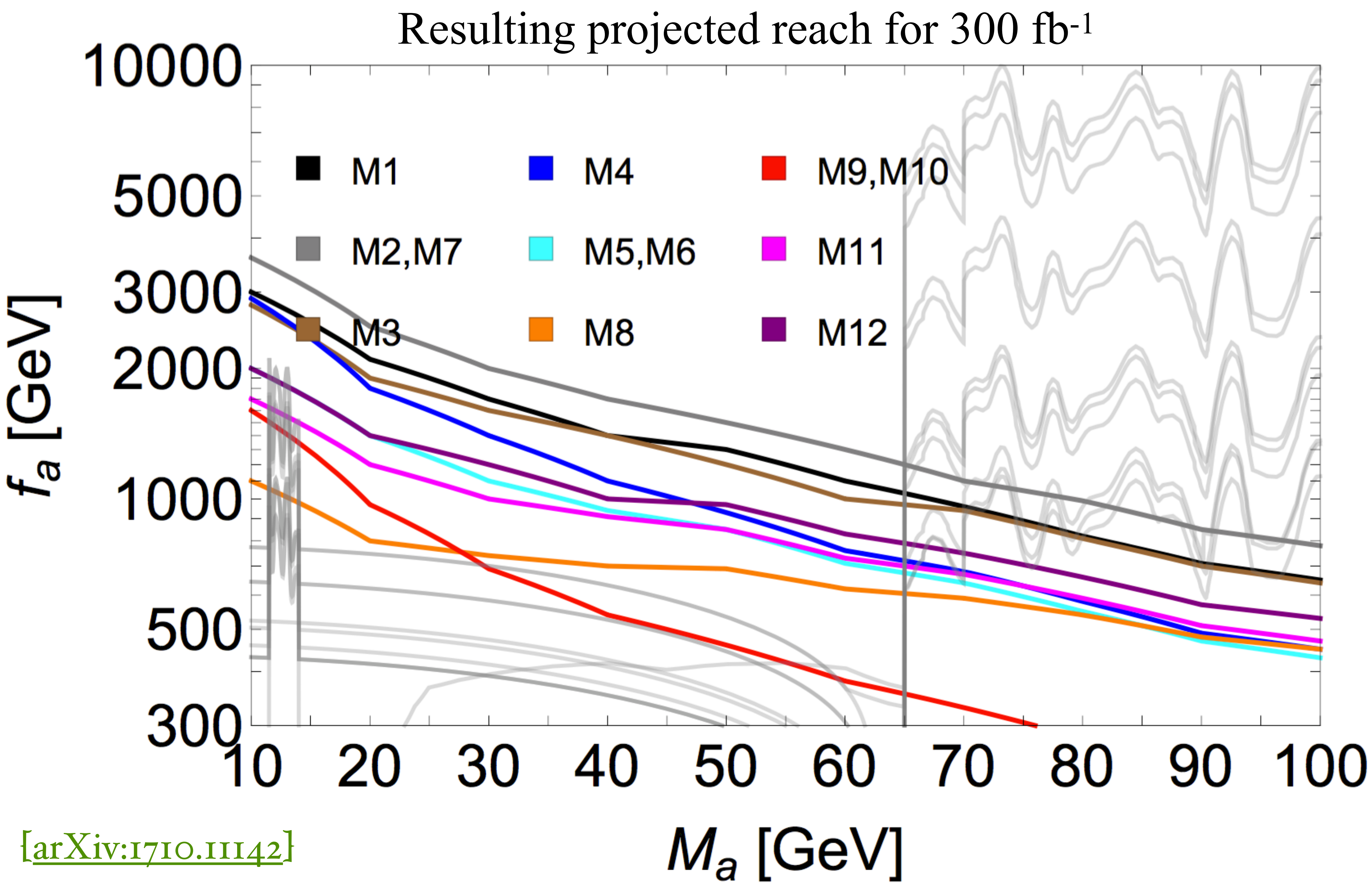
Z/γ^*+jets: 35 fb,

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.

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



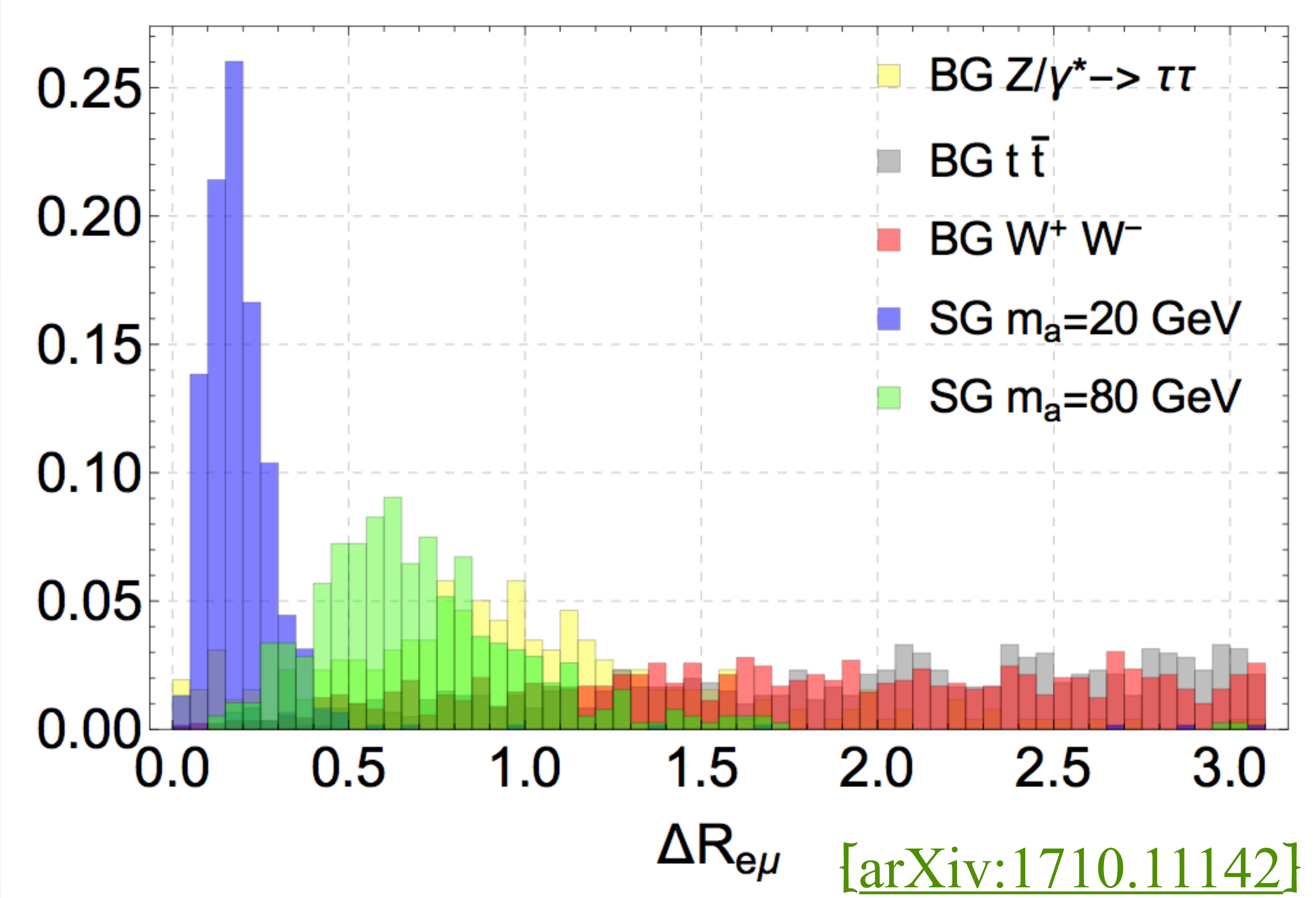
[arXiv:1710.11142]

Upshot: these light composite pNGBs are not ruled out and are testable.

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.]

Common exotic VLQ decays

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

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

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

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

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

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

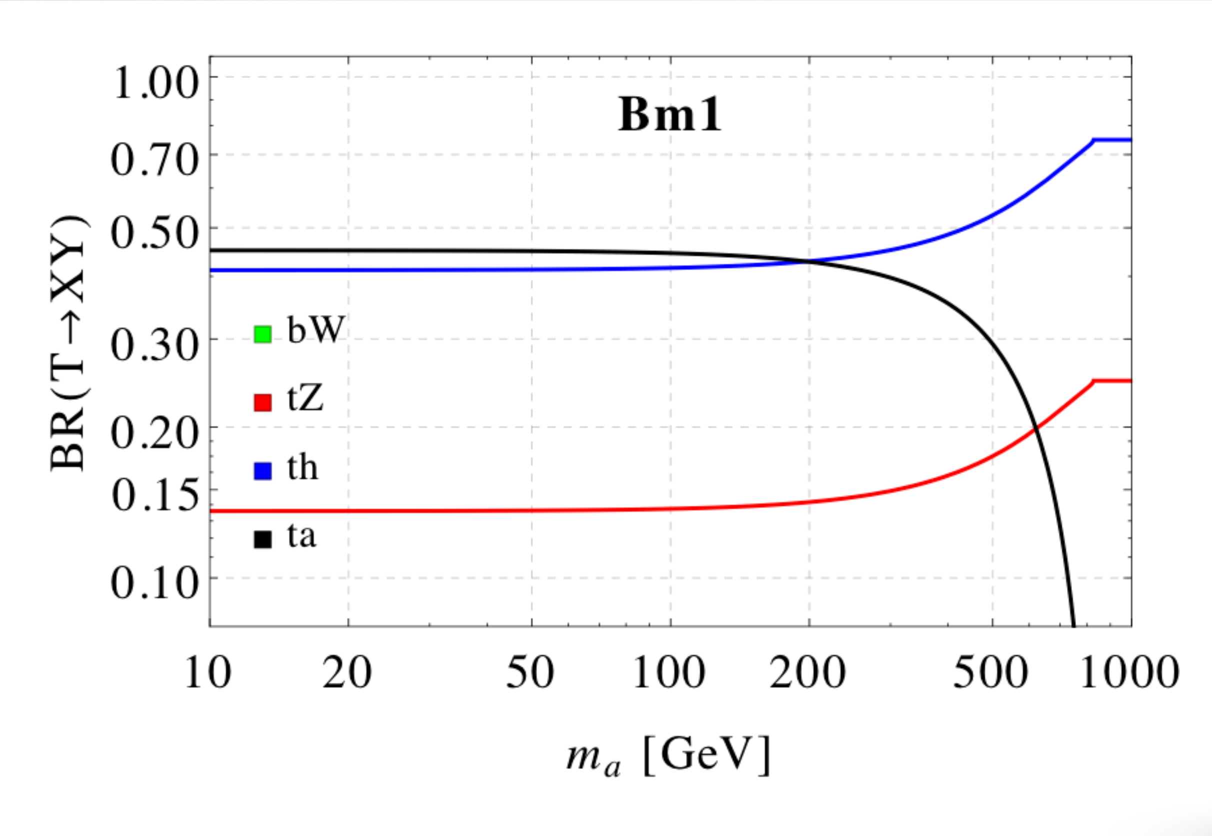
Common exotic VLQ decays

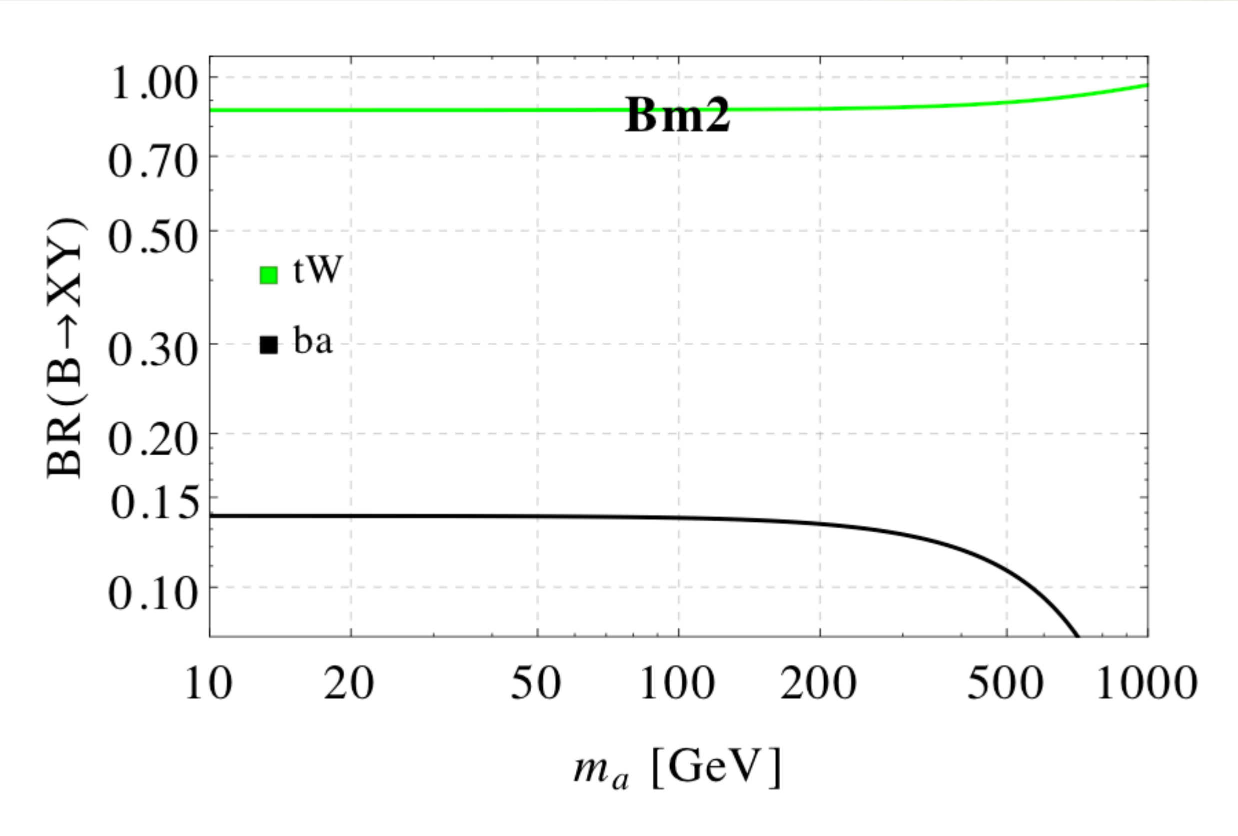
Benchmark parameters (obtained as eff. parameters from UV model):

$$\text{Bm1}: \quad M_T = 1\ \text{TeV}\ , \quad \kappa^{\text{T}}_{\text{Z,R}} = -0.03\ , \quad \kappa^{\text{T}}_{\text{h,R}} = 0.06\ , \quad \kappa^{\text{T}}_{\text{a,R}} = -0.24\ , \quad \kappa^{\text{T}}_{\text{a,L}} = -0.07\ ;$$

$$\text{Bm2}: \quad M_B = 1.38\ \text{TeV}\ , \quad \kappa^{\text{B}}_{\text{W,L}} = 0.02\ , \quad \kappa^{\text{B}}_{\text{W,R}} = -0.08\ , \quad \kappa^{\text{B}}_{\text{a,L}} = -0.25\ , \tag{2.3}$$

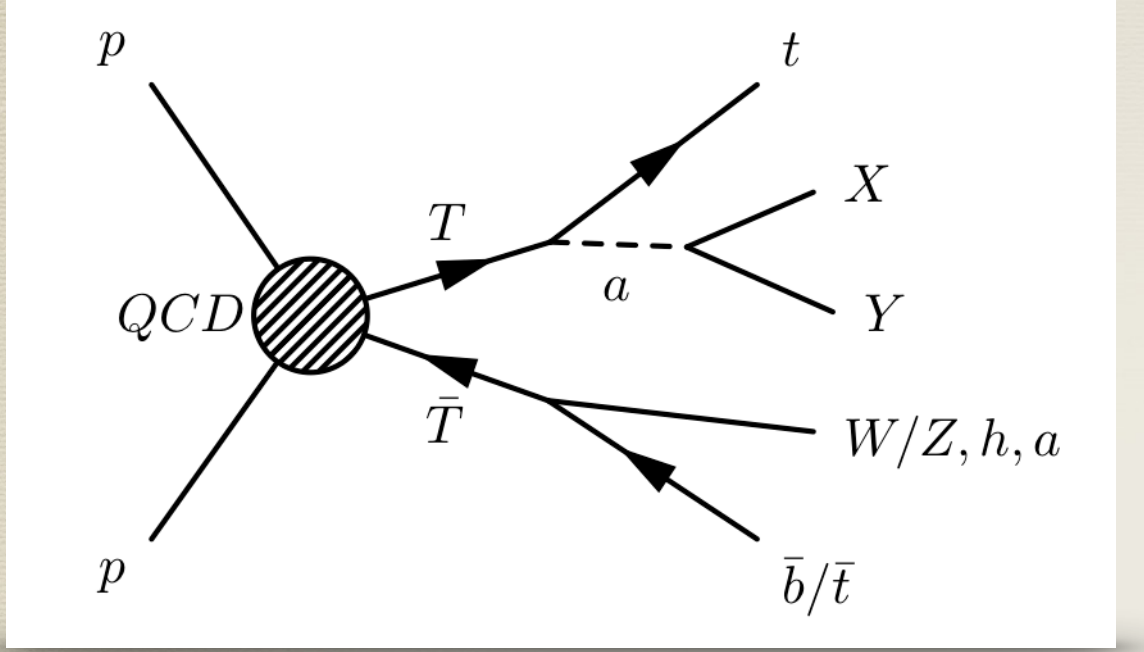
Branching ratios of quark partners to *a* in these benchmarks:

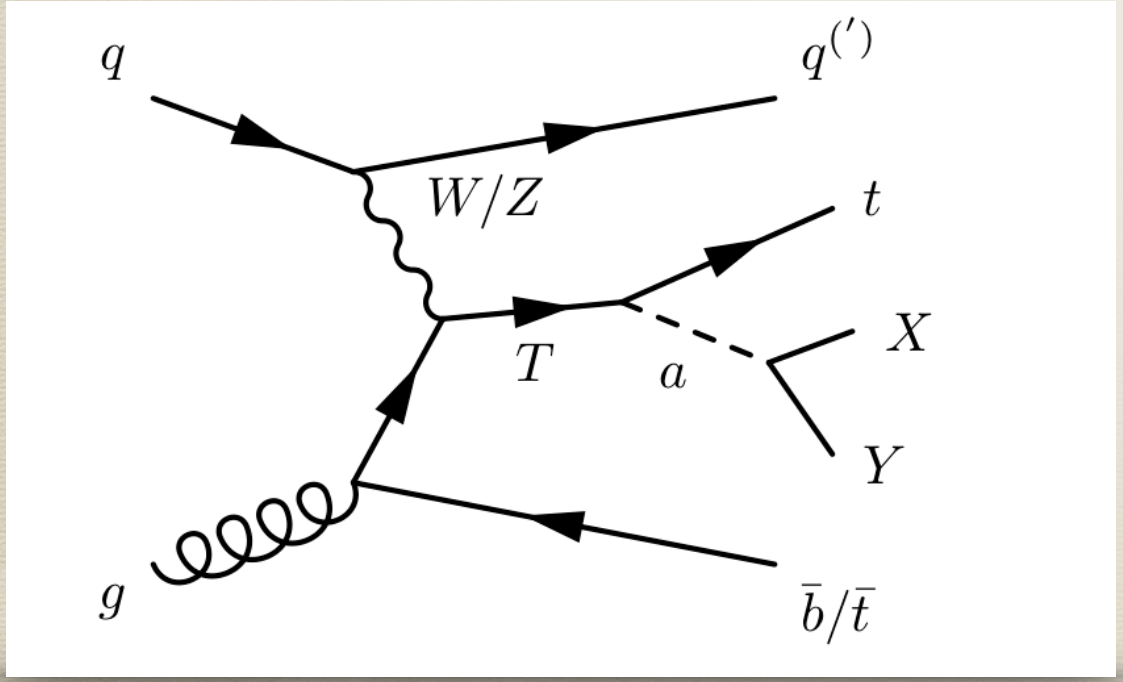




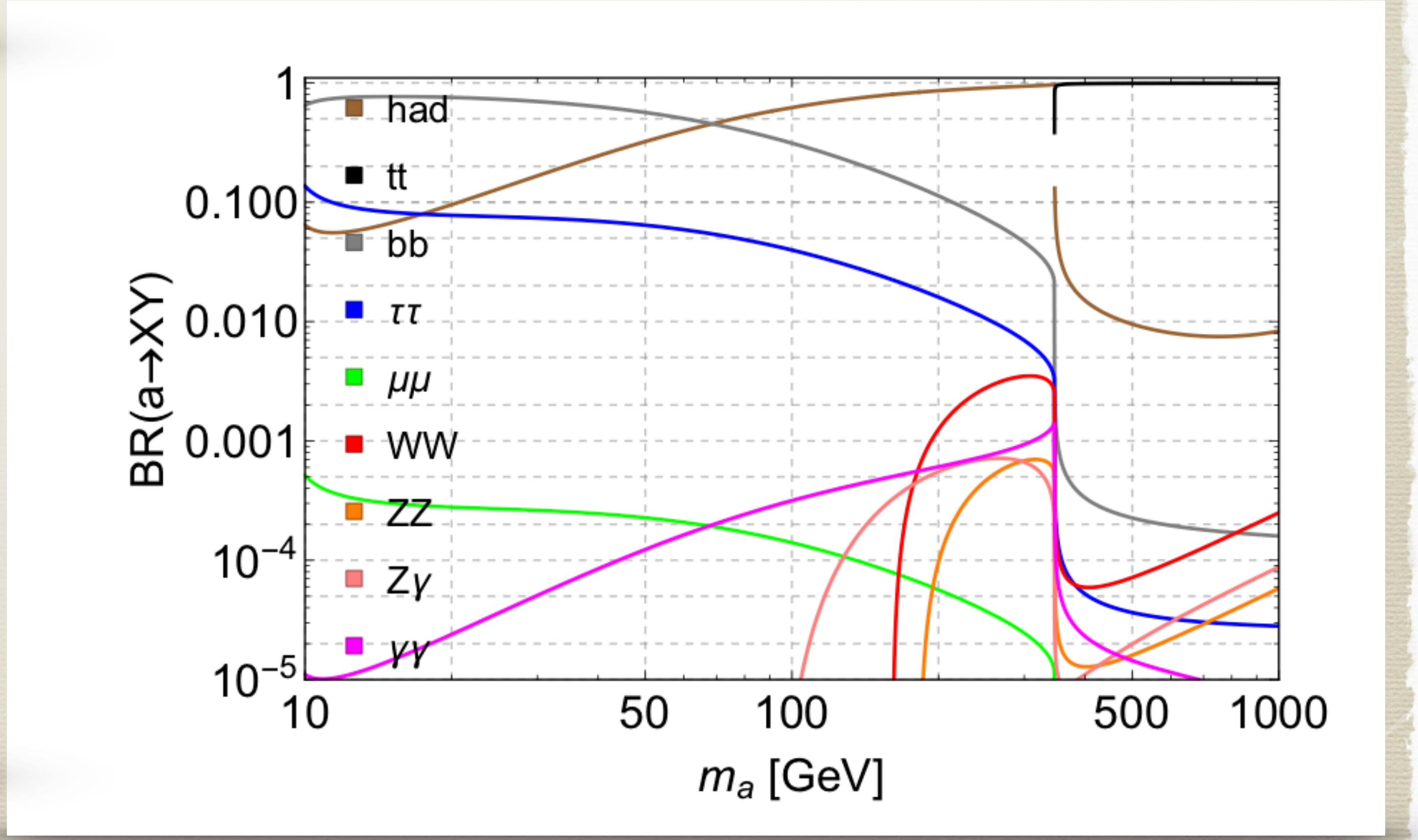
Common exotic VLQ decays

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



EVLQ

Common exotic VLQ decays

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

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

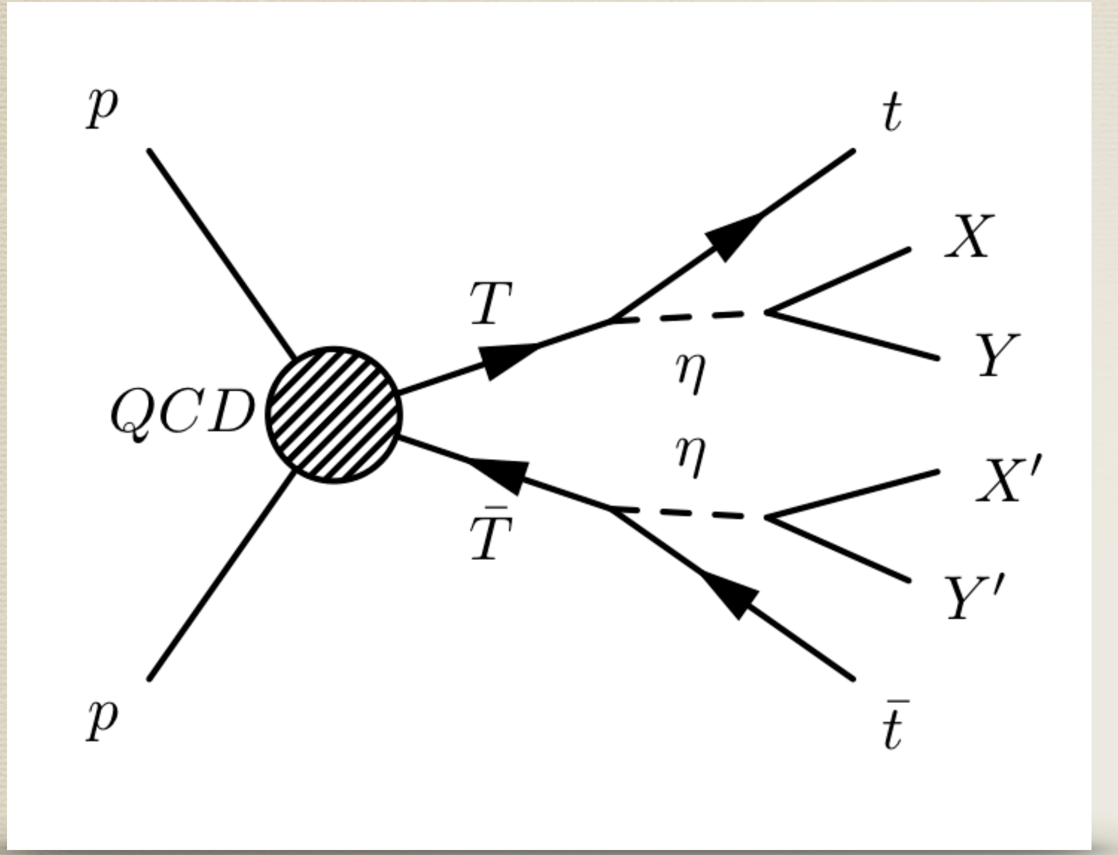
Effective Lagrangian:

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

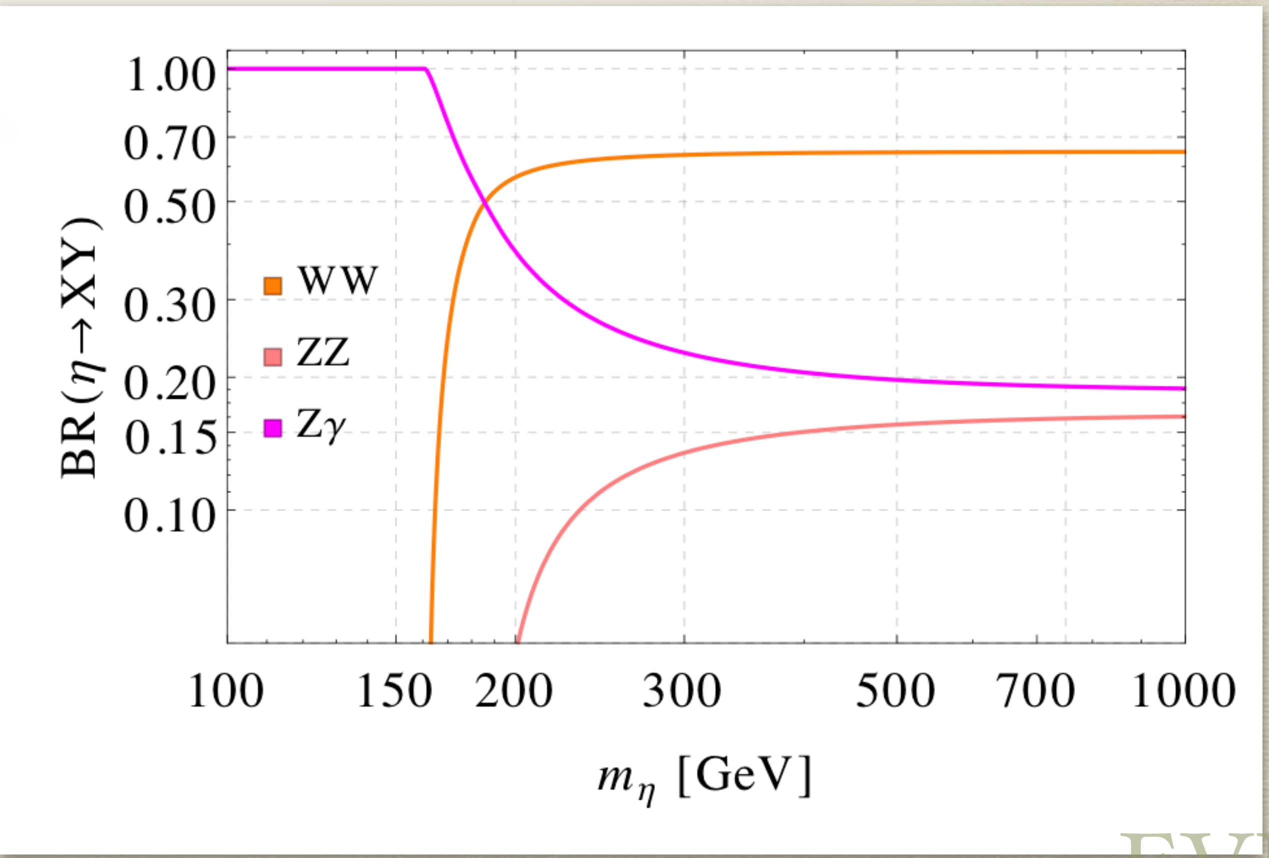
$$\mathcal{L}_\eta = \frac{1}{2}(\partial_\mu\eta)(\partial^\mu\eta) - \frac{1}{2}m_\eta^2\eta^2 + \frac{g_s^2 K_g^\eta}{16\pi^2 f_\eta}\eta G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{g^2 K_W^a}{8\pi^2 f_\eta}\eta W^+_{\mu\nu}\tilde{W}^{-,\mu\nu}$$
$$+ \frac{e^2 K_\gamma^\eta}{16\pi^2 f_\eta}\eta A_{\mu\nu}\tilde{A}^{\mu\nu}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

[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).



EVLQ

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.

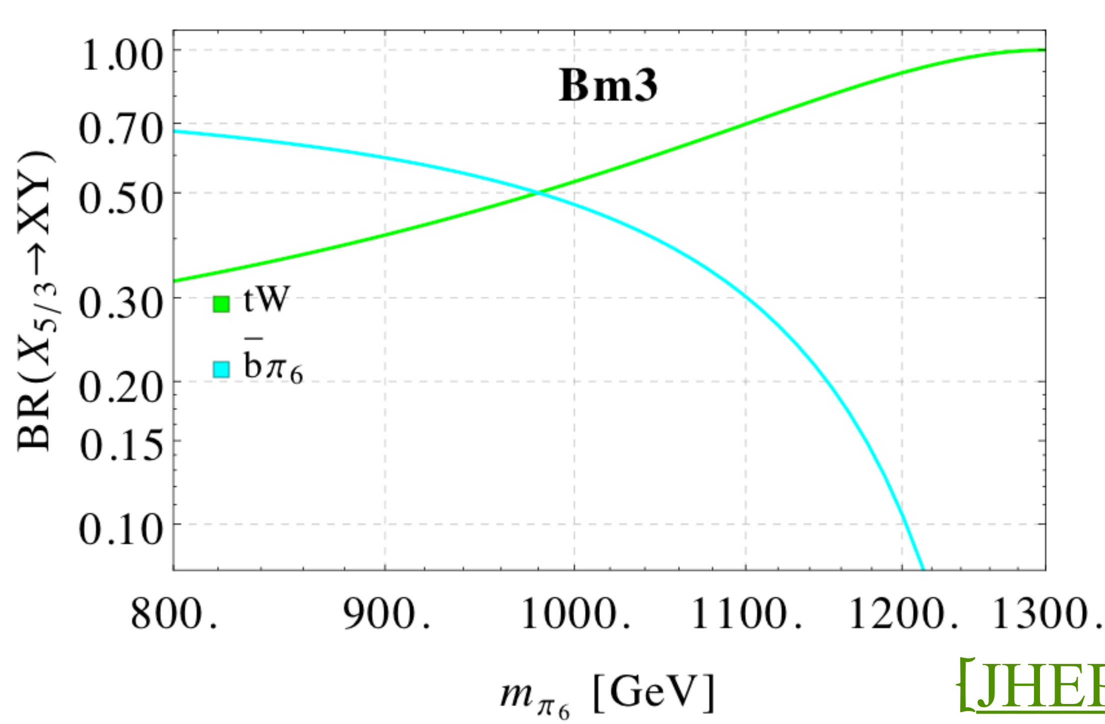
Effective Lagrangian:

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

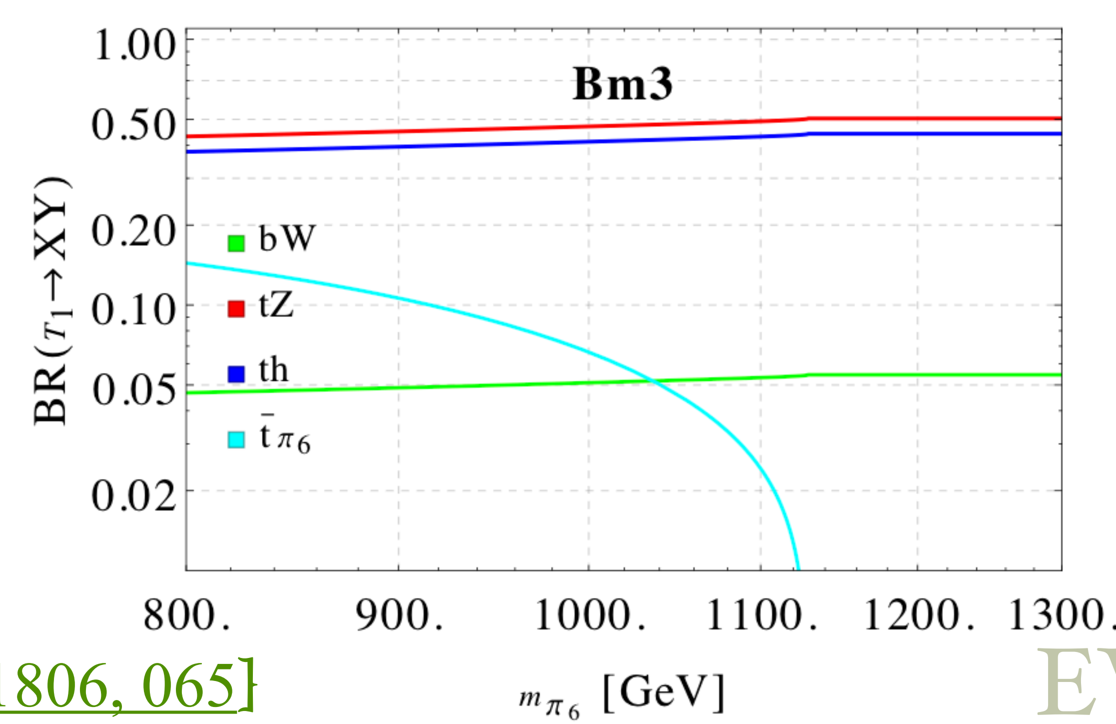
$$\mathcal{L}_{\pi_6} = |D_\mu \pi_6|^2 - m^2_{\pi_6}|\pi_6|^2 + \left(i\kappa^{\pi_6}_{tt,R}\,\bar{t}\pi_6 (P_R t)^c + L \leftrightarrow R + \text{ h.c. }\right)$$

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

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

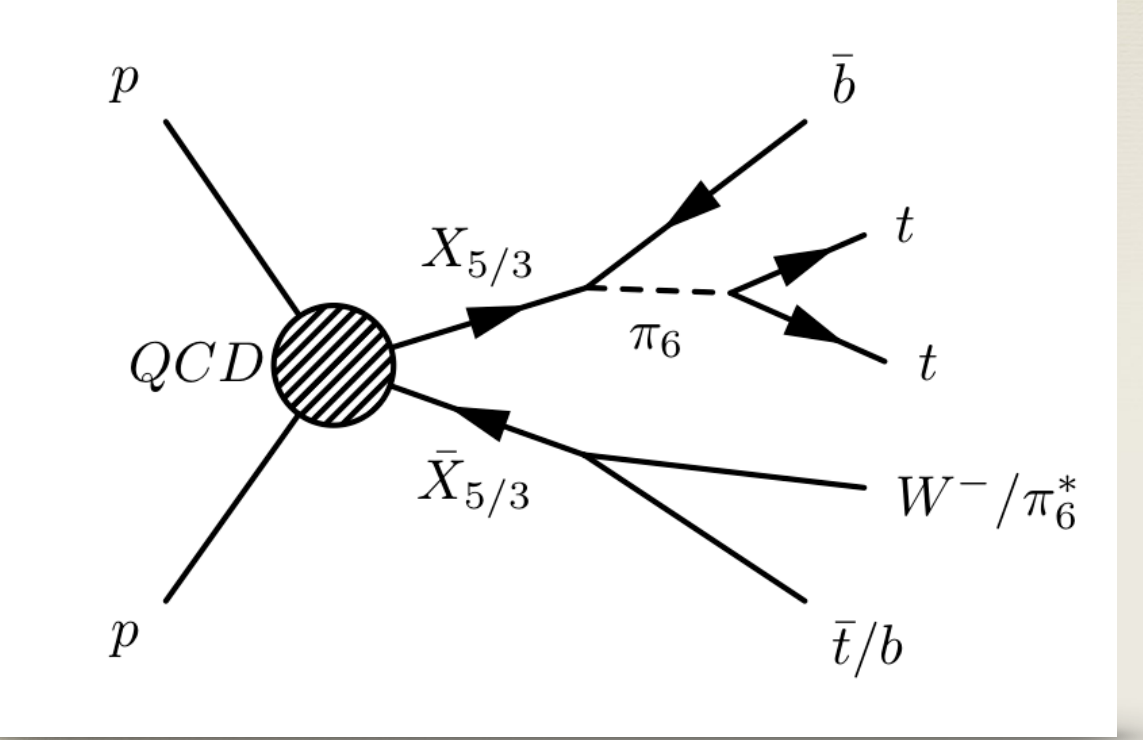


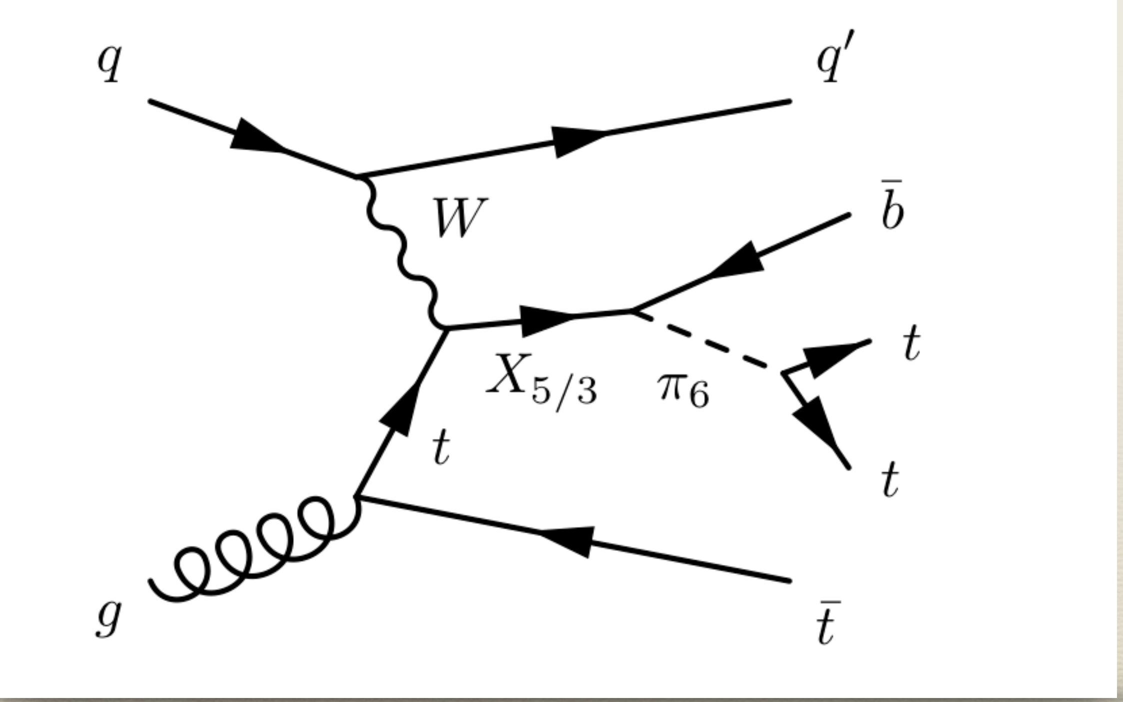
[JHEP 1806, 065]



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.

EVLQ

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:

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

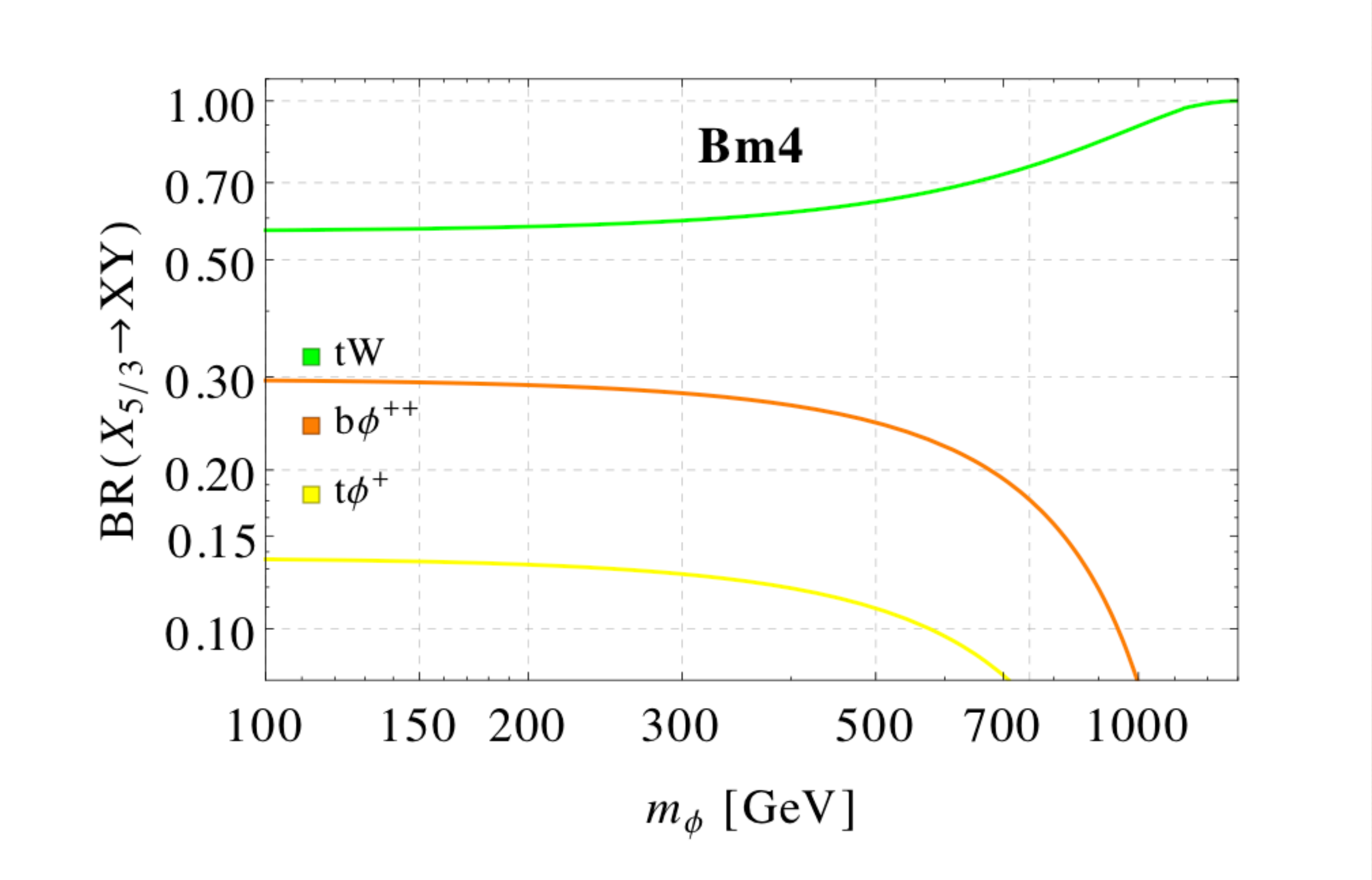
$$\mathcal{L}_{\phi} = \sum_{\phi=\phi^+,\phi^{++}}\left(|D_\mu\phi|^2 - m^2_\phi|\phi|^2\right) + \left(\frac{egK^\phi_{W\gamma}}{8\pi^2 f_\phi}\phi^+ W^-_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{g^2 c_w K^\phi_{WZ}}{8\pi^2 f_\phi}\phi^+ W^-_{\mu\nu}\tilde{B}^{\mu\nu}\right.$$
$$\left. + \frac{g^2 K^\phi_W}{8\pi^2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

[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:

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

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

EVLQ

Common exotic VLQ decays

Examples of processes: