

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](#)]

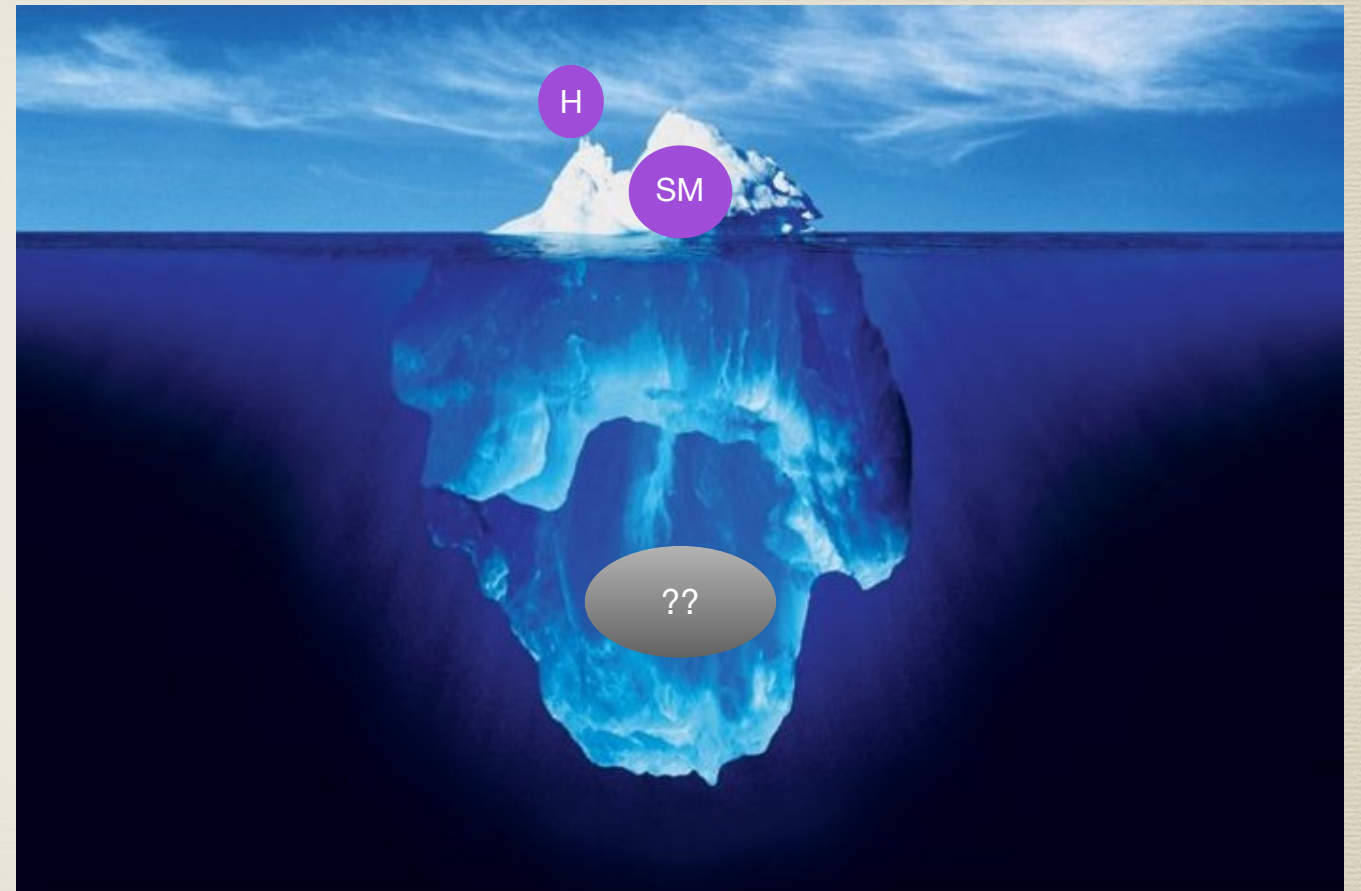
G. Cacciapaglia, T. Flacke, Myeonghun Park, Mengchao Zhang [[PLB798, 135015 \(2019\)](#)]

G. Cacciapaglia, A. Deandrea, T. Flacke, A. Iyer [appearing soon]

**IBS-PNU Joint Workshop on Physics beyond the Standard Model,
Busan, Dec. 5th 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: $T \rightarrow t a$, $a \rightarrow gg$ or $a \rightarrow bb$
 - Example 2: Exotic charge $5/3$ VLQ decays
- Conclusions



Motivation for Vector-like quarks: a composite Higgs

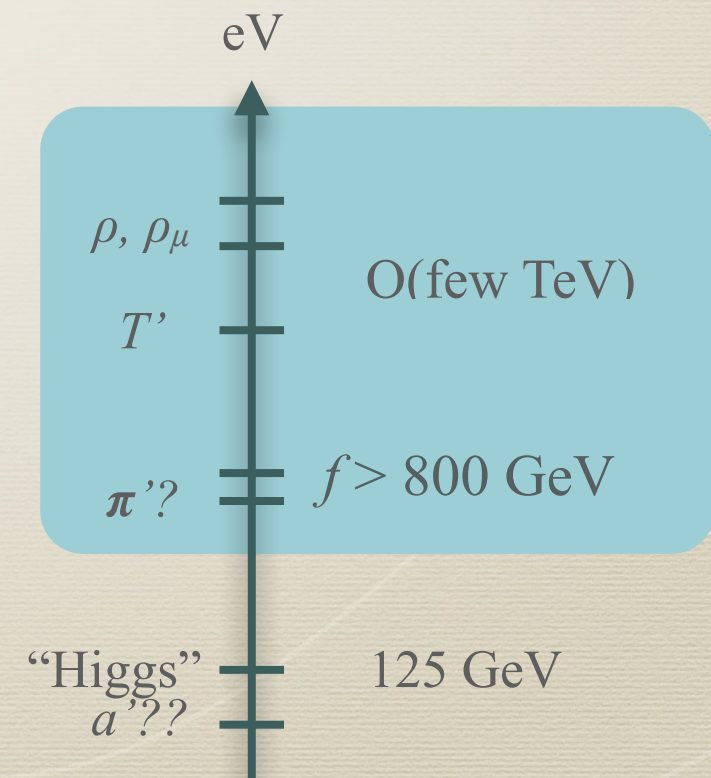
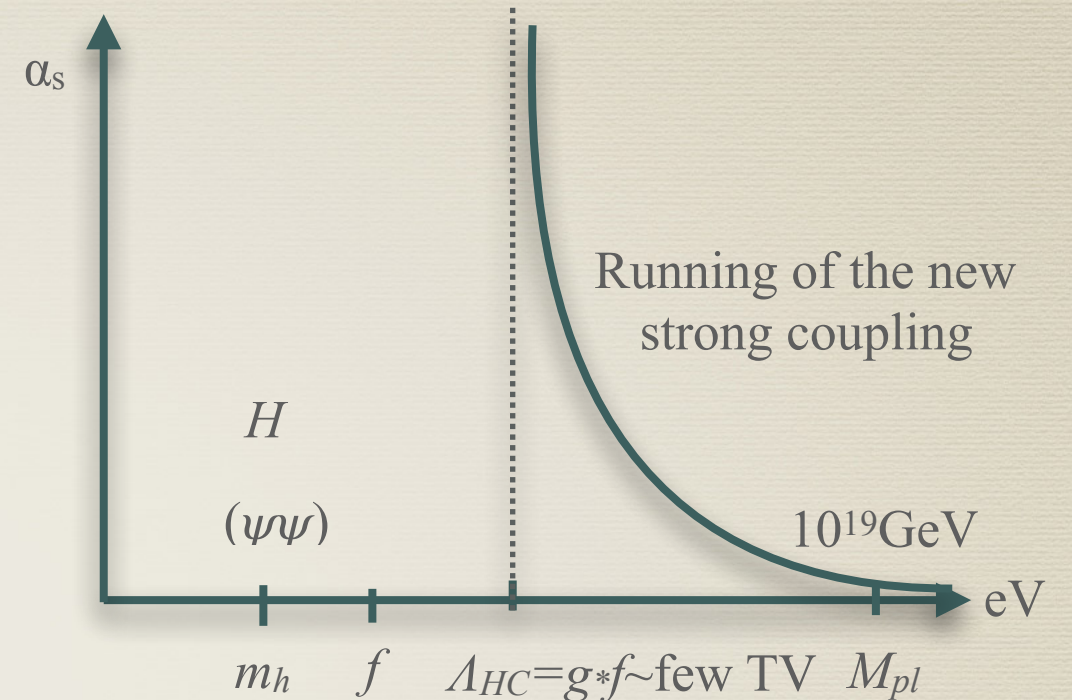
An alternative solution to the hierarchy problem:

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

[Georgi, Kaplan (1984)]

The price to pay:

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



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 $GHC = Sp(2N_c)$

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

Underlying field content

[JHEP1511,201]

Bound states of the model

	spin	$SU(4) \times SU(6)$	$Sp(4) \times SO(6)$	names
$\psi\psi$	0	(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 ψ_5
$\chi\psi\bar{\psi}$	1/2	(6, 6)	(1, 6) (5, 6)	ψ_1 ψ_5 ψ_2 ψ_2
$\psi\bar{\chi}\bar{\psi}$	1/2	(1, 6)	(1, 6)	ψ_3
$\psi\bar{\chi}\psi$	1/2	(15, 6)	(5, 6) (10, 6)	ψ_4^5 ψ_4^{10} ψ_4
$\bar{\psi}\sigma^\mu\psi$	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) \times SU(6)/SO(6)				
$SO(N_{\text{HC}})$	$5 \times \mathbf{S}_2$	$6 \times \mathbf{F}$	$N_{\text{HC}} \geq 55$	$\frac{5(N_{\text{HC}}+2)}{6}$	1/3	/	
$SO(N_{\text{HC}})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$N_{\text{HC}} \geq 15$	$\frac{5(N_{\text{HC}}-2)}{6}$	1/3	/	
$SO(N_{\text{HC}})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{\text{HC}} = 7, 9$	$\frac{5}{6}, \frac{5}{12}$	1/3	$N_{\text{HC}} = 7, 9$	M1, M2
$SO(N_{\text{HC}})$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{\text{HC}} = 7, 9$	$\frac{5}{6}, \frac{5}{3}$	2/3	$N_{\text{HC}} = 7, 9$	M3, M4
Real		Pseudo-Real	SU(5)/SO(5) \times SU(6)/Sp(6)				
$Sp(2N_{\text{HC}})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$2N_{\text{HC}} \geq 12$	$\frac{5(N_{\text{HC}}+1)}{3}$	1/3	/	
$Sp(2N_{\text{HC}})$	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	$2N_{\text{HC}} \geq 4$	$\frac{5(N_{\text{HC}}-1)}{3}$	1/3	$2N_{\text{HC}} = 4$	M5
$SO(N_{\text{HC}})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{\text{HC}} = 11, 13$	$\frac{5}{24}, \frac{5}{48}$	1/3	/	
Real		Complex	SU(5)/SO(5) \times SU(3) ² /SU(3)				
$SU(N_{\text{HC}})$	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \bar{\mathbf{F}})$	$N_{\text{HC}} = 4$	$\frac{5}{3}$	1/3	$N_{\text{HC}} = 4$	M6
$SO(N_{\text{HC}})$	$5 \times \mathbf{F}$	$3 \times (\mathbf{Spin}, \bar{\mathbf{Spin}})$	$N_{\text{HC}} = 10, 14$	$\frac{5}{12}, \frac{5}{48}$	1/3	$N_{\text{HC}} = 10$	M7
Pseudo-Real		Real	SU(4)/Sp(4) \times SU(6)/SO(6)				
$Sp(2N_{\text{HC}})$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$2N_{\text{HC}} \leq 36$	$\frac{1}{3(N_{\text{HC}}-1)}$	2/3	$2N_{\text{HC}} = 4$	M8
$SO(N_{\text{HC}})$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{\text{HC}} = 11, 13$	$\frac{8}{3}, \frac{16}{3}$	2/3	$N_{\text{HC}} = 11$	M9
Complex		Real	SU(4) ² /SU(4) \times SU(6)/SO(6)				
$SO(N_{\text{HC}})$	$4 \times (\mathbf{Spin}, \bar{\mathbf{Spin}})$	$6 \times \mathbf{F}$	$N_{\text{HC}} = 10$	$\frac{8}{3}$	2/3	$N_{\text{HC}} = 10$	M10
$SU(N_{\text{HC}})$	$4 \times (\mathbf{F}, \bar{\mathbf{F}})$	$6 \times \mathbf{A}_2$	$N_{\text{HC}} = 4$	$\frac{2}{3}$	2/3	$N_{\text{HC}} = 4$	M11
Complex		Complex	SU(4) ² /SU(4) \times SU(3) ² /SU(3)				
$SU(N_{\text{HC}})$	$4 \times (\mathbf{F}, \bar{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \bar{\mathbf{A}}_2)$	$N_{\text{HC}} \geq 5$	$\frac{4}{3(N_{\text{HC}}-2)}$	2/3	$N_{\text{HC}} = 5$	M12
$SU(N_{\text{HC}})$	$4 \times (\mathbf{F}, \bar{\mathbf{F}})$	$3 \times (\mathbf{S}_2, \bar{\mathbf{S}}_2)$	$N_{\text{HC}} \geq 5$	$\frac{4}{3(N_{\text{HC}}+2)}$	2/3	/	

[JHEP1701,094]

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

$\gtrsim 1$ TeV

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]
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

$\gtrsim 1$ TeV

Electro-weak coset	$SU(2)_L \times U(1)_Y$
$SU(5)/SO(5)$	$\mathbf{3}_{\pm 1} + \mathbf{3}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{1}_0$
$SU(4)/Sp(4)$	$\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$
$SU(4) \times SU(4)' / SU(4)_D$	$\mathbf{3}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{2}'_{\pm 1/2} + \mathbf{1}_{\pm 1} + \mathbf{1}_0 + \mathbf{1}'_0$
Color coset	$SU(3)_c \times U(1)_Y$
$SU(6)/SO(6)$	$\mathbf{8}_0 + \mathbf{6}_{(-2/3 \text{ or } 4/3)} + \bar{\mathbf{6}}_{(2/3 \text{ or } -4/3)}$
$SU(6)/Sp(6)$	$\mathbf{8}_0 + \mathbf{3}_{2/3} + \bar{\mathbf{3}}_{-2/3}$
$SU(3) \times SU(3)' / SU(3)_D$	$\mathbf{8}_0$

[Agugliaro etal]

[JHEP1511,201]

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

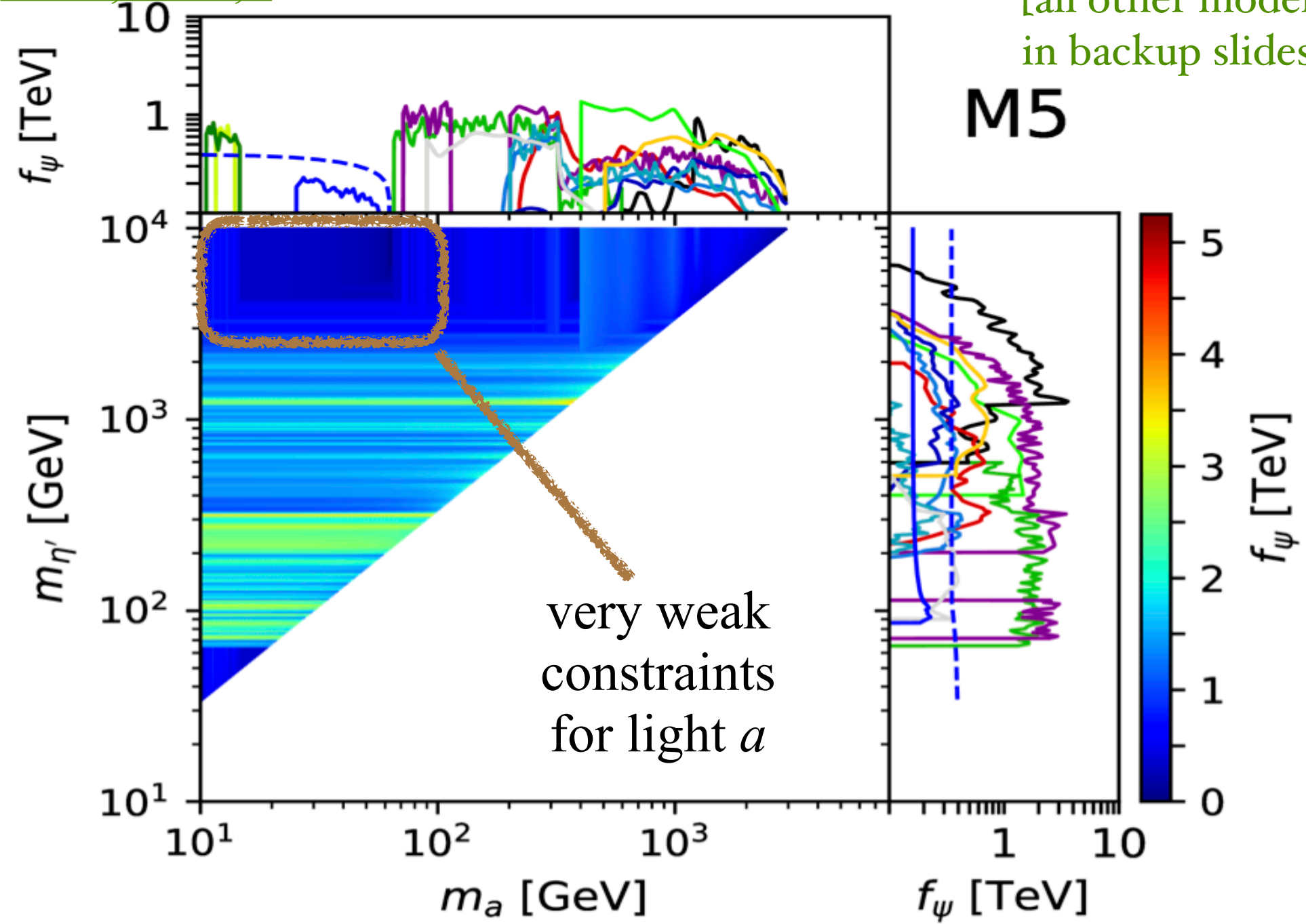
$$\begin{aligned} \mathcal{L}_{\text{eff}} \supset & \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}m_\phi^2 \phi^2 \\ & + \frac{\phi}{16\pi^2 f_\psi} \left(g_s^2 K_g^\phi G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + g^2 K_W^\phi W_{\mu\nu}^i \tilde{W}^{i\mu\nu} + g'^2 K_B^\phi B_{\mu\nu} \tilde{B}^{\mu\nu}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

- m_a must result from *explicit* breaking of the U(1)s. m_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 .

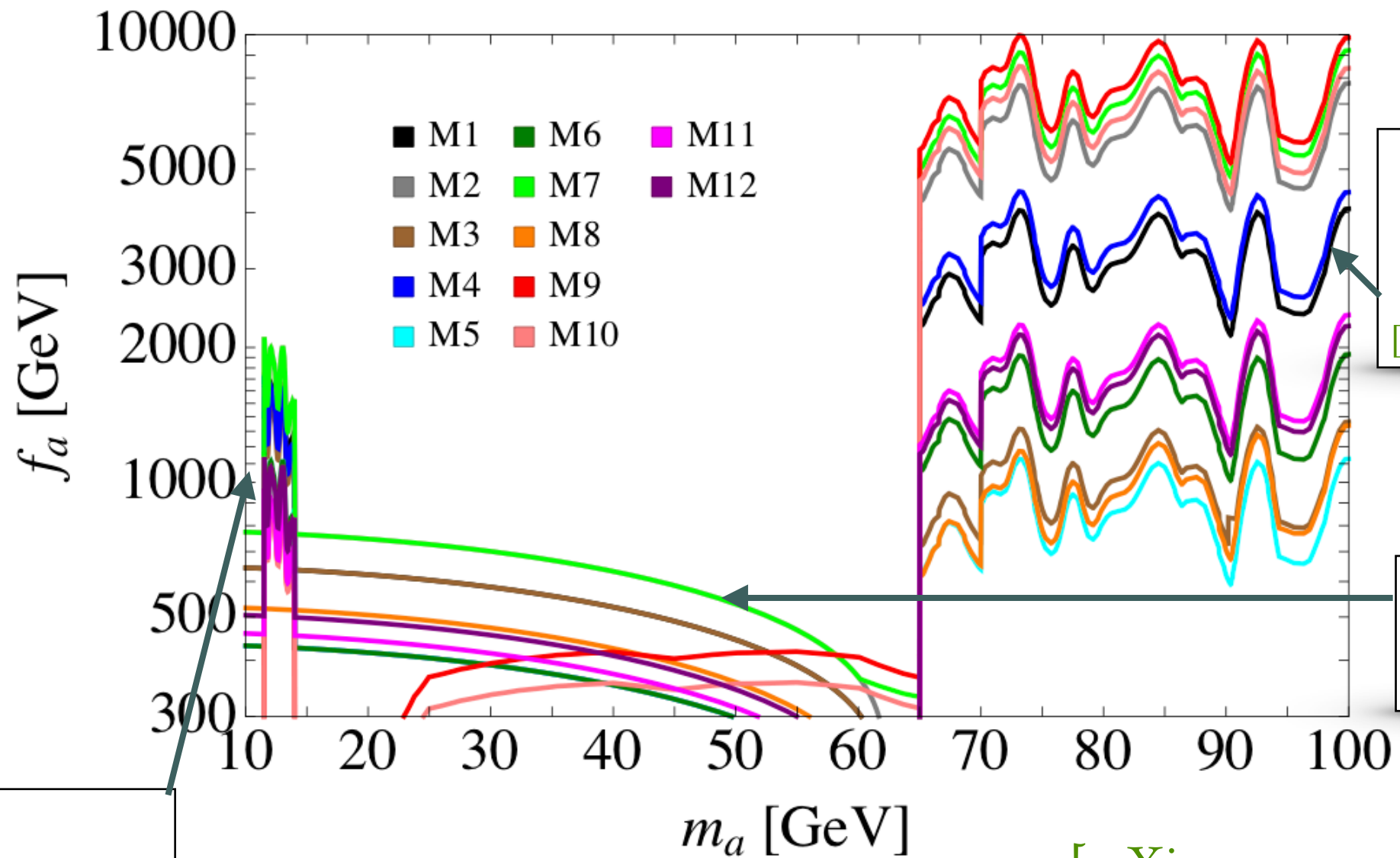
[arXiv:1902.06890]

[all other models in backup slides]

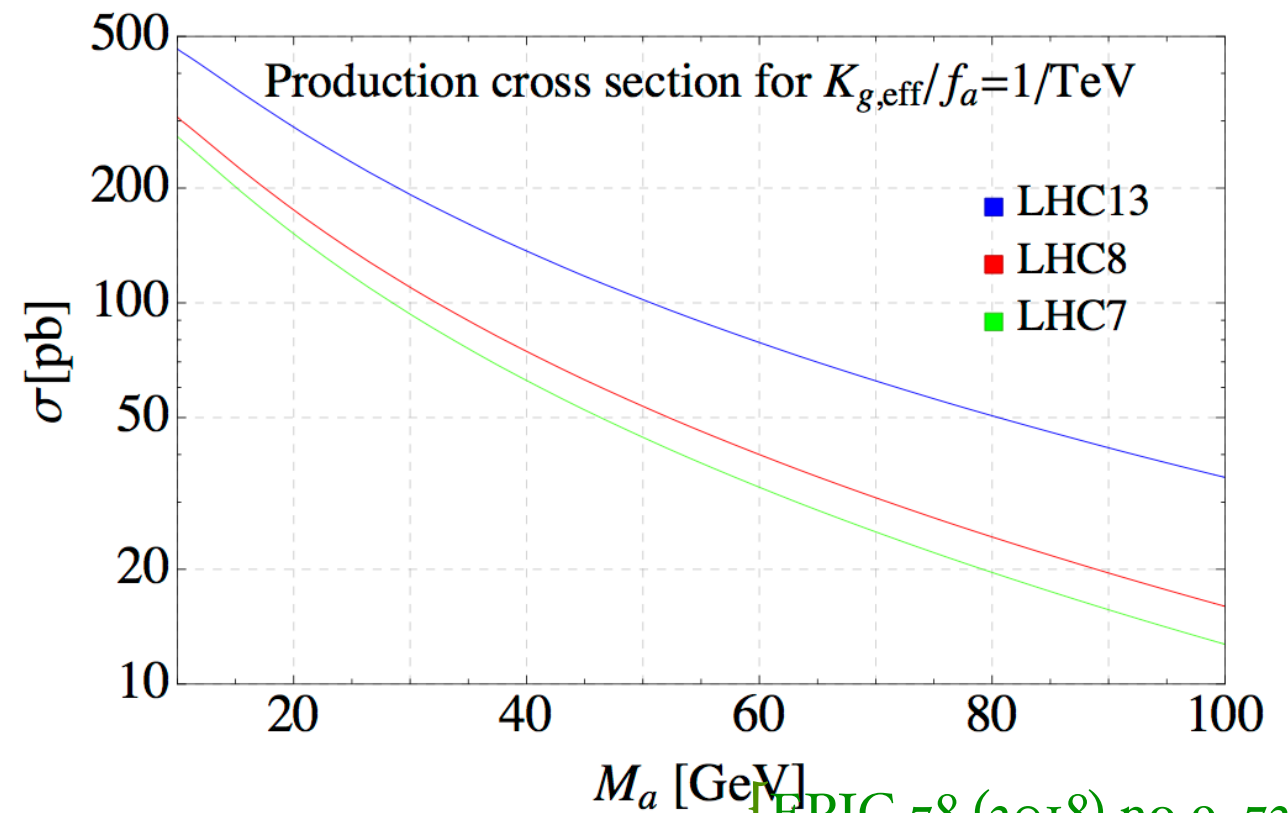
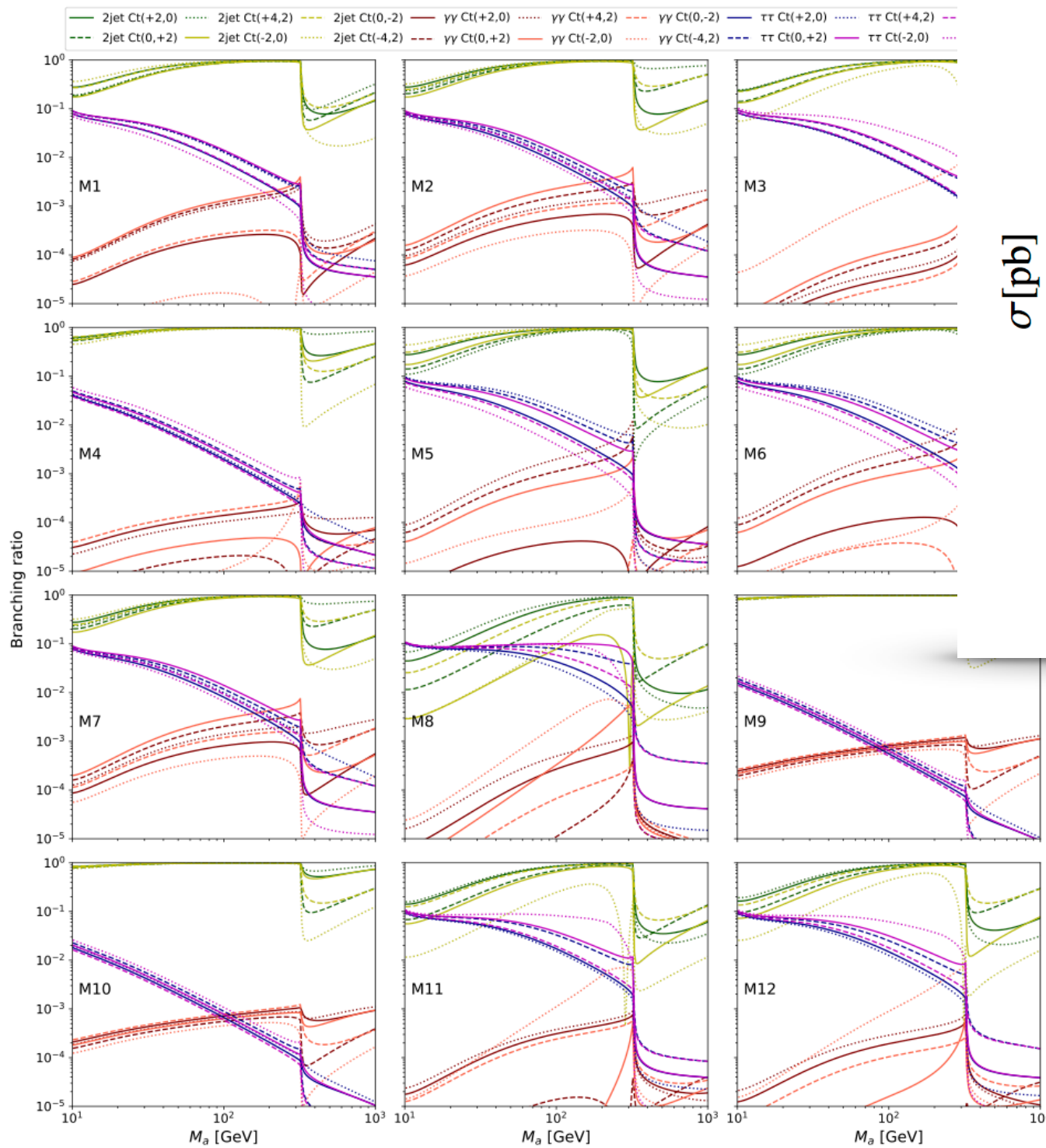


—	2jet	—	WW	—	$t\bar{t}@8$	—	$\tau\tau$
—	Zh	—	ZZ	—	$\mu\mu@8$	- - -	Br_{BSM}^h
—	$\gamma\gamma@8$	—	$Z\gamma$	—	$t\bar{t}$	—	$Br_{bb\mu\mu}^h$
—	$\gamma\gamma$	—	$\mu\mu@7$				

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



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



[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.

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).

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 $gg \rightarrow a \rightarrow \tau\tau$ system (at the cost of production cross section, but we have enough).

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

- $p_{T\mu} > 42$ GeV (for triggering)
- $p_{Te} > 10$ GeV
- $\Delta R_{\mu j} > 0.5, \Delta R_{ej} > 0.5,$
- $\Delta R_{\mu e} < 1.0$
- no lower cut on $\Delta R_{\mu e}$!
- $m_{\mu e} > 100$ GeV

Main background:

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

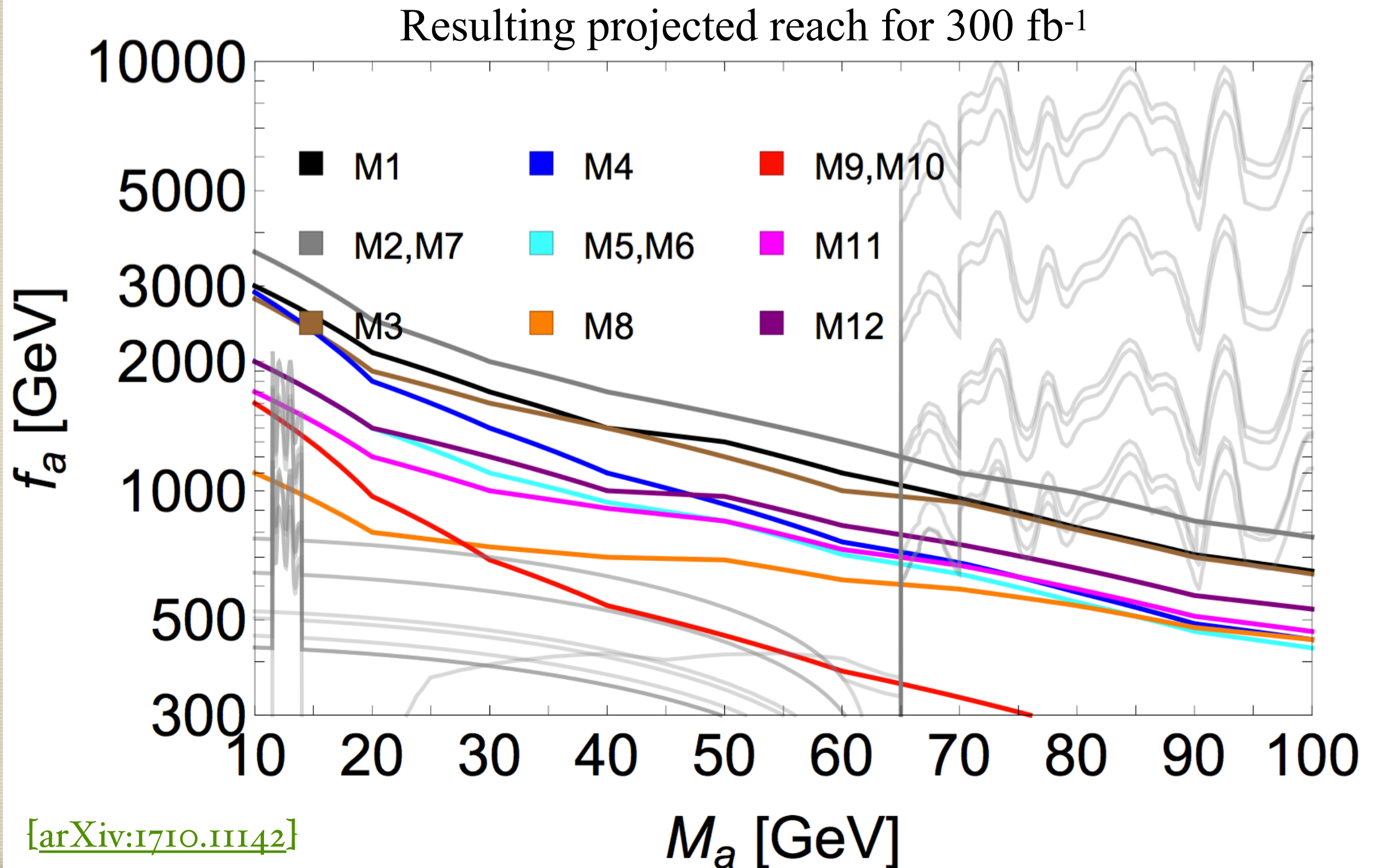
$t\bar{t} + \text{jets}$: 70 fb, $Wt + \text{jets}$:

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

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

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

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



[[arXiv:1710.11142](https://arxiv.org/abs/1710.11142)]

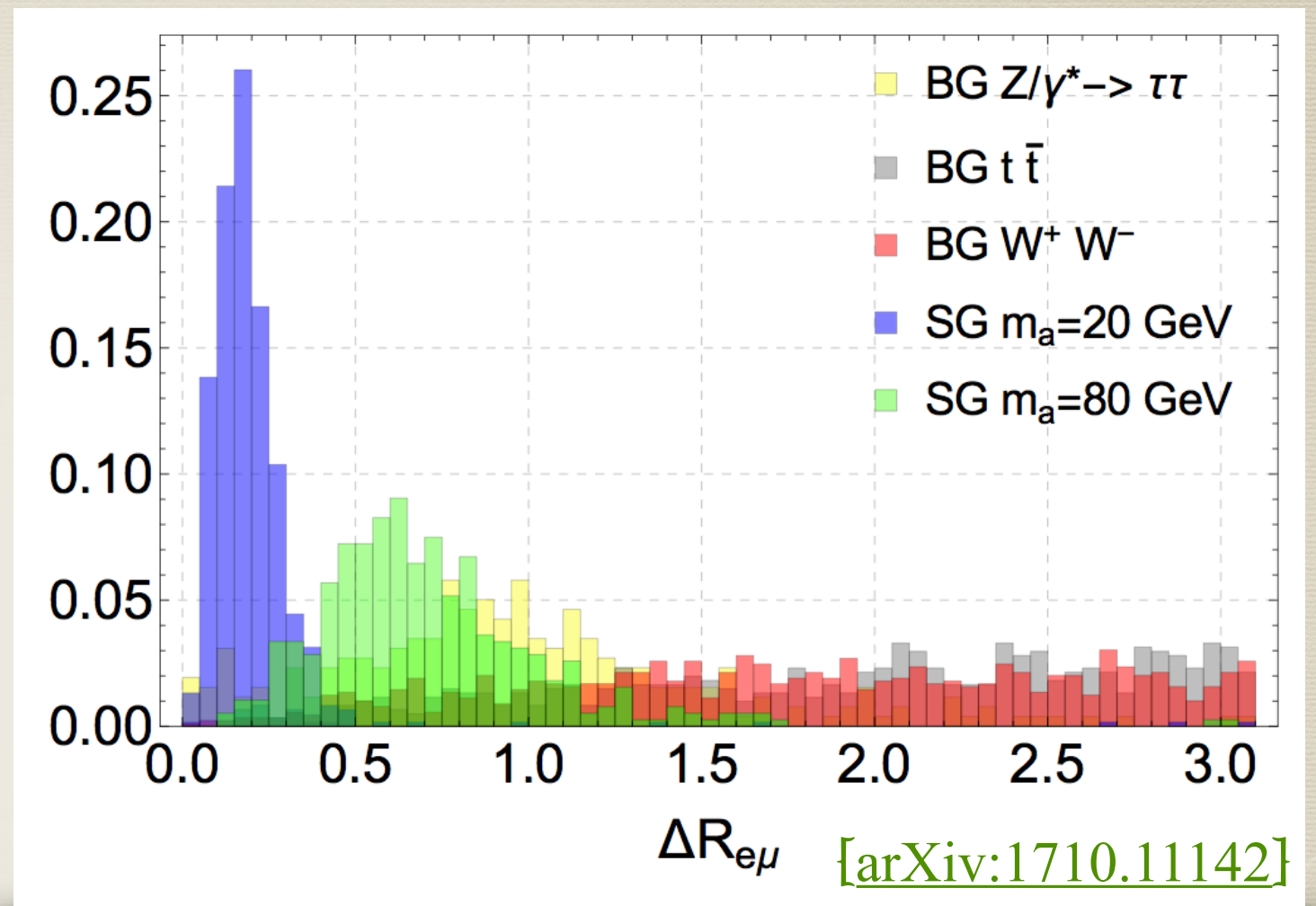
Upshot: these light composite pNGBs are not ruled out and are testable. 13/35

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

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

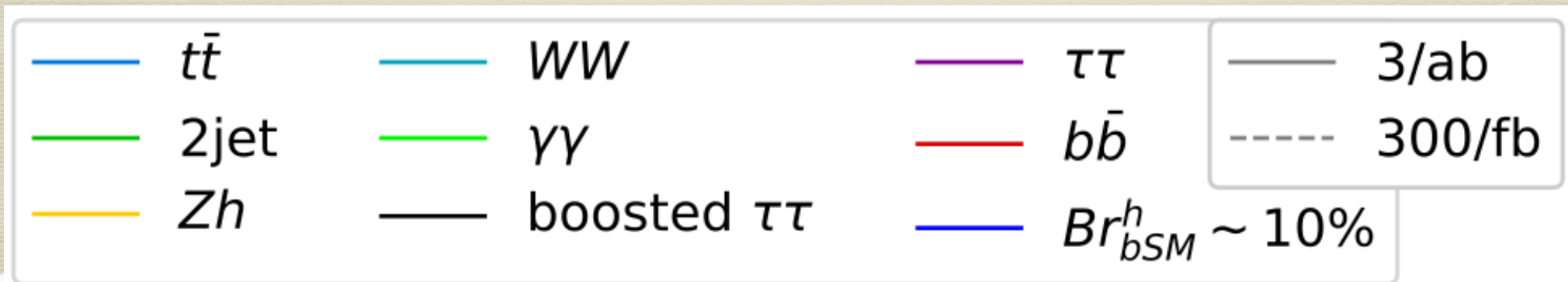
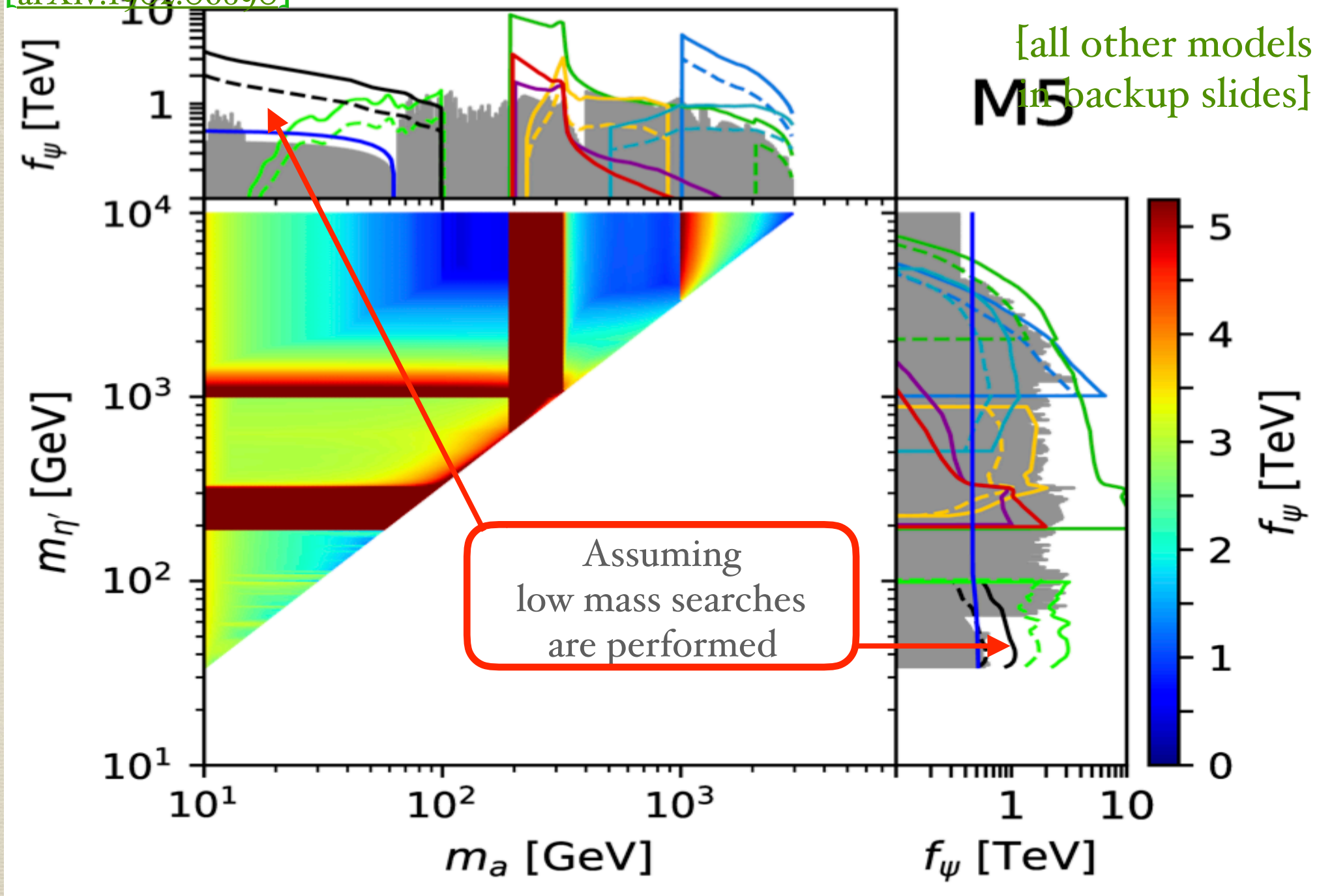
- Cutting harder on $\Delta R_{\mu e}$ can substantially increase background suppression for the lighter mass range.
- We did not use any τ ID or triggers.
- We only used the OSOF lepton channel. $\tau_\mu\tau_\mu$, $\tau_\mu\tau_{had}$, $\tau_{had}\tau_{had}$ have larger branching ratios but require 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.]



Projected reach at HL-LHC

[arXiv:1902.06890]



Colored PNGBs (the color octet Φ)

Effective Lagrangian:

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

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

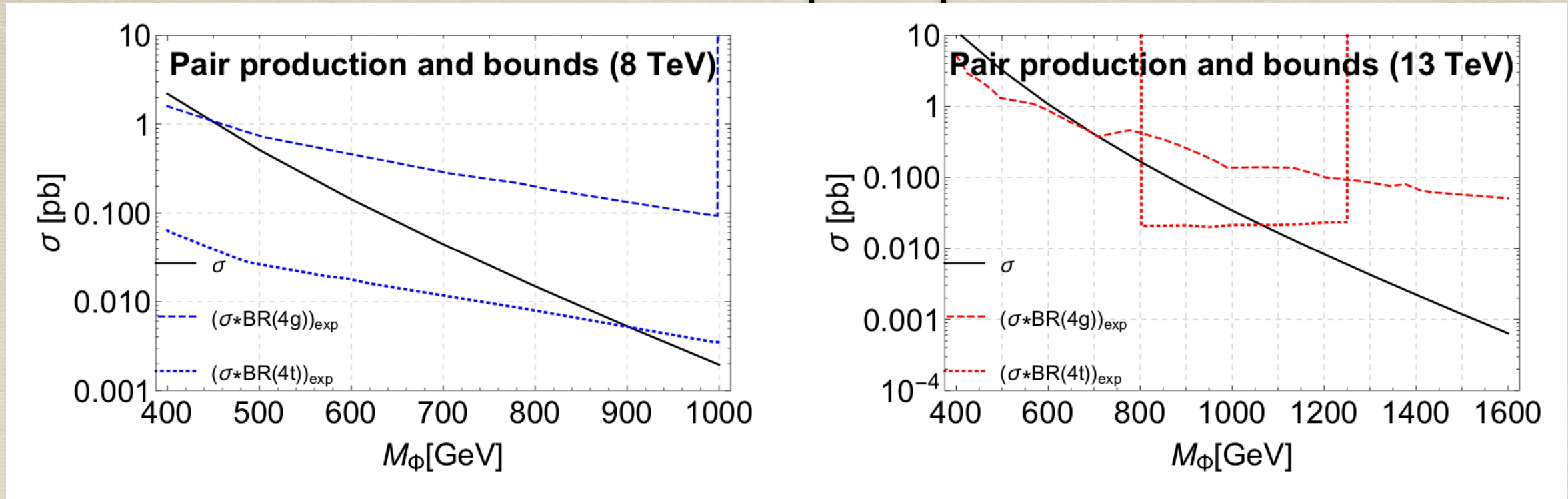
where in CH UV embeddings: $\kappa_g = 2Y_\chi$, $M_\Phi \sim C_g \frac{3}{4} g_s^2 f_\Phi^2$

Phenomenology

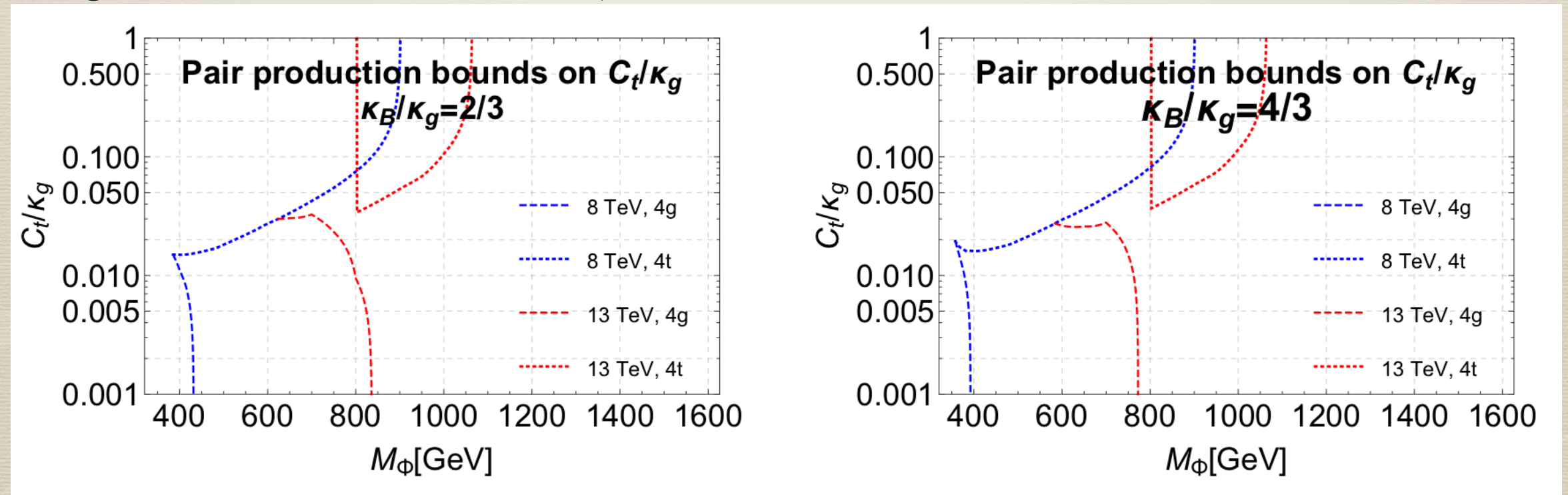
- Φ is single-produced in gluon fusion or pair-produced through QCD.
- Φ decays to gg , $g\gamma$, gZ , $t\bar{t}$ with fully determined branching fractions into dibosons:
- For $Y_\chi = 1/3$: $gg/g\gamma/gZ = 1 / .05 / .015$, $Y_\chi = 2/3$: $gg/g\gamma/gZ = 1 / .19 / .06$.
- The resonance is narrow.

Colored PNGBs

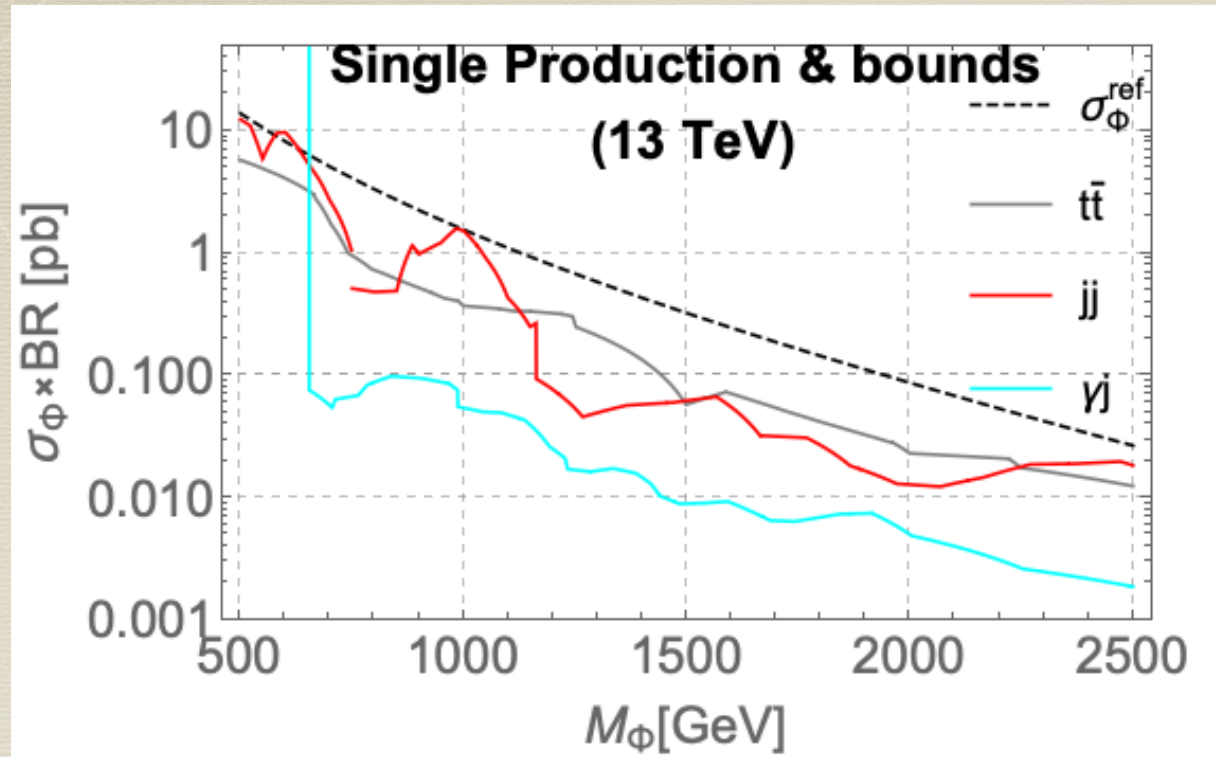
Constraints from pair production:



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

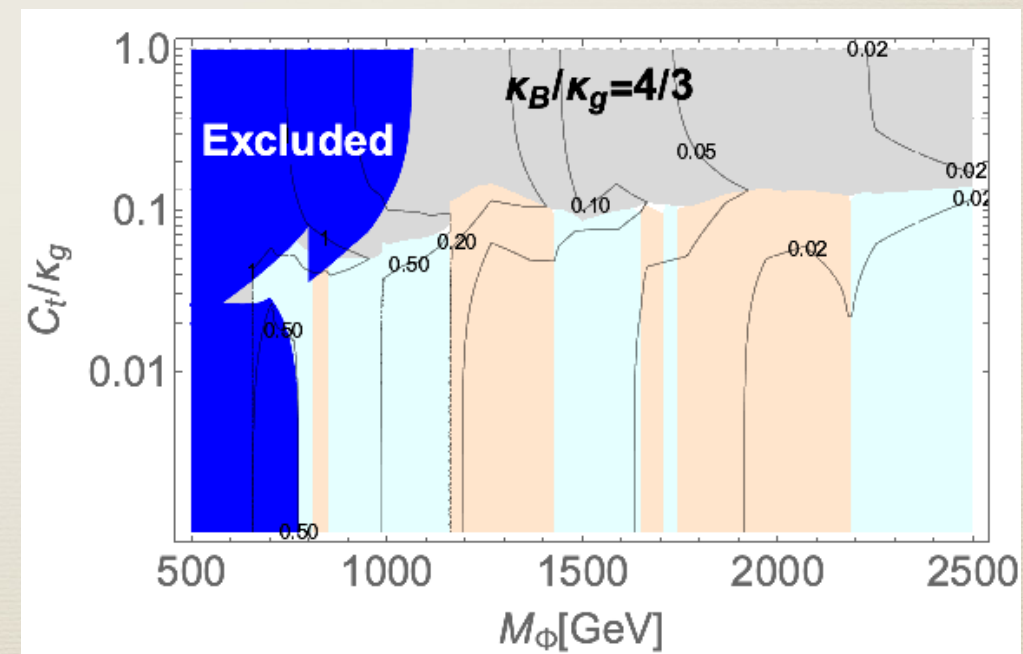
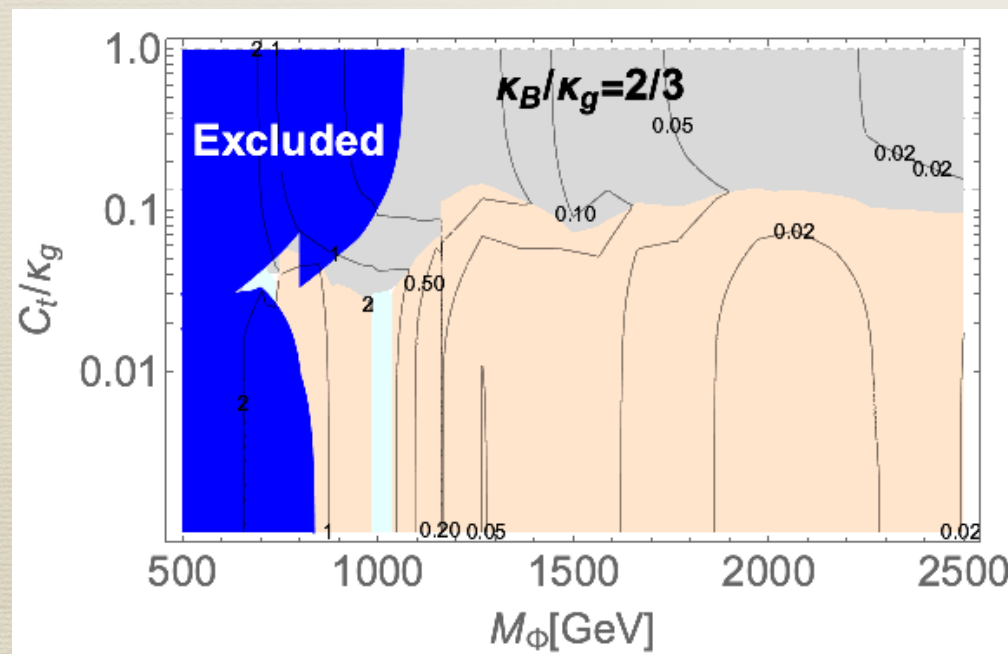


Colored PNGBs, constraints from single production:



(Using ATLAS & CMS searches for dijets, ditops, and excited quarks).

$$\sigma_{\Phi}^{\text{ref}} \text{ has } \frac{\kappa_g}{f_{\Phi}} = 10 \text{ TeV}^{-1}$$



Channels with the strongest bound: gg (red), $\gamma\gamma$ (cyan), $t\bar{t}$ (gray).

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

Colored PNGBs, constraints from single production:

Note:

- From underlying models, we expect \sim TeV scale mass and

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.

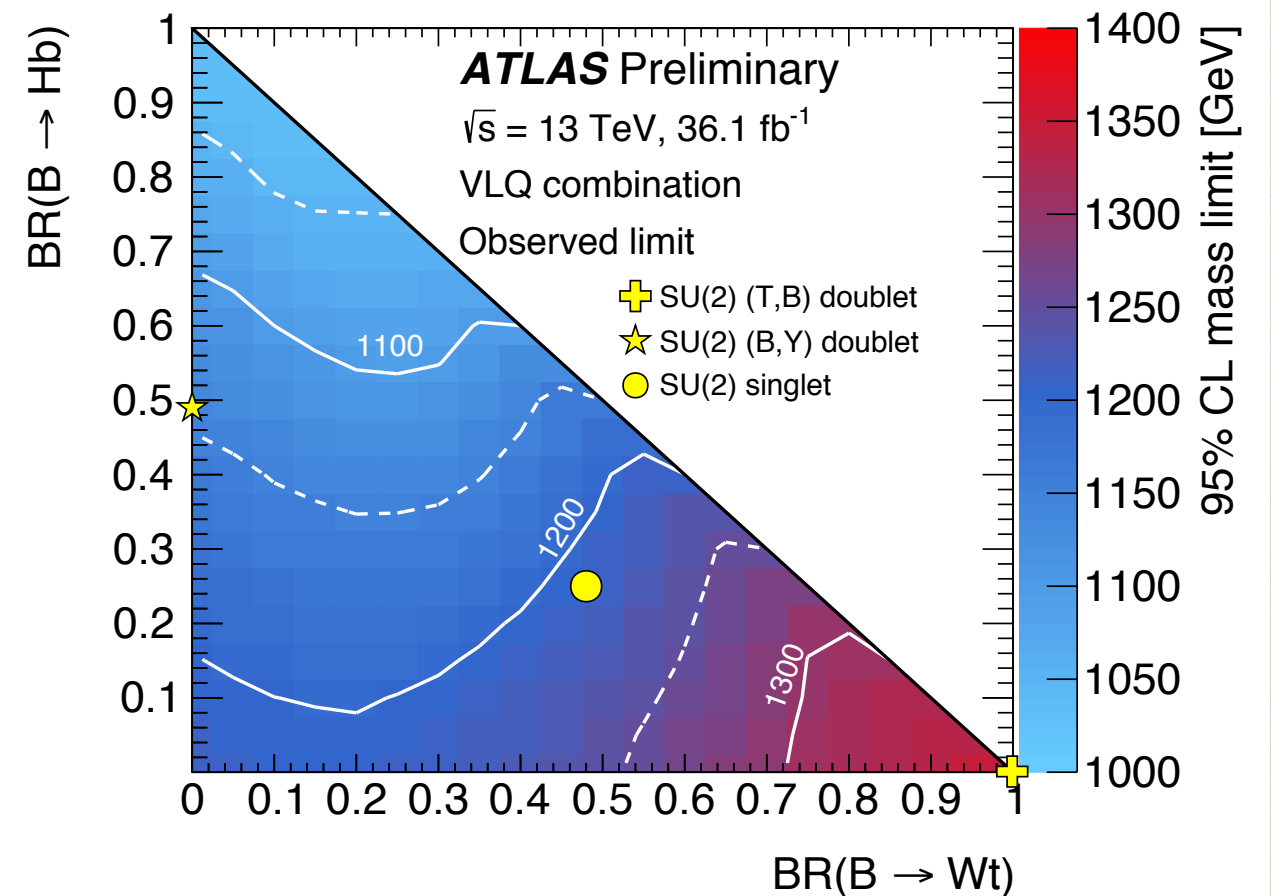
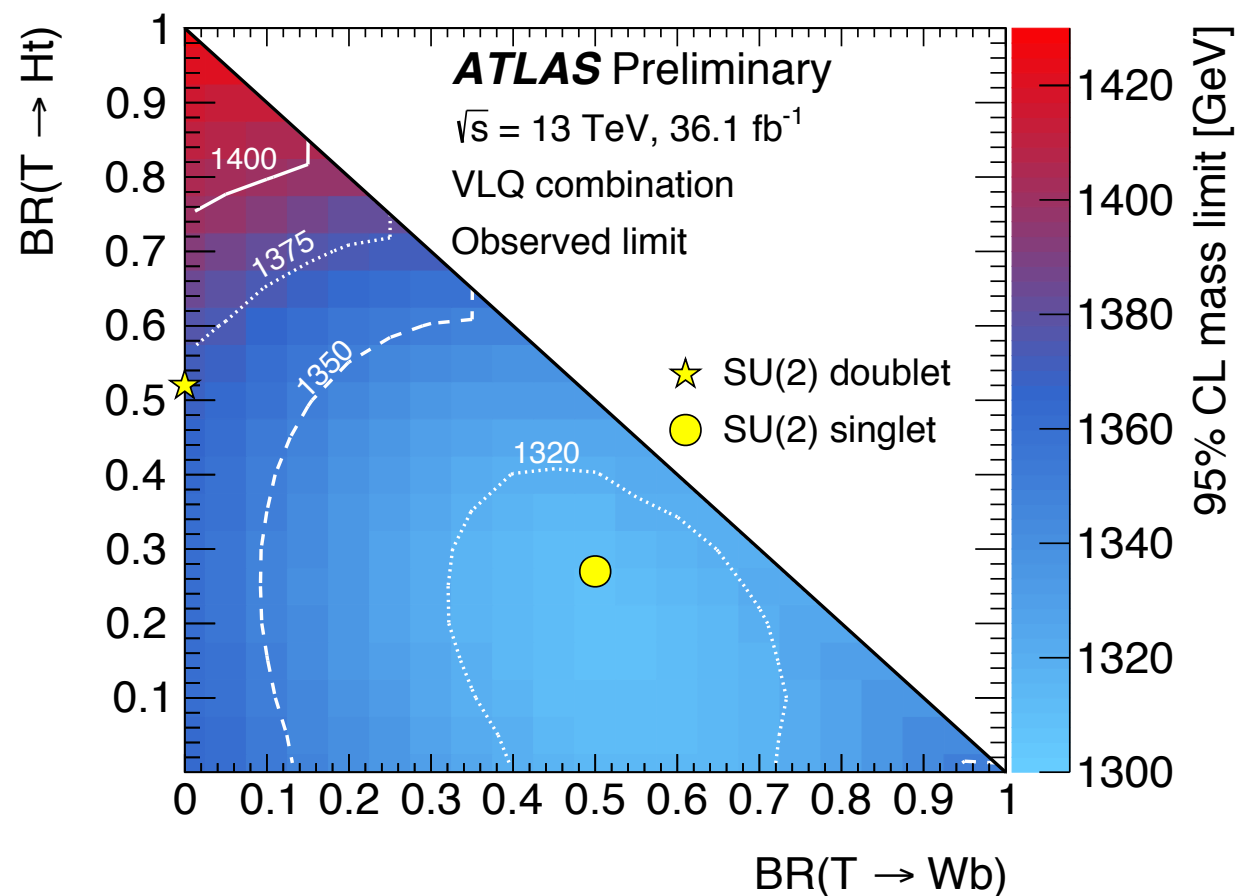
For (tt)(tt), recasts are required for the latest ATLAS and CMS searches (see [Fuks etal \(2018\)](#)).

Pair-production channels involving $\Phi \rightarrow g\gamma$ decays are not searched for and have discovery potential (to appear, soon).

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

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

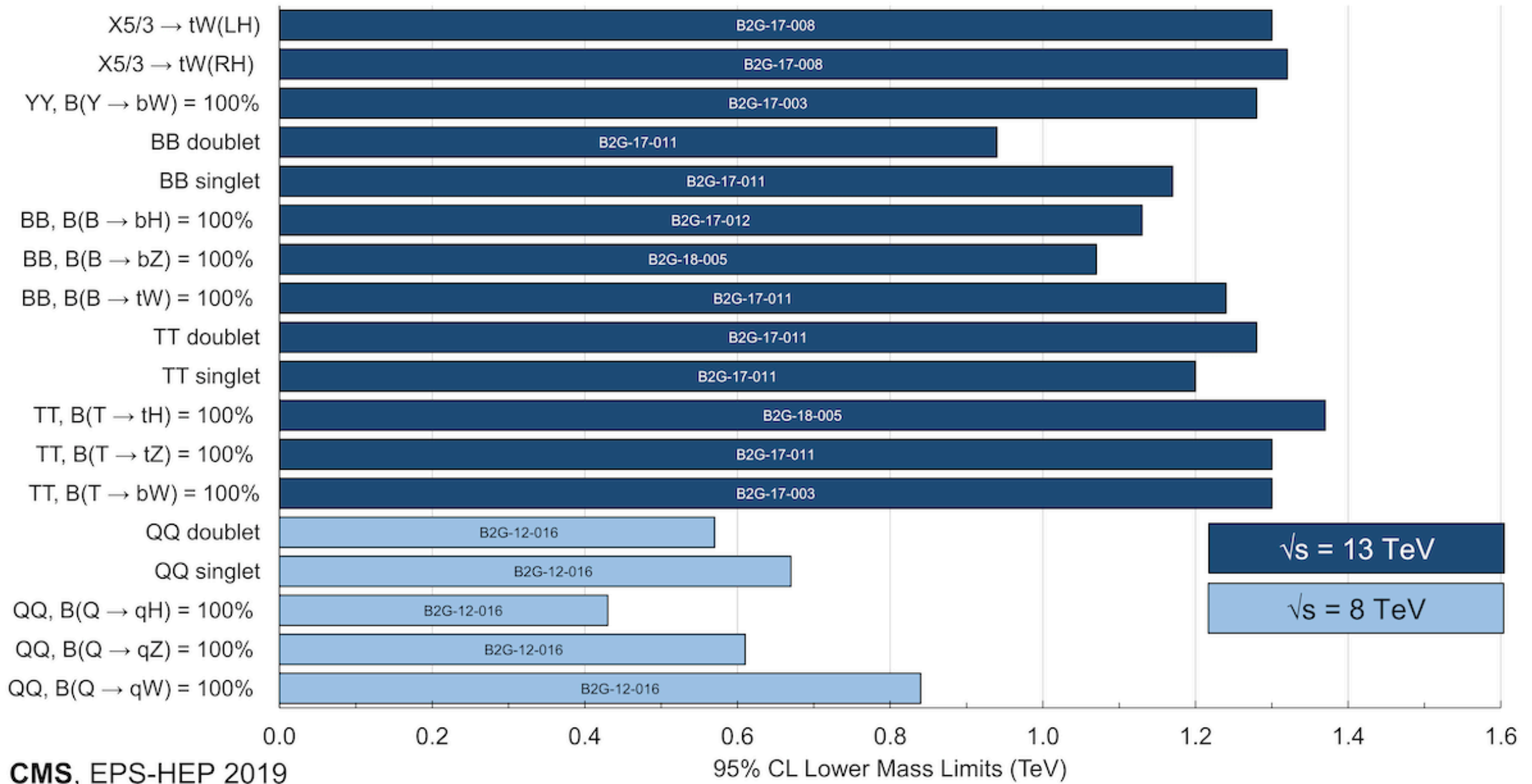
T & B : Combined bounds on pair-produced top partners



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

CMS bounds on pair production

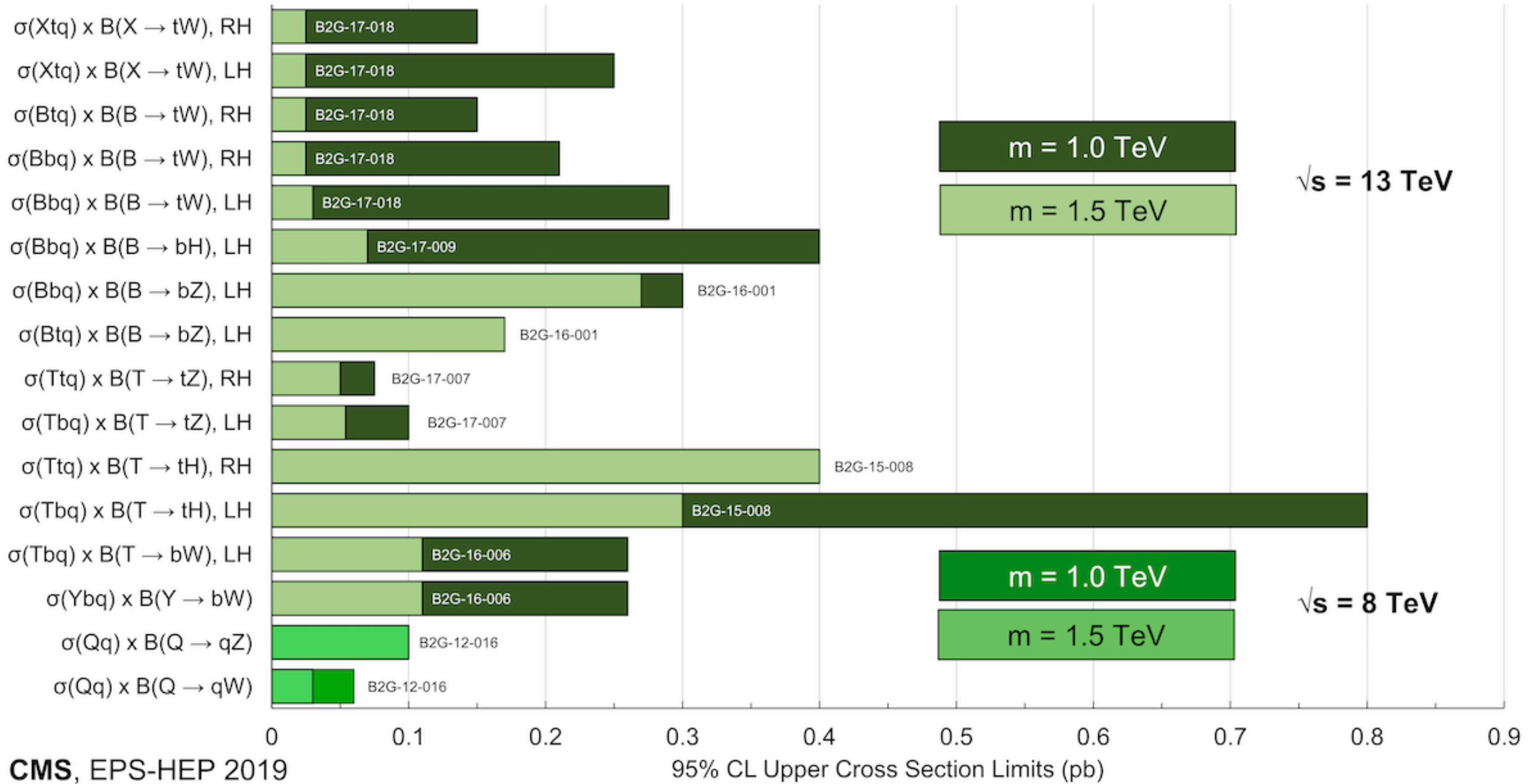
Vector-like quark pair production



[CMS B2G Summary Plots]

CMS bounds on single production

Vector-like quark single production



CMS, EPS-HEP 2019

[CMS B2G Summary Plots]

...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. $X_{5/3} \rightarrow \bar{b} \pi_6$ (with subsequent $\pi_6 \rightarrow t t$),
 4. $X_{5/3} \rightarrow t \phi^+$, $X_{5/3} \rightarrow b \phi^{++}$.
- Decays of the pNGBs yield manifold novel multi-body decay modes and LHC signatures.

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

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

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

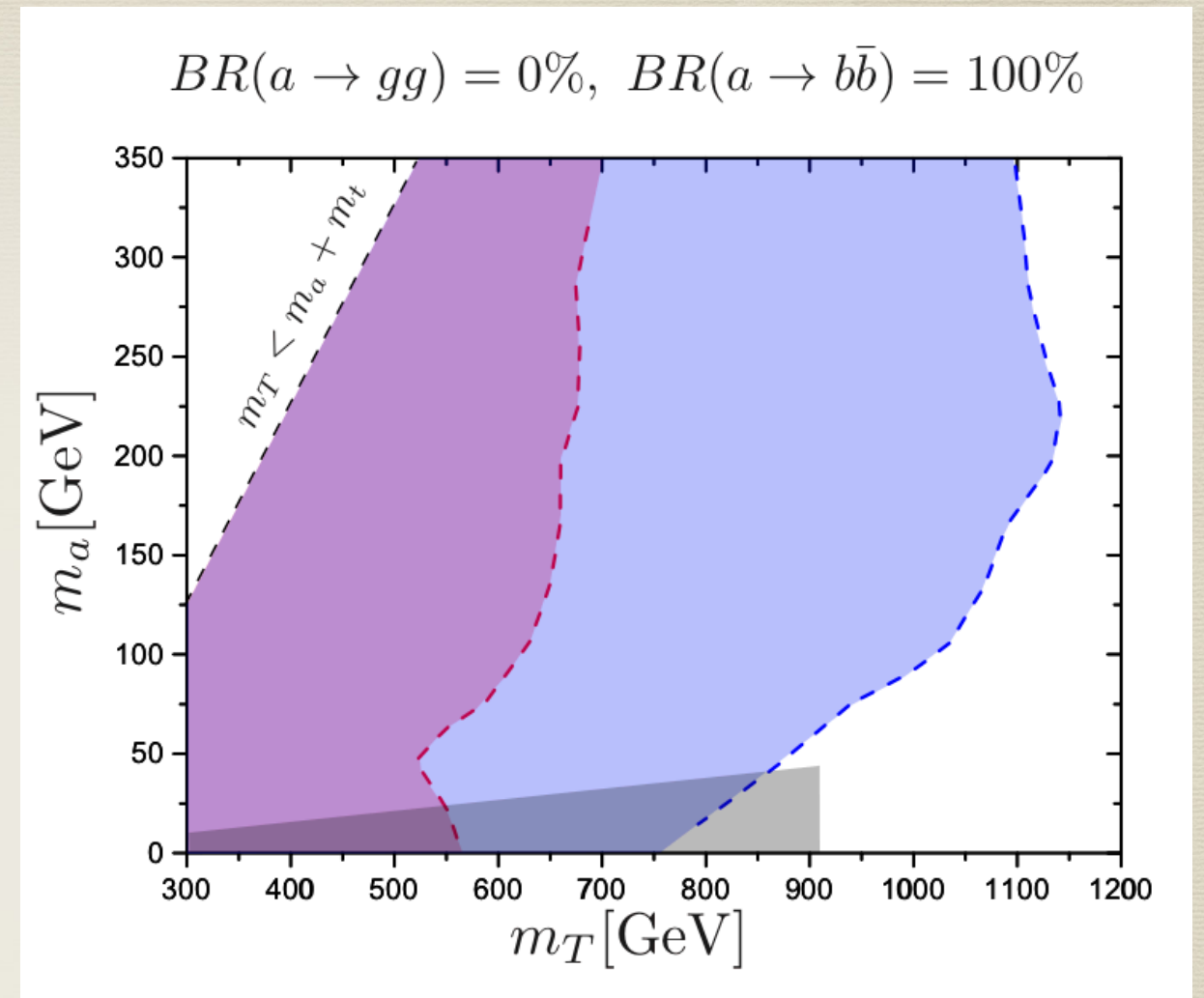
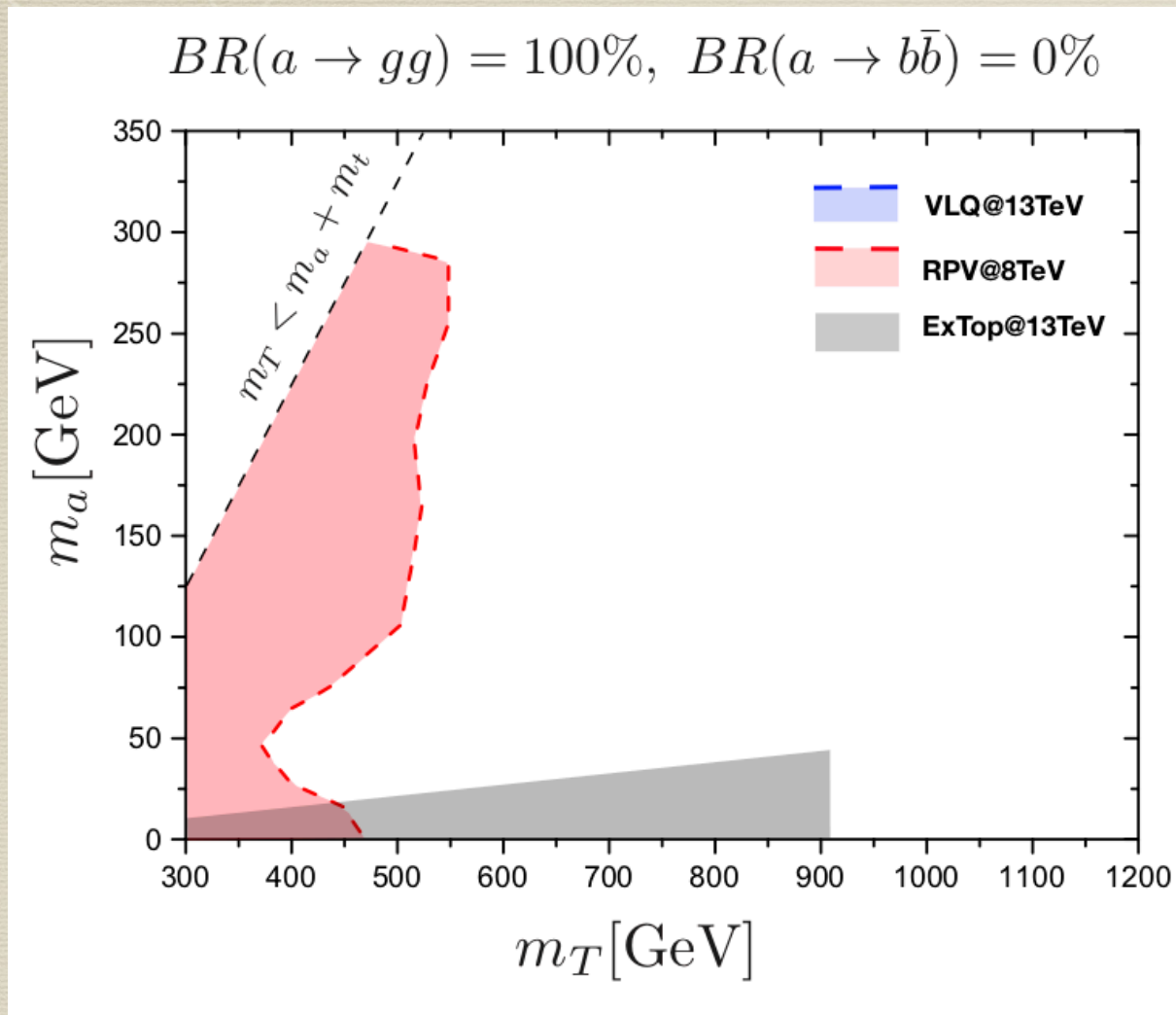
$$\mathcal{L}_T = \bar{T} (i\not{D} - M_T) T + \left(\kappa_{W,L}^T \frac{g}{\sqrt{2}} \bar{T} W^+ P_L b + \kappa_{Z,L}^T \frac{g}{2c_W} \bar{T} Z P_L t - \kappa_{h,L}^T \frac{M_T}{v} \bar{T} h P_L t + i\kappa_{a,L}^T \bar{T} a P_L t + L \leftrightarrow R + \text{h.c.} \right),$$

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

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

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

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



Recast searches

Red:

RPV-SUSY (hadronic)

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

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

Blue:

VLQ search

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

Gray:

Excited top search

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

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

[[PLB798, 135015 \(2019\)](#)]

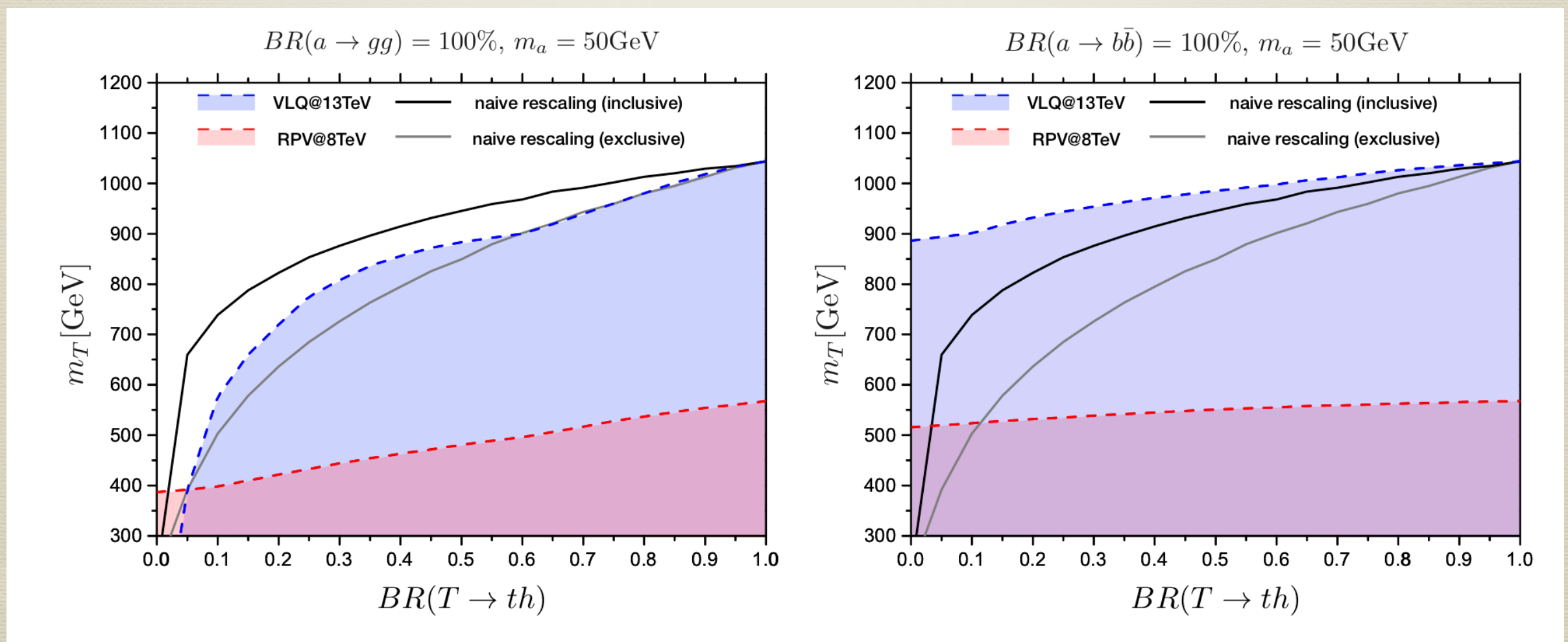
For light a : Bounds on $pp \rightarrow TT \rightarrow t a t h$, with $a \rightarrow gg$ or $a \rightarrow bb$

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

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

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

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



[PLB798, 135015 (2019)]

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

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

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

Effective Lagrangian:

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

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

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

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

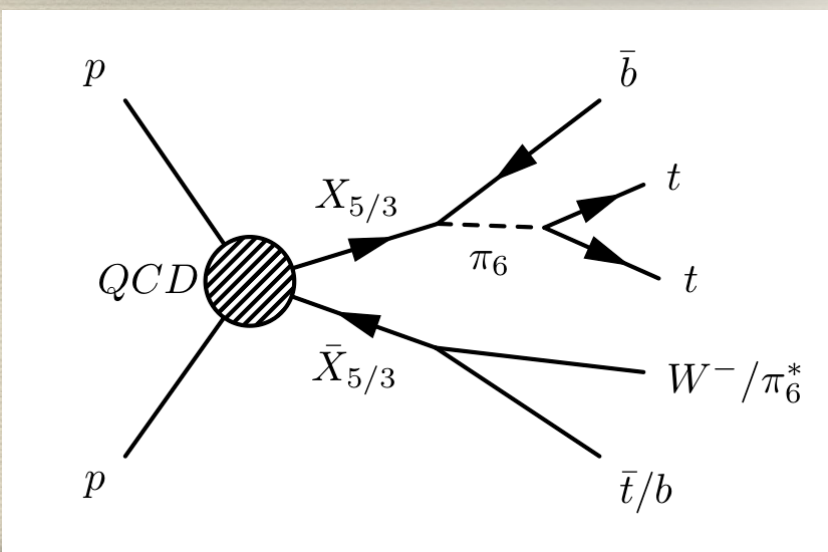
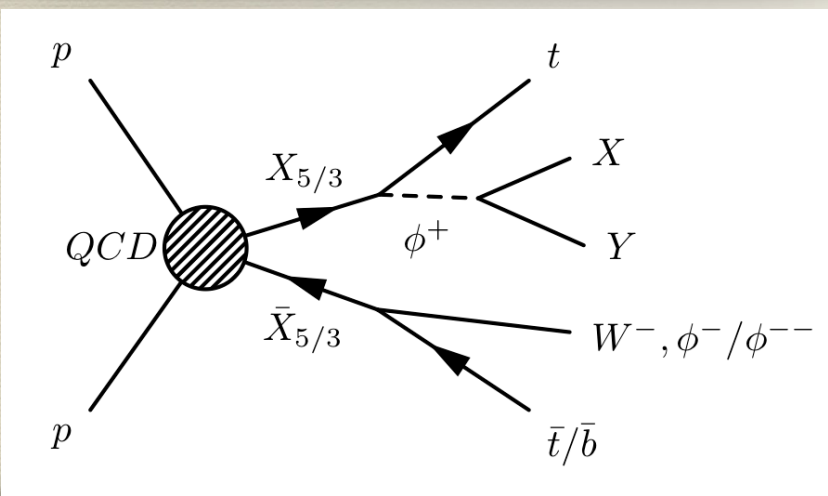
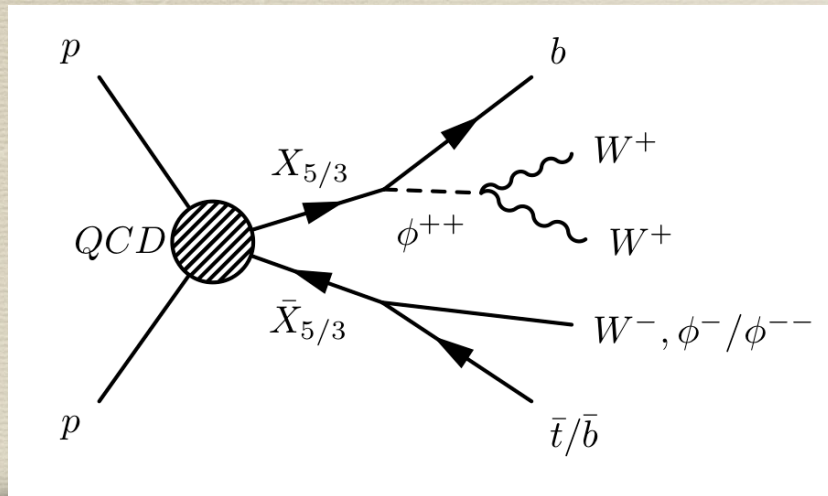
In models with SU(5)/SO(5) breaking in the EW sector, we have charged (and doubly charged) pNGBs.

Effective Lagrangian:

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

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

Examples of processes:



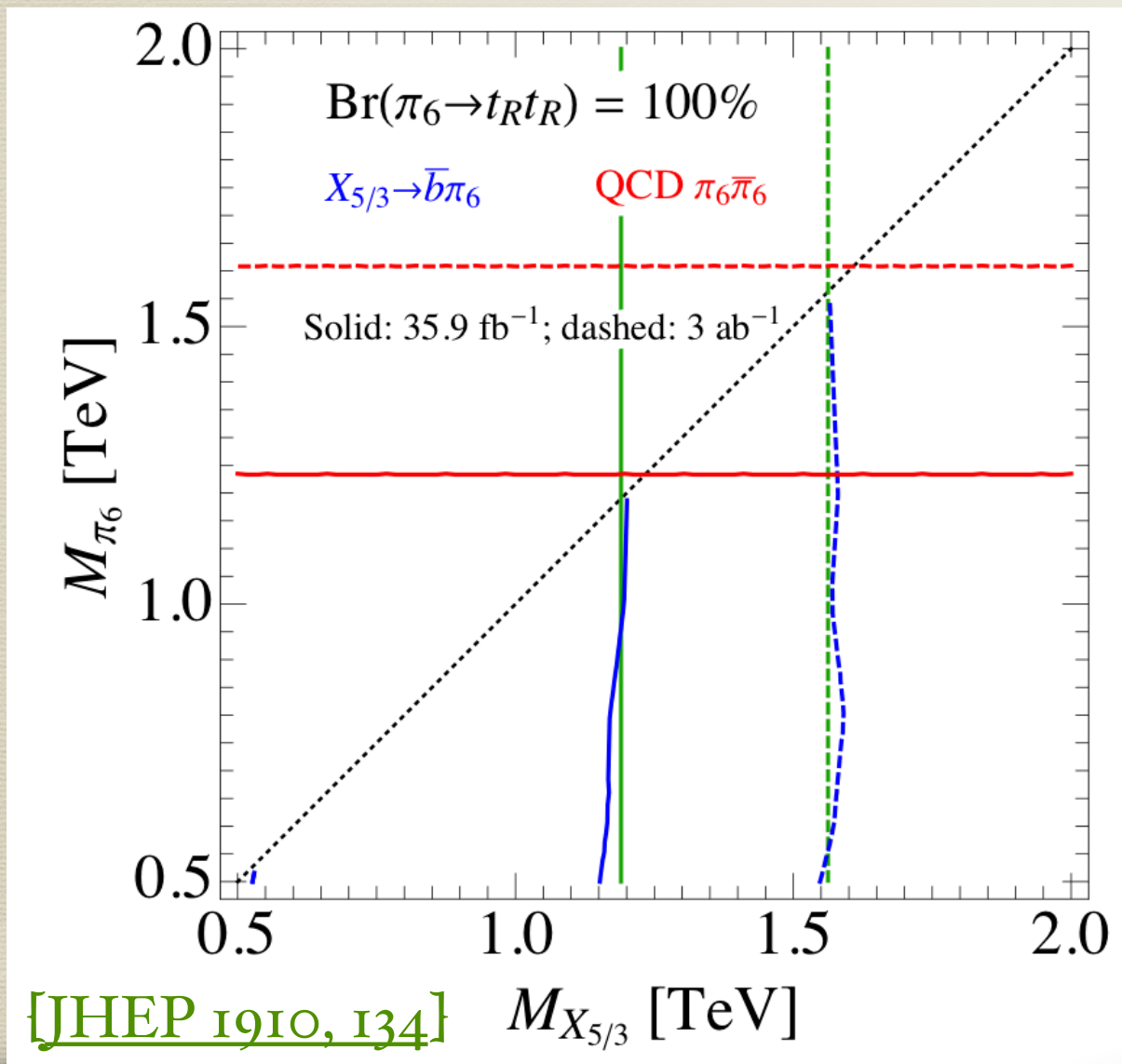
Full list of final states from $X_{5/3}$ pair-production:

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

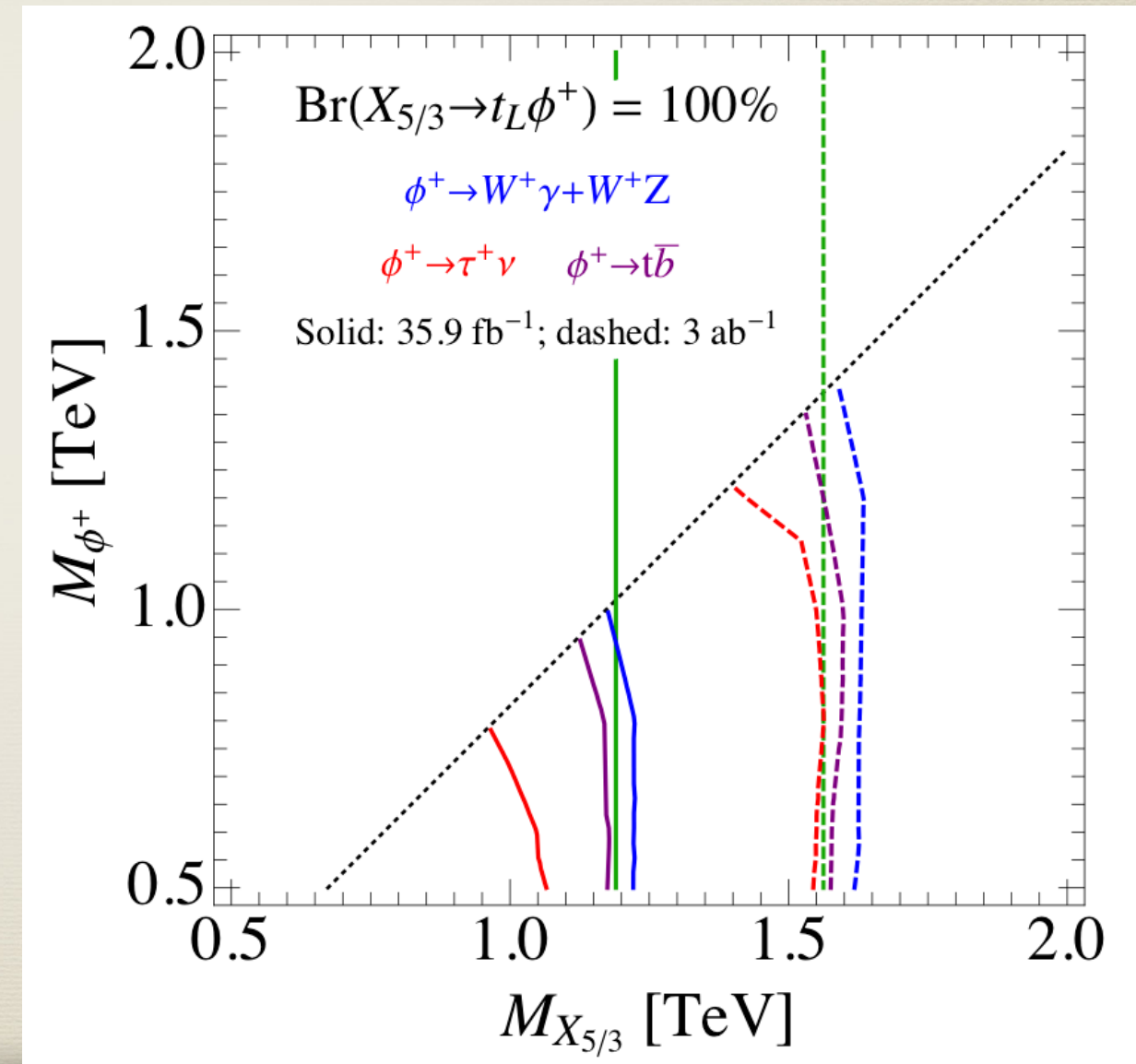
2

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 :

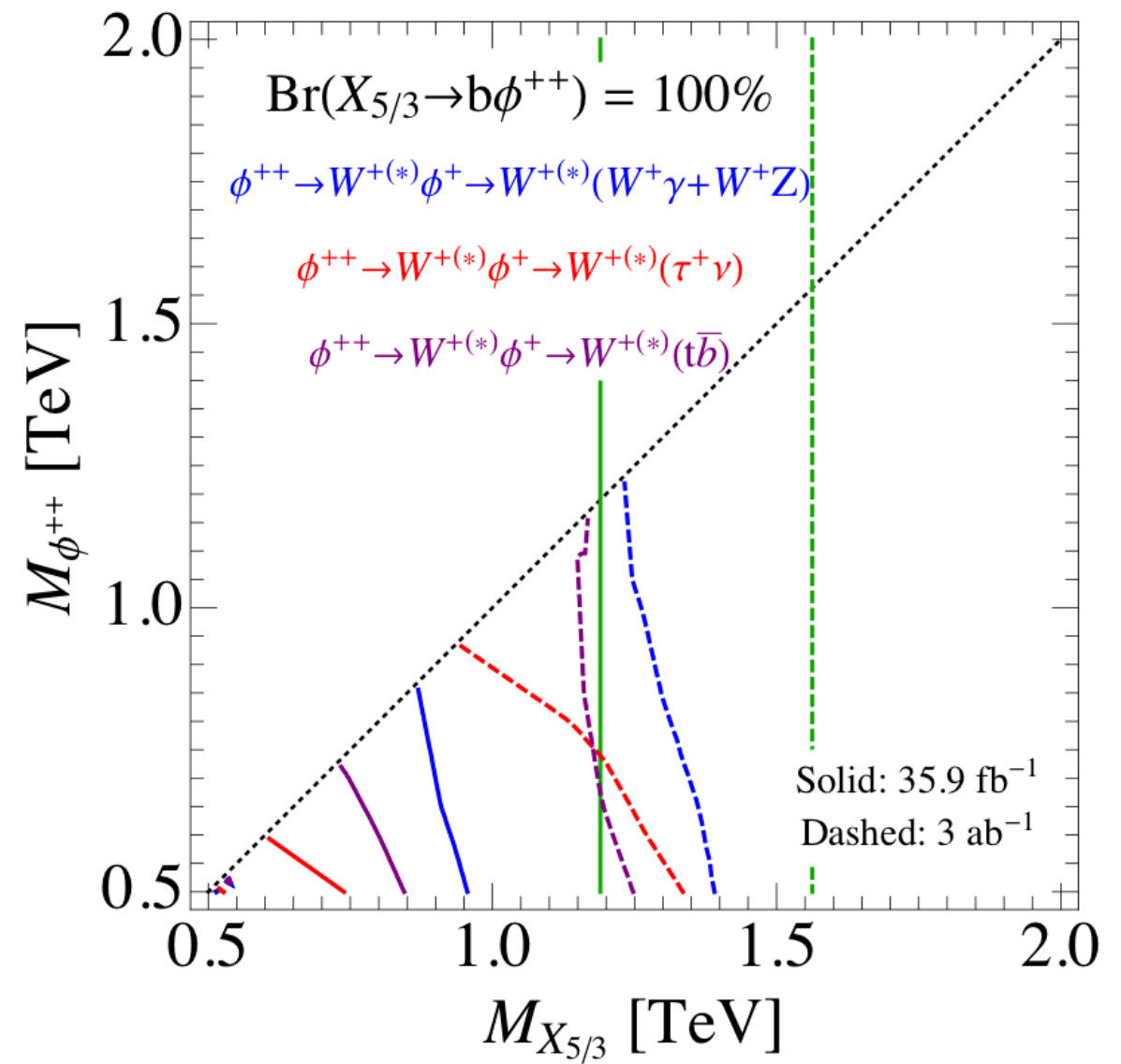
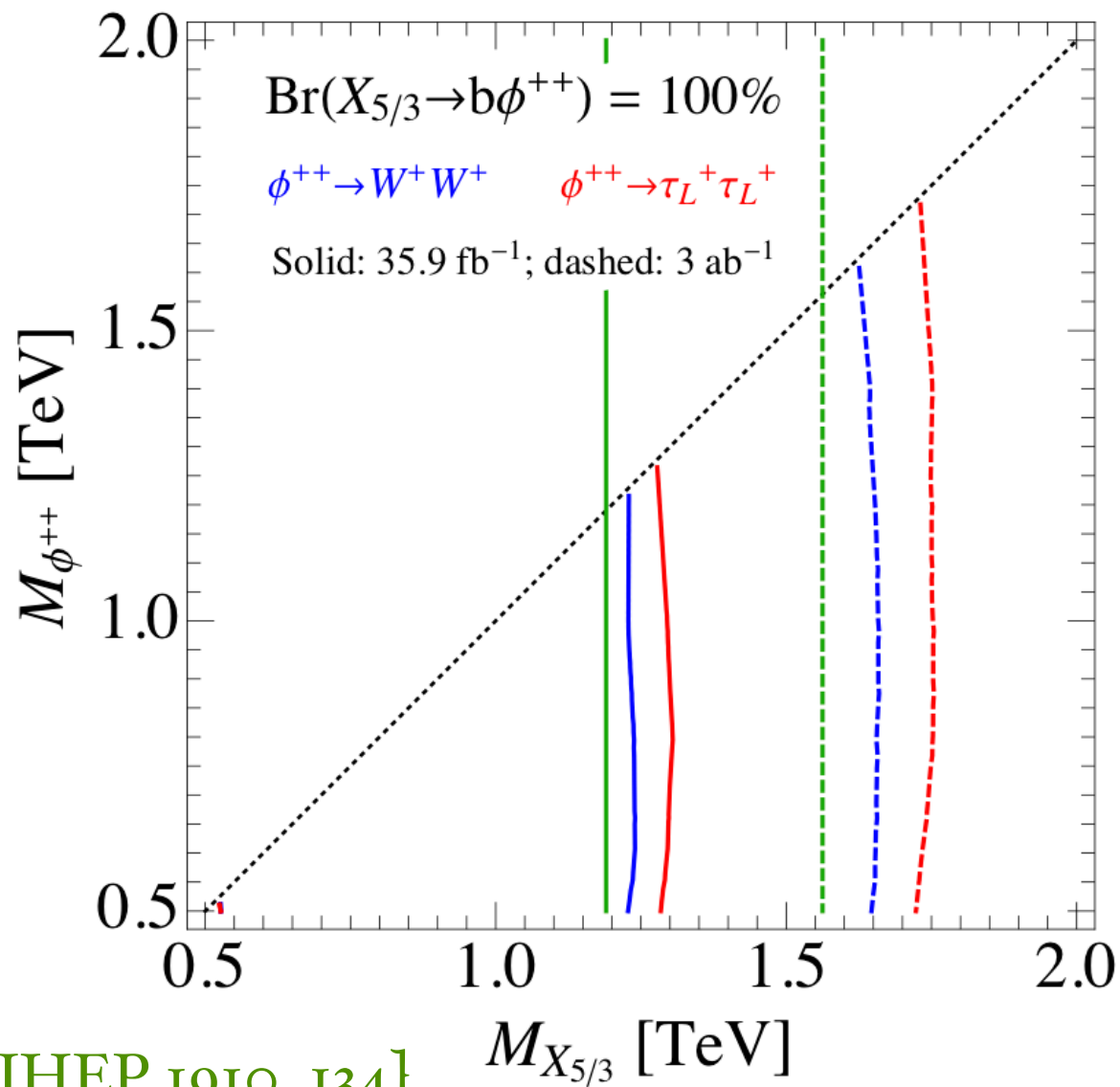


ϕ^+ :



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

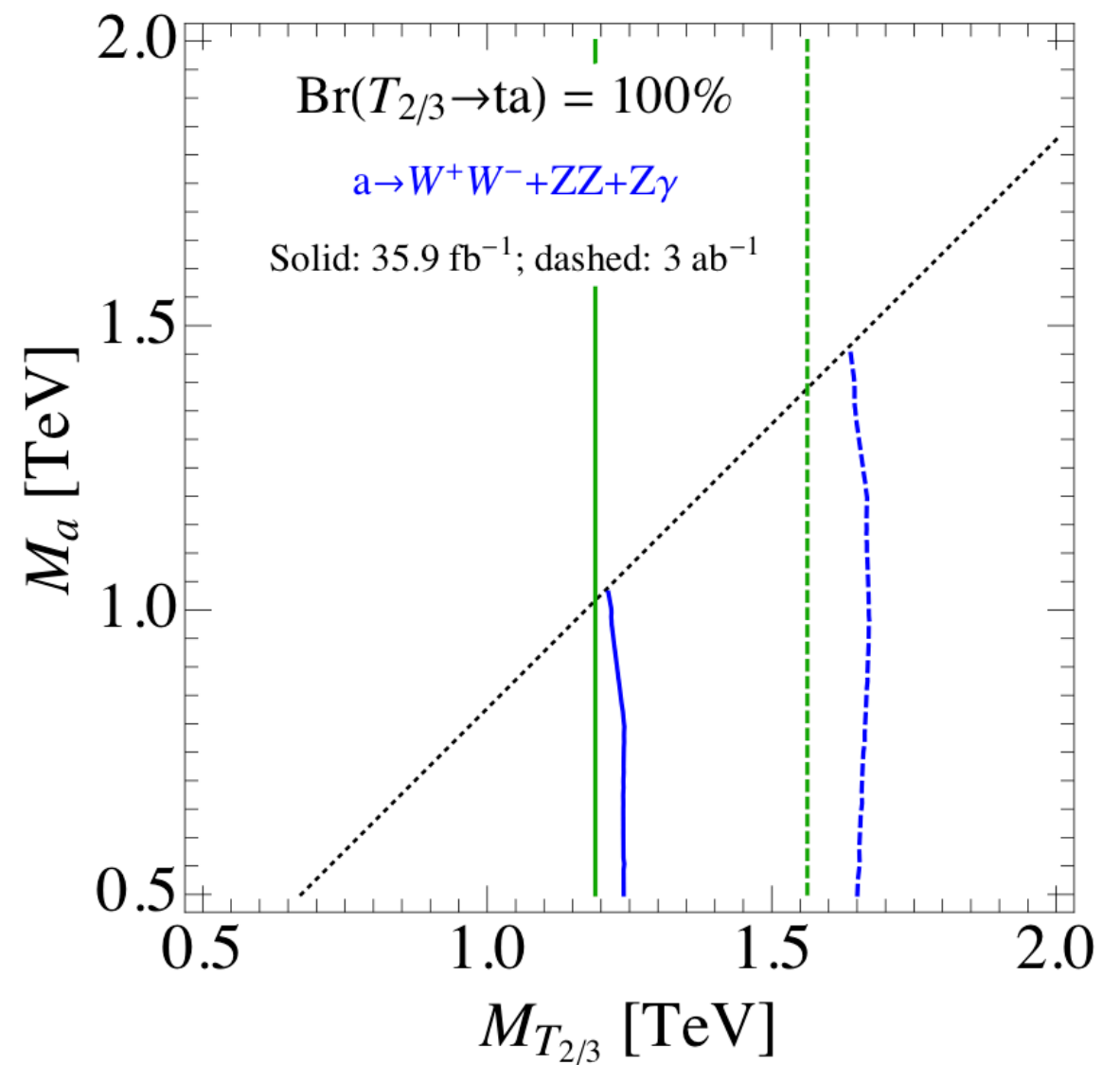
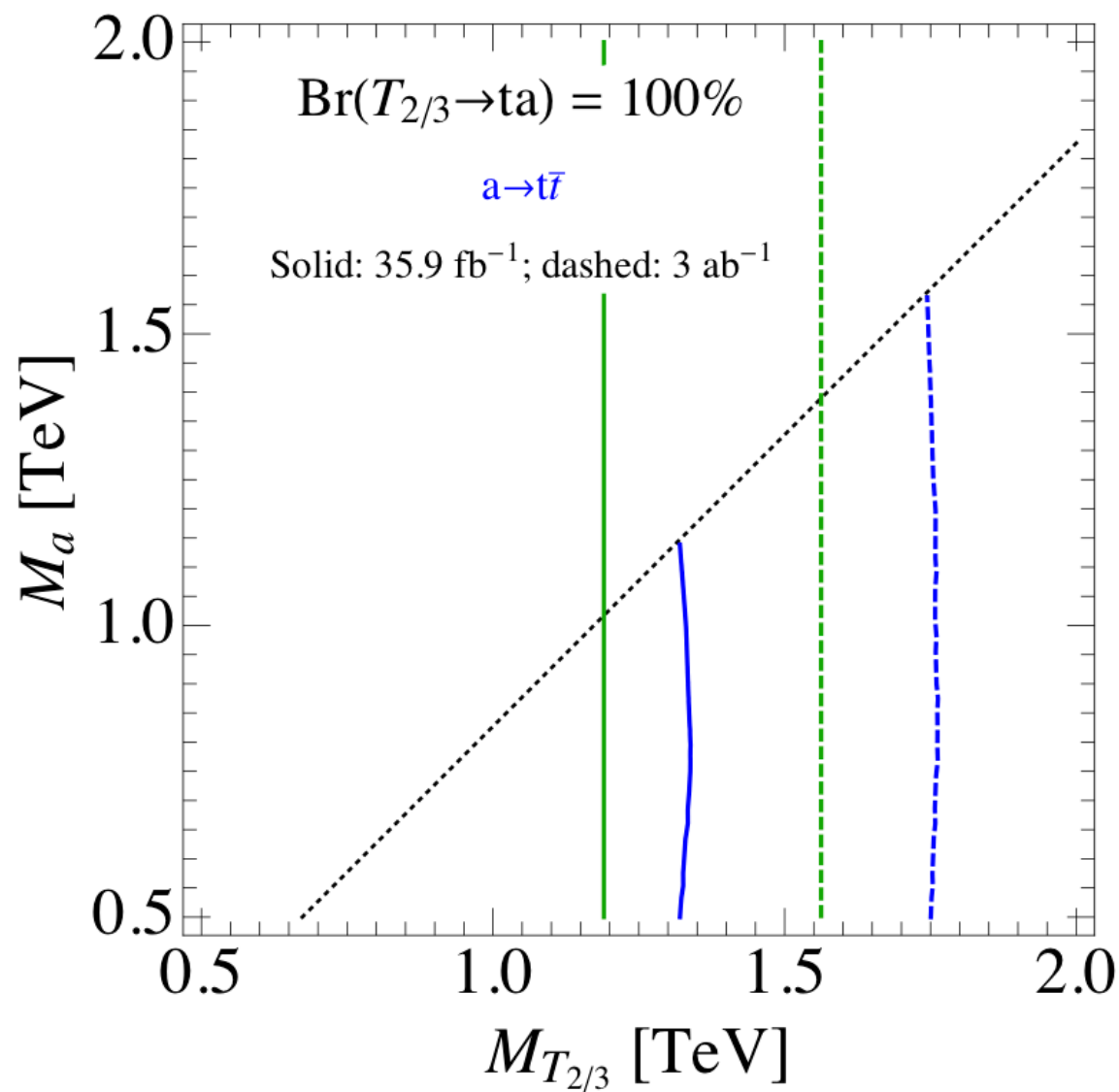
ϕ^{++} :



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

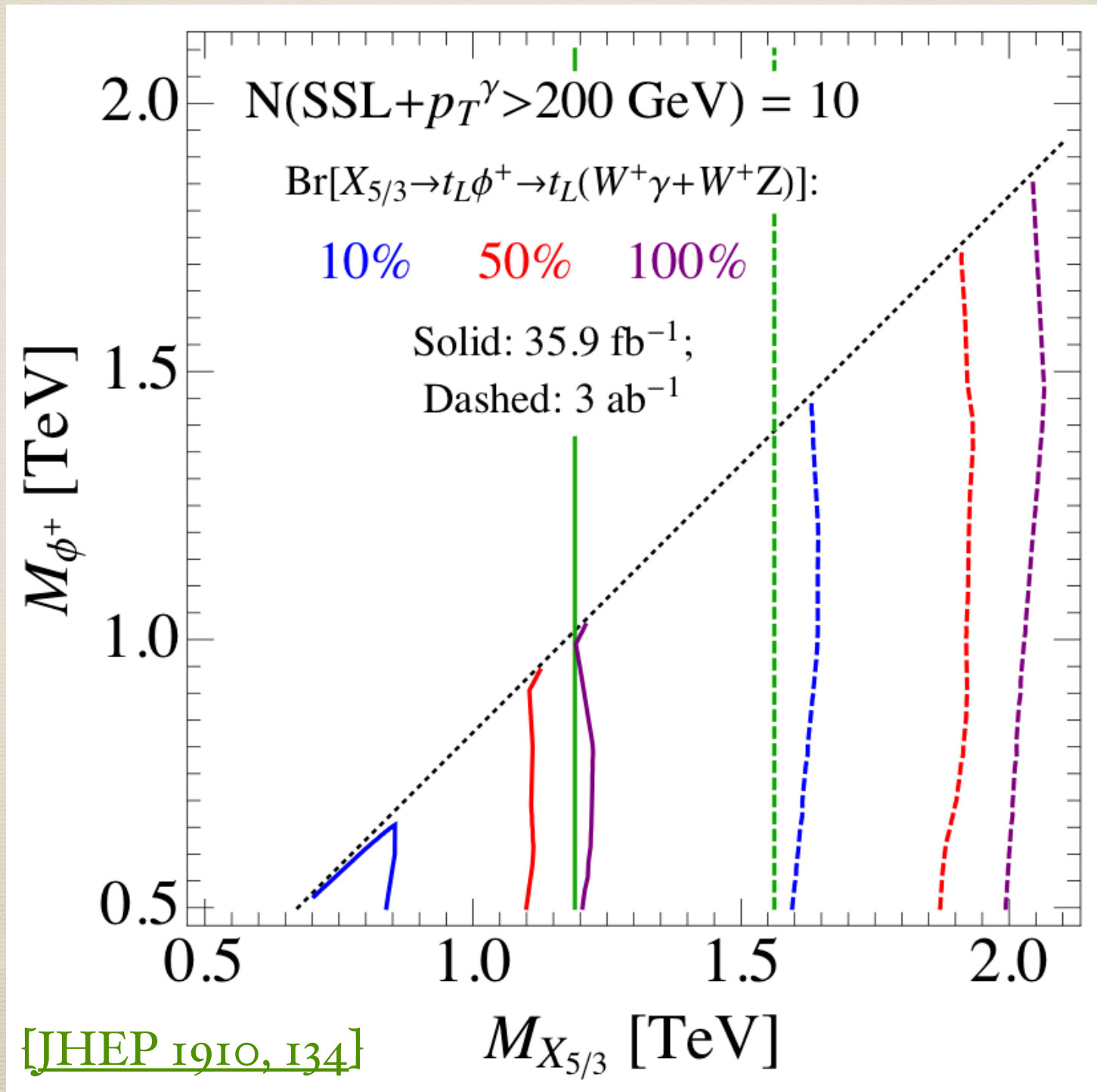
Bonus Plots

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



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

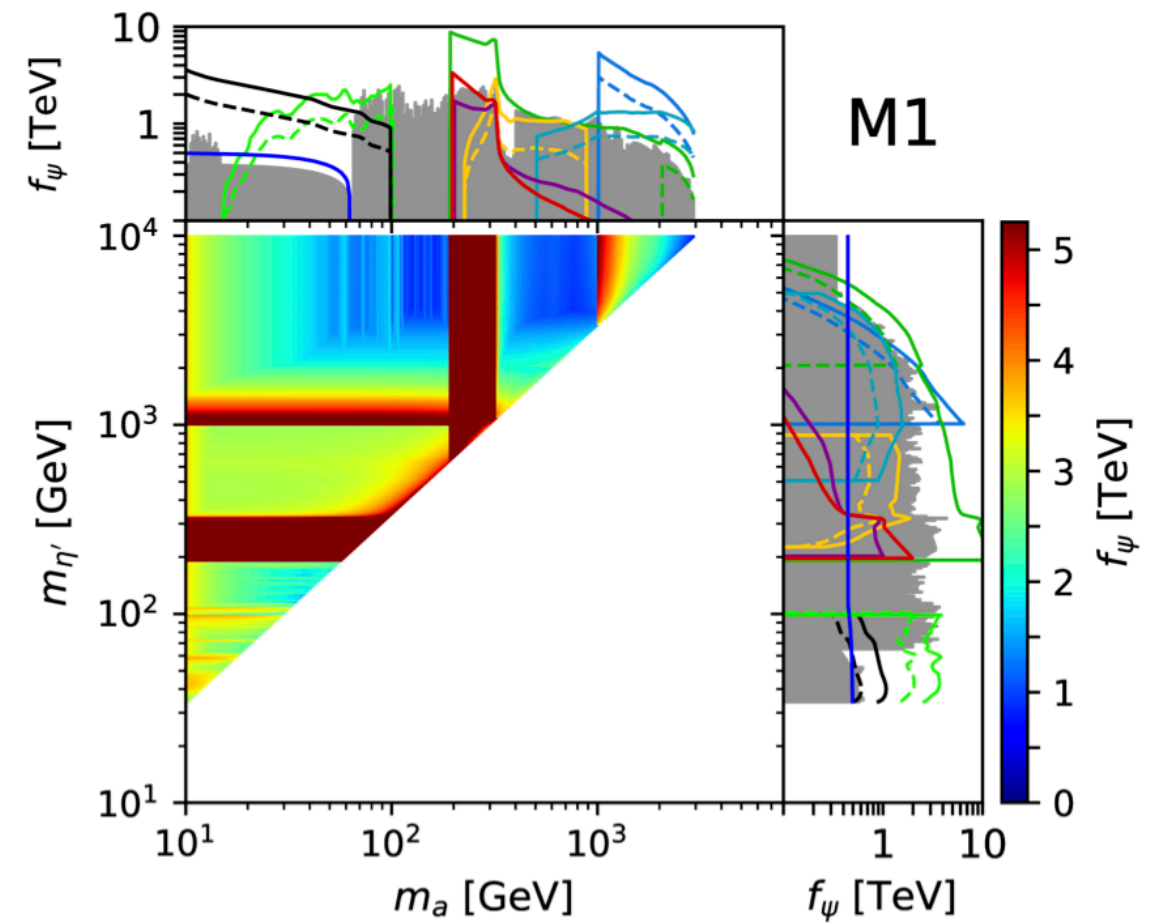
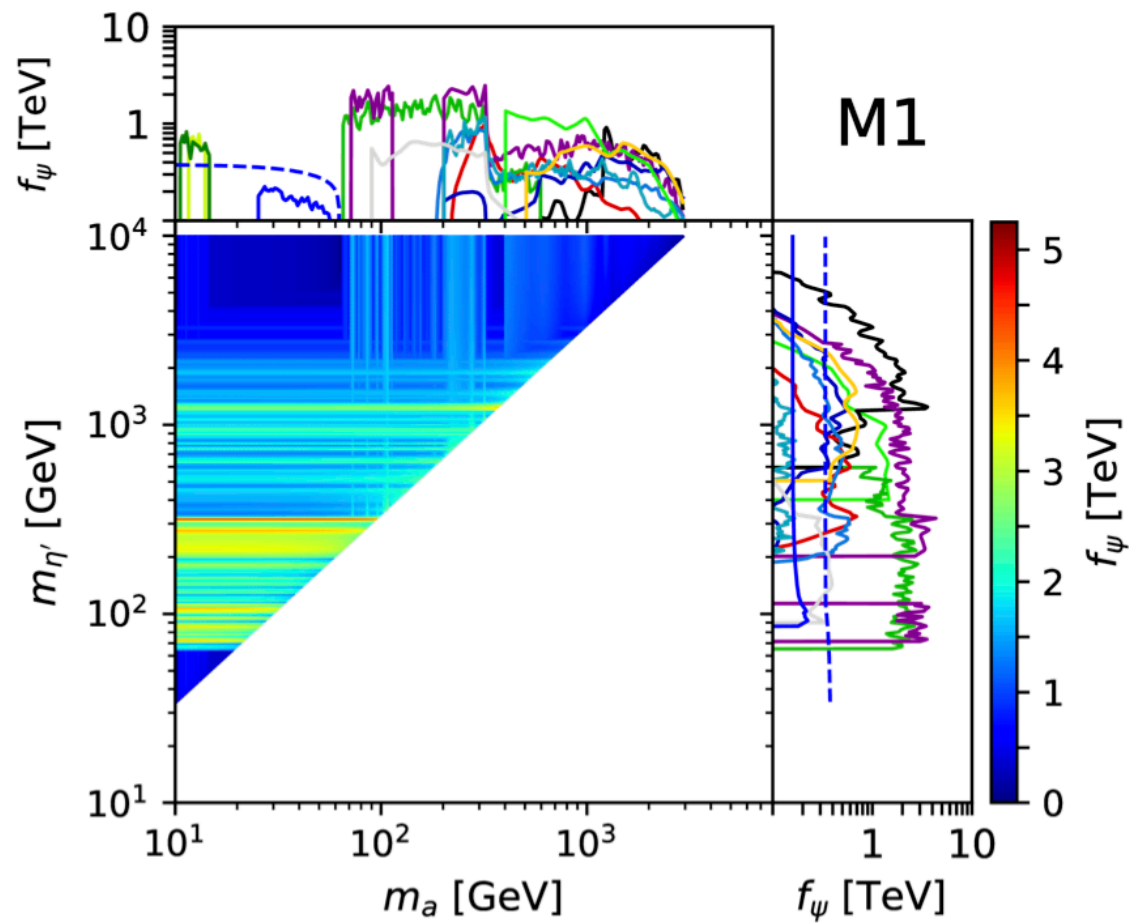
Some exotic decay channels provide opportunities to substantially increase sensitivity. E.g.: $X_{5/3} \rightarrow t\phi^+ \rightarrow tW^+\gamma$ with a hard photon in the FS.

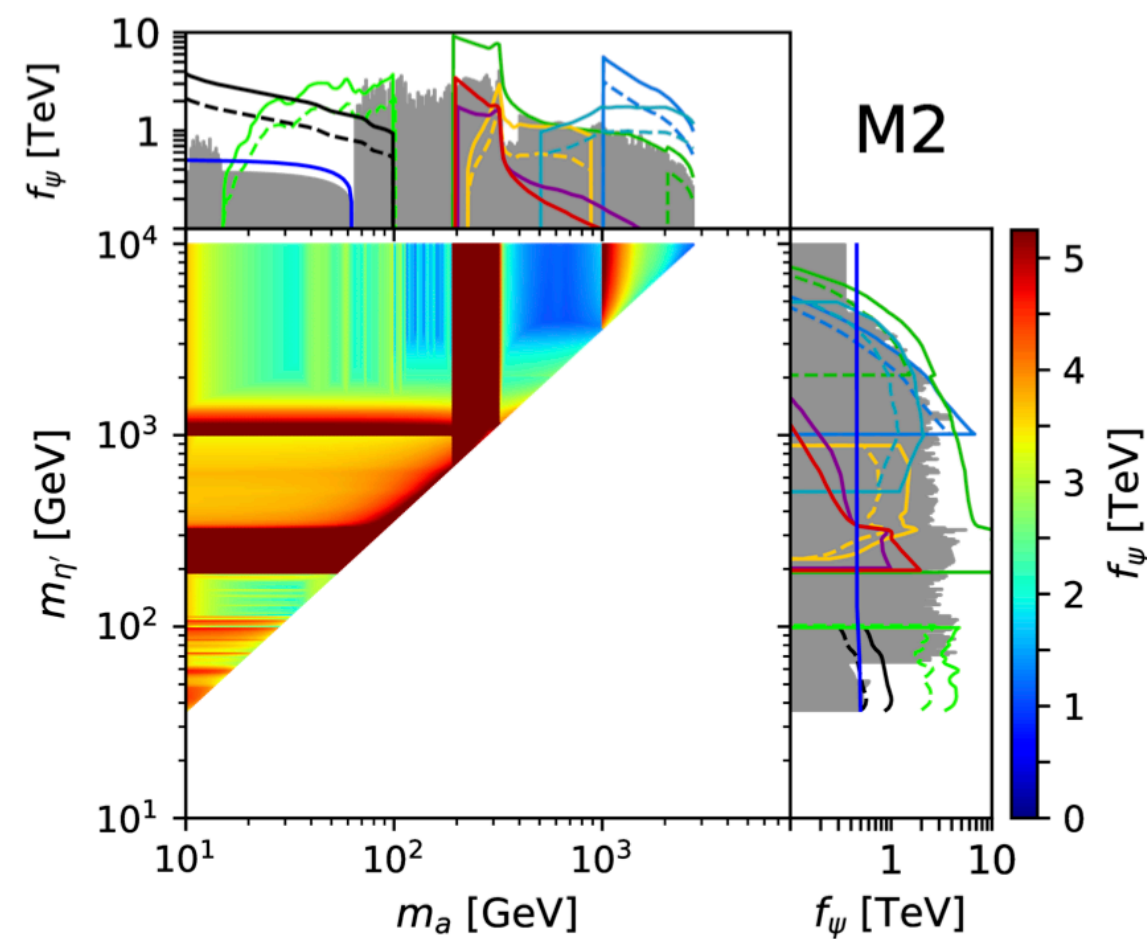
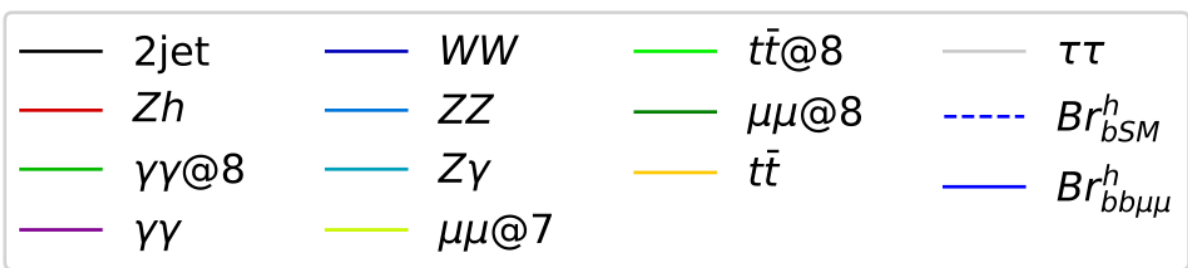
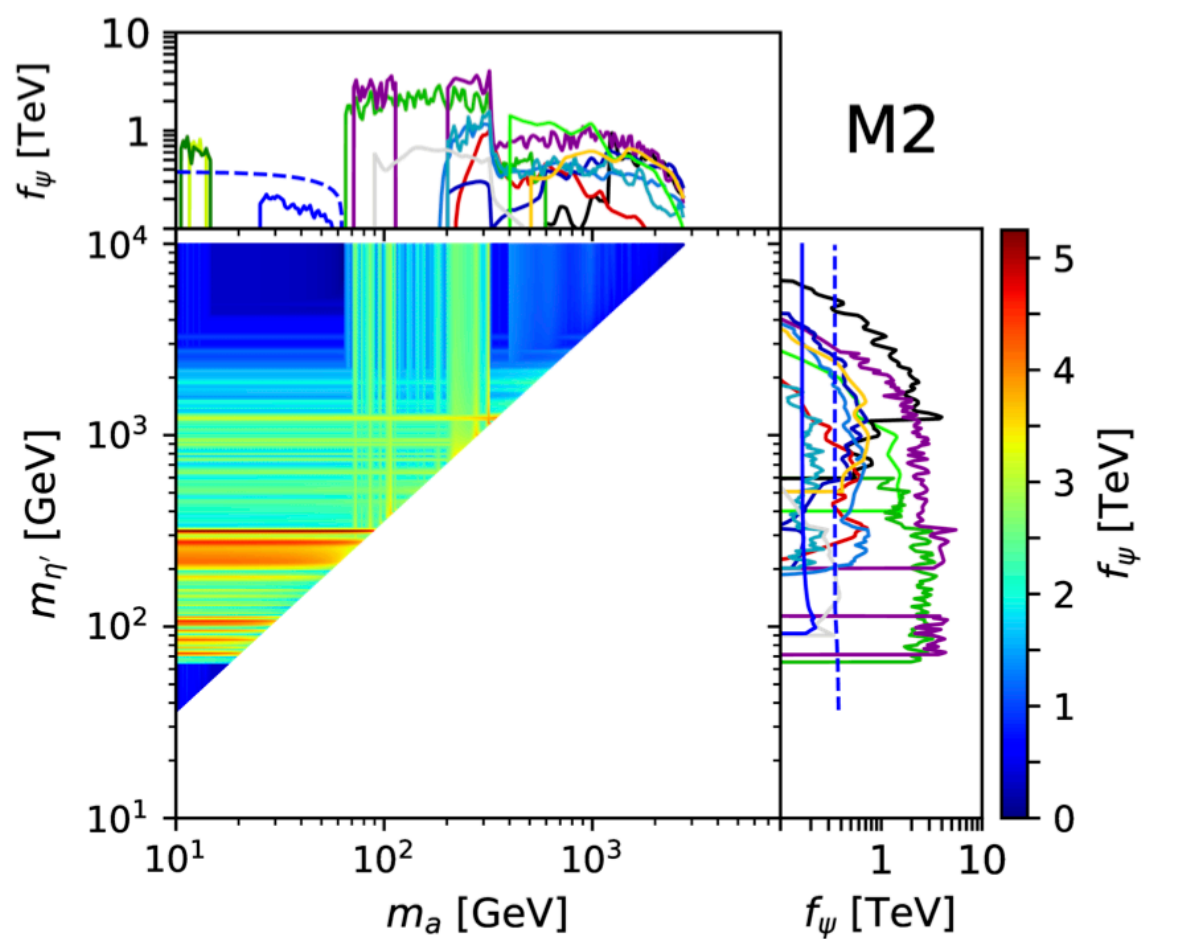


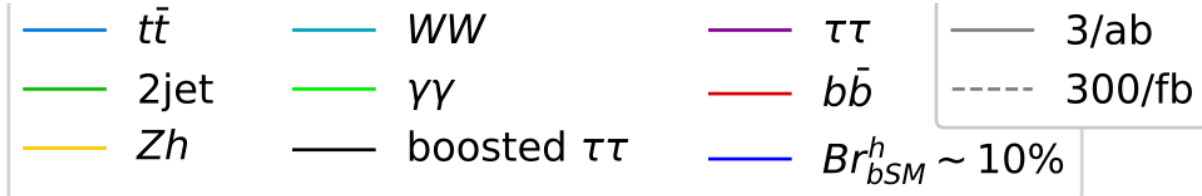
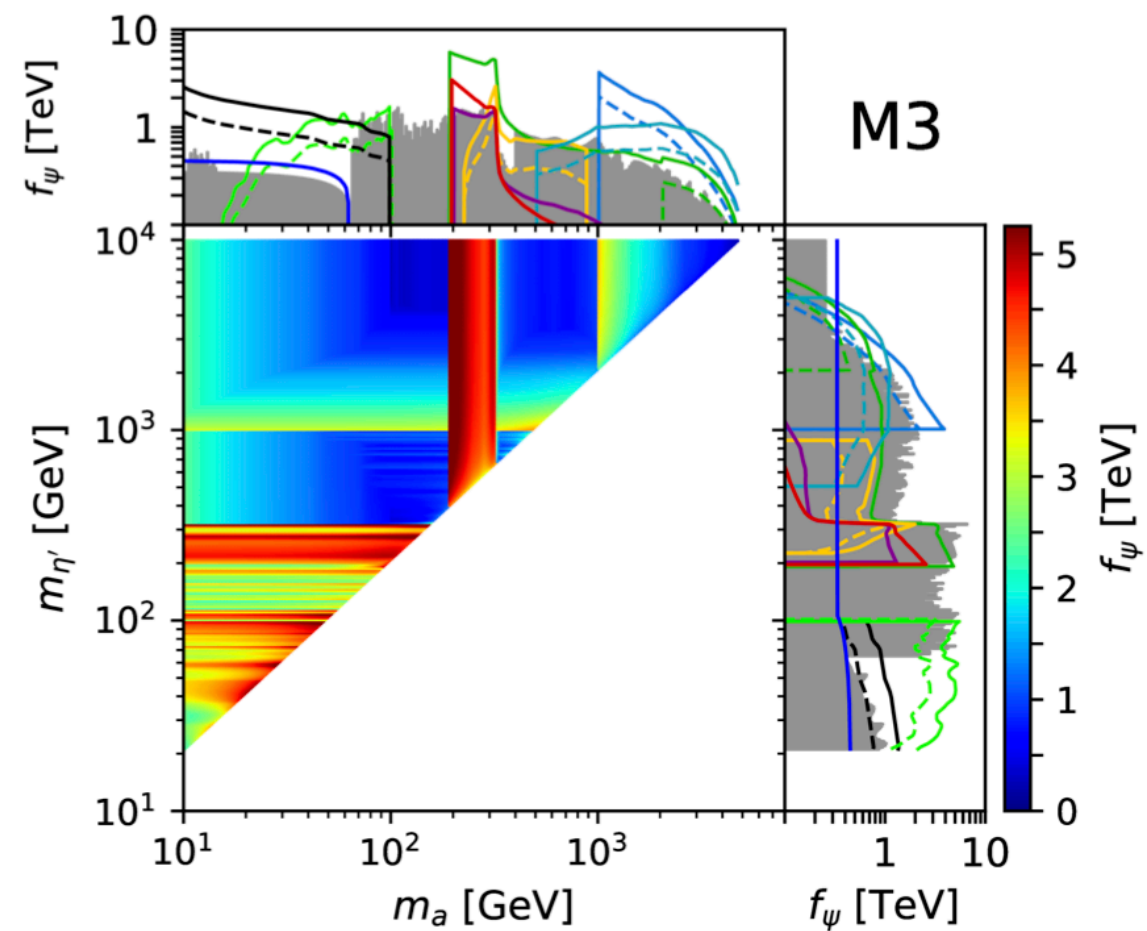
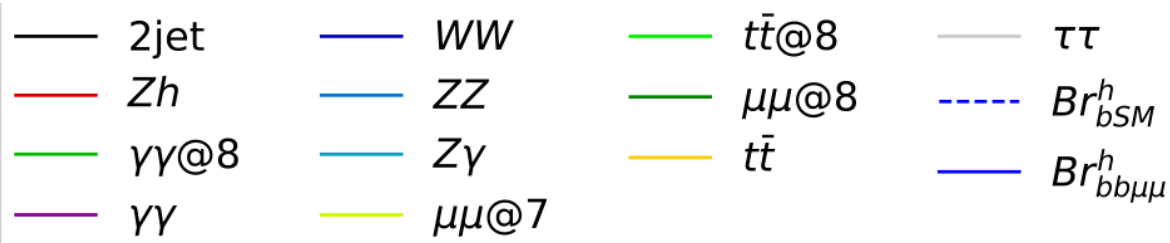
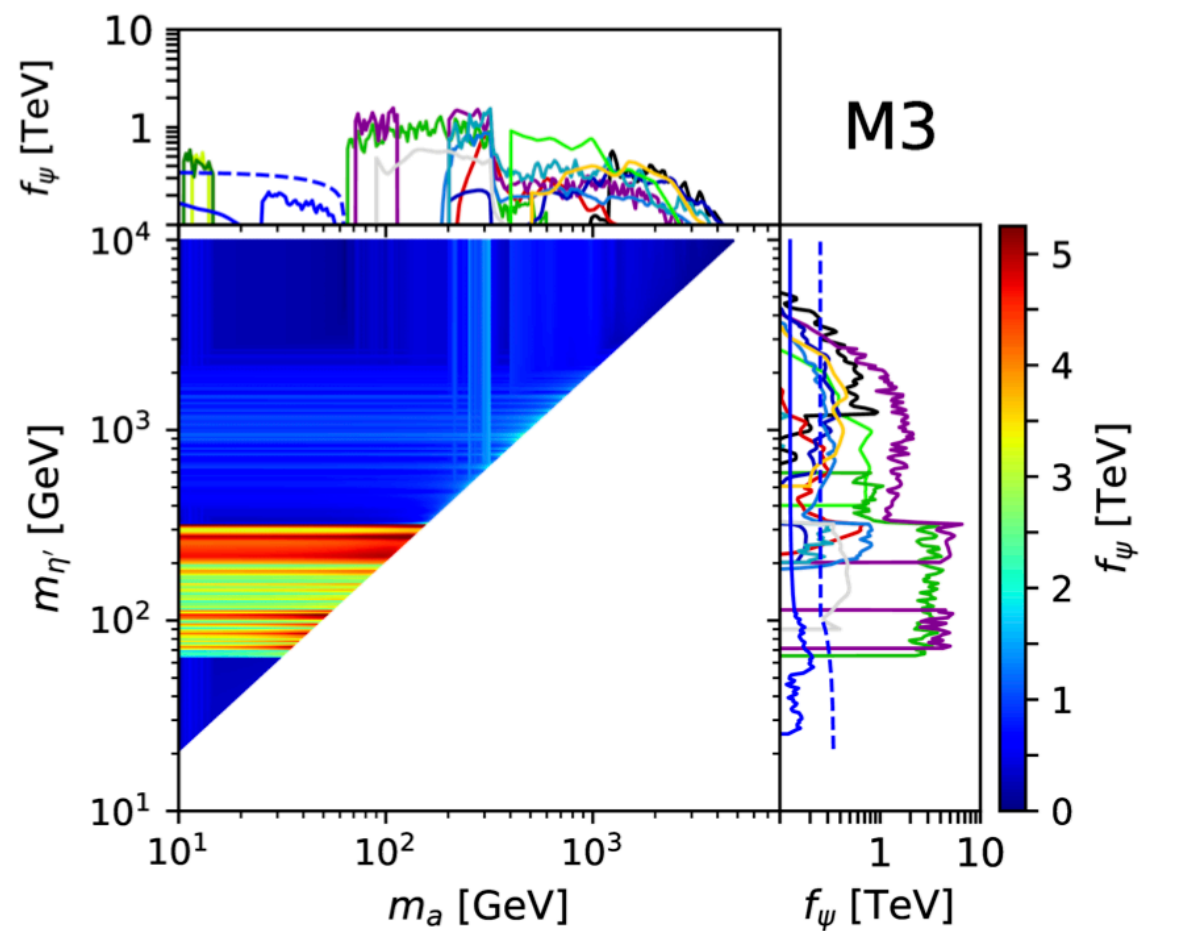
Conclusions

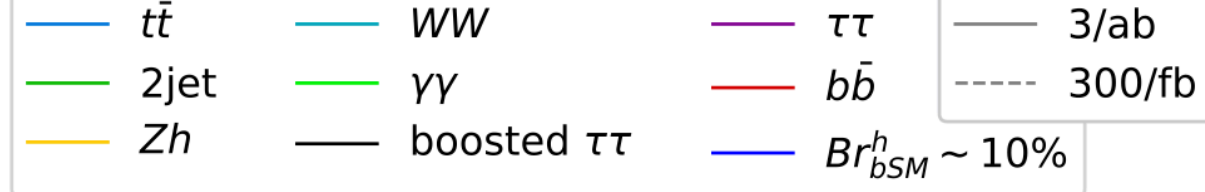
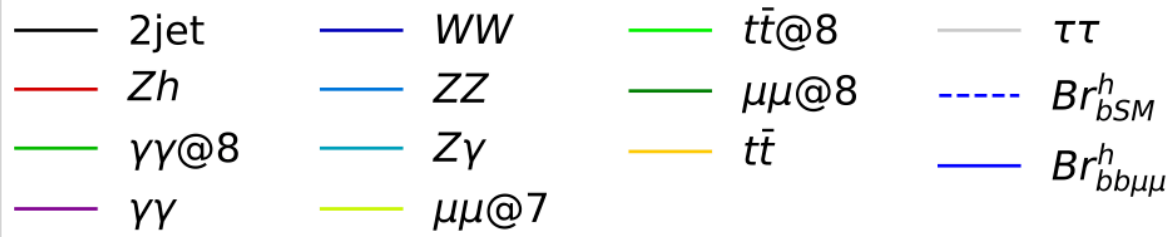
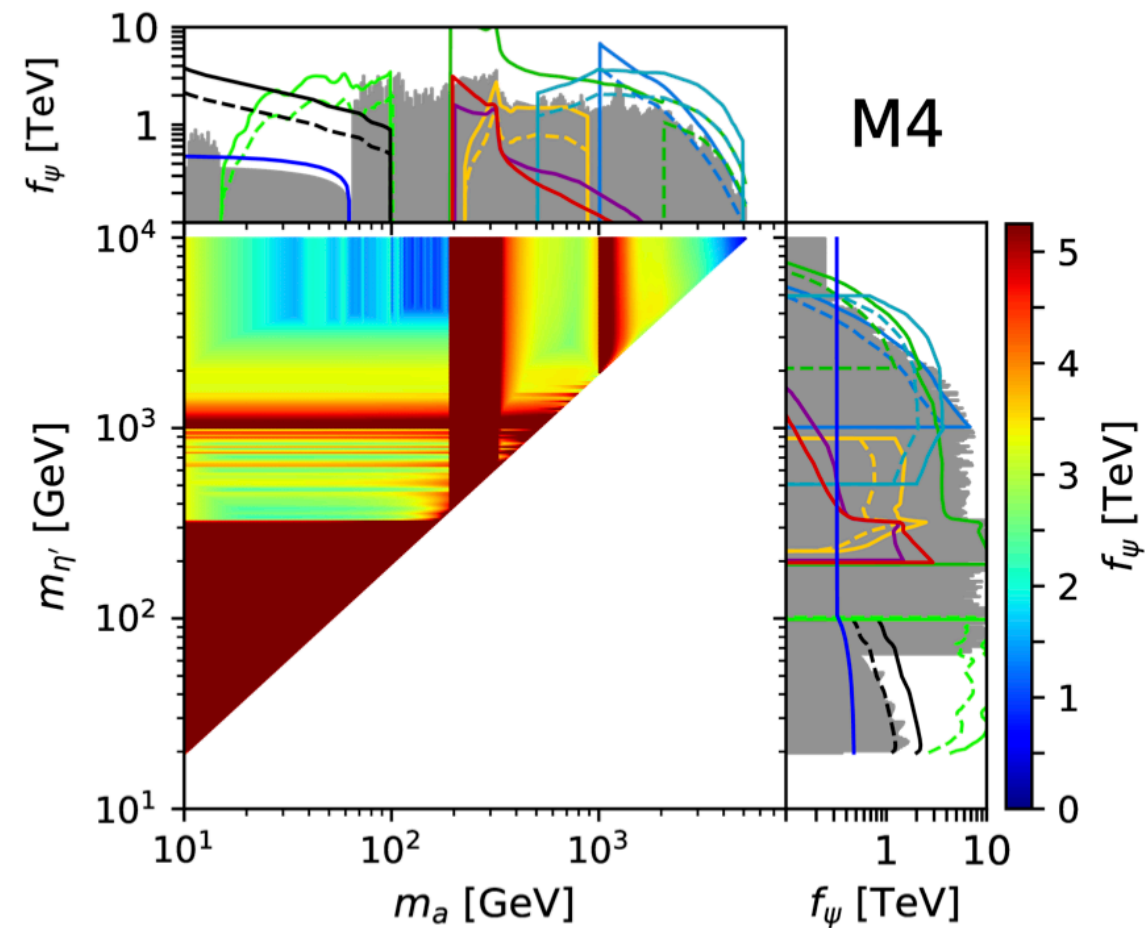
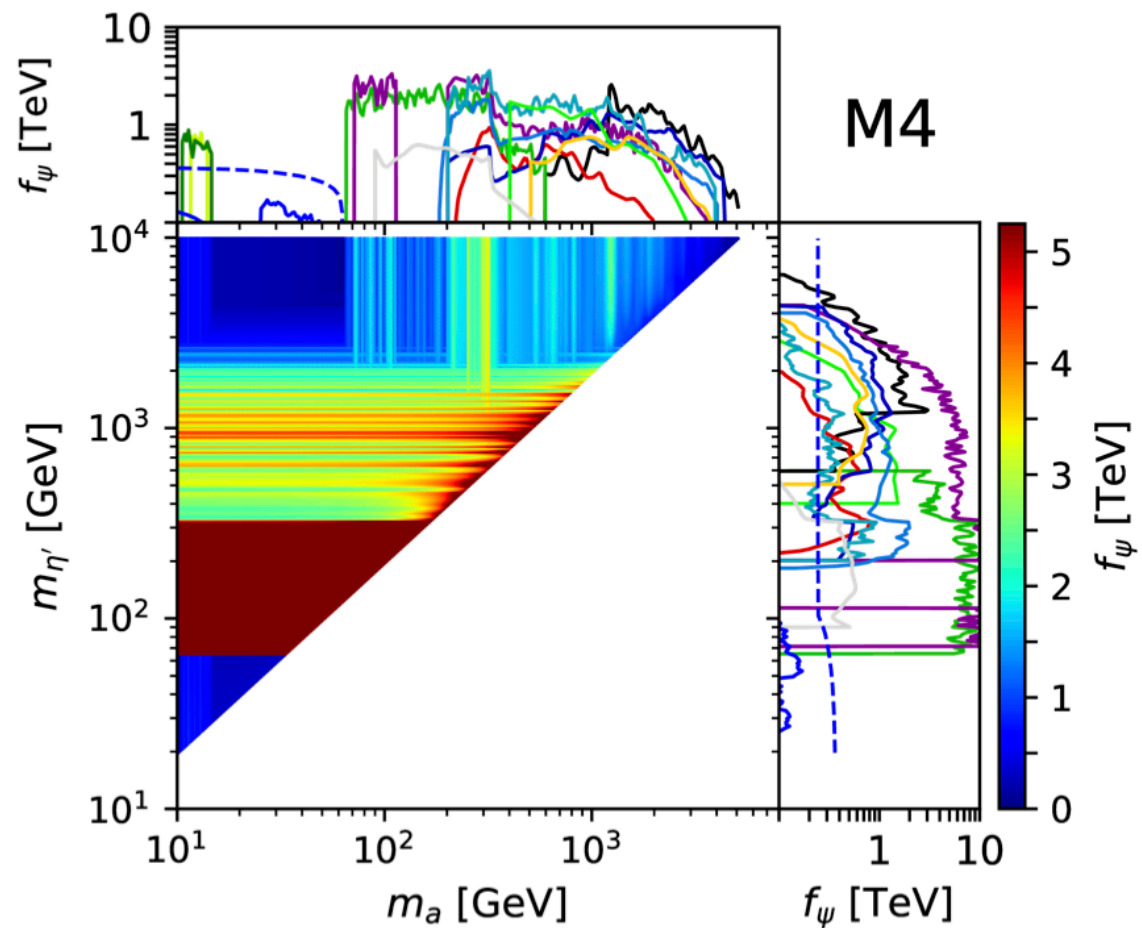
- Composite Higgs models provide a viable solution to the hierarchy problem but they still provide many challenges and room for exploration in theory and model-building.
- Light pNGBs as motivated from CH UV embeddings (neutral, charged and colored) are being tested by the LHC, but not in all relevant channels, are they are far from being ruled out. We only start to explore the interesting parameter space.
- ‘Exotic’ decays of top partners to $t/b + \text{pNGBs}$ 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 $T \rightarrow t a$ with $a \rightarrow gg$ or $a \rightarrow bb$. For these decays (especially for $T \rightarrow t a \rightarrow t g g$), bounds from existing searches on m_T are substantially weaker than for standard VLQ decays.

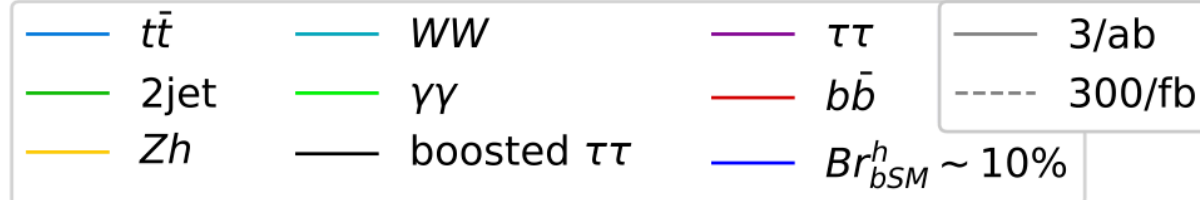
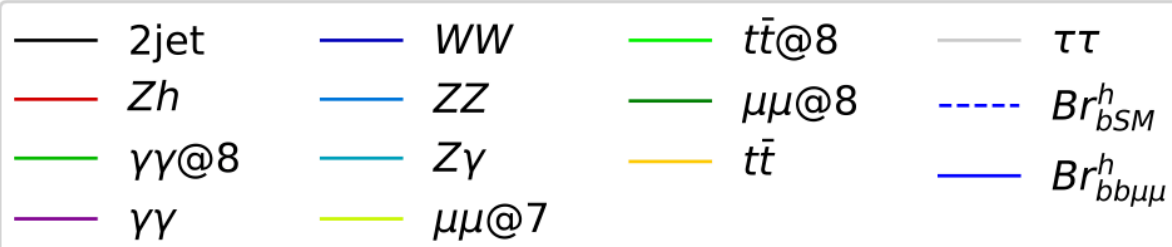
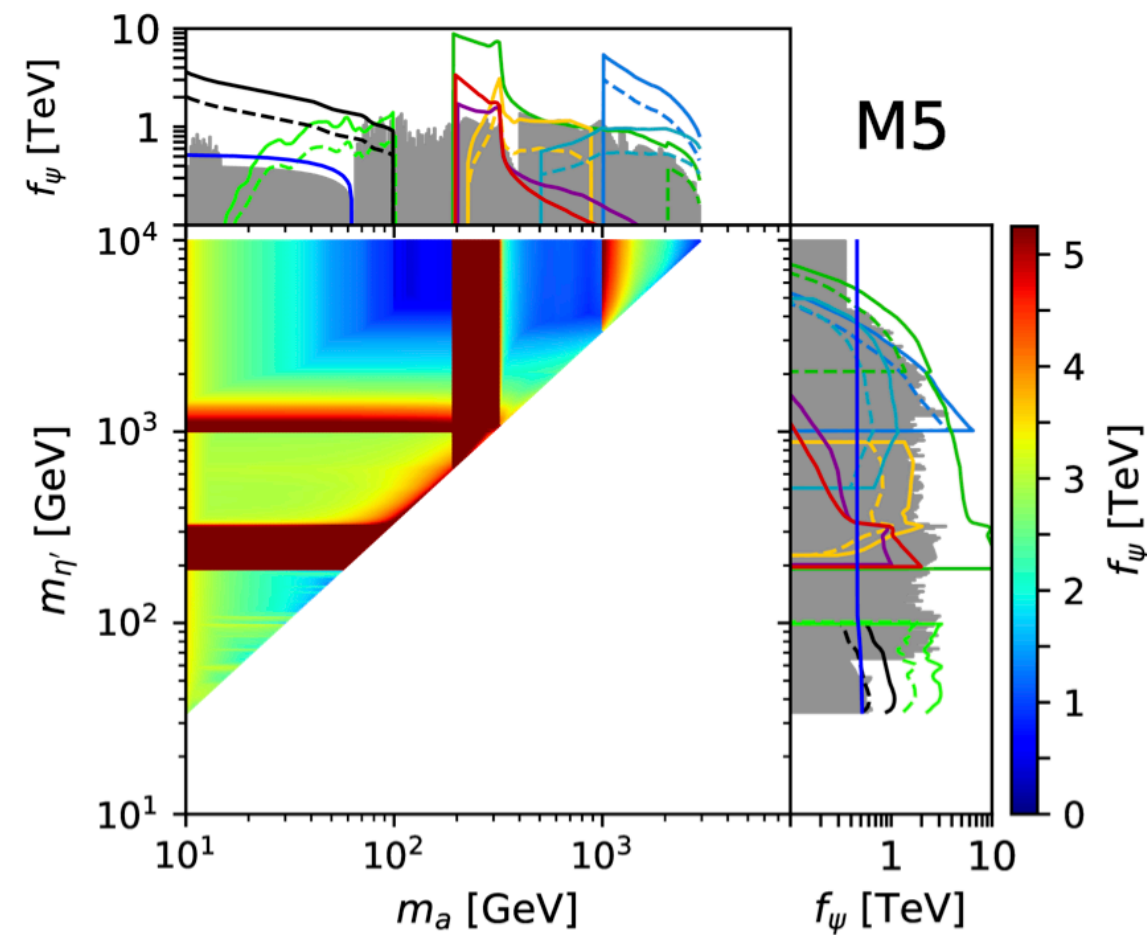
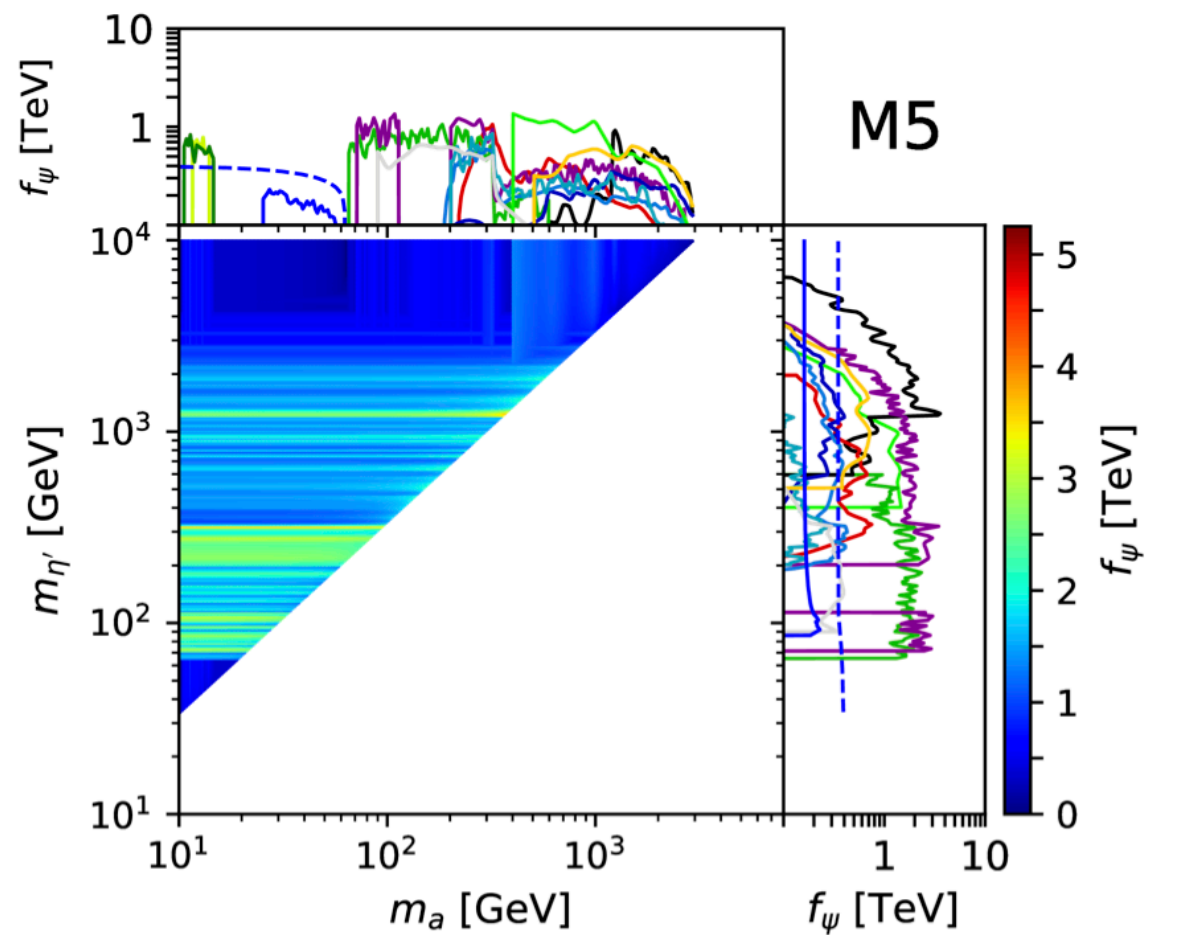
Backup

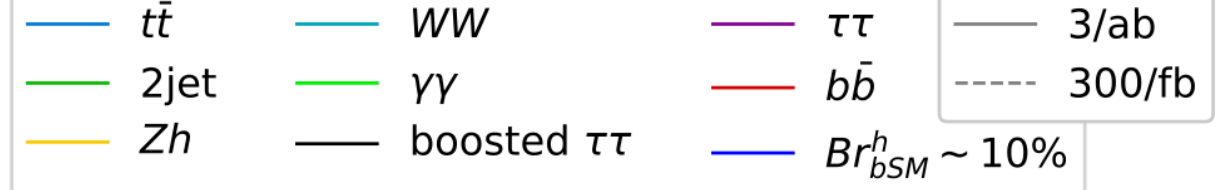
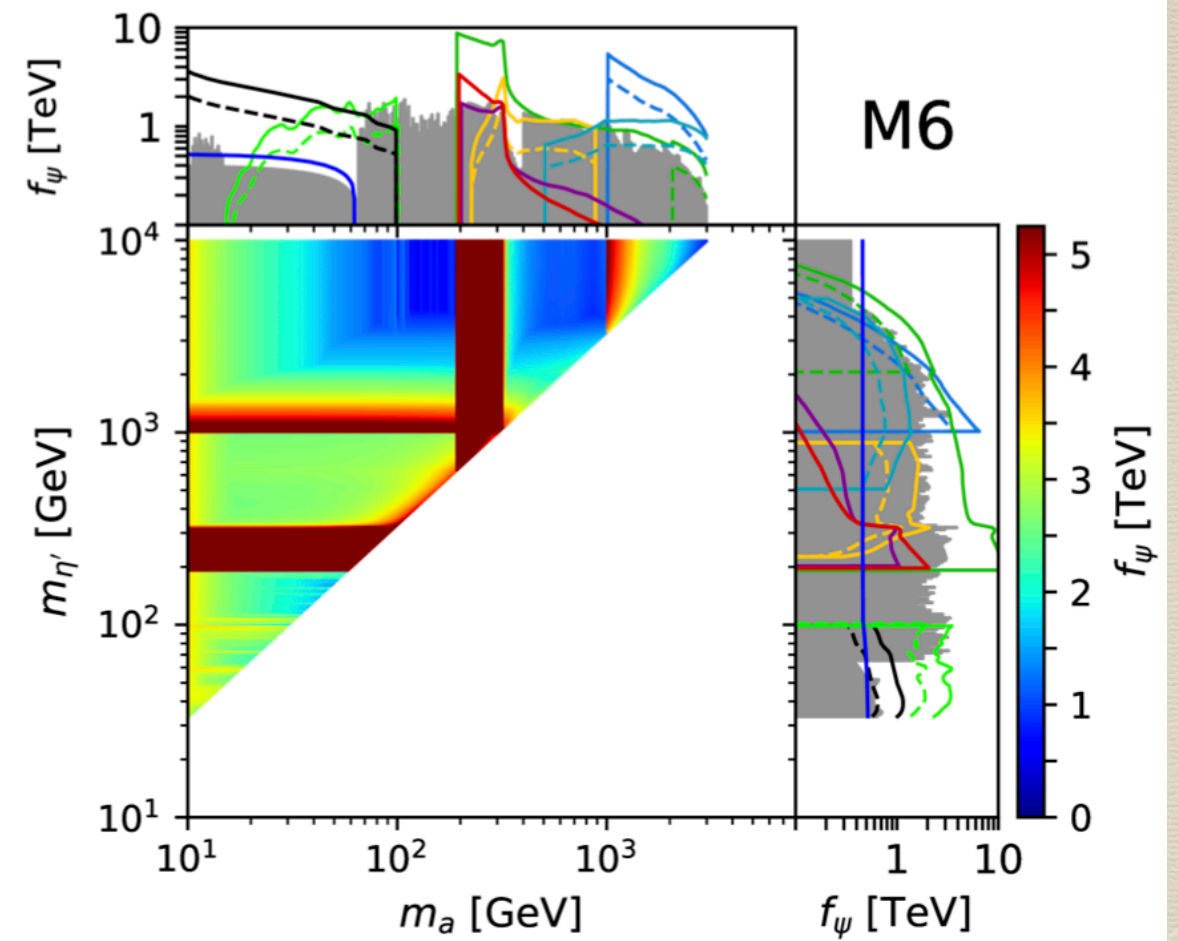
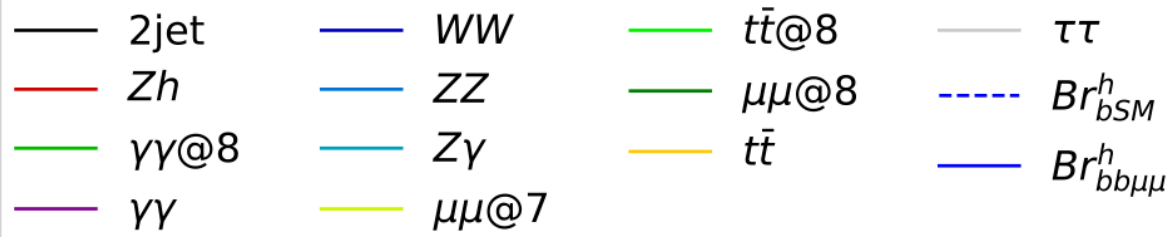
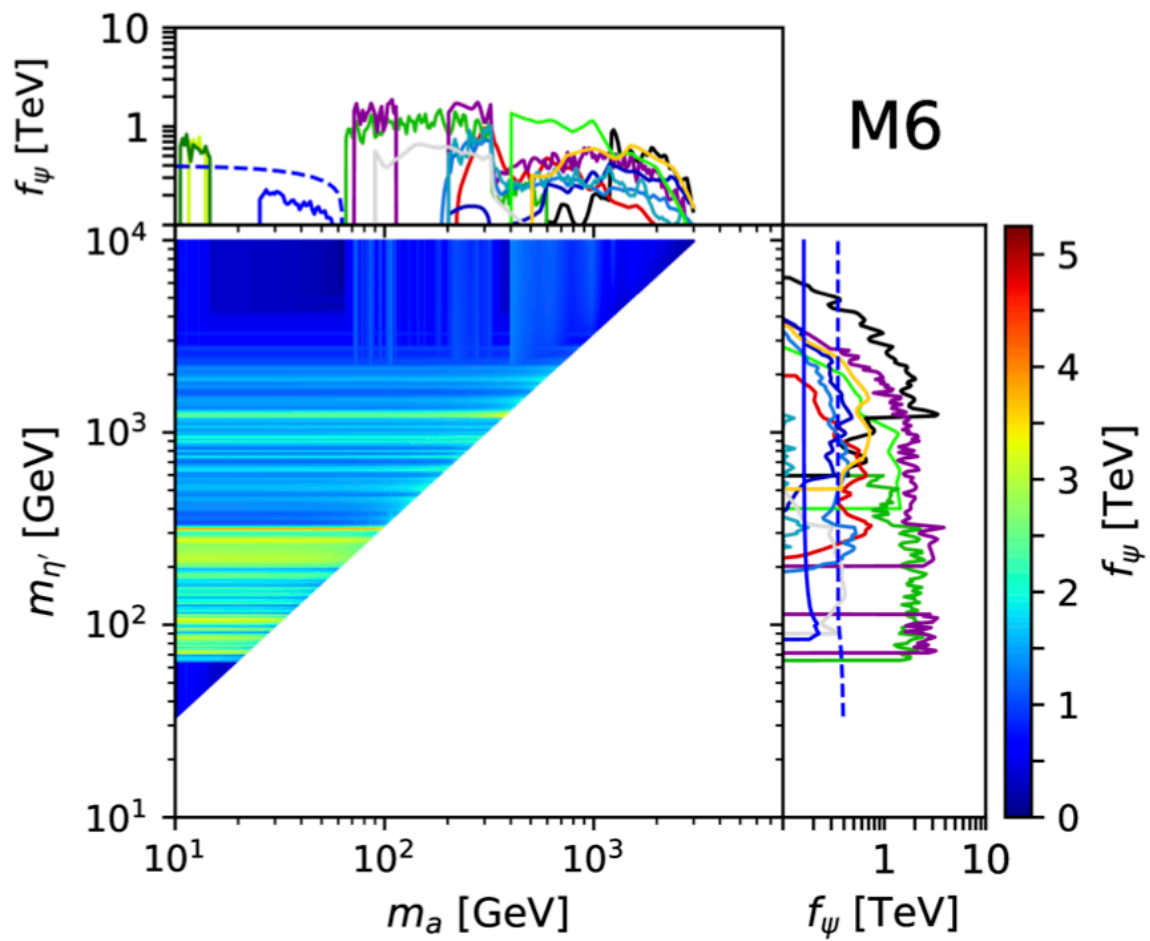


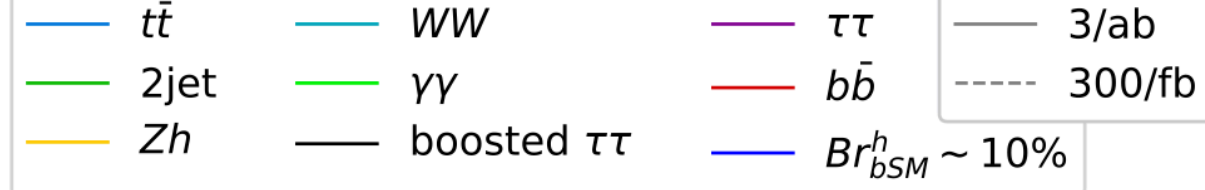
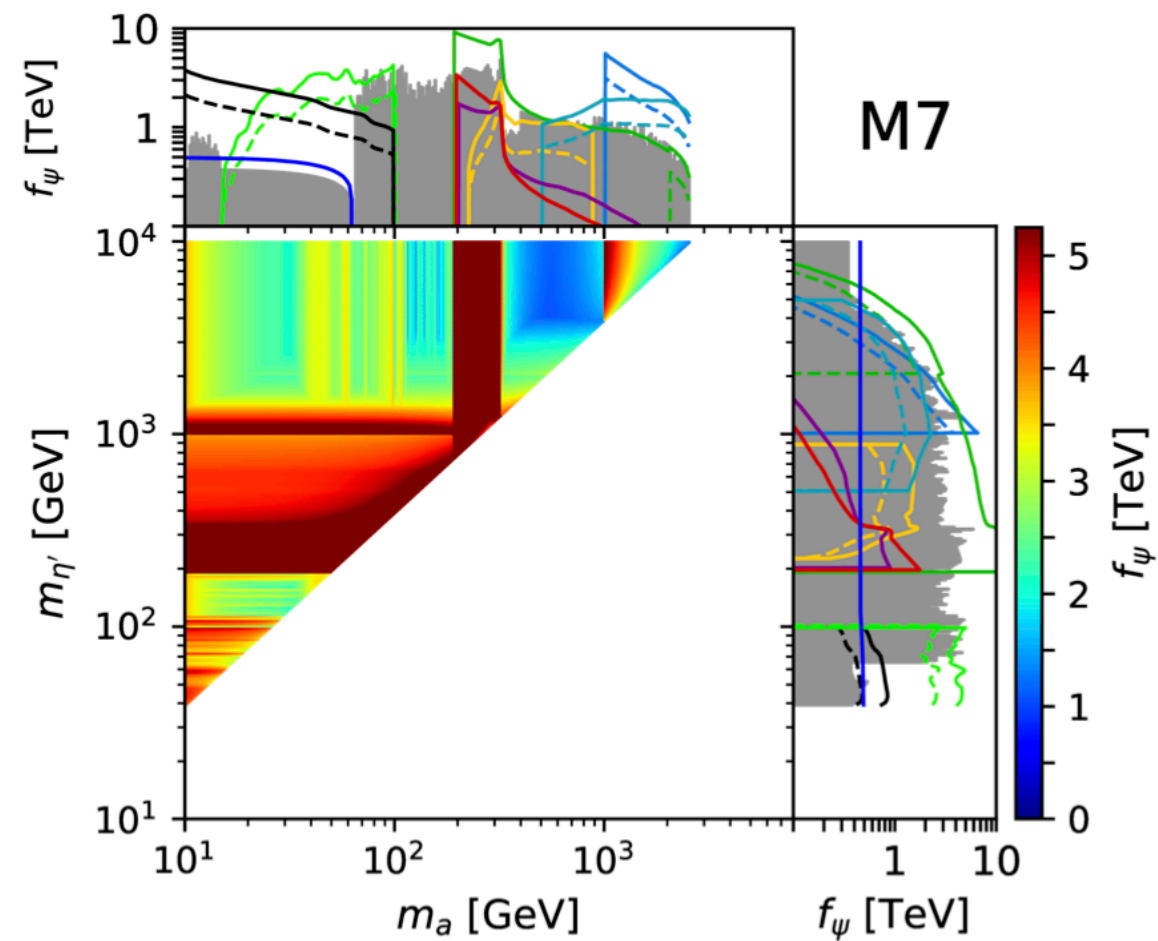
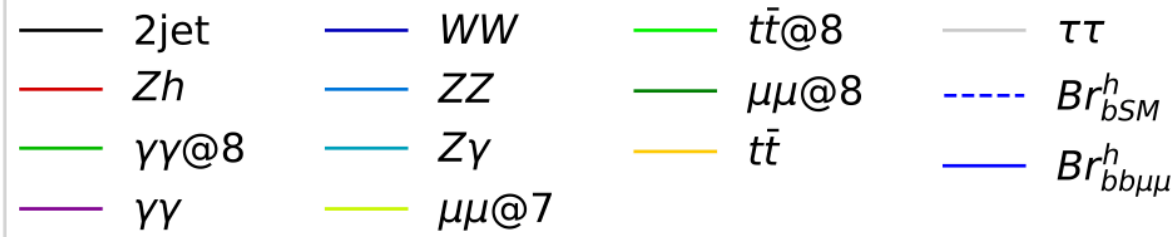
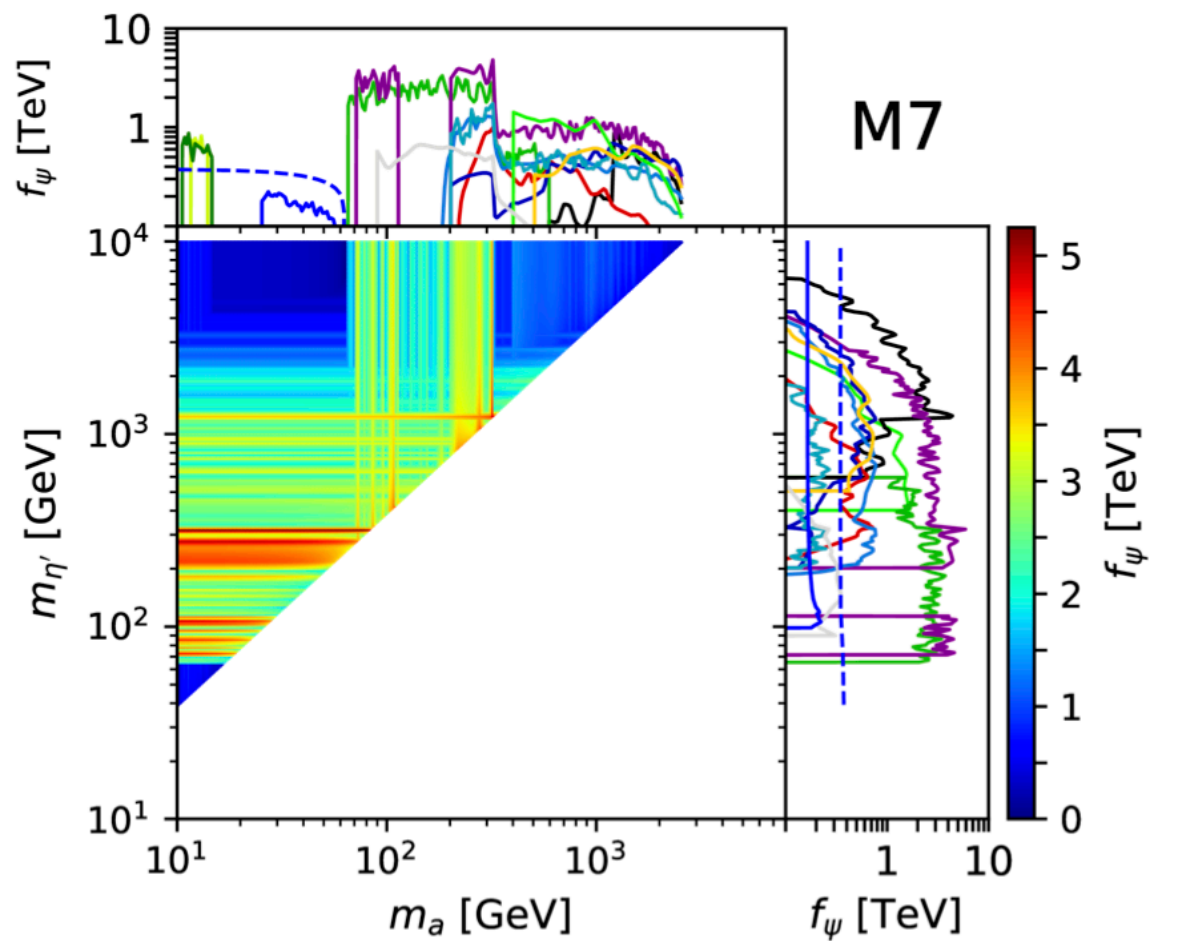


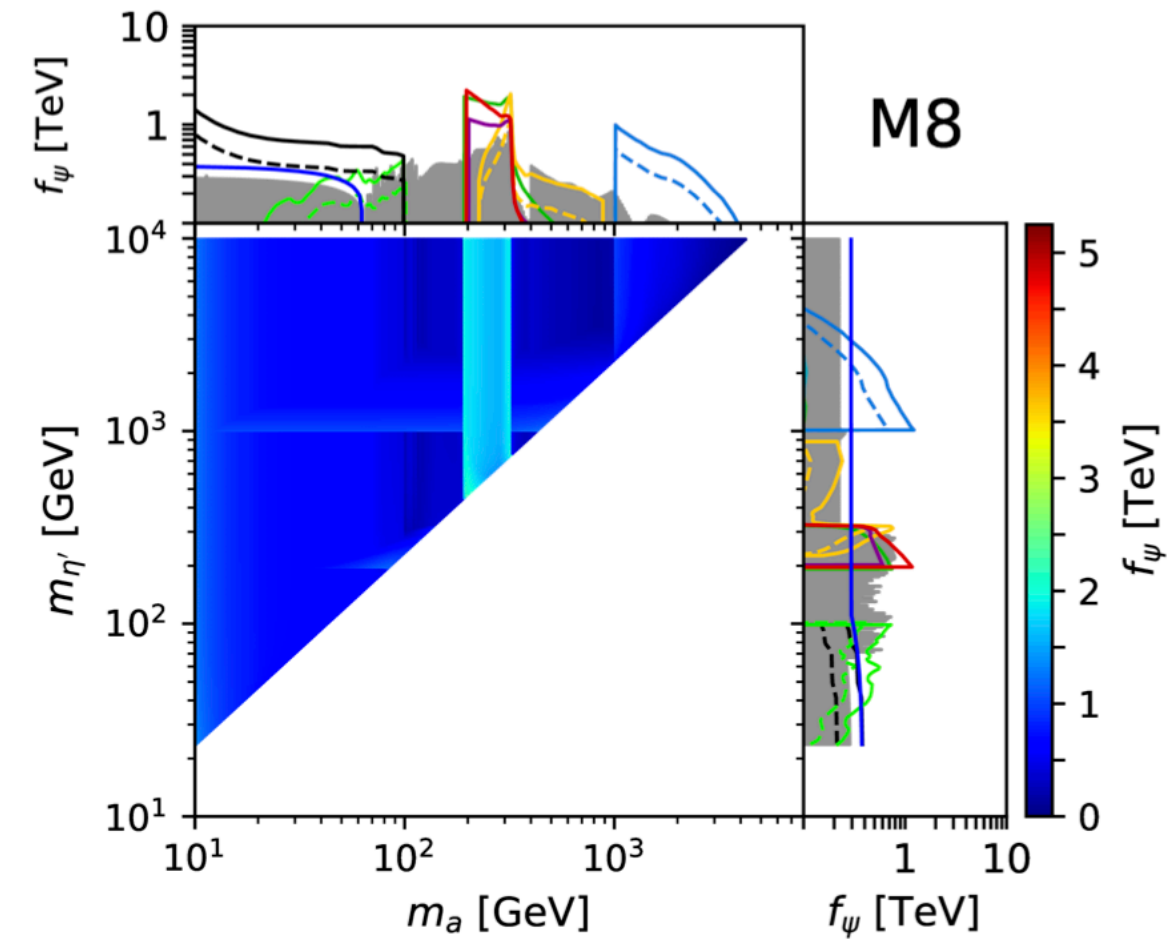
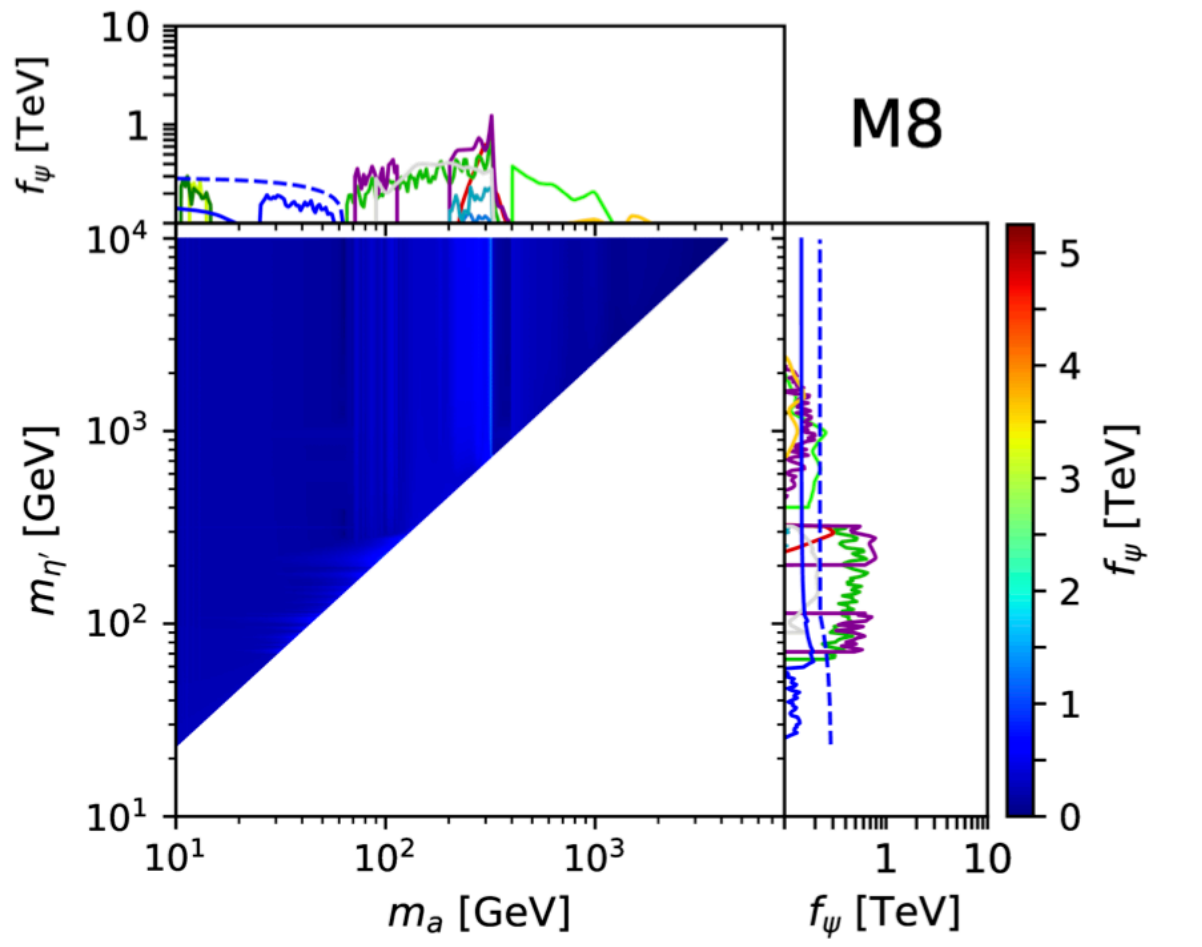






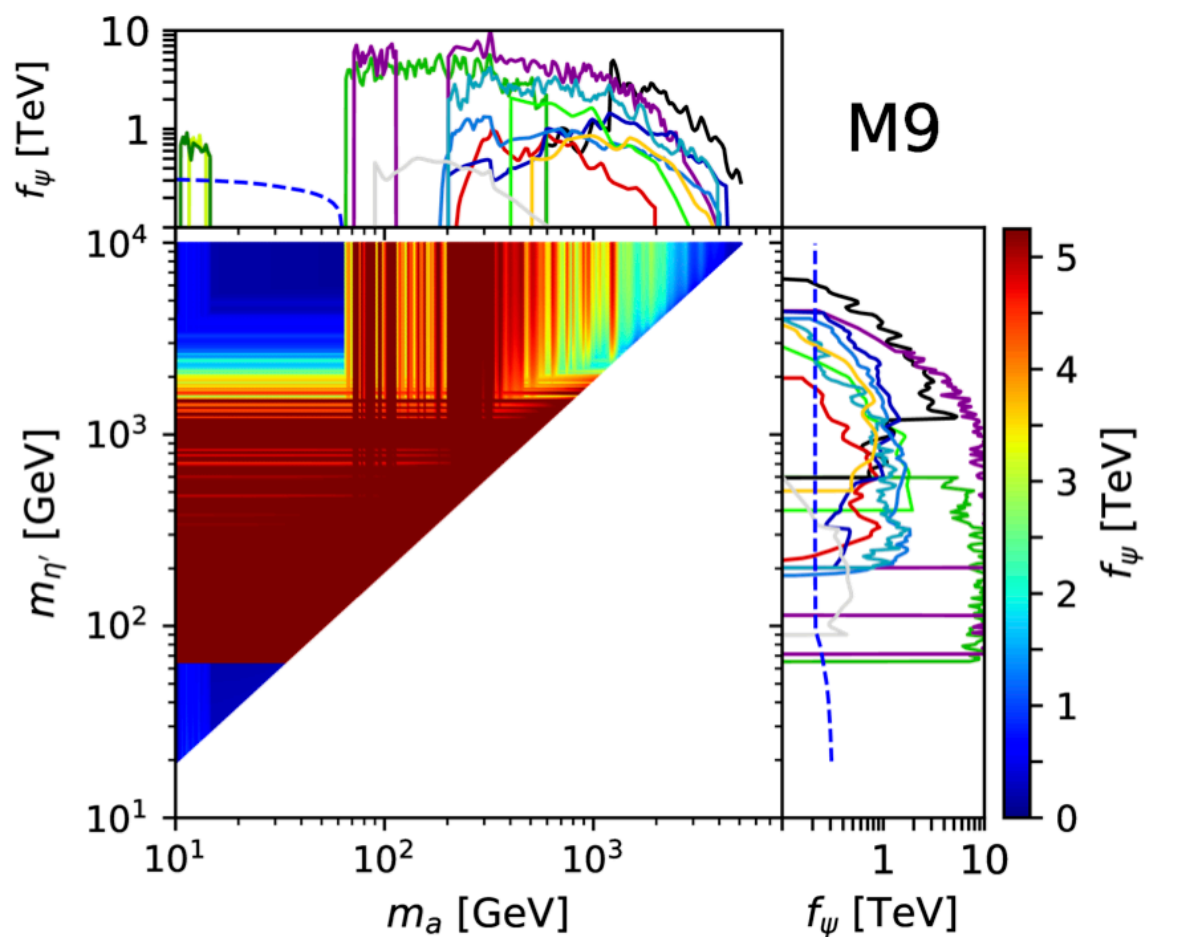




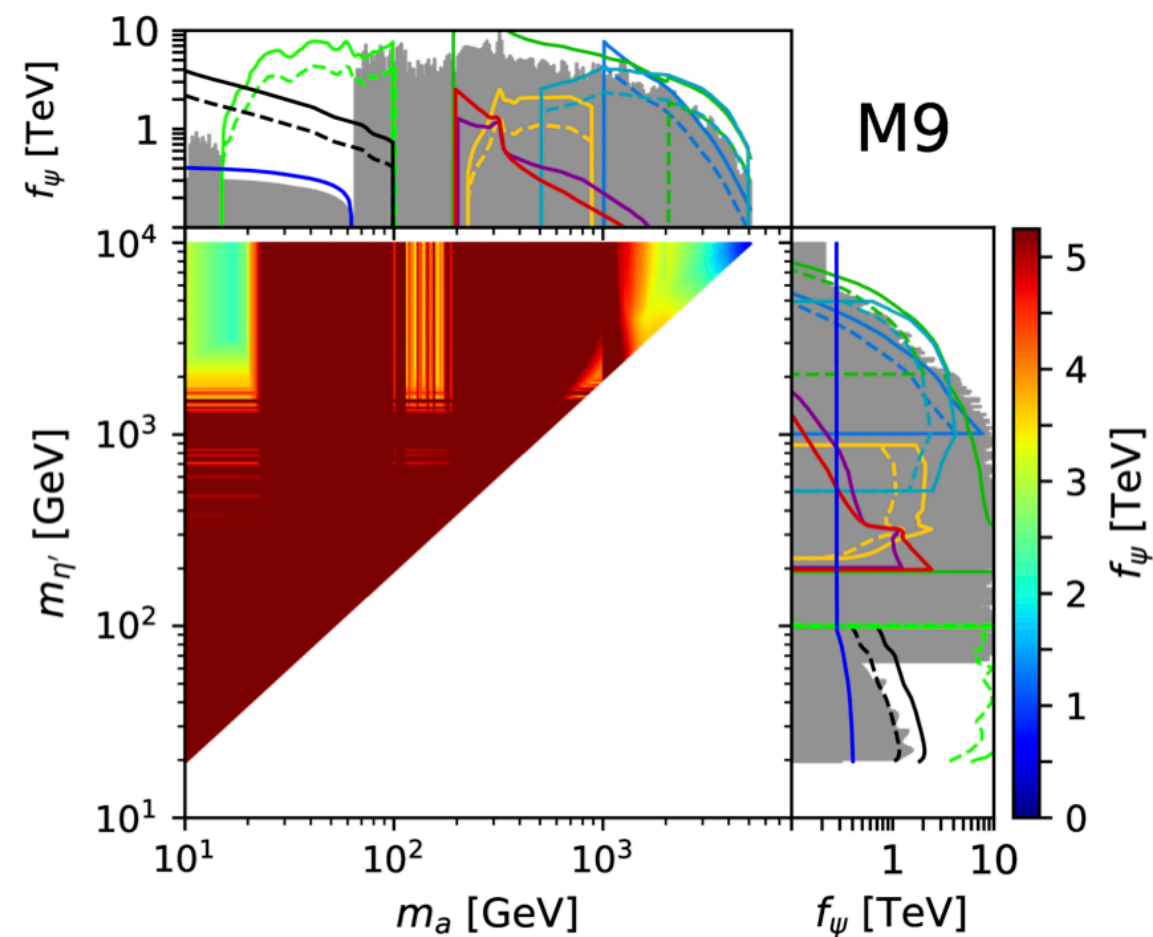


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|--------------------|--------------|----------------|---------------------|
| — 2jet | — WW | — $t\bar{t}@8$ | — $\tau\tau$ |
| — Zh | — ZZ | — $\mu\mu@8$ | - - - Br_{bSM}^h |
| — $\gamma\gamma@8$ | — $Z\gamma$ | — $t\bar{t}$ | — $Br_{bb\mu\mu}^h$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

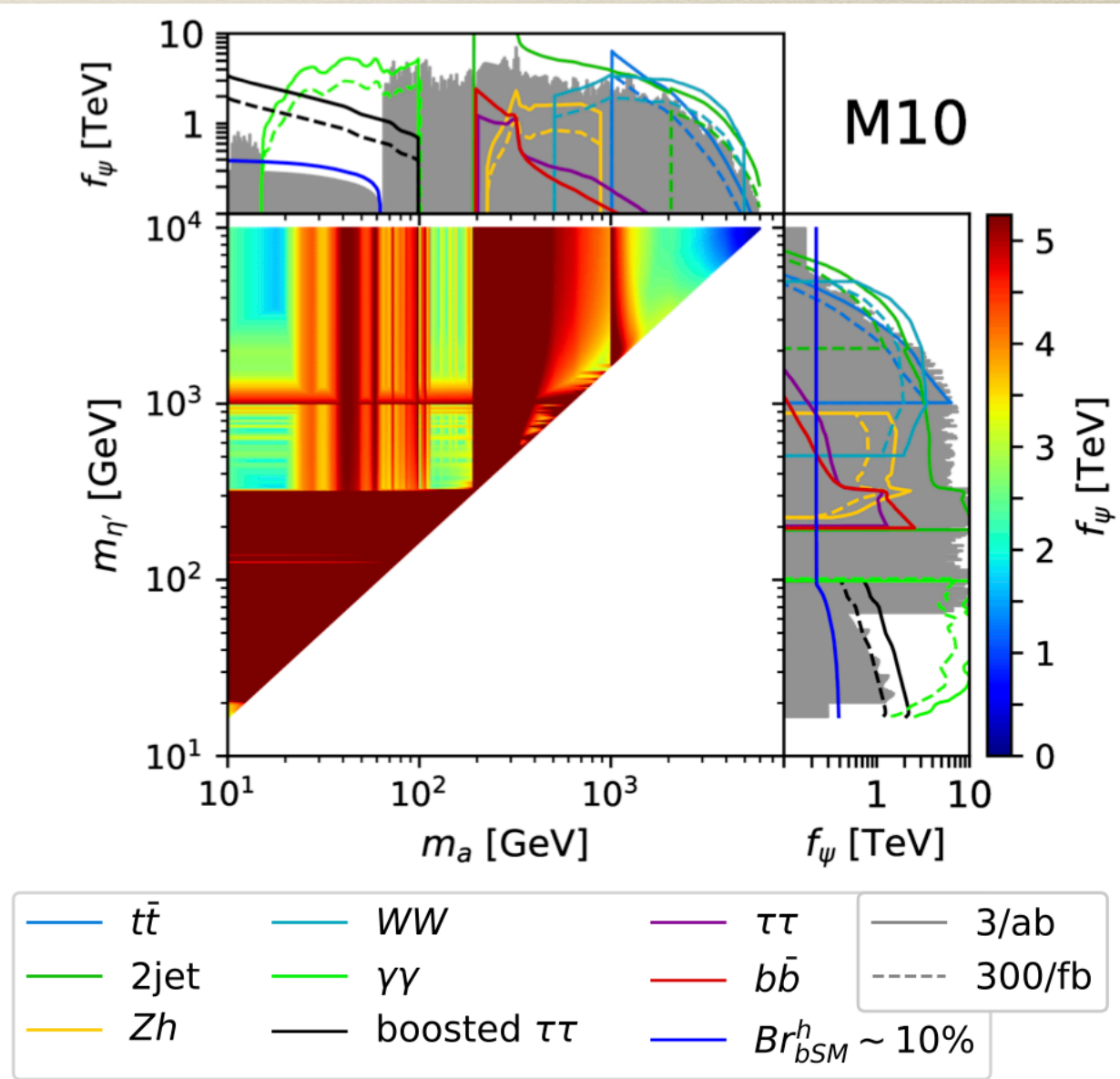
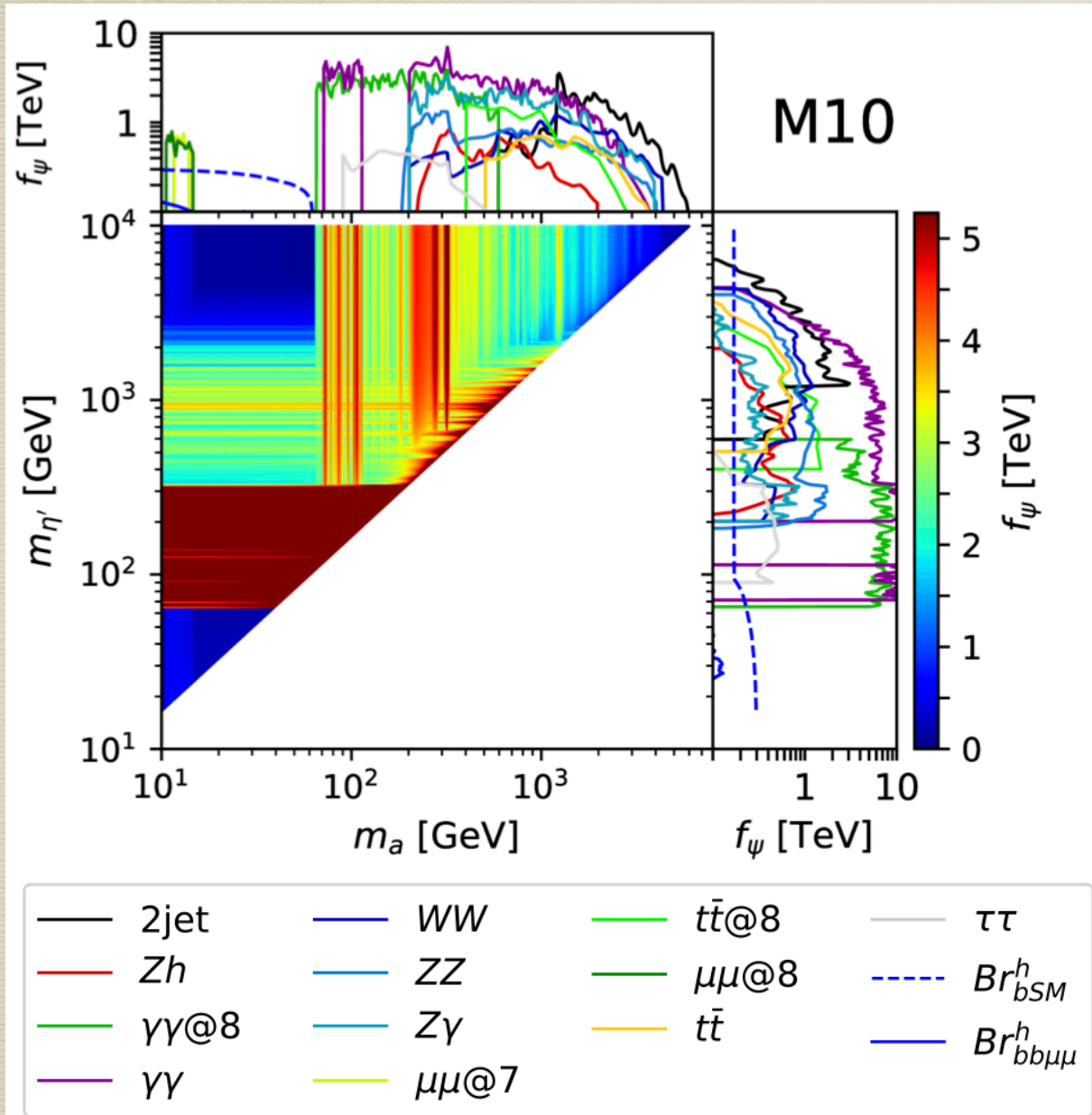
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|--------------|----------------------|--------------------------|--------------|
| — $t\bar{t}$ | — WW | — $\tau\tau$ | — $3/ab$ |
| — 2jet | — $\gamma\gamma$ | — $b\bar{b}$ | - - - 300/fb |
| — Zh | — boosted $\tau\tau$ | — $Br_{bSM}^h \sim 10\%$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

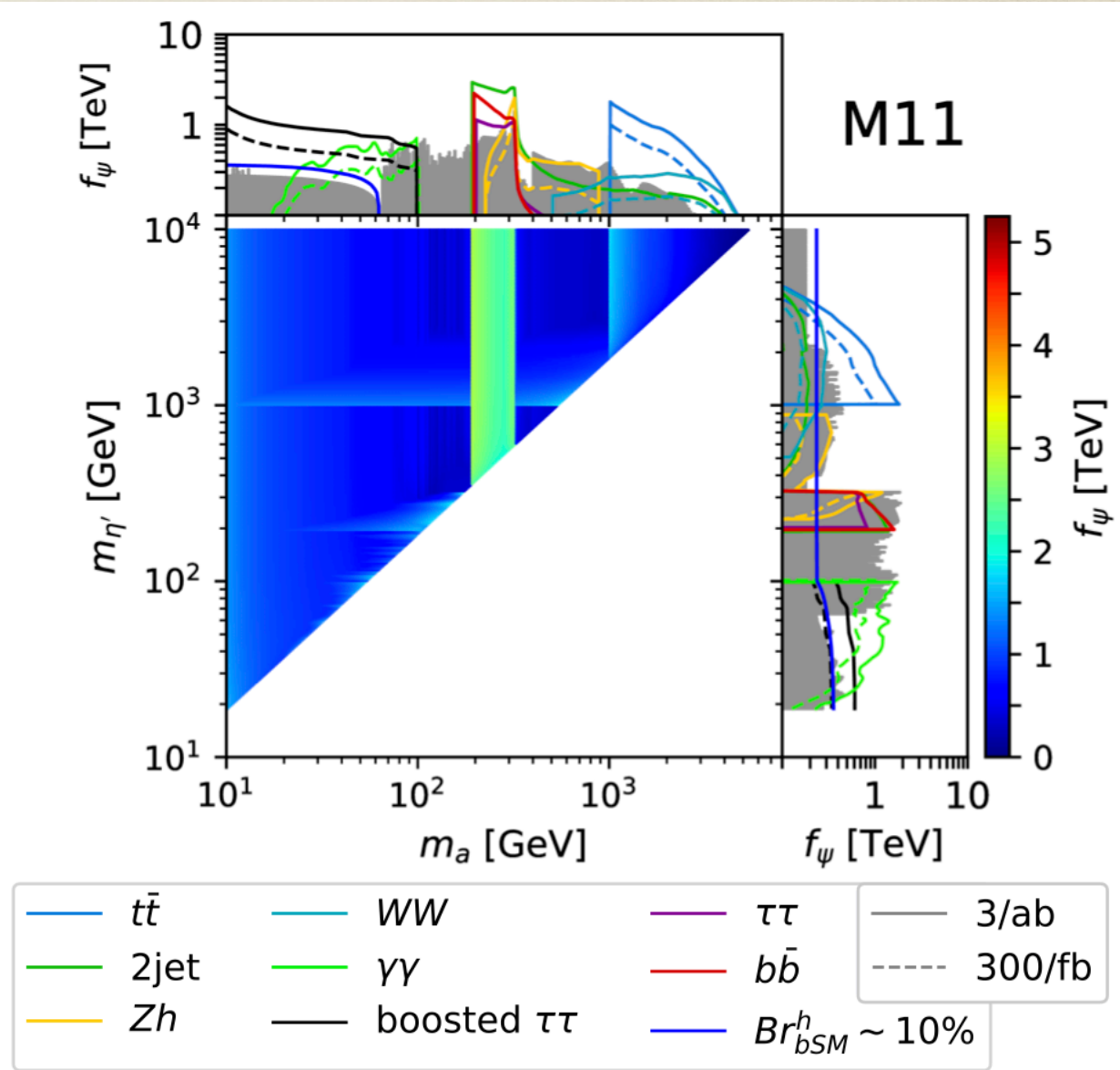
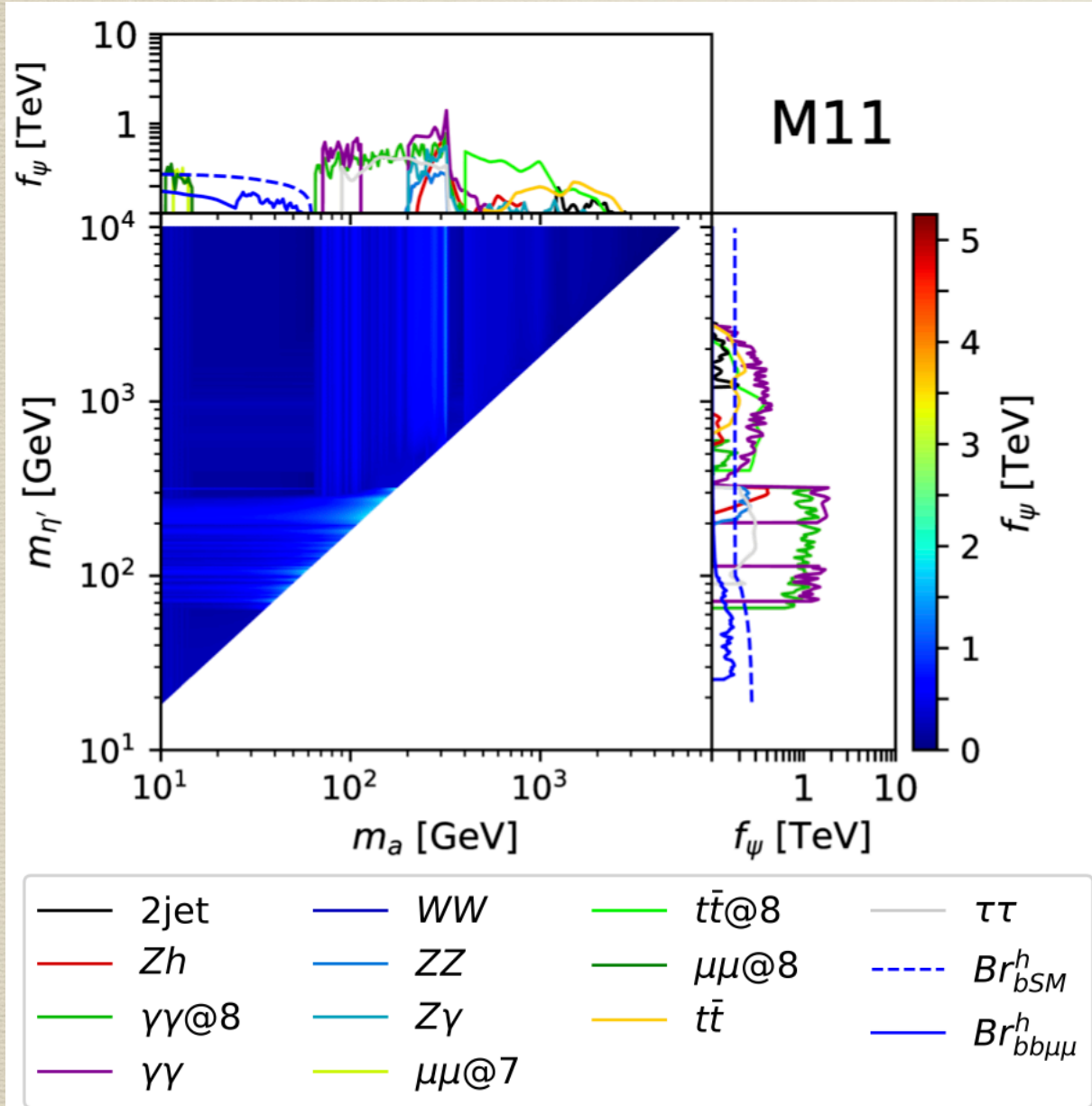


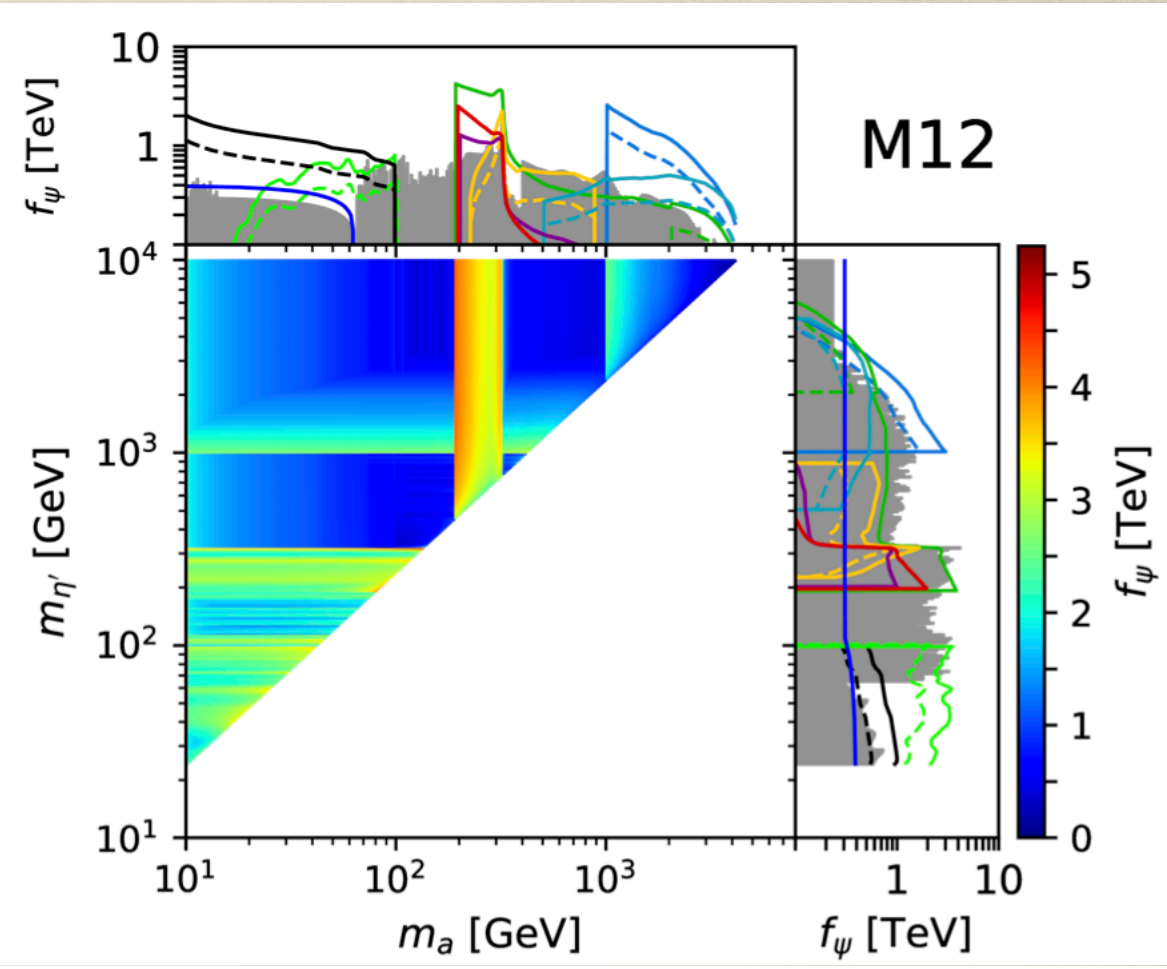
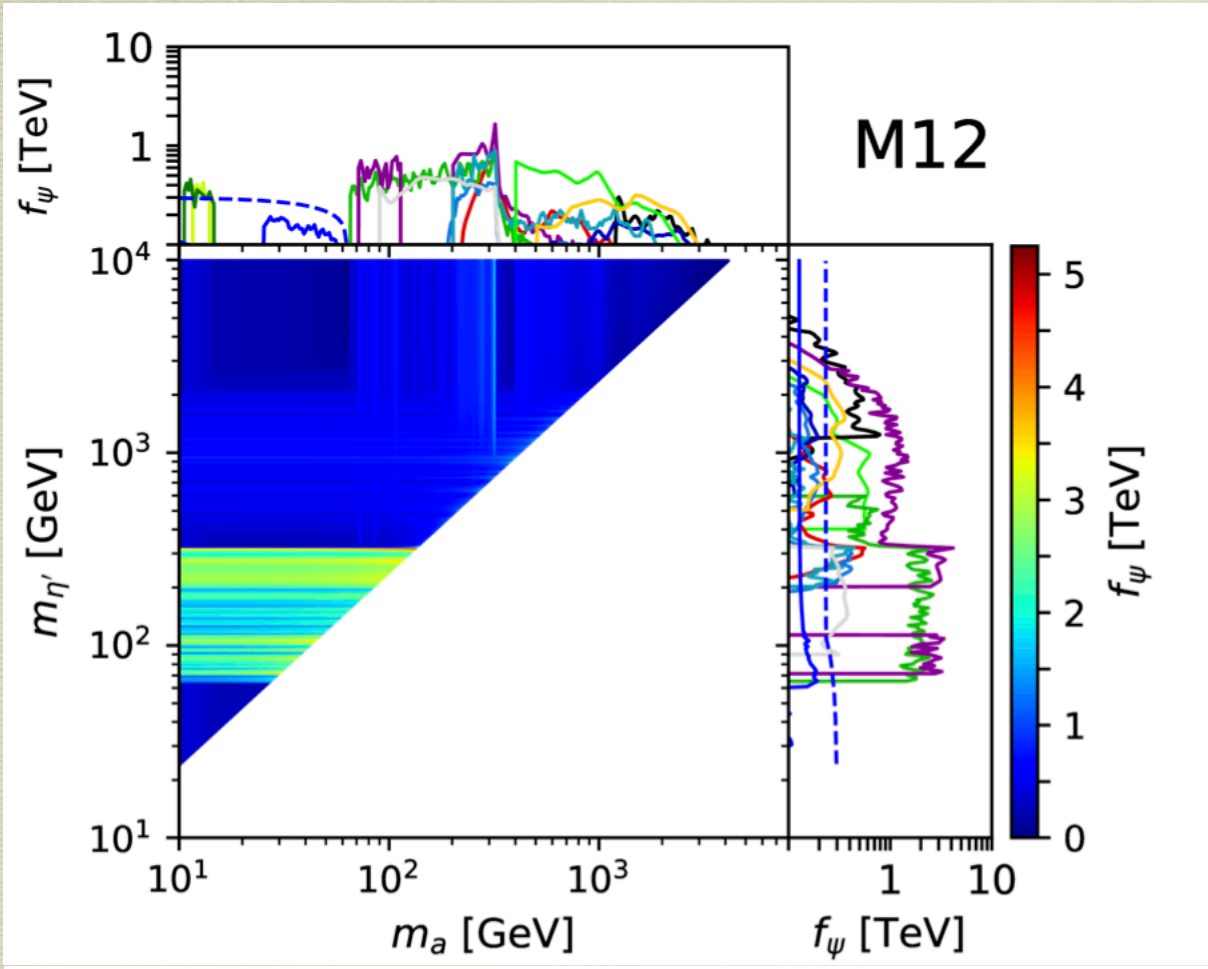
- | | | | |
|--------------------|--------------|----------------|---------------------|
| — 2jet | — WW | — $t\bar{t}@8$ | — $\tau\tau$ |
| — Zh | — ZZ | — $\mu\mu@8$ | - - - Br_{bSM}^h |
| — $\gamma\gamma@8$ | — $Z\gamma$ | — $t\bar{t}$ | — $Br_{bb\mu\mu}^h$ |
| — $\gamma\gamma$ | — $\mu\mu@7$ | |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



- | | | | |
|--------------|----------------------|--------------------------|--------------|
| — $t\bar{t}$ | — WW | — $\tau\tau$ | — 3/ab |
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- | | | | |
|--------------------|--------------|----------------|---------------------|
| — 2jet | — WW | — $t\bar{t}@8$ | — $\tau\tau$ |
| — Zh | — ZZ | — $\mu\mu@8$ | - - - Br_{bSM}^h |
| — $\gamma\gamma@8$ | — Z γ | — $t\bar{t}$ | — $Br_{bb\mu\mu}^h$ |
| — $\gamma\gamma$ | — $\mu\mu@7$ | | |

- | | | | |
|--------------|----------------------|--------------------------|--------------|
| — $t\bar{t}$ | — WW | — $\tau\tau$ | — 3/ab |
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Common exotic VLQ decays

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

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

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

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

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

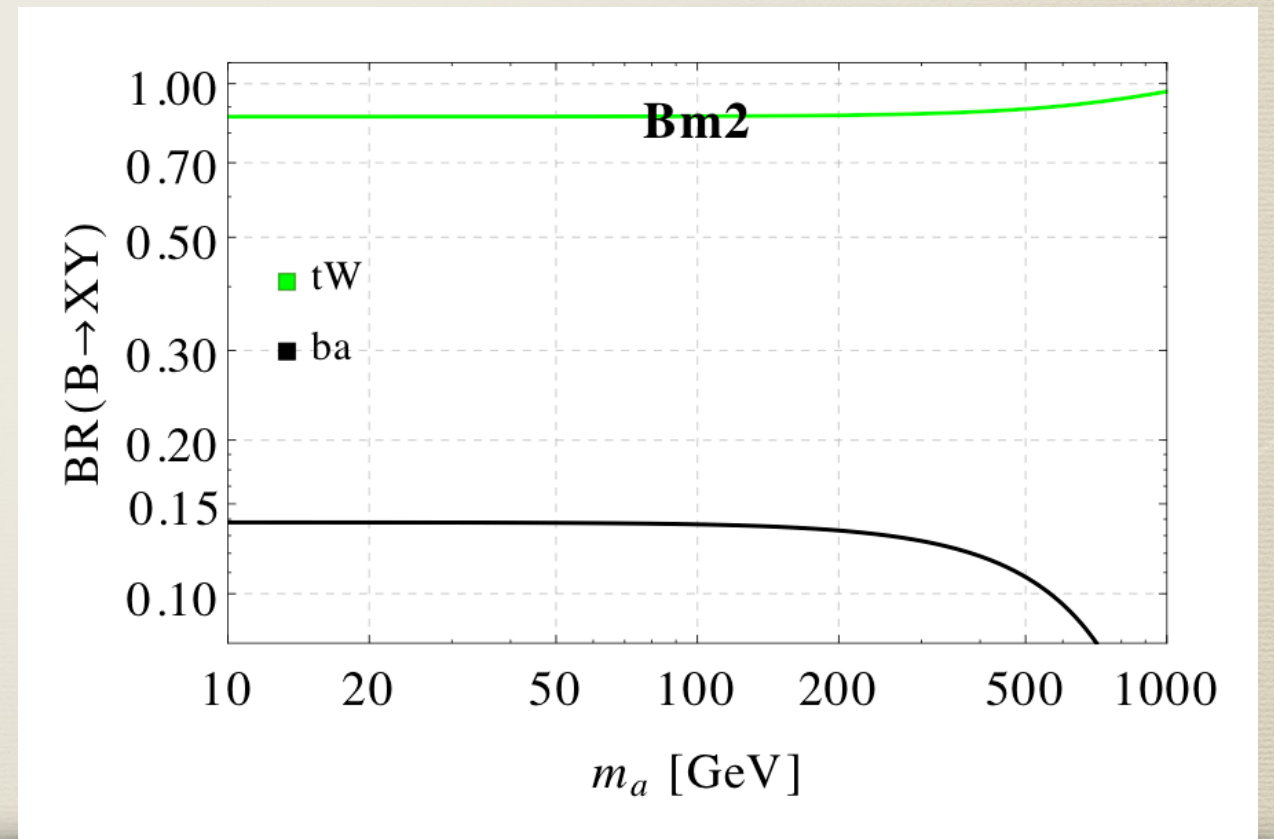
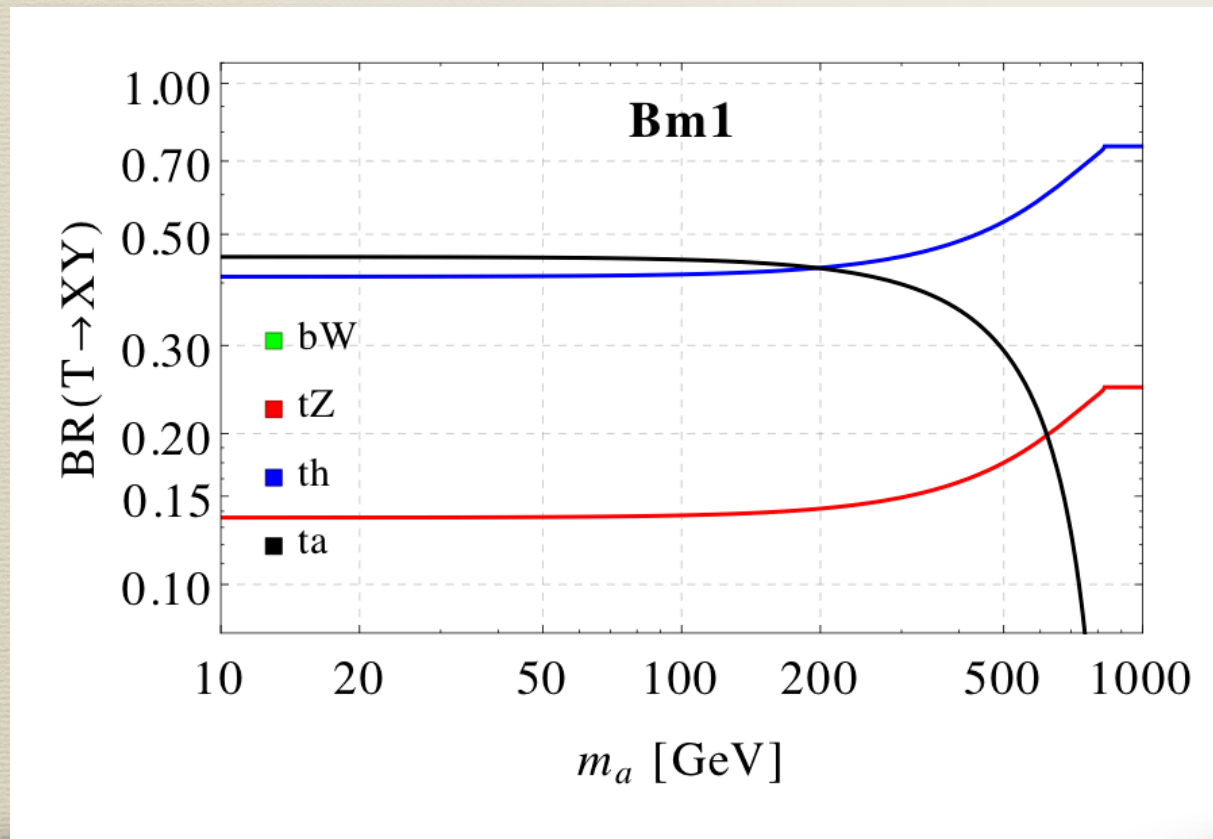
$$+ \frac{g_s^2 K_g a}{16\pi^2 f_a} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \frac{g^2 K_W a}{16\pi^2 f_a} W_{\mu\nu}^i \tilde{W}^{i\mu\nu} + \frac{g'^2 K_B a}{16\pi^2 f_a} B_{\mu\nu} \tilde{B}^{\mu\nu}$$

Common exotic VLQ decays

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

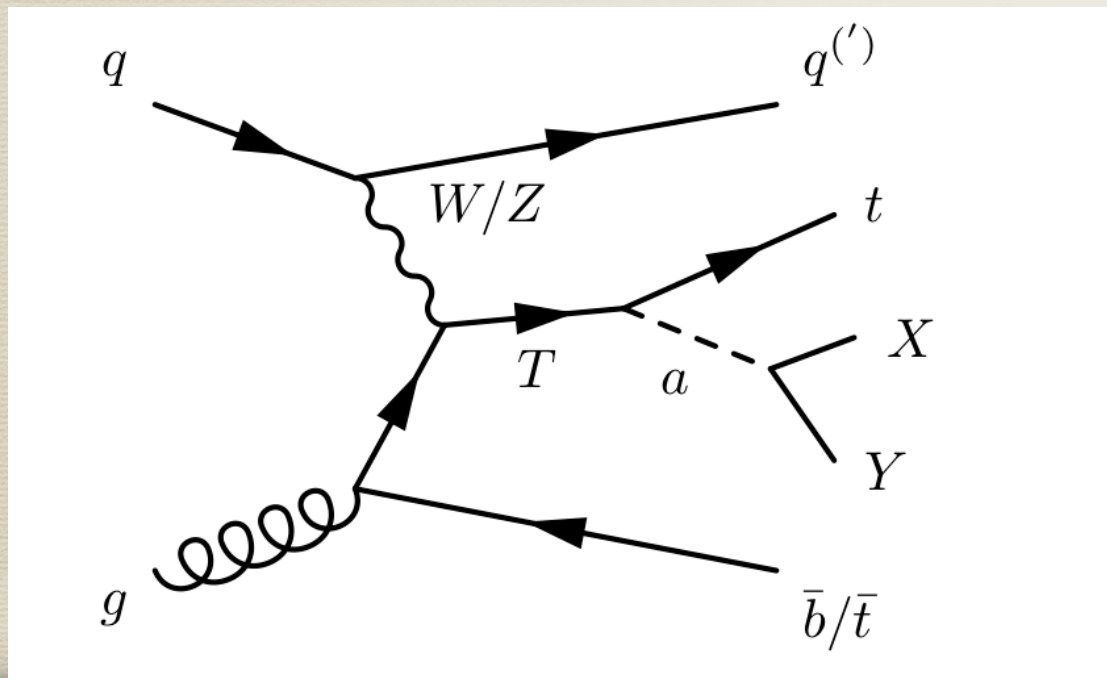
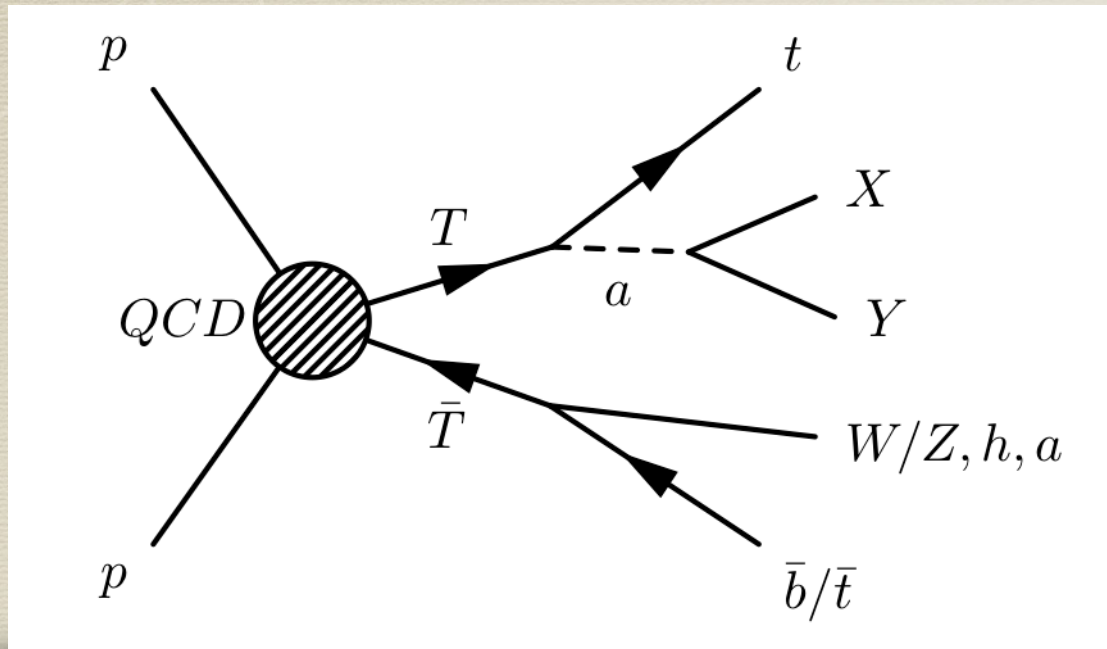
$$\begin{aligned} \text{Bm1 : } & M_T = 1 \text{ TeV , } \kappa_{Z,R}^T = -0.03 , \kappa_{h,R}^T = 0.06 , \kappa_{a,R}^T = -0.24 , \kappa_{a,L}^T = -0.07 ; \\ \text{Bm2 : } & M_B = 1.38 \text{ TeV , } \kappa_{W,L}^B = 0.02 , \kappa_{W,R}^B = -0.08 , \kappa_{a,L}^B = -0.25 , \end{aligned} \quad (2.3)$$

Branching ratios of quark partners to a in these benchmarks:

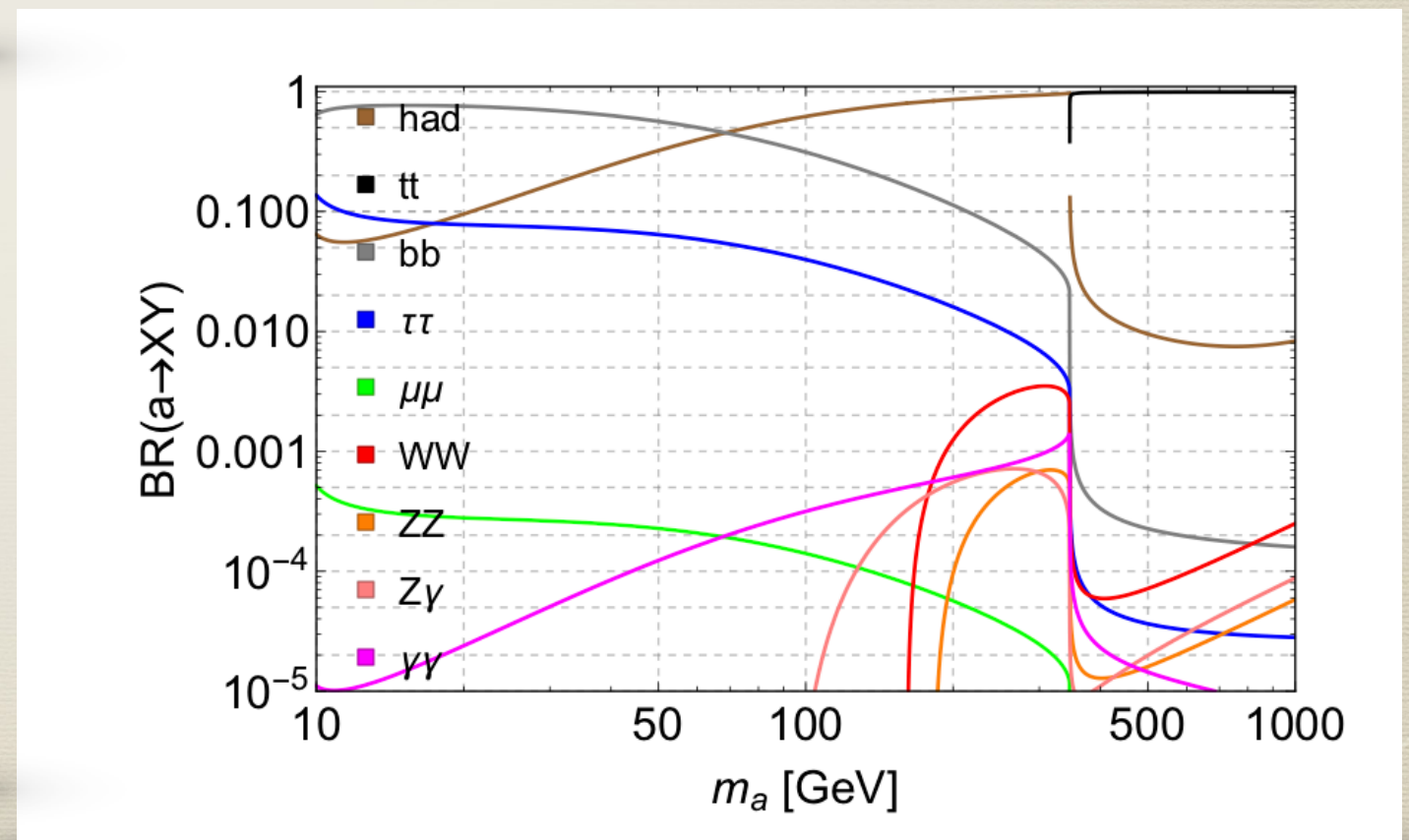


Common exotic VLQ decays

Examples of diagrams:



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



Common exotic VLQ decays

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

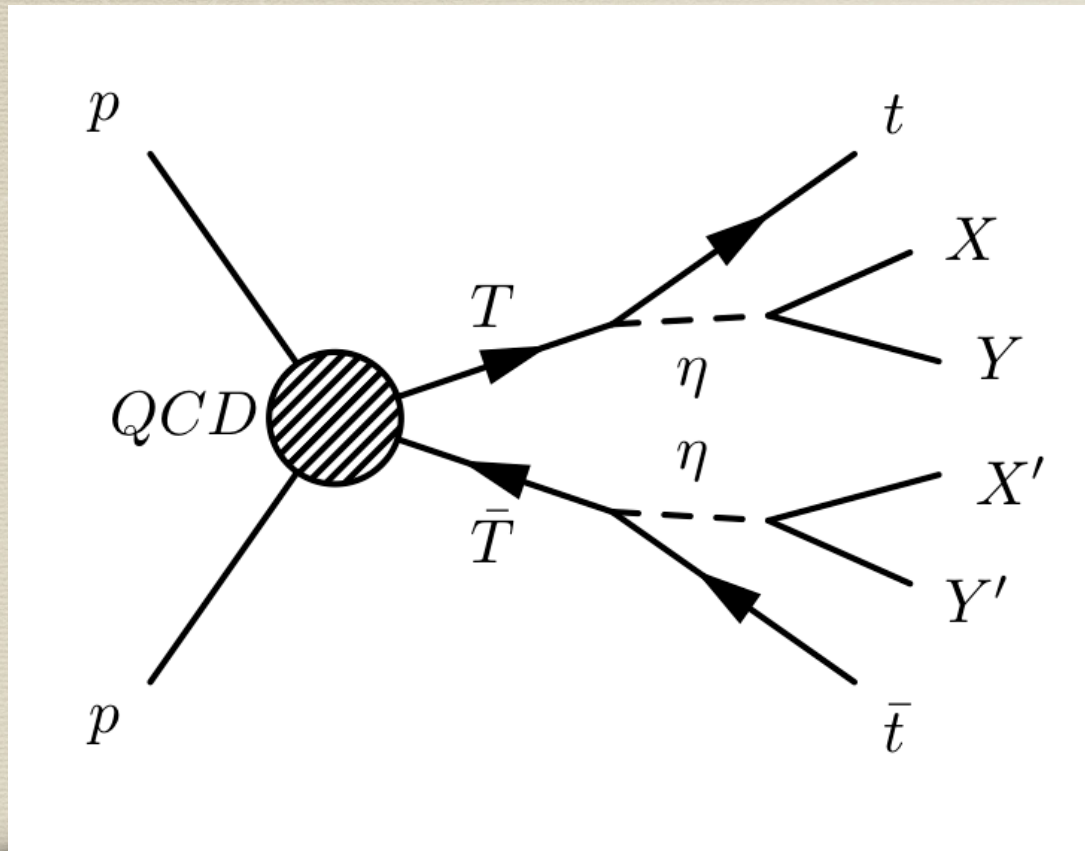
In models with SU(4)/Sp(4) breaking, one specific top partner couples only to the CP-odd SM singlet pNGB η . Both are odd under η -parity. η -parity is broken by EW anomaly couplings, and η decays to WW, ZZ, $Z\gamma$.

Effective Lagrangian:

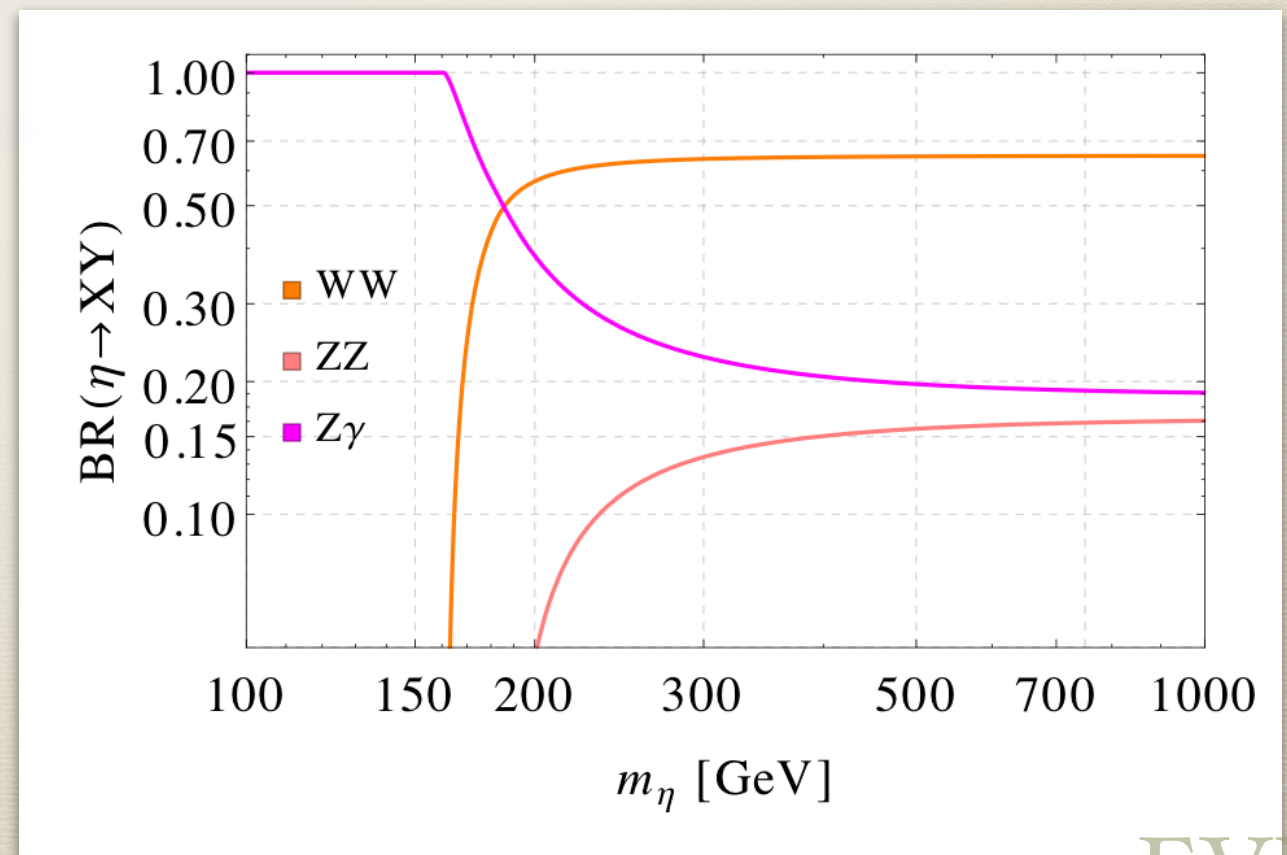
$$\mathcal{L}_{\tilde{T}} = \bar{\tilde{T}} (i\not{D} - M_{\tilde{T}}) \tilde{T} - \left(i\kappa_{\eta,L}^{\tilde{T}} \bar{\tilde{T}} \eta P_L t + L \leftrightarrow R + \text{h.c.} \right)$$

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

Common exotic VLQ decays



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



Common exotic VLQ decays

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

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

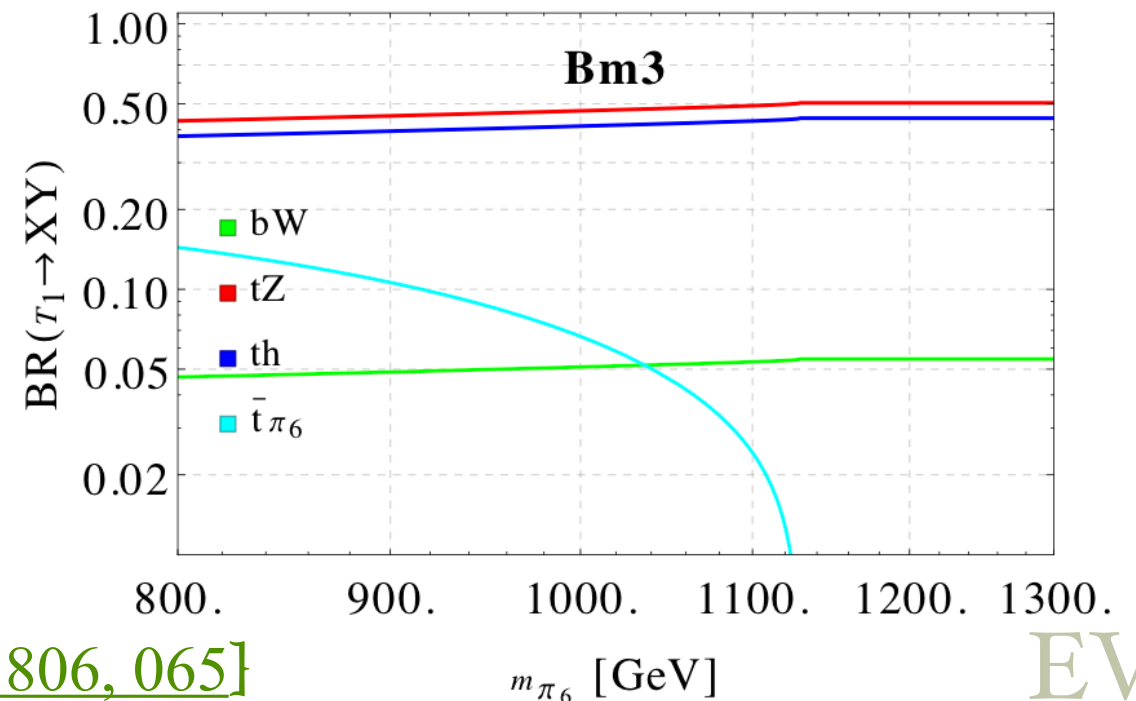
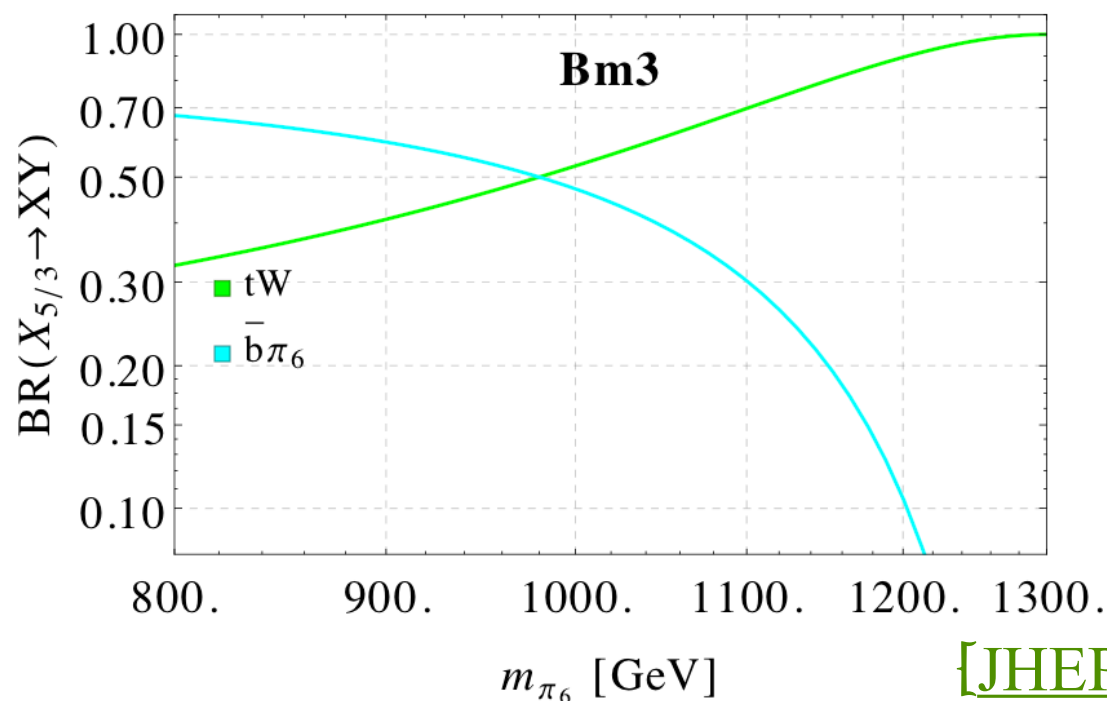
Effective Lagrangian:

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

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

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

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

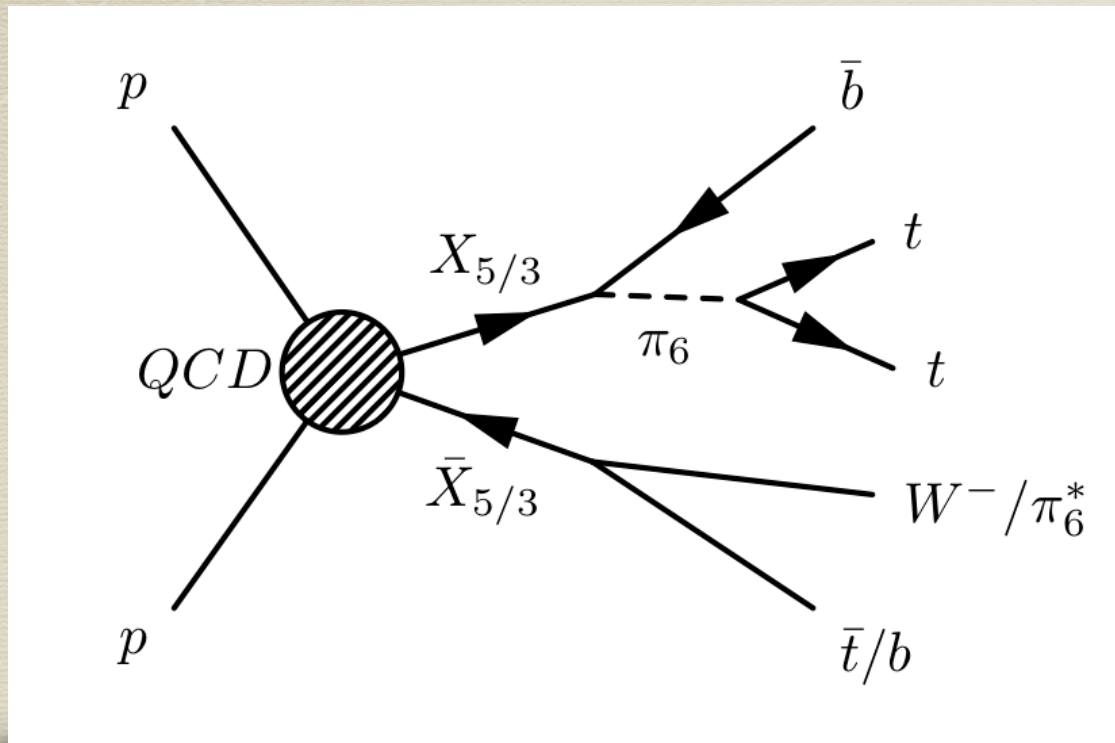


[JHEP 1806, 065]

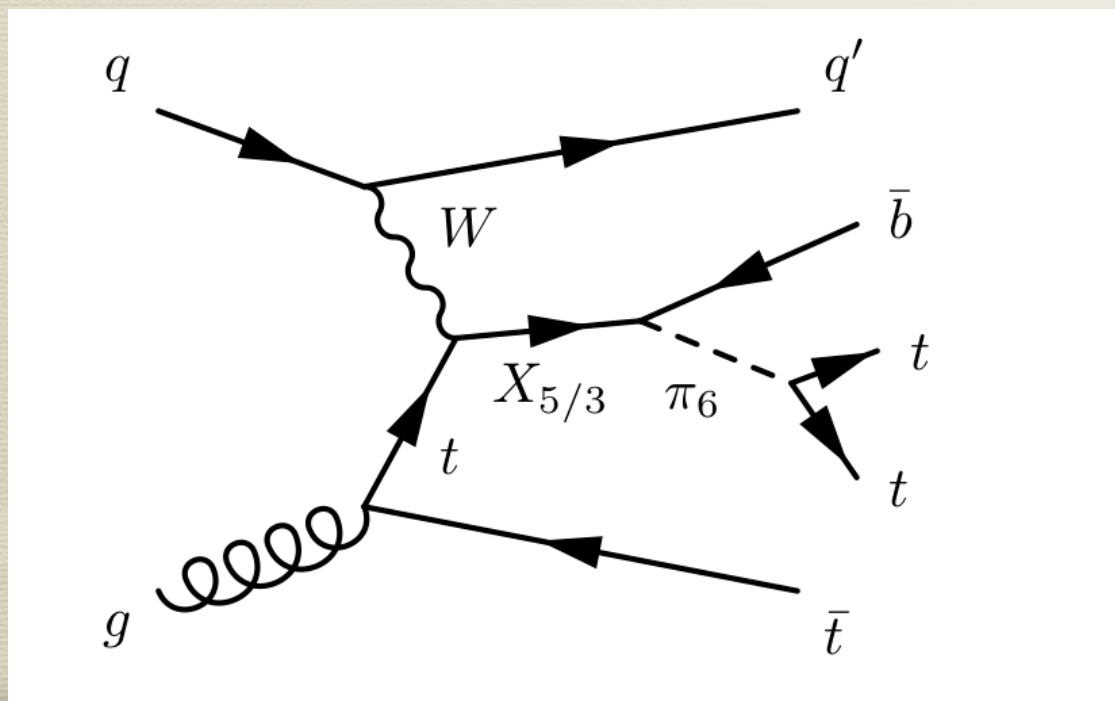
EV LQ

Common exotic VLQ decays

Examples of diagrams:



- $X_{5/3}$ and B can be produced in QCD pair production or single production.
- π_6 decays to $t t$.



Common exotic VLQ decays

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

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

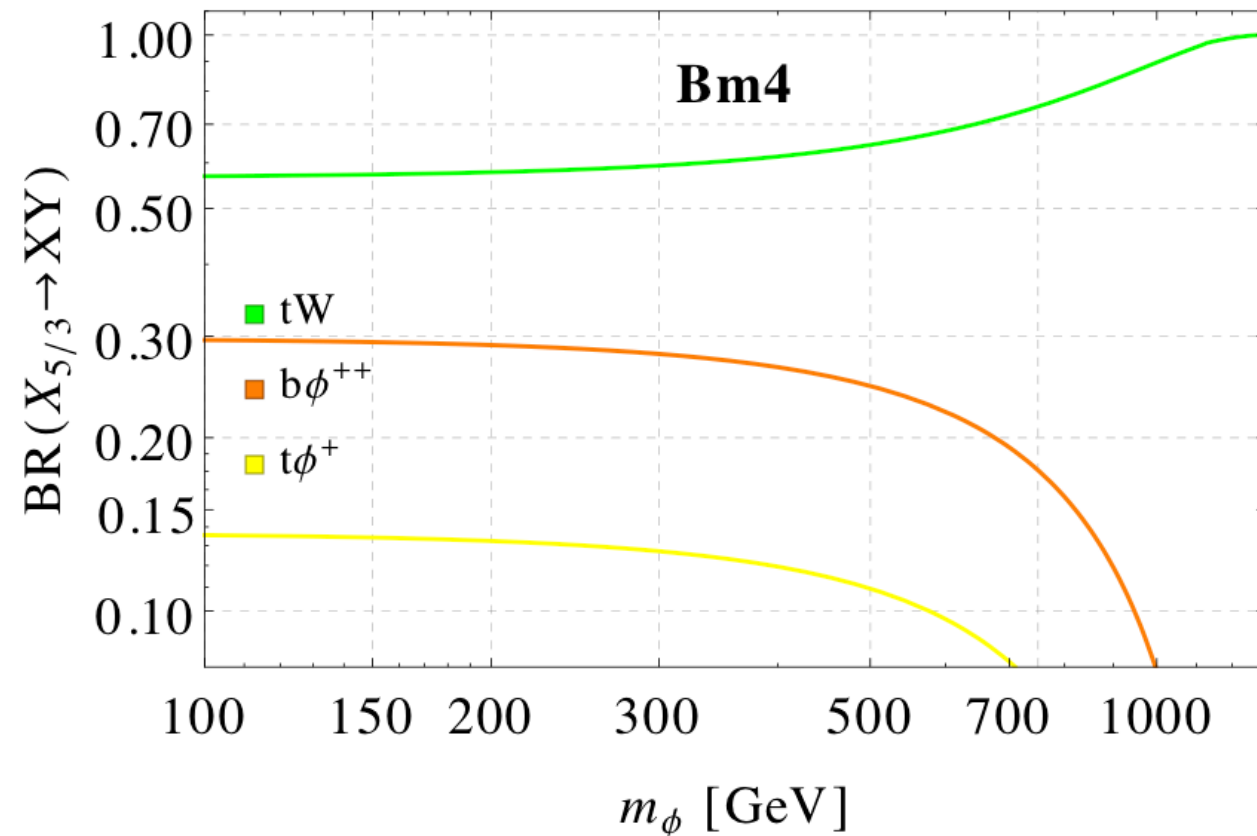
Effective Lagrangian:

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

Common exotic VLQ decays

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

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



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

Decays of the pNGBs:

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

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

Common exotic VLQ decays

Examples of processes:

