Common exotic decays of top partners

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G. Cacciapaglia, T. Flacke, S.J. Lee, A. Parolini, H. Serodio [JHEP 1506 (2015) 085]
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G. Cacciapaglia, H. Cai, A. Carvalho, A Deandrea, T. Flacke, B. Fuks, D. Majumder, H.-S. Shao [JHEP 1707 (2017), 005]
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G. Cacciapaglia, G. Ferretti,T. Flacke, H. Serodio [arXiv:1710.11142]
N. Bizot, G. Cacciapaglia, T. Flacke [arXiv:1803.00021]

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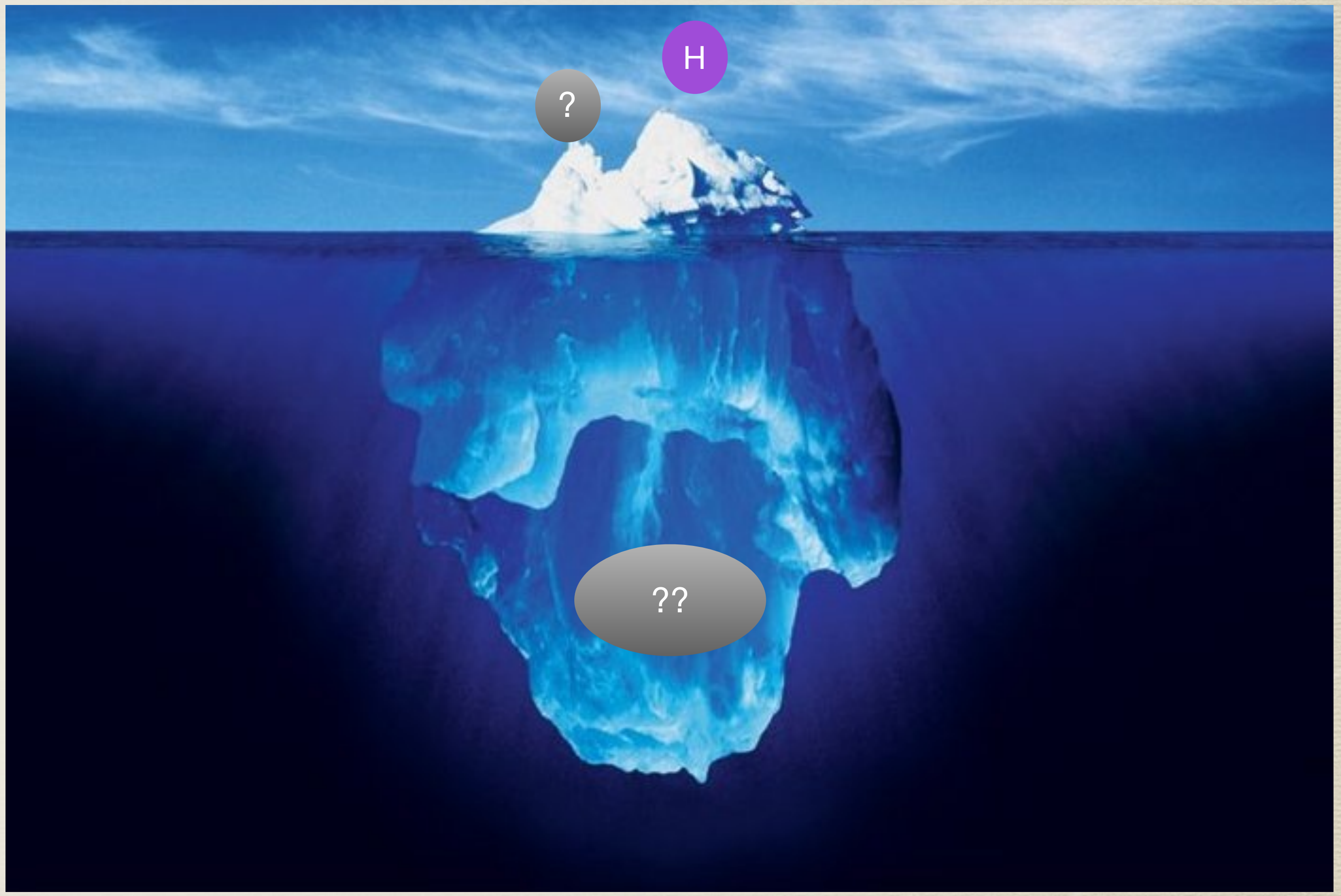
Outline

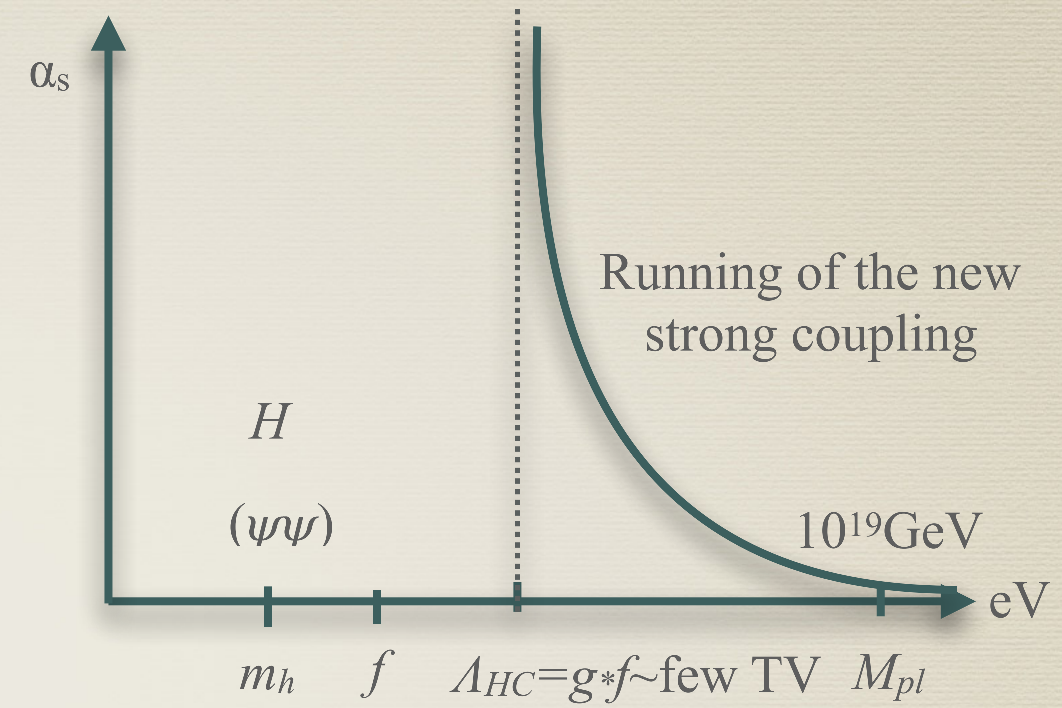
- Motivation & Introduction
- Towards UV embeddings of a composite Higgs: Models
- New light pseudo-Nambu Goldstone bosons
- Top-partners and common exotic decays / new signatures
- Conclusions



Motivation for a composite Higgs

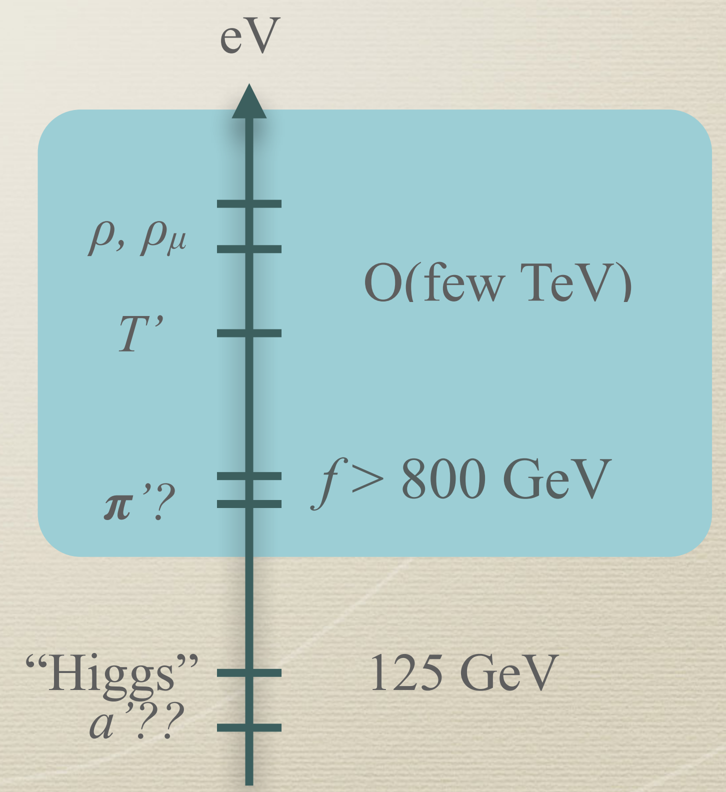
An alternative solution to the hierarchy problem:

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



The price to pay:

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



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

Ferretti etal. [JHEP 1403, 077] classified candidate models which:

c.f. also Gherghetta etal (2014), Vecchi (2015), Ferretti (2016) for related works on individual models

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

The resulting models have several common features:

- All models require two types of hyper-quarks $\psi, \ \chi$. The Higgs is realized as a $\psi\psi$ bound state. Top partners are realized as $\psi\psi\chi$ or $\psi\chi\chi$ bound states.
- None of the models has the minimal EW coset *SO(5)/SO(4)* which yields only the Higgs multiplet as pNGBs. The smallest EW cosets are instead *SU(4)/Sp(4)*, *SU(5)/SO(5)*, or *SU(4)xSU(4)/SU(4),* and all contain additional colored and uncolored pNGBs.

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

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

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

[JHEP1511,201]

Bound states of the model:

	spin	SU(4)×SU(6)	Sp(4)×SO(6)	names
$\psi\psi$	0	$(\mathbf{6},\mathbf{1})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{5},\mathbf{1})$	σ π
$\chi\chi$	0	$(\mathbf{1},\mathbf{21})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{1},\mathbf{20})$	σ_c π_c
$\chi\psi\psi$	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_1^1 ψ_1^5
$\chi\overline{\psi}\overline{\psi}$	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_2^1 ψ_2^5
$\psi\overline{\chi}\overline{\psi}$	1/2	$(\mathbf{1},\overline{\mathbf{6}})$	$(\mathbf{1},\mathbf{6})$	ψ_3
$\psi\overline{\chi}\overline{\psi}$	1/2	$(\mathbf{15},\overline{\mathbf{6}})$	$(\mathbf{5},\mathbf{6})$ $(\mathbf{10},\mathbf{6})$	ψ_4^5 ψ_4^{10}
$\overline{\psi}\sigma^\mu\psi$	1	$(\mathbf{15},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$ $(\mathbf{10},\mathbf{1})$	a ρ
$\overline{\chi}\sigma^\mu\chi$	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: $(8,1,1)_0 \oplus (6,1,1)_{4/3} \oplus (\overline{6},1,1)_{-4/3}$

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

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

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

Full list of "minimal" CHM UV embeddings

$G_{\rm HC}$	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]

New PNGBs and their phenomenology

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.
   [JHEP1701,094, arXiv:1710.11142]
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

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

[JHEP1511,201]

Direct bounds on other composite PNGBs

- ***a* and *η'*** : Studied in JHEP1701,094 , arXiv:1710.11142:

  tested in many channels: gg, $\gamma\gamma$, Zγ, ZZ, WW, tt, bb, $\tau\tau$, $\mu\mu$

  CH decay constants are being constrained, but no mass is excluded. 15 GeV < m_a < 65 GeV is poorly covered by existing searches.

- $\boldsymbol{\pi}_8$: Studied in JHEP1701,094:

  bounds on mass (QCD pair prod., decay to tops, gg, gγ): ~1 TeV.

- $\boldsymbol{\pi}_6$: Partially studied in JHEP1511,201:

  bounds on mass (QCD pair production, decay to tops): ~1 TeV

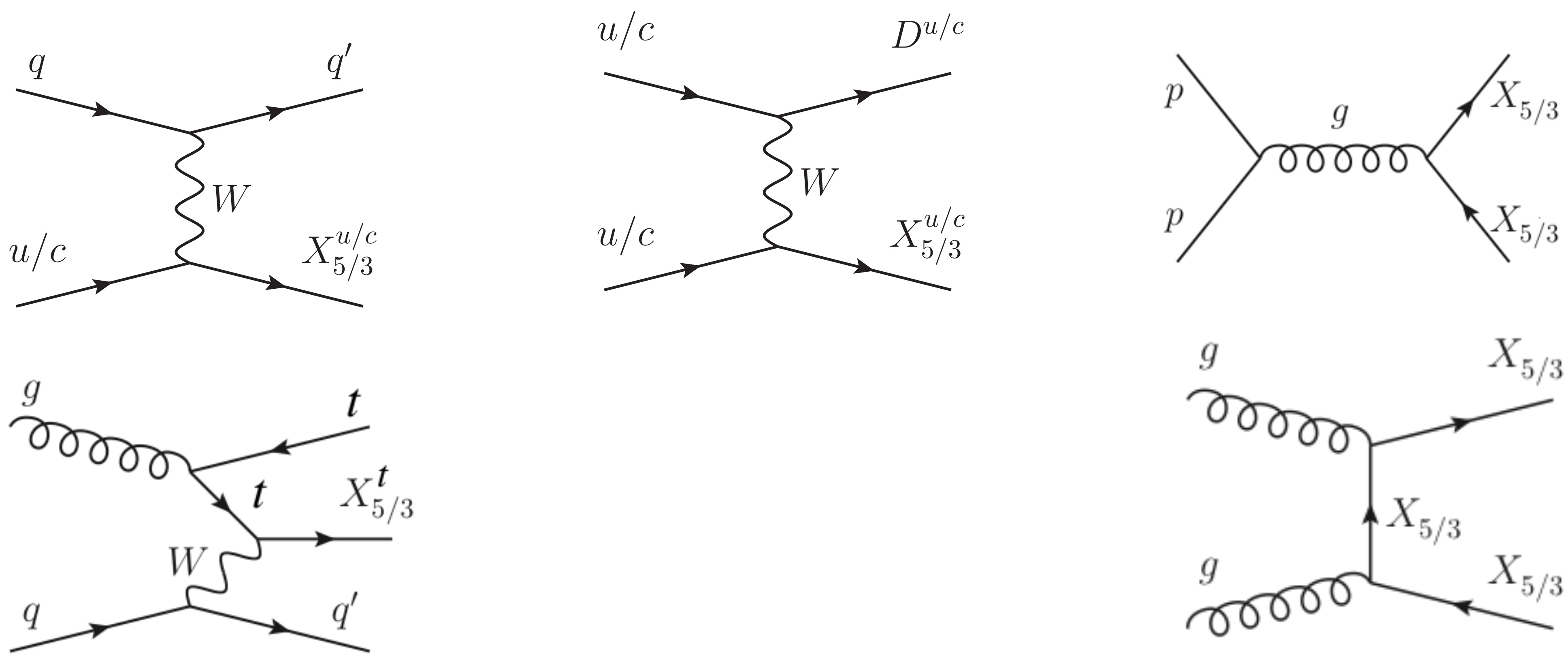
- $\boldsymbol{\pi}_3$: To my knowledge not studied in detail for composite models.

- Other un-colored pNGBs: only produced through EW interactions (if SU(2)×U(1) charged) or EW Wess-Zumino-Witten terms (if SM neutral). Thus bounds on the mass are expected to be weak.

Other CH model signatures

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

Production mechanisms (shown here: $X_{5/3}$ prod. for partners of up-type quarks)



(a) EW single production (b) EW pair production (c) QCD pair production

Decays:

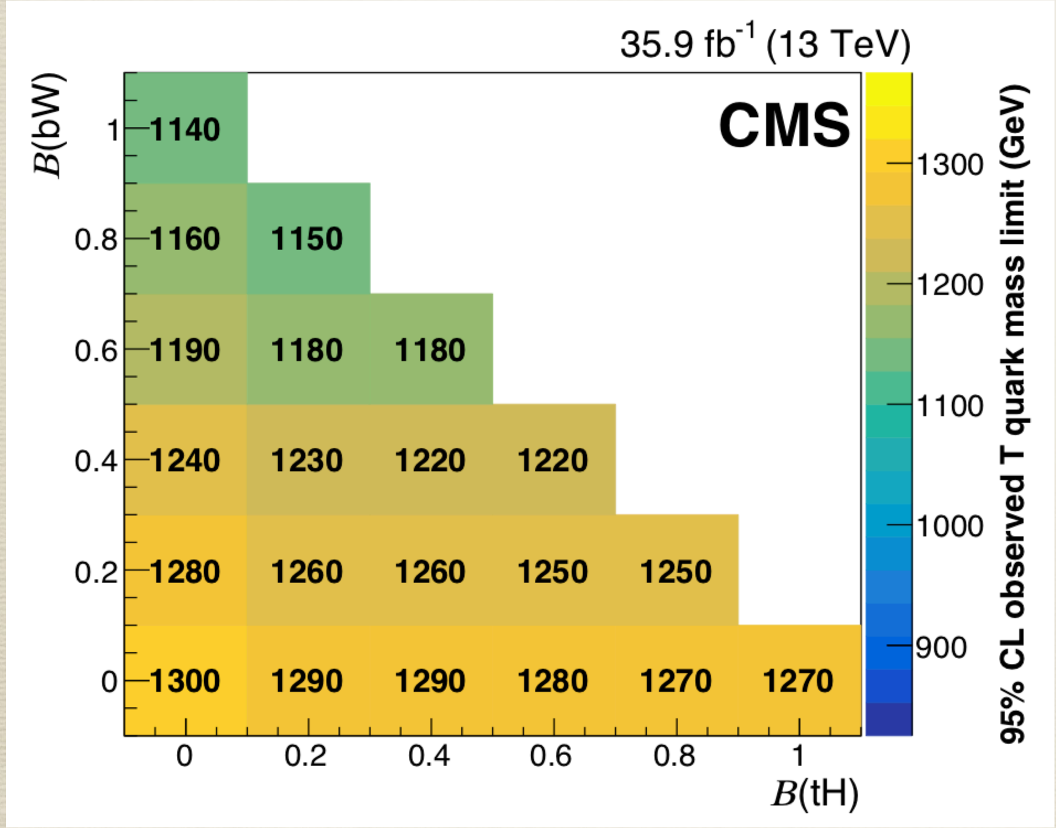
- $X_{5/3} \to W^+ t$ (100%),
- $B \to W^- t$ ($\sim$ 100%),
- $T_{f1}, T_{f2}, T_s \to W^- b, Zt, ht$ (with parameter-dependent BRs)

Bounds on VLQ masses

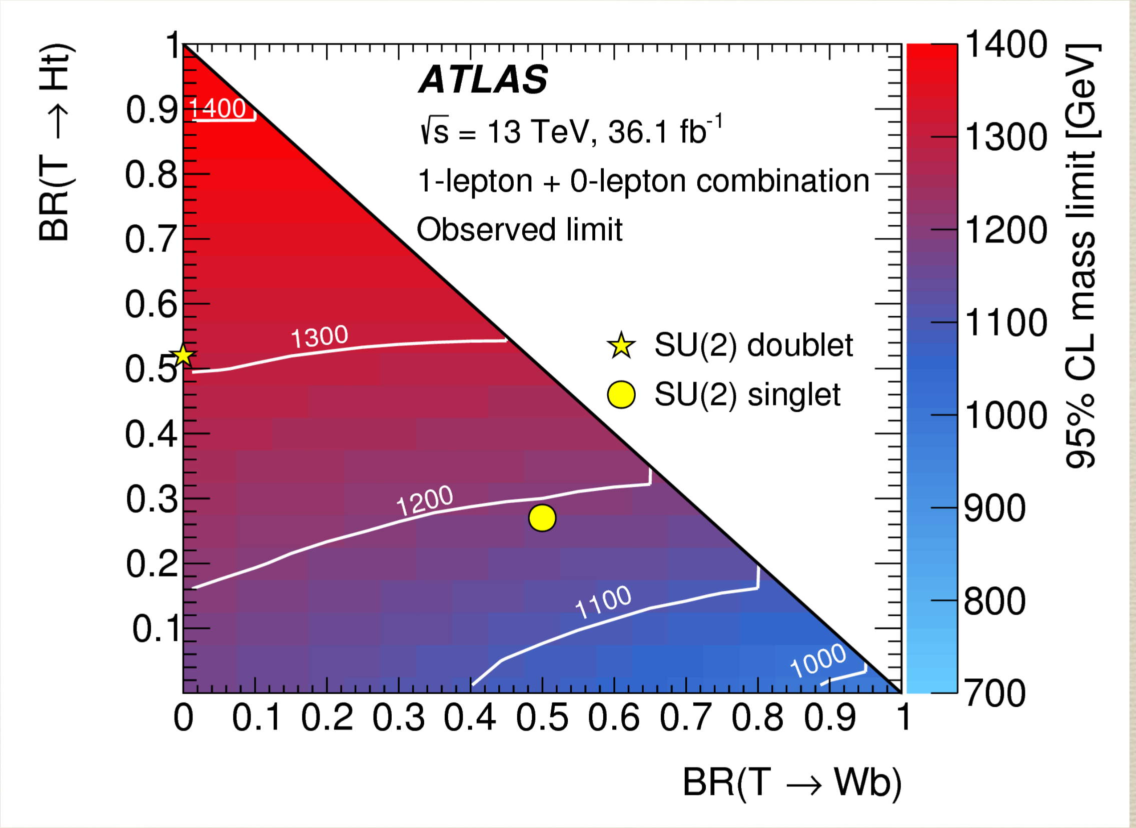
$X_{5/3}$: Run I: $M_X \gtrsim 800$ GeV, [ATLAS: JHEP 1381,104; CMS: PRL 112(2014), 171801]

Run II: $M_X \gtrsim 1.3$ TeV, [CMS PAS B2G-16-019]

T : Run II (examples):



[arXiv:1805.04758]



[ATLAS-EXOT-2016-13, arXiv:1803.09678]

Bounds on VLQ masses

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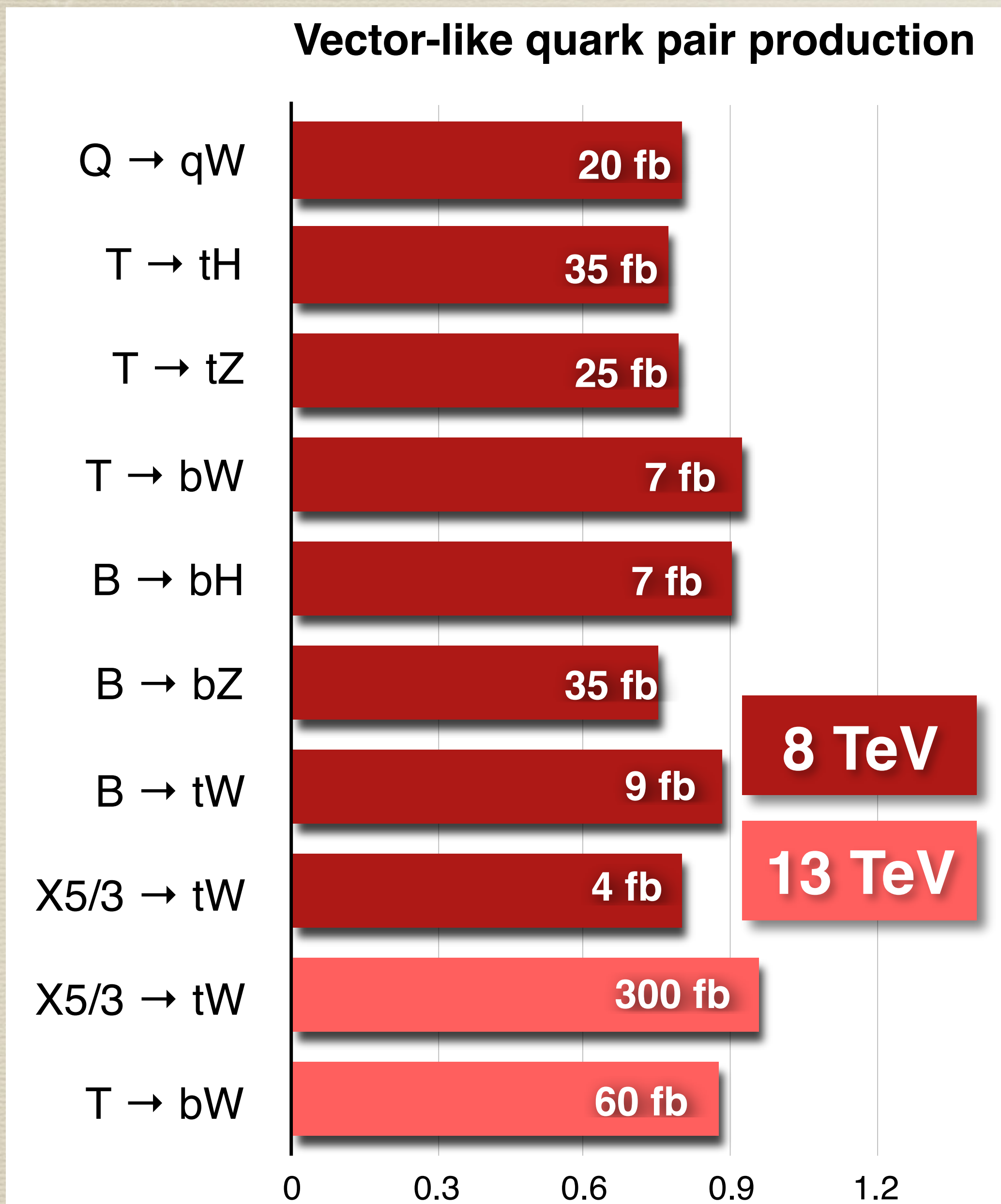
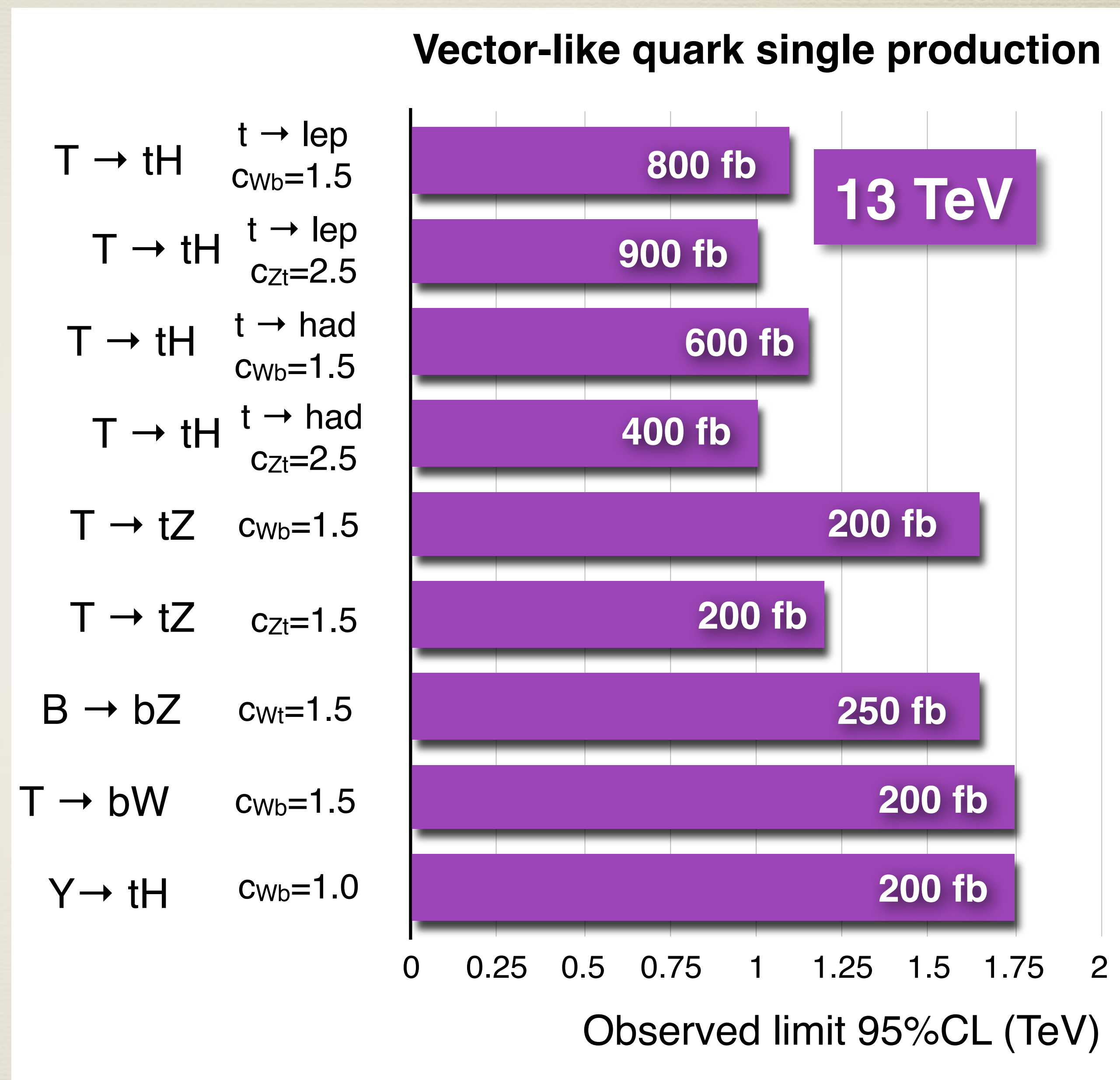




[CMS B2G Summary Plots]

…are we missing other “common” top partner decays?

- 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.

- To determine branching ratios to h/W/Z vs new pNGBs, can we find relations between the top partner couplings to different pNGBs?
  YES, WE CAN! [arXiv:1803.00021]

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

Relating top partner couplings to Higgs and other pNGBs

Example: [arXiv:1803.00021]

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

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

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

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

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

Common exotic VLQ decays

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

Effective Lagrangian(s): [arXiv:1803.00021]

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

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

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

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

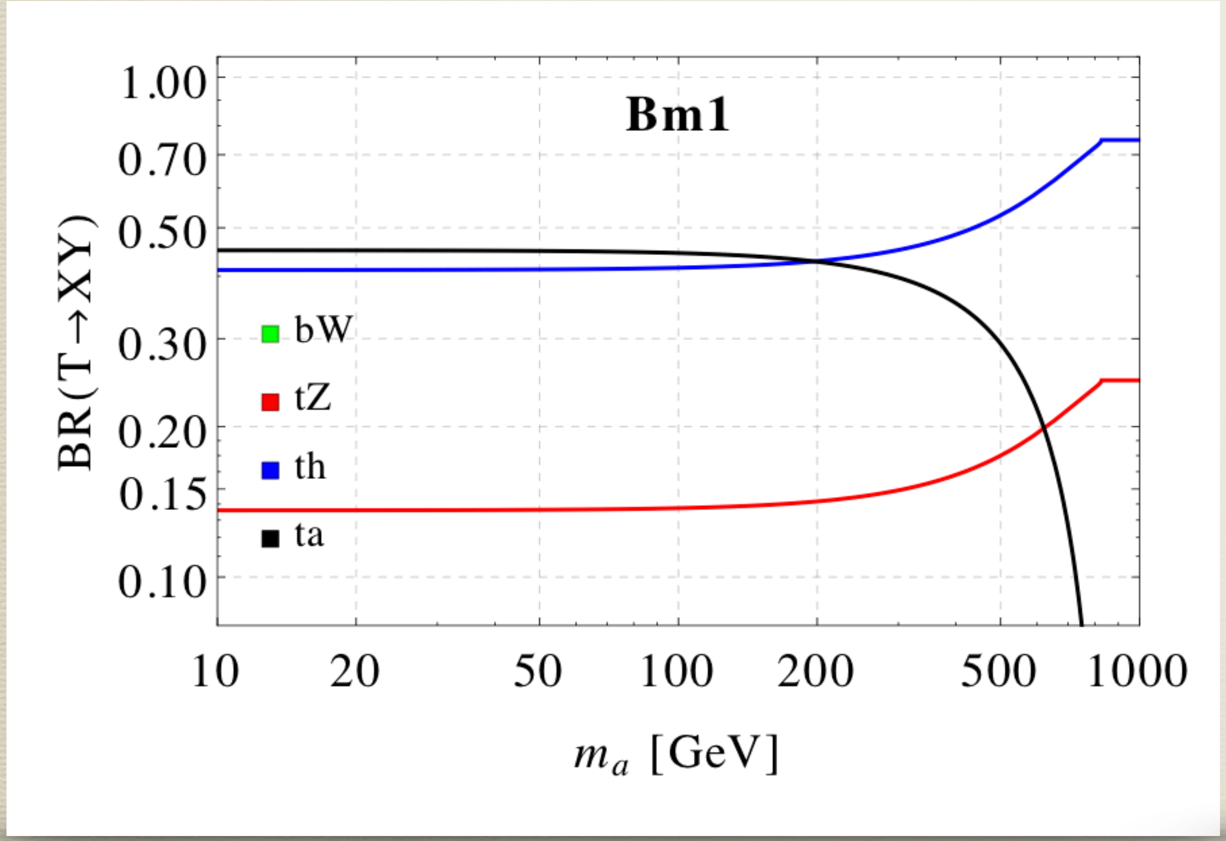
Common exotic VLQ decays

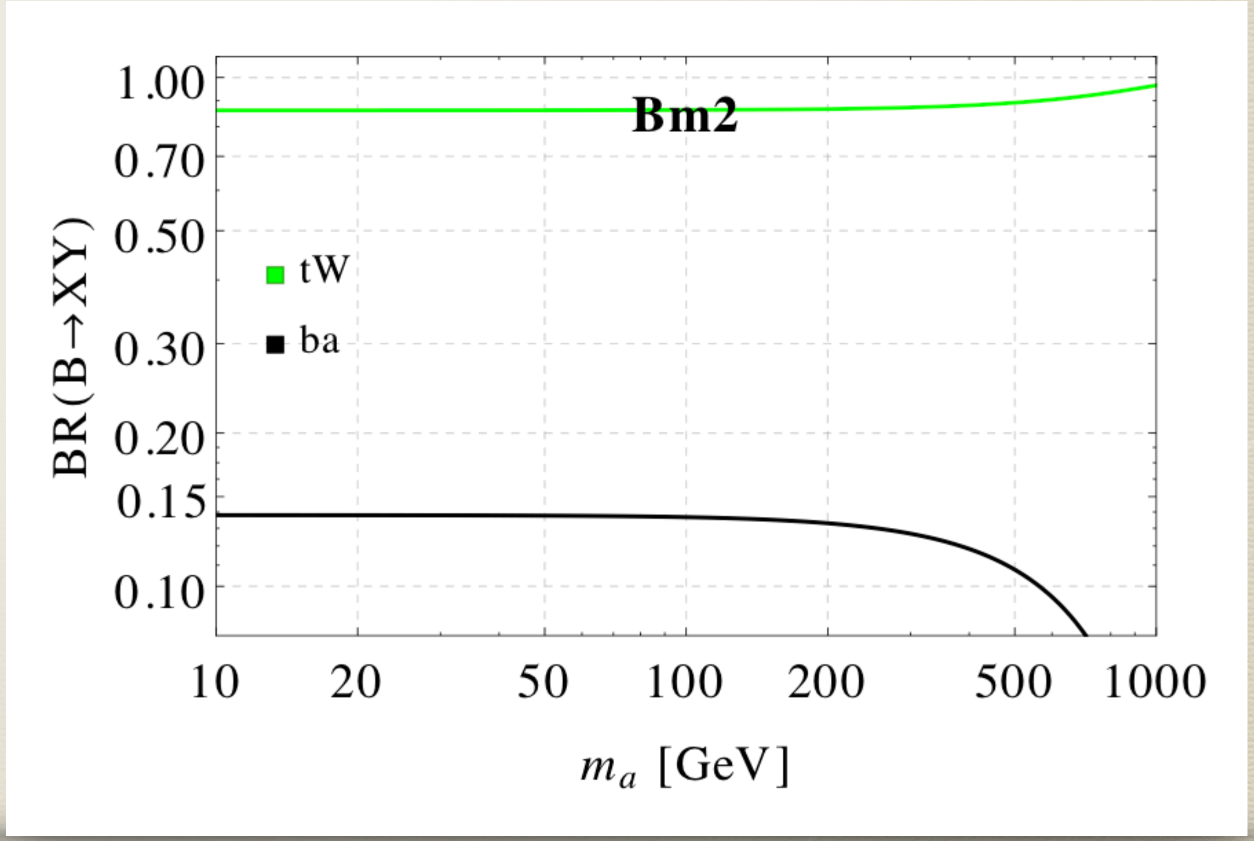
Benchmark parameters (obtained as eff. parameters from UV model):

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

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

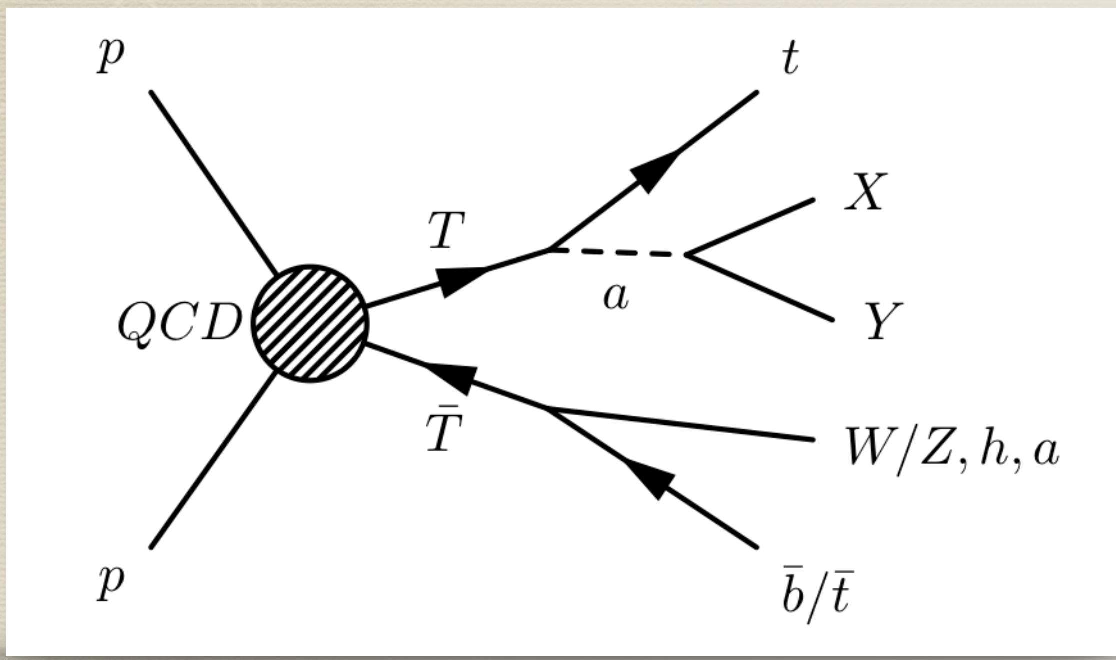
Branching ratios of quark partners to *a* in these benchmarks:

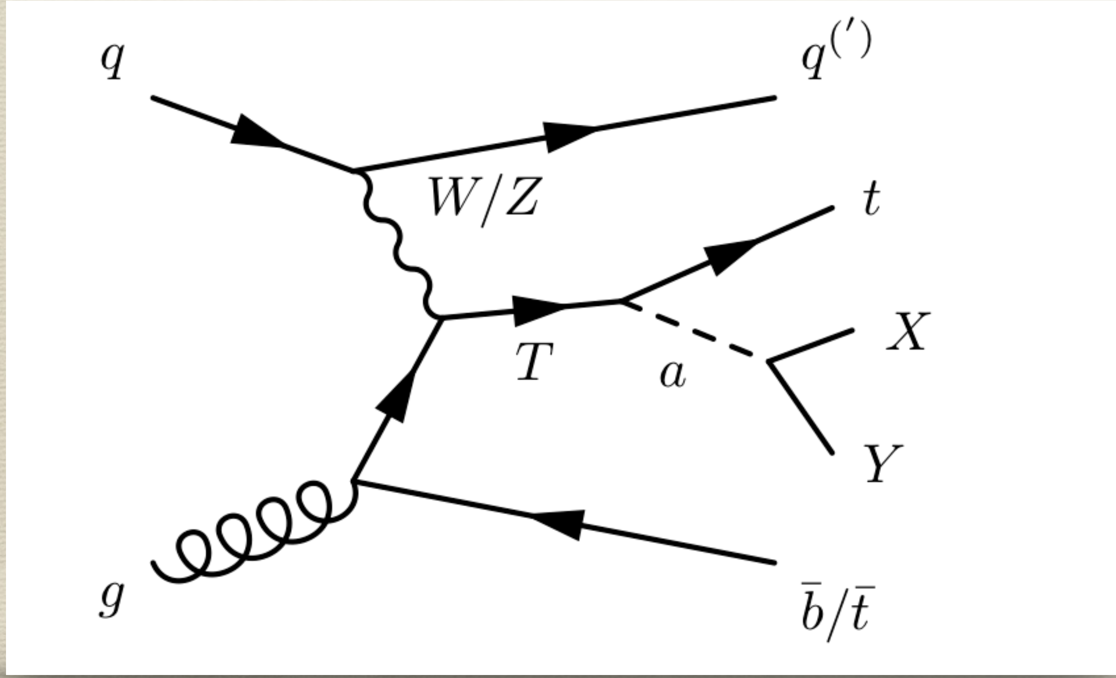




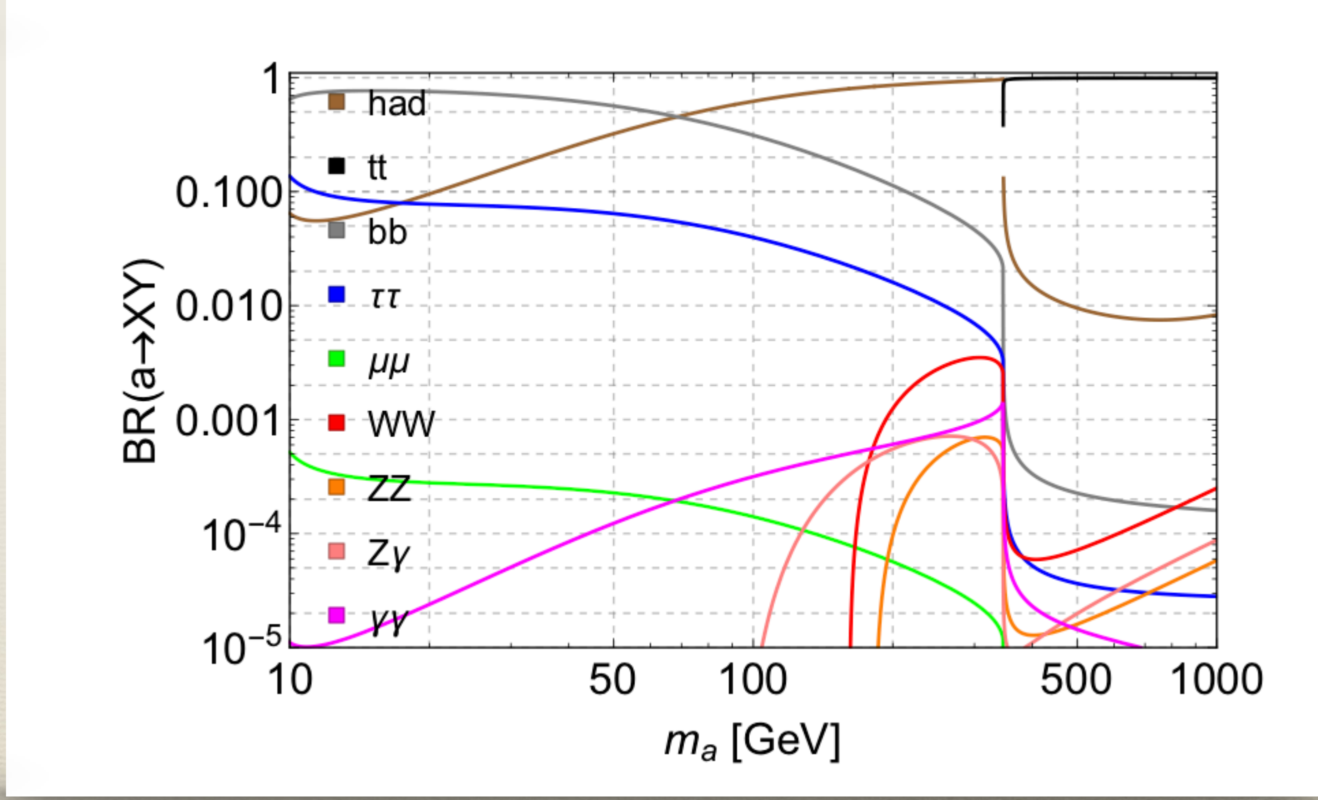
Common exotic VLQ decays

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



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.

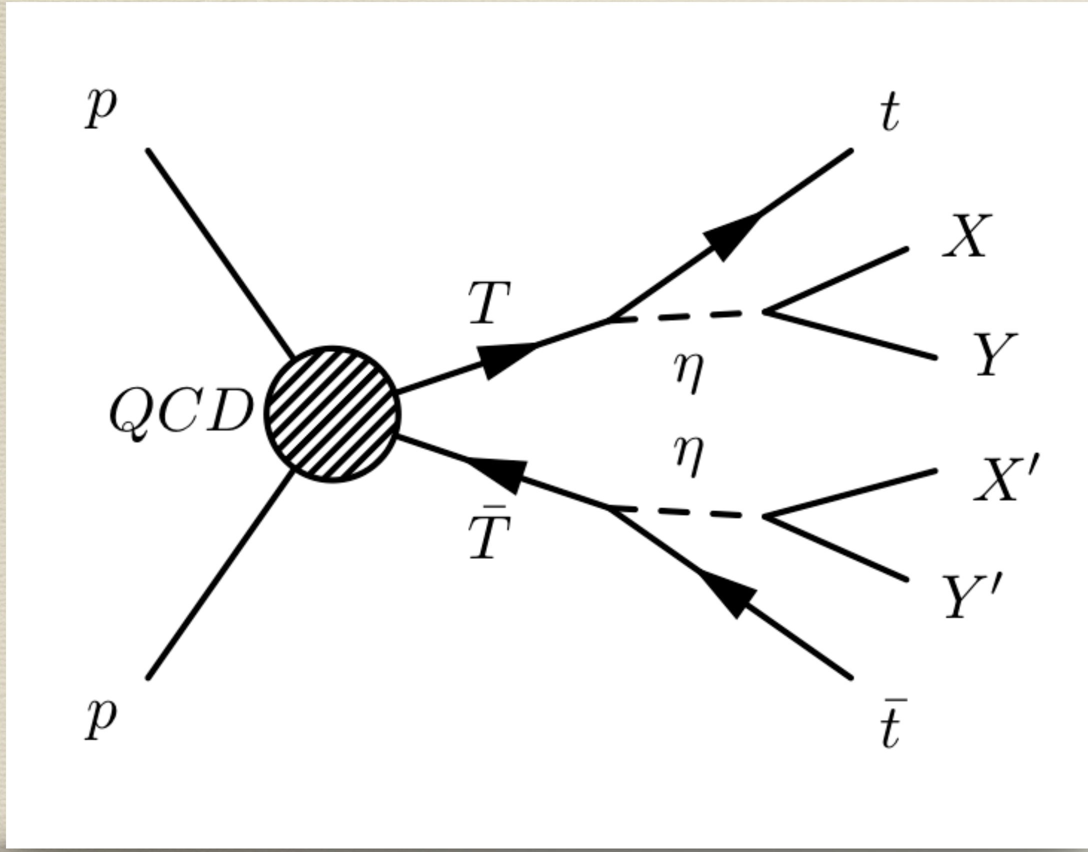
Effective Lagrangian:

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

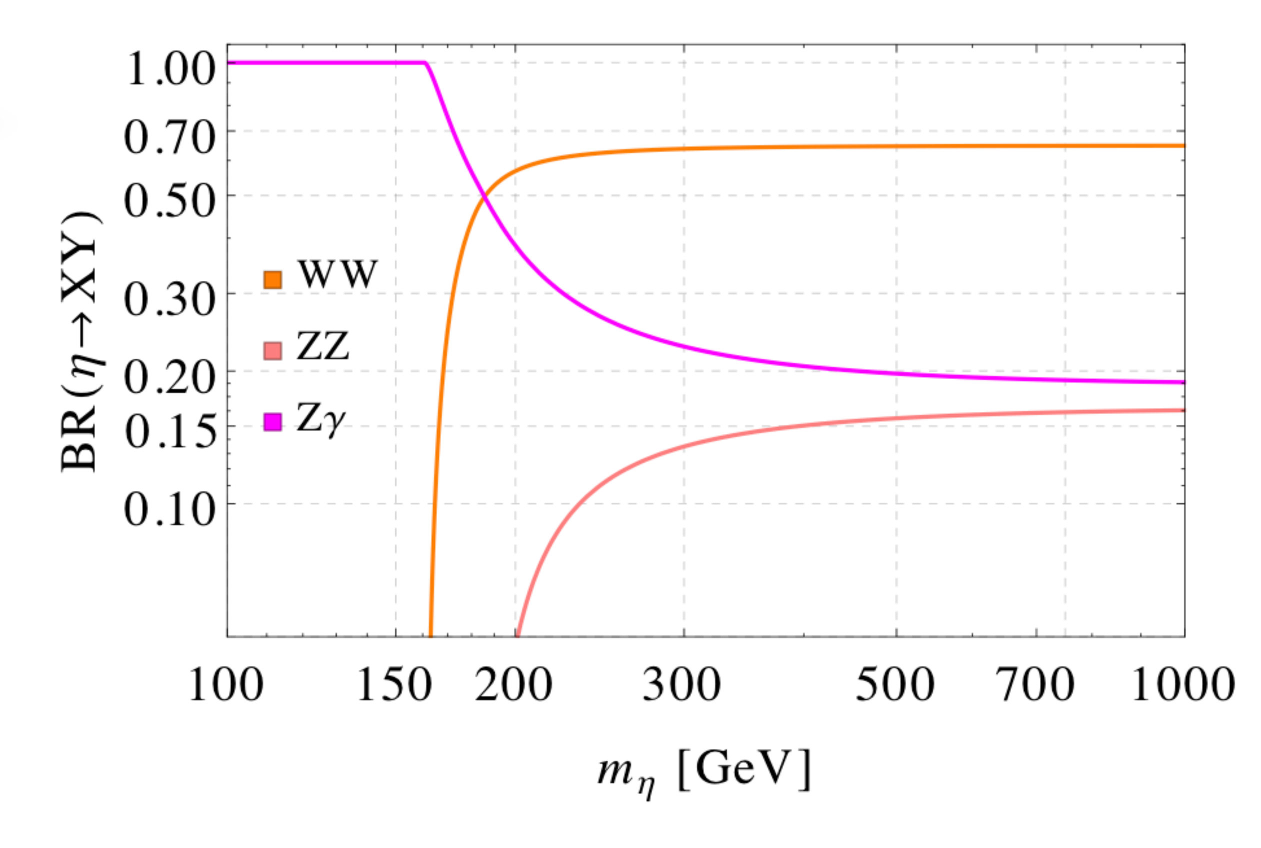
$$\mathcal{L}_\eta = \frac{1}{2}(\partial_\mu\eta)(\partial^\mu\eta) - \frac{1}{2}m_\eta^2\eta^2 + \frac{g_s^2 K_g^\eta}{16\pi^2 f_\eta}\eta G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{g^2 K_W^a}{8\pi^2 f_\eta}\eta W^+_{\mu\nu}\tilde{W}^{-,\mu\nu}$$
$$+\frac{e^2 K_\gamma^\eta}{16\pi^2 f_\eta}\eta A_{\mu\nu}\tilde{A}^{\mu\nu}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

[arXiv:1803.00021]

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).



Common exotic VLQ decays

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

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

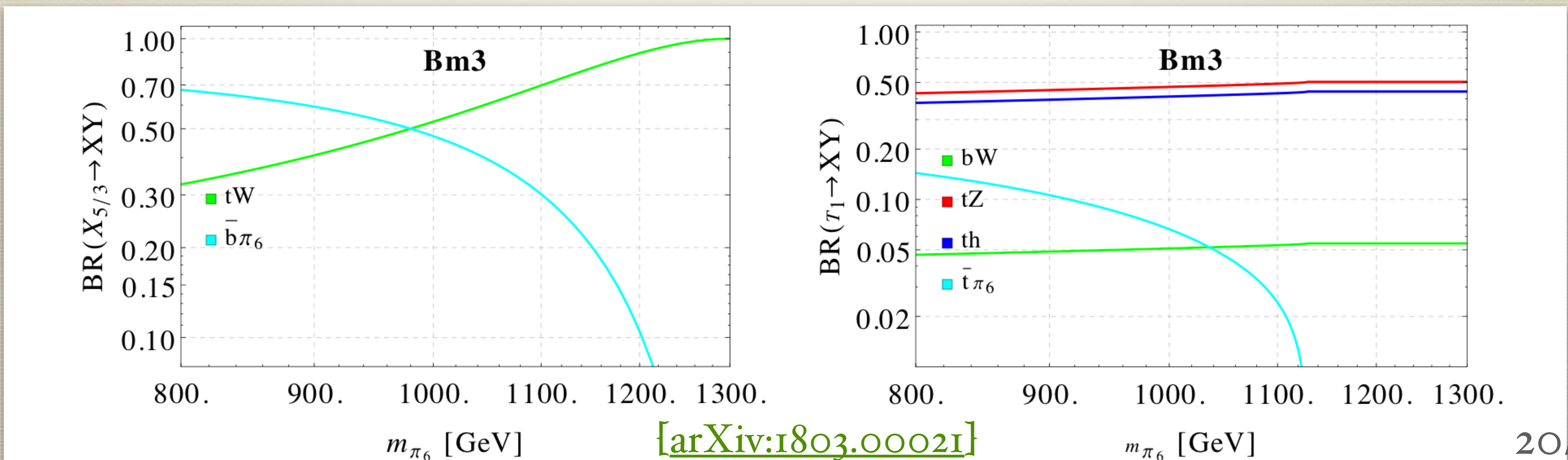
Effective Lagrangian:

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

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

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

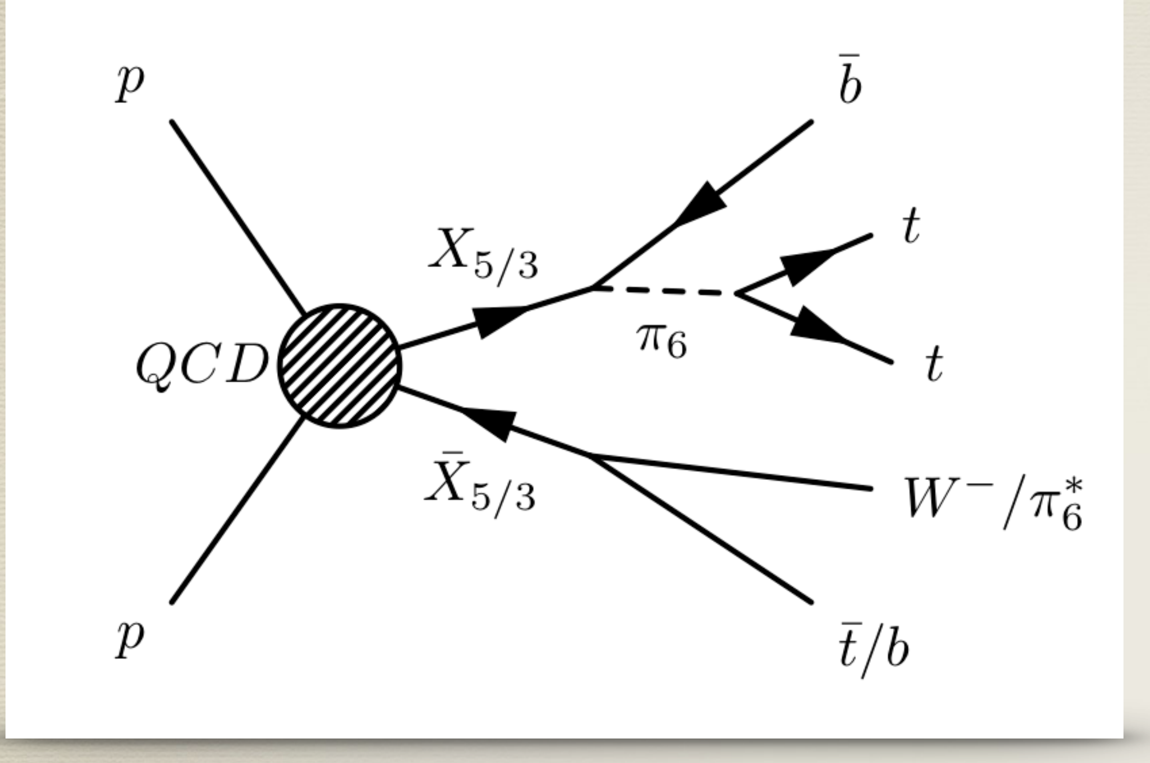
$$\text{Bm3}: \quad M_{X_{5/3}} = 1.3\text{ TeV}, \quad \kappa^{\text{X}}_{\text{W,L}} = 0.03, \quad \kappa^{\text{X}}_{\text{W,R}} = -0.11, \quad \kappa^{\text{X}}_{\pi_6\text{,L}} = 1.95, \quad \kappa^{\pi_6}_{\text{tt,R}} = -0.56$$

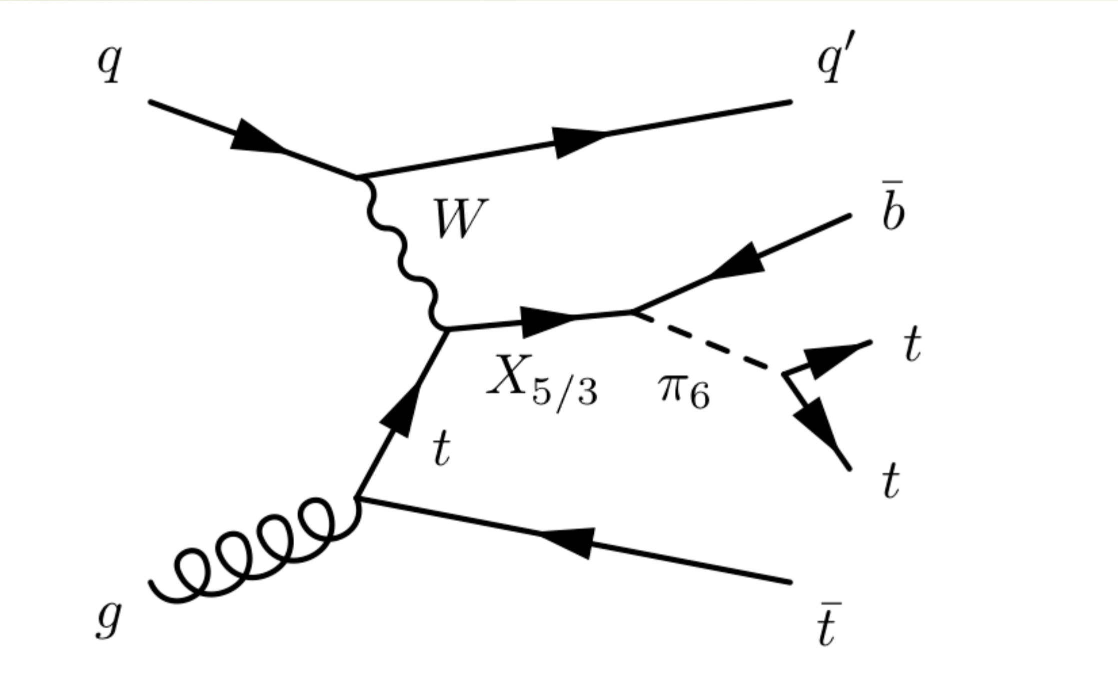


[arXiv:1803.00021]

Common exotic VLQ decays

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: $X_{5/3} \to t\ \phi^+$ 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:

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

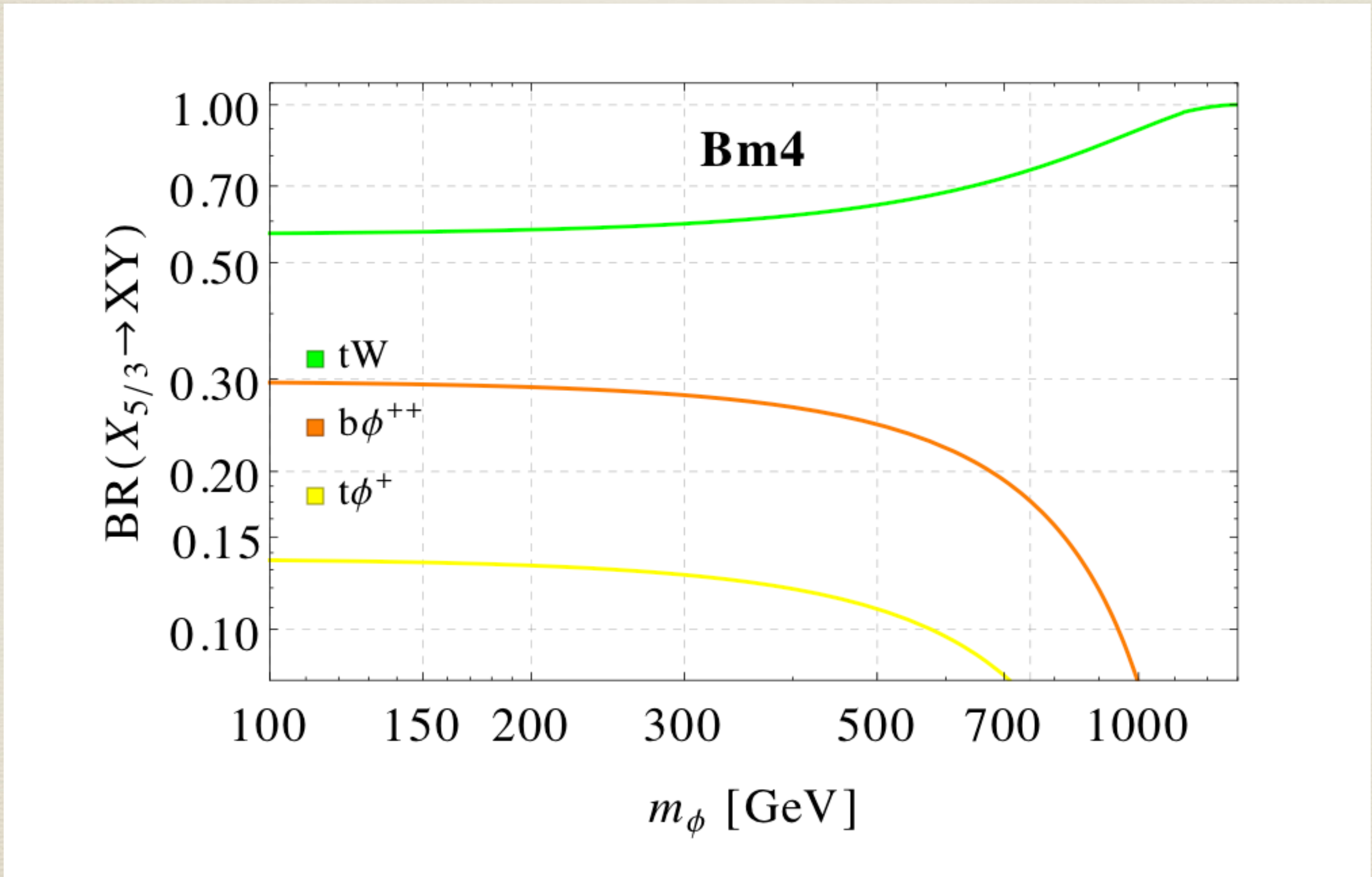
$$\mathcal{L}_\phi = \sum_{\phi=\phi^+,\phi^{++}}\left(|D_\mu\phi|^2 - m^2_\phi\,|\phi|^2\right) + \left(\frac{egK^\phi_{W\gamma}}{8\pi^2 f_\phi}\phi^+ W^-_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{g^2 c_w K^\phi_{WZ}}{8\pi^2 f_\phi}\phi^+ W^-_{\mu\nu}\tilde{B}^{\mu\nu}\right.$$
$$\left. + \frac{g^2 K^\phi_W}{8\pi^2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

[arXiv:1803.00021]

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.

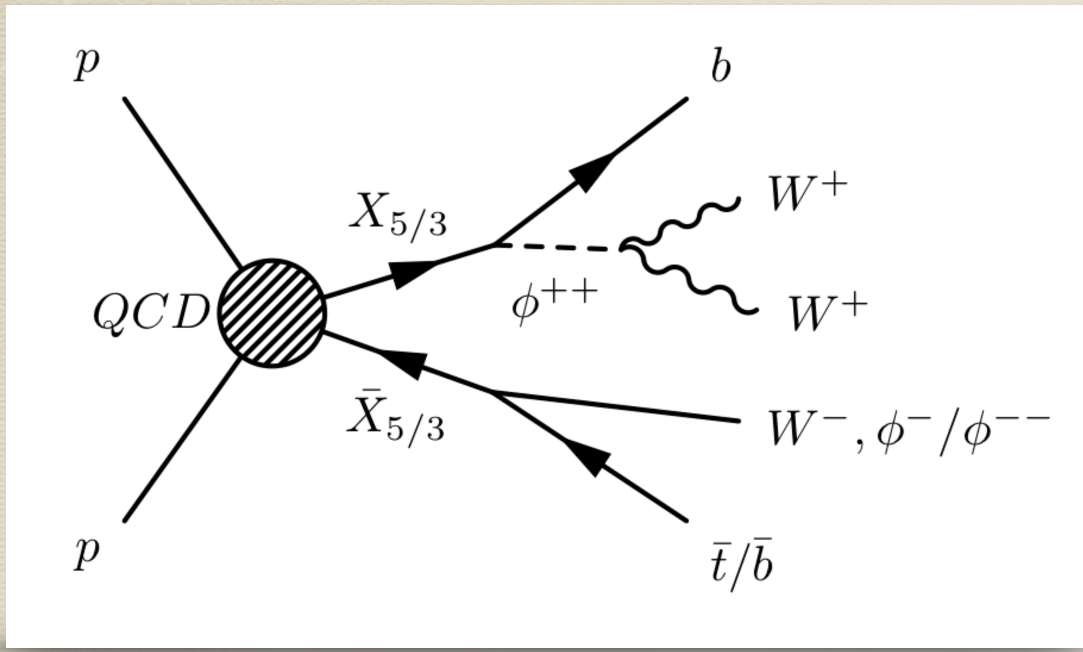
Decays of the pNGBs:

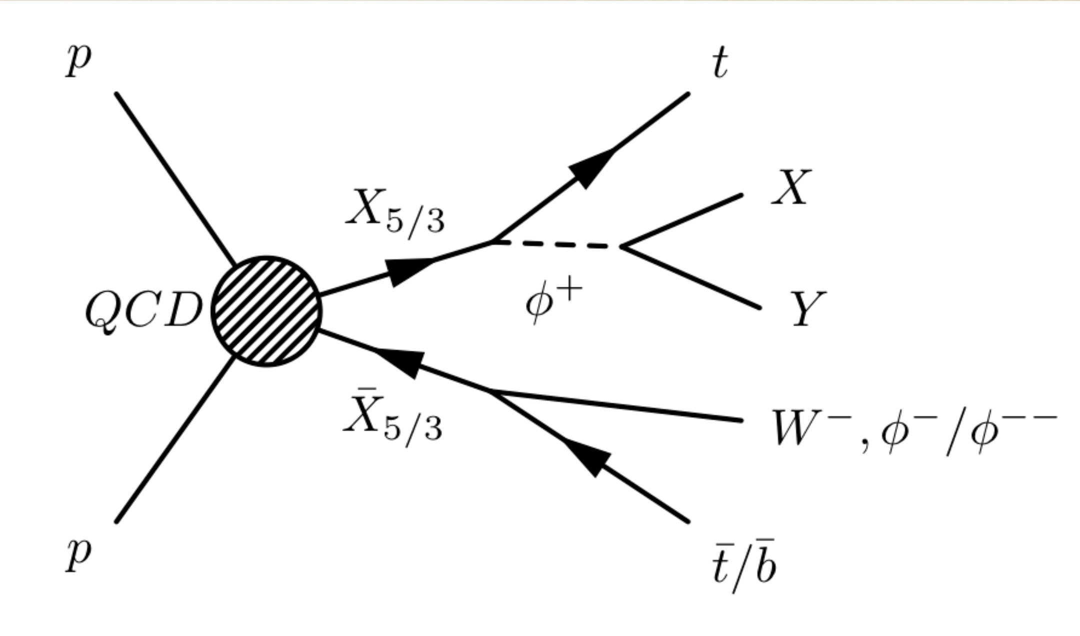
$\phi^{++} \to W^+ W^+$

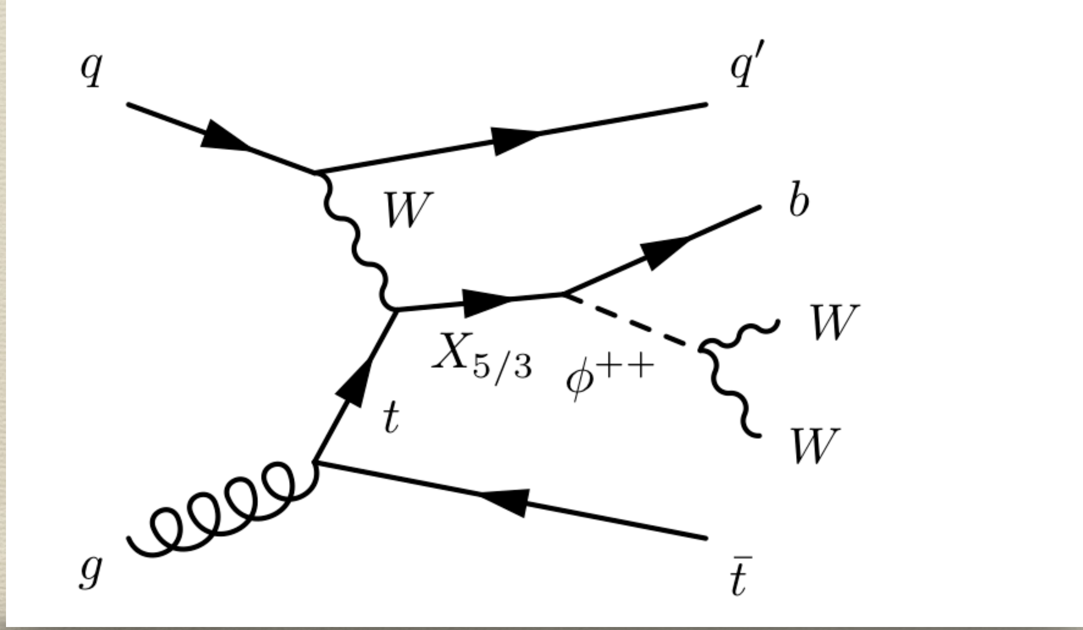
$\phi^{+} \to tb, W^+ Z, W^+ \gamma$

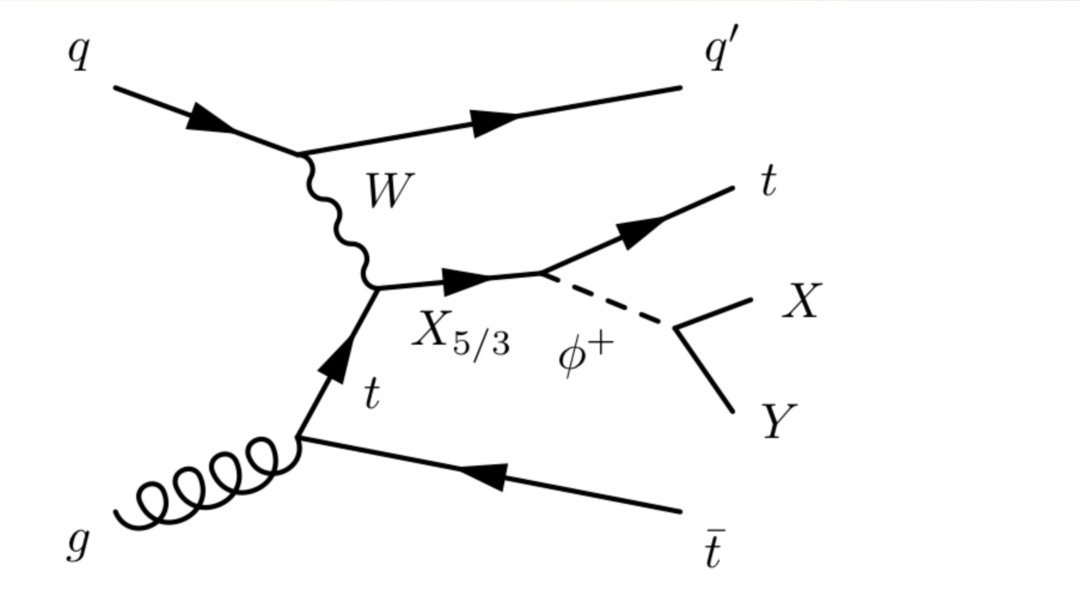
Common exotic VLQ decays

Examples of processes:









Conclusions

- Composite Higgs Models provide a viable solution to the hierarchy problem but — being strongly coupled theories — they still provide many challenges and room for exploration.
- EFT descriptions of composite Higgs models are only part of the story. UV embeddings need to be studied in more detail, and they lead to novel (as well as already well-known) BSM LHC signatures.
- We showed that additional pNGBs are present in CH UV embeddings (colored as well as uncolored ones) and summarized constraints for the SM singlet and the color octet pNGB.
- 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 targeted by current LHC searches. (Recasts of existing searches can provide some coverage).

There is lots to do!

Backup

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 √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?

TH

Couplings of pNGBs to SM gauge bosons:

The underlying fermions are charged under the SM gauge fields, and thus ABJ anomalies induce couplings of the Goldstone bosons to the SM fields which are fully determined by the underlying quantum numbers. [JHEP1701,094]

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

where

r	coset ψ	C^ψ_W	C^ψ_B	coset χ	C^χ_G	C^χ_B
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: $$\mathcal{L}_{\rm WZW} \supset \frac{\sqrt{\alpha_A \alpha_{A'}}}{4\sqrt{2}\pi} c_5 \frac{C^r_{AA'}}{f_r} c^{abc}\ \pi^a_r\ \varepsilon^{\mu\nu\alpha\beta} A^a_{\mu\nu} {A'}^b_{\alpha\beta}\,,$$

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

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

- One model ⇔ one set of Branching ratios.

- Only unknown parameters are decay constants f_r.

TH

Couplings to tops and top mass: [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 **ψ** 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

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

NOTE:

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

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

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

The masses of the pNGBs are

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

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

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.

$$\mathcal{L}_{\pi_0} = \frac{1}{2}\left(\partial_\mu \pi_0 \partial^\mu \pi_0 - M_{\pi_0}^2 \pi_0^2\right) + i\, C_t \frac{m_t}{f_\pi}\, \pi_0\, \bar{t}\gamma_5 t$$
$$+ \frac{\alpha_s}{8\pi}\frac{\kappa_g}{f_\pi}\, \pi_0 \left(\epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} + \frac{g_2^2}{g_3^2}\frac{\kappa_W}{\kappa_g}\epsilon^{\mu\nu\rho\sigma} W^i_{\mu\nu} W^i_{\rho\sigma} + \frac{g_1^2}{g_3^2}\frac{\kappa_B}{\kappa_g}\epsilon^{\mu\nu\rho\sigma} B_{\mu\nu} B_{\rho\sigma}\right)$$

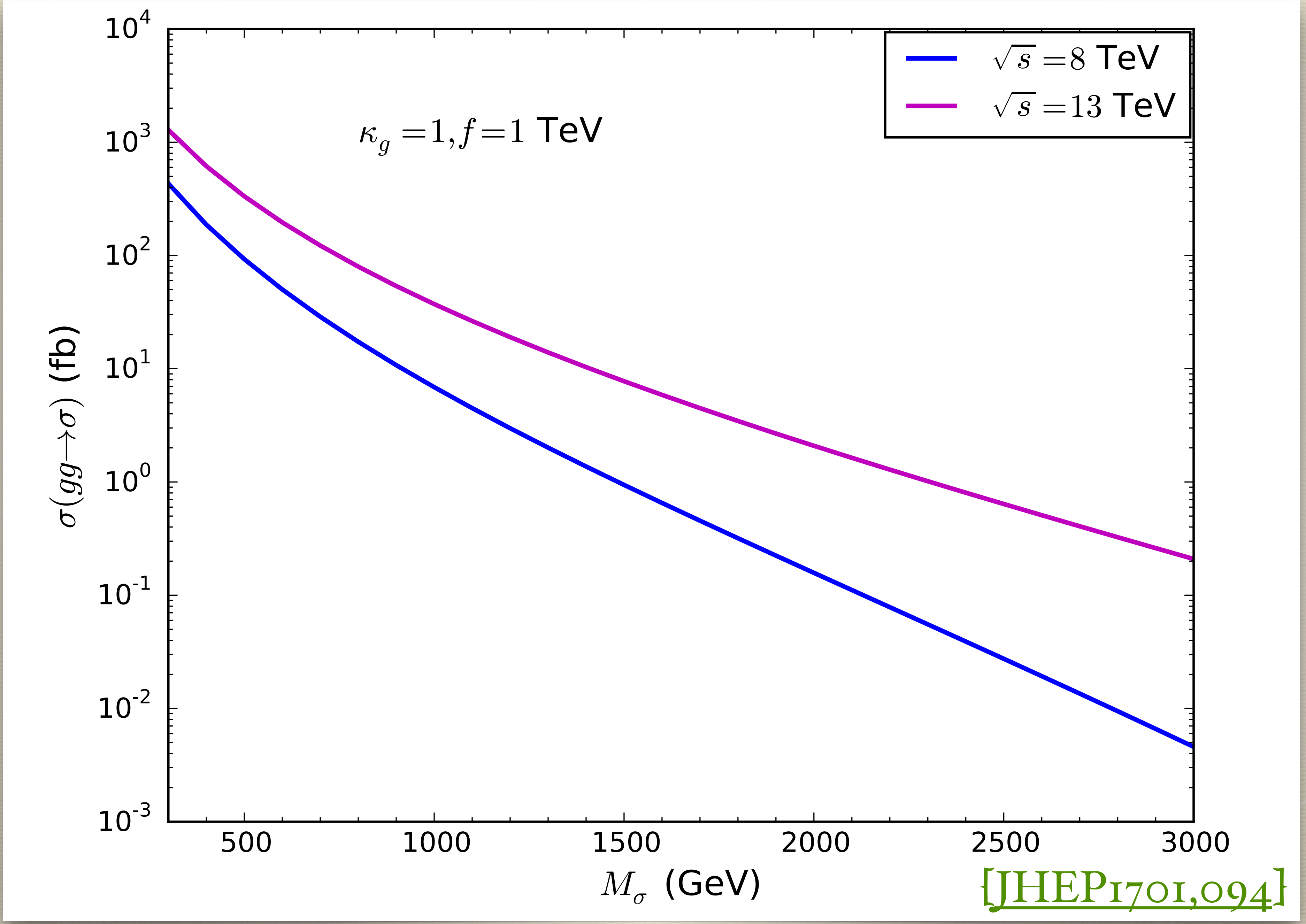
- The mass m_a must result from *explicit* breaking of the U(1) symmetries (e.g. through mass terms for the underlying χ). m_η also obtains mass from instantons.
- $f_{\pi 0}$ results from chiral symmetry breaking. .
- The WZW coefficients κ_i are fully determined by the quantum numbers of χ, ψ.
- The coefficient C_t is also fixed (depends on spurion charge of dominantly mixing top-partner)

Phenomenology

- $\boldsymbol{\pi_0}$ is produced in gluon fusion (controlled by κ_g/f_π).
- $\boldsymbol{\pi_0}$ decays to gg, WW, ZZ, $Z\gamma$, $\gamma\gamma$, $t\bar{t}$, ff with fully determined branching ratios. (controlled by κ_B/κ_g, κ_W/κ_g, C_t/κ_g)
- The resonance is narrow.

TCP

Production cross section for a pseudo-scalar



[JHEP1701,094]

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Partial widths

(here, tree-level expressions; in analysis we use full 1-loop results)

$$\begin{aligned}
\Gamma(\pi_0 \to gg) &= \frac{\alpha_s^2 \kappa_g^2 M_{\pi_0}^3}{8\pi^3 f_\pi^2}\,, \\
\Gamma(\pi_0 \to WW) &= \frac{\alpha_W^2 \kappa_W^2 M_{\pi_0}^3}{32\pi^3 f_\pi^2} \left(1 - 4\frac{m_W^2}{M_{\pi_0}^2}\right)^{\frac{3}{2}}\,, \\
\Gamma(\pi_0 \to ZZ) &= \frac{\alpha_W^2 \cos^4\theta_W \left(\kappa_W + \kappa_B \tan^4\theta_W\right)^2 M_{\pi_0}^3}{64\pi^3 f_\pi^2} \left(1 - 4\frac{m_Z^2}{M_{\pi_0}^2}\right)^{\frac{3}{2}}\,, \\
\Gamma(\pi_0 \to Z\gamma) &= \frac{\alpha\alpha_W \cos^2\theta_W \left(\kappa_W - \kappa_B \tan^2\theta_W\right)^2 M_{\pi_0}^3}{32\pi^3 f_\pi^2} \left(1 - \frac{m_Z^2}{M_{\pi_0}^2}\right)^{3}\,, \\
\Gamma(\pi_0 \to \gamma\gamma) &= \frac{\alpha^2 \left(\kappa_W + \kappa_B\right)^2 M_{\pi_0}^3}{64\pi^3 f_\pi^2}\,, \\
\Gamma(\pi_0 \to t\bar{t}) &= \frac{3C_t^2 M_{\pi_0}}{8\pi}\frac{m_t^2}{f_\pi^2} \left(1 - 4\frac{m_t^2}{M_{\pi_0}^2}\right)^{1/2}\,,
\end{aligned}$$

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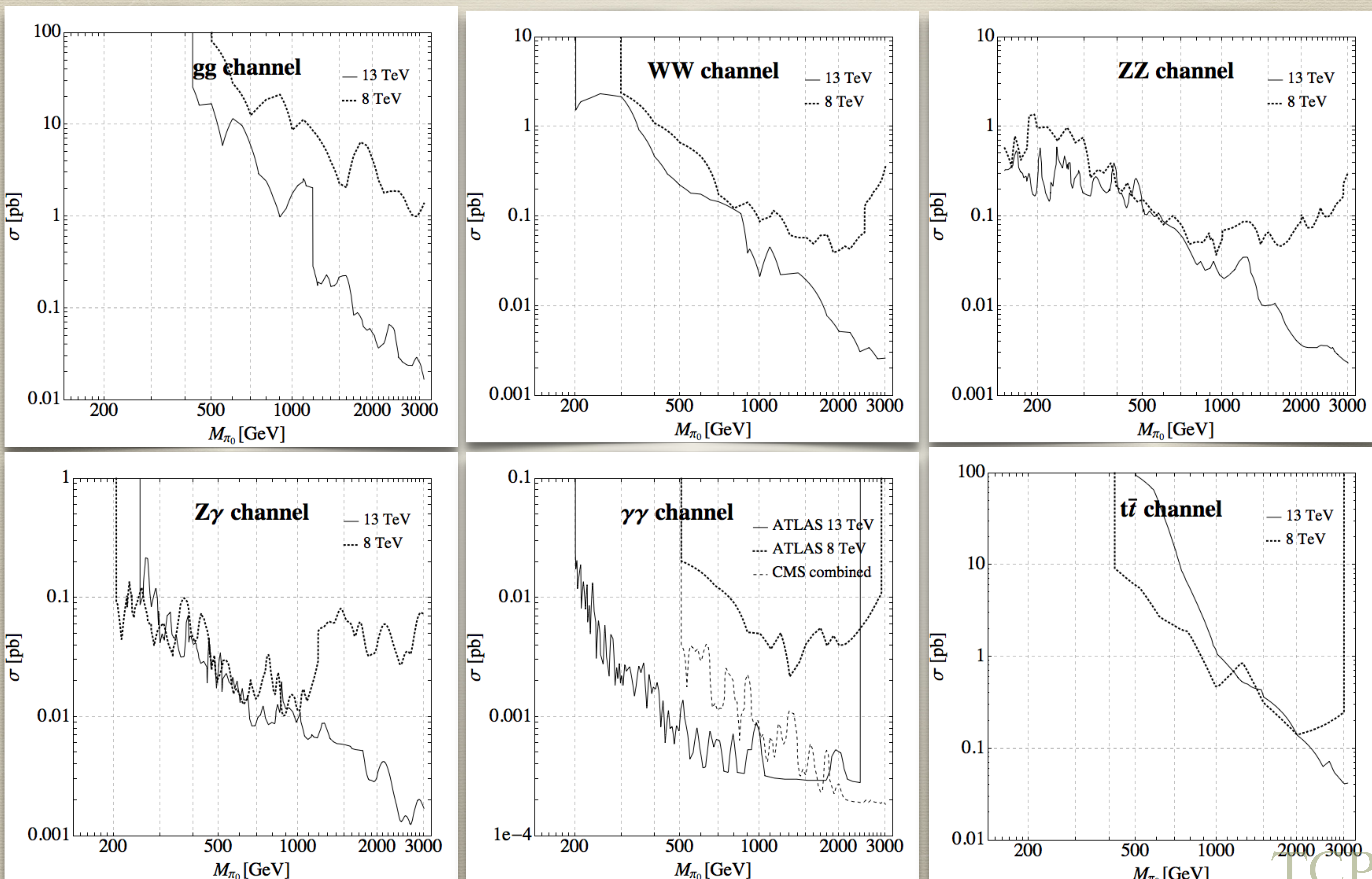
Experimental constraints at "high mass": (37 studies, 44 "bounds" included),ATLAS and CMS @ 8 TeV and 13 TeV (see JHEP 1701 (2017) 094 for full refs)



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Coefficients of *a* for sample models M1 - M12

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

[arXiv:1710.01730]

C_t:

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

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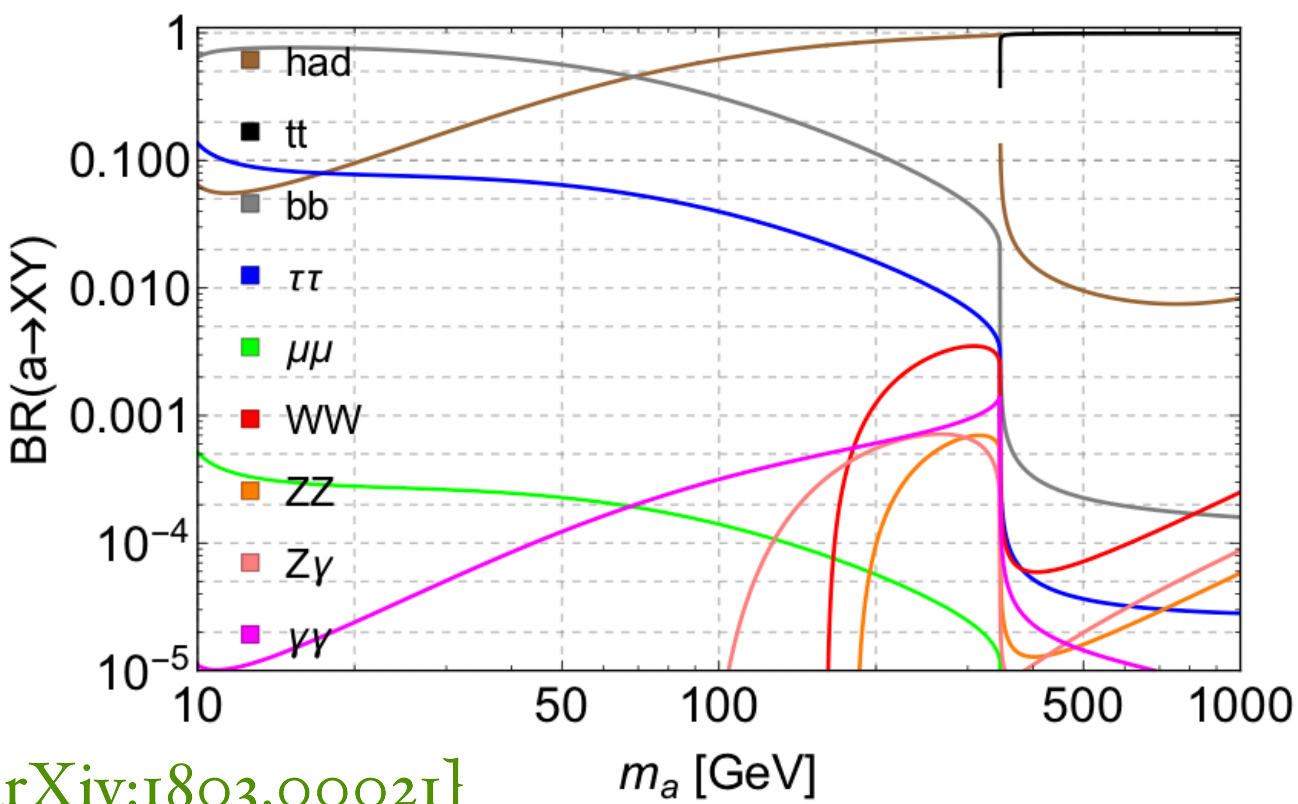
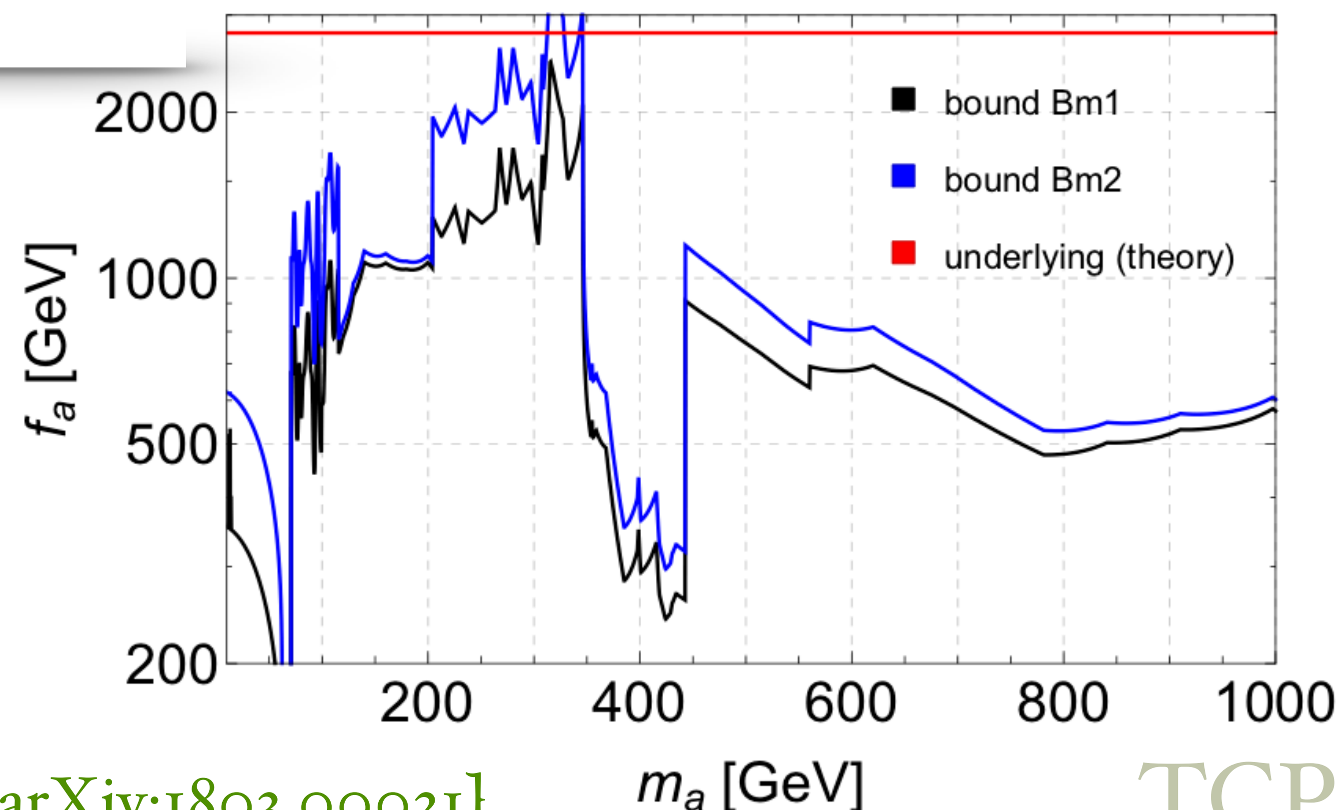
[arXiv:1710.01730]

For a given model, we can combine all channels to get a bound on f_a .



[arXiv:1803.00021]



[arXiv:1803.00021]

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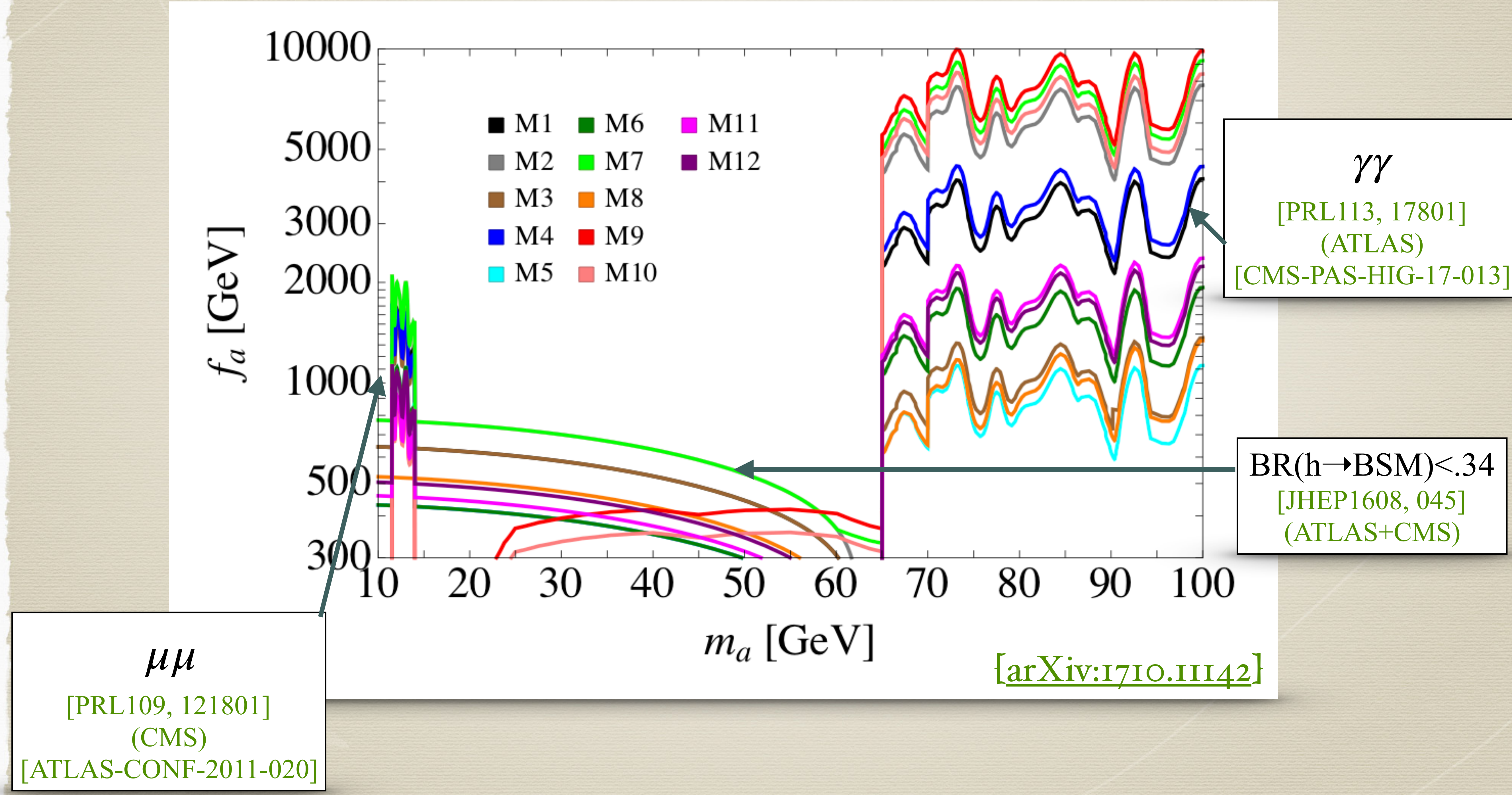
NOTE: Low mass region has a "gap" between 15 - 65 GeV.



[arXiv:1710.11142]

TCP

Light pNGB: How can we search the gap at low mass?

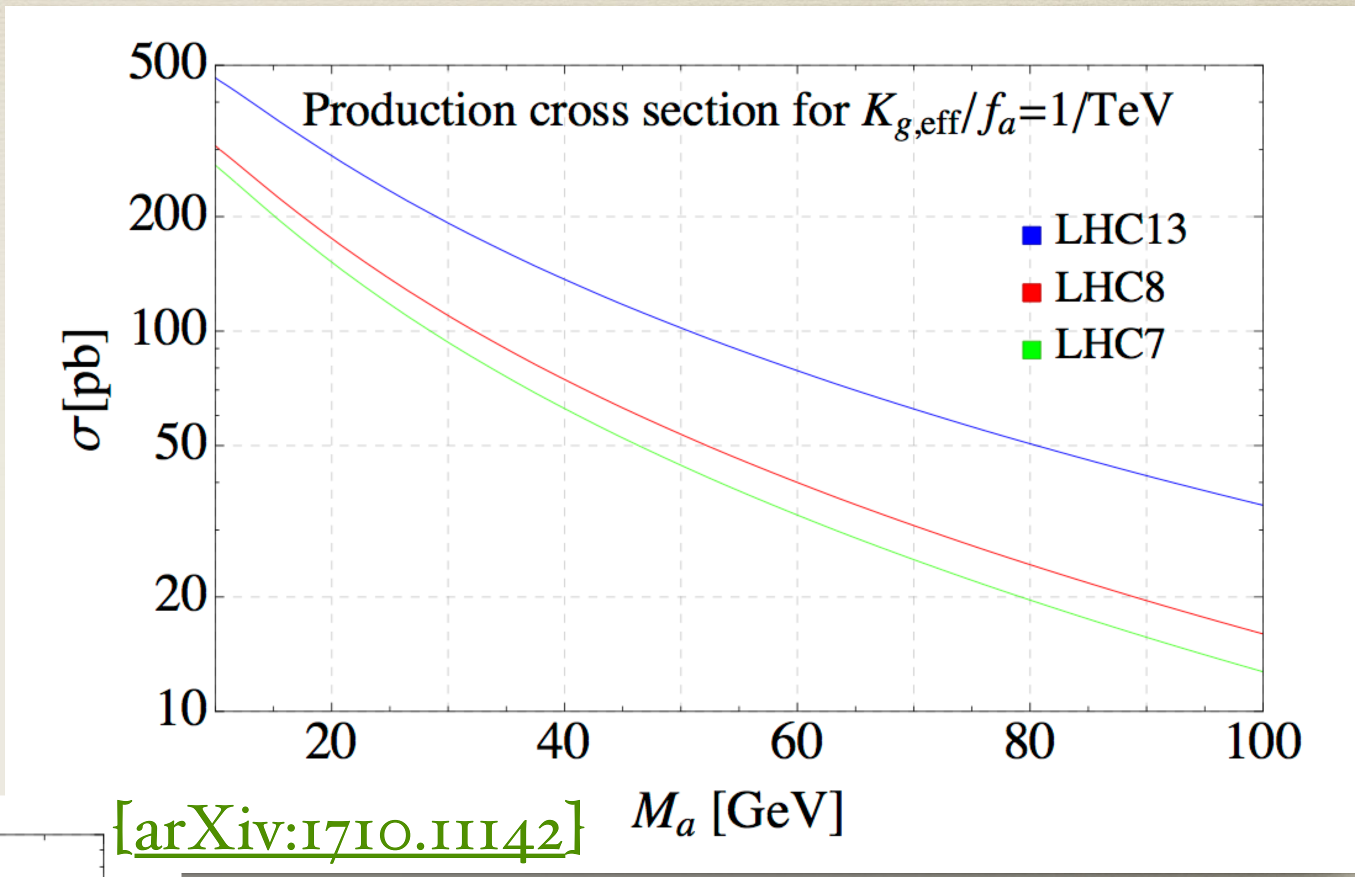
[arXiv:1710.11142]

The models are poorly constrained in the mass range 15 - 65 GeV.

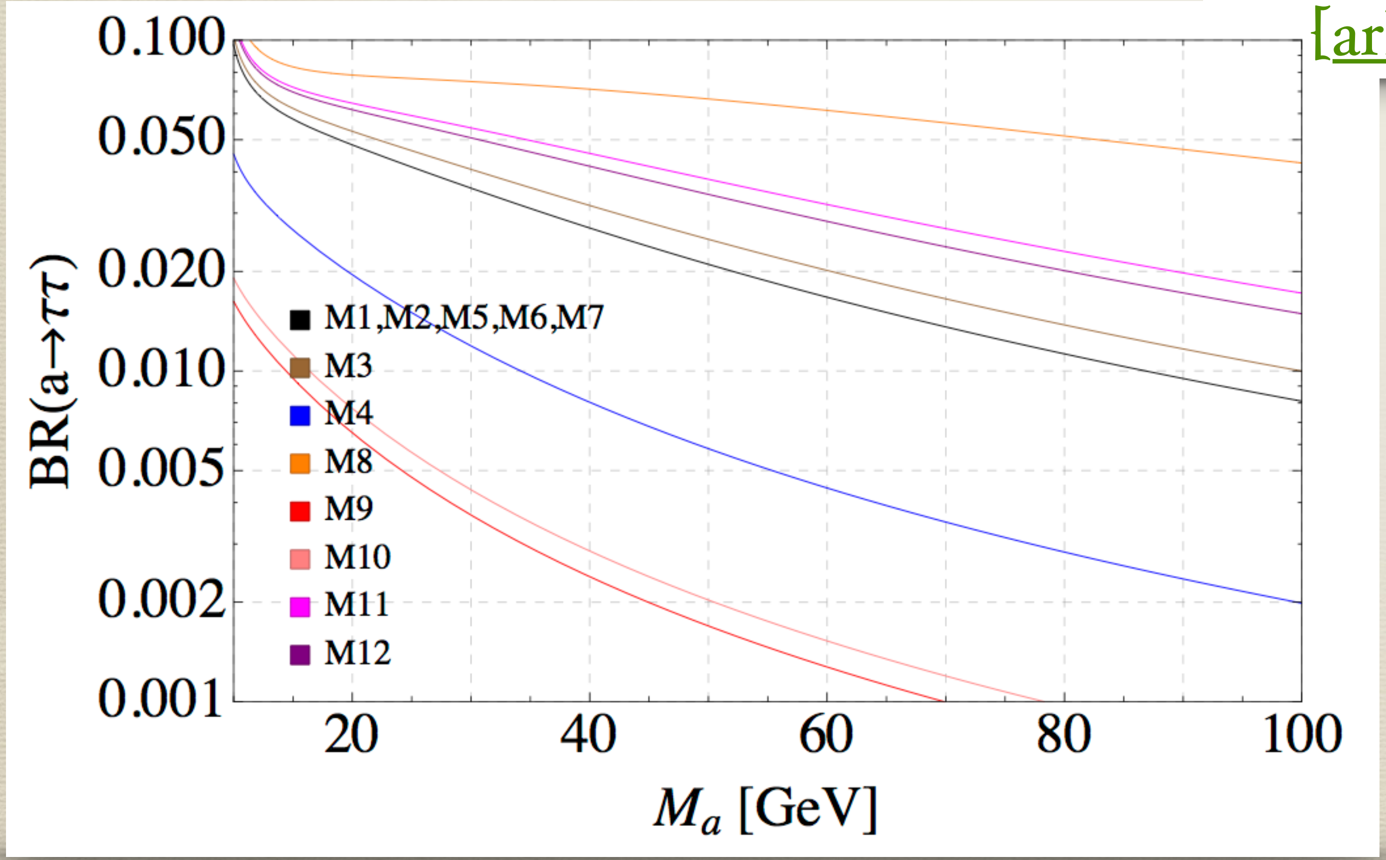
- Weak indirect bounds from $h \to aa$ (BSM) which will not dramatically increase as the bound on f_a scales with $\mathrm{Br}(h \to aa)^{1/4}$.
- $h \to aa \to 4\gamma$, $bb\mu\mu$, $bb\tau\tau$, etc. have very low signal rate due to small haa coupling and small $a \to \gamma\gamma, ff$ branching ratios.
- same applies to $h \to Za$.
- *b*-associated production is small.
- *t*-associated production could yield bounds in future searches. [EPJC 75, 498]
- Extending high resolution $\mu\mu$ resonance searches to higher mass?
- Extending $\gamma\gamma$ resonance searches to even lower mass?
- …or looking for other decay channels: $\tau\tau$!

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

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



[arXiv:1710.11142]



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

TCP

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

Soft $\tau_{\rm lep}$ or $\tau_{\rm had}$ 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

m_a [GeV]	10	20	30	40	50	60	70	80	90	100
M1	37.	18.	12.	8.8	6.8	5.0	3.8	2.7	2.2	1.6
M2	54.	26.	17.	13.	9.9	7.3	5.5	3.9	3.2	2.3
M3	32.	15.	11.	8.2	6.5	4.8	3.7	2.7	2.2	1.6
M4	34.	14.	7.8	5.1	3.7	2.6	1.9	1.3	1.1	0.77
M5	17.	8.0	5.3	3.9	3.1	2.3	1.7	1.2	1.0	0.72
M6	17.	8.0	5.3	3.9	3.1	2.3	1.7	1.2	1.0	0.72
M7	54.	26.	17.	13.	9.9	7.3	5.5	3.9	3.2	2.3
M8	4.9	2.7	2.3	2.1	2.0	1.7	1.5	1.2	1.0	0.79
M9	10.	3.9	2.0	1.3	0.90	0.63	0.45	0.32	0.26	0.18
M10	10.	3.9	2.0	1.3	0.90	0.62	0.45	0.32	0.26	0.18
M11	12.	5.9	4.5	3.7	3.1	2.4	1.9	1.4	1.2	0.86
M12	16.	8.1	6.1	4.8	4.0	3.0	2.4	1.8	1.5	1.1

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.

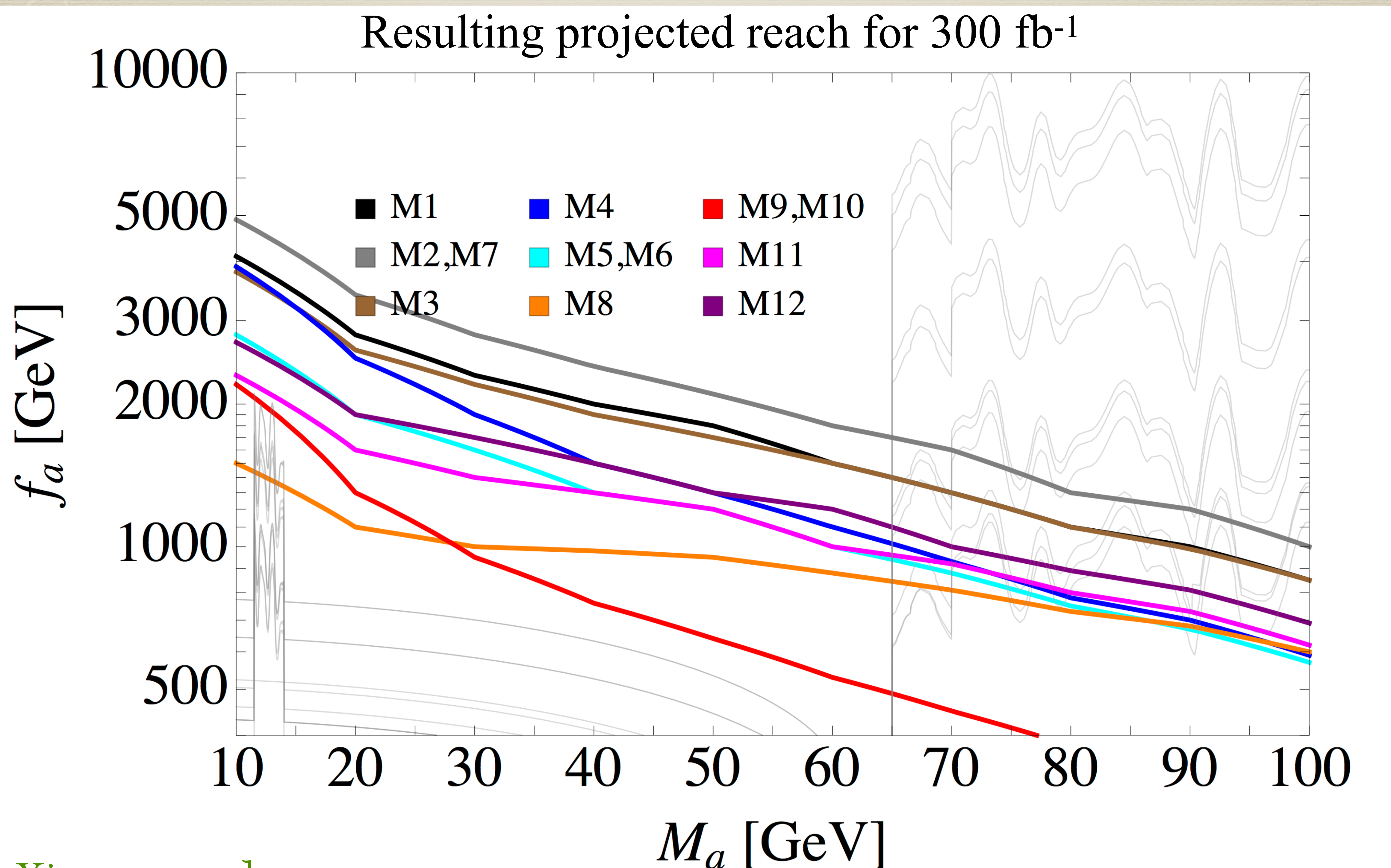
[arXiv:1710.11142]

Main background:

Z/γ^*+jets: 35 fb,

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

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



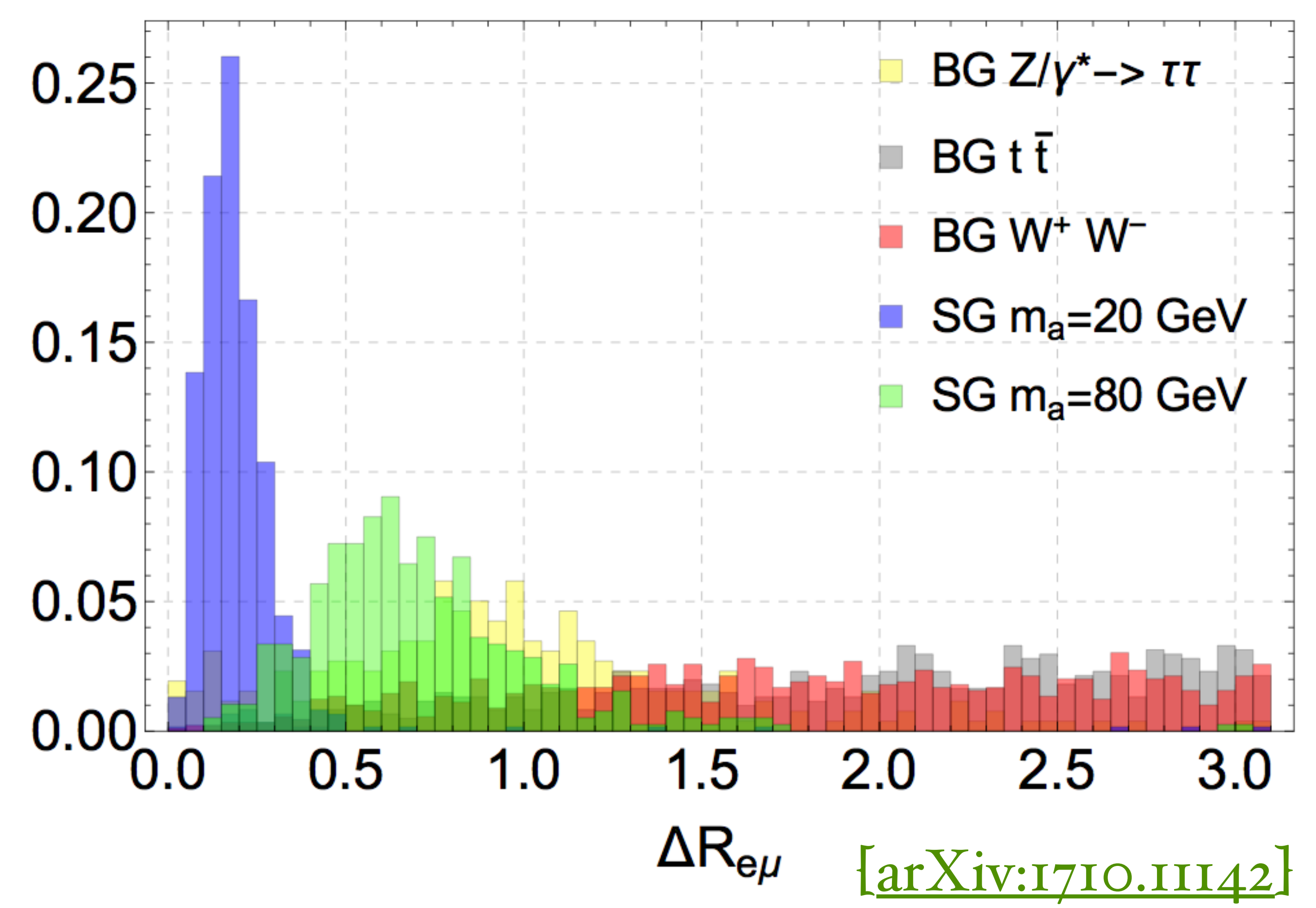
[arXiv:1710.11142]

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

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

Effective Lagrangian:

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

where in the CH UV embeddings:

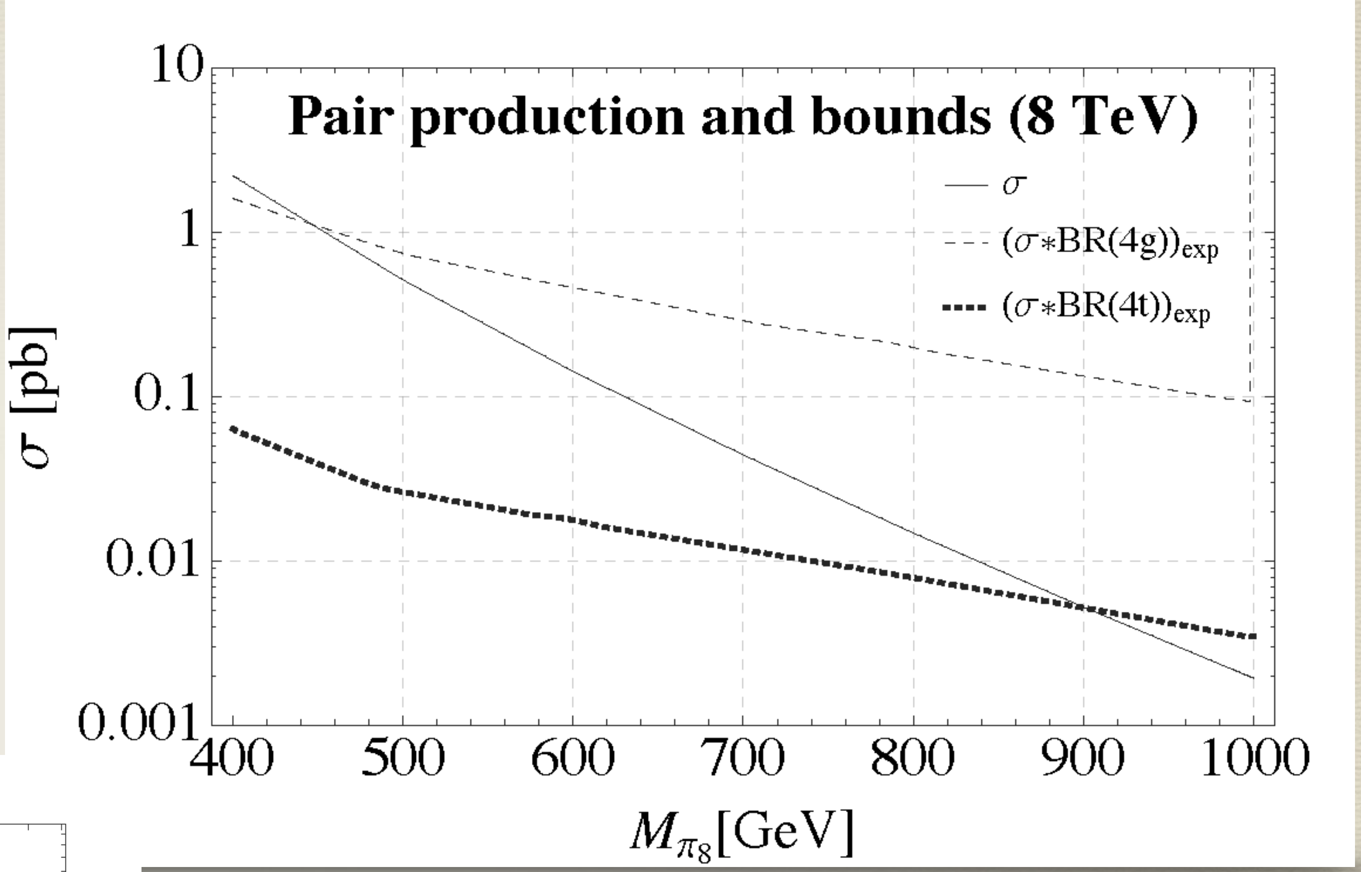
$$\kappa_{g8} = \sqrt{2} c_5\, d_\chi\,, \quad \kappa_{B8} = \sqrt{2} c_5\, 2Y_\chi\, d_\chi, \quad C_{t8} = n_\chi \sqrt{2} c_5 \quad , \qquad m_{\pi_8}^2 \sim \frac{m_a^2}{\xi_\chi \sin^2\zeta} + C_g \frac{3}{4} g_s^2\, f_\chi^2$$

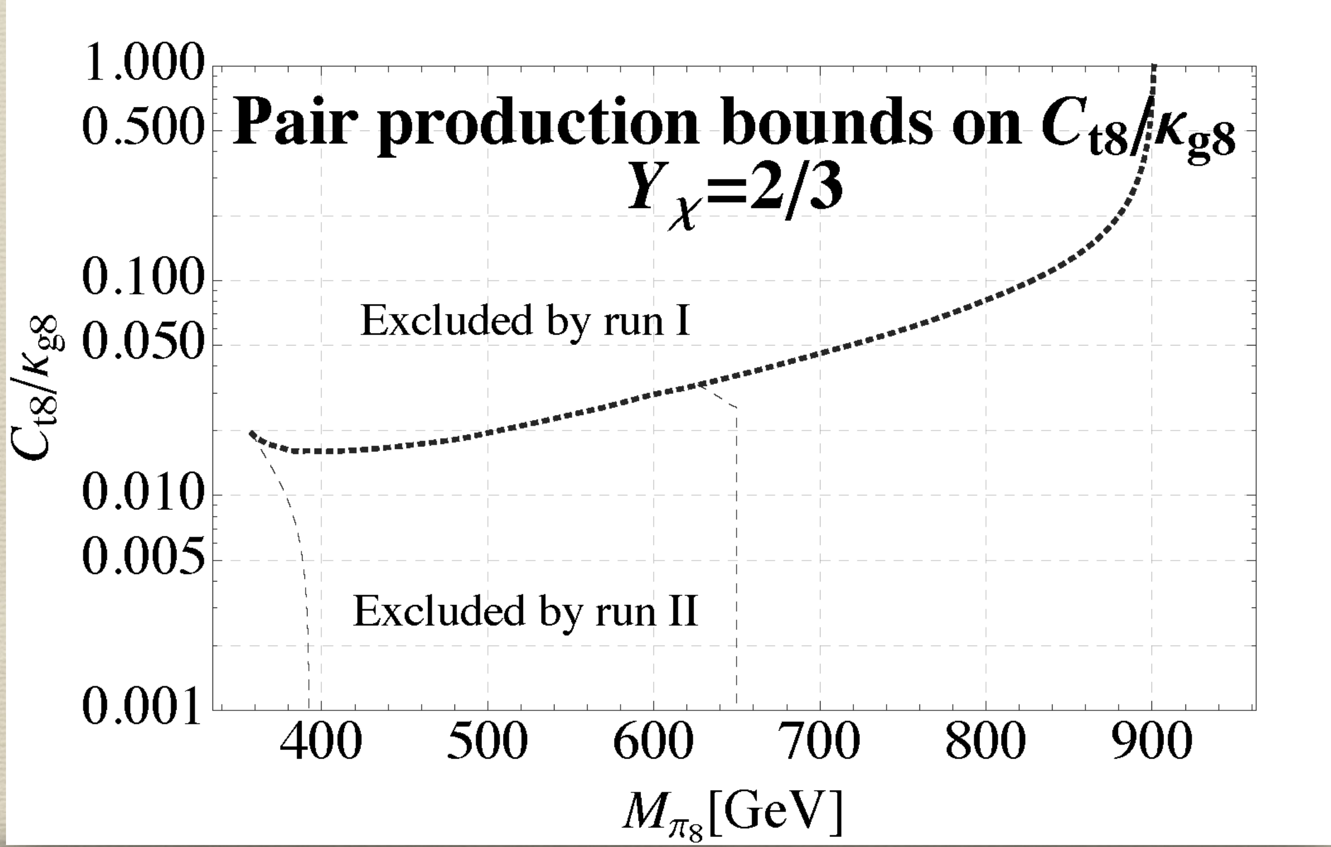
Phenomenology

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

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

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



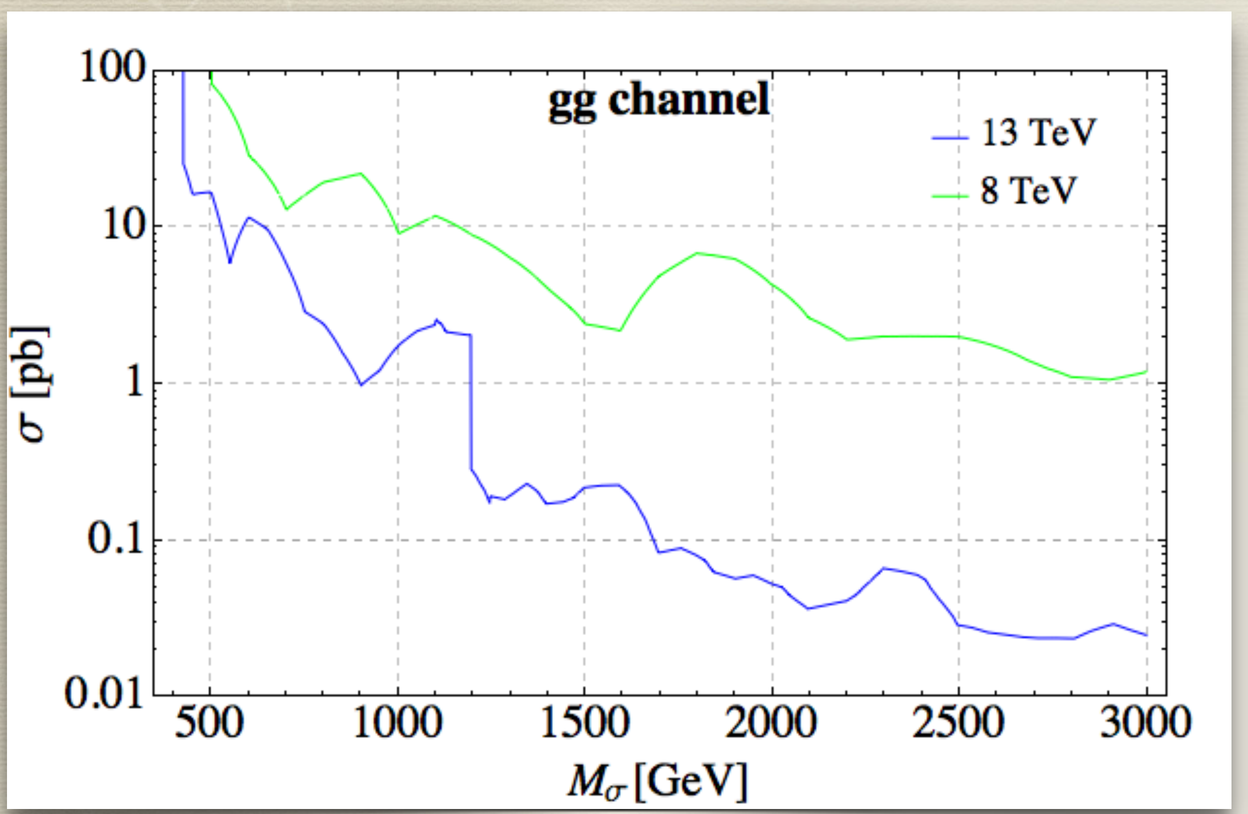


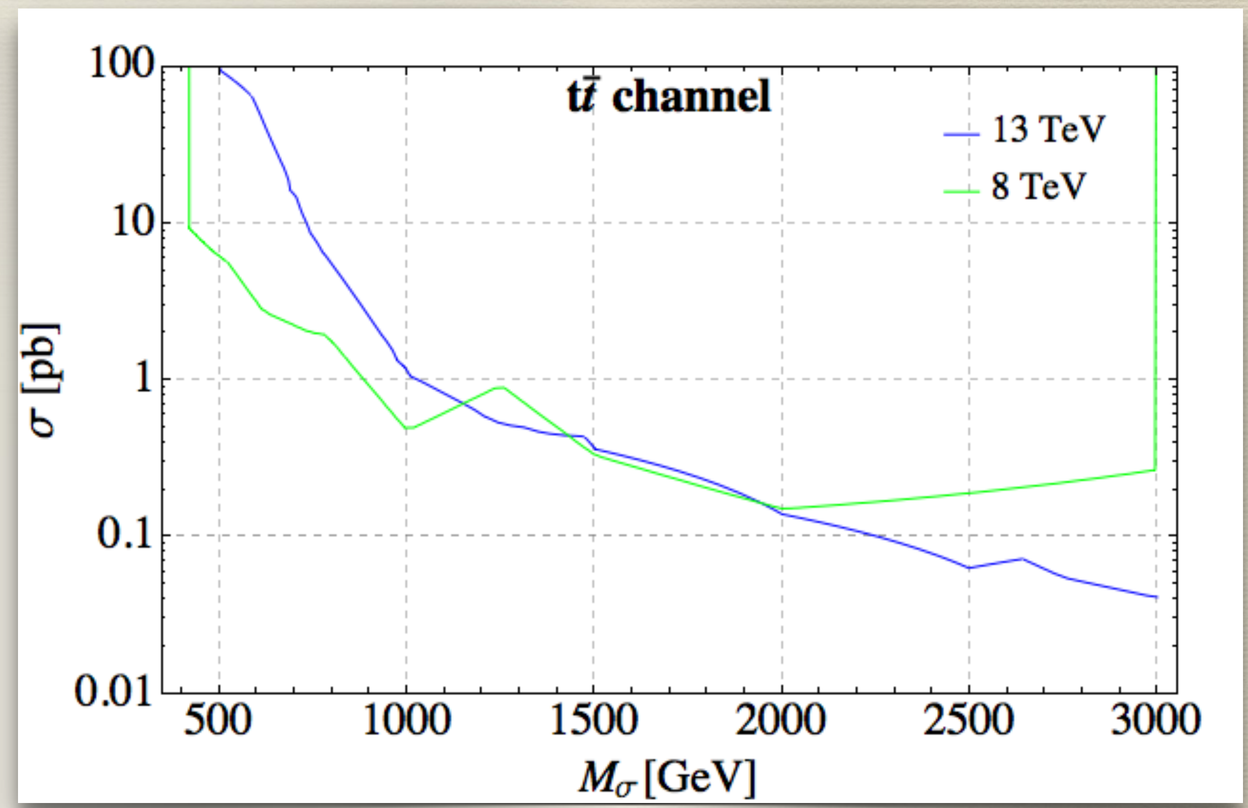
Left: Implied bounds on the C_{t8}/κ_g vs. M_{π_8} parameter space.

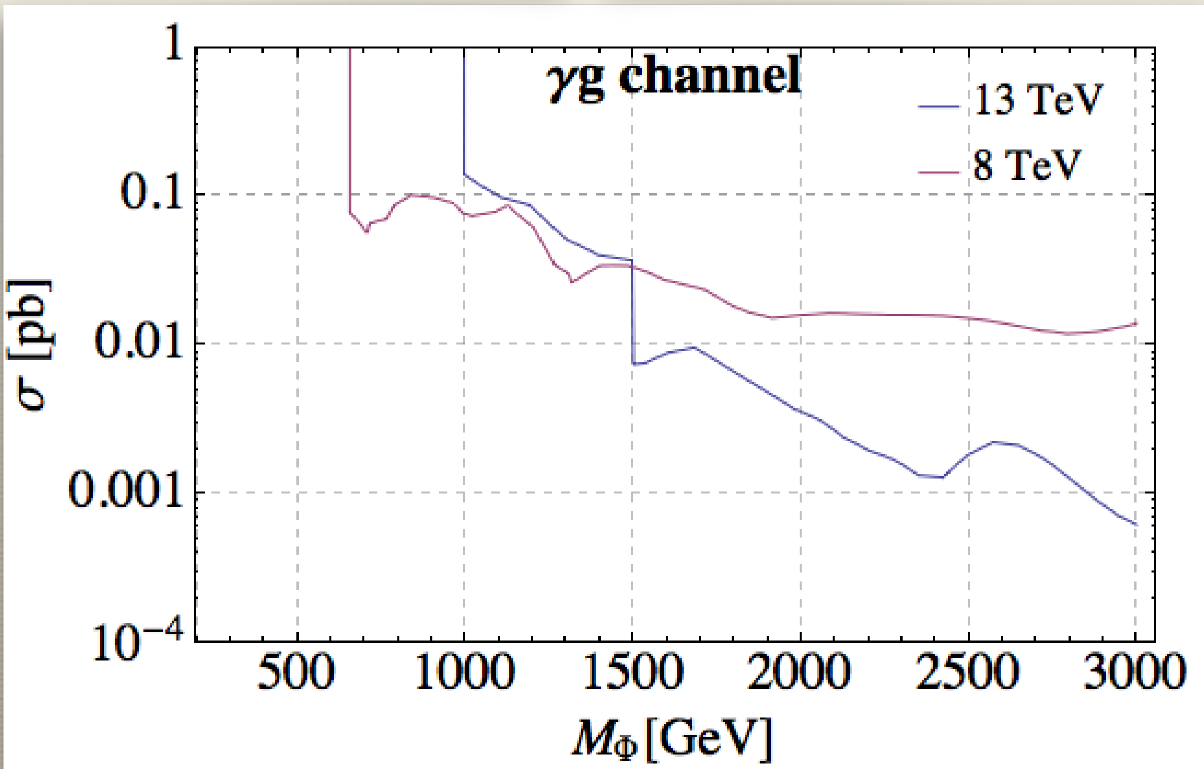
13 TeV bound from ICHEP on di-jet pairs [ATLAS-CONF-2016-084]

Colored PNGBs Constraints from single production:

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





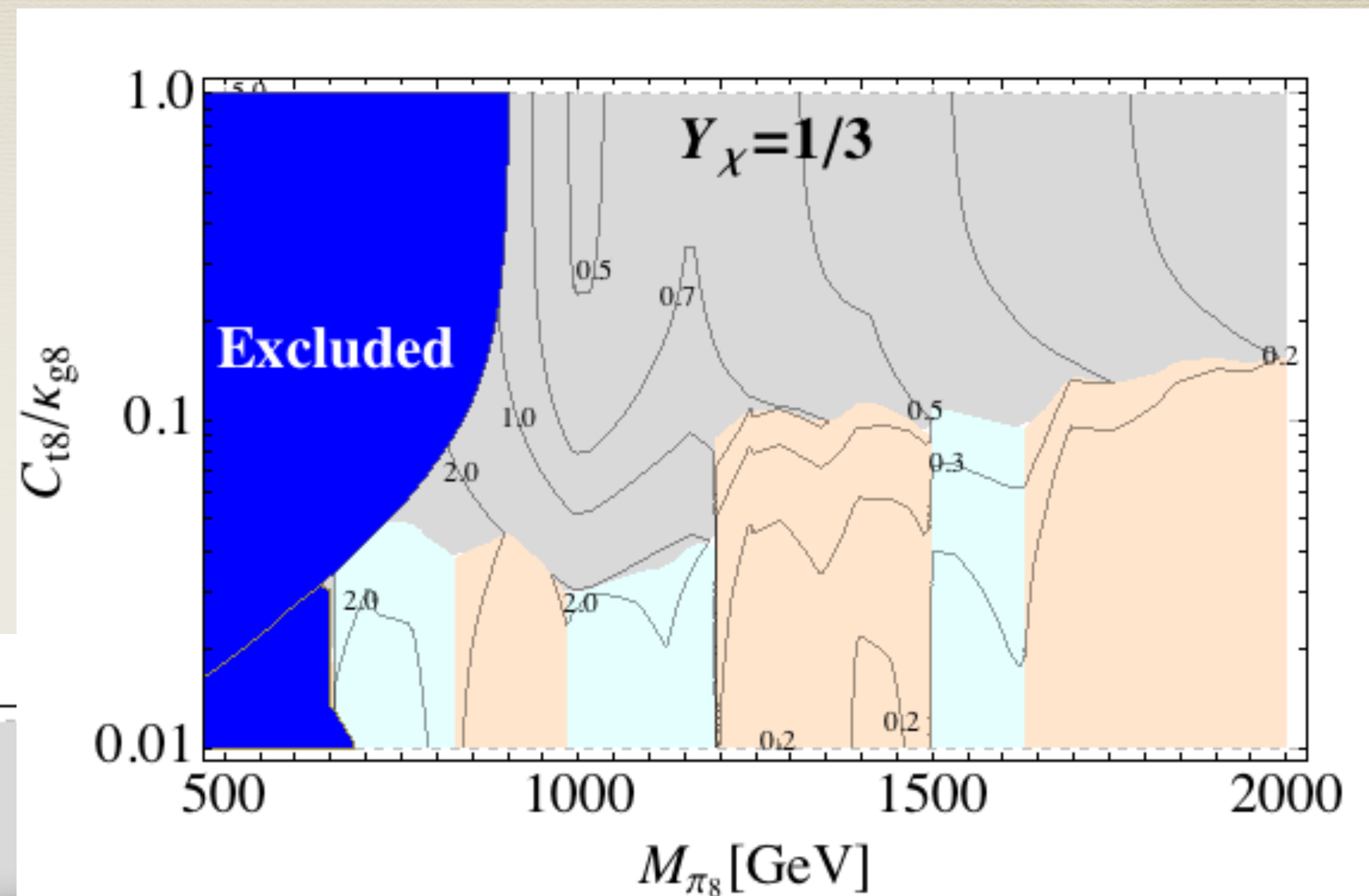


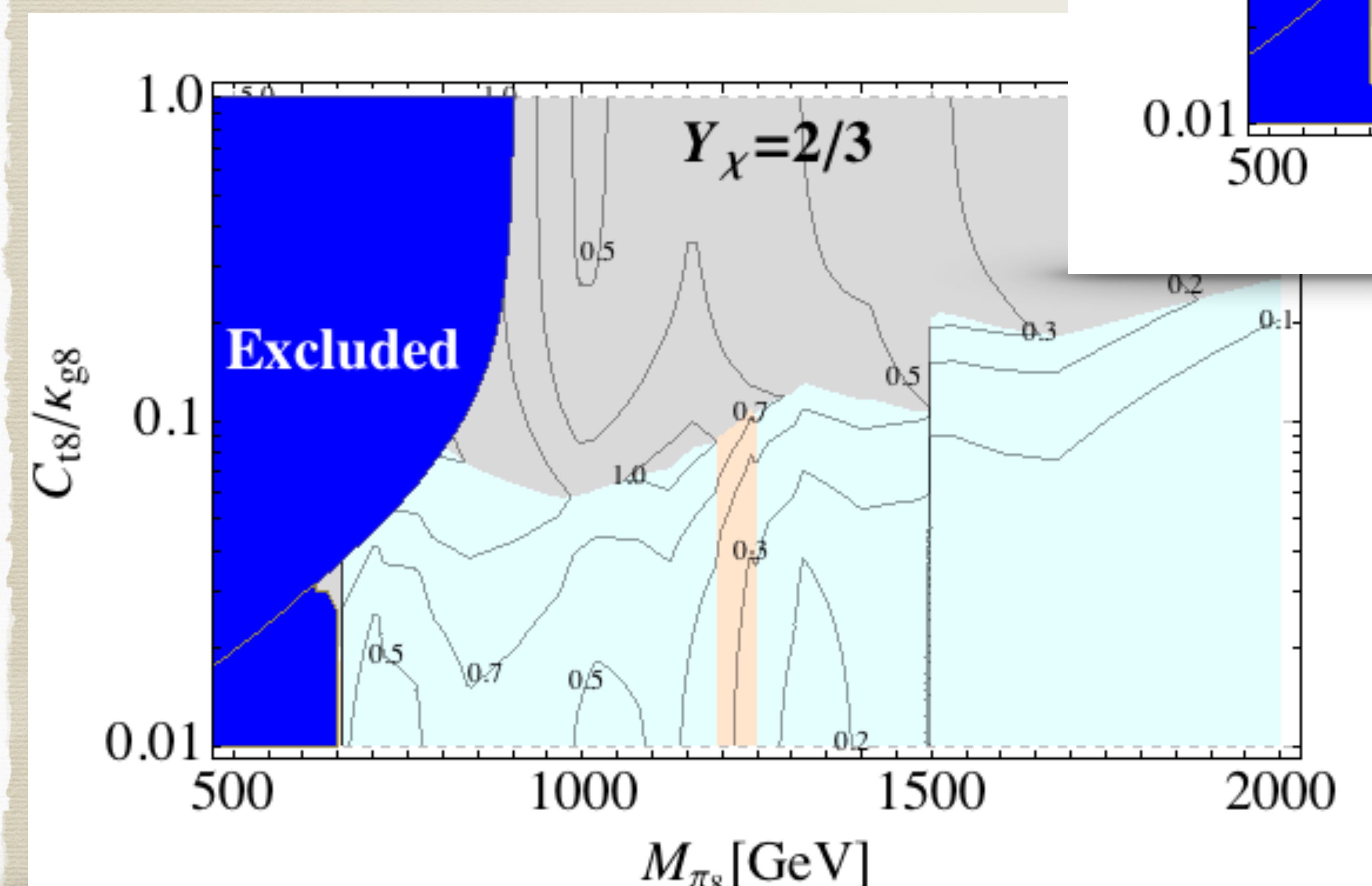
CPNGB

Colored PNGBs
Constraints from single and pair production:

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

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





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

T' single production, exclusion and discovery reach study

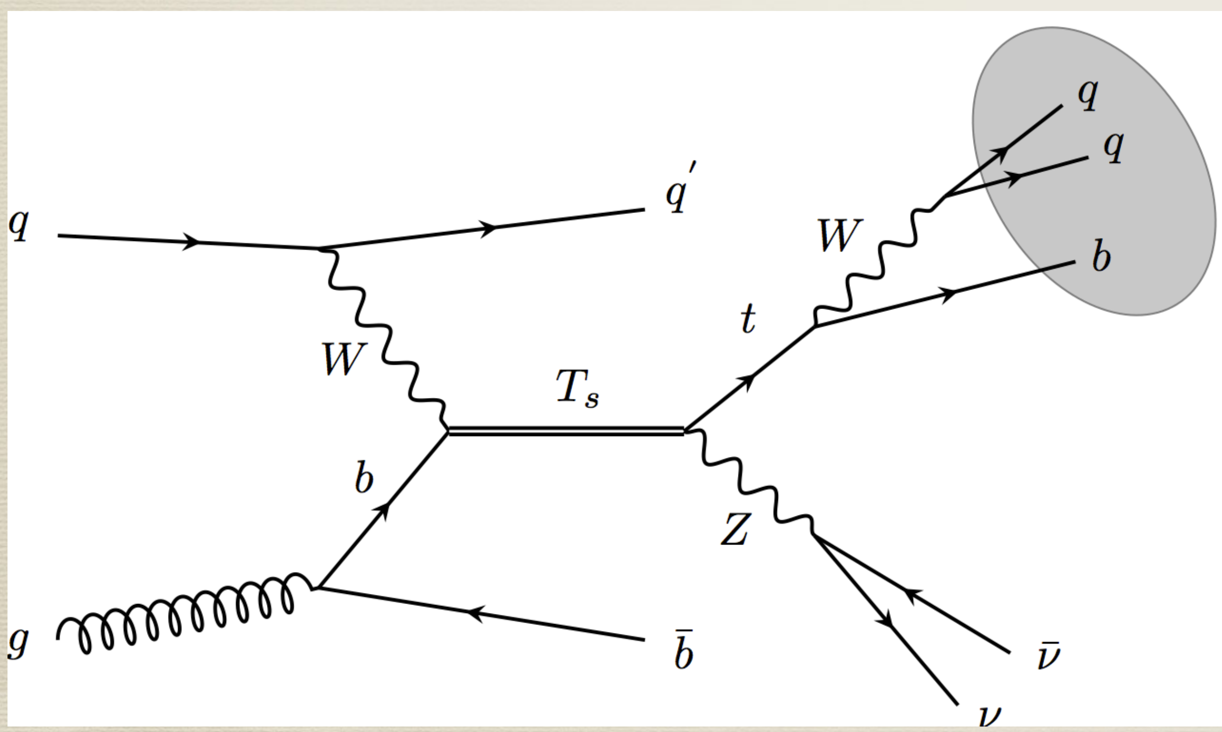
[M. Backovic, TF, J.H. Kim, S.J. Lee; JHEP 1604, 014]

Charge 2/3 3rd family partners can decay to ht, Zt, Wb

⇒ many potential final states (leptonic/hadronic decays of t,Z,W,h …).

We performed a survey study for exclusion and discovery potential in many single-production channels.

One example: $T \rightarrow Zt \rightarrow t_{had}\, Z_{ll}$ vs. $t_{had}\, Z_{MET}$:



Kinematical features / cuts which can be exploited:

- high H_T cut (500 (750) GeV for 1.0 (1.5) TeV $M_{T'}$ target mass)
- Jet-substructure techniques to tag the boosted top (we used template-overlap method)
- forward-jet-tag
- typical Z_{ll} reconstruction for lep. channel
- high MET cut (500 (750) GeV for 1.0 (1.5) TeV $M_{T'}$ target mass) for Z_{MET}

VLQ

T' single production, exclusion and discovery reach study

[M. Backovic, TF, J.H. Kim, S.J. Lee; JHEP 1604, 014]

$T' \to Z_{\rm inv} t_{\rm had}$	$M_{T'} = 1.0$ TeV search						$M_{T'} = 1.5$ TeV search					
	signal	$t\bar{t}$	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}\,(100\,{\rm fb}^{-1})$	signal	$t\bar{t}$	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}\,(100\,{\rm fb}^{-1})$
preselection	4.9	26000	21000	44	0.00011	0.23	1.3	5200	5300	12	0.00012	0.12
Basic Cuts	3.5	900	6100	11	0.00050	0.42	1.0	140	1200	2.4	0.00074	0.27
$Ov_3^t > 0.6$	2.7	510	840	6.5	0.0020	0.75	0.87	81	230	1.6	0.0028	0.49
b-tag	1.8	300	28	4.1	0.0055	1.0	0.51	42	6.7	0.9	0.010	0.72
$\not\!\!E_T > 400\,(600)$ GeV	1.2	13	8.3	0.84	0.055	2.6	0.39	0.95	1.4	0.13	0.16	2.5
$N_{\rm fwd} \geq 1$	0.75	2.5	1.2	0.25	0.19	3.8	0.26	0.19	0.23	0.039	0.58	3.9
$\lvert\Delta\phi_{\not\!\!E_T,j}\rvert > 1.0$	0.62	0.89	0.91	0.21	0.31	4.4	0.21	0.072	0.17	0.031	0.78	4.1

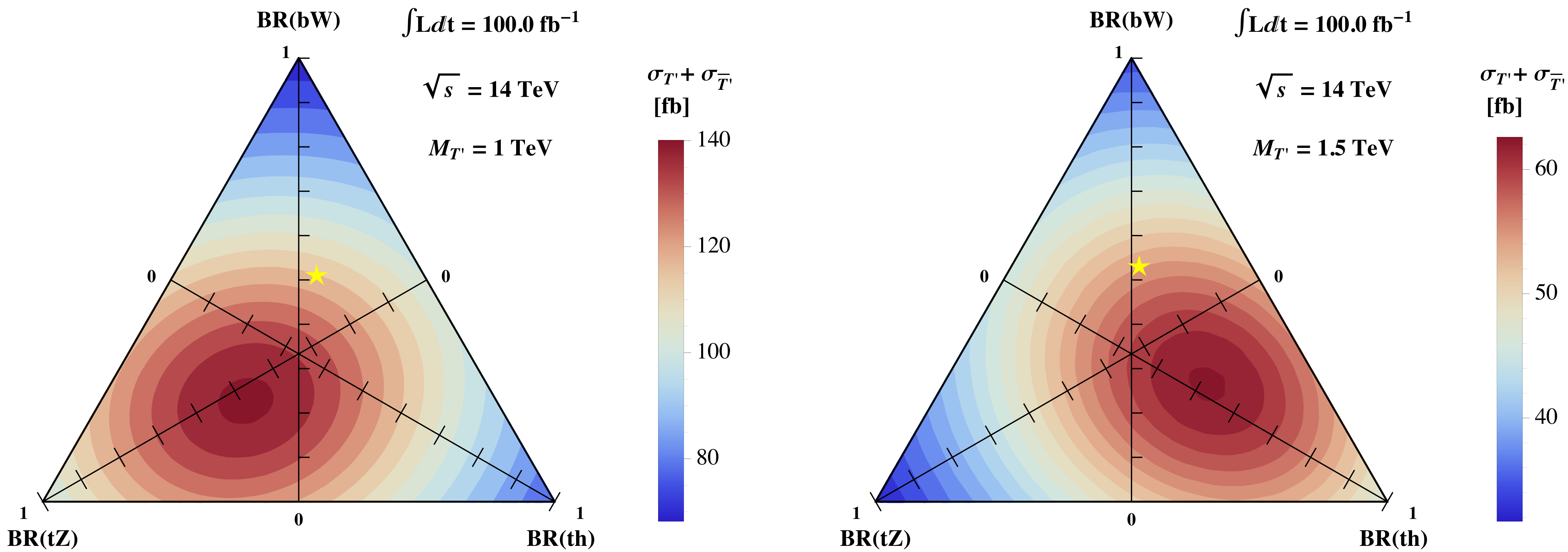
$T' \to Z_{ll} t_{\rm had}$	$M_{T'} = 1.0$ TeV search					$M_{T'} = 1.5$ TeV search				
	signal	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}$	signal	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}$
preselection	1.6	4800	13	3.3×10^{-4}	0.23	0.42	1300	3.5	3.3×10^{-4}	0.12
Basic Cuts	1.1	750	1.3	0.0014	0.39	0.30	170	0.36	0.0018	0.23
$Ov_3^t > 0.6$	0.71	71	0.61	0.010	0.85	0.24	19	0.14	0.012	0.54
b-tag	0.49	2.6	0.40	0.16	2.8	0.14	0.64	0.082	0.19	1.7
$\Delta R_{ll} < 1.0$	0.49	2.6	0.39	0.16	2.8	0.14	0.64	0.081	0.20	1.7
$\lvert m_{ll} - m_Z\rvert < 10$ GeV	0.44	2.4	0.35	0.16	2.7	0.13	0.58	0.074	0.19	1.6
$N_{\rm fwd} \geq 1$	0.28	0.38	0.10	0.58	4.0	0.084	0.098	0.018	0.72	2.5

T' single production, exclusion and discovery reach study

[M. Backovic, TF, J.H. Kim, S.J. Lee; JHEP 1604, 014]

We also studied Wb and ht channels and found $W_{lep}b$ and $h_{bb}t_{had}$ to be most promising.

Combined results:



Expected discovery reach for a T' with mass of 1 TeV (left) and 1.5 TeV (right) in terms of T' production cross section for the LHC at 14 TeV with 100 fb^{-1} of data. The yellow star marks the branching ratios at the sample model point used for simulation.

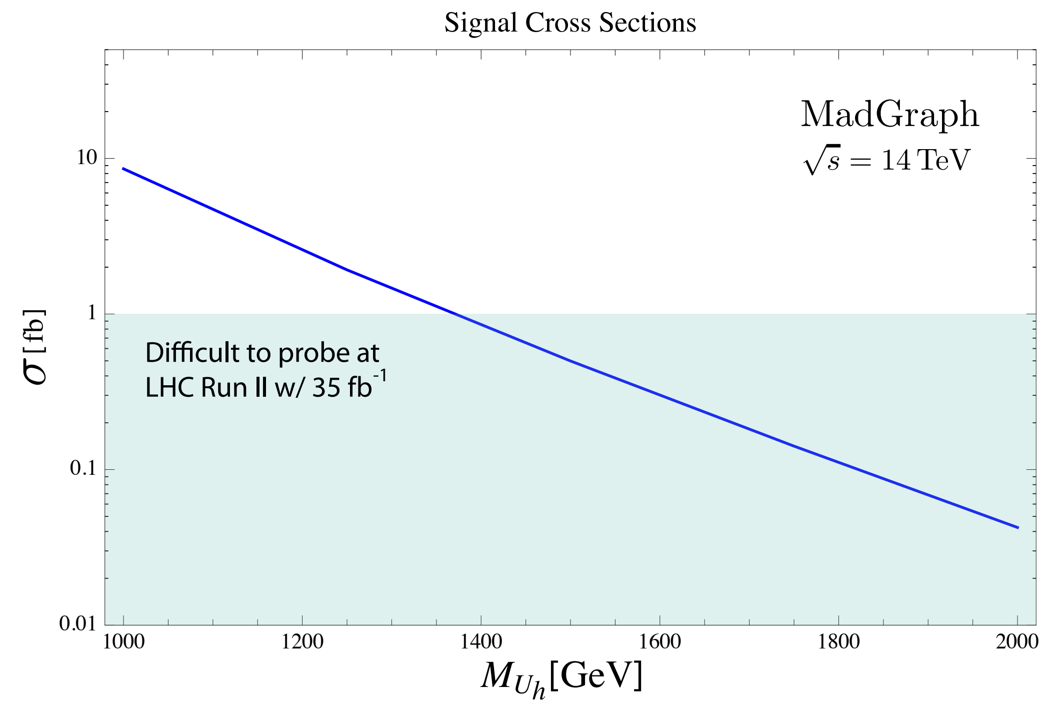
VLQ

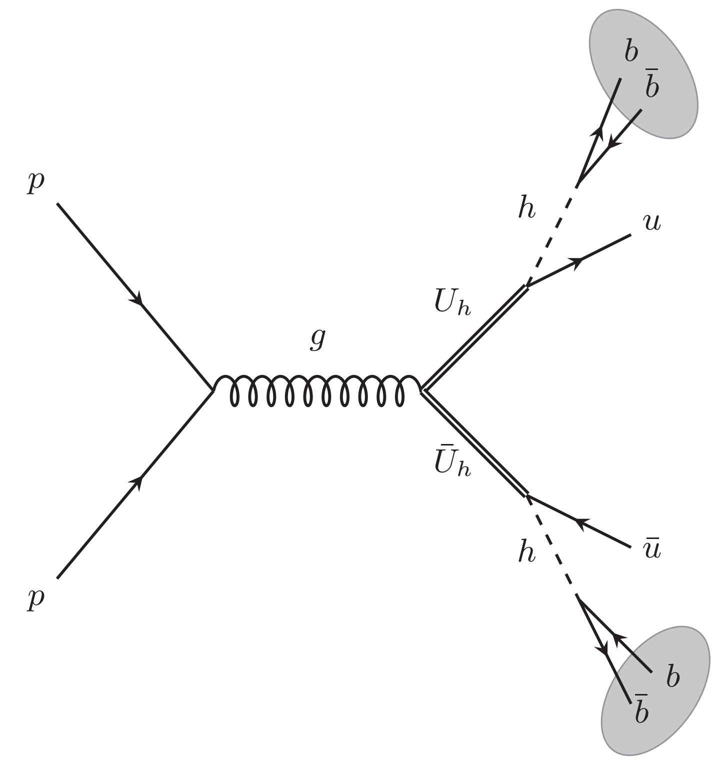
An unconventional di-Higgs final state from light quark partners

[M. Backovic, TF, J.H. Kim, S.J. Lee; JHEP 1504, 082]

Search for light quark singlet partners in the *hhjj* final state with $h \to b\bar{b}$ decays.

M. Backović, TF, J. H. Kim, S. J. Lee [JHEP 1504, 082]





Cut Scheme	Basic Cuts	Demand at least four fat jets ($R = 0.7$) with $p_T > 300$ GeV, $\lvert\eta\rvert < 2.5$
		Declare the two highest p_T fat jets satisfying $Ov_2^h > 0.4$ and $Ov_3^t < 0.4$ to be Higgs candidate jets. At least 1b-tag on both Higgs candidate jets.
		Select the two highest p_T light jets ($r = 0.4$), with $p_T > 25$ GeV to be the u quark candidates.
	Complex Cuts	$\lvert\Delta_h\rvert < 0.1$ $\lvert\Delta_{U_h}\rvert < 0.1$ $m_{U_{h1,2}} > 800$ GeV

Table III: Summary of the Event Selection Cut Scheme.

VLQ

An unconventional di-Higgs final state from light quark partners

[M. Backovic, TF, J.H. Kim, S.J. Lee; JHEP 1504, 082]

	σ_s [fb]	$\sigma_{t\bar{t}}$ [fb]	$\sigma_{b\bar{b}}$ [fb]	$\sigma_{\text{multi-jet}}$ [fb]	S/B	$S/\sqrt{B}$
Preselection Cuts	6.8	4.6×10^2	8.4×10^3	2.8×10^5	2.4×10^{-5}	7.5×10^{-2}
Basic Cuts	1.2	4.6	16.0	6.8×10^2	1.7×10^{-3}	2.7×10^{-1}
$\|\Delta_{mh}\| < 0.1$	8.2×10^{-1}	1.7	6.5	2.8×10^2	2.9×10^{-3}	2.9×10^{-1}
$\|\Delta_{mU}\| < 0.1$	5.6×10^{-1}	5.5×10^{-1}	2.0	87.0	6.3×10^{-3}	3.5×10^{-1}
$m_{U_{h1,2}} > 800$ GeV	5.0×10^{-1}	3.6×10^{-1}	1.6	67.0	7.3×10^{-3}	3.6×10^{-1}
b-tag	3.4×10^{-1}	4.4×10^{-2}	1.1×10^{-2}	1.5×10^{-2}	**4.8**	**7.5**

Table IV: $M_{U_h} = 1$ TeV , $\sigma_s = 6.8$ fb , $\mathcal{L} = 35$ fb^{-1}

	σ_s [fb]	$\sigma_{t\bar{t}}$ [fb]	$\sigma_{b\bar{b}}$ [fb]	$\sigma_{\text{multi-jet}}$ [fb]	S/B	$S/\sqrt{B}$
Preselection Cuts	2.4	4.6×10^2	8.4×10^3	2.8×10^5	8.15×10^{-6}	2.6×10^{-2}
Basic Cuts	6.0×10^{-1}	4.6	16.0	6.8×10^2	8.6×10^{-4}	1.4×10^{-1}
$\|\Delta_{mh}\| < 0.1$	3.9×10^{-1}	1.7	6.5	2.8×10^2	1.4×10^{-3}	1.4×10^{-1}
$\|\Delta_{mU}\| < 0.1$	2.7×10^{-1}	5.5×10^{-1}	2.0	87.0	3.0×10^{-3}	1.7×10^{-1}
$m_{U_{h1,2}} > 1000$ GeV	2.2×10^{-1}	1.9×10^{-1}	1.0	45.0	4.8×10^{-3}	1.9×10^{-1}
b-tag	1.34×10^{-1}	2.2×10^{-2}	8.5×10^{-3}	1.2×10^{-2}	**3.1**	**3.8**

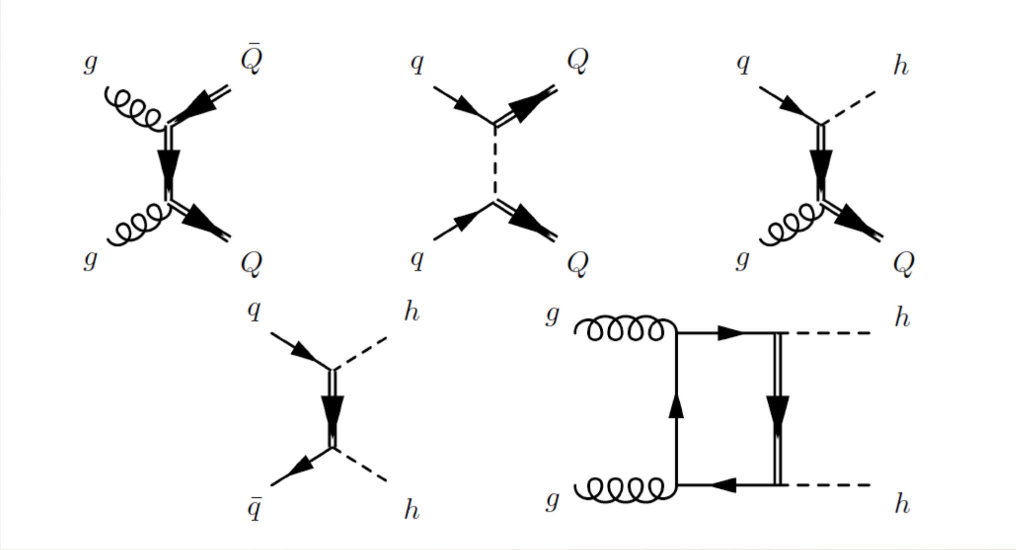
Table V: $M_{U_h} = 1.2$ TeV , $\sigma_s = 2.4$ fb , $\mathcal{L} = 35$ fb^{-1}

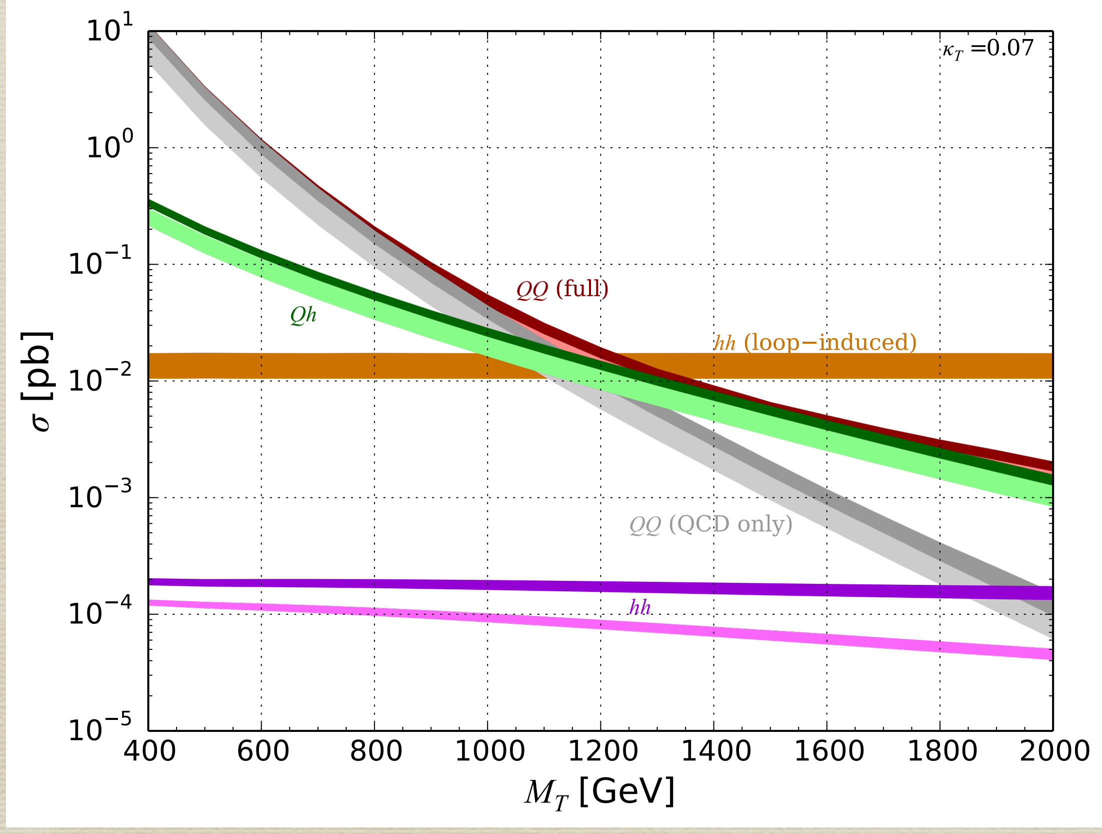
Unconventional (di-)Higgs final states from light quark partners facing ATLAS / CMS-like di-Higgs search strategies

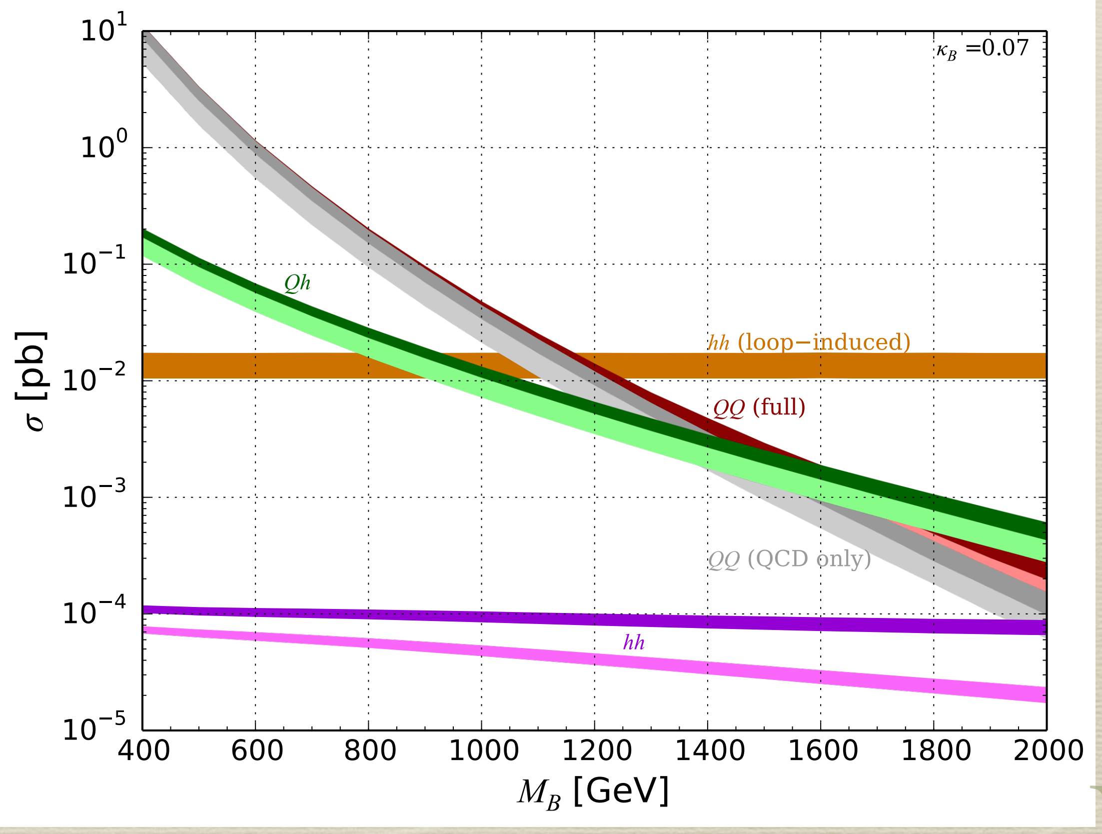
[G. Cacciapaglia, H. Cai, A. Carvalho, A Deandrea, T. Flacke, B. Fuks, D. Majumder, H.-S. Shao [[JHEP 1707 (2017), 005]]

VLQ quark partners coupling to q and h offer more exotic (di-) Higgs production channels.

To study them in more detail (and lay ground work for future studies), we set up a full Madgraph implementation at NLO…







VLQ

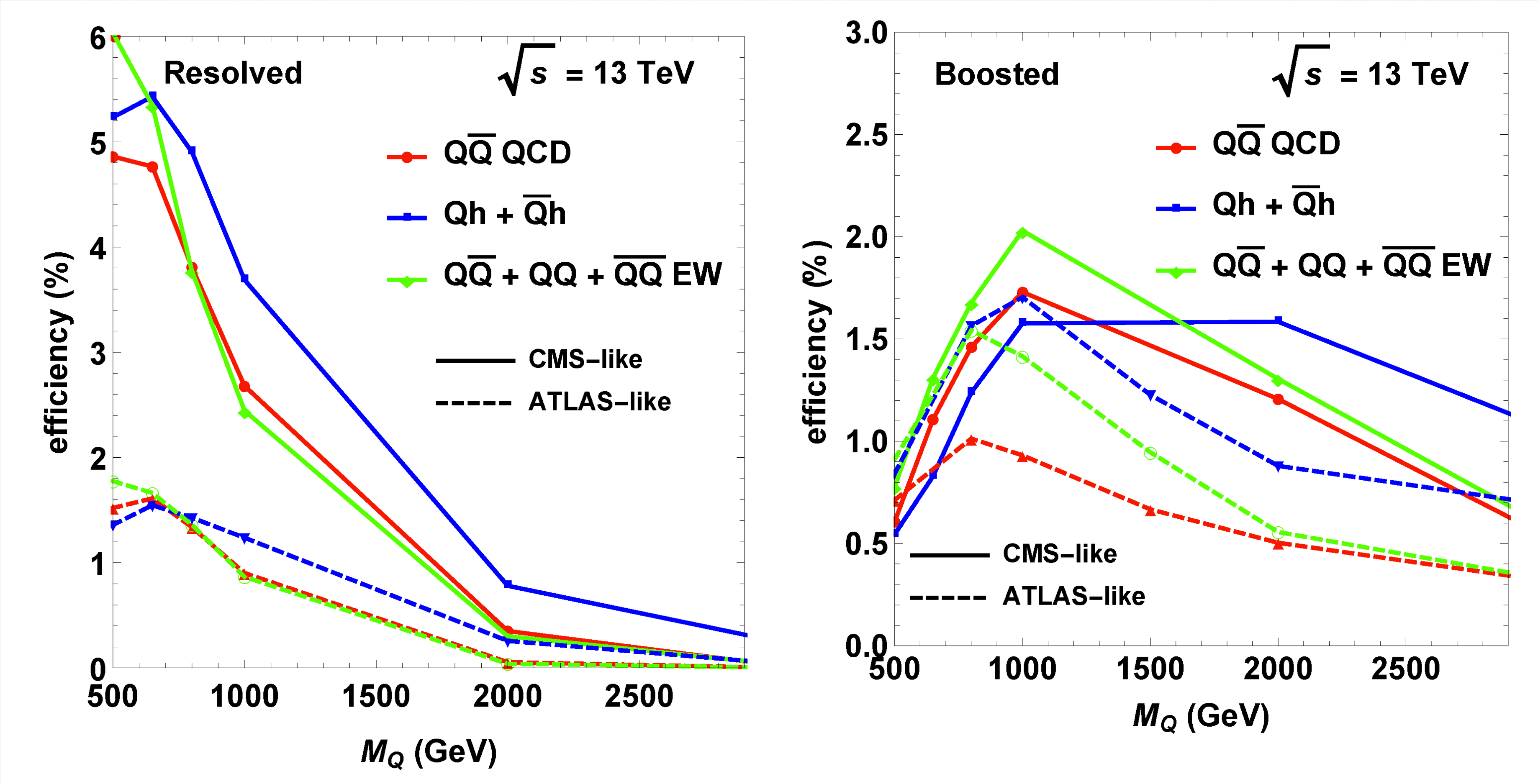
Unconventional (di-)Higgs final states from light quark partners facing ATLAS / CMS-like di-Higgs search strategies

[G. Cacciapaglia, H. Cai, A. Carvalho, A Deandrea, T. Flacke, B. Fuks, D. Majumder, H.-S. Shao [[JHEP 1707 (2017), 005]]

…and determined efficiencies of ATLAS and CMS-like di-Higgs resolved and boosted cut-settings, oriented at:

[ATLAS-CONF-2016-049]

[CMS-PAS-B2G-16-008]



We also provide numerous kinematical distributions (at LO and NLO) which can be used to optimize cut-schemes if desired.

Analysis	Data	SM	Signals (for given VLQ masses)			
			0.5 TeV	0.8 TeV	1 TeV	2 TeV
ATLAS-resolved (3.2 fb^{-1})	44	47.6 ± 3.8	47.0	3.34	0.78	-
ATLAS-boosted (3.2 fb^{-1})	20	14.6 ± 2.4	23.5	2.82	0.933	0.024
CMS-resolved (2.3 fb^{-1})	797	n.a.	120	7.27	1.68	-
CMS-boosted (2.7 fb^{-1})	15	n.a.	17.6	2.99	1.10	0.04

Table 1. Number of data and predicted signal and background events for four VLQ masses of M_Q = 500, 800, 1000, and 2000 GeV, as obtained in the four reinterpreted LHC analyses and for $\kappa_T = 0.07$.

VLQ