Colored pNGBs in composite Higgs models (and how to find them)

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

G. Cacciapaglia, T. Flacke, Ke-Pan Xi [JHEP 1910, 134]

G. Cacciapaglia, A. Deandrea, T. Flacke, A. Iyer [JHEP 05 (2020) 027]

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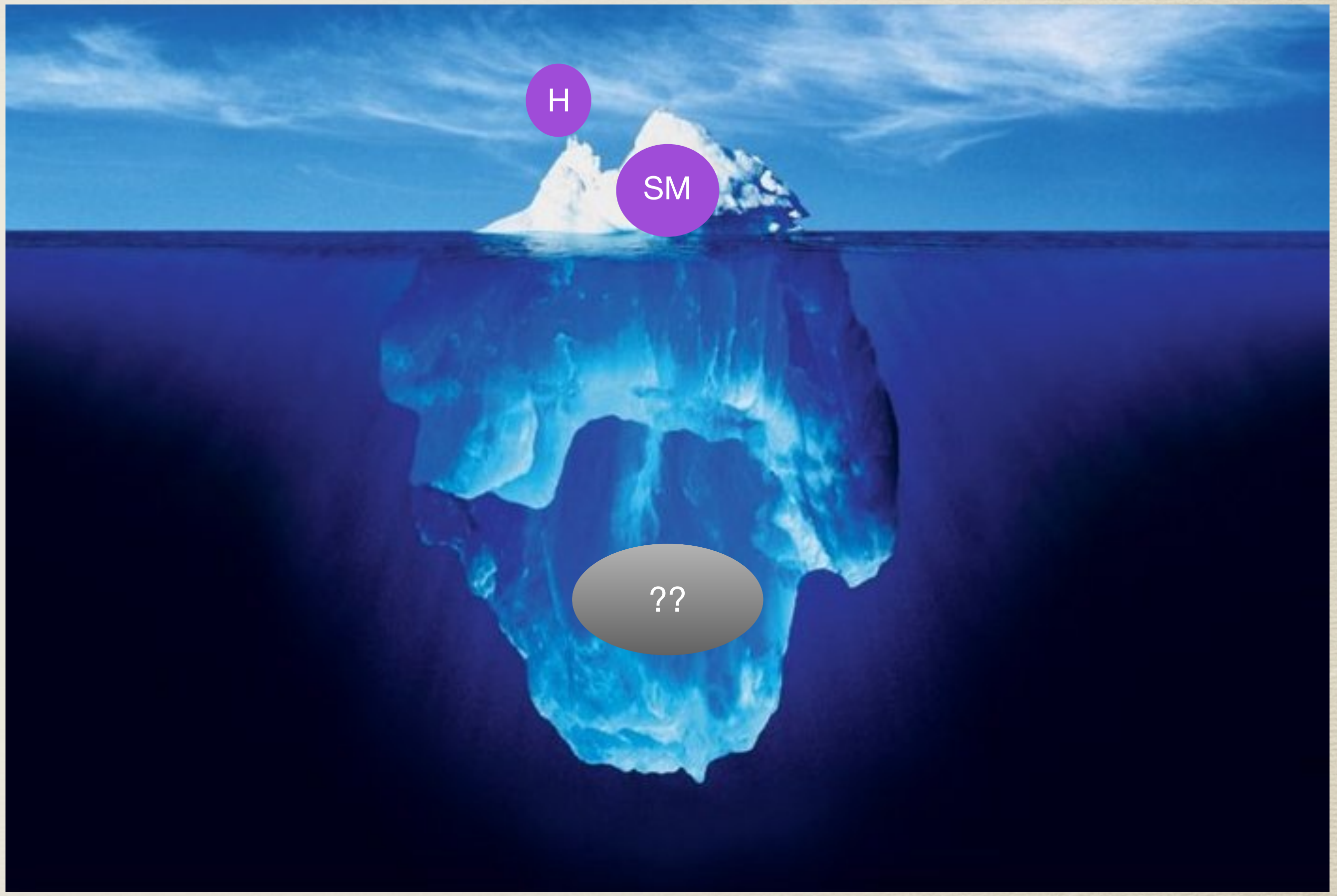
Outline

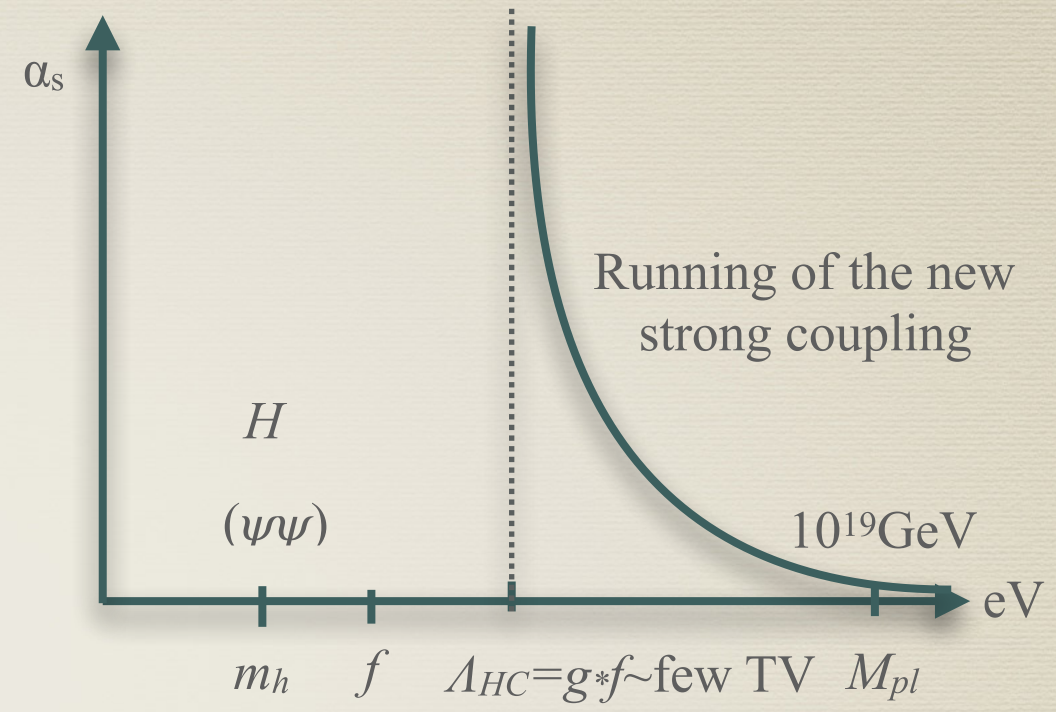
- Motivation for composite Higgs models and new "light" colored states.
- Color octet pseudo Nambu Goldstone bosons and their phenomenology.
- Discovery potential for color octets in a jet-photon resonance pair search.
- Color sextet pseudo Nambu Goldstone bosons and their phenomenology.
- A remark on vector-like quark decay options into colored pseudo Nambu Goldstone bosons.
- Conclusions



Motivation for a composite Higgs

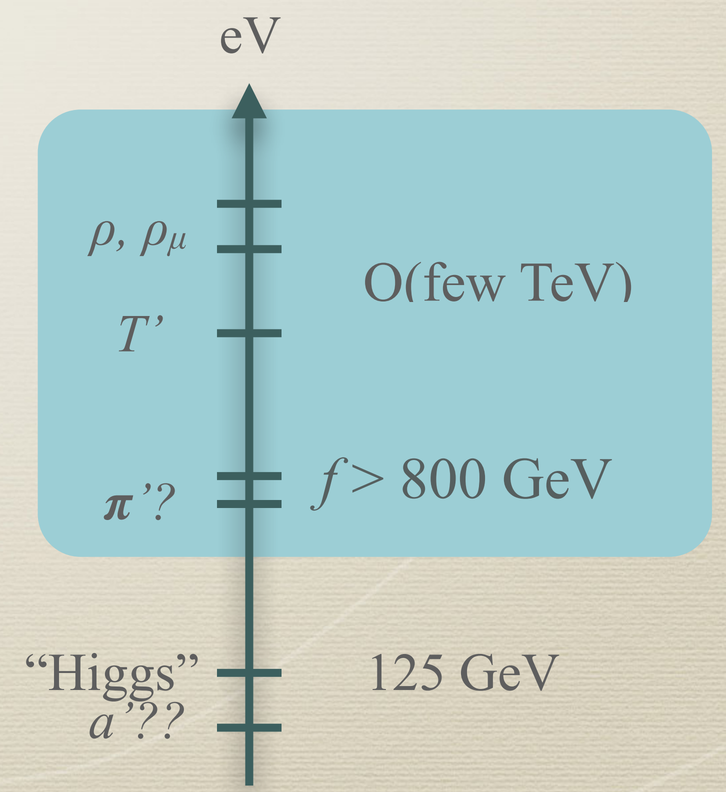
An alternative solution to the hierarchy problem:

- 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.
  [Georgi, Kaplan (1984)]



The price to pay:

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



Composite Higgs Models: Towards underlying models

A wish list to construct and classify candidate models:
Underlying models of a composite Higgs should
Gherghetta etal (2015), Ferretti etal (2014), PRD 94 (2016) no 1, 015004, JHEP 1701, 094

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

The resulting models have several common features:

- All models contain several top partner multiplets.
- All models predict SM neutral, electroweak and colored pNGBs beyond the Higgs multiplet.

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]

Composite Higgs Models: colored pNGBs

Colored pNGBs are generic in underlying models with a composite Higgs and top partners.

- Suppose the Higgs is a composite state $\langle\psi\psi\rangle$, then ψ has to carry EW charge.
- To get colored top partner bound states ($\langle\psi\psi\chi\rangle$ or $\langle\psi\chi\chi\rangle$) requires additional underlying fermions χ which carry color.
- Thus, underlying models also contain $\langle\chi\chi\rangle$ bound states which are colored.

- Underlying models have been classified. [Ferretti etal]
  ALL models contain a pNGB color octet bound state.
- As this state is a pNGB, it is likely to be the lightest colored BSM state in these models.

[JHEP 01 (2017) 094]

Electro-weak coset	$SU(2)_L \times U(1)_Y$
$SU(5)/SO(5)$	$\mathbf{3}_{\pm1} + \mathbf{3}_0 + \mathbf{2}_{\pm1/2} + \mathbf{1}_0$
$SU(4)/Sp(4)$	$\mathbf{2}_{\pm1/2} + \mathbf{1}_0$
$SU(4)\times SU(4)'/SU(4)_D$	$\mathbf{3}_0 + \mathbf{2}_{\pm1/2} + \mathbf{2}'_{\pm1/2} + \mathbf{1}_{\pm1} + \mathbf{1}_0 + \mathbf{1}'_0$

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

Color octet PNGBs: effective Lagrangian

[JHEP2005, 027]

Effective Lagrangian:

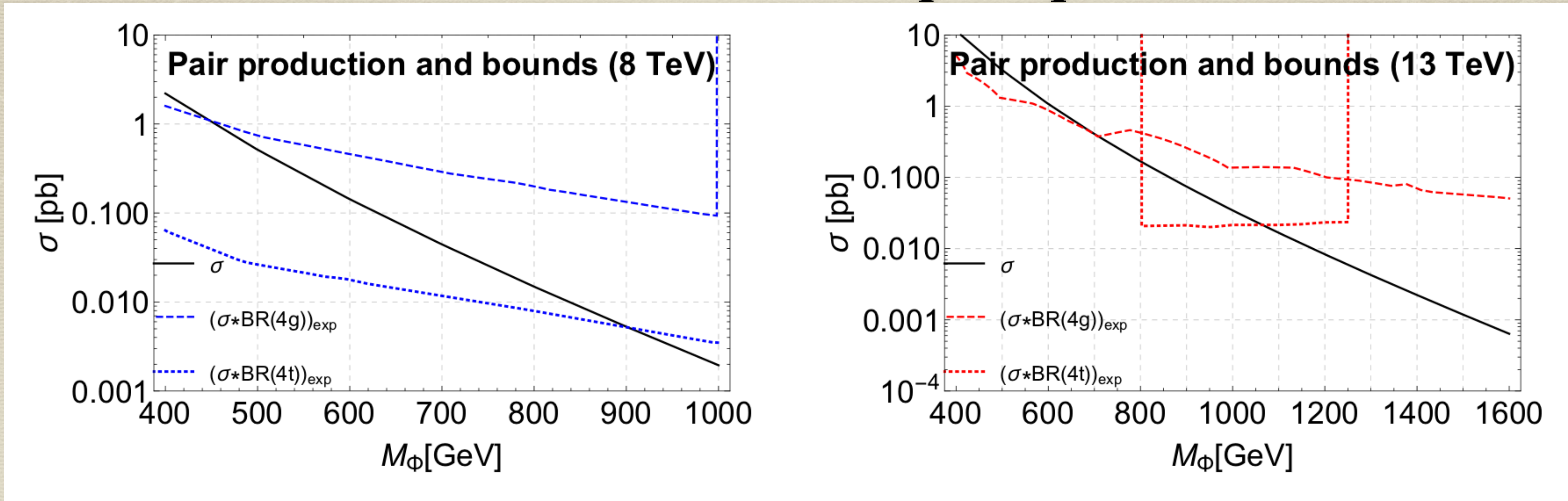
$$\mathcal{L}_\Phi = \frac{1}{2}(D_\mu \Phi^a)^2 - \frac{1}{2}M_\Phi^2 (\Phi^a)^2 + i\, C_t \frac{m_t}{f_\Phi}\Phi^a\ \bar{t}\gamma_5 \frac{\lambda^a}{2} t$$
$$+ \frac{\alpha_s \kappa_g}{8\pi f_\Phi}\Phi^a\ \epsilon^{\mu\nu\rho\sigma}\left[\frac{1}{2}d^{abc}\ G^b_{\mu\nu}G^c_{\rho\sigma} + \frac{g'\kappa_B}{g_s\kappa_g}\ G^a_{\mu\nu}B_{\rho\sigma}\right]$$

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

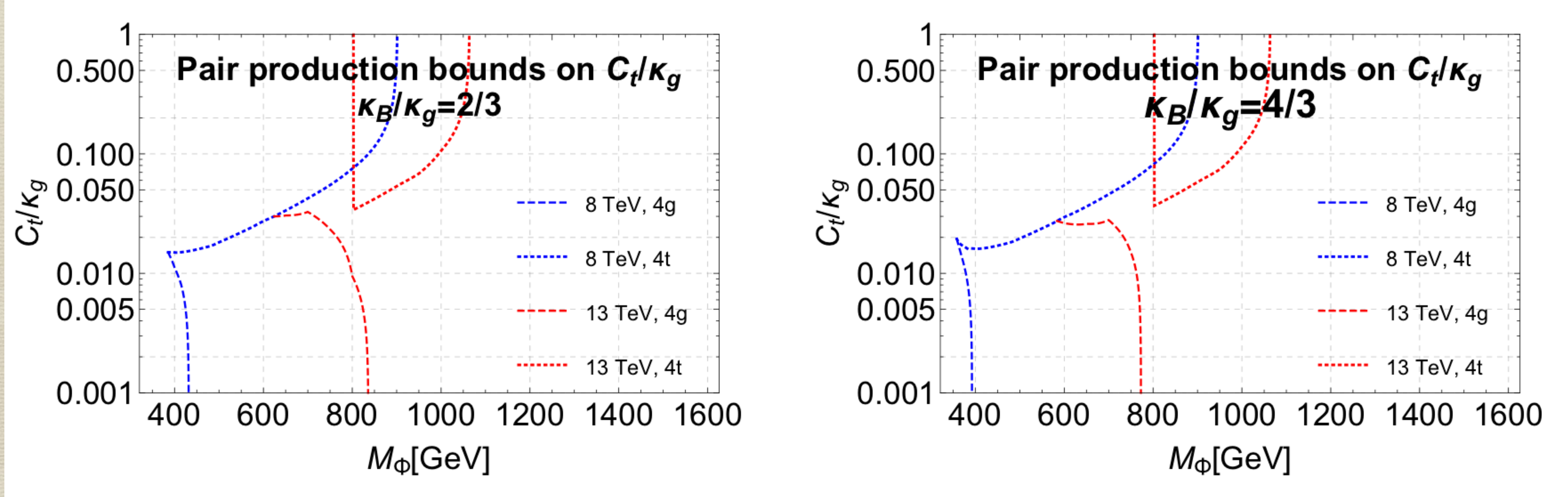
Phenomenology

- **Φ** is single-produced in gluon fusion or pair-produced through QCD.
- **Φ** decays to *gg, 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.

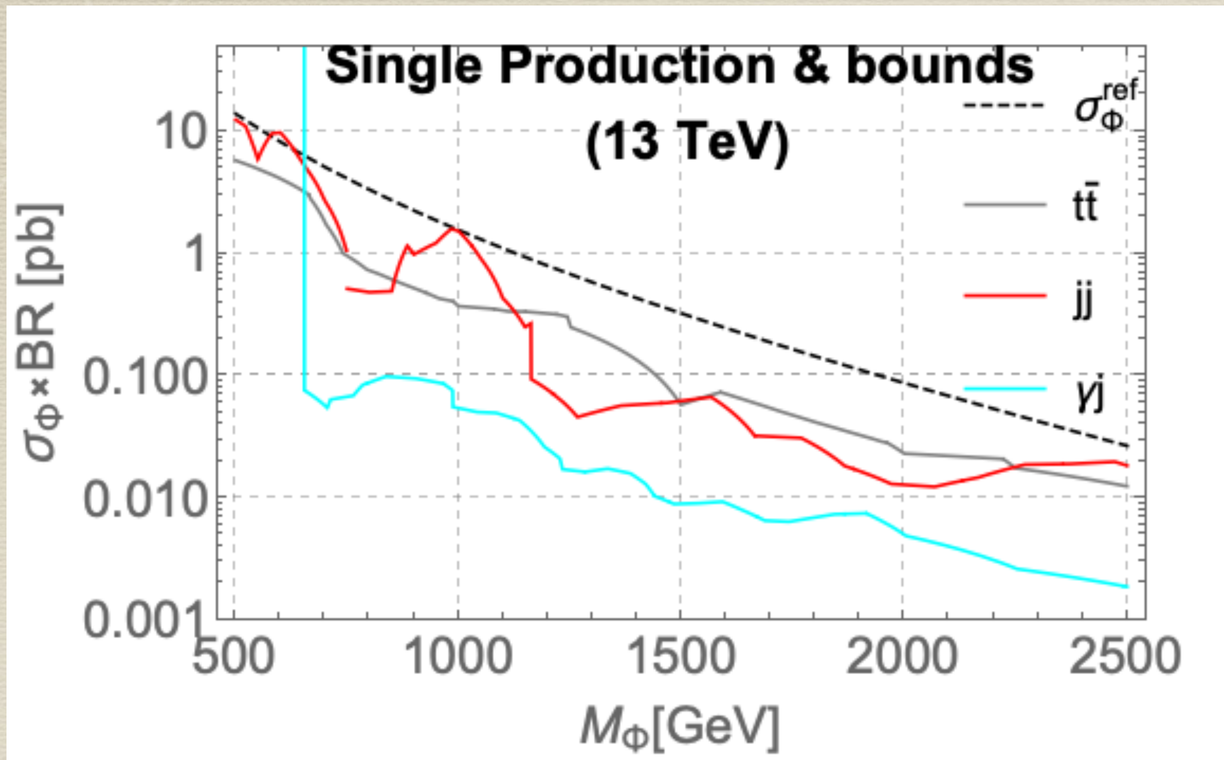
Current constraints from pair production:



Using ATLAS & CMS searches for dijet-pairs: e.g. CMS-EXO-17-021 , ATLAS-SUSY-2016-09
2 di-top resonance searches: e.g. CMS-EXO-13-08 , ATLAS-EXO-2013-16
and the 4t-sgluon search recast Fuks etal (2018). (see JHEP 05 (2020) 027 for full list of references)

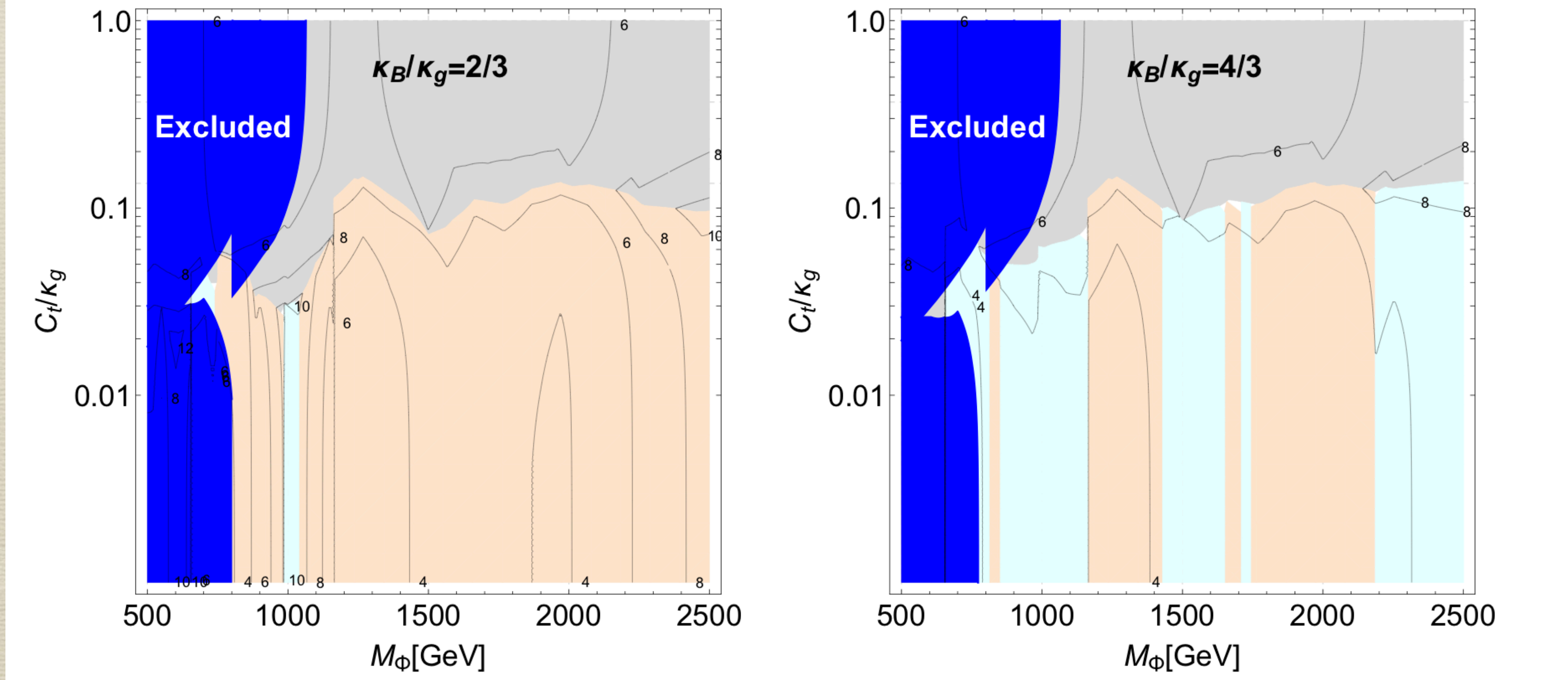


Current constraints from single production:



Using ATLAS & CMS searches for dijets, ditops, and excited quarks.
(see JHEP 05 (2020) 027 for full list of references)

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



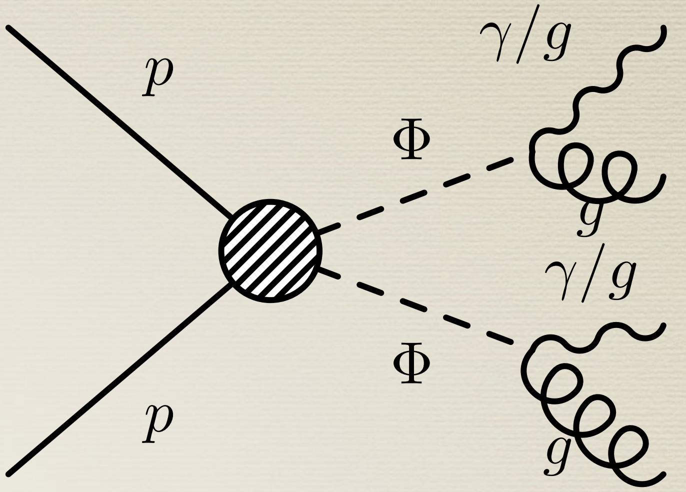
Channels with the strongest bound: *gg* (red), *gγ* (cyan), *tt* (gray). Contours give bounds on κ_g/f_Φ in TeV^{-1}.

Note:

- From underlying models, we expect ~TeV scale mass.
  We are only now starting to probe the interesting parameter space.
- For pair-production, only the (jj)(jj) final state is directly covered by existing 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 yet searched for, and they have high discovery potential.**

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

CMS performed a search for di-jet pairs CMS-EXO-17-021. We are interested in the same topology with one or two jets replaced by photons.



We closely mimic the CMS search strategy with minimal adaptations to the replacement of jets with photons, demanding $p_{T,sum} > 1.5$ TeV and

	$jjjj$	$jjja$	$jjaa$
final state	$N_j \geq 4$	$N_j \geq 3, \quad N_a = 1$	$N_j \geq 2, \quad N_a = 2$
p_T cuts	$p_T^j > 80$ GeV	$p_T^j > 150$ GeV,	$p_T^a > 50$ GeV
pairs id.	min. $\sum_{i=\text{pairs}} \lvert\Delta R_i - 0.8\rvert$		min. $\Delta R_{a_1 j_i}$
asymmetry parameters	$\frac{\lvert m_{jj_1} - m_{jj_2}\rvert}{m_{jj_1} + m_{jj_2}} < 0.1$ $\lvert\eta_{jj_1} - \eta_{jj_2}\rvert < 0.1$	$\frac{\lvert m_{ja} - m_{jj}\rvert}{m_{ja} + m_{jj}} < 0.1$ $\lvert\eta_{ja} - \eta_{jj}\rvert < 0.1$	
binning	none	m_{ja}	m_{ja_1}

Colored PNGBs, LHC prospects for $\Phi \rightarrow g\gamma$

For simulation of backgrounds and signals we generate events with Madgraph5, showered with Pythia 8, and Delphes 3 (with the CMS Delphes card, and the JetFakeParticle module with a jet-to-photon fake rate of 10^{-4}). Jets are reconstructed with Fastjet, using the anti-kt algorithm with R=0.4 and p_T = 20 GeV.

- For the 4j channel, we use backgrounds provided by the CMS study.
- For the *jjja* channel, the dominant background is SM 4j with one jet misidentified as a photon.
- For the *jaja* channel, the dominant background is SM jjjγ background with one jet misidentified as a photon.

	$jjjj$	$jjja$	$jjaa$	
Signal acceptance ϵ_S ($M_\Phi = 1$ TeV)	0.008	0.008	0.67	
Background acceptance ϵ_B	Data	0.002	0.69	0.009
Background cross section (fb)	Data	1.34×10^3	7	1.34×10^3

We define 4 benchmark points with $(M_\Phi\ [\mathrm{GeV}], \sigma_{\mathrm{pair}}\ [\mathrm{fb}])$

$$\mathrm{BP1} :: (900, 74.2),\quad \mathrm{BP2} :: (1000, 34.4),\quad \mathrm{BP3} :: (1100, 16.7),\quad \mathrm{BP4} :: (1200, 8.3).$$

Significances are determined using a binned sensitivity function on the reconstructed resonance mass:

$$Z^{\mathrm{bin}} = \sqrt{\sum_i \left(2(s_i + b_i)\log\left[1 + \frac{s_i}{b_i}\right] - 2s_i\right)}$$

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

	BP1 (900,74.2)			BP3 (1100,16.7)	
	$Y_\chi = 1/3$	$Y_\chi = 2/3$		$Y_\chi = 1/3$	$Y_\chi = 2/3$
Z_{gggg}	10.32	7.48	Z_{gggg}	4.8	3.54
$Z_{ggg\gamma}$	5.02	13.03	$Z_{ggg\gamma}$	1.09	3.06
$\delta_{ggg\gamma}$	**0.48**	**1.74**	$\delta_{ggg\gamma}$	**0.22**	**0.86**
$Z_{gg\gamma\gamma}$	1.91	21.08	$Z_{gg\gamma\gamma}$	0.47	5.31
$\delta_{gg\gamma\gamma}$	**0.18**	**2.81**	$\delta_{gg\gamma\gamma}$	**0.09**	**1.5**

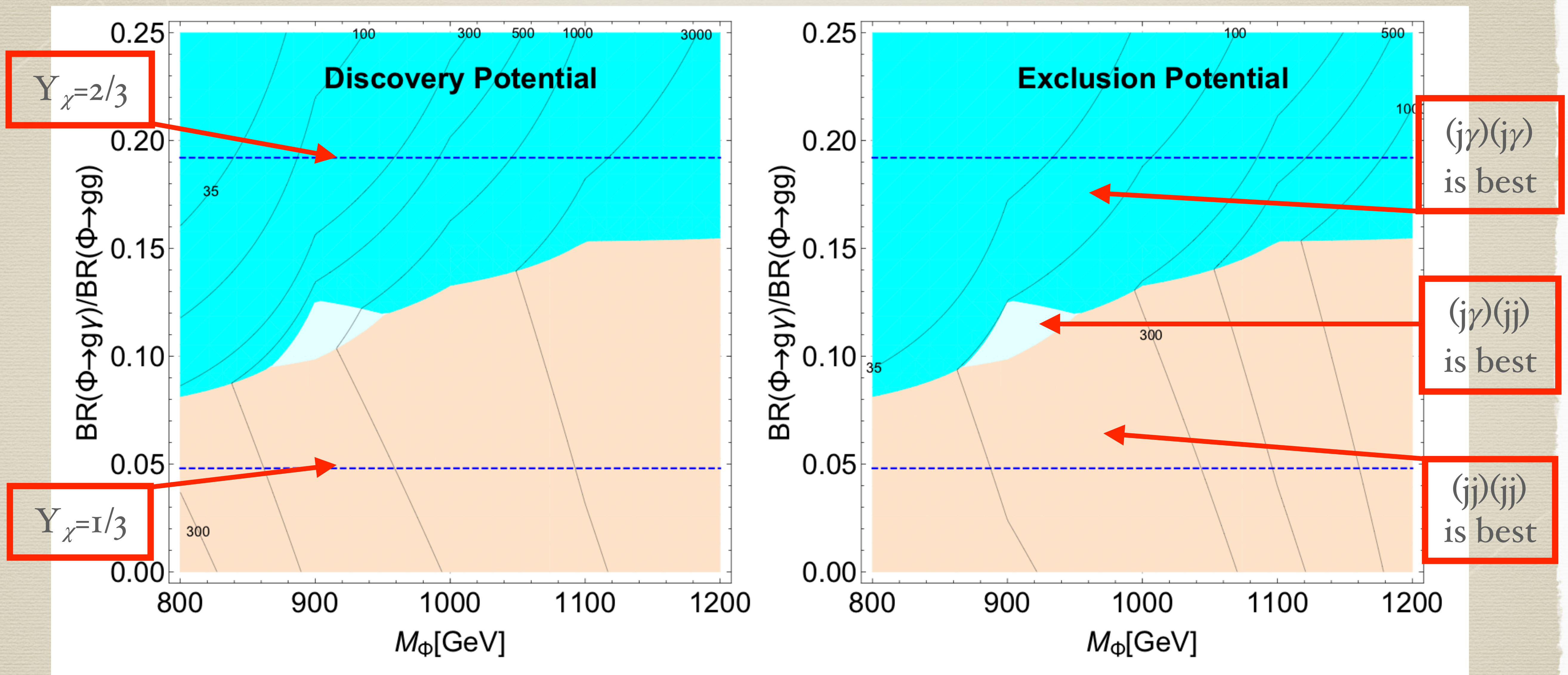
	BP2 (1000,34.4)			BP4 (1200,8.3)	
	$Y_\chi = 1/3$	$Y_\chi = 2/3$		$Y_\chi = 1/3$	$Y_\chi = 2/3$
Z_{gggg}	7.5	5.45	Z_{gggg}	2.6	1.91
$Z_{ggg\gamma}$	2.19	6.07	$Z_{ggg\gamma}$	0.63	1.77
$\delta_{ggg\gamma}$	**0.29**	**1.11**	$\delta_{ggg\gamma}$	**0.24**	**0.92**
$Z_{gg\gamma\gamma}$	0.98	10.97	$Z_{gg\gamma\gamma}$	0.25	2.83
$\delta_{gg\gamma\gamma}$	**0.13**	**2.01**	$\delta_{gg\gamma\gamma}$	**0.09**	**1.48**

Table 6. Estimation of signal sensitivities (Z) and ratio δ for different channels at HL-LHC with 3 ab^{-1} of integrated luminosity. The multi-jet background at this luminosity is obtained by scaling the events multiplicities from 35 fb^{-1}. The benchmark points are denoted by (M_Φ [GeV], σ_{prod} [fb]).

$$\delta_{ggg\gamma} \equiv \frac{Z_{ggg\gamma}}{Z_{gggg}} = \frac{S_{ggg\gamma}/\sqrt{B_{jjja}}}{S_{gggg}/\sqrt{B_{jjjj}}}\,, \quad \delta_{gg\gamma\gamma} \equiv \frac{Z_{gg\gamma\gamma}}{Z_{gggg}} = \frac{S_{gg\gamma\gamma}/\sqrt{B_{jjaa}}}{S_{gggg}/\sqrt{B_{jjjj}}}\,,$$

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

[JHEP 05 (2020) 027]



Contours indicate required integrated luminosity in fb^{-1} @ LHC.

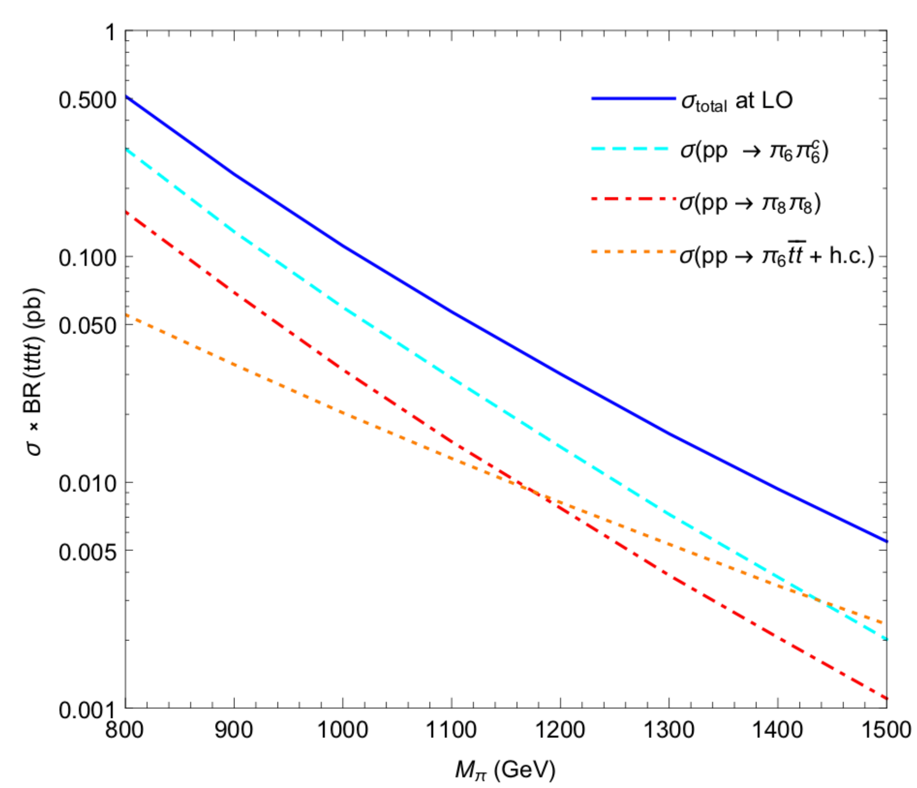
(The projection is based on a naive, non-optimized cut scheme, closely following the two di-jet search CMS-EXO-17-021).

Color sextet PNGBs: effective Lagrangian

Effective Lagrangian:

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

- π_6 carries charge 4/3.
- π_6 is pair-produced through QCD. Single production is only possible via top-fusion.
- π_6 decays exclusively to $t\, t$.
- The resonance is narrow.

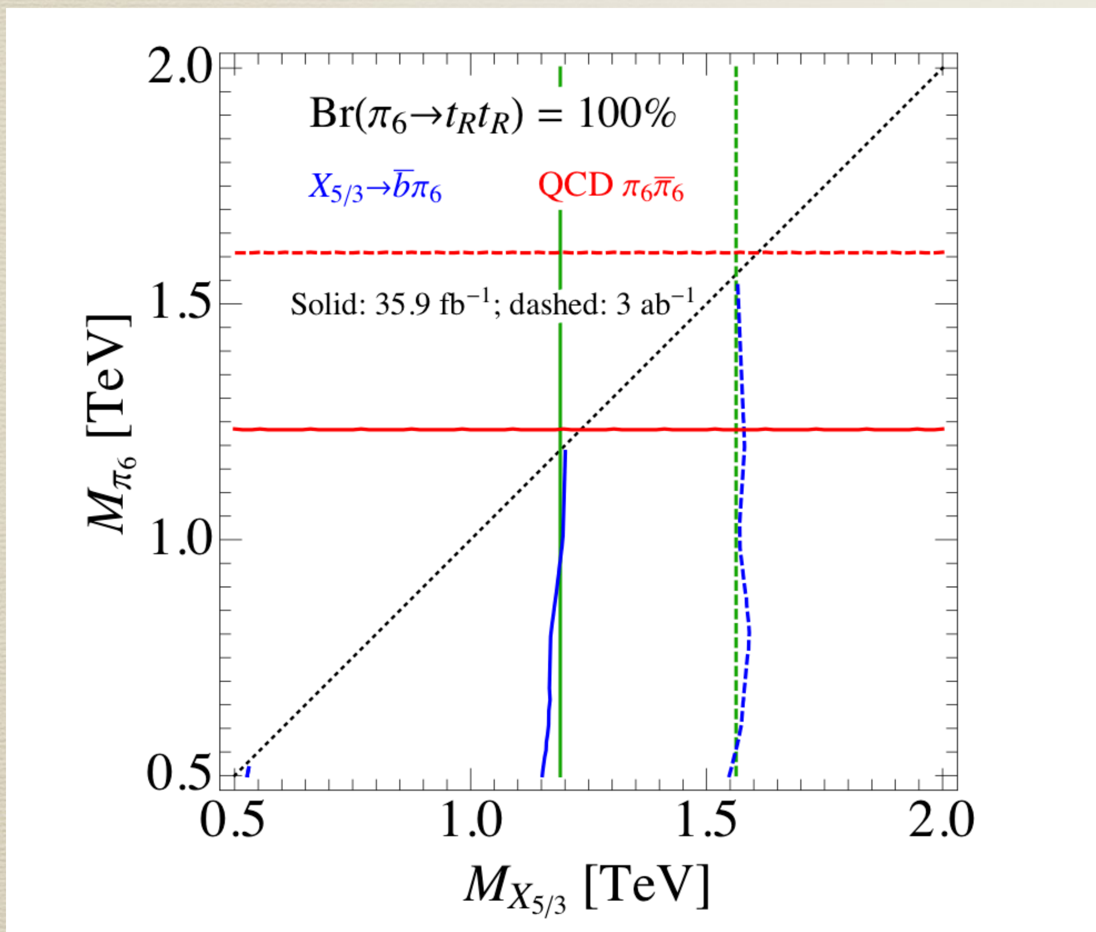


Cross sections for the sextet and octet scalar production at the LHC 13 TeV

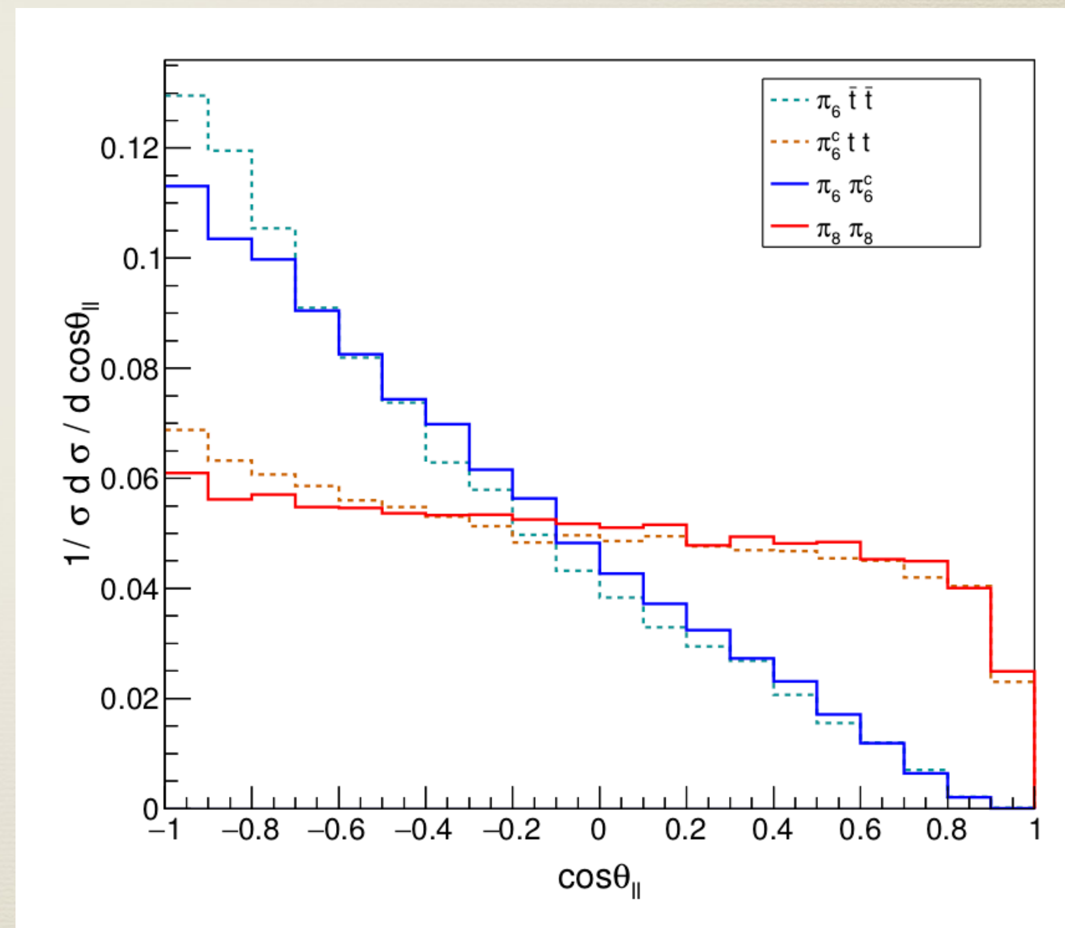
[JHEP1511,201]

Color sextet PNGB can be searched for in the 4t channel (or same-sign lepton searches)

- The signature is really a pair of top-pair resonances.
- Hadronic tops in the final state would allow to reconstruct invariant masses, but backgrounds are large (SM tt~ + jets). ⇒ Challenging but not hopeless given the developments in ML and boosted-top tagging algorithms.
- If two tops (or two anti-tops) decay leptonically, we have a same-sign lepton signature which has very low backgrounds (and searches are available).
  We recast the CMS search of CMS-B2G-17-014 (charge 5/3 top partner search in the same-sign lepton channel), and determine existing bounds as well as projected reach (for LHC with 3 ab). JHEP 1910, 134



We recast the CMS search of CMS-B2G-17-014 (charge 5/3 top partner search in the same-sign lepton channel), and determine existing bounds as well as projected reach (for LHC with 3 ab). [JHEP1910,134]



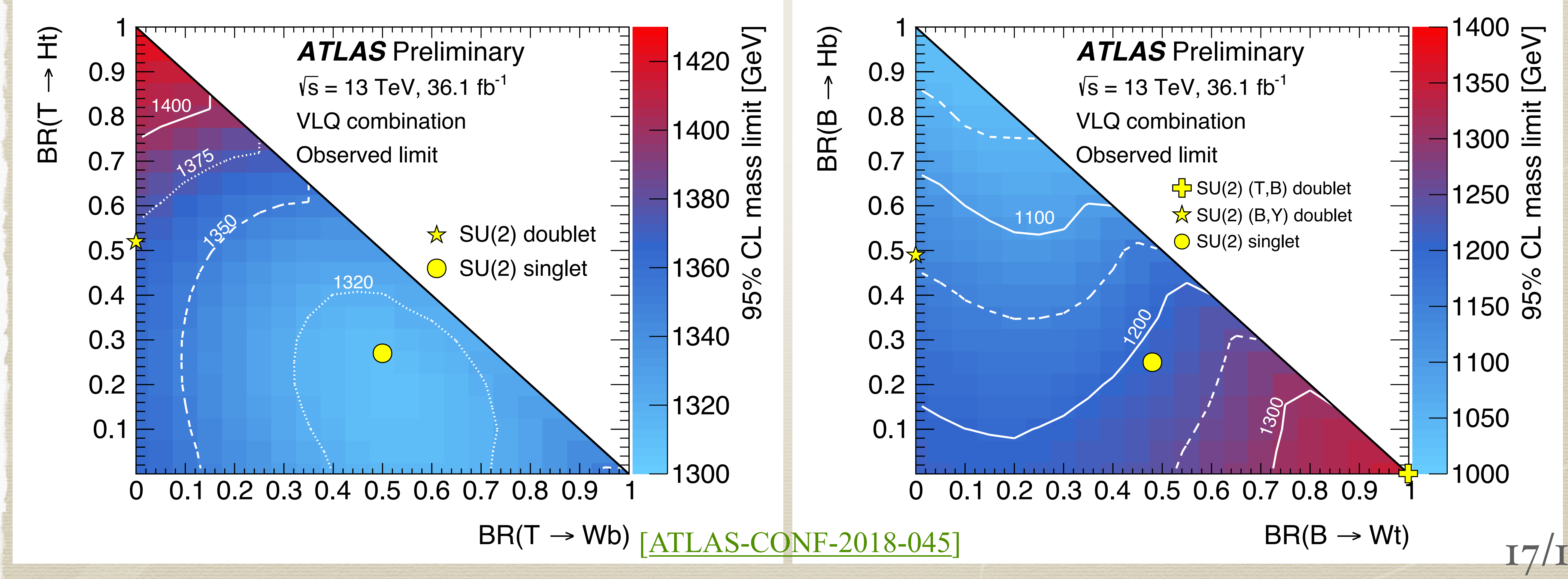
Fun-fact: In SSL searches, 4t from color-octets and color-sextets can easily be distinguished via the SSL opening angle. [JHEP1511,201]

Color Vector-like Quarks (VLQs) and color PNGBs

Vector-like quarks (with charge 5/3, 2/3, -1/3, -4/3) are actively searched for at the LHC.

$X_{5/3}$ (with $X_{5/3} \to tW^+$): $M_X \gtrsim 1.3$ TeV,

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



[ATLAS-CONF-2018-045]

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 respect to colored pNGBs:

$$
\begin{aligned}
X_{5/3} &\to \bar{b}\pi_6 \to \bar{b}tt \\
T &\to t\pi_8 \to t\bar{t}t \\
&\qquad\quad\; \to tgg \\
&\qquad\quad\; \to tg\gamma \\
B &\to b\pi_8 \to b\bar{t}t \\
&\qquad\quad\; \to bgg \\
&\qquad\quad\; \to bg\gamma
\end{aligned}
$$

⇒ Many new possible final states for VLQ pair- and single-production which are currently not targeted and which deserve further studies.
Common features: (many) tops, (many) jets, (for some) hard photons.

Conclusions

- Colored scalars in the TeV mass range are well-motivated in Composite Higgs models (and other Standard Model extensions).
- The color octet pair production cross section only depends on M_{Φ} , as the production occurs through the QCD interaction.We surveyed current LHC searches to obtain a bound of $M_{\Phi} >$ 600 -1000 GeV (depending on the dominant decay channel(s) of the color octet scalar).
- We demonstrated that a search for ($(j\gamma)(j\gamma)$ (or $(j\gamma)(jj)$) resonance pairs has a high discovery potential.
  Our feasibility study closely follows an existing CMS study for $(jj)(jj)$ resonance pairs.
  Further optimization of background suppression is possible.
- For color sextets, we established a bound of $M_{\pi 6} > 1250$ GeV, and a projected LHC reach of $M_{\pi 6} = 1600$ GeV within search strategies already used by CMS.
- Colored scalars could also be produced indirectly, in decays of vector-like quarks. If VLQs are light enough to be produced at the LHC, their decays can be tested in numerous new final states.

Backup

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

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

[JHEP1511,201]

Underlying field content

Bound states of the model

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