Hunting Composite Higgs model UV embeddings in di-boson, $t\bar{t}$ and other exotics searches at the LHC

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based on:

G. Cacciapaglia, H. Cai, A. Deandrea, T. Flacke, S.J. Lee, A. Parolini [JHEP 1511 (2015) 201]

H. Cai, T. Flacke, M. Lespinasse [arXiv:1512.04508]

A. Belyaev, G. Cacciapaglia, H. Cai, T. Flacke, H. Serodio, A. Parolini [PRD 94 (2016) no 1, 015004]

A. Belyaev, G. Cacciapaglia, H. Cai, G. Ferretti, T. Flacke, H. Serodio, A. Parolini [in preparation]

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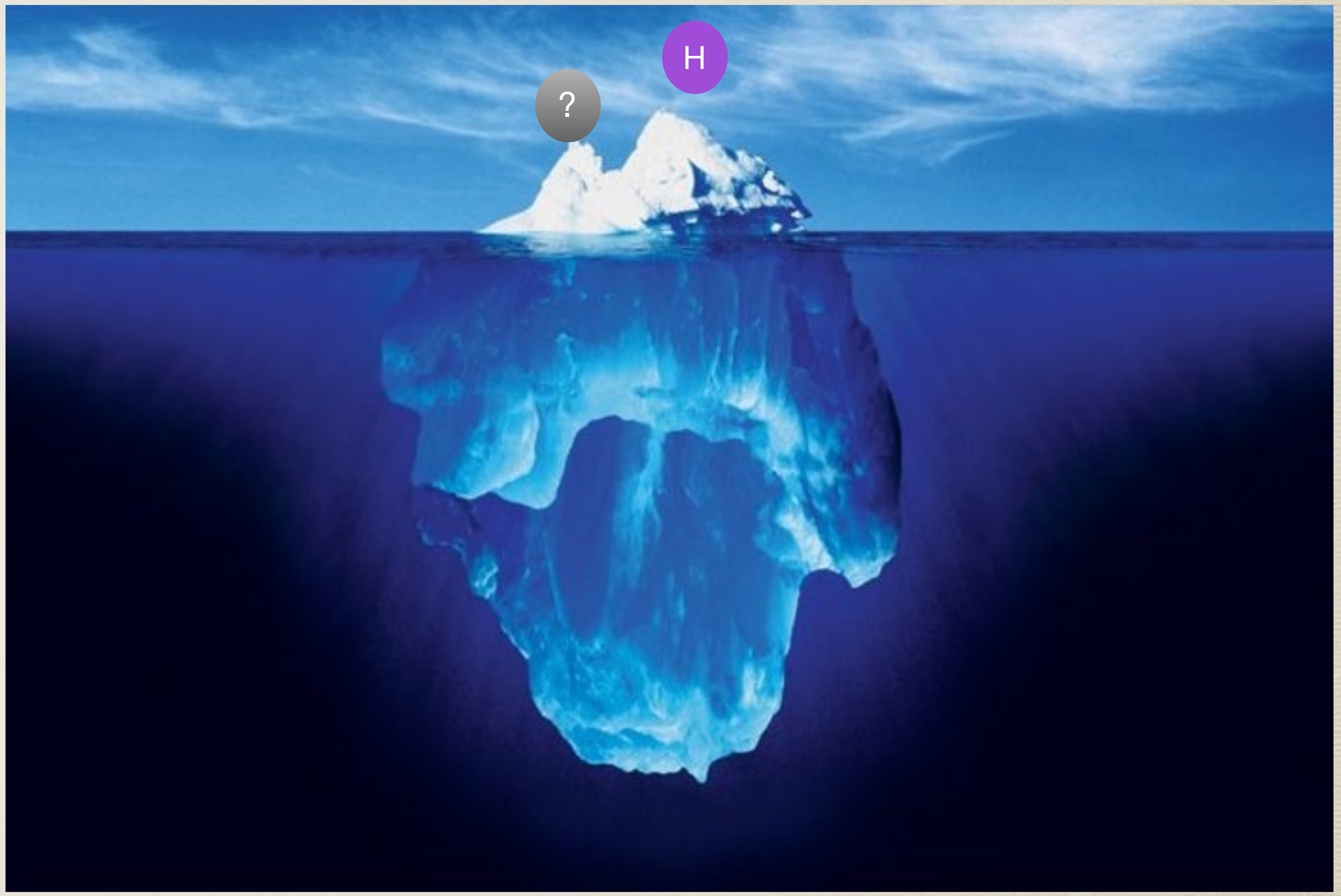
Outline

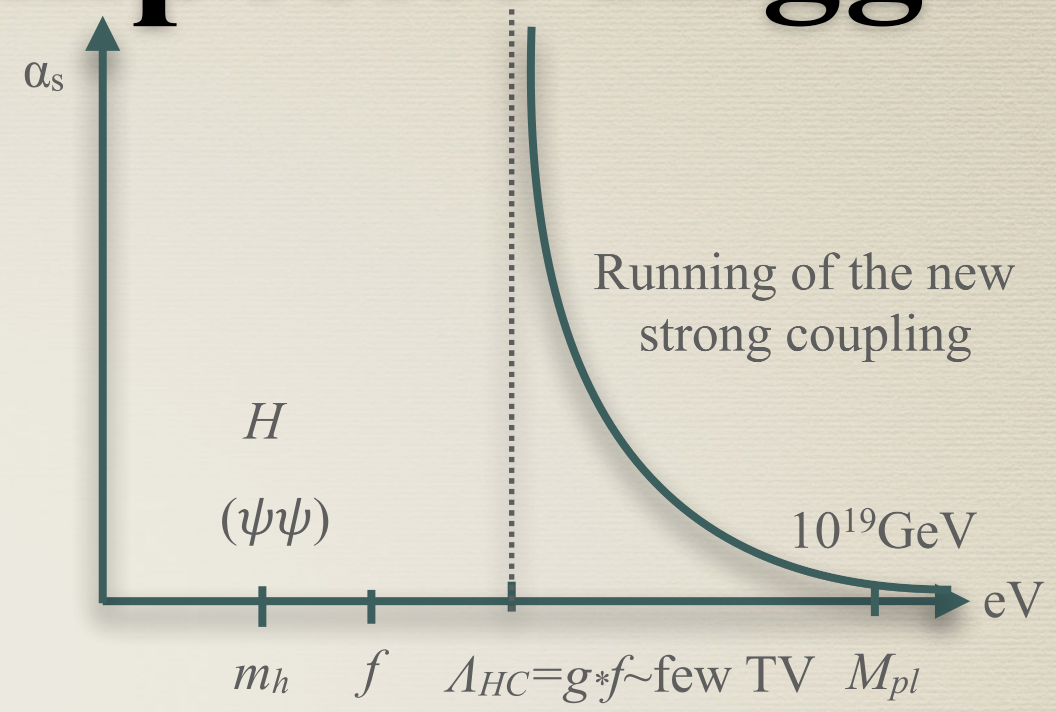
- Motivation & Overview
- Towards UV embeddings of composite Higgs models
- Di-boson signatures as a common feature of CHM UV embeddings
- Colored light states in CHM UV embeddings
- Conclusions



Motivation for a composite Higgs

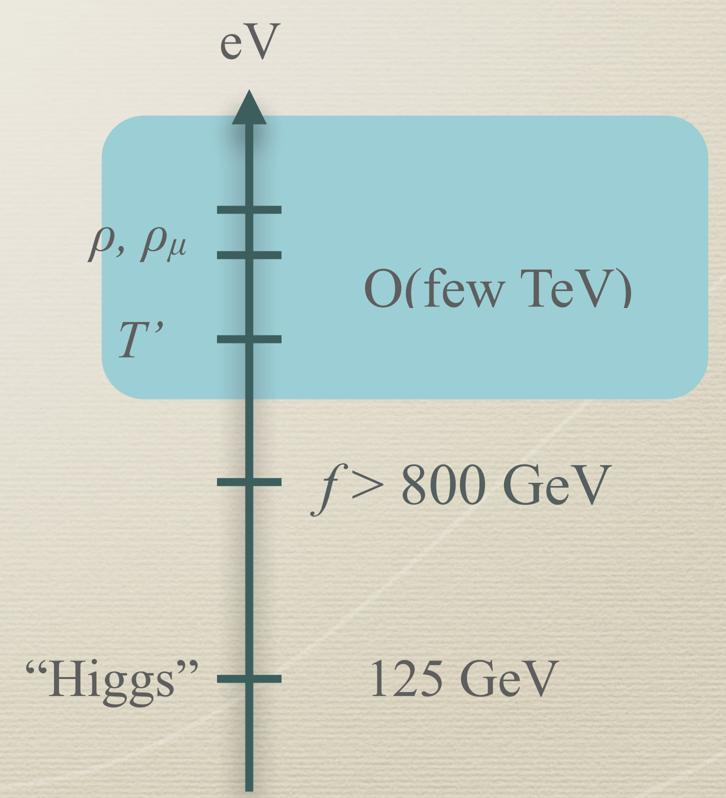
An alternative solution to the hierarchy problem:

- 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.
- …and many model-building questions …



Some questions in composite Higgs models

- What are suitable underlying UV theories?
- What are field content and global symmetries in the confined phase?
- How are quark masses generated?
- (How) can top-partners be light?
- How can problems with FCNCs be avoided?
- What are bounds from electroweak precision measurements?
- What are the ``best'' LHC search channels, optimized search strategies and tools, and what are the bounds and indication for
  - vector resonances
  - top- (or other quark-) partners
  - other composite resonances
  - modified Higgs couplings or signatures?

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

Ferretti etal. [JHEP 1403, 077, arXiv:1604.06467] classified candidate models which:
c.f. also Gherghetta etal (2014), Vecchi (2015) for early 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 ψ, χ . 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)*. The smallest EW cosets are instead *SU(4)/Sp(4)*, *SU(5)/SO(5)*, or *SU(4)xSU(4)/SU(4)*.

BUT: There are two more common features of all models.

1. All models contain colored pNGBs. In particular, all models contain a pNGB transforming as an octet of $SU(3)_c$.
   [c.f. JHEP1511,201 for a first study on the phenomenology and bounds on colored pNGBs in CH UV embeddings.]
2. All models contain two spontaneously broken U(1) symmetries (global phases of χ, ψ), which are singlets under the Standard Model group. One linear combination (η') is anomalous under the hyper color group (and hence expected to be heavy). The orthogonal combination (a) is an SM singlet which couples to the SM only through the Wess-Zumino-Witten anomaly.
   Hence, a pNGB with (calculable and fixed) WZW couplings is a genuine prediction of the UV completions under consideration.
   [arXiv:1512.07242]

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

[JHEP1511,201]

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	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$			

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	**(1, $\overline{6}$)**	**(1, 6)**	ψ_3
$\psi\overline{\chi}\overline{\psi}$	1/2	**(15, $\overline{6}$)**	**(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

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

Full list of "minimal" CHM UV embeddings

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

The column “Restrictions” denotes the obvious requirements such as asymptotic freedom and compatibility with the reality properties of the irrep (e.g. the $\mathbf{A}_2$ of SU(N_{HC}) is real only for N_{HC} = 4).

The “Non Conformal” column indicates the sub-range for which the model is likely outside of the conformal region: a “/” indicates that there are no solutions, i.e. all models are likely conformal.

The $-q_\chi/q_\psi$ column indicates the ratio of charges of the fermions under the non-anomalous U(1) combination.

Chiral Lagrangian for the pNGBs

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 , π^a are the non-abelian Goldstones, T^a are the corresponding broken generators, $\Sigma_{0,r}$ is the EW preserving vacuum, and a are the U(1) Goldstones parameterized via the Goldstone boson matrices. (c_5 is $\sqrt{2}$ for real reps and 1 otherwise).

The lowest order chiral Lagrangian is

$$\mathcal{L}_{\chi pt} = \sum_{r=\psi,\chi} \frac{f_r^2}{8c_5^2}\,\mathrm{Tr}[(D_\mu\Sigma_r)^\dagger(D^\mu\Sigma_r)] + \frac{f_{a_r}^2}{2c_5^2}\,(\partial_\mu\Phi_r)^\dagger(\partial^\mu\Phi_r)\,.$$

where we chose the normalization such that $m_W = \frac{g}{2} f_\psi \sin\theta$ where θ is the vacuum misalignment angle.

In the large N limit, expect $f_{a_r} = \sqrt{N_r} f_r$.

Sources of masses and couplings of the pseudo Goldstone bosons:

1. The SM gauge group is weakly gauged, which explicitly breaks the global symmetry. This yields mass contributions for SM charged pNGBs. As the underlying fermions are SM charged, it also yields anomaly couplings of pNGBs to SM gauge bosons.
2. The elementary quarks (in particular tops) need to obtain masses. This can be achieved through linear mixing with composite fermionic operators (“top partners”), which explicitly break the global symmetries.
3. Mass terms for the underlying fermions explicitly break the global symmetries and give (correlated) mass contributions to all pseudo Goldstones.

Weak gauging and partial compositeness is commonly used in composite Higgs models to explain the generation of a potential for the Higgs (aka EW pNGBs). On the level of the underlying fermions, such mixing requires 4-fermion operators.

What are the implications of the above points for the SM singlet, and the color-octet pNGB?

Couplings of pNGBs to SM gauge bosons:

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

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

where

r	coset ψ	C_W^ψ	C_B^ψ	coset χ	C_G^χ	C_B^χ
complex	SU(4)×SU(4)/SU(4)	d_ψ	d_ψ	SU(3)×SU(3)/SU(3)	d_χ	$6Y_\chi^2 d_\chi$
real	SU(5)/SO(5)	d_ψ	d_ψ	SU(6)/SO(6)	d_χ	$6Y_\chi^2 d_\chi$
pseudo-real	SU(4)/Sp(4)	$d_\psi/2$	$d_\psi/2$	SU(6)/Sp(6)	d_χ	$6Y_\chi^2 d_\chi$

Non-abelian pNGBs:

$$\mathcal{L}_{\mathrm{WZW}} \supset \frac{\sqrt{\alpha_A \alpha_{A'}}}{4\sqrt{2}\pi} c_5 \frac{C^r_{AA'}}{f_r} c^{abc}\ \pi_r^a\ \varepsilon^{\mu\nu\alpha\beta} A^a_{\mu\nu} A'^b_{\alpha\beta}\,,$$

where

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

Underlying fermion mass terms:

The SM singlet pNGBs cannot obtain mass through the weak gauging. To make them massive, we add mass terms for $\boldsymbol{\chi}$ (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

$$m_{\pi_r}^2 = 2B_r \mu_r \,, \quad m_{a_r}^2 = 2N_r \frac{f_r^2}{f_{a_r}^2} B_r \mu_r = \xi_r \, m_{\pi_r}^2$$

Couplings to tops and top mass:

We want to realize top masses through partial compositeness, i.e.

$$\mathcal{L}_{mix} \supseteq y_L \; \bar{q}_L \Psi_{q_L} + y_R \; \bar{\Psi}_{t_R} t_R + h.c.$$

where $\boldsymbol{\psi}$ are the composite top partners, depending on the model either $\psi\psi\boldsymbol{\chi}$ or $\psi\boldsymbol{\chi}\boldsymbol{\chi}$ 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 $\psi\psi\boldsymbol{\chi}$:

$$y_L \,,\; y_R \sim (\pm 2, 1)\,,\; (0,-1)\,, \quad \Rightarrow m_{\text{top}} \sim (\pm 4, 2)\,, \;\; (0, \pm 2)\,, \;\; (\pm 2, 0)\,,$$

The singlet-to-top coupling Lagrangian can be written as

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

NOTE:

- The term that generates the top mass also generates couplings of the pNGBs to tops.
- The possible top couplings depend on the model and top partner embedding, with a discrete set of choices.
- For the singlet pNGBs, the coupling never vanishes as in no case $n_\psi = 0 = n_\chi$.
- The analogous argument yields zero coupling of $\boldsymbol{\pi}_8$ to tops if $n_\chi = 0$.

Singlets: masses and mixing

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

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

The singlet mass terms (including contributions from underlying fermion masses) is thus

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

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

The masses of the pNGBs are

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

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

$$\tan\alpha = \tan\zeta \left(1 - \frac{\Delta m_{\eta'}^2 + \Delta m_a^2 - \sqrt{(\Delta m_{\eta'}^2 - \Delta m_a^2)^2 - 4\Delta m_{\eta'}^2\, \Delta m_a^2 \tan^{-2}\zeta}}{2\Delta m_{\eta'}^2}\right)$$

Singlet pNGB summary and phenomenology

ALL composite Higgs model embeddings studied contain two SM singlet pseudo scalars a and η' which both are described by the effective Lagrangian

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu \sigma \partial^\mu \sigma - M_\sigma^2 \sigma^2\right) + i\, C_\sigma \frac{m_t}{f_\sigma}\, \sigma\, \bar{t}\gamma_5 t$$
$$+ \frac{g_3^2}{32\pi^2}\frac{\kappa_g}{f_\sigma}\, \sigma \left(\epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} + \frac{g_2^2}{g_3^2}\frac{\kappa_W}{\kappa_g}\epsilon^{\mu\nu\rho\sigma} W^i_{\mu\nu} W^i_{\rho\sigma} + \frac{g_1^2}{g_3^2}\frac{\kappa_B}{\kappa_g}\epsilon^{\mu\nu\rho\sigma} B_{\mu\nu} B_{\rho\sigma}\right)$$

- 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_σ results from chiral symmetry breaking. .
- The WZW coefficients κ_i are fully determined by the quantum numbers of χ, ψ.
- The coefficient C_a coefficient is also fixed in each individual model.

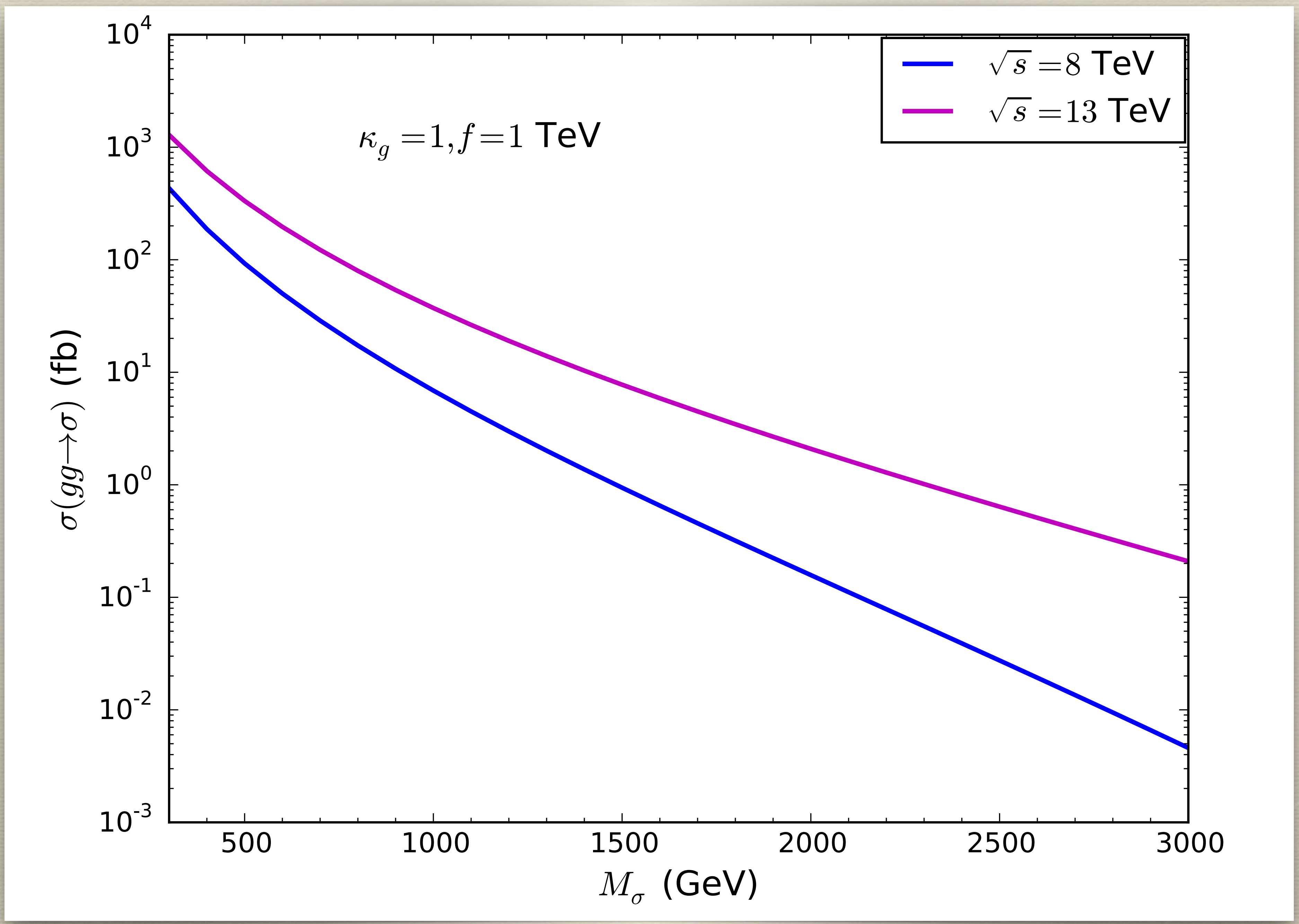
Phenomenology

- $\boldsymbol{\sigma}$ is produced in gluon fusion.
- $\boldsymbol{\sigma}$ decays to gg, WW, ZZ, $Z\gamma$, $\gamma\gamma$, $t\bar{t}$ and with fully determined branching ratios.
- The resonance is narrow.

$\tilde{a}$ model	$\tan\zeta$	κ_g	$\frac{\kappa_W}{\kappa_g}$	$\frac{\kappa_B}{\kappa_g}$	$\frac{C_t}{\kappa_g}$ (2,0)	(0,2)	(4,2)/(2,4)	(-4,2)/(2,-4)
1	-0.913	-3.11	-1.05	-0.38	-0.3	0.25	0.2	-0.8
2	-0.456	-3.84	-1.35	-0.68	-0.3	0.125	-0.05	-0.55
3	-0.913	-2.72	-1.37	1.29	-0.34	0.286	-0.4	0.97
4	-1.83	-4.56	-1.067	1.6	-0.133	0.22	-0.044	0.489
5	-1.83	-2.03	-0.75	-0.083	-0.3	0.5	0.7	-1.3
6	-1.29	-2.58	-0.9	-0.23	-0.3	0.5	0.7	-1.3
7	-0.323	-4.01	-1.5	-0.83	-0.3	0.125	-0.05	-0.55
8	-0.41	-0.77	-1.2	1.47	-1.2	0.4	-2	2.8
9	-3.27	-4.29	-0.54	2.12	-0.068	0.182	0.045	0.32
10	-3.27	-3.90	-0.6	2.07	-0.075	0.2	0.05	0.35
11	-0.816	-1.55	-1	1.67	-0.5	0.33	-0.67	1.33
12	-0.385	-2.07	-1.125	1.54	-0.45	0.2	-0.7	1.1

$\tilde{\eta}'$ model	$\tan\zeta$	κ_g	$\frac{\kappa_W}{\kappa_g}$	$\frac{\kappa_B}{\kappa_g}$	$\frac{C_t}{\kappa_g}$ (2,0)	(0,2)	(4,2)/(2,4)	(-4,2)/(2,-4)
1	-0.913	3.41	0.875	1.54	0.25	0.25	0.75	-0.25
2	-0.456	8.40	0.28	0.95	0.0625	0.125	0.31	-0.19
3	-0.913	2.98	1.14	3.81	0.28	0.286	0.86	-0.28
4	-1.83	2.50	3.55	6.22	0.444	0.22	1.11	-0.667
5	-1.83	1.11	2.5	3.167	1	0.5	2	0
6	-1.29	2.0	1.5	2.167	0.5	0.5	1.5	-0.5
7	-0.323	12.4	0.156	0.823	0.03	0.125	0.28	-0.22
8	-0.41	1.89	0.2	2.87	0.2	0.4	0.8	0
9	-3.27	1.31	5.82	8.48	0.73	0.182	1.63	-1.27
10	-3.27	1.19	6.4	9.07	0.8	0.2	1.8	-1.4
11	-0.816	1.90	0.67	3.33	0.33	0.33	1	-0.33
12	-0.385	5.39	0.167	2.83	0.067	0.2	0.33	0.067

Production cross section for a pseudo-scalar $\boldsymbol{\sigma}$



Partial widths:

$$\Gamma(\sigma \to gg) = \frac{g_3^4 \kappa_g^2 M_\sigma^3}{128 f_\sigma^2 \pi^5},$$

$$\Gamma(\sigma \to WW) = \frac{g_2^4 \kappa_W^2 \left(M_\sigma^2 - 4M_W^2\right)^{\frac{3}{2}}}{512 f_\sigma^2 \pi^5},$$

$$\Gamma(\sigma \to ZZ) = \frac{g_2^4 \cos^4\theta_W \left(\kappa_W + \kappa_B \tan^4\theta_W\right)^2 \left(M_\sigma^2 - 4M_Z^2\right)^{\frac{3}{2}}}{1024 f_\sigma^2 \pi^5},$$

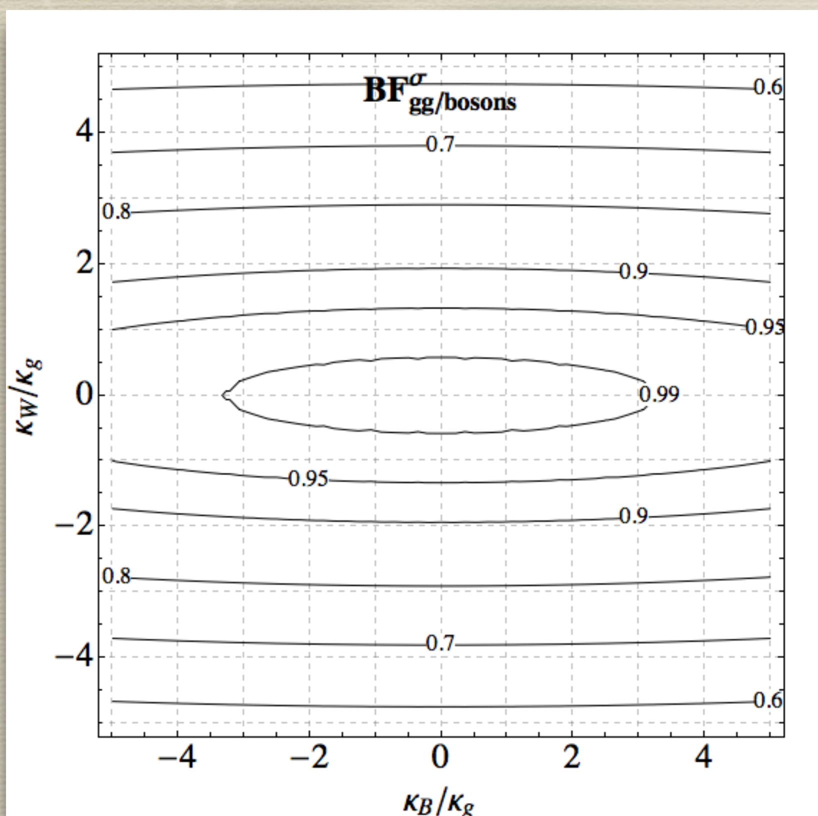
$$\Gamma(\sigma \to Z\gamma) = \frac{e^2 g_2^2 \cos^2\theta_W \left(\kappa_W - \kappa_B \tan^2\theta_W\right)^2 \left(M_\sigma^2 - M_Z^2\right)^3}{512 f_\sigma^2 \pi^5 M_\sigma^3},$$

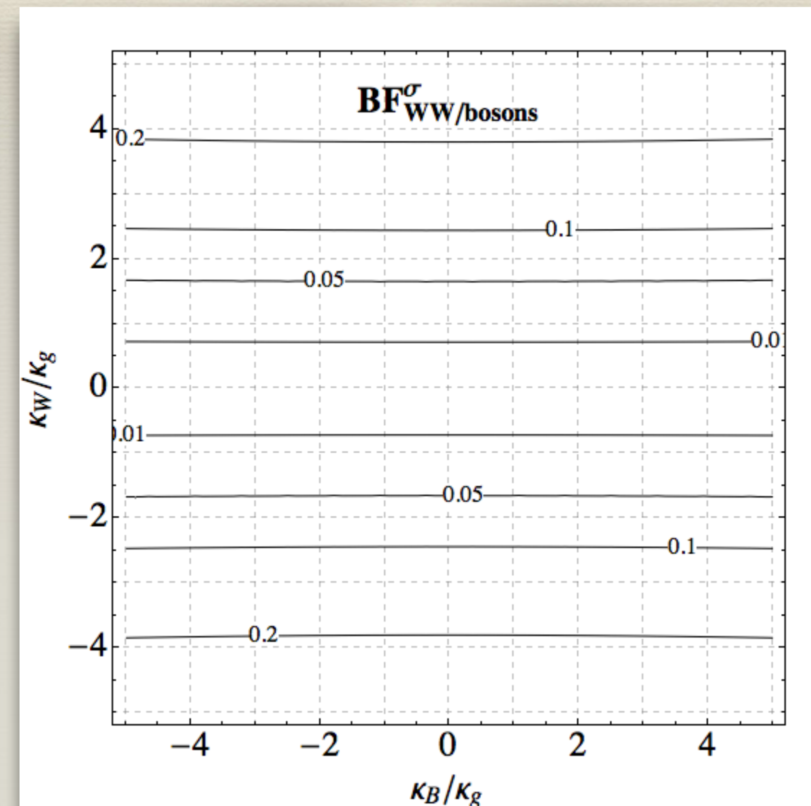
$$\Gamma(\sigma \to \gamma\gamma) = \frac{e^4 \left(\kappa_W + \kappa_B\right)^2 M_\sigma^3}{1024 f_\sigma^2 \pi^5},$$

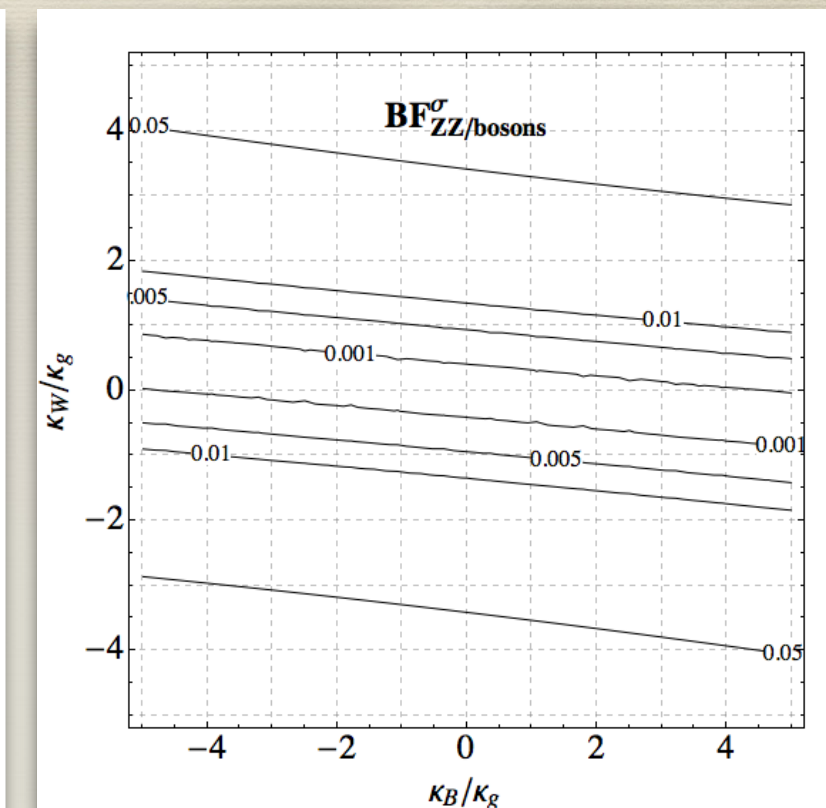
$$\Gamma(\sigma \to t\bar{t}) = \frac{3C_\sigma^2}{8\pi} \frac{m_t^2}{f_\sigma^2} (M_\sigma^2 - 4m_t^2)^{1/2},$$

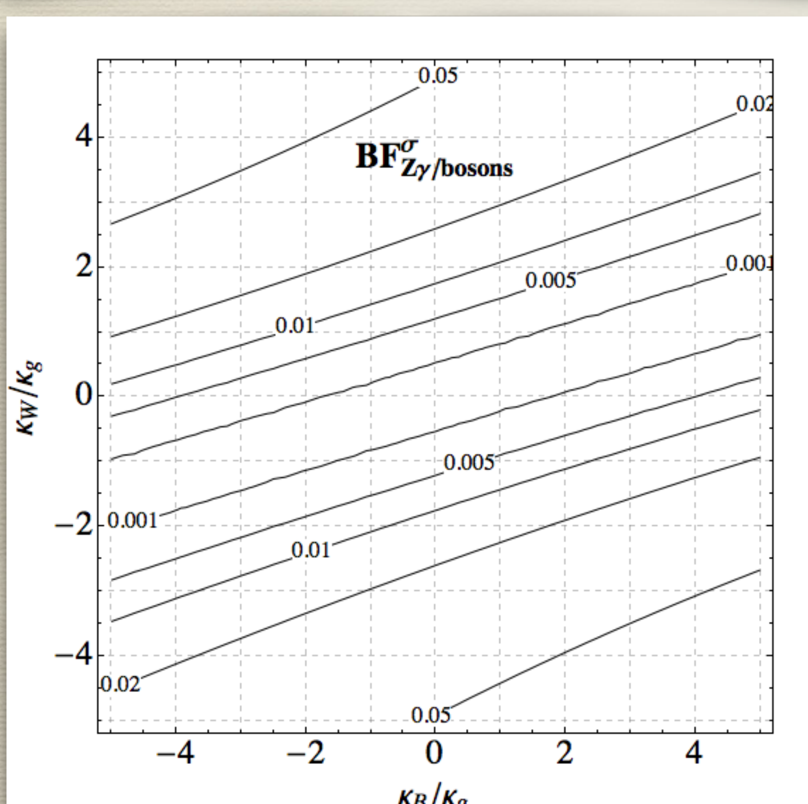
Note: Branching fractions are independent of f_σ.

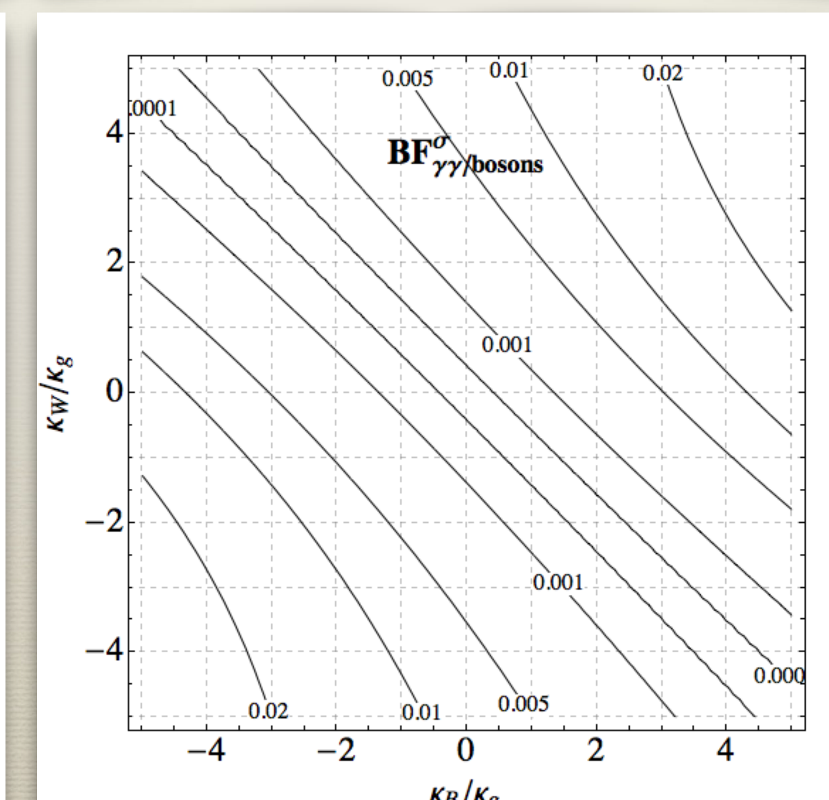
Branching fractions:

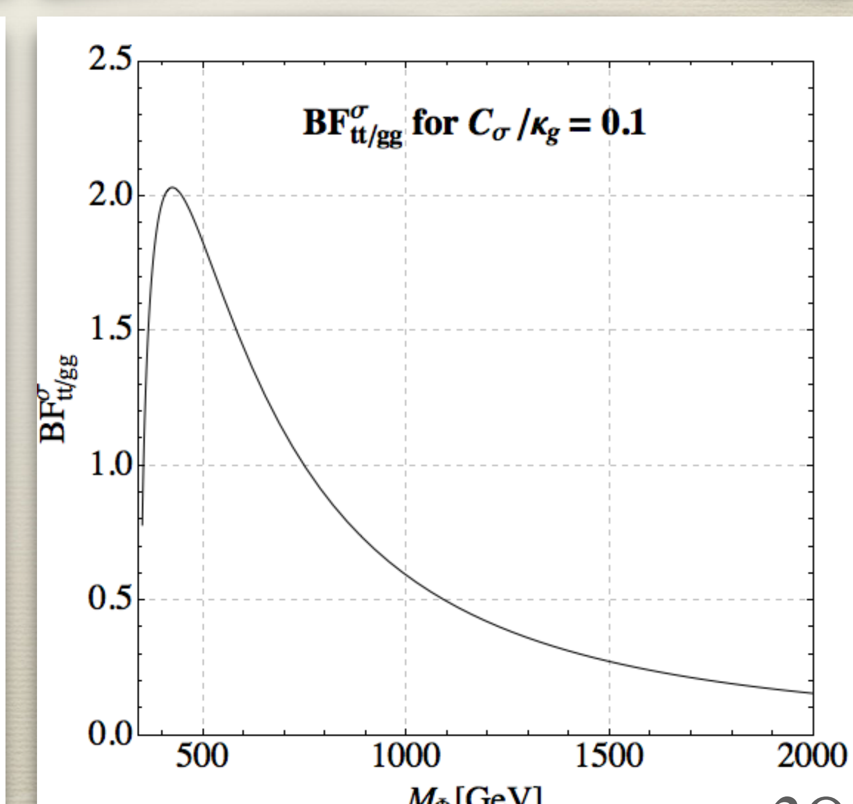




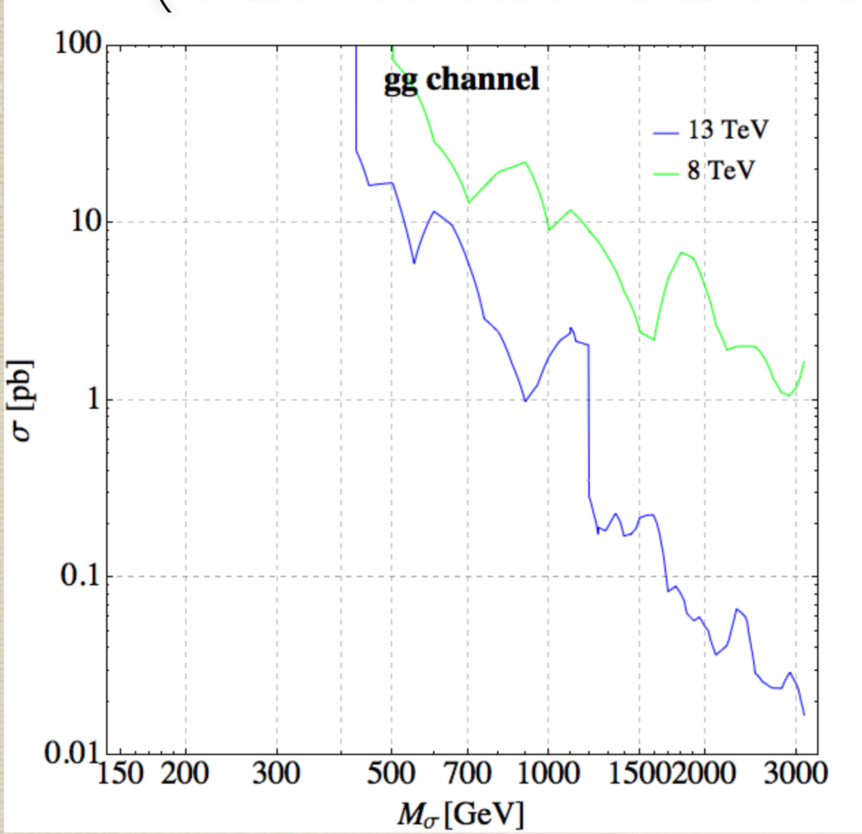


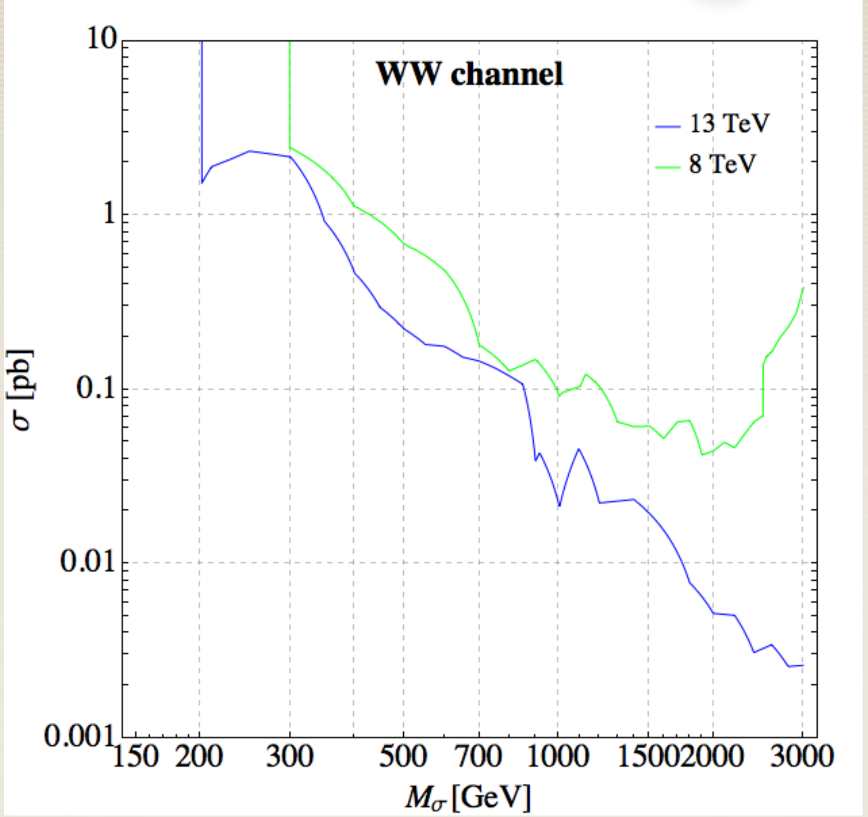


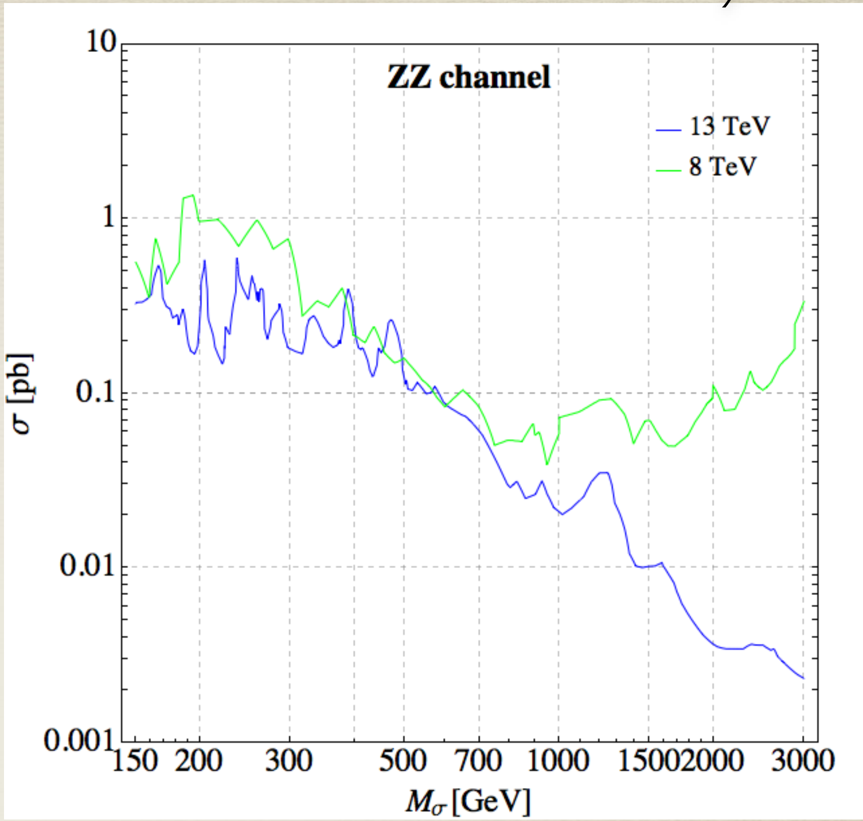


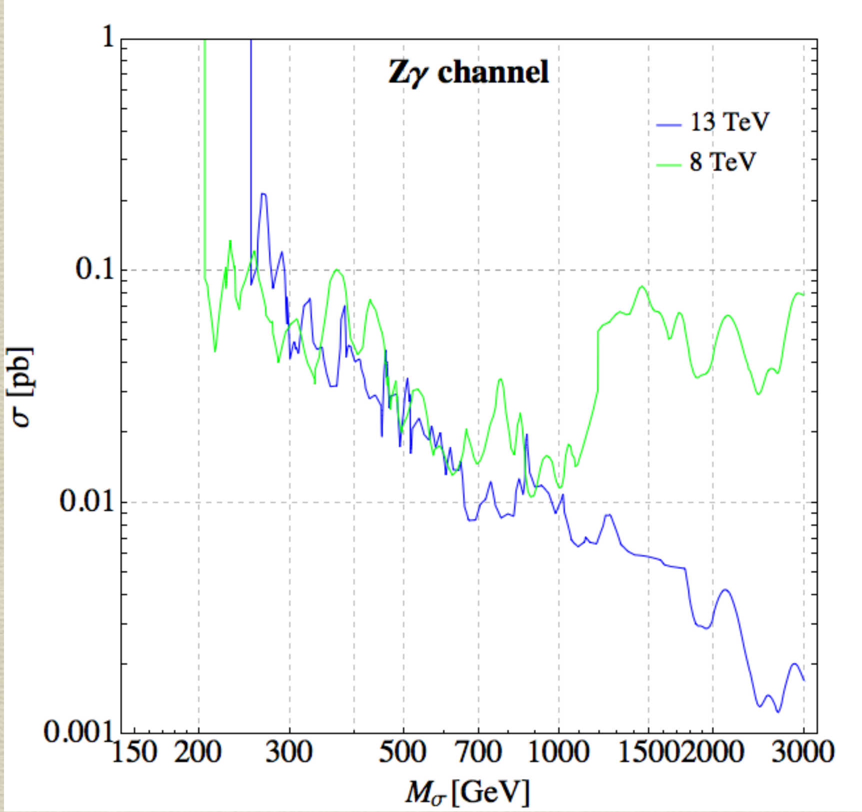


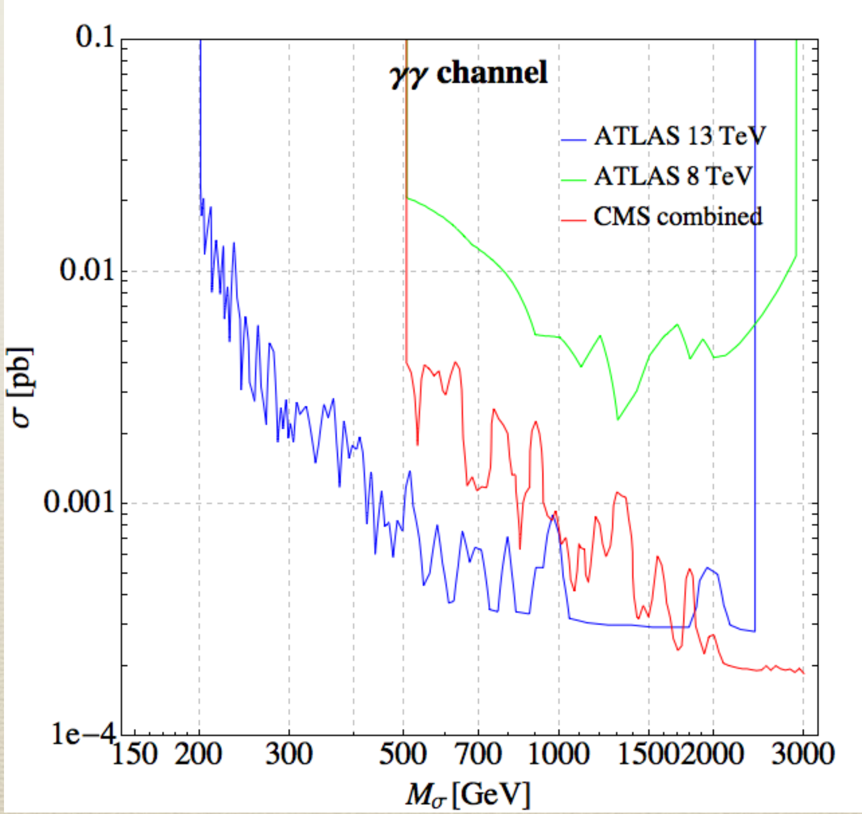
(Current) experimental constraints: (Summarized ATLAS and CMS @ 8 TeV and 13 TeV)

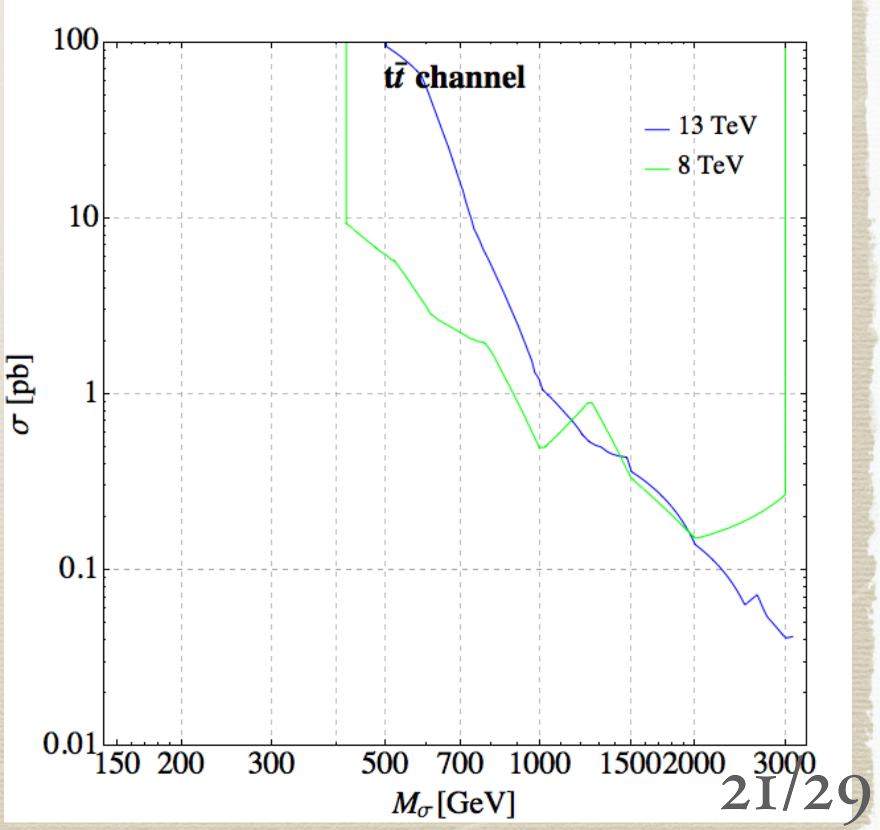




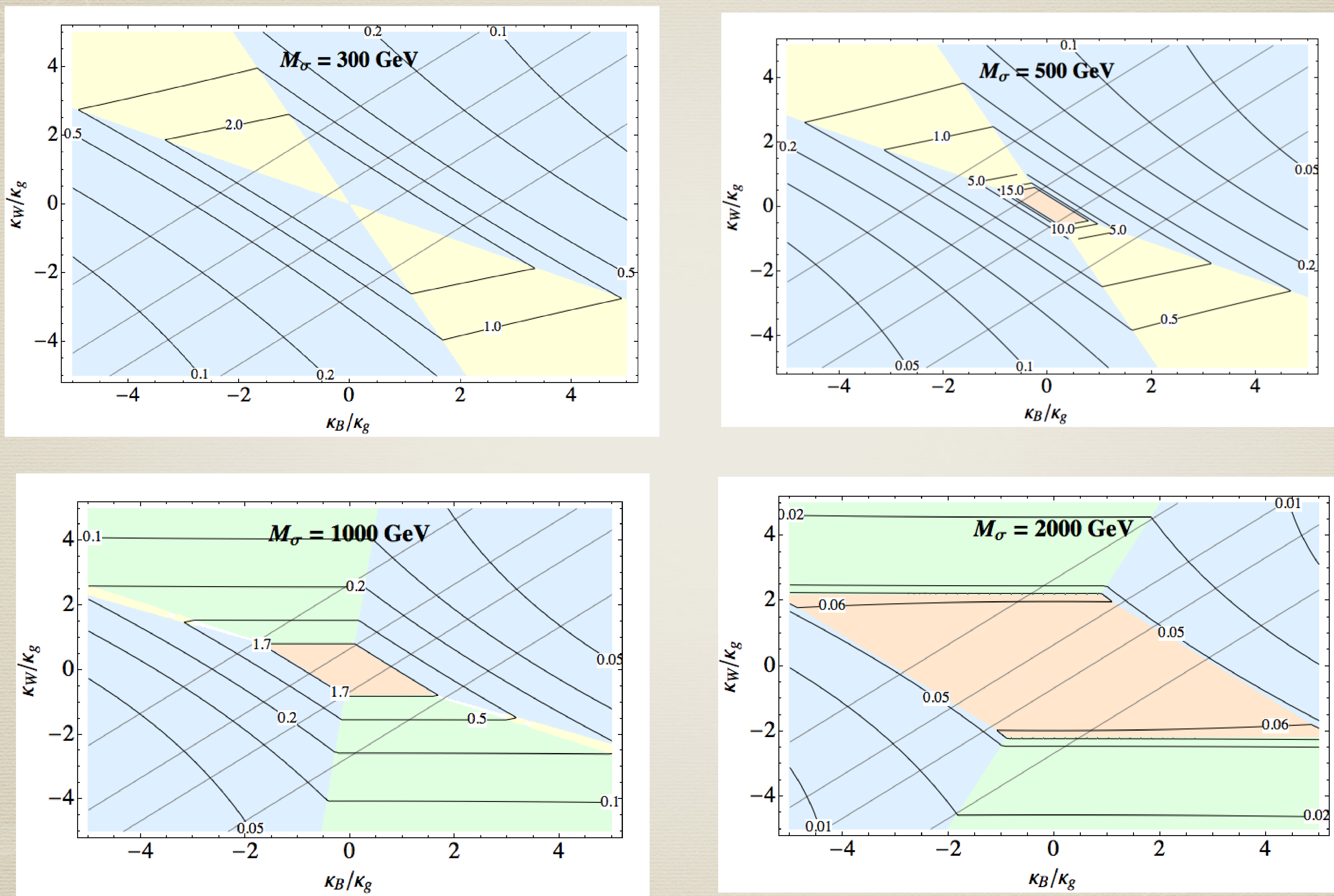






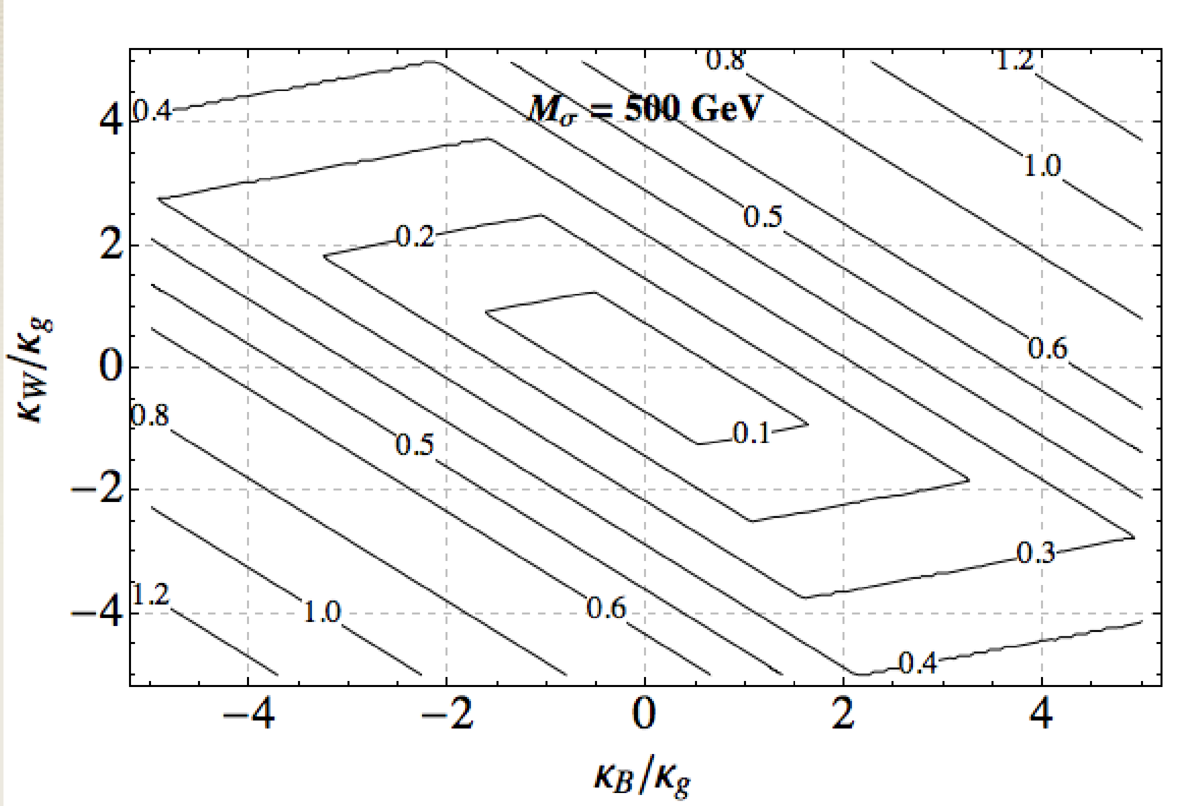


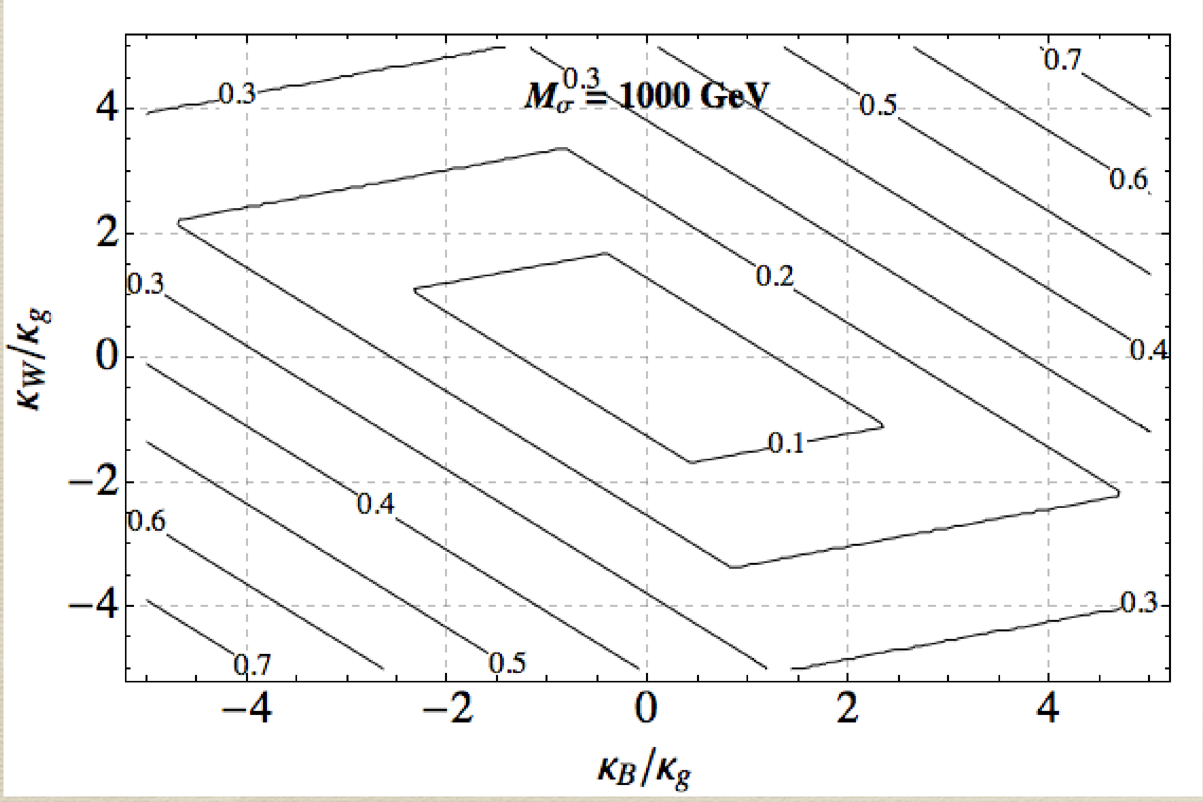
Resulting bounds on pNGB production cross section [pb]

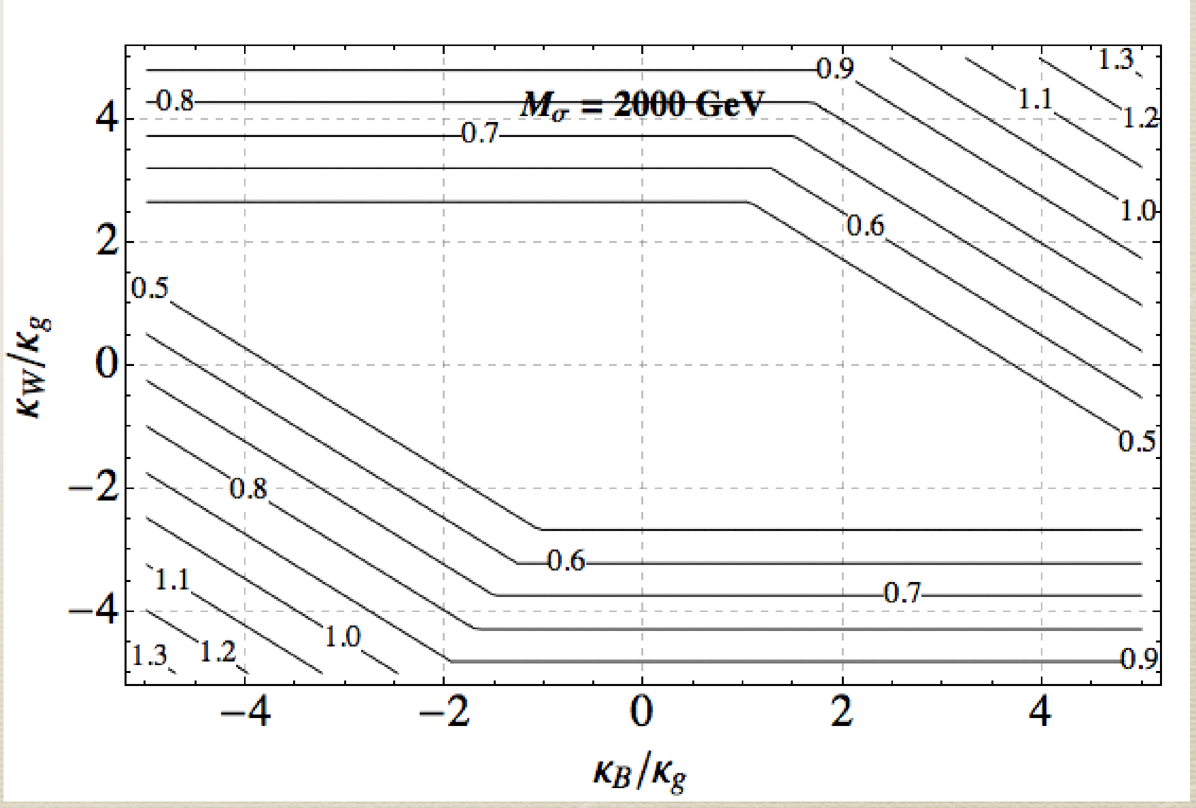


Bounds on the pNGB production cross section in pb for different masses as function of the anomaly coefficients. Dominant channels: *gg* (red), *WW* (green), *γγ*(blue), *Zγ* (yellow).

Values of C_{σ}/κ_g above which resonant top pair searches dominate:







Colored PNGBs

CH UV embeddings contain color sextet or color triplet pNGBs (model-dependent), but *all* models contain a color octet pNGB **ϕ .**

Effective Lagrangian:

$$\mathcal{L}_\Phi = Tr\left[(D_\mu\Phi)^2 - m_\Phi^2\Phi^2\right] + i\, C_\Phi \frac{m_t}{f_\Phi}\, \bar{t}\gamma_5\Phi t$$
$$+\frac{g_3^2\kappa_g^\Phi}{32\pi^2 f_\Phi}\Phi^a \epsilon^{\mu\nu\rho\sigma}\left[\frac{1}{2}d^{abc}\, G^b_{\mu\nu}G^c_{\rho\sigma} + \frac{g'\kappa_B^\Phi}{g_3\kappa_g^\Phi}\, G^a_{\mu\nu}B_{\rho\sigma}\right],$$

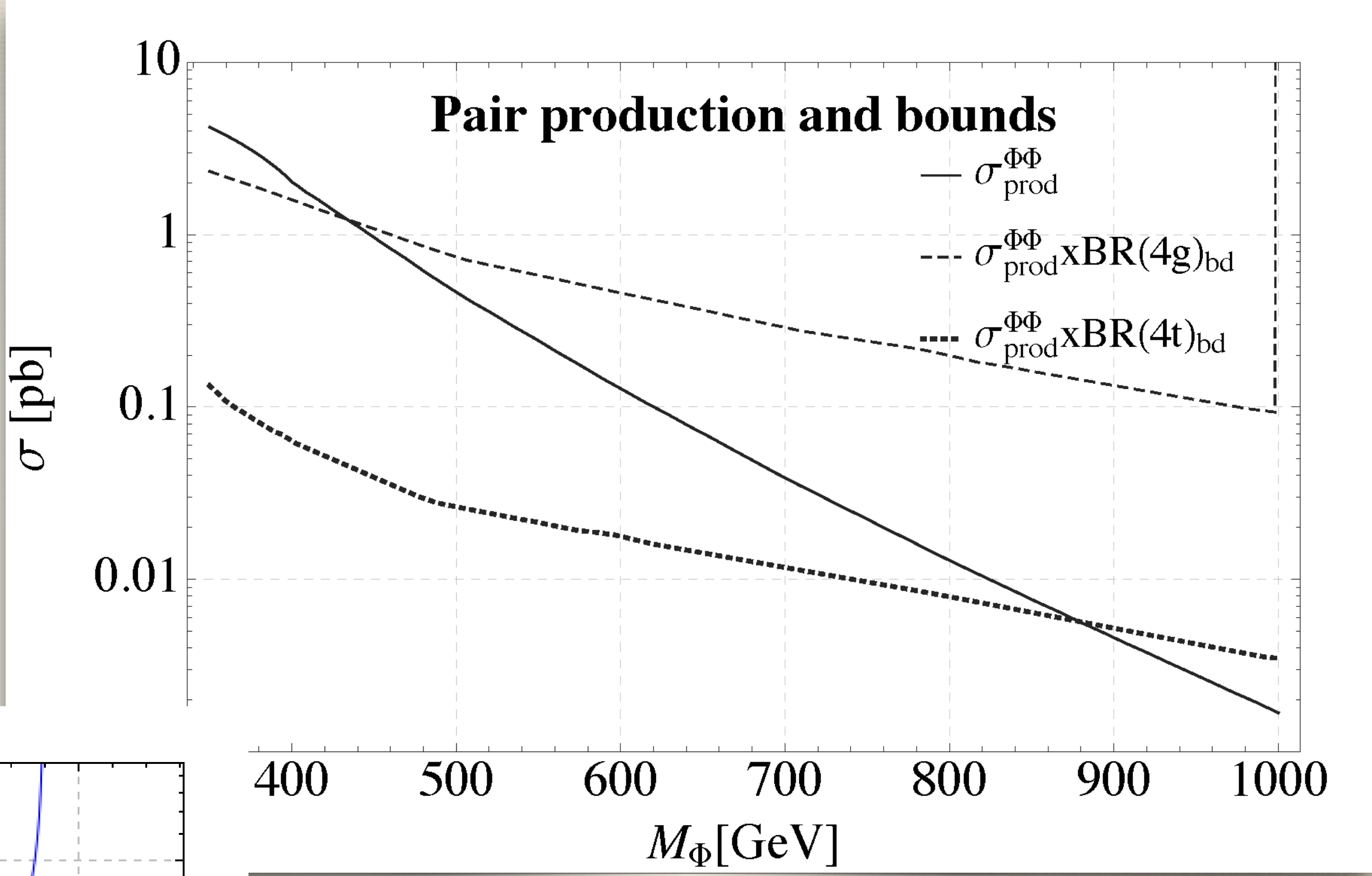
where in the CH UV embeddings: $\kappa_g^\Phi = d_\chi\,, \quad \kappa_B^\Phi = Y_\chi\, d_\chi$, $m^2_{\pi_8} \sim \dfrac{m_a^2}{\xi_\chi \sin^2\zeta} + C_g \dfrac{3}{4} g_s^2\, f_\chi^2$

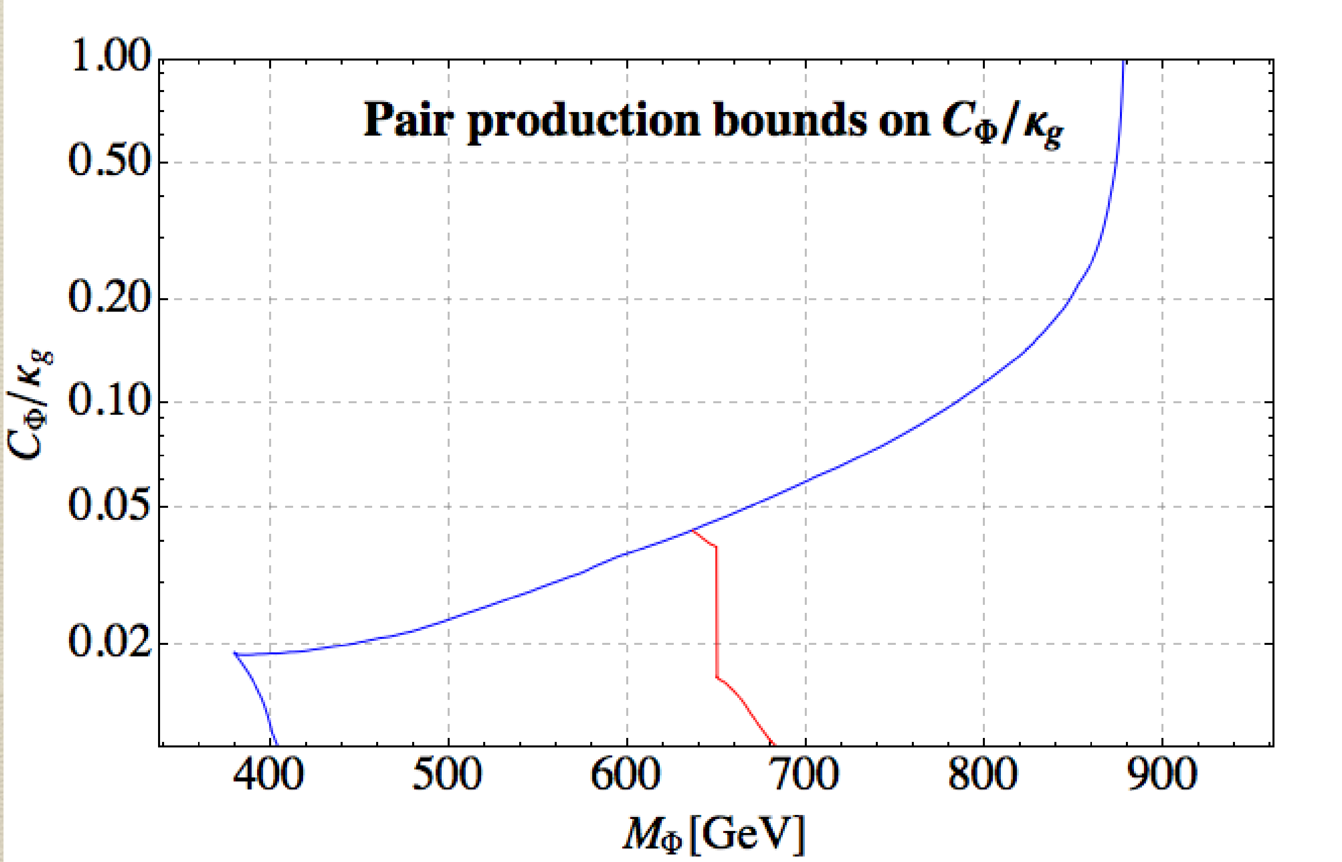
Phenomenology

- **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 / .019 / .06.
- The resonance is narrow.

Colored PNGBs
Constraints from pair production:

Right: Pair production cross section and bounds from pair produced di-jet searches [CMS, PLB747, 98] and 4t searches [ATLAS, JHEP08,105 and JHEP10, 150]. All data from LHC @ 8 TeV, still.

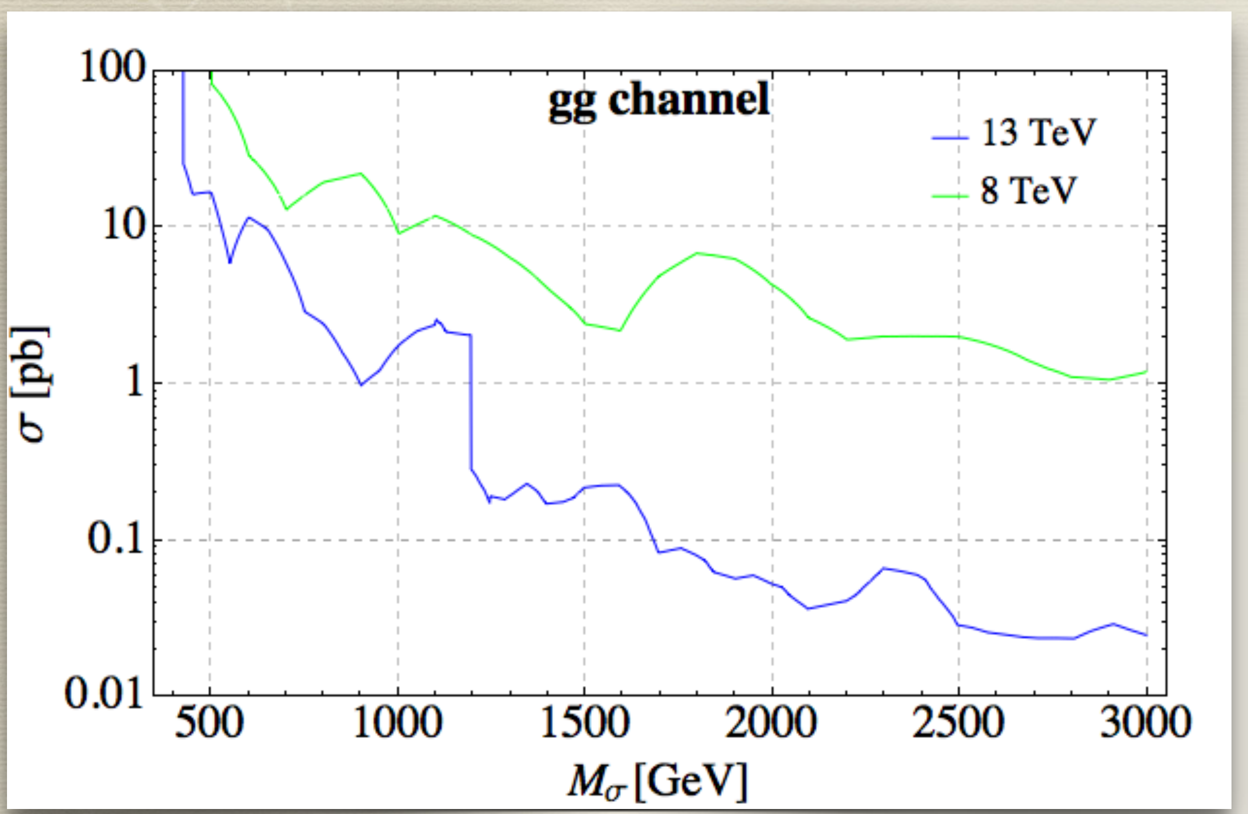


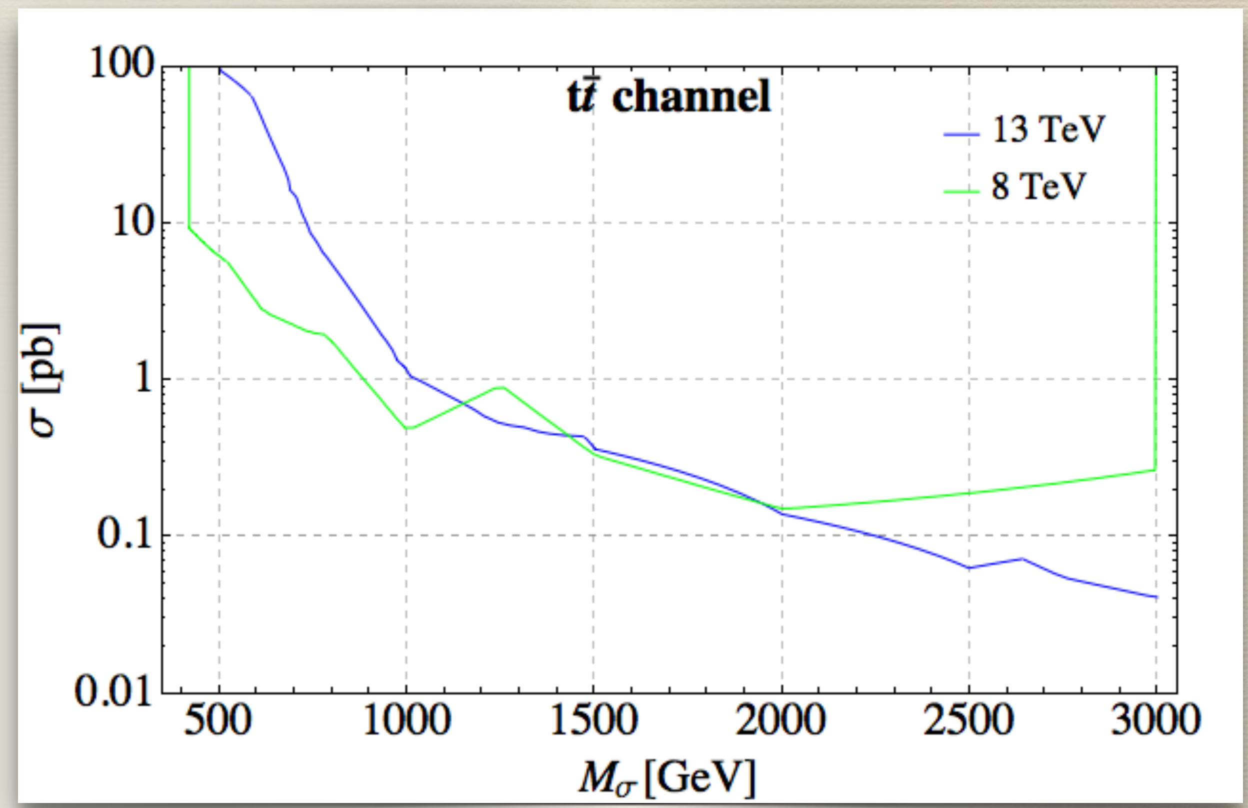


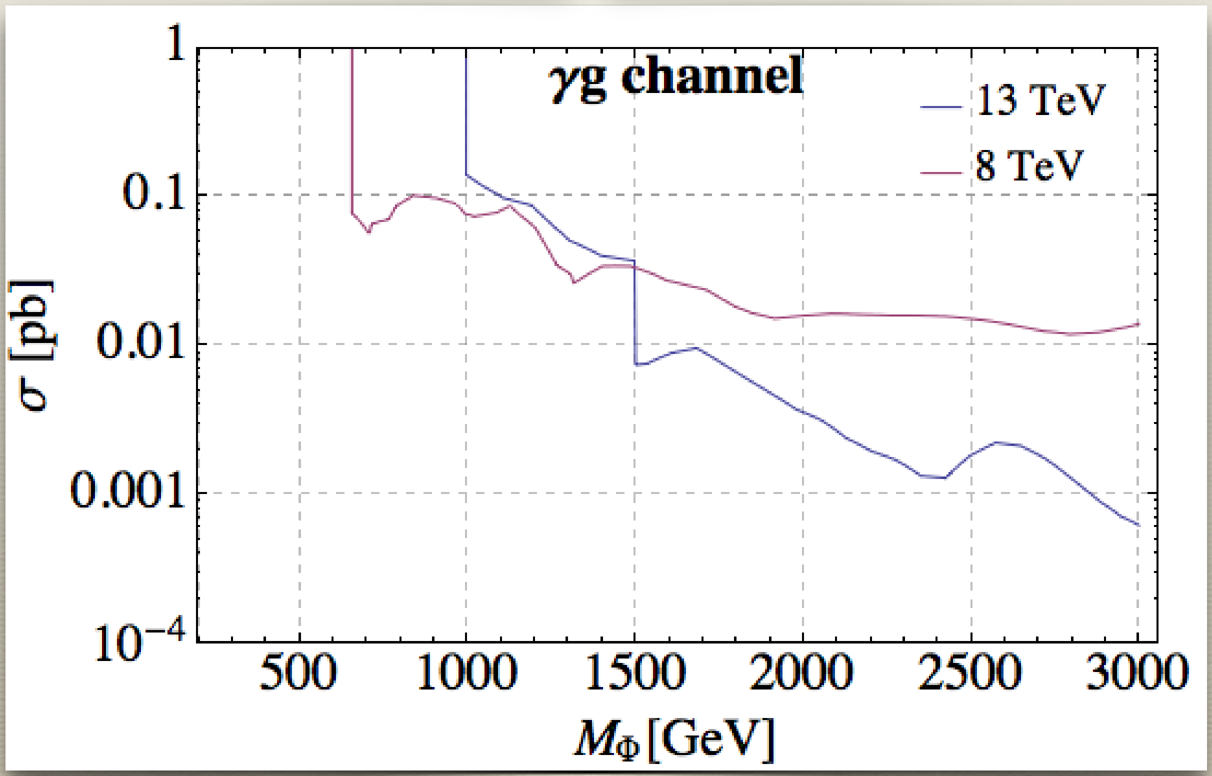
Left: Implied bounds on the C_ϕ/κ_g vs. M_ϕ parameter space.

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

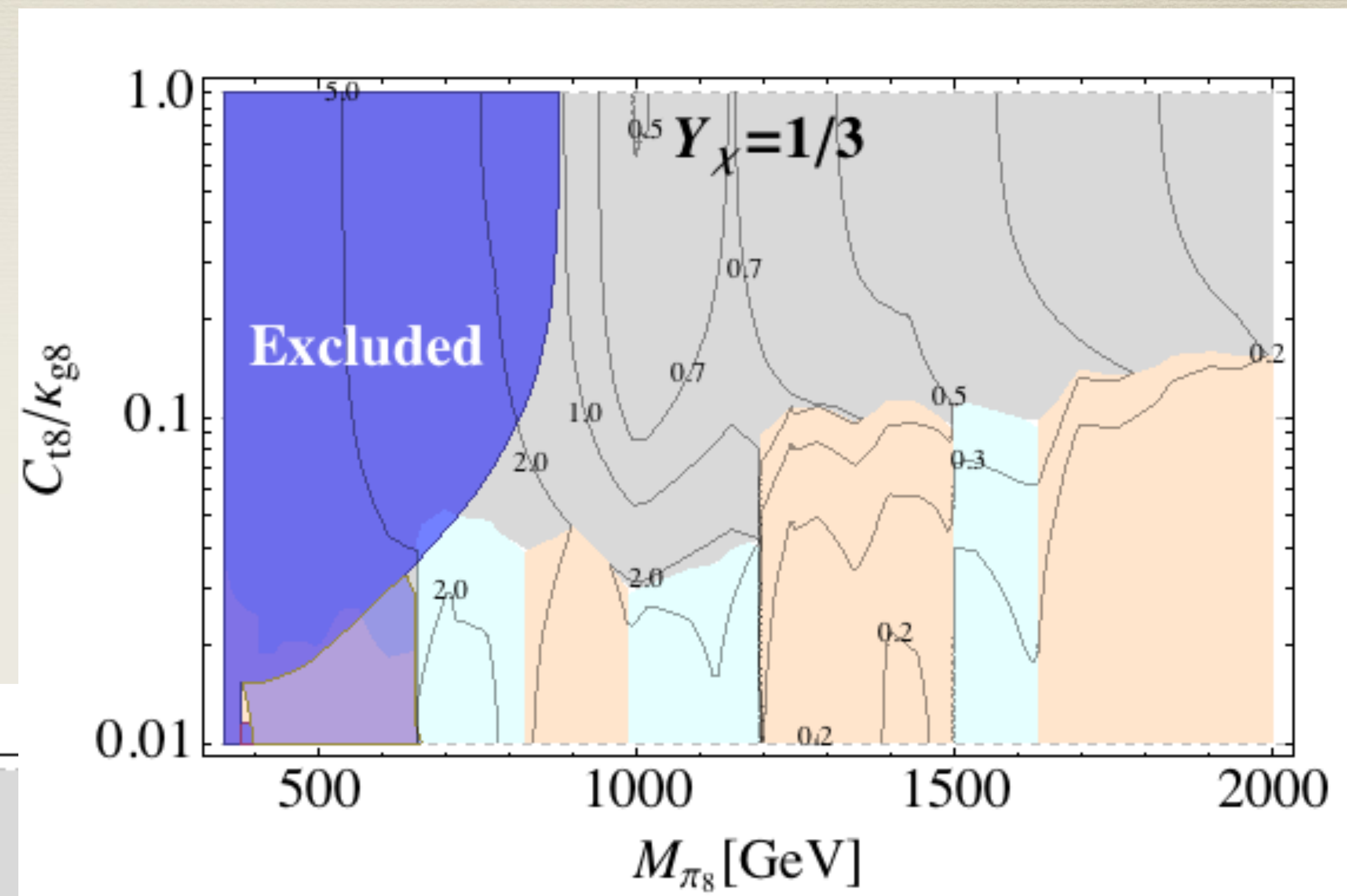
Colored PNGBs
Constraints from single production:

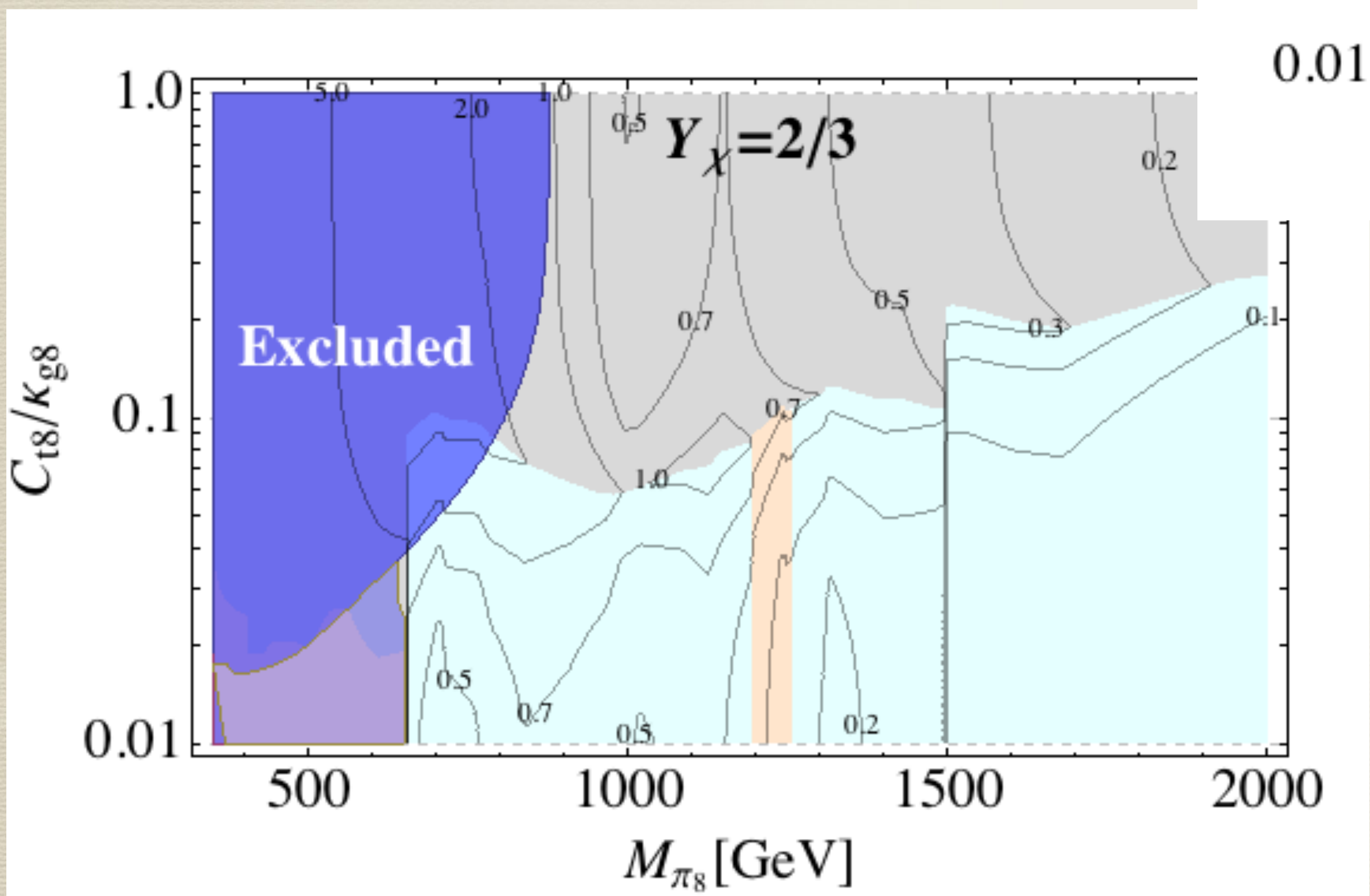






Colored PNGBs
Constraints from single production:



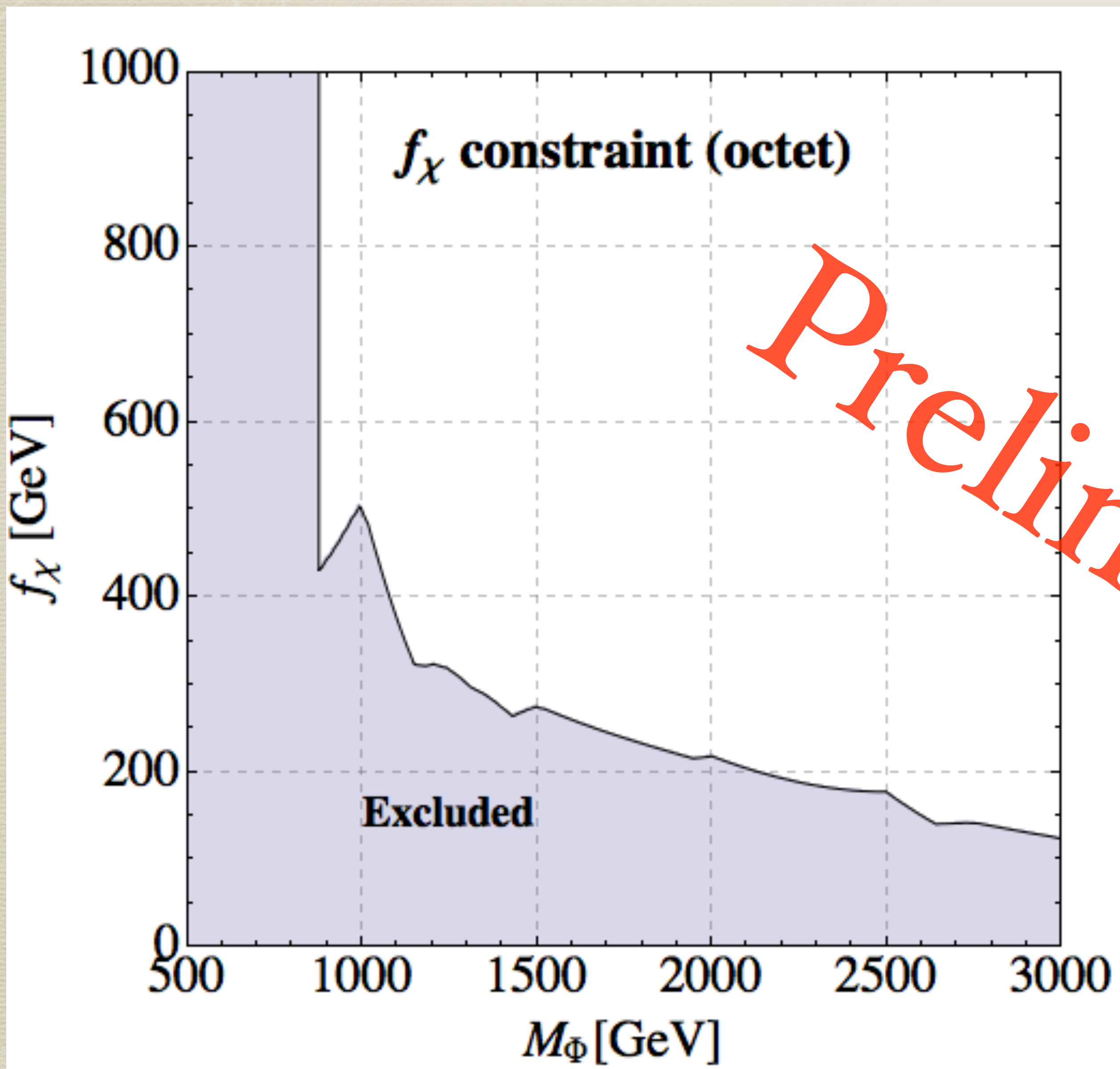


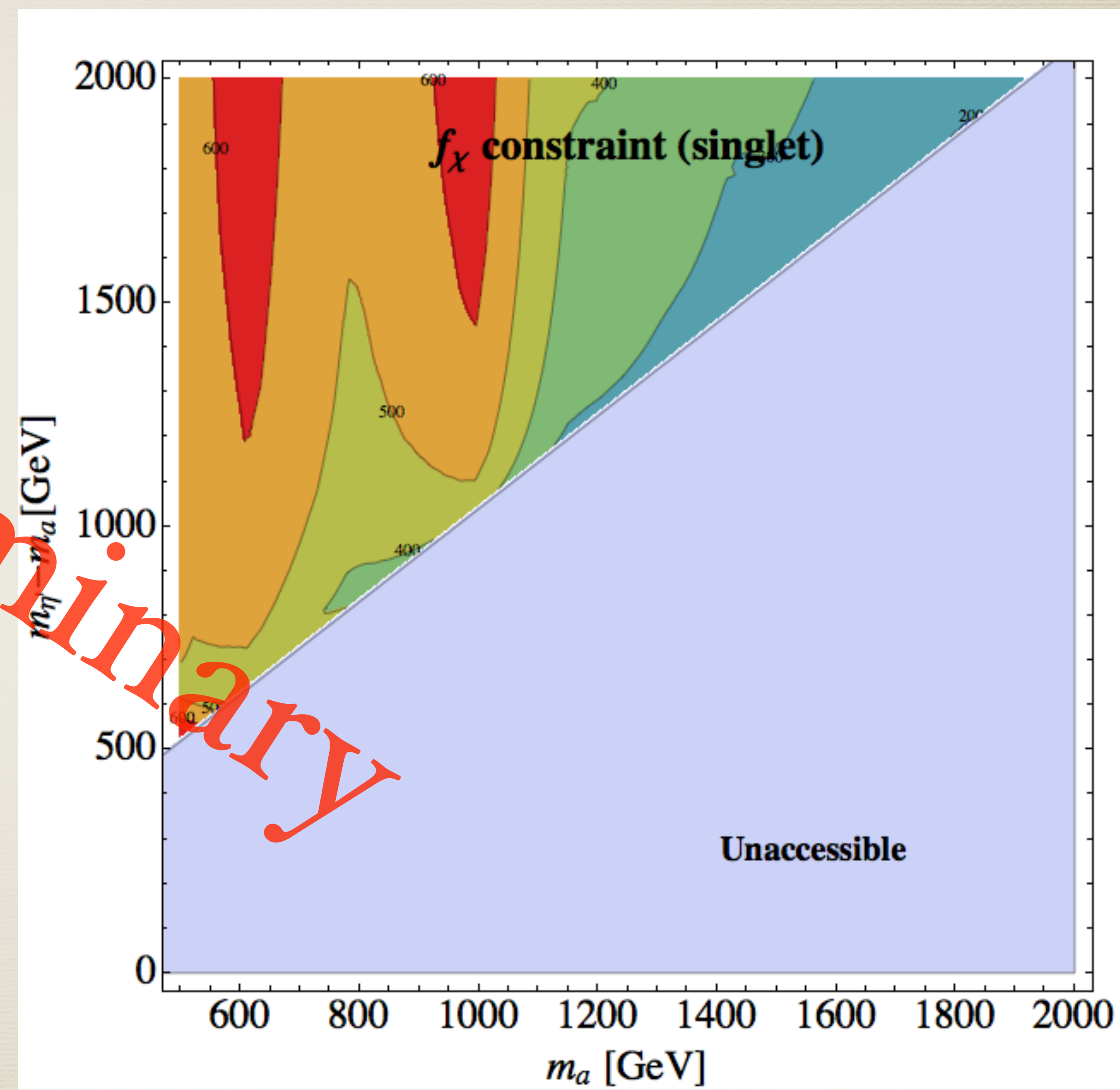
Channels with the strongest bound: gg (red), $g\gamma$ (cyan), $\bar{t}t$ (gray).

Example: Bounds on f_χ in "Model 6"

$$\left(SU(N_{\rm HC}) \middle| \; 5 \times \mathbf{A}_2 \; \middle| \; 3 \times (\mathbf{F}, \overline{\mathbf{F}}) \; \middle| \; N_{\rm HC} = 4 \; \middle| \; \tfrac{5}{3} \; \middle| \; 1/3 \; \middle| \; N_{\rm HC} = 4 \right)$$

with n_χ= 4, n_ψ=-2)





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 will lead to novel (as well as already well-known) BSM LHC signatures.
- We showed that di-boson signatures are predicted in a large class of CH UV embeddings. The models are highly predictive because the branching ratios of different di-boson channels are fully determined by the quantum numbers of the underlying fermion field content.
- Another feature common to all models we considered are potentially light colored scalar resonances which can be tested at the LHC.