Diboson production at LHC and future colliders
[or: Hunting for composite, pseudoscalar resonances]

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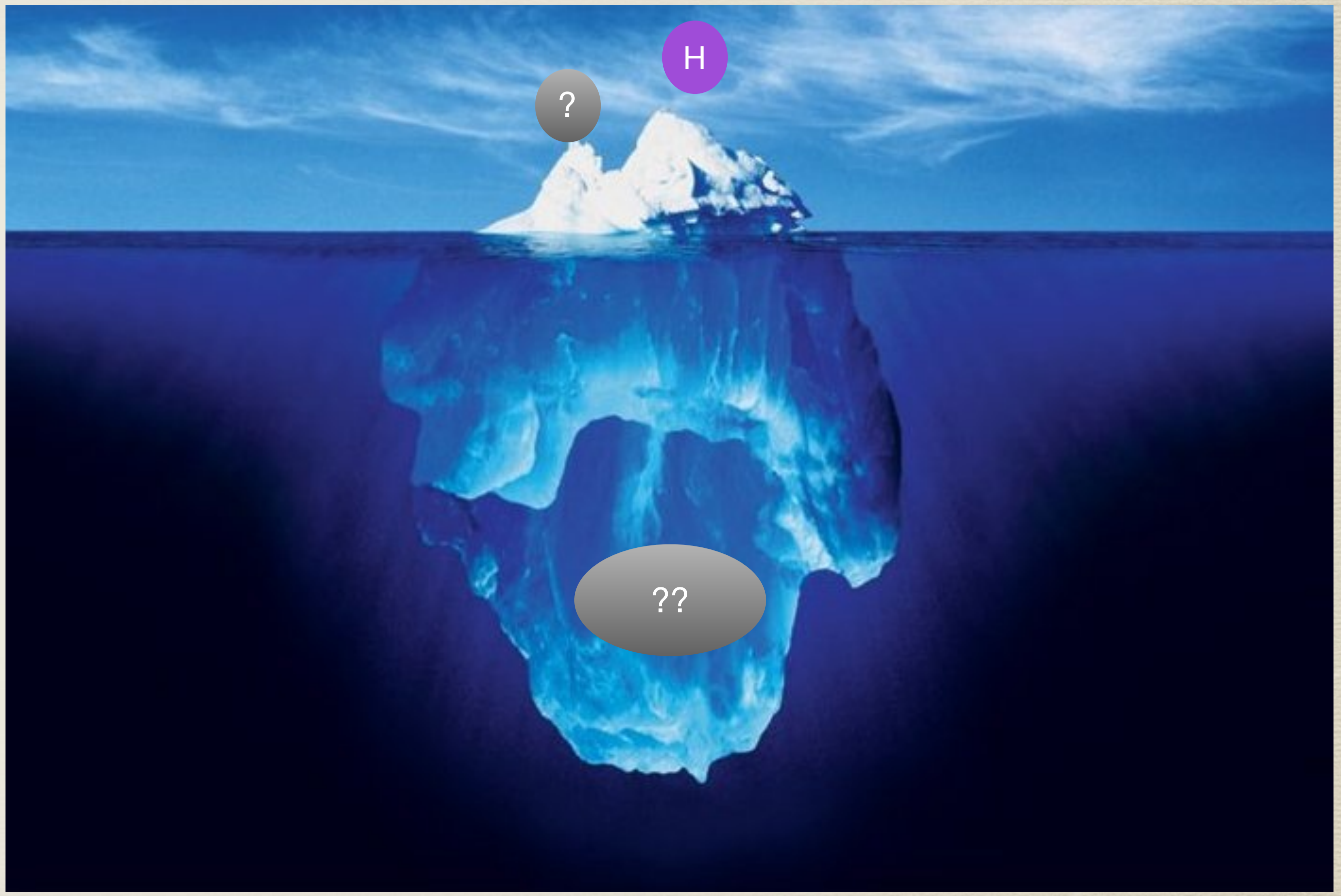
based on: H. Cai,
G. Cacciapaglia, H. Cai, A. Deandrea, T. Flacke, S.J. Lee, A. Parolini [JHEP 1511 (2015) 201]
H. Cai, T. Flacke, M. Lespinasse [arXiv:1512.04508]
A. Belyaev, G. Cacciapaglia, H. Cai, T. Flacke, H. Serodio, A. Parolini [PRD 94 (2016) no 1, 015004]
A. Belyaev, G. Cacciapaglia, H. Cai, G. Ferretti, T. Flacke, H. Serodio, A. Parolini [JHEP 1701 (2017) 094]
G. Cacciapaglia, G. Ferretti,T. Flacke, H. Serodio, [in progress]

Diboson physics at LHC meeting,
Seoul National University, Sep. 14th, 2017

Outline

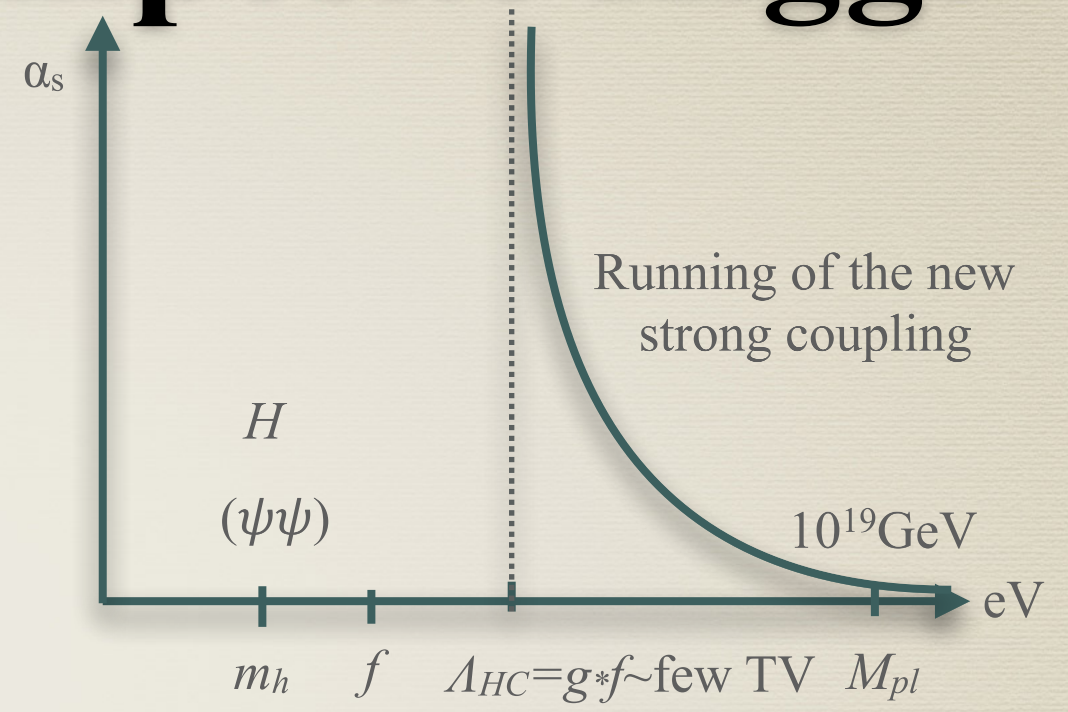
- A sample setup: UV embeddings of composite Higgs models
- Diboson signatures as a common feature of CHM UV embeddings
- An effective parametrization for pseudo-scalar searches in diboson channels
- Collection of existing bounds for “heavy” diboson resonances
- The case of a light (10-100 GeV) pseudo-scalar
- Colored states in CHM UV embeddings
- Conclusions



Motivation for a composite Higgs

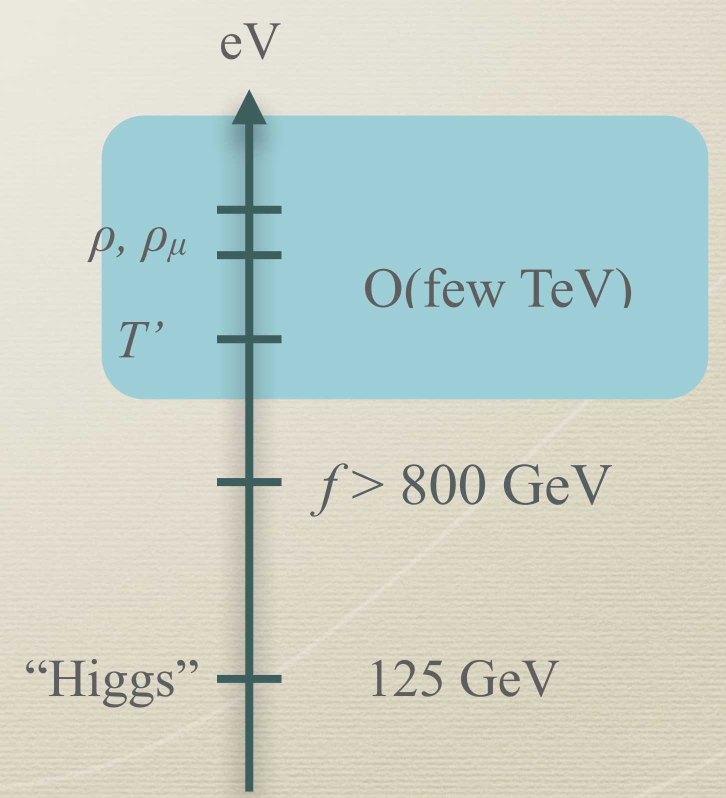
An alternative solution to the hierarchy problem:

- 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)×SU(3)×SU(2)×U(1)*, and the global symmetries *SU(4)×SU(6)×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	$(\mathbf{6},\mathbf{1})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{5},\mathbf{1})$	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

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

[JHEP 1701, 094]

$G_{\rm HC}$	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
	Real	Real	SU(5)/SO(5) $\times$ SU(6)/SO(6)				
$SO(N_{\rm HC})$	$5\times\mathbf{S}_2$	$6\times\mathbf{F}$	$N_{\rm HC}\geq 55$	$\frac{5(N_{\rm HC}+2)}{6}$	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) $\times$ 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) $\times$ 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) $\times$ 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) $\times$ 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) $\times$ 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	/	

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 $f_{a_r} = \sqrt{N_r} f_r$.

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.

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

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

where $$C^r_{AA'} c^{abc} = d_r \mathrm{Tr}[T_\pi^a \{S^b, S^c\}]$$

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.

Couplings to tops and other fermions:

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 $\psi\boldsymbol{\chi\chi}$ bound states. The spurions $y_{L,R}$ thus carry charges under the $\mathrm{U}(1)_{\boldsymbol{\chi},\psi}$.
The top mass in partial compositeness is proportional to $y_{L*}\, y_R$ fand thus also has definite $\mathrm{U}(1)_{\boldsymbol{\chi},\psi}$ charges $n_{\psi,\boldsymbol{\chi}}$. For $\psi\psi\boldsymbol{\chi}$:

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

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 $n_\psi = 0 = n_{\boldsymbol{\chi}}$.
- The analogous argument yields zero coupling of $\boldsymbol{\pi}_8$ to tops if $n_{\boldsymbol{\chi}} = 0$.

Upshot: - pNGBs couple to top-pairs.
- there is a discrete set of possible couplings per model.

Underlying fermion mass terms:

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 pNGBs arise from explicit breaking.
- masses of singlet and non-abelian pNGBs are related.
- ratios can be estimated, but calculating them needs the Lattice

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

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

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

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

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

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

Upshot: - The $\langle\chi\chi\rangle$ and $\langle\psi\psi\rangle$ pNGBs mix through an anomaly term and through their mass terms.
- The models contains one true (potentially light) pNGB a and one anomalous (potentially heavy) would-be pNGB η'

Singlet pNGBs: EFT parametrization

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

$$\mathcal{L}_{\pi_0} = \frac{1}{2}\left(\partial_\mu \pi_0 \partial^\mu \pi_0 - M_{\pi_0}^2 \pi_0^2\right) + i\, C_t \frac{m_t}{f_\pi}\, \pi_0\, \bar{t}\gamma_5 t$$

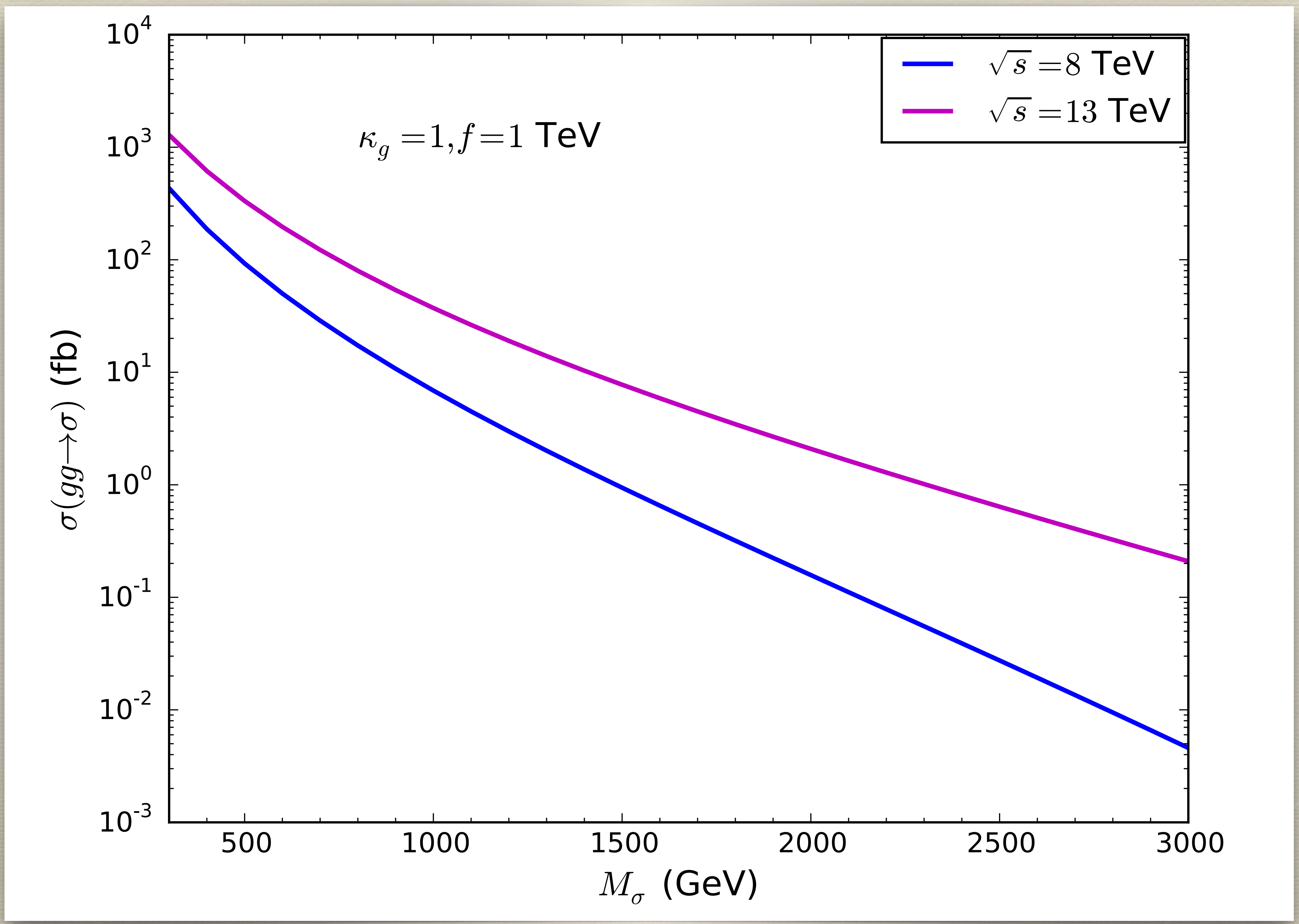
$$+ \frac{\alpha_s}{8\pi}\frac{\kappa_g}{f_\pi}\, \pi_0 \left(\epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} + \frac{g_2^2}{g_3^2}\frac{\kappa_W}{\kappa_g}\epsilon^{\mu\nu\rho\sigma} W^i_{\mu\nu} W^i_{\rho\sigma} + \frac{g_1^2}{g_3^2}\frac{\kappa_B}{\kappa_g}\epsilon^{\mu\nu\rho\sigma} B_{\mu\nu} B_{\rho\sigma}\right)$$

- The mass $M_{\pi 0}$ must result from *explicit* breaking of the U(1) symmetries
  → treated as free parameter in the effective theory.
- $f_{\pi 0}$ results from chiral symmetry breaking and is related (but not identical) to f_ψ.
  → treated as free parameter in the effective theory (f_ψ ≳800 GeV implies typically f_a ≳2 - 4 TeV).
- The WZW coefficients κ_i are fully determined by the quantum numbers of χ, ψ.
- The coefficient C_t are also fixed in each individual model.

Phenomenology

- π_0 is produced in gluon fusion (controlled by κ_g/f_π).
- π_0 decays to $gg, WW, ZZ, Z\gamma, \gamma\gamma, t\bar{t}$ with fully determined branching ratios. (controlled by κ_B/κ_g, κ_W/κ_g, C_t/κ_g)
- The resonance is narrow.

Production cross section for a pseudo-scalar $\boldsymbol{\pi}_0$

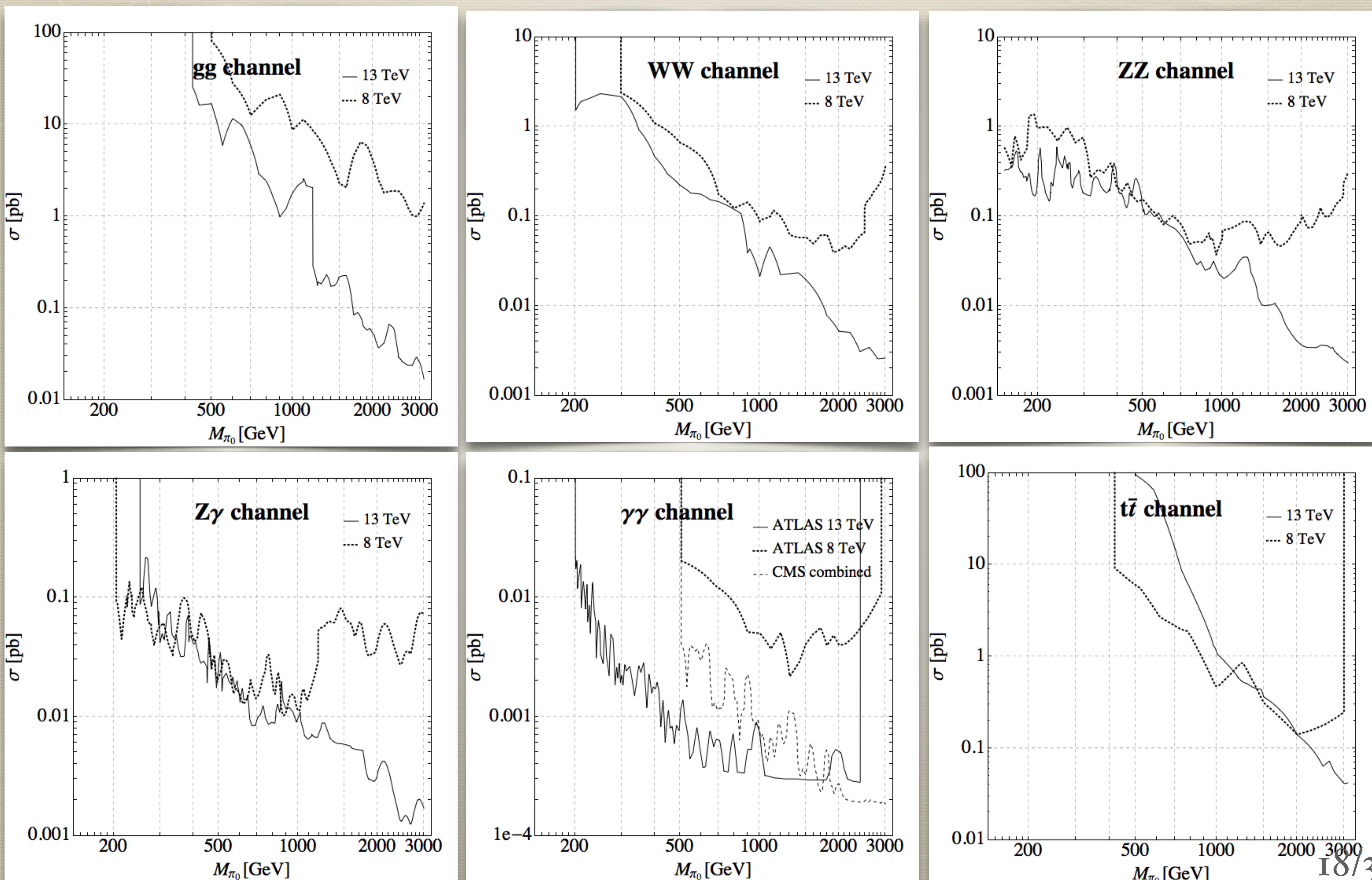


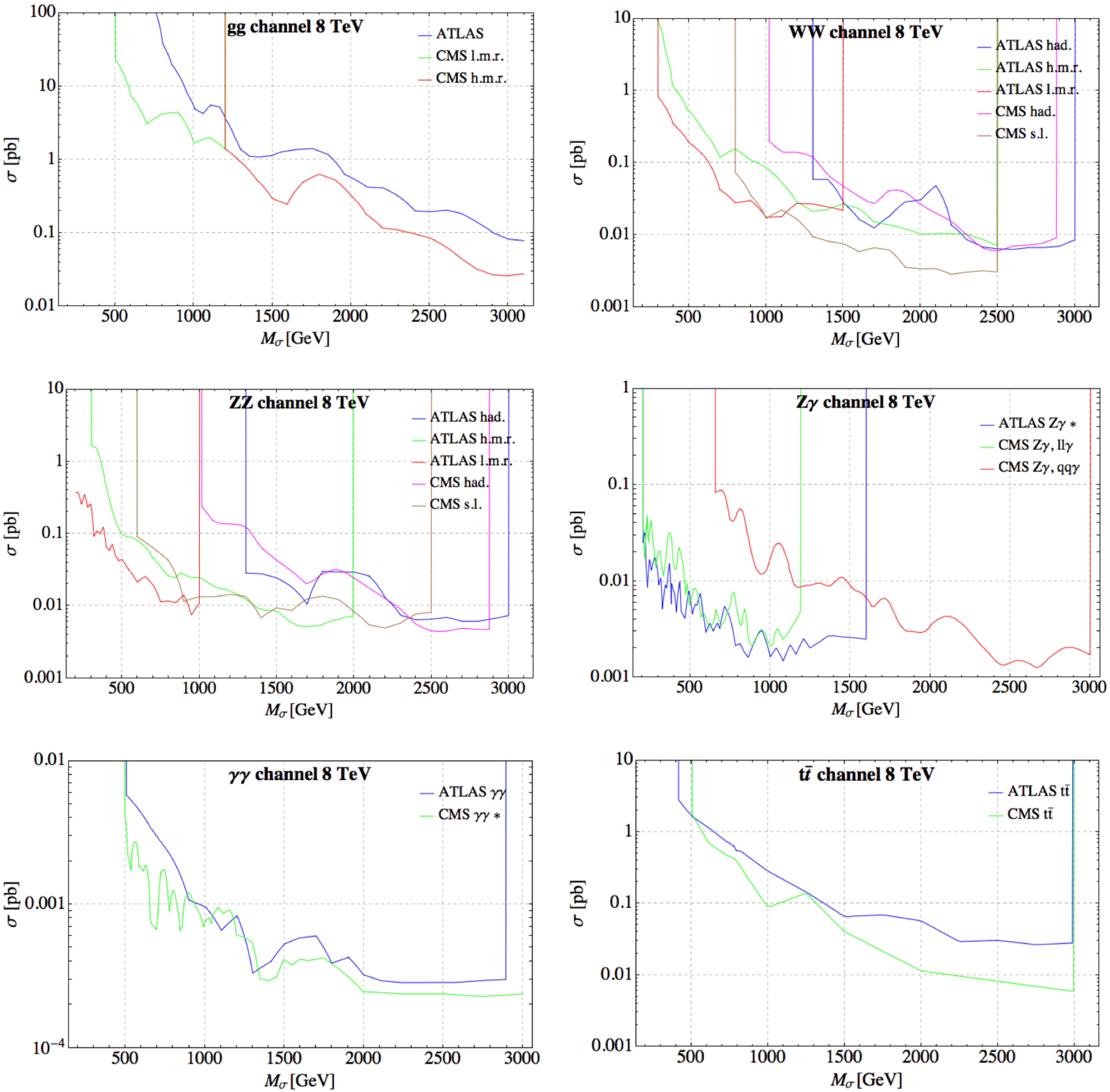
Partial widths:

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

Note: Branching fractions are independent of f_π.

Experimental constraints: (Status: after ICHEP 2016, 37 studies, 44 “bounds”) ATLAS and CMS @ 8 TeV and 13 TeV (c.f. JHEP 1701, 094 for full details)





gg:

- PRD91, 052007(ATLAS)
- CMS-PAS-EXO-14-005
- PRD91, 052009(CMS)

WW:

- JHEP1601,032(ATLAS)
- EJPC75,209(ATLAS)
- JHEP1512,055(ATLAS)
- JHEP1408,173(CMS)
- JHEP1408,174(CMS)

ZZ:

- JHEP1512,055(ATLAS)
- JHEP1408,173(CMS)
- JHEP1408,174(CMS)
- EPJC75,69(ATLAS)
- EPJC76,45(ATLAS)

$Z\gamma$:

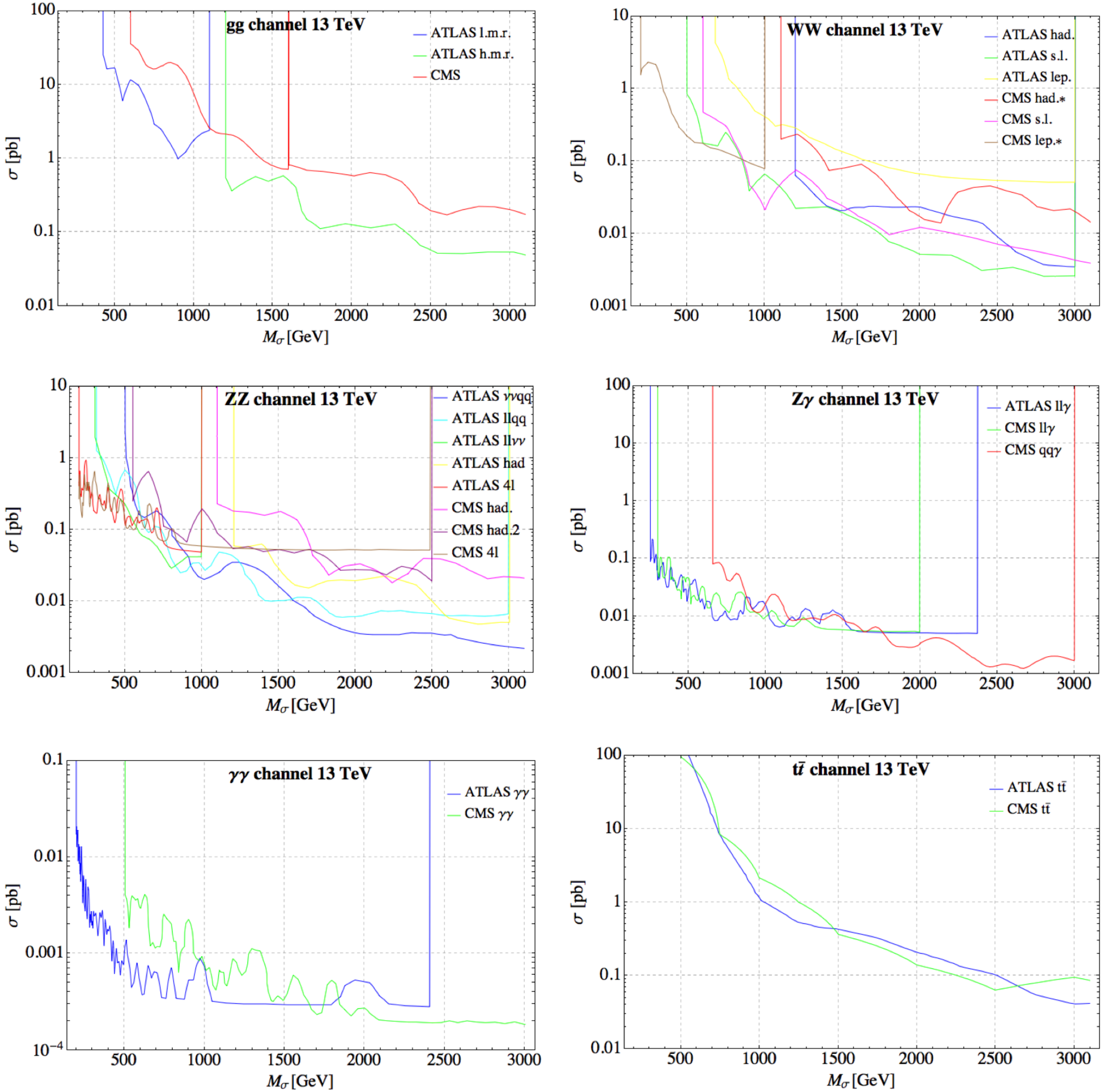
- PLB738,428(ATLAS)
- CMS-PAS-HIG-14-031
- CMS-PAS-EXO-16-025

$\gamma\gamma$:

- PRD92,032004(ATLAS)
- CMS-PAS-EXO-12-045

tt:

- JHEP1508,148(ATLAS)
- PRD93,012001(CMS)



gg:

- ATLAS-CONF-2016-030
- ATLAS-CONF-2016-069
- CMS-PAS-EXO-16-032

WW:

- ATLAS-CONF-2016-074
- ATLAS-CONF-2016-062
- ATLAS-CONF-2016-055
- CMS-PAS-EXO-15-002
- CMS-PAS-HIG-16-023
- CMS-PAS-B2G-16-020

ZZ:

- JHEP1512,055(ATLAS)
- ATLAS-CONF-2016-079
- ATLAS-CONF-2016-082
- ATLAS-CONF-2016-056
- CMS-PAS-EXO-15-002
- CMS-PAS-B2G-16-010.
- CMS-PAS-HIG-16-033

$Z\gamma$:

- ATLAS-CONF-2016-044
- CMS-PAS-EXO-16-034
- CMS-PAS-EXO-16-035

$\gamma\gamma$:

- ATLAS-CONF-2016-059
- .CMS-PAS-EXO-16-018

tt:

- ATLAS-CONF-2016-014
- CMS-PAS-B2G-15-002

Proclaimer 1: The combined constraints are obtained by comparing ATLAS and CMS bounds on models and signatures which are very similar to ours, but we did not perform a detailed recast of each study, and we did not combine statistically combine results. We only (naively) took the strongest bound for each channel at each given mass. For details of the assumptions made in the extracting the bounds, see JHEP 1701, 094.

Proclaimer 2: The combined constraints are at the status of post-ICHEP 2016. Since then, ATLAS and CMS published numerous additional studies.

The new results partially increase the bounds as compared to the published bounds on composite Higgs pNGBs in JHEP 1701, 094.

Recent new results include:

gg: 1703.09127(ATLAS), CMS PAS EXO-16-056, CMS-EXO-B2G-17-001

WW: ATLAS-CONF-2017-051, 1708.04445(ATLAS), CMS-PAS-B2G-17-001, CMS-PAS-B2G-16-023, CMS-PAS-B2G-16-021, CMS-PAS-B2G-16-007, CMS-PAS-B2G-16-004

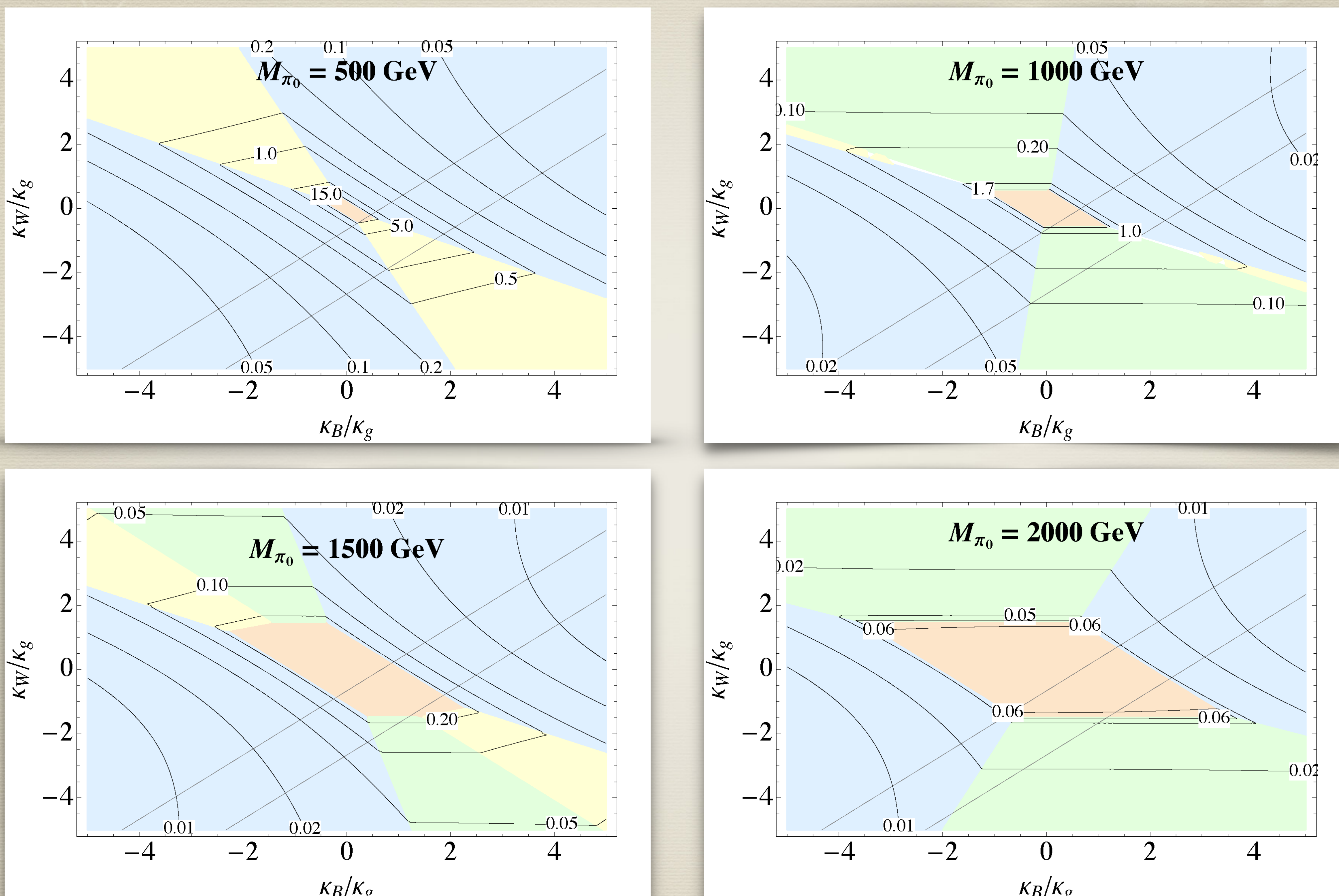
ZZ: 1708.04445(ATLAS), 1708.09638 (ATLAS), CMS-PAS-B2G-17-001, CMS-PAS-B2G-17-005, CMS-PAS-B2G-16-023, CMS-PAS-B2G-16-021, CMS-PAS-B2G-16-007, CMS-PAS-B2G-16-004

$Z\gamma$: CMS-PAS-EXO-17-005

$\gamma\gamma$: 1707.04147(ATLAS)

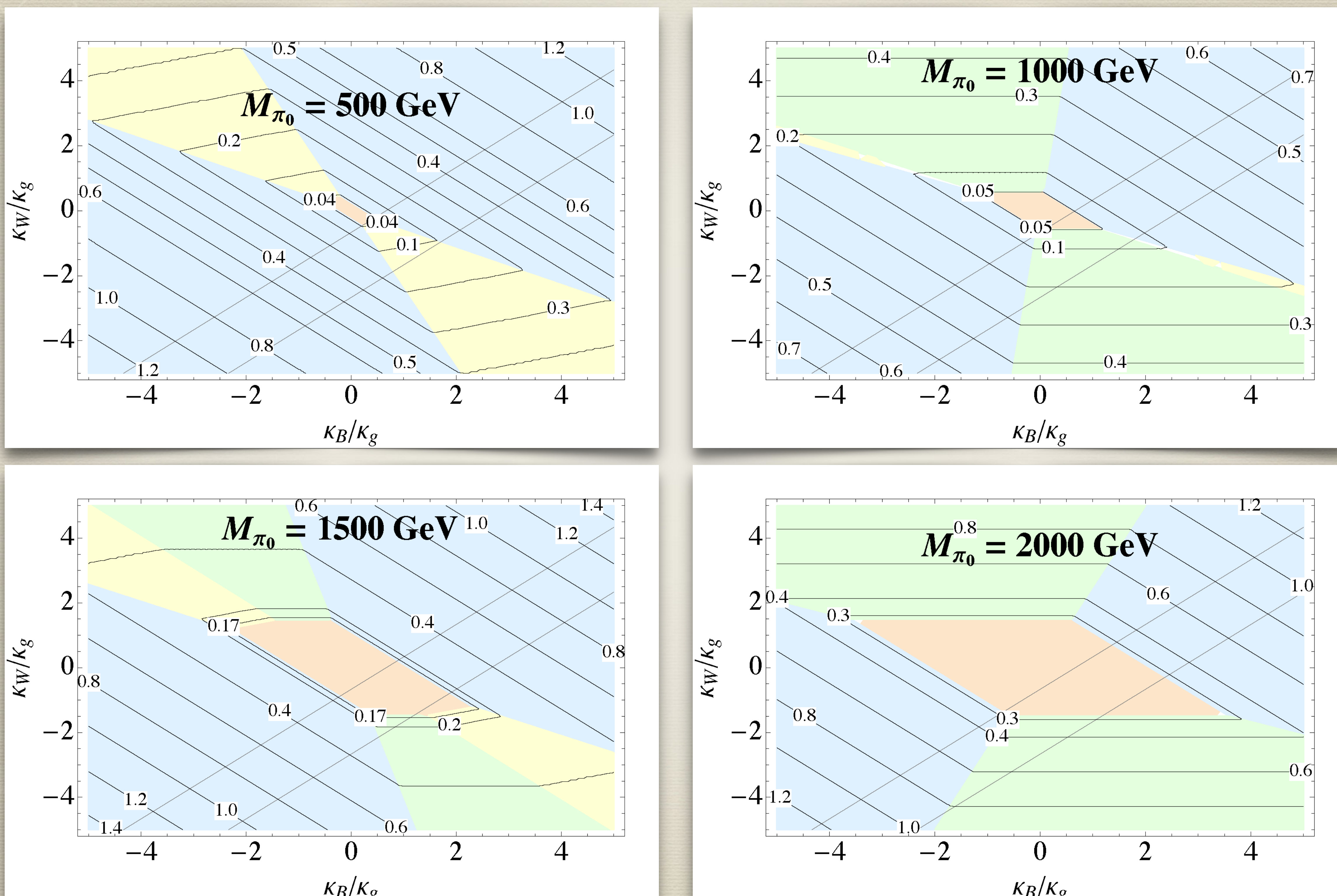
tt: CMS-PAS-B2G-16-015

Resulting bounds on pseudo-scalar 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:



Implications of the model-independent bounds for CHM UV embeddings:

In the composite Higgs model UV embeddings, the couplings of the PNGBs to gauge bosons and tops are fixed by the quantum numbers of the underlying quarks.

The only non-determined parameters are the decay constants f_χ, f_ψ and the PNGB masses.

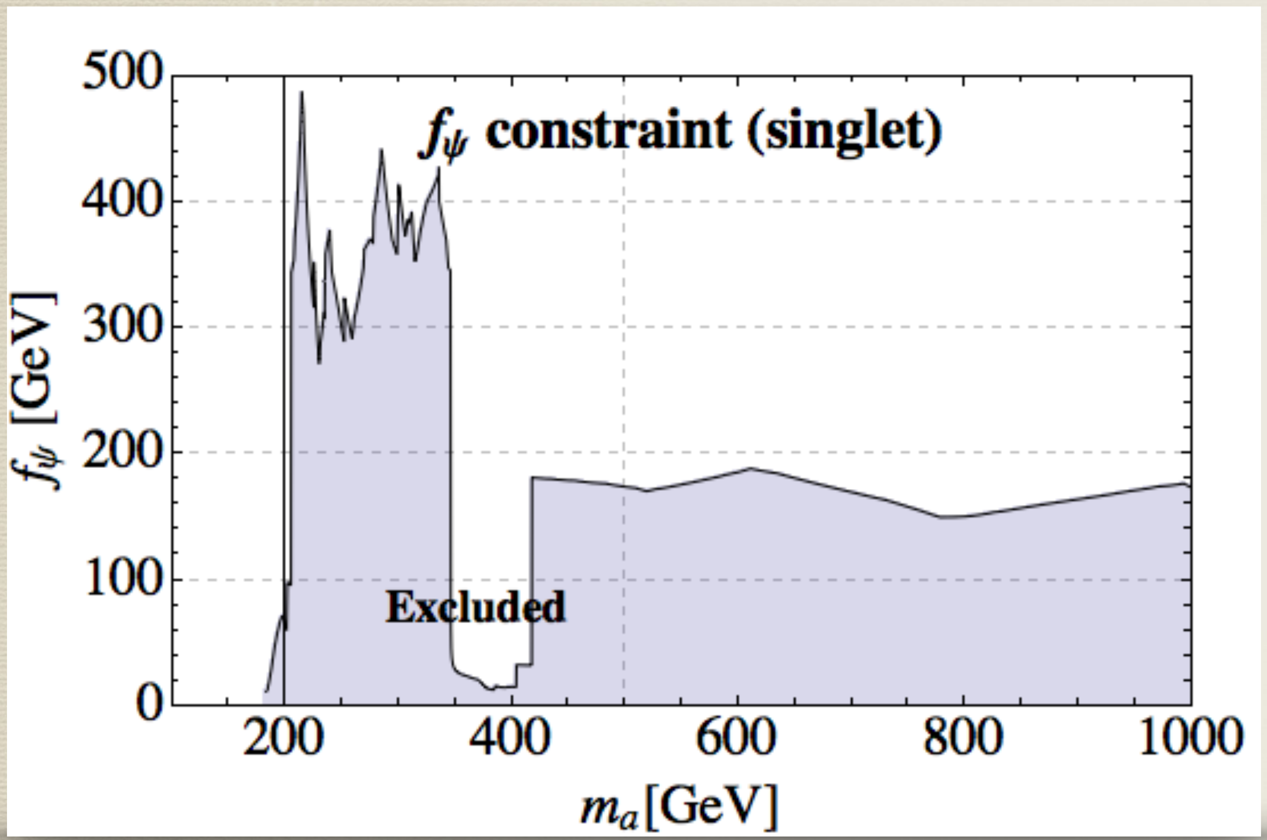
Hence we can use the experimental constraints to determine bounds on f_χ, f_ψ as a function of the masses.

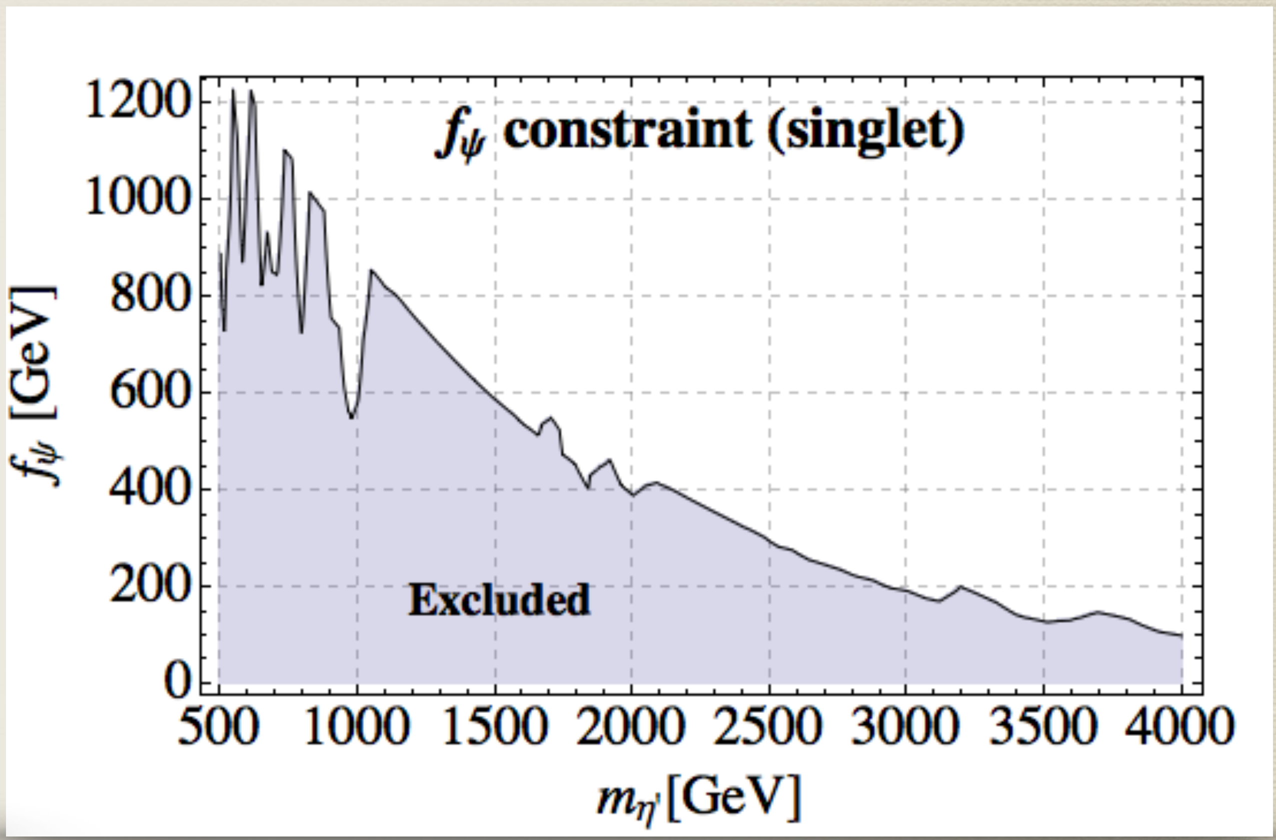
Model		$\tan\alpha$	κ_g	κ_B	κ_W	C_t (n_ψ, n_χ)			
						$(2,0)$	$(0,2)$	$(4,2)$	$(-4,2)$
M3	π_8	–	14.	18.7	–	0.	4.	4.	4.
	a	-.913 (-.388)	-2.72 (-1.46)	-3.53 (.921)	3.74 (4.72)	.934 (1.18)	-.778 (-.417)	1.09 (1.94)	-2.65 (-2.78)
	η'		2.98 (3.77)	11.4 (11.9)	3.41 (1.83)	.853 (.457)	.853 (1.08)	2.56 (1.99)	-.853 (.162)
M4	π_8	–	18.	24.	–	0.	4.	4.	4.
	a	-1.83 (-.592)	-4.56 (-2.65)	-7.29 (1.64)	4.86 (8.71)	.608 (1.09)	-1.01 (-.589)	.203 (1.59)	-2.23 (-2.77)
	η'		2.50 (4.47)	15.5 (17.1)	8.88 (5.16)	1.11 (.645)	.555 (.993)	2.77 (2.28)	-1.66 (-.296)
M8	π_8	–	7.07	9.43	–	0.	2.83	2.83	2.83
	a	-0.408 (-.196)	-.771 (-.393)	-1.13 (-.067)	.926 (.981)	.926 (.981)	-.309 (-.157)	1.54 (1.81)	-2.16 (-2.12)
	η'		1.89 (2.00)	5.42 (5.53)	.378 (.193)	.378 (.193)	.756 (.801)	1.51 (1.19)	0. (.416)
M9	π_8	–	15.6	20.7	–	0.	2.83	2.83	2.83
	a	-3.27 (-.740)	-4.29 (-2.67)	-9.11 (-.689)	2.34 (6.43)	.293 (.804)	-.781 (-.486)	-.195 (1.12)	-1.37 (-2.09)
	η'		1.31 (3.61)	11.2 (14.4)	7.65 (4.76)	.956 (.595)	.239 (.656)	2.15 (1.85)	-1.67 (-.533)
M10	π_8	–	14.1	18.9	–	0.	2.83	2.83	2.83
	a	-3.27 (-.740)	-3.90 (-2.43)	-8.07 (-.042)	2.34 (6.43)	.293 (.804)	-.781 (-.486)	-.195 (1.12)	-1.37 (-2.09)
	η'		1.20 (3.28)	10.8 (13.5)	7.65 (4.76)	.956 (.595)	.239 (.656)	2.15 (1.85)	-1.67 (-.533)
M11	π_8	–	8.49	11.3	–	0.	2.83	2.83	2.83
	a	-.816 (-.356)	-1.55 (-.822)	-2.58 (-.309)	1.55 (1.88)	.775 (.942)	-.516 (-.274)	1.03 (1.61)	-2.07 (-2.16)
	η'		1.90 (2.31)	6.32 (6.82)	1.26 (.671)	.632 (.336)	.632 (.769)	1.90 (1.44)	-.632 (.098)
M12	π_8	–	14.1	18.9	–	0.	2.83	2.83	2.83
	a	-.385 (-.186)	-2.07 (-1.05)	-3.20 (-.355)	2.33 (2.46)	.933 (.983)	-.415 (-.211)	1.45 (1.76)	-2.28 (-2.18)
	η'		5.39 (5.68)	15.3 (15.6)	.898 (.457)	.359 (.183)	1.08 (1.14)	1.80 (1.50)	.359 (.770)

TABLE X: Couplings for models with top partners of the form $\psi\psi\chi$, for $f_\chi = f_\psi$, normalised to f_ψ.

Example 1: Bounds on f in "Model 8", (n_χ,n_ψ)=(2,0)

$$\left(\quad Sp(2N_{\rm HC}) \middle| \quad 4\times\mathbf{F} \quad \middle| \quad 6\times\mathbf{A}_2 \quad \middle| \quad 2N_{\rm HC}\le 36 \middle| \frac{1}{3(N_{\rm HC}-1)} \middle| \; 2/3 \; \middle| \quad 2N_{\rm HC}=4 \quad \right)$$

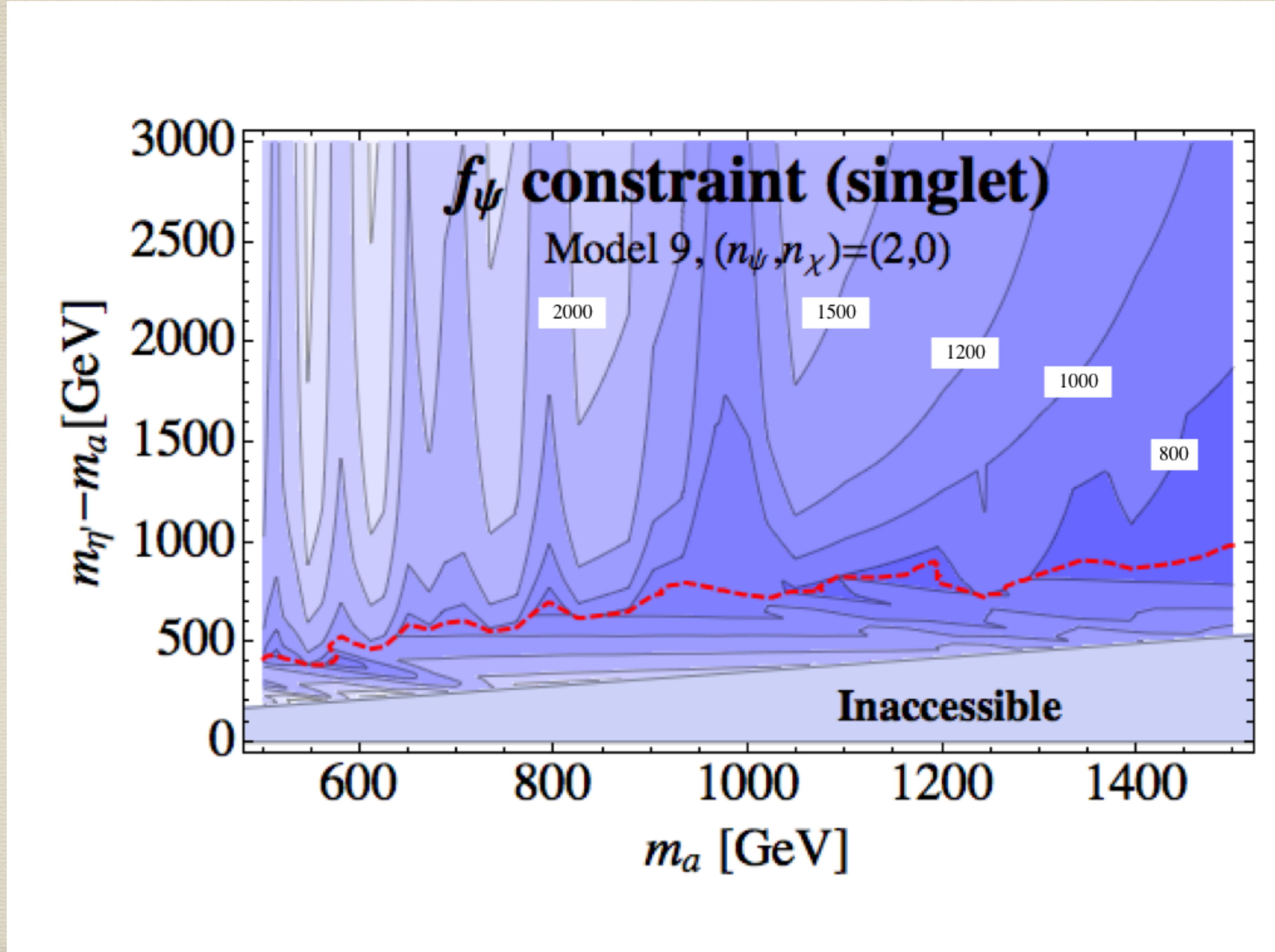




The Higgs sector of Composite Higgs Models imposes a bound of $f_\psi \gtrsim 800$ GeV. For this model, diboson searches are not (yet) competitive…

Example 2: Bounds on f in "Model 9", $(n_{\chi},n_{\psi})=(2,0)$

$SO(N_{\rm HC})$	$4\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{\rm HC}=11,13$	$\frac{8}{3},\ \frac{16}{3}$	$2/3$	$N_{\rm HC}=11$



For this model, diboson searches exceed bounds from the Higgs sector of composite Higgs models in almost all of the parameter space…

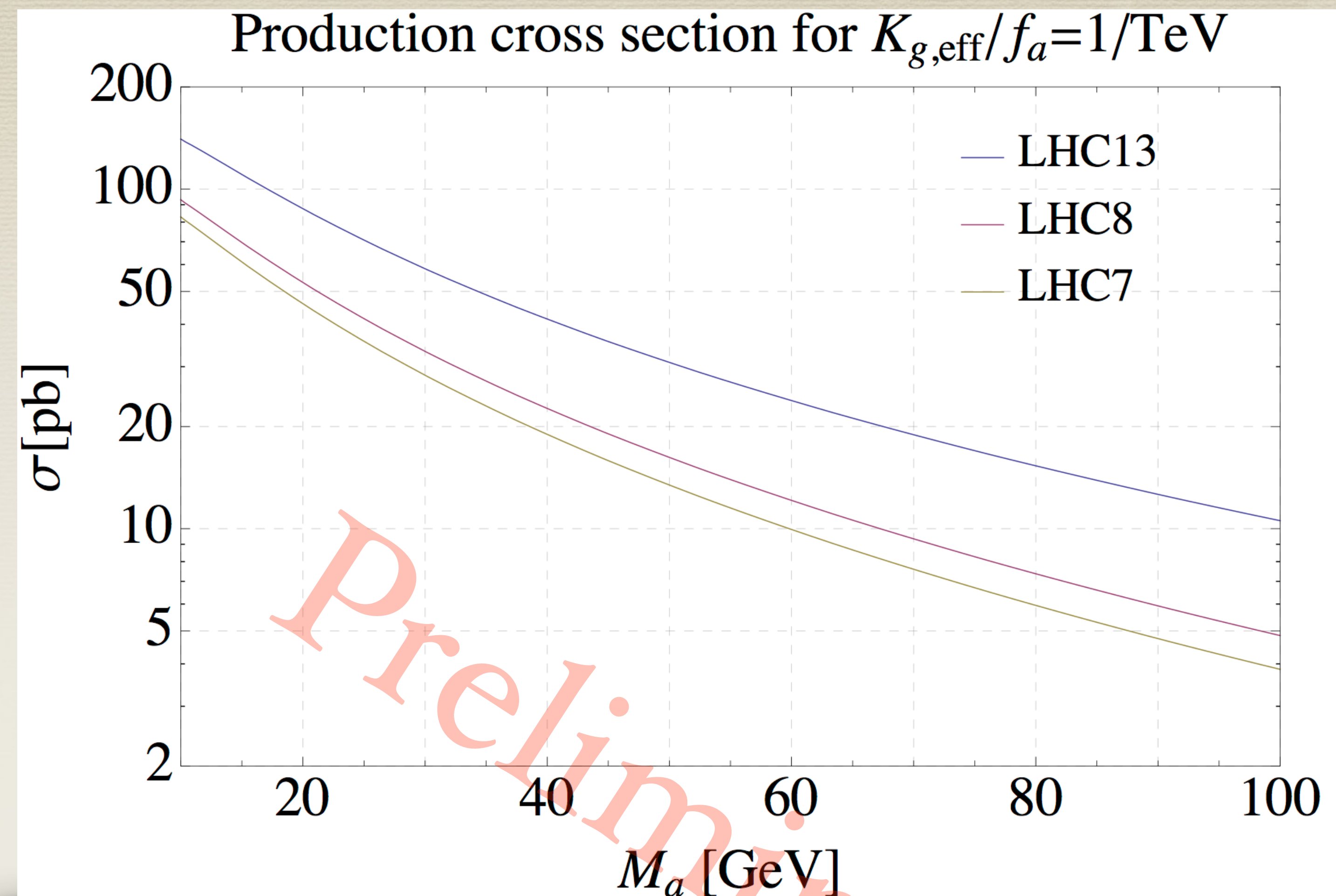
The case of a light (10 - 100 GeV) pseudoscalar

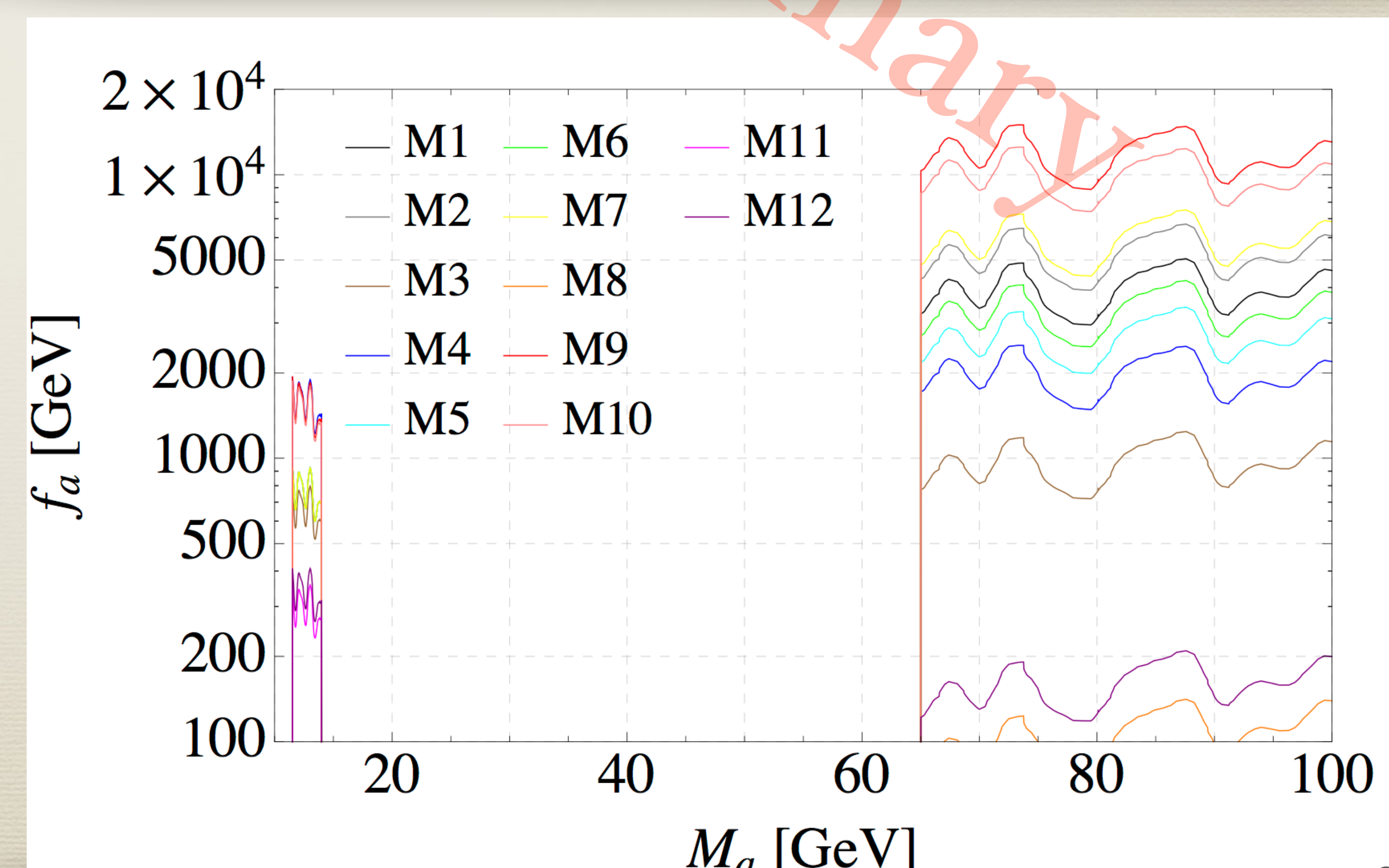
[Cacciapaglia, Ferretti, Flacke, Serodio, to appear]

So far, we focussed on searches BSM diboson and ditop searches in the "heavy" mass range (above m_{h}). But …

- The Higgs arises as a pNGB multiplet from the strong sector and obtains a mass from explicit breaking via an underlying hyperquark mass m_{χ}, top-partner loops, and gauging of the SM electroweak group.
- The SM singlet pNGB a only receives mass from the underlying hyperquark masses $m_{\chi,\psi}$, so it is not necessarily heavier.
- There are no direct LEP constraints on a, as its associated production with Z-bosons is strongly suppressed.
- Electroweak precision bounds are weak [Bauer, Neubert, Thamm, 1708.00443]
- For generic pseudoscalars, h $\rightarrow aa$ and/or h $\rightarrow Za$ (and subsequent a decays) yield important bounds and opportunities for searches [Bauer, Neubert, Thamm, 1708.00443], but for our composite pNGB, these couplings are small *and* $a \rightarrow \gamma\gamma$ and $a \rightarrow ll$ have low branching ratios.

- At the same time, the production cross section via gluon fusion is not small.
- The only existing bounds we found in the mass range 10 - 100 GeV are low-mass resonance searches for dimuons [PRL 109 (2012) 121801 (CMS7), ATLAS-CONF-2011-020] and diphotons [PRL 113, (2014) 171801 (ATLAS8), CMS-PAS-HIG-14-037].
- Can dimuon searches be extended above 15 GeV? Can diphoton searches extended below 65 GeV? Can ditau searches (boosted against ISR) help?





Colored PNGBs

CH UV embeddings contain color sextet or color triplet pNGBs (model-dependent), but *all* models contain a color octet pNGB $\boldsymbol{\pi}_8$ **.**

Effective Lagrangian:

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

where in the CH UV embeddings:

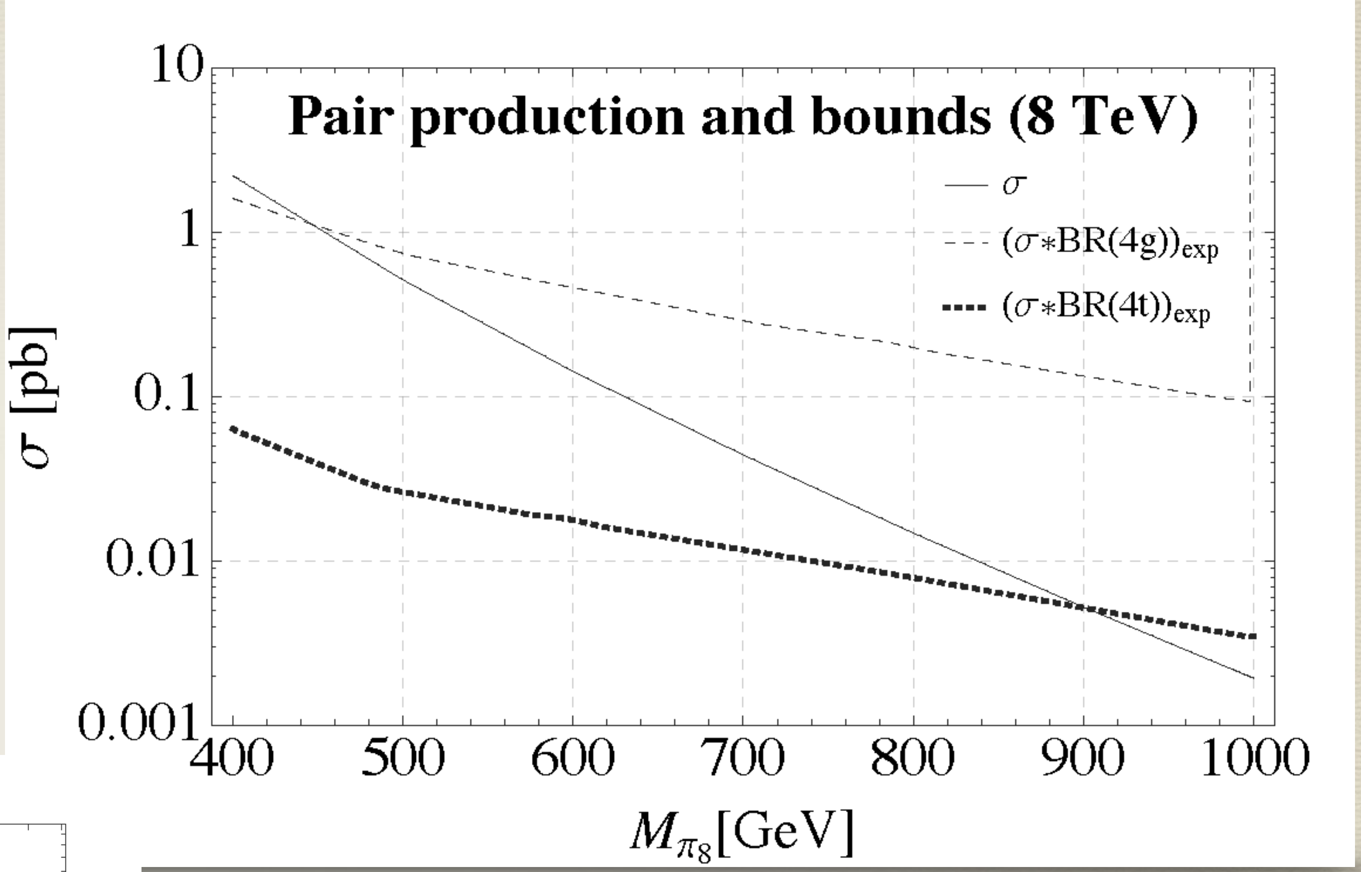
$$\kappa_{g8} = \sqrt{2} c_5\, d_\chi\,, \quad \kappa_{B8} = \sqrt{2} c_5\, 2Y_\chi\, d_\chi, \quad C_{t8} = n_\chi \sqrt{2} c_5 \quad , \quad m_{\pi_8}^2 \sim \frac{m_a^2}{\xi_\chi \sin^2 \zeta} + C_g \frac{3}{4} g_s^2\, f_\chi^2$$

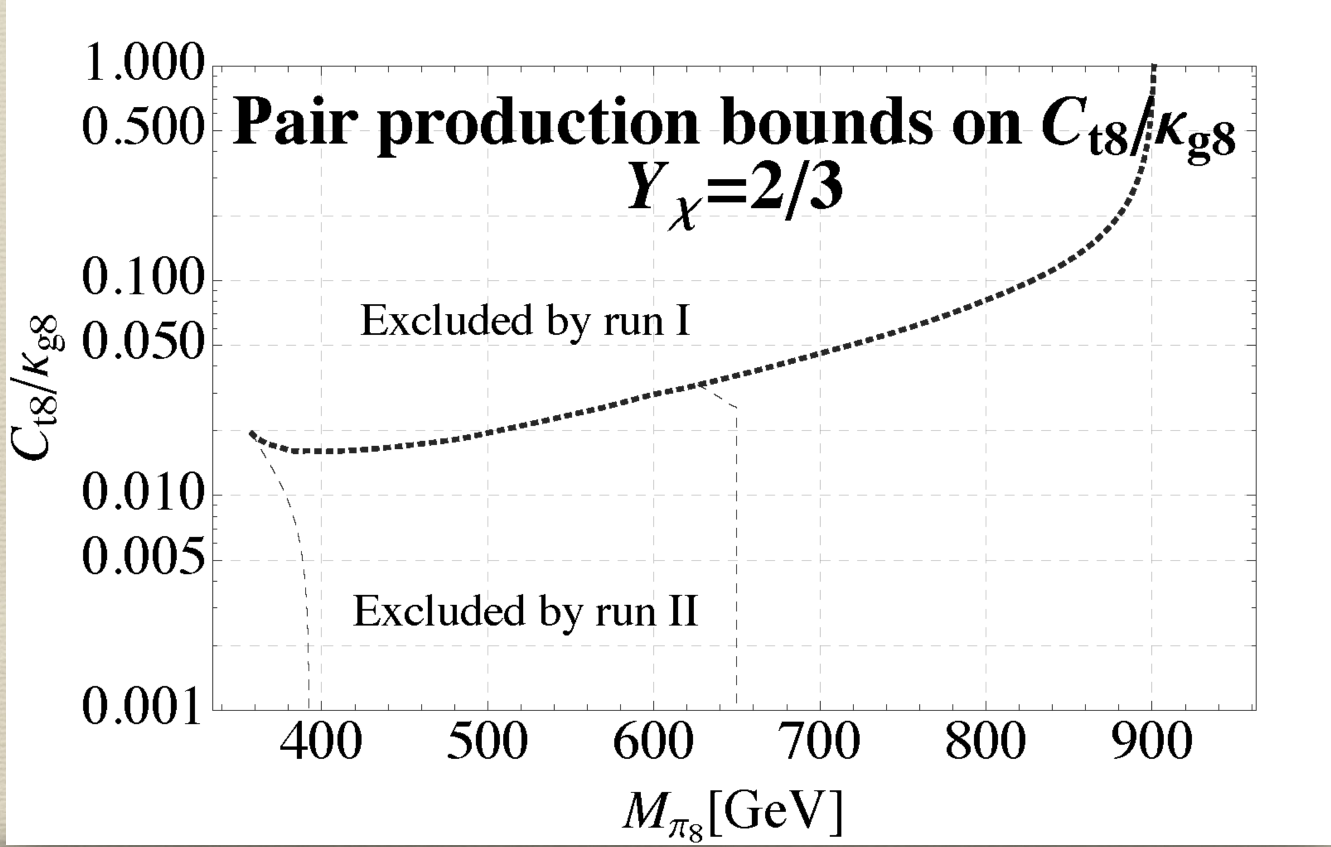
Phenomenology

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

Colored PNGBs
Constraints from pair production:

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

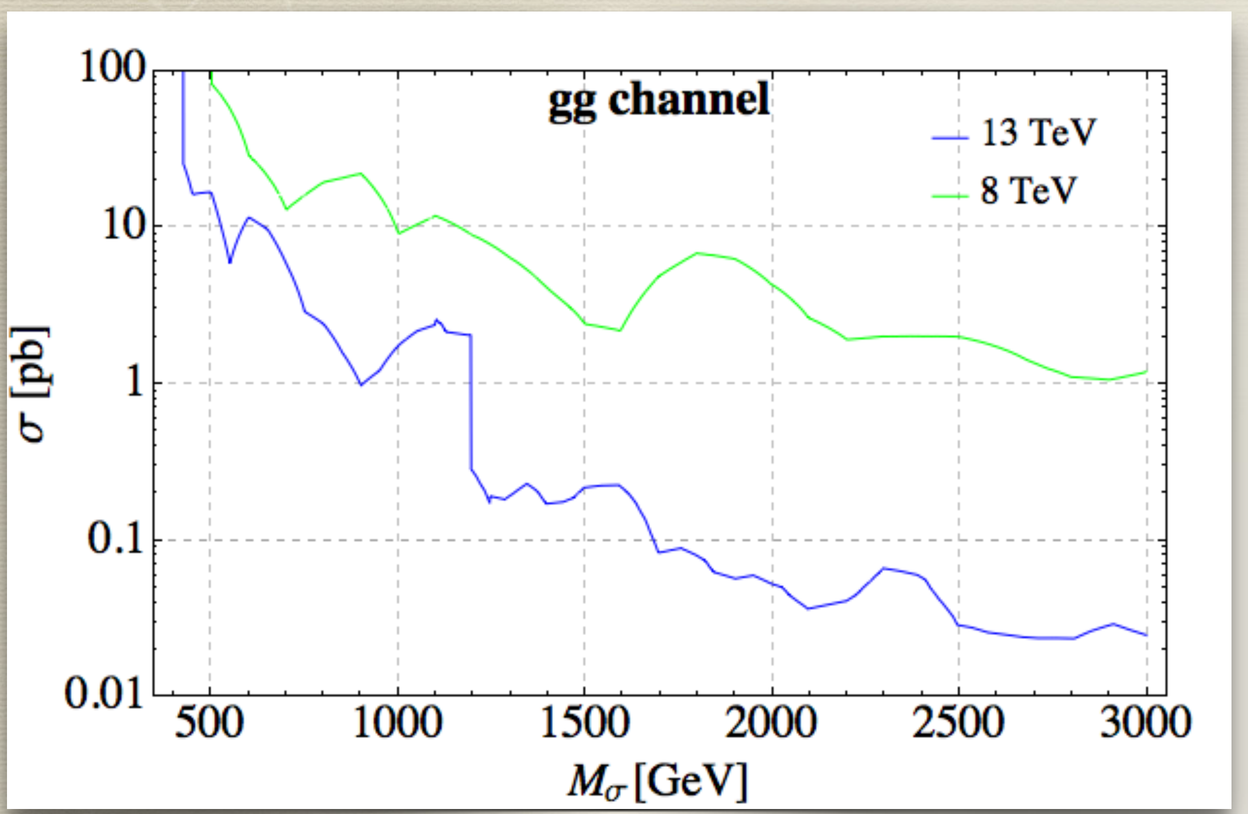


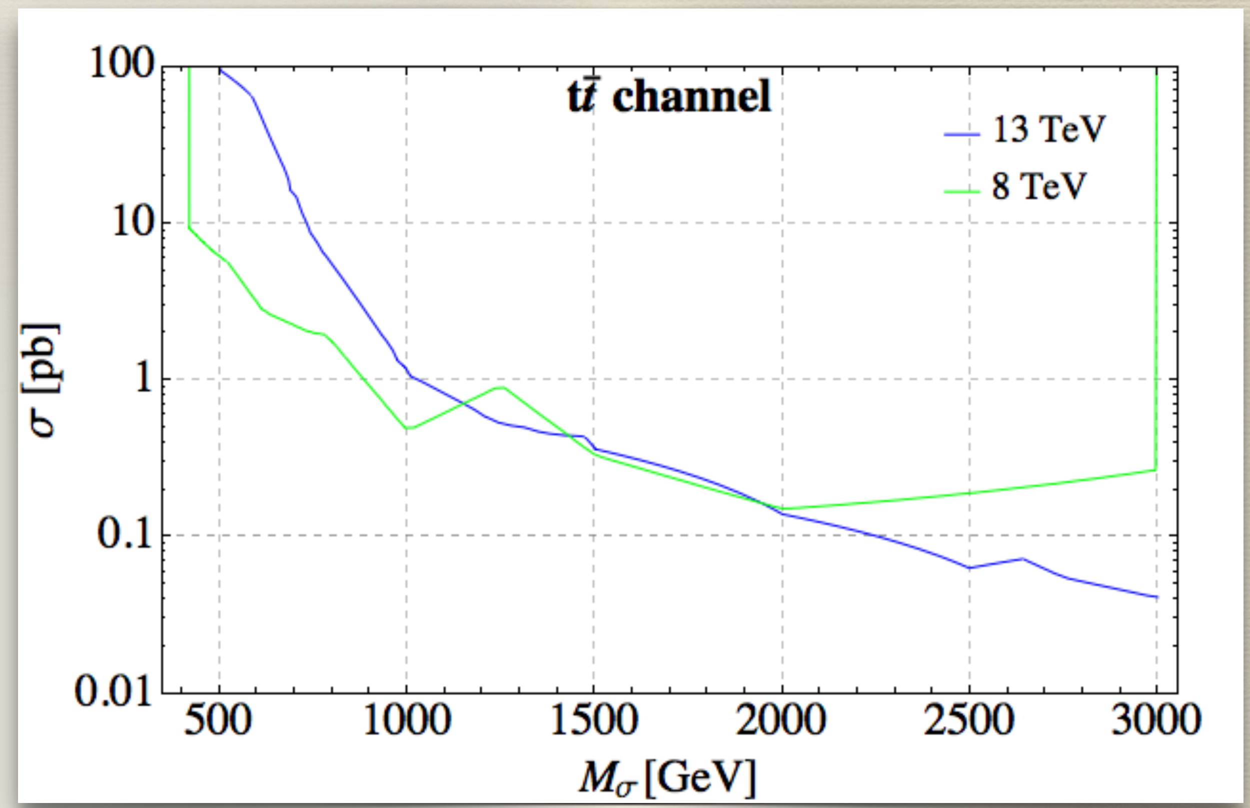


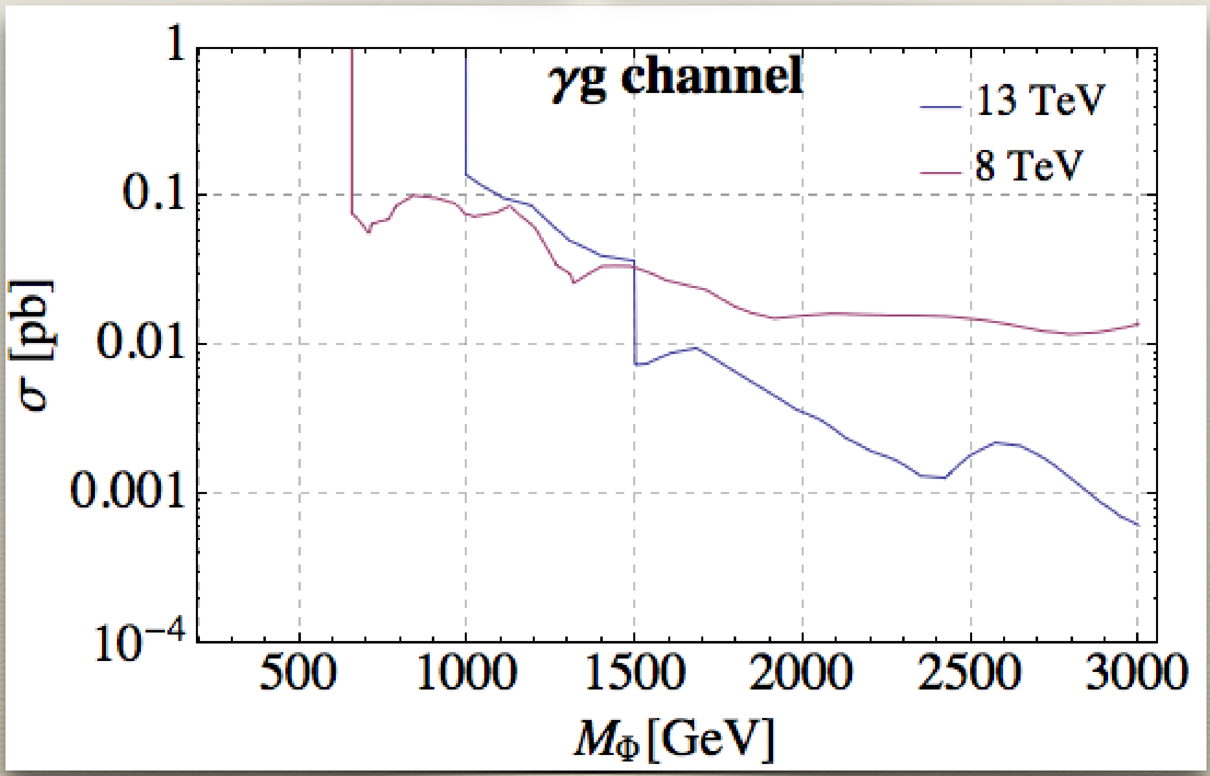
Left: Implied bounds on the C_{t8}/κ_g vs. M_ϕ parameter space.

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

Colored PNGBs
Constraints from single production:



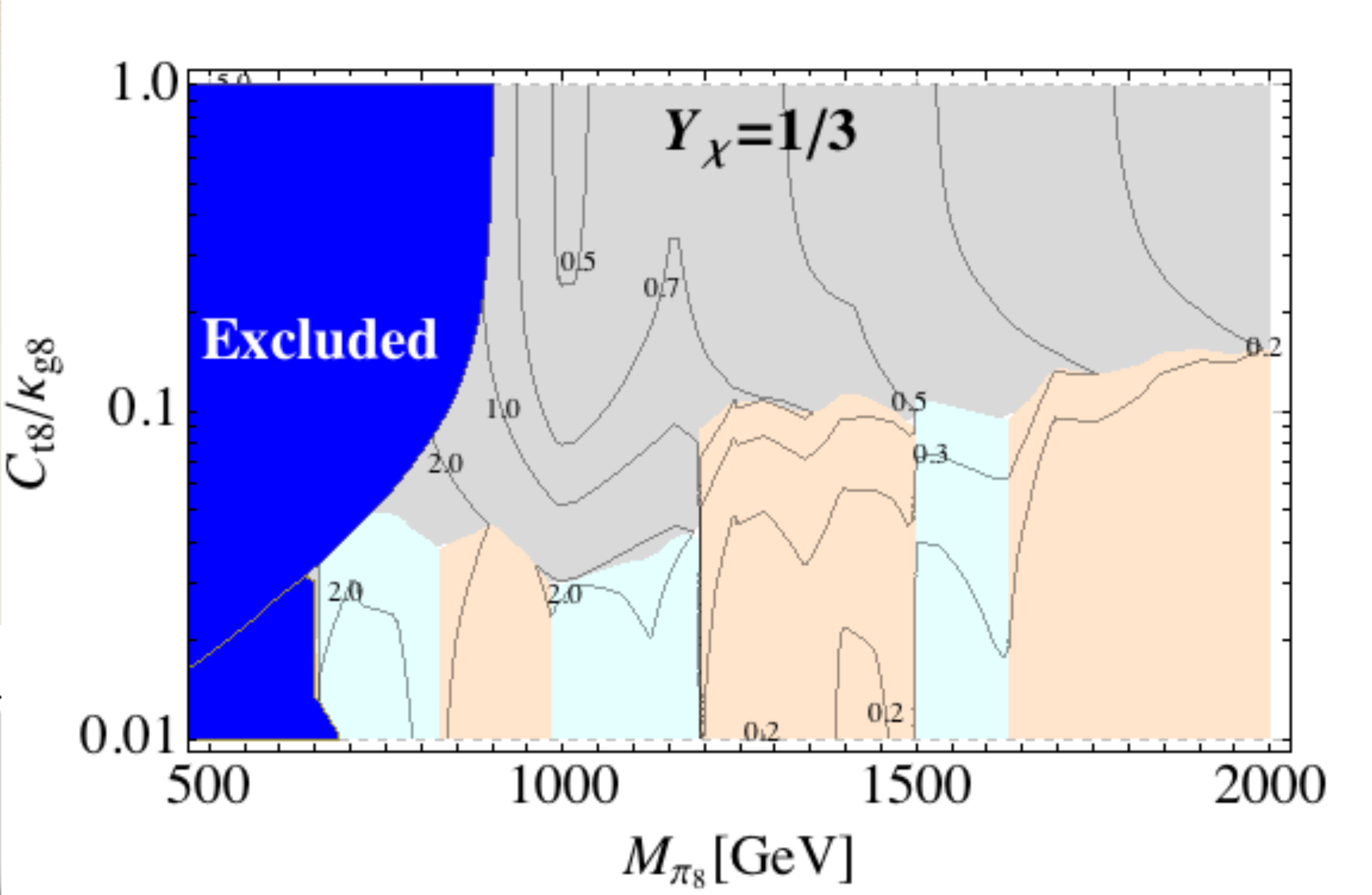


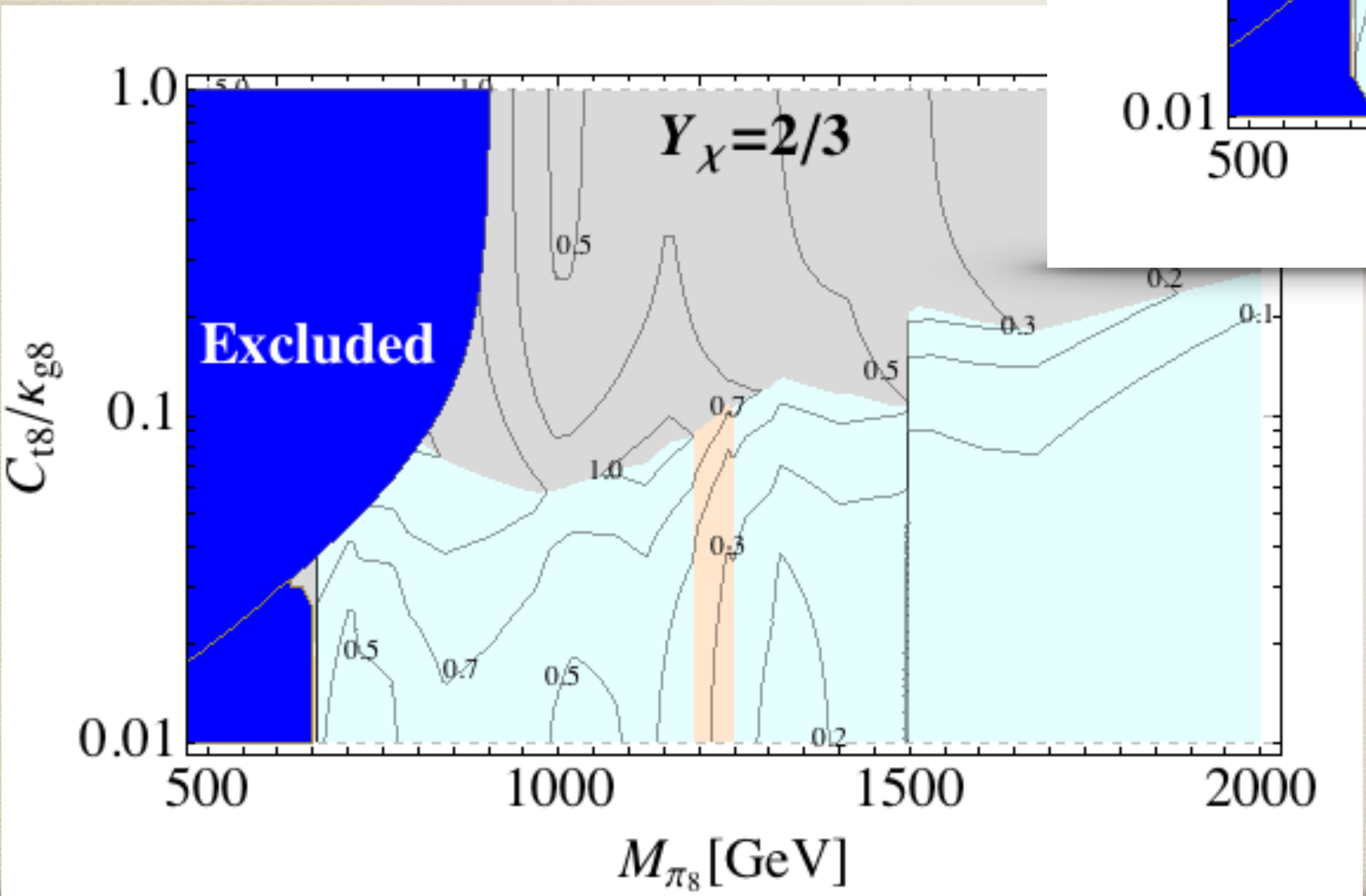


Colored PNGBs
Constraints from single and pair production:

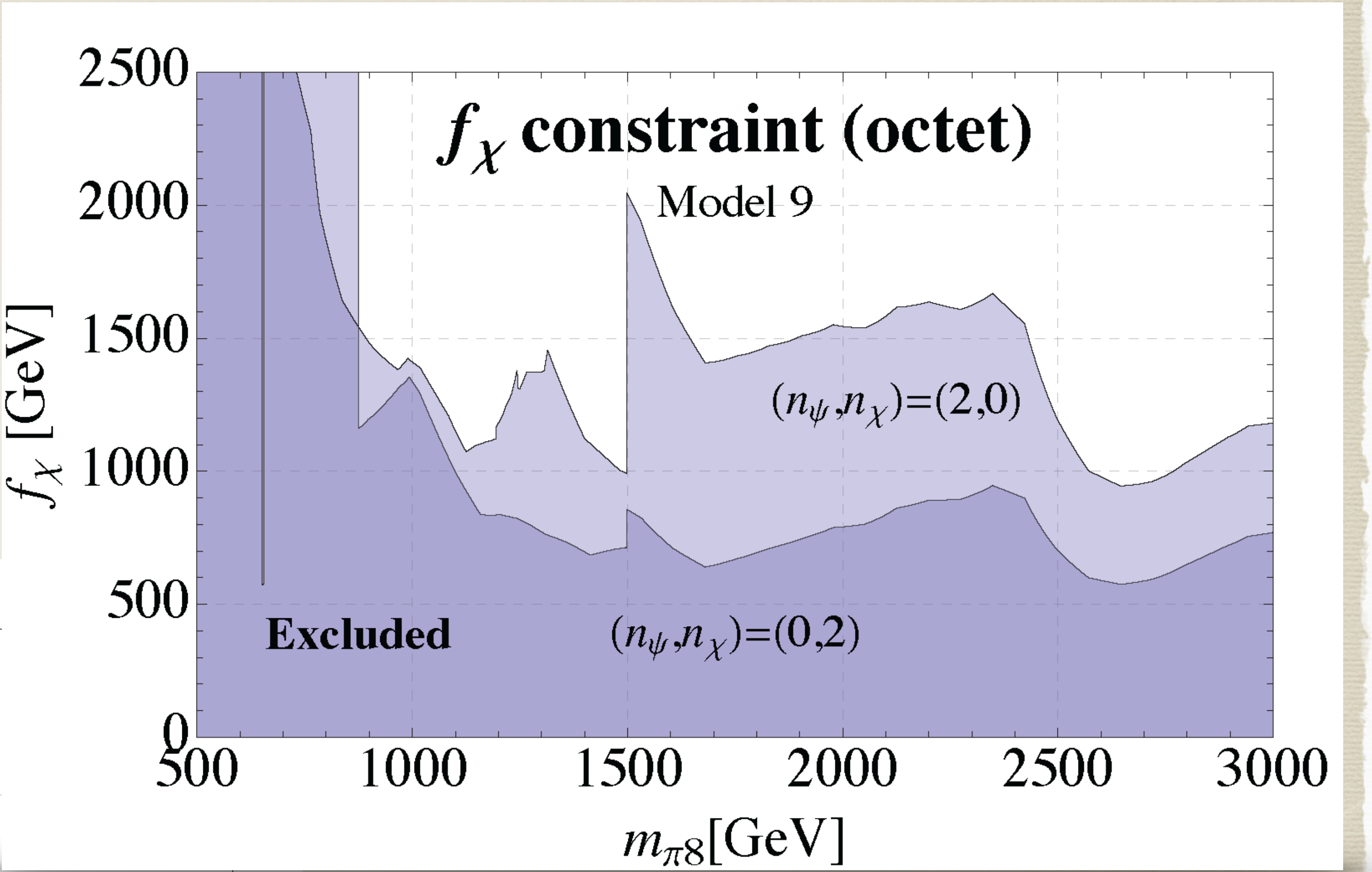
Channels with the strongest bound: *gg* (red), *gγ* (cyan), *tt* (gray).

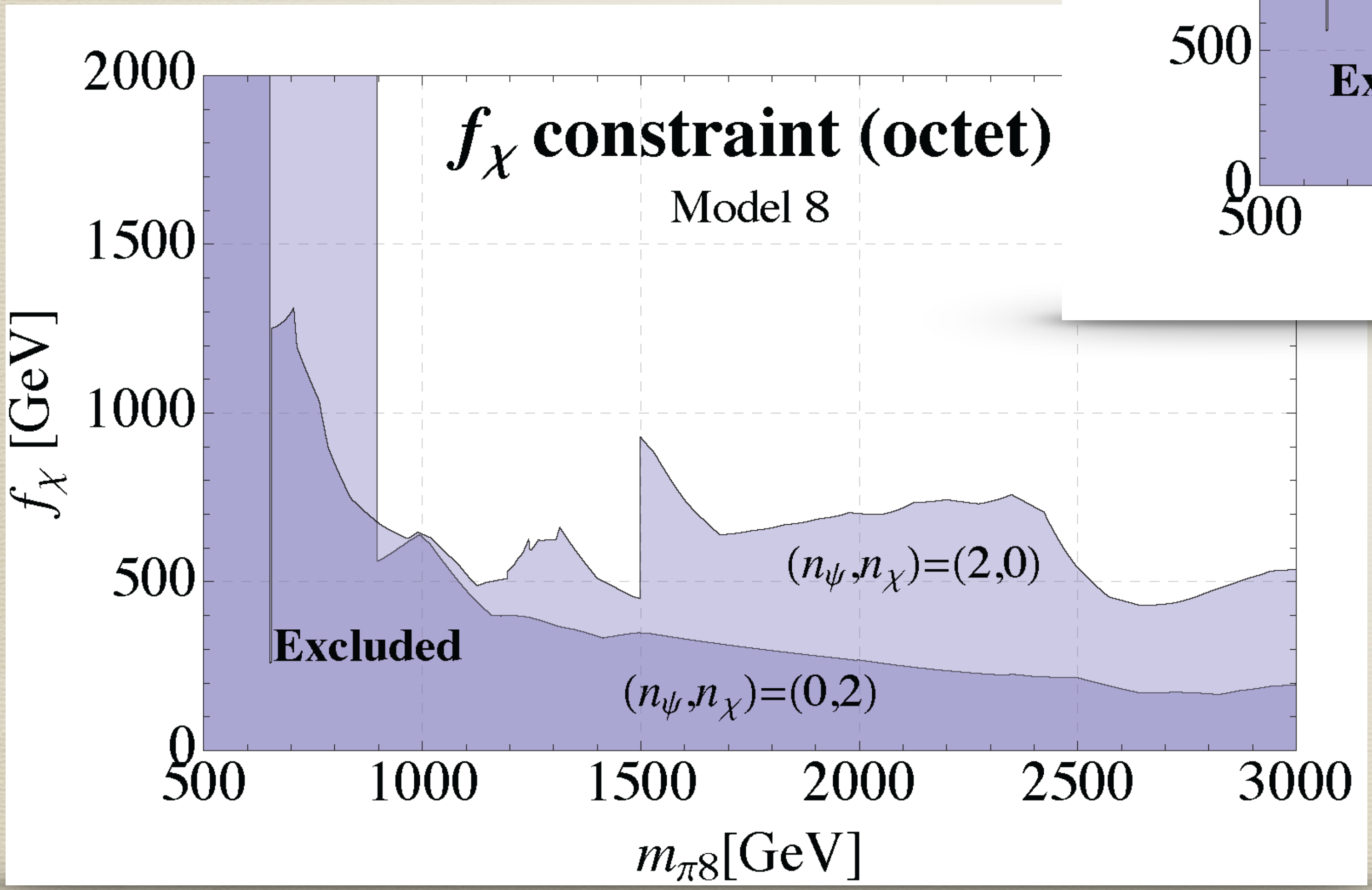
Contours give bounds on the $\boldsymbol{\pi}_8$ production cross section in pb.





Implications of the model-independent bounds for CHM UV embeddings:





Conclusions

- We showed that diboson signatures are predicted in a large class of Composite Higgs UV embeddings. The models are highly predictive because the branching ratios of different diboson channels are fully determined by the quantum numbers of the underlying fermion field content.
- We presented a simple low-energy effective model description suitable for presentation and combination of diboson (and ditop) searches for a larger class of models.
- Current diboson searches provide competitive tests for CH UV completions, but a lot of parameter space is still open, even in the TeV regime.
- Low-mass (10-100 GeV) pNGBs can have avoided all experimental constraints so far, but at the same time be copiously produced at hadron colliders.
  Searches should not only focus at high mass, and dedicated search strategies for low-mass resonances (potentially including ISR) are needed to close the gap.
- Another feature common to all models we considered are potentially light colored scalar resonances which can be tested at the LHC.