Composite Higgs models (… and how to find them)

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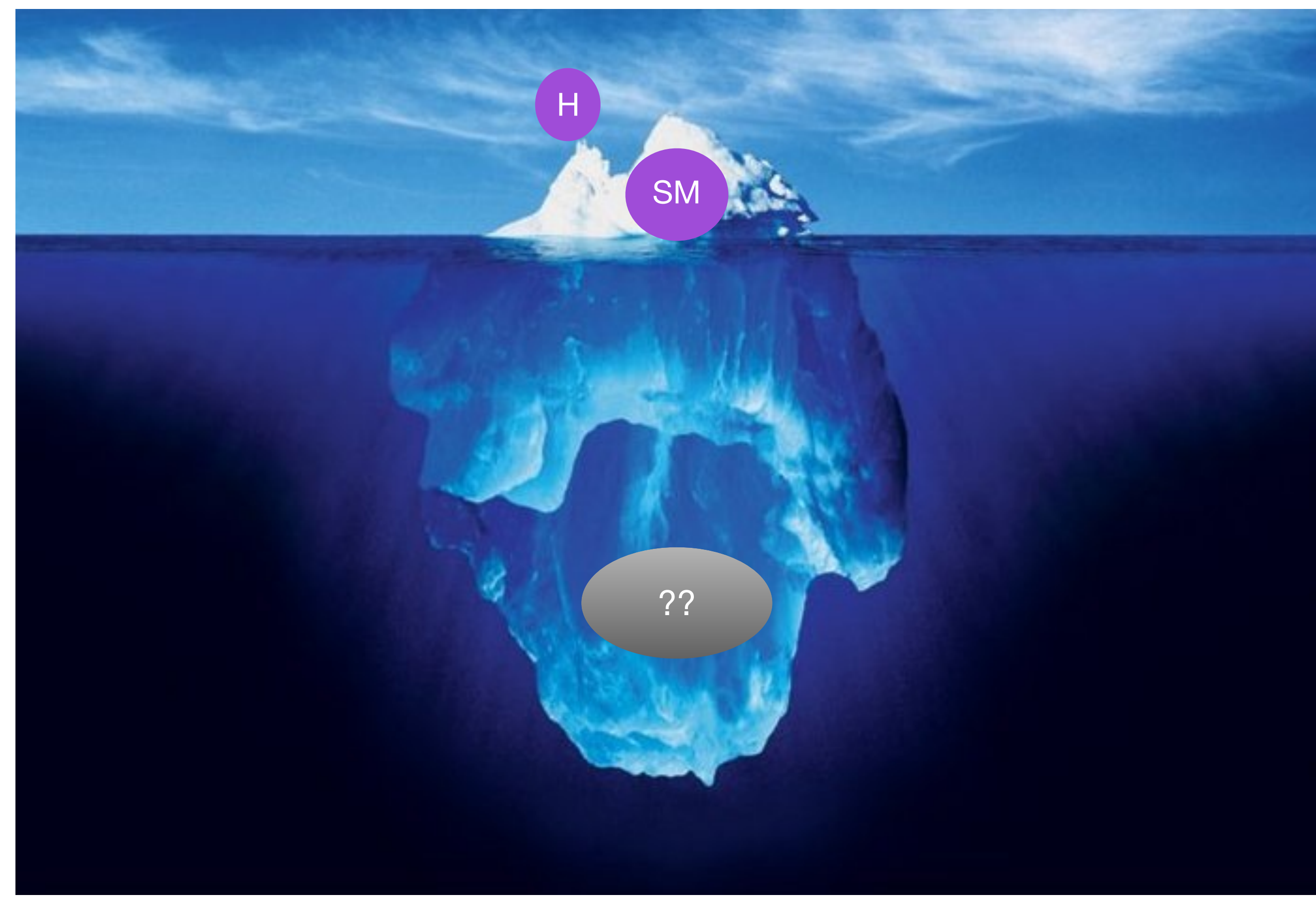
The second MadAnalysis 5 workshop on LHC recasting @ Korea

KIAS, Feb 17th 2020

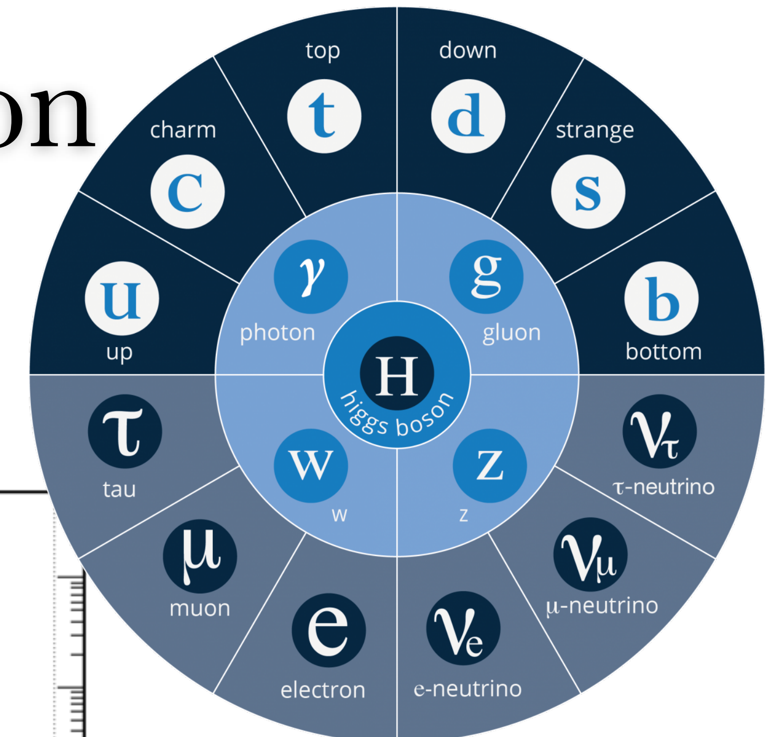
Outline

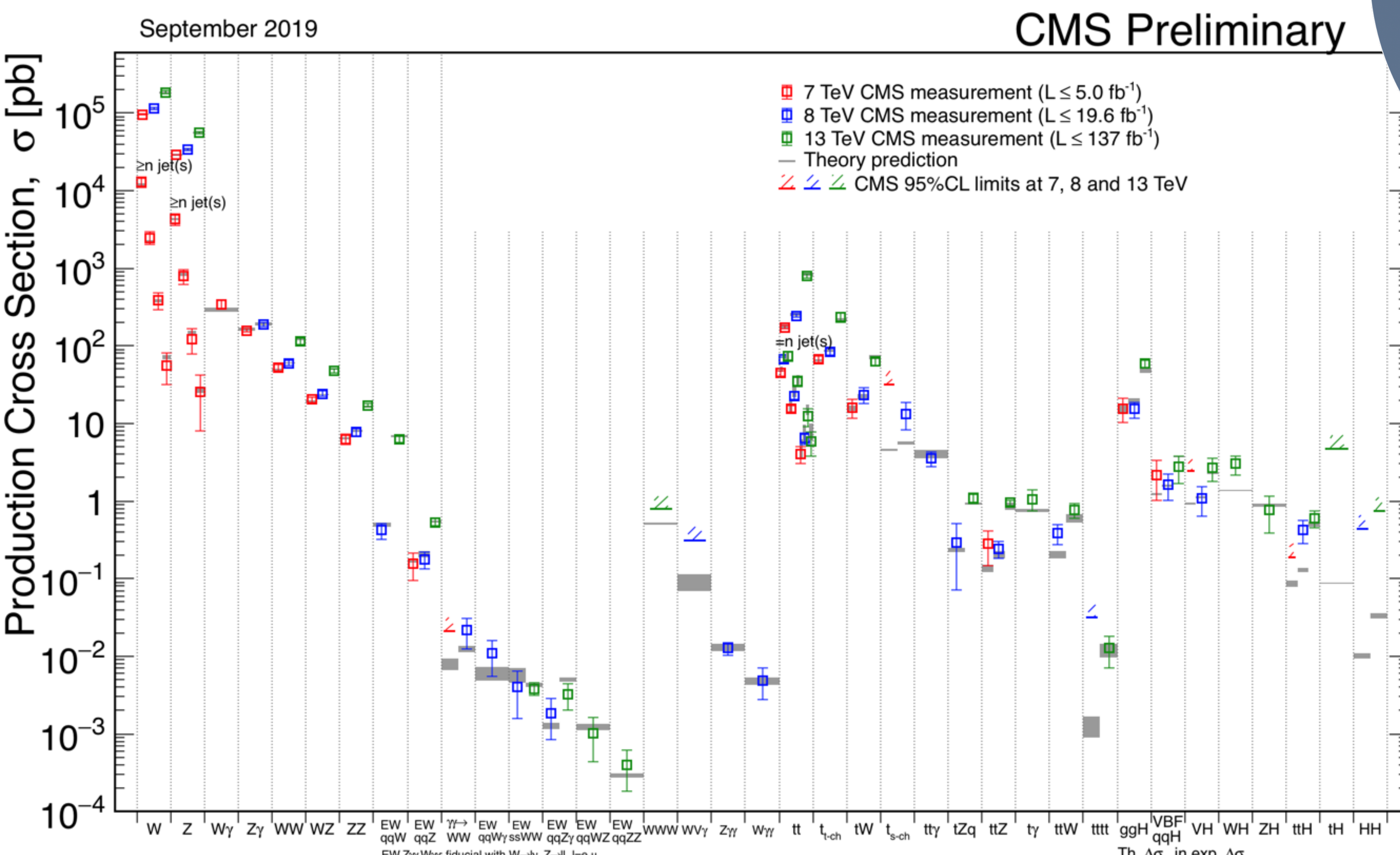
- Motivation
- The minimal composite Higgs model
- Towards underlying models of a composite Higgs
- New particle searches
  - new scalars
  - Vector-like quarks
- Conclusions



LHC is testing the Standard Model

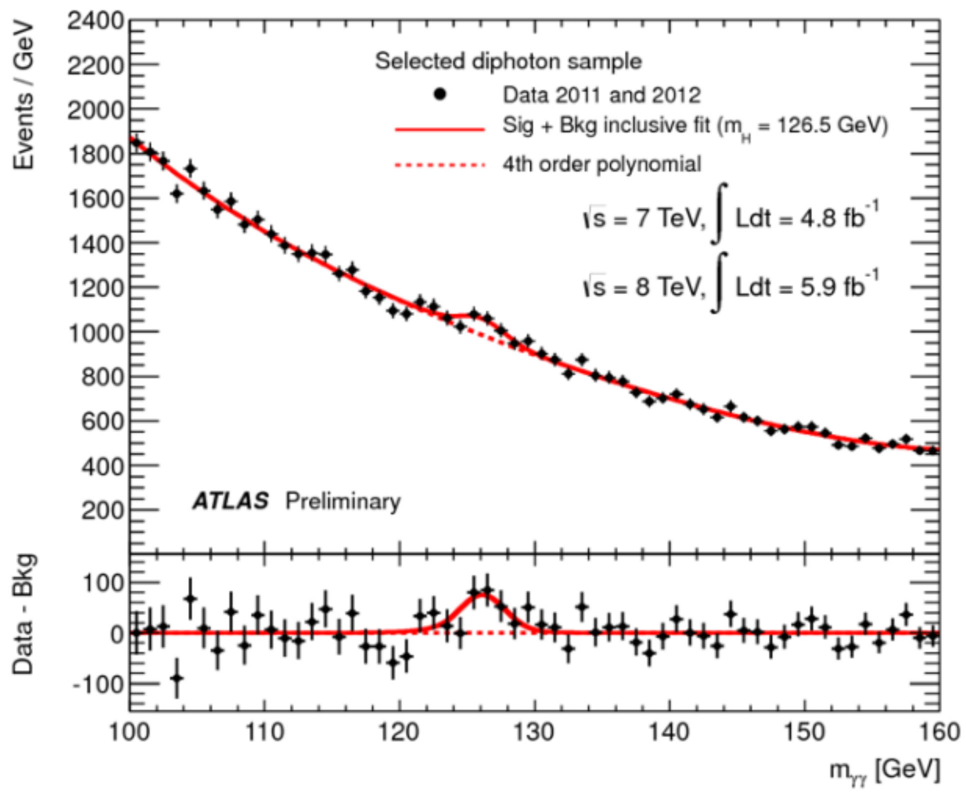
to unprecedented precision

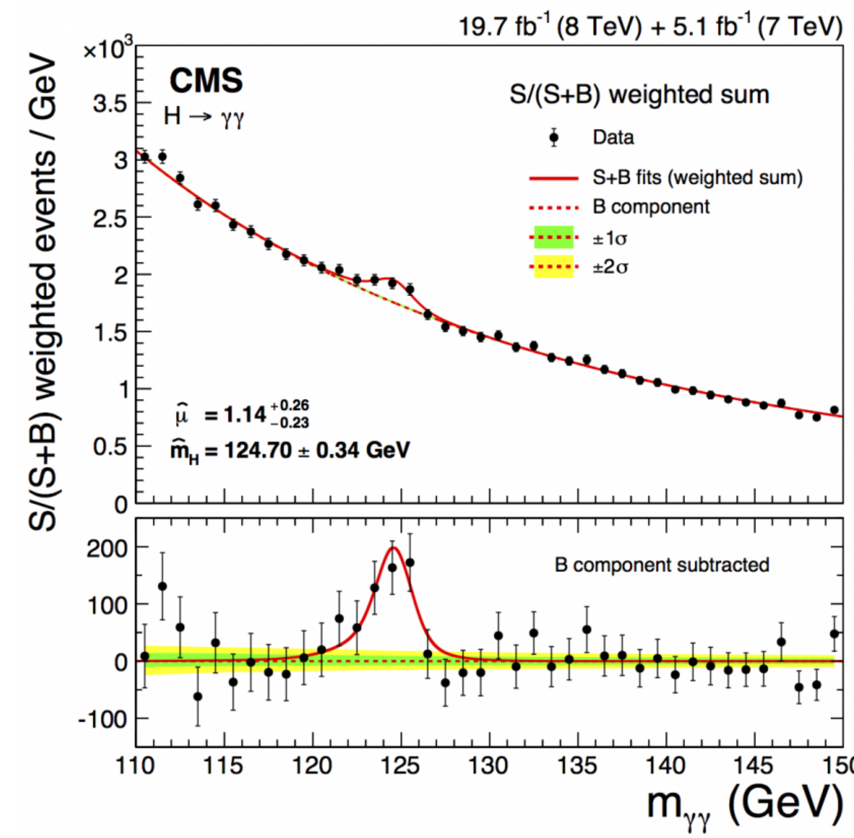




[CMS summary plots]

A Higgs was found

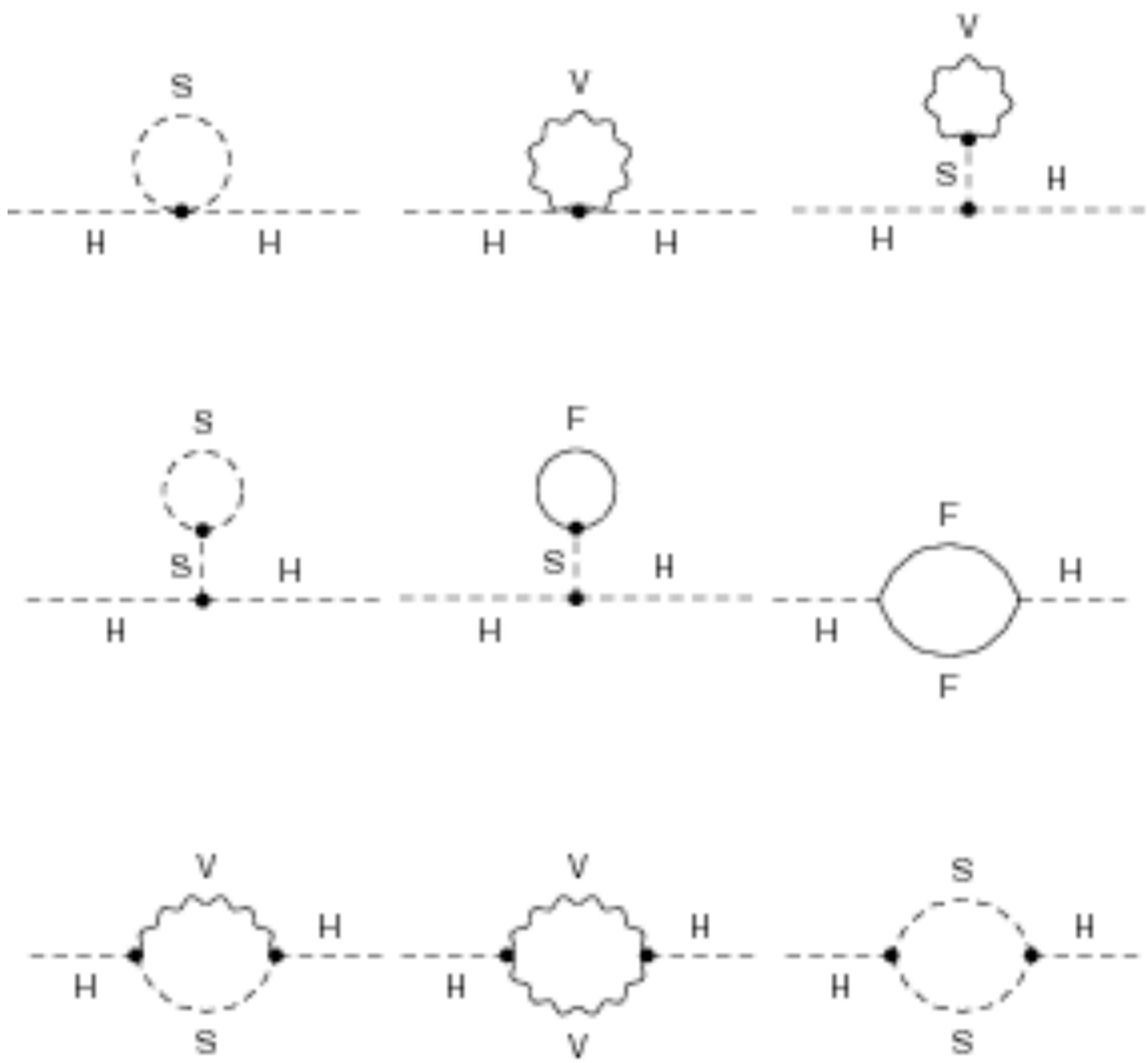




2012

The Standard Model hierarchy problem

- Absent new symmetries/dynamics, Higgs condensate and Higgs mass are unstable to quantum corrections & dragged-up to very large energy scales



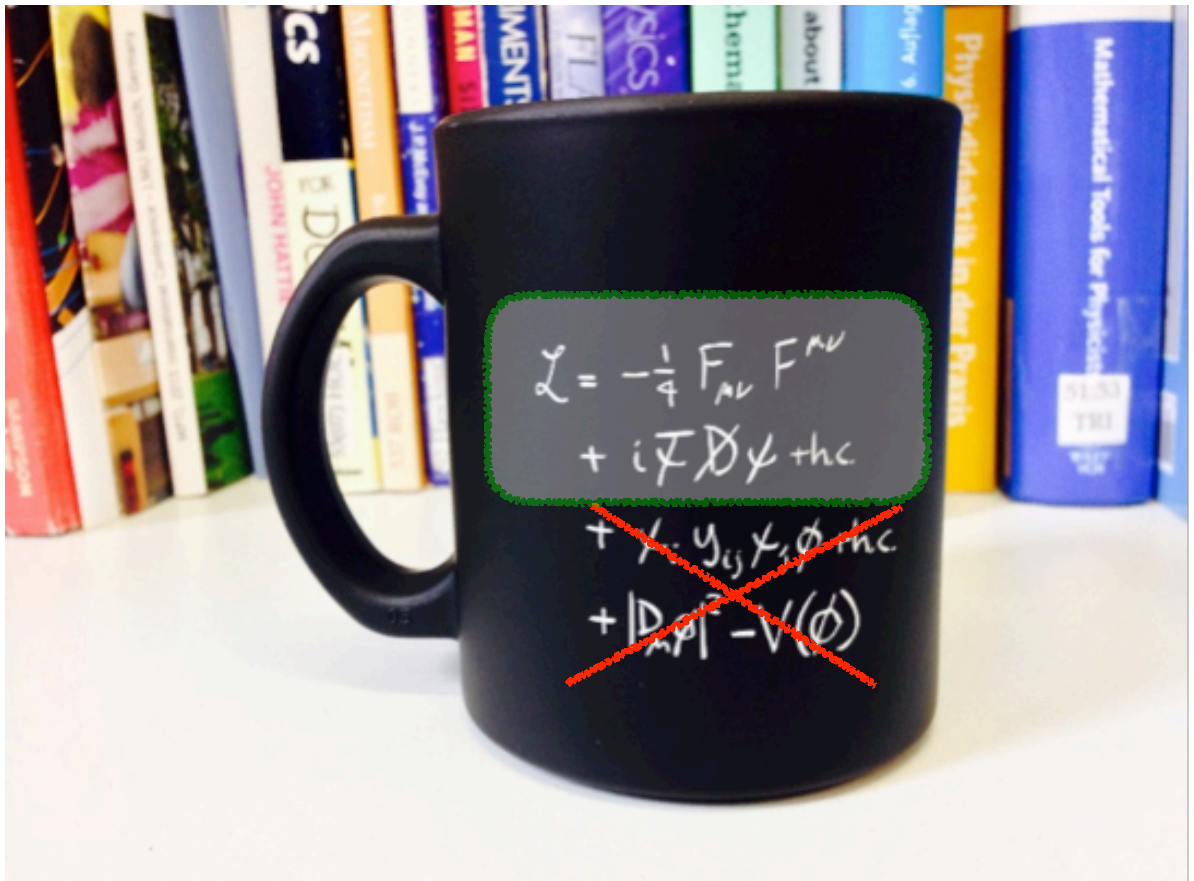
$$\frac{\delta v^2}{v^2} \simeq \sum_i \pm \frac{g_i^2}{16\pi^2}\left(\frac{M_i^2}{v^2}\right) \gg 1$$

proxy for unknown heavy mass scales (gravity, GUTs, flavour, DM,...)

[from: Colloquium talk J. March-Russell, Oxford]

What if there were no Higgs?

(QCD breaks electroweak symmetry; just wrongly)



Gauge group: $SU(3)_c \times SU(2)_L \times U(1)_Y$

1st family quarks: q_L, u_R, d_R

Global symmetry: $SU(2)_l \times SU(2)_r$
(of QCD sector)

At the QCD scale: chiral condensation

$$\langle \bar{q}_L q_R \rangle = -f_\pi B_0 \sim (200\,\mathrm{MeV})^3$$

$$SU(2)_l \times SU(2)_r \rightarrow SU(2) \Rightarrow \text{ 3 Goldstone bosons } \pi^{0,+,-}$$

Problems:

- $m_W = m_Z \sim 100$ MeV; wrong mass scale,
- no Higgs d.o.f. at the scale of $m_{W,Z}$
- $U(1)_{em} = U(1)_Y$, i.e. no / wrong Weinberg angle
- no masses for quarks (or leptons)

…. but the hierarchy problem would be solved!

Experimentalist

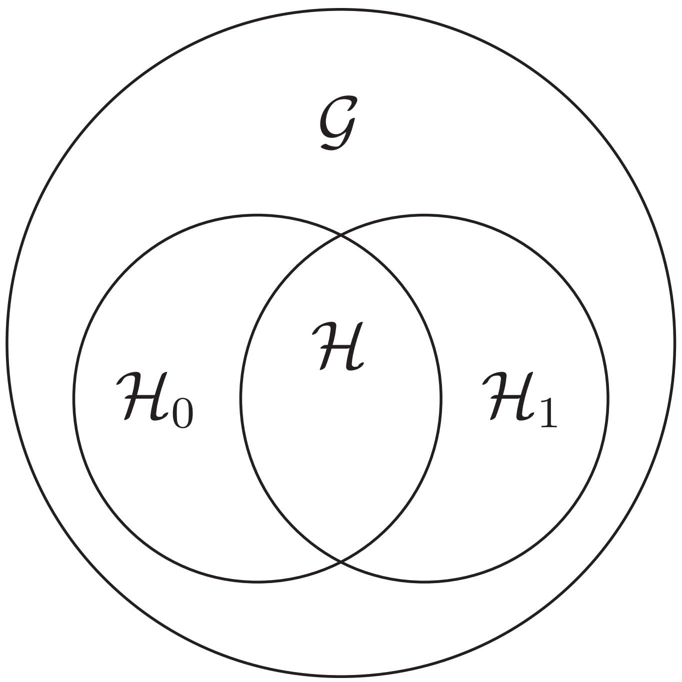
Phenomenologist

Model-builder

Formal Theorist

The minimal composite Higgs model

Agashe, Contino, Pomarol (2005)
Contino TASI lectures (2009)
Goertz ALPS2018 Proceedings



G: global symmetry of the strong sector (at energy above confinement)

H_1 : global symmetry group in confined phase below scale f

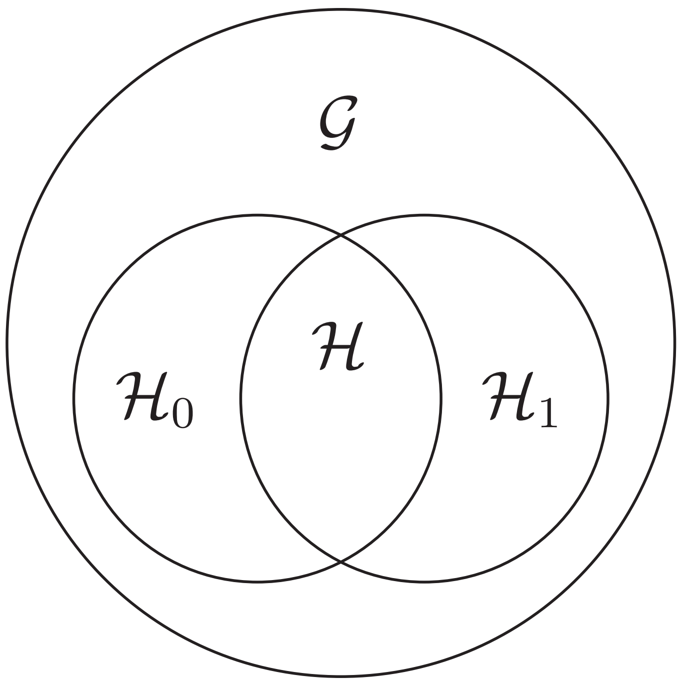
H_0 : SM electroweak gauge group

H : unbroken gauge group

What are the smallest groups which can give electroweak symmetry breaking and a Higgs?

The minimal composite Higgs model

Contino TASI lectures (2009)



G: $SO(5) \times U(1)_X$

H_1 : $SO(4) \times U(1)_X \sim SU(2)_L \times SU(2)_R \times U(1)_X$

H_0 : $SU(2)_L \times U(1)_Y$

H : $U(1)_{em}$

$SO(5) \to SO(4)$ spontaneous breaking

$\Rightarrow$ 4 Goldstone bosons in $(2,2)$ of $SU(2)_L \times SU(2)_R$

$Y = T^{3R} + X$

($U(1)_X$ is needed to assign correct hypercharges to fermions)

The minimal composite Higgs model

Contino TASI lectures (2009)

The Goldstone boson sector (aka Higgs multiplet) can be parameterized as a linear field Σ.

$$\Sigma(x) = \Sigma_0 e^{\Pi(x)/f} \qquad \Sigma_0 = (0,0,0,0,1)$$

$$\Pi(x) = -i T^{\hat{a}} h^{\hat{a}}(x)\sqrt{2}\,,$$

$$\Sigma = \frac{\sin(h/f)}{h}\left(h^1, h^2, h^3, h^4, h\cot(h/f)\right), \qquad h \equiv \sqrt{(h^{\hat{a}})^2}$$

The gauge interactions of Σ follow from $\mathscr{L}_\Sigma = \frac{1}{2}\left(D_\mu \Sigma\right)^T D^\mu \Sigma$

$$\mathscr{L}_{\text{eff}}^V = \frac{f^2}{8}\sin^2\left(\frac{\langle h\rangle + h}{f}\right)\left(W_\mu^i W^{i\mu} - 2W_\mu^3 B^\mu + B_\mu B^\mu\right) + \cdots$$

$$= \left(1 + 2\sqrt{1-\xi}\,\frac{h}{v} + (1-2\xi)\,\frac{h^2}{v^2} + \cdots\right)\left(m_W^2 W_\mu^+ W^{-\mu} + \frac{m_Z^2}{2} Z_\mu Z^\mu\right) + \cdots$$

where $\xi = \dfrac{v^2}{f^2}$

The minimal composite Higgs model

Fermion masses and couplings: Partial compositeness

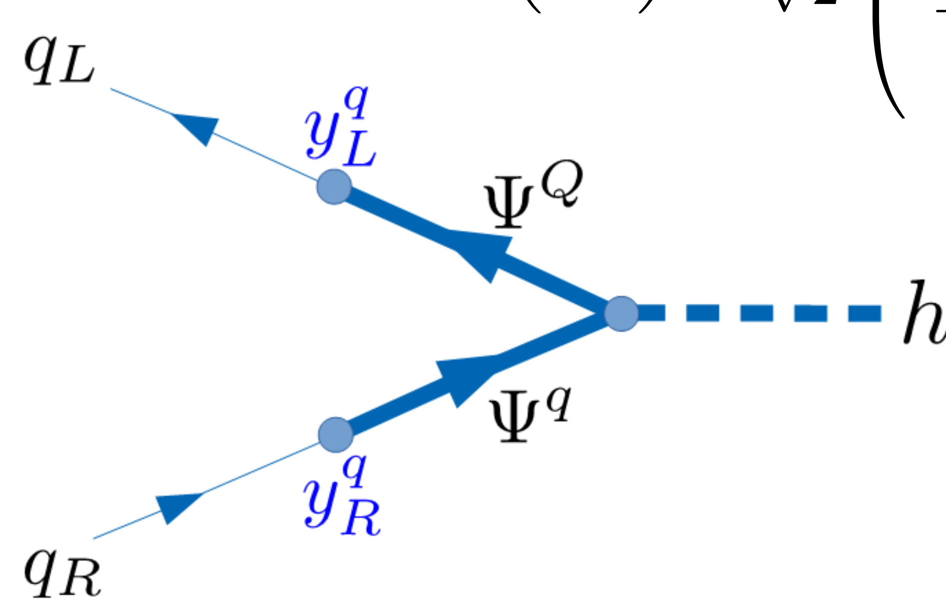
The Higgs transforms non-linearly under G . We cannot write down the standard Yukawa interactions if fermions are elementary (transform linearly).
One solution: Mix elementary fermions with composite resonances.

Elementary fermions (in SO(5) rep.)   Composite fermions (in SO(5) rep.)

$$q_L^5 \equiv \frac{1}{\sqrt{2}}\,(id_L\,,d_L\,,iu_L\,,-u_L\,,0)^T$$

$$u_R^5 \equiv (0\,,0\,,0\,,0\,,u_R)^T$$

$$\psi = \begin{pmatrix} Q \\ \tilde{U} \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} iD - iX_{5/3} \\ D + X_{5/3} \\ iU + iX_{2/3} \\ -U + X_{2/3} \\ \sqrt{2}\tilde{U} \end{pmatrix}$$



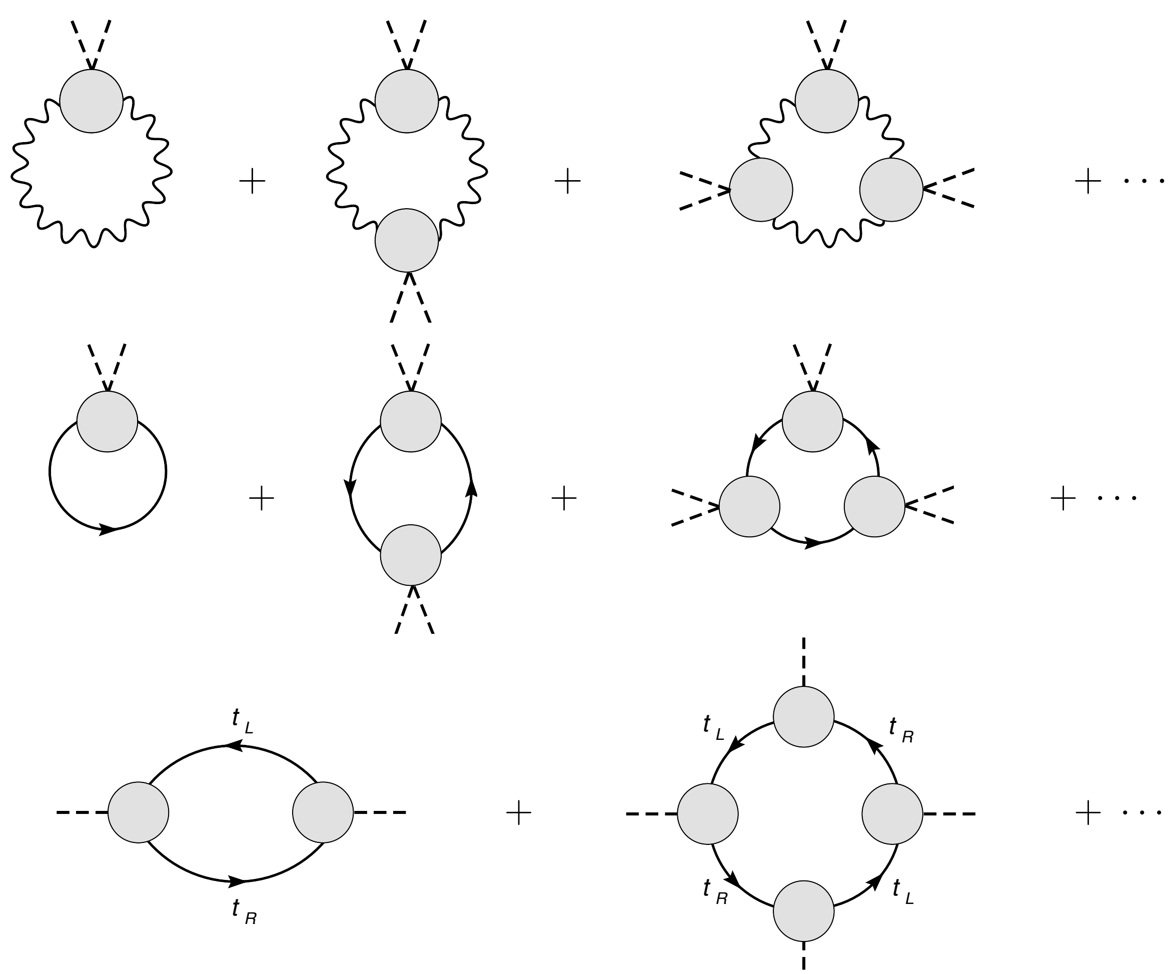
The minimal composite Higgs model

Higgs potential: Contino TASI lectures (2009)

The Higgs multiplet are Goldstone bosons. But:

- Only the electroweak group is gauged, not the full SO(5) x U(1)
  The global symmetry is explicitly broken by the gauge symmetries.

- Elementary fermions are embedded in SO(5) reps, but the reps are not complete.
  The global symmetry is explicitly broken by partial compositeness.



V

t

t

The minimal composite Higgs model

MCHM summary before phenomenology:

- Higgs - gauge couplings get modified:

$$g_{VVh} = g_{VVh}^{SM}\sqrt{1-\xi}\,, \qquad g_{VVhh} = g_{VVhh}^{SM}(1-2\xi \qquad \text{where } \xi = \frac{v^2}{f^2}$$

- Higgs - fermion couplings get modified:

$$\frac{\lambda_{hff}^{(4)}}{\lambda_{ffh}^{SM}} \sim \sqrt{1-\xi} \qquad \frac{\lambda_{hff}^{(5)}}{\lambda_{ffh}^{SM}} \sim \frac{1-2\xi}{\sqrt{1-\xi}}$$

- Obtaining the correct top mass requires not too heavy top partners:

$$m_t \sim \lambda_L \lambda_R v \frac{f}{M_*}$$

- Obtaining small *v/f* requires partial cancellation between gauge and top loop contributions.

- Results depend on fermion embeddings (and model parameters).

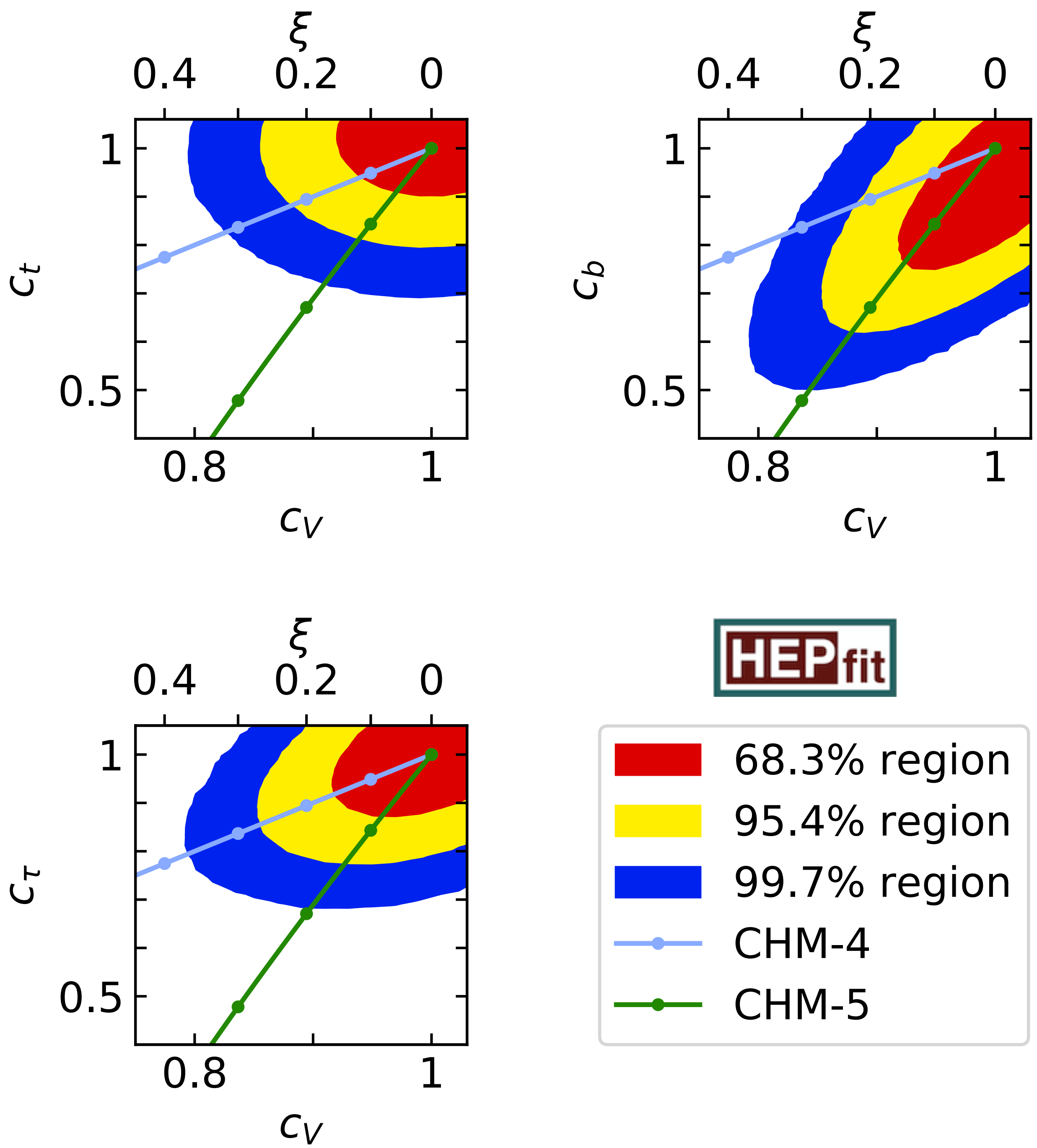
- Additional particles are expected at $\Lambda_* \sim g_* f \lesssim 4\pi f$

The minimal composite Higgs model

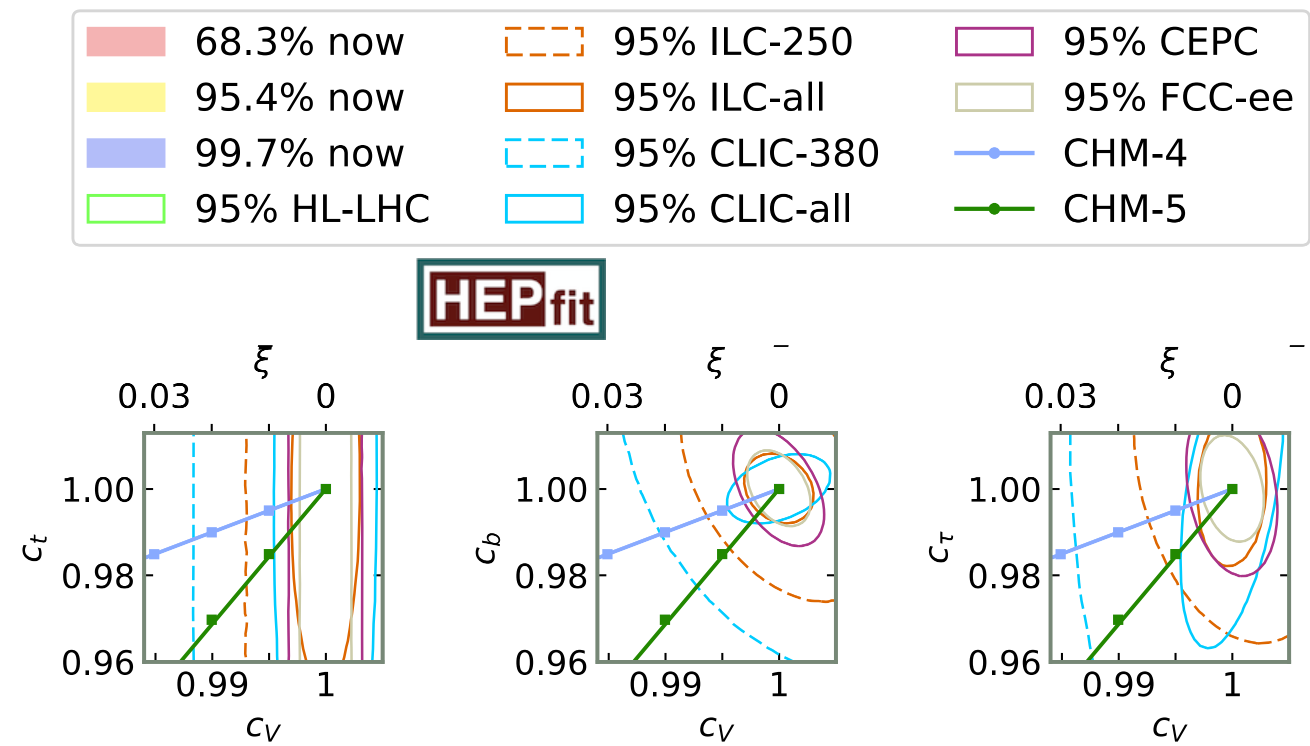
Phenomenology: Global fit to Higgs measurements

de Blas, Eberhardt, Krause (2018)

$$\mathcal{L}_{\rm fit} = 2c_V\left(m_W^2 W_\mu^+ W^{-\mu} + \tfrac{1}{2} m_Z^2 Z_\mu Z^\mu\right)\frac{h}{v} - \sum_\psi c_\psi m_\psi \bar{\psi}\psi \frac{h}{v}$$



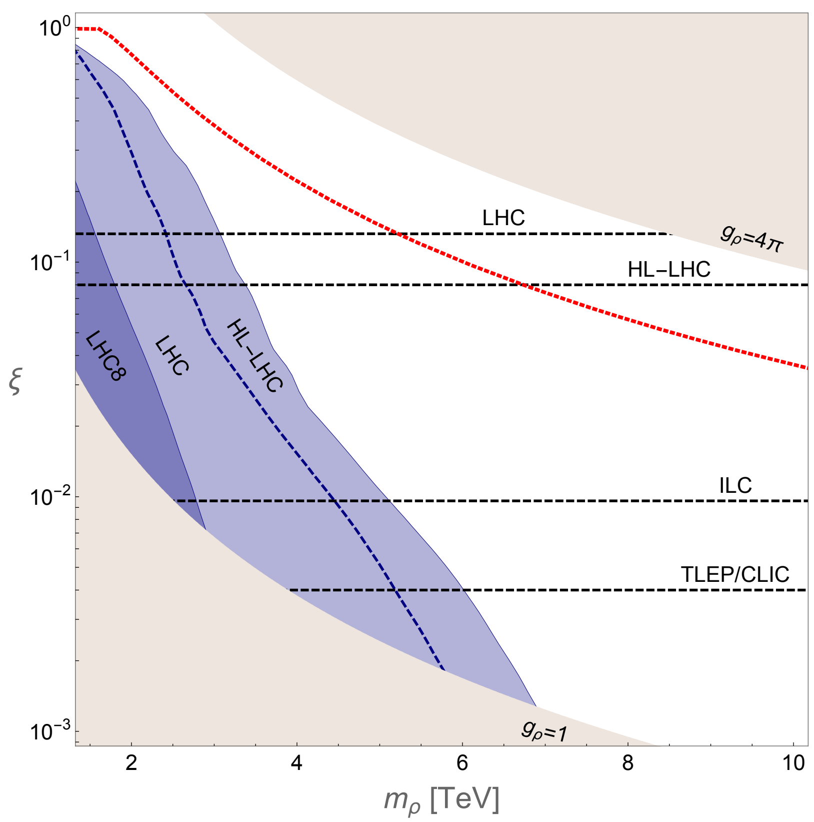
Current

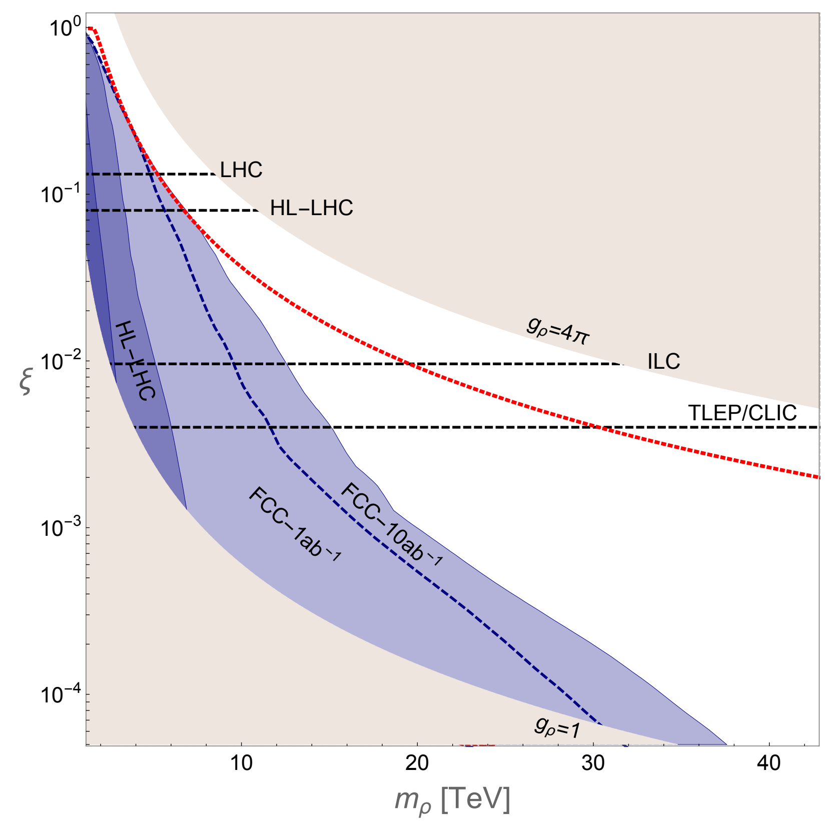


Future projection

The minimal composite Higgs model

Phenomenology: Electroweak precision & new vector resonances [Thamm, Torre, Wulzer (2015)]

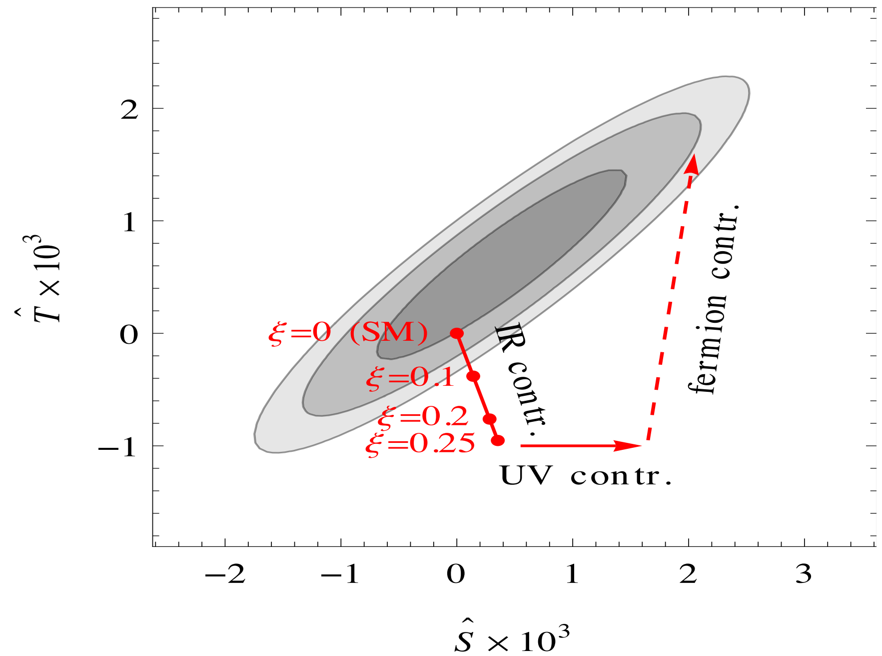




Assuming the simplified vector triplet model and not including top partner EWPT contributions, and

$$\xi = \frac{g_\rho^2}{m_\rho^2} v^2$$

Note: obtaining reliable EWPT bounds in composite models is difficult. [Grojean etal. (2013)]

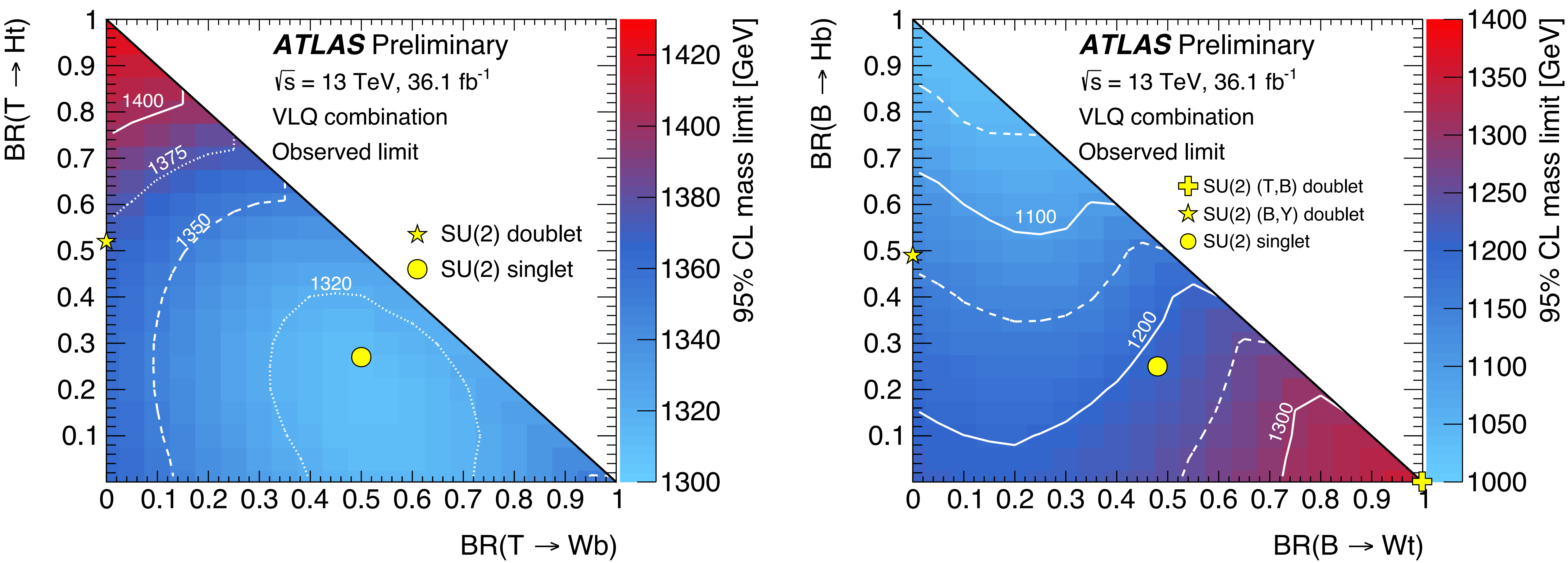


The minimal composite Higgs model

Phenomenology: Searches for to partners with charge 5/3, 2/3, -1/3, -4/3

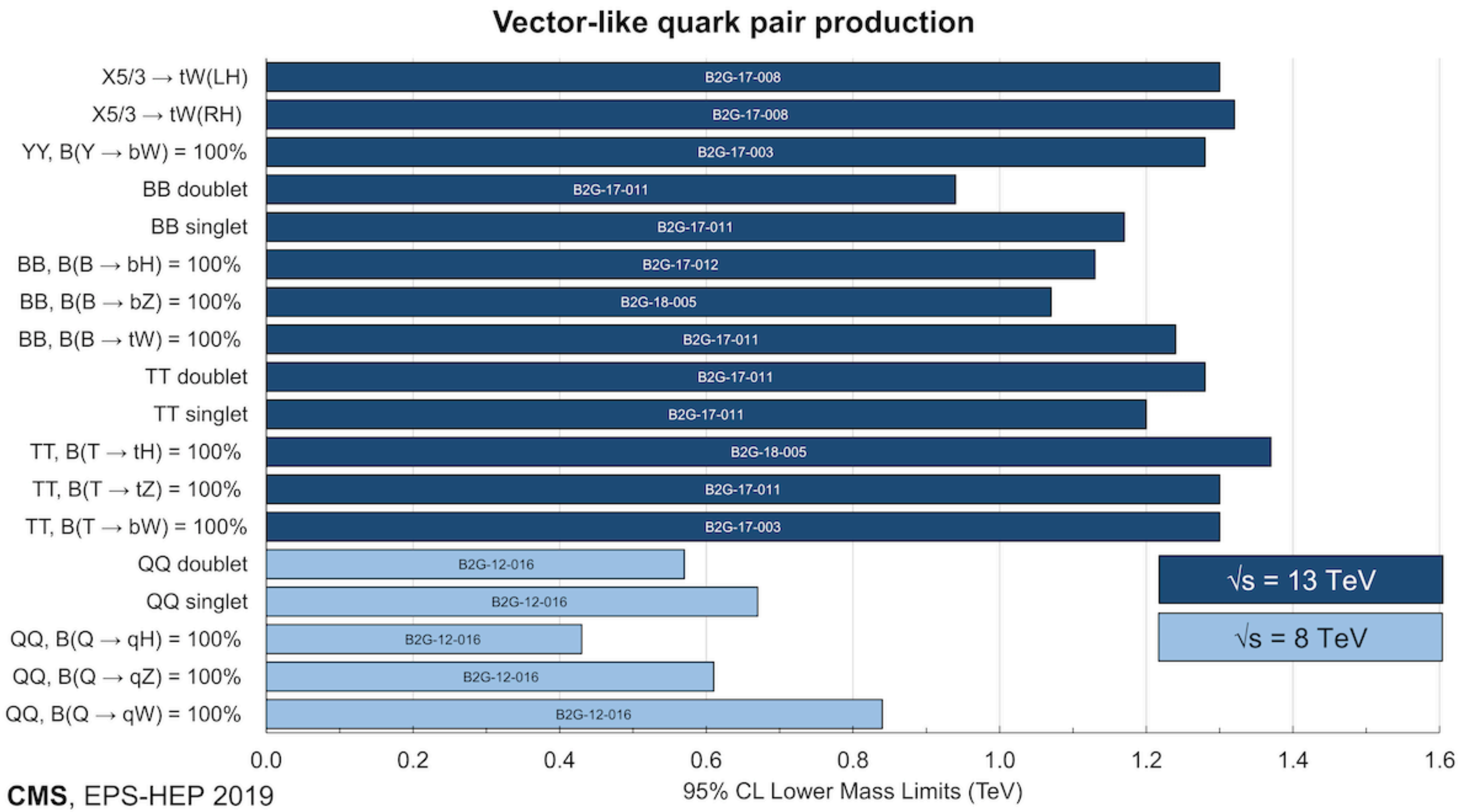
$X_{5/3}$: $M_X \gtrsim 1.3$ TeV, [CMS PAS B2G-16-019, ATLAS: 1806.01762]

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



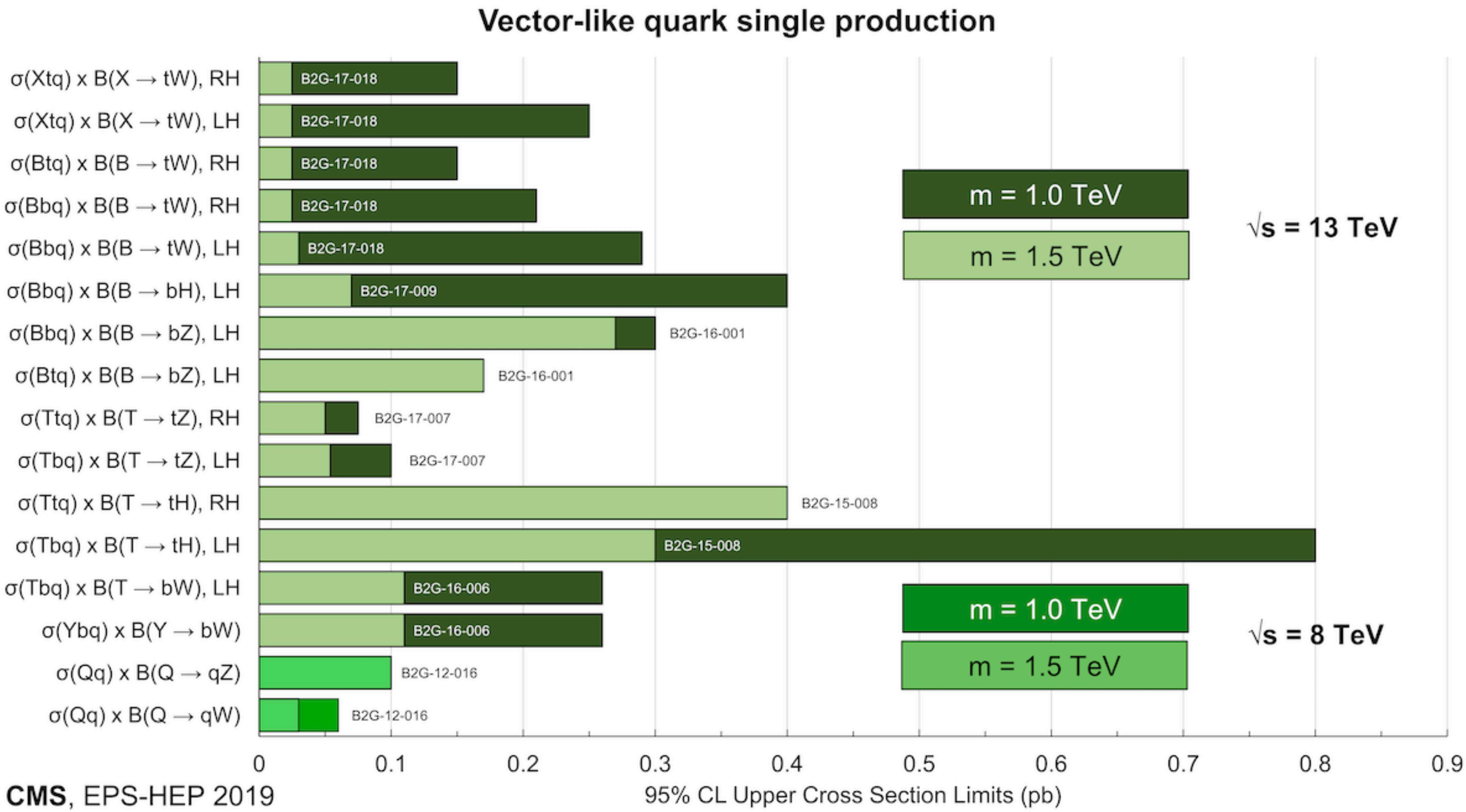
[ATLAS-CONF-2018-032]

CMS bounds on pair production



[CMS B2G Summary Plots]

Bounds on single production



[CMS B2G Summary Plots]

Status in the MCHM

- Currently, there is no sign of Higgs compositeness.
- Higgs measurements require $\xi \lesssim 0.2 \Leftrightarrow f \gtrsim 560\ \mathrm{GeV}$.
- Electroweak precision yield/similar stronger bounds on f, but are more model dependent (masses / reps of heavy states) and require more assumptions about UV contributions.
- Top partners must be heavier than ~1.3 TeV.
- Bounds on composite vector resonances are stronger.

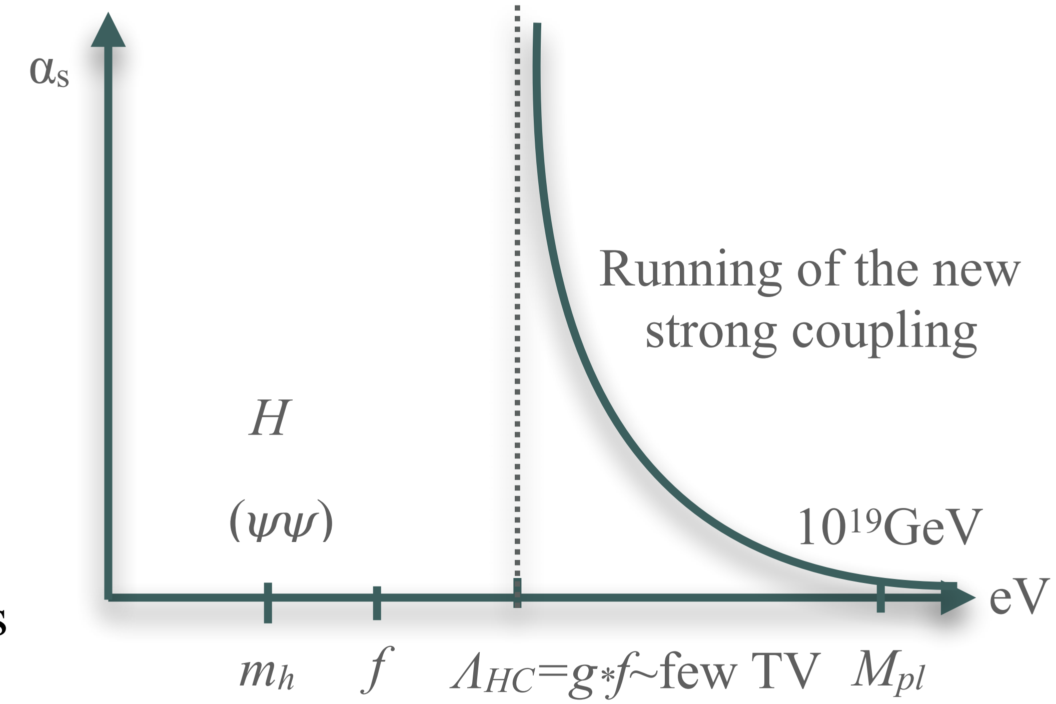
NOTE:

- The MCHM is an effective model.
- Global symmetry and breaking pattern is chosen "by hand".
- Representations of top partners (and other composite resonances) are chosen "by hand".
- UV embeddings can be constructed in Randall-Sundrum models, Agashe, Contino, Pomarol (2005) but not (easily) in QCD-like models with underlying strong gauge group and fermions.

Towards underlying models

A solution to the hierarchy problem:

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

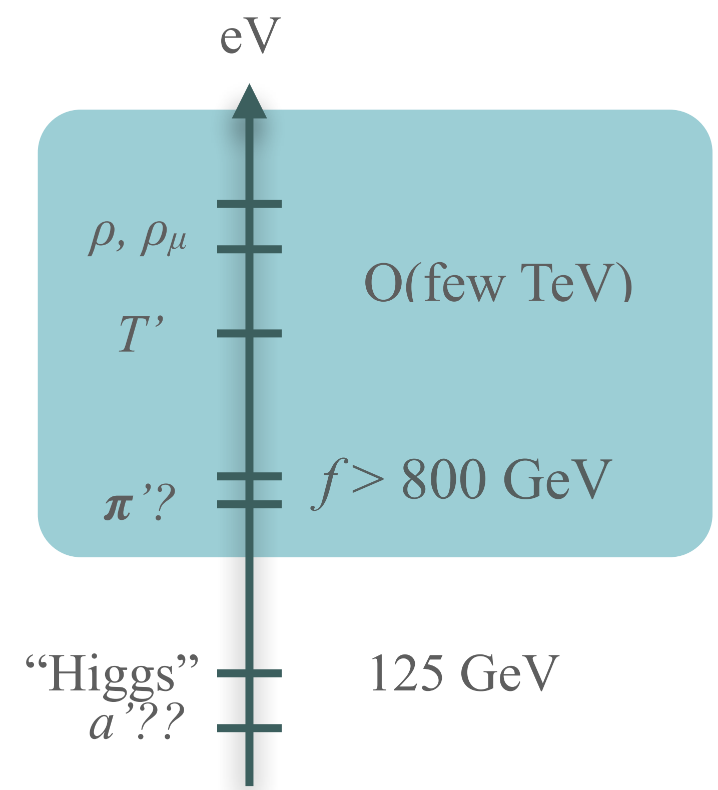


Disadvantage of underlying compared to effective models:

- From the generic setup, one expects many additional resonances (vectors, vector-like fermions, scalars) around Λ_{HC} (and additional light pNGBs).
- Results will depend on the model.

Advantages:

- Quantum numbers of resonances (and pNGBs) are dictated by the underlying model.
- Models can be used to check whether interesting phenomenology has been missed in the ``generic'' EFT approach.
- Model parameters (resonance masses / couplings etc.) can be determined from underlying dynamics (in principle).
- Dynamics of EWSB can be studied (in principle).



Composite Higgs Models: Towards underlying models

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

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

The resulting models have several common features:

- All models contain several top partner multiplets.
- All models predict pNGBs beyond the Higgs multiplet.

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

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

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.
   [[PRD 94 (2016) no 1, 015004, JHEP1701,094, EPJC 78 (2018) no.9, 724]
2. ALL models:
   $\boldsymbol{\pi}_8$: 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 , EPJC78, 9, 724:
  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, 2002.01474:
  bounds on mass (QCD pair prod., decay to tops, gg, gγ): ~1 TeV.
- $\boldsymbol{\pi}_6$: Studied in JHEP1511,201,JHEP 1910, 134:
  bounds on mass (QCD pair production, decay to tops): 1.2 TeV
- $\boldsymbol{\pi}_3$: To my knowledge not studied within underlying 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. To my knowledge not comprehensively studied within underlying models.

Upshot: composite pNGBs are not exhaustively studied. Several are not ruled out even if much lighter than a TeV and they are testable at the LHC.

Top partners in CH UV embeddings

[JHEP 1806, 065]

- UV embeddings of composite Higgs models come with additional pNGBs, which are naturally lighter than the top-partners, so decays of top partners to top / bottom and a pNGB are kinematically possible.
- With an underlying model specified, one can relate branching ratios of top partners to h/W/Z and to other BSM pNGBs.
- Scanning through the different underlying models we looked for "common exotic" top partner decays and found several scenarios:

1. decays of T (and B) to the singlet pseudo-scalar singlet a,
2. decays of T to the "exclusive pseudo-scalar" η,
3. $X_{5/3} \to \bar{b}\, \pi_6$ (with subsequent $\boldsymbol{\pi}_6 \to$ t t),
4. $X_{5/3} \to t\, \phi^+$, $X_{5/3} \to b\, \phi^{++}$.

- Decays of the pNGBs yield manifold novel multi-body decay modes and LHC signatures.

Common exotic VLQ decays

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

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

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

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

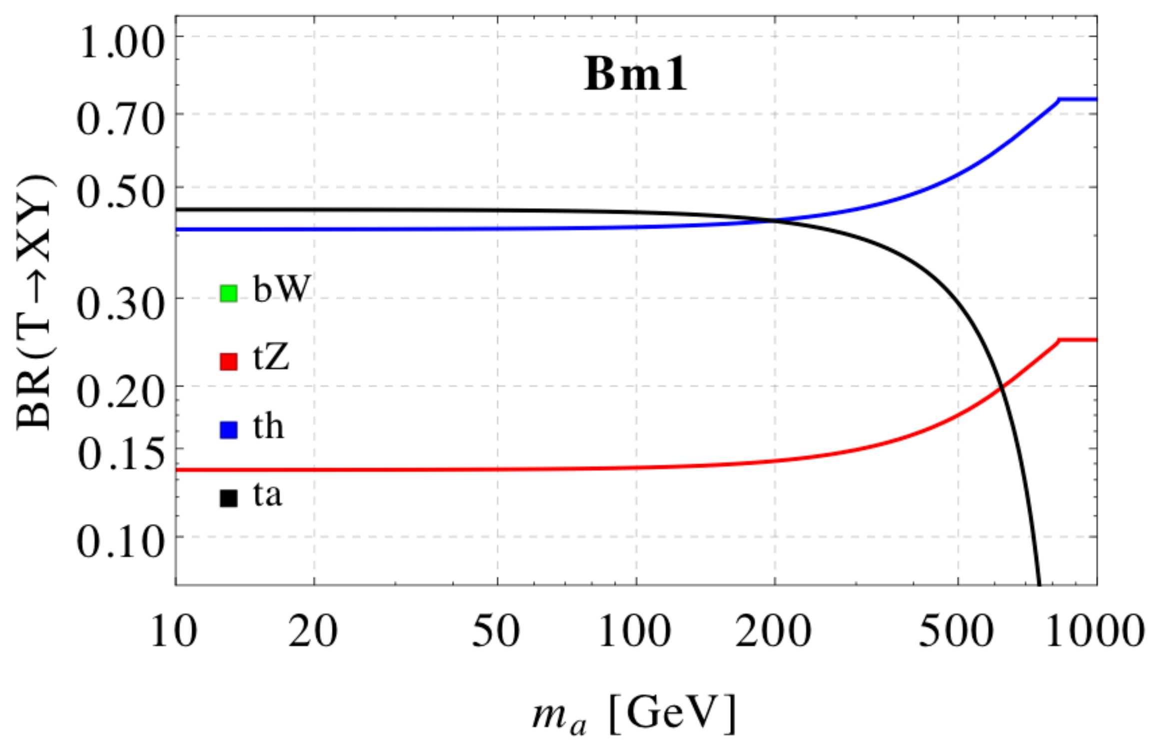
$$+\frac{g_s^2 K_g a}{16\pi^2 f_a}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{g^2 K_W a}{16\pi^2 f_a}W^i_{\mu\nu}\tilde{W}^{i\mu\nu} + \frac{g'^2 K_B a}{16\pi^2 f_a}B_{\mu\nu}\tilde{B}^{\mu\nu}$$

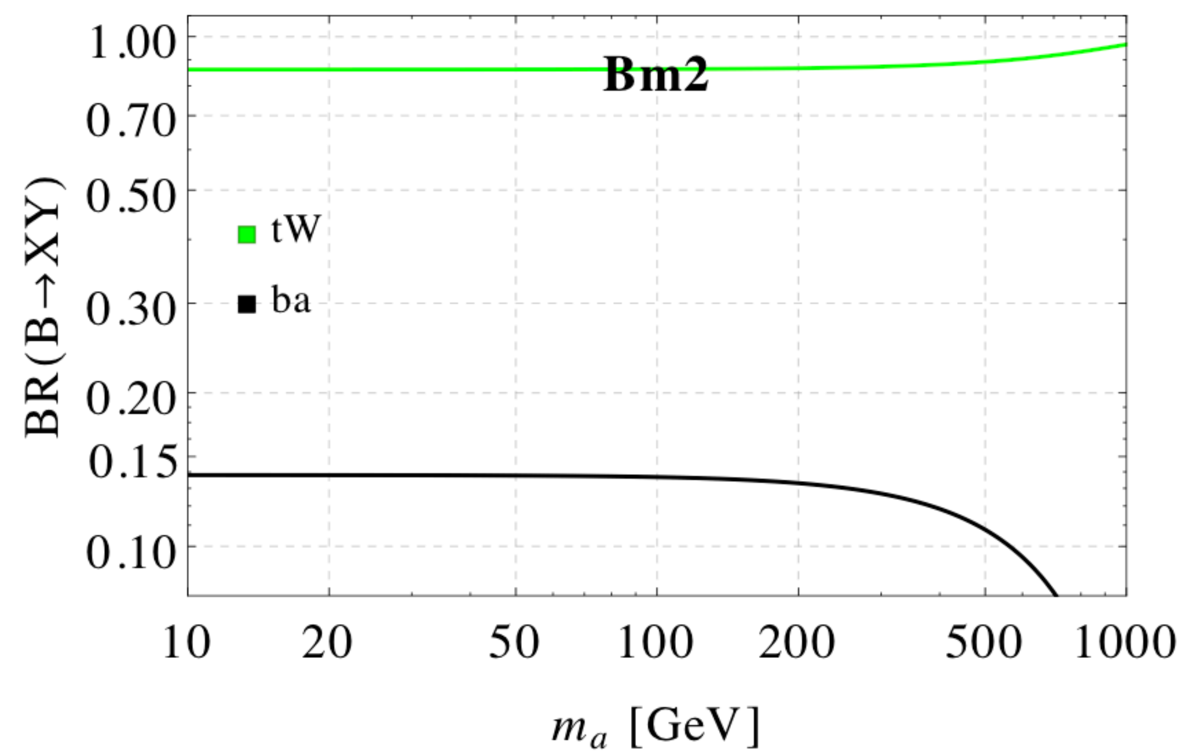
Common exotic VLQ decays

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

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

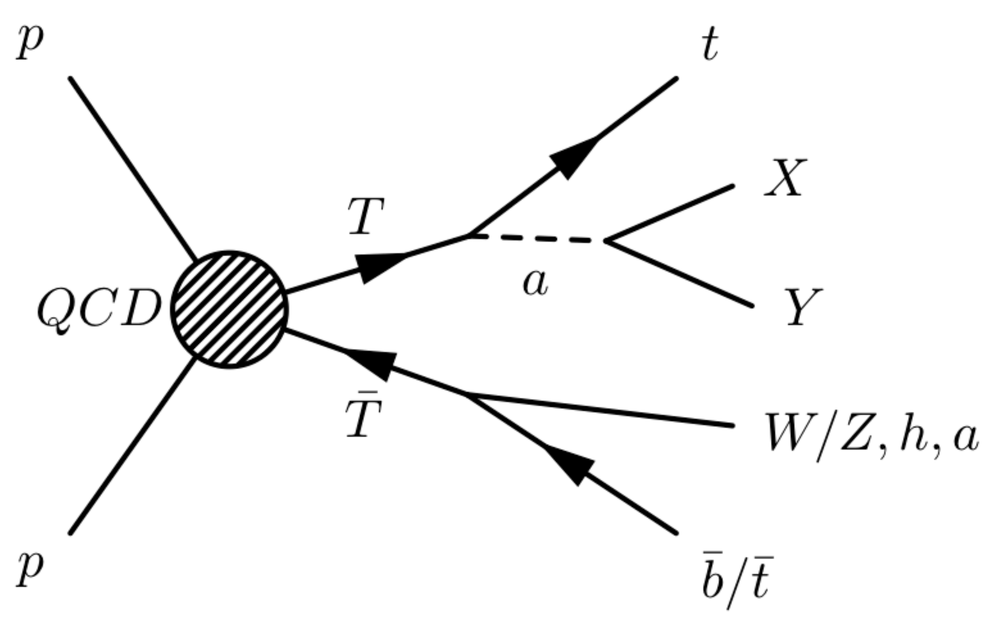
Branching ratios of quark partners to *a* in these benchmarks:

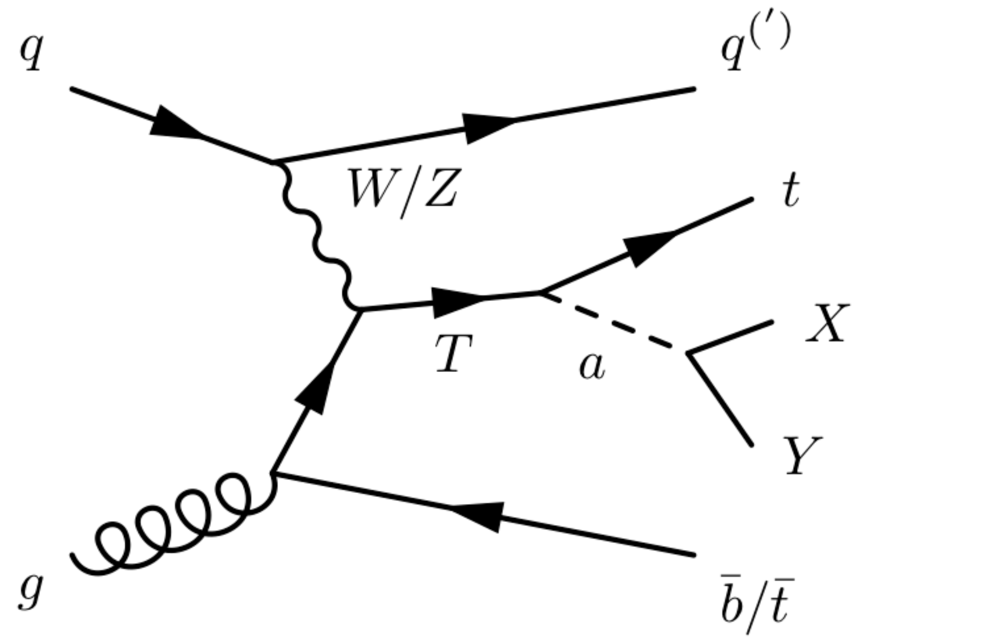




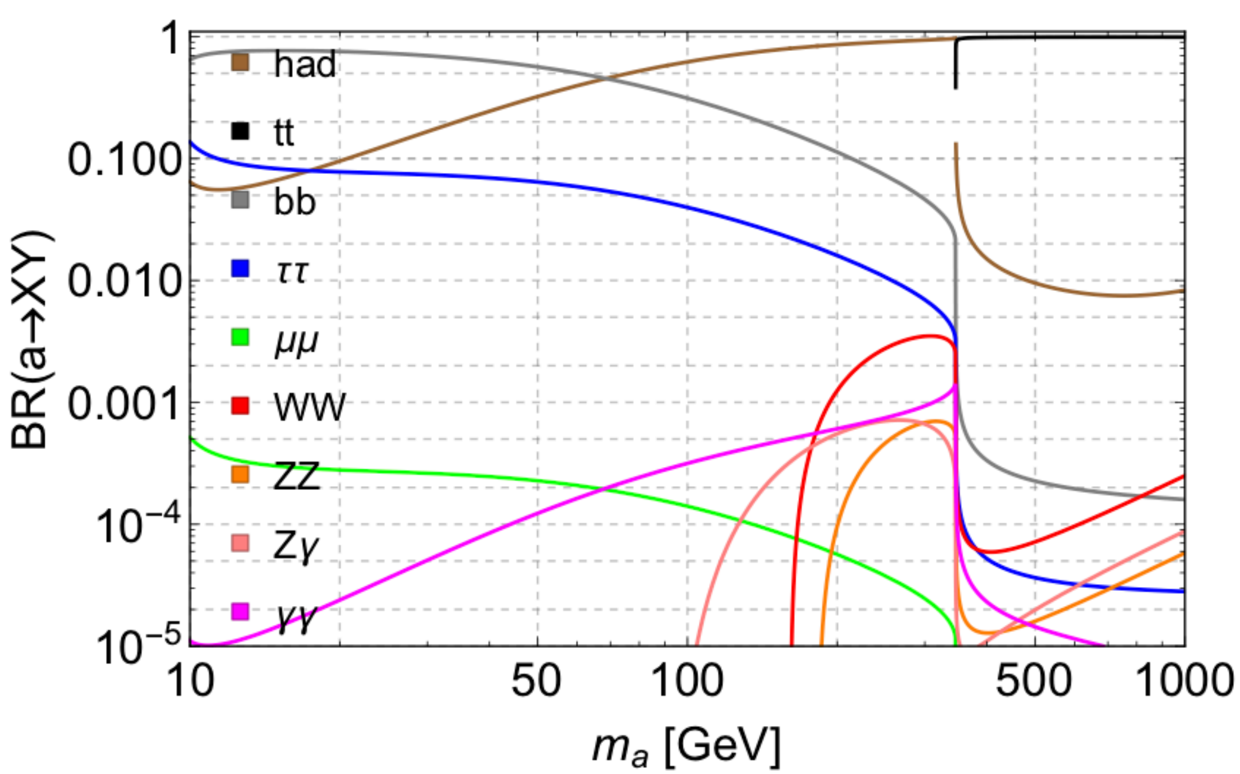
Common exotic VLQ decays

Examples of diagrams:



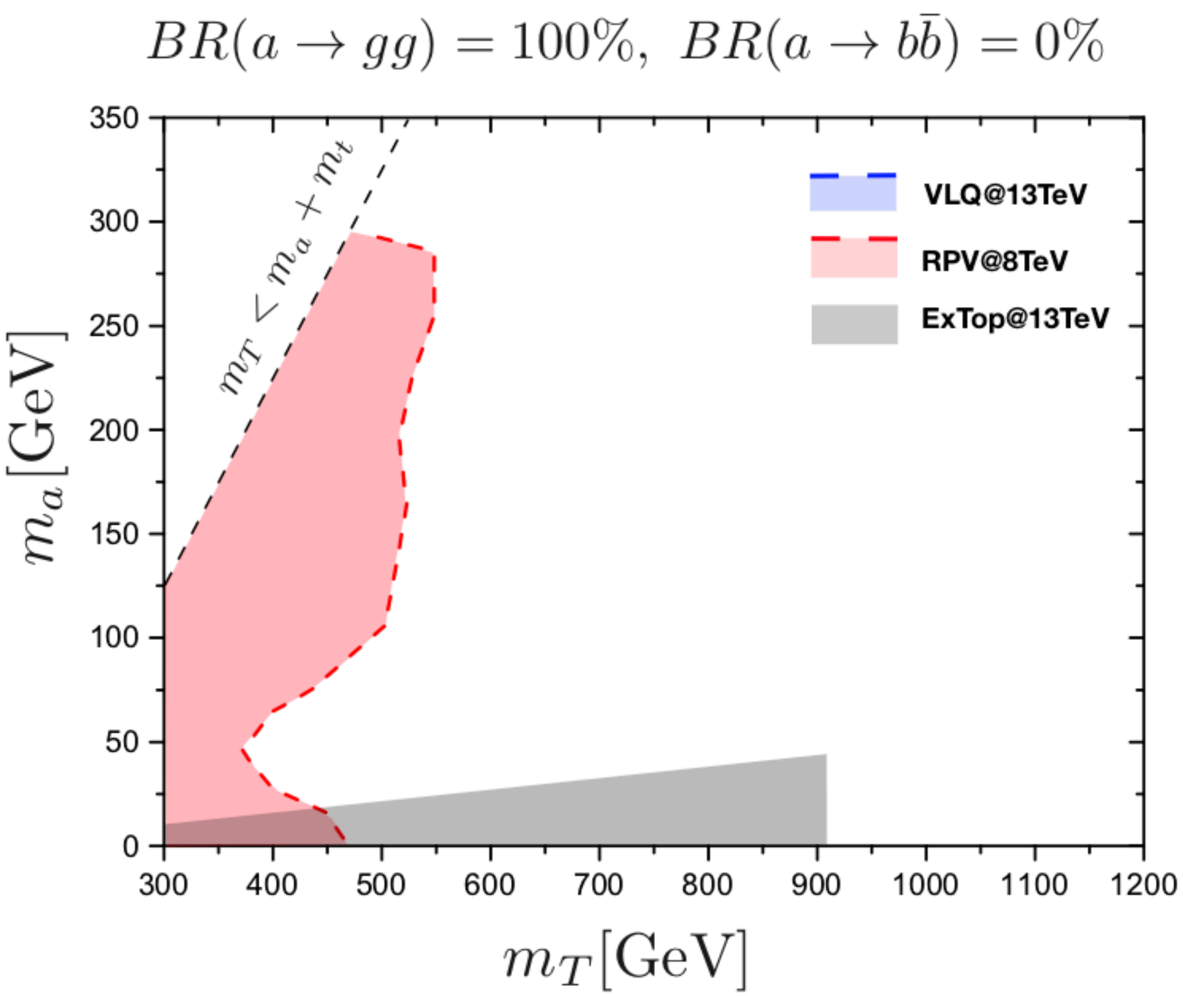


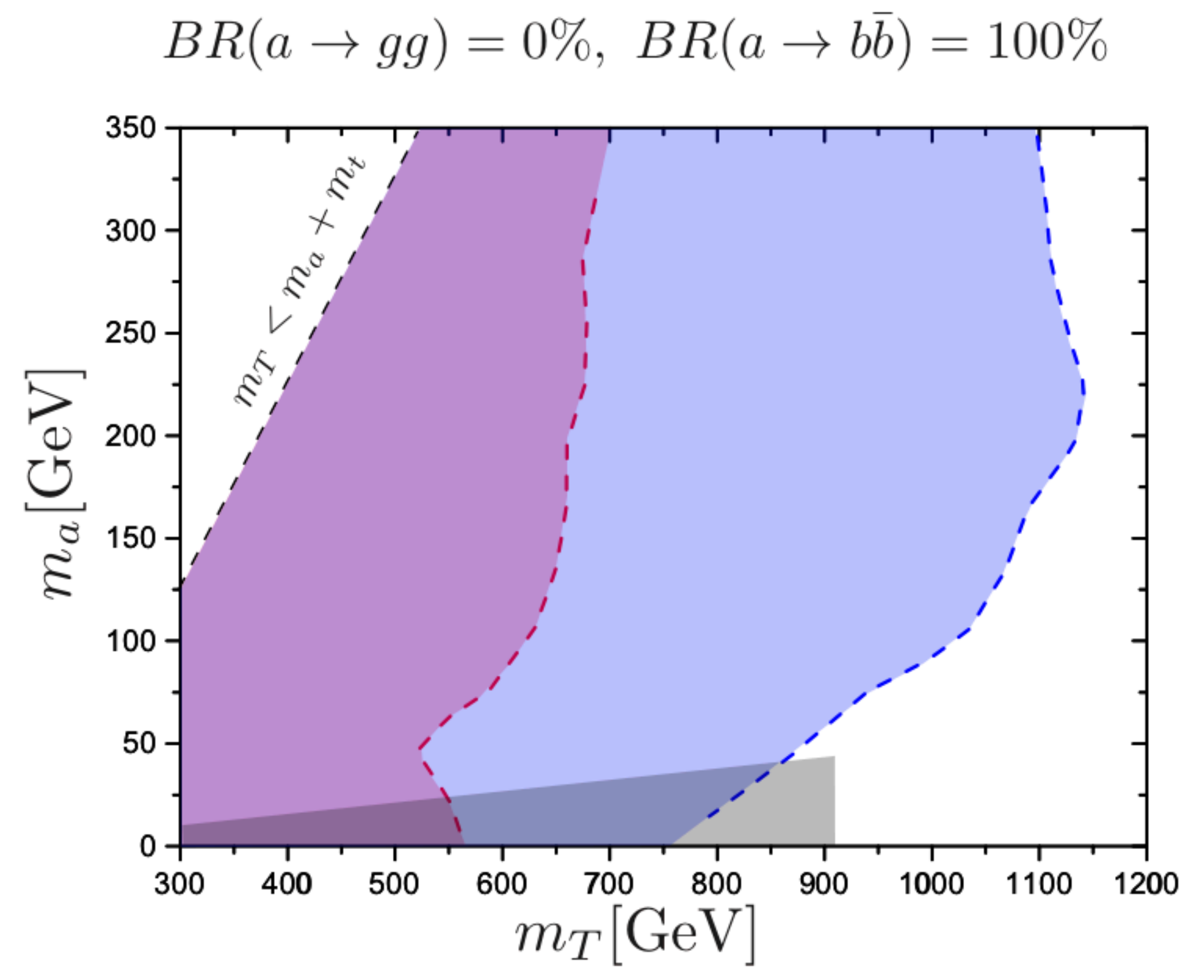
- T and B can be produced like "standard" top partners: QCD pair production or single production.
- New final states: MANY, depending on m_a and single- or pair-production



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

[PLB798, 135015 (2019)]





Recast searches

Red:	Blue:	Gray:
RPV-SUSY (hadronic)	VLQ search	Excited top search
CERN-EP-2015-020 (ATLAS) CERN-EP-2017-298 (ATLAS)	CERN-EP-2018-031 (ATLAS)	CERN-EP-2017-272 (CMS)

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

Conclusions

- Composite Higgs Models provide a viable solution to the hierarchy problem but they still provide many challenges and room for exploration in theory and model-building.
- EFT descriptions of composite Higgs models / the Minimal Composite Higgs Model are only part of the story. UV embeddings provide information on the BSM particle content and its representations.
- Additional pNGBs are present in CH UV embeddings (colored as well as uncolored ones). Some of them are weakly constrained and can be searched for at the LHC. Many are not exhaustively studied, yet.
- 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, which need to be studied in more detail.
- There are many more topics (results from the Lattice, baryogenesis, gravitational waves, dark matter, cosmology, …) which I did not cover, here.

There is lots to do!

Backup

Singlet pNGB 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 $\kappa_g/f_{\boldsymbol{\pi}}$).
- $\boldsymbol{\pi}_0$ 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

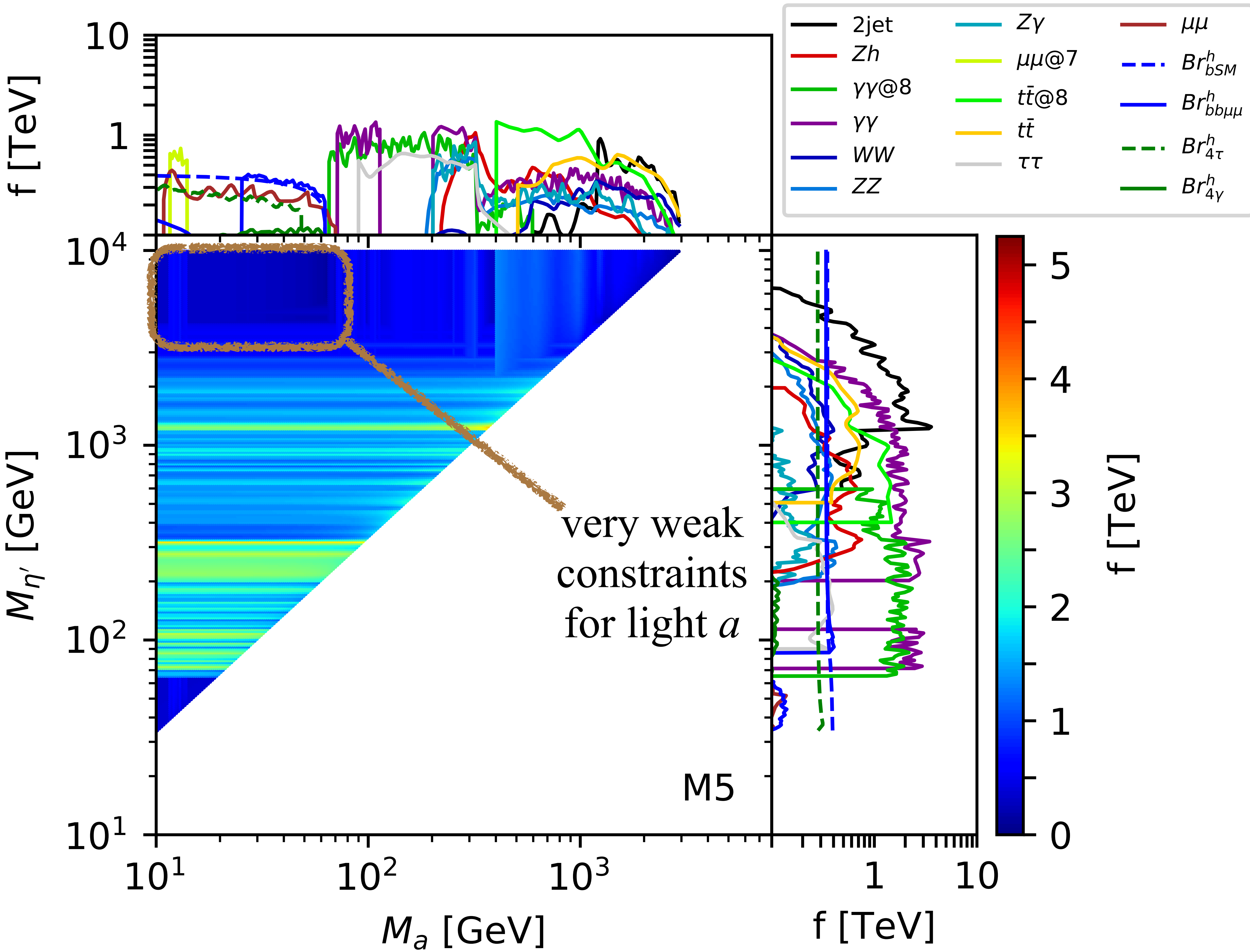
Coefficients of *a* for sample models M1 - M12

	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

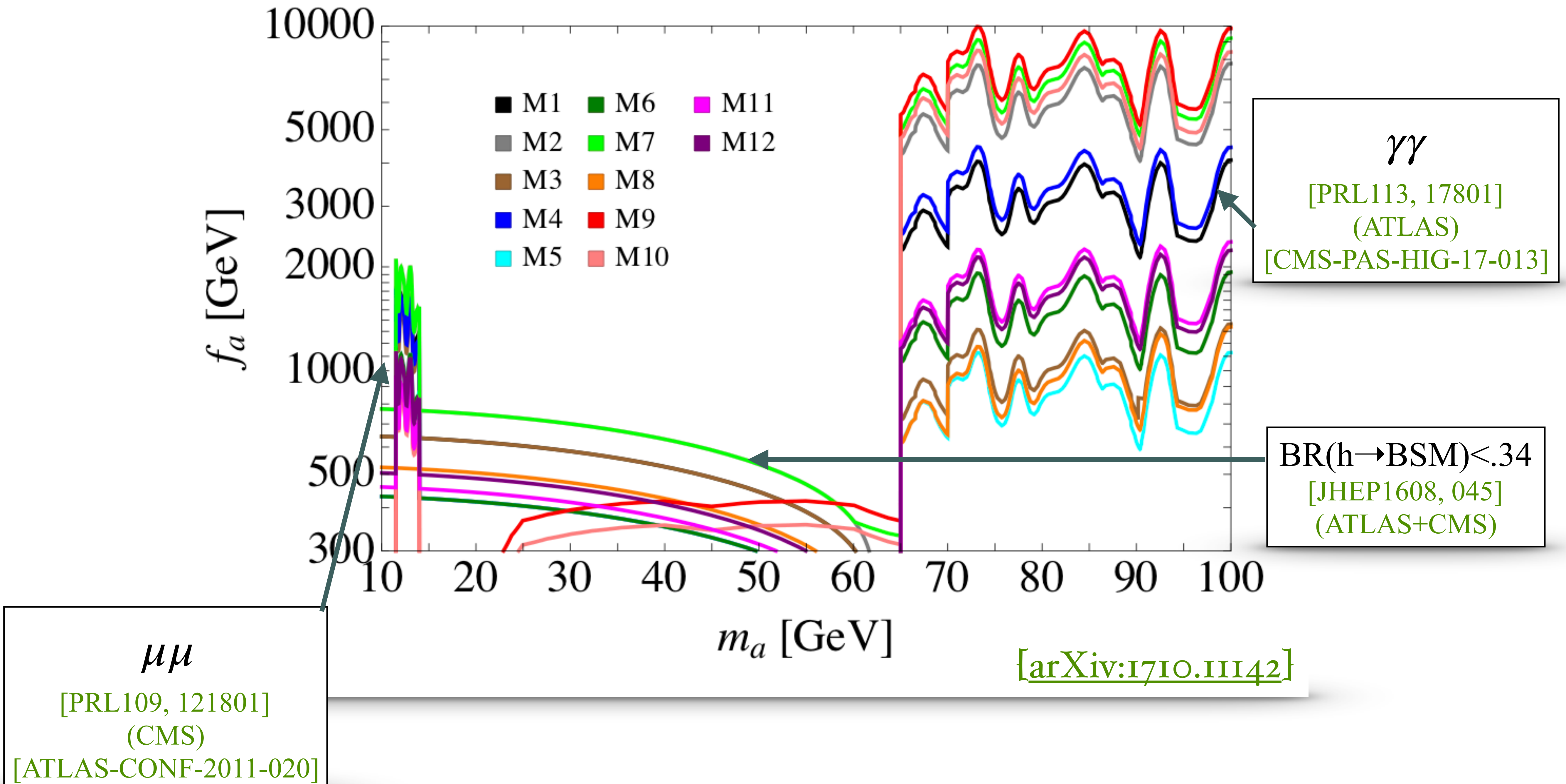
C_t:

(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

For a given model, we can combine bounds and sensitivities from resonance searches to get a bound on the compositeness scale f .



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



[arXiv:1710.11142]

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

[arXiv:1710.11142]

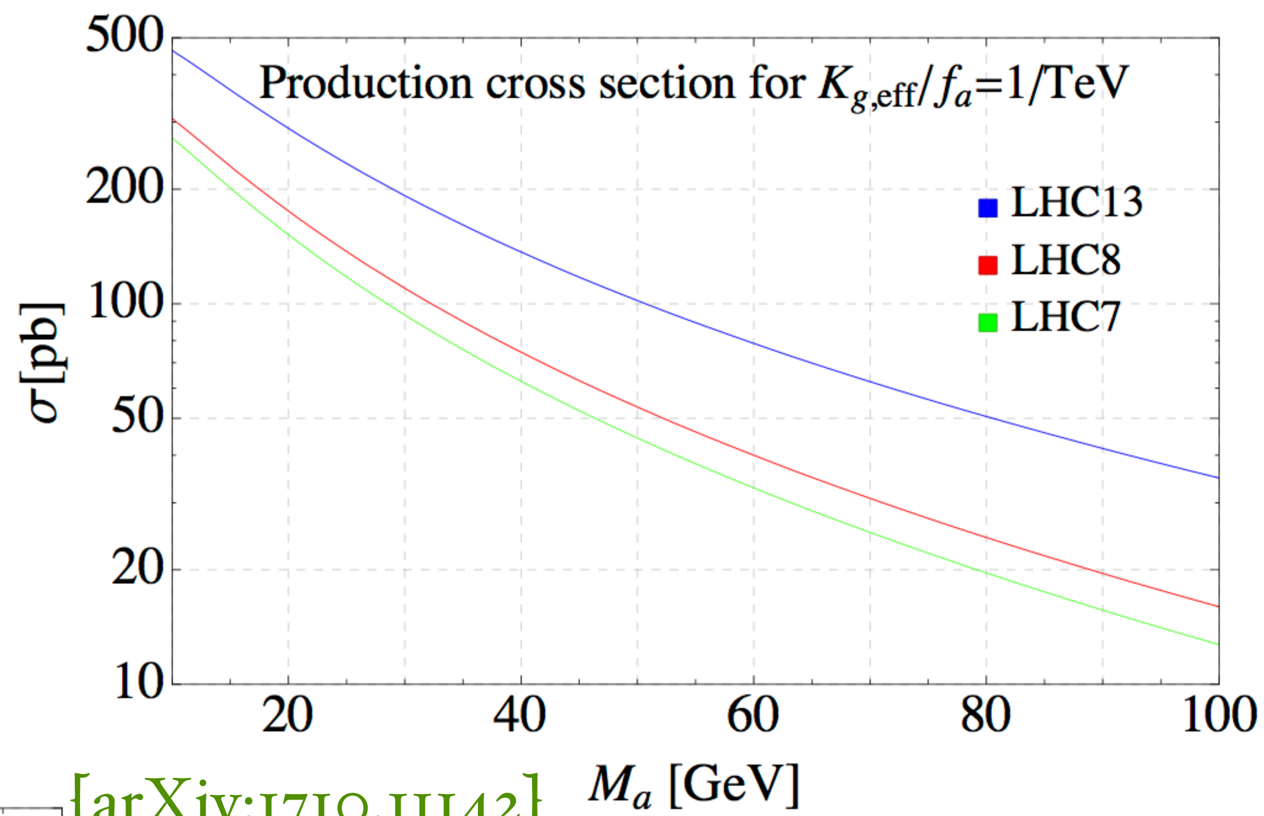
The models are poorly constrained in the mass range 15 - 65 GeV.

- 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: $\tau\tau$!

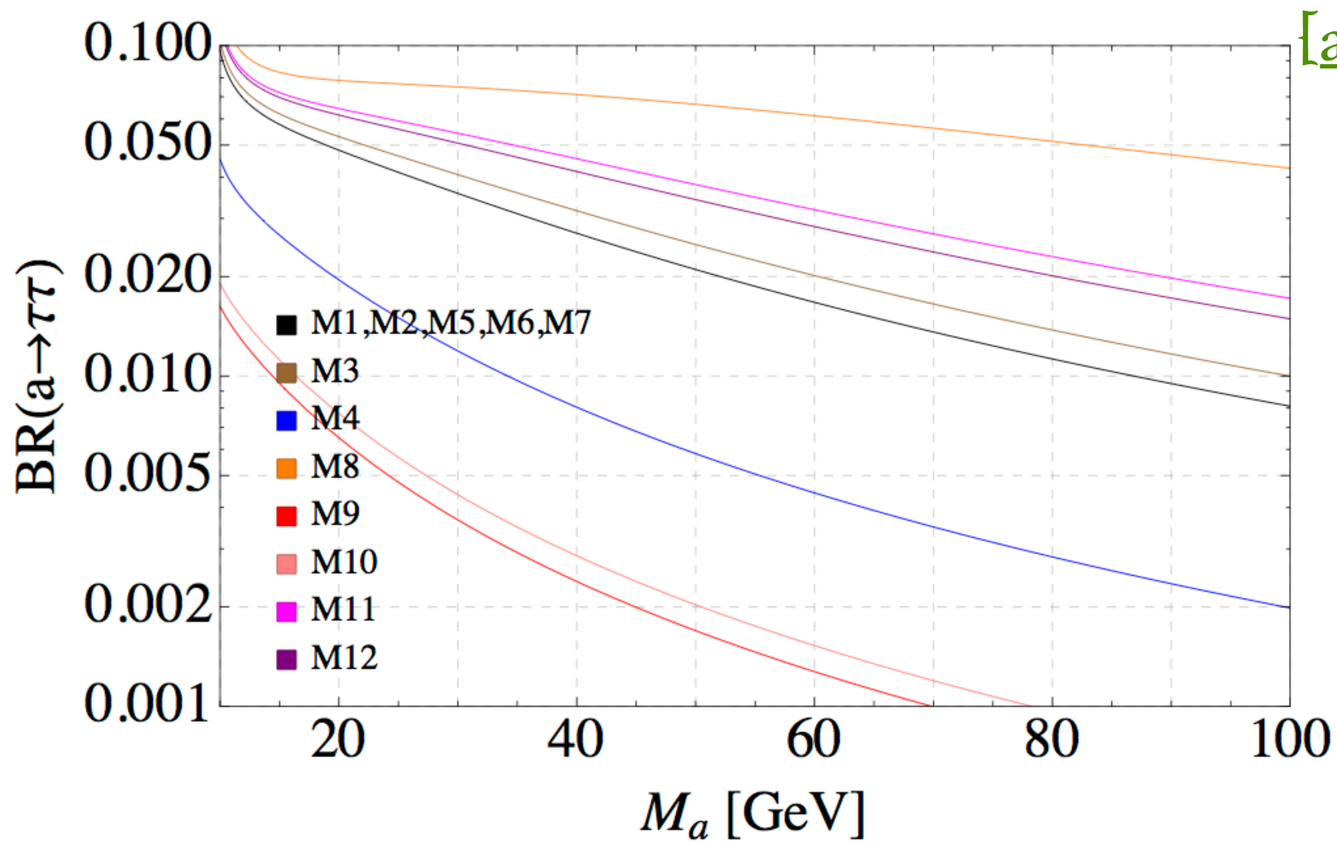
TCP

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 τ_{lep} or τ_{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

Main background:

Z/γ^*+jets: 35 fb,

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

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

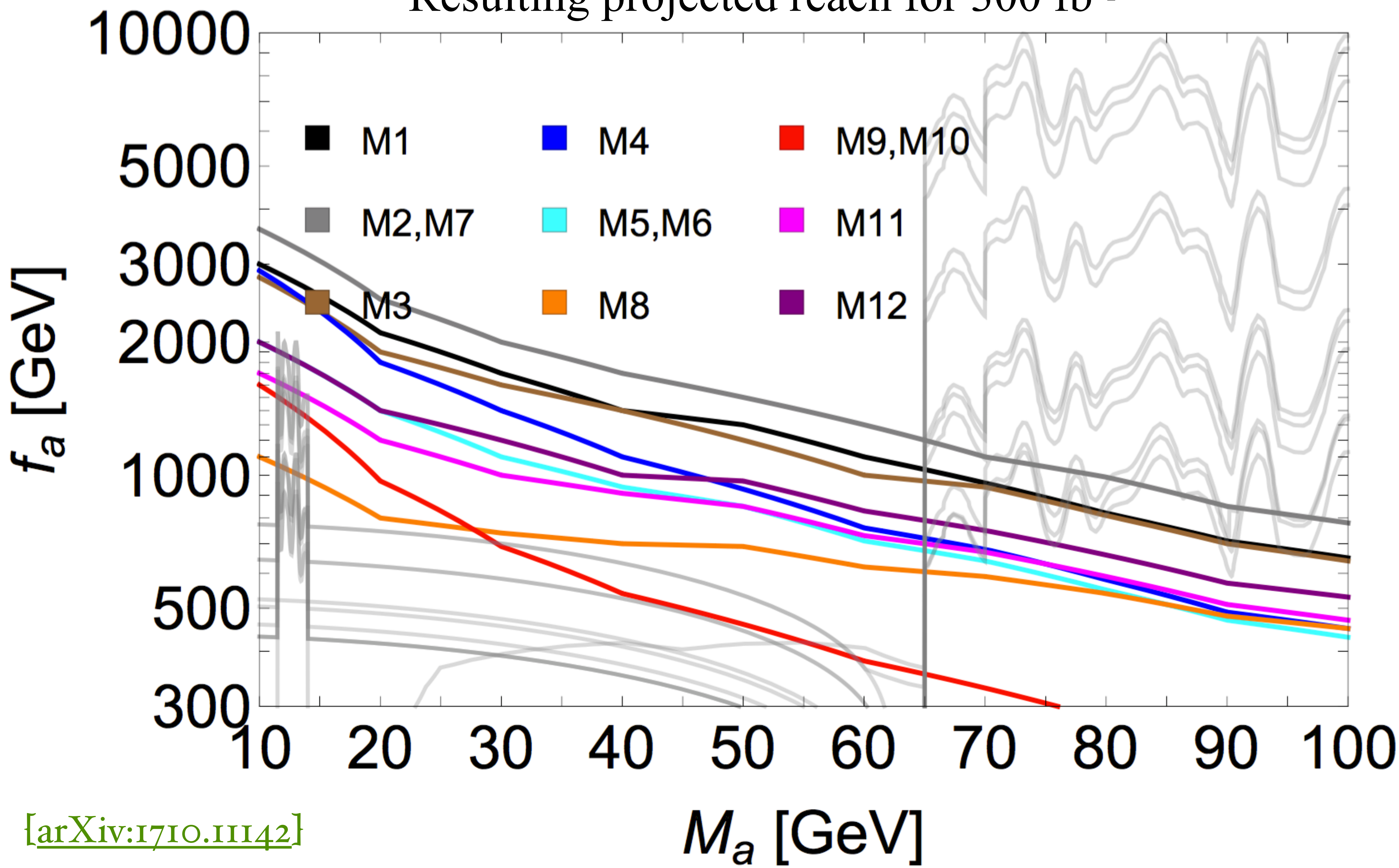
TABLE II: The values of $\sigma_{\text{prod.}} \times BR_{\tau\tau} \times \epsilon$ in fb for $f_a = 1$ TeV and $m_a = 10 \cdots 100$ GeV for each of the models defined in Table I.

[arXiv:1710.11142]

TCP

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

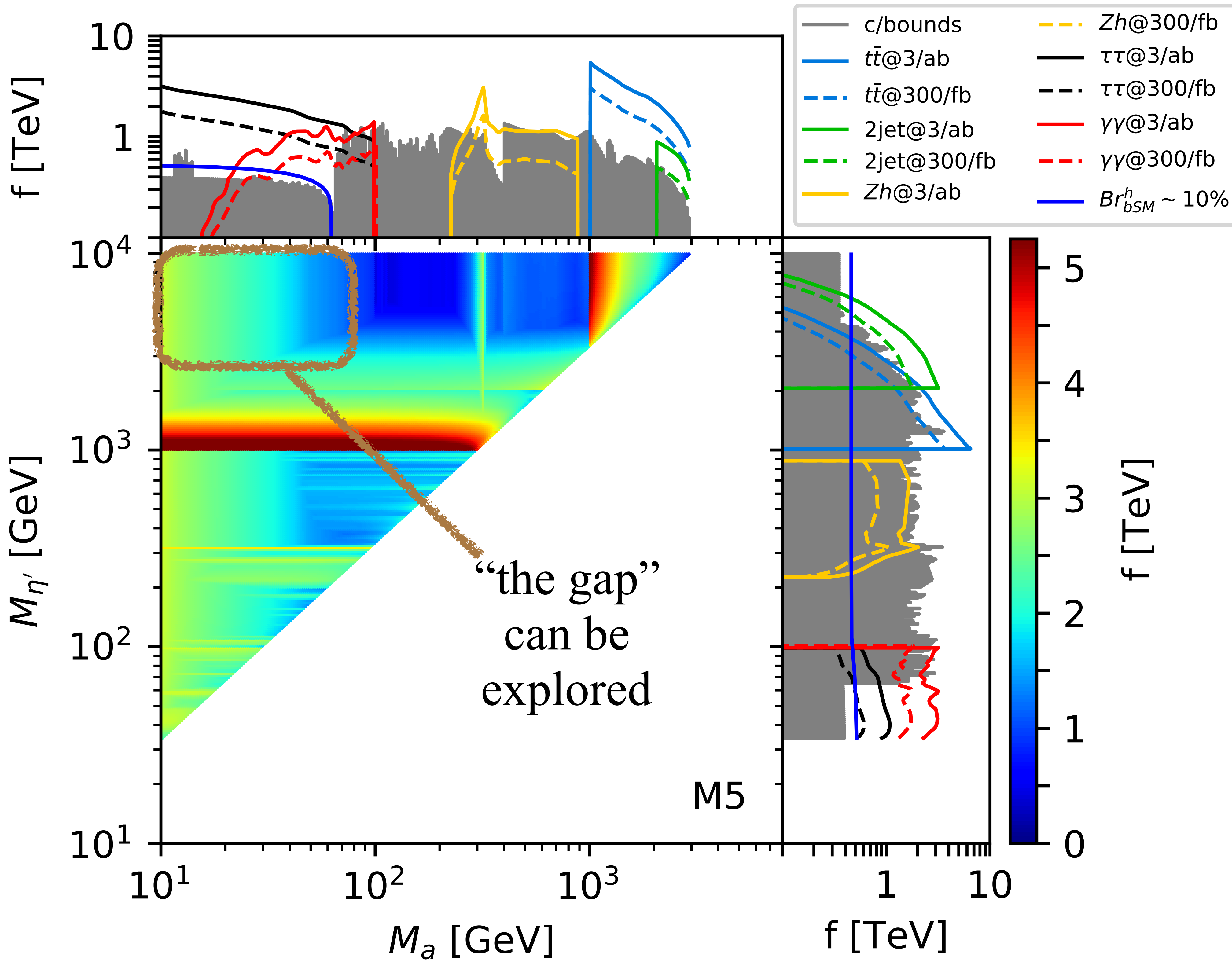
Resulting projected reach for 300 fb^{-1}



[arXiv:1710.11142]

TCP

Projected sensitivities on the compositeness scale f .



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

Colored PNGBs (the color octet ϕ)

Effective Lagrangian:

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

$$\frac{\alpha_s \kappa_g}{8\pi f_\Phi}\Phi^a\ \epsilon^{\mu\nu\rho\sigma}\left[\frac{1}{2} d^{abc}\ G^b_{\mu\nu} G^c_{\rho\sigma} + \frac{e\kappa_\gamma}{g_s\kappa_g}\ G^a_{\mu\nu} F_{\rho\sigma} - \frac{e\tan\theta_W \kappa_Z}{g_s \kappa_g}\ G^a_{\mu\nu} Z_{\rho\sigma}\right]$$

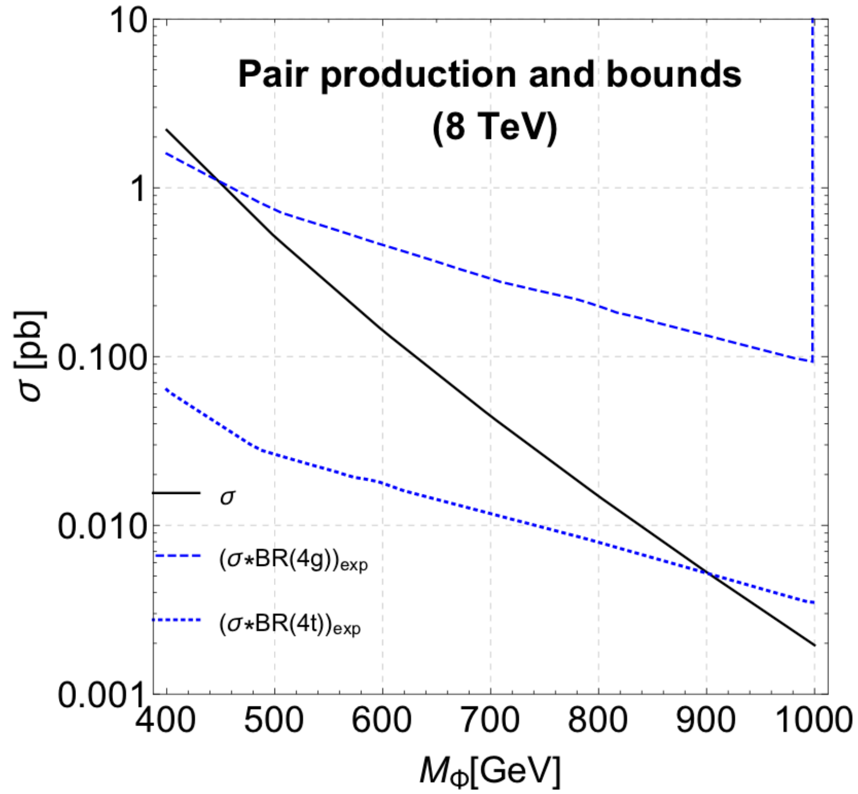
where in the CH UV embeddings: $\kappa_\gamma = \kappa_Z \equiv \kappa_B$

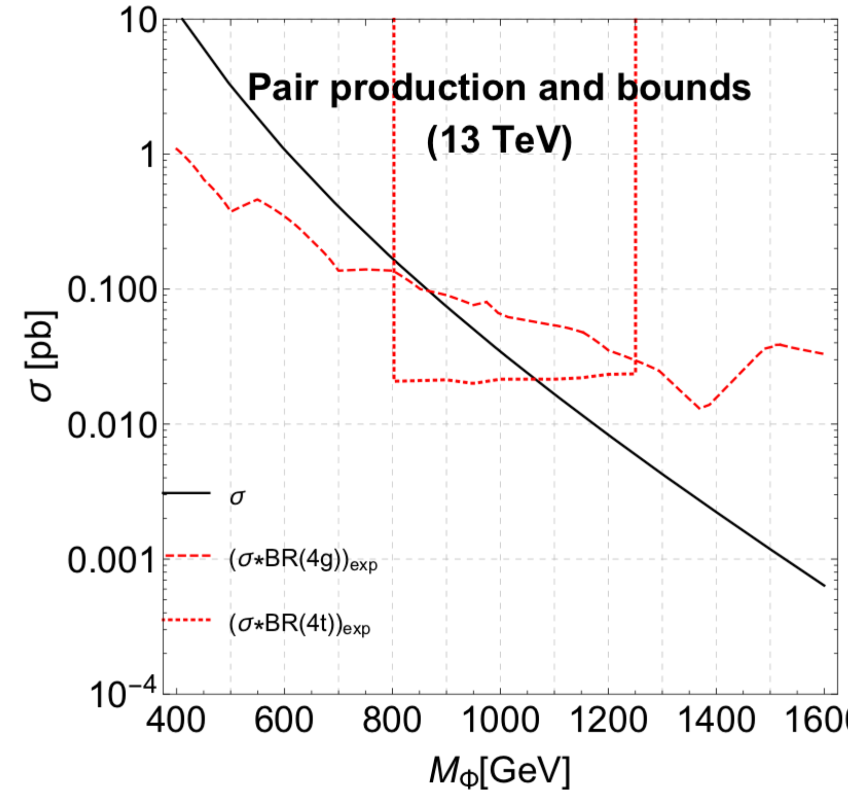
Phenomenology

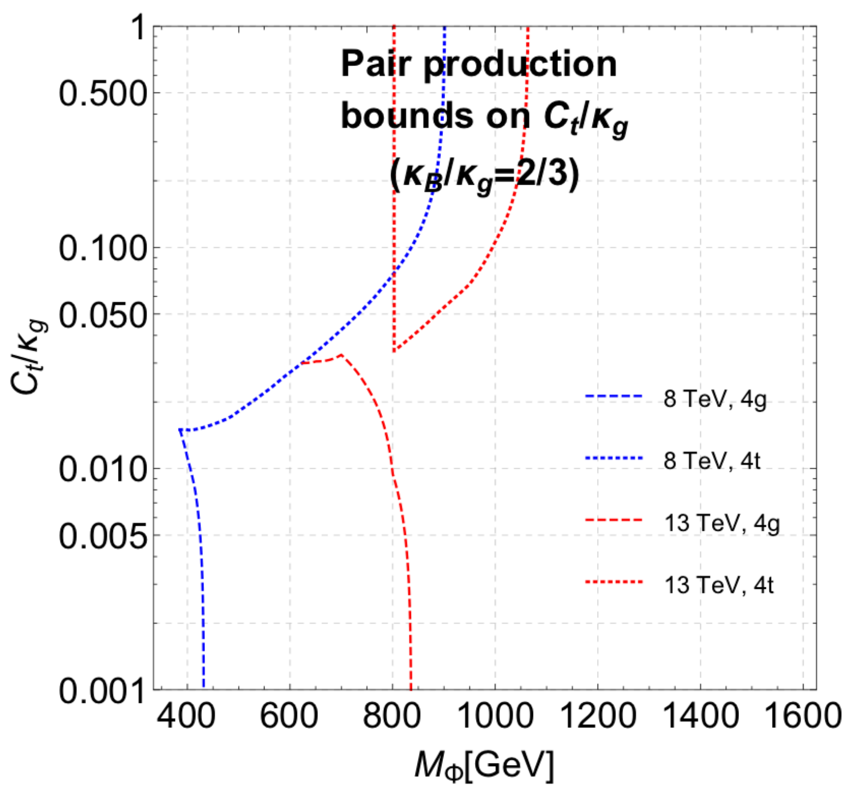
- ϕ is single-produced in gluon fusion or pair-produced through QCD.
- ϕ decays to *gg, gγ, gZ,* $t\bar{t}$ with fully determined branching fractions into dibosons:
- For Y_χ =1/3: *gg/gγ/gZ* = 1 / .06 / .014, Y_χ =2/3: gg/gγ/gZ = 1 / .19 / .05.
- The resonance is narrow.

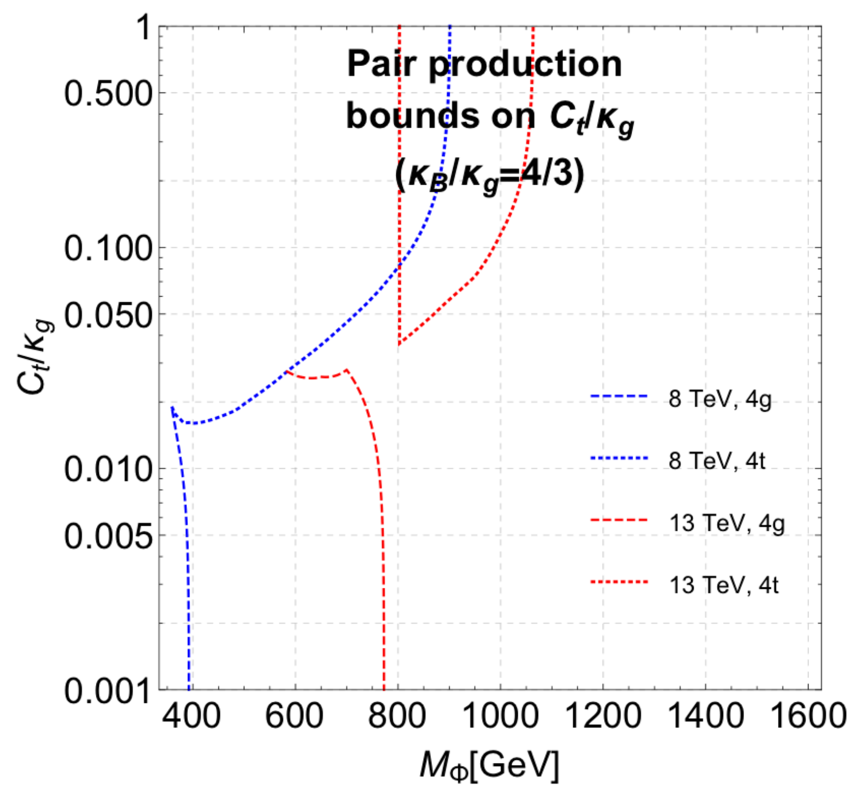
Colored PNGBs
Constraints from pair production: [2002.01474]

Right: Pair production cross section and bounds from pai produced di-jet searches [1412.7706,1710.07171, 1808.03124] and 4t searches [1504.04605,1505.04306, 1710.10614,1805.10835].







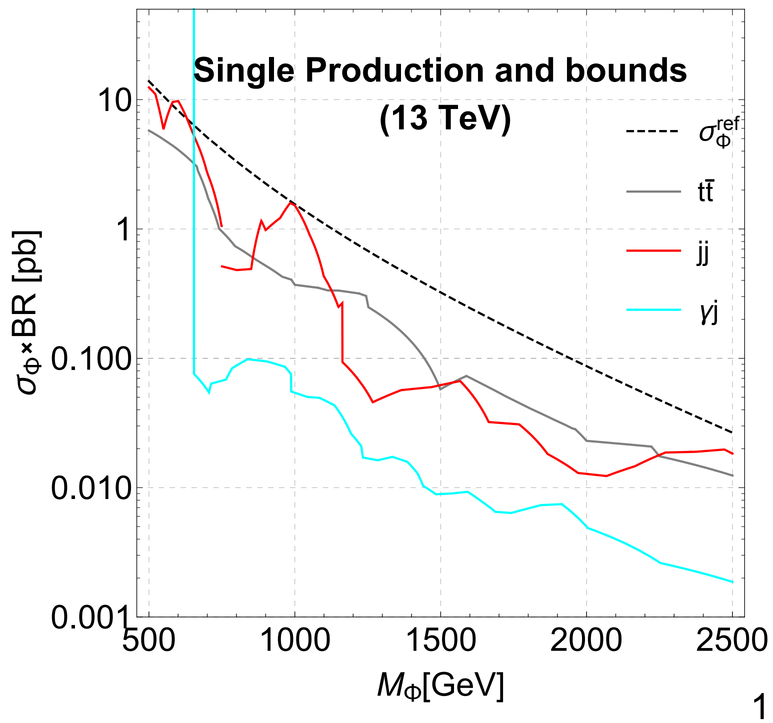


Left: Implied bounds on the C_t/κ_g vs. $M\phi$ parameter space.

CPNGB

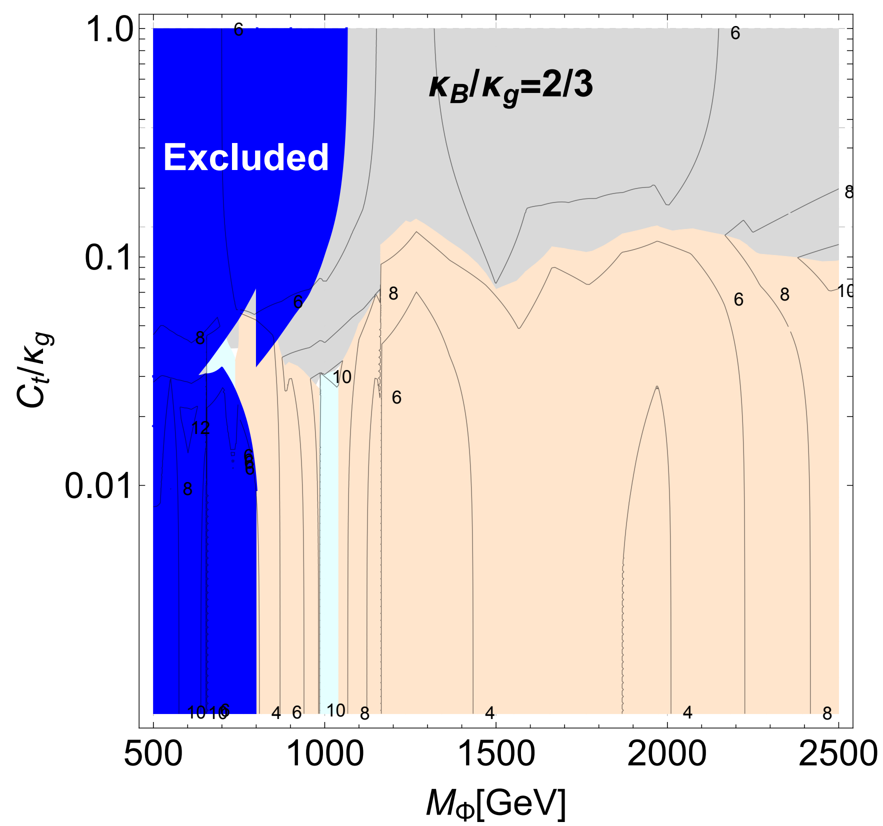
Colored PNGBs Constraints from single production:

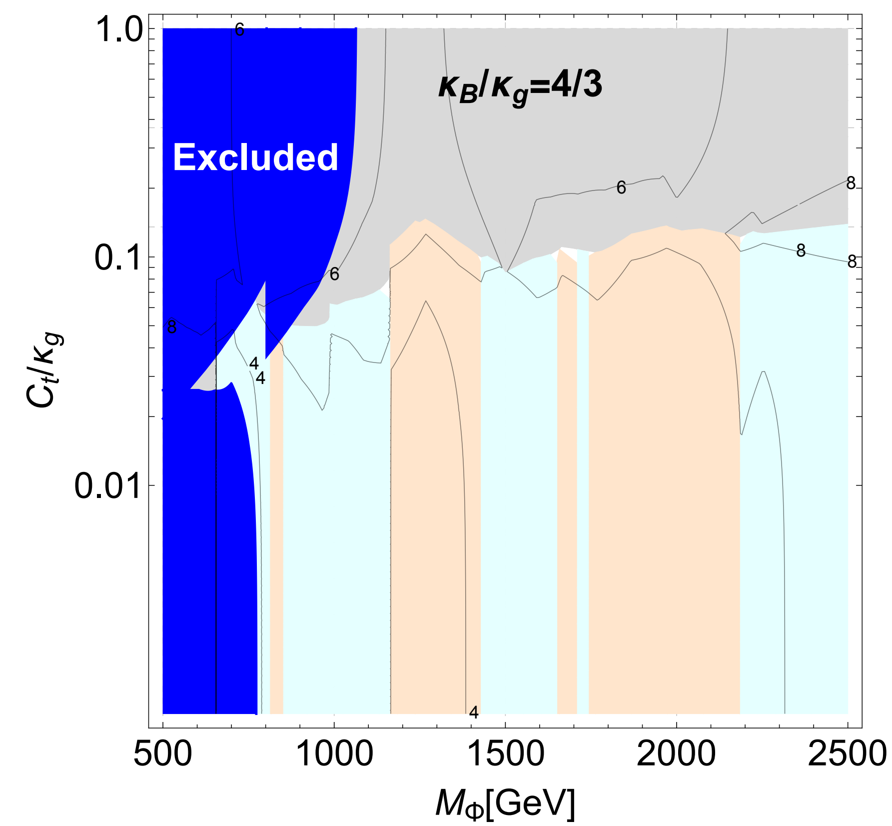
(see [2002.01474] for studies included)



Left: Single-production cross section for κ_g= 10 TeV^{-1} and bounds from di-top, di-jet, and excited quark searches.

Right: Bounds κ_g in TeV^{-1}. Dark blue: excluded from pair-production.
Grey: strongest bound from di-tops.
Red: strongest bound from di-jets.
Cyan: strongest bound from excited quarks.

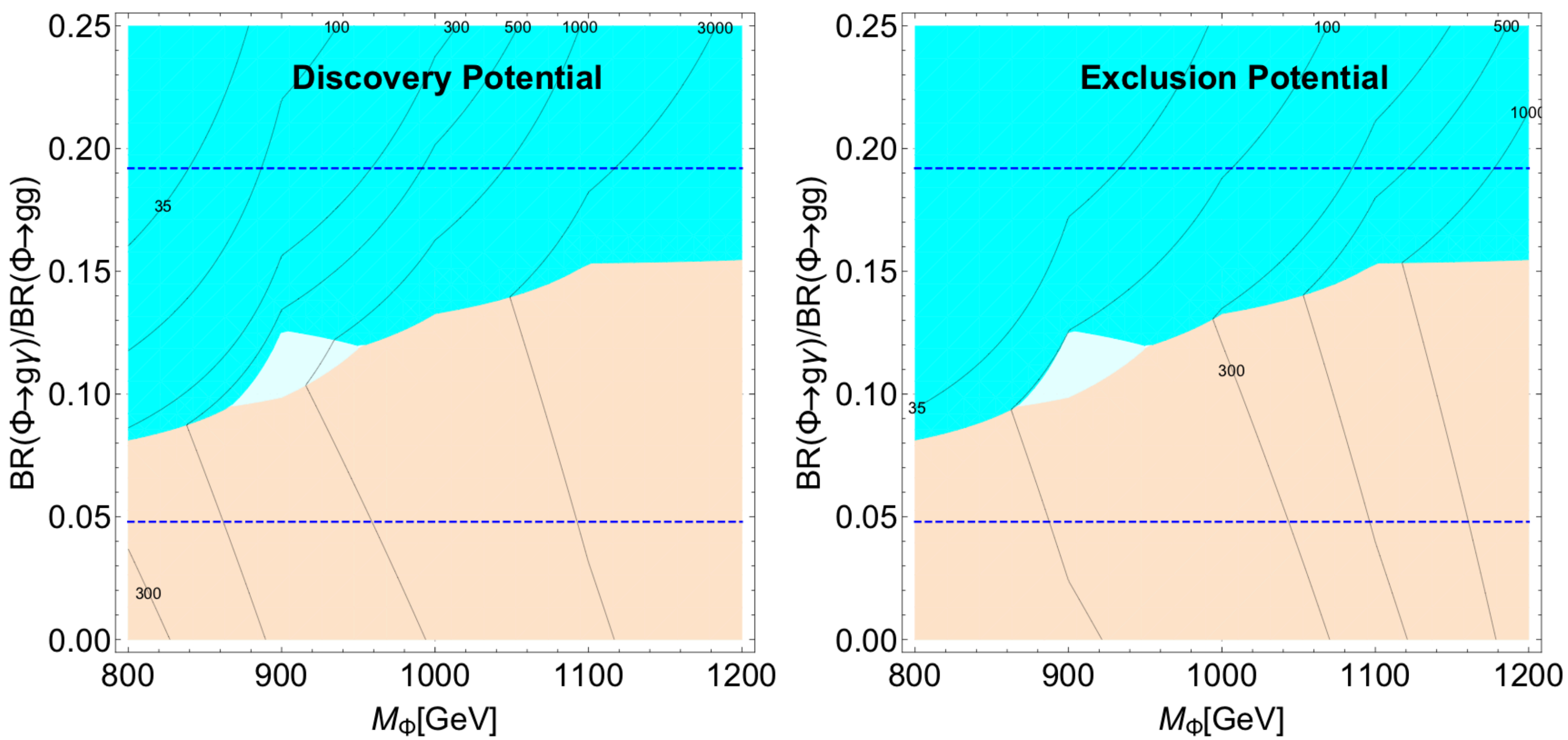




Improving the reach for low C_t: With an "excited quark pair-production" search

([2002.01474])

Mimicking the CMS di-jet-pair search 1808.03124 strategy (but replacing one or two jets with photons), we estimate the potential to constrain color octet pNGBs in (ja)(ja) and (ja)(jj) resonance pair searches and provide projections for HL-LHC (via purity estimates for existing data and naive rescaling with S/√B).



Contours of expected Luminosity for discovery and exclusion of pair-produced color-octet scalars, with best bounds from (jj)(jj) (red), (ja)(jj) (light cyan) and (ja)(ja) (dark cyan). Dashed blue lines indicate branching ratios as predicted in underlying composite models.

Upshot: an "excited quark pair-production" search for (ja)(ja) resonance pairs has highest discovery (and exclusion) potential in parts of the color octet pNGB parameter space.

CPNGB

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

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:

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

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

[JHEP 1806, 065]

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

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:

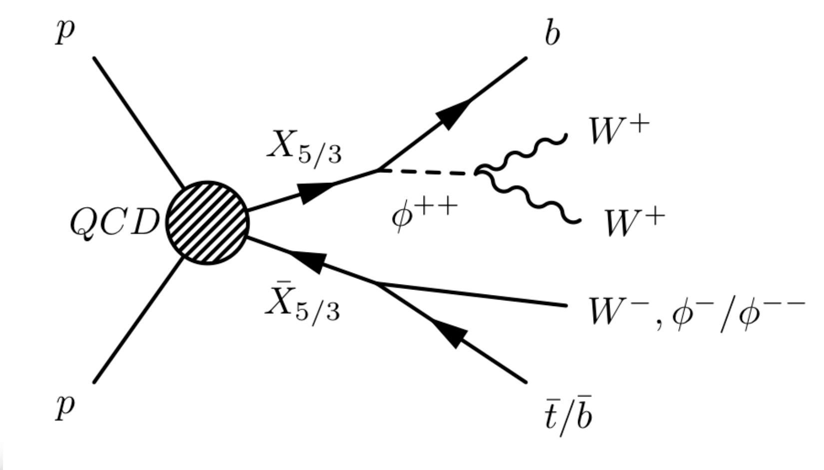
$$\mathcal{L}^{\phi}_{X_{5/3}} = \overline{X}_{5/3}\left(i\not{D} - M_{X_{5/3}}\right)X_{5/3} + \left(\kappa^{X}_{W,L}\frac{g}{\sqrt{2}}\overline{X}_{5/3}\not{W}^{+}P_L t \right.$$
$$\left. + i\kappa^{X}_{\phi^+,L}\overline{X}_{5/3}\phi^{+}P_L t + i\kappa^{X}_{\phi^{++},L}\overline{X}_{5/3}\phi^{++}P_L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

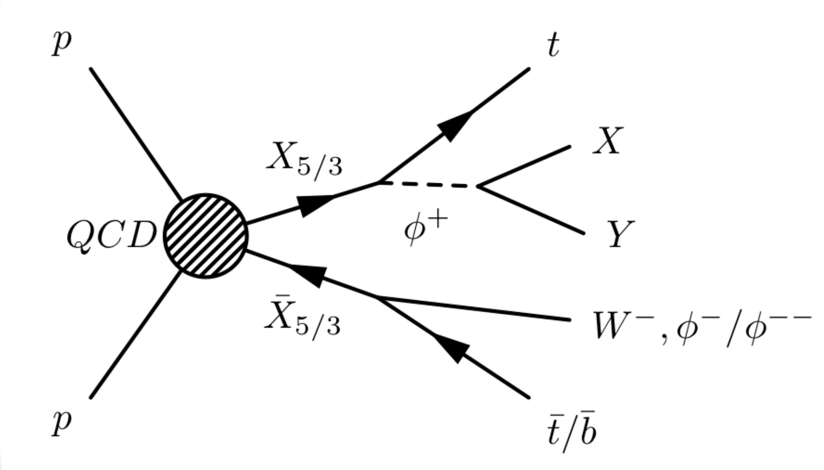
$$\mathcal{L}_{\phi} = \sum_{\phi=\phi^+,\phi^{++}}\left(|D_\mu\phi|^2 - m^2_\phi\,|\phi|^2\right) + \left(\frac{egK^{\phi}_{W\gamma}}{8\pi^2 f_\phi}\phi^{+}W^{-}_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{g^2 c_w K^{\phi}_{WZ}}{8\pi^2 f_\phi}\phi^{+}W^{-}_{\mu\nu}\tilde{B}^{\mu\nu}\right.$$
$$\left. + \frac{g^2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

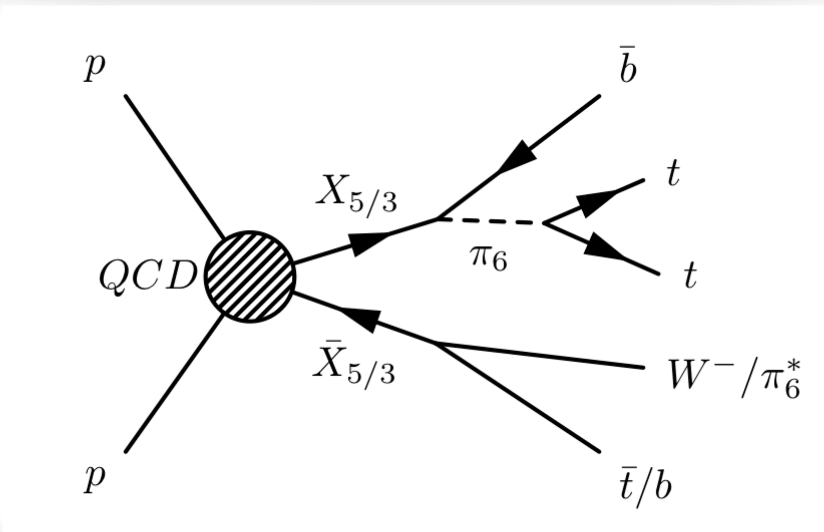
[JHEP 1806, 065]

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

Examples of processes:







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

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

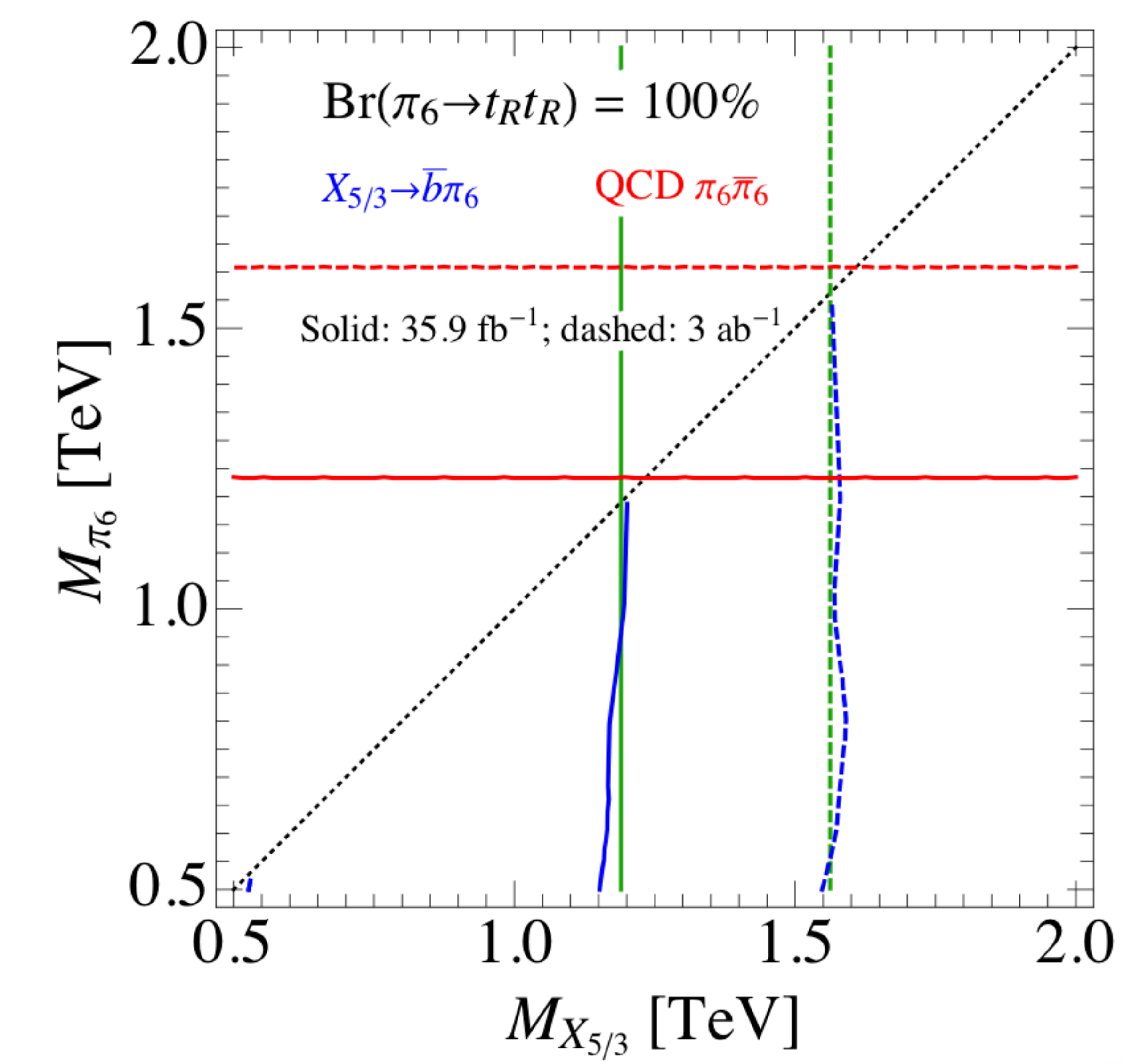
$|\ldots|^2$

X53

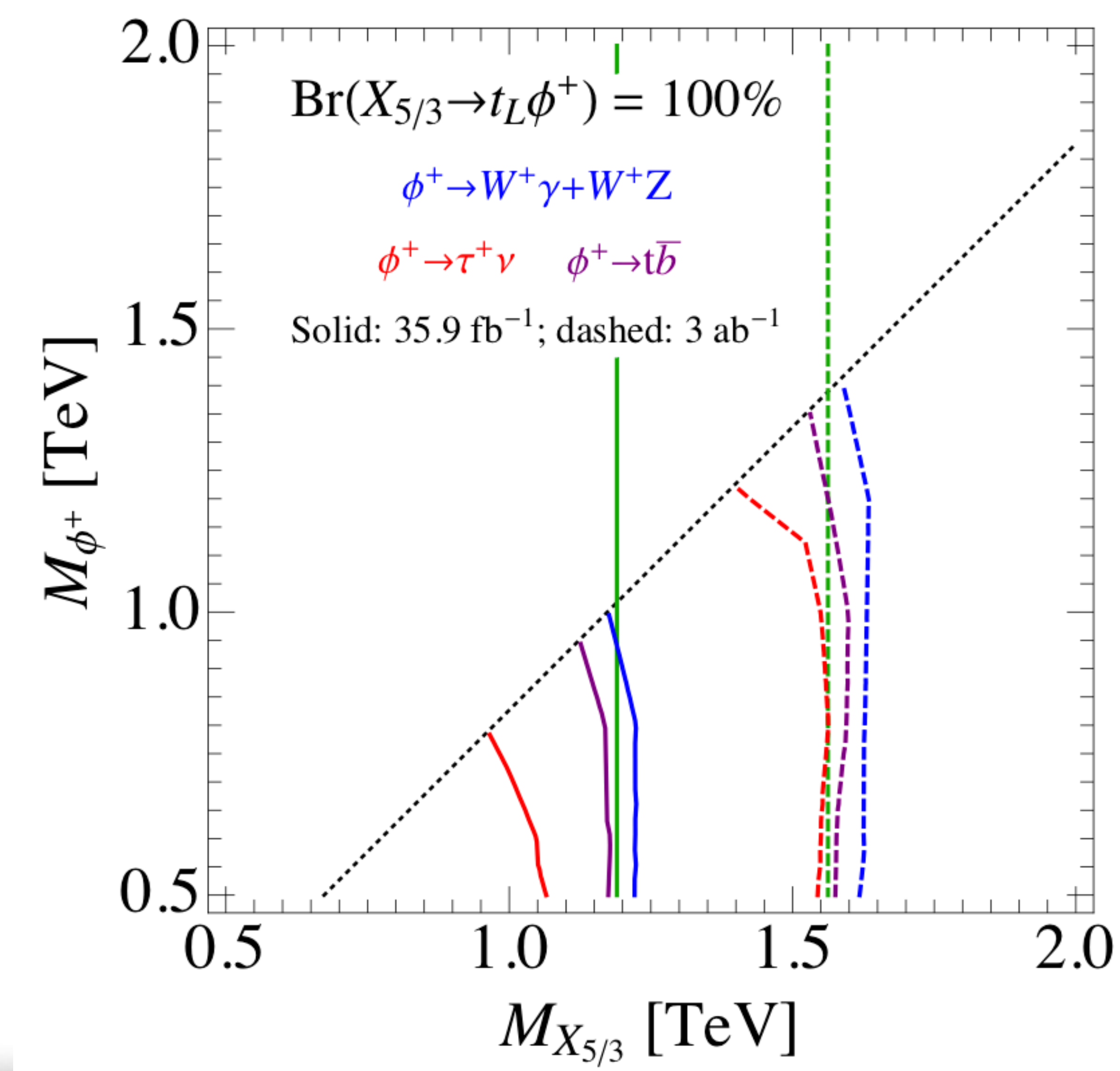
Common exotic VLQ decays: $X_{5/3}$

Recasting the most recent CMS $X_{5/3}$ same-sign lepton search JHEP 1903, 082 we obtain bounds on $X_{5/3}$ pair-production with exotic $X_{5/3}$ decays:

π_6:



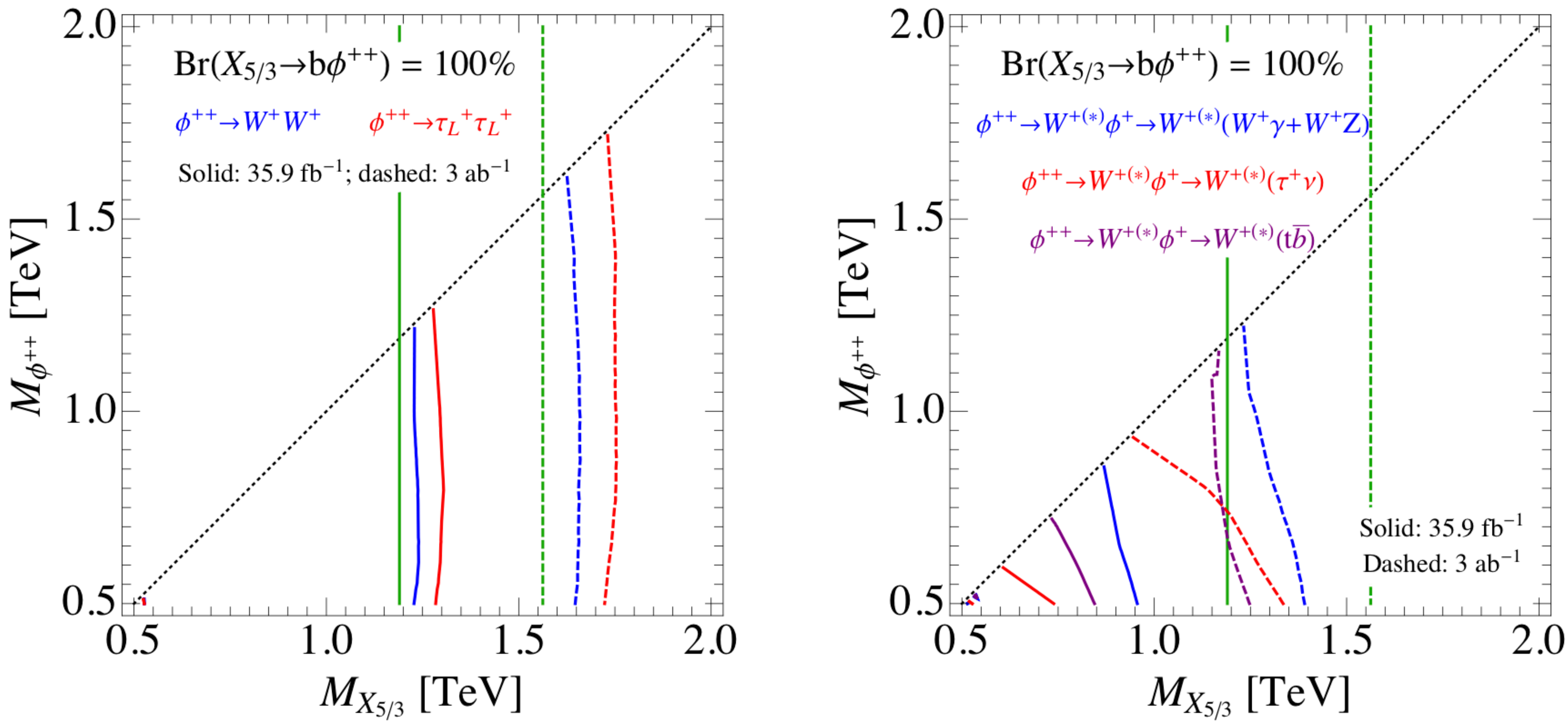
ϕ^+:



[JHEP 1910, 134]

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

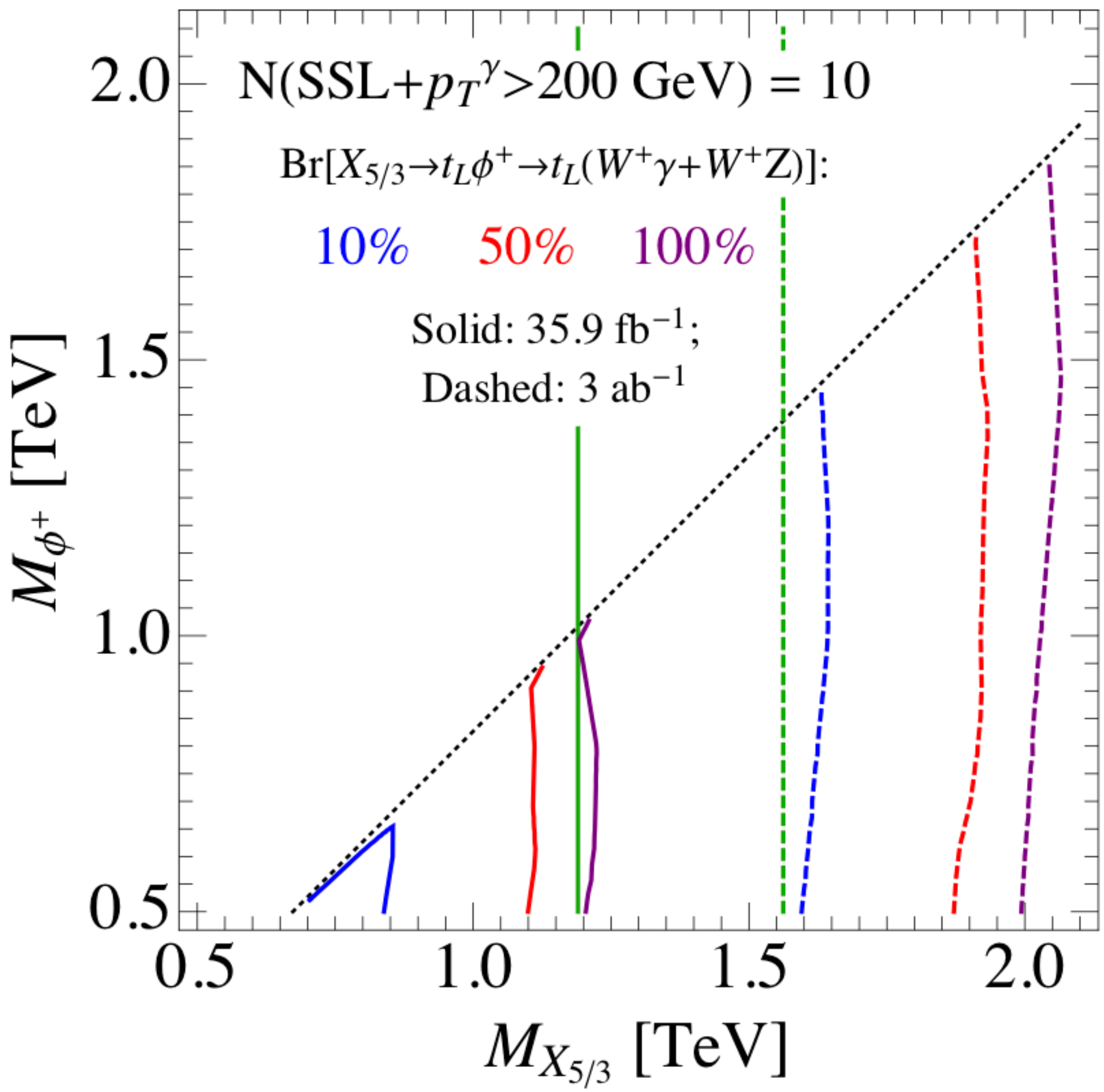
$\boldsymbol{\phi}^{++}$:



[1907.05894]

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

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



[1907.05894]

X53

Relating top partner couplings to Higgs and other pNGBs

Example: [JHEP 1806, 065]

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).

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

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 $y_{1,5}$.