A reappraisal of top-partner hunting

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Motivations

- Composite Higgs models: non-SUSY solutions to Hierarchy problem
- pNGB Higgs boson + top quark mass by partial compositeness
- Partial compositeness framework predicts vector-like quarks (top-partners).
- Several ongoing searches for VLQs at LHC and more proposals to come
- Popular approach: use simplified models (with unknown couplings)
- Our objective:
  - ✓ Bridge the gap between simplified models and more concrete scenarios of partial compositeness (reduction of parameters)
  - ✓ Formulate a TeV scale Lagrangian
  - ✓ Look for universal features which are independent of specific UV realizations
- Formulate a strategy for top-partner search at LHC:
  - ✓ Find interesting channels to search top-partners at LHC
  - ✓ Tackle the theoretical challenges
  - ✓ Provide benchmark for prospective search topologies

Schematic Lagrangian @TeV scale

$$\Sigma \equiv \exp\left(i\frac{\Pi}{f}\right)$$

$$\mathcal{L}_{\Psi^2} = \text{tr}\left[\bar{\Psi} i \not{D} \Psi\right] - M \text{tr}\left[\bar{\Psi}\Psi\right] + \kappa_{L,R} \text{tr}\left[\bar{\Psi}_{L,R} \not{\partial} \Sigma \Psi_{L,R}\right]$$

$$\mathcal{L}_{\text{elem.}} = \bar{q}_L i \not{D} q_L + \bar{t}_R i \not{D} t_R + \bar{b}_R i \not{D} b_R$$

$$\mathcal{L}_{\text{P.C.}} = y_L f \bar{q}_L \Sigma \Psi_R + y_R f \bar{\Psi}_L \Sigma t_R$$

$$\mathcal{L} = \mathcal{L}_{\text{pNGB}} + \mathcal{L}_{\text{pot.}} + \mathcal{L}_{\text{anom.}} + \mathcal{L}_{\text{elem.}} + \mathcal{L}_{\Psi^2} + \mathcal{L}_{\text{P.C.}}$$

$$\mathcal{L}_{\text{pNGB}} = \frac{f^2}{2} \text{tr}\left[(D_\mu \Sigma)^\dagger (D^\mu \Sigma)\right]$$

$$\mathcal{L}_{WZW} = \chi_i^0 \left[c_{\gamma\gamma} F\tilde{F} + c_{ZZ} Z\tilde{Z} + c_{Z\gamma} F\tilde{Z} + c_{WW} W^+ \tilde{W}^-\right] + \chi_i^+ \left[c_{ZW} Z\tilde{W}^- + c_{\gamma W} F\tilde{W}^-\right] + \chi_i^{++} \left[c_{W^-W^-} W^- \tilde{W}^-\right]$$

$$\mathcal{L}_{\text{pot.}} = \frac{1}{2} m_h^2 h^2 + \frac{1}{2} m_i^2 \chi_i^2 + \mathcal{O}(\chi^3, \chi^4)$$

Examples: pNGBs and top-partners

$\frac{\mathrm{SU}(4)}{\mathrm{Sp}(4)}$ $\quad \mathbf{5} \to (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1}) \to \mathbf{2}_{\pm 1/2} + \mathbf{1}_0 \equiv (H,\eta)$ SHIFT Collab:[1907.05929]

$\frac{\mathrm{SU}(5)}{\mathrm{SO}(5)}$ $\quad \mathbf{14} \to (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1}) \to \mathbf{3}_0 + \mathbf{3}_{\pm 1} + \mathbf{2}_{\pm 1/2} + \mathbf{1}_0 \equiv (\Phi_0, \Phi_\pm, H, \eta)$

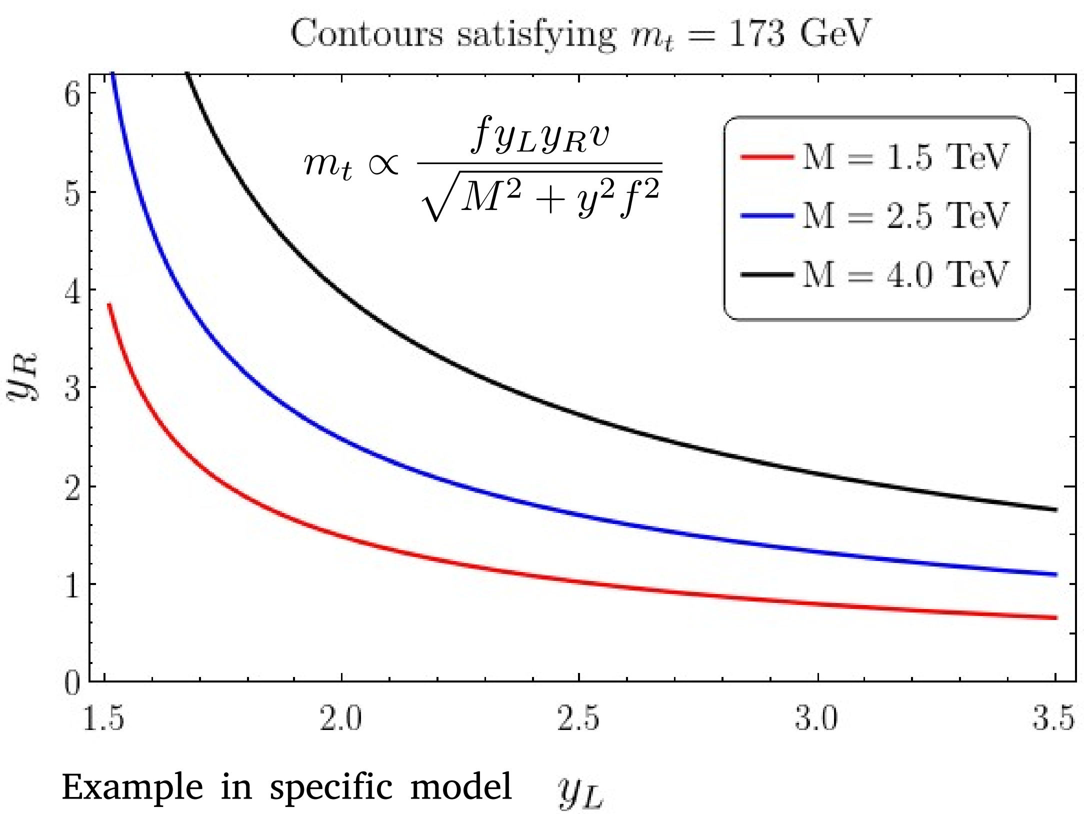
- Top-partners: consider lowest dimensional representations

Irrep name	$\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$ multiplets			
Ψ_4	$\mathbf{2}_{\frac{1}{6}}: \begin{pmatrix} T_{\frac{2}{3}} \\ B_{-\frac{1}{3}} \end{pmatrix}$	$\mathbf{2}_{\frac{7}{6}}: \begin{pmatrix} X_{\frac{5}{3}} \\ X_{\frac{2}{3}} \end{pmatrix}$		
Ψ_6	$\mathbf{3}_{\frac{2}{3}}: \begin{pmatrix} Y_{\frac{5}{3}} \\ Y_{\frac{2}{3}} \\ Y_{-\frac{1}{3}} \end{pmatrix}$	$\mathbf{1}_{\frac{5}{3}}: \tilde{X}_{\frac{5}{3}}$	$\mathbf{1}_{\frac{2}{3}}: \tilde{T}_{\frac{2}{3}}$	$\mathbf{1}_{-\frac{1}{3}}: \tilde{B}_{-\frac{1}{3}}$
Ψ_9	$\mathbf{3}_{\frac{2}{3}}: \begin{pmatrix} Y_{\frac{5}{3}} \\ Y_{\frac{2}{3}} \\ Y_{-\frac{1}{3}} \end{pmatrix}$	$\mathbf{3}_{\frac{5}{3}}: \begin{pmatrix} U_{\frac{8}{3}} \\ U_{\frac{5}{3}} \\ U_{\frac{2}{3}} \end{pmatrix}$	$\mathbf{3}_{-\frac{1}{3}}: \begin{pmatrix} V_{\frac{2}{3}} \\ V_{-\frac{1}{3}} \\ V_{-\frac{4}{3}} \end{pmatrix}$	

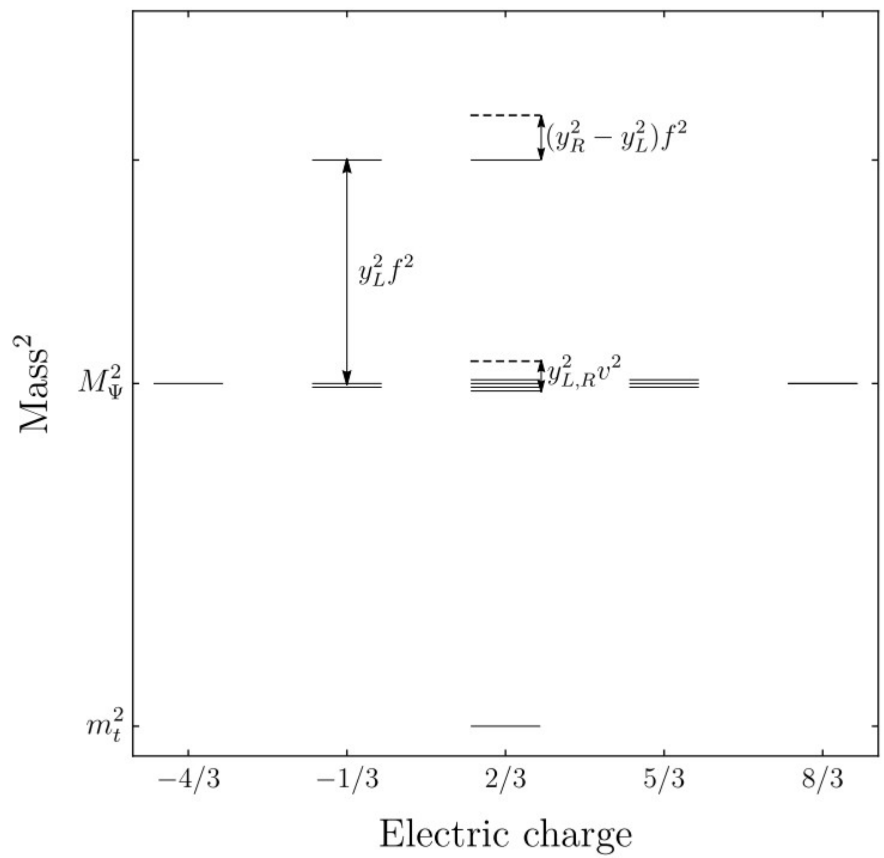
Generic mass-matrix and spectra

$$\mathcal{M}_{2/3} = \left(\begin{array}{c|c} 0 & \omega^t_L(v)^T \\ \hline \omega^t_R(v) & M\mathbb{I}_{n-1} \end{array} \right)$$

- (n-3) degenerate states with mass M
- One state shifted by $\sim y^2v^2$
- Others shifted by $\sim y^2f^2$



Example in specific model

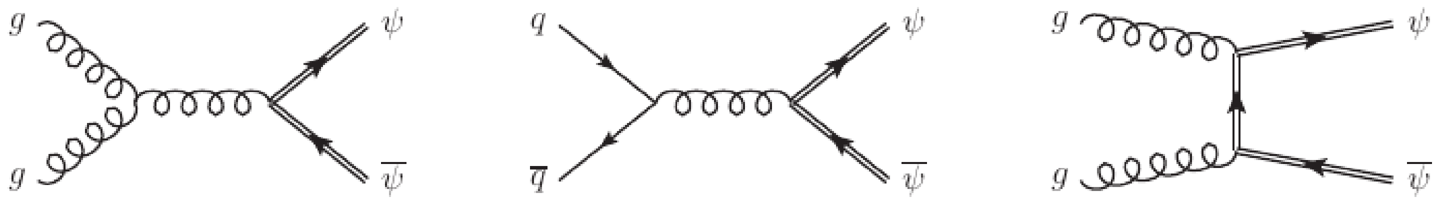


$$\mathcal{M}_{-1/3} = \left(\begin{array}{c|c} y_b v & \omega^b_L(v)^T \\ \hline 0_{n-1\times 1} & M\mathbb{I}_{n-1} \end{array} \right)$$

- (n-2) degenerate states with mass M
- Masses of exotic charged top-partners: $m_{-4/3} = m_{5/3} = m_{8/3} = M$

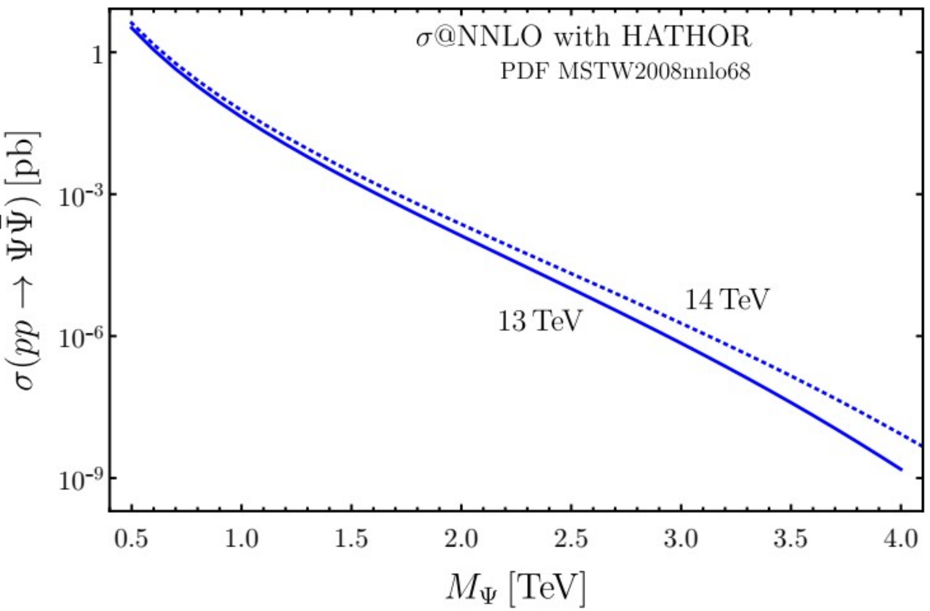
Phenomenology of top-partners

- Double production of top-partners at LHC: Model independent

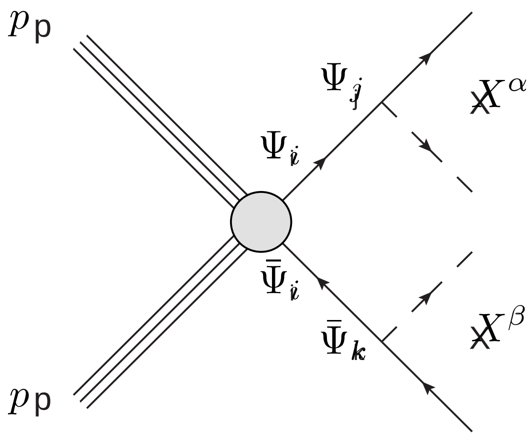


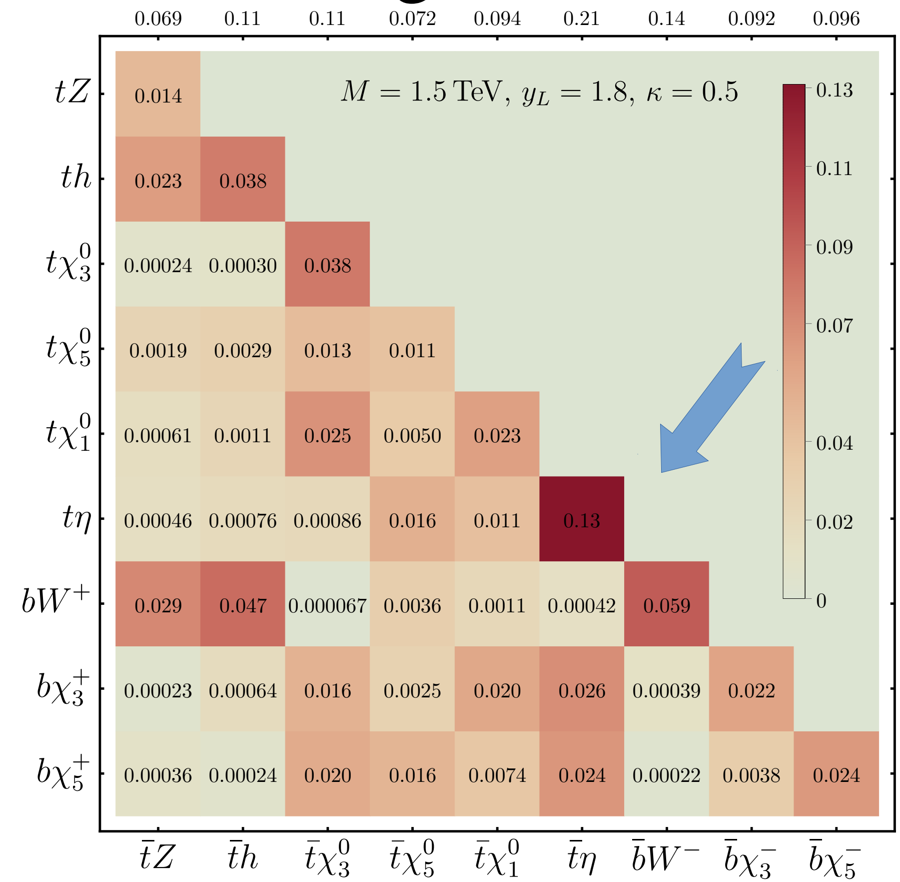
- Decays of top-partners:

Top-partner	Decays to SM final states	Decays to BSM final states $\frac{SU(4)}{Sp(4)}$	Decays to BSM final states $\frac{SU(5)}{SO(5)}$
$T_{\frac{2}{3}}$	th, tZ	$t\eta$	$t\chi_3^0$, $t\chi_5^0$, $t\chi_1^0$, $t\eta$
	bW^+		$b\chi_3^+$, $b\chi_5^+$
$B_{-\frac{1}{3}}$	bh, bZ	$b\eta$	$b\chi_3^0$, $b\chi_5^0$, $b\chi_1^0$, $b\eta$
	tW^-		$t\chi_3^-$, $t\chi_5^-$
$X_{\frac{5}{3}}$	tW^+	–	$t\chi_3^+$, $t\chi_5^+$
			$b\chi_5^{++}$
$X_{-\frac{4}{3}}$	tW^-W^-	–	$t\chi_5^{--}$
	bW^-		$b\chi_3^-$, $b\chi_5^-$
$X_{\frac{8}{3}}$	tW^+W^+	–	$t\chi_5^{++}$

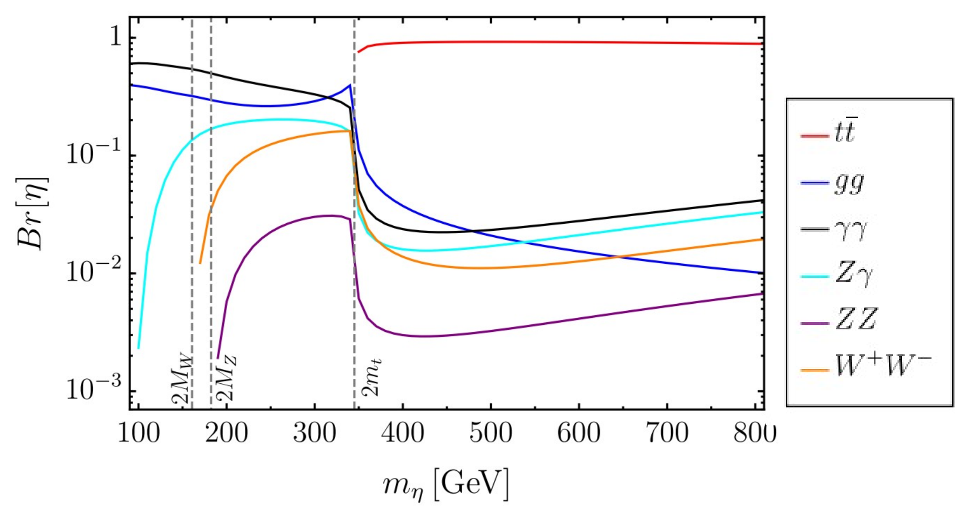


Degenerate states and branching ratios





- Theoretical Challenges:
- Deal with the degenerate states
- One-loop self energy is off-diagonal
- Consider matrix Breit-Wigner propagators
- Large width (10%-20%)



$$\sigma(pp \to \Psi\bar{\Psi} \to X^\alpha X^\beta) \overset{\text{NWA}}{=} N_\Psi \sigma(pp \to \Psi\bar{\Psi}) \mathcal{BR}_2(\Psi\bar{\Psi} \to X^\alpha X^\beta)$$

$$\mathcal{BR}_2(\Psi\bar{\Psi} \to X^\alpha X^\beta) \neq \mathcal{BR}(\Psi \to X^\alpha)\mathcal{BR}(\bar{\Psi} \to X^\beta)$$

Summary

- Aim: bridging the gap between simplified models and concrete models of partial compositeness
- Lots of generic features in the top-partner sector (Ex: mass matrix, spectra)
- Specific models may lead to interesting non-standard search topologies
- Technical challenges involve dealing with nearly degenerate states, large width
- Trying to find a best case scenario for diphoton signal in composite Higgs models

will appear on arXiv soon...

Thank you!