Composite Higgs Models: on Flavor, UV completions and Collider Phenomenology

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C. Delaunay, TF, J. Gonzales-Fraile, S.J. Lee, G. Panico, G. Perez [JHEP 02 (2014) 055]

TF, J.H. Kim, S. J. Lee, S. H. Lim [JHEP 1405, 123]

M. Backović, TF, S. J. Lee, G. Perez [arXiv: 1409.0409]

M. Backović, TF, J. H. Kim, S. J. Lee [JHEP 1504, 082, Phys.Rev. D92 (2015) 011701, arXiv: 1507.06568]

G. Cacciapaga, H. Cai, TF, S. J. Lee, A. Parolini, H. Serodio [JHEP 1506, 085]

G. Cacciapaga, H. Cai, A. Deandrea, TF, S. J. Lee, A. Parolini [arXiv: 1507.02283]

CTPU Workshop 2015, 2015/08/17

Outline

- Motivation and introduction
- Composite Higgs models and flavor
- Towards a UV completion and on its phenomenology

Motivation

☺ Atlas and CMS found a Higgs-like resonance with a mass $m_h \sim 125$ GeV and couplings to $\gamma\gamma$, WW, ZZ, bb, and $\tau\tau$ compatible with the Standard Model (SM) Higgs.

☹ The Standard Model suffers from the hierarchy problem.

$\Rightarrow$ Search for an SM extension with a Higgs-like state which provides an explanation for why $m_h, v \ll M_{pl}$.

One possible solution: Composite Higgs Models (CHM)

- Consider a model which gets strongly coupled at a scale $f \sim \mathcal{O}(1\,\mathrm{TeV})$.
  $\rightarrow$ Naturally obtain $f \lll M_{pl}$.
- Assume a global symmetry which is spontaneously broken by dimensional transmutation $\rightarrow$ strongly coupled resonances at f and Goldstone bosons (to be identified with the Higgs sector).
- Assume that the only source of explicit symmetry breaking arises from Yukawa-type interactions.
  $\rightarrow$ The Higgs-like particles become pseudo-Goldstone bosons
  $\Rightarrow$ Naturally generates a scale hierarchy $v \sim m_h < f \lll M_{pl}$.

Composite Higgs model: general setup

Simplest realization:
The minimal composite Higgs model (MCHM) Agashe, Contino, Pomarol [2004]
Effective field theory based on $SO(5) \to SO(4)$ global symmetry breaking.

- The Goldstone bosons live in $SO(5)/SO(4) \to 4$ d.o.f.
- $SO(4) \simeq SU(2)_L \times SU(2)_R$
  Gauging $SU(2)_L$ yields an $SU(2)_L$ Goldstone doublet.
  Gauging T^3_R assigns hyper charge to it. Later: Include a global $U(1)_X$ and gauge $Y = T^3_R + X$.
  $\Rightarrow$ Correct quantum numbers for the Goldstone bosons
  to be identified as a non-linear realization of the Higgs doublet.

How to include quarks and quark masses?
One solution Kaplan [1991]: Include elementary fermions q as incomplete linear representations of $SO(5)$ which couple to the strong sector via

$$\mathcal{L}_{mix} = y\overline{q}_{I_\mathcal{O}}\mathcal{O}^{I_\mathcal{O}} + \text{h.c.}\,,$$

where $\mathcal{O}$ is an operator of the strongly coupled theory in the representation $I_\mathcal{O}$.
Note: The Goldstone matrix $U(\Pi)$ transforms non-linearly under $SO(5)$, but linearly under the $SO(4)$ subgroup $\to \mathcal{O}^{I_\mathcal{O}}$ has the form $f(U(\Pi))\mathcal{O}'_{fermion}$.

Simplest choice for quark embedding:

$$q_L^5 = \frac{1}{\sqrt{2}} \begin{pmatrix} id_L \\ d_L \\ iu_L \\ -u_L \\ 0 \end{pmatrix}, \quad u_R^5 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ u_R \end{pmatrix}, \quad \psi = \begin{pmatrix} Q \\ \tilde{U} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} iD - iX_{5/3} \\ D + X_{5/3} \\ iU + iX_{2/3} \\ -U + X_{2/3} \\ \sqrt{2}\tilde{U} \end{pmatrix}.$$

BSM particle content (per u-type quark):

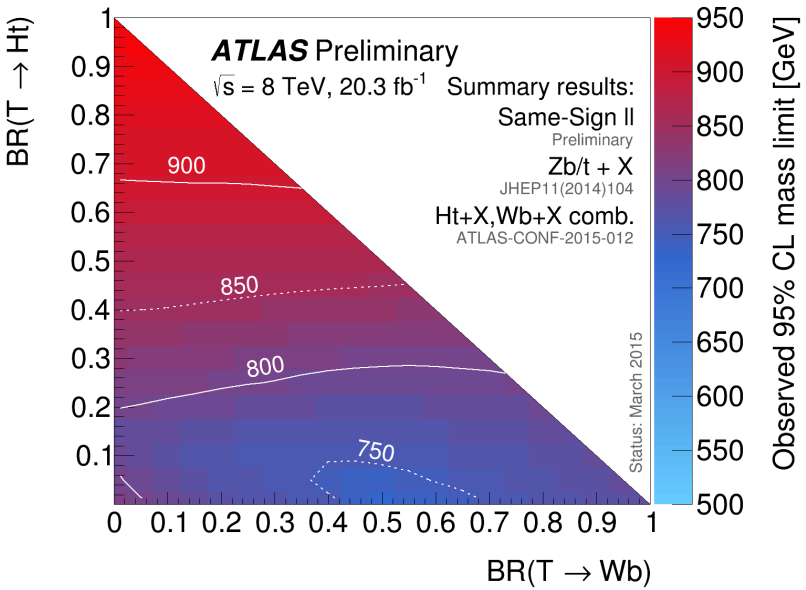
	U	$X_{2/3}$	D	$X_{5/3}$	$\tilde{U}$
$SO(4)$	**4**	**4**	**4**	**4**	**1**
$SU(3)_c$	**3**	**3**	**3**	**3**	**3**
$U(1)_X$ charge	$2/3$	$2/3$	$2/3$	$2/3$	$2/3$
EM charge	$2/3$	$2/3$	$-1/3$	$5/3$	$2/3$

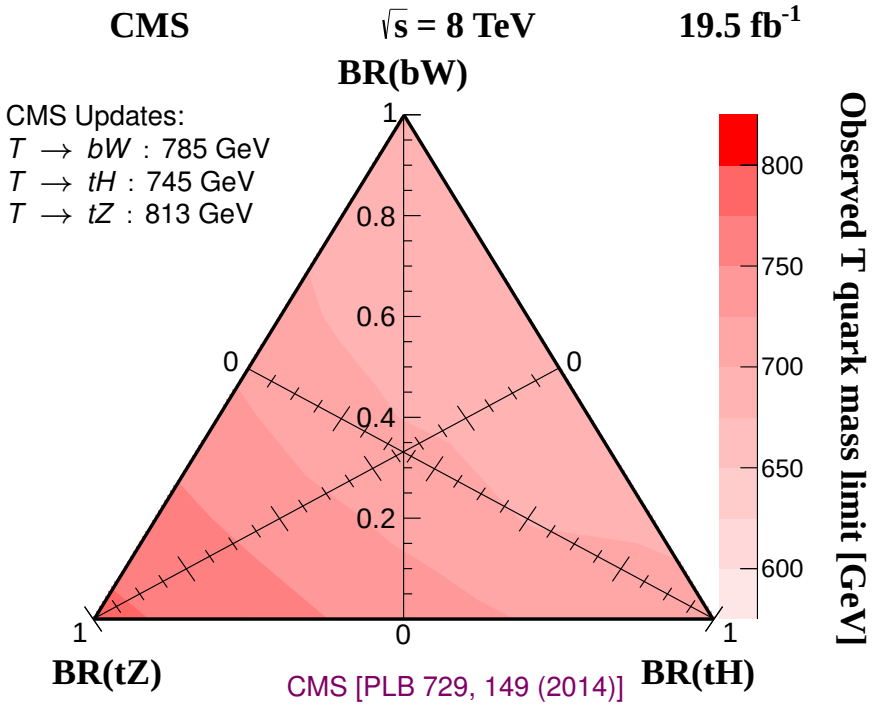
Fermion Lagrangian:

$$\begin{aligned} \mathcal{L}_{comp} &= i\,\overline{Q}(D_\mu + ie_\mu)\gamma^\mu Q + i\overline{\tilde{U}}\not{D}\tilde{U} - M_4\overline{Q}Q - M_1\overline{\tilde{U}}\tilde{U} + \left(ic\overline{Q}^i\gamma^\mu d_\mu^i\tilde{U} + \text{h.c.}\right), \\ \mathcal{L}_{el,mix} &= i\,\overline{q}_L\not{D}q_L + i\,\overline{u}_R\not{D}u_R - y_L f\overline{q}_L^5 U_{gs}\psi_R - y_R f\overline{u}_R^5 U_{gs}\psi_L + \text{h.c.} \end{aligned}$$

Bounds on top partners from Run I

- Searches for partners of light quarks yield bounds of $M \gtrsim 500 - 600\,\text{GeV}$.
  Delaunay, TF, Gonzales-Fraile, S.J. Lee, Panico, Perez [JHEP 02 (2014) 055]
- ATLAS and CMS determined bounds on (QCD) pair-produced top partners with charge $5/3$ (the $X_{5/3}$) in the same-sign di-lepton channel.
  $M_{X_{5/3}} > 770\,\text{GeV}$ ATLAS [JHEP 1411 (2014) 104] , $M_{X_{5/3}} > 800\,\text{GeV}$ CMS [PRL 112 (2014) 171801]
- ATLAS and CMS determined a bound on (QCD) pair-produced top partners with charge $2/3$ (applicable for the T_s, T_{f1}, T_{f2}). [Similar bounds for B]





CMS [PLB 729, 149 (2014)]

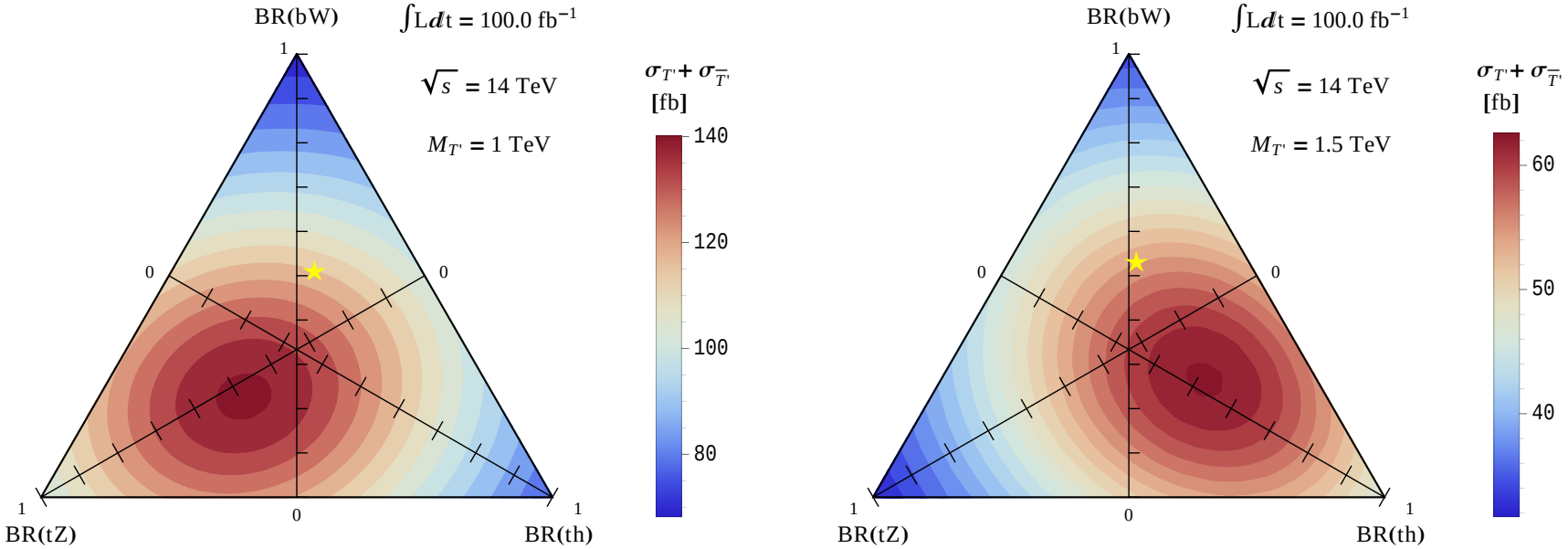
Prospects for composite quark partner searches at LHC Run II

- More energy ⇒ searches are sensitive to higher quark partner masses.
- Single-production channels (if present) will become more important as compared to QCD pair production channels.
- For heavier quark partners, their decay products become strongly boosted.

⇒ LHC Run I search strategies and channels need to be re-analyzed refined.

M. Backović, TF, S. J. Lee, G. Perez [arXiv: 1409.0409],
M. Backović, TF, J. H. Kim, S. J. Lee [JHEP 1504, 082, Phys.Rev. D92 (2015) 011701, arXiv: 1507.06568]

c.f. talk by Jeong Han Kim on Tuesday (16:30).



Expected discovery reach for a T' with mass of 1 TeV (left) and 1.5 TeV (right) in terms of T' production cross section for the LHC at 14 TeV with 100 fb^{-1} of data.

M. Backović, TF, J. H. Kim, S. J. Lee [arXiv: 1507.06568]

Composite Higgs models and flavor

Why is flavor a problem in CHM?
The Lagrangian up-sector Lagrangian (for Q, q, t in **5**)

$$\begin{aligned}\mathcal{L}_{comp} =& i\overline{Q}_{L,R}\left(D+E\right)Q_{L,R} + i\overline{\tilde{T}}_{L,R}D\tilde{T}_{L,R} - M_4\left(\overline{Q}_L Q_R + \overline{Q}_R Q_L\right)\\ &- M_1\left(\overline{\tilde{T}}_L\tilde{T}_R + \overline{\tilde{T}}_R\tilde{T}_L\right) + ic_L\overline{Q}^i_L\gamma^\mu d^i_\mu\tilde{T}_L + ic_R\overline{Q}^i_R\gamma^\mu d^i_\mu\tilde{T}_R + \text{h.c.}\\ -\mathcal{L}_{mix} =& y_{L4,1}f\overline{q}^5_{3L}U\psi_R + y_{R4,1}f\overline{t}^5_R U\psi_L + \text{h.c.}\\ =& y_{L4}f\left(\overline{b}_L B_R + c^2_{\theta/2}\overline{t}_L T_R + s^2_{\theta/2}\overline{t}_L X_{2/3R}\right) - \frac{y_{L1}f}{\sqrt{2}}s_\theta\overline{t}_L\tilde{T}_R\\ &+ y_{R4}f\left(\frac{s_\theta}{\sqrt{2}}\overline{t}_R T_L - \frac{s_\theta}{\sqrt{2}}\overline{t}_R X_{2/3L}\right) + y_{R1}fc_\theta\overline{t}_R\tilde{T}_L + h.c.\,,\end{aligned}$$

(where $\theta = \frac{h+\langle h\rangle}{f}$).
...plus a similar down-sector lagrangian
... plus additional composite resonances (scalars, vectors, ...).
All quarks obtain mass from PC $\Rightarrow$ promote all M, y, c to matrices in flavor space.
$\Rightarrow$ many (!!) angles and phases $\Rightarrow$ FCNCs from Z, h, and resonance exchange.

Composite Higgs models and flavor

First solution: Minimally Flavor violating composite Higgs setup.

Redi, Weiler [JHEP 1111 (2011) 108]

- Assume fully flavor symmetric strong sector.
- Assume $\lambda_R \propto \mathbb{1}$.
- Adjust λ_L to reproduce quark masses and CKM matrix.

This produces a scenario in which RH quarks are mostly composite, and all quark partners have similar mass.
Other solutions:

- Avoid large FCNC's by postulating flavor symmetries on all (or only the light) families Barbieri *et al.* [JHEP 1207,181], Niehoff, Stangl, Straub [arXiv:1508.00569]
- "RS / 5D inspired" *c.f. e.g.* Csaki etal. [JHEP 0804, 006 (2008)], Csaki, Falkowski, Weiler [JHEP 0809, 008], Csaki, Perez, Surujon, Weiler [PRD81 (2010) 075025

All these approaches yield partners to all quarks at a similar scale.

Question: Can a model with only 3rd generation partners pass flavor bounds?

The setup

- Realize one up-type quark ("the top") as partially composite.
- Realize one down-type quark ("the bottom") as partially composite.
  [One economic way: Embed the b_R into 14. This allows PC mixing term:

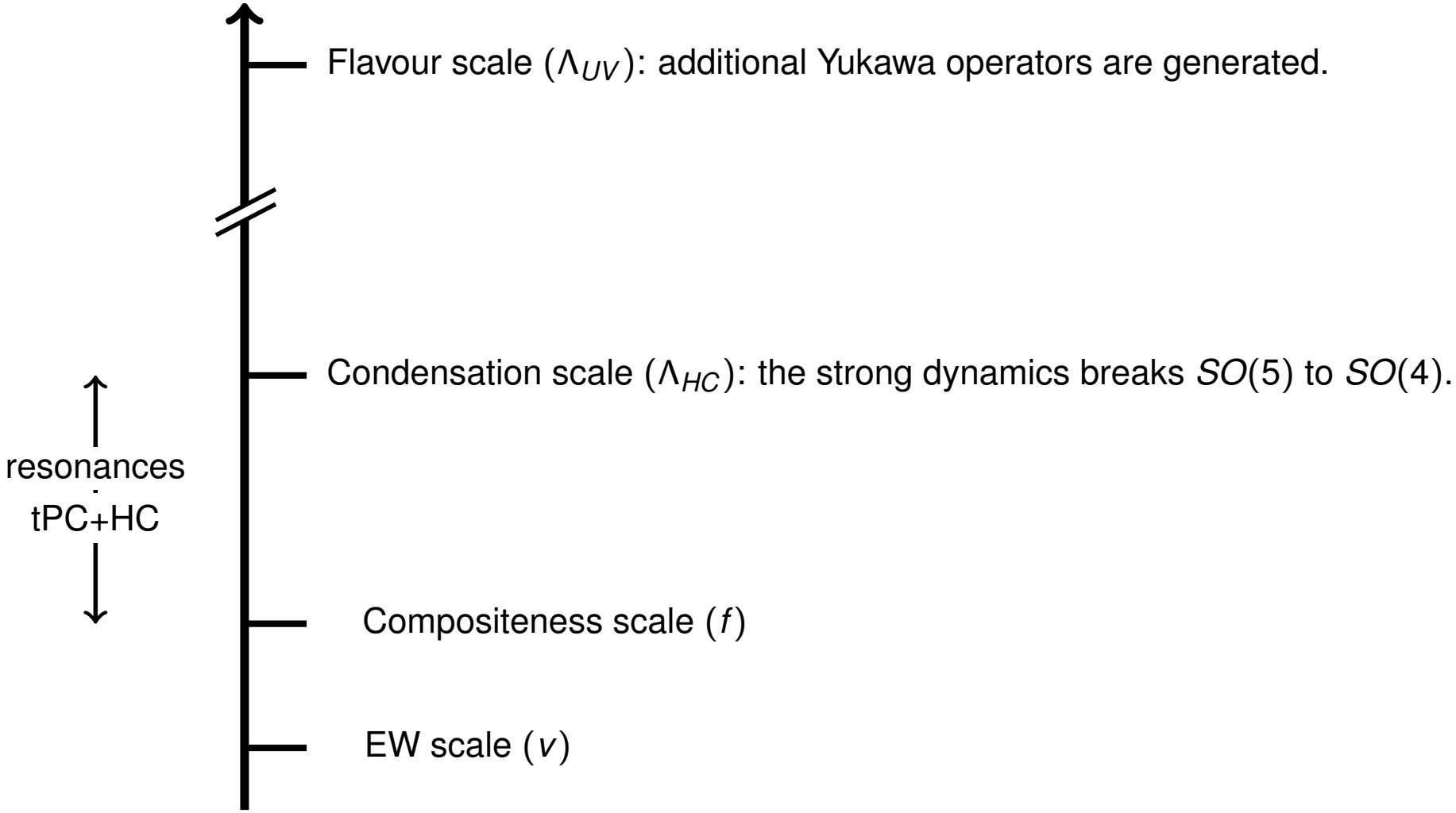
$$\mathcal{L} = y_R f \overline{\psi}_L U^t d_{3R}^{14} \Sigma + h.c. = \frac{1}{2} y_R f s_\theta \overline{B}_L b_R + h.c. .$$

  where $\Sigma = U \cdot (0,0,0,0,1)^T$.]
- Assume that new high-scale physics ($\sim 10^5\,\mathrm{TeV}$) induces "light" masses for quark bilinears (mass à la technicolor):

$$\begin{aligned}
\mathcal{L}_Y &= \overline{q}_{L,\alpha} \lambda^u_{\alpha,\beta} u_{R,\beta}\, \mathcal{O}_u + \overline{\tilde{q}}_{L,\alpha} \lambda^d_{\alpha,\beta} d_{R\beta}\, \mathcal{O}_d + h.c. \\
&\to \sqrt{2}\, (\overline{q}_{\alpha L}{}^5 \Sigma) m^u_{\mathrm{UV}\alpha\beta} (\Sigma^T u^5_{\beta R}) + \sqrt{2}\, (\overline{\tilde{q}}^5_{\alpha L} \Sigma) m^d_{\mathrm{UV}\alpha\beta} (\Sigma^T d^5_{\beta R}) + h.c. \\
&= \frac{s_{2\theta}}{2} \left[\overline{u}_{\alpha L} m^u_{\mathrm{UV}\alpha\beta} u_{\beta R} + \overline{d}_{\alpha L} m^d_{\mathrm{UV}\alpha\beta} d_{\beta R} \right] + h.c.
\end{aligned}$$

  where $\tilde{m}^{u,d}_{\alpha\beta} \equiv s_{2\epsilon} m^{u,d}_{\mathrm{UV}} \sim O(m_c, m_s)$.

The setup


Flavour scale (Λ_{UV}): additional Yukawa operators are generated.
Condensation scale (Λ_{HC}): the strong dynamics breaks $SO(5)$ to $SO(4)$.
resonances
tPC+HC
Compositeness scale (f)
EW scale (v)

Such a setup yields mass matrices

$$M_{\rm up} = \begin{pmatrix} \tilde{m}[\epsilon]_{11} & \tilde{m}[\epsilon]_{12} & \tilde{m}[\epsilon]_{13} & 0 & 0 & 0 \\ \tilde{m}[\epsilon]_{21} & \tilde{m}[\epsilon]_{22} & \tilde{m}[\epsilon]_{23} & 0 & 0 & 0 \\ \tilde{m}[\epsilon]_{31} & \tilde{m}[\epsilon]_{32} & \tilde{m}[\epsilon]_{33} & f y_{L4} \cos^2 \frac{\epsilon}{2} & f y_{L4} \sin^2 \frac{\epsilon}{2} & -f \frac{y_{L1}}{\sqrt{2}} \sin \epsilon \\ 0 & 0 & f \frac{y_{R4}^*}{\sqrt{2}} \sin \epsilon & M_4 & 0 & 0 \\ 0 & 0 & -f \frac{y_{R4}^*}{\sqrt{2}} \sin \epsilon & 0 & M_4 & 0 \\ 0 & 0 & f y_{R1}^* \cos \epsilon & 0 & 0 & M_1 \end{pmatrix}.$$

and Yukawa matrices

$$Y_{\rm up}^{mix} = \begin{pmatrix} \tilde{y}[\epsilon]_{11} & \tilde{y}[\epsilon]_{12} & \tilde{y}[\epsilon]_{13} & 0 & 0 & 0 \\ \tilde{y}[\epsilon]_{21} & \tilde{y}[\epsilon]_{22} & \tilde{y}[\epsilon]_{23} & 0 & 0 & 0 \\ \tilde{y}[\epsilon]_{31} & \tilde{y}[\epsilon]_{32} & \tilde{y}[\epsilon]_{33} & -\frac{y_{L4}}{2} \sin \epsilon & \frac{y_{L4}}{2} \sin \epsilon & -\frac{y_{L1}}{\sqrt{2}} \cos \epsilon \\ 0 & 0 & \frac{y_{R4}^*}{\sqrt{2}} \cos \epsilon & 0 & 0 & 0 \\ 0 & 0 & -\frac{y_{R4}^*}{\sqrt{2}} \cos \epsilon & 0 & 0 & 0 \\ 0 & 0 & -y_{R1}^* \sin \epsilon & 0 & 0 & 0 \end{pmatrix},$$

where $\tilde{y}[\epsilon]_{\alpha\beta} \equiv c_{2\epsilon} \frac{m^u_{{\rm UV}\alpha\beta}}{f}$ (and analogous for the down-sector).

Block-diagonalizing the mass matrix yields:

$$\begin{aligned} m_U &\simeq \frac{s_{2\epsilon}}{2} m^u_{\rm UV} + m_t \delta_{33} \\ y_u &\simeq \frac{m_U}{f s_{2\epsilon}/2}\left(1 - \frac{1}{2} s^2_{2\epsilon}\right) + B_u\,, \quad \text{where} \quad B_u \sim \frac{\Sigma_u}{M_*^2}\,, \end{aligned}$$

with

$$\Sigma_u \sim \begin{pmatrix} m_c^2 & m_c^2 & m_c m_t \\ m_c^2 & m_c^2 & m_c m_t \\ m_c m_t & m_c m_t & m_t^2 \end{pmatrix}.$$

...and analogous for the down-type sector.
Charged and neutral currents are also proportional to $B_{u,d}$.
Finally, diagonalizing the light sector fully yields

$$m_U = V_{uL} M_U^{diag} V_{uR}^\dagger \quad \text{where} \quad V_{uL,R} \sim \begin{pmatrix} O(1) & O(1) & O(\frac{m_c}{m_t}) \\ O(1) & O(1) & O(\frac{m_c}{m_t}) \\ O(\frac{m_c}{m_t}) & O(\frac{m_c}{m_t}) & 1 \end{pmatrix}.$$

Key point: Flavor changing observables with light quarks are suppressed by additional powers of m_c/m_t and/or m_s/m_b as compared to the "standard " calculation.

One can go through the standard list of constraints. We looked at

- effects from h, Z, W exchange,
- effects from heavy resonance exchange,
- UV contributions from heavy flavor scale physics

on

- $Z \to b\bar{b}$,
- CKM unitarity,
- $\Delta F = 2$ FCNCs,
- $\Delta F = 1$ FCNCs.

Resulting bounds on V_{dL} (setting $V_{uR,L}$ to the values from above)

$$\begin{aligned}
\text{Z boson FCNCs} \quad &\Rightarrow \quad |V^*_{dL33} V_{dL13}| < 10^{-1}\,, \ |V^*_{dL33} V_{dL23}| < 10^{-1/2}\,, \ |V^*_{dL13} V_{dL23}| < 10^{-5/2}\,, \\
\text{CKM unitarity} \quad &\Rightarrow \quad |V_{dL13}| < 10^{-1}\,, \quad |V_{dL23}| < 10^{-1/2}\,, \\
\text{Scalar resonance} \quad &\Rightarrow \quad |z_4^{db}| < 1 \div 10^{-2}\,, \quad |z_4^{sb}| < 1 \div 10^{-1/2}\,, \quad |z_4^{ds}| < 10^{-4} \div 10^{-6}\,, \\
\text{Vector resonance} \quad &\Rightarrow \quad |V^*_{dL33} V_{dL31}| < 10^{-1} \div 10^{-3}\,, \quad |V^*_{dL33} V_{dL32}| < 1 \div 10^{-2}\,, \\
&\qquad |V^*_{dL32} V_{dL31}| < 10^{-3} \div 10^{-5}\,.
\end{aligned}$$

where

$$z_4^{d_\alpha d_\beta} = V^*_{dL3\alpha} V_{dL3\beta} \sum_{\gamma\delta} V_{dR\gamma\beta} V^*_{dR\delta\alpha}\,.$$

... in good accord with m_s/m_b suppressions in expected form of V_{dL}.

Problems:

- To fully reproduce the CKM matrix, the UV flavor scale mass matrix needs to be specified.
- Neutron EDM (requires knowledge of UV flavor scale mass matrix).

Virtues:

- We looked at generalizations to other quark and quark partner embeddings into $SO(5)$, and find that the key point (suppression of FCNCs by powers of m_c/m_t) occurs for generic quark embeddings.
- We looked at generalizations to larger cosets. The suppressions mainly depend on the $SU(2) \times U(1)$ quantum numbers of the partners. Therefore the concept still applies. The only thing that needs to be checked individually: Interactions with / FCNCs from additional Goldstone Bosons.

Towards a CH UV completion and its (new) phenomenology

So far we discussed composite Higgs models in terms of a low-energy EFT.

Are there candidates for a UV completion (and what is the confining group, what are the Higgs and quark partner constituents ("preons"))?

Ferretti, Karateev [JHEP 1403 (2014) 077] classified candidate models which

- contain only fermions,
- have a simple hyper-color group G_{HC},
- have a Higgs candidate amongst its Goldstone bosons,
- have a top partner candidate amongst its bound states,
- satisfy other consistency conditions (asymptotic freedom, no anomalies, ...),
- (no SM gauge group Landau pole near the EW scale).

...they find only few models satisfying this wish-list, with the minimal co-sets $SU(5)/SO(5)$ or $SU(4)/Sp(4) \simeq SO(6)/SO(5)$ c.f. Barnard, Gherghetta, Ray [JHEP 1402 (2014) 002].

The model: SU(4)/Sp(4) coset based on $G_{\rm HC} = \mathrm{Sp}(2N_c)$

Field content of the microscopic fundamental theory and property transformation under the gauged symmetry group $Sp(2N_c) \times SU(3)_c \times SU(2)_L \times U(1)_Y$, and under the global symmetries $SU(4) \times SU(6) \times U(1)$.

	$\mathrm{Sp}(2N_c)$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	SU(4)	SU(6)	U(1)
Q_1 Q_2	$\square$	**1**	**2**	0	**4**	**1**	$-\frac{6N_c}{2N_c+1} q_\chi$
Q_3	$\square$	**1**	**1**	$1/2$			
Q_4	$\square$	**1**	**1**	$-1/2$			
χ_1 χ_2 χ_3	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	**3**	**1**	x	**1**	**6**	q_χ
χ_4 χ_5 χ_6	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\overline{\mathbf{3}}$	**1**	$-x$			

The model: SU(4)/Sp(4) coset based on $G_{\rm HC} = {\rm Sp}(2N_c)$

Bound states of the model with spin and group properties with respect to the global flavour group and the unbroken subgroups.

	spin	SU(4)×SU(6)	Sp(4)×SO(6)	names
QQ	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
χQQ	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_1^1 ψ_1^5
$\chi\overline{Q}\overline{Q}$	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_2^1 ψ_2^5
$Q\overline{\chi}\overline{Q}$	1/2	$(\mathbf{1},\overline{\mathbf{6}})$	$(\mathbf{1},\mathbf{6})$	ψ_3
$Q\overline{\chi}\overline{Q}$	1/2	$(\mathbf{15},\overline{\mathbf{6}})$	$(\mathbf{5},\mathbf{6})$ $(\mathbf{10},\mathbf{6})$	ψ_4^5 ψ_4^{10}
$\overline{Q}\sigma^\mu Q$	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

The model: $SU(4)/Sp(4)$ coset based on $G_{\rm HC} = {\rm Sp}(2N_c)$

Key-observations:

- Before gauging $SU(3)_c$ the model exhibits an $SU(6)$ global symmetry which is broken to $SO(6)$ by the condensate $\langle\chi\chi\rangle$, leading to $35 - 15 = 20$ colored Goldstone bosons $\pi_c = (\mathbf{8},\mathbf{1},\mathbf{1})_0 \oplus (\mathbf{6},\mathbf{1},\mathbf{1})_{2x} \oplus (\overline{\mathbf{6}},\mathbf{1},\mathbf{1})_{-2x}$.
- The global $SU(6)$ is explicitly broken by gauging $SU(3)_c$, couplings to the top, and an overall $SU(6)$ breaking (but $SO(6)$ preserving) mass term. The former two induce a (small) mass splitting between π_6 and π_8.
- As π_6 and π_8 are pseudo-Goldstone bosons, they are expected to be the lighter than other bound states (vector-resonances, top-partners).

Upshot:

- The "wish-list" strongly constrains potential UV completions in terms of the hyper-color gauge group and the global symmetry group breaking pattern.
- The model under consideration ($SU(4)/Sp(4)$ coset based on $G_{\rm HC} = Sp(2N_c)$) predicts additional light states which can affect the LHC phenomenology of composite Higgs models with a perspective for a UV completion.

Effective description and phenomenology

With the gained insight on the $SU(4)/Sp(4)$ coset based on $G_{\rm HC} = Sp(2N_c)$), we set up an effective model to describe novel aspects of its LHC phenomenology.

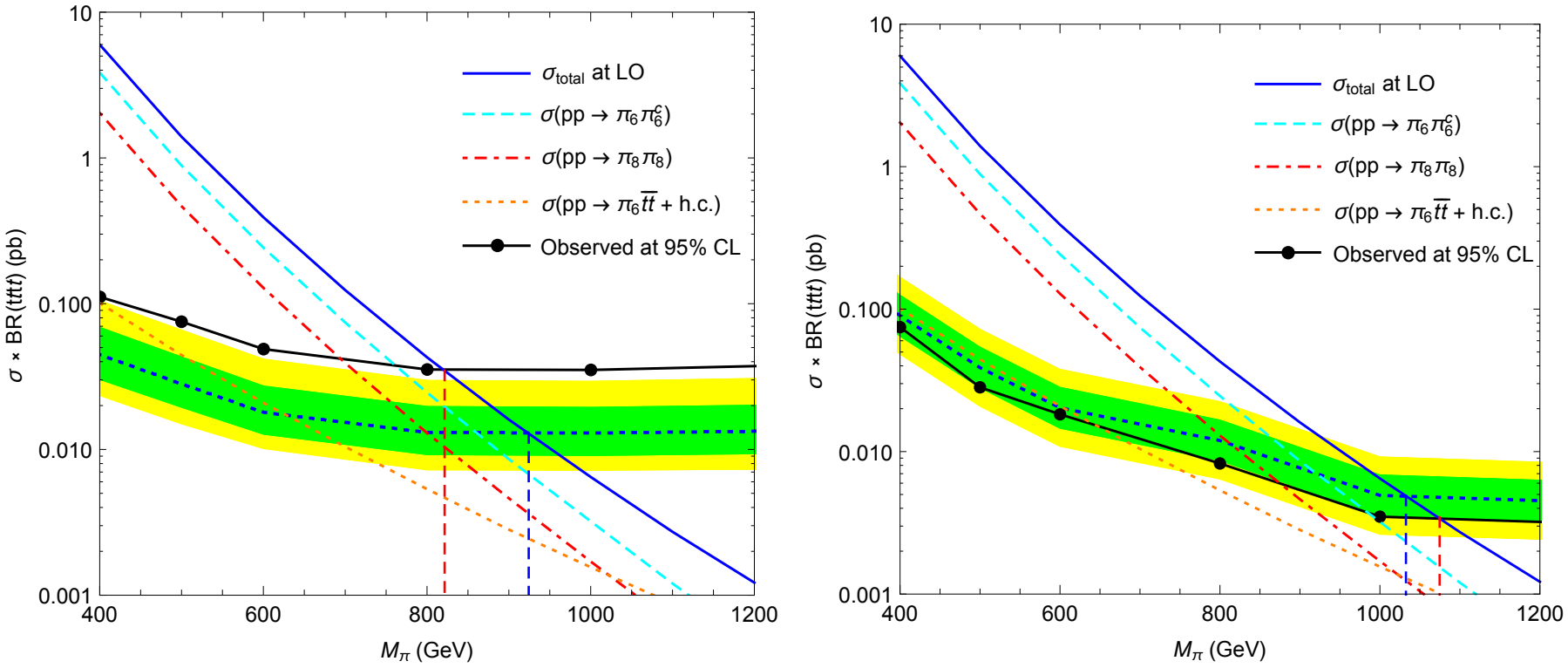
$$\begin{aligned}\mathcal{L}_{eff} &= |D_\mu \pi_6|^2 - m^2_{\pi_6}|\pi_6|^2 + \frac{1}{2}(D_\mu \pi_8)^2 - \frac{1}{2}m^2_{\pi_8}(\pi_8)^2 - V_{\rm scalar}(\pi_6, \pi_8) \\ &\quad + a_R\, \pi_6 t^c_R t^c_R + a_L\, \pi^c_6 t_L t_L + b\, \pi_8 t^c_R t_L + h.c.,\end{aligned}$$

The coupling term $\propto a_R$ is gauge invariant while the terms $\propto a_L, b$ can only be generated via EW symmetry breaking, which implies

$$\frac{a_L}{a_R} \sim \mathcal{O}(v^2/\Lambda^2)\,, \quad \frac{b}{a_R} \sim \mathcal{O}(v/\Lambda)\,.$$

Therefore, the π_6 can be QCD pair produced or single produced via the a_R coupling while π_8 is always dominantly QCD pair produced. π_6 decays to tt while π_8 decays to $t\bar{t}$.
$\Rightarrow$ The model predicts BSM excesses in the $t\bar{t}t\bar{t}$ final state with $t\bar{t}$ and tt resonances.

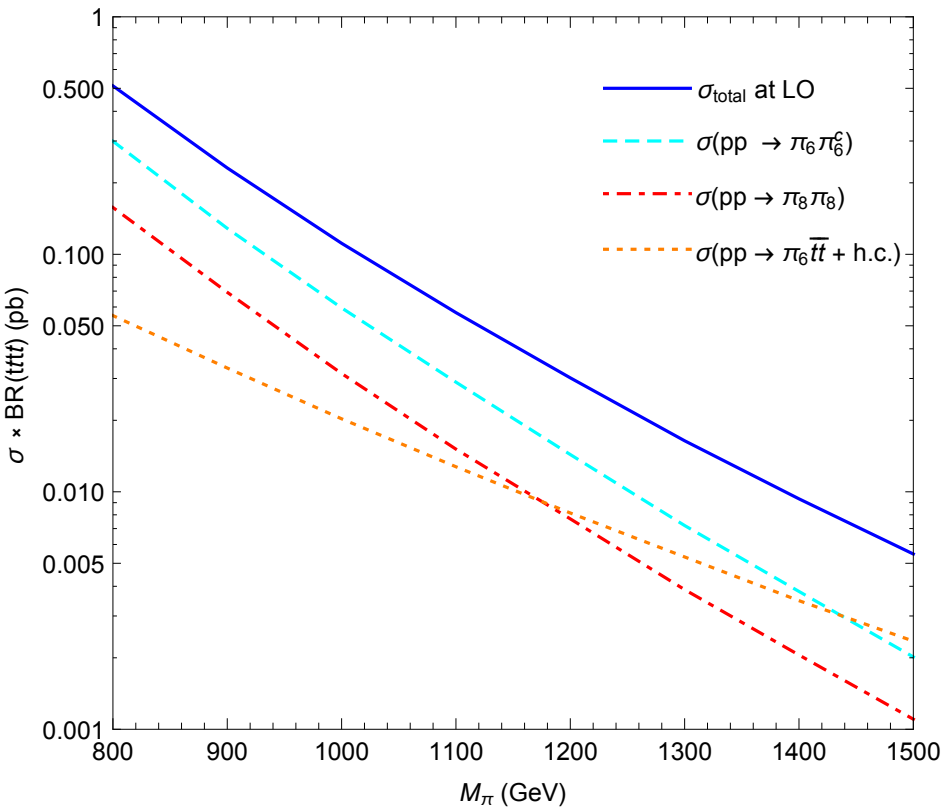
Effective description and phenomenology



G. Cacciapaga, H. Cai, A. Deandrea, TF, S. J. Lee, A. Parolini [arXiv: 1507.02283]

Cross sections for the sextet and octet scalars at the LHC at 8 TeV, with $a_R = 1$. Left panel: comparison with the ATLAS 2SSL search [ATLAS, arXiv:1504.04605], where the green (yellow) band is for 1σ (2σ) expected limit and the solid black curve is the observed limit. Right panel: comparison with the ATLAS 1-lepton search observed limit [ATLAS, arXiv:1505.04306].

Effective description and phenomenology



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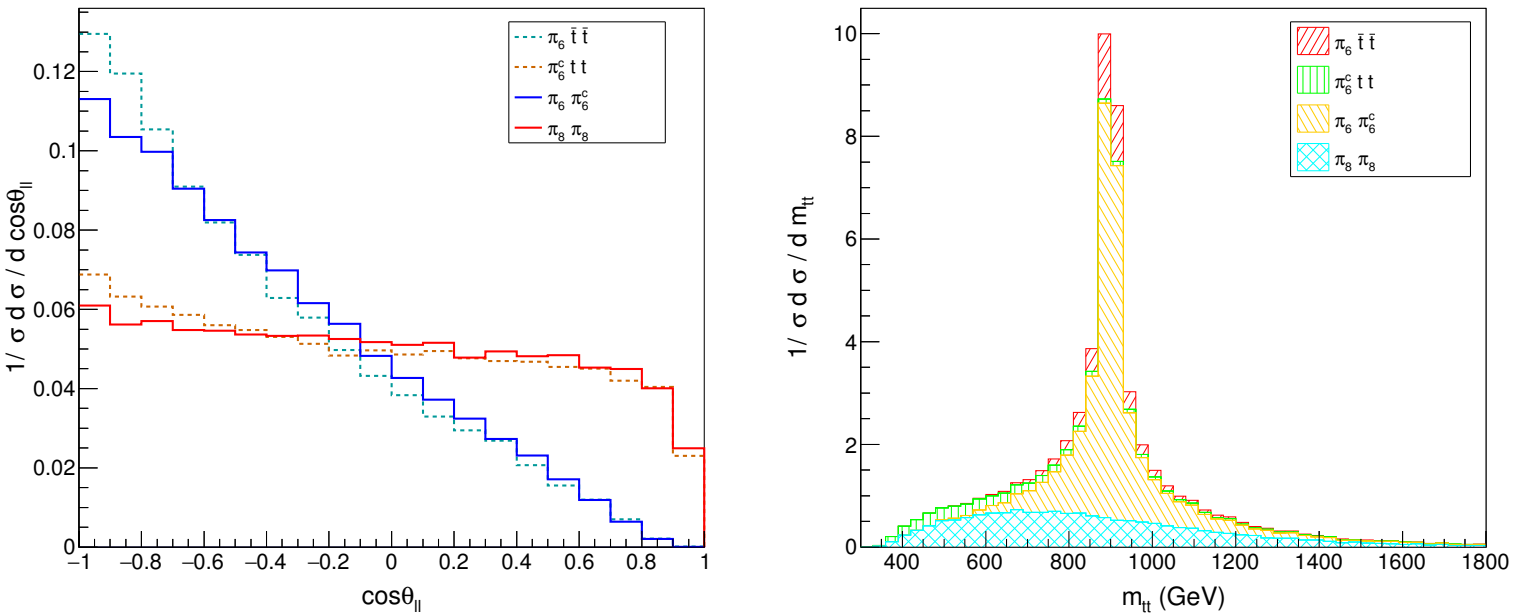
Cross sections for the sextet and octet scalar production at the LHC 13 TeV, with $a_R = 1$.

Effective description and phenomenology

If an excess in the $t\bar{t}t\bar{t}$ same-sign dilepton channel is seen, can π_6 and π_8 resonances be distinguished? Yes!



G. Cacciapaga, H. Cai, A. Deandrea, TF, S. J. Lee, A. Parolini [arXiv: 1507.02283]

- A heavy $\pi_6 \to tt$ resonance yields a large opening angle between the same-sign dileptons, while for a π_8 resonance, the same-sign dileptons are only weakly correlated (left plot).
- Performing an invariant mass reconstruction of the $(l^+\nu b)(l^+\nu b)$ system yields a peak for a π_6 resonance but not for π_8 (right plot).

Conclusions

- Composite Higgs models provide a viable solution to the hierarchy problem. Realizing quark masses via partial compositeness requires quark partners.
- Top partners (in the MCHM) are constraint from Run I to $M_X \gtrsim 800\,\mathrm{GeV}$.
- (Constraints on light quark partners are weaker; only $M_X \gtrsim 525\,\mathrm{GeV}$. For light quark singlet partners, even only $M_X \gtrsim 310\,\mathrm{GeV}$.)
- For Run II, single-production channels and strongly boosted top, W, Higgs, and Z searches become important. (C.f. Jeong Han Kim's talk for dedicated analyses and results for the most promising LHC Run II channels.)
- Flavor physics poses a challenge to composite Higgs models, but several solutions are known. We presented a new solution which requires only partners of third generation quarks at the TeV scale.
- There are first steps towards all-fermionic UV completions of composite Higgs models. Possible hyper-flavor groups and preon content are restricted and have implications for LHC Run II phenomenology as we showed for the example of a model based on a $SU(4)/Sp(4)$ coset with $G_{\mathrm{HC}} = Sp(2N_c)$.