ALPs from Composite Higgs models at the LHCb

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Outline

1. Composite Higgs (CH) and Partial compositeness (PC)
2. Abelian pseudo-Nambu-Goldstone bosons (pNGB) as axion-like particles (ALP)
3. ALPs at the LHCb
4. Conclusion

1-Composite Higgs (CH) and Partial Compositeness (PC)

- Technicolor (TC): 4D confining gauge theory G_{HC} with fermionic matter $\rightarrow$ dynamical EW symmetry breaking (hierarchy problem)

$$\langle\psi\psi\rangle \sim f^3 \rightarrow f = v$$

- Composite Higgs (CH): Vacuum misalignment (Higgs is a pNGB) (Little-hierarchy problem and doublet nature of Higgs)

$$v = f \sin\theta$$

Model example (Gripaios, Pomarol, Riva, Serra 0902.1483):

	Sp(4)	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	SU(4)	SU(6)
$\binom{\psi_1}{\psi_2}$	$\Box$	**1**	**2**	0	**4**	**1**
$\psi_{3,4}$	$\Box$	**1**	**1**	$\pm 1/2$		**1**

Condensation: the raise of electroweak scale and pNGBs

- UV Lagrangian

$$\mathcal{L}_{\rm UV} = \bar{\psi}^I {\rm i}\not{D}\psi^I + \delta\mathcal{L}_m + \delta\mathcal{L}$$

- Global symmetry at quantum level (from kinetic terms) (U(1) is explicitely broken by gauge anomaly)

$$\rm G = SU(4)$$

- Gauge interactions, fermion masses and other interactions might break the global symmetry
- Condensation at scale $\Lambda \sim 4\pi f$

$$\langle \psi^I_{\alpha,c}\psi^J_{\beta,c'}\epsilon^{\alpha\beta}\epsilon^{cc'}\rangle \sim f^3 E^{IJ}_\psi$$

- Spontaneously breaks

$$\rm SU(4) \to Sp(4)$$

- The direction of the vacuum can be parametrized by the vacuum misalignment angle

$$E_\psi = \cos\theta E_\psi^- + \sin\theta E_\psi^{\mathrm{B}}$$

- $E_\psi^\pm$: vacua that leave the EW symmetry intact.
  E_ψ^{B}: vacuum breaking EW symmetry to $\mathrm{SU}(2)_V$ (custodial)
- Effective Lagrangian can be constructed with the pNGB Π_ψ "around" the vacuum

$$\Sigma_\psi = \exp\left[2\sqrt{2}\, i \frac{\Pi_\psi}{f_\psi}\right] E_\psi, \quad \Pi_Q = \sum_{i=1}^{5} \Pi_Q^i X_Q^i\,, \quad h \equiv \Pi_Q^4\,, \quad \eta \equiv \Pi_Q^5$$

$$\mathcal{L}_{\mathrm{eff}} = \frac{f^2}{8} \mathrm{Tr}\,[D_\mu \Sigma_\psi^\dagger D^\mu \Sigma_\psi] - V_{\mathrm{eff}}$$

- Generates hierarchy between compositeness scale f and EW vev v

$$v = f \sin\theta$$

- $\frac{\partial V}{\partial\theta} = 0$, $f \gtrsim 1.2(0.6)$ TeV EWPO (h measurements)

Partial Compositeness

- CH: flavour scale $\Lambda_F > 10^4$ TeV $\gg \Lambda_{TC}$ generates low energy 4-fermion interactions ($Q =$SM fermions, $\psi =$ hyper-fermions)

$$\alpha\frac{\bar\psi\psi\bar\psi\psi}{\Lambda_F^2} + \underbrace{\boxed{\beta\frac{\bar\psi\psi\bar Q Q}{\Lambda_F^2}}}_{\text{ETC}} + \underbrace{\boxed{\kappa\frac{\psi\psi\psi Q}{\Lambda_F^2} + h.c.}}_{\text{PC}} + \underbrace{\boxed{\gamma\frac{\bar Q Q \bar Q Q}{\Lambda_F^2}}}_{\text{FCNC}}$$

  - Extended Technicolor (ETC) (Dimopoulos, Susskind 79, Eichten, Lane 80)
  - Partial Compositeness (PC) (Kaplan 91)
  - Yukawa is NOT the only relevant operator. Enhanced w.r.t. 4-fermion FCNC operators? $\rightarrow$ Walking Technicolor and large anomalous dimension (Holdom 81)

Barnard, Gherghetta, Ray 1311.6562, Ferretti, Karateev 1312.5330

	Sp(4)	SU(3)$_c$	SU(2)$_L$	U(1)$_Y$	SU(4)	SU(6)
$\binom{\psi_1}{\psi_2}$	$\square$	**1**	**2**	0	**4**	**1**
$\psi_{3,4}$	$\square$	**1**	**1**	$\pm 1/2$		**1**
$\chi_{1,2,3}$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	**3**	**1**	$2/3$	**1**	**6**
$\chi_{4,5,6}$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\bar{\mathbf{3}}$	**1**	$-2/3$	**1**	

PC models

Ferretti, Karateev, 13, Cacciapaglia, Ferretti, Flacke, Serôdio 17, 19

Coset	HC	ψ	χ	$-q_\chi/q_\psi$	Baryon	Name	Lattice
$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{SO(6)}$	SO(7)	$5 \times \mathbf{F}$	$6 \times \mathbf{Sp}$	5/6	$\psi\chi\chi$	M1	
	SO(9)			5/12		M2	
	SO(7)	$5 \times \mathbf{Sp}$	$6 \times \mathrm{F}$	5/6	$\psi\psi\chi$	M3	
	SO(9)			5/3		M4	
$\frac{SU(5)}{SO(5)} \times \frac{SU(6)}{Sp(6)}$	Sp(4)	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	5/3	$\psi\chi\chi$	M5	$\surd$
$\frac{SU(5)}{SO(5)} \times \frac{SU(3)^2}{SU(3)}$	SU(4)	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	5/3	$\psi\chi\chi$	M6	$\surd$
	SO(10)	$5 \times \mathbf{F}$	$3 \times (\mathbf{Sp}, \overline{\mathbf{Sp}})$	5/12		M7	
$\frac{SU(4)}{Sp(4)} \times \frac{SU(6)}{SO(6)}$	Sp(4)	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	1/3	$\psi\psi\chi$	M8	$\surd$
	SO(11)	$4 \times \mathbf{Sp}$	$6 \times \mathbf{F}$	8/3		M9	
$\frac{SU(4)^2}{SU(4)} \times \frac{SU(6)}{SO(6)}$	SO(10)	$4 \times (\mathbf{Sp}, \overline{\mathbf{Sp}})$	$6 \times \mathbf{F}$	8/3	$\psi\psi\chi$	M10	
	SU(4)	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	2/3		M11	$\surd$
$\frac{SU(4)^2}{SU(4)} \times \frac{SU(3)^2}{SU(3)}$	SU(5)	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}_2})$	4/9	$\psi\psi\chi$	M12	

pNGBs

- pNGBs π from $\langle\psi\psi\rangle$ condensate gets masses from electroweak loops, hyper-fermion masses and top interactions
  $\rightarrow m_{\pi_c}^2 \sim \mathcal{O}(g^2 f^2, m_t^2, m_\psi f)$
- pNGBs π_c from $\langle\chi\chi\rangle$ condensate gets masses from gluon loops and hyper-fermion masses, $\rightarrow m_{\pi_c}^2 \sim \mathcal{O}(g_s^2 f^2, m_\chi f)$

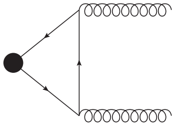
Electro-weak coset	$SU(2)_L \times U(1)_Y$
$SU(5)/SO(5)$	$\mathbf{3}_{\pm 1} + \mathbf{3}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{1}_0$
$SU(4)/Sp(4)$	$\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$
$SU(4) \times SU(4)'/SU(4)_D$	$\mathbf{3}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{2'}_{\pm 1/2} + \mathbf{1}_{\pm 1} + \mathbf{1}_0 + \mathbf{1'}_0$

Color coset	$SU(3)_c \times U(1)_Y$
$SU(6)/SO(6)$	$\mathbf{8}_0 + \mathbf{6}_{(-2/3 \text{ or } 4/3)} + \bar{\mathbf{6}}_{(2/3 \text{ or } -4/3)}$
$SU(6)/Sp(6)$	$\mathbf{8}_0 + \mathbf{3}_{2/3} + \bar{\mathbf{3}}_{-2/3}$
$SU(3) \times SU(3)'/SU(3)_D$	$\mathbf{8}_0$

2 - Abelian pNGBs as axion like particles (ALP)

(Belyaev, Cacciapaglia, Cai, Ferretti, Flacke, Parolini, Serodio 16')

- In the PC models, 2 hyper-fermion representations. Full symmetry: $G \times G' \times \mathrm{U}(1)^2$. Example model M8: $\mathrm{U}(4) \times \mathrm{U}(6) \equiv \mathrm{SU}(4) \times \mathrm{SU}(6) \times \mathrm{U}(1) \times \mathrm{U}(1)$.
- Only one U(1) is anomaly-free.



$$\sim q_\psi N_\psi T(\psi) + q_\chi N_\chi T(\chi) = 0$$

- Masses from hyper-fermion current mass and anomaly generated mass

$$-\mathcal{L} \supset \frac{1}{2}\left(m_{a_\psi}^2 a_\psi^2 + m_{a_\chi}^2 a_\chi^2 + m_{anomaly}^2 a_{anomaly}^2 \right)$$

$$a_{anomaly} = \cos\zeta a_\chi - \sin\zeta a_\psi, \quad \tan\zeta = \frac{q_\chi f_{a_\chi}}{q_\psi f_{a_\psi}}, \quad f_{a_r} = \sqrt{N_r} f_r$$

Coupling to fermions and bosons

- Top quark mass via PC

$$\mathcal{L} \supset y_L \bar{q}_L \Psi_{q_L} + y_R \Psi_{t_R} t_R + \text{h.c.}, \quad \Psi \sim \psi\psi\chi \text{ or } \psi\chi\chi$$

$$\xrightarrow{\text{condensation}} m_{top} \bar{t}t + i \left(n_\psi \frac{a_\psi}{f_{a_\psi}} + n_\chi \frac{a_\chi}{f_{a_\chi}} \right) \bar{t}t + \cdots$$

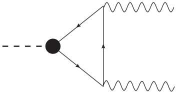
- Other fermions (f) masses via bilinear

$$\mathcal{L} \supset \frac{y}{\Lambda_F^2} \bar{f} f \bar{\psi}\psi \xrightarrow{\text{condensation}} m_f \bar{f} f + 2i \frac{m_f}{f_{a_\psi}} a_\psi \bar{f} \gamma_5 f + \cdots$$

- Bosons (WZW terms)

$$\mathcal{L} \supset \frac{K_{AA',r}}{16\pi^2 f} A^{\mu\nu,a} \widetilde{A'}^a_{\mu\nu} a_r$$

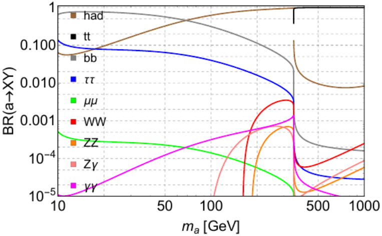
$$A, A' = B, W, g, \; r = \psi, \chi, \; K_{AA',r} = g_A g_{A'} d_r \text{Tr}\left[S^A, S^{A'}\right]$$

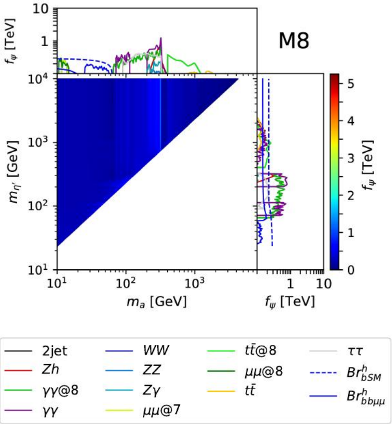


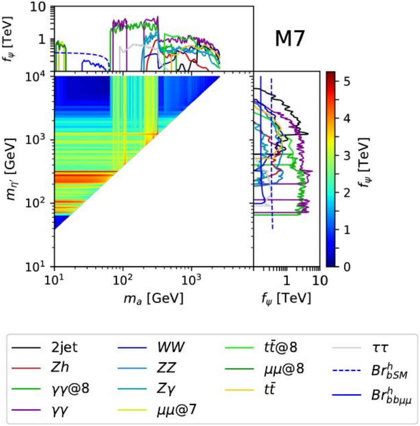
Searches

Cacciapaglia, Ferretti, Flacke, Serôdio 19'

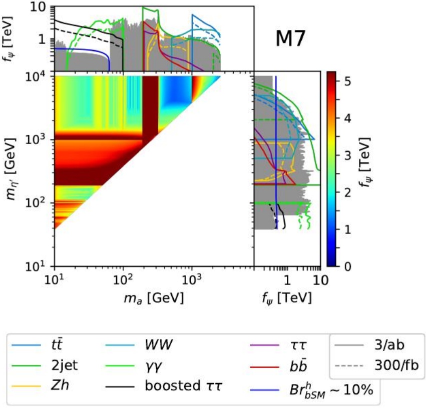
Production via gluon fusion and prompt decay.







M7
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
2jet
Zh
γγ@8
γγ
WW
ZZ
Zγ
μμ@7
$t\bar{t}$@8
μμ@8
$t\bar{t}$
ττ
Br^h_{bSM}
$Br^h_{bb\mu\mu}$



M7
f_ψ [TeV]
$m_{\eta'}$ [GeV]
m_a [GeV]
$t\bar{t}$
2jet
Zh
WW
γγ
boosted ττ
ττ
$b\bar{b}$
$Br^h_{bSM} \sim 10\%$
3/ab
300/fb

Composite Dark Matter

Alanne, DBF, Frandsen, Rosenlyst 18'

	Sp(4)	SU(3)$_c$	SU(2)$_L$	U(1)$_Y$
$\binom{\psi_1}{\psi_2}$	$\square$	**1**	**2**	0
$\psi_{3,4}$	$\square$	**1**	**1**	$\pm 1/2$
$\chi_{1,2,3}$	$\begin{array}{c}\square\\\square\end{array}$	**3**	**1**	$2/3$
$\chi_{4,5,6}$	$\begin{array}{c}\square\\\square\end{array}$	$\bar{\mathbf{3}}$	**1**	$-2/3$
$\lambda_{\rm L}$	Adj	**1**	**1**	0
$\widetilde{\lambda}_{\rm L}$	Adj	**1**	**1**	0

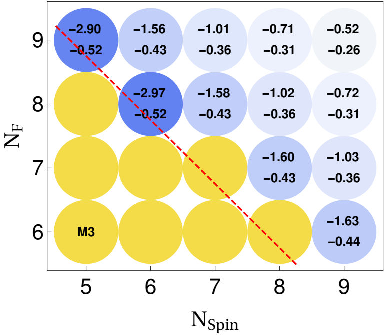
- Two non-anomalous light abelian states!

$$q_Q T(F) + q_\chi T(A_2) + q_\lambda T(G) = 0 \Rightarrow q_\lambda = -\frac{1}{3} q_Q - q_\chi \,.$$

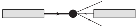
- with weaker diluted couplings due to the inert components.

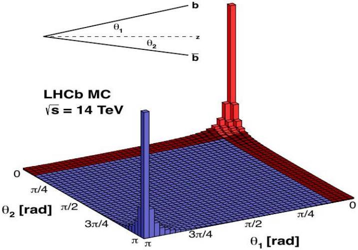
Conformal window and large anomalous dimension

DBF, Ferretti 19'



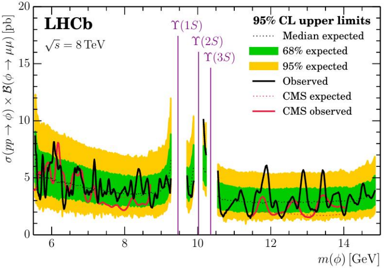
- PC needs large anomalous dimensions of the top partner operators in near conformal dynamics,
- which requires increasing the matter content.
- Has an effect on the abelian bosons, diluting couplings and changing the ratio charge q_ψ/q_χ.

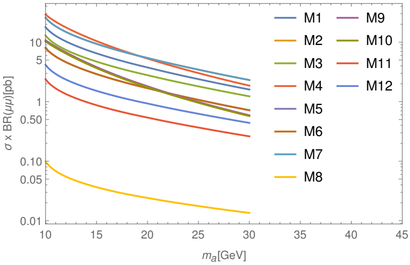
Low mass systems are naturally boosted at the LHC due to the parton distribution functions 

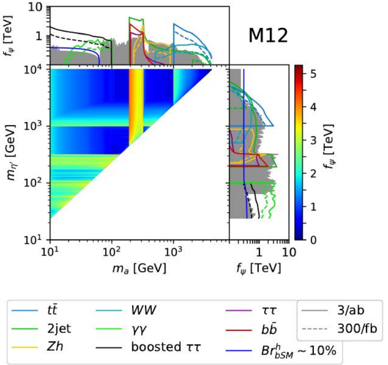


Competitive to CMS and ATLAS

LHCb 1805.09820, CMS 1206.6326



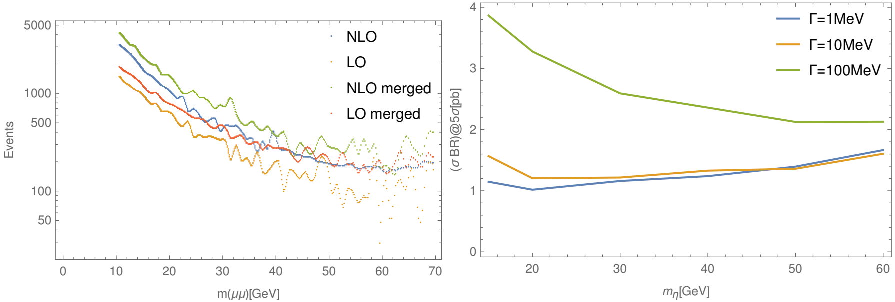




- Goal is to include low mass LHCb exclusion (also more precise),
  On-going work/discussion in progress with Cacciapaglia, Flacke, Ferretti, Vázquez Sierra, Vidal, ...

$$2 < |\eta(\mu^\pm)| < 4.5 \quad p_T(\mu^\pm) > 1\,\text{GeV}$$
$$p(\mu^\pm) > 20\,\text{GeV} \quad \max(p_T(\mu^+), p_T(\mu^-) > 1.8\,\text{GeV}$$

$L = 1.6\text{fb}^{-1}$



- Drell-Yan (background) aMC@NLO+FxFx+Pythia
- Detector simulation (DELPHES?) needed!

Other channels

- $a \to \tau^+\tau^-$, $\frac{BR(\tau\tau)}{BR(\mu\mu)} \approx \frac{m_\tau^2}{m_\mu^2} \approx 283$
  - Decay channels: $BR(\tau \to \pi\pi\pi\nu) \sim 10\%$, $BR(\tau \to \ell\nu\nu) \sim 17\%$, $283 \to 20$
  - Neutrinos $\to$ no mass reconstruction.
  - Backgrounds: Drell-Yan, $b\bar{b}$,...
- $a \to b\bar{b}$, $\frac{BR(b\bar{b})}{BR(\mu\mu)} \approx \frac{m_b^2}{m_\mu^2} \approx 1980$
  - $a \to B\bar{B} + X$ (near threshold) $m_a \gtrsim 10.6\,\text{GeV}$, $X = \pi, K$ (jets?).
  - Decay channels: $BR(B^+ \to \overline{D}_0\pi^+, \overline{D}_0\rho^+, \overline{D}_0 \to K^-\pi^+) \sim 0.073\%$, $1980 \to 1.4$
  - Mass reconstruction possible. Background?
- $a \to c\bar{c}$, $\frac{BR(c\bar{c})}{BR(\mu\mu)} \approx \frac{m_c^2}{m_\mu^2} \approx 144$
  - $a \to D\bar{D} + X$ (near threshold) $m_a \gtrsim 3.8\,\text{GeV}$, $X = \pi, K$ (jets?).
  - Decay channels: $BR(D^0 \to K^-\pi^+) \sim 3.9\%$, $BR(D^+ \to K^+\pi^+\pi^-) \sim 9.5\%$, $144 \to 0.4$
  - Mass resolution possible. Background?

3 - Conclusions

- Composite Higgs models are very promising candidates to address the hierarchy problem(s).
  (also DM, unification, inflation, baryogenesis, $\cdots$)
- Top-quark partial compositeness promising mechanism to give mass to the top quark.
- An ubiquitous prediction of this class of models is the presence of a light "abelian" pNGB a,
  - LHCb search for $a \to \mu\mu$ competitive to CMS.
  - $a \to \tau\tau$, $a \to b\bar{b}$, $a \to c\bar{c}$ might have an advantage.
- Other CH+PC signatures:
  - EW pNGBs π is a signature of PC, $m_\pi \sim \mathcal{O}(v - f)$
  - QCD charged pNGBs π_c, $m_{\pi_c} \sim \mathcal{O}(10 m_\pi)$
  - FCNC (3-4 sigma tensions at LHCb and Belle, Sannino, Stangl, Straub, Thomsen 17, 19)
  - Heavy resonances $m \sim gf$, $1 \lesssim g \lesssim 4\pi$, vector, axial-vector, top partners, ...