Baryon Spectroscopy in the Sextet Gauge Model

Chik Him (Ricky) Wong

Lattice Higgs Collaboration (LatHC):
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Outline

- Review: Sextet Model as a Composite Higgs candidate model
- Baryon Spectroscopy in the Sextet Model
  - Operator Construction
  - Preliminary Lattice Simulation Results
- Sextet Baryons as Dark Matter Candidates?
- Conclusion

Review:
Sextet Model as Composite Higgs candidate

- Goal: Look for a Composite Higgs model:
  An infrared fixed point almost exists + Confining $\Rightarrow$ models at the edge of conformal window
- After Higgs boson discovery : Light 0^{++} Higgs + reproduce detected phenomenology
- Parameter Space: N_C, N_f, Representations of $SU(N_C)$
- Focus of this talk: $SU(3)$ $N_f = 2$ Sextet(Two-index symmetric) Model

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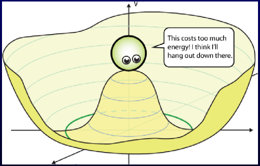
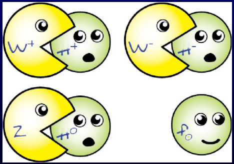
- Sextet Model
  - $SU(3)$ gauge theory with $N_f = 2$ fermions in Two-index symmetric representation: $(a, b = 0, 1, 2)$

$$\psi^L_{ab} = \psi^L_{ba} \equiv \begin{pmatrix} u^L_{ab} \\ d^L_{ab} \end{pmatrix}, \quad \psi^R_{ab} = \psi^R_{ba} \equiv \begin{pmatrix} u^R_{ab} & d^R_{ab} \end{pmatrix}$$

  Flavor symmetry: $SU(2)_L \times SU(2)_R \times U(1)$
  - "Minimal" Composite Higgs Theory:
  $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V \Rightarrow SU(2)_W \times U(1)_Y \rightarrow U(1)_{em}$





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  - $U(1)$ remains unbroken $\Rightarrow$ Baryon number conservation

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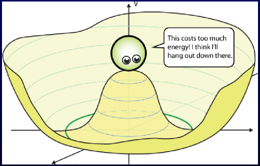

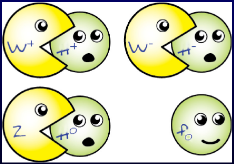

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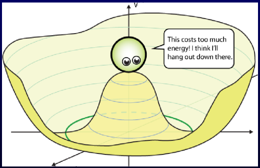

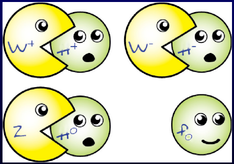

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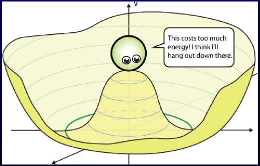

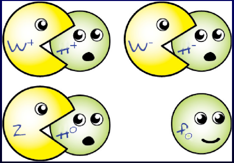

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  - Intrinsically close to Conformal Window
  - β function investigation is ongoing (Fodor et al, PoS (LATTICE 2014) 419)
  - Consistent evidence of χSB
    - Chiral Condensate: non-zero (Fodor et al, PoS (LATTICE 2013) 089)
    - Potential: Confining(Fodor et al, PoS (Lattice 2012) 025)
    - Hadron Spectrum: consistent with χSB (Fodor et al, Phys.Lett B **718**, p. 657-666)
  - Meson Spectroscopy: (Fodor et al, PoS (LATTICE 2014) 419)
    - f_0 seems to be light $\Rightarrow$ Composite Higgs Impostor
    - Masses of a_0, a_1 and ρ's are within LHC reach
  - Baryon Spectroscopy: (Fodor et al, PoS (LATTICE 2014) 281)
    What are the predictions from the Baryon Spectrum?
    Can the Sextet Baryons serve as Dark Matter candidates?

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Baryon Spectroscopy - Operator Construction

- Color structure
  - In fundamental representation (QCD), the baryon color singlet is given by three fermions:

$$3 \otimes 3 \otimes 3 = 1 \oplus 2 \times 8 \oplus 10,$$

where ψ_a transforms as $\psi_{a'} \to U_{a'a}\ \psi_a$, and the constructed color singlet is Anti-symmetric:

$$\varepsilon_{abc}\ \psi_a\ \psi_b\ \psi_c$$

  - In the sextet representation, a color singlet can also be obtained by three fermions:

$$6 \otimes 6 \otimes 6 = 1 \oplus 2 \times 8 \oplus 10 \oplus \overline{10} \oplus 3 \times 27 \oplus 28 \oplus 2 \times 35,$$

where ψ_{ab} transforms as $\psi_{a'b'} \to U_{a'a}\ \psi_{ab}\ U^T_{bb'}$, and the constructed color singlet is Symmetric, in sharp contrast with QCD:

$$\varepsilon_{abc}\ \varepsilon_{a'b'c'}\ \psi_{aa'}\ \psi_{bb'}\ \psi_{cc'} \equiv T_{ABC}\Psi_A\Psi_B\Psi_C,$$

where $A, B, C = 0, 1, 2, 3, 4, 5$

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- Spin-Flavor structure
  - Symmetric Color Structure $\Rightarrow$ Anti-symmetric Spin-Flavor Structure
  - In non-relativistic limit, a spin-up Sextet Nucleon is given by anti-symmetrizing $|\uparrow u \uparrow d \downarrow u\rangle$:

$$|\uparrow N\rangle = \ |\uparrow u \uparrow d \downarrow u\rangle + |\downarrow u \uparrow u \uparrow d\rangle + |\uparrow d \downarrow u \uparrow u\rangle$$
$$- |\downarrow u \uparrow d \uparrow u\rangle - |\uparrow d \uparrow u \downarrow u\rangle - |\uparrow u \downarrow d \uparrow d\rangle$$

  - The lattice operators that respect the Spin-flavor structure belong to a suitable multiplet of taste $SU(4)$

    (H. Kluberg-Stern et al, Nucl. Phys. B 220, 447 (1983), M. F. L. Golterman et al, Nucl. Phys. B 255, 328 (1985))

- The lattice Sextet Nucleon operator that respect the overall structure, in Dirac basis, takes the form

$$N^{\alpha i}(2y) = T_{ABC}\, u_A^{\alpha i}(2y)\, \left[u_B^{\beta j}(2y)\, (C\gamma_5)_{\beta\gamma}\, (C^*\gamma_5^*)_{ij}\, d_C^{\gamma j}(2y)\right],$$

C : charge conjugation matrix, y : elementary staggered hypercubes

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N^{\alpha i}(2y) = T_{ABC}\, u_A^{\alpha i}(2y)\, \left[u_B^{\beta j}(2y)\, (C\gamma_5)_{\beta\gamma}\, (C^*\gamma_5^*)_{ij}\, d_C^{\gamma j}(2y) \right],
$$

C : charge conjugation matrix, y : elementary staggered hypercubes

Baryon Spectroscopy - Operator Construction

- Spin-Flavor structure
  - Symmetric Color Structure $\Rightarrow$ Anti-symmetric Spin-Flavor Structure
  - In non-relativistic limit, a spin-up Sextet Nucleon is given by anti-symmetrizing $|\uparrow u \uparrow d \downarrow u\rangle$:

$$
\begin{aligned}
|\uparrow N\rangle = \; & |\uparrow u \uparrow d \downarrow u\rangle + |\downarrow u \uparrow u \uparrow d\rangle + |\uparrow d \downarrow u \uparrow u\rangle \\
& - |\downarrow u \uparrow d \uparrow u\rangle - |\uparrow d \uparrow u \downarrow u\rangle - |\uparrow u \downarrow d \uparrow d\rangle
\end{aligned}
$$

  - The lattice operators that respect the Spin-flavor structure belong to a suitable multiplet of taste $SU(4)$

(H. Kluberg-Stern et al, Nucl. Phys. B 220, 447 (1983), M. F. L. Golterman et al, Nucl. Phys. B 255, 328 (1985))

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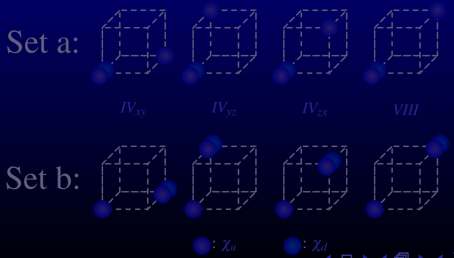
Baryon Spectroscopy - Operator Construction

- Substituting $q^{\alpha i}(2y) = \frac{1}{8}\sum_\eta \Gamma_\eta^{\alpha i}\chi_q(2y+\eta)$ and combining parity-opposite channels for locality in time:

$$N^{\alpha i}(2y) = -\frac{1}{8^3} T_{ABC} \sum_{\vec{\eta}'} \Gamma_{\vec{\eta}'}^{\alpha i}\, \chi_u^A(2y+\vec{\eta}') \cdot \sum_{\vec{\eta}} S(\vec{\eta})\, \chi_u^B(2y+\vec{\eta})\, \chi_d^C(2y+\vec{\eta}),$$

where $\Gamma = \gamma_1^{\eta_1}\gamma_2^{\eta_2}\gamma_3^{\eta_3}\gamma_4^{\eta_4}$ and $S(\eta) = \pm 1$

- Local terms vanish due to symmetric color structure
- Surviving terms have the u quark and the diquark at diagonally opposite corners, e.g.:



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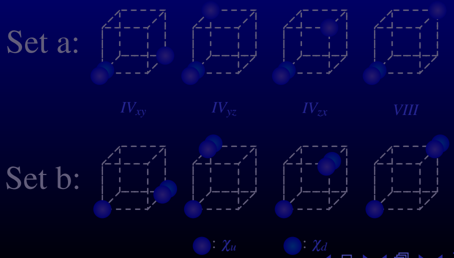

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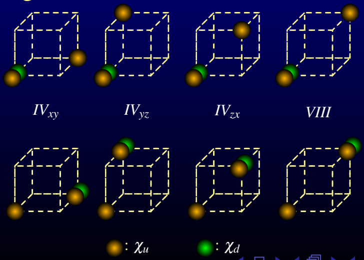
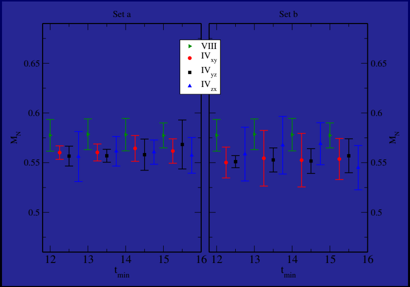


Baryon Spectroscopy - Preliminary Lattice Simulation Results

- Action: Tree-level Symanzik-Improved gauge action with Staggered $N_f = 2$ Sextet SU(3) fermions
- RHMC algorithm with multiple time scales and Omelyan integrator
- Lattices used: ($\sim 1000 - 1500$ Trajectories each)

$\beta \equiv 6/g^2$	L	T	m_q
3.20	48	96	0.003
	32	64	0.004, 0.005, 0.006, 0.007, 0.008

- Comparison of operators:
  ($V = 32^3 \times 64$, $m_q = 0.007$, 1000 trajectories, $t_{\max} = 20$)



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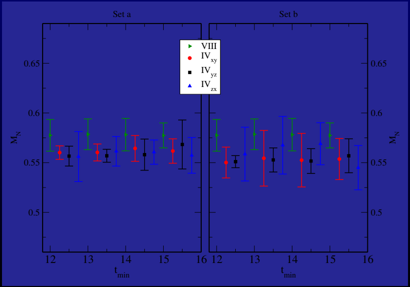

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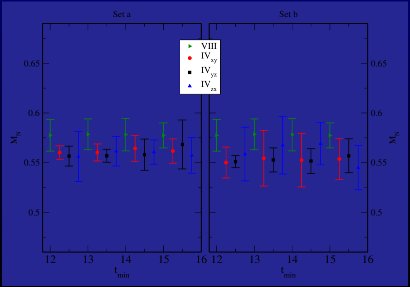

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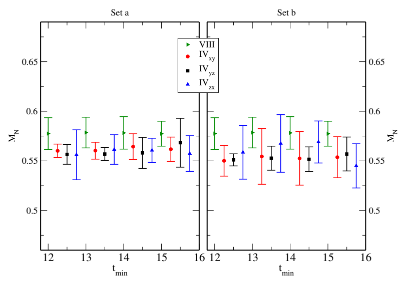

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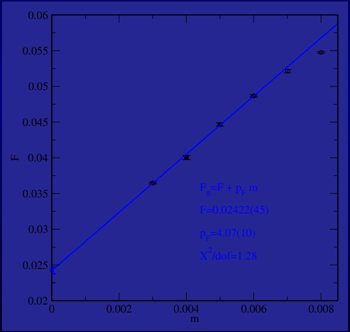

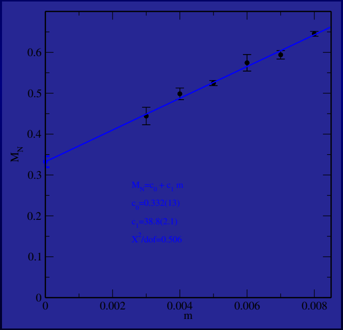

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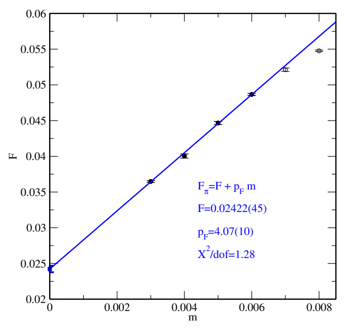

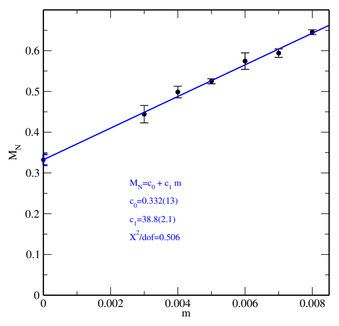

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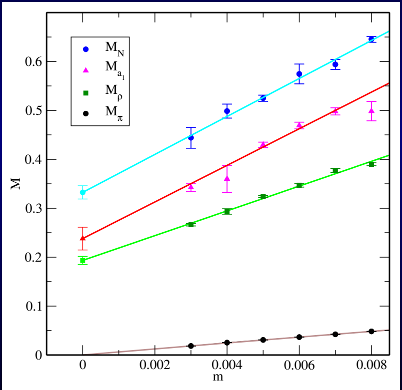
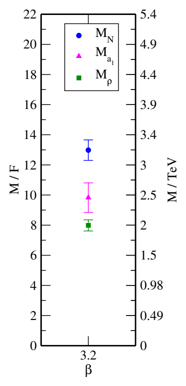
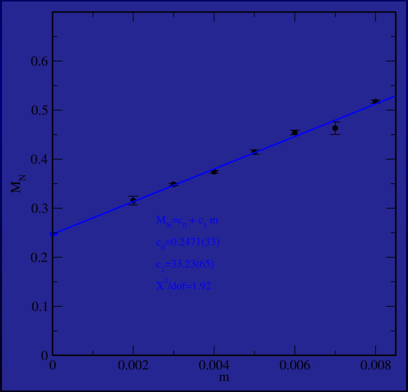




Baryon Spectroscopy - Preliminary Lattice Simulation Results

- $\beta = 3.25$ is being investigated
- Preliminary results: (with ~ 250 trajectories of $V = 48^3 \times 96$ at $m = 0.002, 0.003$)



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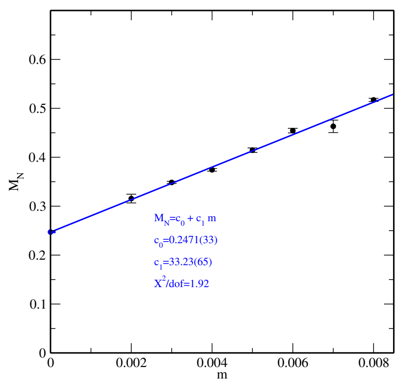

Dark Matter Candidates?

- Lightest Sextet Baryon as we know so far:
  - Mass could be in the range of $3\ TeV$
  - Stable
- *If* the Sextet model is a viable composite Higgs candidate, Can the Sextet Baryons be **Dark Matter** candidates?
  - if Yes $\rightarrow$ Can any predictions be made?
  - if No $\rightarrow$ Look for variants and extensions (or find a better model)
- Embedding Electroweak interaction:
  - ABJ Anomaly Free $\Rightarrow \mathrm{Tr}\, Y = \mathrm{Tr}\, Y^3 = 0$
  - Hypercharge generator: $Y = 2(Q - T_3)$
  - $\Rightarrow Q_{u^L} = Q_{u^R} = \frac{1}{2},\ Q_{d^L} = Q_{d^R} = -\frac{1}{2}$ is a consistent choice
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  - Mass could be in the range of 3 *TeV*
  - Stable
- *If* the Sextet model is a viable composite Higgs candidate,
  Can the Sextet Baryons be **Dark Matter** candidates?
  - if Yes → Can any predictions be made?
  - if No → Look for variants and extensions (or find a better model)
- Embedding Electroweak interaction:
  - ABJ Anomaly Free ⇒ $\text{Tr } Y = \text{Tr } Y^3 = 0$
  - Hypercharge generator: $Y \equiv 2(Q - T_3)$
  - $\Rightarrow Q_{u^L} = Q_{u^R} = \frac{1}{2},\ Q_{d^L} = Q_{d^R} = -\frac{1}{2}$ is a consistent choice
  - $\Rightarrow Y_{u^L} = Y_{d^L} = 0,\ Y_{u^R} = 1,\ Y_{d^R} = -1$
  - The Lightest Sextet Baryons : Sextet Nucleons (*uud* and *udd*)
  - $Q_{uud} = \frac{1}{2},\ Q_{udd} = -\frac{1}{2}$ as Dark Matters
    $\Rightarrow$ Fractionally CHArged Massive Particle (FCHAMP) Category

*Background picture taken and modified from
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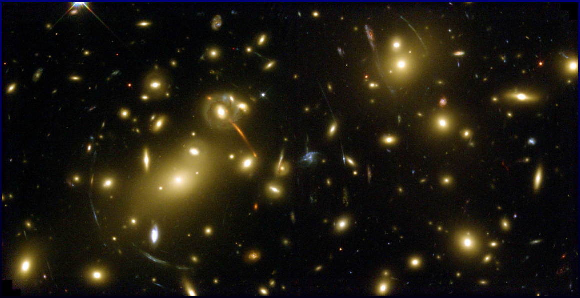

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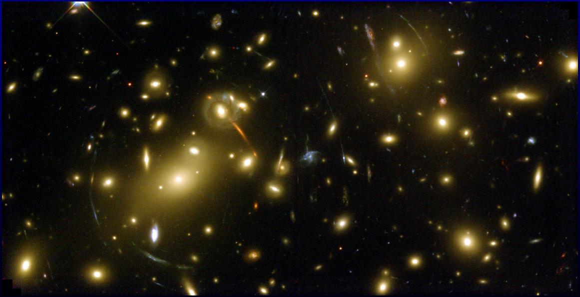

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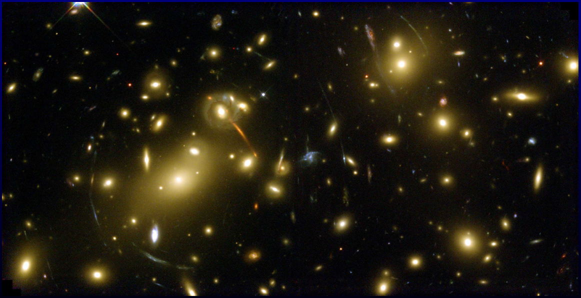

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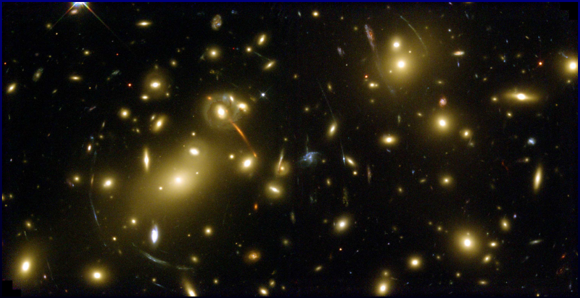

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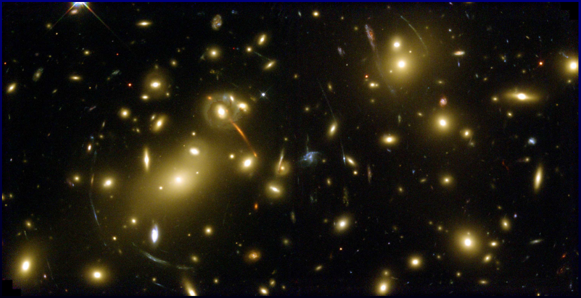

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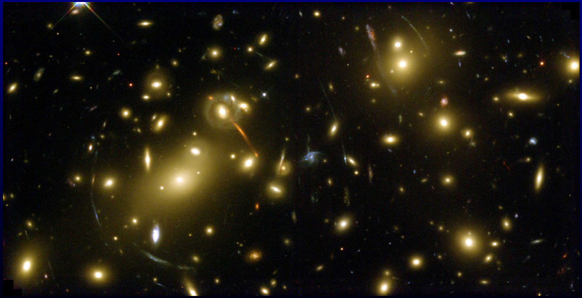

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