Sp(4) gauge theories and beyond the standard model physics

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Motivations

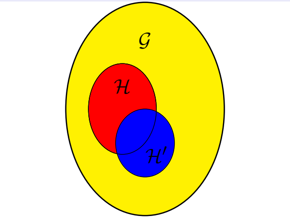
1. Fundamental mechanism for electroweak symmetry breaking
2. Dark matter/dark energy
3. Insights on gauge dynamics
4. Connections with analytic frameworks
5. ...

All important, but this talk will focus on motivations related to Dynamical Electroweak Symmetry Breaking (DEWSB)

The DEWSB framework

Motivation: provide a fundamental Electroweak Symmetry Breaking Mechanism based on strong dynamics that solves the hierarchy problem

Consider a gauge theory with some gauge group $\mathcal{G}'$ coupled to fermionic matter



Global symmetry group $\mathcal{G}$ spontaneously broken to $\mathcal{H} \subset \mathcal{G}$
$\Rightarrow$ Number of Goldstone bosons: $\text{dim}_{\mathcal{G}}$ - $\text{dim}_{\mathcal{H}}$

Gauge some $\mathcal{H}' \subset \mathcal{G}$ such that $SU(2)_L \otimes U(1)_Y \subset H'$

Two main possible scenarios:

- Technicolour if $\mathcal{H}' \cap \mathcal{H} \neq \mathcal{H}'$
- Pseudo-Nambu-Goldstone-Boson (PNGB) Higgs if $\mathcal{H}' \subset \mathcal{H}$

The Higgs as a PNGB

Little Hierarchy Problem: if the Higgs boson is composite, how can its mass be significantly lower than that of other states of the novel strong interaction?

Possible solution: the Higgs is a PNGB arising from the global symmetry breaking (GSB) of the new strong interaction [Kaplan and Georgi, 1984]

Patterns of GSB $G \mapsto H$ for a theory with N_f Dirac fermions

1. SU(N) gauge group: $\mathrm{SU}(N_f)_V \times \mathrm{SU}(N_f)_A \mapsto \mathrm{SU}(N_f)_V$
2. Real gauge group: $\mathrm{SU}(2\,N_f) \mapsto \mathrm{SO}(2\,N_f)$
3. Pseudoreal gauge group: $\mathrm{SU}(2\,N_f) \mapsto \mathrm{Sp}(2\,N_f)$

Embedding of the standard model: $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \subset H \subset G$
$\hookrightarrow$ The physical Higgs is identified with four of the pions

Partial Top Compositeness [Kaplan, 1991]: the mixing between the top quark and a hybrid (chimera) baryon, formed by fermions in two different representations, can explain the large mass of the top quark itself
Necessary conditions: large anomalous dimension of the chimera baryon

Hunting for candidate models

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)	$5 \times \mathbf{F}$	$6 \times \mathbf{Sp}$	$5/12$	$\psi\chi\chi$	M2	
	SO(7)	$5 \times \mathbf{Sp}$	$6 \times \mathrm{F}$	$5/6$	$\psi\psi\chi$	M3	
	SO(9)	$5 \times \mathbf{Sp}$	$6 \times \mathrm{F}$	$5/3$	$\psi\psi\chi$	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)	$5 \times \mathbf{F}$	$3 \times (\mathbf{Sp}, \overline{\mathbf{Sp}})$	$5/12$	$\psi\chi\chi$	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)	$4 \times \mathbf{Sp}$	$6 \times \mathbf{F}$	$8/3$	$\psi\psi\chi$	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)	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	$2/3$	$\psi\psi\chi$	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	

G. Ferretti and T. Karataev, arXiv:1312.5330
J. Barnard, T. Gherghetta and T. S. Ray, arXiv:1311.6562
G. Cacciapaglia, G. Ferretti, T. Flacke and H. Serodio, arXiv:1902.06890

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The lattice programme (Bennett *et al.*, arXiv:1712.04220)

Goal: establish whether the SU(4) $\mapsto$ Sp(4) global symmetry breaking pattern is viable as a mechanism of DEWSB

Target calculation

1. Sp(4) gauge theory with two fundamental Dirac flavours and three antisymmetric Dirac flavours
2. compute spectral observables and decay constants
3. extract parameters of the effective field theory
4. compare with experiments

Needed validations

1. Study the pure gauge model
2. Compute the quenched spectrum
3. Study separately the gauge system with fundamental dynamical matter only and with antisymmetric dynamical matter only
4. Perform calculations of the chimera baryon in a quenched and partially quenched setup

Status: most of the validation calculations have been completed or are nearly completed, and initial exploratory results for the target calculations are available (Earlier exploration of Sp$(2N)$ at finite temperature: Holland, Pepe and Wiese, hep-lat/0312022)

Sp(2N) groups

Sp($2N$) can be defined as the subgroup of SU($2N$) whose elements U fulfil the condition

$$U\Omega U^T = \Omega \,, \qquad \Omega = \begin{pmatrix} 0 & \mathbb{I} \\ -\mathbb{I} & 0 \end{pmatrix}$$

This constrains the structure of U as follows:

$$U = \begin{pmatrix} A & B \\ -B^* & A^* \end{pmatrix} \,, \qquad \text{with } AA^\dagger + BB^\dagger = \mathbb{I} \text{ and } A^T B = B^T A$$

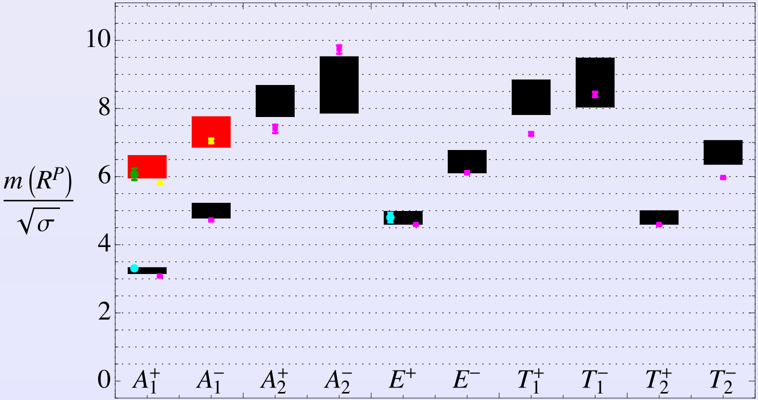
For an element **u** in the algebra, this implies

$$\mathbf{u} = \begin{pmatrix} \mathbf{a} & \mathbf{b} \\ \mathbf{b}^* & -\mathbf{a}^* \end{pmatrix} \,, \qquad \text{with } \mathbf{a} = \mathbf{a}^\dagger \text{ and } \mathbf{b} = \mathbf{b}^T$$

Other properties:

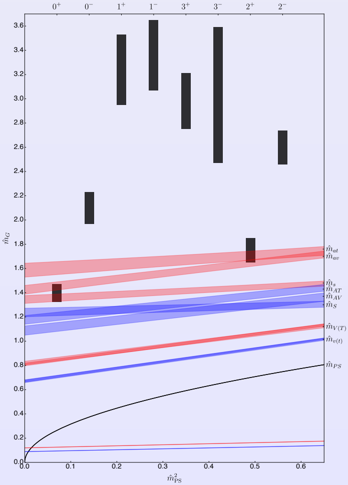
1. The dimension of the group is $N(2N+1)$
2. The group is pseudoreal
3. The group has rank N $\Rightarrow$ N independent SU(2) subgroups

The glueball spectrum for Sp(∞)



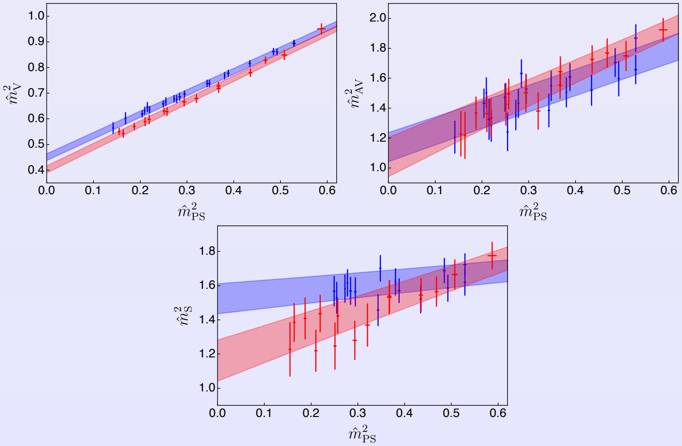
[E. Bennett *et al.*, arXiv: 2010.15781]

The quenched spectrum of Sp(4) Yang-Mills



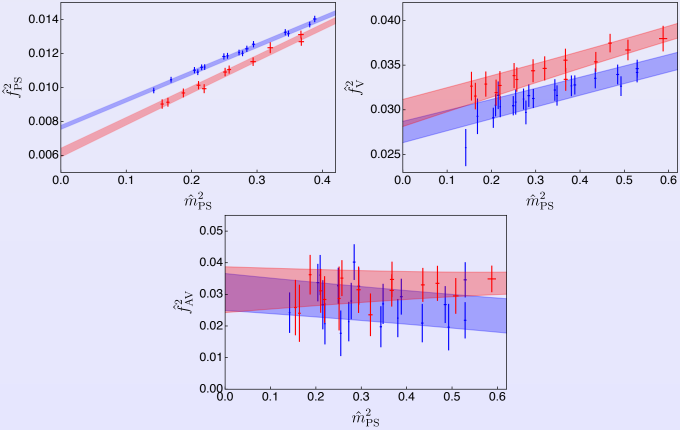
Glueball data from E. Bennett *et al.*, arXiv: 2010.15781
Meson data from E. Bennett em et al., arXiv:1912.06505

$N_f = 2$ Meson spectrum: quenched vs unquenched



[E. Bennett *et al.*, arXiv:1909.12662]

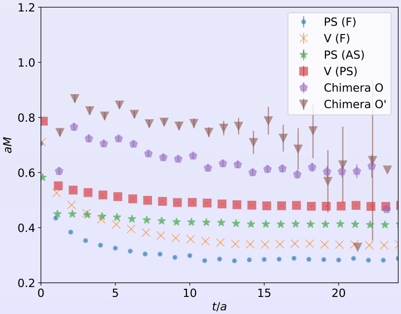
$N_f = 2$ decay constants: quenched vs unquenched



[E. Bennett *et al.*, arXiv:1909.12662]

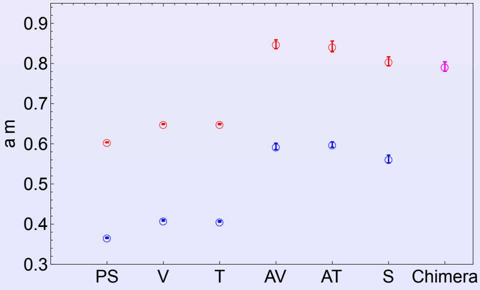
Partially quenched spectrum

Sp(4) gauge theory with three dynamical antisymmetric Dirac flavours and two quenched fundamental Dirac flavours



Clear identification of parity partner baryons

Mixed representation spectrum



Mass hierarchy for mesons qualitatively similar to the quenched case

Conclusions and outlook

- Strongly interacting theories other than QCD are relevant for both phenomenology and theory
- Motivated originally by phenomenology, we have started a comprehensive programme of investigations in Sp($2N$) models
- The string tension and the glueball spectrum have been studied in pure Yang-Mills in the large-N limit, yielding values that are compatible with the extrapolation of SU(N)
- The mesonic spectrum has been studied in Sp(4) in the quenched case, for fermions in the fundamental and in the antisymmetric representation
- Quenched results for the fundamental fermion case have been compared to the dynamical theory with $N_f = 2$
- We have provided first results for the partially quenched chimera baryon
- A preliminary calculation of the spectrum for the mixed representation case has been presented

A full simulation of the target phenomenological model is now within reach