Sp(4) gauge theory on the Lattice

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Nature of Dark Matter (DM) unclear

- Only gravitational effects observed
- Hypothesis: Particle Dark Matter
  - Coupling to Standard Model (SM) extremely weak
  - Stable over tens of billions of years
- Density distribution of DM constrains theories!
Dark matter as a thermal relic

- Thermal equilibrium in early Universe
  - Dark Matter particles deplete as Universe cools
  - At some $T$: DM and SM decouple ("freeze out")
- Relevant depletion process constrains DM!
- Example: WIMPs
  - deplete by $2 \text{ DM} \rightarrow 2 \text{ SM}$
  - Masses typically around $\mathcal{O}(1 \text{ TeV})$
Strongly Interacting Massive Particles (SIMPs)

- Depletion by $3 \text{ DM} \rightarrow 2 \text{ DM}$
- Requires additional mediator for SM-equilibrium
- Masses typically around $\mathcal{O}(100 \text{ MeV})$
- Need a mechanism that can provide $3 \text{ DM} \rightarrow 2 \text{ DM}$

[1402.5143, 1411.3727, 1512.07917]
3 $\to$ 2 occurs in chiral effective theories!

- Chiral symmetry breaking with $\geq 5$ Goldstones
- 5-point interaction $\mathcal{L}_{WZW}$ between Goldstones $\Pi$

$$\mathcal{L}_{WZW} \propto \epsilon_{\mu\nu\rho\sigma} \text{Tr}[\Pi \partial_{\mu} \Pi \partial_{\nu} \Pi \partial_{\rho} \Pi \partial_{\sigma} \Pi]$$

*Idea*: Gauge theory with $\mathcal{L}_{WZW}$ in EFT and Goldstones as Dark Matter candidates (+ mediator to SM)
**Sp(4) gauge theory as a SIMP model**

- $N_f = 2$ fundamental sufficient for WZW Term
- Massive fermions $u, d$, so that $\Pi$ are massive
- Introduce small mass difference between Fermions
  - Allows hierarchy: One $\Pi$ is lighter than the others

\[
\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{u}(i\not{D} + m_u)u + \bar{d}(i\not{D} + m_d)d
\]

\[
m_d = m_u + \Delta m
\]
Chiral symmetry breaking:

- 5 pseudo-Goldstone bosons

Same pattern for all symplectic groups

$SU(4) \rightarrow Sp(4)$

$m_u = m_d \neq 0$

$m_u \neq m_d$ breaks symmetry further

$[\text{hep-ph/0001171, 1205.4205}]$
Particle content of the theory

- 5 pseudo-Goldstones $\Pi$, 10 vectors $P$, ...
- No baryons (for any $Sp(N)_c$ group)
- Glueballs heavier than mesons
- $m_u \neq m_d$ lifts degeneracy

$$5\Pi \rightarrow 4\Pi(\text{flavoured}) + 1\Pi(\text{unflavoured})$$
$$10P \rightarrow 4P(\text{flavoured}) + 6P(\text{unflavoured})$$

- What is the hierarchy of the mesons masses?

[1712.04220, 1909.12662] [Kulkarni et. al. (in preparation)]
Sp(4) Nf=2 : pseudo-Goldstones’ Π and iso-non-singlet vector mesons’ $P$ masses

lightest degenerate meson mass set to 300 MeV

PRELIMINARY

degenerate dark quark masses
unflavoured pseudo-Goldstone is
the lightest bound state

light vectors get lighter
than heavy pseudo-Goldstones

flavoured pseudo-Goldstones II
unflavoured pseudo-Goldstone II
flavoured vectors $P$
unflavoured vectors $P$
Summary

- Mesonic spectrum of $Sp(4)$ with $N_f = 1 + 1$
- Strong isospin-splitting in non-$SU(N)$ theory
  - 5 Pseudo-Goldstones are not degenerate
  - **Lightest state: Unflavoured Pseudo-Goldstone**
  - Large $\Delta m$: Unflavoured Vectors relevant
Outlook

• On the lattice:
  ◦ Additional channels (axialvectors, tensors, ...)
  ◦ More low energy constants (chiral condensate,...)
  ◦ scattering processes: $2 \rightarrow 2$ and $3 \rightarrow 2$

Coupling to the SM, consequences for cosmology, astrophysics, direct detection and collider searches within the FWF funded research group FG1
References (1/2)

References (2/2)

- [1512.07917] Hochberg, Kuflik, Murayama. JHEP05, 2016
- [1712.04220] Bennett, Hong, Lee, Lin, Lucini, Piai, Vadacchino. JHEP03, 2018
- [1909.12662] Bennett, Hong, Lee, Lin, Lucini, Piai, Rantaharju, Vadacchino. JHEP12, 2019
- [Kulkarni et. al.] Kulkarni, Maas, Mee, Nikolic, Pradler, Zierler (in preparation)
Back-up Slides
Sp(4) Nf=2 : $\Pi$ and $P$ decay constants

lightest degenerate meson mass set to 300 MeV

PRELIMINARY

flavoured pseudo-Goldstones $\Pi$
unflavoured pseudo-Goldstone $\Pi$
flavoured vectors $P$
unflavoured vectors $P$
$SU(3)$ vs. $Sp(4)$

- in case of $N_f = 2$
- $Sp(N)$ always larger
- general property of pseudo-real and complex fermion representation

\[
SU(3) \text{ vs. } Sp(4)
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