Beyond the Standard Model with Sp(2N) Gauge Theory: Meson Spectroscopy and Scattering

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`based on work with`: E.Bennett, Y.Dengler, N.Forzano, DK.Hong, H.Hsiao, S.Kulkarni, JW.Lee, CJD.Lin, B.Lucini, A.Maas, S.Mee, M.Nikolic, M.Piai, J.Pradler, F.Pressler, D.Vadacchino

QCD-like gauge theories

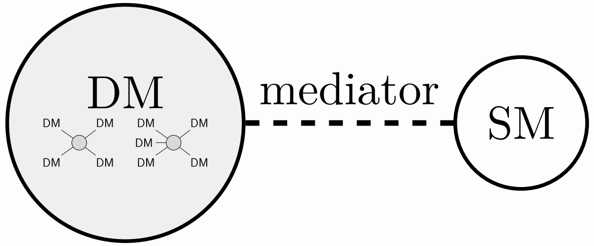
- New non-SM gauge force with fermions
  - Composite Higgs Models: hyper-gluons and hyperquarks
  - Dark Matter Models: dark gluons and dark quarks
- Depending on the BSM model they can carry SM charges or not

- I will use the QCD nomenclature:
  - e.g. π: 0^-nonsinglet, ρ: 1^- nonsinglet, . . .
  - these states are **not** the QCD hadrons
  - but they are similar in terms of their fermion structure

[1] see e.g. Bullock,Boylan-Kolchin [1707.04256], Tulin, Yu [1705.02358]

QCD-like Gauge Theories in Dark Matter Models

- With fermions: Global symmetries make Dark Matter stable
- With mediator: Dark sector coupled to SM
- Lightest dark Hadrons (here pions) are DM candidates



$$\mathcal{L}_{\rm DM} = -\frac{1}{2}{\rm Tr} F_{\mu\nu}F^{\mu\nu} + \bar{\psi}_f (i\not{D} - m_f)\psi_f$$

- Non-vanishing self-scattering cross-section arise

$$\langle v\sigma_{\pi\pi\to\pi\pi}\rangle \neq 0$$

- Dark Matter Relic density driven by strong processes
  - Scattering cross-sections are required input

Theories With Multiple Fermion Representations

[1] Ferretti, Karateev [1312.5330]

$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}_i\left(i\not{D} - m_i\right)\psi_i + \bar{\Psi}_j\left(i\not{D} - m_j\right)\Psi_j$$

- Gauge theory of group G with field strength tensor $F_{\mu\nu}$
- Two species of fermions ψ and Ψ under different irreps of G

- Composite Higgs Models with partial top compositeness
  - Composite Higgs from one Goldstone sector
  - Composite Top partner from $\psi\psi\Psi$ or $\psi\Psi\Psi$
  - Global Symmetries must contain $SU(3)$ and $SU(2)\times U(1)$

Chiral Symmetry and Goldstone Bosons

- One breaking pattern for every fermion representation
  - complex: $SU(N_f) \times SU(N_f) \rightarrow SU(N_f)$
  - pseudoreal: $SU(2N_f) \rightarrow Sp(2N_f)$
  - real: $SU(2N_f) \rightarrow SO(2N_f)$
- And one axial $U(1)$ for every representation
  - one linear combination broken by axial anomaly!
  - Additional $U(1)$ Goldstone at finite N_c for multirep!

Why Symplectic Gauge Theories?

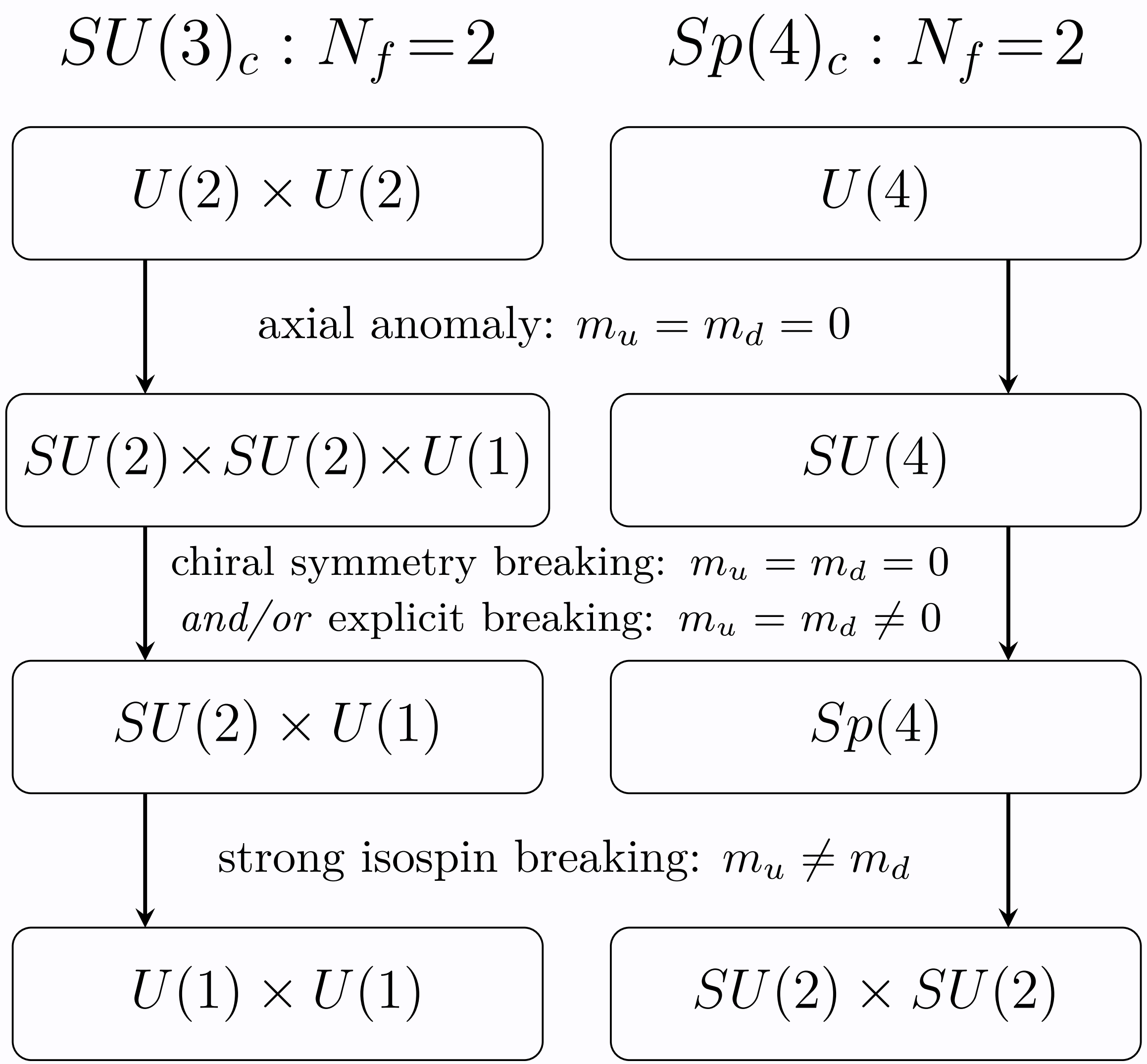
- Fermions in real or pseudo-real representations
- **Dark Matter**: *Strongly Interactive Massive Particles*
  - Semi-annihilation process: $3\pi \to 2\pi$ sets DM relic density
  - $Sp(2N)$ groups with $N_f > 2$ favoured by χPT over $SU(N)$, $SO(N)$
- **Composite Higgs Models**: with partial top compositeness
  - two fundamental fermions: allow pseudo-Goldstone Higgs
  - three anti-symmetric fermions: top composite partner

BSM wishlist from the lattice

1. Masses and decay constants of dark hadrons
    - Non-singlet and singlet mesons, glueballs
2. Scattering of pions
    - $2\pi \to 2\pi$ for self-interaction crossection
    - $3\pi \to 2\pi$ for SIMP semi-annihilation
3. Applicability of χPT and related EFTs

Meson Spectrum of two-flavour Sp(4)

SIMPs from $Sp(4)$ gauge theory



- Pseudo-real representation: [1]
  $\Rightarrow$ more pseudo-Goldstones
  $\Rightarrow$ no fermionic bound states
- $N_f = 2$: exactly 5 Goldstones
  - Allows $3\pi \to 2\pi$ [2] DM semi-annihilation

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Sp(4) with two fermions is
a minimal SIMP DM realisation
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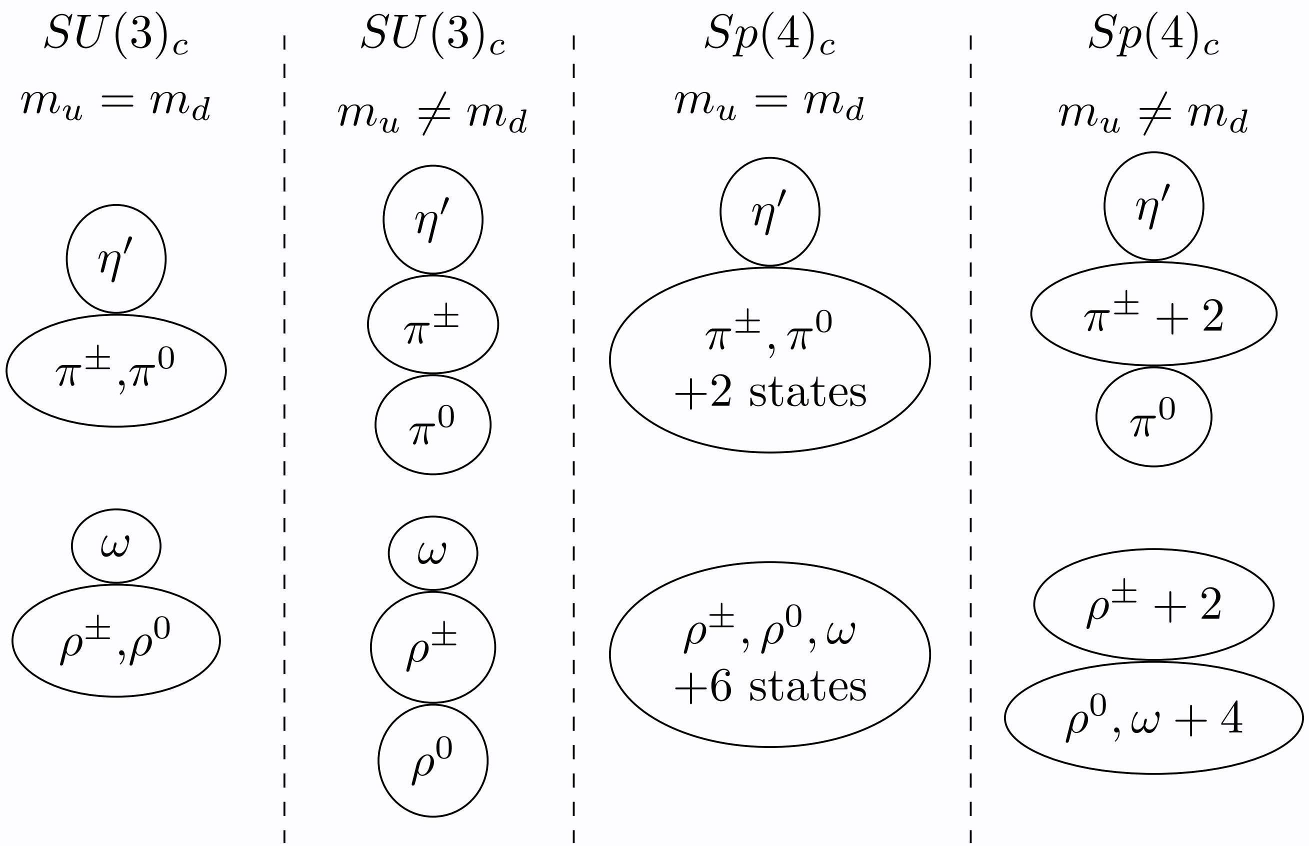
[1] Kosower (Phys.Lett.B. 1984)
[2] Hochberg et. al. [1411.3727] [1512.07917]

Pseudoscalar (PS) and vector (V) multiplets

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The same patterns persist for other channels.
Similar for anti-symmetric fermions
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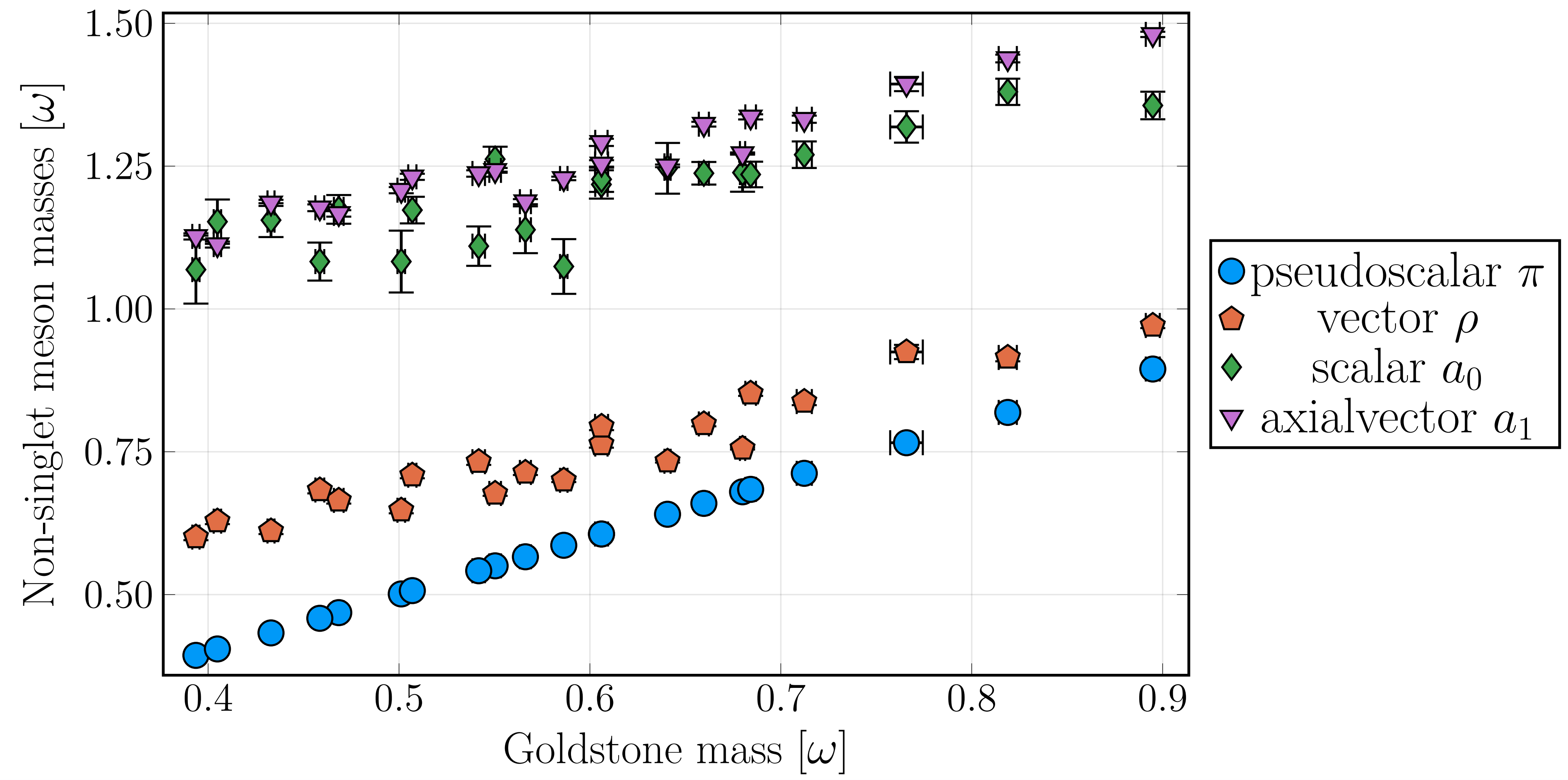
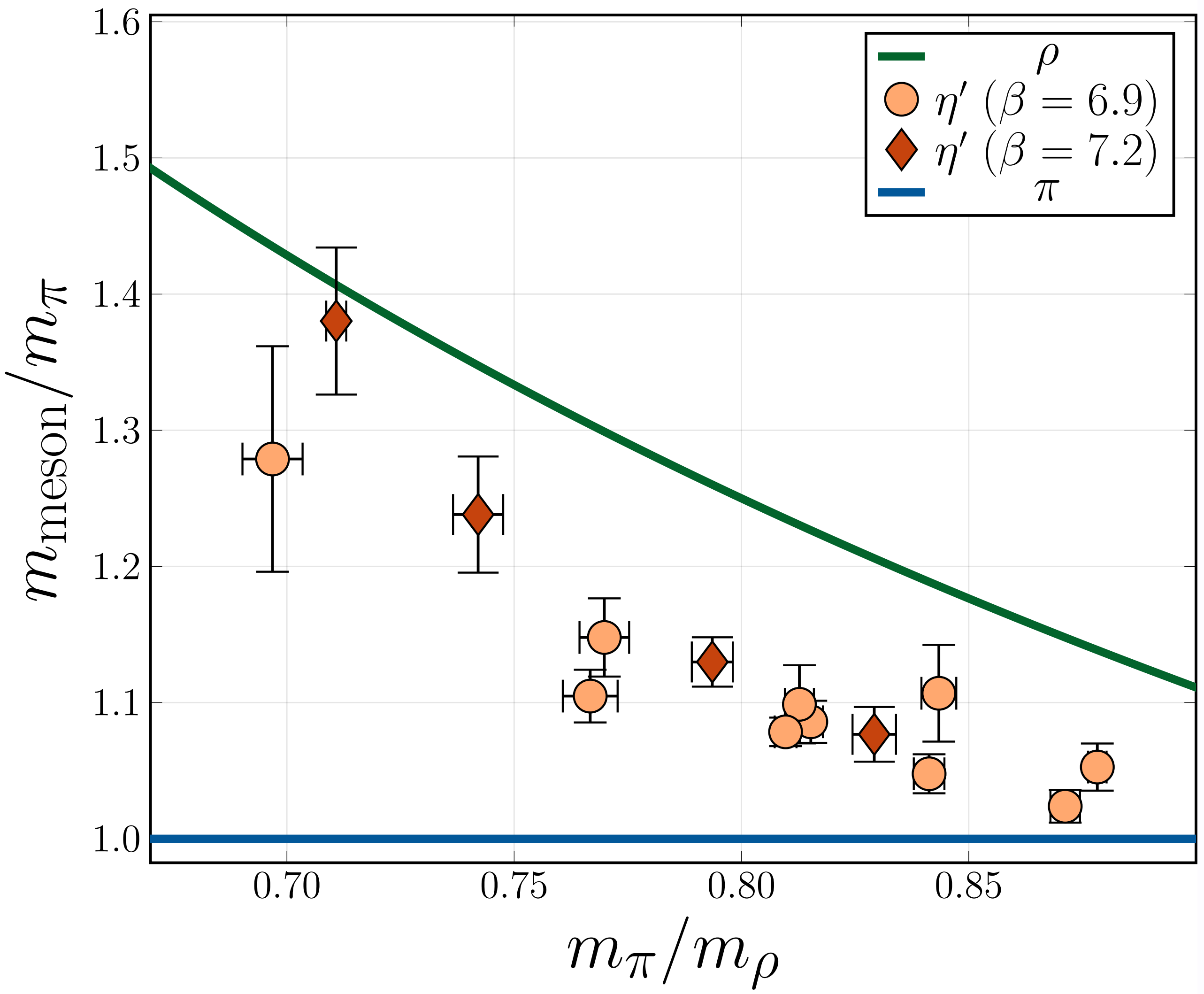
Non-singlet spectrum

Bennett et. al. [1909.12662]



The pseudoscalar and vector mesons are the lightest non-singlets.

The pseudoscalar singlet η' is surprisingly light!



- Phenomenologically relevant:
  - $m_\rho > m_{\eta'}$ different from QCD
  - relevant low-energy dof
  - η' relevant for $\pi\pi$ scattering
  - more accessible channels for decays into SM

Interesting! Is this surprising?

Bennett et. al. [2304.07191]

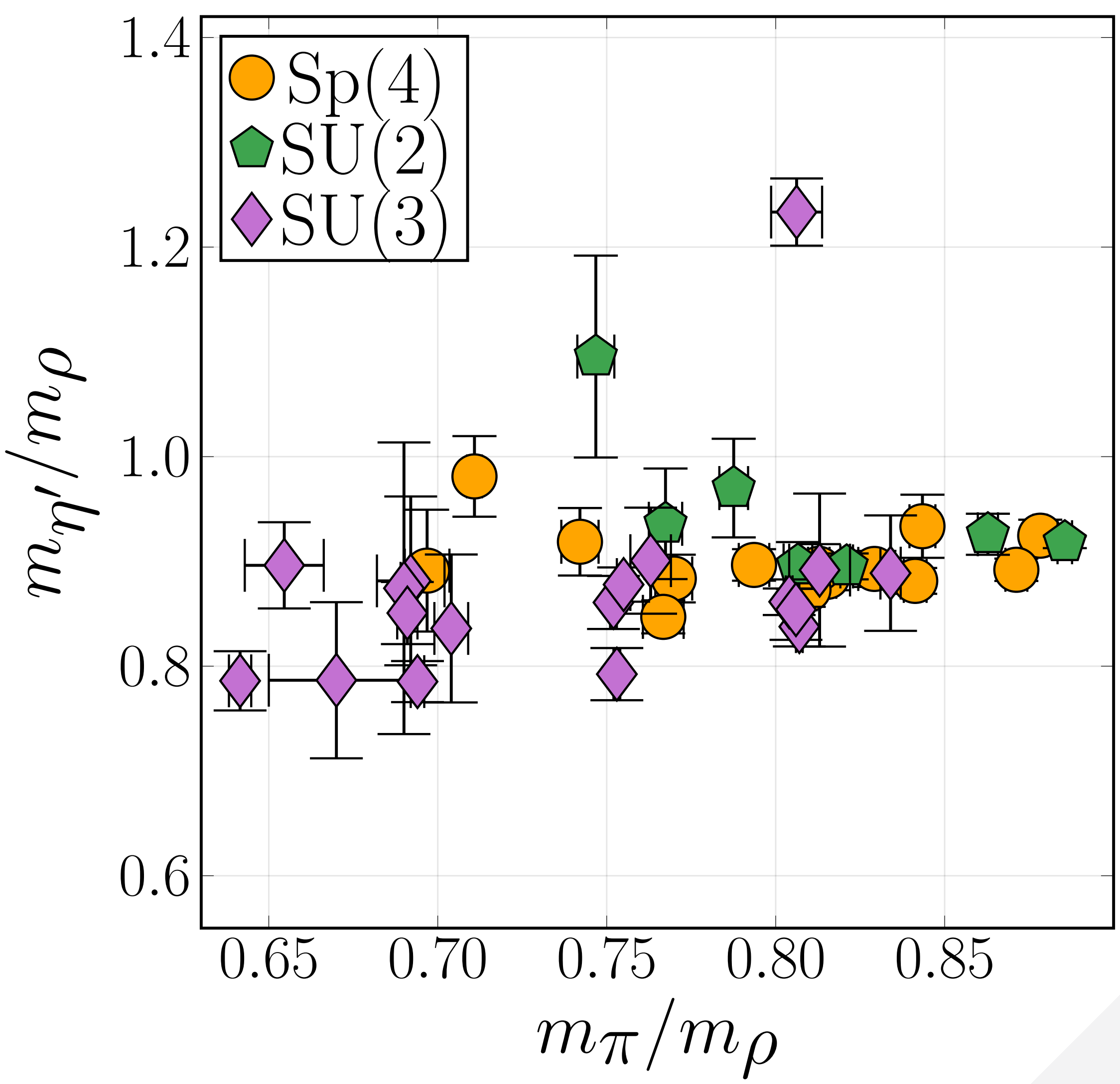
Consider different theories:

- Large N_c: $m_{\eta'} - m_\pi \propto N_f / N_c$
  - $N_f = 2$ could be "small"
  - $N_c = 4$ could be "large"

SU(2) and SU(3) comparison:

- Similarities:generic $N_f = 2$ feature?
- QCD: strong N_f dependence
- Differences may arise $m_\pi / m_\rho \to 0$

mass driven by flavour content!



Consequences for Dark Matter

- Mass hierarchies: limit χPT validity
  - inclusion of other states than π required, e.g. η' and ρ
  - additional tests needed (fermions are fairly heavy)
- Light unprotected states such as η' allow decays into SM
  - no protection from symmetry
  - could become relevant in thermal history of DM

Isospin-2 $\pi\pi$ scattering in two-flavour Sp(4)

Dark Matter Scattering on the Lattice

- Pions are in the 5-dimensional representations
- A two pion scattering is in one of three irreps

$$5 \times 5 = 14 \oplus 10 \oplus 1$$

- Corresponds to the usual QCD channels
  - $14 \Leftrightarrow$ isospin $I = 2$ in QCD, e.g. $\pi^+\pi^+$
  - $10 \Leftrightarrow$ isospin $I = 1$ in QCD, e.g. $\rho \to \pi\pi$
  - $0 \Leftrightarrow$ isospin $I = 0$ in QCD, e.g. $\sigma / f_0 \to \pi\pi$

Scattering information from the lattice

- Scattering phase shift $\delta_0(p)$ from finite volume energy

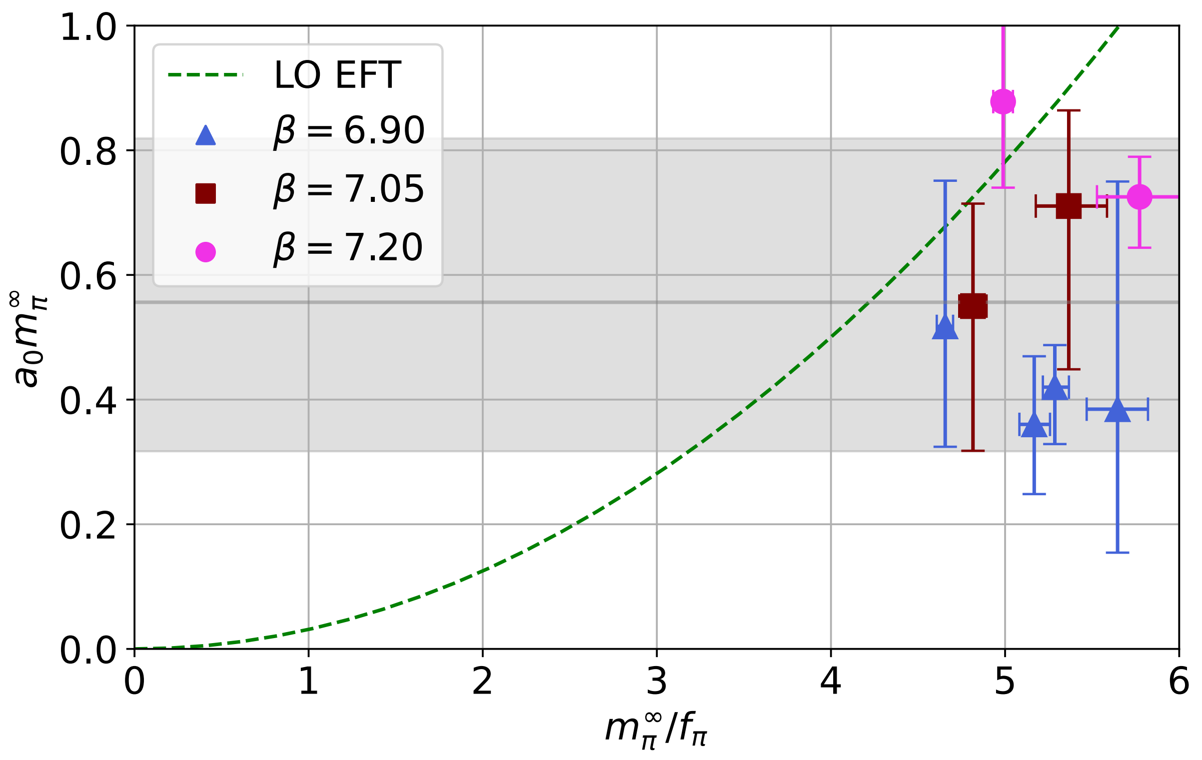
$$\tan(\delta_0(q)) = \frac{\pi^{\frac{3}{2}} q}{\mathcal{Z}_{00}^{\vec{0}}(1, q^2)}, \quad q = p^* \frac{L}{2\pi}$$

$$\cosh\left(\frac{E_{\pi\pi}}{2}\right) = \cosh(m_{\pi\pi}) + 2\sin\left(\frac{p^*}{2}\right)^2$$

- Low-velocity behaviour: Scattering length a_0

$$p \cot \delta_0 = -\frac{1}{a_0} + \frac{p^2}{2r_0^{-1}} + \mathcal{O}(p^4)$$

First investigation of isospin-2 scattering



- few lattice energy levels available $\Rightarrow$ systematics
- repulsive, roughly matches χPT
- first step towards other channels and resonances

Isosinglet Mesons in Mixed Representation Sp(4)

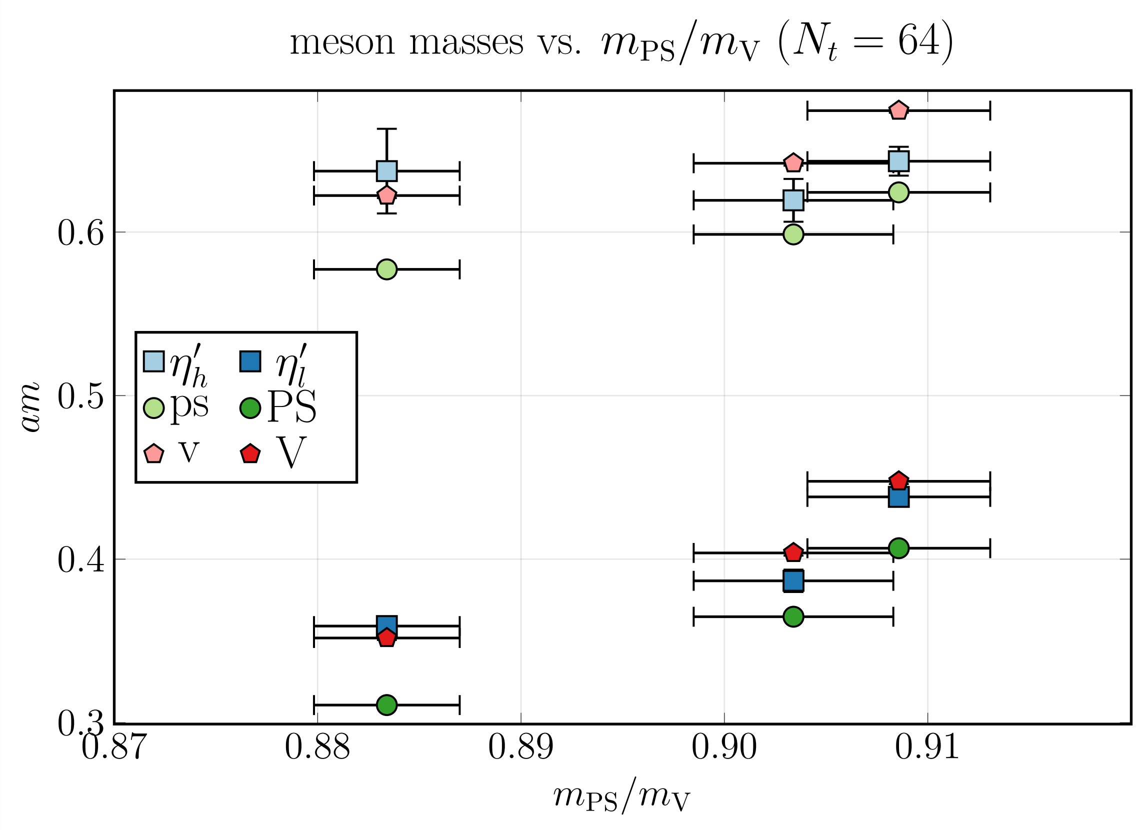
The axial $U(1)$ states: Isosinglet Pseudoscalars

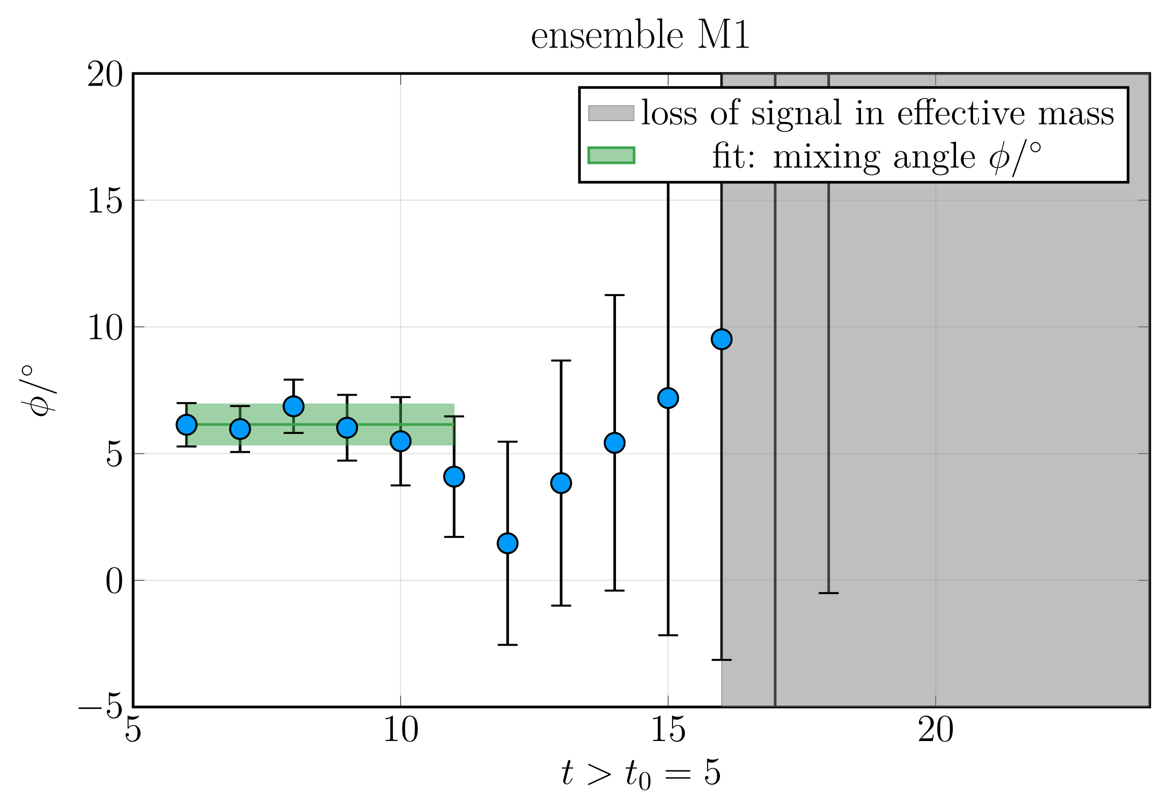
- Two fundamental, three anti-symmetric fermions
- pseudoscalar flavour-singlets: similar to η and η' of QCD
- probed by the following operators

$$O_{\eta^{\mathrm{f}}} = \left(\bar{\psi}_1\gamma_5\psi_1 + \bar{\psi}_2\gamma_5\psi_2\right)/\sqrt{2}$$
$$O_{\eta^{\mathrm{as}}} = \left(\bar{\Psi}_1\gamma_5\Psi_1 + \bar{\Psi}_2\gamma_5\Psi_2 + \bar{\Psi}_3\gamma_5\Psi_3\right)/\sqrt{3}$$

- These two states will mix: Light PNGB state η'_l + heavier state η'_h
  - mixing angle $\phi \neq 0$
  - Effective field theory in chiral limit is known

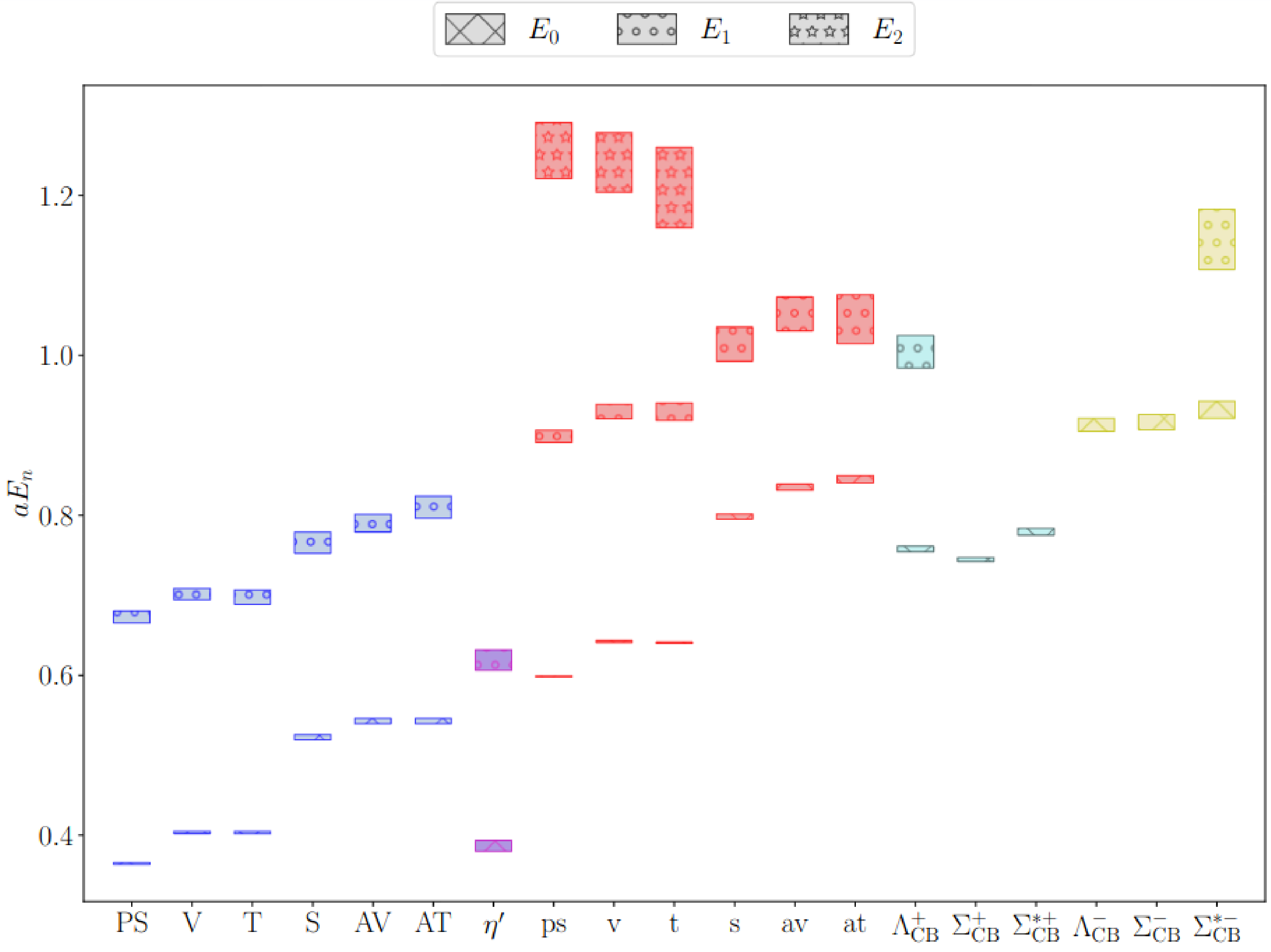
We are able to determine their masses and mixing angle!





- Encouraging proof of principle
- Caveat: Only heavy fermion masses accessible for now!

Example: Hadrons on a selected ensemble



Mesons and Baryons are accesible with our lattice methods

Summary

- Full light hadron spectrum of two-flavour $Sp(4)$
  - surprisingly light η' for moderately heavy fermions
  - first determination of isospin-2 $\pi\pi$ scattering
- Exploratory hadron spectrum of $Sp(4)$ with $N_f = 2^{(f)} + 3^{(as)}$

Outlook

- Full scattering analysis of $2\pi \to 2\pi$ and $3\pi \to 2\pi$ and resonances
- Better understanding of singlets and scattering states:
- Singlet spectroscopy closer to the chiral limit
- Lighter fermions for mixed-representation