dark matter from one-flavor SU(2) gauge theory

Anthony Francis
Renwick J. Hudspith
Randy Lewis
Sean Tulin

York University (Toronto)

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outline

- motivation
- the basic theory
- preliminary lattice explorations
- coupling to the standard model

motivation

- a minimal non-Abelian dark sector
- dark matter stability exists naturally

SU(2) with one Dirac flavor

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} + i\bar{Q}\gamma^\mu D_\mu Q + mQ^T CEQ$$

where $Q = \begin{pmatrix} \chi_L \\ C\bar{\chi}_R^T \end{pmatrix}, \quad E = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$

Q has no standard model quantum numbers.

$\mathcal{L}$ has an unbroken global SU(2), $Q \to e^{i\sum_{i=1}^3 T_i\alpha_i}Q$, which is the generalization of baryon number.

For m=0, $\mathcal{L}$ has an unbroken (but anomalous) global U(1), $Q \to e^{i\beta}Q$, like the axial U(1) in QCD. We expect the U(1) to be broken dynamically by a mass-like vev.

For $N_f > 1$, the global SU(2) would be SU(2N_f).

the particle spectrum

The theory will have mesons, baryons and glueballs.
Simple operators for mesons: $\bar{Q}\Gamma Q$
Simple operators for baryons: $Q^T C\Gamma E Q$

Recall $E = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$

The spectrum forms multiplets of the global SU(2).

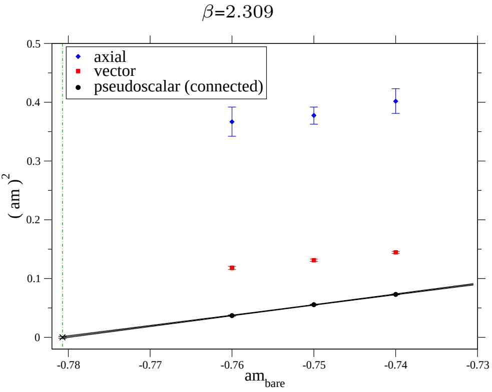
Examples:
$\bar{Q}\gamma_5 Q$ is a singlet. Let's name it η.
$\bar{Q}\gamma_\mu Q$ and baryon and antibaryon form a triplet $\rho^{\pm,0}$.

lattice ensembles

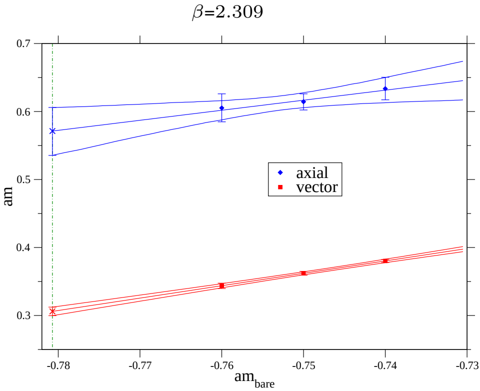
plaquette gauge action
Wilson fermion action
HiRep code [Del Debbio, Patella, Pica, PRD81, 094503 (2010)]

β	2.2	2.309
lattice dimensions	$20^3 \times 56$	$28^3 \times 56$
number of configurations	2000	1540
acceptance	73%	74%
unitary m_{bare}	-0.865	-0.76
partially quenched m_{bare}	-0.845, -0.855	-0.74, -0.75
average plaquette	0.5989	0.6255
aw_0	1.430(5)	1.956(7)
$m_V L$	9.0(2)	8.8(2)

preliminary lattice spectrum

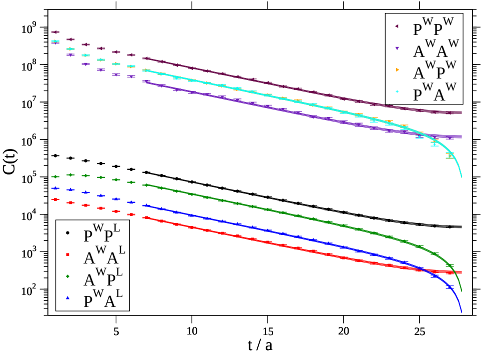


linear extrapolations



pseudoscalar correlators

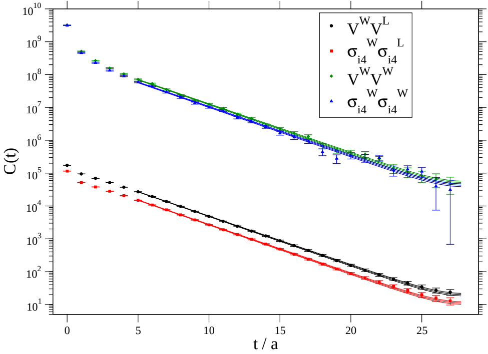
connected part only, β=2.309, $am_{\mathrm{bare}} = -0.76$



W=wall (Coulomb gauge fixed), L=local

vector correlators

β=2.309, $\quad am_{\rm bare} = -0.76$



W=wall (Coulomb gauge fixed), L=local

a large N_c limit

For $N_c > 2$,
one-flavor SU(N_c) does *not* have the global SU(2).

But recall SU(2) = Sp(2).

The global SU(2) is present for Sp(N_c). (N_c is even.)

In Sp(N_c),
the η becomes massless as $N_c \to \infty$ and $m_Q \to 0$.
In this double limit, the global U(1) is only broken dynamically and the η is its Goldstone boson.

particle spectrum for $N_c \to \infty$

How can the global SU(2) remain unbroken?

Mesons have this fermion content: $M = \sum_{i=1}^{N_c} \bar{Q}_i Q_i$
Baryons: ??? $X = \sum_{i,j,\cdots k=1}^{N_c} Q_i Q_j \ldots Q_k$??? No.

Sp(N_c) baryons are $B = \sum_{i=1}^{N_c} \sum_{j=1}^{N_c} Q_i E_{ij} Q_j$

X operators reduce to a collection of B operators.

Thus the global SU(2) remains unbroken.
Baryons B and mesons M remain degenerate.

Higgs couplings to the dark sector

Can dim=5 BSM physics destabilize dark matter? No.

$$\begin{array}{lll} \text{dim 5}: & \delta\mathcal{L} \sim \bar{Q}\gamma_5 Q H^\dagger H & (\text{couples to } \eta) \\ \text{dim 6}: & \delta\mathcal{L} \sim \bar{Q}\gamma^\mu Q H^\dagger \nabla_\mu H & (\text{couples to } \rho) \end{array}$$

Dark matter, ρ, is stable at dimension 5.

This feature is specific to the one-flavor theory.

Like SM proton decay, ρ decay is dimension 6.
Thus ρ can be stable for the life of the universe.

fermion mass with parity violation

The dark fermion gets mass from 2 sources:
BSM (dimension 4) and the SM Higgs (dimension 5):

$$\begin{aligned} \delta\mathcal{L} &= -m_4\cos\theta_4\bar{Q}Q - m_4\sin\theta_4\bar{Q}i\gamma_5 Q \\ &\quad -\frac{v^2}{\Lambda}\cos\theta_5\bar{Q}Q\left(1+\frac{h}{v}\right)^2 - \frac{v^2}{\Lambda}\sin\theta_5\bar{Q}i\gamma_5 Q\left(1+\frac{h}{v}\right)^2 \end{aligned}$$

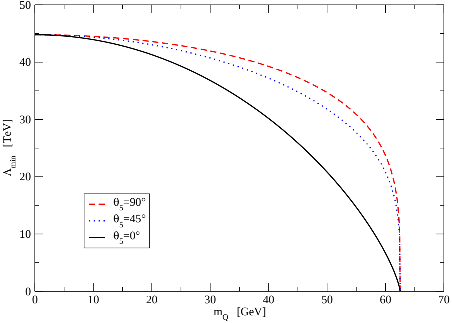
Λ=BSM scale. v=246 GeV. Parity violation allowed.

Mass terms: $\delta\mathcal{L} = m\bar{Q}_{\rm tw}Q_{\rm tw}$ where $Q_{\rm tw} \equiv e^{i\gamma_5\alpha/2}Q$.

Vector and axial hadrons are invariant under $Q \to Q_{\rm tw}$.

invisible Higgs decays for SU(2)

The experimental bound $\Gamma(h \to Q\bar{Q}) < 1.2$ MeV gives



decays from the dark sector

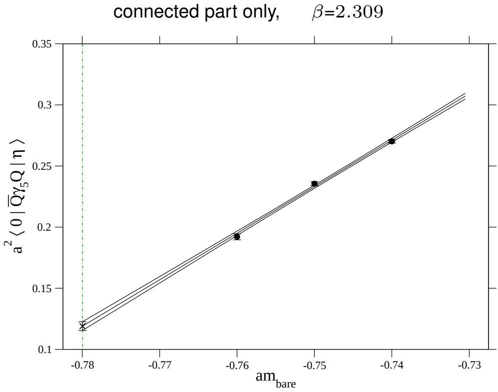
The only dark$\rightarrow$SM decays are through Higgs bosons.
If $\theta_5 \neq 0$, then η can decay through a single Higgs.

Recall: ρ is essentially stable due to the global SU(2).

Example:
BBN $\Rightarrow$ lifetime of η < 1 second.
Use $\langle 0|\bar{Q}\gamma_5 Q|\eta\rangle$ from lattice to bound $\frac{\sin\theta_5}{\Lambda}$.
For $m_\eta \ll m_H$,

$$\Gamma_\eta = \left|\langle 0|\bar{Q}\gamma_5 Q|\eta\rangle\right|^2 \frac{m_\eta \sin^2\theta_5}{2\pi\Lambda^2 m_H^4} \sum_{f\in\mathrm{SM}} m_f^2 \left(1 - \frac{4m_f^2}{m_\eta^2}\right)^{3/2}$$

amplitude useful for η decay



also in progress

1. direct detection: ρ scattering from a SM nucleon.

2. relic density:
Options for $m_\eta < m_\rho$ include • $\rho\rho \to \eta\eta$
• asymmetric dark matter
Options for $m_\eta > m_\rho$ include • $\rho\rho\rho \to \rho\rho$

Future lattice simulations will reveal $m_\eta - m_\rho$ ordering.
Disconnected diagrams are required.

For disconnected calculations in the 2-flavour theory, see Arthur, Drach, Hietanen, Pica, Sannino, 1607.06654 and Drach, Monday 14:15

summary

1-flavor SU(2) is a minimal non-Abelian dark sector.

It has a *global* SU(2) to stabilize dark matter.

It has no dark matter decay at dimension 5.

1 Goldstone boson should emerge for Sp($N_c \rightarrow \infty$).

SU(2)=Sp(2) lattice explorations are in progress.