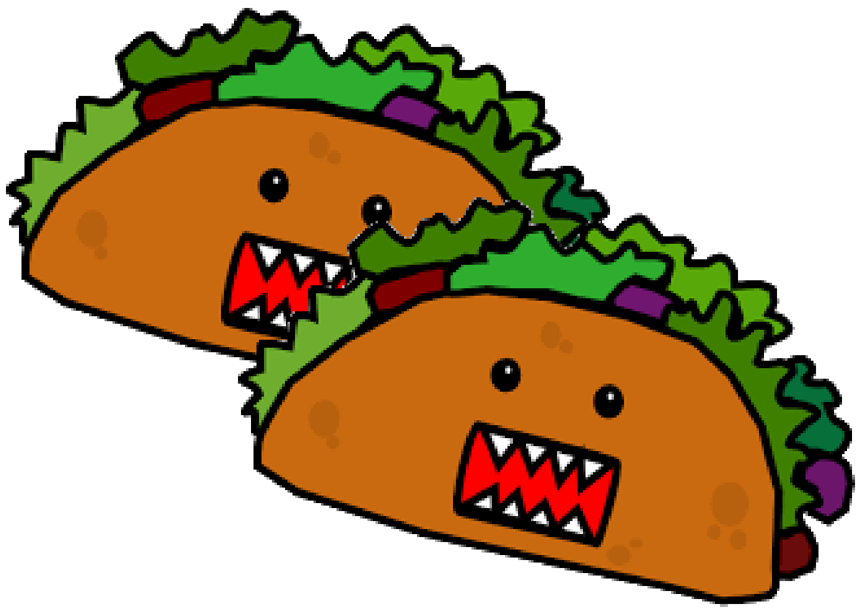
Partial compositeness on the lattice: $SU(4)$ gauge theory with fermions in multiple representations

Presented by Daniel Hackett
April 5, 2018
Lattice for BSM Physics 2018

The TACoS Collaboration



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Overview

Ferretti's model & our lattice deformation

- Composite Higgs, partially composite top quark
- Only fermions and gauge bosons; no fundamental scalars; no SUSY
- Multiple fermion representations: "multirep theory"
- First ever lattice investigation of a multirep theory [w/o SUSY, in 4D]

Results:

- Zero-temperature spectrum
  - Pseudoscalars, vectors, baryons
- Finite-temperature phase structure

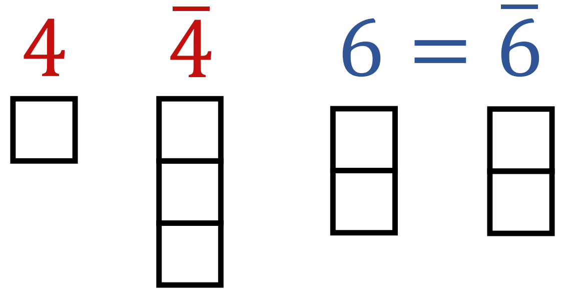
Ferretti's Model [arXiv:1404.7137]

"Hypercolor" $\mathrm{SU}(4)$ gauge theory coupled to

$N_4 = 3$ Dirac flavors of fundamental fermion (cf. QCD) q

$N_6^w = 5$ Weyl flavors of sextet (two-index antisymmetric) fermion Q

[**Note:** 6 is a real irrep of $\mathrm{SU}(4)$]



β function → QCD-like

Chiral symmetry breaking pattern

$$\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R \times \mathrm{U}(1)_X \times \mathrm{SU}(5) \times \mathrm{U}(1)_A \to \mathrm{SU}(3)_c \times \mathrm{U}(1)_X \times \mathrm{SO}(5)$$

[$\mathrm{U}(1)_A$ a non-anomalous superposition of $\mathrm{U}(1)_{A(4)}$ and $\mathrm{U}(1)_{A(6)}$]

Custodial symmetry in unbroken chiral subgroups:

$\mathrm{SU}(3)_c \times \mathrm{SO}(5) \times \mathrm{U}(1)_X$

$\supset G_{cus.} = \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_X$ [**Note:** $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \simeq \mathrm{SO}(4) \subset \mathrm{SO}(5)$]

$\supset G_{SM} = \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

Gauge $\mathrm{SU}(3)_c$ → QCD in Standard Model

Gauge $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ → Electroweak force in Standard Model

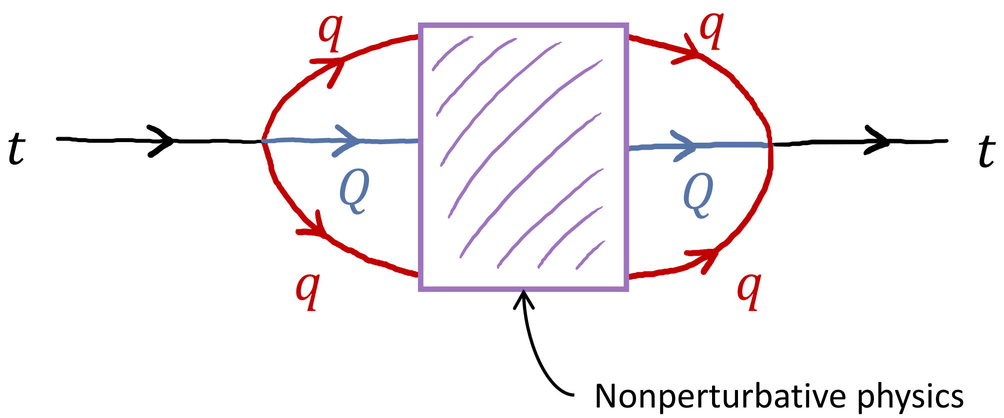
Ferretti model hadrons

Mesons

- $\bar{q}q$ fundamental pNGBs, vectors
- $QQ, \bar{Q}Q, \bar{Q}\bar{Q}$ sextet pNGBs, vectors
  - Ferretti limit $m_6 \to 0$: Higgs is massless sextet NGB
    - Higgs potential from SM interactions
    - Fermion masses from quadratic mixing $u\bar{u}H \to u\bar{u}QQ$
- Non-anomalous $\mathrm{U}(1)_A \to$ axial singlet pNGB (ζ meson)

Baryons

- Fundamental $qqqq$ [Boson]
- Sextet $QQQQQQ$ [Boson]
- Chimera Qqq [Fermion]
  - t partner: Mixes linearly with t via $tQqq = t\mathcal{O}_{PC}$
  - Qqq mass $\sim \Lambda_{HC} > \Lambda_{SM} \Rightarrow$ Large mass for t



Ferretti's model on the lattice

Goal: Investigate (semi-quantitatively) strong dynamics

Simulated theory: "Lattice-deformed Ferretti model" or "the multirep theory"

$\mathrm{SU}(4)$ gauge theory coupled to $N_4 = 2$ Dirac flavors of fundamental fermion
$N_6 = 2$ Dirac flavors ($N_6^w = 4$ Weyl flavors) of sextet fermion

Easier flavor content for lattice, $\sim$ same physics

- Same (types of) states as Ferretti model: ζ axial singlet pNGB, Qqq chimera baryon

Lattice action

- Wilson gauge action
  - + nHYP Dislocation Suppressing (NDS) term [DeGrand, Shamir, Svetitsky 2014]
- Clover-improved Wilson fermions with nHYP smearing
- 3D bare parameter space: β, κ_4, κ_6

Technical details

Simulate with Multirep MILC [Shamir]

Spectroscopy

Extract masses by fitting two-point functions

Measure fermion masses with Axial Ward Identity (AWI)

$$\partial_\mu \left\langle A_\mu^{(r)}(x) P^{(r)}(0) \right\rangle = 2m_r \left\langle P^{(r)}(x) P^{(r)}(0) \right\rangle$$

Pseudoscalar, vector decay constants from

$$\left\langle 0 \middle| A_\mu^{(r)} \middle| P^{(r)} \right\rangle \sim p_\mu F_P \qquad [F_\pi = 130\ \mathrm{MeV}\ \text{convention}]$$

$$\left\langle 0 \middle| V_i^{(r)} \middle| V_j^{(r)} \right\rangle = \delta_{ij} M_{Vr} F_{Vr}$$

Scale setting

Wilson flow with definitions adjusted for $N_c = 4$ [DeGrand 2016]

$$\langle t_0^2 E(t_0) \rangle = 0.1 N_c = 0.4$$

[Notation: any quantity without explicit as has been scaled by appropriate factors of t_0]

Zero-temperature data & analysis

$\mathcal{O}(40)$ ensembles

Volumes: $16^3 \times 18$, $16^3 \times 32$, $24^3 \times 48$

Masses: $0.5 \lesssim M_P/M_V \lesssim 0.8$

General approach:

Have ensembles at many m_4, m_6, a

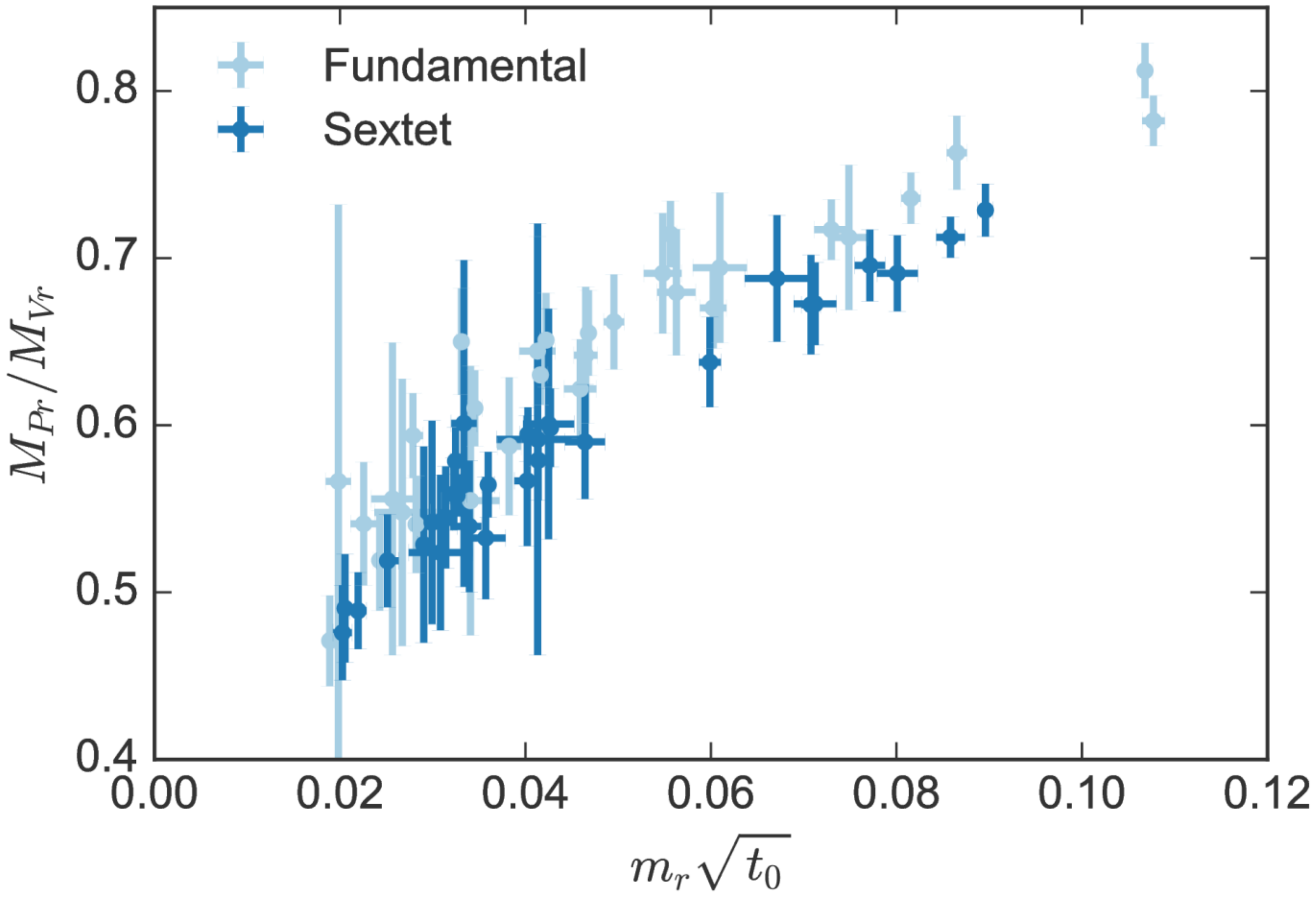
Fit **all** data to model in m_4, m_6, a

Model aware of a dependence

→ Can take continuum limit $a \to 0$

Model aware of m_r dependence

→ Can take chiral limits $m_r \to 0$



Modeling the pseudoscalar sector with χPT

Model

- Multirep χPT gives expressions for M_{P4}, M_{P6}, F_{P4}, F_{P6} as a function of m_4, m_6
  - [arXiv:1605.07738]
- Wilson fermions break chiral symmetry
  - Use Wilson χPT to account for lattice artifacts

Analysis: Fit lattice measurements of M_{P4}, M_{P6}, F_{P4}, F_{P6} to measure

B_4, B_6	[GMOR: $M_{Pr}^2 = 2B_r m_r + \cdots$]
F_4, F_6, F_ζ	[ζ sector has its own decay constant]
…and NLO LECs	[including LECs for a dependence]

Chiral fit works: $\chi^2/\mathrm{dof} = 0.48$ for $(172$ observations$)$ – $(21$ fit params$)$ = 151 dof

For more analysis details, see our paper [arXiv:1710.00806]

ζ meson contributes chiral logs to M_{P4}^2, M_{P6}^2

→ Chiral fit indirectly measures ζ sector! [In practice, use LO M_ζ and measure F_ζ]

ζ meson mass

Reconstruct M_ζ as a function of m_4, m_6 from chiral fit

Phenomenology:

In $m_6 \to 0$ limit, $M_\zeta < M_{P4}$

$\Rightarrow$ ζ meson lightest (massive) state in the spectrum

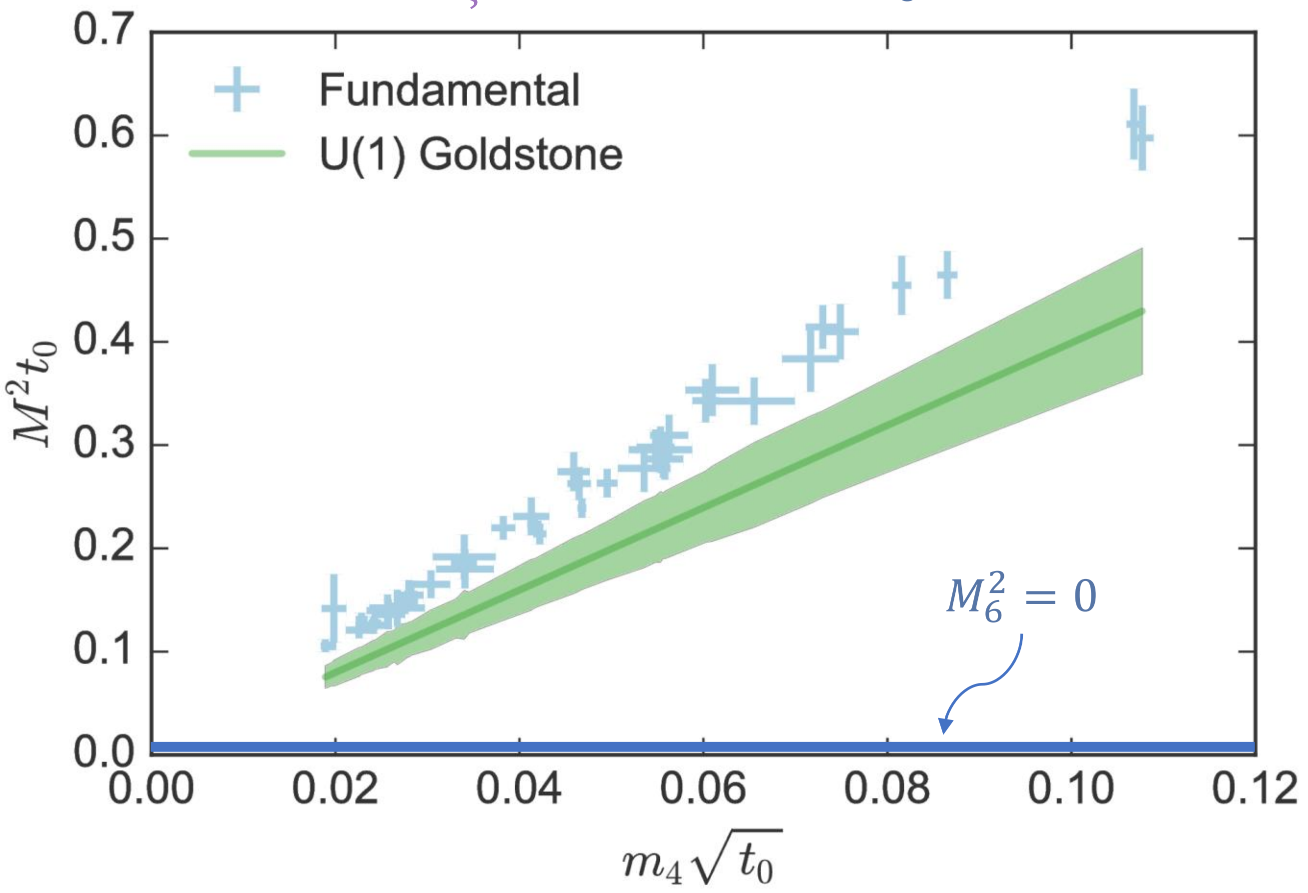
[Sextet pNGB is exactly massless]

Axial singlets decay to two SM gauge bosons

[Ferretti et al. arXiv:1610.06591]

$\Rightarrow$ Experimental constraints?

M_ζ in Ferretti limit ($m_6 \to 0$)



Vector meson decay widths from KSRF

Assuming vector meson dominance, predict widths of vector resonances:

$$\frac{\Gamma_{V\to PP}}{M_V} \approx \frac{M_V^2}{48\pi F_P^2}$$

Works (qualitatively) in QCD

For physical ρ, predicts ~ 0.23 vs experimental ~ 0.19

Analysis: Take $a \to 0$ by subtracting lattice artifacts

Fit data from 30 ensembles

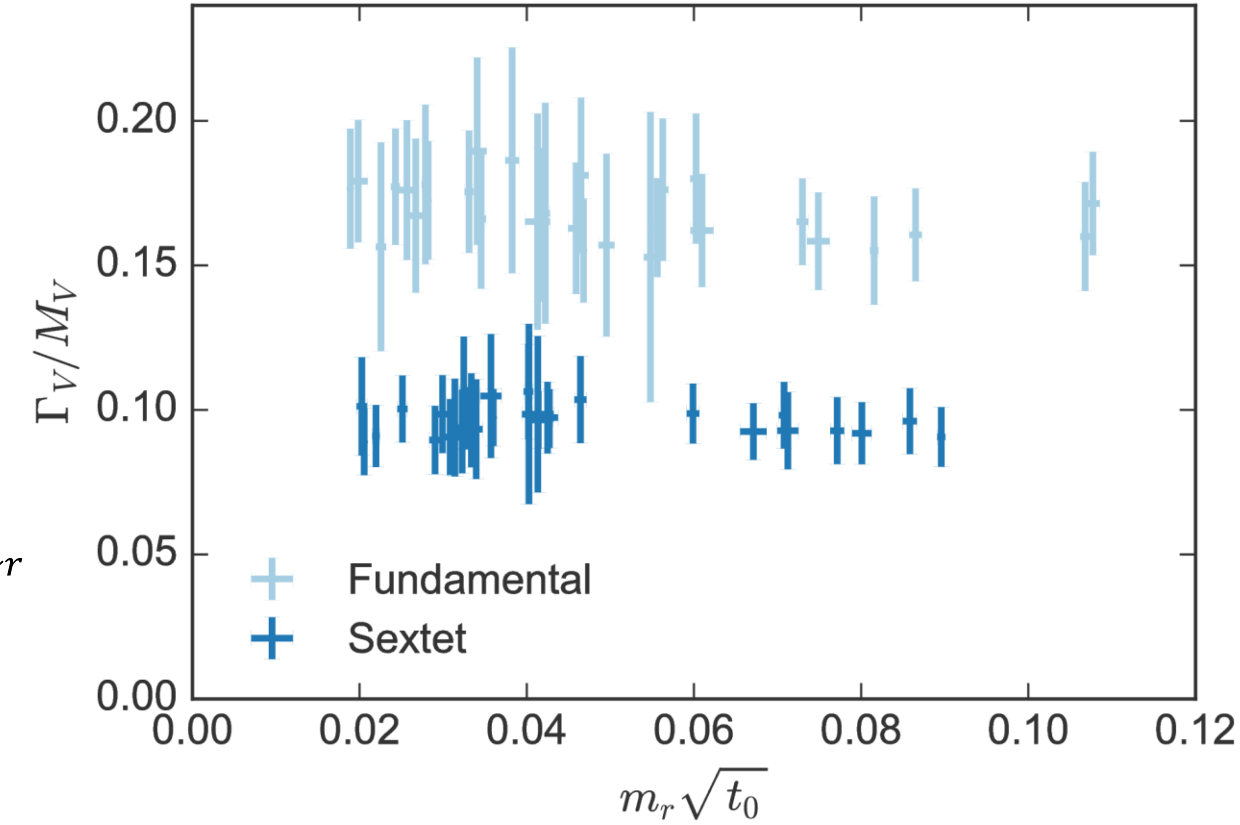
Empirical model for M_{Vr}, F_{Vr}: linear in a and same-rep m_r

Prediction: broad vector resonances

[but narrower than QCD]

[KSRF: Kawarabayashi, Suzuki 1966; Riazuddin, Fayyazuddin 1966]

[After subtracting lattice artifacts]



Baryon spectrum: quark model

Fermions acquire dynamical mass, so define "constituent masses"

$$m_4^{(c)} = C_4 + C_{44} m_4 \qquad m_6^{(c)} = C_6 + C_{66} m_6$$

Baryon masses: constituent masses + rotor splitting [J is total spin]

$$M_{q^4} = 4m_4^{(c)} + \cdots J(J+1) + \cdots a$$

$$M_{Q^6} = 6m_6^{(c)} + \cdots J(J+1) + \cdots a$$

Chimera baryons Qqq get additional rotor corrections [I is spin of qq]

$$M_{Qqq} = 2m_4^{(c)} + m_6^{(c)} + C + \cdots a + \cdots J(J+1) + \cdots I(I+1)$$

[Can justify more rigorously as $1/N_c$ expansion. See preprint: arXiv:1801.05809]

Quark model fit

Baryon masses for 12 ensembles

- Baryons noisy, difficult to fit

10 baryon masses per ensemble

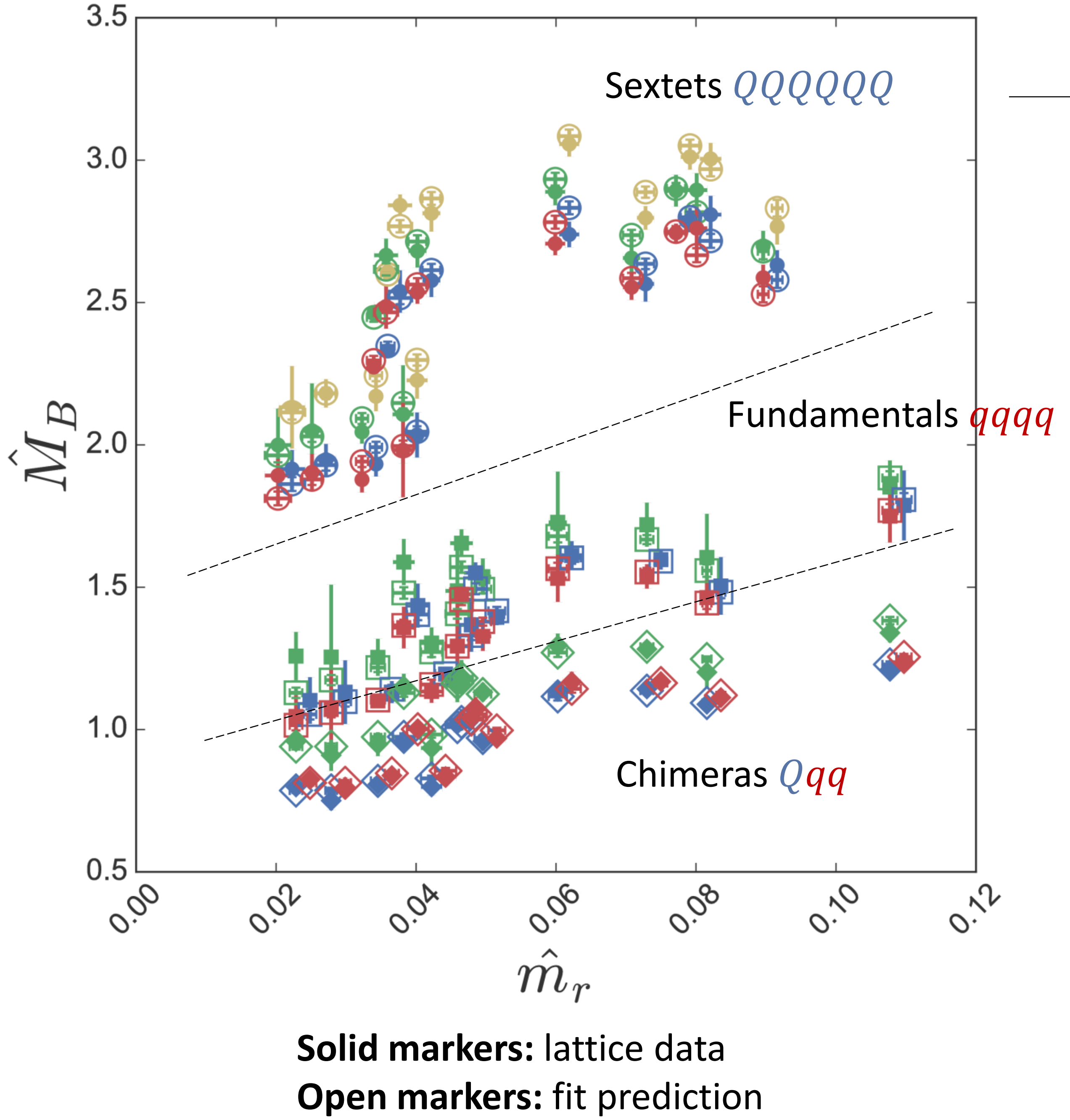
- Sextet Q^6 with $J = 0,1,2,3$
- Fundamental q^4 with $J = 0,1,2$
- Chimera Qqq with

$$(J, I) = \left(\frac{1}{2}, 0\right), \left(\frac{1}{2}, 1\right), \left(\frac{3}{2}, 1\right)$$

Top partner

Simultaneous fit to all 120 baryon masses

- 120 measurements – 11 fit params = 109 dof
- Good fit: $\chi^2/\mathrm{dof} = 0.85$



Baryon spectrum in Ferretti limit

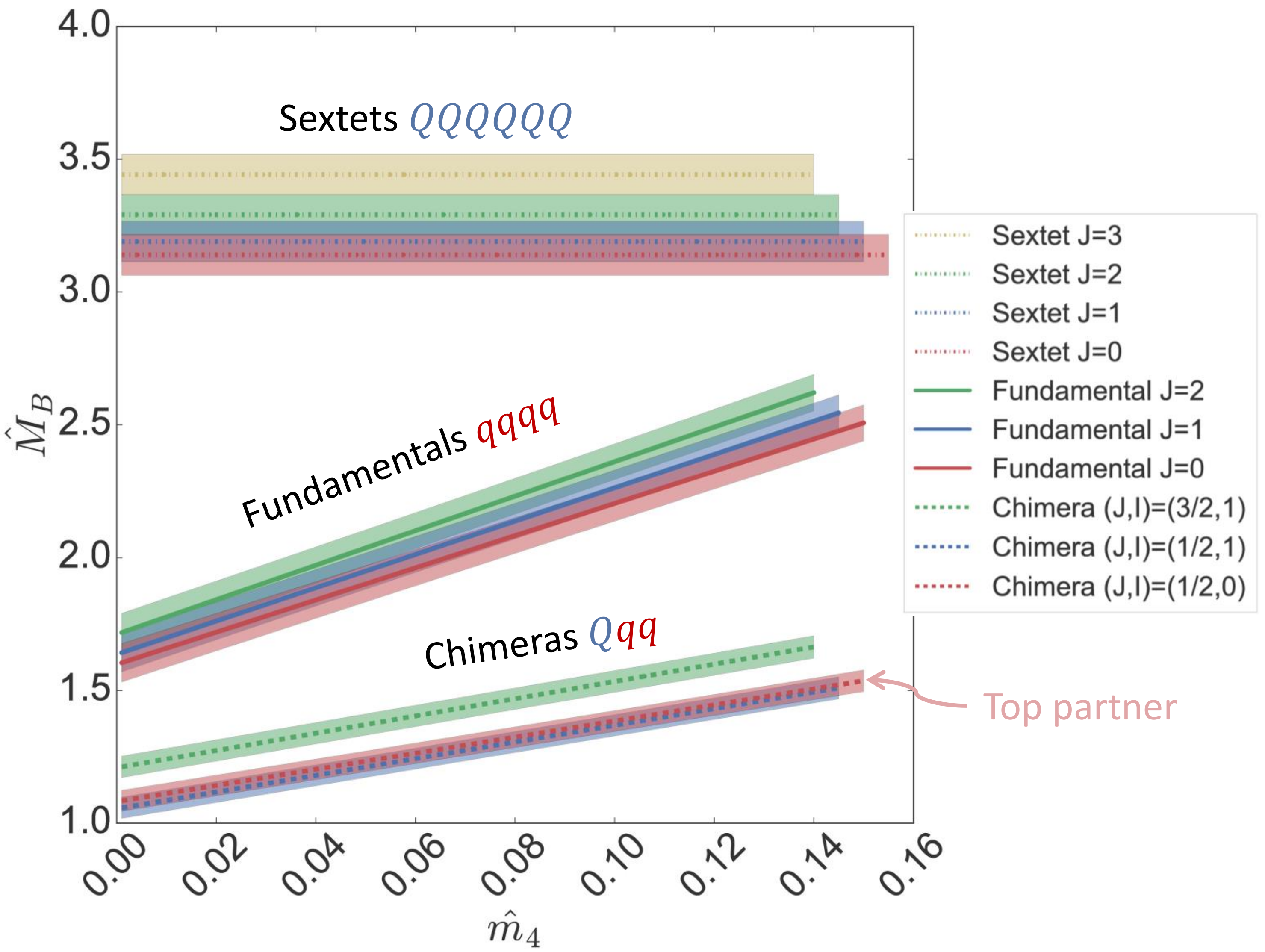
Use model to take $a \to 0$, $m_6 \to 0$

Sextet masses constant by construction

Top partner:

$\sim$ degenerate with $(1/2, 1)$ chimera

Lightest states in baryon spectrum



Spectrum in Ferretti limit

Experimental constraints:

$$F_6 \gtrsim 1.1\ \mathrm{TeV}$$

$\Rightarrow M \gtrsim 6.5\ \mathrm{TeV}$ for top partner

See our paper for details [arXiv:1801.05809]

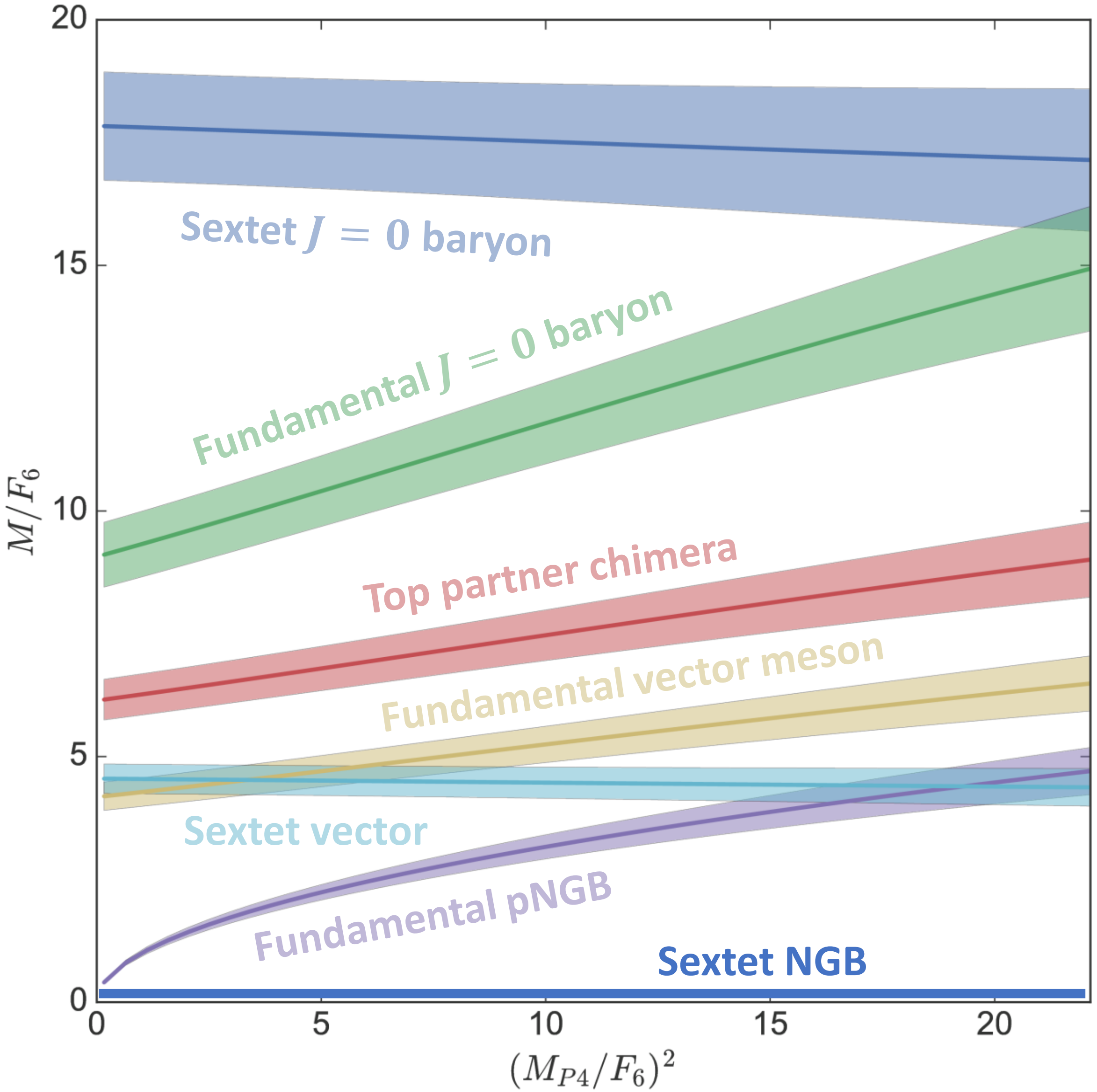
Summary: set of models predicts

Ms, Fs for pseudoscalar and vector mesons

Baryon masses

...in the continuum limit, as a function of m_4, m_6

$\Rightarrow$ Measure one mass, predict entire spectrum!



Thermodynamics

Zero-temperature results: both fermion species are chirally broken

Theory is asymptotically free

$\Rightarrow$ Both fermion species deconfined at high temperature

Questions:

- How many phase transitions between $T = 0$ and $T = \infty$?
  - Tumbling/condensation in to Most Attractive Channel [Raby, Susskind, Dimopolous 1980]
  - Prediction: sextets condense before fundamentals, intermediate "partially confined" phase
- Order of phase transition(s)?
- Transition temperature(s)?

[arXiv:1802.09644]

Numerical details

$\mathcal{O}(500)$ ensembles

Mostly $12^3 \times 6$ and $16^3 \times 8$

Mostly at $\beta = 7.4, 7.75$

Spectroscopy

Lattices with short temporal extent

→ Measure screening masses

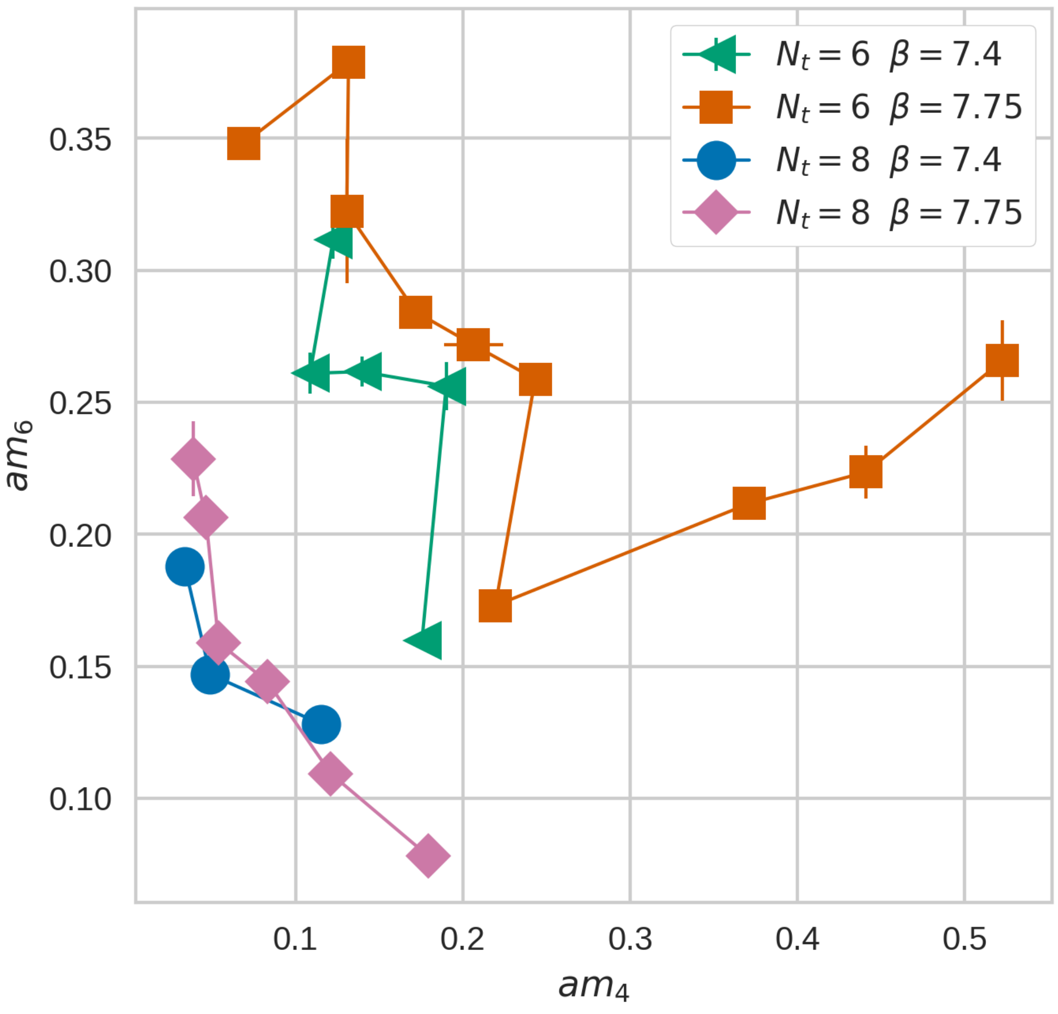
Scale setting

t_0 contaminated by finite-a effects in regions of interest

Instead, use t_1: $\langle t_1^2 E(t_1) \rangle = \frac{2}{3}\frac{N_c}{3} = \frac{8}{9}$

[Sommer arXiv:1401.3270]

Lattice-units fermion masses near transition

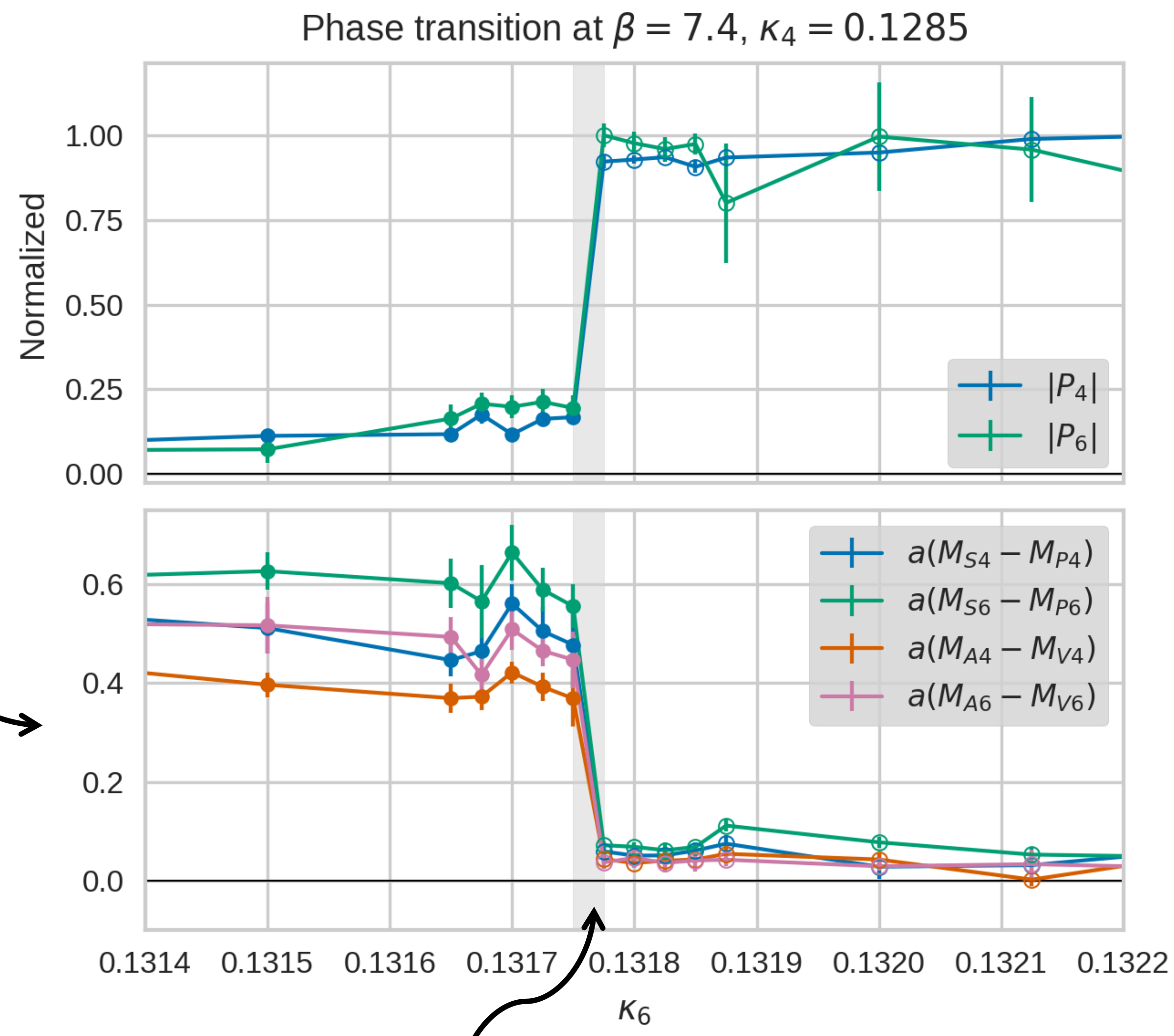


No intermediate phase

(Normalized) Confinement Diagnostics
(Polyakov loop for each irrep is small when species is confined, large when deconfined)

Chiral Transition Diagnostics
(Parity doubling: when irrep is chirally restored, S and PS (V and PV) mesons become degenerate)

Typical slice for explored regions of parameter space
⇒ Only two phases, like in QCD



Gray band: all transitions occur simultaneously

Transition is first-order

All observables jump at the transition

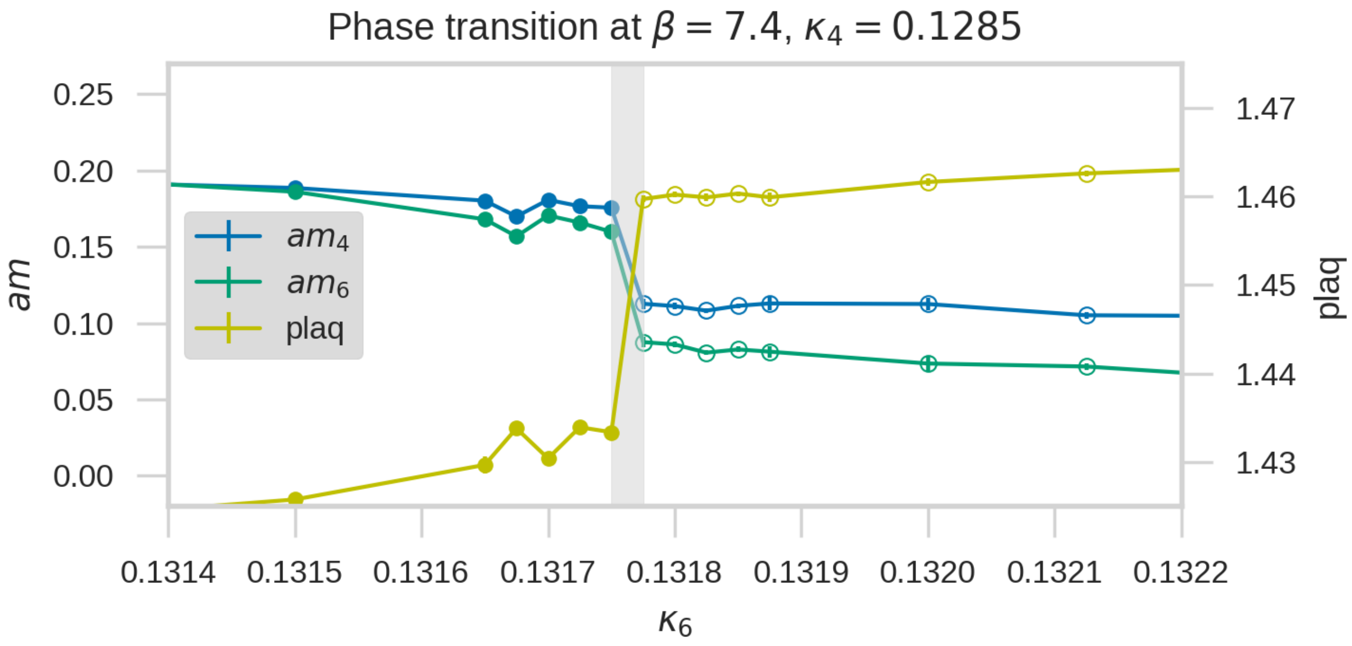
Discontinuity is present everywhere

Transition is sharp

Observables are either "confined-like" or "deconfined-like," with no interpolation

Also observe metastability in equilibration

⇒ (Violently) first-order transition!



Phenomenology: first-order transitions in the early universe make gravitational waves

[Schwaller arXiv:1504.07263]

[LISA arXiv:1610.06481]

Same slice as previous slide
Left axis: axial Ward identity quark masses in lattice units
Right axis: Plaquette (roughly, energy density of gauge sector)

Analytics: “multirep Pisarski-Wilczek”

Generalization of calculation by Pisarski and Wilczek [PW 1984]

Recently extended to high order for complex, real irreps [Pellisetto, Vicare 2003, 2005, 2005’]

Idea: Does 3D EFT of scalar/pseudoscalar modes have any stable fixed points?

If not, transition must be first order!

Inputs:

Chiral symmetry breaking pattern

$$\mathrm{SU}(N_4)_L \times \mathrm{SU}(N_4)_R \times \mathrm{SU}(N_6^w) \times \mathrm{U}(1)_A \rightarrow \mathrm{SU}(N_4)_V \times \mathrm{SO}(N_6^w)$$

Transition occurs simultaneously for 4 and 6 (as observed)

Work to first order in ϵ expansion

Result: No stable fixed points ⇒ Transition must be first-order

Applies to both Ferretti model and lattice deformation

[arXiv:1712.01959]

Transition temperature

Roughly: $T_c \sim 0.2/\sqrt{t_1}$

Comparison with QCD:

In QCD: $1/\sqrt{t_0} \approx 1380$ MeV

[MILC arXiv:1503.02769]

$\Rightarrow 1/\sqrt{t_1} = 770$ MeV

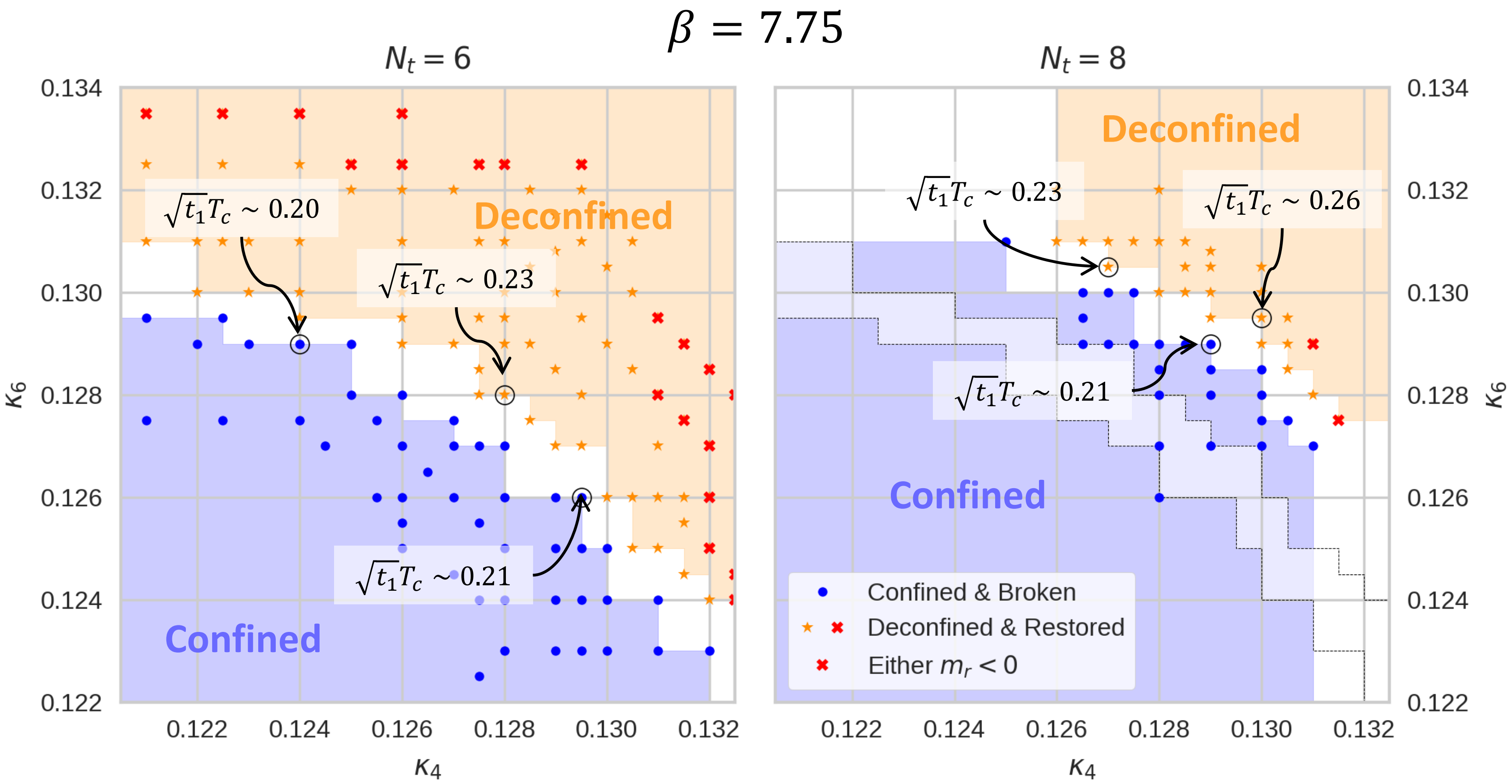
$\Rightarrow T_c \sim 150$ MeV

Phenomenology:

Experimental bound: $F_6 \gtrsim 1.1$ TeV

$\Rightarrow 1/\sqrt{t_1} \gtrsim 3.7$ TeV

$\Rightarrow T_c \gtrsim 720$ GeV



Conclusions

Theory "acts like QCD"

- Pseudoscalar spectrum described by χPT
- Vector resonances probably broad [but narrower than QCD]
- Baryon spectrum described by quark model
- Phase structure like QCD's [except transition is first-order]
- Transition temperature QCD-like

Fitting to models (physically-motivated and empirical) has been a very fruitful, efficient approach

Many predictions to make contact with phenomenology