Spectroscopy of SU(4) gauge theory with multiple fermion representations

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USQCD All Hands Meeting 2016

[with T. DeGrand (CU), W. Jay (CU), D. Hackett (CU), Y. Shamir (Tel Aviv), B. Svetitsky (Tel Aviv)]

Why multiple fermion representations?

- Never studied dynamically before. Does chiral symmetry breaking look different? Potential hierarchy of scales,

$$\langle \bar{\psi}_a \psi_a \rangle \gg \langle \bar{\psi}_b \psi_b \rangle ?$$

- Dynamical scale separation would be a rich playground for model building (some tenuous connections to old literature on “tumbling”)

- Further motivation from composite Higgs models, particularly when partial compositeness is used to generate top quark mass.

Composite Higgs and partial compositeness

- Technicolor models: $SU(2)_L$ broken by chiral condensate <ψψ>, gives EW scale v~f. Higgs boson emerges from dynamics of theory; pseudo-dilaton? Some lattice interest (LSD, LatHC proposals.)

- Composite Higgs: $SU(2)_L$ preserved by chiral condensate <ψψ>. Higgs state is exact Goldstone: potential generated by interactions breaks EW, leading to v<f. Limited study on lattice to date.

- In either framework, SM fermion masses from four-fermion interactions:

Extended technicolor:

$$\bar{q}q\bar{\psi}\psi \sim \bar{q}q\mathcal{O}_{ETC}$$

Partial compositeness:

$$q\psi\psi\psi \sim q\mathcal{O}_{PC}$$

mass mixing!

- Partial compositeness is argued to improve FCNC bounds (with walking/large anomalous dimensions), but we are more agnostic: interesting to study the mechanism in any model where viable top-quark partners can arise.

Multiple irreps for partial compositeness

from G. Ferretti, "Gauge theories of partial compositeness", arXiv:1604.06467:

(irreps)[1]. The requirement of two different irreps arises from the need to construct top-partners carrying both color and EW quantum numbers. With the notable exception of a model by L. Vecchi [9], this requires at least two separate irreps; one, generically denoted by ψ, carrying EW quantum numbers in addition to hypercolor, the other, χ, carrying ordinary color as well as hypercolor.

At low energies, the theory is expected to confine after having spent a part of the RG evolution

- Two fermion species: ψ (EW charged), χ (color charged)
- Top partners must be fermions with <u>both</u> electroweak and QCD charge: can arise as ψχψ, or χψχ. (Five-fermion bound states possible, but would require even bigger anomalous dims…)
- See reference for an attempt to catalogue theories by gauge group and fermion content

Our model: SU(4) with two irreps

- Identified in Ferretti classification as one of the simplest UV completions! SU(4) gauge group, with two kinds of fermions: **χ** (fundamental [4] rep) and **ψ** (two-index antisymmetric [6] rep)
- The **ψ**'s are in a real representation. Chiral symmetry breaks $SU(N_Q)/SO(N_Q)$; Higgs boson is produced as one of these PNGBs. (No model detail in this talk: see 1604.06467.)
- Bound states?

"Mesons":

$\bar{\chi}\chi$

$\bar{\psi}\psi, \psi\psi$

"Baryons":

$\chi\chi\chi\chi$

$\psi\psi\psi\psi\psi\psi$

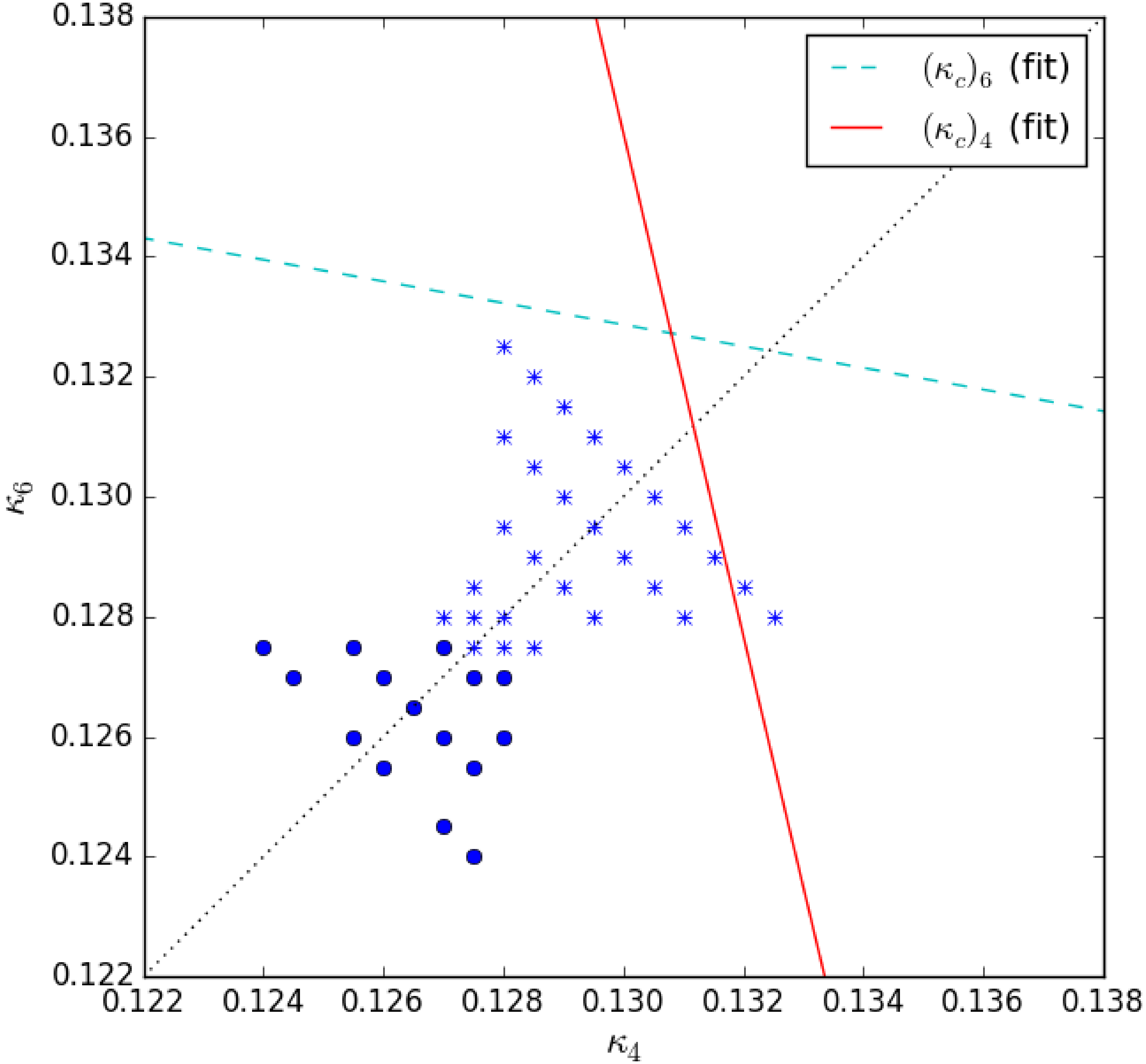
"Chimeras":

$\chi\chi\psi$ ← top-quark partner!

Software: “multirep MILC”

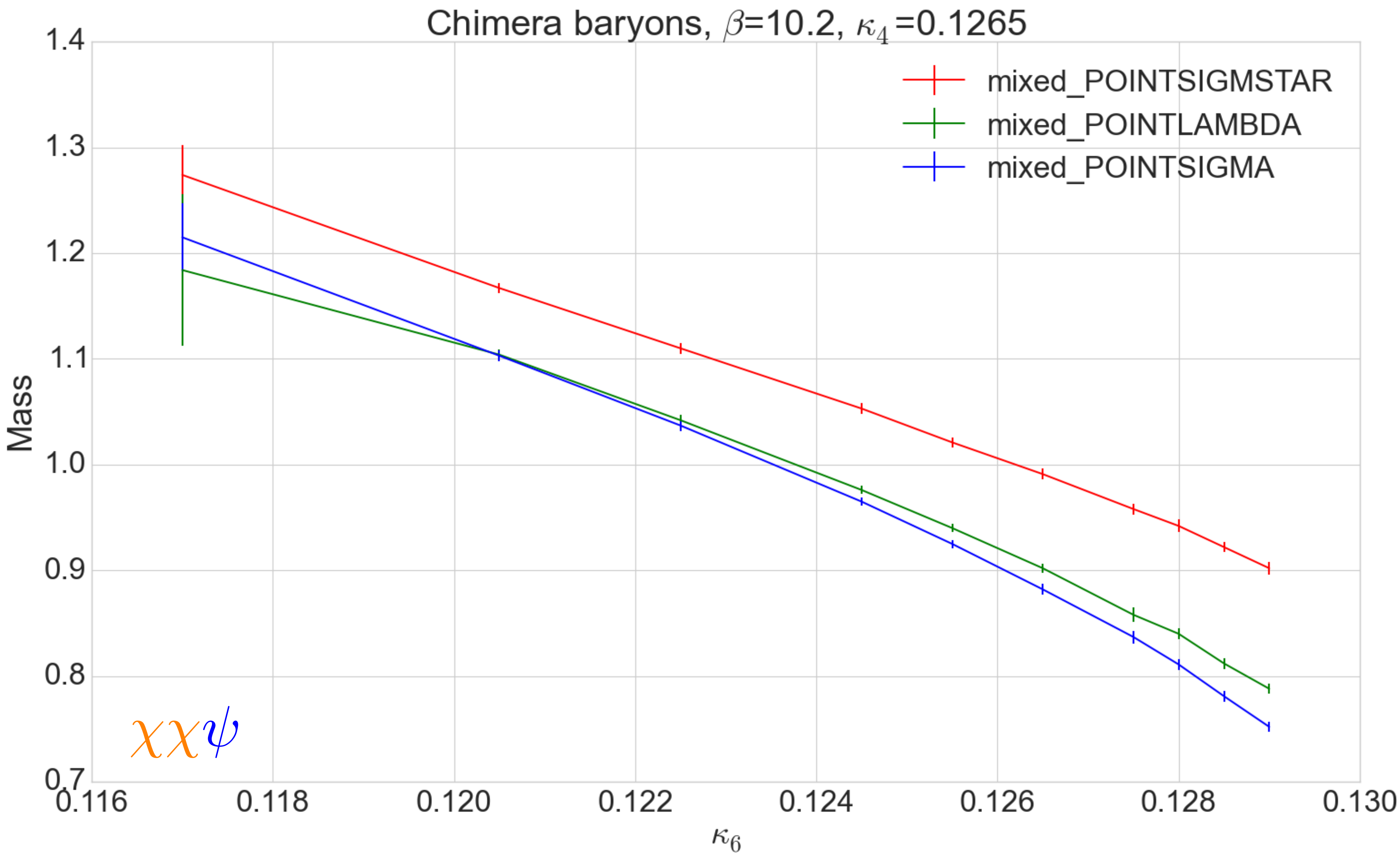
- Based on a branch of the MILC v7 code, focused on Wilson fermions
- Dynamical code generation using Perl: N_c and representation(s) are fixed in code generation, allowing C compiler to optimize matrix ops
- Bells and whistles: clover term, nHYP smearing, Hasenbusch preconditioning, multi-level integrator, dislocation-suppressing “NDS” action (DeGrand, Shamir, Svetitsky: 1407.4201)
- We use all of the above, i.e. clover nHYP fermions w/NDS action; c_{SW} set to 1 (shown to work well w/smearing)

Preliminary results: finite-T phase diagram, β=7.75, 12^3x6



(from D. Hackett)

Preliminary results: partially-quenched study of chimeras, 16^3x32



"Sigma"-like state (I=1) lighter than "lambda"-like (I=0) at small m_6 - inverted from QCD

(from W. Jay)

Resource request

- Initial study of spectroscopy; attempt to make contact with ChPT.
- Maintain roughly $r_1/a \sim 3.0$ ($a \sim 0.1$fm in QCD) and $M_\pi L > 4$
- Extrapolate along three lines: decreasing m_4, m_6, and both
- Cost estimates using standard scaling from $12^3 \times 24$ pilot study

$$\text{cost} = \frac{24,000 \text{ core-hr}}{\text{ktraj}} \left(\frac{\mathrm{V}}{16^3 \times 32}\right)^{5/4} \left(\frac{1.43}{\mathrm{r_1 M_{\pi,4}}}\right)^2 \left(\frac{1.75}{\mathrm{r_1 M_{\pi,6}}}\right)^2$$

V	$r_1 M_{\pi,4}$	$r_1 M_{\pi,6}$	$M_{\pi,4} L$	$M_{\pi,6} L$	cost/ktraj	# traj
$16^3 \times 32$	1.5	1.5	8.0	8.0	30k	4000
$16^3 \times 32$	1.5	1.2	8.0	6.4	46k	4000
$16^3 \times 32$	1.5	0.9	8.0	4.8	82k	4000
$16^3 \times 32$	1.2	1.5	6.4	8.0	46k	4000
$16^3 \times 32$	0.9	1.5	4.8	8.0	82k	4000
$16^3 \times 32$	1.2	1.2	6.4	6.4	72k	4000
$16^3 \times 32$	0.9	0.9	4.8	4.8	229k	4000
$24^3 \times 48$	1.5	0.6	16.0	6.4	1.41m	1000
$24^3 \times 48$	0.6	1.5	6.4	16.0	1.41m	1000
total					5.17m	

Conclusion

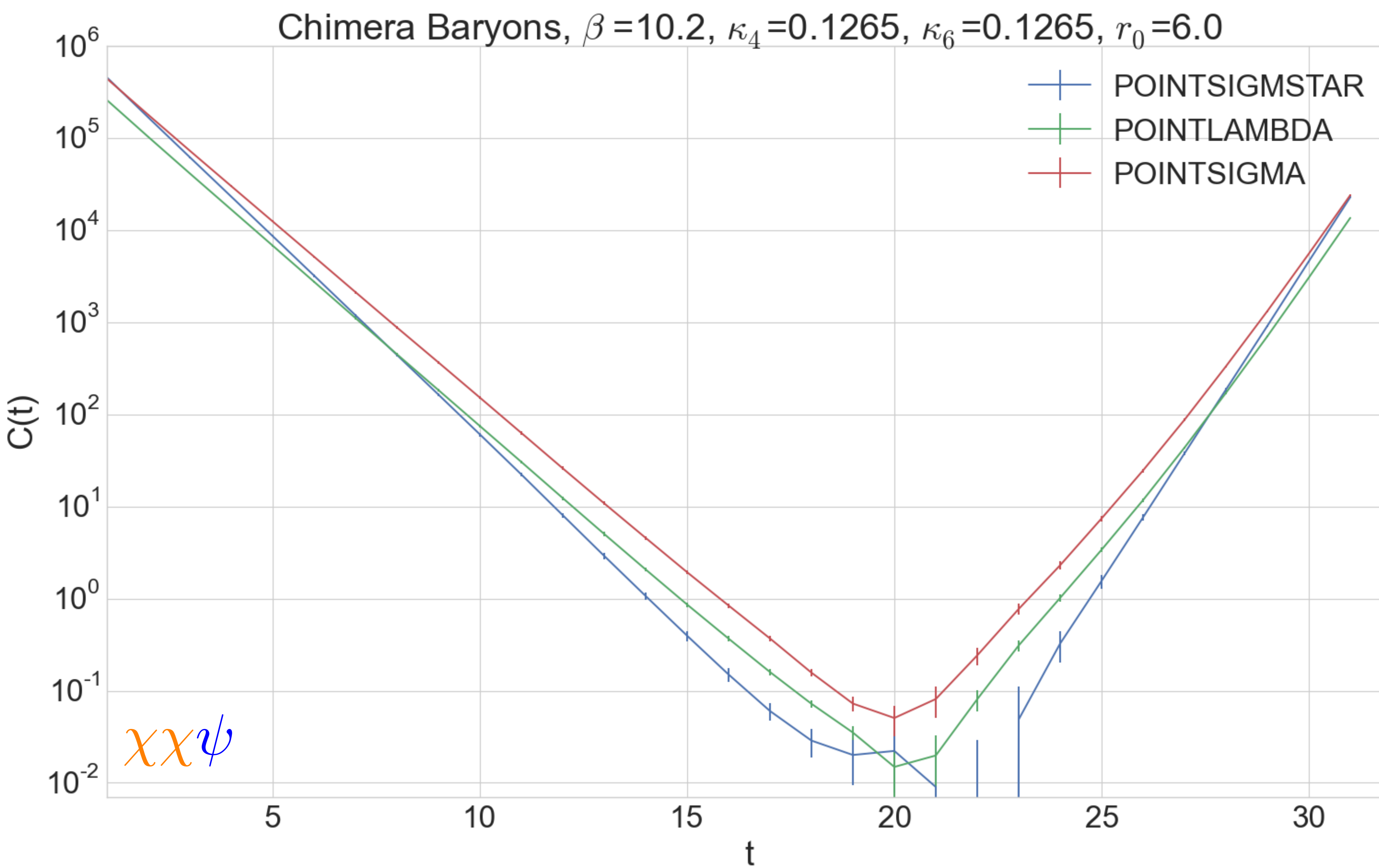
- Gauge theory with multiple fermion irreps is well-motivated, and has not been studied dynamically. High interest in context of partial compositeness BSM models.

- SU(4) two-irrep target theory is one of the simpler examples, many interesting quantities can be studied for composite Higgs phenomenology, and we can look for dynamical scale separation

- We request **5.17 million** J/Psi core-hours for our calculation, and 0.5 terabytes of storage

Backup slides

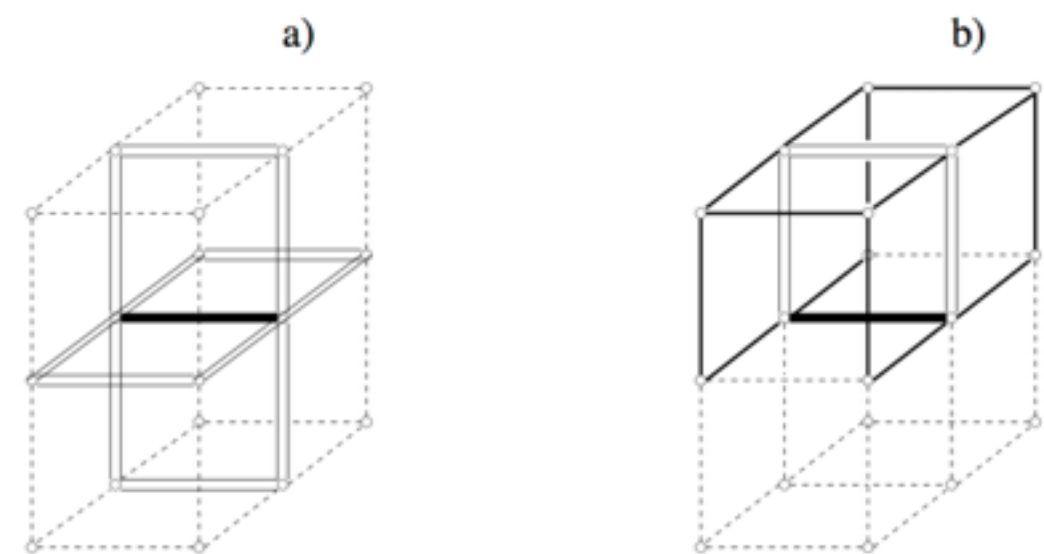
Preliminary results: partially-quenched chimera baryon correlator



NDS action (arXiv:1407.4201)

- HYP smearing: staple sum over “fat links” added to original link. nHYP normalizes the smeared link W, i.e.

$$V = \Omega(\Omega^\dagger \Omega)^{-1/2}$$



- $Q^{-1/2}=(\Omega^\dagger\Omega)^{-1/2}$ appears in the fermion force, and small eigenvalues can cause spikes. “nHYP dislocation suppressing” action cancels these with additional marginal gauge terms:

$$S_{\rm NDS} = \frac{1}{2N_c}\sum_x \mathrm{tr}\left(\gamma_1 \sum_\mu \tilde{Q}^{-1}_{x,\mu} + \gamma_2 \sum_{\mu\neq\nu} \bar{Q}^{-1}_{x,\mu;\nu} + \gamma_3 \sum_{\rho\neq\xi} Q^{-1}_{x,\rho;\xi}\right).$$

- Bare gauge coupling depends on β and γ; we fix the ratio and adjust β to move lattice spacing.