The Baryon Spectrum of a Composite Higgs Theory

PRD **97**, 114505 (2018) [1801.05809]

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Lattice 2018

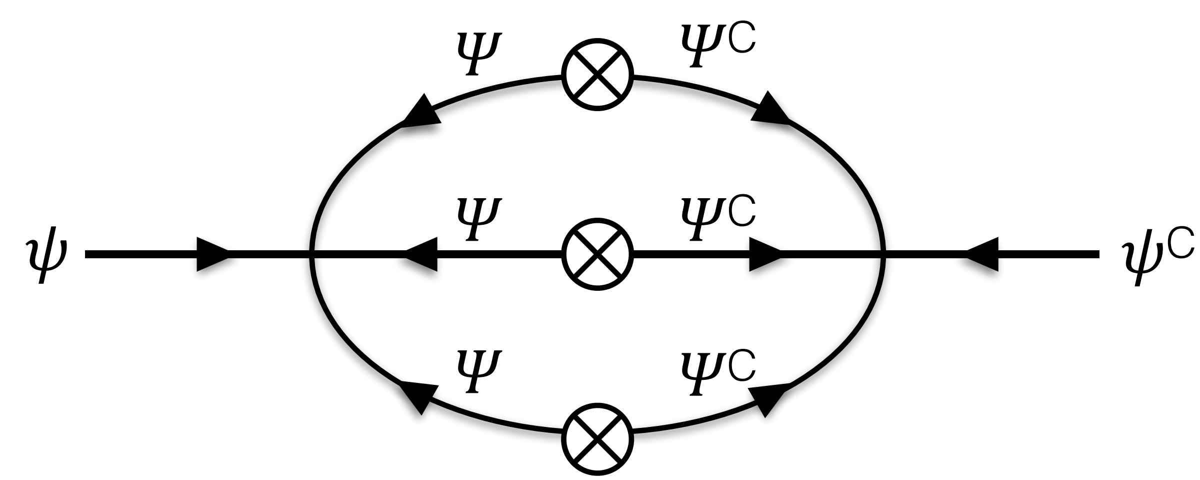
with the TACo Collaboration
(Ayyar, DeGrand, Hackett, Neil, Svetitsky, Shamir)

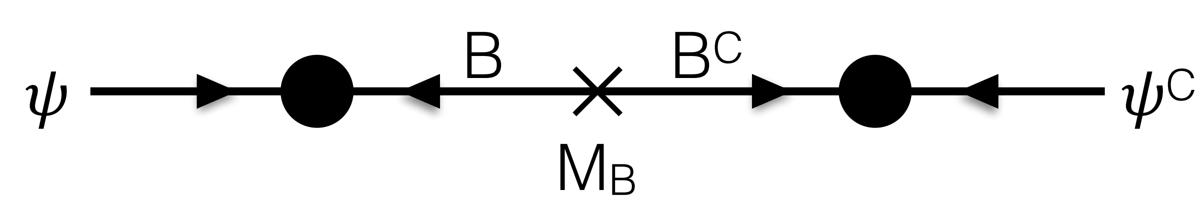
Could masses in the EW sector come from new strong dynamics?

- EWSB from a composite Higgs
    - Chiral condensate preserves $SU(2)_L$
    - Higgs arises from SSB as an exact Goldstone boson
    - SM loops generate a potential for the Higgs and trigger EWSB
- Fermion masses from 4-fermion interactions
    - Quadratic coupling to UV bosonic operators —"extended technicolor"
    - Linear coupling to UV fermionic operators — "partial compositeness"
    - D.B. Kaplan, Nucl Phys B365 (1991) 259-278

$$\psi\psi\Psi\Psi \sim \psi\psi\mathcal{O}_{\mathrm{ETC}}$$

$$\psi\Psi\Psi\Psi \sim \psi\mathcal{O}_{\mathrm{PC}}$$

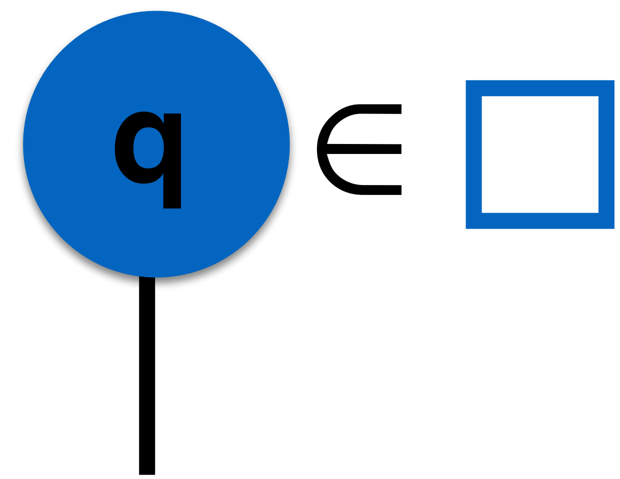


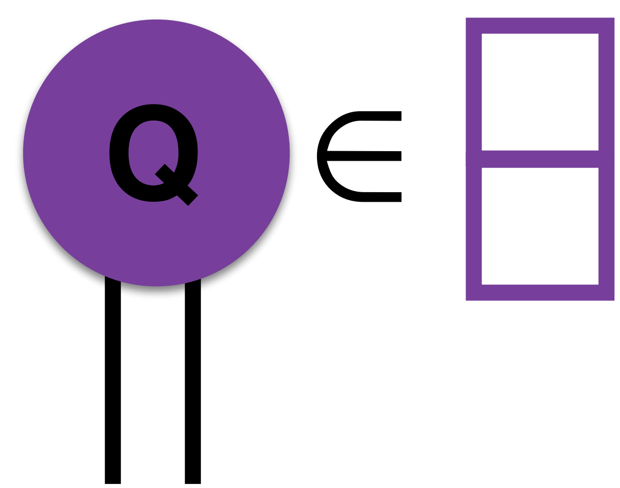


Ferretti's Model

Composite Higgs + partially composite top [1404.7137]

- SU(4) gauge theory
- 3 flavors of fundamental Dirac fermions
- 5 flavors of "sextet" Majorana fermions
  - 5 Majorana ↔ "2.5 Dirac"
- Symmetries and the Standard Model
  - $SU(3) \times SU(3)' \rightarrow SU(3)_{diag} \times U(1)_X$
  - $SU(5) \rightarrow SO(5) \supset SO(4)$ "≌" $SU(2)_L \times SU(2)_R$
- Physical limit: $m_6 \rightarrow 0$ ("sextet mass to zero")
- Tunable parameter of model: m_4





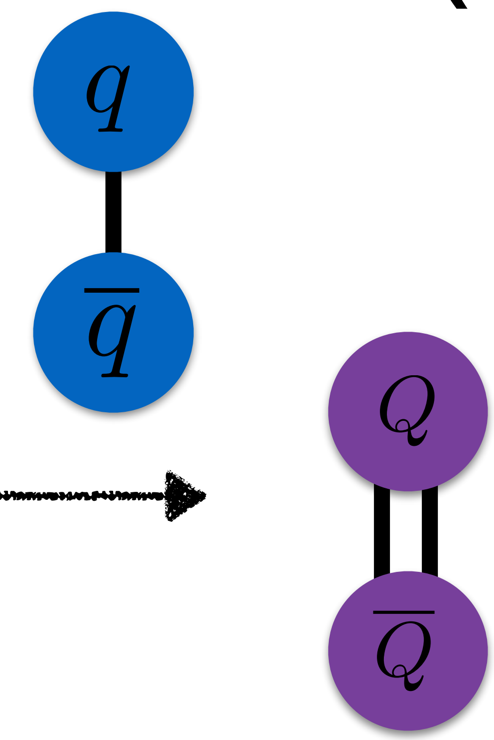
Technical details

- SU(4) gauge theory, but modified matter content
  - 3 $\mapsto$ 2 Dirac fundamental SU(4) fermions
  - 2.5 $\mapsto$ 2 Dirac sextet SU(4) fermions
- Multirep MILC code (Y. Shamir)
- NDS gauge action (T. Degrand, Y. Shamir, and B. Svetitsky [1407.4201])
- Clover-improved Wilson fermions
- 12 ensembles
  - 6 different β values
  - $V = 16^3 \times 32$
  - About 50 – 100 configurations / ensemble
- Set the scale with the Wilson flow scale [$\sqrt{t_0} = 0.14$ fm in QCD]
  - Flow scale: $1 \lesssim t_0/a^2 \lesssim 2.7$ ["0.08 fm $\lesssim$ a $\lesssim$ 0.13 fm"]
- Masses: $0.5 \lesssim M_P/M_V \lesssim 0.8$ [QCD: "$M_P \gtrsim 450$ MeV"]

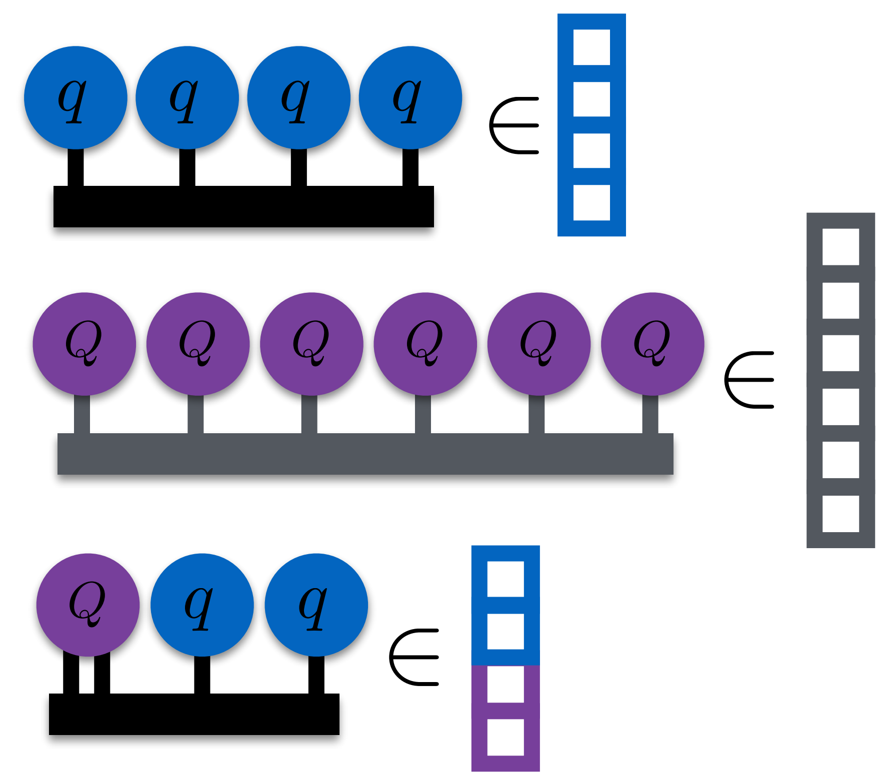
$$\hat{m} = (m \cdot a) \times (\sqrt{t_0}/a) = \text{dimensionless}$$

States in Multirep SU(4)

- Mesons: color-singlet two-fermion object
  - Fundamental — analogous to QCD
  - Sextet — similar
  - See PRD **97**, 074505 (2018) [1710.00806] or talk to me for details of the mesons

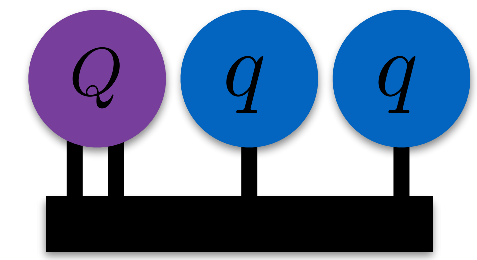


- Baryons
  - Fundamental-only: $(qqqq)_{SU(4)}$
  - Sextet-only: $(QQQQQQ)_{SO(6)}$
  - Mixed-representation: $(Qqq)_{SU(4)}$
    “Chimera baryons”



Chimera Baryons

and the top quark partner



- Intuition: hyperons (S=-1) in QCD: Σ^*, Σ, Λ
- Sextet **Q** plays the role of a (light) strange quark
- Ferretti's model: fundamental **q** are charged under SU(3) color; sextet **Q** is neutral under SU(3) color
- Recall: $3 \otimes 3 = 6 \oplus \bar{3}$ → Antisymmetric

Symmetric

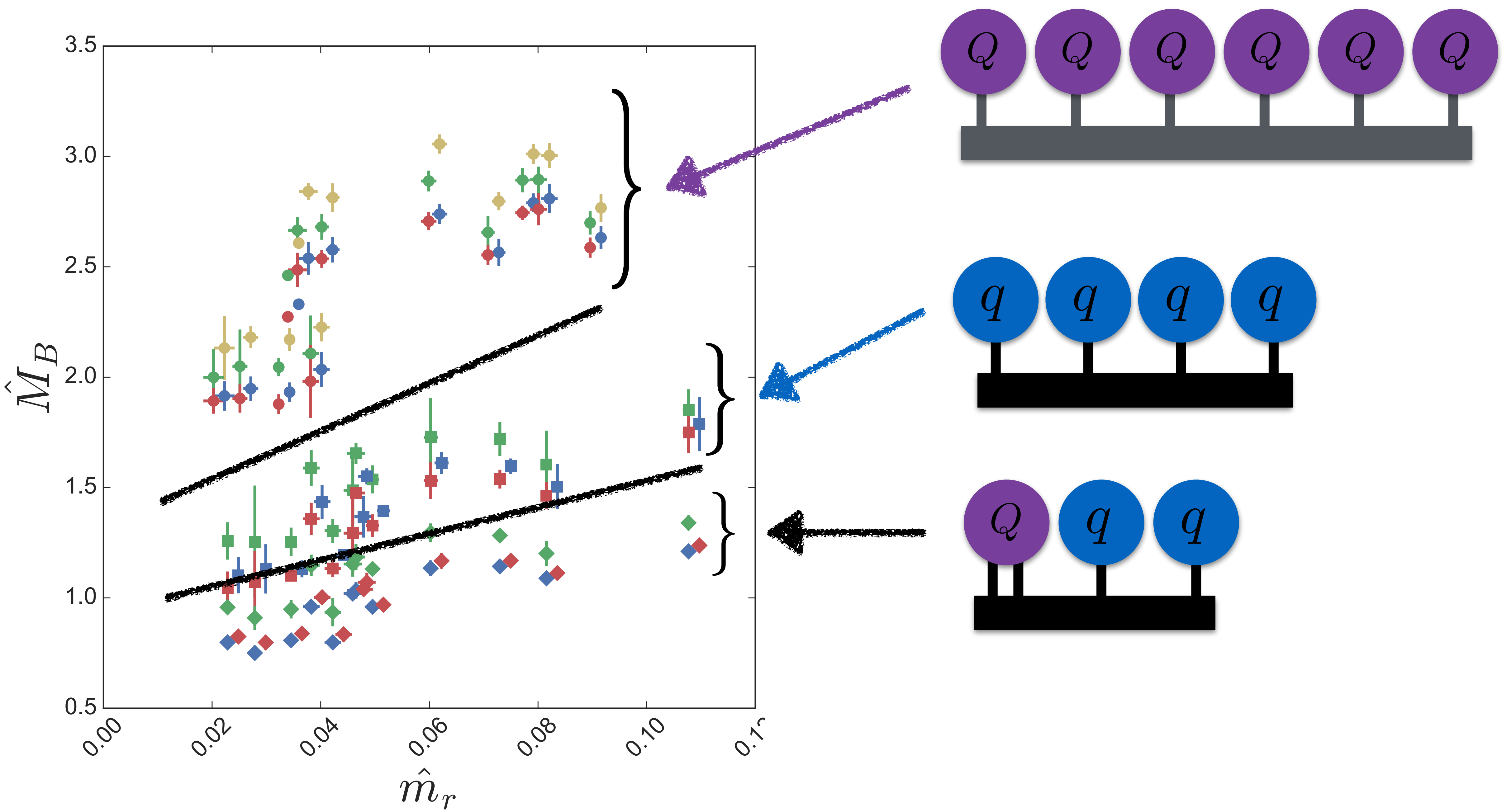
Top partner

$\Sigma : (J, I) = (1/2, 1)$

$\Lambda : (J, I) = (1/2, 0)$

Baryons in a multirep theory

Raw lattice data

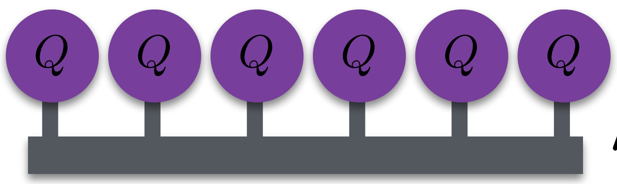


Large-N_C Predictions

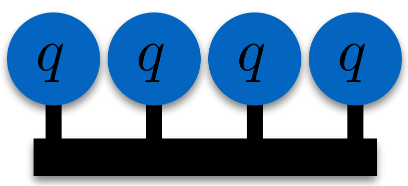
- Large-N_C predicts the baryon spectrum, requires no model assumptions
- Suggestive interpretation with constituent fermions

$$\begin{aligned} M_B =& C_0 \times N + C_1 + C_2/N + \ldots \\ =& (\text{num. fermions}) \times (\text{constituent mass}) \\ & + (\text{splitting}) \times J(J+1)/N \\ & + (\text{lattice artifacts}) \end{aligned}$$

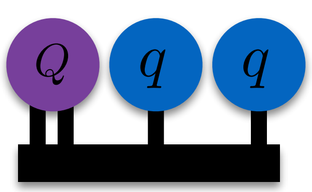
Estimating constituent mass



$$/6 \simeq M_Q$$

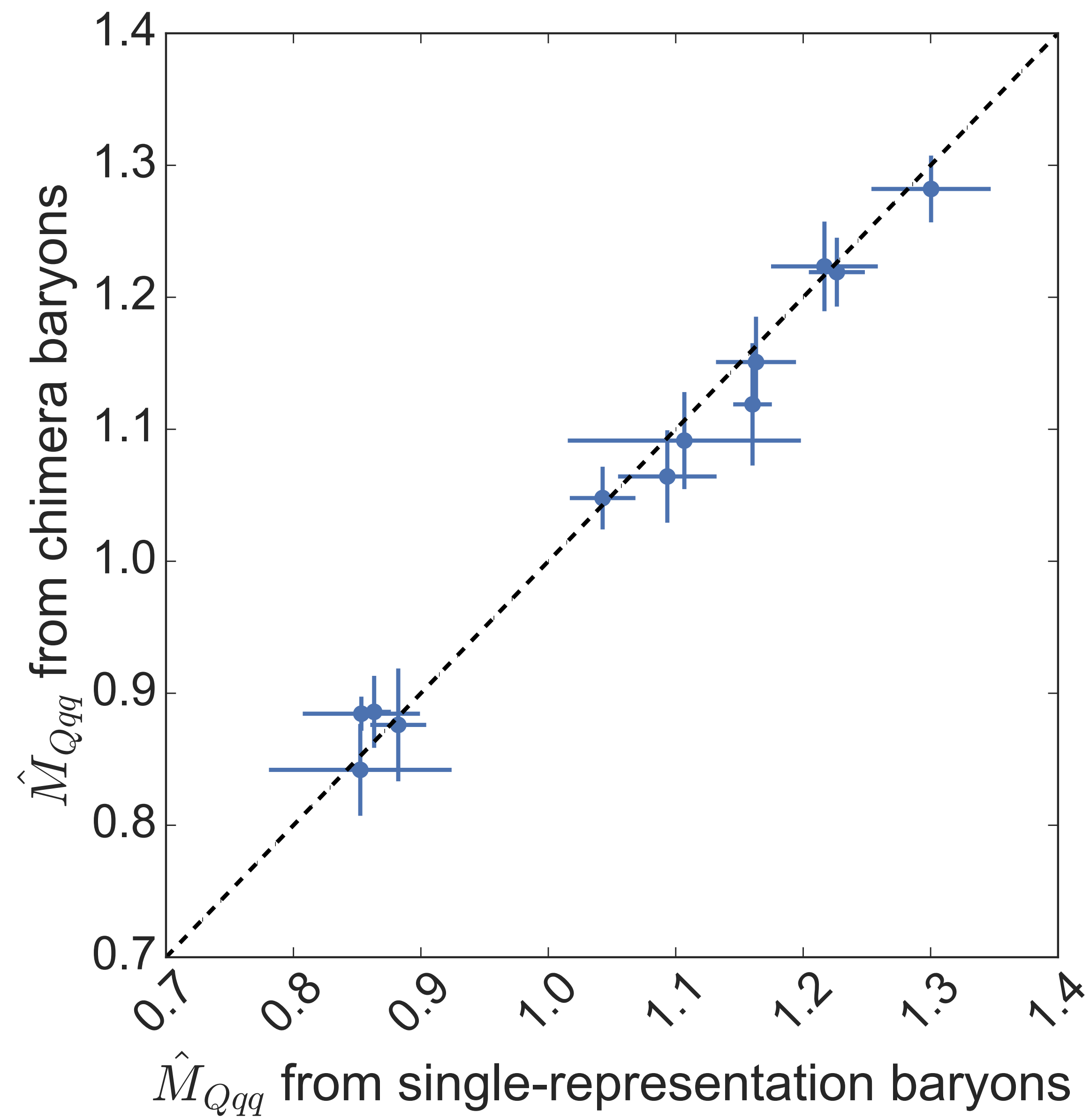


$$/4 \simeq M_q$$



$$\simeq M_{Qqq}$$

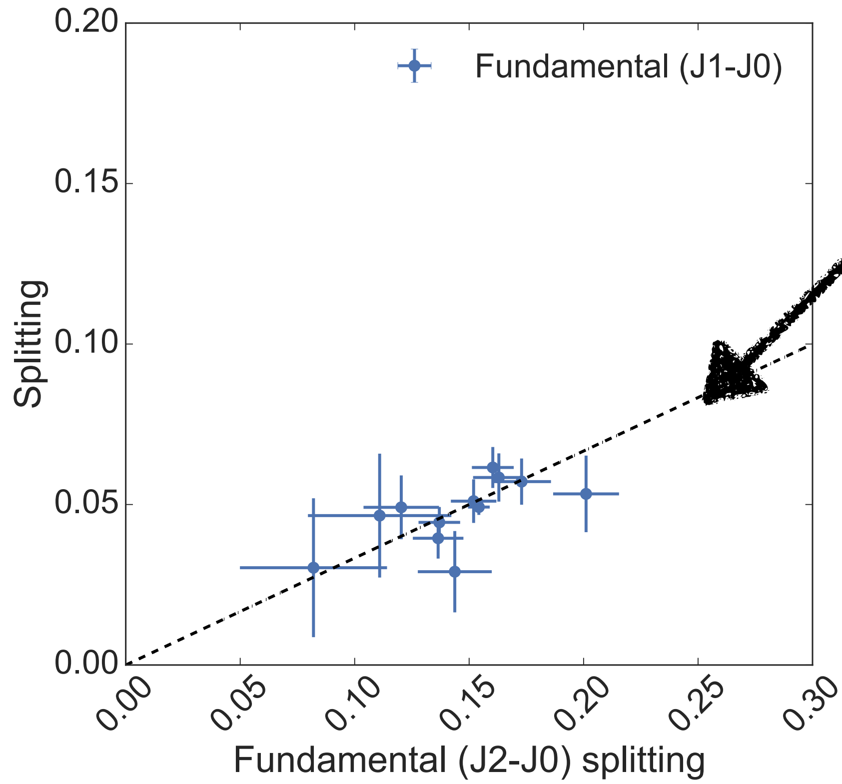
$$M_{Qqq} \stackrel{?}{=} (M_Q + 2M_q)$$



*Raw data — NOT fits

The Landé interval rule

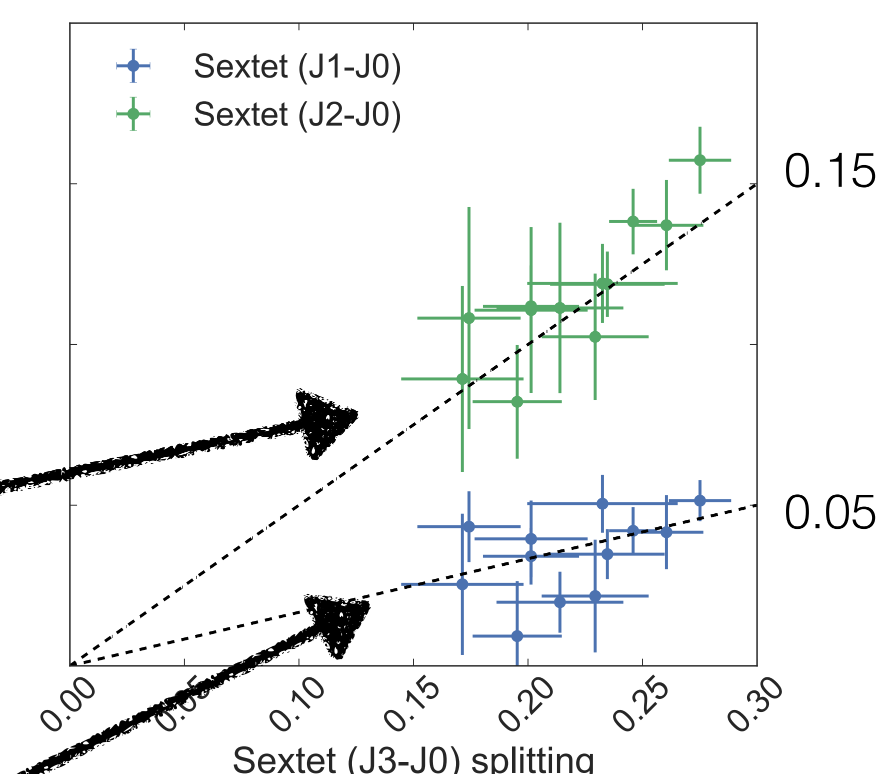
Checking slopes predicted from J(J+1) splittings



$$\frac{1(1+1)}{2(2+1)} = \frac{1}{3}$$

$$\frac{2(2+1)}{3(3+1)} = \frac{1}{2}$$

$$\frac{1(1+1)}{3(3+1)} = \frac{1}{6}$$



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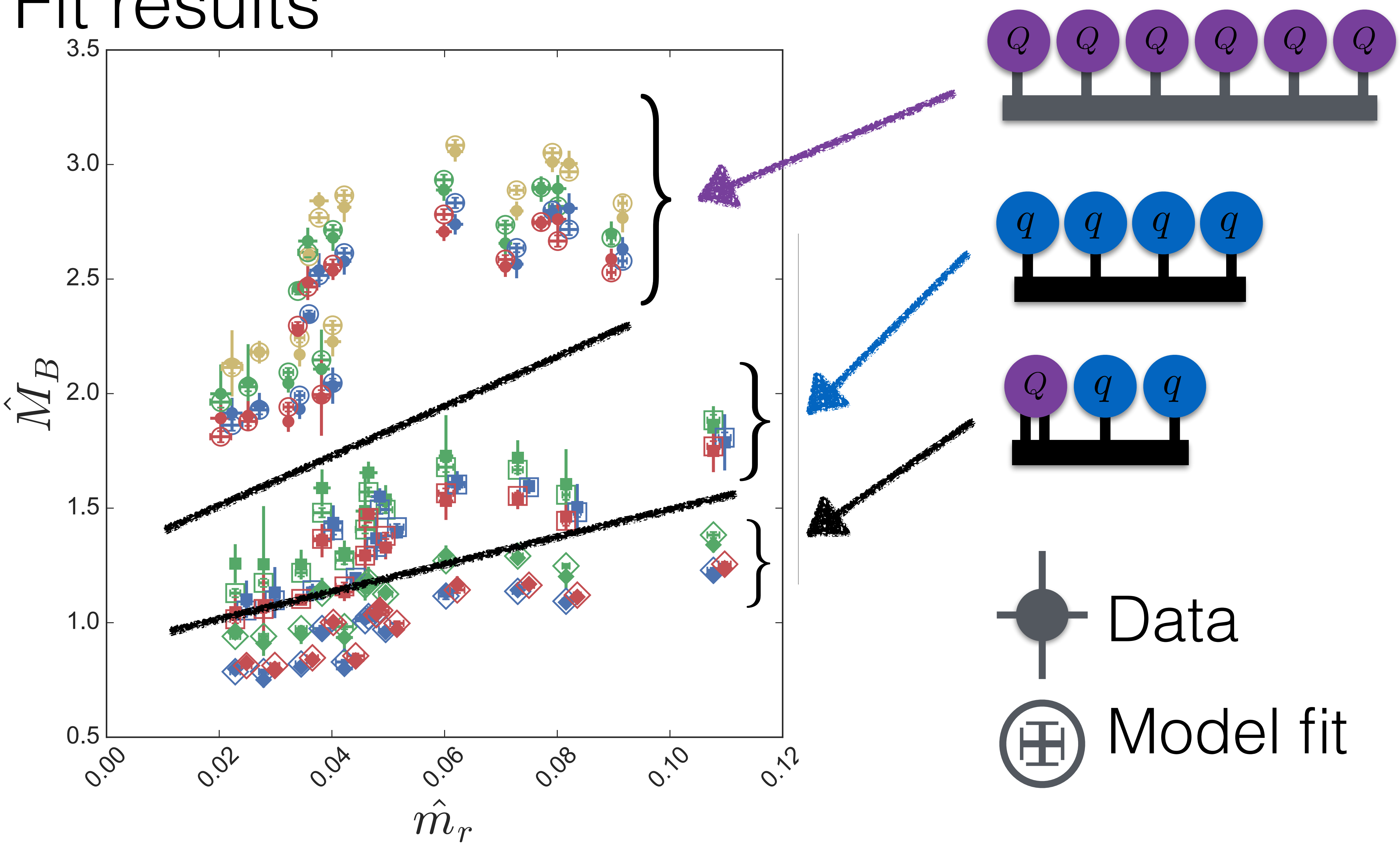
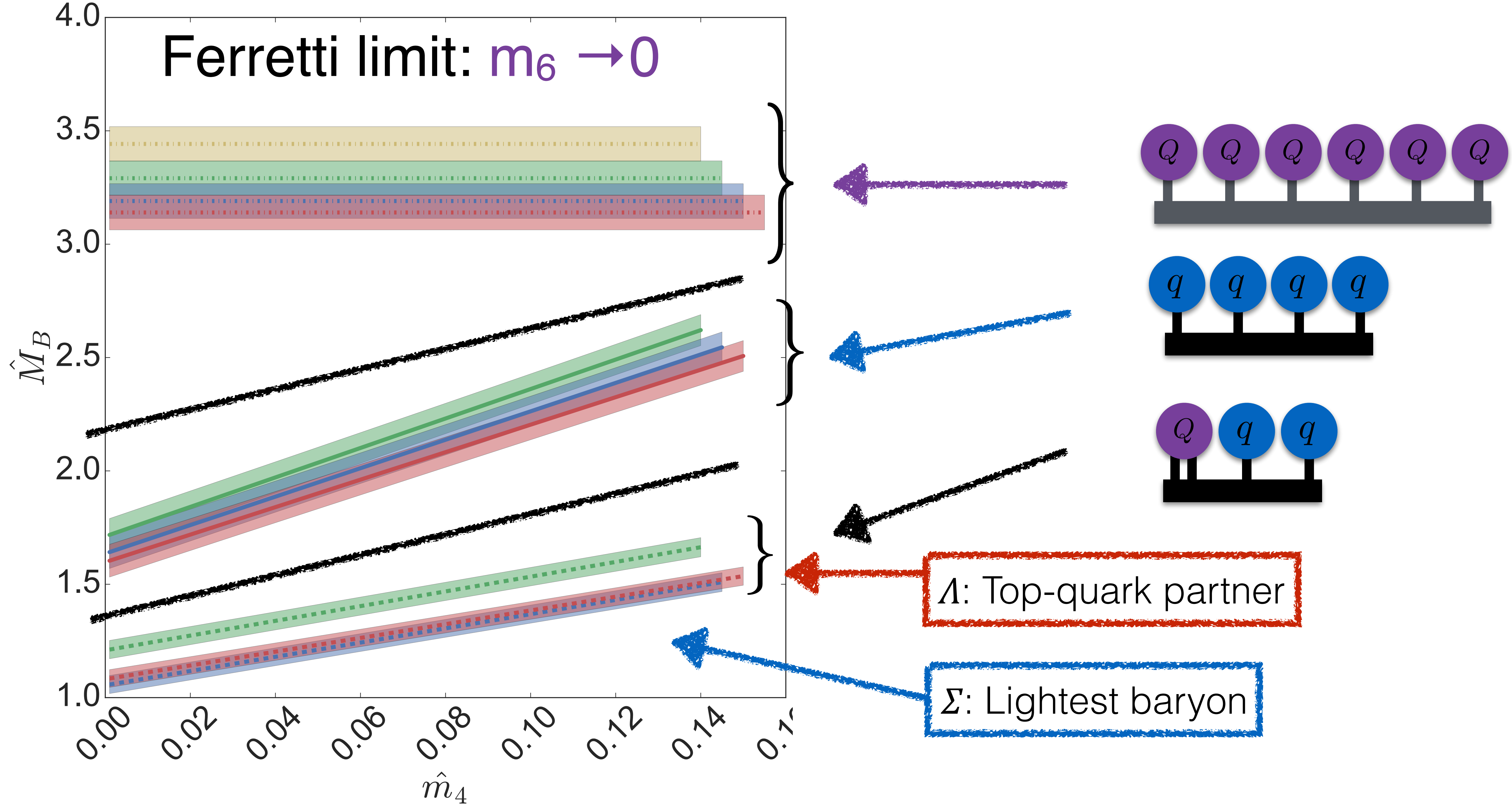
Baryons in a multirep theory

Fit results



Joint fit: χ^2/DOF [DOF] = 0.85 [109], 11 free parameters

Continuum baryon masses



Setting experimental constraints

- Composite Higgs scenarios modify the shape of the standard model Higgs potential

- Departures from the standard model appear with powers of $\xi \sim (v/F_6)^2$, where v = 246 GeV.

- Experiments measure of Higgs couplings

  $\Rightarrow \xi \lesssim 0.1 \Rightarrow F_6 \gtrsim 1.1$ TeV

- Upshot: “In the physical limit, units of F_6 are TeV”

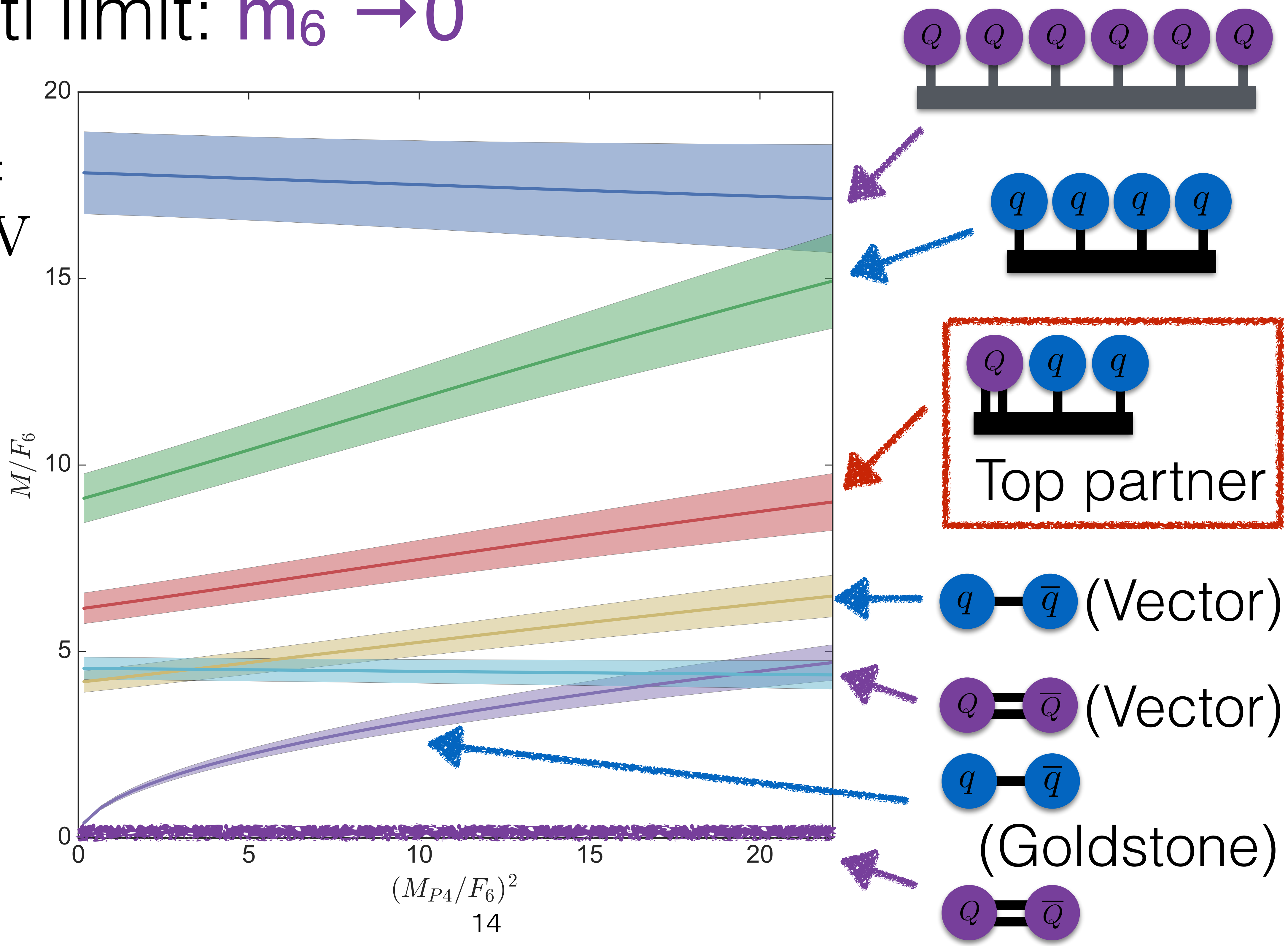
The physical spectrum

Ferretti limit: $m_6 \to 0$

From experiment:

$F_6 \gtrsim 1.1\,\text{TeV}$

~M [TeV]



Summary

- Large-N_C describes the baryon spectrum well and has a suggestive “constituent fermion” interpretation
- The “chimera” Qqq states are the lightest baryons. The top partner is a chimera.
- In the “physical limit” ($m_6 \to 0$), the top partner Λ is nearly mass-degenerate with another state Σ
- The mass of top partner is $m_\Lambda \gtrsim 6.5$ TeV

Back-up slides

Baryon masses

$$\hat{M}_{Q^6} = 6\left[C_6 + C_{66}\hat{m}_6\right] + \frac{B_{66}}{6}J(J+1) + A_6\hat{a}$$

$$\hat{M}_{q^4} = 4\left[C_4 + C_{44}\hat{m}_4\right] + \frac{B_{44}}{4}J(J+1) + A_4\hat{a}$$

Constituent masses

Lattice artifacts

$$\hat{M}_{Qqq} = 2\left[C_4 + C_{44}\hat{m}_4\right] + \left[C_6 + C_{66}\hat{m}_6\right] + C_{\mathrm{mix}} + A_{\mathrm{mix}}\hat{a} + B_{46}\frac{J(J+1)}{\sqrt{24}} + \left(\frac{B_{44}}{4} - \frac{B_{46}}{\sqrt{24}}\right)I(I+1).$$

Models of Compositeness

(Composite Higgs + partially composite top)

- Lattice simulations need a specific model
- Ferretti and Karateev [1312.5330] classified possible theories using group theory

A. Gauge group is anomaly-free

B. Global symmetry contains SM gauge group + custodial SU(2)

C. Theory is asymptotically free

} "Healthy" physical theory

D. Matter fields are fermionic irreps of the gauge group } (Sufficient?) Condition for partial compositeness

Ferretti's Model: FAQs

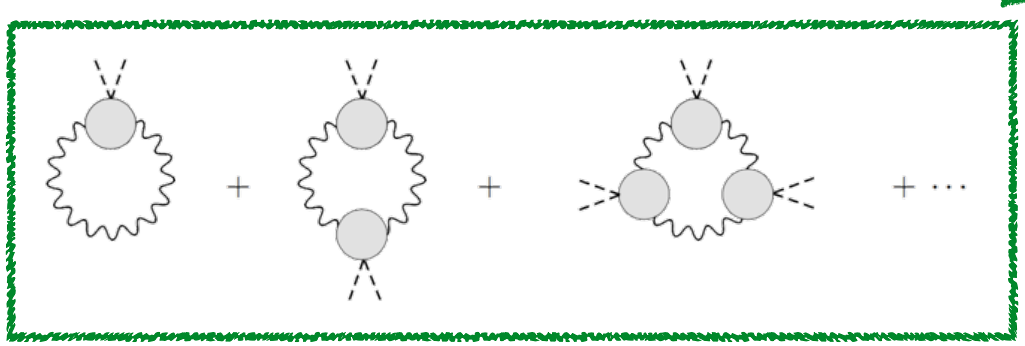
- Why SU(4) gauge theory?
  - ➡ Maintains asymptotic freedom for the desired fermion content
- Ok, so why the fermion content?
  - ➡ Need to embed (and then gauge) the Standard Model within the unbroken global symmetry group:
    - ✦ $G_F \to H_F = SU(3)_{diag} \times SU(2)_L \times SU(2)_R \times U(1)_X = G_{cust.} \supset G_{SM}$
    - ✦ Fundamentals: $SU(3) \times SU(3)' \to SU(3)_{diag} \times U(1)_X$
    - ✦ Sextets $SU(5) \to SO(5) \supset SO(4)$ "$\cong$" $SU(2)_L \times SU(2)_R$
    - ✦ Higgs boson lives in coset $SO(5)/SO(4)$

Ferretti's Model

EWSB via top-driven vacuum misalignment

- χSB occurs in UV, where the future Higgs begins life as an exact Goldstone boson.
- Then include perturbative interactions with the Standard Model:
  - EW gauge bosons induce a positive potential via the mechanism of "vacuum alignment."
    - The physics is identical to EM mass splittings between pions in QCD.
    - These interactions do *not* trigger EWSB.
  - The top quark induces a negative potential. If this effect is large enough, "vacuum misalignment" drives the formation of a Higgs VEV and triggers EWSB.

$$V_{\text{eff}}(h) \sim (\alpha - \beta) \left(\frac{h}{f}\right)^2 + \mathcal{O}(h^4)$$



Low-energy constants, Calculable on the lattice

The Higgs Potential

- The Higgs begins life as an exact Goldstone boson from broken chiral symmetry in the UV
- EW gauge bosons induce a positive potential via the mechanism of "vacuum alignment."*
  - ✦ The physics is identical to EM mass splittings between pions in QCD.
  - ✦ These interactions do *not* trigger EWSB.

Compute this LEC on the lattice

$$V_{\text{eff}}(h) \sim (\alpha - \beta)\left(\frac{h}{f}\right)^2 + \mathcal{O}(h^4)$$

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 \sim \underbrace{\frac{\alpha_{\text{EM}}}{4\pi}\Lambda_{\text{QCD}}^2}_{\text{Dimensional analysis}} \sim \frac{\alpha_{\text{EM}}}{f_\pi^2}\int_0^\infty \underbrace{dQ^2 \Pi_{\text{LR}}(Q^2)}_{\text{Careful computation in field theory, Das (1967)}}$$

Dimensional analysis

Careful computation in field theory, Das (1967)

*Proof that α>0: E. Witten, "Some Inequalities Among Hadron Masses," PRL 51, 2351 (1983)

QCD version: Das *et al* (1967), Phys. Rev. Lett., 18, 759–761

The Higgs Potential

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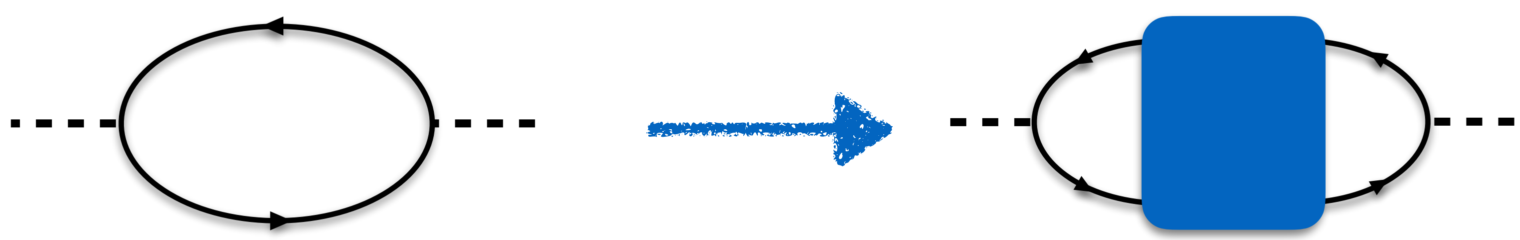
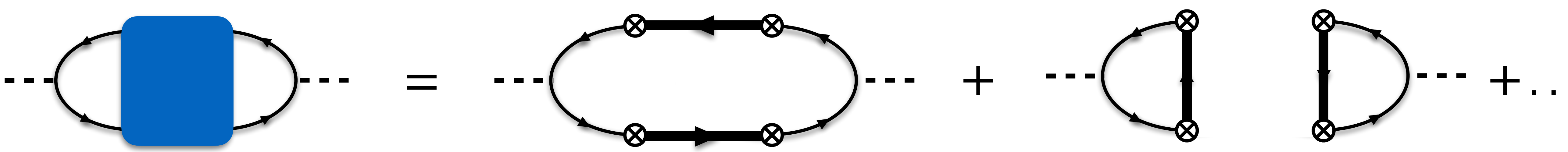
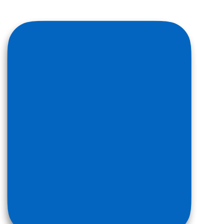


SM Top Loop

Partial Compositeness





= lattice task = baryon 4-pt function

- Technically challenging, see 1502.00390 and 1707.06033
- Factorization at large-N?

The NDS Action

nHYP Dislocation Suppressing Action

- nHYP is a smearing scheme invented and optimized by Hasenfratz and Knechtli. It involves fat links V built from thin links U.
  - The usual gauge links U are “thin” links. The fat link V is “smeared” link — a sum of products of gauge links connecting points on the lattice.
  - Smearing provides a smoother background for fermion propagation. This smoothing reduces lattice artifacts.
- “Dislocation suppression” refers to taming large spikes in the fermion force during evolution with hybrid Monte Carlo
  - Enacted by extra marginal gauge terms
  - Creates a “repulsive potential” to cancel out the offending large spikes in the fermion force.

Setting the scale

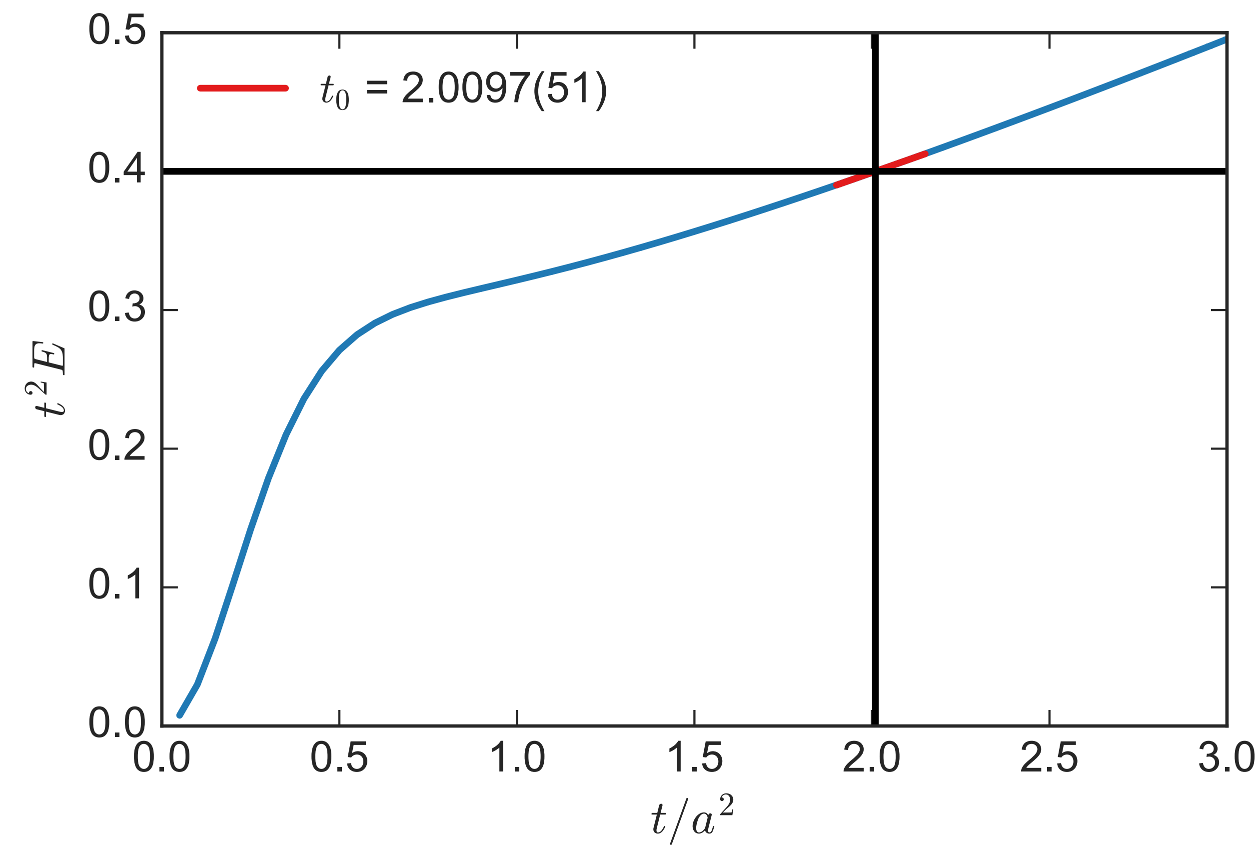
"Always look at dimensionless ratios"

- Set the scale with the Wilson flow scale, t_0
- In QCD, $\sqrt{t0}$ = 0.14 fm, related to scales from static potential (e.g., Lüscher: 1006.4518)
- Idea: diffusive smoothing ("flow") in a fictitious 5th dimension

$$\langle E(t) \rangle) \sim \langle G^2(t) \rangle$$

$$t_0^2 \langle E(t_0) \rangle \stackrel{!}{=} M(N_c)$$

- QCD: $M(N_c{=}3) = 0.3$
- Large-N: $t_0 \sim N_c$, so take $M(N_c{=}4) = 0.4$
- DeGrand (1701.00793) gives details, compares to other scale setting schemes, and provides more careful connection to large-N



$$\hat{m} = (m \cdot a) \times (\sqrt{t_0}/a)$$
$$= \text{dimensionless}$$