

Spectroscopy of chimera baryons on $Sp(4)$ lattice gauge theory

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Numerical calculations are accomplished by [arXiv:0805.2058](https://arxiv.org/abs/0805.2058)
modifying the HiRep code.

repository: <https://github.com/sa2c/HiRep>

Outline

- Introduction:
 - ▶ $Sp(4)$ gauge theory: A Composite Higgs model
 - ▶ Chimera baryon operators
- Preliminary results
 - ▶ Projections
 - ▶ Mass hierarchy of chimera baryons
 - ▶ $m_{ps}^{(f)}$ massless limit
- Summary

Composite Higgs Models

| Name | Gauge group | ψ | χ | Baryon type |
|------|-------------|---|---|------------------------------|
| M1 | $SO(7)$ | $5 \times \mathbf{F}$ | $6 \times \mathbf{Spin}$ | $\psi\chi\chi$ |
| M2 | $SO(9)$ | $5 \times \mathbf{F}$ | $6 \times \mathbf{Spin}$ | $\psi\chi\chi$ |
| M3 | $SO(7)$ | $5 \times \mathbf{Spin}$ | $6 \times \mathbf{F}$ | $\psi\psi\chi$ |
| M4 | $SO(9)$ | $5 \times \mathbf{Spin}$ | $6 \times \mathbf{F}$ | $\psi\psi\chi$ |
| M5 | $Sp(4)$ | $5 \times \mathbf{A}_2$ | $6 \times \mathbf{F}$ | $\psi\chi\chi$ |
| M6 | $SU(4)$ | $5 \times \mathbf{A}_2$ | $3 \times (\mathbf{F}, \bar{\mathbf{F}})$ | $\psi\chi\chi$ |
| M7 | $SO(10)$ | $5 \times \mathbf{F}$ | $3 \times (\mathbf{Spin}, \bar{\mathbf{Spin}})$ | $\psi\chi\chi$ |
| M8 | $Sp(4)$ | $4 \times \mathbf{F}$ | $6 \times \mathbf{A}_2$ | $\psi\psi\chi$ |
| M9 | $SO(11)$ | $4 \times \mathbf{Spin}$ | $6 \times \mathbf{F}$ | $\psi\psi\chi$ |
| M10 | $SO(10)$ | $4 \times (\mathbf{Spin}, \bar{\mathbf{Spin}})$ | $6 \times \mathbf{F}$ | $\psi\psi\chi$ |
| M11 | $SU(4)$ | $4 \times (\mathbf{F}, \bar{\mathbf{F}})$ | $6 \times \mathbf{A}_2$ | $\psi\psi\chi$ |
| M12 | $SU(5)$ | $4 \times (\mathbf{F}, \bar{\mathbf{F}})$ | $3 \times (\mathbf{A}_2, \bar{\mathbf{A}}_2)$ | $\psi\psi\chi, \psi\chi\chi$ |

The minimal model
Barnard et al, arXiv:1311.6562

D. Franzosi and G. Ferretti, arXiv:1905.08273

Our choice of model

- $Sp(4)$ gauge theory with $2\mathbf{F}+3\mathbf{AS}$ Dirac fermions
- Breaking pattern: $4\mathbf{F}+6\mathbf{AS}$ 2 component Weyl fermions



$$G/H = \underline{SU(4)} \times SU(6) / Sp(4) \times SO(6)$$

Enhanced global symmetry due to the (pseudo-) reality

- $SU(4)/Sp(4)$ gives 5 goldstone bosons.
 - ▶ 4: SM Higgs doublet
 - ▶ 1: made heavy in model building
- $SU(3)$ embedded in antisymmetric representation:

$$SU(6) \rightarrow SO(6) \supset SU(3)$$



QCD colour $SU(3)$

Chimera Baryon

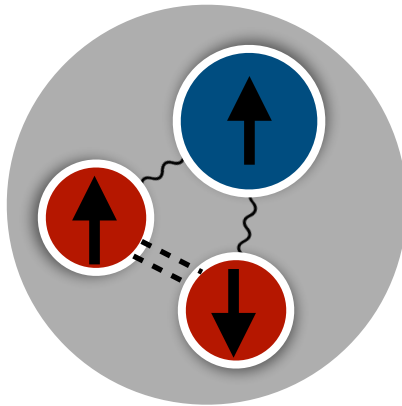
- Interpolating operators

- Λ type: $\mathcal{O}_{\text{CB},\gamma^5} = (\bar{\psi}^1 a \gamma^5 \psi^2 b) \Omega_{bc} \chi^{k ca}$

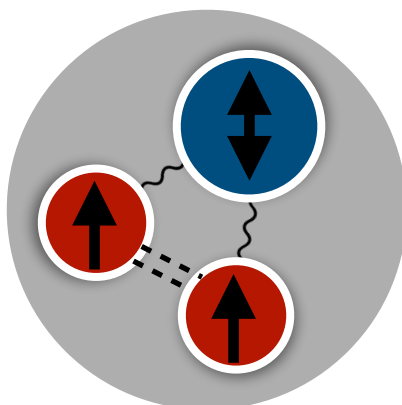
└ Carry QCD colour

$J = 1/2$

*top partner: mixing with top and generate m_t

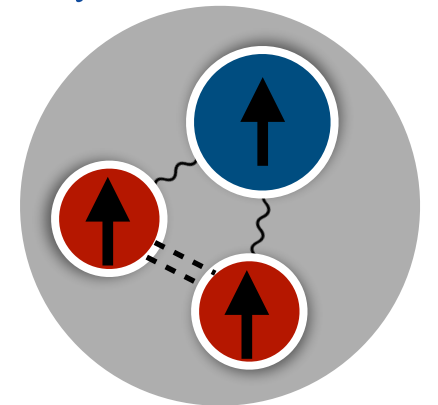


- Σ type: $\mathcal{O}_{\text{CB},\gamma^\mu} = (\bar{\psi}^1 a \gamma^\mu \psi^2 b) \Omega_{bc} \chi^{k ca}$

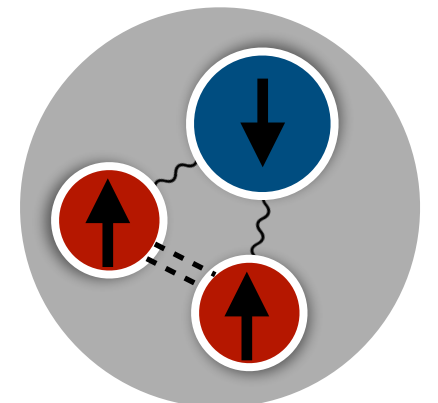


Spin projection

$J = 3/2: \Sigma^*$



$J = 1/2: \Sigma$



Chimera Baryon

- Spin projector for Σ -type baryon:

$$(P^{3/2})^{ij} = \delta^{ij} - \frac{1}{3}\gamma^i\gamma^j$$

$$(P^{1/2})^{ij} = \frac{1}{3}\gamma^i\gamma^j$$

- Two-point function

$$C_{ij}(t) = \sum_{\vec{x}} \left\langle \mathcal{O}_{\text{CB}}^i(x) \bar{\mathcal{O}}_{\text{CB}}^j(0) \right\rangle \text{ with } \mathcal{O}_{\text{CB}}^i = (\bar{\psi}\gamma^i\psi)\chi$$

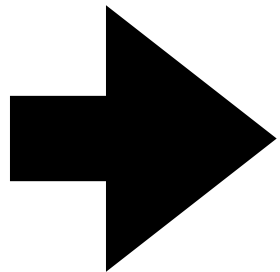
$$\rightarrow C_{\Sigma}^{1/2}(t) = \text{Tr} \left[(P^{1/2})^{ij} C_{jk}(t) \right]$$

Chimera Baryon

- Parity projection

$$C_{\text{CB}}(t) = \sum_{\vec{x}} \langle \mathcal{O}_{\text{CB}}(x) \bar{\mathcal{O}}_{\text{CB}}(0) \rangle$$
$$\rightarrow P_e [c_e e^{-m_e t} + c_o e^{-m_o(T-t)}] - P_o [c_o e^{-m_o t} + c_e e^{-m_e(T-t)}]$$

Projector:



$$P_{eo} = \frac{1}{2}(1 \pm \gamma^0)$$

Study Plan

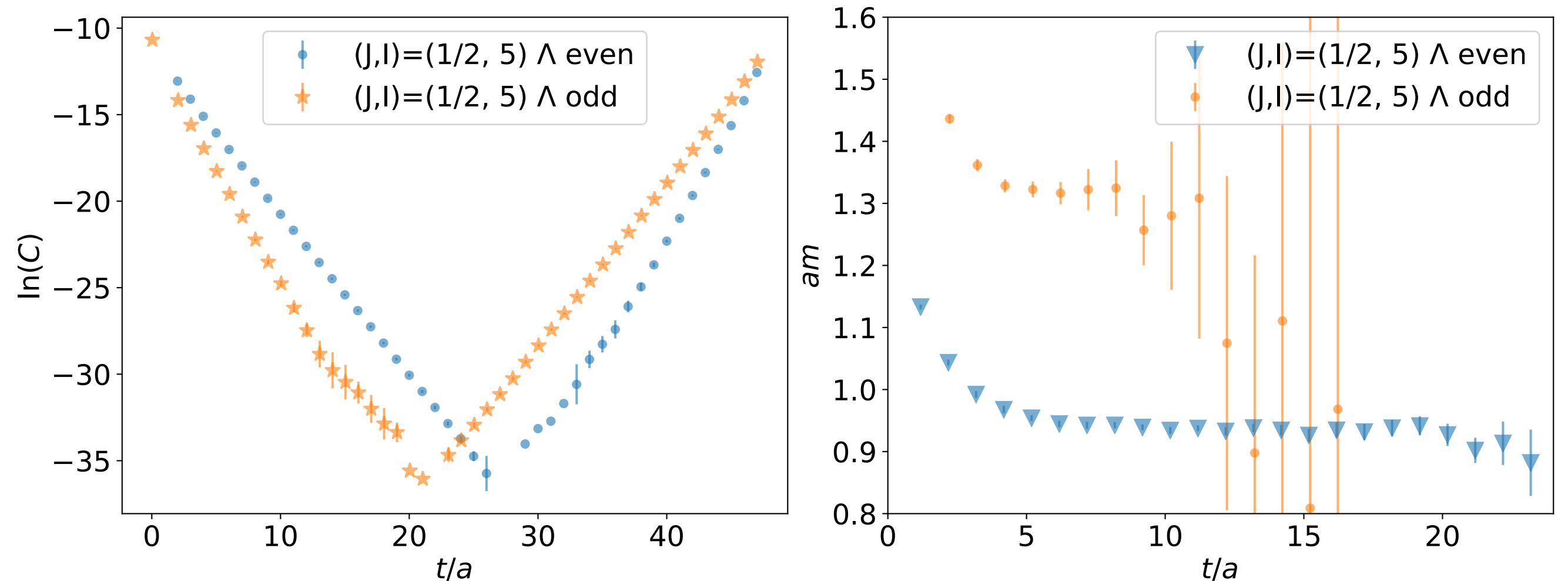
- Quenched fundamental and antisymmetric fermions [arXiv:1912.06505](#)
- $N_f = 2$ dynamical **fundamental** fermions [arXiv:1909.12662](#)
- $n_f = 3$ dynamical **antisymmetric** fermions (Ongoing)
- Fully dynamical **2F** + **3AS** fermions [arXiv:2202.05516](#)
 - Chimera baryon (quenched studies first)
 - 4-fermion operator matrix elements (relevant to generating Higgs mass)



Preliminary results

Preliminary results

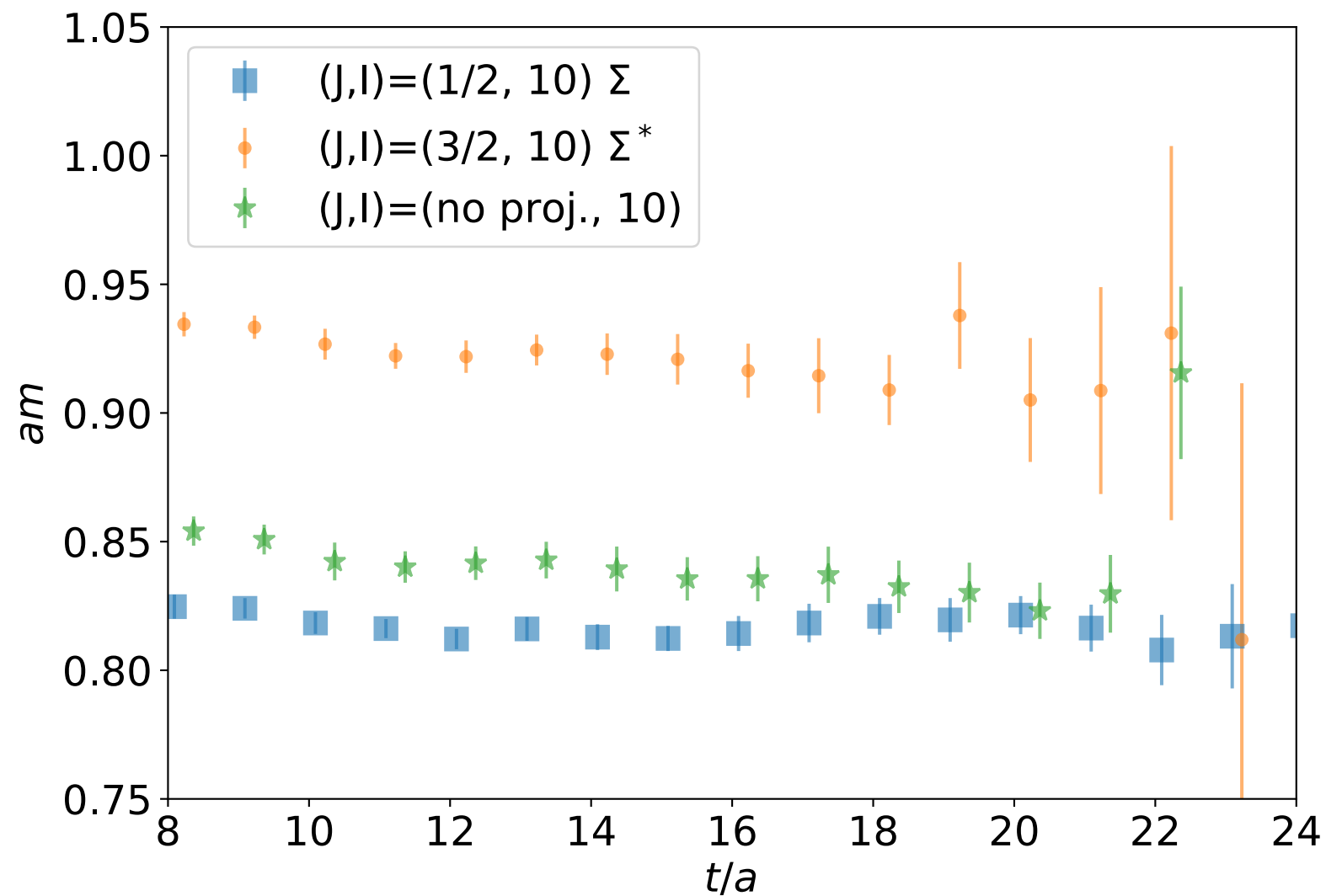
Projection-Parity



The log plot of the chimera baryon correlators (left) and their effective mass plot (right) with the parity projection obtained with quenched approximation.

Preliminary results

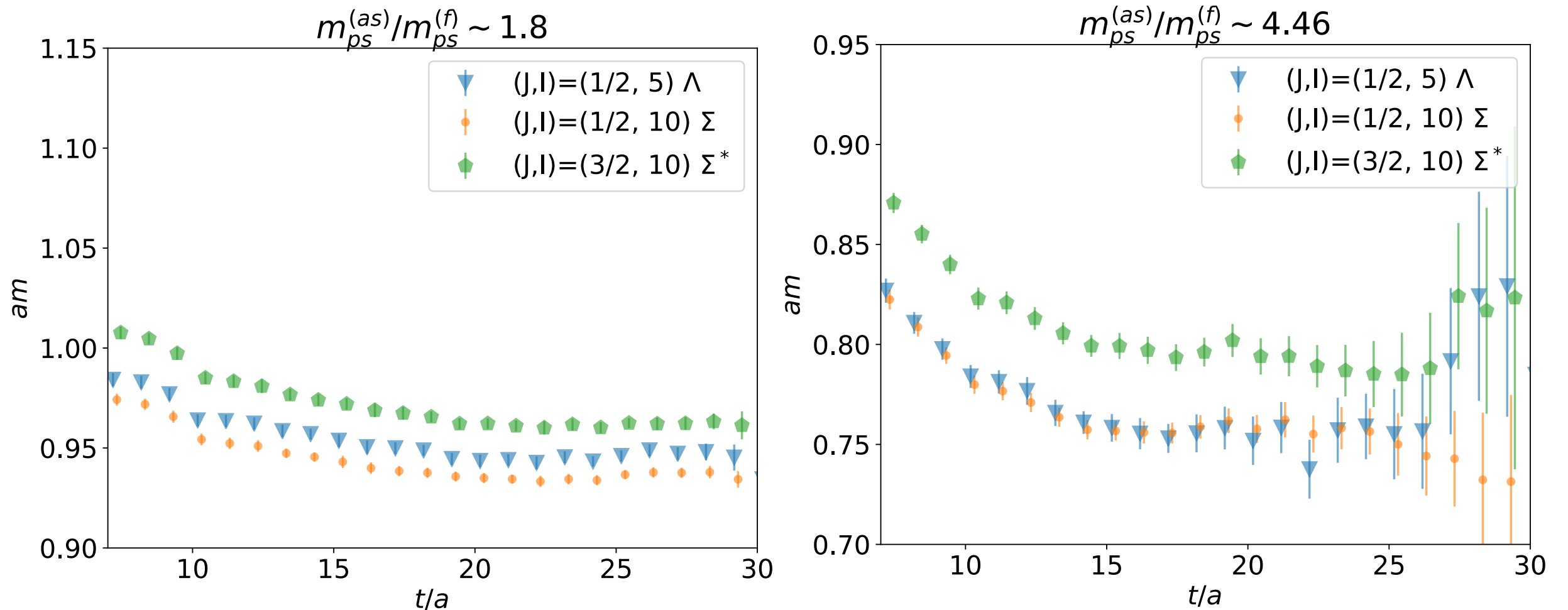
Projection-Spin



Comparison of effective mass plot between two spin projected states and the state without spin projection.

Preliminary results

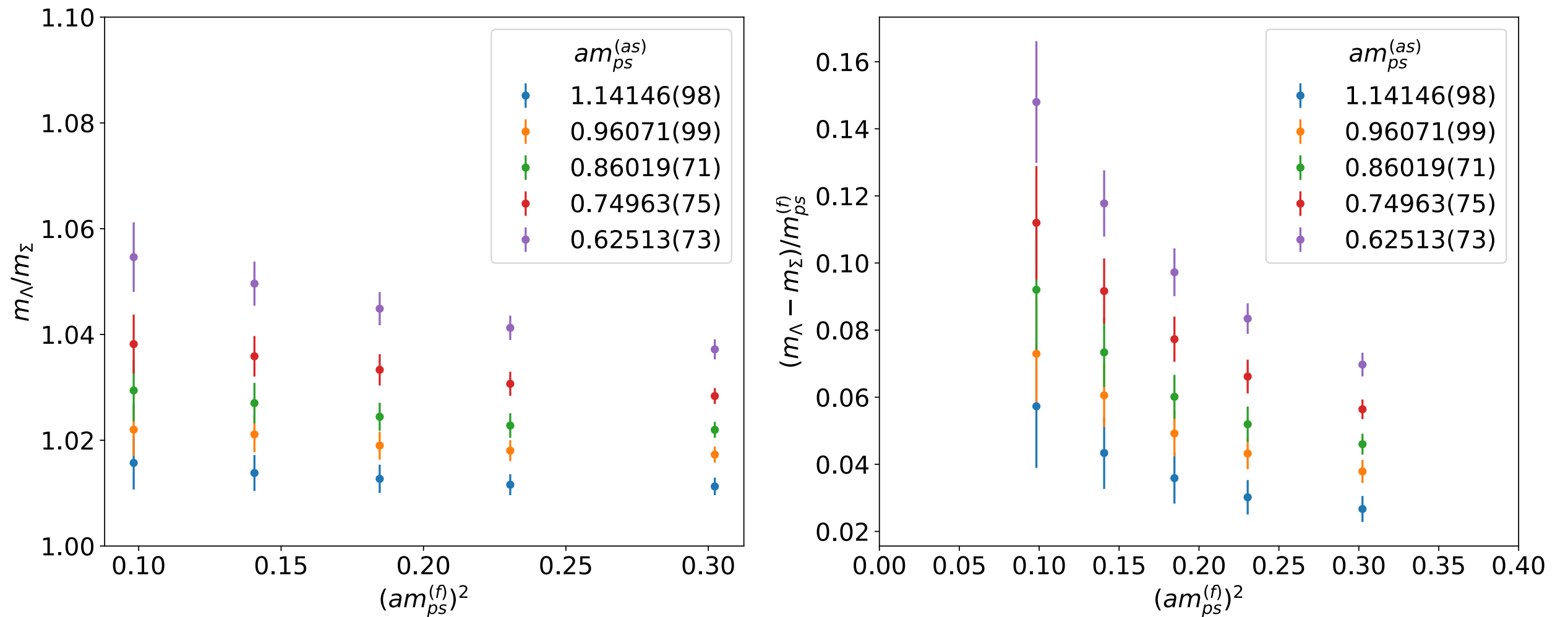
Mass hierarchy



Effective mass plot of chimera baryons calculated with different F bare masses $m_0^{(f)} = -0.6$ (left) and $m_0^{(f)} = -0.69$ (right) at fixed AS bare mass $m_0^{(as)} = -0.81$. The lattice size is 60×48^3 with $\beta = 8.0$.

Preliminary results

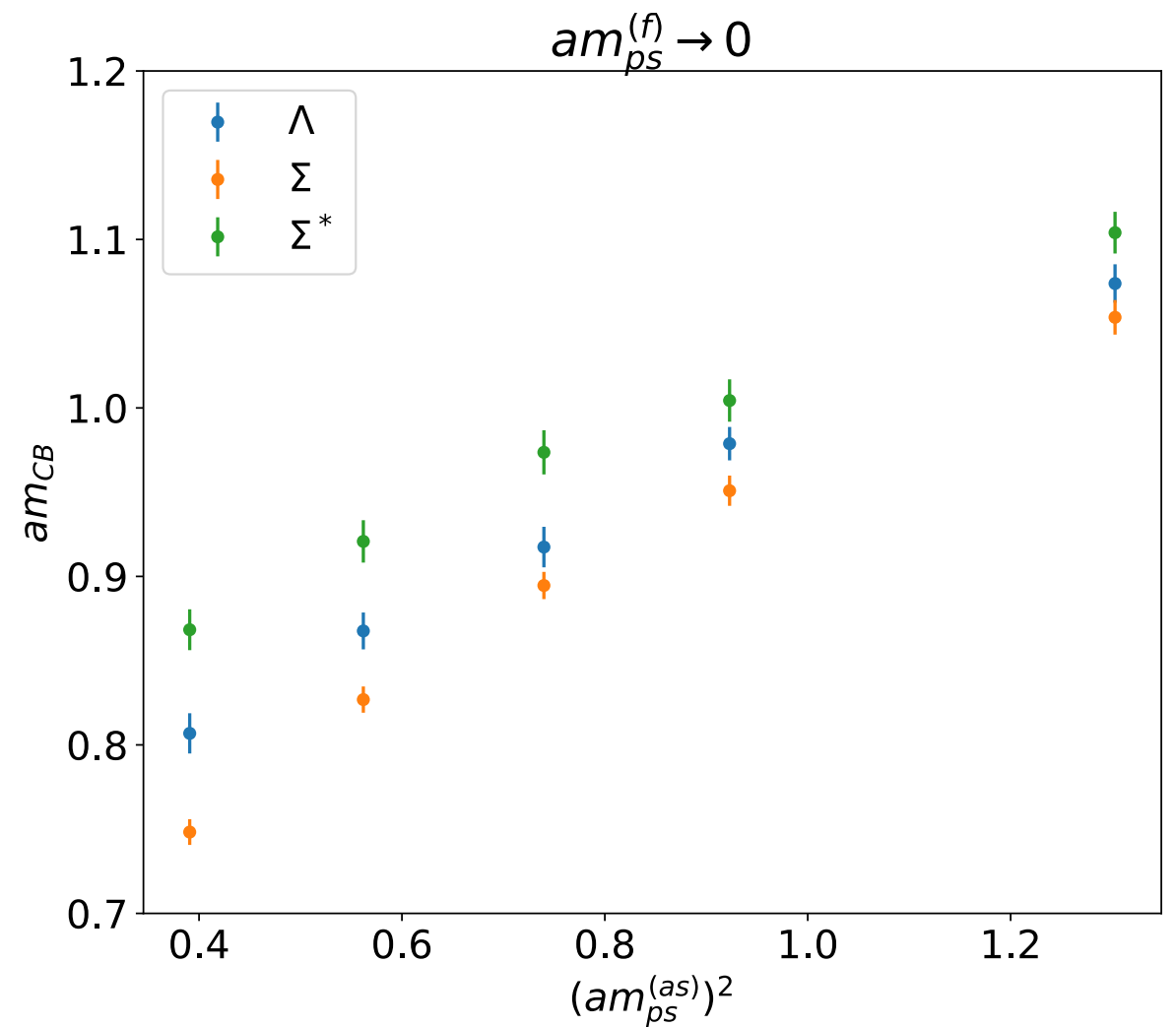
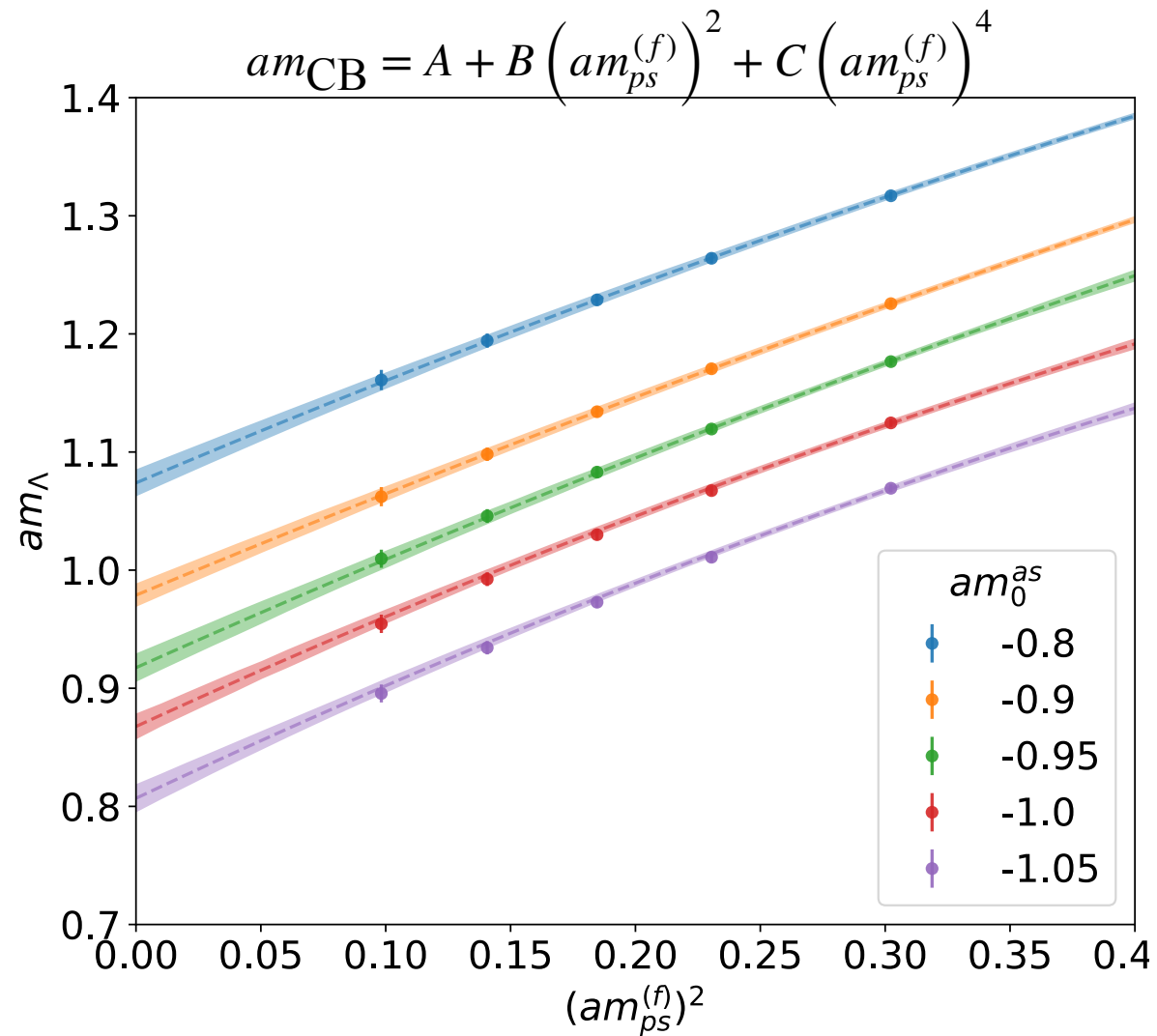
Mass hierarchy



Mass ratios calculated with different bare masses on a 48×24^3 and $\beta = 7.62$ lattice.

Preliminary results

$m_{ps}^{(f)}$ Massless limit



| am_0 | -0.8 | -0.9 | -0.95 | -1.0 | -1.05 |
|------------------------|------|------|-------|------|-------|
| $\chi^2/\text{d.o.f.}$ | 0.12 | 0.03 | 0.36 | 0.97 | 1.2 |

Summary

- Chimera baryons
 - Λ : Top partner in composite Higgs model
 - Σ and Σ^* with different spin
- Projection
 - Spin
 - Parity
- The mass hierarchy of chimera baryons ——— model building
- Exploratory spectrum of chimera baryon at the $m_{ps}^{(f)}$ massless limit as a guide for fully dynamical study.

END

Backup Slides

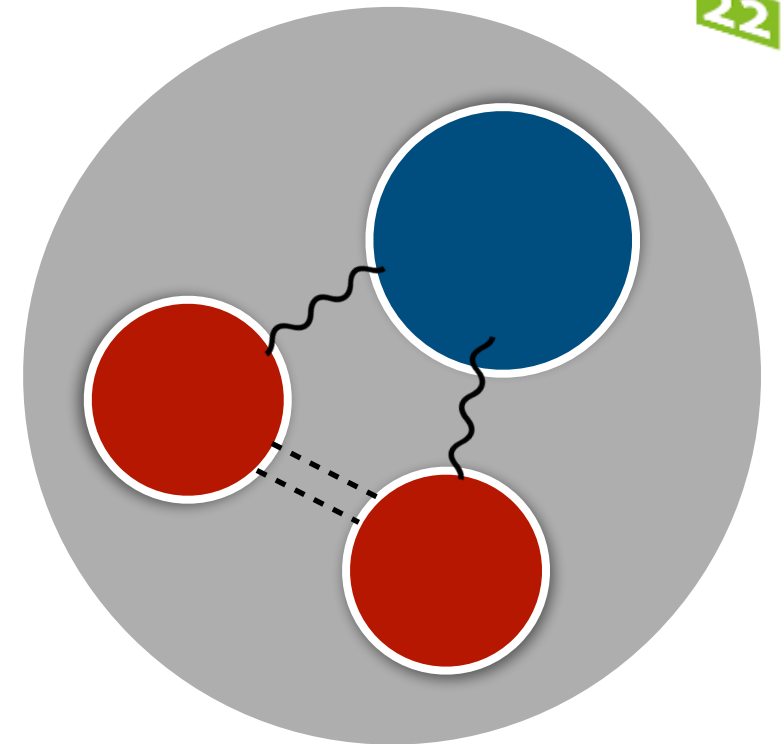
Our choice of model

- Top partner — Chimera baryon

$$\Psi = (\psi\psi\chi)$$

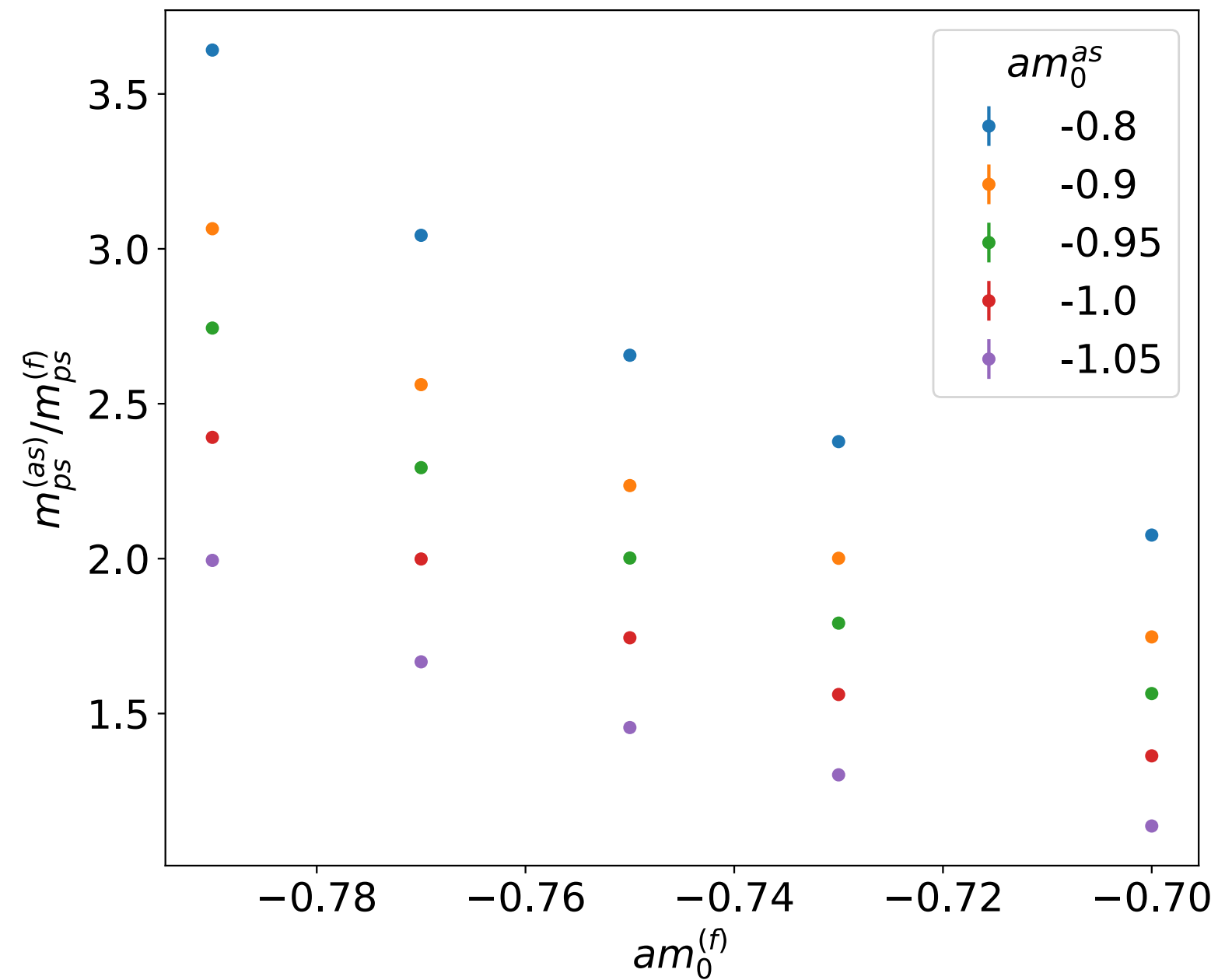
└─ Carry QCD colour

- ➡ Colour neutral under $\text{Sp}(4)$ gauge
- ➡ Having same quantum number \Rightarrow mixing with the top quark, providing an origin of its mass — partial top compositeness
- ➡ Similar to the well-know see-saw mechanism



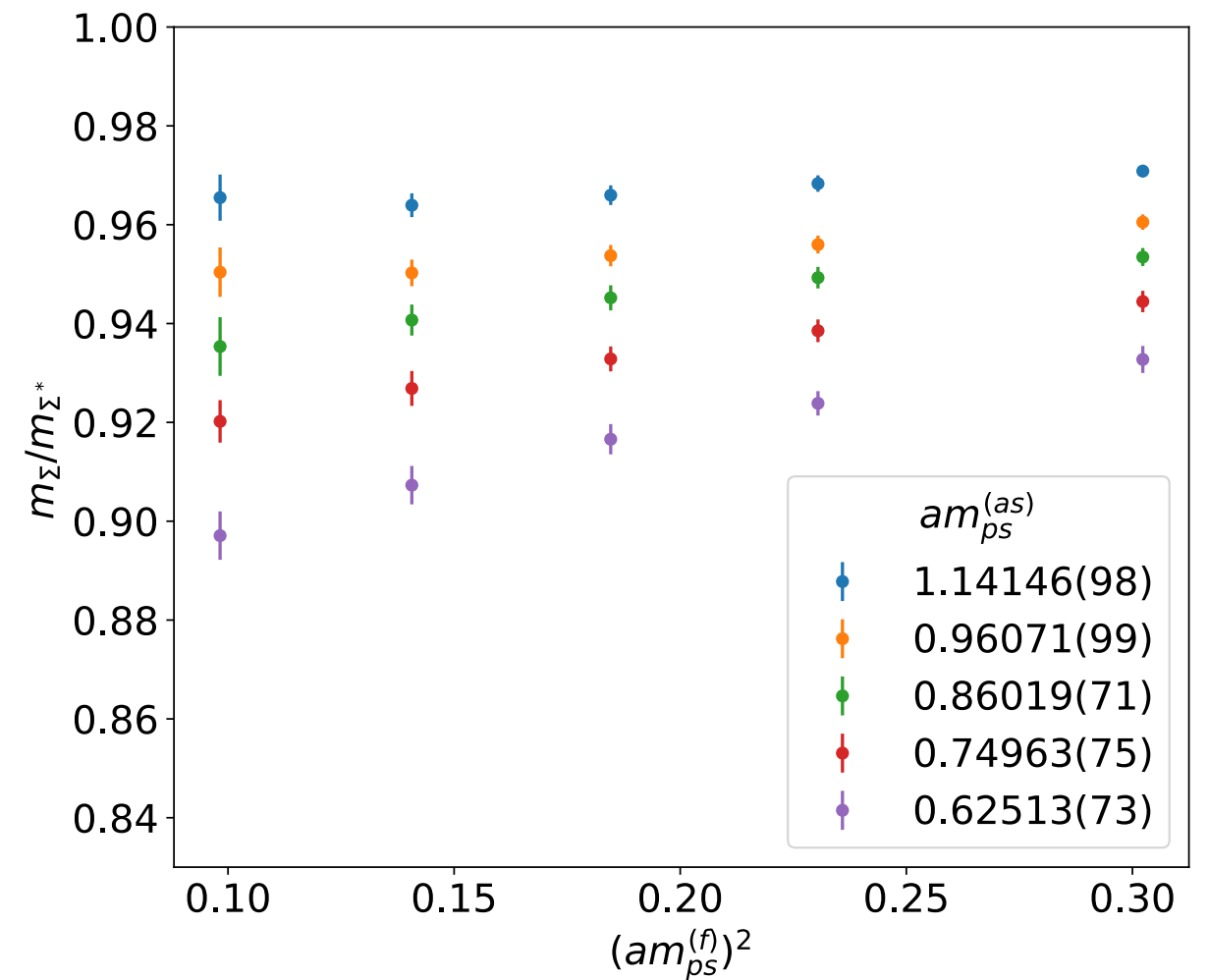
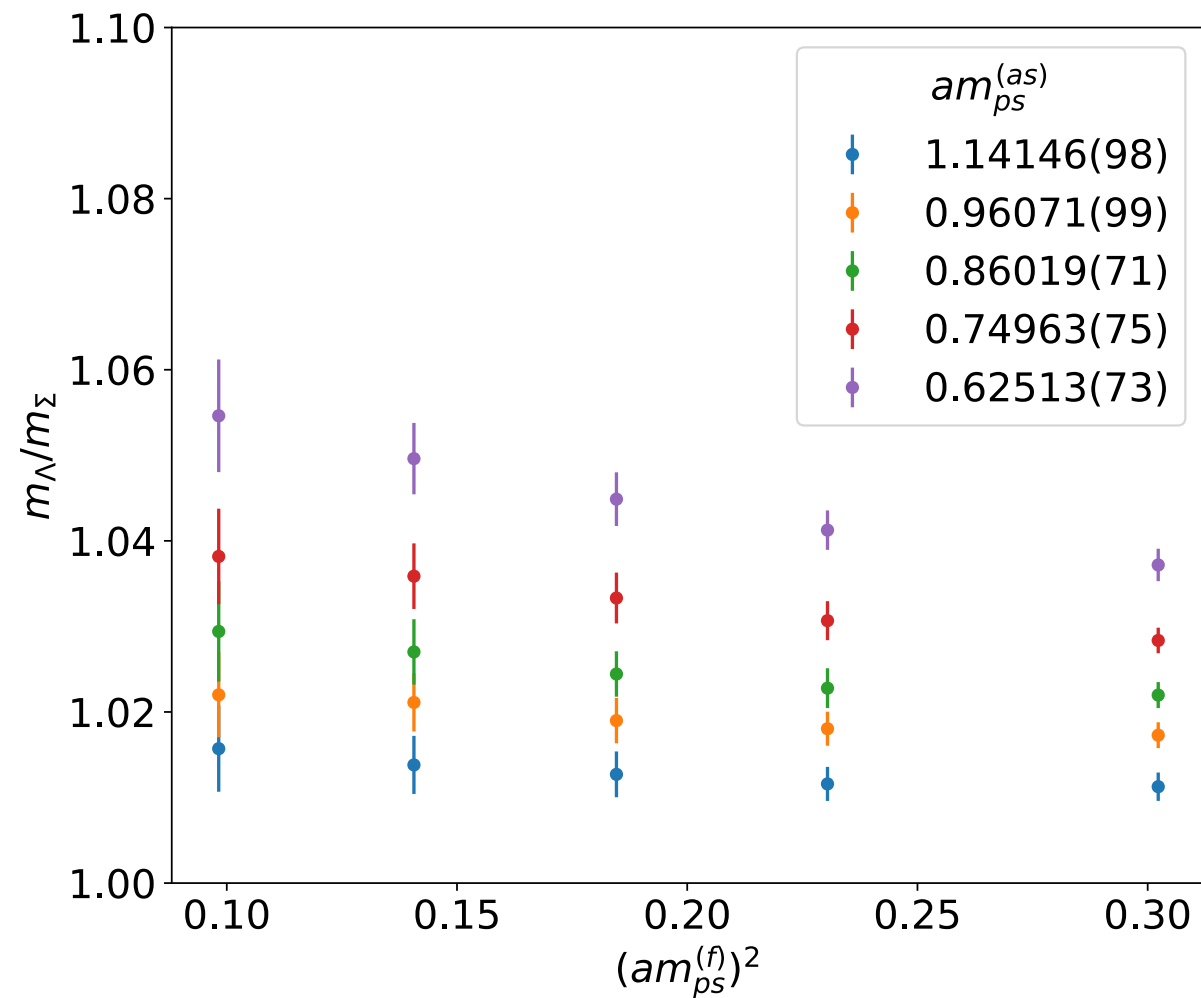
Preliminary results

Mass hierarchy



Preliminary results

Mass hierarchy



Mass ratios calculated with different bare masses on a 48×24^3 and $\beta = 7.62$ lattice.

Summary

- **Chimera baryons** are an important feature of composite Higgs models, which play role of top partner in **partial top compositeness**.
- We present the interpolating operator of Λ and Σ (in QCD analogy) chimera baryons. The former is the **top partner**, and the later can be further separate into two states through **spin projection**.
- We perform the **parity projection** to extract our interest state in this study, the parity even state.
- The **mass hierarchy** of chimera baryons depends on the input bare masses, such behaviour is important to model buildings.
- We explore the spectrum of chimera baryon at the $m_{ps}^{(f)}$ **massless limit** using a single ensemble in quenched approximation, which could be a guide for fully dynamical study.