Chimera Baryon Spectrum of the Composite Higgs Model with Sp(4) gauge group

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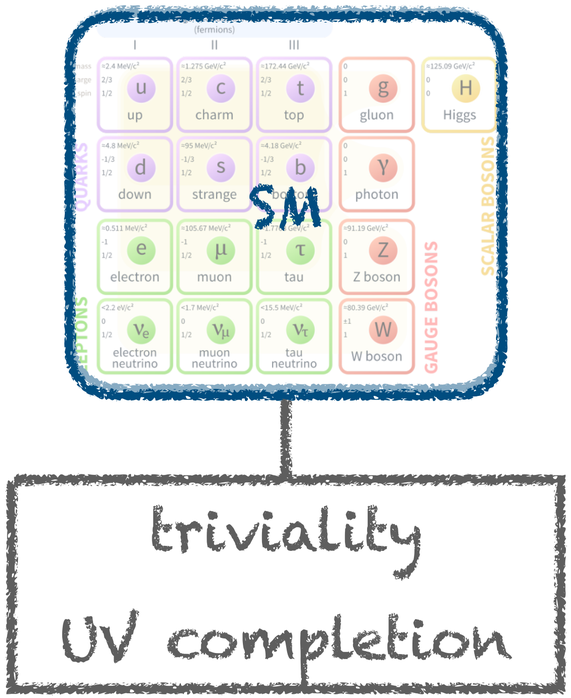
Outline

- Introduction:
  - A Composite Higgs model: Sp(4) gauge theory
  - Top partner: Chimera baryon
- Results
  - Mass hierarchy of chimera baryons
  - Chiral EFT fit and Akaike Information Criterion
- Summary and Outlook

Composite Higgs Model



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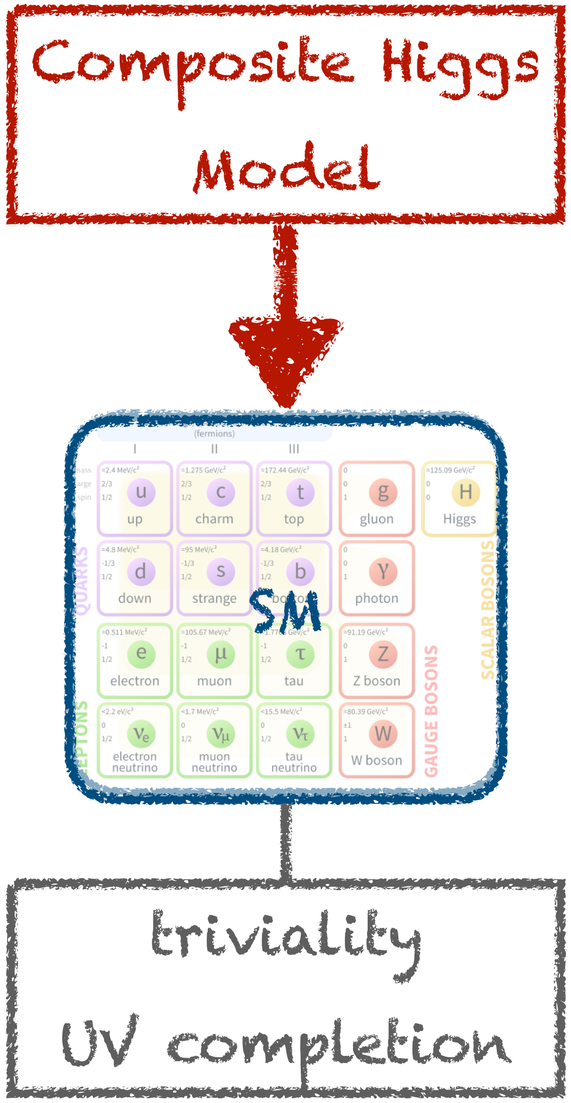

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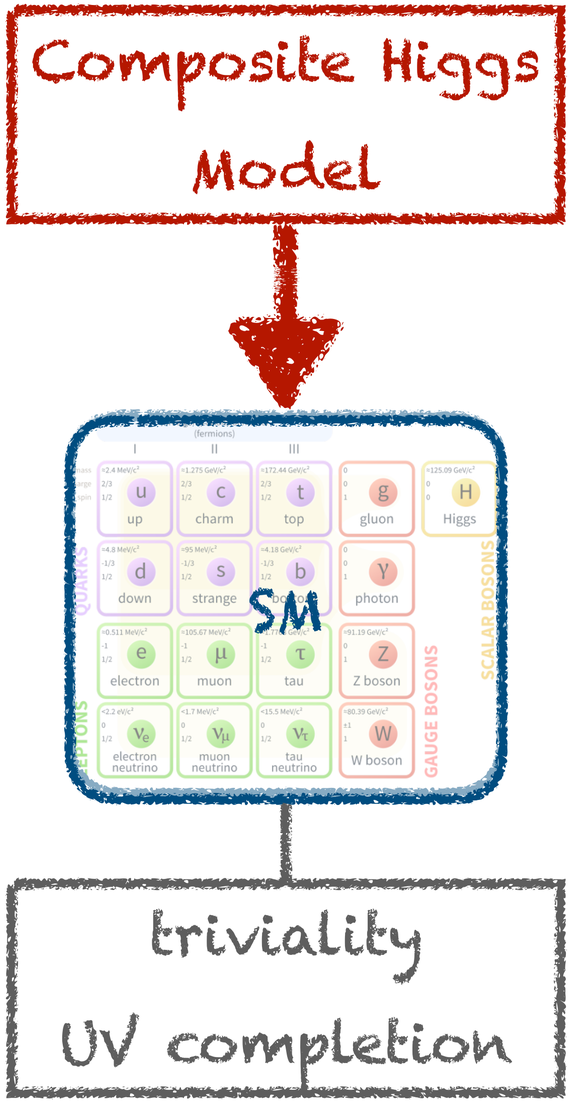

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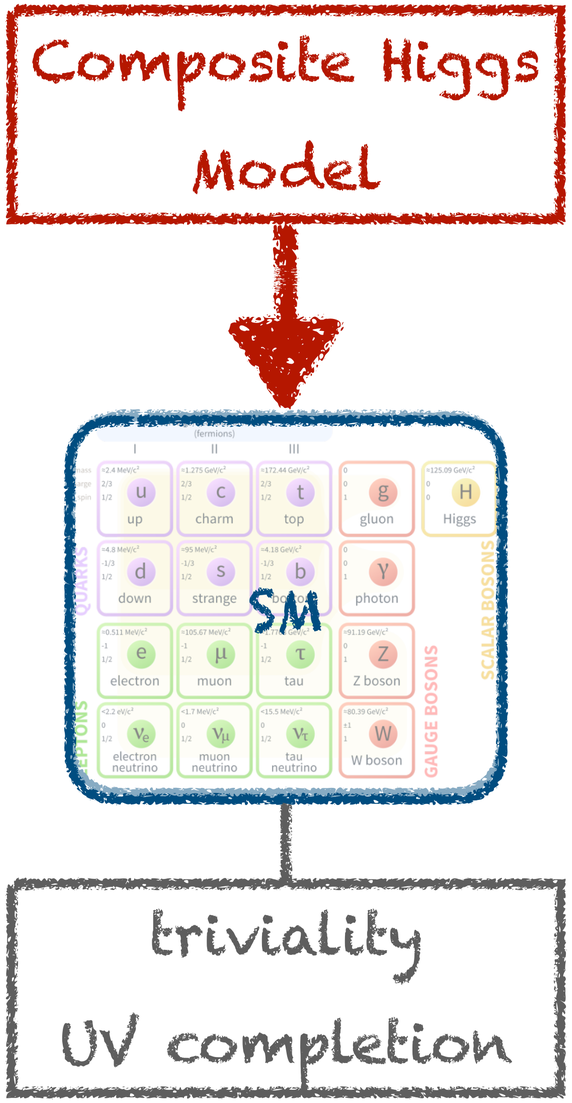

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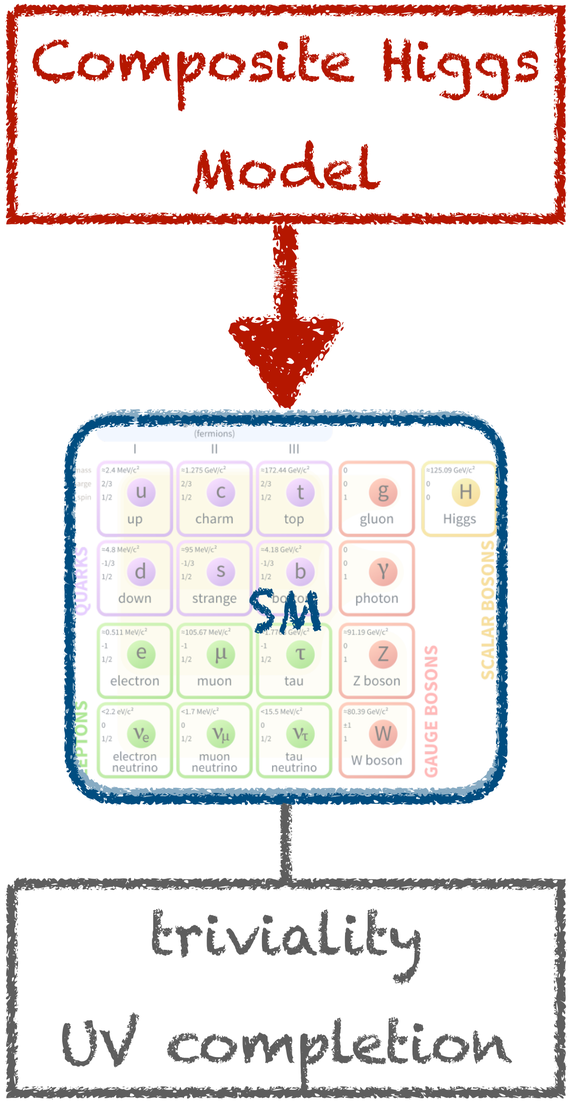

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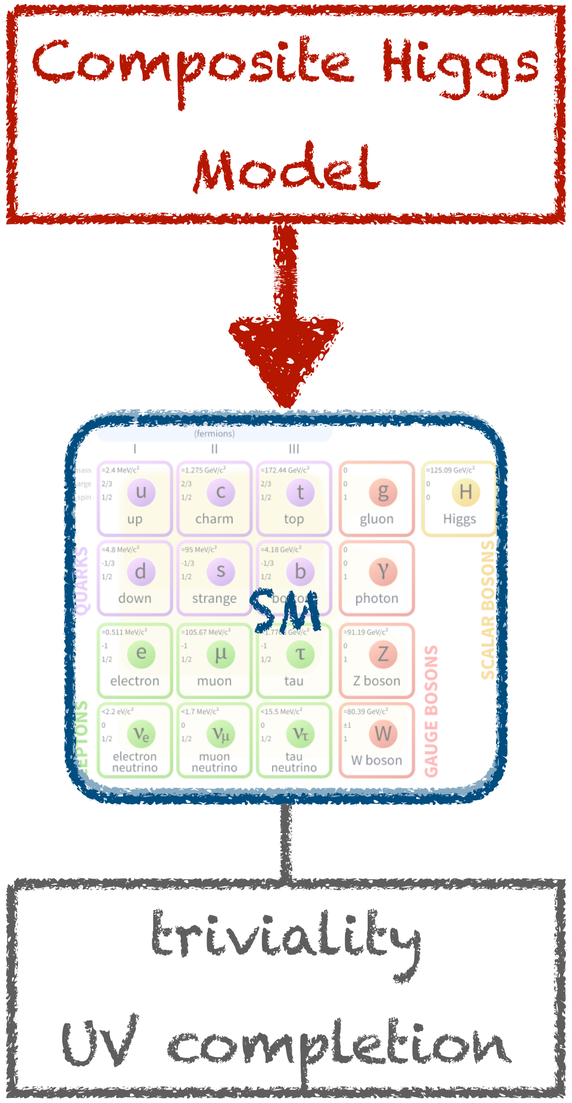

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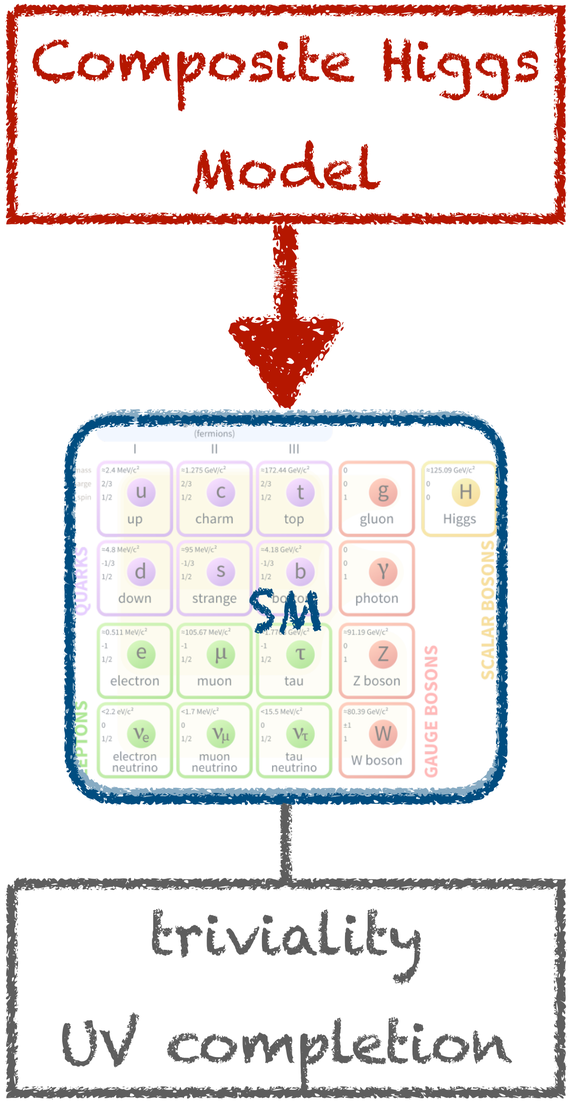

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- An UV complete theory.
- Can embed top partial compositeness with fermions in a higher representation.

Composite Higgs Models

*Weyl fermions

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	$SU(4)$	$5 \times \mathbf{A_2}$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$\psi\chi\chi$
M7	$SO(10)$	$5 \times \mathbf{F}$	$3 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$\psi\chi\chi$
M8	$Sp(4)$	$4 \times \mathbf{F}$	$6 \times \mathbf{A_2}$	$\psi\psi\chi$
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M12	$SU(5)$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A_2}, \overline{\mathbf{A_2}})$	$\psi\psi\chi$, $\psi\chi\chi$

D. Franzosi and G. Ferretti, arXiv:1905.08273

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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 2F+3AS Dirac fermions

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- SU(3) embedded in antisymmetric representation:

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

↳ QCD colour SU(3)

Composite Higgs Model

Top partial compositeness

Top partner:

- Carry QCD colour charge and share the same quantum number as the top (mixing)
- A spin-1/2 bound states emerging from the novel strong-interaction sector
- A hypercolour-neutral particle (the necessity of introducing higher representation)
- Give the mass to the top through see-saw mechanism

$$y_t \approx G_L G_R \frac{Z_L Z_R}{M_B F}$$

$$m_t \approx y_t v$$

Chimera Baryon

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

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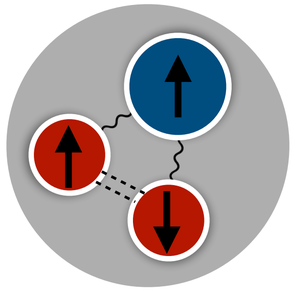

$(J, R) = (1/2,5)$

a, b, c: hypercolour
Ω: 4×4 symplectic matrix
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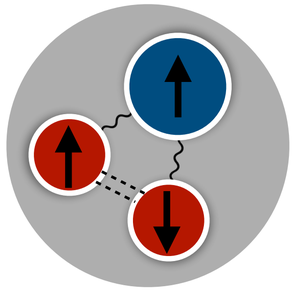

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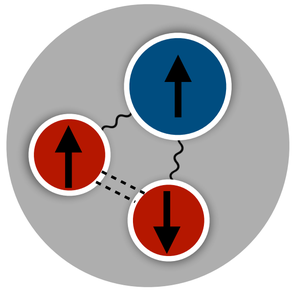

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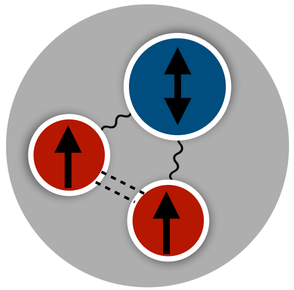

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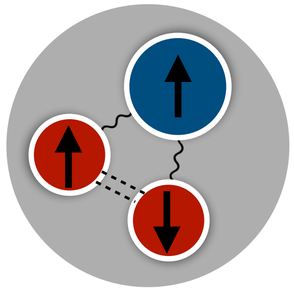

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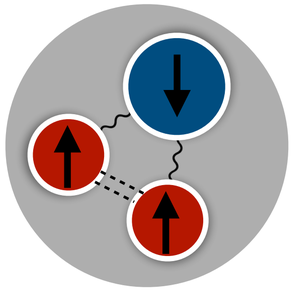
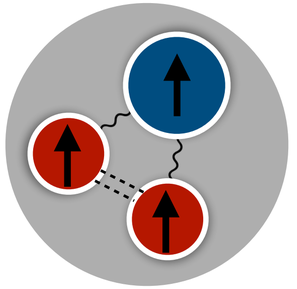
Spin projection



Σ: $(J, R) = (1/2,10)$



Σ^*: $(J, R) = (3/2,10)$

Chimera Baryon

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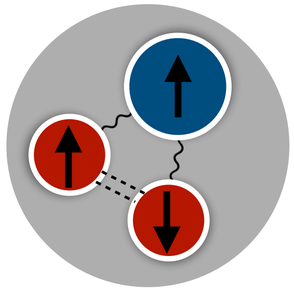

$(J, R) = (1/2,5)$
*top partner

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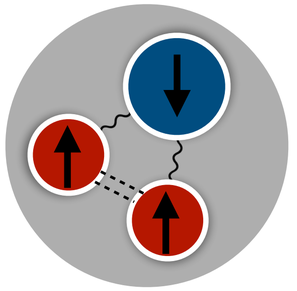

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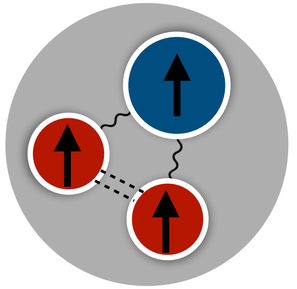

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Lattice setup

- Generate the ensemble in quenched approximation with the standard Wilson action

$$S_g \equiv \beta \sum_x \sum_{\mu<\nu} \left(1 - \frac{1}{2N} \mathrm{ReTr}\, \mathscr{P}_{\mu\nu}\right) , \text{ with } \mathscr{P}_{\mu\nu}(x) \equiv U_\mu(x) U_\nu(x+\hat{\mu}) U_\mu^\dagger(x+\hat{\nu}) U_\nu^\dagger(x) .$$

- Consider the Wilson fermion for the spectroscopic measurements

$$D_m^R \psi_j^R(x) \equiv (4/a + m_0^R)\psi_j^R(x) - \frac{1}{2a} \sum_\mu \left\{ (1-\gamma_\mu) U_\mu^R(x) \psi_j^R(x+\hat{\mu}) + (1+\gamma_\mu) U_\mu^{R,\dagger}(x-\hat{\mu}) \psi_j^R(x-\hat{\mu}) \right\} .$$

- Use gradient-flow method to set the scale

- Ensembles:

Ensemble	β	$N_t \times N_s^3$	$\langle P \rangle$	ω_0/a
QB1	7.62	48×24^3	0.60192	1.448(3)
QB2	7.7	60×48^3	0.608795	1.6070(19)
QB3	7.85	60×48^3	0.620381	1.944(3)
QB4	8.0	60×48^3	0.630740	2.3149(12)
QB5	8.2	60×48^3	0.643228	2.8812(21)

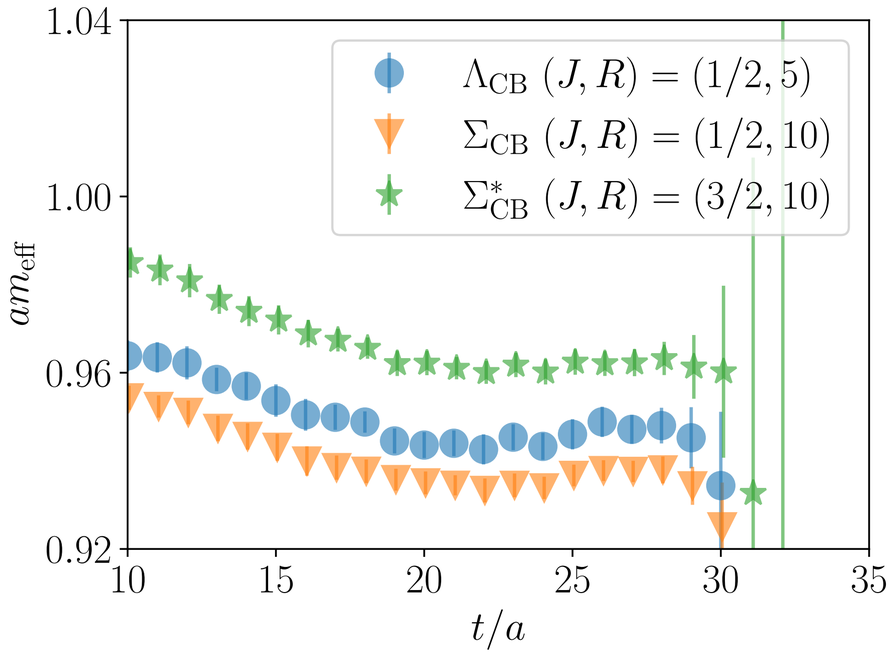
Results

Quenched approximation

Results

Mass hierarchy

heavy F fermion mass



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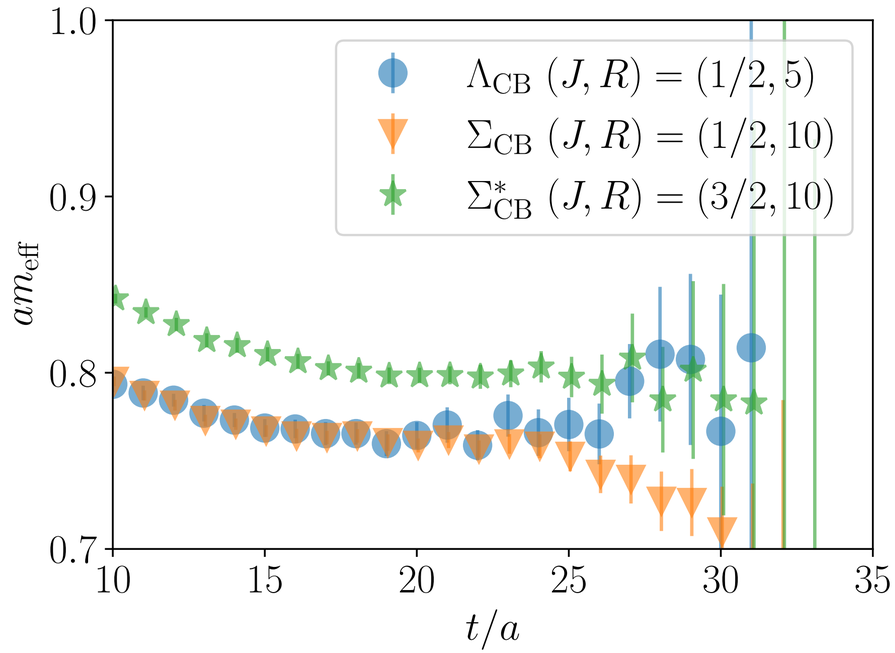
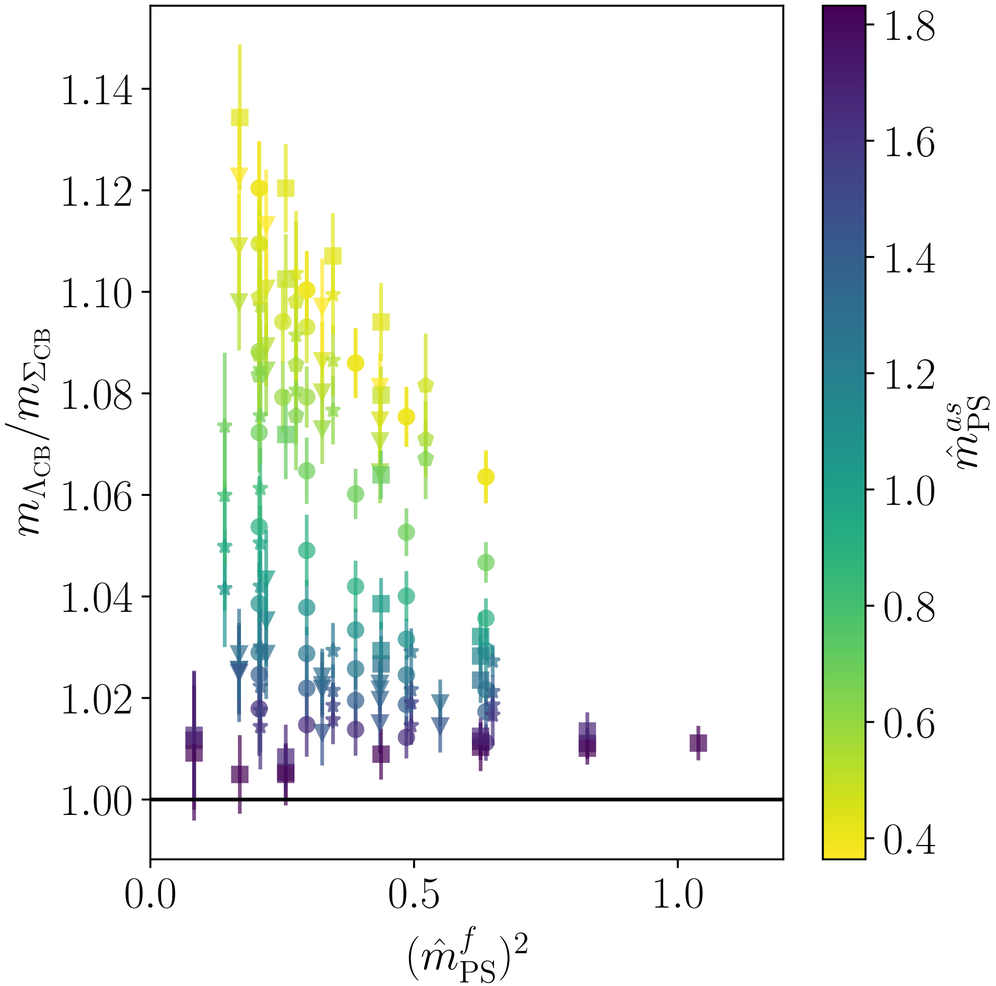
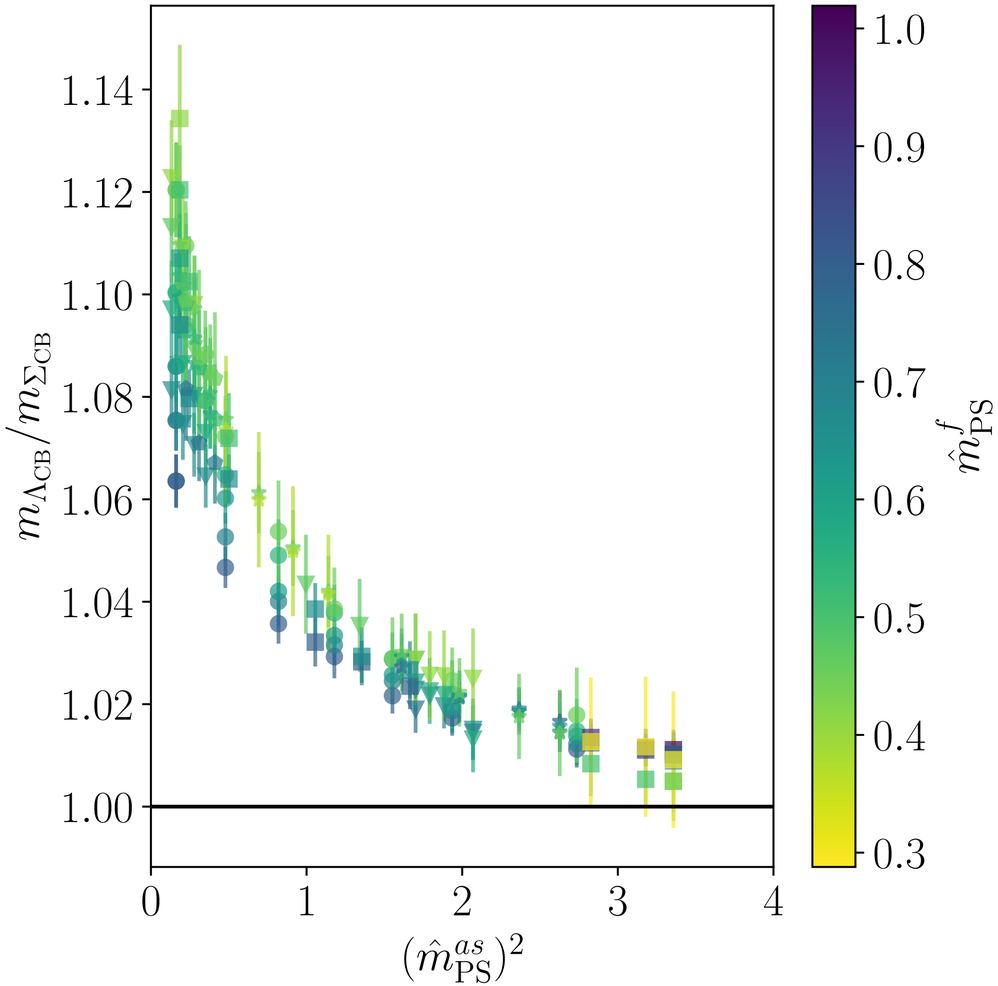


Effective mass plot of chimera baryons calculated with different F fermion masses, at fixed AS fermion mass. The lattice size is 60×48^3 with $\beta = 8.0$.

Results

Mass hierarchy





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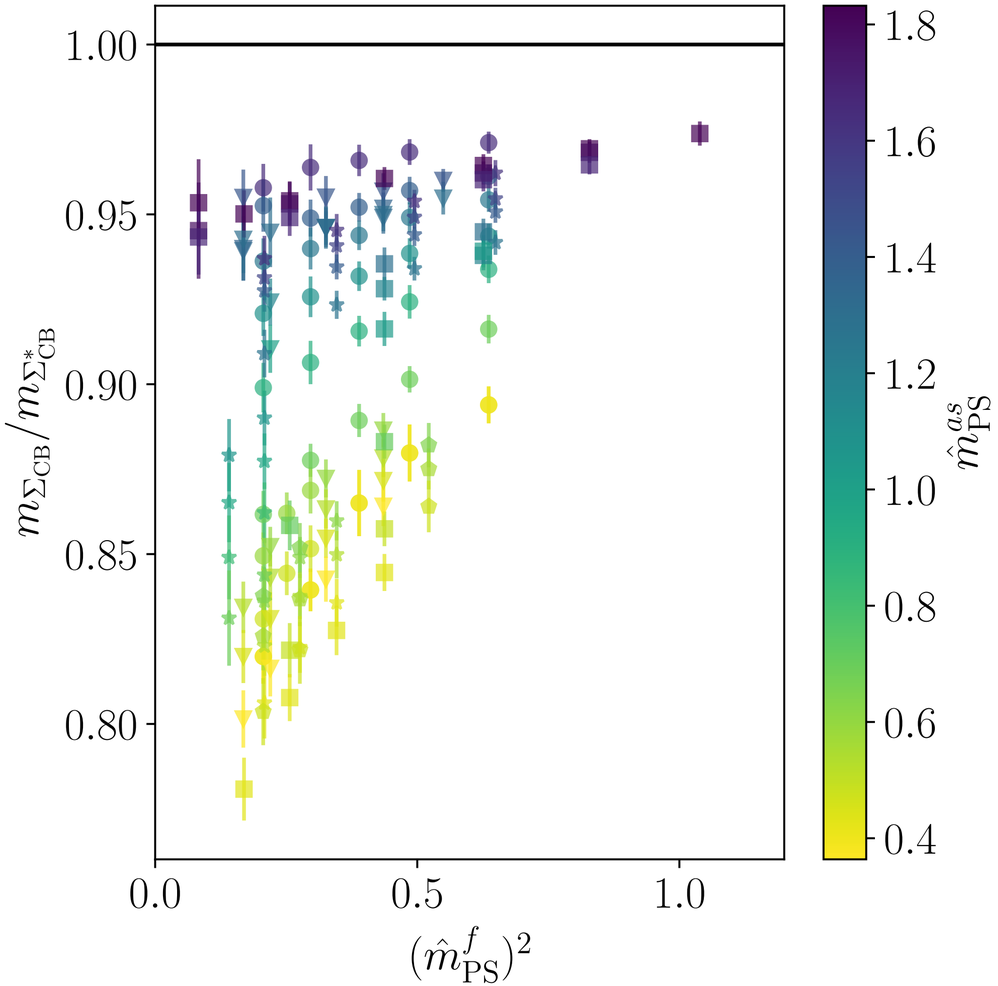

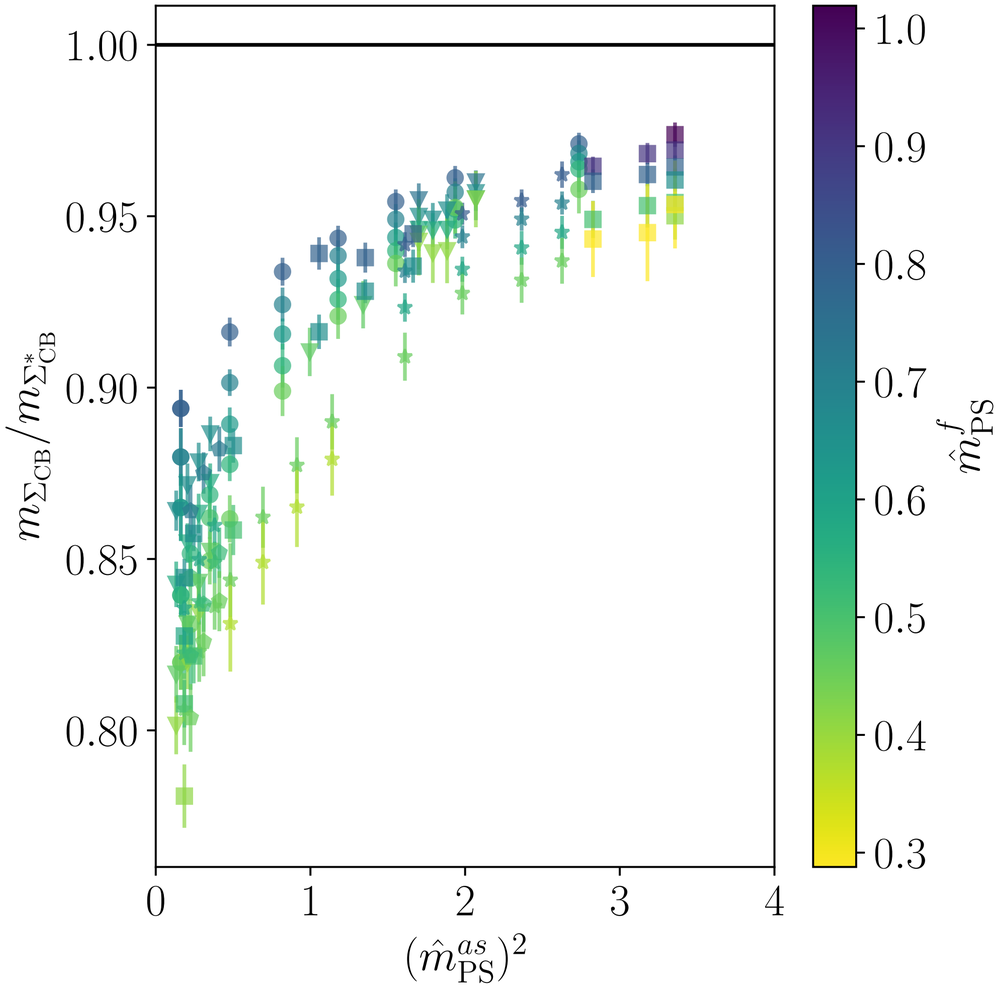

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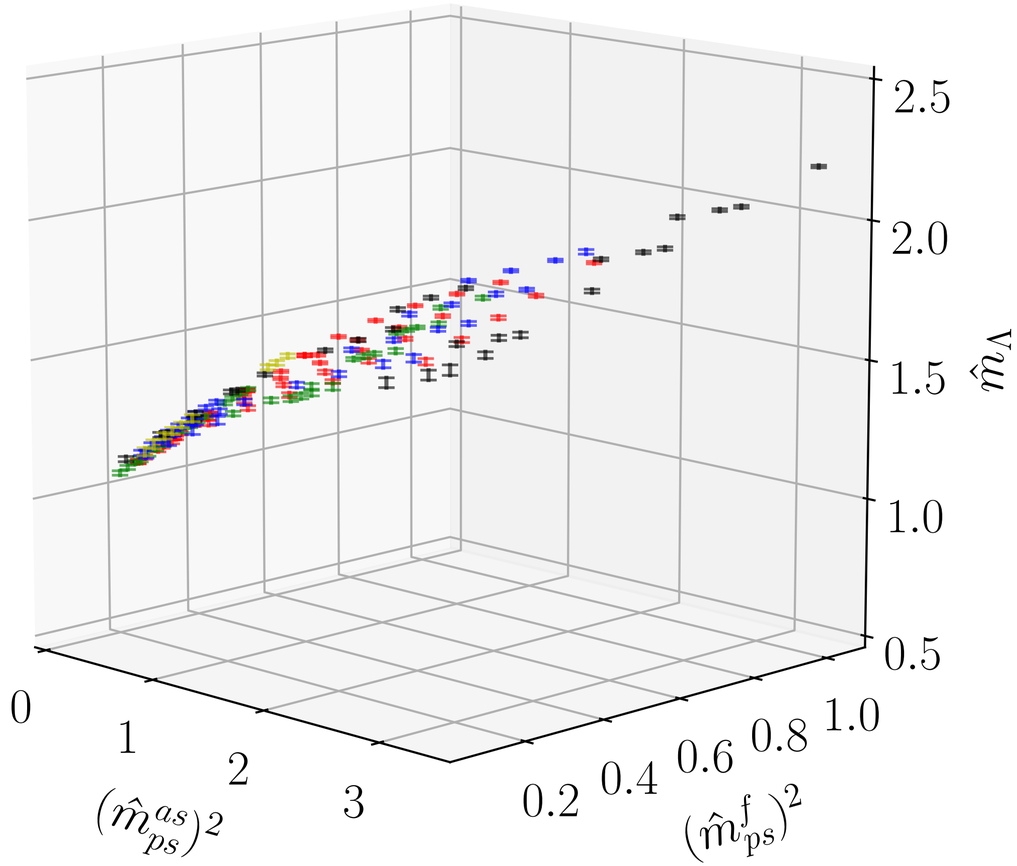
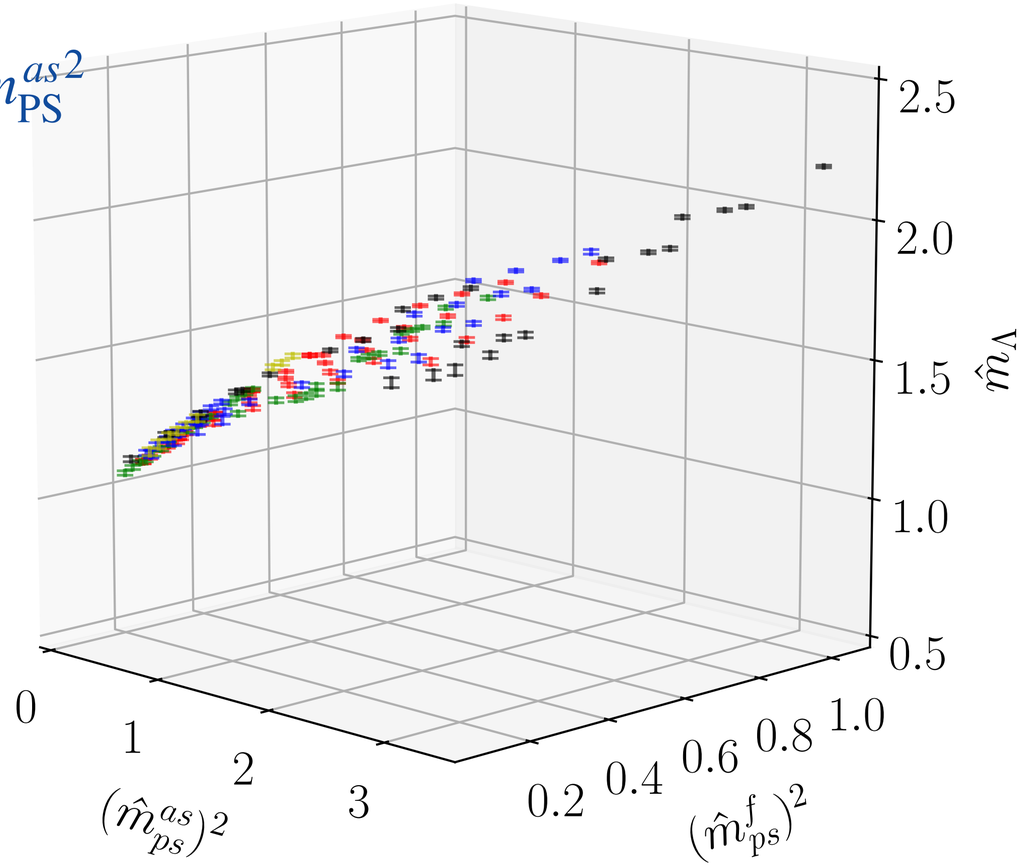

2.5
2.0
1.5
1.0
0.5
$\hat{m}_\Lambda$
0
1
2
3
$(\hat{m}_{ps}^{as})^2$
0.2
0.4
0.6
0.8
1.0
$(\hat{m}_{\rm ps}^{\rm f})^2$

Results

- Apply tree level baryon chiral perturbation theory

$$m_{\mathrm{CB}} = m_0 + F_1 {m_{\mathrm{PS}}^f}^2 + A_1 m_{\mathrm{PS}}^{as2} + L_1(a/\omega_0)$$
$$+ F_2 {m_{\mathrm{PS}}^f}^3 + A_2 m_{\mathrm{PS}}^{as3} + L_{2F}(a/\omega_0){m_{\mathrm{PS}}^f}^2 + L_{2A}(a/\omega_0) m_{\mathrm{PS}}^{as2}$$
$$+ F_3 {m_{\mathrm{PS}}^f}^4 + A_3 m_{\mathrm{PS}}^{as4} + C_3 {m_{\mathrm{PS}}^f}^2 m_{\mathrm{PS}}^{as2}$$



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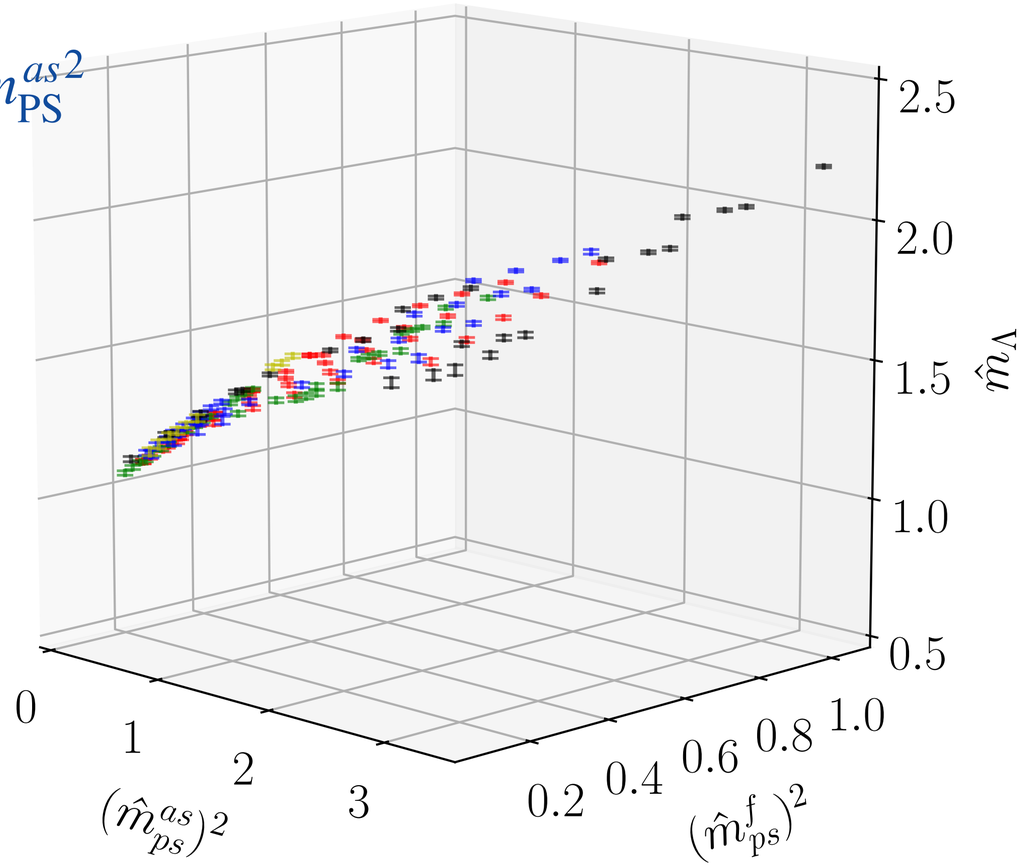
$$m_{\mathrm{CB}} = m_0 + F_1 m_{\mathrm{PS}}^{f\,2} + A_1 m_{\mathrm{PS}}^{as\,2} + L_1 (a/\omega_0) \quad \text{---------- M2}$$
$$+ F_2 m_{\mathrm{PS}}^{f\,3} + A_2 m_{\mathrm{PS}}^{as\,3} + L_{2F} (a/\omega_0) m_{\mathrm{PS}}^{f\,2} + L_{2A} (a/\omega_0) m_{\mathrm{PS}}^{as\,2}$$
$$+ F_3 m_{\mathrm{PS}}^{f\,4} + A_3 m_{\mathrm{PS}}^{as\,4} + C_3 m_{\mathrm{PS}}^{f\,2} m_{\mathrm{PS}}^{as\,2}$$



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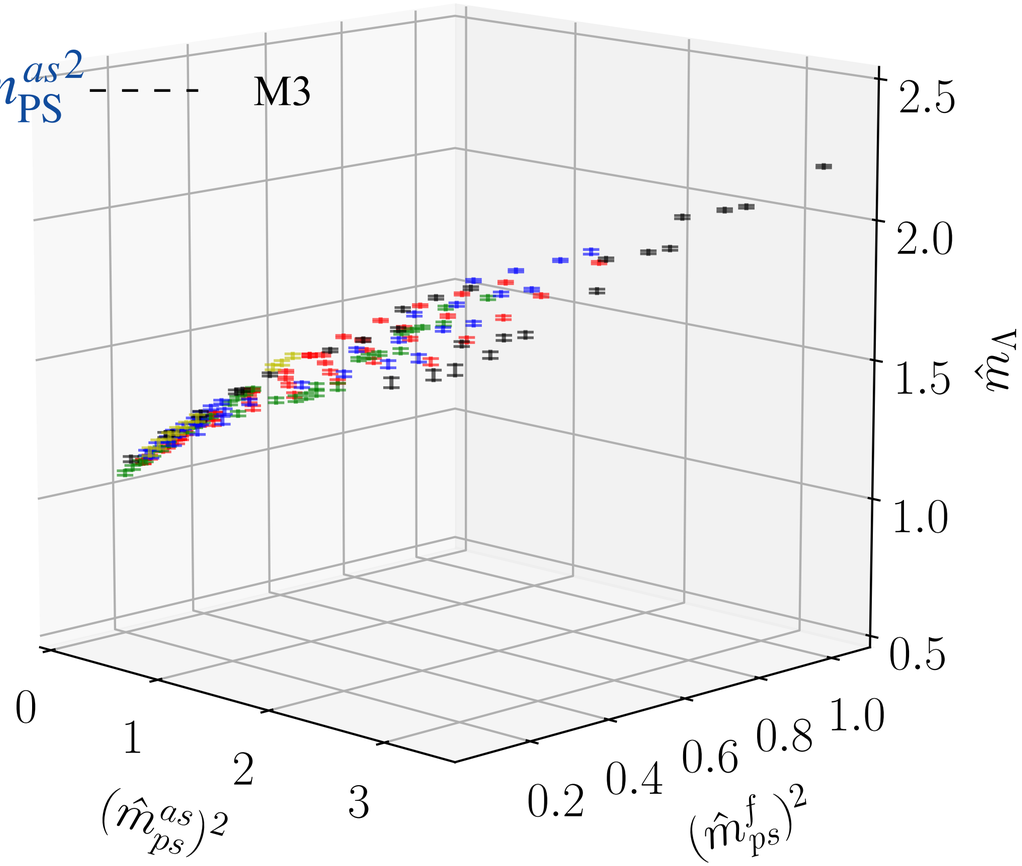
$$+ F_3 m_{\mathrm{PS}}^{f\,4} + A_3 m_{\mathrm{PS}}^{as\,4} + C_3 m_{\mathrm{PS}}^{f\,2} m_{\mathrm{PS}}^{as\,2}$$



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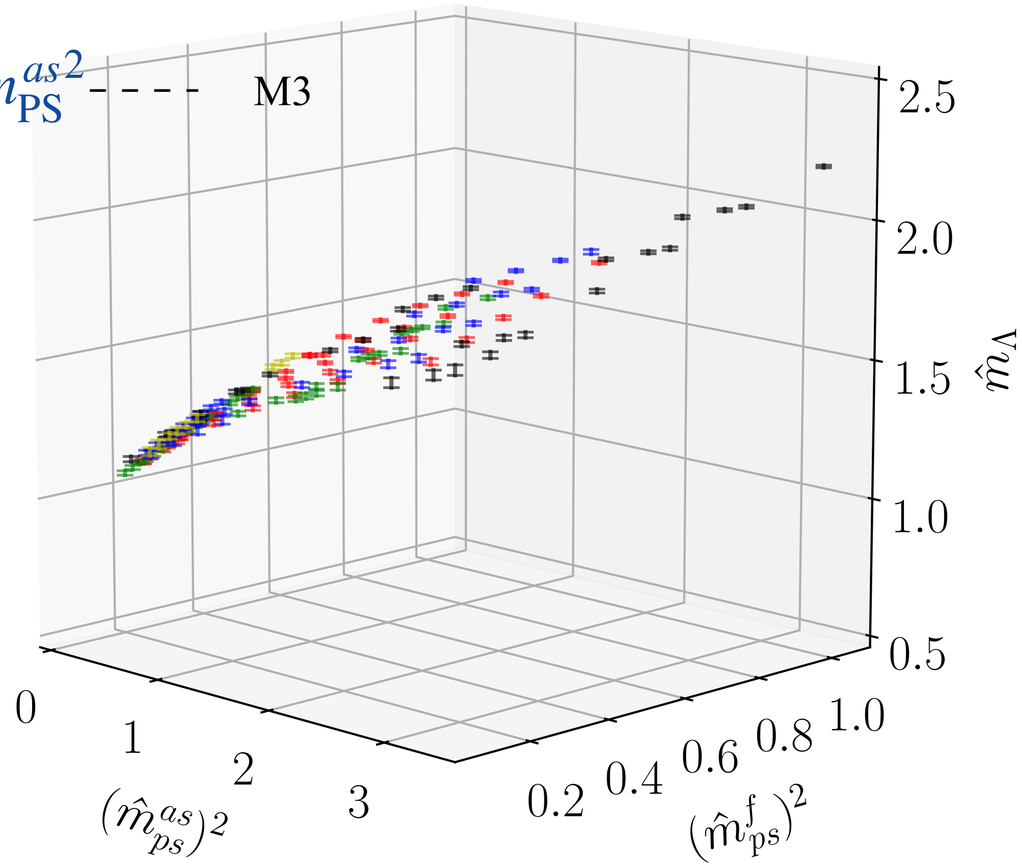
$$m_{\mathrm{CB}} = m_0 + F_1 m_{\mathrm{PS}}^{f\,2} + A_1 m_{\mathrm{PS}}^{as\,2} + L_1(a/\omega_0) \quad \text{M2}$$

$$+ F_2 m_{\mathrm{PS}}^{f\,3} + A_2 m_{\mathrm{PS}}^{as\,3} + L_{2F}(a/\omega_0) m_{\mathrm{PS}}^{f\,2} + L_{2A}(a/\omega_0) m_{\mathrm{PS}}^{as\,2} \quad \text{M3}$$

$$+ \underbrace{F_3 m_{\mathrm{PS}}^{f\,4} + A_3 m_{\mathrm{PS}}^{as\,4} + C_3 m_{\mathrm{PS}}^{f\,2} m_{\mathrm{PS}}^{as\,2}}_{\text{MF4}}$$



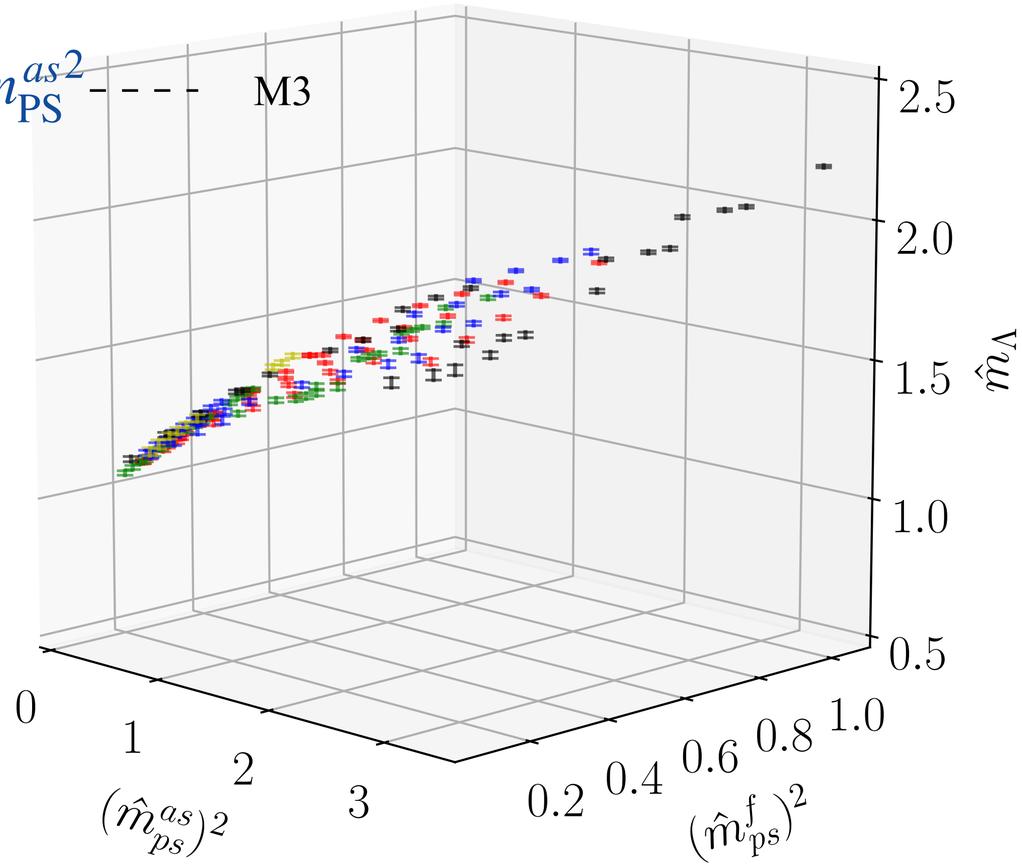
Results

- Apply tree level baryon chiral perturbation theory

$$m_{\mathrm{CB}} = m_0 + F_1 m_{\mathrm{PS}}^{f\,2} + A_1 m_{\mathrm{PS}}^{as\,2} + L_1 (a/\omega_0) \quad \text{M2}$$

$$+ F_2 m_{\mathrm{PS}}^{f\,3} + A_2 m_{\mathrm{PS}}^{as\,3} + L_{2F} (a/\omega_0) m_{\mathrm{PS}}^{f\,2} + L_{2A} (a/\omega_0) m_{\mathrm{PS}}^{as\,2} \quad \text{M3}$$

$$+ \underbrace{F_3 m_{\mathrm{PS}}^{f\,4}}_{\text{MF4}} + \underbrace{A_3 m_{\mathrm{PS}}^{as\,4}}_{\text{MA4}} + C_3 m_{\mathrm{PS}}^{f\,2} m_{\mathrm{PS}}^{as\,2}$$



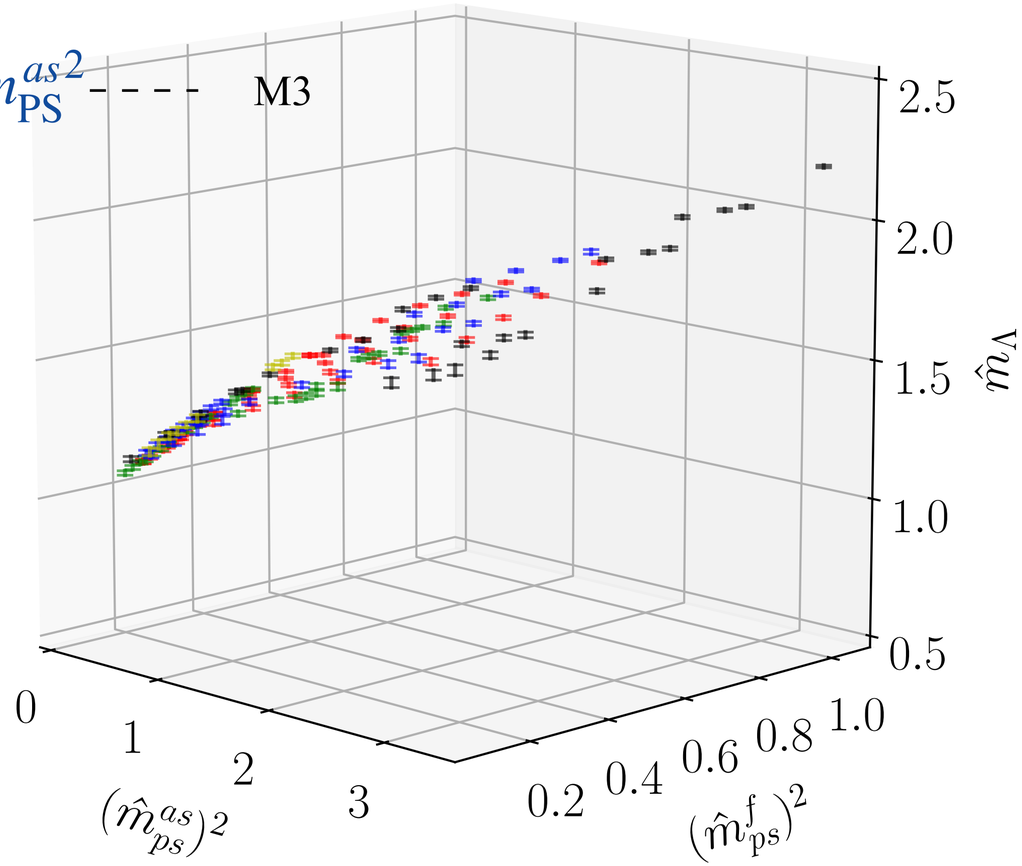
Results

- Apply tree level baryon chiral perturbation theory

$$m_{\mathrm{CB}} = m_0 + F_1 m_{\mathrm{PS}}^{f\,2} + A_1 m_{\mathrm{PS}}^{as\,2} + L_1(a/\omega_0) \quad \text{M2}$$

$$+ F_2 m_{\mathrm{PS}}^{f\,3} + A_2 m_{\mathrm{PS}}^{as\,3} + L_{2F}(a/\omega_0) m_{\mathrm{PS}}^{f\,2} + L_{2A}(a/\omega_0) m_{\mathrm{PS}}^{as\,2} \quad \text{M3}$$

$$+ \underbrace{F_3 m_{\mathrm{PS}}^{f\,4}}_{\text{MF4}} + \underbrace{A_3 m_{\mathrm{PS}}^{as\,4}}_{\text{MA4}} + \underbrace{C_3 m_{\mathrm{PS}}^{f\,2} m_{\mathrm{PS}}^{as\,2}}_{\text{M2C}}$$



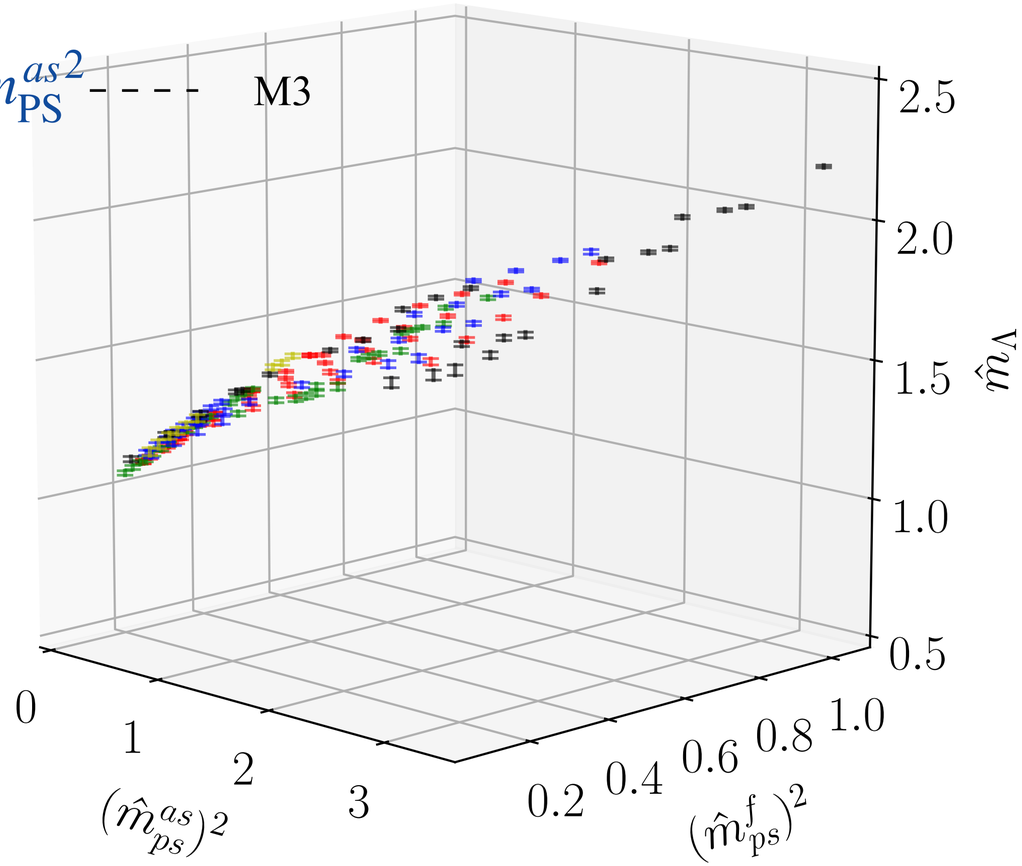
Results

- Apply tree level baryon chiral perturbation theory

$$m_{\mathrm{CB}} = m_0 + F_1 {m_{\mathrm{PS}}^f}^2 + A_1 m_{\mathrm{PS}}^{as\,2} + L_1(a/\omega_0) \quad \text{M2}$$

$$+ F_2 {m_{\mathrm{PS}}^f}^3 + A_2 m_{\mathrm{PS}}^{as\,3} + L_{2F}(a/\omega_0) {m_{\mathrm{PS}}^f}^2 + L_{2A}(a/\omega_0) m_{\mathrm{PS}}^{as\,2} \quad \text{M3}$$

$$+ \underbrace{F_3 {m_{\mathrm{PS}}^f}^4}_{\text{MF4}} + \underbrace{A_3 m_{\mathrm{PS}}^{as\,4}}_{\text{MA4}} + \underbrace{C_3 {m_{\mathrm{PS}}^f}^2 m_{\mathrm{PS}}^{as\,2}}_{\text{M2C}}$$



- Goodness of a fit: Akaike information criterion (AIC)

$$\mathrm{AIC} \equiv \chi^2 + 2\mathrm{k} + 2\mathrm{N}_{\mathrm{cut}}$$

- probability weight

$$W_D = \frac{1}{\mathcal{N}} \exp\left[-\frac{1}{2}\mathrm{AIC_D}\right]$$

Results

Fittings of Λ_{CB}

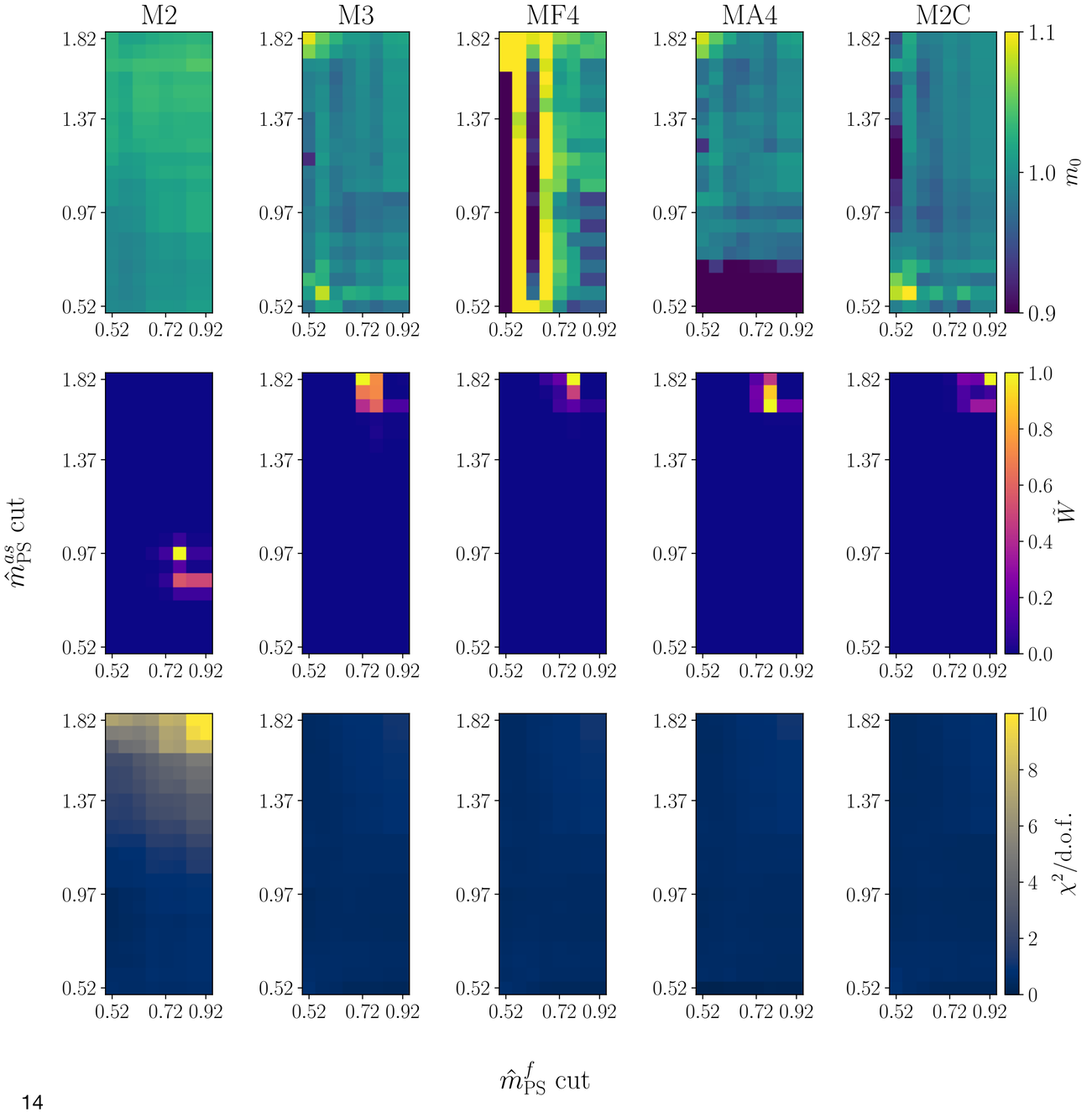
- Apply tree level baryon chiral perturbation theory

M2 $m_{\mathrm{CB}} = m_0 + F_1 m_{\mathrm{PS}}^{f\,2} + A_1 m_{\mathrm{PS}}^{as\,2} + L_1(a/\omega_0)$

M3 $+ F_2 m_{\mathrm{PS}}^{f\,3} + A_2 m_{\mathrm{PS}}^{as\,3} + L_{2F}(a/\omega_0) m_{\mathrm{PS}}^{f\,2} + L_{2A}(a/\omega_0) m_{\mathrm{PS}}^{as\,2}$

$+ F_3 m_{\mathrm{PS}}^{f\,4} + A_3 m_{\mathrm{PS}}^{as\,4} + C_3 m_{\mathrm{PS}}^{f\,2} m_{\mathrm{PS}}^{as\,2}$

MF4 MA4 M2C

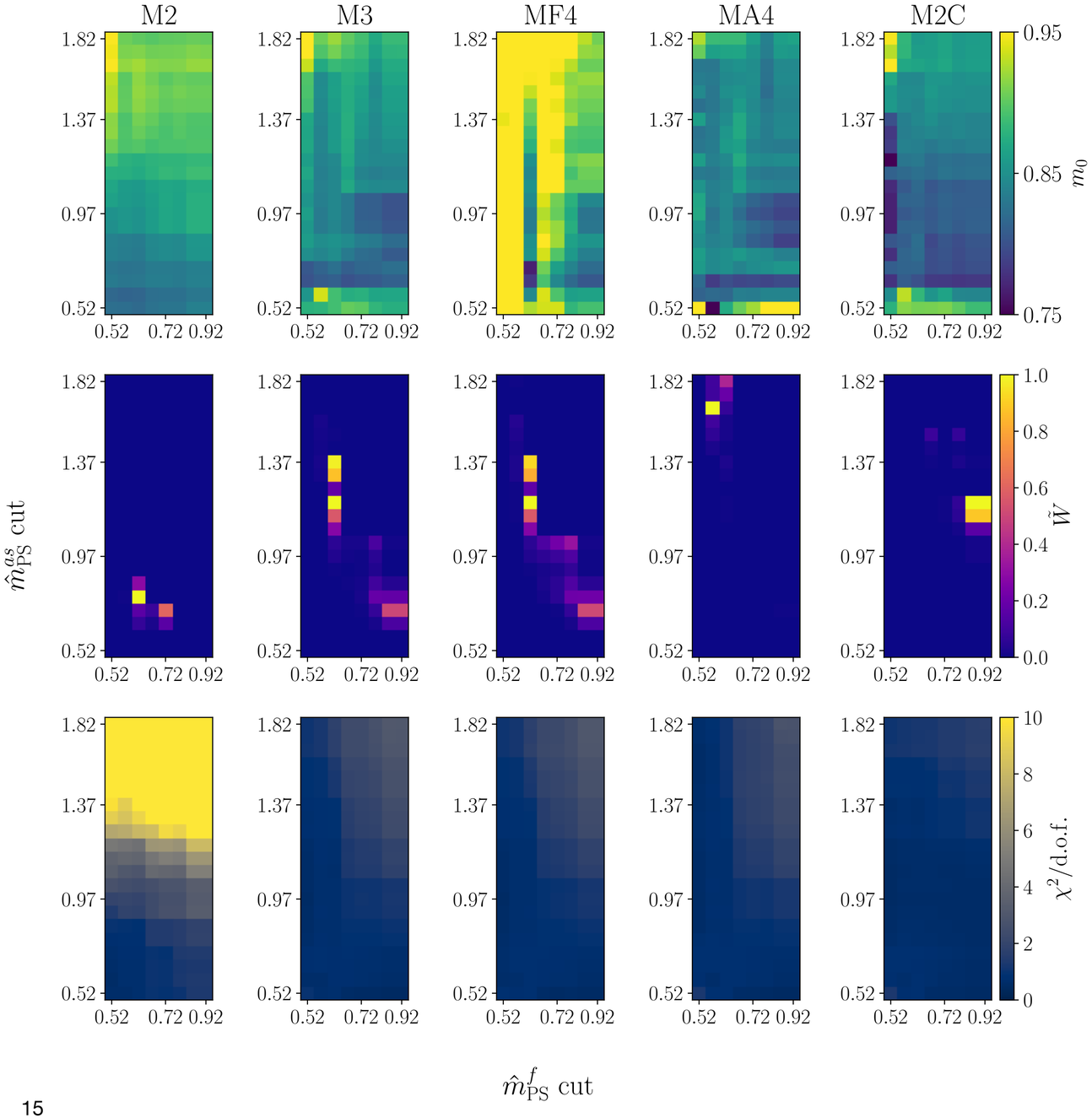


Results

Fittings of Σ_{CB}

- Apply tree level baryon chiral perturbation theory

$$m_{CB} = m_0 + F_1 m_{PS}^{f\,2} + A_1 m_{PS}^{as\,2} + L_1(a/\omega_0) + F_2 m_{PS}^{f\,3} + A_2 m_{PS}^{as\,3} + L_{2F}(a/\omega_0) m_{PS}^{f\,2} + L_{2A}(a/\omega_0) m_{PS}^{as\,2} + F_3 m_{PS}^{f\,4} + A_3 m_{PS}^{as\,4} + C_3 m_{PS}^{f\,2} m_{PS}^{as\,2}$$

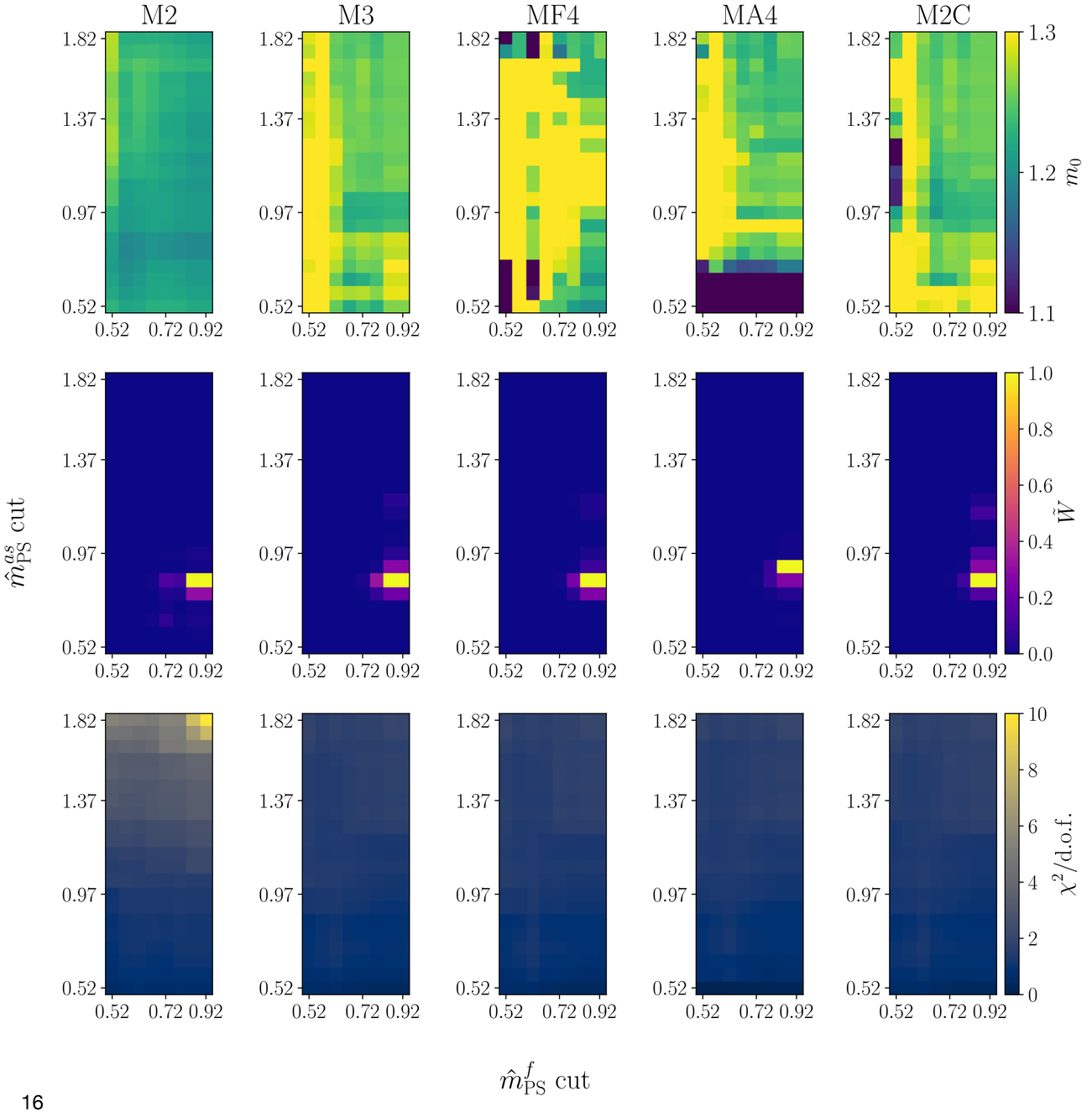


Results

Fittings of Σ^*_{CB}

- Apply tree level baryon chiral perturbation theory

$$m_{\mathrm{CB}} = m_0 + F_1 m_{\mathrm{PS}}^{f\,2} + A_1 m_{\mathrm{PS}}^{as\,2} + L_1(a/\omega_0) + F_2 m_{\mathrm{PS}}^{f\,3} + A_2 m_{\mathrm{PS}}^{as\,3} + L_{2F}(a/\omega_0) m_{\mathrm{PS}}^{f\,2} + L_{2A}(a/\omega_0) m_{\mathrm{PS}}^{as\,2} + F_3 m_{\mathrm{PS}}^{f\,4} + A_3 m_{\mathrm{PS}}^{as\,4} + C_3 m_{\mathrm{PS}}^{f\,2} m_{\mathrm{PS}}^{as\,2}$$



Results

Sense check

- Apply tree level baryon chiral perturbation theory

$$
\begin{aligned}
m_{\mathrm{CB}} = m_0 &+ F_1 {m_{\mathrm{PS}}^f}^2 + A_1 m_{\mathrm{PS}}^{as\,2} + L_1 (a/\omega_0) \\
&+ F_2 {m_{\mathrm{PS}}^f}^3 + A_2 m_{\mathrm{PS}}^{as\,3} + L_{2F} (a/\omega_0) {m_{\mathrm{PS}}^f}^2 + L_{2A} (a/\omega_0) m_{\mathrm{PS}}^{as\,2} \\
&+ F_3 {m_{\mathrm{PS}}^f}^4 + A_3 m_{\mathrm{PS}}^{as\,4} + C_3 {m_{\mathrm{PS}}^f}^2 m_{\mathrm{PS}}^{as\,2}
\end{aligned}
$$

Results

Sense check

- At a fixed $\hat{m}_{\mathrm{PS}}^{as}$, the fitting function becomes

$$m_{\mathrm{CB}} = m_0 + F_1 {m_{\mathrm{PS}}^f}^2 + A_1 {m_{\mathrm{PS}}^{as}}^2 + L_1(a/\omega_0)$$
$$+ F_2 {m_{\mathrm{PS}}^f}^3 + A_2 {m_{\mathrm{PS}}^{as}}^3 + L_{2F}(a/\omega_0){m_{\mathrm{PS}}^f}^2 + L_{2A}(a/\omega_0){m_{\mathrm{PS}}^{as}}^2$$
$$+ F_3 {m_{\mathrm{PS}}^f}^4 + A_3 {m_{\mathrm{PS}}^{as}}^4 + C_3 {m_{\mathrm{PS}}^f}^2 {m_{\mathrm{PS}}^{as}}^2$$

$$\Rightarrow m_0(m_{\mathrm{PS}}^{as}, A, L, (a/\omega_0)) + F_1 {m_{\mathrm{PS}}^f}^2 + F_2 {m_{\mathrm{PS}}^f}^3 + F_3 {m_{\mathrm{PS}}^f}^4$$

Results

Sense check

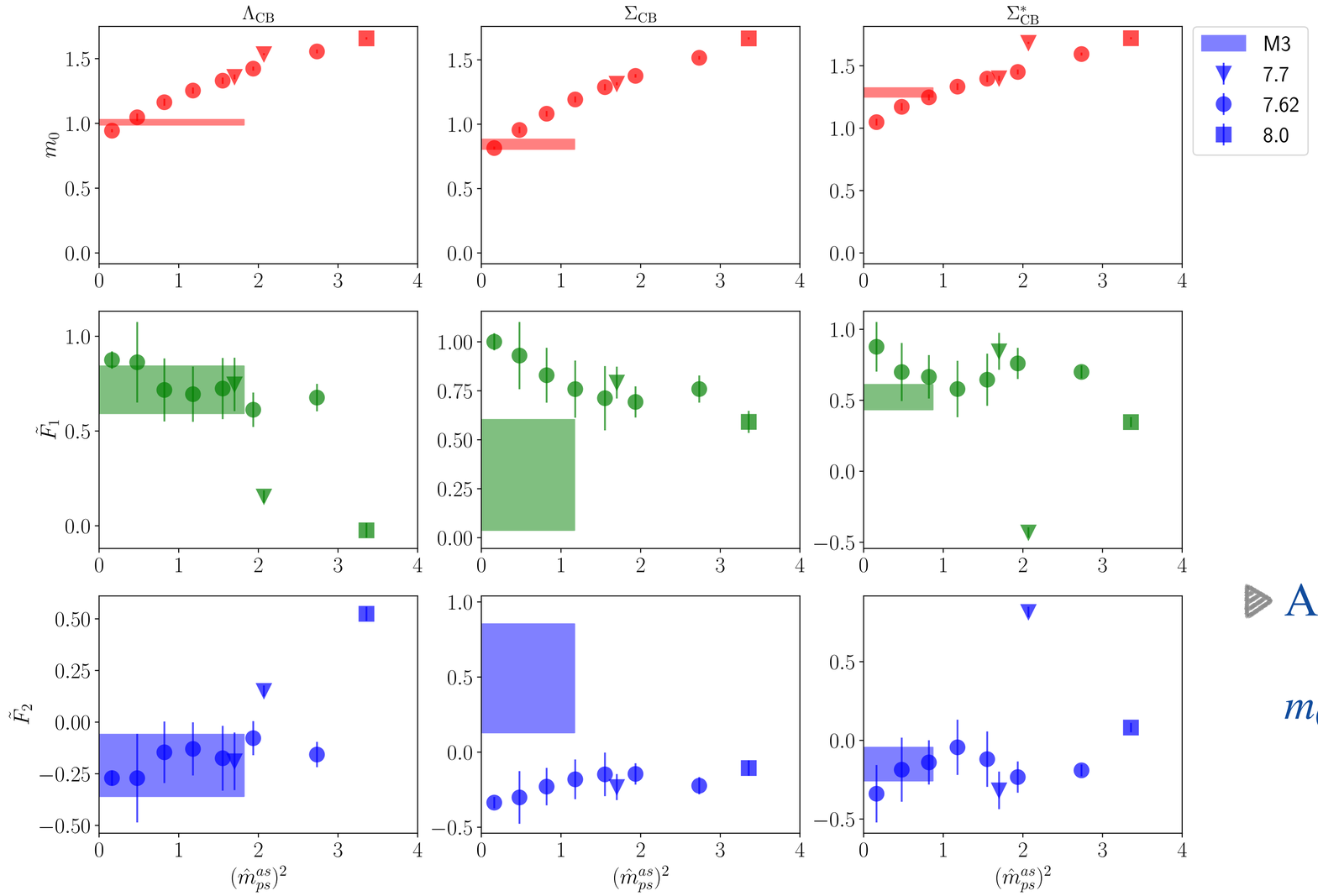
- At a fixed $\hat{m}_{\mathrm{PS}}^{as}$, the fitting function becomes

$$m_{\mathrm{CB}} = m_0 + A_1 m_{\mathrm{PS}}^{as\,2} + L_1(a/\omega_0) + A_2 m_{\mathrm{PS}}^{as\,3} + L_{2A}(a/\omega_0) m_{\mathrm{PS}}^{as\,2} + A_3 m_{\mathrm{PS}}^{as\,4}$$
$$+ F_1 m_{\mathrm{PS}}^{f\,2} + C_3 m_{\mathrm{PS}}^{f\,2} m_{\mathrm{PS}}^{as\,2} + L_{2F}(a/\omega_0) m_{\mathrm{PS}}^{f\,2}$$
$$+ F_2 m_{\mathrm{PS}}^{f\,3} + F_3 m_{\mathrm{PS}}^{f\,4}$$

$$\Rightarrow m_0(m_{\mathrm{PS}}^{as}, A, L, (a/\omega_0)) + \tilde{F}_1(m_{\mathrm{PS}}^{as}, C, L, (a/\omega_0)) m_{\mathrm{PS}}^{f\,2} + \tilde{F}_2 m_{\mathrm{PS}}^{f\,3} + F_3 m_{\mathrm{PS}}^{f\,4}$$

Results

Sense check

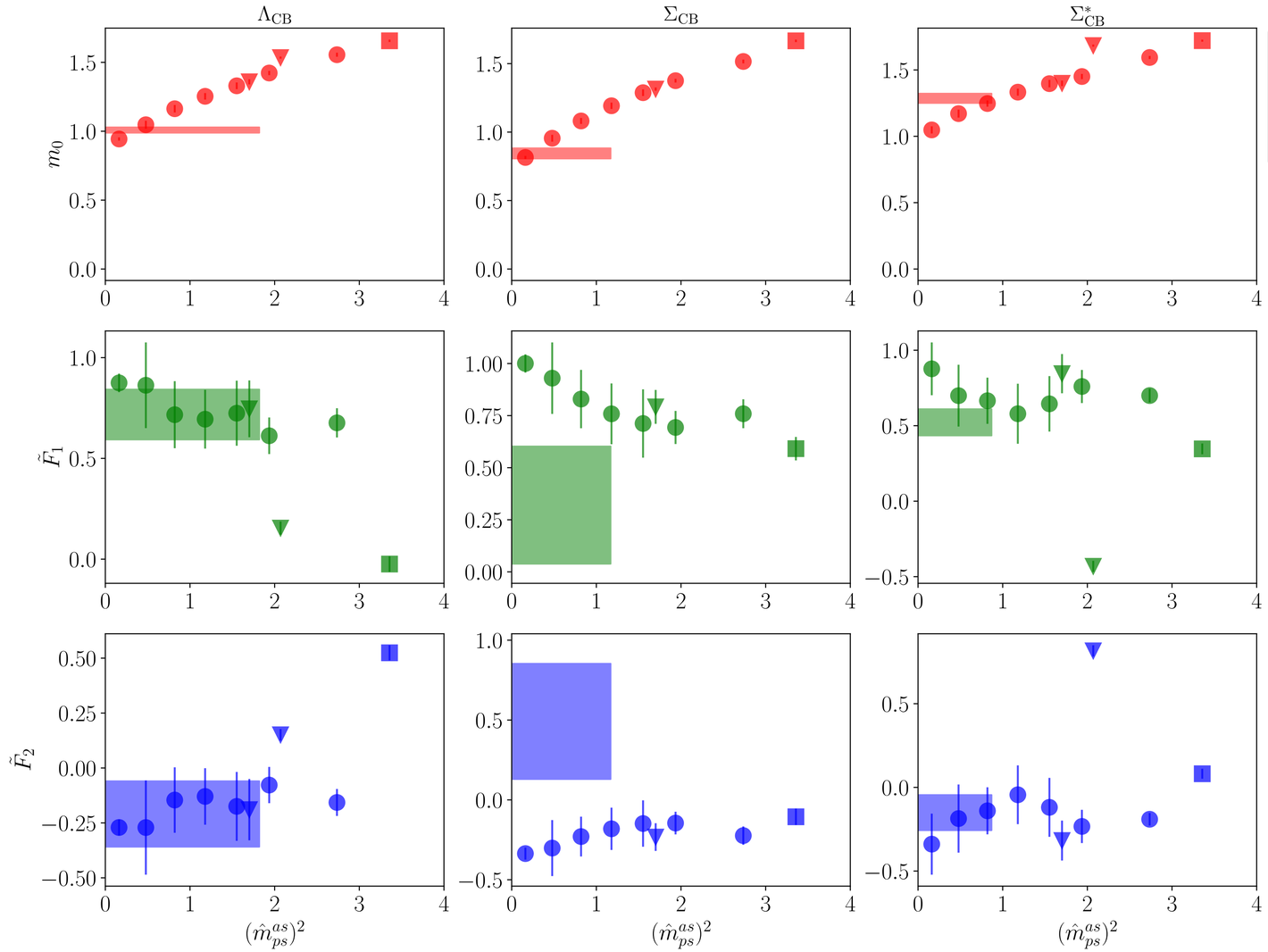


- At a fixed $\hat{m}^{as}_{\mathrm{PS}}$

$$m_{\mathrm{CB}} = m_0(m^{as}_{\mathrm{PS}}, A, L, (a/\omega_0)) + \tilde{F}_1(m^{as}_{\mathrm{PS}}, C, L, (a/\omega_0)) {m^f_{\mathrm{PS}}}^2 + \tilde{F}_2 {m^f_{\mathrm{PS}}}^3$$

Results

Sense check



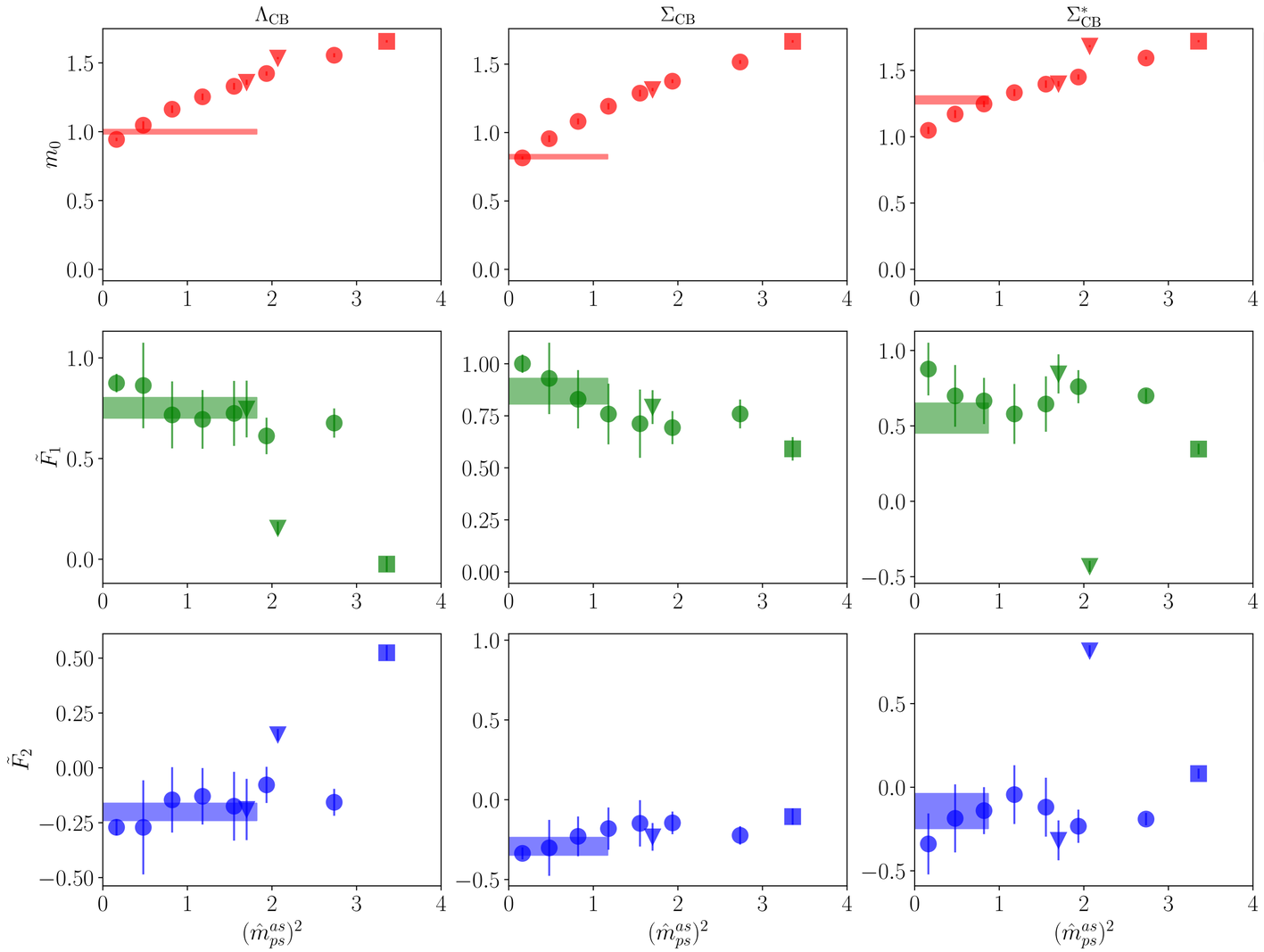
$$m_{CB} = m_0 + F_1 m_{PS}^{f\,2} + A_1 m_{PS}^{as\,2} + L_1(a/\omega_0) + F_2 m_{PS}^{f\,3} + A_2 m_{PS}^{as\,3} + L_{2F}(a/\omega_0) m_{PS}^{f\,2} + L_{2A}(a/\omega_0) m_{PS}^{as\,2} + \cancel{F_3 m_{PS}^{f\,4} + A_3 m_{PS}^{as\,4} + C_3 m_{PS}^{f\,2} m_{PS}^{as\,2}}$$

- At a fixed $\hat{m}^{as}_{PS}$

$$m_{CB} = m_0(m^{as}_{PS}, A, L, (a/\omega_0)) + \tilde{F}_1(m^{as}_{PS}, C, L, (a/\omega_0)) m_{PS}^{f\,2} + \tilde{F}_2 m_{PS}^{f\,3}$$

Results

Sense check



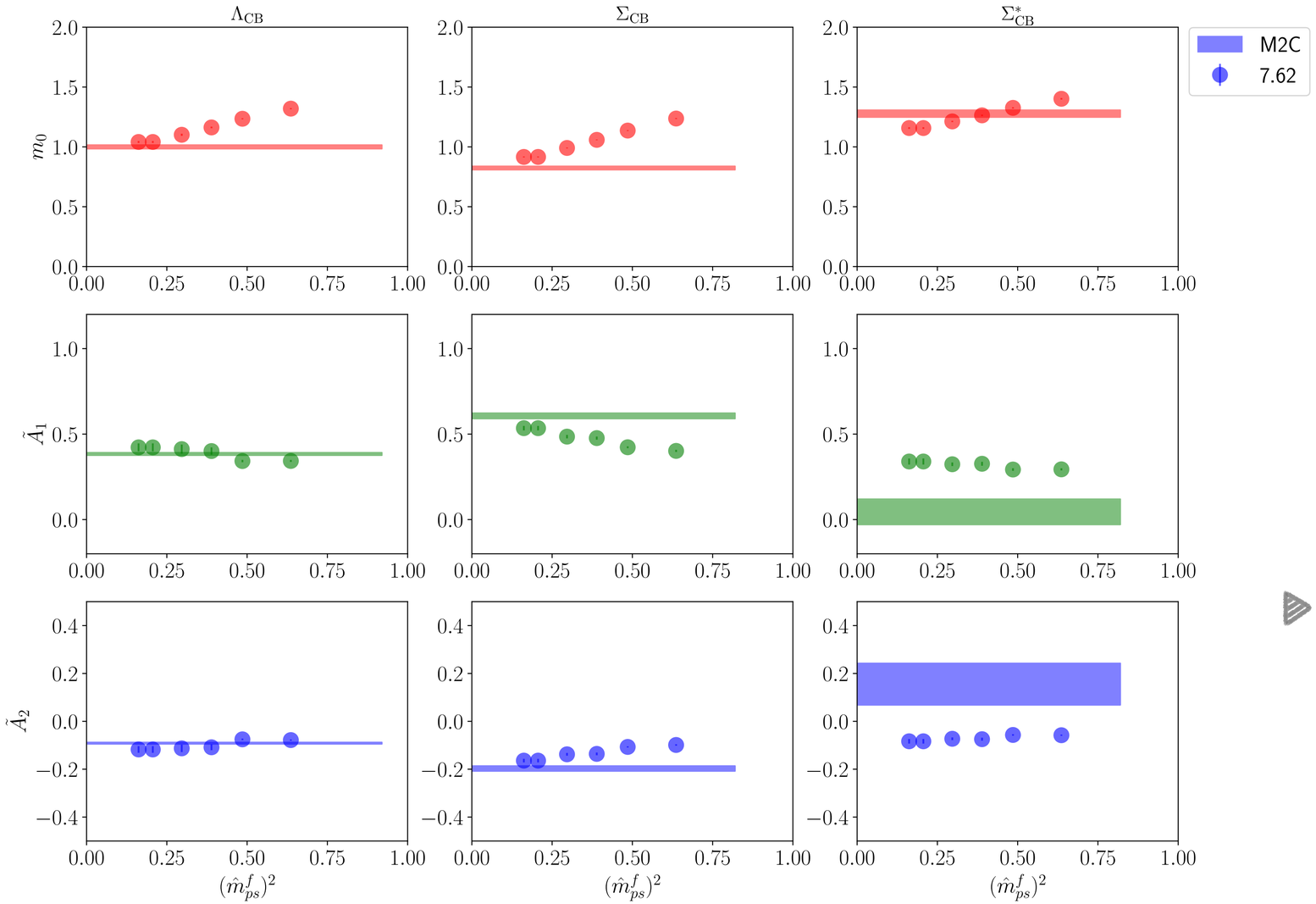
$$m_{CB} = m_0 + F_1 m_{PS}^{f\,2} + A_1 m_{PS}^{as\,2} + L_1(a/\omega_0) + F_2 m_{PS}^{f\,3} + A_2 m_{PS}^{as\,3} + L_{2F}(a/\omega_0) m_{PS}^{f\,2} + L_{2A}(a/\omega_0) m_{PS}^{as\,2} + \cancel{F_3 m_{PS}^{f\,4}} + \cancel{A_3 m_{PS}^{as\,4}} + C_3 m_{PS}^{f\,2} m_{PS}^{as\,2}$$

- At a fixed $\hat{m}^{as}_{PS}$

$$m_{CB} = m_0(m^{as}_{PS}, A, L, (a/\omega_0)) + \tilde{F}_1(m^{as}_{PS}, C, L, (a/\omega_0)) m_{PS}^{f\,2} + \tilde{F}_2 m_{PS}^{f\,3}$$

Results

Sense check



- At a fixed $\hat{m}^f_{\mathrm{PS}}$

$$m_{\mathrm{CB}} = m_0(m^f_{\mathrm{PS}}, F, L, (a/\omega_0)) + \tilde{A}_1(m^f_{\mathrm{PS}}, C, L, (a/\omega_0))m^{as}_{\mathrm{PS}}{}^2 + \tilde{A}_2 m^{as}_{\mathrm{PS}}{}^3$$

Results

Comparison among the best fits

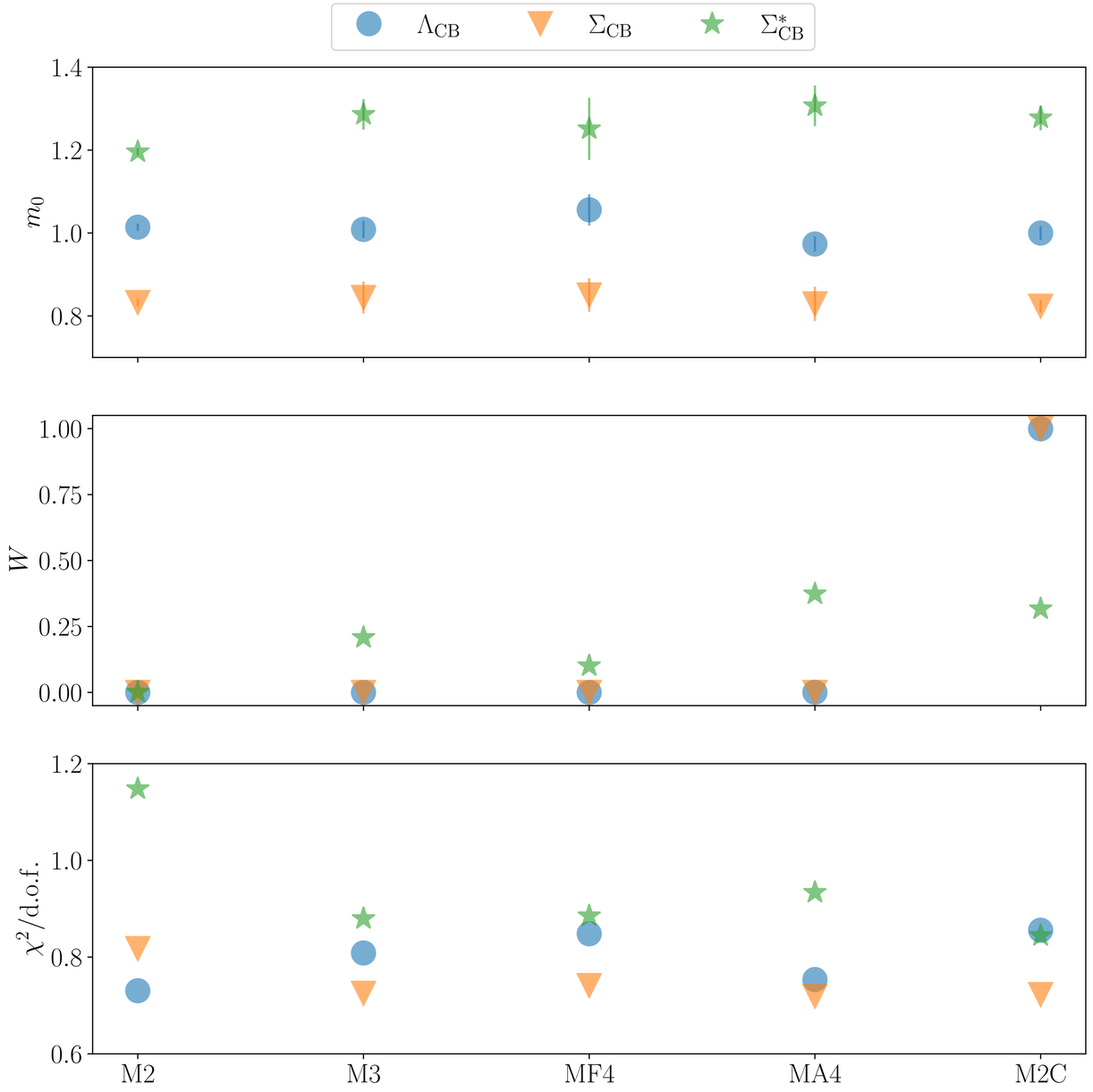
- Apply tree level baryon chiral perturbation theory

M2 $m_{\rm CB} = m_0 + F_1 m_{\rm PS}^{f\,2} + A_1 m_{\rm PS}^{as\,2} + L_1(a/\omega_0)$

M3 $+ F_2 m_{\rm PS}^{f\,3} + A_2 m_{\rm PS}^{as\,3} + L_{2F}(a/\omega_0) m_{\rm PS}^{f\,2} + L_{2A}(a/\omega_0) m_{\rm PS}^{as\,2}$

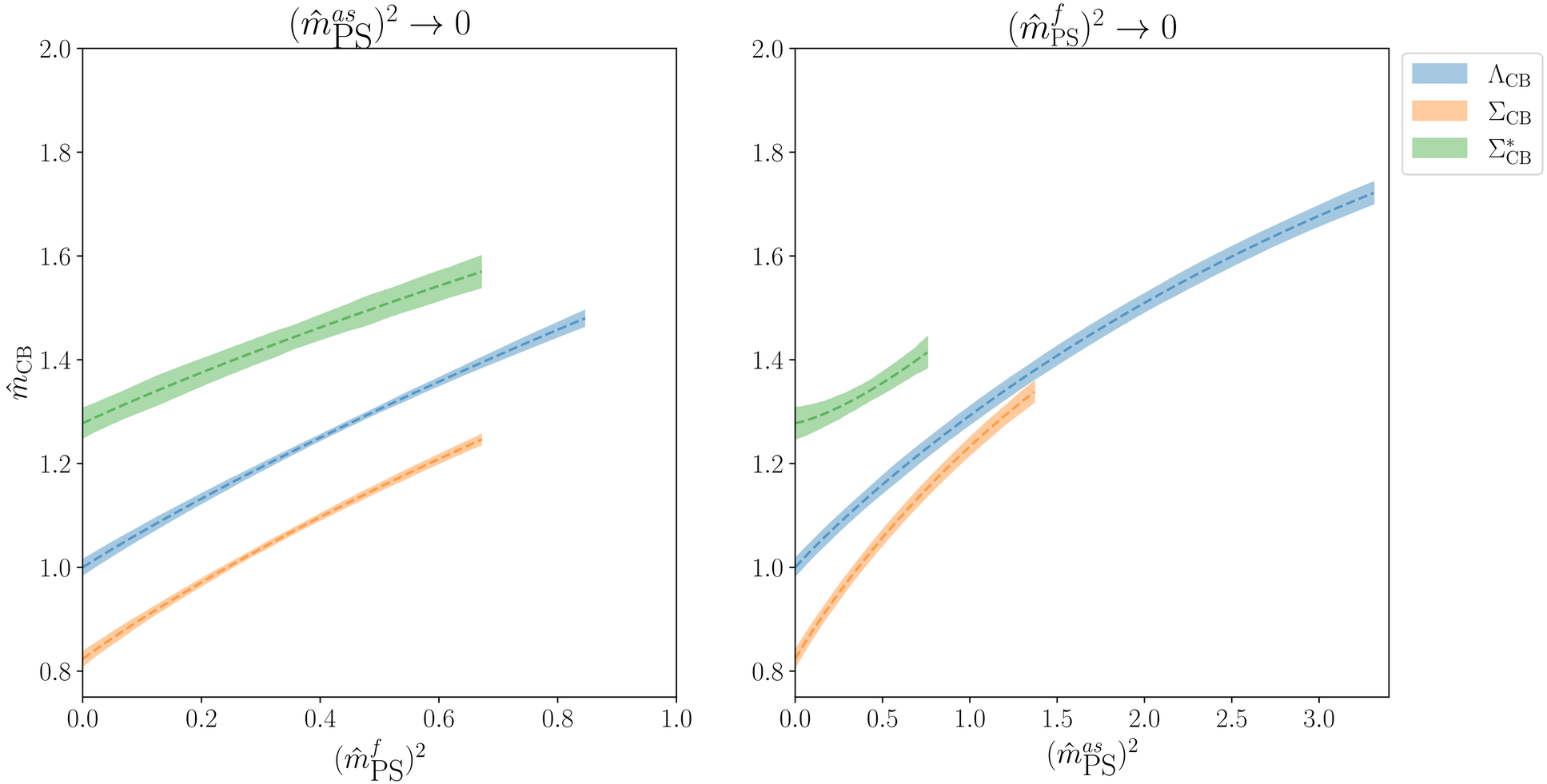
$+ \underline{F_3 m_{\rm PS}^{f\,4}} + \underline{A_3 m_{\rm PS}^{as\,4}} + \underline{C_3 m_{\rm PS}^{f\,2} m_{\rm PS}^{as\,2}}$

MF4 MA4 M2C



Results

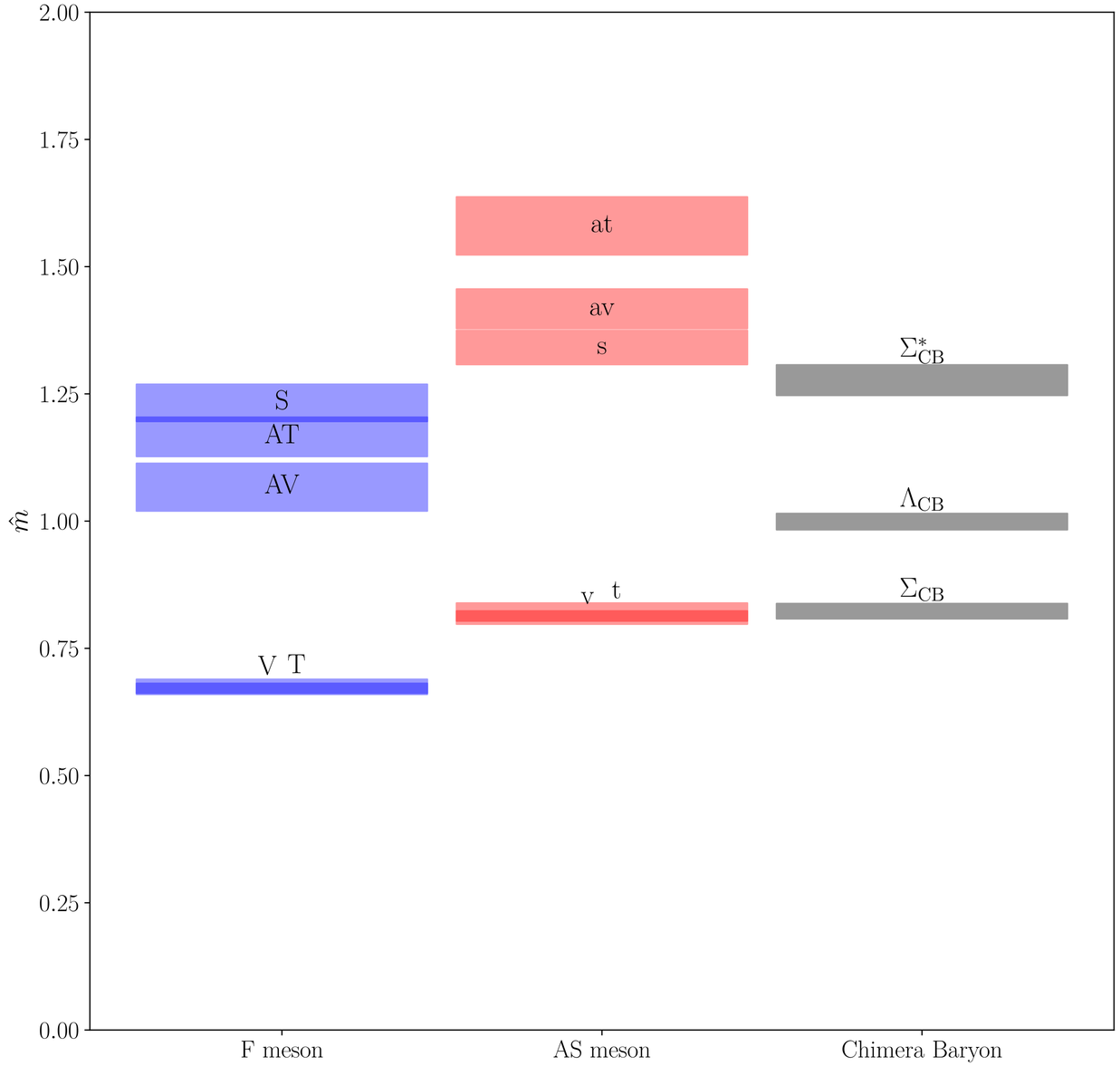
Massless-continuum limit



Results

Massless-continuum limit

Masses of mesons in quenched approximation for fermions in the fundamental (blue bands) and antisymmetric (red bands) representation of $Sp(4)$, as a function of the pseudoscalar mass squared.

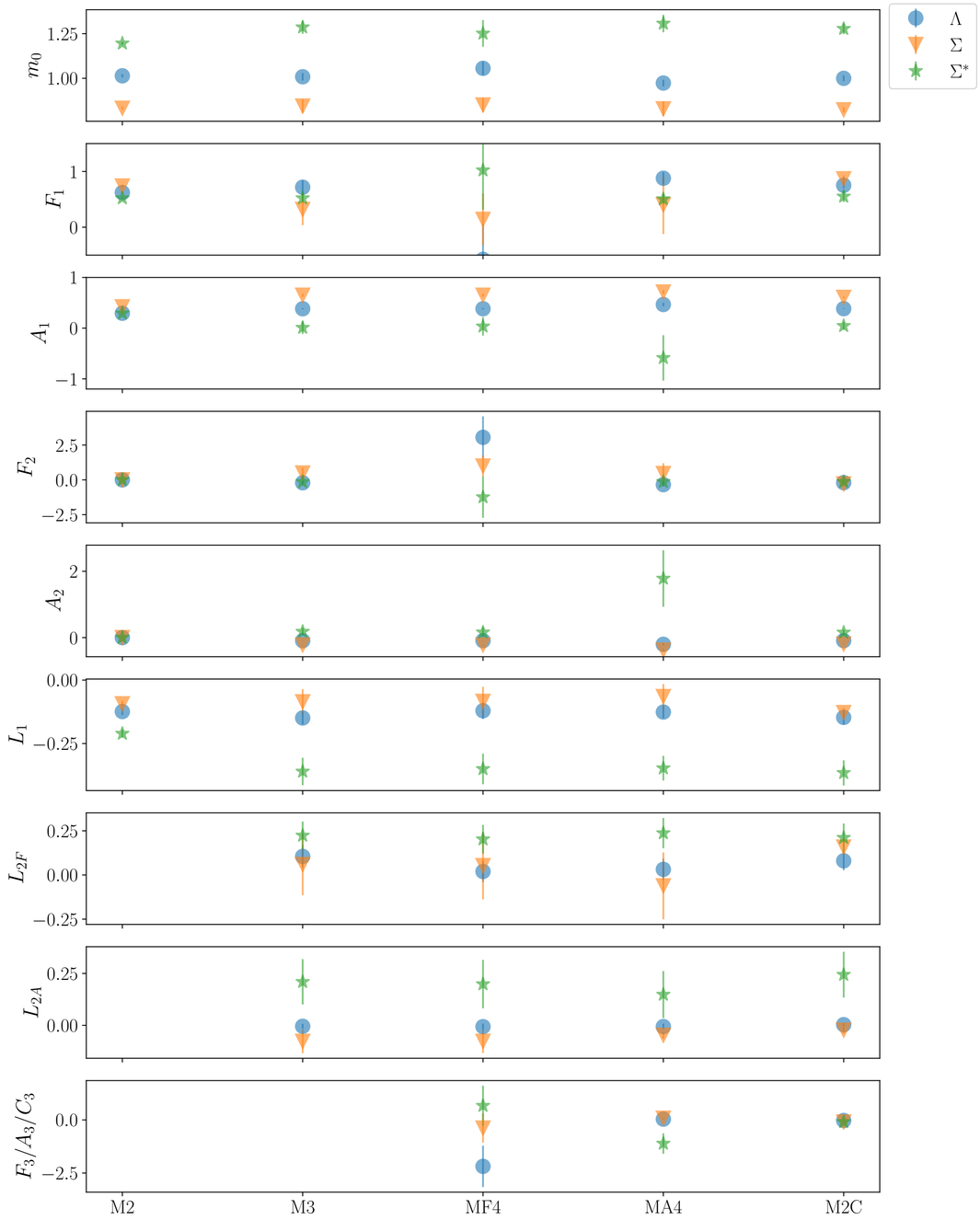


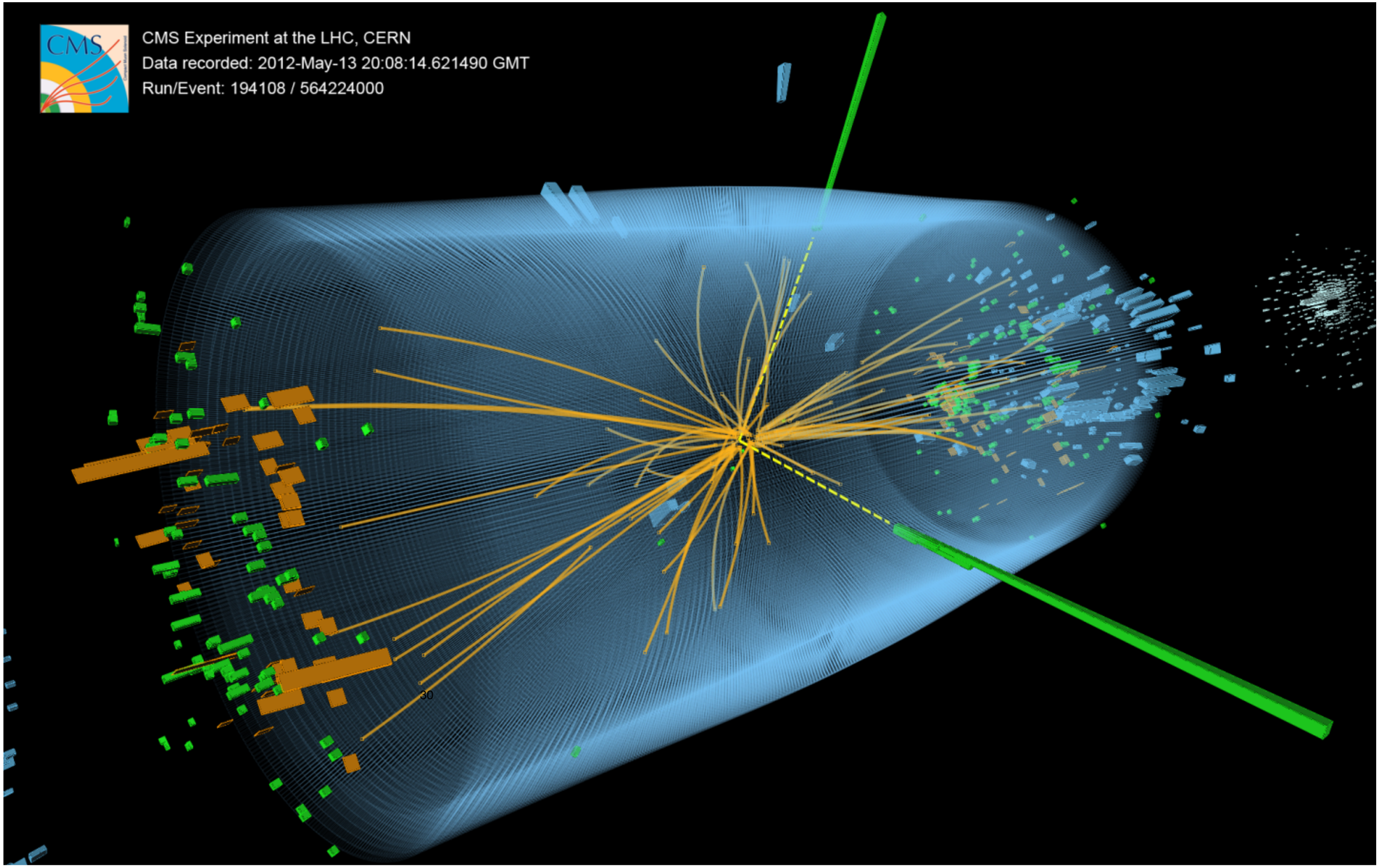
Summary and Outlook

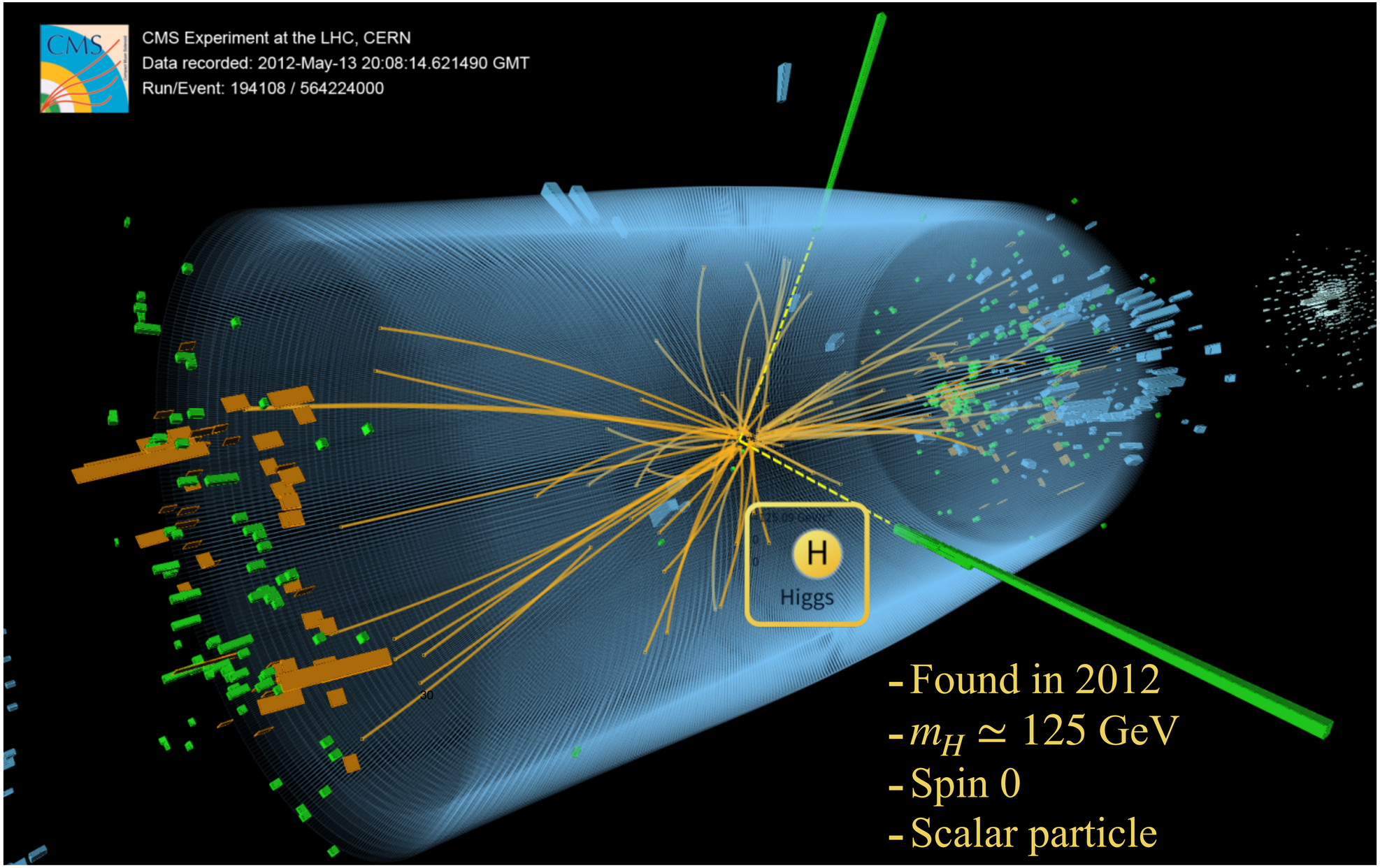
- ☑ Composite Higgs model
- ☑ Chimera baryons
  - Λ and Σ: Top partner candidates in our model
  - Σ^* with spin-3/2
- ☑ The mass hierarchy of chimera baryons —— model building
- ☑ Chiral effective field theory
- ☐ 4-fermion operator
- ☐ Dynamical studies

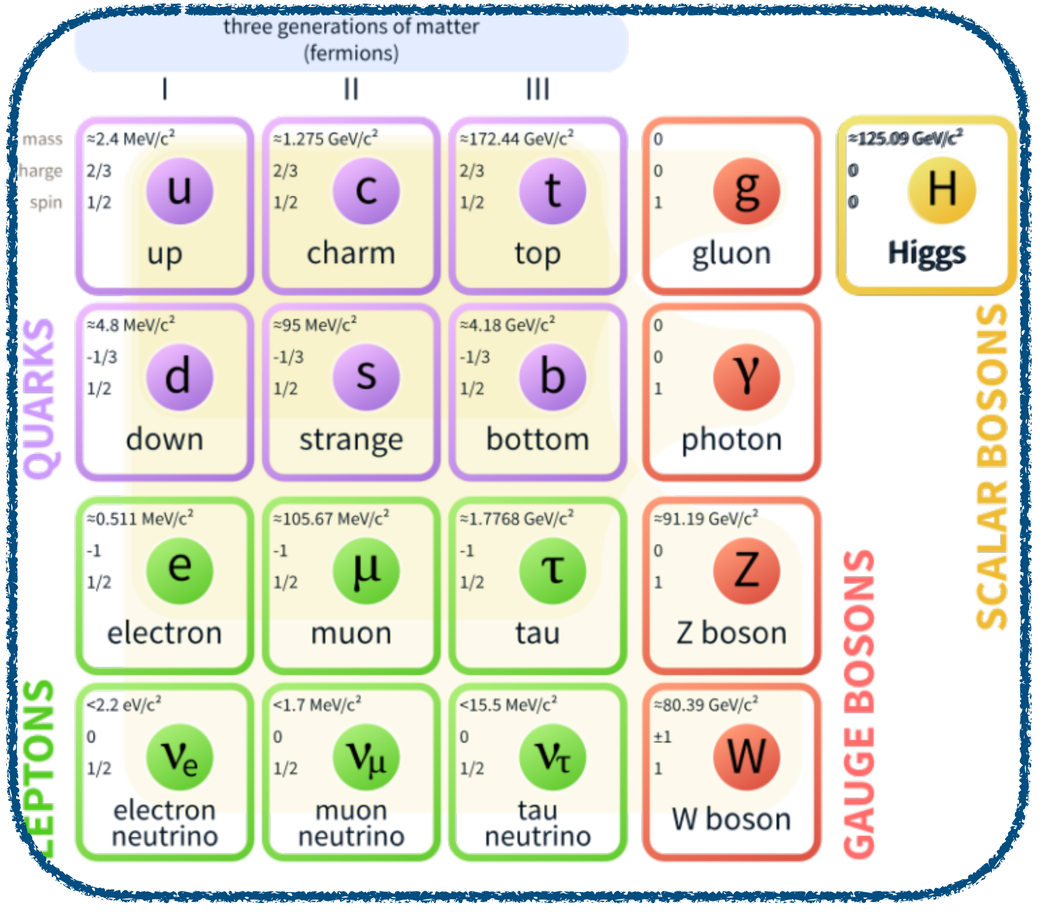

END

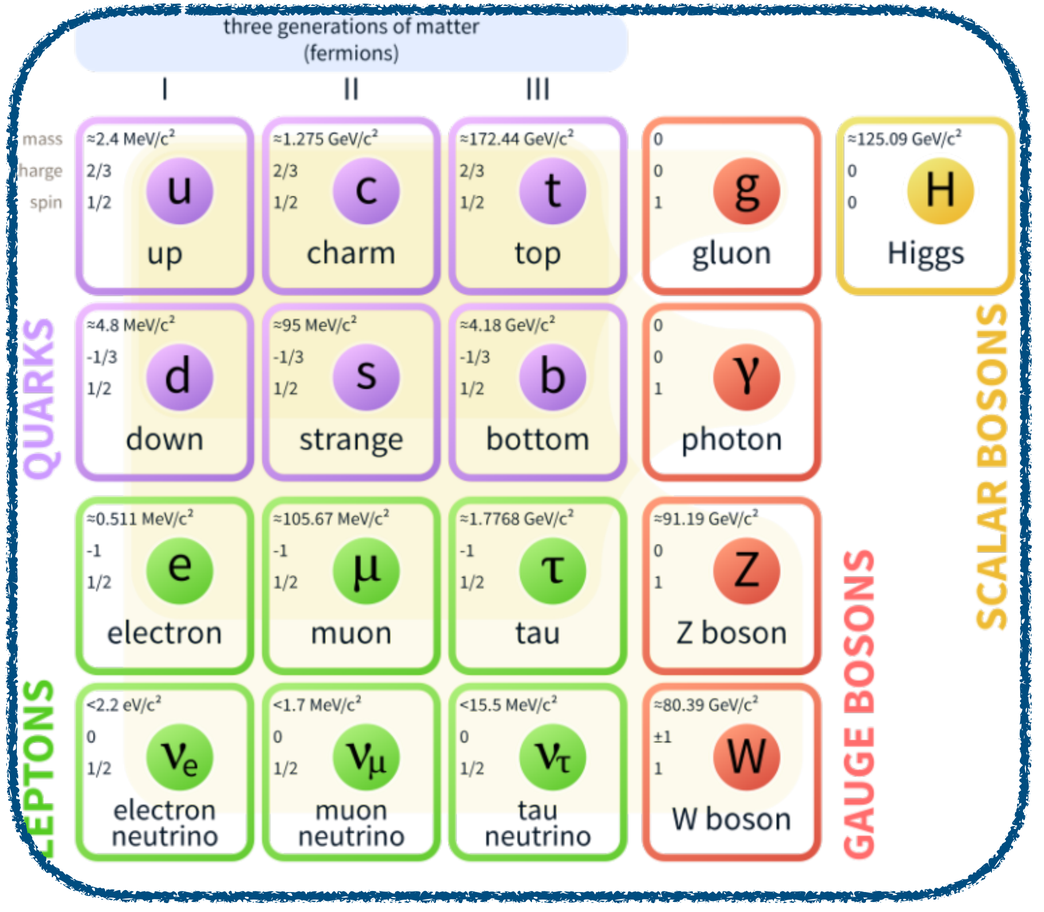
Backup slides

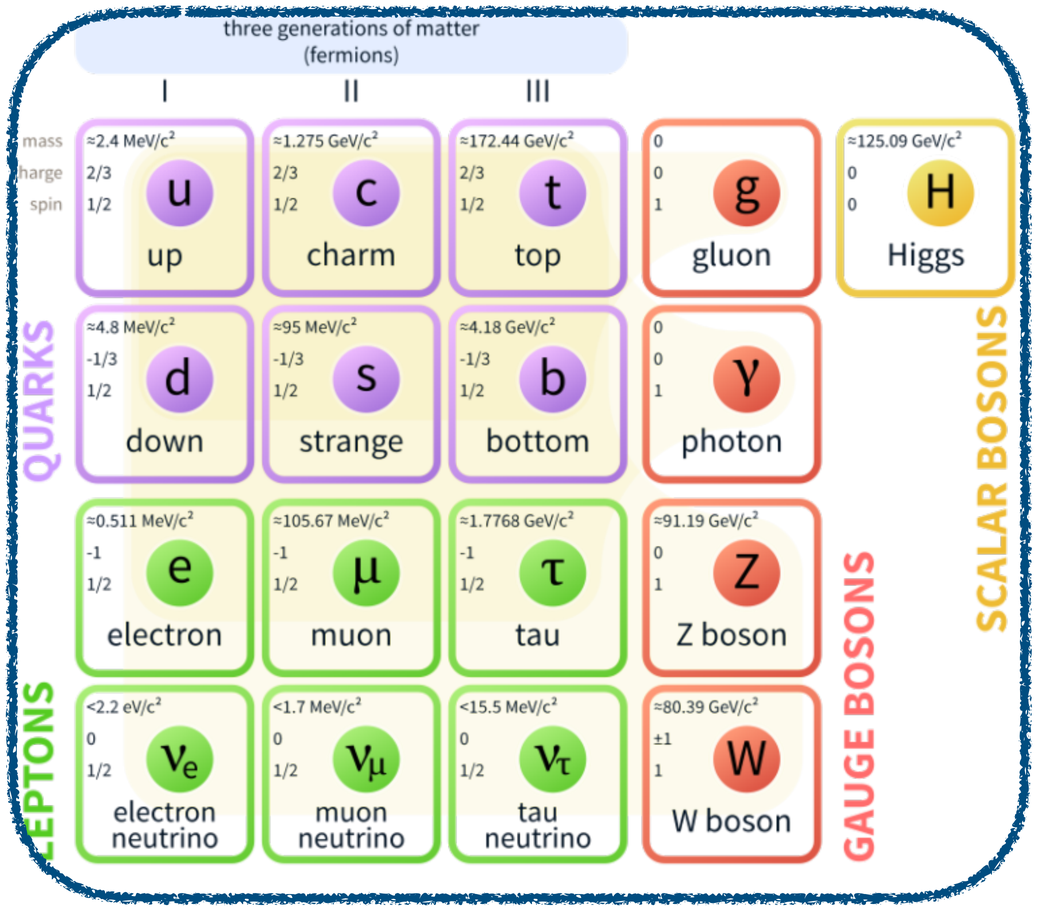

m_0
1.25
1.00
F_1
1
0
A_1
1
0
−1
F_2
2.5
0.0
−2.5
A_2
2
0
L_1
0.00
−0.25
L_{2F}
0.25
0.00
−0.25
L_{2A}
0.25
0.00
$F_3/A_3/C_3$
0.0
−2.5
M2
M3
MF4
MA4
M2C
Λ
Σ
Σ*

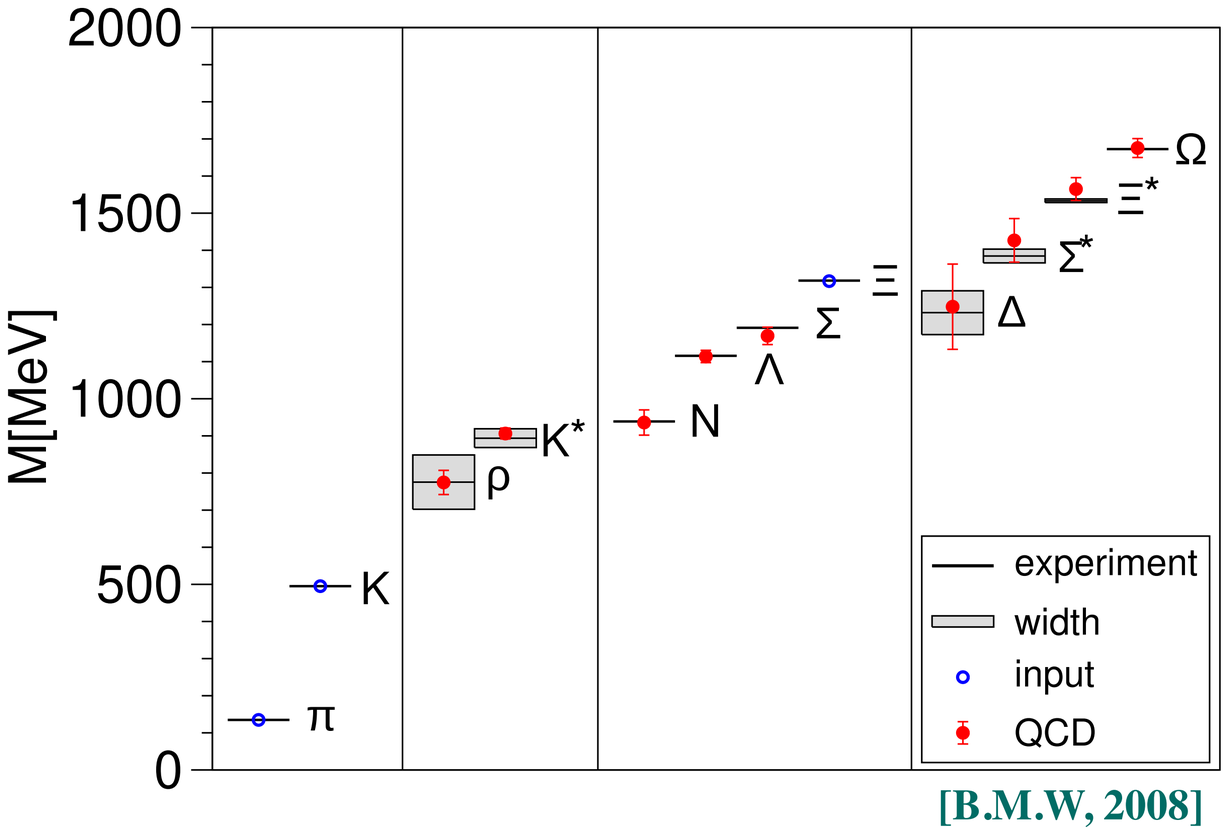

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
30


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H
Higgs
- Found in 2012
- $m_H \simeq 125$ GeV
- Spin 0
- Scalar particle


three generations of matter
(fermions)
I
II
III
mass
harge
spin
≈2.4 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈172.44 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈125.09 GeV/c²
0
0
H
Higgs
QUARKS
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
SCALAR BOSONS
≈0.511 MeV/c²
-1
1/2
e
electron
≈105.67 MeV/c²
-1
1/2
μ
muon
≈1.7768 GeV/c²
-1
1/2
τ
tau
≈91.19 GeV/c²
0
1
Z
Z boson
GAUGE BOSONS
<2.2 eV/c²
0
1/2
νe
electron neutrino
<1.7 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
≈80.39 GeV/c²
±1
1
W
W boson

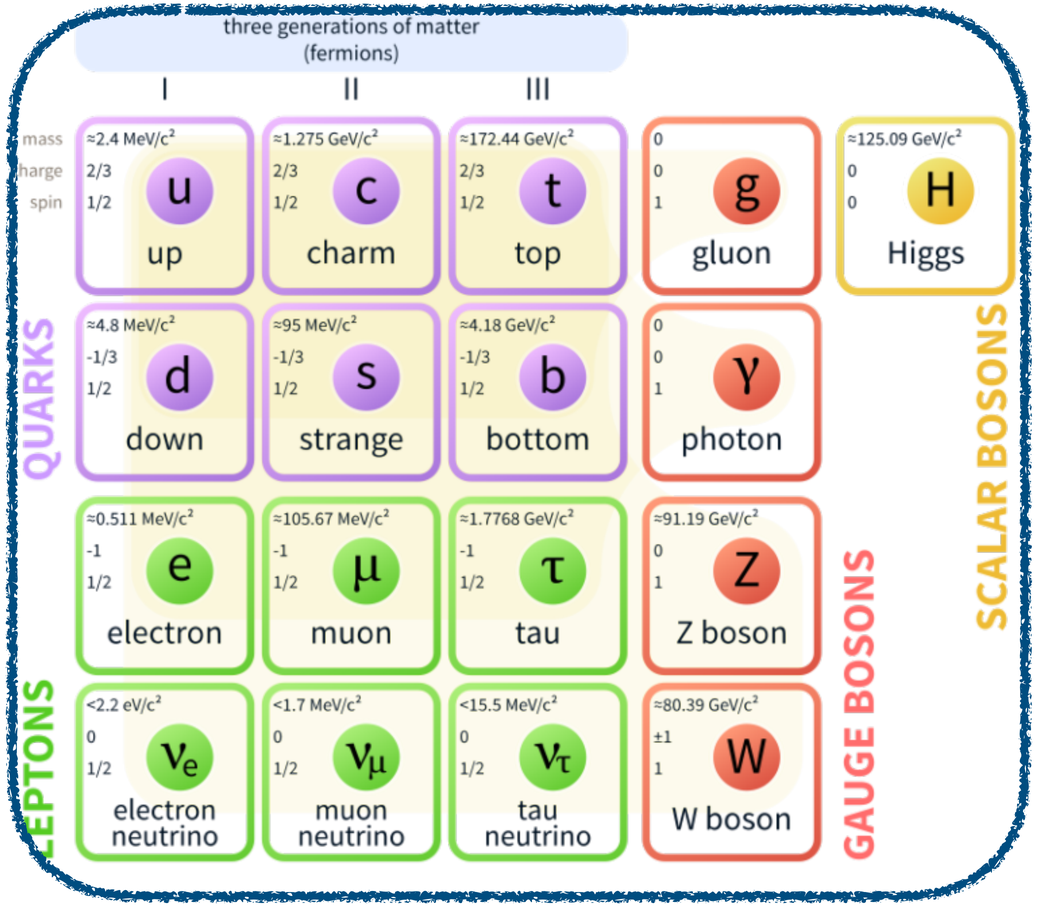

three generations of matter
(fermions)
I
II
III
mass
harge
spin
≈2.4 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈172.44 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈125.09 GeV/c²
0
0
H
Higgs
QUARKS
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
SCALAR BOSONS
≈0.511 MeV/c²
-1
1/2
e
electron
≈105.67 MeV/c²
-1
1/2
μ
muon
≈1.7768 GeV/c²
-1
1/2
τ
tau
≈91.19 GeV/c²
0
1
Z
Z boson
GAUGE BOSONS
<2.2 eV/c²
0
1/2
νe
electron neutrino
<1.7 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
≈80.39 GeV/c²
±1
1
W
W boson





[B.M.W, 2008]

The lattice calculation of QCD light hadron spectrum.

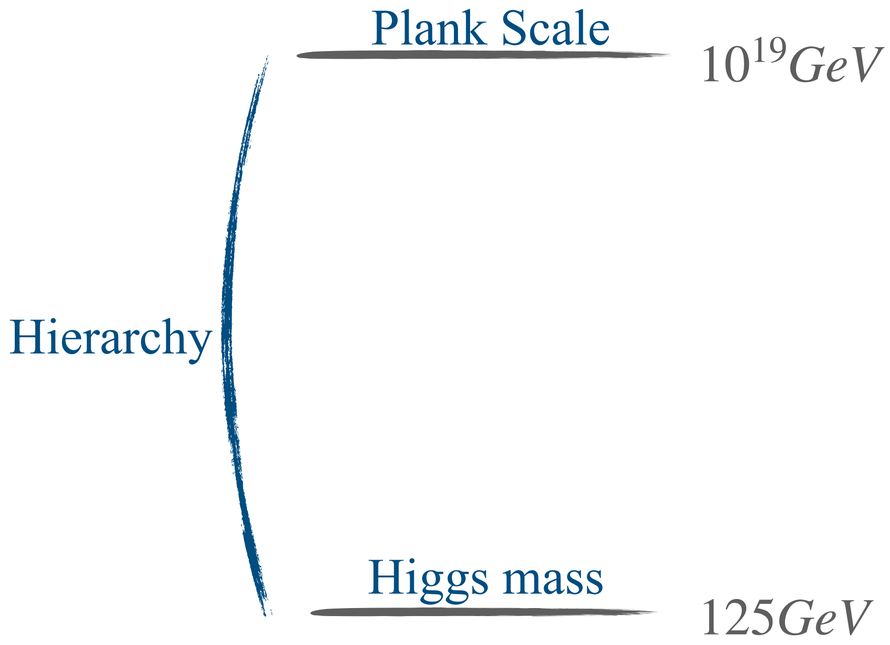


triviality of the scalar sector

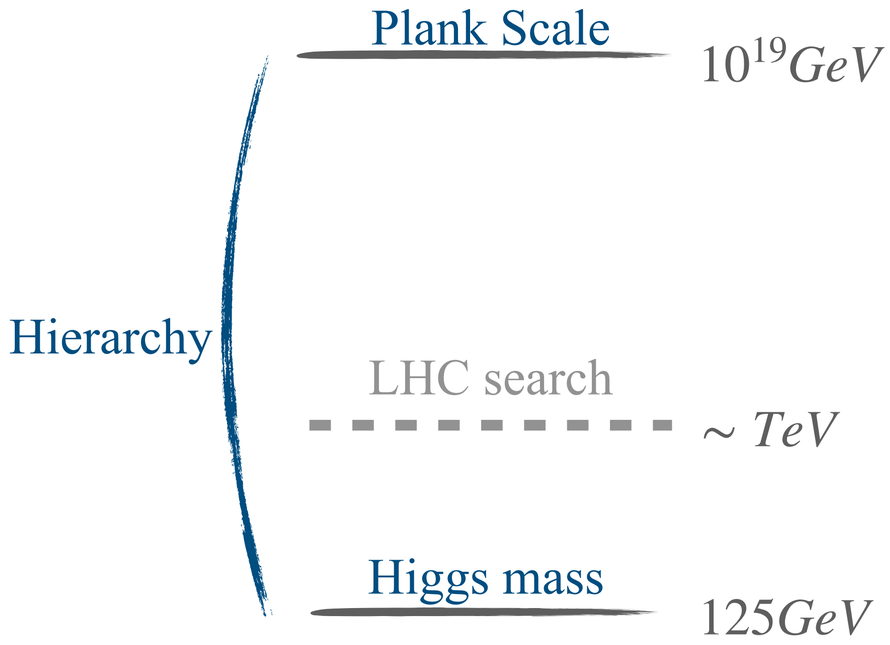
UV completion

→SM is an EFT

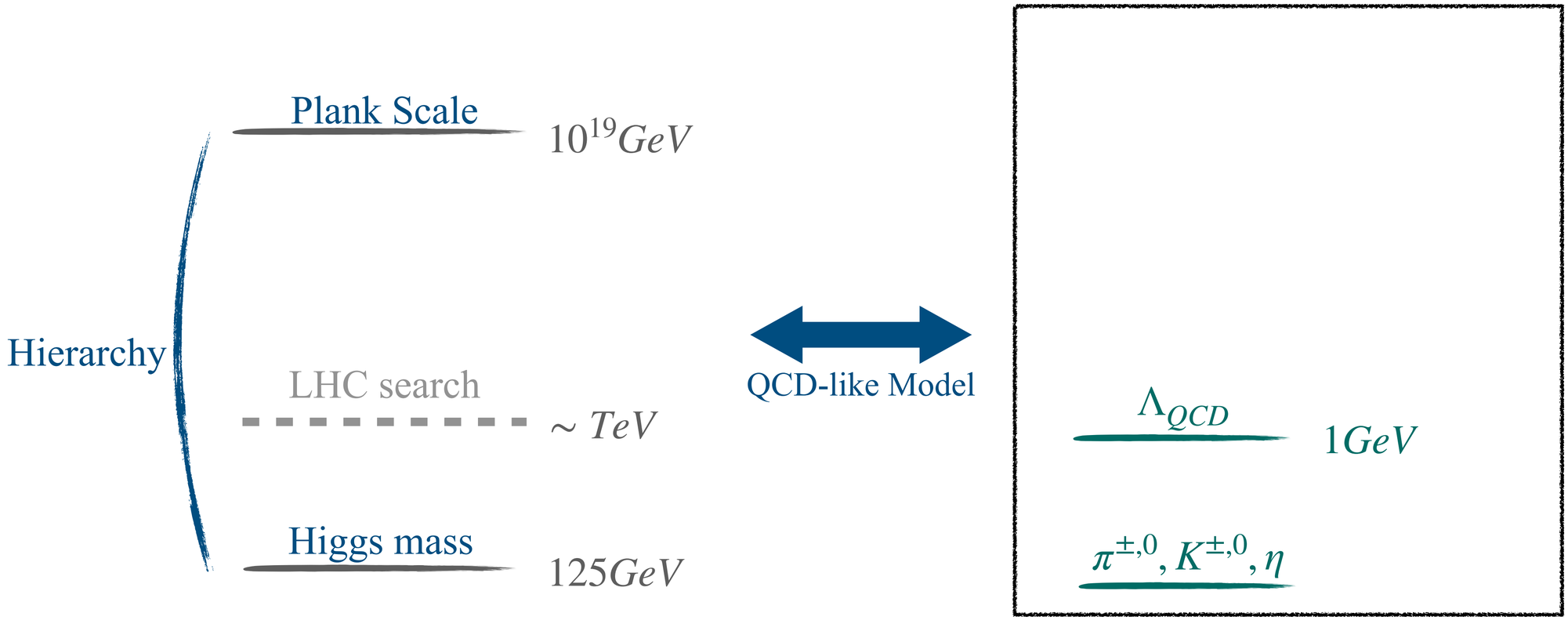
Composite Higgs Model



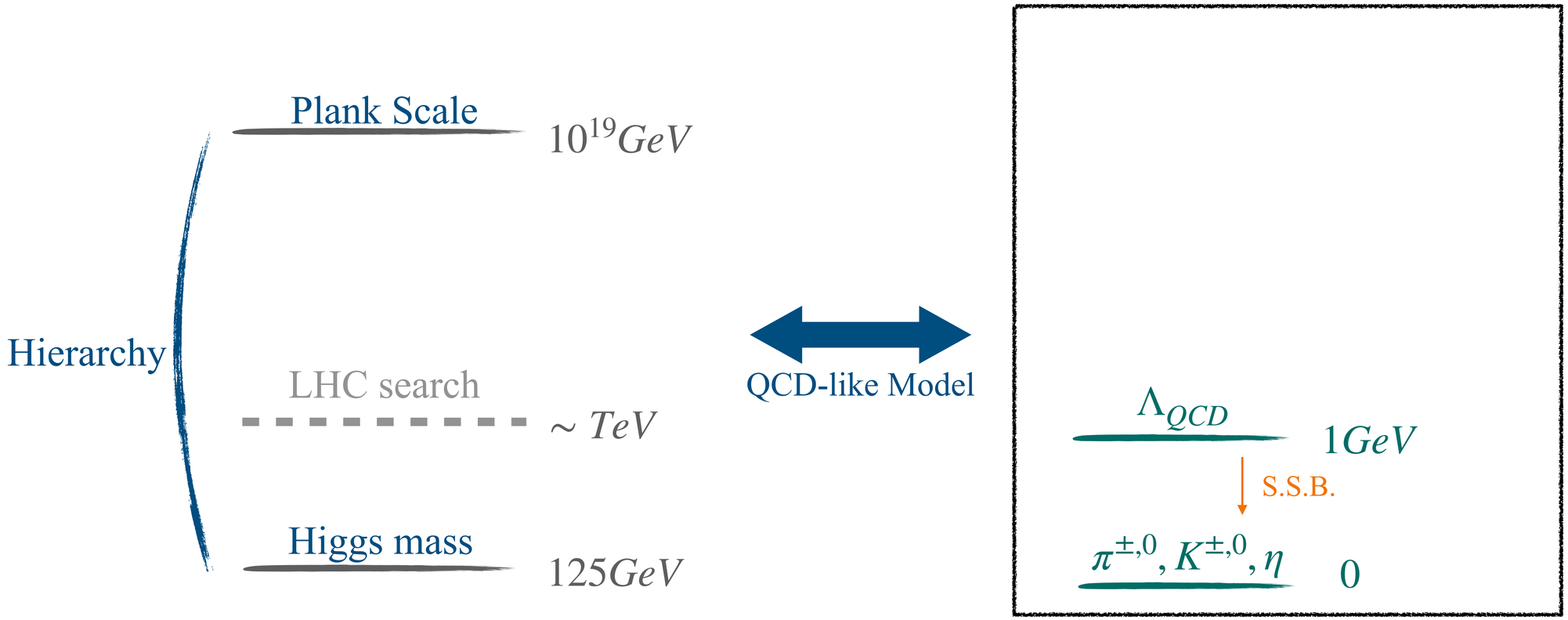
Composite Higgs Model



Composite Higgs Model



Composite Higgs Model



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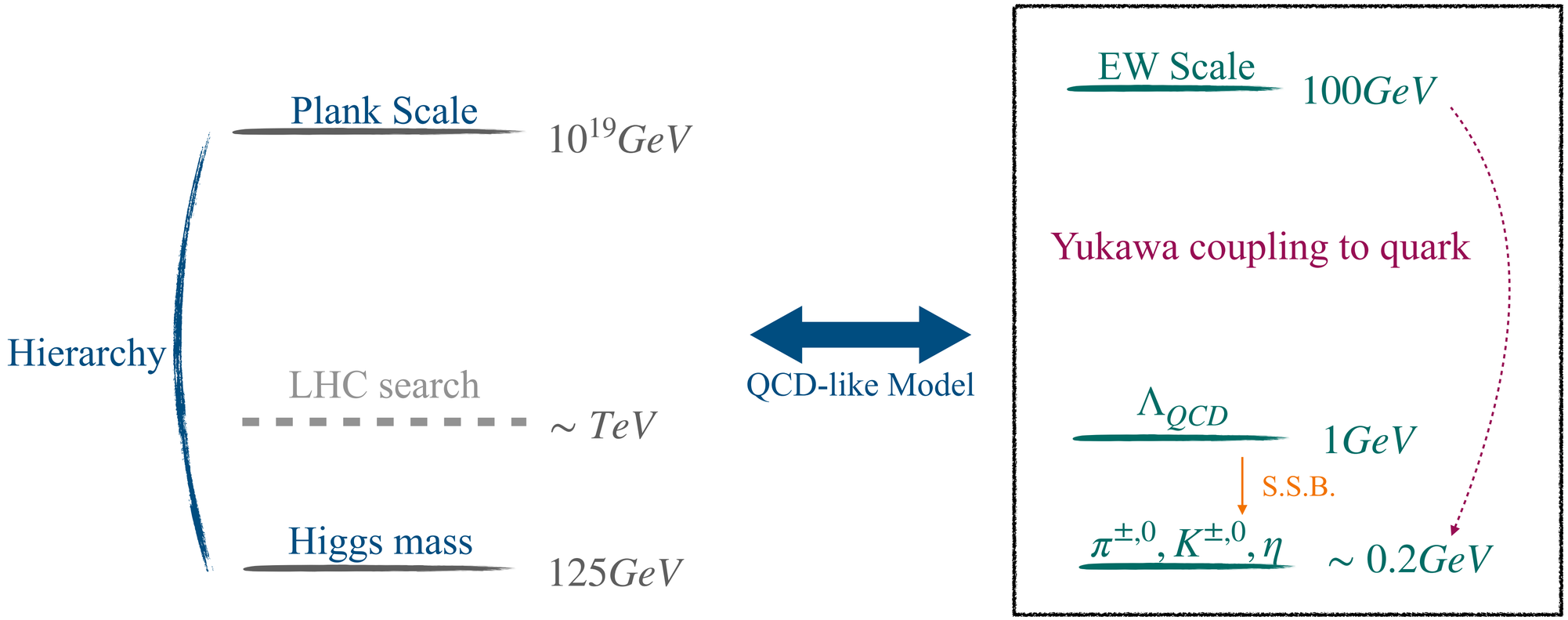

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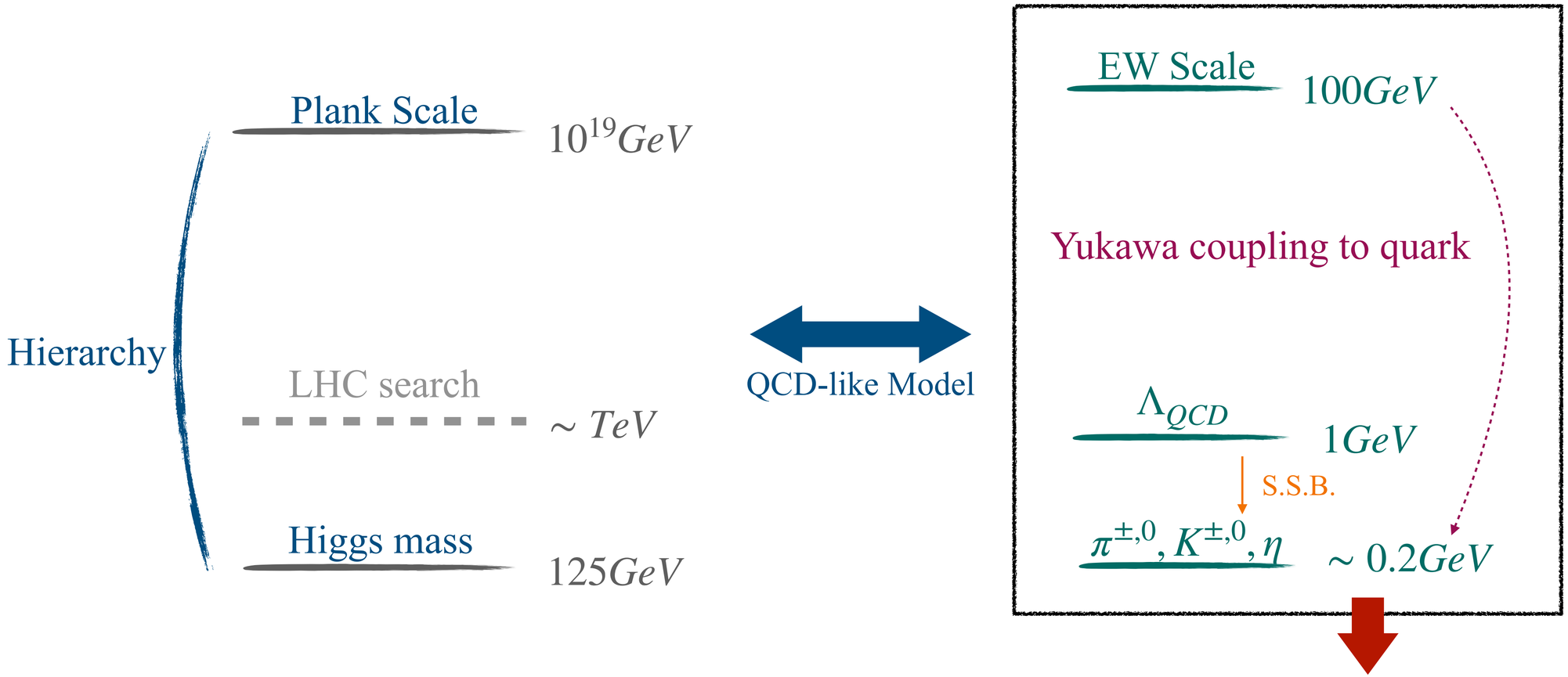
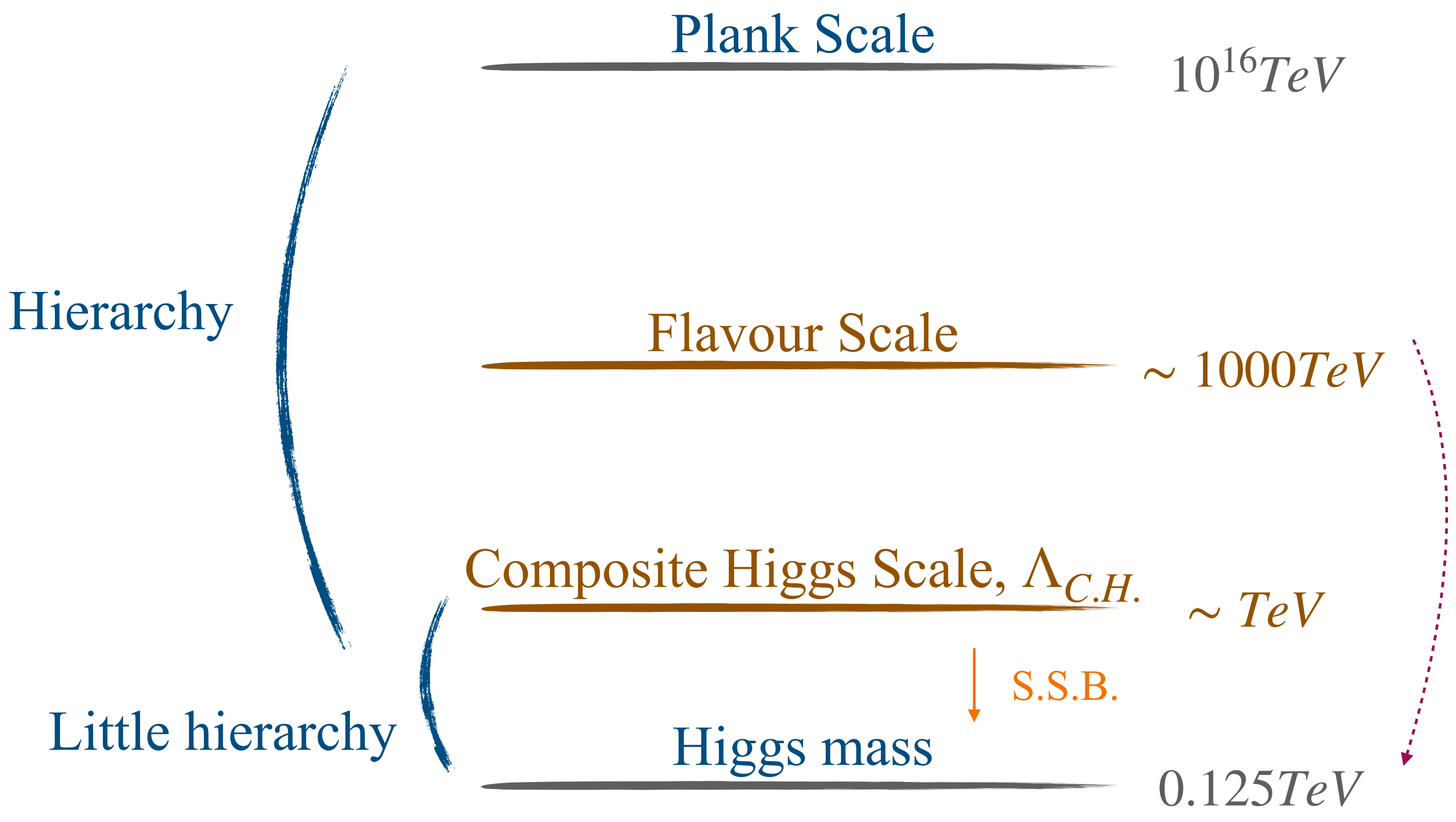


light —— pseudo Nambu-Goldstone Boson

Composite Higgs Model



Higgs boson as a bound state of new strong dynamics, which is lighter because of being a pseudo Nambu-Goldstone Boson.

Study Plan

- Meson spectrum with quenched fundamental and antisymmetric fermions
- Meson spectrum with $N_f = 2$ dynamical fundamental fermions
- Meson spectrum with $n_f = 3$ dynamical antisymmetric fermions
- Fully dynamical 2F + 3AS fermions
  - Chimera baryon (quenched studies)
  - 4-fermion operator matrix elements (relevant to generating Higgs mass)

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Results

Projection-CB two-point function

- Interpolating operator

$$\mathcal{O}^{\gamma}_{\mathrm{CB}}(x) \equiv \left(Q^{i\,a}{}_{\alpha}(x) \Gamma^{1\,\alpha\beta} Q^{j\,b}{}_{\beta}(x) \right) \Omega_{ad} \Omega_{bc} \Gamma^{2\,\delta\gamma} \Psi^{k\,cd}{}_{\gamma}(x)$$

- two-point function

$$\begin{aligned} C^{\gamma\gamma'}(t) &\equiv \sum_{\vec{x}} \langle \mathcal{O}^{\gamma}_{\mathrm{CB}}(x) \overline{\mathcal{O}^{\gamma'}_{\mathrm{CB}}}(0) \rangle \\ &= - \sum_{\vec{x}} \left(\Gamma^2 S_{\Psi}^{k\,cd}{}_{c'd'}(x,0) \overline{\Gamma^2} \right)_{\gamma\gamma'} \Omega_{cb} \Omega^{b'c'} \Omega_{ad} \Omega^{d'a'} \\ &\quad \times \mathrm{Tr} \left[\Gamma^1 S_Q^{b}{}_{b'}(x,0) \overline{\Gamma^1} S_Q^{a}{}_{a'}(x,0) \right] \end{aligned}$$

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Projection-CB two-point function

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At large Euclidean time

$$\rightarrow P_e \left[c_e e^{-m_e t} + c_o e^{-m_o (T-t)} \right] - P_o \left[c_o e^{-m_o t} + c_e e^{-m_e (T-t)} \right]$$

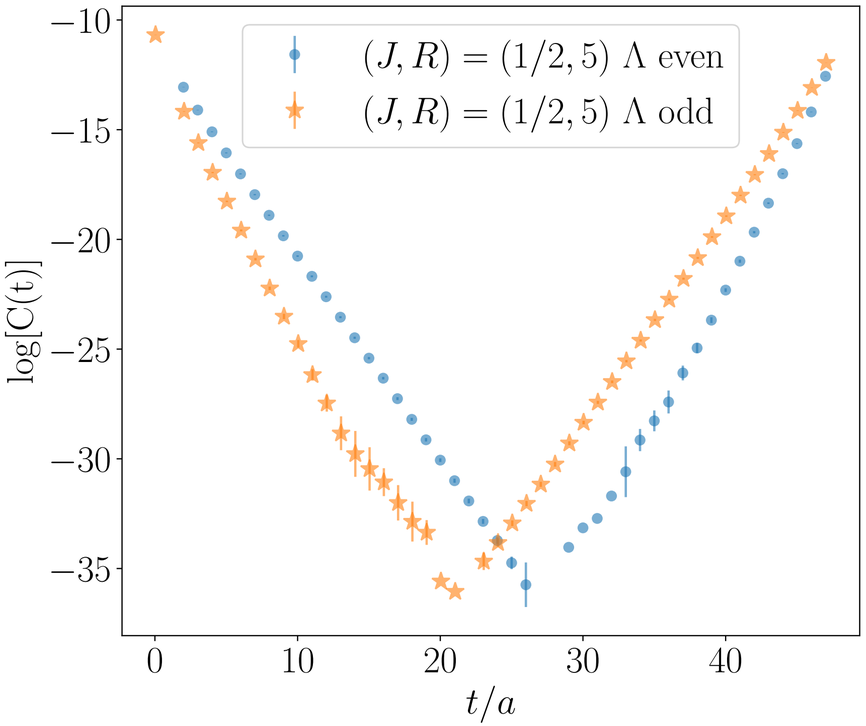
$$P_e \equiv \frac{1}{2}(1+\gamma^0) \text{ and } P_o \equiv \frac{1}{2}(1-\gamma^0)$$

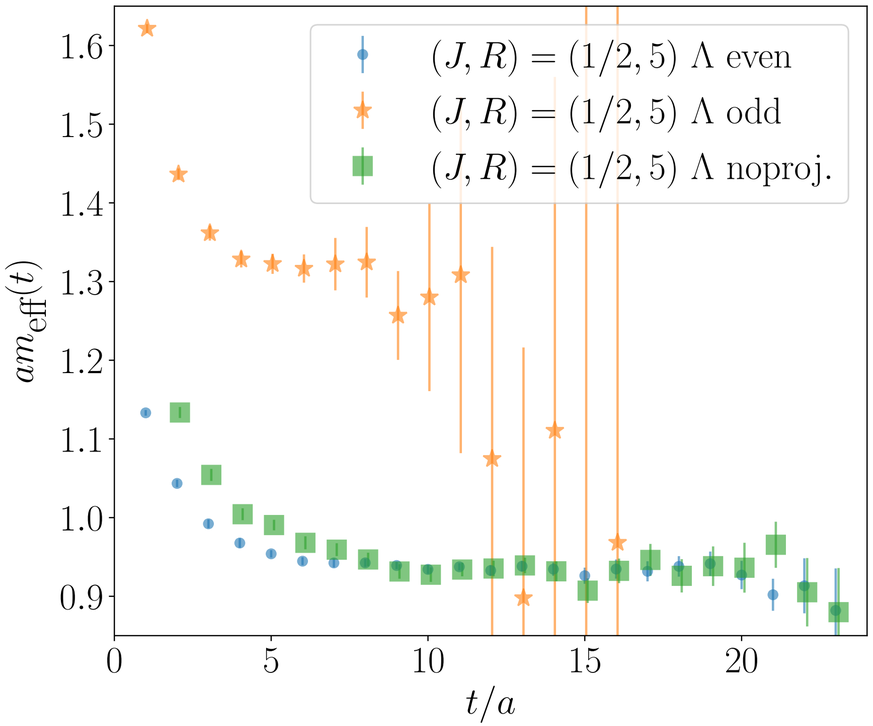
Results

Projection-Parity

$$C_{\mathrm{CB}}(t) \to P_e \left[c_e e^{-m_e t} + c_o e^{-m_o (T-t)}\right] - P_o \left[c_o e^{-m_o t} + c_e e^{-m_e (T-t)}\right]$$

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





Chimera Baryon

- Spin projector for Σ-type baryon:

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

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

- Two-point function

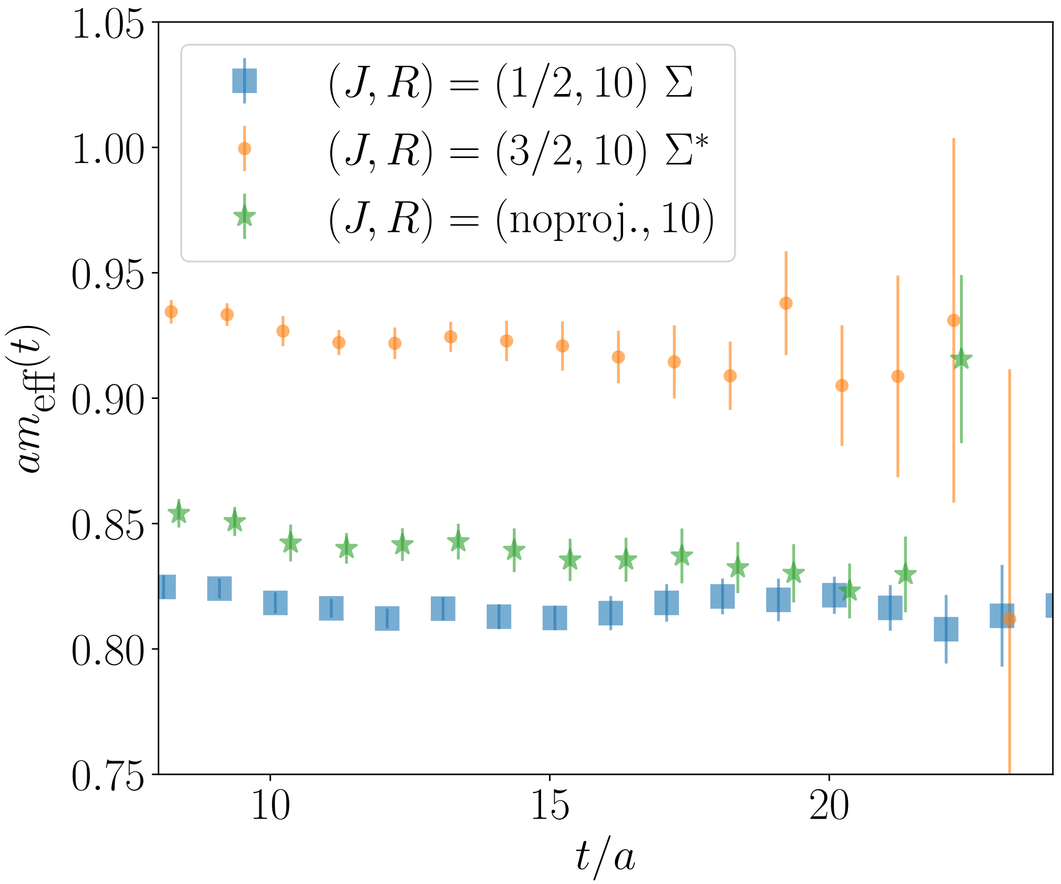
$$C_{ij}(t) = \sum_{\vec{x}} \left\langle \mathcal{O}^i_{\mathrm{CB}}(x)\bar{\mathcal{O}}^j_{\mathrm{CB}}(0) \right\rangle \text{ with } \mathcal{O}^i_{CB} = \left(\bar{\psi}\gamma^i\psi\right)\chi$$

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

Results

Projection-Spin

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



Results

Optimal search

- Try including different order of corrections
- Calculate AICs for each data set, and scan through all the possible cuts:
  - ➡ Fix the cut value for $\hat{m}^{f}_{\mathrm{PS}}$ and vary $\hat{m}^{as}_{\mathrm{PS}}$
  - ➡ Increase the fixed value of $\hat{m}^{f}_{\mathrm{PS}}$