Chimera baryon spectrum in the Sp(4) gauge theory

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The collaboration

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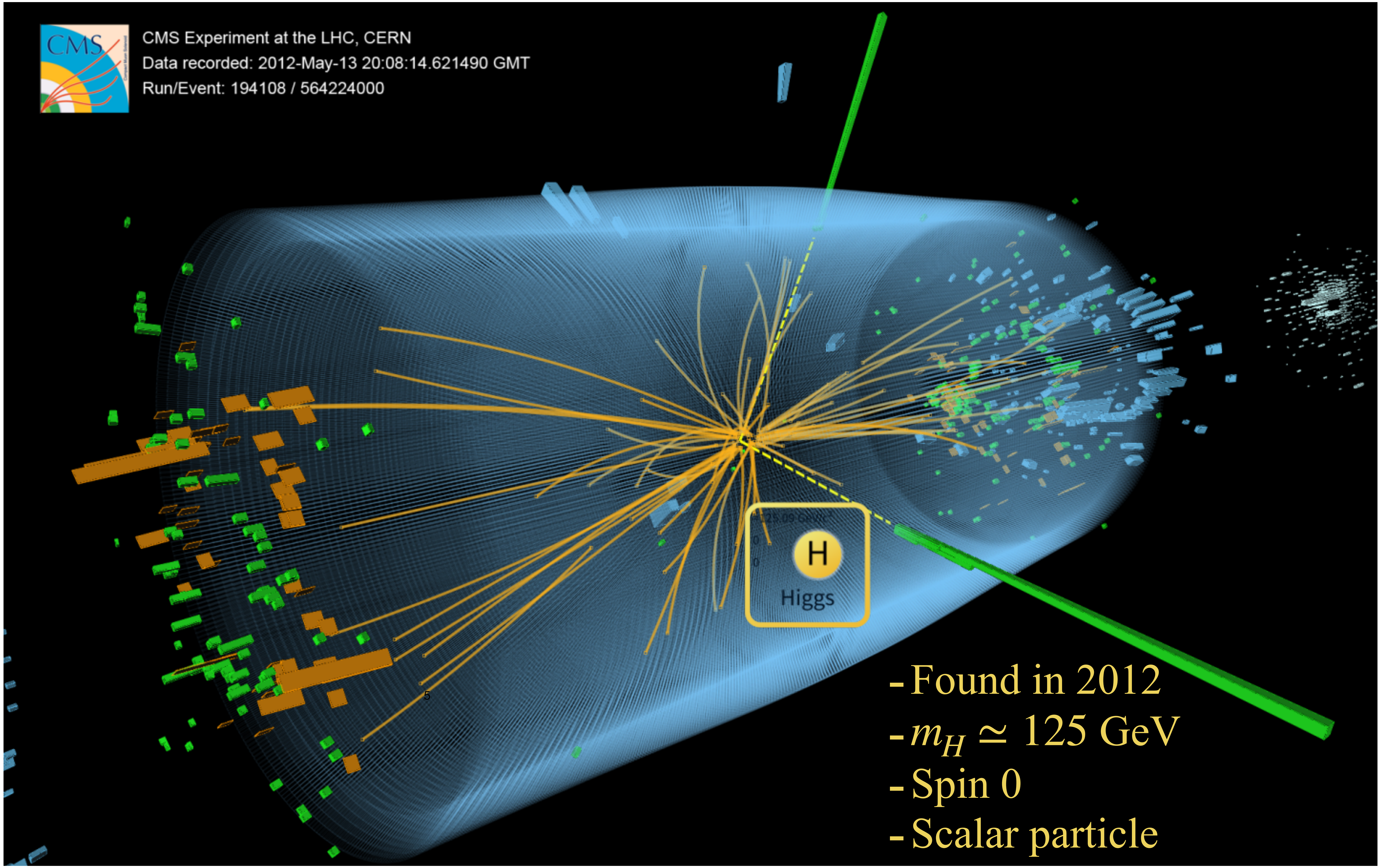
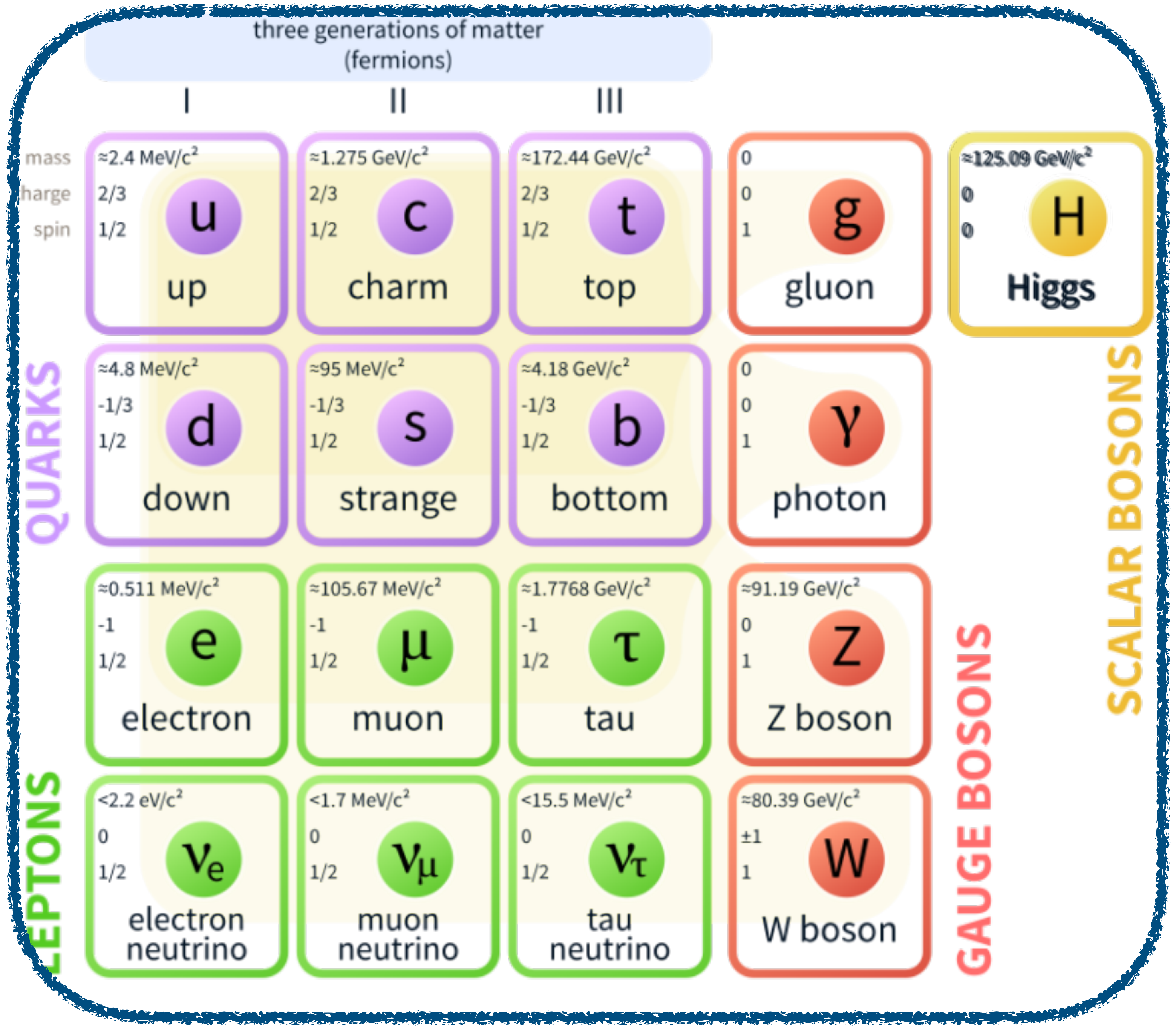
Outline

- Motivation: why composite Higgs?
- Lattice studies: our works and the chimera baryon
- Conclusion and outlook

Why composite Higgs?

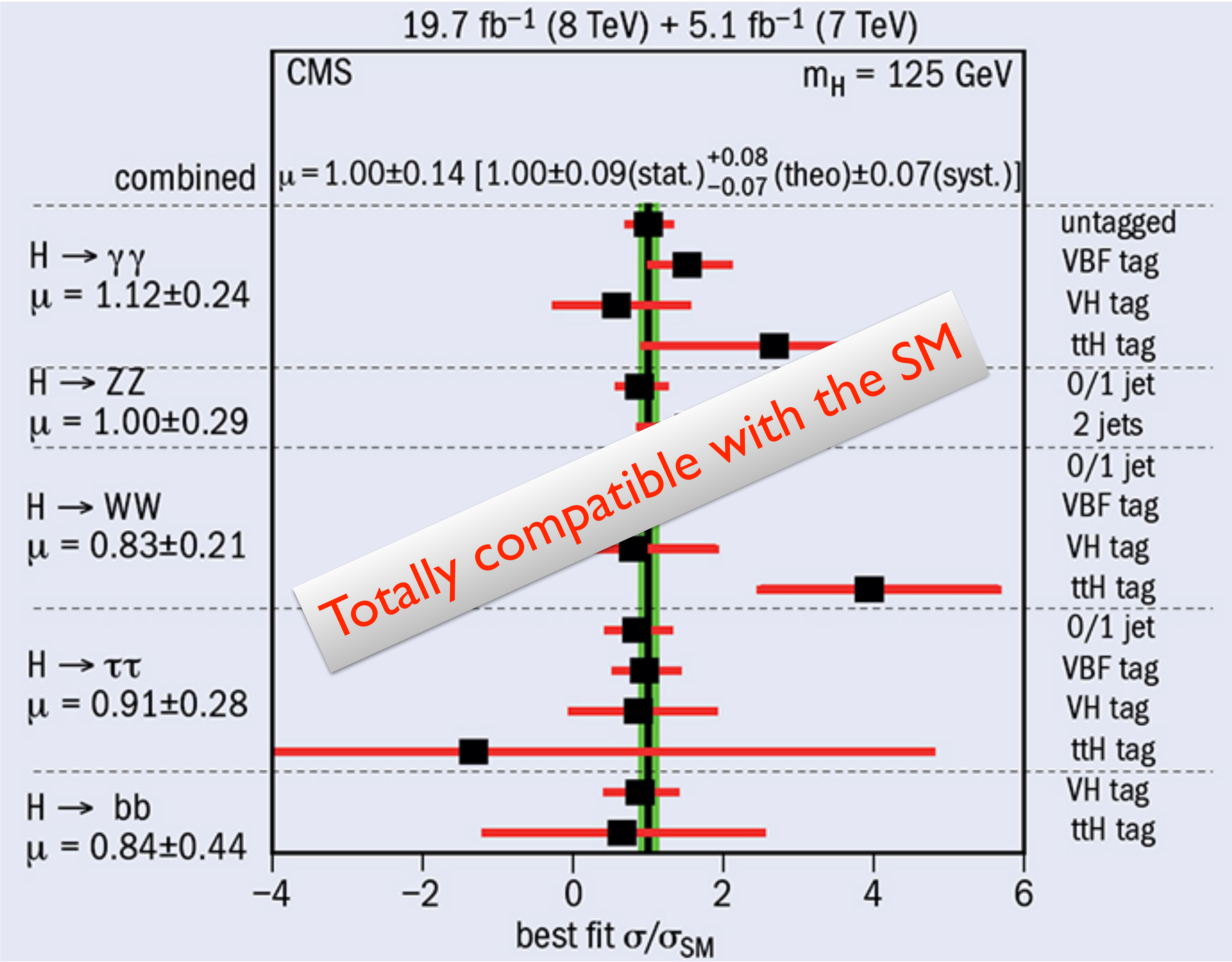

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H
Higgs
- Found in 2012
- $m_H \simeq 125$ GeV
- Spin 0
- Scalar particle

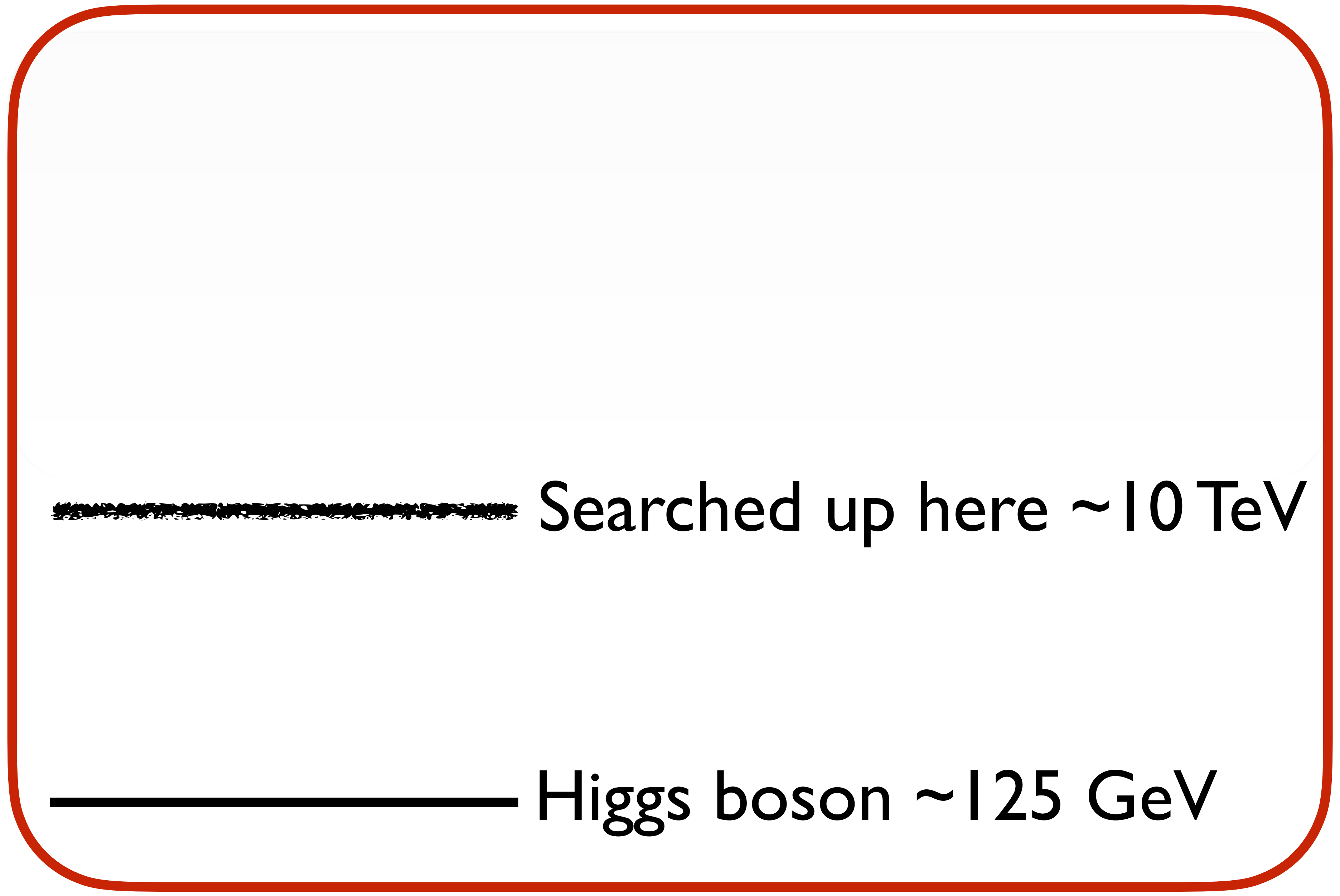


triviality of the scalar sector

→SM is an EFT

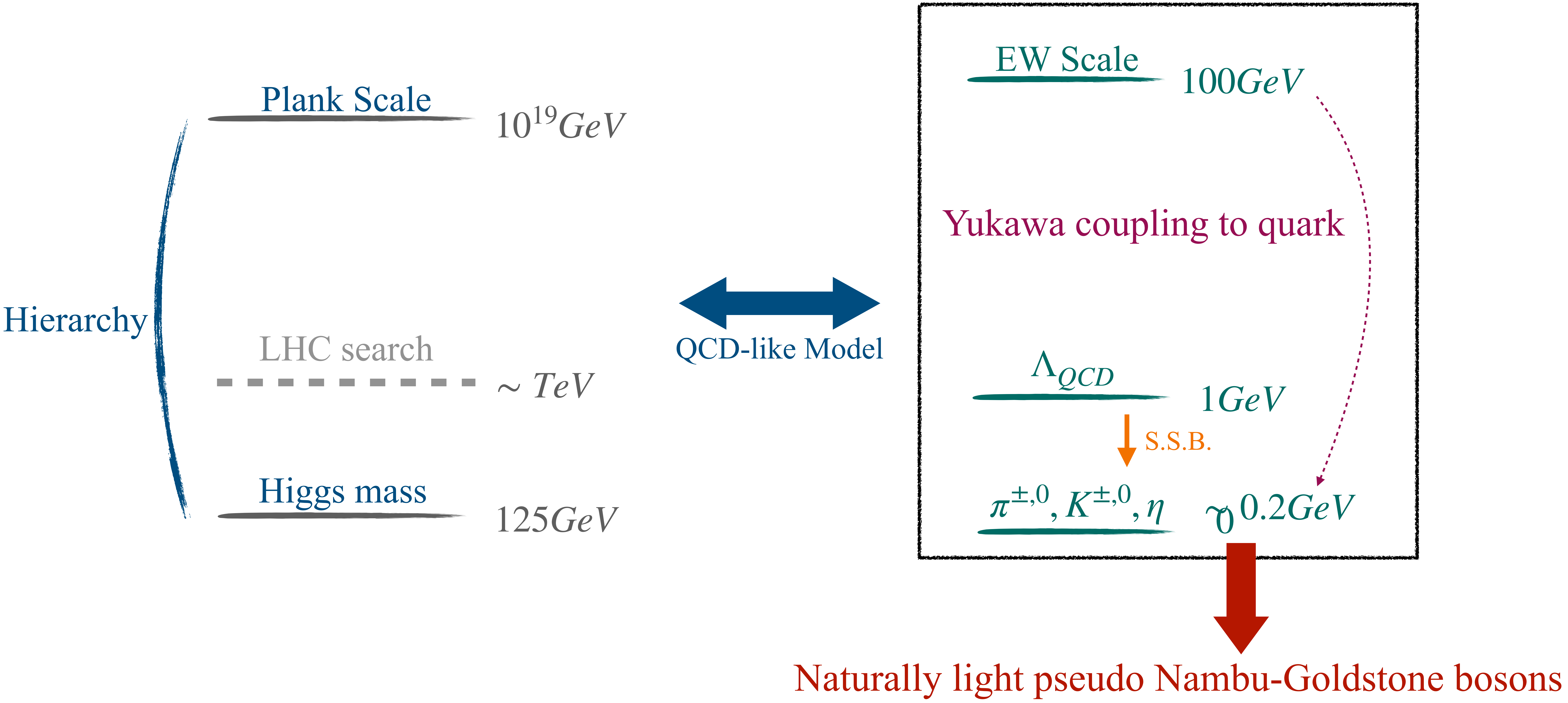
On the other hand…





Why is the Higgs boson so light?

Lesson from QCD



Composite Higgs models: Hierarchy of scales

Plank Scale $10^{16} TeV$

Hierarchy

Flavour Scale $\sim 1000 TeV$

Couple

Composite Higgs Scale, $\Lambda_{C.H.}$ $\sim TeV$

S.S.B.

Little hierarchy

Higgs mass $0.125 TeV$

Higgs boson as a PNGB

Composite Higgs models: Generic features

D.B. Kaplan, H. Georgi, M. Dugan, S. Dimopoulos,… *circa* 1985

- Global symmetry G broken to H
- Standard model global $G_W \subset H$
- The Higgs boson $\in G/H$
  → *c.f.*, technicolour where Higgs $\in H$
- Higgs mass generated *via* vacuum misalignment
  → $v << f \sin\langle\theta\rangle,\ f = |\vec{F}| \sim \Lambda_{HC}$
- Top-quark mass generated *via* partial compositeness
  → Spin-1/2 bound states mixing with top quark

D.B. Kaplan, 1991

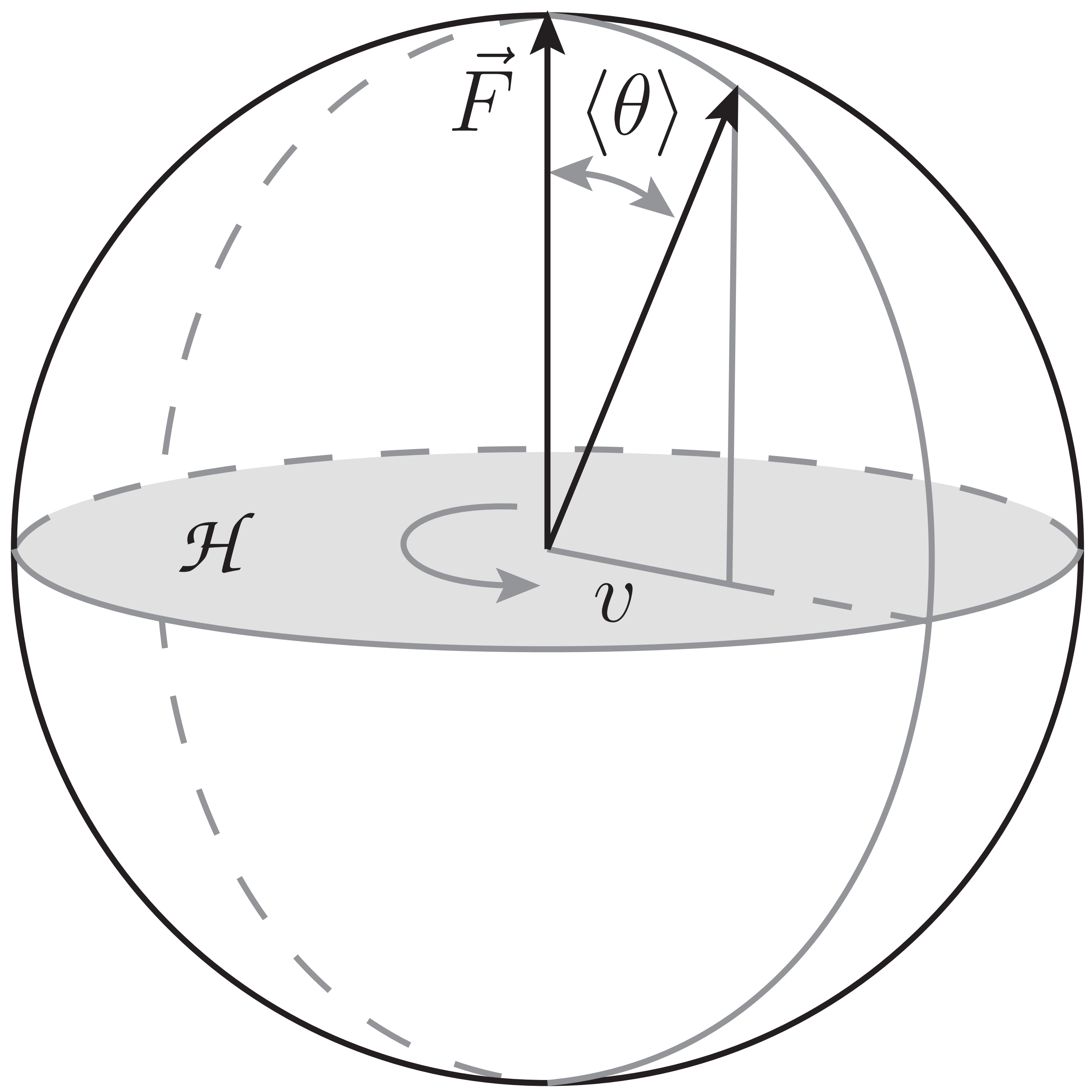


Figure from G. Panico and A. Wulzer, 1506.01961

UV completion of composite Higgs models

*Two-component relativistic 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	$Sp(4)$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$\psi\psi\chi$
M9	$SO(11)$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$\psi\psi\chi$
M10	$SO(10)$	$4 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$6 \times \mathbf{F}$	$\psi\psi\chi$
M11	$SU(4)$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	$\psi\psi\chi$
M12	$SU(5)$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}_2})$	$\psi\psi\chi$, $\psi\chi\chi$

The minimal model

Barnard et al, arXiv:1311.6562

D. Franzosi and G. Ferretti, arXiv:1905.08273

Fermion representations and global symmetry

M. Peskin, 1980

For N_f flavours of Dirac fermions

Gauge group representation	Global symmetry breaking pattern
Complex	$SU(N_f) \times SU(N_f) \to SU(N_f)$
Real	$SU(2N_f) \to SO(2N_f)$
Pseudo-real	$SU(2N_f) \to Sp(2N_f)$

Our choice of model

- Sp(4) gauge theory with 2F+3AS Dirac fermions

$\downarrow$ 4F+6AS 2-component Weyl fermions

- Breaking pattern:

$$G/H = \underbrace{SU(4)\times SU(6)}_{\text{Enhanced global symmetry due to the (pseudo-) reality}} \,/\, Sp(4)\times SO(6)$$

$SU(4)/Sp(4)$ gives 5 goldstone bosons.

- 4: SM Higgs doublet
- 1: made heavy in model building

SU(3) embedded in antisymmetric representation:

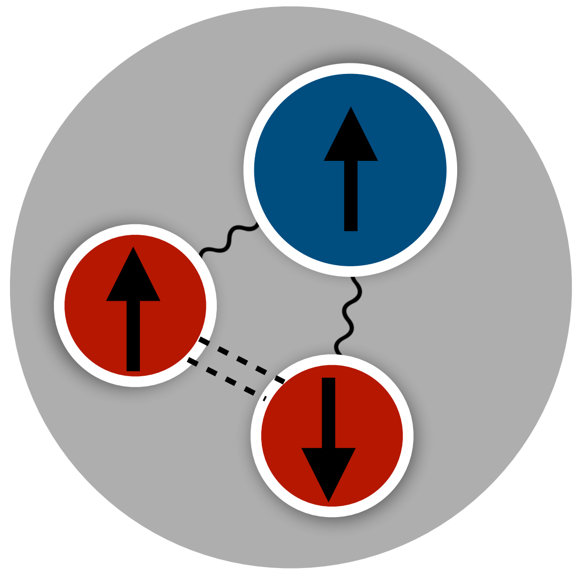
$$SU(6) \rightarrow SO(6) \supset SU(3)$$

$\hookrightarrow$ QCD colour SU(3)

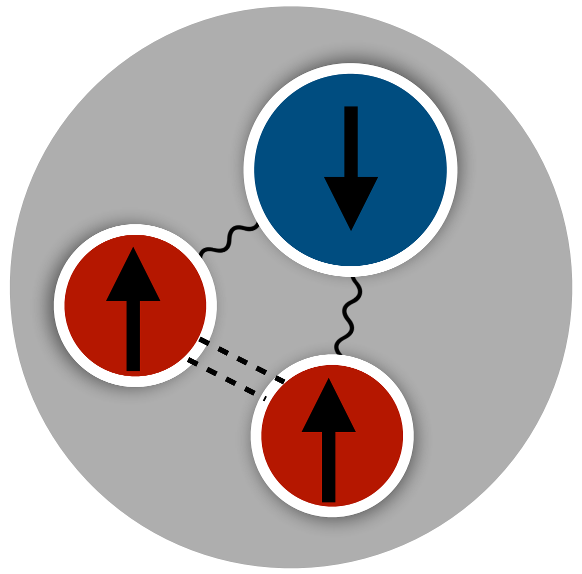
The low-lying chimera baryon states

a, b, c: hypercolour
Ω: 4×4 symplectic matrix
J: spin
R: irreducible rep. of the fundamental sector

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

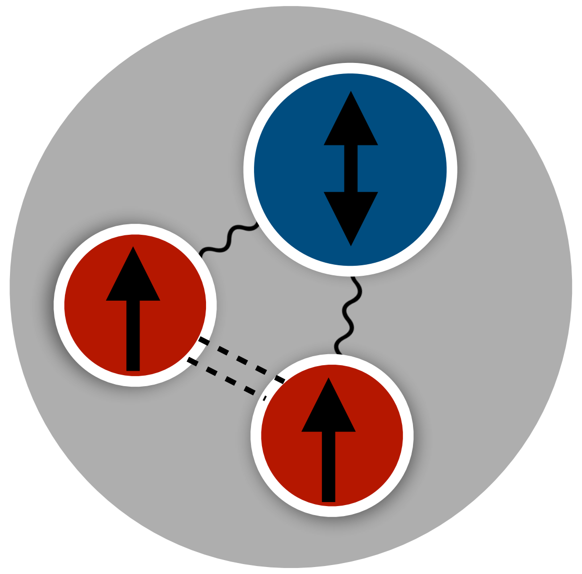


$(J, R) = (1/2, 5)$
*top partner

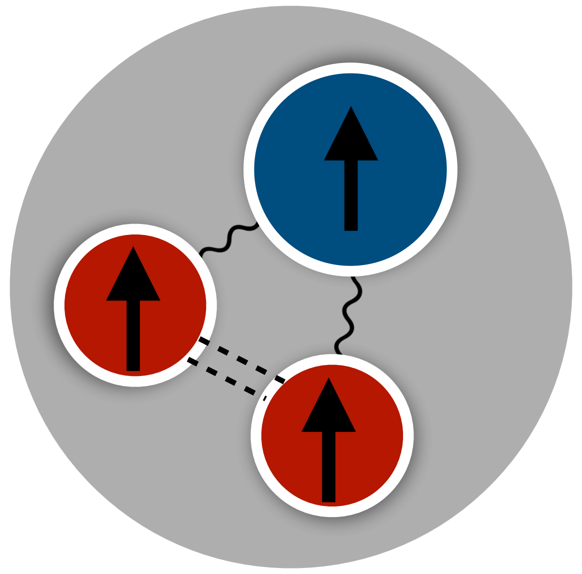


Σ: $(J, R) = (1/2, 10)$
*top partner

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



Spin projection



Σ^*: $(J, R) = (3/2, 10)$

$$m_{\mathrm{top}} \sim 1/m_{\mathrm{CB}}$$

Lattice studies

Major works from our collaboration

- Quenched fundamental mesons

  JHEP 03 (2018) 185, arXiv:1712.04220

- $N_f = 2$ dynamical fundamental mesons

  JHEP 12 (2019) 053, arXiv:1909.12662

- Quenched fundamental and antisymmetric mesons

  Phys. Rev. D 101 (2020) 7, 074516, arXiv:1912.06505

- Quenched glueballs

  Phys. Rev. D 103 (2021) 5, 054509, arXiv:2010.15781

- General features of $N_f = 2$ fundamental and $n_f = 3$ antisymmetric dynamical hyperquarks

  Phys. Rev. D 106 (2022) 1, 014501, arXiv:2202.05516

- Quenched chimera baryons

  Submitted to Phys. Rev. D, arXiv:2311.14663

Quenched chimera baryons

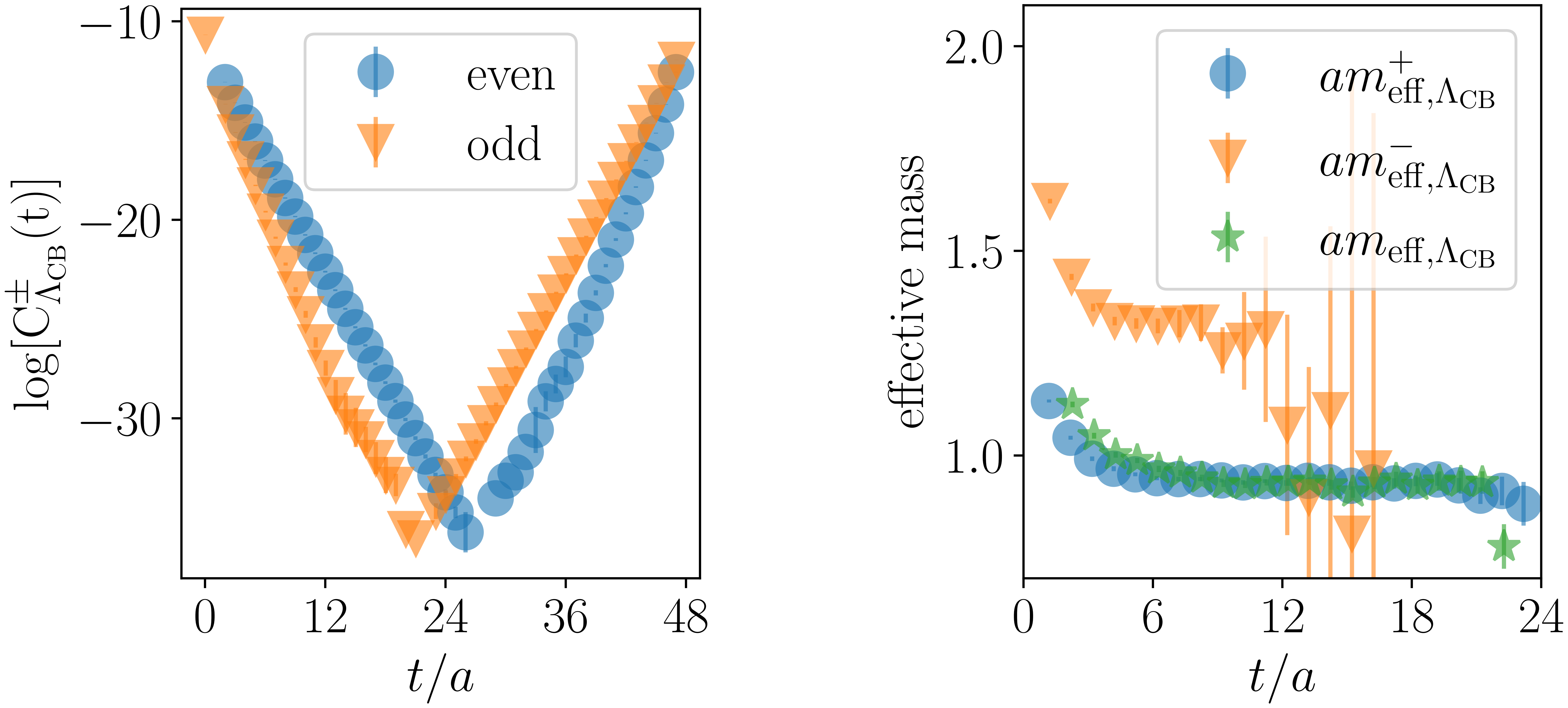
- Scan of parameter space
- Wilson plaquette and Wilson fermion actions

Ensemble	β	$N_t \times N_s^3$	$\langle P \rangle$	w_0/a
QB1	7.62	48×24^3	0.6018898(94)	1.448(3)
QB2	7.7	60×48^3	0.6088000(35)	1.6070(19)
QB3	7.85	60×48^3	0.6203809(28)	1.944(3)
QB4	8.0	60×48^3	0.6307425(27)	2.3149(12)
QB5	8.2	60×48^3	0.6432302(25)	2.8812(21)

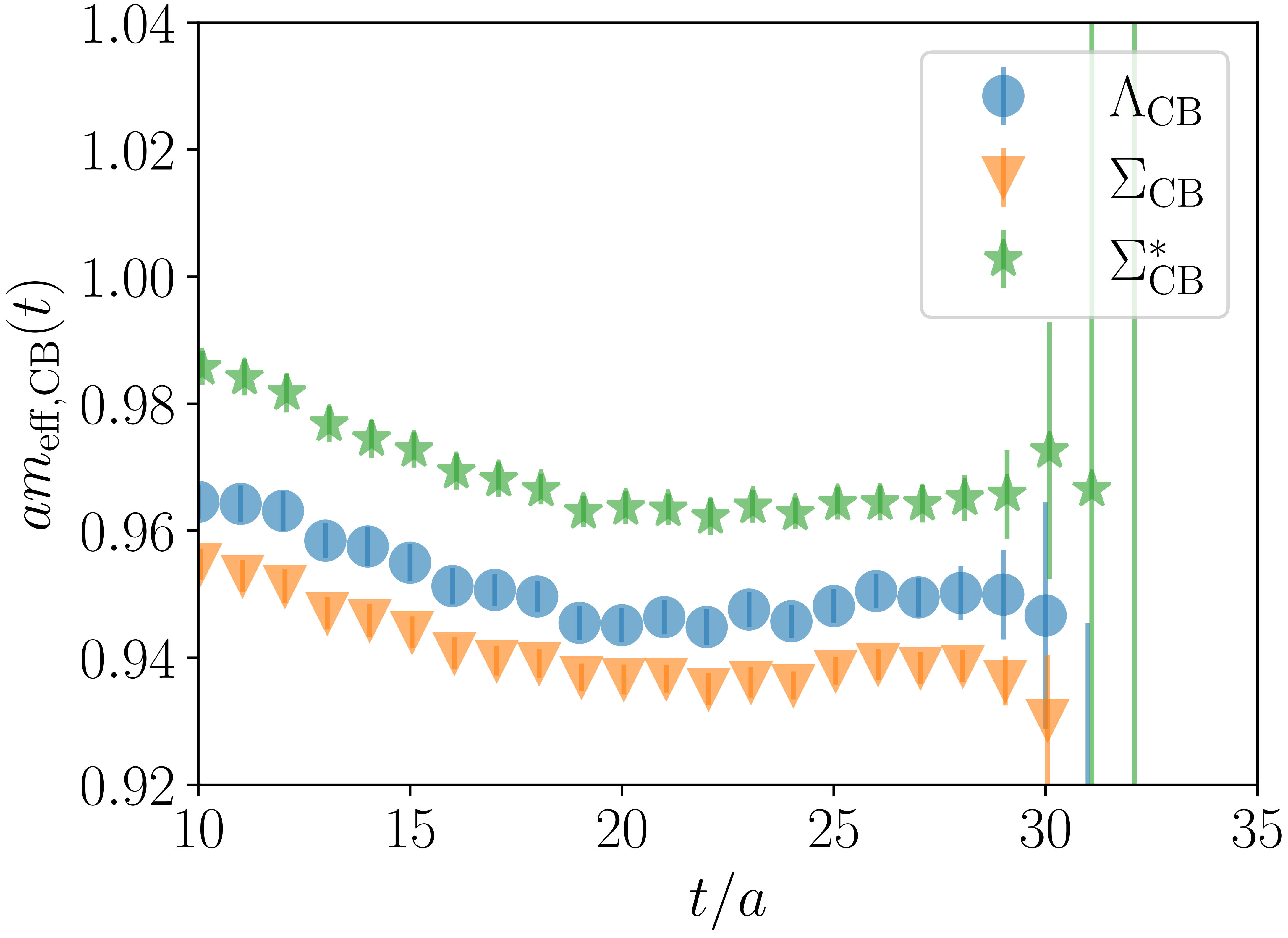
Parity partners: who is lighter?

$$C_{\mathrm{CB}}(t) \xrightarrow{0 \ll t \ll T} P_+ \left[c_+ e^{-m^+ t} - c_- e^{-m^-(T-t)} \right] + P_- \left[c_- e^{-m^- t} - c_+ e^{-m^+(T-t)} \right]$$

$$C^{\pm}_{\mathrm{CB}}(t) \equiv P_{\pm}\, C_{\mathrm{CB}}(t)$$

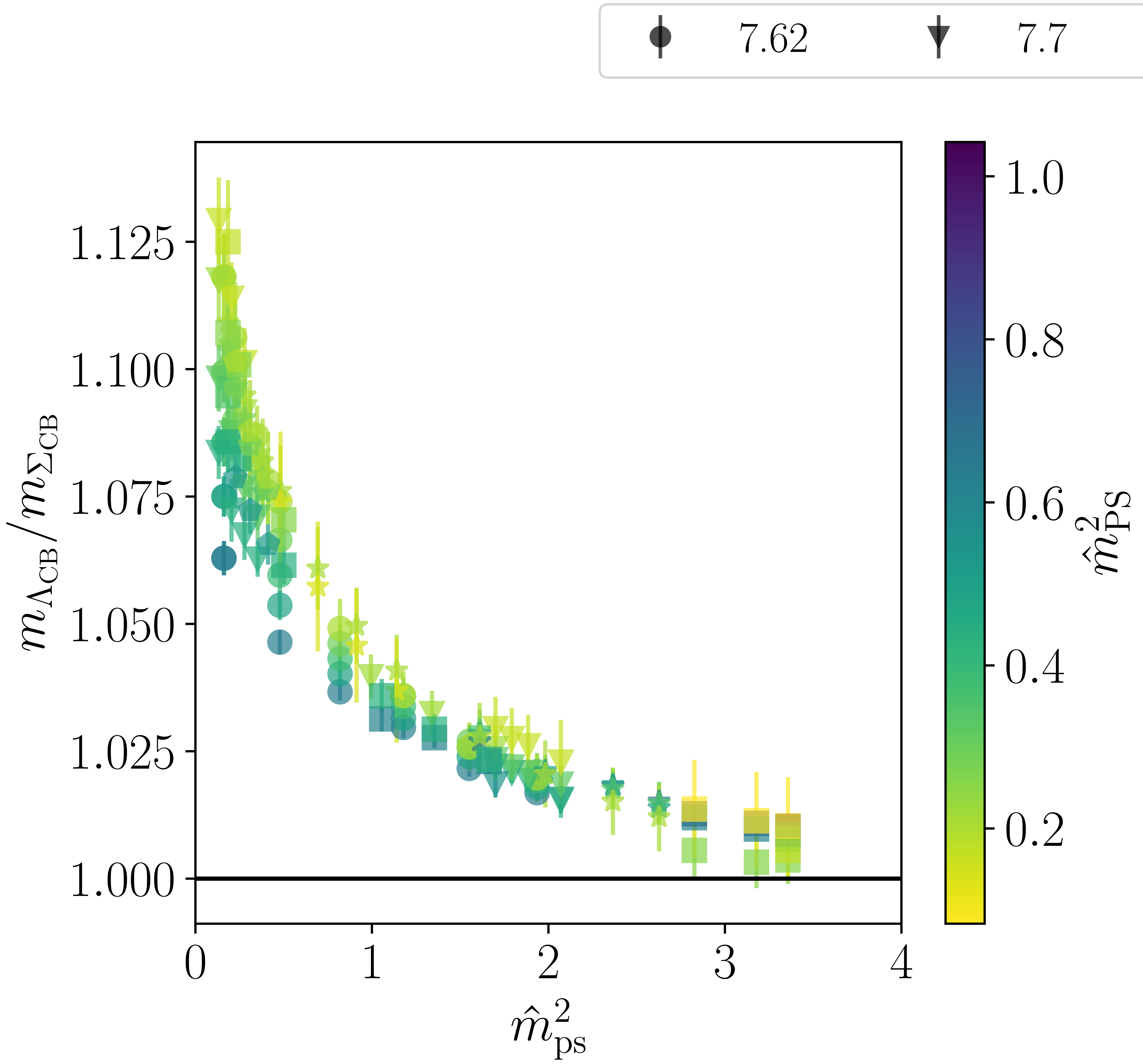


Typical mass hierarchy

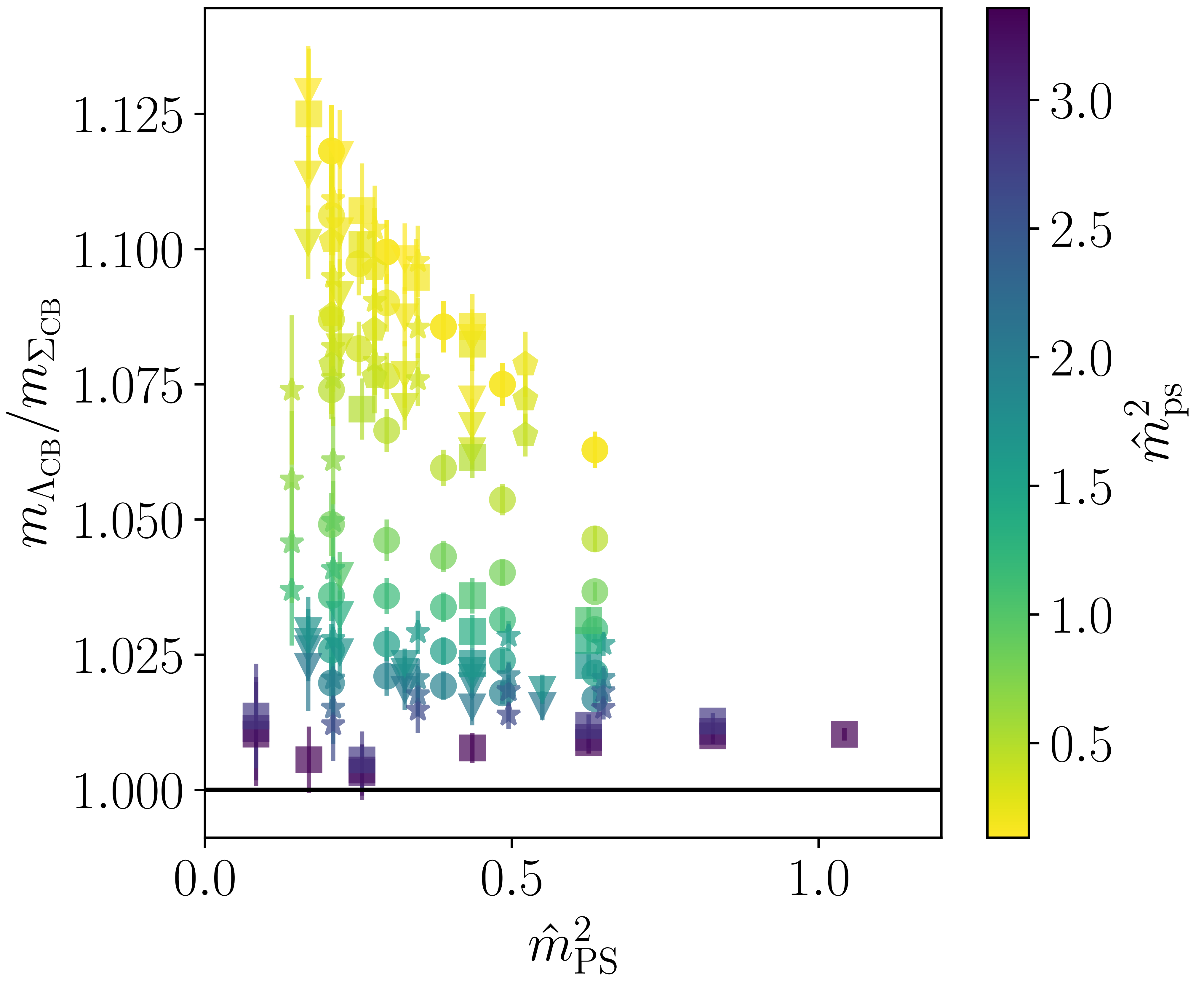


- $\Lambda_{\rm CB}$ is not lighter than $\Sigma_{\rm CB}$
- *c.f.*, QCD where $m_\Lambda < m_\Sigma$

Typical mass hierarchy

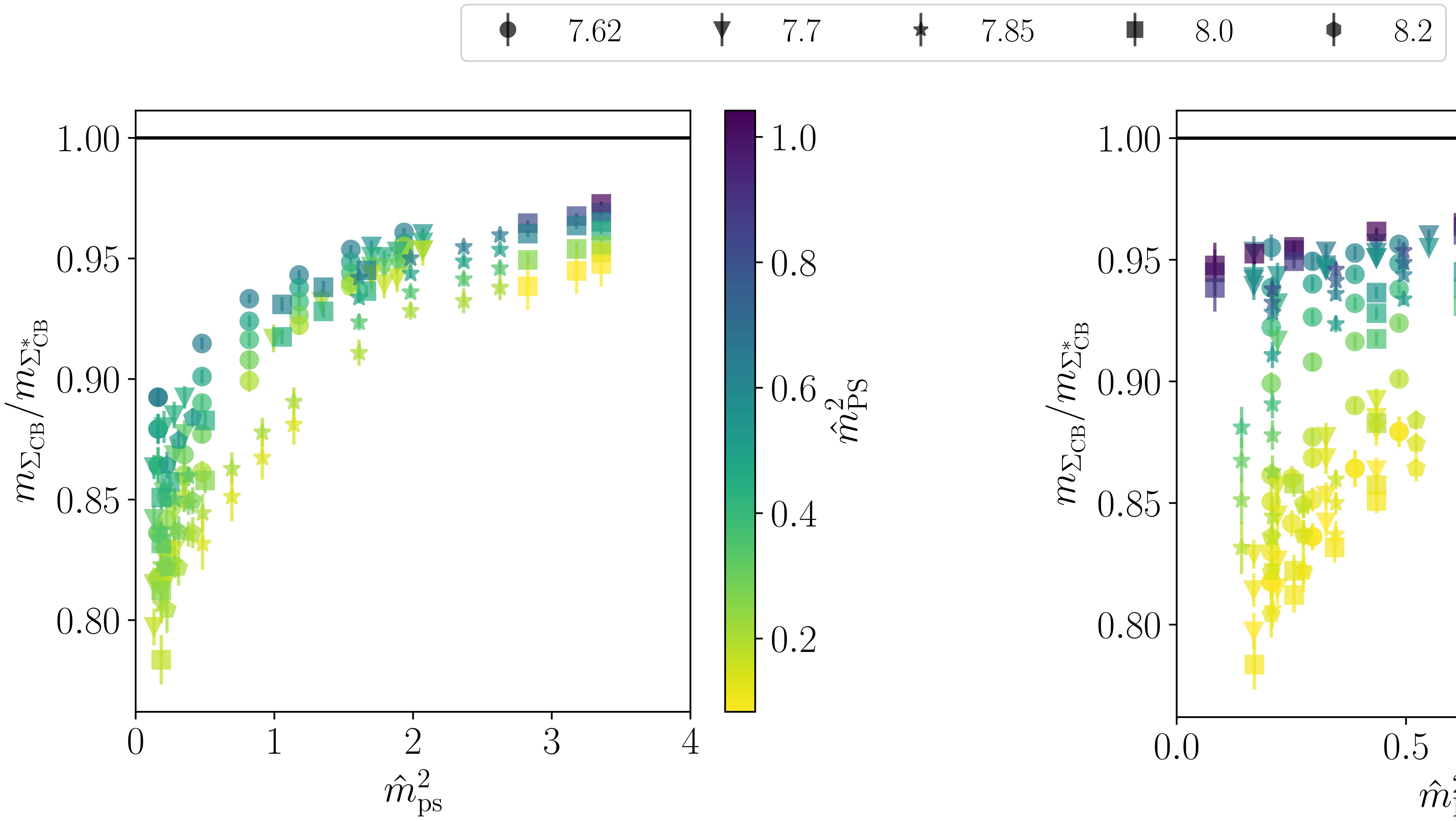


Antisymmetric

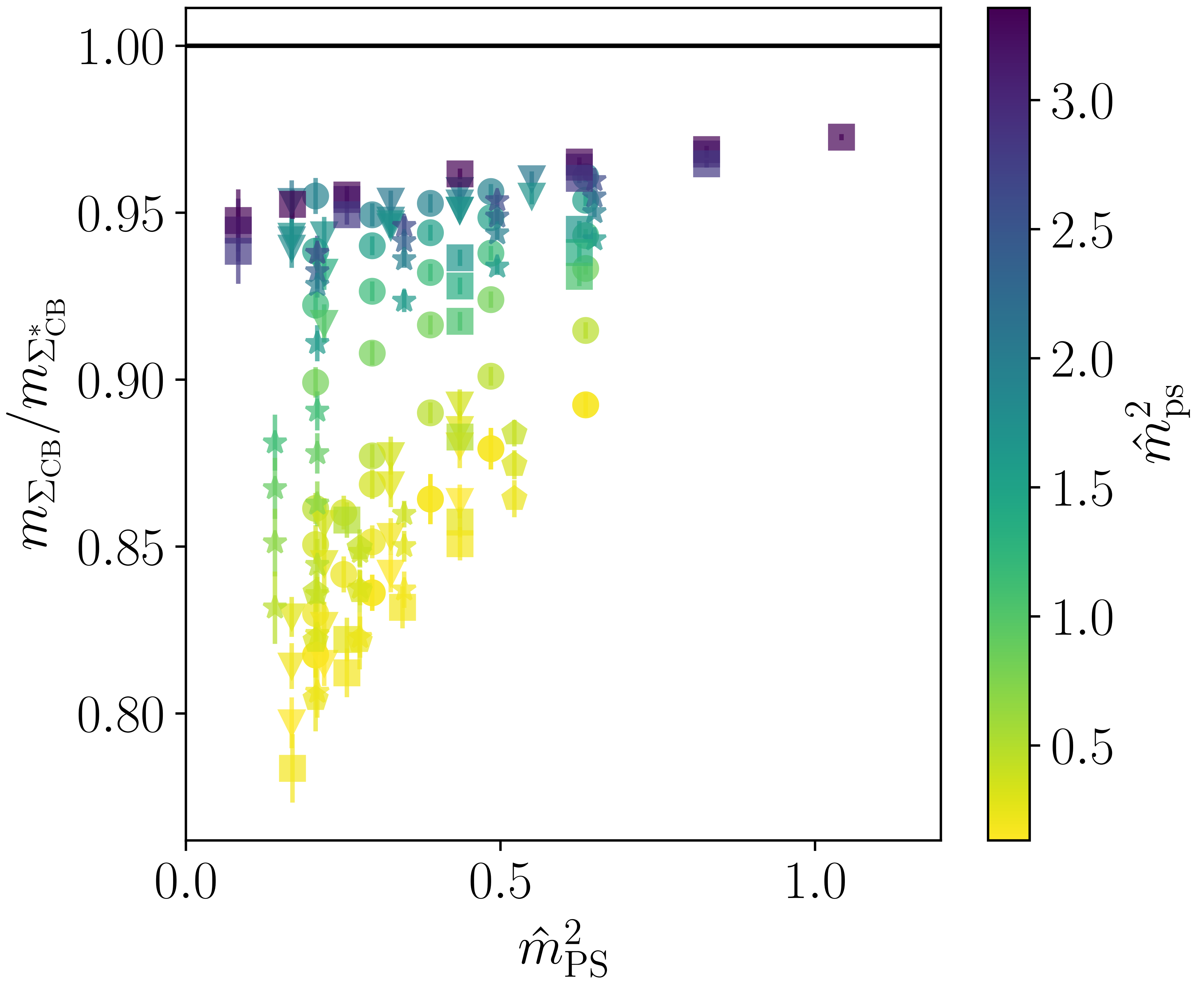


Fundamental

Typical mass hierarchy



Antisymmetric



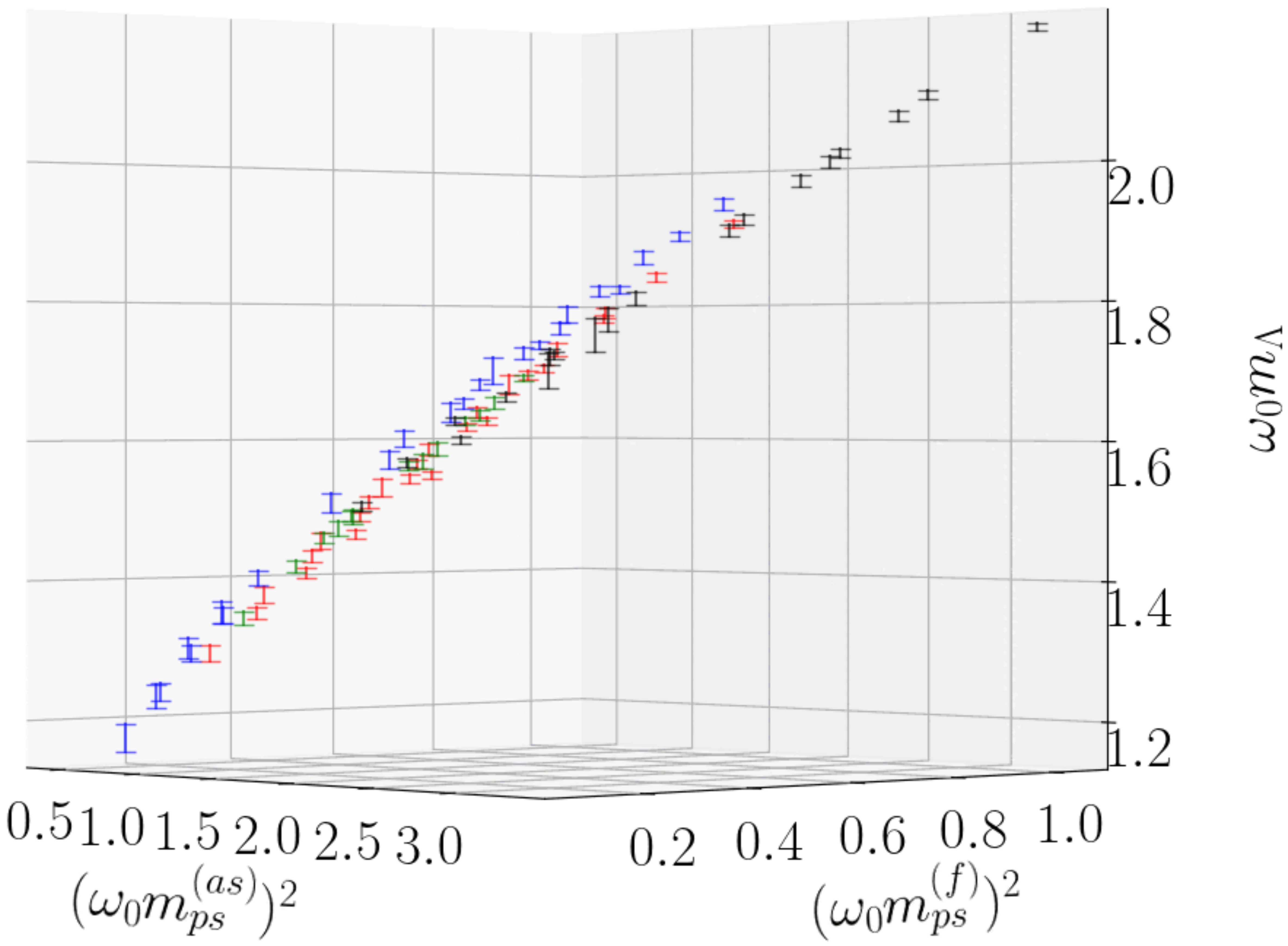
Fundamental

Hyperquark mass dependence

- Fit to analytic terms in baryon chiral perturbation theory

$$m_{\mathrm{CB}} = m^{\chi}_{CB} + F_2\hat{m}^2_{\mathrm{PS}} + A_1\hat{m}_{\mathrm{ps}}{}^2 + L_1\hat{a} + F_3\hat{m}^3_{\mathrm{PS}} + A_3\hat{m}^3_{\mathrm{ps}} + L_{2F}\hat{a}\hat{m}^2_{\mathrm{PS}} + L_{2A}\hat{a}\hat{m}^2_{\mathrm{ps}} + F_4\hat{m}^4_{\mathrm{PS}} + A_4\hat{m}^4_{\mathrm{ps}} + C_4\hat{m}^2_{\mathrm{PS}}\hat{m}^2_{\mathrm{ps}}$$

- Cannot obtain stable fits
- Removing heavy-mass data does not help



Hyperquark mass dependence

- Fit to analytic terms in baryon chiral perturbation theory

$$
\begin{aligned}
m_{\mathrm{CB}} = m^{\chi}_{CB} &+ F_2\hat{m}^2_{\mathrm{PS}} + A_1\hat{m}_{\mathrm{ps}}{}^2 + L_1\hat{a} && \text{--------- M2}\\
&+ F_3\hat{m}^3_{\mathrm{PS}} + A_3\hat{m}^3_{\mathrm{ps}} + L_{2F}\hat{a}\hat{m}^2_{\mathrm{PS}} + L_{2A}\hat{a}\hat{m}^2_{\mathrm{ps}} && \text{---- M3}\\
&\underbrace{+ F_4\hat{m}^4_{\mathrm{PS}}}_{\text{MF4}} \underbrace{+ A_4\hat{m}^4_{\mathrm{ps}}}_{\text{MA4}} \underbrace{+ C_4\hat{m}^2_{\mathrm{PS}}\hat{m}^2_{\mathrm{ps}}}_{\text{MC4}}
\end{aligned}
$$

Fit Ansatz	$\hat{m}^{\chi}_{\mathrm{CB}}$	$\hat{m}^2_{\mathrm{PS}}$	$\hat{m}^2_{\mathrm{ps}}$	$\hat{m}^3_{\mathrm{PS}}$	$\hat{m}^3_{\mathrm{ps}}$	$\hat{m}^4_{\mathrm{PS}}$	$\hat{m}^4_{\mathrm{ps}}$	$\hat{m}^2_{\mathrm{PS}}\hat{m}^2_{\mathrm{ps}}$	$\hat{a}$	$\hat{m}^2_{\mathrm{PS}}\hat{a}$	$\hat{m}^2_{\mathrm{ps}}\hat{a}$
M2	✓	✓	✓	-	-	-	-	-	✓	-	-
M3	✓	✓	✓	✓	✓	-	-	-	✓	✓	✓
MF4	✓	✓	✓	✓	✓	✓	-	-	✓	✓	✓
MA4	✓	✓	✓	✓	✓	-	✓	-	✓	✓	✓
MC4	✓	✓	✓	✓	✓	-	-	✓	✓	✓	✓

Procedures for the hyper quark-mass extrapolation

- Try the five fit ansatze
- Systematically include data points with $am_{\mathrm{PS}} < 1$ and $am_{\mathrm{ps}} < 1$
  → 263 data sets
- $263 \times 5 = 1315$ analysis procedures
- For each procedure, compute $\mathrm{AIC} \equiv \chi^2 + 2k + 2N_{\mathrm{cut}}$

  $2N_{\mathrm{cut}}$: # of removed data points

  $2k$: # of fit parameters
- Probability weight $W = \dfrac{1}{\mathcal{N}} \exp\left[-\dfrac{1}{2}\mathrm{AIC}\right]$

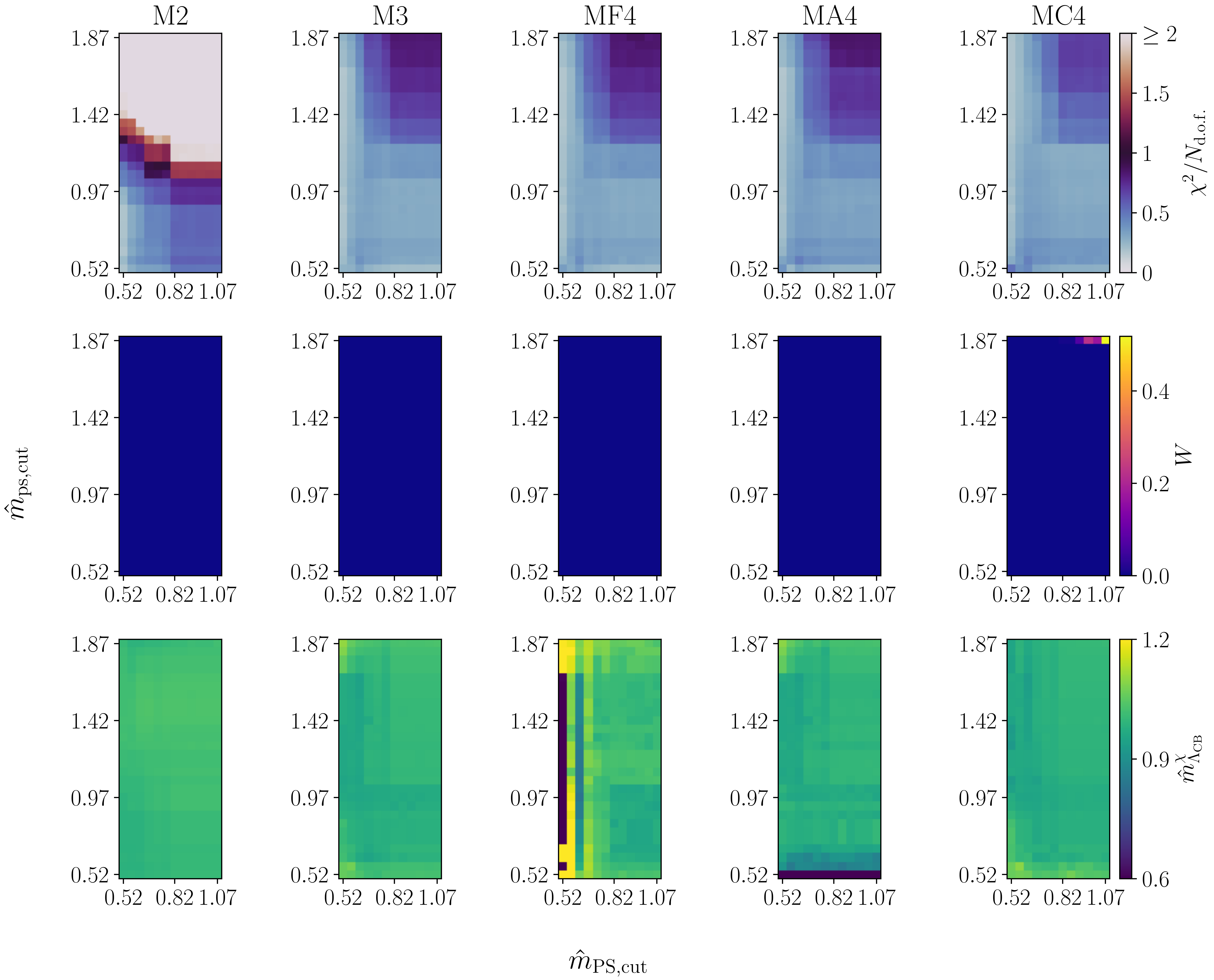
Fit results for $m_{\Lambda_{\rm CB}}$

- Polynomial terms in baryon chiral perturbation theory

$$m_{\rm CB} = m^{\chi}_{CB} + F_2\hat{m}_{\rm PS}^2 + A_1\hat{m}_{\rm ps}{}^2 + L_1\hat{a} \quad \text{------ M2}$$

$$\text{M3 ------} \quad + F_3\hat{m}_{\rm PS}^3 + A_3\hat{m}_{\rm ps}^3 + L_{2F}\hat{a}\hat{m}_{\rm PS}^2 + L_{2A}\hat{a}\hat{m}_{\rm ps}^2$$

$$\underbrace{+F_4\hat{m}_{\rm PS}^4}_{\rm MF4} \underbrace{+A_4\hat{m}_{\rm ps}^4}_{\rm MA4} \underbrace{+C_4\hat{m}_{\rm PS}^2\hat{m}_{\rm ps}^2}_{\rm M4C}$$



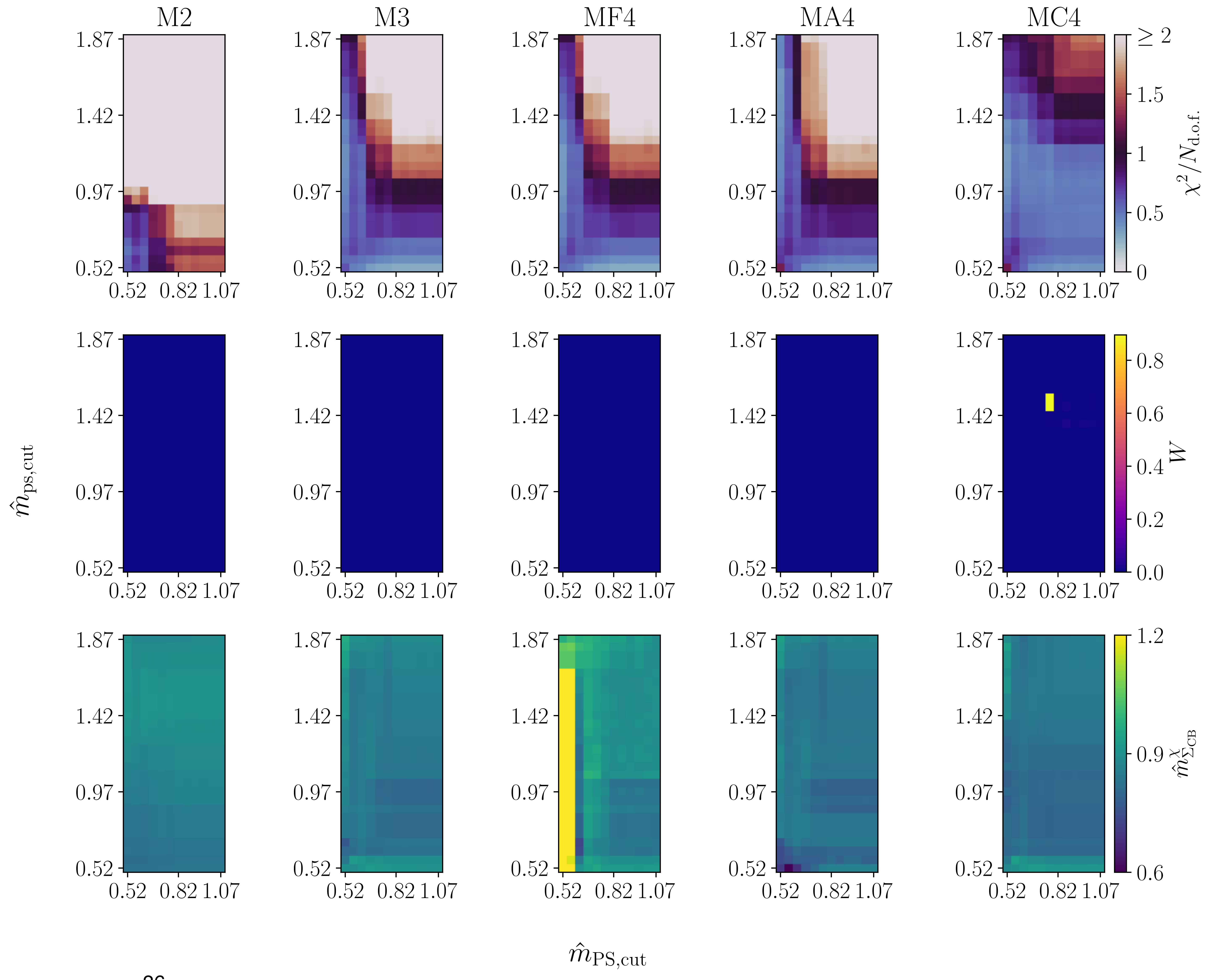
Fit results for $m_{\Sigma_{\mathrm{CB}}}$

- Polynomial terms in baryon chiral perturbation theory

$$m_{\mathrm{CB}} = m^{\chi}_{CB} + F_2\hat{m}^2_{\mathrm{PS}} + A_1\hat{m}_{\mathrm{ps}}{}^2 + L_1\hat{a} \quad \text{------ M2}$$

$$\text{M3 ------} \quad + F_3\hat{m}^3_{\mathrm{PS}} + A_3\hat{m}^3_{\mathrm{ps}} + L_{2F}\hat{a}\hat{m}^2_{\mathrm{PS}} + L_{2A}\hat{a}\hat{m}^2_{\mathrm{ps}}$$

$$+ \underbrace{F_4\hat{m}^4_{\mathrm{PS}}}_{\text{MF4}} + \underbrace{A_4\hat{m}^4_{\mathrm{ps}}}_{\text{MA4}} + \underbrace{C_4\hat{m}^2_{\mathrm{PS}}\hat{m}^2_{\mathrm{ps}}}_{\text{M4C}}$$



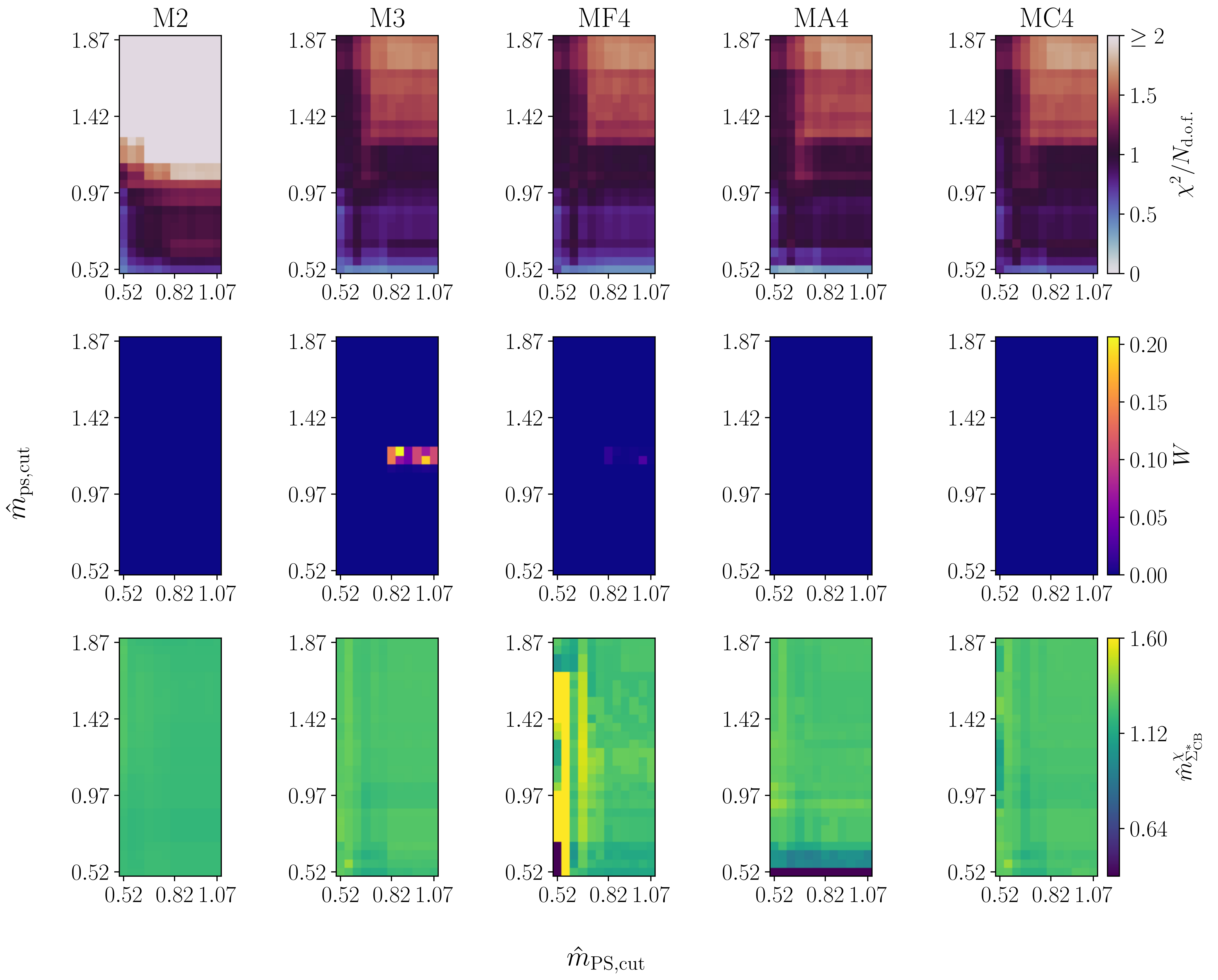
Fit results for $m_{\Sigma^*_{\rm CB}}$

- Polynomial terms in baryon chiral perturbation theory

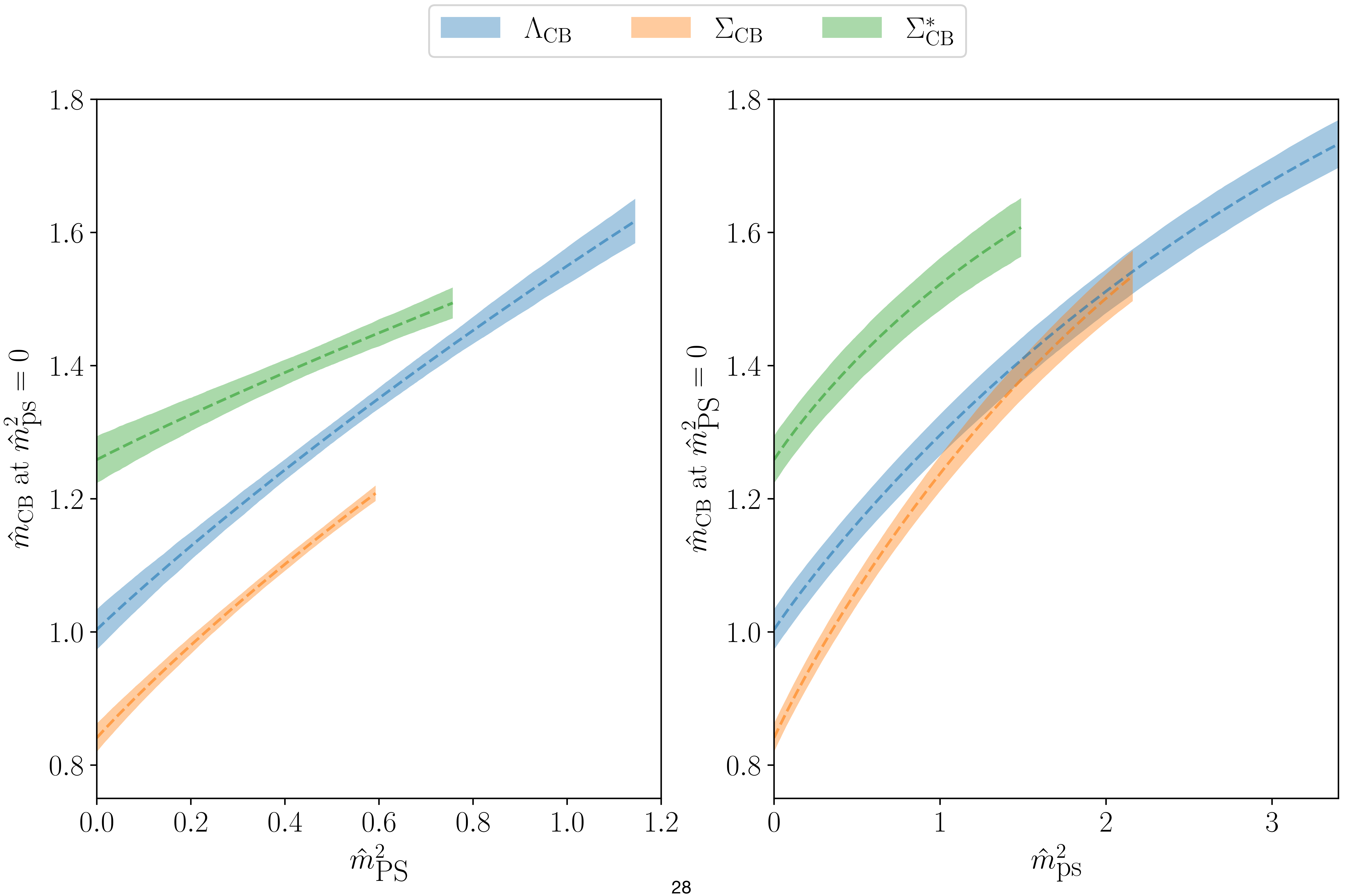
$$m_{\rm CB} = m^{\chi}_{CB} + F_2\hat{m}^2_{\rm PS} + A_1\hat{m}_{\rm ps}{}^2 + L_1\hat{a} \quad \text{------ M2}$$

$$\text{M3 ------} \quad + F_3\hat{m}^3_{\rm PS} + A_3\hat{m}^3_{\rm ps} + L_{2F}\hat{a}\hat{m}^2_{\rm PS} + L_{2A}\hat{a}\hat{m}^2_{\rm ps}$$

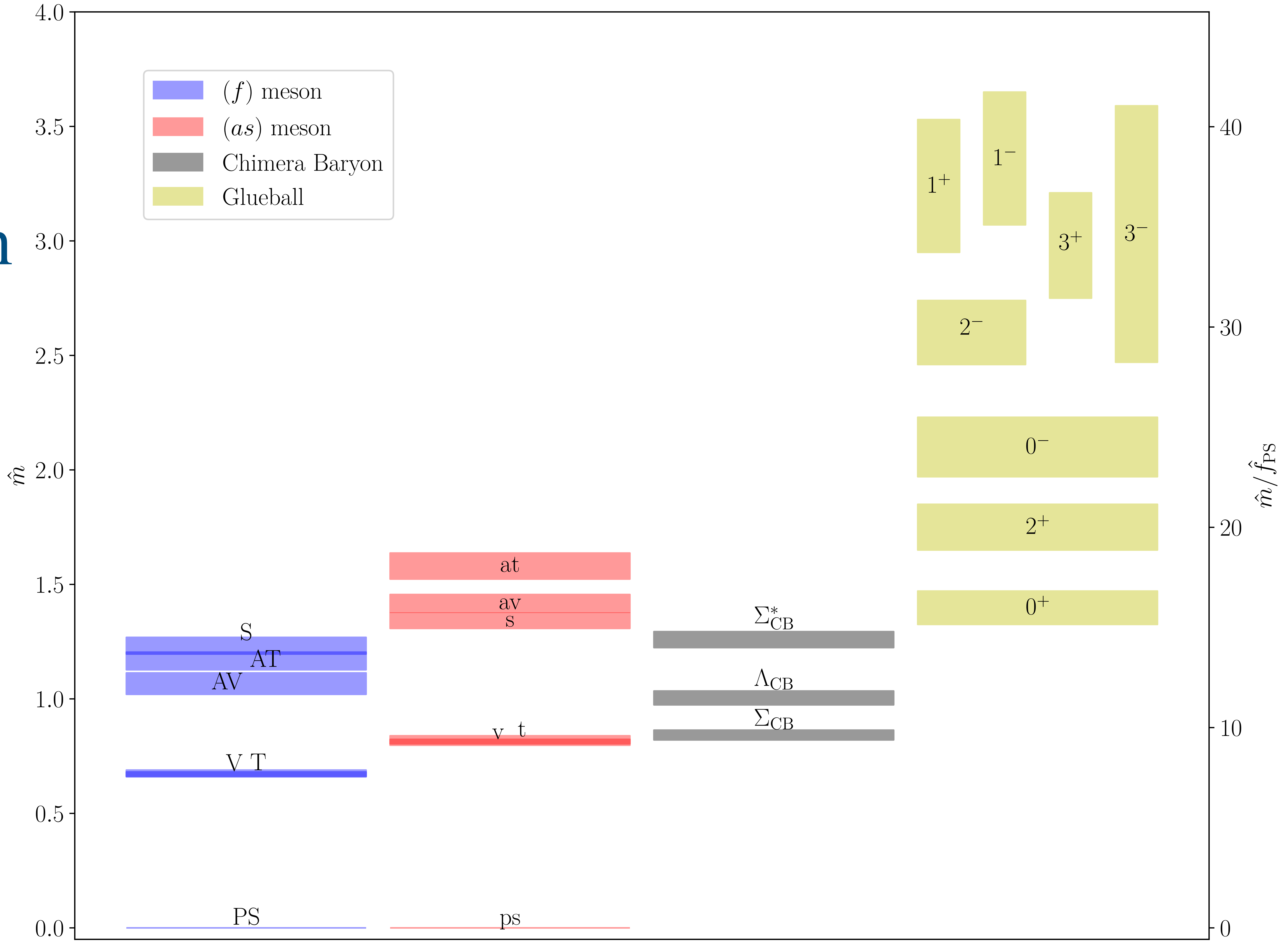
$$+ \underbrace{F_4\hat{m}^4_{\rm PS}}_{\text{MF4}} + \underbrace{A_4\hat{m}^4_{\rm ps}}_{\text{MA4}} + \underbrace{C_4\hat{m}^2_{\rm PS}\hat{m}^2_{\rm ps}}_{\text{M4C}}$$



Hyperquark-mass dependence



Quenched spectrum



Conclusion and outlook

- First lattice study of the chimera baryon masses in the Sp(4) gauge theory
  - → Key difference from QCD: Λ_{CB} may not be lighter than Σ_{CB}
- Fully-dynamical simulations in progress
- Mixing strength with the top quark, also large anomalous dimension
- Also in the Sp(4) gauge theory: the Higgs potential

Backup slides

Gauge group repn and global coset

M. Peskin, 1980

- ★ Real : $(T^a)^* = (T^a)^{\mathrm{T}} = -S^{-1} T^a S, \qquad SS^* = 1.$
- ★ Pseudoreal : $(T^a)^* = (T^a)^{\mathrm{T}} = -S^{-1} T^a S, \qquad SS^* = -1.$

$$\boxed{\Psi = \begin{pmatrix} \Psi_L \\ \Psi_R \end{pmatrix} \equiv \begin{pmatrix} \psi_\alpha \\ \bar{\chi}^{\dot{\beta}} \end{pmatrix} = \begin{pmatrix} \psi_\alpha \\ (\chi^\beta)^* \end{pmatrix}, \quad \overline{\Psi}\Psi = \epsilon^{\alpha\beta} \chi^{ia}_\beta \psi_{\alpha i a} + \text{h.c.}}$$

gauge repn	condensate	global symmetry
Complex	$\epsilon^{\alpha\beta} \psi^{i(\bar{r})}_\beta \psi^{(r)}_{\alpha i} + \text{h.c.}$	$SU(N_f) \times SU(N_f) \to SU(N_f)$
Real	$\epsilon^{\alpha\beta} \psi^{ia}_\beta \psi^b_{\alpha i} S^{-1}_{ab}$	$SU(2N_f) \to SO(2N_f)$
Pseudoreal	$\epsilon^{\alpha\beta} \psi^{ia}_\beta \psi^{jb}_\alpha S^{-1}_{ab} E_{ij}$	$SU(2N_f) \to Sp(2N_f)$

The top partner and the top mass

$$\Psi_{ij}^{\alpha} = (\psi_i \chi^{\alpha} \psi_j), \; \Psi_{ij}^{c,\alpha} = (\psi_i \chi^{c,\alpha} \psi_j)$$

$$\mathcal{L}^{\rm mix} = -\frac{1}{2}\left\{ \lambda_1 M_* \left(\frac{M_*}{\Lambda}\right)^{d_\Psi - 5/2} \Psi_1^T \tilde{C} t^c + \lambda_2 M_* \left(\frac{M_*}{\Lambda}\right)^{d_{\Psi^c} - 5/2} t^T \tilde{C} \Psi_2^c + \right.$$
$$\left. + \lambda M_* \left[\Psi_1^T \tilde{C} \Psi_1^c + \Psi_2^T \tilde{C} \Psi_2^c\right] + y v_W \left[\Psi_1^T \tilde{C} \Psi_2^c + \Psi_2^T \tilde{C} \Psi_1^c\right] \right\} + \text{h.c.}$$

$$m_t^2 \simeq \frac{\lambda_1^2 \lambda_2^2 y^2 \left(\frac{M_*}{\Lambda}\right)^{2d_\Psi + 2d_{\Psi^c} - 10} v_W^2 M_*^4}{m_1^2 m_2^2}$$

where

$$m_1^2 \simeq \left(\lambda^2 + \lambda_1^2 \left(\frac{M_*}{\Lambda}\right)^{2d_\Psi - 5}\right) M_*^2 ,$$
$$m_2^2 \simeq \left(\lambda^2 + \lambda_2^2 \left(\frac{M_*}{\Lambda}\right)^{2d_{\Psi^c} - 5}\right) M_*^2$$

- ★ Need $d_\Psi = d_{\Psi^c} < 5/2$, *ie*, large anomalous dimension
  - ➙ IR conformality with more fermion flavours?
- ★ These couplings can be important for Higgs potential
  - ➙ Four-fermion operators

Composite Higgs with Sp(4) gauge group

J. Barnard, T. Gherghetta, T.S. Ray, 2014

Field	$Sp(4)$ gauge	$SU(4)$ global
A_μ	10	1
ψ	4	4

- ★ Two Dirac fermions in the fundamental repn
  pseudoreal
- ★ The Higgs doublet in the coset $SU(4)/Sp(4)$
- ★ The SM $SU(2)_L \times SU(2)_R$ in the unbroken global $Sp(4)$