CHARMED BOTTOM BARYON SPECTROSCOPY

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OUTLINE

- Landscape of heavy baryon spectroscopy
- Details of our calculation
- Extrapolations
- Results

LANDSCAPE

- Significant experimental progress in recent years
  Many singly heavy baryon observations

  Ω_b, Ξ_{cc} CONTROVERSY

- Productive period for LQCD spectroscopy of heavy baryons

Group	N_f	S_H	a_t^{-1} (GeV)	L (fm)
Bowler et al.	0	tree clover	2.9	1.63
Lewis et al.	0	D234	1.8, 2.2, 2.6	1.97
Mathur et al.	0	NRQCD	1.8, 2.2	2.64, 2.1
Flynn et al.	0	NP clover	2.6	1.82
Chiu et al.	0	ODWF	2.23	1.77
Na et al.	$2+1$	Fermilab	2.2, 1.6, 1.3	2.5
Liu et al.	$2+1$	RHQ	1.6	2.5
Briceño et al.	$2+1+1$	RHQ	1.6, 2.2, 3.4	2.7 - 4.1
Alexandrou et al.	2	Osterwalder-Seiler	3.5, 2.8, 2.2	1.8 - 2.74
Namekawa et al.	$2+1$	RHQ	2.2	2.9

from H.W. Lin [1] (extended to present)

LANDSCAPE

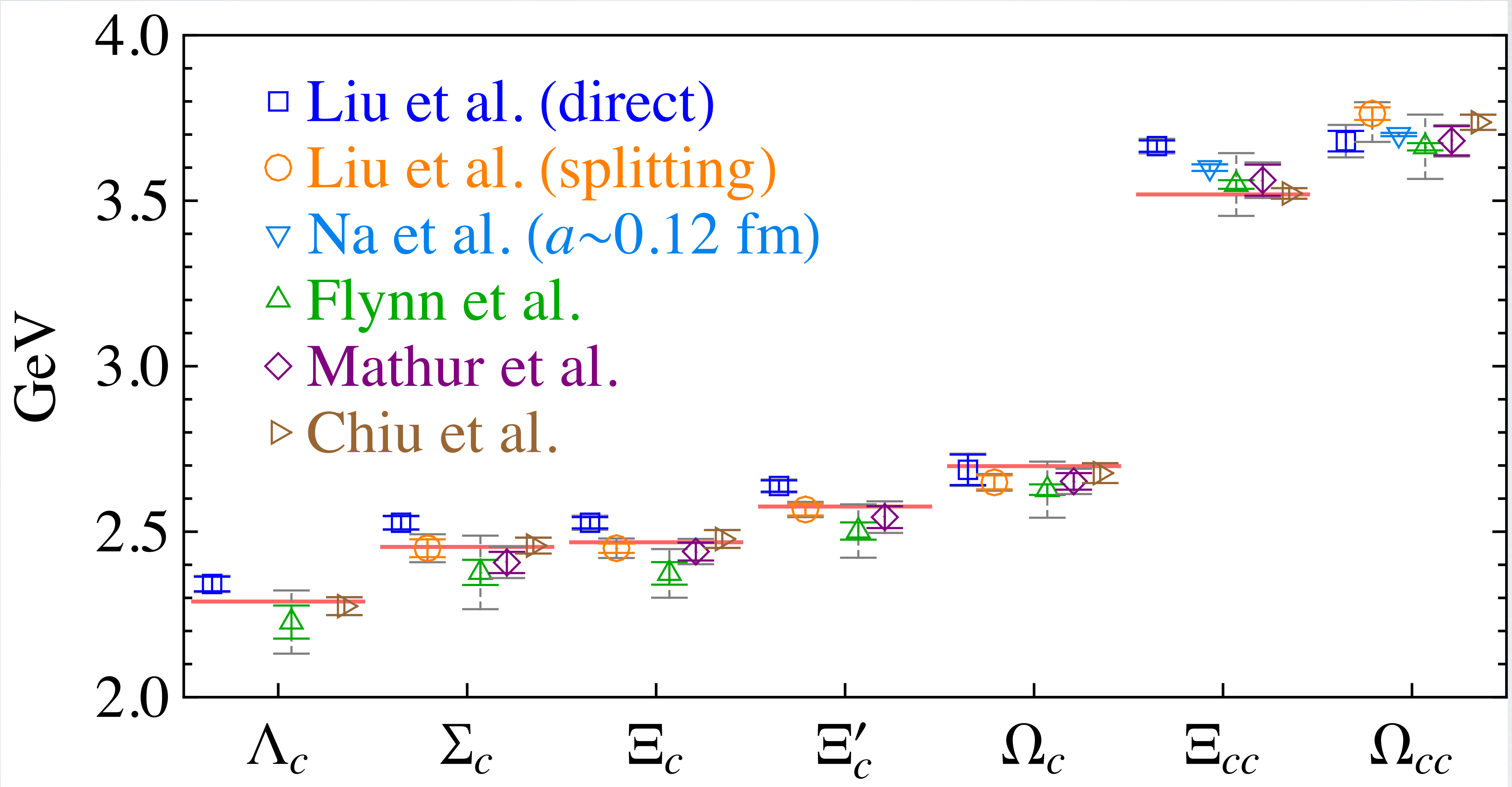
from H.W. Lin [1] (not current)

	Splitting(Stat)(Extrap)(Scale)	Experiment
$B_s - B_d$	71.2(2.2)(1.2)(4.2)	87.1(0.6)
$\Lambda_b - B_d$	340(11)(8.1)(24)	341.0(1.6)
$\Xi_b - B_d$	484.7(7.7)(6.2)(32)	513(3)
$\Sigma_b - B_d$	615(15)(12)(40)	554(3)
$\Xi'_b - B_d$	672(10)(9.1)(44)	–
$\Omega_b - B_d$	749.2(9.8)(9.0)(49)	786(7)/886(16)
$\Lambda_b - B_s$	261(10)(8.5)(19)	253.9(1.7)
$\Xi_b - \Lambda_b$	157.2(5.2)(3.4)(9.0)	172(3)
$\Sigma_b - \Lambda_b$	274(13)(13)(17)	213(3)
$\Xi'_b - \Lambda_b$	335(15)(10)(20)	–
$\Omega_b - \Lambda_b$	414(12)(9.5)(25)	445(7)/545(16)
$\Xi'_b - \Sigma_b$	62.6(2.6)(2.0)(3.9)	–
$\Omega_b - \Xi'_b$	81.5(2.7)(3.4)(4.9)	–

- Test agreement between lattice/expt. and lattice/lattice

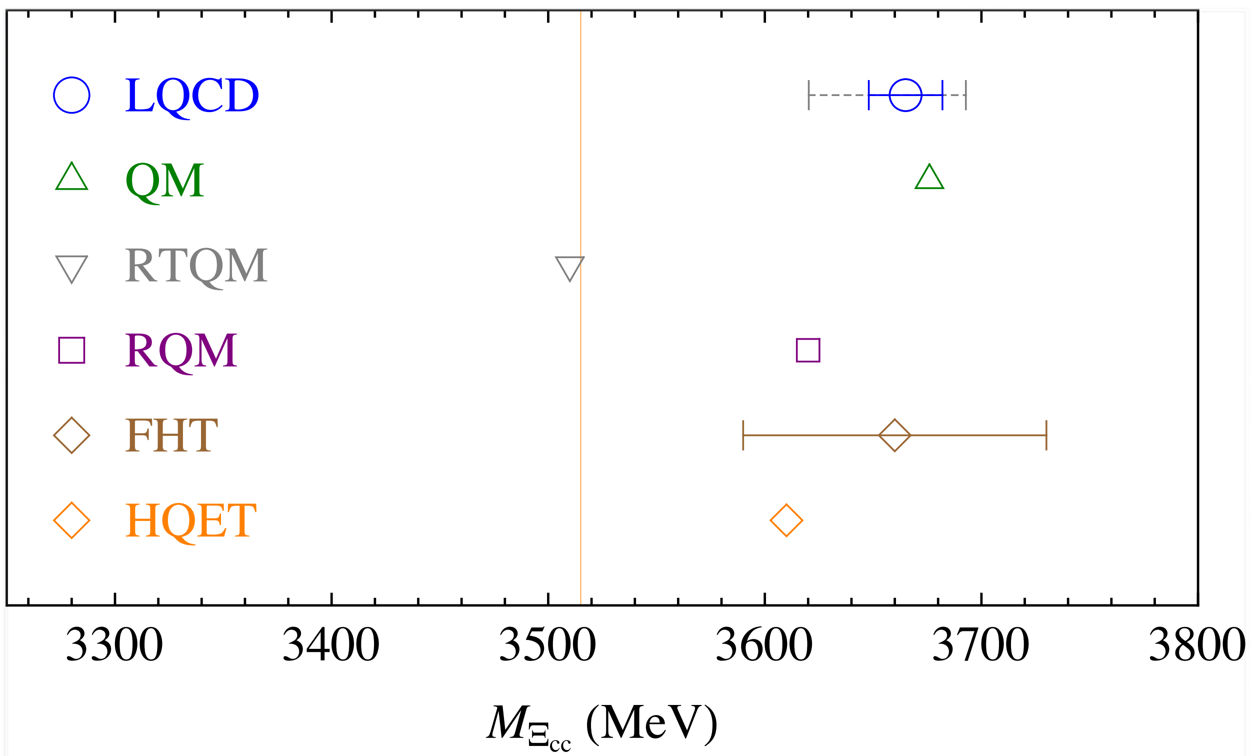
LANDSCAPE

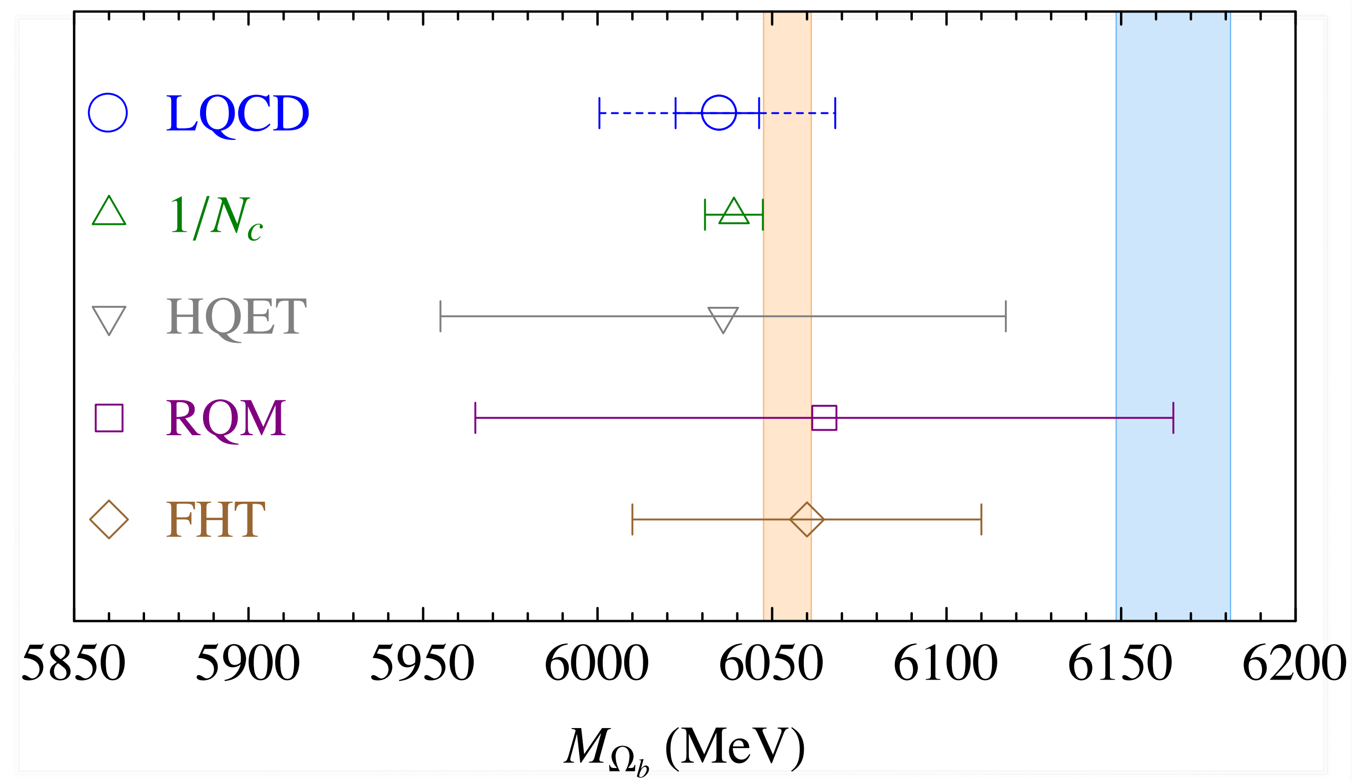
from PDG [2]



- Test agreement between lattice/expt. and lattice/lattice

LANDSCAPE



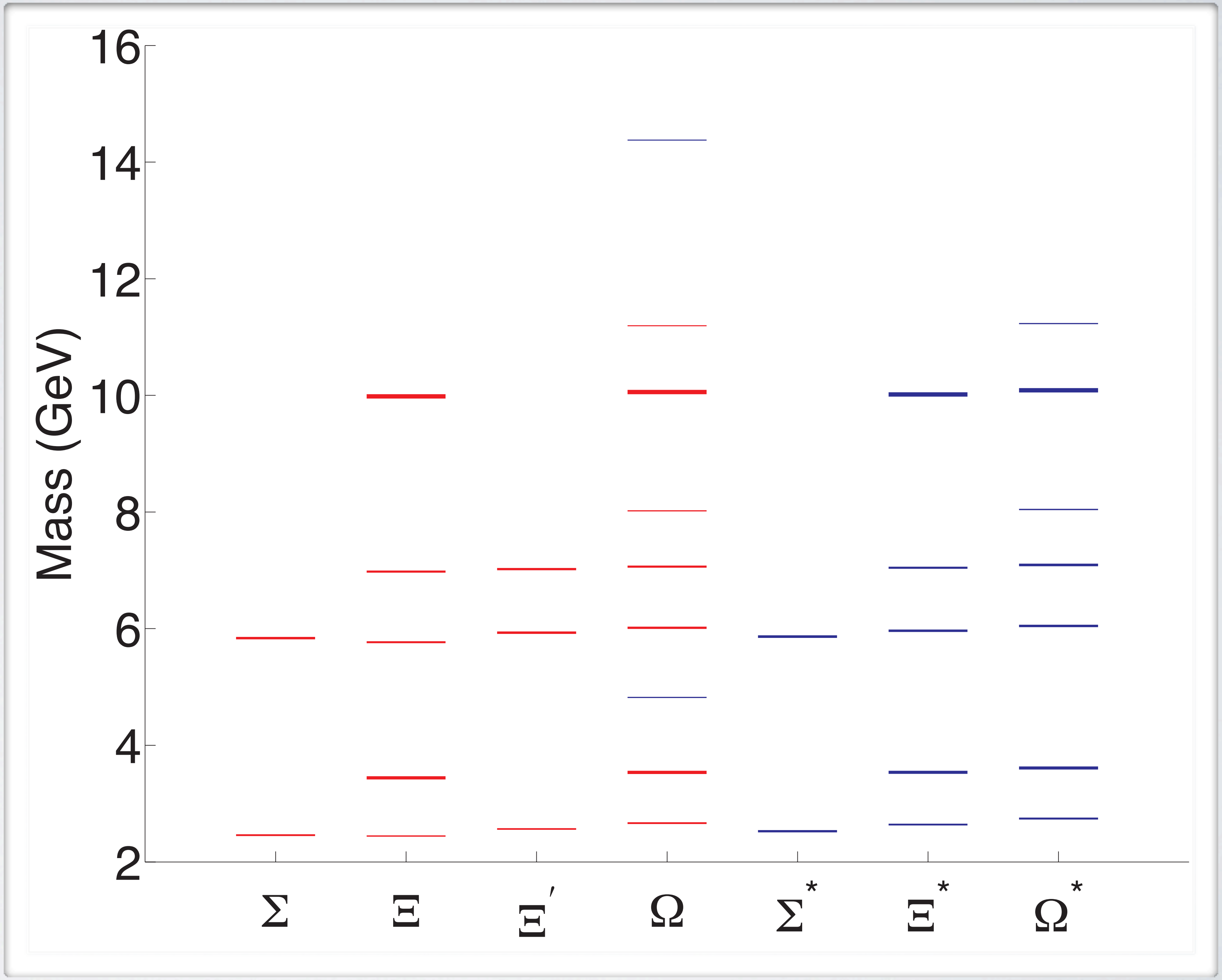


from H.W. Lin [2] and Refs. therein

- Test agreement between lattice/models

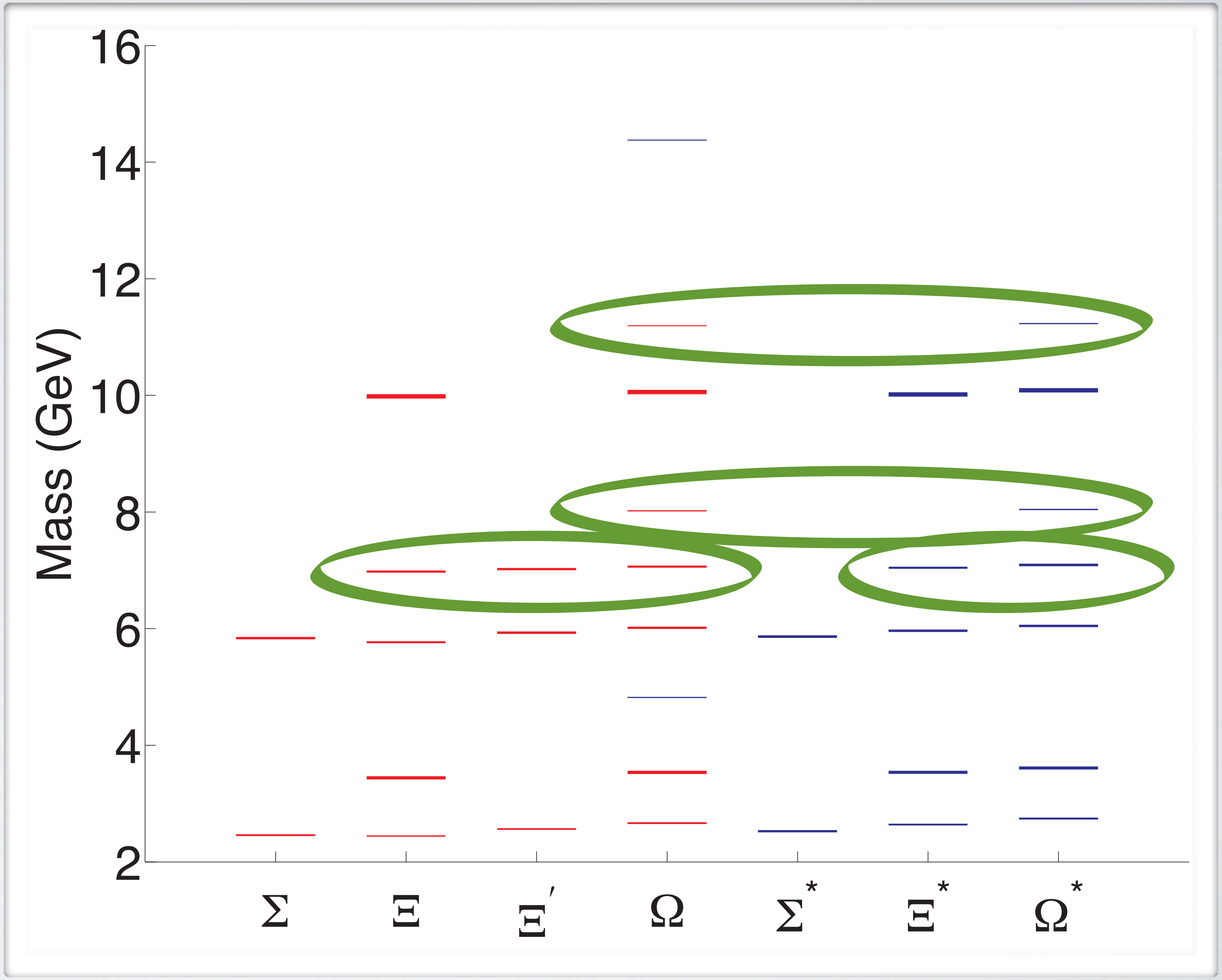
GOAL OF OUR CALCULATION:

- Comprehensive calculation of the low lying heavy baryon spectrum Include all states with charmed and bottom quarks.



GOAL OF OUR CALCULATION:

- Comprehensive calculation of the low lying heavy baryon spectrum Include all states with charmed and bottom quarks.
- Include mixed charmed bottom baryons



DETAILS OF THE CALCULATION

- Use ensembles generated by RBC/UKQCD collaboration [3]
  - Iwasaki gauge action
  - $a \sim 0.0849,\ 0.1119\ \mathrm{fm} \quad L \sim 2.7\mathrm{fm}$
  - 2+1 flavors of dynamical DWF with $L_5 = 16$
  - Mass ranges: $m_\pi^{vv} = (227 - 352)\,\mathrm{MeV},\ m_\pi^{ss} = (295 - 352)\,\mathrm{MeV}$

    $m_K^{vv} = (523 - 586)\,\mathrm{MeV}$
- Relativistic heavy quark action [4] for charmed quarks
  - Non-perturbatively tune ν and m_0
  - Use tree level values for c_E and c_B
- NRQCD for bottom accurate through order v^4
  - One loop improved c_4 calculated by Tom Hammant [5]

INTERPOLATING OPERATORS AND FITTING METHODOLOGY: BARYON OPS

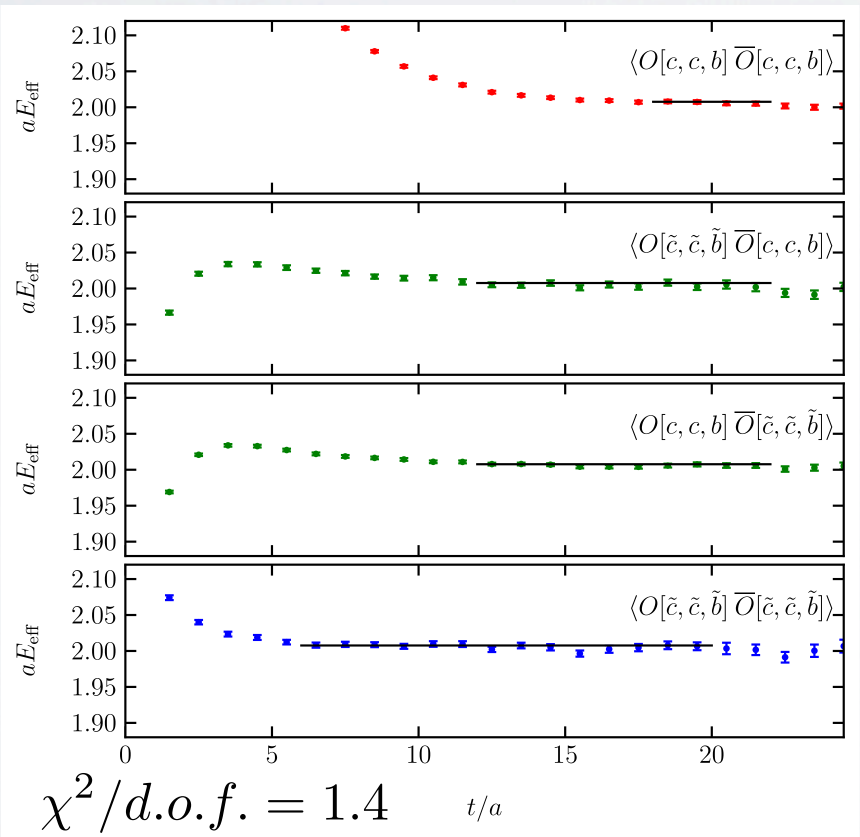
- Use baryon operators of the form:

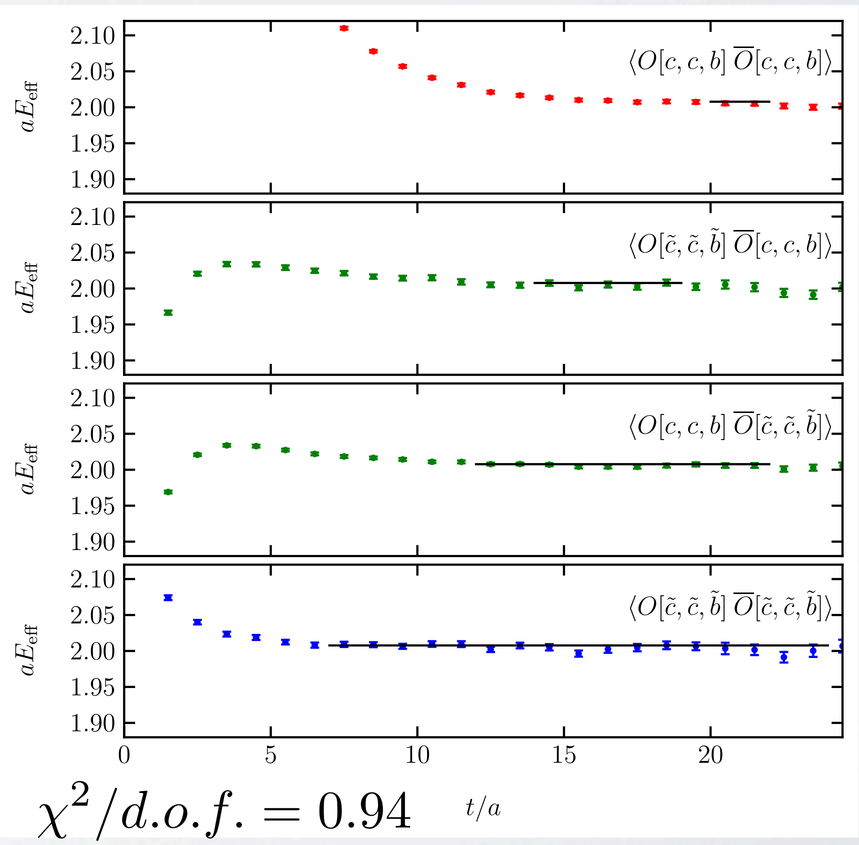
$$O_5[q,q',q'']_\alpha = \epsilon_{abc}\,(C\gamma_5)_{\beta\gamma}\;q^a_\beta\;q'^b_\gamma\;(P_+q'')^c_\alpha,$$
$$O_j[q,q',q'']_\alpha = \epsilon_{abc}\,(C\gamma_j)_{\beta\gamma}\;q^a_\beta\;q'^b_\gamma\;(P_+q'')^c_\alpha,$$

- Use different smearing to construct operator basis:

2 x 4 for {qqQ, qQQ}
2 x 2 for {QQQ}

- Simultaneous matrix fits, optimized ranges:





CHIRAL / CONTINUUM EXTRAPOLATIONS

$$M_B = M_0(\mu) + \Delta_B(\mu) + M_1^{(B)}(\mu) + M_{3/2}^{(B)}(\mu) + \mathcal{O}\left(a^2\right)$$

- Tiburzi [6] for singly heavy (coupled fits, SU(2), extended to $\mathcal{O}\left(1/m_Q\right)$):

$$\begin{bmatrix} M_\Lambda \\ M_\Sigma \\ M_{\Sigma^*} \end{bmatrix} = M_0 + \begin{bmatrix} 0 \\ \Delta_{\Sigma,\Lambda} \\ \Delta_{\Sigma^*,\Lambda} \end{bmatrix} + \frac{f^2}{8} \begin{bmatrix} \frac{\tilde{\lambda}_3}{2} \\ \tilde{\lambda}_1 \\ \tilde{\lambda}_1 \end{bmatrix} m_{\pi_{vv}}^2 + \frac{f^2}{4} \begin{bmatrix} \tilde{\lambda}_4 \\ \tilde{\lambda}_2 \\ \tilde{\lambda}_2 \end{bmatrix} m_{\pi_{ss}}^2 + g_3^2 \begin{bmatrix} \tilde{M}_{g_3,\Lambda}^{(3/2)} \\ \tilde{M}_{g_3,\Sigma}^{(3/2)} \\ \tilde{M}_{g_3,\Sigma^*}^{(3/2)} \end{bmatrix} + g_2^2 \begin{bmatrix} 0 \\ \tilde{M}_{g_2,\Sigma}^{(3/2)} \\ \tilde{M}_{g_2,\Sigma^*}^{(3/2)} \end{bmatrix}$$

- Mathur et. al [7] for doubly heavy (coupled fits, SU(2)):

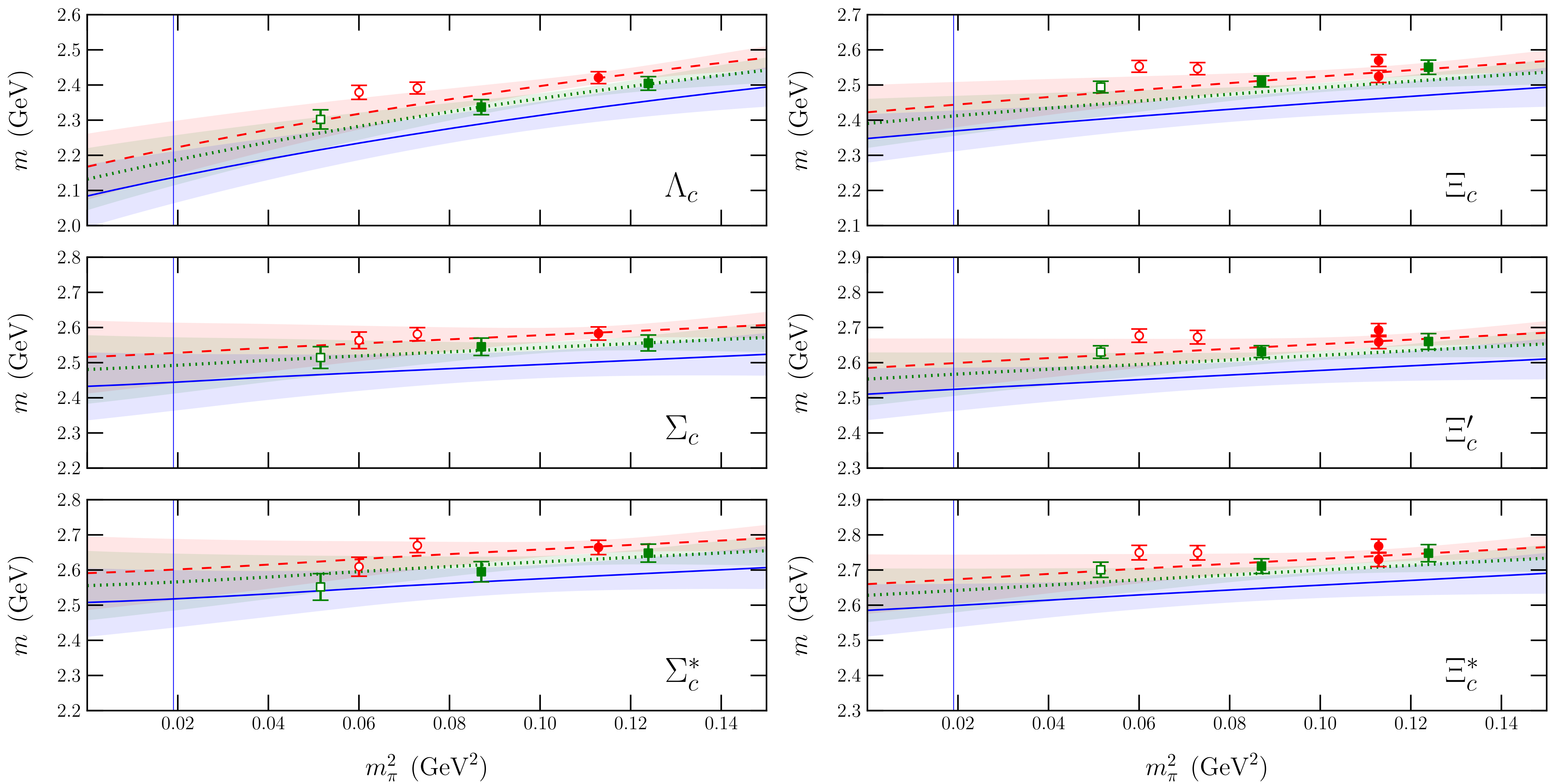
$$\begin{bmatrix} M_\Xi \\ M_{\Xi^*} \end{bmatrix} = M_0 + \begin{bmatrix} -(1/2) \\ (1/4) \end{bmatrix} \Delta_H - \frac{f^2\tilde{\sigma}}{2} m_{\pi_{vv}}^2 - f^2\tilde{\sigma}' m_{\pi_{ss}}^2 + g_1^2 \begin{bmatrix} \tilde{M}_{\Xi_{QQ}}^{(3/2)} \\ \tilde{M}_{\Xi_{QQ}^*}^{(3/2)} \end{bmatrix}.$$

- Assume chiral dependence to be negligible for triply heavy:

$$M_{\Omega_{QQQ}^{(*)}} = M_0 + c_a a^2$$

FV corrections from Detmold et al. [8],
g widths from Detmold et al. [9]

CHIRAL / CONTINUUM EXTRAPOLATIONS



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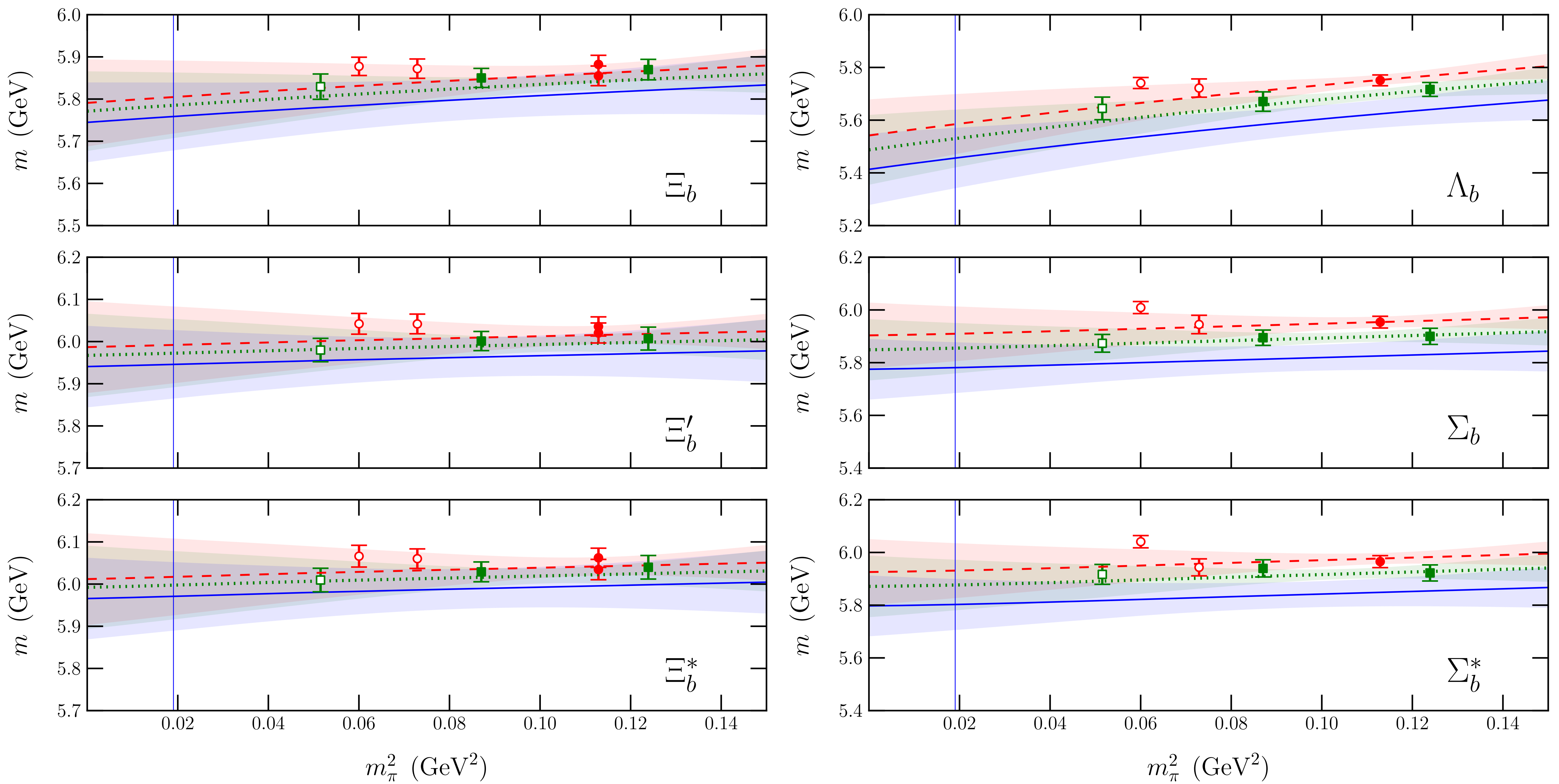

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CHIRAL / CONTINUUM EXTRAPOLATIONS: RESULTS

Baryon	Lattice (GeV)	Expt. (GeV)	Baryon	Lattice (GeV)	Expt. (GeV)
Λ_c	2.137(74)	2.286	Λ_b	5.456(114)	5.619
Σ_c	2.444(81)	2.454	Σ_b	5.781(96)	5.811
Σ_c^*	2.518(82)	2.518	Σ_b^*	5.802(97)	5.832
Ξ_c	2.372(58)	2.467	Ξ_b	5.760(80)	5.791
Ξ_c'	2.526(62)	2.575	Ξ_b'	5.947(81)	-
Ξ_c^*	2.600(62)	2.645	Ξ_b^*	5.971(81)	-
Ω_c	2.615(67)	2.685	Ω_b	6.008(80)	6.071
Ω_c^*	2.690(67)	2.765	Ω_b^*	6.036(80)	-

CHIRAL / CONTINUUM EXTRAPOLATIONS: RESULTS

Baryon	Lattice (GeV)	Baryon	Lattice (GeV)	Baryon	Lattice (GeV)
Ξ_{cc}	3.558(39)	Ξ_{cb}	6.877(52)	Ξ_{bb}	10.185(53)
Ξ^*_{cc}	3.627(54)	Ξ^*_{cb}	6.915(62)	Ξ^*_{bb}	10.191(56)
Ω_{cc}	3.689(38)	Ω_{cb}	6.973(48)	Ω_{bb}	10.250(51)
Ω^*_{cc}	3.773(38)	Ω^*_{cb}	7.040(48)	Ω^*_{bb}	10.283(51)
Ω_{ccc}	4.794(9)	Ω_{ccb}	7.989(11)	Ω^*_{ccb}	8.012(12)
Ω_{cbb}	11.177(9)	Ω^*_{cbb}	11.206(11)	Ω_{bbb}	14.370(10)

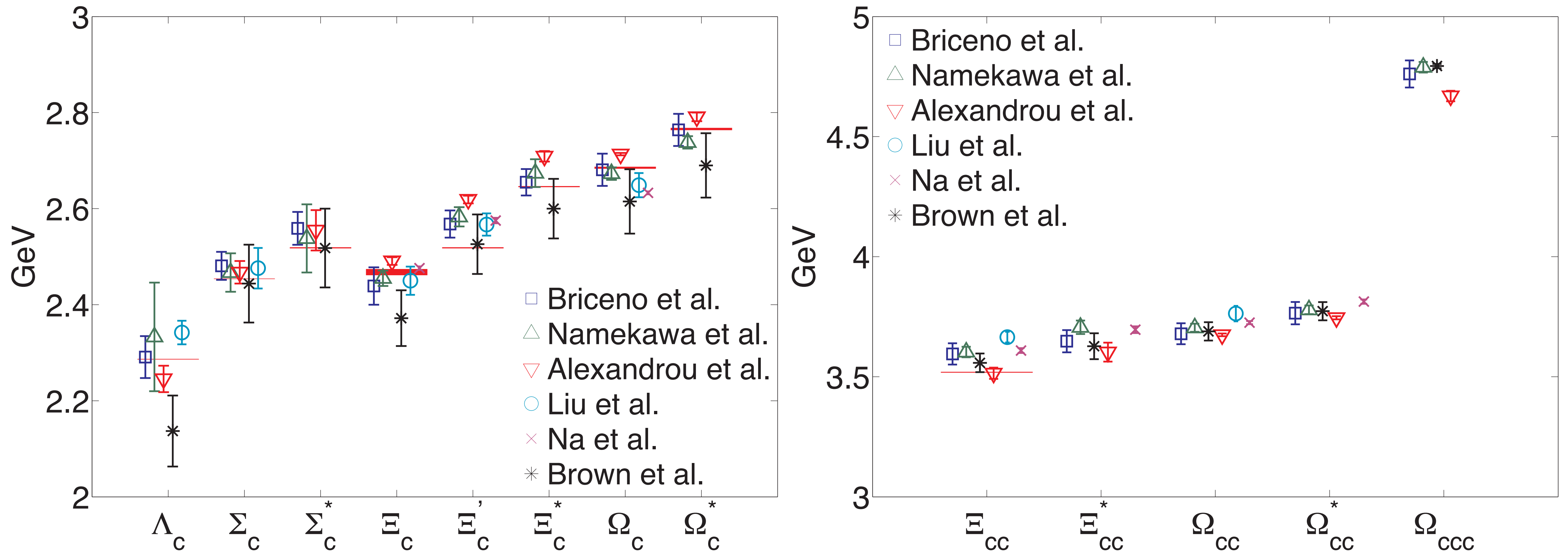
CONSIDERATION OF UNCERTAINTIES

- All statistical uncertainties
- Systematics may enter through several sources:
  - Optimization routine for extracting masses
  - Absence of NNLO correction terms to chiral extrapolations

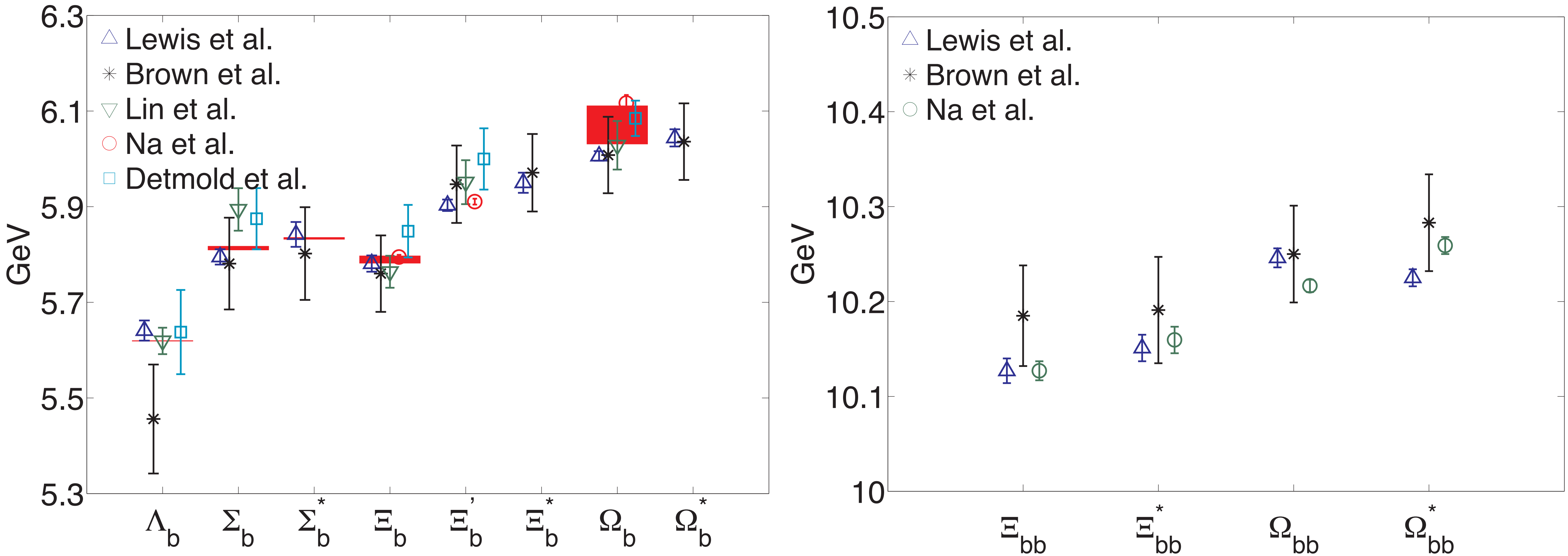
$$M = M_0 + \mathcal{O}\left(m^4_{\pi_{vv}}\right) + \mathcal{O}\left(m^4_{\pi_{vs}}\right) + \mathcal{O}\left(m^2_{\pi_{vv}} m^2_{\pi_{vs}}\right)$$

- Currently being explored... but how do our results compare?

RESULTS: CHARM COMPARISONS



RESULTS: BOTTOM COMPARISONS



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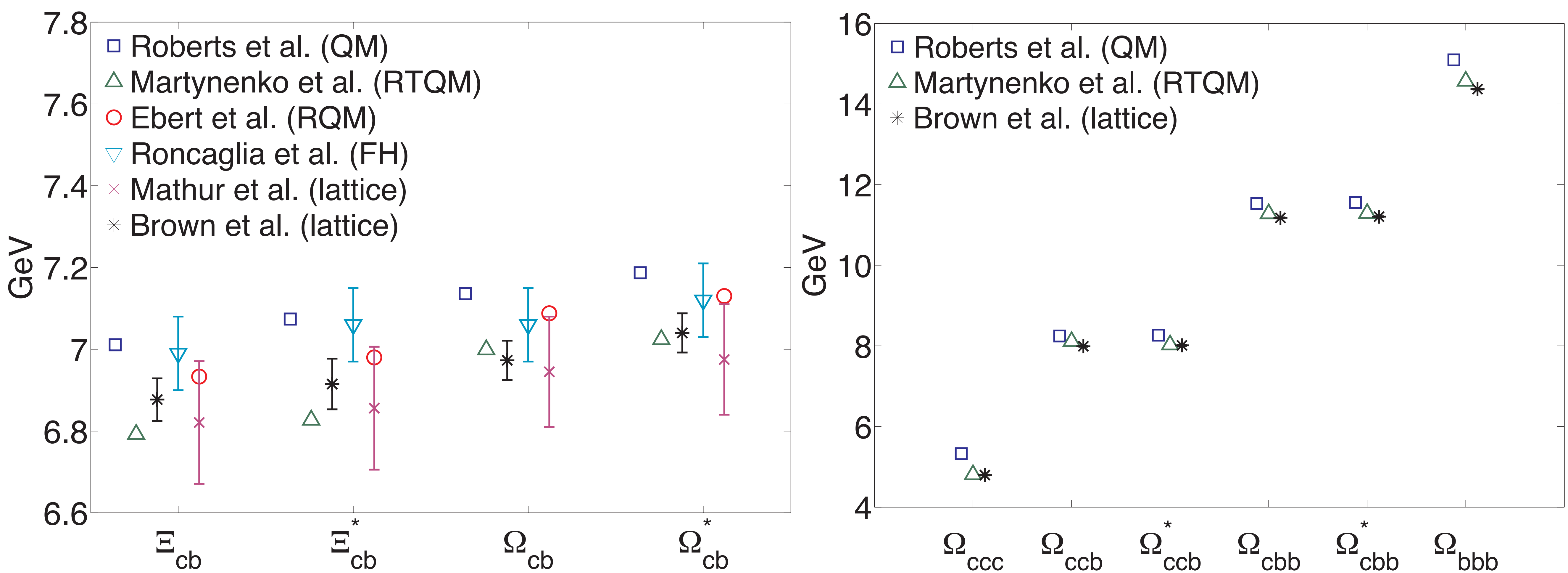
RESULTS: MIXED COMPARISONS



FUTURE OUTLOOK

- Still need to nail down systematic uncertainties

- Possible repetition of calculation with larger operator basis and relativistic bottom quarks?

THANK YOU

- References:

[1] J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012)

[2] H. W. Lin, Chin. J. Phys. 49 (2011) 827 [arXiv:1106.1608 [hep-lat]]

[3] Y. Aoki et al., "Continuum Limit Physics from 2+1 Flavor Domain Wall QCD," Phys.Rev., vol. D83, p. 074508, 2011.

[4] A. X. El-Khadra, A. S. Kronfeld, and P. B. Mackenzie, Phys. Rev. D55, 3933 (1997), hep-lat/9604004

[5] T. C. Hammant, A. G. Hart, G. M. von Hippel, R. R. Horgan and C. J. Monahan, Phys. Rev. Lett. 107, 112002 (2011) [arXiv:1105.5309 [hep-lat]]

[6]B. C. Tiburzi, "Baryon masses in partially quenched heavy hadron chiral perturbation theory," Phys.Rev., vol. D71, p. 034501, 2005.

[7]T. Mehen and B. C. Tiburzi, "Doubly heavy baryons and quark-diquark symmetry in quenched and partially quenched chiral perturbation theory," Phys.Rev., vol. D74, p. 054505, 2006.

[8] W. Detmold, C.-J. D. Lin, and S. Meinel, "Axial couplings in heavy hadron chiral perturbation theory at the next-to-leading order," Phys.Rev., vol. D84, p. 094502, 2011.

[9] W. Detmold, C.-J. D. Lin, and S. Meinel, "Axial couplings and strong decay widths of heavy hadrons," Phys.Rev.Lett., vol. 108, p. 172003, 2012.