April 8, 2015 GHP15 - APS meeting

Charm & Bottom Baryon spectrum

Kostas Orginos
JLab/W&M

with

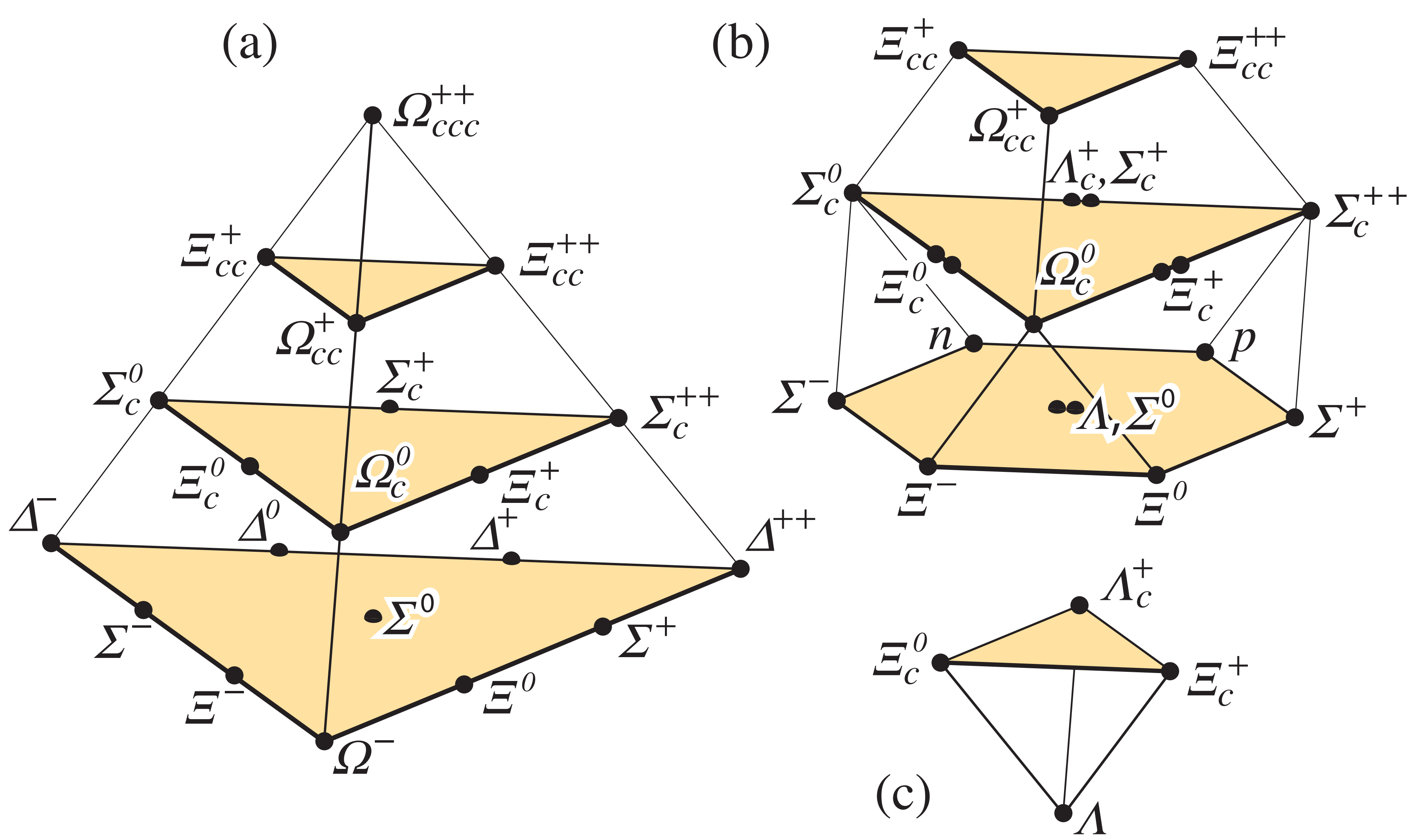
Zachary Brown **Stefan Meinel** **William Detmold**

PhysRevD.90.094507 [arXiv:1409.0497]

Summary

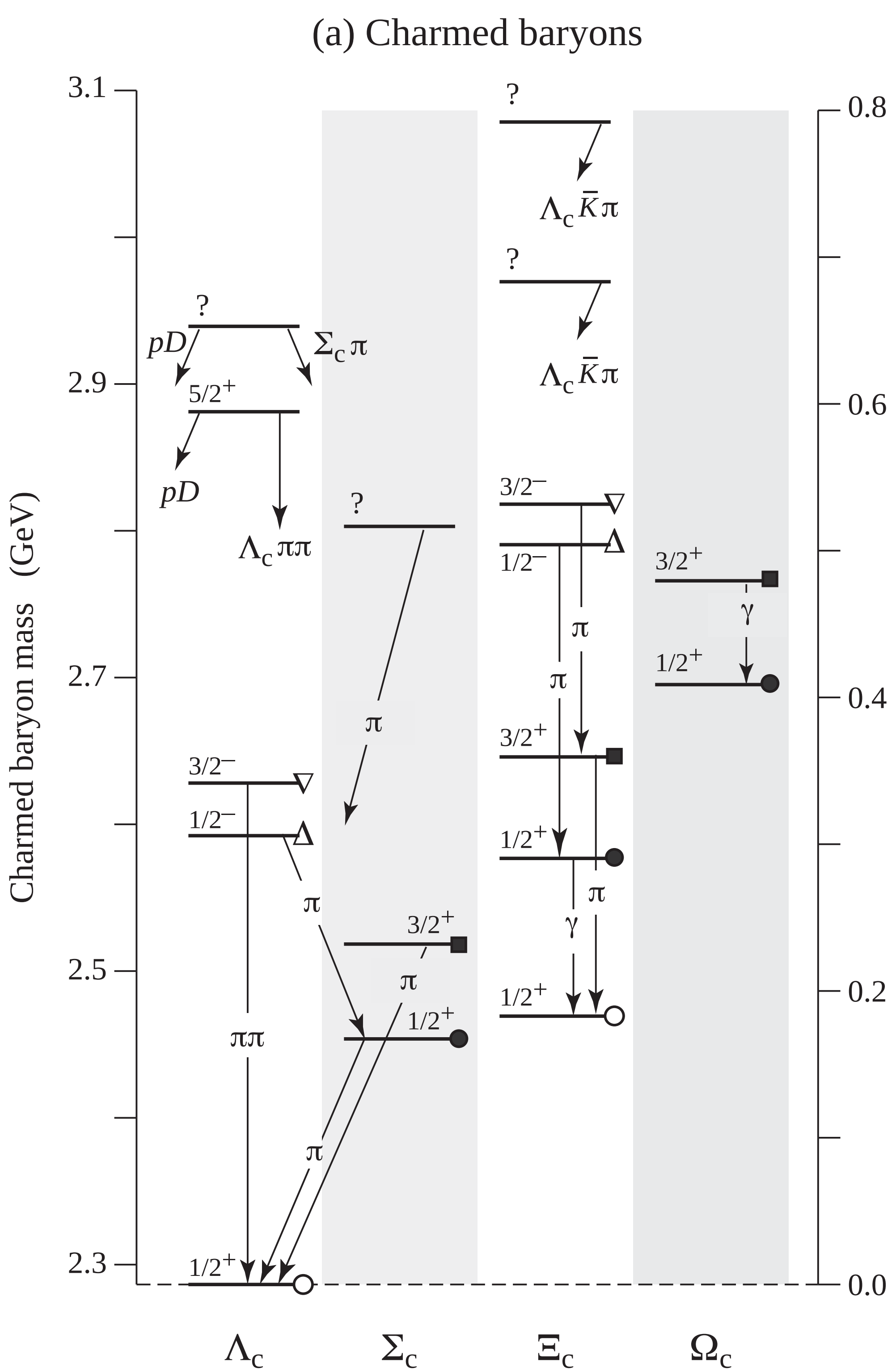
- Charmed and Baryon spectrum
    - observations
- Lattice QCD calculation
    - Methodology
    - Heavy quarks on the lattice
    - Results and comparisons with models and observations

Charmed baryons

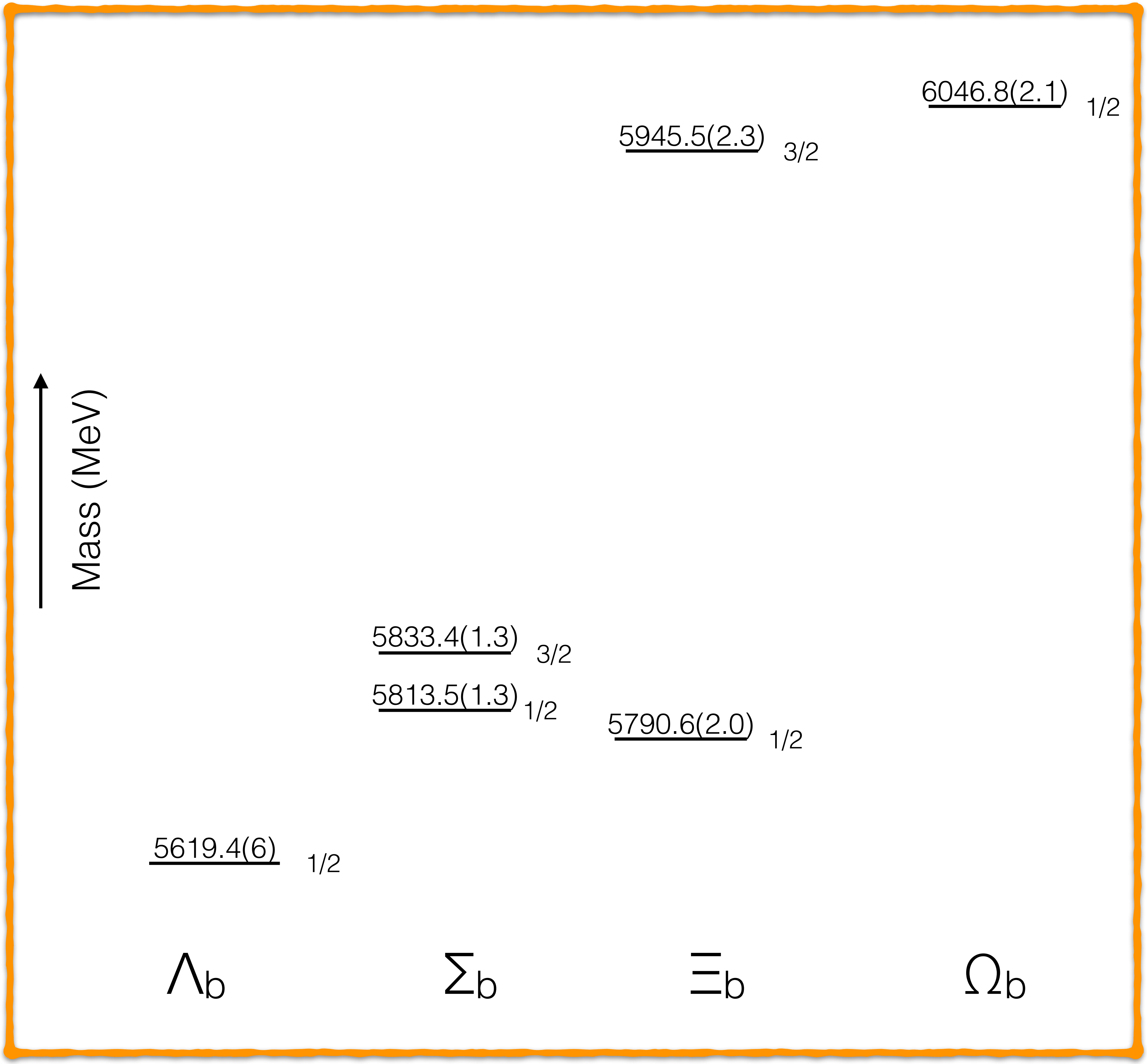


Charmed Baryon spectrum

PDG 2012



Bottom Baryon spectrum



PDG 2014

Unobserved states

Multi-charm	Multi-bottom	Mixed flavor	
Ξ_{cc}	Ξ_{bb}	Ξ_{bc}	
Ω_{cc}	Ω_{bb}	Ω_{bc}	
Ω_{ccc}	Ω_{bbb}	Ω_{bbc}	Ω_{bcc}

Controversies

Ξ_{cc}^{+} Reported by SELEX

. Phys. Rev. Lett. 89 (2002) 112001, arXiv:hep-ex/0208014

Not found by FOCUS, BaBar, Belle LHCb

Nucl. Phys. Proc. Suppl. 115 (2003) 33–36 .

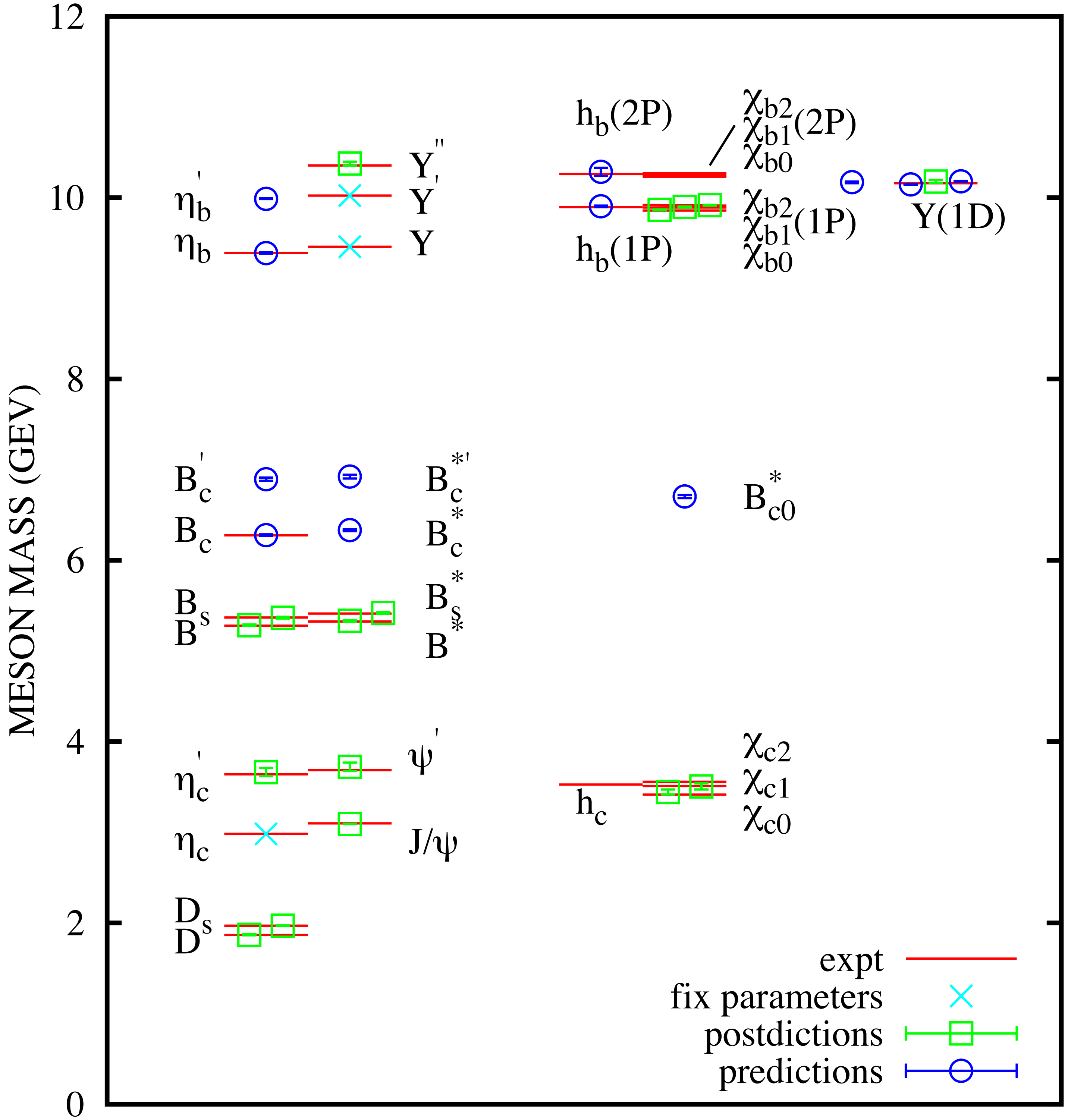
Phys. Rev. D 74 (2006) 011103, arXiv:hep-ex/0605075

Phys. Rev. Lett. 97 (2006) 162001, arXiv:hep-ex/0606051

JHEP 1312 (2013) 090, arXiv:1310.2538 [hep-ex]

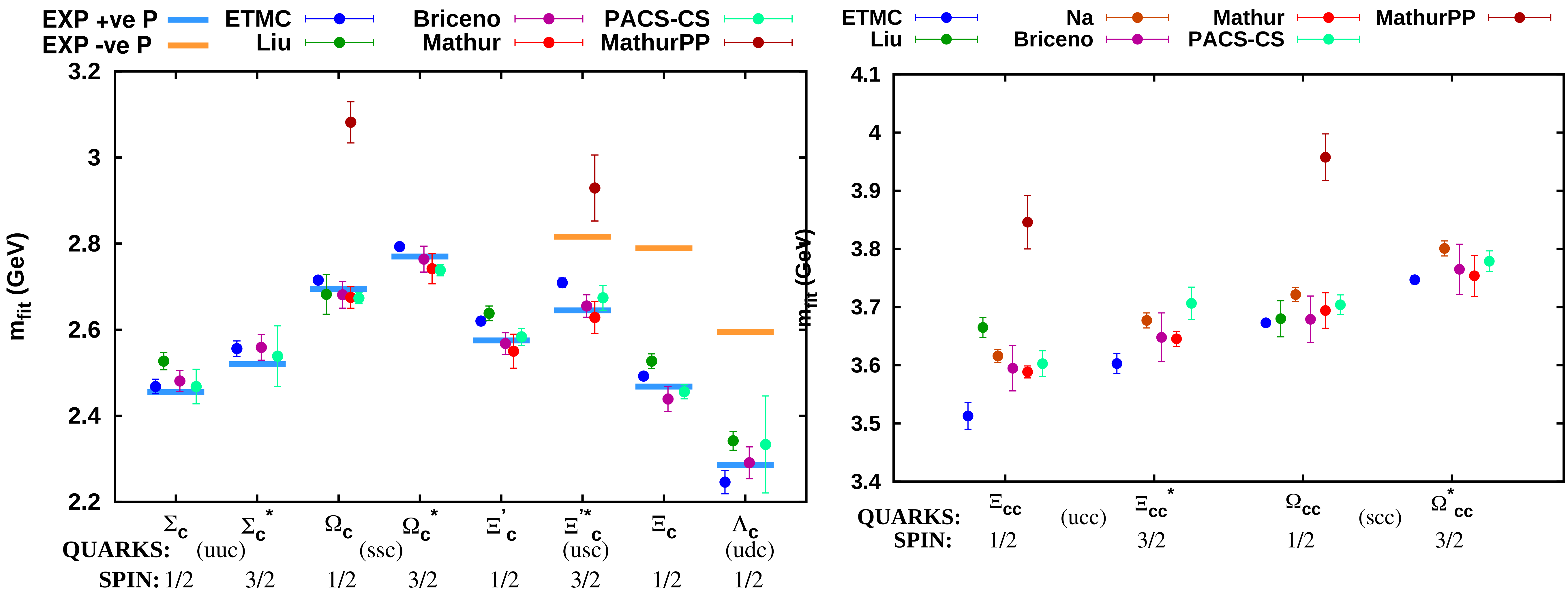
- First principles calculations can predict masses of unobserved states
- Can help resolve controversies
- Complete Lattice QCD calculations of the ground state masses are now possible

Botomonium Spectrum (LQCD vs Exp)



HPQCD: R. J. Dowdall et al., Phys. Rev. D86, 094510 (2012)

Flavored baryons (LQCD vs Exp)



C. Alexandrou et al., Phys. Rev. D86, 114501 (2012).

L. Liu et al., Phys. Rev. D81, 094505 (2010).

R. A. Briceno, H. -W. Lin, and D. R. Bolton, Phys. Rev. D86, 094504 (2012).

Y. Namekawa [PACS-CS Collab.], PoS LATTICE 2012, 139 (2012).

S. Basak et al., PoS LATTICE 2012, 141 (2012).

H. Na and S.A. Gottlieb, PoS LAT2007, 124 (2007); PoS LATTICE2008, 119 (2008).

PDG 2014

Outline of LQCD calculations

- Include the vacuum polarization effects
  - 2 light (up down) 1 heavy (strange)
  - ... and ... 1 very heavy (charm)

- Finite Volume
  - Compute in multiple and large volumes
- Continuum Limit
  - Compute with several lattice spacings
- Quark masses
  - Compute with several values for the quark masses
  - Study quark mass dependence of QCD
  - Physical light (up down) quark masses

Light quark actions

- Light quarks (up, down, strange) $m_q \ll \Lambda_{QCD} \sim 250 MeV$

- Straight forward to put on the lattice
- Fermion doubling problem
  - Wilson action, Kogut-Susskind action
    - Chiral symmetry breaking
    - Flavor symmetry breaking (KS)
- Domain Wall fermions or Overlap fermions
  - Chiral symmetry
  - $O(a^2)$ lattice spacing errors

The heavy quark action

- Light quarks (up, down, strange) $m_q \ll \Lambda_{QCD} \sim 250 MeV$
- Heavy quarks (charm, bottom, top) $m_q \gg \Lambda_{QCD}$

$$\begin{aligned} m_{charm} &\sim 1300\ MeV \\ m_{bottom} &\sim 4200\ MeV \\ m_{top} &\sim 174200\ MeV \end{aligned}$$

- Lattice fermion Lagrangians assume for light quirks $a\, m_q << 1$

$$\mathcal{L} = \mathcal{L}_{wilson} + \mathcal{O}(a)$$

- For typical lattice QCD calculations (a=0.125fm, 0.09fm, 0.06fm)

$$\begin{aligned} 0.4 < \quad am_{charm} &< 0.8 \\ 1.3 < \quad am_{bottom} &< 2.7 \end{aligned}$$

- Special care is needed in treating heavy quarks on the lattice
  - Or use very small lattice spacing ($a < 0.01$fm).....

The heavy quark action (charm)

- Fermilab action: Symanzik improvement taking into account $a\, m_q \sim 1$

A. X. El-Khadra, A. S. Kronfeld, and P. B. Mackenzie, Phys. Rev. D55, 3933 (1997)

$$S = S_0 + S_B + S_E$$

$$S_0 = \sum_x \bar{q}(x)[m_0 + (\gamma_0 \nabla_0 - \frac{1}{2}\triangle_0) + \nu \sum_i (\gamma_i \nabla_i - \frac{1}{2}\triangle_i)]q(x)$$

- For Wilson action $\nu = 1$ for light quarks. For heavy quarks ν needs to be adjusted to remove lattice artifacts $O(m\, a)$.

- The $O(a)$ lattice artifacts are removed by the terms

$$S_B = -\frac{1}{2}c_B \sum_x \bar{q}(x)(\sum_{i<j} \sigma_{ij} F_{ij})q(x) \qquad S_E = -\frac{1}{2}c_E \sum_x \bar{q}(x)(\sum_i \sigma_{0i} F_{0i})q(x)$$

- These coefficients can be computed perturbatively. At tree-level (with tatdpole improvement)

P. Chen, Phys. Rev. D64, 034509 (2001)

$$c_B = \frac{\nu}{u_0^3}, \quad c_E = \frac{1}{2}(1+\nu)\frac{1}{u_0^3}$$

Heavy quark action (cont.)

Tune v and m_0 so that the speed of light is 1 and the spin averaged meson mass matches experiment

$$\overline{M} = \frac{3}{4}E_{J/\psi}(0) + \frac{1}{4}E_{\eta_c}(0).$$

$$c^2(\mathbf{p}) = \frac{E^2_{J/\psi}(\mathbf{p}) - E^2_{J/\psi}(0)}{\mathbf{p}^2}$$

Heavy quark action (Bottom quark)

Typical momenta of the bottom quark in a baryon is betwee
0.5 and 1.5 GeV resulting velocities of v=0.1c

Non-relativistic approximation is applicable NRQCD

$$S_\psi = a^3 \sum \psi^\dagger(\mathbf{x},t)\big[\psi(\mathbf{x},t) - K(t)\,\psi(\mathbf{x},t-a)\big]$$

$$H_0 = -\frac{\Delta^{(2)}}{2m_b},$$

O(v²)

$$\delta H = -c_1\,\frac{\left(\Delta^{(2)}\right)^2}{8m_b^3} + c_2\,\frac{ig}{8m_b^2}\left(\boldsymbol{\nabla}\cdot\widetilde{\mathbf{E}} - \widetilde{\mathbf{E}}\cdot\boldsymbol{\nabla}\right)$$
$$-c_3\,\frac{g}{8m_b^2}\,\boldsymbol{\sigma}\cdot\left(\widetilde{\boldsymbol{\nabla}}\times\widetilde{\mathbf{E}} - \widetilde{\mathbf{E}}\times\widetilde{\boldsymbol{\nabla}}\right) - c_4\,\frac{g}{2m_b}\,\boldsymbol{\sigma}\cdot\widetilde{\mathbf{B}}$$
$$+c_5\,\frac{a^2\Delta^{(4)}}{24m_b} - c_6\,\frac{a\left(\Delta^{(2)}\right)^2}{16n\,m_b^2}.$$

O(v⁴)

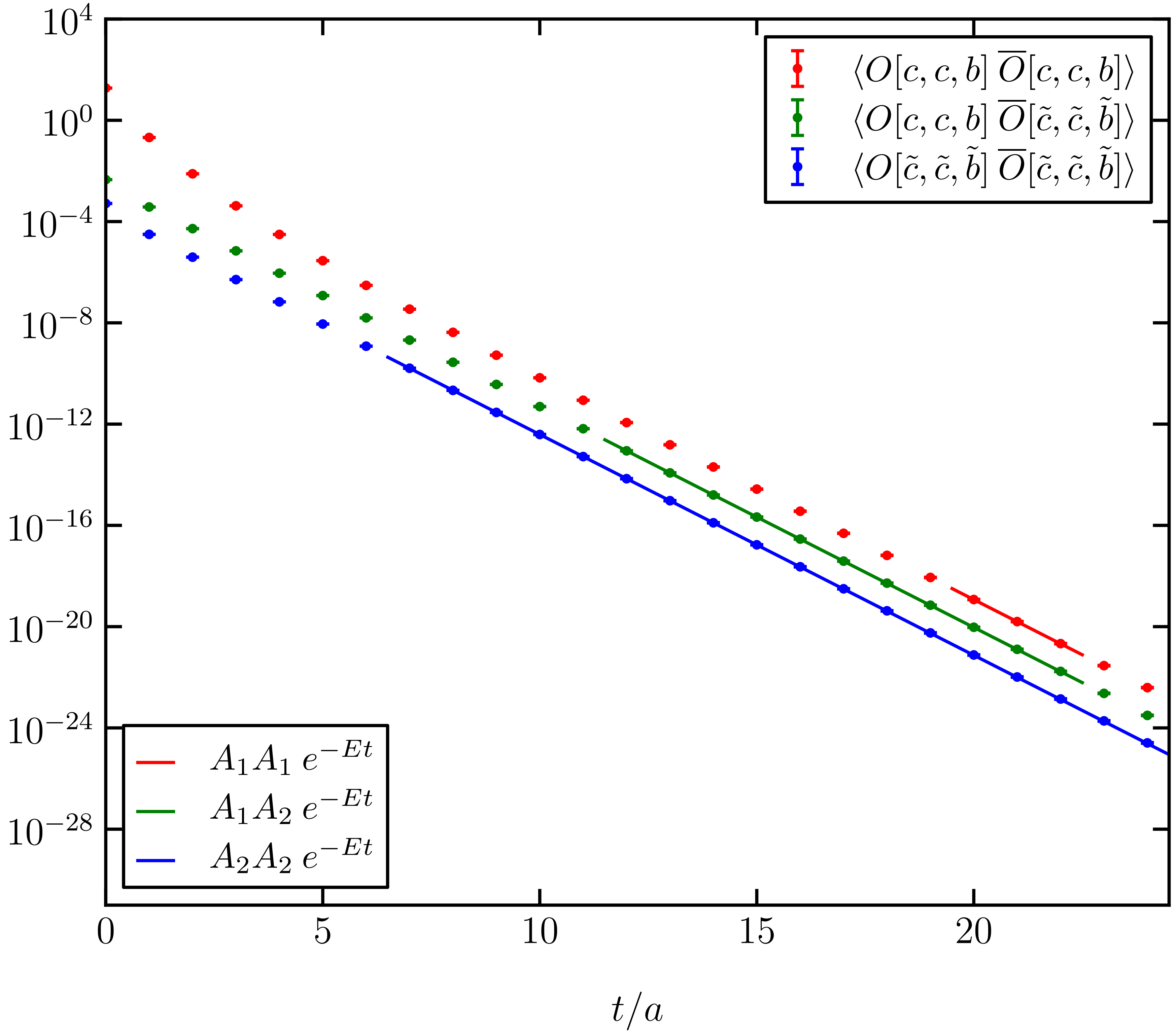
tadpole improved tree level matching

Lattice calculation set up

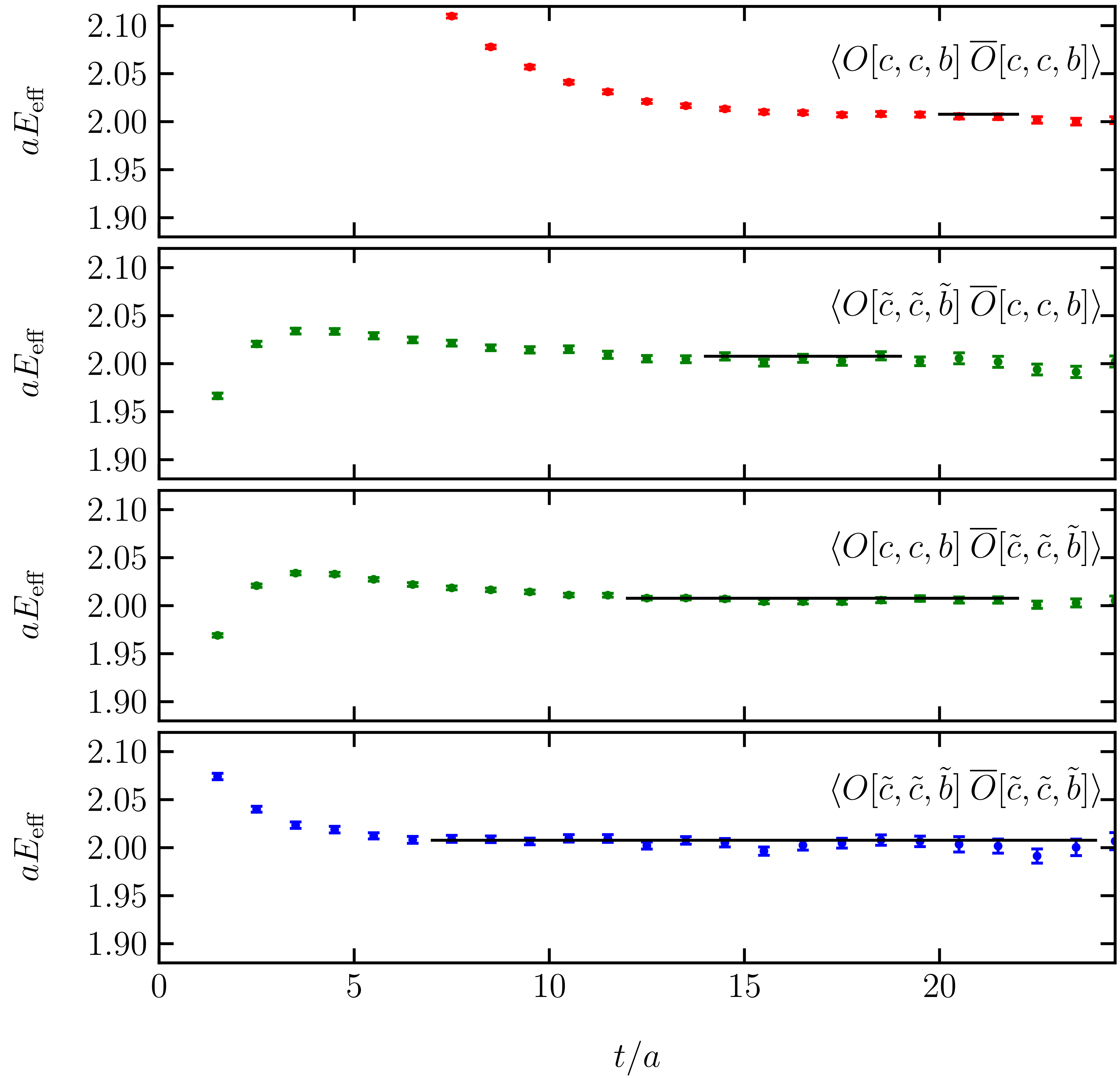
- Domain wall fermions for the light quarks (RBC/UKQCD)
- Relativistic heavy quark action for charm quark
- NRQCD for botom quark
- Two lattice spacings (0.11fm and 0.085fm determined from botomonium spectroscopy)
- Pion mass range 220MeV - 420MeV
  - Extrapolate to the physical pion mass point
- Single volume of about 2.7fm
- Combined chiral and continuum extrapolations based on HBchiPT

Mass computation

- Use simplest non-relativistic interpolating fields for spin 1/2 , 3/2 baryons
- Smeared quark sources (with several smearing widths)
- Masses where estimated from fits to exponentials of the euclidean time dependence of two point functions



10^{4}
10^{0}
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
0
5
10
15
20
t/a
$\langle O[c,c,b]\,\overline{O}[c,c,b]\rangle$
$\langle O[c,c,b]\,\overline{O}[\tilde{c},\tilde{c},\tilde{b}]\rangle$
$\langle O[\tilde{c},\tilde{c},\tilde{b}]\,\overline{O}[\tilde{c},\tilde{c},\tilde{b}]\rangle$
$A_1A_1\;e^{-Et}$
$A_1A_2\;e^{-Et}$
$A_2A_2\;e^{-Et}$



$\langle O[c,c,b]\,\overline{O}[c,c,b]\rangle$
$\langle O[\tilde{c},\tilde{c},\tilde{b}]\,\overline{O}[c,c,b]\rangle$
$\langle O[c,c,b]\,\overline{O}[\tilde{c},\tilde{c},\tilde{b}]\rangle$
$\langle O[\tilde{c},\tilde{c},\tilde{b}]\,\overline{O}[\tilde{c},\tilde{c},\tilde{b}]\rangle$
aE_{eff}
2.10
2.05
2.00
1.95
1.90
0
5
10
15
20
t/a

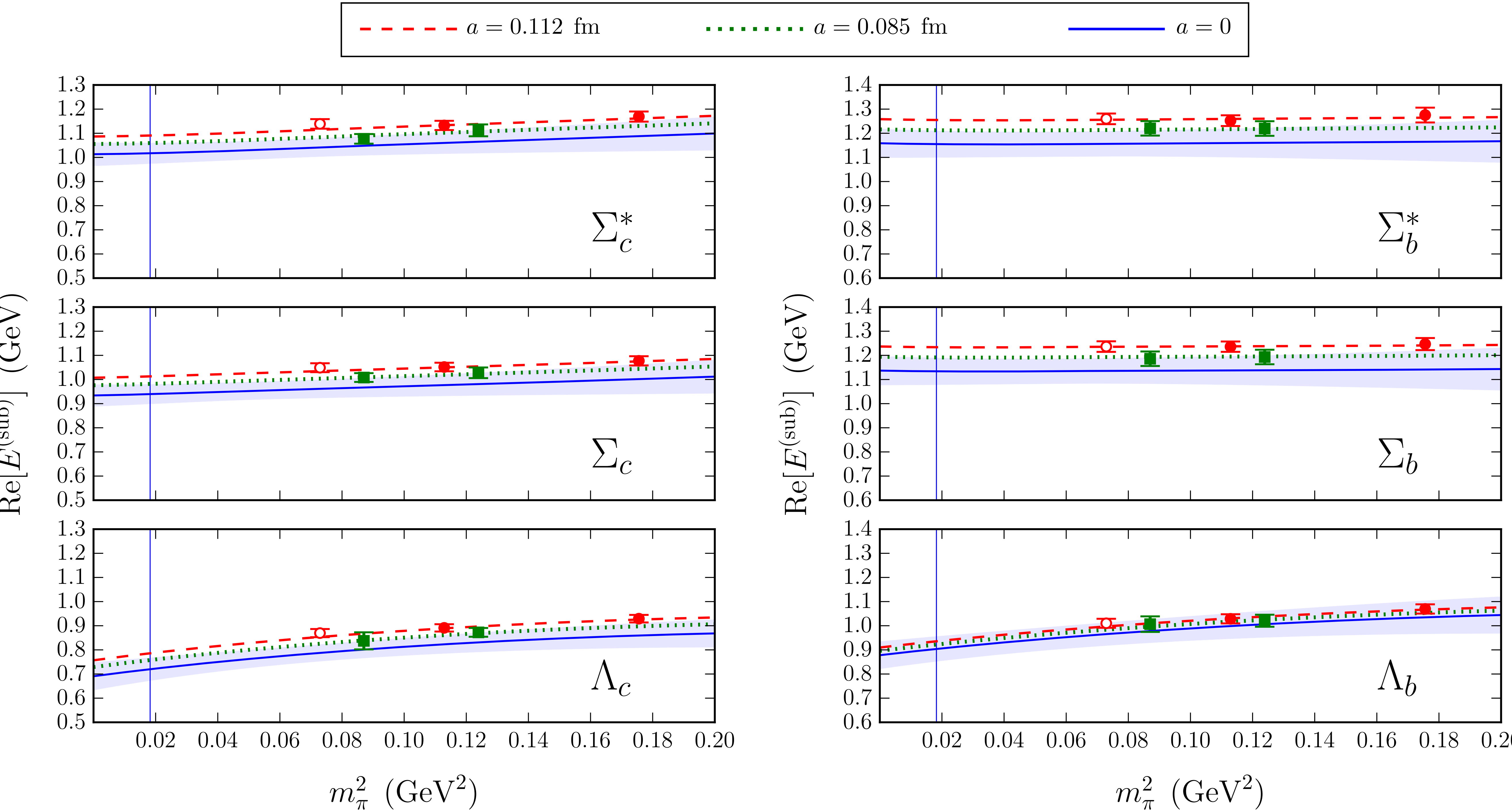
Chiral and continuum extrapolations

$$E_{\Lambda_Q}^{(\mathrm{sub})} = E^{(\mathrm{sub},0)} + d_\pi^{(\mathrm{vv})} \frac{[m_\pi^{(\mathrm{vv})}]^2}{4\pi f} + d_\pi^{(\mathrm{ss})} \frac{[m_\pi^{(\mathrm{ss})}]^2}{4\pi f} + \mathcal{M}_{\Lambda_Q} + d_a\, a^2 \Lambda^3\,,$$

$$E_{\Sigma_Q}^{(\mathrm{sub})} = E^{(\mathrm{sub},0)} + \Delta^{(0)} + c_\pi^{(\mathrm{vv})} \frac{[m_\pi^{(\mathrm{vv})}]^2}{4\pi f} + c_\pi^{(\mathrm{ss})} \frac{[m_\pi^{(\mathrm{ss})}]^2}{4\pi f} + \mathcal{M}_{\Sigma_Q} + c_a\, a^2 \Lambda^3\,,$$

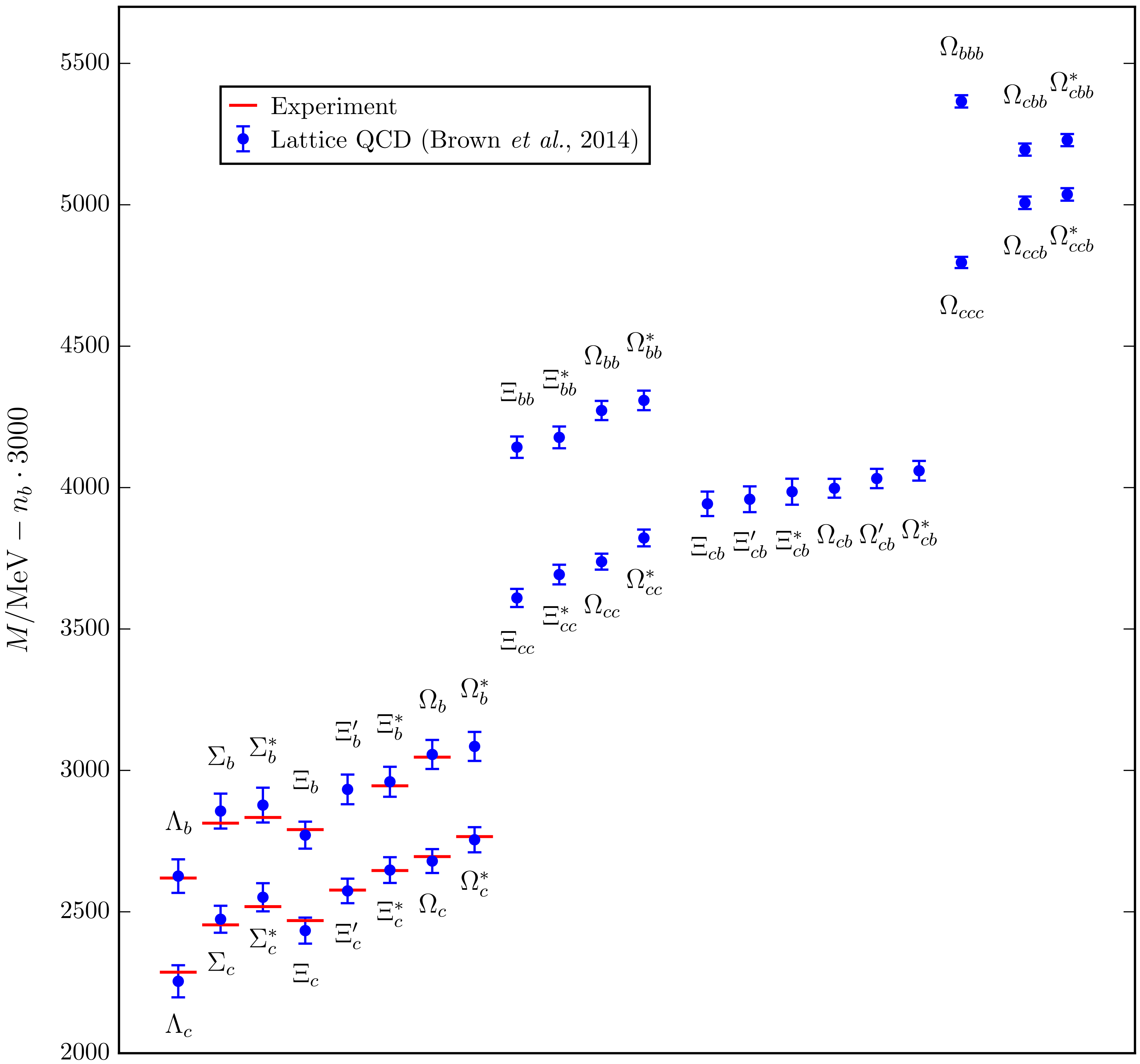
$$E_{\Sigma_Q^*}^{(\mathrm{sub})} = E^{(\mathrm{sub},0)} + \Delta^{(0)} + \Delta_*^{(0)} + c_\pi^{(\mathrm{vv})} \frac{[m_\pi^{(\mathrm{vv})}]^2}{4\pi f} + c_\pi^{(\mathrm{ss})} \frac{[m_\pi^{(\mathrm{ss})}]^2}{4\pi f} + \mathcal{M}_{\Sigma_Q^*} + c_a\, a^2 \Lambda^3\,,$$

B. C. Tiburzi, “Baryon masses in partially quenched heavy hadron chiral perturbation theory,” Phys. Rev. D 71 (2005) 034501, arXiv:hep-lat/0410033.

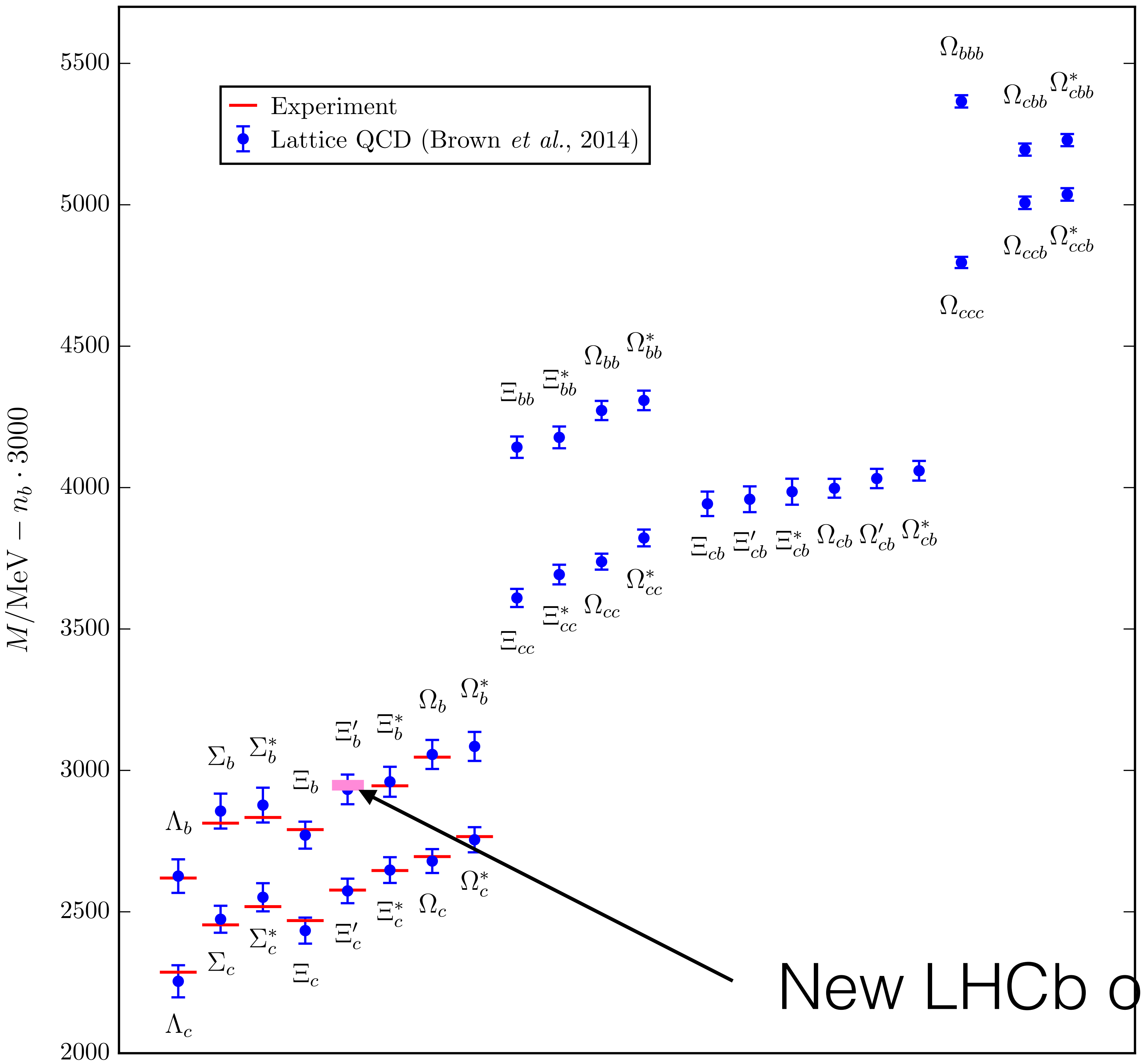


$a = 0.112$ fm
$a = 0.085$ fm
$a = 0$
Σ_c^*
Σ_c
Λ_c
Σ_b^*
Σ_b
Λ_b
$\mathrm{Re}[E^{(\mathrm{sub})}]$ (GeV)
m_π^2 (GeV^2)

Results

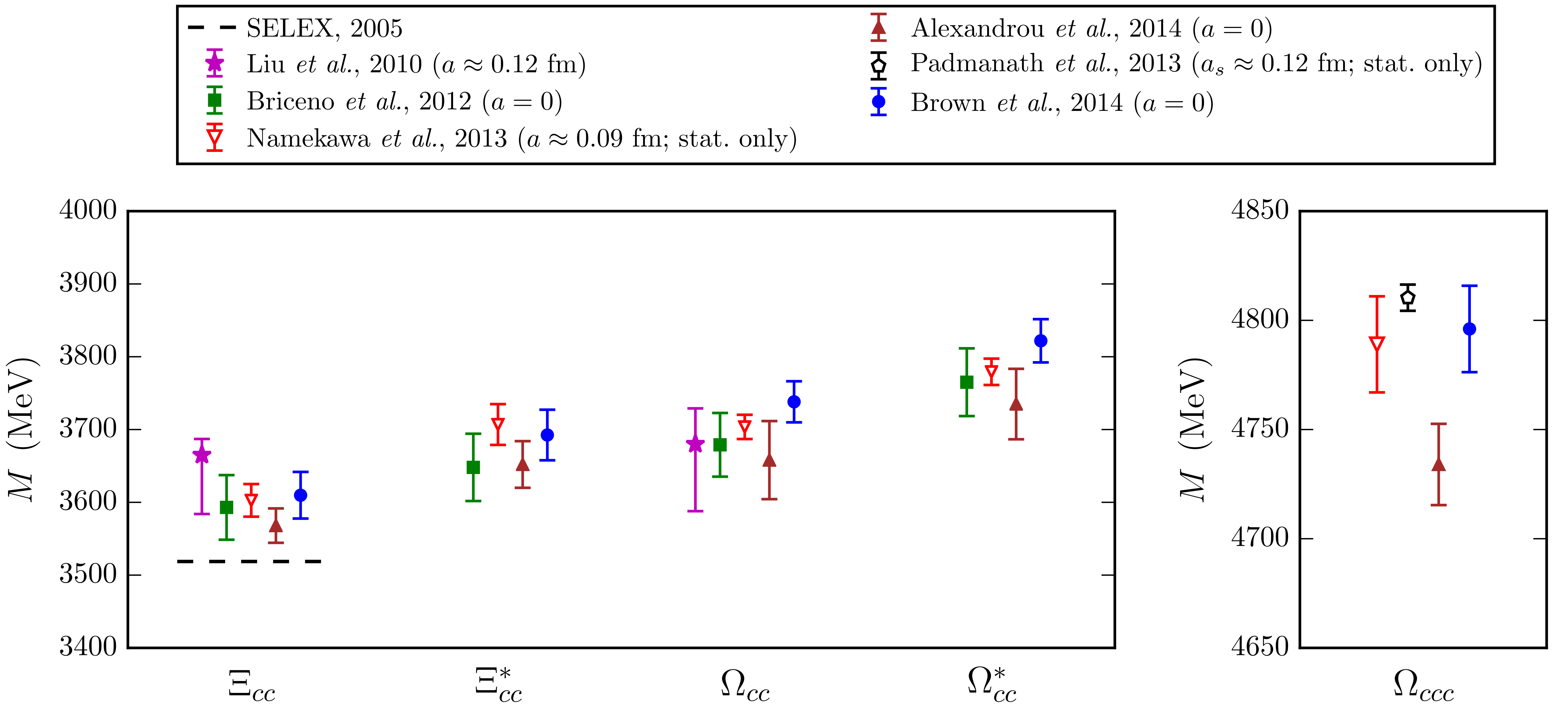


Experiment
Lattice QCD (Brown et al., 2014)
$M/\mathrm{MeV} - n_b \cdot 3000$
5500
5000
4500
4000
3500
3000
2500
2000
Λ_b Σ_b Σ_b^* Ξ_b Ξ_b' Ξ_b^* Ω_b Ω_b^*
Λ_c Σ_c Σ_c^* Ξ_c Ξ_c' Ξ_c^* Ω_c Ω_c^*
Ξ_{bb} Ξ_{bb}^* Ω_{bb} Ω_{bb}^*
Ξ_{cc} Ξ_{cc}^* Ω_{cc} Ω_{cc}^*
Ξ_{cb} Ξ_{cb}' Ξ_{cb}^* Ω_{cb} Ω_{cb}' Ω_{cb}^*
Ω_{bbb} Ω_{cbb} Ω_{cbb}^* Ω_{ccb} Ω_{ccb}^* Ω_{ccc}

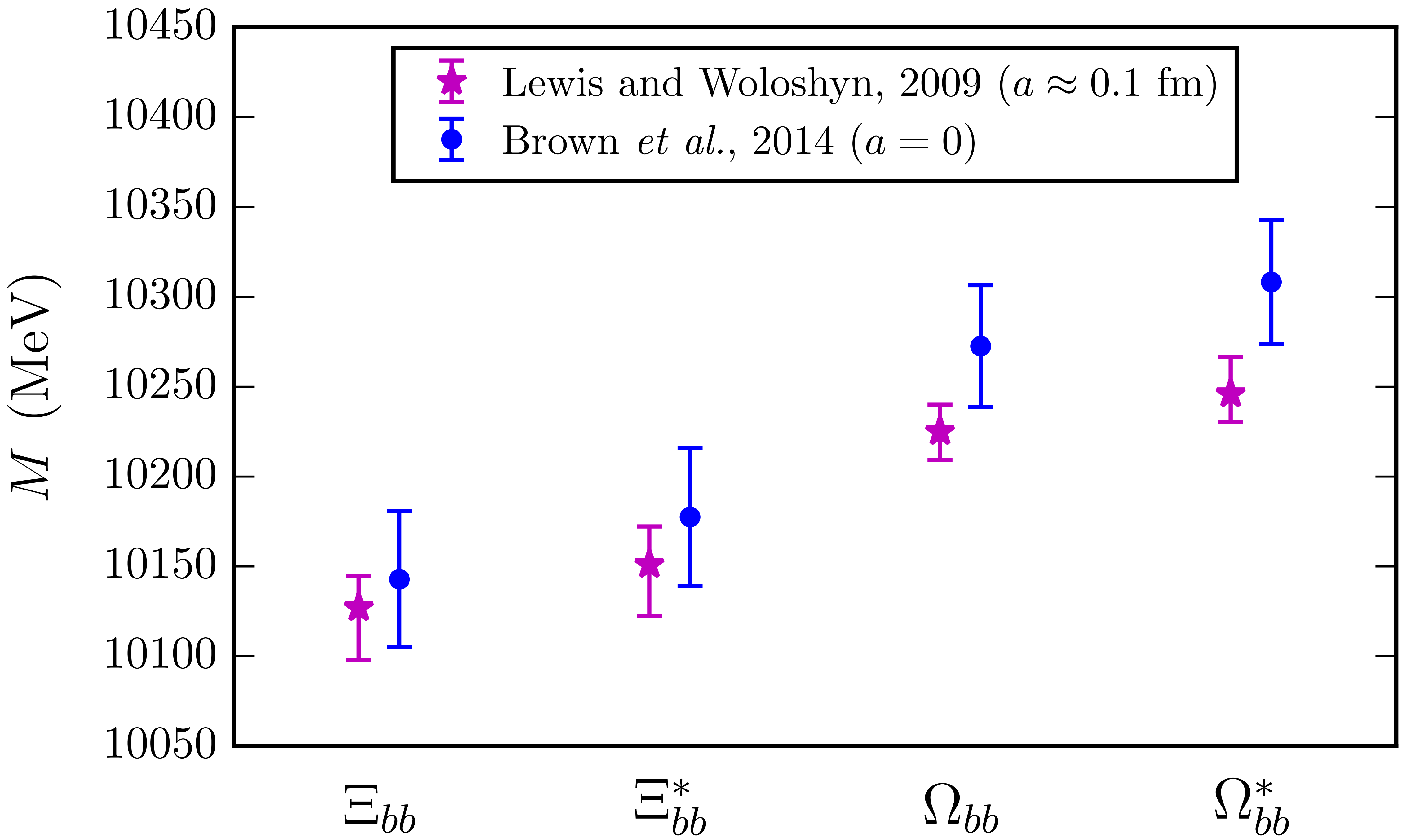


New LHCb observation

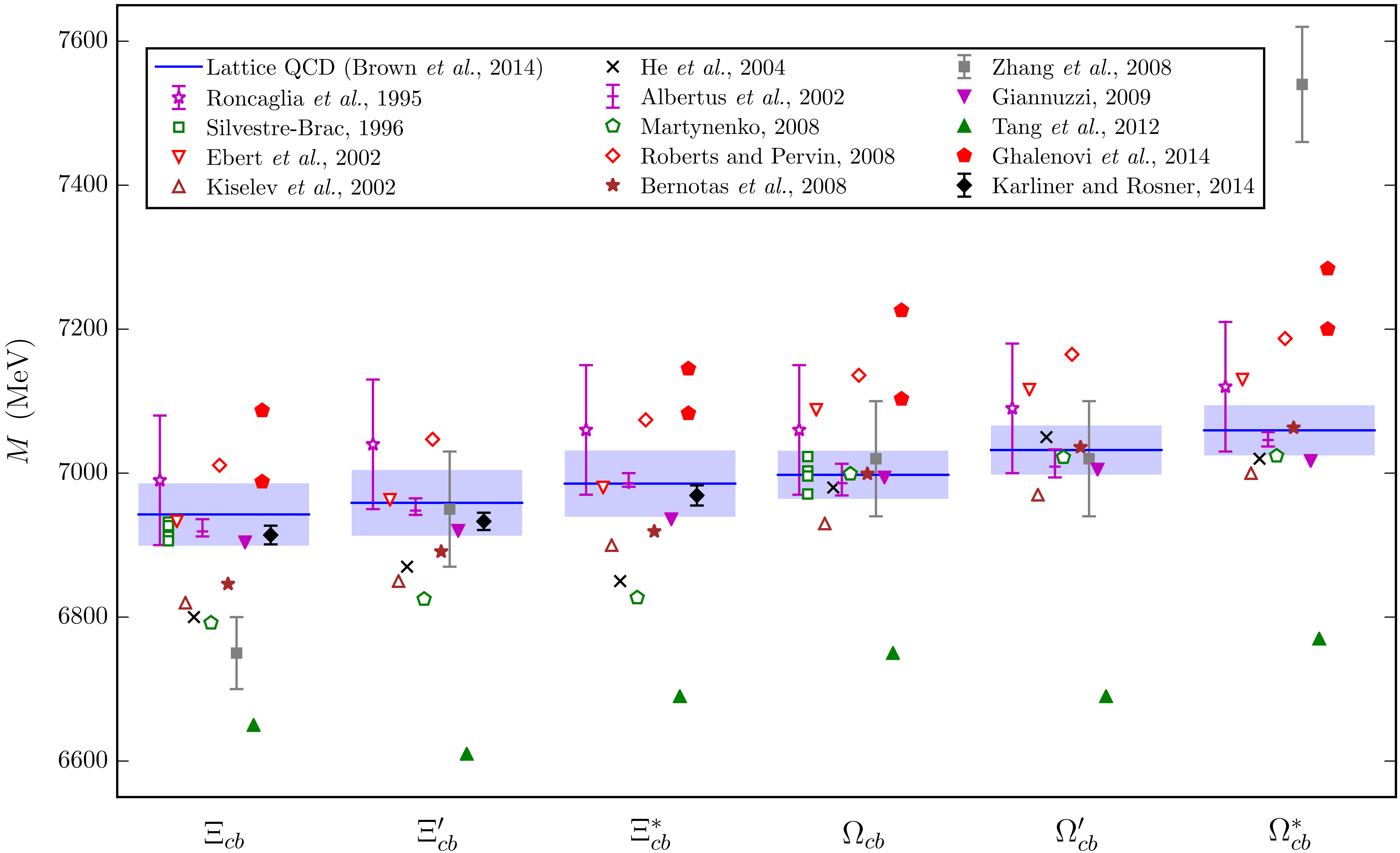
LHCb PhysRevLett.114.062004



SELEX, 2005
Liu et al., 2010 (a ≈ 0.12 fm)
Briceno et al., 2012 (a = 0)
Namekawa et al., 2013 (a ≈ 0.09 fm; stat. only)
Alexandrou et al., 2014 (a = 0)
Padmanath et al., 2013 (a_s ≈ 0.12 fm; stat. only)
Brown et al., 2014 (a = 0)
M (MeV)
4000
3900
3800
3700
3600
3500
3400
Ξ_{cc}
Ξ^*_{cc}
Ω_{cc}
Ω^*_{cc}
4850
4800
4750
4700
4650
Ω_{ccc}



10450
10400
10350
10300
10250
10200
10150
10100
10050
M (MeV)
Lewis and Woloshyn, 2009 ($a \approx 0.1$ fm)
Brown *et al.*, 2014 ($a = 0$)
Ξ_{bb}
Ξ_{bb}^{*}
Ω_{bb}
Ω_{bb}^{*}



Lattice QCD (Brown et al., 2014)
Roncaglia et al., 1995
Silvestre-Brac, 1996
Ebert et al., 2002
Kiselev et al., 2002
He et al., 2004
Albertus et al., 2002
Martynenko, 2008
Roberts and Pervin, 2008
Bernotas et al., 2008
Zhang et al., 2008
Giannuzzi, 2009
Tang et al., 2012
Ghalenovi et al., 2014
Karliner and Rosner, 2014
M (MeV)
7600
7400
7200
7000
6800
6600
Ξ_{cb}
Ξ'_{cb}
Ξ^*_{cb}
Ω_{cb}
Ω'_{cb}
Ω^*_{cb}

Conclusions

- We have presented a comprehensive study of the baryon spectrum with charm and botom quarks for both spin 1/2 and spin 3/2 baryons
- Our results are in good agreement with experiment
- We make a large number of predictions states yet to be observed
- LHCb has already confirmed one of our predictions
- Hopefully more to come…