Bottom baryon mass and sigma term on lattice QCD

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2026.8.20

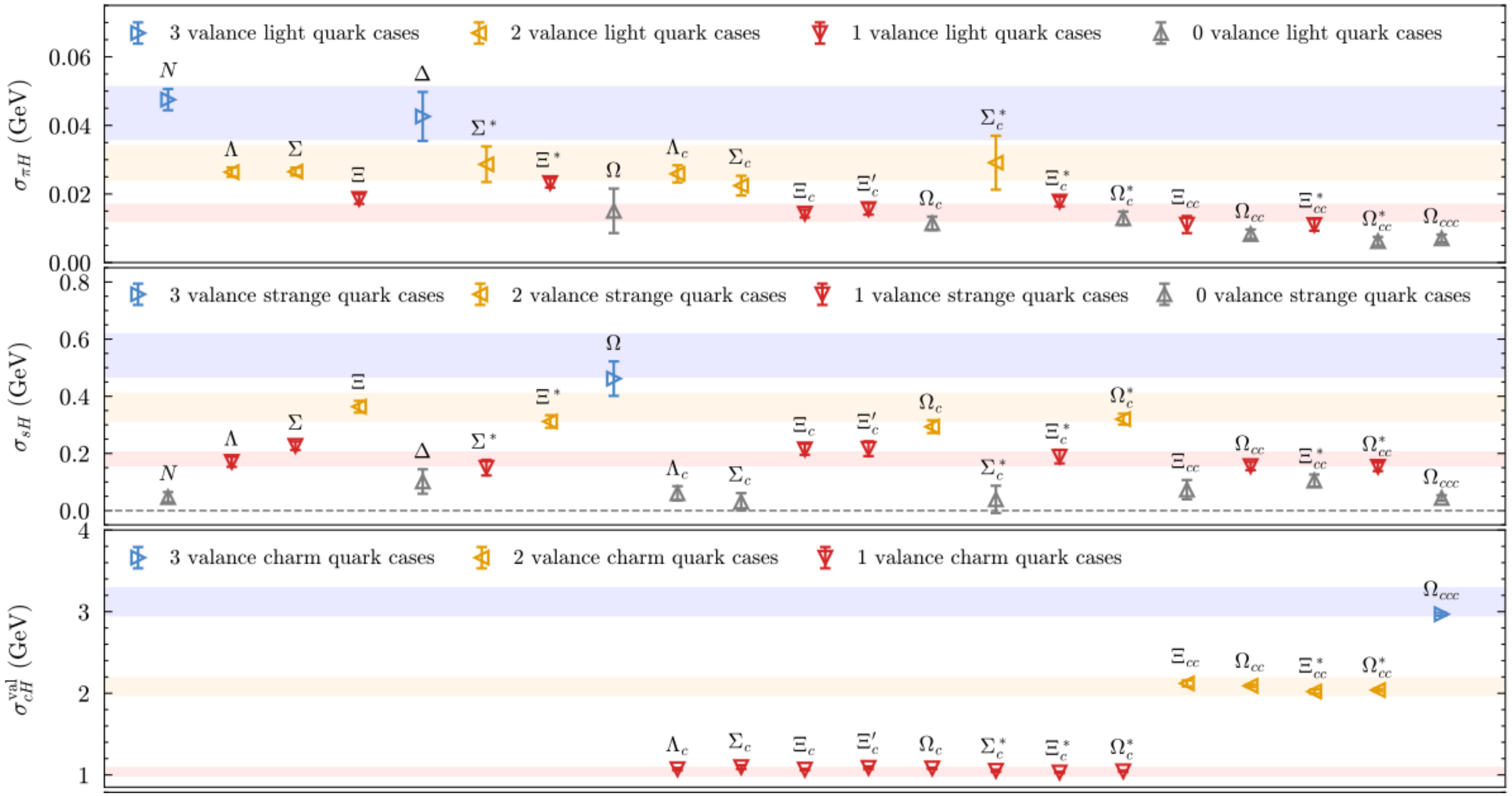
Hadron Mass Decomposition

- Hadron mass decomposition: $m_H = \sum_q \sigma_{q,H} + \gamma_m \sum_q \sigma_{q,H} + \frac{\beta(\alpha_s)}{2\alpha_s} \langle G^{\mu\nu} G_{\mu\nu} \rangle_H$
- Sigma term: quark flavor contribution $\sigma_{q,H} \equiv m_q \langle \bar{q}q \rangle_H$, where $\langle \bar{q}q \rangle_H$ with $\langle O \rangle_H \equiv \langle H | O | H \rangle / \langle H | H \rangle$ can be understood as the condensate of quark and antiquark within the hadron H.
- Scale violation of quark mass dimension $\gamma_m = \frac{2}{\pi} \alpha_s + O(\alpha_s^2)$
- Gluon trace anomaly part: $\frac{\beta(\alpha_s)}{2\alpha_s} = (-\frac{11}{8\pi} + \frac{N_f}{12\pi})\alpha_s + O(\alpha_s^2)$
- Extract sigma term: Feynman-Hellman theorem $\sigma_{q,H}^{\mathrm{FH}} = m_q^{\mathrm{PC}} \frac{\partial m_H}{\partial m_q^{\mathrm{PC}}}$ or directly 3-pt calculation.

Hadron Mass Decomposition

Light and charmed baryon case

- Hadron mass decomposition:
  $$m_H = \sum_q \sigma_{q,H} + \gamma_m \sum_q \sigma_{q,H} + \frac{\beta(\alpha_s)}{2\alpha_s}\langle G^{\mu\nu}G_{\mu\nu}\rangle_H$$
- Flavor-dependent enhancement for quark contribution: 4-8 for light quark, 2-3 for strange quark and 1.2-1.3 for charm quark.
- What about bottom case?



Bolun Hu, Hai-Yang Du, et.al, 2411.18402

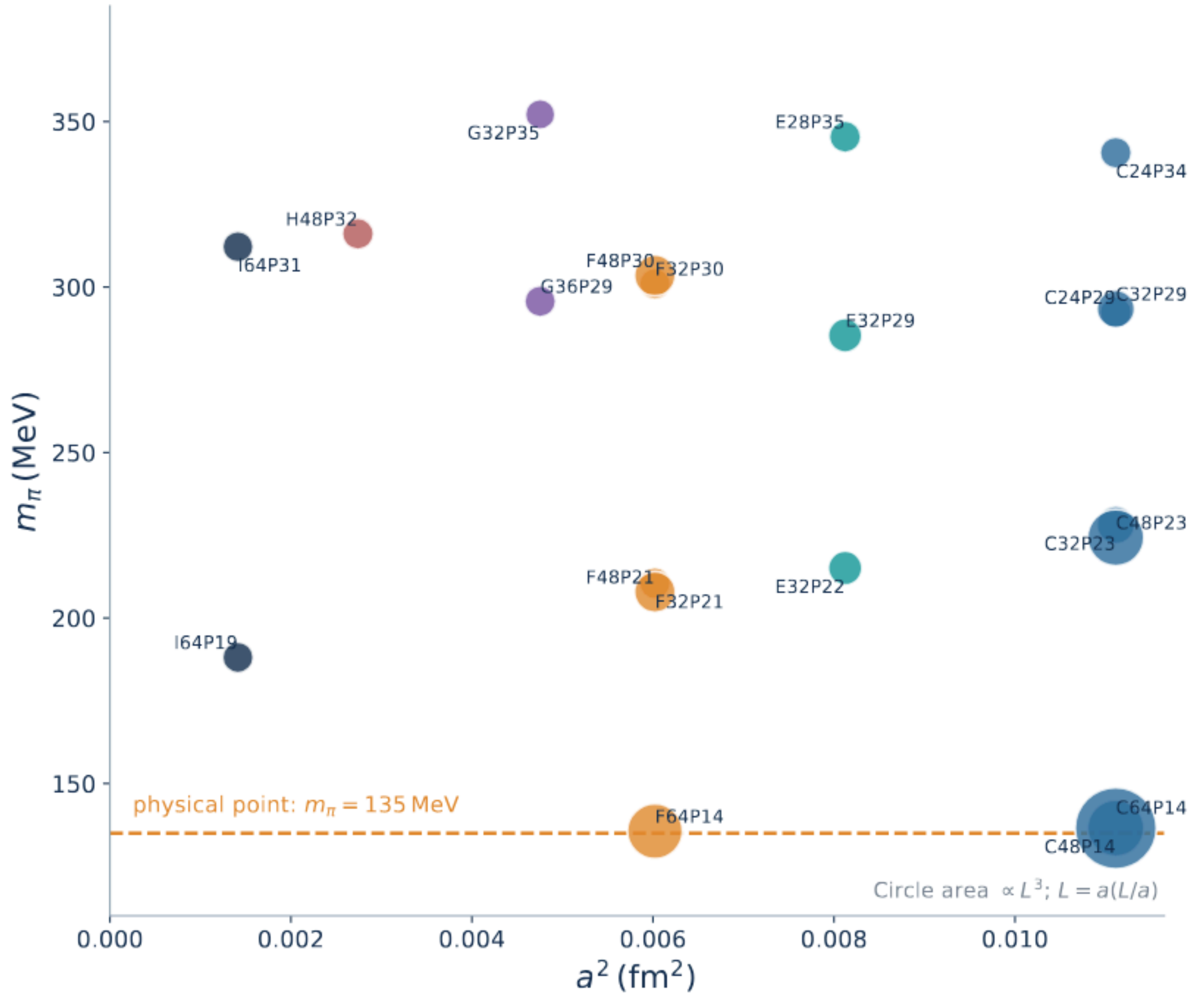
Ensemble Information

CLQCD clover ensembles

- CLQCD Collaboration ensembles: 2+1 clover action, 6 lattice spacing, several sea π and η_s mass and different volume.
- More than 4000 configurations.
- Chiral and continuum extrapolation.
- Simulate light, strange and charm quark very well.

Z.-C. Hu et al. (CLQCD), *Phys.Rev.D*, 109, 054507 (2024).

H-Y. Du et al. (CLQCD), *Phys.Rev.D*, 111, 054504 (2025).



Bottom Quark on Lattice QCD

Anisotropic clover action

- Heavy quark discretization error of bottom quark: order $(m_b a)^2$ and even $(m_b a)^4$, need finer lattice spacing.
- Extrapolation from lighter masses, Heavy Quark Effective Theory (HQET), Non-Relativistic QCD (NRQCD).
- Physical bottom quark on lattice QCD: Anisotropic clover action for bottom quark

$$S_Q = a^4 \sum_x \bar{Q}[m_Q + \gamma_4 \nabla_4 - \frac{a}{2}\nabla_4^2 + \nu \sum_{i=1}^{3} (\gamma_i \nabla_i - \frac{a}{2}\nabla_i^2) - c_E \frac{a}{2} \sum_{i=1}^{3} \sigma_{0i} F_{0i} - c_B \frac{a}{4} \sum_{i,j=1}^{3} \sigma_{ij} F_{ij}]Q$$

Z. S. Brown, et.al *Phys.Rev.D*, 90(9) 094507.

L. Liu, et.al *Phys.Rev.D*, 81 094507

- Anisotropic valence bottom quark on isotropic gauge ensembles.
- Clover coefficients $c_E = \dfrac{1+\nu}{2u_0^3}, c_B = \dfrac{\nu}{u_0^3}$. Heavy quark anisotropy ν.

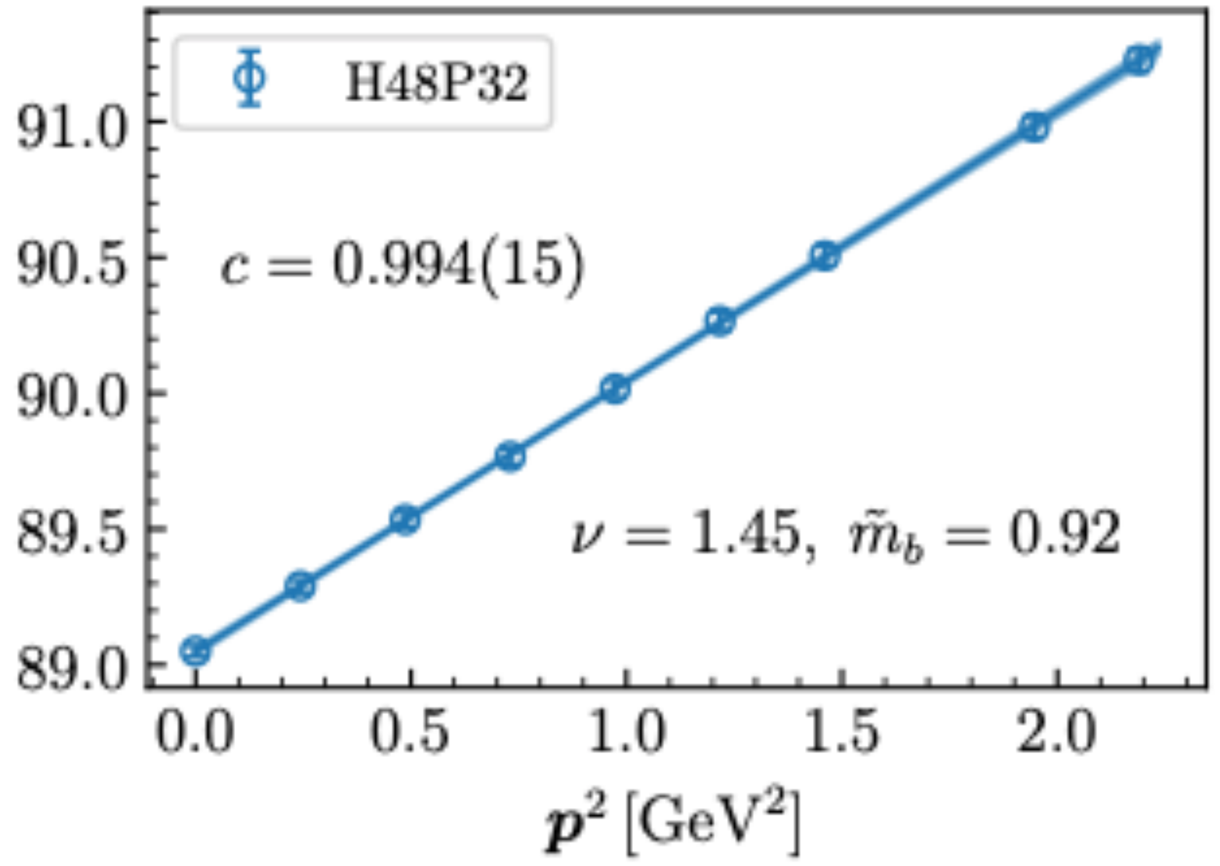
P. Chen, *Phys.Rev.D*, 64 034509

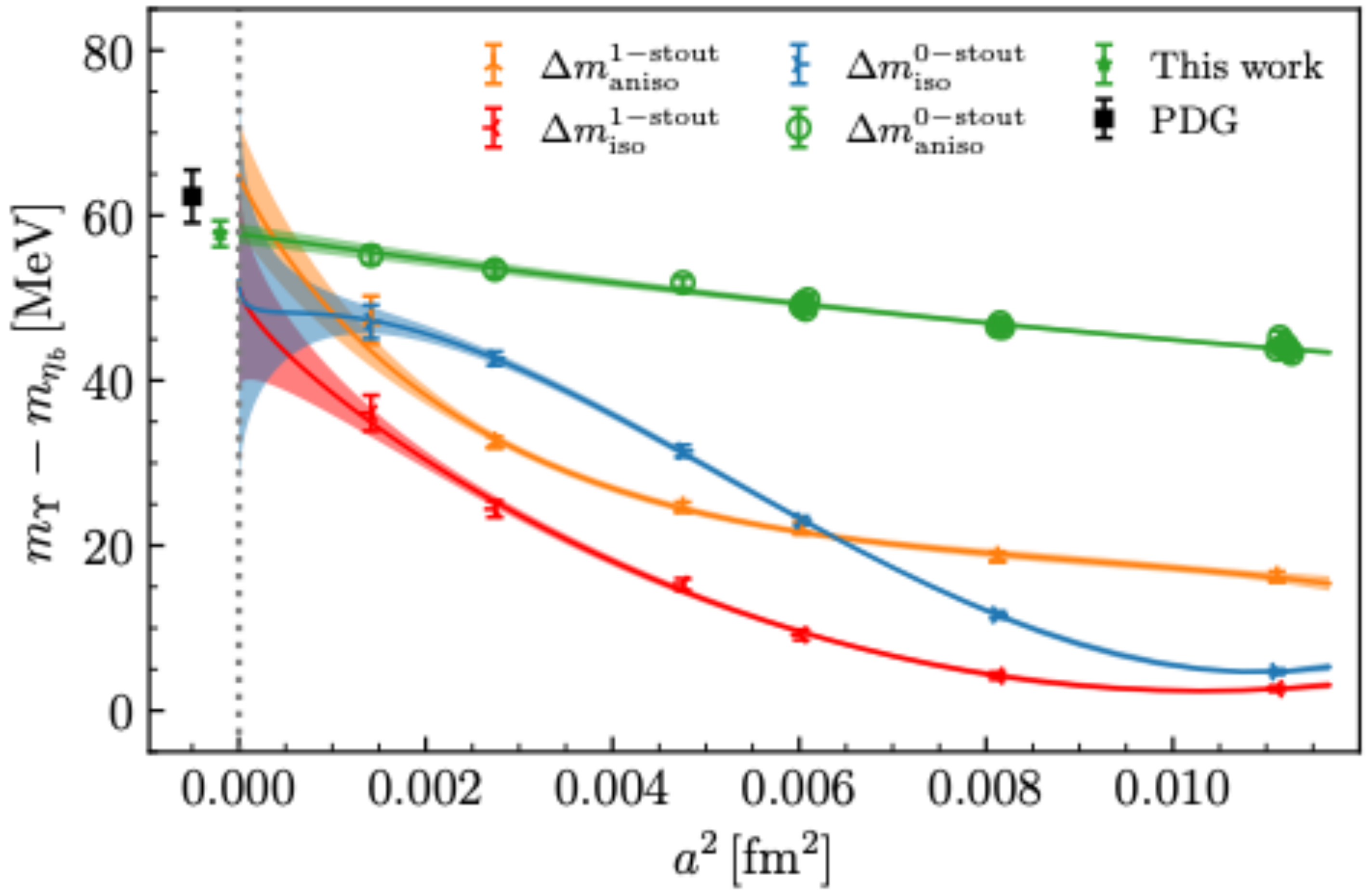
- Turning the values of m_Q and ν to satisfy dispersion relation and physical Υ (1S vector bottomonium) mass: $E_V(\vec{p})^2 = m_V^2 + c^2 p^2, c = 1, \ \ m_V = m_\Upsilon = 9460.40(10)$ MeV.

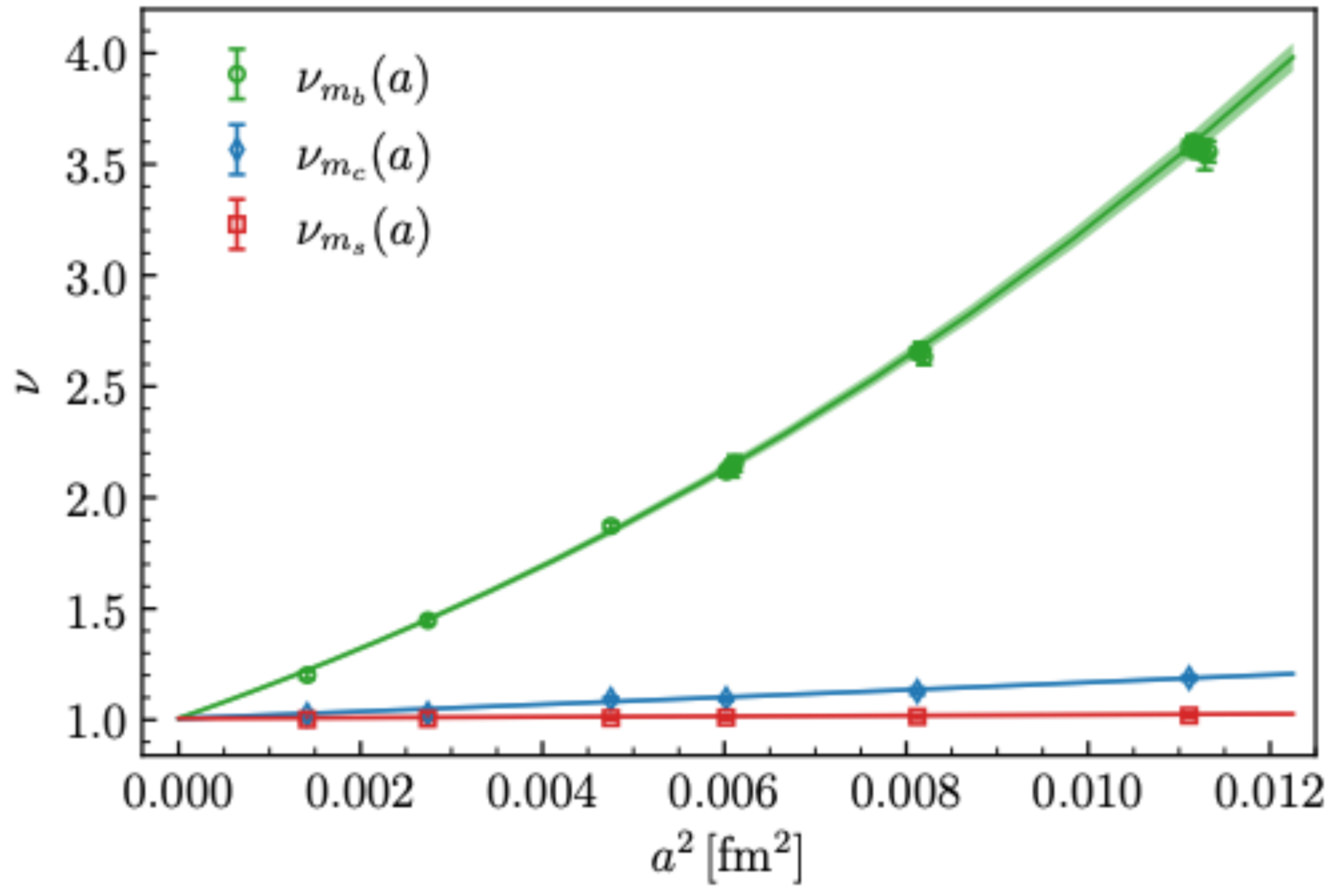
Bottom Quark on Lattice QCD

Parameters turning

- Turning the values of m_Q and ν to satisfy dispersion relation and physical Υ (1S vector bottomonium) mass:
  $E_V(\vec{p})^2 = m_V^2 + c^2p^2, c = 1, \quad m_V = m_\Upsilon = 9460.40(10)$ MeV
- Bottomonium hyperfine splitting with 0-step stout-link smearing and anisotropic bottom action: $\Delta^{bb}_{\mathrm{HFS}} \equiv m_\Upsilon - m_{\eta_b} = 57.8(1.2)(1.0)$ MeV agree with PDG well.
- ν tends to 1 in continuum.
- Empirical formula: $\nu = \dfrac{\mathrm{Sinh}(cm_Va)}{cm_Va} \times [1 + c_1(m_\pi^2 - m_{\pi,phy}^2) + c_2(m_{\eta_s}^2 - m_{\eta_s,phy}^2)]$





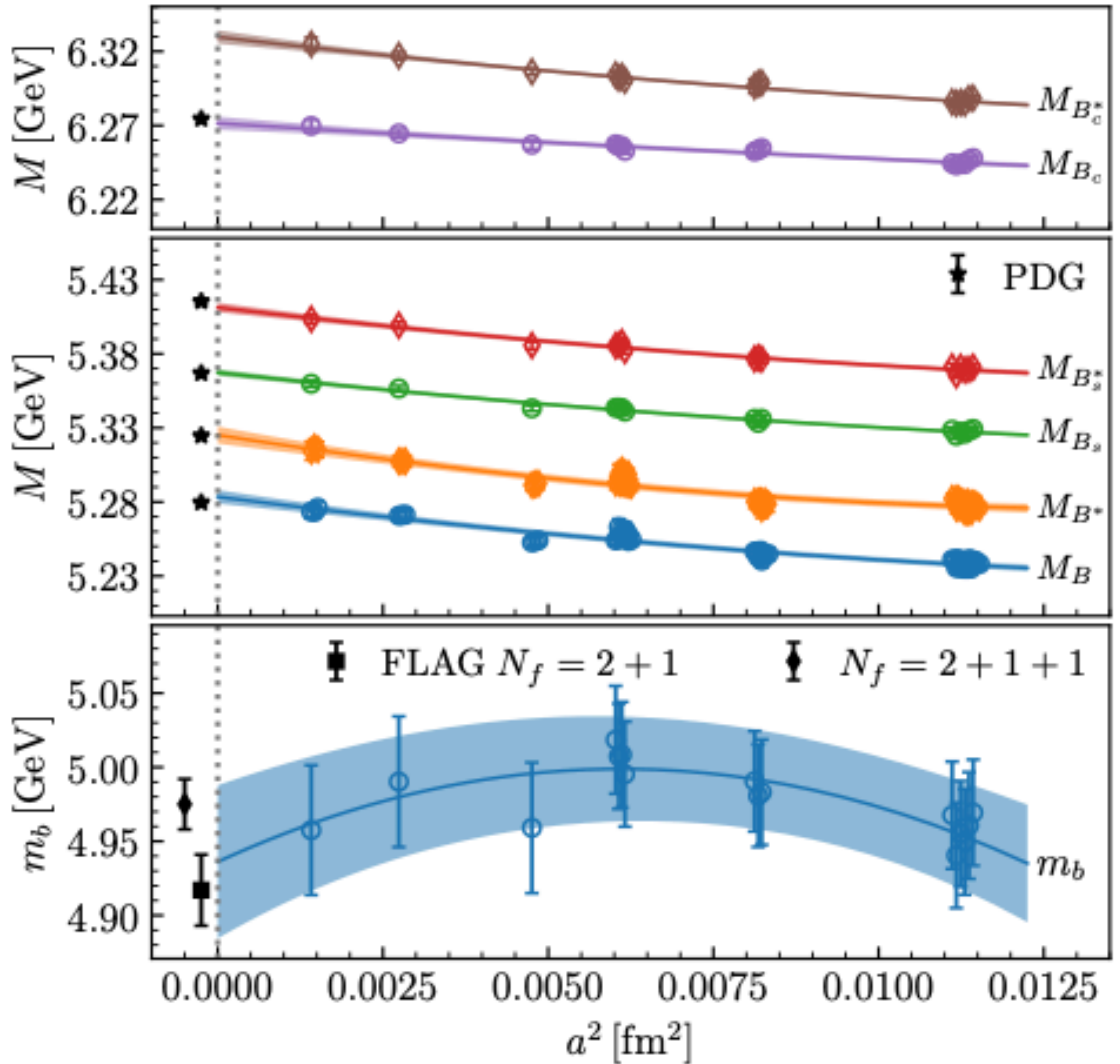


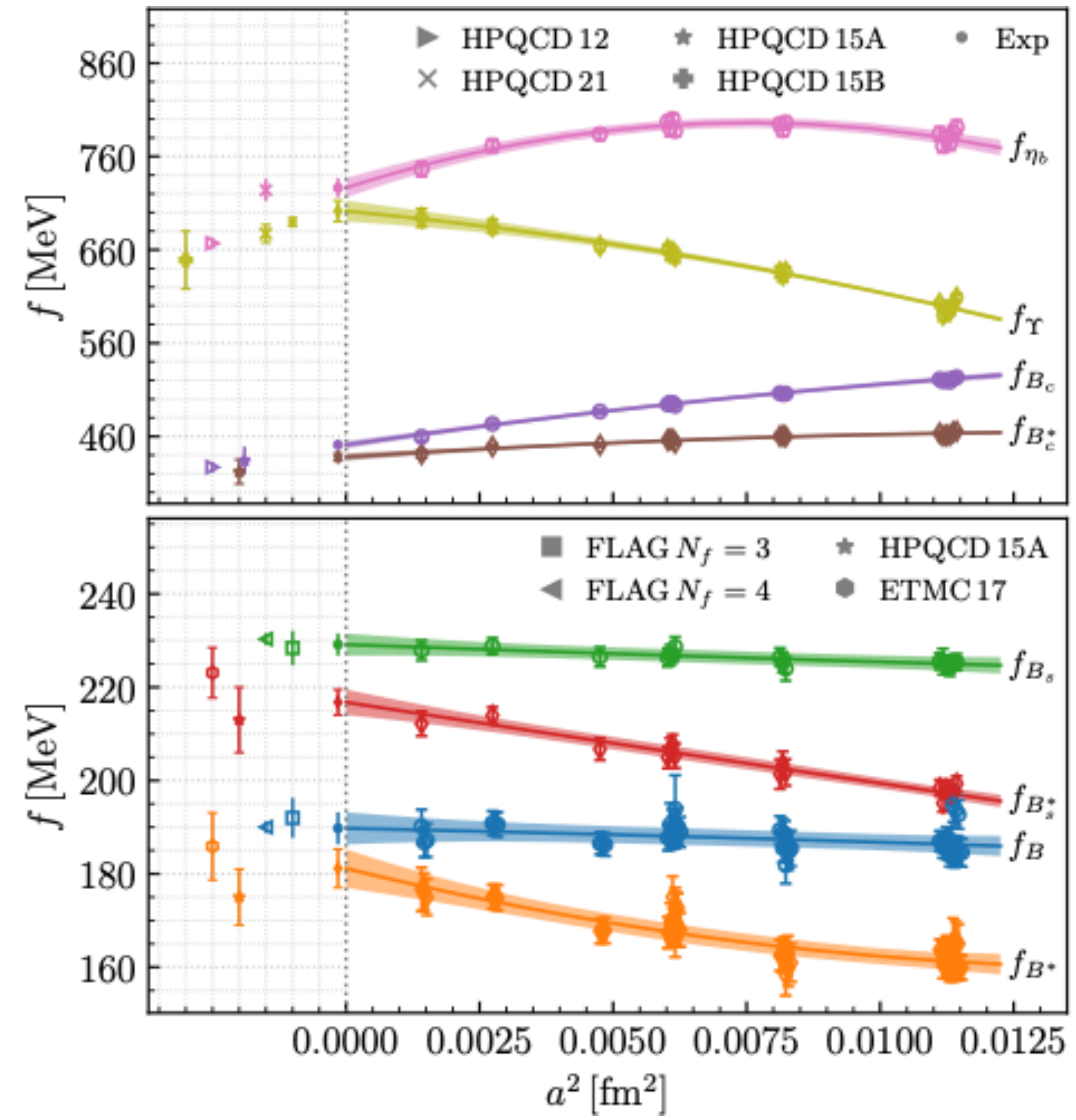
Mengchu Cai, Hai-Yang Du, et.al, 2603.01846

Bottom Quark on Lattice QCD

Meson results

- Bottom quark mass at $\overline{\text{MS}}$ 2 GeV.
- Open bottom meson mass.
- Decay constants of bottom meson.





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Bottom Baryon

Interpolating field

- Bottom baryon in quark model: $SU(5)_F$ symmetry.
- Interpolating field on lattice QCD:

- Spin-1/2, Σ-type: $\Sigma : \epsilon^{abc}P^{+}(Q_a^T C\gamma^5 q_b)q_c$. For Σ_Q, q is u or d and for Ω_Q, q is s.
- Spin-1/2, Ξ'-type: $\Xi' : \frac{1}{\sqrt{2}}\epsilon^{abc}P^{+}[(q_a^T C\gamma^5 Q_b)q'_c + (q_a'^T C\gamma^5 Q_b)q_c]$ where q is u or d, $q' = s$.
- Spin-1/2, Λ-type: octet lambda $\Lambda_o : \frac{1}{\sqrt{6}}\epsilon^{abc}P^{+}[2(q_a^T C\gamma^5 q'_b)Q_c + (q_a^T C\gamma^5 Q_b)q'_c - (q_a'^T C\gamma^5 Q_b)q_c]$ where $q = u, q' = d$ for Λ_Q, and $q = u, q' = s$ for Ξ_Q.
- Spin-3/2, $\Sigma^* : \frac{1}{\sqrt{3}}\epsilon^{abc}P^{+}[2(Q_a^T C\gamma^\mu q_b)q_c + (q_a^T C\gamma^\mu q_b)Q_c]$ $\Xi_Q^* : \frac{2}{\sqrt{3}}\epsilon^{abc}P^{+}[(q_a^T C\gamma^\mu q'_b)Q_c + (q_a'^T C\gamma^\mu Q_b)q_c + (Q_a^T C\gamma^\mu q_b)q'_c]$
- Interchange the role of light and heavy fields for double heavy quark.

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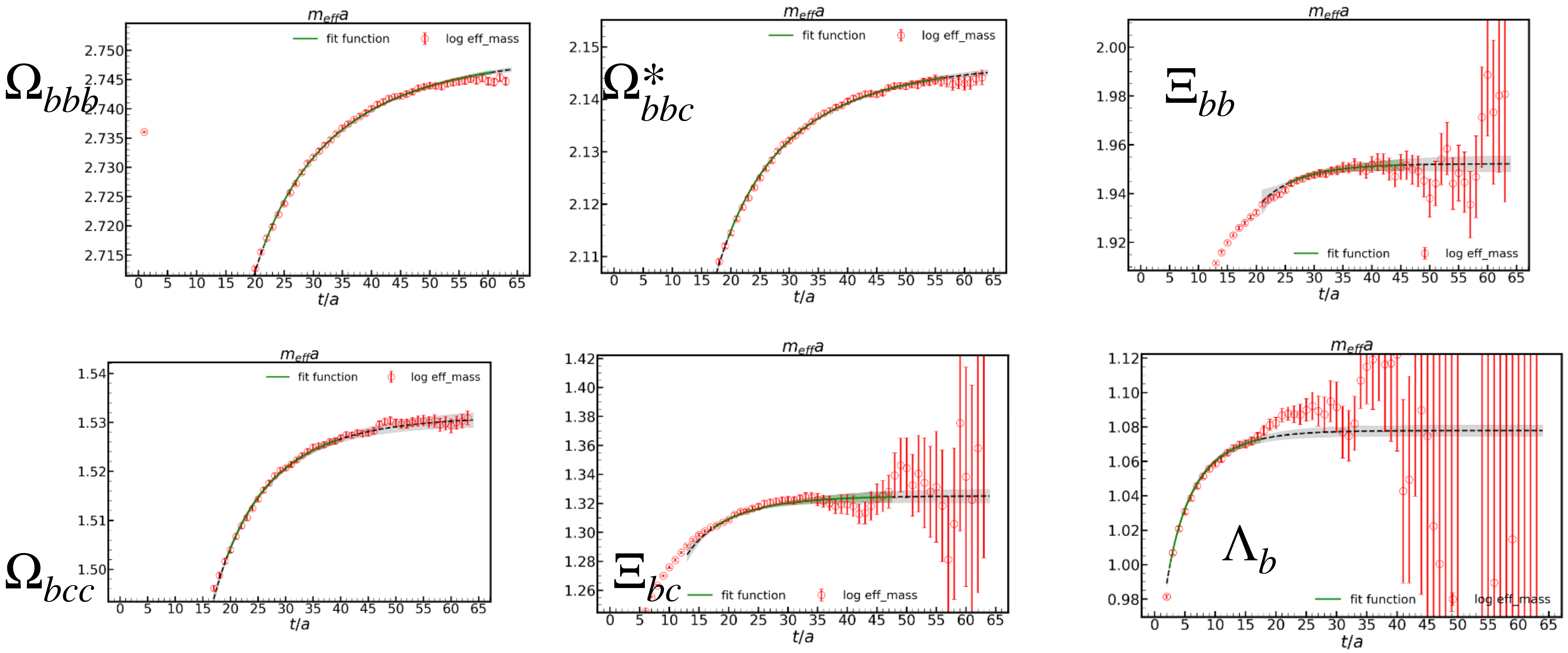
Bottom Baryon

CLQCD preliminary

Two state fit for baryon mass

- $m_H = c_0 e^{-m_H t}(1 + c_1 e^{-Et})$ I64P30



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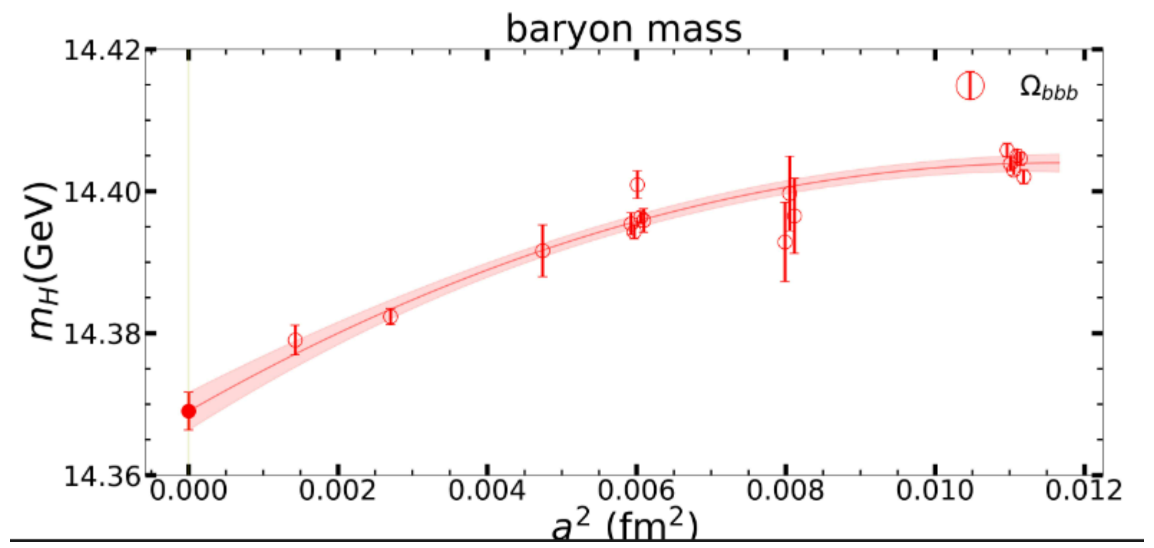
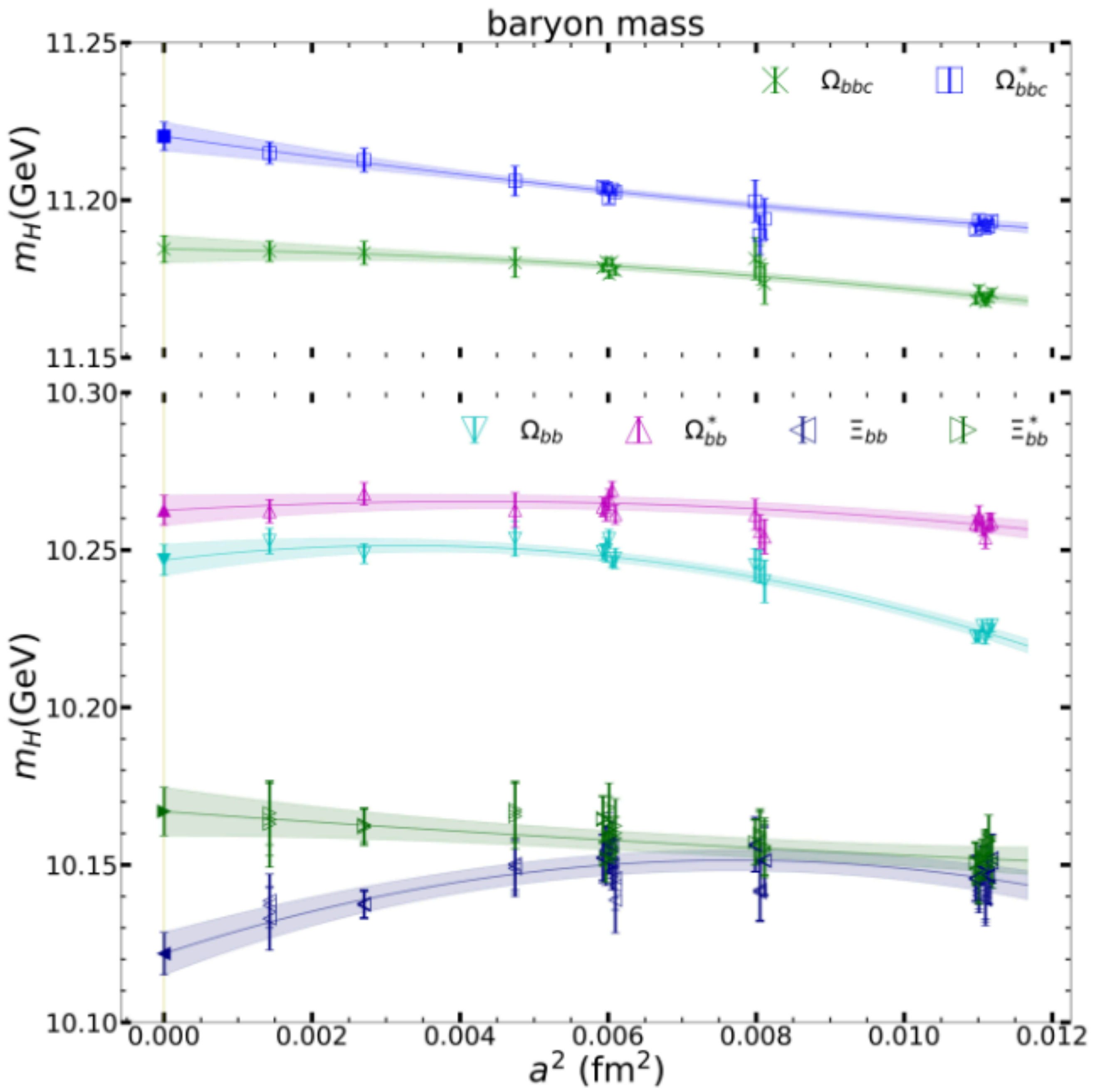
Bottom Baryon

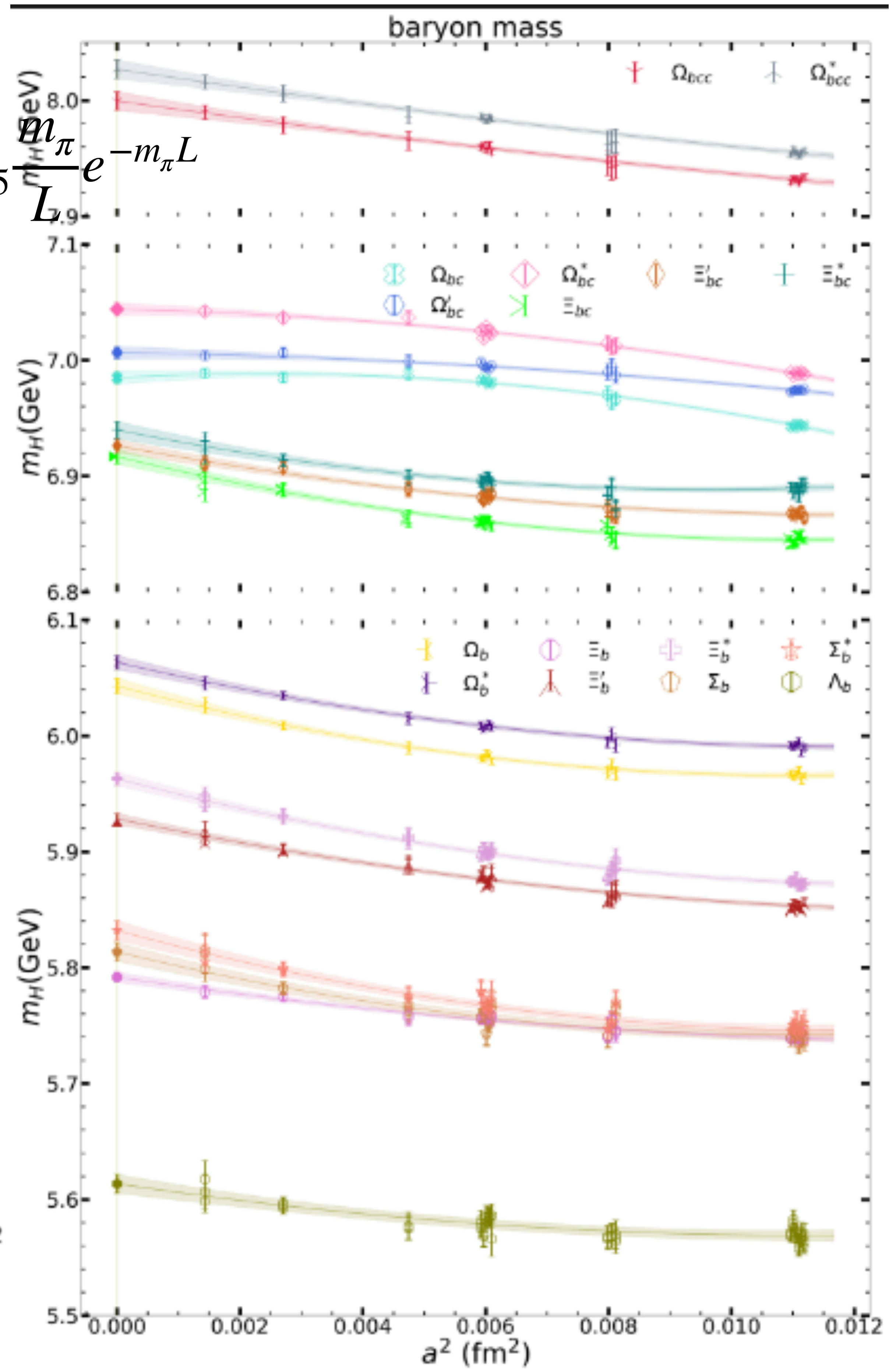
CLQCD preliminary

Global fit on baryon mass

- Global fit: $m_H(m_{\pi,\text{val}}, m_{\pi,\text{sea}}, m_{\eta_s,\text{sea}}, a) = m_H^{\text{phy}} + c_1(m^2_{\pi,\text{val}} + m^2_{\pi,\text{sea}} - m^2_{\pi,\text{phy}}) + c_2(m^2_{\eta_s,\text{sea}} - m^2_{\eta_s,\text{phy}}) + c_3 a^2 + c_4 a^4 + c_5 \frac{m_\pi}{L} e^{-m_\pi L}$
- The joint fit interpolates valence, sea and strange masses to the physical point.
- Smooth lattice-spacing dependence enables a controlled continuum extrapolation.
- Consistent trends across channels support the preliminary mass determination.







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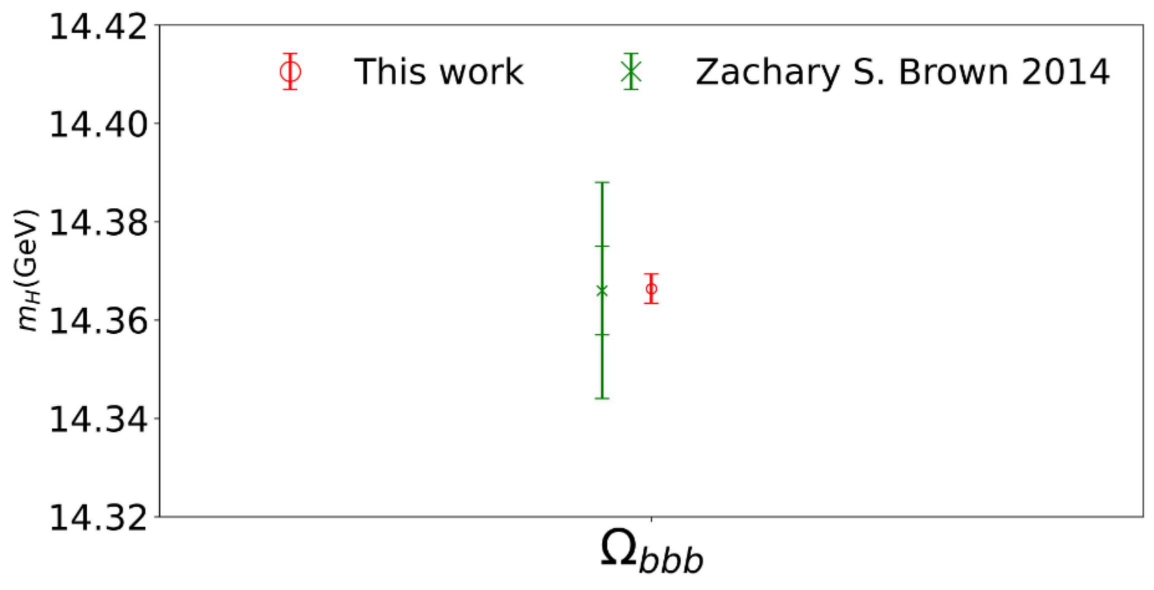
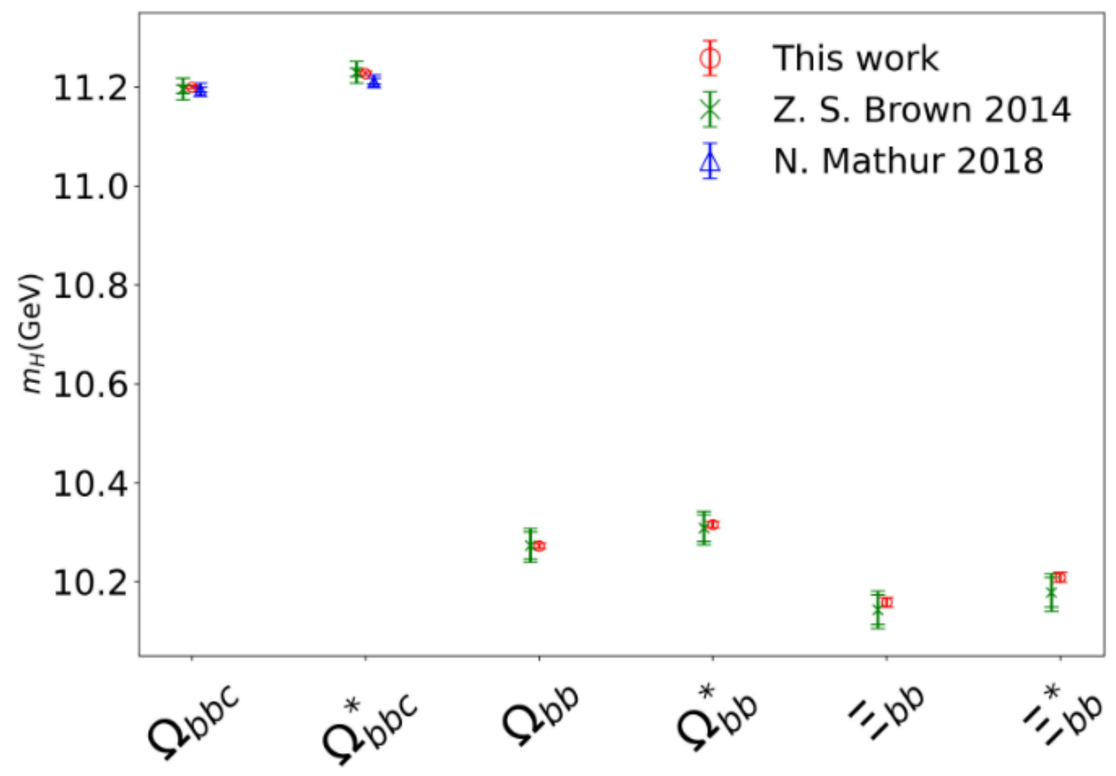
Bottom Baryon

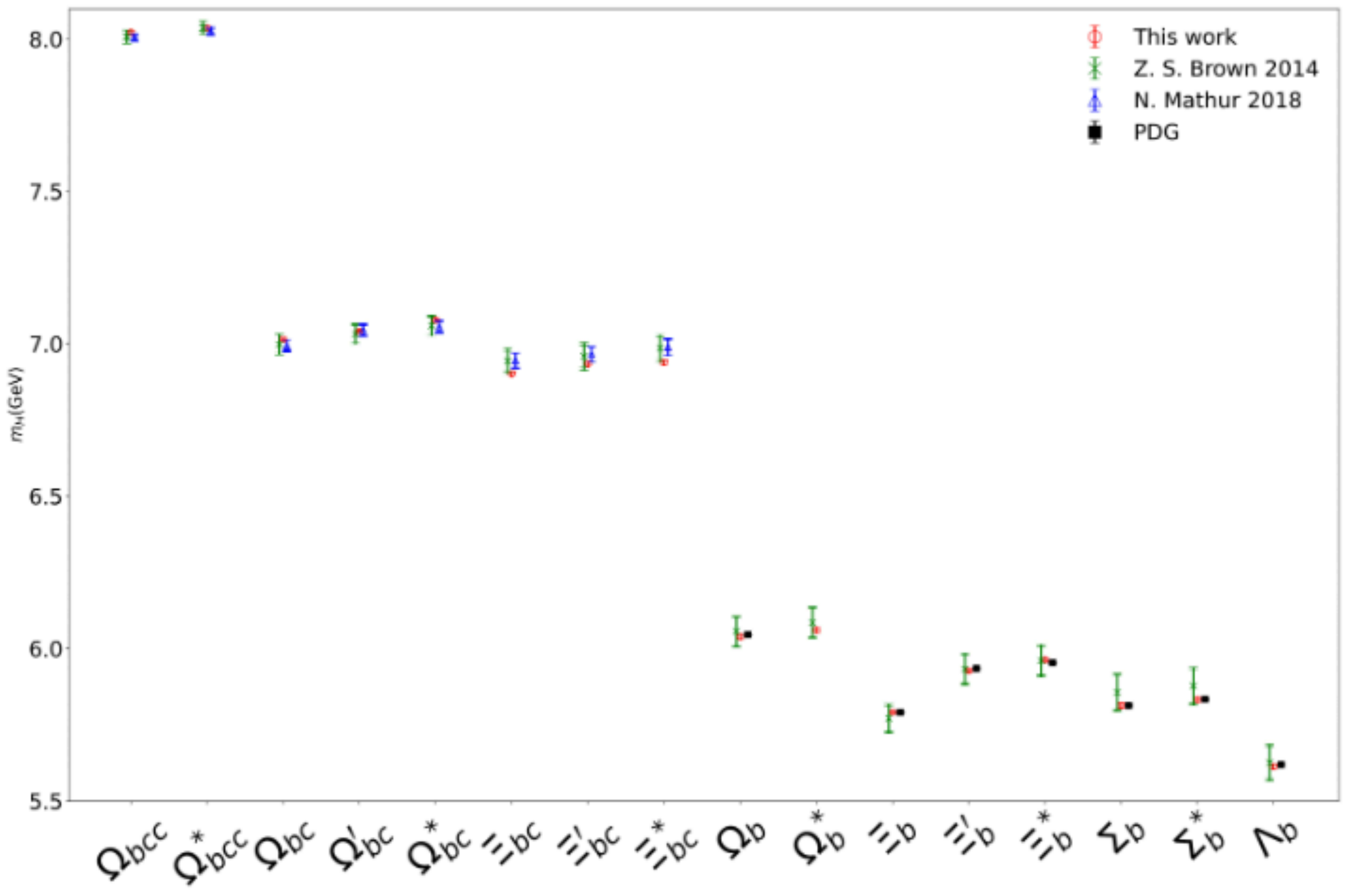
CLQCD preliminary

Bottom baryon mass results

- For the experimentally known single-bottom states, this work is consistent with the PDG values within the quoted uncertainties.
- The results are also compatible with previous lattice calculations, and our results have higher precision.
- The agreement across single-, double- and mixed-heavy channels supports the control of the physical-bottom tuning and continuum effects. The unobserved states therefore provide useful lattice predictions.







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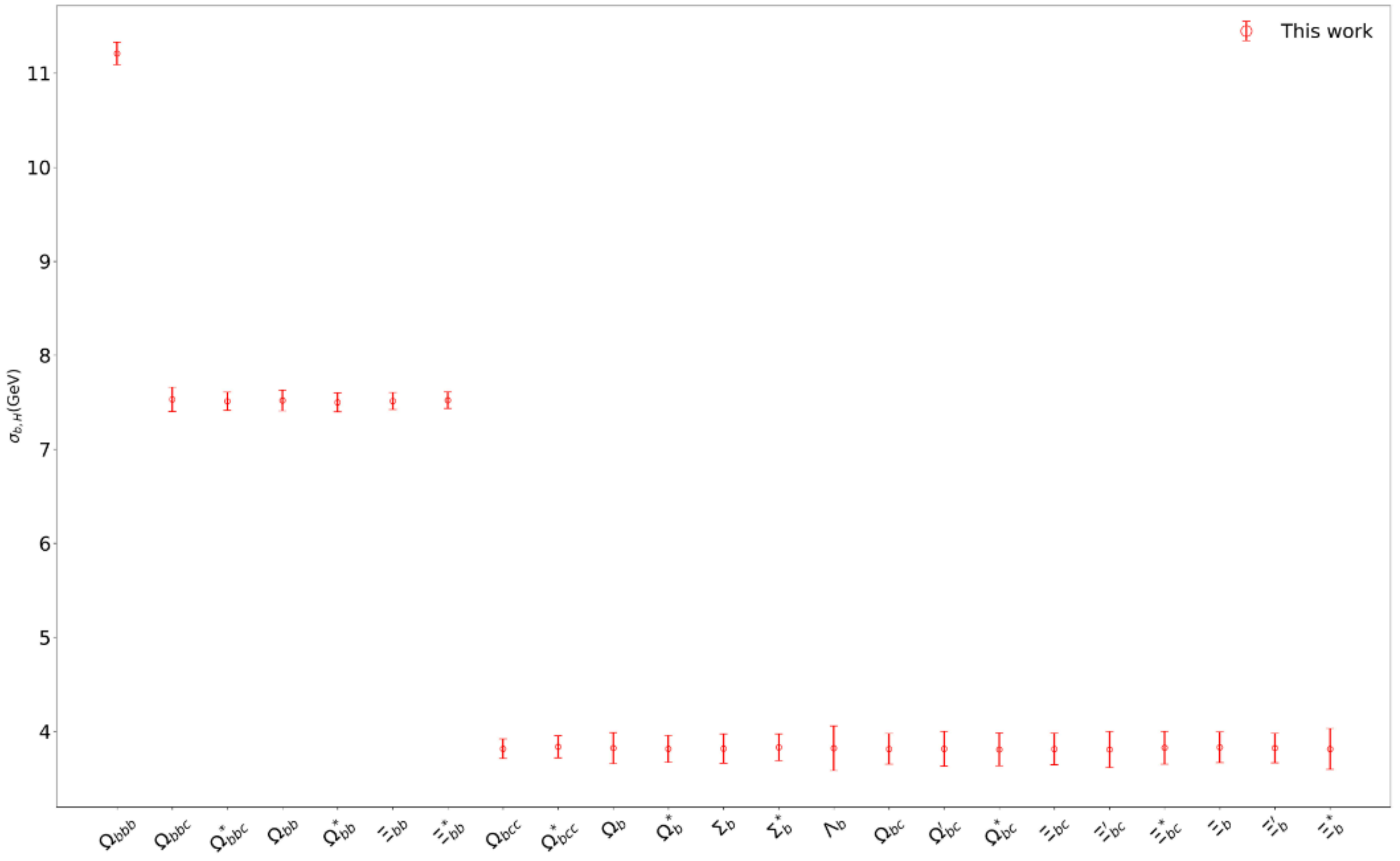
Bottom Baryon

CLQCD preliminary

Sigma term calculation: valence bottom, charm and strange

- Extract valence bottom, charm and strange sigma term using Feynman-Hellman theorem $\sigma^{\mathrm{FH}}_{q,H} = m_q^{\mathrm{PC}} \dfrac{\partial m_H}{\partial m_q^{\mathrm{PC}}}$ on each ensemble.
- Global fit: sea mass and lattice spacing dependence
  $\sigma_{b,H}(m_{\pi,\mathrm{val}}, m_{\pi,\mathrm{sea}}, m_{\eta_s,\mathrm{sea}}, a) = \sigma^{\mathrm{phy}}_{b,H} + c_1(m^2_{\pi,\mathrm{sea}} - m^2_{\pi,\mathrm{phy}}) + c_2(m^2_{\eta_s,\mathrm{sea}} - m^2_{\eta_s,\mathrm{phy}}) + c_3 a^2 + c_4 a^4 + c_5 e^{-m_\pi L}$
- Valence bottom contribution: $\sigma_{b,H}/n_b$: ~3.74(4) GeV for thiple bottom quarks (Ω_{bbb}), ~3.75(5) GeV for double bottom quarks and ~3.82(17) GeV for single bottom quarks



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Bottom Baryon

CLQCD preliminary

Sigma term calculation: sea light and strange

- Sea mass contribution from quark mass: sea mass dependence of $m_s^{\rm val}$, $m_c^{\rm val}$ and $m_b^{\rm val}$ lead to correction of sea light and sea strange sigma term.

$$\delta m_H = \delta m_l^{\rm sea}\langle \bar{l}l\rangle_H^{\rm sea} + \delta m_s^{\rm sea}\langle \bar{s}s\rangle_H^{\rm sea} + \delta m_s^{\rm val}\langle \bar{s}s\rangle_H^{\rm val} + \delta m_c^{\rm val}\langle \bar{c}c\rangle_H^{\rm val} + \delta m_b^{\rm val}\langle \bar{b}b\rangle_H^{\rm val}$$

$$= \delta m_l^{\rm sea}(\langle \bar{l}l\rangle_H^{\rm sea} + \frac{\partial m_s^{\rm val}}{\partial m_l^{\rm sea}}\langle \bar{s}s\rangle_H^{\rm val} + \frac{\partial m_c^{\rm val}}{\partial m_l^{\rm sea}}\langle \bar{c}c\rangle_H^{\rm val} + \frac{\partial m_b^{\rm val}}{\partial m_l^{\rm sea}}\langle \bar{b}b\rangle_H^{\rm val}) + \delta m_s^{\rm sea}(\langle \bar{s}s\rangle_H^{\rm sea} + \frac{\partial m_s^{\rm val}}{\partial m_s^{\rm sea}}\langle \bar{s}s\rangle_H^{\rm val} + \frac{\partial m_c^{\rm val}}{\partial m_s^{\rm sea}}\langle \bar{c}c\rangle_H^{\rm val} + \frac{\partial m_b^{\rm val}}{\partial m_s^{\rm sea}}\langle \bar{b}b\rangle_H^{\rm val})$$

$$\sigma_{\pi,H} = \sigma_{\pi,H}^{\rm val} + \sigma_{\pi,H}^{\rm sea}$$

$$\sigma_{\pi,H}^{\rm val} = m_l^{\rm phy}\frac{\partial m_H(m_\pi^{\rm val}, m_\pi^{\rm phy}, m_{\eta_s}^{\rm phy}, 0, 0)}{\partial m_l^{\rm val}}|_{m_l^{\rm val}=m_l^{\rm phy}} = (m_\pi^{\rm phy})^2\frac{\partial m_H(m_\pi^{\rm val}, m_\pi^{\rm phy}, m_{\eta_s}^{\rm phy}, 0, 0)}{\partial (m_\pi^{\rm val})^2}|_{m_\pi^{\rm val}=m_\pi^{\rm phy}}$$

$$\sigma_{\pi,H}^{\rm sea} = m_l^{\rm phy}[\frac{\partial m_H(m_\pi^{\rm phy}, m_\pi^{\rm sea}, m_{\eta_s}^{\rm phy}, 0, 0)}{\partial m_l^{\rm sea}}|_{m_l^{\rm sea}} - \frac{\partial m_s^{\rm val}}{\partial m_l^{\rm sea}}\langle \bar{s}s\rangle_H^{\rm val} - \frac{\partial m_c^{\rm val}}{\partial m_l^{\rm sea}}\langle \bar{c}c\rangle_H^{\rm val} - \frac{\partial m_b^{\rm val}}{\partial m_l^{\rm sea}}\langle \bar{b}b\rangle_H^{\rm val}]$$

$$= (m_\pi^{\rm phy})^2[\frac{\partial m_H(m_\pi^{\rm val}, m_\pi^{\rm phy}, m_{\eta_s}^{\rm phy}, 0, 0)}{\partial (m_\pi^{\rm val})^2}|_{m_\pi^{\rm sea}} - \frac{\partial m_s^{\rm val}}{\partial (m_\pi^{\rm sea})^2}\langle \bar{s}s\rangle_H^{\rm val} - \frac{\partial m_c^{\rm val}}{\partial (m_\pi^{\rm sea})^2}\langle \bar{c}c\rangle_H^{\rm val} - \frac{\partial m_b^{\rm val}}{\partial (m_\pi^{\rm sea})^2}\langle \bar{b}b\rangle_H^{\rm val}]$$

$$\sigma_{s,H} = \sigma_{s,H}^{\rm val} + \sigma_{s,H}^{\rm sea}$$

$$\sigma_{s,H}^{\rm val} = m_s^{\rm phy}\frac{\partial m_H(m_\pi^{\rm sea}, m_\pi^{\rm sea}, m_{\eta_s}^{\rm phy}, 0, 0)}{\partial m_s^{\rm val}}|_{m_s^{\rm val}=m_s^{\rm phy}} = (m_{\eta_s}^{\rm phy})^2\frac{\partial m_H(m_\pi^{\rm sea}, m_\pi^{\rm sea}, m_{\eta_s}^{\rm phy}, 0, 0)}{\partial (m_{\eta_s}^{\rm val})^2}|_{m_{\eta_s}^{\rm val}=m_{\eta_s}^{\rm phy}}$$

$$\sigma_{s,H}^{\rm sea} = m_s^{\rm phy}[\frac{\partial m_H(m_\pi^{\rm phy}, m_\pi^{\rm phy}, m_{\eta_s}^{\rm sea}, 0, 0)}{\partial m_s^{\rm sea}}|_{m_s^{\rm sea}} - \frac{\partial m_s^{\rm val}}{\partial m_s^{\rm sea}}\langle \bar{s}s\rangle_H^{\rm val} - \frac{\partial m_c^{\rm val}}{\partial m_s^{\rm sea}}\langle \bar{c}c\rangle_H^{\rm val} - \frac{\partial m_b^{\rm val}}{\partial m_s^{\rm sea}}\langle \bar{b}b\rangle_H^{\rm val}]$$

$$= (m_{\eta_s}^{\rm phy})^2[\frac{\partial m_H(m_\pi^{\rm phy}, m_\pi^{\rm phy}, m_{\eta_s}^{\rm sea}, 0, 0)}{\partial (m_{\eta_s}^{\rm val})^2}|_{m_{\eta_s}^{\rm sea}} - \frac{\partial m_s^{\rm val}}{\partial (m_{\eta_s}^{\rm sea})^2}\langle \bar{s}s\rangle_H^{\rm val} - \frac{\partial m_c^{\rm val}}{\partial (m_{\eta_s}^{\rm sea})^2}\langle \bar{c}c\rangle_H^{\rm val} - \frac{\partial m_b^{\rm val}}{\partial (m_{\eta_s}^{\rm sea})^2}\langle \bar{b}b\rangle_H^{\rm val}]$$

$$\sigma_{c,H} = \sigma_{c,H}^{\rm val}$$

$$\sigma_{b,H} = \sigma_{b,H}^{\rm val}$$

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Bottom Baryon

CLQCD preliminary

Sigma term contribution to baryon mass

- Total sigma term: sum over all flavor contributions, including valence and sea.
- Valence bottom, charm and strange quark sigma term approximately proportional to the number of quark in bottom baryon.
- Sea strange sigma term contribution: ~30 MeV
- Sea light sigma term contribution: ~10 MeV
- Total sigma term is the main component of the bottom baryon mass.
- Remain part: trace anomaly.

	m_H	σ_H	$\sigma_{b,H}$	$\sigma_{c,H}$	$\sigma^{\text{val}}_{s,H}$	$\sigma^{\text{sea}}_{s,H}$	$\sigma_{s,H}$	$\sigma^{\text{val}}_{\pi,H}$	$\sigma^{\text{sea}}_{\pi,H}$	$\sigma_{\pi,H}$
Ω_{bbb}	14.3664(30)	11.061(18)	11.023(16)	0	0	0.0212(72)	0.0212(72)	0	0.01588(38)	0.01588(38)
Ω_{bbc}	11.1991(30)	8.442(22)	7.446(20)	0.9584(65)	0	0.0254(55)	0.0254(55)	0	0.01136(28)	0.01136(28)
Ω^*_{bbc}	11.2270(36)	8.450(32)	7.442(28)	0.962(12)	0	0.0353(61)	0.0353(61)	0	0.01132(32)	0.01132(32)
Ω_{bb}	10.2720(55)	7.657(33)	7.510(30)	0	0.097(11)	0.037(10)	0.134(16)	0	0.01229(50)	0.01229(50)
Ω^*_{bb}	10.3156(62)	7.632(42)	7.485(39)	0	0.092(13)	0.042(11)	0.134(18)	0	0.01256(56)	0.01256(56)
Ξ_{bb}	10.158(10)	7.540(85)	7.481(83)	0	0	0.044(18)	0.044(18)	0.00467(38)	0.01065(97)	0.01531(92)
Ξ^*_{bb}	10.2086(98)	7.571(76)	7.520(74)	0	0	0.033(19)	0.033(19)	0.00423(32)	0.0134(10)	0.0176(10)
Ω_{bcc}	8.0228(48)	5.784(50)	3.782(47)	1.951(13)	0	0.0425(52)	0.0425(52)	0	0.00747(29)	0.00747(29)
Ω^*_{bcc}	8.0359(54)	5.739(62)	3.750(59)	1.926(14)	0	0.0560(65)	0.0560(65)	0	0.00789(35)	0.00789(35)
Ω_{bc}	7.0149(43)	5.017(47)	3.806(42)	1.041(17)	0.1077(82)	0.0541(67)	0.162(11)	0	0.00860(33)	0.00860(33)
Ω'_{bc}	7.0403(46)	4.976(39)	3.788(35)	1.030(12)	0.0971(94)	0.0522(69)	0.149(12)	0	0.00890(35)	0.00890(35)
Ω^*_{bc}	7.0777(52)	4.971(33)	3.789(29)	1.014(10)	0.1034(75)	0.0552(83)	0.159(11)	0	0.00938(42)	0.00938(42)
Ξ_{bc}	6.9023(68)	4.927(95)	3.804(91)	1.059(23)	0	0.051(11)	0.051(11)	0.00356(24)	0.00955(56)	0.01311(59)
Ξ'_{bc}	6.9348(67)	4.873(82)	3.780(78)	1.029(21)	0	0.053(11)	0.053(11)	0.00346(26)	0.00827(58)	0.01174(58)
Ξ^*_{bc}	6.9565(71)	4.813(90)	3.749(85)	1.002(23)	0	0.049(11)	0.049(11)	0.00356(25)	0.00925(60)	0.01281(62)
Ω_b	6.0390(79)	4.106(39)	3.809(35)	0	0.229(16)	0.058(13)	0.286(21)	0	0.01053(65)	0.01053(65)
Ω^*_b	6.0608(79)	4.112(31)	3.798(27)	0	0.233(11)	0.070(13)	0.303(18)	0	0.01112(65)	0.01112(65)
Ξ_b	5.7802(78)	3.98(10)	3.758(99)	0	0.190(18)	0.018(14)	0.207(23)	0.00568(18)	0.01045(62)	0.01614(65)
Ξ'_b	5.9332(79)	4.020(87)	3.813(85)	0	0.137(12)	0.054(12)	0.191(18)	0.00375(23)	0.01275(64)	0.01650(63)
Ξ^*_b	5.9561(78)	3.972(95)	3.781(93)	0	0.123(15)	0.050(12)	0.174(20)	0.00328(29)	0.01387(68)	0.01714(64)
Σ_b	5.813(11)	3.856(81)	3.803(78)	0	0	0.030(20)	0.030(20)	0.00747(43)	0.0151(10)	0.0226(10)
Σ^*_b	5.828(12)	3.796(95)	3.760(92)	0	0	0.012(22)	0.012(22)	0.00702(49)	0.0165(11)	0.0236(11)
Λ_b	5.625(12)	3.89(11)	3.83(11)	0	0	0.034(22)	0.034(22)	0.01513(52)	0.0079(12)	0.0230(12)

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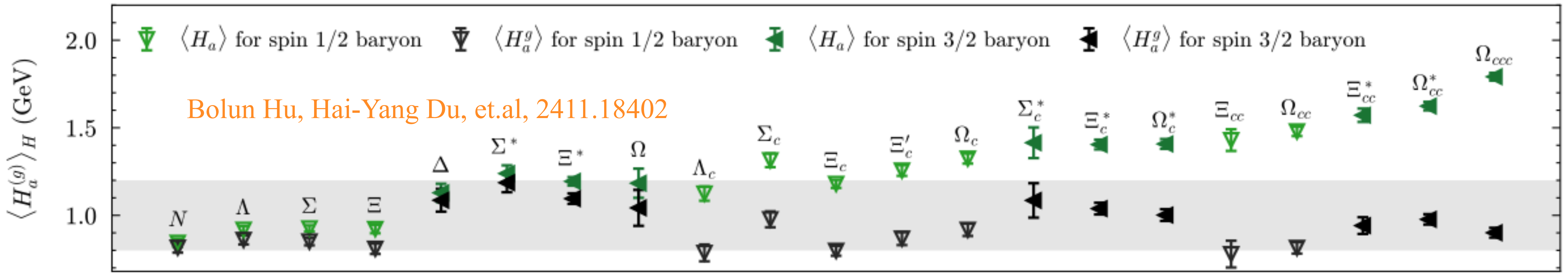
Bottom Baryon

CLQCD preliminary

Trace anomaly contribution

- Hadron mass decomposition: $m_H = \sum_q \sigma_{q,H} + \gamma_m \sum_q \sigma_{q,H} + \frac{\beta(\alpha_s)}{2\alpha_s} \langle G^{\mu\nu} G_{\mu\nu} \rangle_H$
- Trace anomaly: $\langle H_a \rangle_H = m_H^{\text{phy}} - \sigma_H$, $\langle H_a^g \rangle_H = m_H^{\text{phy}} - (1+\gamma_m)\sigma_H$. Scale dependence for both quark and gluon part.
- $\gamma_m = 0.295$ at $\overline{\text{MS}}$ 2 GeV: $\langle H_a \rangle_H \sim 14.4$ GeV for Ω_{bbb}, ~ 9.7 GeV for Ξ_{bb}, ~ 4.9 GeV for Σ_b. $\langle H_a^g \rangle_H$ at $\overline{\text{MS}}$ 2 GeV: ~ 0 GeV for Ω_{bbb}, ~ 0.4 GeV for Ξ_{bb}, ~ 0.9 GeV for Σ_b.
- Light and charmed baryon: gluon trace anomaly ~ 1 GeV at $\overline{\text{MS}}$ 2 GeV.



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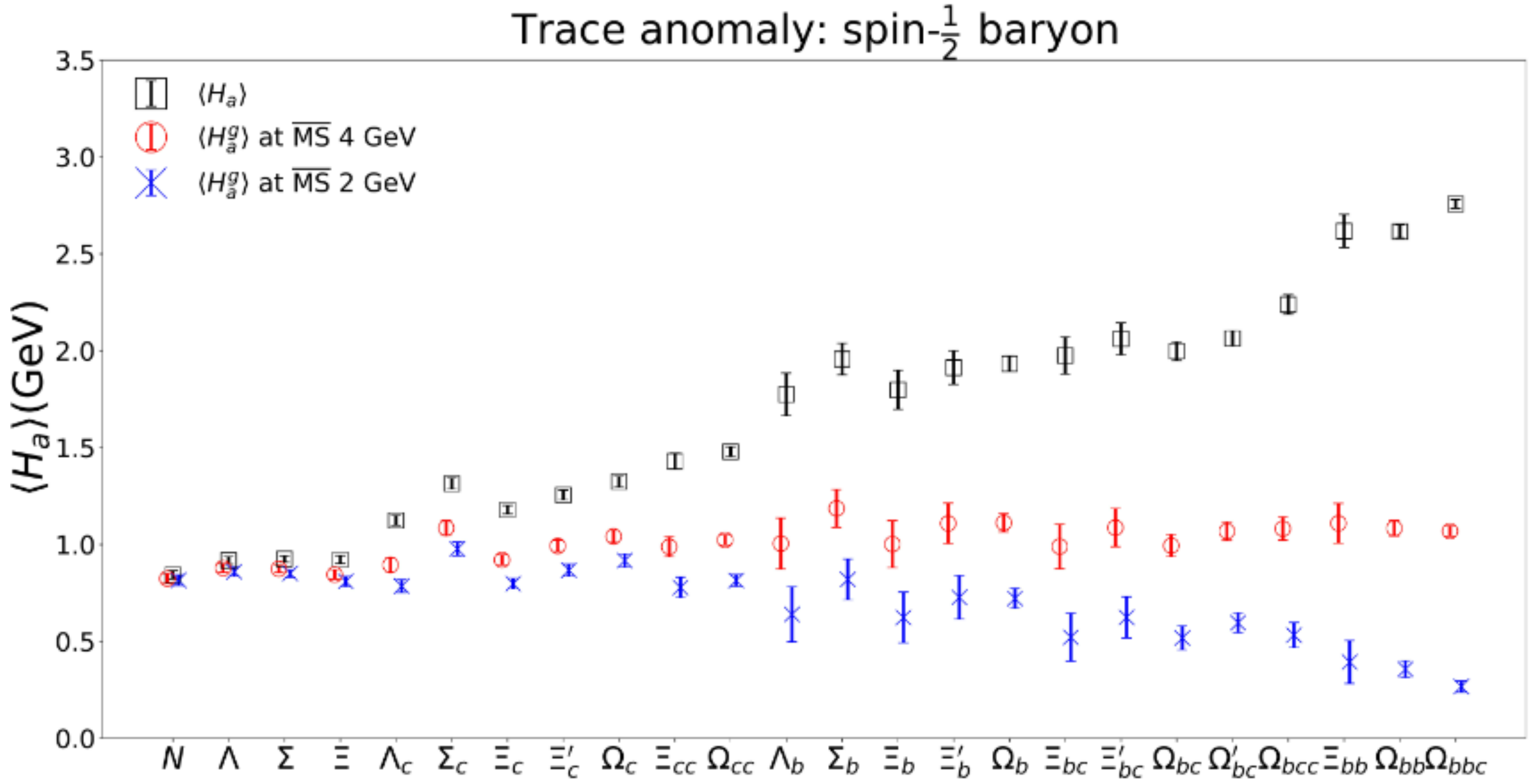
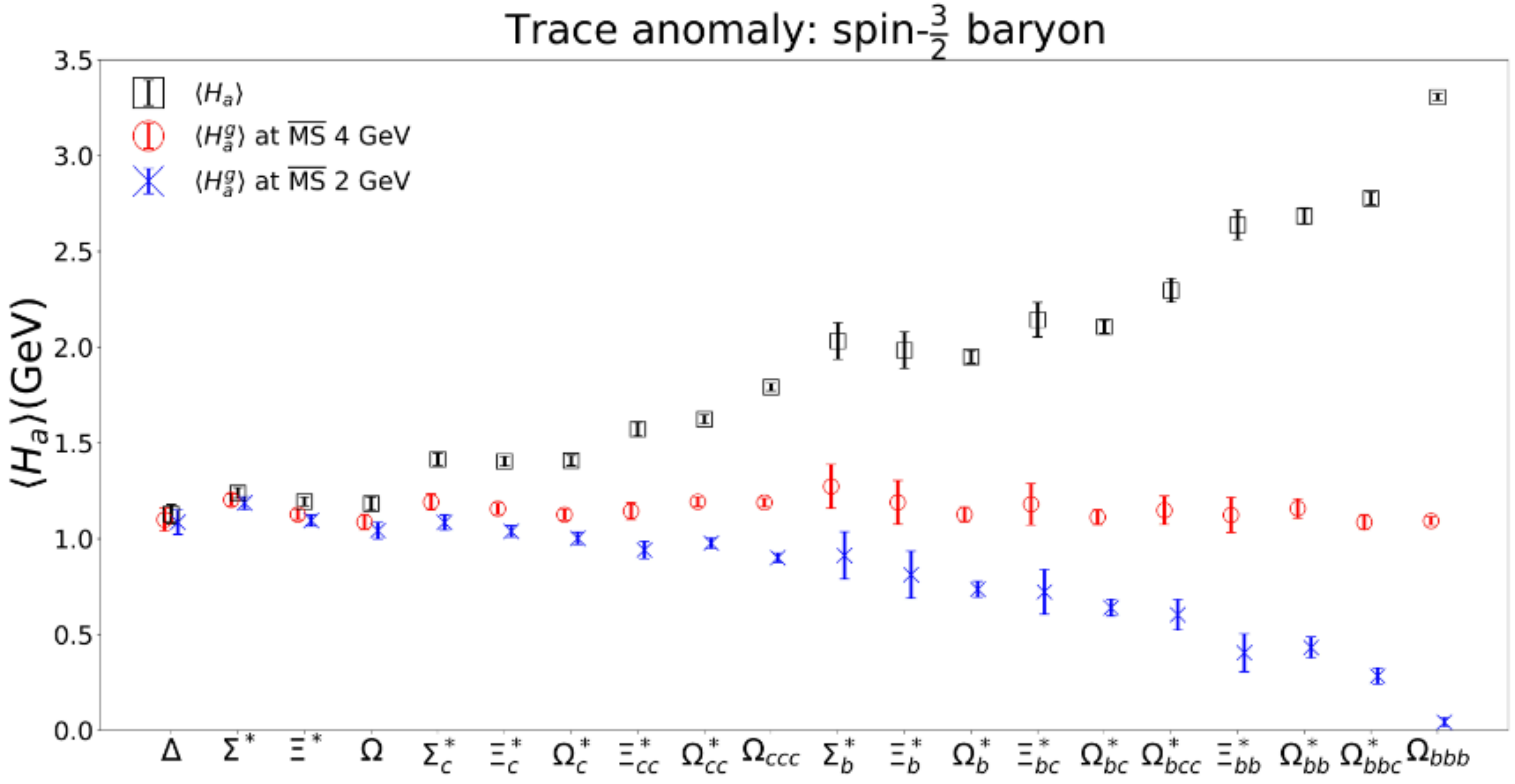
Bottom Baryon

CLQCD preliminary

Scale dependence of trace anomaly

- $m_H = \sum_q \sigma_{q,H} + \gamma_m \sum_q \sigma_{q,H} + \frac{\beta(\alpha_s)}{2\alpha_s}\langle G^{\mu\nu}G_{\mu\nu}\rangle_H$, $\langle H_a\rangle_H = m_H^{\text{phy}} - \sigma_H$, $\langle H_a^g\rangle_H = m_H^{\text{phy}} - (1+\gamma_m)\sigma_H$.
- $\gamma_m = 0.2$ at $\overline{\text{MS}}$ 4 GeV:





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Summary

- Anisotropic clover action for heavy quark: relativistic action for bottom quark, with discretization error better controlled.
- Bottom meson mass have good agreement with PDG, and given high precision decay constants.
- High precision lattice results on bottom baryon, and predicted the baryon mass with experimentally undiscovered.
- Sigma term contributions to bottom baryon mass.
- Trace anomaly contributions to bottom baryon mass, and its scale dependence.