RECENT RESULTS ON DOUBLY HEAVY TETRAQUARKS

Santa Fe Workshop, August 29, 2019

with A. Francis, J. Hudspith, R. Lewis and B. Colquhoun

FHLM16: Francis, Hudspith, Lewis, KM PRL 118 (2017) 142001 [1607.05214]
FHLM18: Francis, Hudspith, Lewis, KM PRD 99 (2019) 054505 [1810.10550]
CFHLM19: Colquhoun, Francis, Hudspith, Lewis, KM, in progress

HadSpec17: Cheung, Thomas, Dudek, Edwards, JHEP 1711 (2017) 033 [1709.01417]
JMP18: Junnarkar, Mathur, Padmanath, PRD 99 (2019) 034507 [1810.12285]
LMPW19: Leskovec, Meinel, Pflaumer, Wagner, PRD 100 (2019) 014503 [1904.04197]

Attractive interactions for a localized doubly heavy $qq'\bar{Q}\bar{Q}'$ system absent for the corresponding well-separated heavy meson pair

- **Color Coulomb attraction for $\bar{Q}\bar{Q}'$ in 3_c**
  - binding proportional to $\bar{Q}\bar{Q}'$ reduced mass μ_h, dominant as $\mu_h \to \infty$
  - J_h=0, 1 (Q≠Q'), J_h=1 (Q=Q') for s-wave $\bar{Q}\bar{Q}'$

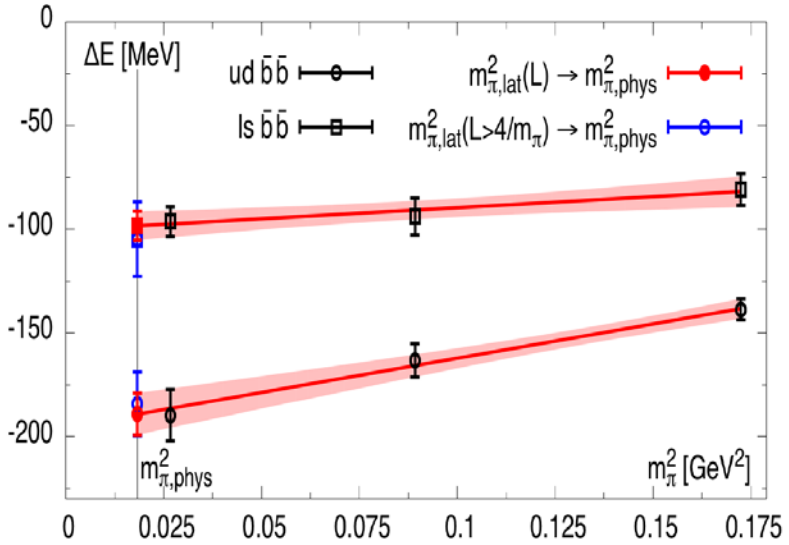
- **Attraction for *qq'* in Jaffe's "good" light diquark configuration**
  - constraints on "good" $(J = 0, F = \bar{3}, C = \bar{3})$ vs "bad" $(J = 1, F = 6, C = \bar{3})$ light diquark (brown muck) configuration from heavy baryon splittings

    $\Sigma_b - \Lambda_b$ = 194 MeV $\Sigma_c - \Lambda_c$ = 167 MeV
    $\Xi_b' - \Xi_b$ = 142 MeV $\Xi_c' - \Xi_c$ = 109 MeV
  - good *ud, ℓs* diquark attraction relative to corresponding spin averages: ~145, 105 MeV
    ⇒ *increasing* attraction with *decreasing* m_q
  - h=c < h=b splittings: residual light-heavy repulsion increasing with decreasing m_h

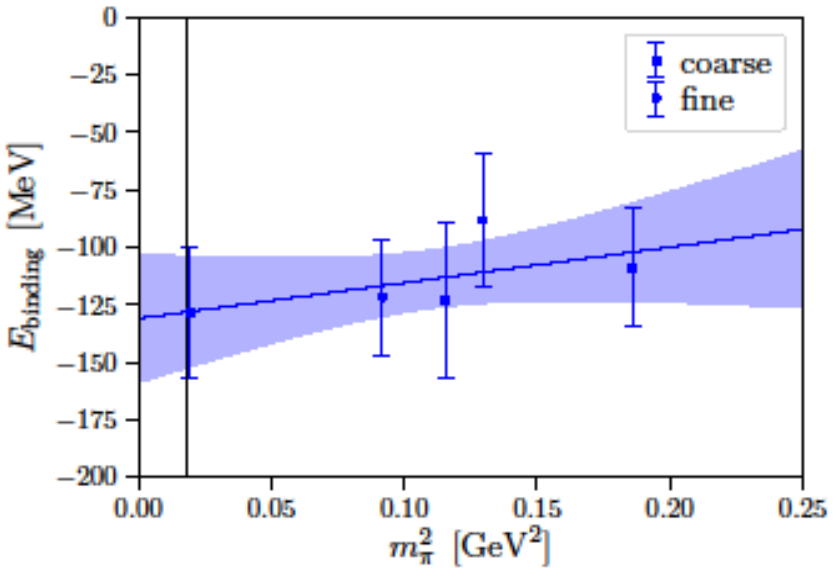
- **⇒ J^P=1^+ $ud\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$ channels best bound doubly heavy tetraquark candidates**

RECENT $qq'\bar{b}\bar{b}$ RESULTS, n_f=2+1, 2+1+1, NRQCD FOR $\bar{b}$

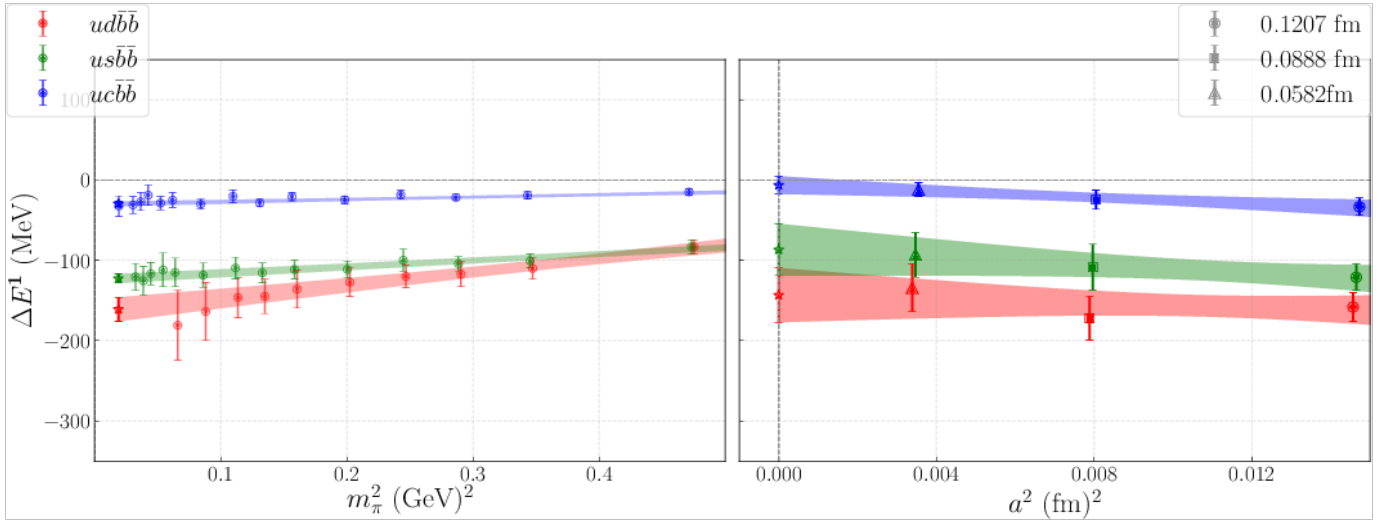
FHLM16



LMPW19



JMP18



➢ $ud\bar{c}\bar{b}$ studies

❖ FHLM18 + preliminary updates (CFHLM19); Mathur *et al.* in progress

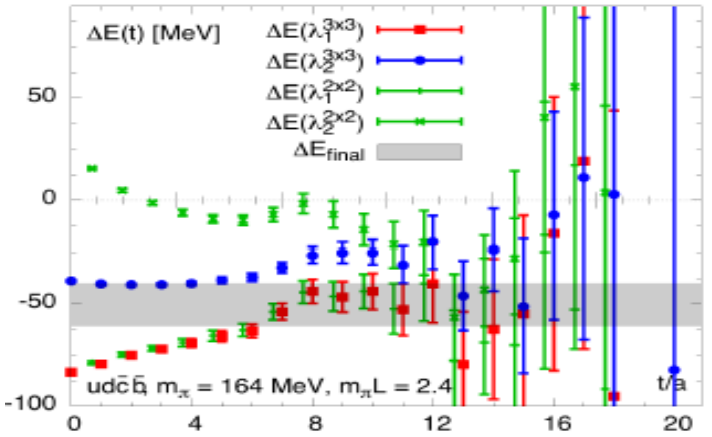
❖ FHLM18

- n_f = 2+1 PACS-CS as for FHLM16 $qq'\bar{b}\bar{b}$
- Charm: Tsukuba RHQ; bottom: NRQCD
- As in FHLM16: gauge-fixed wall sources, local sinks, local "meson-meson" ("DB*", "D*B"), "diquark-antidiquark" operators
- $I(J^P) = 0(1^+)$ only

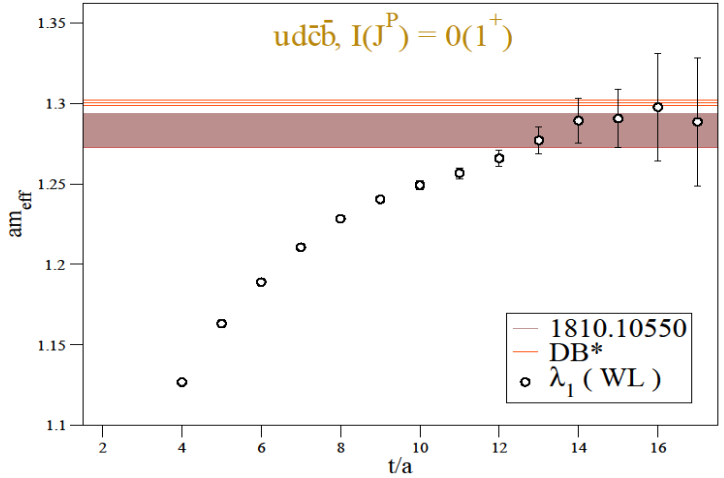
❖ CFHLM19 (B. Colquhoun + FHLM)

- Expanded local operator set
- Extended (box) sinks
- Supplement PACS-CS with new Wilson-clover, Iwasaki gauge ensembles
- $I(J^P) = 0(0^+)$ in addition to $0(1^+)$

FMLM18, 32^3x64, κ_l=0.13781, 195 configs, WL, GEVP



CFHLM19, 48^3x64, κ_l=0.13781, 94 configs, WL, GEVP



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  - $I(J^P) = 0(1^+)$ only
- ❖ CFHLM19 (B. Colquhoun + FHLM)
  - Expanded local operator set
  - **Extended (~0.5 fm) "box" sinks**
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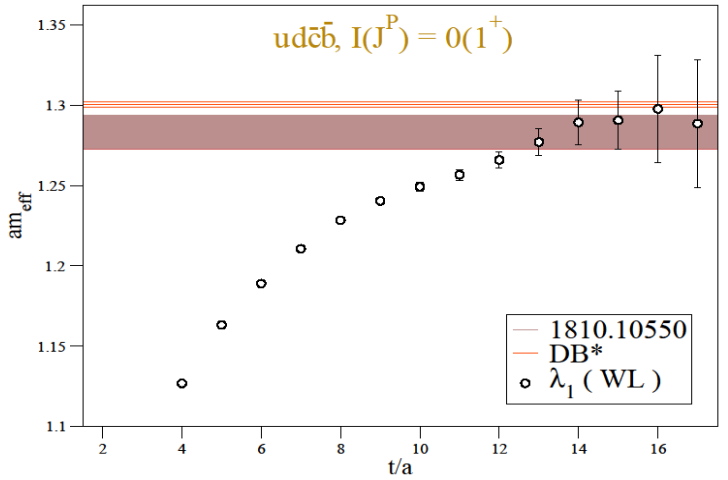

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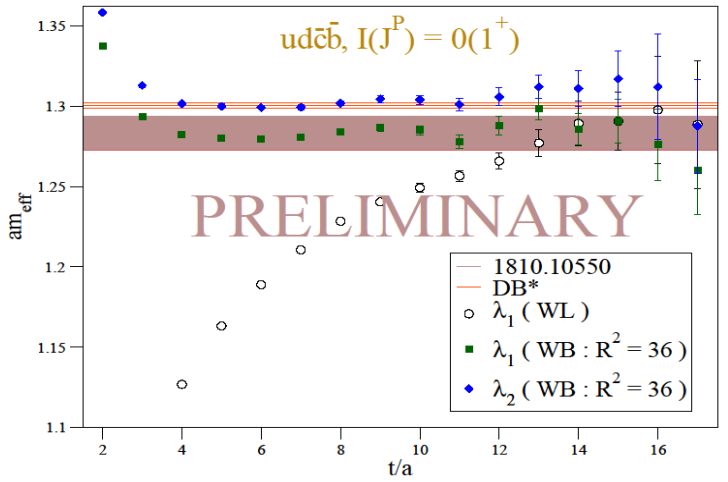

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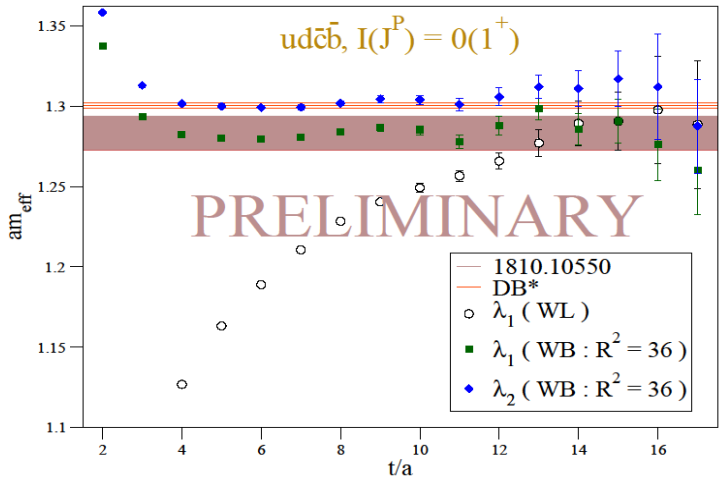
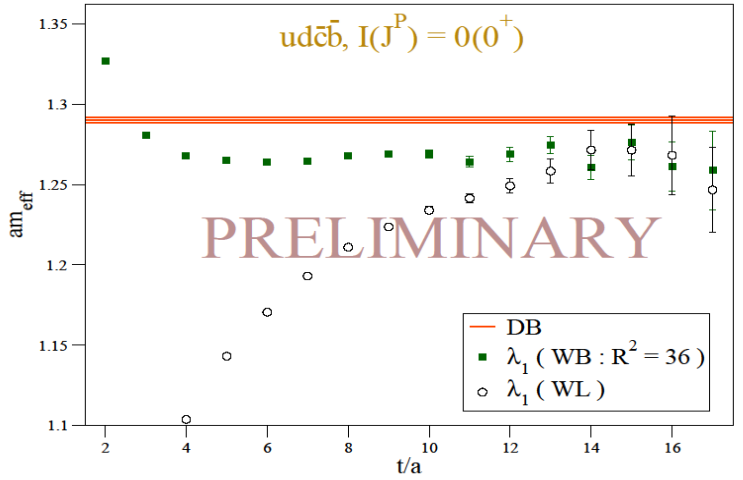
  - **$I(J^P) = 0(0^+)$ in addition to $0(1^+)$**

  $0(0^+)$ below DB, $0(1^+) \Rightarrow 0(1^+) \rightarrow 0(0^+)+\gamma$

CFMLM19, 48^3x64, κ_l=0.13781, 94 configs, WB, GEVP



47(3) MeV (stat only) below DB*



37(3) MeV (stat only) below DB

33(1) MeV (stat only) below $0(1^+)$

➢ For completeness: the $I(J^P) = 0(1^+)$ $ud\bar{c}\bar{c}$ channel

❖ HadSpec17

- n_f=2+1, anisotropic clover + improved Symanzik gauge, $m_\pi = 391$ MeV
- large "meson-meson" + tetraquark basis
- No evidence for $ud\bar{c}\bar{c}$ or $\ell s\bar{c}\bar{c}$ tetraquark binding

❖ JMP18

- Overlap on MILC n_f=2+1+1, $m_\pi = 257 \rightarrow 688$ MeV (PQ), 3 lattice spacings
- Continuum, physical m_π extrapolation: $ud\bar{c}\bar{c}$ bound by 23(11) MeV, $\ell s\bar{c}\bar{c}$ not bound

❖ For future investigation

- differing HadSpec17, JMP18 $ud\bar{c}\bar{c}$ conclusions due to larger HadSpec17 m_π (reduced good light diquark attraction)?
- FV effects on small JMP18 $ud\bar{c}\bar{c}$ binding?

UPCOMING/FUTURE WORK

- Mathur *et al.:* $udc\bar{c}\bar{b}$ runs in progress, I(J^P) = 0(0^+), 0(1^+) results expected this fall

- $udc\bar{c}\bar{c}$: FV, additional near-physical m_π desirable to test shallow JMP18 binding, clarify relation of JMP18 and HadSpec17 results

- CFHLM near-term/in progress
  - $ud\bar{b}\bar{b}$, $udc\bar{b}$ updates with a=0.09 fm, $\kappa_l = 0.13777, 0.13779, 0.13781$, 32^3x64 and 48^3x64 ensembles
  - 200-300 configurations per ensemble, $\kappa_l \leftrightarrow m_\pi \lesssim 200$ MeV
  - Wall-box setup (expect significant improvements of FHLM16 $ud\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$ plateaus)
  - c.f. CFHLM19 results: so far, 94 configs, a=0.09 fm, $\kappa_l = 0.13781$, 48^3x64 only (c.f. 195 for near-physical-point a=0.09 fm, $\kappa_l = 0.13781$, 32^3x64 PACS-CS in FHLM16, FHLM18)

BACKUP SLIDES

➢ Recent $qq'\bar{b}\bar{b}$ channel study specifics

➢ Earlier work with Born-Oppenheimer, static b quark potential

❖ recent e.g.: Bicudo, Scheunert, Wagner [1612.02758]

➢ Studies with non-static (NRQCD) b

❖ FHLM16: qq' = ud, ℓs

n_f = 2+1, PACS-CS Wilson-clover; Iwasaki gauge

a= 0.091 fm, m_π = 164 → 415 MeV

❖ JMP18: qq' = ud, ℓs

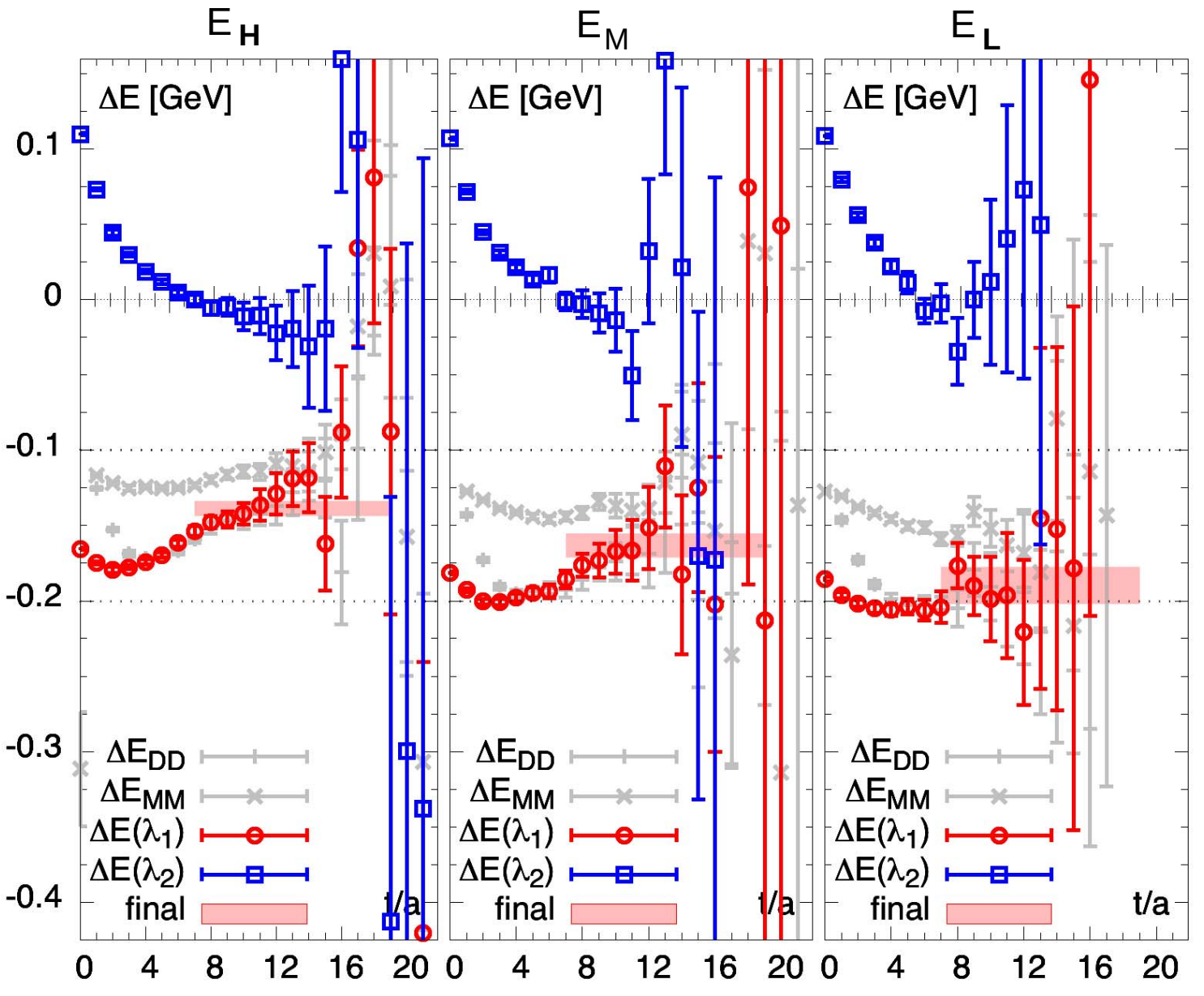
overlap on n_f = 2+1+1 MILC HISQ, one-loop, tadpole-improved Symanzik gauge

a = 0.058, 0.089, 0.121 fm, $m_\pi = 257/189 \rightarrow 688$ MeV (all $m_l = m_s/5$, PQ)

❖ LMPW19: qq' = ud

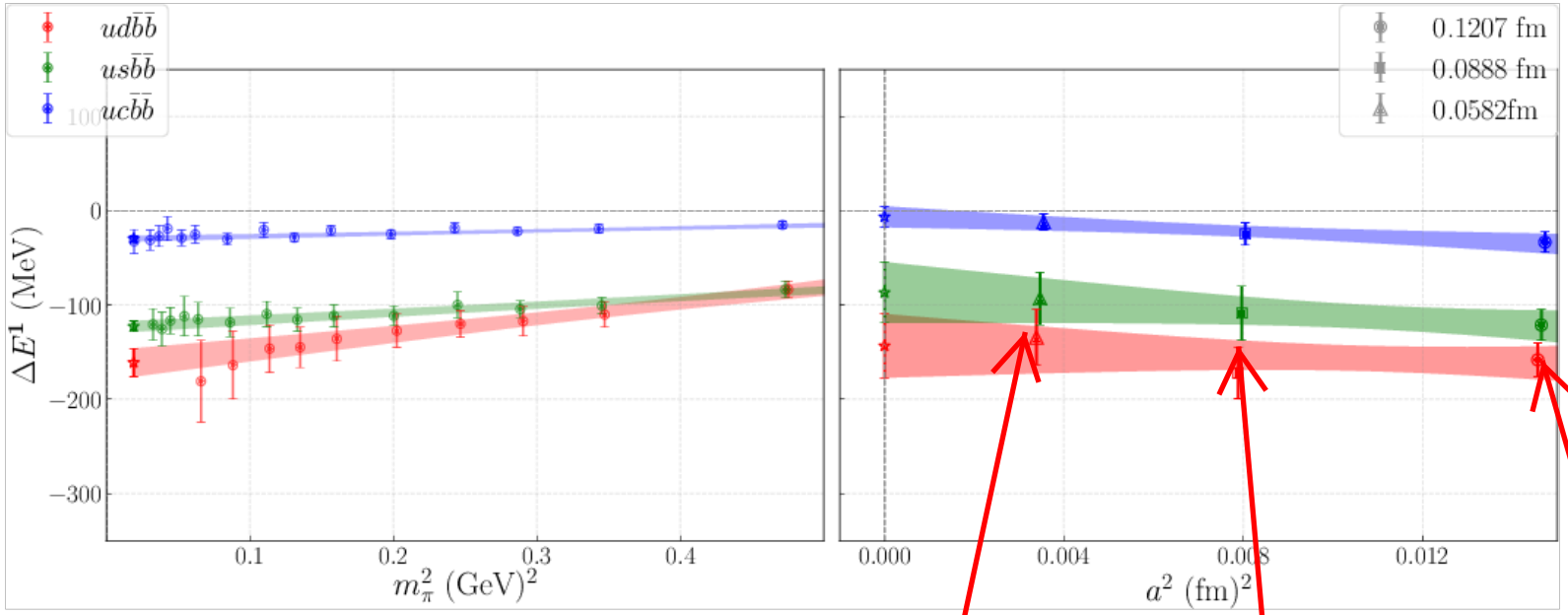
n_f = 2+1 RBC/UKQCD DWF; Iwasaki gauge

a = 0.083, 0.111, 0.114 fm, $m_\pi = 139 \rightarrow 431$ MeV


E H
E M
E L
ΔE [GeV]
0.1
0
-0.1
-0.2
-0.3
-0.4
ΔE_DD
ΔE_MM
ΔE(λ1)
ΔE(λ2)
final
t/a
0
4
8
12
16
20

GEVPs. udbb

a=0.12 fm



Linear-in-m_π^2 fit ranges: 545-685 MeV, 345-688 MeV, 257/186-689 MeV

LMPW19 m_π = 340 MeV FIT RESULTS

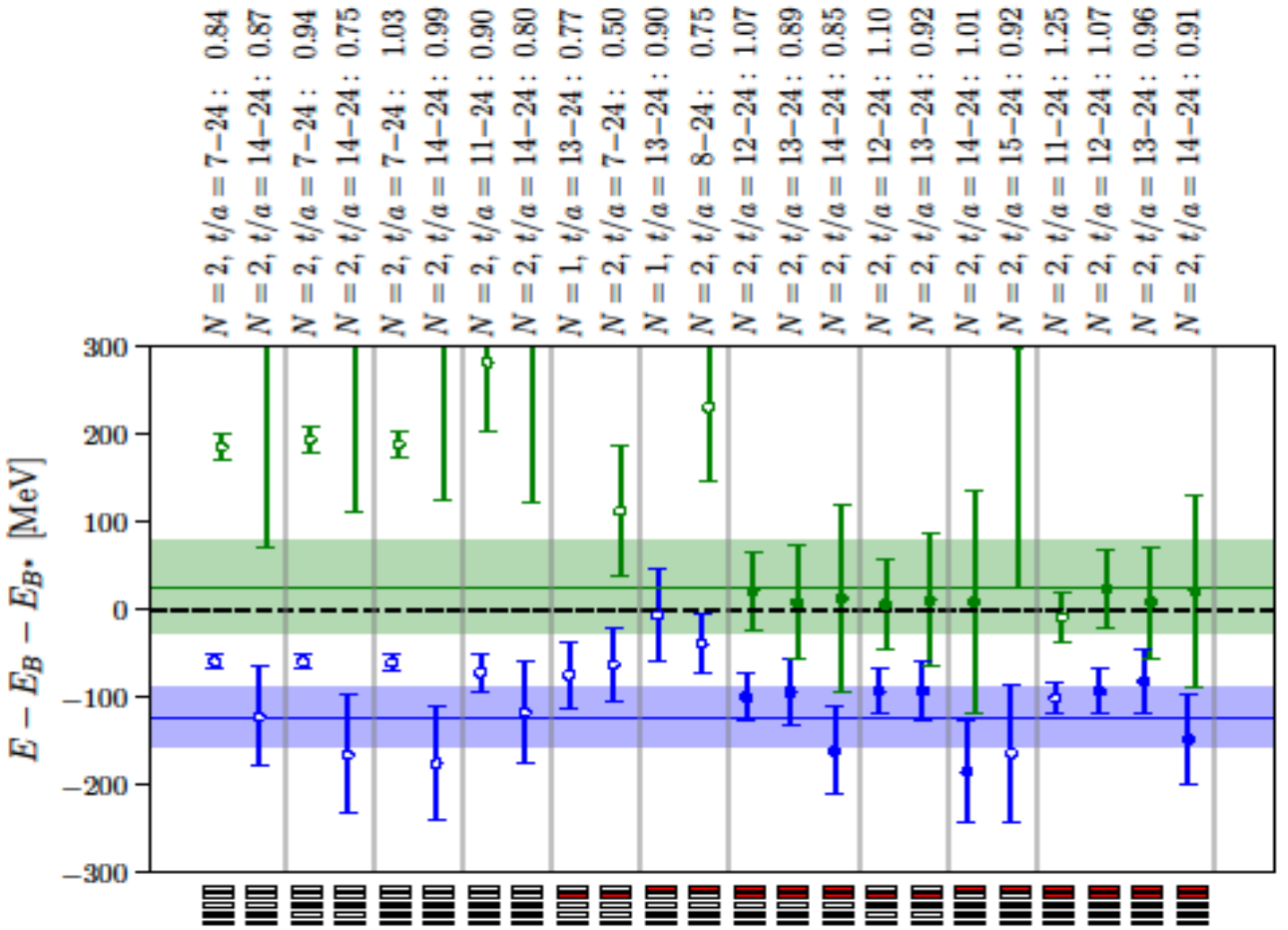


FIG. 4. Results for the lowest two $\bar{b}\bar{b}ud$ energy levels relative to the BB^* threshold, $\Delta E_n = E_n - E_B - E_{B^*}$, as determined on ensemble C005 from several different fits. The five bars below each column indicate the interpolators used, as explained in the main text. Above each column, we give the number of exponentials, the fit range, and the value of χ^2/d.o.f.. The shaded horizontal bands correspond to our final estimates of ΔE_0 and ΔE_1, obtained from a bootstrap average of the subset of fits that are shown with filled symbols.

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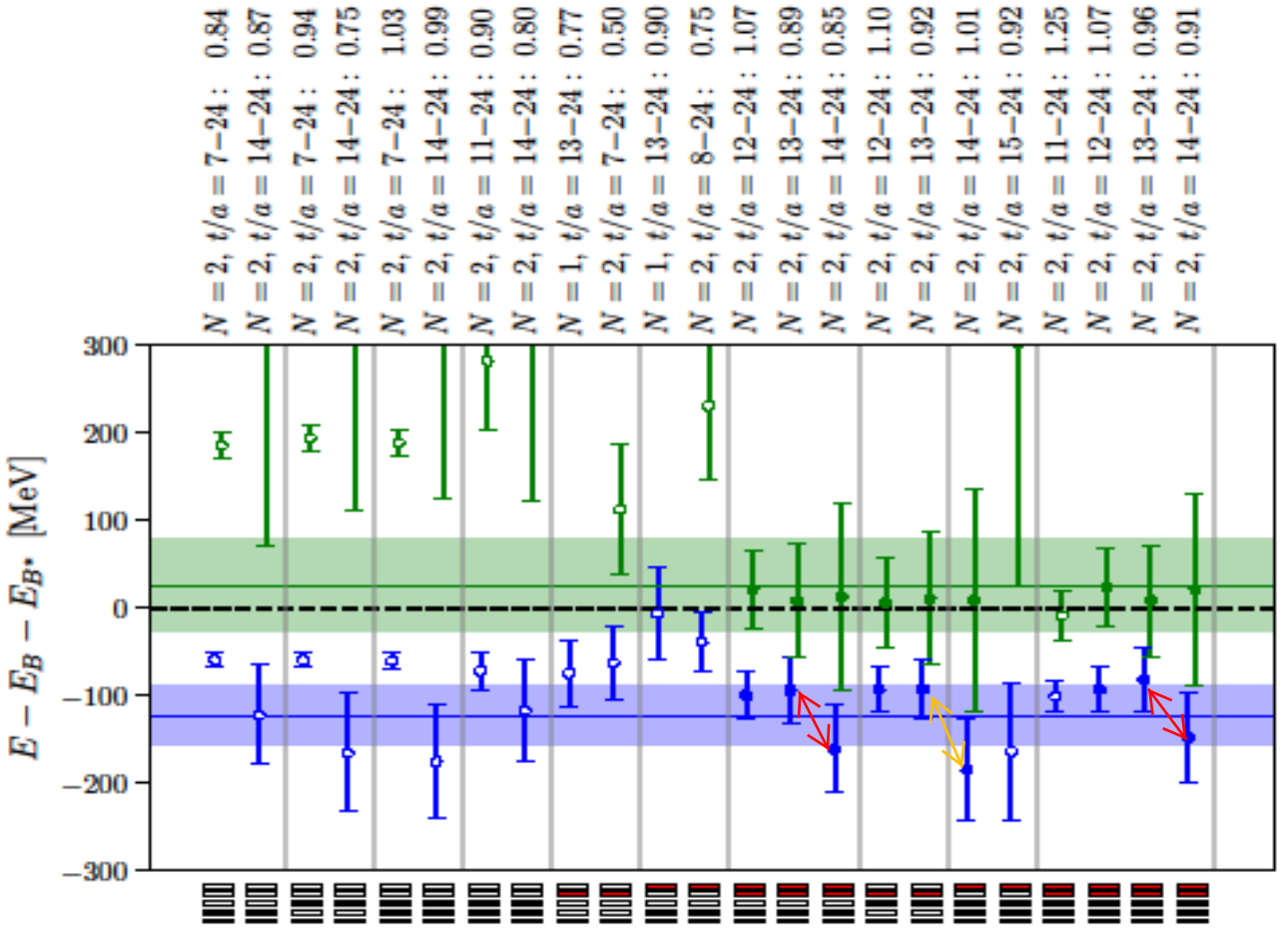

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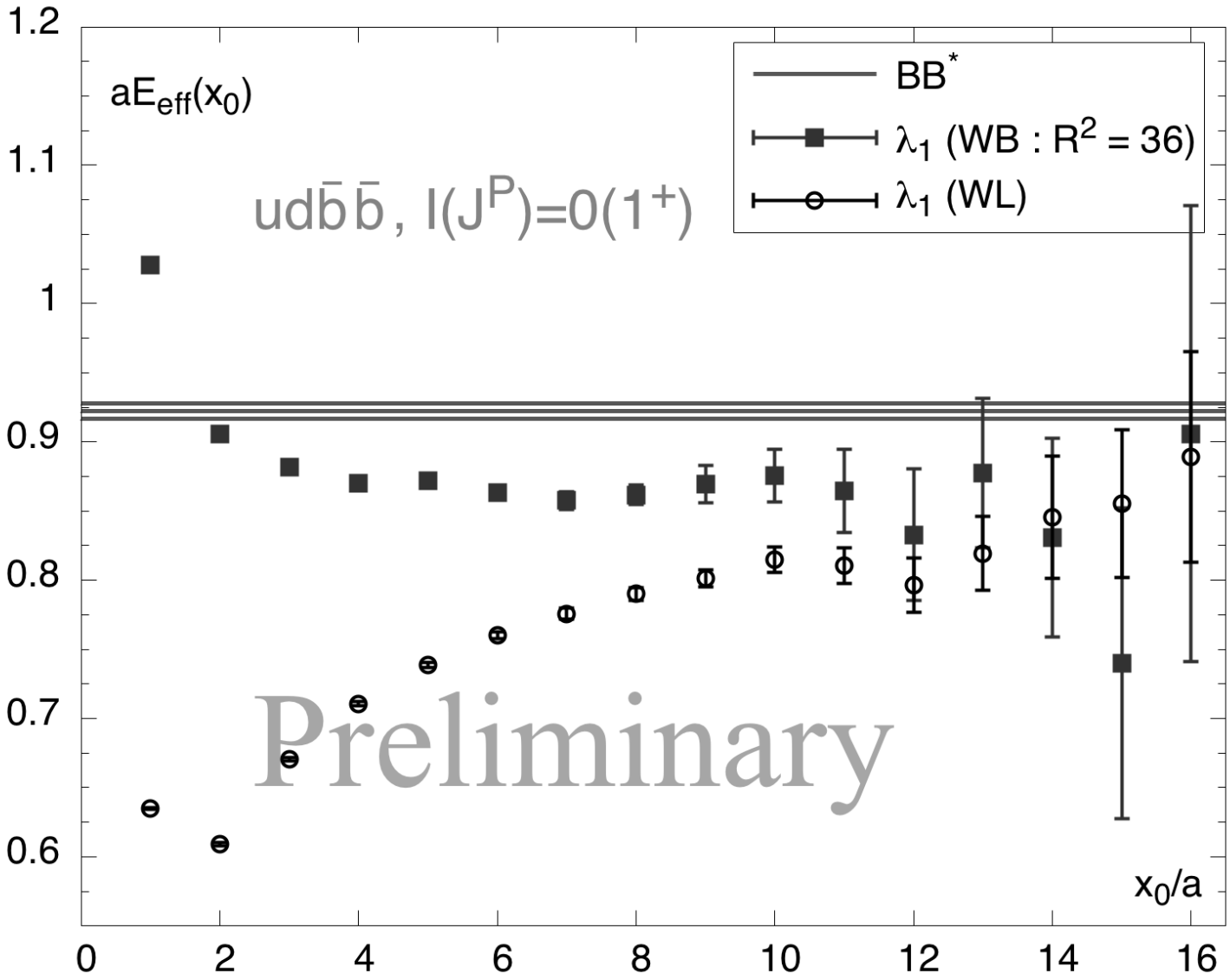
Preliminary udbb 32^3x64, kappa=0.13781 update (WB improvement, 63 configurations only)



➢ Summary of current status for $\mathrm{ud}\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$

❖ $ud\bar{b}\bar{b}$: FHLM16, JMP18, LMPW19 all see sub-BB^*-threshold $I(J^P) = 0(1^+)$ state

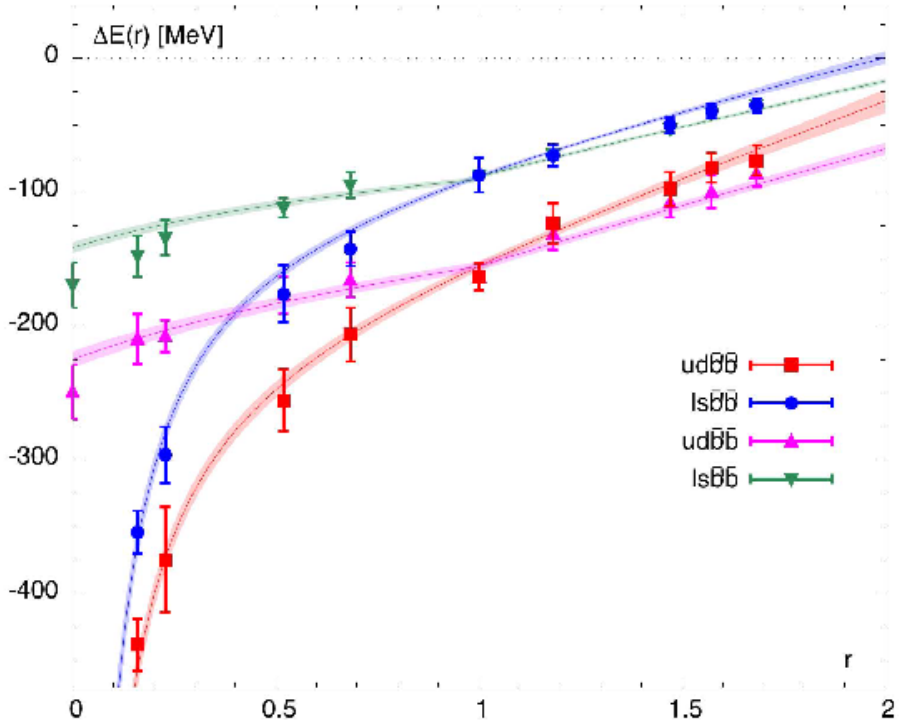
- Binding in all cases below EM decay threshold ⇒ weak decays only
- All see increased binding with decreasing m_q, as per good-light-diquark expectation
- LMPW19 L$\ddot{u}$scher analysis confirms bound state interpretation
- FHLM16 updates (FHLM+Colquhoun) in progress: larger volumes, more light m_q, *extended sinks for improved plateaus* (preliminary results: no volume dependence)

❖ $\ell s\bar{b}\bar{b}$: FHLM16, JMP18 both see bound $J^P = 1^+$ isodoublet

- Also below EM decay threshold, weak decays only
- Less bound than $I(J^P)= 0(1^+)$, as per expected light-quark mass dependence of good diquark attraction
- FHML16 updates as for $ud\bar{b}\bar{b}$ $I(J^P)= 0(1^+)$ in progress

➢ Test of color-Coulomb + good-light-diquark binding picture

- ❖FHLM18 [1810.10550] study, $m_\pi = 299$ MeV ensemble
- ❖ $qq'\bar{b}\bar{b}', qq'\bar{b}'\bar{b}'$ with $m_{b'}$ in range $0.6m_b \rightarrow 6.3m_b$ still amenable to use of NRQCD
- ❖ Fit to model with expected color Coulomb + good light diquark m_q, m_Q dependence
- ❖ Suggests $ud\bar{c}\bar{b}$ as next best channel for study



❖ Current status CFHLM 32^3x64 and 48^3x64 configurations

Size	κ_l	Current # configs	Target # configs
32^3x64	0.13781	145	~200
	0.13779	278	completed
	0.13777	306	completed
48^3x64	0.13781	175	~200
	0.13779	48	~200
	0.13777	200	completed