STRONG INTERACTION STABLE HEAVY TETRAQUARKS FROM THE LATTICE

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HADRON 2019, 桂林 , Aug. 16-21, 2019

OUTLINE

- Basic features of doubly heavy tetraquark channels
- Brief review of doubly bottom results
- Variable b mass test of underlying binding picture
- Bottom-charm results
- $I(J^P) = 0(0^+), 0(1^+)$ bottom-strange channel results
- Conclusions and future work

BASIC FEATURES OF DOUBLY HEAVY TETRAQUARK CHANNELS

o Interactions in localized $qq'\bar{Q}\bar{Q}'$ absent for separated heavy meson pairs

- $\bar{Q}\bar{Q}'$ 3_c color Coulomb attraction
  - binding proportional to $\bar{Q}\bar{Q}'$ reduced mass μ_h
  - dominant as $\mu_h \to \infty$ ($\Rightarrow$ bound tetraquarks for Q=Q', $m_Q \to \infty$)
  - for s-wave $\bar{Q}\bar{Q}'$: $J_h=1$ (Q=Q'); $J_h=0, 1$ ($Q \neq Q'$)

- Attractive "good" light qq' diquark interaction in field of heavy 3_c source
  - "good" ($J = 0, F = \bar{3}, C = \bar{3}$) vs "bad" ($J = 1, F = 6, C = \bar{3}$) qq' configuration
  - phenomenological constraints from heavy baryon splittings

$\Sigma_b - \Lambda_b$ = 194 MeV $\qquad$ $\Sigma_c - \Lambda_c$ = 167 MeV

$\Xi_b' - \Xi_b$ = 142 MeV $\qquad$ $\Xi_c' - \Xi_c$ = 109 MeV

➢ Implications/observations

- $\Sigma_b - \Lambda_b = 194$ MeV ↑
  $\Xi_b' - \Xi_b = 142$ MeV ↓

- good ud, ℓs diquark attraction relative to corresponding spin averages: ~145, 105 MeV
  ⇒ *increased* attraction with *decreased* m_q

- $\Sigma_c - \Lambda_c = 167$ MeV ↑
  $\Xi_c' - \Xi_c = 109$ MeV ↓

- h=c vs. h=b: residual ($\propto 1/m_h$) light-heavy interactions eat into good diquark attraction with decreasing m_h

- Coulomb BE $\propto \mu_h$

- ⇒ Binding most likely for $J^P=1^+$ $ud\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$

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  $\Sigma_c - \Lambda_c = 167$ MeV ↕

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- h=c vs. h=b: residual ($\propto 1/m_h$) light-heavy interactions eat into good diquark attraction with decreasing m_h

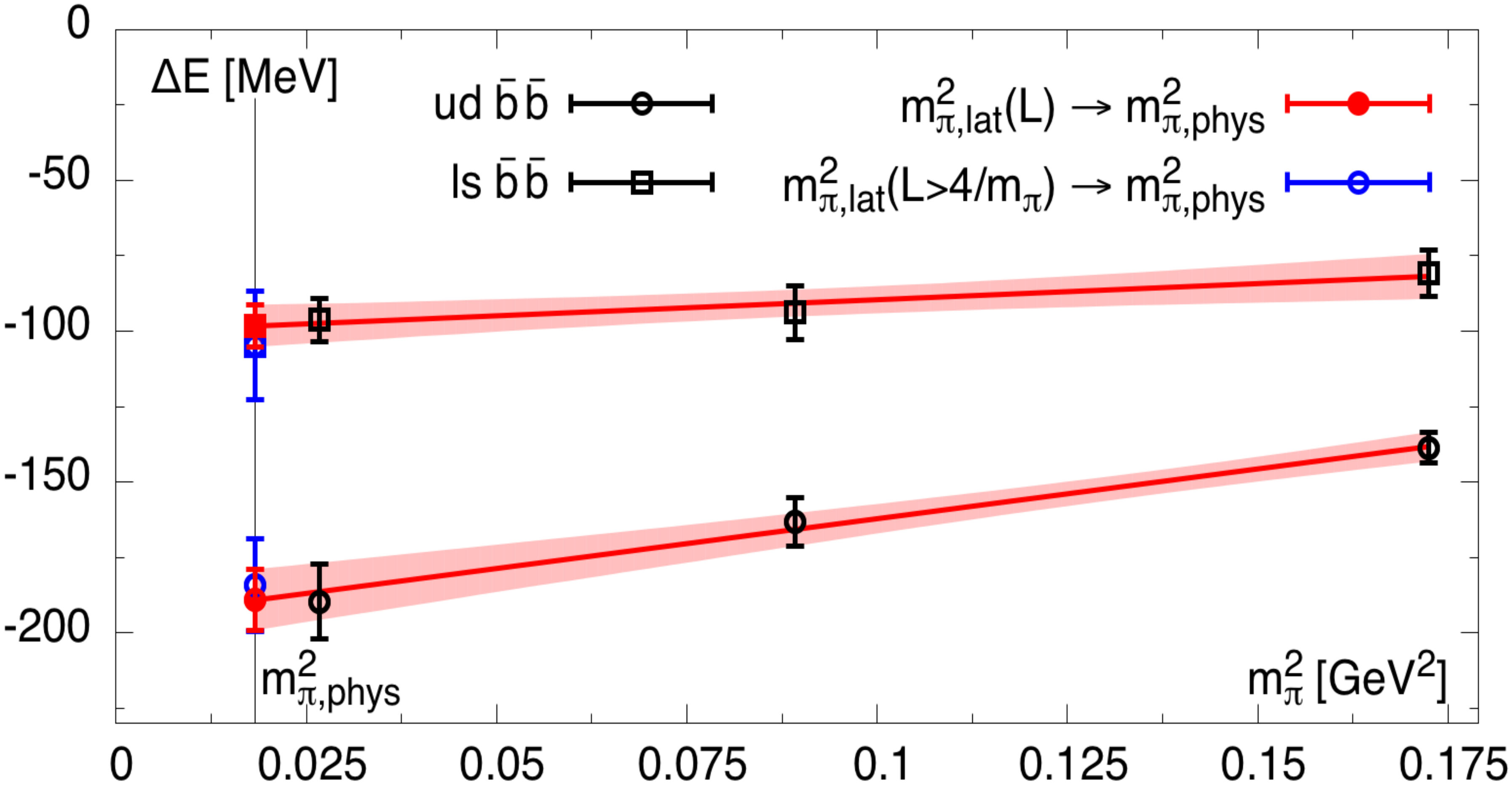
- $\Rightarrow$ Binding most likely for $J^P=1^+$ $ud\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$

o Lattice studies/results for doubly bottom channels

- Earlier work with Born-Oppenheimer, static b quark potential
  - recent e.g.: Bicudo, Scheunert, Wagner [1612.02758]

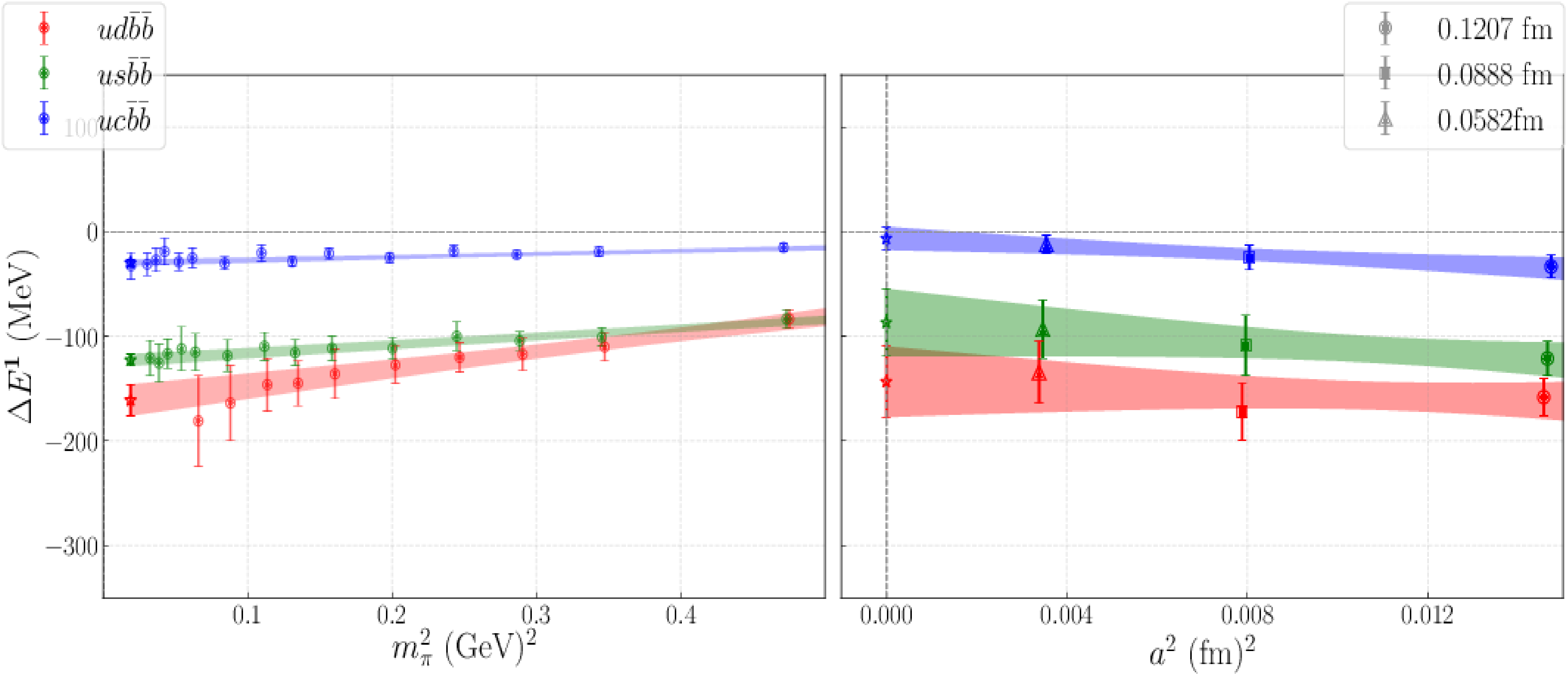
- Studies with non-static (NRQCD) b
  - Francis, Hudspith, Lewis, KM: qq' = ud, ℓs [1607.05214] (FHLM16)
    n_f = 2+1, PACS-CS Wilson-clover; Iwasaki gauge
    a= 0.091 fm, m_π = 164 → 415 MeV
  - Junnarkar, Mathur, Padmanath: qq' = ud, ℓs [1810.12285] (JMP18)
    overlap on n_f = 2+1+1 MILC HISQ; one-loop, tadpole-improved Symanzik gauge
    a = 0.058, 0.089, 0.121 fm, $m_\pi = 257\ (ud), 189\ (\ell s) \rightarrow 688$ MeV (PQ)
  - Leskovec, Meinel, Pflaumer, Wagner: qq' = ud [1904.04197] (LMPW19)
    n_f = 2+1 RBC/UKQCD DWF; Iwasaki gauge
    a = 0.083, 0.111, 0.114 fm, $m_\pi = 139 \rightarrow 431$ MeV

➢ FHLM16



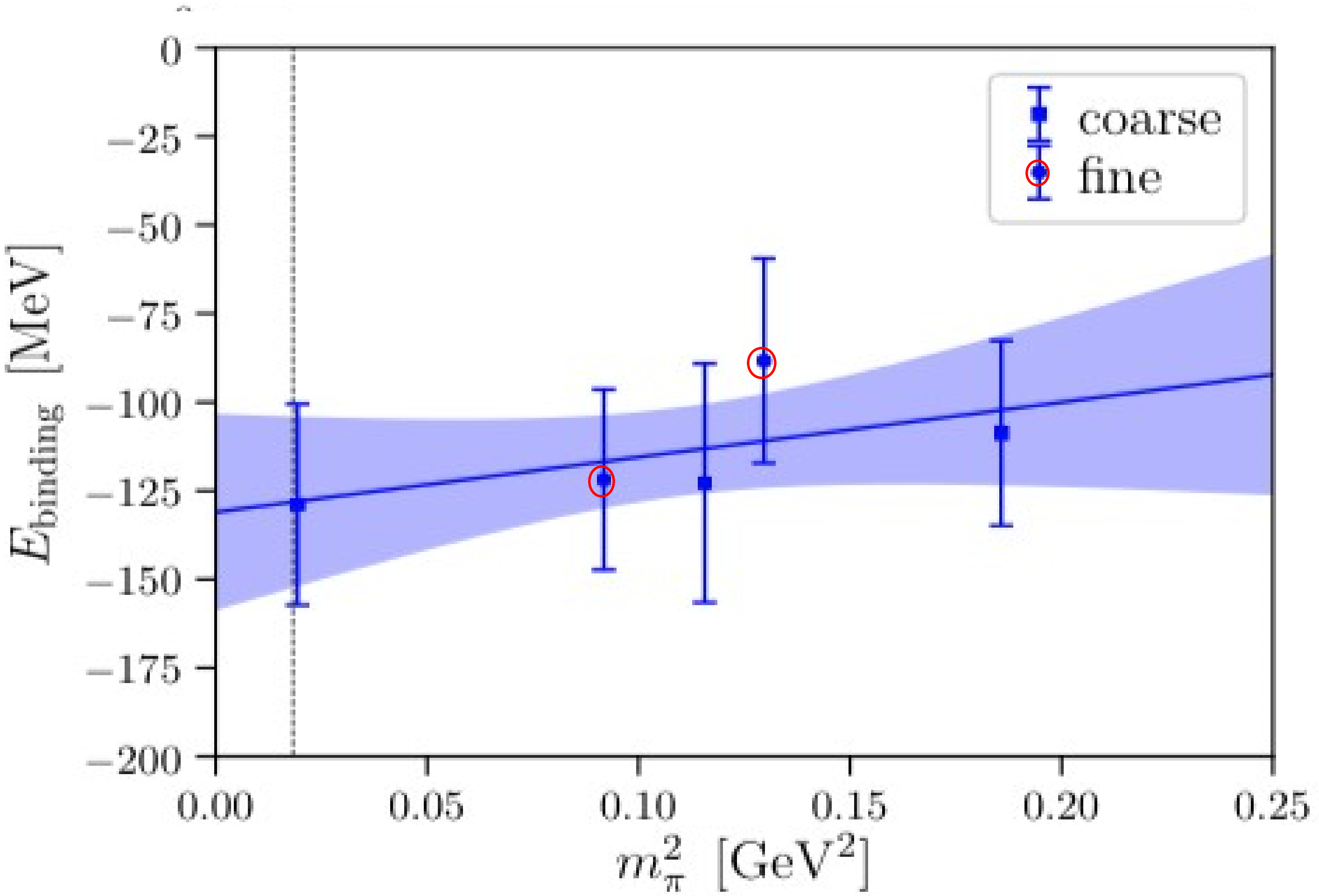
ΔE [MeV]
$ud\,\bar{b}\bar{b}$
$ls\,\bar{b}\bar{b}$
$m^2_{\pi,lat}(L) \to m^2_{\pi,phys}$
$m^2_{\pi,lat}(L>4/m_\pi) \to m^2_{\pi,phys}$
$m^2_{\pi,phys}$
m^2_π [GeV^2]
0
-50
-100
-150
-200
0
0.025
0.05
0.075
0.1
0.125
0.15
0.175

➢ JMP18



$ud\bar{b}\bar{b}$
$us\bar{b}\bar{b}$
$uc\bar{b}\bar{b}$
100
0
−100
−200
−300
ΔE^1 (MeV)
0.1
0.2
0.3
0.4
m_π^2 (GeV)^2
0.1207 fm
0.0888 fm
0.0582fm
0.000
0.004
0.008
0.012
a^2 (fm)^2

➢ **LMPW19**



coarse
fine
0
−25
−50
−75
−100
−125
−150
−175
−200
E_{binding} [MeV]
0.00
0.05
0.10
0.15
0.20
0.25
m_π^2 [GeV^2]

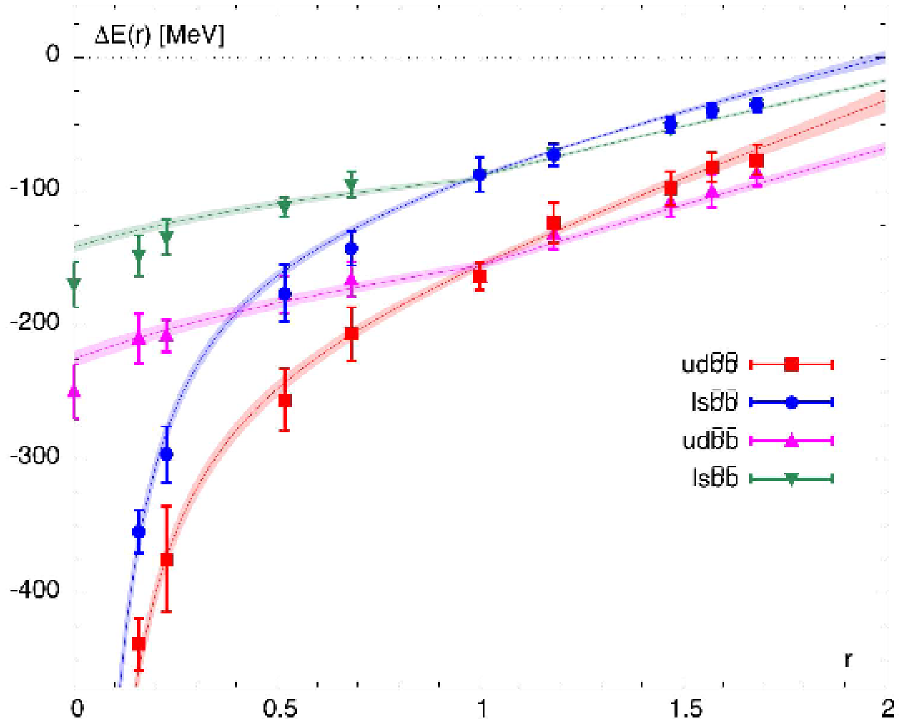
Summary of current status for $ud\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$

- $ud\bar{b}\bar{b}$: 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 Lüscher 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



o The $ud\bar{c}\bar{b}$ (and $ud\bar{c}\bar{c}$) channels

- Detecting doubly bottom state exclusive decay modes experimentally challenging: low production rates, low weak exclusive mode BFs, low daughter BFs and experimental efficiencies in sequential decay chains

- Alternate Gershon, Poluetkov [1810.06657] suggestion (inclusive search at LHCb using B_c's coming from displaced vertices) still challenging

- Much higher production rates expected for states with one or both $\bar{b}$'s replaced by a $\bar{c}$, IF such states exist

- Though NRQCD breakdown prevents variable b' mass study from reaching b'=c, results suggest $ud\bar{c}\bar{b}$ most likely among bottom-charm, charm-charm channels to support a bound tetraquark state

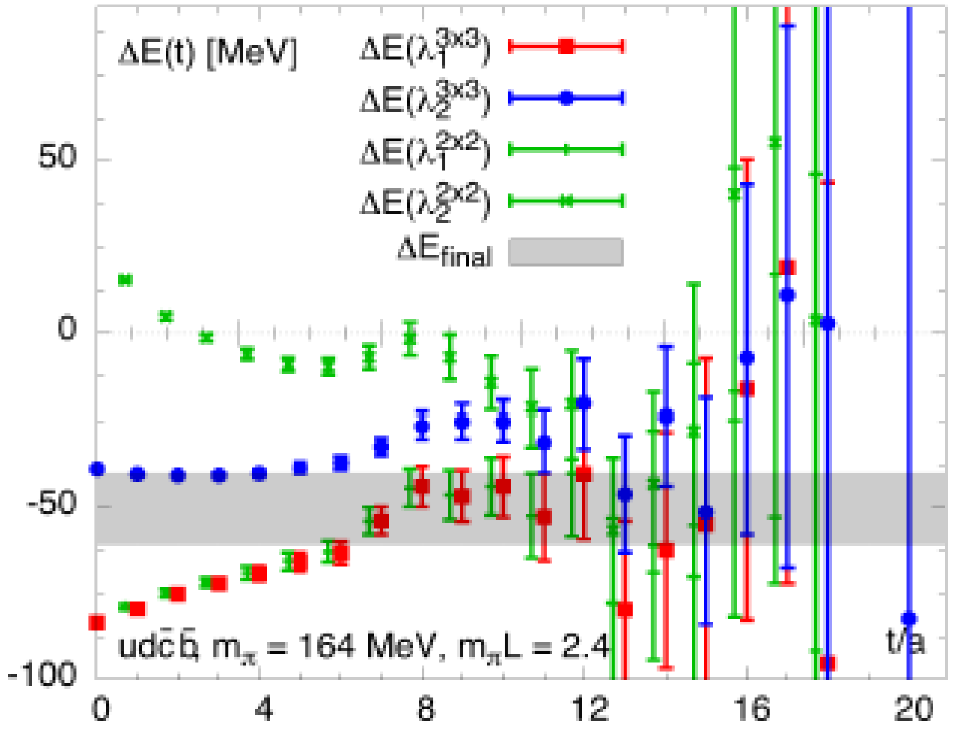
➢ $ud\bar{c}\bar{b}$ studies

- FHLM18 [1810.10550] + preliminary updates (CFHLM19); Mathur *et al.* in progress
- FHLM18
  - n_f = 2+1 PACS-CS (32^3x64, $m_\pi = 164, 299, 415$ MeV) as for FHLM16 $ud\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$
  - Charm: Tsukuba RHQ action [Namekawa *et al*. 1104.4600 tuning]; bottom: NRQCD
  - Also as in FHLM16: gauge-fixed wall sources, local sinks, local discrete "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 $0(1^+)$

➢ FHLM18: I(J^P) = 0(1^+) $ud\bar{c}\bar{b}$ results

- No binding for $m_\pi = 415$ MeV
- Evidence for binding ~ 15 → 61 MeV from m_π = 299, 164 MeV ensembles

- E.g. m_π=164 MeV GEVP results for ground, first excited states
- Reduced binding c.f. $ud\bar{b}\bar{b}$, as per expectations
- Improved ground-excited state separation, better ground state plateau, FV study desirable

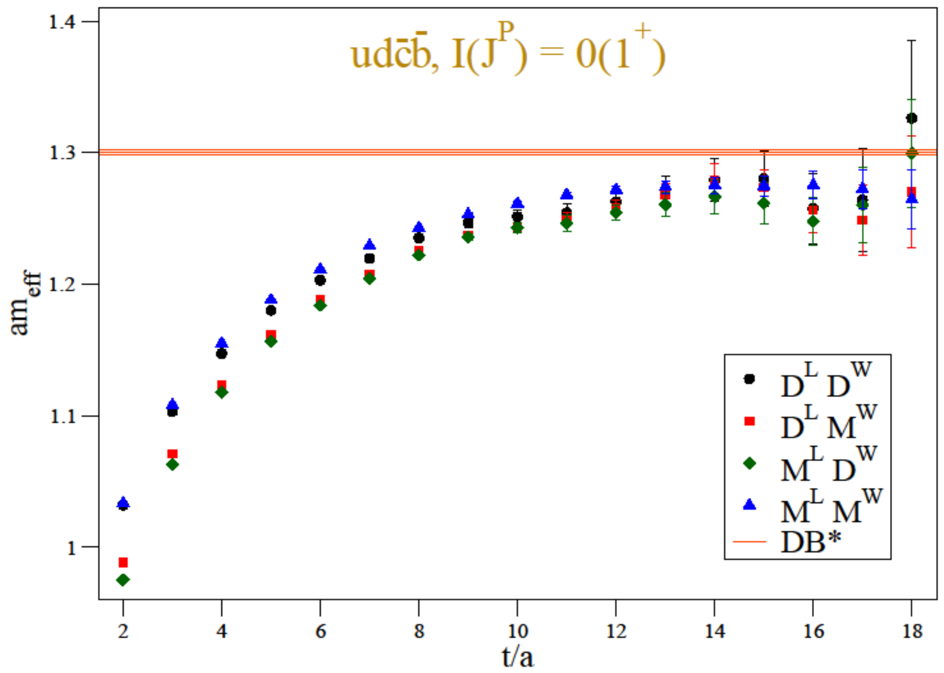


➢ CFHLM19 (1): $ud\bar{c}\bar{b}$, I(J^P)=0(1^+): old-style WL, larger V, m_{eff} results

- E.g.: with 94 new 48^3x64, κ=0.13781 configs (c.f. FHLM18: 195 PACS-CS 32^3x64, κ=0.13781)

- Wall source, local sink (as in FHLM18): both "meson-meson" and "diquark-antidiquark" operators show good overlap with ground state

- Effective mass plateaus late (also as in FHLM18)



➢ CFHLM19 (2): $ud\bar{c}\bar{b}$, I(J^P)=0(1$^+$) update 1: WL with expanded basis

- 48^3x64, κ=0.13781 results (currently: ~1/2 FHLM18 statistics, more to come)
- Wall-local setup, as in FHLM18
- Increased local operator basis
- 4x4 GEVP: ground state effective mass c.f. FHLM18 range

* Improvements:

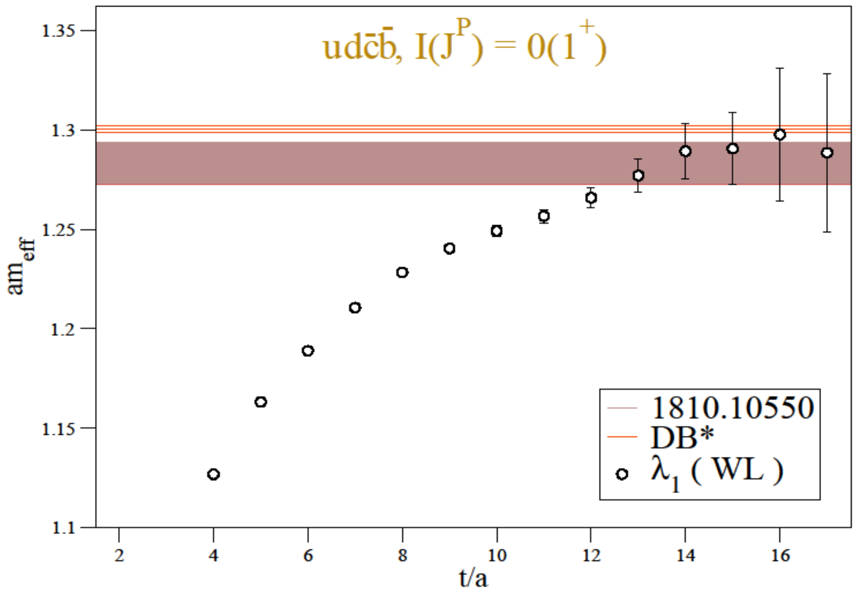
- Increased operator basis
- Wall-box set-up

$$D_{P,V_i} = (u_b^T C\gamma_5 d_c)\left[(\bar{c}_b C\gamma_i \bar{b}_c^T) - (\bar{c}_c C\gamma_i \bar{b}_b^T)\right]$$

$$D_{A_t,\sigma_{it}} = (u_b^T C\gamma_t\gamma_5 d_c)\left[(\bar{c}_b C\gamma_i\gamma_t \bar{b}_c^T) - (\bar{c}_c C\gamma_i\gamma_t \bar{b}_b^T)\right]$$

$$M_{P,V_i} = (\bar{c}_a\gamma_5 u_a)(\bar{b}_b\gamma_i d_b) - (\bar{c}_a\gamma_5 d_a)(\bar{b}_b\gamma_i u_b),$$

$$M_{I,A_i} = (\bar{c}_a I u_a)(\bar{b}_b\gamma_i\gamma_5 d_b) - (\bar{c}_a I d_a)(\bar{b}_b\gamma_i\gamma_5 u_b).$$



➢ CFHLM19 (3): $ud\bar{c}\bar{b}$, I(J^P)=0(1^+) update 2: extended sinks

- 48^3x64, κ=0.13781 results (currently: ~1/2 FHLM18 statistics, more to come)
- Local sink → extended (~0.5 fm) "box" sink for improved ground state overlap
- Increased local operator basis
- 4x4 GEVP: ground state effective mass c.f. FHLM18 range
- 47(3) MeV (stat only) below DB*

* Improvements:

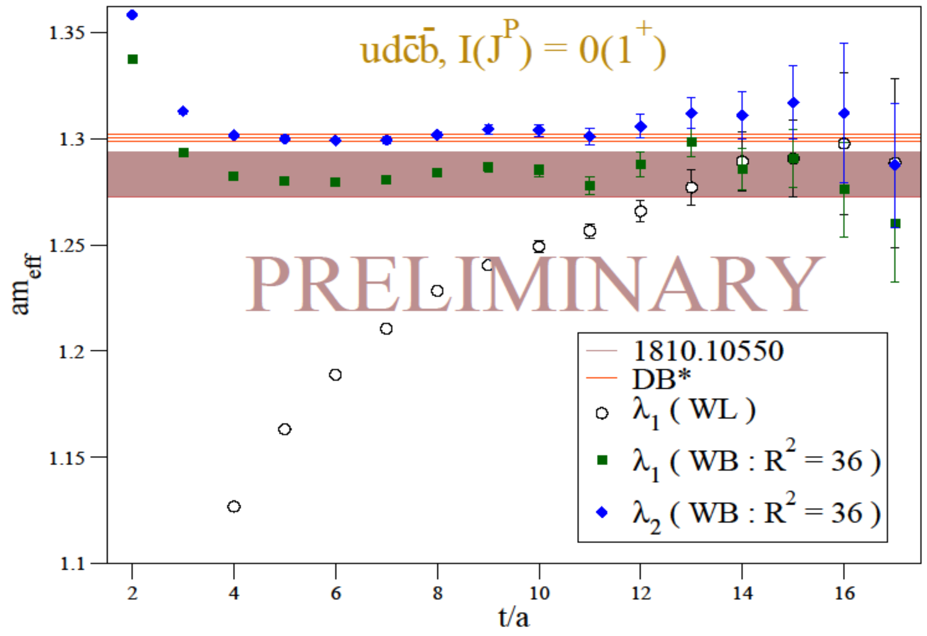
- Increased operator basis
- Wall-box set-up

$$D_{P,V_i} = (u_b^T C\gamma_5 d_c)\,[\,(\bar{c}_b C\gamma_i \bar{b}_c^T) - (\bar{c}_c C\gamma_i \bar{b}_b^T)\,]$$

$$D_{A_t,\sigma_{it}} = (u_b^T C\gamma_t\gamma_5 d_c)\,[\,(\bar{c}_b C\gamma_i\gamma_t \bar{b}_c^T) - (\bar{c}_c C\gamma_i\gamma_t \bar{b}_b^T)\,]$$

$$M_{P,V_i} = (\bar{c}_a\gamma_5 u_a)(\bar{b}_b\gamma_i d_b) - (\bar{c}_a\gamma_5 d_a)(\bar{b}_b\gamma_i u_b),$$

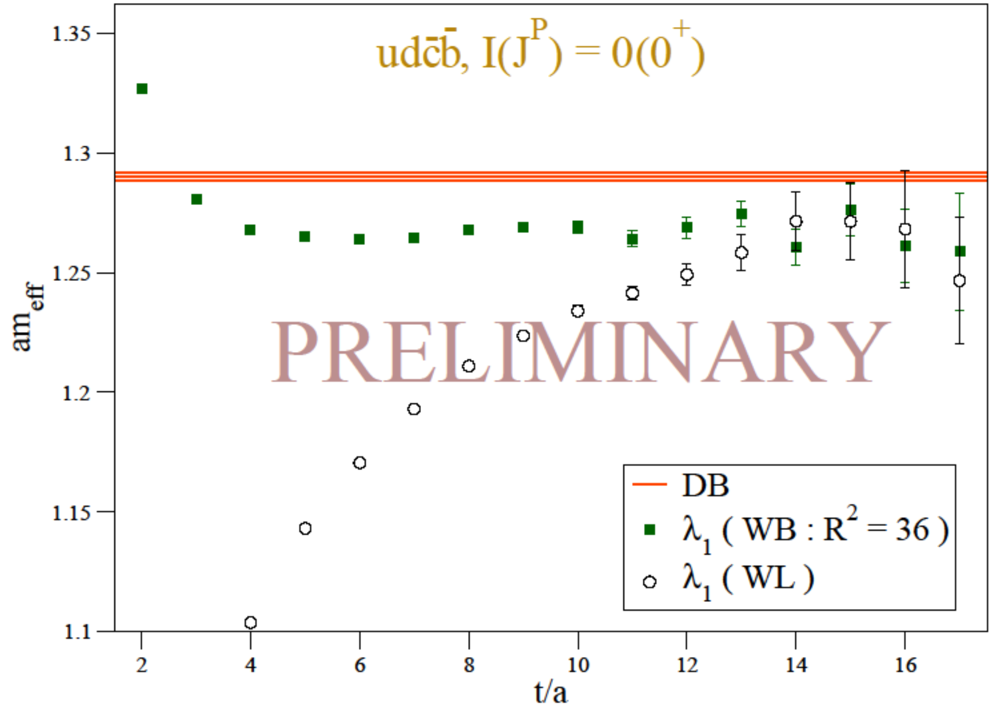
$$M_{I,A_i} = (\bar{c}_a I u_a)(\bar{b}_b\gamma_i\gamma_5 d_b) - (\bar{c}_a I d_a)(\bar{b}_b\gamma_i\gamma_5 u_b).$$



➢ CFHLM19 (4): preliminary results $ud\bar{c}\bar{b}$ $I(J^P)=0(0^+)$

- 48^3x64, κ=0.13781 (more statistics, more $m_\pi < 200$ MeV to come)
- 4x4 GEVP, wall-box setup for improved ground state plateau, as for $I(J^P) = 0(1^+)$
- 37(3) MeV (stat error only) below DB
- 33(1) MeV below $I(J^P) = 0(1^+)$

  $\Rightarrow 0(1^+)$ decay to $0(0^+) + \gamma$



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

❖ HadSpec [1709.01417]

- 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 $\ell s\bar{c}\bar{c}$ bound tetraquarks

❖ JMP18 [1810.12285]

- MILC n_f=2+1+1, $m_\pi = 257 \rightarrow 688$ MeV (PQ), 3 lattice spacings
- Results extrapolated to continuum, physical m_π: $ud\bar{c}\bar{c}$ bound by 23(11) MeV, no sign of binding for $\ell s\bar{c}\bar{c}$

❖ **For future investigation**

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

➢ The singly bottom I(J^P) = 0(1^+), 0(0^+) $ud\bar{s}\bar{b}$ channels

- ❖ Further exploration of light-quark configurations accessible in the field of a heavy color source (good light *ud* diquark for localized $ud\bar{s}\bar{b}$, but impact of $\bar{s}$?)

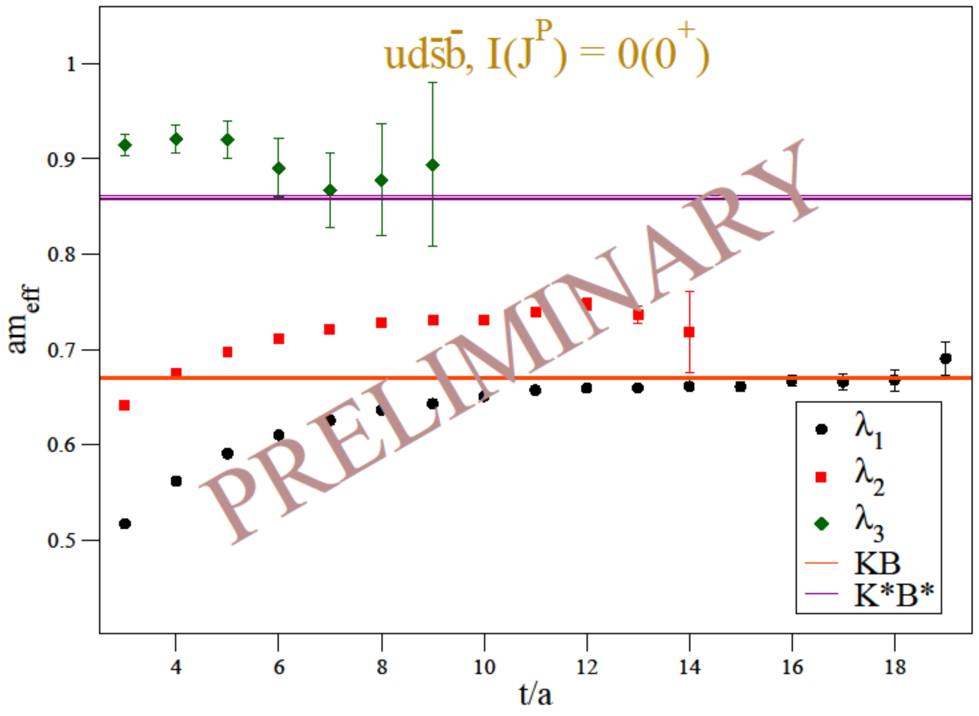
- ❖ Light-quark configuration not present in ordinary mesons, baryons, hence (unlike doubly heavy channels) no phenomenological constraints from the ordinary hadron spectrum

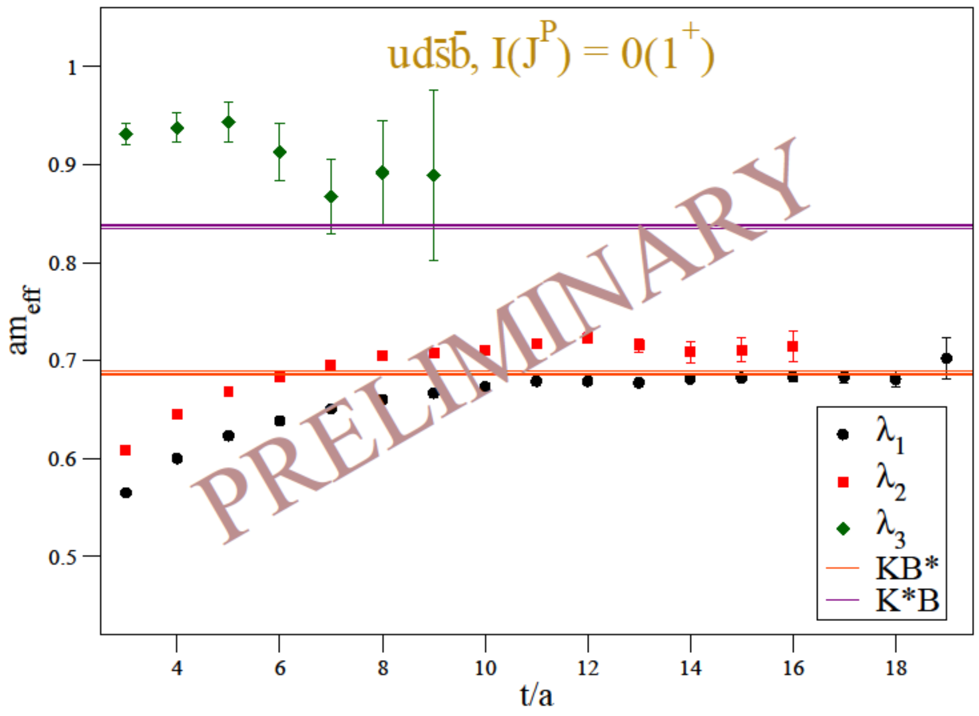
- ❖ Initial X(5568) motivation, binding wrt B*K, BK in some phenomenological models, e.g., Chen & Ping [1806.10505], Huang & Ping [1902.05778], but some model light-quark interactions necessarily unconstrained by fits to ordinary meson and baryon spectra

- ❖ Situation unlike that of the doubly heavy sector, where phenomenology constrains the dominant (color Coulomb and light-quark spin-spin) interactions ⇒ success of models in predicting bound doubly heavy states no guarantee of utility for other exotic channels

❖ $uds\bar{b}$ results: no binding for either $I(J^P) = 0(0^+)$ or $0(1^+)$

- Preliminary 3x3 GEVP results with 94 new 48^3x64, $\kappa_l = 0.13781$ configurations





CURRENT STATUS, DOUBLY HEAVY TETRAQUARK STATES

- Agreement on $\bar{3}_F$ of doubly bottom $J^P = 1^+$ tetraquarks bound wrt strong and EM decay thresholds (but challenging experimentally)

- Previous evidence for $I(J^P) = 0(1^+)$ $ud\bar{c}\bar{b}$ bound below DB* threshold (hence also strong-interaction-stable) significantly strengthened

- New results show good evidence for second $ud\bar{c}\bar{b}$ tetraquark, with $I(J^P) = 0(0^+)$
  - bound wrt both DB and $0(1^+)$ tetraquark partner
  - $\Rightarrow$ expect $0(1^+)$ tetraquark decay to $0(0^+)+\gamma$, $0(0^+)$ by weak decay only

- Further work needed on doubly charmed states

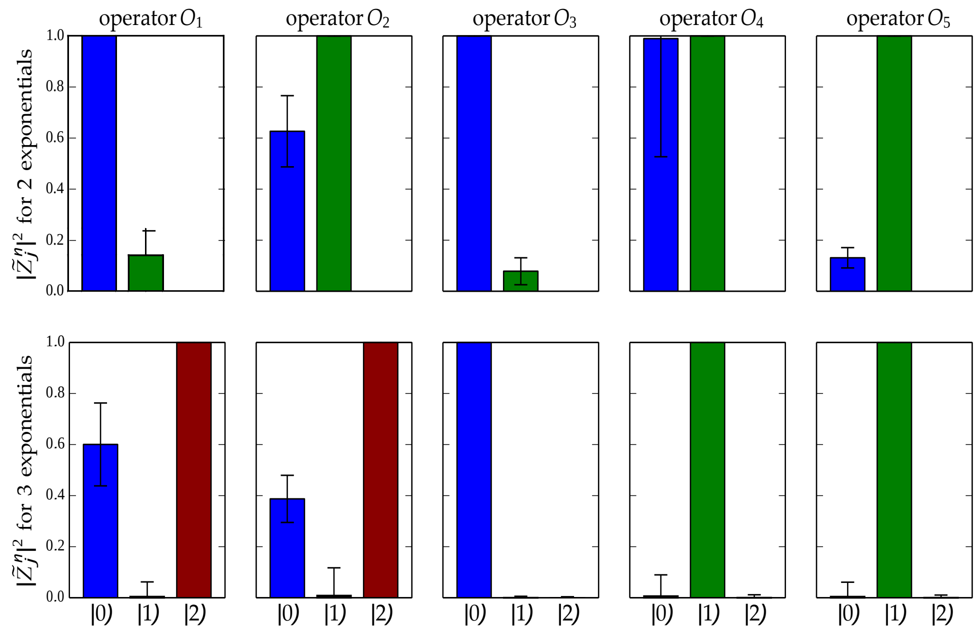
A COUPLE OF QUALITATIVE OBSERVATIONS

- Absence of binding in doubly heavy analogue I(J^P) = 0(0^+), 0(1^+) $ud\bar{s}\bar{b}$ channels, contrary to some model expectations ⇒ caution required when using models in channels where previously untested and/or unconstrained aspects of the models become relevant

- Similar couplings of nominally "meson-meson", "diquark-antidiquark" **local** operators to tetraquark ground states: "meson-meson" coupling does NOT mean these states are meson-meson molecules: caution re interpreting nature of exotic states based solely on the *discrete* structure of local operators to which they couple (a problem in some sum rule literature)

LMPW19 overlap factors

- O_1: local "BB*" operator
- O_2: local "B*B*" operator
- O_3: local diquark-antidiquark operator
- O_4: non-local "BB*" operator
- O_5: non-local "B*B*" operator
- Normalized to largest overlap



two-exponential fit

three exponential fit

FIG. 5. The normalized overlap factors $|\tilde{Z}_j^n|^2$ as determined on ensemble C005, indicating the relative contributions of the energy eigenstates $|n\rangle$ to the trial state $O_j^\dagger|\Omega\rangle$. The upper row corresponds to a two-exponential fit with $11 \le t/a \le 24$, while the lower row corresponds to a three-exponential fit with $10 \le t/a \le 24$.

FUTURE WORK

- Forthcoming/desirable
  - Upcoming (2019) Mathur *et al.* $I(J^P) = 0(0^+), 0(1^+)$ $ud\bar{c}\bar{b}$ analysis
  - FV-dependence, additional near-physical m_π for $ud\bar{c}\bar{c}$ to clarify relation of JMP18 to HadSpec results

- CFHLM near-term/in progress
  - Updated $ud\bar{b}\bar{b}$, $ud\bar{c}\bar{b}$ results with a=0.09 fm, $\kappa_l = 0.13777, 0.13779, 0.13781$, 32^3x64 and 48^3x64 ensembles
    - 48^3 vs. 32^3 for volume dependence studies
    - $\kappa_l \leftrightarrow m_\pi \lesssim 200$ MeV $\Rightarrow$ improved physical point extrapolation
    - Wall-box setup (improved ground state plateaus)
    - c.f. FHLM16, FHLM18: PACS-CS, a=0.09 fm, $\kappa_l = 0.13754, 0.13770, 0.13781$, 32^3x64 ensembles, $m_\pi = 164, 299, 415$ MeV
    - 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 ensemble used in FHLM16, FHLM18)

❖ 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

❖ Stay tuned for more

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BACKUP SLIDES

LMPW19 m_π = 340 MeV FIT RESULTS

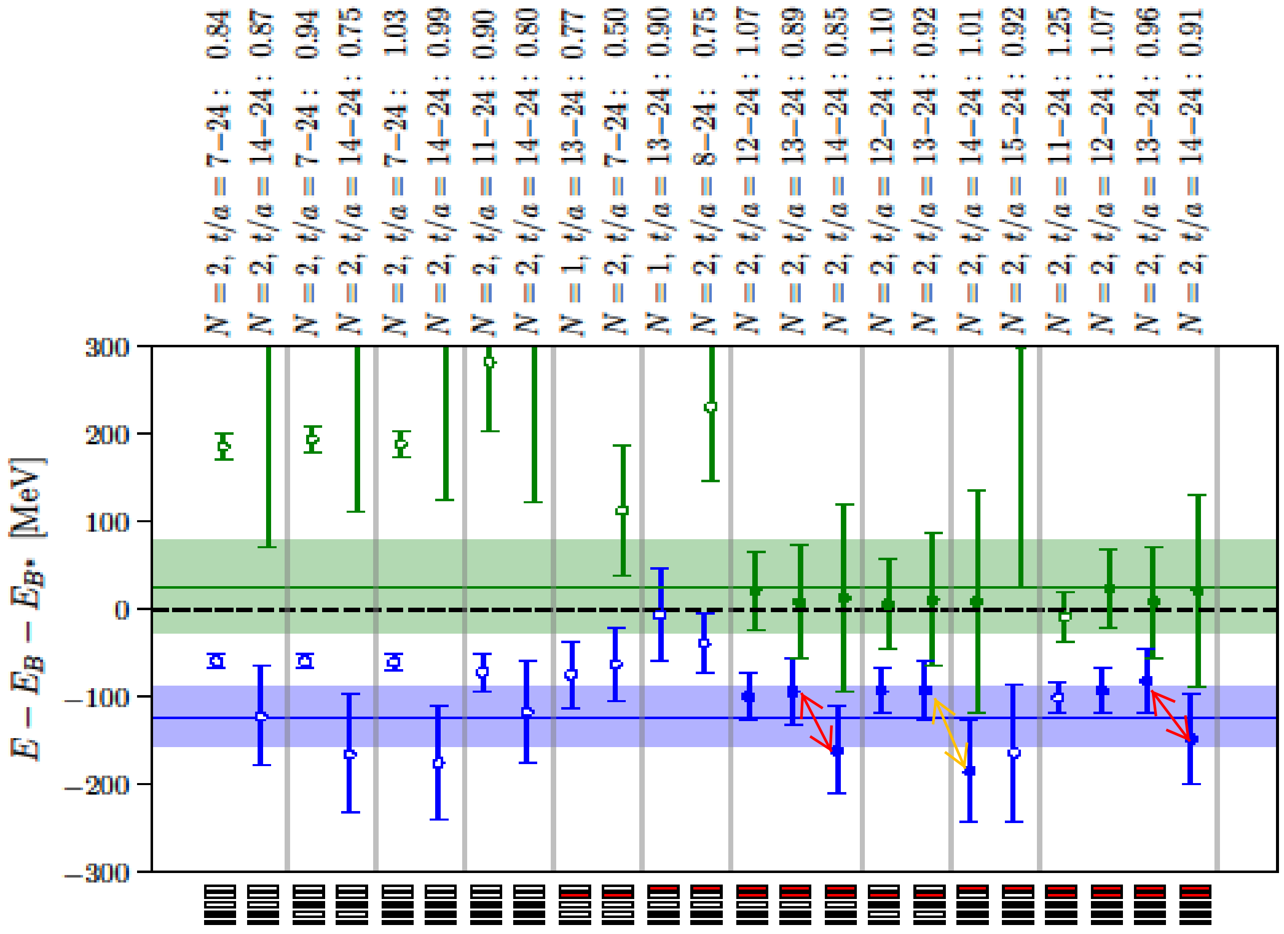

FIG. 4. Results for the lowest two $\bar{b}\bar{b}ud$ energy levels relative to the BB^* threshold, $\Delta E_n = E_n - E_B - E_{B^*}$, as determined on ensemble C005 from several different fits. The five bars below each column indicate the interpolators used, as explained in the main text. Above each 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.