

STRONG-INTERACTION-STABLE DOUBLY BOTTOM AND BOTTOM-CHARM TETRAQUARKS

KM, R.J. Hudspith, R. Lewis, A. Francis

PRL 118 (2017) 142001, and work in progress

Workshop on Exotic Hadrons and Flavor Physics

Simons Center for Geometry and Physics

May 31, 2018

OUTLINE

- “Good light diquarks” and the heavy baryon spectrum
- Implications for doubly heavy tetraquark channels
- Lattice results for candidate doubly bottom strong-interaction-stable tetraquarks (including tests of the underlying qualitative picture)
- Preliminary results for the bottom-charm sector
- Future prospects

“Good” vs. “bad” light diquarks in a heavy 3_c field: the heavy baryon system

- *The non-strange case:* “Good” ($I = J = 0, C = \bar{3}$) vs. “bad” ($I = J = 1, C = \bar{3}$) ud diquarks
 - $\Sigma_b - \Lambda_b$: 194 Mev
 - $\Sigma_c - \Lambda_c$: 167 Mev
- *The light-strange case:* “Good” ($F = \bar{3}, J = 0, C = \bar{3}$) vs. “bad” ($F = 6, J = 1, C = \bar{3}$) us diquarks
 - $\Xi'_b - \Xi_b$: 142 Mev
 - $\Xi'_c - \Xi_c$: 109 Mev

- Basic observations

- $\Sigma_b - \Lambda_b$ splitting (maximally suppressed heavy-quark spin interactions) $\Rightarrow \sim 145$ MeV “good” ud attraction c.f. spin average
- $\Xi'_b - \Xi_b$ splitting $\Rightarrow \sim 106$ MeV “good” us diquark attraction c.f. spin average
- \Rightarrow increased spin-dependent “good diquark” attraction with **decreasing** light quark mass
- Reduced splittings in charm sector \Rightarrow less suppressed residual spin-dependent charm-light interactions eat into “good diquark” binding

- In doubly heavy tetraquark channels $\bar{Q}\bar{Q}'\ell\ell'$
 - * $J_h = 1$, $C_h = 3$, $J^P = 1^+$ allows $F = \bar{3}$, $J_\ell = 0$, $C_\ell = \bar{3}$, “good light diquark” configuration, no heavy quark spatial excitation
 - * $1/m_h$ suppression \Rightarrow spin-dependent attraction in asymptotic B^*B , B^*D , D^*D $J^P = 1^+$ states small c.f. “good diquark” attraction available to tetraquark
 - * Additional $\bar{Q}\bar{Q}'$, $C_h = 3$ color Coulomb attraction for tetraquark not present for 2-meson thresholds [$\propto \mu_{red}$, dominant for $m_h \rightarrow \infty$]
- \rightarrow doubly heavy tetraquark bound wrt 2-meson threshold likely, for $\bar{b}b\ell\ell'$ case at least

Lattice study, $ud\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$ cases

- PACS-CS, $n_f = 2 + 1$ Iwasaki gauge, Wilson-Clover fermion ensembles, $1/a = 2.194(10)$ GeV, m_π down to near physical, physical valence m_s

Label	E_H $32^3 \times 64$	E_M $32^3 \times 64$	E_L $32^3 \times 64$
m_π (MeV)	415	299	164
m_K (MeV)	597	552	511
$m_\pi L$	6.1	4.4	2.4

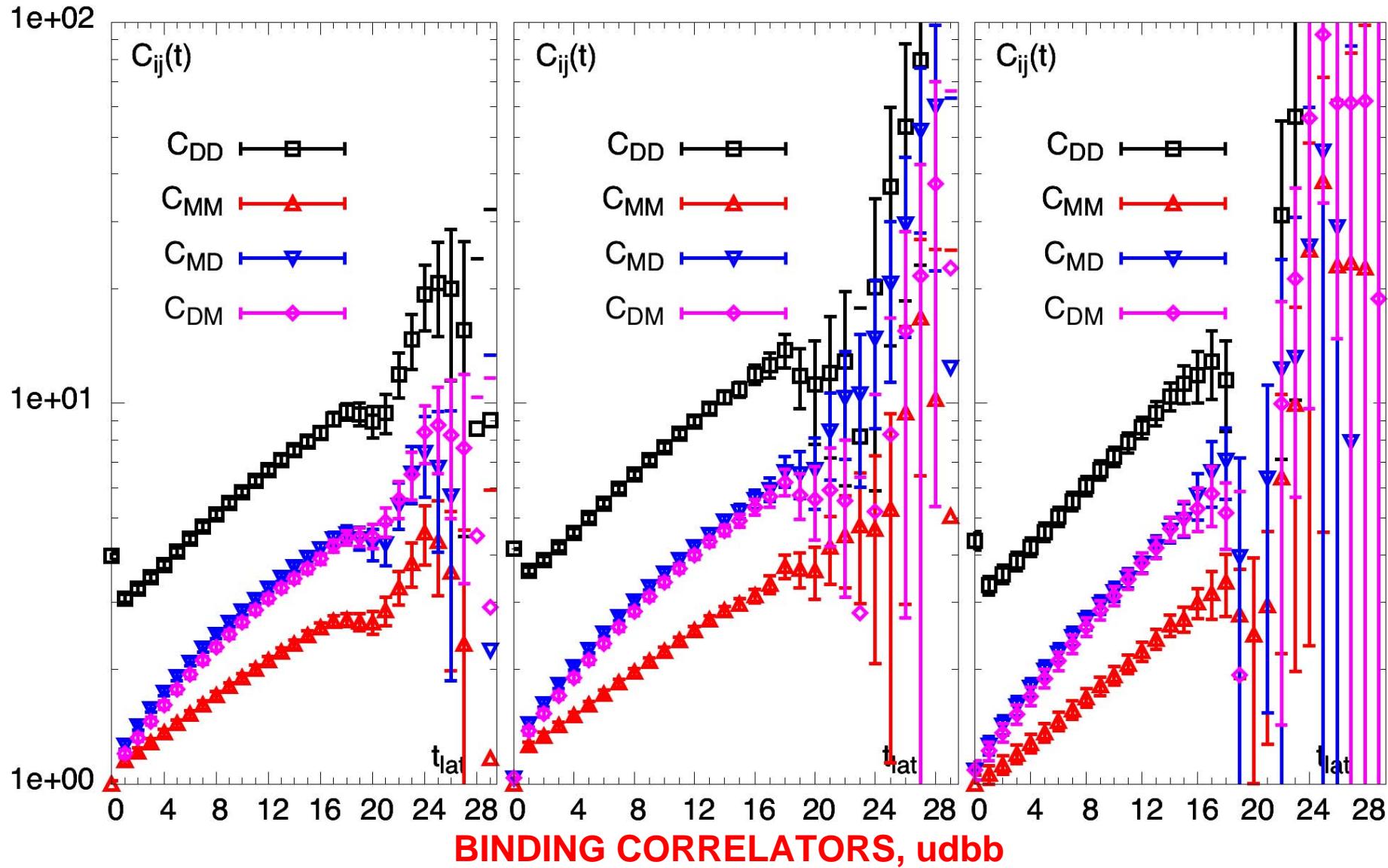
- NRQCD for heavy \bar{b}
- PRL 118 (2017) 142001 for details

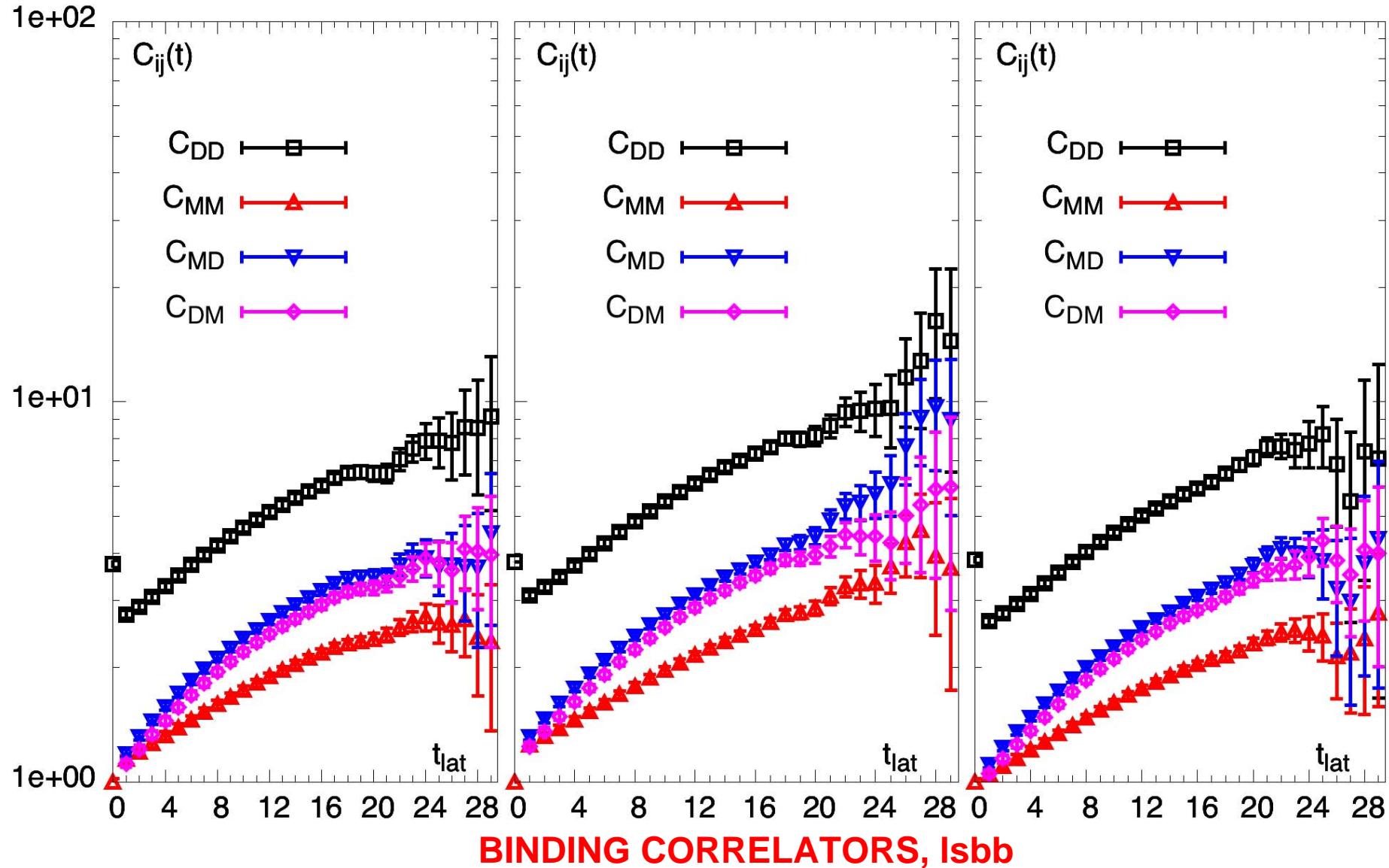
- Local interpolating operators:
 - “Diquark-antidiquark” (D): good light-diquark, heavy anti-diquark discrete structure
 - “Meson-meson” (M): discrete VP , 2-meson threshold (B^*B , B^*B_s) structure
- Single-channel and 2×2 GEVP analyses
- Binding correlators: e.g., $B_T = C_T/[C_V C_P]$, $T = DD$, DM , MM , $B_T \sim \exp(-[E_0 - M_V - M_P]t)$ for large t
(B_T growth with t for ground state bound wrt VP)
- FIGURES: $ud\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$, binding correlators, GEVP ΔE results, extrapolation to physical m_π

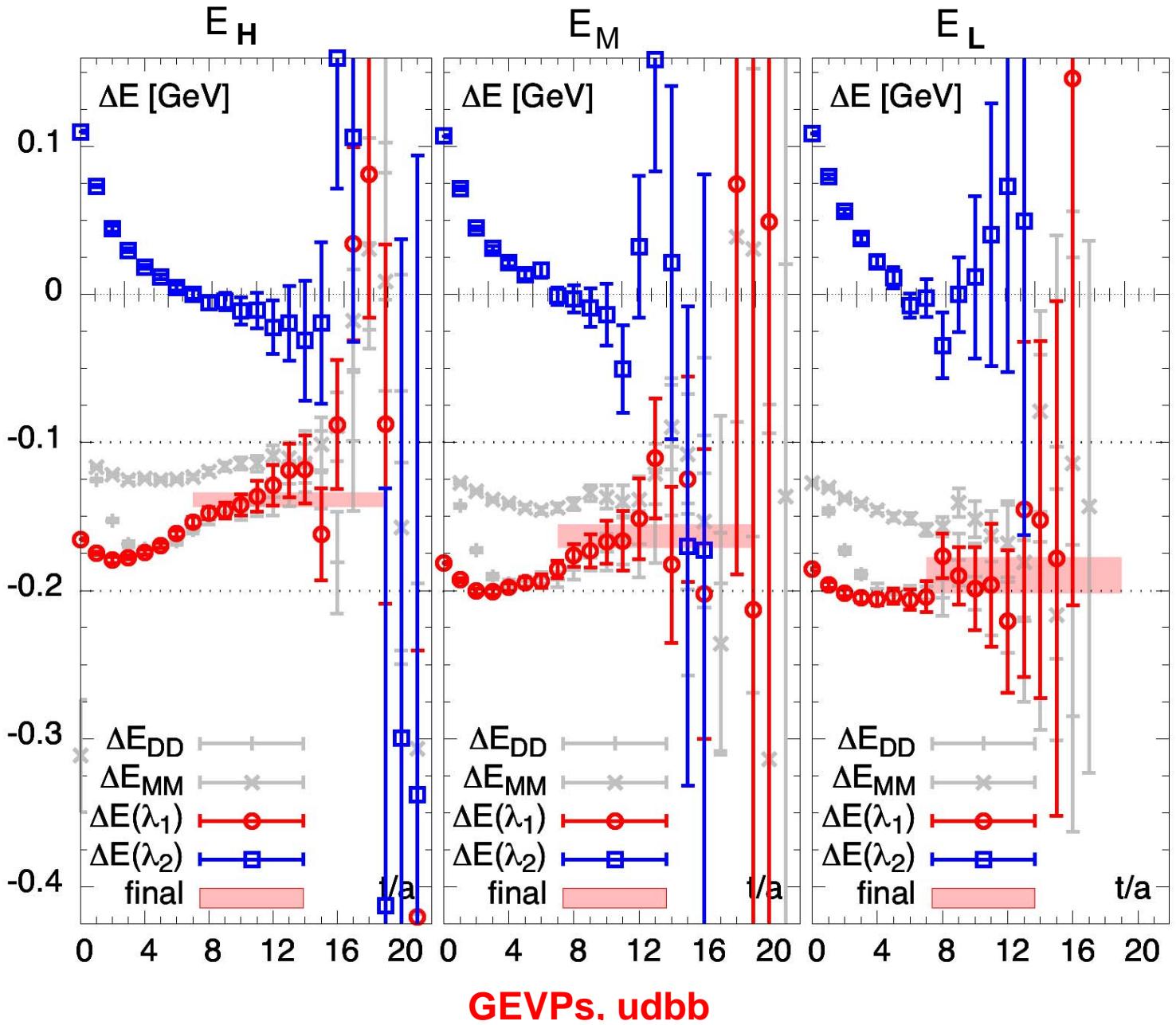
$m_\pi L = 6.1, m_\pi = 415$ MeV

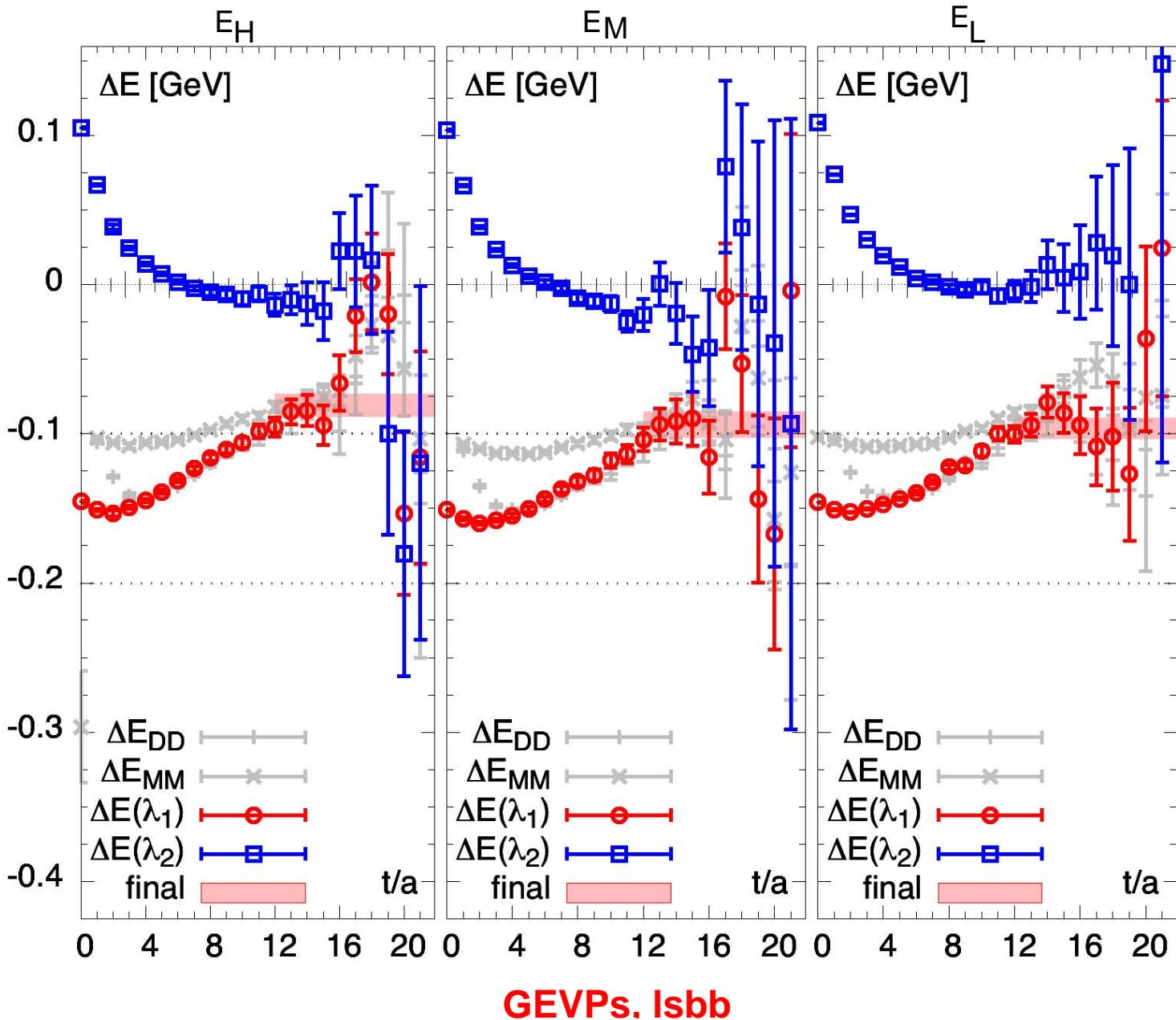
$m_\pi L = 4.4, m_\pi = 299$ MeV

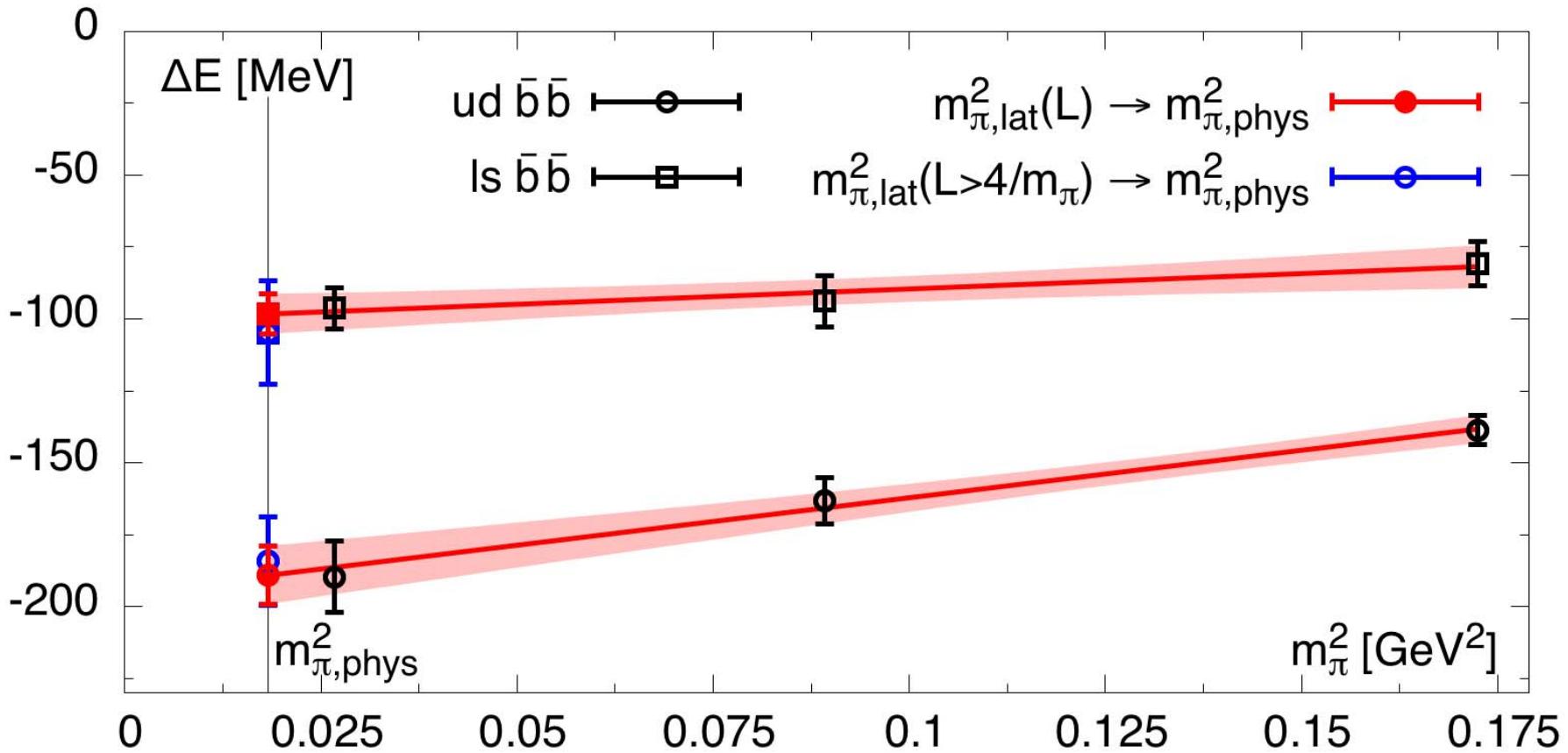
$m_\pi L = 2.4, m_\pi = 164$ MeV



$m_\pi L = 6.1, m_\pi = 415 \text{ MeV}$ $m_\pi L = 4.4, m_\pi = 299 \text{ MeV}$ $m_\pi L = 2.4, m_\pi = 164 \text{ MeV}$ 





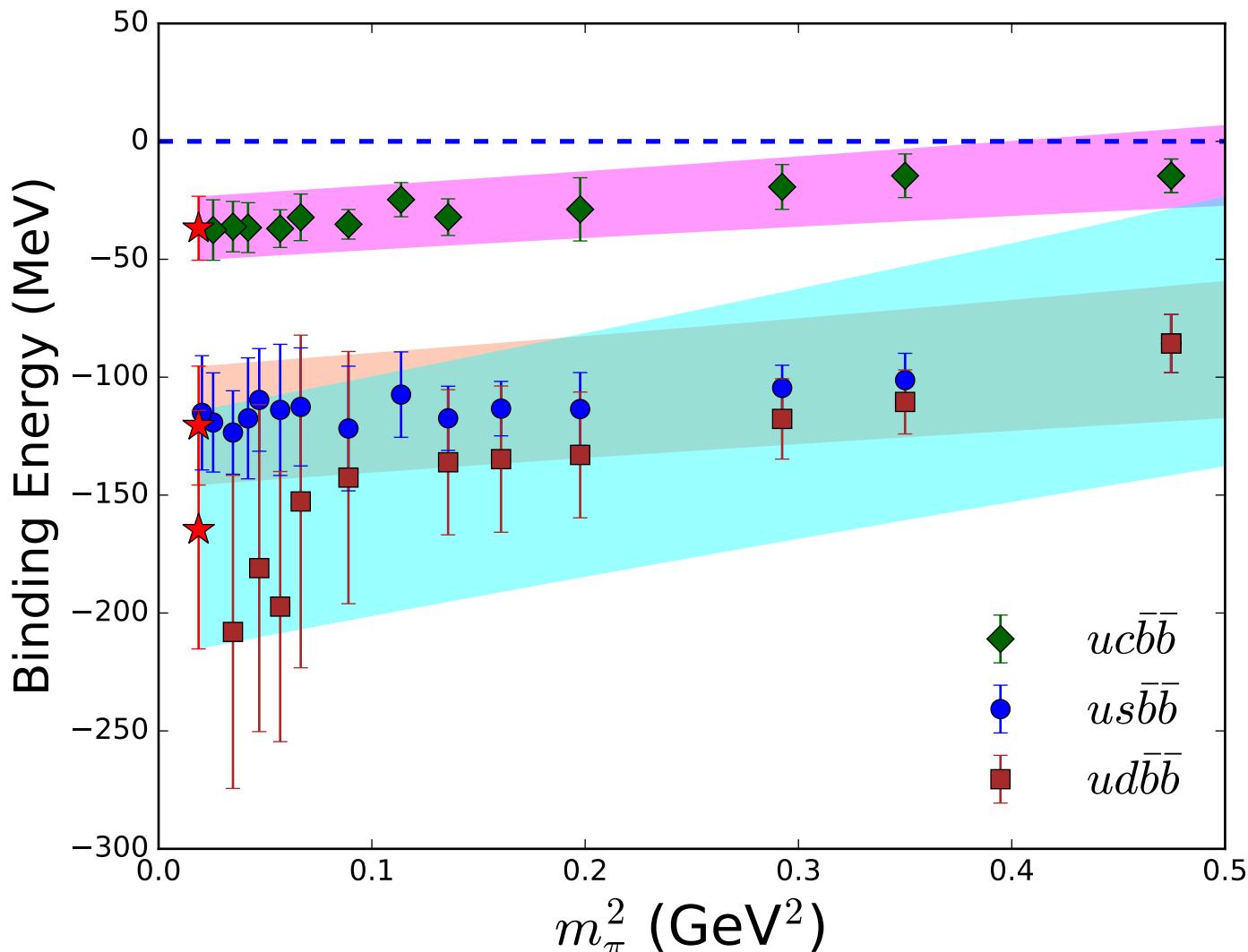


RESULTS FOR $J^P = 1^+$ $udbb$, ℓsbb CHANNELS

Ensemble	ΔE_{udbb} (MeV)	$\Delta E_{\ell sbb}$ (MeV)
E_H	-139(5)	-81(8)
E_M	-163(8)	-94(9)
E_L	-190(12)	-96(7)
Physical	-189(10)(3)	-98(7)(3)

- Agreement with “good diquark” + heavy anti-diquark colour Coulomb attraction picture expectations
- Binding energies, observed heavy baryon splittings \Rightarrow spin-dependent “good diquark” attraction larger binding source for physical m_b (c.f. colour Coulomb domination for $m_b \rightarrow \infty$)

- Other lattice results for $J^P = 1^+$ doubly-bottom states
 - Bicudo, Cichy, Peters, Wagner and collaborators
[PRD 93 (2016) 034501 and earlier Refs therein]
 - * Born-Oppenheimer approach, model \bar{b} - \bar{b} potential form fitted to static \bar{b} quark lattice data
 - * $\Delta E = -90^{+36}_{-43}$ MeV
 - Preliminary Mathur, Junmarkar, Padmanath results, MILC $n_f = 2 + 1 + 1$ ensembles [arXiv:1712.08400] + FIGURE for recent update



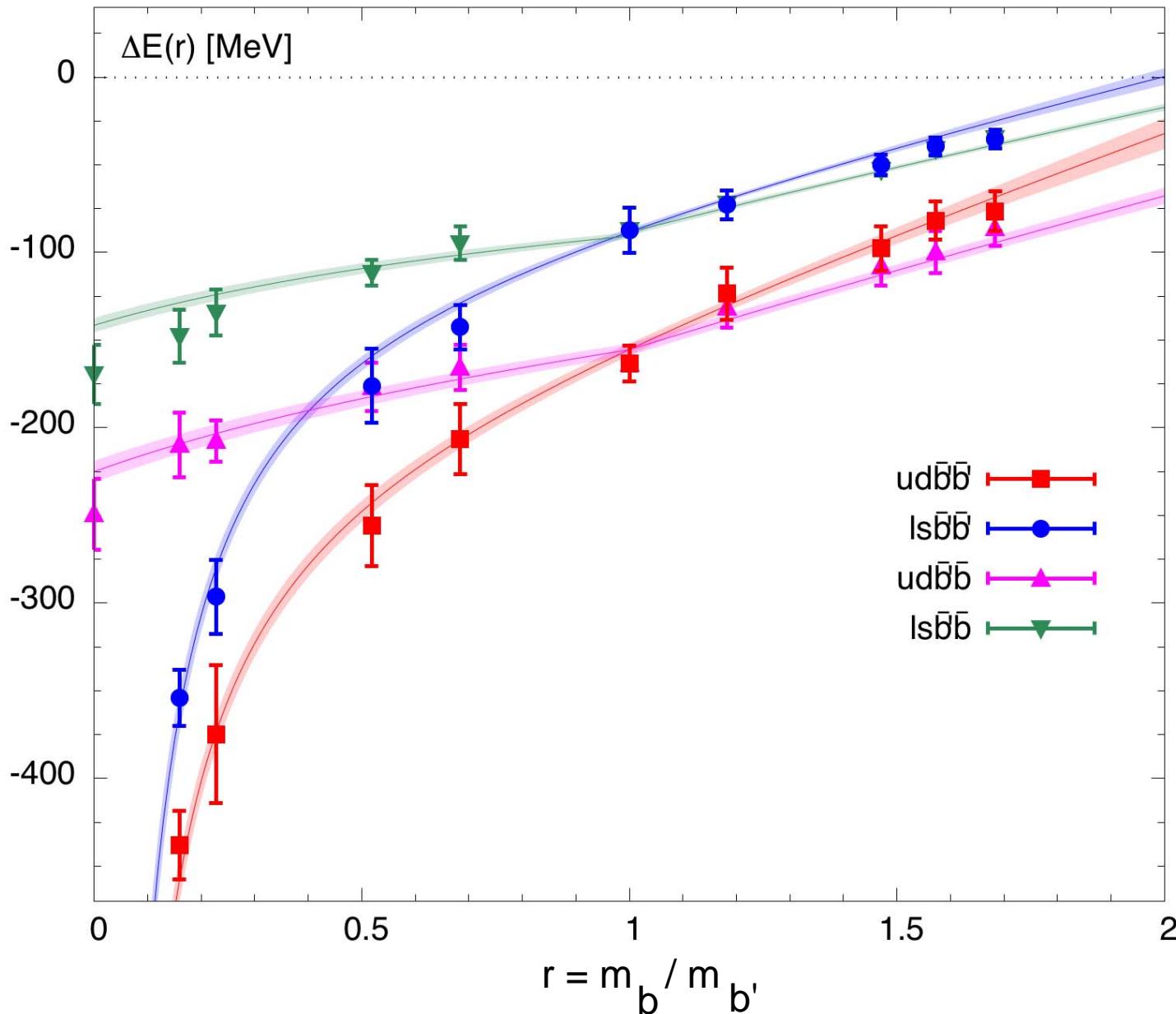
VARIABLE m_b TESTS OF BINDING PICTURE

- Variable mass b' , NRQCD OK down to $m_{b'}/m_b \simeq 0.6$
- $qq'\bar{b}'\bar{b}'$ and $qq'\bar{b}'\bar{b}$ channels, $qq' = ud, \ell s$
- “Good light diquark” + colour Coulomb tetraquark binding picture \Rightarrow leading dependence of binding energy, ΔE , on heavy-quark mass(es) of the form

$$D_0 \mu_{red}^h + D_1^{qq'} + D_2^{qq'} \left(\frac{1}{m_{h1}} + \frac{1}{m_{h2}} \right) + D_{th}^{qq'} \left(\frac{1}{m_{h1}}, \frac{1}{m_{h2}} \right)$$

- $D_0 \mu_{red}^h$: heavy antiquark-antiquark colour Coulomb, proportional to heavy-heavy reduced mass

- $D_1^{ud,\ell s}$: leading contribution from good ud , ℓs di-quark attraction
- $D_2^{ud,\ell s} \left(\frac{1}{m_{h1}} + \frac{1}{m_{h2}} \right)$: residual heavy antiquark- $ud/\ell s$ diquark interaction in tetraquark configuration
- $D_{th}^{ud,\ell s} \left(\frac{1}{m_{h1}}, \frac{1}{m_{h2}} \right)$: $1/m_h$ -suppressed heavy-light spin-dependent interactions in 2-meson thresholds
 - * thresholds: $B_{b'}^* B_{b'}$ for $qq'\bar{b}'\bar{b}'$; $B_{b'}^* B_b$ for $qq'\bar{b}'\bar{b}$, $m_{b'} > m_b$; $B_b^* B_{b'}$ for $qq'\bar{b}'\bar{b}$, $m_{b'} < m_b$
 - * Values fixed by observed $B^* - B$, $D^* - D$, $B_s^* - B_s$, $D_s^* - D_s$, splittings, assuming $1/m_h$ dependence
- Picture provides good representation of lattice results over wide range of $r = m_b/m_{b'}$ (**FIGURE**)

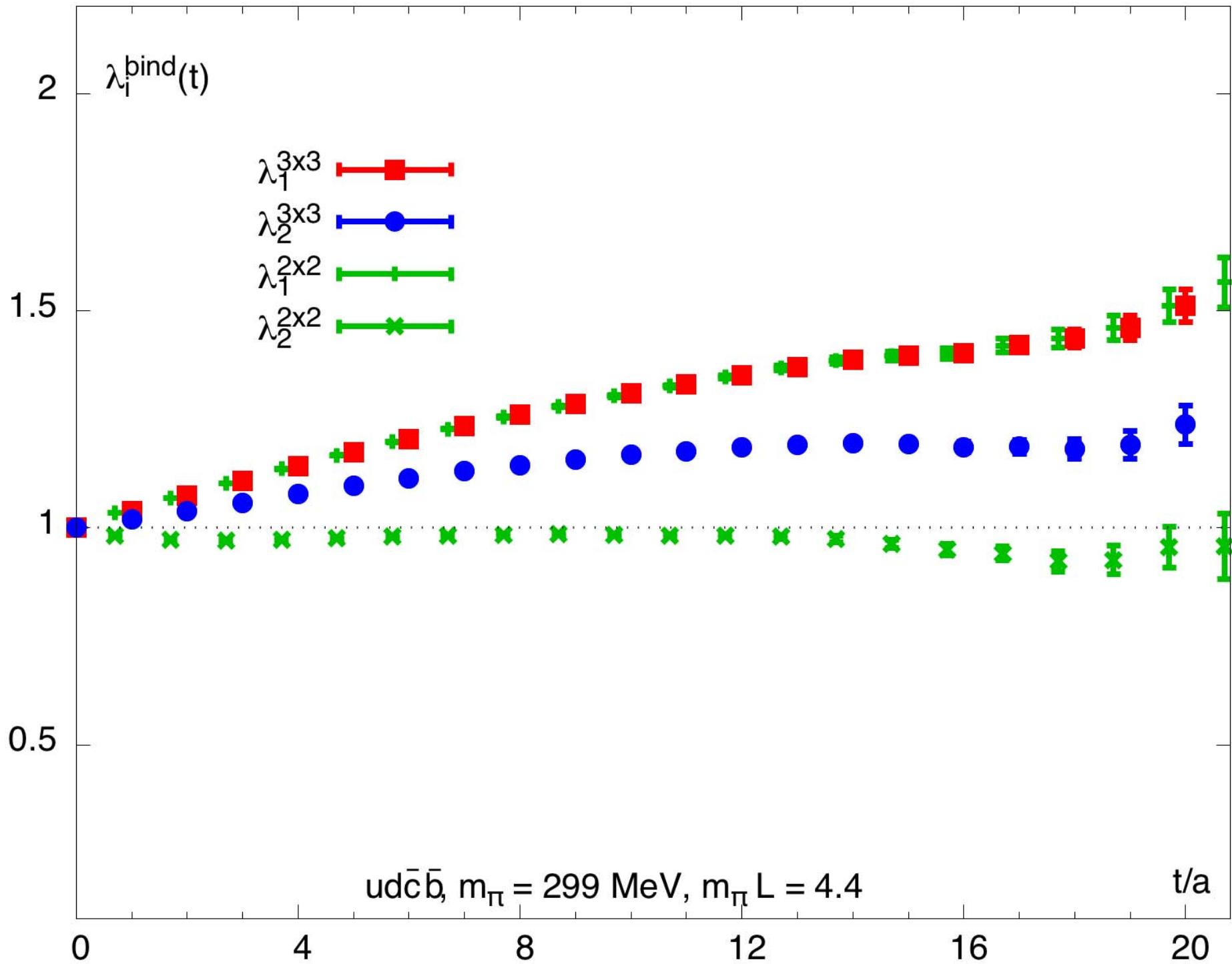


PRELIMINARY $ud\bar{b}\bar{c}$ CHANNEL RESULTS

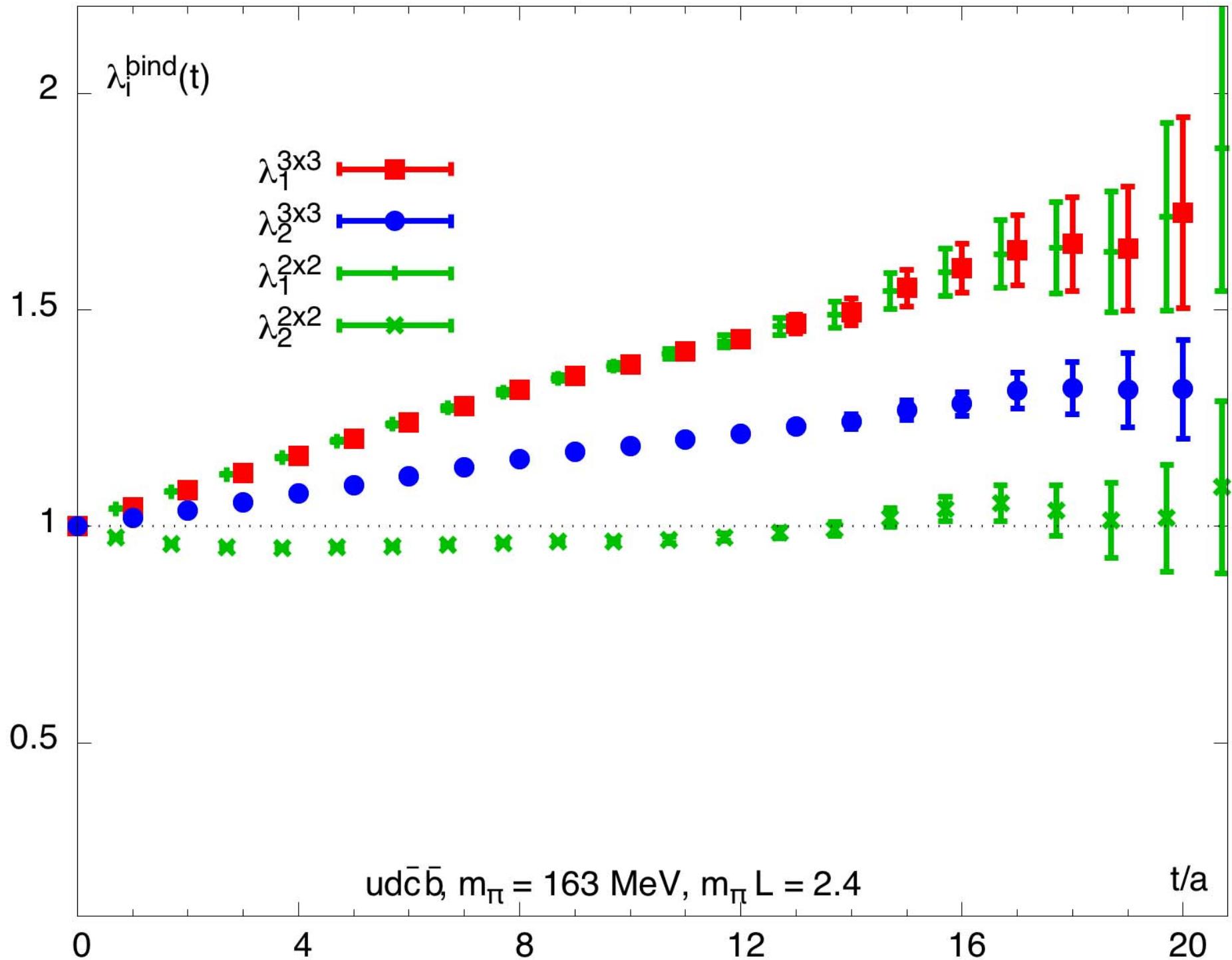
- Strong-interaction-stable $J^P = 1^+$ $ud\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$ tetraquarks theoretically solid, but experimentally challenging
- Doubly so given
 - doubly bottom baryons not yet observed
 - binding well below EM decay thresholds, hence weak decays only \Rightarrow displaced vertices, BUT almost certainly many exclusive decay modes, small BFs
- Motivates looking for bottom-charm candidates

- Variable b mass study $\Rightarrow u\bar{d}\bar{b}\bar{c}$ clearly most likely
- Expect significantly reduced ΔE c.f. $u\bar{d}\bar{b}\bar{b}$ due to
 - relative lowering of 2-meson threshold (DB^* c.f. BB^* : increased spin-dependent D attraction c.f. B)
 - reduced $\bar{b}\bar{c}$ c.f. $\bar{b}\bar{b}$ colour Coulomb
 - increased residual good-light-diquark-heavy-antidiquark repulsion for lighter antidiquark pair
- Use same PACS-CS $n_f = 2+1$ ensembles, NRQCD for b , Tsukuba relativistic heavy quark action for c
- **FIGURES:** preliminary $u\bar{d}\bar{b}\bar{c}$ binding correlator, GEVP ΔE results

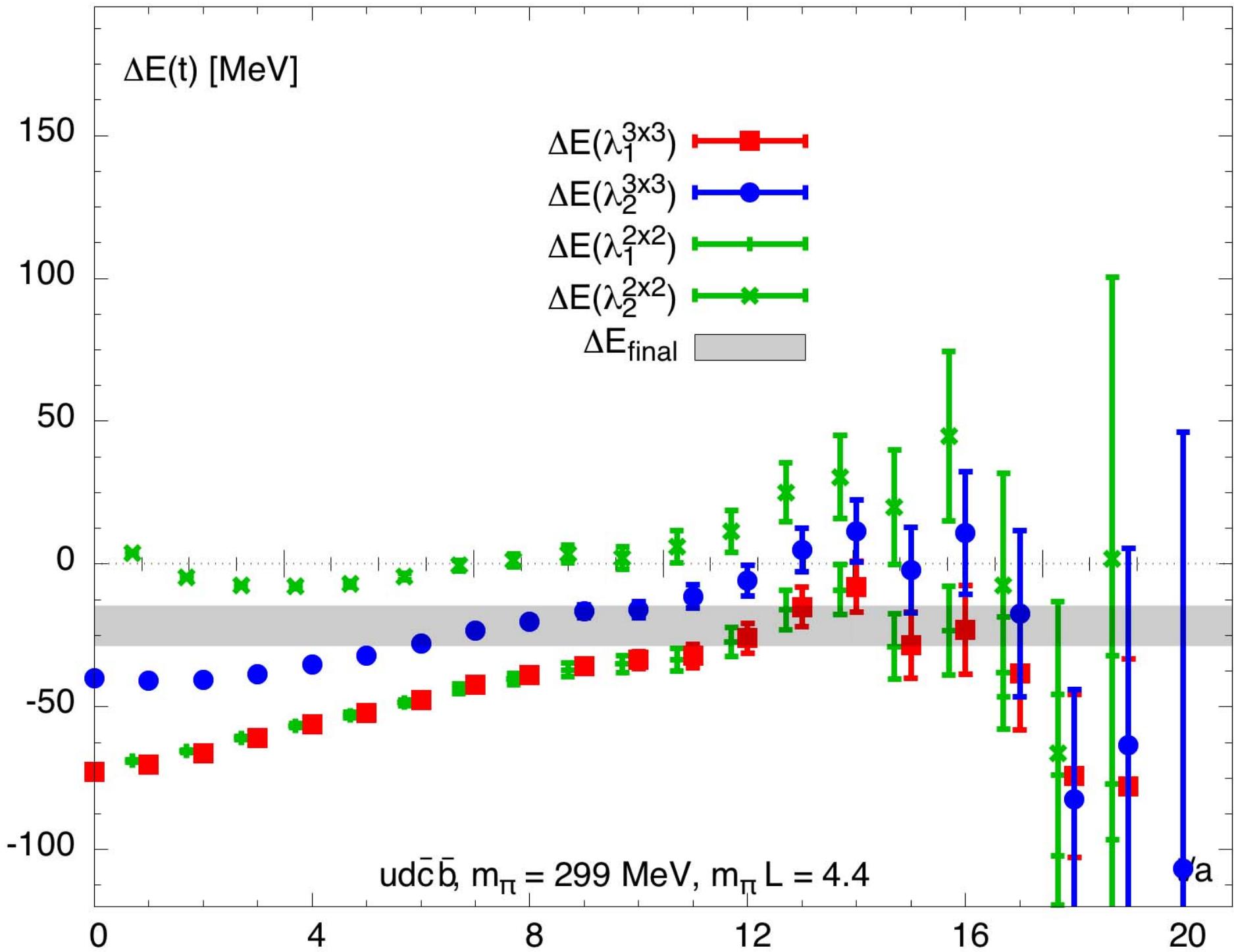
udbc binding correlator results, E_M



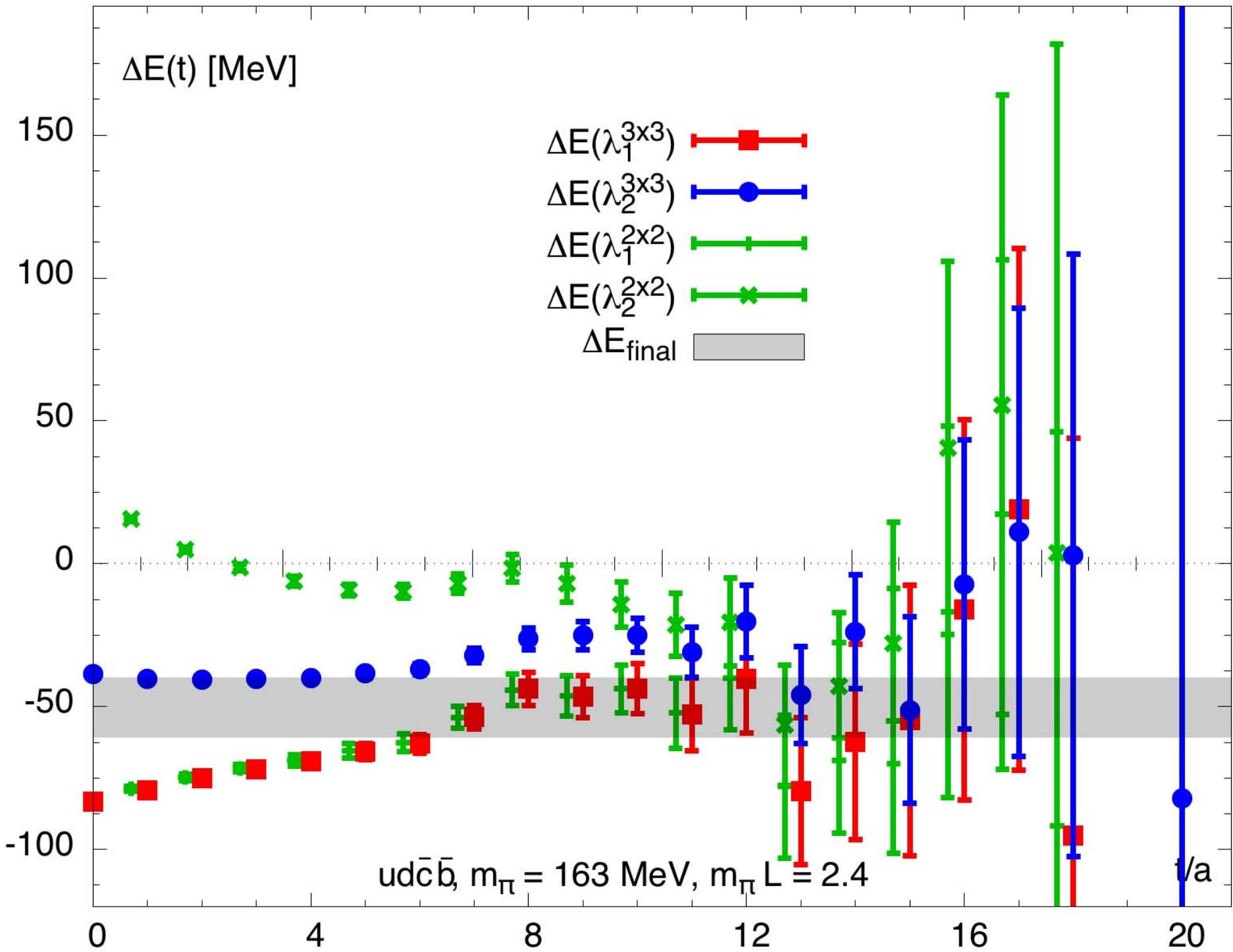
udbc binding correlator results, E_L



udbc, binding energy, E_M



udbc binding energy, E_L



- Preliminary results $ud\bar{b}\bar{c}$ $J^P = 1^+$ channel

Ensemble	ΔE_{udbc} (MeV)
E_H	-4(9)
E_M	-22(7)
E_L	-50(11)

- $m_\pi = 415$ MeV (E_H) case likely unbound
- Smaller binding \Rightarrow FV systematic more important
- Binding likely for physical m_π but above or below EM decay threshold ($\Delta E = -45$ MeV) unclear

FUTURE PROSPECTS/DIRECTIONS

- Currently generating larger $48^3 \times 64$, 64^4 ensembles
 - significantly improved $m_\pi L$ for lightest m_π
 - will allow FV studies (bound vs. scattering-state interpretation issue for small ΔE)
- More ensembles with lighter m_π for both new volumes (important due to increase of binding with decreasing light quark mass, especially in bottom-charm sector)
- Extended sources for earlier plateaus
- The 1^+ double-charm and 0^+ bottom-charm channels

CONCLUSIONS

- Clear evidence for deeply bound strong-interaction-stable $J^P = 1^+ I = 0 u d \bar{b} \bar{b}$ and $I = 1/2 \ell s \bar{b} \bar{b}$ tetraquark states
- Binding for doubly bottom states such that only weak decays possible (displaced vertices, but low production rates, low exclusive mode BFs)
- Evidence for strong-interaction-stable $J^P = 1^+ I = 0 u d \bar{b} \bar{c}$, but larger volumes, more light m_π desirable
- Doubly charmed $J^P = 1^+$ channels, larger L , more light m_π all in progress

- Comments on experimental detection possibilities
 - $ud\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$
 - * Few observed $(\bar{b}b)(\bar{b}b)$, no $b\bar{b}\ell$ baryons \Rightarrow current production rates likely low
 - * Multiple weak decay modes, low BFs \Rightarrow exclusive mode detection statistically challenging
 - $ud\bar{b}\bar{c}$
 - * Few 10^3 B_c already, $b\bar{c}\ell$ soon (we hope)
 - * \Rightarrow more favorable $ud\bar{b}\bar{c}$ production rate
 - * Smaller ΔE \Rightarrow possibility of open EM $BD\gamma$ decay channel ($\sim 100\%$ BF, closely collimated D , B , if reasonable tetraquark boost in lab)