Spectroscopy of heavy-light mesons

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THE SPECTRUM OF B, B_s & B_c MESONS: MOTIVATION

- Heavy quarks provide a rich environment for spectroscopy - with many and unexpected exotic states discovered already.

- Completing the story in heavy quark spectroscopy:

  - Charmonium: JHEP1207 (2012) 126, JHEP 1612 (2016) 089.
  - Open charm: JHEP 05 (2013) 021 & JHEP12 (2016) 089.
  - Bottomonium: JHEP02 (2021) 213.

- Unlike charm sector only a handful of states determined experimentally in any of B, B_S, B_C: map the spectrum of excited and exotic states to $J \leq 4$ in a lattice calculation.

- Fruitful scattering analyses in $D\pi$, DK [JHEP 10 (2016) 011, JHEP 07 (2021) 123, JHEP 02 (2021) 100]. Similar picture in $B\pi$ etc?

LATTICE DETAILS

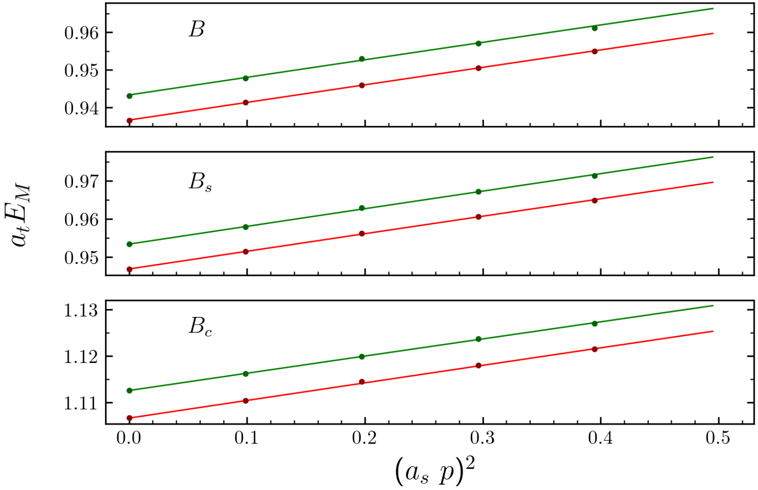
- Symanzik-improved anisotropic gauge action with tree-level tadpole-improved coefficients and $N_f = 2 + 1$.
  Anisotropic clover fermion action with stout-smeared spatial links.
- $\xi = a_s/a_t = 3.5$; $a_s \approx 0.12\,\mathrm{fm}$, $a_t^{-1}(m_\Omega) = 5.67(4)\,\mathrm{GeV}$.
- $20^3 \times 128$ volume; $m_\pi \sim 396\,\mathrm{MeV}$. $16^3, 24^3$ volumes available for volume dependence study.
- Distillation for quark propagation.
- Operators of definite momenta constructed with up to 3 derivatives.

Λ	A_1	A_2	E	T_2	T_1
Λ^+	18	10	26	36	44
Λ^-	18	10	26	36	44

- Mass-dependent anisotropy tuning for heavy quarks.

LATTICE DISPERSION RELATIONS

- Fermion action: mass-dependent tuning of m_q and ξ: tuned at η_b.
- Dispersion relations in heavy-light sector $(a_t E)^2 = (a_t M)^2 + \left(\frac{2\pi}{\xi L/a_s}\right)^2 n^2$.



Within 2(B_c) - 4(B)% of target anisotropy.

	ξ
B	3.365(14)
B^*	3.357(21)
B_s	3.371(11)
B_s^*	3.352(14)
B_c	3.447(5)
B_c^*	3.478(13)
Υ	3.574(26)
η_b	3.590(15)

RECIPE FOR (MESON) SPECTROSCOPY

- Construct a basis of local and non-local operators $\bar{\Psi}(x)\Gamma D_i D_j \ldots \Psi(x)$ from distilled fields [PRD80 (2009) 054506].
- Build a correlation matrix of two-point functions

$$C_{ij} = \langle 0|\mathcal{O}_i \mathcal{O}_j^\dagger|0\rangle = \sum_n \frac{Z_i^n Z_j^{n\dagger}}{2E_n} e^{-E_n t}$$

- Solve generalised eigenvalue problem $C_{ij}(t)v_j^{(n)} = \lambda^{(n)}(t)C_{ij}(t_0)v_j^{(n)}$
  - eigenvalues: $\lambda^{(n)}(t) \sim e^{-E_n t}\left[1 + O(e^{-\Delta E t})\right]$ yield principal correlators
  - eigenvectors: $Z_i^{(n)} = \sqrt{2E_n} e^{E_n t_0/2} v_j^{(n)\dagger} C_{ji}(t_0)$ related to overlaps - helps identify continuum spin.

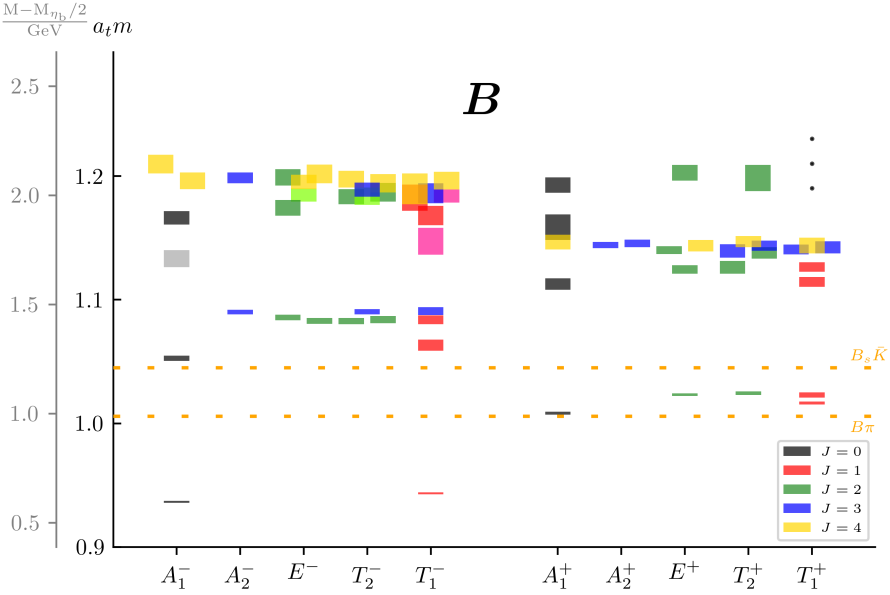
Results

B, B_s, B_c mesons

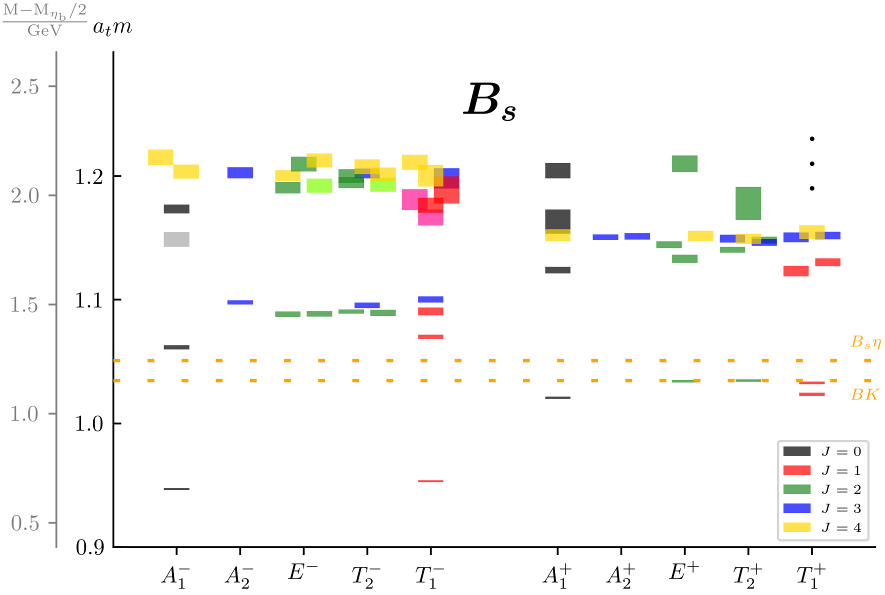
Caveat Emptor

- Spectra determined from single-hadron operators.
- Relatively heavy (∼400MeV) pions
- Single lattice spacing, single volume

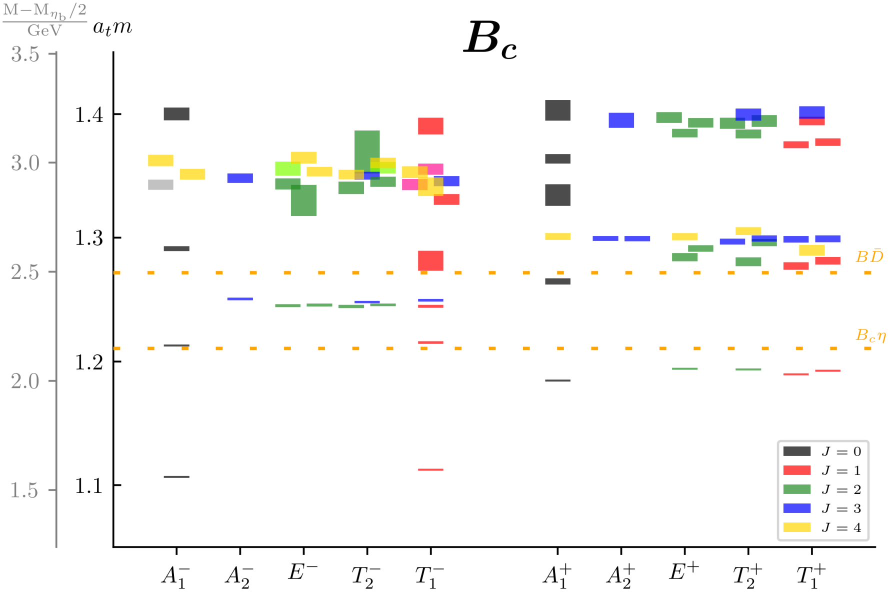
THE LATTICE B MESON SPECTRUM



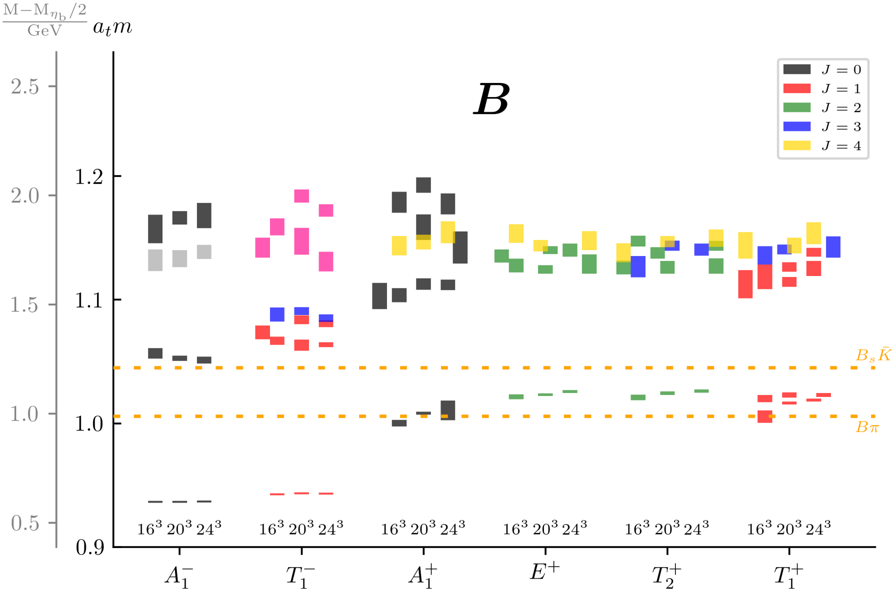
THE LATTICE B_s MESON SPECTRUM



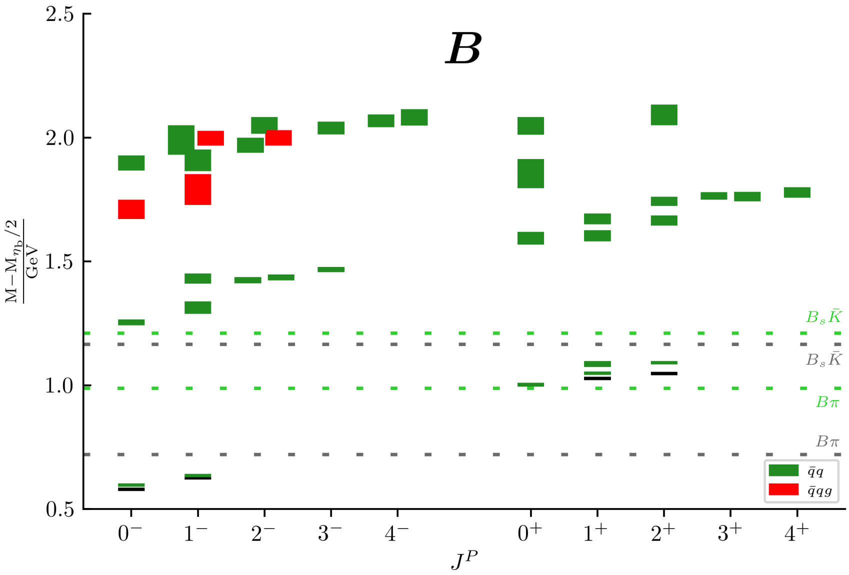
THE LATTICE B_c SPECTRUM



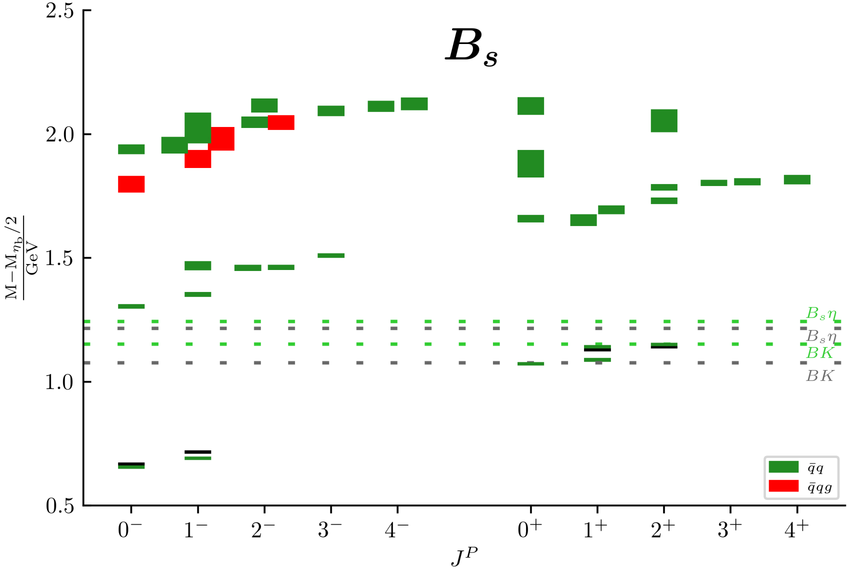
Volume dependence: a study of B mesons



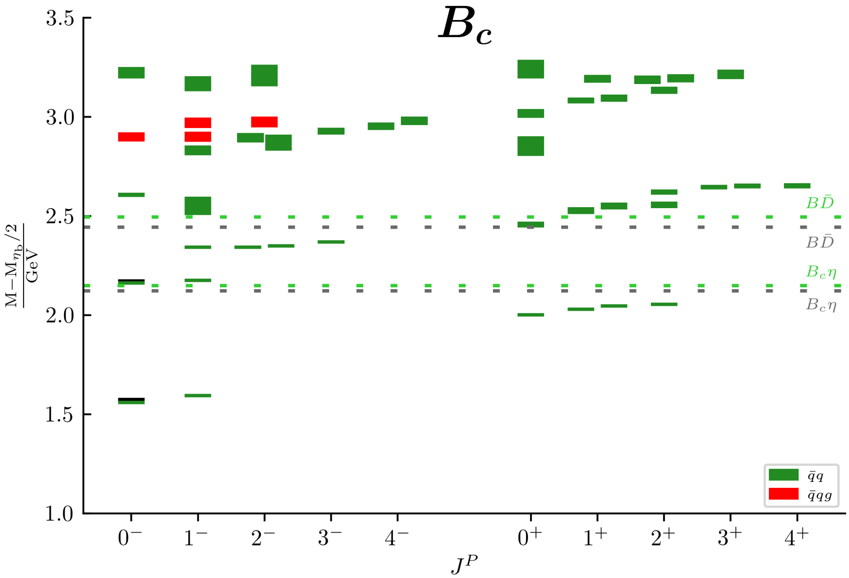
THE B MESON SPECTRUM



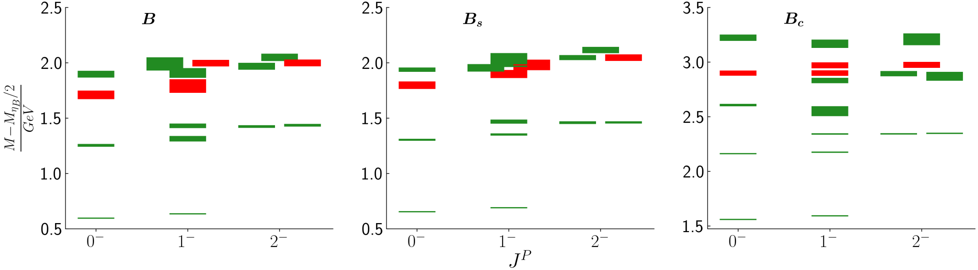
The B_s meson spectrum



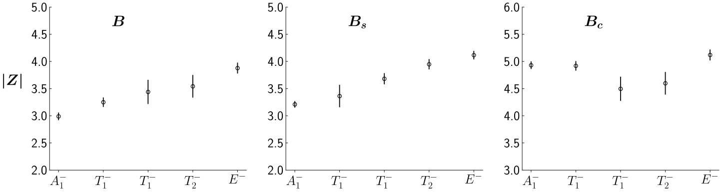
THE LATTICE B_c SPECTRUM



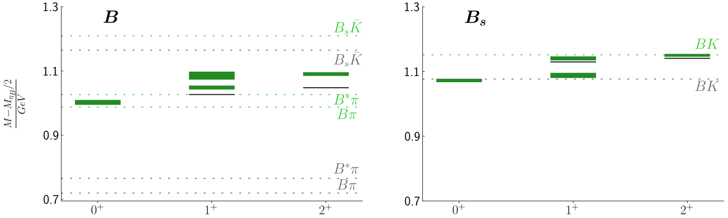
HYBRIDS: LIGHTEST SUPERMULTIPLETS



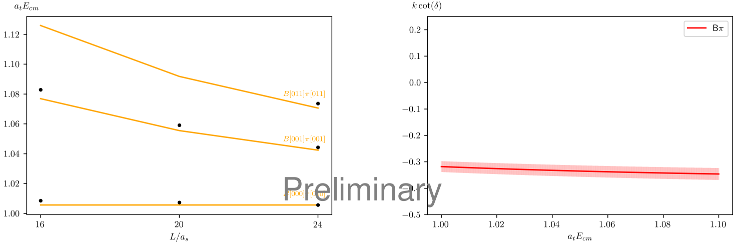
- Evidence of lightest hybrid supermultiplets.
- 1^{-}: mixtures of spin-singlet, spin-triplet.



NEXT STEPS ...



- A number of near-threshold states in positive parity B and Bs spectrum
- Elastic $B\pi$, A_1^+, $I = 3/2$: weakly repulsive interaction. $I = 1/2$ underway.



SUMMARY & OUTLOOK

- A study of heavy meson spectroscopy extended to heavy-light sector.

this work (MeV)		experiment - PDG (MeV)
39(2)	$m_{B^*} - m_B$	45.21 ± 0.21
38.0(8)	$m_{B_s^*} - m_{B_s}$	$48.6^{+1.81}_{-1.5}$
905.79(71)	$m_{B_c} - m_{B_s}$	$907.75 \pm 0.37 \pm 0.27$
602(3)	$m_{B_c}(2S) - m_{B_c}(1S)$	598(1)

- Results for the B, Bs and Bc meson spectra presented:
  - Dispersion relations are consistent between heavy and heavy-light sectors, for parameters tuned once at η_b.
  - Rotation breaking effects are small.
  - Evidence of a hybrid supermultiplet in B, B_s, B_c at energy scale approx 1.3 GeV.
    - similar characteristics in charmonium, open-charm and light mesons.
- The study can be extended to larger volumes and lighter pion masses.
- Paving the way for investigation of studies in $B\pi$, BK and heavy tetraquarks.

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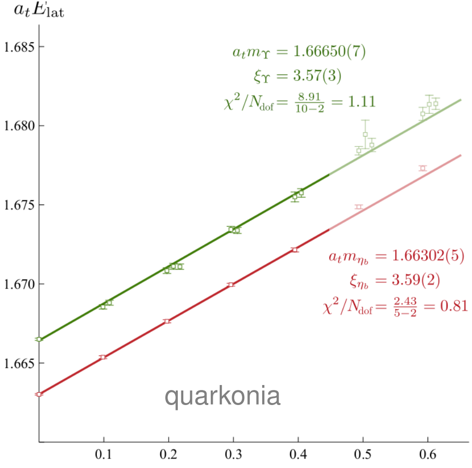
Thanks for listening!

THE LATTICE DISPERSION RELATION

- Fermion action: mass-dependent tuning of m_q and ξ
- $M^{latt}_{\eta_b} = M^{expt}_{\eta_b}$ *and* a relativistic dispersion relat ion recovered.



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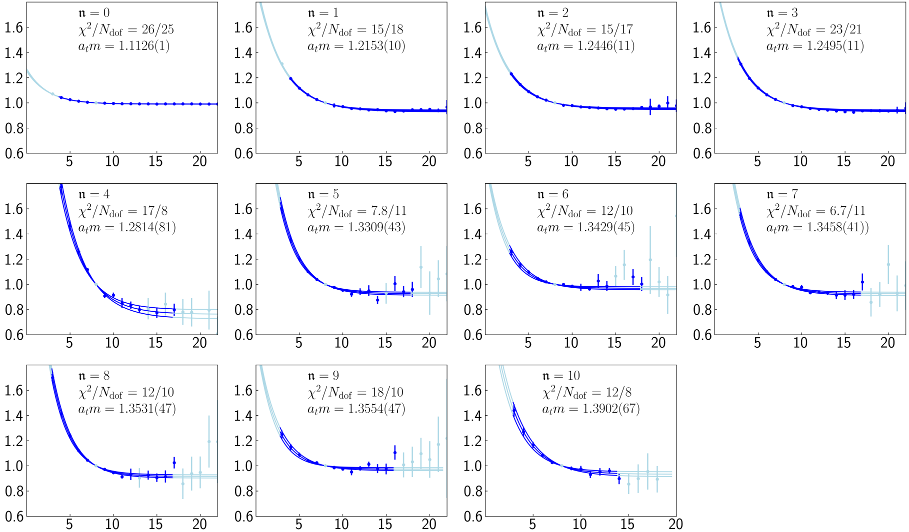
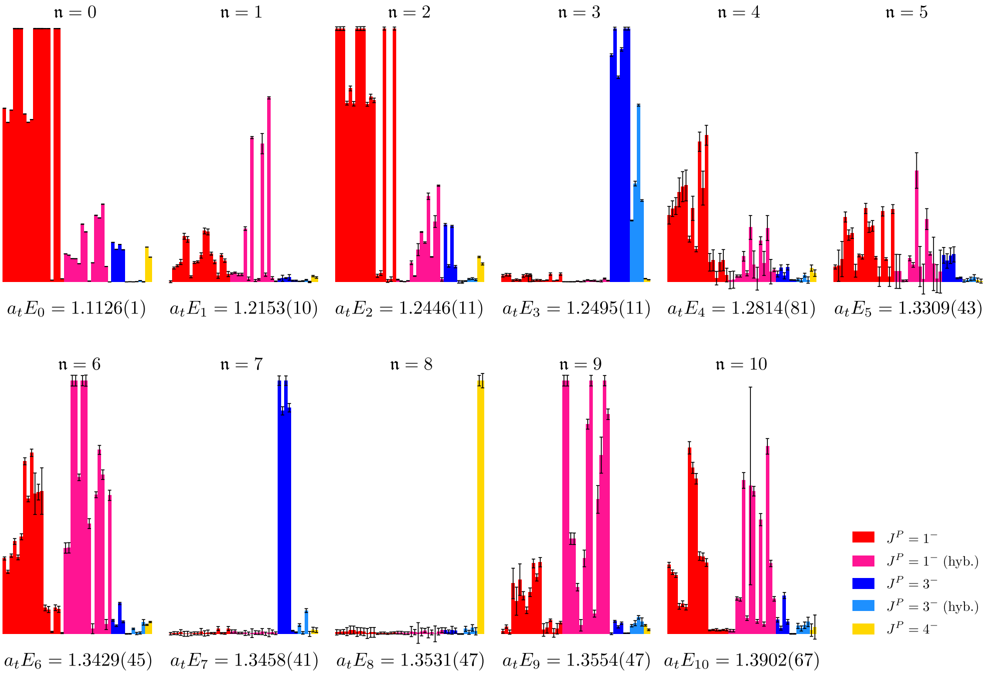
$$(a_t E)^2 = (a_t M)^2 + \left(\frac{2\pi}{\xi L/a_s}\right)^2 n^2.$$

- $n \leq (2,0,0)$ in fits; no significant $(a_s p)^4$ term.
- Rest, kinetic masses consistent.
- Heavy-light dispersion relations determined using these tuned parameters.

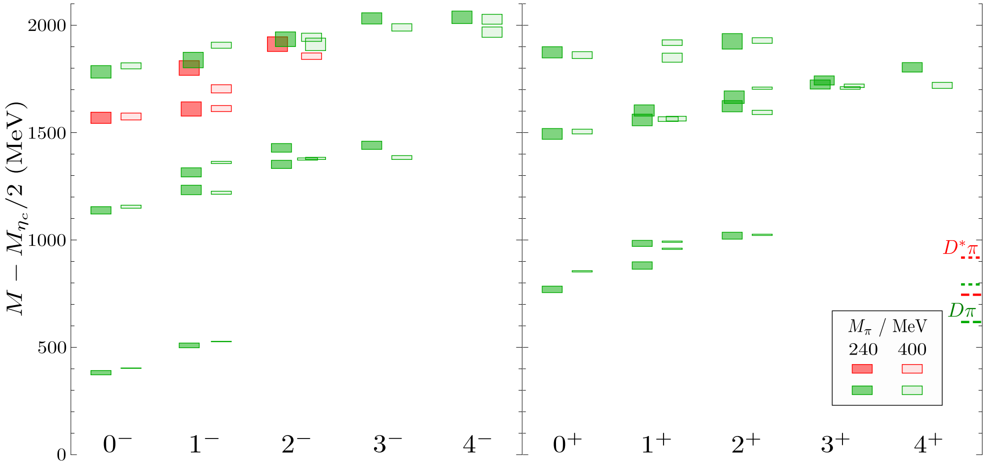


𝔫 = 0
$\chi^2/N_{\rm dof} = 26/25$
$a_t m = 1.1126(1)$
𝔫 = 1
$\chi^2/N_{\rm dof} = 15/18$
$a_t m = 1.2153(10)$
𝔫 = 2
$\chi^2/N_{\rm dof} = 15/17$
$a_t m = 1.2446(11)$
𝔫 = 3
$\chi^2/N_{\rm dof} = 23/21$
$a_t m = 1.2495(11)$
𝔫 = 4
$\chi^2/N_{\rm dof} = 17/8$
$a_t m = 1.2814(81)$
𝔫 = 5
$\chi^2/N_{\rm dof} = 7.8/11$
$a_t m = 1.3309(43)$
𝔫 = 6
$\chi^2/N_{\rm dof} = 12/10$
$a_t m = 1.3429(45)$
𝔫 = 7
$\chi^2/N_{\rm dof} = 6.7/11$
$a_t m = 1.3458(41))$
𝔫 = 8
$\chi^2/N_{\rm dof} = 12/10$
$a_t m = 1.3531(47)$
𝔫 = 9
$\chi^2/N_{\rm dof} = 18/10$
$a_t m = 1.3554(47)$
𝔫 = 10
$\chi^2/N_{\rm dof} = 12/8$
$a_t m = 1.3902(67)$



$\mathfrak{n} = 0$
$a_t E_0 = 1.1126(1)$
$\mathfrak{n} = 1$
$a_t E_1 = 1.2153(10)$
$\mathfrak{n} = 2$
$a_t E_2 = 1.2446(11)$
$\mathfrak{n} = 3$
$a_t E_3 = 1.2495(11)$
$\mathfrak{n} = 4$
$a_t E_4 = 1.2814(81)$
$\mathfrak{n} = 5$
$a_t E_5 = 1.3309(43)$
$\mathfrak{n} = 6$
$a_t E_6 = 1.3429(45)$
$\mathfrak{n} = 7$
$a_t E_7 = 1.3458(41)$
$\mathfrak{n} = 8$
$a_t E_8 = 1.3531(47)$
$\mathfrak{n} = 9$
$a_t E_9 = 1.3554(47)$
$\mathfrak{n} = 10$
$a_t E_{10} = 1.3902(67)$
$J^P = 1^-$
$J^P = 1^-$ (hyb.)
$J^P = 3^-$
$J^P = 3^-$ (hyb.)
$J^P = 4^-$

Extending similar work - open charm for $J \leq 4$



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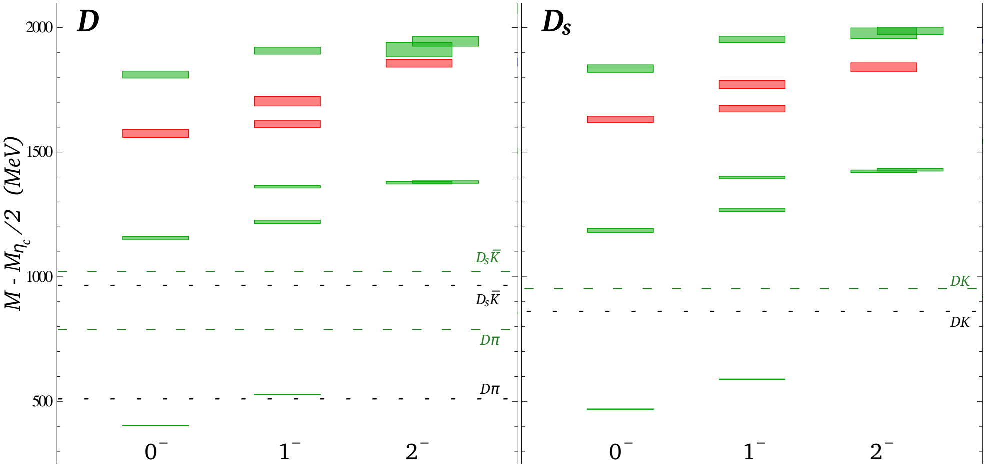
IS THERE A HEAVY-LIGHT HYBRID SUPERMULTIPLET AS IN D?



JHEP05 (2013) 021