B_c spectroscopy using highly improved staggered quarks

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Intro & Motivation

Experimental searches for $B_c(2S)$ before 2019:

- [1407.1032] - ATLAS sees a peak 6842(4)(5) MeV.
- QWG Beijing [1711, 1712.04094] - LHCb null result

Can we use lattice data to identify? [1811.09448]

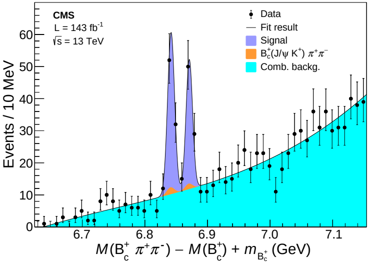
Use 'heavy-HISQ' formalism to access precise B_c physics:

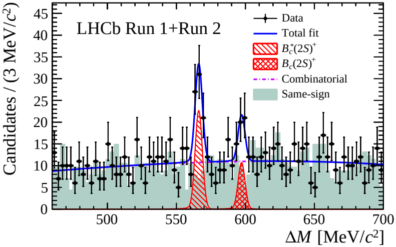
- Fully relativistic b quarks → reduced systematics compared to lattice NRQCD
    - Ground state masses and decay constants [1207.0994]
    - Semileptonic form factors [1611.01987]
    - Excited states? [1811.09448]
- Map out physical heavy quark mass dependence

Fast forward to 2019:

Intro & Motivation

[1902.00571,1904.00081]





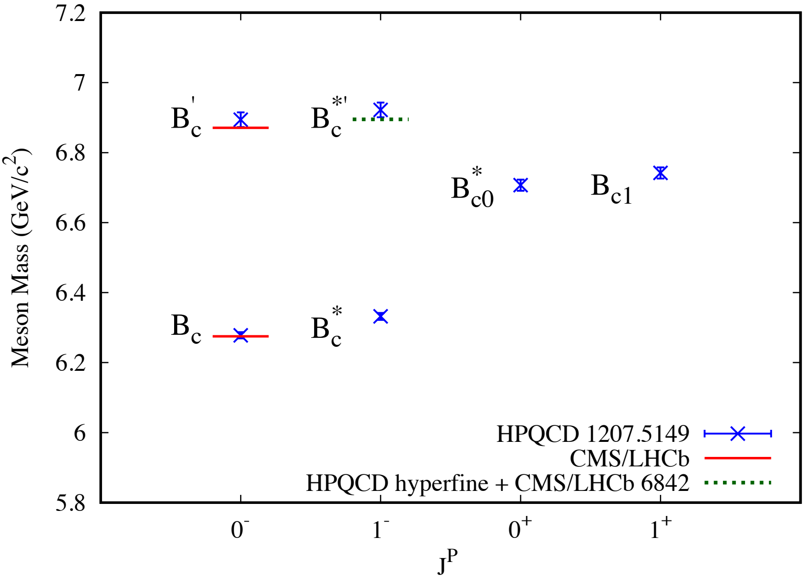
$B_c(2S)$: $6871(1.2)(0.8)(0.8)$ MeV

$B_c^*(2S)$ peak: $6842(2)$ MeV

$6872.1(1.3)(0.1)(0.8)$ MeV

$6841.2(0.6)(0.1)(0.8)$ MeV

B_c spectrum from NRQCD [1207.5149]



Combine theory & exp't

Use hyperfine splitting from theory to 'reconstruct' $B_c^*(2S)$:
$B_c^*(2S)$ peak [expt] + $(B_c^* - B_c)$ [theory] $\rightarrow B_c^*(2S)$

- Accurate determination of B_c^* highly desirable.
- What about the 0^+, 1^+ states?

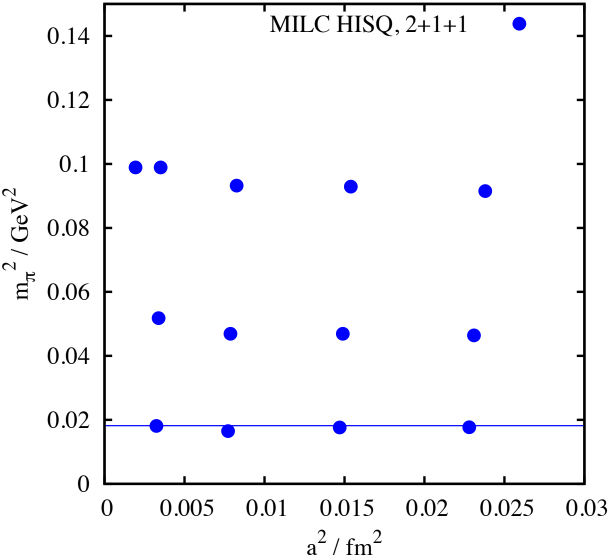
Outline

1. Intro & Motivation
2. Methodology
    - Heavy-HISQ approach
    - Compare w/ NRQCD
3. Results
    - B_c
    - $B_c(2S)$
    - B_{c0}^*
    - B_c^*
4. Summary & Outlook

MILC ensembles [1004.0342, 1212.4768]

- HISQ fermion action. $(\alpha_s a^2,\, \alpha_s \frac{v^2}{c^2}(am_h)^4)$
- Symanzik-improved gauge action, takes into account $\mathcal{O}(N_f \alpha_s a^2)$ effects of HISQ quarks in sea. [0812.0503]
- Multiple lattice spacings down to ~ 0.045 fm.
- Effects of u/d, s, and c quarks in the sea.
- Multiple light-quark input parameters down to physical pion mass.
  - Chiral fits.
  - Reduce statistical errors.

MILC ensemble parameters



Heavy HISQ strategy for b physics

- Use a heavy valence mass h as a proxy for the b quark.
- Work at a range of m_h, with $am_c < am_h \leq 0.8$ on each ensemble. On sufficiently fine ensembles, m_h is near to m_b.
- Map out (physical) dependence on M_{η_h}, remove discretisation effects $\sim (am_h)^{2n}$ using information from several ensembles. Evaluate result at M_{η_b}.

NRQCD

Heavy quark propagators are calculated using a non-relativistic formalism.

Improved Non-relativistic QCD action

- Accurate through $\mathcal{O}(\alpha_s v^4)$.
- Discretisation corrections through $\mathcal{O}(\alpha_s v^2 a^2 p^2)$.
- $v^2 \sim 0.1$ bottomonium, ~ 0.3 charmonium.
- $am > 1 \to b$ quarks on $a = 0.15 - 0.06$ fm (down to $m_b/2$ on $a = 0.15$ fm).

Propagators constructed via an evolution equation,
$G(\mathbf{x}, t + a) = e^{-aH_{\text{eff}}} G(\mathbf{x}, t)$.

NRQCD

$$\begin{aligned}
aH_{\mathrm{NRQCD}} &= aH_0 + a\delta H \\
aH_0 &= -\frac{\Delta^{(2)}}{2am_b} \\
a\delta H &= -c_1 \frac{(\Delta^{(2)})^2}{8(am_b)^3} + c_2 \frac{i}{8(am_b)^2} \left(\nabla \cdot \mathbf{E} - \mathbf{E} \cdot \nabla \right) \\
&\quad - c_3 \frac{1}{8(am_b)^2} \sigma \cdot \left(\nabla \times \mathbf{E} - \mathbf{E} \times \nabla \right) \\
&\quad - c_4 \frac{1}{2am_b} \sigma \cdot \mathbf{B} + c_5 \frac{\Delta^{(4)}}{24am_b} \\
&\quad - c_6 \frac{(\Delta^{(2)})^2}{16n(am_b)^2}
\end{aligned}$$

Results

$B_c(1S)$ from heavy HISQ

- Three lattice spacings $a \approx 0.09, 0.06, 0.045$ fm with $m_l/m_s = 1/5$, additional $a \approx 0.09$ fm ensemble with $m_l/m_s = 1/10$.
- $am_h < 0.8$ (except for $am_h = 0.9$ point on 0.045 fm ensemble, just beyond m_b).
- Only random wall sources at present (no smearing).

$B_c(1S)$ from heavy HISQ

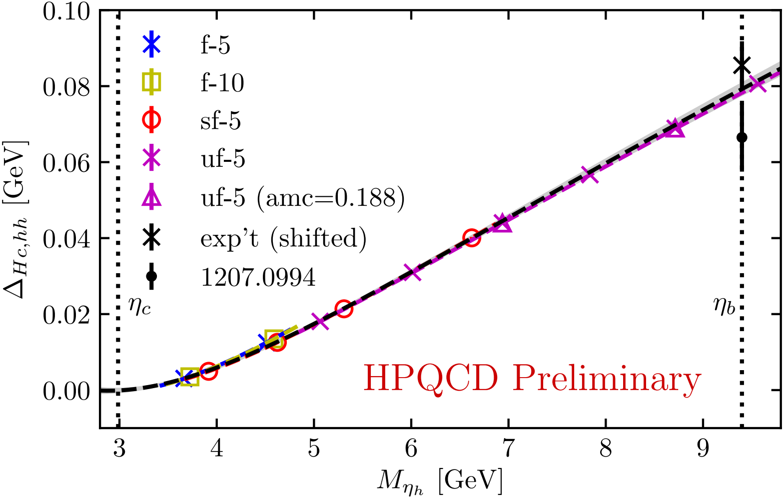
- Calculate the mass difference of H_c to average of associated heavyonium states:

$$\Delta_{H_c,hh} = M_{H_c} - (M_{\eta_h} + M_{\eta_c})/2$$

- Gives a very precise lattice result. Main uncertainties are from missing em and annhilation effects, $\approx -6(6)$ MeV.

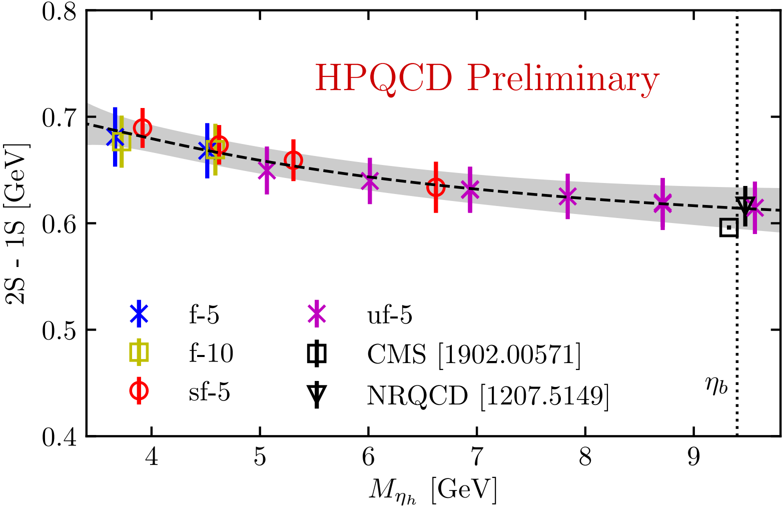
$B_c(1S)$ from heavy HISQ

[1811.09448]

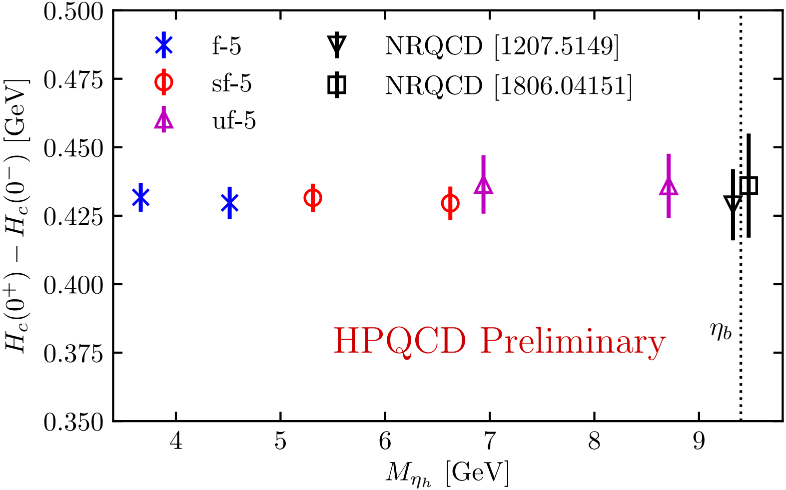


B_c $2S - 1S$ splitting

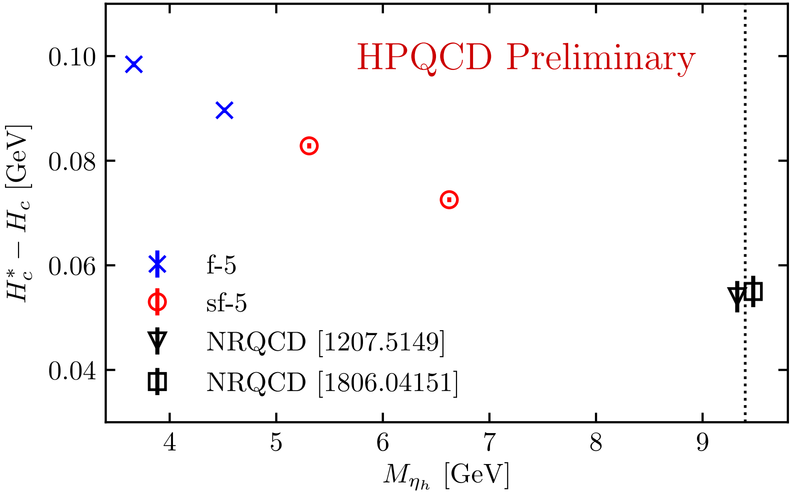
[1811.09448]



$B_c(0^+)$ from heavy HISQ



B_c hyperfine splitting from heavy HISQ

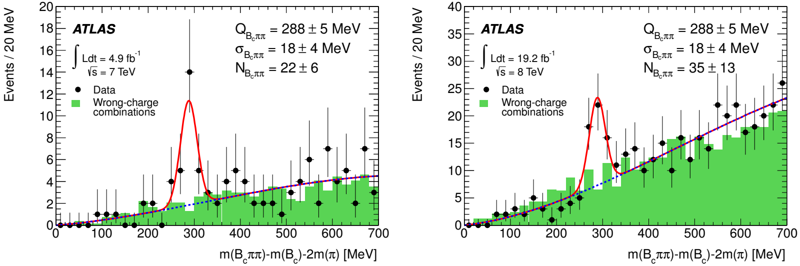


Summary & Outlook

- ‘Heavy-HISQ’ approach is a good way to study B_c spectroscopy:
  - Fully relativistic → no effective theory systematics.
  - Map out physical heavy quark dependence.
- Preliminary studies indicate the ground states in each channel (0^-, 1^-, 0^+, 1^+?) can obtain few-MeV accuracy.
- 1st radial excitation not yet as precise (~ 20 MeV).

Thank you!

[1407.1032]

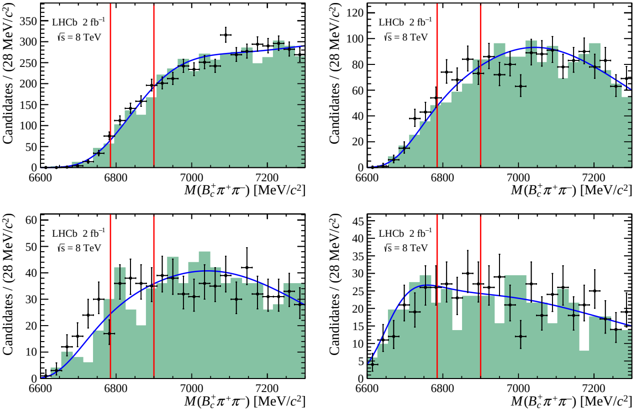


Bc(1S) state well established at 6275 MeV.

Model predictions: $M(B_c(2S))$ in range [6830, 6890] MeV

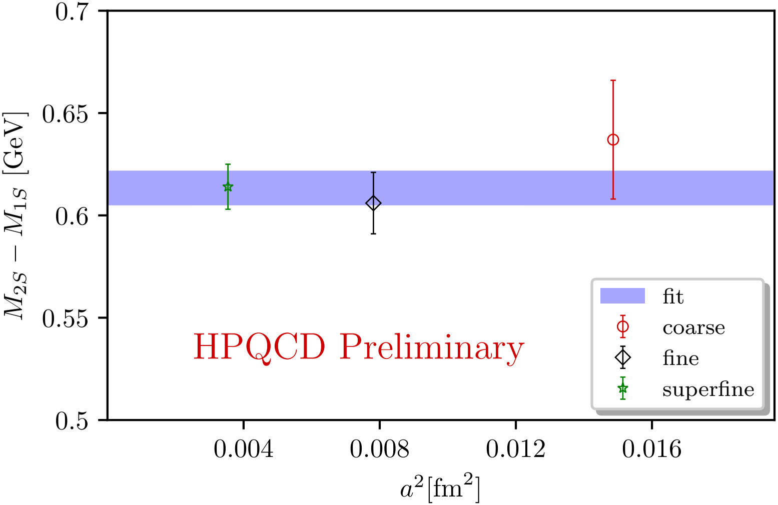
ATLAS identifies a structure at $6842(4)_{\text{syst}}(5)_{\text{stat}}$ MeV.

[1712.04094]

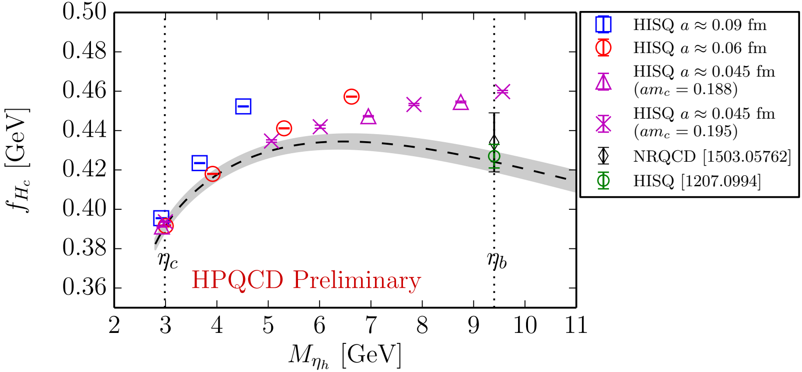


Despite much higher B_c yield, LHCb sees no evidence of a state.

B_c $2S - 1S$ splitting, NRQCD result

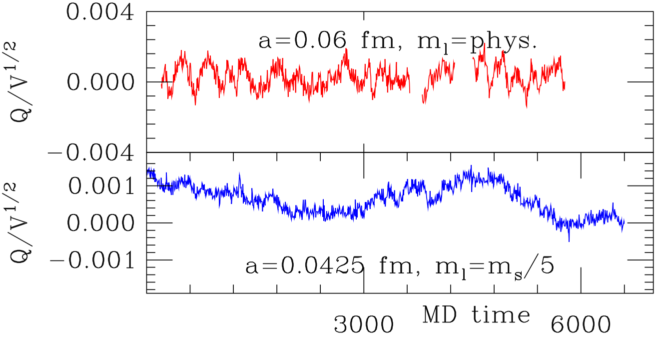


f_{B_c}


0.50
0.48
0.46
0.44
0.42
0.40
0.38
0.36
f_{H_c} [GeV]
2
3
4
5
6
7
8
9
10
11
M_{η_h} [GeV]
η_c
η_b
HPQCD Preliminary
HISQ $a \approx 0.09$ fm
HISQ $a \approx 0.06$ fm
HISQ $a \approx 0.045$ fm ($am_c = 0.188$)
HISQ $a \approx 0.045$ fm ($am_c = 0.195$)
NRQCD [1503.05762]
HISQ [1207.0994]

Topology

Topological “freezing” observed in MC time series of ultrafine ($a \sim 0.045$ fm) ensembles.



The effect of fixed topology on masses and decay constants was analysed using χPT in [1707.05430].

Topology

[1707.05430]

Percentage error in a heavy-light (Hq) decay constant:

$$\frac{\delta f}{f} \approx \frac{1}{2\chi_T V} \cdot \frac{1}{16}\frac{m_{l,\mathrm{sea}}^2}{m_q^2} \cdot \left[1 - \frac{\langle Q^2 \rangle_{\mathrm{sample}}}{\chi_T V}\right]$$

Effect enhanced on 'uf-5' ensemble, where V is small and $m_{l,\mathrm{sea}} = m_s/5$. (here $\frac{\langle Q^2 \rangle_{\mathrm{sample}}}{\chi_T V} \approx 1.3$). Numerically,

$$\frac{\delta f_D}{f_D} \sim \frac{\delta f_B}{f_B} \approx \;\; 1\%$$

$$\frac{\delta f_{D_s}}{f_{D_s}} \sim \frac{\delta f_{B_s}}{f_{B_s}} \approx 0.002\%$$