Charmed-strange and bottom-strange positive parity mesons from Lattice QCD

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Phys. Rev. Lett. 111 (2013) 22, 222001;
Phys. Rev. **D**90 (2014) 3, 034510;
arXiv:1501.01646

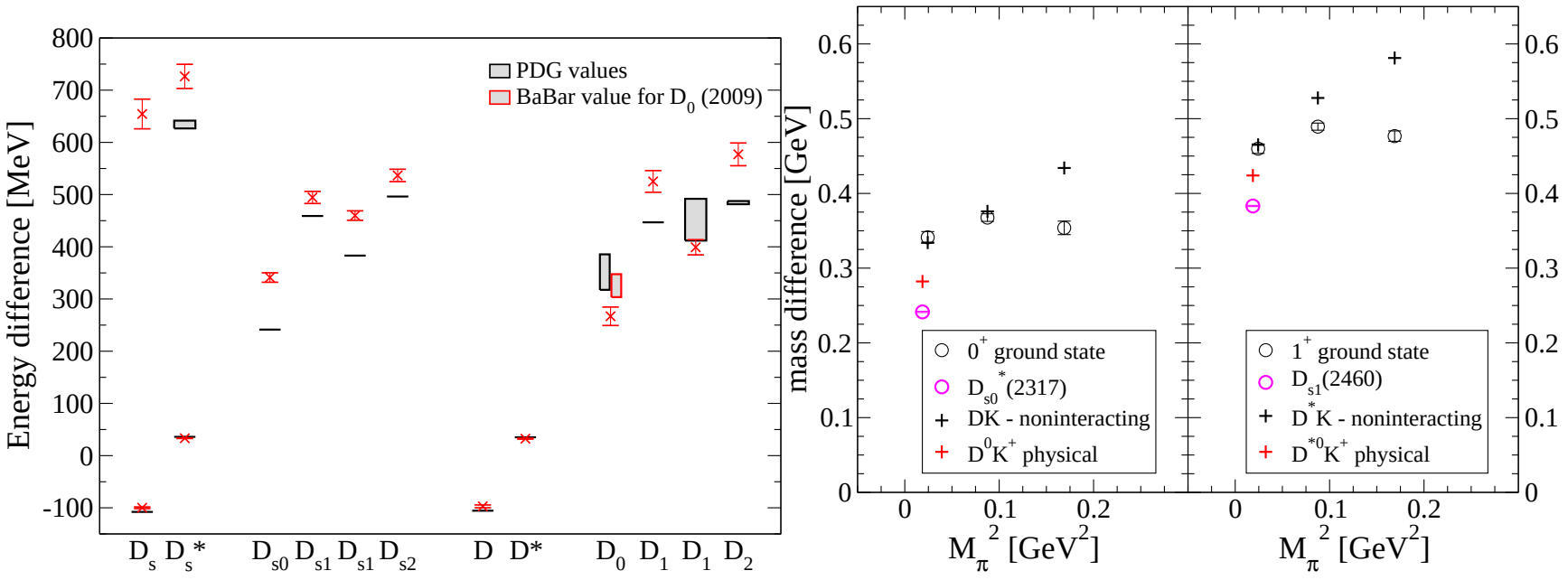
Outline

1. Motivation & Methods
   - Motivation
   - Lattices used
   - Heavy quarks with the Fermilab method
2. Positive parity D_s mesons
   - $D^{(*)}K$ scattering and $D^*_{s0}(2317)$, $D_{s1}(2460)$
3. Positive parity B_s mesons
   - $B^{(*)}K$ scattering and $J^P = 0^+, 1^+$ B_s mesons
4. Conclusions & outlook

Motivation: Experimental D_s spectrum

- Established states:
  - D_s ($J^P = 0^-$) and D_s^* (1^-)
  - $D_{s0}^*(2317)$ (0^+), $D_{s1}(2460)$ (1^+), $D_{s1}(2536)$ (1^+), $D_{s2}^*(2573)$ (2^+)
- More recent discoveries:
  - $D_{s1}^*(2700)$ seen by BaBar, Belle, LHCb (1^-)
  - $D_{sJ}^*(2860)$ seen by BaBar
    LHCb overlapping 1^- and 3^- states
  - $D_{sJ}^*(3040)$ seen by BaBar (1^+?,2^-?)
  - questionable $D_{sJ}^*(2632)$ seen by SELEX (1^-?)
- $j = \frac{1}{2}$ doublet almost mass-degenerate with non-strange states
- Some models suggest a tetraquark/molecular interpretations for controversial states
- (Most) lattice studies using single hadron ($c\bar{s}$) interpolators get too large or badly determined masses
- Large m_π: $D_{s0}^*(2317)$ below DK threshold;
  Small m_π: $D_{s0}^*(2317) \approx DK$ threshold

A previous attempt . . .



Mohler and Woloshyn, PRD 84 054503, 2011

- DK threshold turned out to be unphysical
- Even with light sea-quark masses the lowest states with $J^P = 0^+, 1^+$ remained unphysical
- Including the DK threshold explicitly might be vital

Technicalities: Lattices used

ID	$N_L^3 \times N_T$	N_f	a[fm]	L[fm]	#configs	m_π[MeV]	m_K[MeV]
(1)	$16^3 \times 32$	2	0.1239(13)	1.98	280/279	266(3)(3)	552(2)(6)
(2)	$32^3 \times 64$	2+1	0.0907(13)	2.90	196	156(7)(2)	504(1)(7)

- Ensemble (1) has 2 flavors of nHYP-smeared quarks

  Gauge ensemble from Hasenfratz et al. PRD 78 054511 (2008)

  Hasenfratz et al. PRD 78 014515 (2008)

- Ensemble (2) has 2+1 flavors of Wilson-Clover quarks

  PACS-CS, Aoki et al. PRD 79 034503 (2009)

- On the small volume we use distillation
  On the larger volume we use stochastic distillation

  Peardon et al. PRD 80, 054506 (2009);

  Morningstar et al. PRD 83, 114505 (2011)

Heavy quarks using the *Fermilab method*

El-Khadra et al., PRD 55,3933

- We tune κ for the spin averaged kinetic mass $(M_{\eta_c} + 3M_{J/\Psi})/4$ to assume its physical value
- General form for the dispersion relation

Bernard et al. PRD83:034503,2011

$$E(p) = M_1 + \frac{p^2}{2M_2} - \frac{a^3 W_4}{6} \sum_i p_i^4 - \frac{(p^2)^2}{8M_4^3} + \dots$$

- We compare results from three different fit strategies
- Energy splittings are expected to be close to physical
- For MeV values of masses

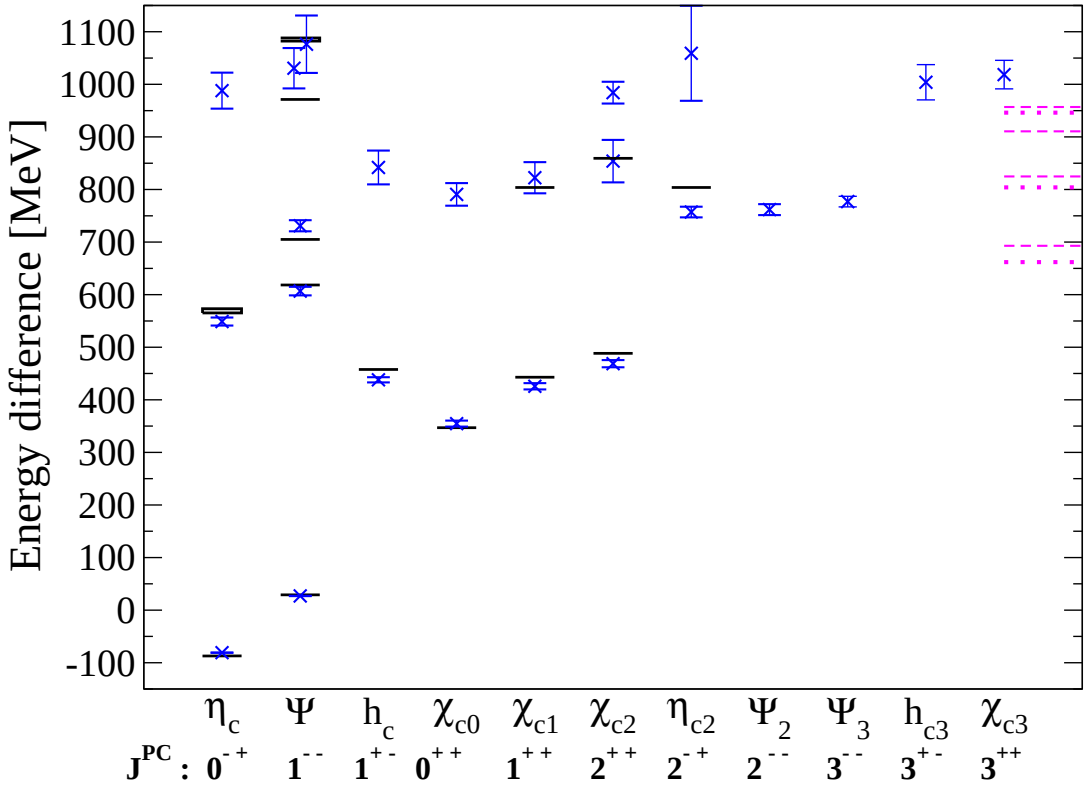
$$M = \Delta M + M_{sa,phys}$$

Testing our tuning: charm and light

	Ensemble (1)	Ensemble (2)	Experiment
m_π	266(3)(3)	156(7)(2)	139.5702(4)
m_K	552(1)(6)	504(1)(7)	493.677(16)
m_ϕ	1015.8(1.8)(10.7)	1018.4(2.8)(14.6)	1019.455(20)
m_{η_s}	732.3(0.9)(7.7)	692.9(0.5)(9.9)	688.5(2.2)*
$m_{J/\Psi} - m_{\eta_c}$	107.9(0.3)(1.1)	107.1(0.2)(1.5)	113.2(0.7)
$m_{D_s^*} - m_{D_s}$	120.4(0.6)(1.3)	142.1(0.7)(2.0)	143.8(0.4)
$m_{D^*} - m_D$	129.4(1.8)(1.4)	148.4(5.2)(2.1)	140.66(10)
$2m_{\overline{D}} - m_{\overline{\bar{c}c}}$	890.9(3.3)(9.3)	882.0(6.5)(12.6)	882.4(0.3)
$2M_{\overline{D_s}} - m_{\overline{\bar{c}c}}$	1065.5(1.4)(11.2)	1060.7(1.1)(15.2)	1084.8(0.6)
$m_{D_s} - m_D$	96.6(0.9)(1.0)	94.0(4.6)(1.3)	98.87(29)

- A single ensemble: Discrepancies due to discretization and unphysical light-quark masses expected

Low-lying charmonium spectrum



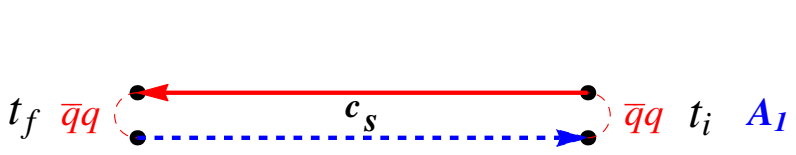
DM, S. Prelovsek, R. M. Woloshyn, PRD 87 034501 (2013);

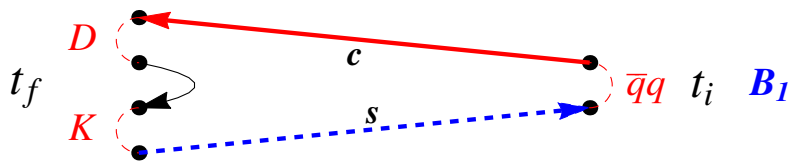
- Serves as further confirmation of our heavy-quark approach
- Data from 1 ensemble; Errors statistical + scale setting

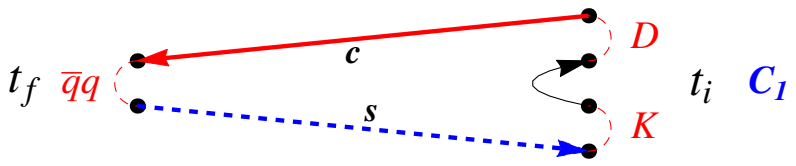
Revisiting the $D_{s0}^*(2317)$ and $D_{s1}(2460)$

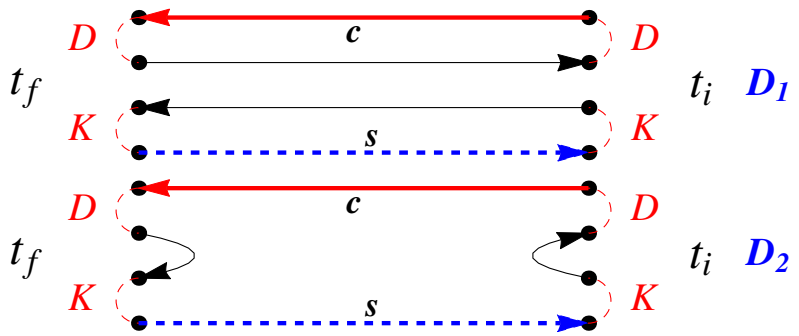
- Use almost physical light quarks
- Work with a partially quenched strange quark
  - Use ϕ meson and η_s to set strange quark mass
  - We obtain $\kappa_s = 0.13666$
- Improve charm quark tuning used for Fermilab charm
  - Use Landau link for $c_{sw,c} = \frac{1}{u_0^3}$
  - Empirically this reduces discretization effects
- Explicitly include DK interpolators into the basis

Contractions







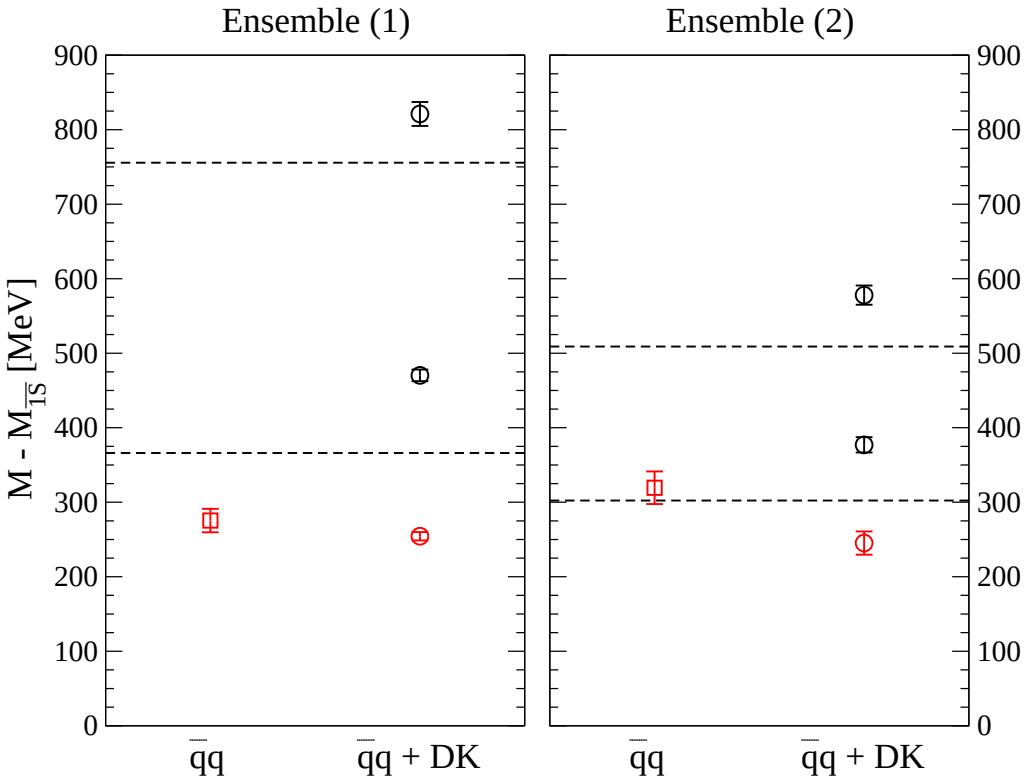


- Handled efficiently within the distillation method

Peardon et al. PRD 80, 054506 (2009)
Morningstar et al. PRD 83, 114505 (2011)

Energy levels for D_s with $J^P = 0^+$

DM, Lang, Leskovec, Prelovsek, Woloshyn, PRL 111 222001 (2013)



- With the combined basis we obtain a much better quality of the ground state plateau
- The variational method yields two low-lying levels and fits are unambiguous

Possible interpretations

(1) A sub-threshold state stable under the strong interaction

- We call this "bound state scenario"
- This is irrespective of the nature of the state
- One expects a negative scattering length in this case

See `Sasaki and Yamazaki, PRD 74 114507 (2006)` for details.

(2) A resonance in a channel with attractive interaction

- The lowest state corresponds to the scattering level shifted below threshold in finite volume
- The additional level would indicate a QCD resonance
- One expects a positive scattering length in this case

This is the situation for the $D_0^*(2400)$

`DM, Prelovsek, Woloshyn, PRD 87 034501 (2013).`

Using Lüscher's formula

- We can test the plausibility of these scenarios using Lüscher's formula and an effective range approximation

M. Lüscher Commun. Math. Phys. 105 (1986) 153; Nucl. Phys. B 354 (1991) 531; Nucl. Phys. B 364 (1991) 237.

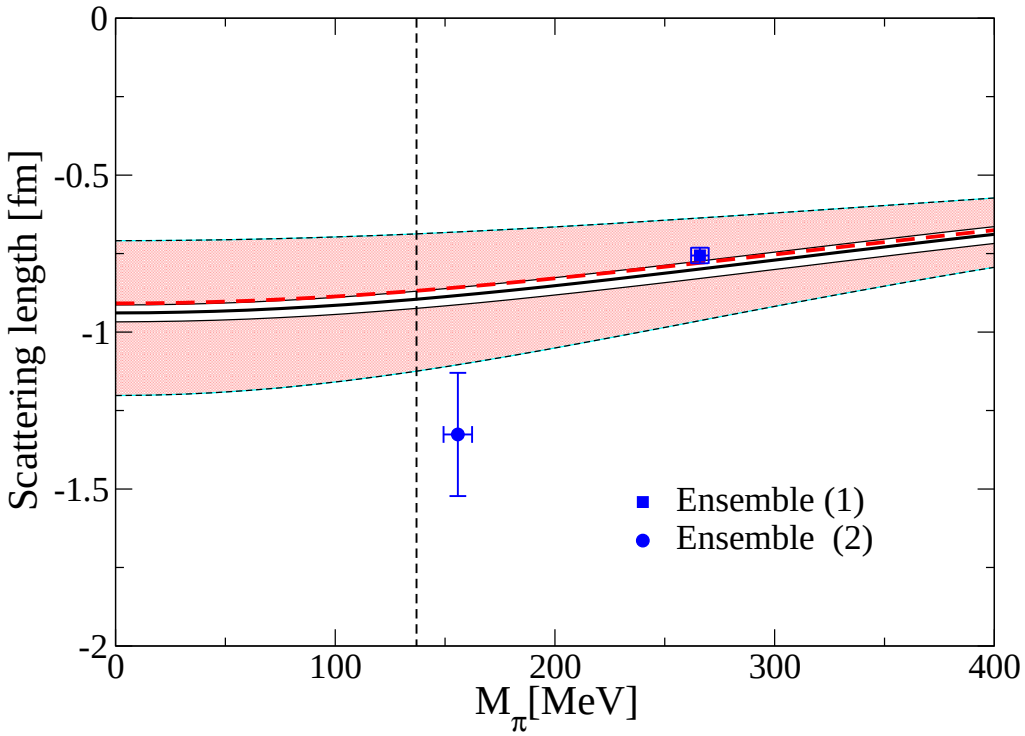
$$K^{-1} = p\cot\delta(p) = \frac{2}{\sqrt{\pi}L} Z_{00}(1;q^2)\ ,$$
$$\approx \frac{1}{a_0} + \frac{1}{2} r_0 p^2\ ,$$

- Results for ensembles (1) and (2)

$$a_0 = -0.756 \pm 0.025\mathrm{fm} \qquad r_0 = 0.056 \pm 0.031\mathrm{fm} \qquad (1)$$
$$a_0 = -1.33 \pm 0.20\mathrm{fm} \qquad r_0 = 0.27 \pm 0.17\mathrm{fm} \qquad (2)$$

Results for the scattering length a_0

DM, Lang, Leskovec, Prelovsek, Woloshyn, PRL 111 222001 (2013)

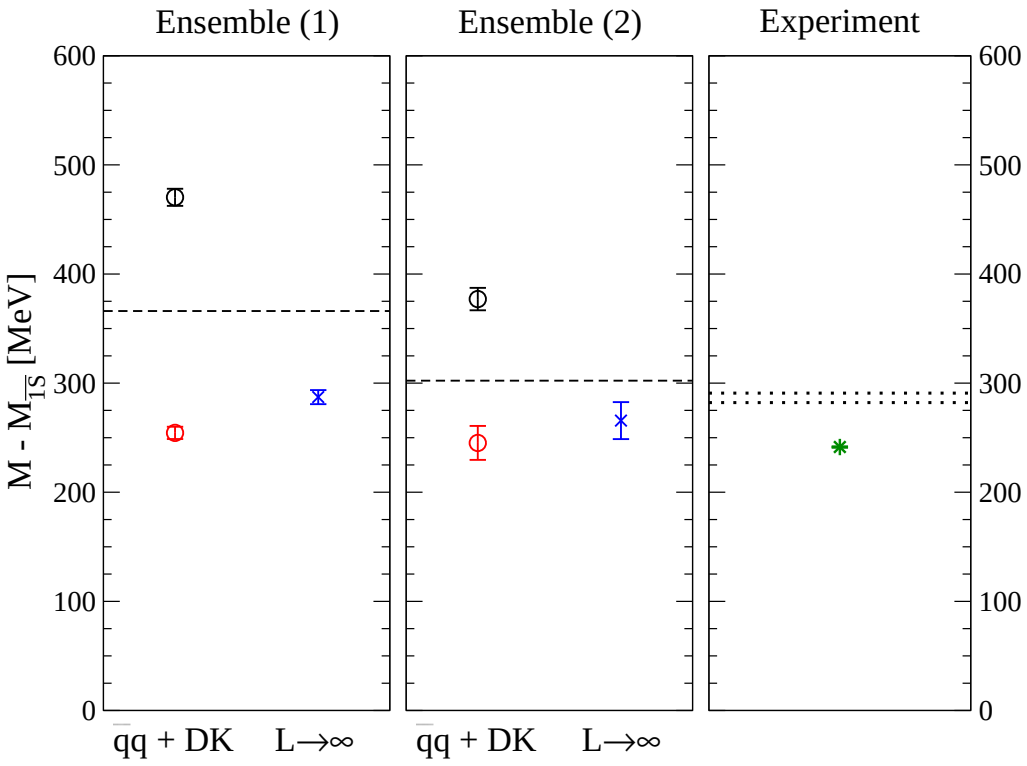


- We compare to the predictions from an indirect calculation

  Liu et al. PRD 87 014508 (2013).
- Our determination robustly leads to negative values.

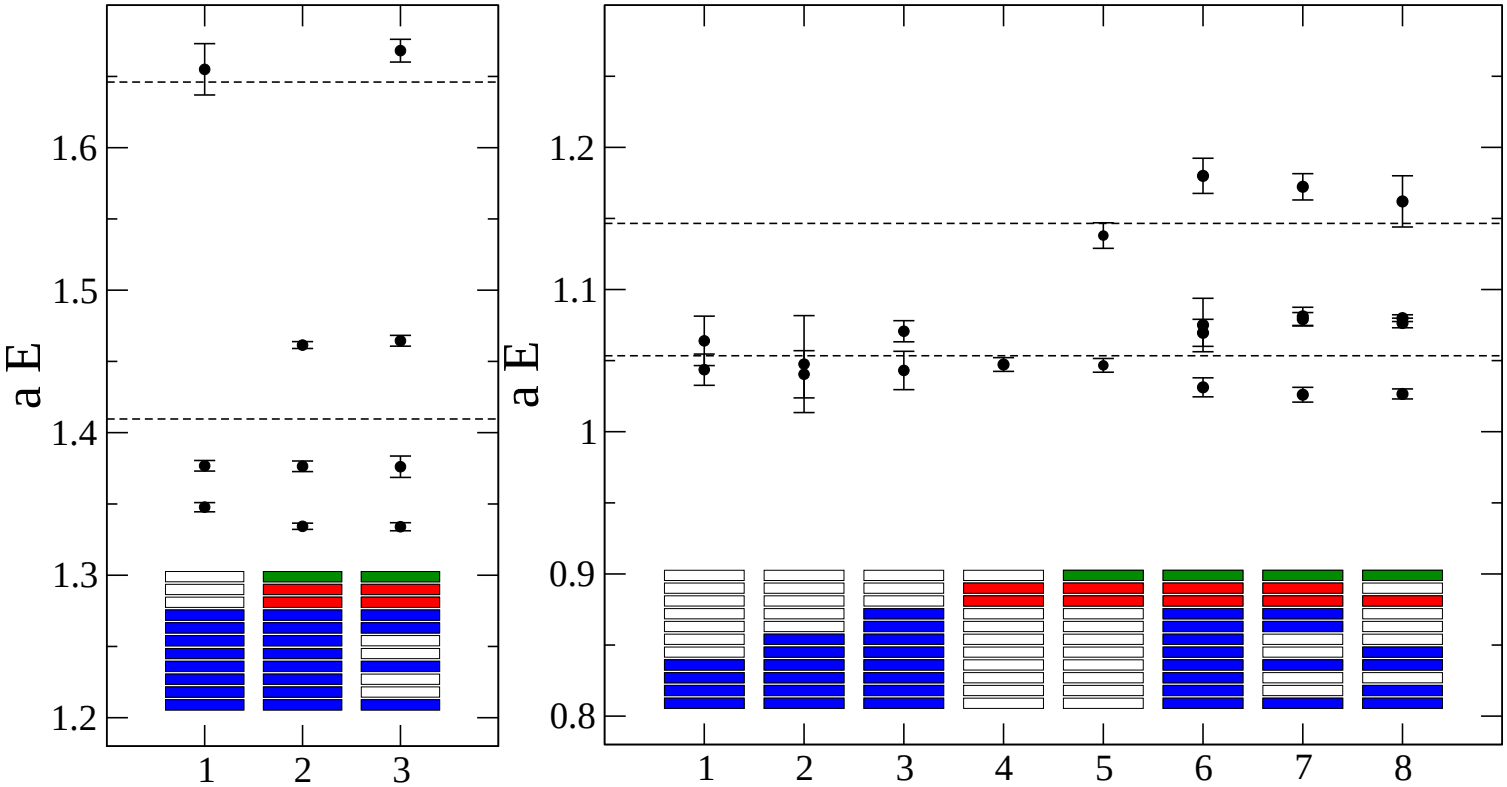
Infinite volume bound states *vs.* experiment

- (Infinite volume)bound state: T-matrix pole for $\cot\delta(i|p_b|) = i$
- Using our a_0 and r_0 we can determine the binding momentum and calculate the corresponding Energy level



Extending our calculation to the $D_{s1}(2460)$

- Assume the heavy quark limit is a good approximation
  $\rightarrow$ $D_{s1}(2536)$ decays only in D-wave
  we extract just a naive energy level

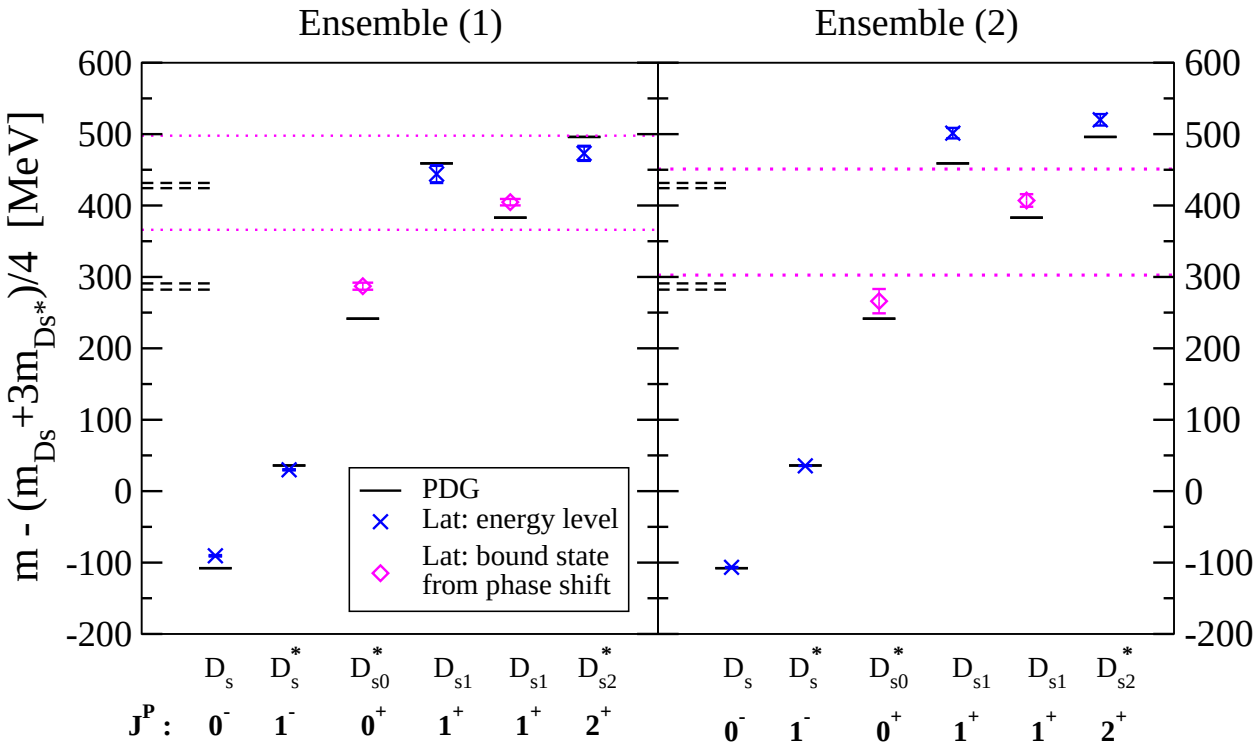


Results in T_1^+

set	$a_0^{D^*K}$ [fm]	$r_0^{D^*K}$ [fm]	$(ap_B)^2$	am_B	$m_K + m_{D^*} - m_B$ [MeV]	$m_B - \frac{1}{4}(m_{D_s} + 3m_{D_s^*})$ [MeV]
Ensemble (1)						
	-0.665(25)	-0.106(37)	-0.0301(15)	1.3511(35)	93.2(4.7)(1.0)	404.6(4.5)(4.2)
Ensemble (2)						
set 1	-1.15(19)	0.13(22)	-0.0071(22)	1.0336(60)	43.2(13.8)(0.6)	408(13)(5.8)
set 2	-1.11(11)	0.10(10)	-0.0073(16)	1.0331(41)	44.2(9.9)(0.6)	407.0(8.8)(5.8)
Experiment						
					44.7	383

set	$m_{D_{s1}(2536)} - \frac{1}{4}(m_{D_s} + 3m_{D_s^*})$ [MeV]	$m_{D_{s1}(2536)} - m_K - m_{D^*}$ [MeV]
Ensemble (1)		
	444(12)	-53(12)
Ensemble (2)		
set 1	507(10)	56(11)
set 2	501(8)	50(8)
Experiment		
	459	31

Resulting D_s P-wave spectrum



- Remaining discrepancies of the size of discretization uncertainties
- Many improvements possible

B_s states from experiment

- Two p-wave states known from experiment:
  $B_{s1}(5830)$ with $M = 5828.7(4)$ MeV
  $B^*_{s2}(5840)$ with $M = 5839.96(20)$ MeV and $\Gamma = 1.6(5)$ MeV
- Discovered in two body decays into $K^- B^+$ at CDF/D0 and also seen by LHCb
- Remaining B^*_{s0} and B_{s1} states not measured
  LHCb is working on this
- Could be seen in electromagnetic transitions, transitions with a single π^0 or transitions through a virtual σ with $\sigma \to 2\pi$.

Bardeen, Eichten, Hill, PRD 68 054024 (2003)

- What can we say?

Predictions for B_s states (models or model+EFT)

	0^+	1^+
Covariant (U)ChPT	5726(28)	5778(26)
NLO UHMChPT	5696(20)(30)	5742(20)(30)
LO UChPT	5725(39)	5778(7)
LO χ-SU(3)	5643	5690
Bardeen, Eichten, Hill	5718(35)	5765(35)
rel. quark model 1	5804	5842
rel. quark model 2	5833	5865
rel. quark model 3	5830	5858

For references see arXiv:1501.01646

- Relevant thresholds at ≈5773 MeV and ≈5819 MeV
- Unitarized ChPT variants: dynamically generated states below threshold
- Quark model predictions: above threshold

Previous lattice results

- NRQCD b quarks and staggered light quarks
  States predicted slightly below the $B^{(*)}K$ thresholds:

$$M_{B^*_{s0}} = 5752(16)(5)(25) \qquad M_{B_{s1}} = 5806(15)(5)(25)$$

Gregory et al. PRD 83 014506 (2011)

- Static-light mesons with the transition amplitude method

McNeile, Michael, Thompson, PRD 70 054501 (2004)

- Static-light mesons plus interpolation between static light states and experiment D_s states

Green et al. PRD 69 094505 (2004)

- Static-light states on quenched and 2 flavor lattices

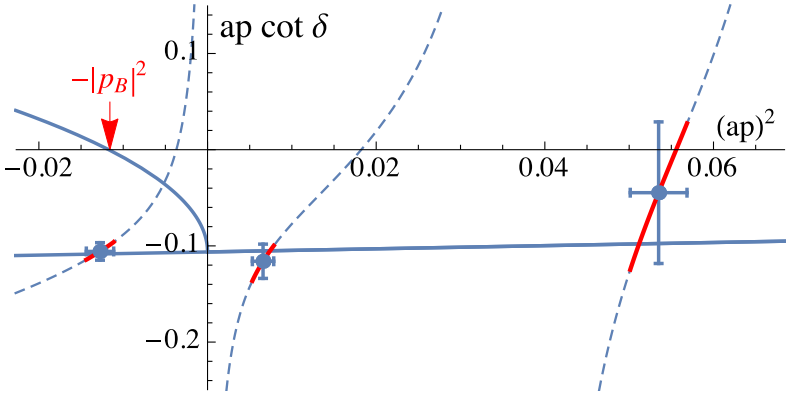
Burch et al. PRD 79 014504 (2009)

Testing our tuning: charm and beauty

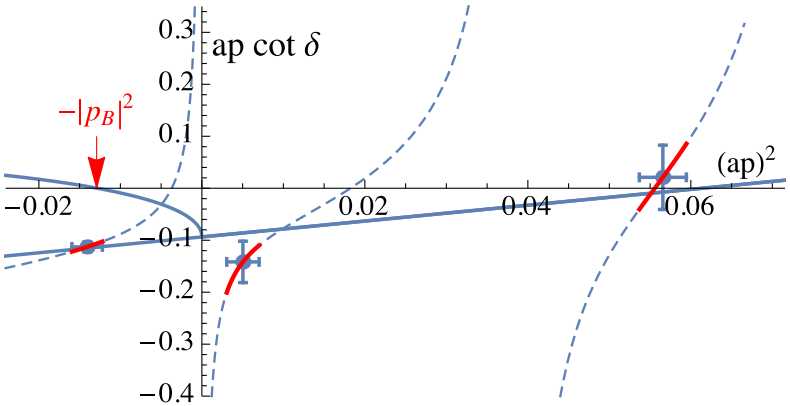
	Ensemble (1)	Ensemble (2)	Experiment
$m_{J/\psi} - m_{\eta_c}$	107.9(0.3)(1.1)	107.1(0.2)(1.5)	113.2(0.7)
$m_{D_s^*} - m_{D_s}$	120.4(0.6)(1.3)	142.1(0.7)(2.0)	143.8(0.4)
$m_{D^*} - m_D$	129.4(1.8)(1.4)	148.4(5.2)(2.1)	140.66(10)
$2m_{\overline{D}} - m_{\overline{\bar{c}c}}$	890.9(3.3)(9.3)	882.0(6.5)(12.6)	882.4(0.3)
$2M_{\overline{D_s}} - m_{\overline{\bar{c}c}}$	1065.5(1.4)(11.2)	1060.7(1.1)(15.2)	1084.8(0.6)
$m_{D_s} - m_D$	96.6(0.9)(1.0)	94.0(4.6)(1.3)	98.87(29)
$m_{B^*} - m_B$	-	46.8(7.0)(0.7)	45.78(35)
$m_{B_{s^*}} - m_{B_s}$	-	47.1(1.5)(0.7)	$48.7^{+2.3}_{-2.1}$
$m_{B_s} - m_B$	-	81.5(4.1)(1.2)	87.35(23)
$m_\Upsilon - m_{\eta_b}$	-	44.2(0.3)(0.6)	62.3(3.2)
$2m_{\overline{B}} - m_{\overline{\bar{b}b}}$	-	1190(11)(17)	1182.7(1.0)
$2m_{\overline{B_s}} - m_{\overline{\bar{b}b}}$	-	1353(2)(19)	1361.7(3.4)
$2m_{B_c} - m_{\eta_b} - m_{\eta_c}$	-	169.4(0.4)(2.4)	167.3(4.9)

- Errors statistical and scale setting only
- Bottom quark slightly to light

B^*_{so} and B_{s1}: Results



$$a_0^{BK} = -0.85(10)\,\mathrm{fm}$$
$$r_0^{BK} = 0.03(15)\,\mathrm{fm}$$
$$M_{B_{s0}} = 5.711(13)\,\mathrm{GeV}$$

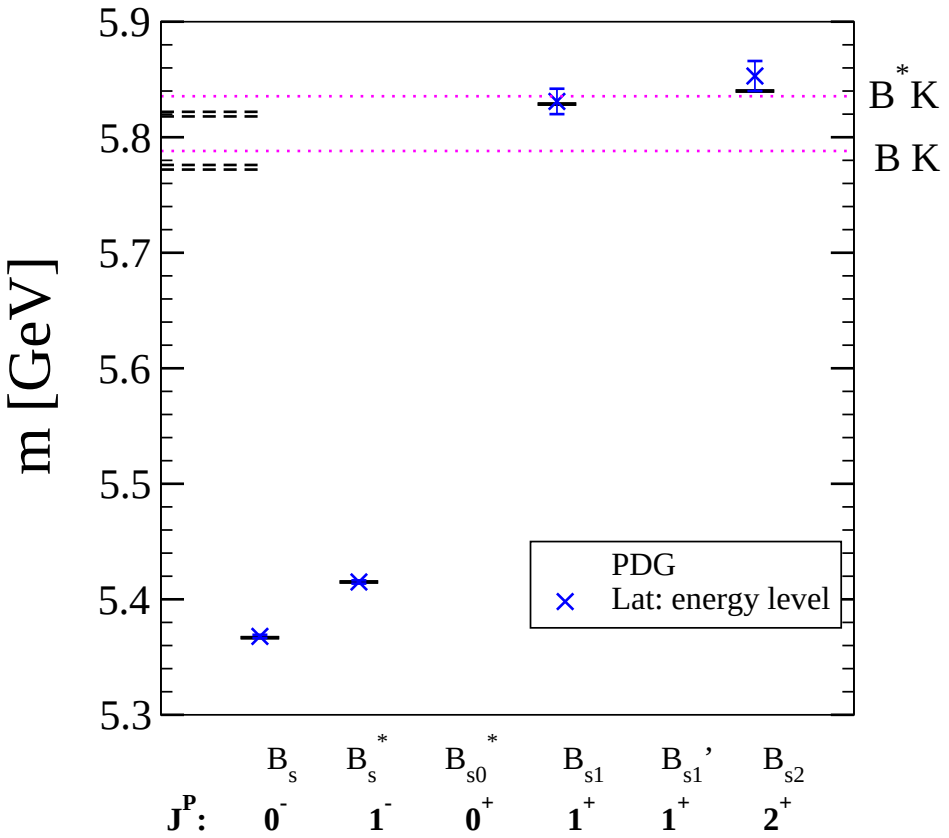


$$a_0^{B^*K} = -0.97(16)\,\mathrm{fm}$$
$$r_0^{B^*K} = 0.28(15)\,\mathrm{fm}$$
$$M_{B_{s0}} = 5.750(17)\,\mathrm{GeV}$$

- Energy from the difference to the $B^{(*)}K$ threshold

A further sanity check

- Discretization errors expected to be smaller than for D_s



$$M_{B'_{s1}} = 5.831(9)(6)\,\mathrm{GeV}$$
$$M_{B_{s2}} = 5.853(11)(6)\,\mathrm{GeV}$$

- Uncertainties just statistics and scale setting

B^*_{so} and B_{s1}: Systematic uncertainties

source of uncertainty	expected size [MeV]
heavy-quark discretization	12
finite volume effects	8
unphysical Kaon, isospin & EM	11
b-quark tuning	3
dispersion relation	2
spin-average (experiment)	2
scale uncertainty	1
3 pt vs. 2 pt linear fit	2
total	19

- discretiation effects from HQET power counting also considering mass mismatches

  Oktay, Kronfeld Phys.Rev. D78 014504 (2008)

- Finite volume from difference between the energy level and the pole

Comparing to models

	0^+	1^+
Covariant (U)ChPT	5726(28)	5778(26)
NLO UHMChPT	5696(20)(30)	5742(20)(30)
LO UChPT	5725(39)	5778(7)
LO χ-SU(3)	5643	5690
Bardeen, Eichten, Hill	5718(35)	5765(35)
rel. quark model	5804	5842
rel. quark model	5833	5865
rel. quark model	5830	5858
HPQCD 2010	5752(16)(5)(25)	5806(15)(5)(25)
this work	5713(11)(19)	5750(17)(19)

Conclusions & outlook

- Determining the the QCD spectrum close to thresholds has just begun
- Meson and baryon states close to threshold(s) can be attacked
- Coupled channel results encouraging (see David Wilson)
- Many improvements to what I presented possible (stay tuned)
- LHCb, BelleII and $\overline{\mathrm{P}}$ANDA will gather a lot of data
  $\rightarrow$ I would like them to compare to QCD, not models!
- Extracting resonance parameters from lattice scattering phase shifts will need (some degree) of modeling, just like in experiment.

Thank you!

Backup slides

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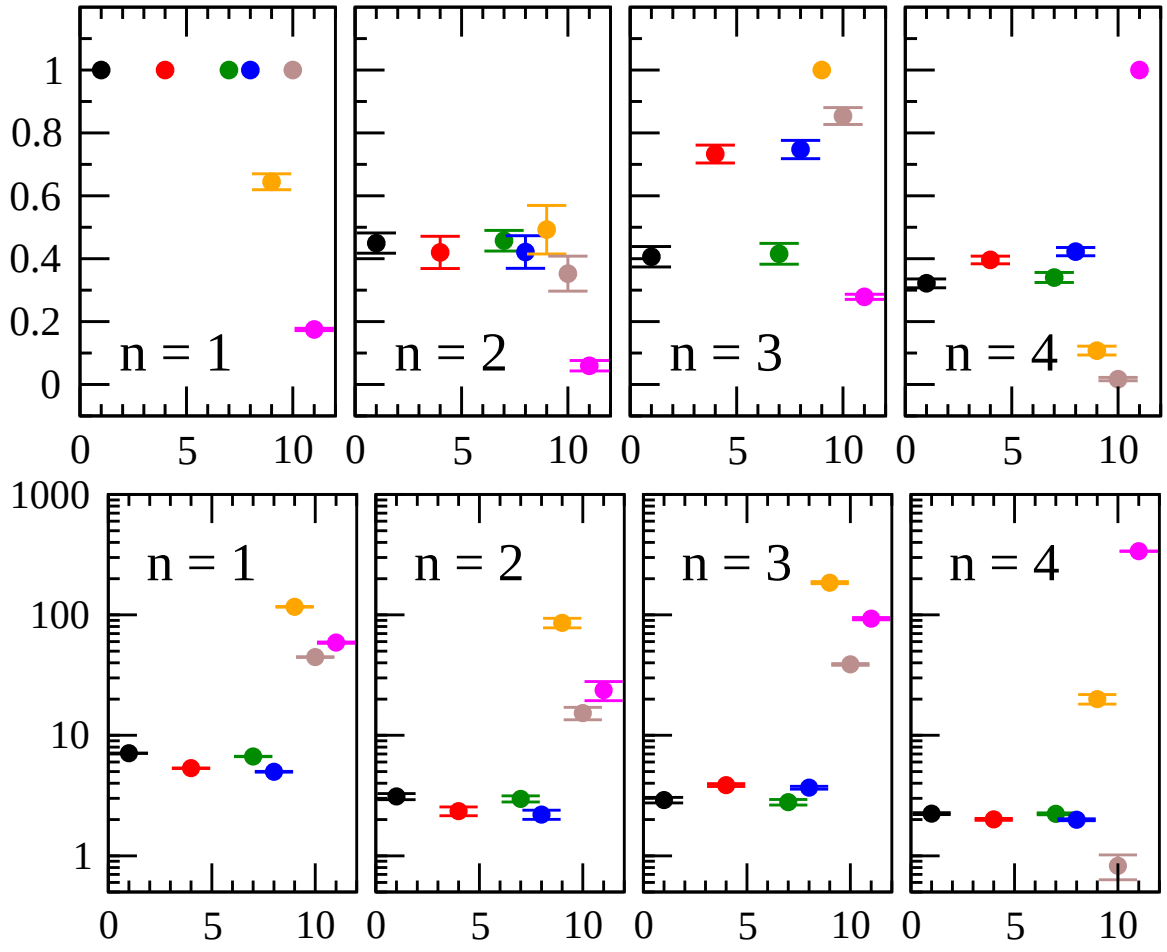
Composition of eigenstates



- Beware: Ambiguity in the normalization (eliminated by ratios)