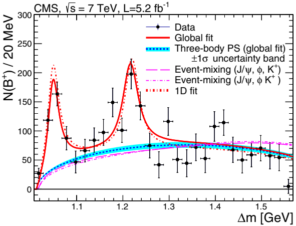
Hadron resonances and bound states with heavy quarks

Daniel Mohler

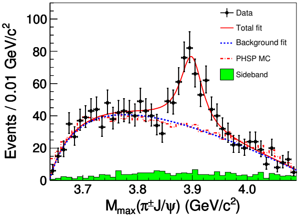
Seattle,
February 5th, 2018

15 years after the $X(3872)$, $D^*_{s0}(2317)$: Many new puzzles

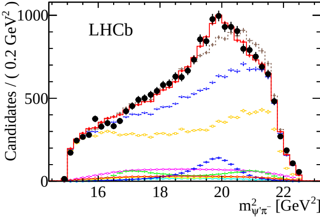
$Y(4140)$: CDF, CMS



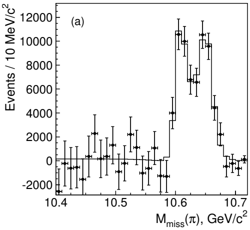
$Z_c(3900)^\pm$: BESIII, Belle, data from Cleo



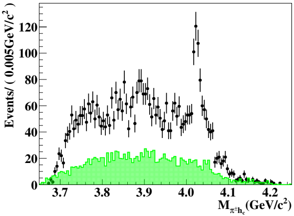
$Z(4430)^\pm$: Belle, LHCb



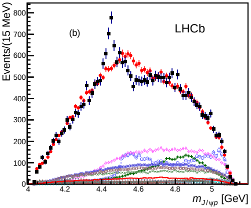
$Z_b(10610)^+, Z_b(10650)^+$: Belle



$Z_c(4020)^\pm$: BESIII



$P_c(4450), P_c(4380)$: LHCb



Motivation vs. lattice reality

- Goal: Learn about the nature of exotic hadrons with heavy quarks

The purpose of computing is insight, not numbers

– Richard Hamming

- Hindered by lattice systematics
  - Need to take the *continuum limit*: $a(g,m) \to 0$
  - Want to exploit (power law) finite volume effects (while keeping exponential effects small)
  - Need to calculate at (or extrapolate to) the physical pion mass
- So far: *exploratory* results for the spectrum (often single pion mass/ lattice spacing)
  - Should be compared only qualitatively to experiment
  - Provide an outlook on future Lattice QCD results
  - To learn about structure, more complicated observables needed (transitions)

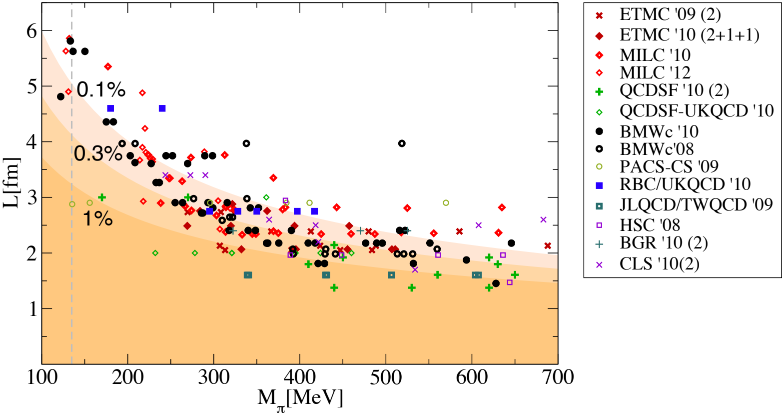
Assignments from the organizers

- Review numerical scattering results with heavy flavors
- Will use the examples below for illustration
  - D_s and B_s results
  - Results for the $X(3872)$
  - χ'_{c0} / $X(3915)$
  - Search for charged charmonium-like Z_c
- Technical issues: Heavy-quark discretization effects
- Prospects and challenges for approaching the physical point
- Importance/construction of interpolator basis
- Outlook

Disclaimers:

- In this talk I will not cover HALQCD results
- I will not cover explicitly exotic mesons with $\bar{b}\bar{b}$

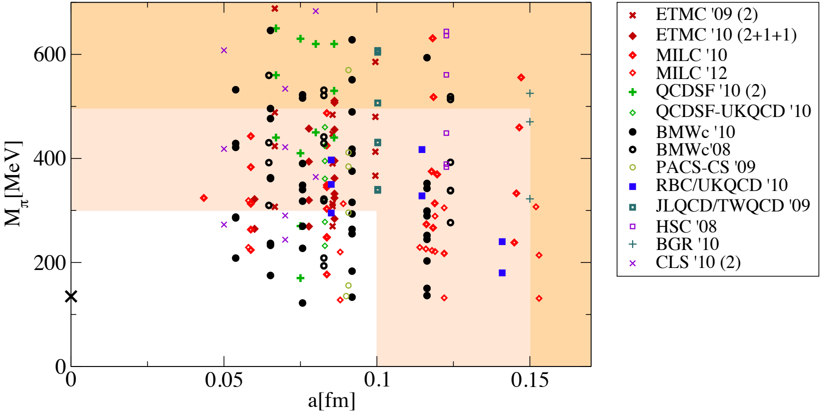
The landscape of lattice simulations



Plots from Christian Hoelbling

Acta Phys.Polon. B45 no.12, 2143, 2014

The landscape of lattice simulations

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Plots from Christian Hoelbling
Acta Phys.Polon.  B45 no.12, 2143, 2014
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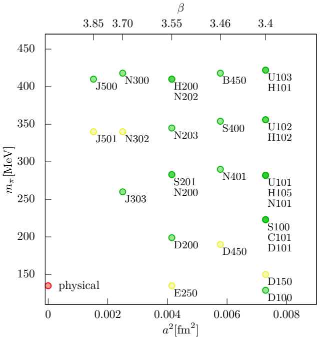
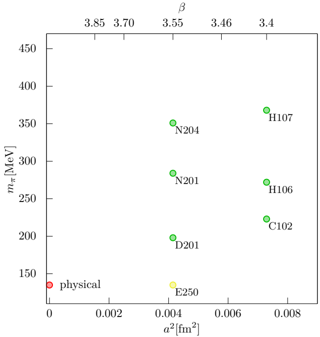
CLS 2+1 flavor ensembles: Overview

Bruno *et al.* JHEP 1502 043 (2015); Bali *et al.* PRD 94 074501 (2016)

$Tr(M) = \text{const.}$



$m_s = \text{const.}$



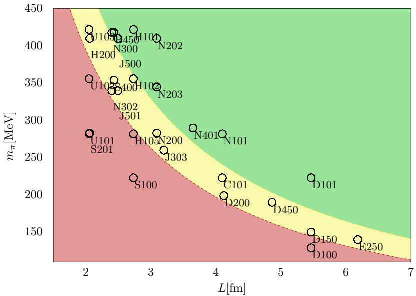
plots by Jakob Simeth, RQCD

- Ensembles at 5 lattice spacings and with a range of $M_\pi \leq 420$MeV
- Ensembles to control (or exploit) finite volume effects

CLS 2+1 flavor ensembles: Volumes used

Bruno *et al.* JHEP 1502 043 (2015); Bali *et al.* PRD 94 074501 (2016)

$Tr(M) = \text{const.}$



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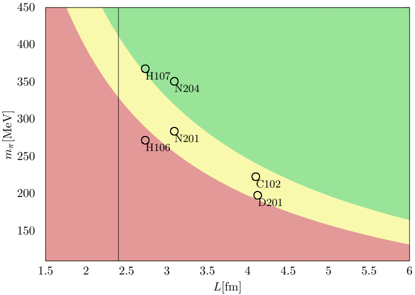


plots by Jakob Simeth, RQCD

- red: $m_\pi L \leq 4$; yellow: $4 \leq m_\pi L \leq 5$; green $5 \leq m_\pi L$
- Most ensembles with $m_\pi L \geq 4$
- Some smaller volumes to check finite size effects

Analysis of discretization effects

- For Wilson-like actions: Qualitative understanding of heavy quark discretization effects in the Fermilab method

  El-Khadra *et al.*, PRD 55,3933

  Oktay & Kronfeld, PRD 78 014504 (2008)
- Provides insights not only when the Fermilab method is followed
- Strategy followed by Fermilab/MILC
  - Take tadpole improved tree-level value for c_B
  - On each ensemble, tune a meson kinetic mass/ combination of masses to be physical
  - Procedure removes large discretization effects in the kinetic energy
  - Results in close-to-physical mass splittings
- Relativistic heavy quark action

  Aoki *et al.* Prog.Theor.Phys. 109 383 (2003)
  - Tune all action parameters, in particular keep two hopping parameters and tune dispersion relation
  - More involved tuning
  - For question, please refer to S. Aoki and Y. Namekawa

Discretization effects – dispersion relation

- General form for the dispersion relation

Bernard et al. PRD83:034503,2011

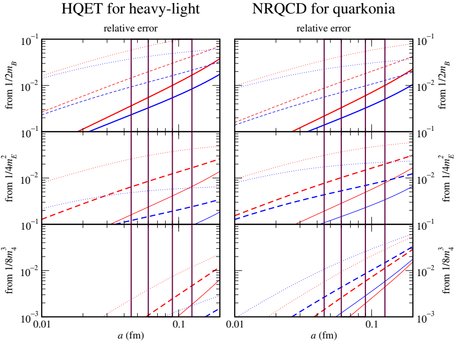
$$E(p) = M_1 + \frac{p^2}{2M_2} - \frac{a^3 W_4}{6} \sum_i p_i^4 - \frac{(p^2)^2}{8M_4^3} + \dots$$

- Example for 2+1 flavor PACS-CS ensemble with $M_\pi \approx 156$MeV

spin average	$\bar{c}c$	D_s	D
M_1	1.20438(15)	0.84606(28)	0.80466(137)
M_2	1.4073(59)	0.9336(105)	0.884(50)
M_4	1.270(63)	0.959(71)	0.98(38)
$\frac{M_2}{M_1}$	1.1685(49)	1.1035(122)	1.099(61)
$M_2[GeV]$	3.062(13)(44)	2.031(23)(39)	1.923(108)(28)
Exp $[GeV]$	3.06861(18)	2.07635(38)	1.97512(12)

- Naive application of Lüscher method problematic (moving frames!)

Discretization effects – mass mismatches



Plot from PRD 78 014504 (2008)

- charm: red; bottom: blue
- lines for
  unimproved/ tree level/ 1 loop

- Relative error compared to $\Lambda / m_Q v^2$
- vanish as a power of a for $am_Q \ll 1$
- in many cases: smaller discretization effects for bottom
  - static approximation better for b
  - NRQCD better for $\bar{b}b$
- For charm: Largish discretization effects everywhere
- Anisotropic lattices alone do not help for spin-splittings

Exotic D_s and B_s candidates

Established s and p-wave D_s and B_s hadrons:

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^+)

B_s ($J^P = 0^-$) and B_s^* (1^-)

$B_{s1}(5830)$ (1^+), $B_{s2}^*(5840)$ (2^+)

- Corresponding $D_0^*(2400)$ and $D_1(2430)$ are broad resonances
- Peculiarity: $M_{c\bar{s}} \approx M_{c\bar{d}} \quad \rightarrow \quad$ exotic structure? (tetraquark, molecule)

- B_s cousins of the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ not (yet) seen in experiment
- The LHCb experiment at CERN should be able to see these

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D_s ($J^P = 0^-$) and D_s^* (1^-)	B_s ($J^P = 0^-$) and B_s^* (1^-)
$D_{s0}^*(2317)$ (0^+), $D_{s1}(2460)$ (1^+),	?
$D_{s1}(2536)$ (1^+), $D_{s2}^*(2573)$ (2^+)	$B_{s1}(5830)$ (1^+), $B_{s2}^*(5840)$ (2^+)

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$D_{s0}^*(2317)$: D-meson – Kaon s-wave scattering

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

Charm-light hadrons

$D_{s0}^*(2317)^\pm$ $I(J^P) = 0(0^+)$
J, P need confirmation.
J^P is natural, low mass consistent with 0^+.

Mass $m = 2317.7 \pm 0.6$ MeV
$m_{D_{s0}^*(2317)^\pm} - m_{D_s^\pm} = 349.4 \pm 0.6$ MeV
Full width $\Gamma < 3.8$ MeV, CL = 95%

$$p \cot \delta_0(p) = \frac{2}{\sqrt{\pi}L} Z_{00}\left(1; \left(\frac{L}{2\pi}p\right)^2\right)$$
$$\approx \frac{1}{a_0} + \frac{1}{2} r_0 p^2$$

Mohler *et al.* PRL 111 222001 (2013)
Lang, DM *et al.* PRD 90 034510 (2014)

Results for ensembles (1) and (2)

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

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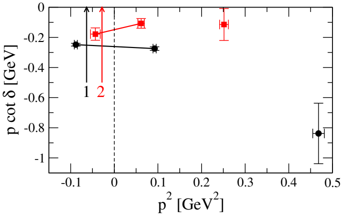

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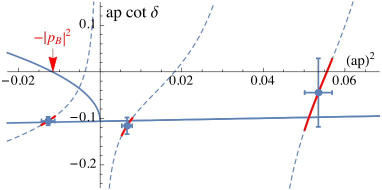
B_{s0}^* and B_{s1}: Results

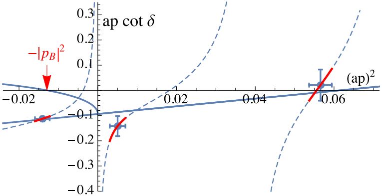
Lang, Mohler, Prelovsek, Woloshyn PLB 750 17 (2015)

B_{s0}^*



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

B_{s1}



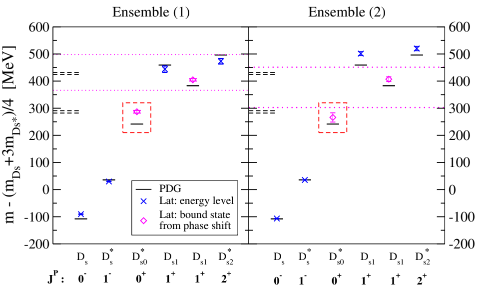
$$a_0^{B^*K} = -0.97(16)\text{ fm}$$
$$r_0^{B^*K} = 0.28(15)\text{ fm}$$
$$M_{B_{s1}} = 5.750(17)\text{ GeV}$$

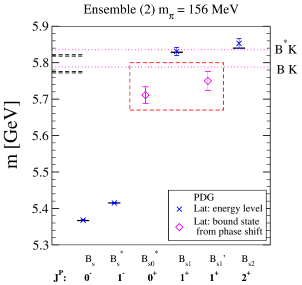
- Energy from the difference to the $B^{(*)}K$ threshold

D_s and B_s: Spectrum results

Mohler *et al.* PRL 111 222001 (2013)
Lang, Mohler *et al.* PRD 90 034510 (2014)

Lang, Mohler, Prelovsek, Woloshyn PLB 750 17 (2015)

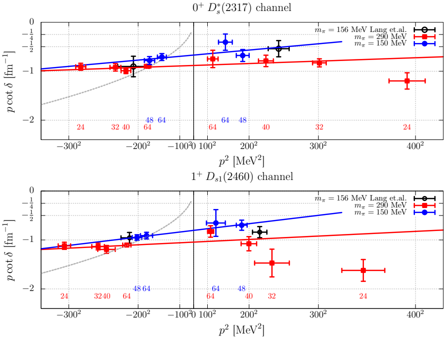




- Discretization uncertainties sizeable for charm
- Many improvements possible for the D_s states
- Full uncertainty estimate only for magenta B_s states
- Prediction of exotic states from Lattice QCD!

Positive parity D_s: More comprehensive results from RQCD

Bali, Collins, Cox, Schäfer, arXiv:1706.01247



- Study with different volumes at pion masses of 150, 290 MeV
- Remaining discretization effects non-negligible
- Caution: Qualitative agreement but different discretization effects expected!

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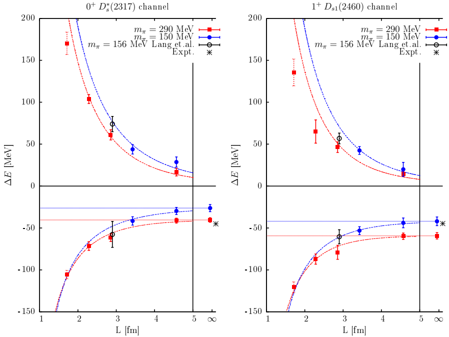

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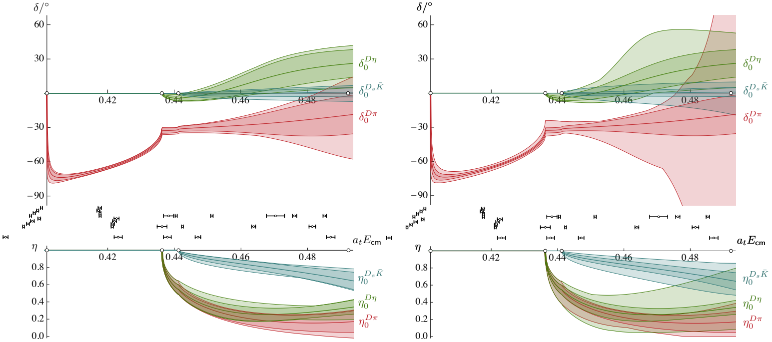
Coupled-channel study of $D\pi$, $D\eta$, D_sK scattering

Moir *et al.*, JHEP 1610 011 (2016)

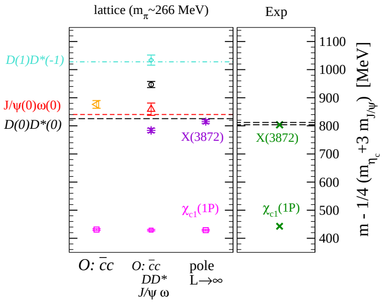
for more coupled channel results see D. Wilson



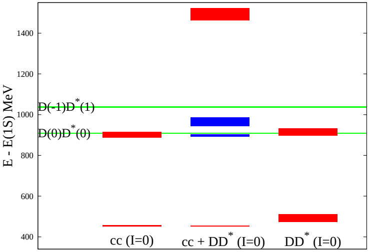
- Lattice data from multiple volumes at $m_\pi = 391$ MeV
- Shallow bound state seen in coupled channel s-wave
- Narrow spin-2 D-wave resonance seen as well
- For older single-channel results see

DM, Prelovsek, Woloshyn PRD 87 034501 (2013)

An $X(3872)$ candidate from Lattice QCD



Prelovsek, Leskovec, PRL 111 192001 (2013)

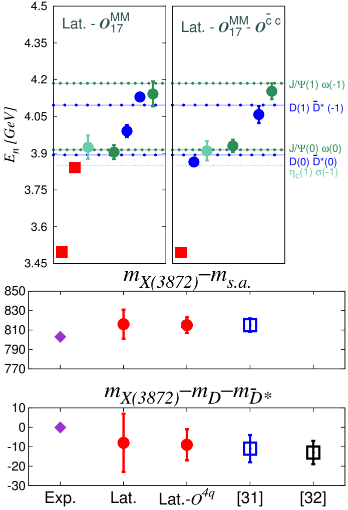


Lee, DeTar, DM, Na, arXiv:1411.1389

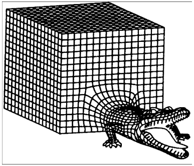
- Neglects charm annihilation and $J/\psi\omega$
- Seen only when $\bar{q}q$ and $\bar{D}^*D$ are used
- The two simulations have vastly different systematics (yet results are similar)

An $X(3872)$ candidate from Lattice QCD II

Padmanath, Lang, Prelovsek, PRD 92 034501 (2015)



- Without $\bar{q}q$ interpolators signal vanishes
- Simulations still unphysical in many ways
- Discretization and finite volume effects sizable!



- Makes interpretation as pure molecule or pure tetraquark unlikely

Search for a Z_c^+ state from Lattice QCD

Prelovsek, Lang, Leskovec, DM, Phys.Rev. D91 014504 (2015)

- Search for a Z_c^+ in the $I^G J^{PC} = 1^+ 1^{+-}$ channel
- Aim at simulating all meson-meson states below ≈ 4.3GeV
- Caveat: Neglects 3-particle states
- Include tetraquark interpolators of type $3_c \times \bar{3}_c$
- Count energy levels and identify them according to their overlaps
- Hope: See an extra level, as would be expected for a (narrow) resonance

More rigorous approach (a la Lüscher) quite challenging

- Coupled channel system with many channels
- Small shifts in finite volume and (largish) discretization effects
- Thresholds should be close to physical
- Suitable ensembles are (probably) not available at the moment.

A look at the spectrum of scattering states

- Expect level close to non-interacting scattering states

$J/\Psi\pi$

$\eta_c\rho$

$J\Psi(1)\pi(-1)$

DD^*

$\Psi_{2S}\pi$

D^*D^*

$\Psi_{3770}\pi$

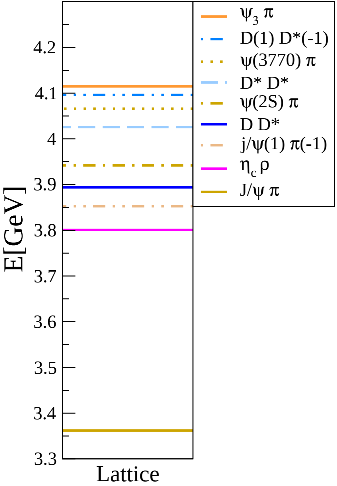
$D(1)D^*(-1)$

$\Psi_3\pi$

$J\Psi(2)\pi(-2)$

$D^*(1)D^*(-1)$

$D(2)D^*(-2)$

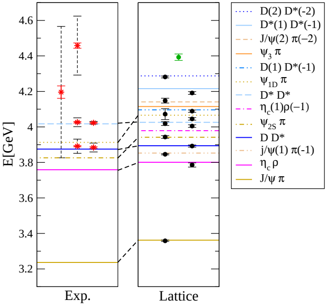


Search for Z_c^+ with $I^G J^{PC} = 1^+1^{+-}$

X(3900) $I^G(J^{PC}) = 1^+(1^{+-})$

Mass $m = 3886.6 \pm 2.4$ MeV (S = 1.6)
Full width $\Gamma = 28.1 \pm 2.6$ MeV

Prelovsek, Lang, Leskovec, DM, Phys.Rev. D91 014504 (2015)



- Simple level counting approach
- We find 13 two meson states as expected
- We find no extra energy level that could point to a Z_c candidate

χ'_{c0} and $X/Y(3915)$

$X(3915)$
was $\chi_{c0}(3915)$

$I^G(J^{PC}) = 0^+(0 \text{ or } 2^{++})$

Mass $m = 3918.4 \pm 1.9$ MeV
Full width $\Gamma = 20 \pm 5$ MeV (S = 1.1)

PDG interpreted $X(3915)$ as a regular charmonium (χ'_{c0})

- Some of the reasons to doubt this assignment:

  Guo, Meissner Phys. Rev. **D**86, 091501 (2012)

  Olsen, PRD 91 057501 (2015)

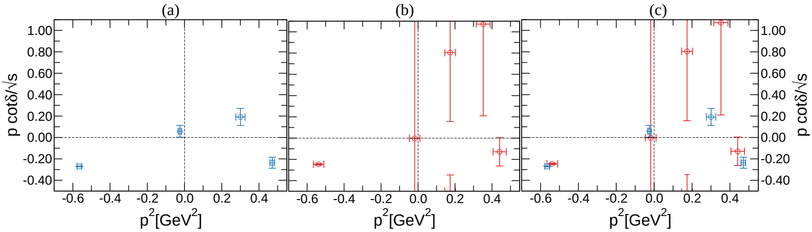
  - No evidence for fall-apart mode $X(3915) \to \bar{D}D$
  - Spin splitting $m_{\chi_{c2}(2P)} - m_{\chi_{c0}(2P)}$ too small
  - Large OZI suppressed $X(3915) \to \omega J/\psi$
  - Width should be significantly larger than $\Gamma_{\chi_{c2}(2P)}$
- Zhou *et al.* (PRL 115 2, 022001 (2015)) argue that what is dubbed X(3915) is the spin 2 state already known and suggests that a broader state is hiding in the experiment data.
- Observation of an alternative $\chi_{c0}(2P)$ by Belle:

  Chilikin *et al.* PRD 95 112003 (2017)

$$M = 3862^{+26+40}_{-32-13}\ \text{MeV} \qquad \Gamma = 201^{+154+88}_{-067-82}\ \text{MeV}$$

χ'_{c0}: Exploratory lattice calculation

Lang, Leskovec, DM, Prelovsek, JHEP 1509 089 (2015)



- Assumes only $\bar{D}D$ is relevant
- Lattice data suggests a fairly narrow resonance with $3.9\text{GeV} < M < 4.0\text{GeV}$ and $\Gamma < 100\text{MeV}$
- Future experiment and lattice QCD results needed to clarify the situation

χ'_{c0}: Improvements and challenges

with G. Bali, S. Collins, M. Padmanath, S. Piemonte, S. Prelovsek

Improvements:

- High-precision determinations of the energy splittings needed
  $\rightarrow$ significantly improve statistics by using CLS ensembles
- Bigger density of energy level needed
  $\rightarrow$ Calculation in multiple volumes: CLS ensembles U101, H105, N101
  $\rightarrow$ Add information from moving frames
- Treatment as a single-channel problem only sensible if $X(3915)$ is indeed a spin-2 state
  $\rightarrow$ consider coupled channel $D\bar{D}$, $J/\psi\omega$ and $D_s\bar{D}_s$

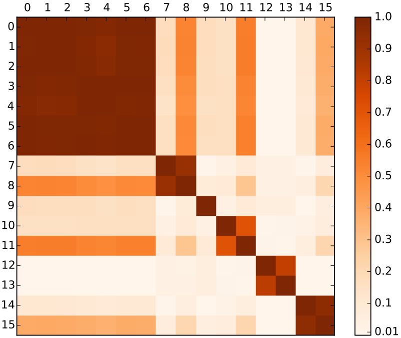
Challenges:

- Need strategy for dealing with (largish) discretization effects
- $Tr(M) =$ const. trajectory means $D_s\bar{D}_s$ threshold lower

Interpolator basis

A_1^{++} $(J^{PC} = 0^{++}, 4^{++}, \ldots)$

Label n	Operator
0	$\bar{q}\, q$
1	$\bar{q}\, \gamma_i \overleftrightarrow{\nabla}_i\, q$
2	$\bar{q}\, \gamma_i\gamma_t \overleftrightarrow{\nabla}_i\, q$
3	$\bar{q}\, \overleftarrow{\nabla}_i \overrightarrow{\nabla}_i\, q$
4	$\bar{q}\, \overleftarrow{\Delta} \overrightarrow{\Delta}\, q$
5	$\bar{q}\, \overleftarrow{\Delta} \gamma_i \overrightarrow{\nabla}_i\, q$
6	$\bar{q}\, \overleftarrow{\Delta} \gamma_i\gamma_t \overrightarrow{\nabla}_i\, q$
7	$O^{\bar{D}(0)D(0)} \sim \bar{c}\gamma_5 l\, \bar{l}\gamma_5 c$
8	$O^{\bar{D}(0)D(0)} \sim \bar{c}\gamma_5\gamma_t l\, \bar{l}\gamma_5\gamma_t c$
9	$O^{\bar{D}(p)D(-p)} \sim \bar{c}\gamma_5 l\, \bar{l}\gamma_5 c$
10	$O^{\bar{D}^*(0)D^*(0)} \sim \bar{c}\gamma_i l\, \bar{l}\gamma_i c$
11	$O^{\bar{D}^*(0)D^*(0)} \sim \bar{c}\gamma_i\gamma_t l\, \bar{l}\gamma_i\gamma_t c$
12	$O^{J/\psi(0)\omega(0)} \sim \bar{c}\gamma_i c\, \bar{l}\gamma_i l$
13	$O^{J/\psi(0)\omega(0)} \sim \bar{c}\gamma_i\gamma_t c\, \bar{l}\gamma_i\gamma_t l$
14	$O^{\bar{D}_s(0)D_s(0)} \sim \bar{c}\gamma_5 s\, \bar{s}\gamma_5 c$
15	$O^{\bar{D}_s(0)D_s(0)} \sim \bar{c}\gamma_5\gamma_t s\, \bar{s}\gamma_5\gamma_t c$



A first look at mass splittings

Preliminary results: Energy splittings from 120 configurations of U101

	$\kappa_c = 0.12522$	$\kappa_c = 0.12315$	Experiment
$m_{J/\Psi} - m_{\eta_c}$	106.9(0.6)(1.1)	98.0(0.5)(1.1)	113.2(0.7)
$m_{D_s^*} - m_{D_s}$	131.3(1.9)(1.4)	118.4(2.0)(1.3)	143.8(0.4)
$m_{D^*} - m_D$	127.8(3.9)(1.4)	115.1(4.1)(1.2)	140.66(10)
$2m_{\overline{D}} - m_{\overline{c}c}$	912.0(7.6)(9.8)	939.7(8.1)(10.1)	882.4(0.3)
$2M_{\overline{D_s}} - m_{\overline{c}c}$	1011.7(4.2)(10.9)	1036.0(4.5)(11.1)	1084.8(0.6)
$m_{D_s} - m_D$	47.2(2.1)(0.5)	45.7(2.2)(0.5)	98.87(29)

- Unphysical $m_{D_s} - m_D$ creates a special challenge!

Challenge: Discretization effects

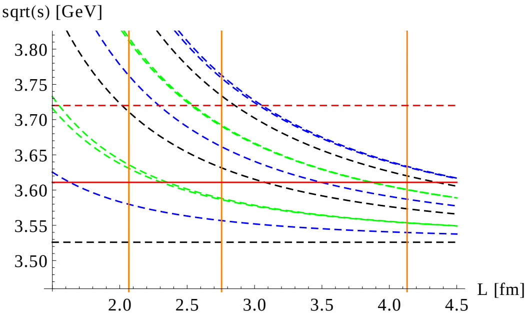
- Naive simulation at small lattice spacings
  - Requires large lattices
- Anisotropic lattices
  - does not address discretization effects in spin-splittings
  - does not avoid topological freezing (effect on η-η' system?)
- Fermilab interpretation a la Fermilab/MILC
  - Need to deal with non-standard dispersion relation
  - Does not replace testing continuum scaling
- Relativistic heavy quark action with non-perturbative tuning
  - As above but with different complications
- Brillouin fermions and the overlap action

Dürr & Koutsou, PRD 83 114512 (2011)
Dürr & Koutsou, arXiv:1701.00726

  - Brillouin fermions show a very good momentum dependence
  - Still issues with $M_1 \neq M_2$
  - Use as an overlap kernel may be an expensive option

Challenge: Statistical accuracy

- Lüscher method relies on statistically significant finite volume shifts to constrain models for the scattering amplitude(s)
- Exponentially suppressed volume effects must be small
- Example: Expected energy levels
  $A1^{++}$ rest frame for χ'_{c0} on CLS-ensembles U101, H105, N101



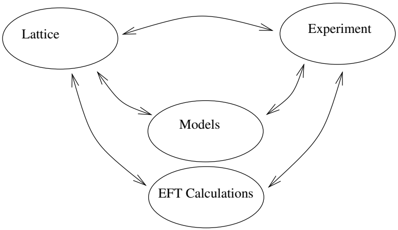
- Brings (stochastic) distillation to its limits (volume scaling!)

Outlook

Some powerful QCD tools:

- Can map out the quark mass dependence of amplitudes
  - heavy quark-mass dependence of a $X(3872)$ pole?
  - do bottom analogues of charm-quark states exist?
- Can investigate properties of short-lived excitations
- Can investigate states hard to produce/detect at current facilities

- Can calculate simple observables directly
- Can test model predictions
- Can use EFT results to relate to experiment
- Don't just calculate numbers



Thank you!

Testing our tuning: charm and beauty

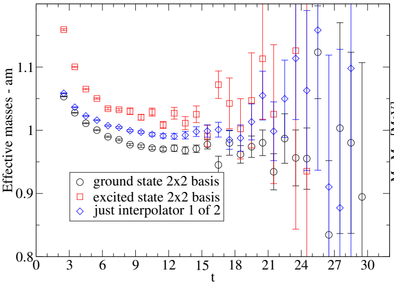
	Ensemble (1)	Ensemble (2)	Experiment
$m_{J/\Psi} - m_{\eta_c}$	107.9(0.3)(1.1)	107.1(0.2)(1.5)	113.2(0.7)
$m_{D_s^*} - m_{D_s}$	120.4(0.6)(1.3)	142.1(0.7)(2.0)	143.8(0.4)
$m_{D^*} - m_D$	129.4(1.8)(1.4)	148.4(5.2)(2.1)	140.66(10)
$2m_{\overline{D}} - m_{\overline{c}c}$	890.9(3.3)(9.3)	882.0(6.5)(12.6)	882.4(0.3)
$2M_{\overline{D_s}} - m_{\overline{c}c}$	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)
$m_Y - m_{\eta_b}$	-	44.2(0.3)(0.6)	62.3(3.2)
$2m_{\overline{B}} - m_{\overline{b}b}$	-	1190(11)(17)	1182.7(1.0)
$2m_{\overline{B_s}} - m_{\overline{b}b}$	-	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)

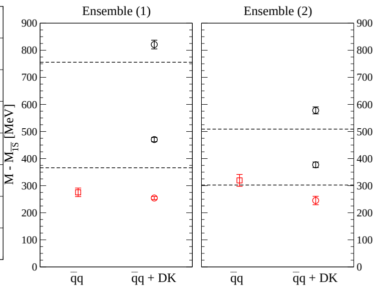
- Errors statistical and scale setting only
- Bottom quark slightly to light

A (by now) obvious lesson about the interpolator basis

- The original plateau crisis

A diverse interpolator basis is vital to determine the true spectrum!





Data from Mohler *et al.* PRL 111 222001 (2013)