Charm (and bottom) baryons and charmonium excitations from the lattice

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Mainz, Germany

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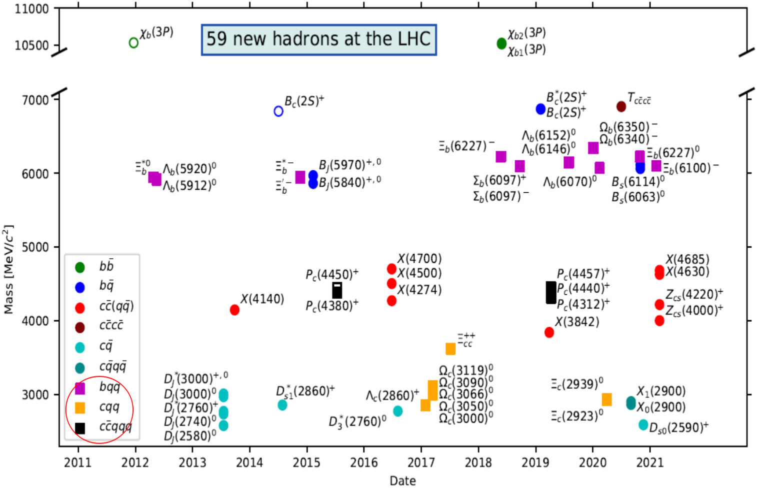
Charm and bottom baryons

Heavy baryons



A significant fraction of them are heavy baryons. LHCb public: https://lhcb-public.web.cern.ch/

An equally similar collection from Belle and interesting prospects at STCF.

Hadron spectroscopy on the lattice

- Euclidean two point current-current correlation functions

$$C_{ji}(t_f - t_i) = \langle 0|O_j(t_f)\bar{O}_i(t_i)|0\rangle = \sum_n \frac{Z_i^{n*} Z_j^n}{2E_n} e^{-E_n(t_f - t_i)}$$

- Quark smearing to improve the overlap with ground states!

$$q(\mathrm{x}, t) = \sum_{\mathrm{y}} S(\mathrm{x}, \mathrm{y}) q_b(\mathrm{y}, t)$$

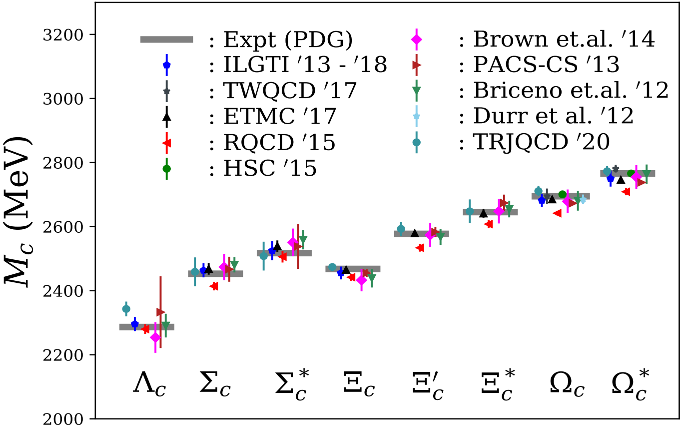
- Correlation matrices out of large basis of hadron interpolating operators ($O_j(t)$) with desired quantum numbers.

$$O_j(t) = \sum_{\mathrm{x}} \overline{q}(\mathrm{x}, t)\Gamma_j(\mathrm{x}, t) q(\mathrm{x}, t)$$

- Variational study (GEVP) to extract physical information

$$C_{ji}(t) v_i^n = \lambda^n(t, t_0) C_{ji}(t_0) v_i^n$$

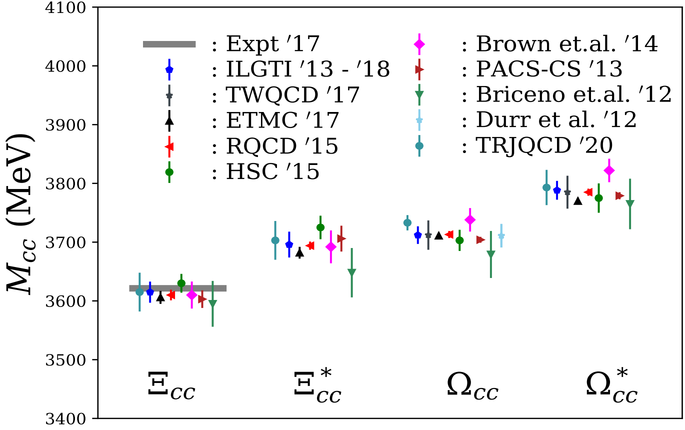
Singly charm baryons



Early quenched lattice calculations : Lewis *et al.* '01; Mathur *et al.* '02; Flynn *et al.* '03

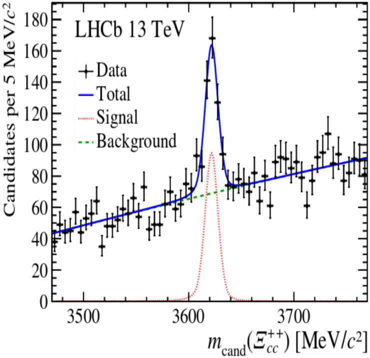
Dynamical (light quark) investigations : Liu *et al.* '10

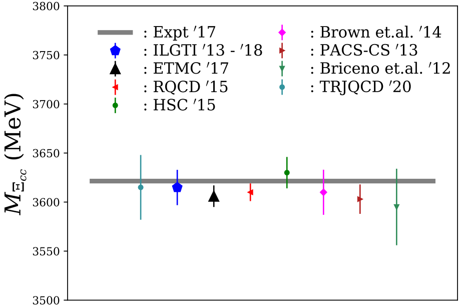
Doubly charm baryons



Another calculation of heavy baryon masses: QCDSF-UKQCD 1711.02485.
Heavy baryon mass splittings : BMW Science**347** 1452 '15

Early quenched lattice calculations : Lewis *et al.* '01; Mathur *et al.* '02; Flynn *et al.* '03
Dynamical (light quark) investigations : Liu *et al.* '10

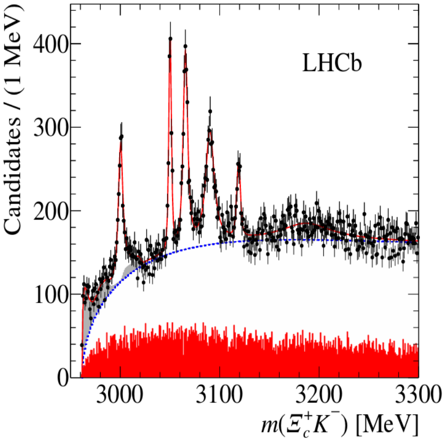




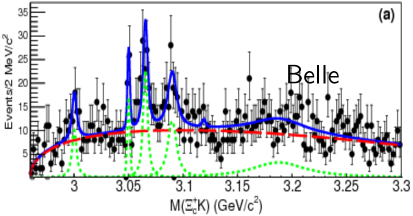
Ξ_{cc} isospin splitting (LQCD), 2.16(11)(17) MeV : BMW Science **347** 1452 '15
SELEX measurement (3519 MeV) : Mattson *et al.* PRL **89** 112001 '02

All lattice calculations disfavors SELEX peak to be a doubly charm baryon.

LHCb discovery of excited Ω_c^0 baryons



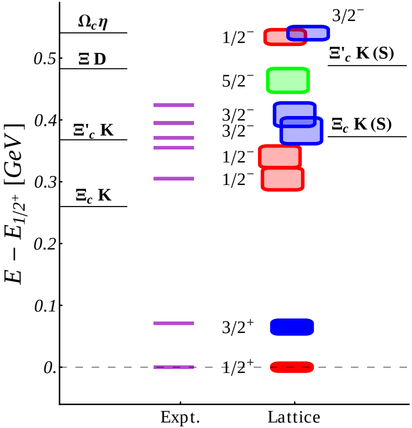
Resonance	Energy	Width	Q.no.
Ω_c^0	2695(2)	-	$1/2^+$
$\Omega_c^0(2770)$	2766(2)	-	$3/2^+$
$\Omega_c^0(3000)$	3000(1)	4.5(1)	?
$\Omega_c^0(3050)$	3050(1)	1(-)	?
$\Omega_c^0(3066)$	3066(1)	3.5(-)	?
$\Omega_c^0(3090)$	3090(1)	8.7(1)	?
$\Omega_c^0(3119)$	3119(1)	1(1)	?



Aaij *et al.* (LHCb) PRL**118** 182001 '17

Confirmation by Belle : Yelton *et al.* (Belle) PRD**97** 051102 '18

Experiment vs. lattice predictions



Energy	Expt.	Lattice
$\Delta E_{\Omega_c^0(3119)}$	422(1)	464(20)
$\Delta E_{\Omega_c^0(3090)}$	395(1)	409(19)
$\Delta E_{\Omega_c^0(3066)}$	371(1)	383(21)
$\Delta E_{\Omega_c^0(3050)}$	355(1)	341(18)
$\Delta E_{\Omega_c^0(3000)}$	305(1)	304(17)
$\Delta E_{\Omega_c^0(2770)}$	70.7(1)	65(11)
$E_{\Omega_c^0} - \frac{1}{2}E_{\eta_c}$	1203(2)	1209(7)

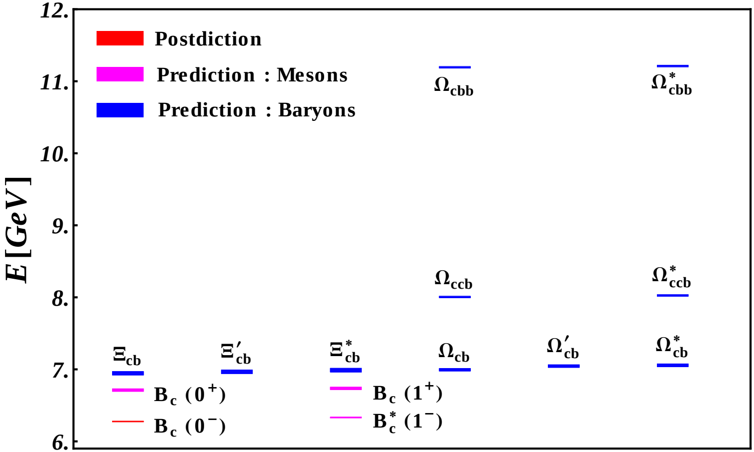
Here $\Delta E = E - E_{\Omega_c^0}$.
The new states correspond to the excited p-wave excitations.

MP & Mathur (HSC) PRL**119** 042001 '17

Spin 1/2, 3/2, 5/2
Ω_{ccc} : HSC PRD**90** 074504 '14
Ξ_{cc} and Ω_{cc} : HSC PRD**91** 094502 '15
Ω_c, Σ_c, Λ_c and Ξ_c : CHARM 2013, 1311.4806

On anisotropic $N_f = 2 + 1$ lattices
$L \sim 1.9$ fm, $a_t m_c = 0.114$
and $m_\pi = 391$ MeV
Edwards *et al.* PRD**78** 054501 '08

Precise determination of *bc* hadron masses

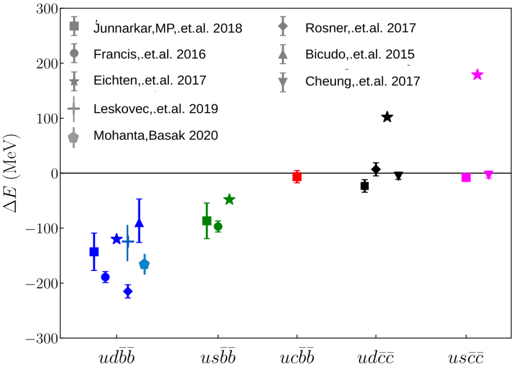


Mathur, MP, Mondal 1806.04151

Results agree with experiment* and with other lattice calculations:

Brown *et al* 1409.0497; HPQCD 1207.5149, 1010.3848; Wurtz *et al* 1505.04410

Doubly heavy tetraquarks



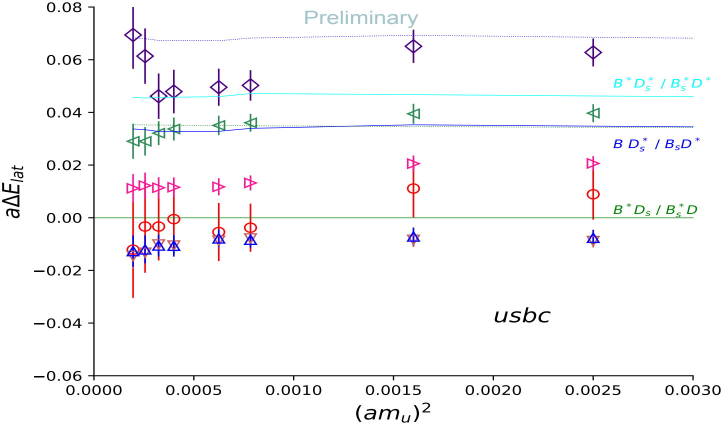
For a sufficiently heavy Q: a strong interaction stable $qq'\bar{Q}\bar{Q}$ tetraquark.

An extensive calculation of various flavor combinations: Hudspith *et al* 2006.14294
Argues no evidence for deeply bound states other than in doubly bottom axialvector channels.

Bicudo *et al* 2101.00723

Investigation on the nature of doubly bottom axialvector tetraquarks.

Bottom-charm tetraquarks

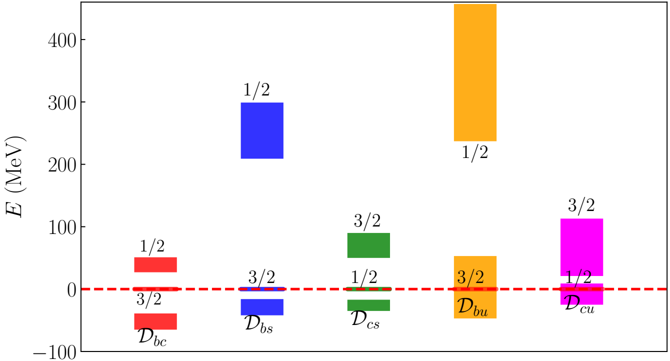


Ongoing investigation on bc tetraquarks. MP, Mathur (ILGTI)

Indicates several finite volume energy levels close to and below the elastic threshold.

Calls for a rigorous finite volume amplitude analysis for definitive statements.

Deutron-like heavy dibaryons

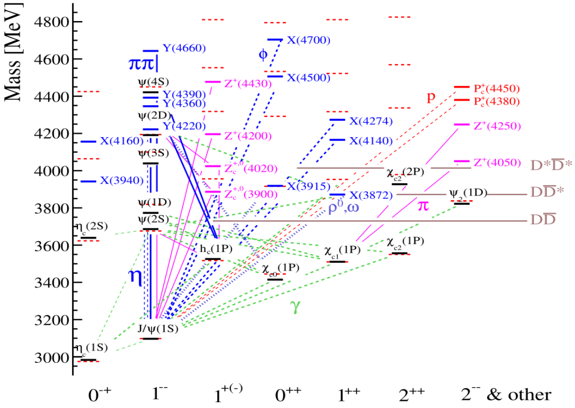


Junnarkar and Mathur 1906.06054

Find indications of large binding energy in bc system.

Charmonium spectra

Charmonium spectra

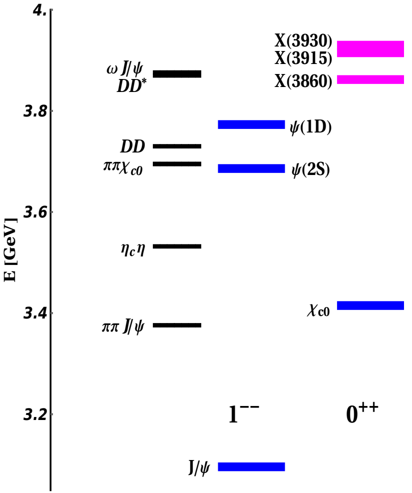


Olsen *et al* 1708.04012

Rich energy spectrum. XYZ states.
$\bar{c}c$ picture works well for states below open charm threshold.
No single description for states above the open charm threshold.

Several lattice calculations assuming a $\bar{c}c$ picture.
RQCD 2018; HSC 2012, 2016; Mohler *et al* 2013, Bali *et al* 2011

Charmonium: channels focussed



Currently we ignore $\eta_c \eta$ and all three particle channels in our entire analysis.

$D\bar{D}$ (and $D_s\bar{D}_s$) scattering.
Involves only spinless scattering particles.

$J^{PC} = 1^{--}$, vector charmonia.
$\Gamma_{\psi(1D)\to D\bar{D}}/\Gamma \sim 93\%$.
Well understood below 4 GeV.
As a proof of concept.

$J^{PC} = 0^{++}$, scalar charmonia.
In search of the $\chi_{c0}(2P)$.
Other excitations, if any exist!
Three experimentally observed states.
X(3860): Belle 1704.01872
X(3915): Belle hep-ex/0408126
X(3930): LHCb 2009.00026

Results are exploratory in nature, considering the assumptions involved.

How do we do?

- Ensemble : CLS
  - U101 $N_f = 2+1$, $L \sim 2$ fm, $N_{ev} = 90$
  - H105 $N_f = 2+1$, $L \sim 2.7$ fm, $N_{ev} = 150$
  - $m_\pi \sim$ 280 MeV, $m_K \sim$ 467 MeV
  - Two charm quark masses: $m_D \sim$ 1762 MeV and 1927 MeV

- Multiple excited state extraction
  Correlation matrices using a large basis of interpolating operators

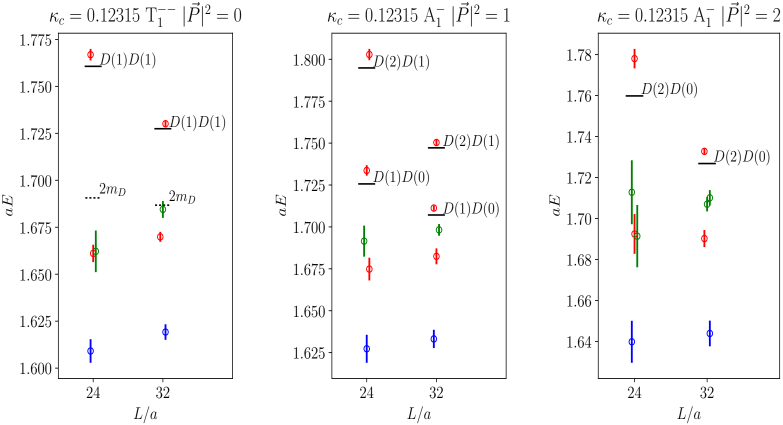
$$C_{ji}(t_f - t_i) = \langle 0|O_j(t_f)\bar{O}_i(t_i)|0\rangle = \sum_n \frac{Z_n^{i*} Z_n^j}{2E_n} e^{-E_n(t_f - t_i)}$$

  Operator state overlap factors : $Z_n^j = \langle 0|O_j|n\rangle$.
  Physical state information from variational analysis of $C_{ji}(t_f - t_i)$.

- Finite volume spectrum including all relevant two-meson operators
  $\mathcal{O} = \bar{Q}\Gamma Q$, $(\bar{Q}\Gamma_1 q)_{1_c}(\bar{q}\Gamma_2 Q)_{1_c}$, $(\bar{Q}\Gamma_1 Q)_{1_c}(\bar{q}\Gamma_2 q)_{1_c}$.

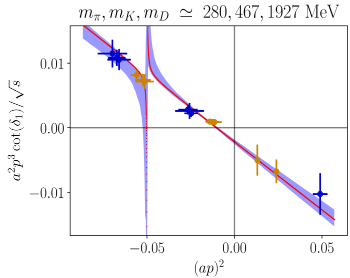
- Determination of scattering amplitudes:
  Utilize "TwoHadronsInBox" toolbox. Morningstar *et al.* 1707.05817

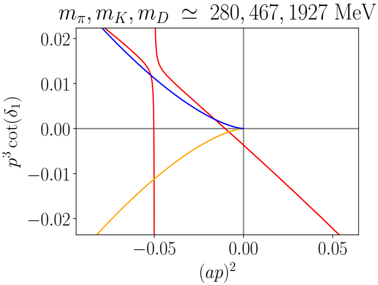
Vector charmonium: finite volume spectrum



Piemonte *et al*, 1905.03506

Elastic analysis: Vector charmonia

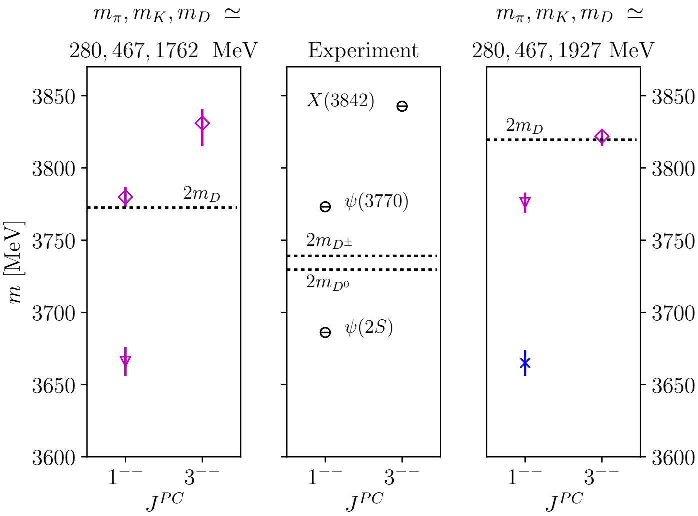




- 1^{--} channel in $\bar{D}D$ scattering in p-wave.
- Reaction matrix(K: $S = (1 + iK)(1 - iK)^{-1}$): $K_1^{-1} = (\frac{G_1^2}{m_1^2 - s} + \frac{G_2^2}{m_2^2 - s})^{-1}$
- (Virtual) bound state constraint: $p^3 cot\delta_1 = (-)(p^2)\sqrt{-p^2}$.
- Results presented for heavier than physical charm quark mass.

Piemonte *et al*, 1905.03506

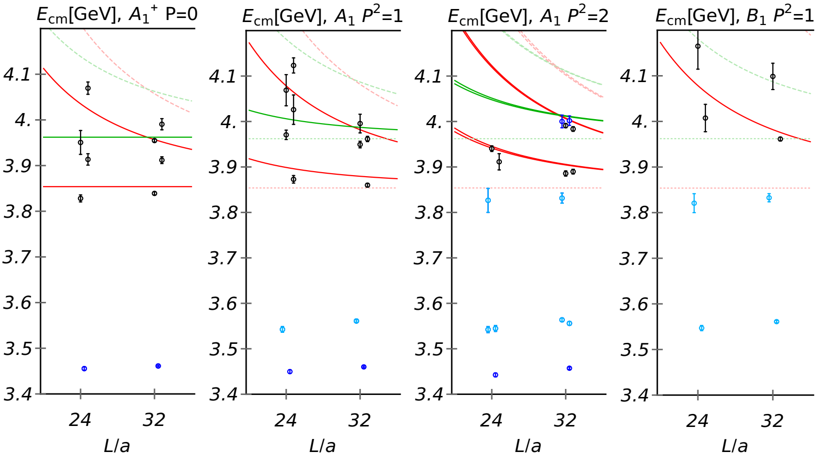
Spectrum summary: Vector charmonia



The coupling $g_{\psi(1D)\to\bar{D}D} = 18.9^{+0.8}_{-0.7}$ for light m_c: $g_{exp} = 18.7(9)$

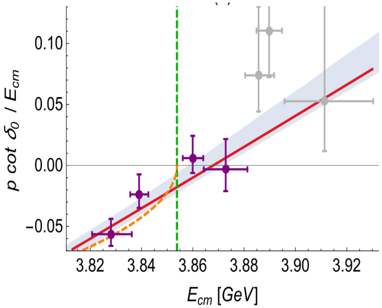
Piemonte *et al*, 1905.03506

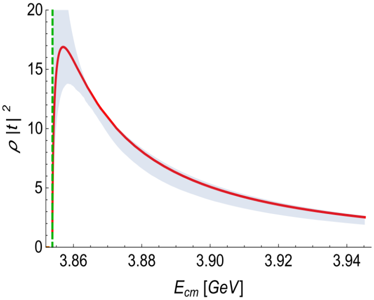
Scalar charmonium: finite volume spectrum



Prelovsek *et al*, 2011.02542

Scalar charmonia around the $D\bar{D}$ threshold

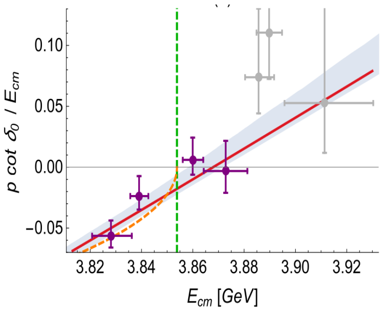


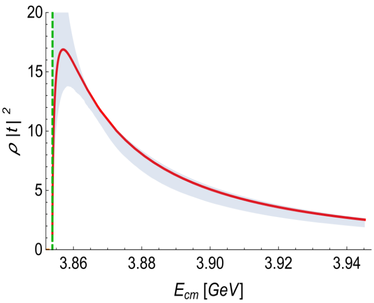


- 0^{++} channel in $\bar{D}D$ scattering in s-wave.
- Reaction matrix(K: $S = (1 + iK)(1 - iK)^{-1}$): $K_1^{-1}/\sqrt{s} = a + b\ s$
- Bound state constraint: $pcot\delta_0 = -\sqrt{-p^2}$.
- A shallow bound state with B.E.: $m - 2m_D = -4.0^{+3.7}_{-5.0}$ MeV
- Results presented for heavier than physical charm quark mass.

Prelovsek *et al*, 2011.02542

Scalar charmonia around the $D\bar{D}$ threshold

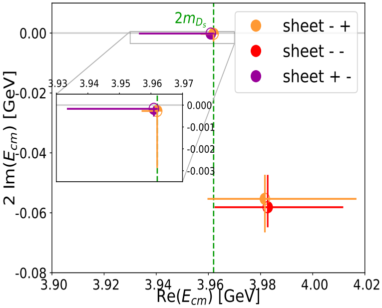


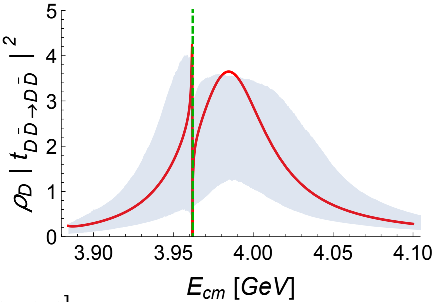


- Signal: An enhancement in the $D\bar{D}$ rate just above threshold.
  $N_{D\bar{D}} \propto \rho|t|^2$
- Physics in a simulation with physical quark masses is yet to be performed.
- Predictions from phenomenological models.

  hep-ph/0612179, 1305.4487, 1605.09649
- Evidences in the experiments 0708.3812, 0712.1758

Scalar charmonia around the $D_s^+ D_s^-$ threshold





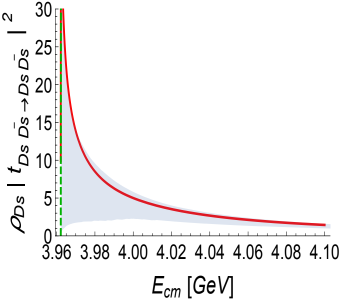
- Coupled channel $\bar{D}D$-$D_s^+ D_s^-$ scattering [s-wave].
  $J\psi - \omega$ and $\eta_c \eta$ are not included in the amplitude analysis.
- Reaction matrix(K: $S = (1 + iK)(1 - iK)^{-1}$):

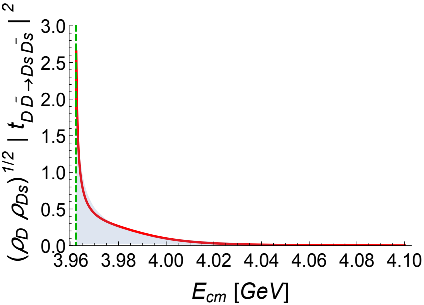
$$\frac{(\tilde{K}^{-1})^{I=0}}{\sqrt{s}} = \begin{pmatrix} a_{11} + b_{11}s & a_{12} \\ a_{12} & a_{22} + b_{22}s \end{pmatrix}$$

- The near threshold pole leads to a dip in $D\bar{D} \to D\bar{D}$ rate and an enhancement in $D_s^+ D_s^- \to D_s^+ D_s^-$ and $D\bar{D} \to D_s^+ D_s^-$ rates.

Prelovsek *et al*, 2011.02542

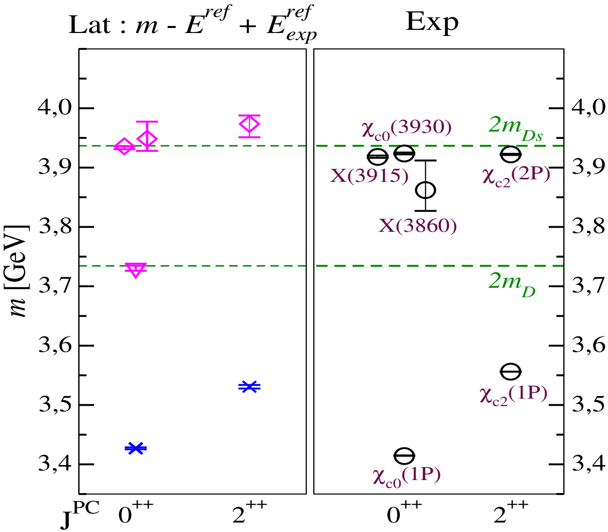
Scalar charmonia around the $D_s^+ D_s^-$ threshold





- The near threshold pole couples strongly (weakly) to $D_s^+ D_s^-$ ($D\bar{D}$). Possibly related to X(3915) and/or X(3930).
- Another pole in sheet $--$ with strong coupling to $D\bar{D}$. Responsible for the peak structure in $D\bar{D} \to D\bar{D}$ rate above the threshold.
- This pole could be related to the X(3860) observed by Belle.

Spectrum summary: 0^{++} charmonia



Results presented for the heavier than physical charm quark mass.

Prelovsek *et al*, 2011.02542

Remarks and future plans

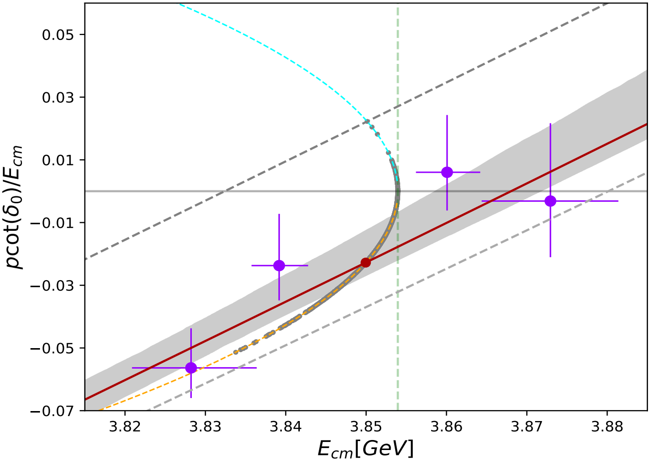
* Lattice results for heavy baryons and more:
  - Singly and doubly charmed baryons.
  - Charmed-bottom hadrons.
  - Doubly heavy tetraquarks.
  - Heavy dibaryons.

* Charmonium studies:
  - Several lattice calculations assuming $\bar{c}c$ picture.
  - Beyond the $\bar{c}c$ picture: Vector channel as a proof of concept.
  - Beyond the $\bar{c}c$ picture: Scalar channel.
    - A shallow (virtual) bound state pole near $D\bar{D}$ threshold.
    - A pole near $D_s^+ D_s^-$ threshold leading to a dip in $D\bar{D}$ rate. Possibly related to X(3915) and/or X(3930).
    - A resonance pole with strong coupling to $D\bar{D}$ channel. Possibly related to X(3860).

Thank you

Back up slides

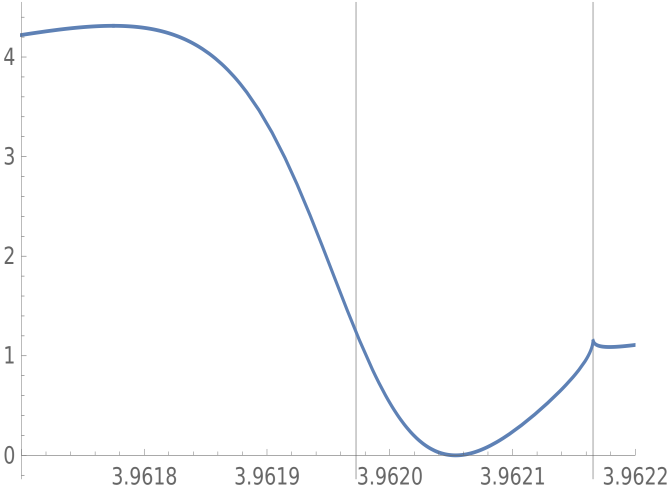
Scalar charmonia around the $D\bar{D}$ threshold



Pole distribution of shallow (virtual) bound state in $D\bar{D}$.

Prelovsek *et al*, 2011.02542

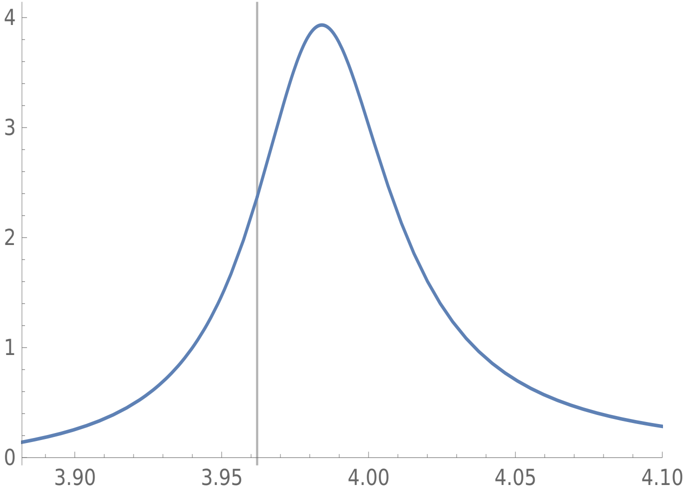
Dip in the $\rho|t_{D\bar{D}\to D\bar{D}}|^2$



Dip in the $D\bar{D} \to D\bar{D}$ rate.

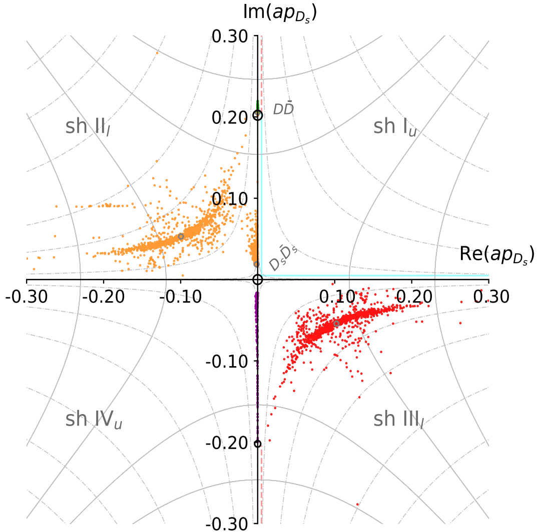
Prelovsek *et al*, 2011.02542

No dip in the $\rho|t_{D\bar{D}\to D\bar{D}}|^2$



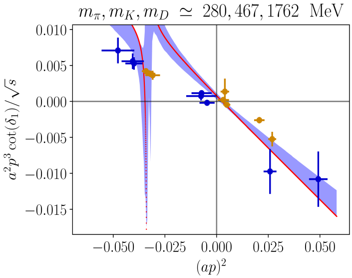
No dip in the $D\bar{D} \to D\bar{D}$ rate, when $K_{12} = 0$. Prelovsek *et al*, 2011.02542

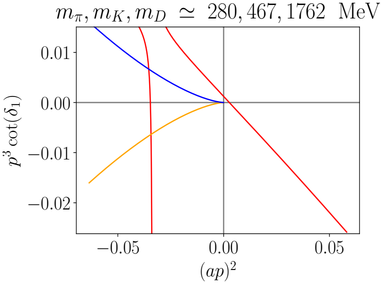
Scalar charmonia around the $D_s^+ D_s^-$ threshold



Pole distribution in $D_s^+ D_s^-$ complex momentum plane. Prelovsek *et al*, 2011.02542

Elastic analysis: vector charmonia

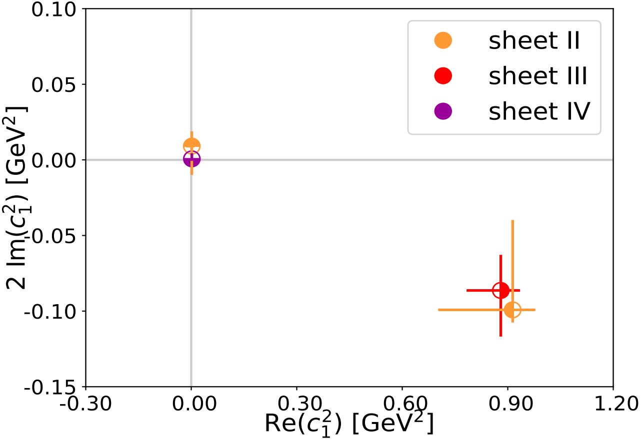




- (Virtual) bound state constraint: $p^3 cot\delta_l = (-)(p^2)\sqrt{-p^2}$
- Two bound states at heavier charm quark mass.
- A bound state and a resonance at lighter charm quark mass.
- An inevitable contamination $J^{PC} = 3^{--}$ excitation and $l = 3$ partial wave in the lattice spectra.
- Reaction matrix, $K = \begin{pmatrix} K_1 & 0 \\ 0 & K_3 \end{pmatrix}$, with $K_3 = \frac{G_3^2}{m_3^2 - s}$

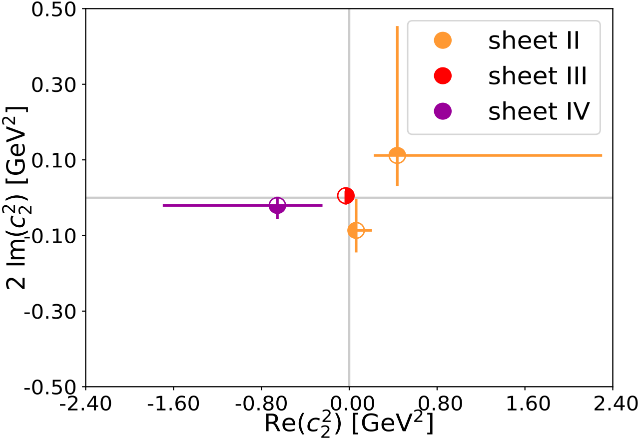
Piemonte *et al*, 1905.03506

Residues (c1): scalar charmonia



Prelovsek *et al*, 2011.02542

Residues (c2): scalar charmonia



Prelovsek *et al*, 2011.02542