

# Heavy hadron spectroscopy and interactions from lattice QCD

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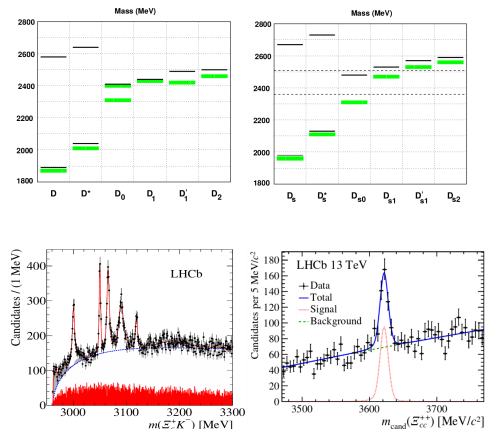
Regensburg, Germany

09<sup>th</sup> Nov. 2017

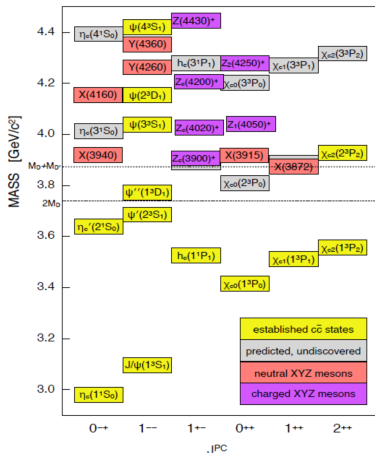
LHCb Implications Workshop 2017

# Motivation from experiments

F. Close and E. Swanson, PRD, 72, 094004, 2008



LHCb PRL, 118, 182001; PRL, 119, 112001, 2017.

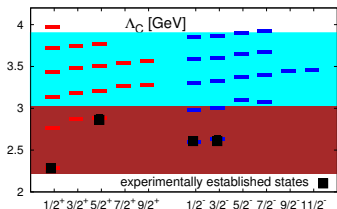


S. L. Olsen, arXiv:1511.01589 [hep-ex]

# Motivation from finite temperature studies

Ebert *et al.*, PRD, **84**, 014025, 2011

Bazavov *et al.*, PLB, **737**, 210, 2014

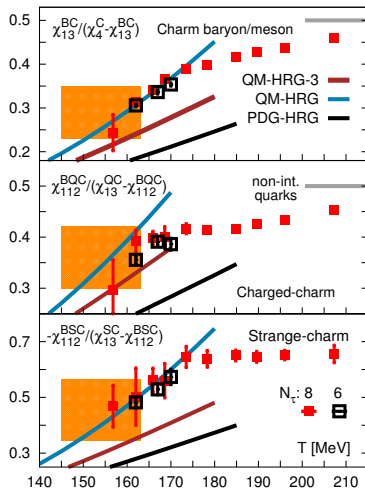


## Charm hadron pressure (HRG) :

$$P(\hat{\mu}_C, \hat{\mu}_B) = P_M \cosh(\hat{\mu}_C) + P_{B,C=1} \cosh(\hat{\mu}_C + \hat{\mu}_B)$$

$$\chi_{kl}^{BC} = \frac{\partial^{(k+l)} [P(\hat{\mu}_C, \hat{\mu}_B) / T^4]}{\partial \hat{\mu}_B^k \partial \hat{\mu}_C^l}$$

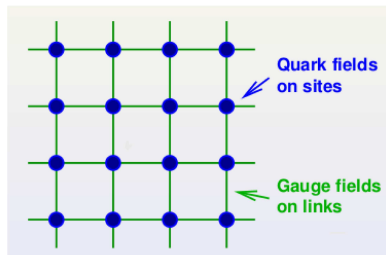
⇒ Existence of additional charm-light baryons in QGP formed in HIC.



# Lattice QCD : theoretical prospects

LQCD : A non-perturbative, gauge invariant regulator for the QCD path integrals.

- Quarks lives on sites
- Gauge fields lives on links
- Lattice spacing : UV cut off
- Lattice size : IR cut off



Discretization  $\Rightarrow$  Finite number of degrees of freedom

$\Rightarrow$  Infinite dimensional path integrals  $\rightarrow$  finite dimensional integrals.

Employ Monte Carlo importance sampling methods on Euclidean metric for numerical studies.

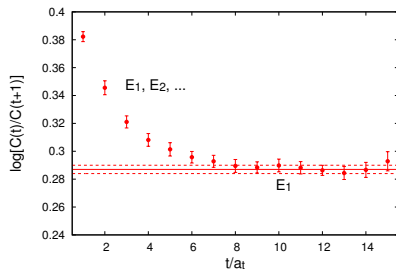
# QCD spectrum from Lattice QCD

- Aim : to extract the physical states of QCD.
- Euclidean two point current-current correlation functions

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

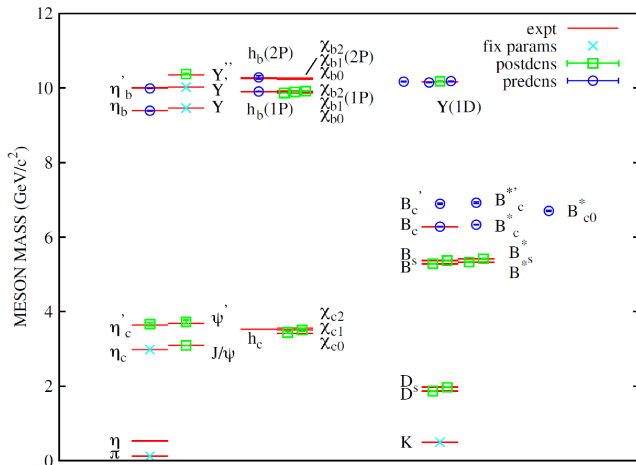
where  $\Phi_j(t_f)$  and  $\bar{\Phi}_i(t_i)$  are the desired interpolating operators and  $Z_j^n = \langle 0 | \Phi_j | n \rangle$ .

- Effective mass defined as  $\log\left[\frac{C(t)}{C(t+1)}\right]$



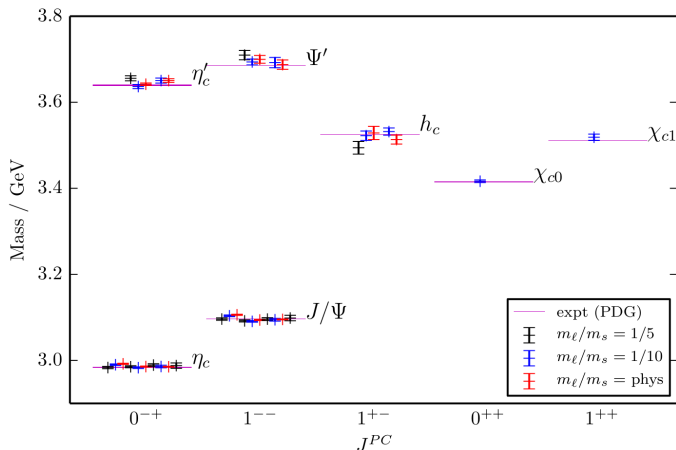
- The ground states : from the exponential fall off at large times.  
Non-linear fitting techniques.

# Heavy meson ground states



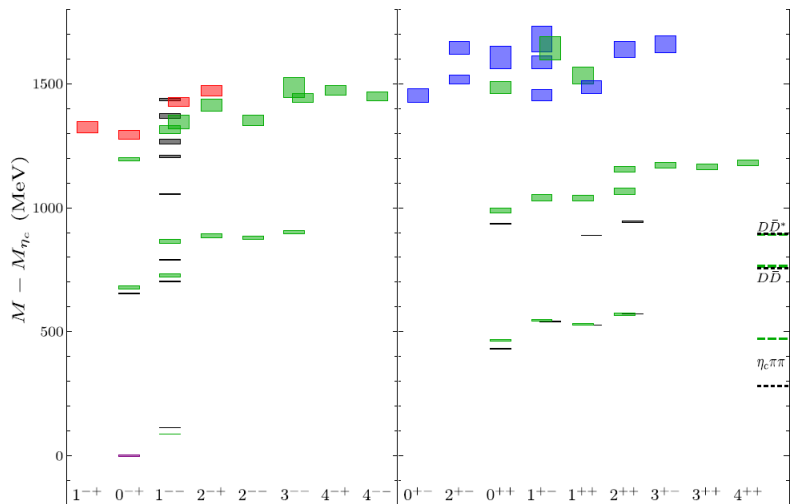
Accurate and precise predictions/post-dictions from lattice QCD.

# Heavy meson ground states



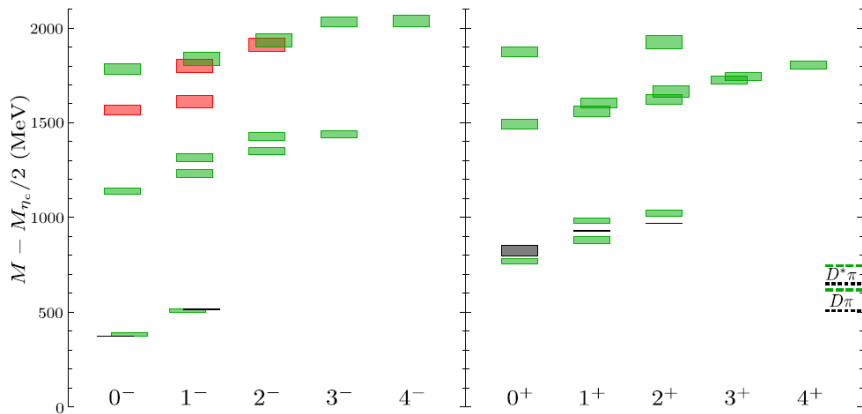
Accurate and precise predictions/post-dictions from lattice QCD.

## Charmonium excited spectrum

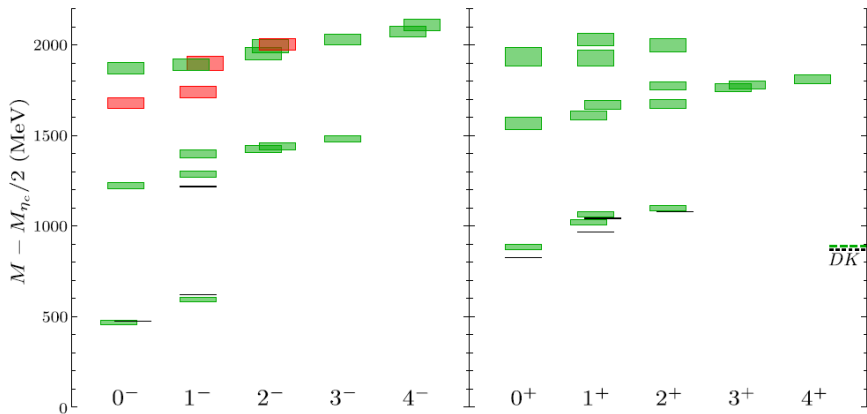




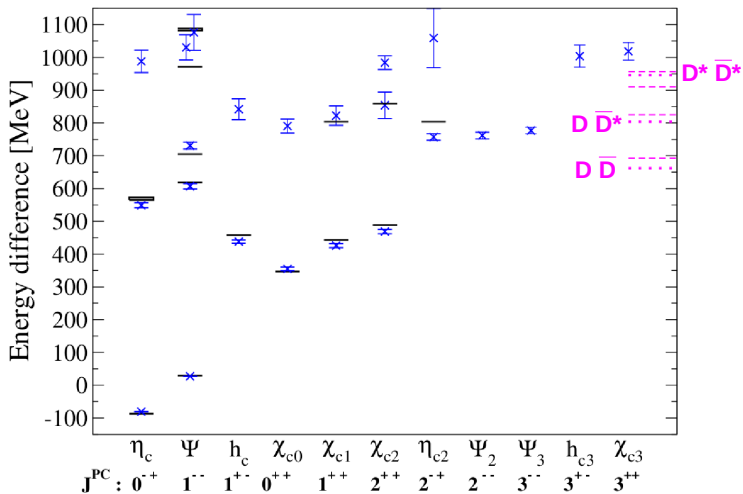
# D-meson excited spectrum



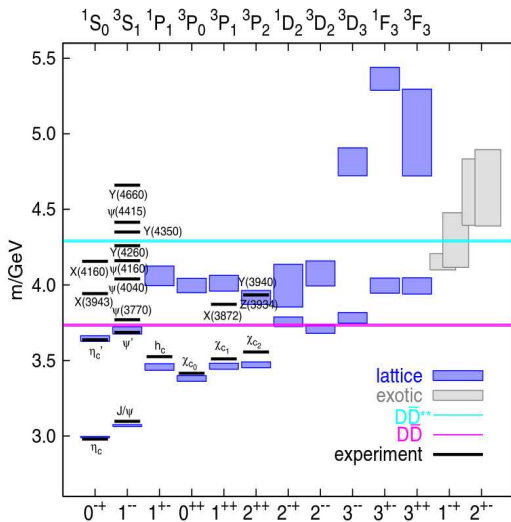
HadSpec Collaboration, JHEP **1612**, 089, 2016

$D_s$ -meson excited spectrumHadSpec Collaboration, JHEP **1612**, 089, 2016

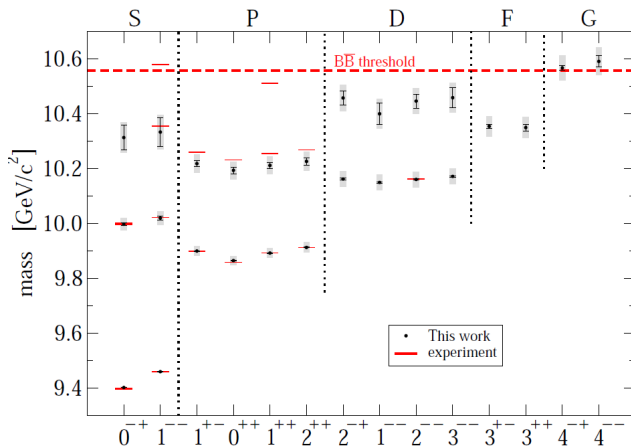
## Charmonium excited spectrum



## Charmonium excited spectrum

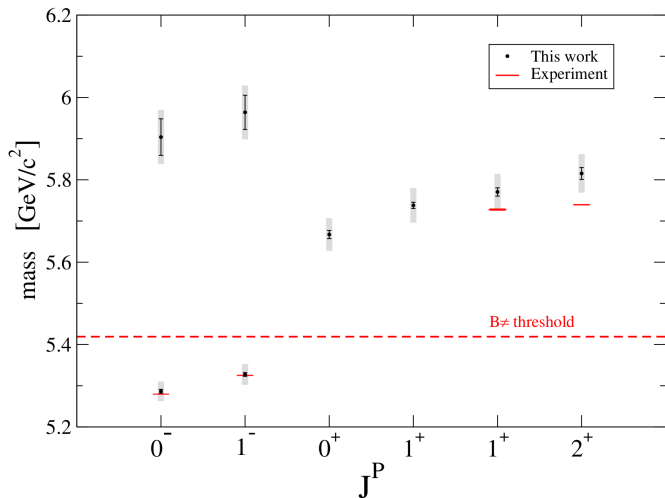


# Bottomonium excited spectrum

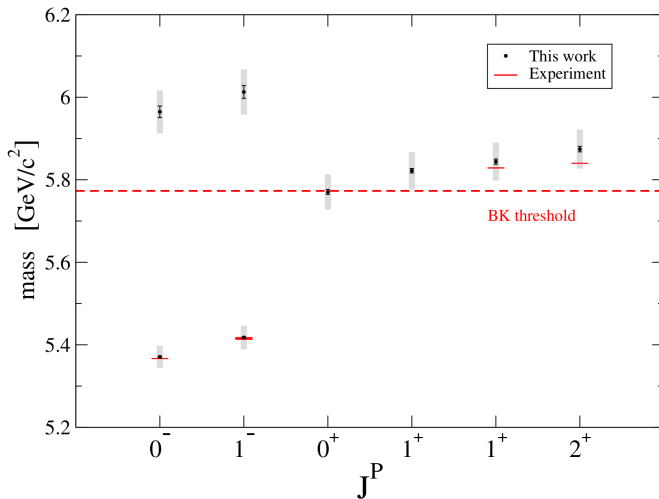


Wurtz et al PRD, **92**, 054504, 2015

# B-meson excited spectrum



# $B_s$ -meson excited spectrum



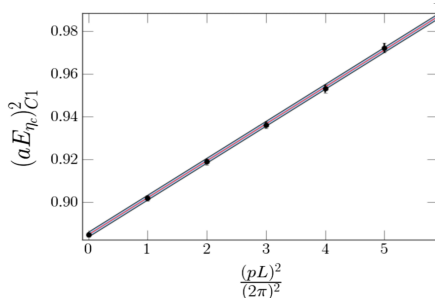
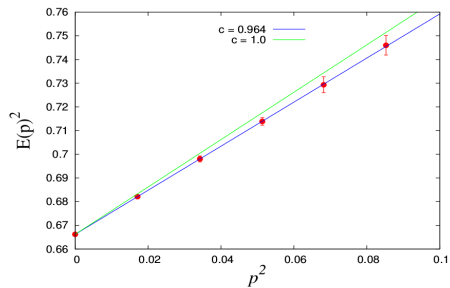
# Caveats!

- Discretization errors :  $\mathcal{O}(am_q)$   
Large discretization uncertainties expected for heavy quarks.
- Unphysical pion masses used in lattice calculations.
- Most importantly discrete energy spectra in finite volume  
Maiani-Testa no-go theorem  
No continuum of states  $\Rightarrow$  No cuts, no sheets, no resonances  
No asymptotic states  $\Rightarrow$  No scattering



# Discretization errors

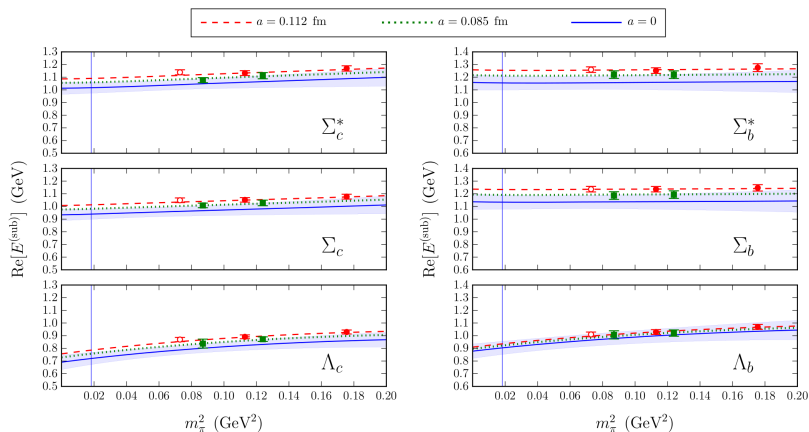
## Dispersion relation and kinetic mass



N. Mathur, M.P. *et al* (ILGTI) work ongoing

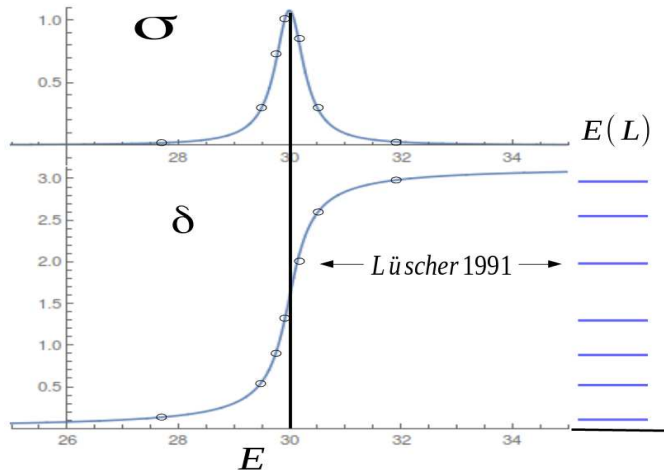
Briceño *et al* PRD, **86**, 094504, 2012

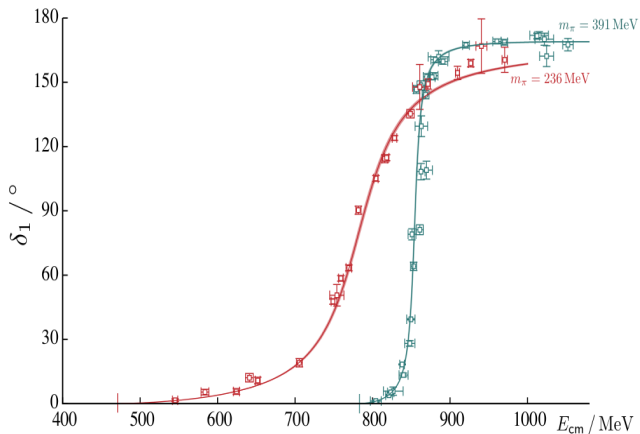
## Chiral and continuum extrapolations



Brown *et al* PRD, **90**, 094507, 2014

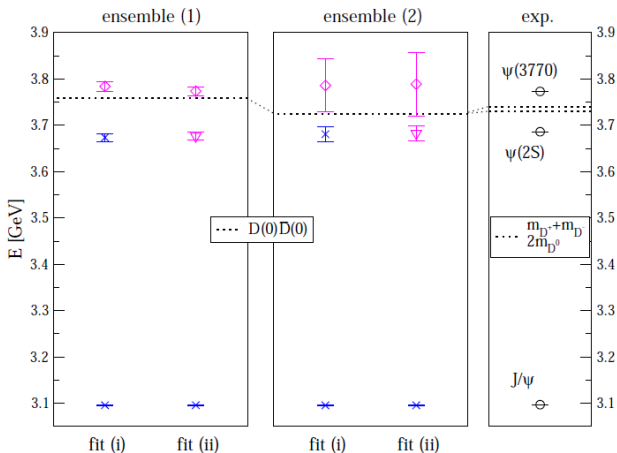
## Resonances on the lattice (elastic) : Lüscher

Infinite volume scattering amplitudes  $\Leftrightarrow$  Finite volume spectrum

Isovector  $\pi\pi$  scattering

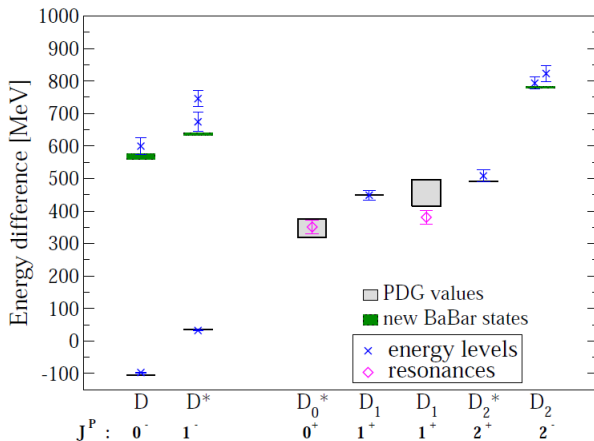
Dudek *et al*, PRD, **87**, 034505, 2012 Wilson *et al*, PRD, **92**, 094502, 2015

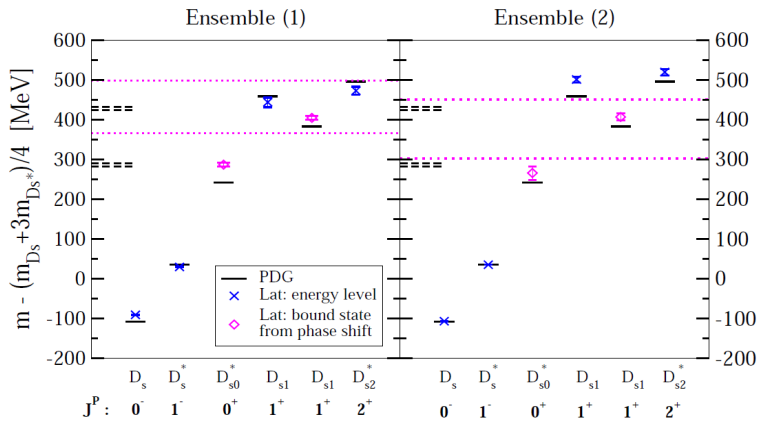


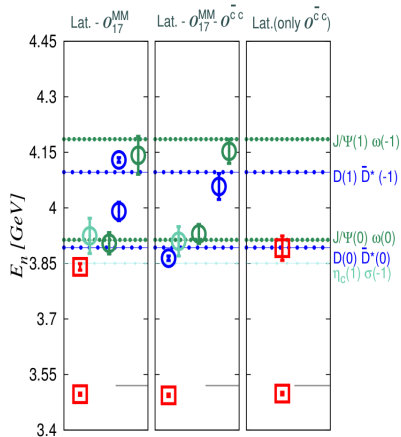
Excited charmonium states :  $(1)J^{PC} = (0)1^{--}$  $\psi(2S)$  and  $\psi(3770)$  from  $D\bar{D}$  elastic scattering

# D-meson excited spectrum

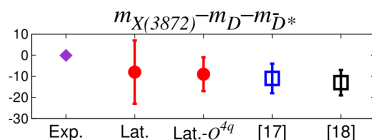
$D_0^*(2400)$  and  $D_1(2430)$  from  $D\pi$  and  $D^*\pi$  elastic scattering



$D_s$ -meson excited spectrum $D_{s0}^*(2317)$  and  $D_{s1}(2460)$  from  $DK$  and  $D^*K$  elastic scattering

Near threshold charmonium states :  $(I)J^{PC} = (0)1^{++}$ M. P. *et al*, PRD, **92**, 034501, 2015

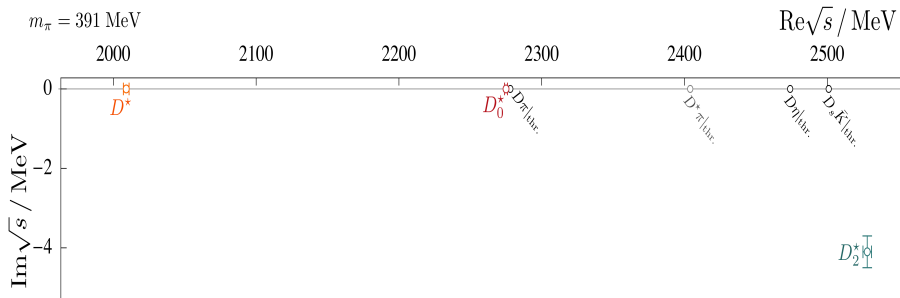
- Without the  $\bar{c}c$  interpolators, signal doesn't appear.
- Amplitude analysis performed on the two levels having dominant overlap with  $\bar{c}c$  and  $\bar{D}^*D$  operators (elastic limit).
- The relative position of the bound state w.r.t the  $\bar{D}^*D$  threshold determined.
- No significant effects on results with inclusion of tetraquark interpolators.

[17] : Prelovsek, Leskovec, PRL, **111**, 192001, 2013[18] : Lee *et al*, arXiv:1411.1389



# Beyond elastic scattering

- Elastic scattering approximation!
- Resonances can couple with multiple scattering channels.
- Generalization and extensions to Lüscher's formalism.  
c.f. Raúl A. Briceño talk at Lattice 2017.
- 2017 Kenneth G. Wilson Award for Excellence in Lattice Field Theory :  
Raúl A. Briceño  
*"For groundbreaking contributions to the study of resonances using lattice QCD"*

Coupled channel  $D\pi$ ,  $D\eta$ ,  $D_s\bar{K}$  scattering

HadSpec Collaboration, JHEP, **1610**, 011, 2016

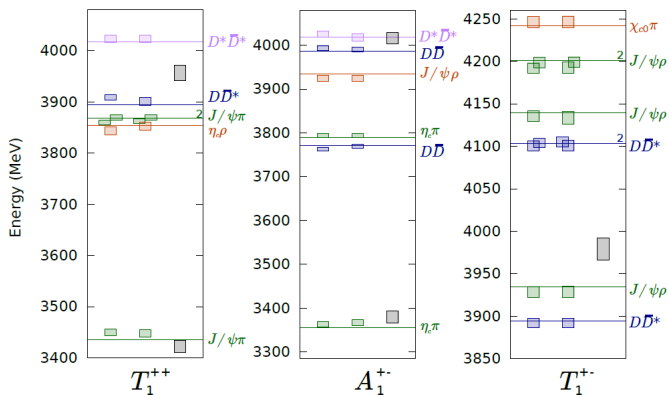
- Evidence for a  $J^P = 2^+$  narrow resonance coupling predominantly to  $D\pi$  resembling  $D_2^*$ .
- Evidence for a shallow bound state with  $J^P = 0^+$  coupling predominantly to  $D\pi$ .  $D_0^*(2400)$  is a wide resonance above  $D\pi$  threshold in experiments.
- Would be interesting to see the results from ensembles with  $m_\pi \sim 240 \text{ MeV}$ .

# Coupled channel $D\bar{D}^*$ , $J/\psi\pi$ , $\rho\eta_c$ scattering

- HALQCD approach to study resonances :  
An alternative approach to study resonances on the lattice
- $Z_c(3900)$  from coupled channel  $D\bar{D}^*$ ,  $J/\psi\pi$ ,  $\rho\eta_c$  scattering  
[HALQCD Collaboration, PRL, 117, 242001, 2016](#)
- The coupling between  $J\psi\pi$  and  $D\bar{D}^*$  scattering channels seems to be crucial to produce a peak resembling the experimental peak for  $Z(3900)$ .

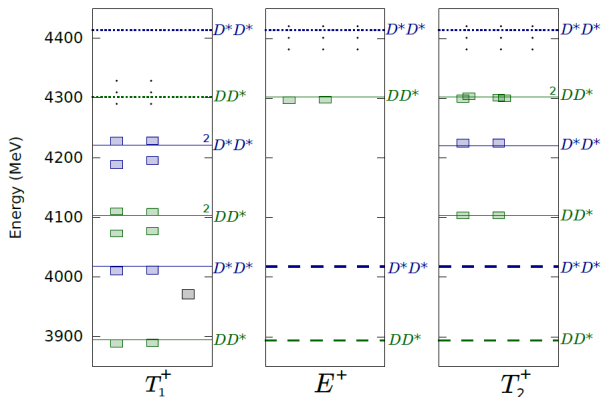
# Tetraquarks : $I = 1; \bar{u}d\bar{c}c$

Spectra insensitive to the addition of tetraquark operators  
to the bases of meson-meson operators



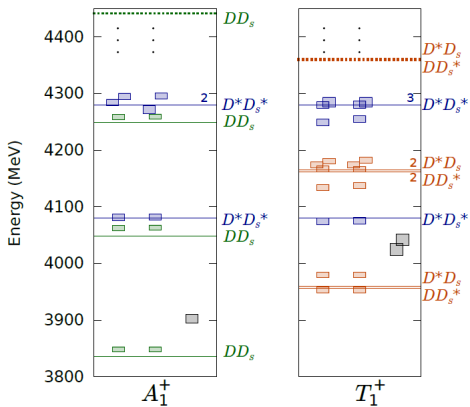
# Tetraquarks : $I = 0; c\bar{c}\bar{l}\bar{l}$

Spectra insensitive to the addition of tetraquark operators  
to the bases of meson-meson operators

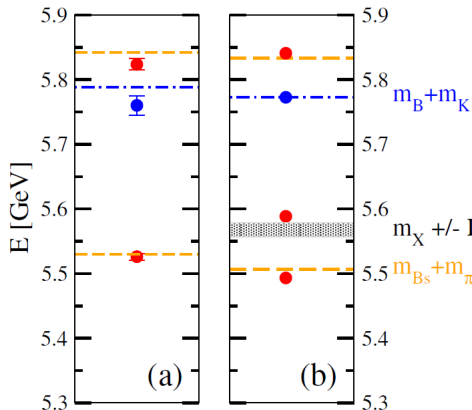


# Tetraquarks : $I = \frac{1}{2}; cc\bar{s}\bar{l}$

Spectra insensitive to the addition of tetraquark operators to the bases of meson-meson operators



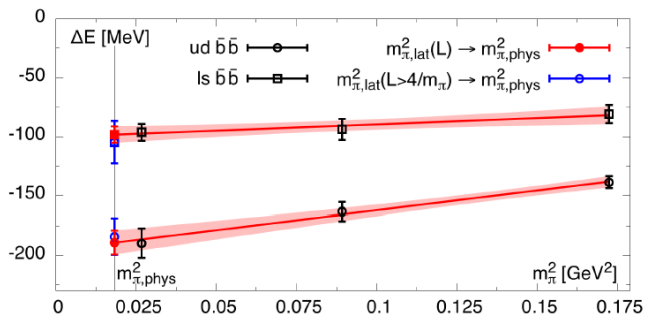
# Tetraquarks : $X(5568)$ with flavor $\bar{b}s\bar{d}u$



- Relatively narrow peak in  $B_s\pi^+$  invariant mass by *D0* collaboration.  
*D0* Collaboration, PRL, **117**, 022003, 2016.
- LHCb results with increased statistics did not find evidence.  
LHCb Collaboration, PRL, **117**, 152003, 2016.
- If  $X(5568)$  with flavor  $\bar{b}s\bar{d}u$  exists, it is elastic to  $B_s\pi^+$  and relatively far below other scattering channels.
- However, no evidence observed on the lattice!

Lang et al, PRD, **94**, 074509, 2016

# Doubly bottom tetraquarks



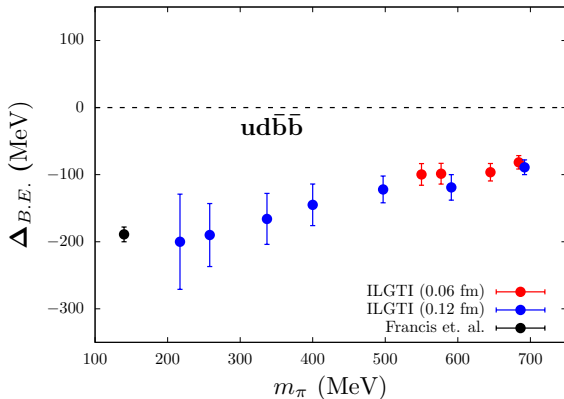
Francis *et al*, PRL, **118**, 142001, 2017

- Evidence for deeply bound tetraquarks in  $J^P = 1^+$  doubly bottom sector.
- $ud\bar{b}\bar{b}$ ;  $I = 0$  : Binding energy = 189(10) MeV.
- $us\bar{b}\bar{b}$ ;  $I = \frac{1}{2}$  : Binding energy = 98(7) MeV.
- Multiple other lattice investigations in the past point to strong attraction in the  $I = 0, J^P = 1^+$  channel.



# Doubly bottom tetraquarks : Preliminary

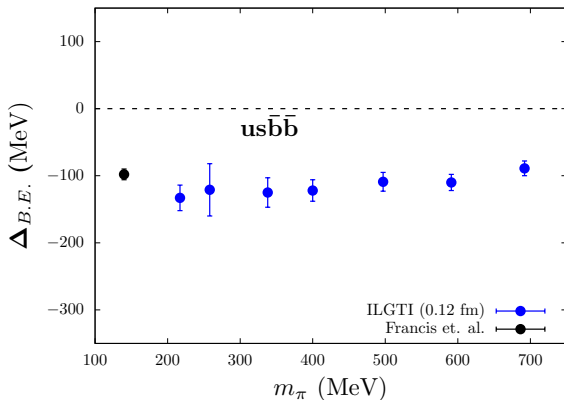
$ud\bar{b}\bar{b}$ ;  $I = 0$  : Similar conclusions from our ongoing investigations



P. Junnarkar, M. P. and N. Mathur ongoing study.

# Doubly bottom tetraquarks : Preliminary

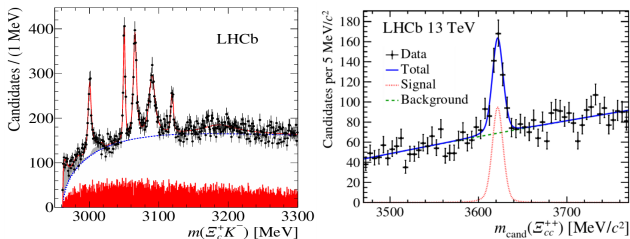
$us\bar{b}\bar{b}$ ;  $I = \frac{1}{2}$  : Similar conclusions from our ongoing investigations



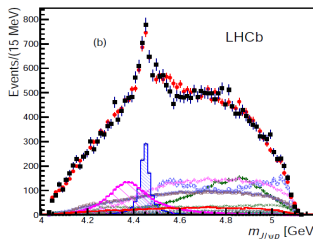
P. Junnarkar, M. P. and N. Mathur ongoing study.

# Heavy baryons

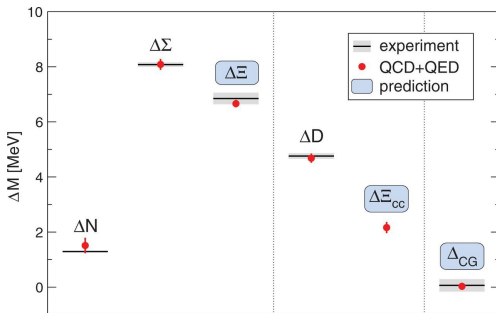
LHCb PRL, **118**, 182001; PRL, **119**, 112001, 2017.



LHCb PRL, **115**, 072001, 2015



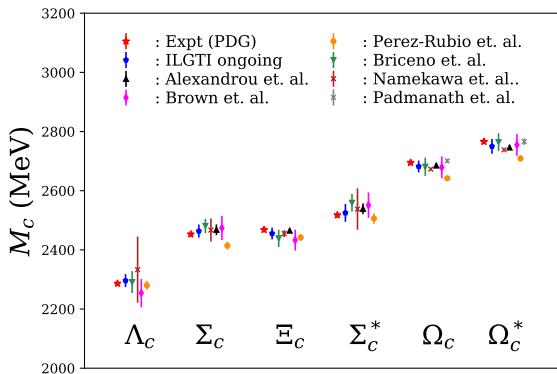
# Isospin splittings in baryons



- Fully controlled ab initio calculation with 1+1+1+1 flavor QCD+QED with clover improved Wilson quarks.
- Precision of low energy description is down to per mil level.
- Precision at a level of challenging the experimental numbers.

Borsanyi, et. al., Science Vol. 347 no. 6229 pp. 1452-1455

## Singly charm baryons



M. P. and N. Mathur, PRL, **119**, 042001, 2017;

Brown *et al* PRD, **90**, 094507, 2014

Pérez-Rubio *et al*, PRD, **92**, 034504, 2015;

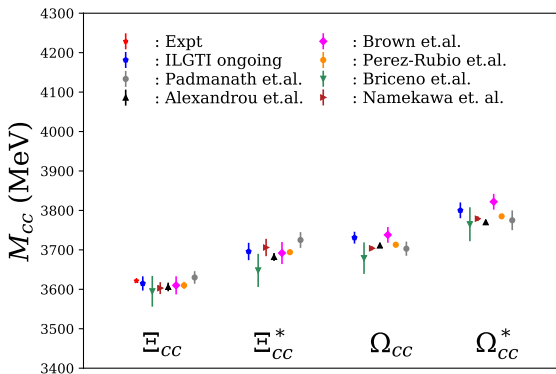
Briceño *et al* PRD, **86**, 094504, 2012

Namekawa *et al* PRD, **87**, 094512, 2013;

Alexandrou *et al* PRD, **90**, 074501, 2014

ILGTI Collaboration, arXiv:1312.3050[hep-lat]

# Doubly charm baryons



M. P. *et al*, PRD, **91**, 094502, 2015;

Pérez-Rubio *et al*, PRD, **92**, 034504, 2015;

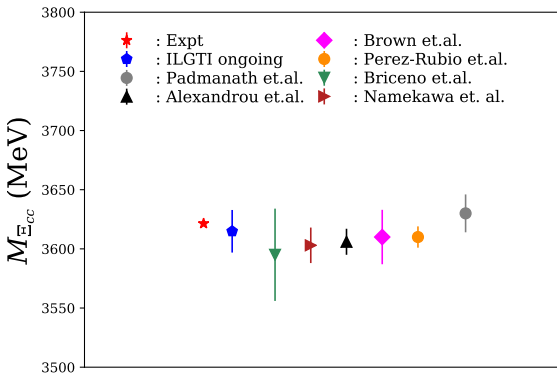
Namekawa *et al* PRD, **87**, 094512, 2013;

ILGTI Collaboration, arXiv:1312.3050[hep-lat]

Brown *et al*, PRD, **90**, 094507, 2014

Briceño *et al* PRD, **86**, 094504, 2012

Alexandrou *et al* PRD, **90**, 074501, 2014

Closer look at  $\Xi_{cc}$ 

M. P. *et al*, PRD, **91**, 094502, 2015;

Brown *et al*, PRD, **90**, 094507, 2014

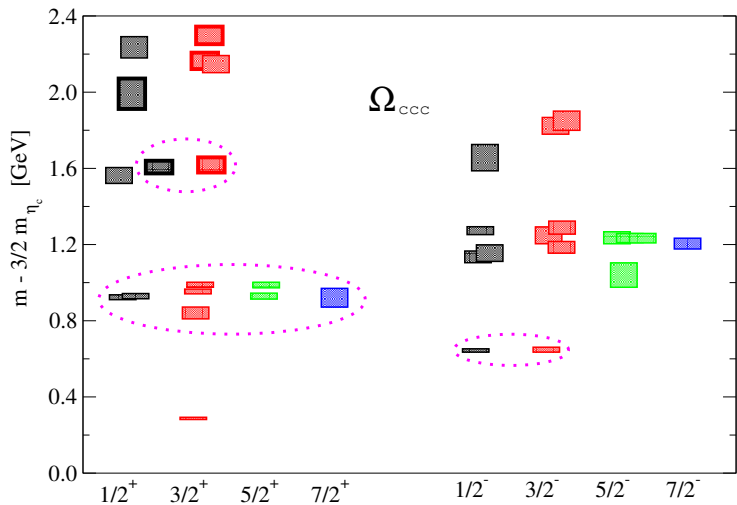
Pérez-Rubio *et al*, PRD, **92**, 034504, 2015;

Briceño *et al* PRD, **86**, 094504, 2012

Namekawa *et al* PRD, **87**, 094512, 2013;

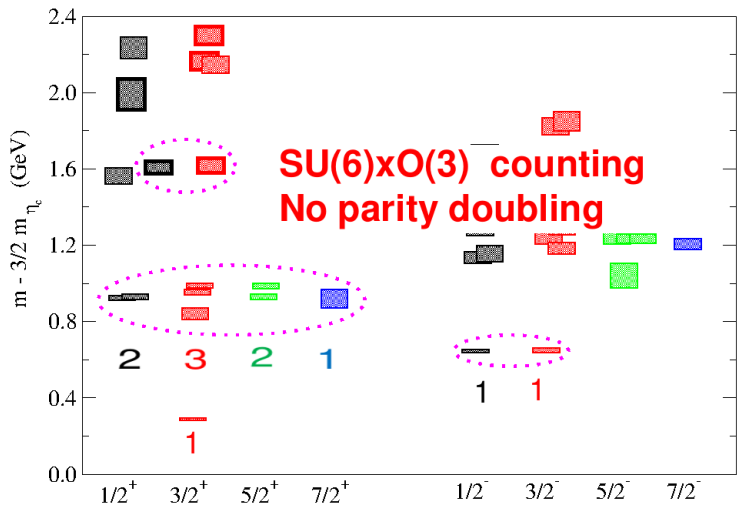
Alexandrou *et al* PRD, **90**, 074501, 2014

ILGTI Collaboration, arXiv:1312.3050[hep-lat]

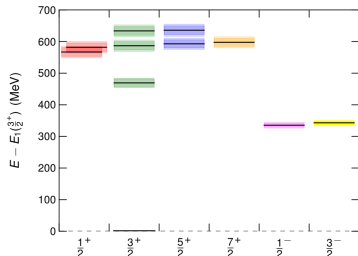
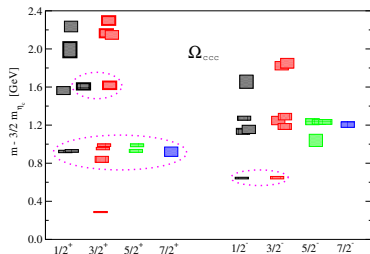
$\Omega_{ccc}$  spectrum

MP *et al.*, PRD 90 074504;  $m_\pi = 391$  MeV



$\Omega_{ccc}$  spectrum

Consistent with  $SU(3)_F \otimes SU(2)_S \otimes O(3)$  expectations

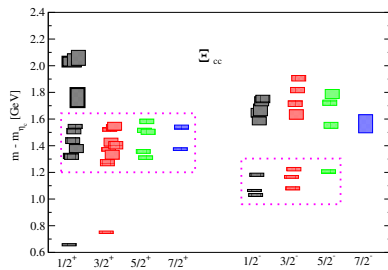
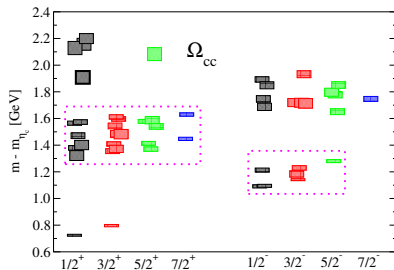
A comparison between  $\Omega_{ccc}$  and  $\Omega_{bbb}$ 

$\Omega_{ccc}$  : M. P. *et al.*, PRD **90** 074504 2014

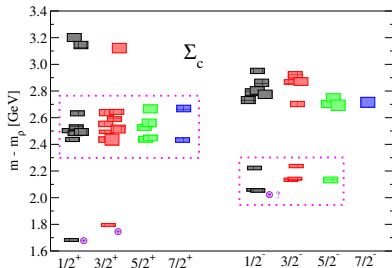
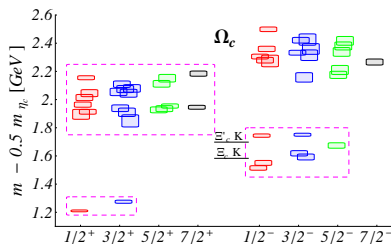
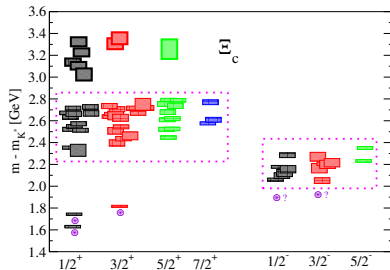
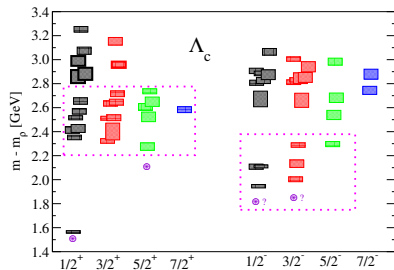
$\Omega_{bbb}$  : Meinel, PRD, **85**, 114510, 2012

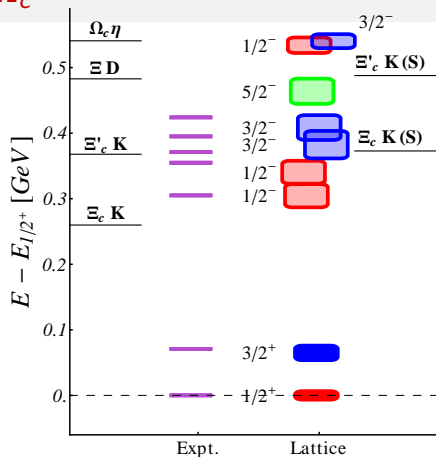
- The spectral pattern remains same up to second excitation band.
- $\Omega_{ccc}$  study with considers relativistic operators also.  
Hence the multitude of states.

## Doubly charm baryon spectrum



## Singly charm baryons



Closer look at  $\Omega_c$ 

LHCb Collaboration, PRL, **118**, 182001; M. P. and N. Mathur, PRL, **119**, 042001, 2017.

### Predictions for quantum numbers from lattice QCD

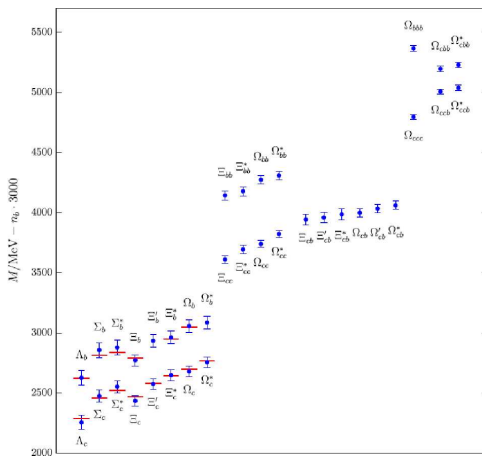
# Closer look at $\Omega_c$

LHCb Collaboration, PRL, **118**, 182001; M. P. and N. Mathur, PRL, **119**, 042001, 2017.

| Energy Splittings ( $\Delta E$ )         | Experiment          |                | Lattice             |         |
|--|---------------------|----------------|---------------------|---------|
|  | $\Delta E$<br>(MeV) | $J^P$<br>(PDG) | $\Delta E$<br>(MeV) | $J^P$   |
| $E_{\Omega_c^0} - \frac{1}{2}E_{\eta_c}$ | 1203(2)             | $1/2^+$        | 1209(7)             | $1/2^+$ |
| $\Delta E_{\Omega_c^0(2770)}$            | 70.7(1)             | $3/2^+$        | 65(11)              | $3/2^+$ |
| $\Delta E_{\Omega_c^0(3000)}$            | 305(1)              | ?              | 304(17)             | $1/2^-$ |
| $\Delta E_{\Omega_c^0(3050)}$            | 355(1)              | ?              | 341(18)             | $1/2^-$ |
| $\Delta E_{\Omega_c^0(3066)}$            | 371(1)              | ?              | 383(21)             | $3/2^-$ |
| $\Delta E_{\Omega_c^0(3090)}$            | 395(1)              | ?              | 409(19)             | $3/2^-$ |
| $\Delta E_{\Omega_c^0(3119)}$            | 422(1)              | ?              | 464(20)             | $5/2^-$ |

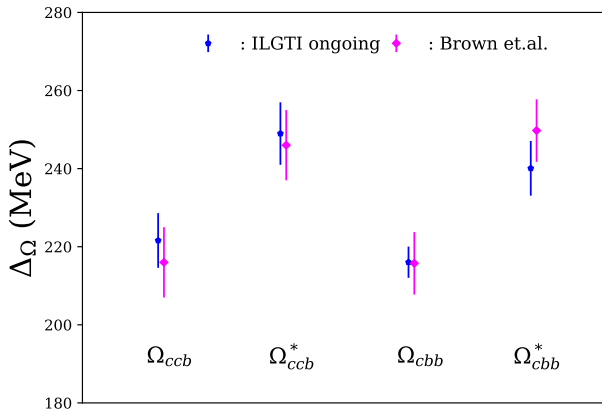
## Predictions for quantum numbers from lattice QCD

# Charm-Bottom baryons



Brown *et al*, PRD, **90**, 094507, 2014

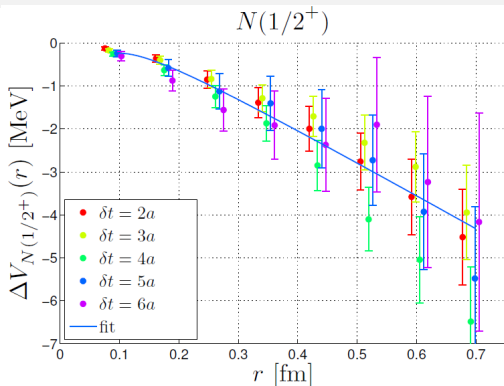
# Charm-Bottom baryons : Preliminary



N. Mathur, M.P. et al (ILGTI) work ongoing



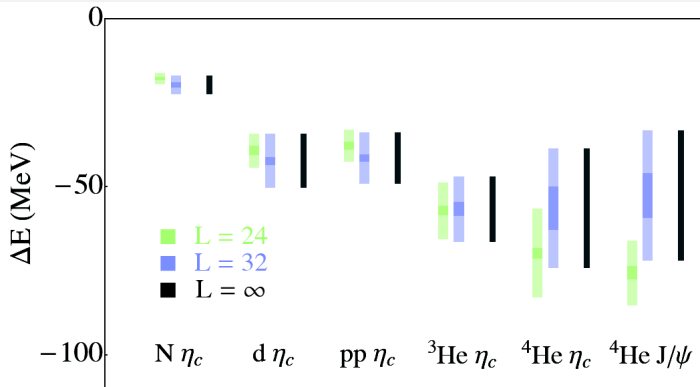
# Pentaquarks : Hadron-quarkonium



Alberti *et al*, PRD, **95**, 074501, 2017

- Studies the modification of the potential between a static quark-anti-quark pair induced by the presence of a hadron.
- All the hadron channels with the quarkonium cores are favored energetically.
- Whether the system supports bound states or resonances : demands further investigations on different ensembles.

# Pentaquarks : Nucleus-Quarkonium binding energies



Beane *et al*, PRD, **91**, 114503, 2015

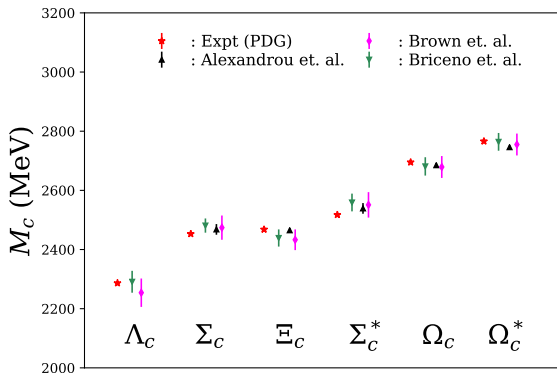
- Another calculation with similar conclusions.
- Calculation at SU(3) flavor symmetric point.
- Chiral limit !

# Summary

- Brief overview over different lattice calculations addressing different sectors of heavy hadron spectrum
  - Ground and excited heavy mesons
  - Bound states and resonances
  - Tetraquarks
  - Charm baryons
  - Charm-Bottom baryons
  - $qqqQ\bar{Q}$  systems.
- More results from different groups on the way.  
Stay tuned!

Thank you...

## Singly charm baryons

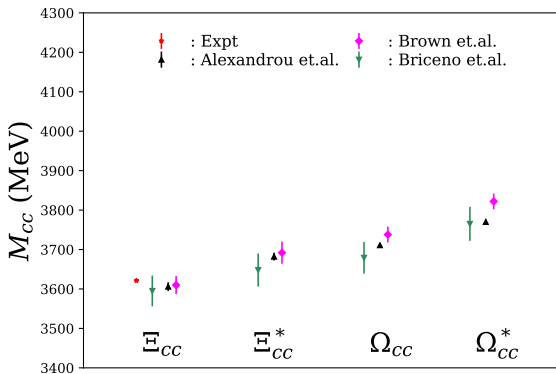


Brown et al PRD, **90**, 094507, 2014

Briceño et al PRD, **86**, 094504, 2012

Alexandrou et al PRD, **90**, 074501, 2014

# Doubly charm baryons



Brown *et al*, PRD, **90**, 094507, 2014

Briceño *et al* PRD, **86**, 094504, 2012

Alexandrou *et al* PRD, **90**, 074501, 2014