Biographical presentation

Padmanath M.

Seminar @ JLab

8th Jan. 2016

Current position : Post-Doctoral fellow, since 2014.

Affiliation : University of Graz, Austria.

Lives in : Graz, Austria.

Padmanath M.

Born (1985) and bought up at : Palakkad, Kerala.

Bachelor's degree (2003-06) : Govt. Victoria College, Palakkad.

Bachelor's project on :
Nuclear magnetic resonance

Padmanath M.

Master's education (2006-08) :
Indian Institute of Technology, Roorkee. (*One of the most renowned higher educational institutions in India*)

Master's project on :
Quantum and classical teleportation

Most notable achievement :
ShyamaPrasad Mukherjee Fellowship, CSIR, India.
(*Awarded for top 3-4 candidates from Physics per year throughout India. Based on National Eligibility Test and interview.*)

Biographical presentation

Padmanath M.

Ph.D (2008-2014) from Tata Institute of Fundamental Research, Mumbai.
(*One of the most prestigious research institutions in India*)

Thesis on
"Baryons from Lattice QCD"

Thesis Advisor :
Prof. Nilmani Mathur

Major involvements :
a) Excited charm baryon spectroscopy.
b) Hadron spectroscopy with chiral fermions.
c) Baryons across deconfinement transition.

Padmanath M.

Post doctoral fellow (2014-16) :
University of Graz, Austria.

Projects I am involved @ Graz :
a) *Charmonium spectroscopy*
b) *Baryon resonance spectroscopy*

Main research achievements

a) *Publications on excited charm baryon spectroscopy.*
Phys. Rev. D 91, no. 9, 094502 (2015)
Phys. Rev. D 90, 074504 (2014)

b) *Invited plenary talk at CHARM 2015, Detroit, MI.*
"Charm baryons on the lattice"
arXiv:1508.07168 [hep-lat]

c) *Publications on charmonium spectroscopy.*
X(3872) Vs tetra-quark?
Phys. Rev. D 92, no. 3, 034501 (2015)

d) *Publication on effects on baryons across deconfinement transition.*
JHEP 1302, 145 (2013)

Research experience

a) *Excited state spectroscopy*

Derivative-based operator construction,
Distillation techniques,
variational fitting techniques.

b) Resonance spectroscopy

Excited baryon and meson operators,
meson-meson scattering operators,
tetra-quark operators,
baryon-meson operators.*

c) Worked with QCD chroma software suite
for excited charm baryon calculations.

d) Implemented baryon and meson two point correlations
in MILC and ILGTI codes.

e) Implemented two point correlations involving tetra-quarks,
baryons and baryon-meson interpolators.

Excited heavy hadrons from lattice QCD

Padmanath M.

Institute of Physics,
University of Graz,
Graz, Austria.

8^{th} Jan. 2016, seminar @ JLab

Outline

a) *Excited charm baryon spectroscopy*

Triply, doubly and singly charm baryons.

Collaborators : R. G. Edwards, Mike Peardon, Nilmani Mathur

For Hadron Spectrum Collaboration

b) *Charmonium spectroscopy*

$J^{PC}=1^{++}$ *using meson, meson-meson and tetra-quark interpolators.*

Collaborators : C. B. Lang, Sasa Prelovsek

c) *Major ongoing projects*

Excited bottom hadrons

Collaborators : Nilmani Mathur

Baryon resonance spectroscopy

Collaborators : C. B. Lang, Sasa Prelovsek

References

Operators :

[1] Basak et al. (LHPC), Phys. Rev. D **72**, 074501 (2005)

Distillation :

[1] M. Peardon *et al*. (HSC), Phys. Rev. D **80**, 054506 (2009)

Variational method and spin identification :

[1] J. J. Dudek *et al*., Phys. Rev. D **77**, 034501 (2008)

HadSpec lattices :

[1] R. G. Edwards *et al*., Phys. Rev. D **78**, 054501 (2008)
[2] H. W. Lin *et al*. (HSC) Phys. Rev. D **79**, 034502 (2009)

Perambulators (quark propagators) :

[1] J. J. Dudek *et al*., Phys. Rev. D **82**, 034508 (2010)
[2] L. Liu *et al*. (HSC), JHEP **1207**, 126 (2012)

Light baryons

[1] R. G. Edwards *et al*. (HSC), Phys. Rev. D **84**, 074508 (2011)
[2] J. J. Dudek and R. G. Edwards (HSC), Phys. Rev. D **85**, 054016 (2012)
[3] R. G. Edwards *et al*. (HSC), Phys. Rev. D **87**, no. 5, 054506 (2013)

Chroma software suite :

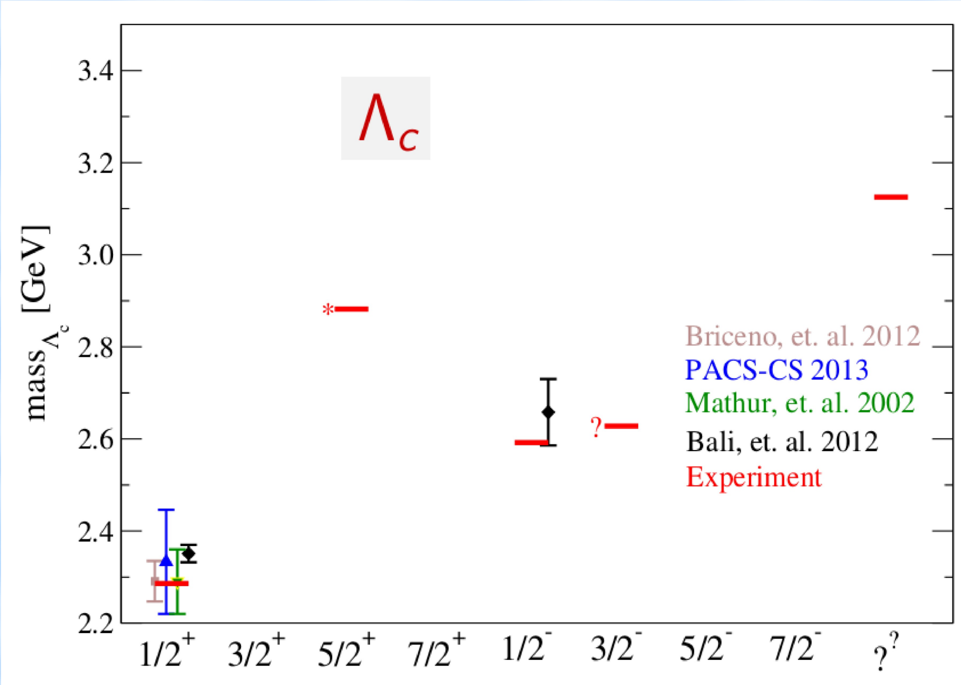
[1] R. G. Edwards and B. Joo, Nucl. Phys. Proc. Suppl. **140**, 832 (2005)

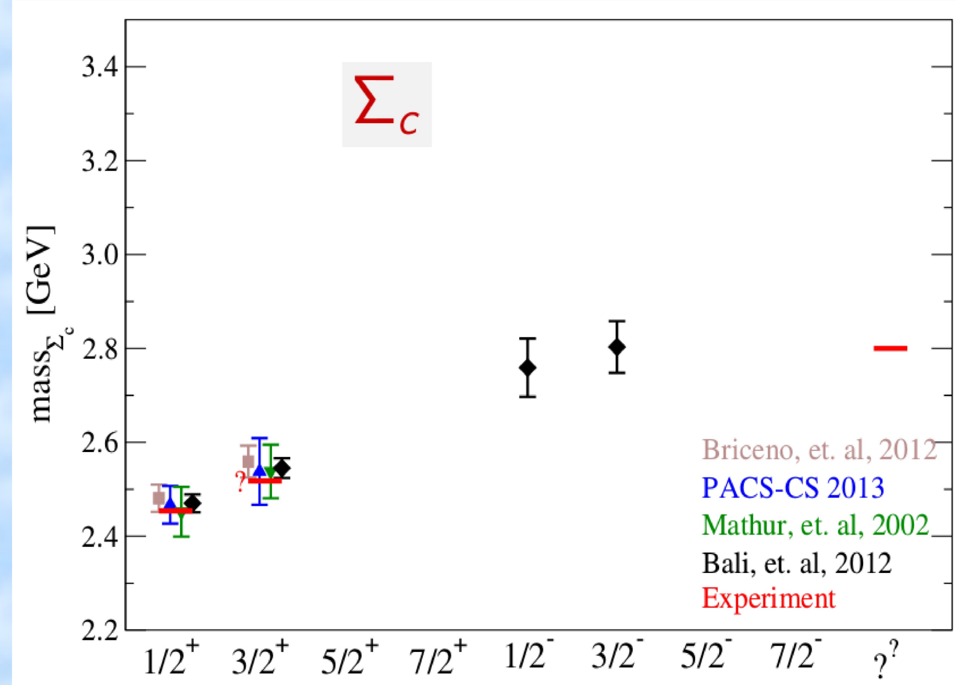
Motivation

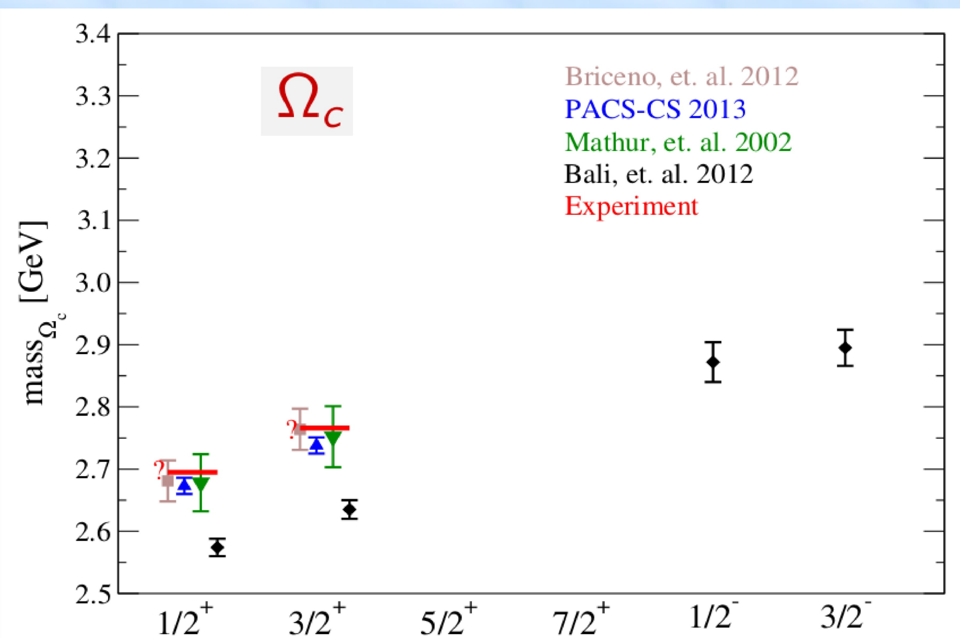
- **Experimental prospects** :
  Not many states observed unlike light baryons.
  LHCb, Belle II, J-PARC.
- **Triply charm baryons** :
  Charmonia analogues in baryons.
  Platform to study quark confinement mechanism.
- **Doubly charm baryons** :
  Observations only by SELEX (losing confidence)
  Failed to be observed in FOCUS, Belle, BaBar and LHCb.
  Very large isospin splittings : 9 and 21 MeV.
  HQS : $\lim(m_Q \to \infty)$ J_{light} is a conserved quantum number.
- **Singly charm baryons** :
  20 states with *** or more.
  More levels expected to be observed.
  Interesting indications for the existence of many charm baryons from finite temperature lattice calculations
  HQS : $\lim(m_Q \to \infty)$ J_{light} is a conserved quantum number.
  Light quark dynamics around a static color source.
  Corrections of the $O(\Lambda_{QCD}/m_Q)$.

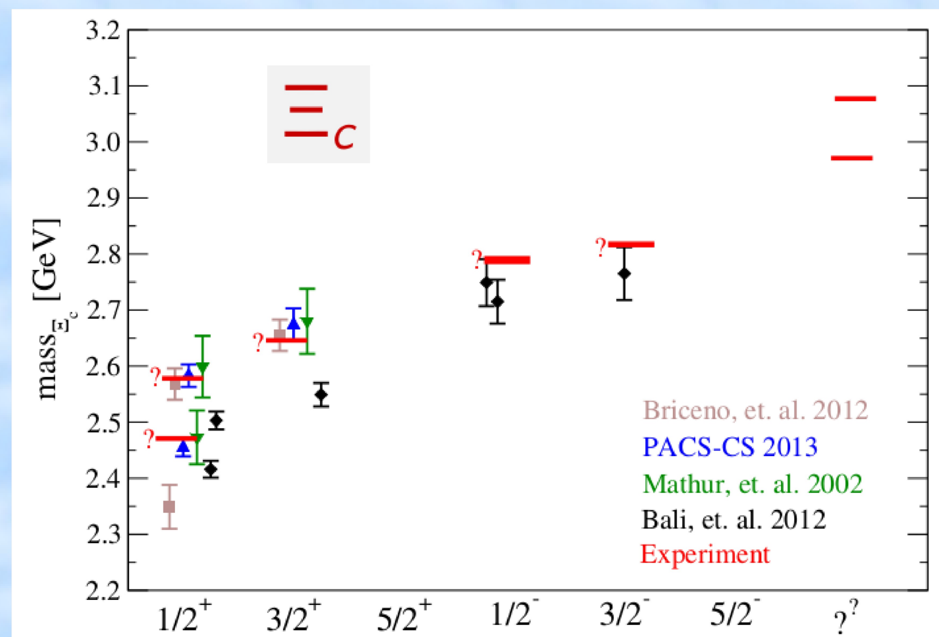
a) ***Excited charm baryons***

Lattice results







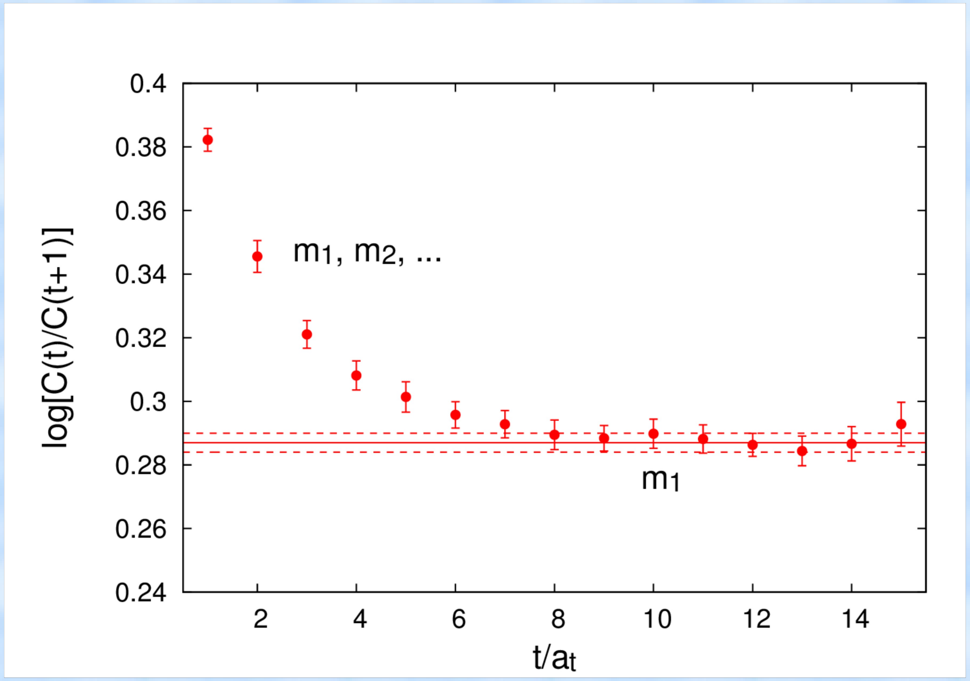


QCD spectrum from Lattice

- 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 $\log[\frac{C(t)}{C(t+1)}]$

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

Challenges

- Charm quarks being heavy $\Rightarrow$ The discretization errors (ma) are generally very large.
- The exponential decay is very rapid.
  Rapid degradation of SNR for highly excited states.

Solution : **Anisotropic lattices**

- Multiple excited state extraction : Multi parameter fit.
  Extremely cumbersome.

Solution : **A large basis of interpolating operators**

- A good analysis procedure for extraction of energy of physical states.
- Spin identification : Highly non-trivial

Solution : **Variational fitting method**

Lattices used

- Anisotropic lattices with $\xi = a_s/a_t \sim 3.5$.
- Dynamical configurations ($N_f = 2 + 1$ sea quarks).
  Gauge field : 4 link sq. plaq. + 6 link rect. plaq.
  Fermions : Wilson + dim. 5 'clover' term
- Lattice spacing : $a_t = 0.035$ fm and $a_t m_c = 0.114 << 1$.
- Lattice size : $16^3 \times 128$; $L_s = a_s\ N_s\ =\ 1.9\ fm$.
- Statistics : 96 cfgs and 4 time sources.

Caveat $m_\pi \sim 400$ MeV

R. G. Edwards, *et al.* Phys. Rev. D **78**, 054501 (2008)

Baryon interpolators

- Aim : Extraction of highly excited states.
  Local operators → low lying states.
  Extended operators → States with radial and orbital excitations.
- Proceeds in two steps
  Construct continuum operators with well defined quantum nos.
  Reduce/subduce into the irreps of the reduced symmetry.
- Used set of baryon continuum operators of the form
  $\Gamma^{\alpha\beta\gamma} q^\alpha q^\beta q^\gamma$, $\Gamma^{\alpha\beta\gamma} q^\alpha q^\beta (D_i q^\gamma)$ and $\Gamma^{\alpha\beta\gamma} q^\alpha q^\beta (D_i D_j q^\gamma)$
- Excluding the color part, the flavor-spin-spatial structure

$$O^{[J^P]} = \left[\mathcal{F}_{\Sigma_F} \otimes \mathcal{S}_{\Sigma_S} \otimes \mathcal{D}_{\Sigma_D}\right]^{J^P}.$$

- γ-matrix convention : $\gamma_4 = \text{diag}[1,1,-1,-1]$;
  Non-relativistic → purely based on the upper two component of q.
  Relativistic → All operators except non-relativistic ones.
- Subset of $D_i D_j$ operators that include $[D_i, D_j] \sim F_{ij}$ → hybrid.

Generalized eigenvalue problem

Solving the generalized eigenvalue problem for $C_{ij}(t)$.

$$C_{ij}(t)v_j^{(n)}(t,t_0) = \lambda^{(n)}(t,t_0)C_{ij}(t_0)v_j^{(n)}(t,t_0)$$

Solve for many t_0's.

Choice of t_0's crucial $\Rightarrow$ Determine quality of extractions.

- Principal correlators given by eigenvalues

$$\lambda_n(t,t_0) \sim (1-A_n)\exp^{-m_n(t-t_0)} + A_n \exp^{-m'_n(t-t_0)}$$

Extraction of a tower of states.

- Eigenvectors related to the overlap factors

$$Z_i^{(n)} = \langle 0|\mathcal{O}_i|n\rangle = \sqrt{2E_n}\exp^{E_n t_0/2} v_j^{(n)\dagger} C_{ji}(t_0)$$

Spin identification.

C. Michael, Nucl. Phys. B 259, 58, (1985)
M. Luscher and U. Wolff, Nucl. Phys. B 339, 222 (1990)

Spin identification

- For example, a continuum operator $O = [ccc \otimes \left(\frac{3}{2}^+\right)^1_S \otimes D^{[2]}_{L=2,S}]^{J=\frac{5}{2}}$.

  Projects on to $\frac{5}{2}^+$.

- In the continuum, $\langle 0|O|\frac{5}{2}^+\rangle = Z$.

- On lattice, O gets subduced over two lattice irreps H_g and G_{2g}.

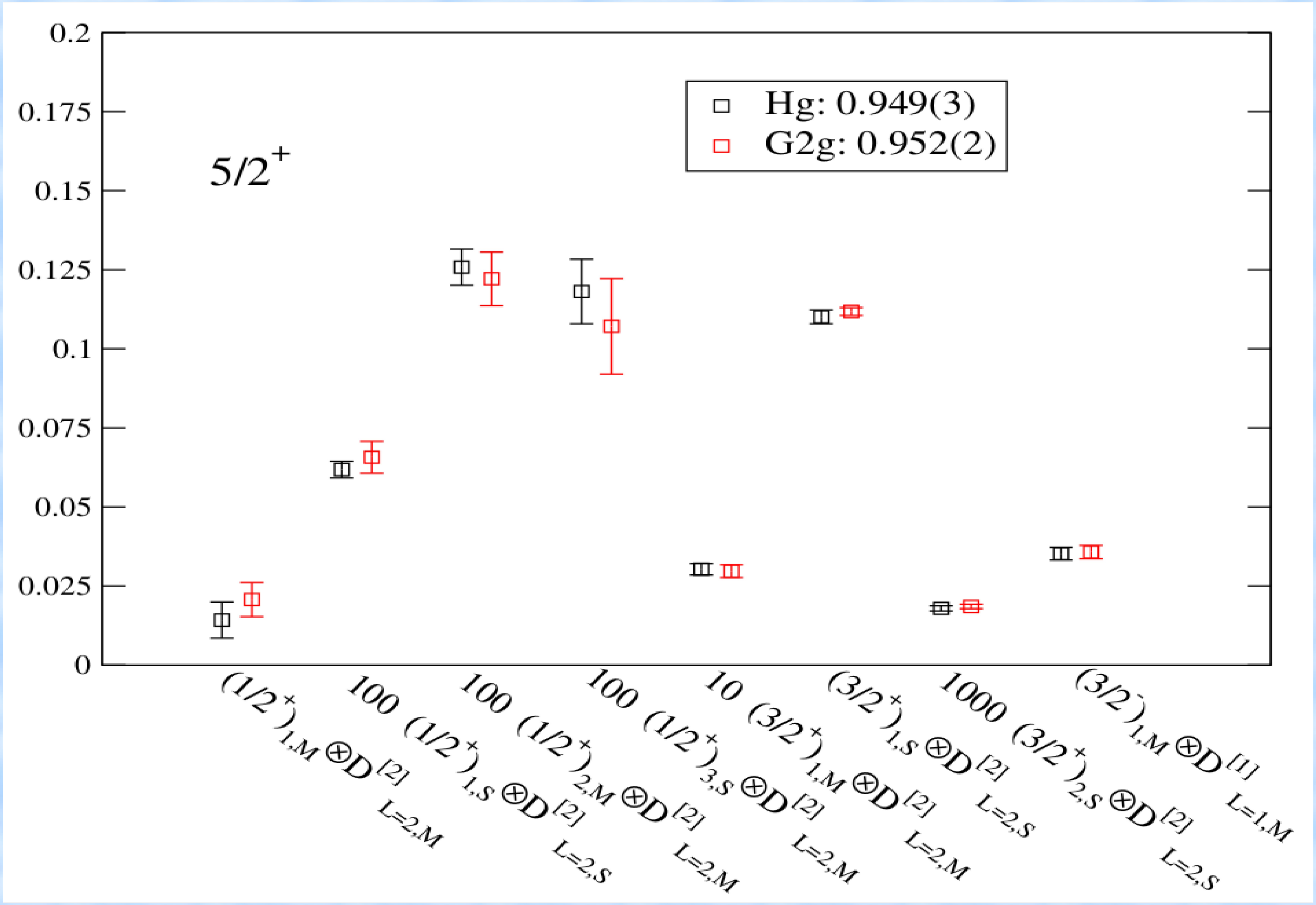
- Then

$$\langle 0|O_{H_g}|\frac{5}{2}^+\rangle = Z_1\alpha \qquad \& \qquad \langle 0|O_{G_{2g}}|\frac{5}{2}^+\rangle = Z_2\beta$$

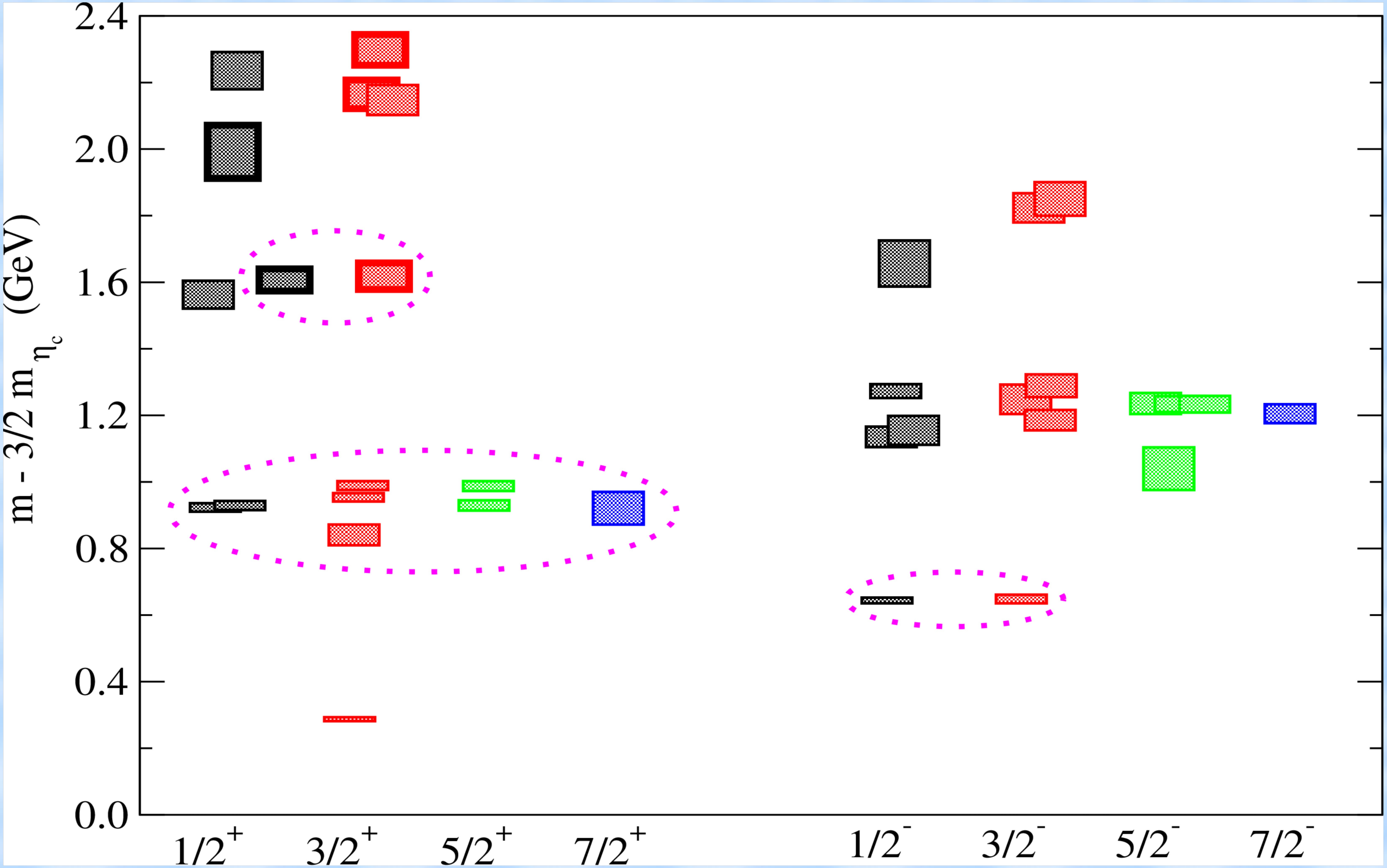
  where α and β are the Clebsch-Gordan coefficients.

- If "close" to the continuum, then $Z \sim Z_1 \sim Z_2$.

Spin identification

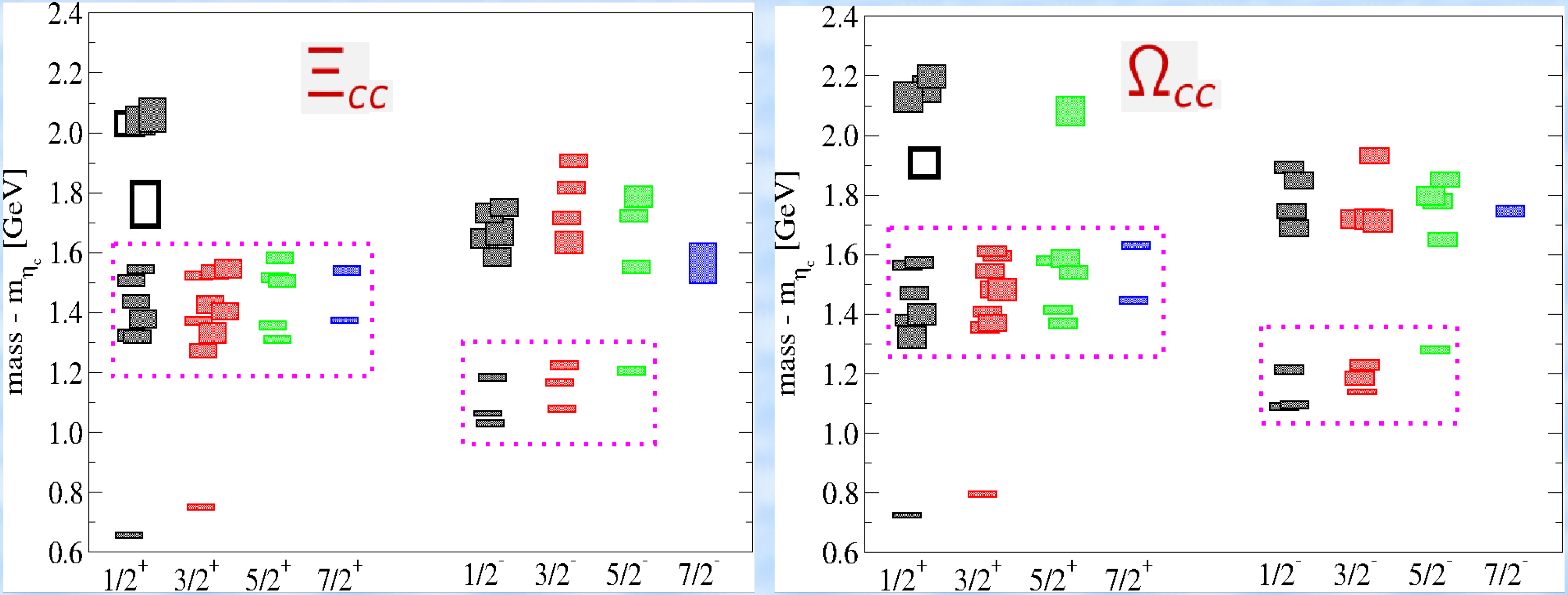


Triply charm baryons



Phys. Rev. D 90, 074504 (2014)

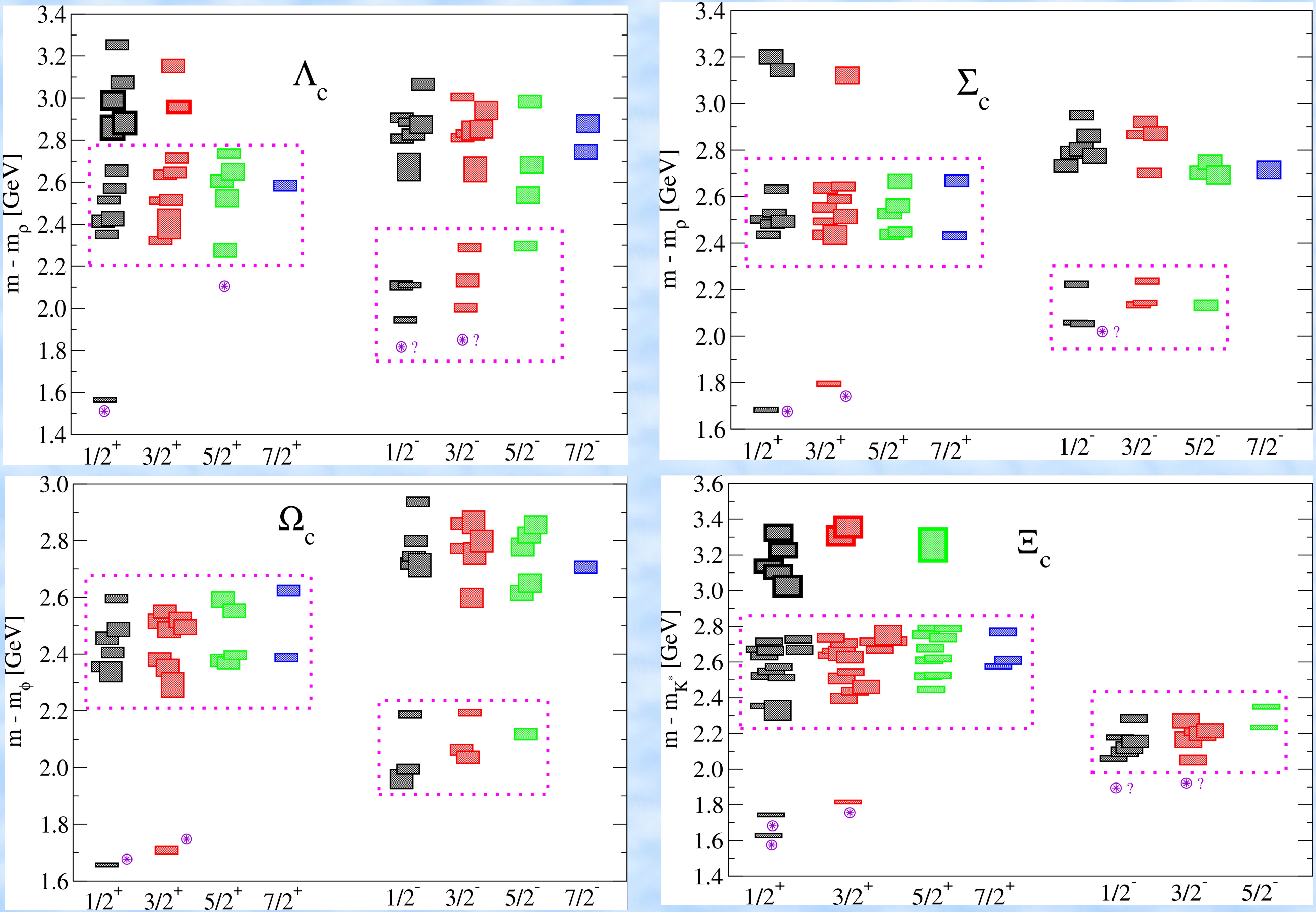
Doubly charm baryons



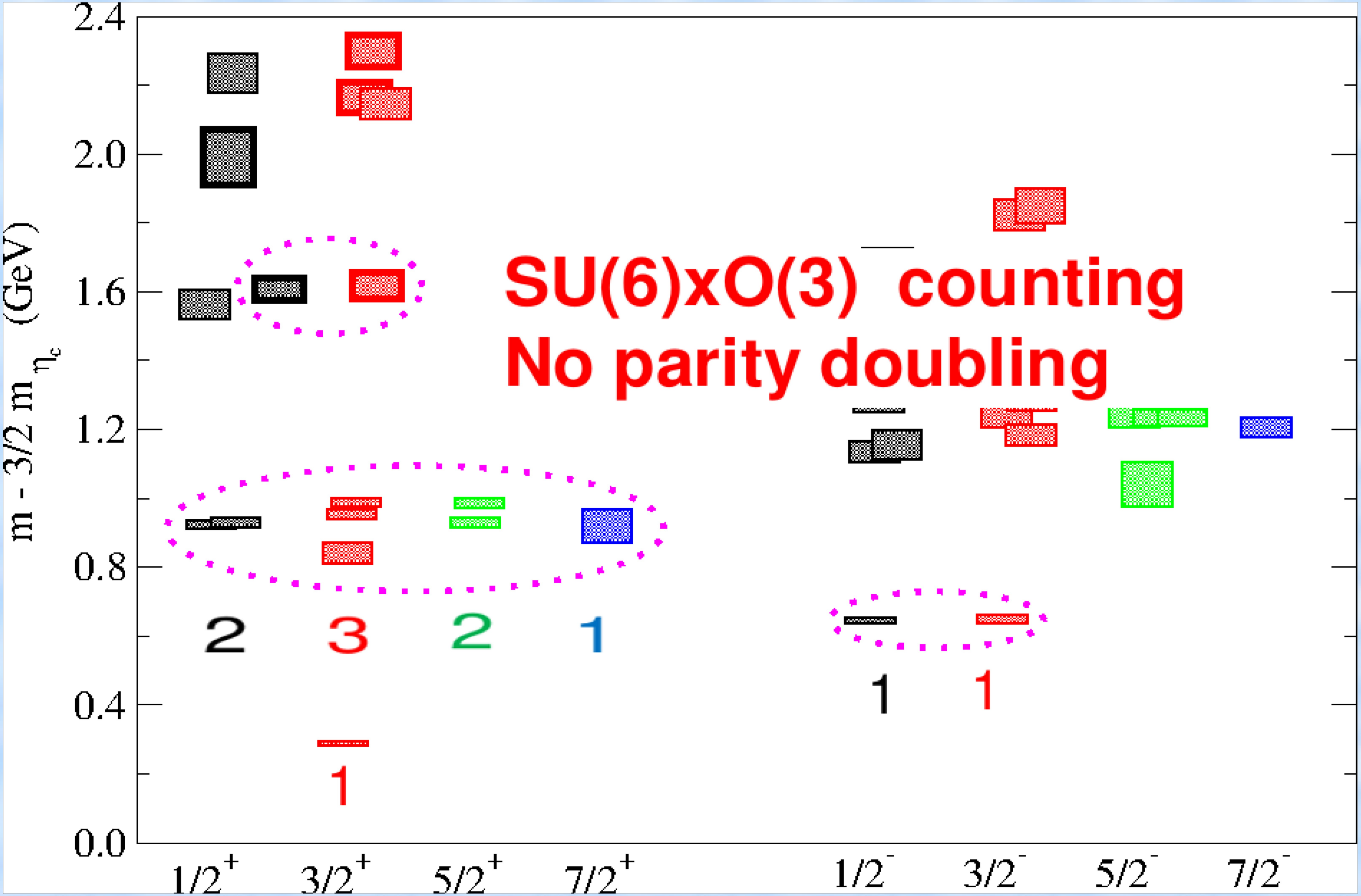
Phys. Rev. D 91, no. 9, 094502 (2015)

a) ***Excited charm baryons***

Singly charm baryons

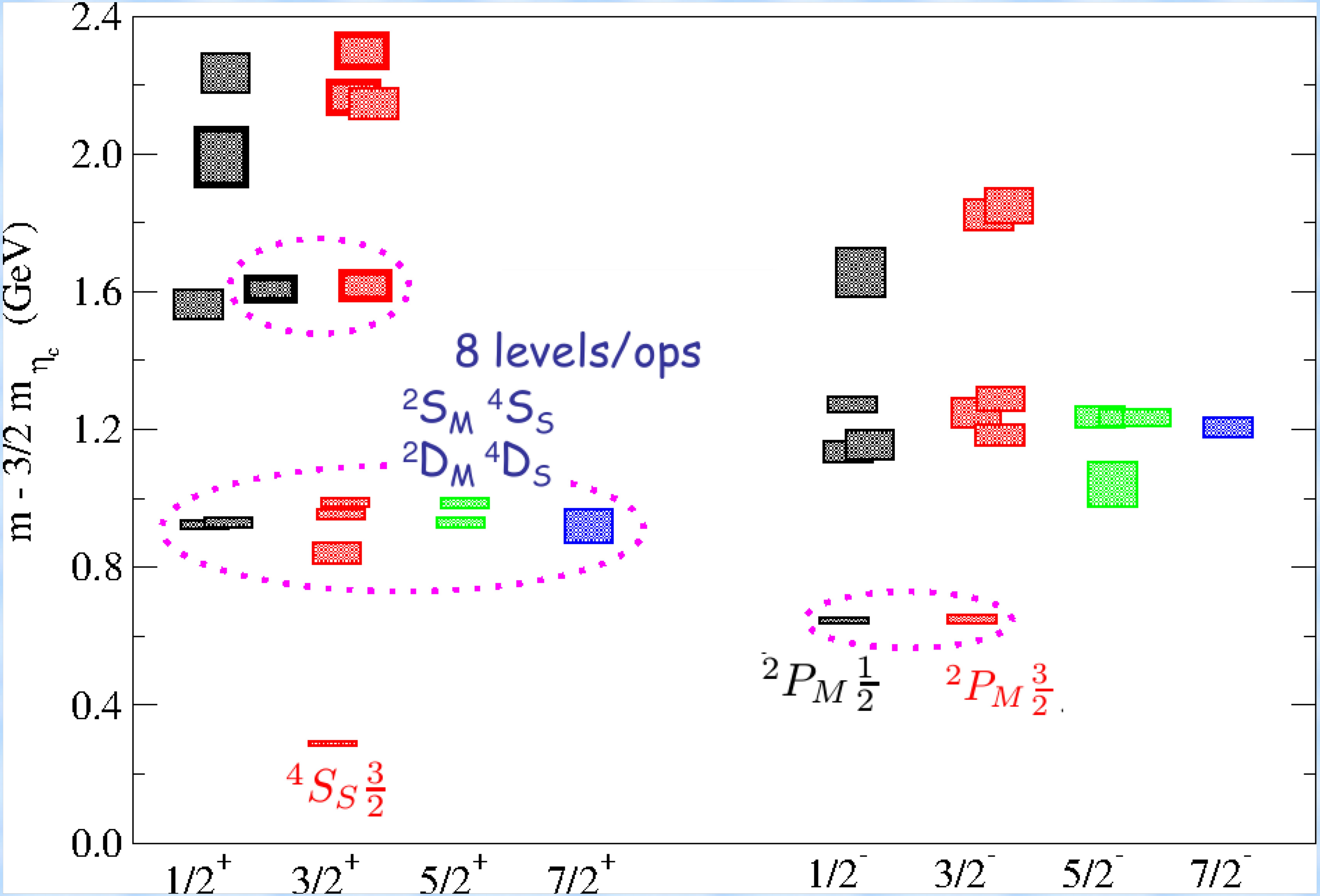


Many other observations



Phys. Rev. D 90, 074504 (2014)

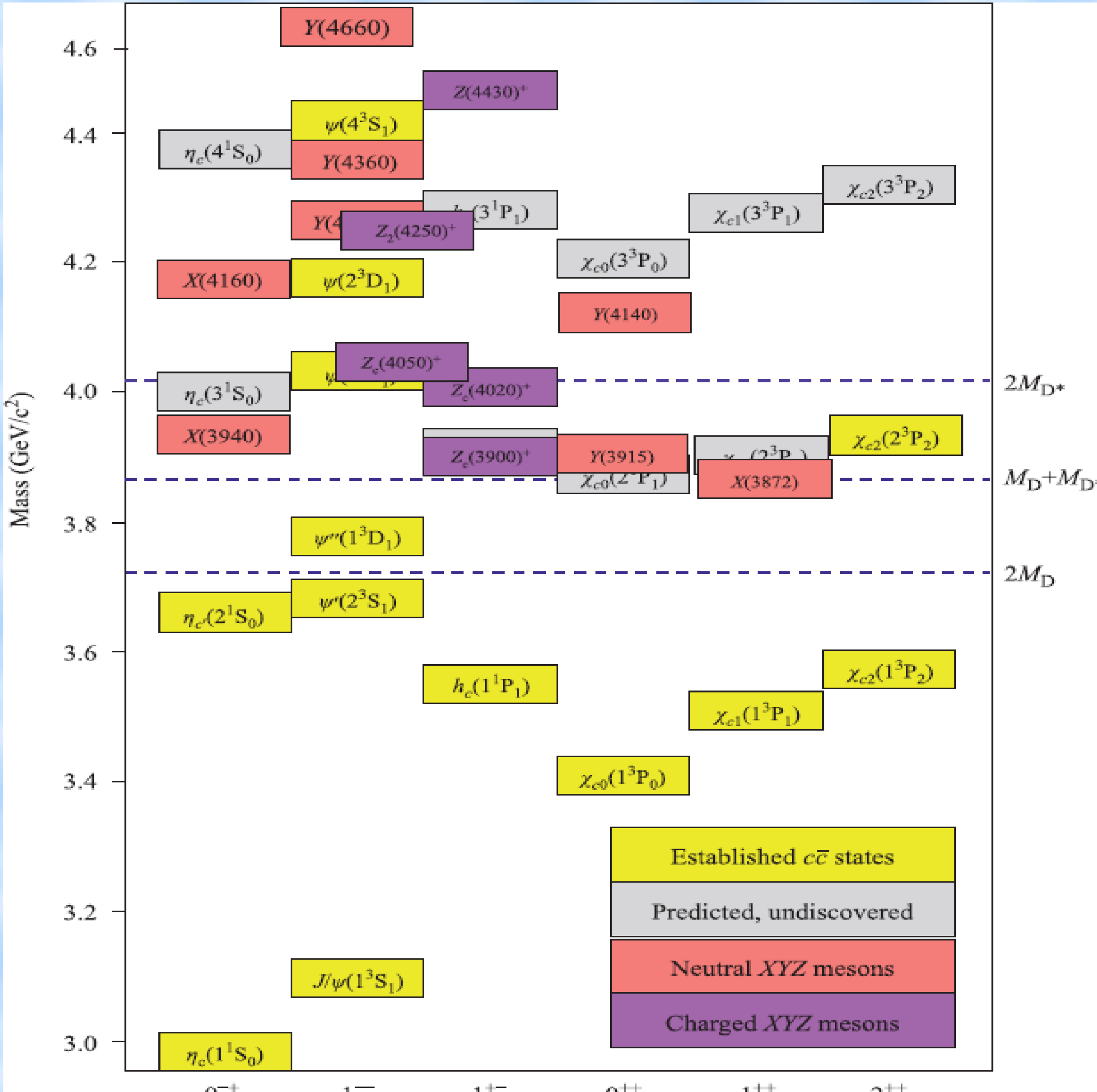
Many other observations



Phys. Rev. D 90, 074504 (2014)

Motivation : $\bar{c}c$ spectrum

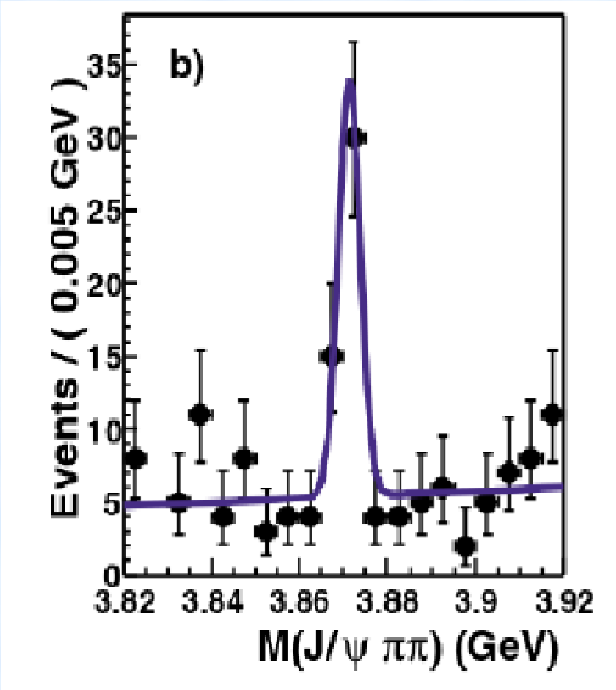
b) ***Charmonium & X*(3872)**



S. L. Olsen,
arXiv:1411.7738v1 [hep-ex]

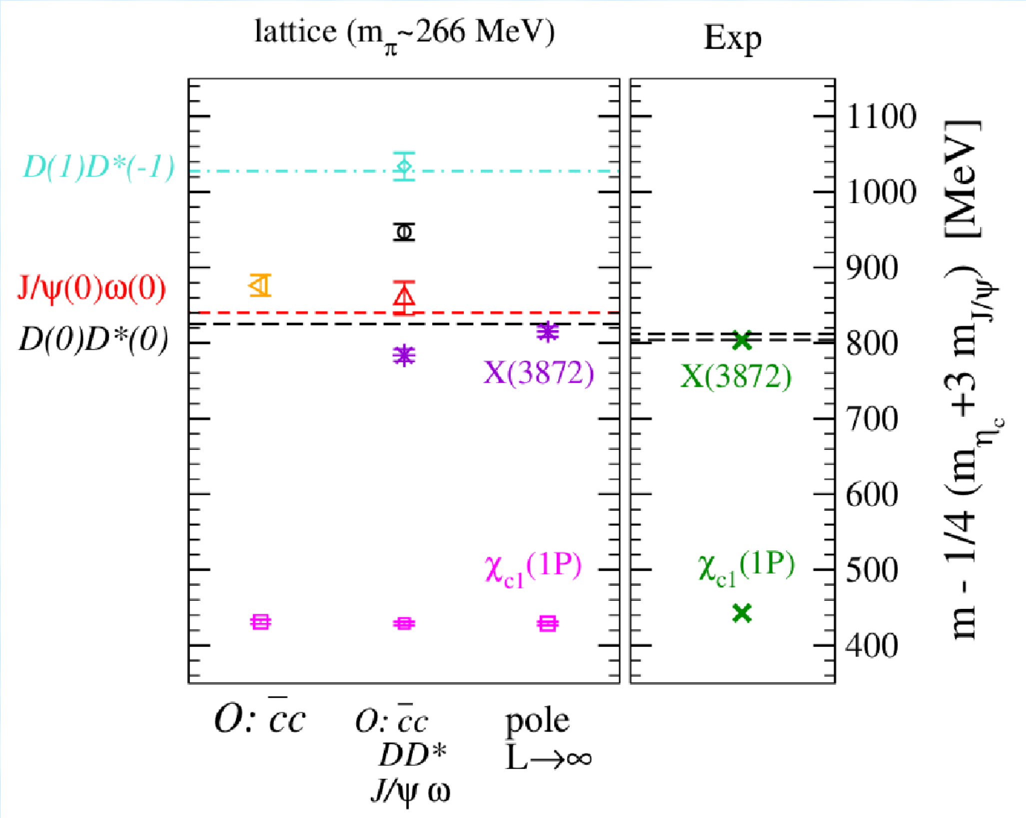
Brief history of X(3872)

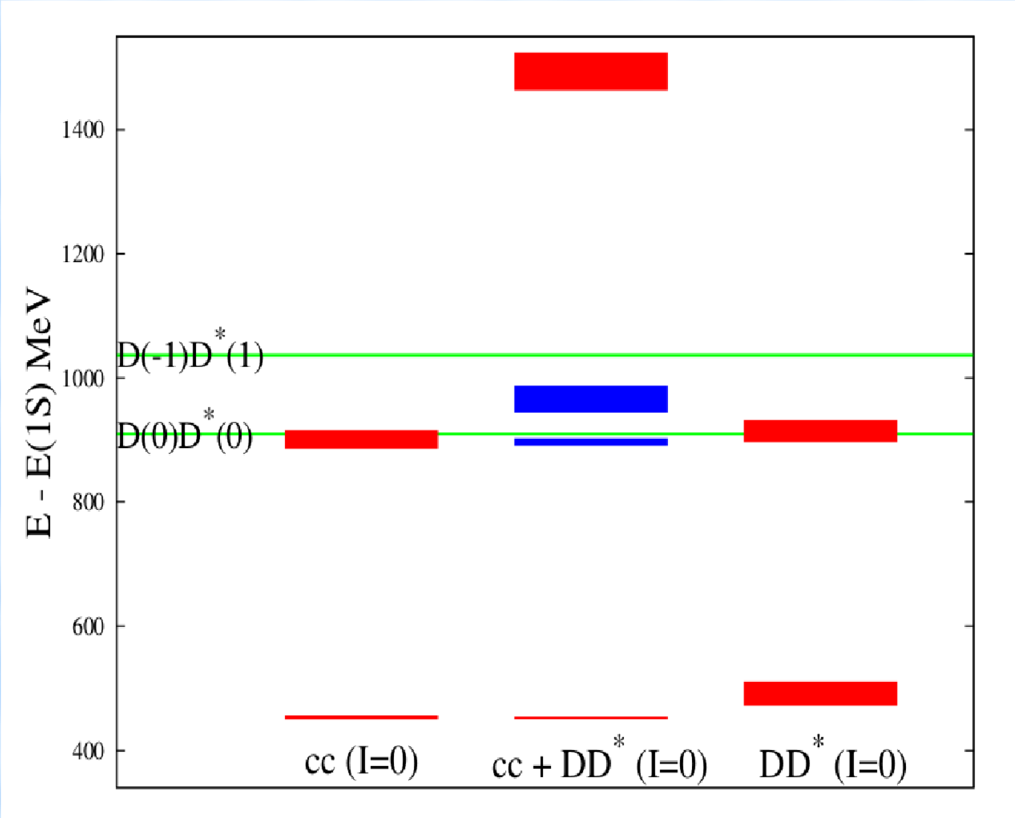
- first observed in Belle 2003 (Belle PRL 2003)
- Quantum numbers, $J^{PC} = 1^{++}$: (LHCb, 2013)
- Appears within 1 MeV below $D^0 \bar{D}^{*0}$ threshold.



- Preferred strong decay modes $J/\psi\ \omega$ and $J/\psi\ \rho$
- The isospin still uncertain
  - * nearly equal branching fraction to $J/\psi\ \omega$ and $J/\psi\ \rho$ decays.
  - * No charge partner candidates observed.

X(3872) candidate from lattice





Prelovsek, Leskovec PRL 2013

Lee et al., PoS Lattice 2014

Interpolators

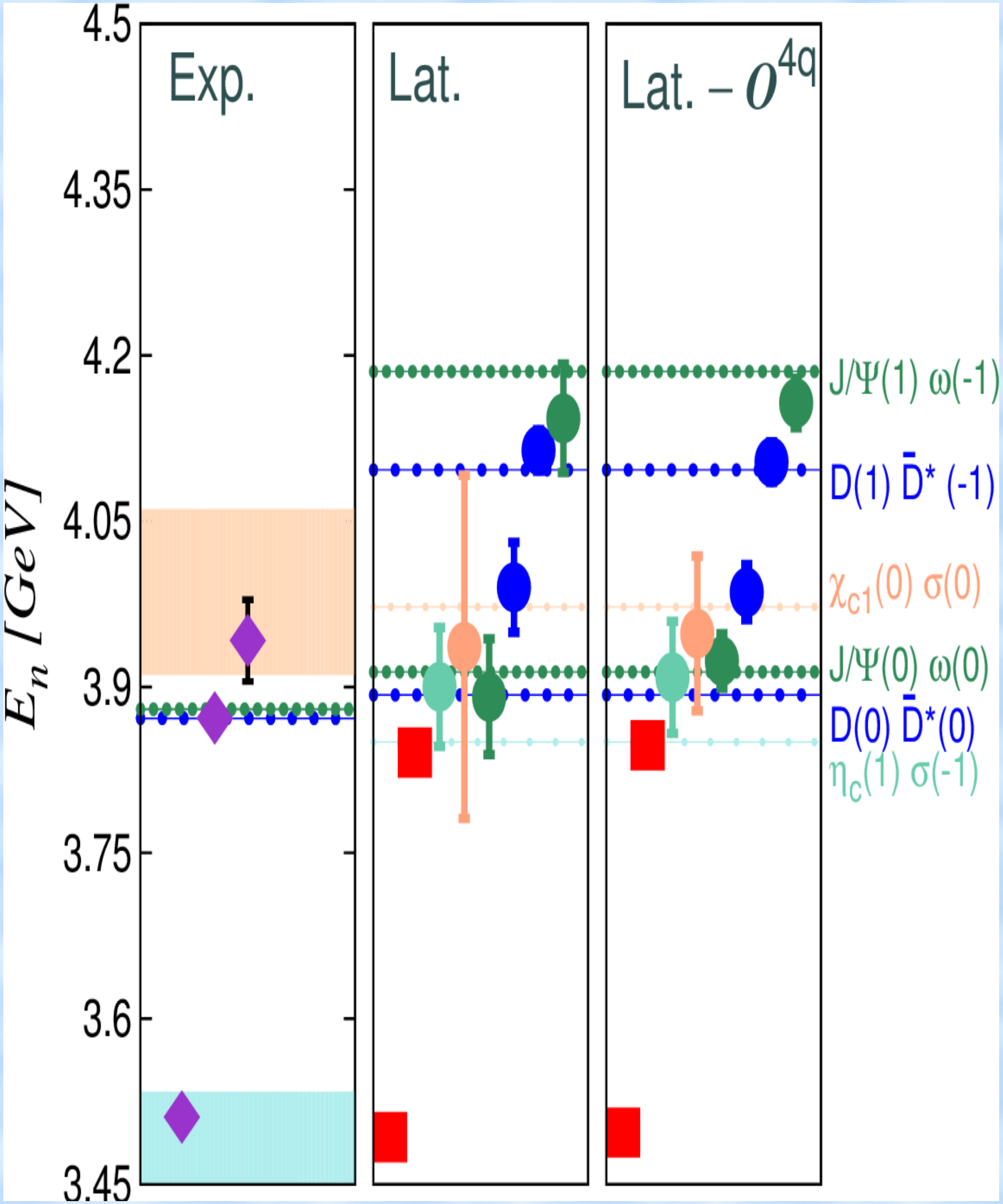
N	$I=0$	$I=1$
$O^{\bar{c}c}_{1-8}$	$\bar{c}\ \hat{\Gamma}\ c$	does not couple
O^{MM}_{9}	$D(0)\bar{D}^*(0)$	$D(0)\bar{D}^*(0)$
O^{MM}_{10}	$J/\psi(0)\omega(0)$	$J/\psi(0)\rho(0)$
O^{MM}_{11}	$D(1)\bar{D}^*(-1)$	$D(1)\bar{D}^*(-1)$
O^{MM}_{12}	$D(0)\bar{D}^*(0)$	$D(0)\bar{D}^*(0)$
O^{MM}_{13}	$J/\psi(0)\omega(0)$	$J/\psi(0)\rho(0)$
O^{MM}_{14}	$J/\psi(1)\omega(-1)$	$J/\psi(1)\rho(-1)$
O^{MM}_{15}	$\eta_c(1)\sigma(-1)$	$\eta_c(1)a_0(-1)$
O^{MM}_{16}	$\chi_{c1}(1)\eta(-1)$	$\chi_{c1}(1)\pi(-1)$
O^{MM}_{17}	$\chi_{c1}(0)\sigma(0)$	$\chi_{c1}(0)a_0(0)$
O^{MM}_{18}	$\chi_{c0}(1)\eta(-1)$	$\chi_{c0}(1)\pi(-1)$
O^{4q}_{19-20}	$[\bar{c}\bar{q}]_{3_c}[cq]_{\bar{3}_c}$	$[\bar{c}\bar{u}]_{3_c}[cd]_{\bar{3}_c}$
O^{4q}_{21-22}	$[\bar{c}\bar{q}]_{\bar{6}_c}[cq]_{6_c}$	$[\bar{c}\bar{u}]_{\bar{6}_c}[cd]_{6_c}$

Two meson scattering levels $\lesssim$ 4.2 GeV

- $I=0$;
  $D(0)\bar{D}^*(0)$, $J/\psi(0)\omega(0)$,
  $D(1)\bar{D}^*(-1)$, $J/\psi(1)\omega(-1)$,
  $\eta_c(1)\sigma(-1)$, $\chi_{c1}(0)\sigma(0)$.
- $I=1$;
  $D(0)\bar{D}^*(0)$, $J/\psi(0)\rho(0)$,
  $D(1)\bar{D}^*(-1)$, $J/\psi(1)\rho(-1)$,
  $\chi_{c1}(1)\pi(-1)$, $\chi_{c0}(1)\pi(-1)$.

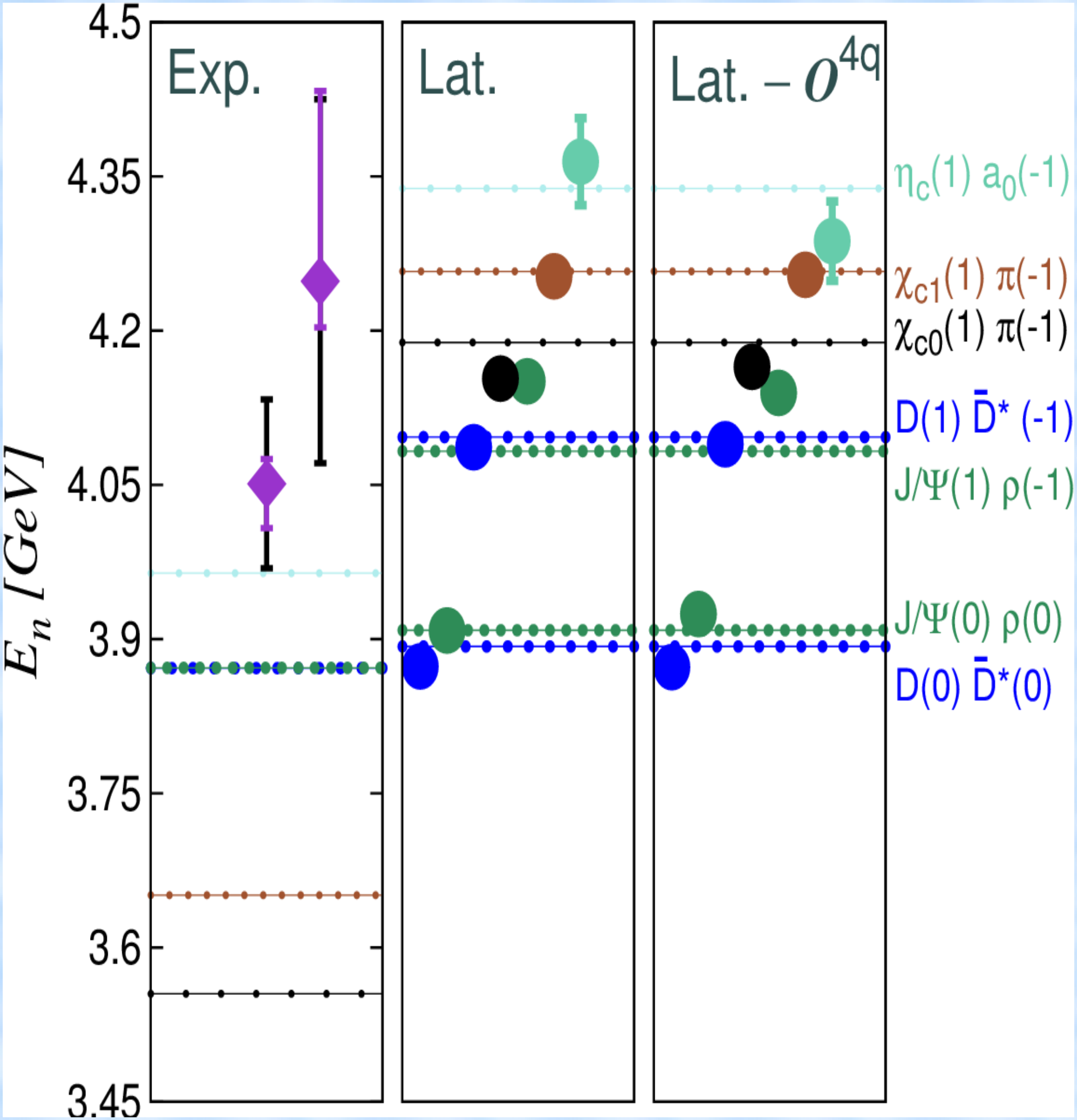
$J^{PC}=1^{++}$ $\bar{c}c$ *spectrum* (I=0)

b) ***Charmonium & X*(3872)**

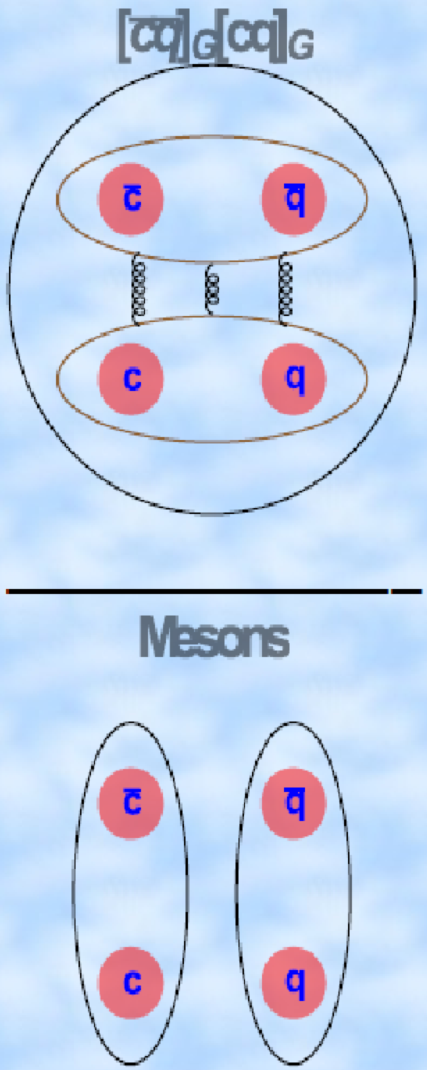


- No significant effects in the low lying spectrum by the inclusion of diquark-antidiquark operators.
- $[\bar{c}\bar{u}]_{\bar{\mathcal{G}}}[cu]_{\mathcal{G}}$ operators related to two-meson operators by Fierz relations.
- Makes the interpretation as a pure molecule or pure tetraquark unlikely.
- Simulation still unphysical in many ways.
- Sizable lattice artifacts.

$J^{PC}=1^{++}$ $\bar{c}c$ *spectrum* (I=1)



Fierz relations



- $[\bar{c}\bar{q}]_{\bar{\mathcal{G}}}[cq]_{\mathcal{G}}$ and two-meson operators are linearly related.

$$O^{4q}(x) = \sum F_i \; M_1^i(x) \; M_2^i(x)$$

- By Fierz rearrangement

$$[\bar{c}\, P\, \bar{q}]_{\mathcal{G}}[c\, N\, q]_{\mathcal{G}}|_{\binom{3_c}{\bar{6}_c}} = -(\bar{c}\, \Gamma_I\, c)_{1_c}(\bar{q}\, G_I\, q)_{1_c} \mp (\bar{c}\, \Gamma_I\, q)_{1_c}(\bar{q}\, H_I\, c)_{1_c}$$

$$\text{where} \quad G_I = \frac{1}{4}(N^T \Gamma_I P)^T \quad \text{and} \quad H_I = \frac{1}{4}(N \Gamma_I P)^T$$

- Any gauge-covariant quark smearing preserves this relation.

Bottom hadrons

> Equally interesting like charm hadrons.
Only very few states experimentally confirmed.
Experimental prospects : LHCb, Belle II.

> On lattice : Discretization errors out of control (ma >1)

> We follow NRQCD formulation for tackling this.
Already in. Cheaper and faster!

> Excited states : Distillation*

> Challenges !
1) Computation time
2) Continuum limit

Baryon resonance spectroscopy

> Even if there are only strong interactions,
almost all hadrons unstable

> Many interesting low lying resonances in light baryons :
N(1440), N(1535), N(1650), Λ(1405), etc.

> Most lattice calculations within single-hadron approx.

> Interesting observations from lattice study involving
baryon-meson operators.
C. B. Lang and V. Verduci, Phys. Rev. D **87**, no. 5, 054502 (2013)
V. Verduci and C. B. Lang, [arXiv:1412.0701 [hep-lat]].

> Plans to study with better control on systematics.

Summary

a) *Excited charm baryon spectroscopy*

Triply, doubly and singly charm baryons.

b) *Charmonium spectroscopy*

$J^{PC}=1^{++}$ *using meson, meson-meson and tetra-quark interpolators.*

c) *Major ongoing projects*

Excited bottom hadrons

Baryon resonance spectroscopy

Thank you!