Hadron Spectroscopy and Resonances : Review

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Lattice 2018

Outline

1. Introduction
2. Ground state hadron spectroscopy
3. Excited hadron spectroscopy
4. Resonances on the lattice
5. Meson resonances on the lattice
6. Light baryon resonances
7. Beyond baryons and mesons

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Hadron spectroscopy on the lattice

- Euclidean two point current-current correlation functions

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

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

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

- Quark smearing to improve the overlap with ground states!

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

- Variational study (GEVP) to extract physical information

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

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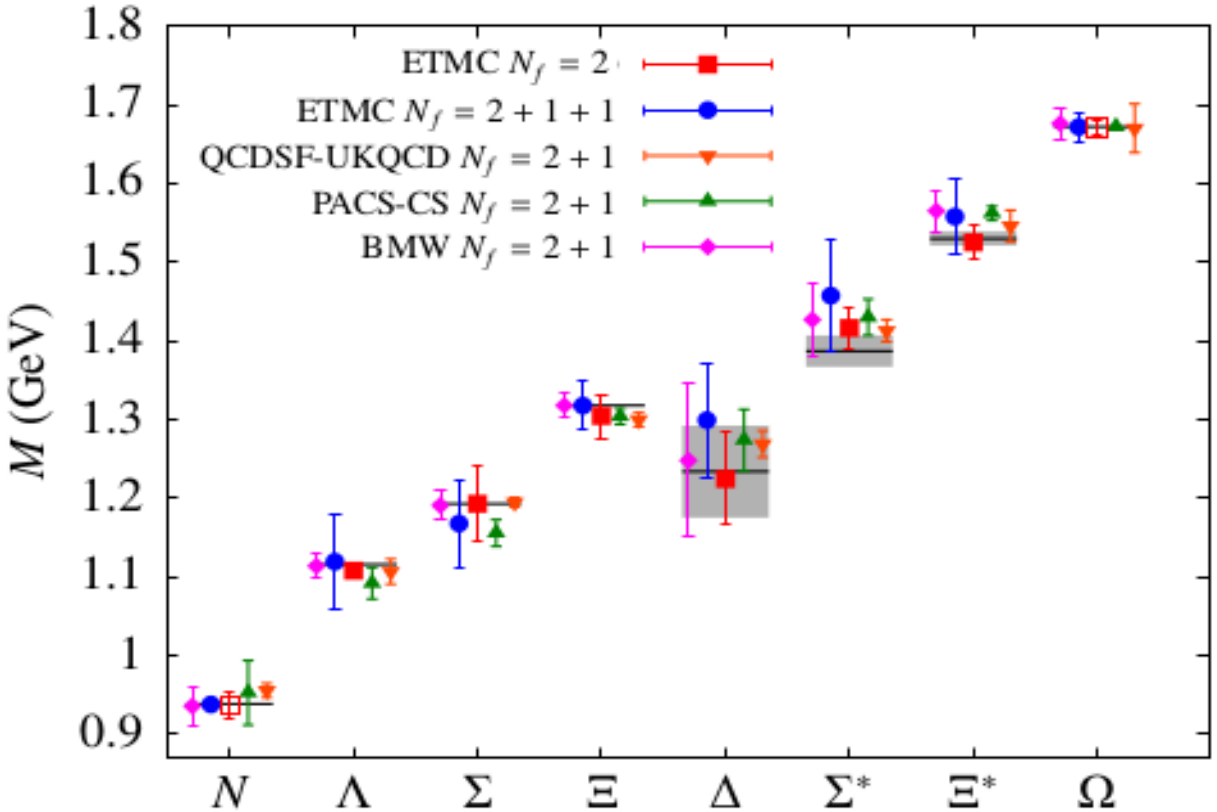
Light baryons



ETMC PRD**90** 074501 '14

PACS-CS PRD**87** 094512 '13

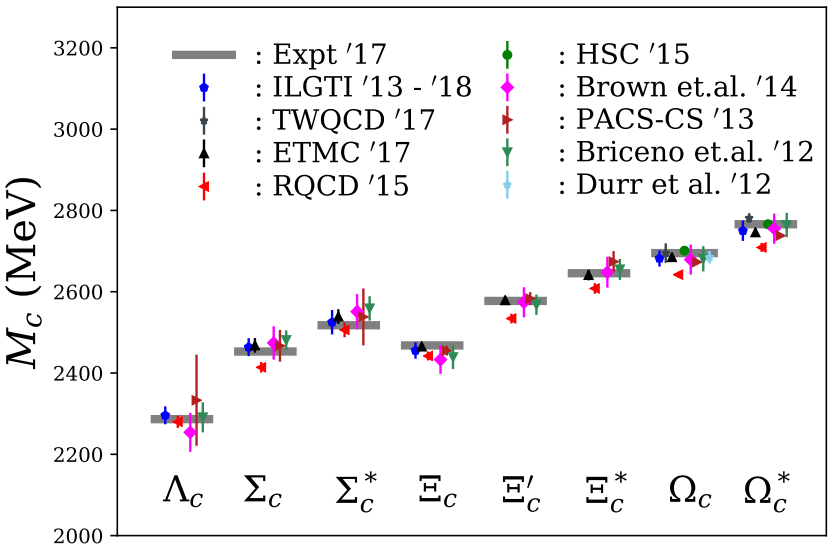
QCDSF-UKQCD PRD**84** 054509 '11

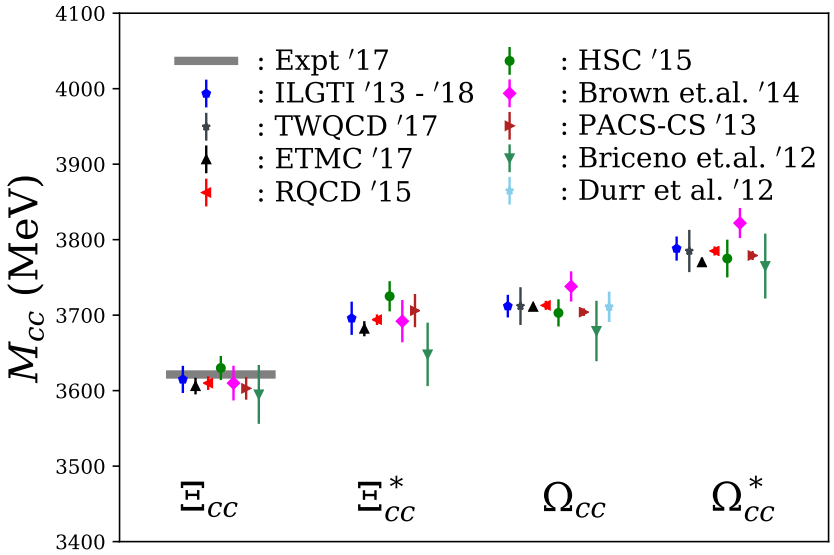
BMW Science**322** 1224 '08

ETMC, $N_f = 2$: Alexandrou and Kallidonis, PRD**96** 034511 '17

- Calculations at physical pion mass (ETMC, $N_f = 2$)
- Other measurements with chiral extrapolation to physical pion mass.
- ETMC, $N_f = 2+1+1$ and BMW results with continuum extrapolation.
- Recently baryon masses and mass splittings : BMW Science**347** 1452 '15; QCDSF-UKQCD 1711.02485; Liu 1612.00103.

Heavy baryons





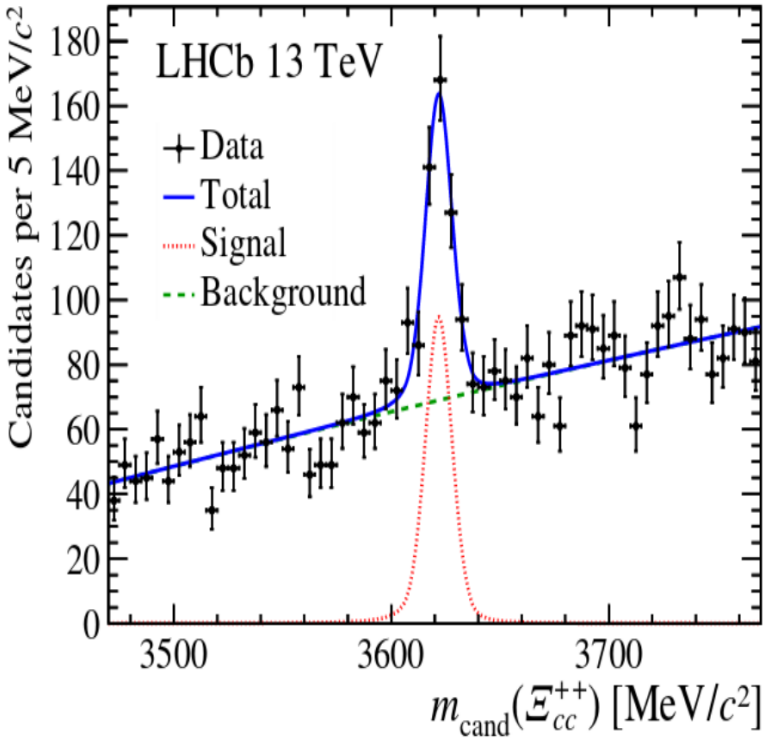
PDG — MP *et al.* (HSC) PRL**119** 042001 '17; PRD**91** 094502 '15
Alexandrou *et al.* (ETMC) PRD**96** 034511 '17 — Brown *et al.* PRD**90** 094507 '14
Briceño *et al.* PRD**86** 094504 '12 — Pérez-Rubio *et al.* (RQCD) PRD**92** 034504 '15
Namekawa *et al.* (PACS) PRD**87** 094512 '13 — ILGTI 1807.00174, 1312.3050
Durr *et al.* PRD**86** 114514 '12 — Chen & Chiu (TWQCD) PLB**767** 193 '17

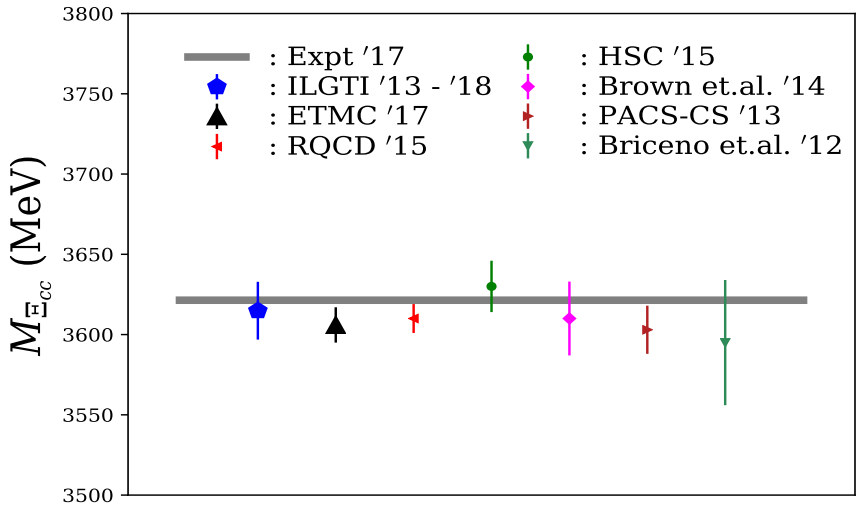
Recently baryon masses and mass splittings : BMW Science**347** 1452 '15; QCDSF-UKQCD 1711.02485.

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

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

Recent highlight : Ξ_{cc}





Aaij *et al.* (LHCb) PRL**119** 112001 '17
Alexandrou *et al.* (ETMC) PRD**96** 034511 '17
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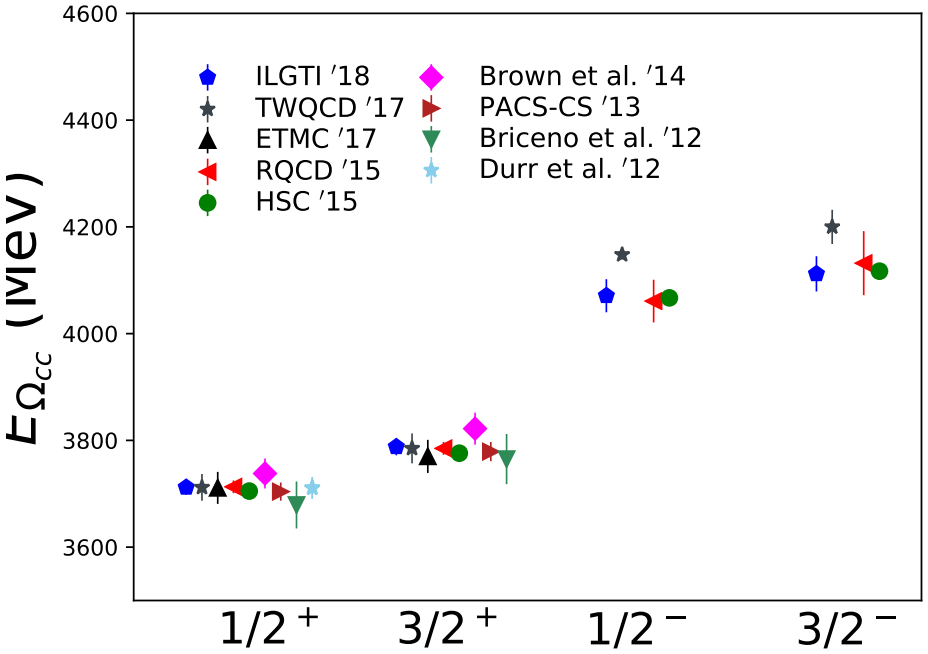
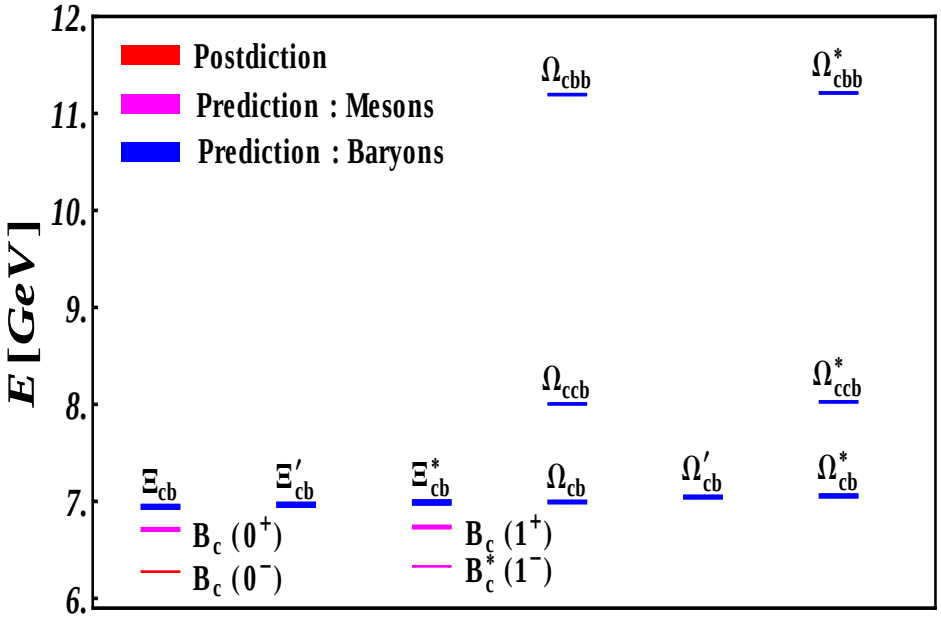
ILGTI 1807.00174, 1312.3050

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
New papers from LHCb on properties of Ξ_{cc} : 1807.01919; 1806.02744

More predictions for heavy hadrons from lattice





Mathur & MP (ILGTI) 1807.00174, 1312.3050 Mathur, MP *et al.* (ILGTI) 1806.04151

Ω_{cc} : probably the next doubly charm baryon to be observed in LHCb.

Precise predictions for charmed-bottom hadrons.
Consistent results with other calculations Brown *et al.* PRD**90** 094507 '14
Both calculations treat bottom quarks with NRQCD.

In this conference, bottom quarks with relativistic action :
Salerno Thu. 09.50 [WDME]; Lytle Fri. 14.20 [HSI]

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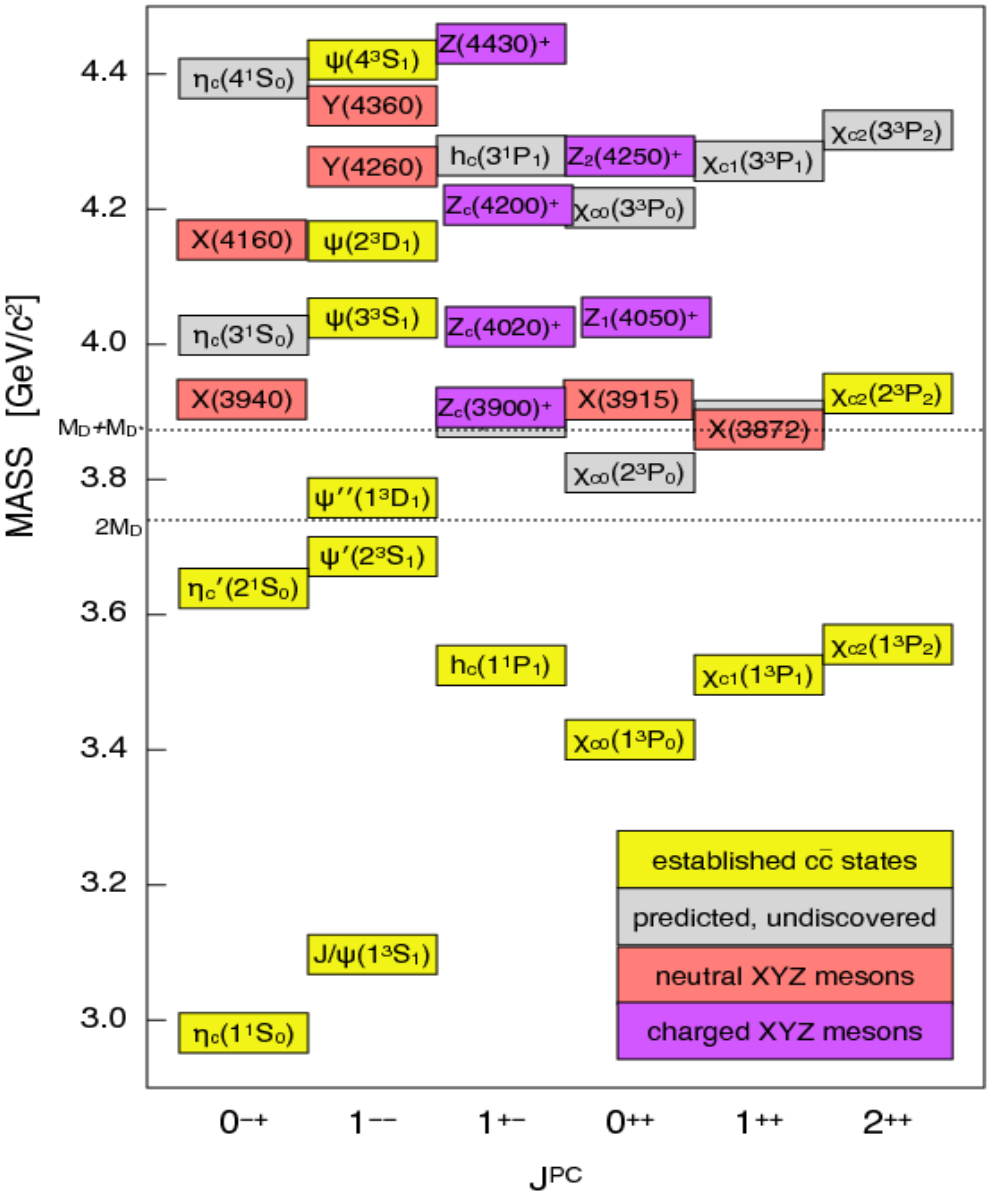
Excited charmonium spectrum : An example



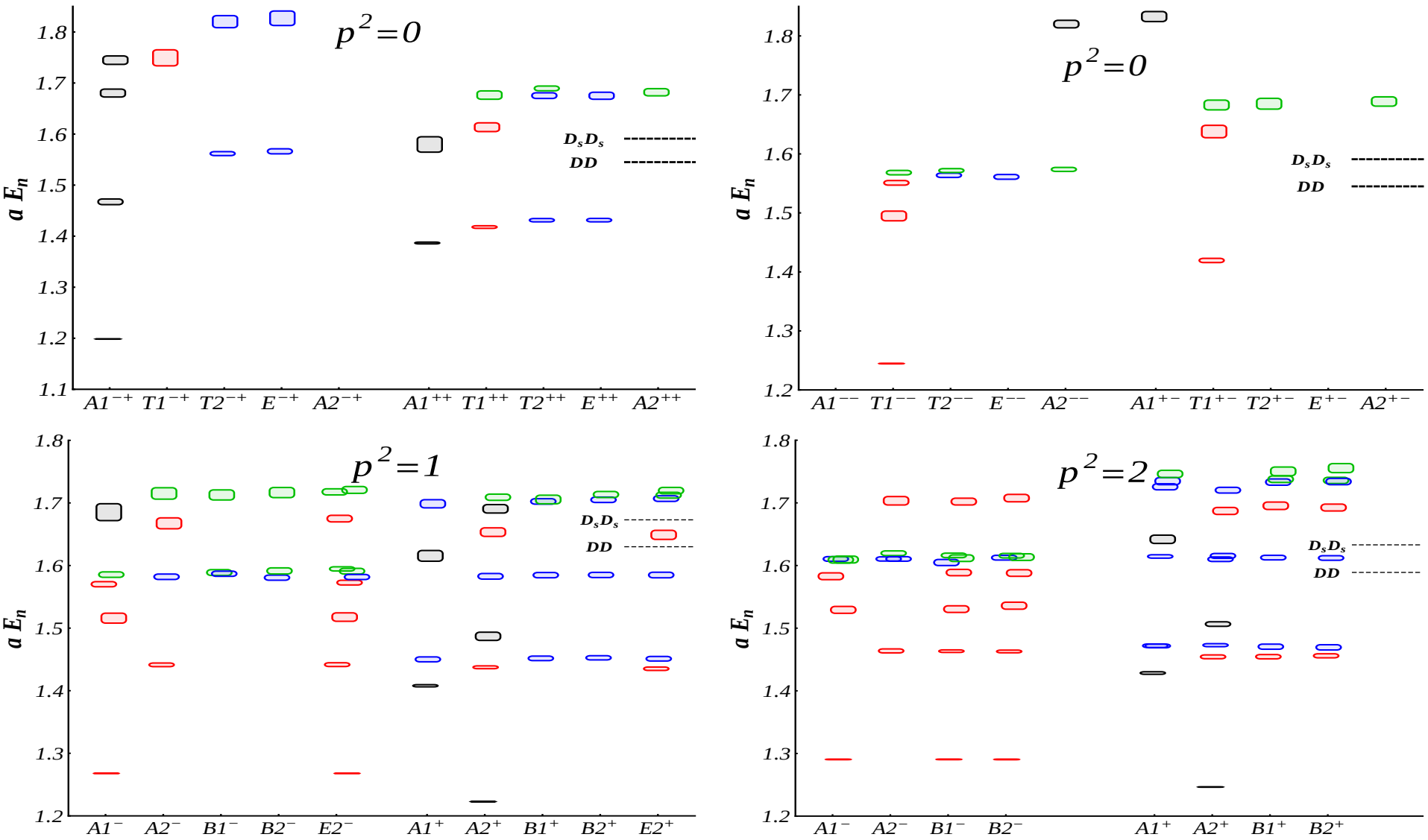
- Established states in yellow
  Predicted, undiscovered
  Neutral XYZ mesons
  Charged XYZ mesons
- Need for a rigorous excited state determination
- Open scattering channels?

Olsen, 1511.01589

Methodology and literature

- Large basis of carefully constructed hadron interpolators
  Mesons : Liao & Manke hep-lat/0210030 '02; Thomas (HSC) PRD**85** 014507 '12
  Baryons : Basak *et al.* (LHPC) PRD**72** 074501, PRD**72** 094506 '05
  Morningstar *et al.* PRD**88** 014511 '13.
- Matrix of correlation functions & Variational study
  Dudek *et al.* PRD**77** 034501 '08, Michael NPB**259** 58 (1985)
- Established and practised by many groups
  1. Light mesons : Dudek *et al.* (HSC) PRL**103** 262001 '09, PRD**82** 034508 '10
     Dudek *et al.* (HSC) PRD**85** 014507 '12
  2. Light baryons : Bulava *et al.* (HSC) PRD**82** 014507, '10
     Edwards *et al.* (HSC) PRD**84** 074508 '11, PRD**87** 054506 '13
  3. Heavy mesons : Liu *et al.* (HSC) JHEP**1207** 126; Moir *et al.* JHEP**1305** 021
     Cheung *et al.* JHEP**1612** 089; Mohler *et al.* PRD**87** 034501 '13
     Bali *et al.* PRD**84** 094506 '11; Wurtz *et al.* PRD**92** 054504 '15
  4. Heavy baryons : Meinel, PRD**85** 114510 '12
     MP *et al.* (HSC) PRD**90** 074504 '14, PRD**91** 094502 '15
     MP & Mathur (HSC) PRL**119** 042001 '17, 1508.07168.
- Single hadron approximation.
  Naive expectation : correct up to $\mathcal{O}(\Gamma)$

Excited hadron spectroscopy on lattice : An example

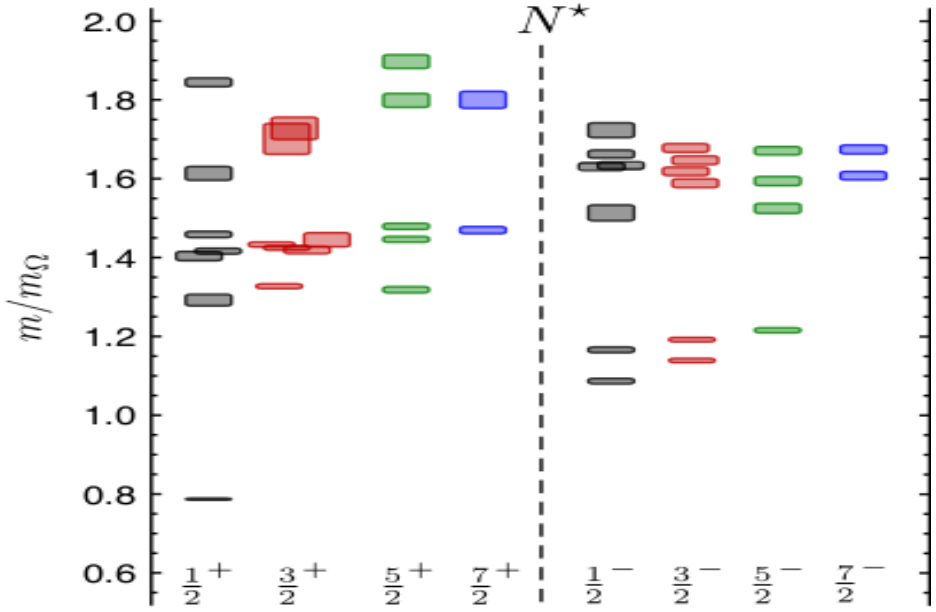


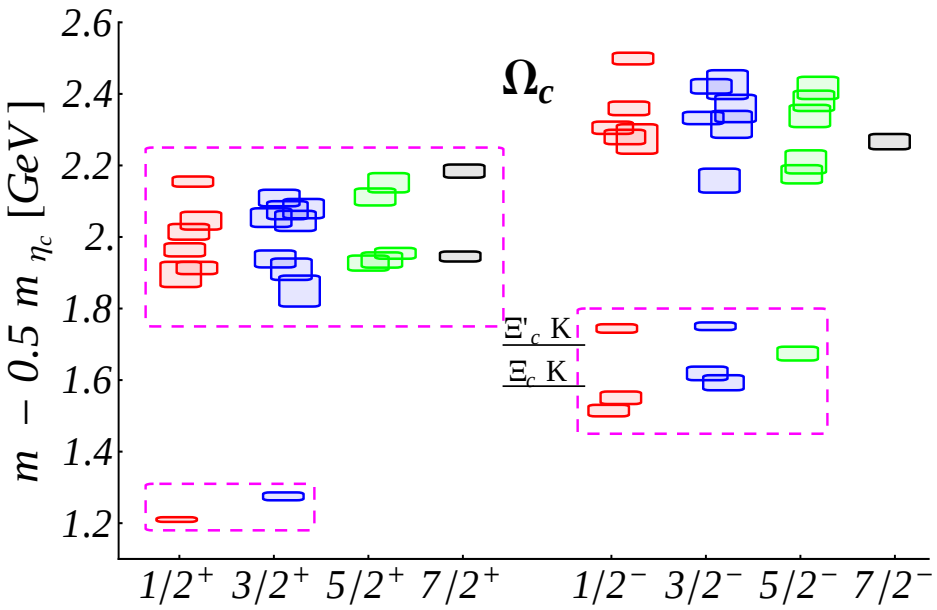
Charmonium spectrum in different inertial frames ($L \sim 2$ *fm*)

Piemonte Fri. 15.20 [HSI]; Collins, MP, *et al.* (RQCD)

Spin 0, 1, 2, 3

Excited baryon spectroscopy : Example



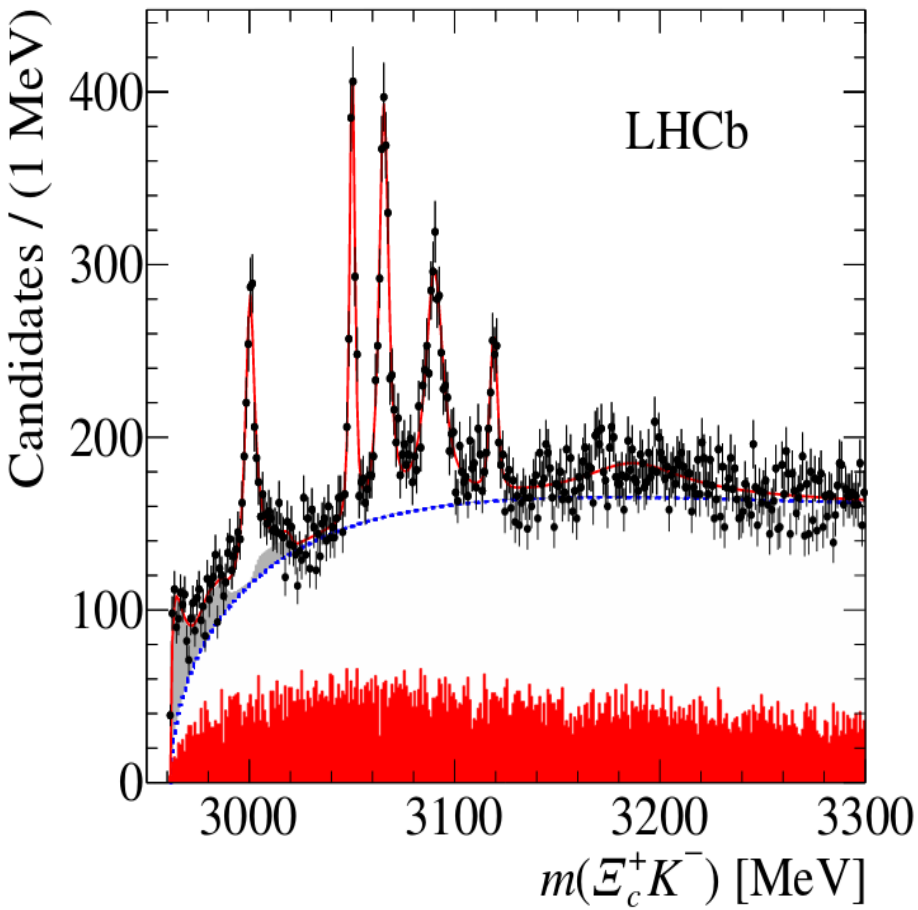


Edwards, *et al.* (HSC) PRD**84** 074508 '11; PRD**87** 054506 '13

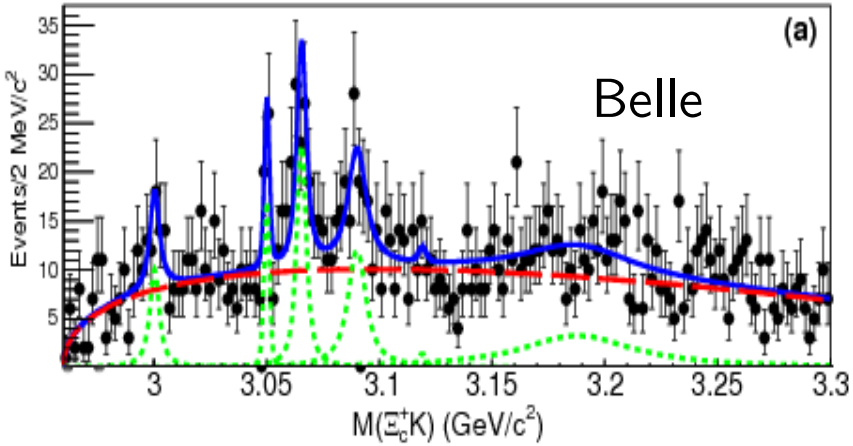
MP & Mathur (HSC) PRL**119** 042001 '17

- Baryon interpolators : Basak *et al.* (LHPC) PRD**72** 074501, PRD**72** 094506 '05
  Morningstar *et al.* PRD**88** 014511 '13.
- Light baryons : Bulava *et al.* PRD**82** 014507, '10
  Edwards *et al.* (HSC) PRD**84** 074508 '11, PRD**87** 054506 '13
- Heavy baryons : Meinel, PRD**85** 114510 '12
  MP *et al.* (HSC) PRD**90** 074504 '14, PRD**91** 094502 '15
  MP & Mathur (HSC) PRL**119** 042001 '17, 1508.07168.

LHCb discovery of excited Ω_c^0 baryons



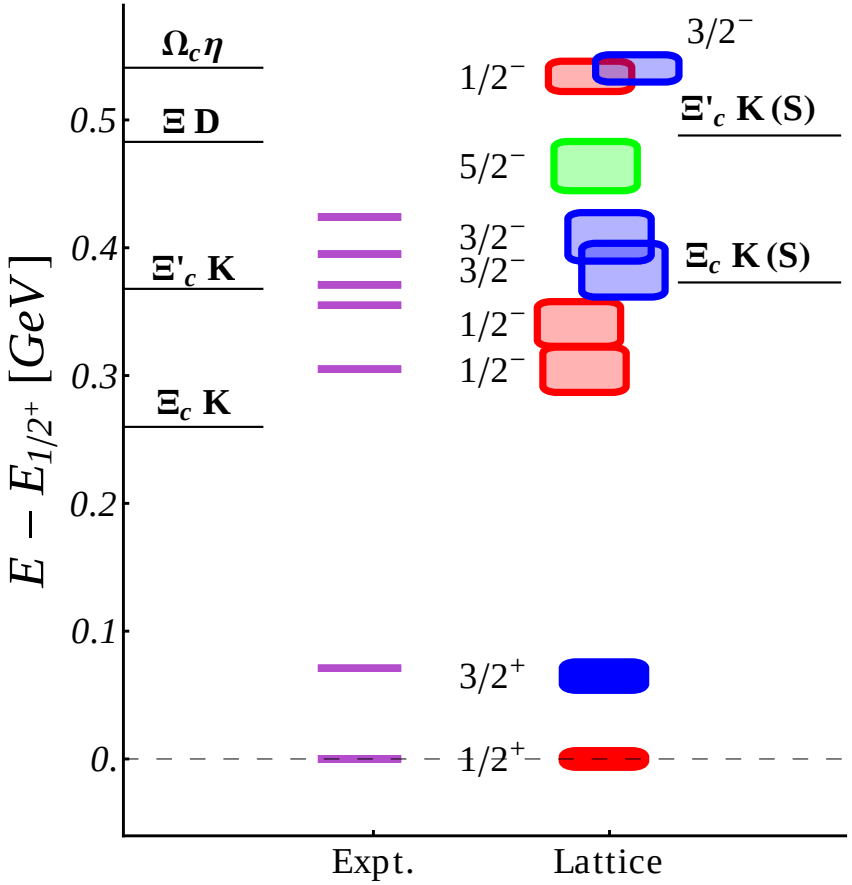
Resonance	Energy	Width	Q.no.
Ω_c^0	2695(2)	-	$1/2^+$
$\Omega_c^0(2770)$	2766(2)	-	$3/2^+$
$\Omega_c^0(3000)$	3000(1)	4.5(1)	?
$\Omega_c^0(3050)$	3050(1)	1(-)	?
$\Omega_c^0(3066)$	3066(1)	3.5(-)	?
$\Omega_c^0(3090)$	3090(1)	8.7(1)	?
$\Omega_c^0(3119)$	3119(1)	1(1)	?



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

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

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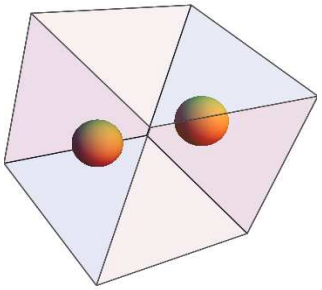
Resonances on the lattice & Lüscher's prescription

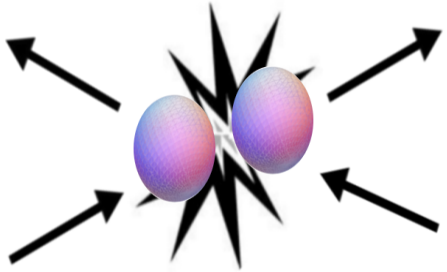
- On a finite volume Euclidean lattice : Discrete energy spectrum
  Maiani-Testa no-go theorem PLB**245** 585 (1990)
  No continuum of states $\Rightarrow$ No resonances, No scattering
- Non-interacting two-meson levels are given by

$$E(L) = \sqrt{m_1^2 + \vec{p}_1^2} + \sqrt{m_2^2 + \vec{p}_2^2}$$

  where $\vec{p}_{1,2} = \frac{2\pi}{L}(n_x, n_y, n_z)$.
- Switching on the interaction makes $\vec{p}_{1,2} \neq \frac{2\pi}{L}(n_x, n_y, n_z)$.
  The interactions induce a shift in the momentum,
  e.g. in 1D $\quad \vec{p}_{1,2} = \frac{2\pi}{L} n + \frac{2}{L}\delta(k)$.
- Lüscher's formula relates Lüscher, NPB**354** 531 (1991)

finite volume level shifts $\Leftrightarrow$ infinite volume phase shifts.





Extensions and other methods

- Extensions within and beyond elastic scattering :
  - different inertial frames, boundary conditions
  - multiple scattering channels
  - particles with different identities
  - Briceño 1411.6944; Hansen 1511.04737
  - Morningstar *et al.* https://github.com/cjmorningstar10/TwoHadronsInBox
  - 3-particle scattering : Sharpe Thu. 11.00; Mai Mon. 16.30 [HSI]
    - Briceño, Hansen, Sharpe PRD**95** 074510, ...
    - Polejaeva and Rusetsky EPJA**48** 67 '12
- HALQCD method : Iritani Fri. 17.10 [HSI]
  - Determine the potential between scattering particles
  - Extract resonance information solving Schrödinger equation.
  - Ishii *et al.* PRL**99** 022001 '07; PLB**712** 437 '12
- finite volume Hamiltonian EFT :
  - Constrain free parameters of the Hamiltonian based on lattice spectrum
  - Solve for EVP to extract resonance information.
  - Hall *et al.* PRD**87** 094510 '12
- Optical potential :
  - Agadjanov *et al.* JHEP**06** 043 '16 [HSI]
  - Hammer, Pang, Rusetsky, JHEP**1709** 109

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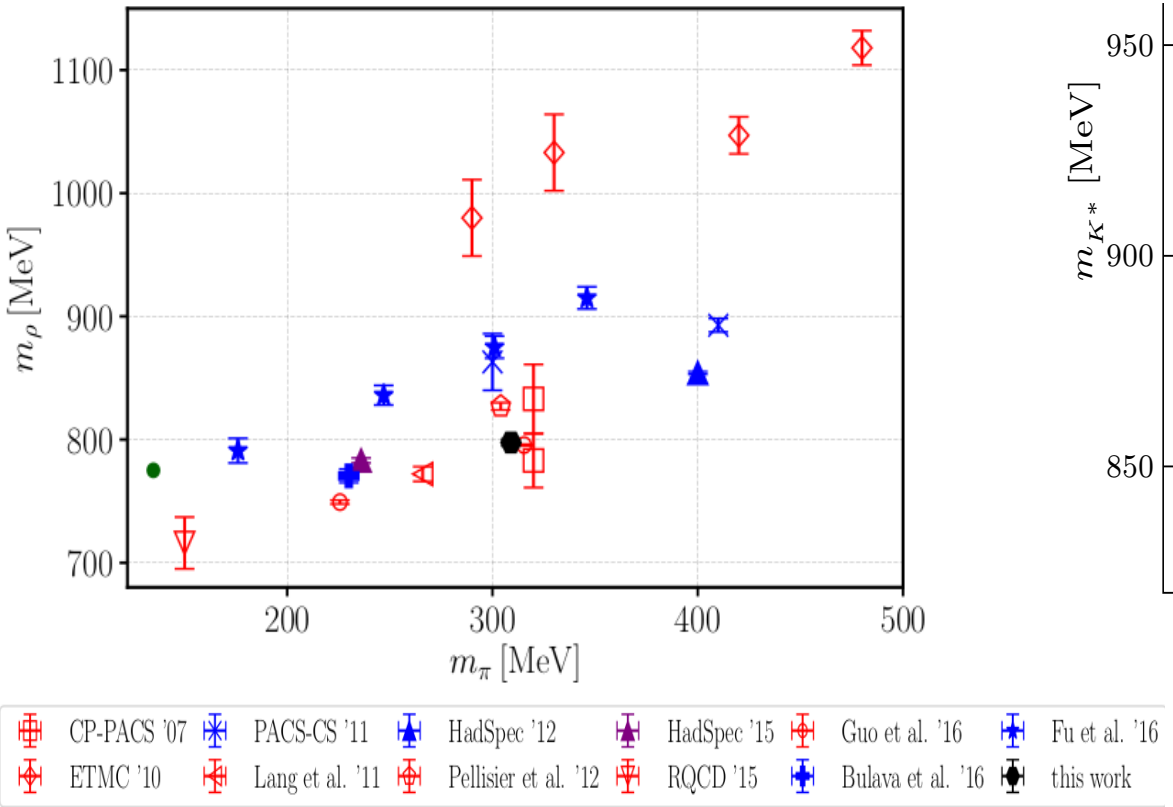
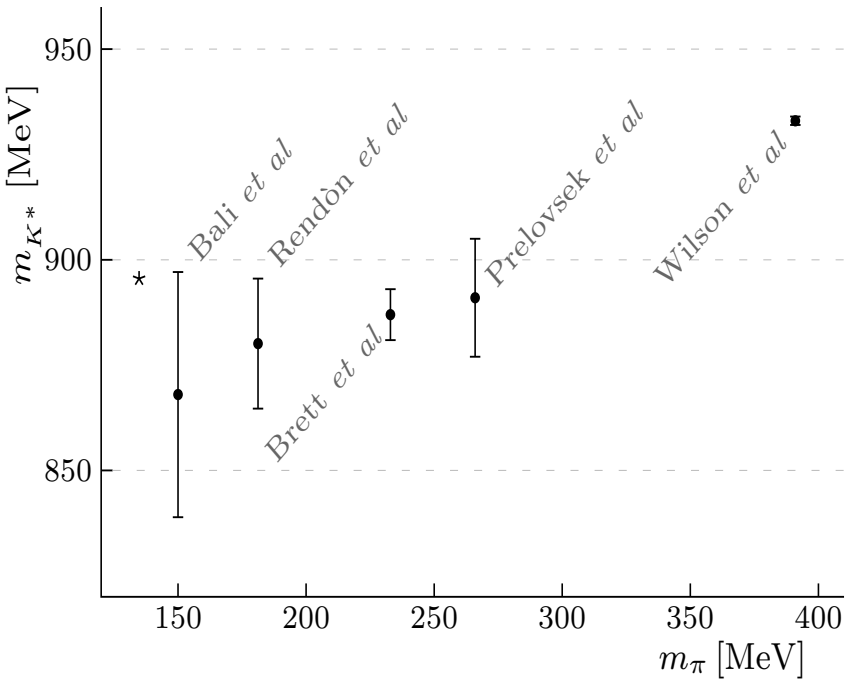
Light mesons : Benchmark investigations





Brett Thu. 08.50 [HSI]
Rendòn Thu. 09.30 [HSI]

Alexandrou *et al.* PRD**96** 034525 '17

Expt : $\Gamma(\rho(770) \to \pi\pi) \sim 100\%$; $\Gamma(K^*(892) \to K\pi) \sim 100\%$

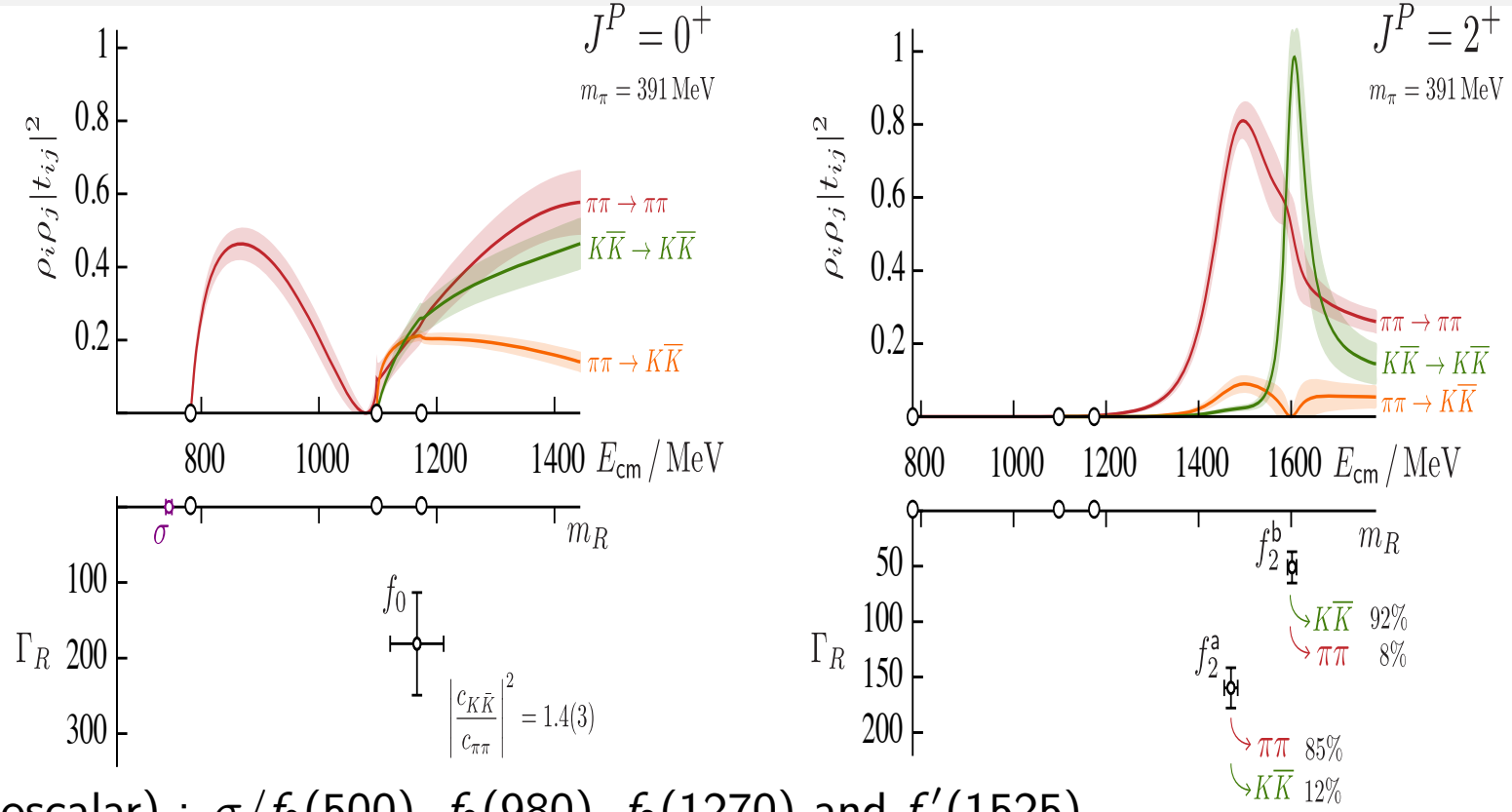
Multiple lattice investigations (mostly using elastic approximation)

Coupled channel study of $\pi\pi, K\bar{K}$ and πK, ηK systems :

Dudek *et al.* PRL**113** 182001 '14; Wilson *et al.* PRD**92** 094502 '15; PRD**91** 054008 '15

More results : Hoying, Wed. 15.00; Pittler Thu. 09.10 [HSI]

Light mesons : σ, f_0 and f_2 resonances

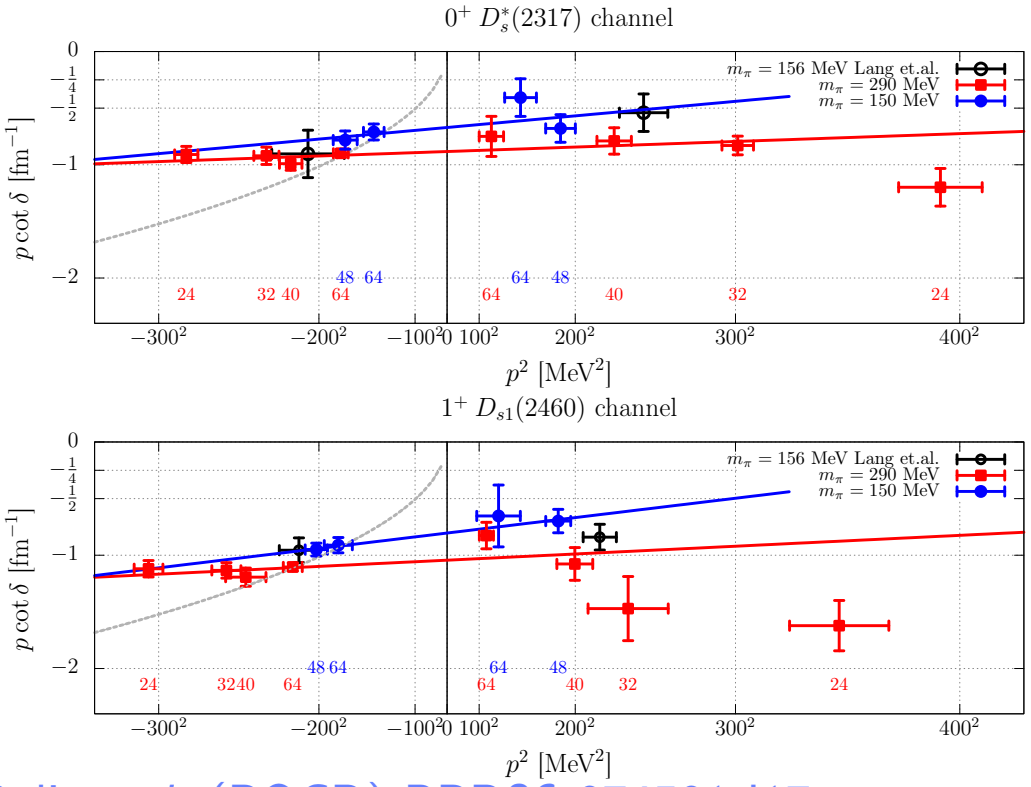


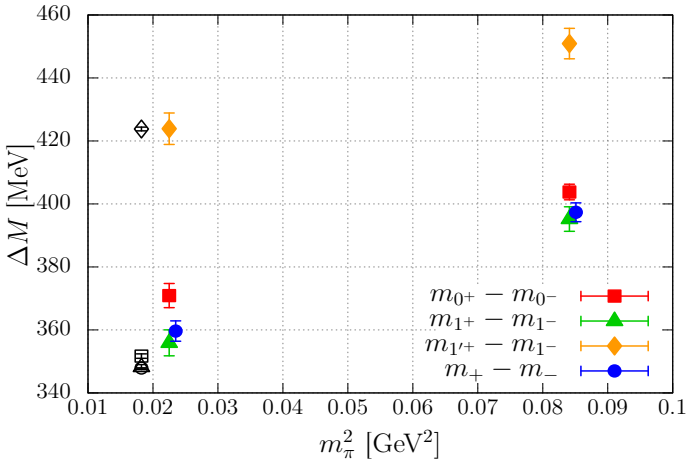
Expt.(Isoscalar) : $\sigma/f_0(500)$, $f_0(980)$, $f_2(1270)$ and $f_2'(1525)$
Coupled channel study in $\pi\pi$, $K\bar{K}$, $\eta\eta$, $I = 0$. σ appears as a stable bound state, whereas $f_0(980)$ manifests as a dip in $\pi\pi$ cross section.
$\Uparrow$ Briceño *et al.* (HSC) PRD**97** 054513 '18, PRL**118** 022002 '17, PRD**88** 094505 '13

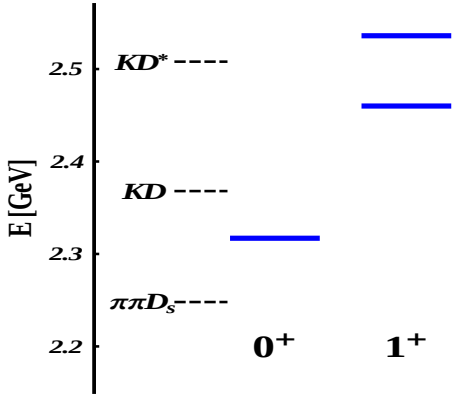
Elastic study of σ meson in $\pi\pi$ scattering : Guo *et al.* PRD**98** 014507 '18

Dynamically coupled partial waves in $\rho\pi$, $I = 2$: Woss *et al.* (HSC) JHEP07 (2018) 043
Include scattering particle with non-zero spin and higher partial wave effects.

Heavy mesons : $D^*_{s0}(2317)$ and $D^*_{s1}(2460)$







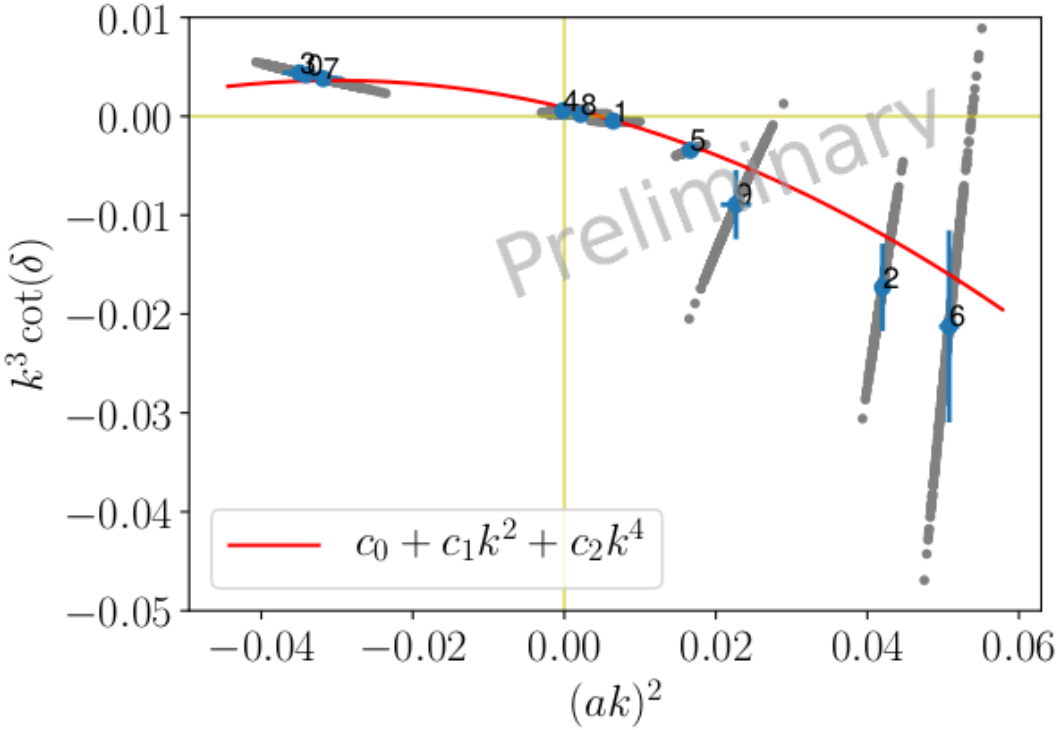
Bali *et al.* (RQCD) PRD**96** 074501 '17

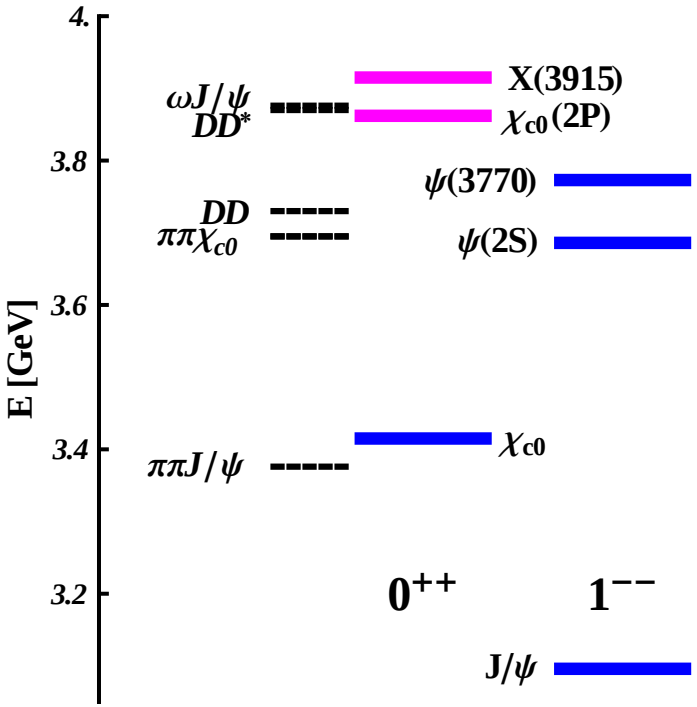
- KD and KD^* elastic scattering on $N_f = 2$ lattices.
- Comparison with previous results Lang *et al.* PRD**90** 034510 '14
- Masses sensitive to pion mass dependence.
- Decay constants : $f_V^{0^+} = 114(11)$ MeV, $f_A^{1^+} = 194(12)$ MeV.

Coupled channel $D\pi, D\eta, D_s\bar{K}$ scattering : Moir *et al.* (HSC) JHEP**1610** 011

KD scattering and $D^*_{s0}(2317)$: Cheung Thu. 09.50 [HSI]

Heavy mesons : 0^+ and 1^- charmonia





Piemonte Fri. 15.20 [HSI]; Bali, MP, *et al.* (RQCD)

- Resonance treatment of charmonium excitations : Lang *et al.* JHEP**1509** 089
- Attempt to investigate 0^+ and 1^- excitations in moving frames.
- On CLS ensembles U101 and H105; $m_\pi \sim 280$ MeV and $m_K \sim 467$ MeV.
  L(U101) ~ 2.05 fm and L(H105) ~ 2.73 fm.
- Recent discovery by Belle : $E = 3860$ MeV compatible with $\chi_{c0}(2P)$.
  Chilikin *et al.* (Belle) PRD**95** 112003 '17

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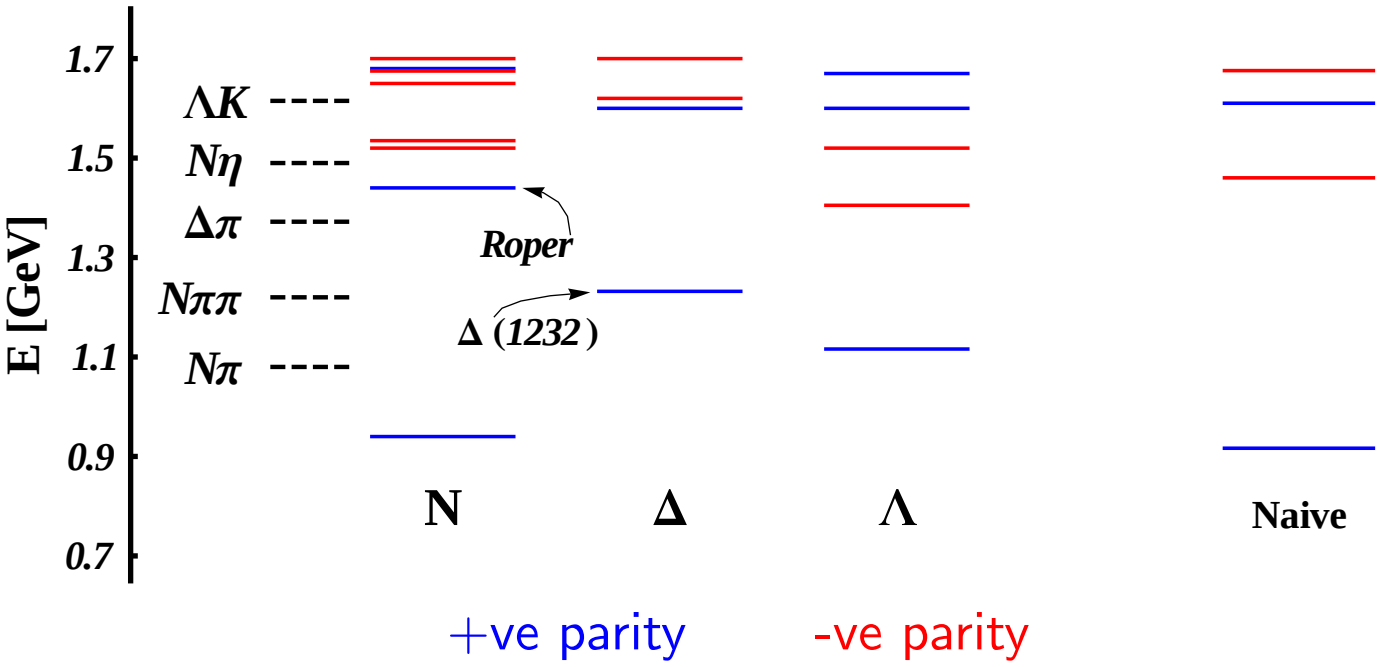
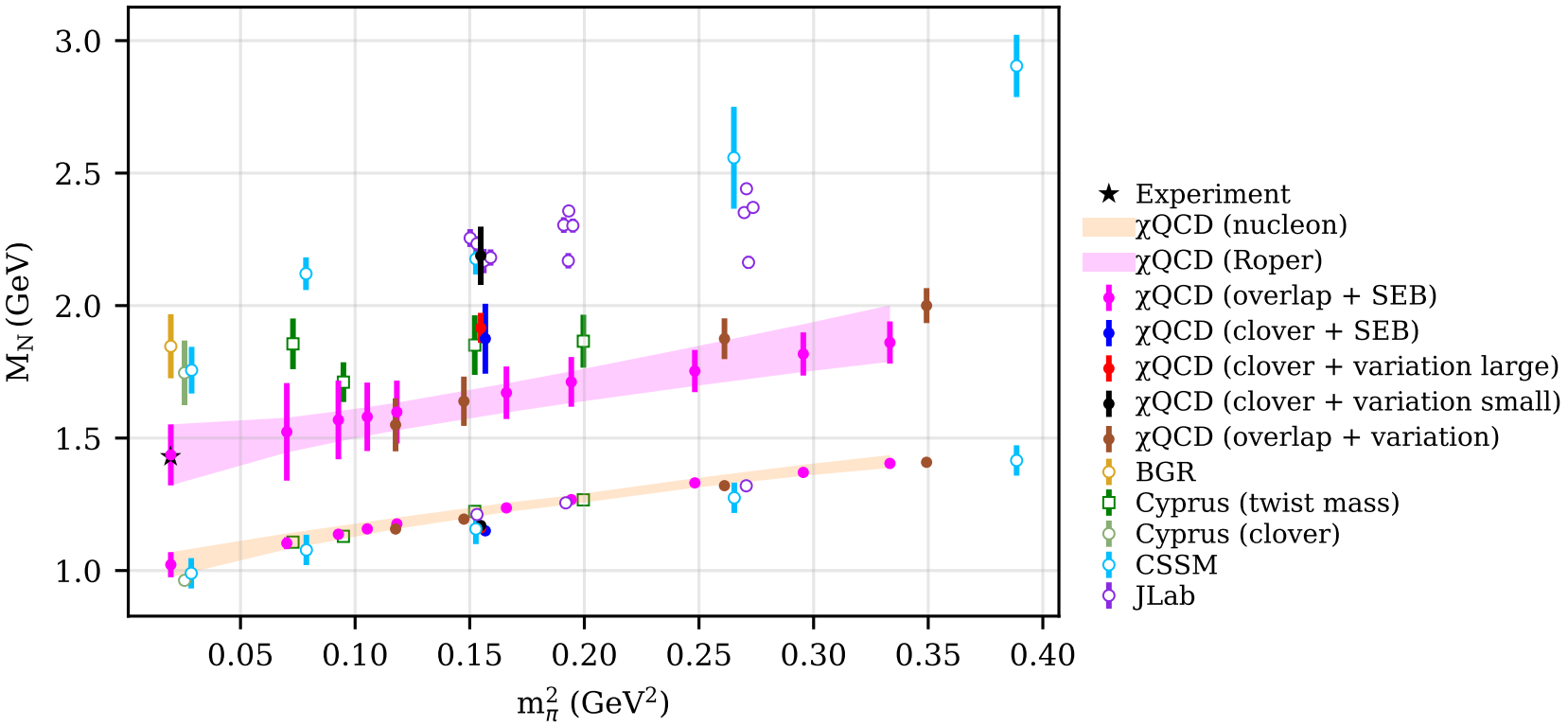
Light baryon spectrum



- Hierarchy contradicting expectations from simple potentials
- Question : Why such a low lying positive parity nucleon excitation (Roper)!
- Models motivated by spontaneously broken chiral symmetry
- Goldstone Boson Exchange models
  Glozman and Riska, hep-ph/9505422 (1996)
- Effective field theories. Suzuki *et al.*, PRL**104** 042302 '10

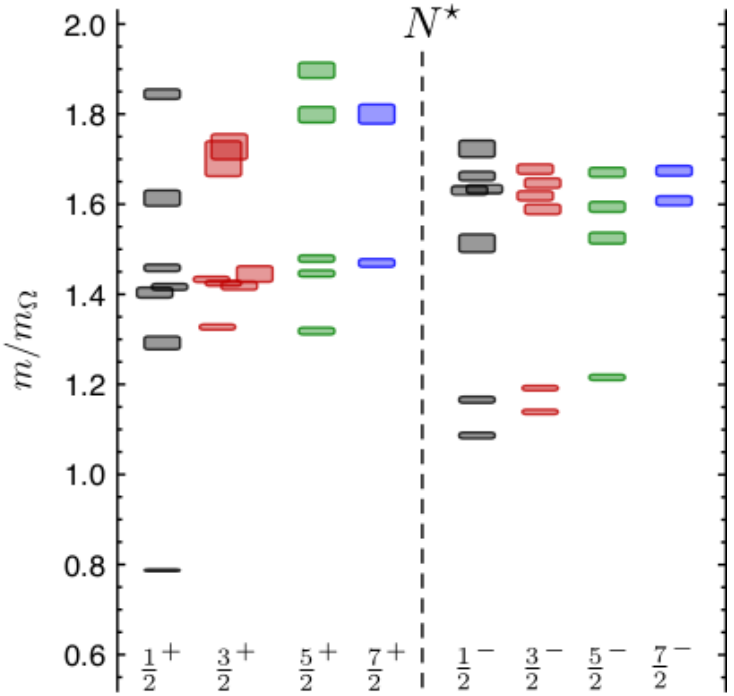
Nucleon spectrum on the lattice

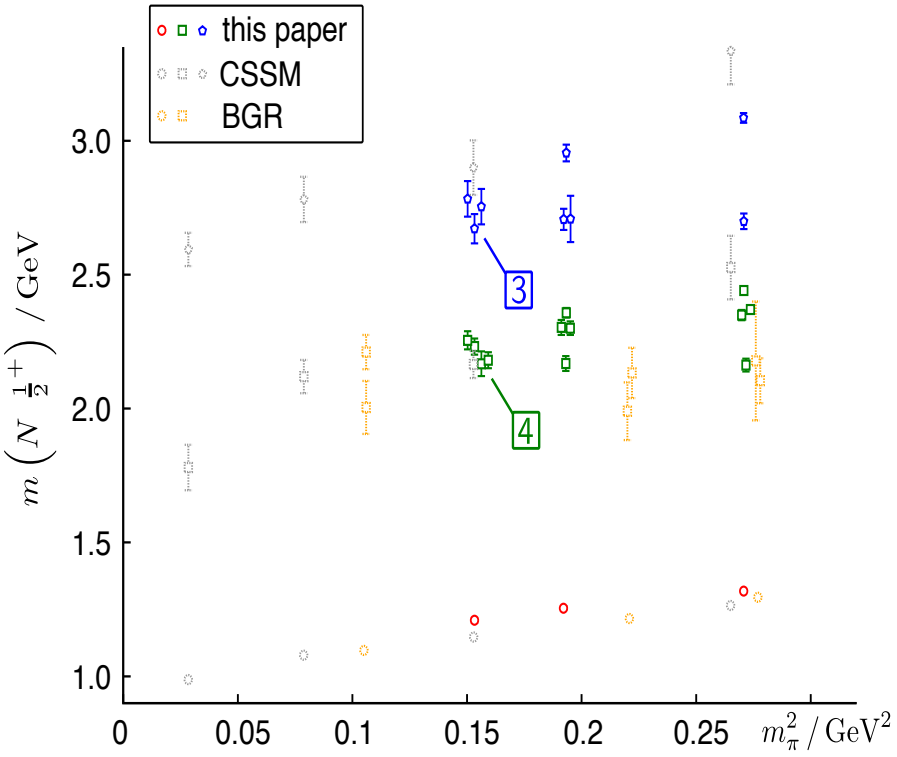


Liu Thu. 12.00 [HSI]

- $\Gamma(N(1440) \to N\pi) \sim 65\%$, with a width of $\sim$350 MeV.
- All lattice calculations using purely *qqq* structures.
- First excited lattice level consistently $\gtrsim$1700 MeV (Roper), except χQCD.
- χQCD uses a chiral overlap action, unlike other calculations.
- A different analysis procedure : Sequential Empirical Bayesian (SEB)!

Nucleon spectrum on the lattice

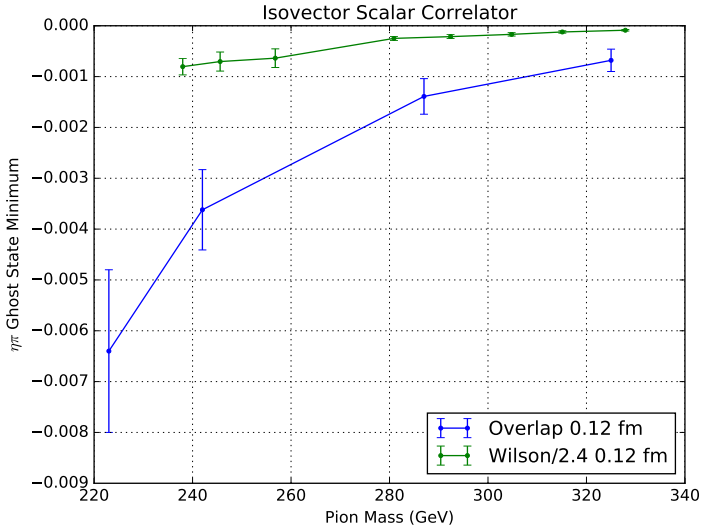


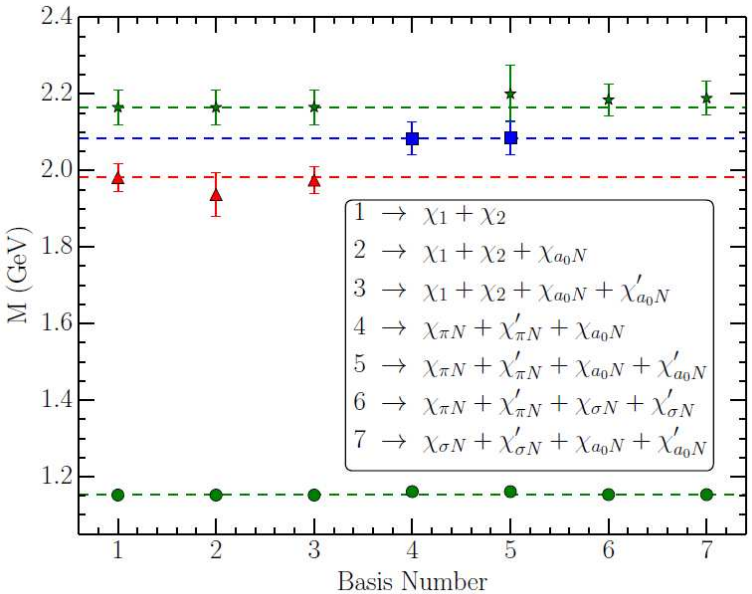


Edwards, *et al.* (HSC) PRD**84** 074508 '11; PRD**87** 054506 '13

- Extensive variational study of light baryon excited states by HSC.
- Using carefully constructed large basis of interpolators.
  Basak *et al.* (LHPC) PRD**72** 074501, PRD**72** 094506 '05
- First excitation of nucleon on lattice found $\gtrsim$ 1700 MeV.

Nucleon spectrum on the lattice





- Need of chiral fermion action like in χQCD studies! Use of Sequential Empirical Bayesian (SEB)! ⇐ Liu Thu. 12.00; Fallica Thu. 12.20 [HSI]
- The efficiency of operators to scan nodal structures! Roberts *et al.* PLB**06** 056 '13; PRD**89** 074501 '14 Liu *et al.* 1403.6847
- Form factors of the nucleon excitations Kamleh *et al.* 1711.05413 Form factors of hadron resonances ⇓ Leskovec Wed. 15.20; Baroni Thu. 10.10 [HSI]
- Old calculations with local $qqqq\bar{q}$ structures. Spectrum lacking any levels untill $\sim$ 1.9 GeV. ⇐ Leinweber 1511.09146, 1608.03051
- All this said, a simple concern remains! No resonance treatment yet!

Looking for Roper resonance on the lattice

- Aim to determine the excited lattice spectrum of nucleon (P=+) and perform a phase shift analysis.

- Challenges : exponential degradation of SNR,
  large no. of Wick contractions, annihilation diagrams,
  huge computational and storage costs,
  non-zero spin and complicated phase shift analysis.
  Silvi Fri. 16.30; Paul Fri. 16.50 [HSI];
  Lang & Verduci PRD**87** 054502 '13

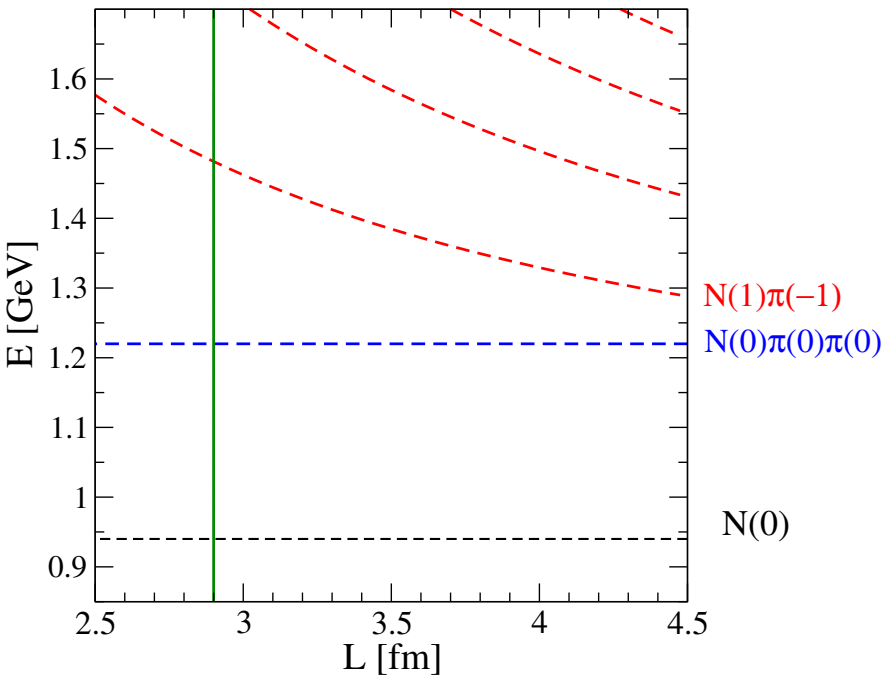
- First attempt, we limit ourselves to zero momentum frame.

- Include interpolators with qqq as well as all baryon-meson scattering channels relevant up to ∼1.65 GeV on the lattice [PACS-CS, $m_\pi \sim 156$MeV, $m_\pi L \sim 2$]

- qqq-type interpolators, $N\pi$ in p-wave and $N\sigma$ in s-wave. e.g.
  $$O^{N\pi} = \sum_{I_z^\pi, I_z^N, m_s, m_l} CG(\tfrac{1}{2},\tfrac{1}{2}|1 m_l, \tfrac{1}{2} m_s) CG(\tfrac{1}{2},\tfrac{1}{2}|1 I_z^\pi, \tfrac{1}{2} I_z^N) \sum_{R \in O_h} Y_{l m_l}(R\mathbf{k}) \pi(R\mathbf{k}) N_{m_s}(-R\mathbf{k})$$
- Work with an assumption : N(1440) from elastic $N\pi$ scattering!

Pion-Nucleon (p-wave, $I = 1/2$) elastic scattering

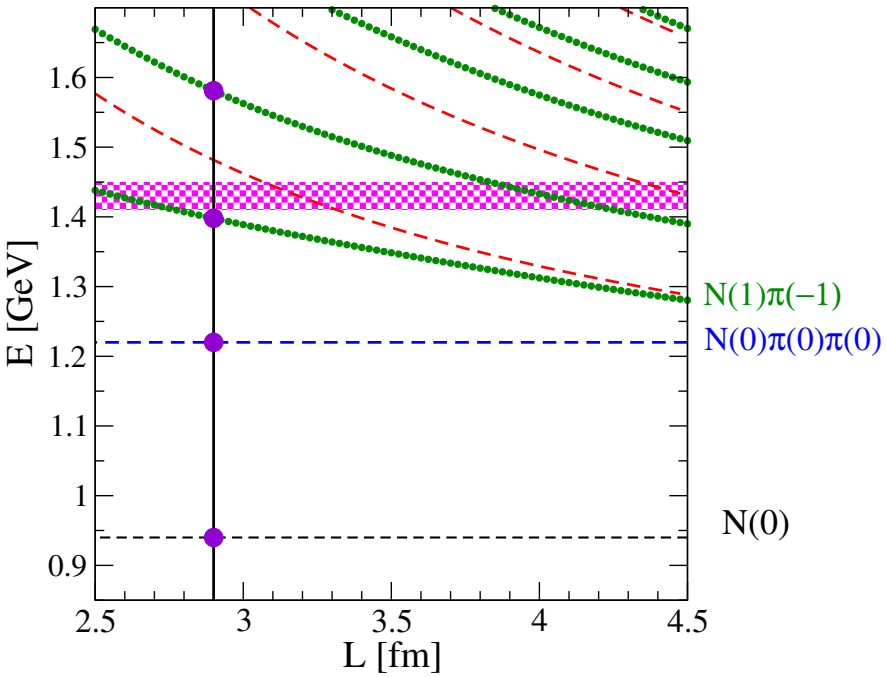
Non-interacting system of $N\pi$ and $N\pi\pi$ scattering channels.

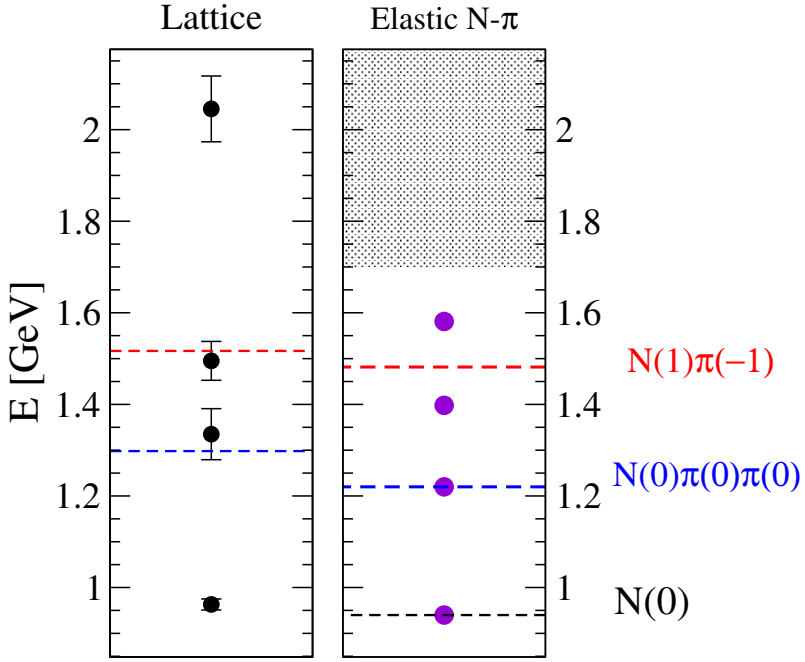


Pion-Nucleon (p-wave, $I = 1/2$) elastic scattering

$N\pi$ coupled with a Roper like resonance.

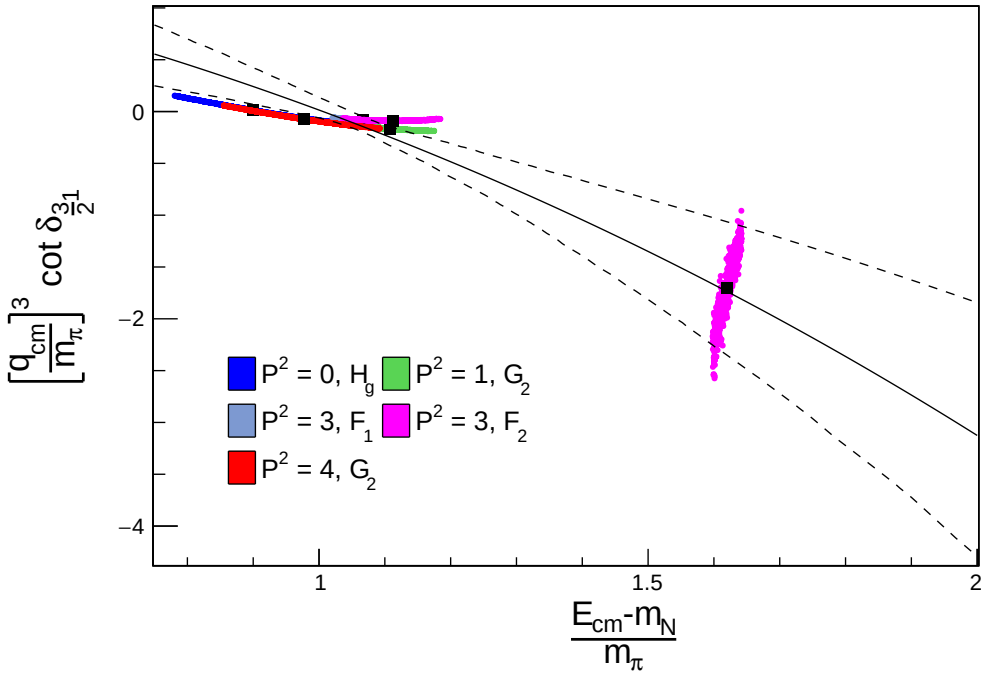
Lang, MP *et al.* PRD**95** 014510, '17





- Low lying Roper resonance does not arise on the lattice within elastic $N\pi$ scattering.
- Coupling between scattering channels? $[N\pi, N\pi\pi(\Delta\pi, N\sigma)]$
  Study of spectral overlaps! $|\langle\Omega|O^{N\sigma}|n = 2(N\pi\pi)\rangle| \lesssim |\langle\Omega|O^{N\sigma}|n = 3(N\pi)\rangle|$
  Comparisons with HEFT predictions!
- Other possible reasons for the absence of resonance related level
  a) Fermions with chiral symmetry! Liu Thu. 12.00; Fallica Thu. 12.20 [HSI]
  b) 3-particle scattering study! Mai Mon. 16.30; Sharpe Thu. 11.00 [HSI]
  c) ... ?

Pion-Nucleon (p-wave, $I = 3/2$) elastic scattering



$\Gamma(\Delta(1232) \to N\pi) \sim 100\%$

$\Gamma^{BW} \sim 117$ MeV

$g^{BW,exp}_{\Delta N\pi} \sim 16.9$

Andersen *et al.* PRD**97** 014506 '17
Darvish Thu. 08.30 [HSI]

- $\Delta(1232)$ as a resonance using lattice QCD.
- $N\pi$ elastic scattering in p-wave and isospin $3/2$.
- $N_f = 2 + 1$ dynamical gauge ensembles [CLS]; $m_\pi \sim 280$ MeV, $m_K \sim 460$ MeV, $L \sim 3.7$ *fm*.
- $m_\Delta = 1344$ MeV and $g^{BW}_{\Delta N\pi} = 19.0(4.7)$

More results in this conference : Silvi Fri. 16.30; Paul Fri. 16.50 [HSI]

Outline

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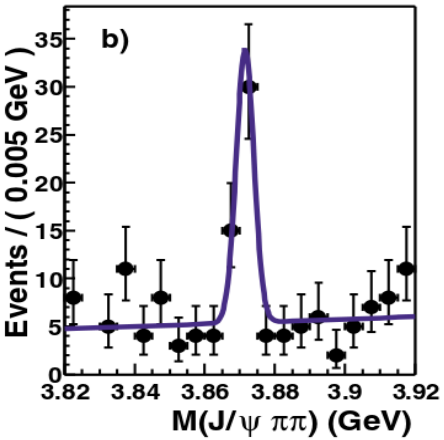
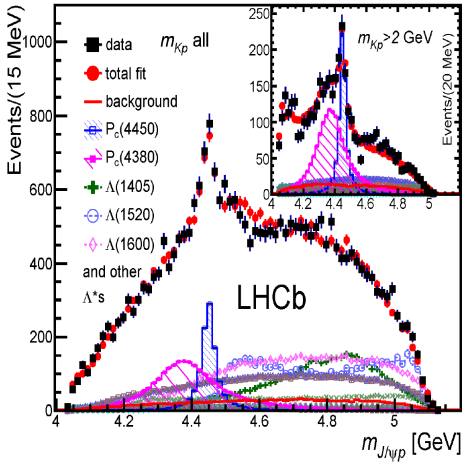
2. Ground state hadron spectroscopy
3. Excited hadron spectroscopy
4. Resonances on the lattice
5. Meson resonances on the lattice
6. Light baryon resonances
7. Beyond baryons and mesons

Beyond baryons and mesons in experiments



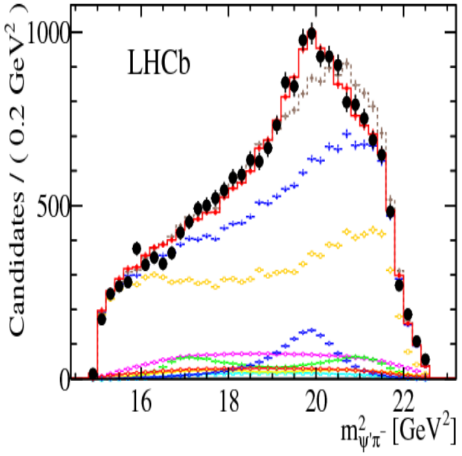
X(3872)

Belle PRL**91** 262001,



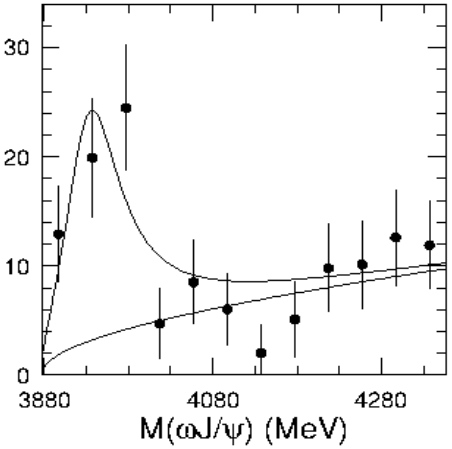
$P_c(4450)$ & $P_c(4380)$

LHCb PRL**115** 072001



$Z(4430)^+$

LHCb PRL**112** 222002,

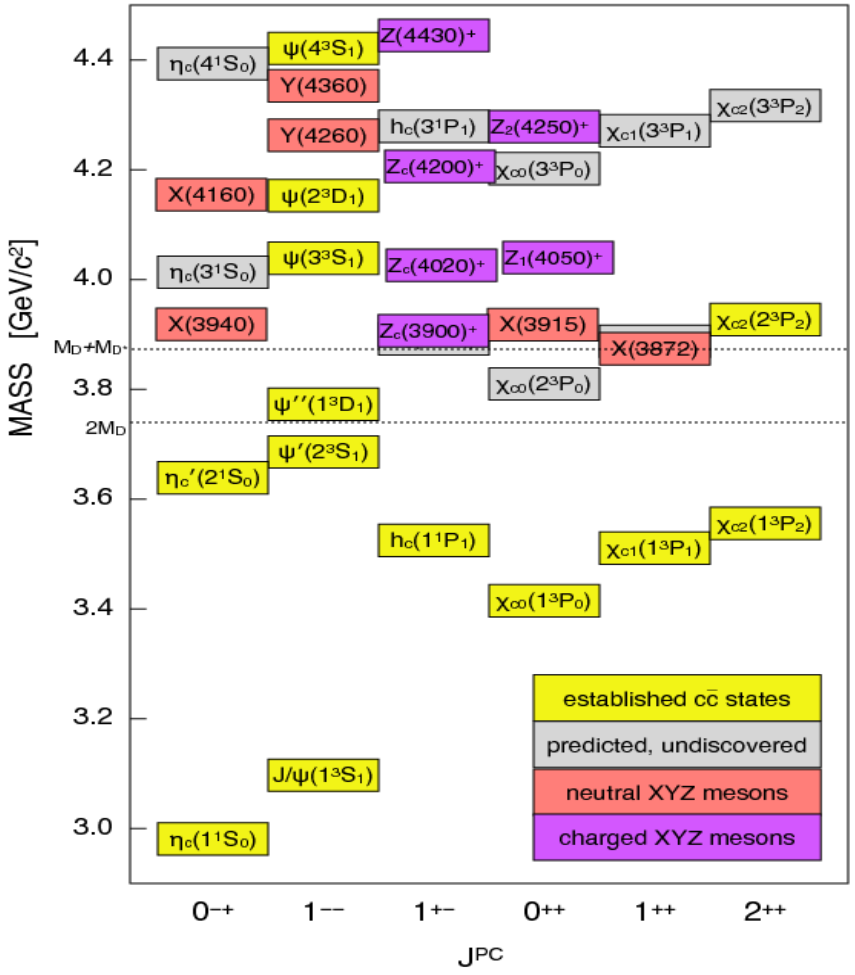


$X(3915)$

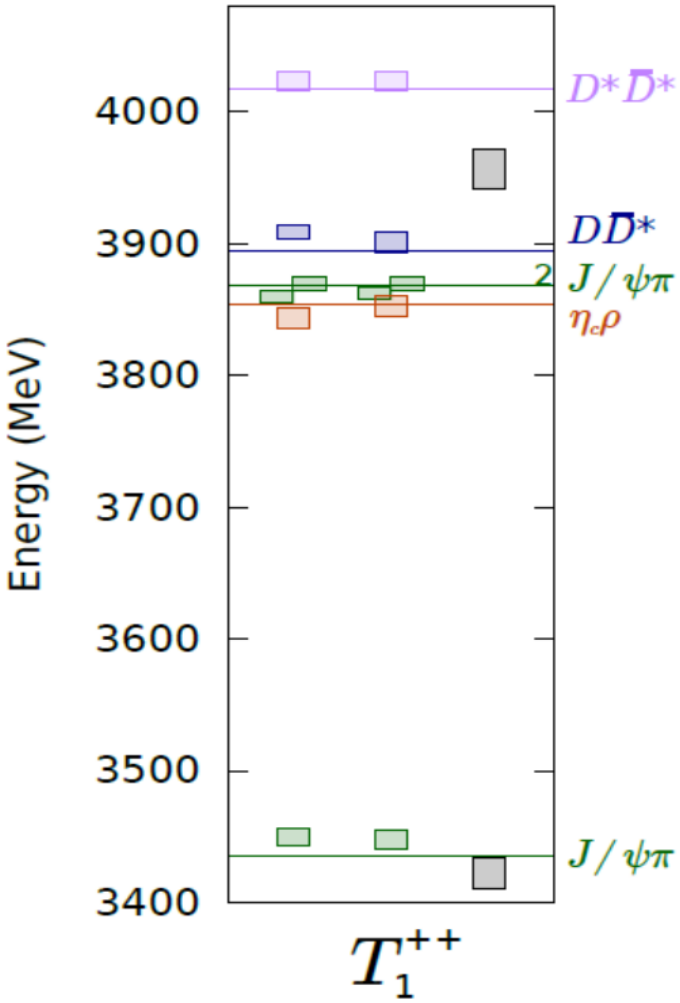
Belle PRL**94** 182002

(was Y(3940))

Olsen, 1511.01589



XYZ studies on the lattice



Cheung *et al.* JHEP**1711** 033

- Lattice studies in search of X(3872) candidate assume $D\bar{D}^*$ elastic scattering.
  Prelovsek and Leskovec PRL**111** 192001 '13
  Lee *et al.* 1411.1389
- Admixture of $\bar{c}c$ and $D\bar{D}^*$. Pure molecule unlikely.
  No significant tetraquark Fock component!
  MP *et al.* PRD**92** 034501 '15
- No explanation for $Z_c(3900)^+$ as well.
  Prelovsek *et al.* PRD**91** 014504 '15
- Many systematics unaddressed.
  All are exploratory studies.
- Extensive and systematic investigation by HSC.
  Looking for candidates with tetraquark signatures.
  In isospin 0 and isospin 1 channel of charmonium-like spectrum.
  No conclusive evidence.
  $\Leftarrow$ Cheung *et al.* JHEP**1711** 033

Doubly heavy tetraquarks : possibly stable system

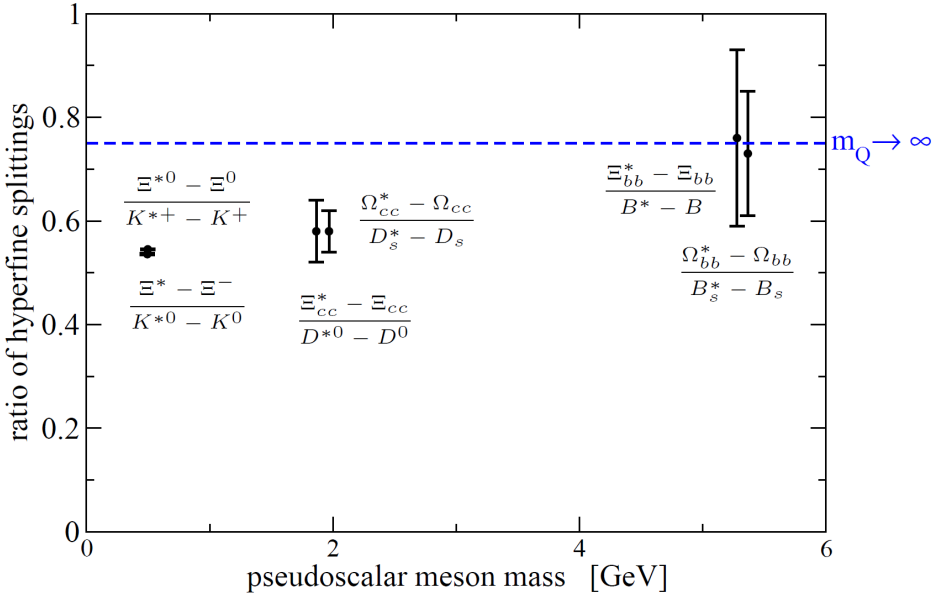
PRL **119**, 202001 (2017) PHYSICAL REVIEW LETTERS week ending 17 NOVEMBER 2017

Discovery of the Doubly Charmed Ξ_{cc} Baryon Implies a Stable $bb\bar{u}\bar{d}$ Tetraquark

Marek Karliner[1,*] and Jonathan L. Rosner[2,†]
[1]*School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel*
[2]*Enrico Fermi Institute and Department of Physics, University of Chicago, 5620 South Ellis Avenue, Chicago, Illinois 60637, USA*
(Received 28 July 2017; published 15 November 2017)

Heavy Quark Symmetry implies for a sufficiently heavy "heavy" quark, the doubly heavy tetraquarks should be stable to strong decays.

Carlson *et al.* PRD**37** 744 (1988); Eichten and Quigg PRL**119** 202002 '17



For a heavy-light meson-like system of doubly charm baryons

$$\frac{M(\Xi^*_{QQ}) - M(\Xi_{QQ})}{M(V_Q) - M(PS_Q)} \to \frac{3}{4}$$

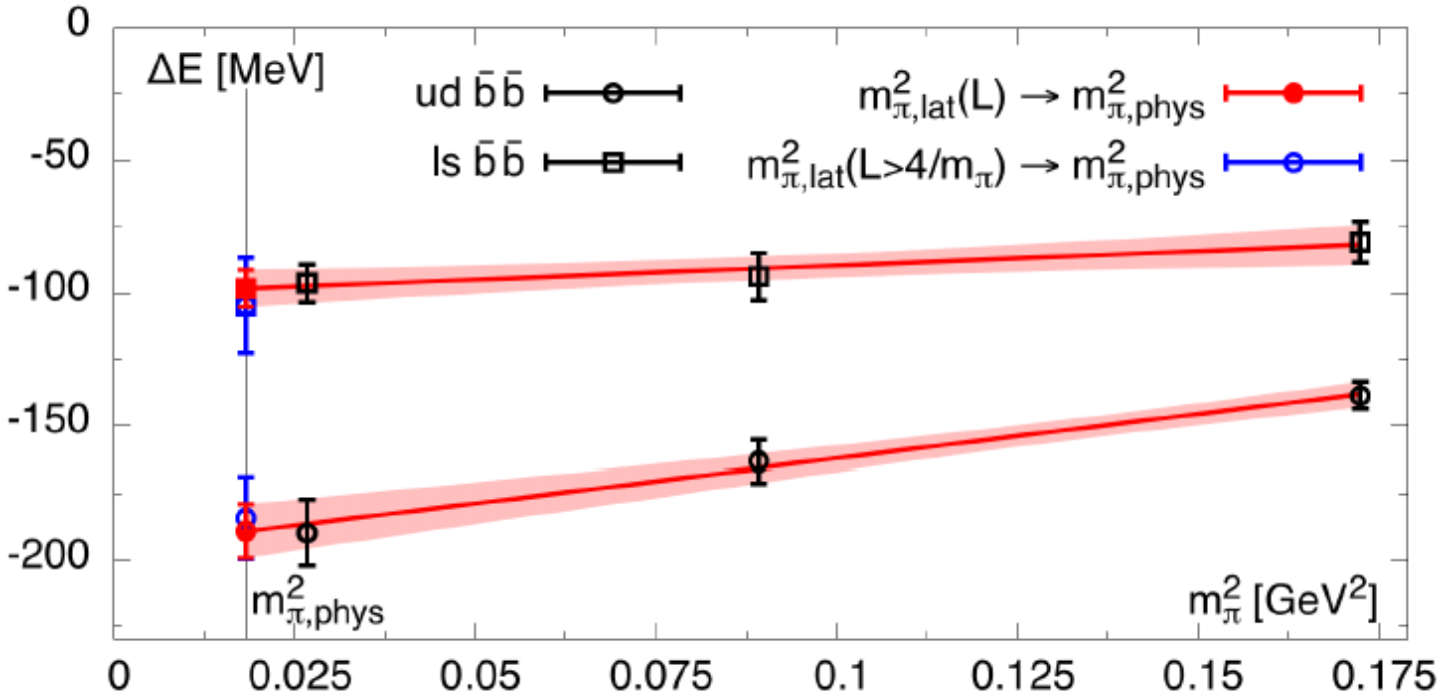
Brambilla *et al* PRD**72** 034021 '05

Data : Brown *et al* PRD**90** 094507 '14

Figure : Lewis CHARM-2018

$\bar{b}\bar{b}ud$ and $\bar{b}\bar{b}ls$ tetraquarks on lattice

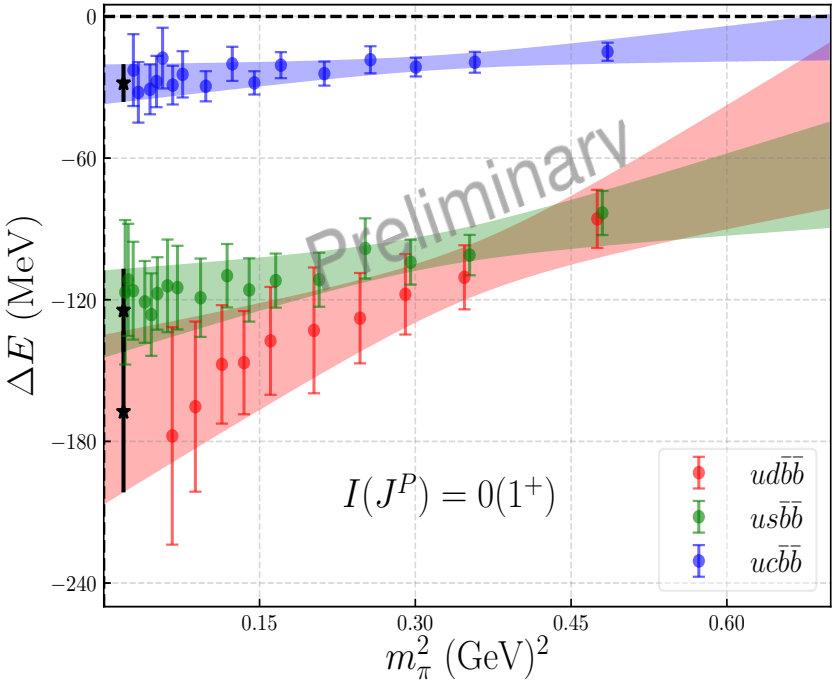
Francis *et al.* PRL**118** 142001 '17

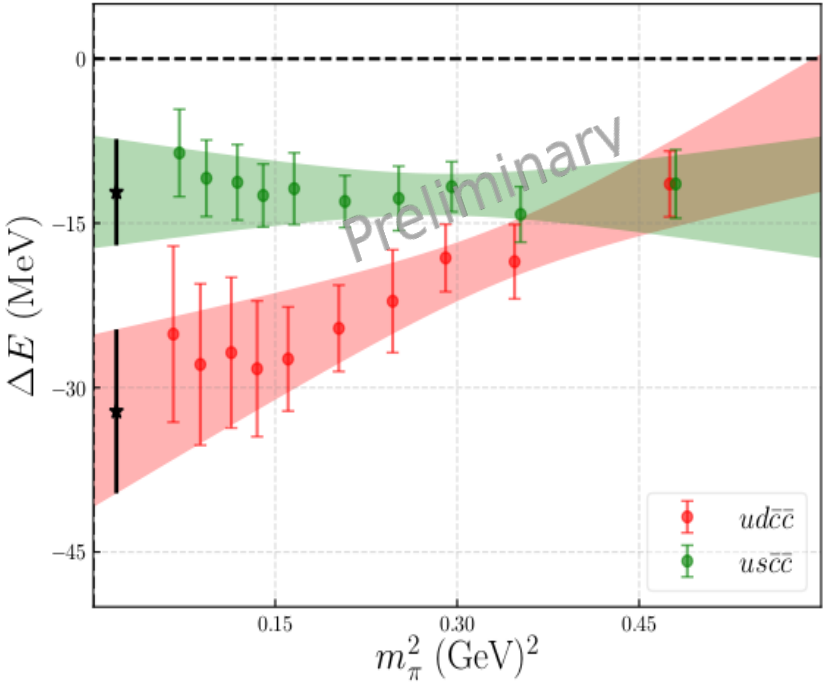


Study of pseudovector doubly bottom tetraquarks on $N_f = 2+1$ PACS-CS lattices
Correlation matrices out of tetraquark as well as meson-meson interpolators
Binding energies : $\Delta E_{\bar{b}\bar{b}ud} = 189(10)$ MeV and $\Delta E_{\bar{b}\bar{b}us} = 98(7)$ MeV

Studies based on LQCD potentials for static quarks in presence of light hadrons indicating bound state in $I(J^P) = 0(1^+)$. $\Delta E_{B.E.} = -90^{+43}_{-36}$ MeV
Bicudo *et al.* PRD**96** 054510 '17

More on doubly heavy tetraquarks

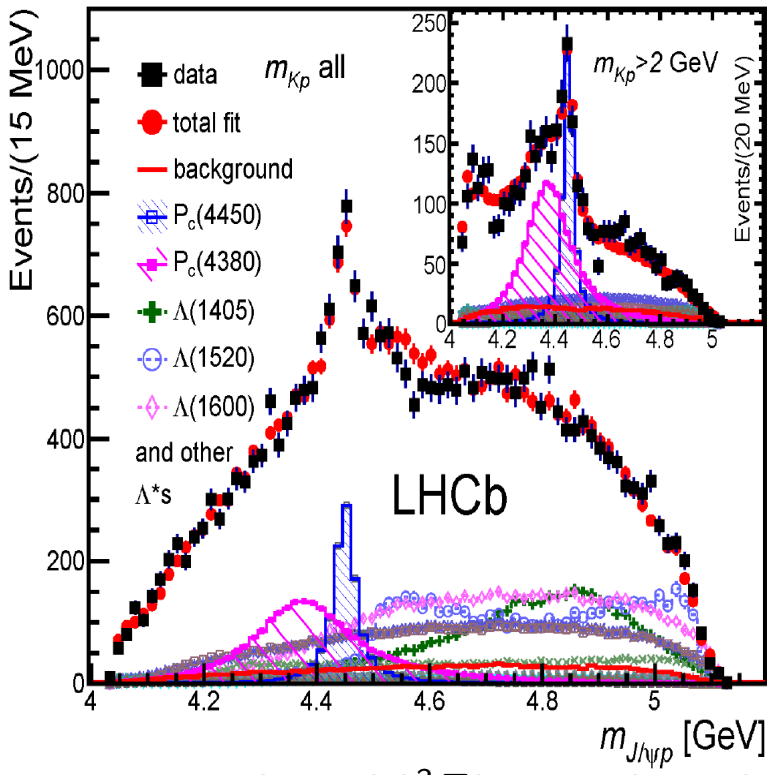




Junnarkar, MP *et al.* (ILGTI) 1712.08400

- Extensive study of quark mass dependence on binding energies of doubly heavy tetraquarks.
- On $N_f = 2 + 1 + 1$ HISQ ensembles (MILC)
- Bottom quark treated non-relativistically.
  Light to charm quark masses using overlap action.
- Correlation matrices out of tetraquark as well as meson-meson interpolators
- Binding energies from difference in the lowest non-interacting levels

Pentaquark ($\bar{Q}Qqqq$) systems

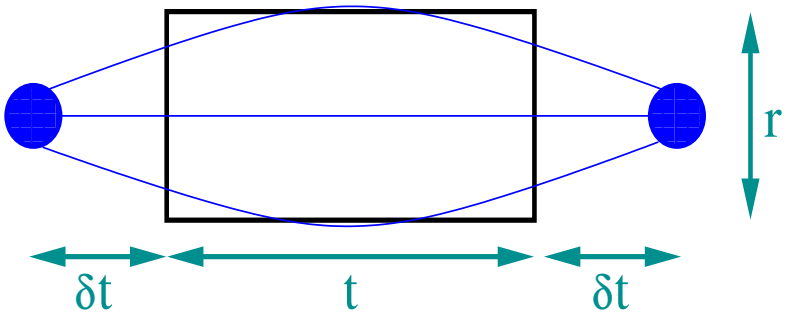


$P_c(4380)(\frac{3}{2}^-)$ & $P_c(4450)(\frac{5}{2}^+)$

$\Lambda_b \to J/\psi p K$: LHCb PRL**115** 072001 '15

Early calculations with significantly large light quark masses.

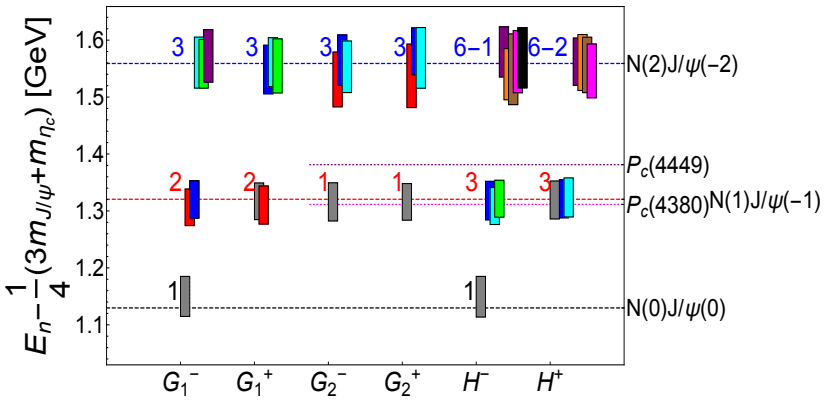
Beane *et al.* (NPLQCD) PRD**91** 114503 '15



Alberti *et al.* PRD**95** 074501 '17

Static quark potential in the presence of light hadrons. $\Delta E \sim [-5, -1]$ MeV robust to FSE.

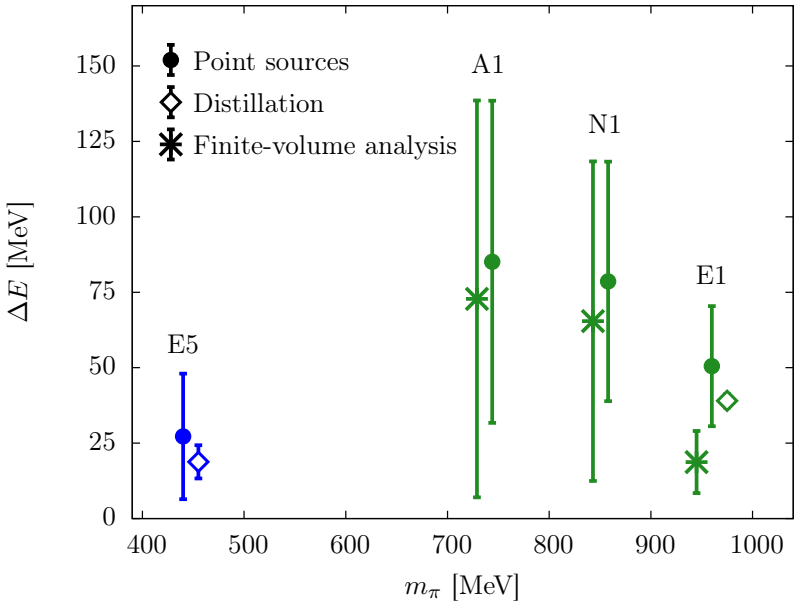
Recent news in this conference ⇓

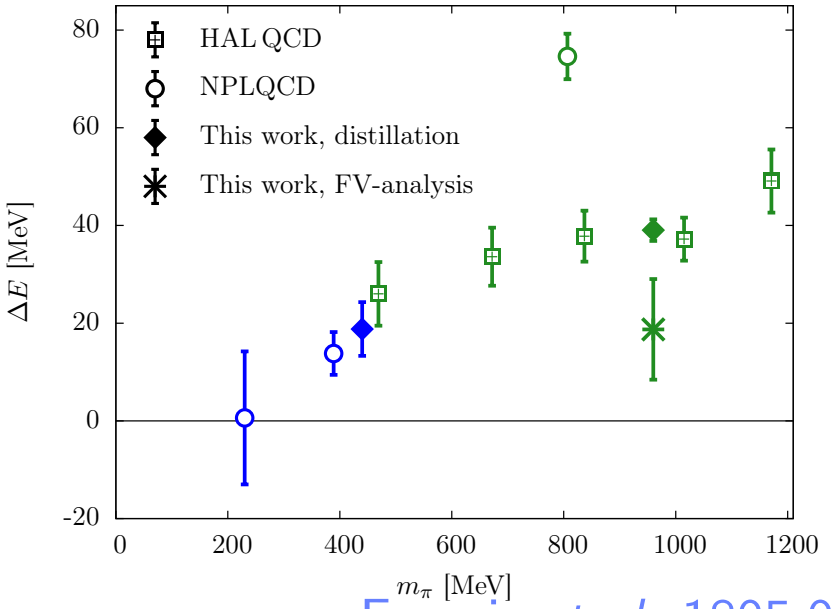


$N - J/\psi$ interaction at m_π =266 MeV.
No signature for pentaquarks.

Skerbis Fri. 15.40 ⇑ Sugiura Fri. 18.10 [HSI]

Beyond hadron spectroscopy : Baryon-baryon interactions





Francis *et al.* 1805.03966

- $N_f = 2$ study of H-dibaryon at SU(3) symmetric point at $m_\pi \sim 960$ MeV.
- Lüscher type analysis on data from multiple inertial frames .
  Binding energy, $\Delta E = 19 \pm 10$ MeV at $m_\pi \sim 960$ MeV.
- This conference : results from $N_f = 2$ and $N_f = 2 + 1$
  Hanlon Thu. 12.40 [HSI]
- Other baryon-baryon interaction studies
  Iritani Fri. 17.10; Doi, Fri. 17.50 [HSI] @ $m_\pi(phys)$ [HALQCD]
  Berkowitz Tue. 11.15 [Plenary]

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Summary

- Precision measurements of ground states are now well established and lattice QCD is quite successful in postdicting/predicting ground state hadrons
- Ground state as well as excited state baryons are being investigated by various groups. Confronting all the challenges, investigating multiple and adequately large volumes are necessary to understand these resonances!
- Different groups are practising resonance treatment to study various hadrons. Very promising direction.
- Coupled channel treatment : Need of the hour.
  Some cases even call for studies involving 3-particle scattering.
  Theory is in development. Mai Mon. 16.30; Sharpe Thu. 11.00 [HSI]
- Beyond baryons and mesons : Promising platforms to study.
  Predictions can motivate experiments to search for such states.
  Still a lot of exercises to do!

Thank you ...

Acknowledgements

- Thanks to the Lattice 2018 organizers for the kind invitation.
- Thanks to my collaborators :
  G. S. Bali, S. Collins, R. G. Edwards, P. Junnarkar, C. B. Lang, L. Leskovec, N. Mathur, D. Mohler, S. Mondal, M. Peardon, S. Piemonte, S. Prelovsek, A. Schäfer and S. Weishäepl.
- Thanks to people who sent/gave me inputs :
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- Acknowledge support from EU funding under grant No. MSCA-IF-EF-ST-744659.
- Thanks to S. Gottlieb for help with LatticeNews.

Others I did not cover! Apologies

- Review on scattering processes from lattice QCD.
  Briceño, Dudek and Young, Rev.Mod.Phys. **90** 025001 '18
- Charm quenching effects on spectral quantities
  Cali' Fri. 14.00 [HSI]
- Hadrons in magnetic fields.
  Bali *et al.* PRD**97** 034505 '18; 1805.10971
- Other topics that I have missed to discuss or not discussed to satisfactory level.