Lattice QCD review of charmonium and open-charm meson spectroscopy

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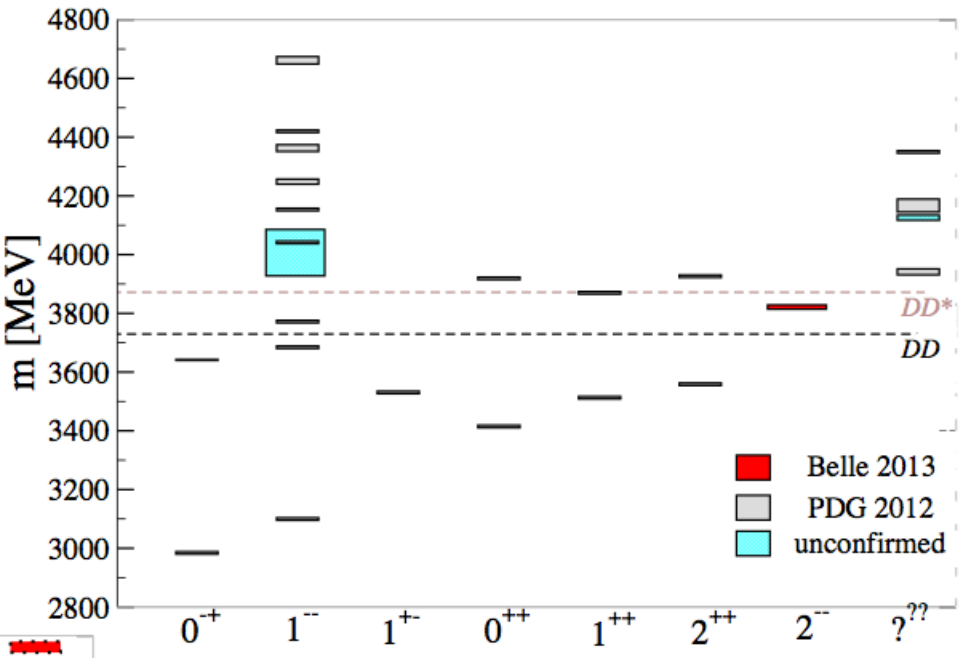
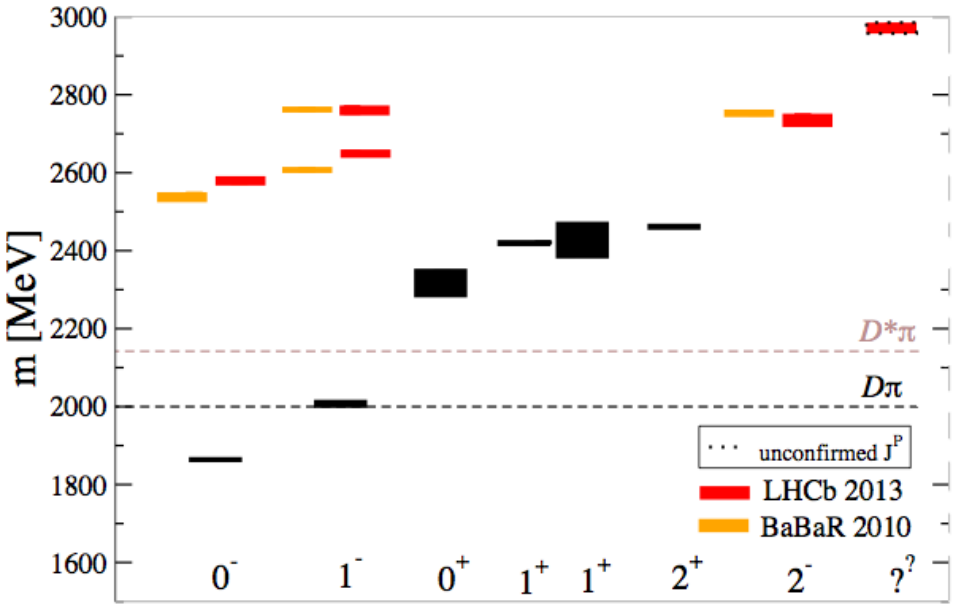
Charm 2013, 31.8-4.9. 2013, Manchester, UK

Experimental status

charmonium (like)



D-mesons



cc 2^{--}: Belle, 1304.3975, PRL

D : LHCb, 1307.4556

Lattice status – general overview: D, D_s , $\underline{c}c$

- States well below strong decay threshold:

  proper treatment & precision calculations already available for some time

- States near threshold and resonances above threshold:

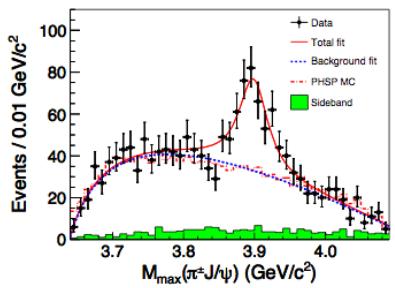
  ★ simulations until 2012: **naive treatment**: - effect of threshold not taken into account
  - strong decays of states ignored

  exception: [Bali, Ehmann, Collins, 2011]

  ★ 2012, 2013, ...: first exploratory simulations with **rigorous treatment**

Experiment: charged charmonium-like

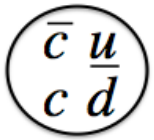
particle	decay	year	coll
$Z^+(4430)$	$\psi(2S)\ \pi^+$	2008	Belle, ~~BABAR~~
$Z^+(4050)$, $Z^+(4250)$	$\chi_{c1}\ \pi^+$	2008	Belle, unconfirmed
$Z_c^+(3900)$	$J/\psi\ \pi^+$	2013	BESIII, Belle, CLEOc
$Z_c^+(4020)$	$h_c(1P)\ \pi^+$	2013	BESIII preliminary
$Z_c^+(4025)$	$(D^*\ D^*)^+$	2013	BES III preliminary



[BESIII, 2013, arXiv:1303.5949]

$Z_c^+(3900) \rightarrow J/\Psi\ \pi^+$

$\underline{c}c\ \ \underline{d}u$



Overview

Spectrum of $\underline{c}c$(like), D, D_s states from lattice QCD:

- States well bellow threshold

- Excited states:

  ★ naive treatment

  ★ rigorous treatment:

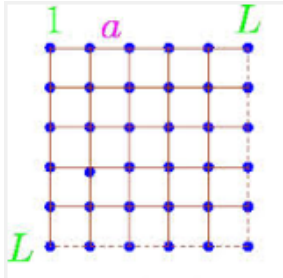
  (1) resonances (above threshold)

  (2) states slightly below threshold

  (3) search for exotic states

"Precision" spectrum:
States well below strong decay threshold

States well below threshold

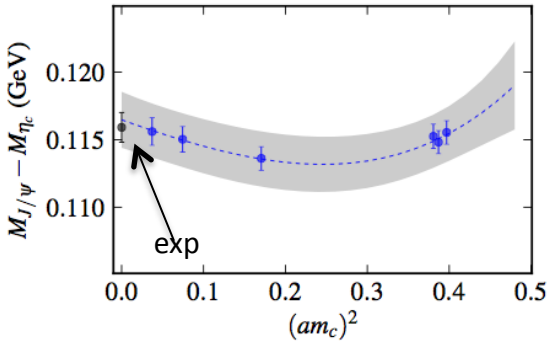


Lattice QCD already determined masses of these states very reliably and precisely O(10 MeV):

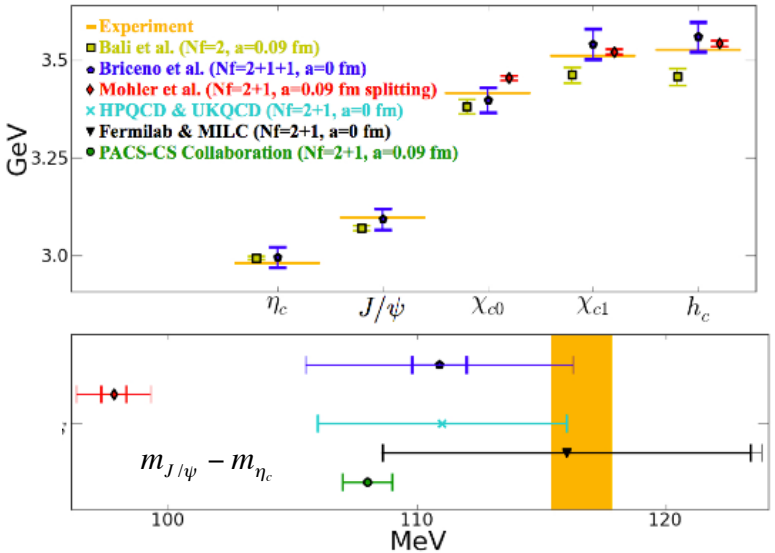
- $\boxed{m=E \quad (\text{for } P=0)}$
- extrapolation : $a \to 0$, $L \to \infty$
- extrapolation or interpolation : $m_q \to m_q^{phy}$
- particular care needed for am_c discretization errors:

  several complementary methods give compatible results

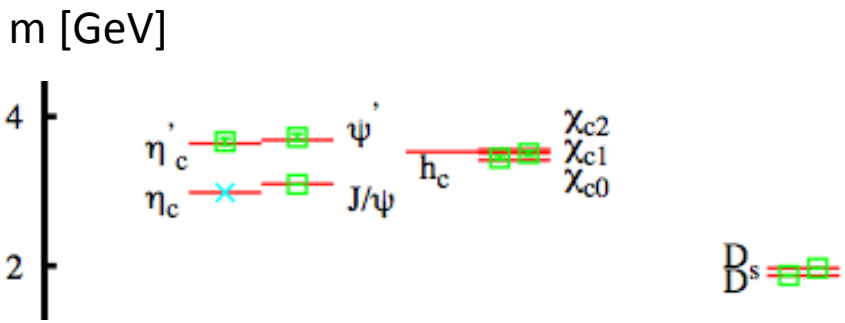
[HPQCD: 1208.2855, PRD]



[Briceno, Lin, Bolton,1207.3536, PRD]



[HPQCD: 1207.5149, PRD]



States well below threshold

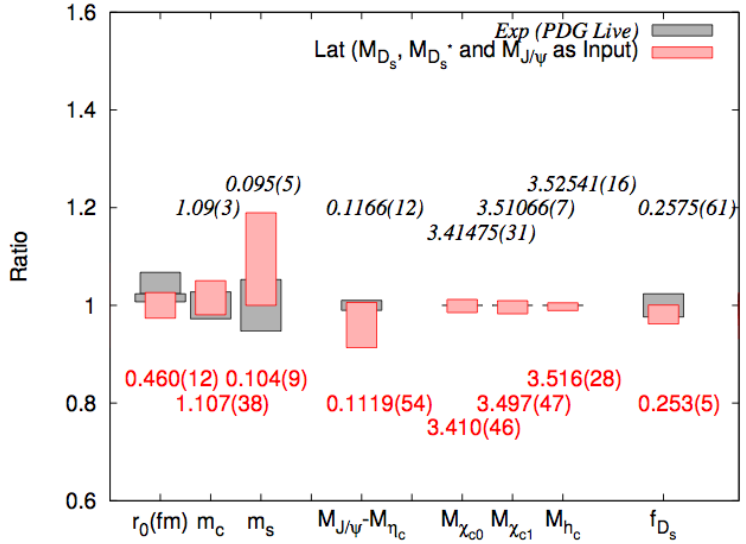
Other recent precision lattice results:

- J/ψ, η_c : spectrum and radiative decays:
  - ★ HPQCD: 1208.2855, PRD
  - ★ D. Becirevic and F. Sanfilippo: 1206.1445, JHEP

- D, D_s spectrum:
  - ★ PACS-CS: 1104.4600, PRD
  - ★ HPQCD: 1207.5149, PRD
  - ★ M. Kalinowski, M. Wagner : 1212.0403, 1304.7974

- charmonium spectrum:
  - ★ D. Mohler @ CHARM 2012: 1209.5790 [review]
  - ★ D. Mohler et al., FNAL/MILC: 1211.2253

[χQCD: 2013, private com.]



"Non-precision" spectrum: excited states

only one or two a, L, $m_{u/d}$

limits $a \to 0$, $L \to \infty$, $m_{u/d} \to m_{u/d}^{phy}$ usually not performed

Excited states: naive treatment

- only interpolating fields $\mathcal{O} \approx \bar{q}\, q$
- assumptions: all energy levels correspond to "one-particle" states

  m=E (for P=0)

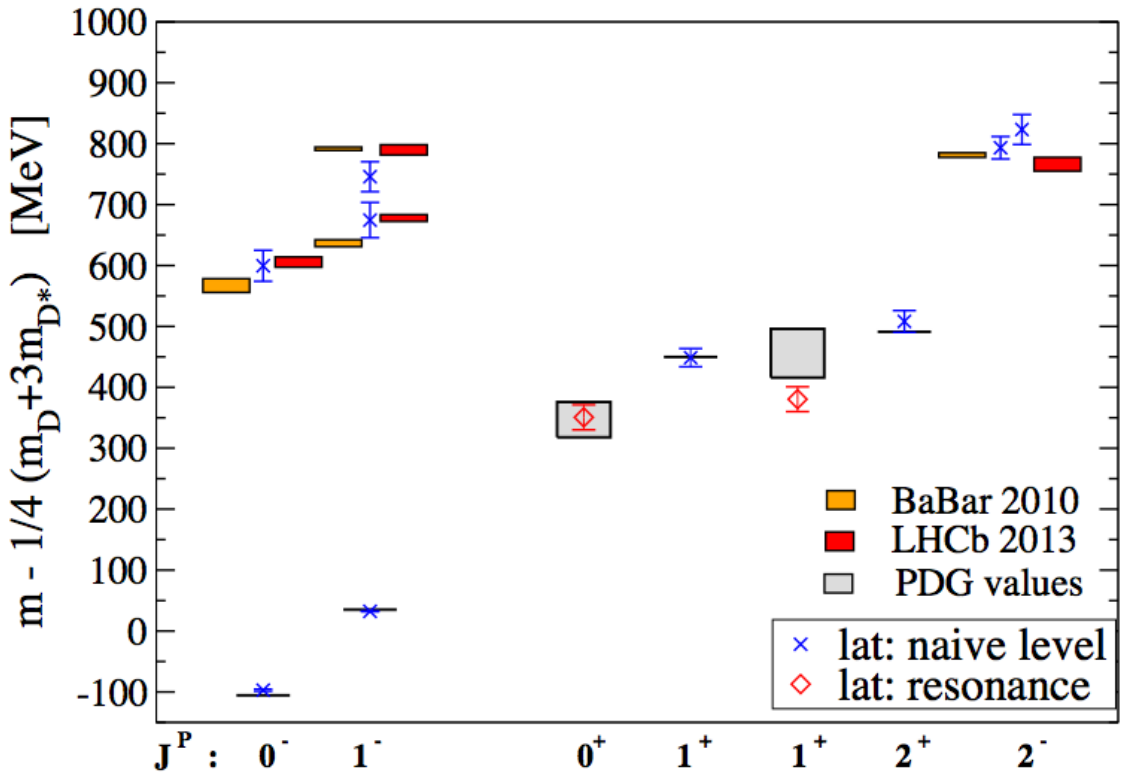
  these are strong assumptions ...

D spectrum: naive treatment

$m-m_{ref}$ usually compared between lat and exp in order to cancel leading am_c discretization effects

1S-2S splitting:

~ 700 MeV

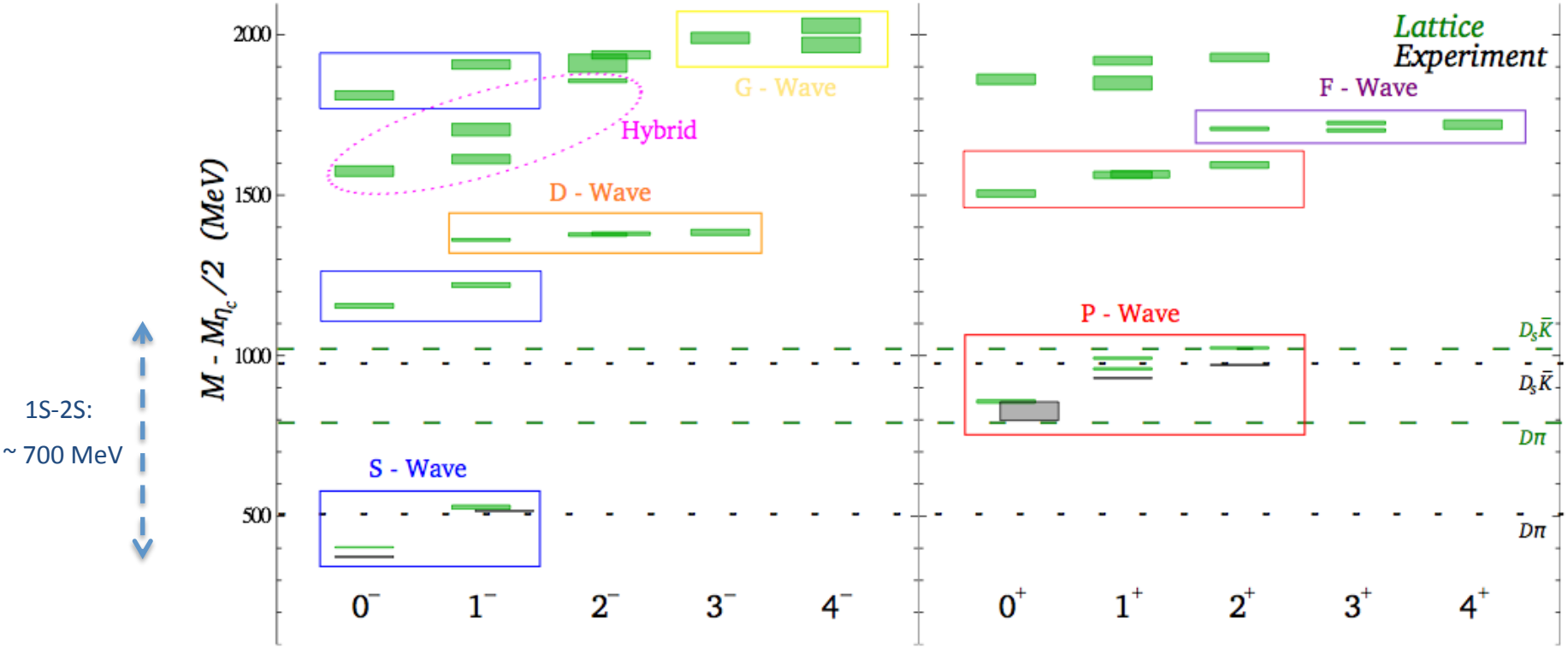


red diamonds: rigorous treatment: discussed later

D. Mohler, S.P. , R. Woloshyn: 1208.4059, PRD:

- $m_\pi \approx 266$ MeV, $L \approx 2$ fm, Nf=2
- crosses: naive lat, diamonds: rigorous lat, lines & boxes: exp

D spectrum: naive treatment



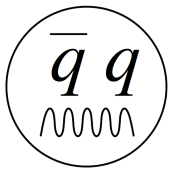
G. Moir et al, HSC (Hadron Spectrum Coll.): 1301.7670, JHEP:

- $m_\pi \approx 400$ MeV, $L \approx 2.9$ fm, Nf=2+1
- reliable J^P determination; many excited states
- identification with $n\ ^{2S+1}L_J$ multiplets using $\langle O|n\rangle$
- green: lat, black: exp

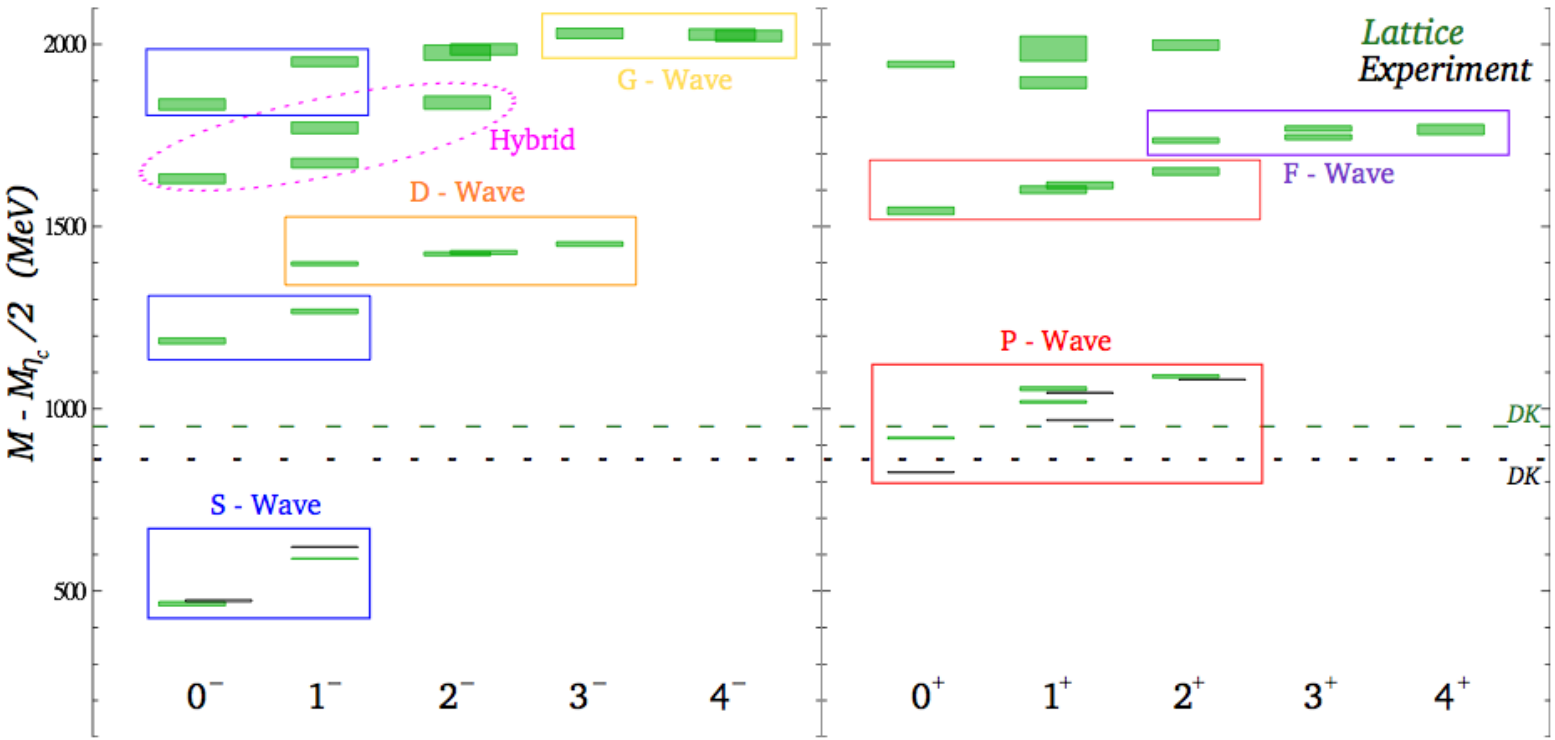
Hybrids:

large overlap with $O = \underline{q}\ F_{ij}\ q$

gluonic tensor $F_{ij} = [D_i, D_j]$



D_s spectrum: naive treatment



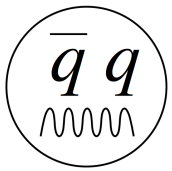
G. Moir et al., HSC : 1301.7670, JHEP:

- $m_\pi \approx 400$ MeV, $L \approx 2.9$ fm, Nf=2+1
- reliable J^{PC} determination
- identification with n $^{2S+1}L_J$ multiplets using $\langle O|n\rangle$
- green: lat, black: exp

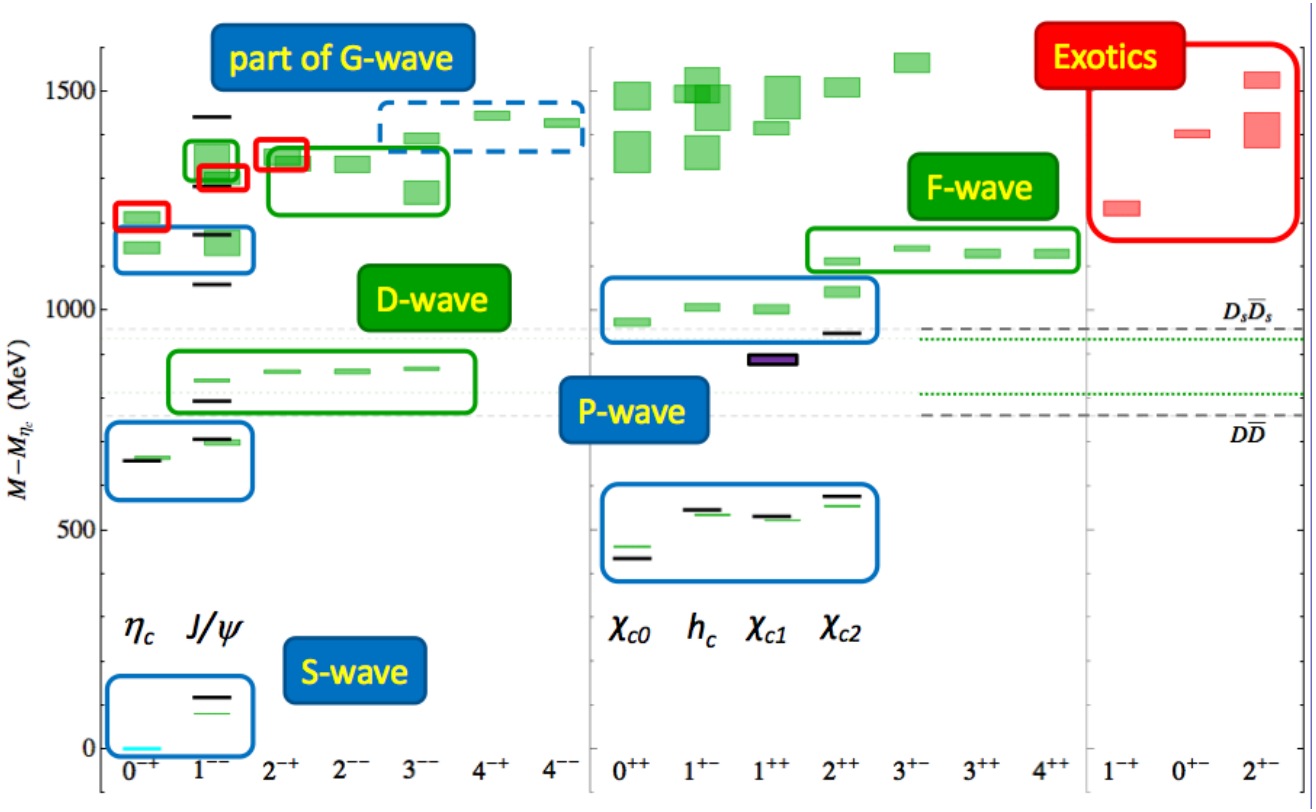
Hybrids:

large overlap with $O = \underline{q}\, F_{ij}\, q$

gluonic tensor $F_{ij} = [D_i, D_j]$



$\underline{c}c$ spectrum: naive treatment



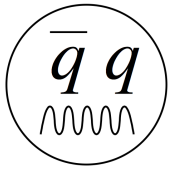
HSC , L. Liu et al: 1204.5425, JHEP:

- $m_\pi \approx 400$ MeV, $L \approx 2.9$ fm, Nf=2+1
- reliable J^{PC} determination
- identification with n $^{2S+1}L_J$ multiplets using $\langle O|n\rangle$
- green: lat, black: exp

Hybrids:

some of them have exotic J^{PC}

large overlap with $O = \underline{q}\, F_{ij}\, q$

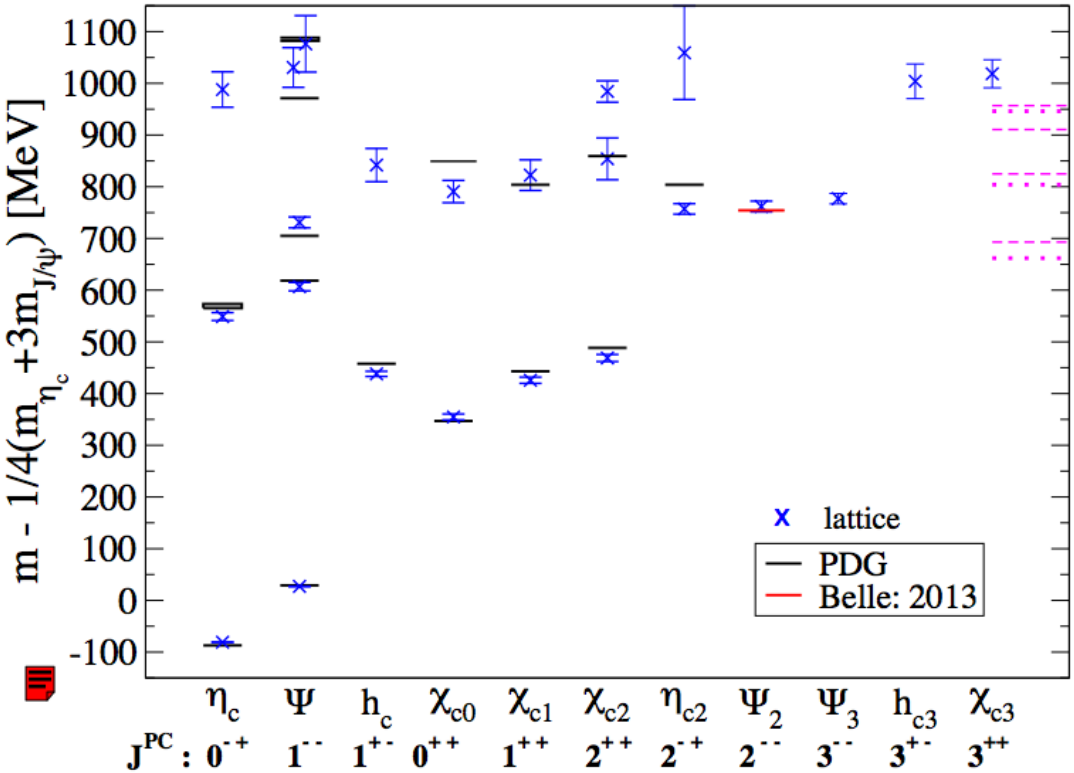


Excited states: naive treatment

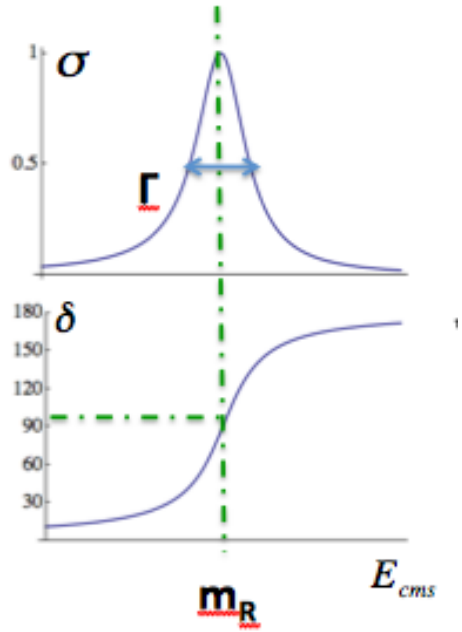
Other recent lattice results:

- ★ G. Bali, S. Collins, P. Perez-Rubio: 1212.0565
- ★ G. Bali et al.: 1108.6147
- ★ D. Mohler and R. Woloshyn: 1103.5506 , PRD
- ★ M. Kalinowski, M. Wagner : 1212.0403, 1304.7974

D. Mohler, S.P. , R. Woloshyn: 1208.4059, PRD



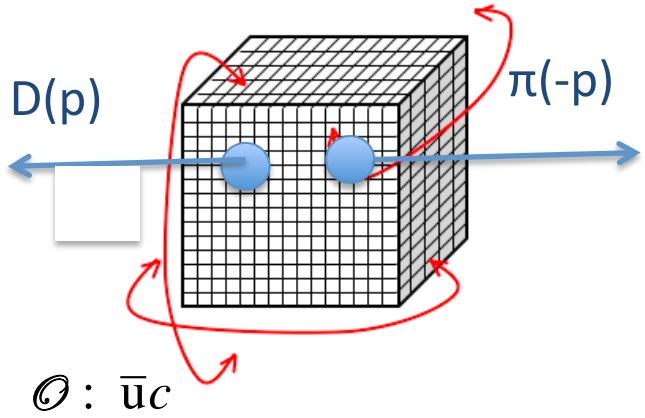
Excited states: rigorous treatment (1) resonances



$D_0^*(2400)$ resonance in Dπ scattering: $J^P=0^+$, I=1/2

"rigorous" treatment illustrated on this example

$$p = n\frac{2\pi}{L}$$



All states with $J^P=0^+$ appear in lat. spectrum:

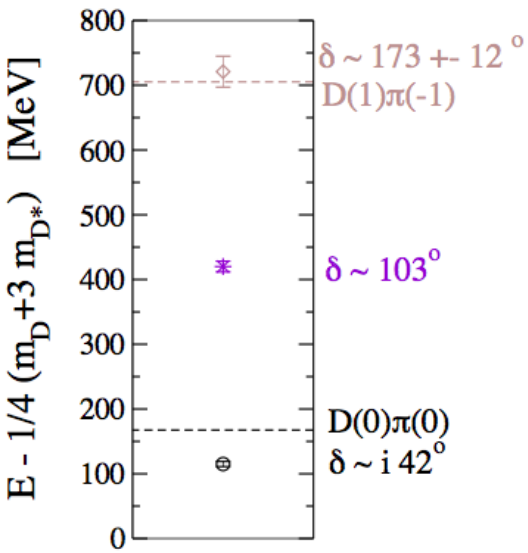
- $D_o^*(2400)$
- D(p) π(-p) with p=n 2π/L : "two-particle" states

horizontal lines indicate their energies in absence of interaction

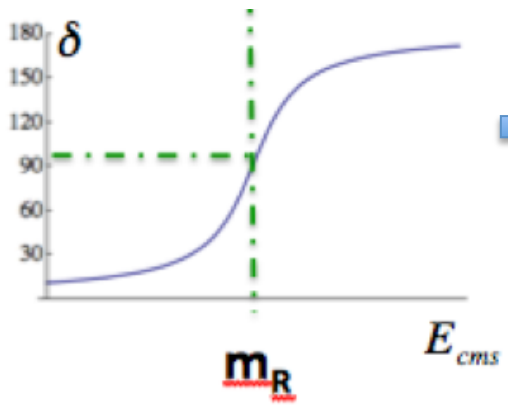
Rigorous relation [M. Luscher , 1991]:

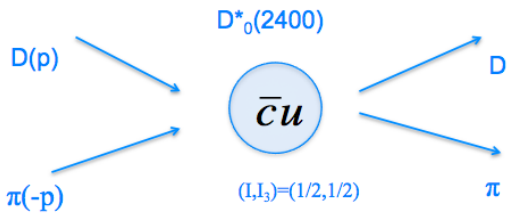
E → δ(E) phase shift for Dπ scattering in s-wave

$$D(\vec{p})\pi(-\vec{p}) \approx [\bar{d}\gamma_5 c]\ [\bar{u}\gamma_5 d]$$



$$\text{BW}: \quad \delta = \text{acot}\frac{m_R^2 - E_{cms}^2}{m_R\,\Gamma}$$





m and Γ

for $D_0^*(2400)$

D. Mohler, S.P. , R. Woloshyn: 1208.4059, PRD

D-meson resonance masses and widths

$$\Gamma(E) \equiv g^2 \frac{p}{E^2}$$

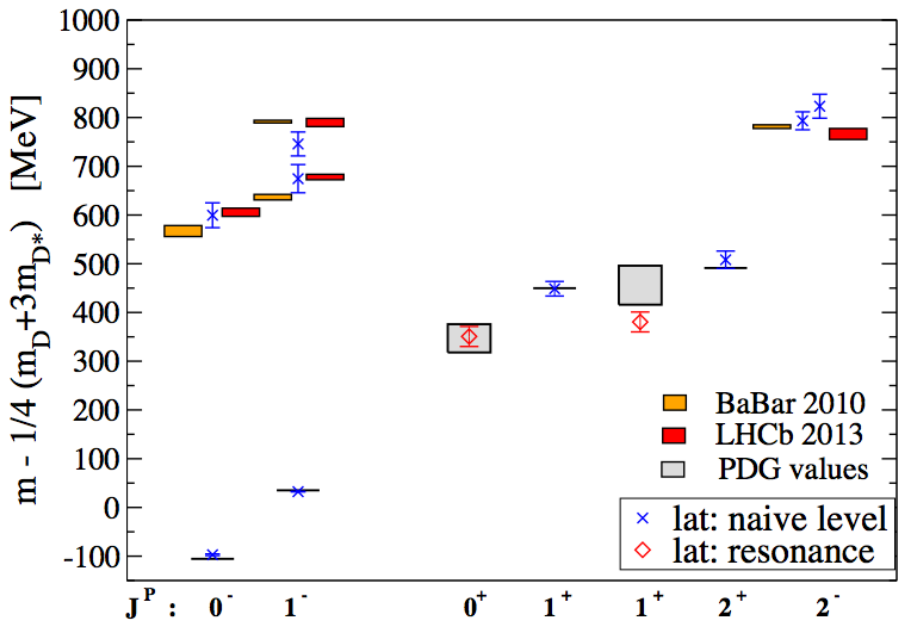
g is compared to exp instead of Γ (Γ depends on phase sp. and m_π)

$J^P=0^+$: D π

$J^P=1^+$: D^* π (analysis of spectrum in this case is based on an assumption given in paper below)

$D_0^*(2400)$	m - 1/4(mD+3 mD*)	g
lat	351 ± 21 MeV	2.55 ± 0.21 GeV
exp	347 ± 29 MeV	1.92 ± 0.14 GeV

$D_1(2430)$	m - 1/4(mD+3 mD*)	g
lat	381 ± 20 MeV	2.01 ± 0.15 GeV
exp	456 ± 40 MeV	2.50 ± 0.40 GeV



first lattice result for strong decay width of a hadron containing charm quark

[D. Mohler, S.P. , R. Woloshyn: 1208.4059, PRD]

- m_π≈266 MeV, L≈2 fm, Nf=2

$J^{PC}=0^{++}$ charmonuim resonance(s): χ_{c0}' ?

PRELIMINARY

By simulating DD scattering in s-wave we find:

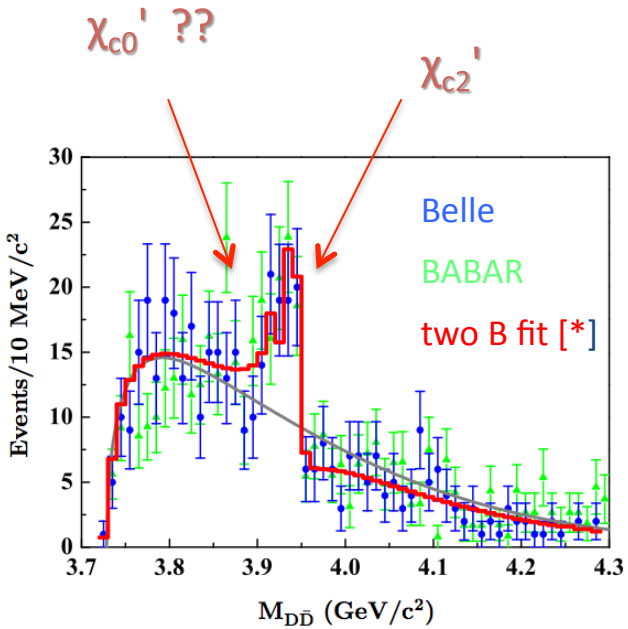
(1) narrow resonance in DD scattering [we call it χ_{c0}']

$$m[\chi_{c0}'] = 3932 \pm 25 \ \ \text{MeV}$$

$$\Gamma[\chi_{c0}' \to \bar{D}D] = 36 \pm 17 \ \ \text{MeV}$$

PDG12: χ_{c0}'=X(3915) ?! Why X(3915)→DD in exp ?!

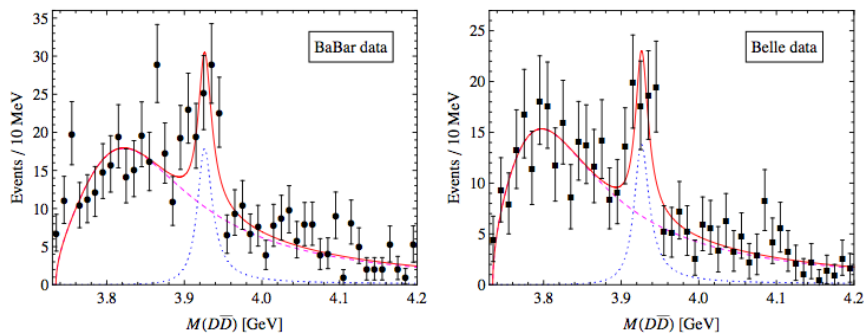
perhaps there is a hit of it [D. Chen et al, 1207.3561, PRD]



(2) additional enhancement of σ(DD) near th. :

could it be related to broad structures ?

[see also F. Guo, U. Meissner, 1208.1134, PRD]



S.P. , L. Leskovec and D. Mohler,

to appear in Lat 2013 proc:

- $m_\pi \approx 266$ MeV, L≈2 fm, Nf=2

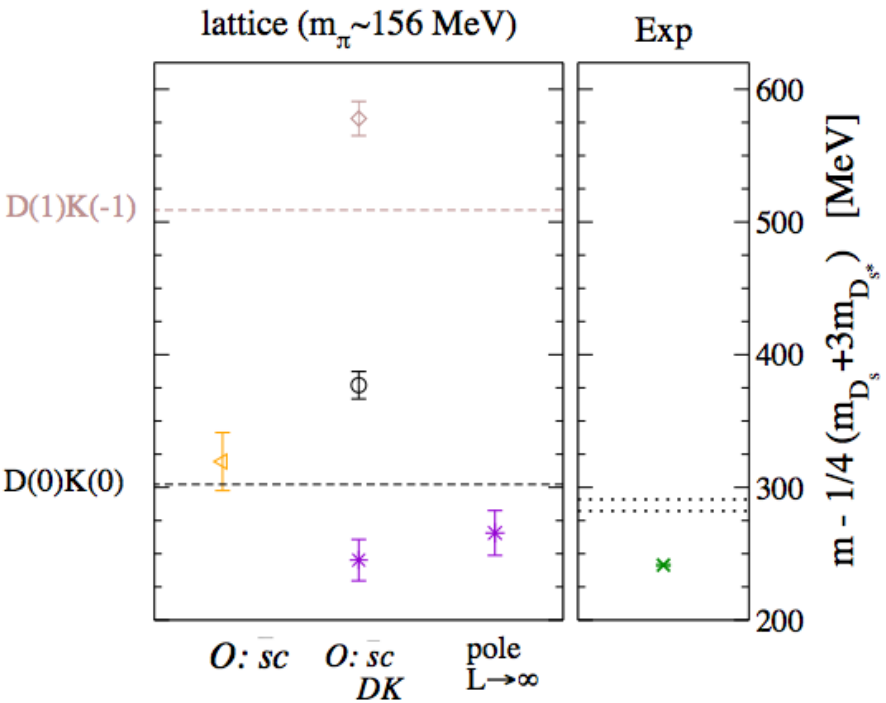
Excited states: rigorous treatment (2) states slightly below threshold

note: most of interesting states are found near threshold:

$D_{s0}^{*}(2317)$, $X(3872)$, $Z_c^{+}(3900)$, Z_b^{+}

$D_{s0}^*(2317)$ and DK scattering ($J^P=0^+$)

$\mathcal{O}: \bar{s}\, c, \quad DK \approx [\bar{d}\gamma_5 c]\,[\bar{s}\gamma_5 d]$



- δ for DK scattering in s-wave

  extracted using Luscher's relation

$$p\cot\delta(p) = \frac{1}{a_0} + \frac{1}{2} r_0 p^2$$

$$a_0 = -1.33 \pm 0.20 \text{ fm}$$

$$r_0 = 0.27 \pm 0.17 \text{ fm}$$

a_0<0 indicates a state below th.

- relation above gives pole position and the mass of $D_{s0}^*(2317)$

$$S \propto [\cot\delta - i]^{-1} = \infty, \quad \cot\delta(p_{BS}) = i$$

$$m_{D_{s0}}^{lat, L\to\infty} = E_D(p_{BS}) + E_K(p_{BS})$$

$D_{s0}^*(2317)$	m - ¼ (m_{Ds}+3m_{Ds^*})
lat	266 ± 16±4 MeV
exp	241.45 ± 0.6 MeV

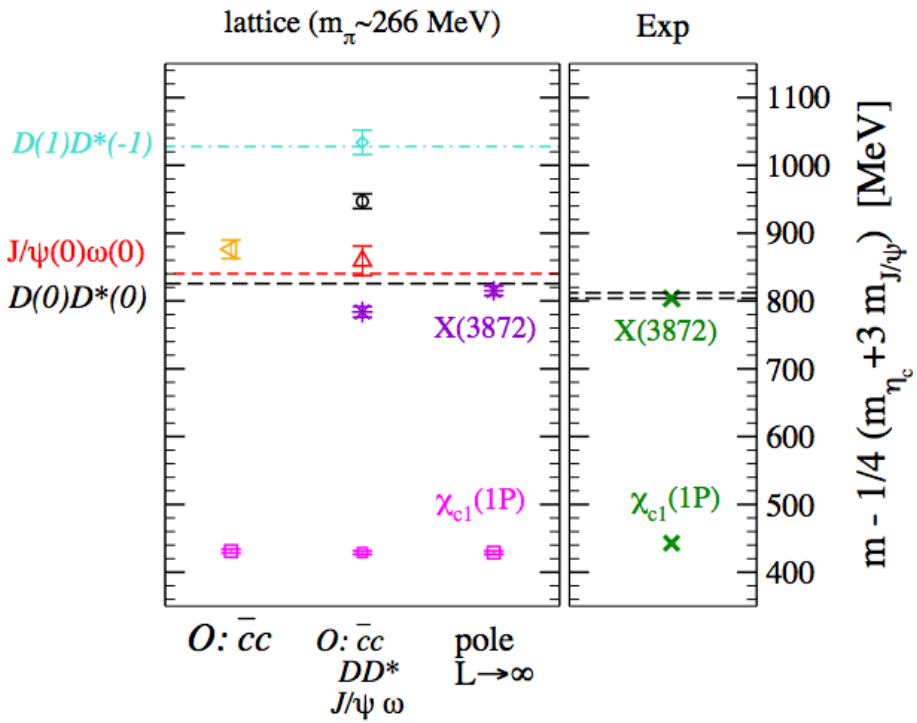
Candidate for $D_{s0}^*(2317)$ is found in addition to the DK states for the first time.

D. Mohler, C. Lang, L. Leskovec, S.P. , R. Woloshyn:

1308.3175: m_π≈156 MeV, L≈2.9 fm, Nf=2+1

X(3872) : $J^{PC}=1^{++}$ [LHCb 2013] , I=0

$\mathcal{O}: \bar{c}\,c, \quad DD^*, \quad J/\psi\,\omega$



Candidate for X(3872) is found in addition to the expected two-particle states for the first time.

S. P. and L. Leskovec : 1307.5172

m_π≈266 MeV, L≈2 fm, Nf=2

- δ for DD* scattering in s-wave

  extracted using Luscher's relation

$$p\cot\delta(p) = \frac{1}{a_0} + \frac{1}{2} r_0 p^2$$

$$a_0 = -1.7 \pm 0.4 \text{ fm}$$

$$r_0 = 0.5 \pm 0.1 \text{ fm}$$

large and a_0<0 indicates a state slightly below DD* threshold: X(3872)

- pole position gives mass of X(3872)

$$S \propto [\cot\delta - i]^{-1} = \infty, \quad \cot\delta(p_{BS}) = i$$

$$m_X^{lat, L\to\infty} = E_D(p_{BS}) + E_{D^*}(p_{BS})$$

X(3872)	m - (m_{D0}+m_{D0*})
lat	- 11 ± 7 MeV
exp	- 0.14 ± 0.22 MeV

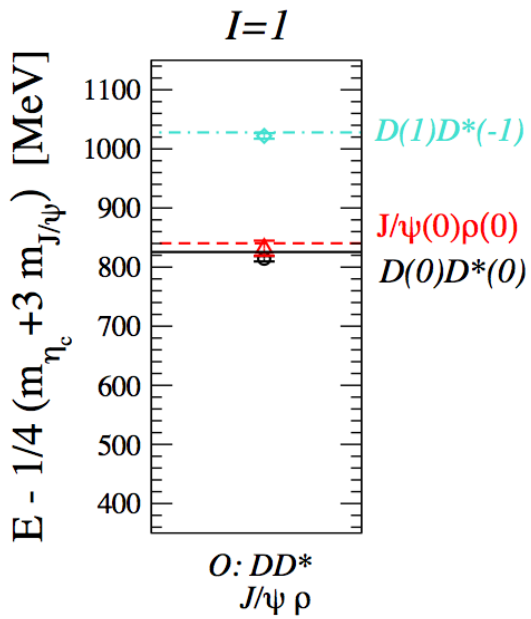
lat: simulations on larger L required

exp: Tomaradze et al., 1212.4191

Composition of established X(3872) with I=0

- it has sizable coupling with $\bar{c}c$ as well as DD^* interpolating fields
- overlaps of X with interpolators : $\langle O_i | X(3872) \rangle$ [see S. P. and L. Leskovec : 1307.5172]

Search for X(3872) with $J^{PC}=1^{++}$ and I=1



S. P. and L. Leskovec : 1307.5172

$m_\pi \approx 266$ MeV, L≈2 fm, Nf=2

Only expected two-particle states observed.
No candidate for X(3872) found.

In agreement with interpretation

$$X(3872) = a_{I=0}|DD^*\rangle_{I=0} + a_{I=1}|DD^*\rangle_{I=1}$$

$$a_{I=1}(m_u = m_d) = 0$$
$$a_{I=1}(m_u \neq m_d) << a_{I=0}$$

isospin breaking: $D^0 D^{0*}$, D^+D^{-*} splitting

In simulation: $m_u=m_d$

(3) Searches for exotic states:

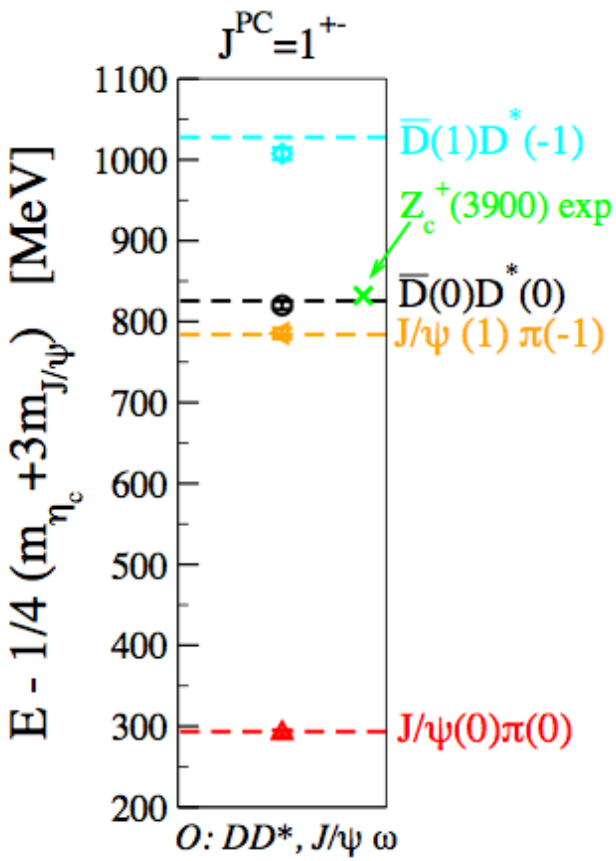
rigorous treatment

Search for $Z_c^+(3900)$ in $J^{PC}=1^{+-}$, I=1 channel

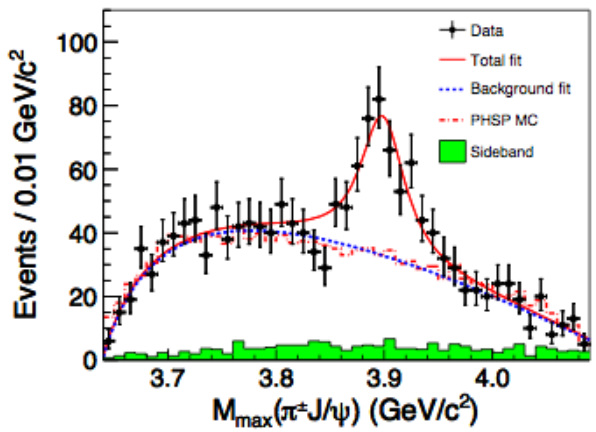
$\mathcal{O}: DD^*, \quad J/\psi\ \pi$

$Z_c^+(3900) \to J/\psi\ \pi^+$

$J^{PC} = ?^{?+} \qquad \bar{c}c\ \bar{d}u$



[BesIII, Belle, CleoC, 2013]



Only expected two-particle states observed.

No candidate for $Z_c^+(3900)$ with $J^{PC}=1^{+-}$ is found.

- Possible reasons:

✧ perhaps $J^{PC}\neq 1^{+-}$ (exp unknown)

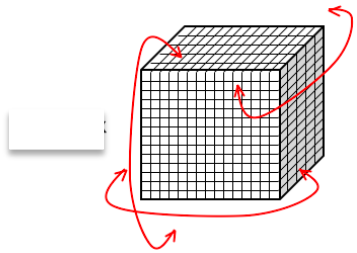
✧ perhaps our interpolators (all of scat. type) are not diverse enough : calls for further simulations

✧ ??

S. P. and L. Leskovec : 1308.2097

$m_\pi \approx 266$ MeV, L≈2 fm, Nf=2

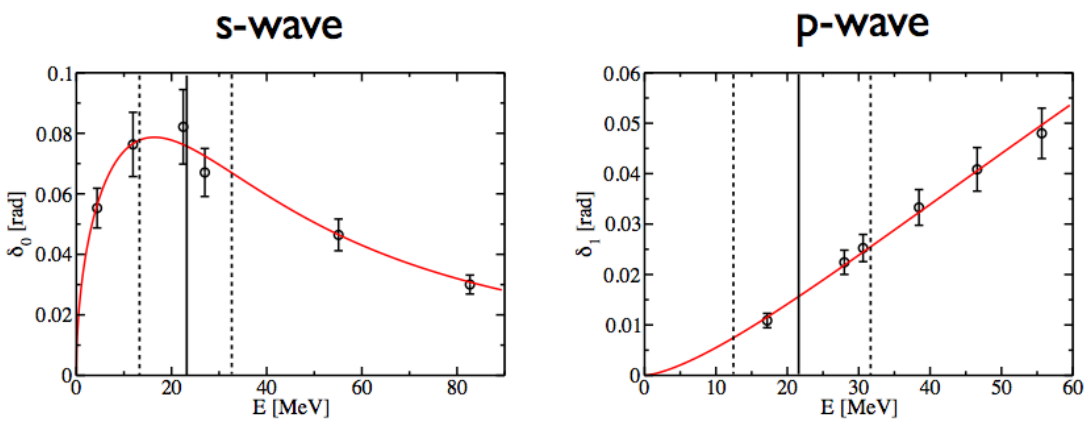
Search for Y(4140) in J/Ψ Φ scattering



Experiment:

- Y(4140) found in J/Ψ Φ , Γ ≈ 11 MeV [CDF 2009]
  not seen in $D_s\underline{D}_s$
- not seen by Belle, LHCb

J/Ψ Φ scattering phase shift [radians]



S. Ozaki and S. Sasaki, 1211.5512, PRD

m_π≈156 MeV, L≈2.9 fm, Nf=2+1

Lattice:

- method to get δ at more E:

twisted BC for valence q.

$$q(x+L) = e^{i\theta}\, q(x)$$

instead of periodic BC (conventional)

$$q(x+L) = q(x)$$

- conclusion:

no resonant structure found at energies reported by CDF

- Caveats:

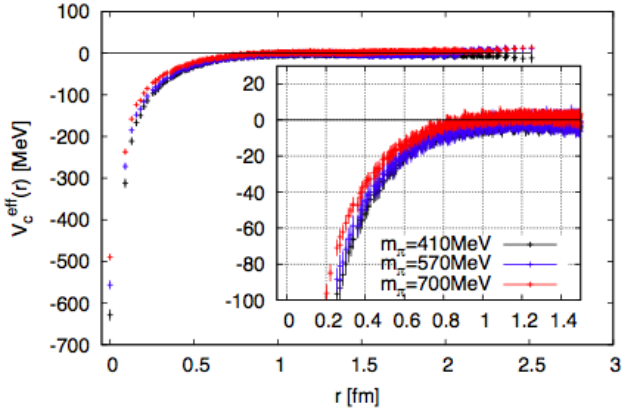
★ s-quark annihilation ignored

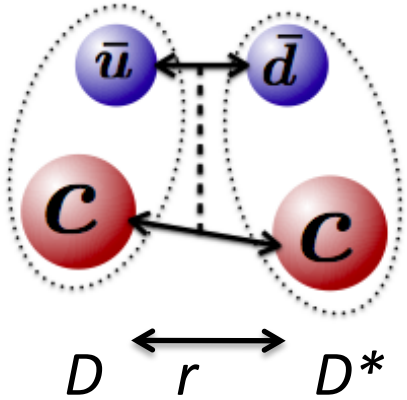
★ twisting is partial: only on valence quarks

Search for bound double charm tetraquark with $J^P=1^+$, I=0

(1) determine potential between D and D*

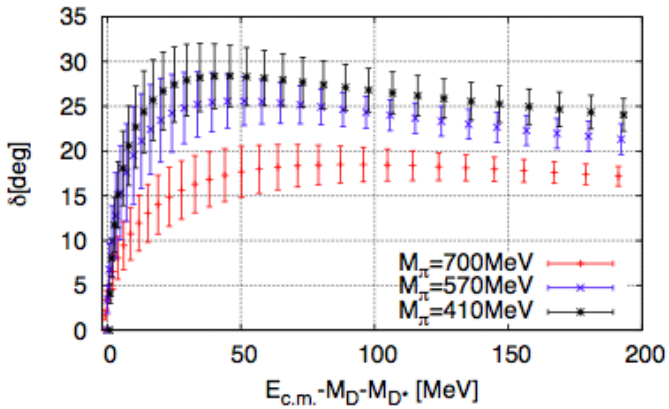
at distance r: HALQCD method: Ishii et al., PLB712, 437 (2012)





(2) Solve Schrodinger equation with given V(r)

and determine DD* scattering phase shift



Conclusion:

- **potential is attractive**
- **no bound tetraquark state** at simulated m_π
- in case of one bound state one would expect δ(E=0)=π due to Levinson's theorem

Y. Ikeda et al, HAL QCD coll. , 2013, private com.

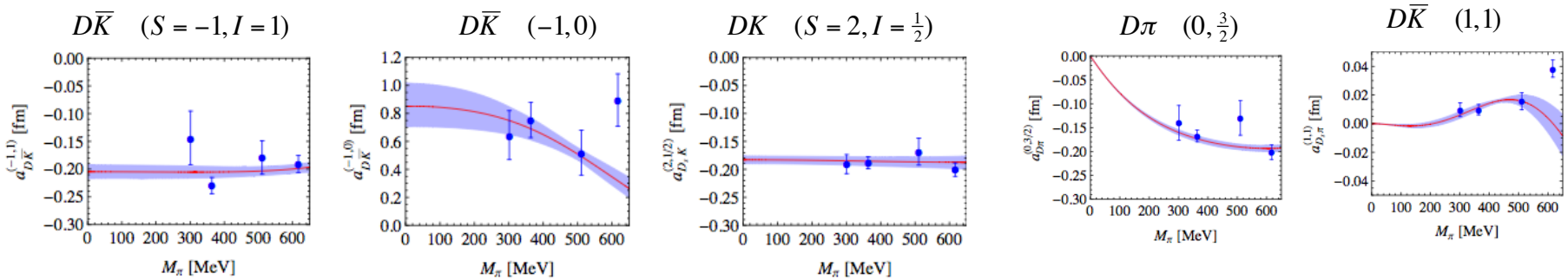
m_π≈410-700 MeV, L≈2.9 fm, Nf=2+1

Related topics

Interactions of charmed mesons with light pseudoscalars

(1) Five channels that do not include Wick contractions  are simulated

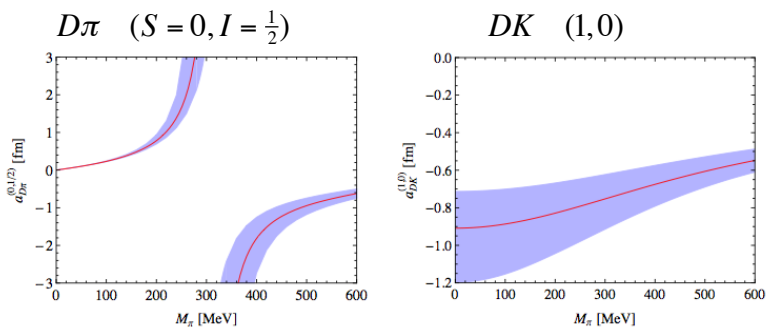
(2) Scattering lengths $a = \lim_{p\to 0} \frac{\tan\delta(p)}{p}$ for four m_π extracted



(3) simultaneous fit using SU(3) unitarized ChPT is performed and LEC's are determined

(4) using these LEC's indirect predictions for:

- scattering length of two resonant-channels with contractions 
- DK (S=1,I=0): pole in the first Riemann sheet found



D_{s0}*(2317)	m	Γ [D_{s0}*→D_s π]
indirect lat	2315^{+18}_{-28} MeV	133±22 keV
exp	2317.8 ±0.6 MeV	< 3.8 MeV

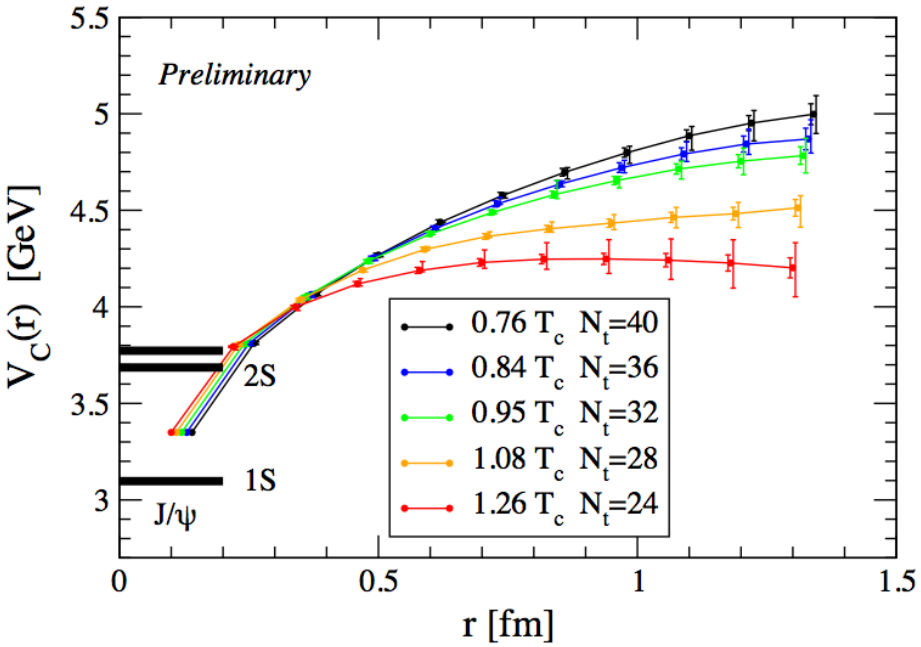
L. Liu, Orginos, Guo, Hanhart, Meissner, 1208.4535, PRD, m_π≈300-620 MeV, Nf=2+1

Charmonium potential at finite temperature

Potential between c and c in charmonium with physical m_c at finite T: HAL QCD method

$$V(r) = V_C(r) + \vec{s}_1 \cdot \vec{s}_2 \, V_S(r)$$

Nf=2+1 [C. Allton, private com.]



Tc: deconfining temperature

Tc ~ 220 MeV (from Polyakov loop)

Conclusions:

- $T<T_c$: linearly rising V(r) at large r
- $T>T_c$: flattening of V(r) at large r

earlier Nf=2 simulation:

Evans, Allton, Skullerud, 1303.5331

Conclusions & outlook

Present status of lattice results for D, D_s, $\underline{c}c$ spectra **:**

- states well below strong decay threshold determined reliably and with good precision

- excited states: naive treatment

  spectra with a number of full qq multiplets and hybrids calculated during 2012, 2013

- excited states: rigorous treatment: first simulations during 2012, 2013

  ★ $D_0^*(2400)$, $D_1(2430)$, $D_{s0}^*(2317)$, X(3872) identified

  ★ $Z_c^+(3900)$, Y(4140), $cc\underline{ud}$ not (yet) found

Precision simulations of these channels will have to be performed in the future.

Conclusions & outlook

Outlook for lattice simulations of D, D_s, $\bar{c}c$ spectra **:**

Which excited states can one treat rigorously in the near future?

- states not to far above strong decay threshold that have one (dominant) decay mode

  example: $Z_c^+(3900)$ is less challenging than $Z^+(4430)$

- states that are *not* accompanied by many lower states of the same quantum number

  example: higher lying 1^- charmonium states would be very challenging for rigorous treatment

Lots of exciting experimental results prompt for lots of exciting lattice simulations

in the near future, encouraged by the pioneering exploratory steps made during the last year!