QCD confronts heavy flavor and exotic hadrons

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Hadrons

G=gluon, q=quark=u,d,s,c,b

Today we know (from exp and theory) that hadrons with the following minimal quark and gluon contents.

There may be more categories, but these are not reliably confirmed yet.

minimal quark (q) and gluon (G) contents

conventional hadrons

$\bar{q}\ q$ meson

$q\ q\ q$ baryon

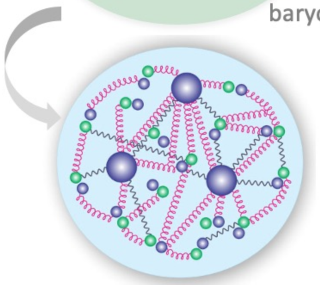


image: https://physicstoday.scitation.org/do/10.1063/PT.5.7167/full/

exotic hadrons — experimentaly discoveded example

$q\ q\ \bar{q}\ \bar{q}$ tetraquark — $cc\bar{u}\bar{d} = T_{cc}$ [LHCb 2021]

$q\ q\ q\ \bar{q}\ q$ pentaquark — $uud\bar{c}c = P_c$ [LHCb 2015]

$\bar{q}\ G\ q$ hybrid — $\bar{u}Gd = \pi_1$ [several exp.] $J^{PC} = 1^{-+}$

LHCb discoveries:

talk by Mikhasenko

This talk: how well QCD confronts (heavy flavor and exotic) hadrons

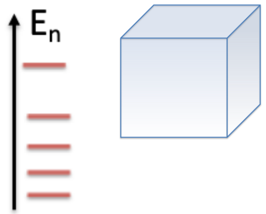
- intro on theory approaches with few examples
- journey to various hadron sectors
- T=0 throught

QCD: $\mathcal{L}_{QCD} = \frac{1}{4} G_a^{\mu\nu} G_a^{\mu\nu} + \bar{q} i \gamma_\mu (\partial^\mu + i g_s G_a^\mu T^a) q - m_q \bar{q} q$ $\quad g_s \cancel{\ll} 1$ at hadronic energy scale

Non-perturbative theory approaches to QCD

Lattice QCD

Main quantity extracted: eigen-energy E_n

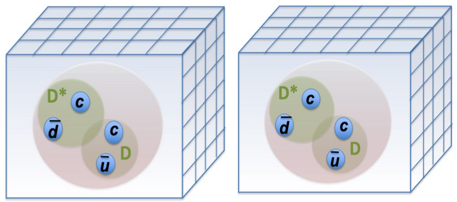


$\sum_n |n\rangle\langle n|$ $\qquad e^{-iE_n t_M}$

Eucledian time

$$C_{ij}(t) = \langle 0 | \mathcal{O}_i(t)\ \mathcal{O}_j^+(0) | 0 \rangle = \sum_n \langle 0 | \mathcal{O}_i | n \rangle\ e^{-E_n t}\ \langle n | \mathcal{O}_j^+ | 0 \rangle$$

t, J^P, I $\qquad$ t=0, J^P, I



$$\langle C \rangle = \int DG\, Dq\, D\bar{q}\, C\, e^{-S^E_{QCD}/\hbar}$$

often "non-precision" studies: single a, $m_{u/d} > m_{u/d}^{phy}$, $m_\pi > 140$ MeV

E_n allow to extract stable hadrons and decaying resonances (as I'll explain later)

This talk: mostly

lattice, lattice + EFT

recent reviews:

N. Brambilla et al. 1907.07583, Phys. Rept

M. Mai, U. Meissner, C. Urbach, 2206.01477

N. Brambilla, 2111.10788

Effective Field Theory (EFT)

- Lagrangian for effective d.o.f. based on symmetries of QCD
- Taylor expansion in a small quantity ($1/m_Q$,p,E,...)
- drawback: dependence on (unknown) parameters

Functional methods (Dyson-Schwinger & Bethe-Salpeter equations): paralell talk by C. Fischer

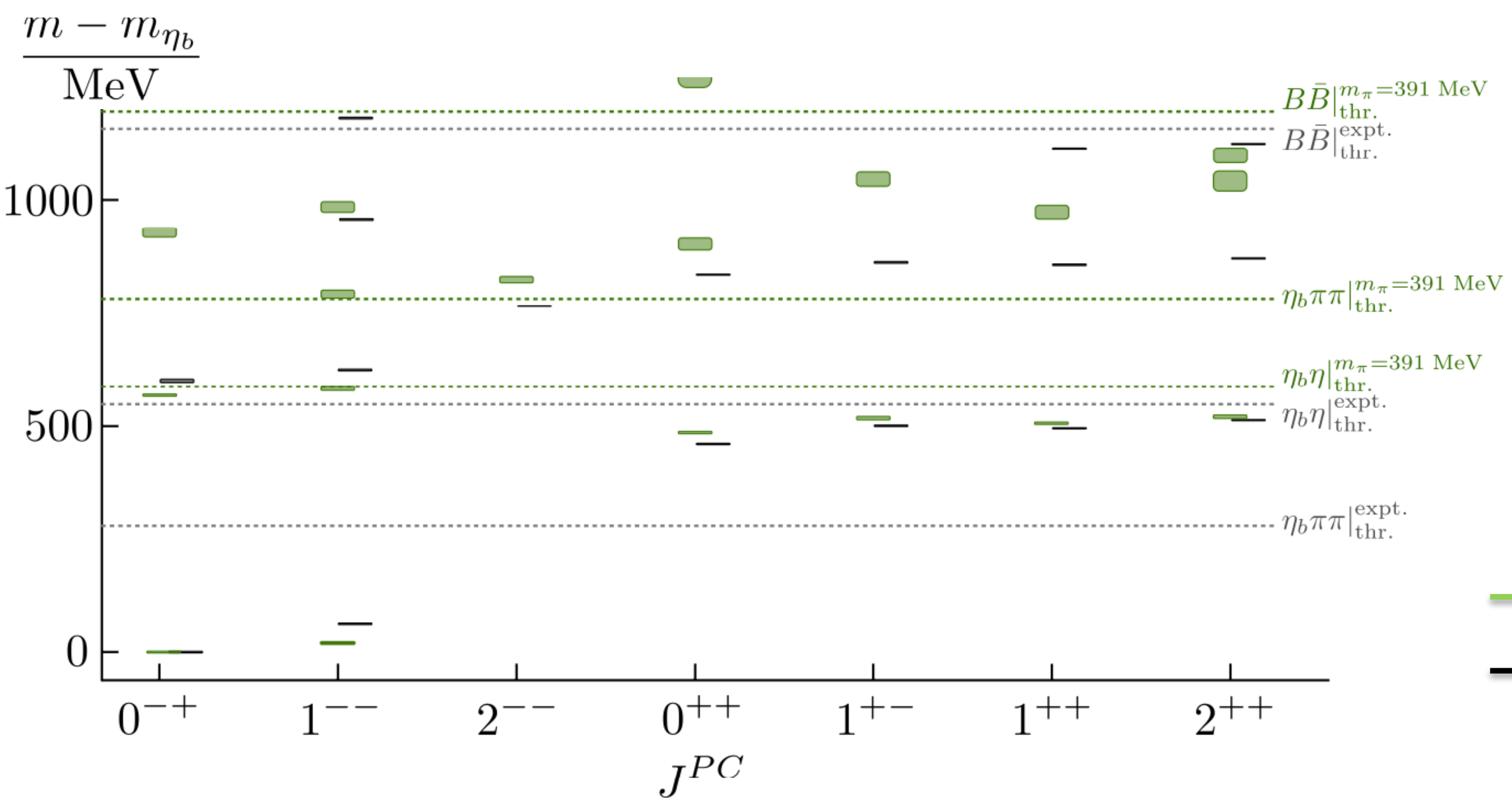
...

Strongly stable hadrons (well below threshold)

$m = E\,(\vec{p}=0)$

Example: bottomonia : reachest spectrum of (almost) strongly stable hadrons

$\bar{b}\,b$



Ryan & Wilson (HadSpec)
2008.02656, JHEP

lat — no a->0 extrapolation, $m_\pi \simeq 391\ \mathrm{MeV}$

exp

lowest lying bb and cc with m_π^{phy} and a->0, QCD+QED

HPQCD, 2101.08103, JHEP, 2204.02137: also other observables

	lat	exp
m(Υ)-m(η_b) [MeV]	57.5 (2.3) (1.0)	62.3 (3.2)

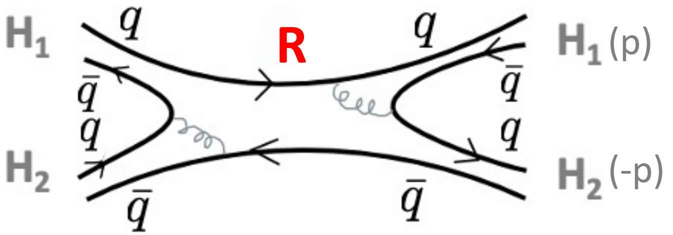
systematic error from omitted bb annihilation

General conclusion on strongly stable hadrons:

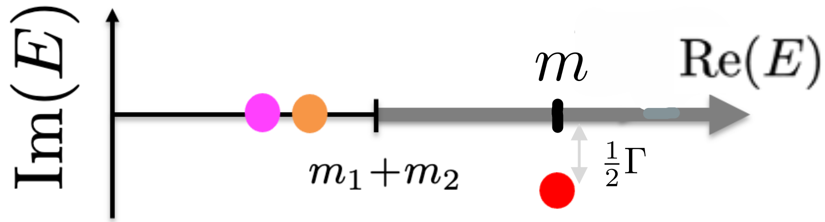
- many precision lattice studies
- QCD confronts exp data well !

Resonances R→ H_1 H_2 , bound states near threshold

see also: plenay by Pelaez



scattering amplitude T(E)

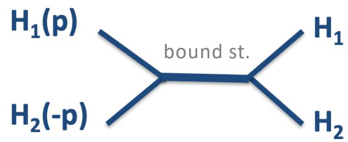


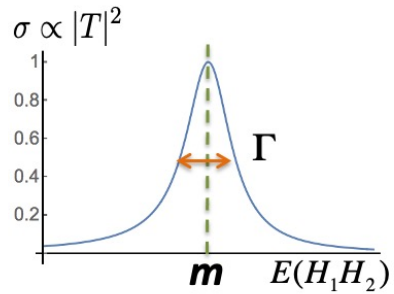
Virtual bound st. | Bound st. | Resonance

p = - i |p| | p = i |p|

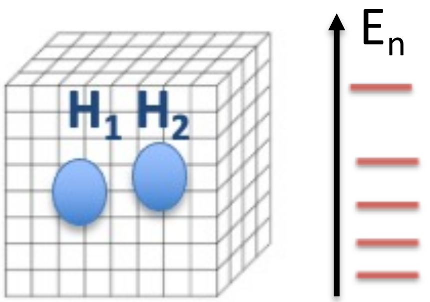
$$T(E) \propto \frac{1}{E^2-m^2}$$

$$T(E) \propto \frac{1}{E^2-m^2+iE\Gamma}$$





Scattering amplitude T(E) from lattice QCD



many resonances and bound states extracted in this way by now
(appologies for not covering all)

real E | for real E | for complex E

$$E \rightarrow T(E) \rightarrow T(E^c)$$

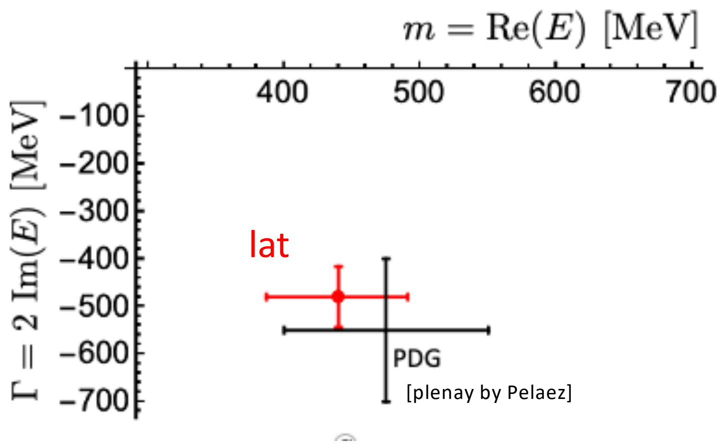
analytic relation:
Luscher 1991
generalizations by many authors

analytic contin.
to complex E

Resonances $R \to H_1 H_2$ examples

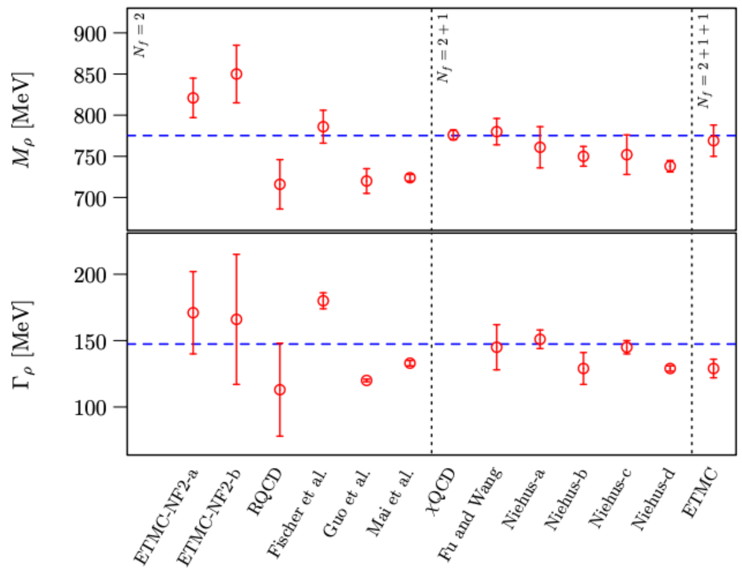
GWU, 1803.02897 $m_\pi = 227, 315$ MeV $\to m_\pi^{phy}$ UChPT

$\sigma \to \pi\pi$



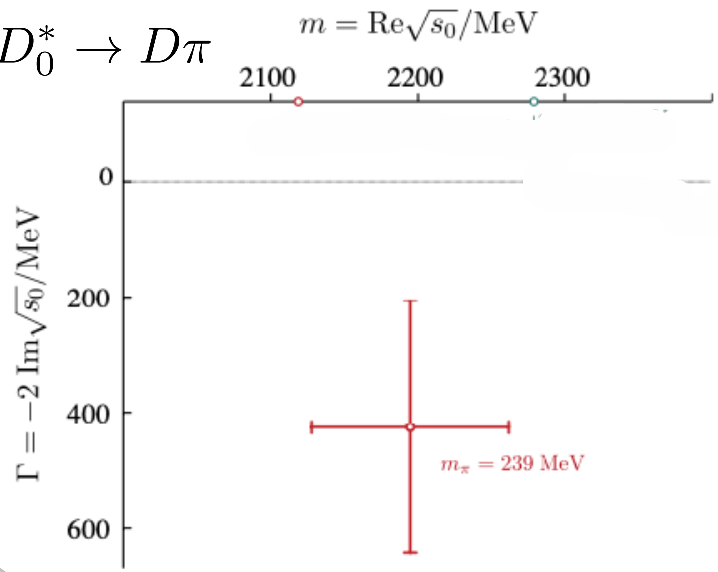
$\rho \to \pi\pi$

from review
Mai, Meissner, Urbach 2206.01477



HadSpec, 2102.04973 JHEP

$D_0^* \to D\pi$



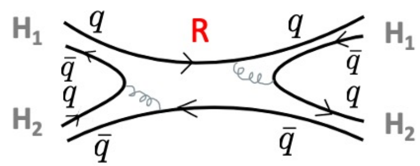
$J^P = 0^+$

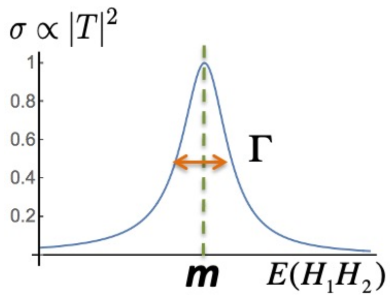
PDG: puzzle

$$m[D_0^*] \simeq m[D_{s0}^*(2317)]$$

lat: OK

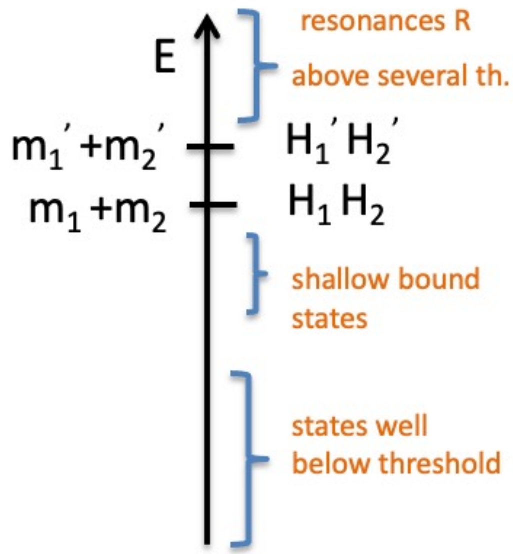
$$m[D_0^*] < m[D_{s0}^*(2317)]$$





see also: plenay by Pelaez

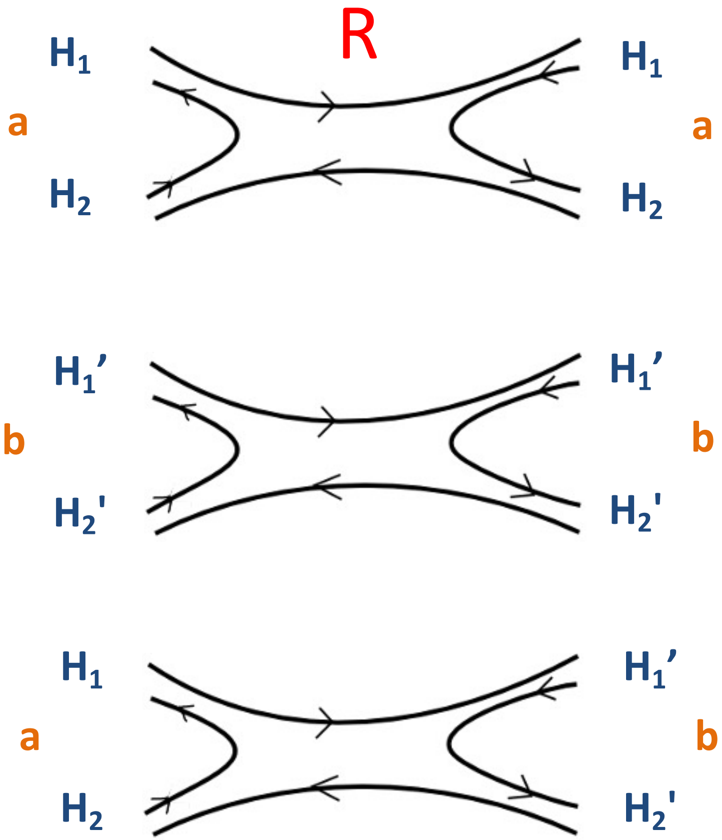
Resonances from coupled-channel scattering



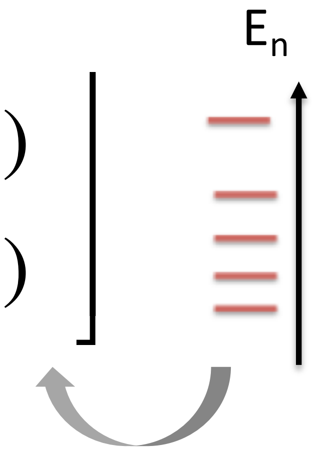
$$R \to H_1 H_2,\ \ H_1' H_2', \ldots$$

channel a : H_1H_2

channel b : $H_1'H_2'$

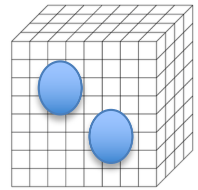


$$T(E) = \begin{array}{cc} \text{a -> a} & \text{a -> b} \\ \left[\begin{array}{cc} T_{aa}(E) & T_{ab}(E) \\ T_{ab}(E) & T_{bb}(E) \end{array}\right] & \\ \text{b->a} & \text{b -> b} \end{array}$$



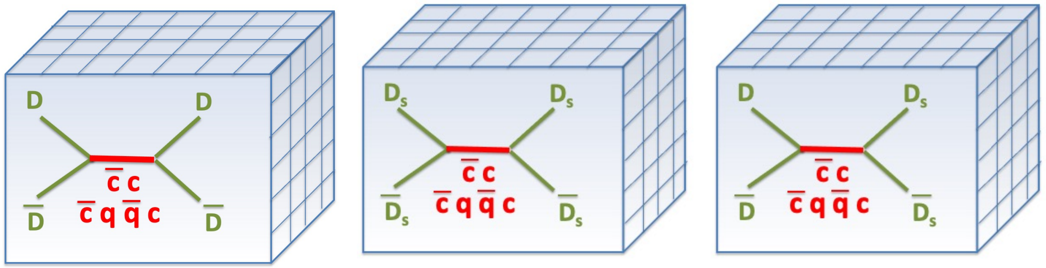
- lattice QCD studies extracted T(E) for several resonances

generalized. Luscher's rel.



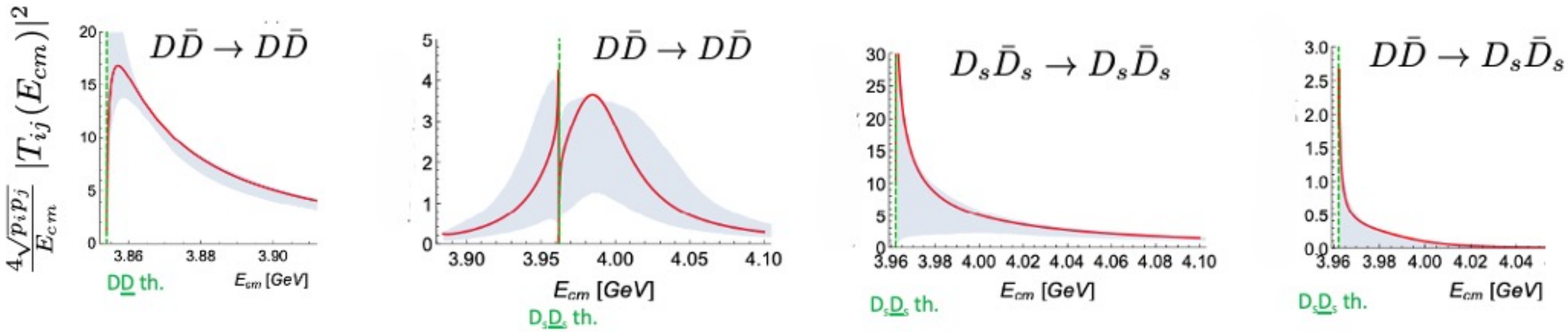
Resonances from coupled-channel scattering

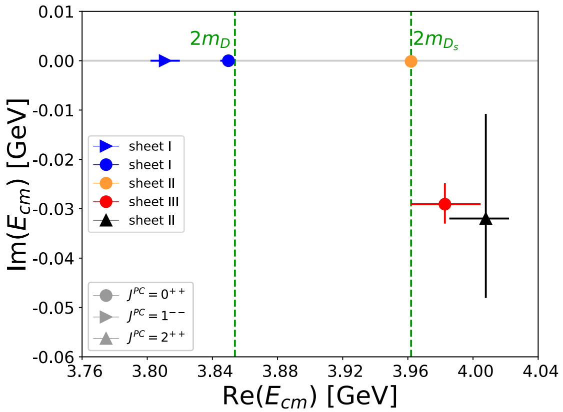
- most results by HadSpec. coll.: mostly light meson sector
- example in heavy-quark sector $\bar{c}c$, $\bar{c}q\bar{q}c$ q=u,d,s $I=0$



two coupled channels

$$D\bar{D} - D_s\bar{D}_s$$





S.P. , Collins, Padmanath, Mohler, Piemonte
2011.02542 JHEP
physics interpretation: two slides later

journey to various hadron sectors

(with heavy quarks)

exciting experimental discoveries by:

LHCb, Belle, BesIII, Babar, ...

most of discovered exotic hadrons contain heavy quarks:

(these are more likely to be quasi-bound due to small kinetic energy of Q)

Q=c,b   q=u,d,s

$\bar{c}c\ ,\quad \bar{c}c\ \bar{q}q$

$\bar{b}b\ ,\quad \bar{b}b\ \bar{q}q$

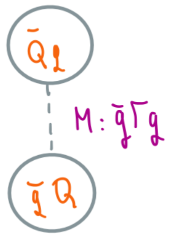
$QQ\ \bar{q}\bar{q}$

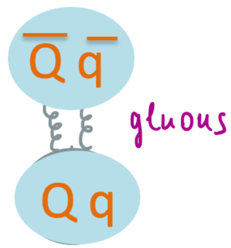
$\bar{Q}q\ ,\quad \bar{Q}q\ \bar{q}q$

dibaryons

possible binding mechanisms

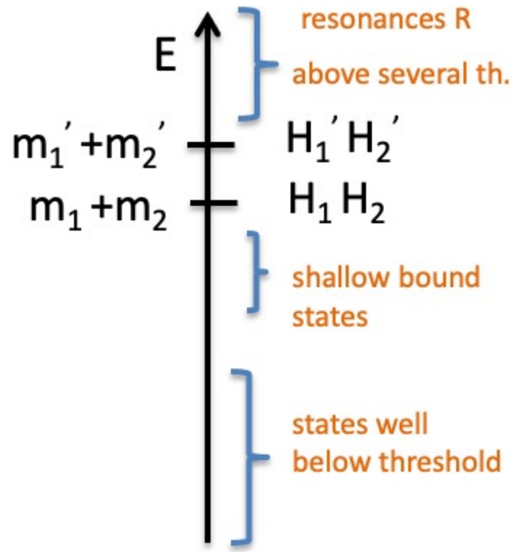
"molecule"





...

analogous



How challenging is a given state for ab-initio study? General rule:

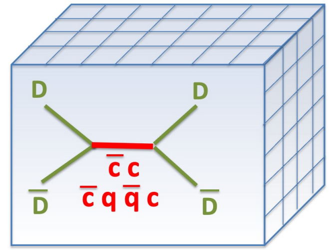
more strong decay channels -> more challenging

charmonium(like) sector

$\bar{c}c$, $\bar{c}q\bar{q}c$

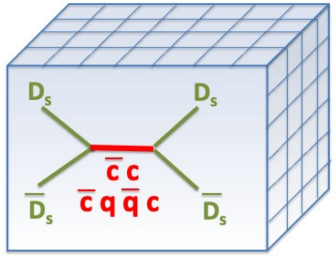
Charmonium(like) resonances and bound states

$\bar{c}c$, $\bar{c}q\bar{q}c$ q=u,d,s $I=0$



$\bar{D}_s D_s$ J^P=0$^+$ state

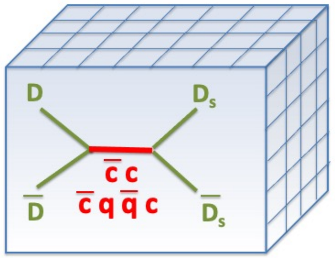
likely related to X(3915) / χ_{c0}(3930) / X(3960)
[BaBar, LHCb 2009.00026, LHCb 2022 indico..../1176505/]
explaining why it has narrow width to $\underline{D}$D.
Supported by some pheno studies:
Lebed, Polosa 1602.08421, Oset et al . 2207.08490,
Guo et al, 2101.01021, ...



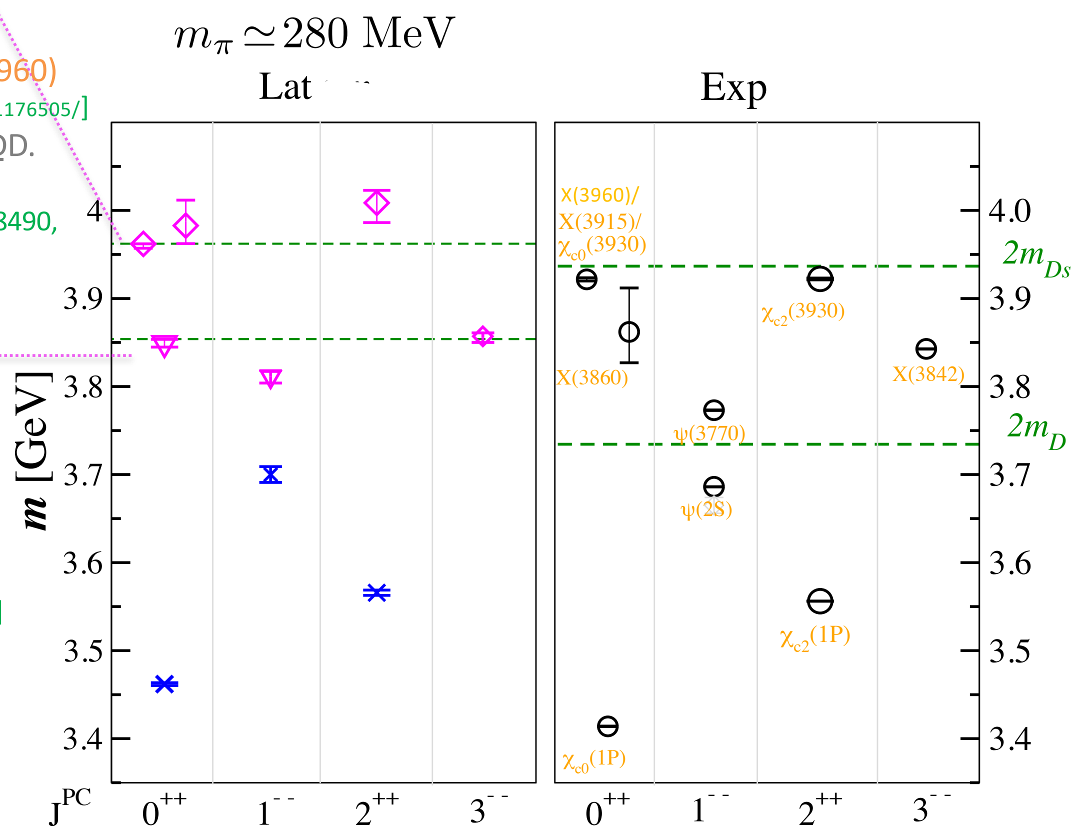
$\bar{D}D$ J^P=0$^+$ state

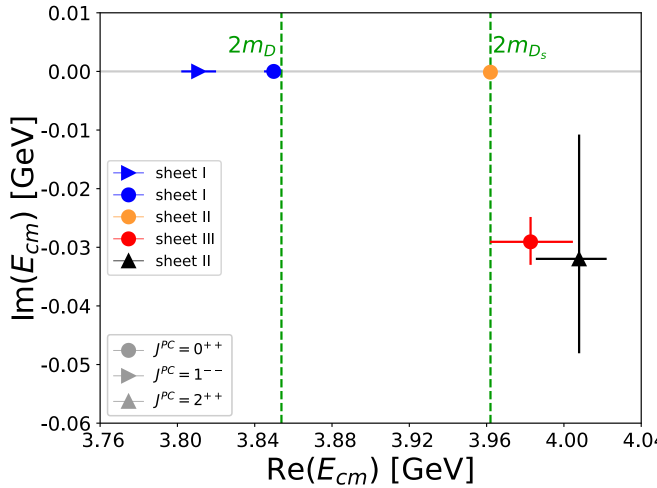
predicted in models [Oset et al, 0612179 PRD, Hildago Duque et al 1305.4487, Baru et al 1605.09649 PLB]

seen in dispersive re-analysis of exp.
[Deineka, Danilkin et al 2111.15033, poster]



+ expected conventional charmonia





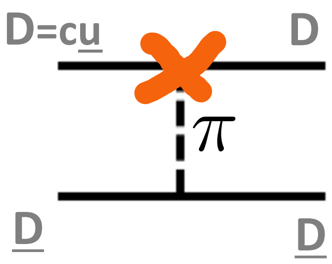
S.P. , Collins, Padmanath, Mohler, Piemonte
2011.02542 JHEP, 1905.03506 PRD, 2111.02934

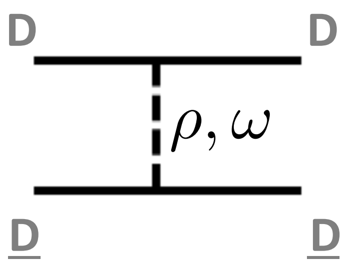
Likely interpretation of some near-threshold states: "molecules" attracted by V exchange

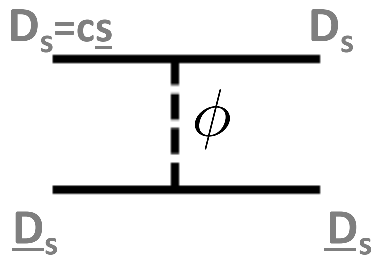
a number of pheno studies
Oset et al, 0612179 PRD,
Wu, Molina, Oset, Zou, 1007.0573, PRL
Guo et al, 2101.01021,...

$\bar{c}q\bar{q}c$ $I=0$ $J^P=0^+$

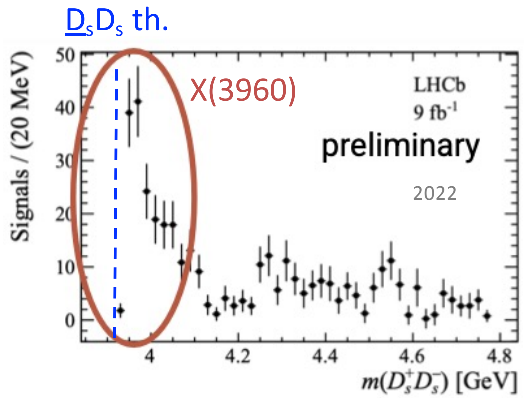
$\bar{D}D$ $\bar{D}_sD_s$







indico.cern.ch/event/1176505/, july 2022

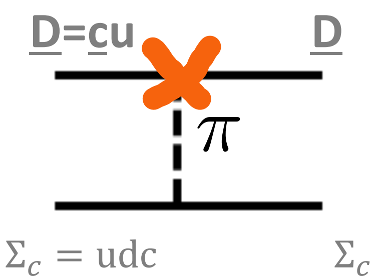


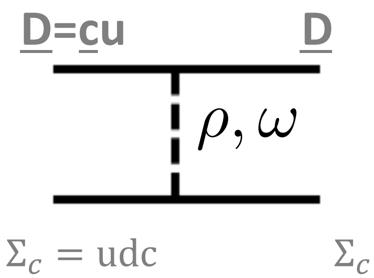
now support also from lattice

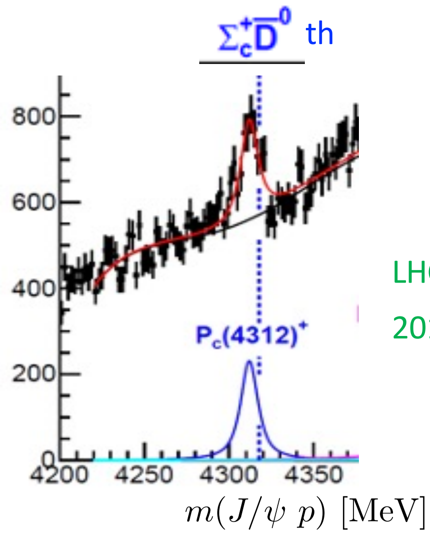
LHCb discoveries:
talk by Mikhasenko

$c\bar{c}uud$

$\bar{D}\Sigma_c$







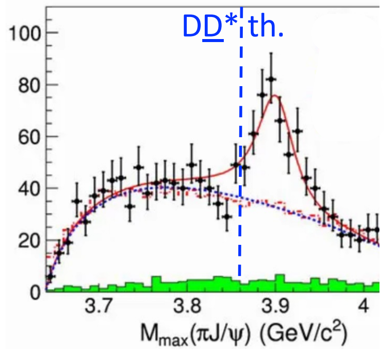
LHCb
2019

currently to challenging for lattice

Charmonium(like) resonances

$\bar{c}c\bar{d}u$ $Z_c(3900)$

[BessIII & Belle 2013]

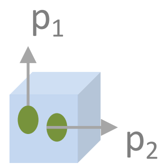


$$\bar{c}c\bar{d}u \to D\bar{D}^*,\ J/\psi\pi$$

status from lattice QCD: still challenging, giving perhaps puzzling results

- E_n close to the non-interacting E_n^{ni}

$$E^{n.i.}(H_1H_2) = \sqrt{\vec{p}_1^2 + m_1^2} + \sqrt{\vec{p}_2^2 + m_2^2} \qquad \vec{p}_i = \vec{n}_i\ \frac{2\pi}{L}$$



- very small interaction between mesons observed
- this should already constrain some models and interpretations
- perhaps consistent with virtual bound st. found by some approaches?
  [talk by Rodriguez Entem]

consistent conclusions from studies via Luscher's method
[Leskovec Mohler Lang SP: 1308.2097, 1405.7623
HadSpec 1709.01417
Liuming Liu et al. 1907.03371, 1911.08560,
M. Sadl, SP, Padmanath, Collins @ lattice 2022]

HALQCD method

Ikeda et al., HALQCD, 1602.03465, PRL

- indication of large coupling between both channels
  that could be responsible for Zc(3900) peak in exp

bottomonium(like) sector

$\bar{b}b$ $\bar{b}b\bar{q}q$

Bottomonia and bottomonium hybrids, I=0

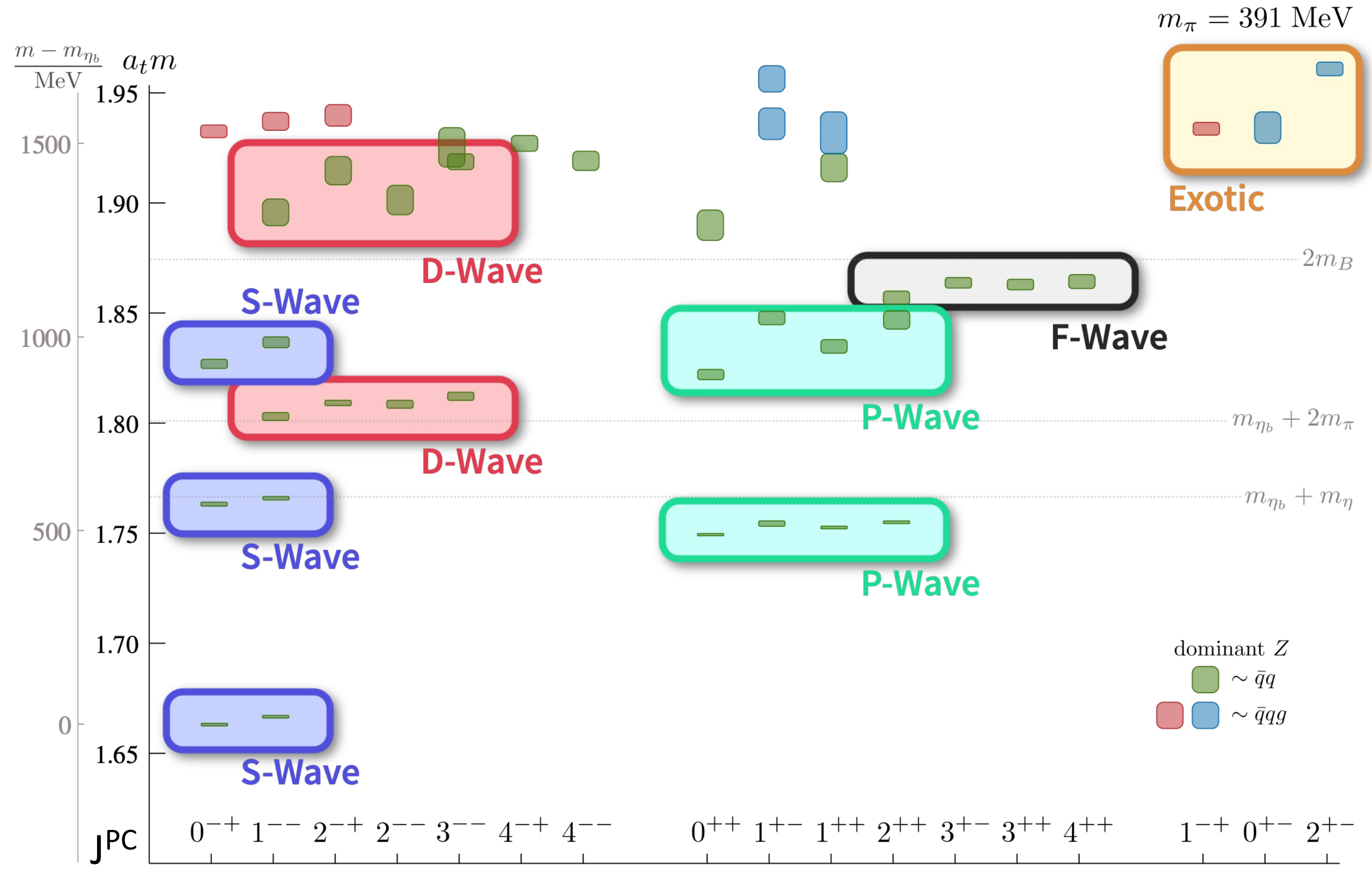
$\bar{b}\, b$ $\bar{b}Gb$

omitting effects from strong decays and thresholds

Lattice QCD
relativistic b quarks
Ryan & Wilson (HadSpec)
2008.02656, JHEP
(same result as shown earlier)

m = E_n(p=0)

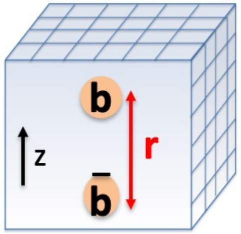
$\frac{m - m_{\eta_b}}{\text{MeV}}$

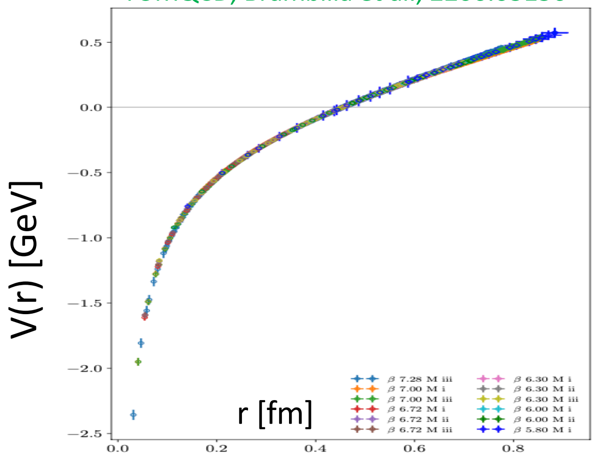


$m_{hybrid} \geq 10.9$ GeV

Bottomonia (I=0) from static potentials & Born Oppenheimer approximation & EFTs

many other determinations, e.g. Wagner et al
TUMQCD, Brambilla et al., 2206.03156





masses of low-lying $\bar{b}\,b$

confinement

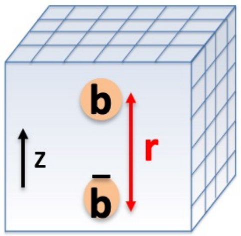
determination of α_s

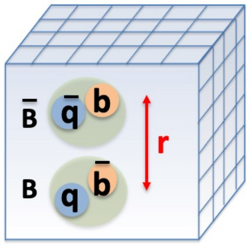
e.g. works of TUMQCD, Leino et a. [2020-2022]

string breaking

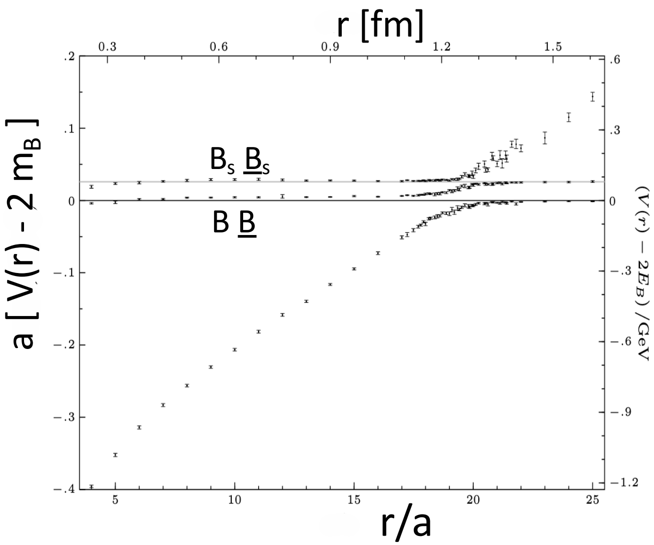
SESAM, Bali et al, 2005, 0505012

Bulava et al, 1902.04006, PLB





q=u,d,s



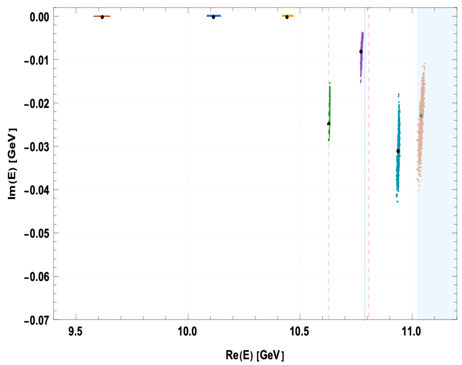
Bicudo, Cardoso, Mueller, Wagner, 2205.11475,

$\tilde{J}$=0: here; $\tilde{J}$=1,2,3 in the paper;

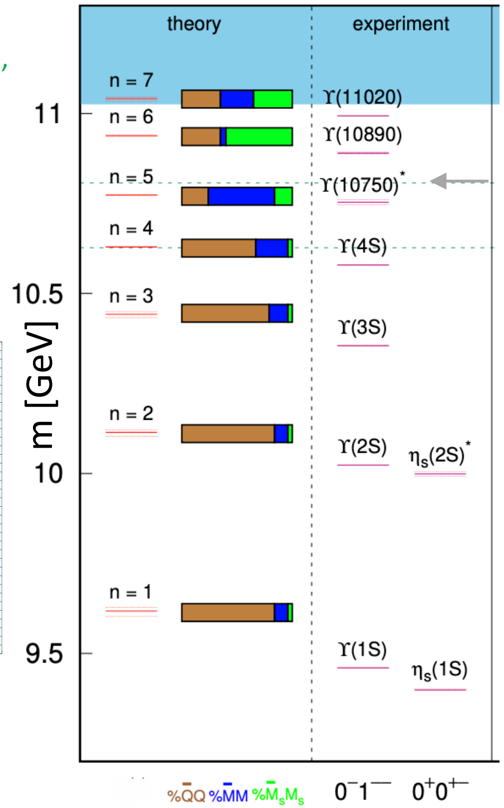
$\tilde{J}$=total ang. mom. without heavy quark spins

$\bar{b}b$ $\bar{b}b\bar{q}q$

poles



see also: Castella, 2207.09365



exotic st [Belle 2019]

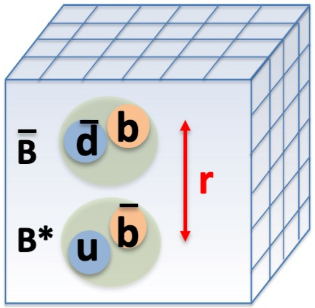
Bottomonium-like states from static potentials & Born Oppenheimer approximation & EFTs

$I=1,\ J^P=1^+$

$\bar{b}b\bar{d}u$

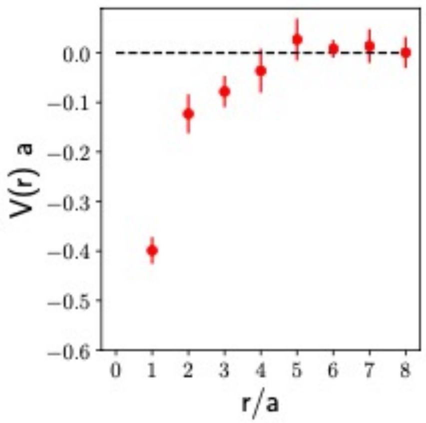
$\bar{b}b\bar{d}u \rightarrow B\bar{B}^*$

$\Upsilon\pi$



Peters, Wagner, Bicudo

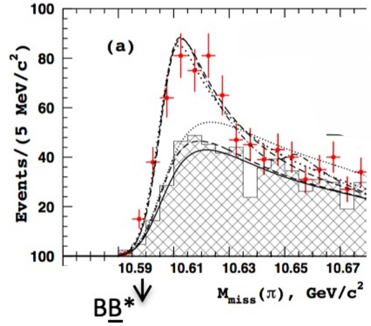
SP, Bahtiyar, Petkovic, Sadl 2019, 2020



bound state just below BB* th.

likely related to

Z_b [Belle, 2011, 2016]



Brambilla, 2111.10788;

Soto & Castella, 2005.00552

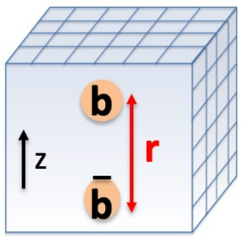
I=0, various J^P

$\bar{b}\, b$

$\bar{b}Gb$

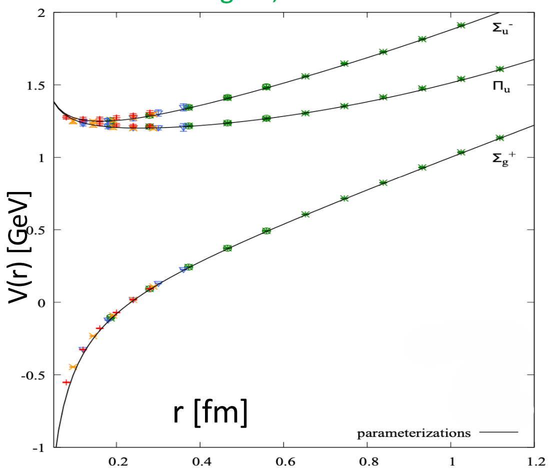
omit strong decays

quenched

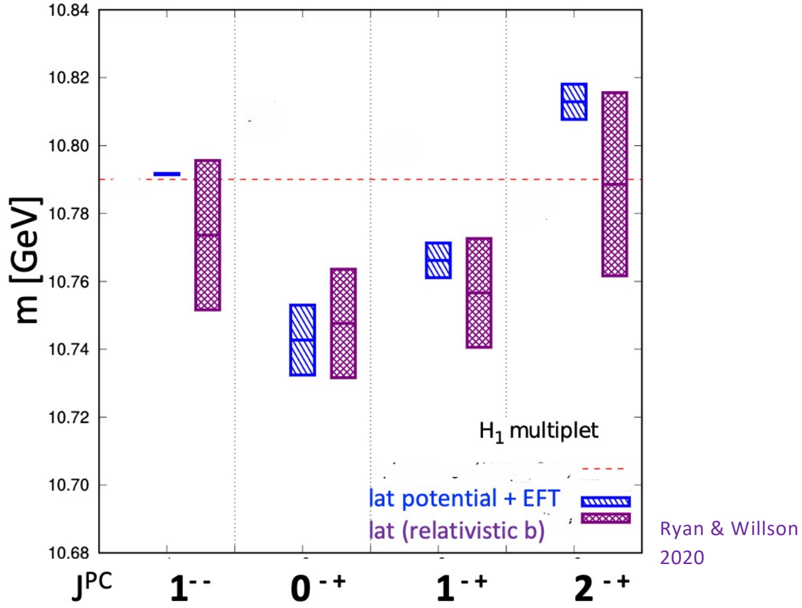


Juge, Kuti, Morningstar, 1997, 1998

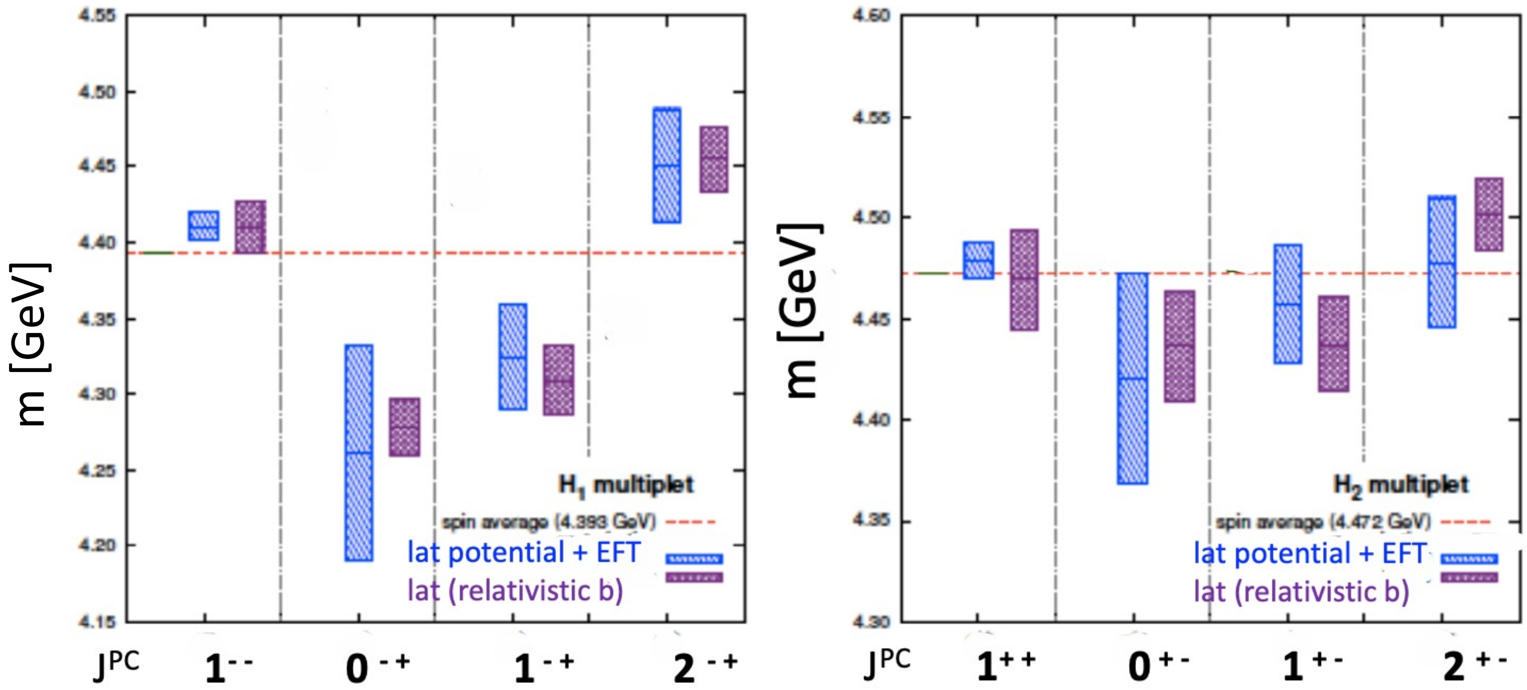
Schlosser & Wagner, 2111.00741



$\bar{b}Gb$ Segovia, Tarrus; Brambilla MITP 2022 (unpublished, with 1/mb spin effects)



see also: Brambilla et al, 1805.07713, 1908.11699, PRD analogous comparison



TUMQCD, Brambilla et al.
Cheung et al, HadSpec, 2016

Doubly heavy tetraquarks

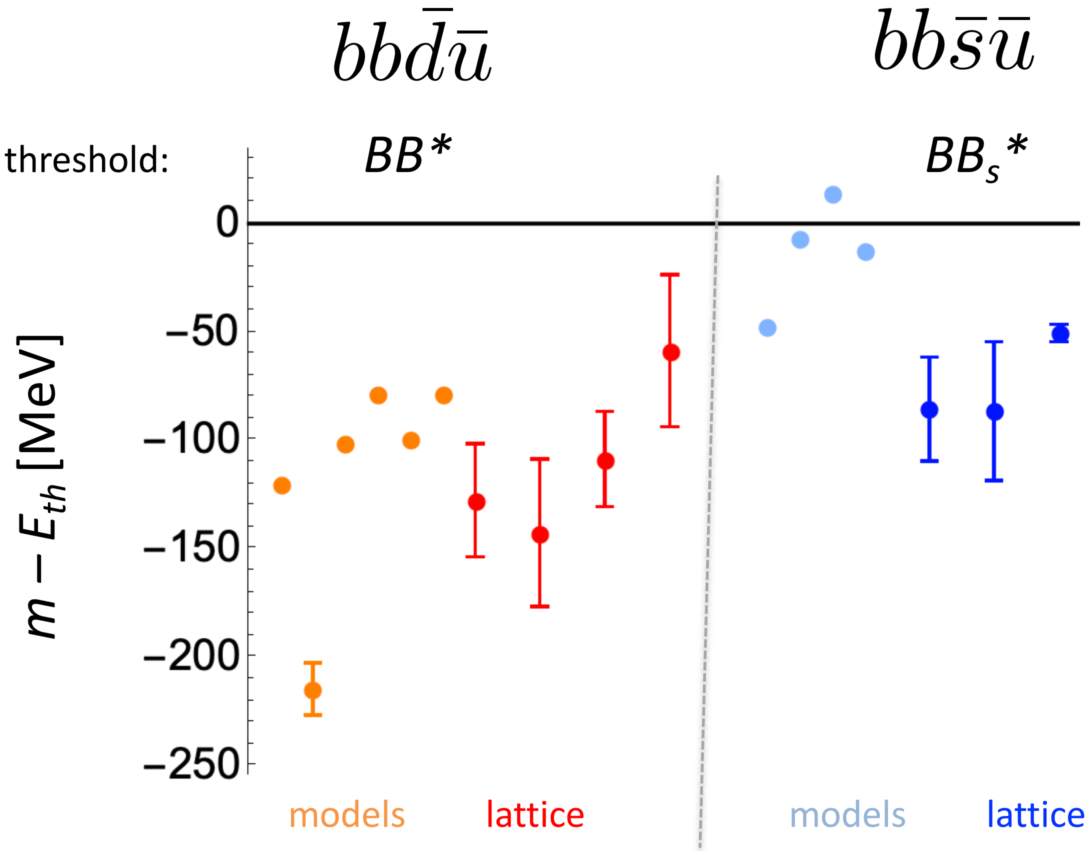
$$QQ'\bar{q}\bar{q}'$$

Q=c,b q=u,d,s

Doubly bottom tetraquarks

not found in exp, difficult to find

$bb\bar{d}\bar{u}$ $bb\bar{s}\bar{u}$ $I=0,\ J^P=1^+$



references from left to right

models (many more references):
Eichten and Quigg (2017) 1707.09575 PRL
Karliner and Rosner (2017) 1707.07666 PRL
Ebert et al. (2007) 0706.3853
Silvestre-Brac and Semay (1993)
Janc and Rosina (2004) hep-ph/0405208

lattice: most updated results
Leskovec, Meinel, Pflaumer, Wagner (2019) 1904.04197
Junnarkar, Mathur, Padmanth (2018) 1810.12285
Frances, Colquhoun, Hudspith, Maltman (2021) preliminary
Bicudo, Wagner et al. 1612.02758 static potentials

models (many more references)
Eichten and Quigg (2017) 1707.09575 PRL
Parket al. (2018) 1809.05257
Ebert et al. (2007) 0706.3853
Silvestre-Brac and Semay (1993)

lattice: most updated results
Meinel, Pflaumer, Wagner (2022) 2205.13982
Junnarkar, Mathur, Padmanth (2018) 1810.12285
Frances, Colquhoun, Hudspith, Maltman (2021) preliminary

lattice	$m_{u/d}$	a [fm]
Leskovec , Pflaumer, Wagner, Meinel	$m_{u/d}$ -> $m_{u/d}^{phy}$	0.08-0.11
Junnarkar et al.	$m_{u/d}$ -> $m_{u/d}^{phy}$	a -> 0
Francis et al	$m_{u/d}$ -> $m_{u/d}^{phy}$	0.09
Bicudo et al.	$m_{u/d}$ -> $m_{u/d}^{phy}$	0.08

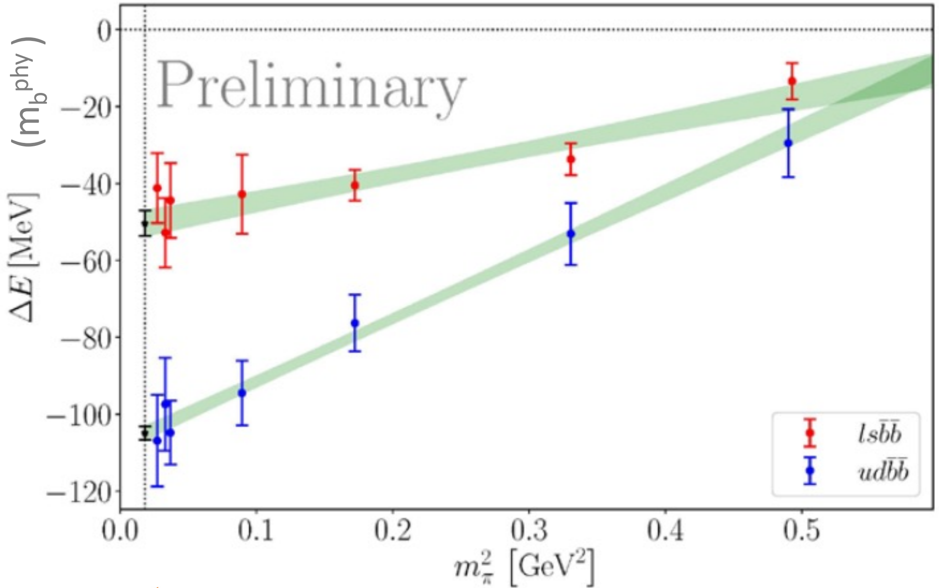
extracted also
$BB_{(s)}{}^*$ scattering amplitudes

earlier results of Frances et al in 1810.10550, 1607.05214 PRL

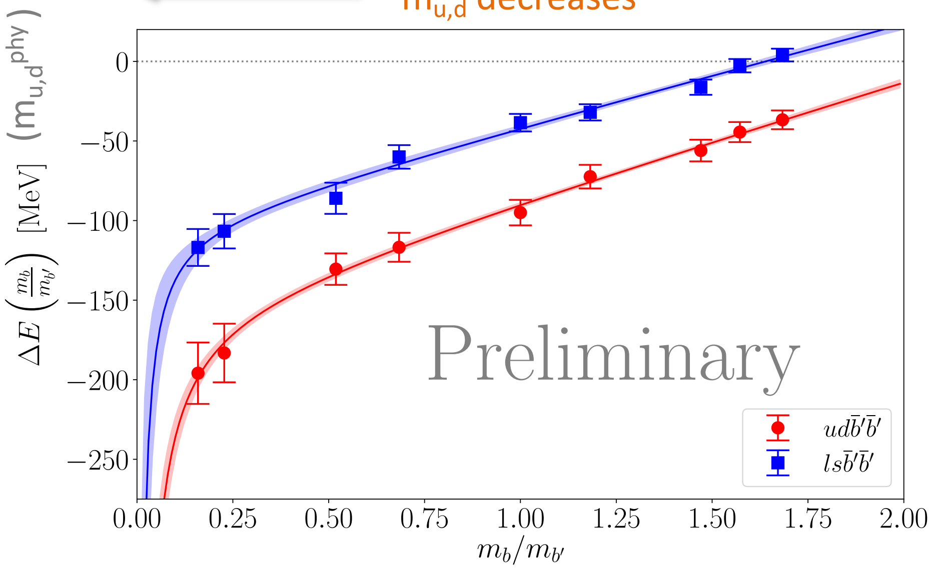
Doubly bottom tetraquarks

$bb\bar{d}\bar{u}$ $bb\bar{s}\bar{u}$ $I=0,\ J^P=1^+$

lattice: dependence on m_b and $m_{u,d}$



$m_{u,d}$ decreases



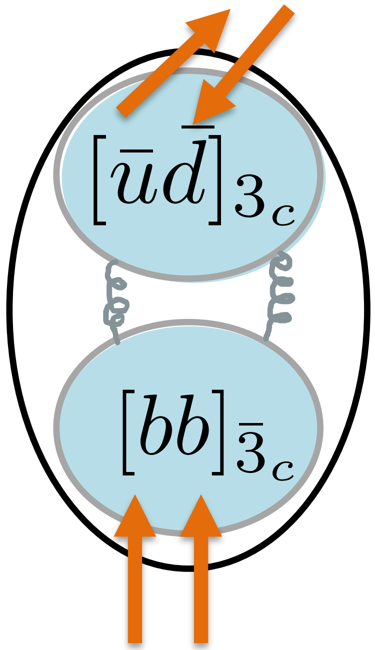
$m_{b'}$ increases

Colquhoun, Francis, Hudspith, Maltman, Lewis
1810.10550 , *PoS* LATTICE2021 (2022) 144
supports internal structure below

supported also by almost all model studes
Karliner and Rosner (2017), Janc and Rosina (2004), ...

color Coulomb

strongly binds bb



these are the only tetraquarks where lattice
finds support for significant [qq][qq]

good and bad diquark properties:
Francis et al, 2201.03332

Other $QQ'\bar{q}\bar{q}'$ and J^P

$b c \bar{d} \bar{u} \quad c c \bar{d} \bar{u}$

Theoretically expected near or above threshold

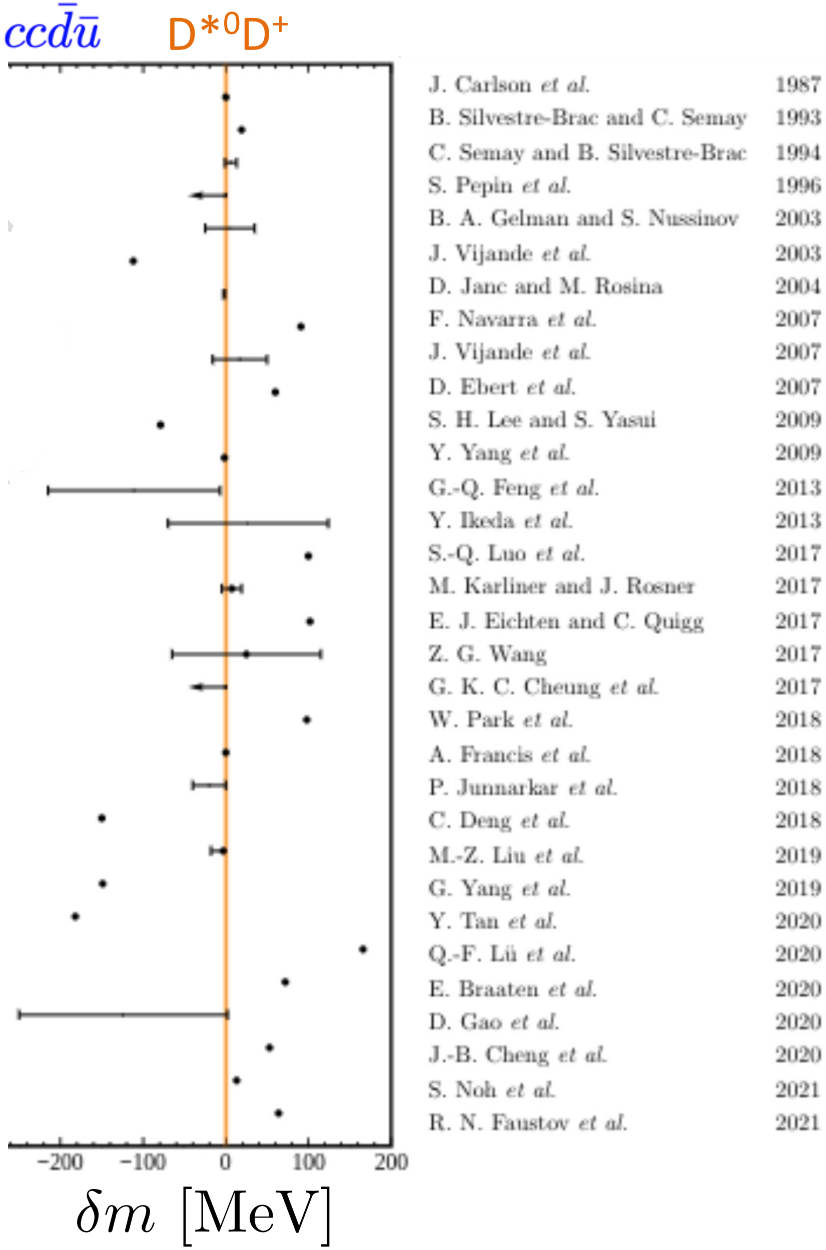
States near or above threshold have to be identified as poles in scattering T(E)

Other $QQ'\bar{q}\bar{q}'$ and J^P

$bc\bar{d}\bar{u}$ $\quad cc\bar{d}\bar{u}$

Theoretically expected near or above threshold

States near or above threshold have to be identified as poles in scattering T(E)



Theoretical predictions for T_{cc} mass (I=0, $J^P=1^+$)

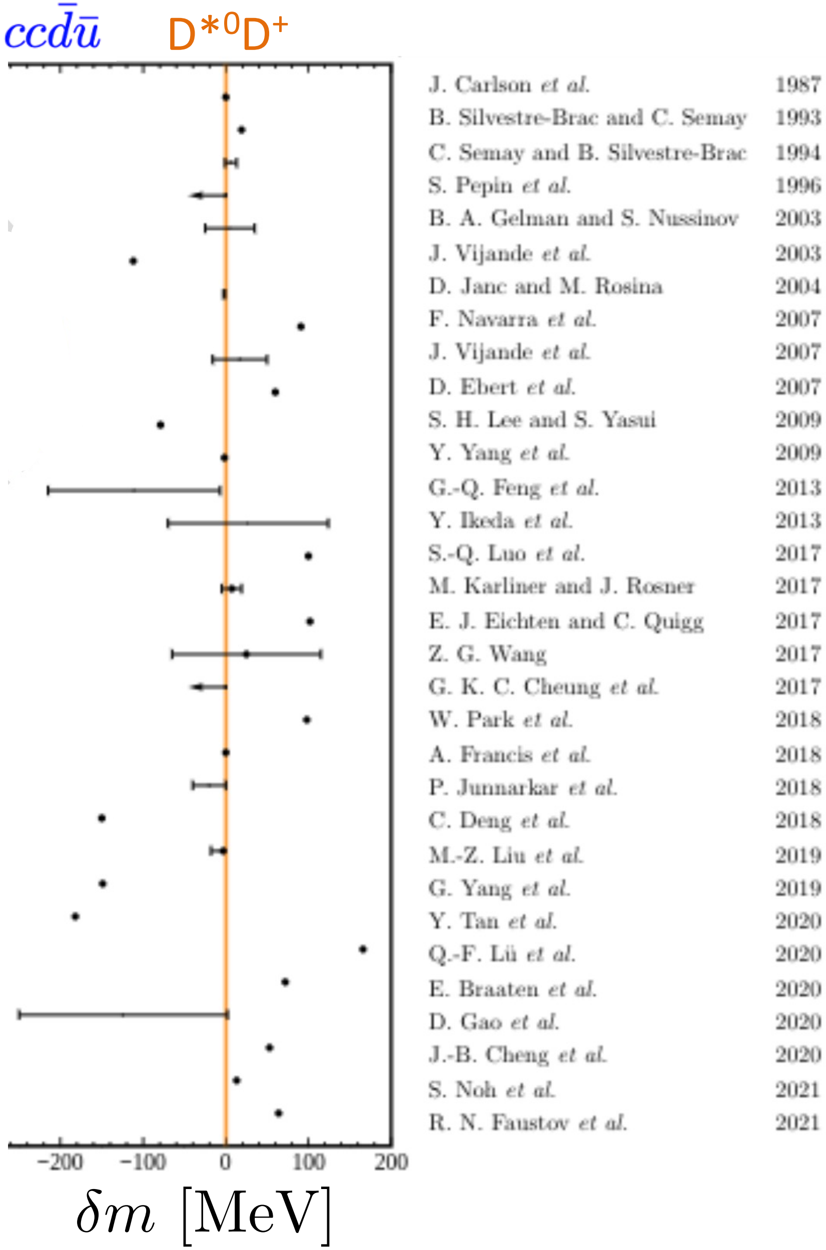
[compilation by Polyakov]

Other $QQ'\bar{q}\bar{q}'$ and J^P

$bc\bar{d}\bar{u}$ $cc\bar{d}\bar{u}$

Theoretically expected near or above threshold

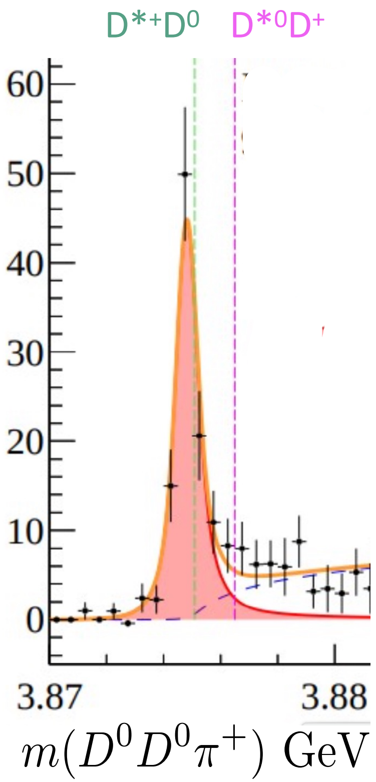
States near or above threshold have to be identified as poles in scattering T(E)



Theoretical predictions for T_{cc} mass (I=0, $J^P=1^+$)

[compilation by Polyakov]

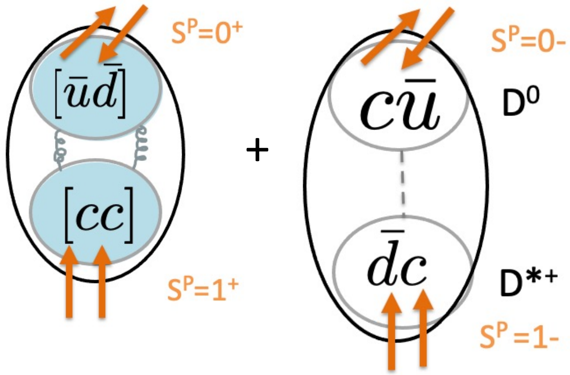
Doubly charm tetraquark T_{cc} $cc\bar{d}\bar{u}$



$$\delta m = m - (m_{D^{*+}} + m_{D^0})$$

$$\delta m_{pole} = -0.36 \pm 0.04 \text{ MeV}$$

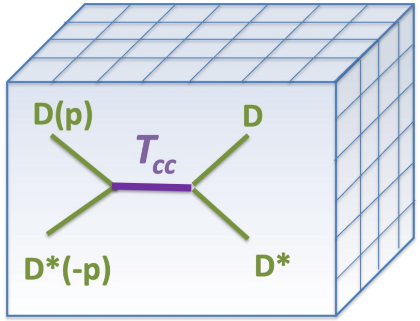
LHCb 2109.01038, 2109.01056, Nature Physics



likely dominant

Doubly charm tetraquark T_{cc} from lattice QCD

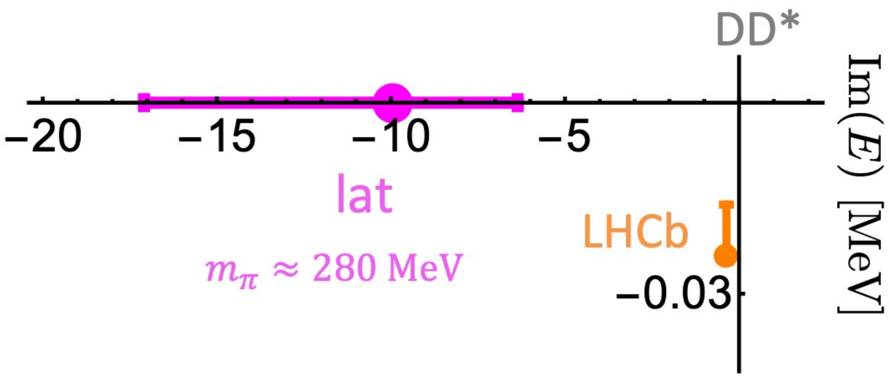
$cc\bar{d}\bar{u}$ $\quad J^P = 1^+,\ I=0$



What is virtual bound state? See supplemental of 2202.10110, PRL

Pole of T(E) ● virtual bound state pole p = -i|p|

$$\delta m_{T_{cc}} = \mathrm{Re}(E) - m_{D^0} - m_{D^{*+}} \ \ [\mathrm{MeV}]$$



- The first lat. study that extracts T(E):
  [Padmanath, SP: 2202.10110, PRL] $m_\pi \approx 280$ MeV
- Evidence for pole related to Tcc
- For $m_{u,d} > m_{u,d}^{phy}$ one expects decreased attraction
  T_{cc} : bound state becomes virtual bound state
  this is indeed found on the lattice

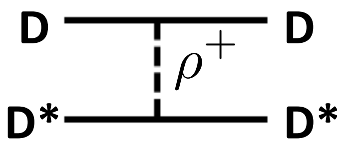
Sketch of expected binding energy

$\delta m = E^p_{cm} - E_{th}$

another recent lattice study: CLQCD, Chen et al. 2206.06185

comparison of I=0,1 : attraction in I=0 channel arises mainly from

$m_\pi \simeq 350$ MeV



prevoious simulations extracted only eigen-energies:

[Junnarkar, Mathur, Padmanath, 1810.12285 PRD ; HadSpec 1709.01417 JHEP]

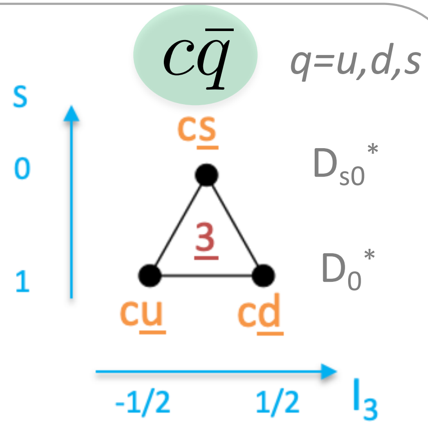
Dyson Schwinger: Fischer et al. 2111.15310: I=0 state near threshold found

Scalar heavy-light mesons

$J^P = 0^+$

Conventional quark model

$c\bar{q}$ q=u,d,s



new paradigm supported by:

- lattice
- effective models ChPT+HQET
- reanalysis of exp data
- states circled by blue seem to feature in the spectrum

Scattering on the lattice

S=1 Mohler et al, 1308.3175, PRL
Lang et al, 1403.8103, PRD
RQCD, 1706.01247, PRD
HadSpec 2008.06432, JHEP

S=0 Mohler et al. 1208.4059, PRD
HadSpec, 1607.07093, JHEP
HadSpec 2102.04973, JHEP
HadSpec 2205.05026

S=-1 HadSpec, 2008.06432, JHEP

New paradigm

$c\bar{q}$ + $c\bar{q}\ q\bar{q}$ q=u,d,s n=u,d

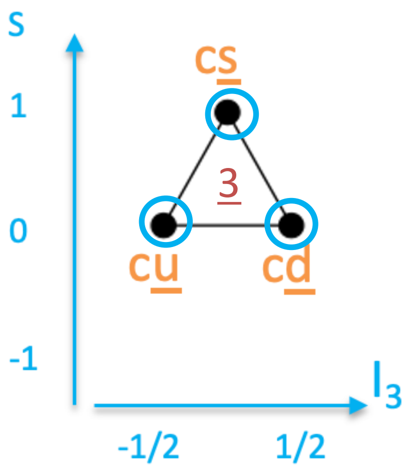
$\underline{3} \otimes 8 = \underline{3} \oplus 6 \oplus 15$ SU(3)$_F$

Du et al, 1712.07957, PRD
Albaladejo et al, 1610.06727, PLB
Lutz et al (2003), 0307133, PLB

Beveren, Rupp; Dmitrasinovic

2.3 GeV

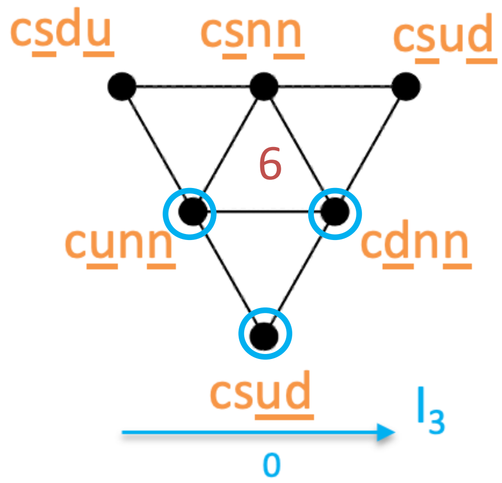
lat: 2.1-2.2 GeV (pole)
PDG: 2.3 GeV (BW)
(see backup)



attractive

mix

~~SU~~(3)$_F$



attractive

mixes with repulsive 15

2.4-2.5 GeV
reanalysis of lat 1607.07093 by Albaladejo 1610.06727

virtual bound state
HadSpec 2008.06432
partner of X(2900)
[LHCb 2009.00025] ?

Di-baryons

binding energy $\Delta E = m - m_{B1} - m_{B2}$

H-dibaryon

many lattice studies:

NPLQCD, CalLAT, Mainz, ...

mostly at mu=md=ms

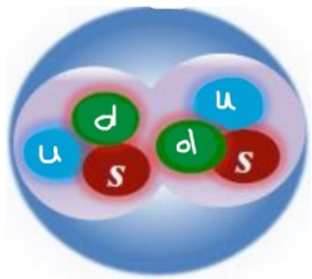
[Mainz group, 2103.01054 PRL]

$$m_\pi = m_K \simeq 420 \text{ MeV}$$

$$\Delta E = -4.56 \pm 1.13_{\text{stat}} \pm 0.63_{\text{syst}} \text{ MeV.}$$

significant discretization effects on ΔE found

physical m_q : ??
experimentally not confirmed (yet)



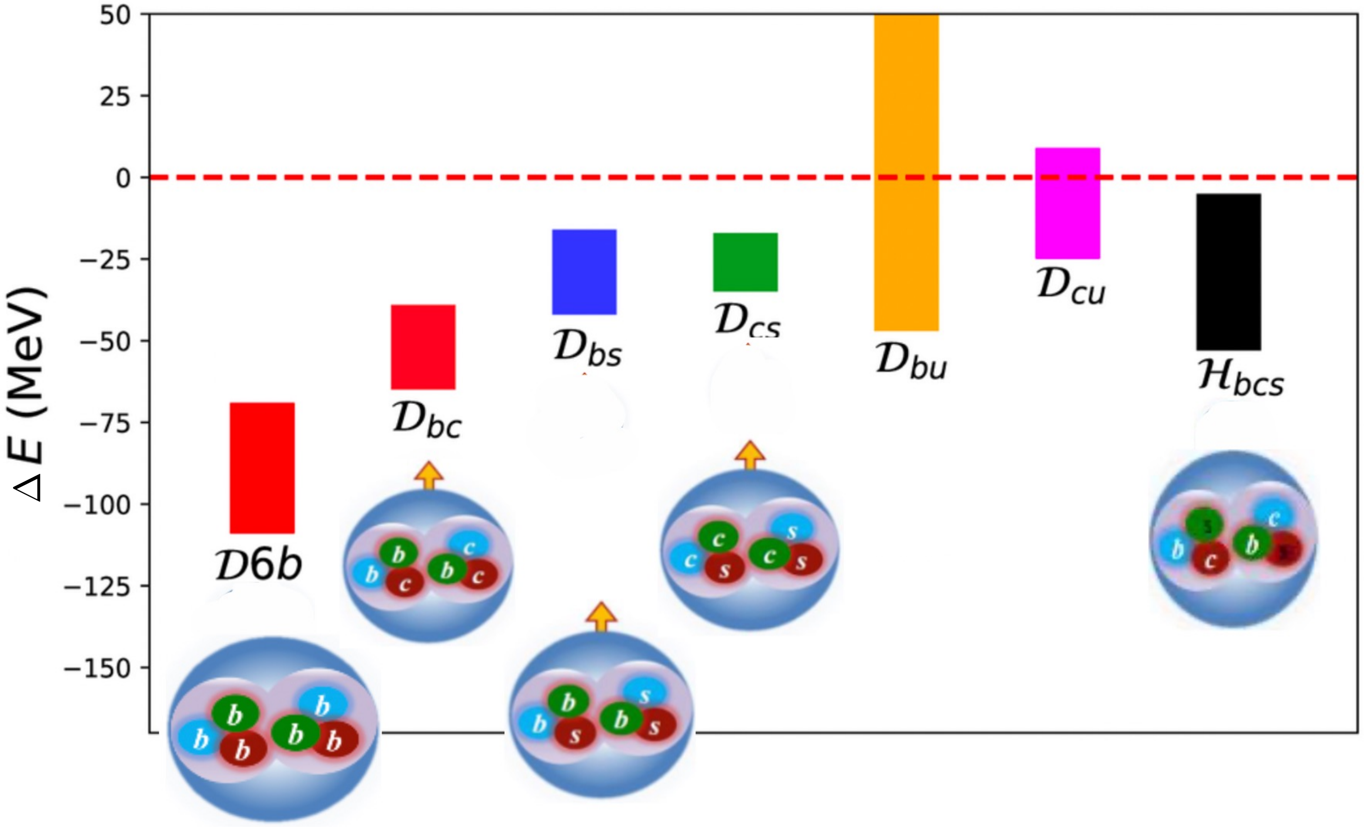
$\Lambda \ \Lambda$

dibaryons with heavy quarks

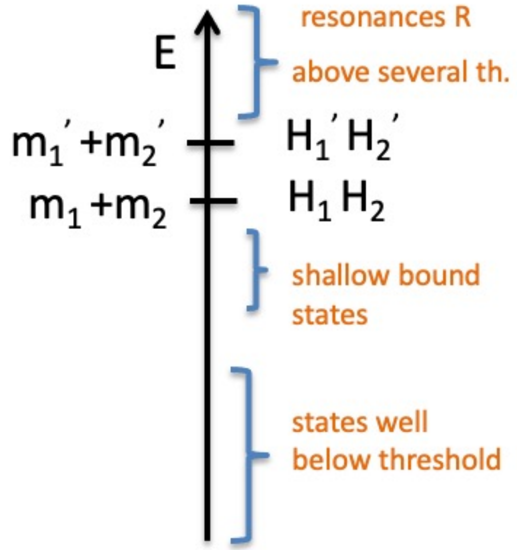
Junnarkar Mathur
1906.06054, PRL 2019

Mathur, Padmanath, Chakraborty
2205.02862

Junnarkar, Mathur, 2206.02942



Conclusions



Compliments to experiments for GREAT results !!

Status on hadrons from Lattice , Lattice + EFTs:

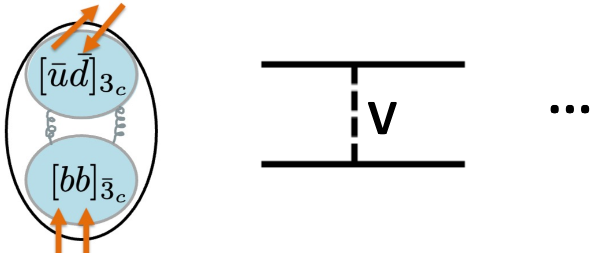
- hadrons that are not resolved (yet)

  strongly decay via many decay channels: P_c , $Z_c(4430)$, X(6900),...

- available: valuable results on conventional and exotic hadrons

  strongly stable ; strongly decaying to 1,2,3 channels

  support for specific binding mechanisms



  one picture can not explain all exotic hadrons

  for each exotic hadron there is at least one viable picture

A direction that might lead to a valuable insight into dynamics of hadrons:

identify and inspect states that can be rigorously studied by theory and well explored by experiments

quark-mass dependence of these states in theory ... could lead to further clues about their nature backup

Hadrons $\bar{Q}Q\bar{q}q,\quad \bar{Q}Qqqq$

Q=c,b q=u,d,s

$Z_b = \bar{b}b\bar{d}u$ [Belle 2011] $P_c = \bar{c}cuud$ [LHCb 2015]

$Z_c = \bar{c}c\bar{d}u$ [BessII, Belle, 2013]

GRRR!

challenging for ab-initio study

due to many decay channels:

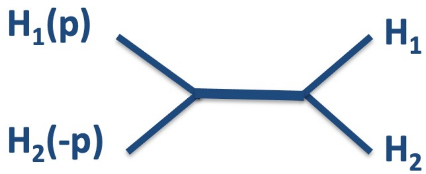
$$\bar{Q}Q\bar{q}q \to \bar{Q}q + \bar{q}Q, \quad \bar{Q}Q + \bar{q}q$$

$$\bar{Q}Qqqq \to \bar{Q}q + Qqq, \quad \bar{Q}Q + qqq$$

Only partial conclusions are available from ab-initio approaches [reviewed e.g. in S.P. 2001.01767]

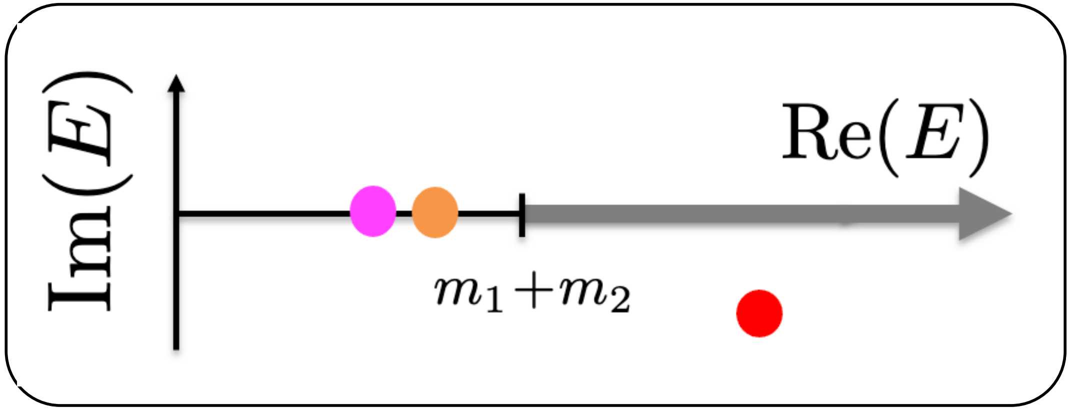
I'll discuss other approaches (also due to lack of time).

Definitions: bound state, virtual bound state & resonance



$$T(E) \propto \frac{1}{E^2 - m^2} \qquad\qquad T(E) \propto \frac{1}{E^2 - m^2 + iE\Gamma}$$

Poles of *T(E)*, *E=E* $_{cm}$



Virtual bound st. Bound st. Resonance

p = - i |p| p = i |p|

$$E = \sqrt{m_1^2 + p^2} + \sqrt{m_2^2 + (-p)^2} \; < \; m_1 + m_2$$

Bound and virtual bound state: simplest example
scattering in square-well potential in QM

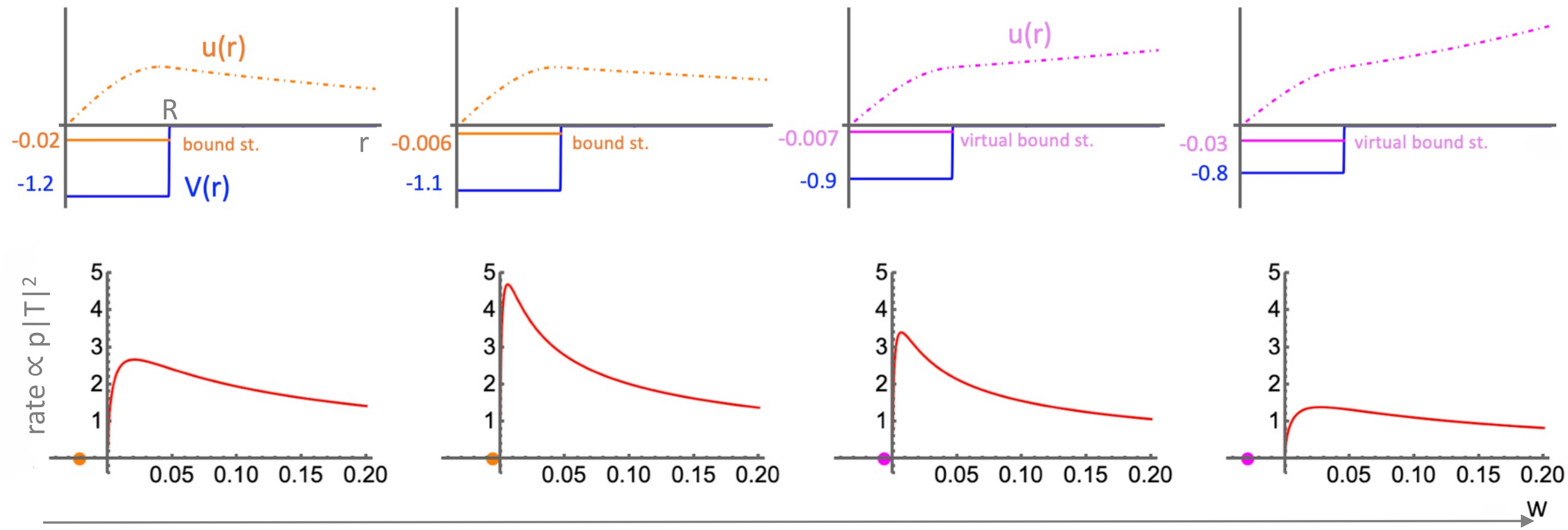
partial wave l=0

$$\delta_l = \arctan[\tan(qR)\tfrac{p}{q}] - pR$$

$u(r) = A\sin(qr)$ $\quad$ $u(r) = B\sin(pr+\delta)$

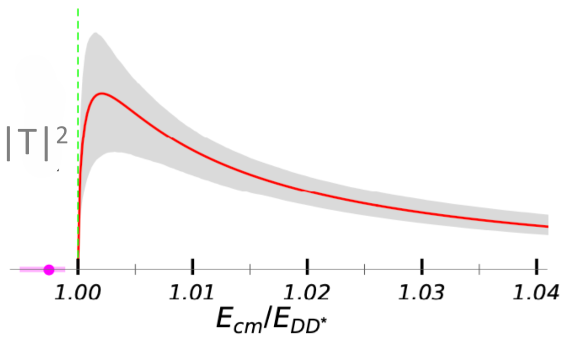
p=i|p| $\quad e^{ipr} = e^{-|p|r}$

p=-i|p| $\quad e^{ipr} = e^{|p|r}$



increasing $m_{u/d}$, decreasing attraction

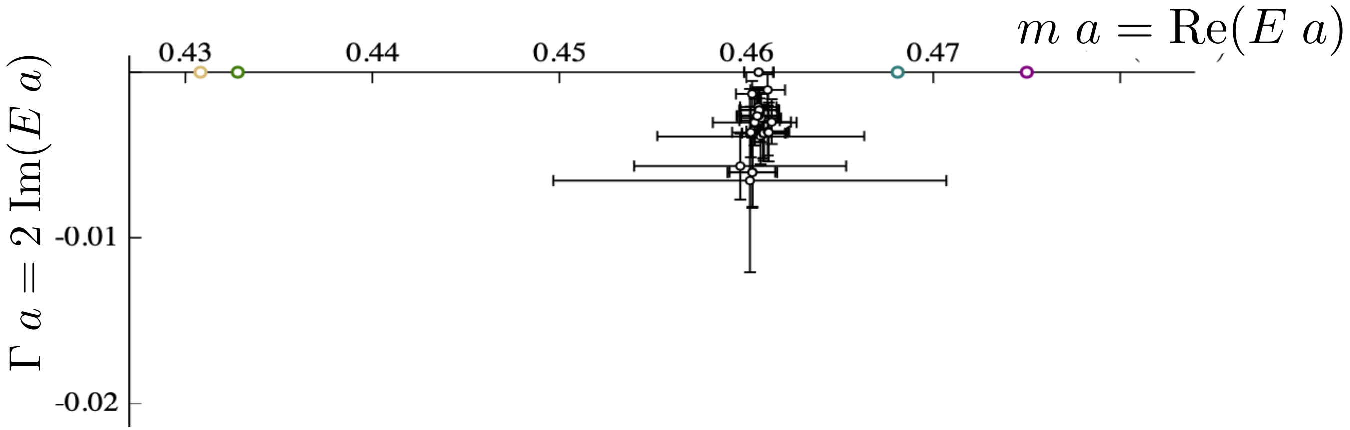
DD* rate ∝ p|T|²



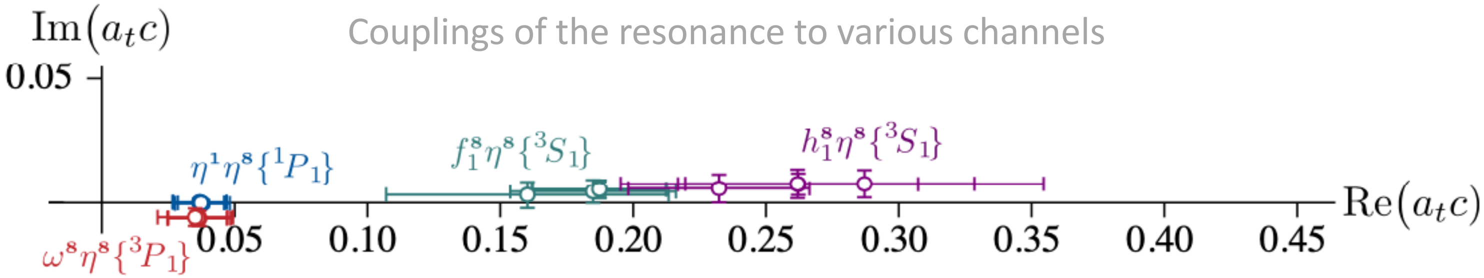
for T_{cc} extracted on lattice

light hybrid meson π_1 from lattice

$\bar{d}Gu$ $\quad J^{PC} = 1^{-+}$



Couplings of the resonance to various channels



$$T_{ij} \sim \frac{c_i\ c_j}{E_p^2 - E^2}$$

Woss et al. (HadSpec) 2009.10034

$m_u = m_d = m_s$, $m_\pi \approx 700\ MeV$

pheno analysis

physical world

$\rho\ \pi$ $\quad \eta'\ \pi$ $\quad f_1\ \pi$ $\quad b_1\ \pi$

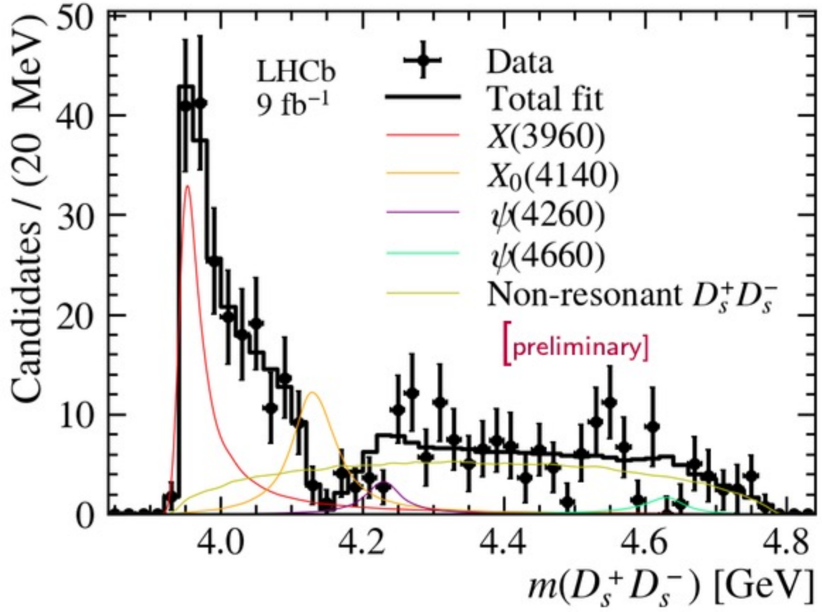
dominant coupling

resemblence to experimental $\pi_1(1564)$: COMPASS+JPAC Rodas 1810.04171 [PRL]

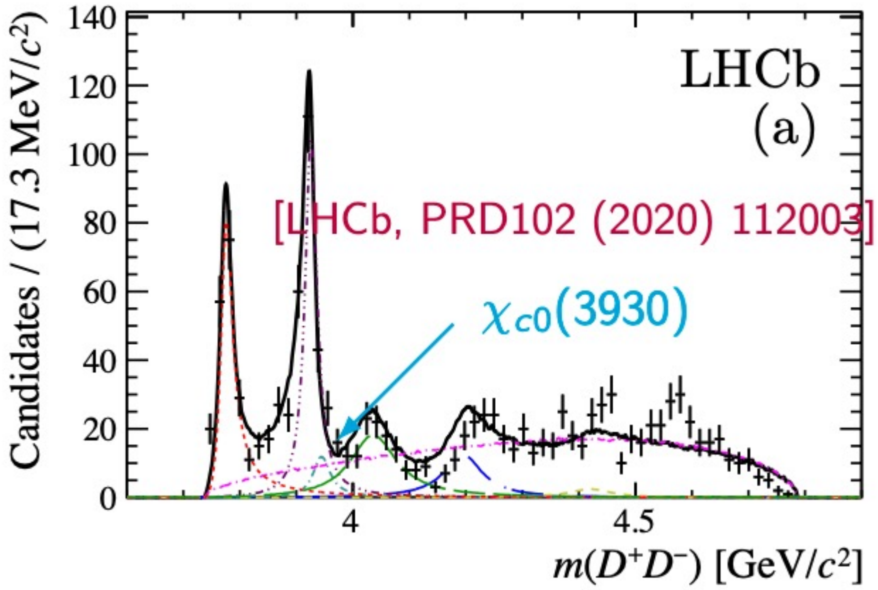
$\pi_1(1564)$ in COMPASS+JPAC replaces two older resonances $\pi_1(1400)$ and $\pi_1(1600)$

Is $X(3960)$ the same as $\chi_{c0}(3930)$ from D^+D^-?

$B^+ \to (D_s^+ D_s^-) K^+$ by LHCb:



$B^+ \to (D^+ D^-) K^+$ by LHCb:



- Assuming to be the same, $\mathcal{B}(\chi_{c0} \to D^+D^-)/\mathcal{B}(\chi_{c0} \to D_s^+D_s^- P) \sim 0.3$
  large molecular component, or large tetraquark component, $T_{\psi\phi}$
- [JHEP 06 (2021) 035] finds a state coupled to $D_s^+D_s^-$ on the lattice

paralell talk by by Mikhasenko [LHCb]