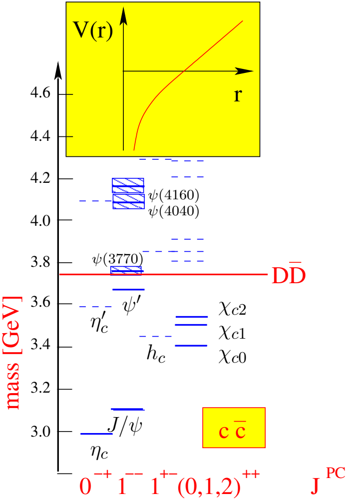
THEORY OF MULTIQUARK STATES

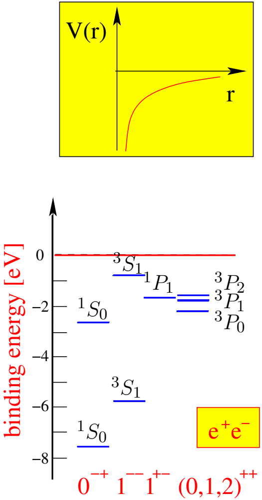
A Challenge to Our Understanding of the Particle Spectrum

March 14, 2024 | Christoph Hanhart | IKP/IAS Forschungszentrum Jülich

CHARMONIUM BEFORE 2003

Quark-Model: Eichten et al. PRD 17 (1978)





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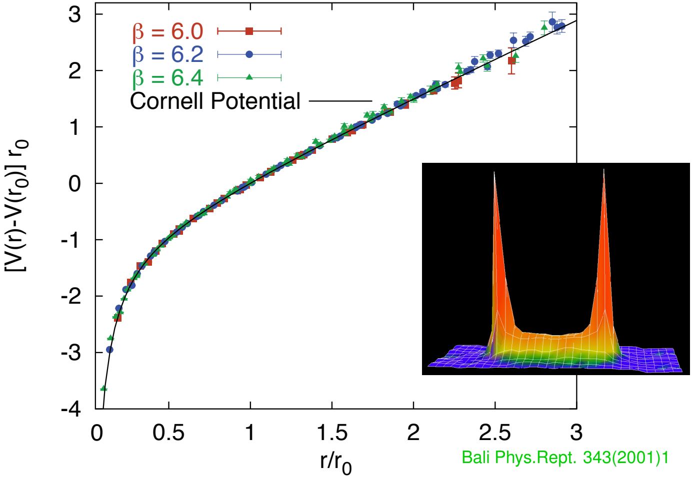
$\bar{Q}Q$ POTENTIAL FROM LATTICE

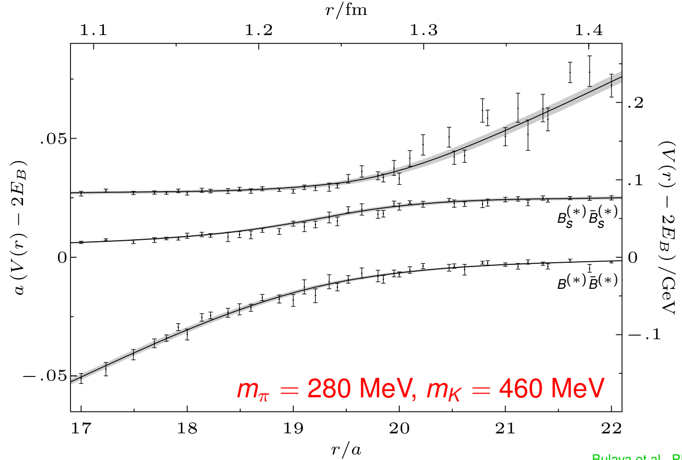
Potential of two static color sources



Bali Phys.Rept. 343(2001)1

STRINGBREAKING

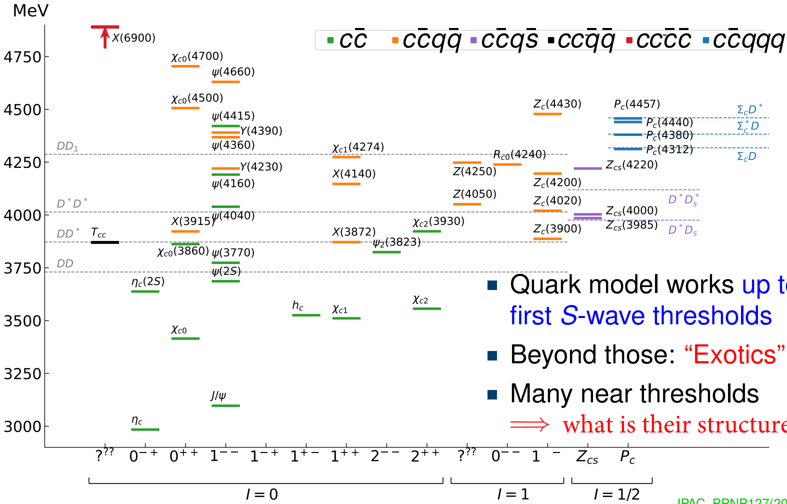
Adding light quarks: $Q\bar{Q} \to (Q\bar{q})(\bar{Q}q)$ becomes possible



Bulava et al., PLB793(2019)493

$\Longrightarrow$ string breaking for energies above first open flavor threshold

... PROVIDES NEW PHENOMENA



- Quark model works up to first *S*-wave thresholds
- Beyond those: “Exotics”
- Many near thresholds

$\Longrightarrow$ what is their structure?

JPAC, PPNP127(2022)103981

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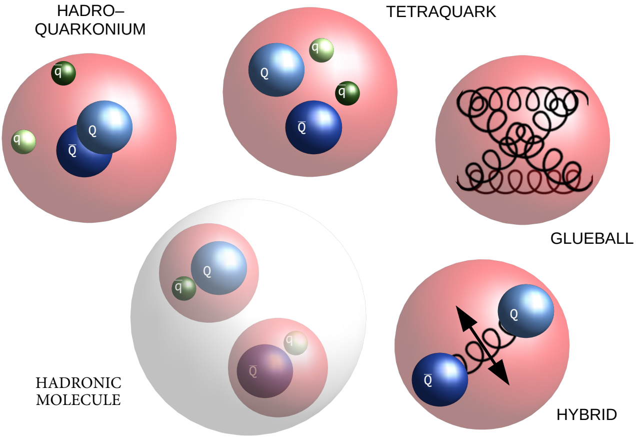
THE NAME OF THE GAME:



Picture by Soeren Lange

How can one disentangle the different multiquark structures?

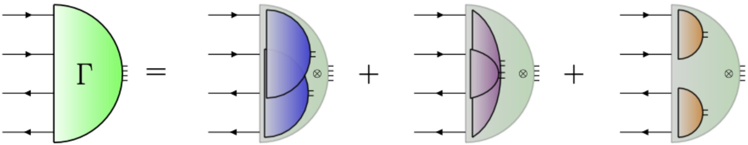
DISCLAIMER

In what follows I focus on individual scenarios, in the spirit of

What if the exotics were pure .... (put your favourite appraoch)

So far little work on the possible mixing of the structures.

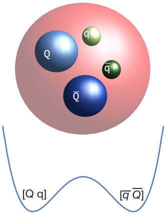
Promising approach: Dyson-Schwinger equations for multiquark states



J. Hoffer, G. Eichmann and C. S. Fischer, [arXiv:2402.12830 [hep-ph]].

So far exploratory studies for spectra, no uncertainty estimates yet ....

HEAVY TETRAQUARKS



- Straightforward extension of the quark model

  M. Gell-Mann, PL8(1964)214

- Mesons as diquark–anti-diquark systems

  Jaffe, PRD15(1977)267, Maiani et al., PRD71(2005)014028

- Building blocks: Spin 0 and 1 heavy-light diquarks
- Separated by potential well

  Selem and Wilczek, hep-ph/0602128; Maiani et al., PLB778(2018)247

- Spin-spin interaction dominant within diquarks — Maiani et al. PRD89(2014)114010
- and tensor force, S_{12}, needs to be considered — Ali et al. EPJC78(2018)29

$$M = 2M_{\mathcal{Q}} + \frac{B_{\mathcal{Q}}}{2}\mathbf{L}^2 + 2a_Y \mathbf{L}\cdot\mathbf{S} + \frac{b_Y}{4}S_{12} + 2\kappa_{cq}\left(\mathbf{S_q}\cdot\mathbf{S_c} + c.c.\right)$$

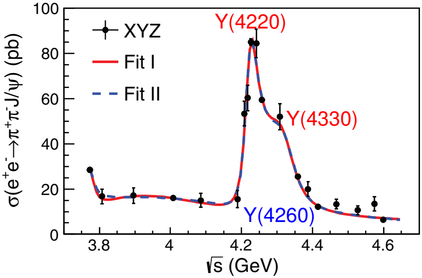
alternative approaches, e.g., Cui et al., HEPNP31(2007)7; Stancu, JPG37(2010) 075017; Bhavsar et al., NPA1000(2020)121856

$\rightarrow$ Already many ground states

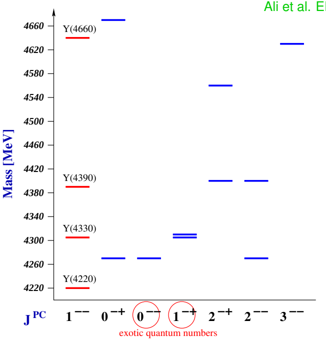
$\rightarrow$ Each level has isovector and isoscalar state (*cf*. ρ and ω)

RESULTS FOR NEGATIVE PARITY STATES

- four 1^{--} ground states: P-wave & $[0,0]_0, [1,0]_1 + [0,1]_1, [1,1]_0, [1,1]_2$
- BESIII claims 2 in $J/\psi\pi\pi$



BESIII, PRL118(2017)092001



Ali et al. EPJC78(2018)29

- Without tensor force very light 3^{--}

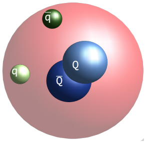
Cleven et al., PRD 92(2015)014005

- Many more states predicted than observed!

  Maybe since di-quark picture too restrictive/constraining?

Richard et al., PRD95(2017)054019

HADROCHARMONIUM



- Extra states are viewed as compact $\bar{Q}Q$ surrounded by light quarks

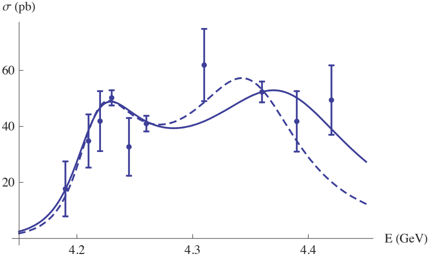
M. B. Voloshin, PPNP61(2008)455

- Provides natural explanation why, e.g., $Y(4260)$ is seen in $J/\psi\pi\pi$ final state but not in $\bar{D}D$

- Heavy quark spin symmetry demands that spin of the core is conserved in decay to charmonia

- Explaining $e^+e^- \to h_c\pi\pi$ needs mixing between states with $s_{\bar{c}c} = 0$ and $s_{\bar{c}c} = 1$ leading to $Y(4260)$ and $Y(4360)$

Li & Voloshin MPLA29(2014)1450060



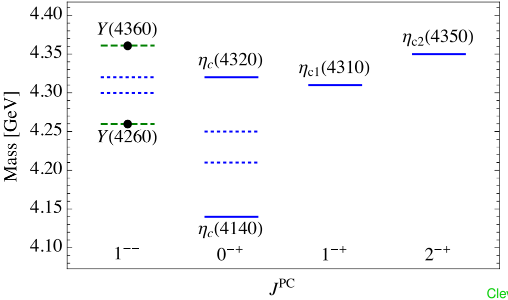
HADROCHARMONIUM: NEW STATES

The above mentioned mixing suggests for the unmixed states:

$$\Psi_3 \sim (1^{--})_{c\bar{c}} \otimes (0^{++})_{q\bar{q}} \qquad \Psi_1 \sim (1^{+-})_{c\bar{c}} \otimes (0^{-+})_{q\bar{q}} \ ,$$

where the heavy cores are ψ' and h_c.

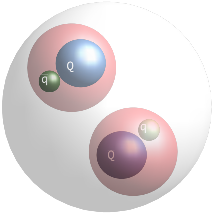
$\longrightarrow$ get spin partners via $\psi' \to \eta_c'$ and $h_c \to \{\chi_{c0},\ \chi_{c1},\ \chi_{c2}\}$



Cleven et al., PRD 92(2015)014005

Special feature: very light 0^{-+} state that should not decay to $D^*\bar{D}$

HADRONIC MOLECULES



review article: Guo et al., Rev. Mod. Phys. 90(2018)015004

- are few-hadron states, bound by the strong force
- do exist: light nuclei.
  e.g. deuteron as *pn* & hypertriton as Λd bound state
- are located typically close to relevant continuum threshold;
  e.g., for $E_B = m_1 + m_2 - M$ ($\gamma = \sqrt{2\mu E_B}$; $\mu = m_1 m_2/(m_1 + m_2)$)
  - $E_B^{\rm deuteron} \;\;\;\;= \;2.22$ MeV ($\gamma = 40$ MeV)
  - $E_B^{\rm hypertriton} = (0.13 \pm 0.05)$ MeV (to Λd) ($\gamma = 26$ MeV)
- can be identified in observables (Weinberg compositeness):

$$\frac{g_{\rm eff}^2}{4\pi} = \frac{4M^2\gamma}{\mu}(1-\lambda^2) \;\rightarrow\; a = -2\left(\frac{1-\lambda^2}{2-\lambda^2}\right)\frac{1}{\gamma}\;;\quad r = -\left(\frac{\lambda^2}{1-\lambda^2}\right)\frac{1}{\gamma}$$

where $(1-\lambda^2)$=probability to find molecular component in bound state wave function

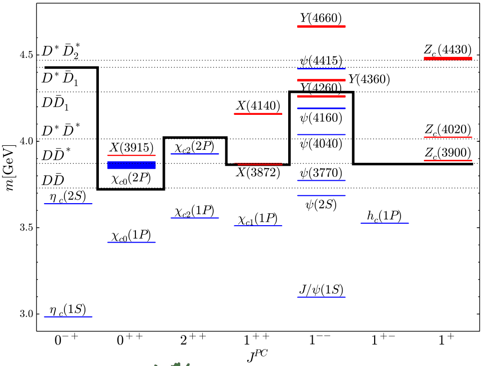
Are there mesonic molecules?

GENERAL CONSIDERATIONS

Constituents must be narrow. Heavy candidates (M, Γ in MeV)

$D\ (0^-, M = 1865, \Gamma \simeq\ \ 0);\ D^*(1^-, M = 2007, \Gamma \simeq 0.1)$
$D_1(1^+, M = 2420, \Gamma \simeq 30);\ D_2^*(2^+, M = 2460, \Gamma \simeq 50)$

$D_0(2400)$ and $D_1(2430)$ with $\Gamma = 300$ MeV too broad ...

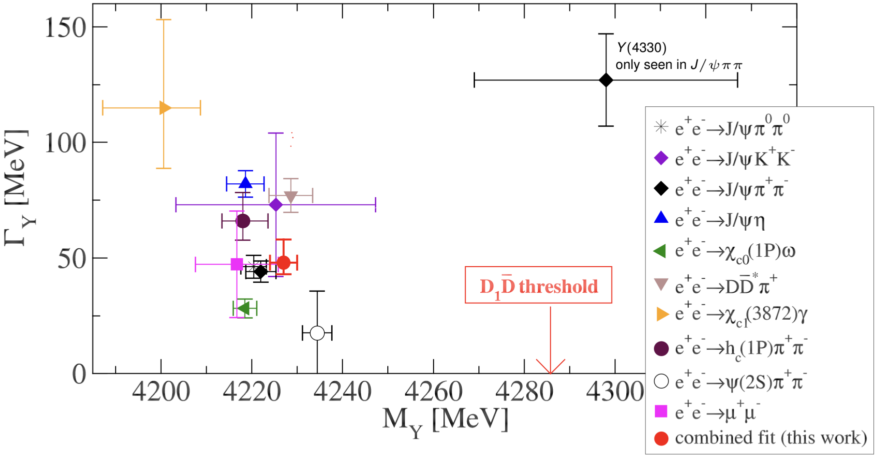


- Explains mass gap
  $M_{Y(4260)} - M_{X(3872)} = 388$ MeV $\simeq$
  $M_{D_1(2420)} - M_{D^*} = 410$ MeV
- Predicts, e.g.,
  $M(0^-) - M(1^-) \simeq M_{D^*} - M_D$
  $\simeq +100$ MeV
  microsopic calc.: T. Ji et al. PRL129(2022)102002

  For tetraquark:
  $M(0^-) - M(1^-) \simeq +\ 50$ MeV
  Ali et al. EPJC78(2018)29

  For hadrocharmonium:
  $M(0^-) - M(1^-) \simeq -100$ MeV
  Cleven et al., PRD 92 (2015) 014005

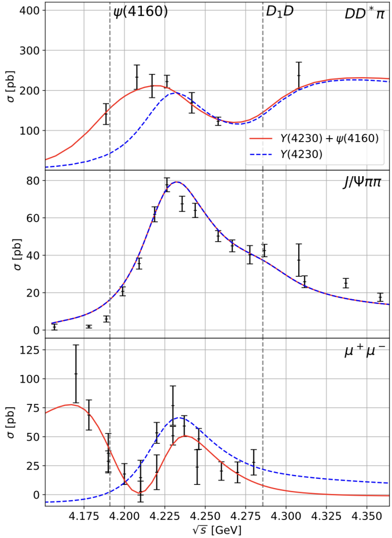
EXAMPLE: $Y(4230)$ AS $D_1\bar{D}$ MOLECULE



- Inclusion of $D_1\bar{D}$ intermediate states (g_{YD_1D} large for molecule)
- Inclusion of charmonium $\psi(4160)$ ($M_{\psi(4160)} = 4191$ MeV)

L. von Detten, V. Baru, CH, Q. Wang, D. Winney, Q. Zhao; arxiv: 2402.03057

IMPACT OF $\psi(4160)$



Well established $\bar{c}c$ state

Parameters from RPP2023:
2023 update of R. L. Workman *et al.* [PDG], PTEP2022 (2022)083C01

$m_{\Psi(4160)} = (4191\pm5)$ MeV
$\Gamma_{\Psi(4160)} = (70\pm10)$ MeV

Experimental extractions:

$D^0 D^{*-}\pi^+$: $\Gamma_Y = (77\pm6.3\pm6.8)$ MeV
BESIII, PRL130(2023) 121901

$J/\psi\pi^+\pi^-$: $\Gamma_Y = (41.8\pm2.9\pm2.7)$ MeV
BESIII, PRD106(2022)072001

in both cases $\psi(4160)$ omitted

$\mu^+\mu^-$: $\Gamma_Y = (47.2\pm22.8\pm10.5)$ MeV
BESIII, PRD102(2020)112009

with $\psi(4160)$ included

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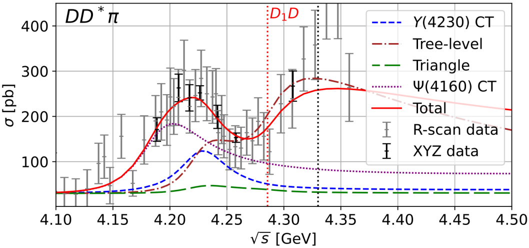
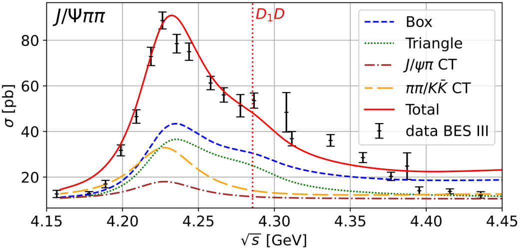
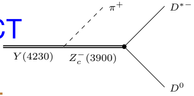
ROLE OF $D_1 \bar{D}$ CUT

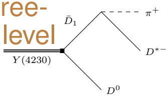


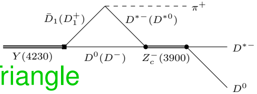


CT



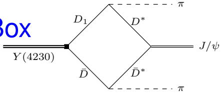
Tree-level

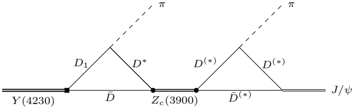




Triangle

Box





Triangle

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SUMMARY AND PERSPECTIVES

- These are exciting times in (heavy meson) spectroscopy
- The recent and future data have the potential to allow us to identify the prominent components in XYZ states

to-do for experiment

- Continue great performance! Especially needed:
  - data for different quantum numbers and
  - data for line shapes

to-do for theory

- Provide more predictions for the different scenarios
- Go beyond most simple approaches
  e.g. study interplay of regular quarkonia with exotics
  - potentially significant mixing

    Kalashnikova et al., PRD80(2009)074004; Takizawa et al., PTEP(2013)093D01; Ortega et al., JPG 40(2013)065107; Coito et al., EPJC73(2013)2351; Cincioglu et al., EPJC76(2016)576
  - negligible mixing

    van Beveren et al., PLB641(2006)265; Hammer et al., EPJA52(2016)330, C.H. et al., PRD106(2022)114003

Thanks a lot for your attention

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Backup Slides

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

Recently growing number of claims for those tetraquarks, e.g.

- from QCD sum rules — Du et al., PRD87(2013)014003
- from lattice QCD — Francis et al. PRL118(2017)142001
- from phenomenology — Ader et al., PRD 25(1982)2370

E.g. from the last work — Karliner and Rosner, PRL119(2017)202001; Eichten and Quigg, PRL119(2017)202002

$$m(QQ\bar{q}\bar{q}) - m(QQq) \simeq m(\bar{Q}\bar{q}\bar{q}) - m(\bar{Q}q)$$

exploiting heavy quark-diquark symmetry:

expansion in $r_{QQ}/r_q \sim \Lambda_{\mathrm{QCD}}/(M_Q v)$ — Savage and Wise, PLB248(1990)177

One finds: The heavier QQ, the more deeply bound $QQ\bar{q}\bar{q}$

cc: From mass of Σ_{cc}: At most very shallow
State found (T_{cc}) — consistent with molecule — LHCb, Nature Commun. 13(2022)3351

bb: No *bb*-baryon mass available; all groups agree that
there should be a tetraquark structure

OTHER CHANNELS

L. von Detten, V. Baru, CH, Q. Wang, D. Winney, Q. Zhao; arxiv: 2402.03057