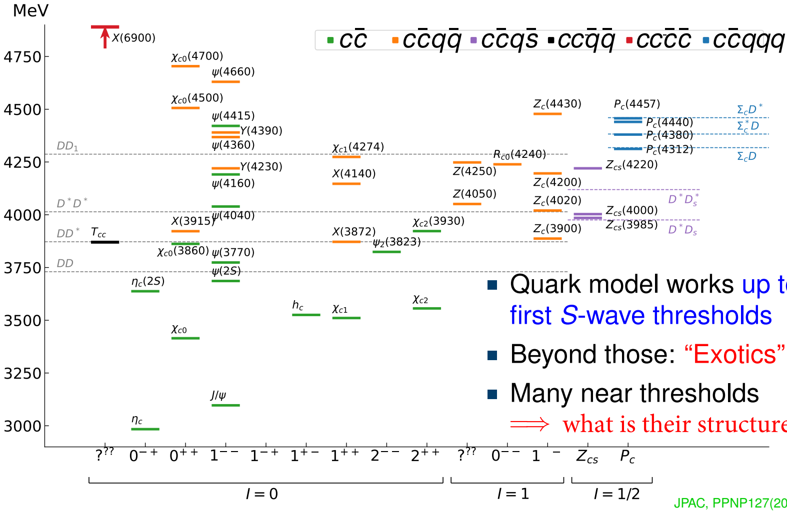
THE LHCB PENTAQUARKS AS HADRONIC MOLECULES

June 25, 2024 | Christoph Hanhart | IAS Forschungszentrum Jülich

SETTING THE STAGE

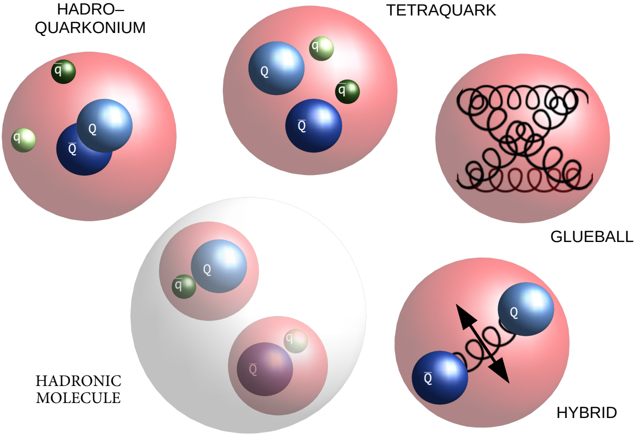


- Quark model works up to first *S*-wave thresholds
- Beyond those: “Exotics”
- Many near thresholds

$\Longrightarrow$ what is their structure?

JPAC, PPNP127(2022)103981

THE NAME OF THE GAME:

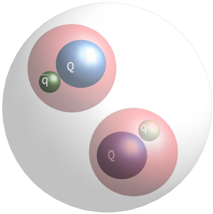


Picture by Soeren Lange

How can one disentangle the different structures?

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):

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

$(1-\lambda^2)$=probability for molecular component in wave function

Corrections are $\mathcal{O}(\gamma R)$

Range corrections: Song, Dai, Oset (2022); Li, Guo, Pang, Wu (2022); Kinugawa, Hyodo (2022)

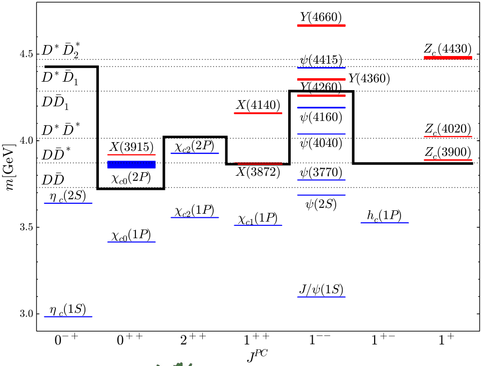
Are there mesonic molecules?

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
  $M_{Y(4230)} - M_{X(3872)} = 358$ 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

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OUTLINE FOR THE REST OF THE TALK

Discussion on the imprint of molecular structures in observables

General: Strong coupling to continuum channel as unique signature

Using three examples:

- Example 1: Exploratory study for $Y(4230)$

  $\Longrightarrow$ Do we need the $Y(4330)$?

  L. von Detten et al., PRD109(2024)116002

- Example 2: Heavy meson effective field theory for Z_b states

  $\Longrightarrow$ Towards a systematic approach to doubly heavy molecules

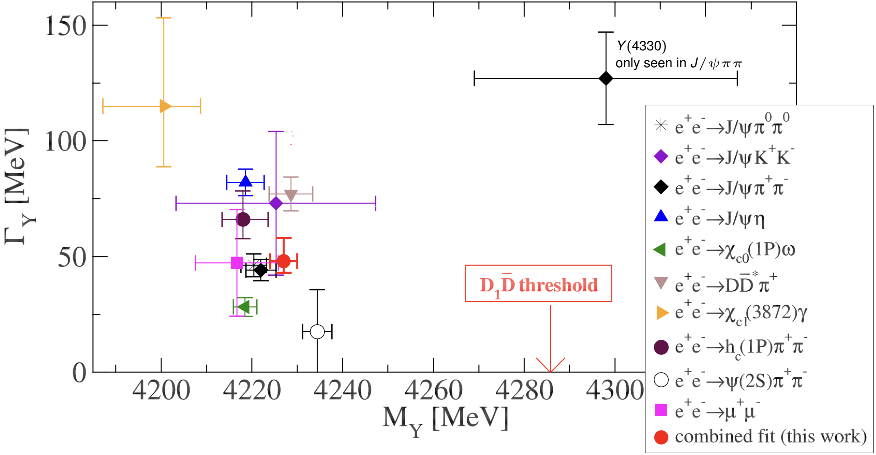
  Q. Wang et al., PRD98(2018)074023

- Example 3: HMEFT for P_c pentaquarks

  $\Longrightarrow$ Molecular signatures in yet unmeasured cross sections

  M. L. Du et al., PRL 124 (2020) 7, 072001; M. L. Du et al., JHEP 08 (2021) 157

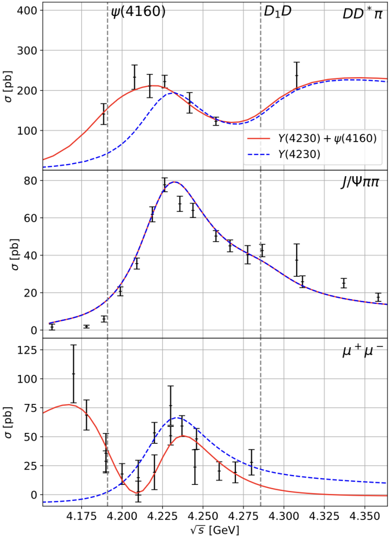
EXAMPLE 1: $Y(4230)$ AS $D_1\bar{D}$ MOLECULE



- 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; PRD109(2024)116002

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

$m_{\psi(4160)} = (4191 \pm 5)$ MeV
$\Gamma_{\psi(4160)} = (70 \pm 10)$ MeV

Experimental extractions:

$D^0 D^{*-}\pi^+$: $\Gamma_Y = (77 \pm 6.3 \pm 6.8)$ MeV

BESIII, PRL130(2023) 121901

$J/\psi\pi^+\pi^-$: $\Gamma_Y = (41.8 \pm 2.9 \pm 2.7)$ MeV

BESIII, PRD106(2022)072001

in both cases $\psi(4160)$ omitted

$\mu^+\mu^-$: $\Gamma_Y = (47.2 \pm 22.8 \pm 10.5)$ MeV

BESIII, PRD102(2020)112009

with $\psi(4160)$ included

NRW-FAIR

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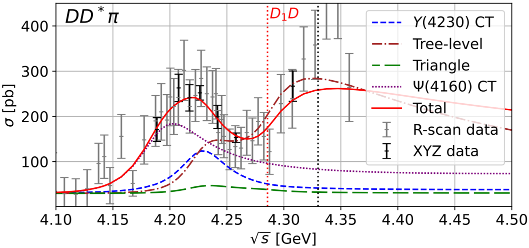
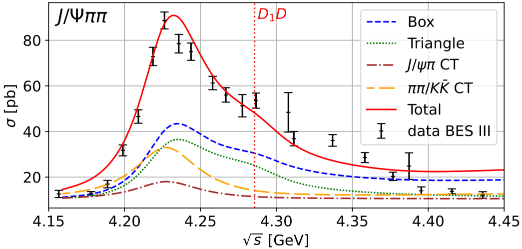
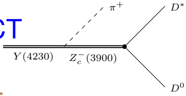
ROLE OF $D_1 \bar{D}$ CUT

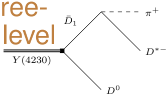


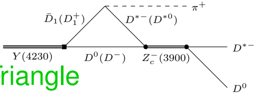


CT



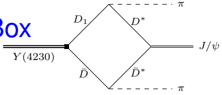
Tree-level

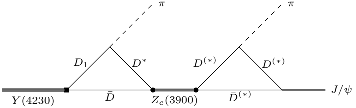




Triangle

Box





Triangle

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HOW TO GO BEYOND ...

- The formalism presented is 'diagnostic' — especially,
  - it does not allow for conclusions on the binding force
  - it allows one only to study individual states.

  To go beyond that we need to include more dynamics

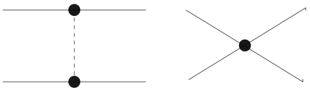
- ChPT for heavy-heavy molecules
  - Most general potential consistent with symmetries
  - Organised by power counting & resummed

S. Weinberg, PLB251(1990)288

Analogous to two nucleon system

Epelbaum et al., RMP81(2009)1773

at LO:



1-π exchange connects
S to D waves
Coupled channels needed!

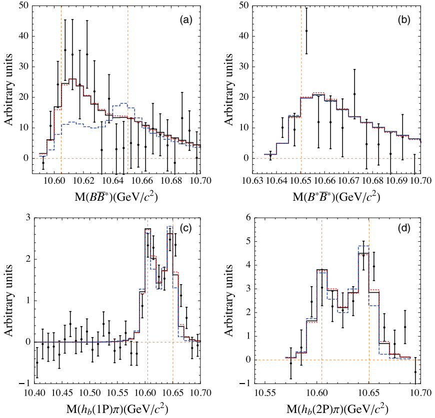
1-π exchange only well defined together with contact terms!

V. Baru et al., PRD91(2015)034002

EXAMPLE 2: HMCHPT FOR Z_b STATES

Results for Z_b spectra: 2 counter terms

Q. Wang et al., PRD98(2018)074023



Three different fits:

Black solid:
Constant contact terms only

Red dotted:
Constant contact terms
+ 1-π-exch. in S–wave

Blue dashed:
Constant contact terms
+ full 1-π-exch.

- The data call for a decoupling of $B\bar{B}^*$ and $B^*\bar{B}^*$ channels
- 1-π-exchange provides a strong transition between these

NRW-FAIR

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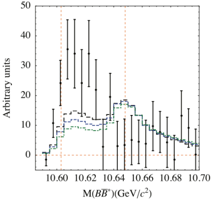
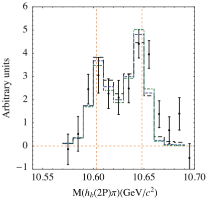
WHAT'S WRONG?

At $B^*\bar{B}^*$–threshold $B^*\bar{B}$ momentum $\sim$ 500 MeV

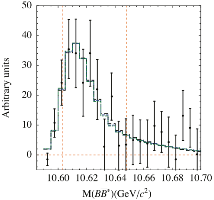
$\Longrightarrow$ No suppression of $S(B^*\bar{B}^*) - D(B^*\bar{B})$ transition

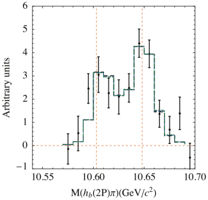




- Strong $B^*\bar{B}^* \to B^*\bar{B}$
- strong Λ dependence
  black: $\Lambda = 800$ MeV
  blue: $\Lambda = 1000$ MeV
  green: $\Lambda = 1200$ MeV

Promote $S - D$ contact term to leading order:





- Fit improves significantly
- Λ dependence gone
- $Z_b' \to B^*\bar{B}$ very small
- NLO $S - S$ CT small

Why $Z_b' \not\to B^*\bar{B}$ not understood

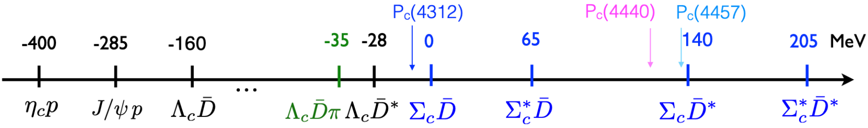
EXAMPLE 3: PENTAQUARKS

Predicted in phenomenological analysis J. J. Wu, R. Molina, E. Oset and B. S. Zou, PRL 105(2010), 232001

Various pion less EFT studies Nieves, Oset, Geng, Valderrama, ...

We here apply formalism from above M. L. Du et al., PRL 124 (2020) 7, 072001

Potentially relevant thresholds:

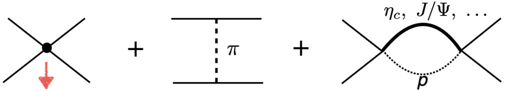


Systematic study of pertinent channels — Idea:

- Formation of states in $\Sigma_c^{(*)} \bar{D}^{(*)}$ channels (elastic channels)
- Aim at fitting experimental data for $\Lambda_b \to K p J/\psi$
- Predictions for $\Lambda_b \to K \Sigma_c^{(*)} \bar{D}^{(*)}$ and $\Lambda_b \to K \eta_c p$
- Is there room for $\Lambda_b \to K \Lambda_c \bar{D}^{(*)}$?

FORMALISM

$V_{\mathrm{LO}}^{\mathrm{eff}}$ =



HQSS: 2 S-S wave LECs at O(Q⁰)
1 S-D wave LEC at O(Q²)

Long range: OPE

Imaginary part from inelastic channels

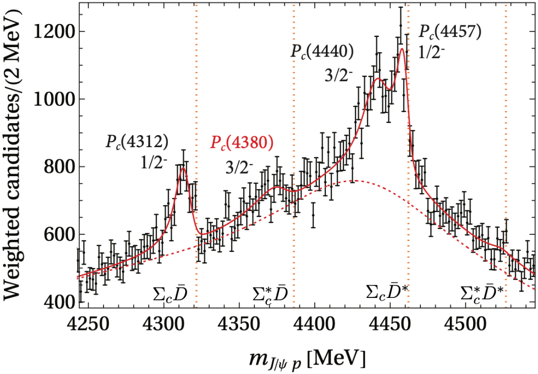
Total number of parameters without/with the $\Lambda_c \bar{D}^{(*)}$ channels

- elastic channels: $\Sigma_c^{(*)}$ has $j_{\,\mathrm{light}} = 1$; $D^{(*)}$ has $j_{\,\mathrm{light}} = 1/2$
  $\Longrightarrow$ 2 counter terms with $j_{\,\mathrm{light}} = 1/2$ & $j_{\,\mathrm{light}} = 3/2$, respectively
- $J/\psi p$ and $\eta_c p$: transitions in S and D wave
  $\Longrightarrow$ 2 parameters for $\Sigma_c^{(*)} \bar{D}^{(*)} \to p(J/\psi/\eta_c)$
- $\Lambda_c^{(*)}$ has $j_{\,\mathrm{light}} = 0$; $D^{(*)}$ has $j_{\,\mathrm{light}} = 1/2$
  $\Longrightarrow$ 1 parameter for $\Lambda_c \bar{D}^{(*)} \to \Sigma_c^{(*)} \bar{D}^{(*)}$
- 1 (2) parameters for the promoted $S - D$ counter terms

$\Longrightarrow$ 5 parameters (7 parameters) control the scattering,
but the 2 first are most important

- .... and 7 parameters to control the production

RESULTS



- Data described well ($\chi^2/dof \approx 1$)
- Without OPE two good fits (different order of the $\Sigma\bar{D}^*$ states)
- With OPE unique fit
- Observe indications for narrow $P_c(4380)$

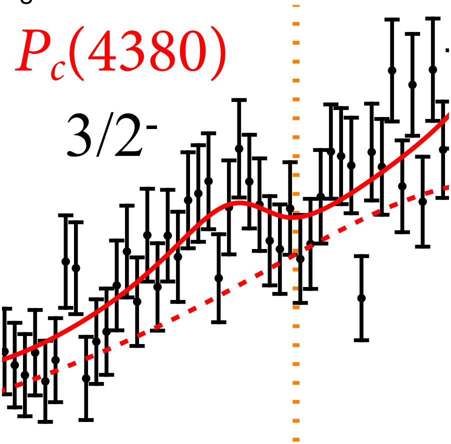
$\Longrightarrow$ Fit provides 1 $\Sigma_c\bar{D}$, 1 $\Sigma_c^*\bar{D}$, 2 $\Sigma_c\bar{D}^*$ and 3 $\Sigma_c^*\bar{D}^*$ molecules

$\Longrightarrow$ basically 2 parameters fixed by fitting 3 states

$\Longrightarrow$ Not all show up in the data (importance of production vector?)

PENTAQUARKS

Zooming in



Fit with spin symmetry unavoidably gives this additional state

Source coupling of $\Sigma_c^* D$ channel different from 0 by 1.7 σ

Its confirmation would provide strong support for the molecular picture!

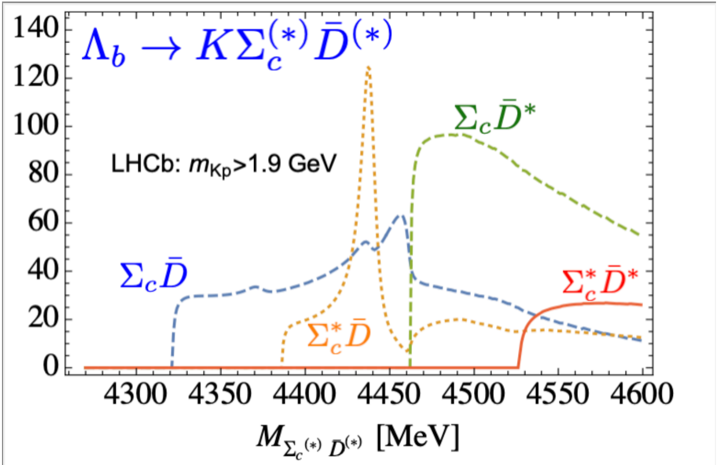
The amount of spin symmetry violation is specific to the structure

M. Cleven et al., PRD92(2015)014005

SIGNATURES IN ELASTIC CHANNELS

Typical spectrum

Du et al., JHEP 08 (2021) 157

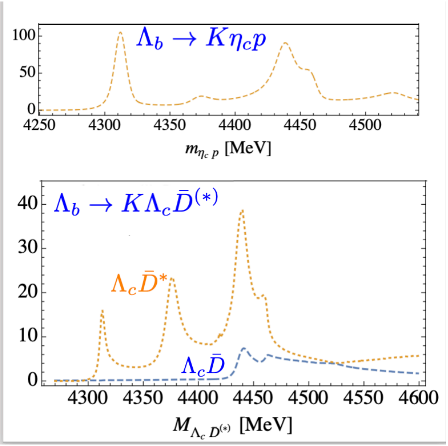


strong threshold enhancement - unavoidable for hadronic molecules

SIGNATURES IN INELASTIC CHANNELS

Du et al., JHEP 08 (2021) 157

- For $\Sigma_c^{(*)}\bar{D}^{(*)} \to \Lambda_c\bar{D}^{(*)}$ OPE + two add. para. (S-S and S-D)



- $\eta_c p$ channel similar to $J/\psi p$ (spin symmetry!)
- $\Lambda_c\bar{D}^{(*)}$ final states not constrained yet
- Shown: Some typical spectrum
- Data even compatible with very weak signal
- $(\Lambda_c\bar{D}\to\Sigma_c\bar{D})_{\rm S-wave} = 0$
  $(\Lambda_c\bar{D}\to\Sigma_c^*\bar{D})_{\rm DS-wave} = 0$

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