CHIRAL EFTS FOR SINGLE- AND DOUBLE-HEAVY HADRONIC MOLECULES

June 12, 2026 | Christoph Hanhart | IAS Forschungszentrum Jülich

color meets flavor

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Systematic Approaches to QCD

$$\mathcal{L}_{\text{QCD}} = \sum_f \bar{q}_f \left(\gamma_\mu D^\mu - m_f\right) q_f - \frac{1}{4}\text{Tr}\left(F^{\mu\nu} F_{\mu\nu}\right)$$

with $D^\mu = \partial^\mu + i g_s \sum_a t^a A^{a\,\mu}$ and $F^{\mu\nu} = [D^\mu, D^\nu]$ systematically studied for low Q^2 by

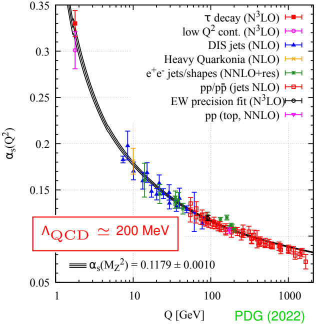
- Lattice QCD

  Numerical solution in discretised space-time

- Effective Field Theories
  - Quarks and gluons as degrees of freedom
    Neubert, Beneke, Wise, Manohar, Brambilla, Vairo, Soto, ...
  - Born-Oppenheimer EFT
    Brambilla et al., Braaten/Bruschini
  - Hadrons as degrees of freedom

    $\Longrightarrow$ Ideal to study hadronic molecules

    previous and this talk



PDG (2022)

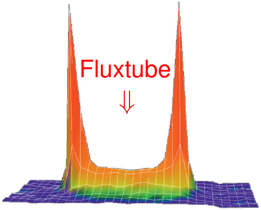
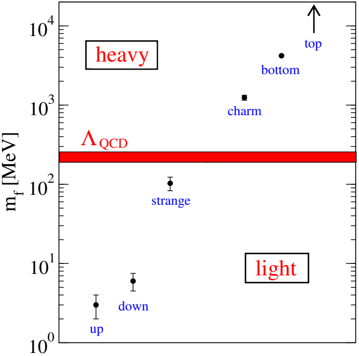


figure curtesy of G. Bali

Quarkmasses and EFTs



Since α_s probed at different scales,

Λ_{QCD} sorts quarks into

- light (up, down, strange) and
- heavy (charm, bottom, top)
  (top too short lived to hadronize)

Groups show different phenomenology

(QCD has no SU(4)-flavor sym.)

Limit of massless light Quarks + infinitely heavy heavy Quarks

Weinberg, Gasser, Leutwyler, Meißner ... and Isgur, Wise, Neubert, Beneke, Manohar, Caswell, Lepage, Brambilla, Vairo, ...

- L and R light Quarks decouple + spontaneous symmetry breaking
- Independence of Heavy Quark Spin and Flavour

$\Longrightarrow$ Heavy Hadron Chiral Perturbation Theory (HHChPT)

Outline:

- Investigate states beyond naive quark model ($\bar{q}q$, qqq)
- Identify observables sensitive to molecular structures
- Provide predictions

Diquark–Anti-diquark

Hadronic Molecule

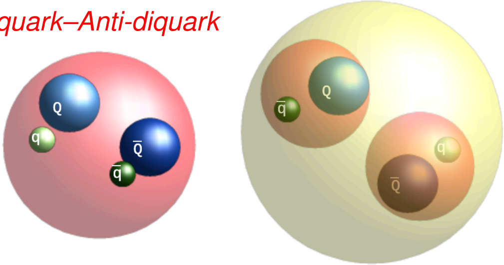
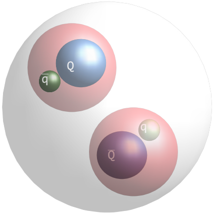


Figure curtesy of Soeren Lange

Outline for the rest of the talk

- The Weinberg criterion: What is a molecule?
- Singly heavy molecules: Chiral symmetry at work
- Doubly heavy molecules: New types of nuclei
- Summary

Hadronic Molecules



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

- Few-hadron states, bound by residual strong force
  no fluxtubes but meson exchange (e.g. π)
- do exist: light nuclei.
  e.g. deuteron as *pn* & hypertriton as Λd bound state
- are located typically close to relevant continuum threshold;
  $E_B^{\rm deuteron} = 2.22$ MeV; $E_B^{\rm hypertriton} = (0.13 \pm 0.05)$ MeV (to Λd)
- Observable (Weinberg compositeness): using $\gamma = \sqrt{2\mu E_B}$

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

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

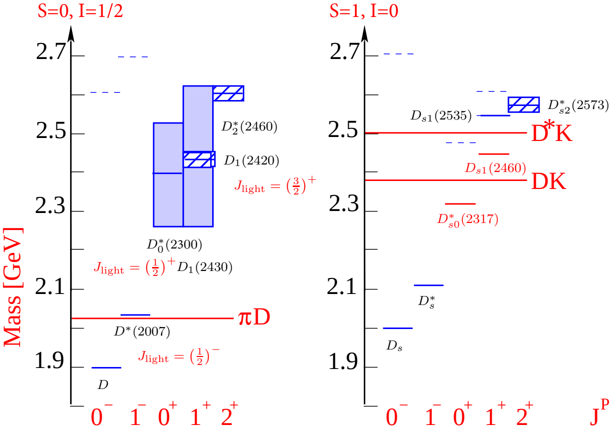
Corrections are $\mathcal{O}(\gamma R)$ — positive for r in single channel

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

Are there hadronic molecules with other building blocks?

extensions/further studies: Baru et al., Sekihara, Hyodo, Oset, Oller, Nieves, Jido, Hosaka, Guo ...

Singly heavy states: *D*-mesons



Quark Modell: M. Di Pierro and E. Eichten, PRD 64 (2001) 114004

Puzzles: Why are/is

1. $M(D_{s1}) - M(D_{s0}^*) \simeq M(D^*) - M(D)$?
2. $M(D_{s1})$ & $M(D_{s0}^*)$ so light?
3. $M(D_0^*) \simeq M(D_{s0}^*)$? $M(D_1) \simeq M(D_{s1})$?
4. Why do we have $M(D_0)^{\text{ChPT}} \approx M(D_0)^{\text{lat.}} \ll M(D_0)^{\text{exp.}}$?

All those puzzles disappear, if the states are hadronic molecules

Goldstone boson-$D^{(*)}$ scattering

- In the chiral limit ($m_u = m_d = m_s = 0$): Goldstone Theorem

  $\Longrightarrow$ GBs ($\pi,\ \eta,\ K$) massless & decouple for vanishing momenta

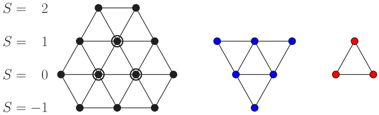
- Leading order HHChPT has no free parameters

  $\Longrightarrow$ Weinberg–Tomozawa term for $P\phi$ scattering in channel a:

  $$\mathcal{A}_a = C_a E_{\phi\,a}/F_0^2 \qquad (F_0 = \pi \text{ decay constant})$$

  Interaction of kaons significantly stronger than that of pions

  $\Longrightarrow$ group theory fixes the C_a:



$[\bar{3}] \otimes [8] = [\overline{15}] \quad \oplus \quad [6] \quad \oplus \quad [\bar{3}]$

$[\overline{15}]$ repulsive,
$[6]$ attractive,
$[\bar{3}]$ most attractive

Albaladejo et al., PLB767(2017)465

- NLO: 6 parameters; controlled quark mass dependence

Unitarisation (ChPT $\rightarrow$ UChPT)

- Chiral perturbation theory only perturbatively consistent with unitarity
- Energy dependent interaction hits unitarity bound quickly

$\Longrightarrow$ Unitarisation; allows for generation of bound states and resonances

Truong, Dorado, Pelaez, Kaiser, Weise, Oller, Oset, Lutz, Kolomeitsev, Guo, Meißner, C.H., ...

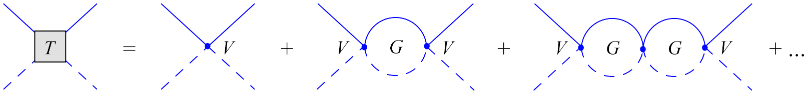
Observe $\mathrm{Im}(t(s)) = \sigma(s)\,|t(s)|^2$ implies $\mathrm{Im}\left(t(s)^{-1}\right) = -\sigma(s)$

$\Longrightarrow$ write subtracted dispersion integral for $t(s)^{-1}$

$\Longrightarrow$ fix $\mathrm{Re}(t(s)^{-1})$ by matching to ChPT

Oller and Meißner, PLB500(2001)263

Effectively this gives



with ChPT expression for V ... and additional parameter $a(\mu)$ (from the loop)

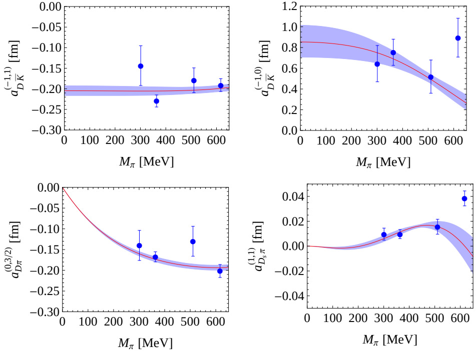
Dependence on unitarization method & left-hand cuts needs to be clarified!

Lutz et al., PRD106(2022)114038; Korpa et al., PRD107(2023)L031505

Fit to lattice data

Liu et al. PRD87(2013)014508

fit 6+1 para. to lattice data for $a^{(S,I)}_{D_x\phi}$ in selected channels + $D_{(s)}$ masses



controlled quark mass dependence
Fit range up to $M_\pi = 500$ MeV

- $\pi/K/\eta$–$D^{(*)}/D_s^{(*)}$ scattering fixed (chiral sym: πD int. weaker than KD)
- $D^*_{s0}(2317)$ emerges as molecule with $M_{D^*_{s0}} = 2315^{+18}_{-28}$ MeV

  since $E_b(D_{s0}) = E_b(D^*_{s1}) + \mathcal{O}(1/M_D) \Longrightarrow$ puzzle 1+2 solved

The S $=$ 0 sector

Lattice: $@M_\pi = 391$ MeV pole at 2275.9 ± 0.9 MeV

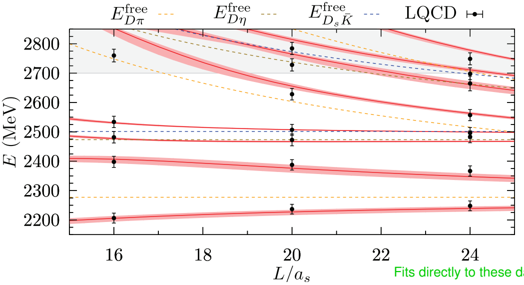
Had.Spec.Coll. JHEP10(2016)011

$@M_\pi = 239$ MeV pole at $2196 \pm 64 - i(210 \pm 110)$ MeV

HadSpec, JHEP07(2021)123

UChPT for $M_\pi = 391$ (parameters fixed in 2013):

Albaladejo et al., PLB767(2017)465

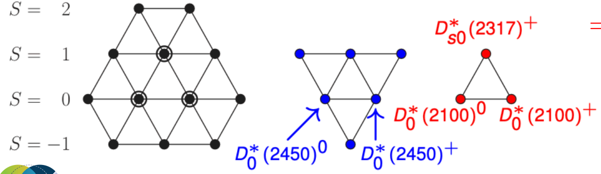


finds poles for

- $M_\pi \simeq 391$ MeV at (2264, 0) MeV [000] & (2468, 113) MeV [110]
- $M_\pi = 139$ MeV at (2105, 102) MeV [100] & (2451, 134) MeV [110]

why seocnd pole was first missed: Asokan et al., EPJC83(2023)850

Fits directly to these data: Guo et al., EPJC 79(2019)13; Lutz et al., PRD106(2022)114038

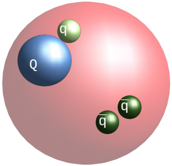


$\Longrightarrow$ puzzle 3 solved

- Quark Model only $[\bar{3}]$
- Diquark Model all

Compact tetraquarks

CH & Guo, Commun.Theor.Phys.77(2025)125201



Heavy-light diquarks, cq, in flavor $[3]_{\{cq\}}$

Light diquarks, $\bar q\bar q$ in flavor $[\bar 3]_{\bar q}\otimes[\bar 3]_{\bar q} = \underbrace{[3]_{\{\bar q\bar q\}}}_{anti-sym.} \oplus \underbrace{[\bar 6]_{\{\bar q\bar q\}}}_{sym.}$

Fermi symmetry: [color] $\otimes$ [flavor] $\otimes$ [spin] anti-symmetric

diquarks anti-sym. in color (attractive one gluon exchange) $\Longrightarrow$

- $\bar q\bar q$ spin 0 (anti-sym.) must be combined with flavor $[3]_{\{\bar q\bar q\}}$

  adding cq diquark: $[3]^{0/1}_{\{cq\}}\otimes[3]^{0}_{\{\bar q\bar q\}} = [\bar 3]^{0\otimes 0/1\otimes 0}_{\{cq\}\{\bar q\bar q\}}\oplus[6]^{0\otimes 0/1\otimes 0}_{\{cq\}\{\bar q\bar q\}}$

  L. Maiani et al. PRD110 (2024) 3

- $\bar q\bar q$ spin 1 (sym.) must be combined with flavor $[\bar 6]_{\{\bar q\bar q\}}$

  adding cq diquark: $[3]^{0/1}_{\{cq\}}\otimes[\bar 6]^{1}_{\{\bar q\bar q\}} = [\bar 3]^{0\otimes 1/1\otimes 1}_{\{cq\}\{\bar q\bar q\}}\oplus[\overline{15}]^{0\otimes 1/1\otimes 1}_{\{cq\}\{\bar q\bar q\}}$

  't Hooft int. pushes $[\bar 3]$ up: Dmitrasinovic, PRD70(2004)096011

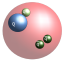
From phenomenology: $M^{S=1}_{cq} - M^{S=0}_{cq} \approx M^{S=1}_{qq} - M^{S=0}_{qq} \approx 150$ MeV

Comparison of 1^+ and 0^+

lightest compact tetraquarks:

spin 0: $[\bar{3}]^{0\otimes 0}_{\{cq\}\{\bar{q}\bar{q}\}} \oplus [6]^{0\otimes 0}_{\{cq\}\{\bar{q}\bar{q}\}}$;

spin 1: $[\bar{3}]^{1\otimes 0}_{\{cq\}\{\bar{q}\bar{q}\}} \oplus [6]^{1\otimes 0}_{\{cq\}\{\bar{q}\bar{q}\}} \oplus [\overline{15}]^{0\otimes 1}_{\{cq\}\{\bar{q}\bar{q}\}}$;

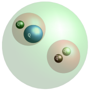


spin 1 and 0 behave differently

lightest hadronic molecules:

spin 0: $[\bar{3}]^{0\otimes 0}_{\{c\bar{q}\}\{q\bar{q}\}} \oplus [6]^{0\otimes 0}_{\{c\bar{q}\}\{q\bar{q}\}}$;

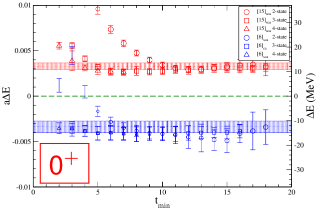
spin 1: $[\bar{3}]^{1\otimes 0}_{\{c\bar{q}\}\{q\bar{q}\}} \oplus [6]^{1\otimes 0}_{\{c\bar{q}\}\{q\bar{q}\}}$ $[\overline{15}]$ absent;

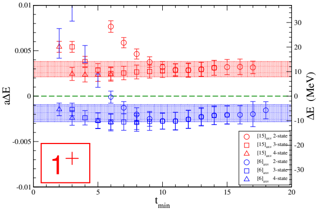


spin 1 and 0 behave equally

To see which scenario is realised: Lattice simulation

E.B. Gregory et al., EPJA61(2025)226





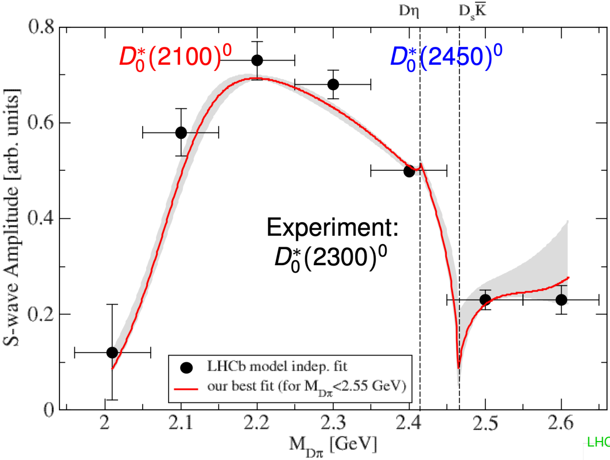
consistent levels for 0^+ and 1^+

$[\overline{15}]$ repulsive

$\Longrightarrow$ D_0 states molecular

$D\pi$ S-wave from $B^- \to D^+\pi^-\pi^-$

Du et al., PRD98(2018)094018; for more results see Du et al., PRD99(2019)114002, PRL126(2021)192001



LHCb, PRD94(2016)072001

Effect of higher thresholds enhanced, by pole at $\sqrt{s_p} \sim (2451 - i134)$ MeV on nearby unphysical sheet $\Longrightarrow$ puzzle 4 solved

Charmed states: Q&A

Why are $M(D_{s1})\&M(D_{s0}^*)$ so light?	Since they are are DK and D^*K bound states (=hadronic molecules)
Why is $M(D_{s1})-M(D_{s0}^*) \simeq M(D^*)-M(D)$?	Since spin symmetry gives equal binding
Why is $M(D_0^*) \simeq M(D_{s0}^*)$? and $M(D_1) \simeq M(D_{s1})$?	Since listings need to be corrected: Lightest D_0@2100 MeV & D_1@2240 MeV
Why do we have $M(D_0^*)^{\rm ChPT} \simeq M(D_0)^{\rm lat.} \ll M(D_0)^{\rm exp.}$?	Since structure at 2300 MeV is made of two poles analogous to $\Lambda(1405)$ from 2 poles Oller and Meißner, PLB500(2001)263

Combination of EFT, lattice QCD and experiment provides consistent picture for the whole family of states

$\Longrightarrow$ blueprint for other reactions

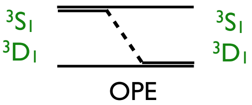
EFT for doubly heavy states

Schemes currently proposed (only initial work cited)—analogous to *NN*

- Contact EFT: no pions — AlFiky et al., PLB640(2006)238
- *X*-EFT: pert. pions — Fleming et al., PRD76(2007)034006
- chiral EFT: non.-pert. pions — Baru et al., PRD84(2011)074029
  - largest energy range of applicability
  - Pion dynamics fully under control $\Longrightarrow$ use this in what follows

Thus we solve LS-equation — Du et al., PRD105(2022)014024

$T = V + VGT$ with $V_{LO} =$



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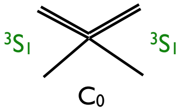


employing the expansion parameter $\chi = M_\pi/\Lambda_\chi \approx 0.1$

@ LO : One to twp free parameters per isospin (for each cut off)

@ NLO: energy dep. & M_π^2 dependent counter terms + loops.

However, loops absorbed into counter terms — Chacko et al. PRD 111 (2025)034042

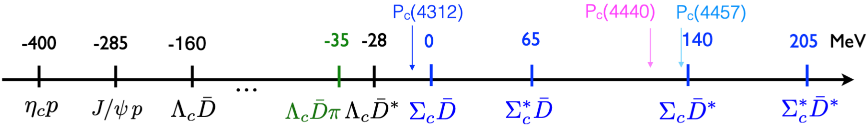
Example: Pentaquarks as Molecules

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 applied pion full EFT & fit to data — M. L. Du et al., PRL 124 (2020) 7, 072001

Potentially relevant thresholds:

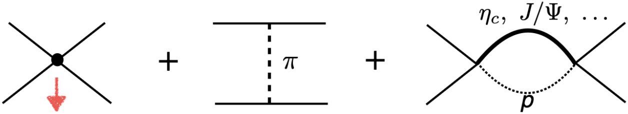


Systematic study of pertinent channels — Idea:

- 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 $\Lambda_b \to K \Lambda_c \bar{D}^{(*)}$? (Predicted by many models)

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

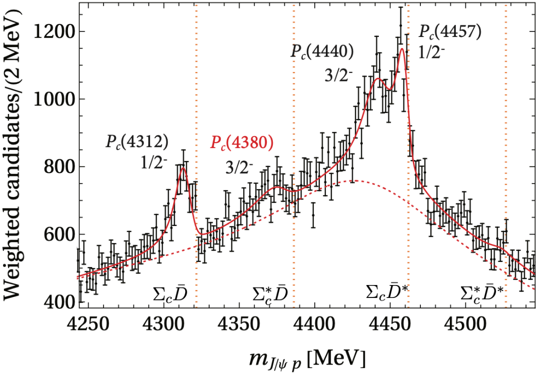
- elastic channels: $\Sigma_c^{(*)}$ has $j_{\,\mathrm{light}} = 1$; $D^{(*)}$ has $j_{\,\mathrm{light}} = 1/2$
  $\Longrightarrow$ 2 counter terms with $j_{\,\mathrm{light}} = 1/2$ & $j_{\,\mathrm{light}} = 3/2$, respectively
- $J/\psi p$ and $\eta_c p$: transitions in S and D wave
  $\Longrightarrow$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

data: LHCb, PRL122 (2019)222001



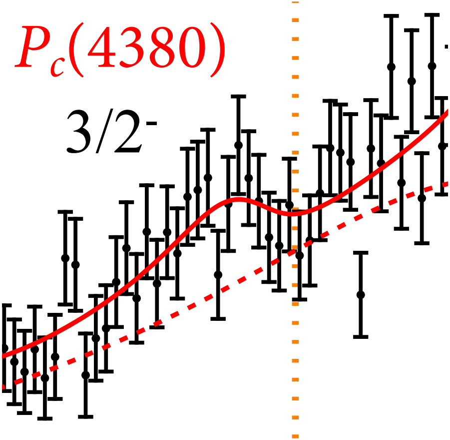
- Data described well ($\chi^2/dof \approx 1$)
- Without OPE two good fits (different order of the $\Sigma\bar{D}^*$ states)
- With OPE unique fit
- Observe indications for narrow $P_c(4380)$

$\Longrightarrow$ Fit provides 1 $\Sigma_c\bar{D}$, 1 $\Sigma_c^*\bar{D}$, 2 $\Sigma_c\bar{D}^*$ and 3 $\Sigma_c^*\bar{D}^*$ molecules (compared to 10 for the diquark picture with different J^P)

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

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

Zooming in ....



Spin symmetric couplings give additional states

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

Its confirmation would provide support for molecular picture!

three states still missing!!

The amount of spin symmetry violation is specific to the structure

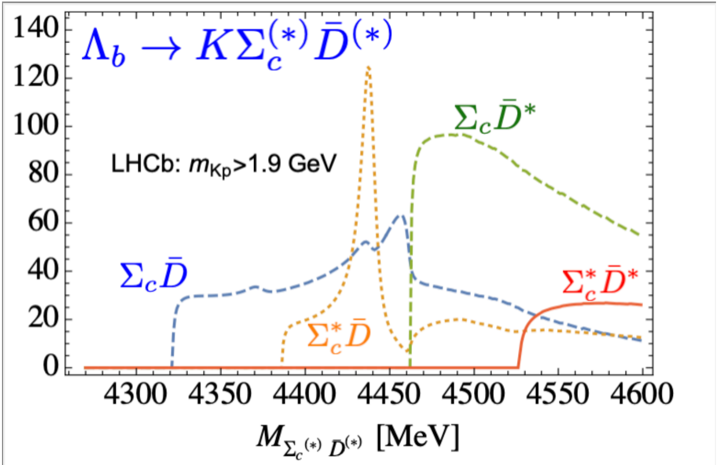
$\Longrightarrow$ Molecules follow the thresholds!

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

Signatures in elastic channels

Typical spectrum

Du et al., JHEP 08 (2021) 157

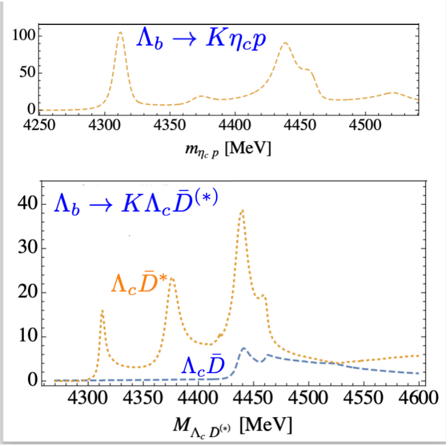


strong threshold enhancement - unavoidable for hadronic molecules

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

- The recent and future data have the potential to allow us to identify the prominent components in exotic states

to-do for experiment

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

to-do for theory

- Provide more predictions for the different scenarios in EFTs as well as lattice QCD
- 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

$\Longrightarrow$ Exploit further BOEFT and Dyson-Schwinger approaches

Thanks a lot for your attention