Heavy hadron spectroscopy and exotics

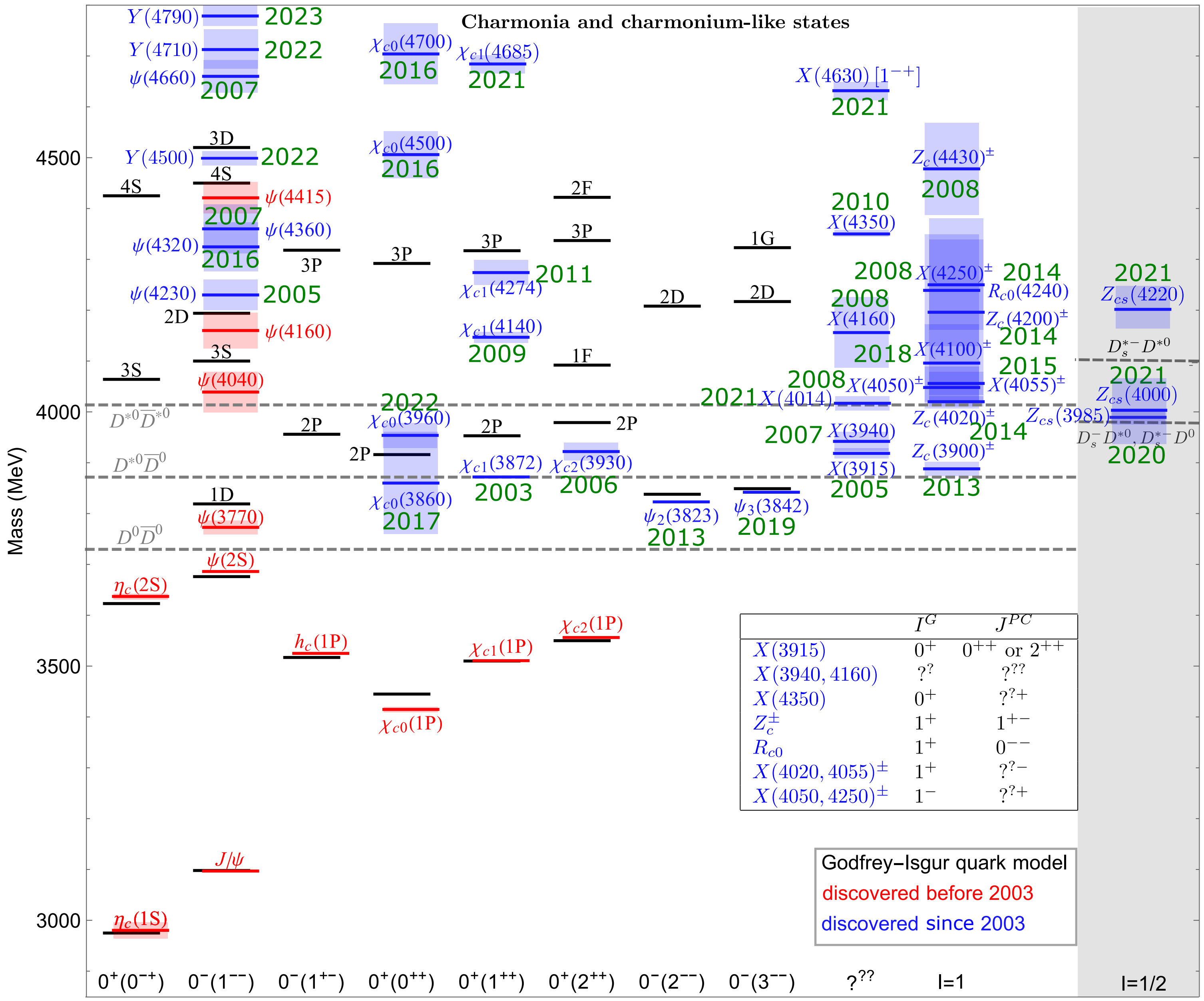
Feng-Kun Guo

Institute of Theoretical Physics, CAS

The 2023 International Workshop on the High Energy Circular Electron-Positron Collider

Oct. 23-27, 2023

Hidden-charm and double-charm hadrons



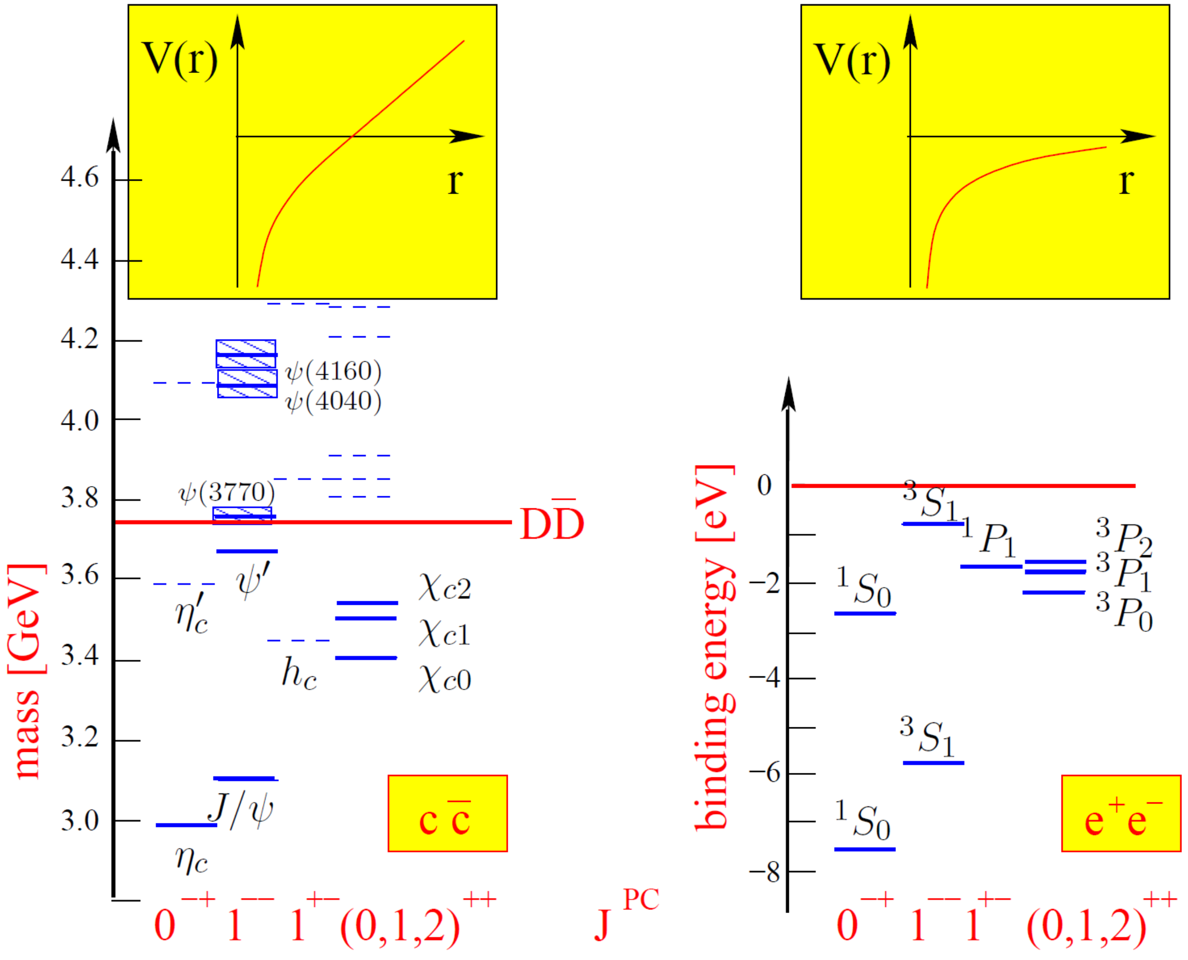
- Hidden-charm and double-charm: one of the foci of hadron spectroscopy at present and in the near future
- Milestones:
  - ✓ $X(3872)$ Belle (2003)
  - ✓ $Z_b(10610,10650)^{\pm}$ Belle (2011)
  - ✓ $Z_c(3900)^{\pm}$ BESIII, Belle (2013)
  - ✓ P_c LHCb (2015, 2019)
  - ✓ T_{cc}^{+} LHCb (2021)

➢ Many structures are near threshold of a pair of open-charm hadrons

➢ Many structures were observed in a single channel or by a single experiment, in reactions with at least 3 hadrons

Heavy quarkonia

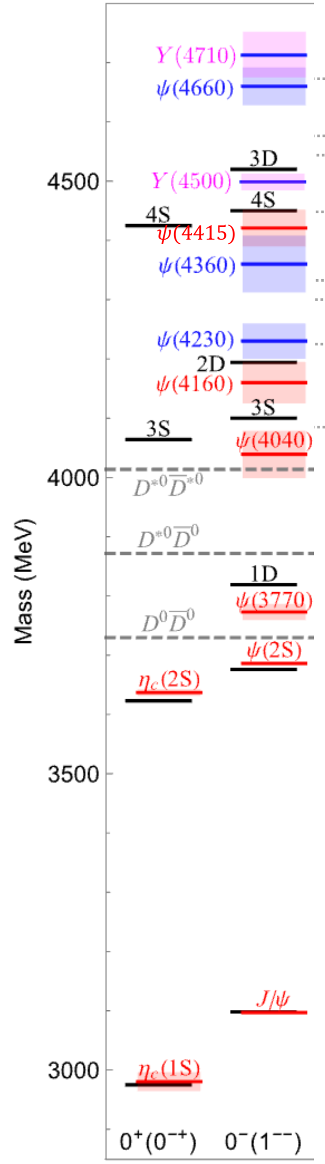
- Charmonium: meson consisting of a charm quark and an anticharm quark
  - The first charmonium: J/ψ
  - Probing both perturbative and nonperturbative QCD
  - Spectroscopy as a probe of confinement mechanism
  - Hadron-hadron thresholds obscure the access to confinement through spectroscopy



Cornell potential model:
Eichten et al., PRD17(1978)3090

From talk by Hanhart at APS2018

Life is difficult



$\psi' f_0(980)$

$D_{s1}\bar{D}_s^*, \Lambda_c^+\bar{\Lambda}_c^-$

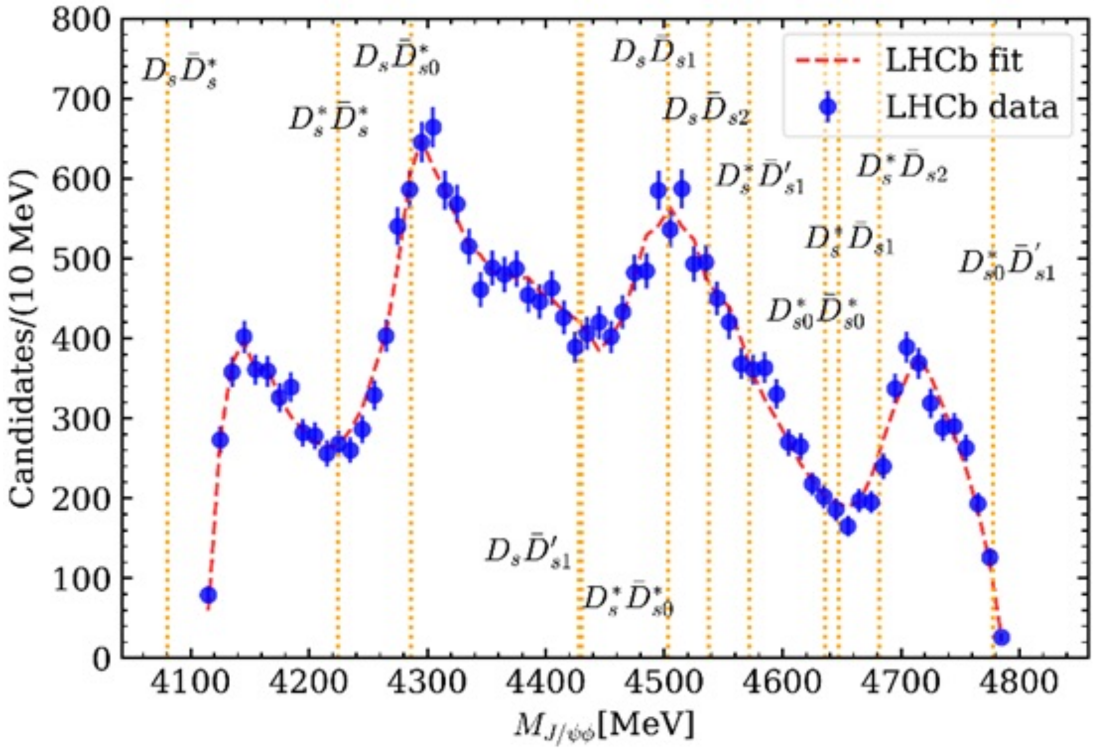
$D_2(2460)\bar{D}^*$ $\chi_{c0,1,2}\phi$ $D_{s0}^*\bar{D}_s^*, D_{s1}\bar{D}_s$

$D_1(2420)\bar{D}^*$

$D_1(2420)\bar{D}$ $\chi_{c0,1,2}\omega$

$J/\psi f_0(980)$

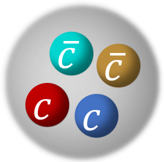
2-body S-wave thresholds



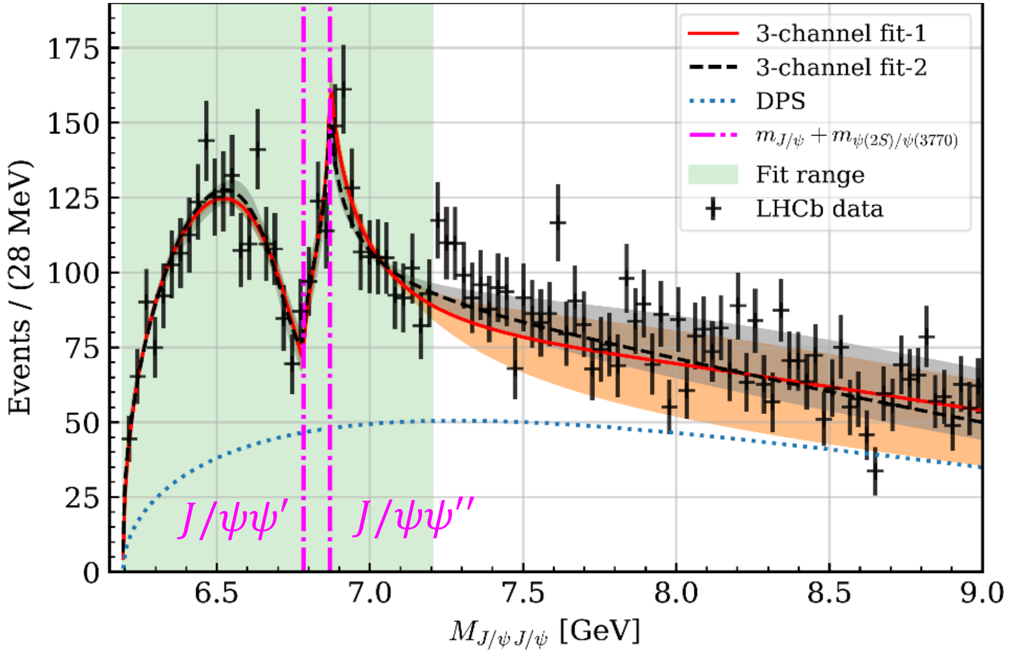
Data: LHCb, PRL 127 (2021) 082001
Plot: X.-K. Dong, FKG, B.-S. Zou, Progr. Phys. 41 (2021) 65 [arXiv:2101.01021]

There are light quarks! $q\bar{q}$ pairs are created and annihilated inside hadrons

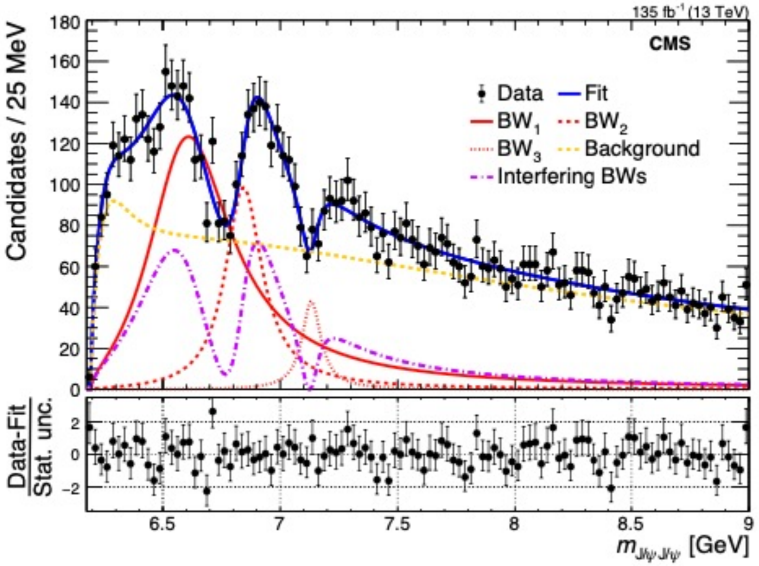
Fully-heavy tetraquarks



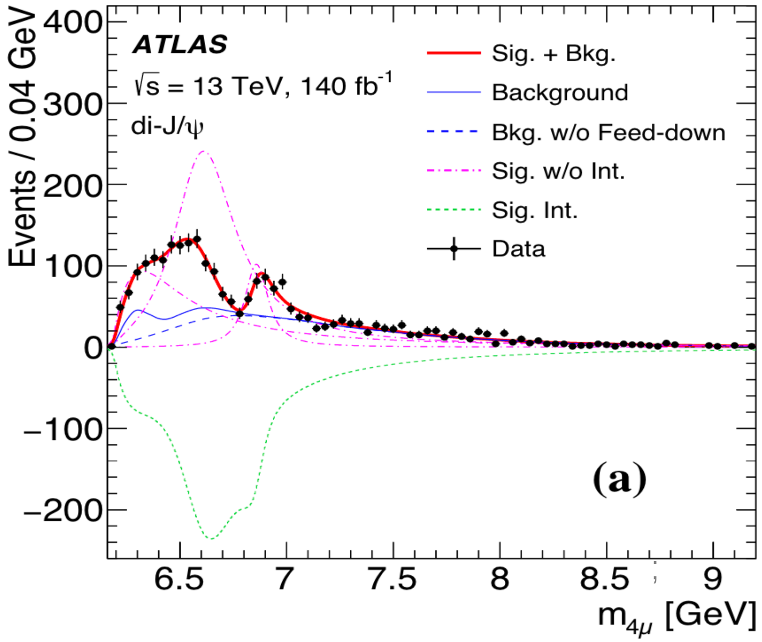
LHCb (2020)
CMS (2022)
ATLAS (2022)



data from LHCb, Sci.Bull.65 (2020) 1983;
fit from X.-K. Dong, Baru, FKG, Hanhart, Nedefiev, PRL126 (2021) 132001



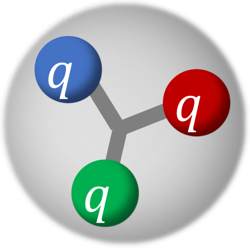
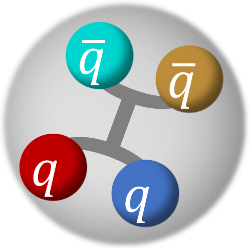
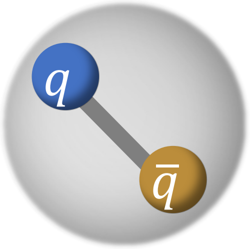
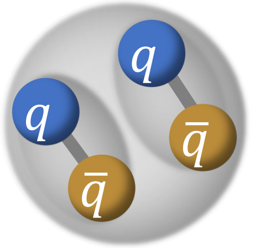
CMS, arXiv:2306.07164



ATLAS, arXiv:2304.08962

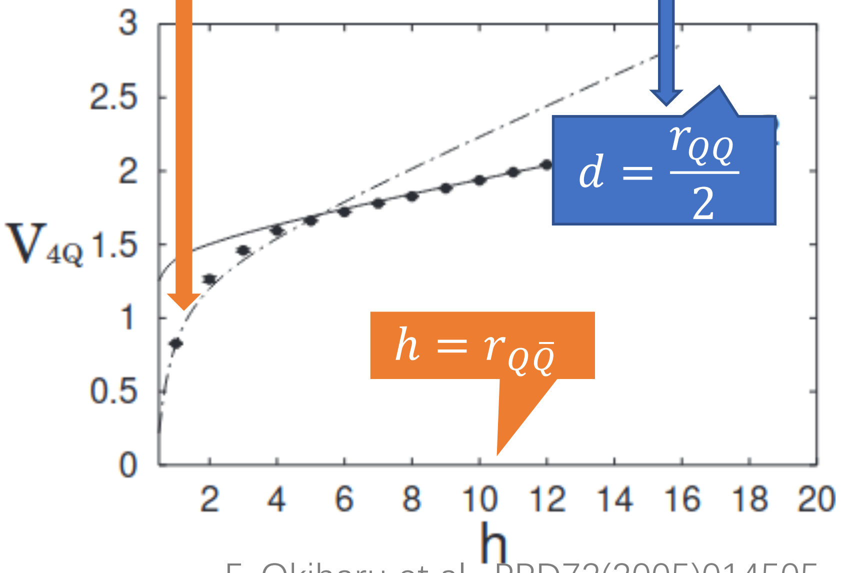
Conventional and exotic hadrons

- Different flux tube configurations: compact multiquarks and hadronic molecules

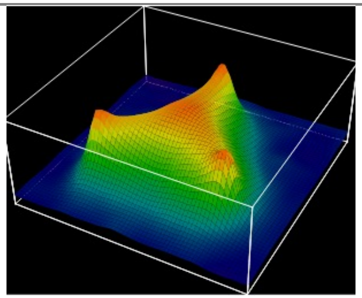
Conventional hadrons	Multiquarks vs hadronic molecules
 baryon	 compact tetraquark
 meson	 hadronic molecule

For large distance between Q and $\bar{Q}$

For small distance between Q and $\bar{Q}$



F. Okiharu et al., PRD72(2005)014505



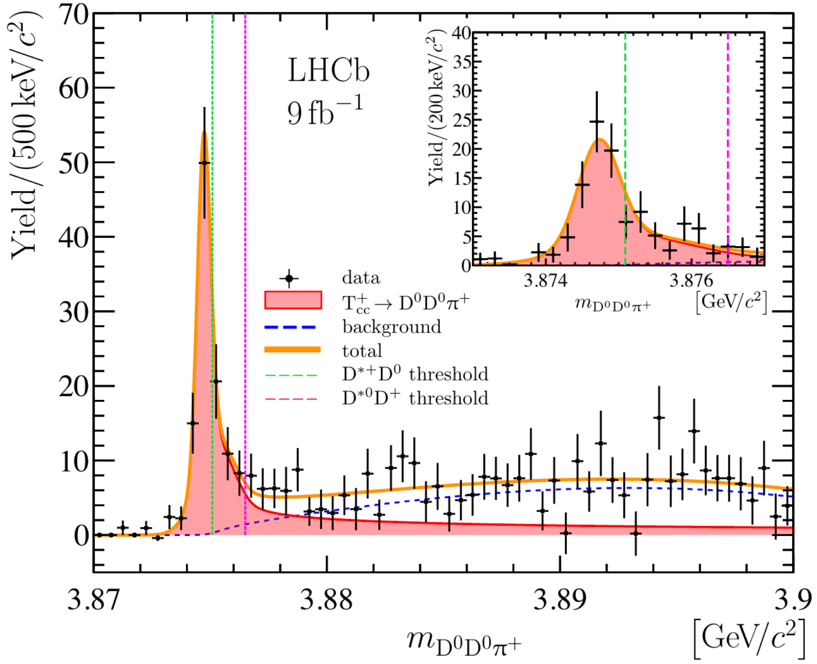
V.G. Bornyakov et al., PRD70(2004)054506

For lattice studies of flux tube picture of multiquarks, see, e.g., F. Okiharu, H. Suganuma, T. T. Takahashi, PRD72(2005)014505; PRL94(2005)192001
An overview: H. Suganuma et al., arXiv:1103.4015

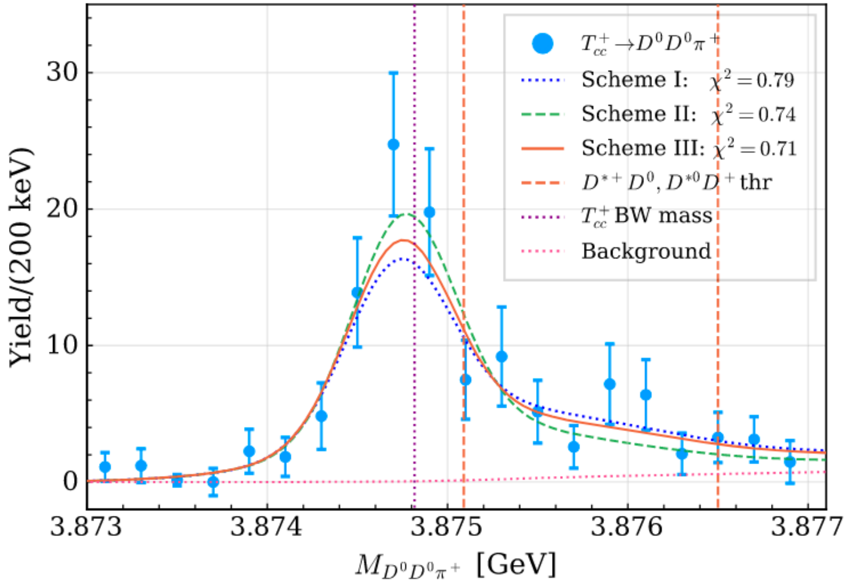
- Hints at confinement mechanism?
- Quark flavor dependent?

Double-charm T_{cc}: molecular

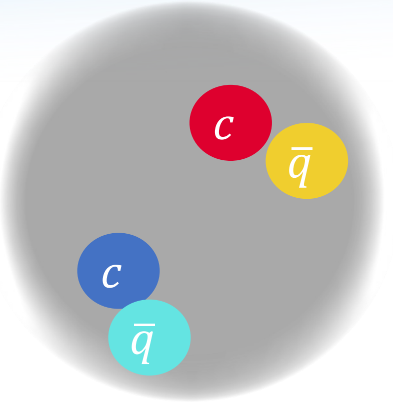
- $T_{cc}(3875)$ is very close to the DD^* thresholds



LHCb, Nature Phys. 18 (2022) 751;
Nature Commun. 13 (2022) 3351



Fit in M.-L. Du et al., PRD 105 (2022) 014024



- Effective field theory analyses of the LHCb data ⇒
- $T_{cc}(3875)$ is a DD^* molecule: ~ 70% $D^{*+}D^0$, ~30% $D^{*0}D^+$

M.-L. Du et al., PRD 105 (2022) 014024;
S. Fleming, R. Hodges, T. Mehen, PRD 104 (2021) 116010; M. Albaladejo, PLB 829 (2022) 137052; ⋯

- Lattice "observations" of T_{cc} from DD^* scattering supports molecular nature

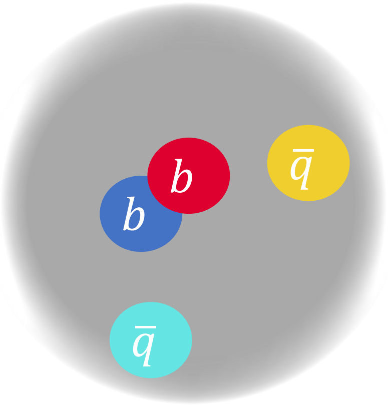
M. Padmanath, S. Prelovsek, PRL 129 (2022) 032002;
S.. Chen et al., PLB 833 (2022) 137391; Y. Lyu et al. [HAL QCD], PRL 131 (2023) 161901

Double-bottom tetraquarks: more compact?

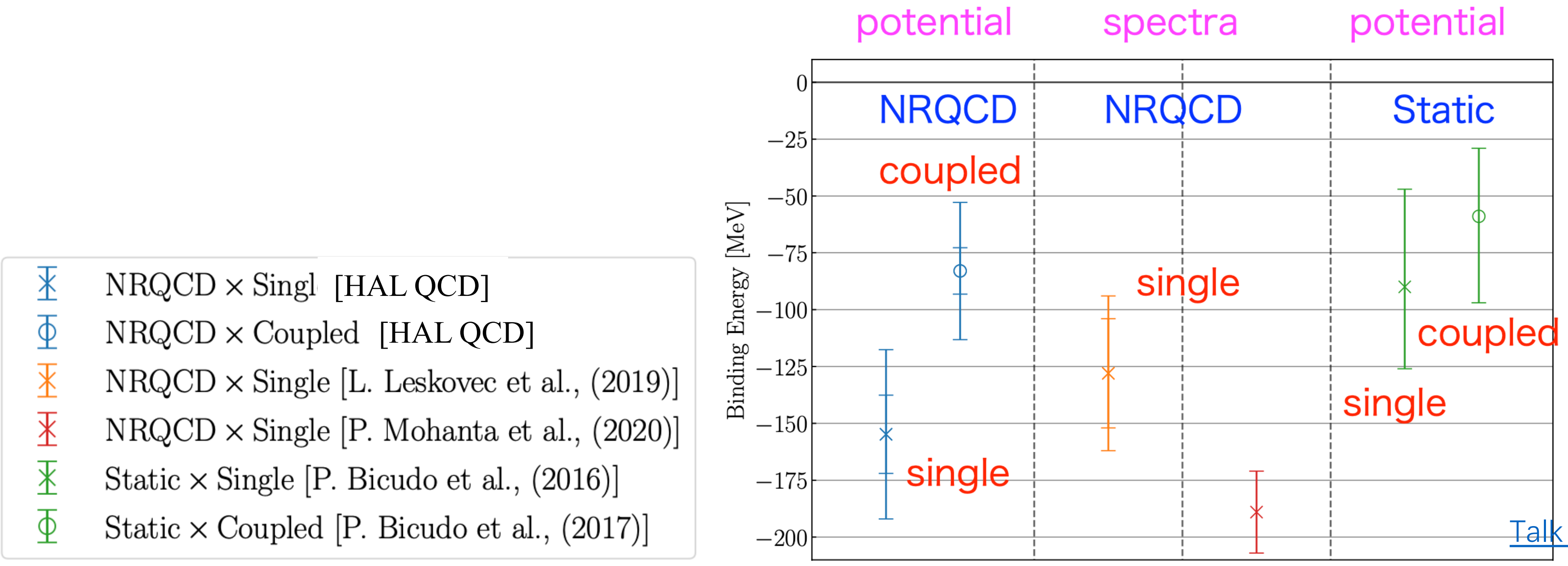
For extremely heavy quarks, QQ behaves like an anti-heavy quark

- Qqq singly-heavy baryon implies the existence of stable $\bar{Q}\bar{Q}qq$ tetraquarks
- If deeply bound, then small hadronic molecular component
- Bottom quark could be heavy enough for the existence of stable $\bar{b}\bar{b}qq$

Manohar, Wise, NPB399(1993)17; see also Carlson, Heller, Tjon, PRD37(1988)744; Karliner, Rosner, PRL119(2017)202001; Eichten, Quigg, PRL119(2017)202002; Czarnecki, Leng, Voloshin, PLB778(2018)233; …



- Support from lattice QCD calculations: $\bar{b}\bar{b}ud$ with $I(J^P) = 0(1^+)$ below the BB^* threshold

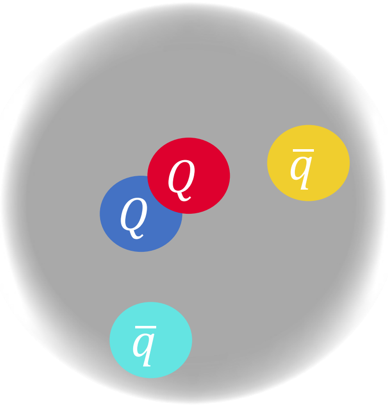


Talk by S. Aoki at Lattice 2022

Double-bottom tetraquarks

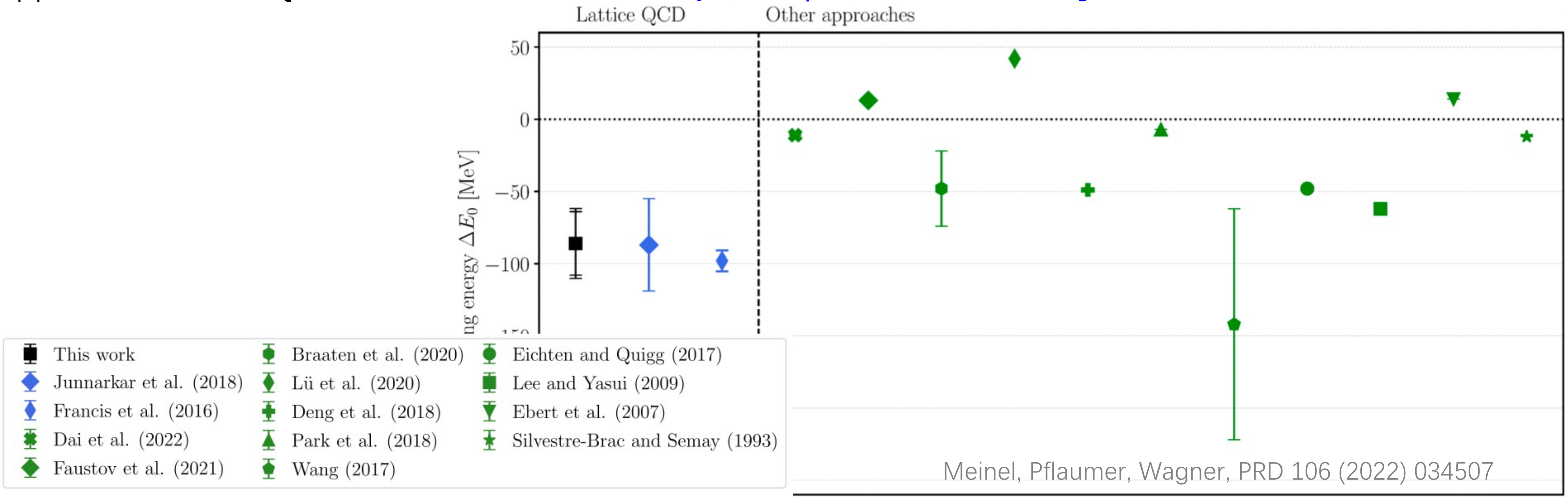
For extremely heavy quarks, QQ behaves like an anti-heavy quark

- Qqq singly-heavy baryon implies the existence of stable $\bar{Q}\bar{Q}qq$ tetraquarks
- If deeply bound, then small hadronic molecular component
- Bottom quark could be heavy enough for the existence of stable $\bar{b}\bar{b}qq$



Manohar, Wise, NPB399(1993)17; see also Carlson, Heller, Tjon, PRD37(1988)744; Karliner, Rosner, PRL119(2017)202001; Eichten, Quigg, PRL119(2017)202002; Czarnecki, Leng, Voloshin, PLB778(2018)233; …

- Support from lattice QCD calculations: $\bar{b}\bar{b}us$ with $I(J^P) = 1/2(1^+)$ below the B_sB^* threshold



Meinel, Pflaumer, Wagner, PRD 106 (2022) 034507

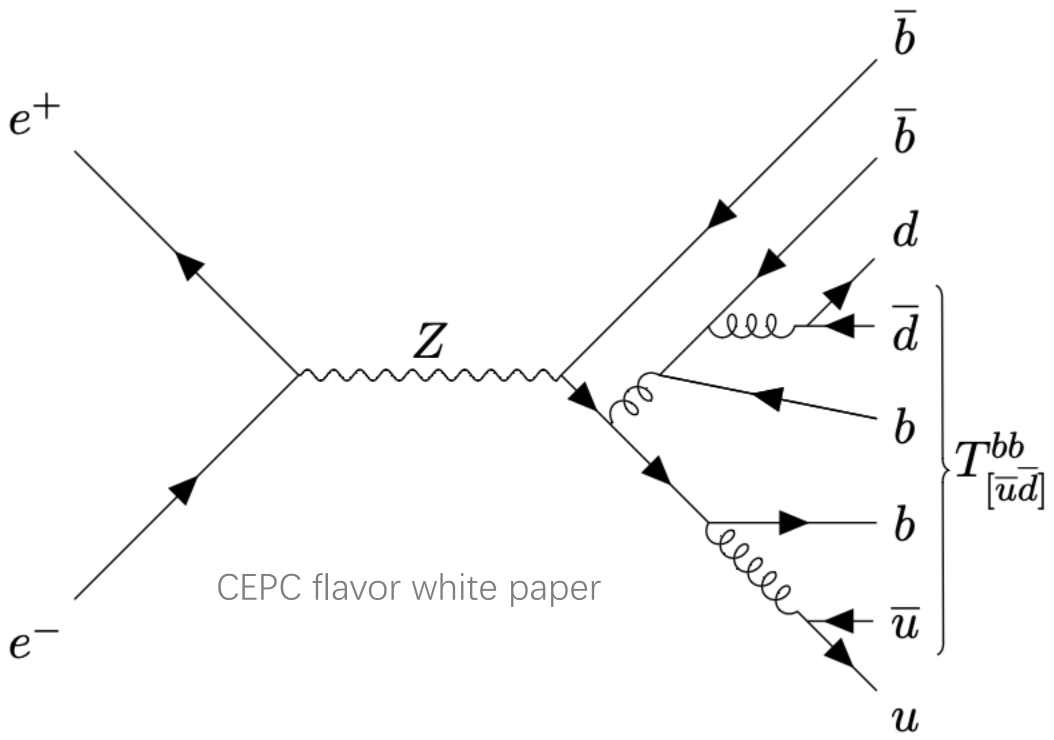
Z branching fractions

Γ_8	hadrons	$(69.911 \pm 0.056)\%$
Γ_9	$(u\bar{u} + c\bar{c})/2$	$(11.6 \pm 0.6)\%$
Γ_{10}	$(d\bar{d} + s\bar{s} + b\bar{b})/3$	$(15.6 \pm 0.4)\%$
Γ_{11}	$c\bar{c}$	$(12.03 \pm 0.21)\%$
Γ_{12}	$b\bar{b}$	$(15.12 \pm 0.05)\%$
Γ_{13}	$b\bar{b}b\bar{b}$	$(3.6 \pm 1.3) \times 10^{-4}$
Γ_{26}	$J/\psi(1S)$ X	$(3.51^{+0.23}_{-0.25}) \times 10^{-3}$
Γ_{27}	$J/\psi(1S)\gamma$	$< 1.4 \times 10^{-6}$
Γ_{28}	$\psi(2S)$ X	$(1.60 \pm 0.29) \times 10^{-3}$
Γ_{34}	$\Upsilon(1S)$ X $+\Upsilon(2S)$ X $+\Upsilon(3S)$ X	$(1.0 \pm 0.5) \times 10^{-4}$

Γ_{42}	$(D^0/\bar{D}^0)$ X	$(20.7 \pm 2.0)\%$
Γ_{43}	$D^{\pm}$ X	$(12.2 \pm 1.7)\%$
Γ_{44}	$D^*(2010)^{\pm}$ X	$(11.4 \pm 1.3)\%$
Γ_{45}	$D_{s1}(2536)^{\pm}$ X	$(3.6 \pm 0.8) \times 10^{-3}$
Γ_{46}	$D_{sJ}(2573)^{\pm}$ X	$(5.8 \pm 2.2) \times 10^{-3}$
Γ_{49}	B^* X	
Γ_{50}	B^+ X	$(6.08 \pm 0.13)\%$
Γ_{51}	B_s^0 X	$(1.59 \pm 0.13)\%$
Γ_{52}	B_c^+ X	searched for
Γ_{53}	Λ_c^+ X	$(1.54 \pm 0.33)\%$
Γ_{54}	Ξ_c^0 X	seen
Γ_{55}	Ξ_b X	seen
Γ_{56}	b-baryon X	$(1.38 \pm 0.22)\%$

Wonderful source for study hadrons with charm and/or bottom

Productions of doubly-heavy tetraquarks at the Z pole



CEPC flavor white paper

- Estimates of the branching fractions of Z decays to doubly-heavy tetraquarks

$$\mathcal{B}\left(Z \to T^{\{cc\}}_{[\bar{u}\bar{d}]} + X\right) = \left(4.1^{+3.4}_{-1.5}\right) \times 10^{-6} ,$$

$$\mathcal{B}\left(Z \to T^{\{cc\}}_{[\bar{u}\bar{s}]} + X\right) = \mathcal{B}\left(Z \to T^{\{cc\}}_{[\bar{d}\bar{s}]} + X\right) = \left(1.0^{+0.8}_{-0.4}\right) \times 10^{-6} .$$

$$\mathcal{B}(Z \to T^{\{bb\}}_{[\bar{u}\bar{d}]} + \bar{b}\bar{b}) = (1.2^{+1.0}_{-0.3}) \times 10^{-6}.$$

Q. Qin, Y.-F. Shen, F.-S. Yu, CPC 45 (2021) 103106

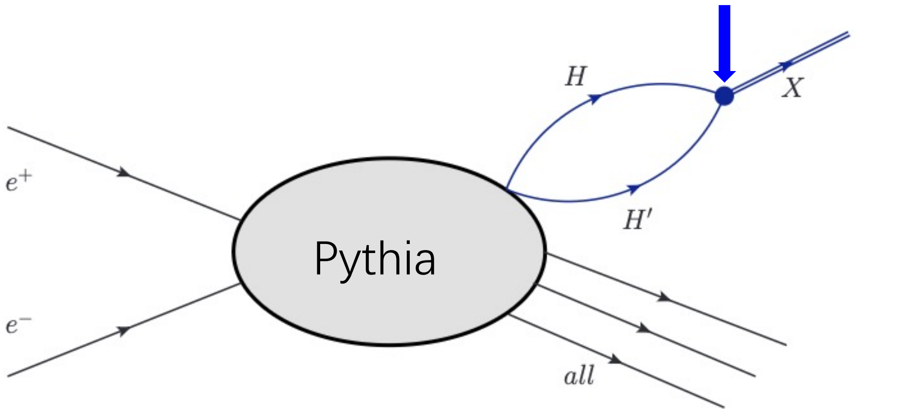
A. Ali, A. Parkhomenko, Q. Qin, W. Wang, PLB 782 (2018) 412

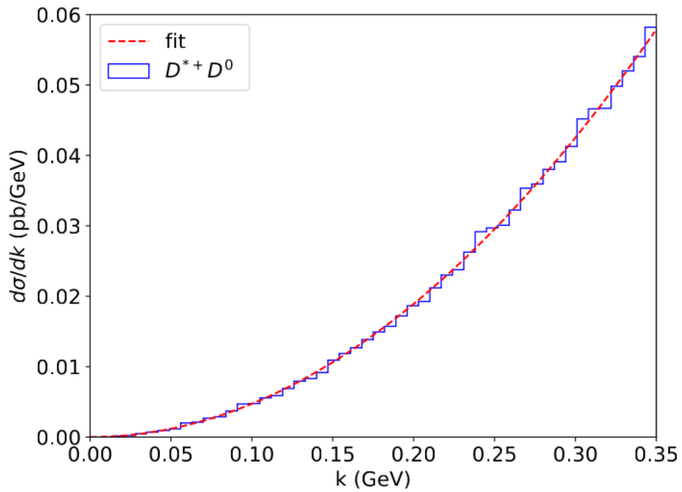
$\Rightarrow \mathcal{O}(10^6)$ double-charm and double-bottom tetraquarks at Tera-Z factories with 10^{12} Z events

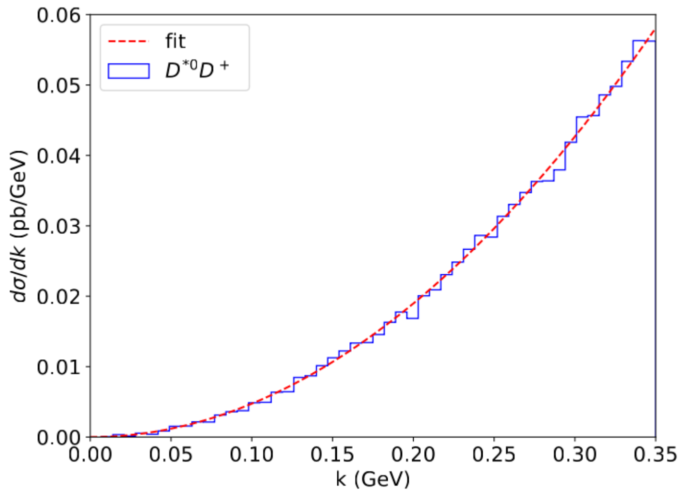
Productions of hadronic molecules at the Z pole

Z.-S. Jia, P.-P. Shi, Z.-H. Zhang, G. Li, FKG, arXiv:231x.yyyyy

- Cross section estimates







✓ The method has successfully reproduce the production cross sections of $X(3872)$ at hadron colliders

Artoisenet, Braaten, PRD 83 (2011) 014019; FKG, Meißner, W. Wang, Z. Yang, EPJC 74 (2014) 3063

✓ Inclusive cross section estimates for CEPC at the Z pole. Examples (many more in the forthcoming paper):

	Constituents	Cross section	Events ($L = 100\ \mathrm{ab}^{-1}$)
$T_{cc}(3875)$	DD^*	$\mathcal{O}(1\sim10\ \mathrm{fb})$	$\mathcal{O}(10^5\sim10^6)$
$X(3872)$	$D\bar{D}^*$	$\mathcal{O}(0.1\sim1\ \mathrm{pb})$	$\mathcal{O}(10^7\sim10^8)$
$Z_c(3900)$	$D\bar{D}^*$	$\mathcal{O}(1\sim10\ \mathrm{pb})$	$\mathcal{O}(10^8\sim10^9)$
$Z_b(10610)$	$B\bar{B}^*$	$\mathcal{O}(0.01\sim0.1\ \mathrm{pb})$	$\mathcal{O}(10^6\sim10^7)$
$P_c(4312)$	$\Sigma_c\bar{D}$	$\mathcal{O}(1\sim10\ \mathrm{fb})$	$\mathcal{O}(10^5\sim10^6)$

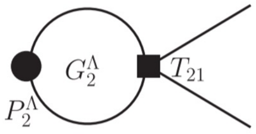
Reconstruction efficiencies not considered in the event estimates

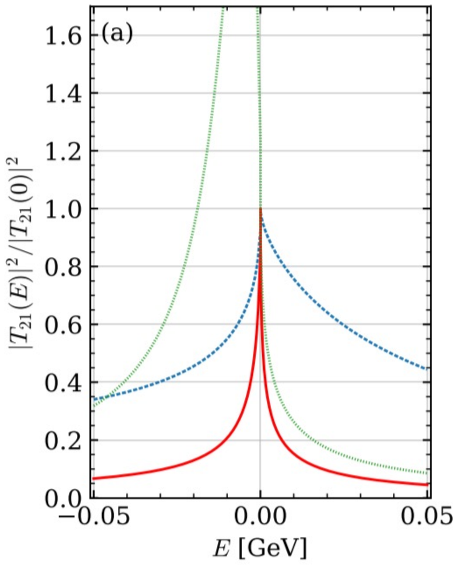
Challenges from the perspective of amplitude analysis

- High statistical data in different processes are the basis for understanding hadron resonances
- Amplitudes with the same pole (hadron resonance) may have distinct line shapes in different reactions

E.g., consider a two-channel problem: X.-K. Dong, FKG, B.-S. Zou, PRL 126 (2021) 152001

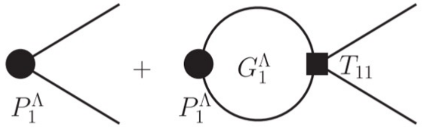
- Dominated by higher ch.
  - Maximal at threshold for positive $\mathrm{Re}(a_{22,\mathrm{eff}})$ (attraction), FWHM $\propto 1/\mu$
    - more pronounced for heavier hadrons and stronger interactions
  - Peaking at pole for negative $\mathrm{Re}(a_{22,\mathrm{eff}})$

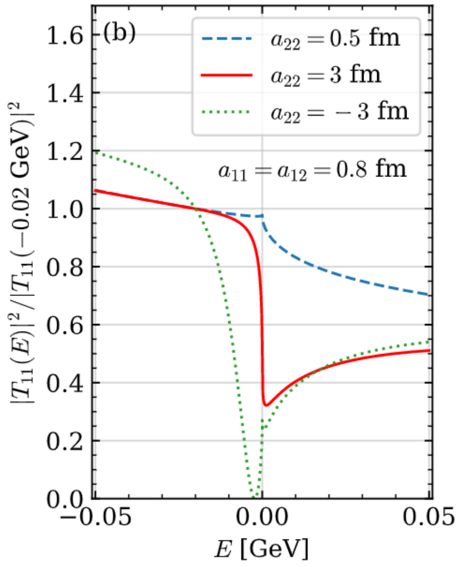




$$T_{21} \propto \frac{1}{a_{22,\mathrm{eff}}^{-1} - i\sqrt{2\mu_2 E}}$$

- Dominated by lower ch.
  - One pole and one zero
  - Universality for large scattering length: for large $|a_{22}|$, there must be a dip around threshold (zero close to threshold)





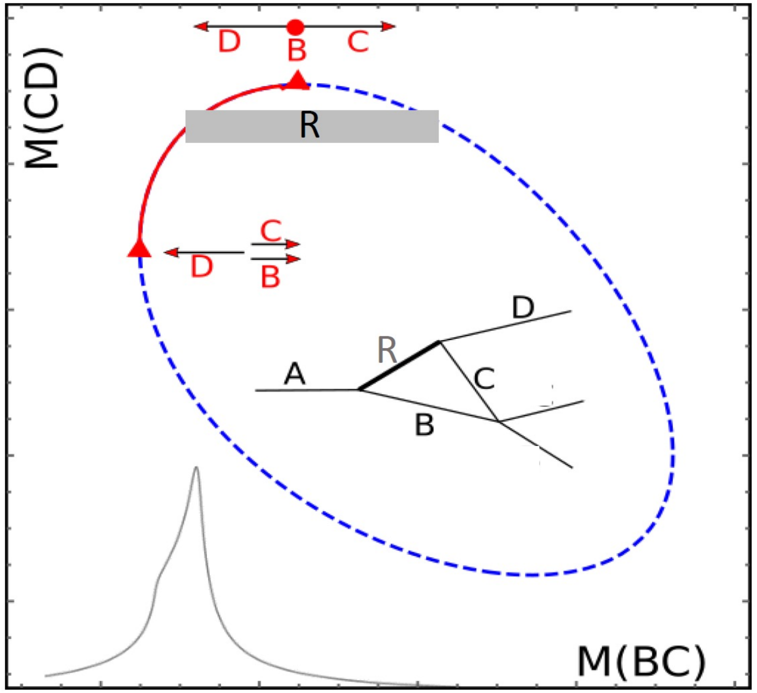
$$T_{11} \propto \frac{a_{22}^{-1} - i\sqrt{2\mu_2 E}}{a_{22,\mathrm{eff}}^{-1} - i\sqrt{2\mu_2 E}}$$

Challenges from the perspective of amplitude analysis

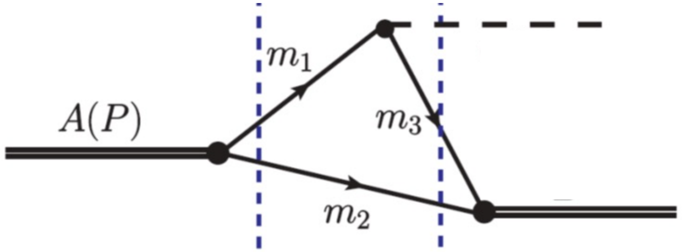
- Kinematic singularities such as triangle singularity may mimic resonance peaks

L.D. Landau (1959); J.D. Bjorken (1959); J. Mathews (1959); N. Nakanishi (1959); Coleman, Norton (1965); Bronzan (1964); Schmid (1967); ⋯

Review: FKG, X.-H. Liu, S. Sakai, PPNP112 (2020) 103757



Logarithmic singularity



$$\frac{1}{2m_A}\sqrt{\lambda(m_A^2, m_1^2, m_2^2)} \equiv \boxed{p_{2,\text{left}} = p_{2,\text{right}}} \equiv \gamma\left(\beta E_2^* - p_2^*\right)$$

On-shell momenta of m_2 at the left and right cuts in the A rest frame

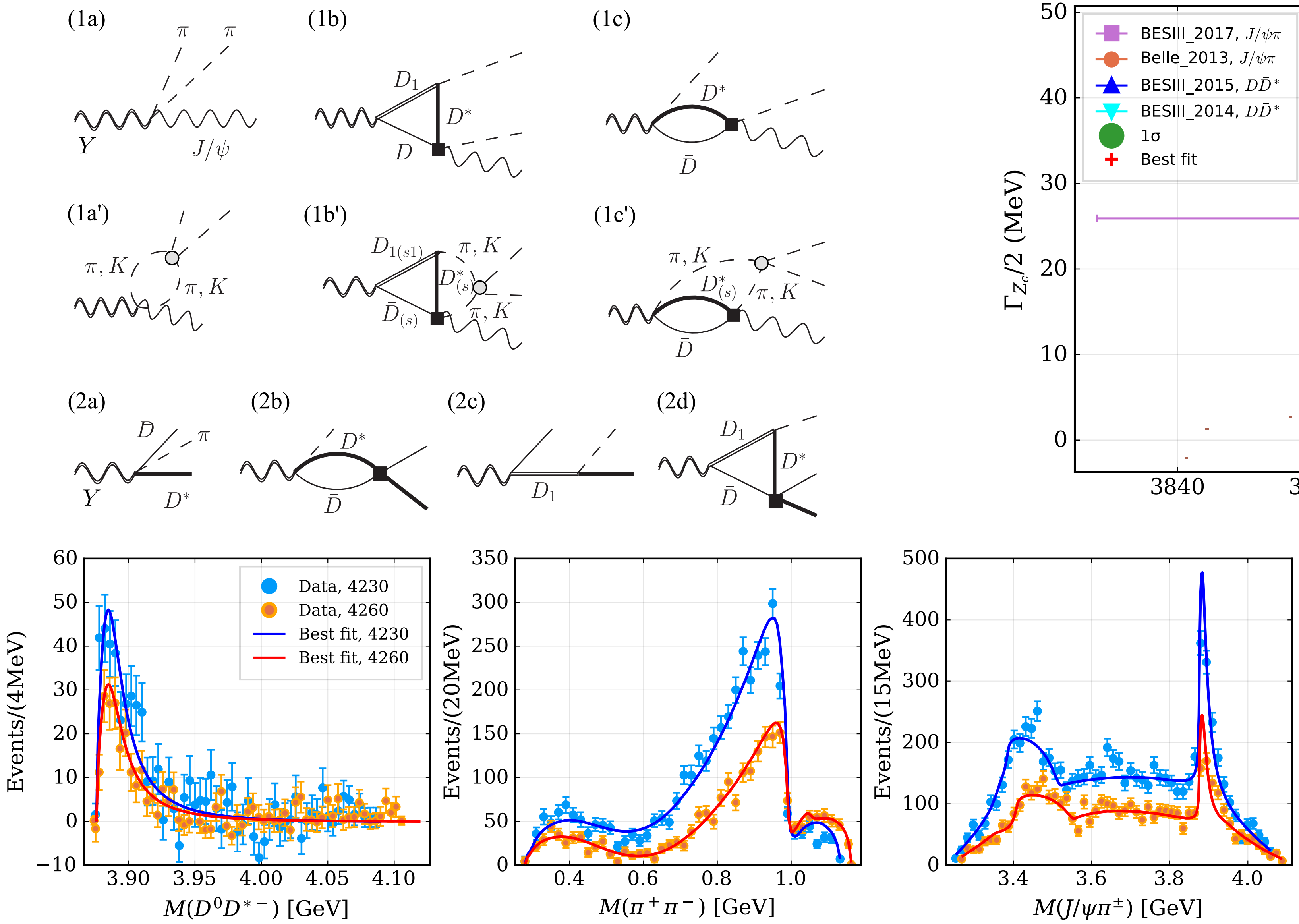
$$v_2 = \beta\frac{E_2^* - p_2^*/\beta}{E_2^* - \beta p_2^*} < \beta, \qquad v_3 = \beta\frac{E_3^* + p_2^*/\beta}{E_3^* + \beta p_2^*} > \beta$$

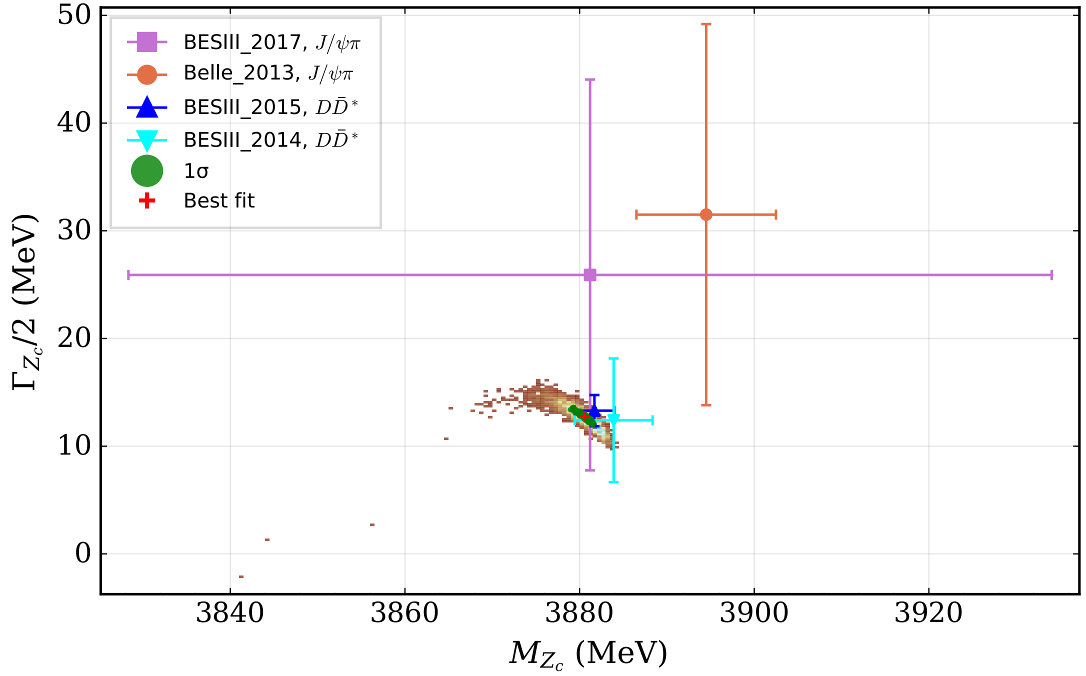
M. Bayar et al., PRD 94 (2016) 074039

- Narrow peaks for S-wave coupling
- Triangle singularities are sensitive to kinematic variables ⇒
  - energy dependence
  - more processes

Example analysis of the $Z_c(3900)$

Y.-H. Chen, M.-L. Du, FKG, arXiv:2310.15965





Conclusion:

$D\bar{D}^*$ molecular and non-molecular components are of similar importance for $Z_c(3900)$

BESIII data: PRD 92 (2015) 092006; PRL 119 (2017) 072001

Summary

- Hadron spectroscopy is still not understood
- Tens of exotic heavy-flavor (hidden or open) hadron candidates were observed in the last two decades
  - Mysteries
  - Many were observed by a single experiment so far
- A tera-Z factory will provide a wonderful source for these exotic hadrons and could be unique for searching for double-bottom tetraquarks

Thank you for your attention