重味近阈强子态

郭奉坤

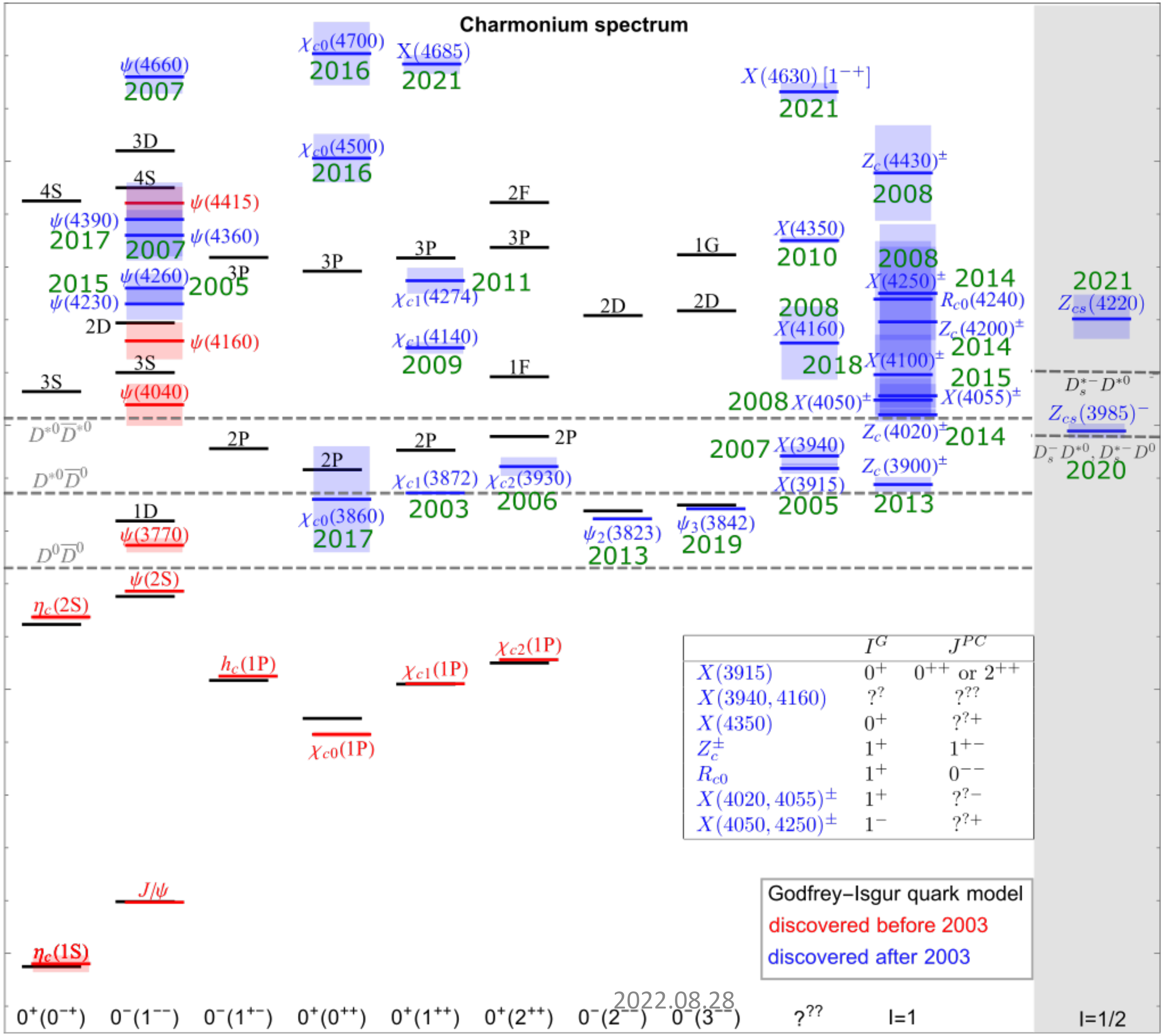
中国科学院理论物理研究所

Symposium on Nuclear Physics Frontiers and Intersections (SYNPFI)

Aug 25, 2022, 8:00 AM → Aug 28, 2022, 6:00 PM Asia/Shanghai

旷真阁 (北京， 香山饭店)

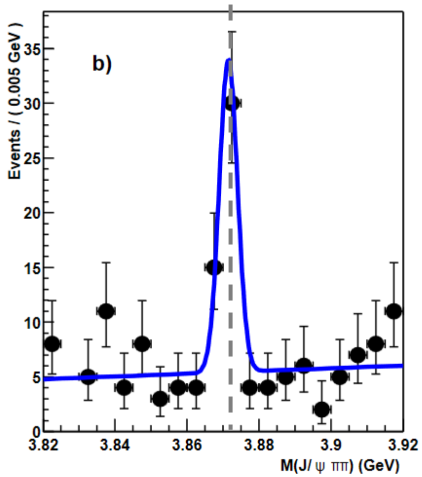
Charmonium(-like) structures

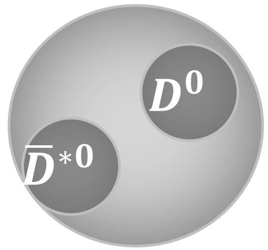


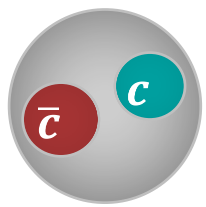
Charmonium-like structures

- X(3872) Belle, PRL91(2003)262001

$D^0\bar{D}^{*0}$ thr.



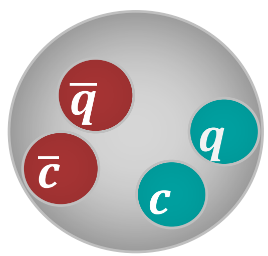




$$\delta \equiv M_{D^0} + M_{D^{*0}} - M_X$$

$$\delta = 0.01 \pm 0.14\ \mathrm{MeV}$$

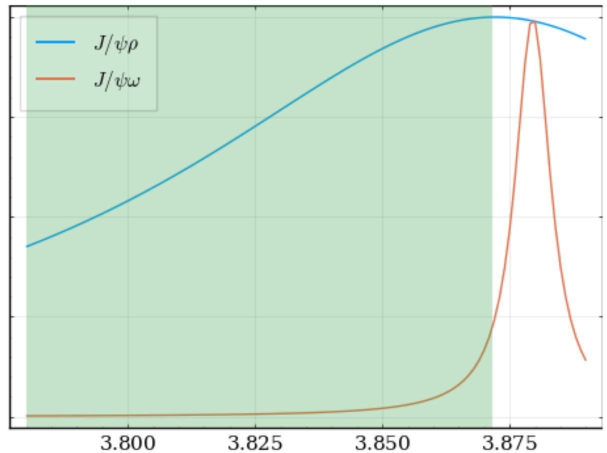
LHCb, PRD102(2020)092005



➢ Huge isospin breaking

$$\frac{\mathcal{B}(X\to\omega J/\psi)}{\mathcal{B}(X\to\rho J/\psi)} = 1.1 \pm 0.4$$

largely from phase space difference



$$\frac{g_{X\rho J/\psi}}{g_{X\omega J/\psi}} = 0.29 \pm 0.04$$

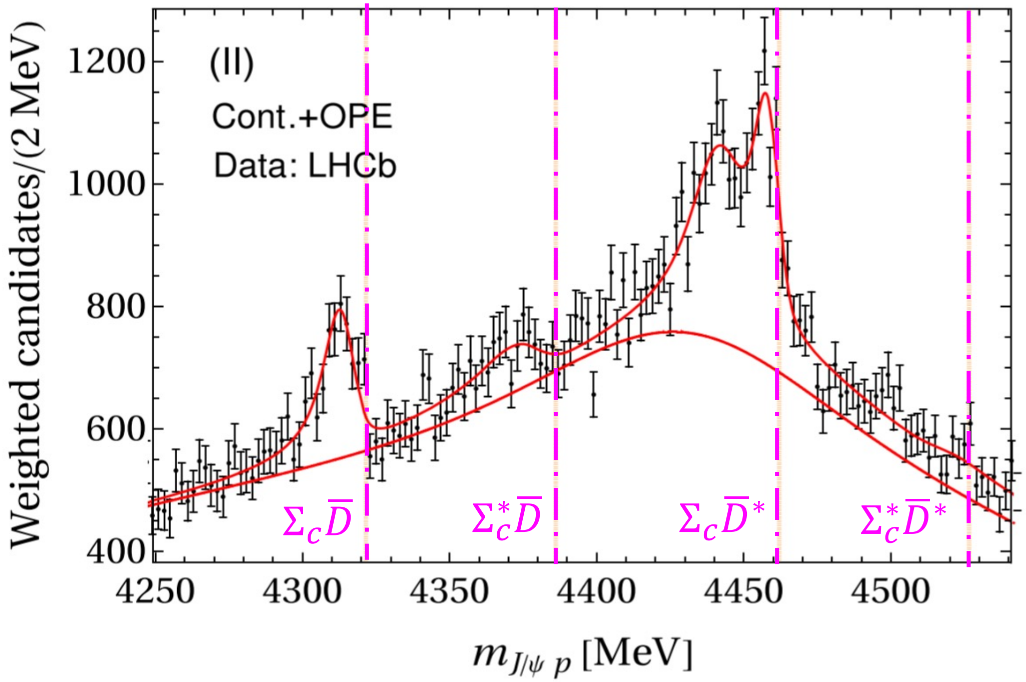
Many new structures are near thresholds of a pair of heavy hadrons.

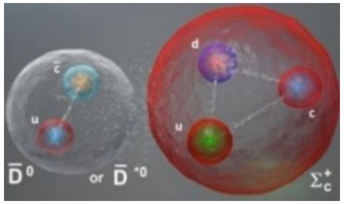
Why are there so many (near-)threshold structures in heavy-hadron spectrum?

Is there any rule?

Charmonium-like structures

- $P_c(4312), P_c(4440), P_c(4457)$





data from LHCb, PRL122 (2019) 222001;
fit from
M.-L. Du, Baru, FKG, Hanhart, Meißner, Oller, Q. Wang, PRL124 (2020) 072001

Many new structures are near thresholds of a pair of heavy hadrons.

Why are there so many (near-)threshold structures in heavy-hadron spectrum?

Is there any rule?

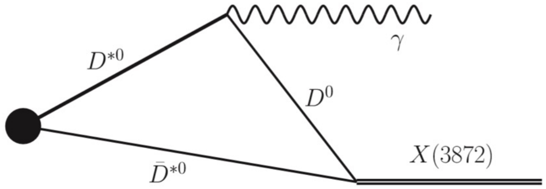
束缚能精确测量的新方法

Triangle singularity: For a review, see FKG, X.-H. Liu, S. Sakai, PPNP 112 (2020) 103757

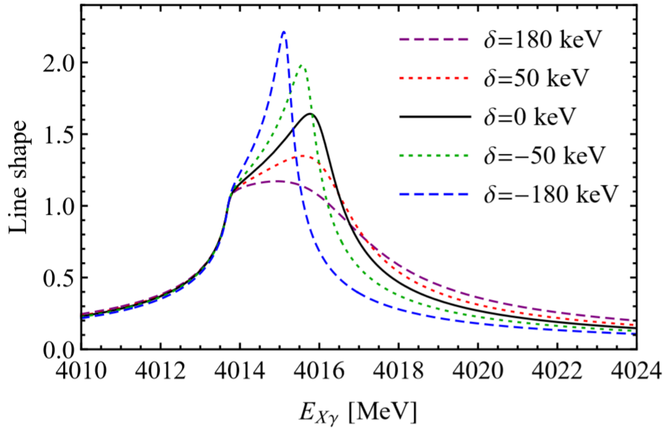
- logarithmic branch point for a triangle diagram
- all intermediate particles are on-shell, and move collinearly
- sensitive to kinematic variables; directly measures the binding energy of a near-threshold particle

FKG, PRL122 (2019) 202002

➢ Precision beyond the limit of mass uncertainties of the constituent particles



$$E_{X\gamma}^{\mathrm{TS}} \simeq 2M_{D^{*0}} + \frac{1}{2M_{D^0}}\left(M_{D^{*0}} - M_{D^0} - 2\sqrt{-M_{D^0}\delta} + \delta\right)^2$$



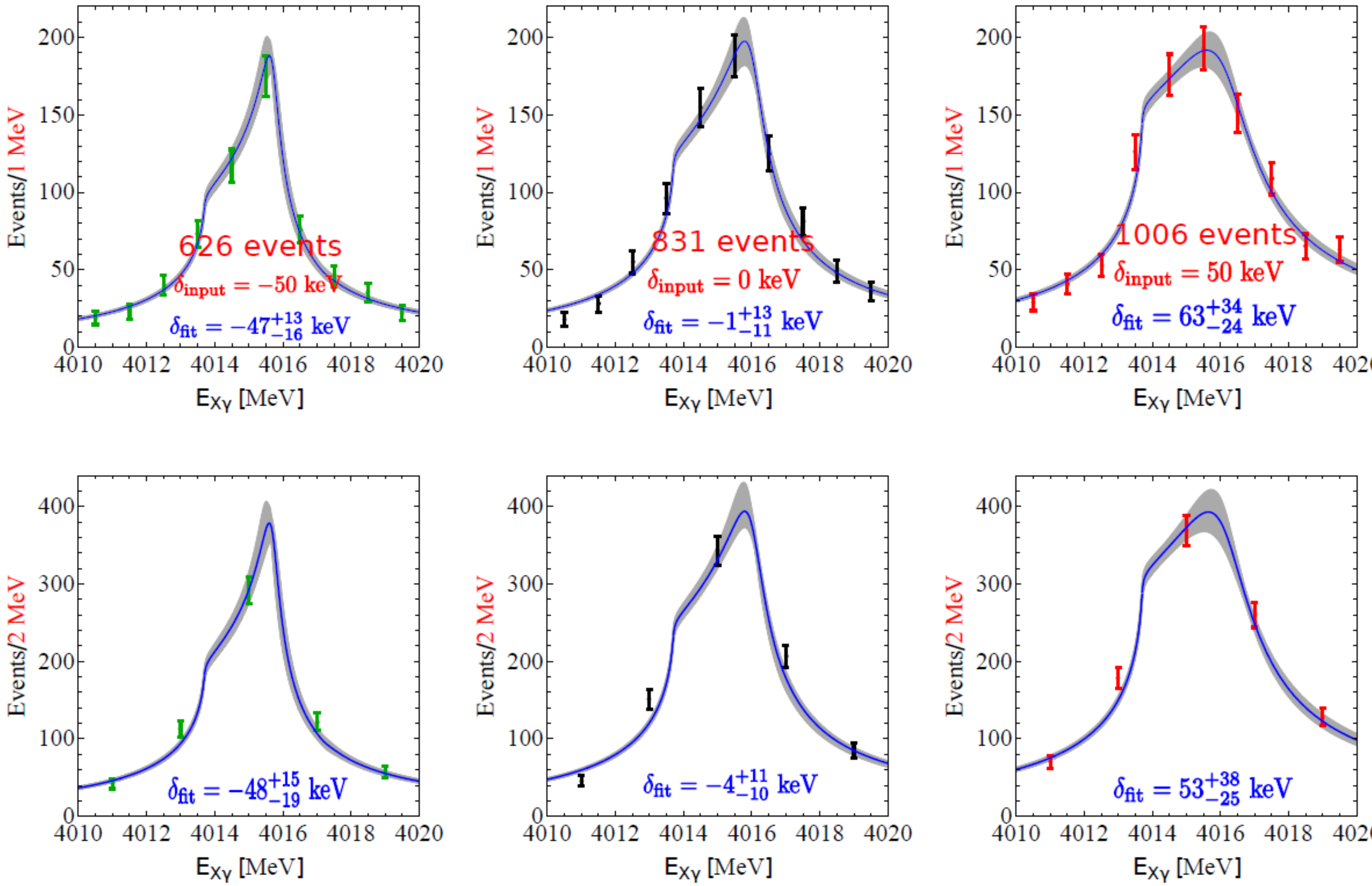
- Cusp fixed at the $D^{*0}\bar{D}^{*0}$ threshold
- Peak fixed at the TS energy:

δ (keV)	$E_{X\gamma}^{\mathrm{TS}}$ (MeV)
-180	$4015.2 - i0.1$
-50	$4015.7 - i0.2$
0	$4016.0 - i0.4$

束缚能精确测量的新方法

Precision simulation from synthetic data:

FKG, PRL122 (2019) 202002

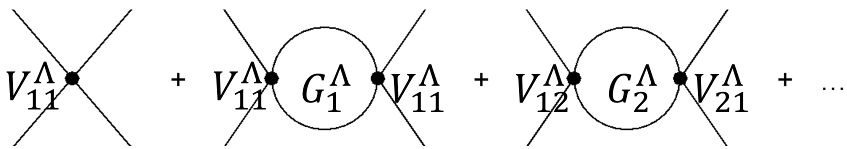


- Effective field theory: the method is universal!
  - applications in measuring binding energies of exotic nuclei?
  - and in other fields?

Near-threshold structures: NREFT

X.-K. Dong, FKG, B.-S. Zou, PRL126,152001(2021)

- Full threshold structure needs to be measured in a lower channel ⇨ coupled channels
- Consider a two-channel system, construct a nonrelativistic effective field theory (NREFT)
  - ➢ Energy region around the higher threshold, Σ_2
  - ➢ Expansion in powers of $E = \sqrt{s} - \Sigma_2$
  - ➢ Momentum in the lower channel can also be expanded



$$\det = \left(\frac{1}{a_{11}} - ik_1\right)\left(\frac{1}{a_{22}} + \sqrt{-2\mu_2 E - i\epsilon}\right) - \frac{1}{a_{12}^2}$$

$$T(E) = 8\pi\Sigma_2 \begin{pmatrix} -\frac{1}{a_{11}} + ik_1 & \frac{1}{a_{12}} \\ \frac{1}{a_{12}} & -\frac{1}{a_{22}} - \sqrt{-2\mu_2 E - i\epsilon} \end{pmatrix}^{-1} = -\frac{8\pi\Sigma_2}{\det} \begin{pmatrix} \frac{1}{a_{22}} + \sqrt{-2\mu_2 E - i\epsilon} & \frac{1}{a_{12}} \\ \frac{1}{a_{12}} & \frac{1}{a_{11}} - ik_1 \end{pmatrix}$$

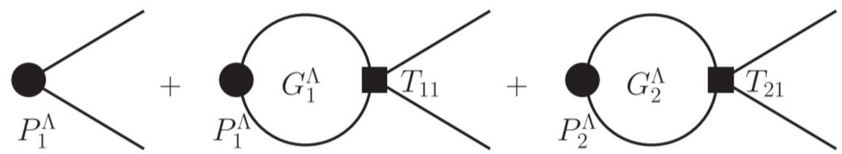
Effective scattering length with open-channel effects becomes complex, $\mathrm{Im}\,\frac{1}{a_{22,\mathrm{eff}}} \leq 0$

$$T_{22}(E) = -\frac{8\pi}{\Sigma_2}\left[\frac{1}{a_{22,\mathrm{eff}}} - i\sqrt{2\mu_2 E} + \mathcal{O}(E)\right]^{-1}$$

NREFT at LO

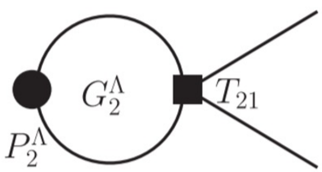
X.-K. Dong, FKG, B.-S. Zou, PRL126,152001(2021)

- Consider a production process, must go through final-state interaction (unitarity)



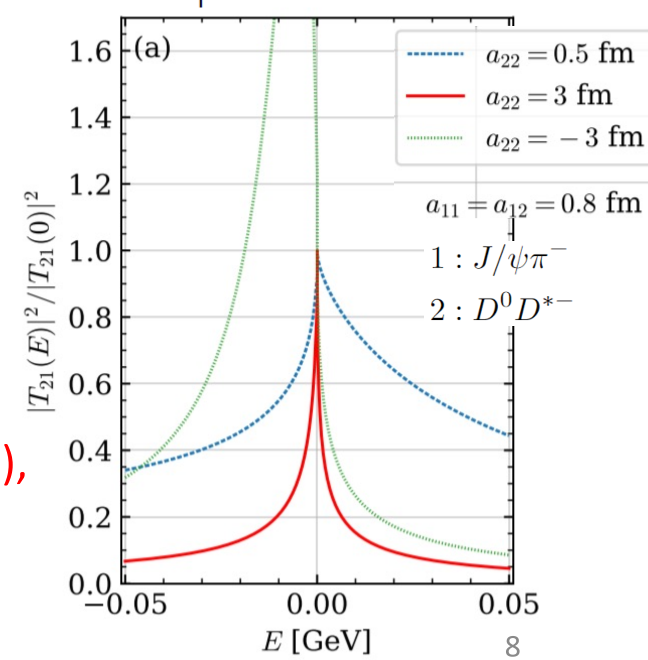
$$P_1^\Lambda[1+G_1^\Lambda T_{11}(E)] + P_2^\Lambda G_2^\Lambda(E) T_{21}(E)$$
$$= P_1^\Lambda (V_{11}^\Lambda)^{-1} T_{11}(E) + \left[P_1^\Lambda (V_{11}^\Lambda)^{-1} V_{12}^\Lambda + P_2^\Lambda\right] G_2^\Lambda T_{21}(E)$$
$$\equiv P_1 T_{11}(E) + P_2 T_{21}(E)$$

- All nontrivial energy dependence are contained in $T_{11}(E)$ and $T_{21}(E)$
- Case-1: dominated by $T_{21}(E)$,



$$T_{21}(E) = \frac{-8\pi\Sigma_2}{a_{12}(1/a_{11} - ik_1)}\left[\frac{1}{a_{22,\mathrm{eff}}} - i\sqrt{2\mu_2 E} + \mathcal{O}(E)\right]^{-1}.$$

$$|T_{21}(E)|^2 \propto |T_{22}(E)|^2 \propto$$
$$\begin{cases} \left[\left(\mathrm{Re}\,\frac{1}{a_{22,\mathrm{eff}}}\right)^2 + \left(\mathrm{Im}\,\frac{1}{a_{22,\mathrm{eff}}} - \sqrt{2\mu E}\right)^2\right]^{-1} & \text{for } E \geq 0 \\ \left[\left(\mathrm{Im}\,\frac{1}{a_{22,\mathrm{eff}}}\right)^2 + \left(\mathrm{Re}\,\frac{1}{a_{22,\mathrm{eff}}} + \sqrt{-2\mu E}\right)^2\right]^{-1} & \text{for } E < 0 \end{cases}$$

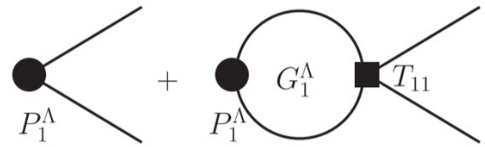


- Maximal at threshold for positive $\mathrm{Re}(a_{22,\mathrm{eff}})$ (attraction), FWHM $\propto 1/\mu$
- Peaking at pole for negative $\mathrm{Re}(a_{22,\mathrm{eff}})$

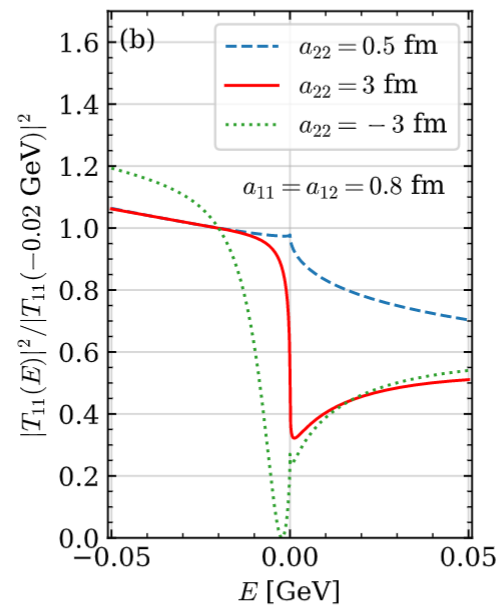
NREFT at LO

X.-K. Dong, FKG, B.-S. Zou, PRL126,152001(2021)

- Case-2: dominated by $T_{11}(E)$



$$T_{11}(E) = \frac{-8\pi\Sigma_2\left(\frac{1}{a_{22}} - i\sqrt{2\mu_2 E}\right)}{\left(\frac{1}{a_{11}} - i\,k_1\right)\left[\frac{1}{a_{22,\mathrm{eff}}} - i\sqrt{2\mu_2 E} + \mathcal{O}(E)\right]}$$



Poles in complex momentum plane:

$(-0.08 - i0.37)\mathrm{GeV}$

$(-0.08 - i0.04)\mathrm{GeV}$

$(-0.08 - i0.09)\mathrm{GeV}$

- One pole and one zero
- For strongly interacting channel-2 (large a_{22}), there must be a dip around threshold (zero close to threshold)

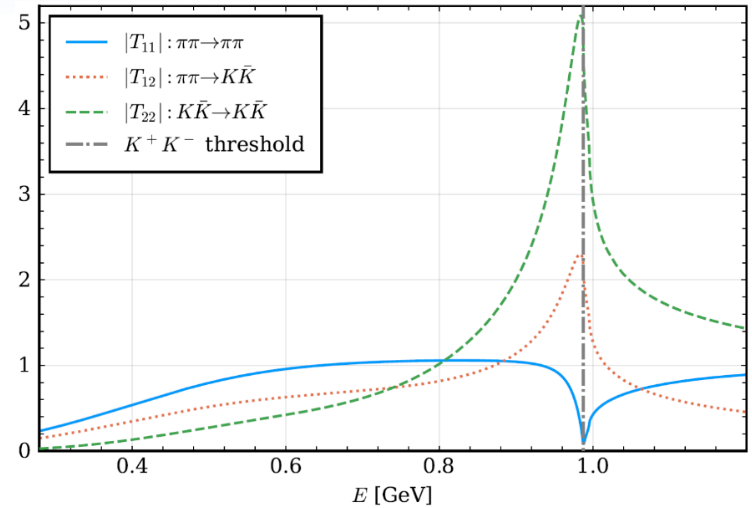
$$\frac{1}{a_{22,\mathrm{eff}}} = \frac{1}{a_{22}} - \frac{a_{11}}{a_{12}^2(1 + a_{11}^2 k_1^2)} - i\frac{a_{11}^2 k_1}{a_{12}^2(1 + a_{11}^2 k_1^2)}.$$

- More complicated line shape if both channels are important for the production

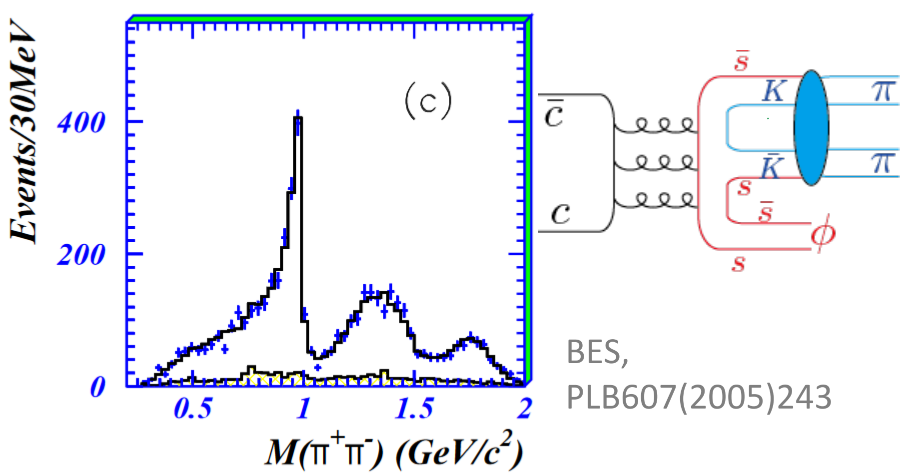
Phenomenology

- T-matrix for $\pi\pi$ and $K\bar{K}$ coupled channels

  with the T-matrix from
  L.-Y. Dai, M. R. Pennington, PRD90(2014)036004



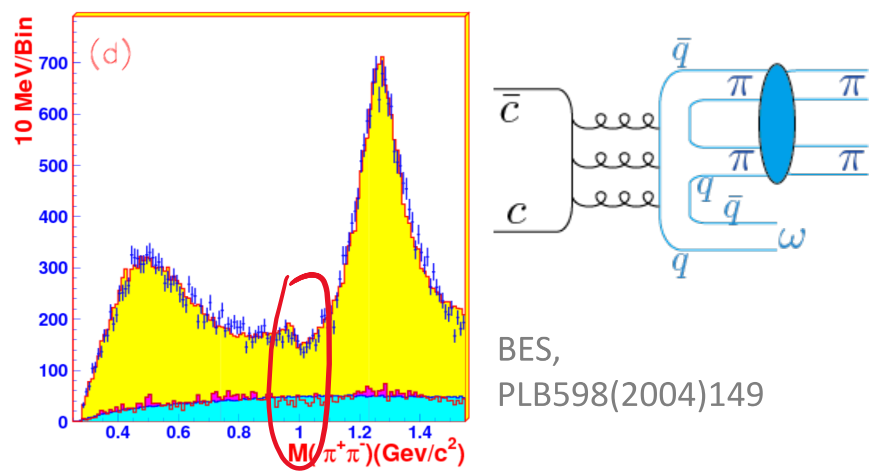
- $f_0(980)$ in $J/\psi \to \phi\pi^+\pi^-$ and $J/\psi \to \omega\pi^+\pi^-$ Channels: $\pi\pi$ and $K\bar{K}$



BES,
PLB607(2005)243

Driving channel: $K\bar{K}$

$J/\psi \to \phi K\bar{K} \to \phi\pi^+\pi^-$



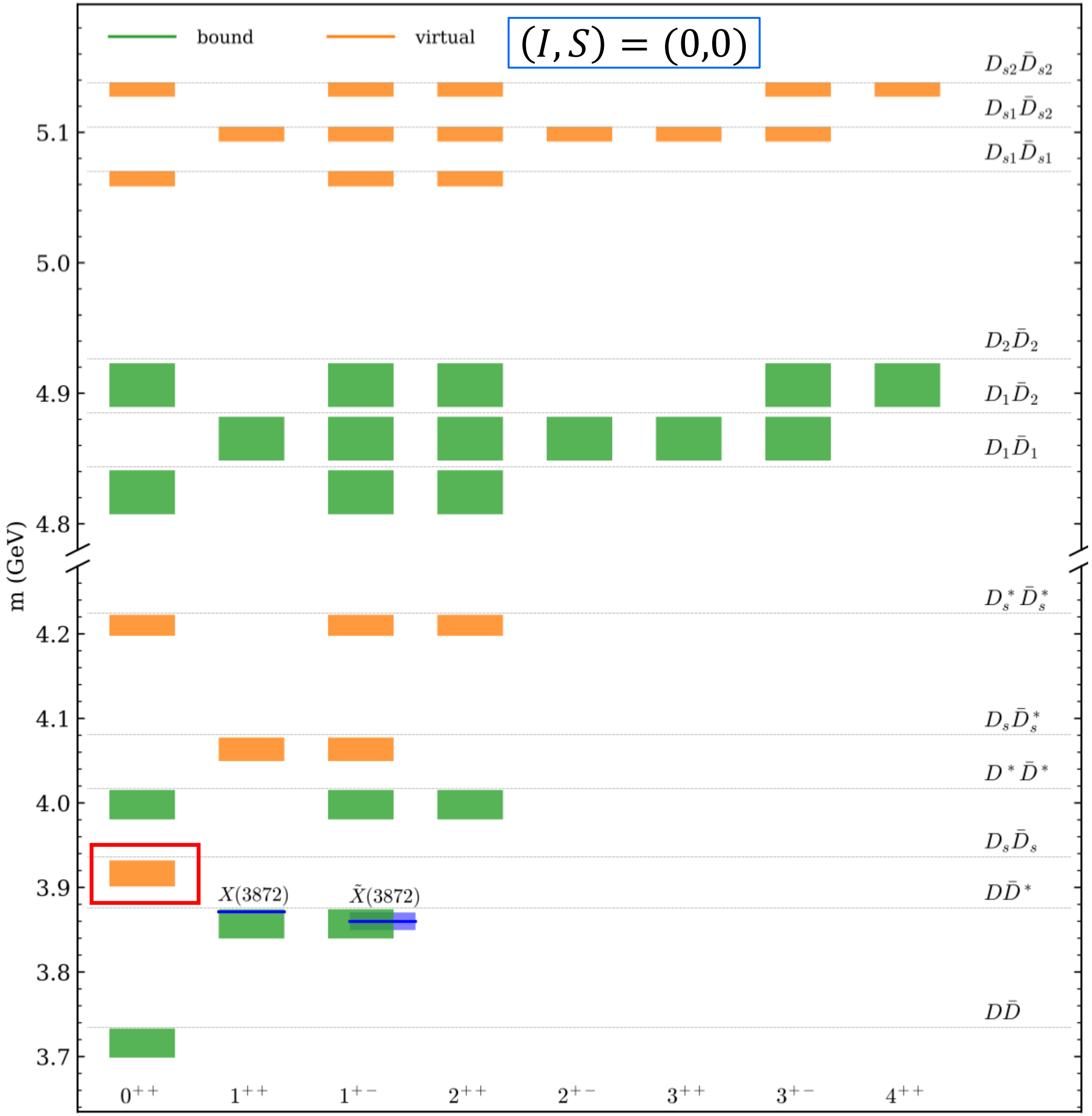
BES,
PLB598(2004)149

Driving channel: $\pi\pi$

$J/\psi \to \omega\pi\pi \to \omega\pi^+\pi^-$

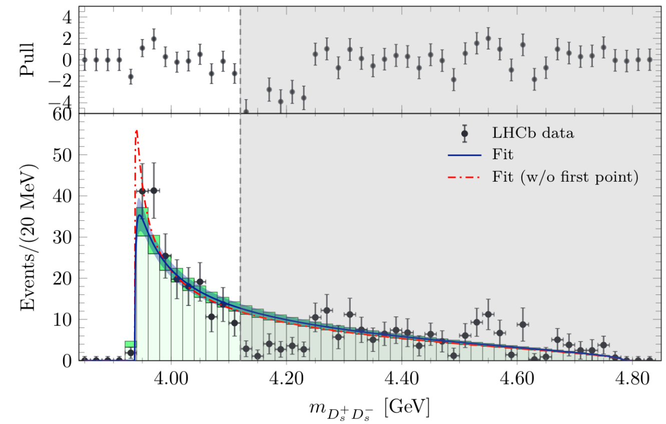
Hadronic molecular spectrum

X.-K. Dong, FKG, B.-S. Zou, 物理学进展 41 (2021) 65



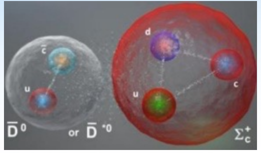
- ✓ $X(3872)$ as a $\bar{D}D^*$ bound state
- ✓ $\tilde{X}(3872)$ COMPASS, PLB783(2018)334
- ✓ $\bar{D}D$ bound state predicted with lattice Prelovsek et al., JHEP2106,035

- ✓ $X(3960)$

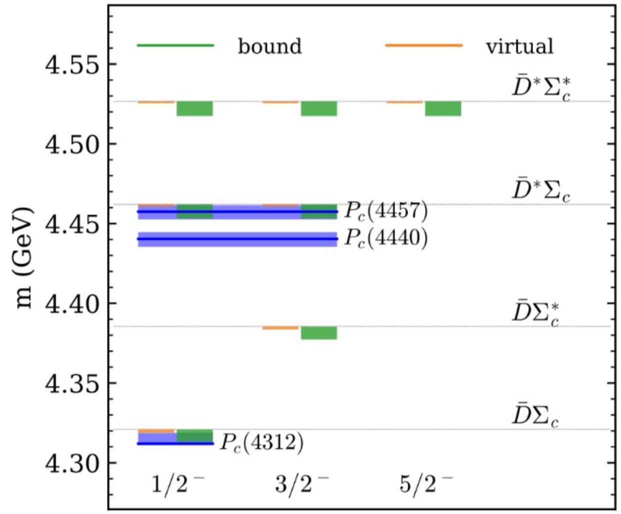


Data from
LHCb seminar by E. Spadaro Norella & Chen Chen, July 05, 2022
Fit in
T. Ji, X.-K. Dong, M. Albaladejo, M.-L. Du, FKG, J. Nieves, arXiv:2207.08563

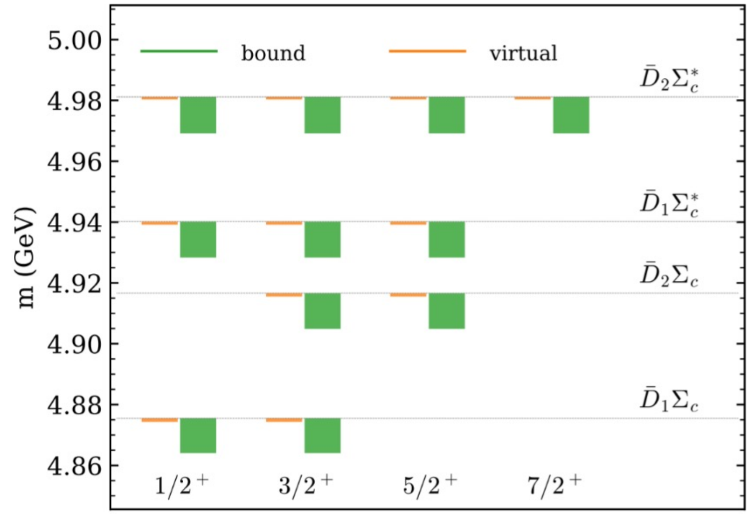
Hadronic molecular spectrum



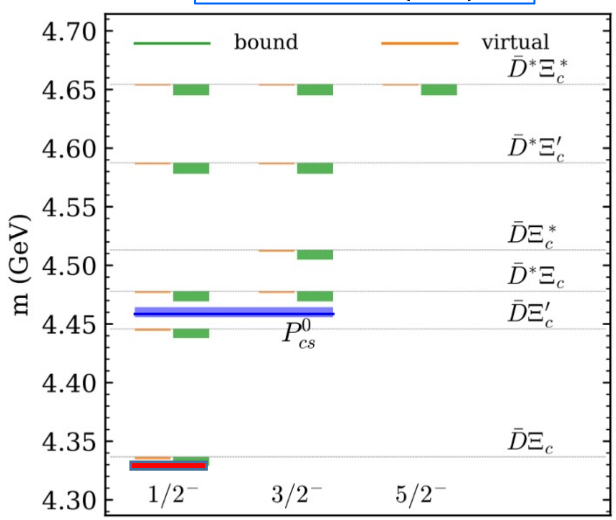
$(I, S) = (1/2, 0)$



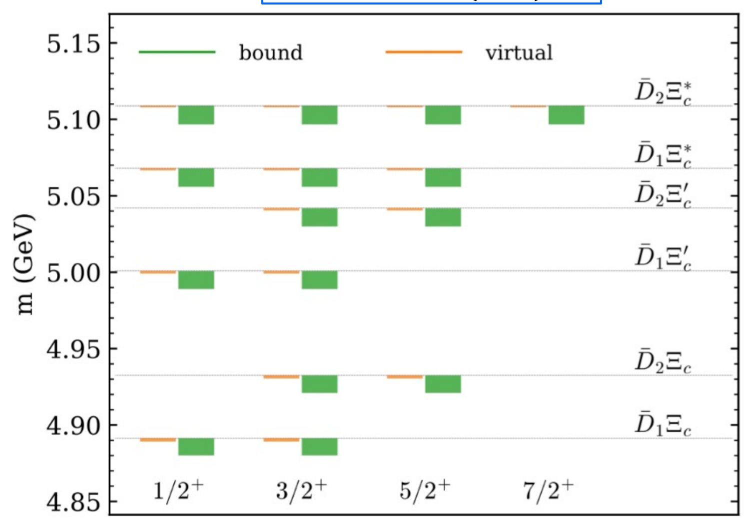
$(I, S) = (1/2, 0)$



$(I, S) = (0, 1)$



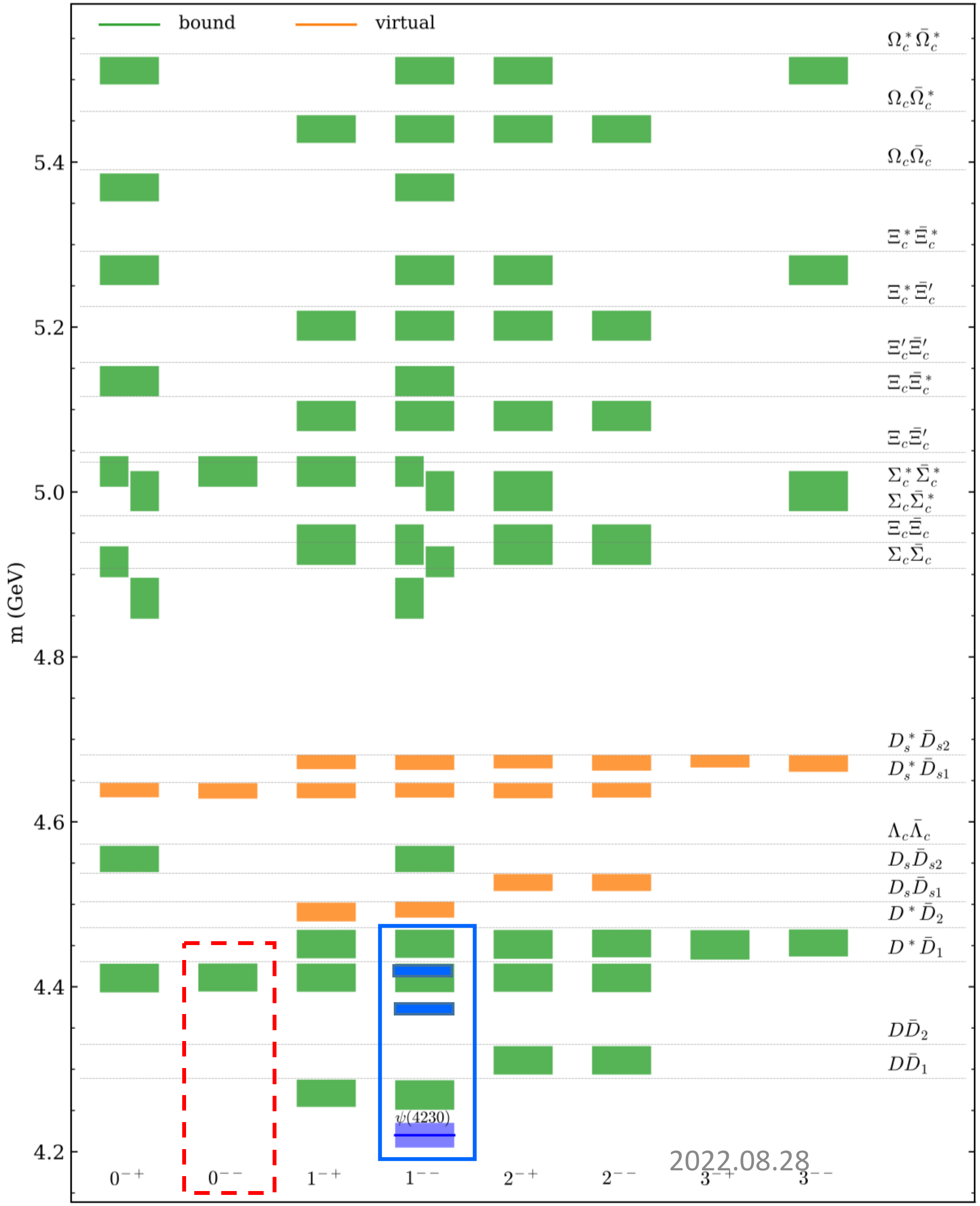
$(I, S) = (0, 1)$



2022.08.28

✓ Many more baryon-antibaryon molecular states above 4.7 GeV

Isoscalar vectors and related states



$(I,S) = (0,0)$

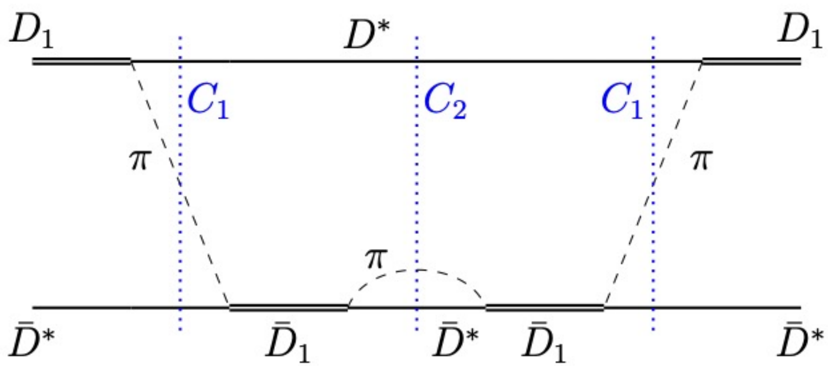
✓ Many 1^{--} states above 4.8 GeV: Belle-II, BEPC-II-Upgrade, STCF(?)

Spin partners of $\psi(4230)[Y(4260)]$

T. Ji, X.-K. Dong, FKG, B.-S. Zou, arXiv:2205.10994 [PRL, in print]

- Prediction of an exotic 0^{--} spin partner $\psi_0(4360)$ $[D^*\bar{D}_1]$ of $\psi(4230), \psi(4360)$, $\psi(4415)$ as $D\bar{D}_1, D^*\bar{D}_1, D^*\bar{D}_2$ hadronic molecules
- Robust against the inclusion of coupled channels and three-body effects

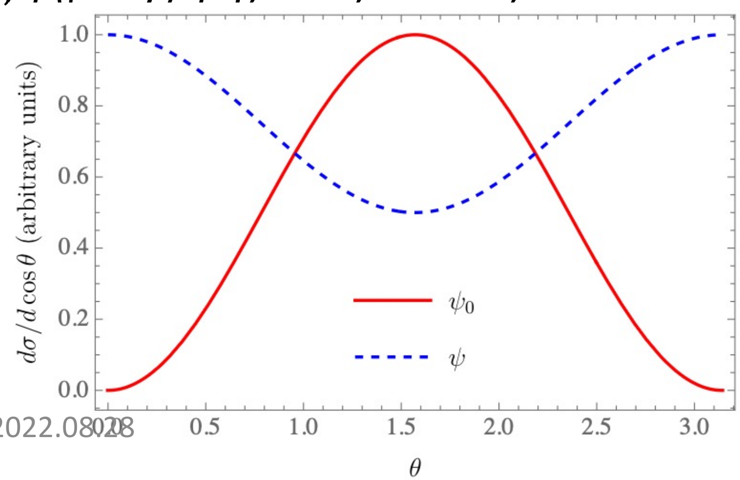
Molecule	Components	J^{PC}	Threshold	E_B
$\psi(4230)$	$\frac{1}{\sqrt{2}}(D\bar{D}_1 - \bar{D}D_1)$	1^{--}	4287	67 ± 15
$\psi(4360)$	$\frac{1}{\sqrt{2}}(D^*\bar{D}_1 - \bar{D}^*D_1)$	1^{--}	4429	62 ± 14
$\psi(4415)$	$\frac{1}{\sqrt{2}}(D^*\bar{D}_2 - \bar{D}^*D_2)$	1^{--}	4472	49 ± 4
ψ_0	$\frac{1}{\sqrt{2}}(D^*\bar{D}_1 + \bar{D}^*D_1)$	0^{--}	4429	$\mathbf{63 \pm 18}$



- May be searched for using $e^+e^- \to \psi_0\eta, \psi_0 \to J/\psi\eta, D\bar{D}^*, D^*\bar{D}^*\pi, \ldots$

$$M = (4366 \pm 18)\ \mathrm{MeV},$$

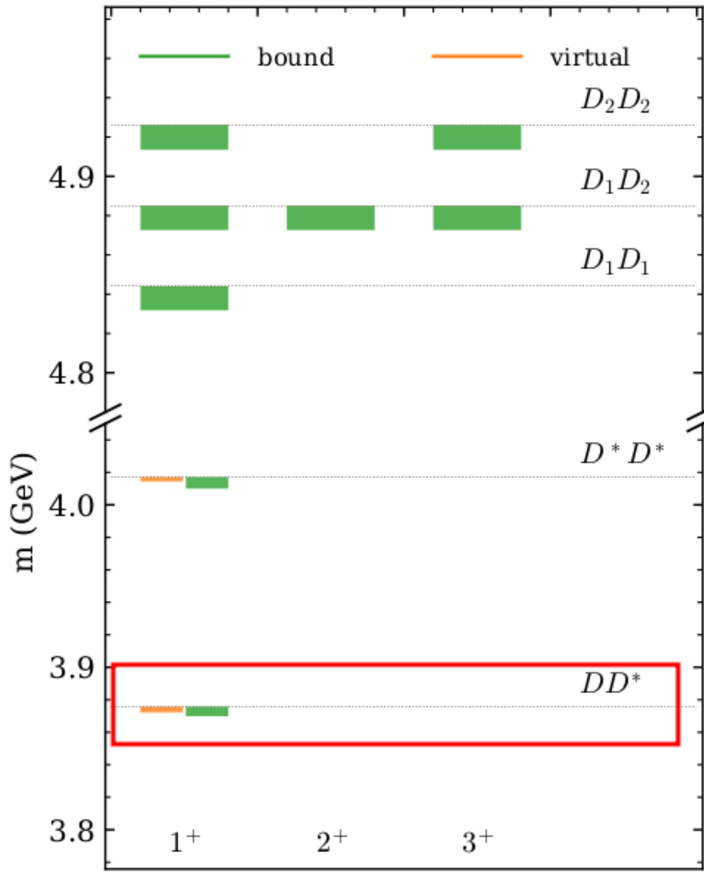
$$\Gamma < 10\ \mathrm{MeV}$$



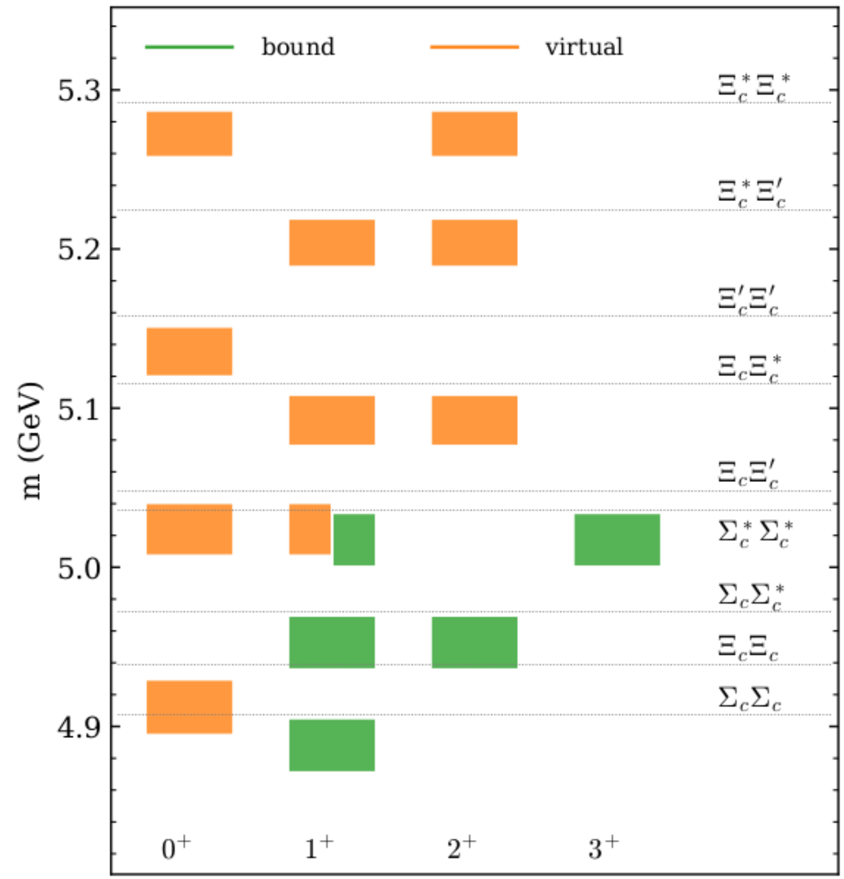
Double-charm

X.-K. Dong, FKG, B.-S. Zou, CTP73(2021)125201

$(I, S, B) = (0,0,0)$



$(I, B) = (0,2)$



- ✓ There is an isoscalar DD^* molecular state
- ✓ It has a spin partner 1^+ D^*D^* state
- ✓ Many (> 100) other similar double-charm molecular states in other sectors

Conclusion

- Possible precision measurement of binding energy of near-threshold particles using triangle singularity; applications in nuclear physics?

- General rule for (near-)threshold structures: S-wave attraction, more prominent for heavier particles and stronger attraction

- A rich spectrum of hadronic molecules is expected from the VMD model; more than 300 hidden/double-charm hadronic molecules were predicted

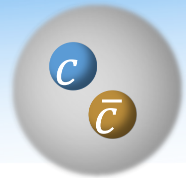
Experiments Lattice

热烈祝贺清华大学物理系复系 40 周年!

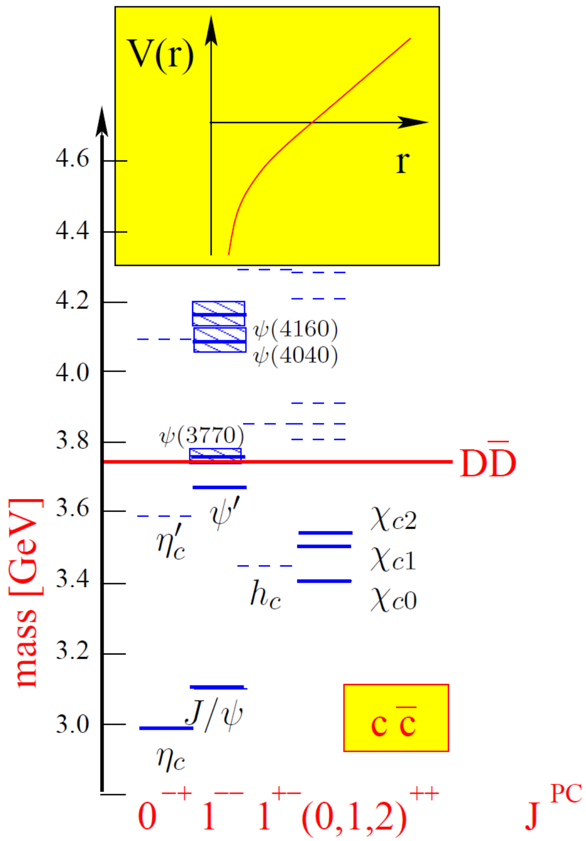
EFT, models

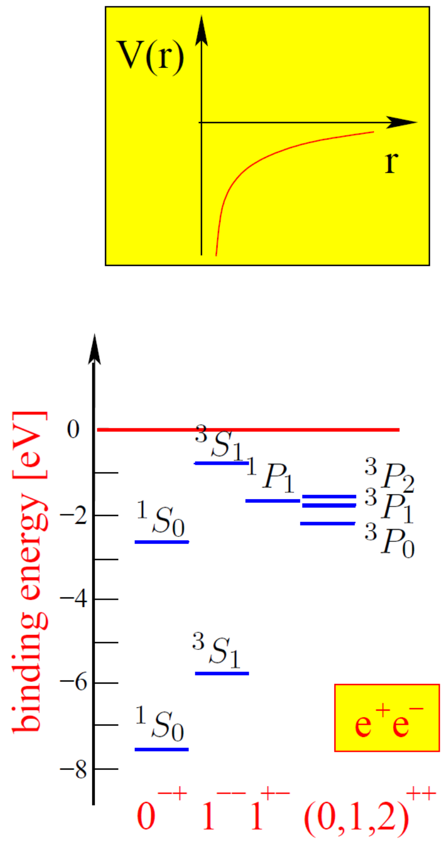
Thank you for your attention!

Charmonium



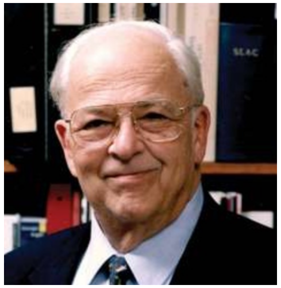
- Meson consisting of a charm quark and an anticharm quark
  - ➢ The first charmonium: J/ψ
  - ➢ Probing both perturbative and nonperturbative QCD

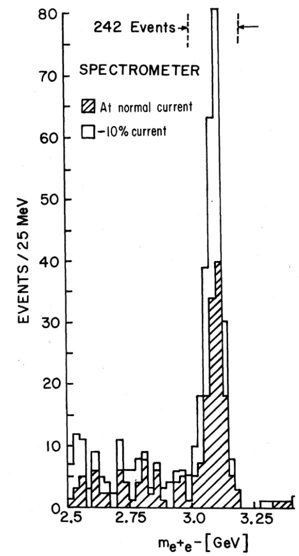




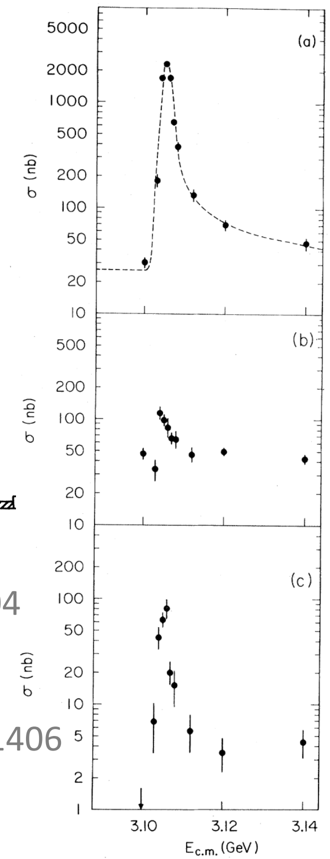
Cornell potential model:
Eichten et al., PRD17(1978)3090

From talk by Hanhart at APS2018





PRL33(1974)1404

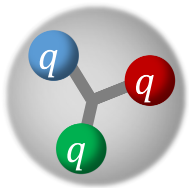


PRL33(1974)1406

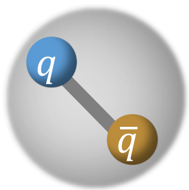
Clue to confinement mechanism?

- Different flux tube configurations: compact multiquarks and hadronic molecules

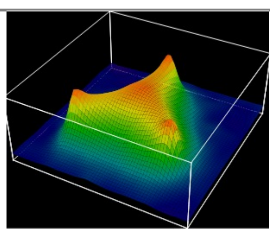
Conventional hadrons



baryon

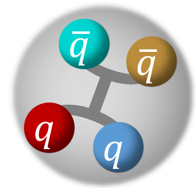


meson

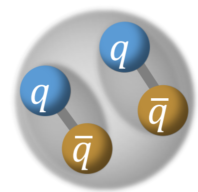


V.G. Bornyakov et al., PRD70(2004)054506

Multiquarks vs hadronic molecules



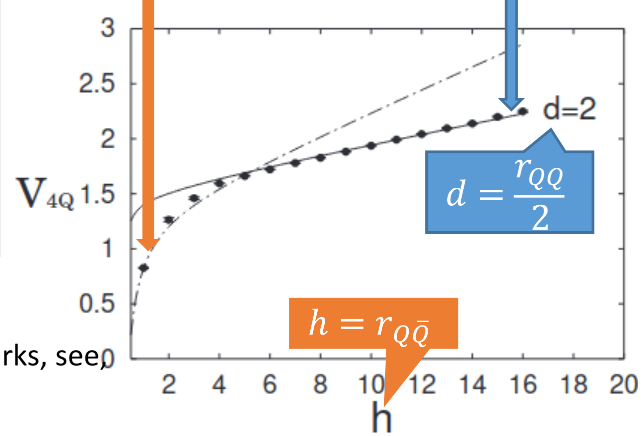
compact tetraquark



hadronic molecule

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

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



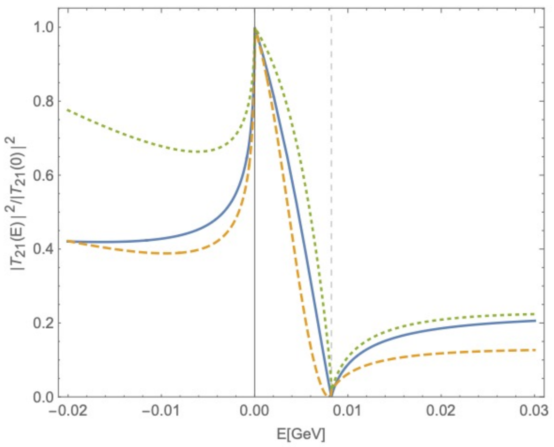
F. Okiharu et al., PRD72(2005)014505

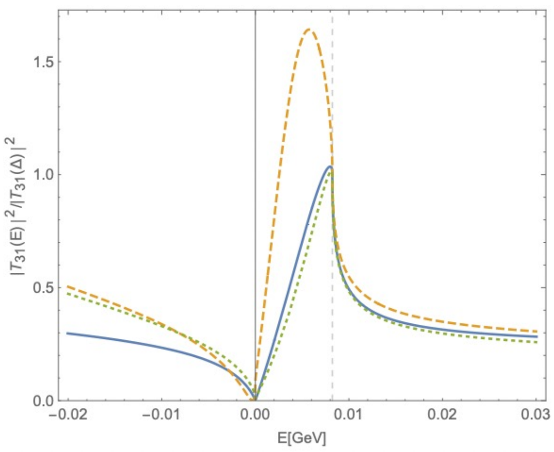
For lattice studies of flux tube picture of multiquarks, see, e.g., F. Okiharu, H. Suganuma, T. T. Takahashi, PRD72(2005)014505; PRL94(2005)192001
An overview: H. Suganuma et al., arXiv:1103.4015

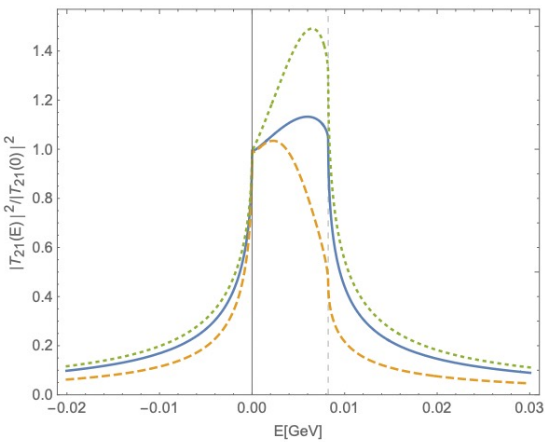
Phenomenology

- Complications due to more channels

Zhang[2], FKG, in preparation







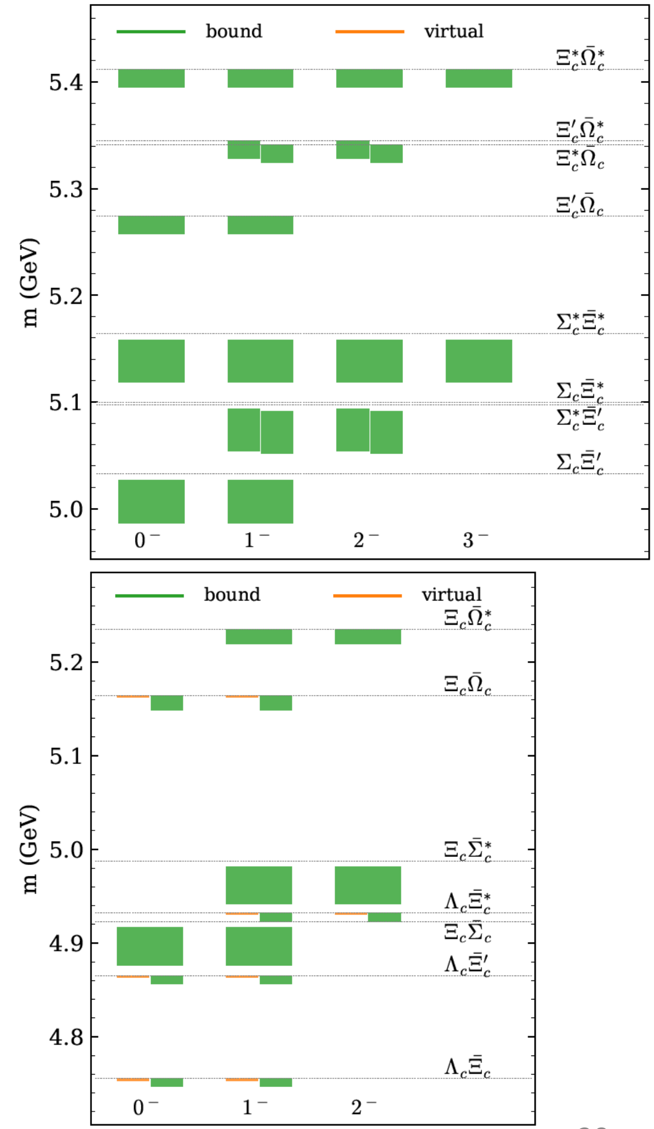
I do not mean that the near-threshold structures are just threshold cusps.

Prominent near-threshold structures imply near-threshold singularities more singular than a threshold cusp!

More states with exotic quantum numbers

$(I, S) = (1,0)$

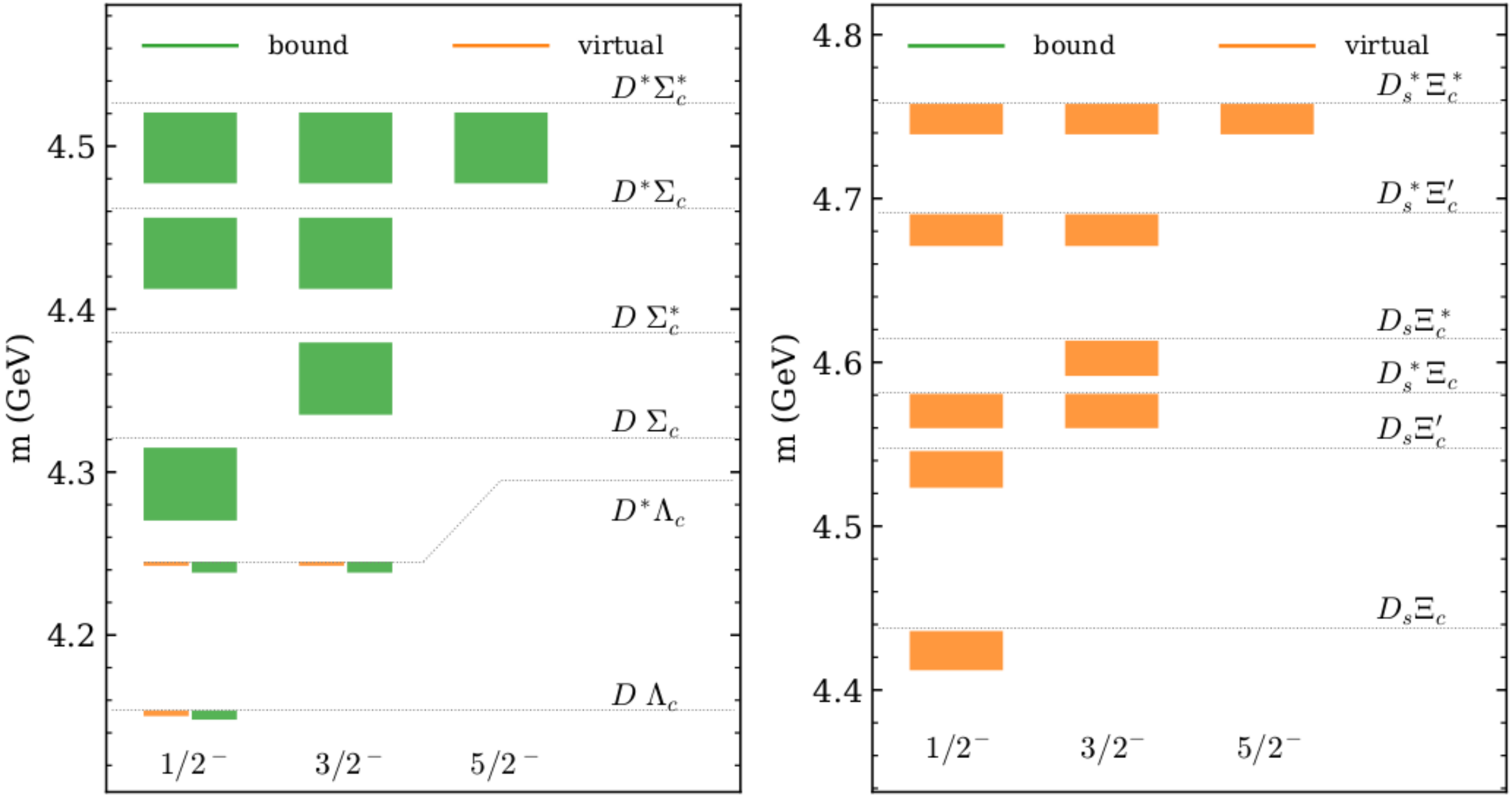
$(I, S) = (1/2,1)$



✓ Many baryon-antibaryon molecular states above 4.7 GeV, beyond the current exp. region

Double-charm

$(I, S, B) = (1/2, -1, 1)$ $(I, S, B) = (0, 0, 1)$



X.-K. Dong, FKG, B.-S. Zou, arXiv:2108.02673

- ✓ The attractions for $D^{(*)}\Sigma_c^{(*)}$ are stronger than those for $\bar{D}^{(*)}\Sigma_c^{(*)}$
- ✓ However, the $D^{(*)}\Sigma_c^{(*)}$ states mix with normal double-charm baryons