第八届全国重味物理与量子色动力学研讨会，2026.04.24-28，重庆

How can Femtoscopy help decipher the nature of exotic hadrons?

Li-Sheng Geng（耿立升）@ Beihang U.

Zhi-Wei Liu, Jun-Xu Lu, LSG*, PRD 107(2023)074019

Zhi-Wei Liu, Jun-Xu Lu, Ming-Zhu Liu, LSG*, Sci.Bull. 70 (2025) 3515-3521

Tian-Wei Wu, Ming-Zhu Liu*, and LSG*, PRL135(2025)031902

Duo-Lun Ge, Zhi-Wei Liu, LSG*, 2603.24980

Ming-Zhu Liu, Ya-Wen Pan, Zhi-Wei Liu, Tian-Wei Wu, Jun-Xu Lu, LSG*, Phys.Rept. 1108 (2025) 1-108

(Image: CERN)

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- ☞ **Femtoscopic correlation functions (CFs)—general features**
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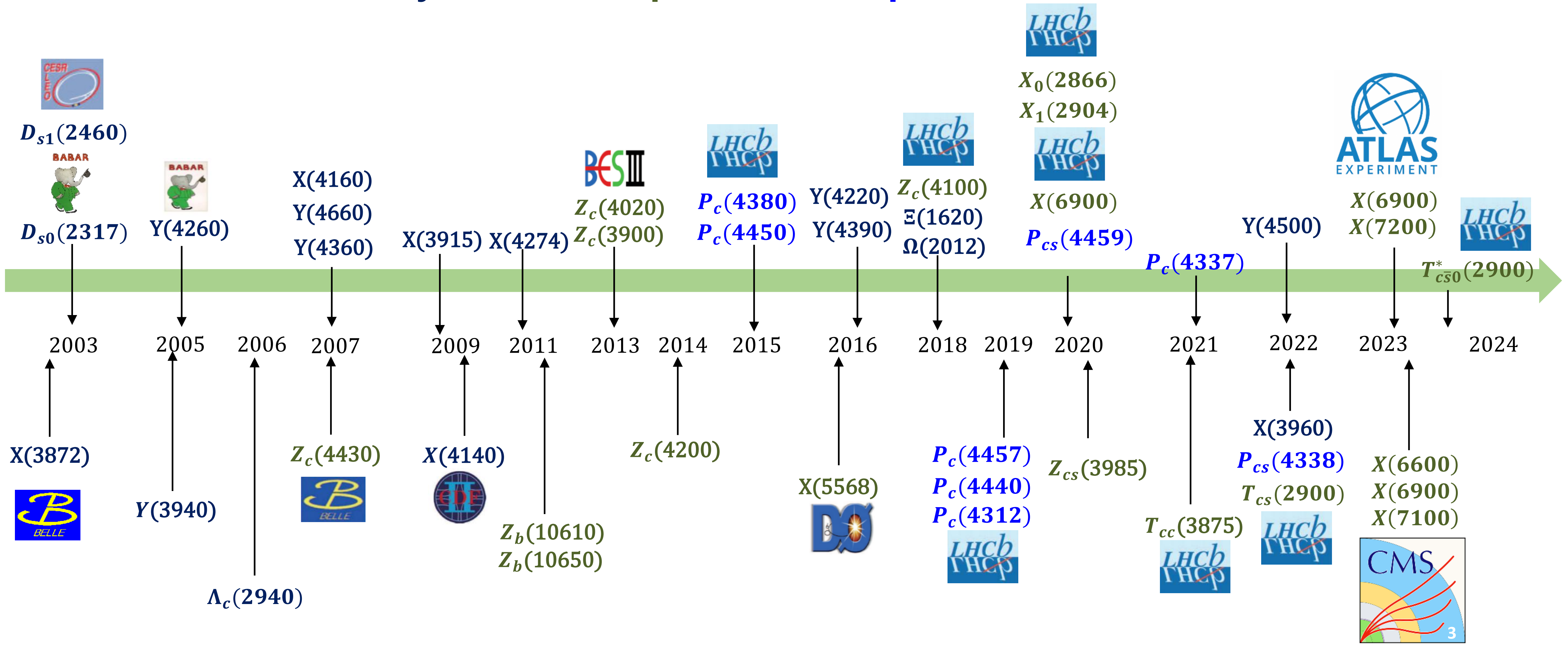
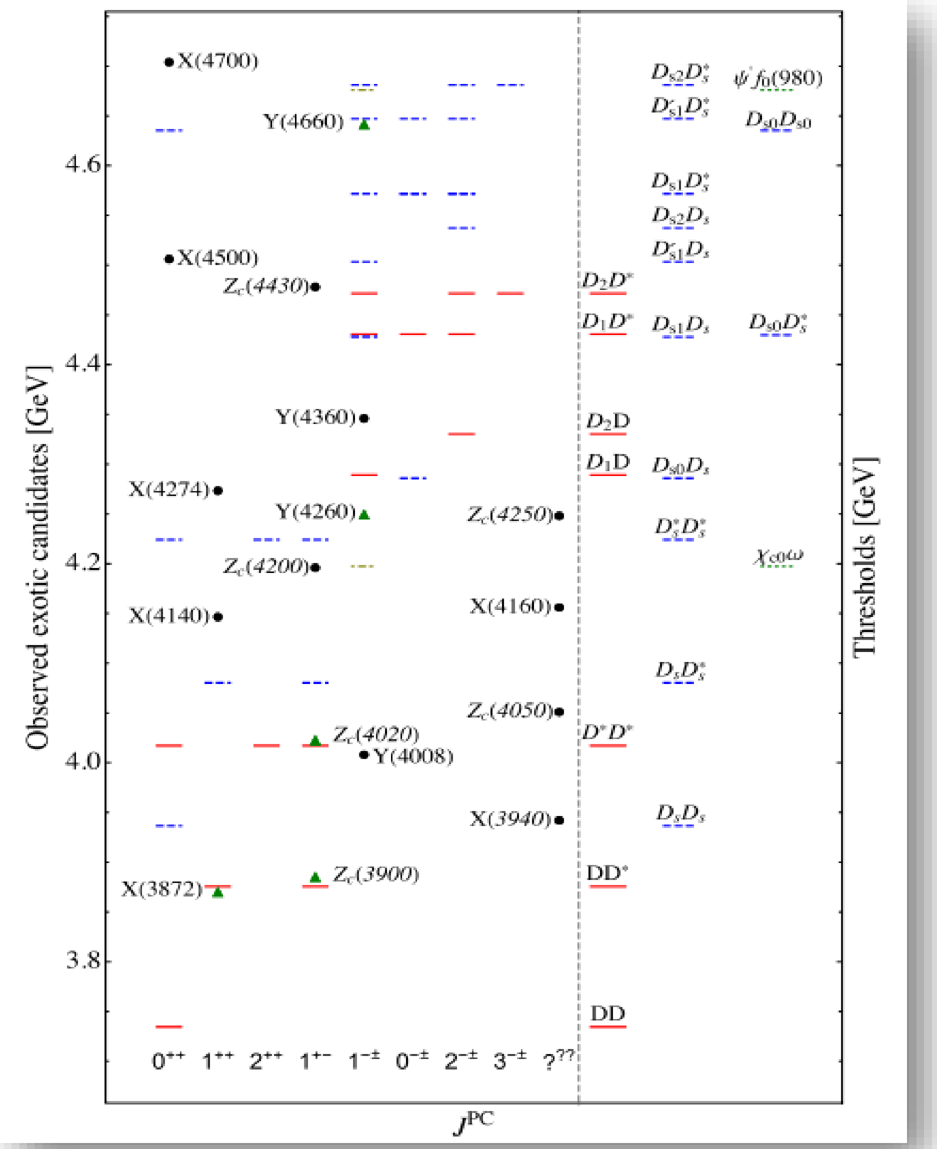
- ☞ **Summary and outlook**

Many more so-called exotic hadrons discovered since then

Exotic mesons and baryons **Tetraquarks** **Pentaquarks**



Many (if not all) of them close to thresholds—molecules



Feng-Kun Guo, Christoph Hanhart, Ulf-G. Meißner, Qian Wang, Qiang Zhao, Bing-Song Zou. Rev.Mod.Phys. 90 (2018) 015004

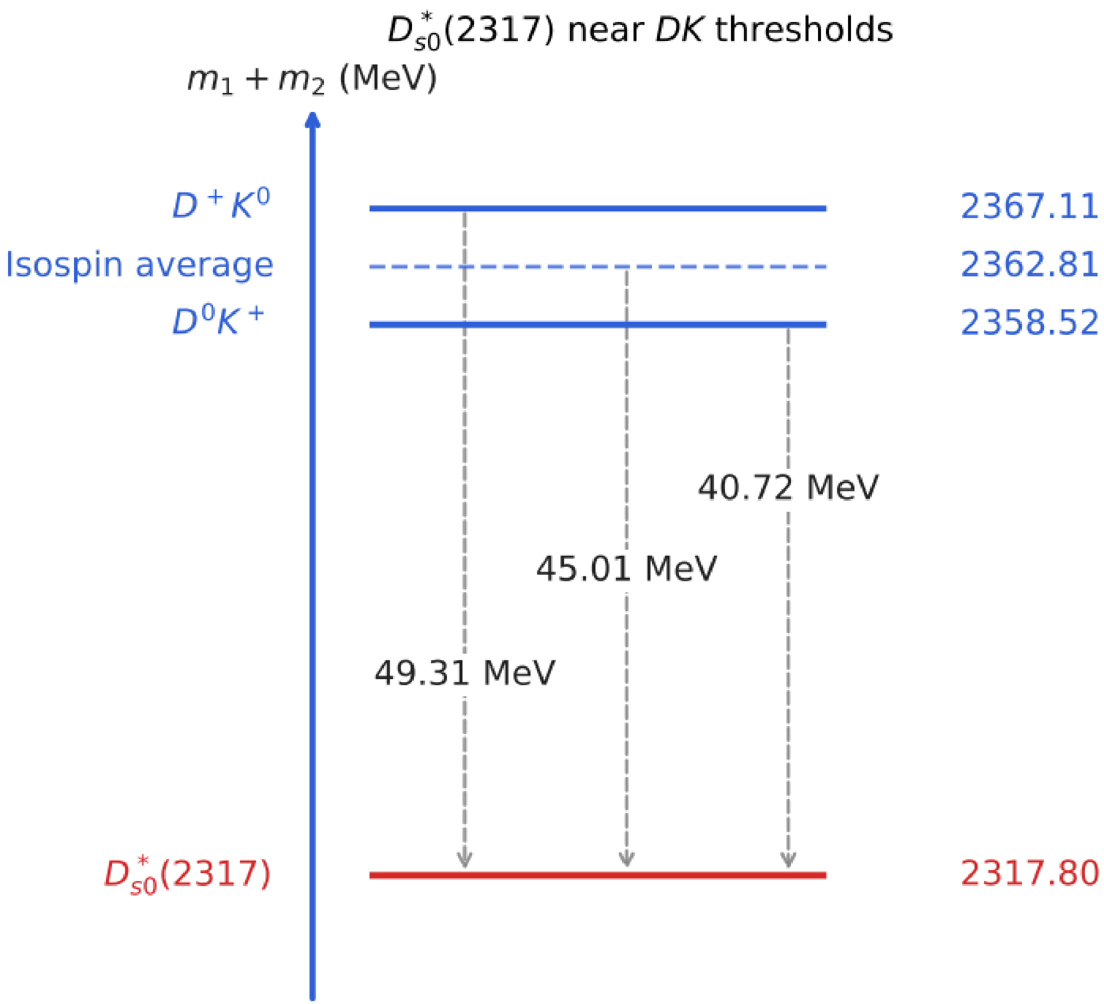
Richard F. Lebed, Ryan E. Mitchell, Eric S. Swanson, Prog.Part.Nucl.Phys. 93 (2017) 143

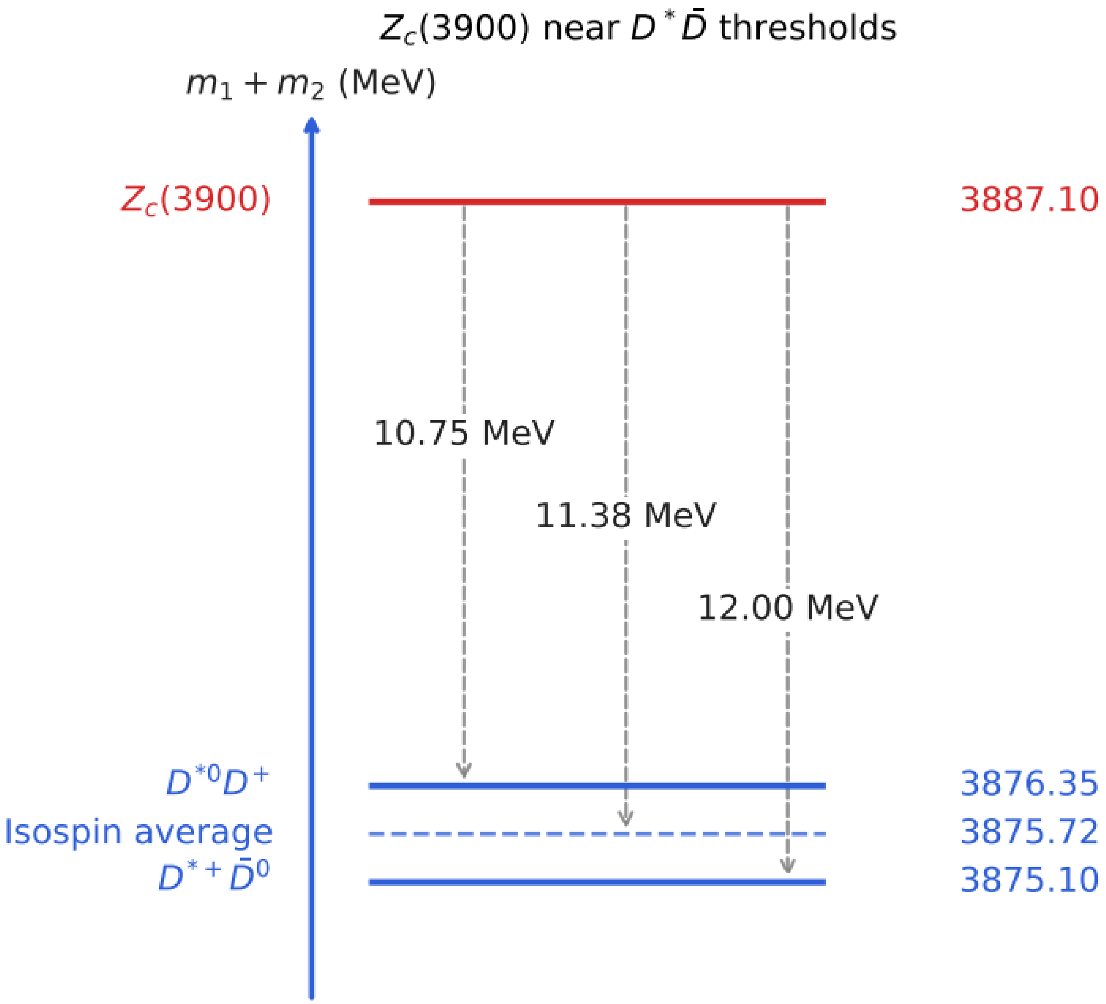
Atsushi Hosaka, Toru Iijima, Kenkichi Miyabayashi, Yoshihide Sakai , Shigehiro Yasui, PTEP 2016 (2016) 062C01

Hua-Xing Chen, Wei Chen, Xiang Liu Shi-Lin Zhu, Phys. Rept.639 (2016) 1

……

X(3872) & Tcc(3875)



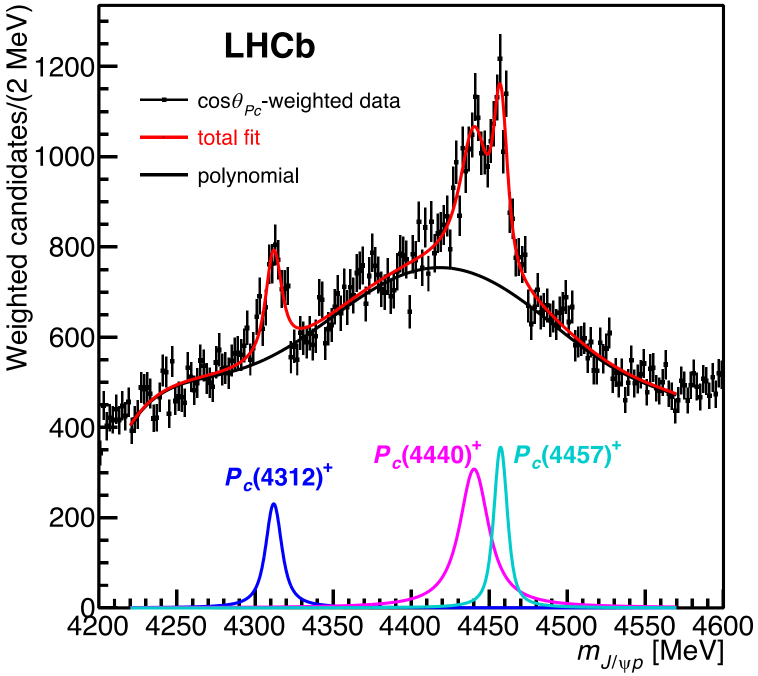


How to check the molecular picture?

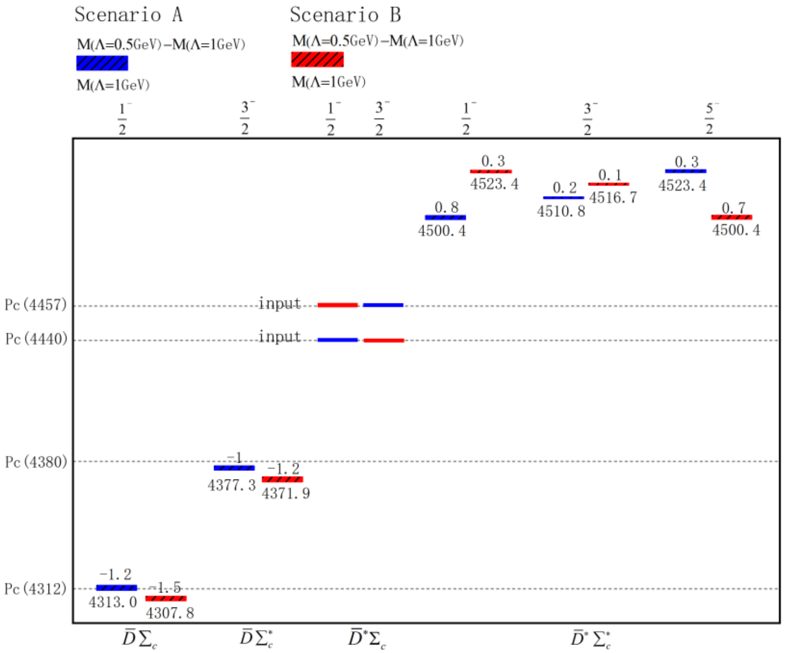
How to verify the molecular picture

Ming-Zhu Liu, Ya-Wen Pan, Zhi-Wei Liu, Tian-Wei Wu, Jun-Xu Lu, **LSG***, Phys.Rept. 1108 (2025) 1-108

- **Symmetries in the two-hadron interactions imply the existence of multiplets of hadronic molecules**
  - **Heavy-quark spin/flavor** symmetry: there are **seven Pc** states



LHCb, PRL 122 (2019) 222001



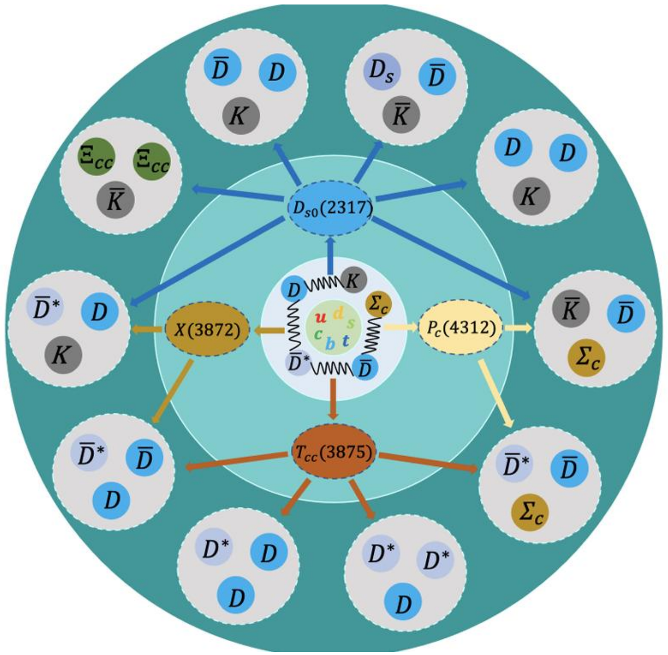
Liu, Pan, Peng, Sánchez, LSG, Hosaka, Valderrama, PRL122, 242001 (2019)

How to verify the molecular picture

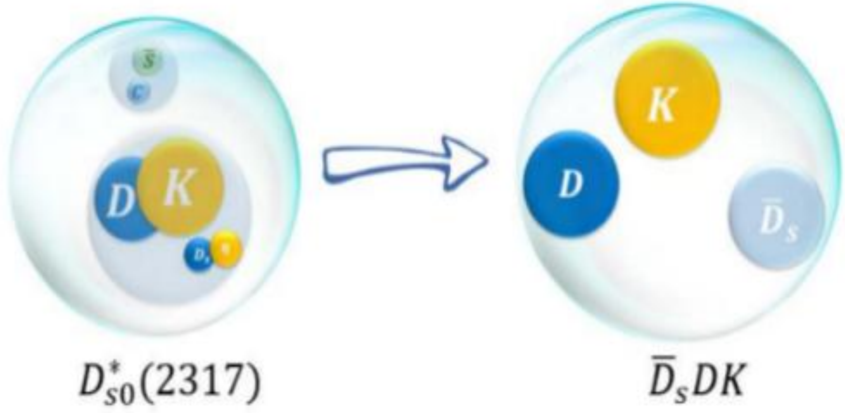
Ming-Zhu Liu, Ya-Wen Pan, Zhi-Wei Liu, Tian-Wei Wu, Jun-Xu Lu, **LSG***, Phys.Rept. 1108 (2025) 1-108

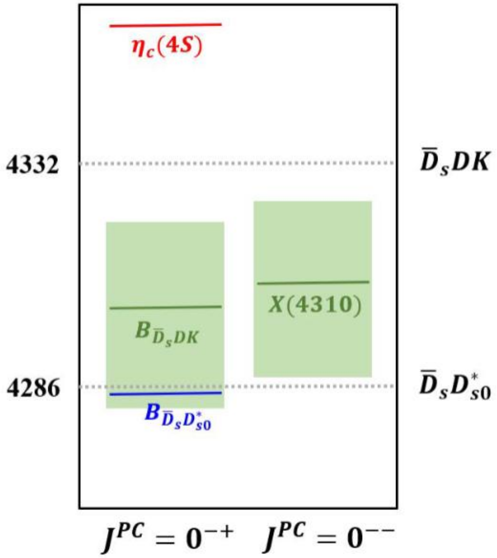
☐ Three hadrons experience pairwise two-body attractions can form three-body molecules

- Treating $\boldsymbol{D_{s0}^*(2317)}$ as a DK state, one can expect a $\bar{D}_s DK$ state



T.W. Wu and LSG, Sci.Bull. 67 (2022) 1735-1738





T.W Wu, M.Z Liu, and LSG, PRL(2025) 031902

How to verify the molecular picture

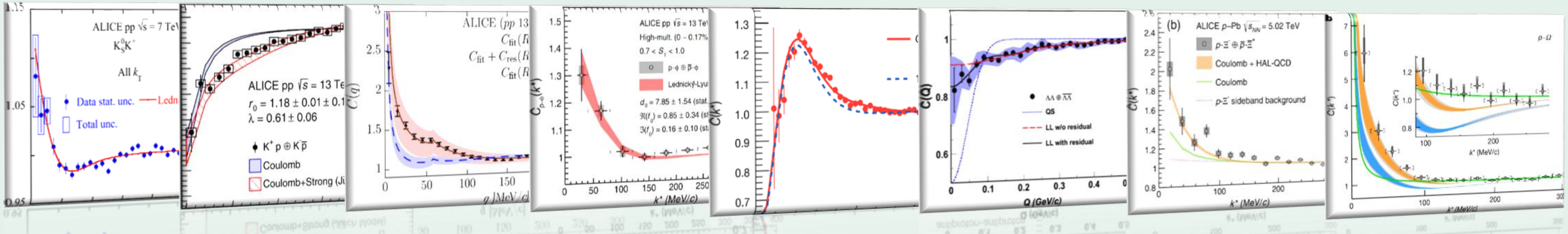
Ming-Zhu Liu, Ya-Wen Pan, Zhi-Wei Liu, Tian-Wei Wu, Jun-Xu Lu, **LSG***, Phys.Rept. 1108 (2025) 1-108

□ Direct measurement of the two-hadron interactions

The Large Hadron Collider

Brookhaven National Laboratory RHIC Relativistic Heavy Ion Collider

$K_S^0K^\pm$ $K^\pm p$ $K^- p$ ϕp $\overline{p}\overline{p}$ $\Lambda\Lambda$ $\Xi^- p$ $\Omega^- p$



PLB 2019 PRL 2020 PRL 2020 PRL 2021 Nature 2015 PRL 2015 PRL 2019 Nature 2020

$K^- d$
$\Sigma^0 p$
$\Lambda\Xi$
$\Xi\Xi$
$\Omega\Omega$
pD
ppp
$pp\Lambda$

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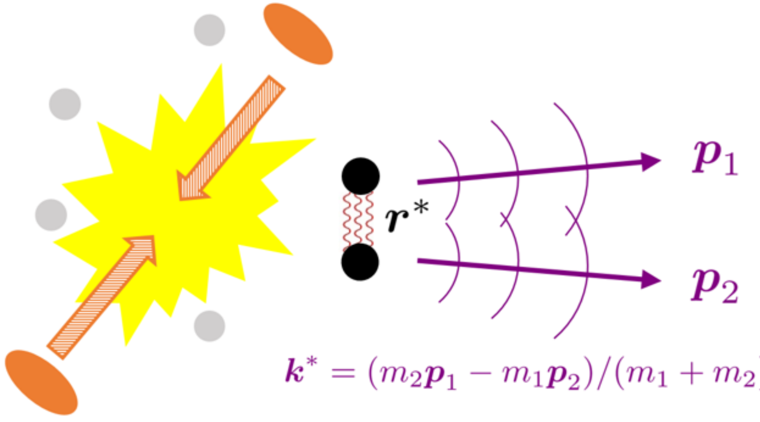
Femtoscopic correlation functions (CFs)

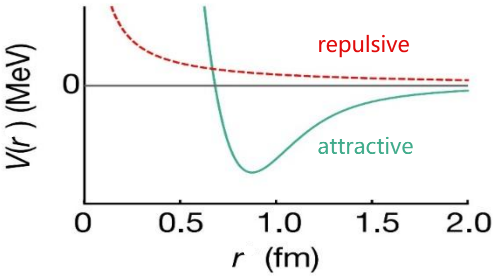
$$C(\boldsymbol{p}_1, \boldsymbol{p}_2) = \frac{\mathrm{P}(\boldsymbol{p}_1, \boldsymbol{p}_2)}{\mathrm{P}(\boldsymbol{p}_1) \cdot \mathrm{P}(\boldsymbol{p}_2)}$$



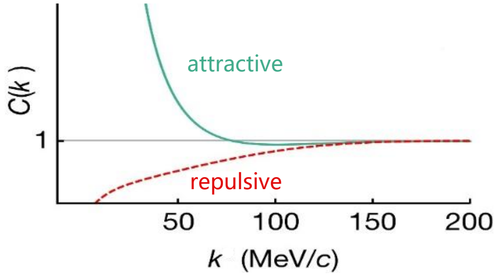
$$\boldsymbol{k}^* = (m_2\boldsymbol{p}_1 - m_1\boldsymbol{p}_2)/(m_1 + m_2)$$

Emission source $S_{12}(\boldsymbol{r}^*)$ Two-particle wavefunction $\psi(\boldsymbol{k}^*, \boldsymbol{r}^*)$

Interacting potential



Correlation function



↓

Schrödinger equation

↓

Two-particle wavefunction $\psi(\boldsymbol{k}\ ,\boldsymbol{r}\ )$

Exp. measurement

mixed-event technique

$$C(k) = \xi(k) \frac{N_{\mathrm{same}}(k)}{N_{\mathrm{mixed}}(k)}$$

N_{same}: the same event distributions

N_{mixed}: the mixed event distributions

ξ: the corrections for experimental effects

Theo. description

Koonin–Pratt formula

$$C(k) = \int S_{12}(\boldsymbol{r})\ |\psi(\boldsymbol{k}, \boldsymbol{r})|^2\ \mathrm{d}\boldsymbol{r}$$

spacial structure

final-state interactions

quantum statistics effects

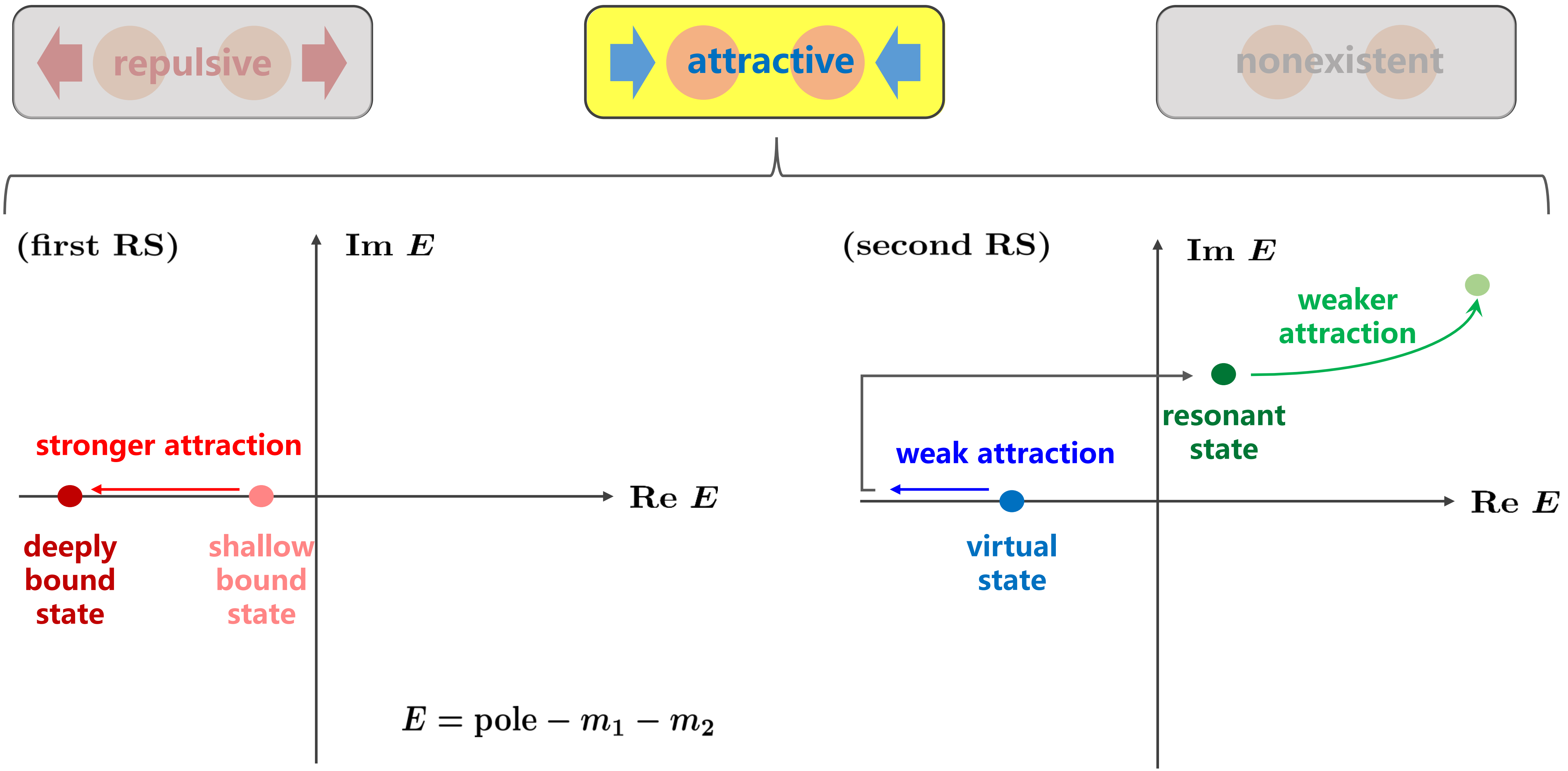
coupled-channel effects

Basic Properties

$C(k)$

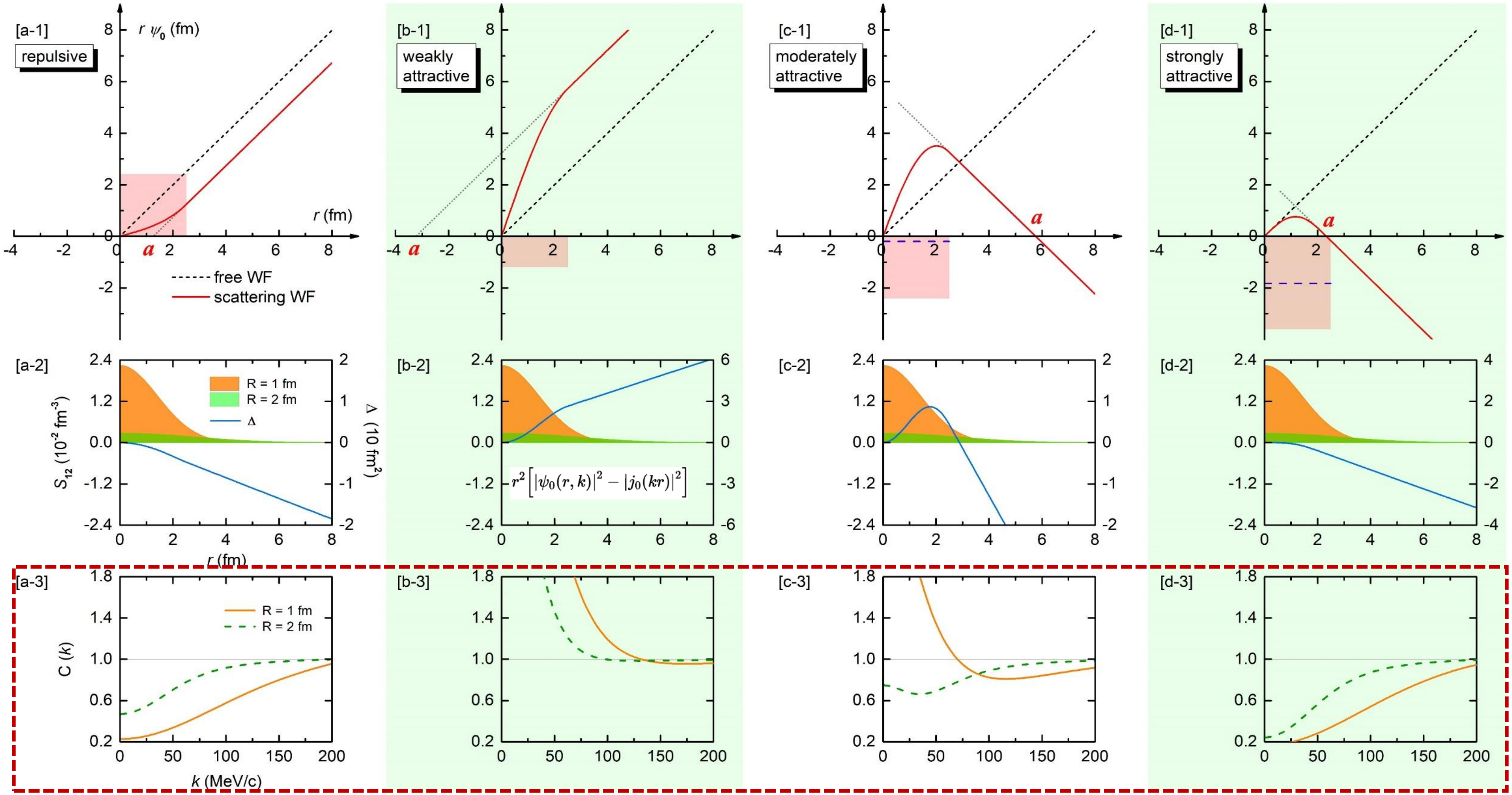
- \>1 if the interaction is attractive
- =1 if there is no interaction
- <1 if the interaction is repulsive

Classification of hadron-hadron interactions



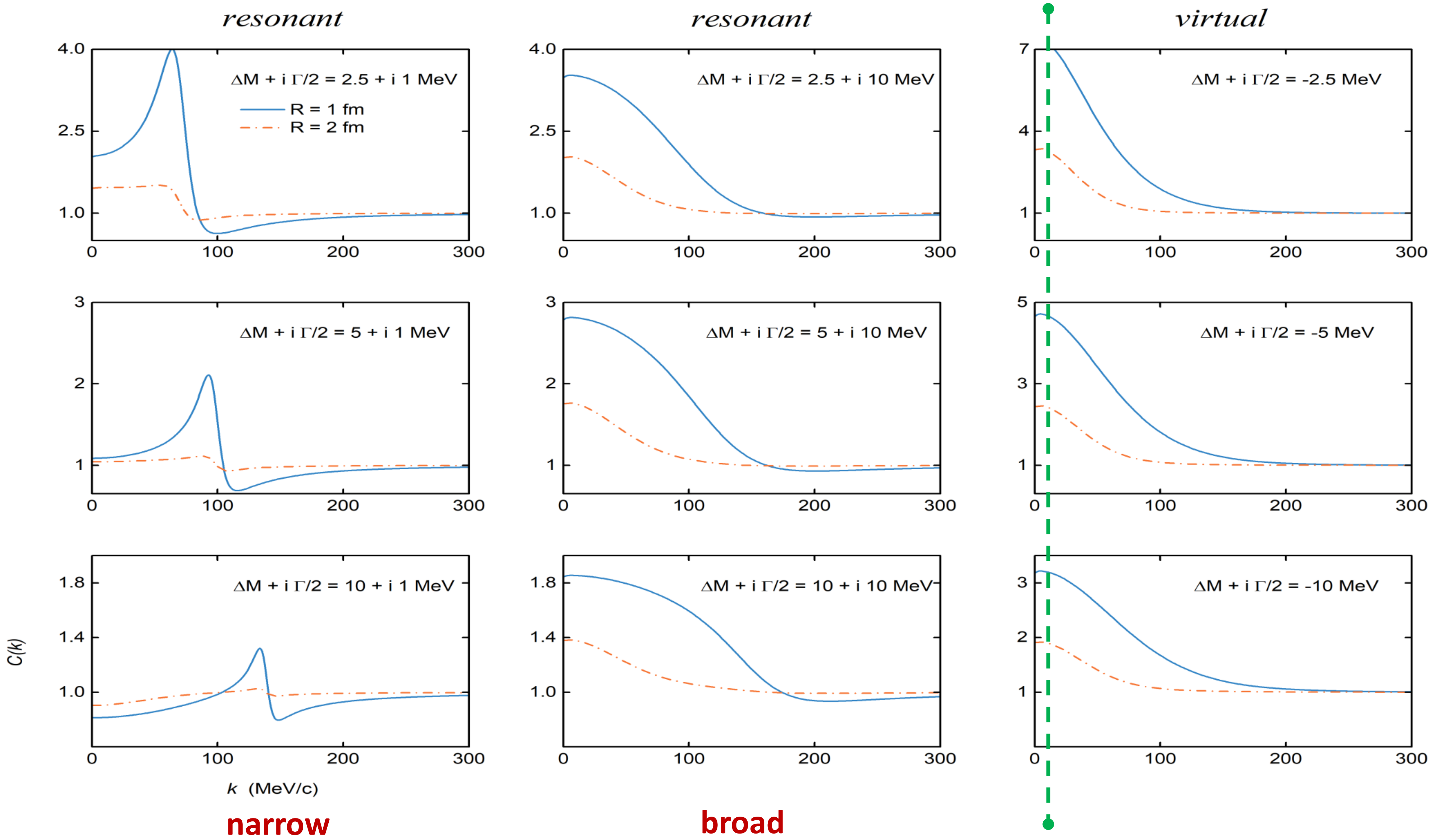
CFs for interactions capable of generating bound states

*Zhi-Wei Liu, Jun-Xu Lu and **LSG***, PRD 107, 074019 (2023)*



CFs for interactions capable of generating resonant/virtual states

Zhi-Wei Liu, Ming-Zhu Liu, Jun-Xu Lu and LSG, Sci.Bull. 70 (2025) 3515-3521*



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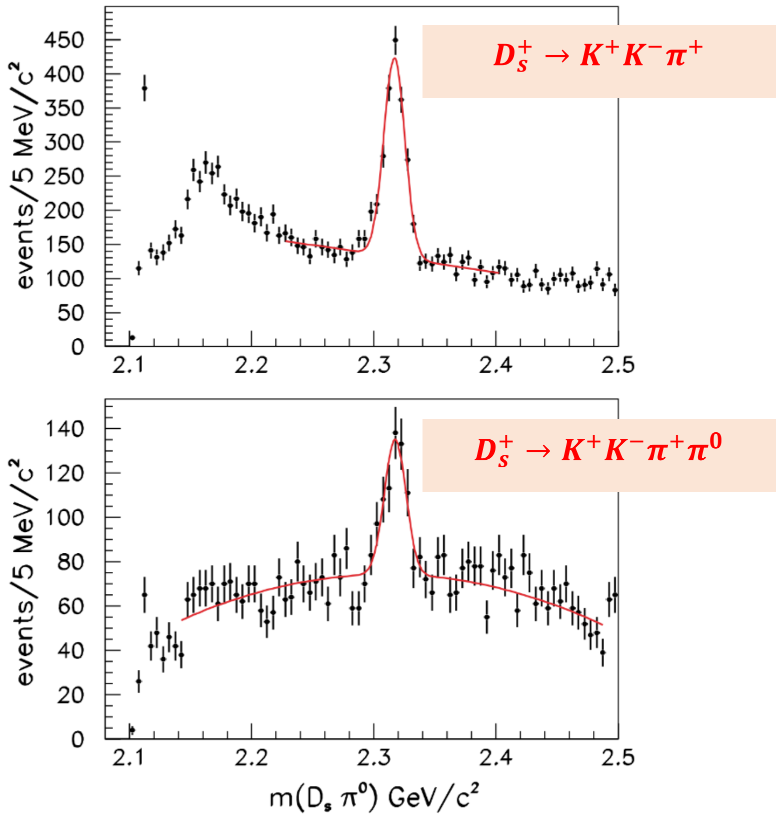
Mysterious exotic hadron $D_{s0}^*(2317)$

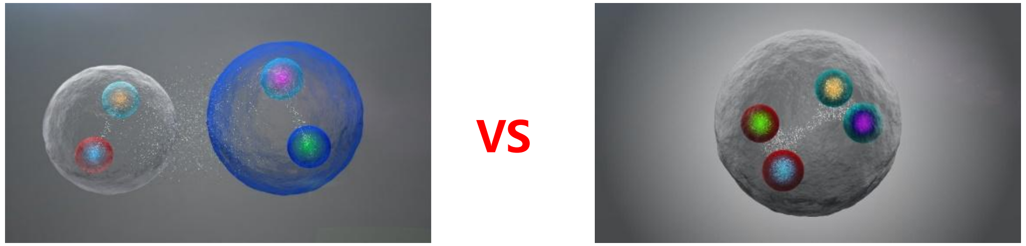
$M = 2317.8 \pm 0.6$ and $\Gamma < 3.8$ MeV



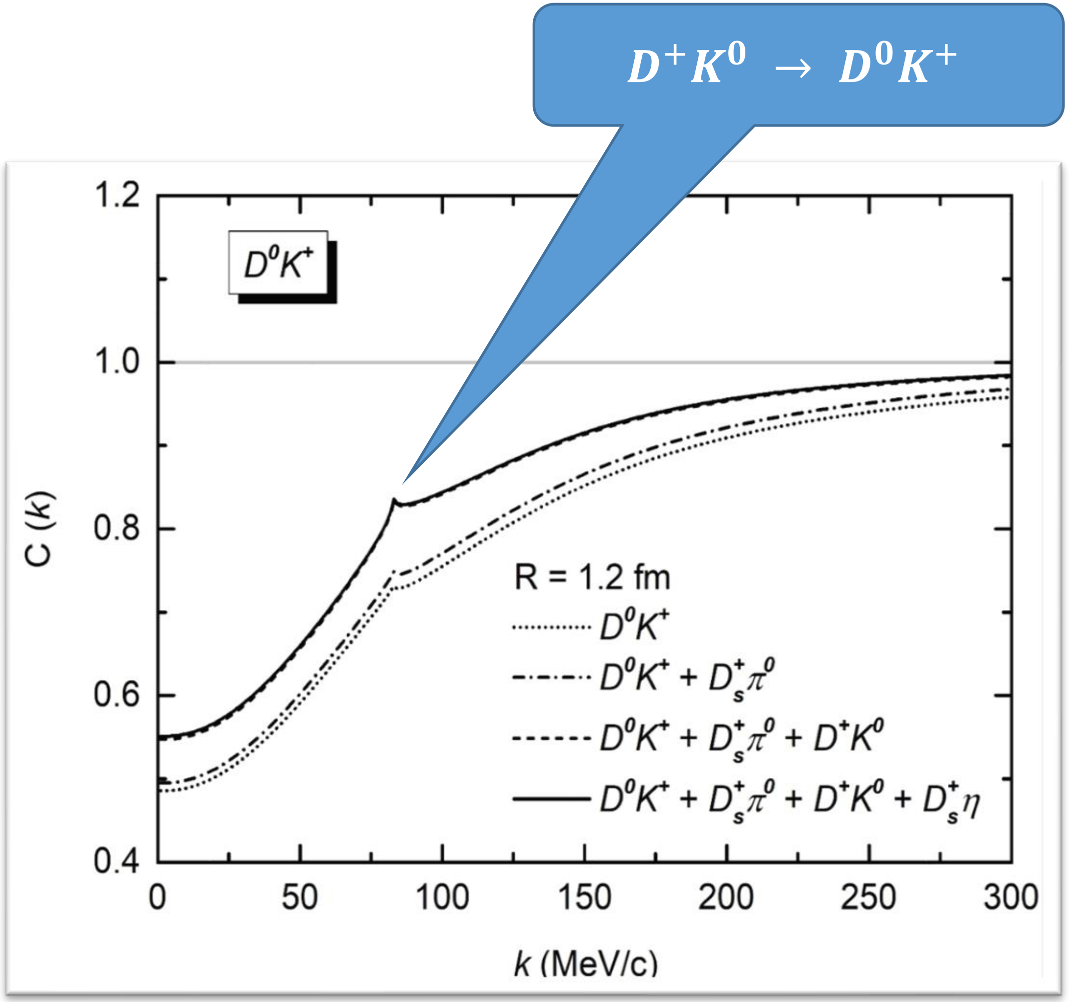
BABAR, PRL90 (2003) 242001

- **160 MeV lower than the quark model predictions – difficult to understand as a conventional charm-strange meson**

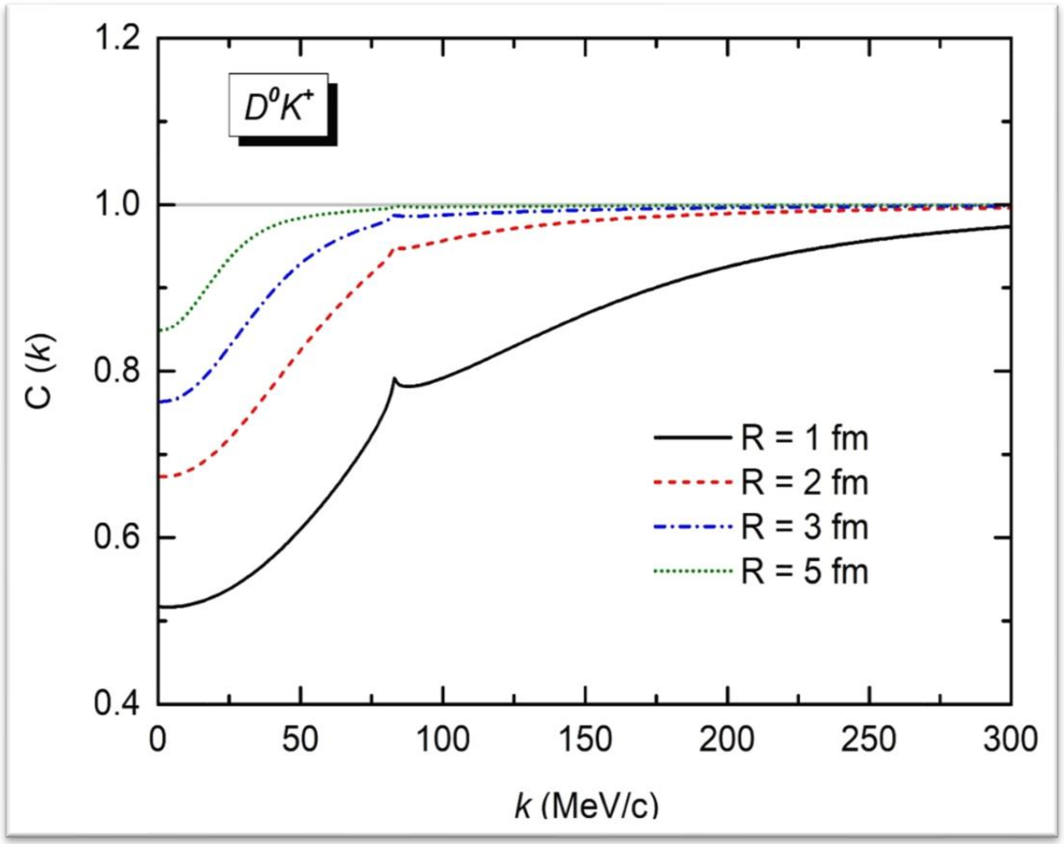
- **It could be a DK bound state**
  - ✓ E. E. Kolomeitsev 2004
  - ✓ F. K. Guo 2006
  - ✓ D. Gamermann 2007
  - ✓ Altenbuchinger, LSG*, Weise, 2014



DK CFs and its source size dependence



Typical feature of deeply bound states



*Zhi-Wei Liu, Jun-Xu Lu and **LSG****, *PRD107(2023)074019*

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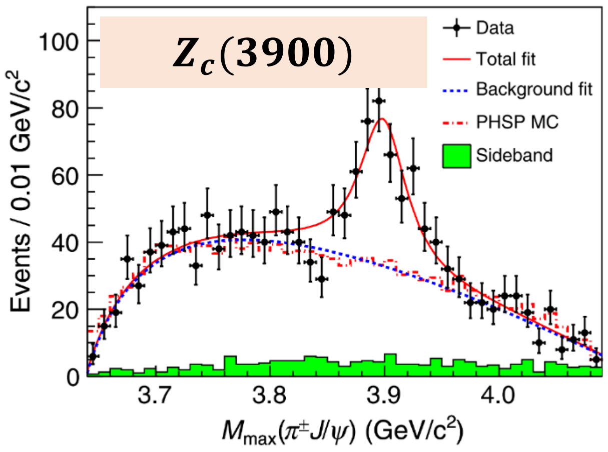
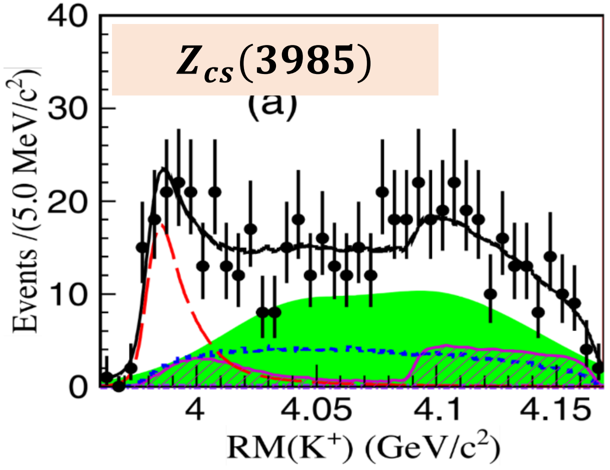
Tetraquark states $Z_c(3900)$ & $Z_{cs}(3985)$



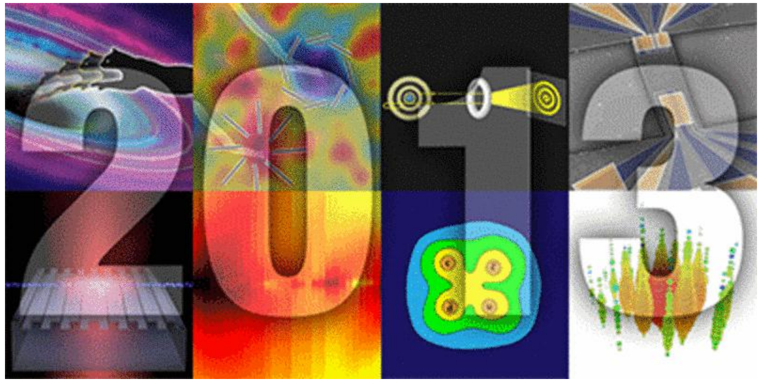
BESIII, PRL110 (2013) 252001

1277 citations



BESIII, PRL126 (2021) 102001

277 citations



Tetraquark states • 2013 APS Highlights

$Z_c(3900)$ & $Z_{cs}(3985)$: Resonant VS Virtual states

Particle Data Group, PTEP 2022 (2022) 083C01

M.-L. Du, M. Albaladejo, F.-K. Guo and J. Nieves, PRD 105 (2022) 074018

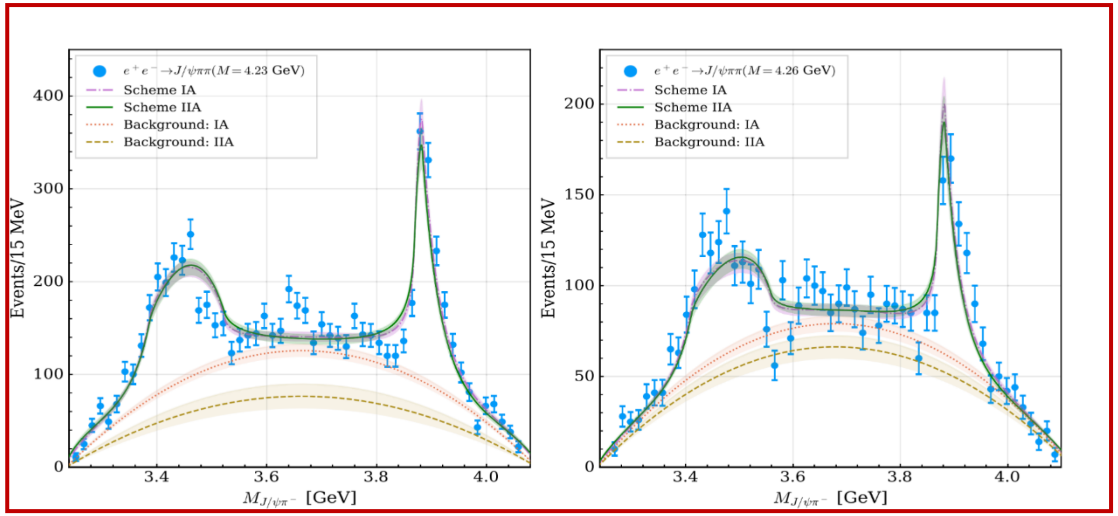
T. Ji, X.-K. Dong, M. Albaladejo, M.-L. Du, F.-K. Guo and J. Nieves, PRD106 (2022) 094002

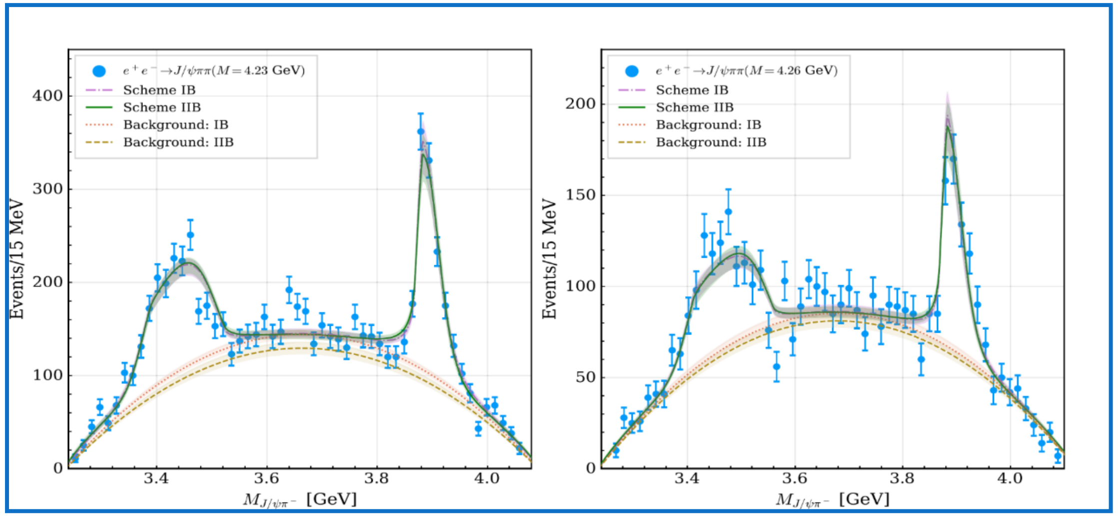
L.-W. Yan, Z.-H. Guo, F.-K. Guo, D.-L. Yao and Z.-Y. Zhou, PRD109 (2024) 014026

Invariant mass distributions fail to distinguish vir. or res.

Virtual state scenario

Resonant state scenario





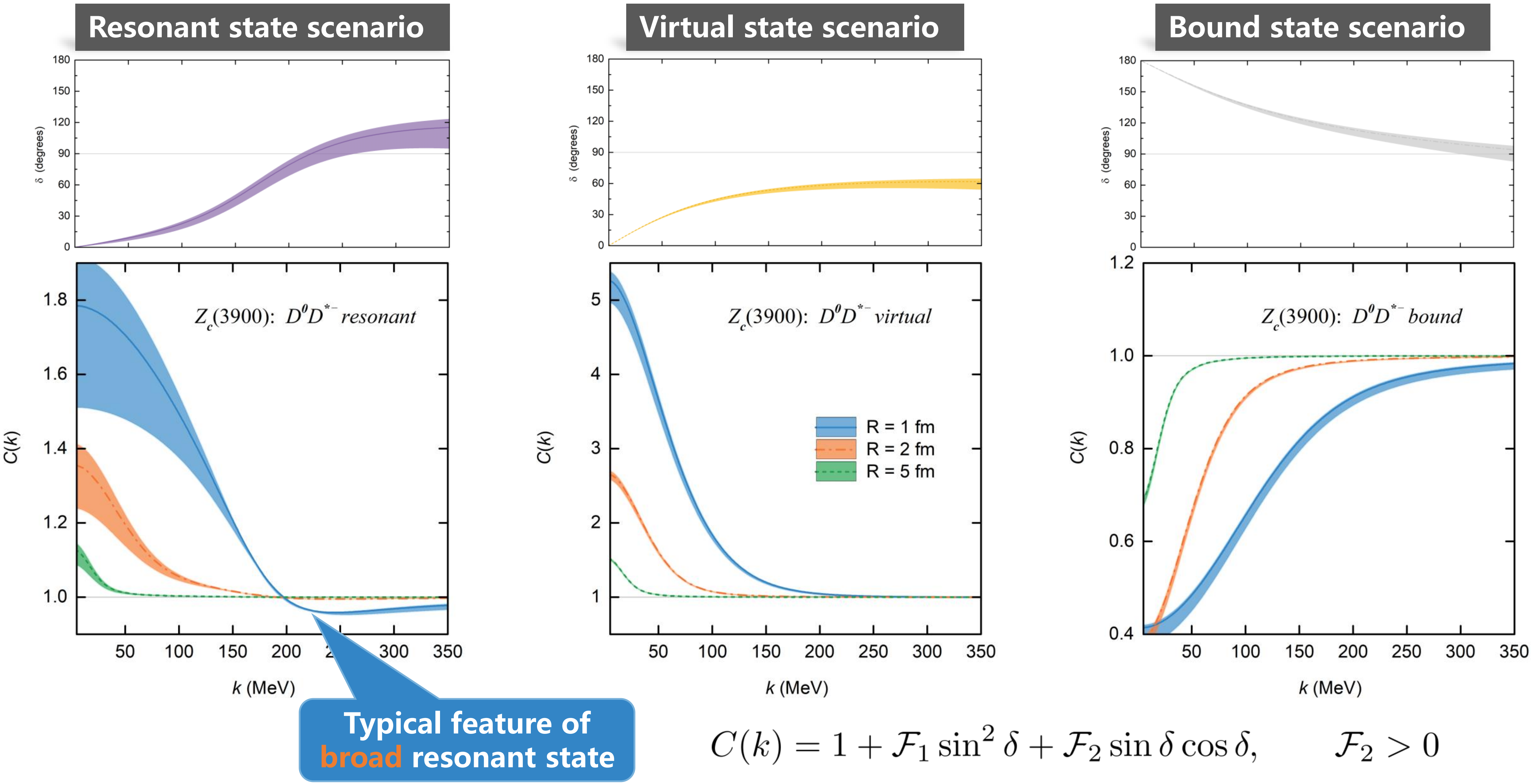
M.-L. Du, M. Albaladejo, F.-K. Guo, and J. Nieves, PRD105(2022)074018

Data are compatible with either a resonant or virtual state.

How to tell which is reality?

$D^0 D^{*-}$ CFs for $Z_c(3900)$

Zhi-Wei Liu, Ming-Zhu Liu, Jun-Xu Lu and **LSG***, Sci.Bull. 70 (2025) 3515-3521

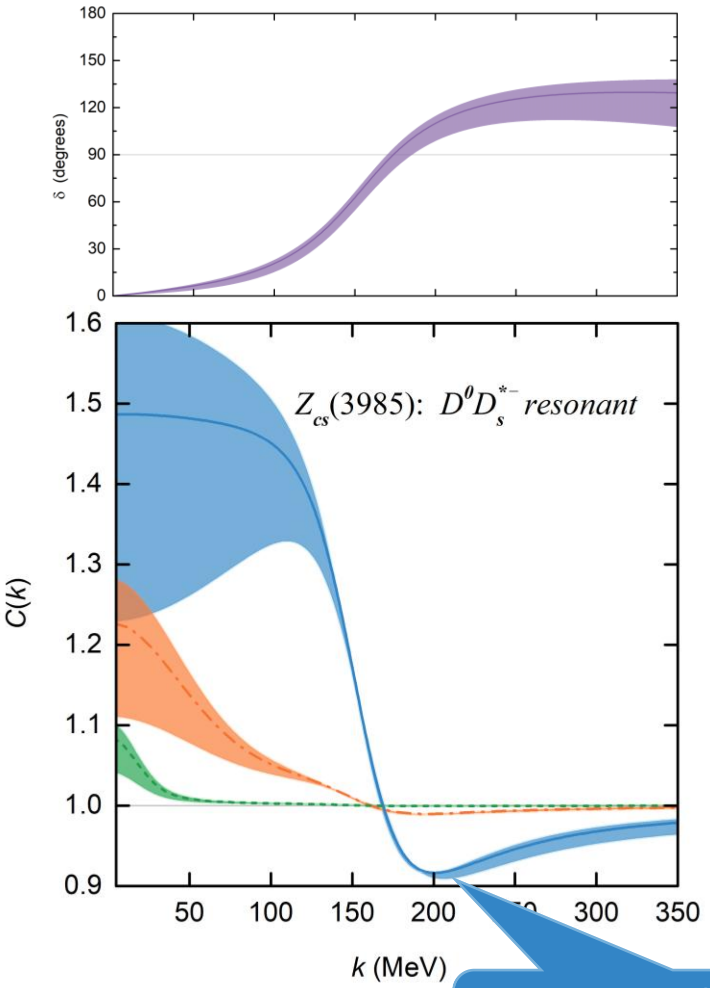


$$C(k) = 1 + \mathcal{F}_1 \sin^2\delta + \mathcal{F}_2 \sin\delta\cos\delta, \qquad \mathcal{F}_2 > 0$$

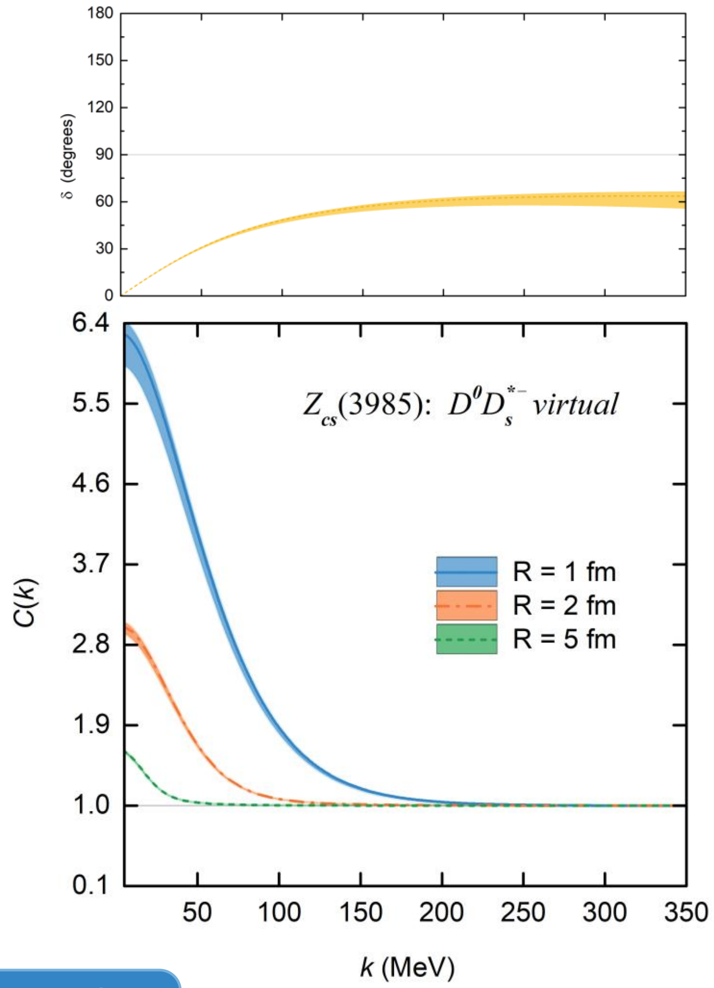
$D^0 D_s^{*-}$ CFs $Z_{cs}(3985)$

Zhi-Wei Liu, Ming-Zhu Liu, Jun-Xu Lu and **LSG***, Sci.Bull. 70 (2025) 3515-3521

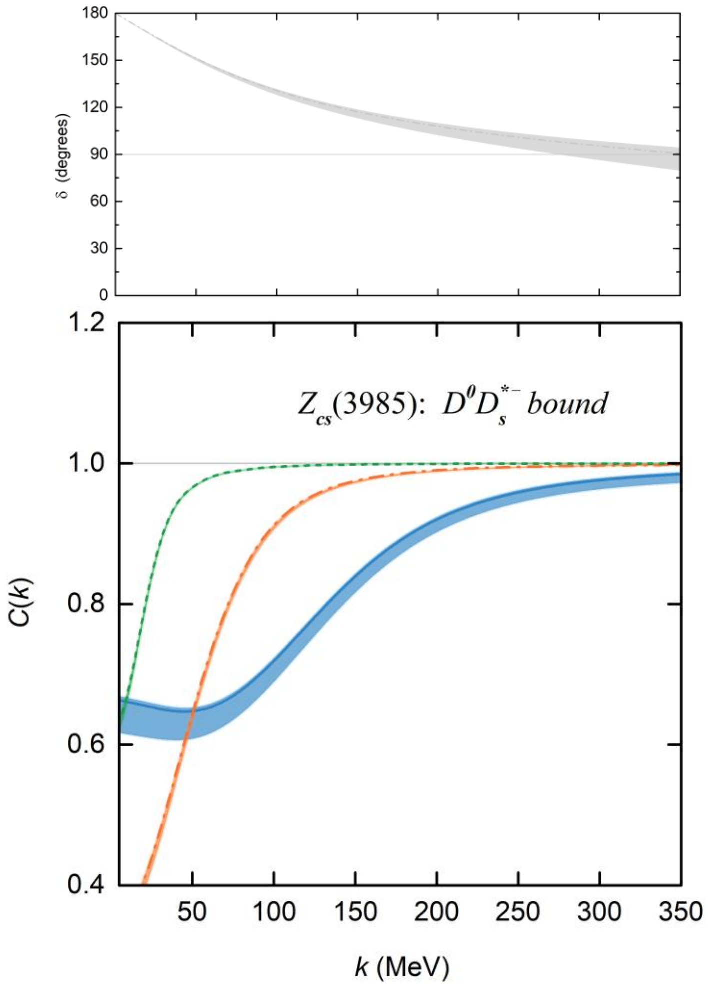
Resonant state scenario



Virtual state scenario



Bound state scenario



Typical feature of narrow resonant state

$$C(k) = 1 + \mathcal{F}_1 \sin^2\delta + \mathcal{F}_2 \sin\delta\cos\delta, \qquad \mathcal{F}_2 > 0$$

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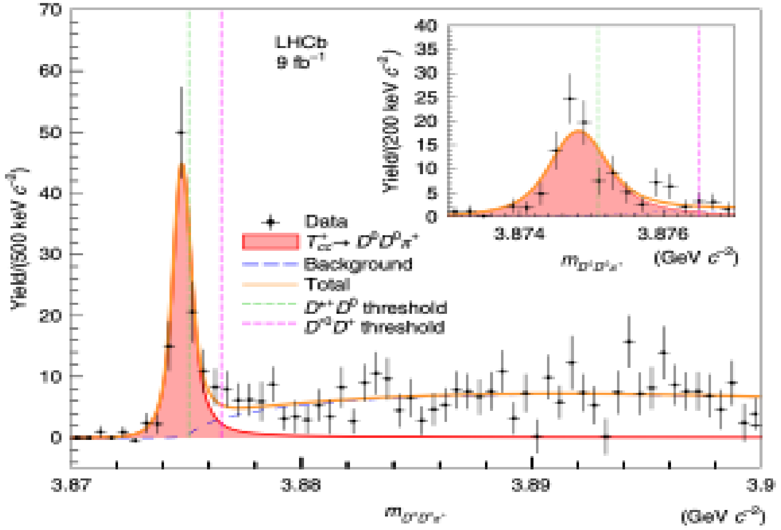
Tcc(3875)—the longest-lived exotic matter yet



☒ **Breit-Wigner** **613 citations**

LHCb, Nature Phys. 18 (2022) 7, 751-754

$$m_{D^{*+}} + m_{D^0} - m = 273 \pm 61 \pm 5^{+11}_{-14}\ \mathrm{keV}$$

$$\Gamma = 410 \pm 165 \pm 43^{+18}_{-38}\ \mathrm{keV}$$

☑ **Unitarized Breit-Wigner** **524 citations**

LHCb, Nature Commun. 13 (2022) 1, 3351

$$m_{D^{*+}} + m_{D^0} - m = 360 \pm 40^{+4}_{-0}\ \mathrm{keV}$$

$$\Gamma = 48 \pm 2^{+0}_{-14}\ \mathrm{keV}$$

✓ **Hadronic Molecule**

- The mass and decay width of T_{cc} can be reasonably explained

  L. Meng, et al. PRD 104 (5) (2021) 051502
  R. Chen, et al. PRD 104 (11) (2021) 114042
  A. Feijoo, et al. PRD 104 (11) (2021) 114015
  L. Qiu, et al. PRD 109 (7) (2024) 076016

- The isoscalar DD^* is likely to form a weakly bound state

  M.Z. Liu, et al. PRD 99 (9) (2019) 094018
  F.Z. Peng, et al. PRD 108 (11) (2023) 114001

- The compositeness analysis indicates DD^* molecule is dominant

  M. Albaladejo, PLB 829 (2022) 137052
  L.R. Dai, et al. PLB 846 (2023) 138200
  T. Kinugawa, et al. PRC 109 (4) (2024) 045205

- A deep learning approach to the pole structure

  J. B. Pagayon, et al. Few Body Syst. 67 (2026) 2, 20

✓ **Compact Tetraquark**

Y. Song, et al. Commun.Theor.Phys 75 (5) (2023) 055201
T.W. Wu, et al. PRD 107 (7) (2023) L071501
S.Y. Li, et al. PRD 110 (9) (2024) 094044
Y. Ma, et al. PRD 109 (7) (2024) 074001
H. Mutuk, EPJC 84 (4) (2024) 395

✓ **Virtual State**

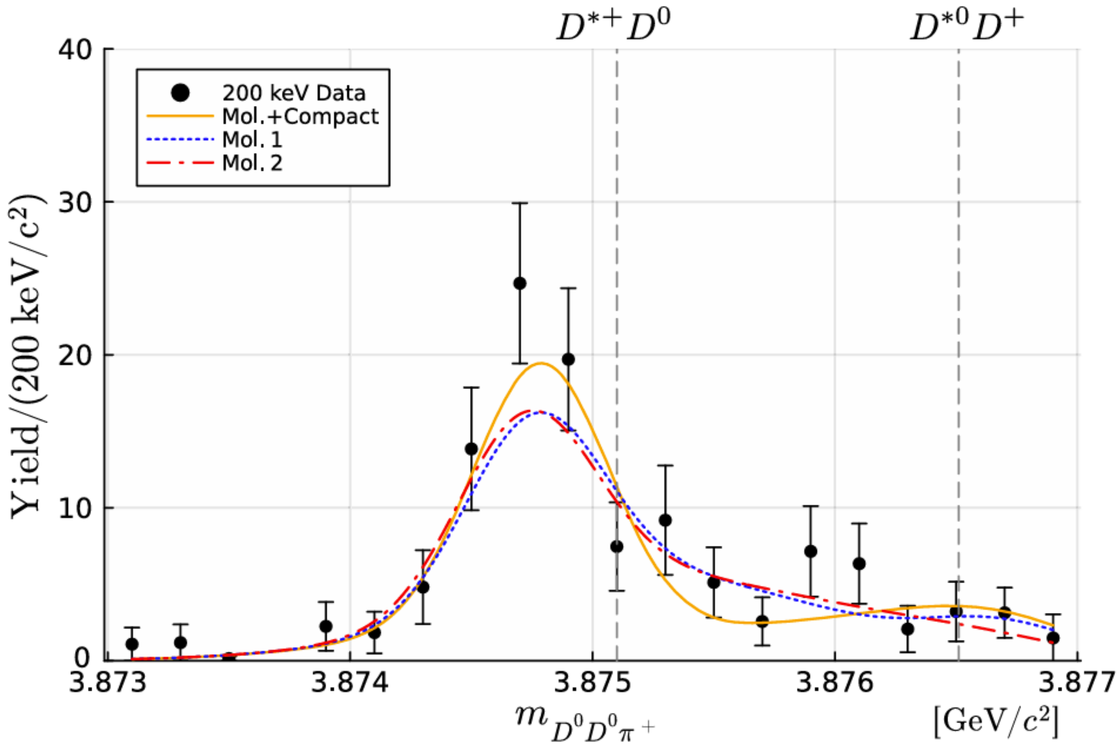
- A virtual state at the DD^* mass threshold according to LQCD

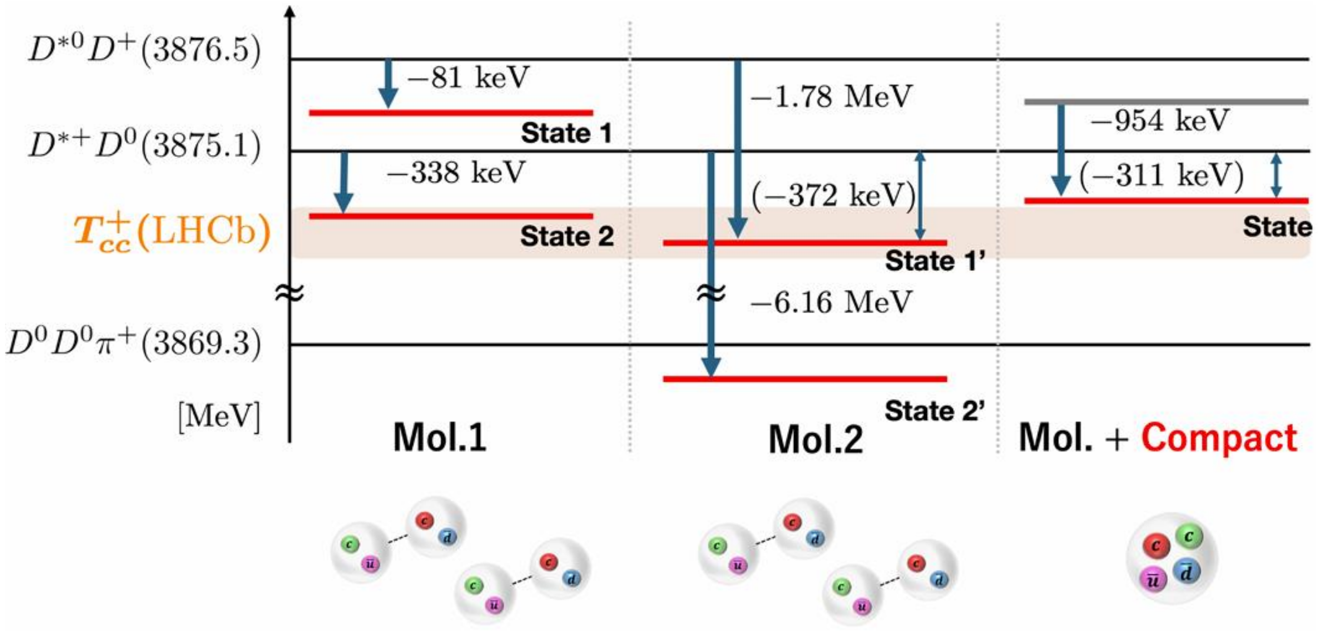
  M. Padmanath, et al. PRL 129 (3) (2022) 032002
  Y. Lyu, et al. PRL 131 (16) (2023) 161901

Tcc(3875)—the longest-lived exotic matter yet

Distinguishing the compact versus molecular nature of $T_{cc}(3875)^+$

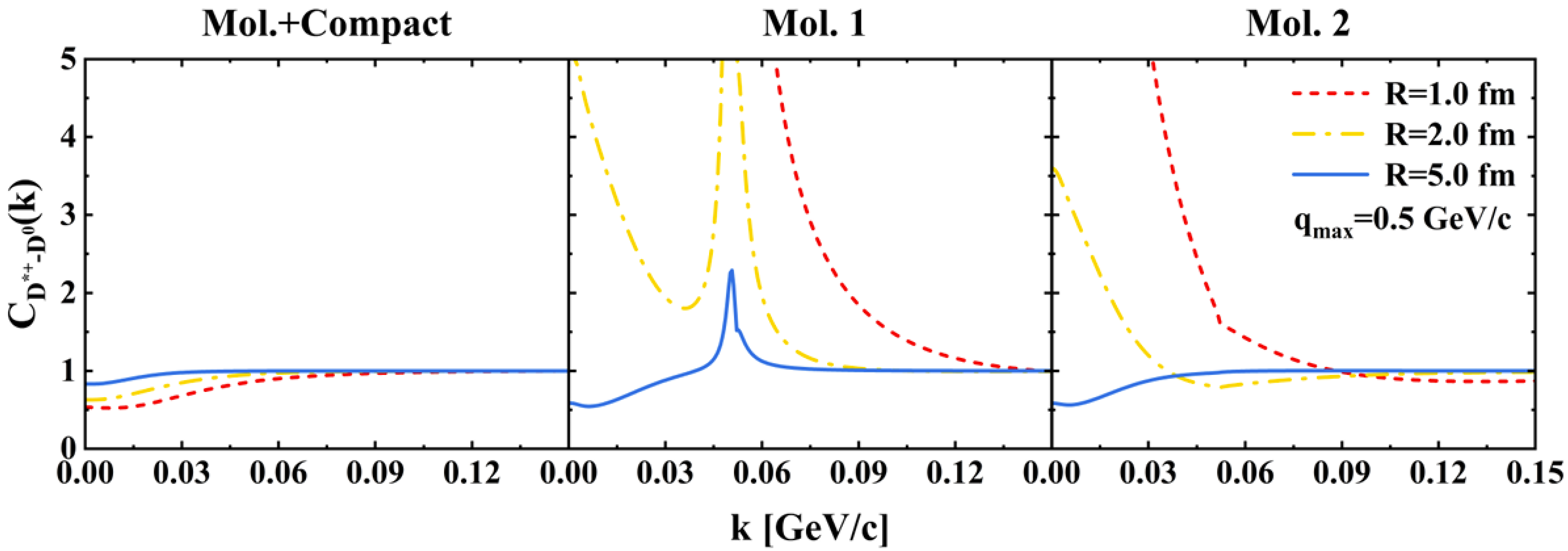
Shota Ampuku, Yasuhiro Yamaguchi, Masayasu Harada, *PRD*113(2026)L031505





Tcc(3875)—the longest-lived exotic matter yet

DD^* **correlation functions in deciphering the nature of** $T_{cc}(3875)^+$



Duo-Lun Ge, Zhi-Wei Liu, LSG, 2603.24980*

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Summary and outlook

- **Femtoscopy offers high-precision tests of the strong interaction between pairs of (un)stable particles and can be valuable to decipher the nature of the many exotic hadrons discovered so far.**
- ✓ $D_{s0}^{*}(2317)$, $Z_c(3900)/Z_{cs}(3985)$, $T_{cc}(3875)$
- ✓ *Pc(4440)/Pc(4457), Pcs(4338), X (3960), X(6200), K1(1270), J/psi-N*
- **With more data from LHC Run3, the future is very promising:**
  - Pp data taking: event count increase: ~3000×
  - Pb-pb data taking: event count increase: ~70×

Thanks a lot for your attention!

(Image: CERN)