极端核物质前沿研讨会（Workshop on extreme nuclear matter frontiers，2026.04.24-28，宜昌

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)

Contents

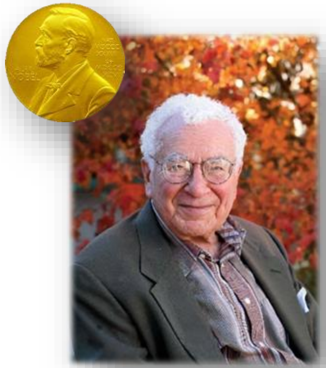
- ☞ **Brief introduction: exotic hadrons and femtoscopy**
- ☞ **Femtoscopic correlation functions (CFs)—general features**
- ☞ **Recent applications**
  - ➢ $D_{s0}^{*}(2317)$、 $Z_c(3900)$ and $Z_{cs}(3985)$、$T_{cc}(3875)$
- ☞ **Summary and outlook**

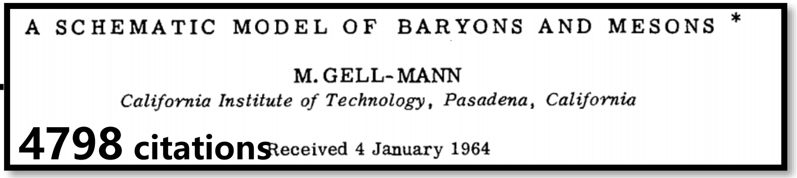
Hadrons in the Constituent Quark Model

- In 1964, Gell-Mann and Zweig proposed the legendary Constituent Quark Model and successfully classified all strongly interacting particles into $q\bar{q}$ mesons and qqq baryons (hadrons)

baryons

mesons

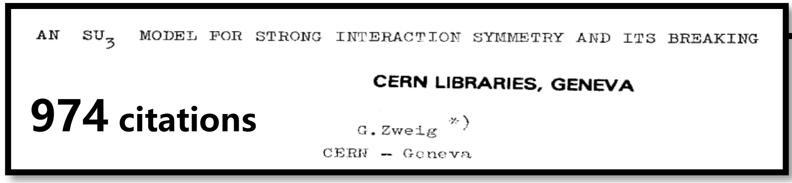



A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

California Institute of Technology, Pasadena, California

4798 citations Received 4 January 1964


AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

CERN LIBRARIES, GENEVA

974 citations

G. Zweig *)

CERN - Geneva

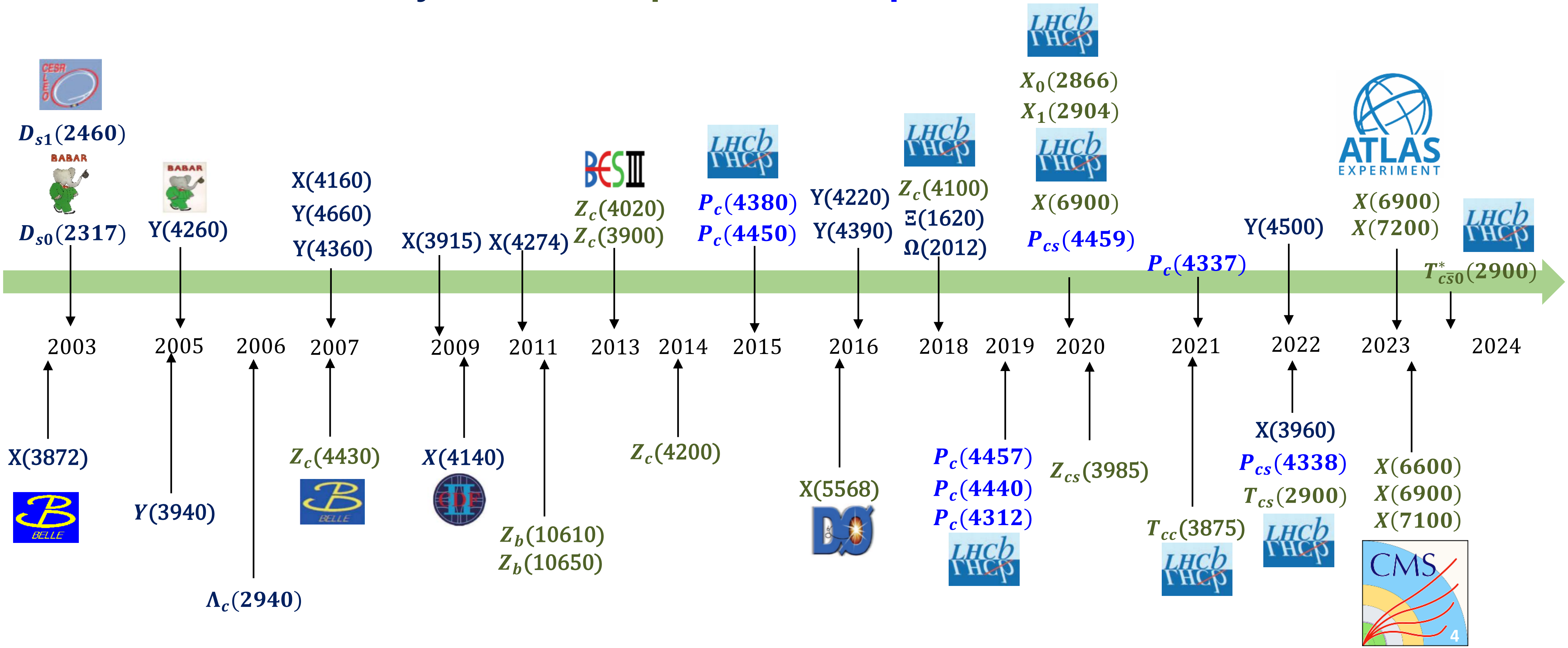
- The constituent QM works extremely well up to circa 2003
  - $\Theta^+(1540)$, LEPS, 0301020, 1219 citations
  - $D^*_{s0}(2317)$, BaBar, 0304021, 1071 citations
  - X(3872), Belle, 0309032, 2948 citation

BABAR

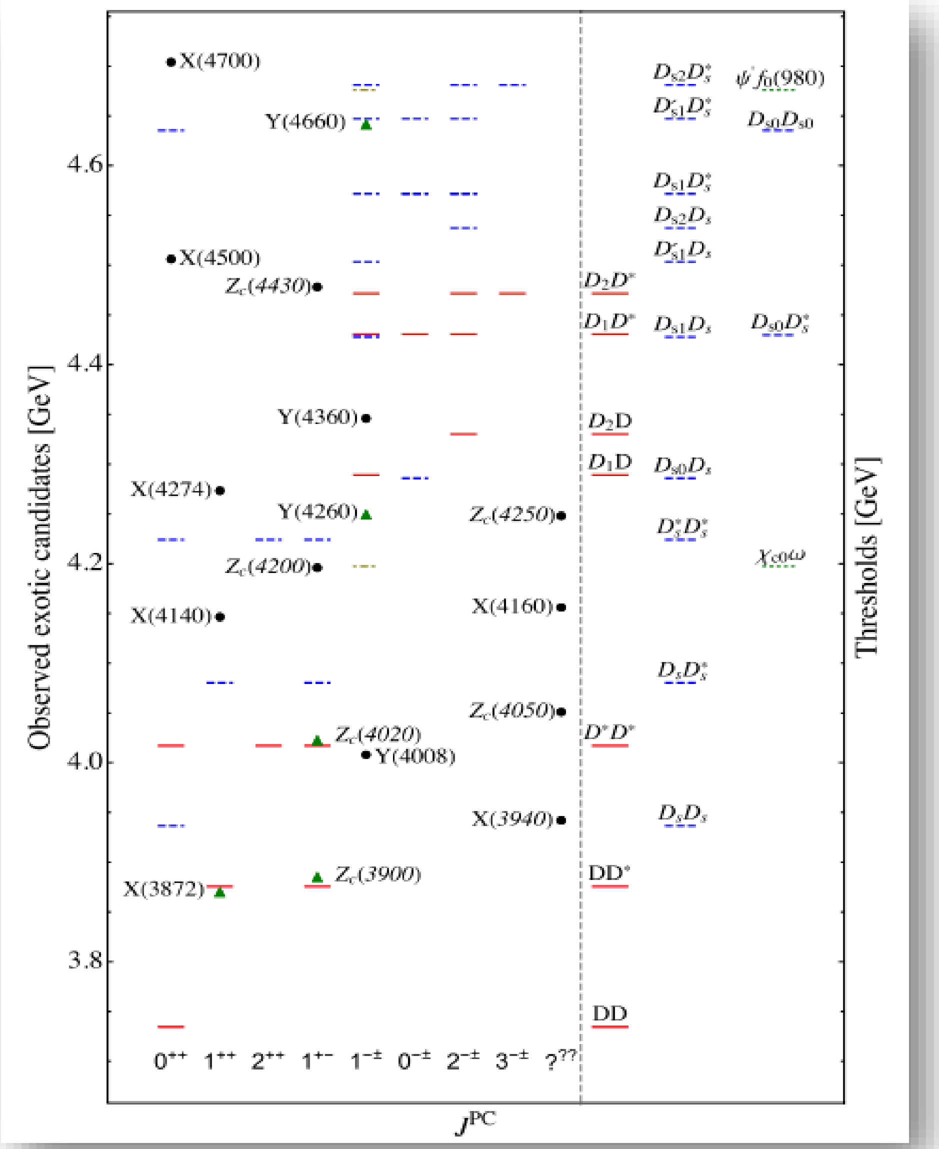
BELLE

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

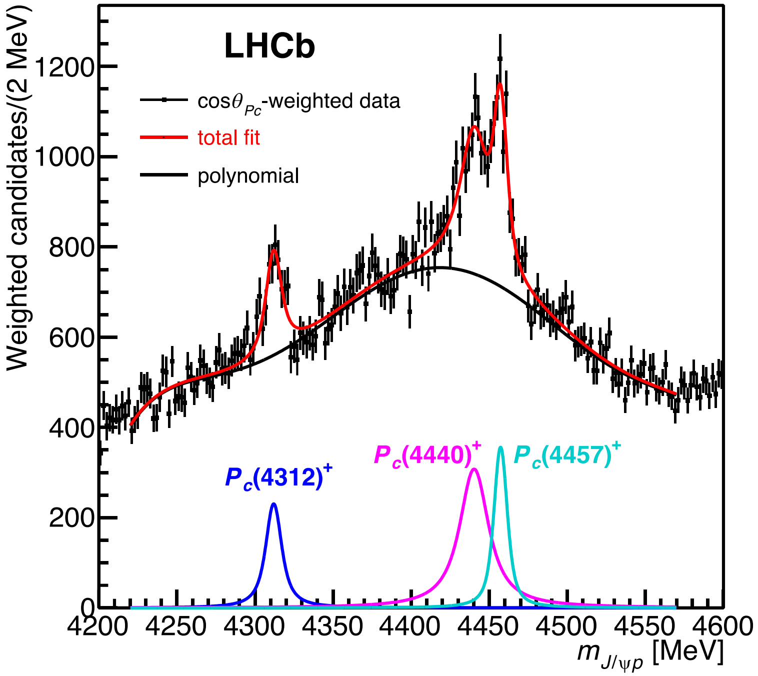
……

How to check the molecular picture?

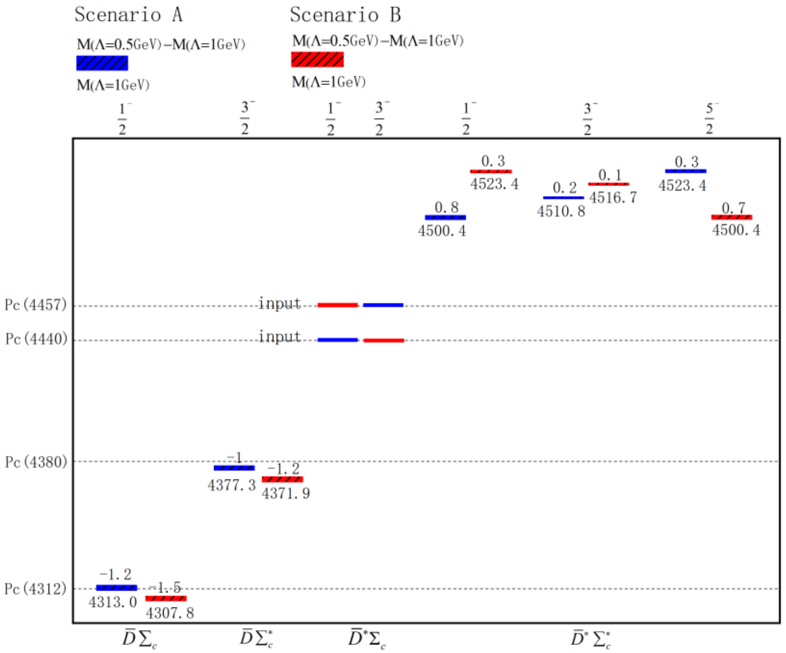
How to verify the molecular picture

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

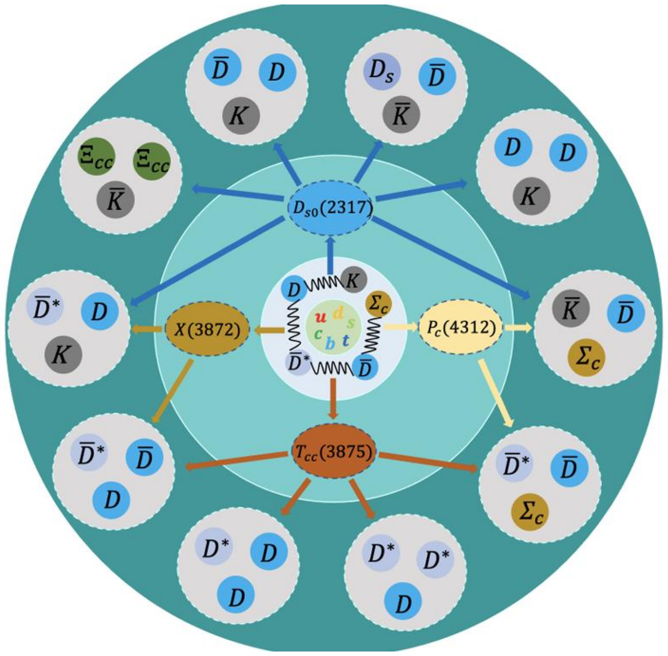


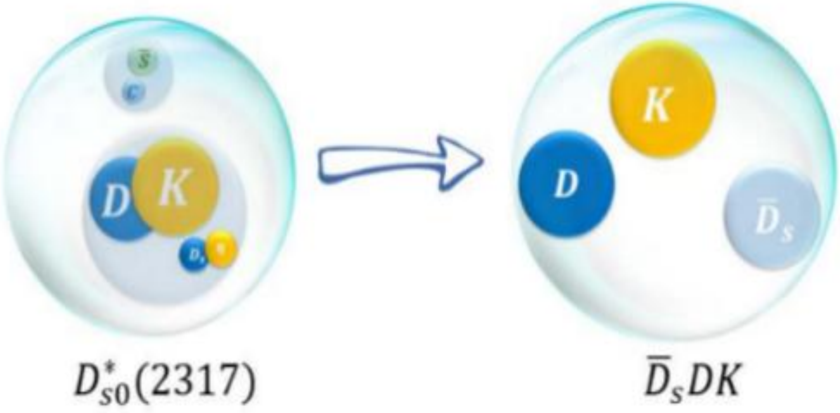
Liu, Pan, Peng, Sánchez, LSG, Hosaka, Valderrama, PRL122, 242001 (2019)

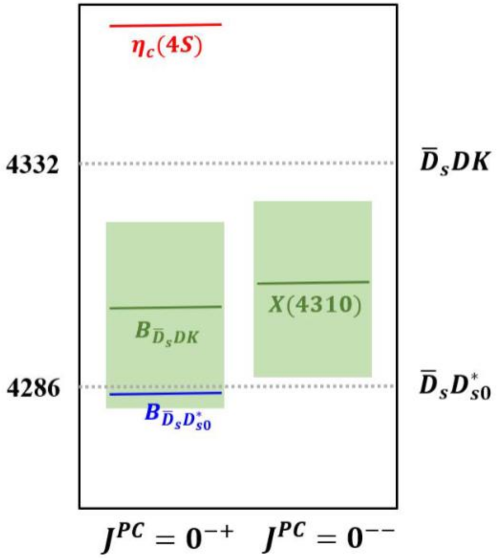
How to verify the molecular picture

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

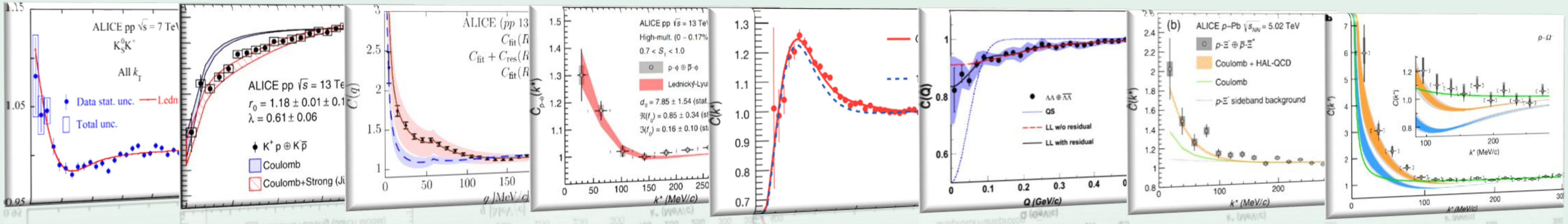
Ming-Zhu Liu, Ya-Wen Pan, Zhi-Wei Liu, Tian-Wei Wu, Jun-Xu Lu, **LSG***, Phys.Rept. 1108 (2025) 1-108

□ Direct measurement of the two-hadron interactions

CERN The Large Hadron Collider

Brookhaven National Laboratory RHIC Relativistic Heavy Ion Collider

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



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)—general features
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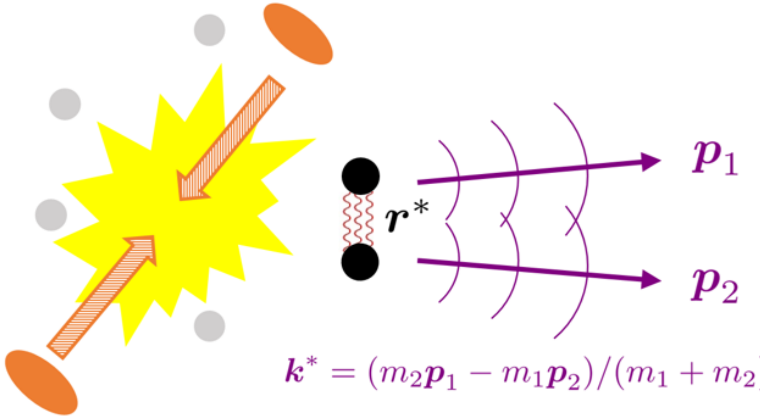
- ☞ Summary and outlook

Femtoscopic correlation functions (CFs)

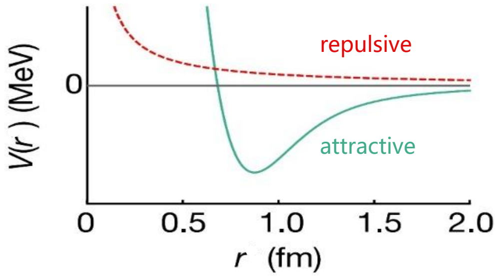
$$C(\boldsymbol{p}_1, \boldsymbol{p}_2) = \frac{\mathrm{P}(\boldsymbol{p}_1, \boldsymbol{p}_2)}{\mathrm{P}(\boldsymbol{p}_1) \cdot \mathrm{P}(\boldsymbol{p}_2)}$$



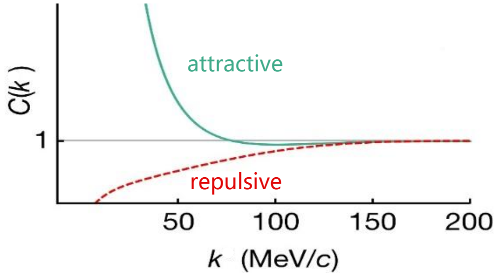
$$\boldsymbol{k}^* = (m_2 \boldsymbol{p}_1 - m_1 \boldsymbol{p}_2)/(m_1 + m_2)$$

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

Interacting potential



Correlation function



Schrödinger equation

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

Exp. measurement

mixed-event technique

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

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

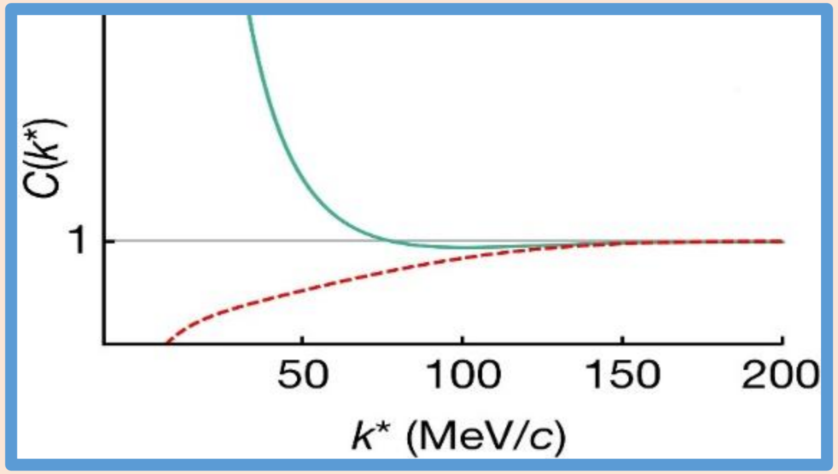
$C(k)$:
- >1 if the interaction is attractive
- =1 if there is no interaction
- <1 if the interaction is repulsive

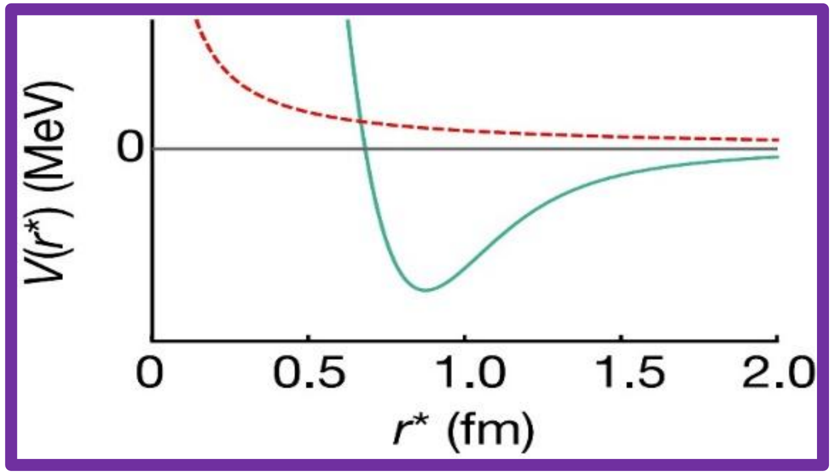
Basic philosophyies

The interaction is known from, e.g., experiments, lattice QCD, or effective field theories

Direct

Predict



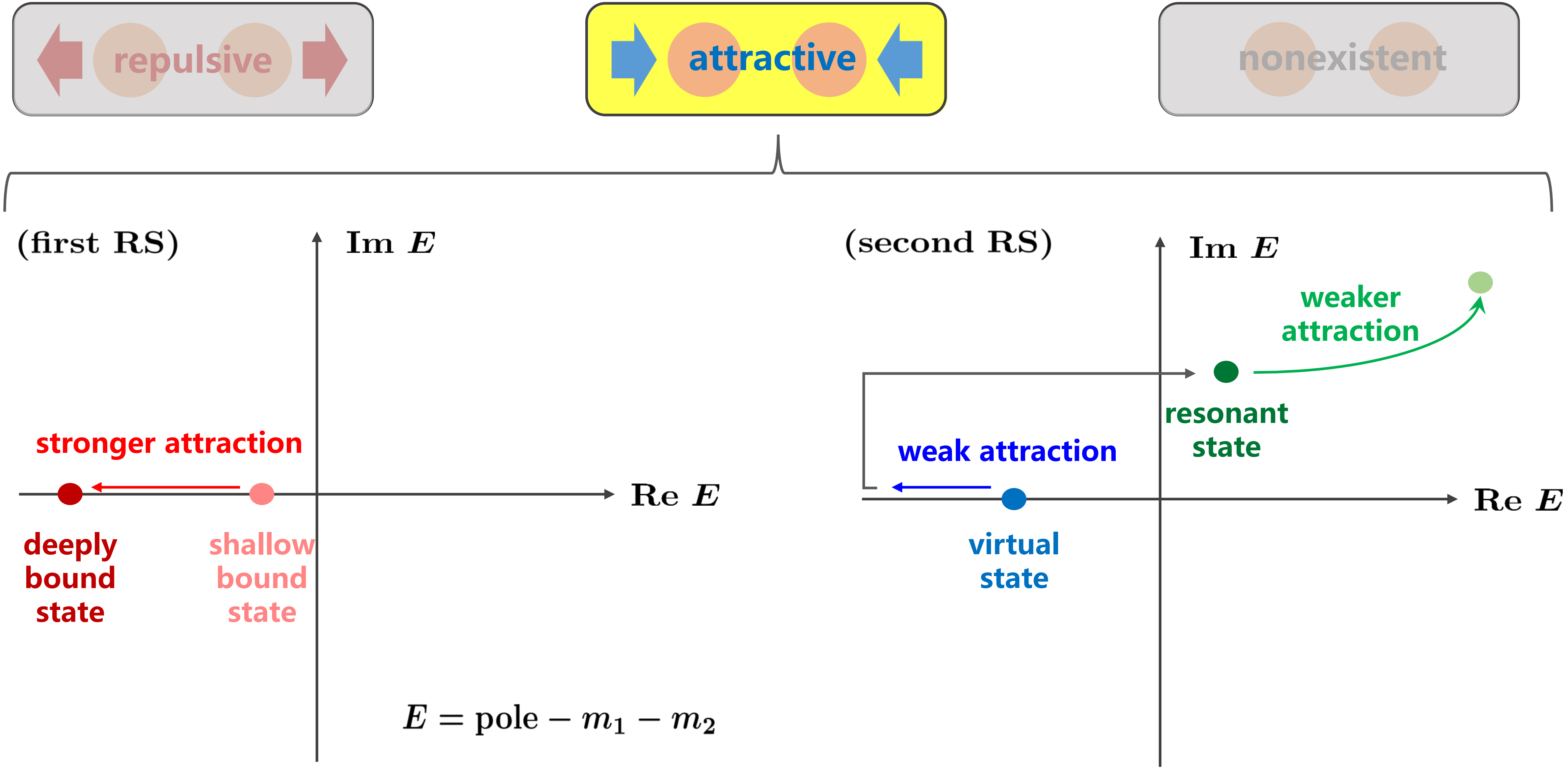


Inverse

Extract

Experiments measure the correlation functions

Classification of hadron-hadron interactions

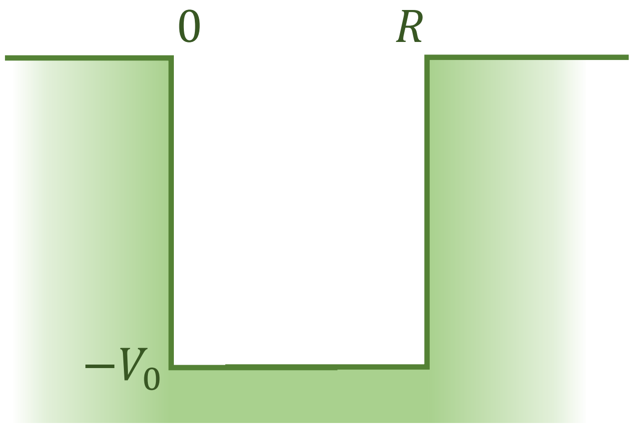


$$E = \text{pole} - m_1 - m_2$$

CFs for interactions capable of generating bound states

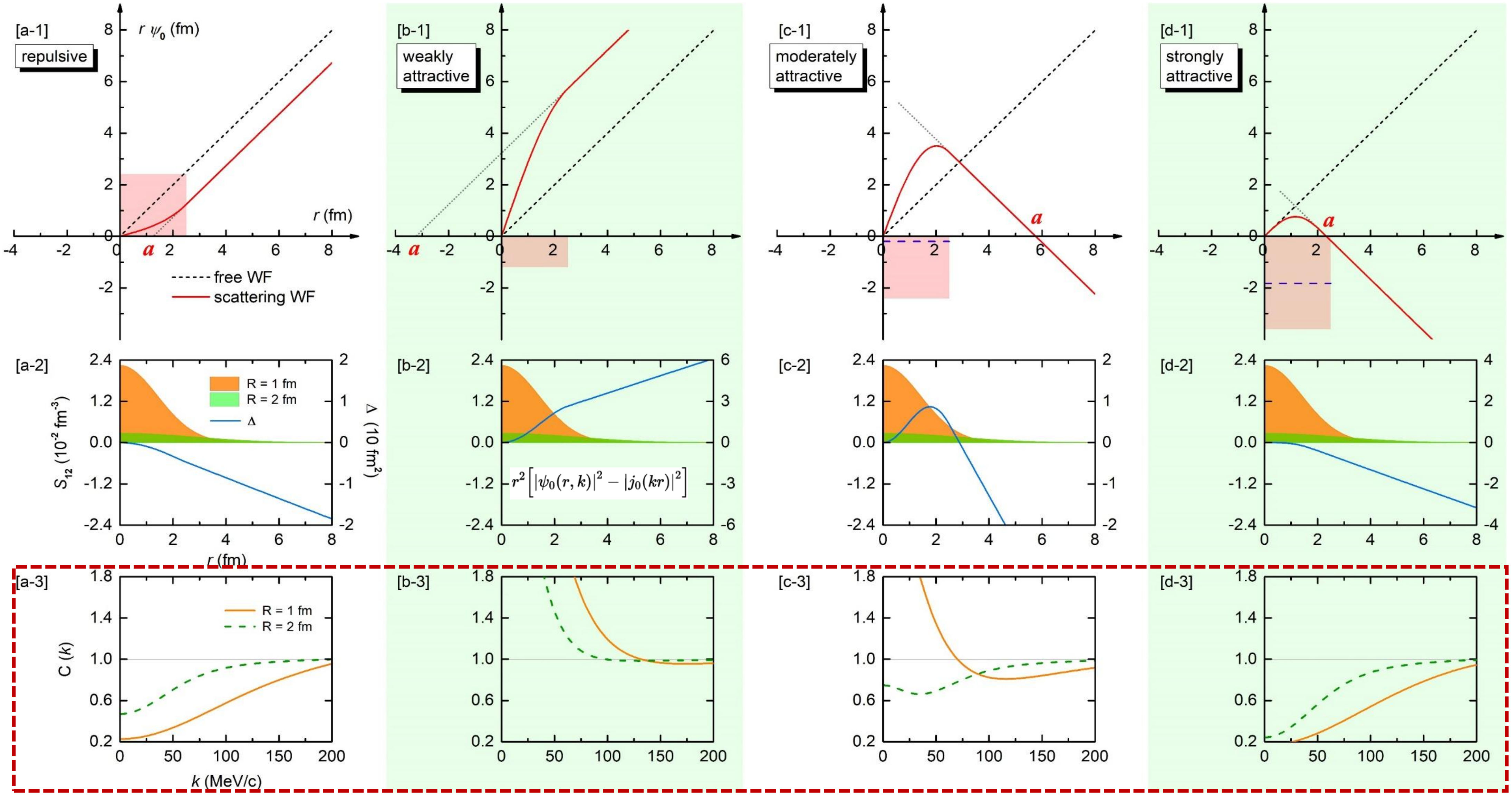
*Zhi-Wei Liu, Jun-Xu Lu and **LSG****, *PRD 107, 074019 (2023)*

Spherical potential well—physically intuitive



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

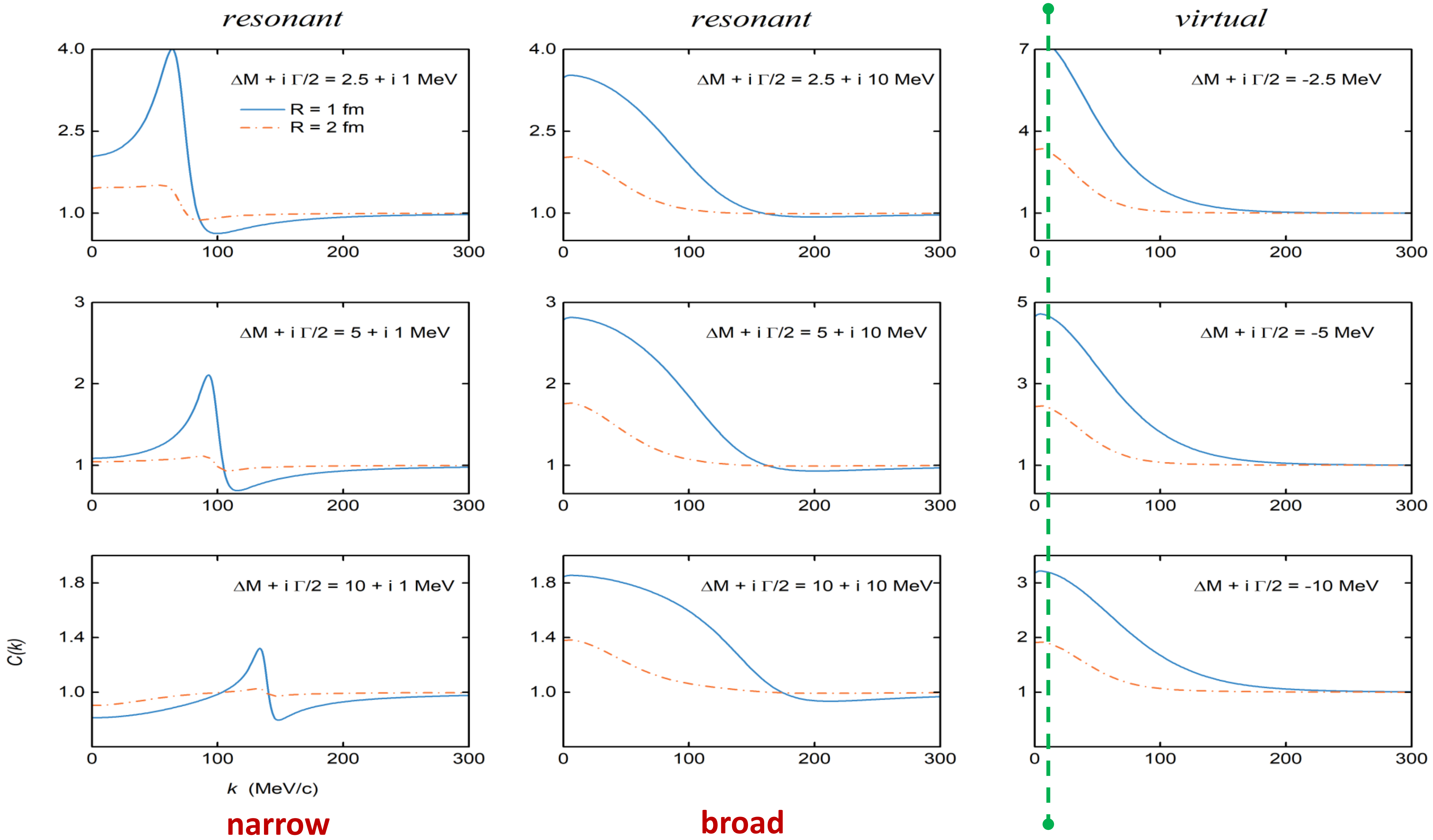
Zhi-Wei Liu, Ming-Zhu Liu, Jun-Xu Lu and LSG, Sci.Bull. 70 (2025) 3515-3521*

EFT potential—model independent:
capable of generating bound, virtual, and resonant states

$$\mathbf{V} = \mathbf{a} + \mathbf{b} \cdot \mathbf{k}^2$$

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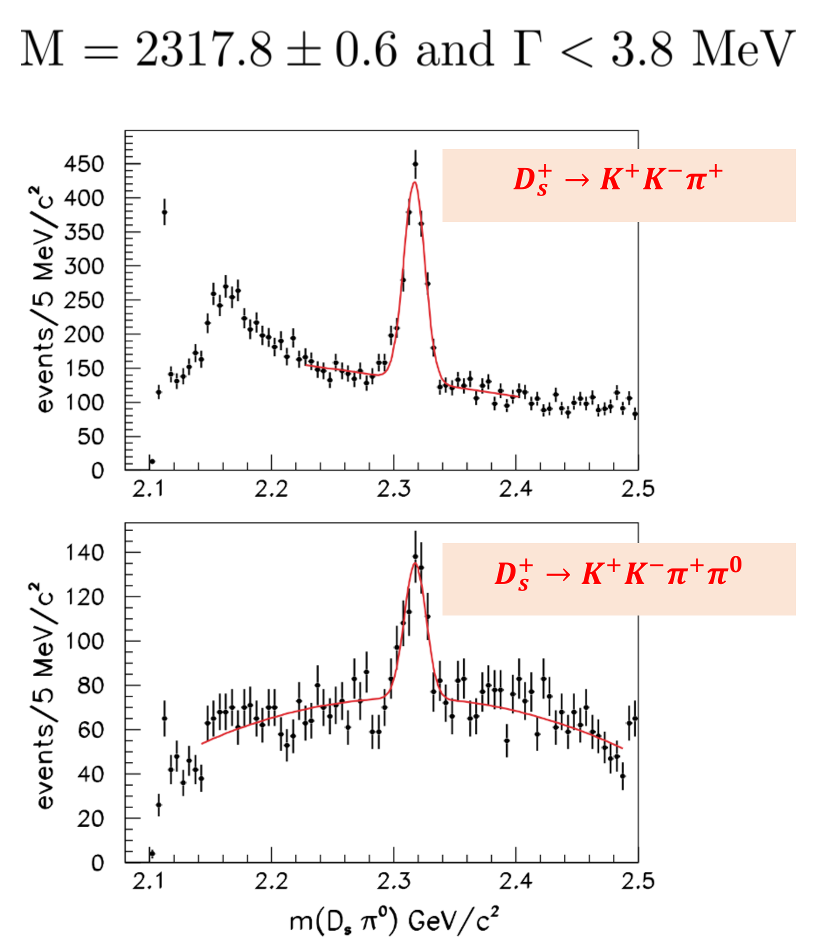
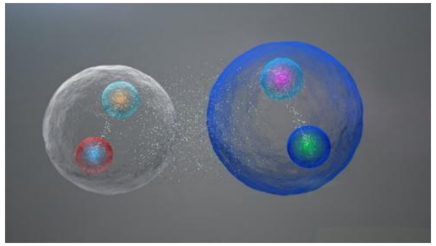
Mysterious exotic hadron $D_{s0}^*(2317)$



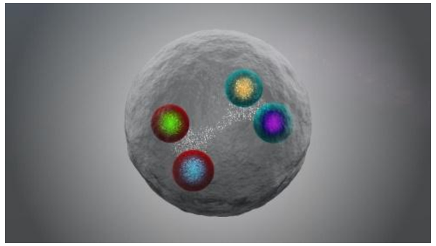
BABAR, PRL90 (2003) 242001

- **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



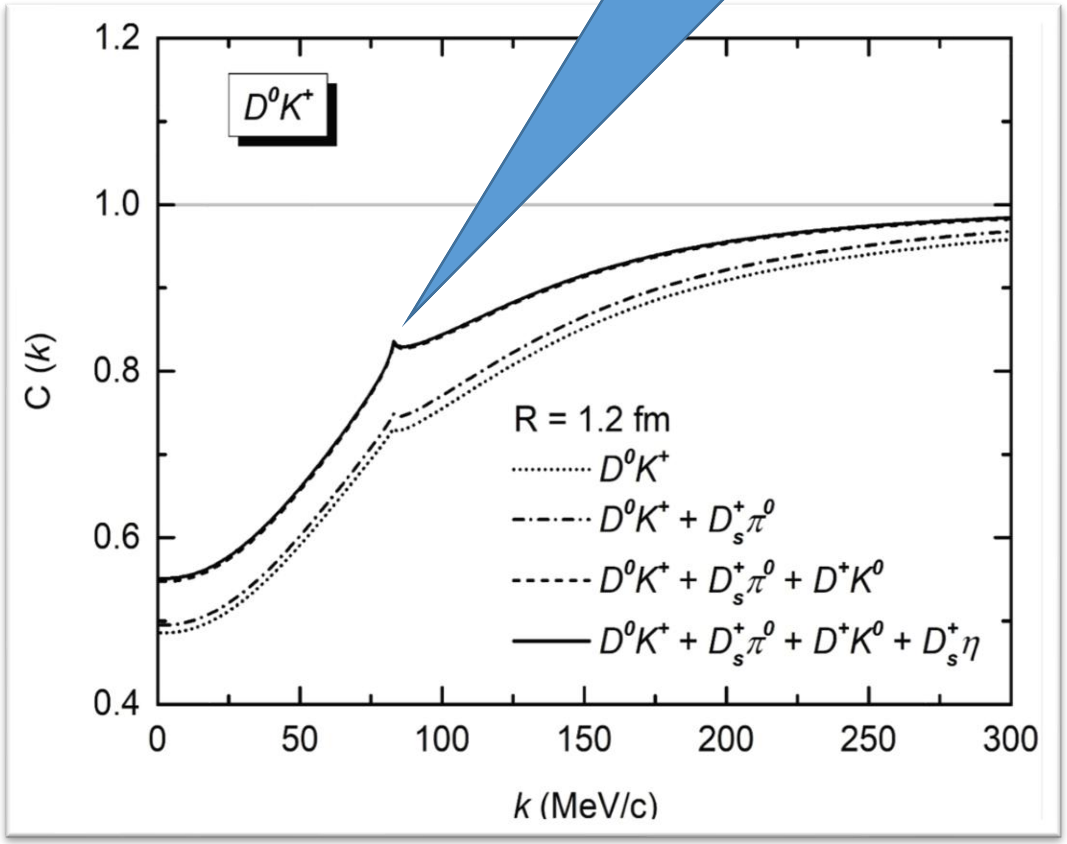
VS

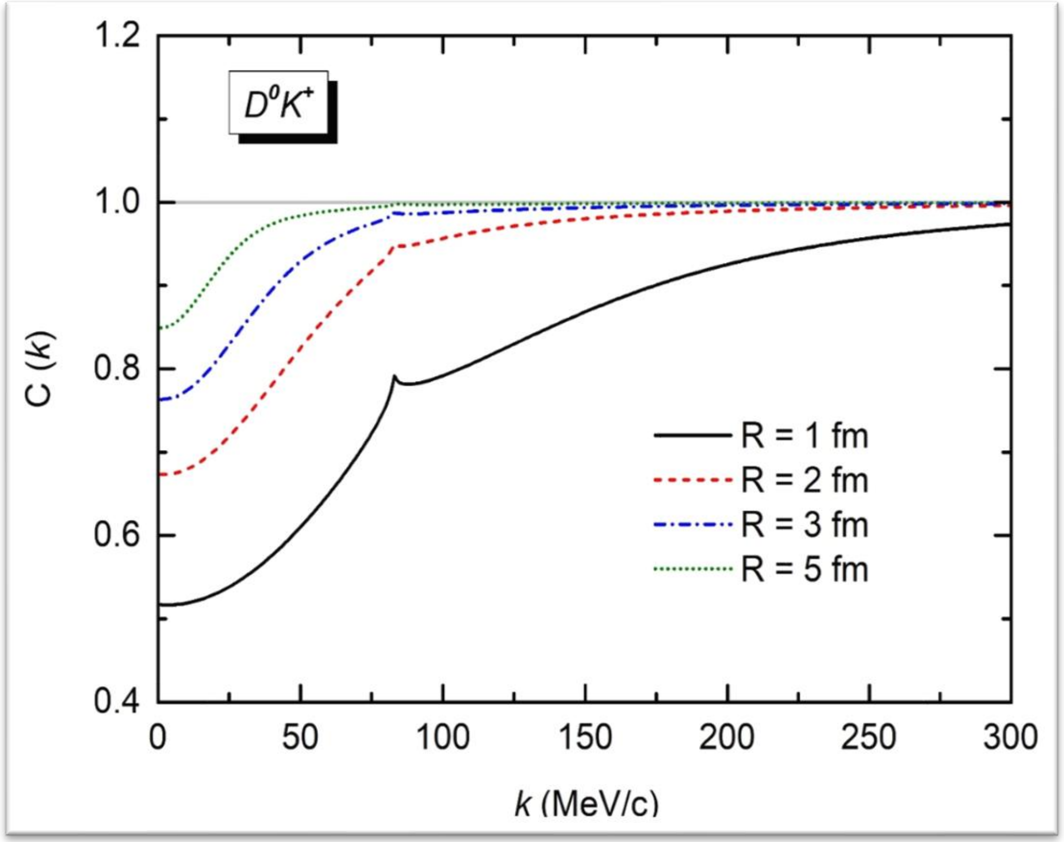


DK CFs and its source size dependence

$D^+K^0 \rightarrow D^0K^+$

Typical feature of deeply bound states





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

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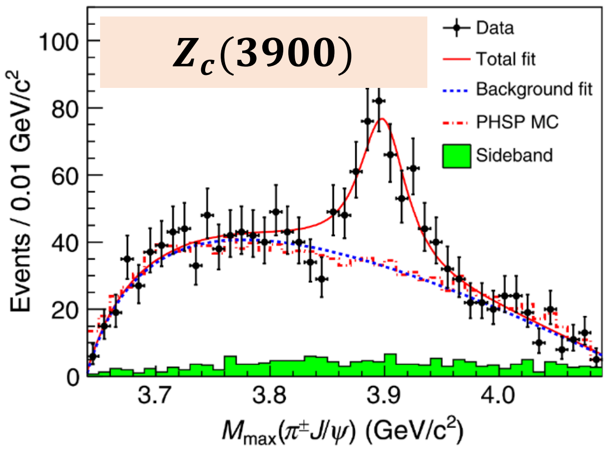
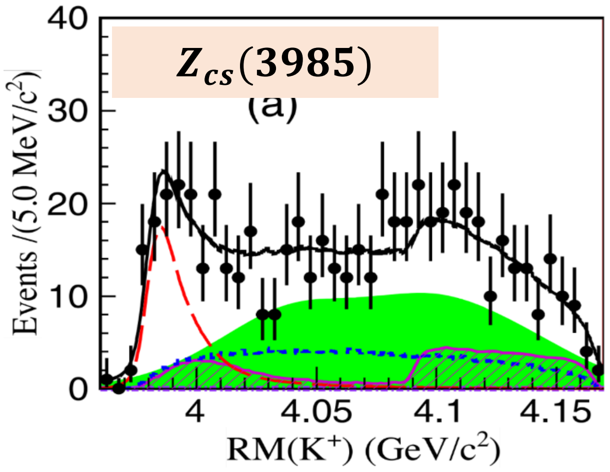
Tetraquark states $Z_c(3900)$ & $Z_{cs}(3985)$



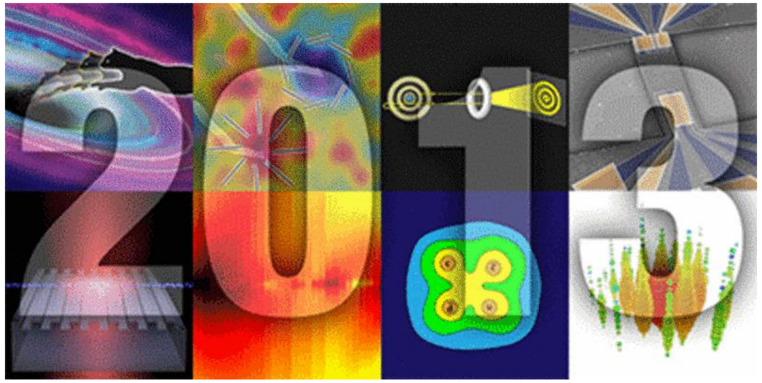
BESIII, PRL110 (2013) 252001

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

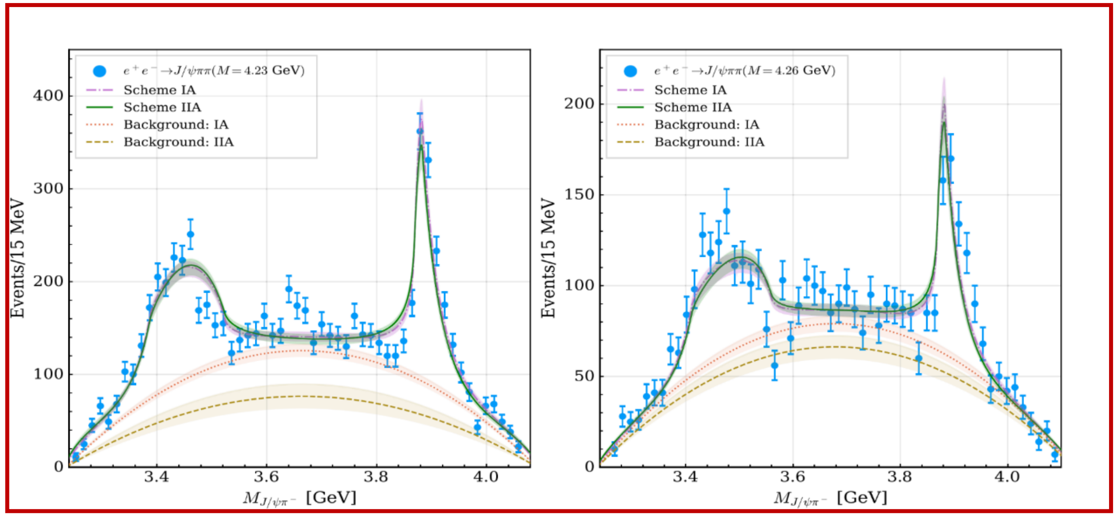
T. Ji, X.-K. Dong, M. Albaladejo, M.-L. Du, F.-K. Guo and J. Nieves, PRD106 (2022) 094002

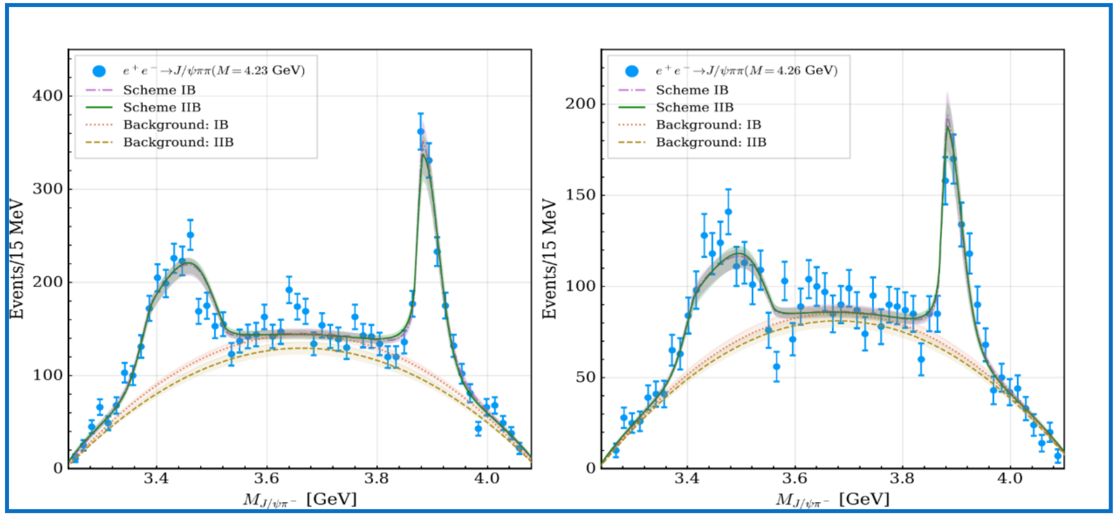
L.-W. Yan, Z.-H. Guo, F.-K. Guo, D.-L. Yao and Z.-Y. Zhou, PRD109 (2024) 014026

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

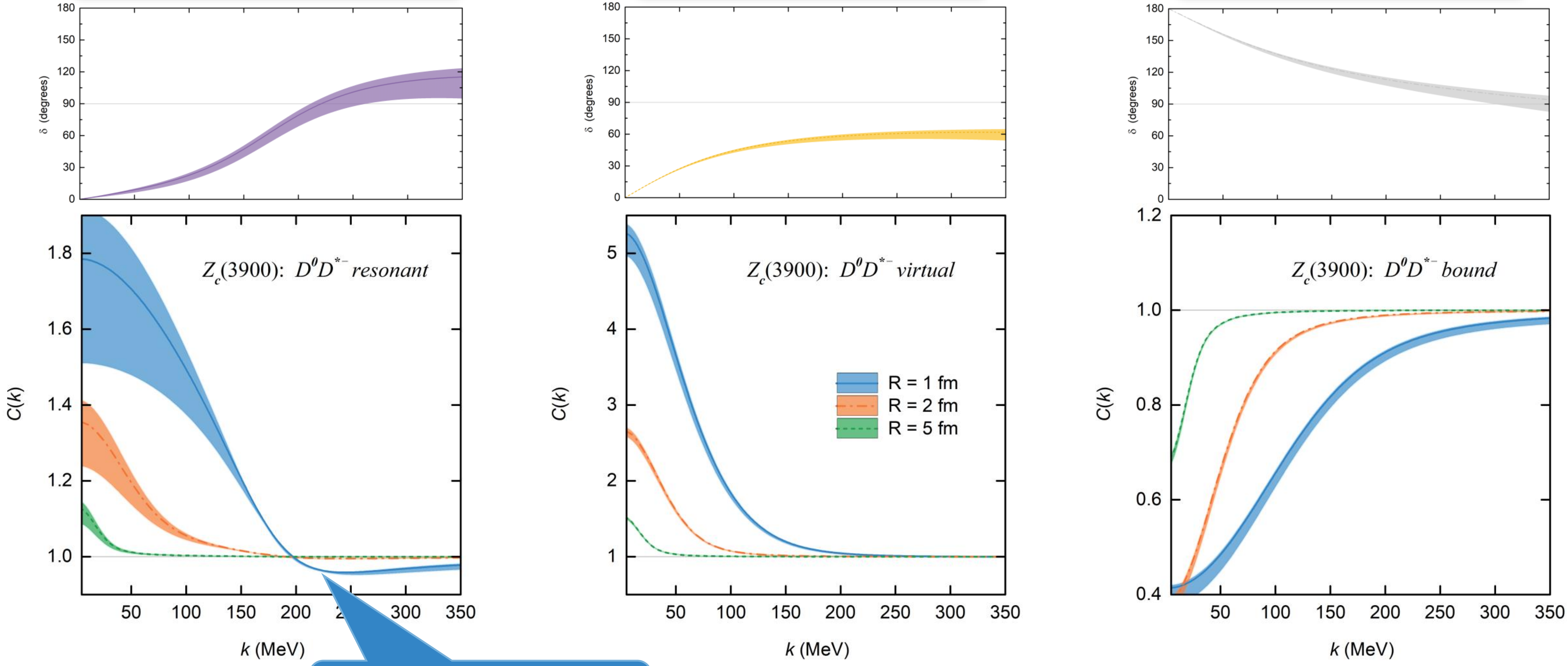
Data are compatible with either a resonant or virtual state.

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

Resonant state scenario | Virtual state scenario | Bound state scenario

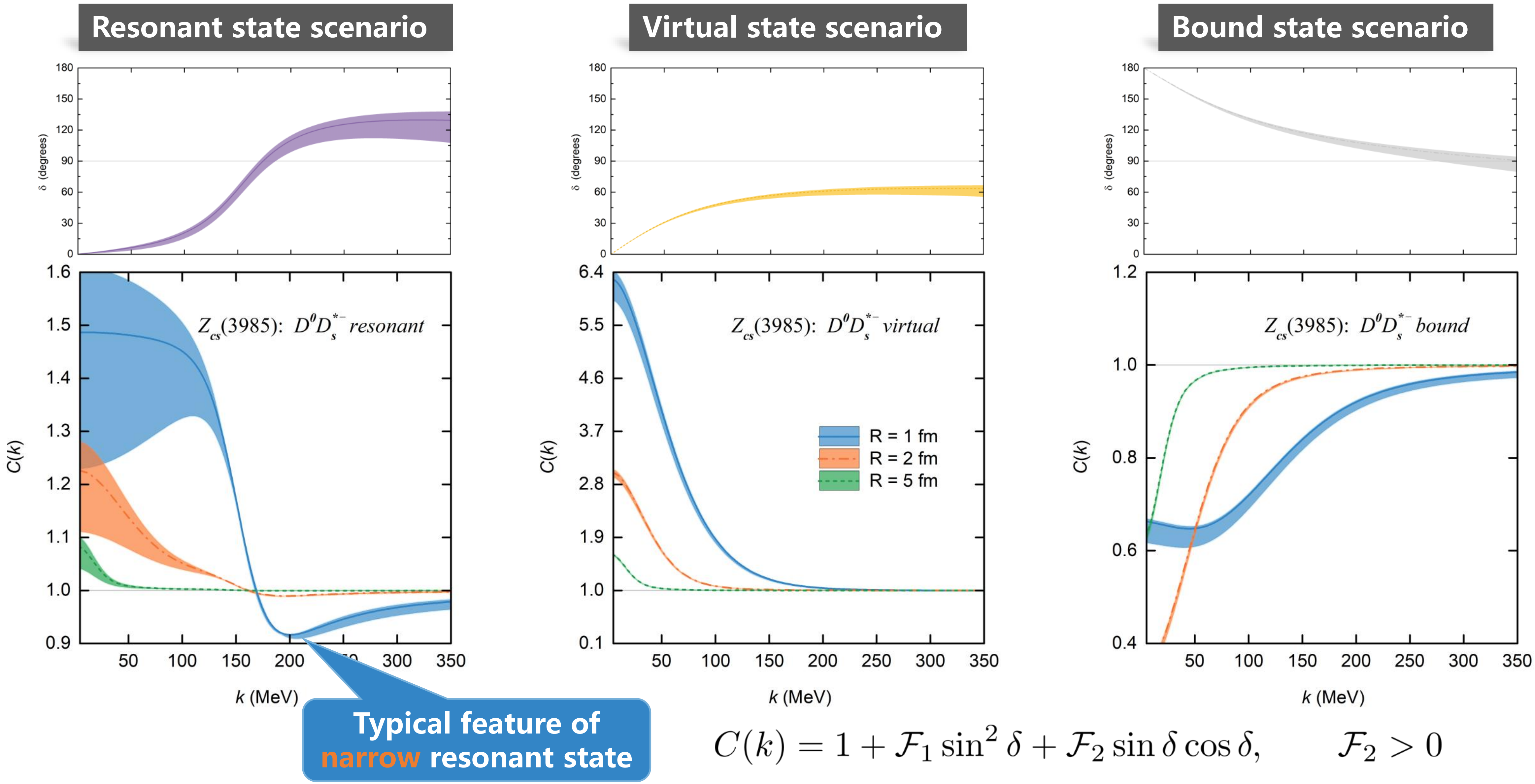


Typical feature of broad resonant state

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

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

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



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

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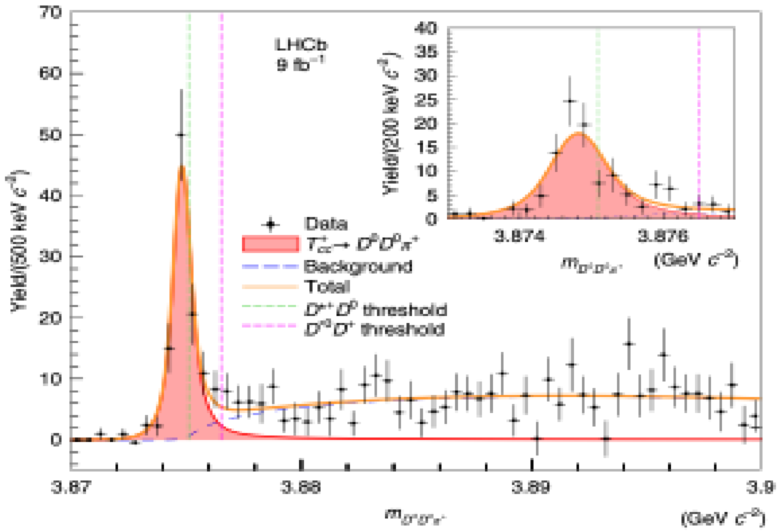
Tcc(3875)—the longest-lived exotic matter yet



☒ **Breit-Wigner** **613 citations**

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

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

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

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

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

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

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

✓ 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

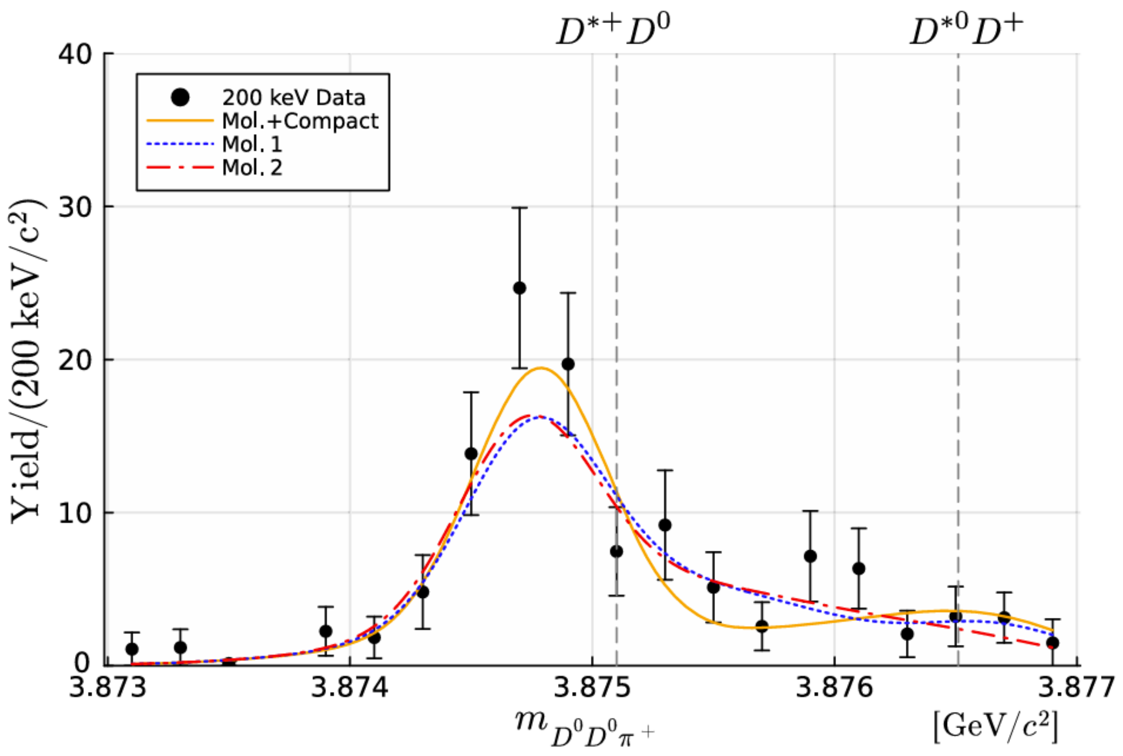
- A virtual state at the DD^* mass threshold according to LQCD

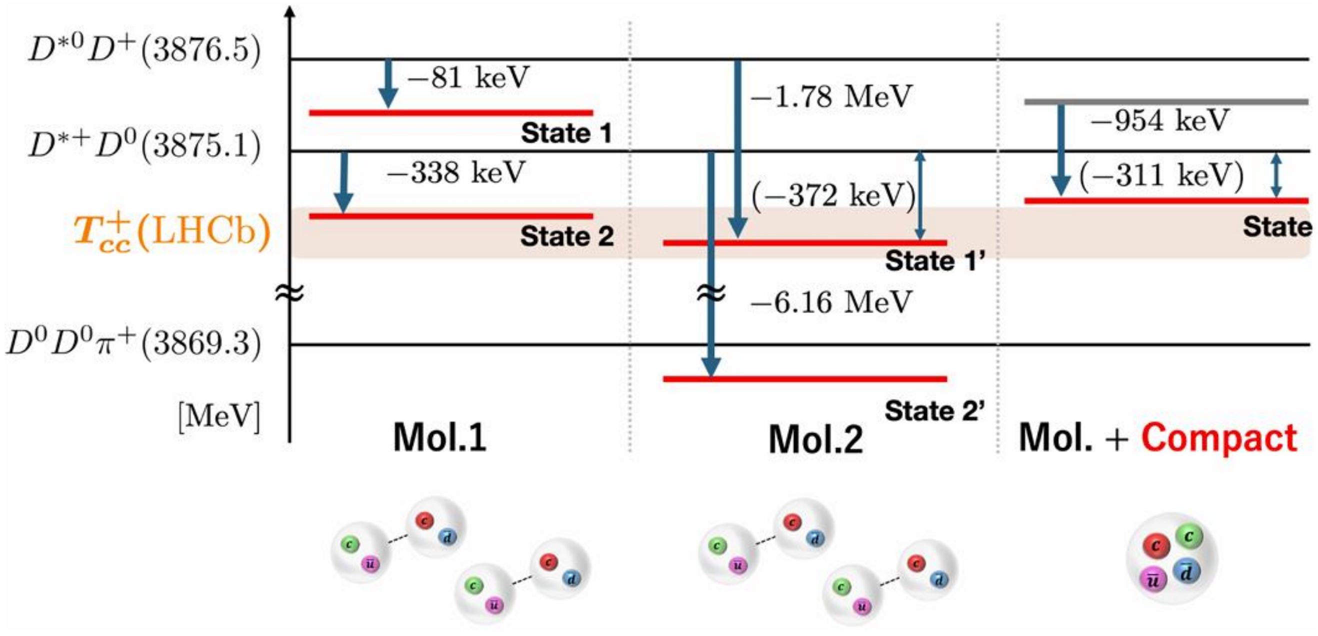
  M. Padmanath, et al. PRL 129 (3) (2022) 032002
  Y. Lyu, et al. PRL 131 (16) (2023) 161901

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

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

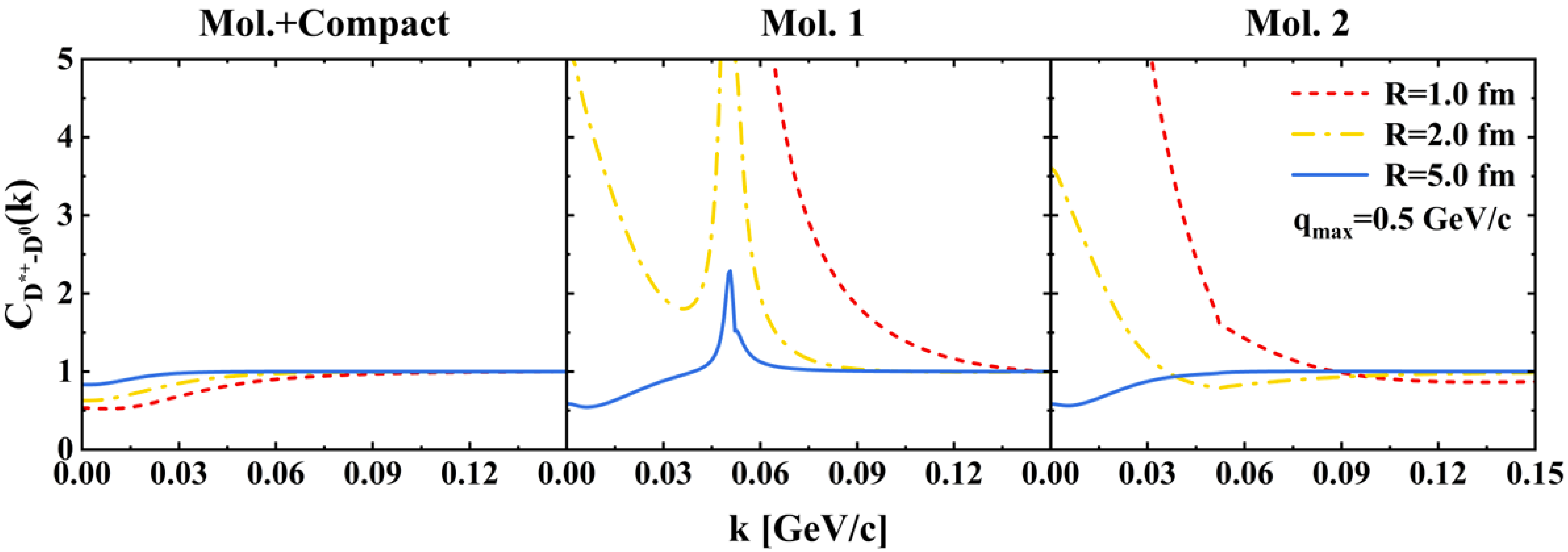
Shota Ampuku, Yasuhiro Yamaguchi, Masayasu Harada, *PRD*113(2026)L031505





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)