NSTAR 2026

Femtoscopy in revealing the nature of exotic hadrons

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Zhi-Wei Liu, Jun-Xu Lu, Ming-Zhu Liu, LSG*, PRD 108 (2023) L031503
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
Duo-Lun Ge, Zhi-Wei Liu, LSG*, PRD 114 (2026) 014054

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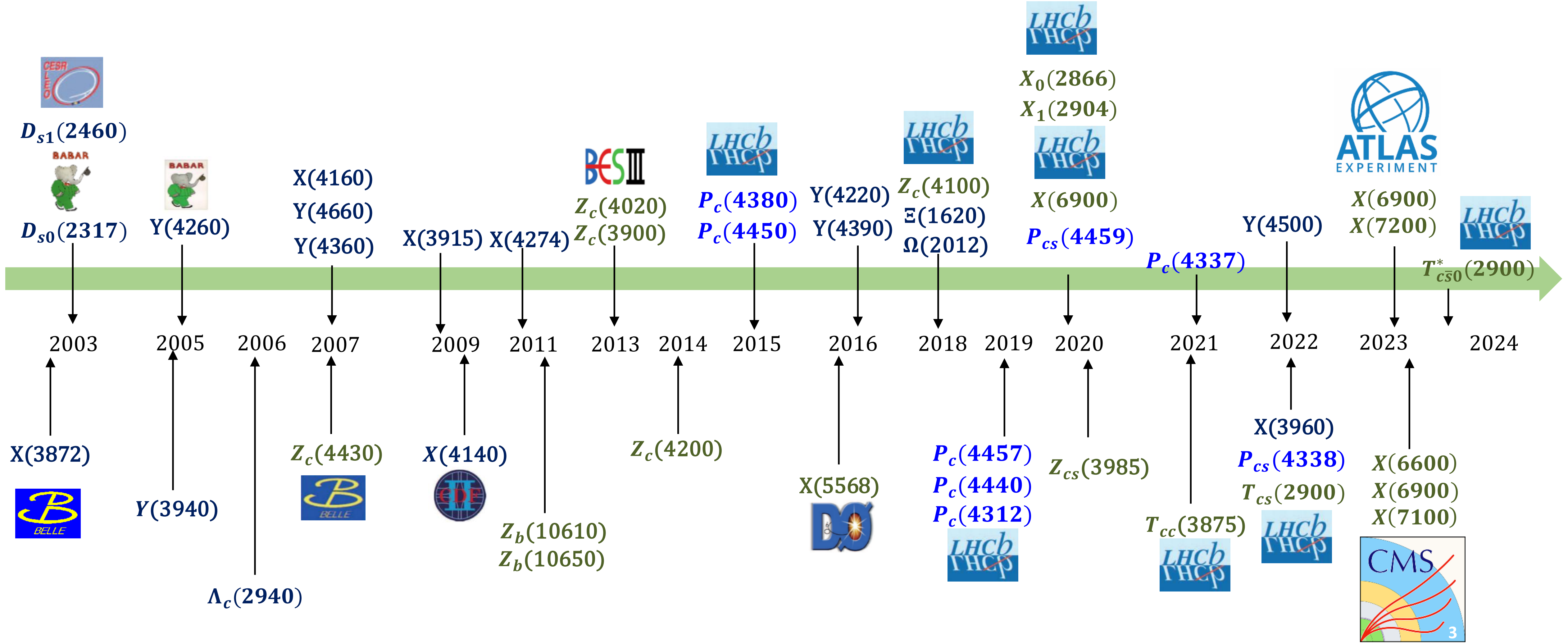
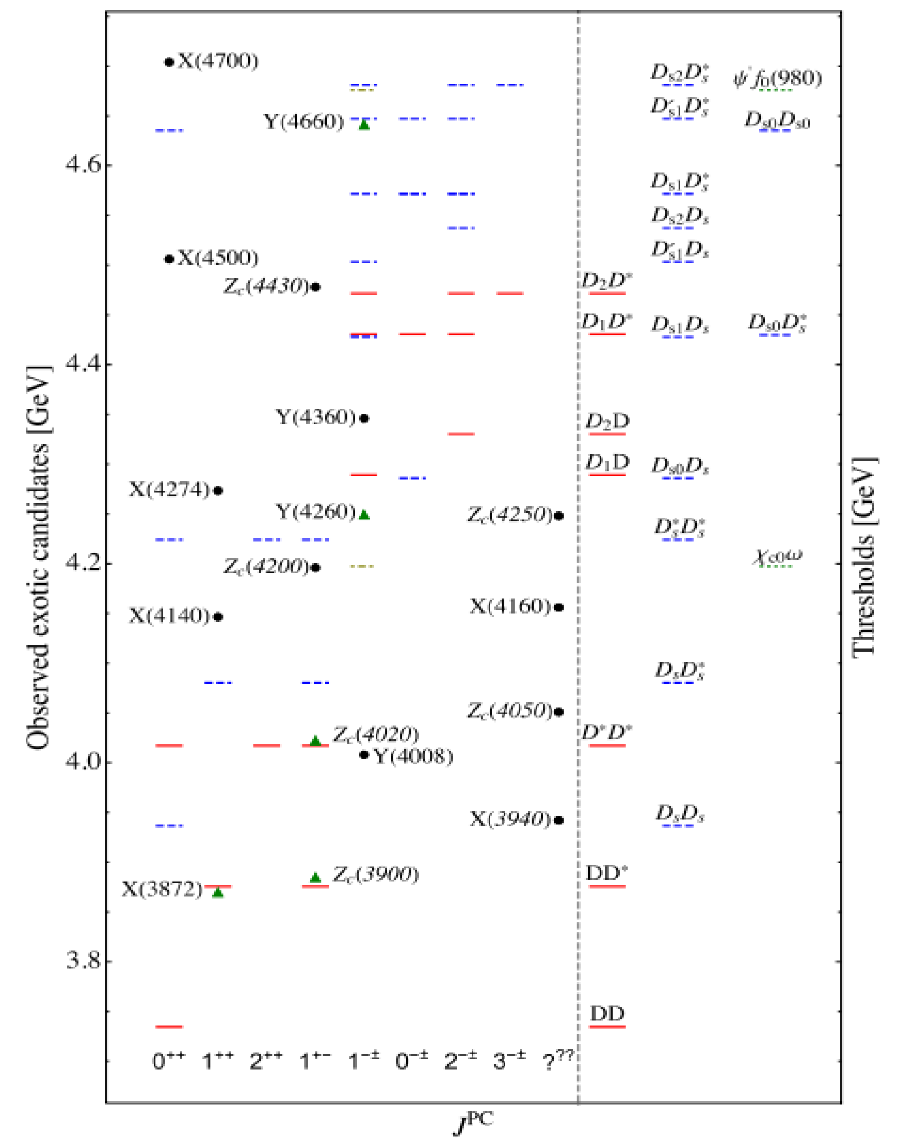
- ☞ Femtoscopic correlation functions (CFs)—general features
- ☞ Recent applications
  - ➢ $D_{s0}^{*}(2317)$, $Z_c(3900)$ and $Z_{cs}(3985)$, $Tcc(3875)$, $P_c(4440)$ and $P_c(4457)$
- ☞ Summary and outlook

Many so-called exotic hadrons discovered since 2003

Exotic mesons and baryons Tetraquarks Pentaquarks



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



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

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

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How to check the molecular picture?

How to check the molecular picture?

Probing the nature of the $\chi_{c1}(3872)$ state using radiative decays

LHCb collaboration†

Abstract

The radiative decays $\chi_{c1}(3872) \to \psi(2S)\gamma$ and $\chi_{c1}(3872) \to J/\psi\gamma$ are used to probe the nature of the $\chi_{c1}(3872)$ state using proton-proton collision data collected with the LHCb detector, corresponding to an integrated luminosity of $9\,\mathrm{fb}^{-1}$. Using the $B^+ \to \chi_{c1}(3872)K^+$ decay, the $\chi_{c1}(3872) \to \psi(2S)\gamma$ process is observed for the first time and the ratio of its partial width to that of the $\chi_{c1}(3872) \to J/\psi\gamma$ decay is measured to be

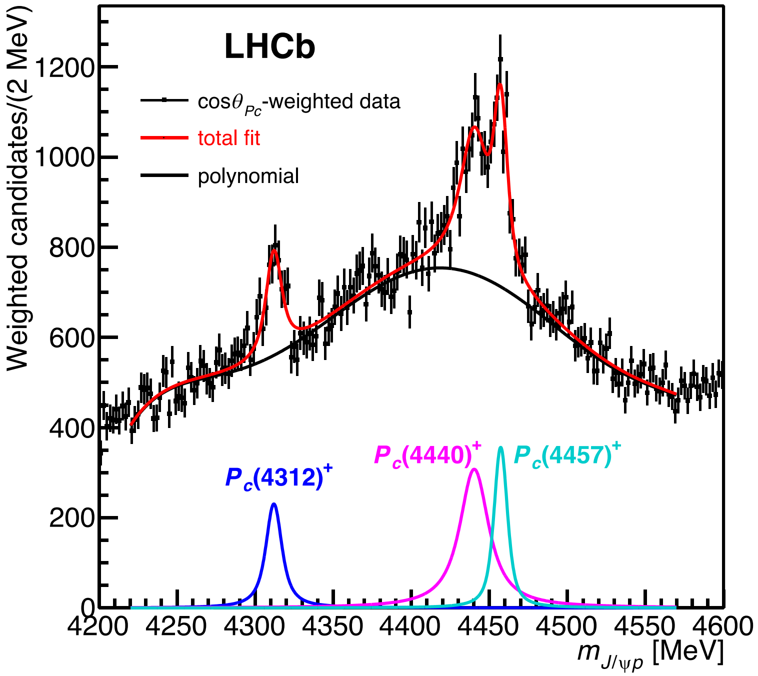
$$\frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04\,,$$

where the first uncertainty is statistical, the second systematic and the third is due to the uncertainties on the branching fractions of the $\psi(2S)$ and J/ψ mesons. The measured ratio makes the interpretation of the $\chi_{c1}(3872)$ state as a pure $D^0\overline{D}^{*0} + \overline{D}^0 D^{*0}$ molecule questionable and strongly indicates a sizeable compact charmonium or tetraquark component within the $\chi_{c1}(3872)$ state.

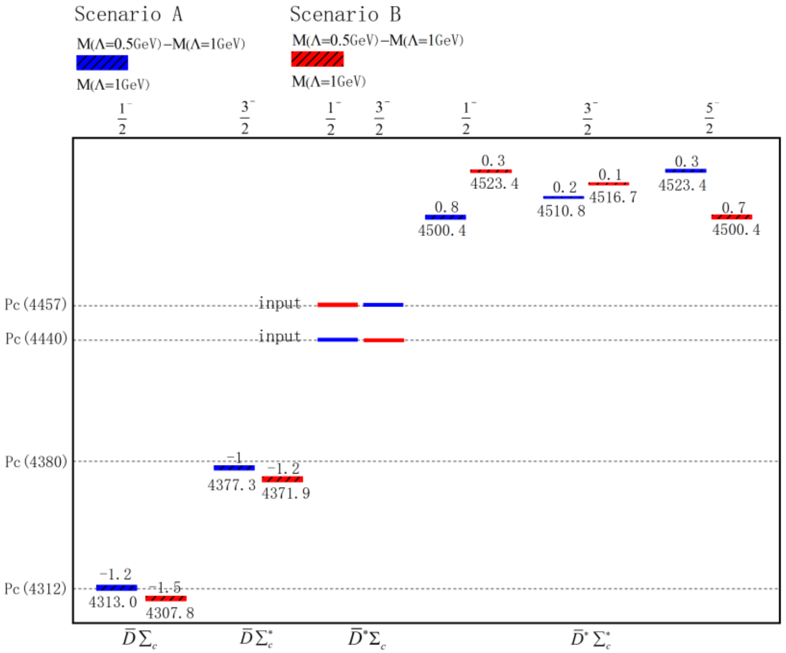
How to verify the molecular picture

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



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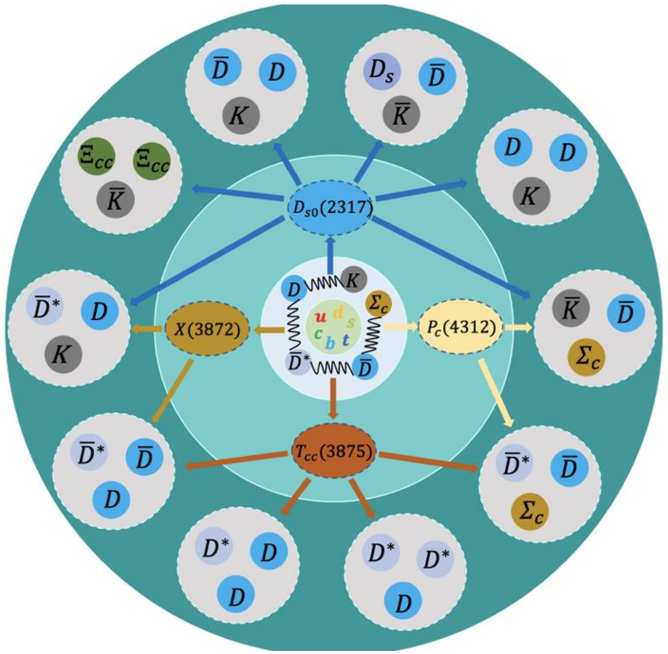
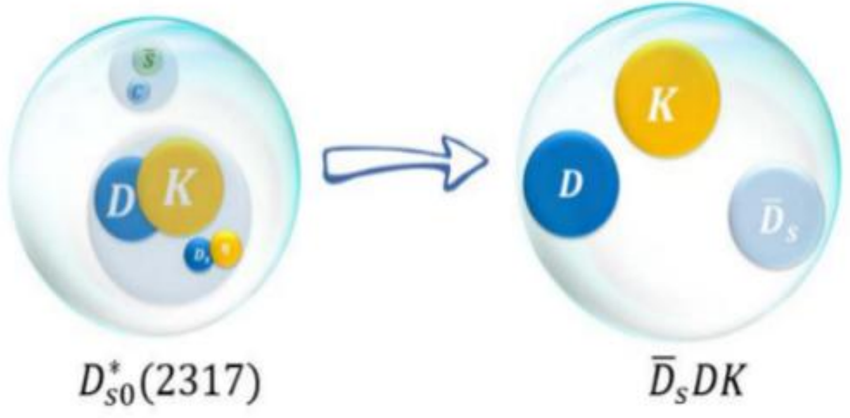
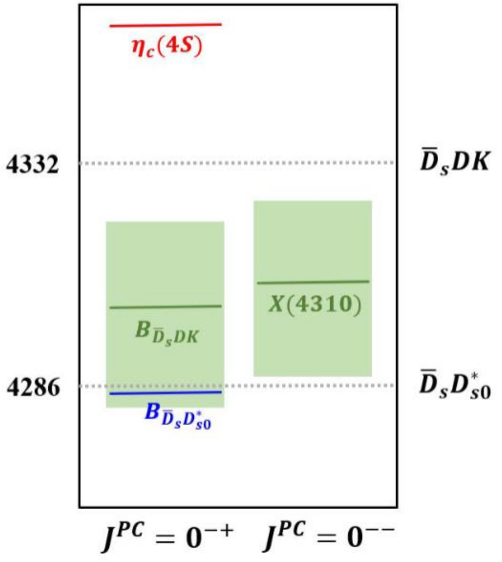
How to verify the molecular picture

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

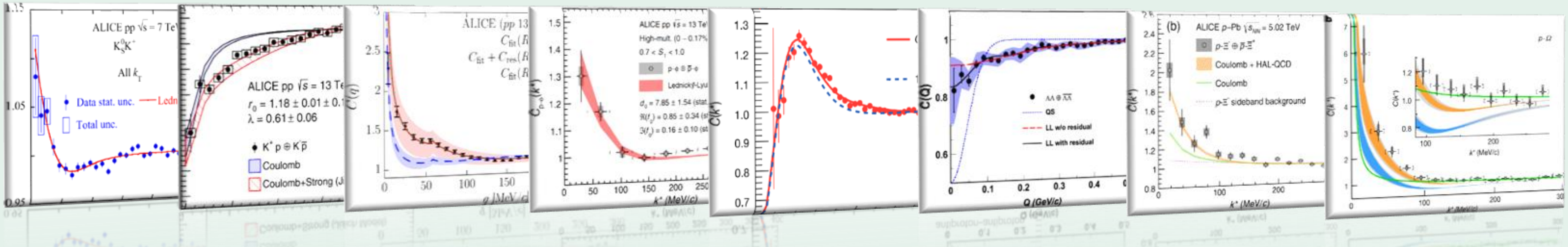
Ming-Zhu Liu, Ya-Wen Pan, Zhi-Wei Liu, Tian-Wei Wu, Jun-Xu Lu, **LSG***, Phys.Rept. 1108 (2025) 1-108

◻ 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 $\overline{p}\overline{p}$ $\Lambda\Lambda$ $\Xi^{-}p$ $\Omega^{-}p$



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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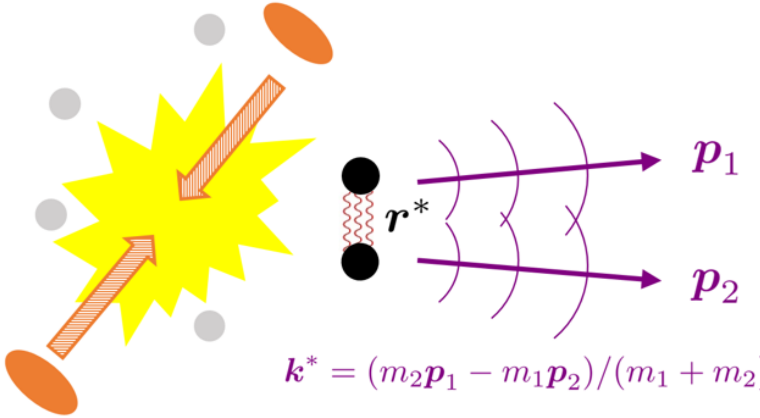
- ☞ **Summary and outlook**

Femtoscopic correlation functions (CFs)

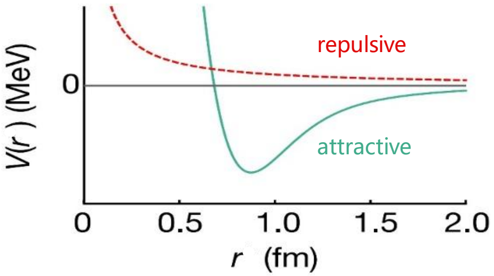
$$C(\boldsymbol{p}_1,\boldsymbol{p}_2) = \frac{\mathrm{P}(\boldsymbol{p}_1,\boldsymbol{p}_2)}{\mathrm{P}(\boldsymbol{p}_1)\cdot\mathrm{P}(\boldsymbol{p}_2)}$$



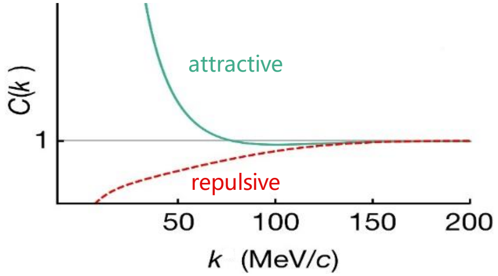
$\boldsymbol{k}^* = (m_2\boldsymbol{p}_1 - m_1\boldsymbol{p}_2)/(m_1+m_2)$

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

Interacting potential



Correlation function



Schrödinger equation

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

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

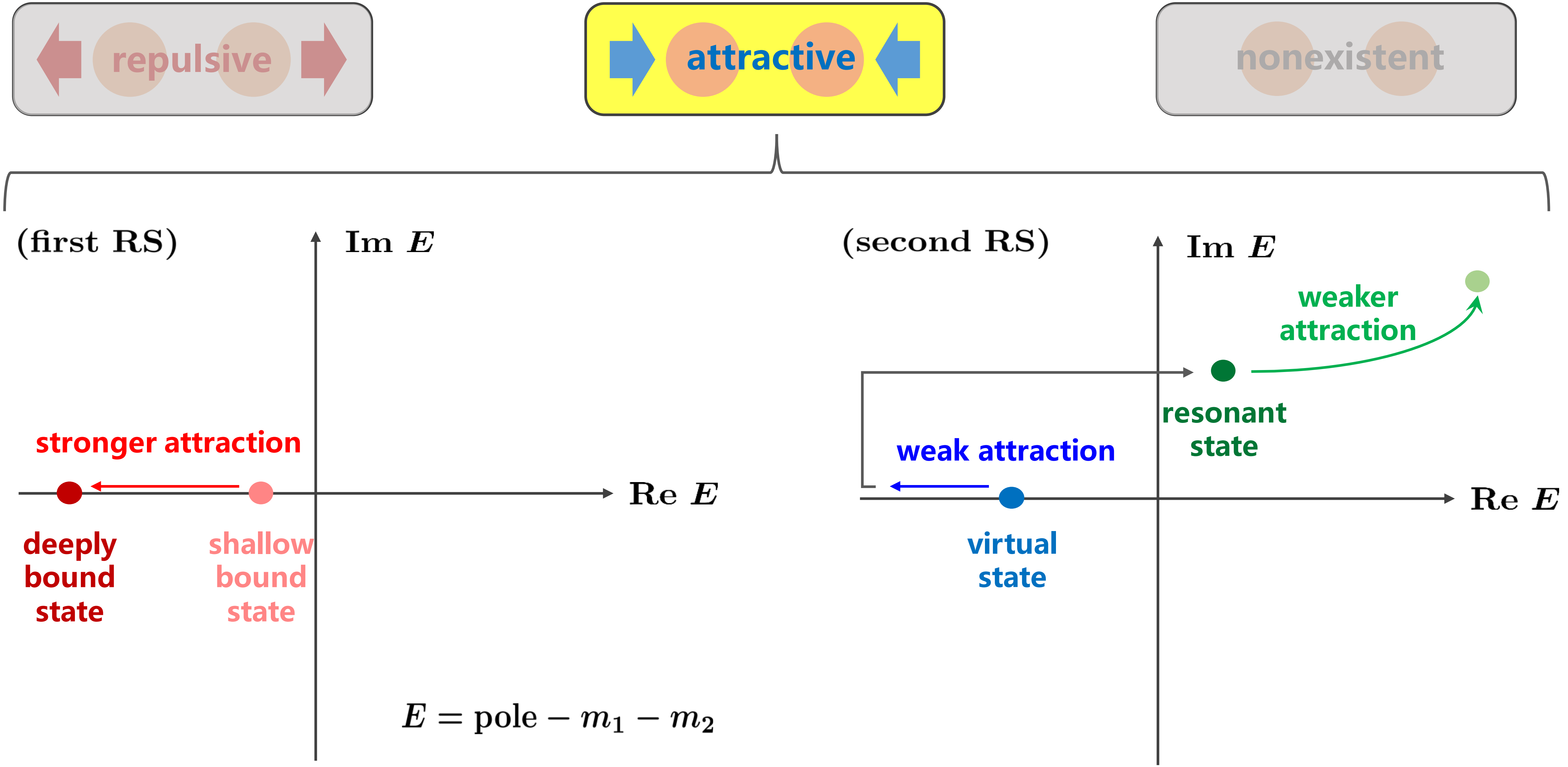
quantum statistics effects

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

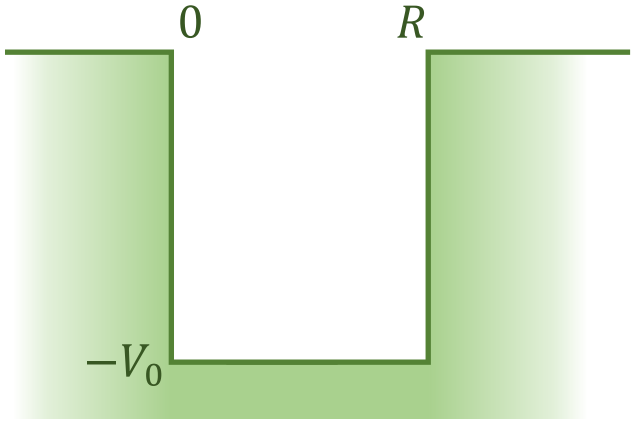
Classification of hadron-hadron interactions



CFs for interactions capable of generating bound states

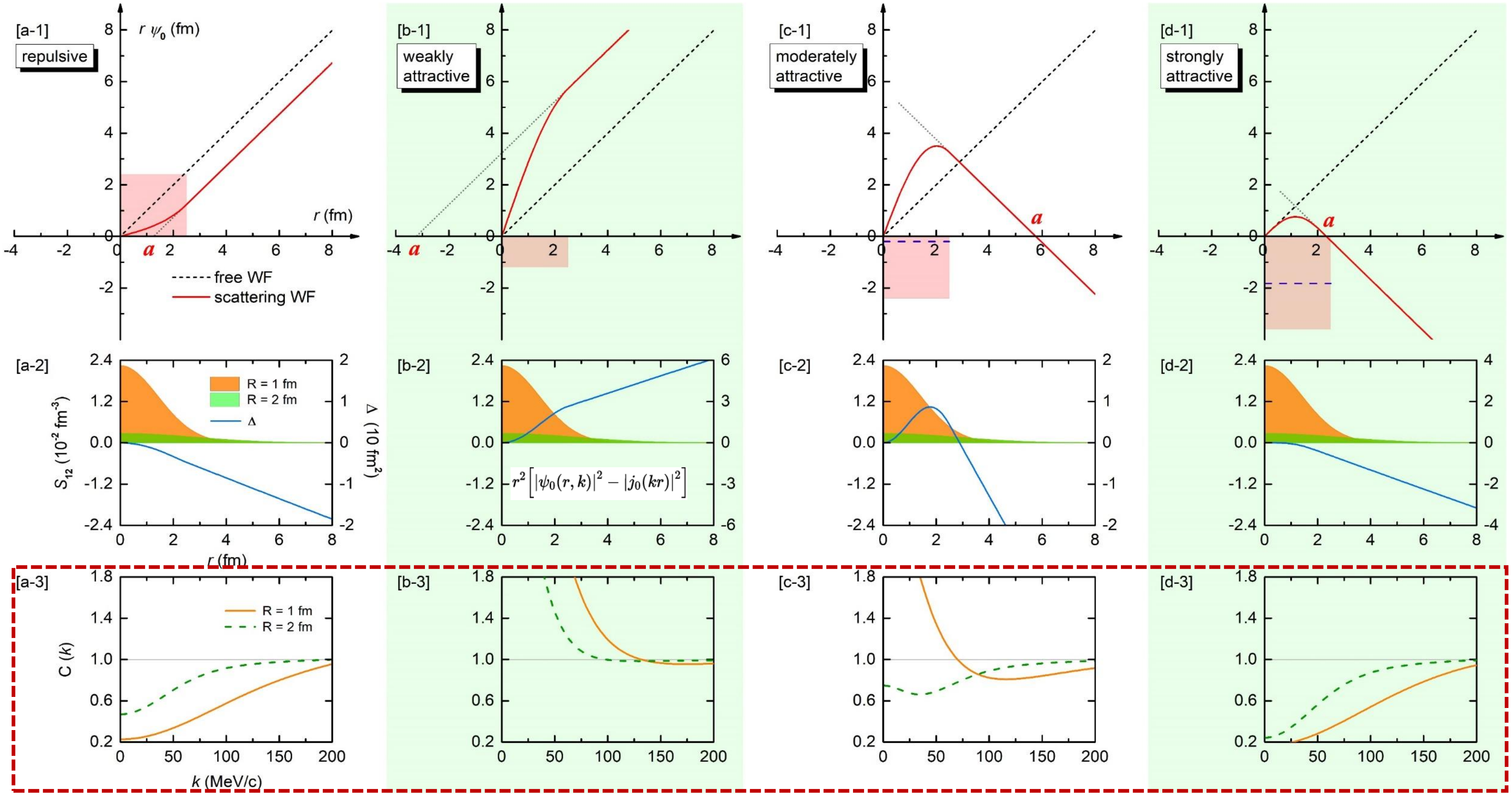
*Zhi-Wei Liu, Jun-Xu Lu and **LSG***, PRD 107, 074019 (2023)*

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

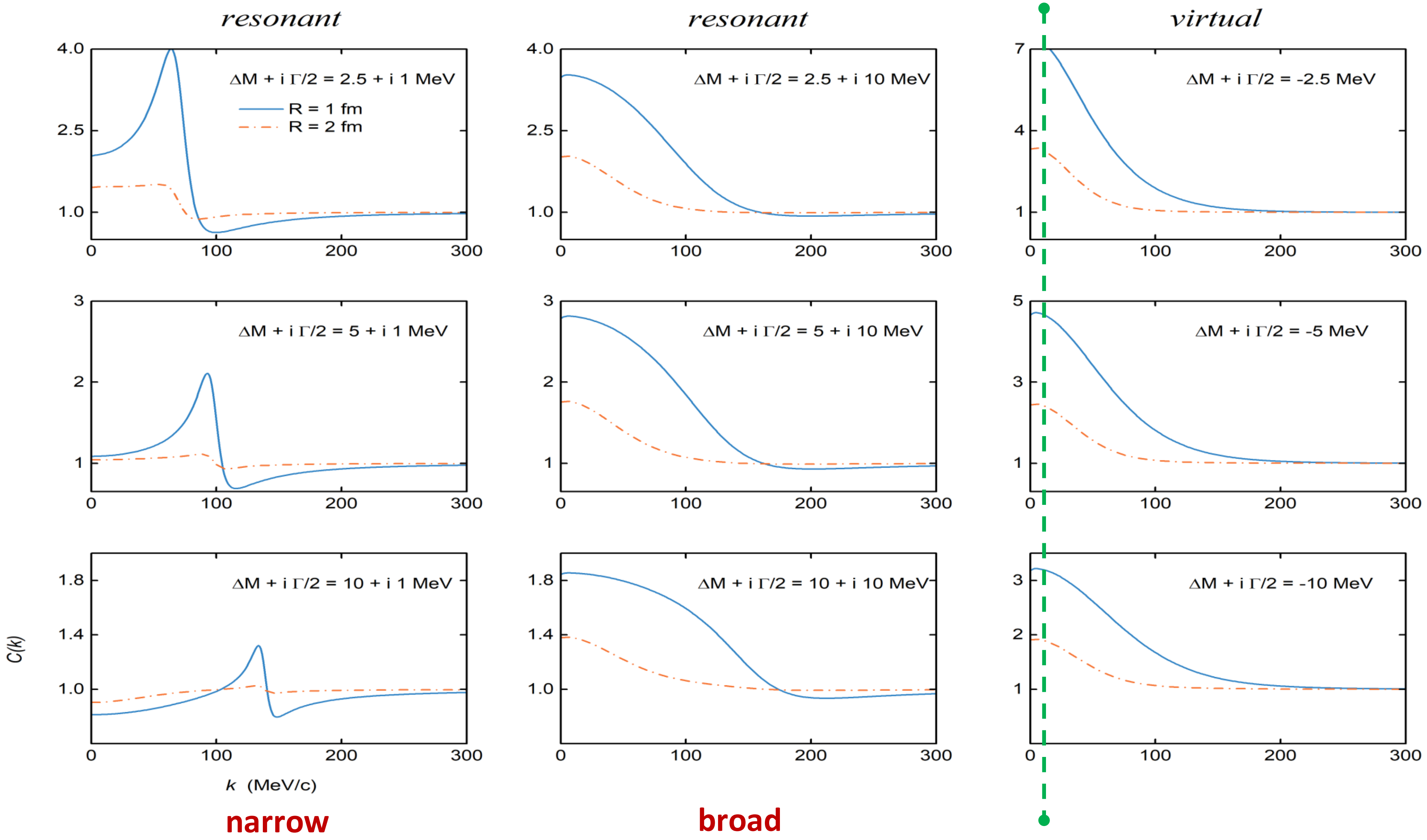
Zhi-Wei Liu, Ming-Zhu Liu, Jun-Xu Lu and LSG, Sci.Bull. 70 (2025) 3515-3521*

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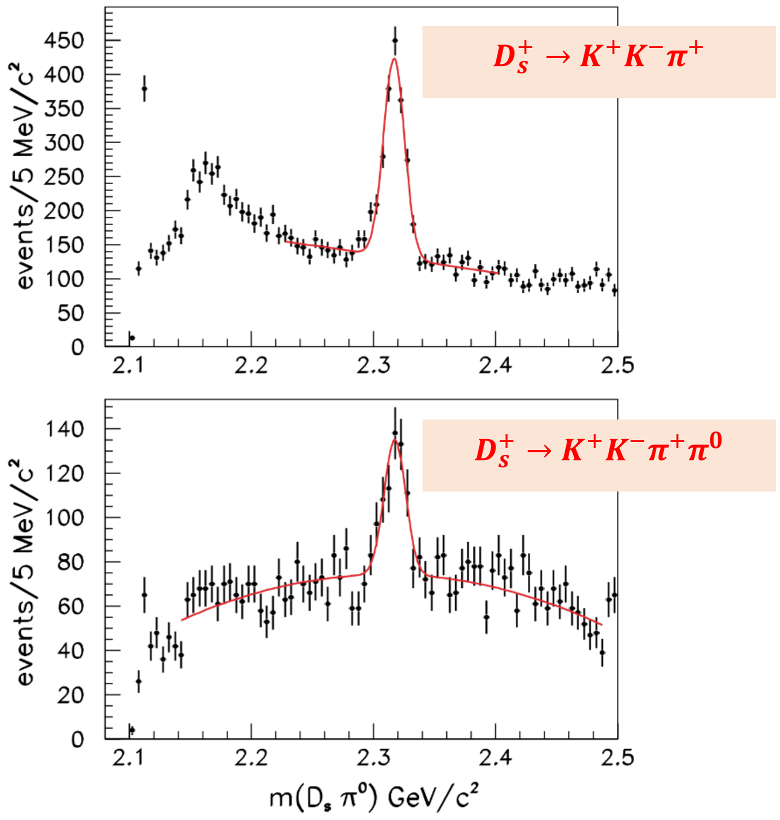
Mysterious exotic hadron $D_{s0}^{*}(2317)$

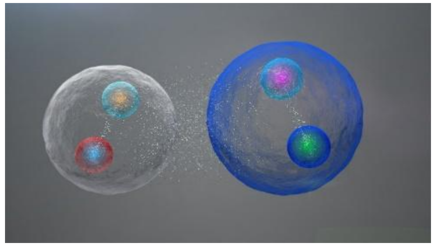
$\mathrm{M} = 2317.8 \pm 0.6$ and $\Gamma < 3.8$ MeV



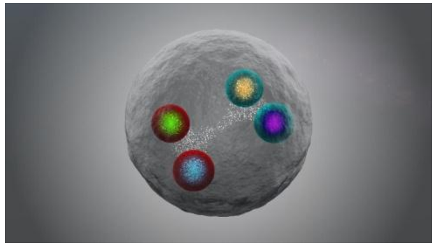
BABAR, PRL90 (2003) 242001

- **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



VS



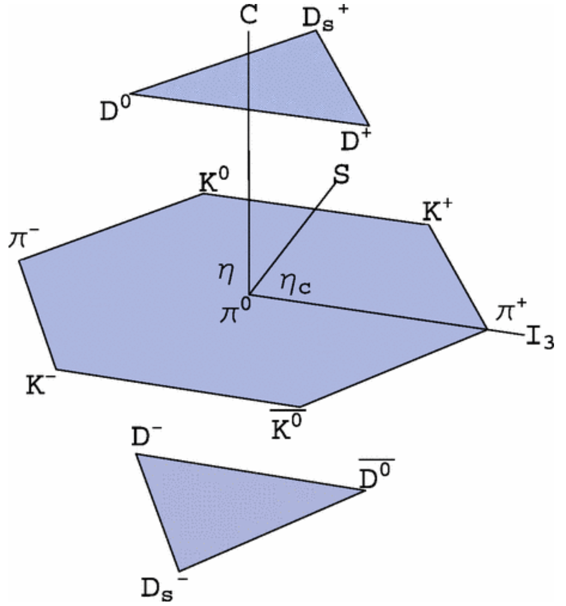
Weinberg-Tomozawa Interaction (leading order)

- **LO interaction between a NGB and a heavy pseudoscalar boson**

$$\mathcal{L} = \frac{1}{4f_\pi^2}\left(\partial^\mu P[\Phi, \partial_\mu \Phi]P^\dagger - P[\Phi, \partial_\mu \Phi]\partial^\mu P^\dagger\right)$$

$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

$$P = \left(D^0, D^+, D_s^+\right)$$

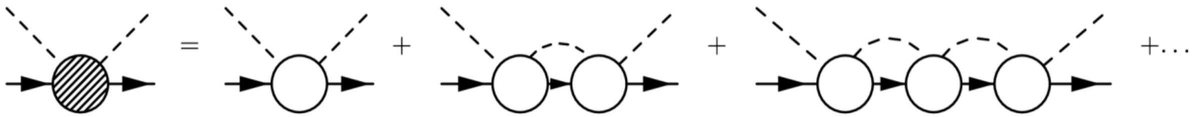


- **Weinberg-Tomozawa (WT) potential – parameter free**

$$V_{\nu'\nu} = \frac{C_{\nu'\nu}}{4f_0^2}\left[(p_1 + p_2)^2 - (p_1 - p_4)\right] \qquad p_{1(3)} = (E_{1(3)}, \boldsymbol{p}^{(\prime)}), \quad p_{2(4)} = (\sqrt{s} - E_{1(3)}, -\boldsymbol{p}^{(\prime)})$$

Scattering wave function

- **Coupled-channel scat. eq.**



$$T_{\nu'\nu}(k',k) = V_{\nu'\nu} \cdot f_{\Lambda_F}(k',k) + \sum_{\nu''} \int_0^\infty \frac{\mathrm{d}k'' k''^2}{8\pi^2} \frac{V_{\nu'\nu''} \cdot f_{\Lambda_F}(k',k'') \cdot T_{\nu''\nu}(k'',k)}{E_{P,\nu''} E_{\Phi,\nu''} (\sqrt{s} - E_{P,\nu''} - E_{\Phi,\nu''} + i\epsilon)}$$

$$f_{\Lambda_F}(k',k) = \exp\left[-\left(\frac{k'}{\Lambda_F}\right)^2 - \left(\frac{k}{\Lambda_F}\right)^2 \right]$$

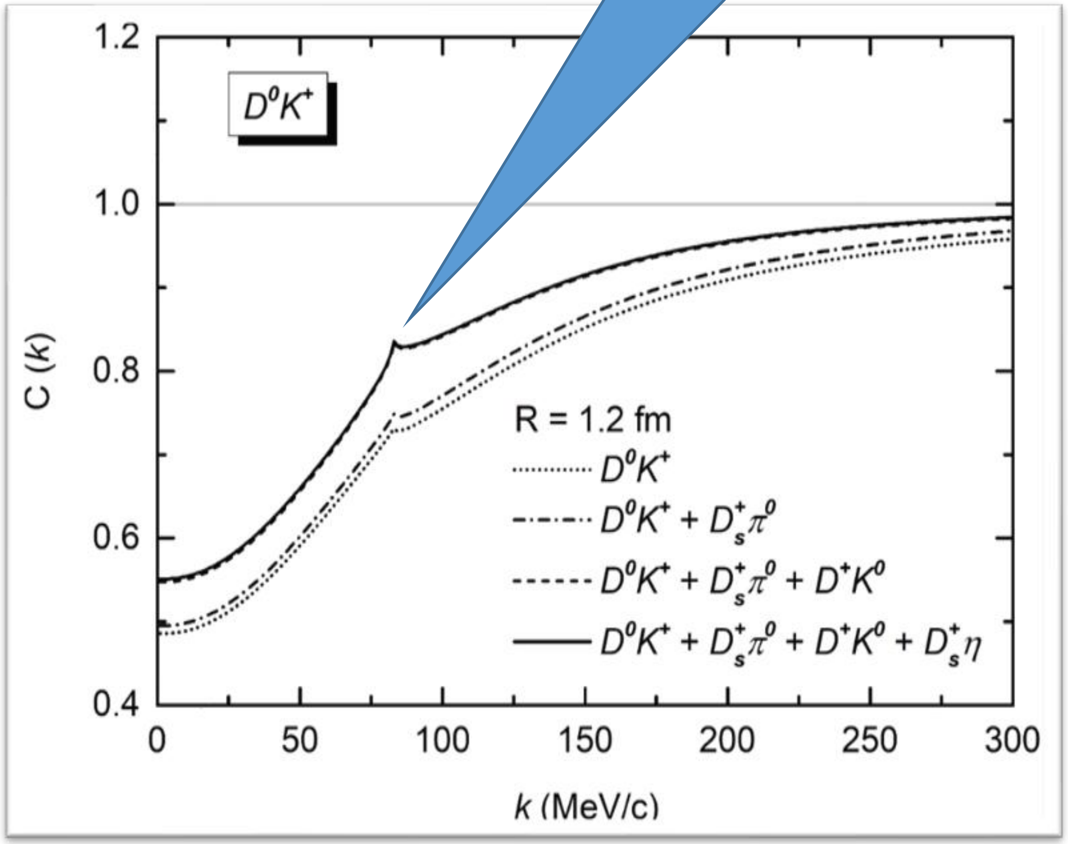
$$\boxed{M_{D^*_{s0}} = 2317.8 \text{ MeV} \rightarrow \Lambda_F = 1107 \text{ MeV}}$$

- **S-wave scattering wave function (including off-shell effect)**

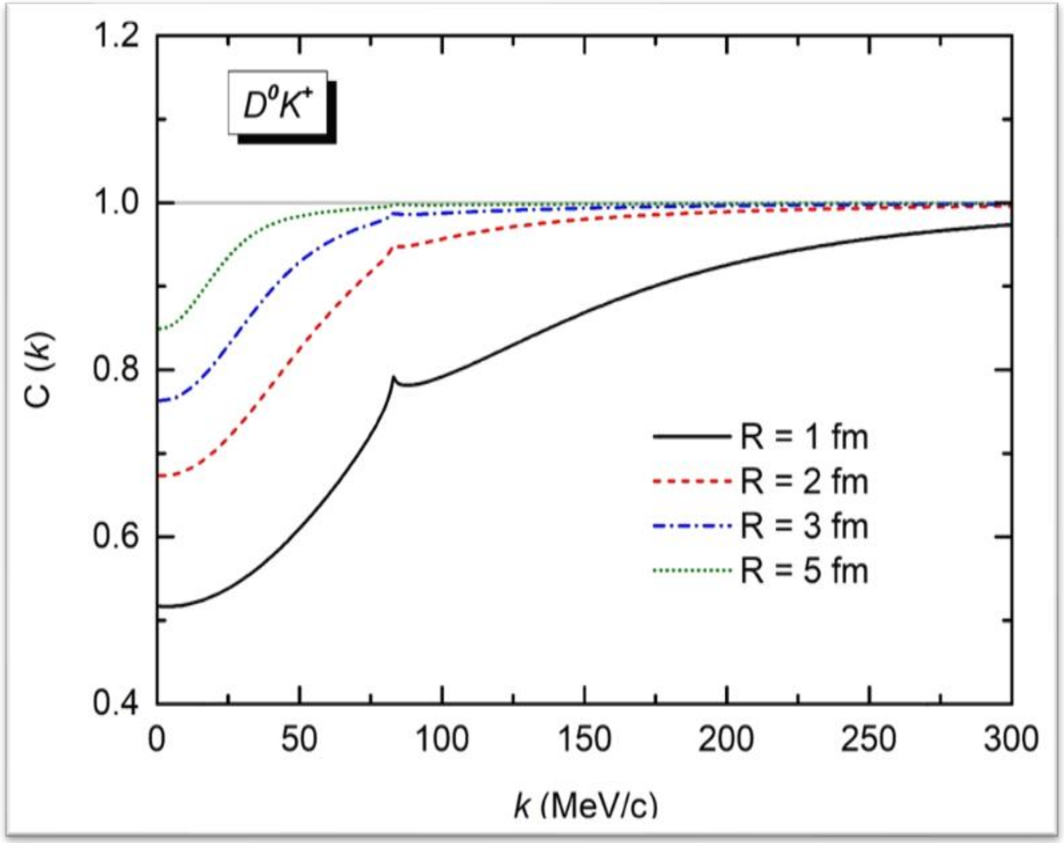
$$\psi_{\nu'\nu}(k,r) = \delta_{\nu'\nu} j_0(kr) + \int_0^\infty \frac{\mathrm{d}k' k'^2}{8\pi^2} \frac{T_{\nu'\nu}(k',k) \cdot j_0(k'r)}{E_{P,\nu'} E_{\Phi,\nu'} (\sqrt{s} - E_{P,\nu'} - E_{\Phi,\nu'} + i\epsilon)}$$

DK CFs and its source size dependence

$D^+K^0 \to D^0K^+$



Typical feature of deeply bound states



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

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  - ➢ $P_{\mathrm{c}}(4440)$ **and** $P_{\mathrm{c}}(4457)$
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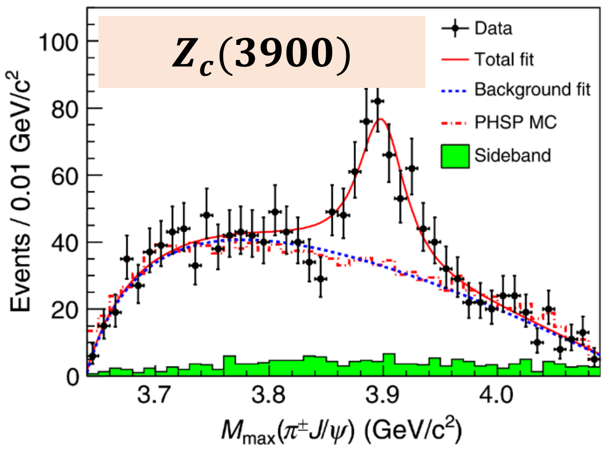
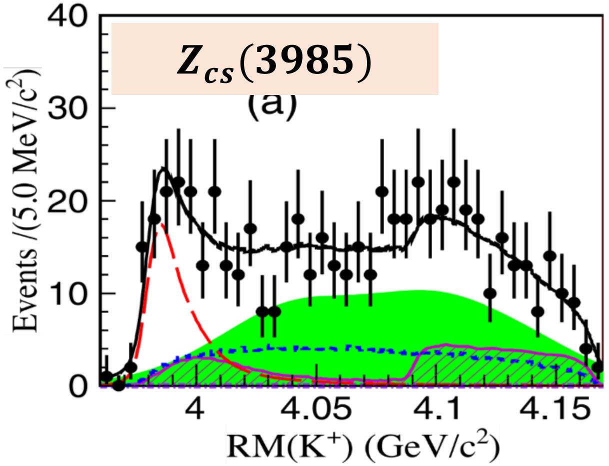
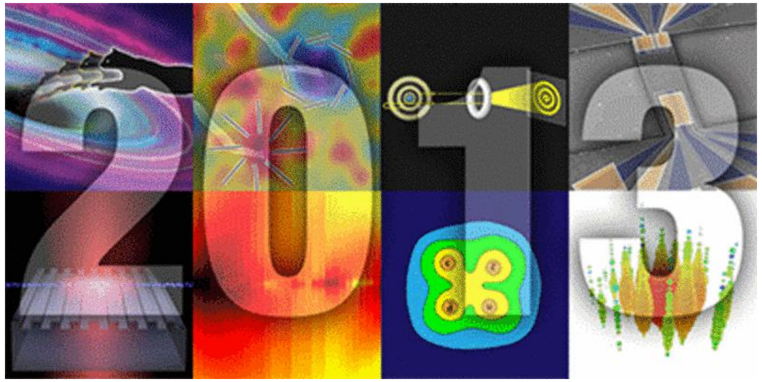
Tetraquark states $Z_c(3900)$ & $Z_{cs}(3985)$



BESIII, PRL110 (2013) 252001



BESIII, PRL126 (2021) 102001



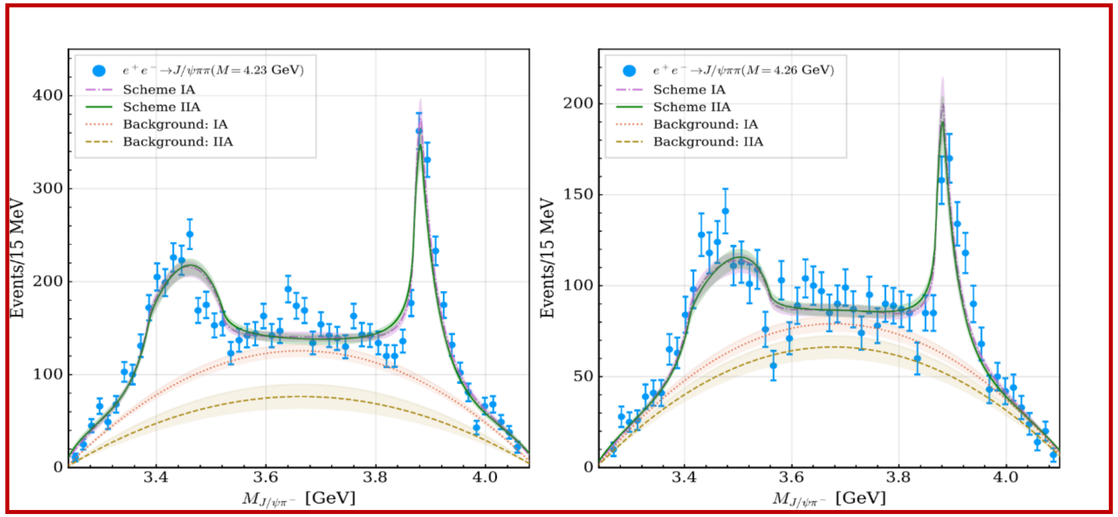
Tetraquark states • 2013 APS Highlights

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

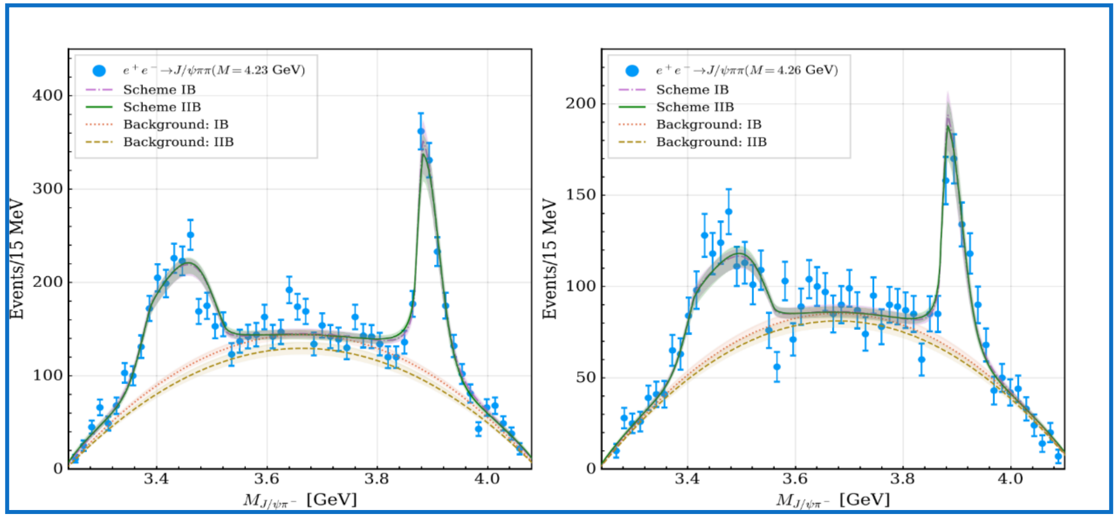
Particle Data Group, PTEP 2022 (2022) 083C01
M.-L. Du, M. Albaladejo, F.-K. Guo and J. Nieves, PRD 105 (2022) 074018
T. Ji, X.-K. Dong, M. Albaladejo, M.-L. Du, F.-K. Guo and J. Nieves, PRD106 (2022) 094002
L.-W. Yan, Z.-H. Guo, F.-K. Guo, D.-L. Yao and Z.-Y. Zhou, PRD109 (2024) 014026

Invariant mass distributions fail to distinguish vir. or res.

Virtual state scenario



Resonant state scenario



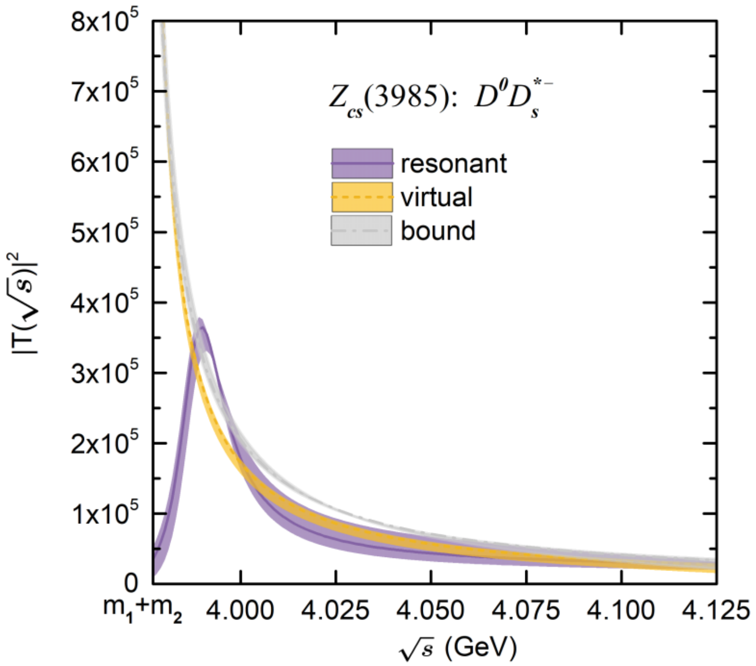
M.-L. Du, M. Albaladejo, F.-K. Guo, and J. Nieves, PRD105(2022)074018

Data are compatible with either a resonant or virtual state.

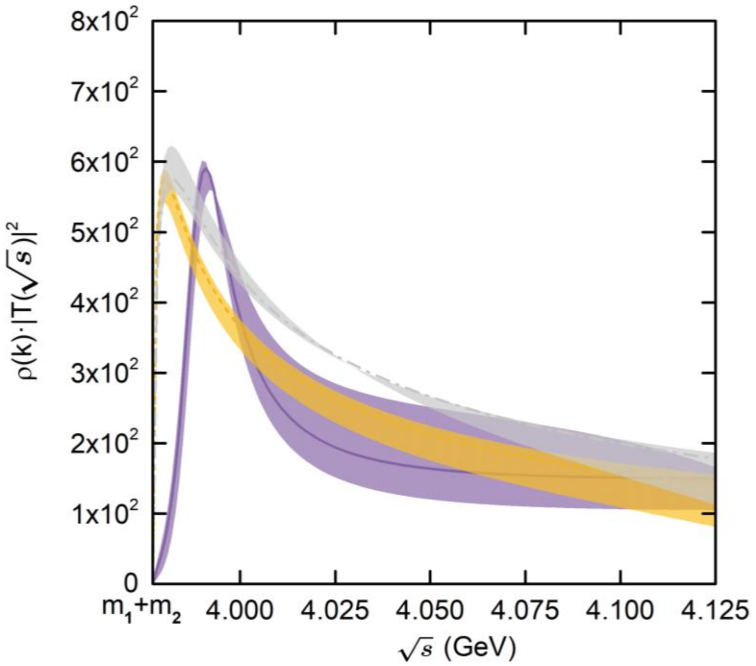
How to tell which is reality?

Phase-space suppression effect

Modulus squared of T-matrix



Line shape of invariant mass spectra

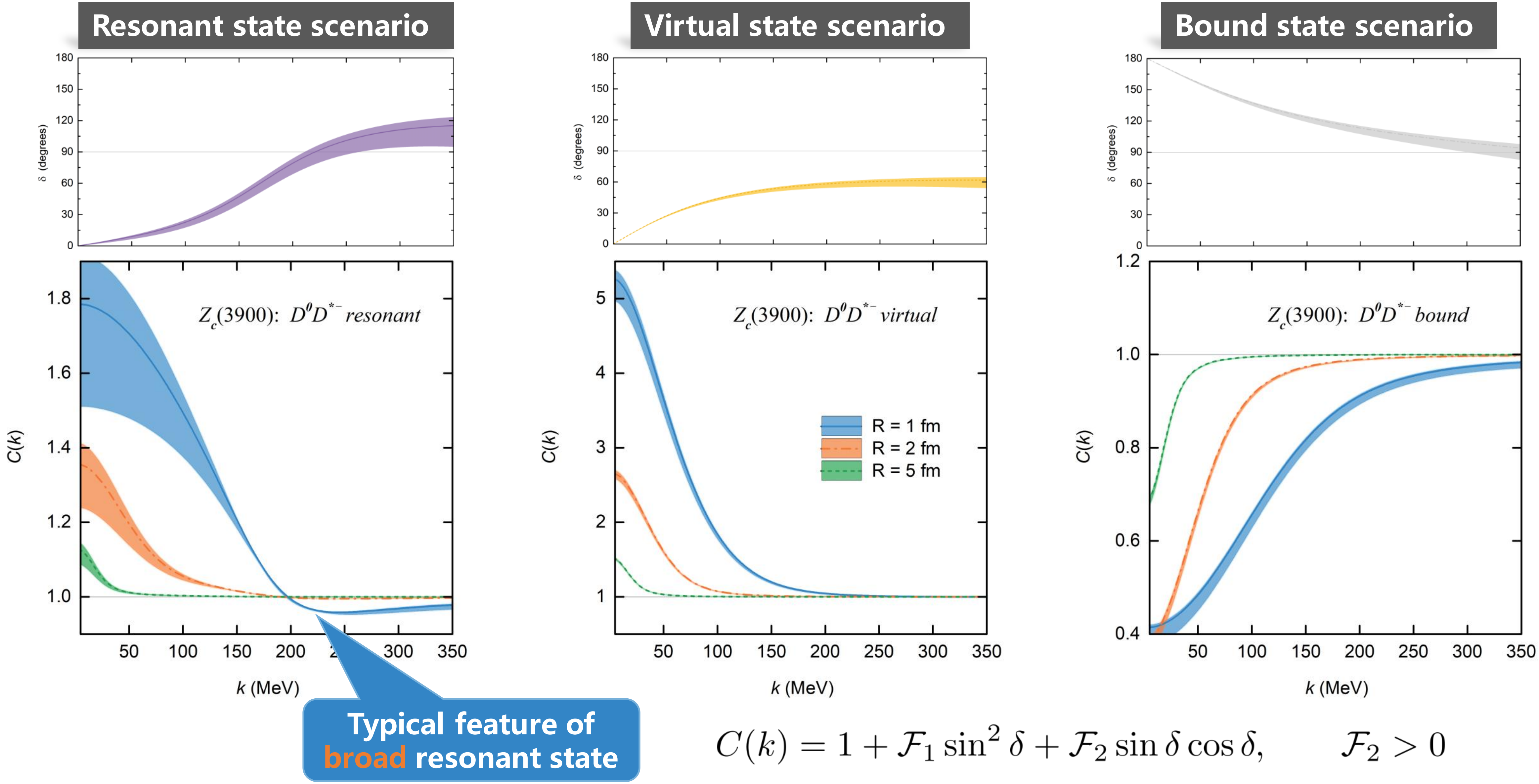


Phase-space suppression makes near-threshold states hard to distinguish using invariant mass spectra alone.

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

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

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

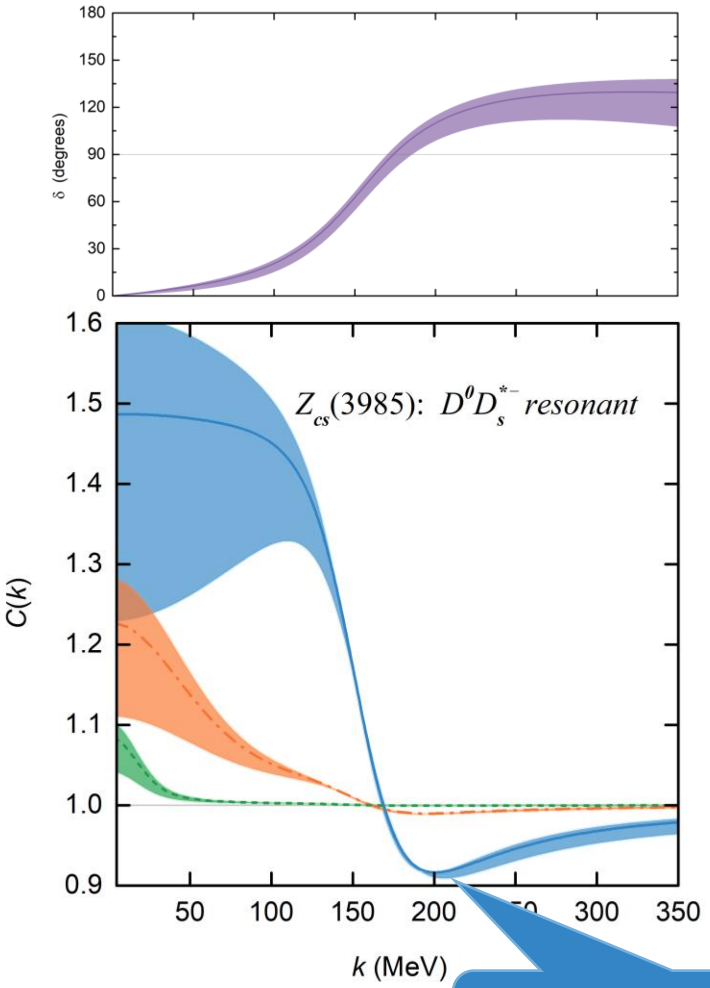


$$C(k) = 1 + \mathcal{F}_1 \sin^2\delta + \mathcal{F}_2 \sin\delta\cos\delta, \qquad \mathcal{F}_2 > 0$$

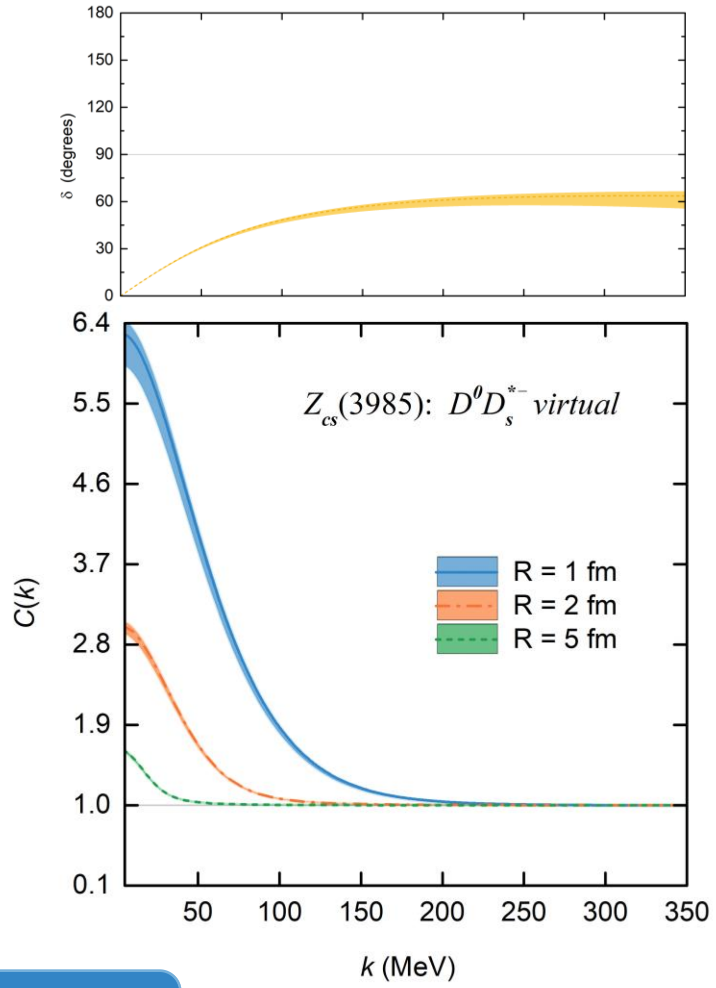
$D^0 D_s^{*-}$ CFs $Z_{cs}(3985)$

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

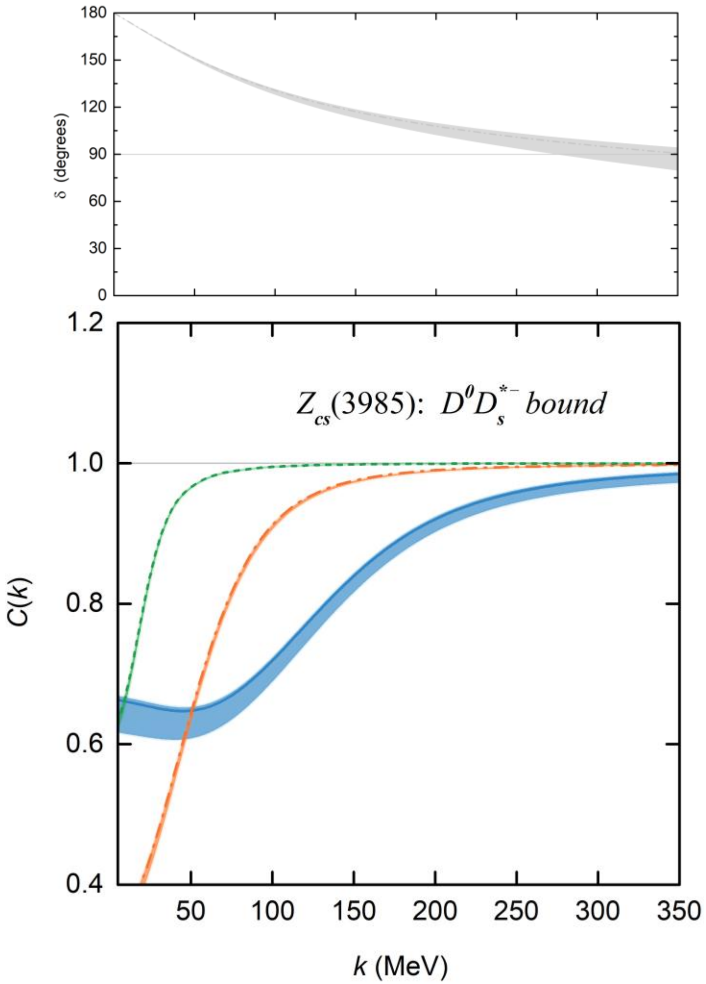
Resonant state scenario



Virtual state scenario



Bound state scenario



Typical feature of narrow resonant state

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

A femtoscopic tale of two C-parities: the $Z_c(3900)$ and the isovector partner of the $X(3872)$

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[2]Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100

[3]School of Physical Sciences, University of Chinese Academy of Sciences, Beijing

[4]Southern Center for Nuclear-Science Theory (SCNT), Institute of Modern Chinese Academy of Sciences, Huizhou 516000, China

Femtoscopy probes of Zc(3900) and Zcs(3985) and the isovector X(3872) partner

4:50 PM - 5:10 PM

Presenter Pan-Pan Shi

Understanding the nature of the exotic $Z_c(3900)$ and $Z_{cs}(3985)$ states, and search isovector partner W_{c1} of the $X(3872)$, remain central challenges in exotic-hadron spectrc the femtoscopic correlation functions (CFs) of the $D^{(*)0}D^{(*)-}_{(s)}$ systems. Since these charm-meson–antimeson pairs are not G-parity eigenstates, their CFs contain contributions from both the C-odd and C-even sectors, providing direct access to the dynamics underlying the Z_c, Z_{cs}, and the predicted isovector exotic W_{c1}. Within a heavy-quark-spin-symmetric coupled-channel framework, we show that the C-even admixture enhances the low-momentum CFs by more than 2.5σ in the vicinity of their thresholds. Free from Coulomb distortions and accessible in high-multiplicity pp collisions at the LHC, these channels offer the first direct femtoscopic probe of the isovector C-even sector and of the elusive W_{c1} state.

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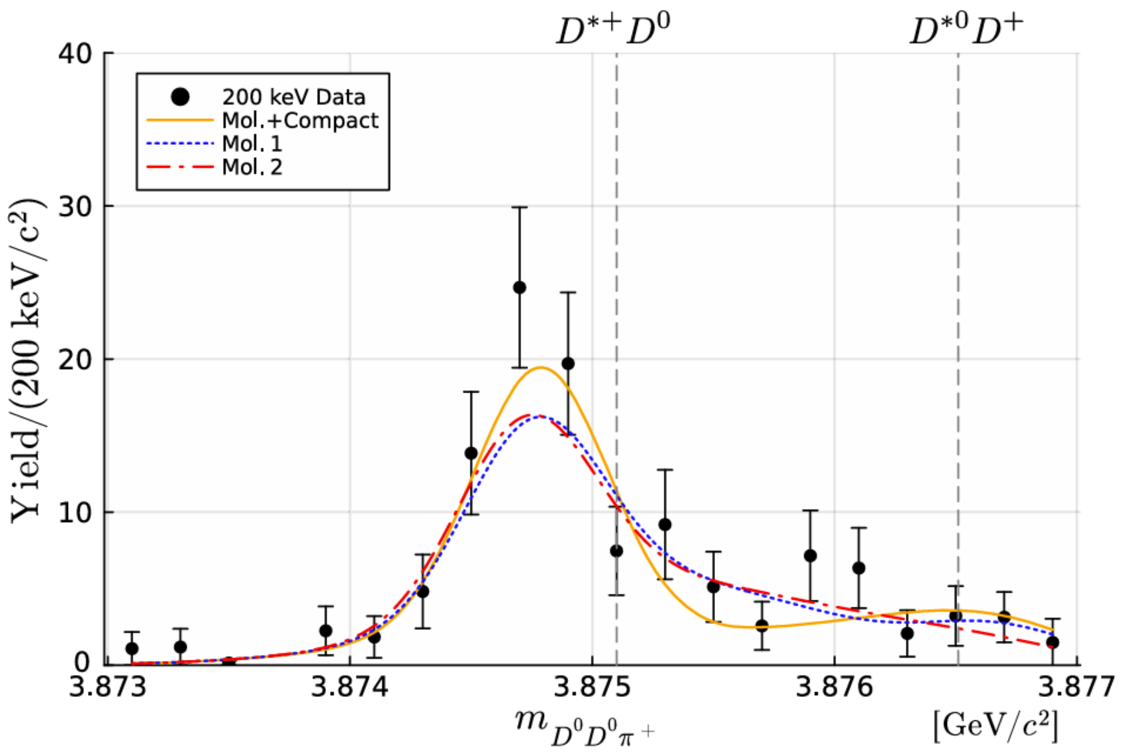
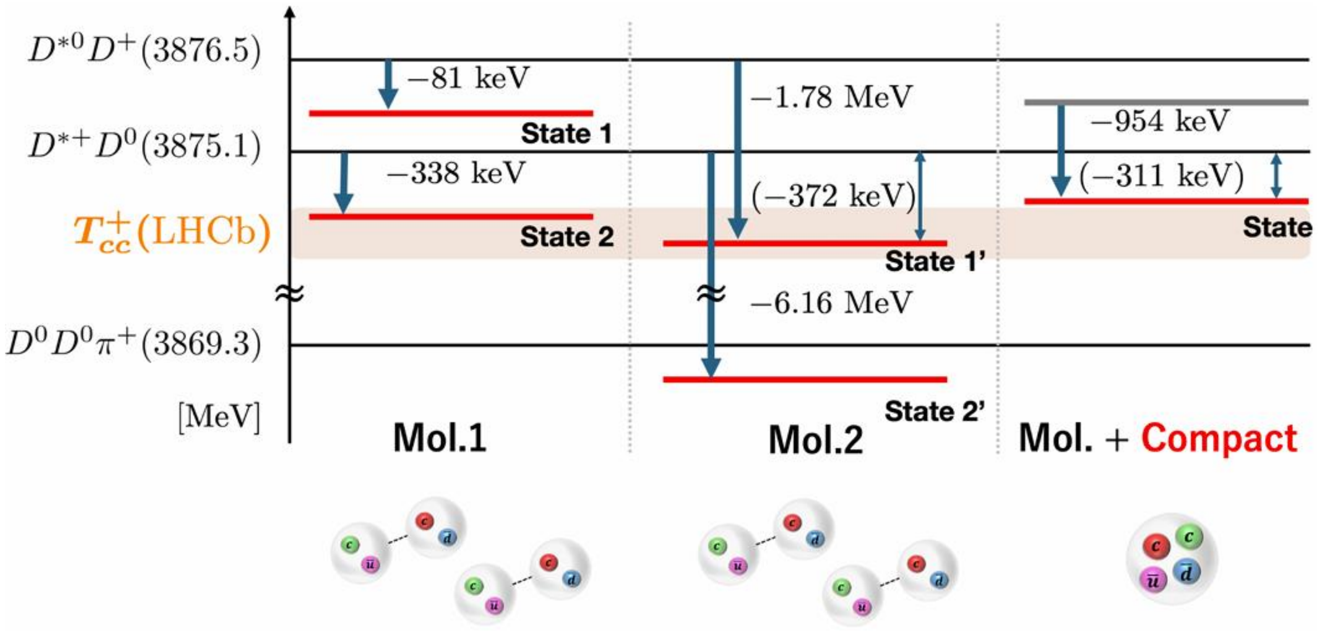
More recent applications—Tcc(3875)

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

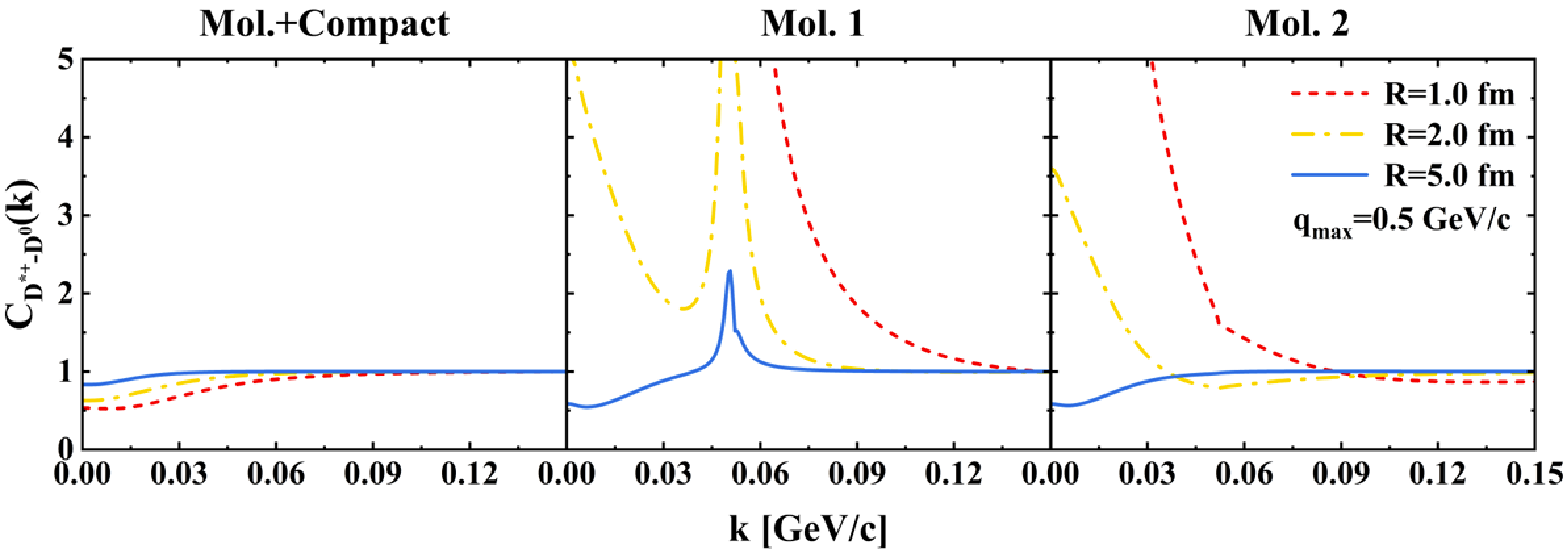
Shota Ampuku, Yasuhiro Yamaguchi, Masayasu Harada, 2511.13003





More recent applications—Tcc(3875)

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



Duo-Lun Ge, Zhi-Wei Liu, LSG, PRD 114 (2026) 014054*

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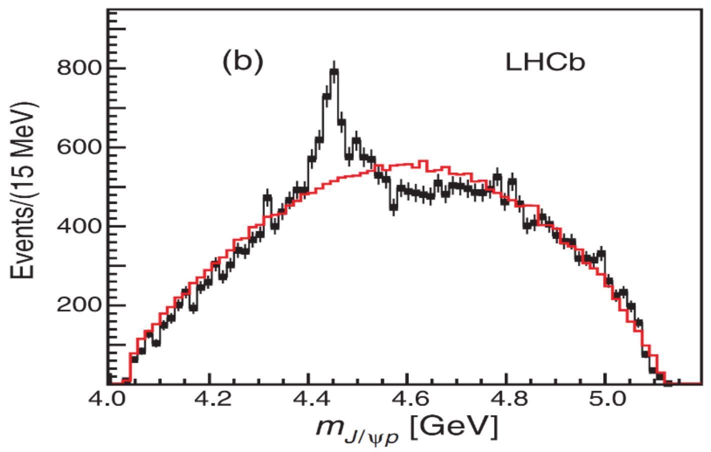
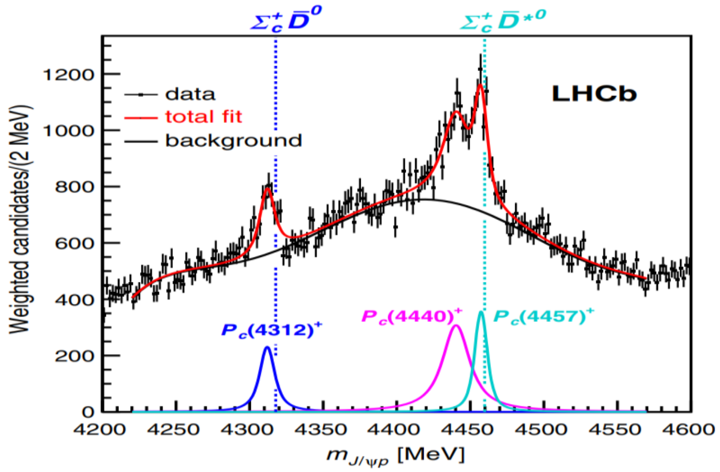
- ☞ **Summary and outlook**

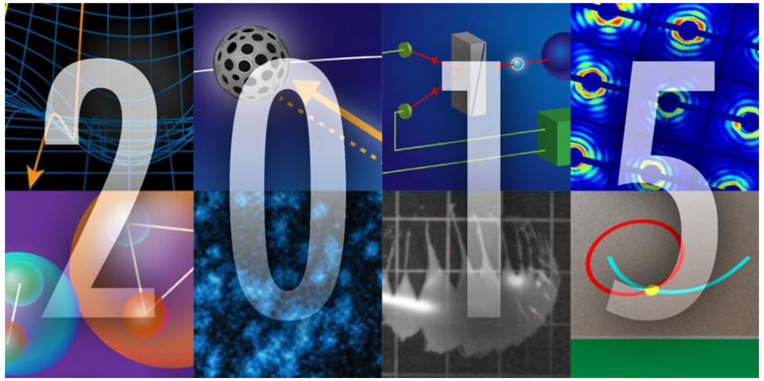
Pentaquark states $P_c(4440)$ & $P_c(4457)$



LHCb, PRL115 (2015) 072001



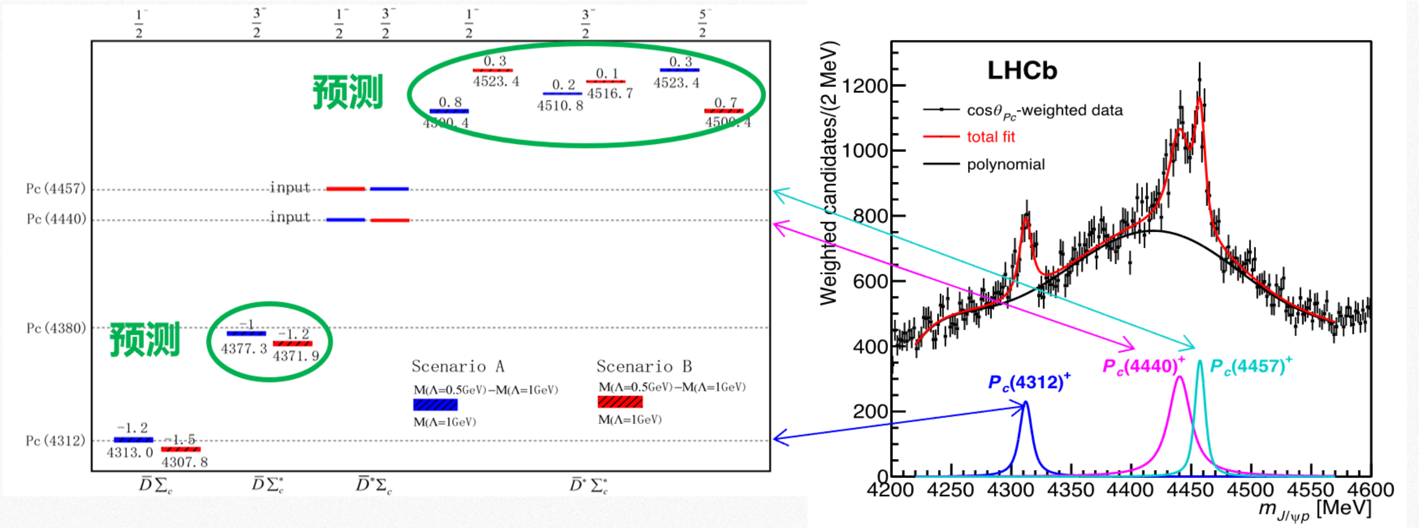
LHCb, PRL122 (2019) 222001



Pentaquark states • 2015 APS Highlights

- **They can be nicely arranged into a $\Sigma_c^{(*)}\bar{D}^{(*)}$ multiplet**

M. Z. Liu, Y. W. Pan, F. Z. Peng, M. Sánchez S, LSG, A. Hosaka, M. P. Valderrama, PR122 (2019) 242001*



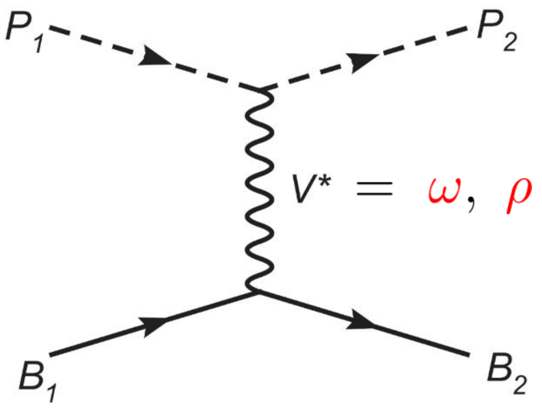
How to distinguish the spins of $P_c(4440)$ and $P_c(4457)$?

Light vector meson exchange interactions

☐ Interactions in the hidden local symmetry approach – parameter free

$$V^{I=\frac{3}{2}}_{\Sigma_c\bar{D}^{(*)}} = 2M_{\Sigma_c}M_{\bar{D}^{(*)}}\widetilde{\beta}_1\widetilde{\beta}_2 g_V^2\left(\frac{1}{m_\omega^2}+\frac{1}{m_\rho^2}\right)$$

$$V^{I=\frac{1}{2}}_{\Sigma_c\bar{D}^{(*)}} = 2M_{\Sigma_c}M_{\bar{D}^{(*)}}\widetilde{\beta}_1\widetilde{\beta}_2 g_V^2\left(\frac{1}{m_\omega^2}-\frac{2}{m_\rho^2}\right)$$



Isospin basis

↕

Charge basis

$$\left|\Sigma_c\bar{D}^{(*)}, I=\frac{3}{2}, I_3=\frac{1}{2}\right\rangle = \sqrt{\frac{1}{3}}\left|\Sigma_c^{++}D^{(*)-}\right\rangle + \sqrt{\frac{2}{3}}\left|\Sigma_c^{+}\bar{D}^{(*)0}\right\rangle$$

$$\left|\Sigma_c\bar{D}^{(*)}, I=\frac{1}{2}, I_3=\frac{1}{2}\right\rangle = \sqrt{\frac{2}{3}}\left|\Sigma_c^{++}D^{(*)-}\right\rangle - \sqrt{\frac{1}{3}}\left|\Sigma_c^{+}\bar{D}^{(*)0}\right\rangle$$

Two different spin assignments

◻ Interaction strengths

$$f_{\Lambda_F}(k',k) = \exp\left[-\left(\frac{k'}{\Lambda_F}\right)^2 - \left(\frac{k}{\Lambda_F}\right)^2\right]$$

$\Lambda_F = 1067$ MeV

deep bound state of $\Sigma_c \bar{D}^*$

$P_c(4440)^+$ Status: *

$P_c(4440)^+$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$4440.3 \pm 1.3^{+4.1}_{-4.7}$	AAIJ	19W	LHCB	pp at 7, 8, 13 TeV

$\Lambda_F = 860$ MeV

shallow bound state of $\Sigma_c \bar{D}^*$

$P_c(4457)^+$ Status: *

$P_c(4457)^+$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$4457.3 \pm 0.6^{+4.1}_{-1.7}$	AAIJ	19W	LHCB	pp at 7, 8, 13 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$4449.8 \pm 1.7 \pm 2.5$	AAIJ [1]	15P	LHCB	Repl. by AAIJ 19W

[1] Considering $P_c(4440)$ and $P_c(4457)$ as a single resonance.

CF for the shallow bound state is **significantly larger** than that for the deep bound

◻ Experimental CFs – spin-averaged

Scenarios A

$$\mathrm{P_c(4440)} : \mathrm{J^P} = (1/2)^- \qquad \mathrm{P_c(4457)} : \mathrm{J^P} = (3/2)^-$$

$$\bar{\mathrm{C}} = 1/3 \cdot \mathrm{C_{deep}} + 2/3 \cdot \mathrm{C_{shallow}}$$

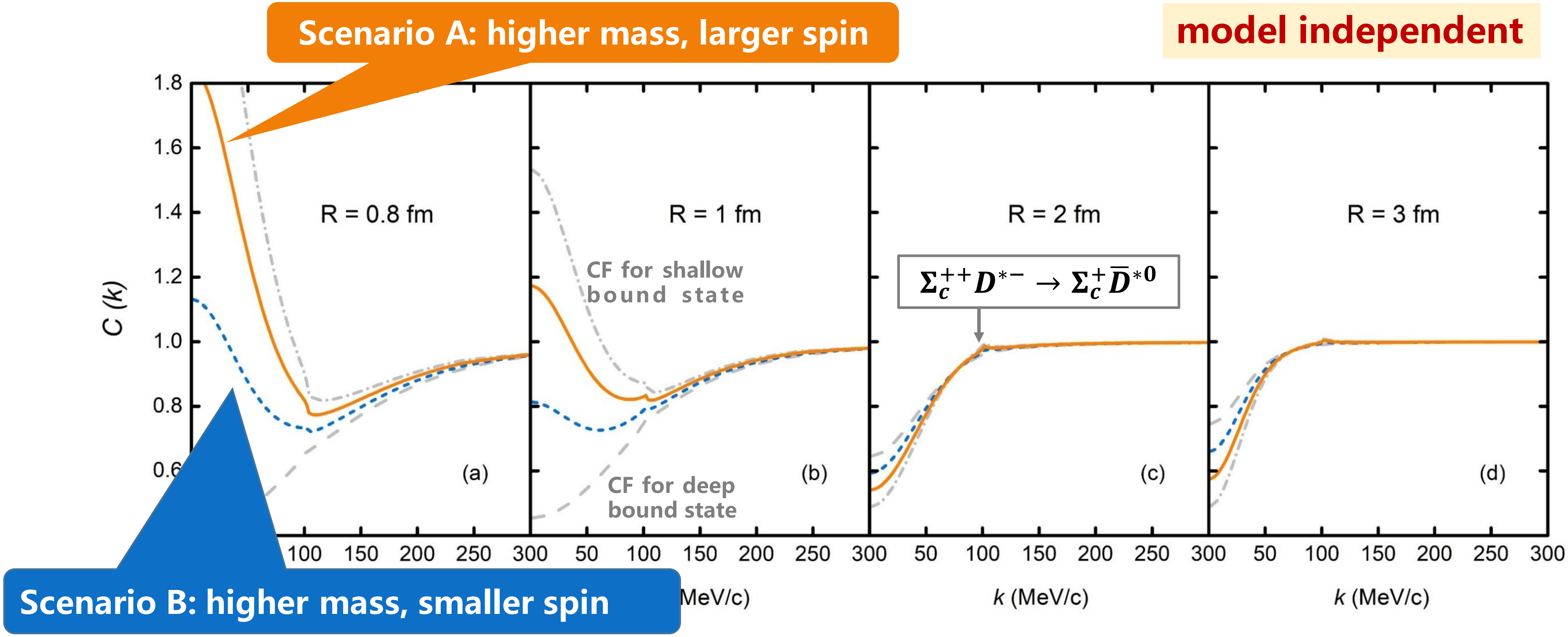
Scenarios B

$$\mathrm{P_c(4440)} : \mathrm{J^P} = (3/2)^- \qquad \mathrm{P_c(4457)} : \mathrm{J^P} = (1/2)^-$$

$$\bar{\mathrm{C}} = 2/3 \cdot \mathrm{C_{deep}} + 1/3 \cdot \mathrm{C_{shallow}}$$

Spin-averaged $\Sigma_c \bar{D}^*$ CFs

model independent



*Zhi-Wei Liu, Ming-Zhu Liu, Jun-Xu Lu and **LSG****, *PRD108(2023)L031503*

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- ☞ **Summary and outlook**

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.**
  - ✓ $D^*_{s0}(2317)$, $Z_c(3900)$ **and** $Z_{cs}(3985)$, $Tcc(3875)$, $P_c(4440)$ **and** $P_c(4457)$

- **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)