QNP2024, Facultat de Biologia, Universitat de Barcelona, 2024.07.08-12

北京航空航天大學
BEIHANG UNIVERSITY

The femtoscopic technique
—an invaluable tool in studies of exotic hadrons

Li-Sheng Geng（耿立升）@ Beihang U.

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Zhi-Wei Liu, Jun-Xu Lu, Ming-Zhu Liu, **LSG*,** PRD 108(2023)L031503

Zhi-Wei Liu, Jun-Xu Lu, Ming-Zhu Liu, **LSG*,** 2404.18607

Ming-Zhu Liu, Ya-Wen Pan, Zhi-Wei Liu, Tian-Wei Wu, Jun-Xu Lu, **LSG*,** 2404.06399

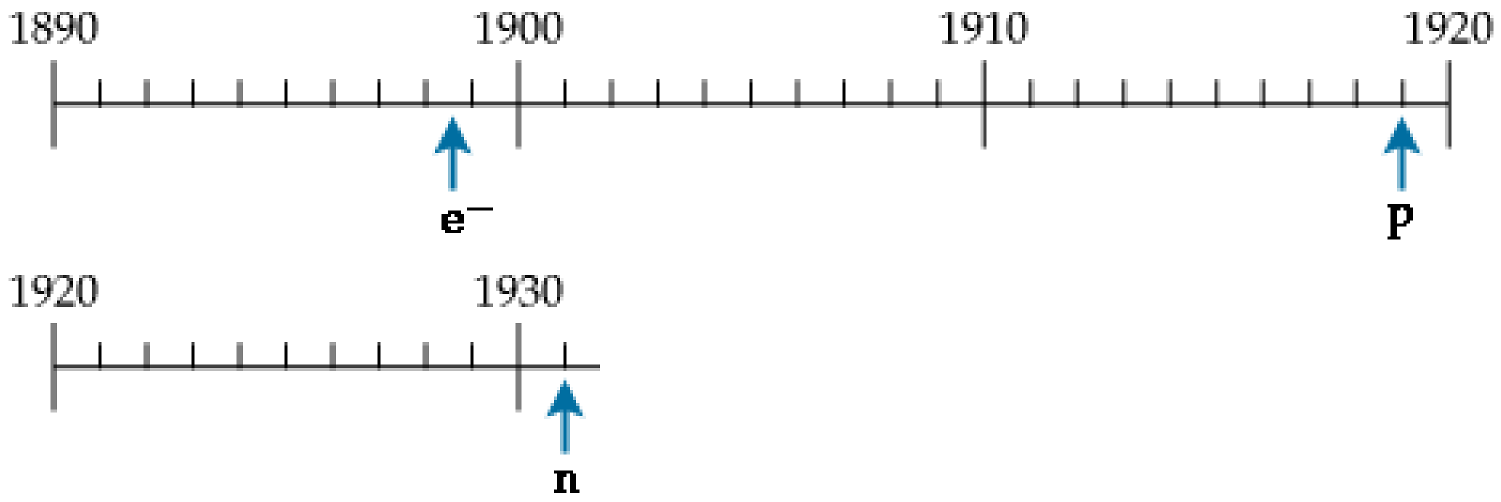
Related 6 talks and 4 posters

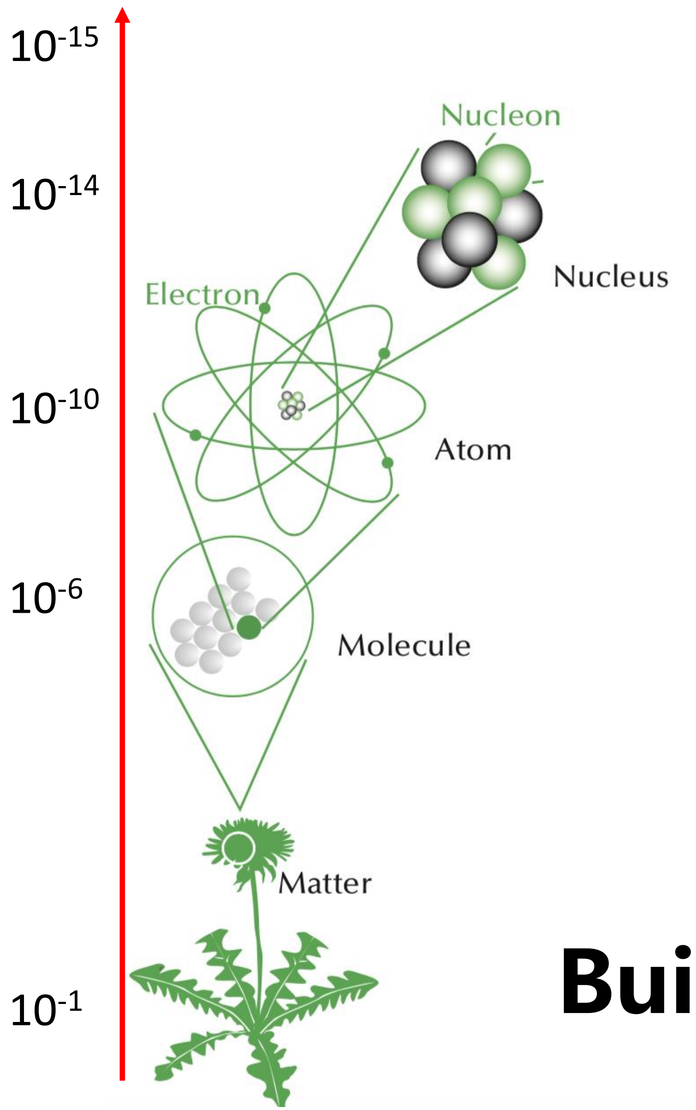
1. Poster: Aula Magna , 11:00-11:30, Monday, Addressing the pΩ femtoscopy correlation function using baryon-baryon effective potentials,
2. M5: Oton Vazquez Doce, 16:50-17:10, Monday, Novel constraints for the multi-strange meson-baryon interaction using correlation measurements with ALICE
3. M5: Maximilian Korwieser, 17:10-17:30, Monday First measurement of the $\rho^{0}\mbox{--}\mathrm{p}$ correlation function with ALICE
4. M2: Luciano Abreu, 17:55-18:15, Monday, Can femtoscopic correlation function shed light on the nature of the lightest, charm, axial mesons?
5. Poster: Pablo Encarnacion, 11:00-11:30, Tuesday, Femtoscopy study of $\pi^-\Lambda$ and $K^- p$ interactions
6. M4: Alejandro Canoa Monsalve, 17:15-17:35, Tuesday, Description of femtoscopic correlations with realistic pion-kaon interactions: the kappa/K0*(700) case
7. Poster: Álvaro Peña Almazán, 11:00-11:30, Wednesday, Approach to meson-baryon femtoscopy correlation functions using effective field theories
8. Poster: Marta Botella Garcia, 11:00-11:30, Wednesday, Dynamically generated resonances in the Lambda K- correlation function
9. **M3, Eulogio Oset, 17:15-17:35, Thursday, Correlation functions for the Ds(2317) and N*(1535)**
10. **Plenary: Laura Fabbietti, 10:20-11:00, Friday, Can we measure genuine three body interactions with femtoscopy?**

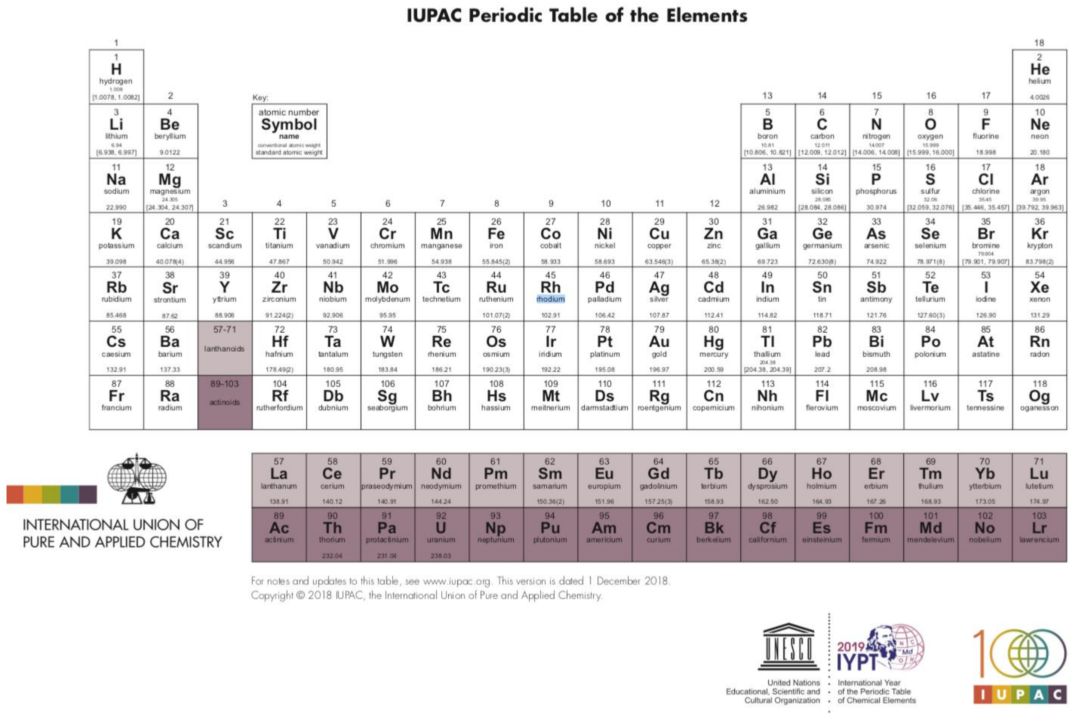
Contents

The world was once very simple

Particles discovered before 1932

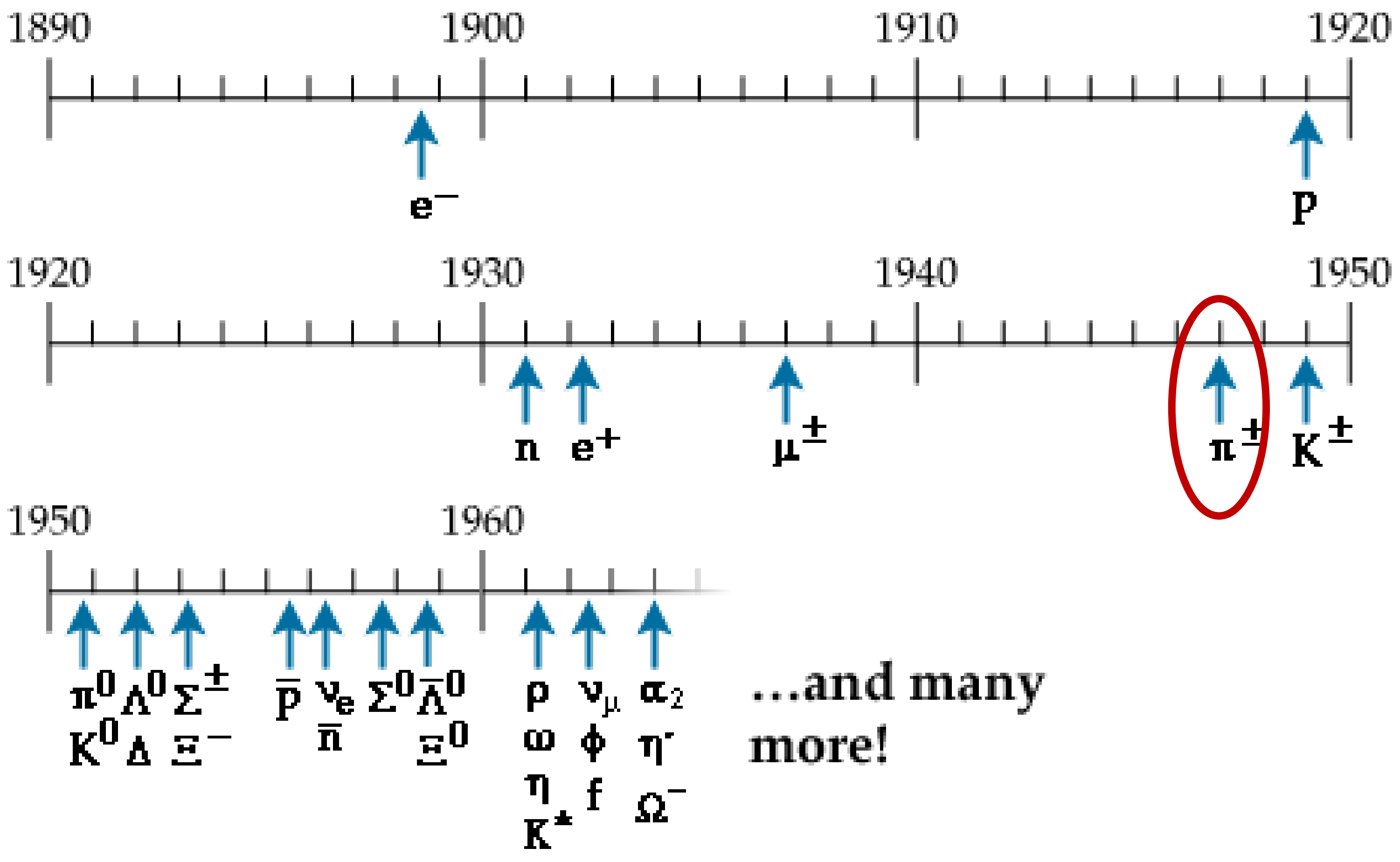






Building up the atomic world

Many particles observed in the 1950/60s

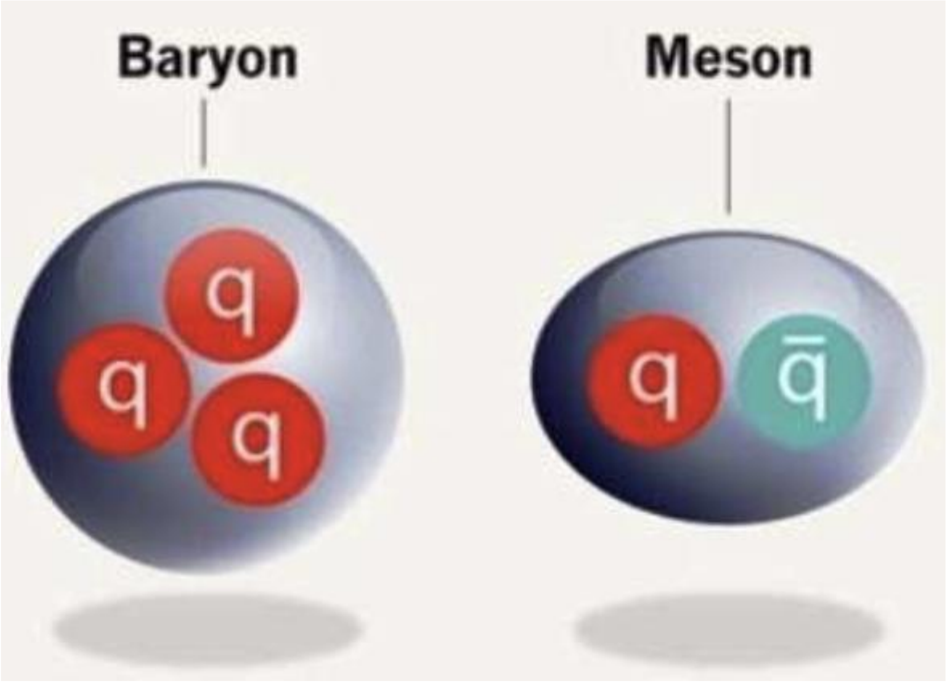


They cannot all be "elementary" !

Naive QM: hadron structure

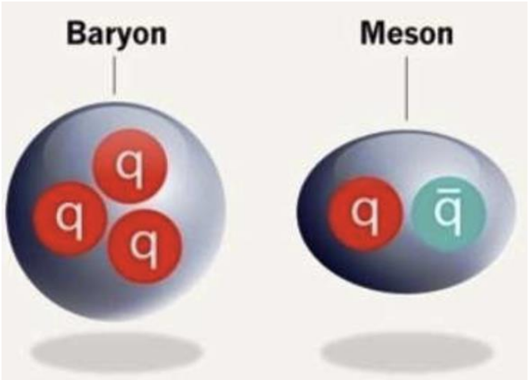
1964

Murray Gell-Mann



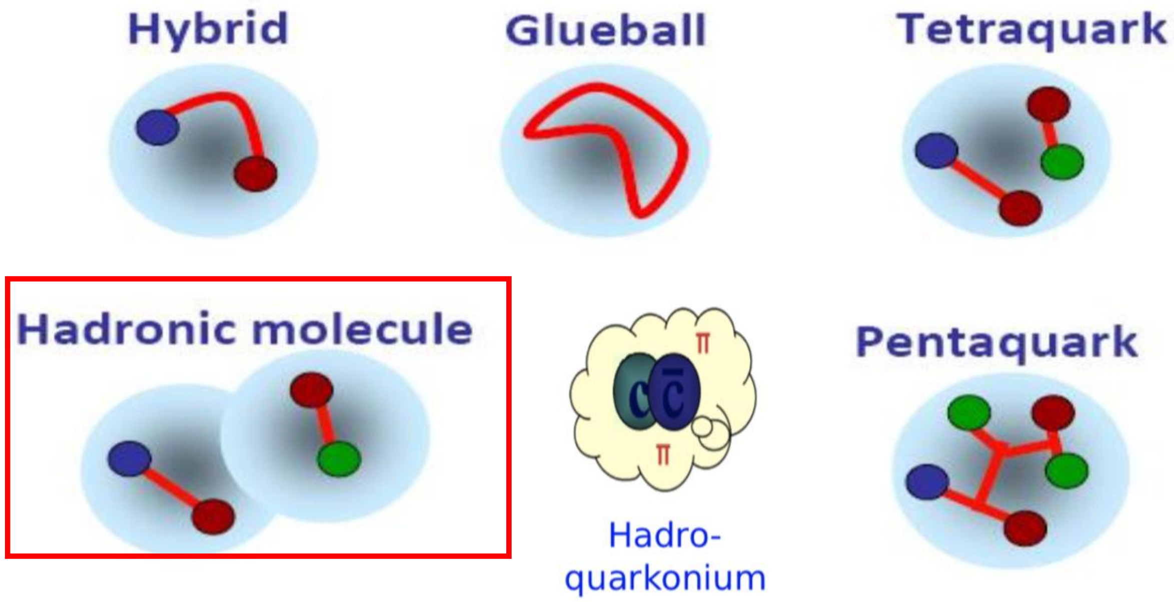
George Zweig

Beyond Naïve QM hadrons, more complicated structures allowed



In the naïve quark model

In principle, QCD allows



Naïve quark models more or less fine until 2003

$\Lambda(1405)$， $N^*(1535)$,...

$f_0(500)$, $f_0(980)$, $a_0(980)$, ...

2003—the beginning of a new era

as of 2024.07.10

LEPS, 0301020
1186

$\Theta^+(1540)$

BaBar, 0304021
999

$D_{s0}^*(2317)$

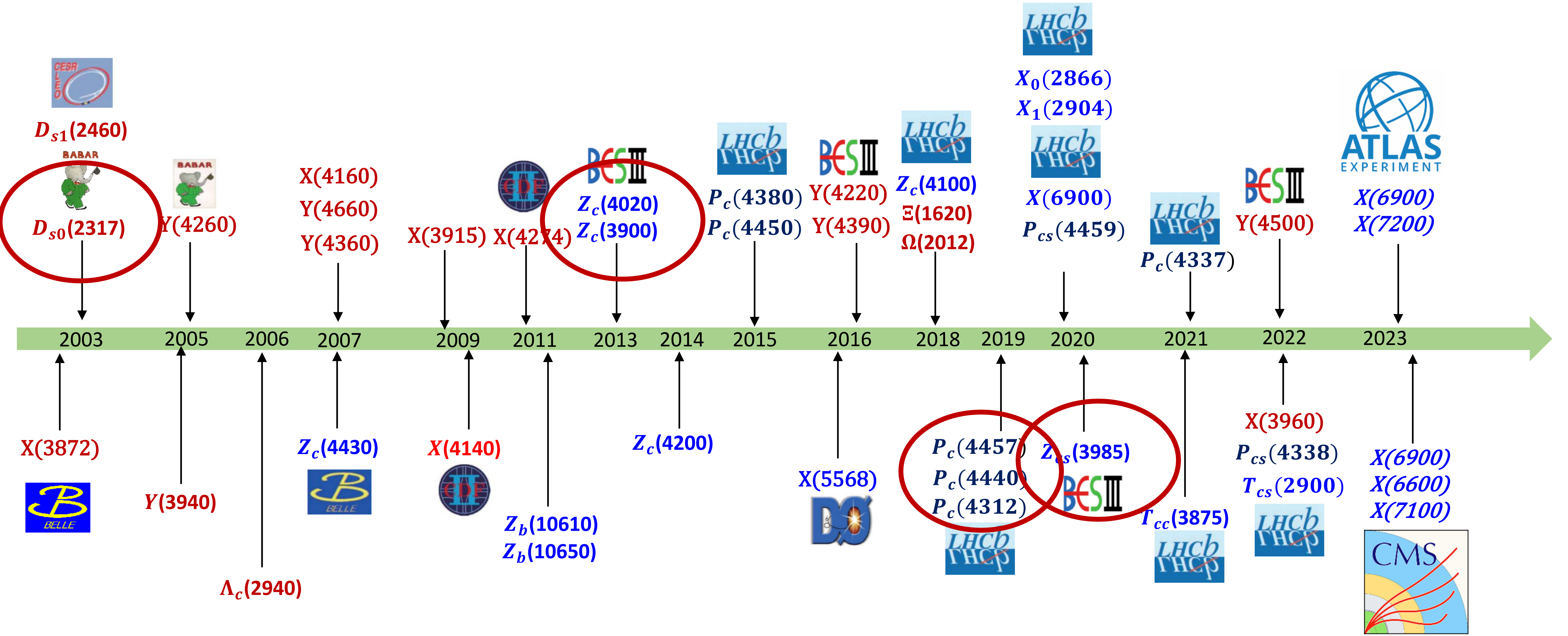
BABAR

Belle, 0309032
2540

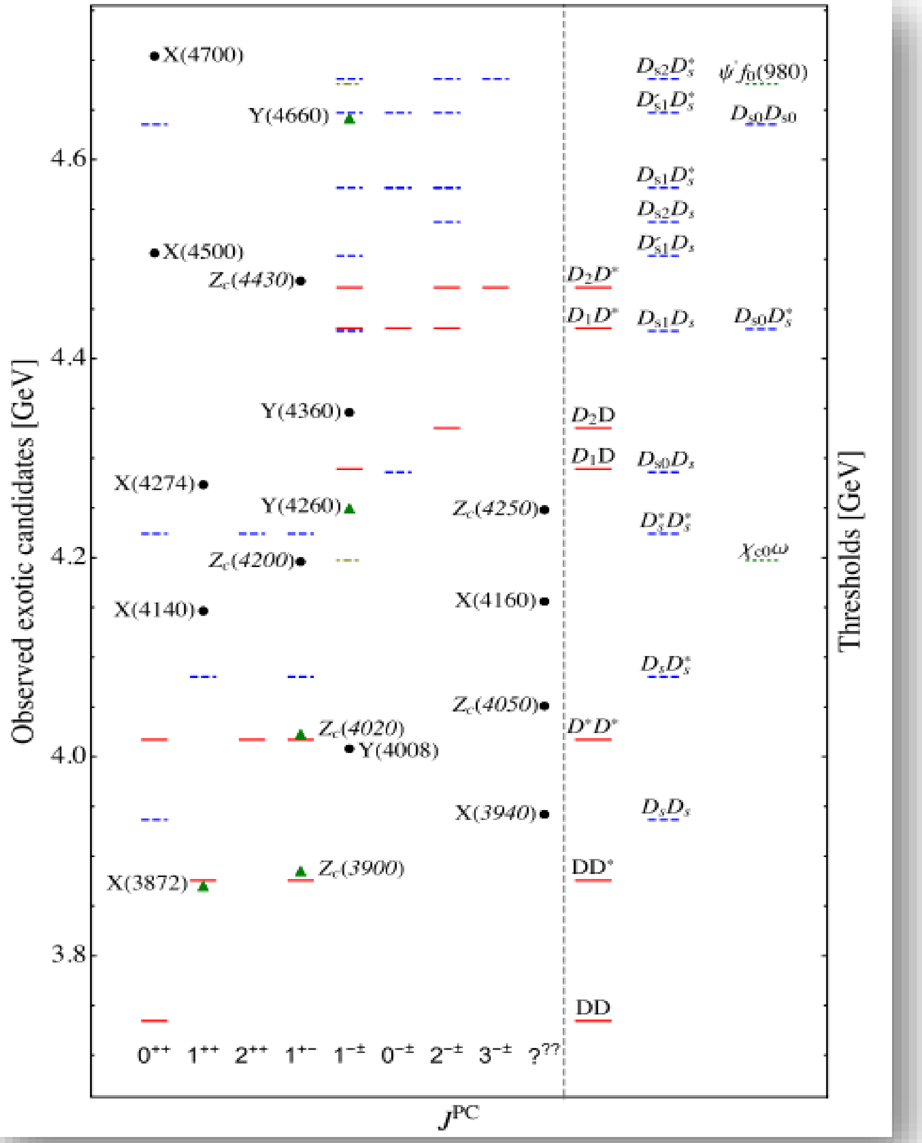
X(3872)

BELLE

Many more exotic hadrons discovered



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



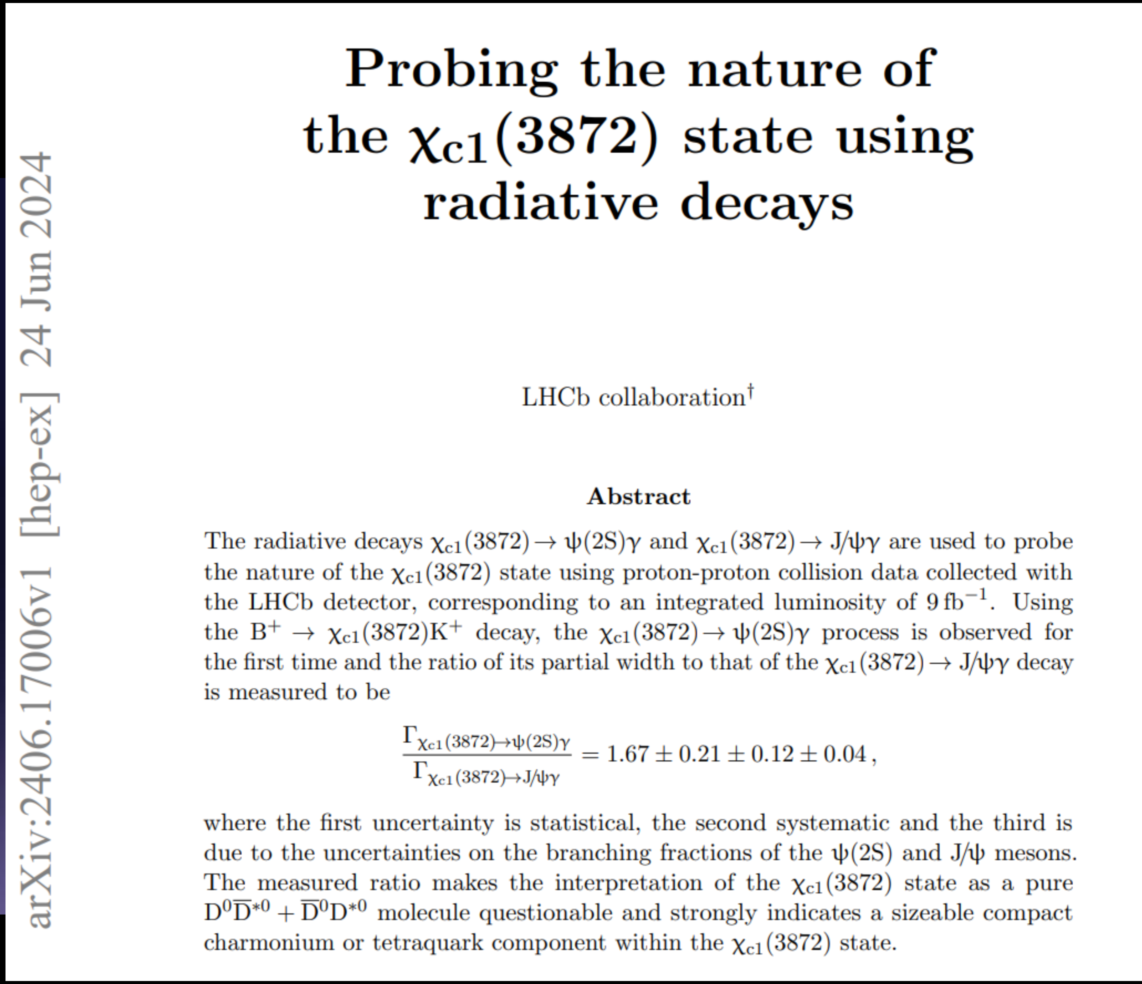
Feng-Kun Guo, Christoph Hanhart, Ulf-G. Meißner, Qian Wang, Qiang Zhao, Bing-Song Zou. Rev.Mod.Phys. 90 (2018) 015004

1153 citations as of 2024.07.10

Hua-Xing Chen, Wei Chen, Xiang Liu and Shi-Lin Zhu, *The hidden-charm pentaquark and tetraquark states*, Phys. Rept.639 (2016) 1

1109 citations as of 2024.07.10

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 $D^0\overline{D}^{*0} + \overline{D}^0D^{*0}$ molecule questionable and strongly indicates a sizeable compact charmonium or tetraquark component within the $\chi_{c1}(3872)$ state.

How to verify the molecular picture

2404.06399, Ming-Zhu Liu, Ya-Wen Pan, Zhi-Wei Liu, Tian-Wei Wu, Jun-Xu Lu, **LSG***

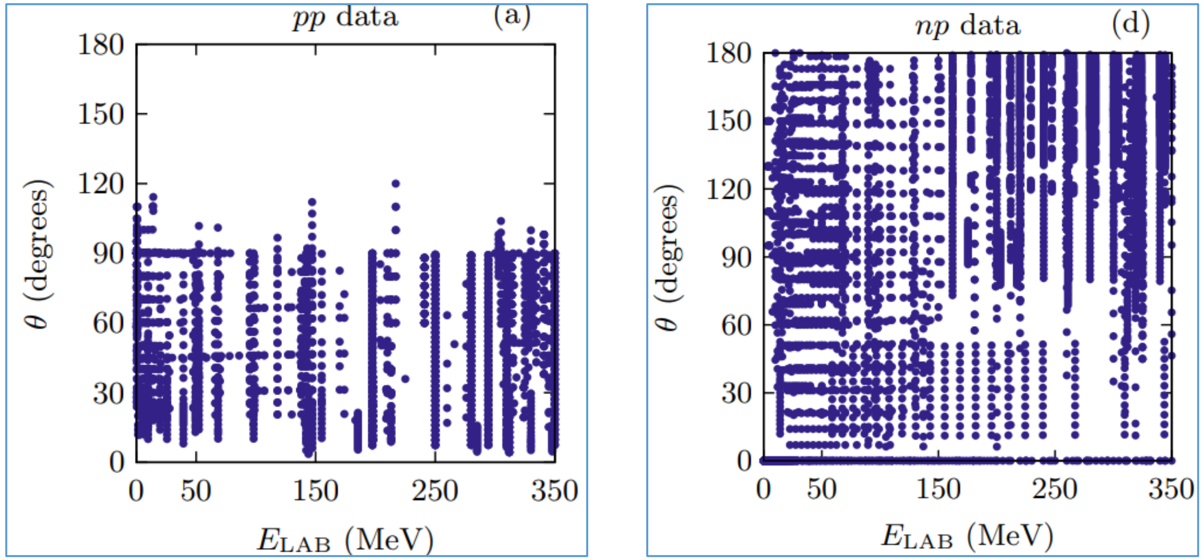
- **Symmetries in the two-hadron interactions imply the existence of multiplets of hadronic molecules**
  - **Heavy-quark spin/flavor** symmetry: there are **seven Pc** states
  - **Heavy antiquark diquark** symmetry: there are **ten dibaryon** states
  - **SU3** symmetry: there are **Pcs** states

- **Three hadrons experience pairwise two-body attractions can form three-body molecules**
  - Treating $\boldsymbol{\Lambda(1405)}$ as a $\bar{K}N$ state, one can expect a $\bar{K}NN$ state
  - Treating $\boldsymbol{D_{s0}^{*}(2317)}$ as a DK state, one can expect a DDK state or $\bar{D}DK$ state

- **Direct measurement of the two-hadron interactions**

Direct verifications of hadron-hadron interactions

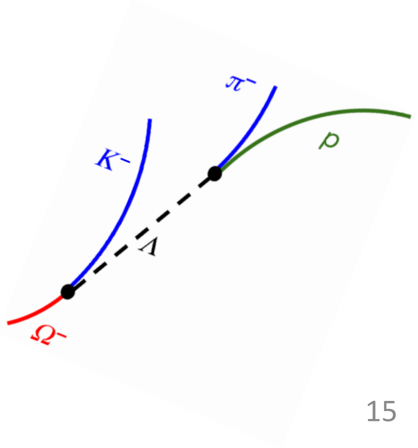
- For stable hadrons, scattering experiments are extremely valuable in extracting their interactions



Phys. *Rev.C* 89 (2014) 064006

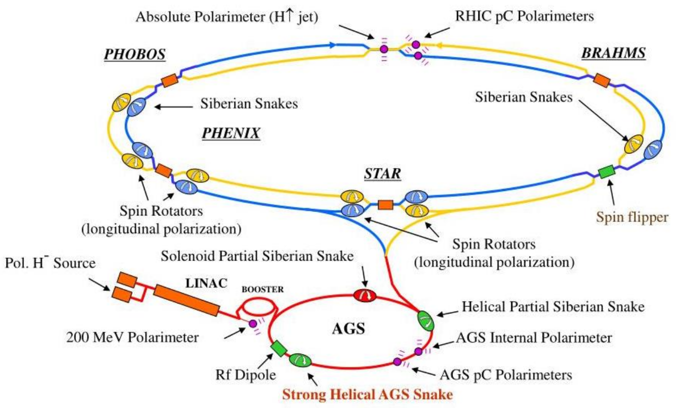
There exist abundant data for nucleon-nucleon scattering (8125)

- For unstable particles, direct scattering experiments are difficult or impossible!

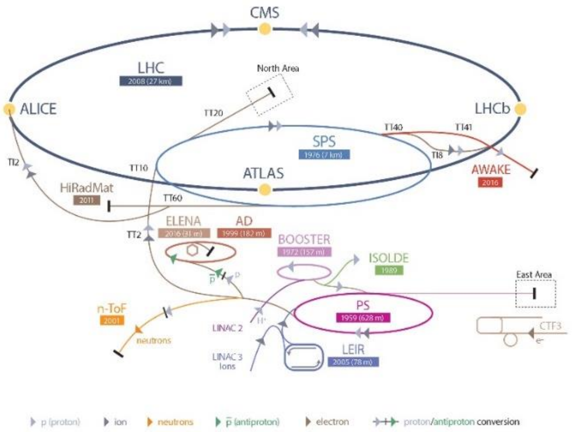


New probe—femtoscopic correlation functions

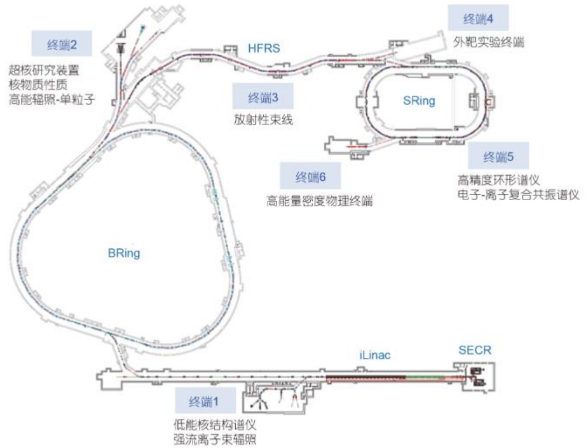
Brookhaven National Laboratory
RHIC
Relativistic Heavy Ion Collider



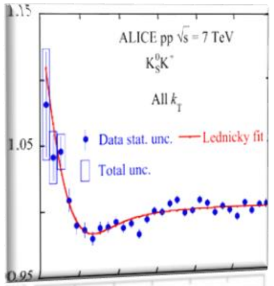
CERN
Large Hadron Collider



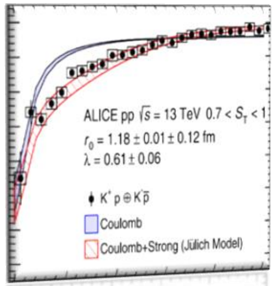
HIAF 强流重离子加速器装置
High Intensity heavy-ion Accelerator Facility



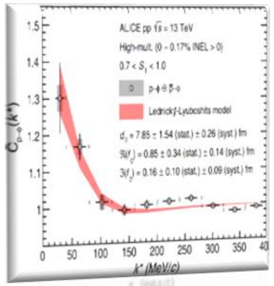
$K^0_S K^{\pm}$
$p+p, \sqrt{s}=7$ TeV



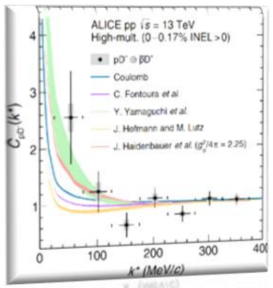
$K^{\pm}p$
$p+p, \sqrt{s}=5, 7, 13$ TeV



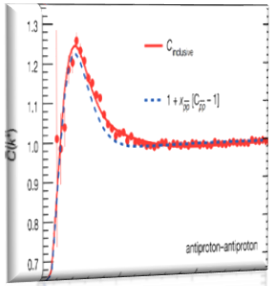
ϕp
$p+p, \sqrt{s}=13$ TeV



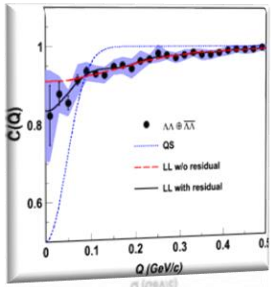
$D^- p$
$p+p, \sqrt{s}=13$ TeV



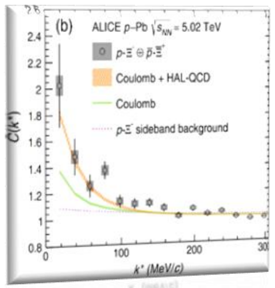
$\bar{p}\,\bar{p}$
Au + Au, $\sqrt{s}=200$ MeV



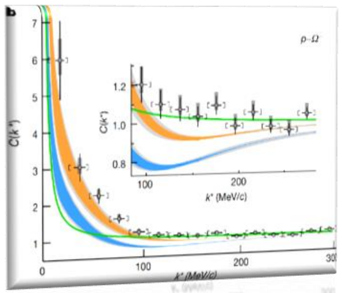
$\Lambda\Lambda$
Au + Au, $\sqrt{s}=200$ MeV



$\Xi^- p$
$p+\text{Pb}, \sqrt{s}=5.02$ TeV



$\Omega^- p$
$p+p, \sqrt{s}=13$ TeV



ON-GOING

*ALICE Collaboration, Phys. Lett. B **790** (2019) 22*

*ALICE Collaboration, Phys. Rev. Lett. **124** (2020) 092301*

*ALICE Collaboration, Phys. Rev. Lett. **127** (2021) 172301*

*ALICE Collaboration, Phys. Rev. D **106** (2022) 052010*

*STAR Collaboration, Nature **527** (2015) 345*

*STAR Collaboration, Phys. Rev. Lett. **114** (2015) 022301*

*ALICE Collaboration, Phys. Rev. Lett. **123** (2019) 112002*

*ALICE Collaboration, Nature **588** (2020) 232*

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- Recent applications
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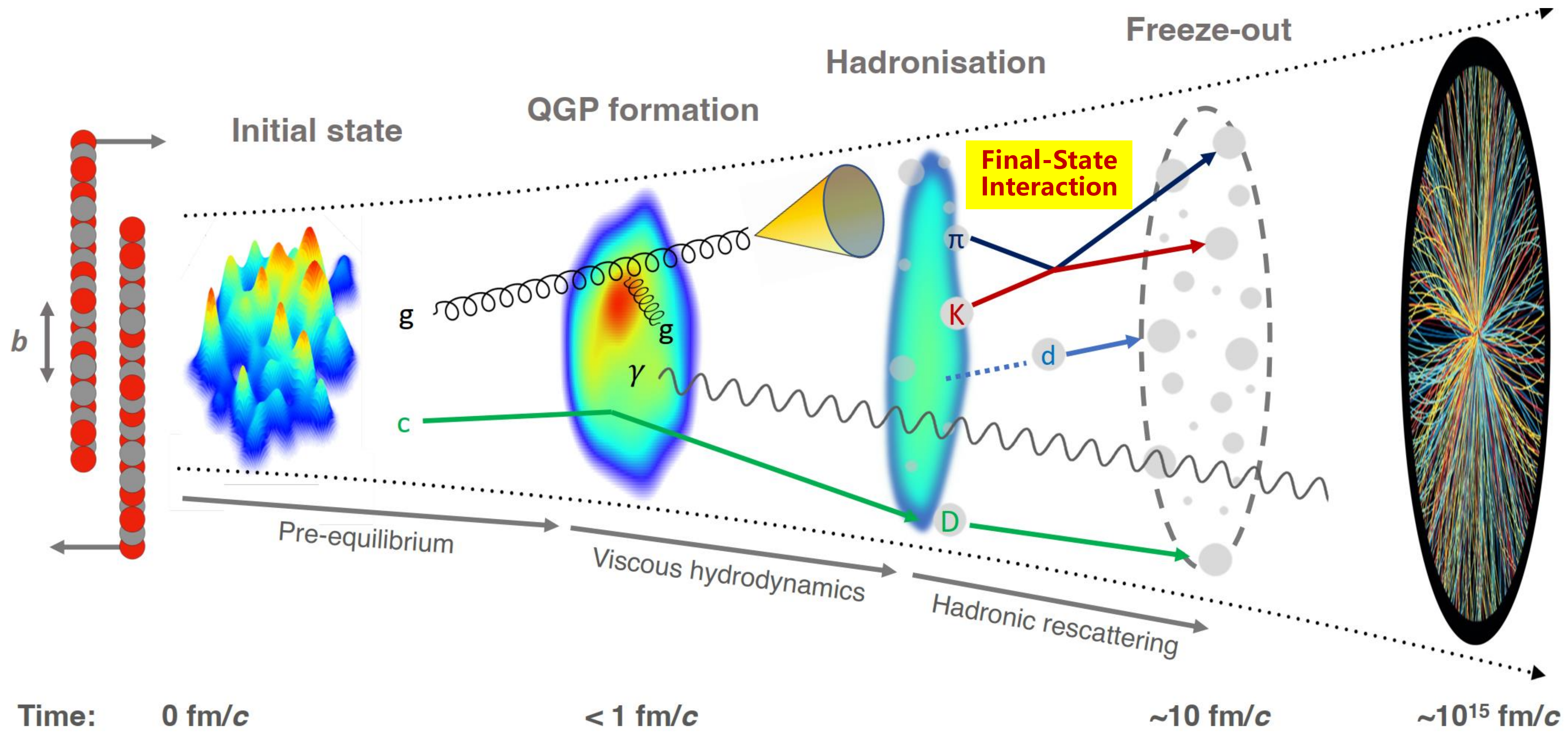
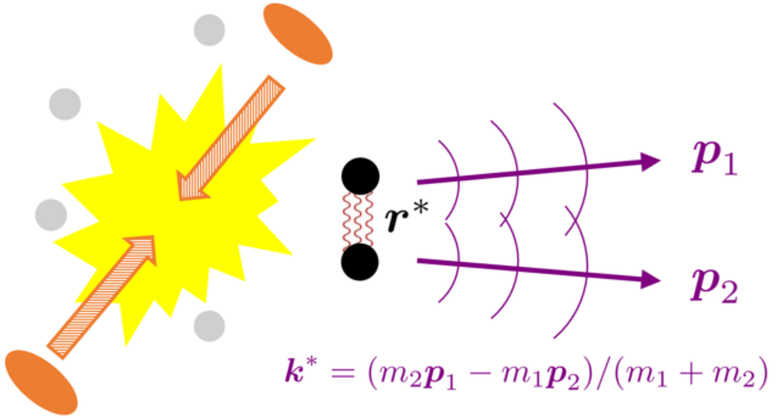
  - $\Sigma_c\bar{D}^*$ CFs for $P_c(4440)$ and $P_c(4457)$
  - $D\bar{D}^*$ and $D\bar{D}_s^*$ CFs for $Z_c(3900)$ and $Z_{cs}(3985)$
- Summary and outlook

Abundant particles produced in AA, pA, and pp collisions



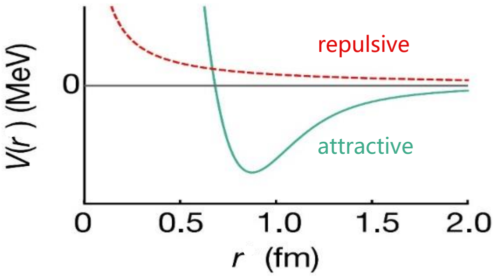
Femtoscopic correlation functions (CFs)

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

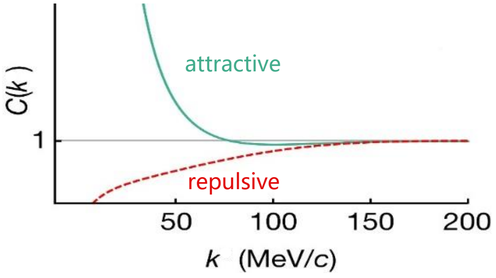


Emission source $S_{12}(\boldsymbol{r}^*)$ Two-particle wavefunction $\psi(\boldsymbol{k}^*, \boldsymbol{r}^*)$

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

Femtoscopic correlation functions (CFs)

Koonin–Pratt (KP) formula

*S. E. Koonin, Phys. Lett. B **70** (1) (1977) 43*
*A. Ohnishi, Nucl. Phys. A **954** (2016) 294*

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

Only S-waves

$$C(k) \simeq 1 + \int_0^\infty 4\pi r^2 \mathrm{d}r\ S_{12}(r)\ \left[|\psi_0(r,k)|^2 - |j_0(kr)|^2\right]$$

- **Common static and spherical Gaussian source**

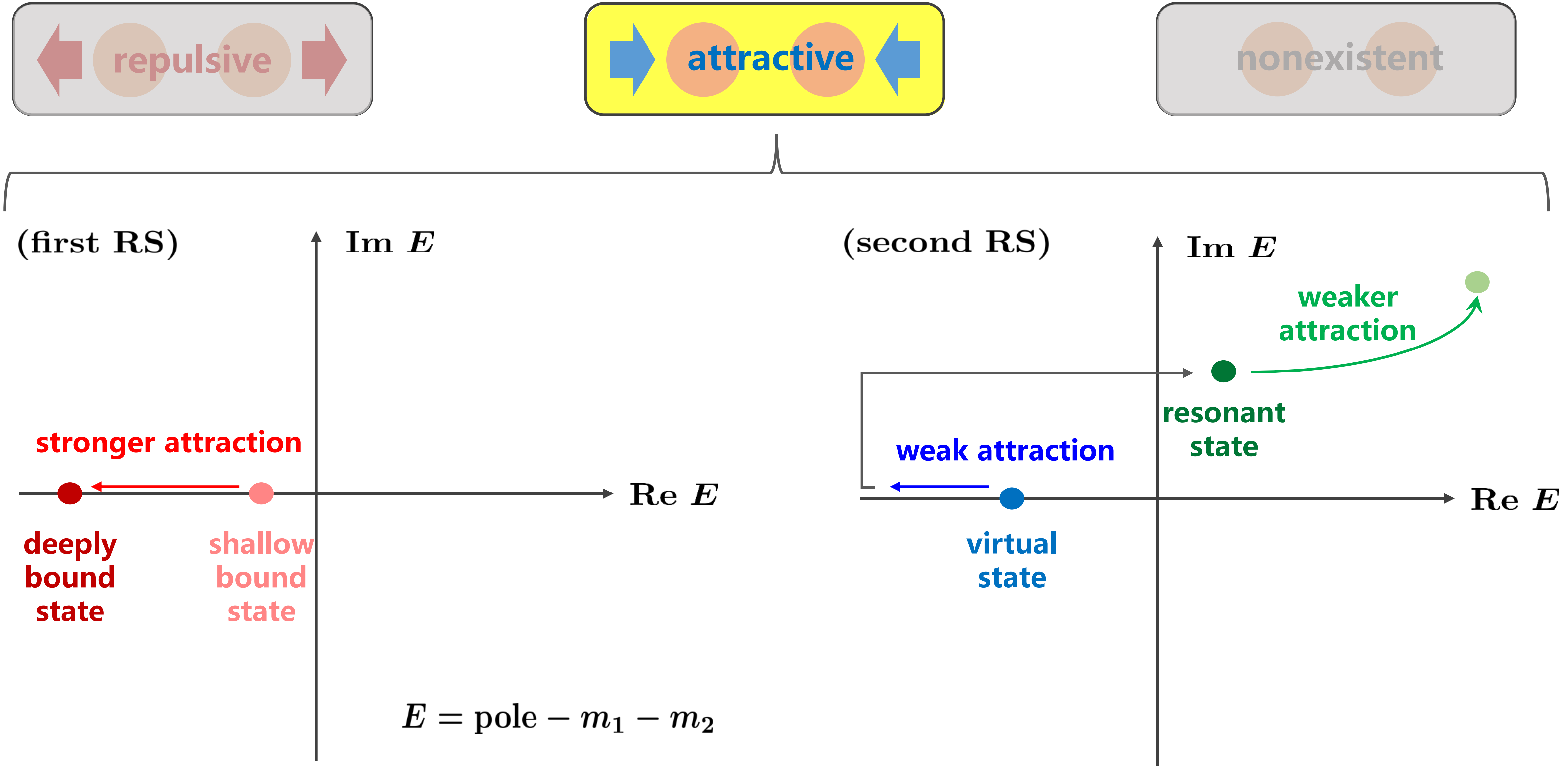
$$S_{12}(r) = \exp[-r^2/(4R^2)]/(2\sqrt{\pi}R)^3$$

- **Scattering wave function**
  - **the Schrödinger equation**
  - **the Lippmann-Schwinger equation**

$$-\frac{\hbar^2}{2\mu}\nabla^2\psi + V\psi = E\psi$$

$$T = V + VGT \quad \Longrightarrow \quad |\psi\rangle = |\phi\rangle + GT|\phi\rangle$$

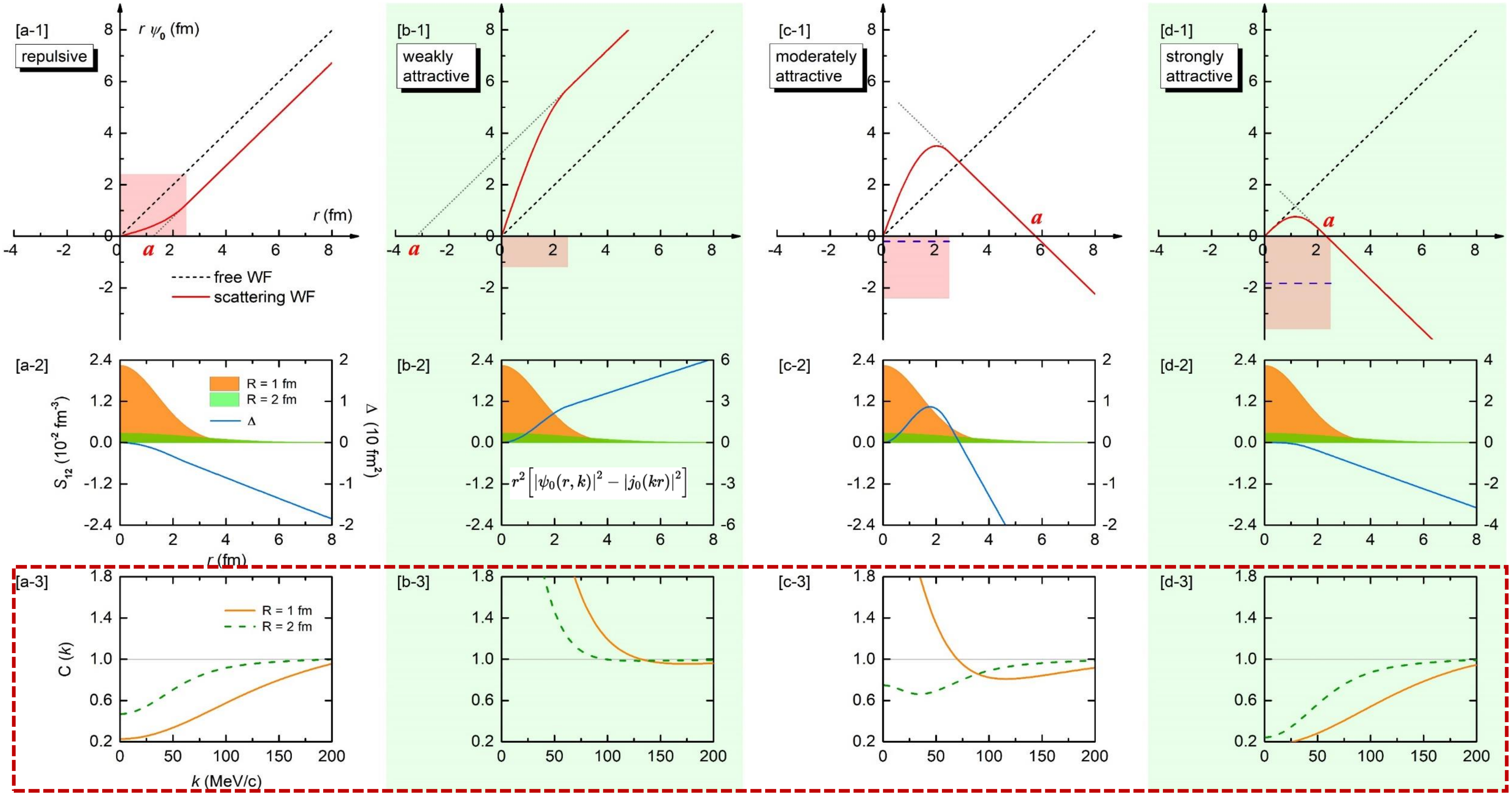
Classification of hadron-hadron interactions



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

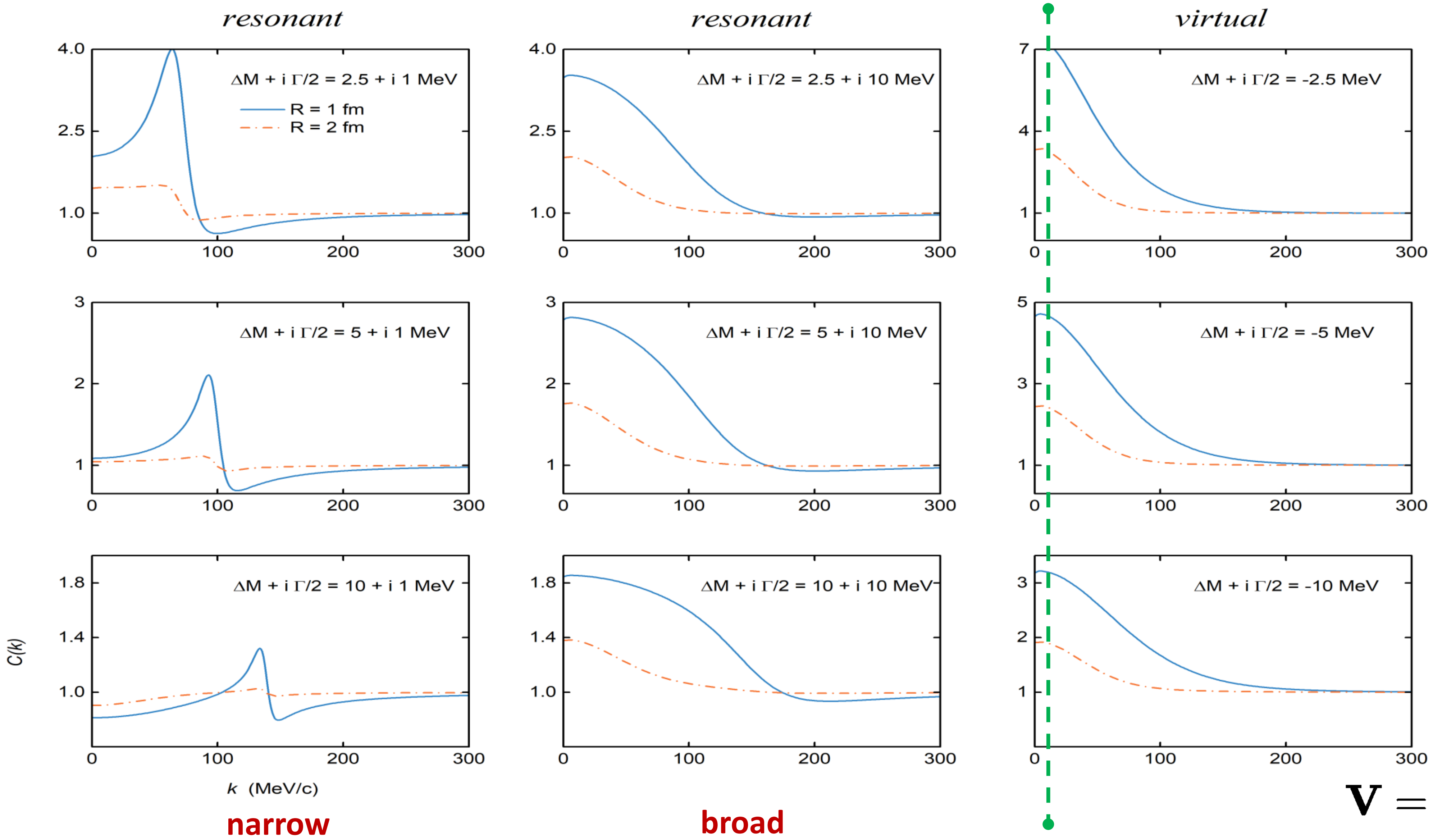
CFs in the presence of bound states

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



CFs in the presence of resonant and virtual states

*Zhi-Wei Liu, Ming-Zhu Liu, Jun-Xu Lu and **LSG*,** 2404.18607*



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

Contents

- ☞Brief introduction: exotic states & femtoscopy
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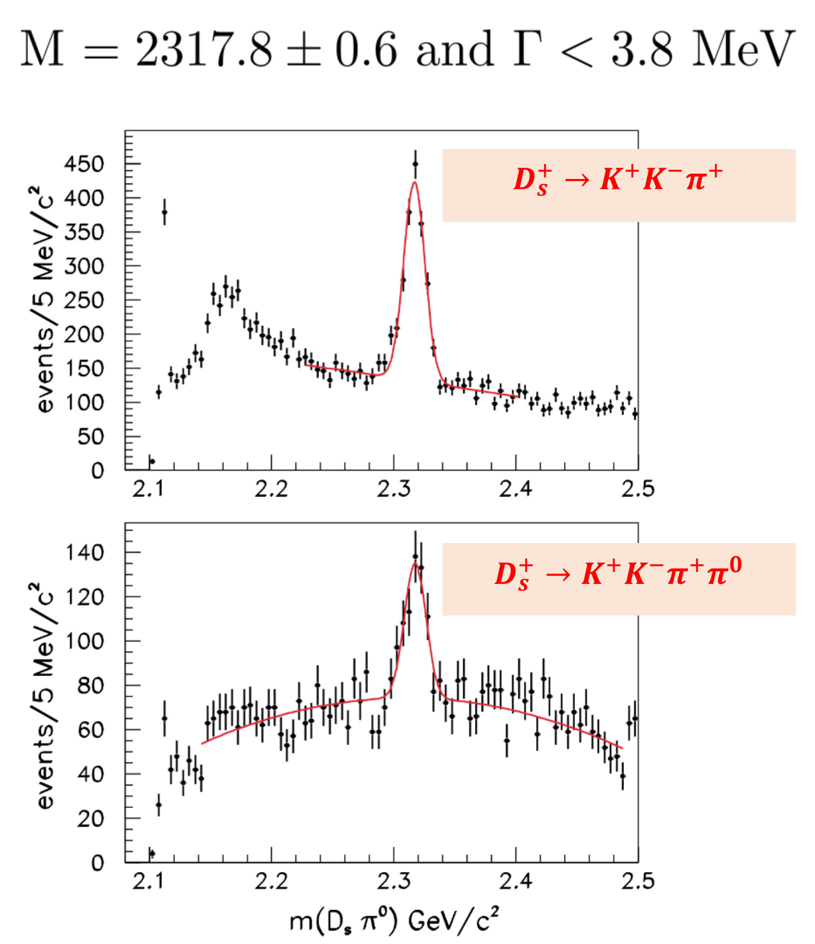
  - ➢$\Sigma_c\bar{D}^*$ CFs for $P_c(4440)$ and $P_c(4457)$
  - ➢$D\bar{D}^*$ and $D\bar{D}_s^*$ CFs for $Z_c(3900)$ and $Z_{cs}(3985)$
- ☞Summary and outlook

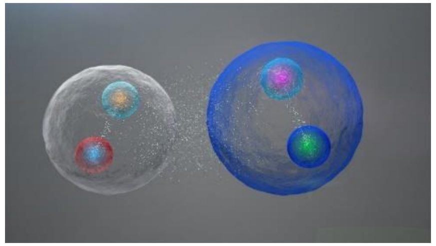
Mysterious exotic hadron $D_{s0}^*(2317)$—999 citations



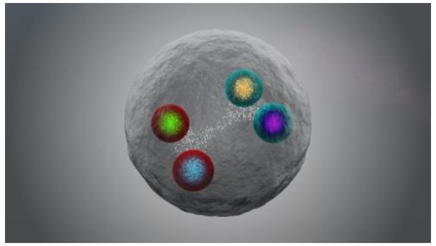
BABAR, PRL90 (2003) 242001

- **160 MeV lower than the quark model predictions – difficult to be understood as a conventional charm-strange meson**
- $m(D_{s1}) - m(D_{s0}^*) \approx m(D^*) - m(D)$
  F. K. Guo, C. Hanhart, U.-G. Meißner, PRL.102 (2009) 242004
- **DK scattering length from LQCD favors molecular scenario**
  L. Liu, K. Orginos, F. K. Guo, C. Hanhart, U.-G. Meißner, PRD87 (2013) 014508

……



VS



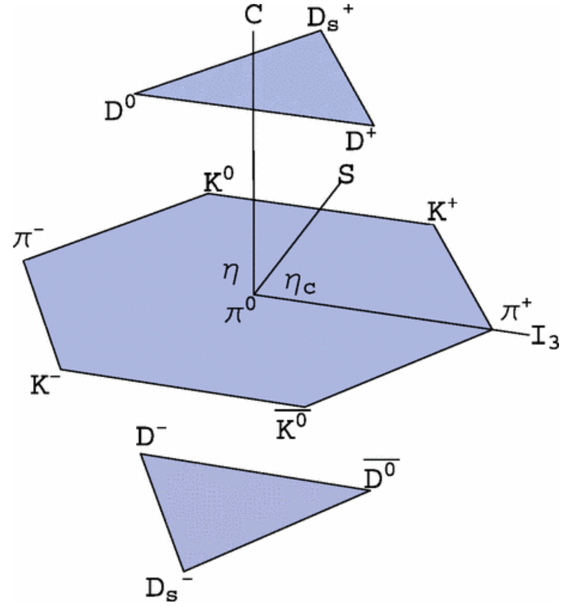
Weinberg-Tomozawa Interaction (leading order)

- LO interaction between a NGB and a heavy pseudoscalar boson

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

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

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

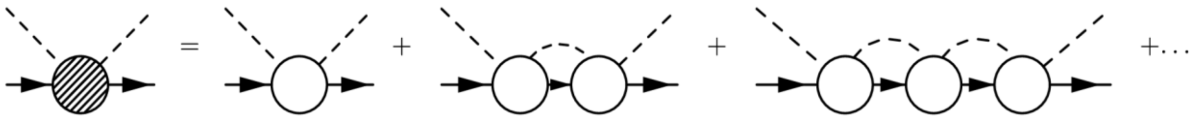


- Weinberg-Tomozawa (WT) potential – parameter free

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

Scattering wave function

◻ Coupled-channel scat. eq.



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

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

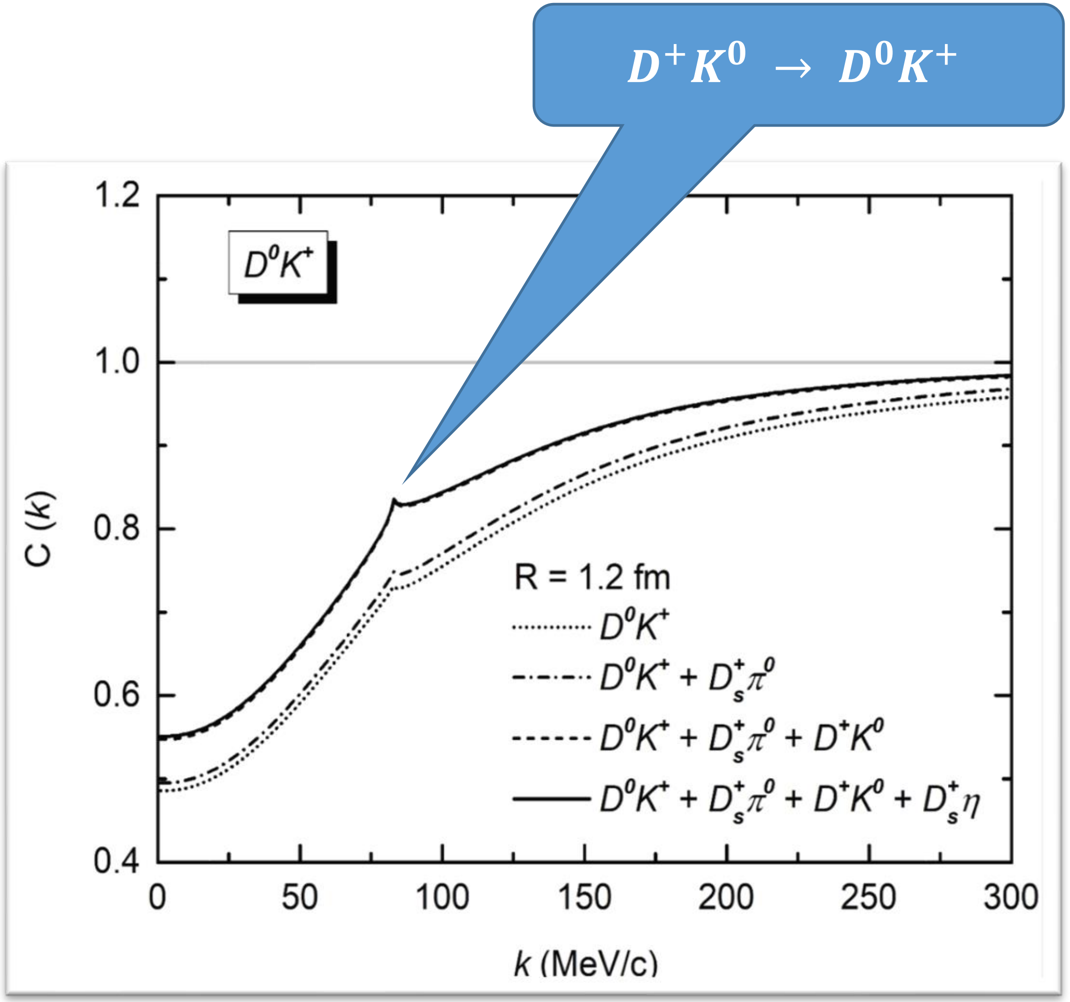
$M_{D^*_{s0}} = 2317.8\ \mathrm{MeV}$ → $\Lambda_F = 1107\ \mathrm{MeV}$

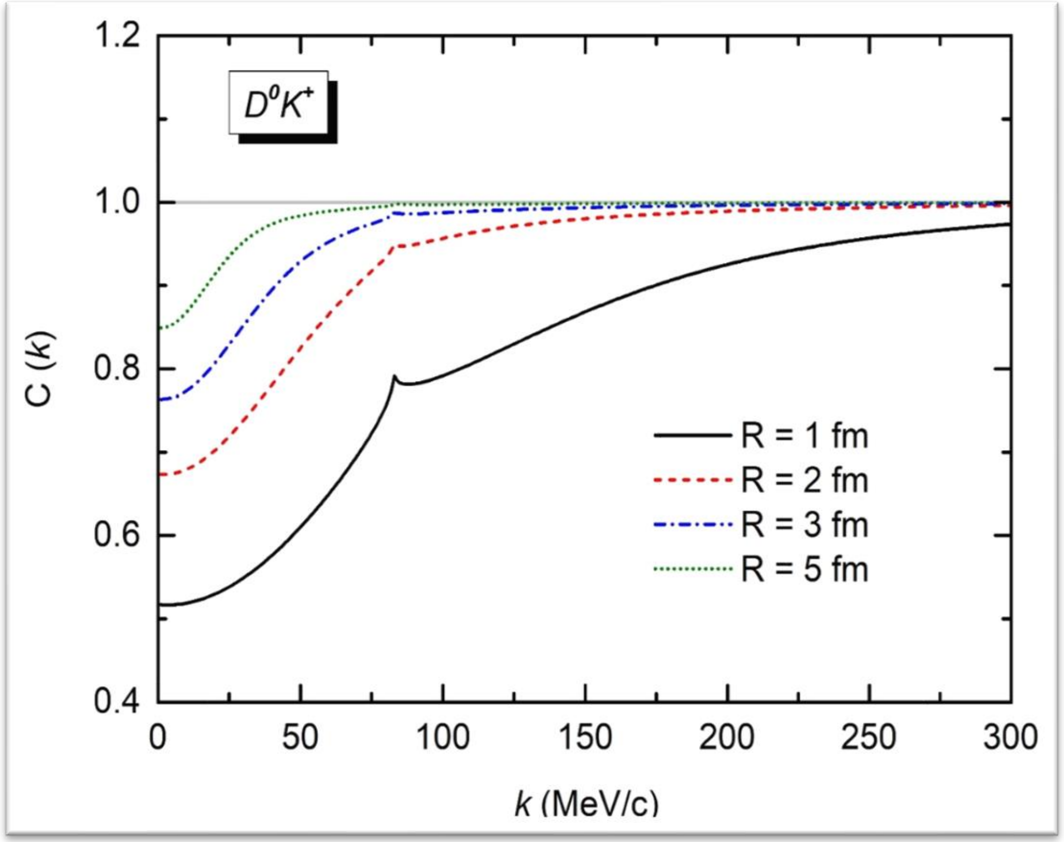
◻ S-wave scattering wave function (including off-shell effect)

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

DK CFs and its source size dependence

Typical feature of deeply bound states





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

Confirmed by two subsequent studies

PHYSICAL REVIEW D **108,** 014020 (2023)

Femtoscopic signatures of the lightest *S*-wave scalar open-charm mesons

M. Albaladejo,[1,*] J. Nieves,[1,†] and E. Ruiz Arriola[2,‡]

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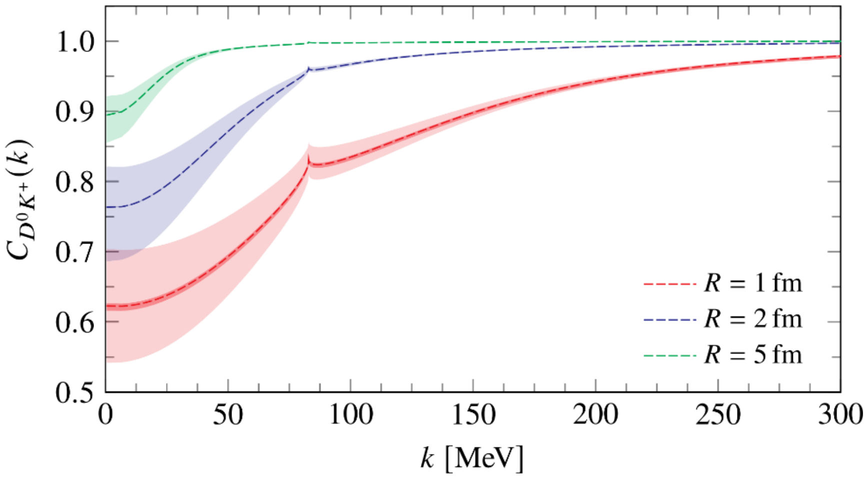

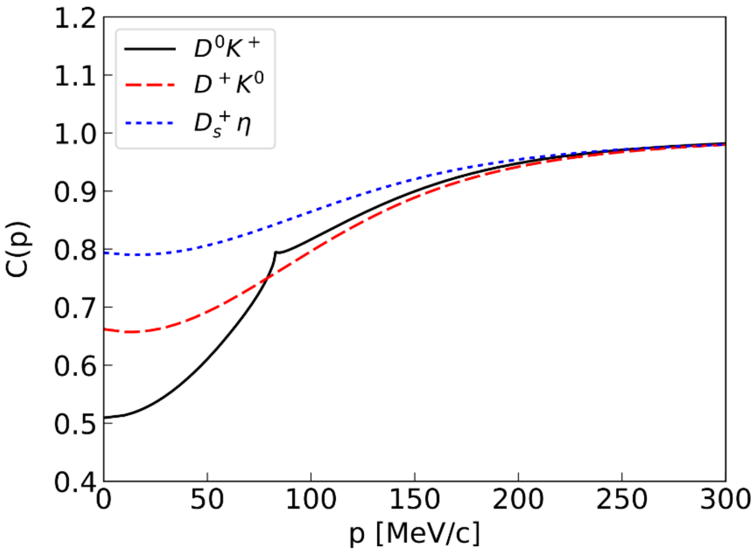

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Letter

Model independent analysis of femtoscopic correlation functions: An application to the $D^*_{s0}(2317)$

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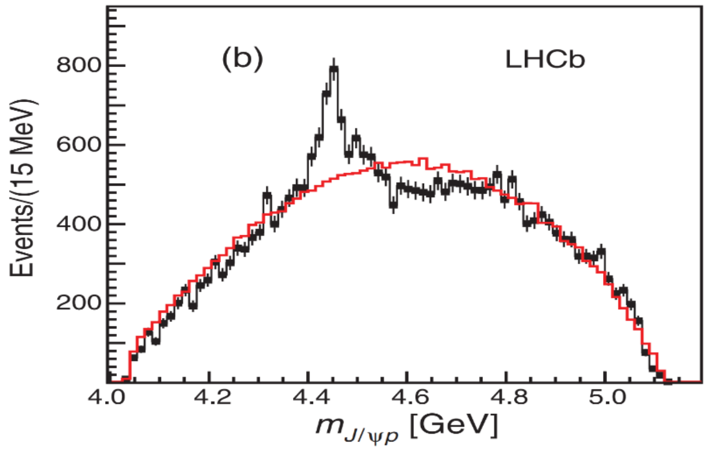
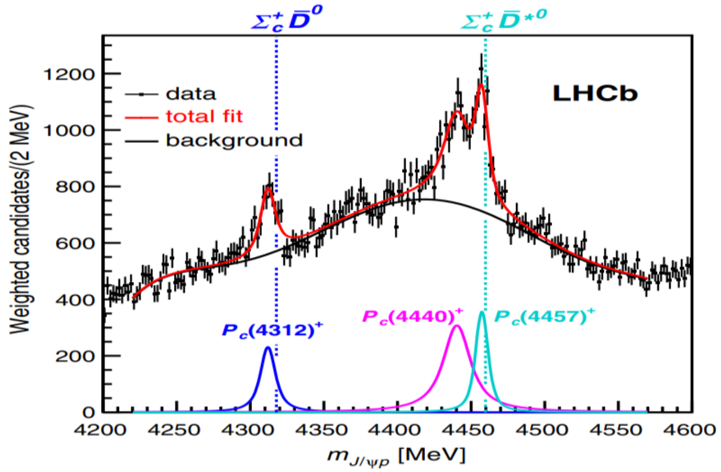
☞ **Summary and outlook**

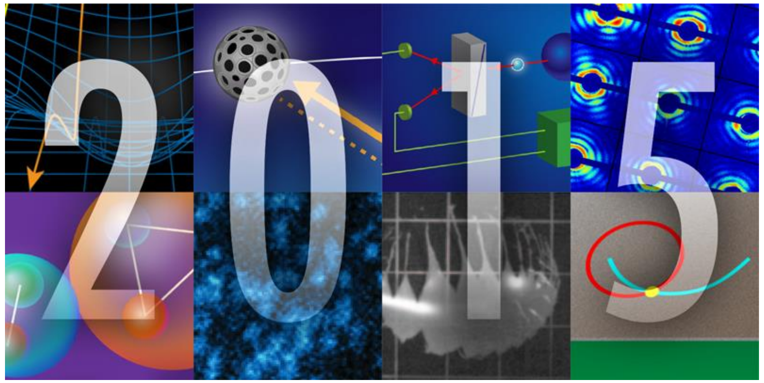
Pentaquark states $P_c(4440)$ & $P_c(4457)$—1772 citation



LHCb, PRL115 (2015) 072001



LHCb, PRL122 (2019) 222001



Pentaquark states • 2015 APS Highlights

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

- **Masses, invariant mass distributions, decays, magnetic momenta, production rates**
  - *M. Z. Liu, Y. W. Pan, F. Z. Peng, M. Sánchez S, LSG*, A. Hosaka, M. P. Valderrama, PR122 (2019) 242001*
  - *M. L. Du, V. Baru, F. K. Guo, C. Hanhart, U. G. Meißner, J. A. Oller, Q. Wang, PRL124 (2020) 072001*
  - *Y. H. Lin, B. S. Zou, PRD100 (2019) 056005*
  - *M. W. Li, Z. W. Liu, Z. F. Sun and R. Chen, PRD104 (2021) 054016*
  - *Q. Wu, D. Y. Chen, PRD100 (2019) 114002*
- **Heavy antiquark diquark symmetry**
  - *Y. W. Pan, M. Z. Liu, F. Z. Peng, M. S. Sánchez, LSG*, M. P. Valderrama, Phys. Rev. D 102 (2020) 011504*
- **Neural network-based approach**
  - *Z. Zhang, J. Liu, J. Hu, Q. Wang, U.-G. Meißner, Sci. Bull. 68 (2023) 981*

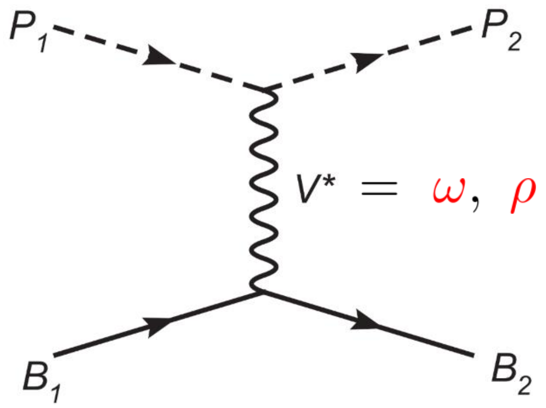
OTHER

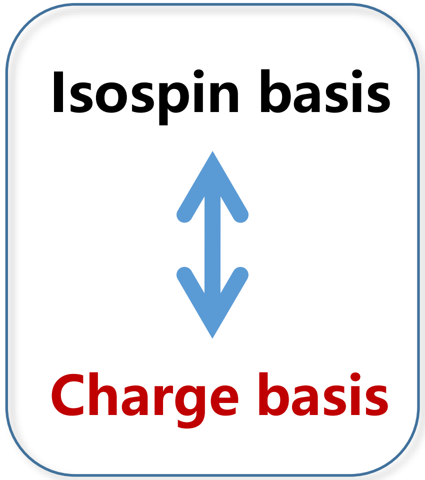
Light vector meson exchange interactions

- **Interactions in The hidden local symmetry approach – parameter free**

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

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





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

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

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 $\Sigma_c\bar{D}^*$

itation: R.L. Workman et al. (Particle Data Group), Prog.Theor.Exp.Phys. 2022, 083C01 (2022) and 2023 upda

$P_c(4440)^+$ Status: ∗

$P_c(4440)^+$ MASS

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
$4440.3\pm1.3^{+4.1}_{-4.7}$	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
$4457.3\pm0.6^{+4.1}_{-1.7}$	AAIJ	19W	LHCB	pp at 7, 8, 13 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$4449.8\pm1.7\pm2.5$	[1] AAIJ	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

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

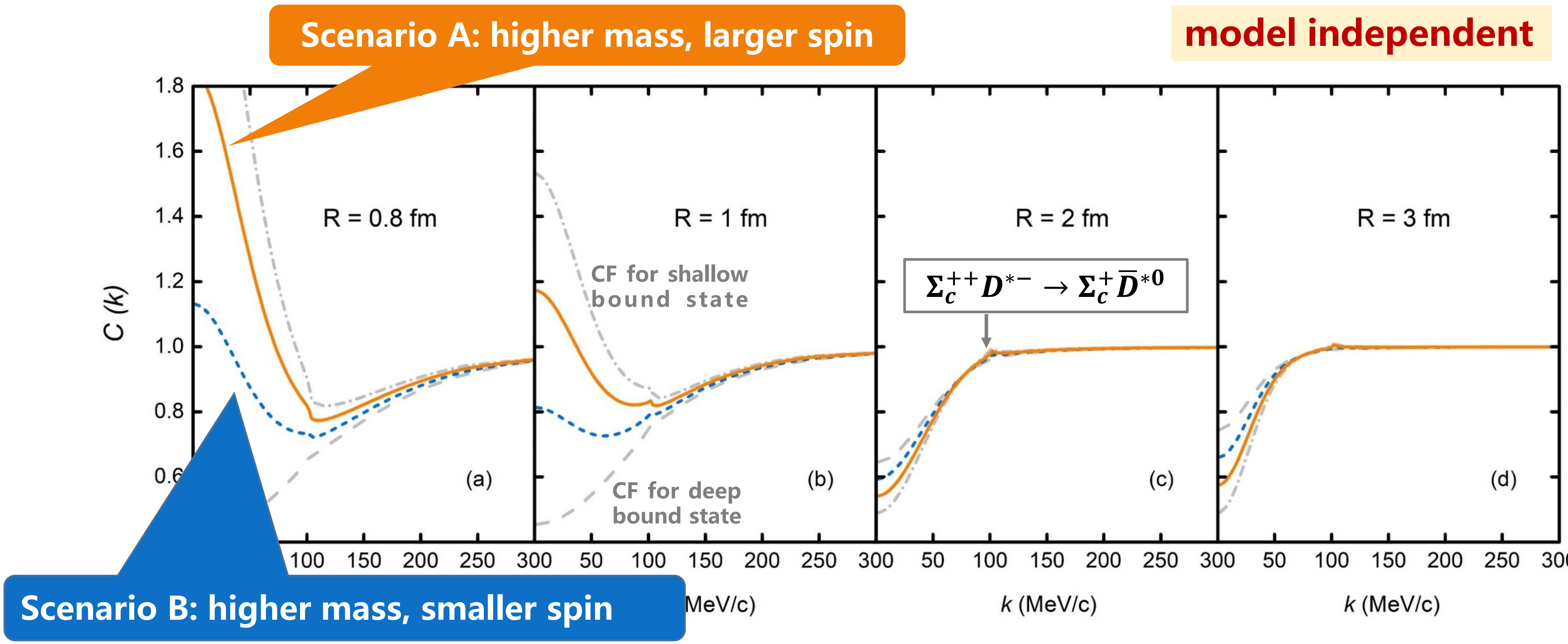
$$\bar{C} = \mathbf{1/3 \cdot C_{deep} + 2/3 \cdot C_{shallow}}$$

Scenarios B

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

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

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



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

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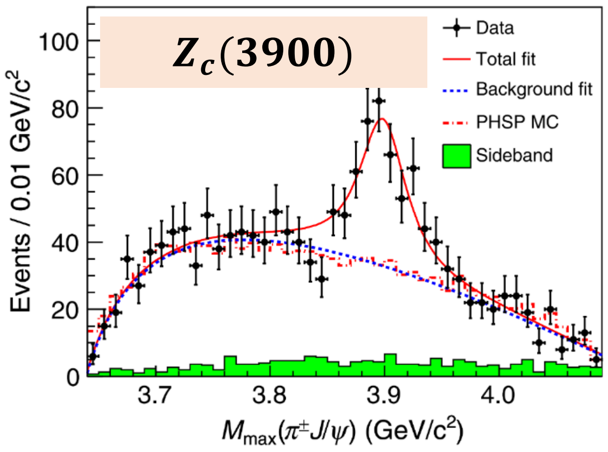
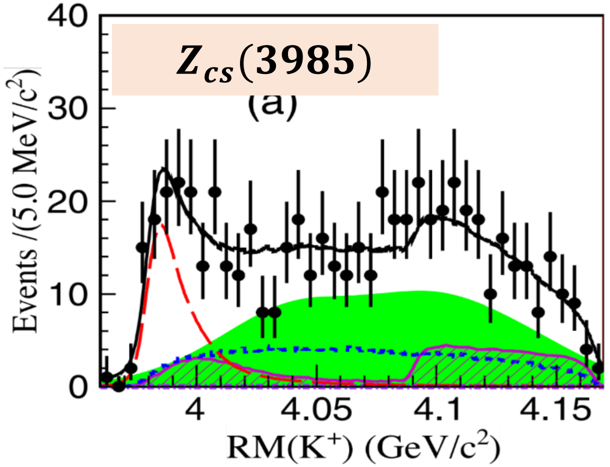
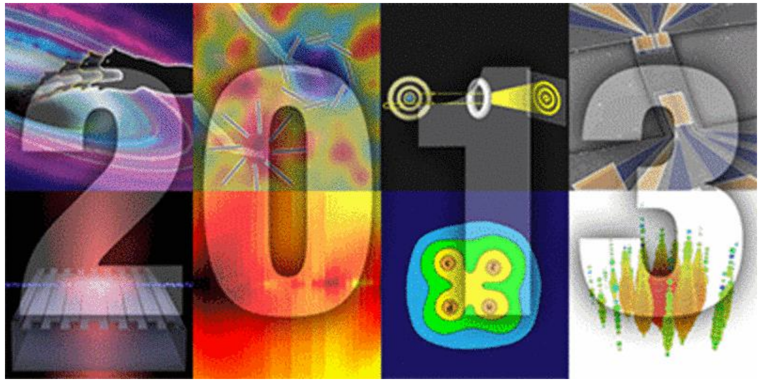
Tetraquark states $Z_c(3900)$ & $Z_{cs}(3985)$—1108 citations



BESIII, PRL110 (2013) 252001



BESIII, PRL126 (2021) 102001



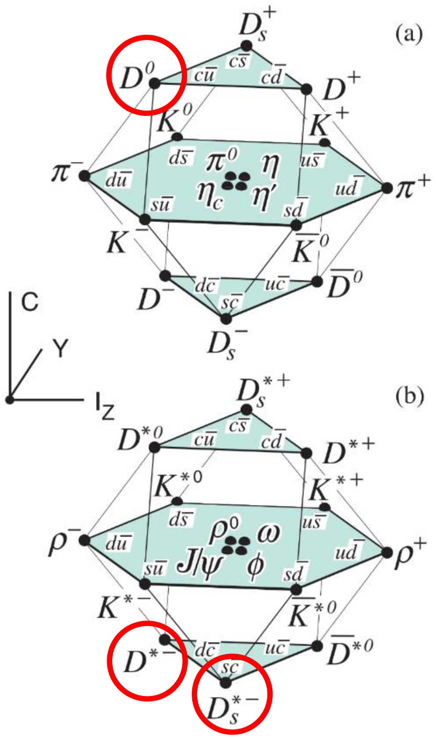
Tetraquark states • 2013 APS Highlights

$Z_c(3900)$ & $Z_{cs}(3985)$: 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

How to tell whether $Z_c(3900)$ and $Z_{cs}(3985)$ are resonant or virtual states ?

General potential from EFTs



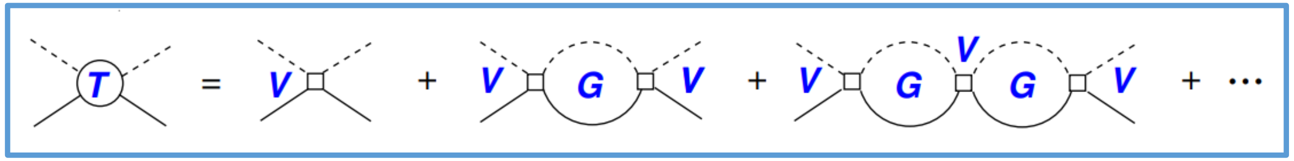
□ Interaction between heavy pseudoscalar bosons

$$\mathbf{V} = \mathbf{a} + \mathbf{b} \cdot \mathbf{k^2}, \qquad \mathbf{k} = \sqrt{[\mathbf{s} - (\mathbf{m_1} + \mathbf{m} + \mathbf{2})^2][\mathbf{s} - (\mathbf{m_1} - \mathbf{m} + \mathbf{2})^2]}/2\sqrt{\mathbf{s}}$$

- ➢ **energy-dependent potential —→ resonant state**
- ➢ **contact-range potential —→ bound or virtual state**

□ Scattering equation – unitarity

$$\mathbf{T} = \mathbf{V} + \mathbf{VGT} \qquad \longleftrightarrow$$



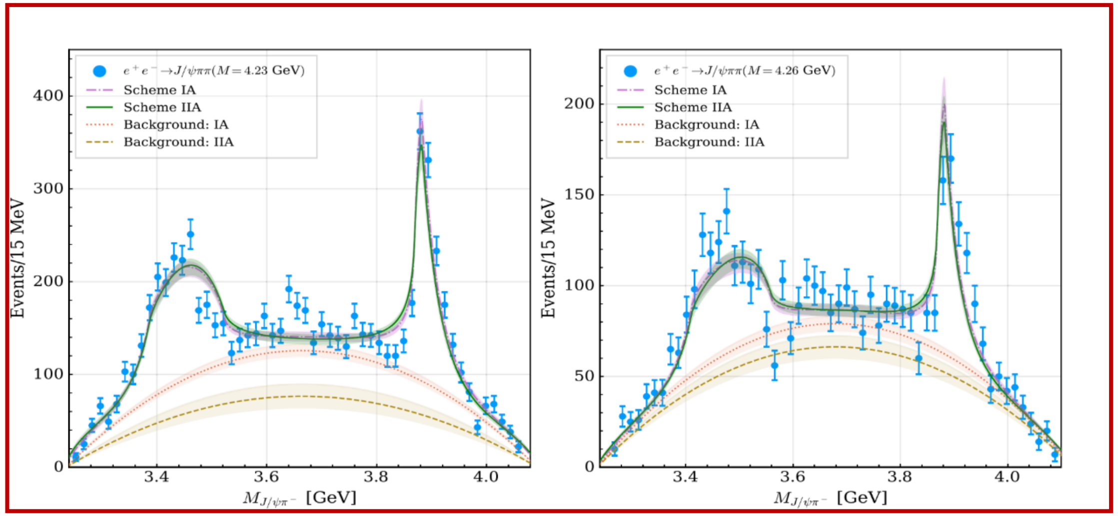
Loop function G with cutoff regularization

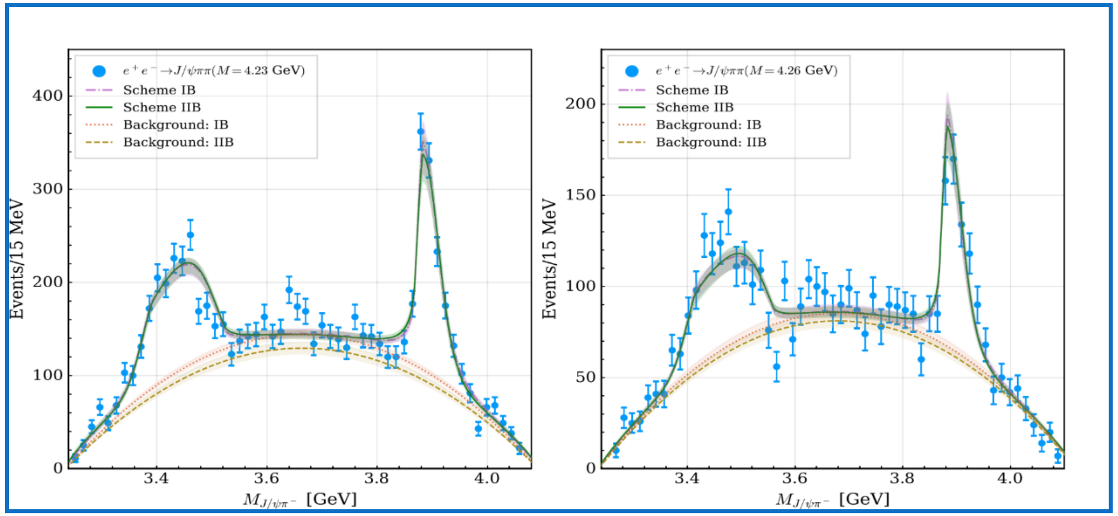
$$\mathbf{G}(\sqrt{\mathbf{s}}) = \int_0^{|q|<\mathbf{q}_{\max}} \frac{\mathbf{d^3k'}}{(2\pi)^3} \frac{\mathbf{E_1(k') + E_2(k')}}{\mathbf{2E_1(k')E_2(k')}} \frac{1}{\sqrt{\mathbf{s}}^2 - [\mathbf{E_1(k') + E_2(k')}]^2 + i\varepsilon}, \qquad \mathbf{q_{max}} \in [0.8, 1.2]\ \mathbf{GeV}$$

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 $Z_c(3900)/Z_{cs}(3985)$ as either a resonant or virtual state.

Interaction strengths determined by fitting to data

	Scenario	M [MeV]	Γ [MeV]	$m_1 + m_2$ [MeV]	a	b [MeV^{-2}]
$Z_c(3900)$	Res. [95]	3887.1	28.4	$D^0 D^{*-}$ (3875.1)	−101.68	−1380.60
	Vir. [27]	3796	0	$D^0 D^{*-}$ (3875.1)	−87.36	0
$Z_{cs}(3985)$	Res. [95]	3988	13	$D^0 D_s^{*-}$ (3977.04)	−84.17	−2894.16
	Vir. [27]	3967	0	$D^0 D_s^{*-}$ (3977.04)	−130.21	0

【95】 *Particle Data Group, PTEP 2022,(2022)083C01*

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

□ Correlation functions with on-shell approximation

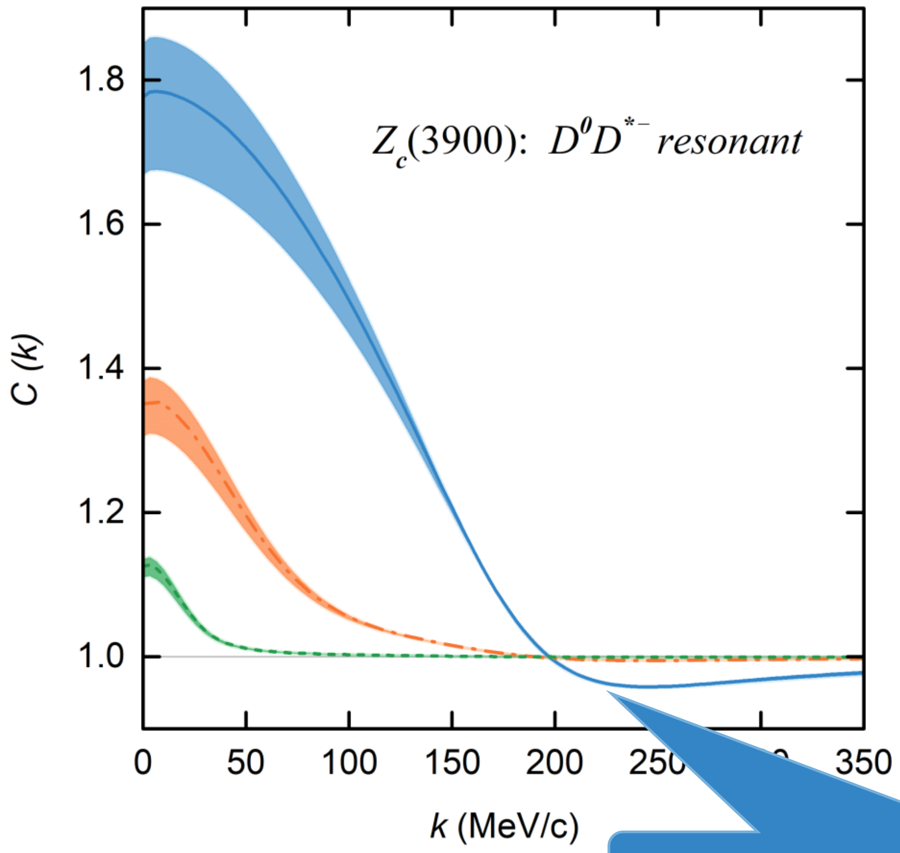
$$\mathbf{C(k) = 1 + \int_0^\infty 4\pi r^2 dr\, S_{12}(r)\, \theta(q_{max} - k) \left[\left| j_0(kr) + T(\sqrt{s})\, \widetilde{G}(r, \sqrt{s}) \right|^2 - |j_0(kr)|^2 \right]}$$

$$\mathbf{\widetilde{G}(r, \sqrt{s}) = \int_0^{|q|<q_{max}} \frac{d^3k'}{(2\pi)^3} \frac{E_1(k') + E_2(k')}{2E_1(k')E_2(k')} \frac{j_0(k'r)}{\sqrt{s}^2 - [E_1(k') + E_2(k')]^2 + i\varepsilon}}$$

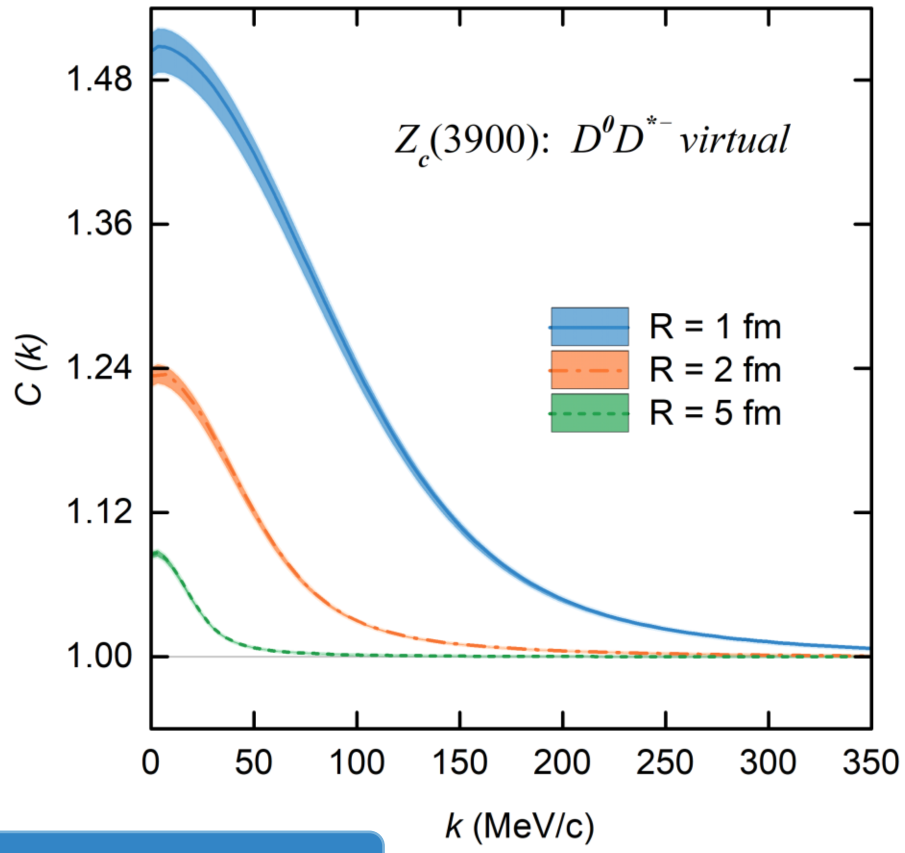
$D^0 D^{*-}$ CFs for $Z_c(3900)$

*Zhi-Wei Liu, Ming-Zhu Liu, Jun-Xu Lu and **LSG***, 2404.18607*

Resonant state scenario



Virtual state scenario

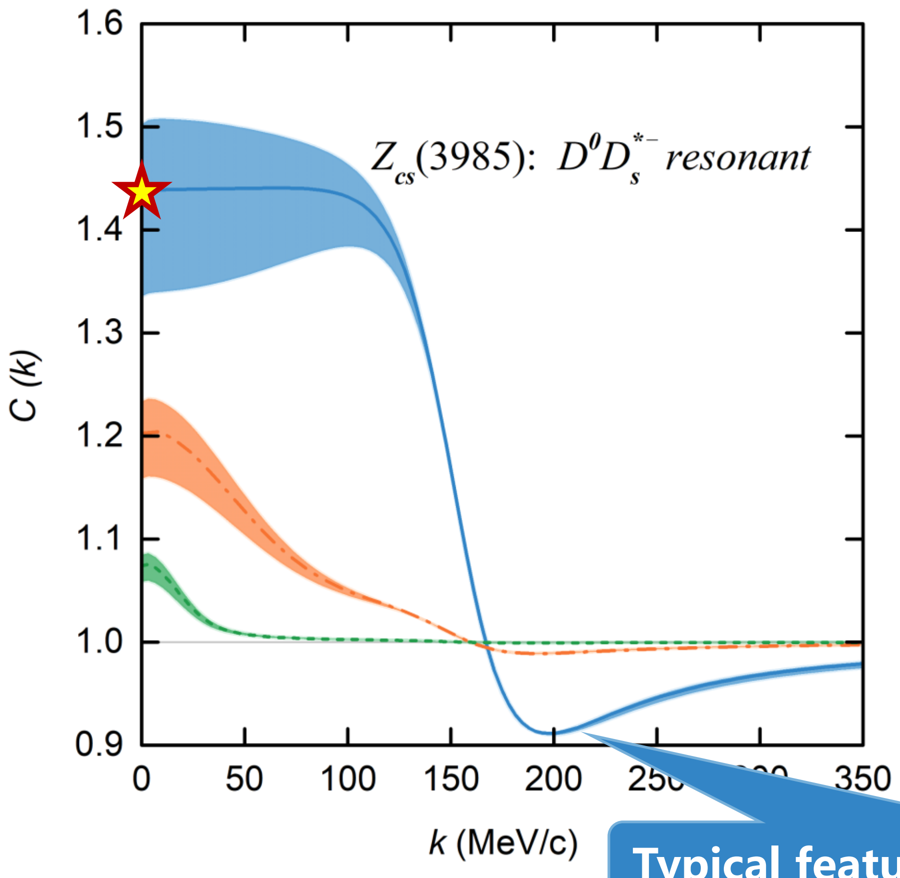


Typical feature of broad resonant state

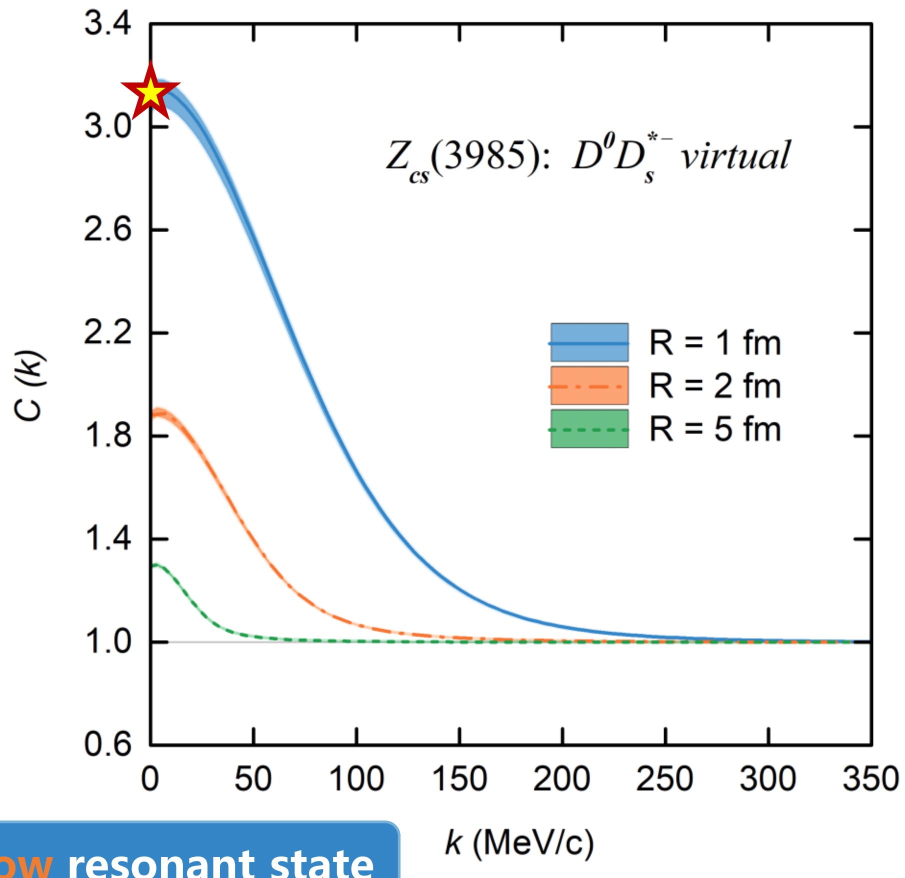
$D^0 D_s^{*-}$ CFs $Z_{cs}(3985)$

Zhi-Wei Liu, Ming-Zhu Liu, Jun-Xu Lu and **LSG*,** 2404.18607

Resonant state scenario



Virtual state scenario



Typical feature of narrow resonant state

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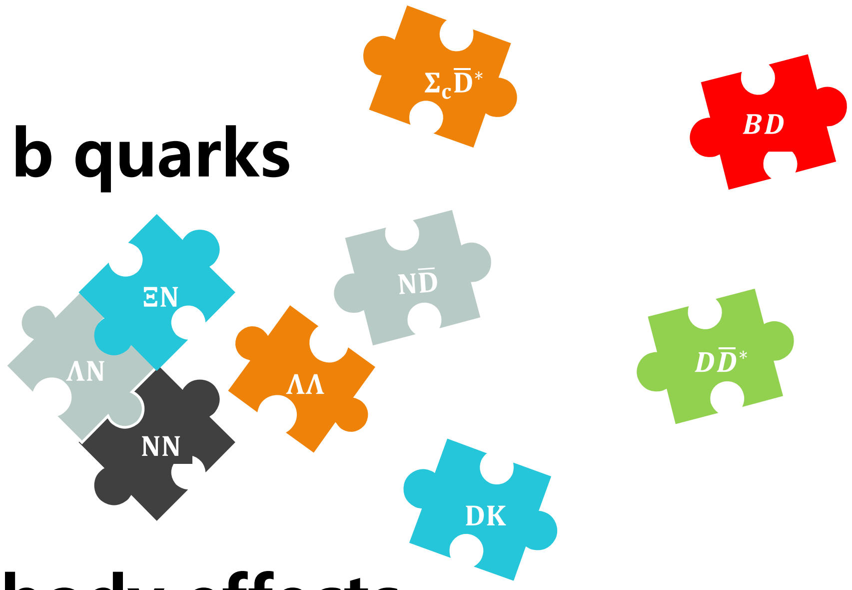
- ☞ **Summary and outlook**

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.**
  - ✓ DK correlation functions can be used to verify or refute the molecular picture of $D_{s0}^*(2317)$
  - ✓ $\Sigma_c\bar{D}^{(*)}$ correlation functions can be used to discriminate the spins of $P_c(4440)$ and $P_c(4457)$
  - ✓ $D\bar{D}^*/D\bar{D}_s^*$ correlation functions can tell whether $Z_c(3900)/Z_{cs}(3985)$ is a resonant or virtual state

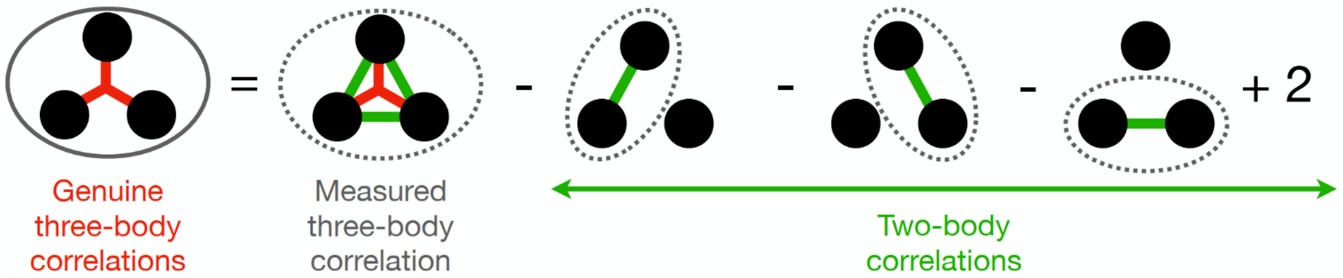
Summary and outlook

☐ More two-hadron correlations involving s, c, b quarks



DD^*, I. Vidana, A. Feijoo, M. Albaladejo, J. Nieves, and E. Oset, PLB 846 (2023) 138201
DD^*, Y. Kamiya, T. Hyodo, and A. Ohnishi, EPJA 58 (2022) 131
BB^*, A. Feijoo, L. R. Dai, L. M. Abreu, and E. Oset, PRD 109 (2024) 016014
BD, H.P. Li, J.Y. Yi, C.W. Xiao, D.L. Yao, W.H. Liang, and E. Oset, CPC (2024)
......

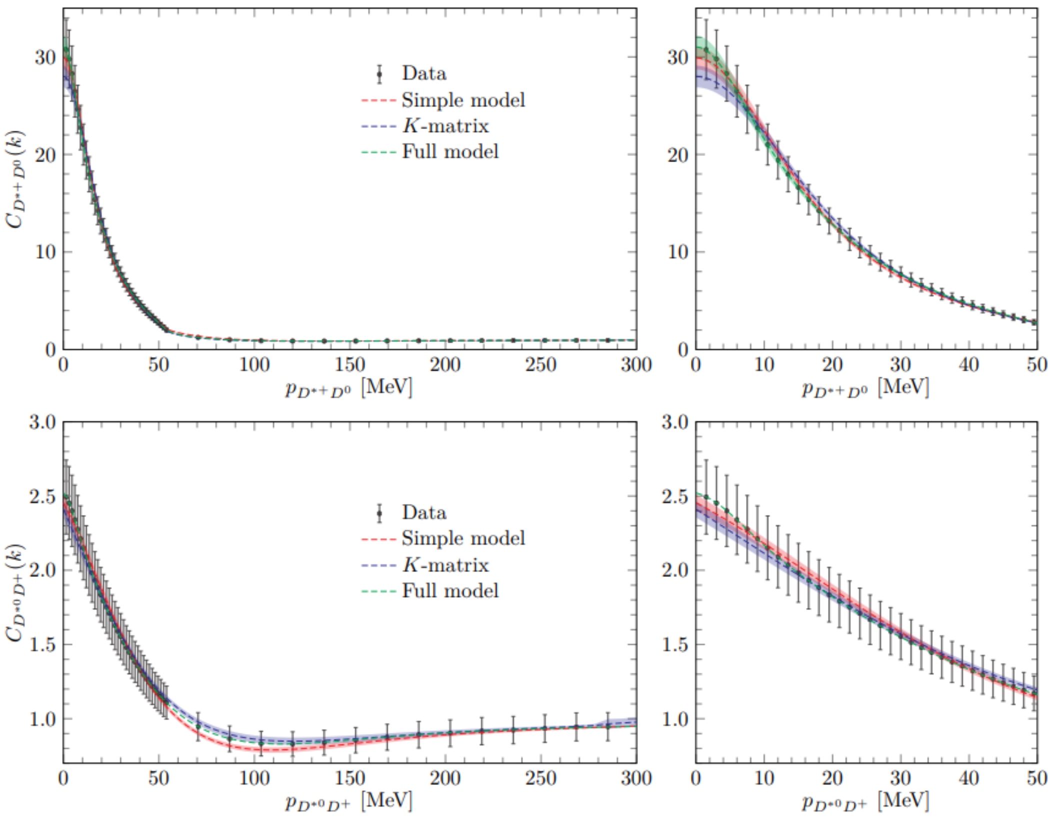
☐ Three-particle correlations — genuine three-body effects



ppp, ppΛ, ALICE Collaboration, Eur. Phys. J. A 59 (2023) 145
$ppK^{\pm}$, ALICE Collaboration, Eur. Phys. J. A 59 (2023) 298
ppp, A. Kievsky and et al., Phys. Rev. C 109 (2024) 034006

Summary and outlook

- One can also perform inverse studies and extract hadron-hadron interaction from the exp. CF data



Inverse problem in femtoscopic correlation functions: The Tcc(3875)+ state,
Albaladejo , Feijoo , Vidaña , Nieves , and Oset, 2307.09873

$$C_{D^0 D^{*+}}(p_{D^0}) = 1 + 4\pi\,\theta(\Lambda - p_{D^0}) \int_0^\infty dr r^2 S_{12}(r) \times \left\{ \left| j_0(p_{D^0} r) + T_{11}(s)\widetilde{G}_1(r;s) \right|^2 + \left| T_{12}(s)\widetilde{G}_2(r;s) \right|^2 - j_0^2(p_{D^0} r) \right\} , \tag{1}$$

$$C_{D^+ D^{*0}}(p_{D^+}) = 1 + 4\pi\,\theta(\Lambda - p_{D^+}) \int_0^\infty dr r^2 S_{12}(r) \times \left\{ \left| j_0(p_{D^+} r) + T_{22}(s)\widetilde{G}_2(r;s) \right|^2 + \left| T_{12}(s)\widetilde{G}_1(r;s) \right|^2 - j_0^2(p_{D^+} r) \right\} , \tag{2}$$