Femtoscopy probes of $Z_c(3900)$, $Z_{cs}(3985)$, and the isovector partner of the $X(3872)$

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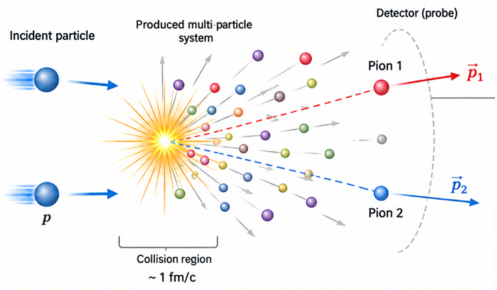
PID2023-147458NB-C21

PPS, M. Albaladejo, F.-K Guo, and J. Nieves, arXiv:2608.01237

Correlation function in experiments

- Femtoscopic correlation function

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

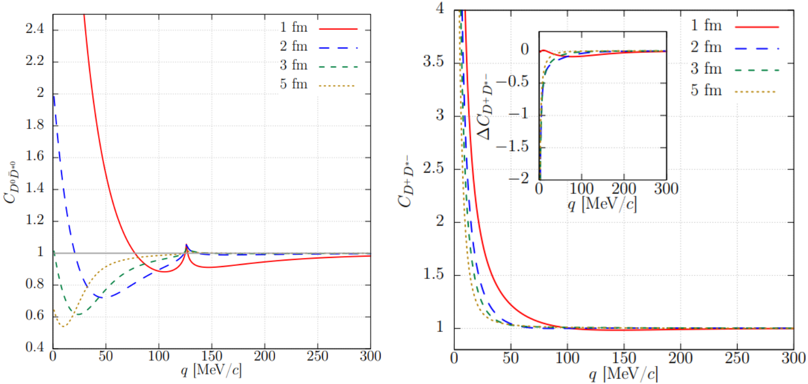


- $\xi(k)$: normalization factor
- $N_{\text{same}}(k^*)$: Events distribution for the correlated two particles
- $N_{\text{mixed}}(k^*)$: Mixed events distribution for the uncorrelated two particles

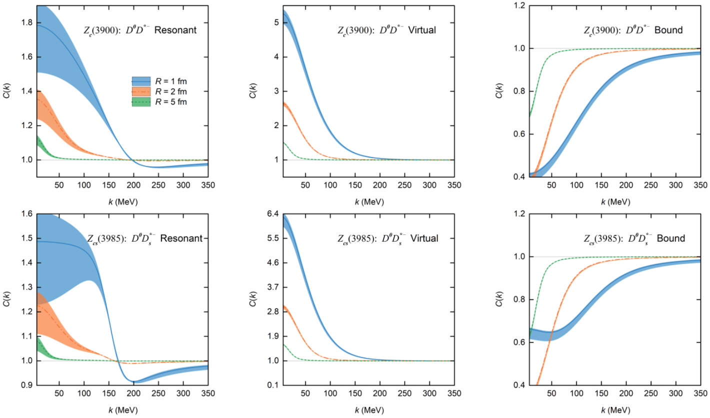
- $\pi\pi$, pp, $p\Lambda$, $\Lambda\Lambda$,... Alice, PRC 92(2015)054908, PRC 99(2019)024001, ...
- $D\pi$ and DK, $\bar{D}p$ and $D\bar{p}$... Alice, PRD 106(2022)052010, PRD 110(2024)032004

CF in hidden-charm system

- $D^0\,\overline{D}^{*0}$–$D^+\,D^{*-}$ system without the contributions from the isovector channel Yuki Kamiya, et al, EPJA 58(2022)131

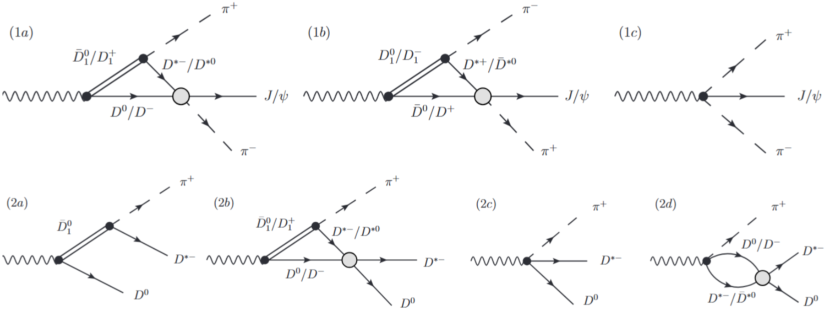


- $D^0 D^{*-}$ and $D^0 D_s^{*-}$ CFs in different scenarios Ming-Zhu Liu, et al, Sci.Bull. 70(2025)3515-3521



Comparing line shapes and the femtoscopic CF

- Production of $Z_c(3900)$ in $e^+e^- \to Y(4230/4260) \to D\bar{D}^*\pi(J/\psi\pi\pi)$: G-parity conservation Meng-Lin Du, et al, PRD 105(2022)074018



- In CF, we do not have definite G-parity: coupled-channel analysis for the $D\bar{D}^*$–$D^*\bar{D}$ systems

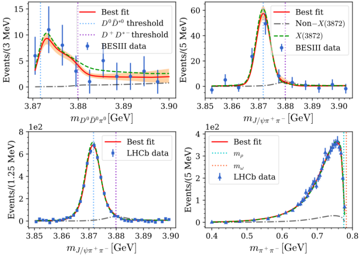
Effect of the C-even channel

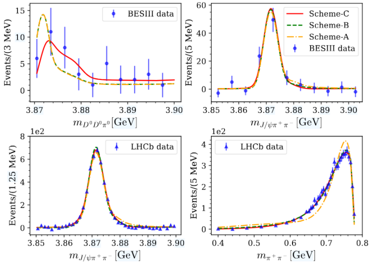
- Contributions from both C-even and C-odd

$$|D\bar{D}^*\rangle_+ = \frac{1}{\sqrt{2}}\left(|D^*\bar{D}\rangle + |D\bar{D}^*\rangle\right) \Longrightarrow |D^*\bar{D}\rangle = \frac{1}{\sqrt{2}}\left(|D\bar{D}^*\rangle_+ + |D\bar{D}^*\rangle_-\right)$$

$$|D\bar{D}^*\rangle_- = \frac{1}{\sqrt{2}}\left(|D^*\bar{D}\rangle - |D\bar{D}^*\rangle\right) \Longrightarrow |D\bar{D}^*\rangle = \frac{1}{\sqrt{2}}\left(|D\bar{D}^*\rangle_+ - |D\bar{D}^*\rangle_-\right)$$

- C-even interaction produces isovector charmonium-like state W_{c1} with $J^{PC} = 1^{++}$ Zhen-Hua Zhang, et al, JHEP 08 (2024) 130; Teng Ji, et al, arXiv:2502.04458





$X(3872)$: $160^{+57}_{-74} - 125^{+23}_{-38}\, i$ keV below the $D^0\bar{D}^{*0}$ threshold

W^0_{c1}: $3.1 \pm 0.7 + 1.3^{+1.9}_{-0.6}\, i$ MeV above the D^+D^{*-} threshold

Correlation function

Koonin-Prat formula A. Francis, et al, PRD99(2019)054505

$$C_i(k) = 1 + 4\pi \int_0^{+\infty} dr r^2 \sum_j S_j(r) \left(w_j |\tilde{\psi}_{ji}(k,r)|^2 - j_0^2(kr)\delta_{ij} \right)$$

- Wave function: $J/\psi\pi^- – D^0 D^{*-} – D^{*0} D^-$ and $J/\psi K^- – D^{*0} D_s^- – D^0 D_s^{*-}$

$$\tilde{\psi}_{ji}(k,r) = \delta_{ji} j_0(kr) + T_{ji}(E)\Theta(\Lambda - k) \int_0^{\Lambda} \frac{q^2 dq}{2\pi^2} \frac{\omega_1^j + \omega_2^j}{2\omega_1^j \omega_2^j} \frac{j_0(qr)}{E^2 - \left(\omega_1^j + \omega_2^j\right)^2 + i\varepsilon}$$

- T-matrix $T(E) = [1 - V(E)G(E)]^{-1} V(E)$

$$V_{ij}(E) = \mathcal{N}_i \widehat{V}_{ij}(E) \mathcal{N}_j\,, \quad \mathcal{N}_i = \sqrt{2m_{1,i} 2m_{2,i}}\,,$$

$$\widehat{V}(E) = \frac{1}{2} \begin{pmatrix} 0 & \sqrt{2}C_{12} & -\sqrt{2}C_{12} \\ \sqrt{2}C_{12} & C_{1X} + C'_{1Z} & C_{1X} - C'_{1Z} \\ -\sqrt{2}C_{12} & C_{1X} - C'_{1Z} & C_{1X} + C'_{1Z} \end{pmatrix}$$

with $C'_{1Z} = C_{1Z} + b\,(E^2 - m_{\rm th}^2)/(2m_{\rm th})$, C_{1X} extracted from the charged W_{c1} mass Meng-Lin Du, et al, PRD 105(2022)074018; Zhen-Hua Zhang, et al, JHEP 08(2024)130

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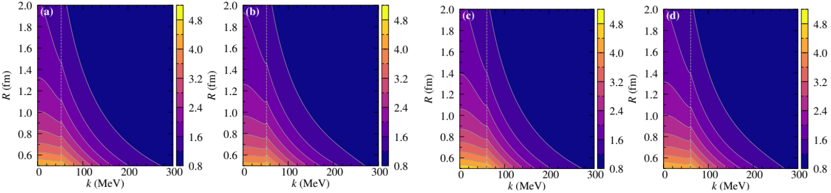
Source function: Gaussian source function

$$S_j(r) = \frac{1}{(\sqrt{4\pi})^3 R_j^3} \exp\left(-\frac{r^2}{4R_j^2} \right)$$

$D^0 D^{*-}$ $D^{*0} D_s^-$

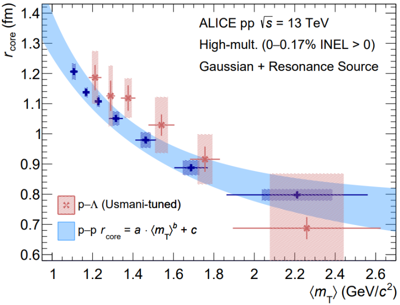


The cutoff dependence of wave function $\tilde{\psi}_{ji}(k,r)$ should be absorbed by the short-range source function to ensure the regulator-independent CFs

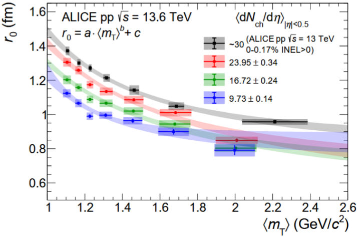
E. Epelbaum, et al, PRL 136(2026)212301, R. Molina, et al, PRD 112(2025)096006

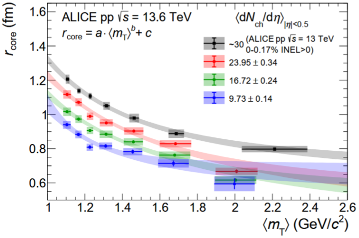
Source size in Alice

- Source size

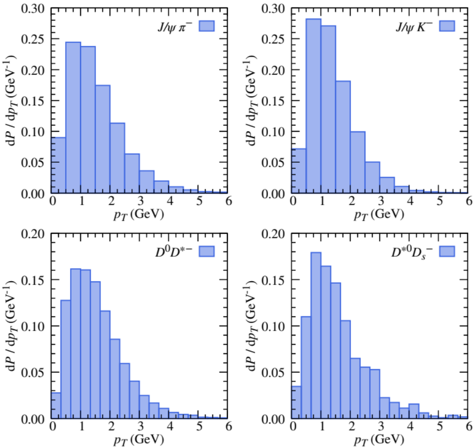


- High-multiplicity: first 0.17% inelastic pp events with $|\eta| < 1$ (Average 30 charged particles in $|\eta| < 0.5$) Alice, Nature 588(2020)232
- Source size: high-multiplicity and transverse mass $\langle m_T \rangle$ Alice, PLB 861(2025)139233, arXiv:2606.28098





Determine the source size



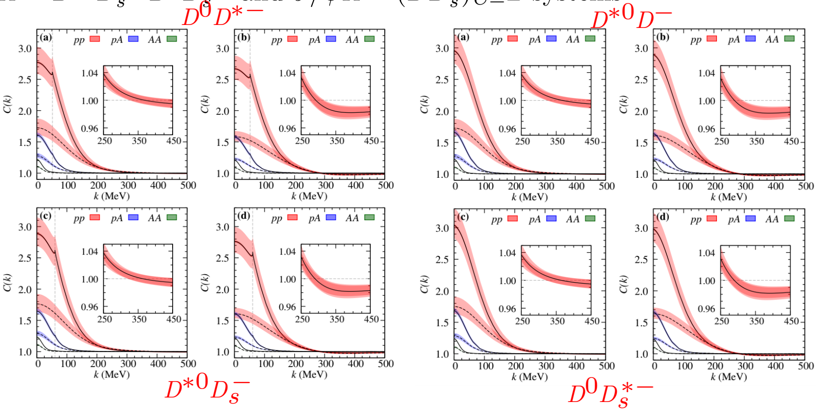
- Pythia 8: Monash 2013; hard QCD $2 \to 2$ process at $\sqrt{s} =$ 14 TeV
- Events selection: Charged pion and kaon $p_T \in [0.14, 4.0]$ and $[0.15, 2.15]$ GeV (V0 detector)
- Hadrom pairs selection: $k <$ 0.4 GeV for charmed meson pair, $k <$ 0.8 GeV for $J/\psi\pi^-$ and $J/\psi K^-$

	$J/\psi\pi^-$	$D^0\,D^{*-}$	$J/\psi K^-$	$D^{*0}\,D_s^-$
$\langle m_T \rangle$ [GeV]	2.229	2.486	2.283	2.548
$R_{\rm core}$ [fm]	0.79(6)	0.77(7)	0.79(6)	0.76(7)
$R_{\rm eff}$ [fm]	0.87(6)	0.84(7)	0.86(6)	0.84(7)

enlarged $R_{\rm core}$ about 10% for primordial resonances decay Alice, PLB 861(2025)139233

Resulting CFs

CFs in the $J/\psi\pi^{-}$–D^0D^{*-}–$D^{*0}D^{-}$ and $J/\psi\pi^{-}$–$(D\bar{D}^{*})_{C=-}$ systems
$J/\psi K^{-}$–$D^{*0}D_s^{-}$–$D^0D_s^{*-}$ and $J/\psi K^{-}$–$(D\bar{D}_s^{*})_{C=-}$ systems

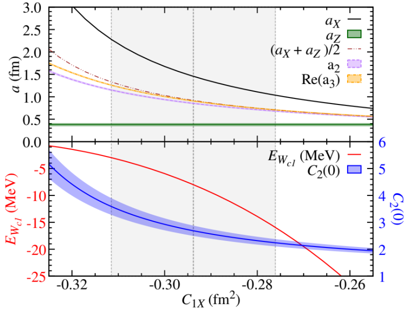


- Cusps: in the $D^{*0}D^{-}$ and $D^0D_s^{*-}$ thresholds
- Compared to the two-channel case, the C_{1X} largely changes CFs
- Resonance: CFs fall below unity ($k \geq 0.29$ GeV) M. Albaladejo, et al, PRD 108(2023)014020
- Cutoff: negligible effect ($\Lambda \in [0.6, 1.4]$ GeV) R. Molina, et al, PRD 112(2025)096006

Sensitivity of CFs to C_{1X}

- Estimate of CFs neglecting the splitting of two thresholds Yuki Kamiya, et al, EPJA 58(2022)131

$$C_{D^0 D^{*-}}(k) = C_{D^{*0} D^-}(k) = \left[\widetilde{C}_{1Z}(k) + \widetilde{C}_{1X}(k)\right]/2$$



- C_{1X} has lettle effect to the C-odd scattering length a_Z
- When W_{c1} pole is not close to the $D^0 D^{*-}$ threshold, $a_2 = a_3 = (a_Z + z_X)/2$
- $D^0 D^{*-}$ CF is sensitive to the variation of C_{1X}

- Such sensitivity can be used to determine the W_{c1} pole position

Summary

The $D^0 D^{*-}/D^{*0} D^-$ and $D^{*0} D_s^-/D^0 D_s^{*-}$ CFs can probe the C-odd and C-even sectors with source size estimating from Pythia8

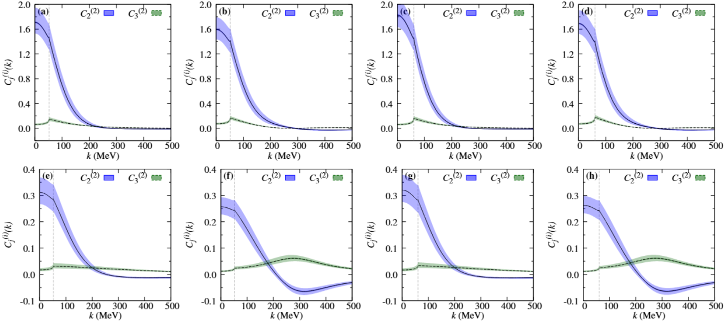
- Three-channel CFs exceed corresponding two-channel CFs $> 2.5\sigma$
- Cusps appear in the $D^{*0} D^-$ and $D^0 D_s^{*-}$ thresholds
- Cutoff has a minor effect to CFs
- CFs are sensitive to the isovector C-even interaction

Our results suggest that the measurement of the $D^0 D^{*-}/D^{*0} D^-$ CFs can probe the W_{c1} pole position; Femtoscopic studies of $D^0 \overline{D}^{*0}$ pairs should incorporate the coupled-channel dynamics of $D^0 \overline{D}^{*0}$–$D^{*0} \overline{D}^0$–$D^+ D^{*-}$–$D^{*+} D^-$.

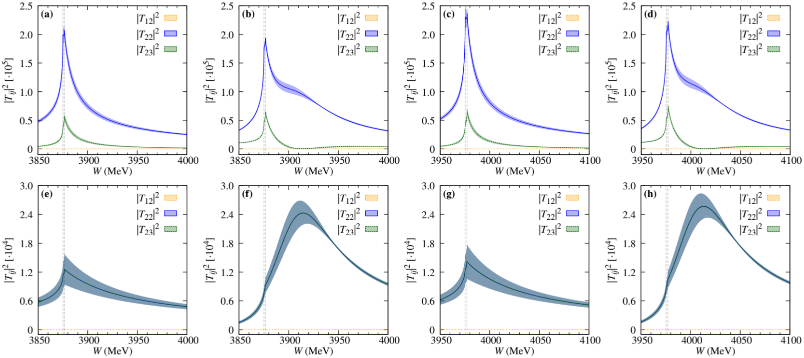
Thanks for your attention!

Backup

- Contributions from each channel



- $|T|^2$ for $C_{1X} \neq 0$ and $C_{1X} = 0$ cases



- Effect of C_{1X} to $D^0 D^{*-}$ and $D^0 D_s^{*-}$ CFs Ming-Zhu Liu, et al, Sci.Bull. 70(2025)3515-3521