NSTAR 2026

Coulomb interactions in hadronic femtoscopy: applications to the pp and $\alpha\alpha$ systems

Miguel Albaladejo (IFIC, CSIC-UV, Valencia)

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Outline

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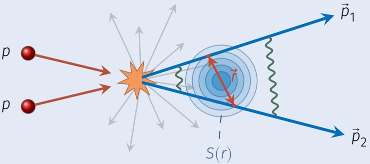
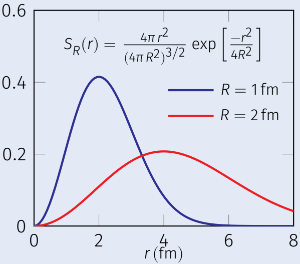
(Very basic introduction to) femtoscopy



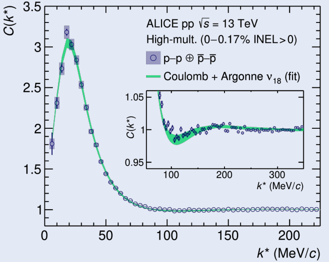
$$C_{\mathrm{exp}}(k) = \xi(k)\,\frac{N_{\mathrm{same}}(k)}{N_{\mathrm{mixed}}(k)}$$

$$C_{\mathrm{th}}(k) = \sum_{\ell=0}(2\ell+1)\int dr\, S_R(r)\,|\psi_\ell(r,k)|^2$$

$$\psi_\ell^{[\mathrm{asy,nr}]}(k,r) = j_\ell(kr) + f_\ell(k)\,\frac{e^{i(kr-\pi\ell/2)}}{r}$$



[ALICE, Phys. Lett. B **805**, 135419 (2020)]



- Known the source $S(r)$, explore interactions (encoded in the wave function)
- A new method to explore hadron interactions

[L. Fabbietti, V. Mantovani Sarti, and O. Vazquez Doce, Ann. Rev. Nucl. Part. Sci. **71**, 377 (2021)]

- Many more details in several talks:
  - W.-H. Liang [Mon 15:30]
  - P.-P. Shi [Mon 16:50]
  - D. Fujii [Mon 19:15]
  - J. M. Nieves [Tue 15:00]
  - J. Torres-Rincón [Tue 15:30]
  - L.-S. Geng [Tue 15:50]
  - K. Khemchandani [Tue 16:10]
  - A. Feijoo [Tue 16:30]
  - O. Vázquez Doce [Tue 16:50]
  - P. Encarnación [Tue 19:15]
  - M. F. Barbat [Tue 19:55]

Coulomb interactions: why they are inevitable

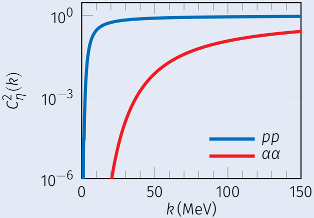
[M. Albaladejo, A. Garcia-Lorenzo, and J. Nieves, PTEP 2025, 093D02 (2025)]

- **Where** Most measured pairs are charged: pp, K^-p, $p\Xi^-$, $\alpha\alpha$, ...
- **Scales**

$$\eta(k) = \frac{k_C}{k}, \qquad k_C = Z_1 Z_2 \alpha_{\rm em}\,\mu = \frac{1}{a_B},$$

$$C_\eta^2 = |\psi_{\vec{k}}(0)|^2 = \frac{2\pi\eta}{e^{2\pi\eta}-1} \quad \text{(Sommerfeld factor)}$$

	k_C	$a_B = 1/k_C$	R
pp	3.4 MeV	57.6 fm	1.25 fm
$\alpha\alpha$	54.4 MeV	3.6 fm	5.4 — 6.5 fm



- **Cross sections vs. CFs**
  - Scattering: $dN/dk \sim k^2|\psi_k|^2$, the phase space suppresses the region $k \lesssim k_C$, precisely where $C_\eta^2 \to 0 \Rightarrow$ Coulomb is a correction, undone through the Coulomb-modified ERE, with δ_ℓ extracted where $\eta \ll 1$
  - Femtoscopy: in $C(k) = \xi(k) N_{\rm same}(k)/N_{\rm mixed}(k)$ the phase space cancels, leaving $\langle|\psi_k|^2\rangle_R$ itself, measured at $k \lesssim 100$ MeV ($\eta \gtrsim 1$) $\Rightarrow$ Coulomb is very relevant

This work

!

- Analytic Coulomb: no Schrödinger equation to be solved numerically
- Beyond LL [R. Lednicky and V. L. Lyuboshits, Yad. Fiz. **35**, 1316 (1981)]: (1) exact unitarity, (2) EFT amplitudes, (3) off-shell effects

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Coulomb interactions: formalism

[M. Albaladejo, A. Garcia-Lorenzo, and J. Nieves, PTEP 2025, 093D02 (2025)]

- **Notation**

• Free (plain) waves	$\vert\vec{k}\rangle$	$[\hat{V}=0]$
• Only Coulomb	$\vert\psi^{(\pm)}_{\vec{k}}\rangle$	$[\hat{V}=\hat{V}_C]$
• Full (Coulomb and strong)	$\vert\phi^{(\pm)}_{\vec{k}}\rangle$	$[\hat{V}=\hat{V}_C+\hat{V}_S]$

$$\widehat{H}=\widehat{H}_C+\hat{V}_S \qquad \widehat{H}_C=\widehat{H}_0+\hat{V}_C$$

- **Amplitudes** Gell-Mann-Goldberger decomposition: (two-potential trick; distorted wave theory)

[J. Nieves, Phys. Lett. B **568**, 109 (2003)]
[X. Kong and F. Ravndal, Nucl. Phys. A **665**, 137 (2000)]

$$T(\vec{k}',\vec{k}) = \langle\vec{k}'|\hat{T}_C|\vec{k}\rangle + \langle\psi^{(-)}_{\vec{k}'}|\hat{T}_{SC}|\psi^{(+)}_{\vec{k}}\rangle \equiv T_C(\vec{k}',\vec{k}) + T_{SC}(\vec{k}',\vec{k})$$

- T_{SC}: strong amplitude in the presence of Coulomb, taken between Coulomb states
- **Origin of T_{SC}** two exact relations: $\left[\hat{T}_{SC}=\hat{V}_S+\hat{V}_S\hat{G}^{(+)}_C\hat{T}_{SC};\ \hat{G}^{(\pm)}_{SC}=\hat{G}^{(\pm)}_C+\hat{G}^{(\pm)}_C\hat{V}_S\hat{G}^{(\pm)}_{SC}\right]$

(a) $\hat{T}_{SC}|\psi^{(+)}_{\vec{k}}\rangle=\hat{V}_S|\phi^{(+)}_{\vec{k}}\rangle$ (b) $|\phi^{(\pm)}_{\vec{k}}\rangle=\sum_{n=0}^{\infty}\left(\hat{G}^{(\pm)}_C(E_k)\hat{V}_S\right)^n|\psi^{(\pm)}_{\vec{k}}\rangle$

$$\Longrightarrow \qquad T_{SC}(\vec{k}',\vec{k}) = \langle\psi^{(-)}_{\vec{k}'}|\hat{V}_S|\phi^{(+)}_{\vec{k}}\rangle = \sum_{n=0}^{\infty}\langle\psi^{(-)}_{\vec{k}'}|\hat{V}_S\left(\hat{G}^{(+)}_C\hat{V}_S\right)^n|\psi^{(+)}_{\vec{k}}\rangle$$

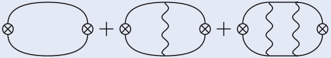
- Contact strong interaction (S-wave): $\langle\vec{q}\,'|\hat{V}_S|\vec{q}\,\rangle=C_0 \Rightarrow$ it factorizes

$$\langle\psi^{(-)}_{\vec{k}'}|\hat{V}_S|\psi^{(+)}_{\vec{k}}\rangle \overset{\text{on-shell}}{=} C_0\left[\psi^{(+)}_{\vec{k}}(\vec{0})\right]^2 = C_0\,C_\eta^2 e^{2i\sigma_0}\,, \qquad \text{each loop: } \langle\vec{0}|\hat{G}^{(+)}_C(E_k)|\vec{0}\rangle = J_0(E_k)$$

$$T_{SC}(E_k) = C_\eta^2 e^{2i\sigma_0}\Big(\overset{n=0}{C_0} + \overset{n=1}{C_0 J_0(E_k) C_0} + \cdots\Big) = \frac{C_\eta^2 e^{2i\sigma_0}}{C_0^{-1}-J_0(E_k)}$$

[M. Albaladejo, A. Garcia-Lorenzo, and J. Nieves, PTEP 2025, 093D02 (2025)]

- **Coulomb propagator** $\hat{G}_C^{(+)}(E_k) = \dfrac{1}{E_k - \widehat{H}_C + i\epsilon}$ resums all Coulomb photons
  - All we need is $\langle \vec{r} | \hat{G}_C^{(+)}(E_k) | \vec{0} \rangle$: $\vec{r} = \vec{0} \to$ amplitude; $r \neq 0 \to$ wave function
- **(Modified) loop function** $J_0(E_k) = \langle \vec{r} | \hat{G}_C^{(+)}(E_k) | \vec{0} \rangle \Big|_{\vec{r}=\vec{0}} = \displaystyle\int \frac{d^3\vec{q}}{(2\pi)^3} \frac{|\psi_{\vec{q}}^{(+)}(0)|^2}{E_k - \frac{\vec{q}^2}{2\mu} + i\epsilon}$

$J_0(E_k) =$  $+ \cdots$

  - UV divergent $\to$ one subtraction

[$\lambda = +1\,(-1)$ for repulsive (attractive) Coulomb; $\eta = \lambda\alpha\mu/k$]

$$J_0(E_k) = J_0(0) - \lambda \frac{\mu^2\alpha}{\pi} H^\lambda(\eta)\,, \qquad H^\lambda(\eta) = h^\lambda(\eta) + i\frac{C_\eta^2}{2\eta}$$

- **Coulomb ERE** $T_{SC}(E_k) = -\dfrac{2\pi}{\mu} C_\eta^2 e^{2i\sigma_0} f_{SC}(k)$, $\quad f_{SC}^{-1}(k) = C_\eta^2 k \left(\cot\delta_0 - i\right)$

$$f_{SC}^{-1}(k) + 2\lambda\alpha\mu H^\lambda(\eta) = -\frac{1}{a_0} + \frac{1}{2} r_0 k^2 + v_2 k^4 + \cdots = -\frac{2\pi}{\mu}\left[C_0^{-1}(k^2) - J_0(0)\right]$$

  - Energy-dependent $C_0(k^2)$: the ERE (or any EFT) fixes the input
- **Wave function** same resummation as in T_{SC}, now at $r \neq 0$:

$$\phi_0^*(r,k) = \psi_0^*(r,k) + \frac{T_{SC}(E_k)\; G_C^{(+)}(E_k; r)}{e^{-\pi\eta/2}\Gamma(1+i\eta)}\,, \quad G_C^{(+)}(E_k; r) = \langle \vec{r} | \hat{G}_C^{(+)}(E_k) | \vec{0} \rangle = -\frac{\mu}{2\pi r}\Gamma(1+i\eta) W_{-i\eta,\frac{1}{2}}(-2ikr)$$

Coulomb interactions: formalism (III)

[M. Albaladejo, A. Garcia-Lorenzo, and J. Nieves, PTEP 2025, 093D02 (2025)]

- **Correlation functions** Koonin-Pratt: $C(E_k) = \int d^3\vec{r}\,\tilde{S}(r)\left|\phi(\vec{r},\vec{k})\right|^2$ $\left[S(r) = 4\pi r^2 \tilde{S}(r)\right]$
- Adding and subtracting $|\psi_0|^2$ (Coulomb) and $|\phi_0|^2$ (asymptotic):

$$C(E_k) = C_C(E_k) + \Delta C_{LL}(E_k) + \delta C(E_k)$$

  - Purely Coulomb CF: $C_C(E_k) = \int d^3\vec{r}\,\tilde{S}(r)\left|\psi(\vec{r},\vec{k})\right|^2$ (all partial waves; dominated by C_η^2)
  - LL term: $\Delta C_{LL}(E_k) = \int dr\, S(r)\left(|\phi_0(r,k)|^2 - |\psi_0(r,k)|^2\right)$ (exact on-shell T_{SC}, asymptotic w.f.)
  - FRP term: $\delta C(E_k) = \int dr\, S(r)\left(|\phi_0^{\text{ex}}(r,k)|^2 - |\phi_0(r,k)|^2\right) \simeq -\beta\dfrac{d_0(k) C_\eta^2 |f_{SC}(k)|^2}{4\sqrt{\pi}R^3}$

(Famous) off-shell effects

$$d_0(k) = r_0 + 4v_2 k^2 + \cdots = 2\frac{d}{dk^2}\left(\text{Re}\, f_{SC}^{-1}(k) + 2\lambda\alpha\mu h^\lambda(\eta)\right)$$

[E. Epelbaum et al., Phys. Rev. Lett. **136**, 212301 (2026)]

Summary of our approach

!

- No numerical sol. of Schrödinger equation
- Connection with EFTs, contact interactions
- Off-shell effects partially included (β)
- Paper: all derivations, connection to other works

Outline

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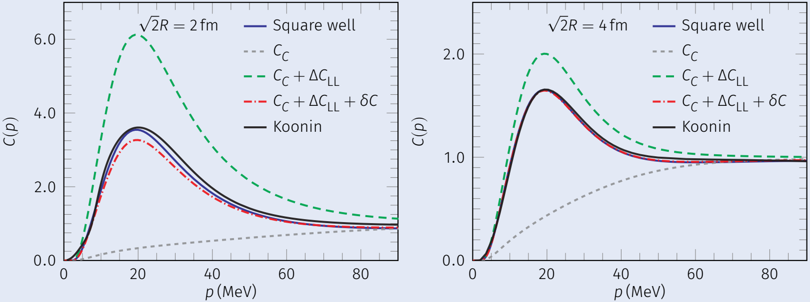
- Koonin: using the Coulomb and RSC central, spin-orbit, and diagonal tensor potentials in all pp channels ($\ell \leqslant 3$) [S. E. Koonin, Phys. Lett. B **70**, 43 (1977)] [R. V. Reid Jr., Annals Phys. **50**, 411 (1968)]
- $C(E_p) \neq 1$ (appreciably) only for a small range of p: $^1S_0$ wave (our case)
- Our input: ERE for $f_{SC}^{-1}(p) = -\dfrac{1}{a_0} + \dfrac{1}{2} r_0 p^2 + v_2 p^4 + \cdots$, same parameters as obtained with RSC
- We compare for several values of R ($\sqrt{2}R = 2 \ldots 6\,\text{fm}$): $\boxed{C(E_p) = C_C(E_p) + \Delta C_{\mathbf{LL}}(E_p) + \delta C(E_p)}$
  - ΔC_{LL} always overestimates the true CF.
  - For $\sqrt{2}R \gtrsim 4\,\text{fm}$, all curves (not LL or C_C) are very similar
  - For $\sqrt{2}R = 2\,\text{fm}$, the FRP can be improved by considering β



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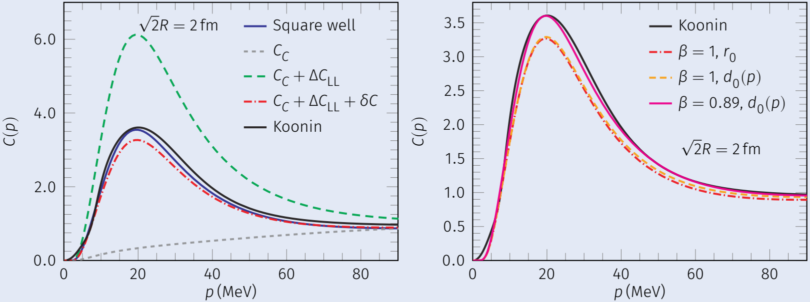

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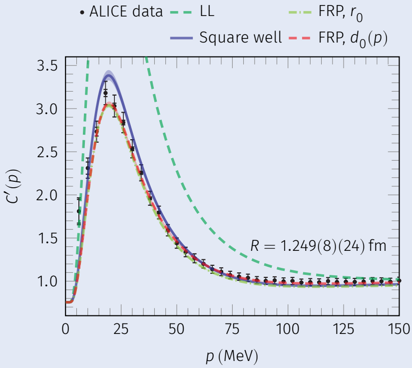
[M. Albaladejo, A. Garcia-Lorenzo, and J. Nieves, PTEP 2025, 093D02 (2025)]

- Analysis of *pp* CF: [ALICE, Phys. Lett. B **805**, 135419 (2020)]
- Data contain feed-down contributions: $C'(p) = 1 + \lambda_{pp}(C_{pp}(p) - 1) + \lambda_{pp_\Lambda}(C_{pp_\Lambda}(p) - 1)$
- $C_{pp_\Lambda}(p)$: protons from the weak Λ decay
- Same formulae for $C_{pp_\Lambda}(p)$ as ALICE (LL formula, same values $\lambda_{pp} = 0.67$, $\lambda_{pp_\Lambda} = 0.223$)
- Genuine *pp* CF [$C_{pp}(p)$]: again, our input is the ERE for $f_{SC}(p)$ (RSC paramaters)
- Results:
  - $\Delta C_{\rm LL}$ overestimates the data
  - Square well near the data



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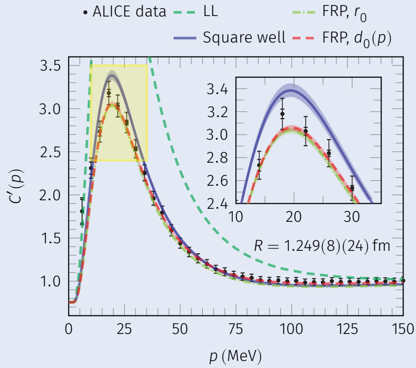

Coulomb interactions: comparison with ALICE pp data

[M. Albaladejo, A. Garcia-Lorenzo, and J. Nieves, PTEP 2025, 093D02 (2025)]

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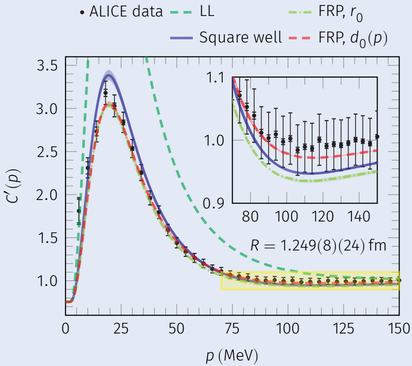

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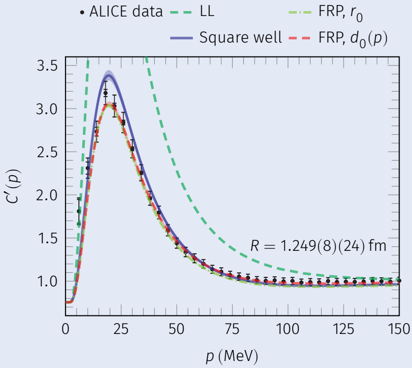
!

- No fit is performed, parameters taken from ALICE or other theoretical works
- This confirms the validity of the scheme presented here

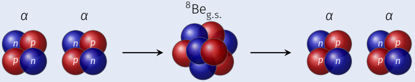


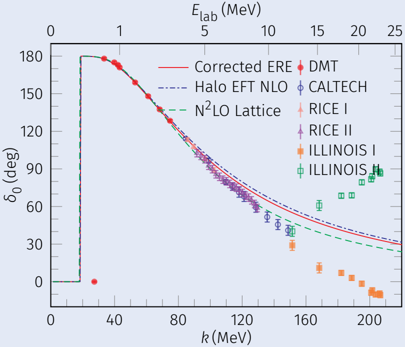
Outline

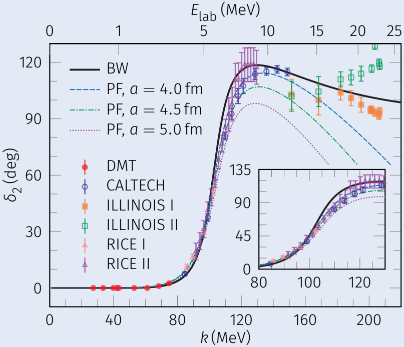
1. Introduction
2. Theoretical approach
3. Applications
   - *pp*: comparison with Koonin (theory)
   - *pp*: comparison with ALICE (experiment)
   - Application to $\alpha\alpha$
4. Conclusions

Femtoscopy for nuclear physics: $\alpha\alpha$ scattering input

[A. Garcia-Lorenzo, M. Albaladejo, A. Feijoo, and J. Nieves, *in preparation* (2026)]







Scattering input

- ^{8}Be(0^+): $E_R = 92(6)$ keV, $\Gamma_R = 5.7(4.0)$ eV, i.e. $a_0 \simeq -1.9 \times 10^3$ fm *vs.* $r_0 \simeq 1.1$ fm
- 2^+: one-level Coulomb R-matrix, $a_c = 4.5$ fm $\simeq r_c(A_1^{1/3} + A_2^{1/3})$
- Theoretical amplitudes (S-wave) fixed **before** any fit to the CF data:

——	ERE	[G. Rasche, Nucl. Phys. A **94**, 301 (1967)]
-·-·-	Halo EFT NLO	[R. Higa, H.-W. Hammer, and U. van Kolck, Nucl. Phys. A **809**, 171 (2008)]
- - -	N^{2}LO Lattice	[S. Elhatisari, T. A. Lähde, D. Lee, U.-G. Meißner, and T. Vonk, JHEP **02**, 001 (2022)]

[A. Garcia-Lorenzo, M. Albaladejo, A. Feijoo, and J. Nieves, *in preparation* (2026)]

Genuine CF Two identical spin-0 bosons $\Rightarrow$ exchange-even projection. Only $\ell = 0, 2$ kept.

$$C_{\alpha\alpha}(k;R) = C_C^{(E)} + 8\pi \sum_{\ell=0,2,\ldots} (2\ell+1) \left\langle |\phi_\ell|^2 - |\psi_\ell|^2 \right\rangle_R + \Delta C_{\text{FRP}}^{(E)}$$

$$\Delta C_{\text{FRP},0}^{(E)} \simeq -4\pi\, d_0(k)\, C_\eta^2 |f_0(k)|^2 S_R(0)$$

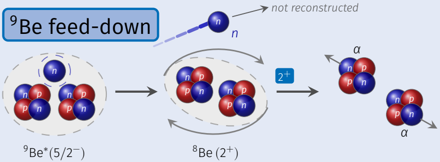
factor 2 from Bose symmetry

What is fitted not the genuine CF:

$$C_{\text{raw}}(k;R) = N\left[1 + \lambda\left(C_{\text{ext}} - 1\right) + \beta\, C_{\text{FRP}} + \gamma\, C_{^9\text{Be}}(k)\right]$$

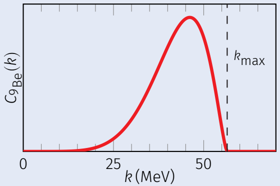
- λ: core–halo dilution
- β: strength of the FRP term ($\beta = 1$ extended source, $\beta = 0$ no FRP correction)
- γ: ^{9}Be feed-down
- N: normalization
- Folded with the momentum resolution, $C_{\text{fit}} = C_{\text{raw}} \otimes G_{\sigma_p}$: it is what smears the $^8\text{Be}_{\text{g.s.}}$ peak
- Fit: R, λ, β, γ, N, σ_p
- The amplitude is fixed beforehand

^{9}Be feed-down



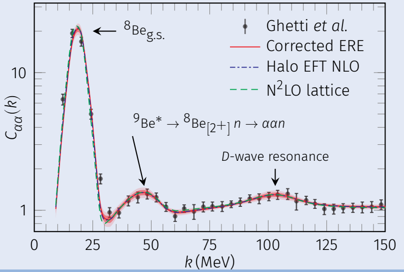
- $N \propto k^{2\ell_{\alpha\alpha}+2}(k_{\max}^2 - k^2)^{\frac{2\ell_n+1}{2}}$, $k_{\max} = 56.5$ MeV
- This mechanism: $(\ell_{\alpha\alpha}, \ell_n) = (2, 1)$

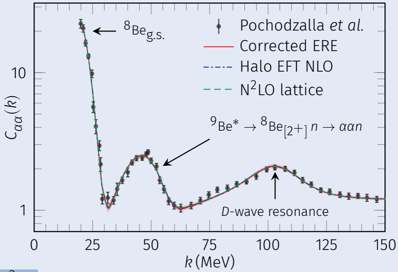
$$C_{^9\text{Be}} = \mathcal{C}_0\, x^6 (1 - x^2)^{3/2} \theta(1 - x)\,, \quad x = k/k_{\max}$$



Femtoscopy for nuclear physics: fits to $\alpha\alpha$ CFs

[A. Garcia-Lorenzo, M. Albaladejo, A. Feijoo, and J. Nieves, *in preparation* (2026)]





Data	Input	R (fm)	σ_p (MeV)	β	$\chi^2_{\rm red}$
Ghetti	Corr. ERE	6.47(35)	3.40(10)	0.40(10)	1.99
	N^{2}LO latt.	6.42(34)	3.29(9)	−0.03(17)	2.14
Pochodzalla	Corr. ERE	5.43(13)	4.09(7)	0.61(3)	1.29
	N^{2}LO latt.	5.58(11)	4.25(7)	0.33(5)	1.24

Halo EFT NLO indistinguishable from the corrected ERE

Data: [R. Ghetti et al., Phys. Rev. C **70**, 027601 (2004)]
[J. Pochodzalla et al., Phys. Rev. C **35**, 1695 (1987)]

- R stable against th. inputs, β is not
- Errors rescaled by $\simeq 3.5$
- $\lambda \simeq 0.5$ absorbs more than core–halo
- Not included: higher waves, other resonances, other feed-downs, ...

Outlook for $\alpha\alpha$/nuclear

!

- We are able to obtain the source (in agreement with exp. expectations)
- With better experiments (statistics, resolution, finer bins) we might be able to discriminate/improve theoretical models
- Could this help in pinning down other nuclear states?

Outline

General conclusions

- Femtoscopy gives new experimental access to hadron and nuclear interactions
- Many measured pairs are charged. Coulomb is not just a correction, but the dominant effect at low energies, and must be treated together with the strong interaction

Coulomb interactions: analytical methods

[PTEP 2025, 093D02 (2025)]

- No need of numerical solution of Sch. eq., possibility to connect with EFTs
- Exact elastic unitarity and full Coulomb left-hand discontinuity
- Finite-range (off-shell) corrections, controlled by $d_0(p) = r_0 + 4v_2 p^2 + \cdots$
- Good agreement with Koonin theoretical calculations and with *pp* ALICE CFs data, with no fit

$\alpha\alpha$: femtoscopy for nuclear physics

[A. Garcia-Lorenzo et al., *in preparation* (2026)]

- First fully theoretical description of the $\alpha\alpha$ CF
- Coulomb-distorted waves, Bose symmetry, 0^+ and 2^+ channels of ^{8}Be, ^{9}Be* feed-down, momentum resolution
- Source radii stable against the three *S*-wave inputs

Outlook

- Decades-old $\alpha\alpha$ data are already sensitive to the interaction model and to the finite-range term
- Precise measurements would turn $\alpha\alpha$ CFs into an independent benchmark of nuclear-cluster dynamics
- Extension to 3α systems, and to any charged pair

Thank you!

Coulomb interactions in hadronic femtoscopy: applications to the pp and $\alpha\alpha$ systems

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Backup slides