INSIGHTS FROM D-MESON FEMTOSCOPY USING T-MATRIX CALCULATIONS

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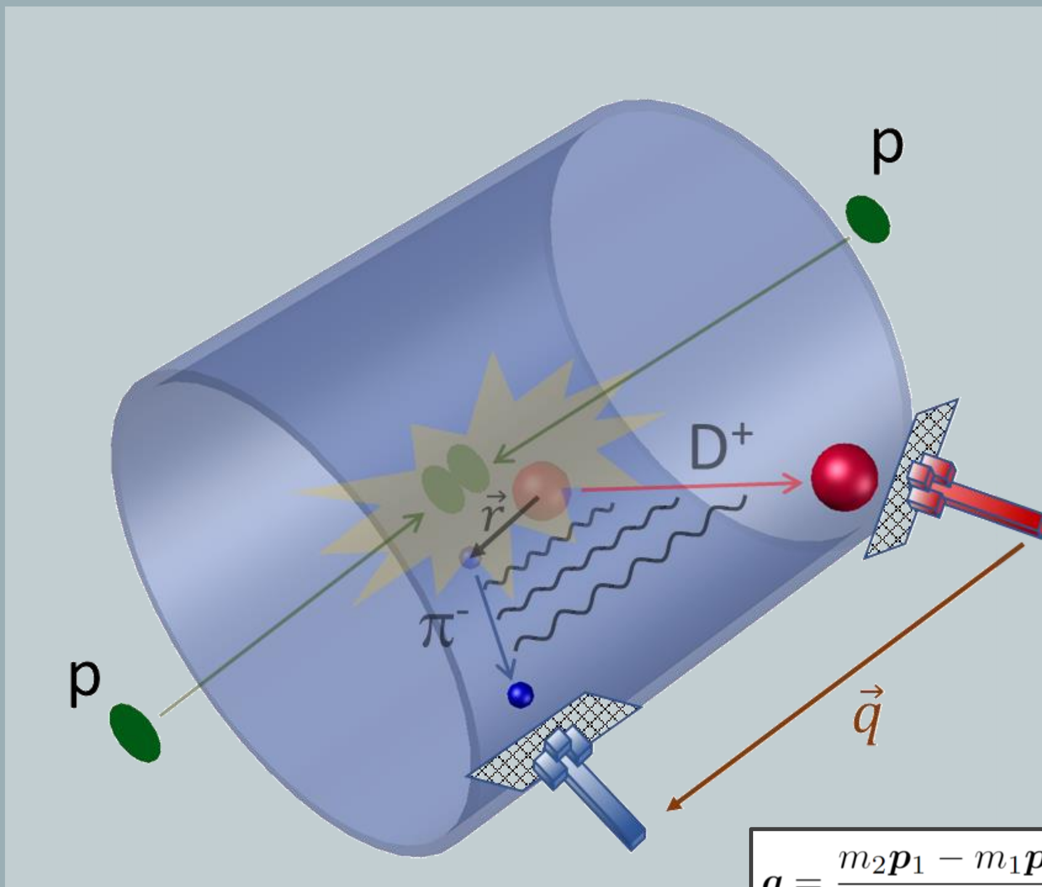
Femtoscopy in RHICs

Heinz, Jacak, *Ann.Rev.Nucl.Part.Sci.* 49 (1999) 529
Lisa, Pratt, Wiedemann,
Ann.Rev.Nucl.Part.Sci. 55 (2005) 357



Pair Correlation Function

$$C(\boldsymbol{q}) = \mathcal{N}\,\frac{N_{\mathrm{same}}(\boldsymbol{q})}{N_{\mathrm{mixed}}(\boldsymbol{q})}$$

$$C(\boldsymbol{q}) > 1 : \text{correlation}$$
$$C(\boldsymbol{q}) < 1 : \text{anticorrelation}$$

$$\boldsymbol{q} = \frac{m_2\boldsymbol{p}_1 - m_1\boldsymbol{p}_2}{m_1 + m_2}$$

Koonin-Pratt formula

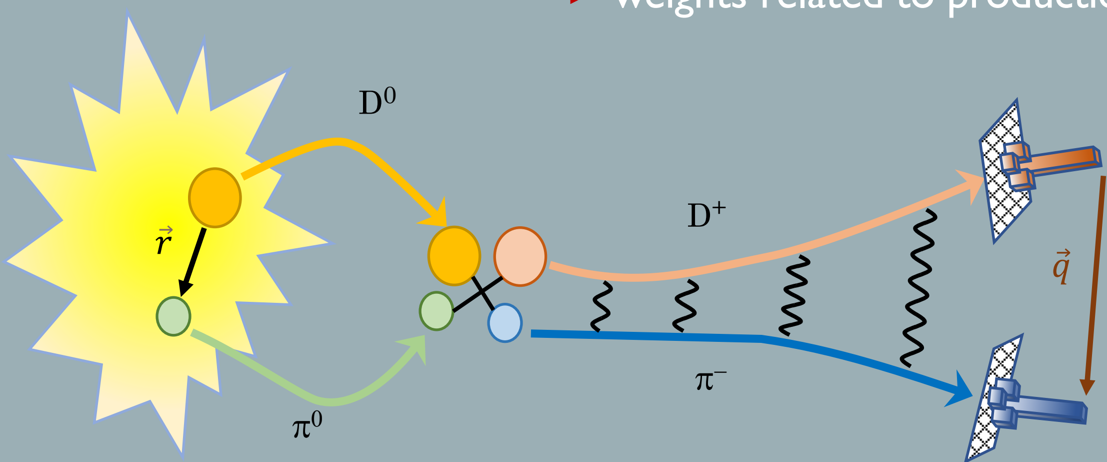
Koonin, *Phys.Lett.B*, 70, 43 (1977)
Pratt, Csorgo, Zimanyi, *Phys.Rev.C*, 42, 2646(1990)

Koonin-Pratt formula

$$C(\boldsymbol{q}) = \int d^3r \sum_i w_i \; S_i(\boldsymbol{r}) \; |\Psi_i(\boldsymbol{q};\boldsymbol{r})|^2$$

Wave function connecting initial channel with observed one

weights related to production mechanism of channels



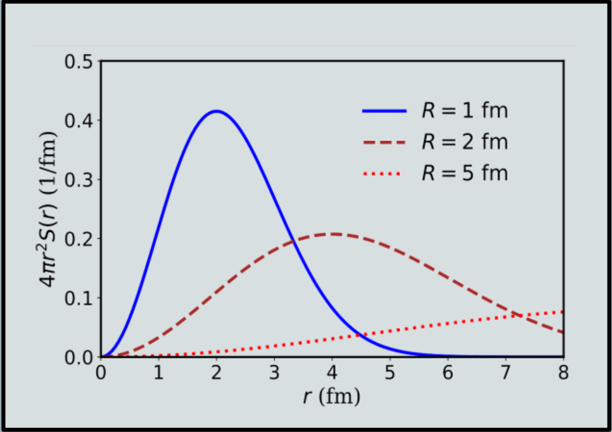
$C(\boldsymbol{q}) > 1$: attraction
$C(\boldsymbol{q}) < 1$: repulsion

Fabbietti, Mantovani Sarti, Vazquez Doce, *Ann. Rev. Nucl. Part. Sci,* 71, 377 (2021)

Correlation function

Gaussian source function

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



Complete Coulomb wave function

$$C(q) = \int d^3r S(r)\, |\Phi_f^{\mathrm{C}}(\boldsymbol{q};\boldsymbol{r})|^2 + \int 4\pi r^2\, dr S(r) \left[\sum_i w_i\, |\varphi_i(q;r)|^2 - |\Phi_{0\,f}^{\mathrm{C}}(q\,r)|^2\right]$$

s-wave strong + Coulomb wf

s-wave Coulomb wf

Joachain, *Quantum Collision Theory* (1975)

Wave function and scattering T matrix

$$\hat{H}|\Psi\rangle = E|\Psi\rangle$$

$$\hat{H}_0|\Phi\rangle = E|\Phi\rangle$$

$$V|\Psi\rangle = T|\Phi\rangle$$

Lippmann-Schwinger equation

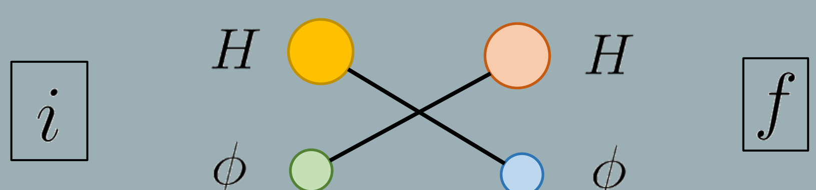
$$|\Psi\rangle = |\Phi\rangle + \frac{1}{E - \hat{H}_0 + i\eta} T\,|\Phi\rangle$$

Interacting wave func.

Free wave func.

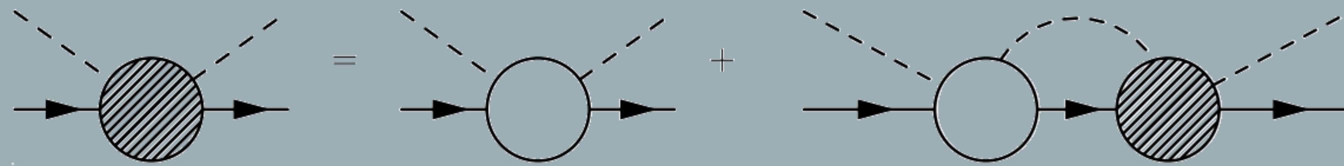
strong
+
Coulomb

$$\varphi_i(q;r) = j_0(qr)\delta_{if} + \int_0^\infty \frac{4\pi q'^2\,dq'}{(2\pi)^3} \frac{T_{if}(q',q;\sqrt{s})\,j_0(q'r)}{2\omega_{H,i}\,2\omega_{\phi,i}(\sqrt{s} - \omega_{H,i} - \omega_{\phi,i} + i\eta)}$$



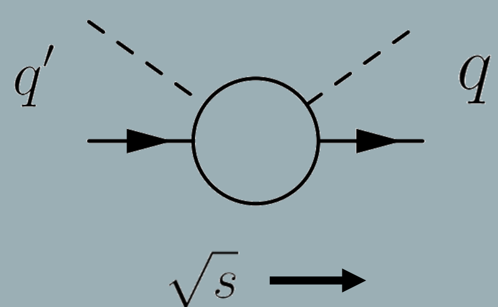
Off-shell T matrix $i \to f$

Off-shell T-matrix equation



$$T_{if}(q', q; \sqrt{s}) = V_{if}(q', q; \sqrt{s}) + \sum_l \int_0^\infty \frac{4\pi k^2 dk}{(2\pi)^3} \frac{V_{il}(q', k; \sqrt{s})\, T_{lf}(k, q; \sqrt{s})}{2\omega_{H,l}\, 2\omega_{\phi,l}\, (\sqrt{s} - \omega_{H,l} - \omega_{\phi,l} + i\eta)}$$

$$V_{if}(q', q; \sqrt{s})$$



q : on-shell
q': off-shell

Regulator: Form Factor

$$f(q, q') = \exp\left(-\frac{q^2 + q'^2}{\Lambda^2}\right)$$

$$\Lambda = 800 \text{ MeV}/c$$

Heavy-meson effective theory

$$
\begin{aligned}
\mathcal{L}_{\rm LO} &= \mathcal{L}_{\rm LO}^{\rm ChPT} + \langle \nabla^\mu H \nabla_\mu H^\dagger \rangle - m_H^2 \langle H H^\dagger \rangle - \langle \nabla^\mu H^{*\nu} \nabla_\mu H_\nu^{*\dagger} \rangle + m_H^2 \langle H^{*\nu} H_\nu^{*\dagger} \rangle \\
&+ ig \langle H^{*\mu} u_\mu H^\dagger - H u^\mu H_\mu^{*\dagger} \rangle + \frac{g}{2m_D} \langle V_\mu^* u_\alpha \nabla_\beta H_\nu^{*\dagger} - \nabla_\beta V_\mu^* u_\alpha H_\nu^{*\dagger} \rangle \epsilon^{\mu\nu\alpha\beta} \ , \\
\mathcal{L}_{\rm NLO} &= \mathcal{L}_{\rm NLO}^{\rm ChPT} - h_0 \langle H H^\dagger \rangle \langle \chi_+ \rangle + h_1 \langle H \chi_+ H^\dagger \rangle + h_2 \langle H H^\dagger \rangle \langle u^\mu u_\mu \rangle + h_3 \langle H u^\mu u_\mu H^\dagger \rangle \\
&+ h_4 \langle \nabla_\mu H \nabla_\nu H^\dagger \rangle \langle u^\mu u^\nu \rangle + h_5 \langle \nabla_\mu H \{u^\mu, u^\nu\} \nabla_\nu H^\dagger \rangle \\
&+ \tilde{h}_0 \langle H^{*\mu} H_\mu^{*\dagger} \rangle \langle \chi_+ \rangle - \tilde{h}_1 \langle H^{*\mu} \chi_+ H_\mu^{*\dagger} \rangle - \tilde{h}_2 \langle H^{*\mu} H_\mu^{*\dagger} \rangle \langle u^\nu u_\nu \rangle - \tilde{h}_3 \langle H^{*\mu} u^\nu u_\nu H_\mu^{*\dagger} \rangle \\
&- \tilde{h}_4 \langle \nabla_\mu H^{*\alpha} \nabla_\nu H_\alpha^{*\dagger} \rangle \langle u^\mu u^\nu \rangle - \tilde{h}_5 \langle \nabla_\mu H^{*\alpha} \{u^\mu, u^\nu\} \nabla_\nu H_\alpha^{*\dagger} \rangle ,
\end{aligned}
$$

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

$$H_\mu^* = \left(D_\mu^{*0} \ D_\mu^{*+} \ D_{s,\mu}^{*+} \right)$$

$$u_\mu = i(u^\dagger \partial_\mu u - u \partial_\mu u^\dagger)$$

$h_i, \tilde{h}_i$: NLO low-energy constants
Guo et al. *Eur. Phys. J.C79*, 1, 13 (2019)

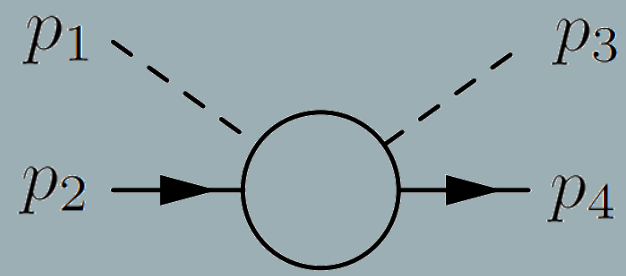
$$u = \exp\left[\frac{i}{\sqrt{2} f_\pi} \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix} \right]$$

Kolomeitsev, Lutz *Phys.Lett. B*582 (2004) 39; Hofmann, Lutz *Nucl.Phys.A*733 (2004) 142; Guo, Hanhart. Krewald, Meissner *Phys.Lett. B*666 (2008) 251; Geng, Kaiser, Martin-Camalich, Weise *Phys.Rev.D*82,05422 (2010); Abreu, Cabrera, Llanes-Estrada, JMT-R. *Annals Phys.* 326 (2011) 2737…

Heavy-meson effective theory

$$V_{ij}(p_1,p_2,p_3,p_4) = \frac{1}{f_\pi^2}\Big[\frac{C_{\rm LO}^{ij}}{4}\left[(p_1+p_2)^2-(p_2-p_3)^2\right] - 4C_0^{ij}h_0 + 2C_1^{ij}h_1$$
$$-2C_{24}^{ij}\Big(2h_2(p_2\cdot p_4) + h_4\big((p_1\cdot p_2)(p_3\cdot p_4)+(p_1\cdot p_4)(p_2\cdot p_3)\big)\Big)$$
$$+2C_{35}^{ij}\Big(h_3(p_2\cdot p_4) + h_5\big((p_1\cdot p_2)(p_3\cdot p_4)+(p_1\cdot p_4)(p_2\cdot p_3)\big)\Big)\Big]$$

$$p_1^\mu = \left(\frac{s+m_1^2-m_2^2}{2\sqrt{s}}, \boldsymbol{p}\right)$$



Montaña, Ramos, Tolos, JMT-R, *Phys.Rev.D*, 102, 096020 (2020),
Montaña, PhD thesis, U. Barcelona 2022

s-wave partial wave

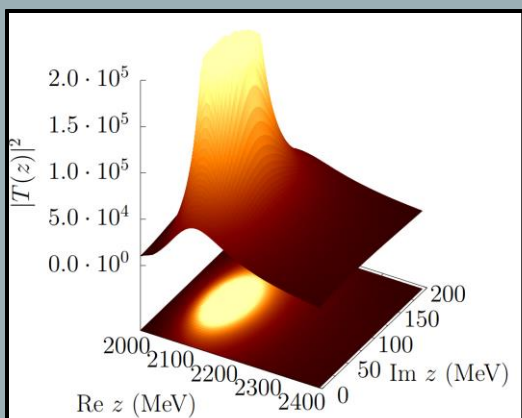
$$V_{ij}^{\rm s-wave}(p,p';\sqrt{s}) = \frac{1}{2}\int_{-1}^{1} d\cos\theta_{\boldsymbol{pp'}}\; V_{ij}(p_1,p_2,p_3,p_4)$$

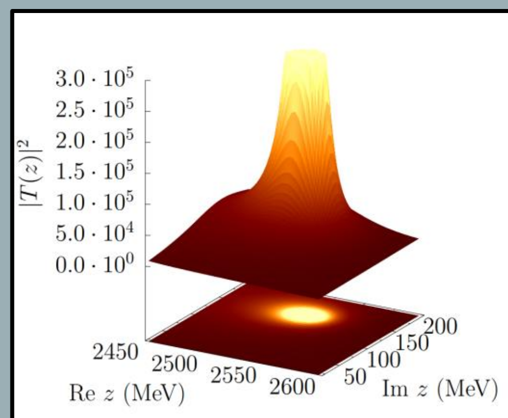
On-shell T-matrix

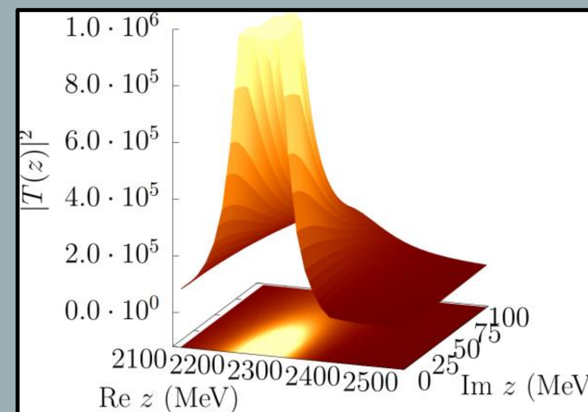
$$T = V(1 - VG)^{-1}$$

Oller, Oset, *Nucl.Phys.A*620 (1997) 438
Oset, Ramos, *Nucl.PhysA*635 (1998) 99

Montaña, Ramos, Tolos, JMT-R
*Phys.Lett.B*806 (2020) 135464
*Phys.Rev.D*102, 096020, (2020)







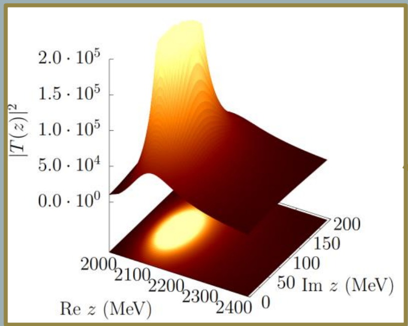
$D_0^*(2300)$

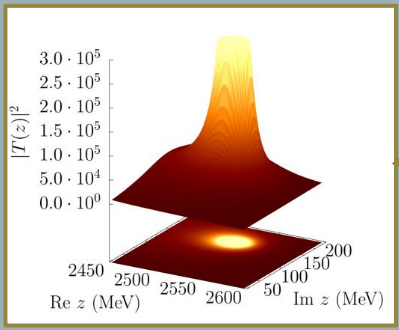
$D_{s0}^*(2317)$

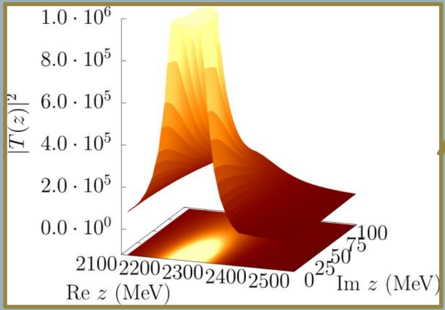
Two-pole structure of $D_0^*(2300)$ (also $D_1^*(2430)$ in *J* = 1)

M. Albadalejo *et al. Phys.Lett.B* 767 (2017) 465 ; Guo *et al. Eur.Phys.J.C*79 (2019)13;
U. Meissner, *Symmetry* 12 (2020) 6, 981; JMT-R, *Symmetry* (2022)13 (2021), 8, 1400

Off-shell vs on-shell







JMT-R, Ramos, Tolos, 2307.03640 [hep-ph]

$J=0$			$J=1$		
Generated state	(S,I)	$\sqrt{s}$ (MeV)	Generated state	(S,I)	$\sqrt{s}$ (MeV)
$D_0^*(2300)$ (lower pole)	$(0,1/2)$	2125	$D_1(2430)$ (lower pole)	$(0,1/2)$	2267
$D_0^*(2300)$ (higher pole)	$(0,1/2)$	2462	$D_1(2430)$ (higher pole)	$(0,1/2)$	2606
$D_{s0}^*(2317)$	$(1,0)$	2320	$D_{s1}(2460)$	$(1,0)$	2464

Off-shell T-matrix

- 2307.03640
- Maxima of |T| on real axis
- Form factor regulator

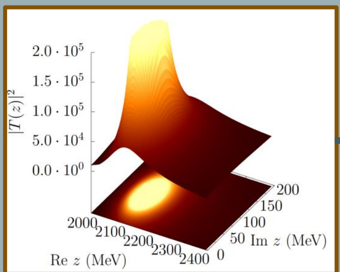
On-shell T-matrix

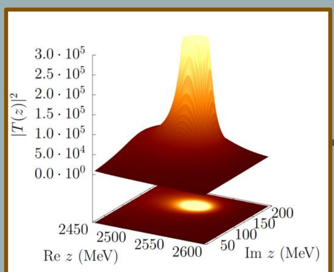
- PRD102, 096020, 7 (2020)
- Poles in complex plane
- Hard cutoff regulator

Consistency between the two!

Scattering lengths

JMT-R, Ramos, Tolos, 2307.03640 [hep-ph]





	(S,Q)	channel (particle)	a [fm]	channel (isospin)	$a_{I_<}$ [fm]	$a_{I_>}$ [fm]
	$(-1,0)$	$D^0\bar{K}^0$	0.071		$(I_< = 0)$	$(I_> = 1)$
Attractive		D^+K^-	0.083			
	$(0,0)$	$D^0\pi^0$	0.056		$(I_< = 1/2)$	$(I_> = 3/2)$
Attractive		$D^+\pi^-$	0.253	$D\eta$	$0.072 + i\,0.066$	
		$D^0\eta$	$0.071 + i\,0.065$		$(I_< = I_> = 1/2)$	
Attractive		$D_s^+K^-$	$-0.114 + i\,0.693$	$D_s\bar{K}$	$-0.114 + i\,0.694$	
Repulsive	$(0,+2)$	$D^+\pi^+$	-0.102			
Attractive	$(1,0)$	$D_s^+\pi^-$	0.0033	$D_s\pi$		0.0032
		D^0K^0	$-0.027 + i\,0.084$			$(I_> = I_< = 1)$
Attractive	$(1,+2)$	$D_s^+\pi^+$	0.0031			
Repulsive		D^+K^+	$-0.026 + i\,0.083$			
Repulsive	$(2,+2)$	$D_s^+K^+$	-0.220		$(I_< = I_> = 1/2)$	

$$a_i = -\frac{T_{ii}(m_1+m_2)}{8\pi(m_1+m_2)}$$

- $a > 0$: attractive
- $a < 0$: repulsive/strongly attractive
- $a \in \mathcal{C}$: open channel below

Coulomb interaction

We add truncated Coulomb potential in T-matrix calculation

$$\varepsilon\alpha = \pm\frac{1}{137}$$

$$V^{\mathrm{C}}(|\boldsymbol{p}' - \boldsymbol{p}|; \mathcal{R}_C) = \int_0^{\mathcal{R}_C} d^3r\ \mathrm{e}^{i(\boldsymbol{p}'-\boldsymbol{p})\cdot\boldsymbol{r}}\ \frac{\varepsilon\alpha}{r} = \frac{4\pi\varepsilon\alpha}{|\boldsymbol{p}'-\boldsymbol{p}|^2}\left[1 - \cos(|\boldsymbol{p}'-\boldsymbol{p}|\mathcal{R}_C)\right]$$

$$\mathcal{R}_C = 60\ \mathrm{fm}$$

s-wave projection:

$$V^{\mathrm{C}}_{\mathrm{s-wave}}(p, p'; \mathcal{R}_C) = \frac{2\pi\varepsilon\alpha}{pp'}\left\{\mathrm{Ci}\left[|p'-p|\mathcal{R}_C\right] - \mathrm{Ci}\left[(p'+p)\mathcal{R}_C\right] + \ln\left(\frac{p'+p}{|p'-p|}\right)\right\}$$

We have numerically checked against known Coulomb wave funcs when $V_{strong}=0$

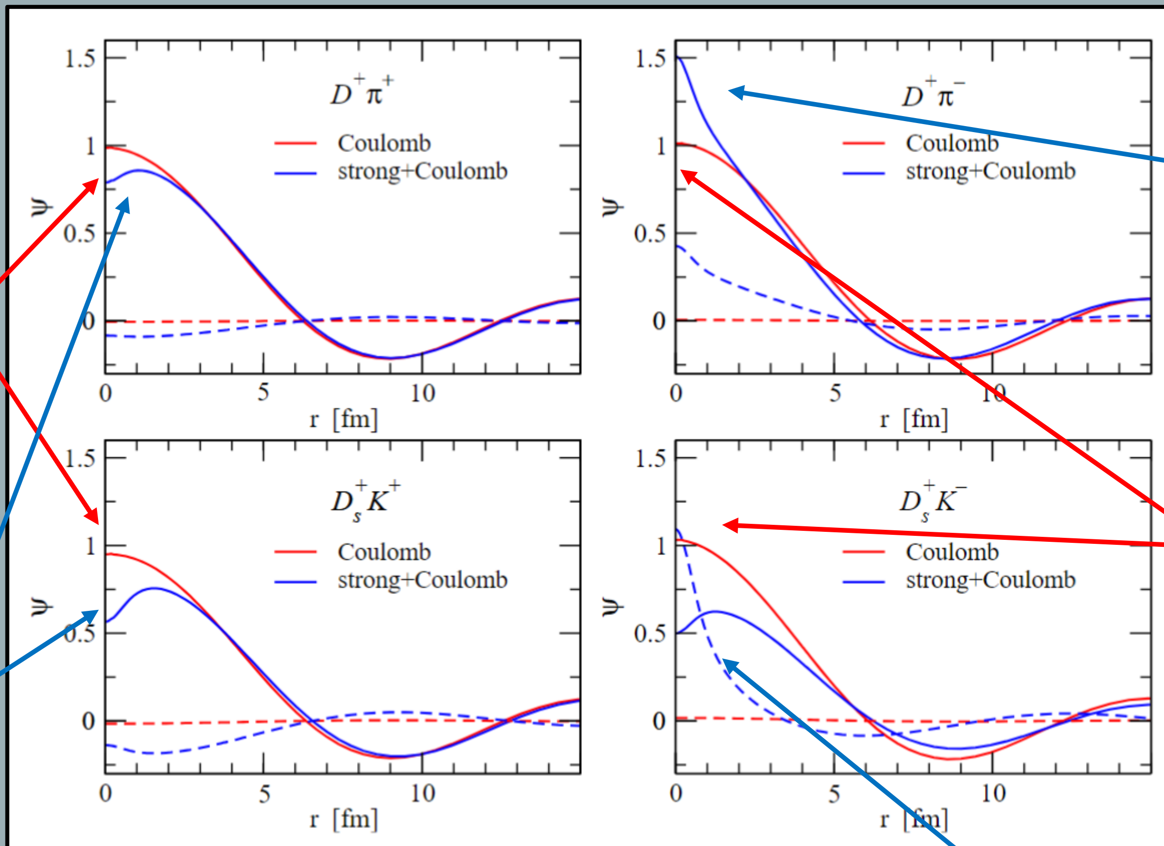
Joachain, Quantum Collision Theory (1975);
Holzenkamp, Holinde, Speth, *Nucl.Pys.A*, 500, 485 (1989)

Total wave function

Solid: Re Ψ
Dashed: Im Ψ

Repulsive Coulomb: $\Psi(0) < 1$

Extra repulsion from V_{strong}



Extra attraction from V_{strong}

Attractive Coulomb: $\Psi(0) > 1$

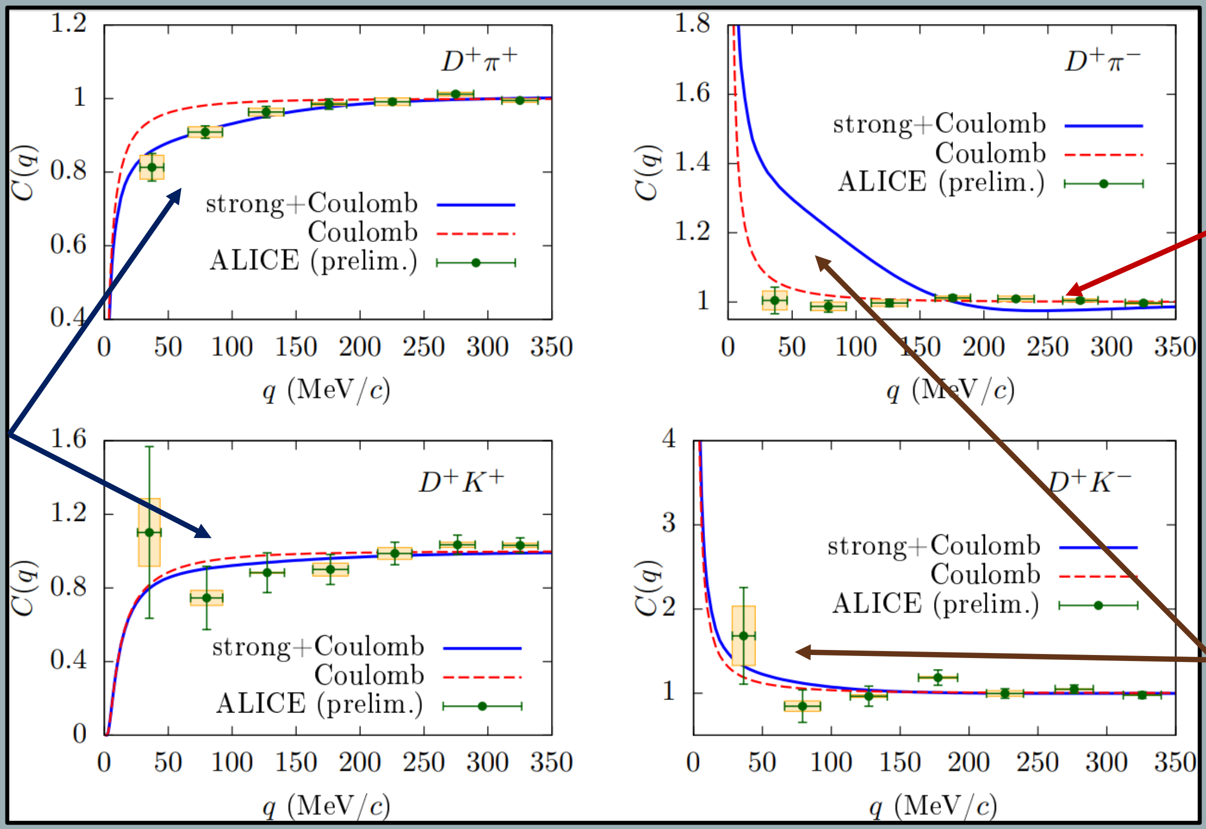
Effect of resonance and open channel

$q = 100$ MeV$/c$

D meson correlation functions

Strong deviations in $D^+\pi^-$ channel!

Strong repulsion in like-sign correlations



Lower pole of $D_0^*(2300)$ makes depletion <1 for q=250 MeV/c

Extra attraction in unlike-sign correlations

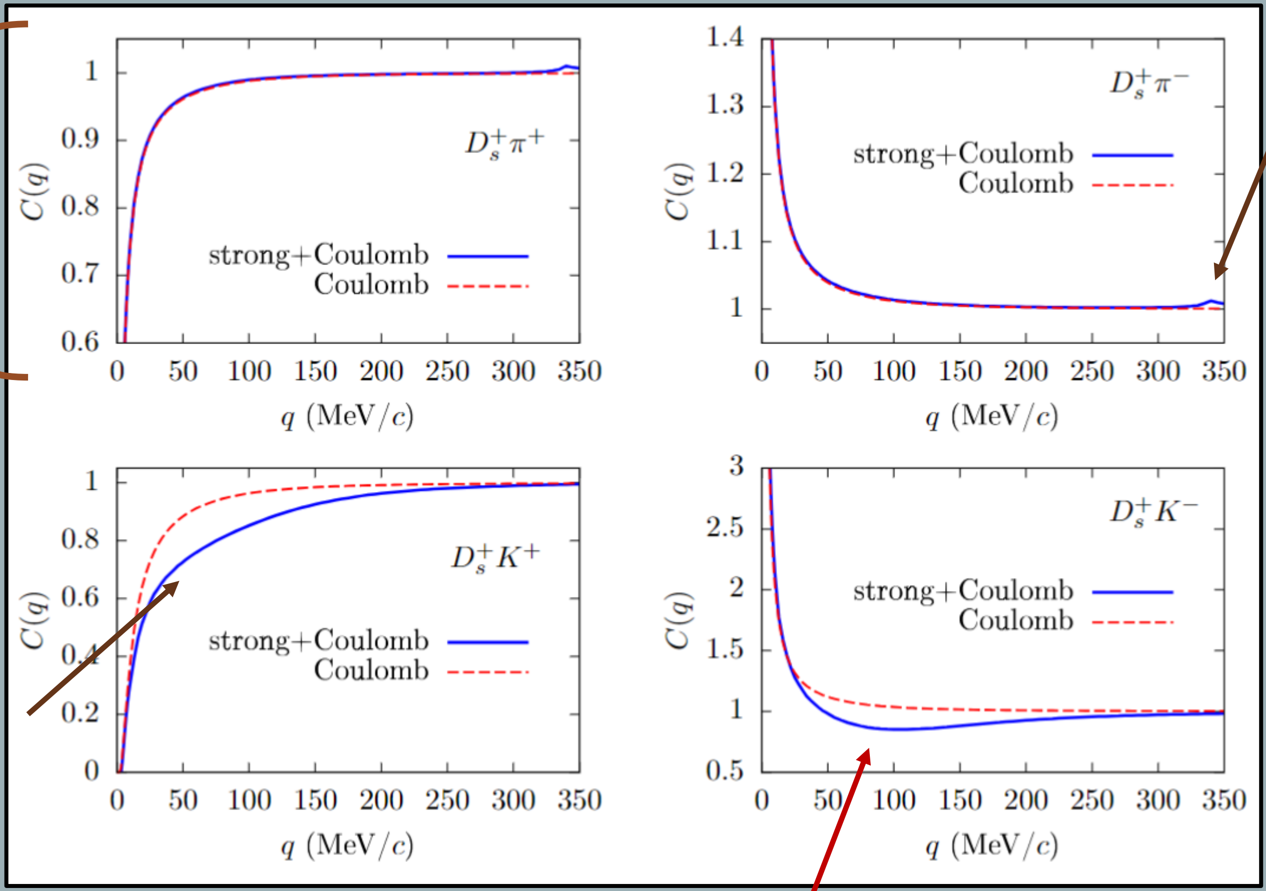
JMT-R, Ramos, Tolos, 2307.03640 [hep-ph]

$R = 1$ fm and $w_i = 1$ for all channels

D_s meson correlation functions

JMT-R, Ramos, Tolos, 2307.03640 [hep-ph]

Small strong effect in pion channels



Cusps due to kinematic threshold

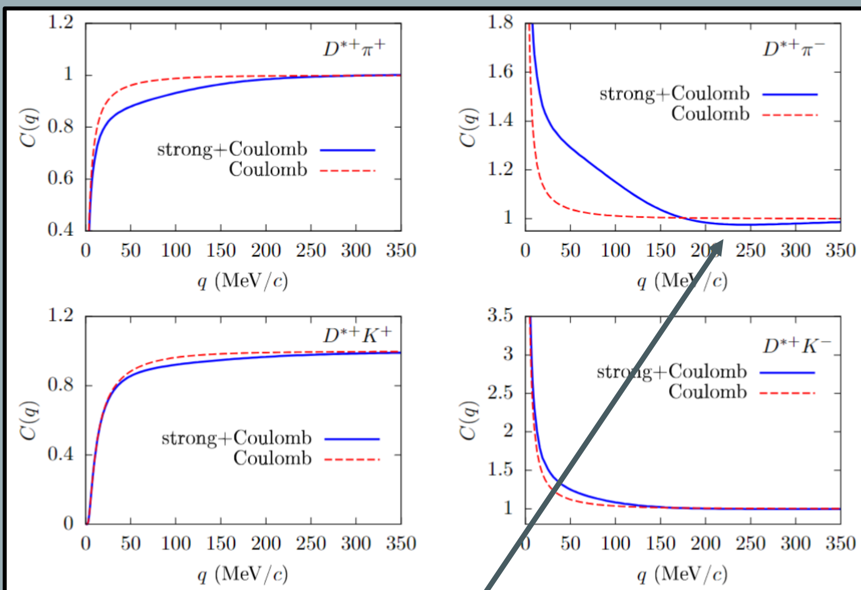
Strong repulsion predicted in $D_s^+K^+$ correlation

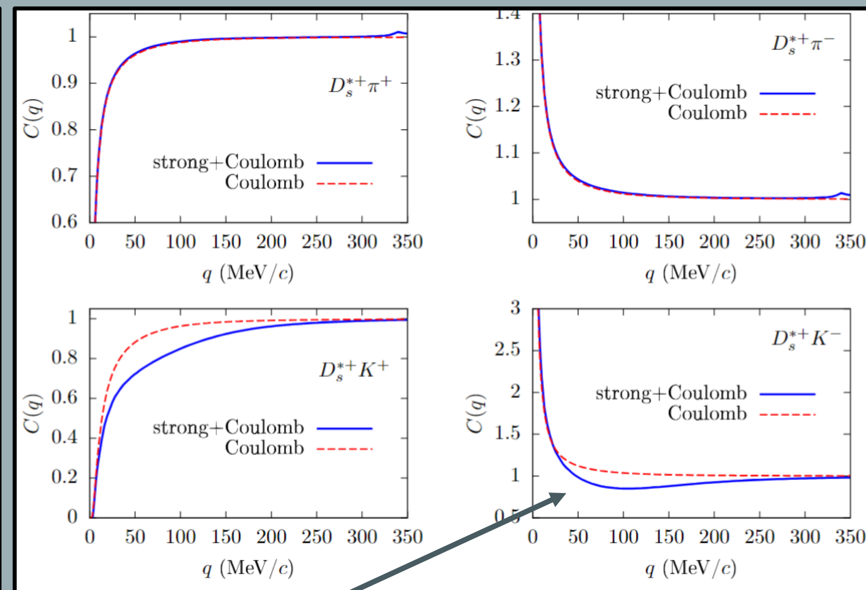
Lower pole of $D_0^*(2300)$ makes depletion <1 for q=100 MeV/c

$R = 1$ fm and $w_i = 1$ for all channels

D^* and D_s^* correlation functions

Similar shape as functions of momenta: heavy-quark spin symmetry



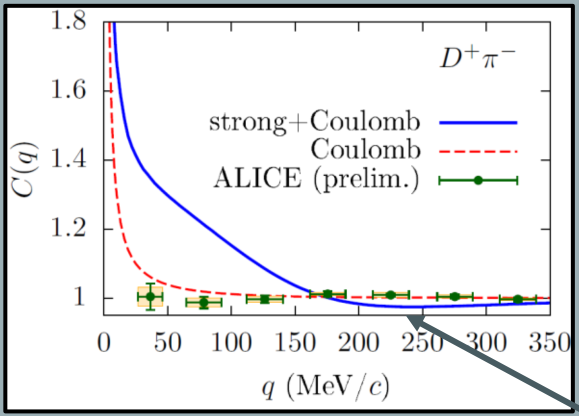


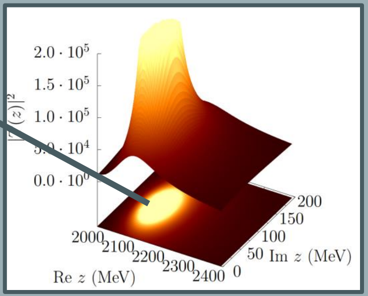
Depletions due to lower pole at q=250 MeV and higher pole at q=100 MeV of $D_1^*(2460)$

also seen in neutral channels: Albaladejo, Nieves, Ruiz-Arriola, 2304.03107 [hep-ph]

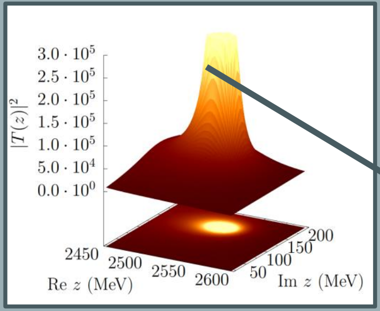
Summary

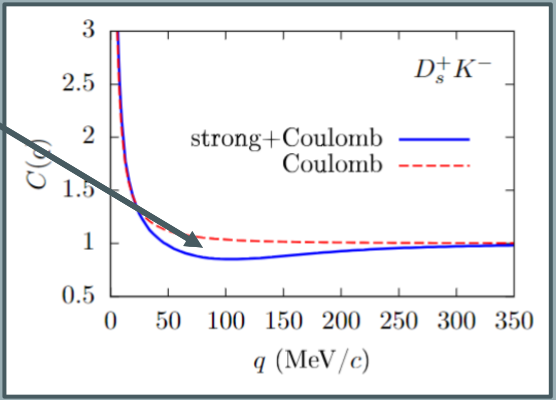
1. Femtoscopy CFs from T matrix
2. Off-Shell T matrix + Coulomb
3. Good agreement with experimental preliminary data **except $D^+\pi^-$**
4. Depletion due to poles of $D_0^*(2300)$
5. Depletion due to poles of $D_1^*(2460)$
6. Revise source and weights





Effects of two-pole state $D_0^*(2300)$ in femtoscopy!





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