MOLECULAR STATES WITH CHARM: INSIGHTS FROM VACUUM & FINITE-TEMPERATURE ANALYSES

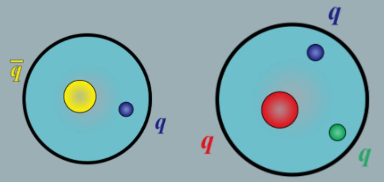
Juan M. Torres-Rincon
Universitat de Barcelona
Institut de Ciències del Cosmos

The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France

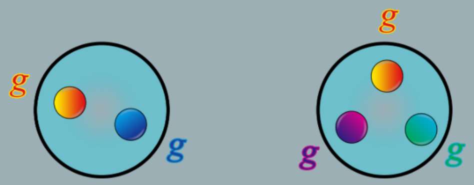
Introduction

Hadrons as aggregates of more fundamental structures

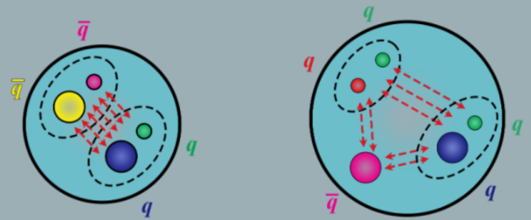
- **Conventional hadrons:** mesons and baryons



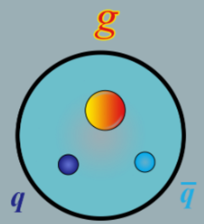
- **Glueballs:** gg, ggg …



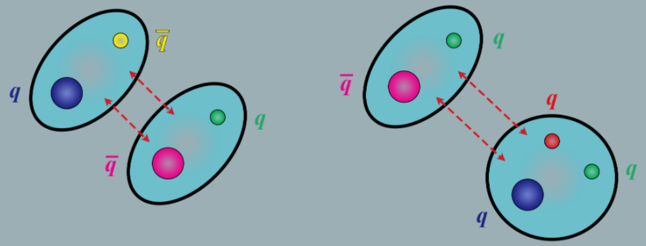
- **Multiquark states:** tetraquarks, pentaquarks…



- **Hybrid:** qqqg, $q\bar{q}g$ …



- **Hadronic molecules:** colorless states bound by the residual strong force



Reviews:

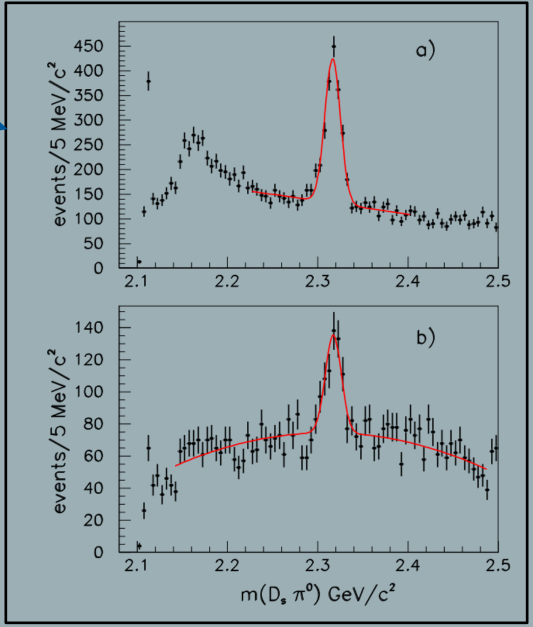
- Chen *et al.*, RPP80 (2017) 7, 076201
- Guo *et al.*, RMP90 (2018) 1, 015004
- Brambilla *et al.*, PR873 (2020) 154
- Chen *et al.*, RPP86 (2023) 2, 026201
- Liu *et al.*, arXiv:2404.06399

Pictures credit:
Chen *et al.* RPP86 (2023) 2, 026201

Heavy-light molecular states

$D_{s0}^*(2317)$ $0(0^+)$
D_{s1} (2460) $0(1^+)$

Exotics: lower masses than $q\bar{q}$ prediction and very narrow (below DK, DK* thresholds)



BaBar coll. PRL90 (2003) 242001

Broad states
$D_0^*(2300)$ ½(0^+)
D_1^* (2430) ½ (1^+)

Heavy-quark spin partners

$D_0^*(2300)$ originally generated as a low-mass pole until "double-pole structure" is proposed
Albaladejo et al. PLB 767 (2017) 465 ; Guo *et al.* EPJC79 (2019)13; Meißner, Sym. 12 (2020) 6, 981; JMT-R, Sym. (2022)13 (2021), 8, 1400

EFT approaches with 2-body dynamics

Chiral SU(3) EFT with heavy mesons

Kolomeitsev, Lutz, PLB582 (2004) 39
Hofmann, Lutz, NPA733 (2004) 142
Guo *et al.* PLB641:278-285 (2006)
Guo, Hanhart. Krewald, Meißner, PLB666 (2008) 251
Tolos, Torres-Rincon, PRD88, 074019 (2013)
Altenbuchinger, Geng, Weise, PRD89, 014026 (2014)

Broken SU(4) EFT

Gamerman *et al.* PRD76: 074016 (2007)

Dominance of hadronic components:

Albaladejo *et al.* EPJC 78 (2018) 9, 722

Other states

D_{sJ} (2860) Guo, Meißner, PRD 84, 014013
X_0 (2866) $[D^*\bar{K}^*]$ Liu *et al.* PRD102 (2020) 091502
…

Heavy-meson effective theory

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

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

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

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

$h_i, \tilde{h}_i$: NLO low-energy constants

Guo *et al.* EPJC79, 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, PLB582 (2004) 39
Hofmann, Lutz, NPA733 (2004) 142
Guo *et al.*, PLB641 (2006) 278
Guo, Shen, Chiang, PLB647 (2007) 133

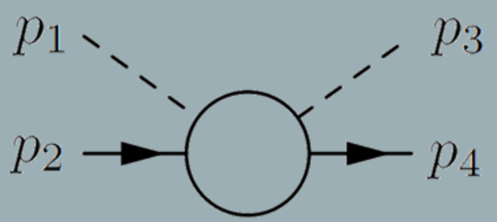
Guo *et al.*, PLB666 (2008) 251
Geng *et al.*, PRD82,05422 (2010)
Abreu *et al.* (JMT-R), AP 326 (2011) 2737
Altenbuchinger, Geng, Weise, PRD89, 014026 (2014)

Heavy-meson effective theory

$$
\begin{aligned}
V_{ij}(p_1,p_2,p_3,p_4) \;=\; & \frac{1}{f_\pi^2}\bigg[\frac{C^{ij}_{\mathrm{LO}}}{4}\left[(p_1+p_2)^2-(p_2-p_3)^2\right] - 4C^{ij}_0 h_0 + 2C^{ij}_1 h_1 \\
& -2C^{ij}_{24}\Big(2h_2(p_2\cdot p_4) + h_4\big((p_1\cdot p_2)(p_3\cdot p_4) + (p_1\cdot p_4)(p_2\cdot p_3)\big)\Big) \\
& +2C^{ij}_{35}\Big(h_3(p_2\cdot p_4) + h_5\big((p_1\cdot p_2)(p_3\cdot p_4) + (p_1\cdot p_4)(p_2\cdot p_3)\big)\Big)\bigg]
\end{aligned}
$$

L=0 partial wave

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



Lippmann-Schwinger equation for the T-matrix elements

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

On-shell reduction: Oller, Oset, NPA620 (1997) 438; Oset, Ramos NPA635 (1998) 99

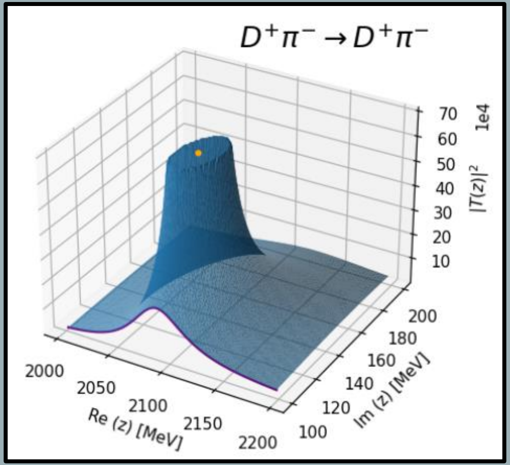
$$
T = V(1-VG)^{-1}
$$

Molecular states as poles of T matrix

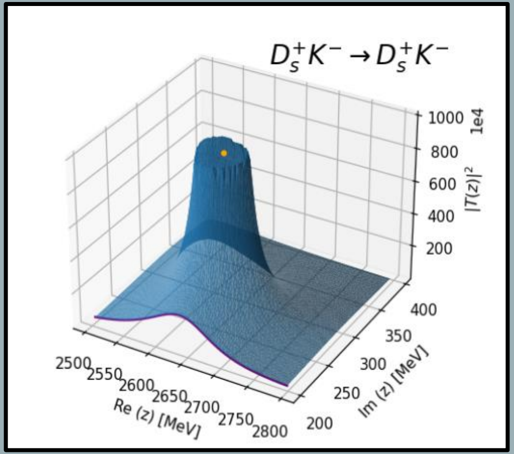
JMT-R, Ramos, Tolos, PRD108, 096008 (2023)

$D_0^*(2300)$

z_{pole} = (2092 + i129) MeV

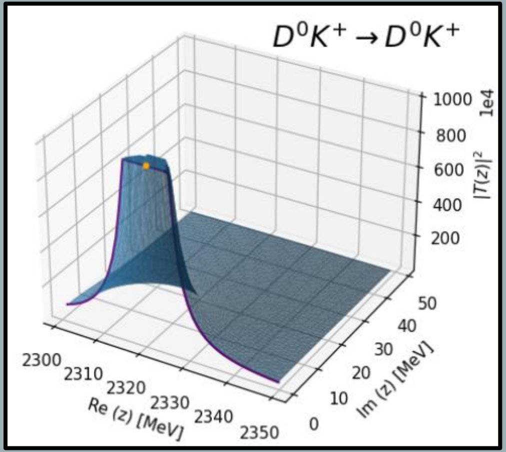


z_{pole} = (2647+ i265) MeV



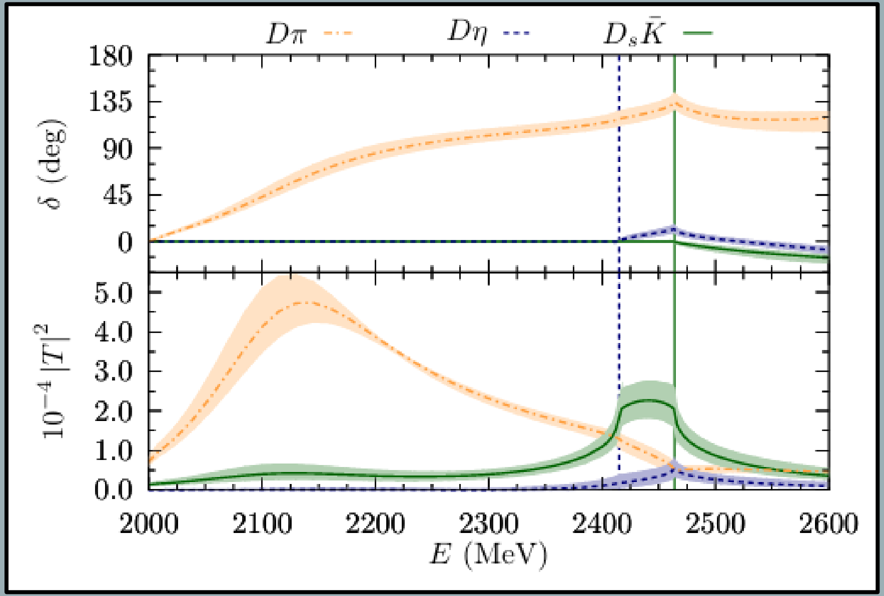
$D_{s0}^*(2317)$

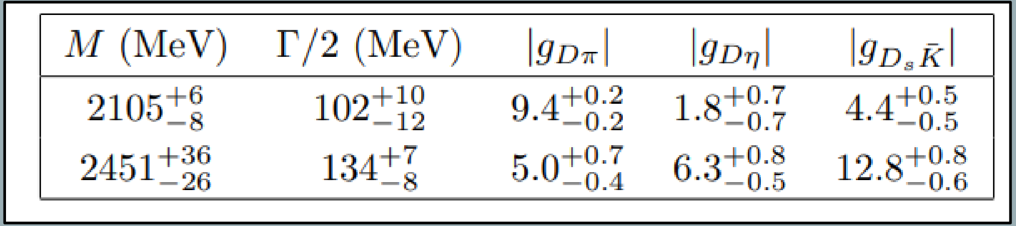
z_{pole}=(2320 + i 0) MeV



Albaladejo *et al.* PLB 767 (2017) 465

$D_0^*(2300)$





M (MeV)	$\Gamma/2$ (MeV)	$\lvert g_{D\pi}\rvert$	$\lvert g_{D\eta}\rvert$	$\lvert g_{D_s\bar{K}}\rvert$
2105^{+6}_{-8}	102^{+10}_{-12}	$9.4^{+0.2}_{-0.2}$	$1.8^{+0.7}_{-0.7}$	$4.4^{+0.5}_{-0.5}$
2451^{+36}_{-26}	134^{+7}_{-8}	$5.0^{+0.7}_{-0.4}$	$6.3^{+0.8}_{-0.5}$	$12.8^{+0.8}_{-0.6}$

Pole parameters

Meson-baryon molecular states

Meson-baryon states with open charm

$\Lambda_c(2595), \Lambda_c(2880), \Sigma_c(2800), \Xi_c(2970)\ldots$

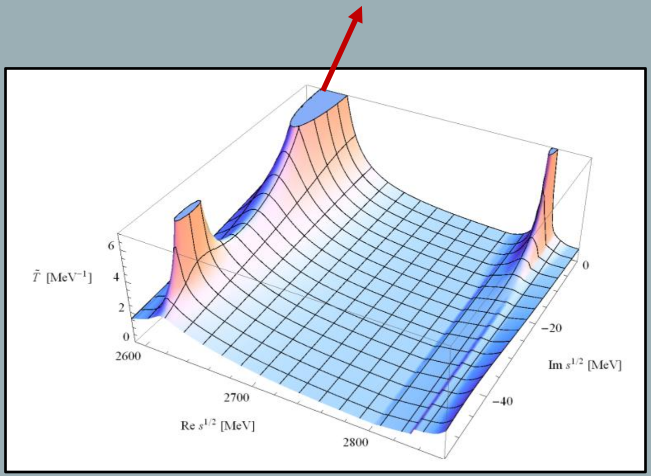
$$V_{ij}(s) = D_{ij}\frac{2\sqrt{s}-M_i-M_j}{4\,f_i f_j}\sqrt{\frac{E_i+M_i}{2M_i}}\sqrt{\frac{E_j+M_j}{2M_j}}$$

$$T(s) = \frac{1}{1-V(s)G(s)}V(s)$$

Contact s-wave interaction:

Lutz, Kolomeitsev, NPA730 (200) 110
Hofmann, Lutz, NPA763 (2005) 90
Mizutani, Ramos, PRC74, 065201 (2006)
He, Liu, PRD82:114029 (2010)
Romanets *et al.* PRD 85, 114032 (2012)

He *et al.*, EPJC51, 883 (2007)
Jimenez-Tejero et al. PRC80, 055206 (2009)
Jimenez-Tejero *et al.*, PRC84, 015208 (2010)
…
see Guo *et al.* RMP90, 015004 (2018)


$\Lambda_c(2595)$

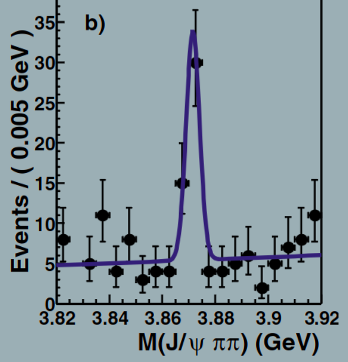
Romanets *et al.*
PRD 85, 114032 (2012)

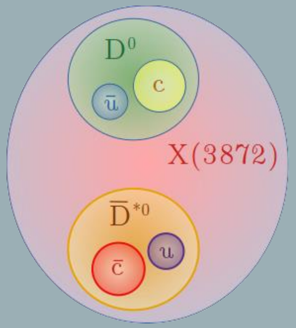
Also **hidden charm pentaquarks** candidates $P_c(4380)$ & $P_c(4450)$ also studied under the molecular assumption $[\Sigma_c(2520)\ D]$ & $[\chi_{c1}\ p]$ (among other possible interpretations), e.g.

Chen et al. , PRL 115, 172001 (2015); Meißner, Oller, PLB751 (2015) 59

X(3872): Heavy-heavy molecular states

- **X (3872)** [Belle Coll. PRL91, 262001 (2003)] seems to have strong coupling to $\mathbf{D\bar{D}^*}$ Törnqvist, ZPC61, 525 (1994)





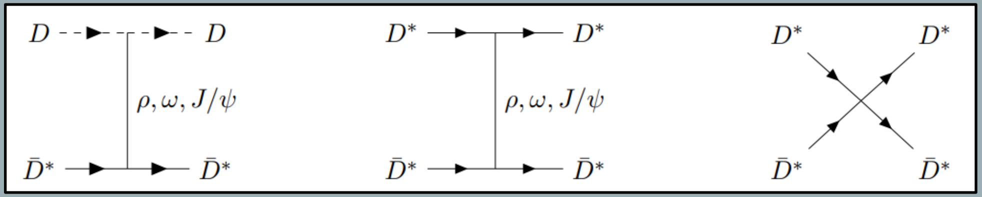
- Quantum number: 1^{++} (LHCb coll., PRL110 (2013) 2220001)
- Nature still not clear: $\mathrm{D\bar{D}^*}$ but also conventional χ_{c1}(2P), tetraquark, hybrid, glueball…
- Mass very close to $\mathrm{D\bar{D}^*}$ threshold. Width extremely small

Molecular description: **Chiral SU(4)** Gamermann, Oset, EPJA33:119,2007 **Local Hidden Gauge** Montaña *et al.* (JMT-R) PRD107(2023)5, 054014

Local Hidden Gauge Lagrangian in SU(4)
Molina, Oset, PRD80 (2009) 114013
Molina *et al.* PRD80 (200) 014025

$$\mathcal{L} = -\frac{1}{4}\langle V_{\mu\nu}V^{\mu\nu}\rangle + \frac{1}{2}m_V^2\left\langle\left(V_\mu - \frac{i}{g}\Gamma_\mu\right)^2\right\rangle$$

Montaña et al. (JMT-R) PRD107(2023)5,054014



X(3872)

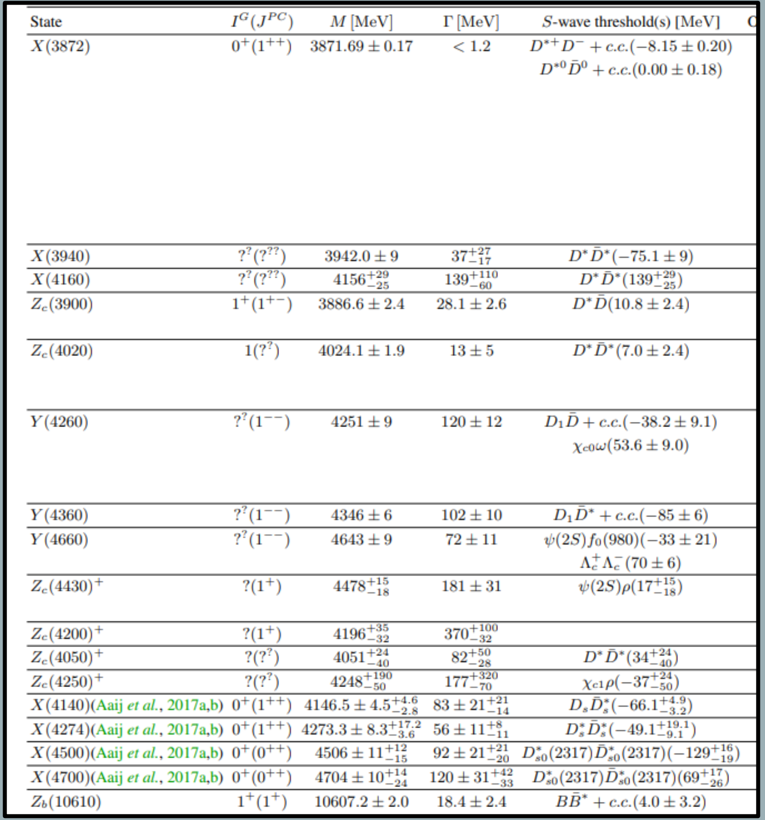
X(4014)

$$T(s) = \frac{1}{1 - V(s)G(s)}V(s)$$

Λ (MeV)	State	Nearest threshold (MeV)	$\sqrt{z_p}$ (MeV)	Couplings (GeV)	
567	$X(3872)$	$m_D + m_{\bar{D}^*} = 3875.80$	$3871.65 + i\,0.00$	$\lvert g_{D\bar{D}^*}\rvert = 9.23$	$\lvert g_{D_s\bar{D}_s^*}\rvert = 3.98$
510	$X(4014)$	$m_{D^*} + m_{\bar{D}^*} = 4017.11$	$4014.31 + i\,0.00$	$\lvert g_{D^*\bar{D}^*}\rvert = 8.56$	$\lvert g_{D_s^*\bar{D}_s^*}\rvert = 3.69$

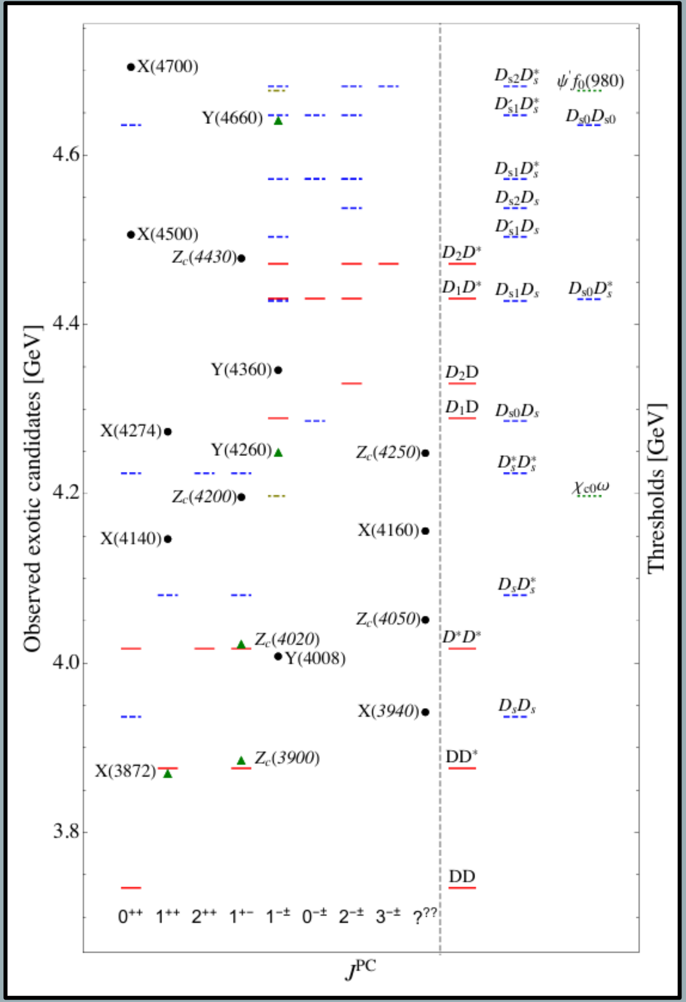
X,Y,Z: Heavy-heavy molecular states

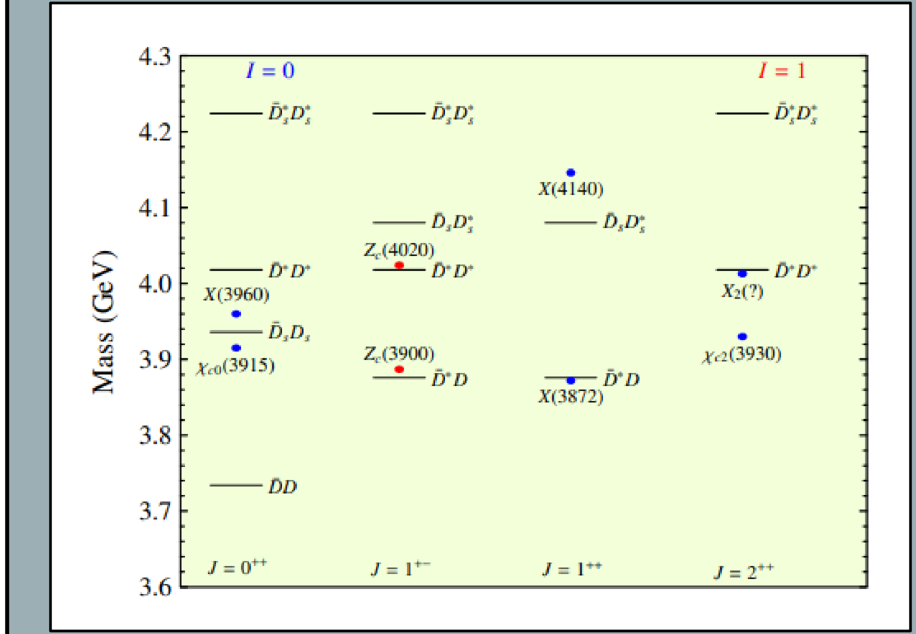
Plethora of heavy-quarkonium like states (+200):



State	$I^G(J^{PC})$	M [MeV]	Γ [MeV]	S-wave threshold(s) [MeV]
$X(3872)$	$0^+(1^{++})$	3871.69 ± 0.17	< 1.2	$D^{*+}D^- + c.c.(-8.15 \pm 0.20)$ $D^{*0}\bar{D}^0 + c.c.(0.00 \pm 0.18)$
$X(3940)$	$?^?(?^{??})$	3942.0 ± 9	37^{+27}_{-17}	$D^*\bar{D}^*(-75.1 \pm 9)$
$X(4160)$	$?^?(?^{??})$	4156^{+29}_{-25}	139^{+110}_{-60}	$D^*\bar{D}^*(139^{+29}_{-25})$
$Z_c(3900)$	$1^+(1^{+-})$	3886.6 ± 2.4	28.1 ± 2.6	$D^*\bar{D}(10.8 \pm 2.4)$
$Z_c(4020)$	$1(?^?)$	4024.1 ± 1.9	13 ± 5	$D^*\bar{D}^*(7.0 \pm 2.4)$
$Y(4260)$	$?^?(1^{--})$	4251 ± 9	120 ± 12	$D_1\bar{D} + c.c.(-38.2 \pm 9.1)$ $\chi_{c0}\omega(53.6 \pm 9.0)$
$Y(4360)$	$?^?(1^{--})$	4346 ± 6	102 ± 10	$D_1\bar{D}^* + c.c.(-85 \pm 6)$
$Y(4660)$	$?^?(1^{--})$	4643 ± 9	72 ± 11	$\psi(2S)f_0(980)(-33 \pm 21)$ $\Lambda_c^+\Lambda_c^-(70 \pm 6)$
$Z_c(4430)^+$	$?(1^+)$	4478^{+15}_{-18}	181 ± 31	$\psi(2S)\rho(17^{+15}_{-18})$
$Z_c(4200)^+$	$?(1^+)$	4196^{+35}_{-32}	370^{+100}_{-32}	
$Z_c(4050)^+$	$?(?^?)$	4051^{+24}_{-40}	82^{+50}_{-28}	$D^*\bar{D}^*(34^{+24}_{-40})$
$Z_c(4250)^+$	$?(?^?)$	4248^{+190}_{-50}	177^{+320}_{-70}	$\chi_{c1}\rho(-37^{+24}_{-50})$
$X(4140)$(Aaij *et al.*, 2017a,b)	$0^+(1^{++})$	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	$D_s\bar{D}_s^*(-66.1^{+4.9}_{-3.2})$
$X(4274)$(Aaij *et al.*, 2017a,b)	$0^+(1^{++})$	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	$D_s^*\bar{D}_s^*(-49.1^{+19.1}_{-9.1})$
$X(4500)$(Aaij *et al.*, 2017a,b)	$0^+(0^{++})$	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	$D_{s0}^*(2317)\bar{D}_{s0}^*(2317)(-129^{+16}_{-19})$
$X(4700)$(Aaij *et al.*, 2017a,b)	$0^+(0^{++})$	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	$D_{s0}^*(2317)\bar{D}_{s0}^*(2317)(69^{+17}_{-26})$
$Z_b(10610)$	$1^+(1^+)$	10607.2 ± 2.0	18.4 ± 2.4	$B\bar{B}^* + c.c.(4.0 \pm 3.2)$

Guo *et al.*, RMP90 (2018) 1, 015004



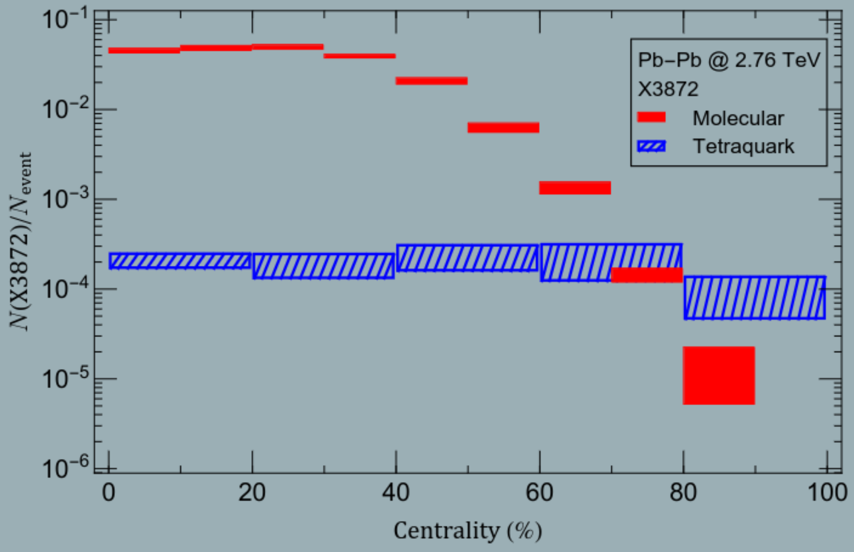


Liu *et al.*, arXiv:2404.06399

X(3872): Molecular vs Tetraquark

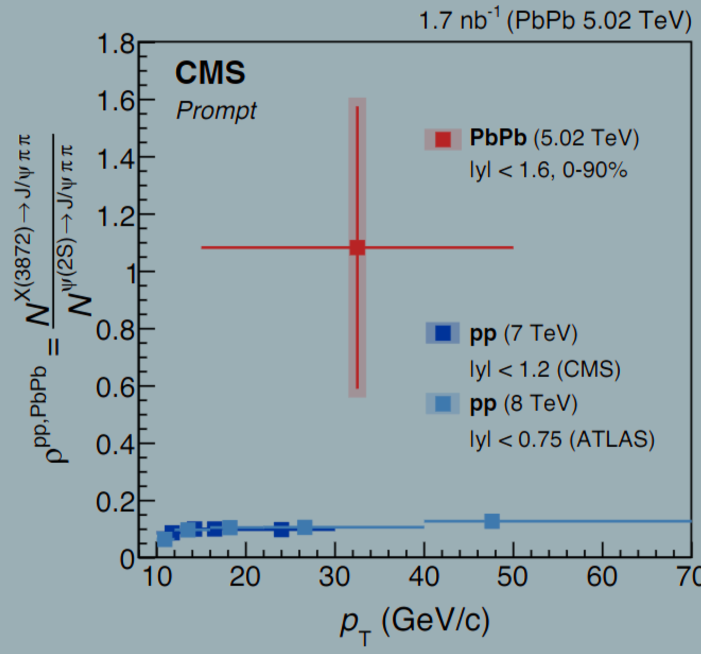
Insights from Heavy-Ion Collisions

- Production of extended molecule (~5 fm) drastically depends on system's volumen
- For tetraquark, compact state (~0.5 fm) it is independent of centrality



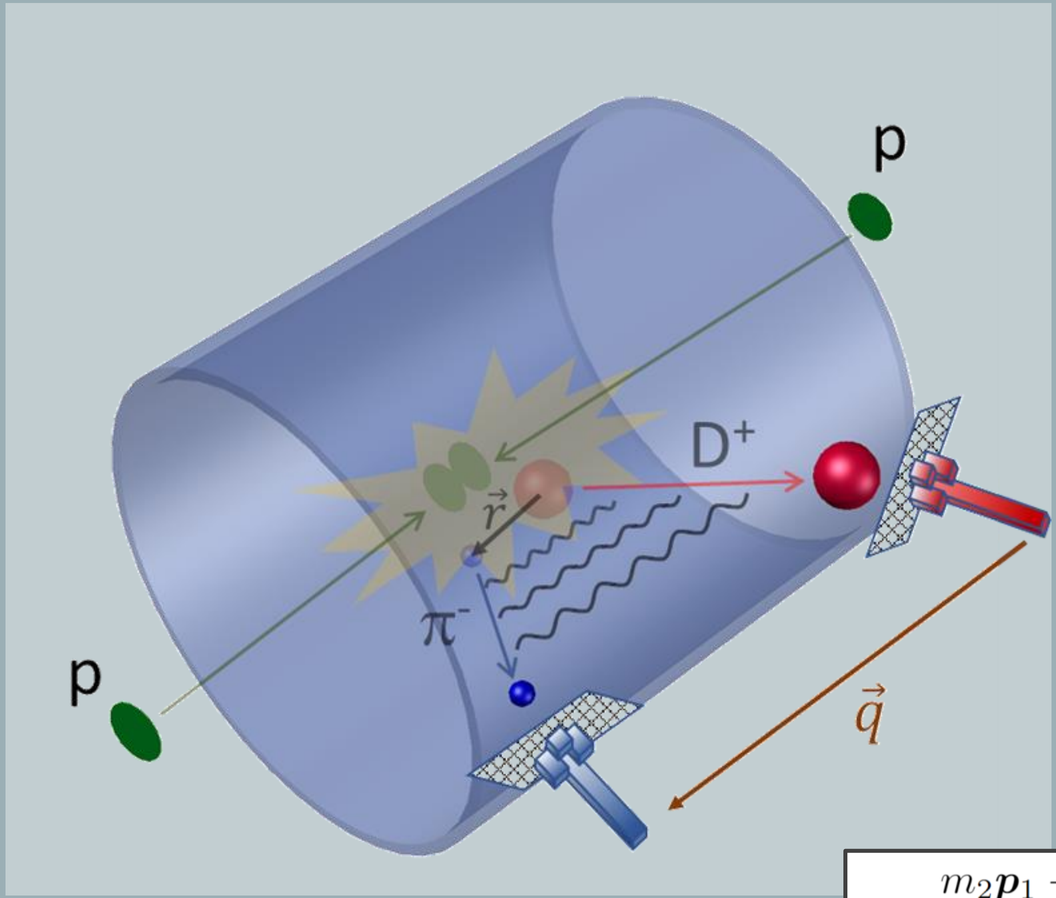
Zhang et al. PRL126, 012301 (2021)

First measurement of X(3872) in Pb-Pb collisions by CMS collaboration:



CMS collaboration PRL128, 032001 (2022)

Femtoscopy in p+p collisions



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

Heinz, Jacak, ARNPS 49 (1999) 529-579
Lisa, Pratt, Wiedemann, ARNPS 55 (2005) 357
Fabbietti, Mantovani Sarti, Vazquez Doce, ARNPS 71, 377 (2021)

Femtoscopy can also help in identifying resonant states

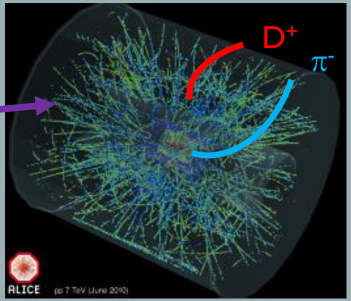
Femtoscopy studies with charm in high multiplicity p+p collisions @ $s^{1/2}$=13 TeV:

$\mathbf{\overline{D}N}$: ALICE coll., PRD 106 (2022) 052010
$\mathbf{D^{(*)}\pi, D^{(*)}K, D^{(*)}\overline{K}}$: ALICE coll, 2401.13541

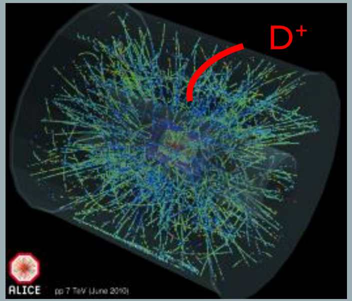
Insights from femtoscopy

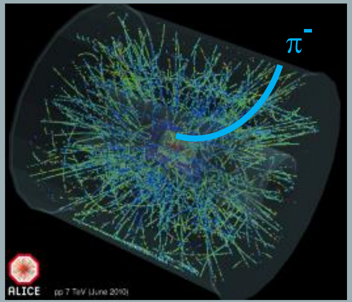
Pair Correlation Function

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



'Event mixing' technique





Koonin-Pratt formula

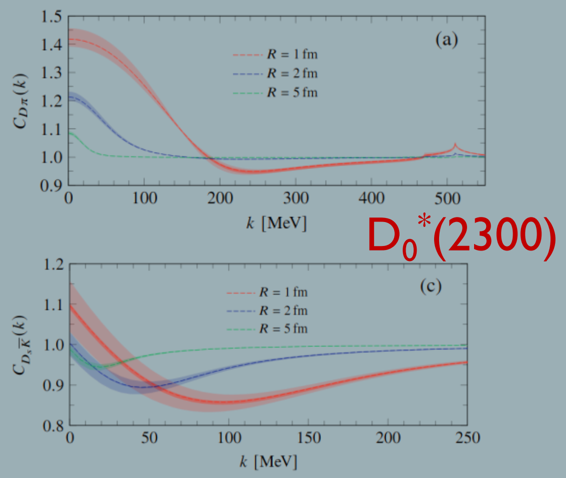
$$C(\boldsymbol{q}) = \int d^3r \sum_i w_i\; S_i(\boldsymbol{r})\; |\Psi_i(\boldsymbol{q};\boldsymbol{r})|^2$$

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

Koonin, PL.B, 70, 43 (1977)
Pratt, Csorgo, Zimanyi, PRC, 42, 2646(1990)

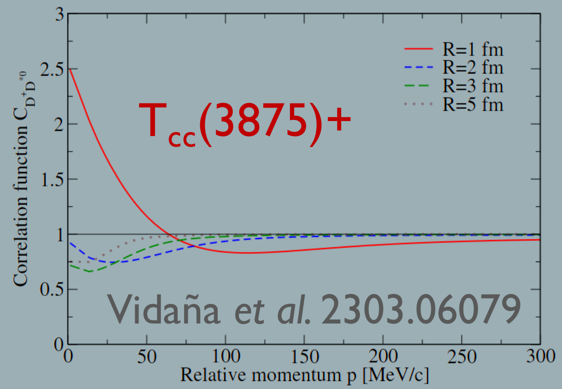
Resonances/bound present characteristic effects

Examples with charm:



$D_0^*(2300)$

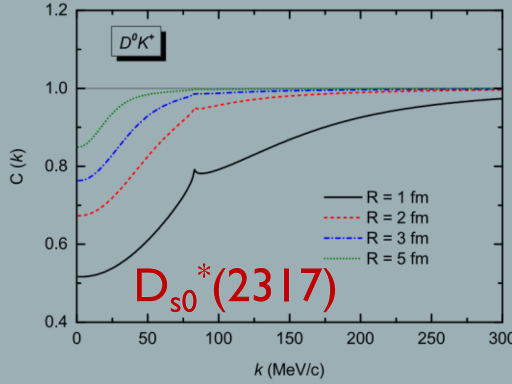
Albaladejo, Nieves, Ruiz Arriola, PRD108 (2023) 1, 014020



$T_{cc}(3875)+$

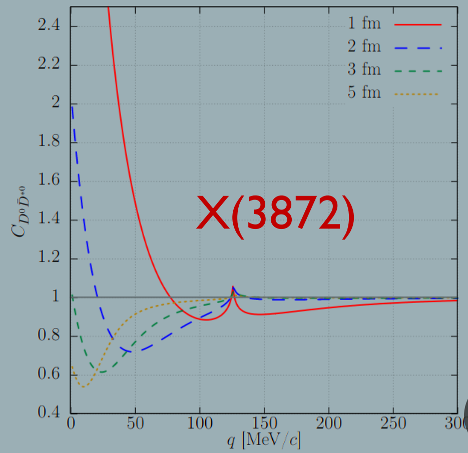
Vidaña *et al.* 2303.06079

Liu, Lu, Geng, PRD107 (2023) 7, 074019



$D_{s0}^*(2317)$

Kamiya, Hyodo, Ohnishi EPJA58 (2022) 7,131



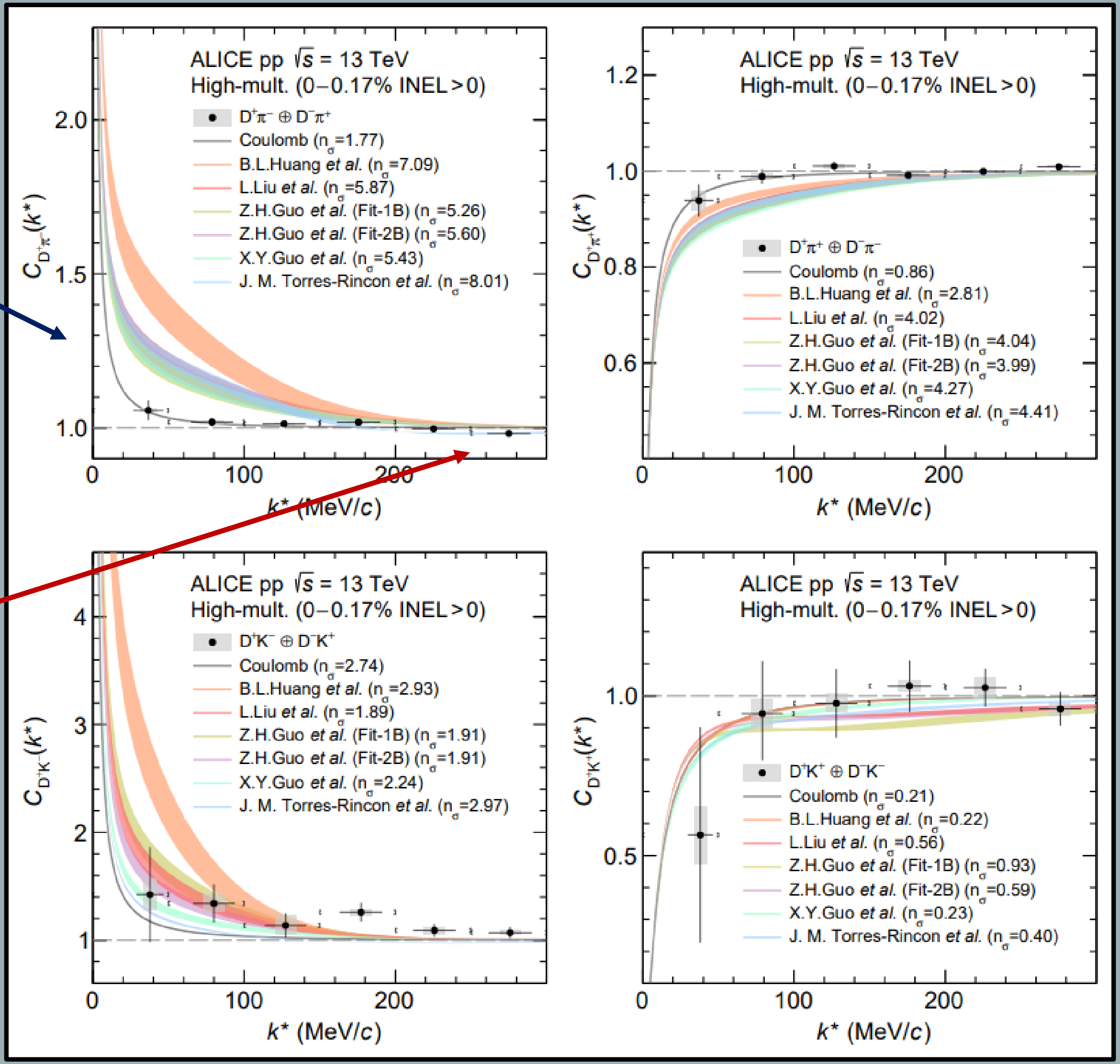
X(3872)

D meson correlation functions

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

but

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



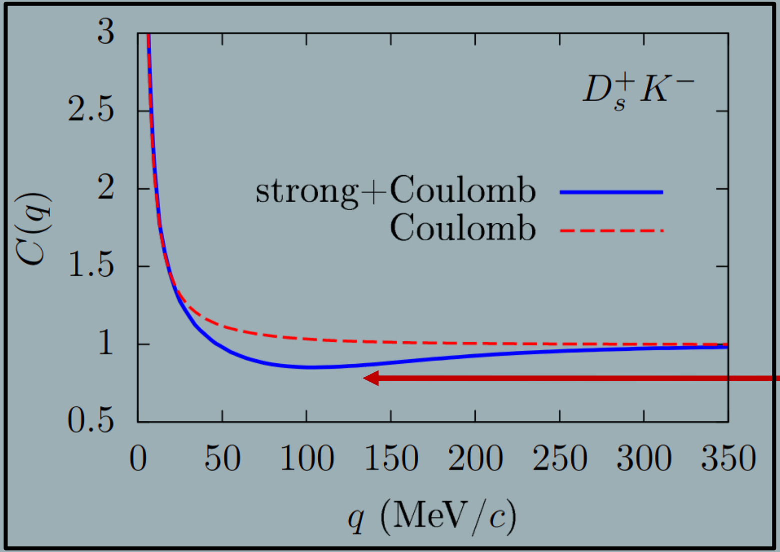
ALICE collaboration
2401.13541

JMT-R, Ramos, Tolos,
PRD108, 096008 (2023)

TROY framework
“T-matrix-based Routine for HadrOn FemtoscopY”

D_s and D* meson correlation functions

One should look also at $\mathbf{D_s^+K^-}$ channel

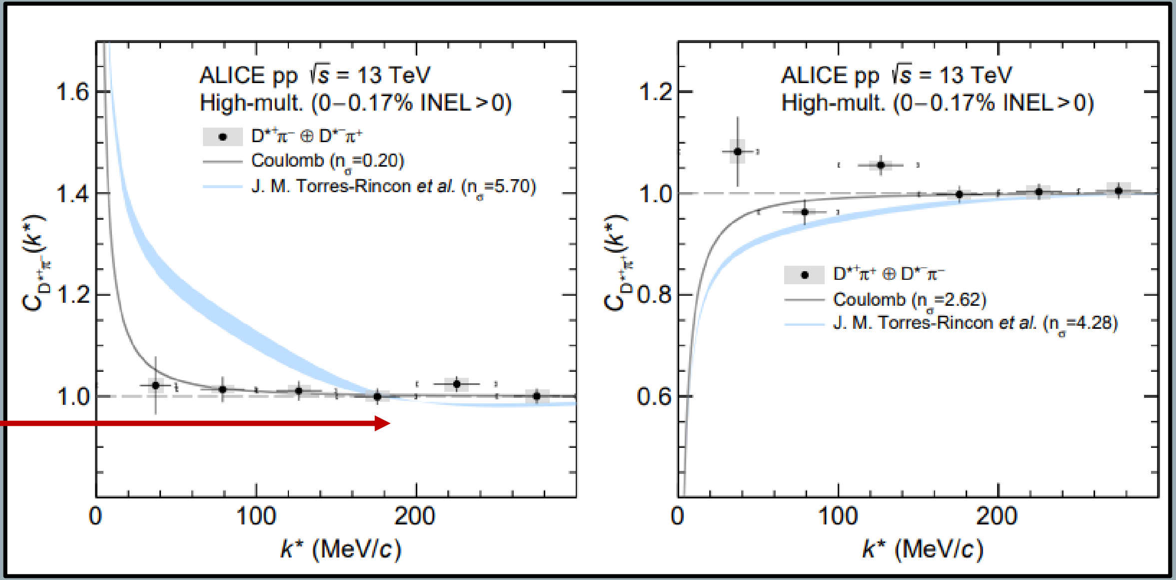


JMT-R, Ramos, Tolos, PRD108, 096008 (2023)

Higher pole of $\mathbf{D_0^*(2300)}$ makes depletion around q=100 MeV/c

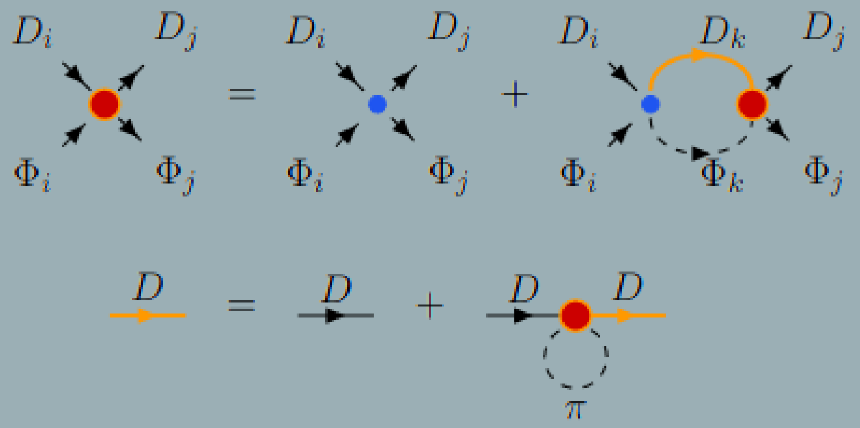
Similar situation for heavy-flavor partners due to HQSS

Lower pole of $\mathbf{D_1^*(2460)}$ makes depletion for q=250 MeV/c



ALICE collaboration 2401.13541

Charm at finite temperature



$$S_D(E,\boldsymbol{q}) = -\frac{1}{\pi}\mathrm{Im}\left(\frac{1}{E^2-\boldsymbol{q}^2-m_0^2-\Pi_D(E,\boldsymbol{q})}\right)$$

D meson at finite temperature

Fuchs *et al.* PRC73,035204, (2006)

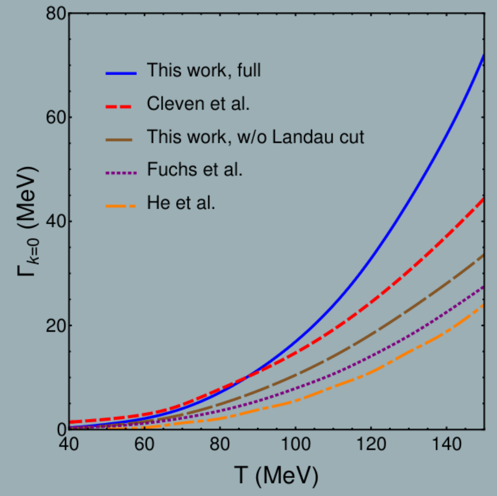
He, Fries, Rapp, PLB701, 445 (2011)

Ghosh, Mitra, Sarkar, NPA917:71 (2013)

Cleven *et al.* PRC96, 045201 (2017)

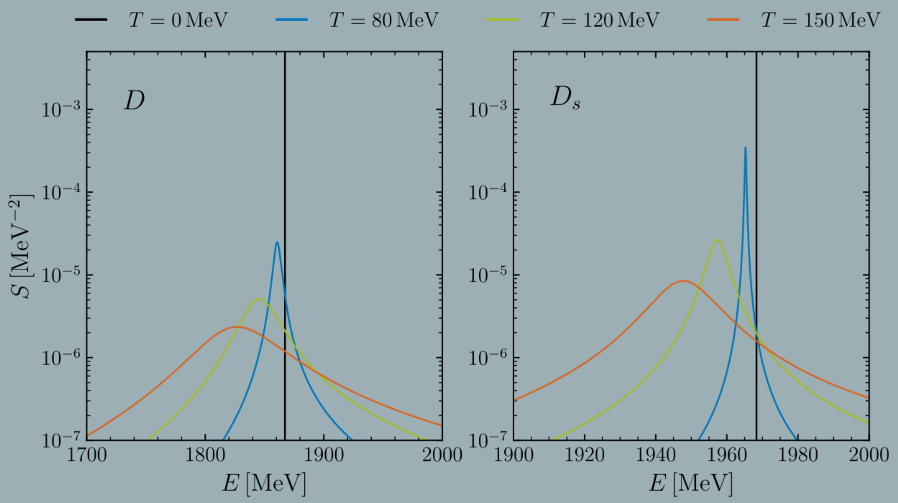
JMT-R *et al.* PRC105, 025203 (2022)

D-meson thermal width



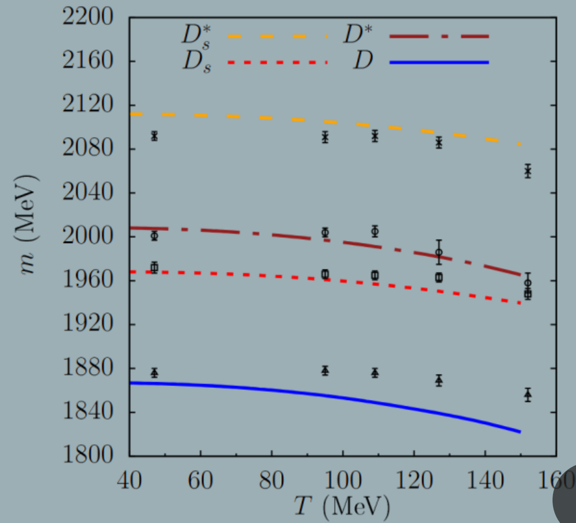
D & D$_s$ spectral functions

Montaña *et al.* (JMT-R),
PLB 806 (2020)135464
&
PRD 102 (2020) 096020

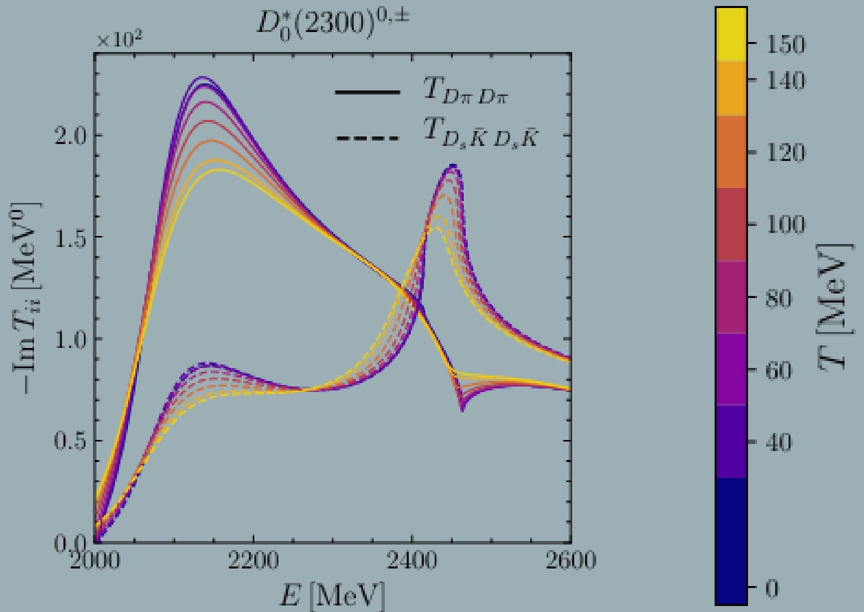


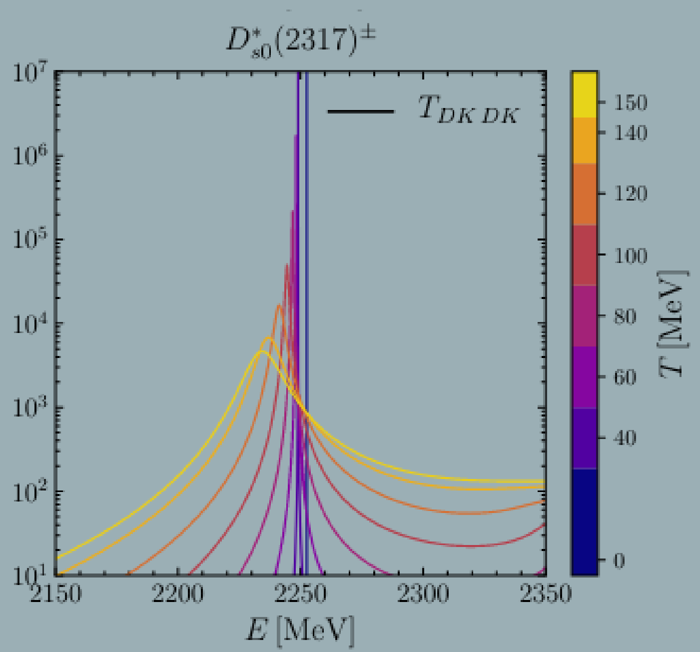
Open charm meson masses

Lattice QCD data:
Aarts *et al.* 2209.14681
m_π = 239(1) MeV

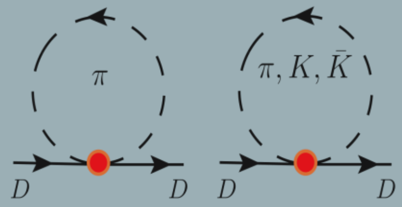


Thermal evolution of charm molecular states



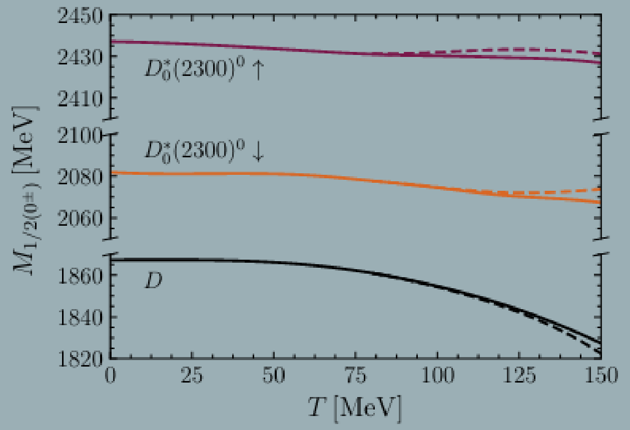


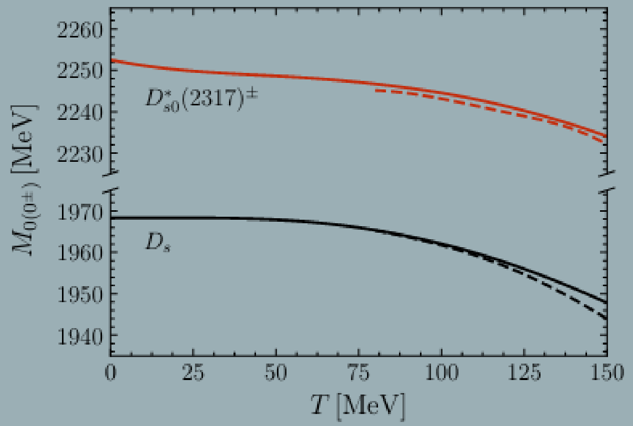
D_{s0}^* (2317)
Acquires thermal broadening for typical freeze-out temperatures



2 poles of **D_0*(2300)** state
Weak dependence on temperature

Montaña *et al.* (JMT-R),
PLB 806 (2020)135464
&
PRD 102 (2020) 096020





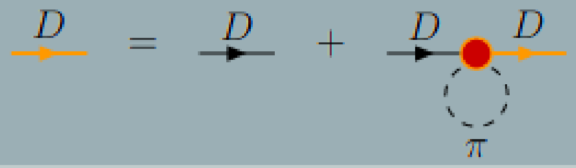
X(3872): In-medium exotics

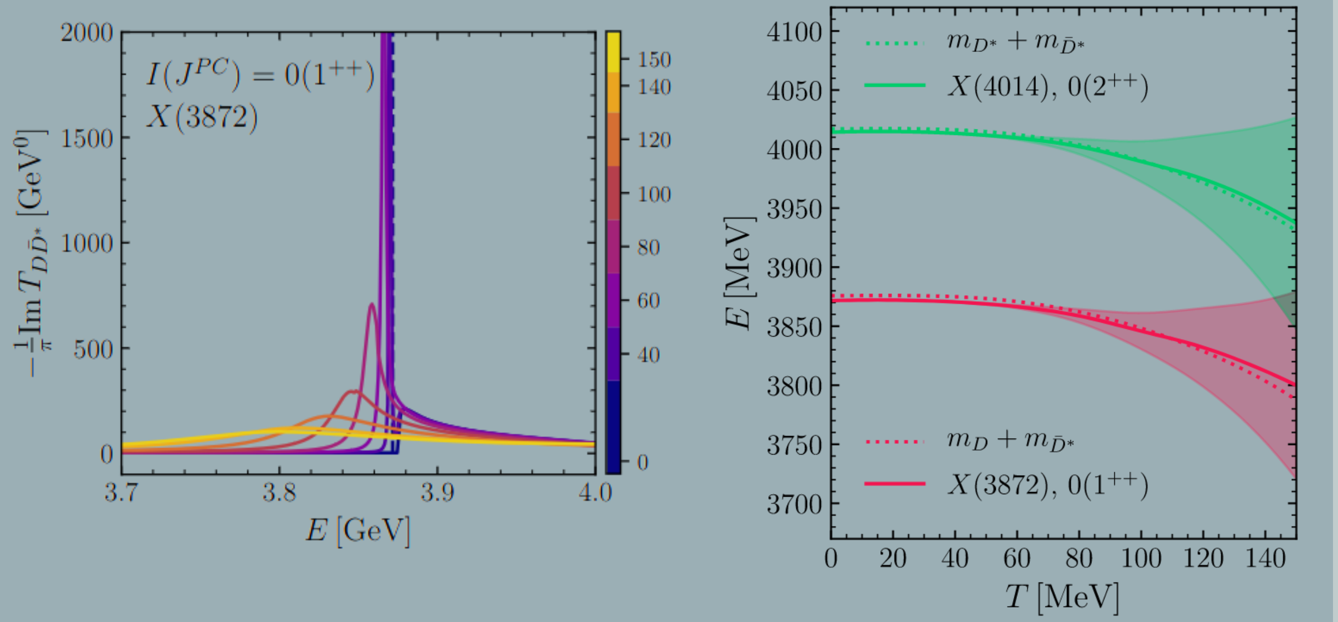
$$G(E,\boldsymbol{P};T) = \int \frac{d^3q}{(2\pi)^3} \int d\omega \int d\omega' \frac{S_1(\omega,\boldsymbol{q};T)S_2(\omega',\boldsymbol{P}-\boldsymbol{q};T)}{E-\omega-\omega'+i\epsilon}[1+f(\omega;T)+f(\omega';T)]$$

$$T(s) = \frac{1}{1-V(s)G(s)}V(s)$$

X(3872), X(4014) as molecules **melt down** around T=110 MeV

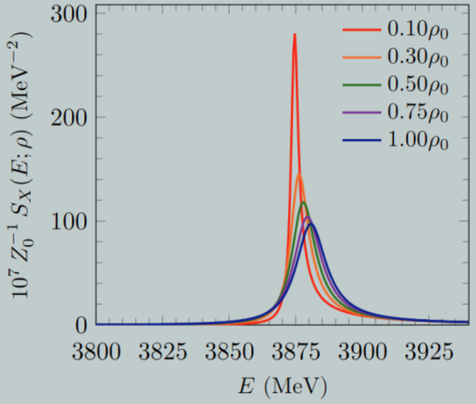
Modified thermal production at freeze out in RHICs?



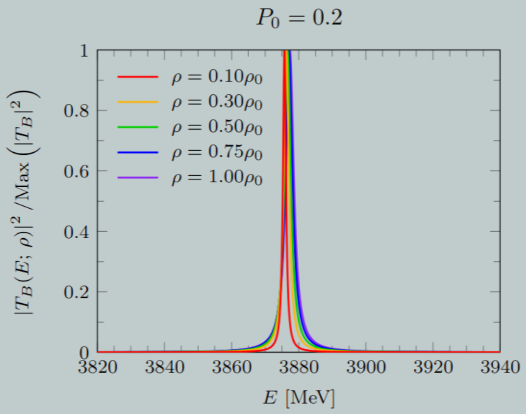


Montaña *et al.* (JMT-R), PRD107, 054014 (2023)

X(3872) and $T_{cc}(3875)^+$ also in dense medium



Albaladejo, Nieves, Tolos, PRC104 (2021) 3, 035203

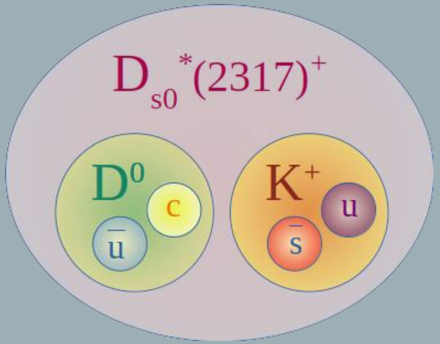


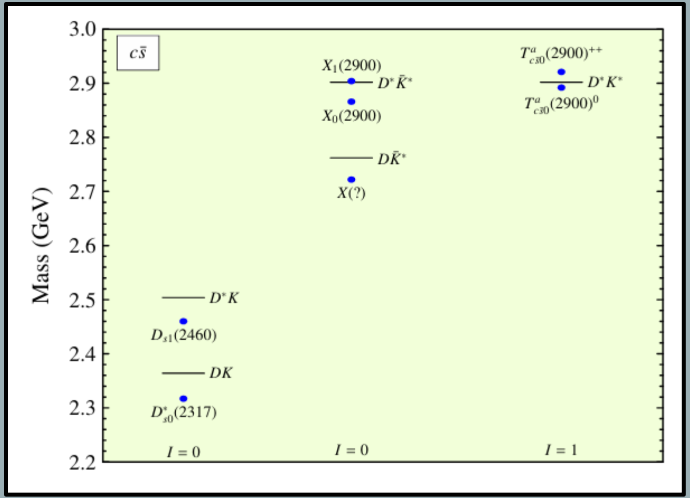
Montesinos *et al.*, PRC108 (2023) 3, 035205

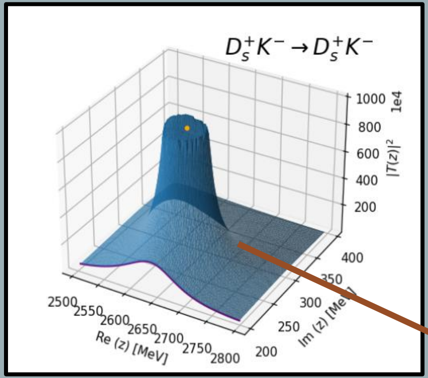
Summary

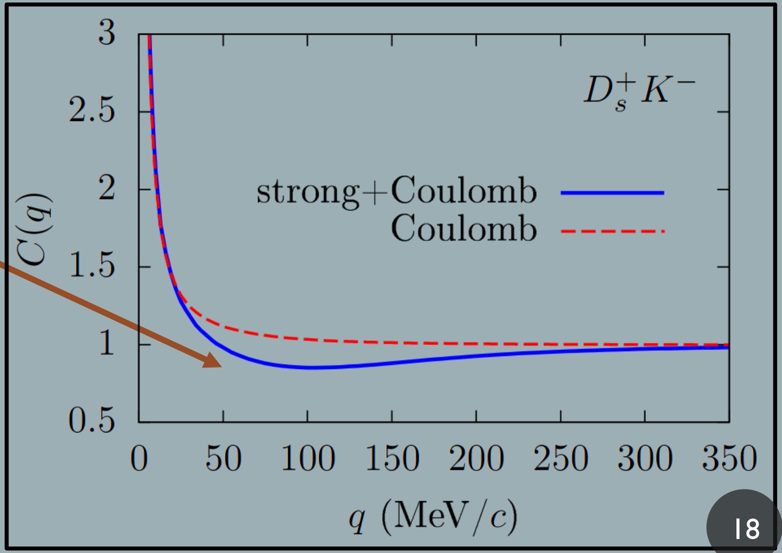
1. Molecular state is a genuine interpretation for many of the seen charm exotic states
2. **Natural option for close-to-threshold states (weakly bound)**
3. Useful information from heavy-ion physics. **Femtoscopy correlation functions can help to identify resonant states**
4. Finite-temperature broadening can affect production and decay products in RHICs

Liu *et al.*, arXiv:2404.06399









JMT-R, Ramos, Tolos, PRD108, 096008 (2023)

MOLECULAR STATES WITH CHARM: INSIGHTS FROM VACUUM & FINITE-TEMPERATURE ANALYSES

Juan M. Torres-Rincon
Universitat de Barcelona
Institut de Ciències del Cosmos

DFG Deutsche Forschungsgemeinschaft
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
CRC-TR 211

SQM 2024
The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France