Resonances and Pentaquarks from Coupled-Channel Dynamics

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Based on: J.A. Marsé-Valera, V.K. Magas, A. R., *Phys. Rev. Lett.* 130 (2023) 9

also: J.M.Torres-Rincon, A. R. , L: Tolos, arXiv:2307.02102

Outline

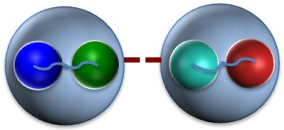
- Introduction to exotic hadrons → charm is the clue
- Pentaquarks within a molecular picture
  → Model: unitarized t-channel vector exchange interaction
  → Prediction of a S=-2 pentaquark
- Femtoscopy of D-mesons and light mesons
- Summary

Exotic hadrons
(anything that goes beyond $q\bar{q}$ and qqq)

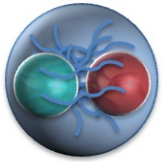
Mesons

compact tetraquark

Glueball



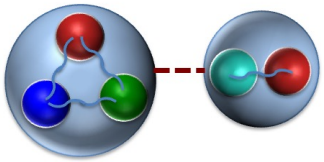
meson-meson molecule



hybrid

Baryons

compact pentaquark



baryon-meson molecule

Since the beginning of the millenium, an increasing amount of data in the charm (hidden charm) sector (collected at Belle, BaBar, LHCb and BESIII…), has provided cleaner evidence for many new **exotic** states which appear to be inconsistent with the predictions of the conventional quark model.

Exotic MESONS (hidden charm)

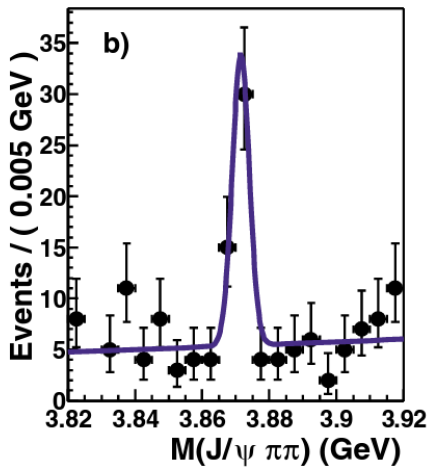
Discovered at Belle, 2003

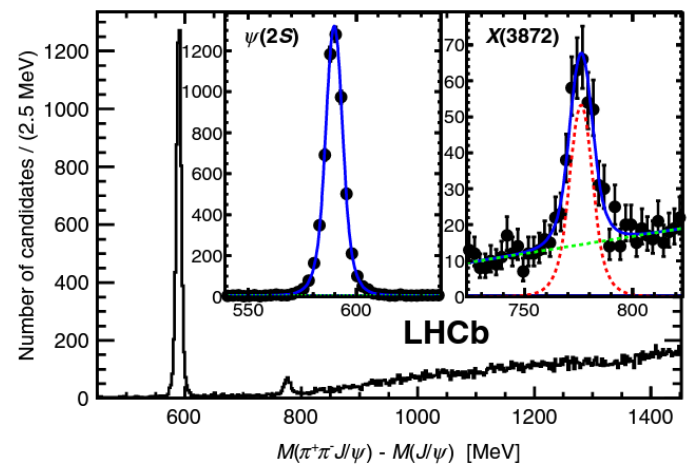
LHCb, PRL 2013

$\chi_{c1}(3872)$

$D^0\overline{D}^{*0}$

$(J^{PC} = 1^{++})$

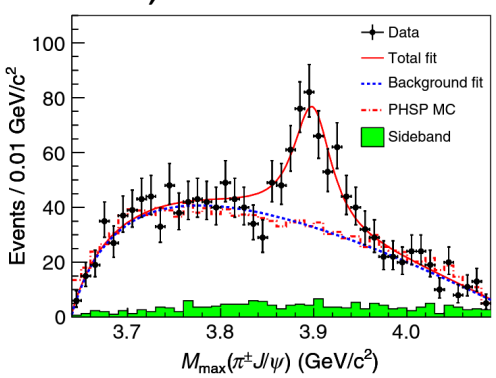




Hidden charm ($c\bar{c}$) but charged (need additional $q\bar{q}$ pair: $u\bar{d}$, $u\bar{s}$)

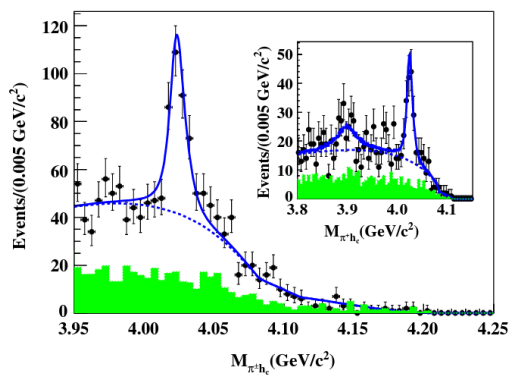
$Z_c(3900)$

BESIII, Belle 2013



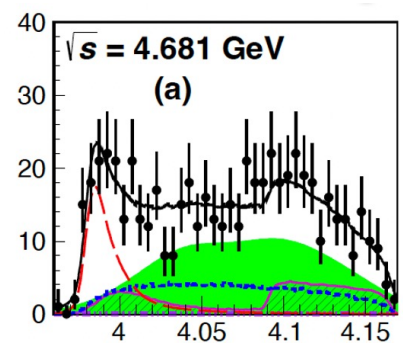
$Z_c(4020)$

BESIII 2013



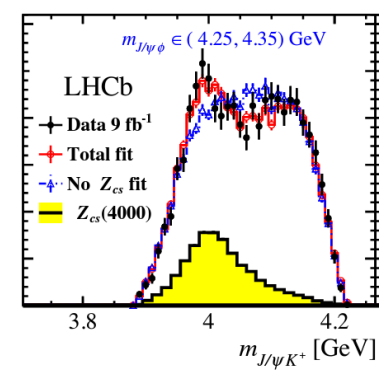
$Z_{cs}(3985)$

BESIII 2021



$Z_{cs}(4000)$

LHCb 2021

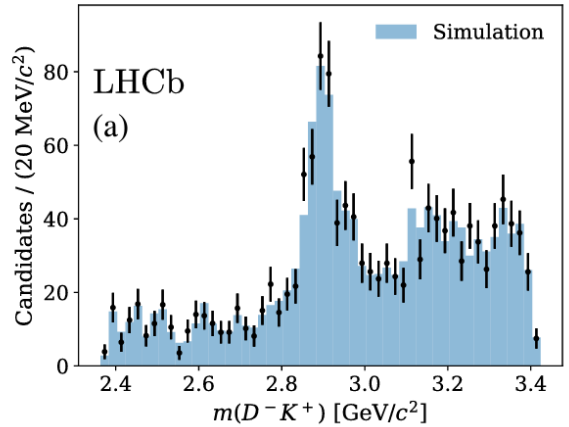


Exotic MESONS (open charm)

LHCb 2021

Charm-strange state (cs): $X_{cs}(2900)$

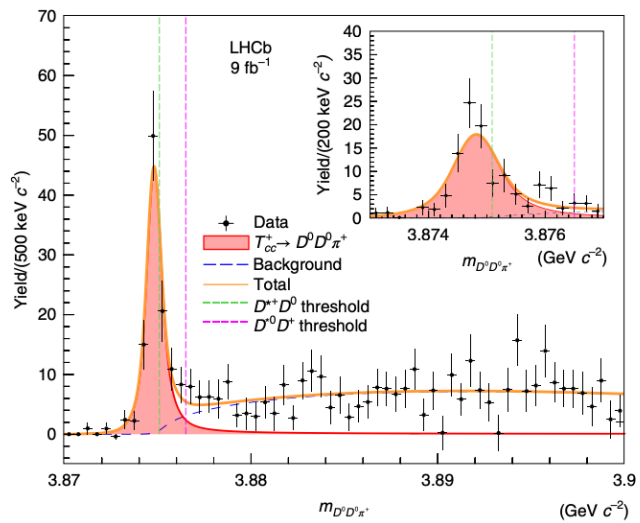
$D^*\overline{K}^*$ molecule?
Molina, Branz, Oset (2010)



Double-charm (cc): $T_{cc}(2900)$

$D^{*+}D^0$

LHCb 2022



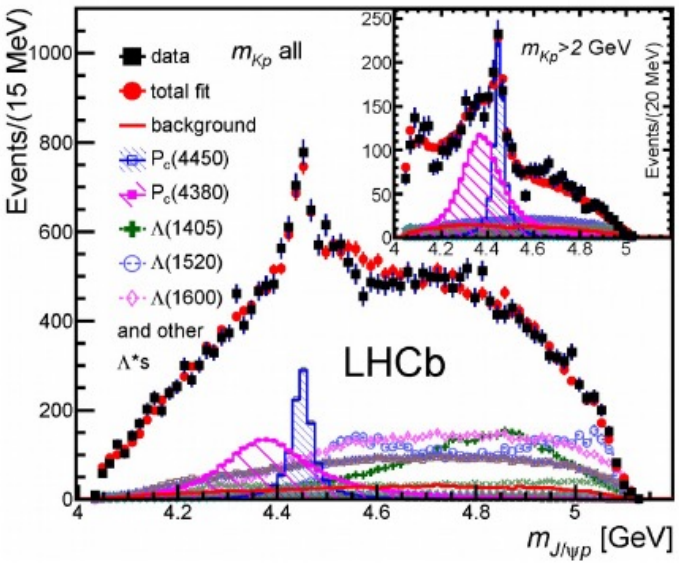
Exotic BARYONS

S=0 $(c\bar{c}qqq)$ $\quad q = u, d$

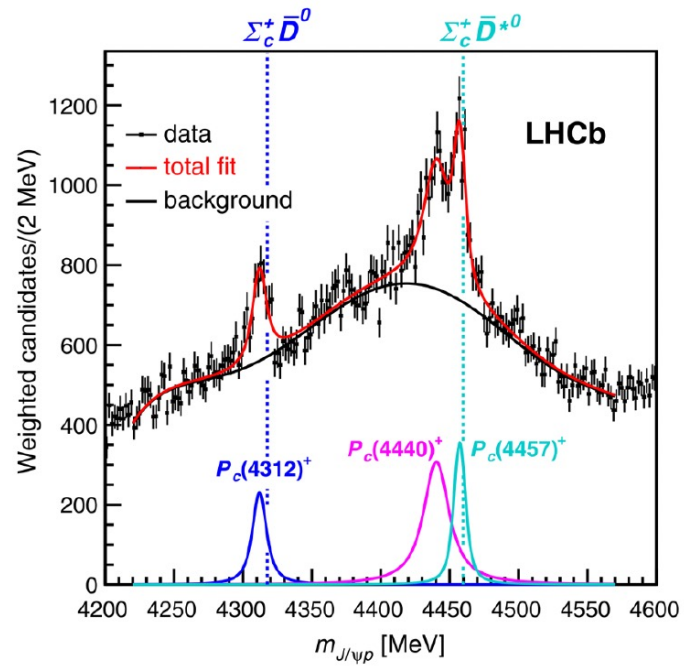
P_c (or P_ψ^N)

$$\Lambda_b \to J/\psi\ p\ K^-$$

LHCb, Run 1, 2015



LHCb, Run 1+Run 2, 2019



$P_c(4380)$

$P_c(4450)$ ⟶

New state: $P_c(4312)$

Broad $P_c(4380)$?

$P_c(4440)$, $P_c(4457)$

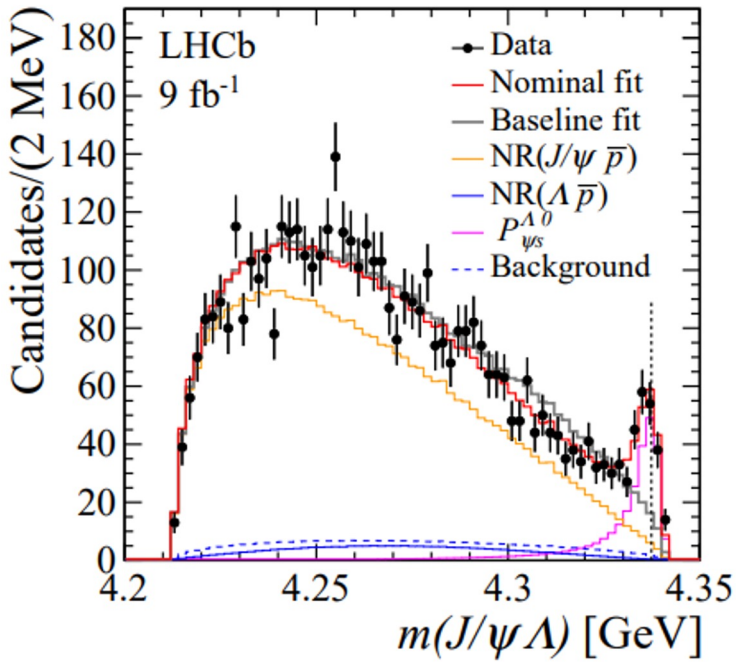
Exotic BARYONS

S=-1 $(c\bar{c}qqs)$ $q = u, d$

P_{cs} (or $P_{\psi s}^{\Lambda}$)

$B^- \to J/\psi \Lambda \bar{p}$

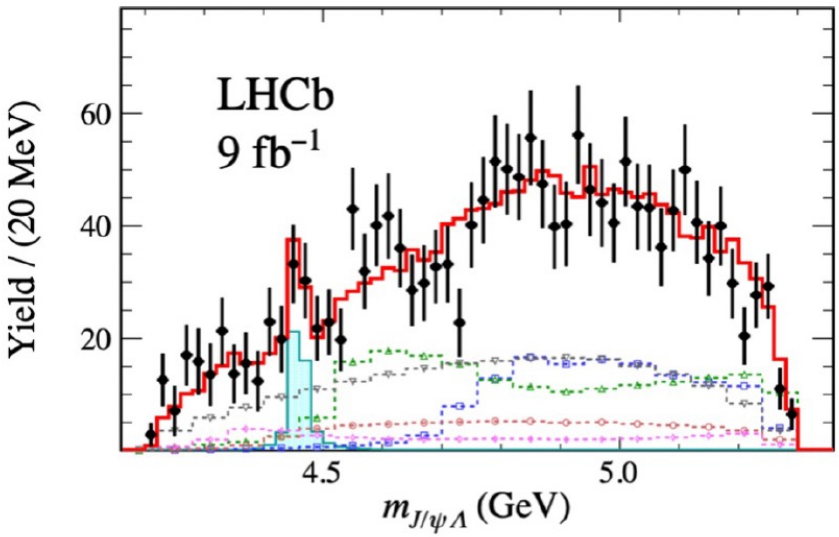
LHCb, arXiv:2210.10346 (Oct 2022)



$P_{cs}(4338)$

$\Xi_b^- \to J/\psi \Lambda K^-$

LHCb, Sci. Bull. 66 (2021) 1278



$P_{cs}(4459)$

- The flavor content of the $P_c(4310)$, $P_c(4440)$, $P_c(4457)$ states is not exotic (uud) but the high mass and the observation from J/ψ p pairs makes them to be unambiguous pentaquark candidates ($c\bar{c}uud$).

In fact, these states find a natural explanation as **meson-baryon** molecules:

$\bar{D}^0\Sigma_c^+$ threshold: 4318 MeV → **$P_c(4312)$**

$\bar{D}^{*0}\Sigma_c^+$ threshold: : 4460 MeV (J=1/2, 3/2) → **$P_c(4440)$, $P_c(4457)$**

and were already predicted in 2010!

J.J.Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. Lett. 105, 232001 (2010); Phys. Rev. C 84, 015202 (2011).

This work also predicted **S=-1** states at **4209 MeV** ($\bar{D}\Xi_c$), **4394 MeV** ($\bar{D}\Xi_c'$) **4368 MeV** ($\bar{D}^*\Xi_c$), **4544 MeV** ($\bar{D}^*\Xi_c'$)

No pentaquarks with **S=-2** were predicted

S=-2 pentaquarks?

P_{css} (or $P_{\psi ss}^{\Xi}$)

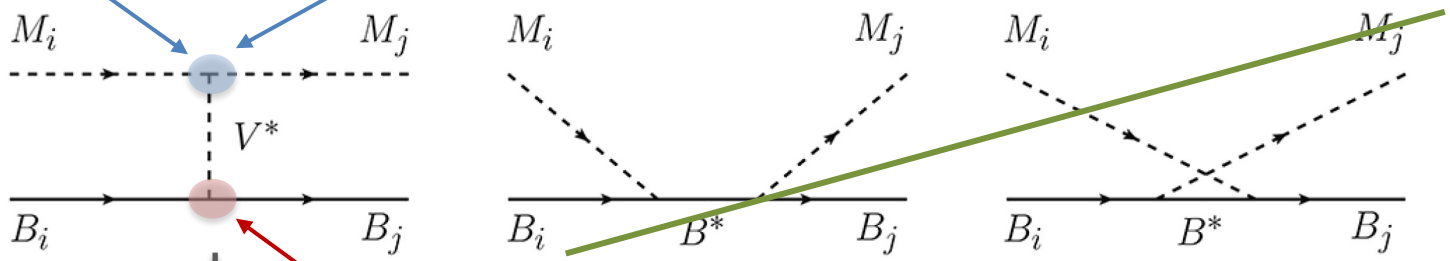
Unitarized t-channel vector-meson exchange interaction

Interaction kernel:

$$\mathcal{L}_{VPP} = -ig\langle[\phi, \partial_\mu \phi]V^\mu\rangle$$

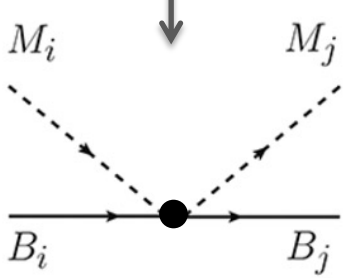
$$\mathcal{L}_{VVV} = ig\langle[V^\mu, \partial_\nu V_\mu]V^\nu\rangle$$

s-wave



$$\mathcal{L}_{VBB} = \frac{g}{2} \sum_{i,j,k,l=1}^{4} \bar{B}_{ijk}\gamma^\mu \left(V^k_{\mu,l} B^{ijl} + 2V^j_{\mu,l} B^{ilk}\right)$$

$t \ll m^2_{V^*}$



$$V_{ij}(\sqrt{s}) = -C_{ij}\frac{1}{4f^2}(2\sqrt{s} - M_i - M_j)\sqrt{\frac{E_i + M_i}{2M_i}}\sqrt{\frac{E_j + M_j}{2M_j}}$$

$$g = \frac{m_V}{2f} \qquad f = 93 \text{ MeV}$$

$$S = -2, I = \frac{1}{2}$$

$$V_{ij}(\sqrt{s}) = -C_{ij}\frac{1}{4f^2}(2\sqrt{s} - M_i - M_j)\sqrt{\frac{E_i + M_i}{2M_i}}\sqrt{\frac{E_j + M_j}{2M_j}}$$

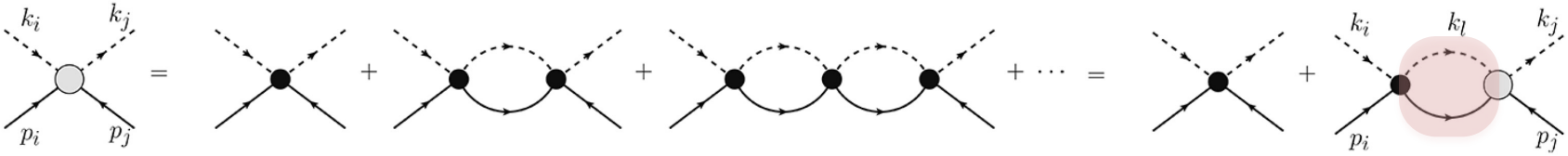
		$\pi\Xi$	$\bar{K}\Lambda$	$\bar{K}\Sigma$	$\eta\Xi$	$\eta'\Xi$	$\eta_c\Xi$	$\bar{D}_s\Xi_c$	$\bar{D}_s\Xi'_c$	$\bar{D}\Omega_c$
light sector	$\pi\Xi(1456)$	2	$\frac{3}{2}$	$\frac{1}{2}$	0	0	0	0	0	$\sqrt{\frac{3}{2}}\kappa_c$
	$\bar{K}\Lambda(1611)$		0	0	$-\frac{3}{2}$	0	0	$-\frac{1}{2}\kappa_c$	$-\frac{\sqrt{3}}{2}\kappa_c$	0
	$\bar{K}\Sigma(1689)$			2	$\frac{3}{2}$	0	0	$\frac{3}{2}\kappa_c$	$-\frac{\sqrt{3}}{2}\kappa_c$	0
	$\eta\Xi(1866)$				0	0	0	κ_c	$\frac{1}{\sqrt{3}}\kappa_c$	$\frac{1}{\sqrt{6}}\kappa_c$
	$\eta'\Xi(2276)$					0	0	$\frac{1}{\sqrt{8}}\kappa_c$	$-\frac{1}{\sqrt{6}}\kappa_c$	$\frac{1}{\sqrt{3}}\kappa_c$
heavy sector	$\eta_c\Xi(4302)$						0	$\sqrt{\frac{3}{2}}\kappa_c$	$\frac{1}{\sqrt{2}}\kappa_c$	$-\kappa_c$
	$\bar{D}_s\Xi_c(4437)$							$-1+\kappa_{cc}$	0	0
	$\bar{D}_s\Xi'_c(4545)$								$-1+\kappa_{cc}$	$-\sqrt{2}$
	$\bar{D}\Omega_c(4565)$									κ_{cc}

$$\kappa_c = \frac{m_\rho^2}{m_{D^*}^2} \sim \frac{1}{4}$$

$$\kappa_{cc} = \frac{m_\rho^2}{m_{J/\psi}^2} \sim \frac{1}{9}$$

Light and heavy sectors are practically "decoupled"

Unitarization: *Bethe-Salpeter equation with on-shell factorization*



$$T_{ij} = V_{ij} + V_{il} G_l T_{lj}$$

$$G_l = i \int \frac{\mathrm{d}^4 q}{(2\pi)^4} \frac{2M_l}{(P-q)^2 - M_l^2 + i\epsilon} \frac{1}{q^2 - m_l^2 + i\epsilon}$$

dim reg.

$$G_l^{\mathrm{DR}} = \frac{2M_l}{16\pi^2}\Big\{ a_l(\mu) + \ln\frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s}\ln\frac{m_l^2}{M_l^2} + \\ + \frac{q_l}{\sqrt{s}}\Big[\ln\left(s + (m_l^2 - M_l^2) + 2q_l\sqrt{s}\right) \\ + \ln\left(s - (m_l^2 - M_l^2) + 2q_l\sqrt{s}\right) \\ - \ln\left(-s - (m_l^2 - M_l^2) + 2q_l\sqrt{s}\right) \\ - \ln\left(-s + (m_l^2 - M_l^2) + 2q_l\sqrt{s}\right)\Big]\Big\}$$

$a_l(\mu) \sim -2 \qquad (\mu = 1\ \mathrm{GeV})$

cut-off

$$G_l^{\mathrm{cut}} = 2M_l \int^{\Lambda} \frac{q^2\,\mathrm{d}q}{4\pi^2} \frac{(\omega_l + E_l)}{\omega_l E_l} \frac{1}{s - (\omega_l + E_l)^2 + \mathrm{i}\epsilon}$$

$\Lambda = 600 - 1000$ MeV

$$a_l(\mu) = \frac{16\pi^2}{2M_l}\left(G_l^{\mathrm{cut}}(\Lambda) - G_l^{\mathrm{DR}}(\mu, a_l = 0)\right)$$

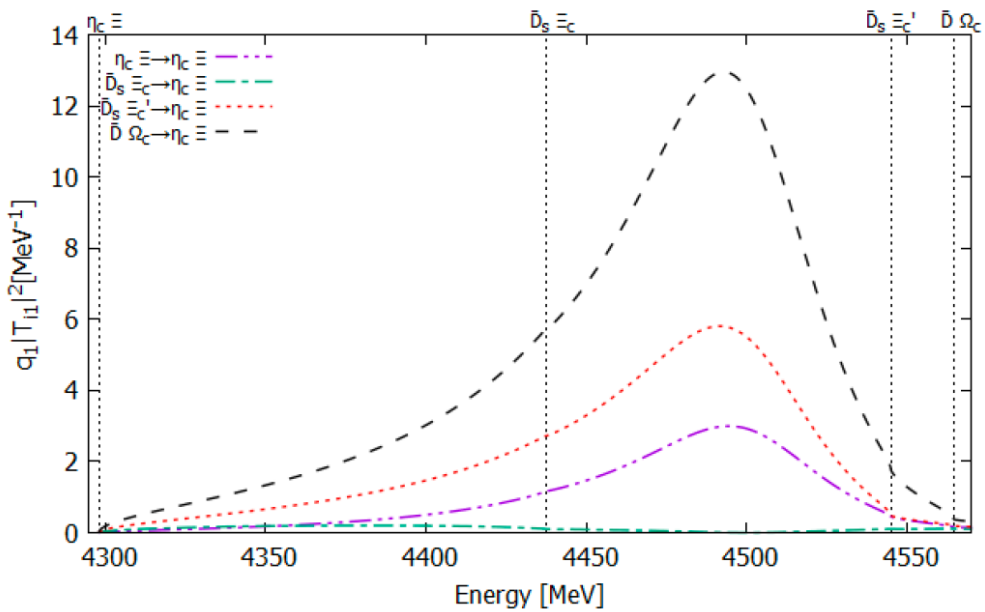
(we employ the cut-off method with Λ~800 MeV)

Results: heavy PB sector

$$J^\pi = \frac{1}{2}^-$$

$0^- \oplus 1/2^+$ PB interaction in the $(I,S) = (1/2,-2)$ sector				
$P^{\Xi}_{\Psi ss}(4493)$		$M_R = 4493.35$ MeV	$\Gamma_R = 73.67$ MeV	
	Threshold Energy (MeV)	g_i	$\lvert g_i \rvert$	χ_i
$\eta_c \Xi$	4298	$-1.60 + i0.34$	1.63	0.220
$\bar{D}_s \Xi_c$	4437	$-0.17 + i0.27$	0.32	0.019
$\bar{D}_s \Xi_c'$	4545	$-2.41 + i0.58$	2.48	0.398
$\bar{D}\Omega_c$	4564	$3.59 - i0.77$	3.67	0.711

We find a $P^{\Xi}_{\psi ss}$ state around **4500 MeV** with a width of 70 MeV, coupling strongly to $\bar{D}_s \Xi_c'$ and $\bar{D}\Omega_c$



J.A. Marsé-Valera, V.K. Magas, A. Ramos, *Phys. Rev. Lett.* 130 (2023) 9

Are meson-baryon molecules expected?

$$V_{ij}(\sqrt{s}) = -C_{ij}\frac{1}{4f^2}(2\sqrt{s} - M_i - M_j)\sqrt{\frac{E_i + M_i}{2M_i}}\sqrt{\frac{E_j + M_j}{2M_j}}$$

$S = 0, I = 1/2$

	$\eta_c N$	$\bar{D}\Lambda_c$	$\bar{D}\Sigma_c$
$\eta_c N$	0	$-\sqrt{\frac{3}{2}}\kappa_c$	$\sqrt{\frac{3}{2}}\kappa_c$
$\bar{D}\Lambda_c$		$-1 + \kappa_{cc}$	0
$\bar{D}\Sigma_c$			$1 + \kappa_{cc}$

repulsion

attraction

one state ←

$S = -1, I = 0$

	$\eta_c\Lambda$	$\bar{D}_s\Lambda_c$	$\bar{D}\Xi_c$	$\bar{D}\Xi'_c$
$\eta_c\Lambda$	0	κ_c	$-\frac{1}{\sqrt{2}}\kappa_c$	$-\sqrt{\frac{3}{2}}\kappa_c$
$\bar{D}_s\Lambda_c$		κ_{cc}	$\sqrt{2}$	0
$\bar{D}\Xi_c$			$1 + \kappa_{cc}$	0
$\bar{D}\Xi'_c$				$1 + \kappa_{cc}$

→ two states

$$\kappa_c = \frac{m_\rho^2}{m_{D^*}^2} \sim \frac{1}{4}$$

$$\kappa_{cc} = \frac{m_\rho^2}{m_{J/\psi}^2} \sim \frac{1}{9}$$

$S = -2, I = 1/2$

	$\eta_c\Xi$	$\bar{D}_s\Xi_c$	$\bar{D}_s\Xi'_c$	$\bar{D}\Omega_c$
$\eta_c\Xi$	0	$\sqrt{\frac{3}{2}}\kappa_c$	$\frac{1}{\sqrt{2}}\kappa_c$	$-\kappa_c$
$\bar{D}_s\Xi_c$		$-1 + \kappa_{cc}$	0	0
$\bar{D}_s\Xi'_c$			$-1 + \kappa_{cc}$	$-\sqrt{2}$
$\bar{D}\Omega_c$				κ_{cc}

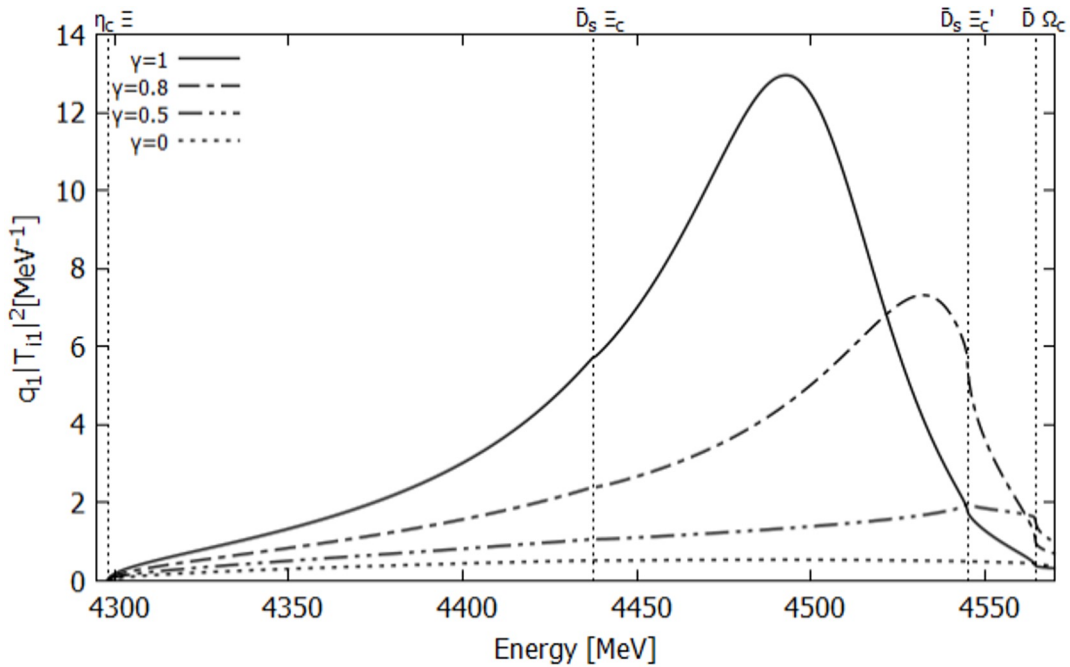
→ no state expected

but...

strong coupled channel effect!
→ induces attraction

Coupled-channel effect

$$C_{34} = -\sqrt{2} \quad \rightarrow \quad C'_{34} = \gamma\, C_{34}$$



The resonance is not generated in the coupling coefficient is reduced by 30%.

This state is generated in a very specific and unique mechanism:

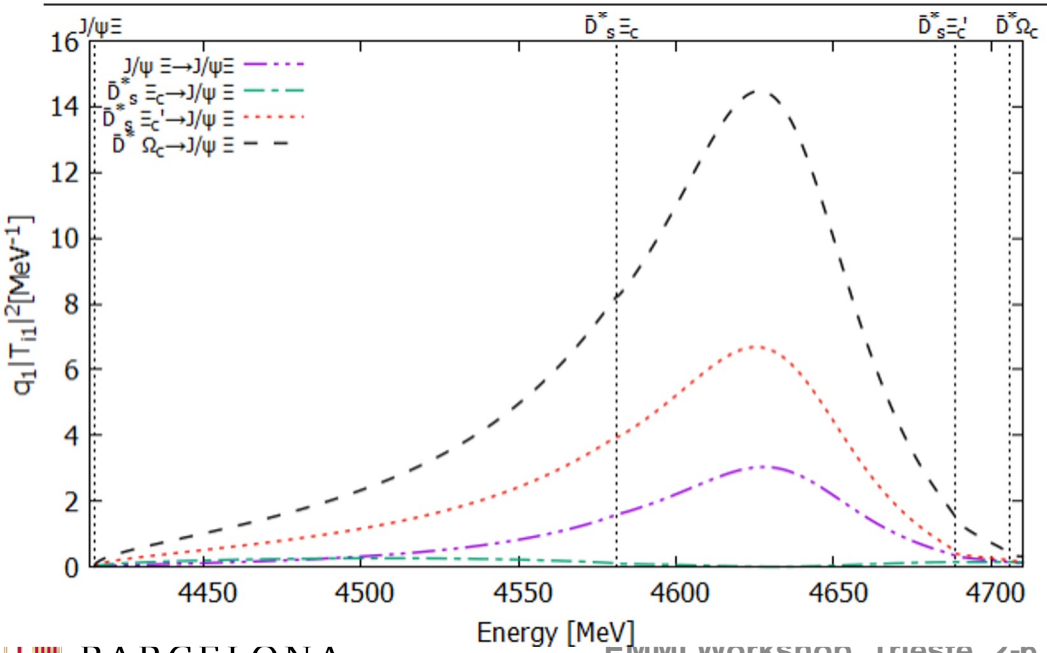
→ via an attraction induced by a strong coupling between the $D_s\Xi_c'$ and $D\Omega_c$ channels

Results: heavy VB sector

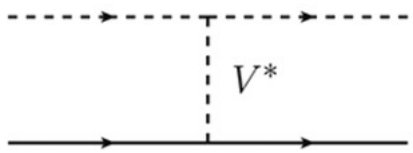
$$J^\pi = \frac{1}{2}^-, \frac{3}{2}^-$$

$1^- \oplus 1/2^+$ VB interaction in the $(I,S)=(1/2,-2)$ sector				
$P^{\Xi}_{\Psi ss}(4633)$		$M_R = 4633.38$ MeV	$\Gamma_R = 79.58$ MeV	
	Threshold Energy (MeV)	g	$\lvert g_i \rvert$	χ_i
$J/\psi\Xi$	4415	$-1.62 + i0.38$	1.66	0.252
$\bar{D}_s^*\Xi_c$	4581	$-0.143 + i0.32$	0.34	0.022
$\bar{D}_s^*\Xi_c'$	4689	$-2.49 + i0.67$	2.58	0.406
$\bar{D}^*\Omega_c$	4706	$3.67 + i0.89$	3.78	0.740

We find a $P^{\Xi}_{\psi ss}$ state around **4630 MeV** with a width of 80 MeV, coupling strongly to $\bar{D}_s^*\Xi_c'$ and $\bar{D}^*\Omega_c$

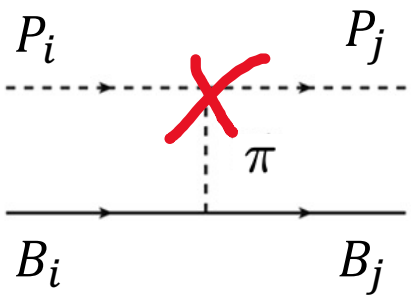


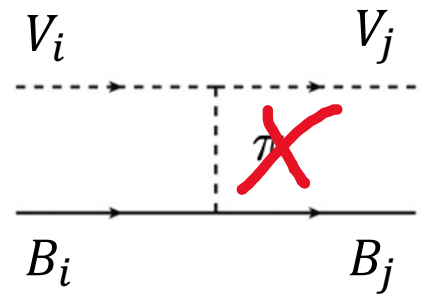
It could be seen as a peak in the invariant mass spectrum of $J/\psi\ \Xi$ pairs produced in the decays: $\Xi_b \to J/\psi\ \Xi\ \phi$ or $\Omega_b \to J/\psi\ \Xi\ \bar{K}$



The t-channel vector-exchange formalism predicts pentaquarks with S=-2: $P^{\Xi}_{\psi ss}$

The alternative molecular picture (long range open-pion-exchange) is forbidden!





Channels:

$\eta_c\Xi \quad \bar{D}_s\Xi_c \quad \bar{D}_s\Xi'_c \quad \bar{D}\Omega_c$

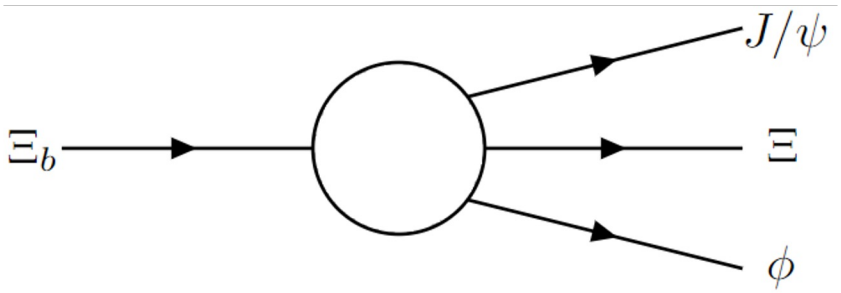
Channels:

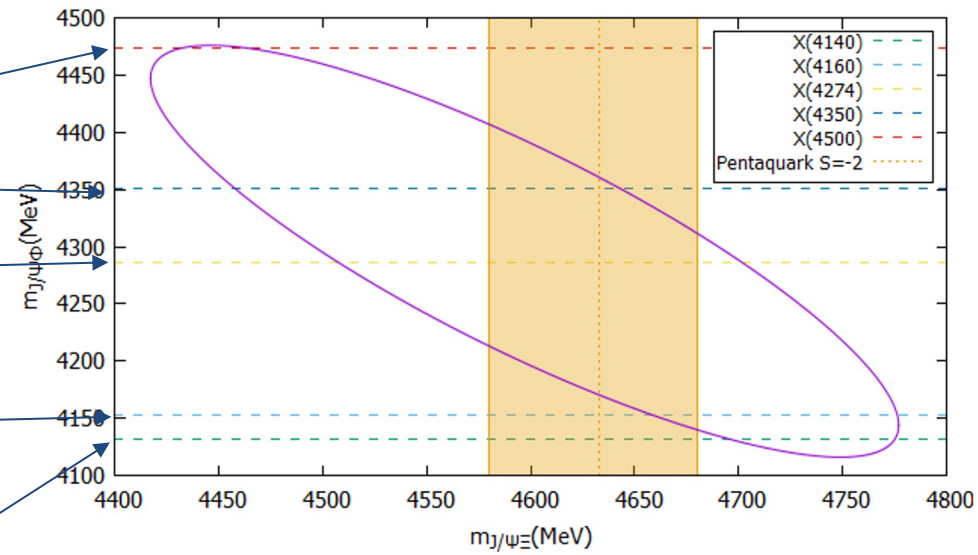
$J/\psi\,\Xi \quad \bar{D}^*_s\Xi_c \quad \bar{D}^*_s\Xi'_c \quad \bar{D}^*\Omega_c$

These transitions cannot proceed via OPE because they involve either an isoscalar meson or baryon

→ **If $P^{\Xi}_{\psi ss}$ are discovered, this would strengthen the validity of unitary t-channel vector-exchange models for meson-baryon molecules**

The decay $\Xi_b \to J/\psi\ \phi\ \Xi$





X(4500)

X(4350)

X(4270)

? X(4160)

seen at Belle, 2008

2^{++} $D_s^* \bar{D}_s^*$ molecule

Molina, Oset, 2009

not seen at LHCb,2017

X(4140)

narrow? CDF, 2009

wide? LHCb, 2017

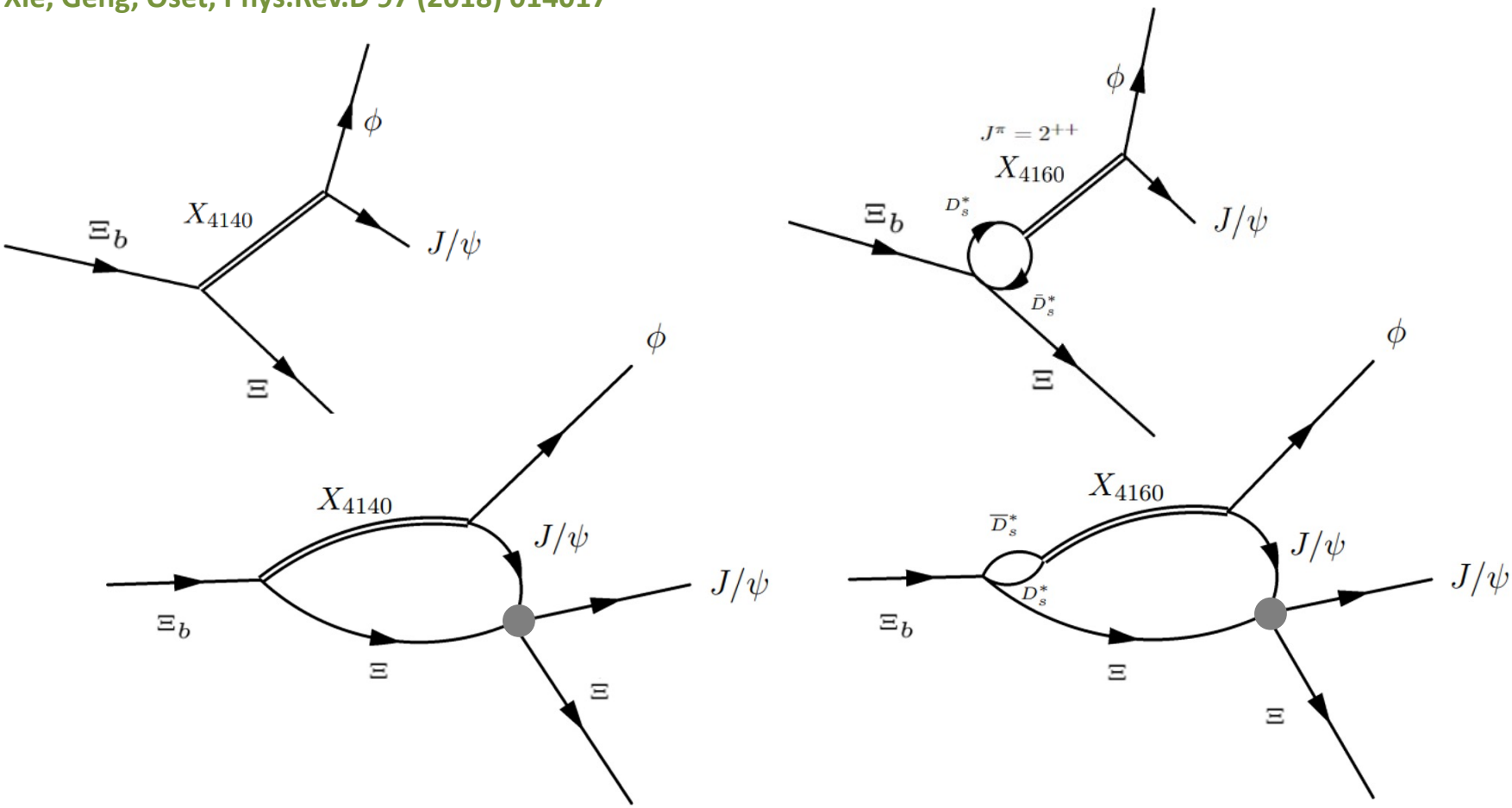
$\Xi_b \to J/\psi\ \phi\ \Xi$

(Similar to the proces $\Lambda_b \to J/\psi\ \phi\ \Lambda$)

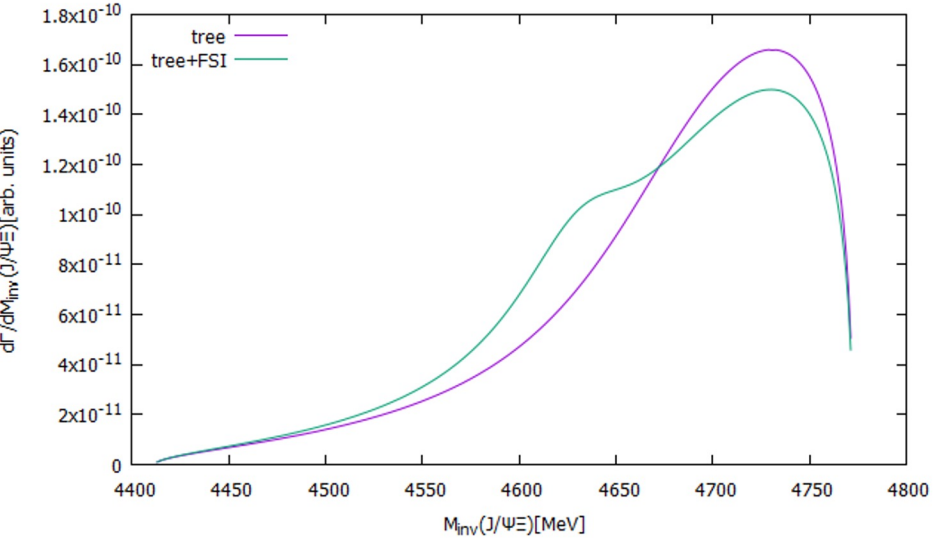
Magas, Ramos, Somasundaram, Phys.Rev.D 102 (2020) 054027

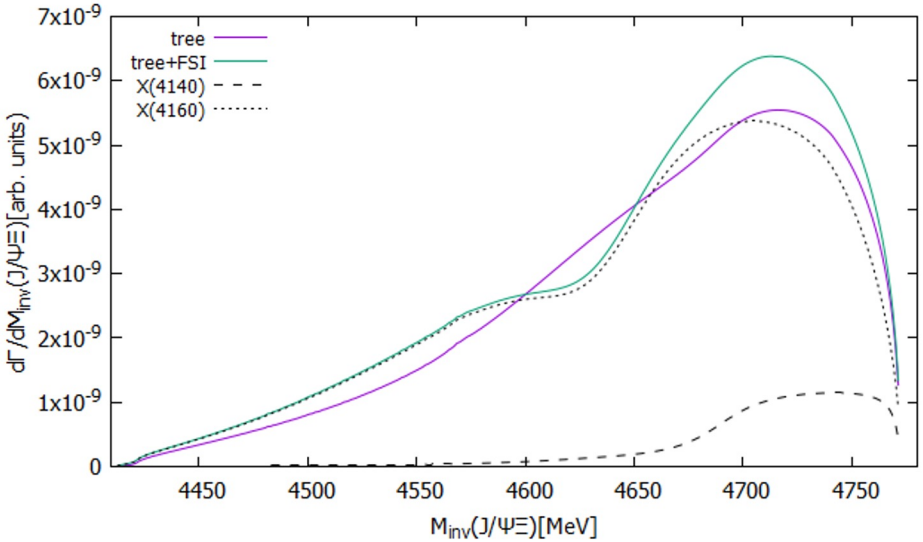
(inspired on $B^+ \to J/\psi\ \phi\ K^+$)

Wang, Xie, Geng, Oset, Phys.Rev.D 97 (2018) 014017

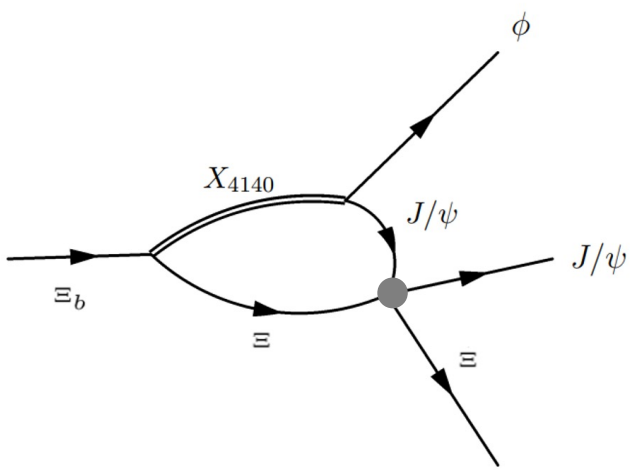


$J/\psi\ \Xi$ invariant mass distribution



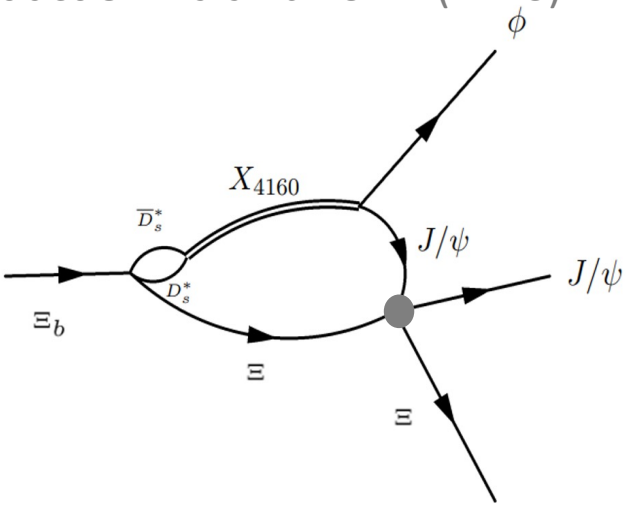


Production via a *wide* X(4140)



+

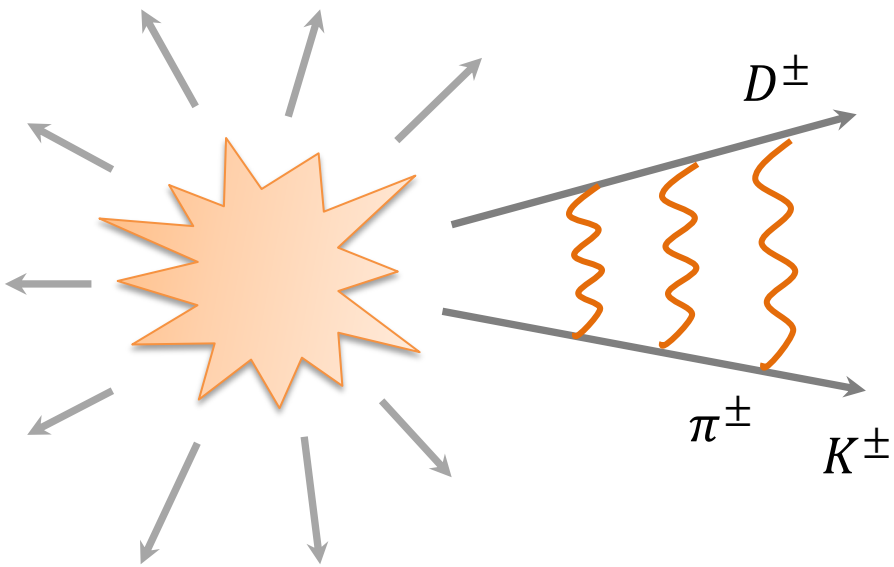
Production via a *narrow* X(4140) + X(4160)

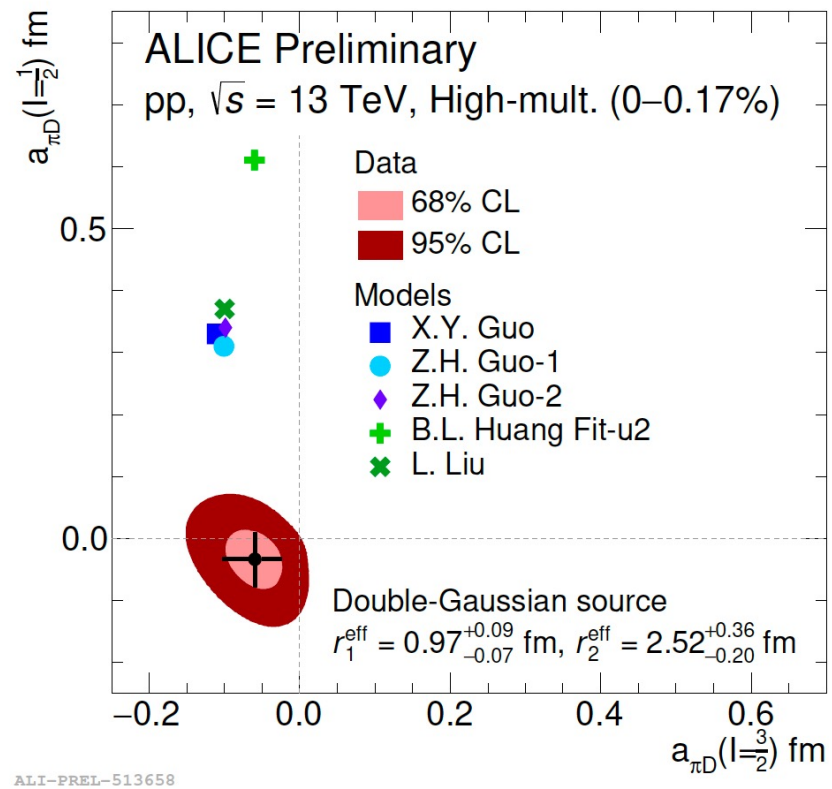


Femtoscopy of D-mesons and light mesons

J.M.Torres-Rincon, A. R. , L: Tolos, arXiv:2307.02102

pp collisions at ALICE at $\sqrt{s} = 13$ TeV





L. Fabbietti, HF-WINC, Torino, Italy. 2022

Correlation function (Koonin-Pratt formula)

$$C(\boldsymbol{q}) = \int d^3r \sum_i w_i \underbrace{S_i(\boldsymbol{r})}_{\text{source}} \underbrace{|\Psi_i(\boldsymbol{q};\boldsymbol{r})|^2}_{\text{wave-function}}$$

We consider the strong interaction in s-wave ($\ell = 0$)

$$\Psi_f(\boldsymbol{q};\boldsymbol{r}) = \Phi_f^{\mathrm{C}}(\boldsymbol{q};\boldsymbol{r}) - \Phi_{0\,f}^{\mathrm{C}}(q\,r) + \varphi_f(q;r)$$ → asymptotic state *f*

$$\Psi_j(\boldsymbol{q};\boldsymbol{r}) = \varphi_j(q;r)$$ → transition wave function from state *j* to the asymptotic *f*

We take a spherically symmetric (and channel-independent) source

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

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

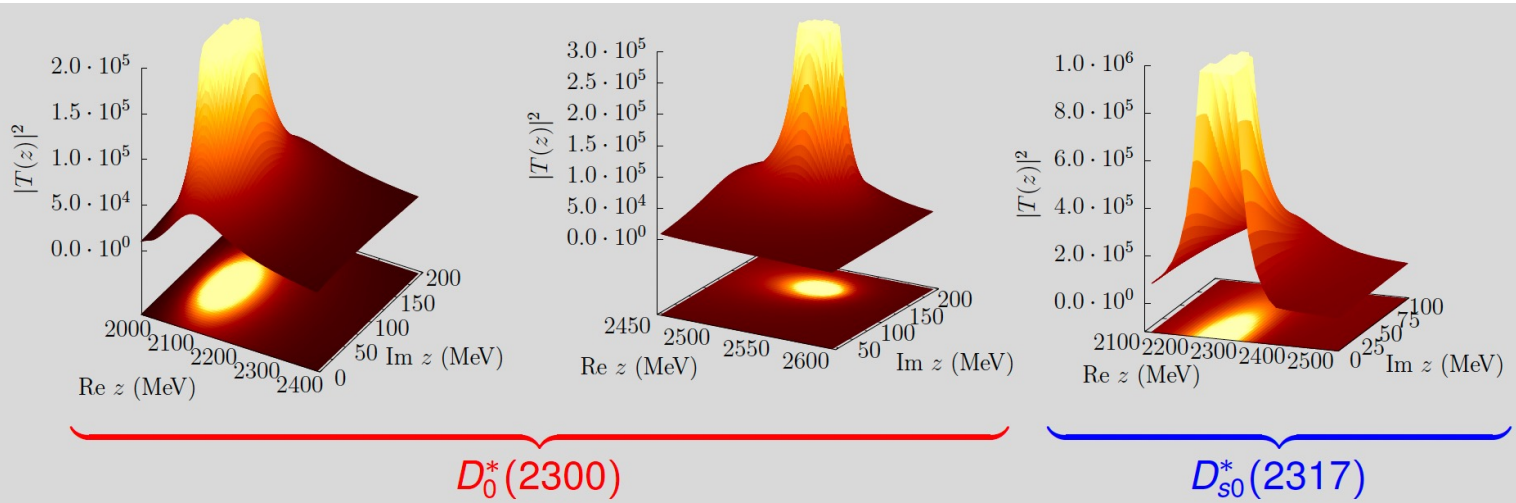
$$\varphi_i(q;r) = j_0(qr)\delta_{if} + \int_0^\infty \frac{4\pi q'^2\, dq'}{(2\pi)^3} \frac{T_{if}(q',q;\sqrt{s})\, j_0(q'r)}{2\omega_{H,i}\, 2\omega_{\phi,i}(\sqrt{s} - \omega_{H,i} - \omega_{\phi,i} + i\eta)}$$

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

$$V_{il} = V_{s-wave}^{strong} + \delta_{il} V_{s-wave}^{Coulomb} \qquad f(q,q') = \exp\left(-\frac{q^2 + q'^2}{\Lambda^2}\right) \qquad \Lambda \sim 800 \text{ fm}$$

The **strong** interaction of the D-mesons with light particles: effective Lagrangian based on both chiral and heavy-quark symmetries.
(similarly as in **Z.-H. Guo, L. Liu, U.-G. Meiβner, J. A. Oller, and A. Rusetsky, 2019**)

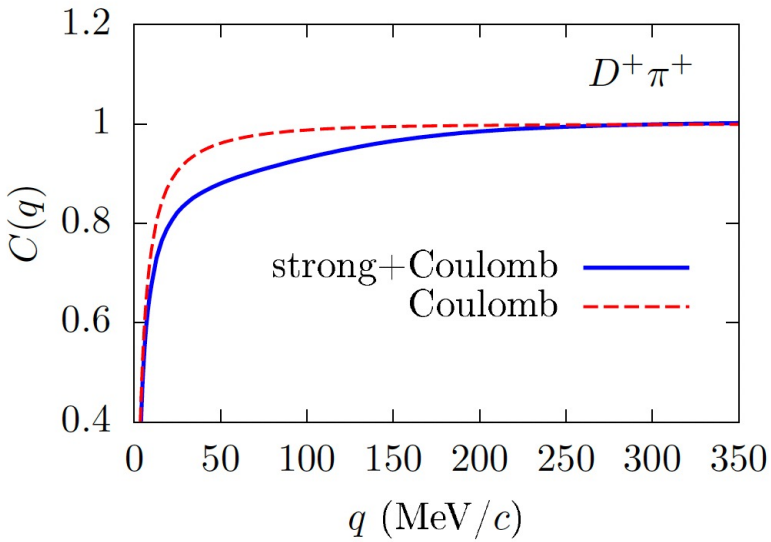
Double pole structure of the $D_0^*(2300)$

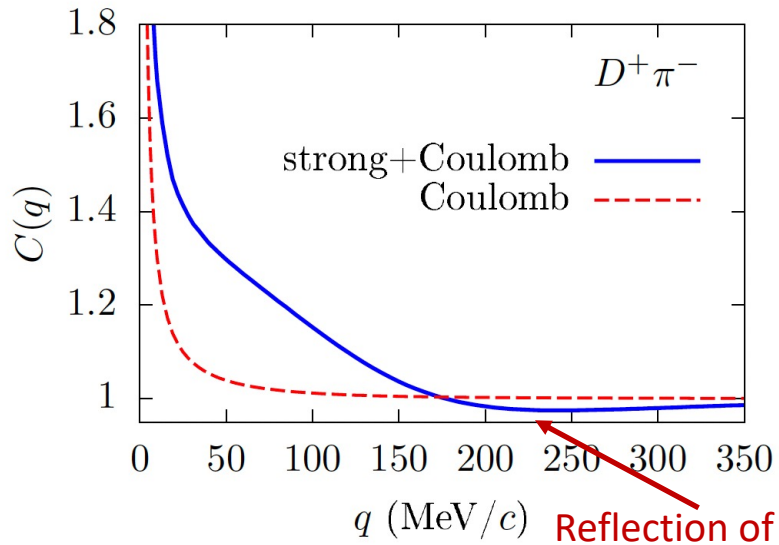


(S,Q)	channel (particle)	a [fm]
$(-1,-1)$	D^0K^-	-0.232
$(-1,0)$	$D^0\bar{K}^0$	0.071
	D^+K^-	0.083
$(-1,+1)$	$D^+\bar{K}^0$	-0.233
$(0,-1)$	$D^0\pi^-$	-0.102
$(0,0)$	$D^0\pi^0$	0.056
	$D^+\pi^-$	0.253
	$D^0\eta$	$0.071+\mathrm{i}\,0.065$
	$D_s^+K^-$	$-0.114+\mathrm{i}\,0.693$
$(0,+1)$	$D^0\pi^+$	0.246
	$D^+\pi^0$	0.073
	$D^+\eta$	$0.074+\mathrm{i}\,0.067$
	$D_s^+\bar{K}^0$	$-0.113+\mathrm{i}\,0.695$
$(0,+2)$	$D^+\pi^+$	-0.102

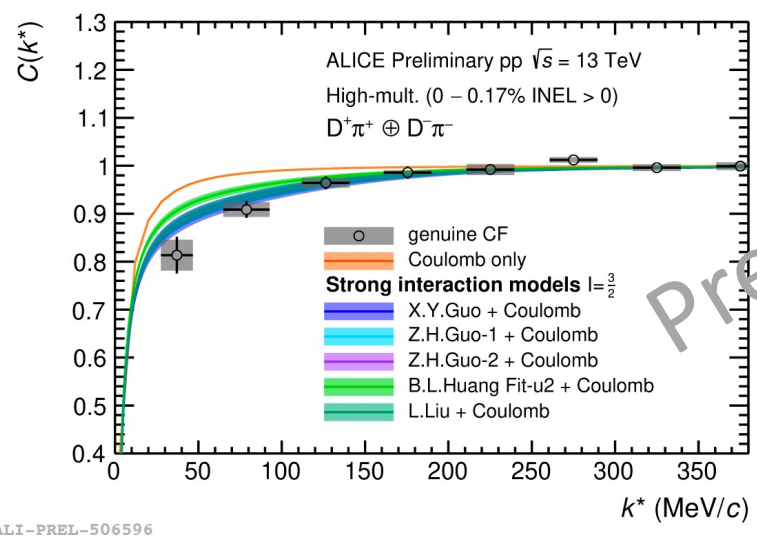
(S,Q)	channel (particle)	a [fm]
$(1,0)$	$D_s^+\pi^-$	0.0033
	D^0K^0	$-0.027+\mathrm{i}\,0.084$
$(1,+1)$	$D_s^+\pi^0$	0.0032
	D^0K^+	$-0.857+\mathrm{i}\,0.020$
	D^+K^0	$-0.647+\mathrm{i}\,0.200$
	$D_s^+\eta$	$-0.324+\mathrm{i}\,0.132$
$(1,+2)$	$D_s^+\pi^+$	0.0031
	D^+K^+	$-0.026+\mathrm{i}\,0.083$
$(2,+1)$	$D_s^+K^0$	-0.222
$(2,+2)$	$D_s^+K^+$	-0.220

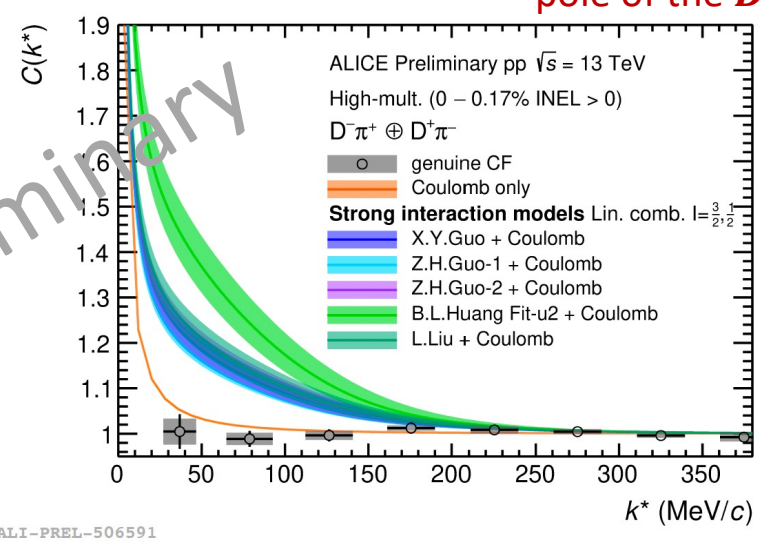
Results: D mesons with pions





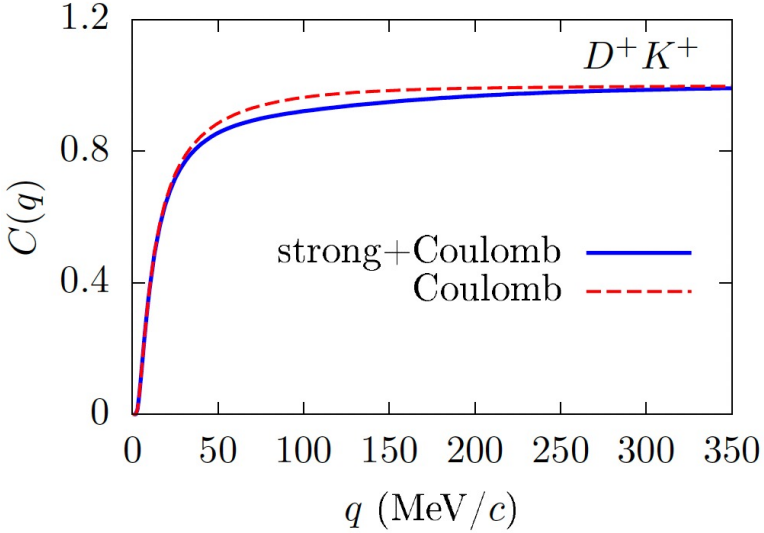
Reflection of the lower pole of the $D_0^*(2300)$

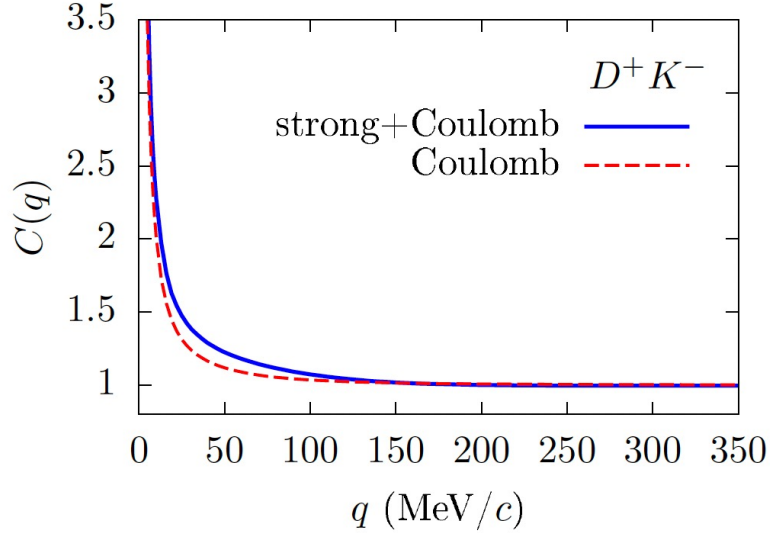


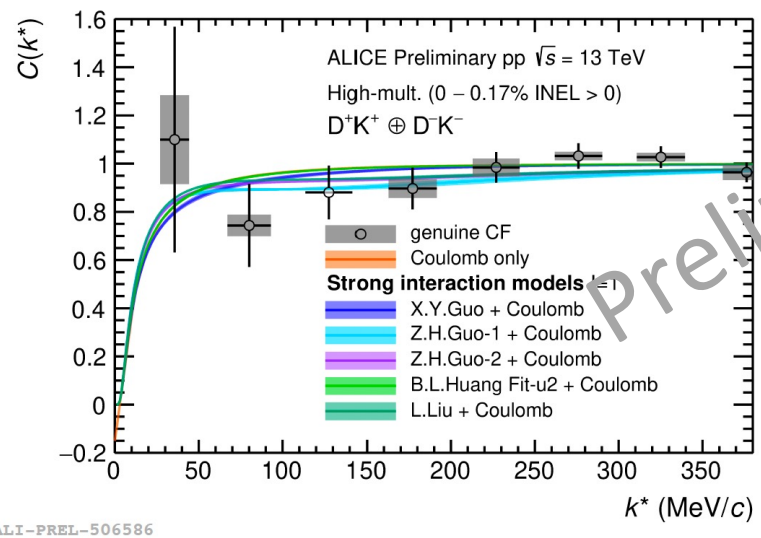


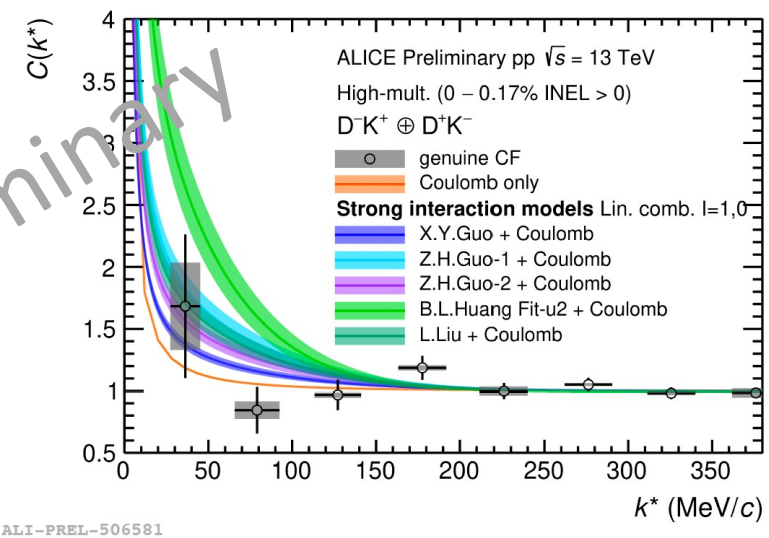
Preliminary

Results: D mesons with kaons









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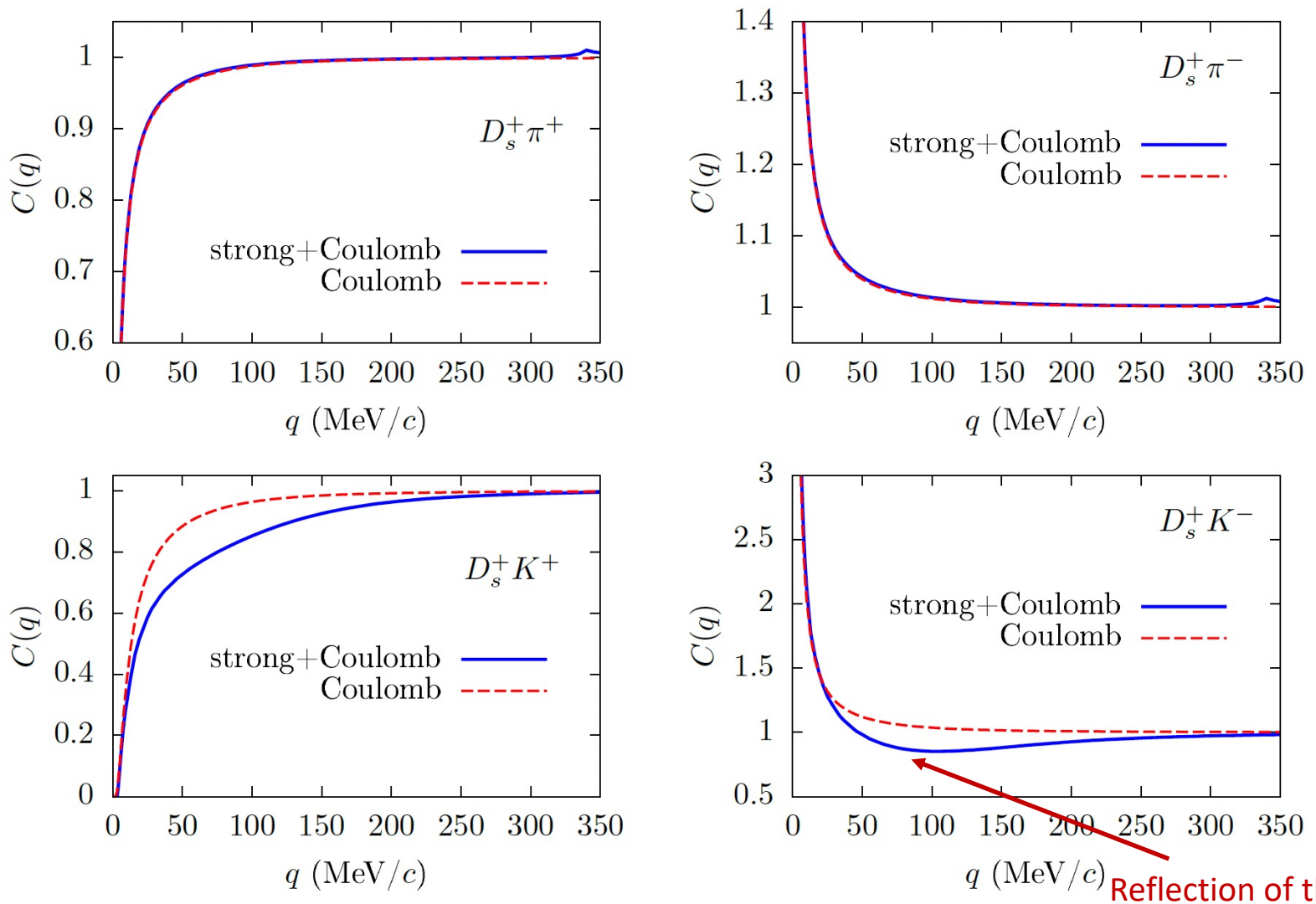
Results: D_s mesons with pions and kaons



Reflection of the higher pole of the $D_0^*(2300)$

Summary

We have revisited the **vector-meson exchange interaction models** to study the possible existence of pentaquarks with strangeness S=−2

→ We predict **S=-2 pentaquarks of molecular nature around 4500 and 4600 MeV**

These $P^{\Xi}_{\psi ss}$ states are generated via a unique **coupled-channels** effect!

→ The **absence in this sector of a long-range OPE** mechanism makes the search of these states especially interesting: if found, their interpretation as **molecules** would require a change of paradigm, since they **could be only bound through heavier-meson exchange** mechanisms.

We have calculated the femtoscopic **correlation functions of charged $\mathbf{D}^{\pm}$ and $\mathbf{D}_s^{+}$ mesons with $\boldsymbol{\pi}^{\pm}$ and $\boldsymbol{K}^{\pm}$** (within a T-matrix formalism employing a strong interaction from an effective field theory + the Coulomb force)

→ compared to preliminary ALICE data: relatively **good agreement** for $D^+\pi^+$, D^+K^-, D^+K^+ and **discrepancy** for $D^+\pi^-$

→ **shallow depletion** in $D^+\pi^-$ around 240 MeV (lower pole of the $D_0^*(2300)$)

→ **more pronounced depletion** in $\mathrm{D}_s^+K^-$ around 100 MeV (higher pole of the $D_0^*(2300)$)

Thank you for your attention