

Hadronic molecules with charm

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- F.K.Guo, C.Hanhart, Ulf-G.Meissner, Q.Wang, Q.Zhao, B.S.Zou, “Hadronic Molecules”, Rev. Mod. Phys. 90 (2018)015004
- X.K.Dong, F.K.Guo, B.S.Zou, “A survey of heavy-antiheavy hadronic molecules”, Progr. Phys. 41 (2021) 65; “A survey of heavy-heavy hadronic molecules”, Commun. Theor. Phys. 73 (2021) 125201

Outline :

- 1. Hadronic molecules with strangeness**
- 2. Hadronic molecules with hidden charm**
- 3. Hadronic molecules with double charm**
- 4. Conclusion**

1. Hadronic molecules with strangeness

Brief history for the discovery of hadronic molecules

1932: Neutron & Deuteron - the 1-st hadronic molecule

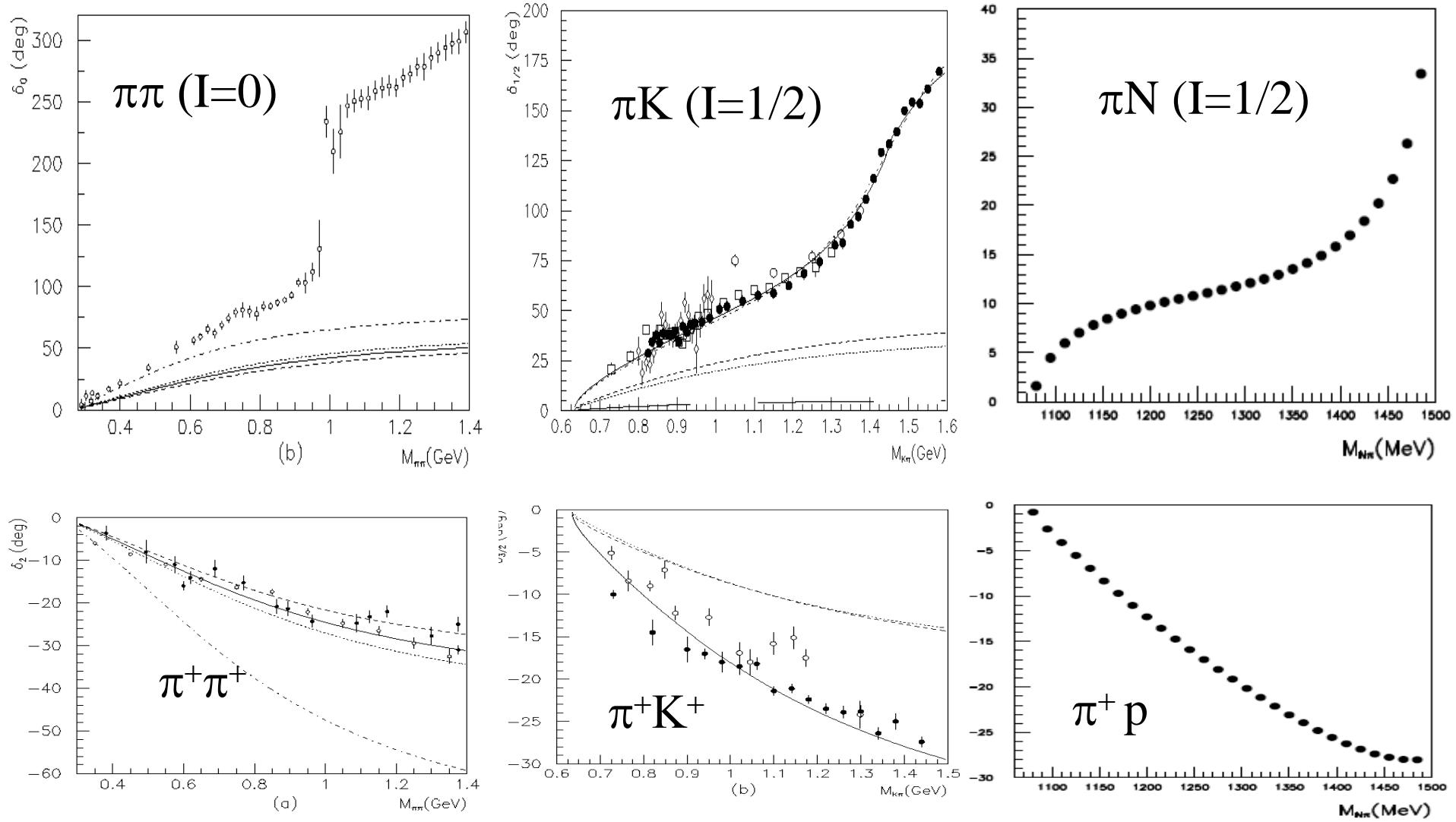
1947: π , K

1959: KN molecule predicted by Dalitz Tuan, PRL2, 425

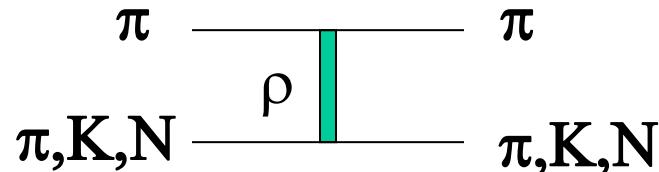
1961: $\Lambda(1405) \rightarrow \Sigma\pi$ observed by Alston et al., PRL6, 698

post-1962:	$f_0(980)$ & $a_0(980)$	$\bar{K}K$ molecules?	Isgur, ...
	$f_1(1420)$	$\bar{K}K^*$ molecule ?	Tornqvist, ...
	$f_0(1710)$	\bar{K}^*K^* molecule ?	Oset, ...
	$N^*(1535)$	$\bar{K}\Sigma$ - $\bar{K}\Lambda$ molecule ?	Kaiser, ...
	$D_{s0}^*(2317)$ & $D_{s1}^*(2460)$	$\bar{K}D$ & $\bar{K}D^*$ molecules?	Barnes, ...
		

Similarity for $\pi\pi$, πK and πN s-wave scattering \rightarrow VMD



Important role by t-channel ρ exchange for all these processes



$\pi\pi$

πK & πN

$$K_{\rho}^{I=0} = -2 K_{\rho}^{I=2}, \quad K_{\rho}^{I=1/2} = -2 K_{\rho}^{I=3/2}$$

D. Lohse, J.W. Durso, K. Holinde, J. Speth, Nucl.Phys.A516, 513 (1990)
B.S.Zou, D.V.Bugg, Phys. Rev. D50, 591 (1994)

U. -G. Meissner, “Low-energy hadron physics from effective chiral Lagrangians with vector mesons”, Phys. Rept. 161 (1988) 213

	$\bar{K}N(I=0)$	$\bar{K}N(I=1)$	$KN(I=0)$	$KN(I=1)$
Phase shifts:	strong +	weaker +	weaker -	strong -
VMD :	$-V_\omega - 3V_\rho$	$-V_\omega + V_\rho$	$V_\omega - V_\rho$	$V_\omega + 3V_\rho$

Similarity between $\pi\Sigma$ - $\bar{K}N(I=0)$ and $\pi\pi$ - $\bar{K}K(I=0)$

dipole structure for $\Lambda(1405) \leftarrow \sigma - f_0(980)$

VMD – ChPT unitarized $\rightarrow N^*(1535)$ as $K\Sigma$ bound state
 Kaiser et al., PLB362(1995)23

Difficulties to pin down hadronic molecules with \bar{q}

Fate of the first hadronic molecule predicted and observed:

- 1959: $\bar{K}N$ molecule predicted by Dalitz-Tuan, PRL2, 425
- 1961: $\Lambda(1405) \rightarrow \Sigma\pi$ observed by Alston et al., PRL6, 698
- 1964: Quark model (uds) for $\Lambda(1405)$
- 1995: $\bar{K}N$ dynamically generated -- Kaiser et al., NPA954, 325
- 2001: 2 pole structure by $\bar{K}N-\Sigma\pi$ -- Oller et al., PLB500, 263

PDG2010: “The clean Λ_c spectrum has in fact been taken to settle the decades-long discussion about the nature of the $\Lambda(1405)$ —true 3-quark state or mere $\bar{K}N$ threshold effect?— unambiguously in favor of the first interpretation.”

Solution: Extension to hidden charm and beauty for baryons

N*(1535) $\bar{s}suud$

N*(4260) $\bar{c}cuud$ J.J.Wu, R.Molina, E.Oset, B.S.Zou.
Phys.Rev.Lett. 105 (2010) 232001

N*(11050) $\bar{b}buud$ J.J.Wu, L.Zhao, B.S.Zou. PLB709(2012)70

$\Lambda^*(1405)$ $\bar{q}quds$

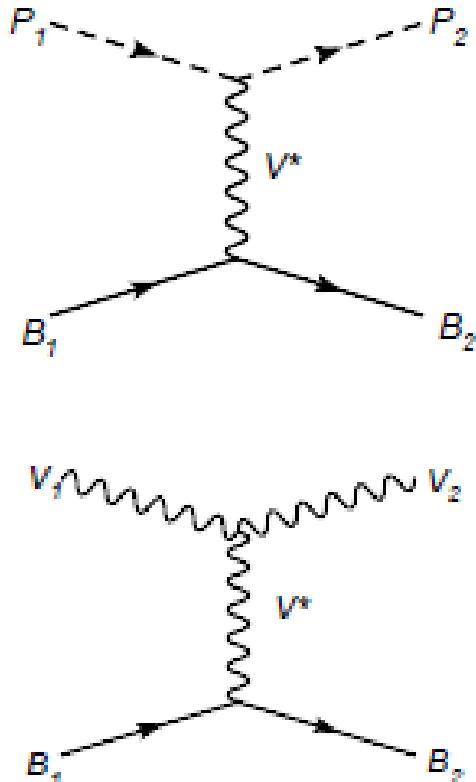
$\Lambda^*(4210)$ $\bar{c}cuuds$ J.J.Wu, R.Molina, E.Oset, B.S.Zou.
Phys.Rev.Lett. 105 (2010) 232001

$\Lambda^*(11020)$ \bar{bbuds} J.J.Wu, L.Zhao, B.S.Zou. PLB709(2012)70

2. Hadronic molecules with hidden charm

“Prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV”,
 Wu, Molina, Oset, Zou, PRL105 (2010) 232001

$K\Sigma, Kp \rightarrow \bar{D}^{(*)}\Sigma_c, \bar{D}^{(*)}\Xi_c$ bound states



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

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

$$\mathcal{L}_{BBV} = g(\langle \bar{B} \gamma_\mu [V^\mu, B] \rangle + \langle \bar{B} \gamma_\mu B \rangle \langle V^\mu \rangle)$$

$$V_{ab(P_1B_1 \rightarrow P_2B_2)} = \frac{C_{ab}}{4f^2}(E_{P_1} + E_{P_2}),$$

$$V_{ab(V_1B_1 \rightarrow V_2B_2)} = \frac{C_{ab}}{4f^2}(E_{V_1} + E_{V_2})\vec{\epsilon}_1 \cdot \vec{\epsilon}_2,$$

$$T = [1 - VG]^{-1}V \quad T_{ab} = \frac{g_a g_b}{\sqrt{s} - z_R}$$

	(I, S)	z_R (MeV)	g_a	J^P
N^*	$(1/2, 0)$		$D\Sigma_c$	$D\Lambda_c^+$
		4269	2.85	0
Λ^*	$(0, -1)$		$D_s\Lambda_c^+$	$D\Xi_c$
		4213	1.37	3.25
		4403	0	0
				2.64

TABLE III: Pole positions z_R and coupling constants g_a for the states from $PB \rightarrow PB$.

	(I, S)	z_R (MeV)	g_a	J^P
N^*	$(1/2, 0)$		$D^*\Sigma_c$	$D^*\Lambda_c^+$
		4418	2.75	0
Λ^*	$(0, -1)$		$D_s^*\Lambda_c^+$	$D^*\Xi_c$
		4370	1.23	3.14
		4550	0	0
				2.53

TABLE IV: Pole position and coupling constants for the bound states from $VB \rightarrow VB$.

Further studies support such hidden charm N*

W.L.Wang, F.Huang, Z.Y.Zhang, B.S.Zou, PRC84(2011)015203:

Chiral quark model → $\bar{D}\Sigma_c$ state ~ 4.31 GeV

Z.C.Yang, Z.F.Sun, J.He, X.Liu, S.L.Zhu, Chin. Phys. C36 (2012) 6

Schoedinger Equation method with $\pi, \eta, \rho, \omega, \sigma$ exchanges
→ $\bar{D}^*\Sigma_c$ ($1/2^-$, $3/2^-$) N* state $\sim 4.36 - 4.46$ GeV

J.J.Wu, T.S.H.Lee, B.S.Zou, PRC85(2012)044002:

EBAC-DCC model → $\bar{D}\Sigma_c$ ($1/2^-$) ~ 4.31 GeV,
 $\bar{D}^*\Sigma_c$ ($1/2^-$, $3/2^-$) $\sim 4.4 - 4.5$ GeV -

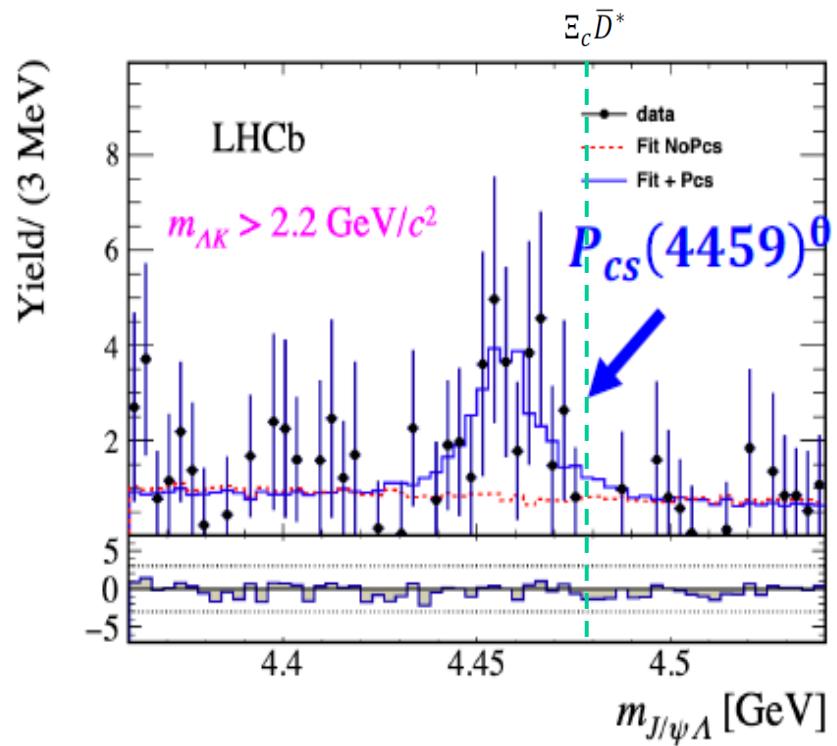
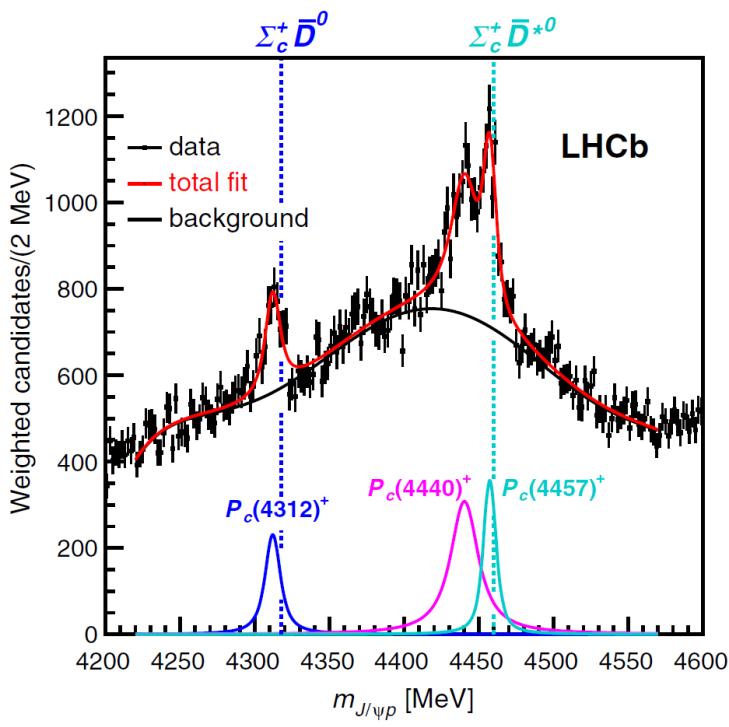
C.W.Xiao, J.Nieves, E.Oset, PRD 88 (2013) 056012:

Heavy quark spin symmetry → 7 such N* molecules

$\bar{D}\Sigma_c$ ($1/2^-$) ~ 4.26 GeV, $\bar{D}\Sigma_c^*$ ($3/2^-$) ~ 4.33 GeV,
 $\bar{D}^*\Sigma_c$ ($1/2^-$, $3/2^-$) $\sim 4.41, 4.42$ GeV,
 $\bar{D}^*\Sigma_c^*$ ($1/2^-$, $3/2^-$, $5/2^-$) $\sim 4.48 - 4.49$ GeV

M.Karliner, J.L.Rosner, PRL115(2015)122001:

Pion exchange → $\bar{D}^*\Sigma_c$ ($1/2^-$, $3/2^-$) ~ 4.5 GeV

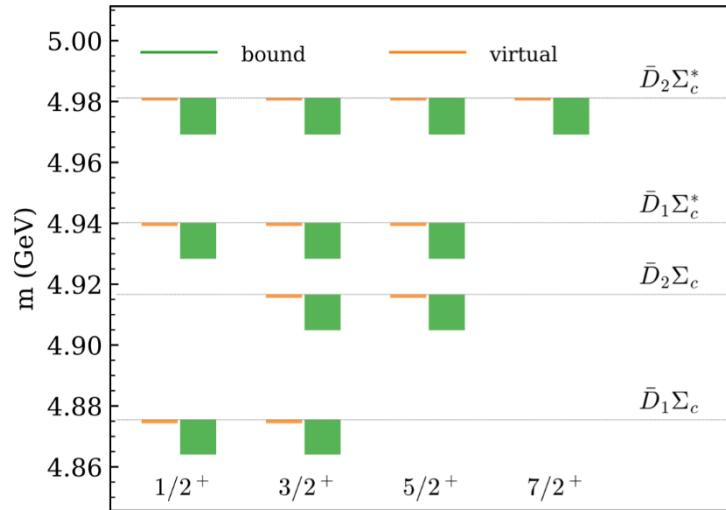
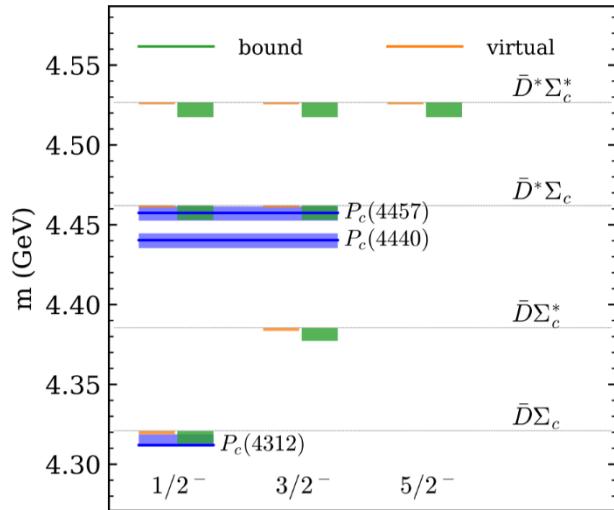


Consistent with expectation for hadronic molecules within theoretical uncertainties → VMD + small effects from π, η, σ

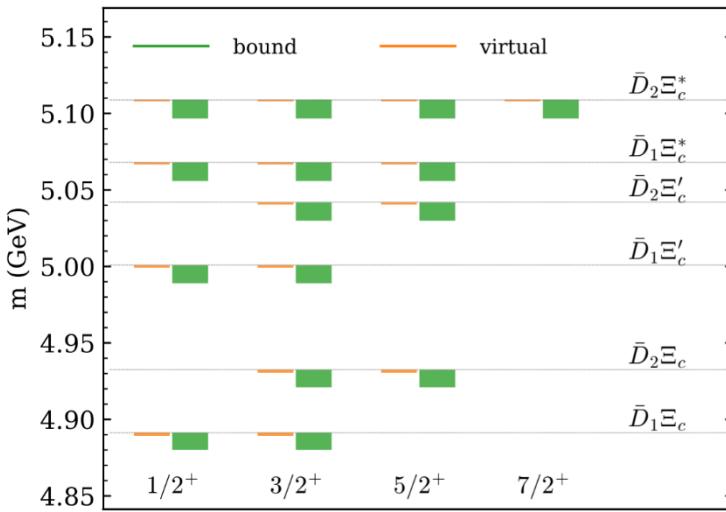
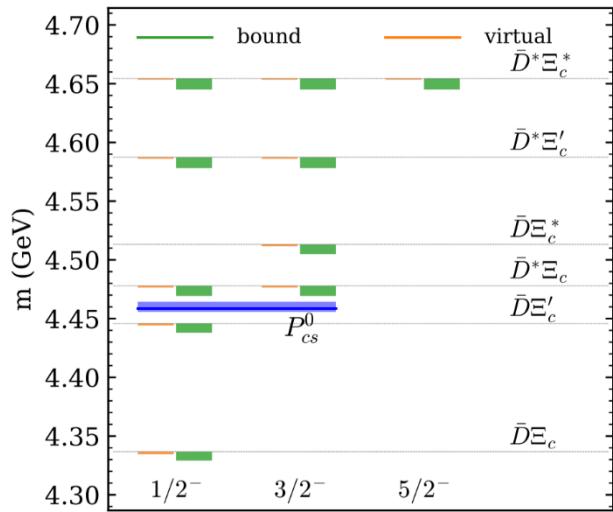
LHCb discoveries – historical achievement for pentaquarks !
very important for understanding whole baryon spectroscopy

A survey of hadronic molecules with hidden charm

X.K.Dong, F.K.Guo, B.S.Zou Progr. Phys. 41 (2021) 65

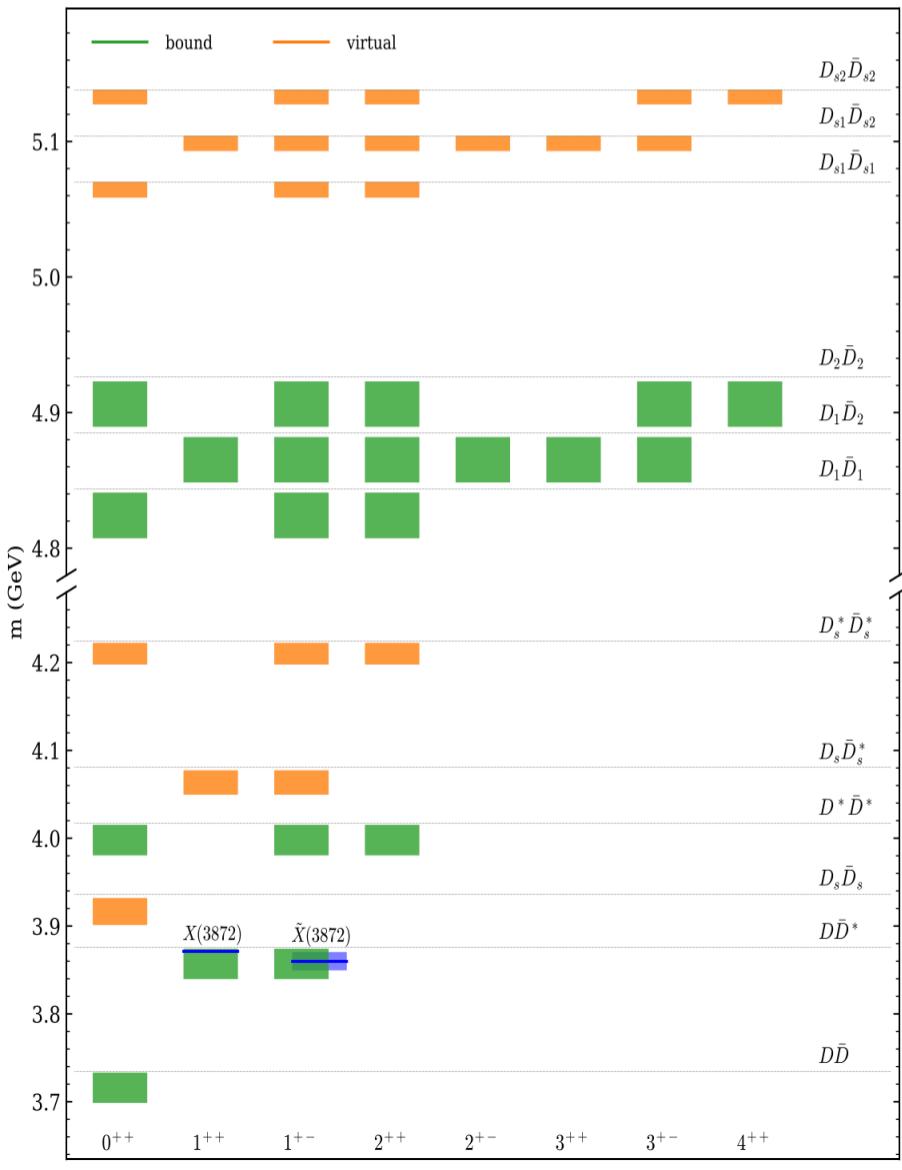


P_c

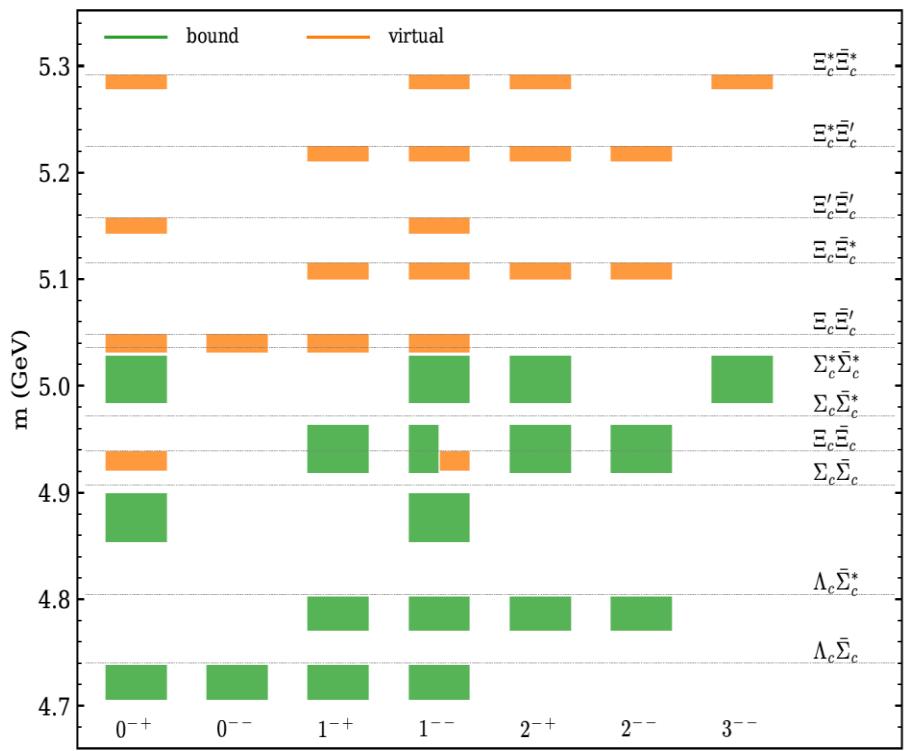


P_{cs}

Meson-meson molecules (I=0)



Baryon molecules (I=1) with $\bar{c}c$



- ✓ Isovector interaction between $D^{(*)}\bar{D}^{(*)}$ from light vector exchange vanishes
- ✓ Charmonia exchange could be important here: $J/\psi, \psi'$ exchange
- ✓ $Z_c(3900, 4020)$ as $\bar{D}^{(*)}D^*$ virtual states
- ✓ $Z_{cs}(3985)$ as $D_s\bar{D}^*, D\bar{D}_s^*$ virtual state
- ✓ $Z_c(4430)$ as $\bar{D}^*\bar{D}_1^*$ virtual states

3. Hadronic molecules with double charm

The lowest possible double charm hadron molecule DD* :

A.V.Manohar, M.B.Wise, Nucl. Phys. B 399 (1993) 17

N.A.Törnqvist, Z. Phys. C 61 (1994) 525

$$V_\pi(\vec{q}) = -\frac{8g^2}{f^2} \vec{I}_1 \cdot \vec{I}_2 \frac{(\vec{S}_{\ell 1} \cdot \vec{q})(\vec{S}_{\ell 2} \cdot \vec{q})}{\vec{q}^2 + m_\pi^2}$$

With V_π only, BB* is bound, DD* is not bound.

But $V_{\rho,\omega}$ provide additional attractive force for I=0!

$$V_{\rho,\omega}(\vec{q}) = \frac{g_V^2}{\vec{q}^2 + m_V^2} \left\{ \frac{1}{2} (\vec{I}^2 - 3/2) + \frac{1}{4} \right\}$$

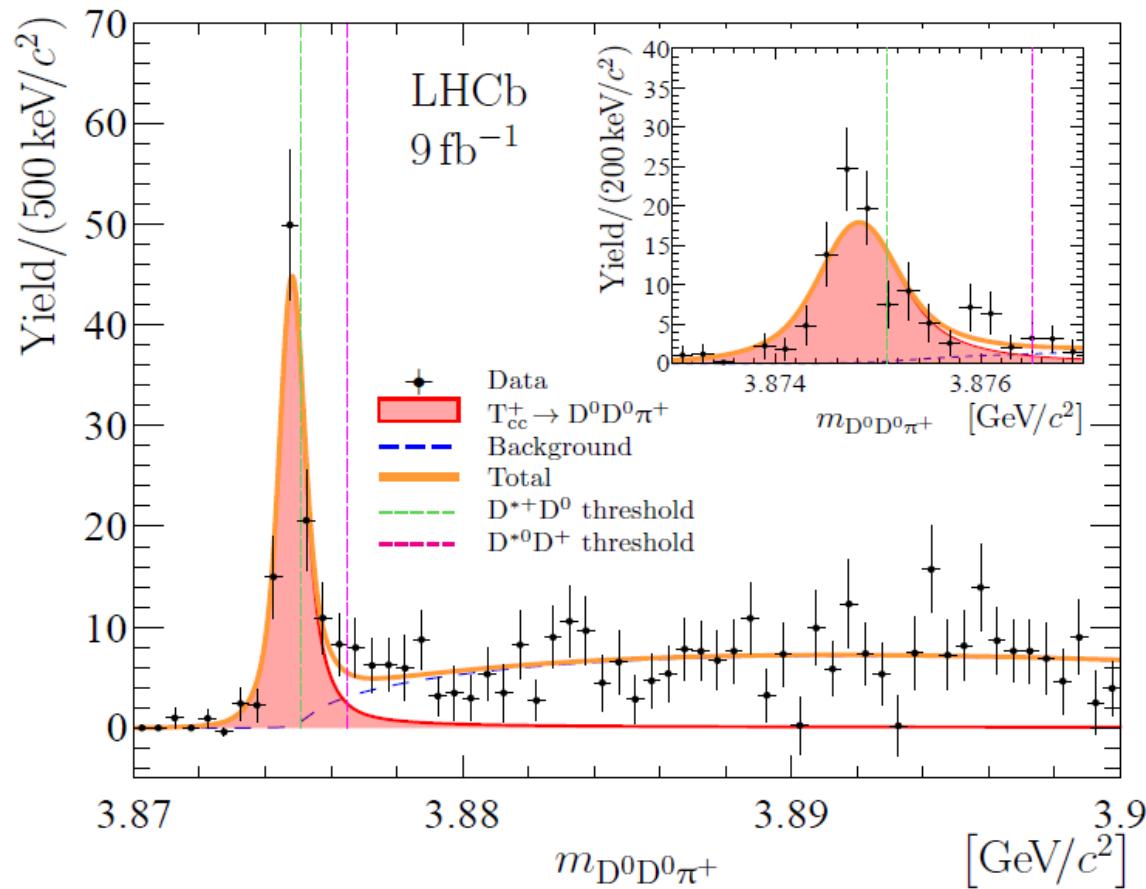
T.Barnes, N.Black, D.Dean, E.Swanson, Phys.Rev.C60(1999)045202
D.Janc, M.Rosina, Few Body Syst. 35(2004)175
Y.Yang, C.Deng, J.Ping, T.Goldman, Phys.Rev.D80(2009)114023
T.Caramés, A.Valcarce, J.Vijande, Phys.Lett.B699(2011)291
S.Ohkoda, Y.Yamaguchi, S.Yasui, K.Sudoh, A.Hosaka, Phys.Rev.D86(2012)034019
N.Li, Z.F.Sun, X.Liu, S.L.Zhu, Phys.Rev.D88(2013)114008
M.Z.Liu, T.W.Wu, M.P.Valderrama, J.J.Xie, L.S.Geng, Phys.Rev.D99(2019)094018
H.Xu, B.Wang, Z.W.Liu, X.Liu, Phys.Rev.D99(2019)014027
M.Z.Liu, J.J.Xie, L.S.Geng, Phys.Rev.D102(2020)091502



$$V_{\rho,\omega} + V_\pi + \dots$$

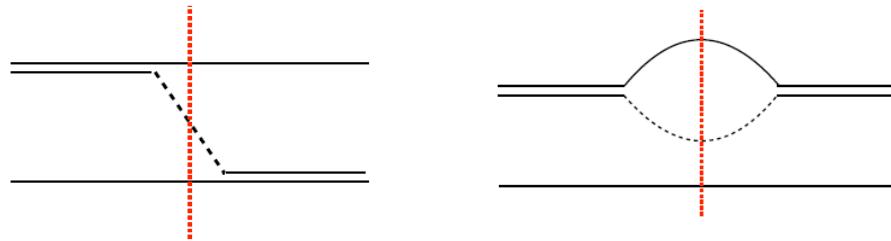
DD*(I=0, J^P=1⁺) bound state -- T_{cc}⁺

Observation of T_{cc}^+ by LHCb, ArXiv:2109.01038



EFT with VMD + π works well for T_{cc}^+

- $m_{T_{cc}^+} > m_{DD\pi} \rightarrow$ three-body cuts
 \hookrightarrow one-pion exchange + self-energy of D^*



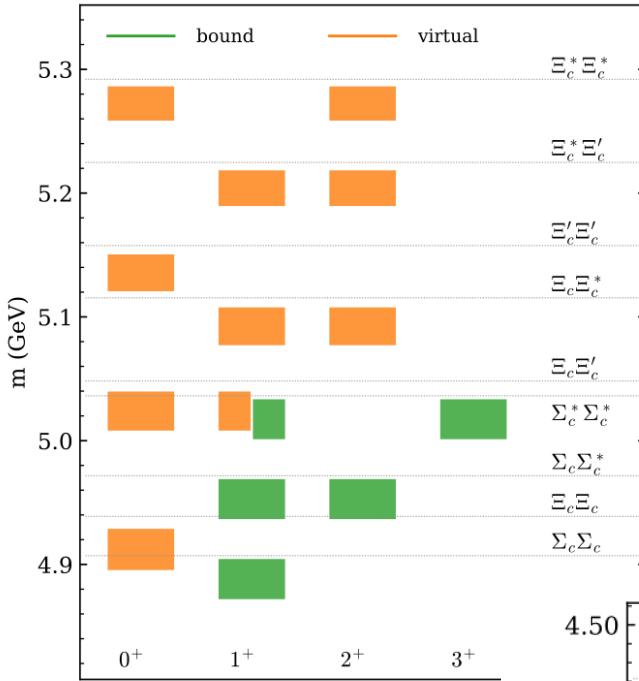
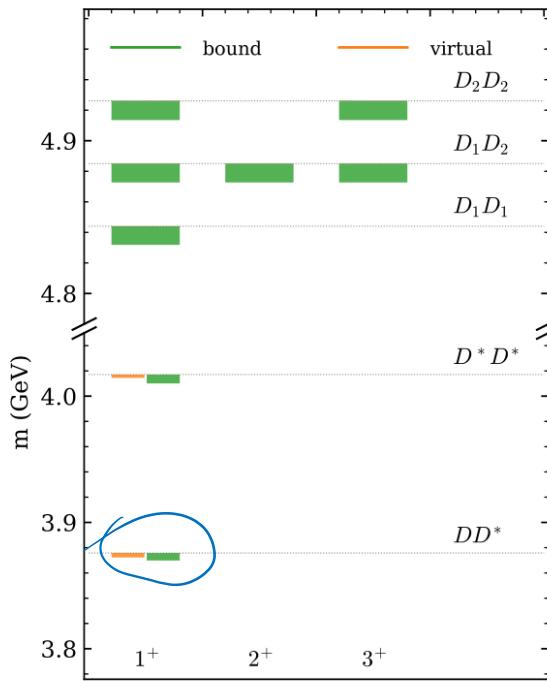
- The width of T_{cc}^+ is sensitive to the details

$$56 \text{ keV} \xrightarrow[\text{OPE}]{\text{remove}} 36 \text{ keV} \xrightarrow[\text{M-dep. of } \Gamma^*]{\text{remove}} 74 \text{ keV}$$

M.L.Du, V.Baru, X.K.Dong et al., arXiv:2110.13765
G.J.Wang, B.Wang, S.L.Zhu, Phys.Rev.D104(2021) L051502

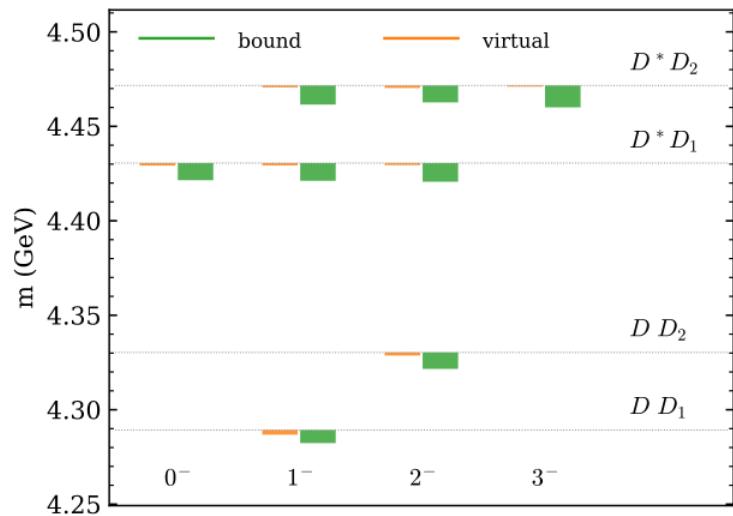
A survey of heavy-heavy hadronic molecules

X.K.Dong, F.K.Guo, B.S.Zou, Commun.Theor.Phys.73(2021)125201



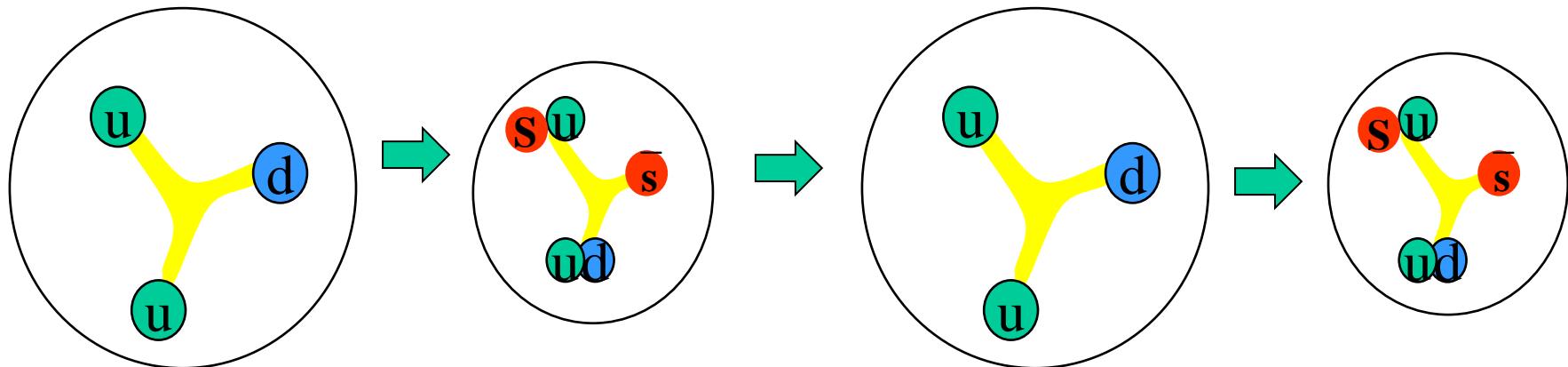
✓ Isoscalar $\Sigma_c^{(*)} \Sigma_c^{(*)}$
dibaryons very likely
bound

- ✓ T_{cc} as an isoscalar DD^* bound or virtual state,
 $D^* D^*$ predicted to be similar, with $P = +$
- ✓ Similar in $P = -$ sector



4. Conclusion

- ◆ all observed exotic states with charm fit in hadronic molecule spectrum with VMD perfectly, many more to be observed.
- ◆ to understand hadron spectrum, quark model needs to be unquenched, with large hadronic molecule components when close to some thresholds.



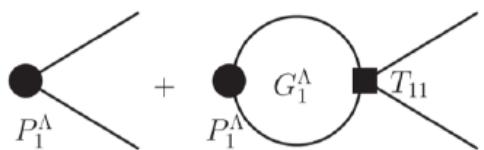
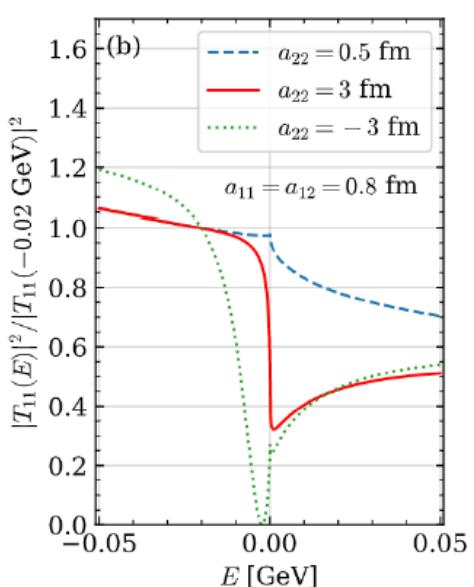
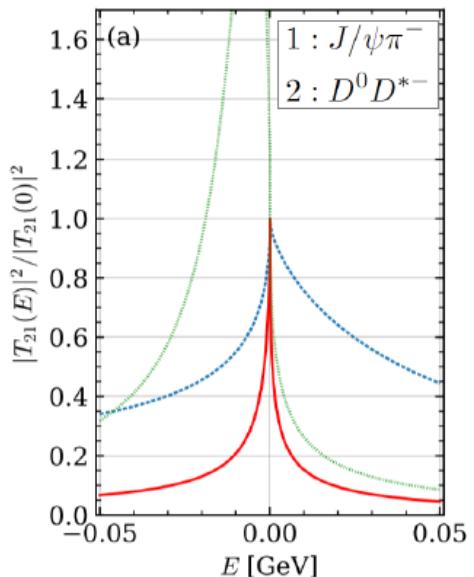
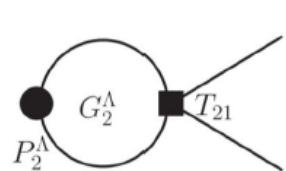
Thank you for
your attention!

(Near-)threshold structures

X.-K. Dong, FKG, B.-S. Zou, Phys. Rev. Lett. 126 (2021) 152001

- (Near-)threshold structures (S-wave)

- There must be nontrivial (near-)threshold structures for attractive interaction
- Either threshold cusp or below-threshold peak
- Peak more pronounced for heavier hadrons and stronger interaction
- That's the why many (near-)threshold structures were observed in hidden-charm and hidden-bottom spectra
- Structures are process dependent



Poles in complex
momentum plane:
 $(0.37 - i0.08) \text{ GeV}$
 $(0.04 - i0.08) \text{ GeV}$
 $(-0.09 - i0.08) \text{ GeV}$

S.G.Yuan, K.W.Wei, J.He, H.S.Xu, B.S.Zou, “Study of $\bar{c}cqqq$ five quark system with three kinds of quark-quark hyperfine interaction,”
Eur. Phys. J. A48 (2012) 61

J^P	<i>CM</i>		<i>FS</i>		<i>Inst.</i>	
	<i>udsc̄</i>	<i>uudc̄</i>	<i>udsc̄</i>	<i>uudc̄</i>	<i>udsc̄</i>	<i>uudc̄</i>
$\frac{1}{2}^-$	4273	4267	4084	3933	4209	4114
$\frac{1}{2}^-$	4377	4363	4154	4013	4216	4131
$\frac{1}{2}^-$	4453	4377	4160	4119	4277	4204
$\frac{1}{2}^-$	4469	4471	4171	4136	4295	4207
$\frac{1}{2}^-$	4494	4541	4253	4156	4360	4272
$\frac{1}{2}^-$	4576		4263		4362	
$\frac{1}{2}^-$	4649		4278		4416	
$\frac{3}{2}^-$	4431	<u>4389</u>	4154	4013	4216	4131
$\frac{3}{2}^-$	4503	<u>4445</u>	4171	4119	4295	4204
$\frac{3}{2}^-$	4549	4476	4263	4136	4362	4272
$\frac{3}{2}^-$	4577	4526	4278	4236	4416	<u>4322</u>
$\frac{3}{2}^-$	4629		4362		4461	
$\frac{5}{2}^-$	4719	4616	4362	4236	4461	4322

J^P	<i>CM</i>		<i>FS</i>		<i>Inst.</i>	
	<i>udsc̄c̄</i>	<i>uudc̄c̄</i>	<i>udsc̄c̄</i>	<i>uudc̄c̄</i>	<i>udsc̄c̄</i>	<i>uudc̄c̄</i>
$\frac{1}{2}^+$	4622	4456	4291	4138	4487	4396
$\frac{1}{2}^+$	4636	4480	4297	4140	4501	4426
$\frac{1}{2}^+$	4645	4557	4363	4238	4520	4426
$\frac{1}{2}^+$	4658	4581	4439	4320	4540	4470
$\frac{1}{2}^+$	4690	4593	4439	4367	4557	4482
$\frac{1}{2}^+$	4696	4632	4467	4377	4587	4490
$\frac{1}{2}^+$	4714	4654	4469	4404	4590	4517
$\frac{1}{2}^+$	4728	4676	4486	4489	4614	4518
$\frac{1}{2}^+$	4737	4714	4492	4508	4616	4549
$\frac{1}{2}^+$	4766	4720	4510	4515	4626	4566
$\frac{3}{2}^+$	4623	<u>4457</u>	4291	4138	4487	4396
$\frac{3}{2}^+$	4638	4515	4297	4140	4501	4426
$\frac{3}{2}^+$	4680	4561	4363	4238	4520	4426
$\frac{3}{2}^+$	4692	4582	4439	4320	4540	4470
$\frac{3}{2}^+$	4695	4625	4439	4367	4557	4482
$\frac{5}{2}^+$	4705	4539	4297	4140	4501	<u>4426</u>
$\frac{5}{2}^+$	4719	4649	4439	4320	4540	4470
$\frac{5}{2}^+$	4773	4689	4467	4367	4587	4482
$\frac{5}{2}^+$	4793	4696	4486	4404	4615	4490
$\frac{5}{2}^+$	4821	4710	4492	4515	4632	4517
$\frac{7}{2}^+$	4945	4841	4638	4508	4698	4566
$\frac{7}{2}^+$	4955	4862	4671	4551	4712	4634
$\frac{7}{2}^+$	4974	4919	4705	4587	4765	4669
$\frac{7}{2}^+$	5010		4759		4797	

M(5/2⁺) – M(3/2⁻) : 130 ~300 MeV