Vector-meson exchange vs chiral dynamics at both quark and hadron levels

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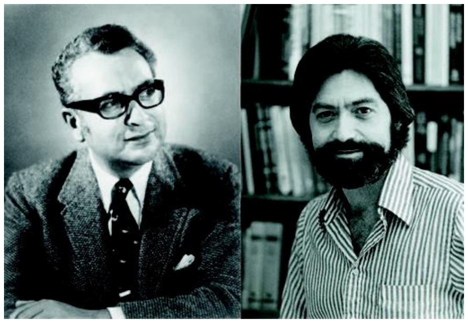
Outline：

1. Quark models and vector-meson exchange
2. Vector-meson exchange for P_c states
3. Predictions for hidden & double heavy hadronic molecules
4. Summary

[1] J.J.Wu, R.Molina, E.Oset, B.S.Zou, Phys. Rev. Lett. 105 (2010) 232001.
[2] N.Yalikun, Y.H.Lin, F.K.Guo, Y.Kamiya, B.S.Zou, Phys. Rev. D104 (2021) 094039.
[3] X.K.Dong, F.K.Guo, B.S.Zou, Progr. Phys. 41 (2021) 65.
[4] X.K.Dong, F.K.Guo, B.S.Zou, Commu. Theor. Phys. 73 (2021) 125201.
[5] B.R.He, M.Harada, B.S.Zou, Phys. Rev. D108 (2023) 054025.
[6] B.R.He, M.Harada, B.S.Zou, Eur. Phys. J. C83 (2023) 1159.

1. Quark models & Vector meson exchange

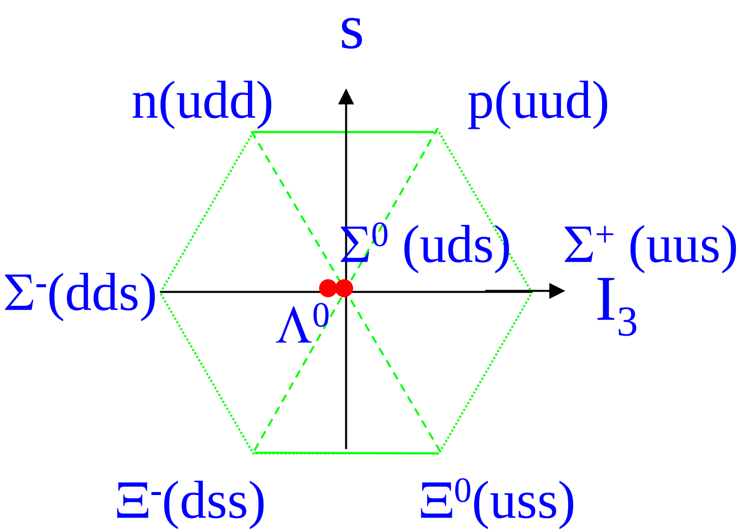
- **1964 – Invention of constituent Quark Model**

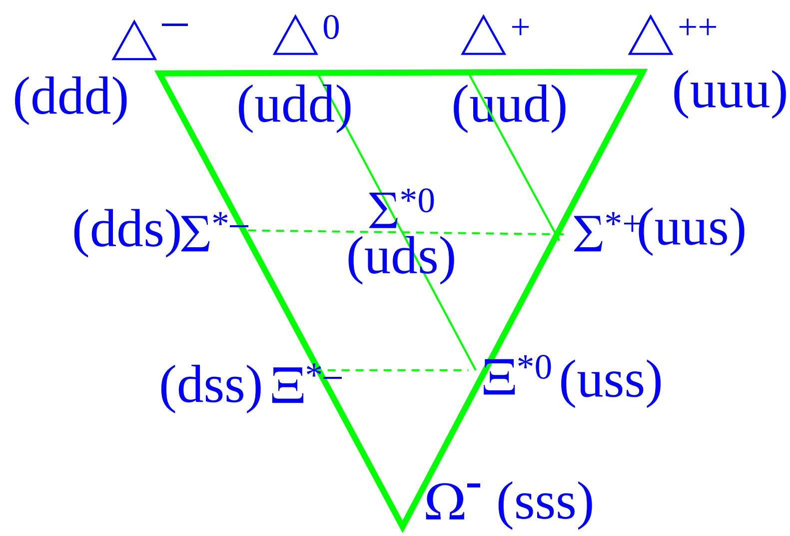


Quark-antiquark meson

Three-quark baryon

Successful for SU(3) mesons and baryons of spatial ground states





1974 – Cornell potential for $\bar{c}c$ spectrum

E.Eichten et al., PRL 34 (1975) 369 1294 cites

$$\hat{H}_0 = \frac{p^2}{m_Q} + V_0(r) + V_{\rm SD}(r)$$

$$V_0(r) = \sigma r - \frac{\frac{4}{3}\alpha_s}{r} + C_0 \qquad \text{(Cornell potential)}$$

$$V_{SD}(r) = \underbrace{V_{LS}(r)(\boldsymbol{L}\cdot(\boldsymbol{S}_Q + \boldsymbol{S}_{\bar{Q}}))}_{\text{fine structure}} + \underbrace{V_{SS}(r)(\boldsymbol{S}_Q\cdot\boldsymbol{S}_{\bar{Q}})}_{\text{hyperfine structure}}$$

$$+\underbrace{V_{ST}(r)\Big((\boldsymbol{S}_Q\cdot\boldsymbol{S}_{\bar{Q}}) - 3(\boldsymbol{S}_Q\cdot\boldsymbol{n})(\boldsymbol{S}_{\bar{Q}}\cdot\boldsymbol{n})\Big)}_{\text{spin tensor force}} \quad \propto \quad \frac{1}{m_Q^2}$$

Extension to light mesons and baryons: surprisingly well !

S. Godfrey, N. Isgur, *PRD* 32 (1985) 189 3251 cites

Mesons in a relativized quark model with chromodynamics

S.Capstick, N. Isgur, *PRD* 34 (1986) 2809 1478 cites

Baryons in a relativized quark model with chromodynamics

1984 – Chiral Quark Model

A. Manohar, H. Georgi, NPB 234 (1984) 189 2328 cites

- quarks with masses generated by SχSB
- pions as Nambu-Goldstone bosons

- K. Shimizu, Phys. Lett. B 148, 418-422 (1984)
  - pseudo-scalar mesons + confining potential (CON)
- I. T. Obukhovsky and A. M. Kusainov, Phys. Lett. B 238, 142-148 (1990).
  - scalar and pseudo-scalar mesons + one-gluon exchange (OGE) + CON
- L. Y. Glozman and D. O. Riska, Phys. Rept. 268, 263-303 (1996); L. Y. Glozman, Nucl. Phys. A 663, 103-112 (2000).
  - pseudo-scalar and vector mesons + CON to study baryon spectrum
- L. R. Dai, Z. Y. Zhang, Y. W. Yu and P. Wang, Nucl. Phys. A 727, 321-332 (2003).
  - scalar, pseudo-scalar, vector mesons + OGE + CON to study phase shift of NN scattering
- J. Vijande, F. Fernandez and A. Valcarce, J. Phys. G 31, 481 (2005); J. Vijande and A. Valcarce, Phys. Lett. B 677, 36-38 (2009); A. Valcarce, H. Garcilazo, F. Fernandez and P. Gonzalez, Rept. Prog. Phys. 68 (2005), 965-1042.
  - scalar, pseudo-scalar mesons + OGE + CON to study meson and baryon spectra.
  - did not include the vector mesons for avoiding the double counting.

slide from Masa Harada

slide from Masa Harada

Problem and Proposal

- A chiral quark model with π and σ provides too much strong attractive force between two quarks which form a good diquark:
  - $M_N^{(exp)} - M_N^{(theo)} = 262\ MeV$
  - $M_{\Lambda_c}^{(exp)} - M_{\Lambda_c}^{(theo)} = 322\ MeV$
  - $M_{\Lambda_b}^{(exp)} - M_{\Lambda_b}^{(theo)} = 359\ MeV$

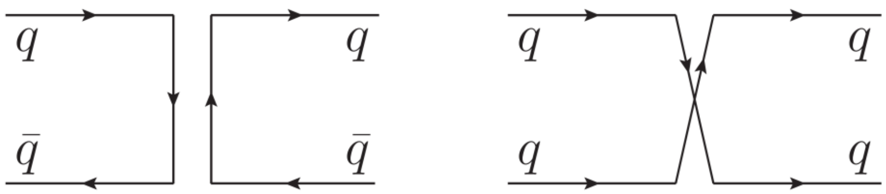
We use best fitted parameters in [J. Vijande, F. Fernandez and A. Valcarce, J. Phys. G 31, 481 (2005)].

- New chiral quark model with vector mesons
  - ρ and ω are included based on the Hidden Local Symmetry(HLS)
  - $m_\rho,\ m_\omega \sim 780\ MeV < \Lambda_\chi$!

● 2023 – Chiral Quark Model w/ Vector meson Ex of HLS

B.R.He, M.Harada, B.S.Zou, PRD 108 (2023) 054025; EPJC 83 (2023) 1159

HLS - a systematic way to include (π, K, η, η') & $(\rho, K^*, \omega, \phi)$



Meson exchange ~ quark exchange effect

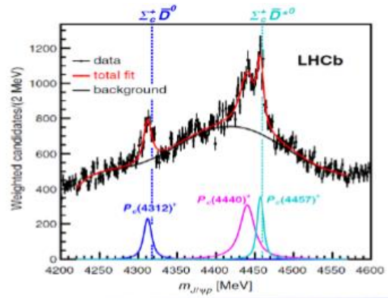
- **Masses of N, Λ_c , Λ_b are fitted well, mainly owing to the effects of ω meson : attractive for $\bar{q}q$ & repulsive for qq**
- **Masses of all observed g.s. hadrons are beautifully fitted, with unobserved ones predicted in agreement with LQCD**
- **T_{cc}-molecule-like structure, T_{bb}-diquark-like structure**

2. Vector-meson exchange for P_c states

Prediction of $\bar{D}\Sigma_c$ & $\bar{D}^*\Sigma_c$ molecules by VME fits P_c states very well !

P_c states: observation vs predictions

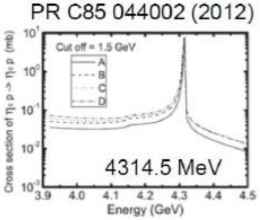
LHCb, PRL122 (2019) 222001



Comparison to numerical predictions

- Many theoretical predictions for $\Sigma_c^+\bar{D}^{(*)0}$ published before 2015, **some in quantitative agreement with the LHCb data**
  - Wu,Molina,Oset,Zou, PRL105, 232001 (2010),
  - **Wang,Huang,Zhang,Zou, PR C84, 015203 (2011),**
  - **Yang,Sun,He,Liu,Zhu, Chin. Phys. C36, 6 (2012),**
  - **Wu,Lee,Zou, PR C85 044002 (2012),**
  - Karliner,Rosner, PRL 115, 122001 (2015)

PR C85 044002 (2012)



ΔE – binding energy

Example:

Nucleon resonances with hidden charm in coupled-channels models

Jia-Jun Wu, T.-S. H. Lee, and B. S. Zou
Phys. Rev. C **85**, 044002 – Published 17 April 2012

arXiv:1202.1036

TABLE III: The pole position ($M - i\Gamma/2$) and "binding energy" ($\Delta E = E_{thr} - M$) for different cut-off parameter Λ and spin-parity J^P. The threshold E_{thr} is 4320.79 MeV of $\bar{D}\Sigma_c$ in PB system and 4462.18 MeV of $D^*\Sigma_c$ in VB system. The unit for the listed numbers is MeV.

		PB System		VB System	
$J^P = \frac{1}{2}^-$	Λ	$M - i\Gamma/2$	ΔE	$M - i\Gamma/2$	ΔE
	650		-		
	800		-	4462.178 − 0.002i	0.002
	1200	4318.964 − 0.362i	1.826	4459.513 − 0.417i	2.667
	1500	4314.531 − 1.448i	6.259	4454.088 − 1.662i	8.092
	2000	4301.115 − 5.835i	19.68	4438.277 − 7.115i	23.90
$J^P = \frac{3}{2}^-$					
	650	-	-	-	-
	800	-	-	4462.178 − 0.002i	0.002
	1200	-	-	4459.507 − 0.420i	2.673
	1500	-	-	4454.057 − 1.681i	8.123
	2000	-	-	4438.039 − 7.268i	23.14

$\Delta E(4312) = 5.8^{+1.0}_{-6.8}$ MeV

$\Delta E(4457) = 2.5^{+4.3}_{-4.1}$ MeV

Λ - cut off on exchanged meson mass.

$\Delta E(4440) = 19.5^{+4.9}_{-4.3}$ MeV

M.L.Du et al., PRL 124 (2020) 072001

Effective contact potential with 2 free parameters' fit to the P_c data compared with expectation from VME only

→ VMD to be a good approximation

	$\bar{D}\Sigma_c$–$1/2^-$	$\bar{D}^*\Sigma_c$–$1/2^-$	$\bar{D}^*\Sigma_c$–$3/2^-$	$\bar{D}\Sigma_c^*$–$3/2^-$	$\bar{D}^*\Sigma_c^*$–$1/2^-$,	$3/2^-$, $5/2^-$
Contact Fit-2	23.6	27.4	21.6	23.6	28.4	25.6
VME	23	23	23	23	23	23

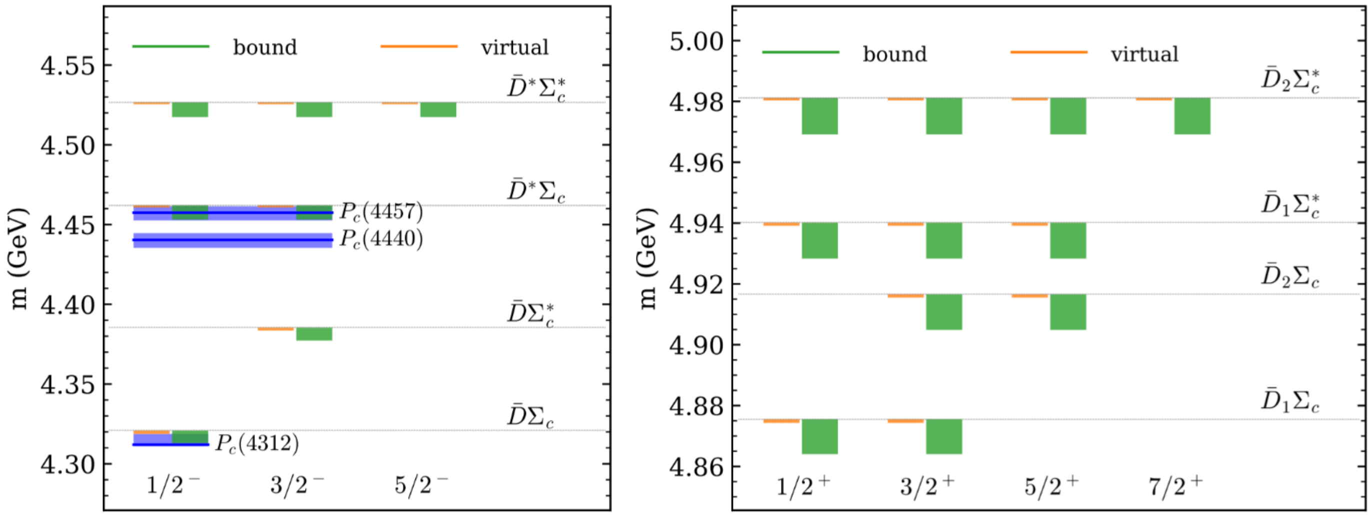
N.Yalikun et al., PRD 104 (2021) 094039

Influence of one-pion-exange potential ? How to deal with its contact δ-term ?

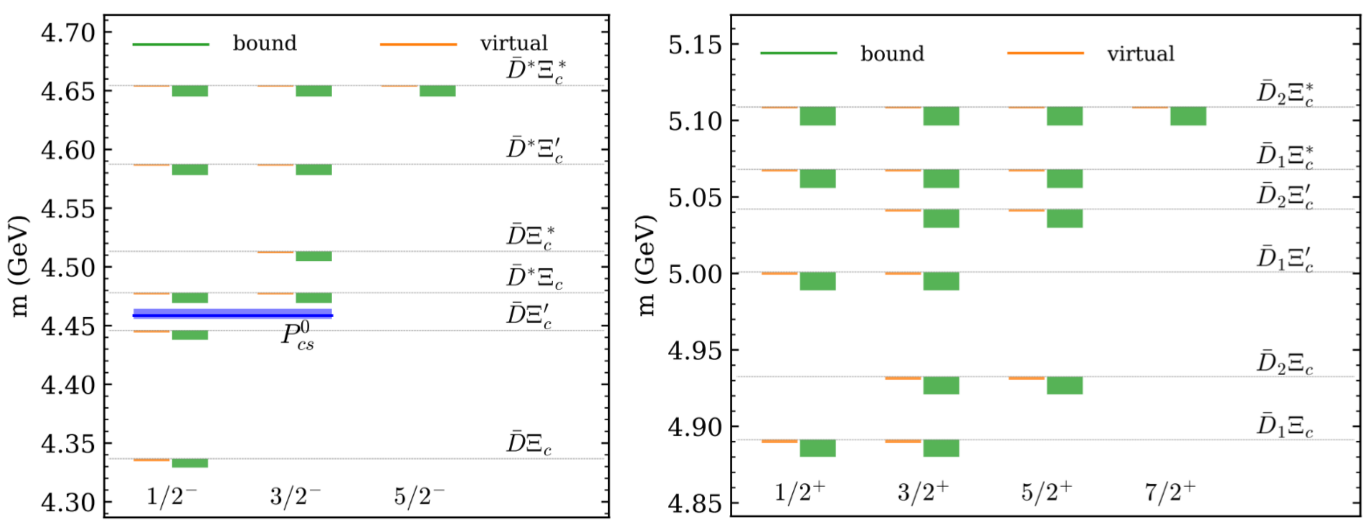
Our preferred solution is to drop 79% of its contact δ-term and save VMD

3. Predictions for hidden & double heavy hadronic molecules

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

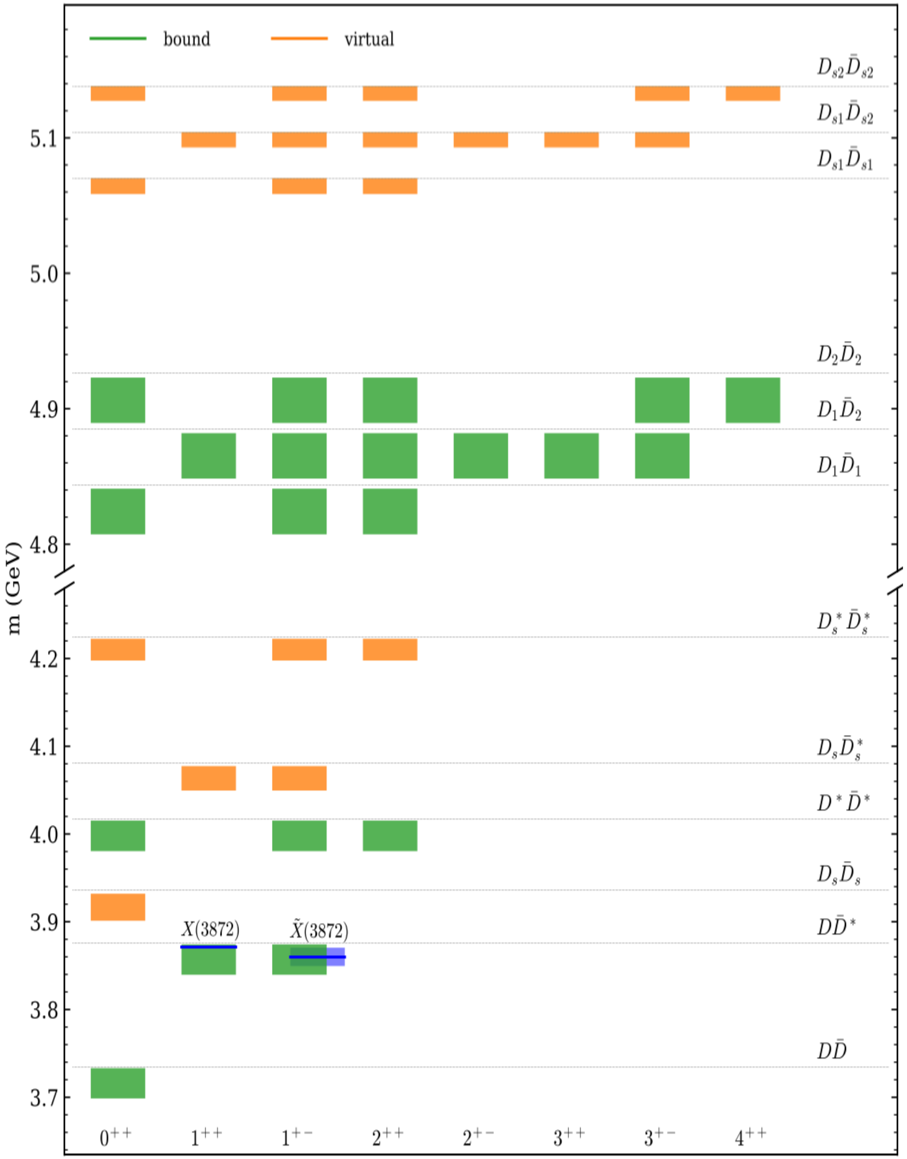


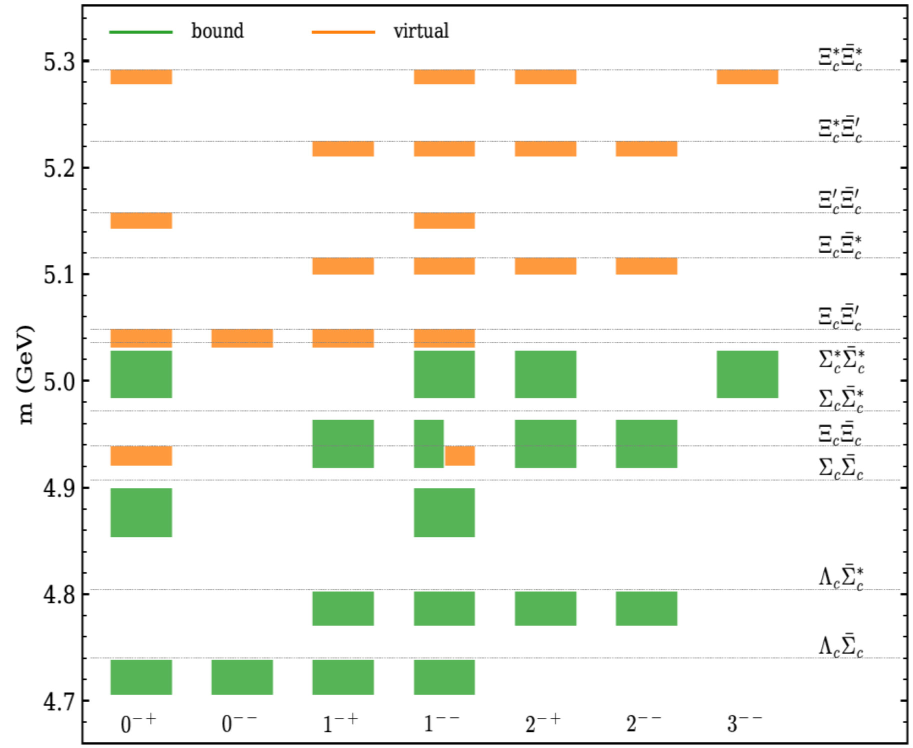
$\mathbf{P_c}$



$\mathbf{P_{cs}}$

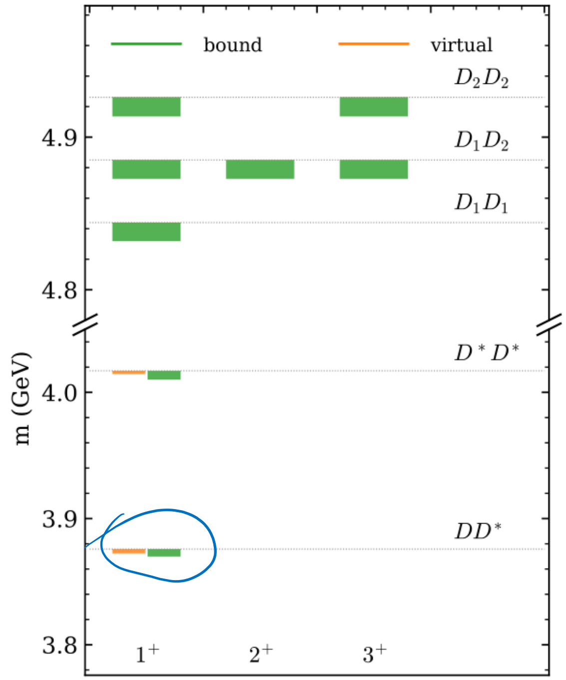
Meson-meson molecules (I=0)　　Baryon molecules (I=1) with $\bar{c}c$

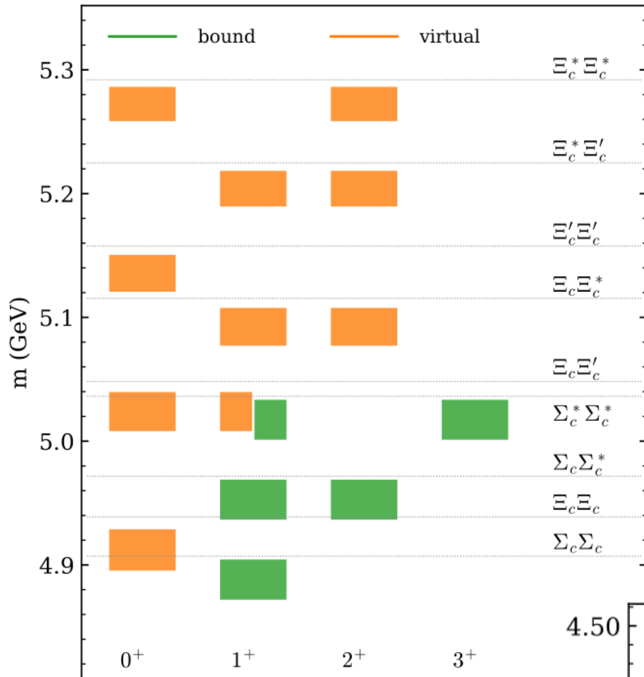




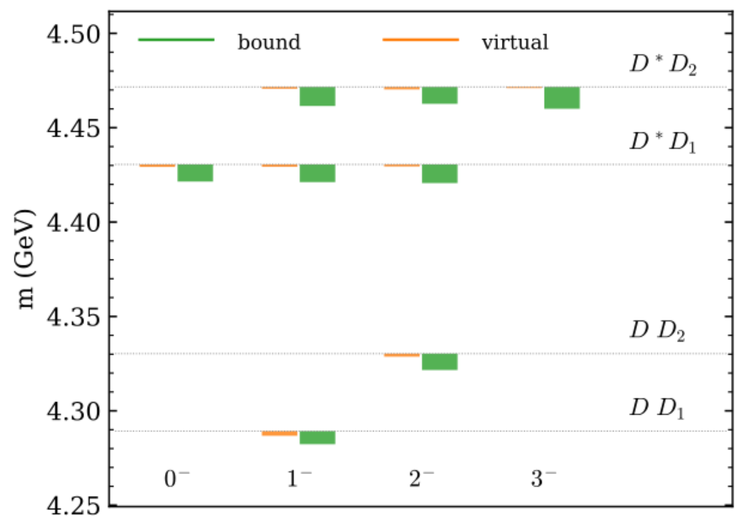
- ✓ Isovector interaction between $D^{(*)}\bar{D}^{(*)}$ from light vector exchange vanishes
- ✓ Charmonia exchange could be important here: J/ψ, ψ' exchange
- ✓ $Z_c(3900{,}4020)$ as $\bar{D}^{(*)}D^*$ virtual states
- ✓ $Z_{cs}(3985)$ as $D_s\bar{D}^*, D\bar{D}_s^*$ virtual state
- ✓ $Z_c(4430)$ as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

Double-charm -- 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

K*Σ, K*Σ* molecules from γp→ϕp reactions

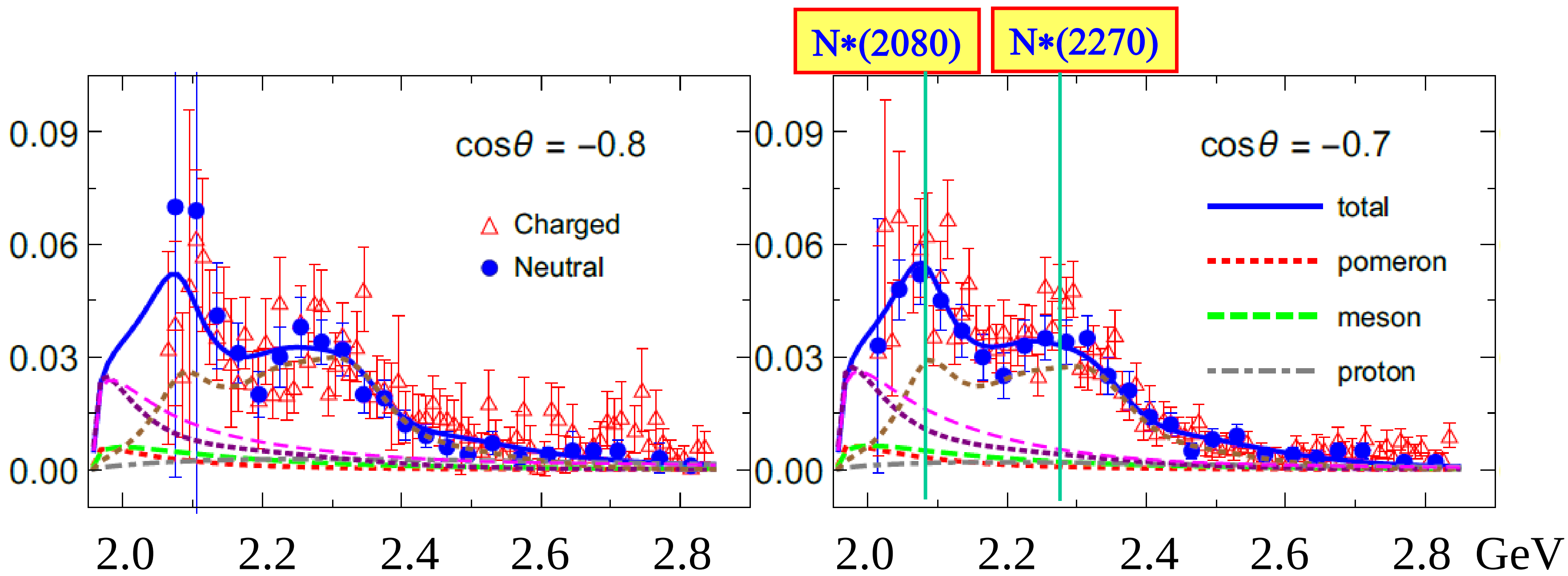
KΣ* ~1880 **N*(1875)**

K*Σ ~ 2086 **N*(2080)**

K*Σ* ~ 2280 **N*(2270)**

$\gamma p \to \phi p$

CLAS, PRC89(2014)019901



S.M.Wu, F.Wang, B.S.Zou, PRC108(2023)045201

4. Summary and prospects

◆ vector meson exchange is very important for light quark interactions as well as for hadron interactions

◆ quark model needs to be unquenched

◆ observed multiquark states can be explained as hadronic molecules, many more are predicted

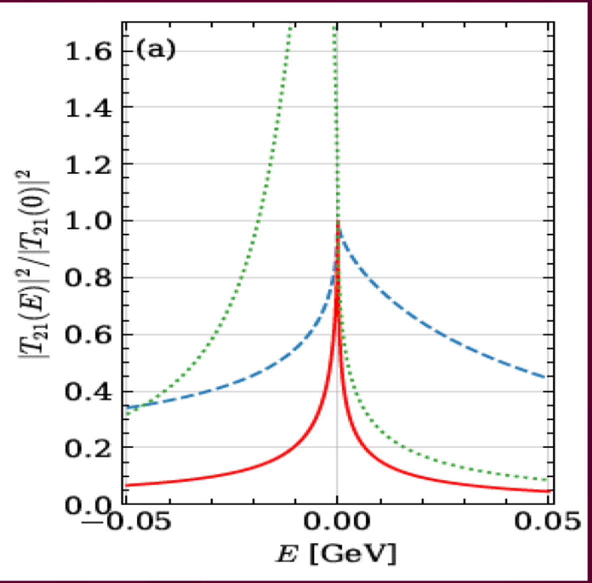
◆ Further experimental confirmation and extension for whole multiquark spectroscopy are necessary

ep/γp@JLab, π10/K10@JPARC, BelleII, BESIII, Eic/EicC, PANDA@FAIR, STCF etc. may play a important role here!

Thank you for your attention!

Explaining the many threshold structures in hadron spectrum with heavy quarks

X.K.Dong, F.K.Guo, B.S.Zou, PRL126 (2021) 152001



Prediction of a narrow exotic D^*D_1 molecule with $J^{PC}=0^{--}$

T.Ji, X.K.Dong, F.K.Guo, B.S.Zou, PRL129 (2022) 102002

$e^+e^- \rightarrow \eta\psi_0(4360) \rightarrow \eta\eta\psi$