Quark Models and Multiquark States

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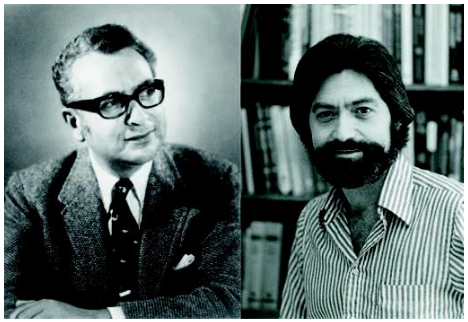
Outline：

1. Quenched quark models
2. Failures of quenched quark models
3. Multi-quark states as hadronic molecules
4. Unquenched quark model
5. Summary

1. Quenched Quark models

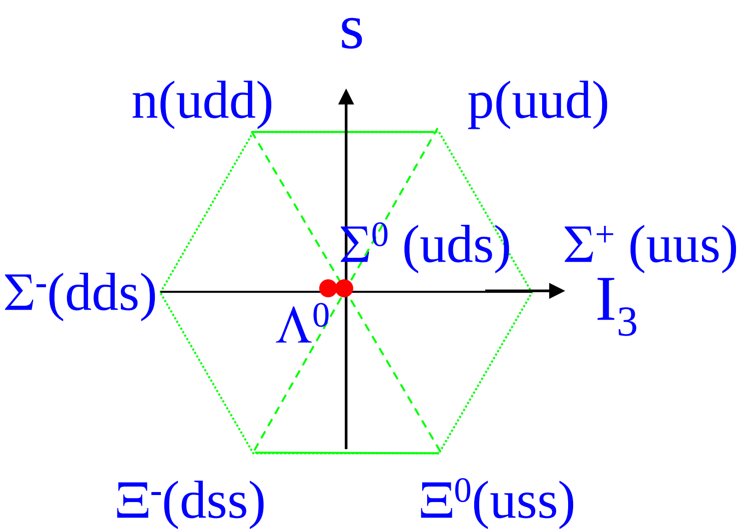
- **1964 – Invention of constituent Quark Model**

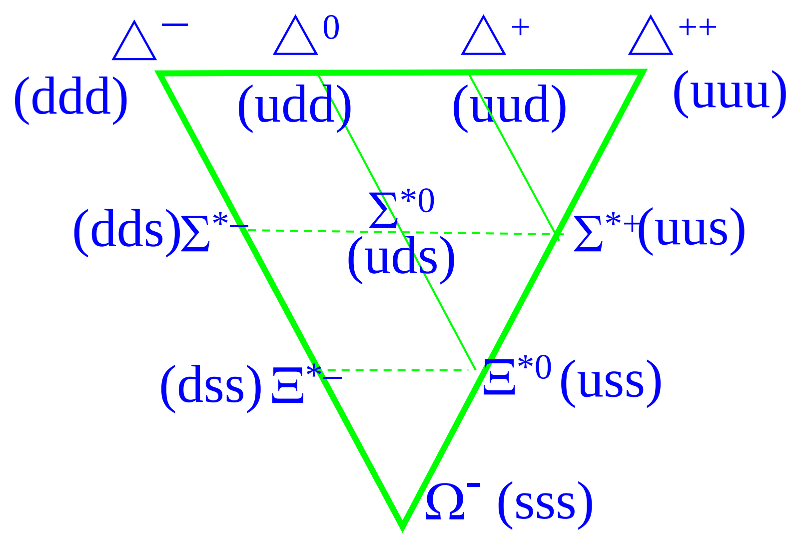


Quark-antiquark meson

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 1281 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 3221 cites

Mesons in a relativized quark model with chromodynamics

S.Capstick, N. Isgur, *PRD* 34 (1986) 2809 1464 cites

Baryons in a relativized quark model with chromodynamics

1984 – Chiral Quark Model

A. Manohar, H. Georgi, NPB 234 (1984) 189 2314 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)].

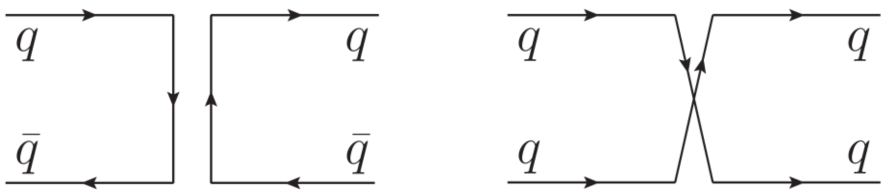
⇩

- 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 with 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. Failures of quenched quark models

- **Five-quark components in the proton**

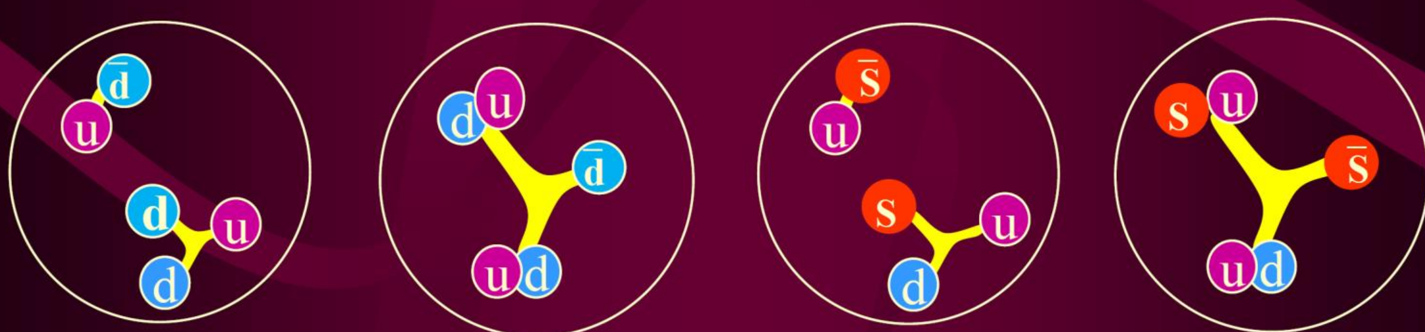
Spin "crisis", $\bar{d} - \bar{u} \sim 0.12$, $\bar{s}(x) \neq s(x)$ puzzles → two possible solutions:

Meson clouds: Thomas, Speth, Weise, Oset, Brodsky, Ma, …

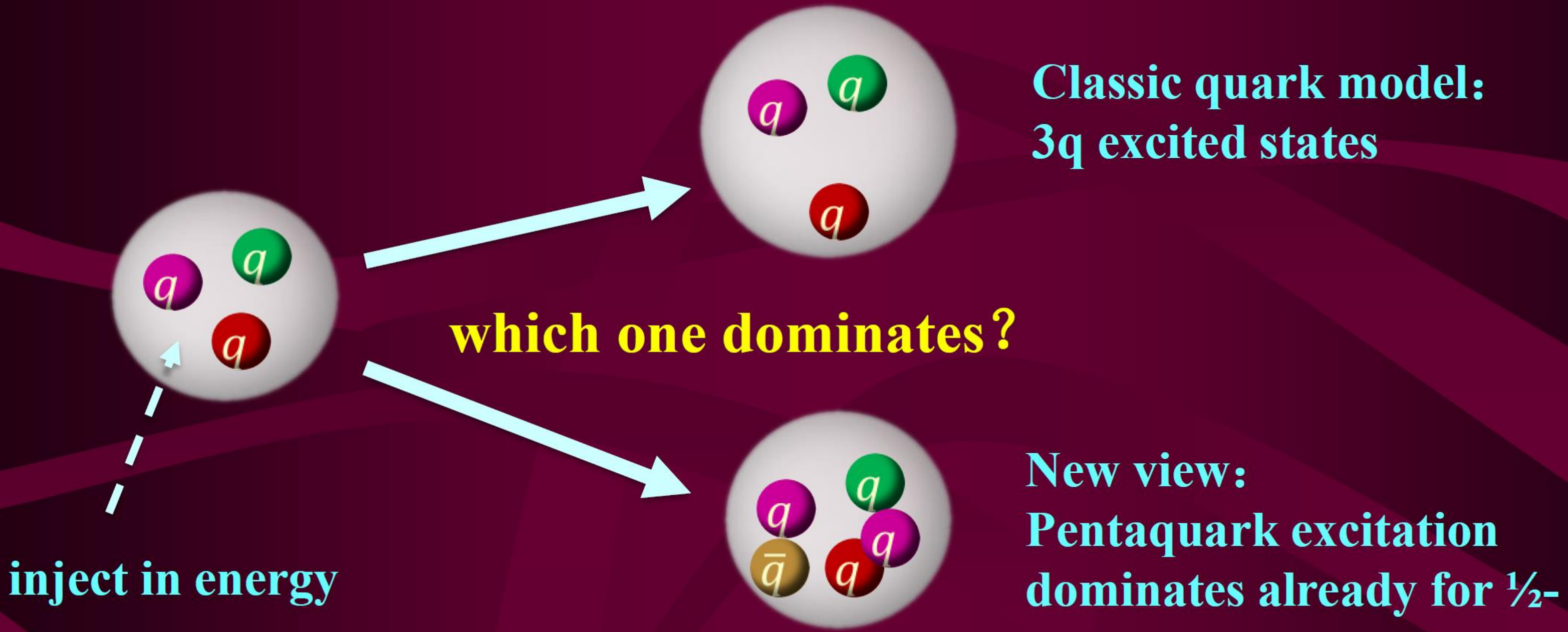
$$| p > \sim | uud > + \varepsilon_1 | n (udd) \pi^+ (\bar{d}u) > + \varepsilon_2 | \Delta^{++} (uuu) \pi^- (\bar{u}d) > + \varepsilon' | \Lambda (uds) K^+ (\bar{s}u) > \ldots$$

diquarks: Riska, Zou, Zhu, …

$$| p > \sim | uud > + \varepsilon_1 | [ud][ud] \bar{d} > + \varepsilon' | [ud][us] \bar{s} > + \ldots$$



~30% pentaquarks in proton → more in excited baryons !



Pentaquark crucial for baryon spectroscopy and structure !

Nature of $1/2^-$ baryon nonet with strangeness

Zou, EPJA 35 (2008) 325

- **Mass pattern : quenched or unquenched ?**

uds (L=1) $1/2^-$	~	$\Lambda^*(1670)$	~	$[us][ds]\,\bar{s}$		$K\Xi - \eta\Lambda$
uud (L=1) $1/2^-$	~	$N^*(1535)$	~	$[ud][us]\,\bar{s}$		$K\Sigma - K\Lambda - \eta N$
uds (L=1) $1/2^-$	~	$\Lambda^*(1405)$	~	$[ud][su]\,\bar{u}$		$\bar{K}N - \pi\Sigma$
uus (L=1) $1/2^-$	~	$\Sigma^*(1390)$	~	$[us][ud]\,\bar{d}$		$\bar{K}N - \pi\Sigma - \pi\Lambda$

Zou et al, NPA835 (2010) 199 ; CLAS, PRC87(2013)035206

- **Strange decays of N*(1535) and Λ*(1670) :**

N*(1535) large couplings $g_{N^*N\eta}$, $g_{N^*K\Lambda}$, $g_{N^*N\eta'}$, $g_{N^*N\phi}$

Λ*(1670) large coupling $g_{\Lambda^*\Lambda\eta}$

- **Nature of the lowest scalar mesons**

$\bar{q}q$ $^3S_1$ nonet

$\phi(1020)$ $\bar{s}s$

$K(892)$ $\bar{s}d$

$\omega(782)$ $\bar{u}u + \bar{d}d$

$\rho(770)$ $\bar{u}u - \bar{d}d$

$\bar{q}q$ $^3P_0$ or $\bar{q}^2q^2$ nonet ?

$a_0(980)$ $\bar{u}u - \bar{d}d$, $[\bar{u}\,\bar{s}][us] - [\bar{d}\,\bar{s}][ds]$

$f_0(980)$ $\bar{s}s$, $[\bar{u}\,\bar{s}][us] + [\bar{d}\,\bar{s}][ds]$

$\kappa(800)$ $\bar{s}d$, $[\bar{s}\,\bar{u}][ud]$

$f_0(600)$ $\bar{u}u + \bar{d}d$, $[\bar{u}\,\bar{d}][ud]$

$D^*_{s0}(2317) \sim \bar{s}c\ (L=1) + [\bar{q}\,\bar{s}][qc] + DK + \ldots$

$D^*_{s1}(2460) \sim \bar{s}c\ (L=1) + D^*K + \ldots$

$X(3872) \sim \bar{c}c\ (L=1) + [\bar{q}\,\bar{c}][qc] + D^*D + \ldots$

Important implications:

- $\bar{q}qqqq$ in S-state more favorable than qqq with L=1 !
  & $\bar{q}qqq$ in S-state more favorable than $\bar{q}q$ with L=1 !

$1/2^-$ baryon nonet ~ $\bar{q}q^2q^2$ state + …

0^+ meson octet ~ $\bar{q}^2q^2$ state + …

Draging out $\bar{q}q$ from gluon field –
an important excitation mechanism for hadrons !
multiquark components are important for hadrons !

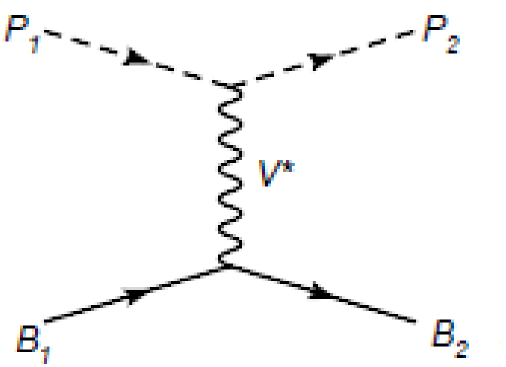
3. Multi-quark states as hadronic molecules

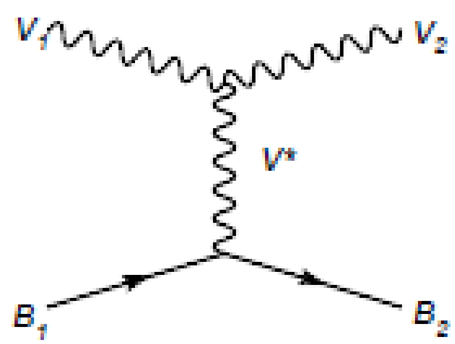
Prediction of pentaquarks with hidden charm & beauty:

From $K\Sigma$, $\bar{K}N \rightarrow \bar{D}\Sigma_c$, $\bar{D}\Xi_c \rightarrow B\Sigma_b$, $B\Xi_b$ bound states

"Prediction of narrow N* and Λ* resonances with hidden charm above 4 GeV",

Wu, Molina, Oset, Zou, PRL105 (2010) 232001





Vector meson exchange from hidden local symmetry

$\bar{s}suud \rightarrow \bar{c}cuud$

- prediction of three P_c pentaquark states → J/ψ-p :
  1 $D\Sigma_c$ molecule + 2 $D^*\Sigma_c$ molecules

  J.J.Wu, R.Molina, E.Oset, B.S.Zou, PRL 105 (2010) 232001
  W.L.Wang, F.Huang, Z.Y.Zhang, B.S.Zou, PRC 84 (2011) 015203
  J.J.Wu, T.H.Lee, B.S.Zou, PRC 85 (2012) 044002

- 4 more broader P_c states with $\Sigma_c \rightarrow \Sigma_c^*$:
  1 $D\Sigma_c^*$ molecule + 3 $D^*\Sigma_c^*$ molecules

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

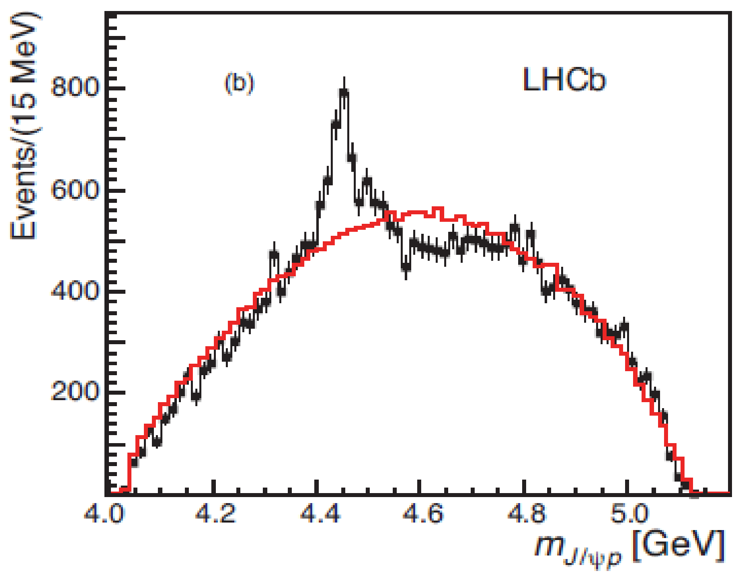
LHCb confirms our prediction of 3 narrow P_c states

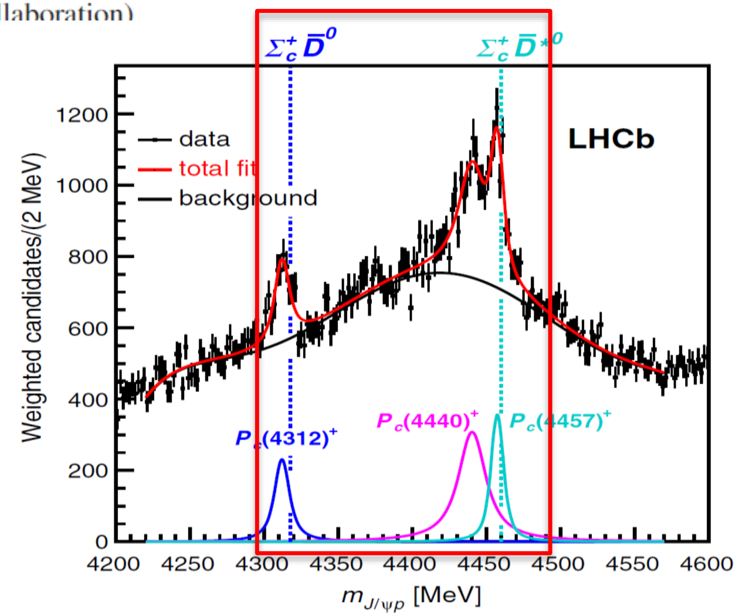
Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

R. Aaij *et al.**
(LHCb Collaboration)

PRL 122 (2019) 222001





A milestone for pentaquark search

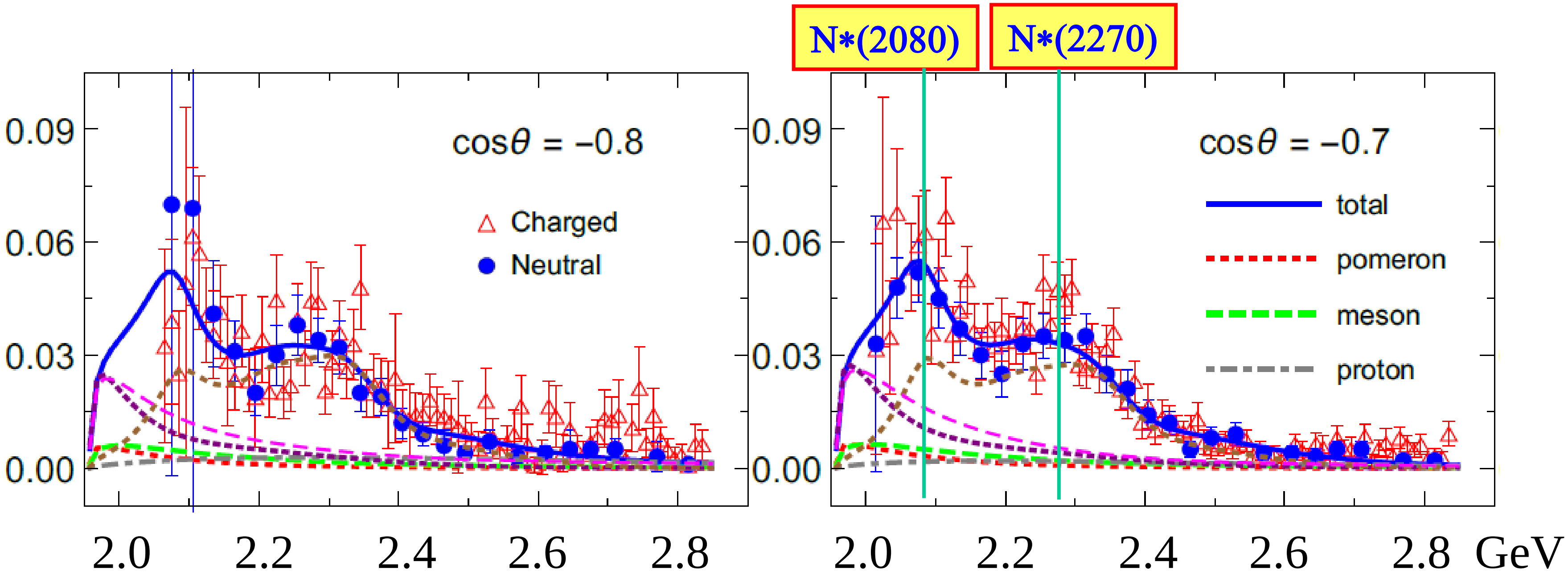
K*Σ, K*Σ* molecules from γp→φp reactions

KΣ* ~1880 **K*Σ ~ 2086** **K*Σ* ~ 2280**

N*(1875) **N*(2080)** **N*(2270)**

$\gamma p \to \phi p$

CLAS, PRC89(2014)019901



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

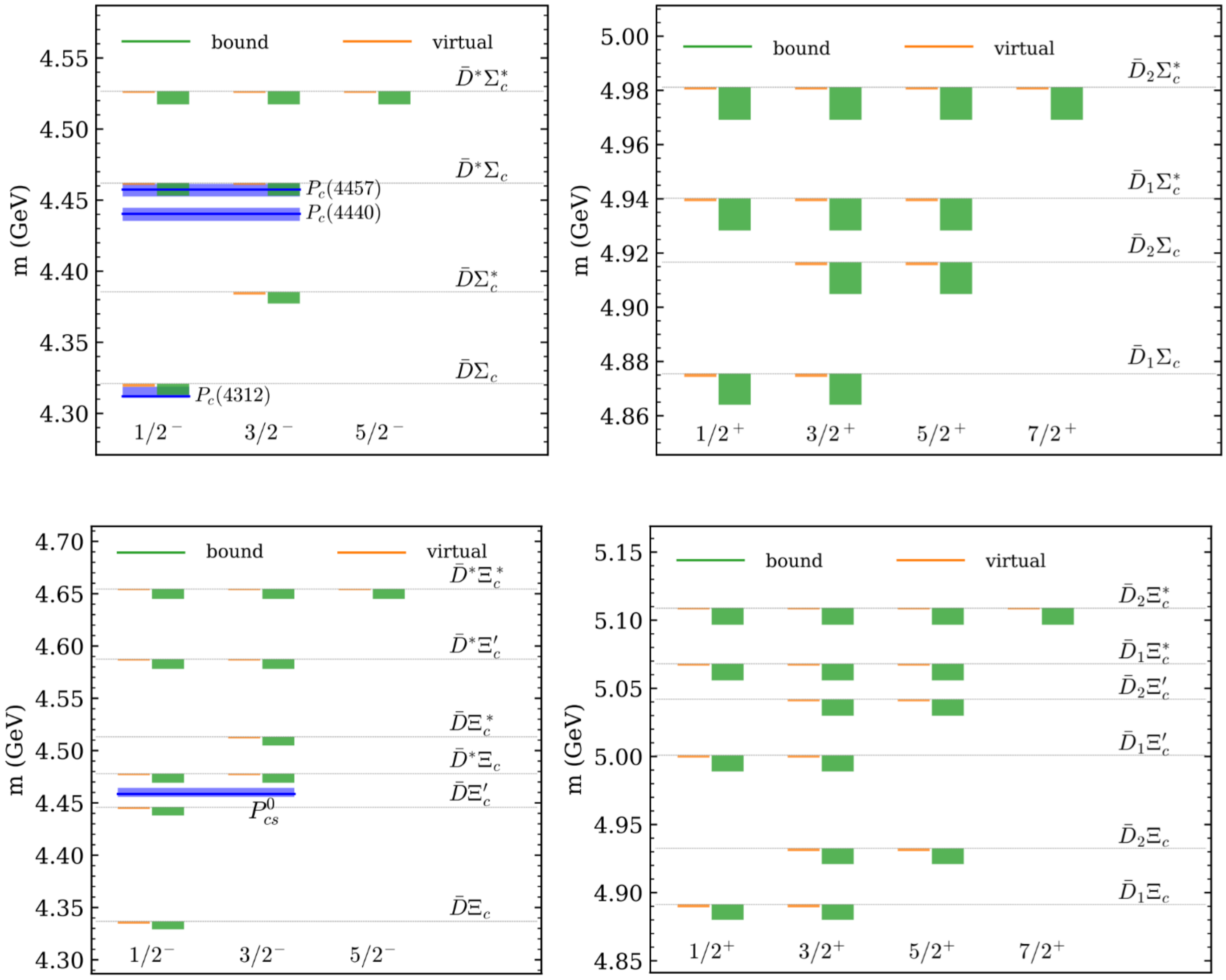
New Particles		relevant thresholds	
$Z_c(3900)$	$\bar{d}u\ \bar{c}c$	$\bar{D}^*D$	3880 MeV
$Z_c(4020)$		$\bar{D}^*D^*$	4020 MeV
$Z_b(10610)$	$\bar{d}u\ \bar{b}b$	$\bar{B}^*B$	10605 MeV
$Z_b(10650)$		$\bar{B}^*B^*$	10650 MeV
$P_c(4312)$	$uud\ \bar{c}c$	$\bar{D}\Sigma_c$	4318 MeV
$P_c(4440)$ & $P_c(4457)$		$\bar{D}^*\Sigma_c$	4459 MeV

Hadron-hadron resonances ?

F.K.Guo, Hanhart, Meissner,Q.Wang,Q.Zhao,Zou, **Rev.Mod.Phys.90 (2018)015004**

A survey of hadronic molecules with hidden charm

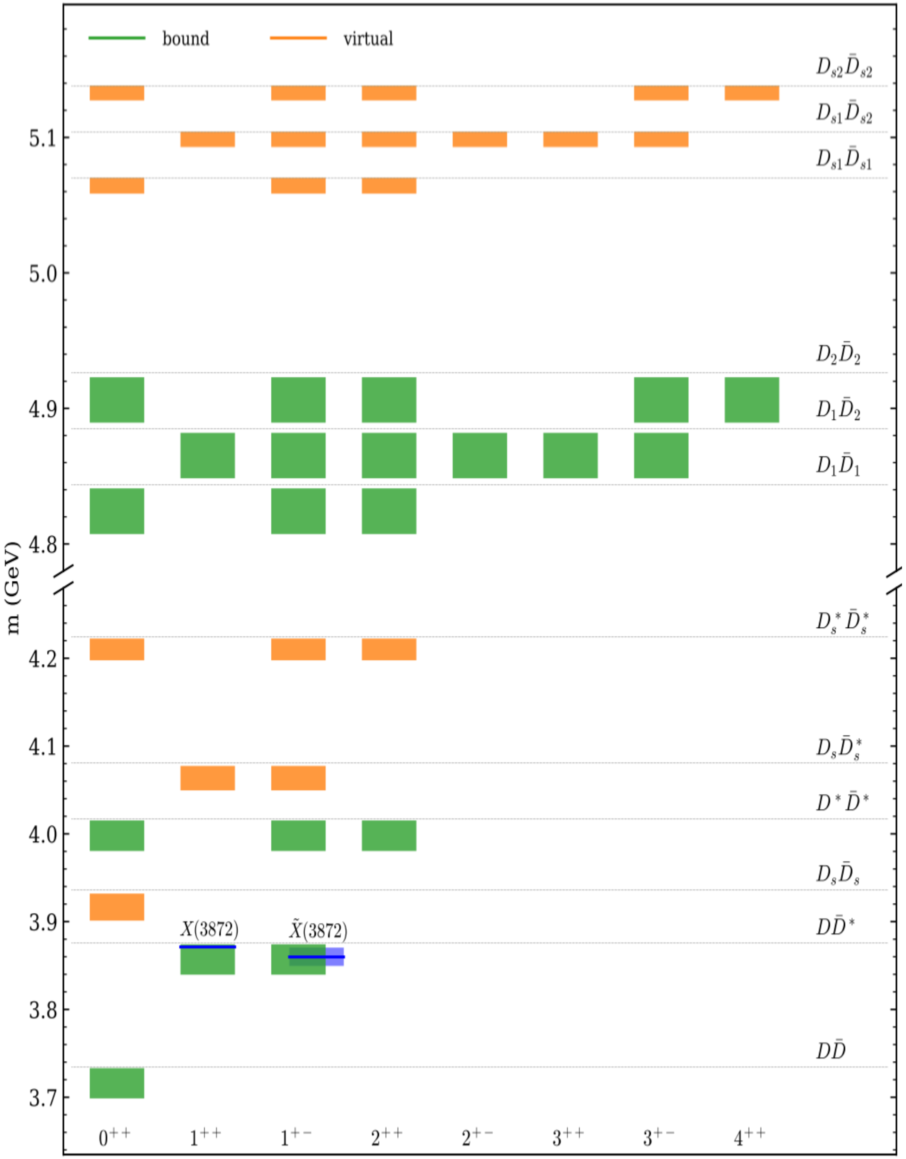
X.K.Dong, F.K.Guo, B.S.Zou Progr. Phys. 41 (2021) 65



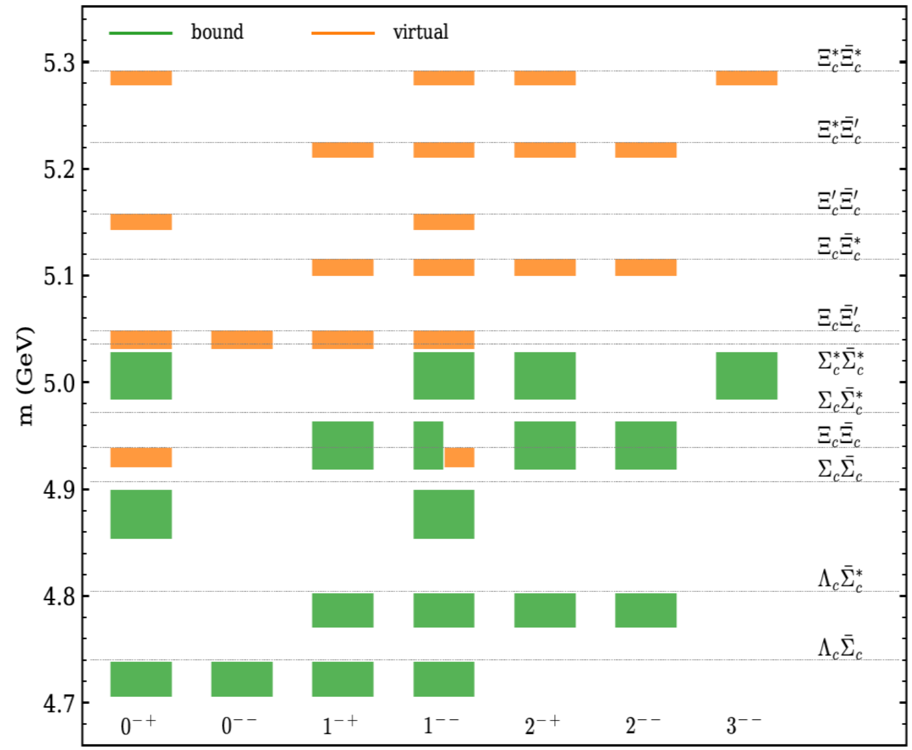
$\mathbf{P_c}$

$\mathbf{P_{cs}}$

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

Hadronic molecules with double charm T_{cc}^{+}

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

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

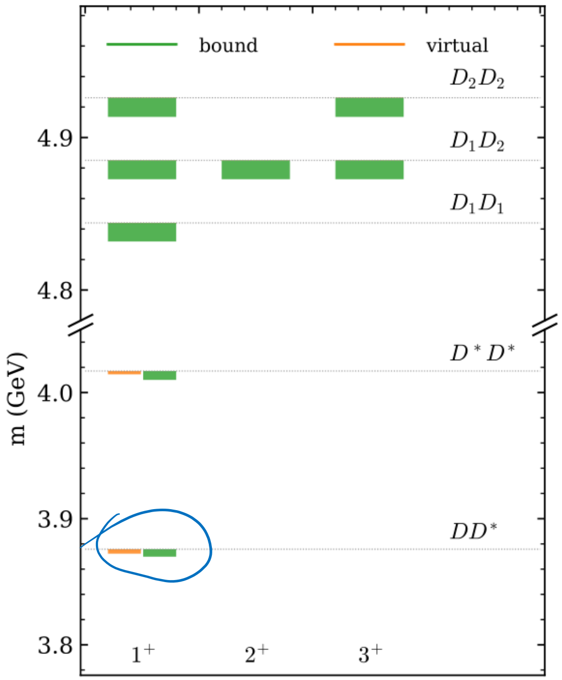
With V_π only, BB* is bound, DD* is not bound.

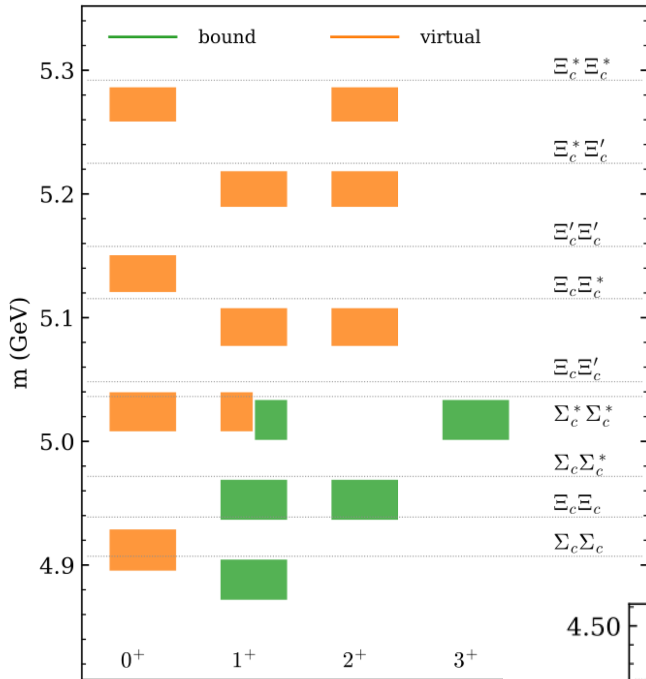
But $V_{\rho,\omega}$ provide additional attractive force for I=0!

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

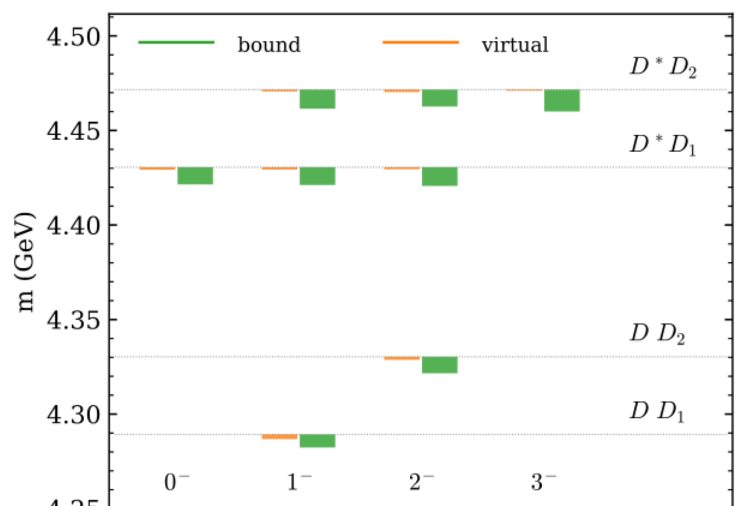
A survey of heavy-heavy hadronic molecules

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





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

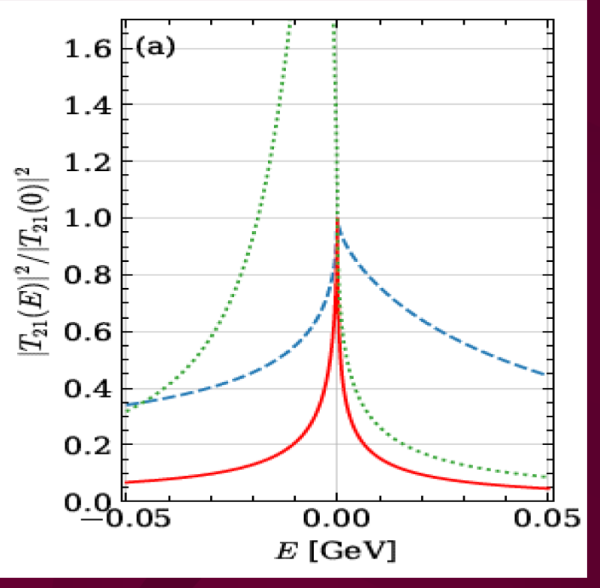


✓ T_{cc} as an isoscalar DD^* bound or virtual state, D^*D^* predicted to be similar, with $P = +$

✓ Similar in $P = -$ sector

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

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

Hybrid, Glueball or hadronic molecules ?

Observation of $\eta_1(1855)$ with exotic $J^{PC}=1^{-+}$ in $J/\psi \to \gamma\eta\eta'$

BESIII Collaboration, PRL 129 (2022) 192002

Interpretation of the $\eta_1(1855)$ as a $\bar{K}K_1$ (1400)+ c.c. molecule

X.K.Dong, Y.H.Lin, B.S.Zou, SCIENCE CHINA PMA 65 (2022) 261011

M.J.Yan, J.M.Dias, A.Guevara, F.K.Guo, B.S.Zou, Universe 9 (2023) 109

Two dynamical generated a_0 resonances by VV interactions

Z.L.Wang, B.S.Zou, EPJC 82 (2022) 509

$\rho\rho$ / $\rho\omega$ molecules → f_0 (1500) / a_0 (1450)

$\bar{K}^*K^*$(I=0,1) molecules → f_0 (1710) / a_0 (1710)

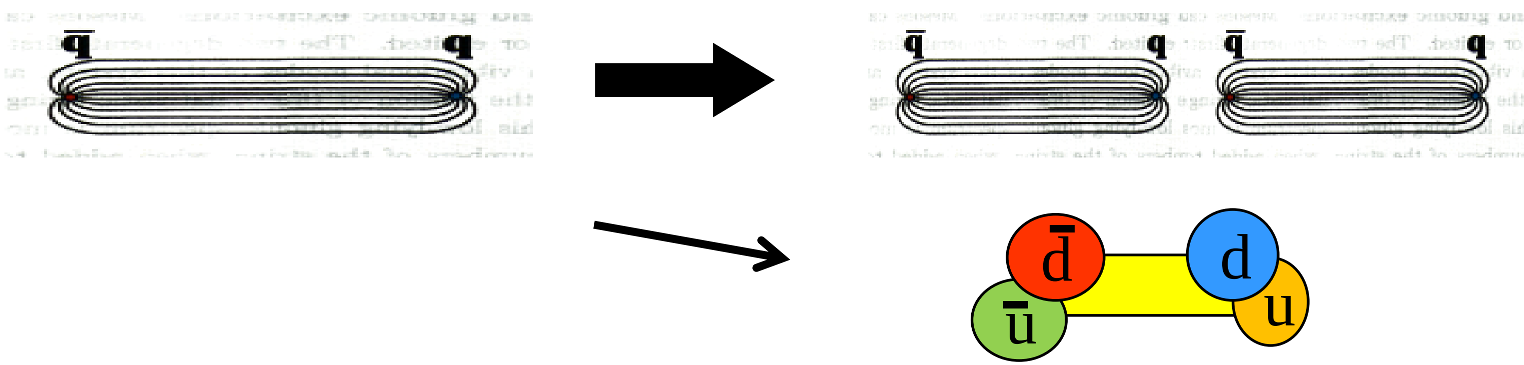
Observation of a_0 (1710) → $K_S^0K^+$ in D_s^+ → $K_S^0K^+\pi^0$ decay

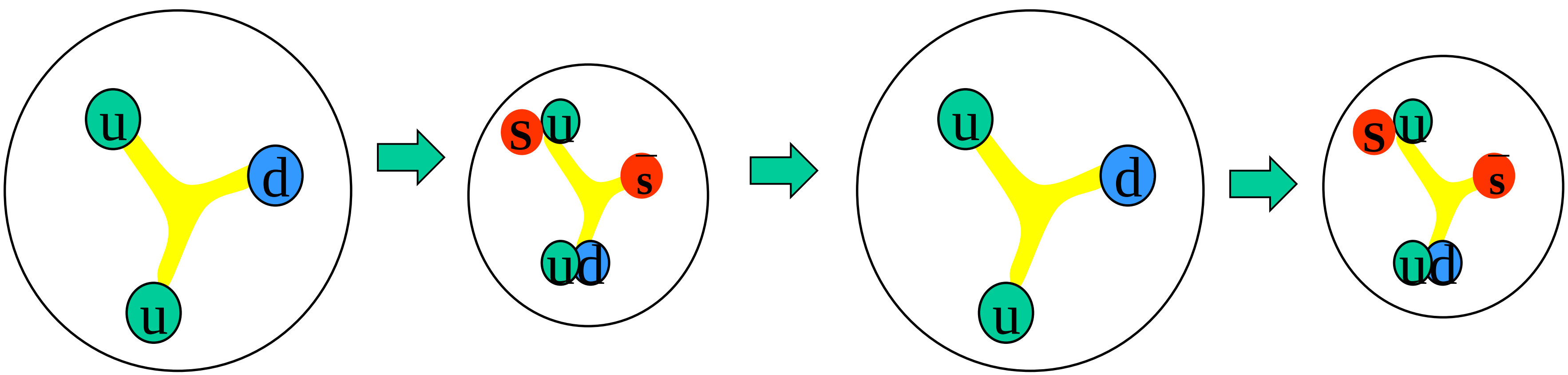
BESIII Collaboration, PRL 129 (2022) 182001

4. Unquenched quark model

Unquenching dynamics: gluons → $\bar{q}q$

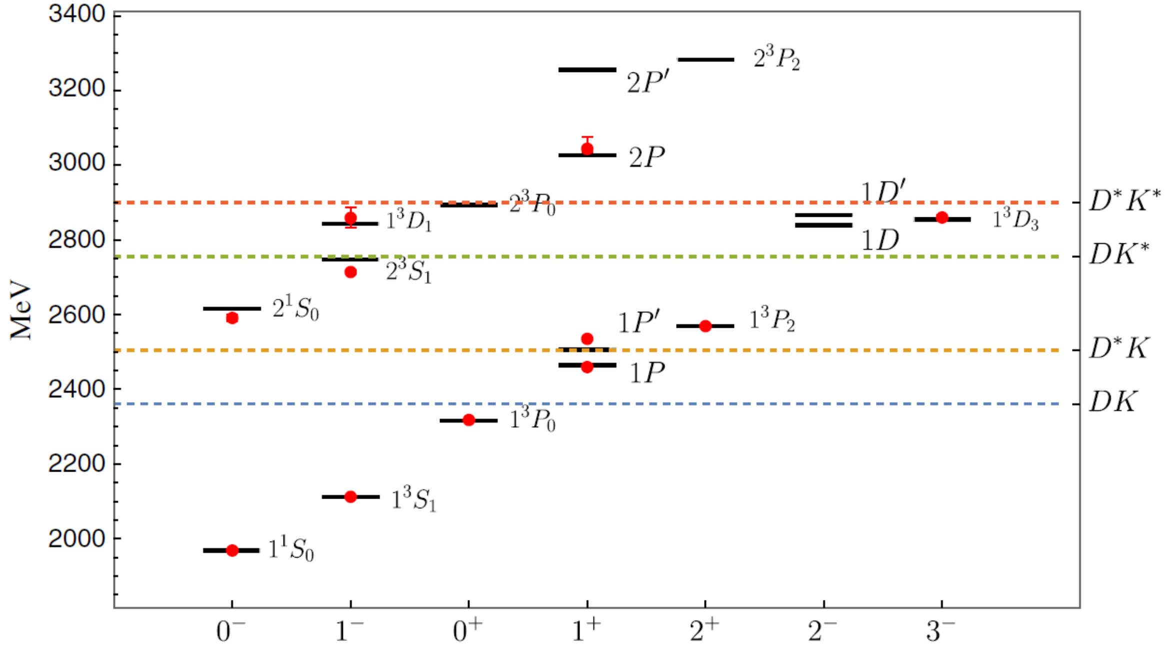
crucial for quark confinement & hadron structure





Unquenched quark model study of the charm-strange meson

W.Hao, Y.Lu, B.S.Zou, PRD106 (2022) 074014



Mass spectrum of Ds mesons

TABLE III. Probabilities (in %) of the coupled channels considered in this work. For the convenience of comparison, values from columns 3 to 12 (various coupled channels) are rescaled by $P_{c\bar{s}}$, such that $P_{c\bar{s}} = 100\%$. e.g., for $D^*_{s0}(2317)$, $P_{c\bar{s}} : P_{DK} = 100 : 45.5$ "–" means that the corresponding channel is open and its contribution to the wave function normalization is discarded, see the discussion below Eq. (15). $P_{c\bar{s}}$ and P_{molecule} represent the probability of the $c\bar{s}$ and the summation of the probability of all the coupled channels, respectively.

$(n_r+1)^{2S+1}L_J$	State	DK	DK^*	D^*K	D^*K^*	$D_s\eta$	$D_s\eta'$	$D_s\phi$	$D^*_s\eta$	$D^*_s\eta'$	$D^*_s\phi$	P_{molecule}	$P_{c\bar{s}}$
1^1S_0	D_s	0.0	4.3	3.5	8.5	0.0	0.0	1.1	0.7	0.2	2.2	17.0	83.0
1^3S_1	D^*_s	2.5	4.2	3.8	13.9	0.4	0.1	1.0	0.7	0.2	3.5	23.2	76.8
1^3P_0	$D^*_{s0}(2317)$	45.5	0.0	0.0	19.9	1.7	0.2	0.0	0.0	0.0	4.2	40.3	59.7
$1P$	$D_{s1}(2460)$	0.0	8.5	42.8	19.1	0.0	0.0	1.3	1.8	0.3	3.8	43.7	56.3
$1P'$	$D_{s1}(2536)$	–	10.8	–	17.9	–	–	1.7	1.9	0.4	3.4	26.5	73.5
1^3P_2	$D^*_{s2}(2573)$	–	8.5	–	22.8	–	0.2	1.4	1.2	0.3	4.0	27.7	72.3
2^1S_0	$D_{s0}(2590)$	–	20.4	–	26.2	–	–	2.0	4.1	0.4	3.7	36.2	63.8
2^3S_1	$D^*_{s1}(2700)$	–	51.3	–	47.3	–	0.2	1.6	–	0.3	4.7	51.3	48.7
1^3D_1	$D^*_{s1}(2860)$	–	–	–	47.6	–	0.5	0.6	–	0.1	5.8	35.3	64.7
$1D$	–	–	–	–	35.4	–	–	2.0	–	0.4	4.1	29.5	70.5
$1D'$	–	–	–	–	46.9	–	–	2.3	–	0.4	3.9	34.9	65.1
1^3D_3	$D^*_{s3}(2860)$	–	–	–	54.4	–	0.2	1.4	–	0.3	3.8	37.5	62.5
2^3P_0	–	–	–	–	167.5	–	0.6	–	–	–	4.0	63.2	36.8

Note: even for Ds (g.s.) there is 17% tetra-quark components

5. 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

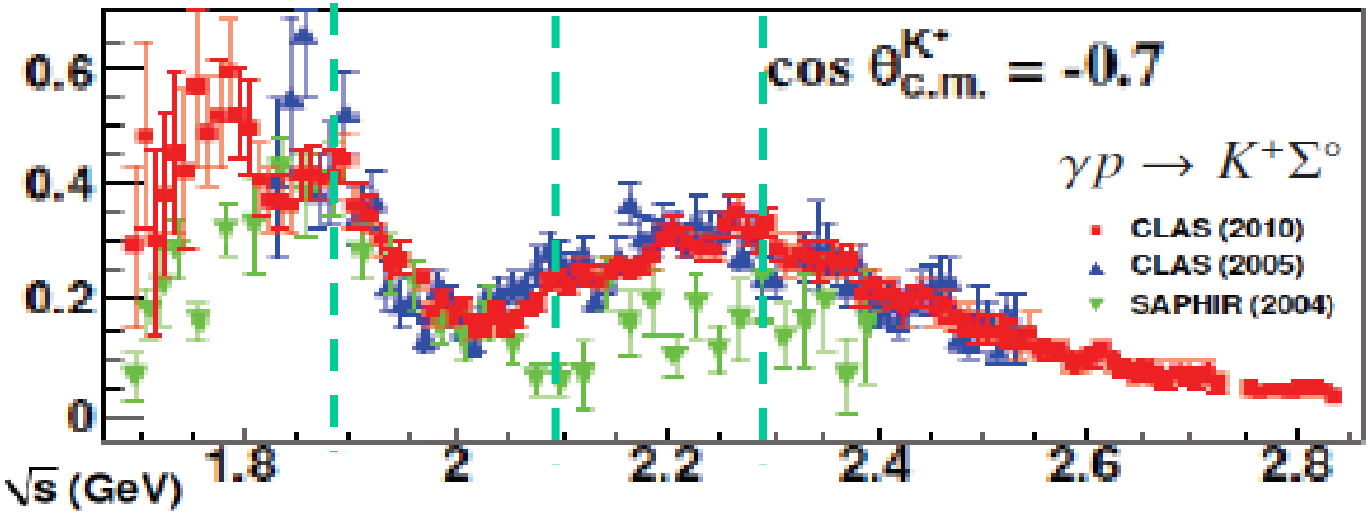
ep/γp@JLab, π10/K10@JPARC, BelleII, BESIII, Eic/EicC, PANDA@FAIR, STCF etc. may play a important role here!

Thank you for your attention!

Strange partners of P_c and P_{cs} states

KΣ* ~1880 **K*Σ ~ 2086** **K*Σ* ~ 2280**

N*(1875) **N*(2080)** **N*(2270)**



KΞ ~1810 **KΞ* ~ 2027** **K*Ξ ~ 2210** **K*Ξ* ~ 2427**

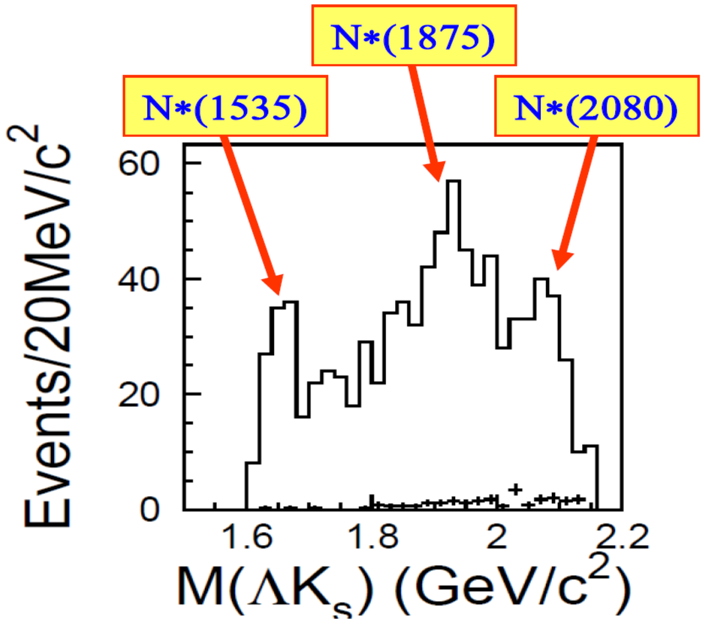
Λ(1/2⁻) **Λ(3/2⁻)** **Λ(1/2⁻,3/2⁻)** **Λ(1/2⁻,3/2⁻,5/2⁻)**

K*N ~1833 : Λ(1800)1/2⁻, Λ(3/2⁻)

Strangeness partners of P_c states at BES ?

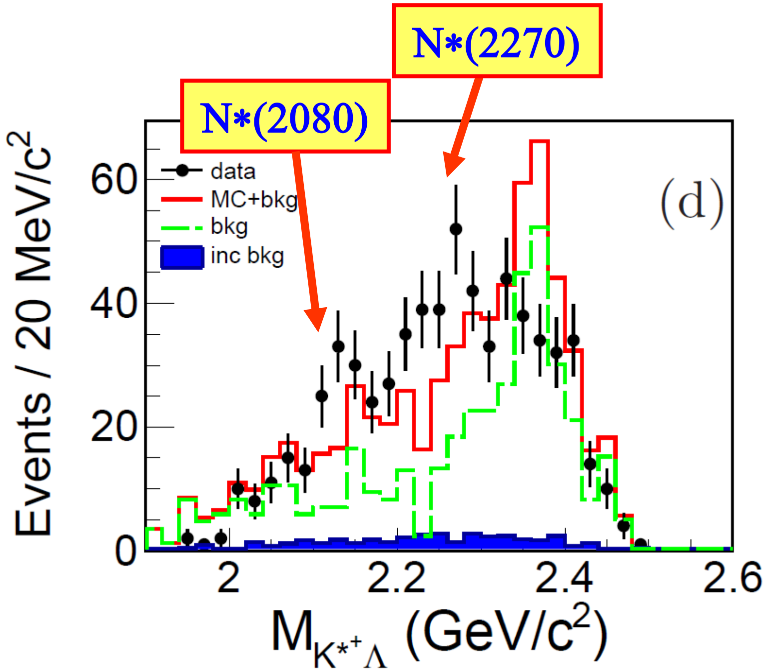
N*(1875) **N*(2080)** **N*(2270)**

KΣ* ~1880 K*Σ ~ 2086 K*Σ* ~ 2280



$J/\psi \to nK_S^0\overline{\Lambda}$

BESII, PLB659 (2008) 789



$\chi_{c0} \to \bar{p}K^{*+}\Lambda$ +c.c.

BESIII, arXiv:1908.02979