# Charmonium, exotic hadrons and hadron structure

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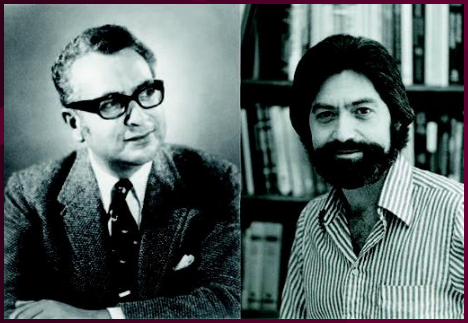
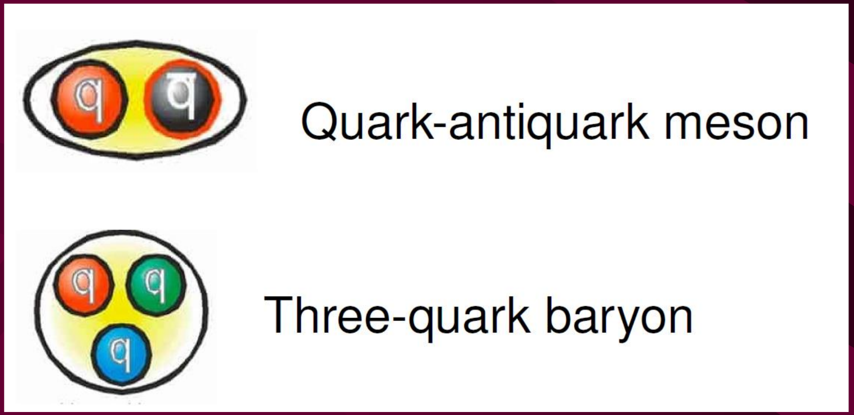
# Outline

1. **QCD inspired quark potential model originated from charmonium**
2. **Quark-gluon structure of proton**
3. **Exotic hadrons**
4. **Unquenched quark model**
5. **Summary and prospects**

1. QCD inspired quark potential model originated from charmonium

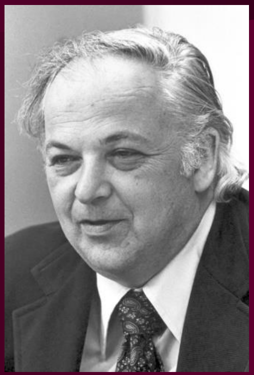
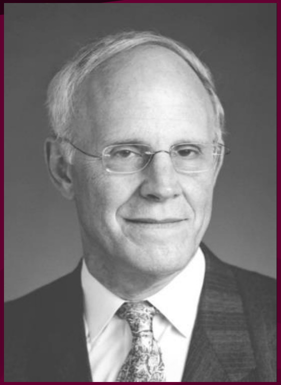
- 1964 – invention of quark model with u,d,s quarks






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

# ● 1974 – $\overline{c}c$ + QCD → QCD inspired quark potential model

  +   

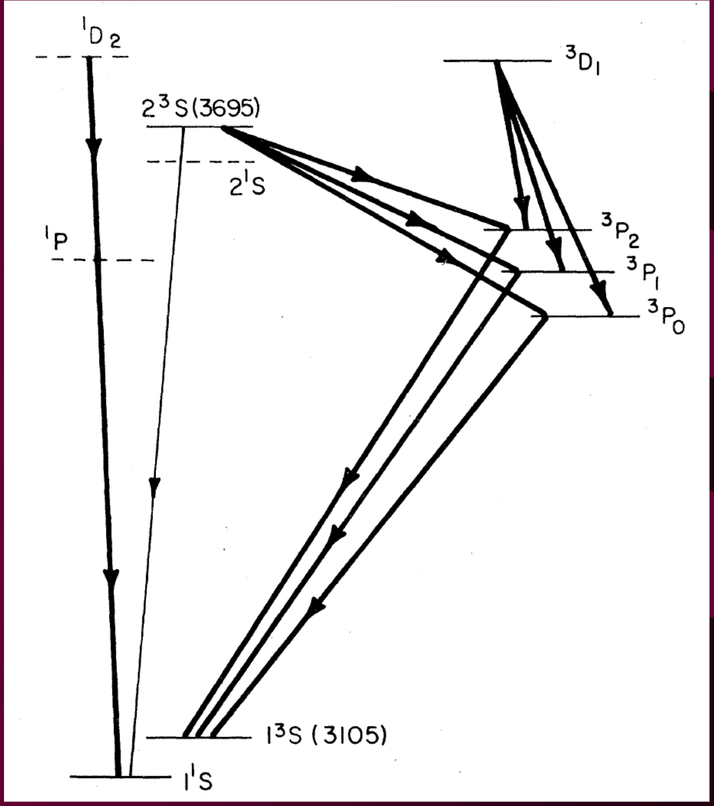
$$\hat{H}_0 = \frac{p^2}{m_Q} + V_0(r) + V_{\rm SD}(r)$$

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

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

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

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



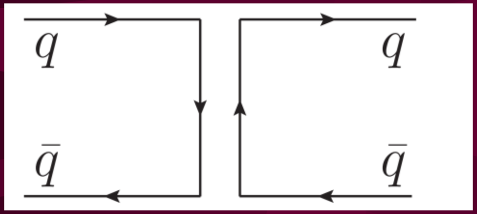
# Extension to light hadrons with various developments

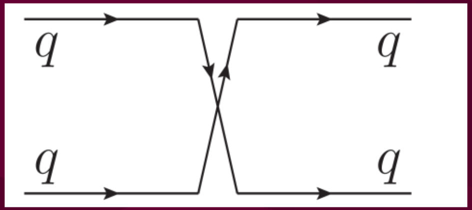
- **Mesons & baryons in a relativized quark model**

S.Godfrey, N.Isgur, PRD32(1985)189; S.Capstick, N.Isgur, PRD34(1986)2809

- **Chiral quark model – quarks with mass generated by SχSB & pions as Nambu-Goldstone bosons**

A.Manohar, H.Georgi, NPB234(1984)189




**Meson exchange ~ quark exchange effect**

- **Chiral quark model with hidden local gauge symmetry – include both pseudoscalar & vector meson exchanges**

L.Y.Glozman, D.O.Riska, Phys.Rept. 268(1996)263

B.R.He, M.Harada, B.S.Zou, PRD108(2023)054025

**Important effects of ω meson exchange: attractive for $\bar{q}q$ & repulsive for qq**

# Both quark models & LQCD can well reproduce the masses of various hadron ground states

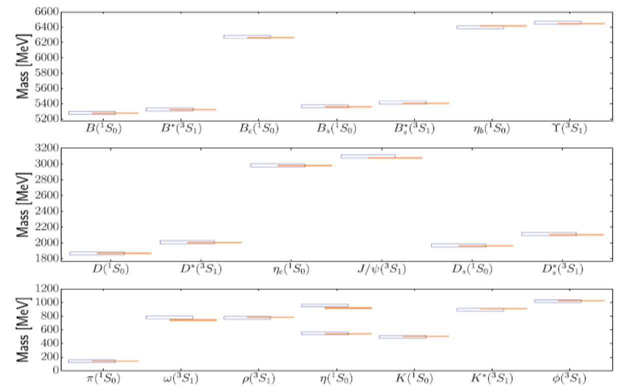



**Fig. 1** Mass spectrum of mesons. Blue boxes represent $m(\text{exp}) \pm \text{Err(sys)}$, while the orange lines represent the predicted masses. The values of $\eta_b$ and $\Upsilon$ shown here are shifted by $-3000$ MeV

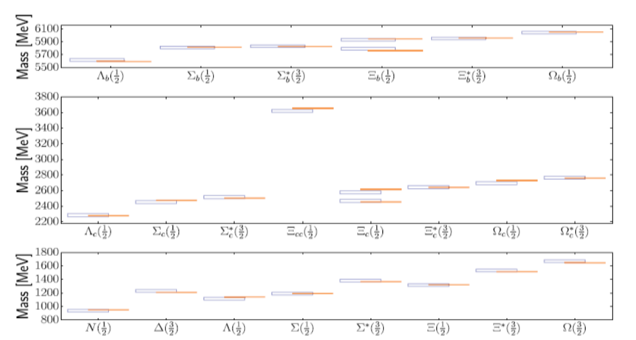
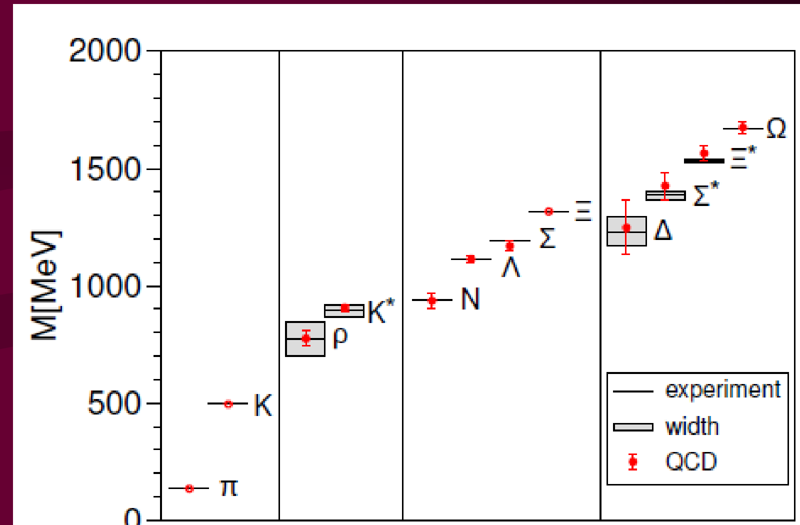



**Fig. 2** Mass spectrum of baryons. The colors have the same meaning as shown in Fig. 1

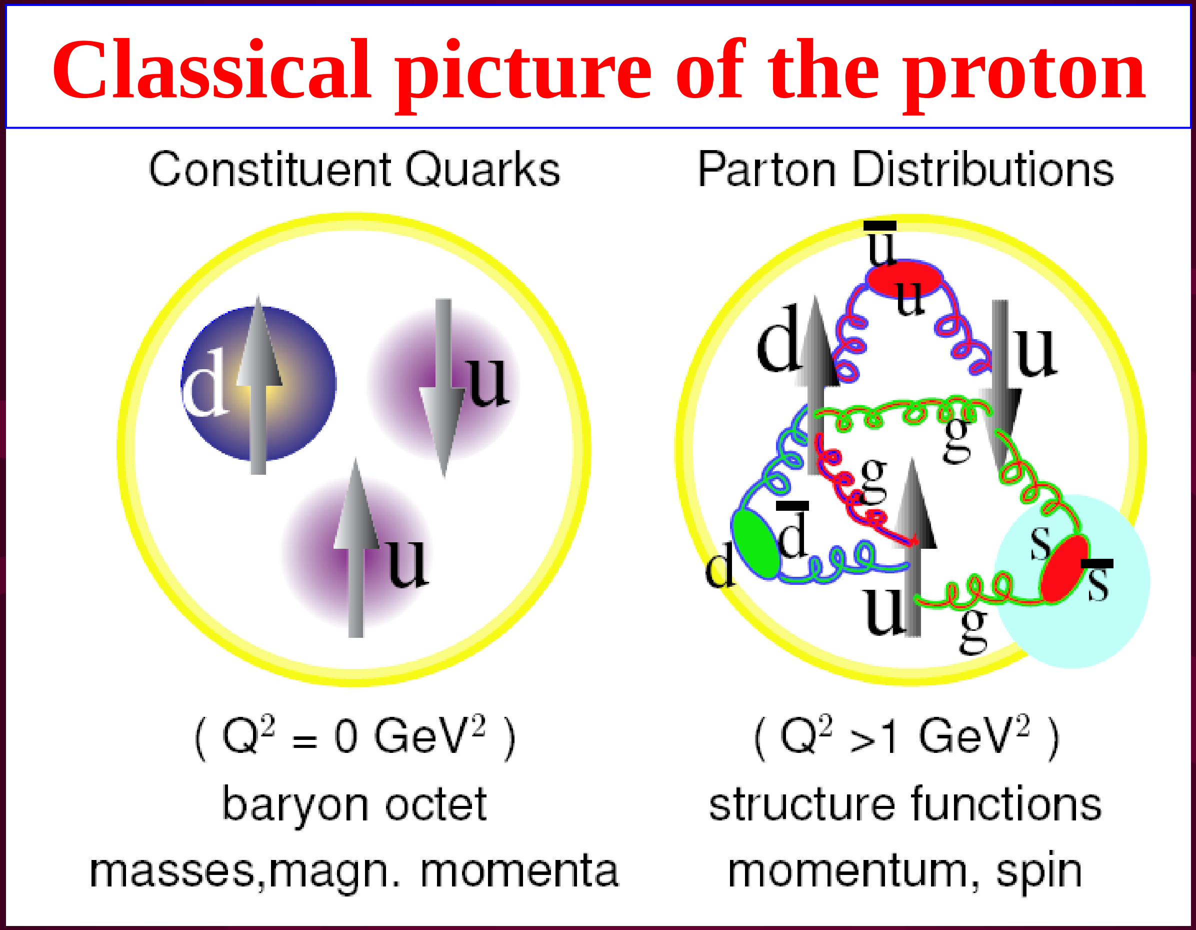
B.R.He, M.Harada, B.S.Zou, EPJC 83 (2023) 1159




S.Durr et al.(BMW Collab.), Science 322, 1224 (2008).

**but various problems exist**

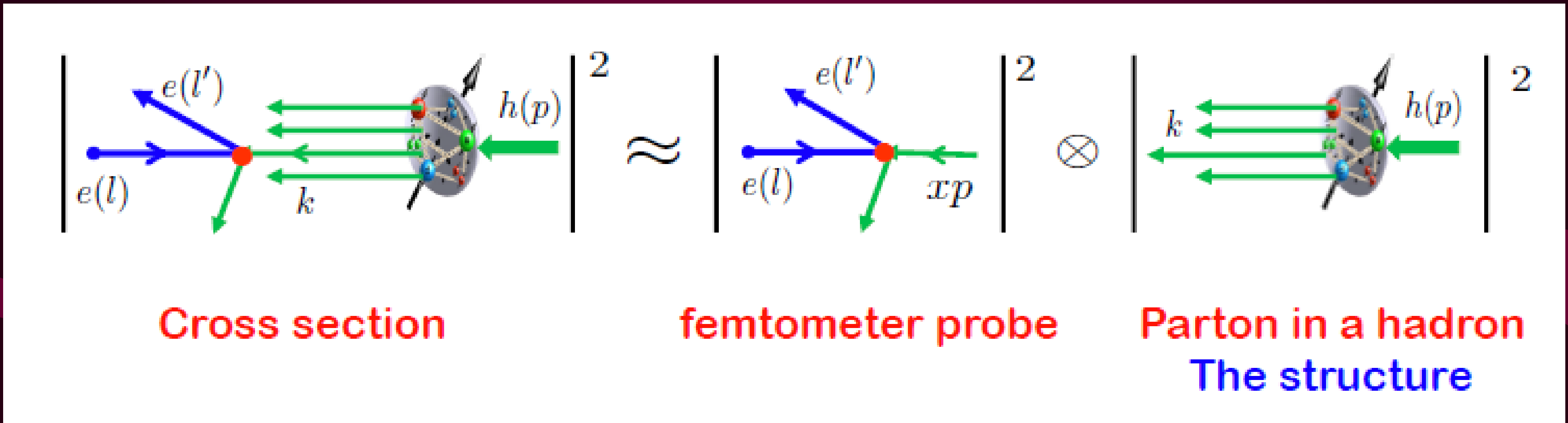
# 2. Quark-gluon structure of proton




$$\bar{u}(x) = \bar{d}(x)\,, \quad \bar{s}(x) = s(x)$$

**1964-1974**

**1974–1992**




**QCD factorization → PDF (flavor, spin, momentum) of nucleon**

**proton spin “crisis” , $\bar{d} - \bar{u} \sim 0.12$, $\bar{s}(x) \neq s(x)$, …**

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

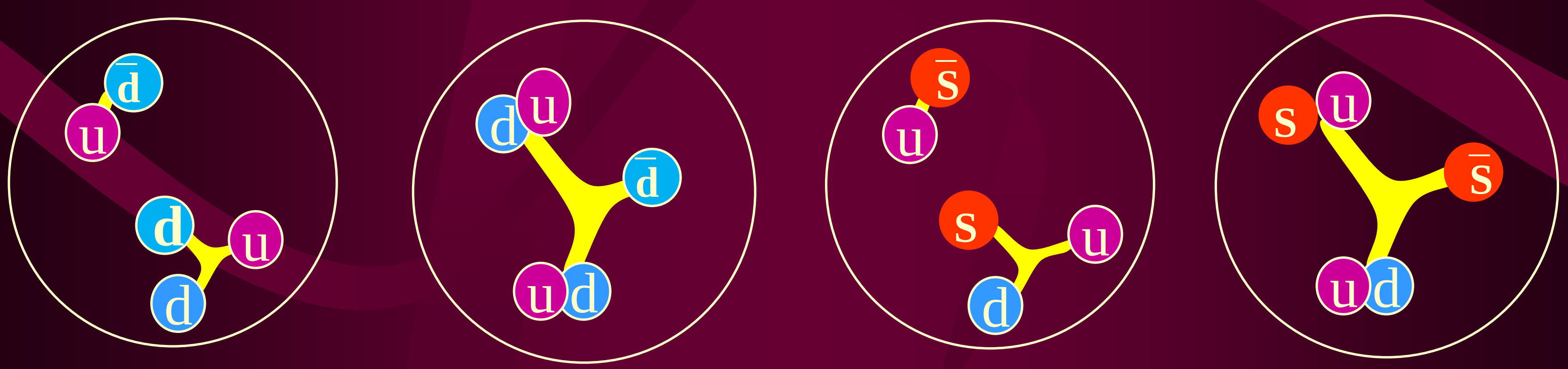
two possible solutions:

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

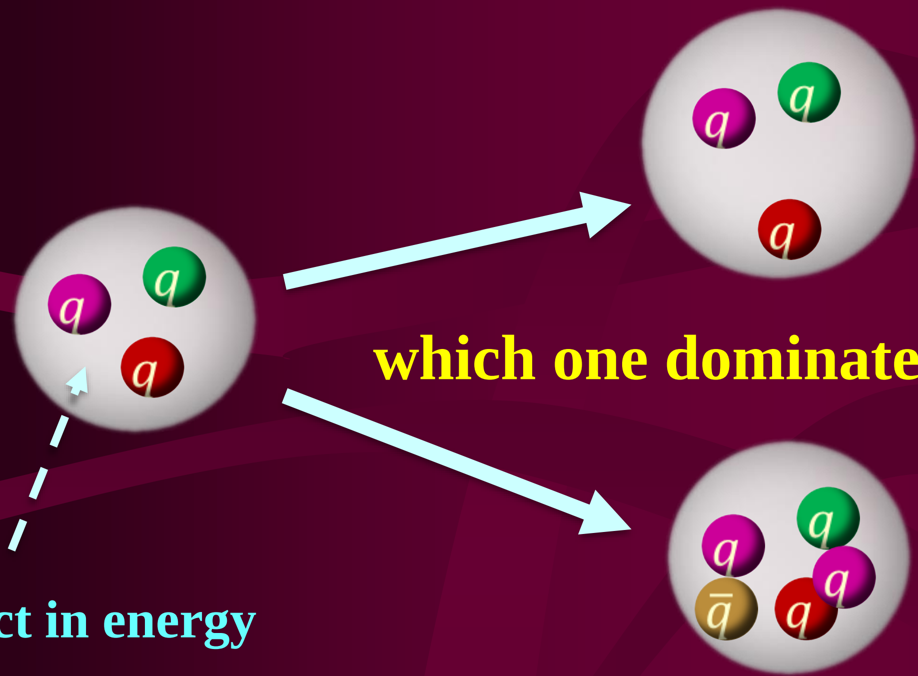
$$| p \rangle \sim | uud \rangle + \varepsilon_1 | n ( udd )\, \pi^+ ( \bar{d}u ) \rangle$$
$$+ \varepsilon_2 | \Delta^{++} ( uuu )\, \pi^- ( \bar{u}d ) \rangle + \varepsilon' | \Lambda (uds)\, K^+ ( \bar{s}u ) \rangle \ldots$$

diquarks: Riska, Zou, Zhu, …

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



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



Classic quark model:
3q excited states

which one dominates?

inject in energy

New view:
Pentaquark excitation
dominates already for ½-

**Pentaquark crucial for baryon spectroscopy and structure !**

# 3. Exotic hadrons

**Fate of the first pentaquark predicted and observed: $1/2^-$**

**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 $\Lambda_c$ 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."**

## Fate of the last famous fading pentaquark $\theta^+(1540)$: $1/2^+$

**1997:** $Z^+(1530)$ predicted by Diakonov et al., ZPA359, 305

**2003:** $\theta^+(1540) \rightarrow K^+n$ claimed by LEPS, PRL91, 012002

**2003:** $\bar{s}$ (ud)(ud) for $\theta(1540)$ by Jaffe&Wilczek, PRL91, 232003

**2003:** $\bar{s}$ ud)(ud) for $\theta(1540)$ by Karliner&Lipkin, PLB575, 249

**2004:** supported by 10 expts $\rightarrow$ $\theta(1540)$ well-established by PDG

**2004:** not supported by BESII, PRD70, 012004

**2005:** not supported by many high stats experiments

**2006:** removed from PDG

**Note:** $\theta^+(1540)$ is not supported by hadronic molecule model & chiral quark model by Huang, Zhang, Yu, Zou, PLB586(2004)69

# $1/2^-$ 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) $1/2^-$ ~ $N^*(1535)$ ~ $[ud][us]\bar{s}$ , $K\Sigma$ - $K\Lambda$-$N\eta$**

**uds (L=1) $1/2^-$ ~ $\Lambda^*(1405)$ ~ $[ud][su]\bar{u}$ , $\bar{K}N$ - $\pi\Sigma$**

**uus (L=1) $1/2^-$ ~ $\Sigma^*(1390)$ ~ $[us][ud]\bar{d}$ , $\bar{K}N$ - $\pi\Lambda$**

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

BESIII, ArXiv: 2407.12270 [hep-ex]

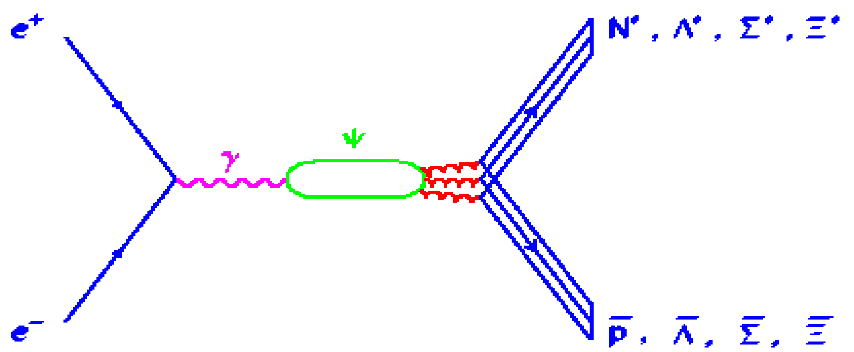
- **Strange decays of N*(1535) and $\Lambda^*(1670)$ :**

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

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

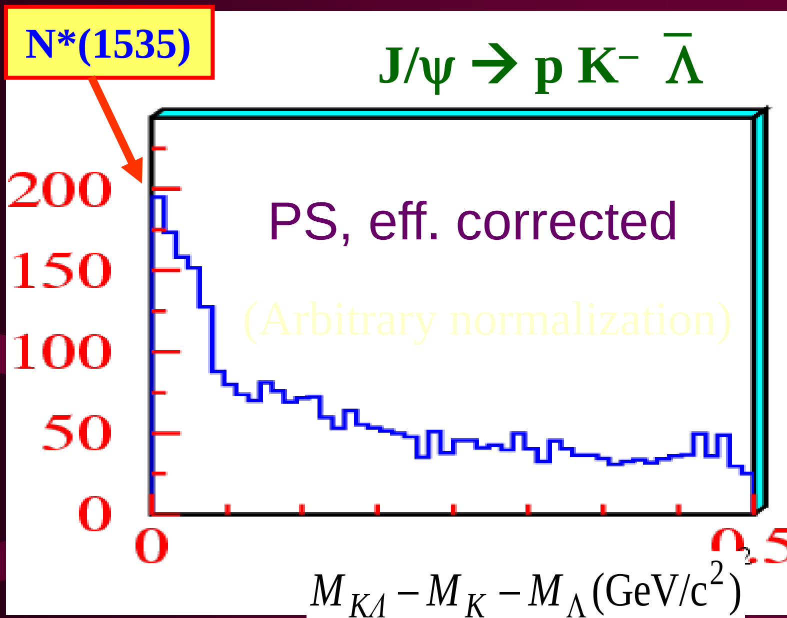
# （N*, Λ*, Σ*, Ξ*, Ω*） baryons from ψ decays at BEPC

$$\Psi \to \overline{B}BM \Rightarrow N^*, \Lambda^*, \Sigma^*, \Xi^*, \Omega^*$$

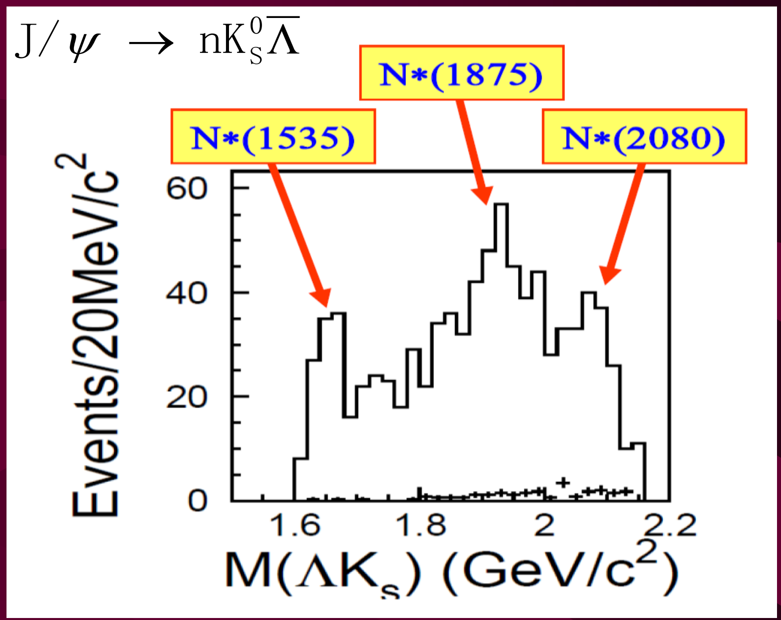



**advantages： ideal isospin and low spin filter comparing to other experiments (ep, γp, πp, Kp)**

# N* observed in J/ψ → $\bar{\Lambda}$ K N




**BESII, IJMPA20 (2005) 1985**




**BESII, PLB659 (2008) 789**

**B.C.Liu, B.S.Zou, PRL96 (2006) 042002 :** **N*(1535) ~ $\bar{s}$suud !**

**KΣ* ~1880 MeV , K*Σ ~ 2086 MeV !**

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

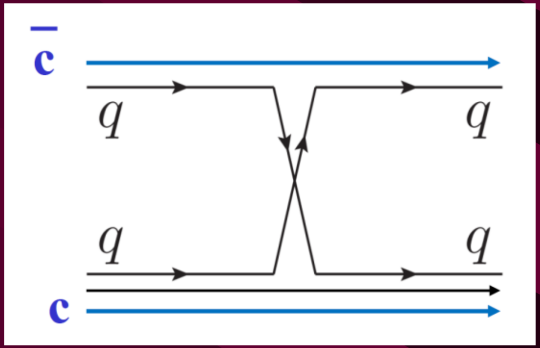
- prediction of three $P_c$ states → $J/\psi$-p :

  1 $\bar{D}\Sigma_c$ molecule + 2 $\bar{D}^*\Sigma_c$ 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

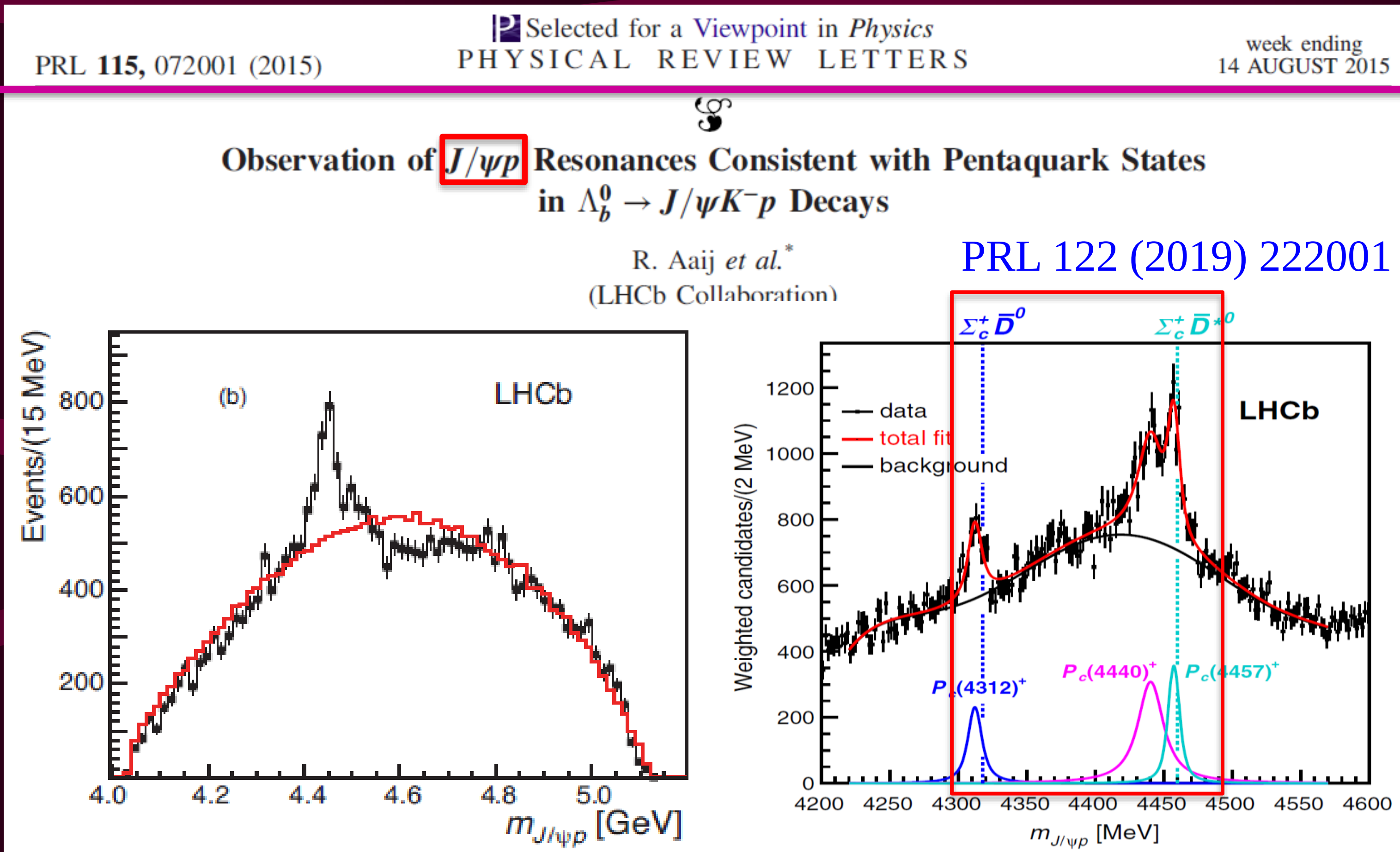



- 4 more broader $P_c$ states with $\Sigma_c \rightarrow \Sigma_c^*$ :

  1 $\bar{D}\Sigma_c^*$ molecule + 3 $\bar{D}^*\Sigma_c^*$ molecules

  C.W.Xiao, J.Nieves, E.Oset, PRD88(2013)056012

# LHCb confirms our prediction of 3 narrow $P_c$ states




**A milestone for pentaquark search**

# Multiquark states – crucial for hadron structure !

X(3872) → top cited paper for Belle (2003) 2603 cites

$Z_c$(3900) → top cited paper for BES (2013) 1137 cites

$P_c$ states → top cited paper for LHCb (2015) 1815 cites

## J/ψ played a crucial role for their discovery!

Belle (2003) : X(3872) → J/ψ π π

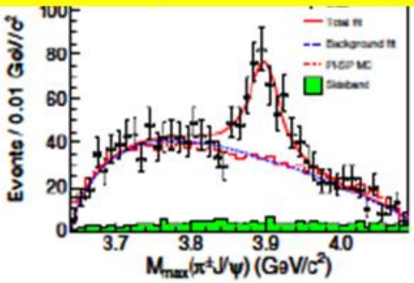
BES (2013) : $Z_c$(3900) → J/ψ π

LHCb (2015): $P_c$ states → J/ψ p

# Discovery of $Z_c$ family at BESIII


### $Zc(3900)^+$

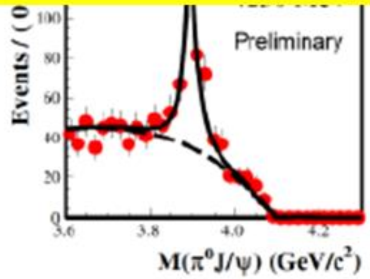
PRL 110, 252001 (2013)




$e^+e^- \to \pi^-\pi^+ J/\psi$

### $Zc(3900)^0$

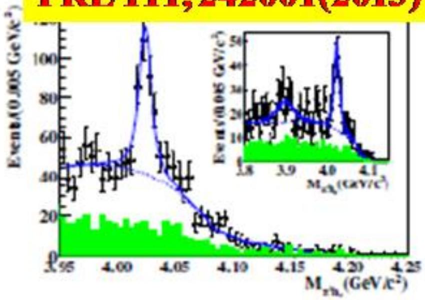
PRL 115, 112003 (2015)




$e^+e^- \to \pi^0\pi^0 J/\psi$

### $Zc(4020)^+$

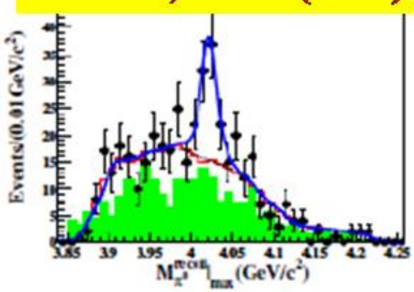
PRL 111, 242001(2013)



$e^+e^- \to \pi^-\pi^+ h_c$

### $Zc(4020)^0$

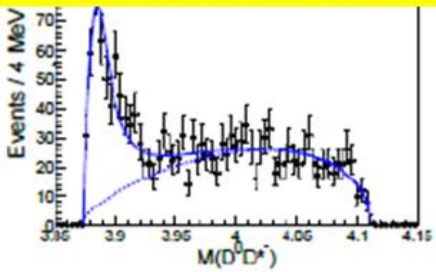
PRL113,212002 (2014)



$e^+e^- \to \pi^0\pi^0 h_c$

### $Zc(3885)^+$

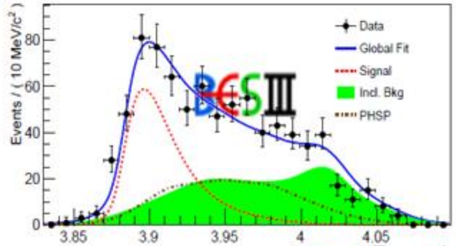
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)




$e^+e^- \to \pi^-(D\bar{D}^*)^+$

### $Zc(3885)^0$

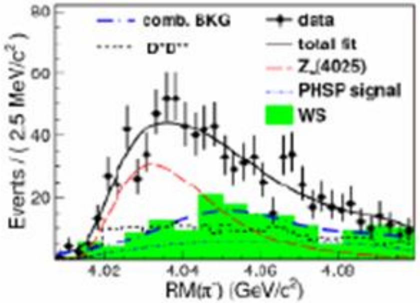
PRL 115, 222002 (2015)




$e^+e^- \to \pi^0(D^*\bar{D})^0$

### $Zc(4025)^+$

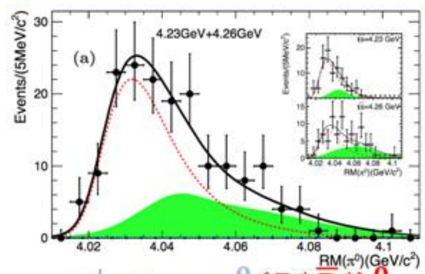
PRL 112, 132001 (2014)




$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

### $Zc(4025)^0$

PRL115, 182002 (2015)

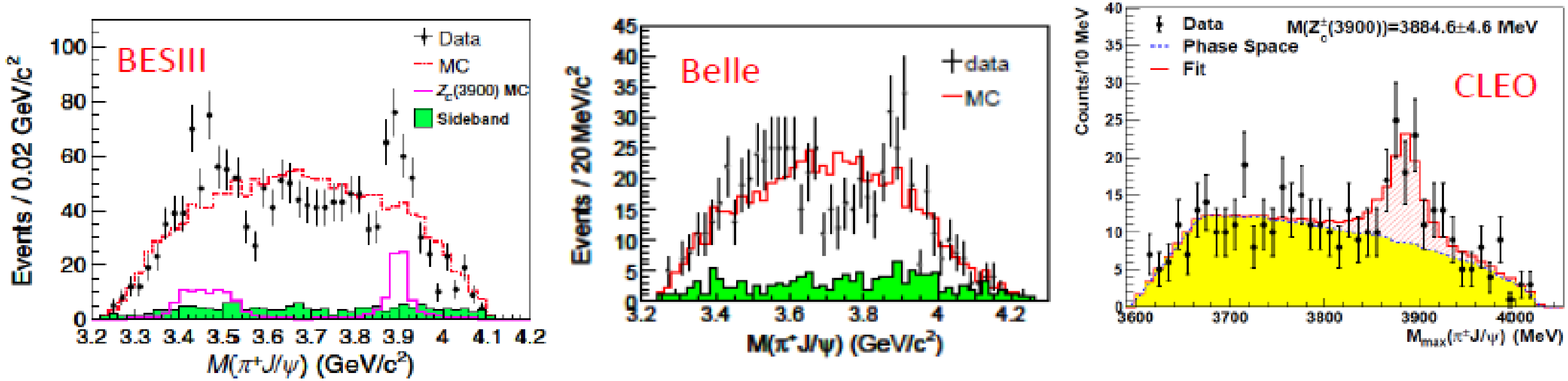


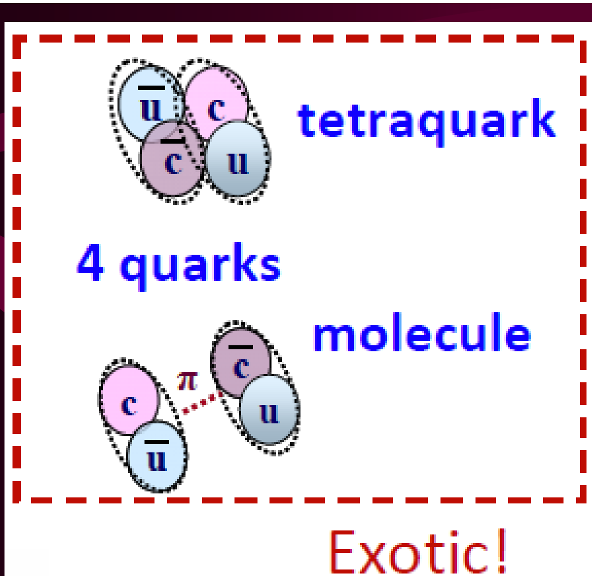

$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

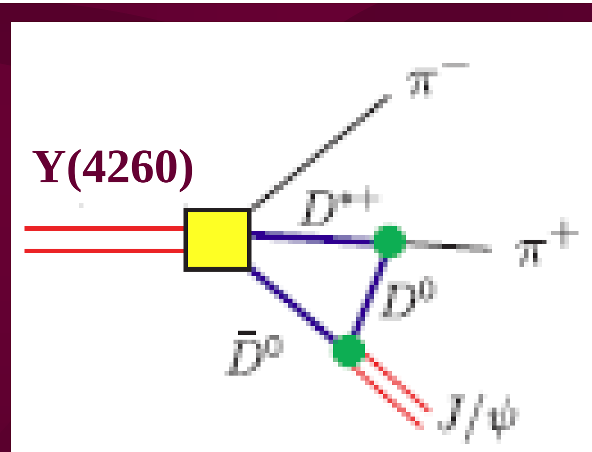
# Production of $Z_c(3900)$ with Y(4260)

PRL 110, 252001 (2013) PHYSICAL REVIEW LETTERS week ending 21 JUNE 2013

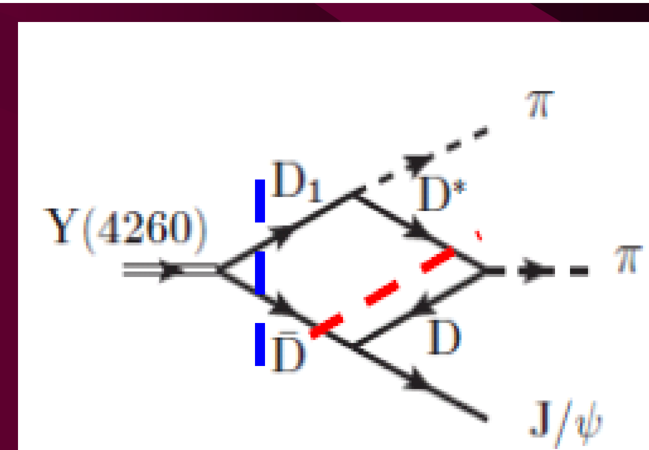
**Observation of a Charged Charmoniumlike Structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV**




D.Y.Chen, X.Liu, PRD84(2011)034032




Q.Wang,C.Hanhart,Q.Zhao PRL111(2013)132003

| 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 |

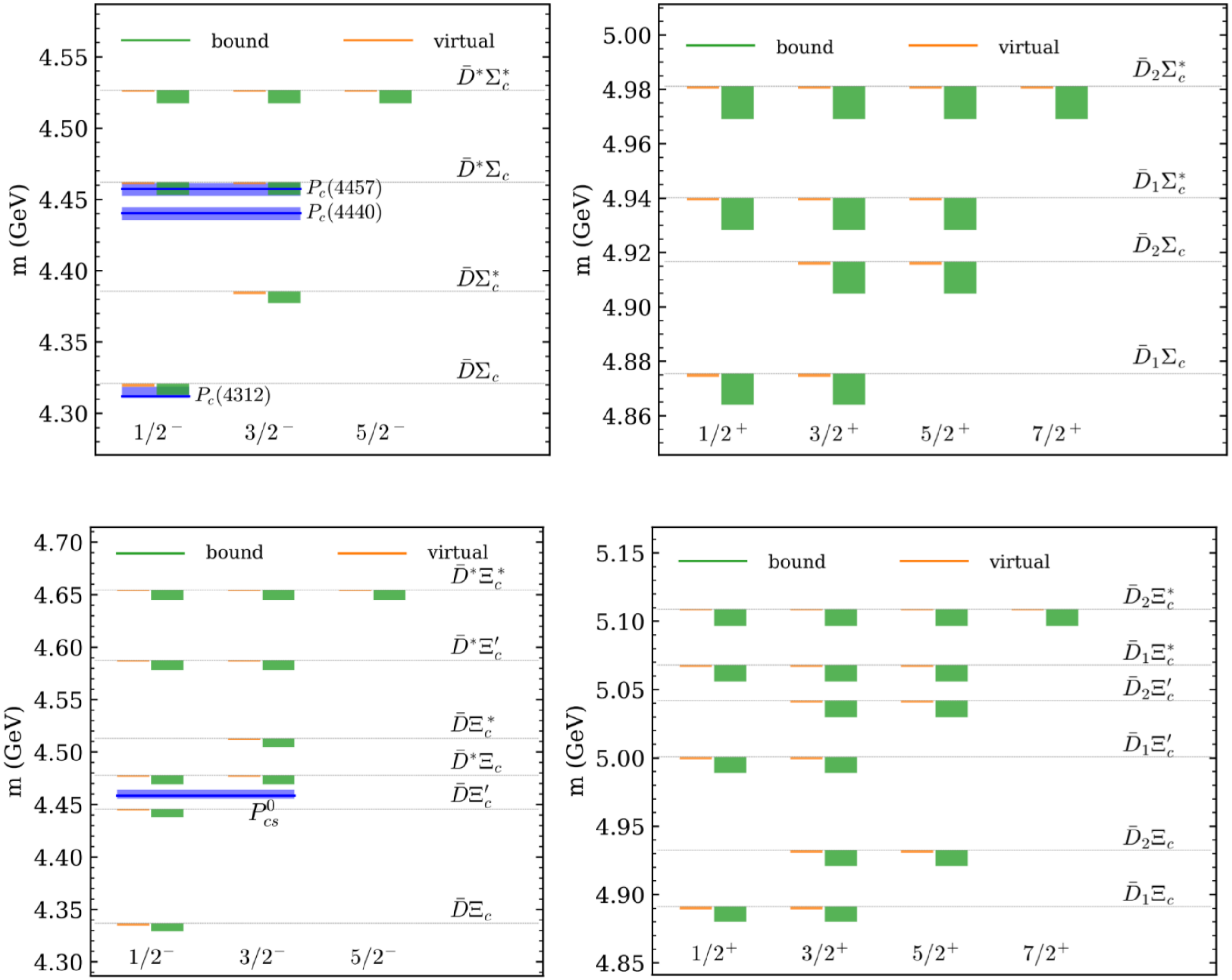
Hadron-hadron resonances ?

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

**H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1**

# A survey of hadronic molecules with hidden charm

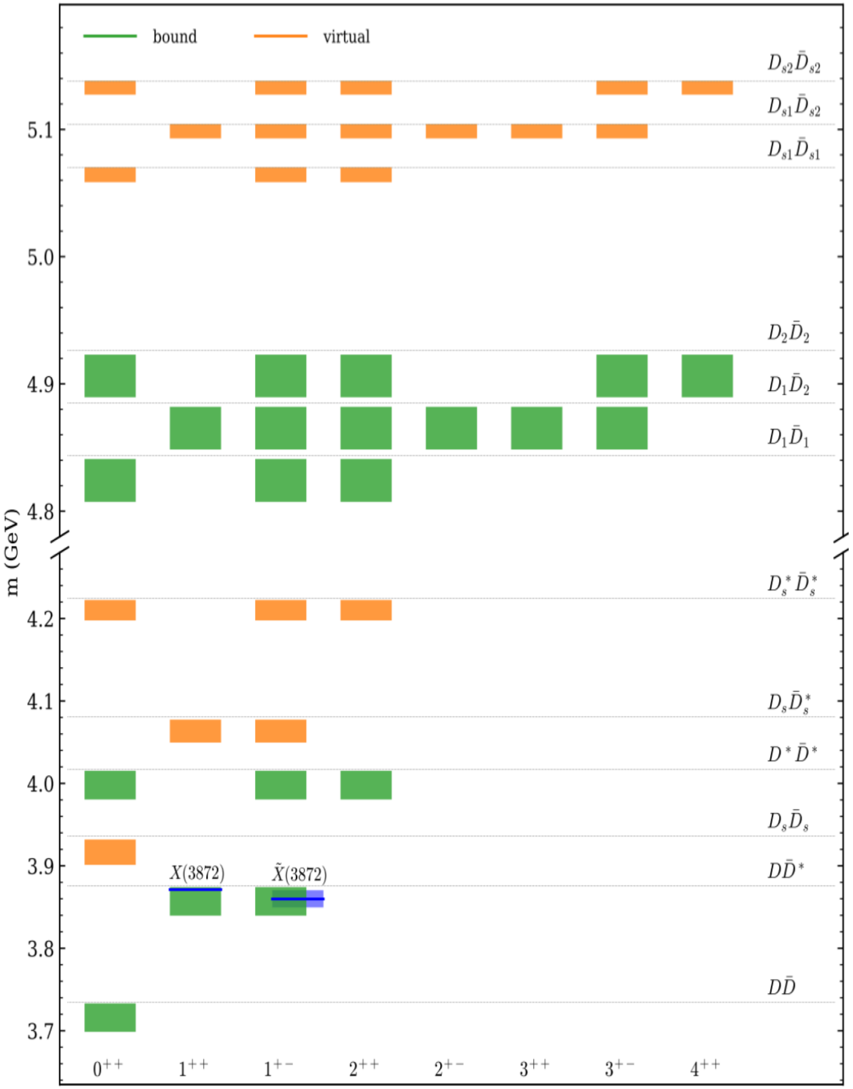
X.K.Dong, F.K.Guo, B.S.Zou Progr. Phys. 41 (2021) 65



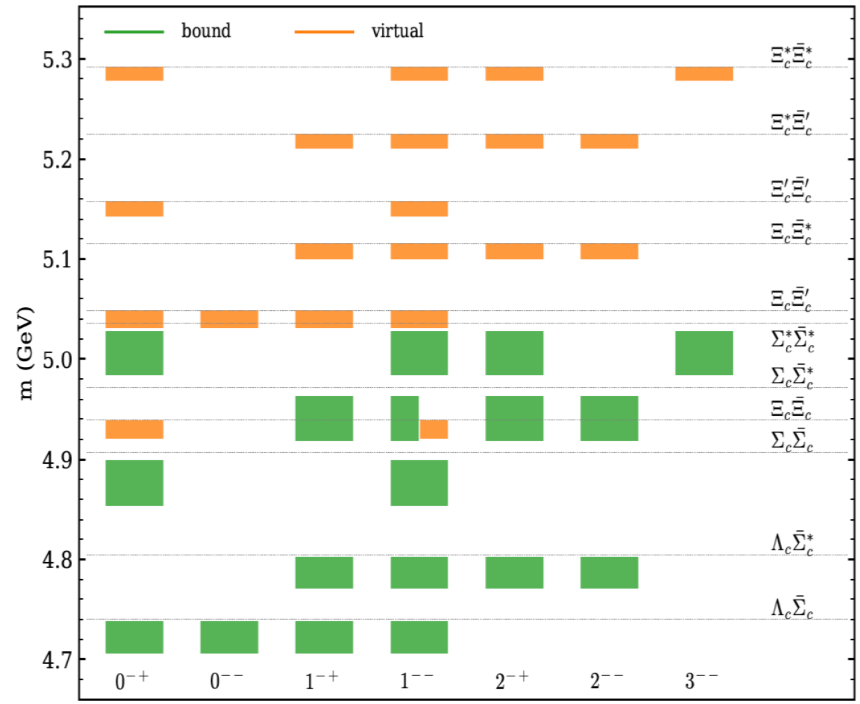

$P_c$

$P_{cs}$

# 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

| $\bar{K}K^*$ | $\bar{D}D^*$ |
| --- | --- |
| **$f_1(1420)$** | **$X(3872)$** |
| **$h_1(1415)$** | **$\tilde{X}(3872)$ ?** |
| **$a_1(1420)$ ?** | **$W_1(3900)$ ??** |
| **$b_1(1420)$ ??** | **$Z_c(3900)$** |

**These $\bar{D}D^*$ dynamically generated states are also supported by the latest LQCD results -- H. Li et al., arXiv:2402.14541[hep-lat]; M. Sadl et al., arXiv:2406.09842 [hep-lat]**

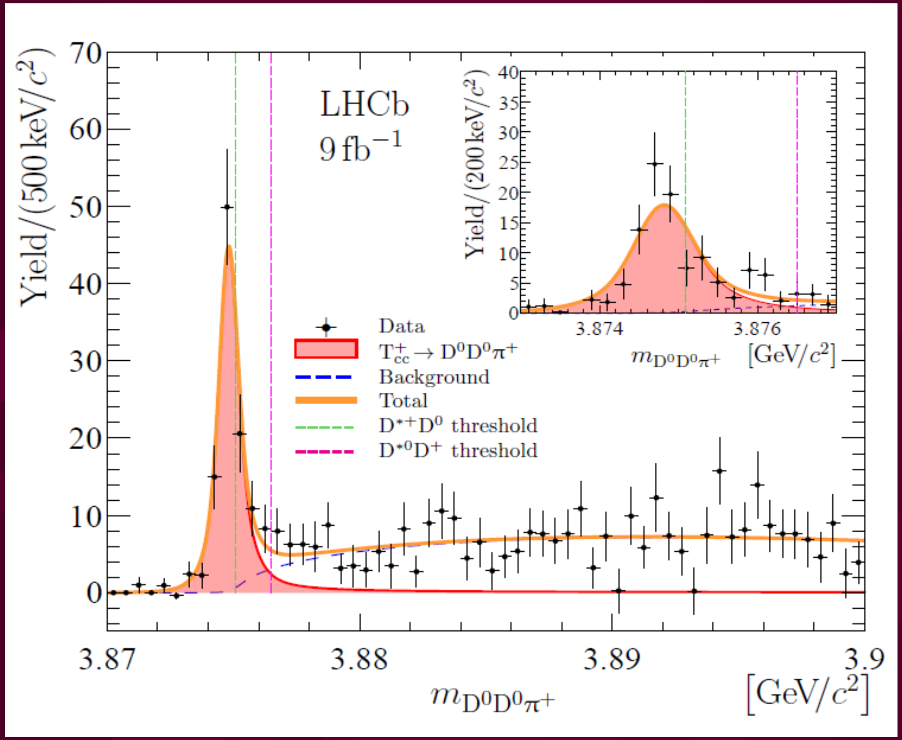
**It is important to look for these $\bar{D}D^*$ states via processes such as**

$$e^+e^- \rightarrow \eta\tilde{X}(3872) \rightarrow \eta\eta J/\psi, \quad e^+e^- \rightarrow \pi W_1(3900) \rightarrow \pi\pi\pi J/\psi$$

Z.-H. Zhang et al., JHEP 08, 130 (2024)

# Observation of $T_{cc}^+$ by LHCb

Nature Phys. 18 (2022) 7, 751




**Consistent with expectation for D*D molecule**

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

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

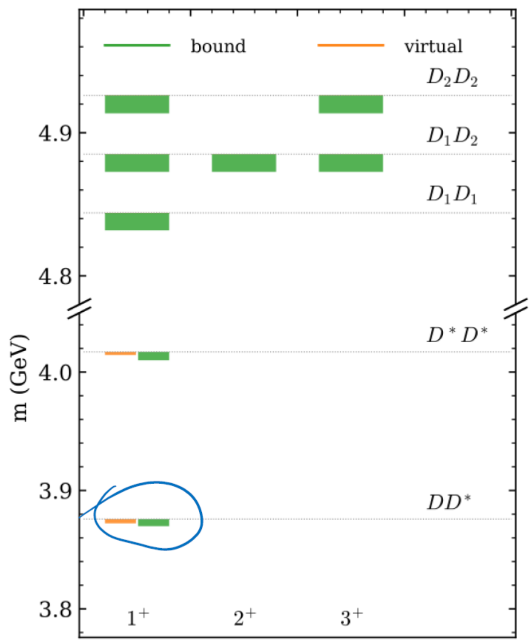
M.Z.Liu, J.J.Xie, L.S.Geng, Phys.Rev.D102(2020)091502

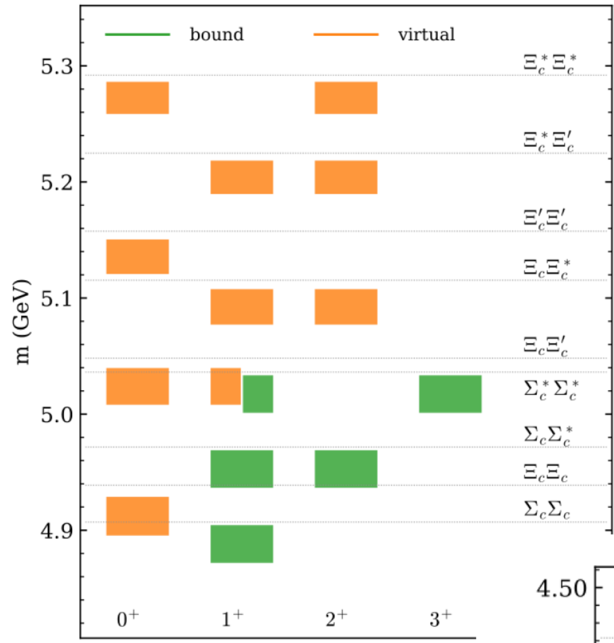
⇓ $V_{\rho,\omega} + V_{\pi} + \dots$

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

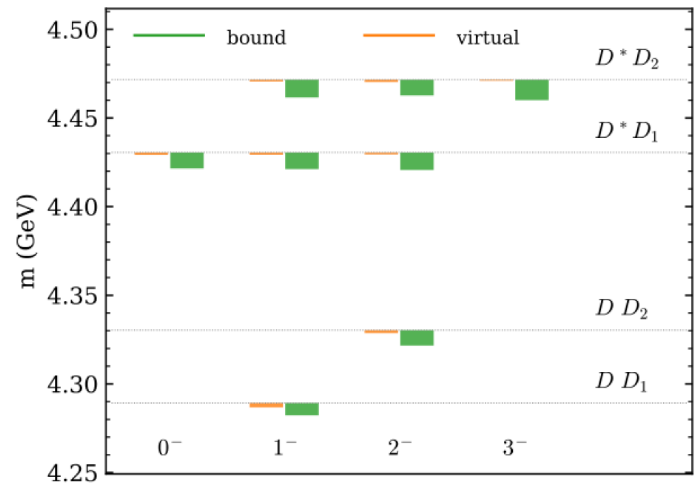
# A survey of heavy-heavy hadronic molecules

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




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

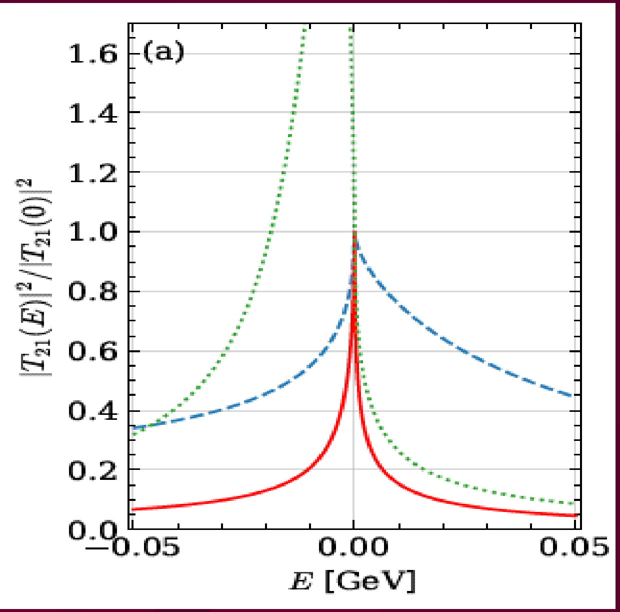



✓ $T_{cc}$ as an isoscalar $DD^*$ bound or virtual state, $D^*D^*$ predicted to be similar, with $P = +$

✓ 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)**

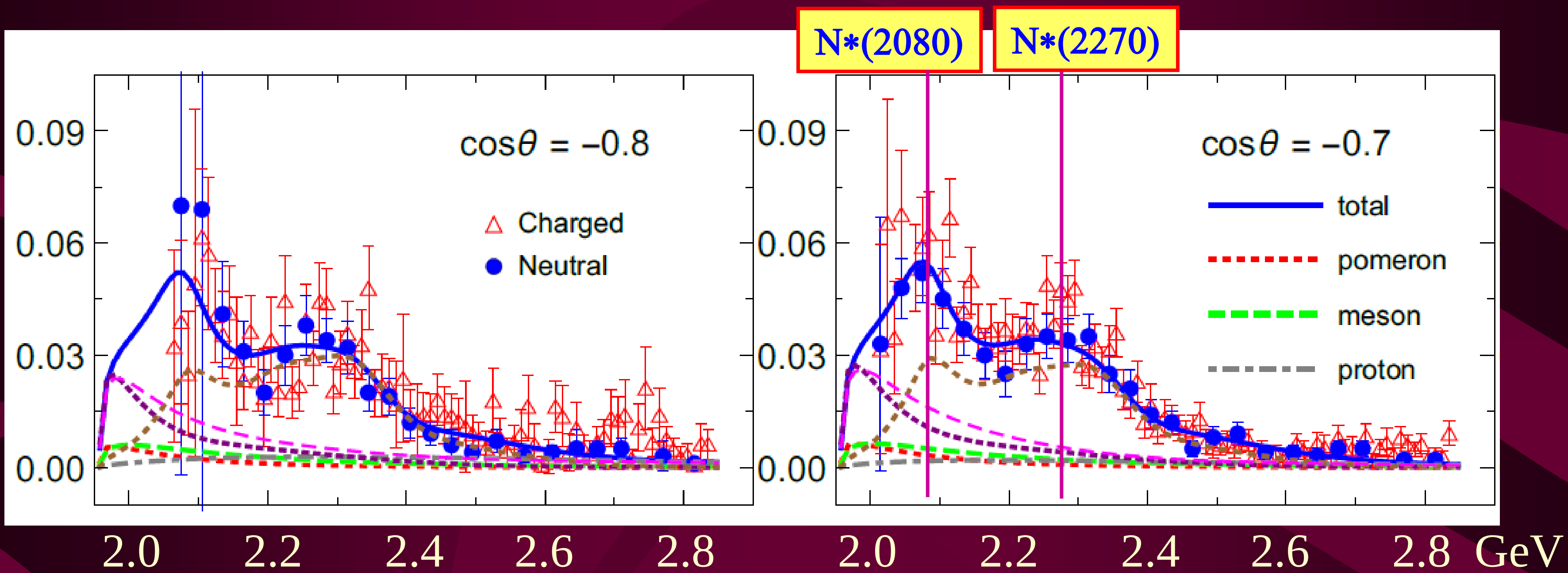
**Observation of $a_0$ (1710) → $K_S^0K^+$ in $D_s^+$→ $K_S^0K^+\pi^0$ decay**

BESIII Collaboration, PRL 129 (2022) 182001

# Strange partners of $P_c$ state from $\gamma p$ reactions

$\gamma p \to \phi p$

CLAS, PRC89(2014)019901



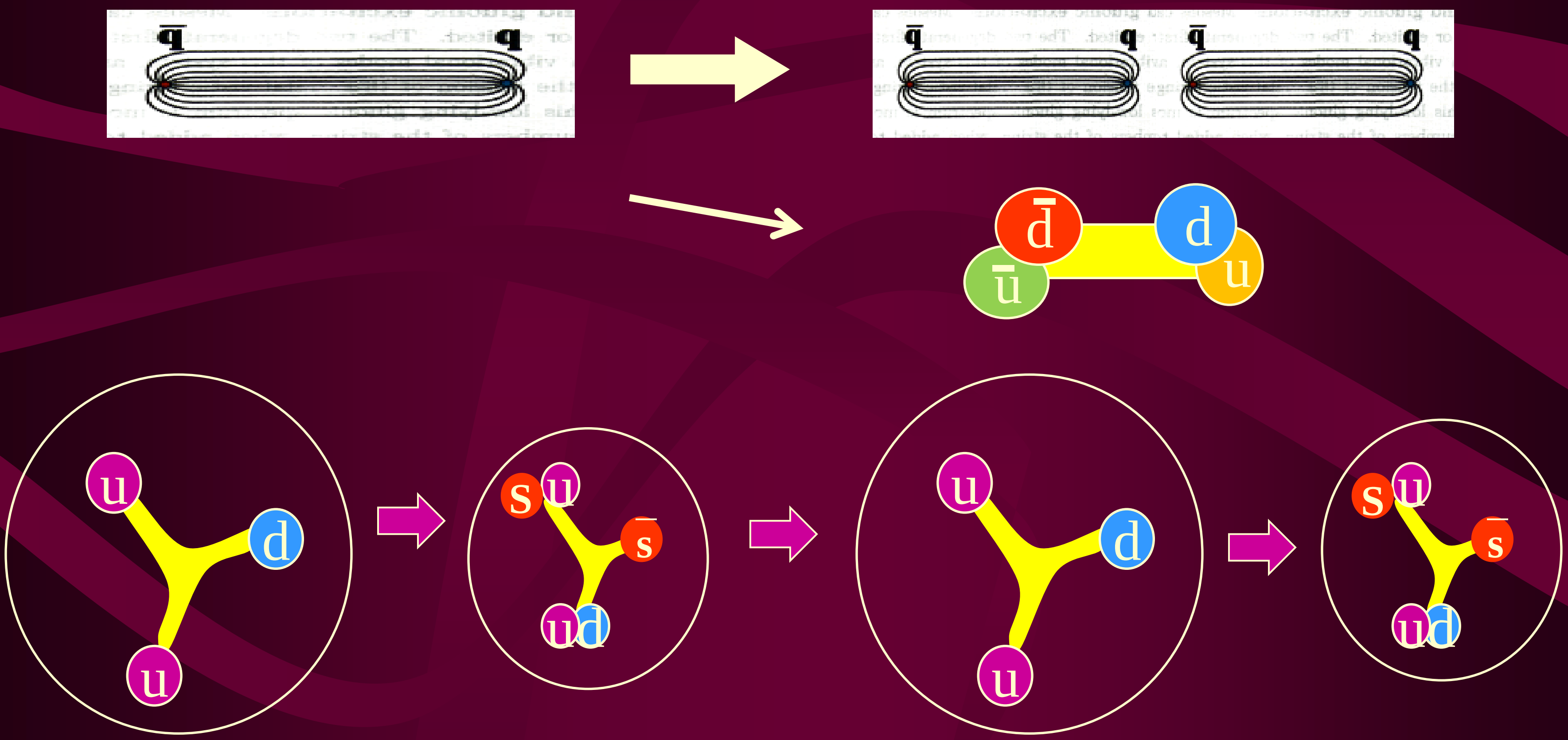

**S.M.Wu, F.Wang, B.S.Zou, PRC108 (2023) 045201**

**K*Σ ~ 2086 K*Σ* ~ 2280**

# 4. Unquenched quark model

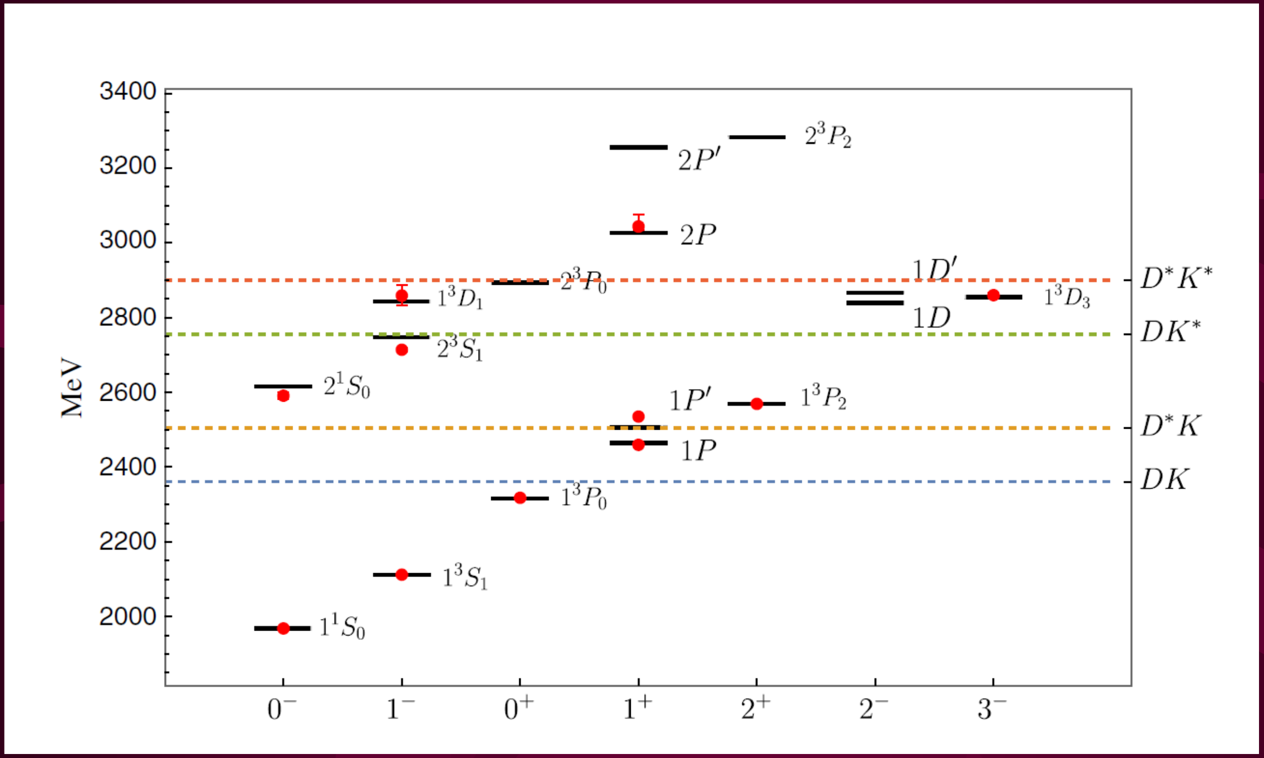
**Unquenching dynamics: gluons → $\bar{q}q$**

**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 $D_s$ 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 $P_{\text{molecule}}$ 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 | $DK$ | $DK^*$ | $D^*K$ | $D^*K^*$ | $D_s\eta$ | $D_s\eta'$ | $D_s\phi$ | $D_s^*\eta$ | $D_s^*\eta'$ | $D_s^*\phi$ | $P_{\text{molecule}}$ | $P_{c\bar{s}}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $1^1S_0$ | $D_s$ | 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 $D_s$ (g.s.) there is 17% tetra-quark components**

# 5. Summary and prospects

- **Productions & decays of J/ψ have played and will continue to play important roles for hadron spectroscopy**
- **All kinds of observed exotic states fit in hadronic molecule picture well, many more to be observed**
- **To understand hadron spectrum, quark models need to be unquenched, with large hadronic molecule components when close to some thresholds**
- **Further experimental confirmation and extension for whole multiquark spectroscopy are necessary**

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**PANDA@FAIR, STCF etc. may play important roles here!**

Thank you for your attention !