

Exotic hadrons with strangeness

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Outline

- Exotic hadrons started from strange hadrons
- Molecules of $K\Sigma$, $K\Sigma^*$, $K^*\Sigma$, $K^*\Sigma^*$, etc.
- Molecules of $\bar{K}K$, \bar{K}^*K , \bar{K}^*K^* , etc.
- Molecules of $\bar{\Lambda}\Lambda$, $\bar{\Lambda}\Sigma$, $\bar{\Sigma}\Sigma$, etc.
- Summary

1. Exotic hadrons started from strange hadrons

- 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 $\Lambda(1405)$
- 1982: $f_0(980)$ & $a_0(980)$ $\bar{K}K$ molecules? Isgur, ...
- 1991: $f_1(1420)$ $\bar{K}K^*$ molecule? Tornqvist, ...
- $f_0(1710)$ \bar{K}^*K^* molecule?
- 1995: $N^*(1535)$ $K\Sigma - K\Lambda$ molecule? Kaiser, ...
- 2003: $D^*_{s0}(2317)$ KD molecules? Barnes, ...

.....

1/2⁻ baryon nonet with strangeness

- Mass pattern : quenched or unquenched ?

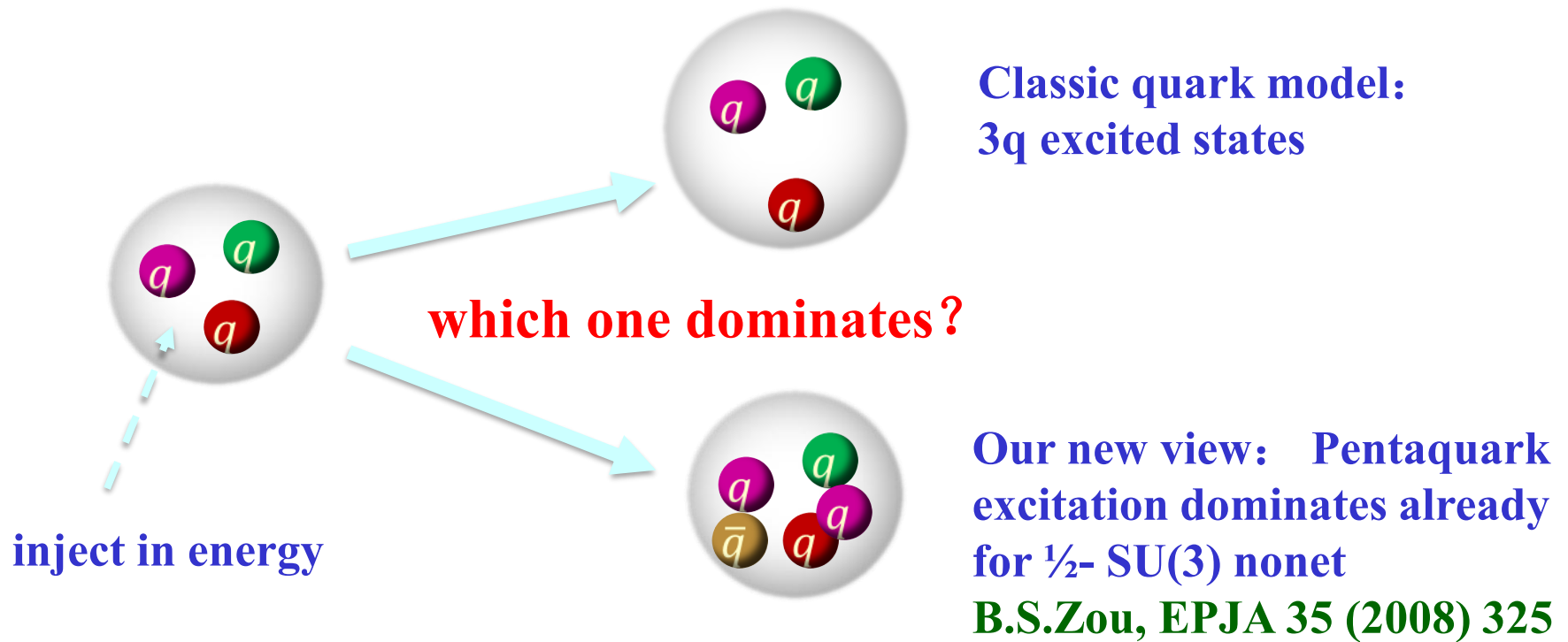
$$\begin{array}{llll}
 \text{uds (L=1) } 1/2^- & \sim & \Lambda^*(1670) & \sim [us][ds] \bar{s} & K\Xi - \eta\Lambda \\
 \text{uss (L=1) } 1/2^- & \sim & \Xi^*(1610) & \sim [us][ds] \bar{d} & \bar{K}\Sigma - \bar{K}\Lambda - \pi\Xi \\
 \text{uud (L=1) } 1/2^- & \sim & N^*(1535) & \sim [ud][us] \bar{s} & K\Sigma - K\Lambda - \eta N \\
 \text{uds (L=1) } 1/2^- & \sim & \Lambda^*(1405) & \sim [ud][su] \bar{u} & \bar{K}N - \pi\Sigma \\
 \text{uus (L=1) } 1/2^- & \sim & \Sigma^*(1390) & \sim [us][ud] \bar{d} & \bar{K}N - \pi\Sigma - \pi\Lambda
 \end{array}$$

Zou et al, NPA835 (2010) 199 ; CLAS, PRC87(2013)035206;
 BESIII, PRL134 (2025) 021901

- 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 $g_{\Lambda^*\Lambda\eta}$, narrower width (35MeV) than Λ*(1405)



Pentaquark crucial for baryon spectroscopy and structure !

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.”

$$\bar{s}s u u d \rightarrow \bar{c} c u u d$$

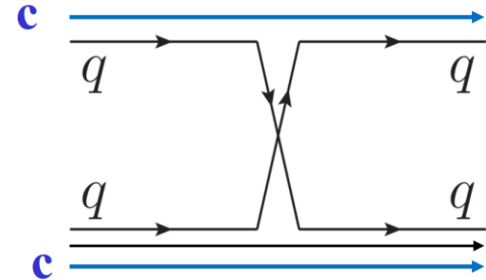
- prediction of three P_c pentaquark states \rightarrow J/ψ -p :

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, PRD 88 (2013) 056012

J. Hofmann, M. Lutz, NPA763(2005)90 \rightarrow $\bar{D}\Sigma_c$ at 3.52 GeV & DN at $\Lambda_c(2595)$

LHCb confirms our prediction of 3 narrow P_c states

PRL 115, 072001 (2015)

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

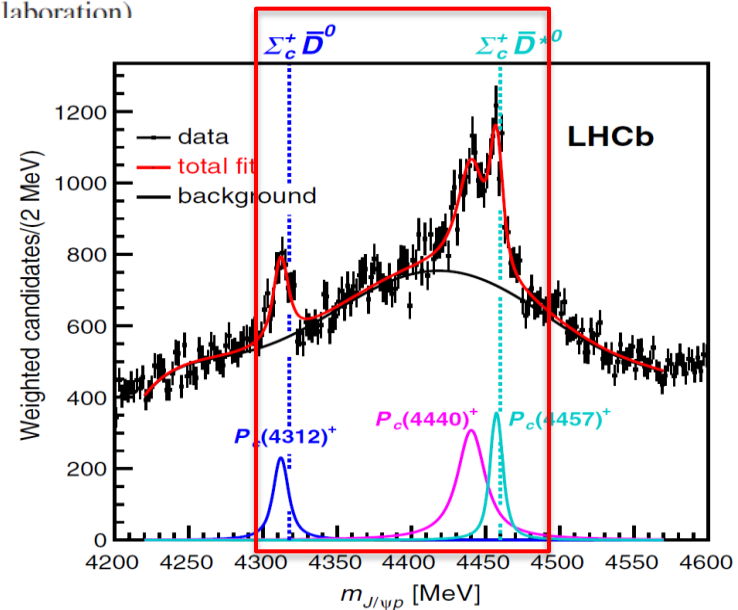
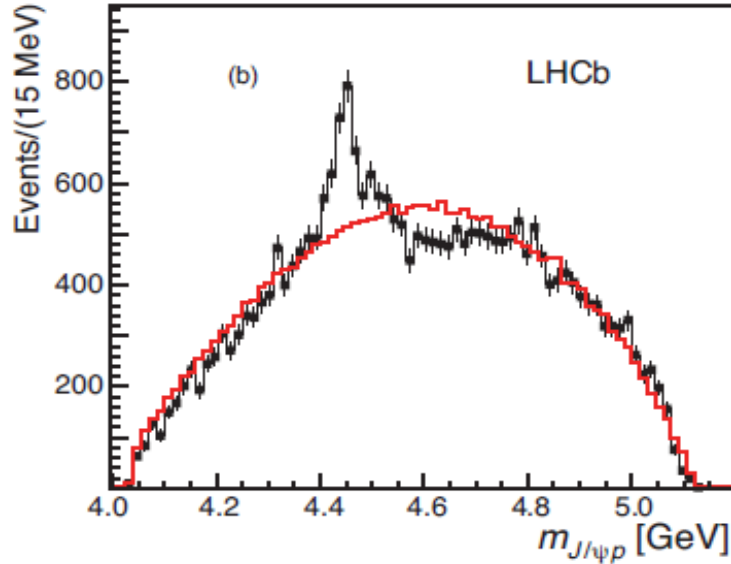
week ending
14 AUGUST 2015



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

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

PRL 122 (2019) 222001



A milestone for pentaquark search

Multiquark states – crucial for hadron structure !

X(3872)	→ top cited paper for Belle (2003)	2927 cites
Z_c(3900)	→ top cited paper for BES (2013)	1272 cites
P_c states	→ top cited paper for LHCb (2015)	2115 cites

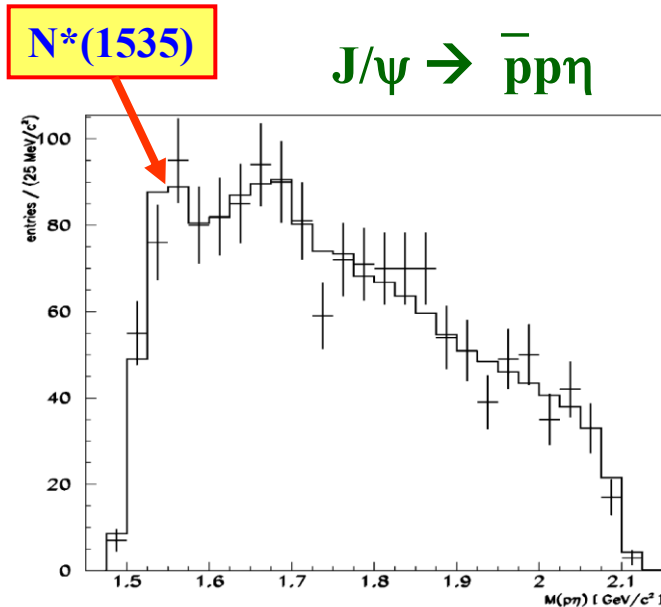
**H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1:
“The hidden-charm pentaquark and tetraquark states” 1383 cites**

**F.K.Guo, C.Hanhart, U.Meissner, Q.Wang, Q.Zhao, B.S.Zou,
Rev.Mod.Phys. 90 (2018)015004: “Hadronic molecules” 1553 cites**

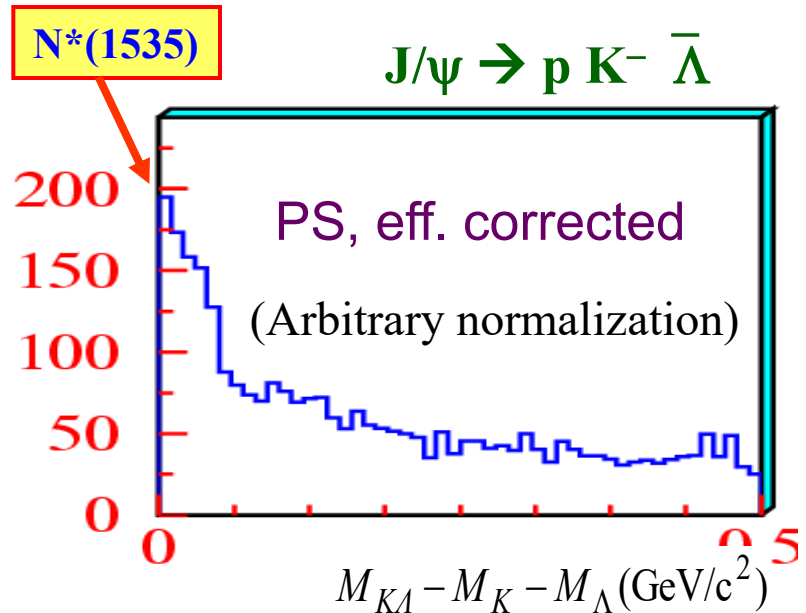
How about strange partners of P_c and Z_c states ?

2. Molecules of $K\Sigma$, $K\Sigma^*$, $K^*\Sigma$, $K^*\Sigma^*$, etc.

$K\Sigma$ molecule - $N^*(1535)$ in J/ψ decays



BES, PLB510 (2001) 75



BESII, IJMPA20 (2005) 1985

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

$K\Sigma^*$, $K^*\Sigma$, $K^*\Sigma^*$ molecules from charmonium decays at BES

$N^*(1875)$

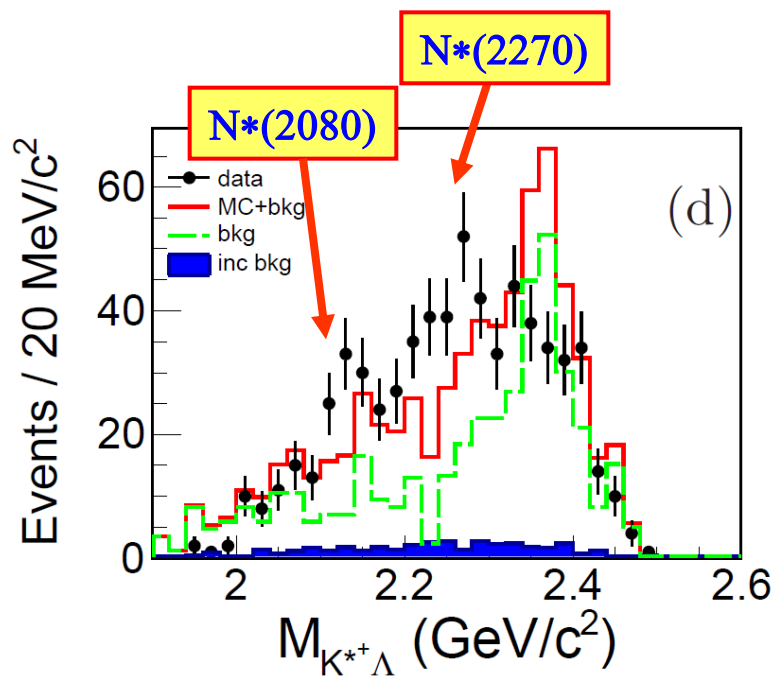
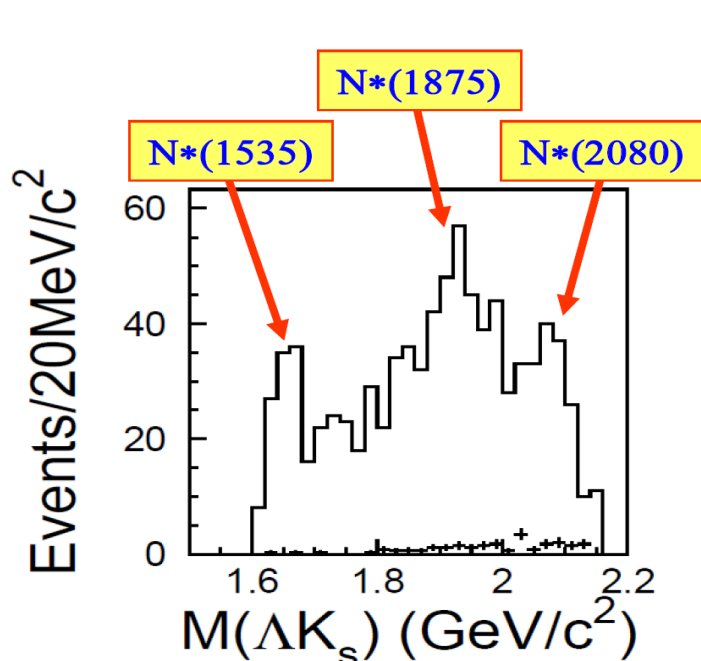
$N^*(2080)$

$N^*(2270)$

$K\Sigma^* \sim 1880$

$K^*\Sigma \sim 2086$

$K^*\Sigma^* \sim 2280$



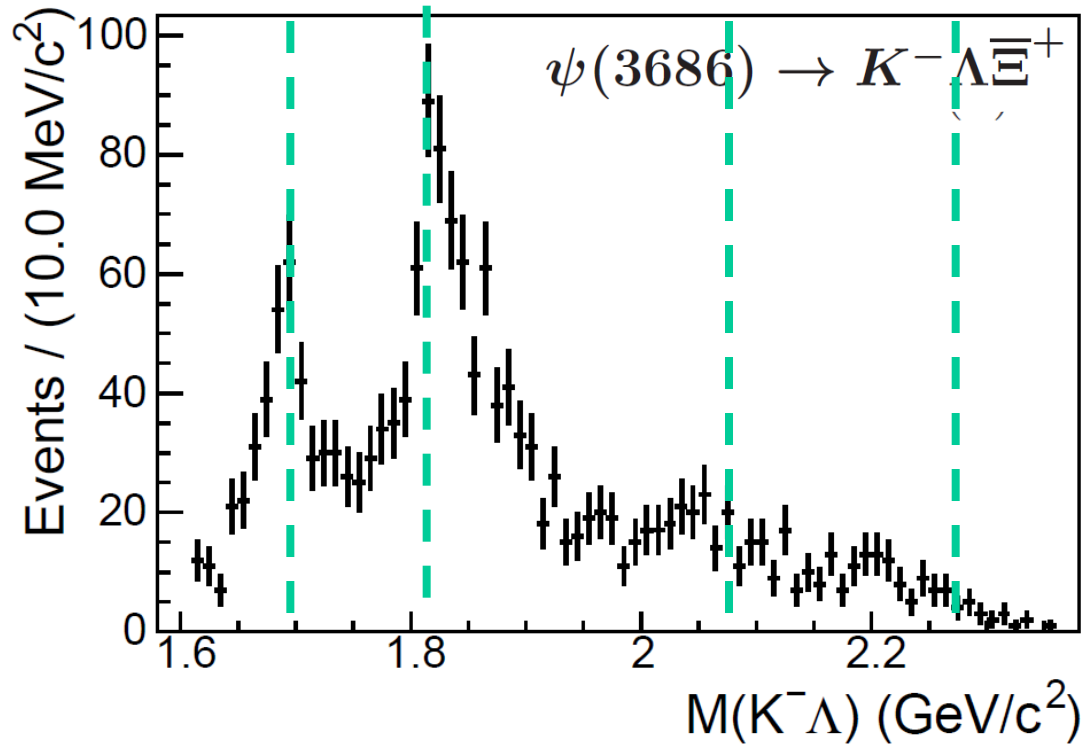
$$J/\psi \rightarrow nK_S^0\bar{\Lambda}$$

BESII, PLB659 (2008) 789

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

BESIII, PRD100(2019)052010

$\bar{K}\Sigma \sim \Xi(1680)$, $\bar{K}\Sigma^* \sim \Xi(1860)$, $\bar{K}^*\Sigma \sim \Xi(2080)$, $\bar{K}^*\Sigma^* \sim \Xi(2270)$



$\bar{K}\Sigma \sim \Xi(1680)$, $\bar{K}\Sigma^* \sim \Xi(1820)$, $\bar{K}^*\Sigma \sim \Xi(2080)$, $\bar{K}^*\Sigma^* \sim \Xi(2270)$

$1/2^-$

$3/2^-$

$K\Sigma^*$, $K^*\Sigma$, $K^*\Sigma^*$ molecules from γp reactions

J.C.Suo, Di Ben, B.S.Zou, PRC112(2025)065208

$K\Sigma^* \sim 1880$

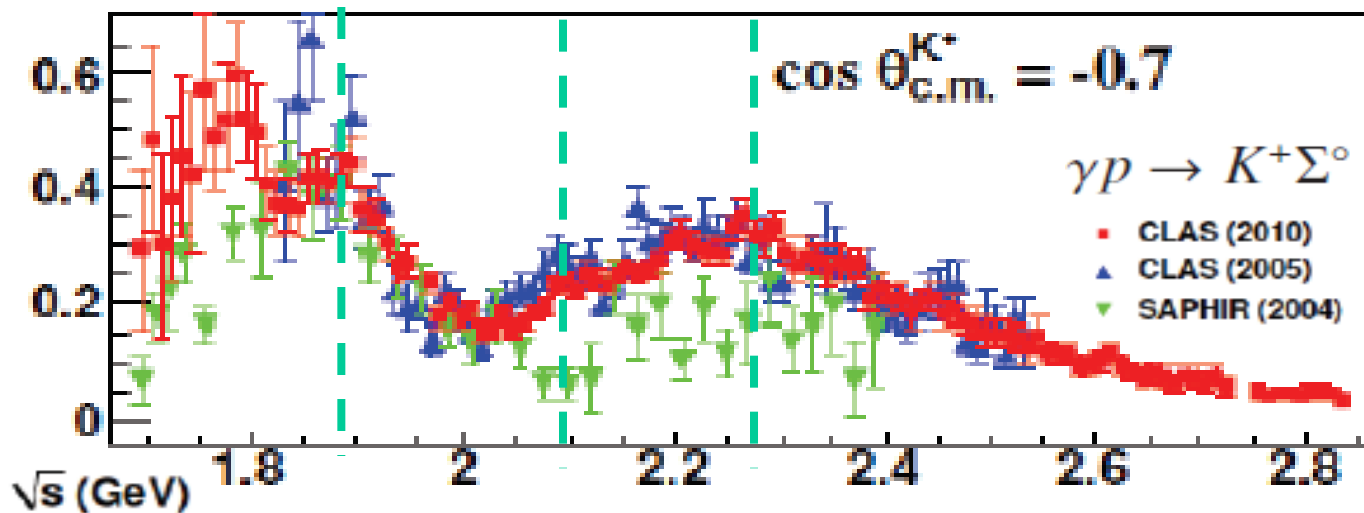
$N^*(1875)$

$K^*\Sigma \sim 2086$

$N^*(2080)$

$K^*\Sigma^* \sim 2280$

$N^*(2270)$



$K\Xi \sim 1810$

$\Lambda(1/2^-)$

$K\Xi^* \sim 2027$

$\Lambda(3/2^-)$

$K^*\Xi \sim 2210$

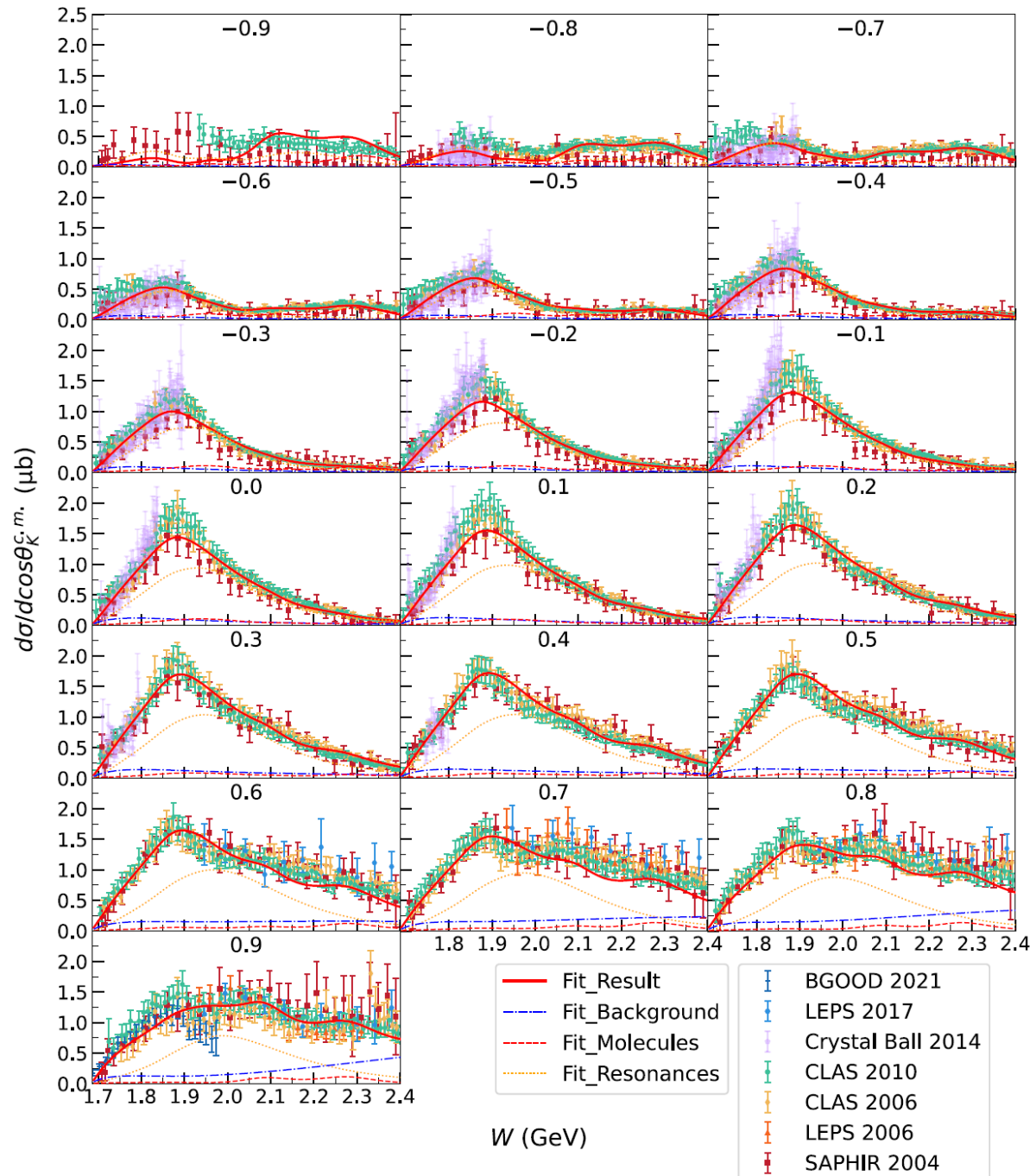
$\Lambda(1/2^-, 3/2^-)$

$K^*\Xi^* \sim 2427$

$\Lambda(1/2^-, 3/2^-, 5/2^-)$

$K^*N \sim 1833$: $\Lambda(1800)1/2^-, \Lambda(3/2^-)$

$\gamma p \rightarrow K^+ \Sigma^0$



without D_{13}

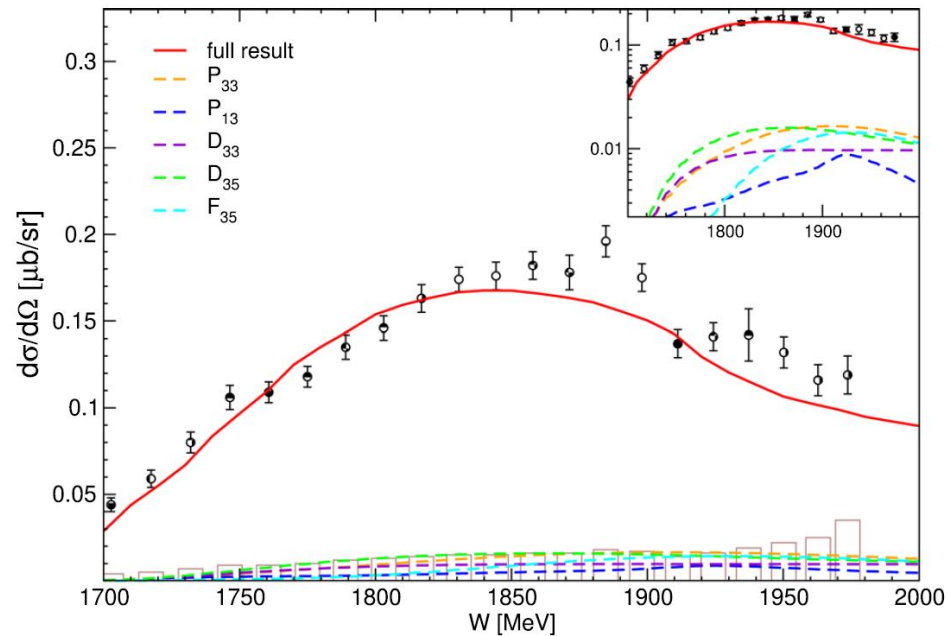
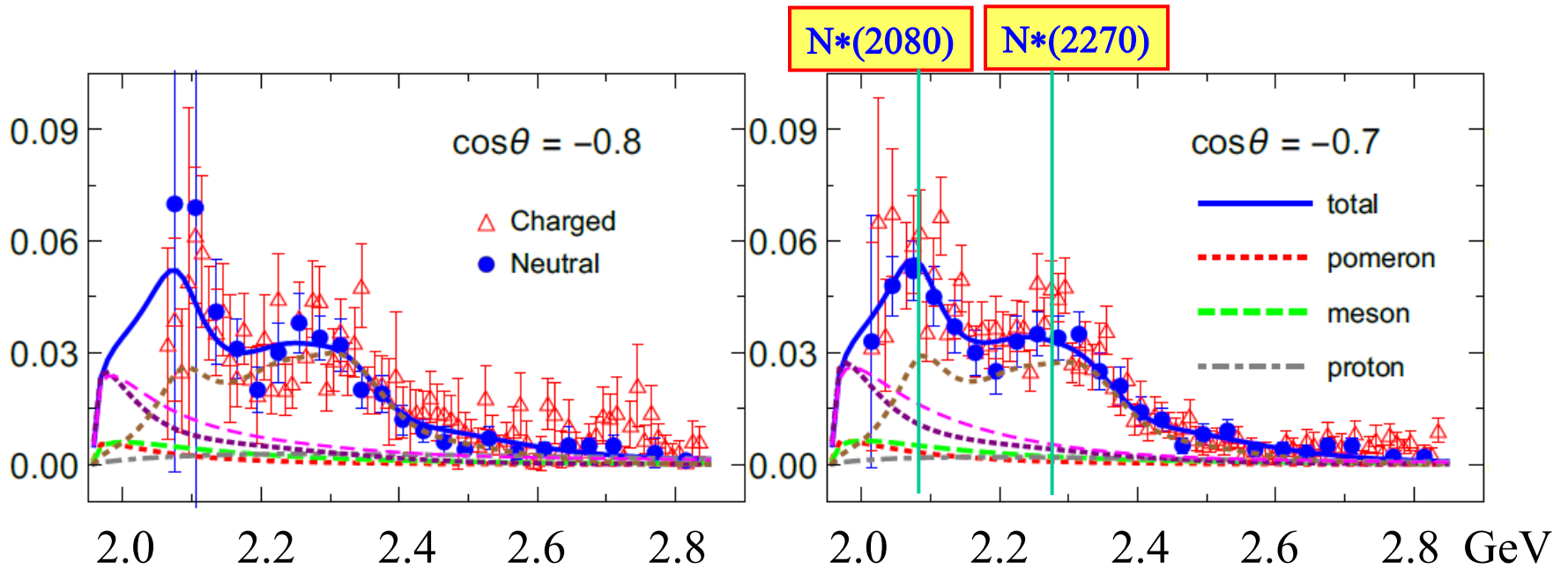


Fig. 12 Forward differential cross section ($\cos\theta > 0.9$) reaction $\gamma p \rightarrow K^+\Sigma^0$. Only dominant partial waves are shown. The box in the upper right corner shows the same picture on a logarithmic scale. Data from Ref. [82] (not included in the fit). We fit the data shown in Fig. 2 from the same reference. Systematic uncertainties of the data are shown as brown bars

$\gamma p \rightarrow \phi p$

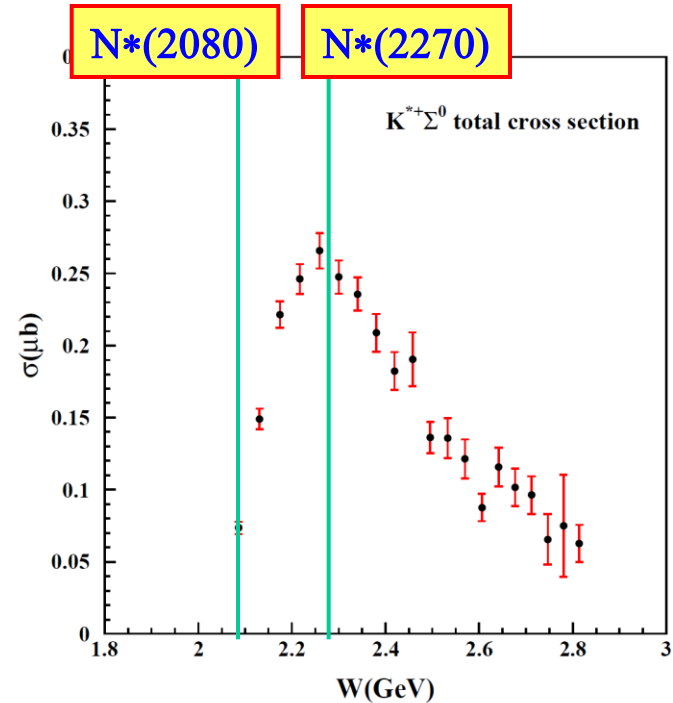
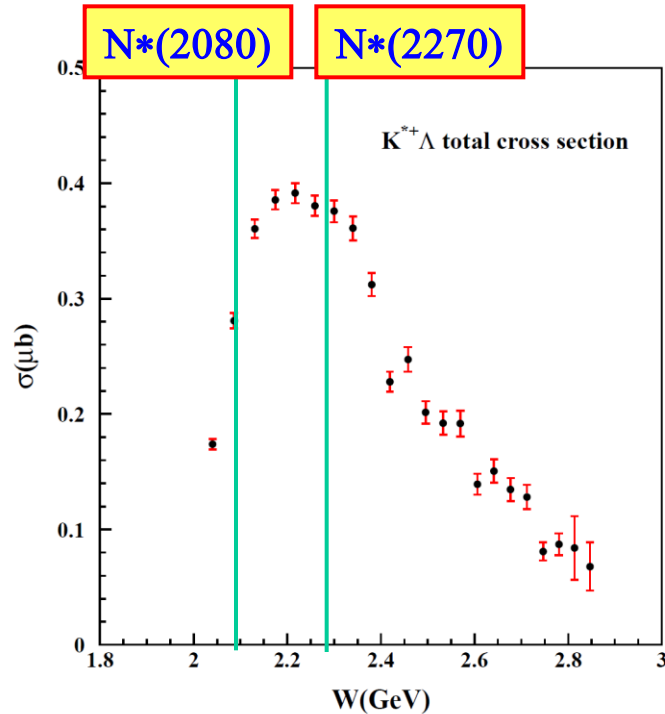
CLAS, PRC89(2014)019901



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

Total cross sections of the reaction $\gamma p \rightarrow K^{*+} \Lambda$ (left) and $\gamma p \rightarrow K^{*+} \Sigma^0$ (right)

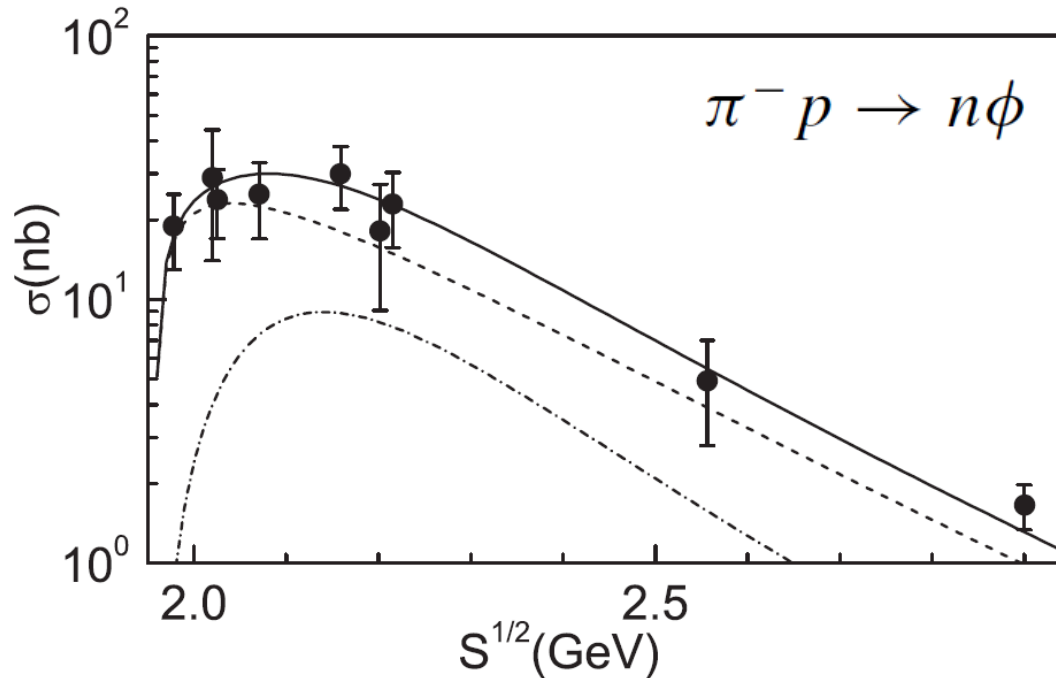
CLAS, PRC 87(2013)065204



Di Ben, A.C.Wang, F.Huang, B.S.Zou, PRC 108 (2023) 065201

J.Shi, B.S.Zou, PRD 111 (2025) 114032

W.Y.Tian, N.C.Wei, F.Huang, B.S.Zou, PRC 112 (2025) 055203

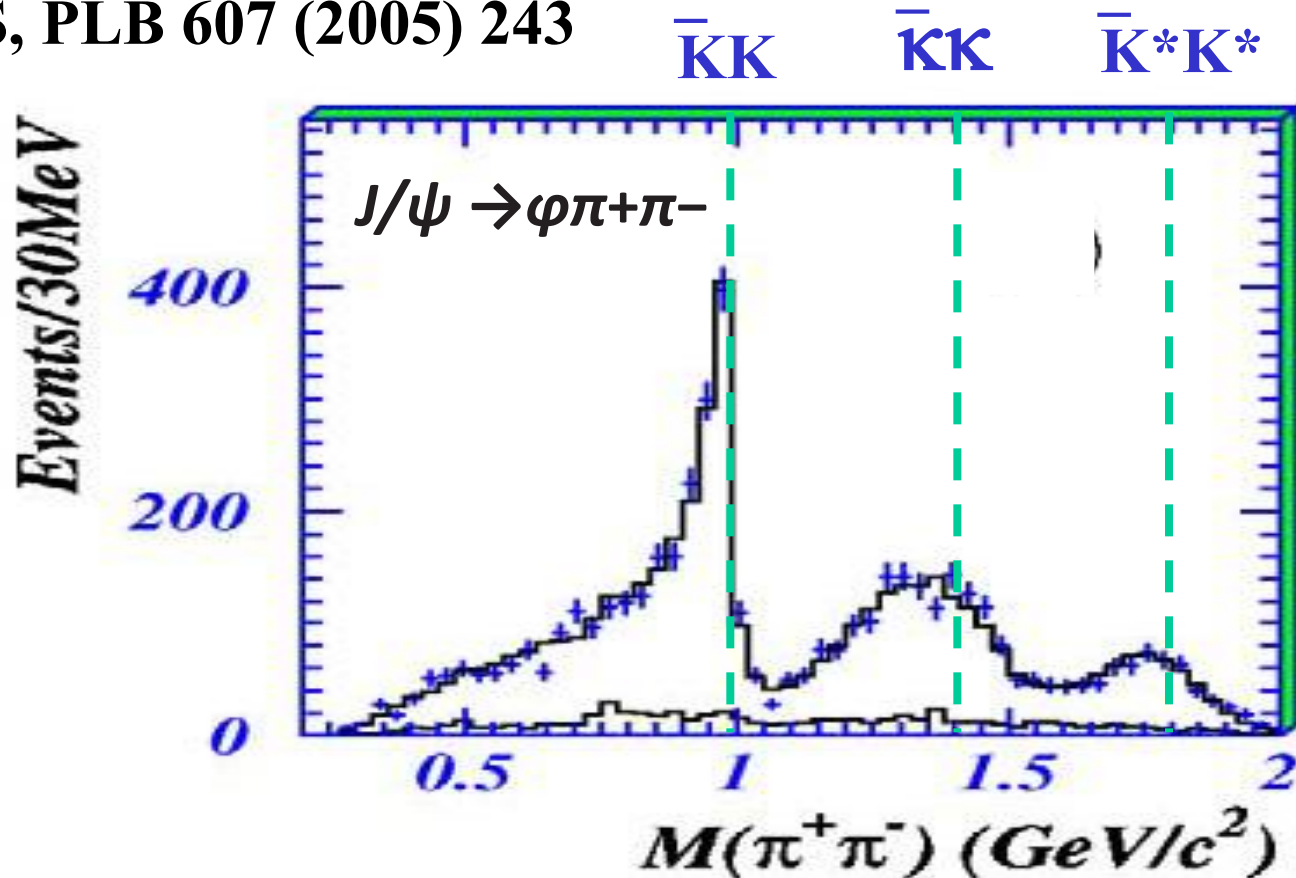


$N^*(1535) + N^*(1900) \frac{1}{2}+$ or $N^*(1875) + N^*(2080) + N^*(2270)$?

More data with angular distribution and polarization information are needed !

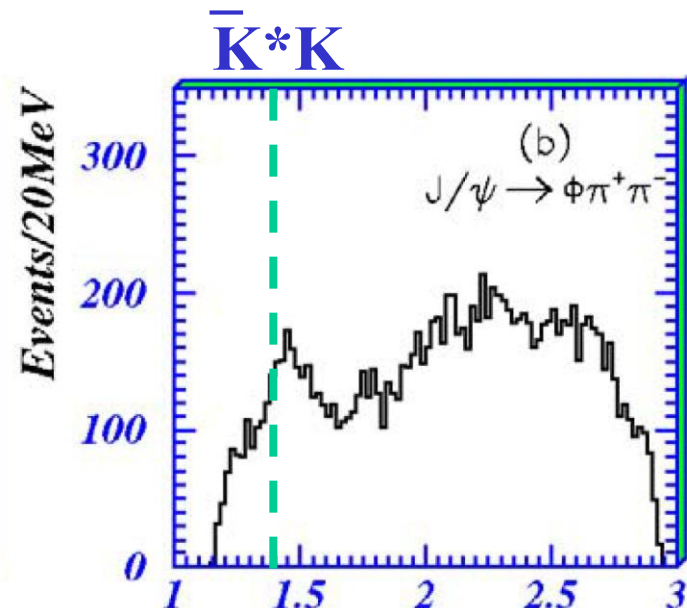
3. Molecules of $\bar{K}K$, \bar{K}^*K , \bar{K}^*K^* , etc.

BES, PLB 607 (2005) 243



Y.Cheng, B.S.Zou, ArXiv: 2602.21853 [hep-ph] : $J/\psi \rightarrow \phi 4\pi$

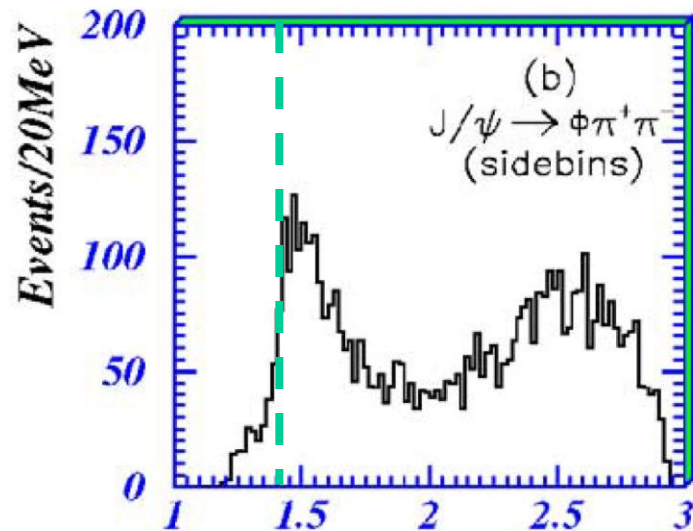
Strange partner of $Z_c(3900)$: $b_1(1430)$?



Other possible \bar{K}^*K states: $f_1/a_1(1420)$,

$h_1(1380)$ - BESIII, PRD 98 (2018) 072005

$a_1(1420)$ - Compass, PRL 115 (2015) 082001



Other hadronic molecules of 2 strange mesons

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

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

L.S.Geng, E.Oset, PRD 79 (2009) 074009; Z.L.Wang, B.S.Zou, EPJC 82 (2022) 509

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

$\bar{K}^*K^*(I=0,1)$ molecules $\rightarrow f_0(1750) / a_0(1750)$

Observation of $a_0(1817) \rightarrow K_s^0 K^+$ in $D_s^+ \rightarrow K_s^0 K^+ \pi^0$ decay

BESIII Collaboration, PRL 129 (2022) 182001

4. Molecules of $\bar{\Lambda}\Lambda$, $\bar{\Lambda}\Sigma$, $\bar{\Sigma}\Sigma$, etc.

L.Zhao, N.Li, S.L.Zhu, B.S.Zou, PRD 87 (2013) 054034 :

$Y(2175) \text{ --- } \bar{\Lambda}\Lambda (^3S_1)$; $\eta(2225) \text{ --- } \bar{\Lambda}\Lambda (^1S_0)$

XK.Dong, F.K.Guo, B.S.Zou, CTP 73 (2021) 125201; *Progr.Phys.* 41 (2021) 65 :

$\bar{\Lambda}\Sigma$, $\bar{\Sigma}\Sigma$ (I=0,1) molecules

Evidence for $I=0$ 0^{-+} molecules of $\bar{\Lambda}\Lambda$ / $\bar{\Sigma}\Sigma$

$$J/\psi \rightarrow \gamma \bar{\Lambda}\Lambda$$

J.P.Dai, Ph.D thesis
(2012)

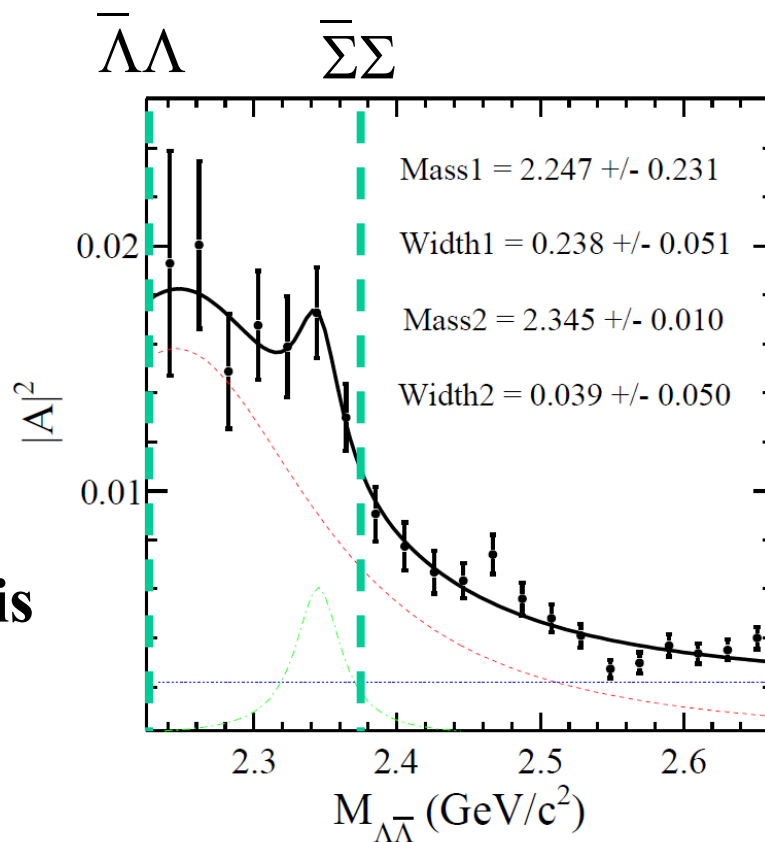
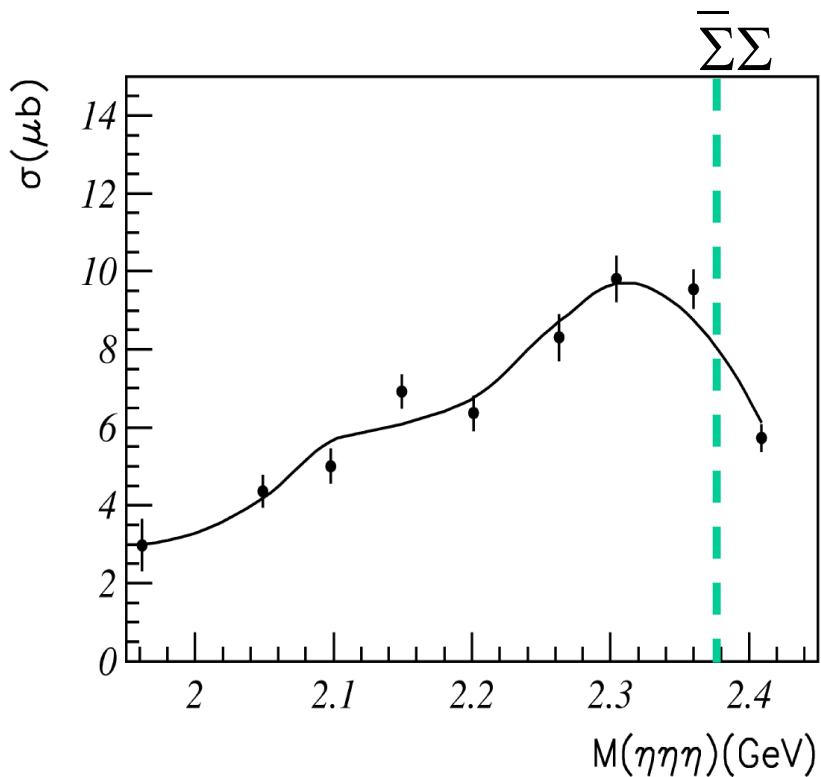


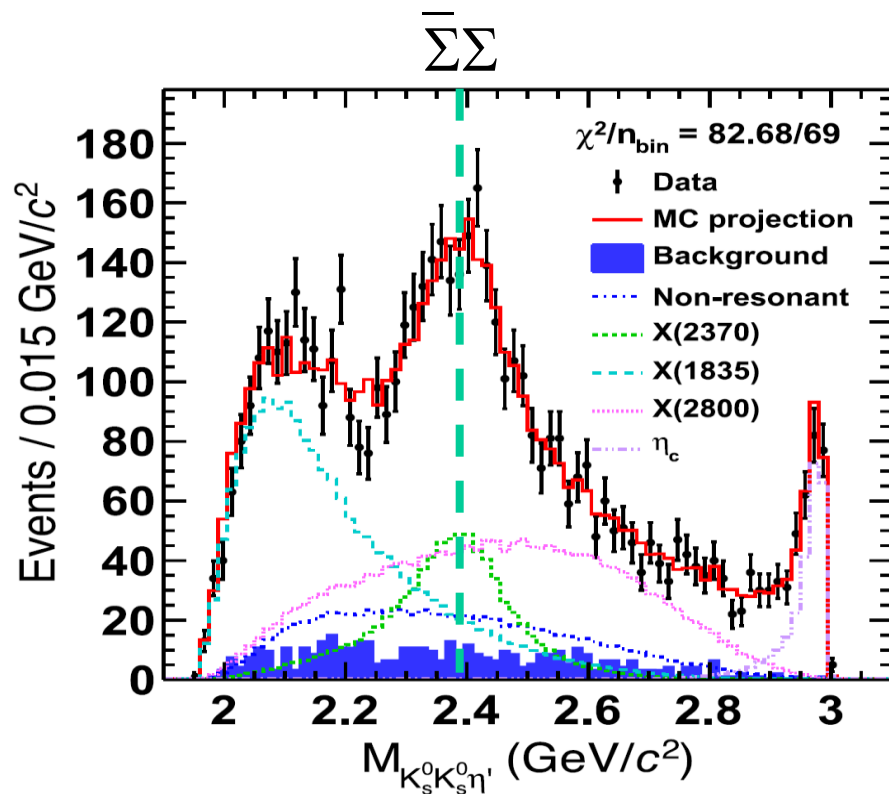
图 4.35: $\Lambda\bar{\Lambda}$ 阈值附近结构的初步研究。其中，虚线（红色）和虚-点线（绿色）曲线代表两个 0^{-+} 共振态粒子的贡献；点线（蓝色）曲线代表常数本底贡献。

$\bar{p}p \rightarrow \eta\eta\eta$



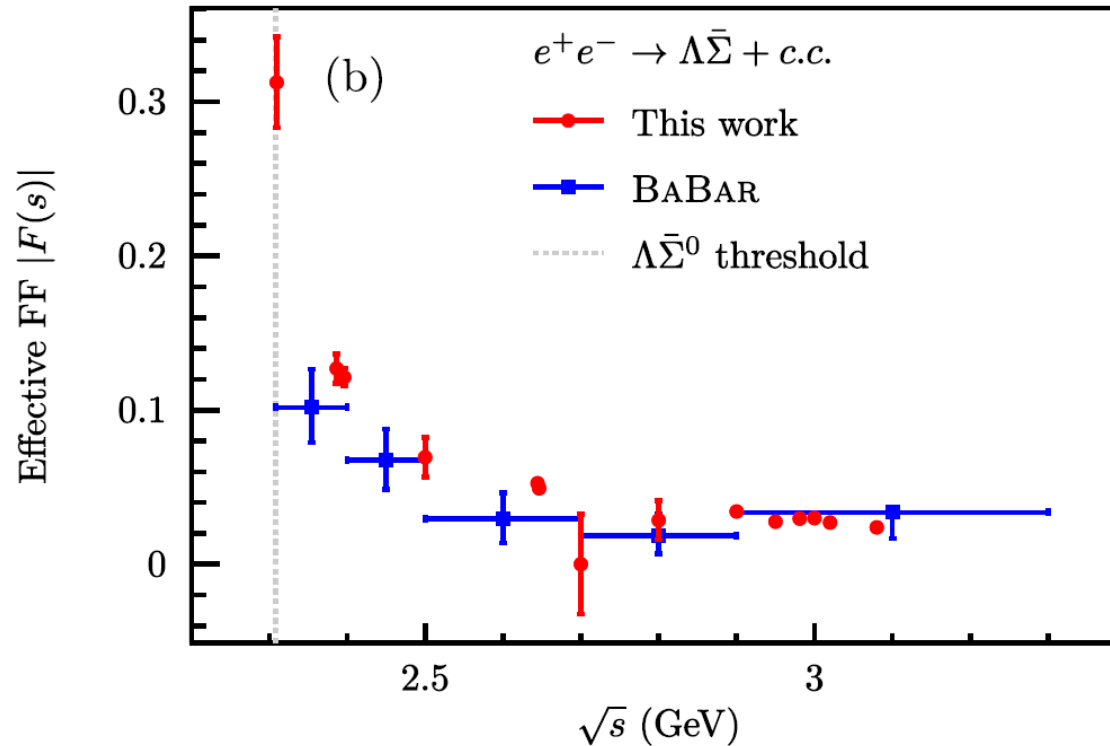
A.V. Anisovich et al., PLB 496 (2000) 145

$J/\psi \rightarrow \gamma K_S^0 K_S^0 \eta'$



BESIII, PRL132(2024)181901

Clear evidence for I=1 $\bar{\Lambda}\Sigma / \bar{\Sigma}\Sigma$ molecule



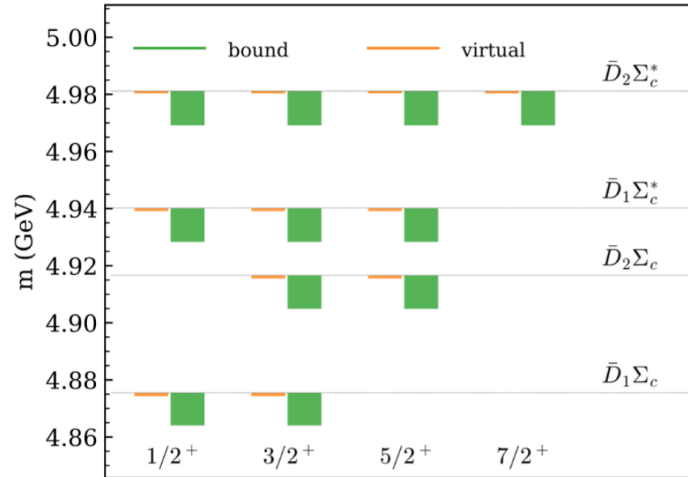
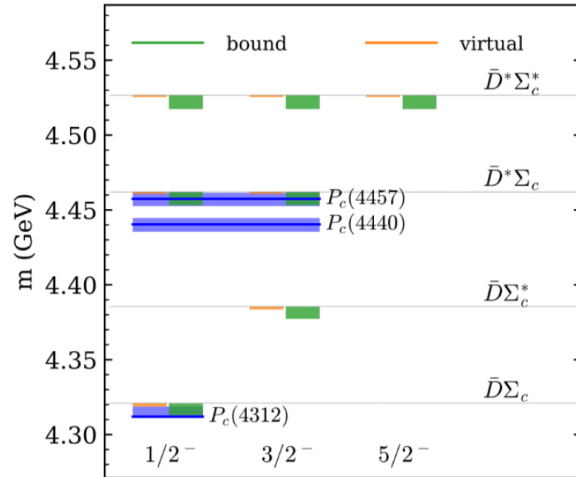
BESIII, PRD 109 (2024) 012002

5. Summary & prospects

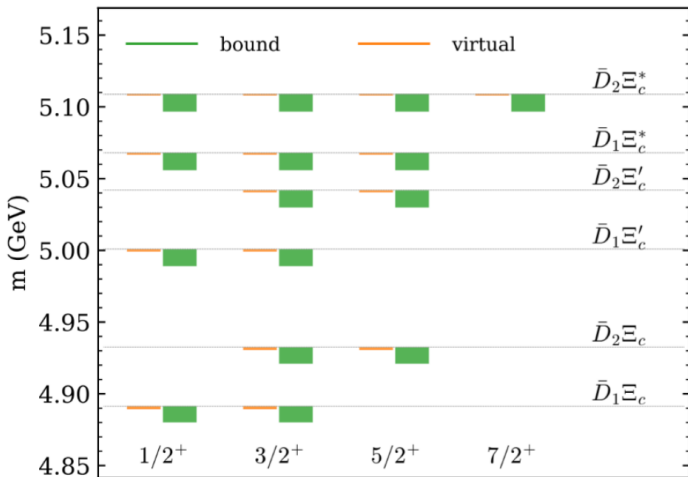
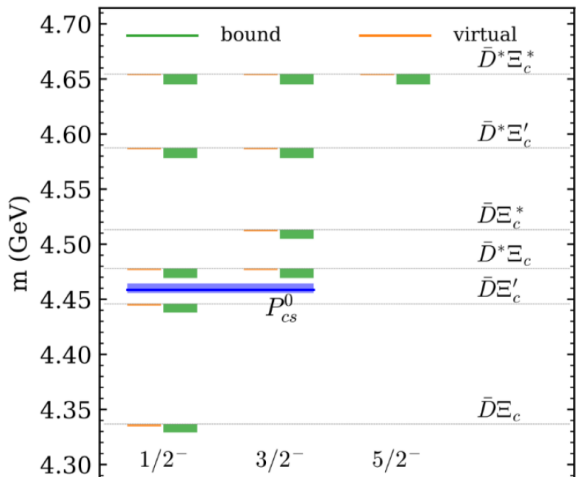
- hundreds strange partners of P_c , Z_c ... states are expected to exist, with strong evidence for some of them in $\bar{c}c$ decays, γp and pp
- more experiments with higher statistics are needed **$ep/\gamma p@JLab$, $\pi/K@JPARC$, BelleII, BESIII, Eic/EicC, PANDA@FAIR, STCF, $\bar{\nu}p$ may play important roles here!**
- To understand hadron spectrum, quark models need to be unquenched, with large hadronic molecule components when close to some thresholds

A survey of hadronic molecules with hidden charm

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

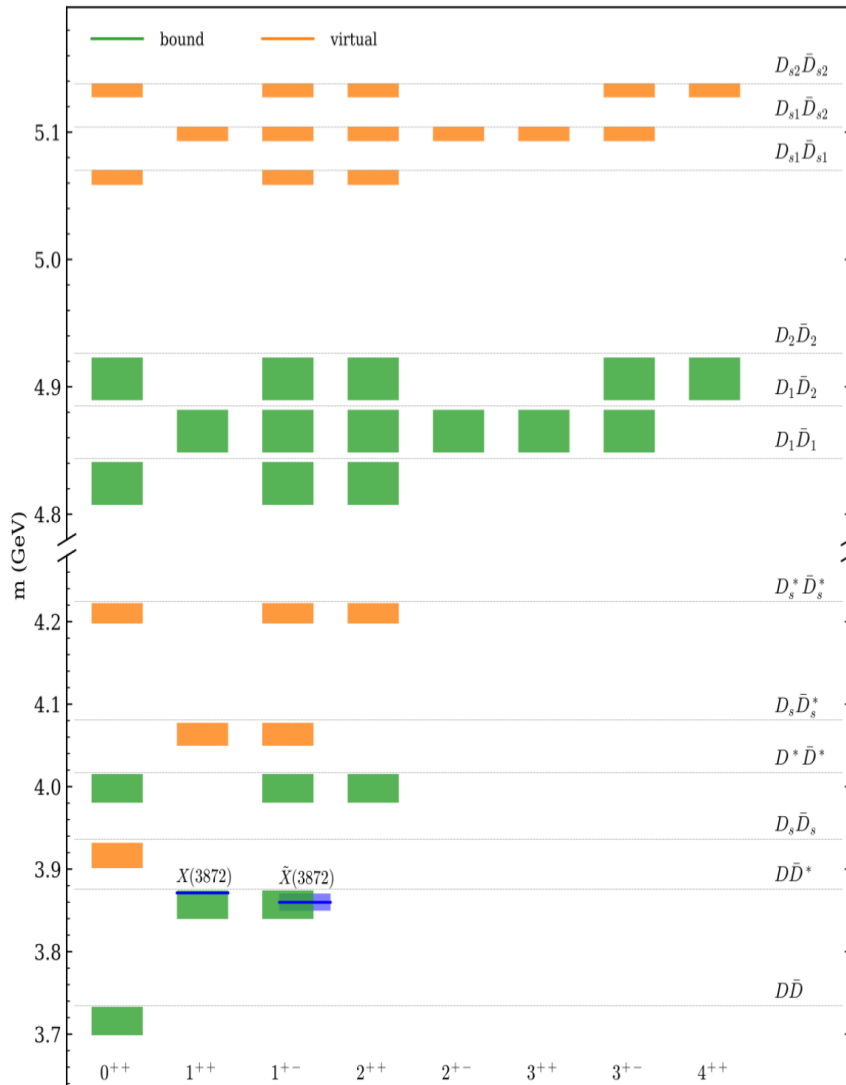


P_c

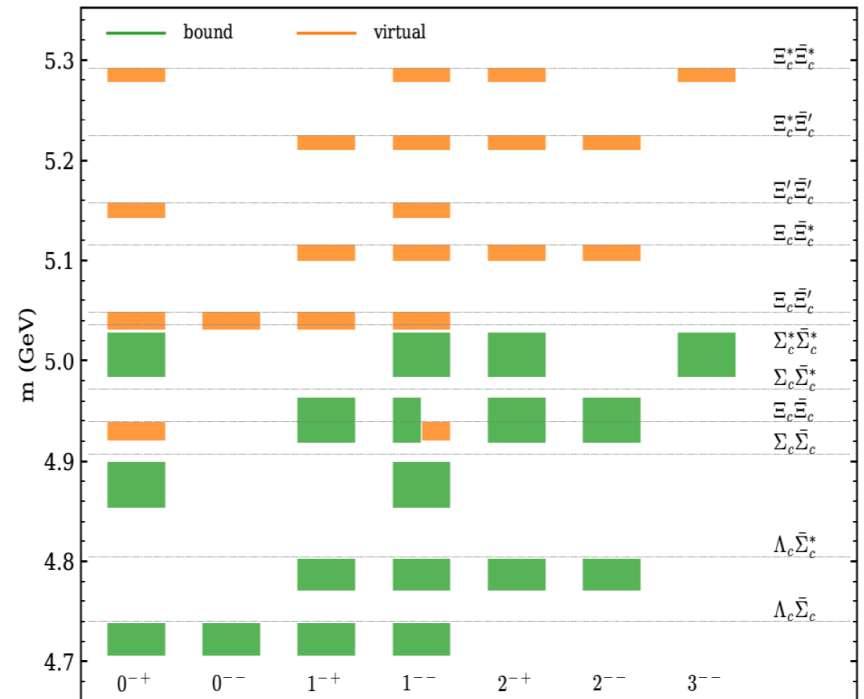


P_{cs}

Meson-meson molecules (I=0)



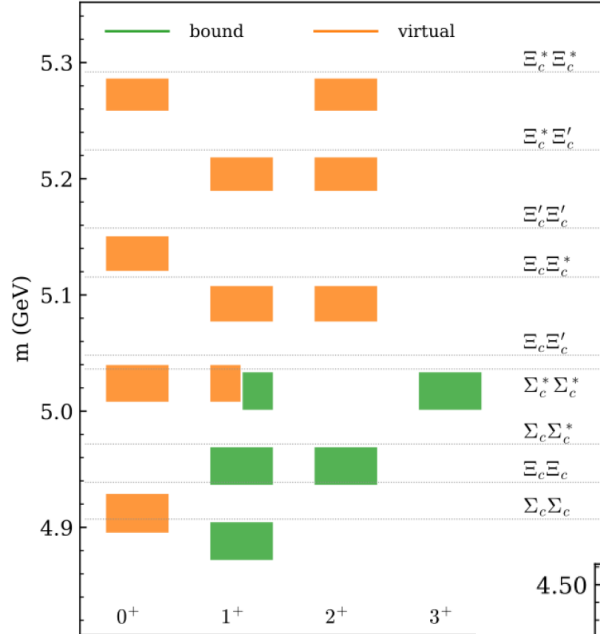
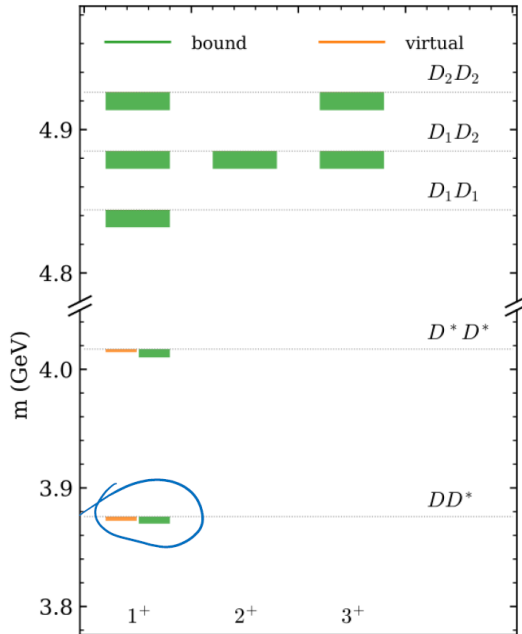
Baryon molecules (I=1) with $\bar{c}c$



- ✓ Isovector interaction between $D^{(*)}\bar{D}^{(*)}$ from light vector exchange vanishes
- ✓ Charmonia exchange could be important here:
 J/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

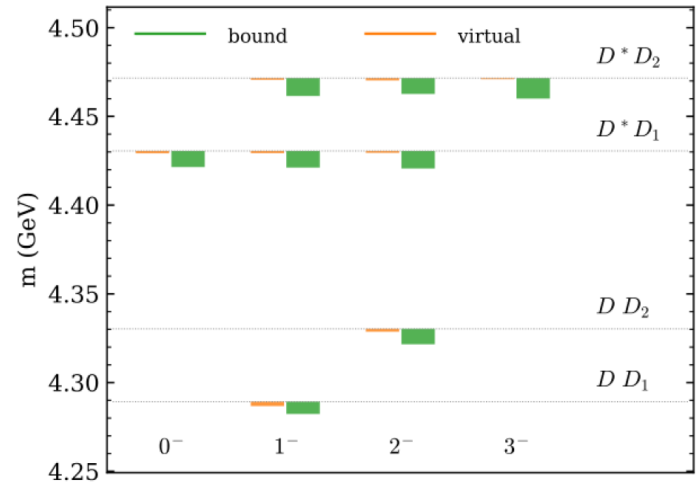
A survey of heavy-heavy hadronic molecules

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

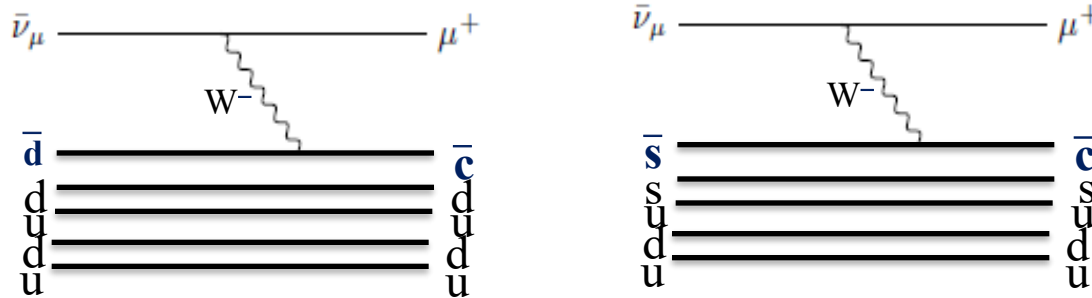


$\bar{\nu}p$ - nice tool for exploring pentaquarks

K.S.Qiao, B.S.Zou, ArXiv: 2510.23370 [hep-ph]

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

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



$\bar{c}dudu$ & $\bar{c}sudu$ pentaquark states are predicted to exist

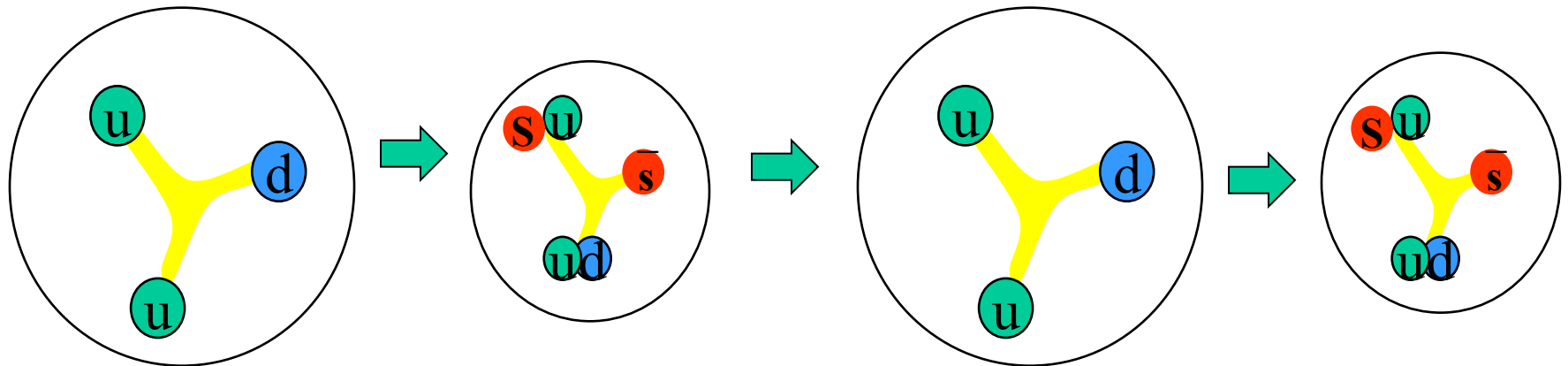
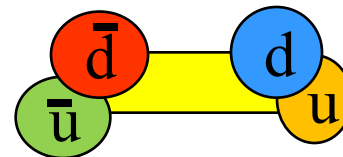
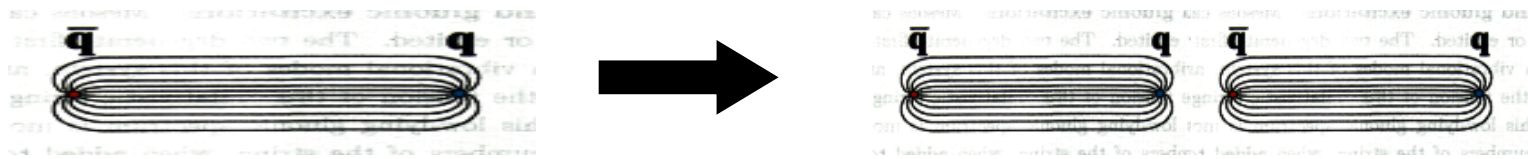
Y. Yamaguchi, S. Yasui, A. Hosaka, PRD 106, 094001 (2022)

N. Yalikul, B.S. Zou, PD 105, 094026 (2022)

Unquenched quark model

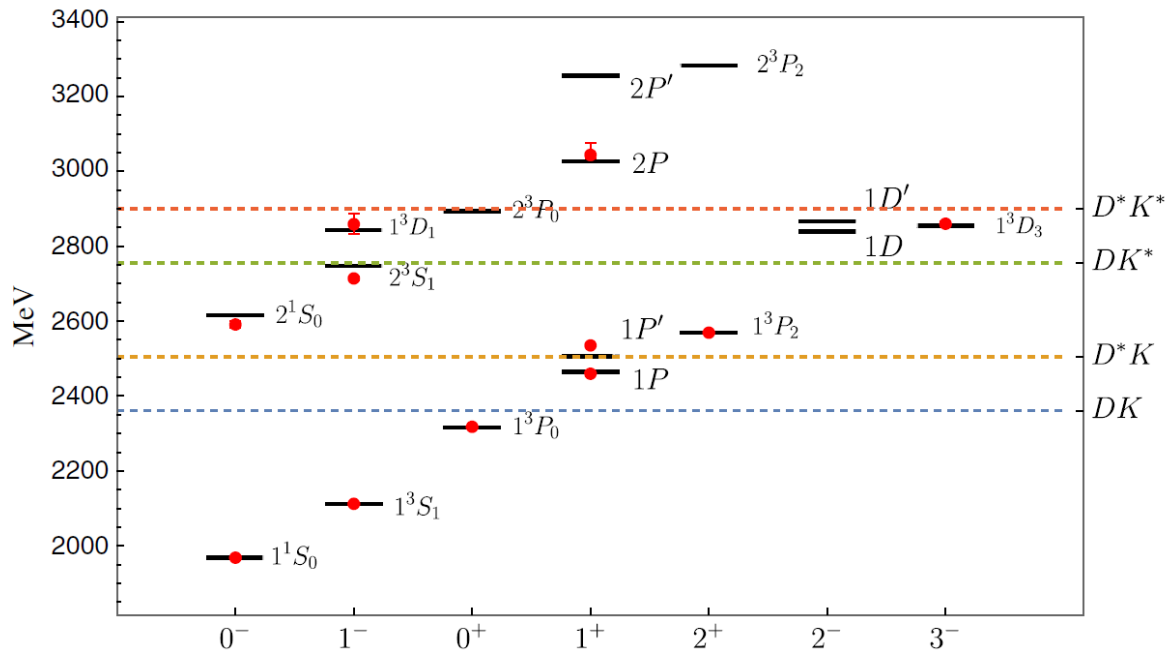
Unquenching dynamics: gluons \rightarrow $\bar{q}q$

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_{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 D_s (g.s.) there is 17% tetra-quark components

Thank you for your attention !

● 1974 – $\bar{c}c$ + QCD \rightarrow QCD inspired quark potential model



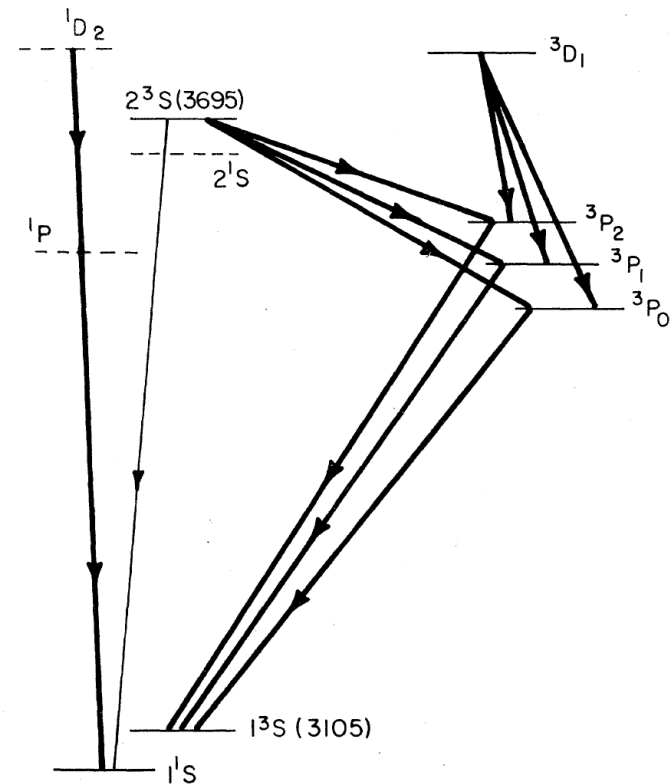
$$\hat{H}_0 = \frac{p^2}{m_Q} + V_0(r) + V_{SD}(r)$$

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

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

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

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



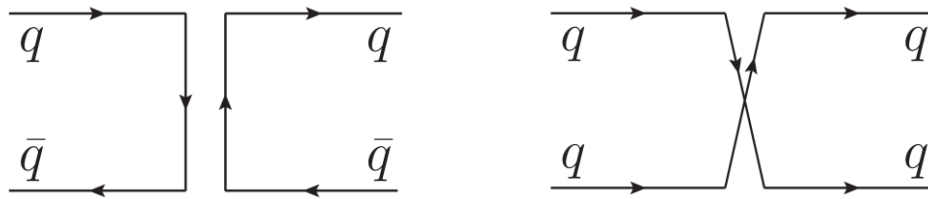
Extension to light hadrons with various developments

- **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 $S\chi SB$ & pions as Nambu-Goldstone bosons**

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



Meson exchange \sim 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