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 ?**

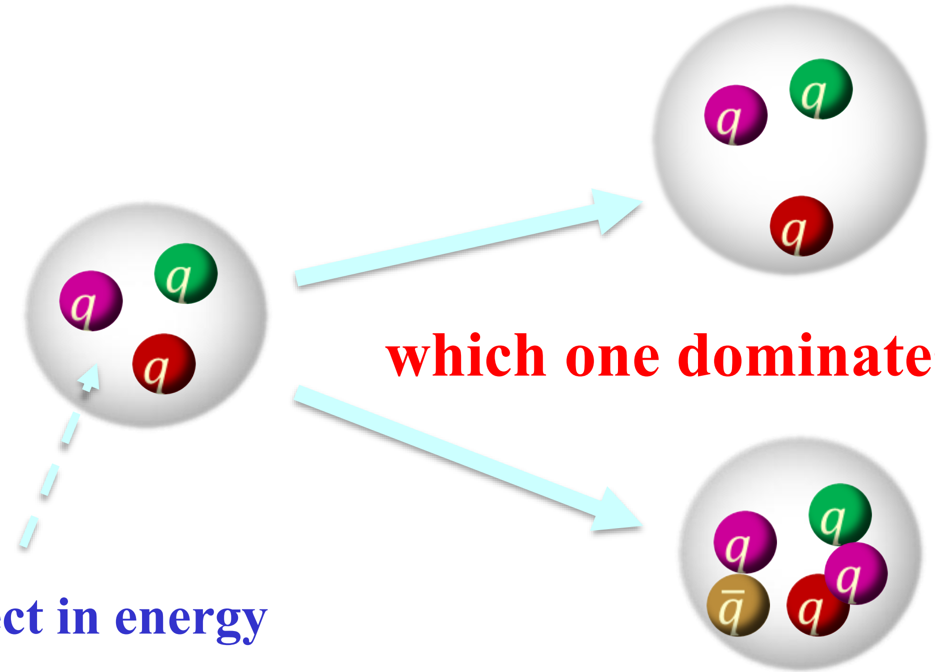
uds (L=1) $1/2^-$	~	$\Lambda^*(1670)$	~	$[us][ds]\,\bar{s}$		$K\Xi - \eta\Lambda$
uss (L=1) $1/2^-$	~	$\Xi^*(1610)$	~	$[us][ds]\,\bar{d}$		$\bar{K}\Sigma - \bar{K}\Lambda - \pi\Xi$
uud (L=1) $1/2^-$	~	$N^*(1535)$	~	$[ud][us]\,\bar{s}$		$K\Sigma - K\Lambda - \eta N$
uds (L=1) $1/2^-$	~	$\Lambda^*(1405)$	~	$[ud][su]\,\bar{u}$		$\bar{K}N - \pi\Sigma$
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;
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)



Classic quark model:
3q excited states

which one dominates?

inject in energy

Our new view: Pentaquark excitation dominates already for ½- SU(3) nonet
B.S.Zou, EPJA 35 (2008) 325

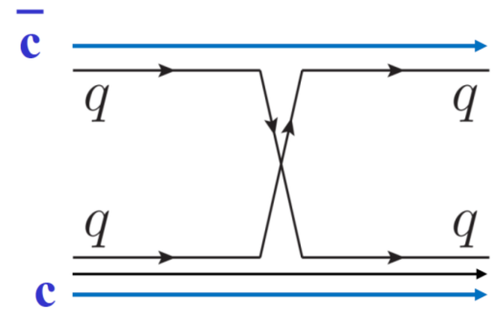
Pentaquark crucial for baryon spectroscopy and structure !

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."

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

- prediction of three P_c pentaquark states → 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

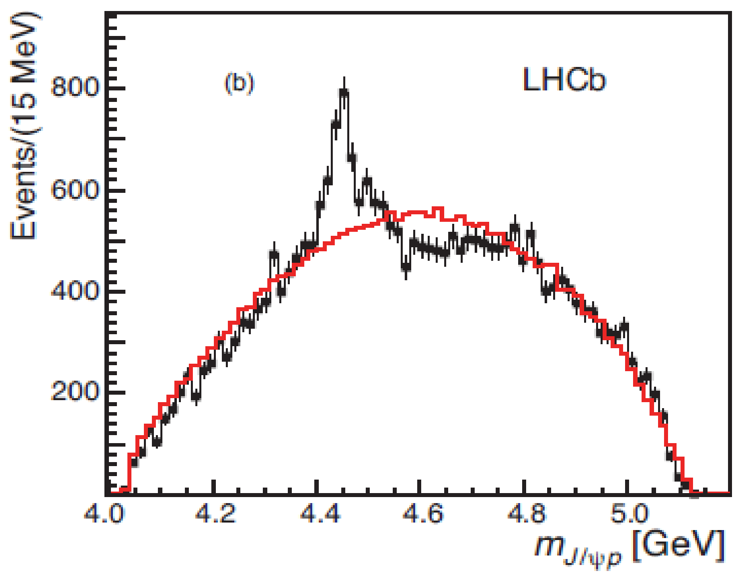
J. Hofmann, M. Lutz, NPA763(2005)90 → $\bar{D}\Sigma_c$ at 3.52 GeV & DN at $\Lambda_c(2595)$

LHCb confirms our prediction of 3 narrow P_c states

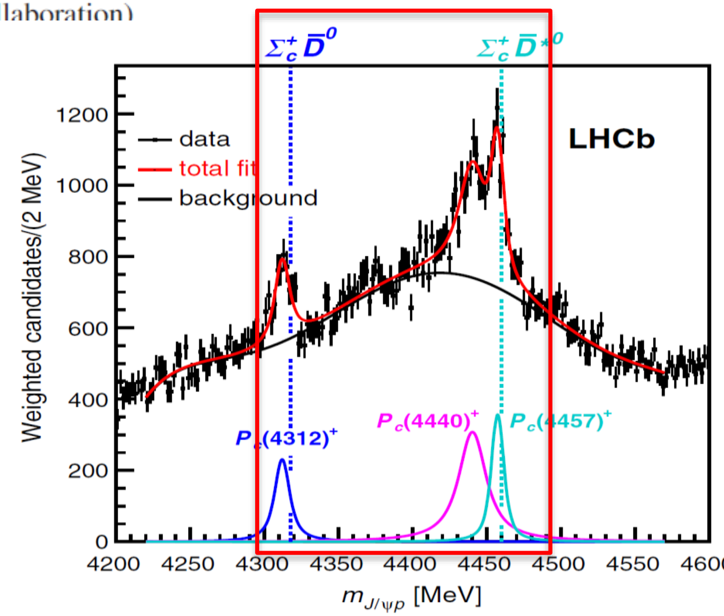
Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

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

Multiquark states – crucial for hadron structure !

X(3872) → top cited paper for Belle (2003) 3038 cites

Z_c(3900) → top cited paper for BES (2013) 1316 cites

P_c states → top cited paper for LHCb (2015) 2209 cites

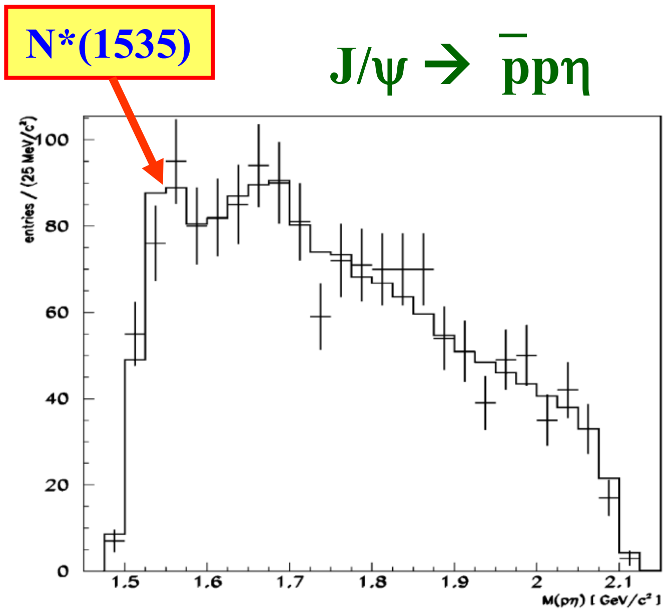
H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1:
"The hidden-charm pentaquark and tetraquark states" 1457 cites

F.K.Guo, C.Hanhart, U.Meissner, Q.Wang, Q.Zhao, B.S.Zou,
Rev.Mod.Phys. 90 (2018)015004: "Hadronic molecules" 1672 cites

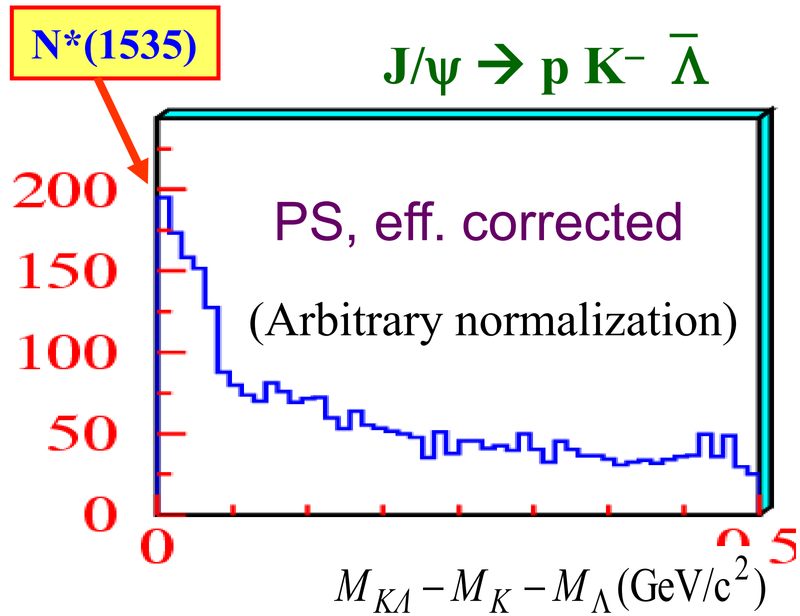
How about strange partners of P_c and Z_c states ?

2. Molecules of KΣ, KΣ*, K*Σ, K*Σ*, etc.

KΣ molecule - N*(1535) in J/ψ decays



BES, PLB510 (2001) 75



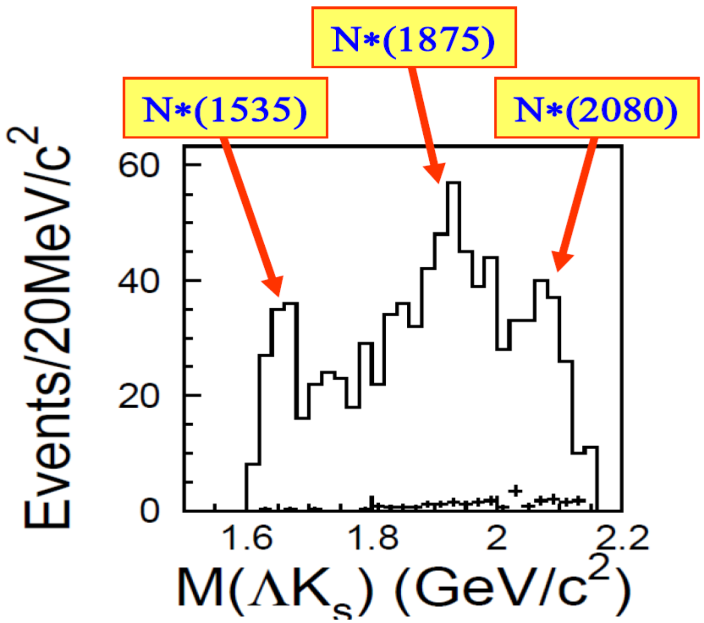
BESII, IJMPA20 (2005) 1985

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

KΣ*, K*Σ, K*Σ* molecules from charmonium decays at BES

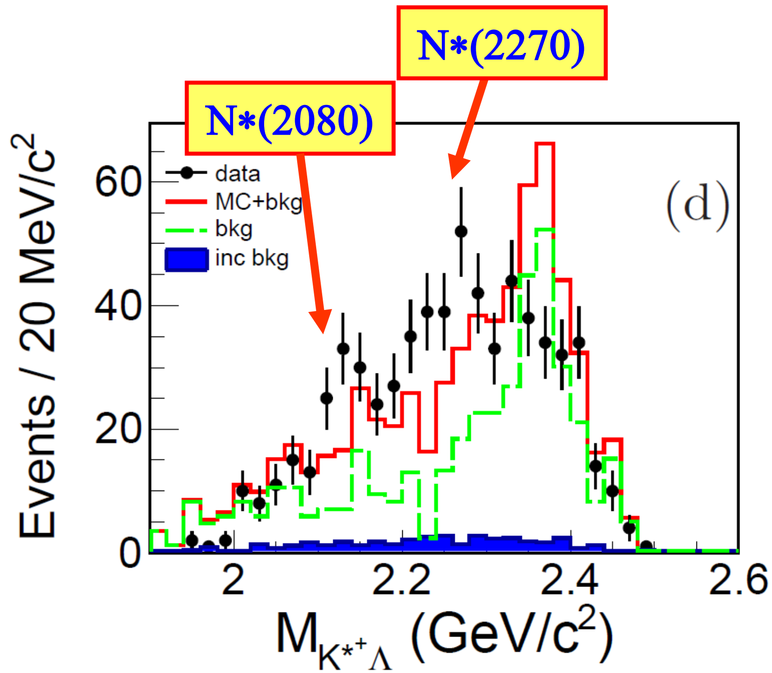
N*(1875)   N*(2080)   N*(2270)

KΣ* ~1880   K*Σ ~ 2086   K*Σ* ~ 2280



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

BESII, PLB659 (2008) 789

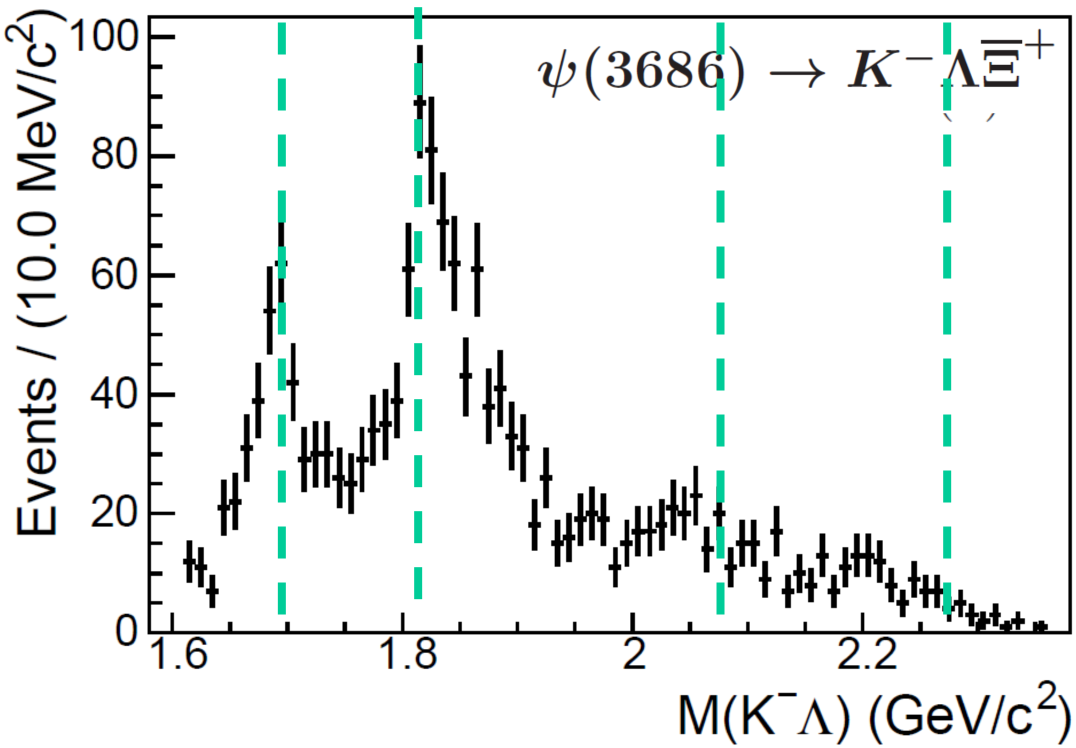


$\chi_{c0} \to \bar{p}K^{*+}\Lambda$ +c.c.

BESIII, PRD100(2019)052010

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

BESIII, PRD 109 (2024) 072008



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

$1/2^-$ **$3/2^-$**

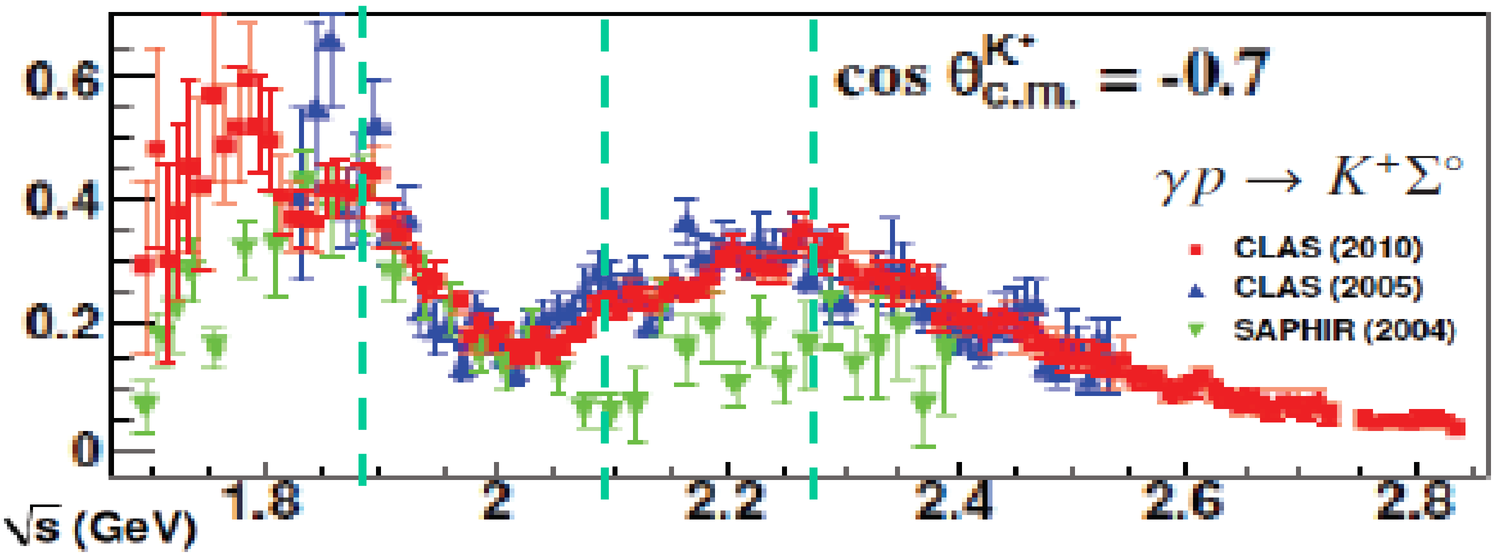
$K\Sigma^*$, $K^*\Sigma$, $K^*\Sigma^*$ molecules from γp reactions

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

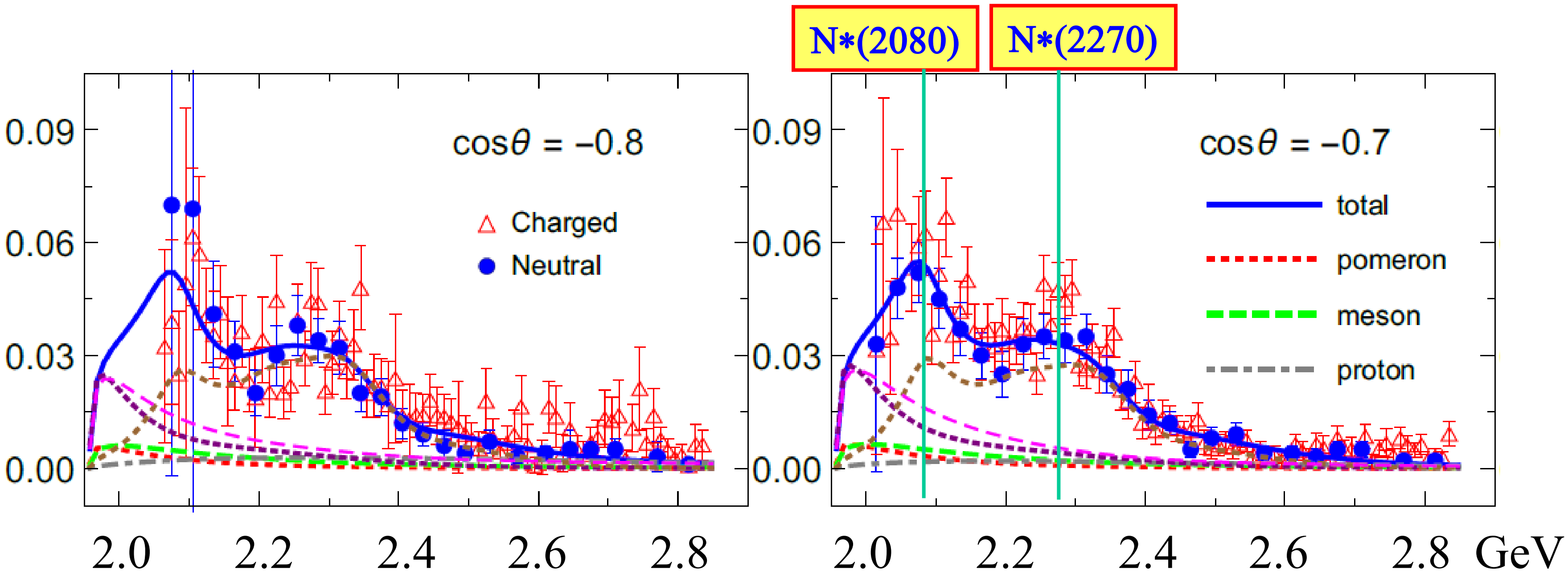
$K\Sigma^*$ ~1880 — N*(1875)

$K^*\Sigma$ ~ 2086 — N*(2080)

$K^*\Sigma^*$ ~ 2280 — N*(2270)



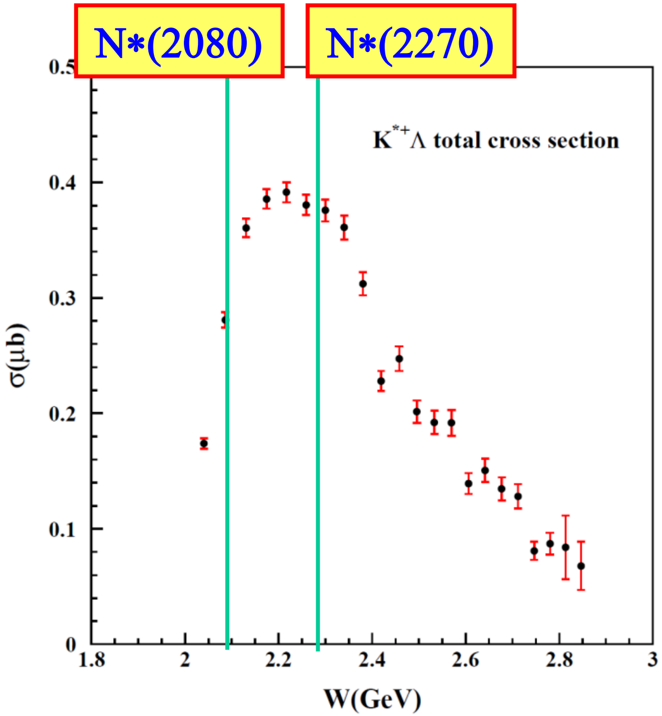
$\gamma p \to \phi p$ CLAS, PRC89(2014)019901

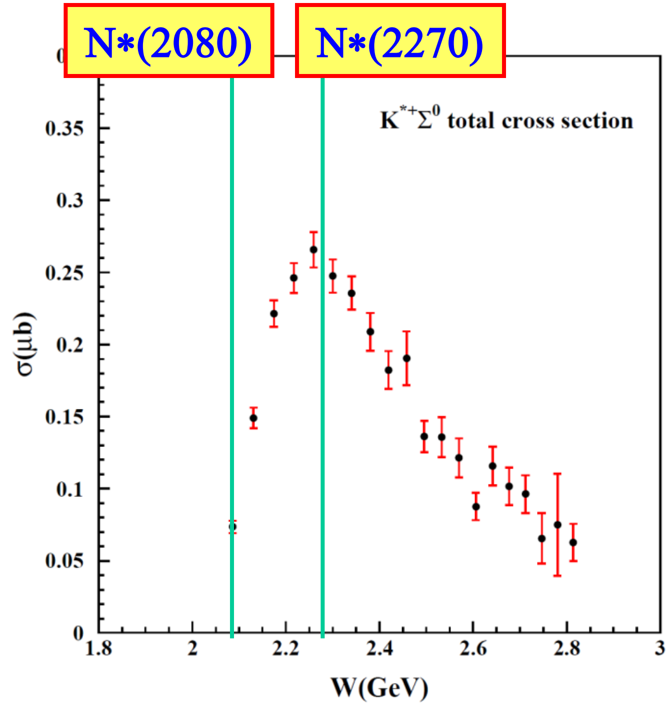


S.M.Wu, F.Wang, B.S.Zou, PRC108(2023)045201

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

CLAS, PRC 87(2013)065204

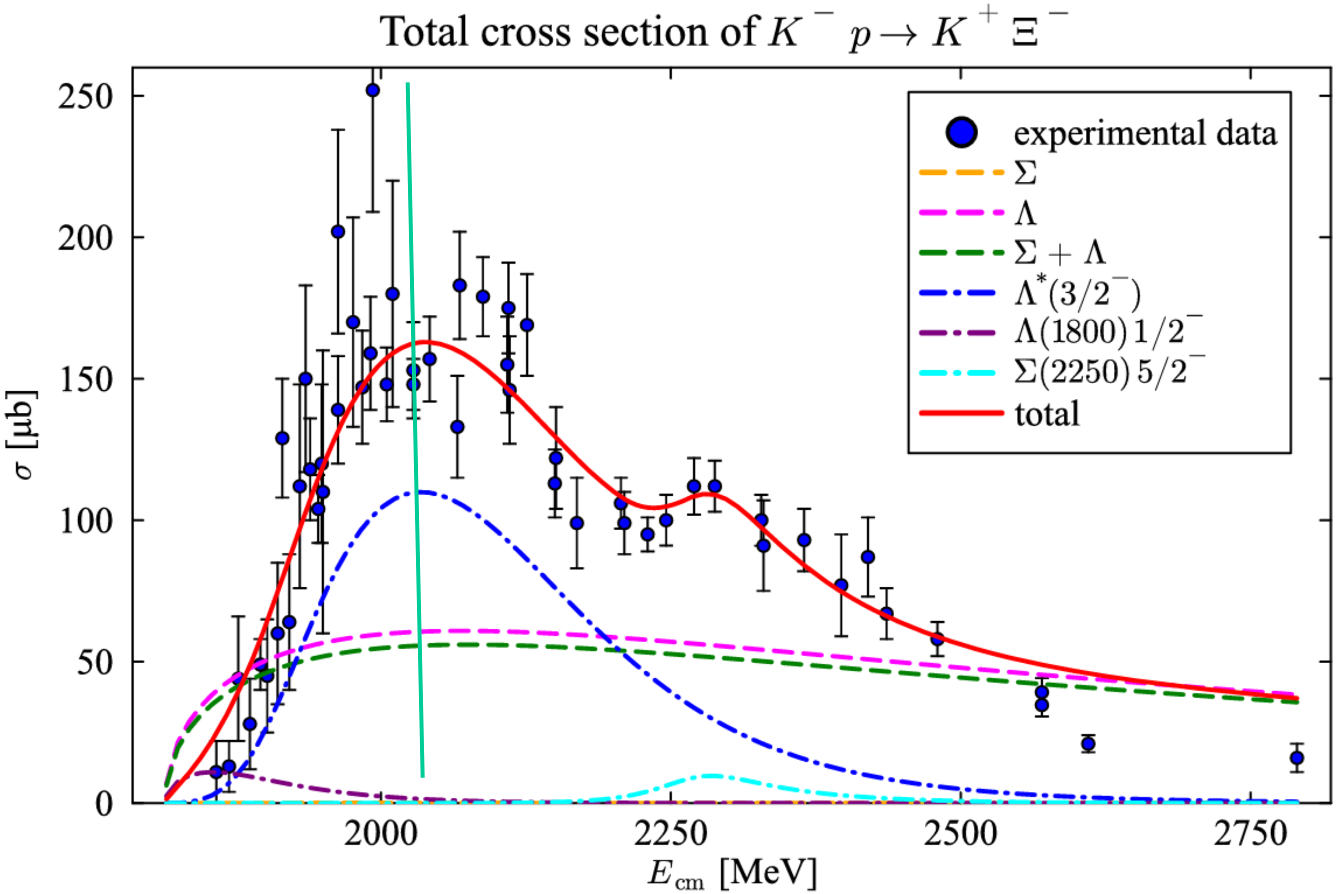




Di Ben, A.C.Wang, F.Huang, B.S.Zou, PRC 108 (2023) 065201
J.Shi, B.S.Zou, PRD 111 (2025) 114032
W.Y.Tian, N.C.Wei, F.Huang, B.S.Zou, PRC 112 (2025) 055203

KΞ* molecule

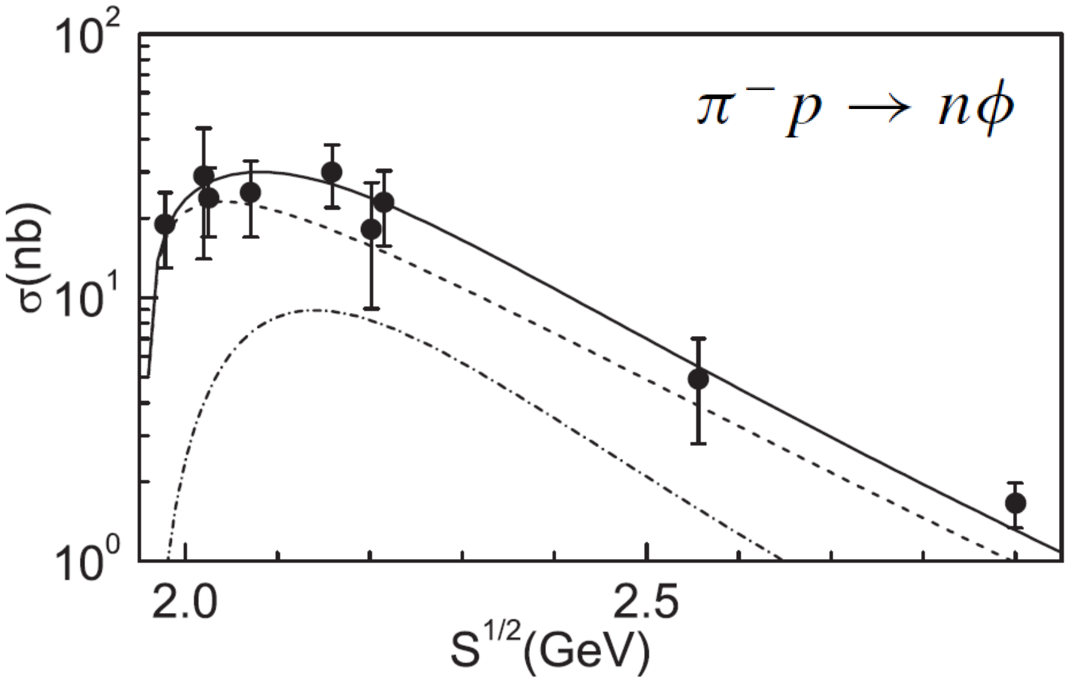
Z.L.Luo, J.J.Wu, B.S.Zou, PRD 114 (2026) 014062



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

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

J.J.Xie, B.S.Zou, H.C.Chiang, PRC77(2008)015206

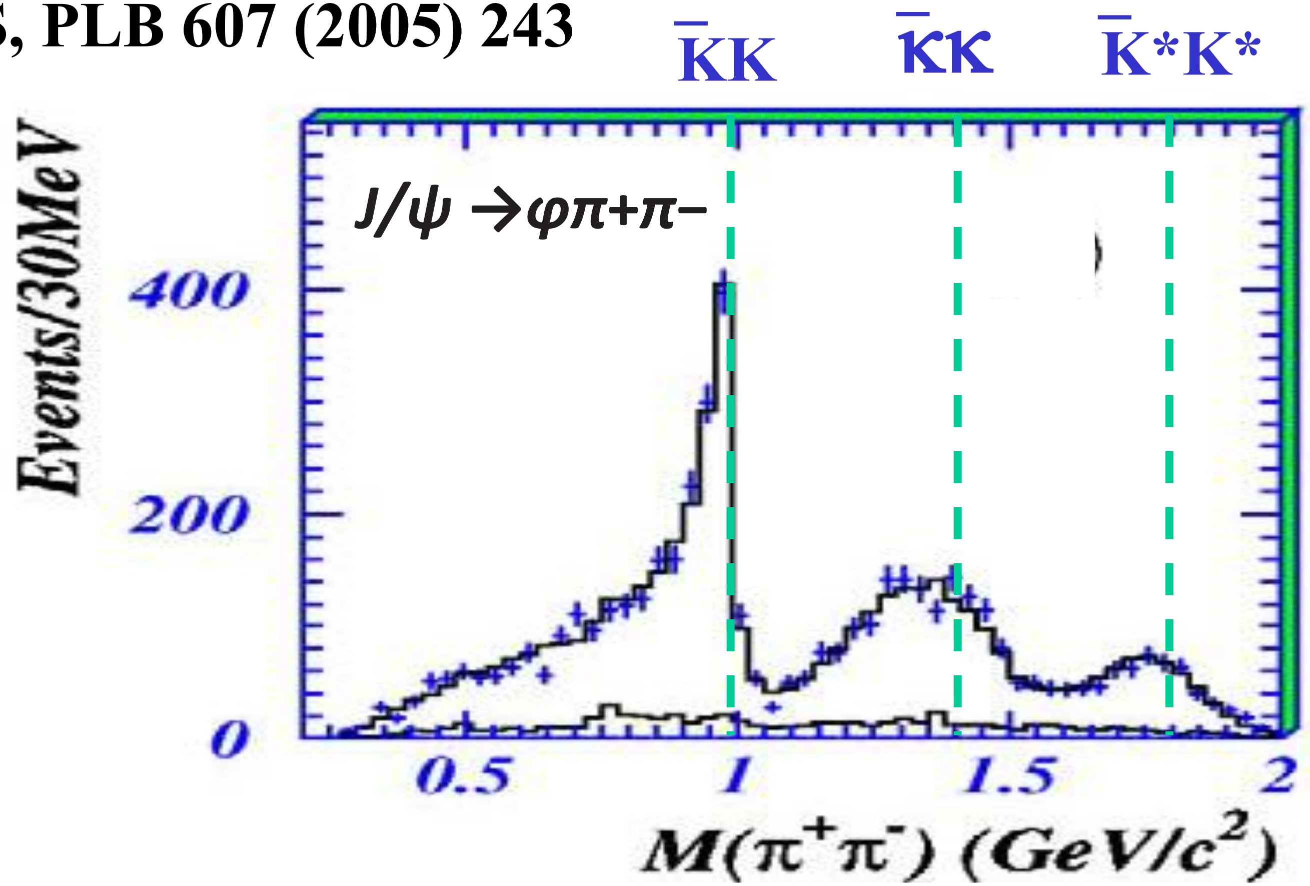


N*(1535) + N*(1900) ½+ or N*(1875)+N*(2080)+N*(2270) ?

More data with angular distribution and polarization information are needed !

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

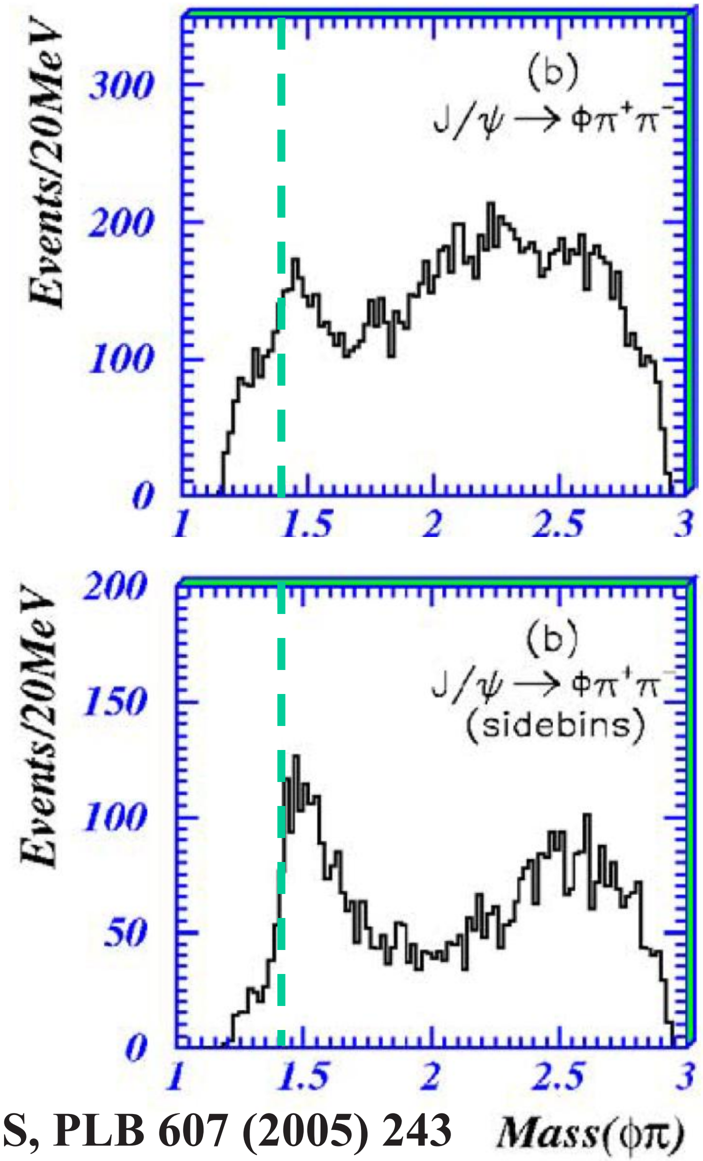
BES, PLB 607 (2005) 243



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

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

$\bar{K}^*K$



BES, PLB 607 (2005) 243

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 $J/\psi \to \gamma\eta\eta'$

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

L.S.Geng, E.Oset, PRD 79 (2009) 074009; 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 (1750) / a_0 (1750)

Observation of a_0 (1817) → $K_S^0K^+$ in D_s^+→ $K_S^0K^+\pi^0$ 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) — $\bar{\Lambda}\Lambda$ ($^3S_1$) ; η(2225) — $\bar{\Lambda}\Lambda$ ($^1S_0$)

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)

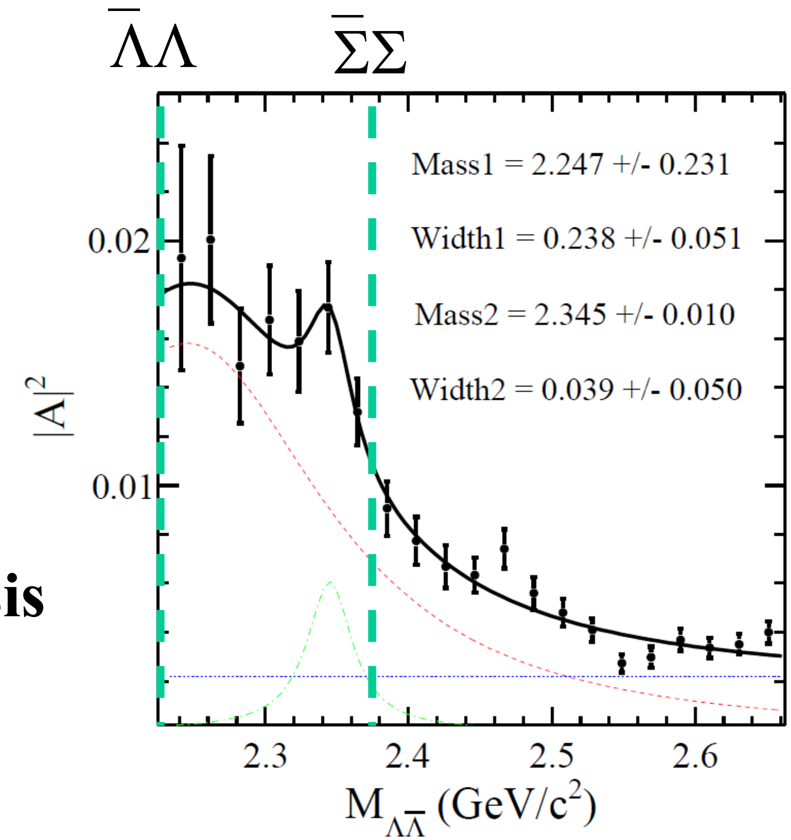
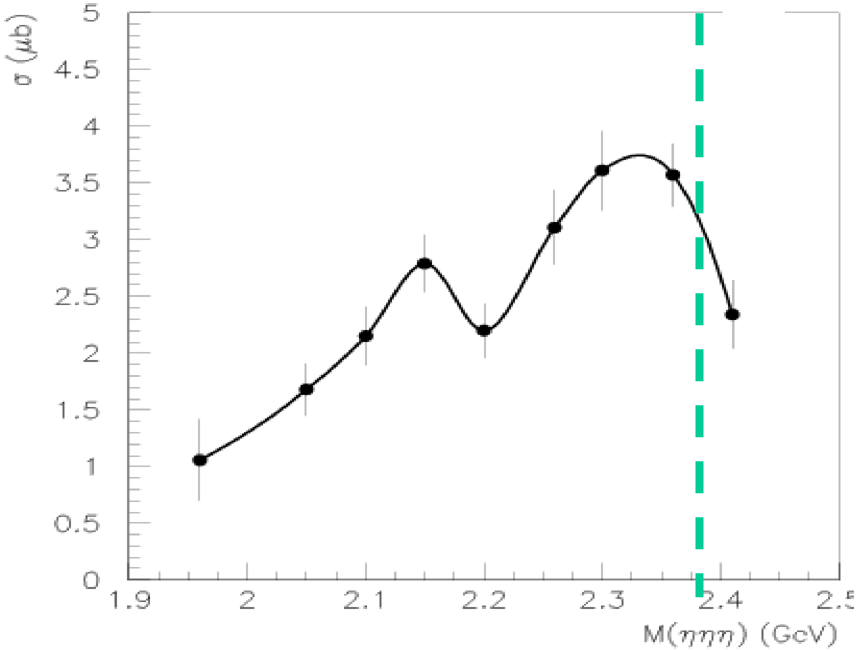


图 4.35: $\Lambda\bar{\Lambda}$ 阈值附近结构的初步研究。其中，虚线（红色）和虚-点线（绿色）曲线代表两个 0^{-+} 共振态粒子的贡献；点线（蓝色）曲线代表常数本底贡献。

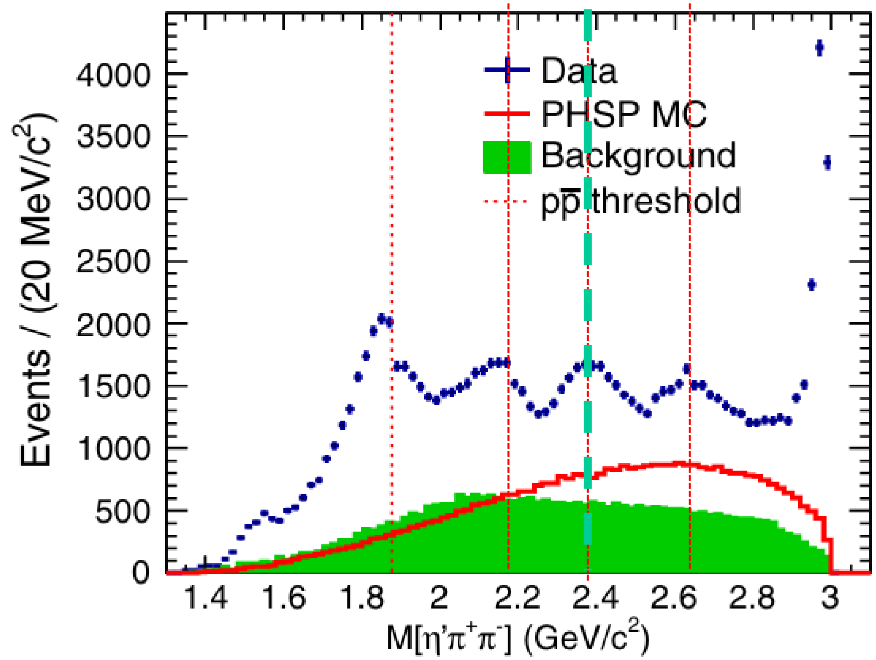
$\bar{p}p \rightarrow \eta\eta\eta$

$\bar{\Sigma}\Sigma$



$J/\psi \rightarrow \gamma\eta'\pi^+\pi^-$

$\bar{\Sigma}\Sigma$ $\bar{\Xi}\Xi$



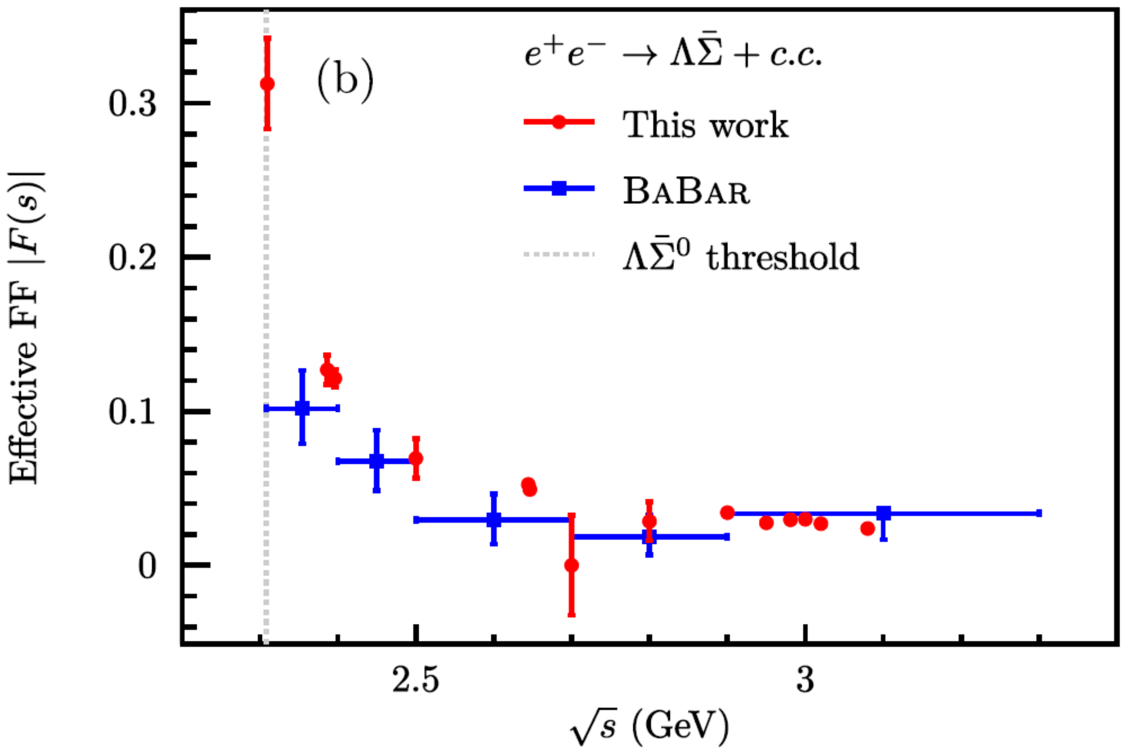
B.S.Zou, NPA655 (1999) 167c
A.V. Anisovich et al., PLB 496 (2000) 145

BESIII, PRL117(2016)042002

η(2320)/X(2370) → ηηη, ππη, $\bar{K}K\pi$, $K_S^0K_S^0\eta'$, $\pi^+\pi^-\eta'$

Its observed decay modes favor it to be a $\bar{\Sigma}\Sigma$ molecule of $\bar{s}s$ $\bar{q}^2q^2$!

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/γp@JLab, π/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

Thank you for your attention !

$$g^2_{\omega NN}/4\pi \sim 2.06, \quad g^2_{\rho NN}/4\pi \sim 0.31$$

Under SU(3) symmetry, the general relation between $g_{K^*N\Sigma}$ and $g_{\rho NN}$ is:

> $g^V_{K^*N\Sigma} = (1 - 2\alpha_V) \cdot g^V_{\rho NN}$

where:

- $g^V_{K^*N\Sigma}$ is the vector coupling constant for the $K^*N\Sigma$ vertex.
- $g^V_{\rho NN}$ is the vector coupling constant for the ρNN vertex.
- α_V is the **F/(F+D) ratio** for vector couplings, which determines the weight of the symmetric (D-type) and antisymmetric (F-type) representations of the SU(3) group in the coupling.

α_V value	Theoretical basis	Relation between $g^V_{K^*N\Sigma}$ and $g^V_{\rho NN}$
$\alpha_V = 1.0$	**SU(6) symmetry**	$g^V_{K^*N\Sigma} = (1 - 2) \cdot g^V_{\rho NN} = -g^V_{\rho NN}$
$\alpha_V = 0.5$	Another common choice	$g^V_{K^*N\Sigma} = (1 - 1) \cdot g^V_{\rho NN} = 0$

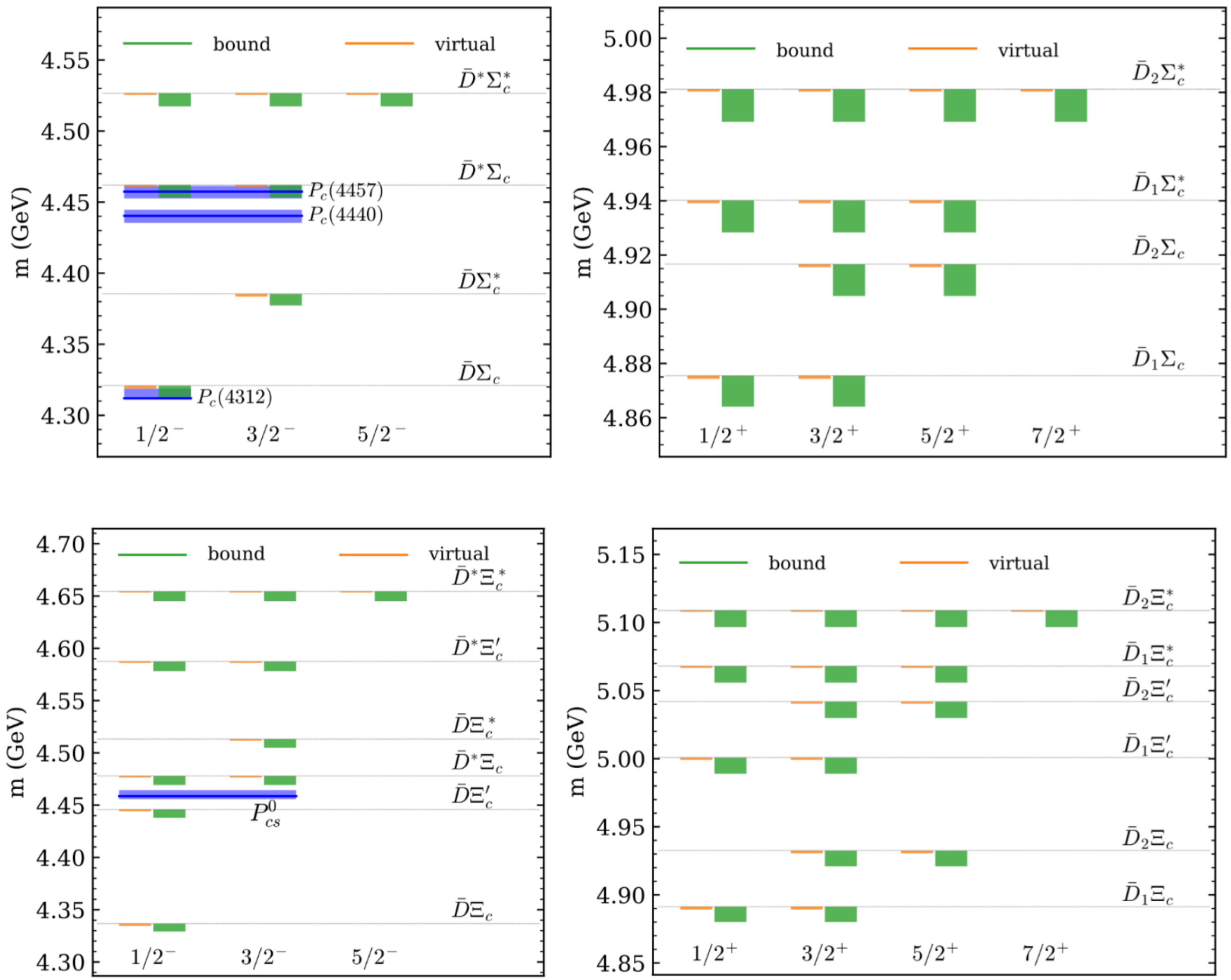
η_c decay modes

Γ_{52}	$p\bar{p}$	$(1.11 \pm 0.12) \times 10^{-3}$	S=1.4	1160
Γ_{53}	$p\bar{p}\pi^0$	$(3.2 \pm 1.2) \times 10^{-3}$		1101
Γ_{54}	$p\bar{p}\pi^+\pi^-$	$(3.4 \pm 0.5) \times 10^{-3}$	S=1.2	1027
Γ_{55}	$\Lambda\bar{\Lambda}$	$(9.4 \pm 1.8) \times 10^{-4}$	S=1.2	991
Γ_{56}	$K^+\bar{p}\Lambda$ + c.c.	$(2.26 \pm 0.34) \times 10^{-3}$		773
Γ_{57}	$\bar{\Lambda}(1520)\Lambda$ + c.c.	$(2.8 \pm 1.2) \times 10^{-3}$		694
Γ_{58}	$\Sigma^+\overline{\Sigma}^-$	$(1.98 \pm 0.35) \times 10^{-3}$		901
Γ_{59}	$\Xi^-\overline{\Xi}^+$	$(8.3 \pm 1.8) \times 10^{-4}$		692

$$g^2_{\eta_c\Sigma\Sigma} : g^2_{\eta_c\Xi\Xi} : g^2_{\eta_c\Lambda\Lambda} : g^2_{\eta_c NN} = 2.3 : 1.3 : 1.0 : 1$$

A survey of hadronic molecules with hidden charm

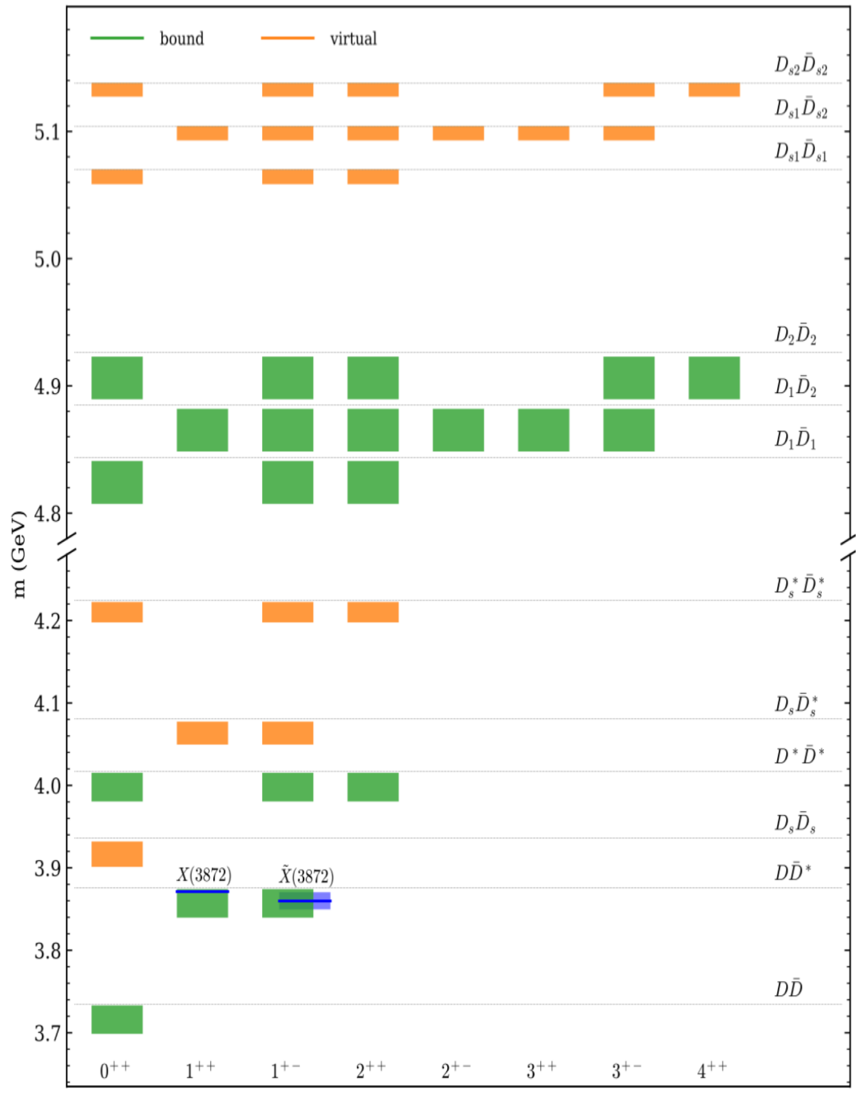
X.K.Dong, F.K.Guo, B.S.Zou Progr. Phys. 41 (2021) 65



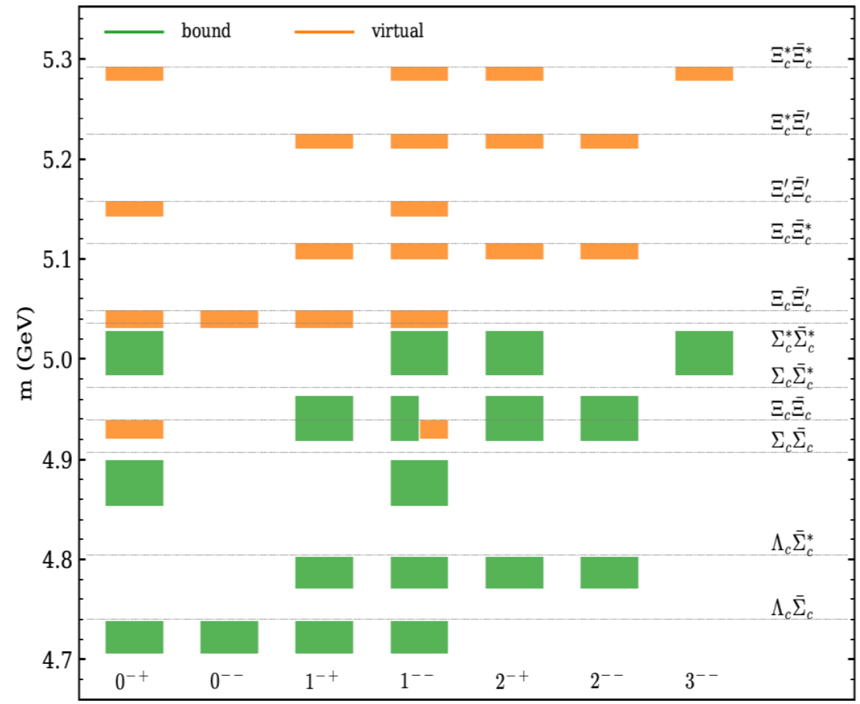
P_c

P_{cs}

Meson-meson molecules (I=0)



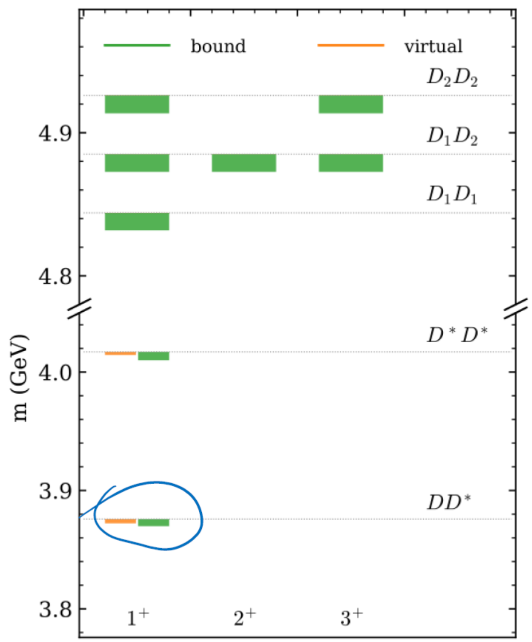
Baryon molecules (I=1) with $\bar{c}c$

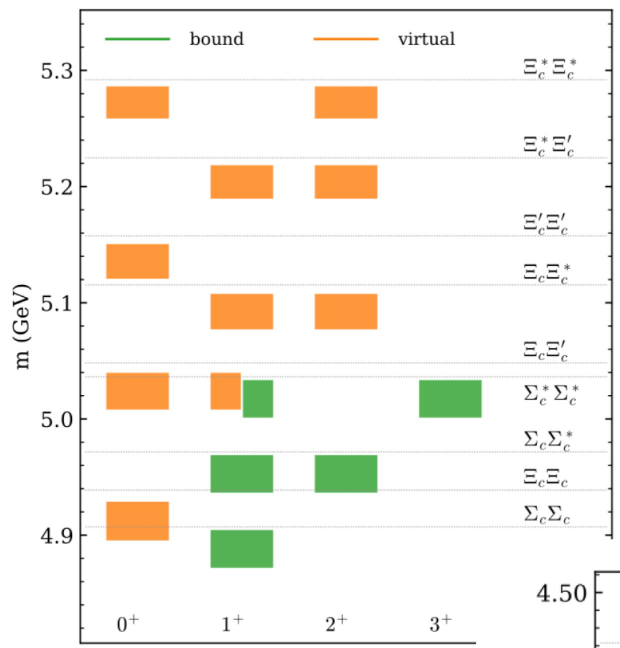


- ✓ Isovector interaction between $D^{(*)}\bar{D}^{(*)}$ from light vector exchange vanishes
- ✓ Charmonia exchange could be important here: J/ψ, ψ' exchange
- ✓ $Z_c(3900,4020)$ as $\bar{D}^{(*)}D^*$ virtual states
- ✓ $Z_{cs}(3985)$ as $D_s\bar{D}^*, D\bar{D}_s^*$ virtual state
- ✓ $Z_c(4430)$ as $\bar{D}^*\bar{D}_1^*$virtual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

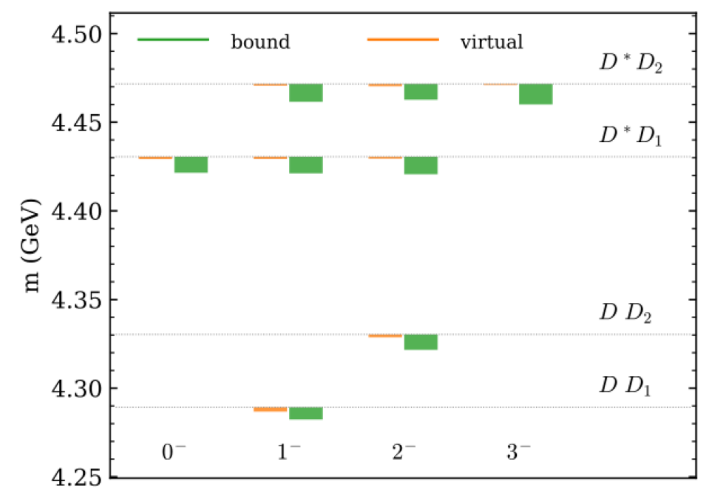
A survey of heavy-heavy hadronic molecules

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 $P = +$

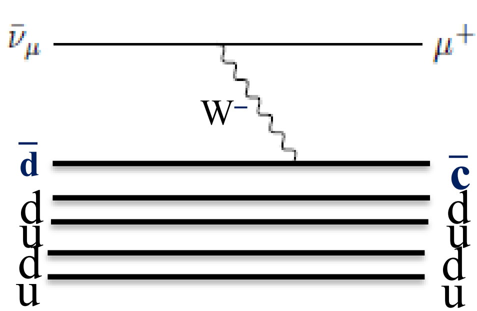
✓ Similar in $P = -$ sector

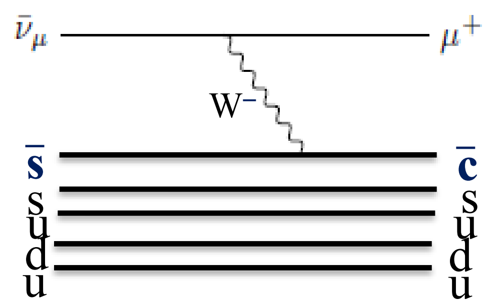
$\bar{\nu}$p - nice tool for exploring pentaquarks

K.S.Qiao, B.S.Zou, PRD 113 (2026) 113005

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

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





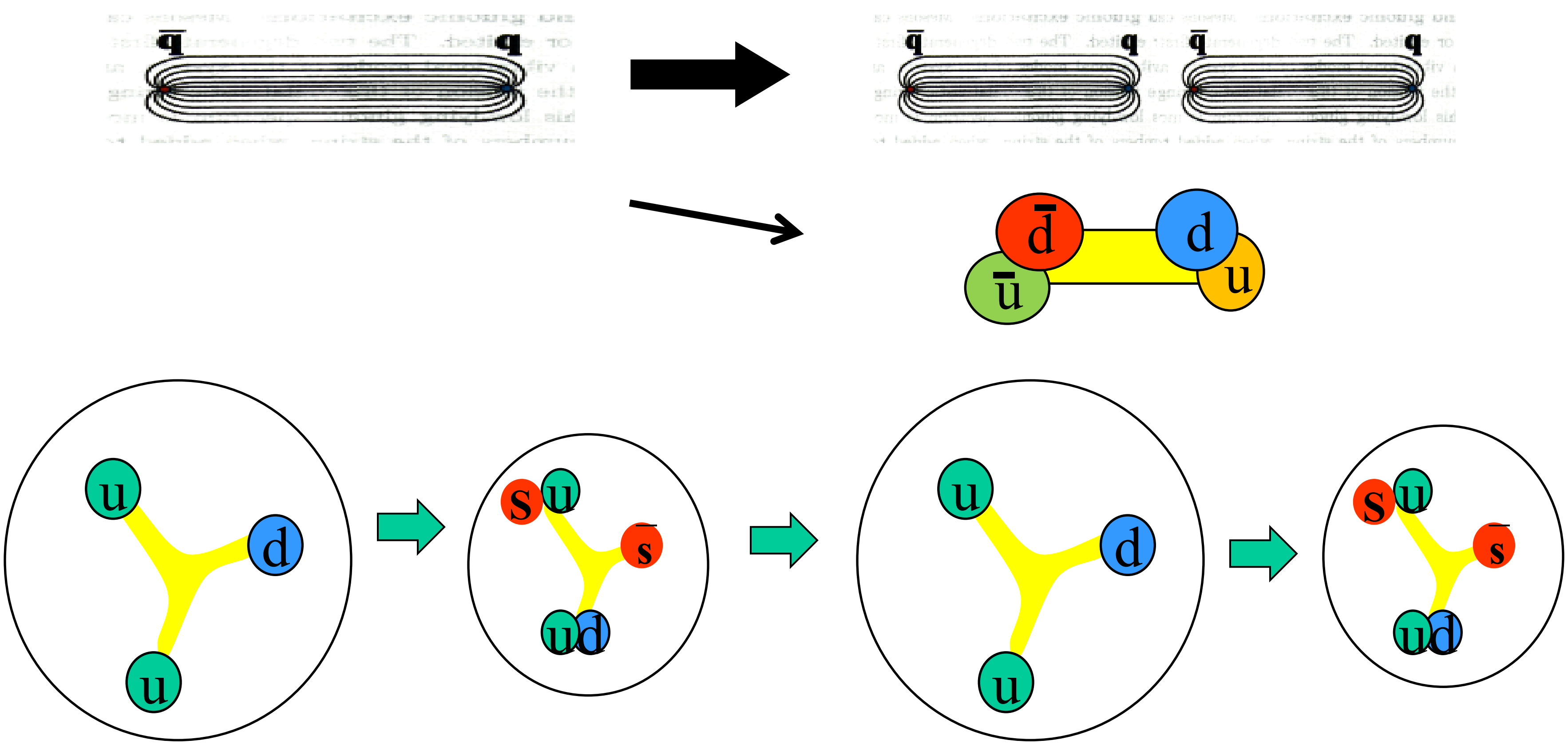
$\bar{c}$dudu & $\bar{c}$sudu pentaquark states are predicted to exist

Y. Yamaguchi, S. Yasui, A. Hosaka, PRD 106, 094001 (2022)
N. Yalikun, B.S. Zou, PD 105, 094026 (2022)

Unquenched quark model

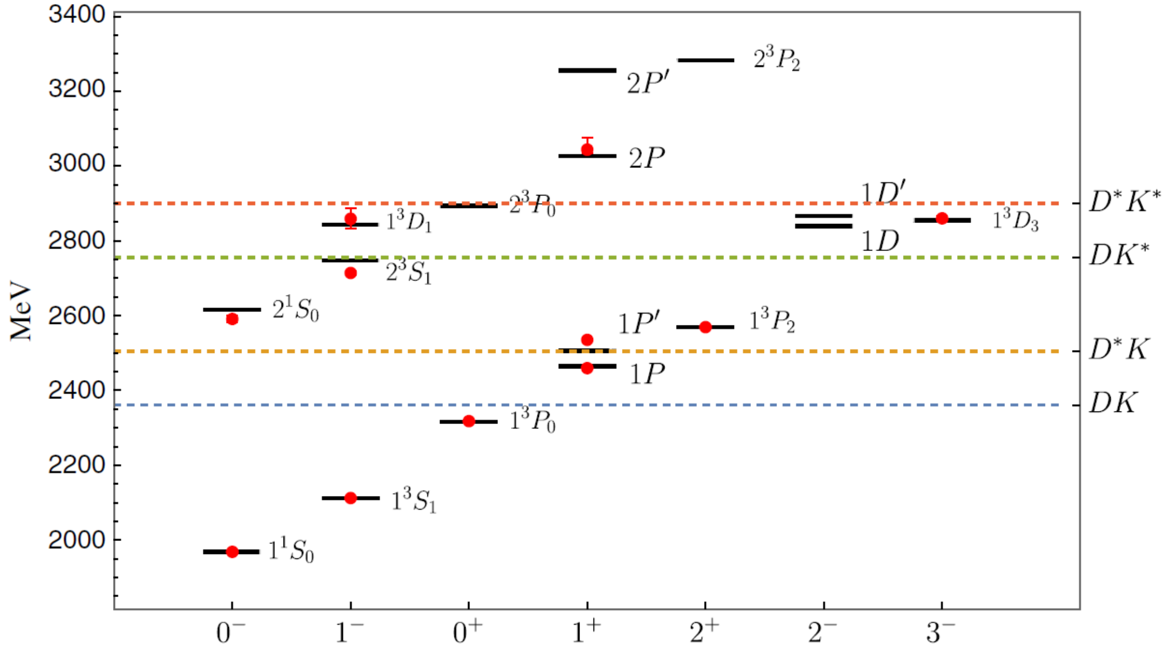
Unquenching dynamics: gluons → $\bar{q}q$

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



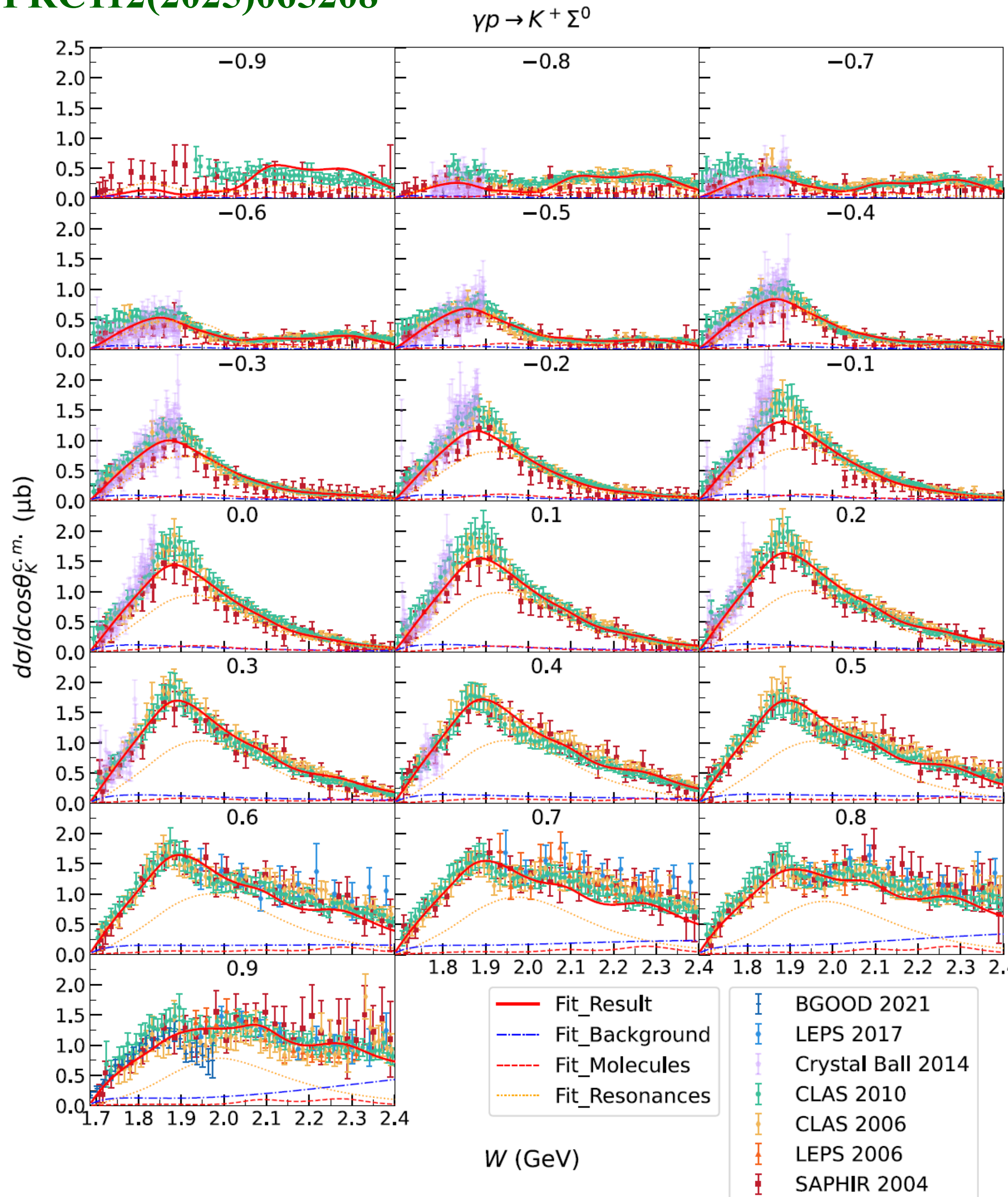
Mass spectrum of D_s mesons

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_{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

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



D.Rochen et al., EPJA58 (2022) 229

without D_{13}

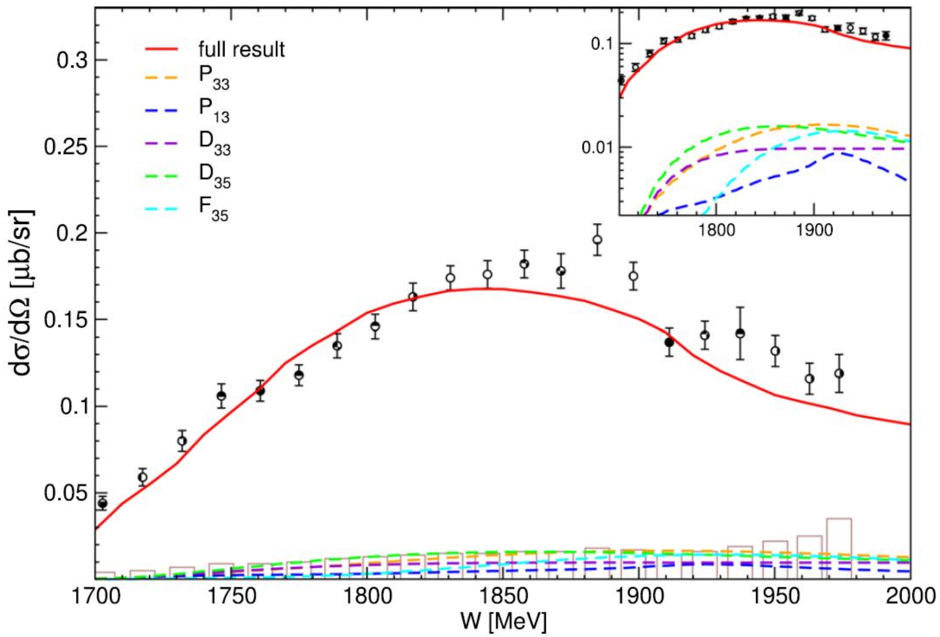


Fig. 12 Forward differential cross section ($\cos\theta > 0.9$) reaction $\gamma p \to K^+\Sigma^0$. Only dominant partial waves are shown. The box in the upper right corner shows the same picture on a logarithmic scale. Data from Ref. [82] (not included in the fit). We fit the data shown in Fig. 2 from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