Exotic hadrons with hidden strangeness

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Outline

- **Brief history of hadronic molecules**
- **Molecules of KΣ, KΣ*, K*Σ, K*Σ*, 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. Brief history of hadronic molecules

1932: Neutron & Deuteron - the 1-st hadronic molecule

1947: π, K

1959: KN molecule predicted by Dalitz Tuan, PRL2, 425

1961: $\Lambda(1405) \rightarrow \Sigma\pi$ observed by Alston et al., PRL6, 698

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: $D^*_{s0}(2317)$ $\bar{K}D$ molecules? Barnes, …

…….

$1/2^-$ baryon nonet with strangeness

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

uds (L=1) $1/2^-$ ~ $\Lambda^*(1670)$ ~ $[us][ds]\bar{s}$ $\bar{K}\Xi - \eta\Lambda$

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

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) : PDG → large $g_{N^*N\eta}$**

$J/\psi \to \bar{p}N^* \to \bar{p}\,(K\Lambda)$ / $\bar{p}\,(p\eta)$ → large $g_{N^*K\Lambda}$

Liu&Zou, PRL96 (2006) 042002; Geng,Oset,Zou&Doring, PRC79 (2009) 025203

$\gamma p \to p\eta'$ & $pp \to pp\eta'$ → large $g_{N^*N\eta'}$

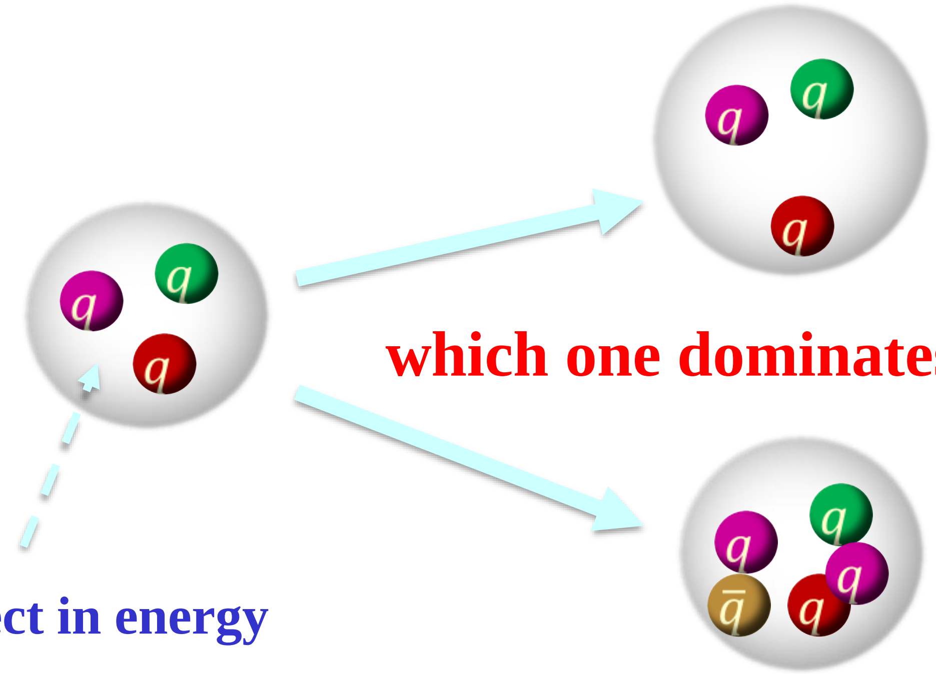
M.Dugger et al., PRL96 (2006) 062001; Cao&Lee, PRC78(2008) 035207

$\pi^- p \to n\phi$ & $pp \to pp\phi$ & $pn \to d\phi$ → large $g_{N^*N\phi}$

Xie, Zou & Chiang, PRC77(2008)015206; Cao, Xie, Zou & Xu, PRC80(2009)025203

- **Strange decays of $\Lambda^*(1670)$: PDG → large $g_{\Lambda^*\Lambda\eta}$**

narrower width (35MeV) than $\Lambda^*(1405)$



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 Λ(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

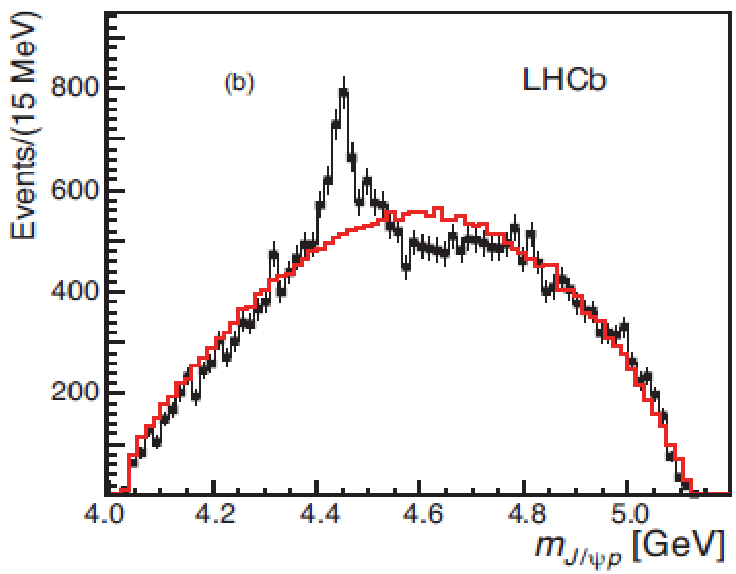
LHCb confirms our prediction of 3 narrow P_c states

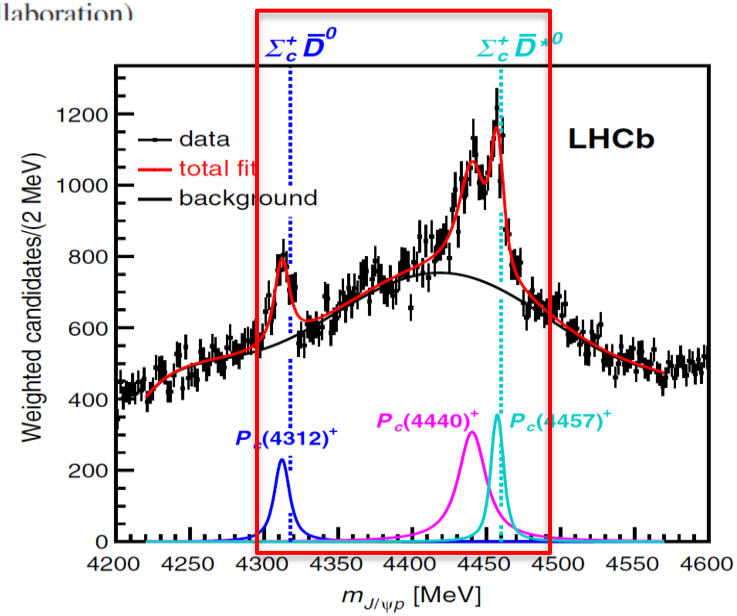
Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

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)	2738 cites
Z_c(3900)	→	top cited paper for BES (2013)	1187 cites
P_c states	→	top cited paper for LHCb (2015)	1931 cites

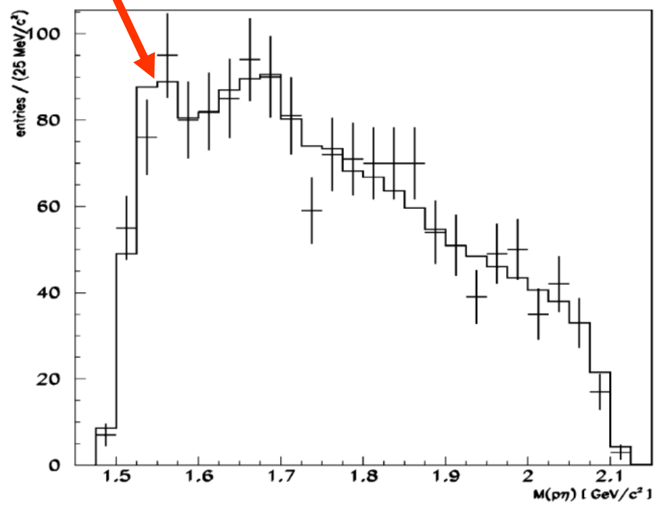
H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1:
"The hidden-charm pentaquark and tetraquark states" 1234 cites

F.K.Guo, C.Hanhart, U.Meissner, Q.Wang, Q.Zhao, B.S.Zou,
Rev.Mod.Phys. 90 (2018)015004: "Hadronic molecules" 1347 cites

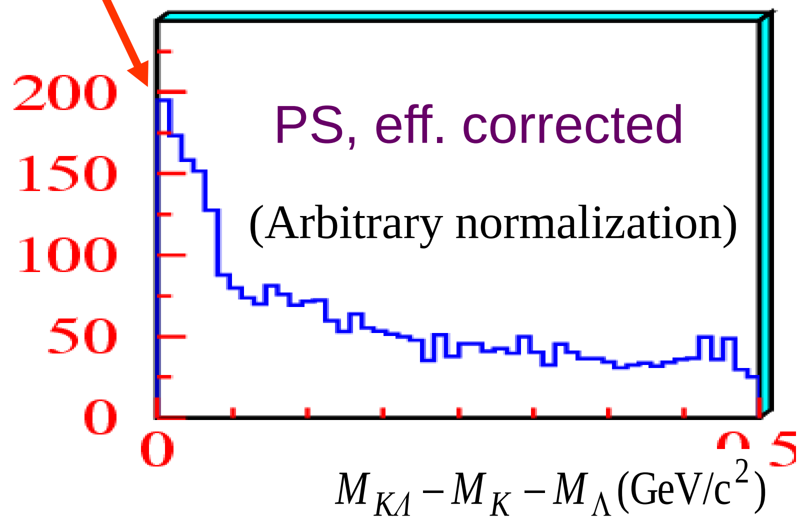
How about strange partners of P_c and Z_c states ?

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

KΣ molecule - N*(1535) in J/ψ decays



BES, PLB510 (2001) 75

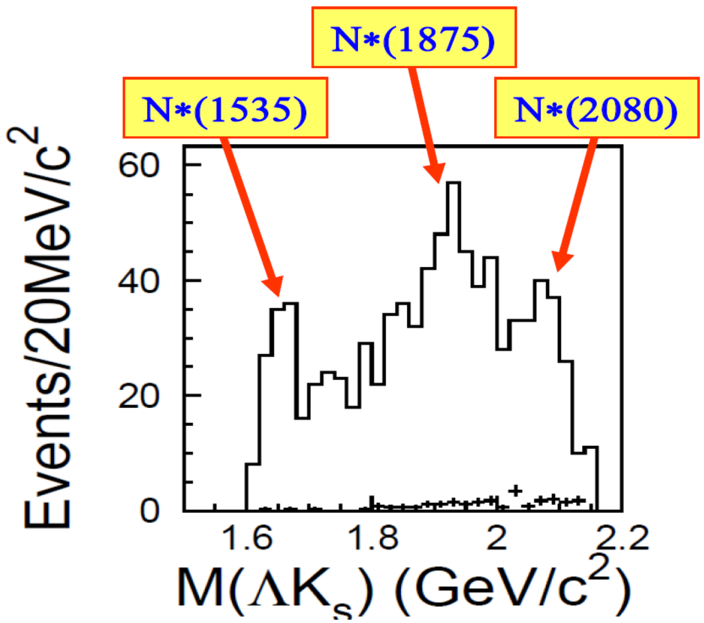


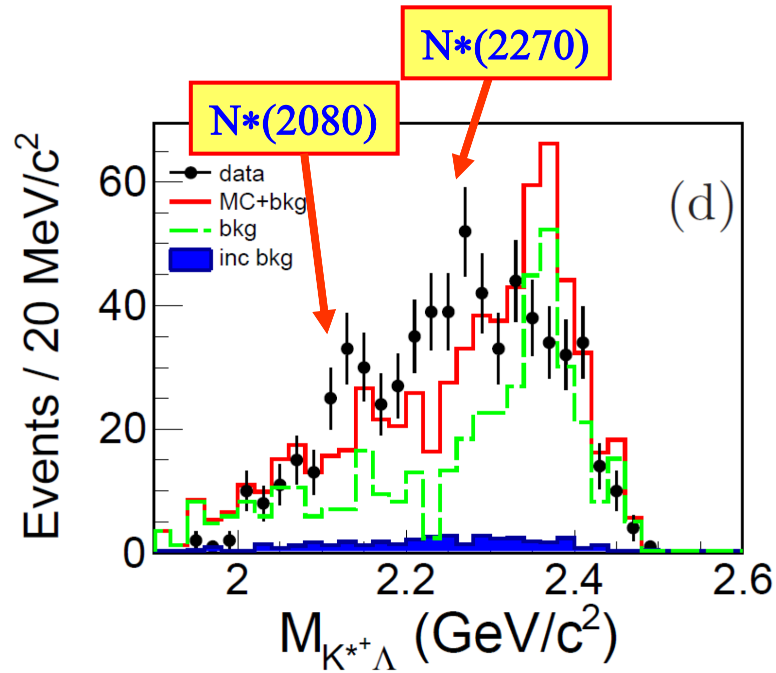
BESII, IJMPA20 (2005) 1985

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

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

N*(1875)	N*(2080)	N*(2270)
$K\Sigma^*$ ~1880	$K^*\Sigma$ ~ 2086	$K^*\Sigma^*$ ~ 2280





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

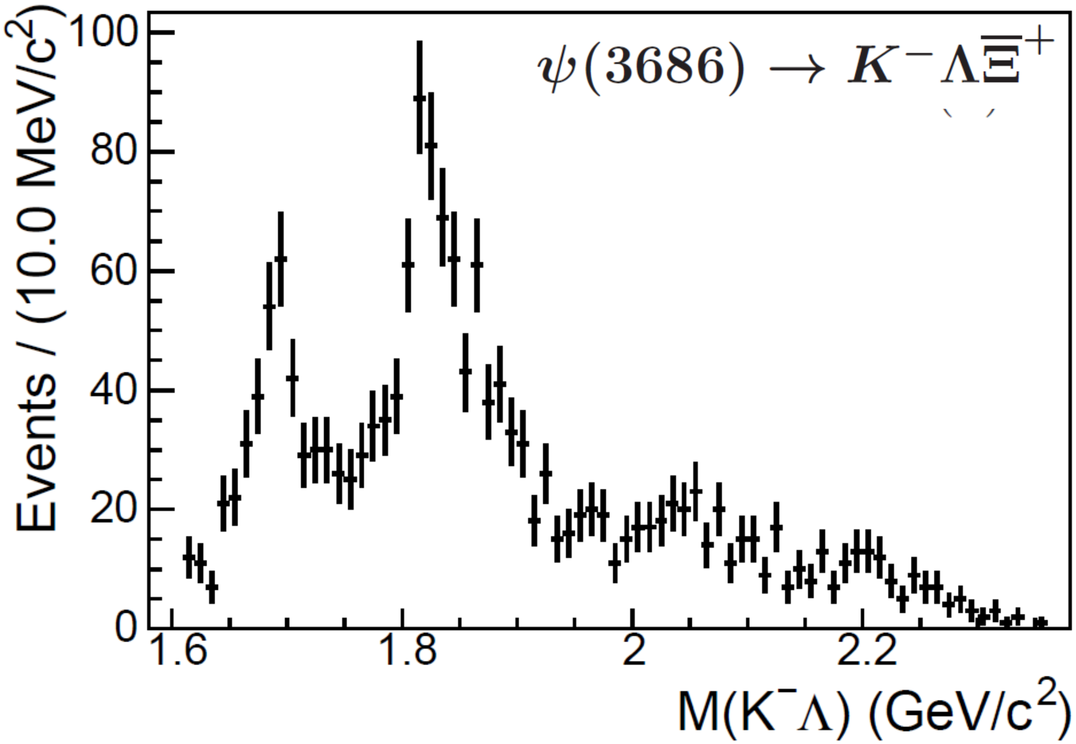
BESII, PLB659 (2008) 789

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

BESIII, PRD100(2019)052010

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

BESIII, PRD 109 (2024) 072008



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

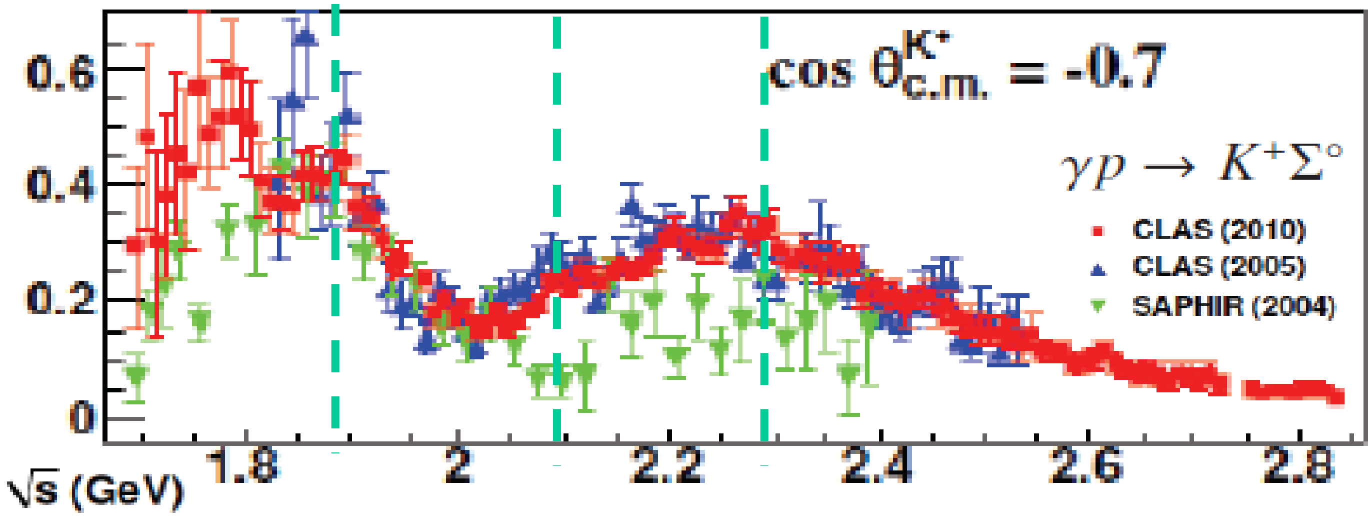
$1/2^-$ **$3/2^-$**

KΣ*, K*Σ, K*Σ* molecules from γp reactions

J.C.Suo, Di Ben, B.S.Zou, ArXiv:2504.05811

KΣ* ~1880 K*Σ ~ 2086 K*Σ* ~ 2280

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

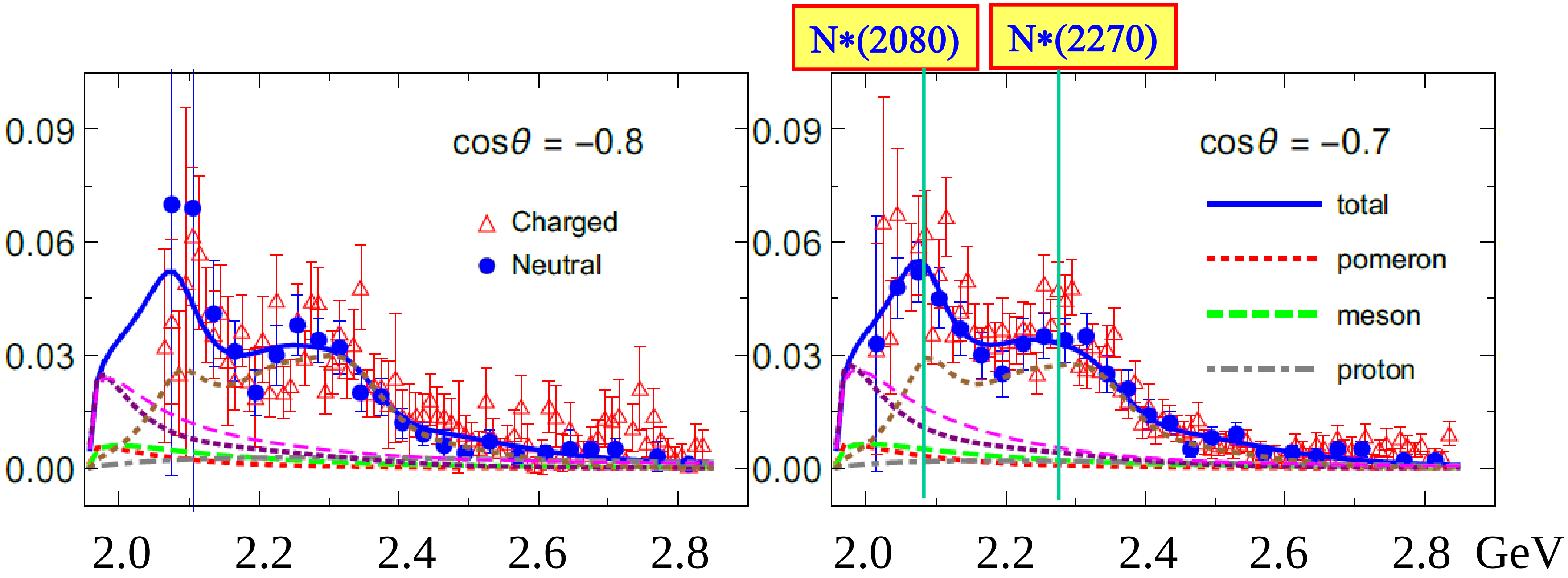


KΞ ~1810 KΞ* ~ 2027 K*Ξ ~ 2210 K*Ξ* ~ 2427

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⁻)

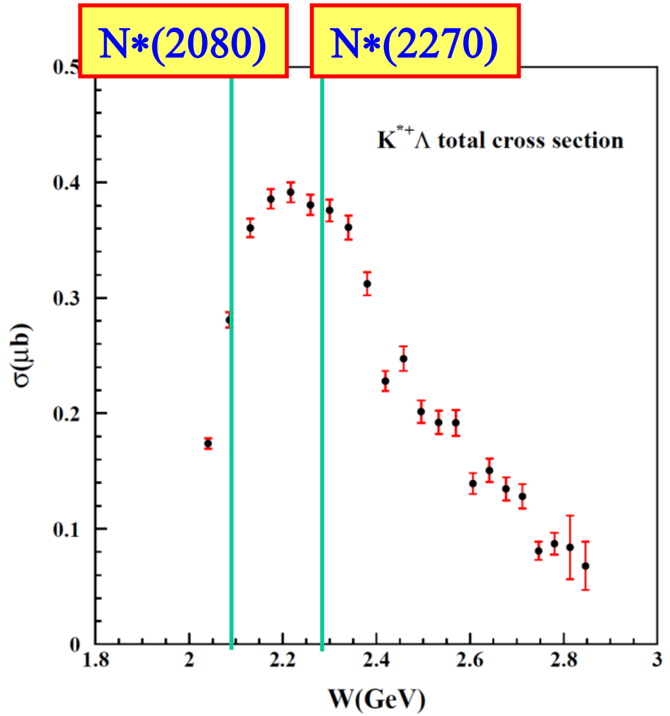
$\gamma p \to \phi p$ CLAS, PRC89(2014)019901

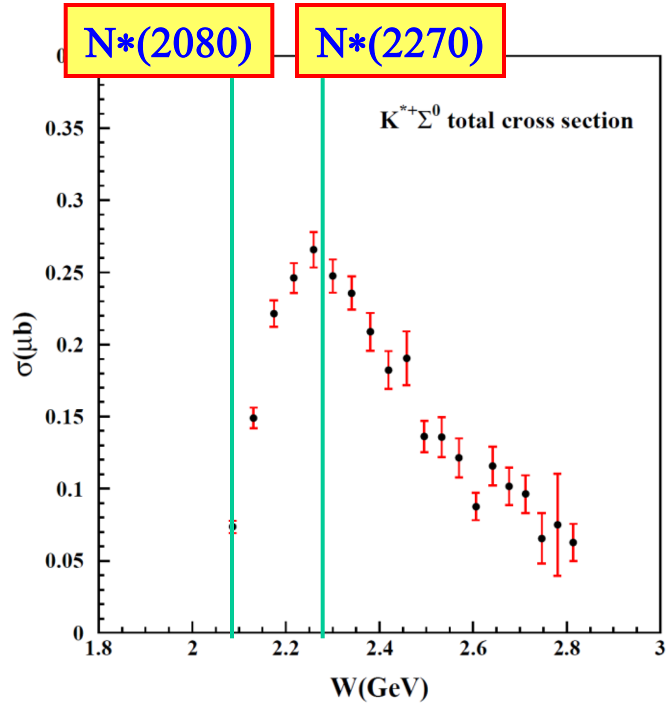


S.M.Wu, F.Wang, B.S.Zou, PRC108(2023)045201

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

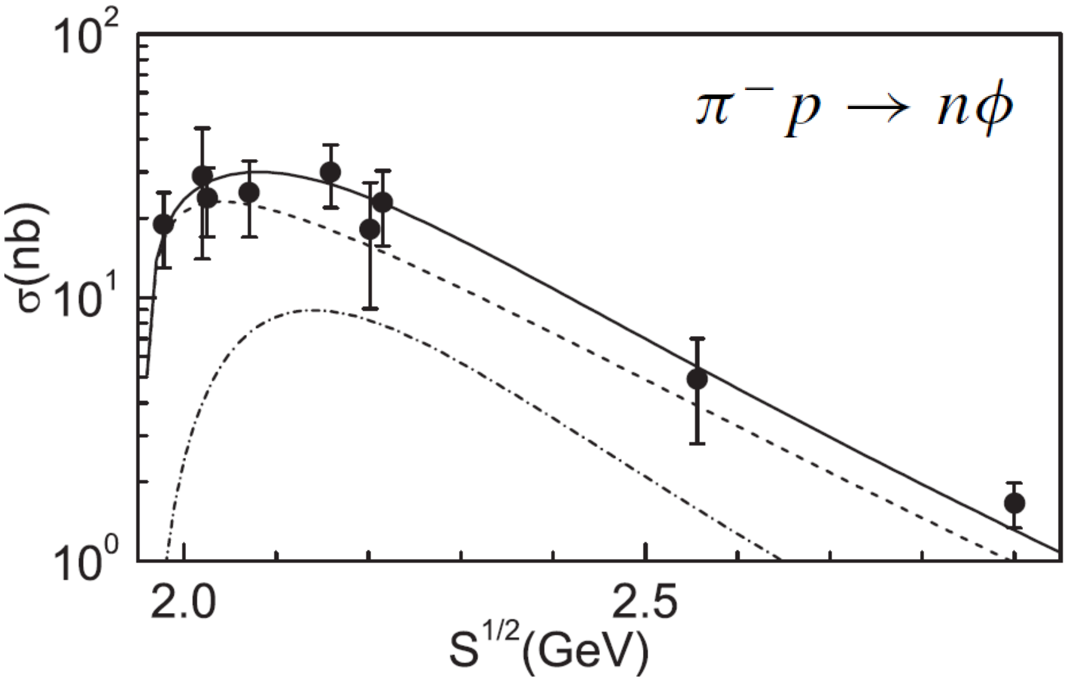
CLAS, PRC 87(2013)065204





Di Ben, A.C.Wang, F.Huang, B.S.Zou, PRC 108 (2023) 065201
W.Y.Tian, N.C.Wei, F.Huang, B.S.Zou, submitted to PRC
J.Shi, B.S.Zou, ArXiv:2504.04333

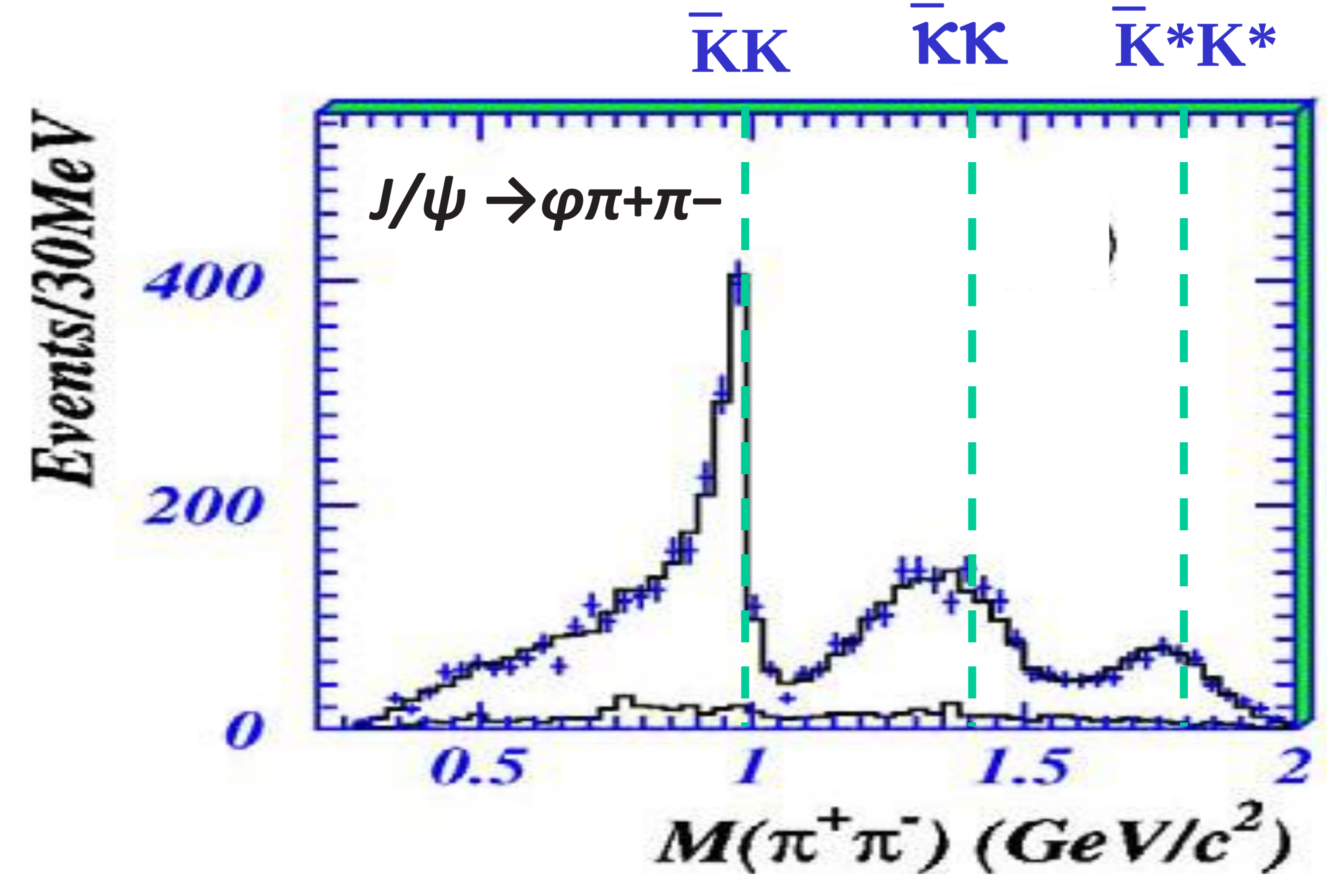
J.J.Xie, B.S.Zou, H.C.Chiang, PRC77(2008)015206



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

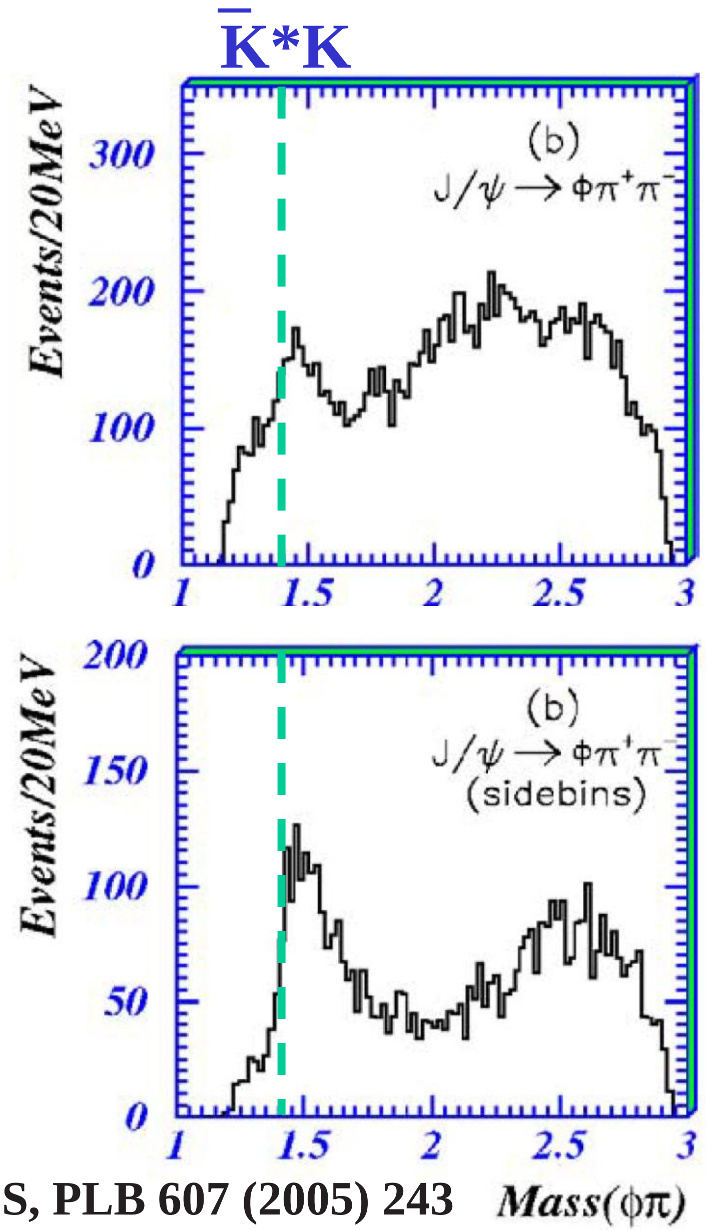
More data with angular distribution and polarization information are needed !

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



BES, PLB 607 (2005) 243

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



BES, PLB 607 (2005) 243

Other possible $\bar{K}^*K$ states: $f_1/a_1(1420)$, $h_1(1380)$ - BESIII, PRD 98 (2018) 072005

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 :

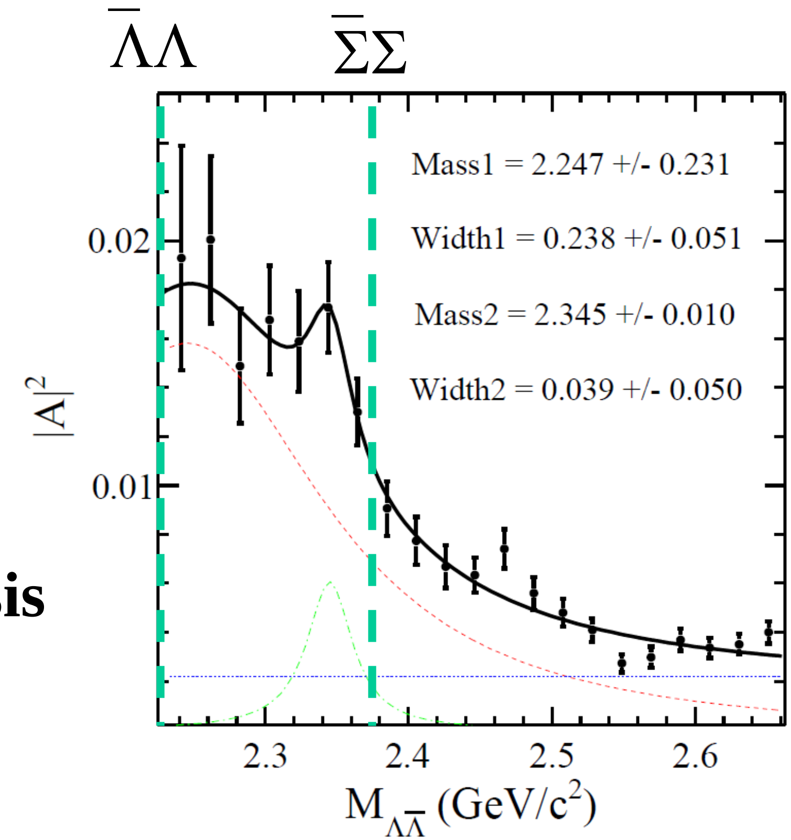
Y(2175) — $\bar{\Lambda}\Lambda\ (^3S_1)$; $\eta(2225)$ — $\bar{\Lambda}\Lambda\ (^1S_0)$

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 $\bar{\Lambda}\Lambda$ / $\bar{\Sigma}\Sigma$

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

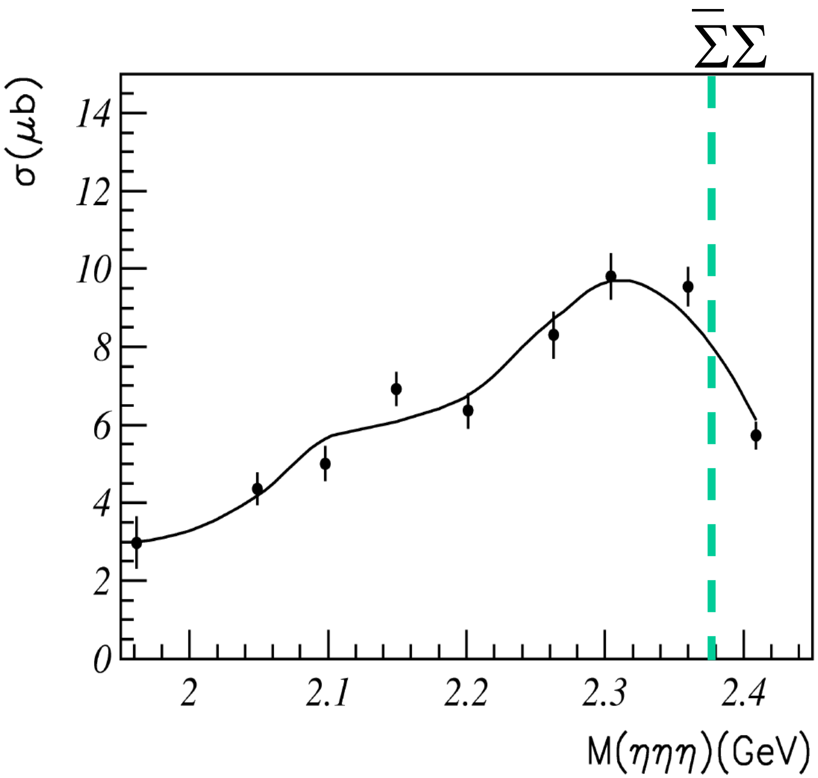


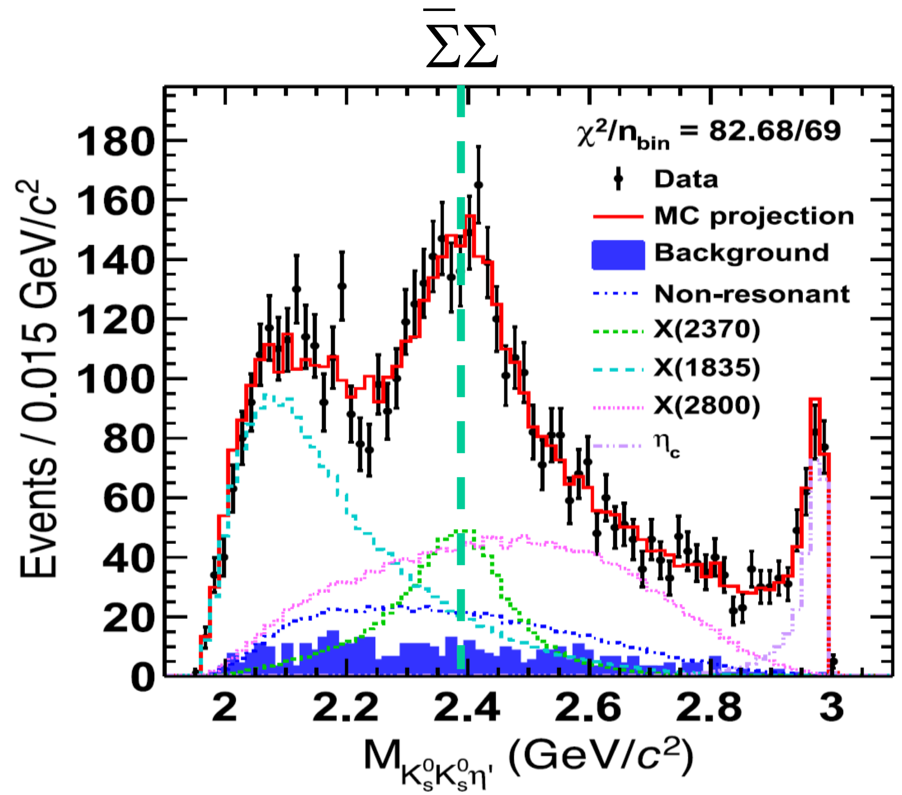
J.P.Dai, Ph.D thesis (2012)

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。

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

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

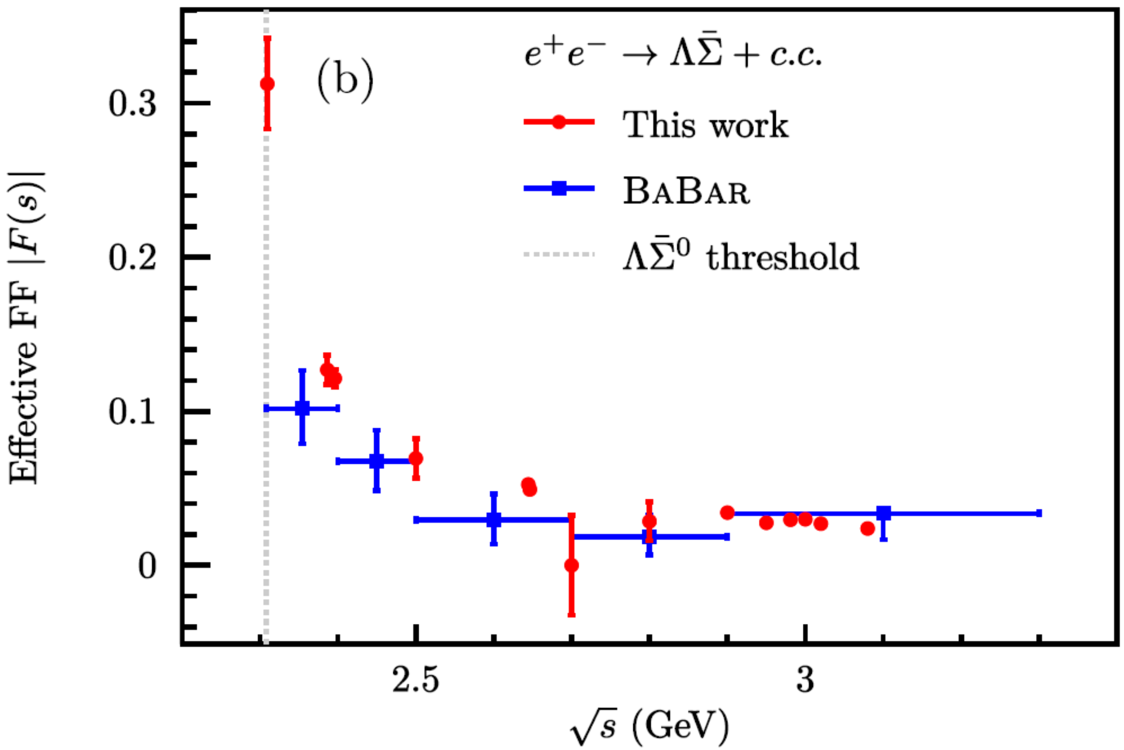




A.V. Anisovich et al., PLB 496 (2000) 145

BESIII, PRL132(2024)181901

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



BESIII, 109 (2024) 012002

5. Summary

- strange partners of P_c, Z_c … states are expected to exist
- strong evidence for their existence in $\bar{c}c$ decays, γp and pp
- more experiments with higher statistics are needed

Thank you for your attention !