Production of penta-quark states with strangeness in various reactions

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Outline

1. **Pentaquarks started from strangeness**
2. **Production of $K\Sigma$, $K\Sigma^*$, $K^*\Sigma$, $K^*\Sigma^*$ molecules**
3. **Production of $\bar{K}\Sigma$, $\bar{K}\Sigma^*$, $\bar{K}^*\Sigma$, $\bar{K}^*\Sigma^*$ molecules**
4. **Production of $K\Xi$, $K\Xi^*$, $K^*\Xi$, $K^*\Xi^*$ molecules**
5. **Summary**

1. Pentaquarks started from strangeness

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: $N^*(1535)$ $K\Sigma$ - $K\Lambda$ dynamic generated -- Kaiser, …

2001: $\Lambda(1405)$ 2 pole structure by $\bar{K}N$-$\Sigma\pi$ -- Oller, …

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.**"

$1/2^-$ baryon nonet with strangeness

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

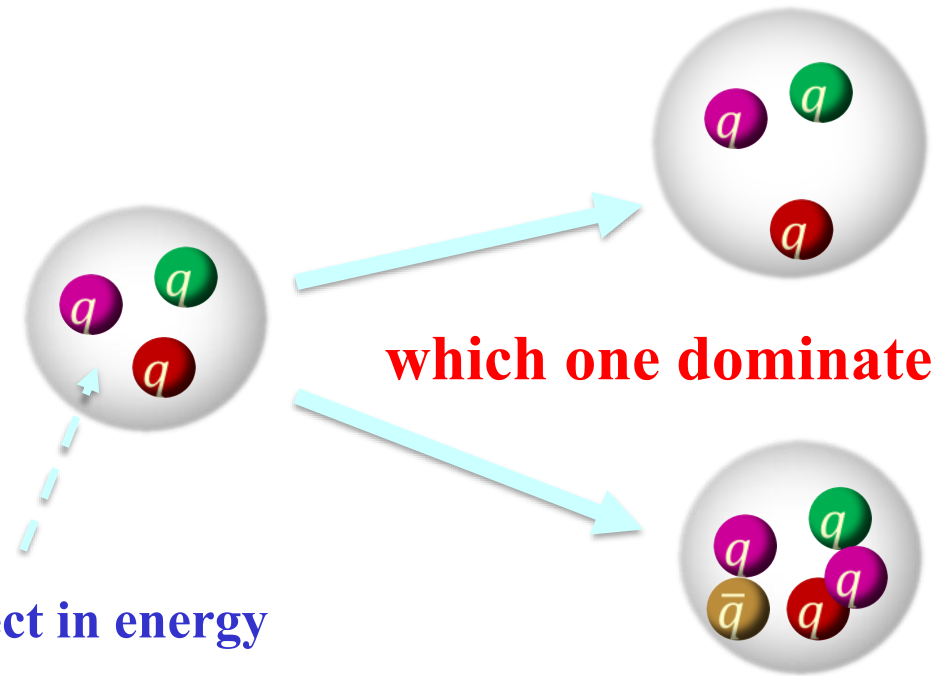
uds (L=1) $1/2^-$	~	$\Lambda^*(1670)$	~	$[us][ds]\bar{s}$		$K\Xi - \eta\Lambda$
uss (L=1) $1/2^-$	~	$\Xi^*(1610)$	~	$[us][ds]\bar{d}$		$\bar{K}\Sigma - \bar{K}\Lambda - \pi\Xi$
uud (L=1) $1/2^-$	~	$N^*(1535)$	~	$[ud][us]\bar{s}$		$K\Sigma - K\Lambda - \eta N$
uds (L=1) $1/2^-$	~	$\Lambda^*(1405)$	~	$[ud][su]\bar{u}$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

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

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

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

- 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

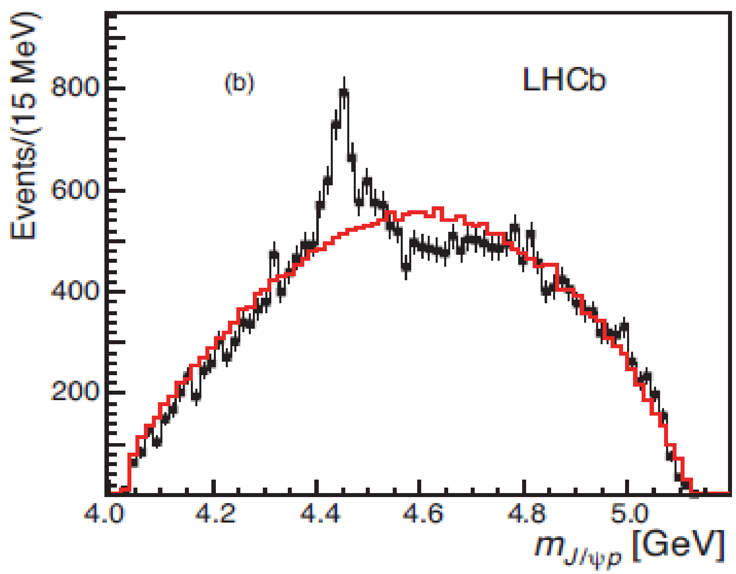
LHCb confirms our prediction of 3 narrow P_c states

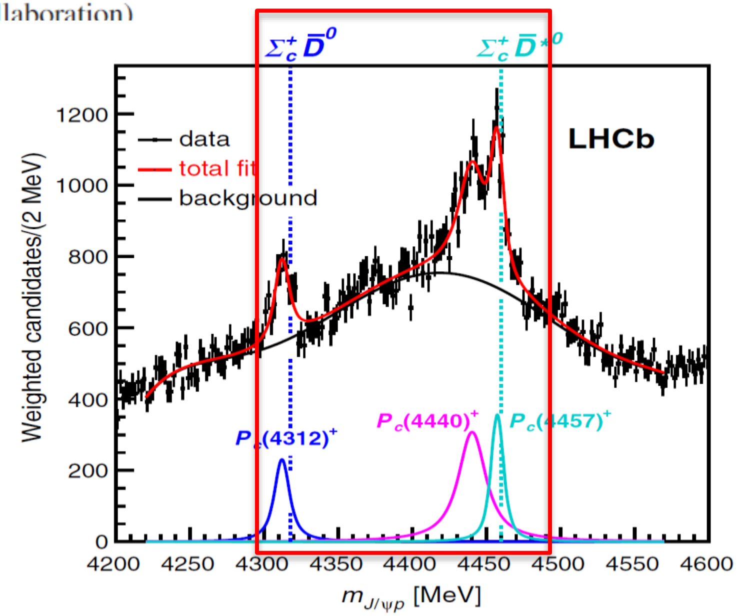
Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

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)	3047 cites
Z_c(3900)	→	top cited paper for BES (2013)	1318 cites
P_c states	→	top cited paper for LHCb (2015)	2215 cites

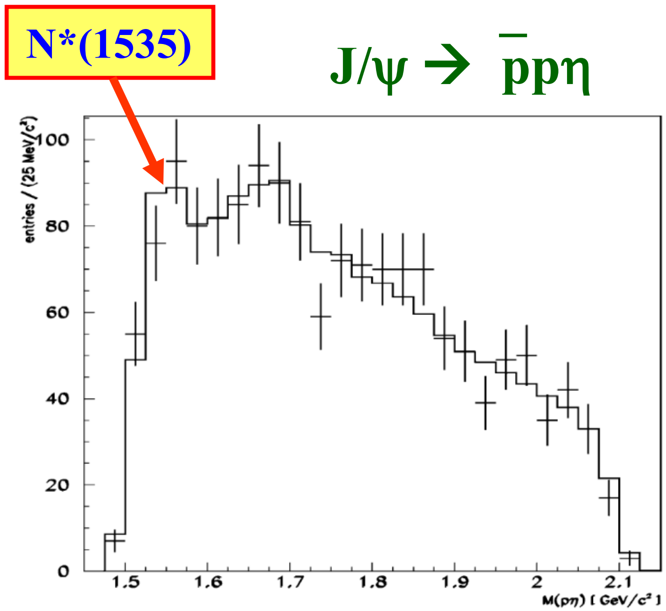
H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1:
"The hidden-charm pentaquark and tetraquark states" 1464 cites

F.K.Guo, C.Hanhart, U.Meissner, Q.Wang, Q.Zhao, B.S.Zou,
Rev.Mod.Phys. 90 (2018)015004: "Hadronic molecules" 1682 cites

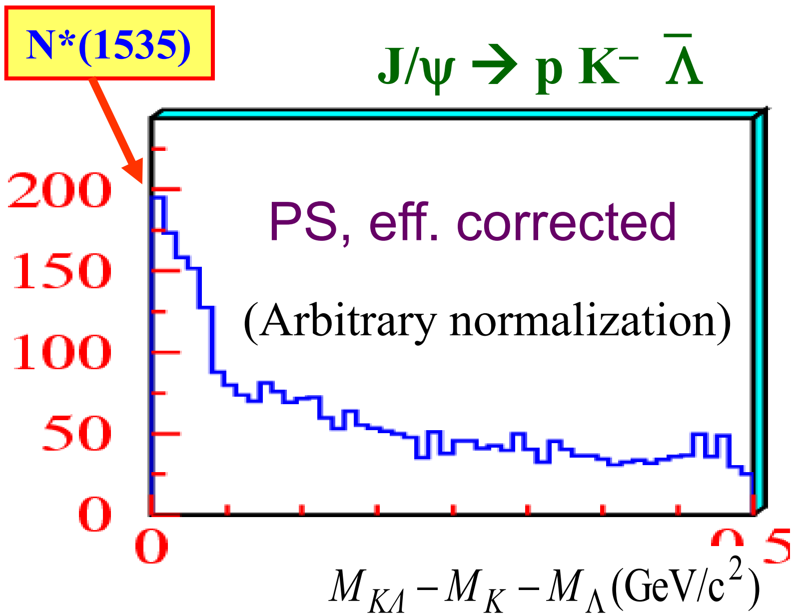
How about strange partners of P_c?

2. Production of KΣ, KΣ*, K*Σ, K*Σ* molecules

KΣ molecule - N*(1535) in J/ψ decays



BES, PLB510 (2001) 75



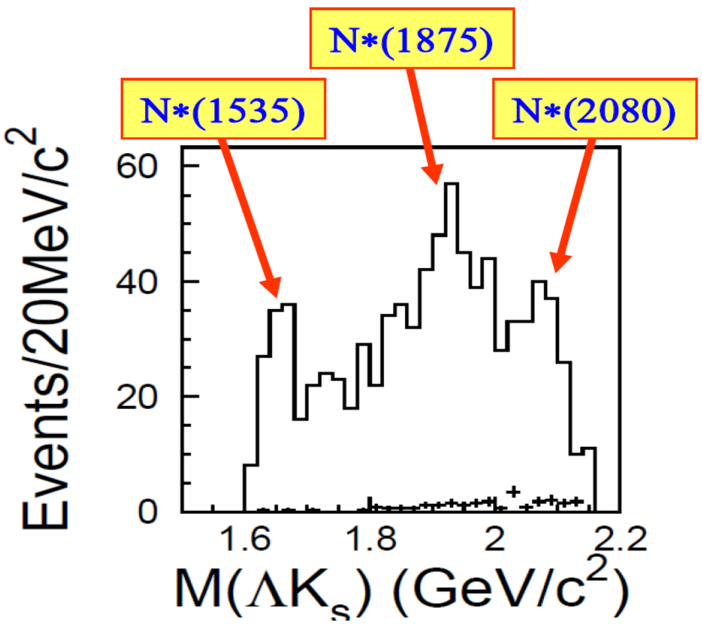
BESII, IJMPA20 (2005) 1985

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

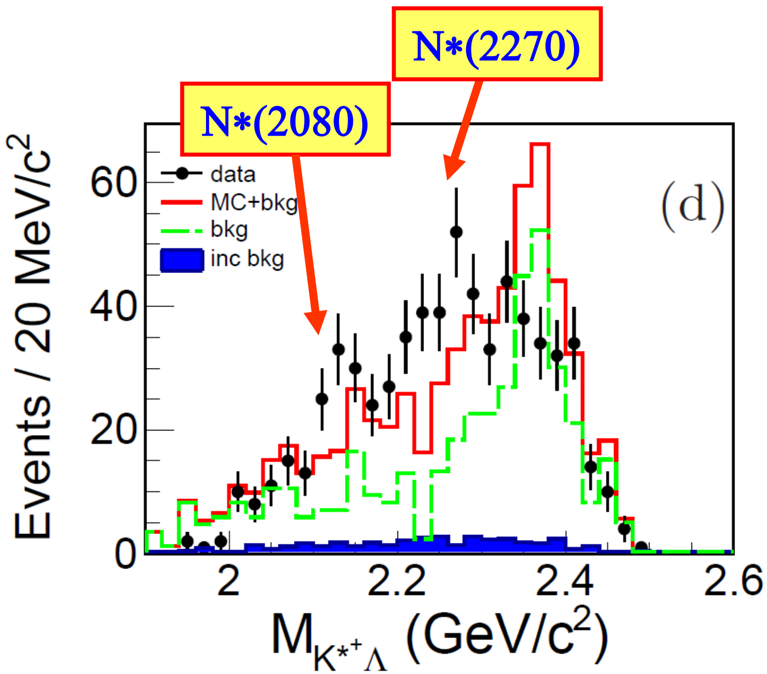
N*(1875) **N*(2080)** **N*(2270)**

$K\Sigma^* \sim 1880$ $K^*\Sigma \sim 2086$ $K^*\Sigma^* \sim 2280$



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

BESII, PLB659 (2008) 789



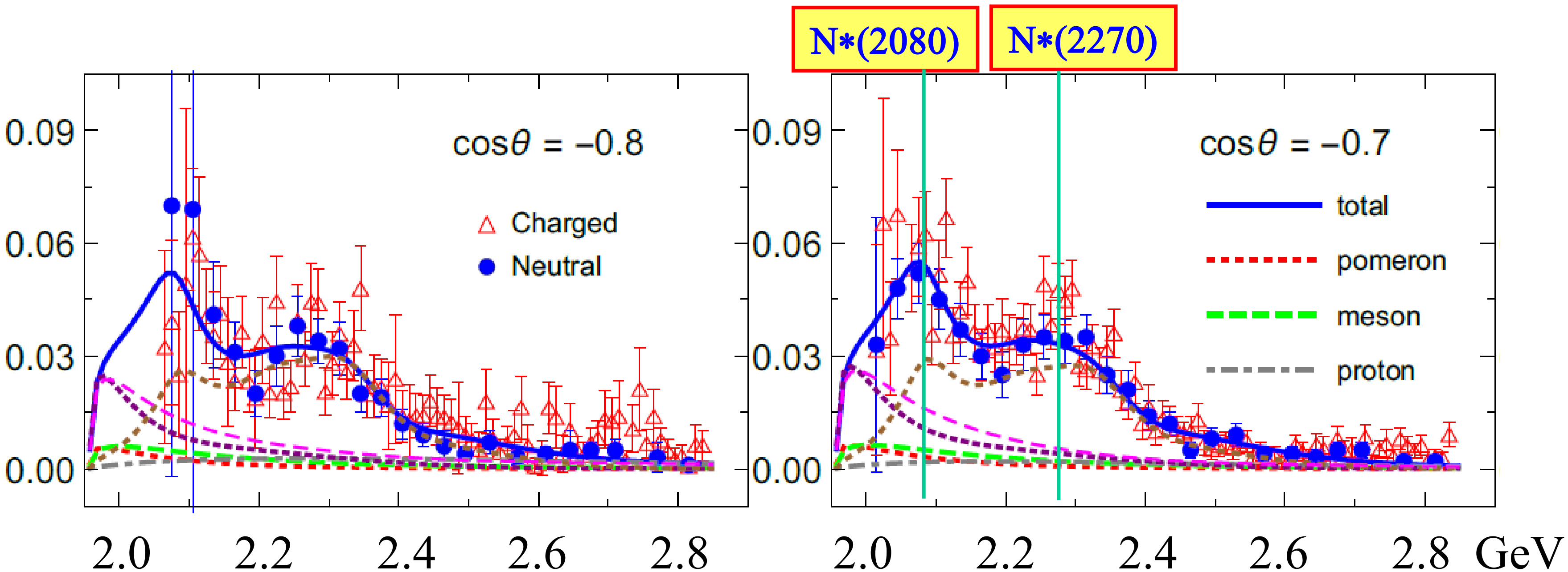
$\chi_{c0} \to \bar{p}K^{*+}\Lambda$ +c.c.

BESIII, PRD100(2019)052010

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

KΣ* ~1880	K*Σ ~ 2086	K*Σ* ~ 2280
N*(1875)	N*(2080)	N*(2270)

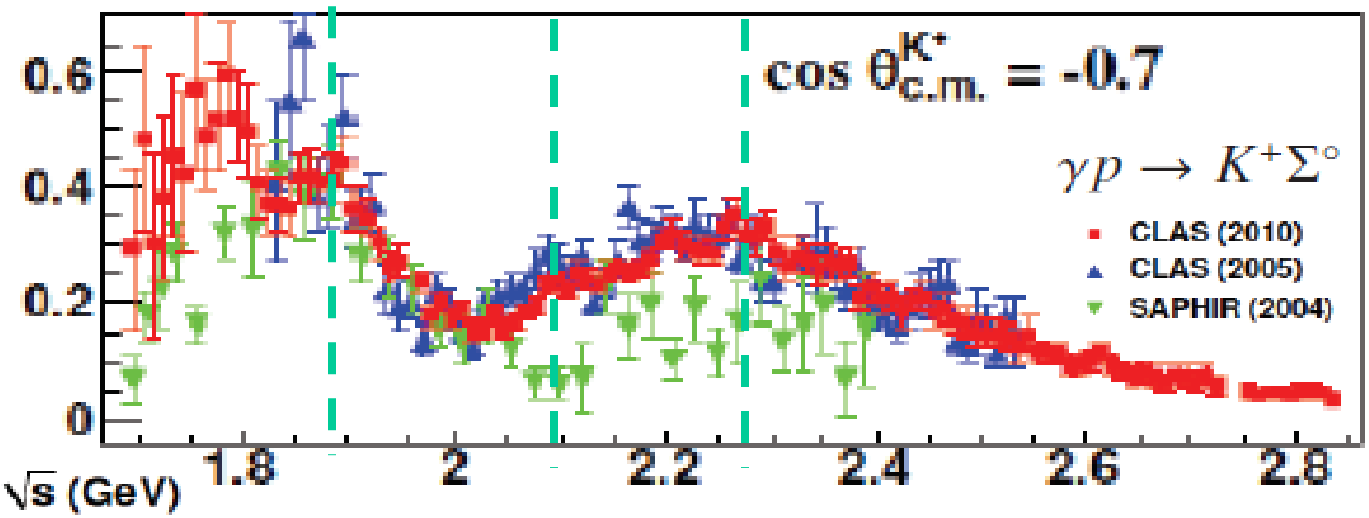
$\gamma p \to \phi p$ CLAS, PRC89(2014)019901



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

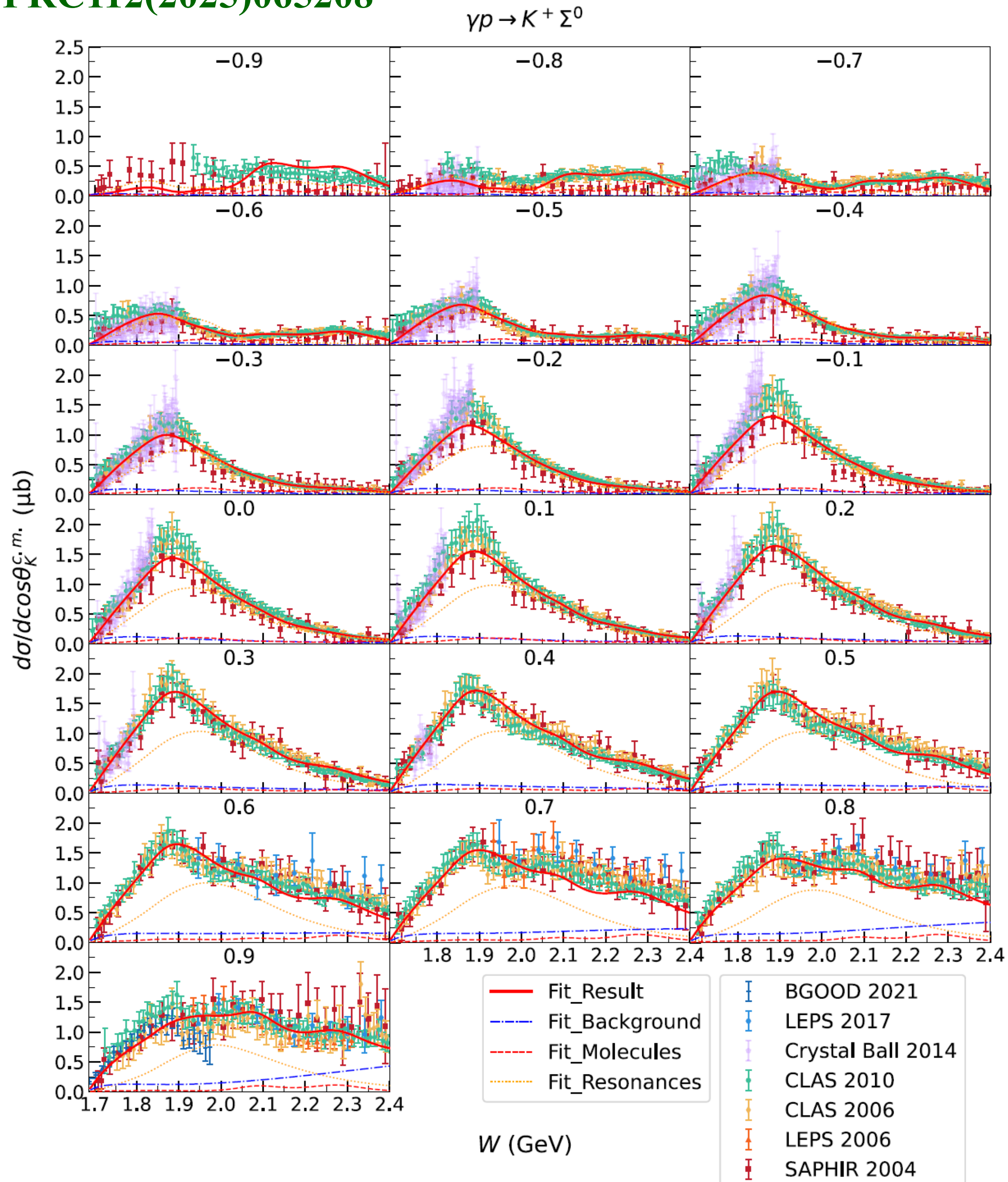
KΣ^* ~1880 **K*Σ ~ 2086** **K*Σ^* ~ 2280**

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



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

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



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

without D_{13}

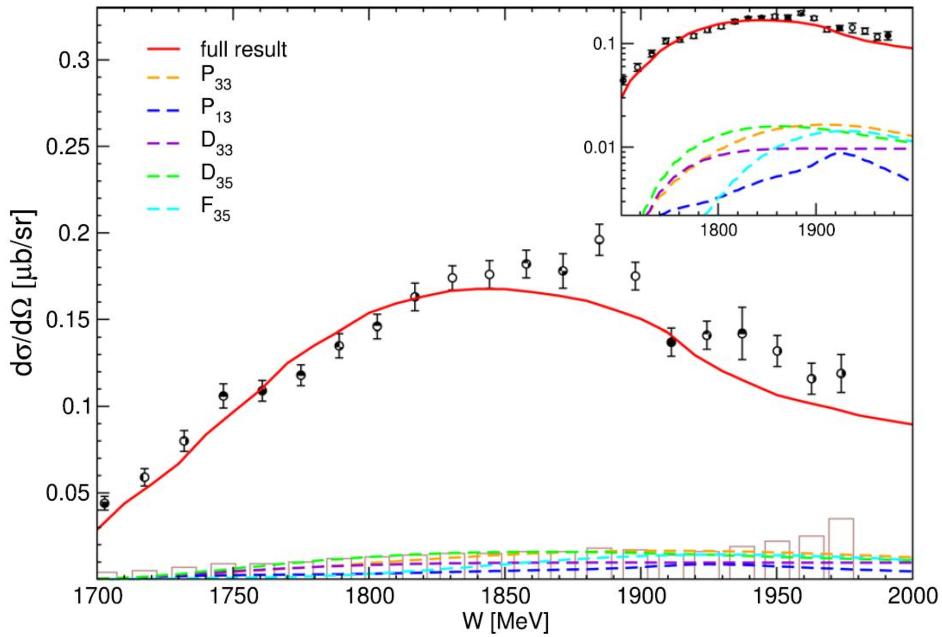
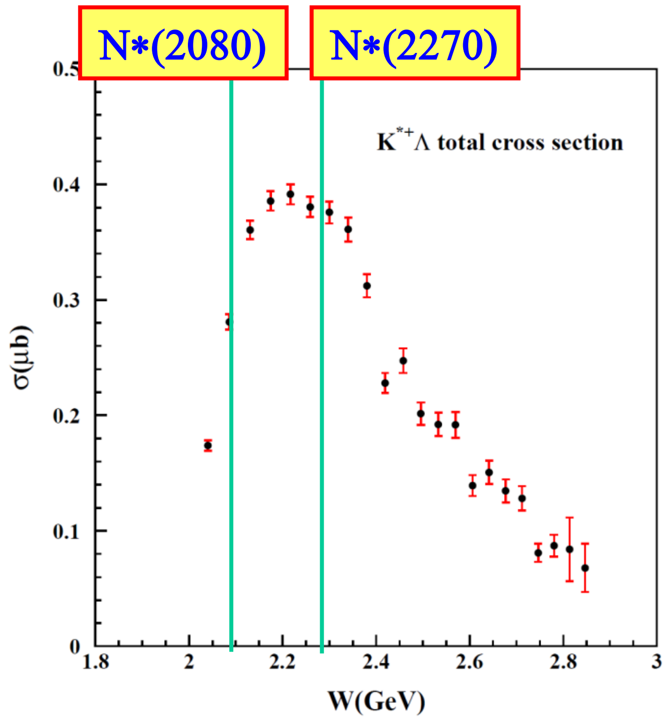
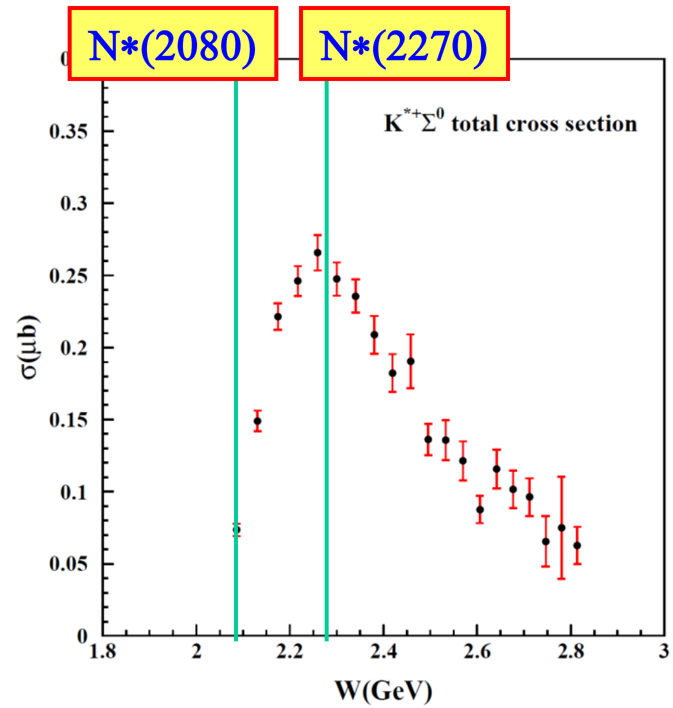


Fig. 12 Forward differential cross section ($\cos\theta > 0.9$) reaction $\gamma p \to K^+\Sigma^0$. Only dominant partial waves are shown. The box in the upper right corner shows the same picture on a logarithmic scale. Data from Ref. [82] (not included in the fit). We fit the data shown in Fig. 2 from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

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

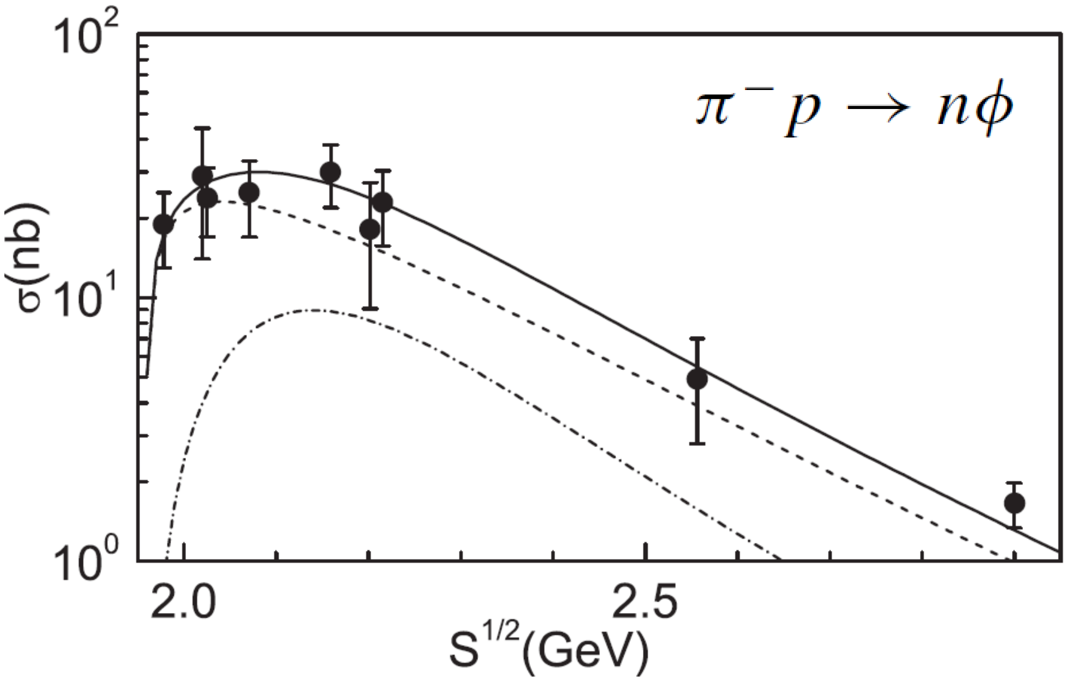
CLAS, PRC 87(2013)065204





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

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

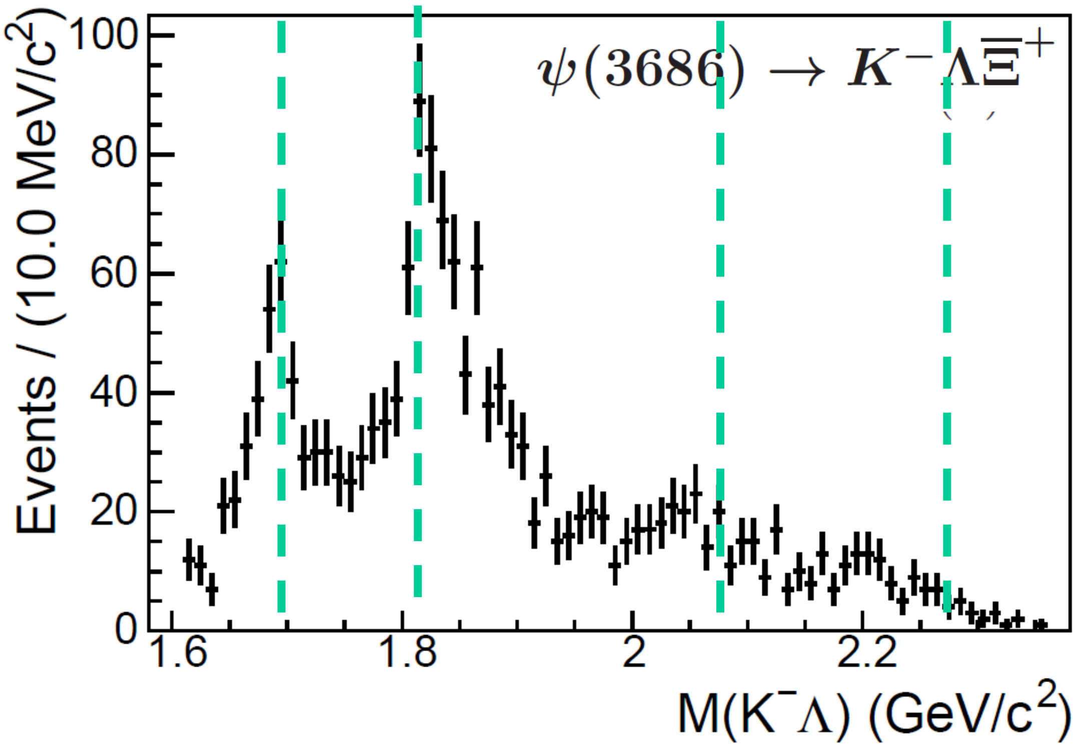


N*(1535) + N*(1900) ½+ or N*(1875)+N*(2080)+N*(2270) ?

More data with angular distribution and polarization information are needed !

3. Production of $\bar{K}\Sigma$, $\bar{K}\Sigma^*$, $\bar{K}^*\Sigma$, $\bar{K}^*\Sigma^*$ molecules

BESIII, PRD 109 (2024) 072008



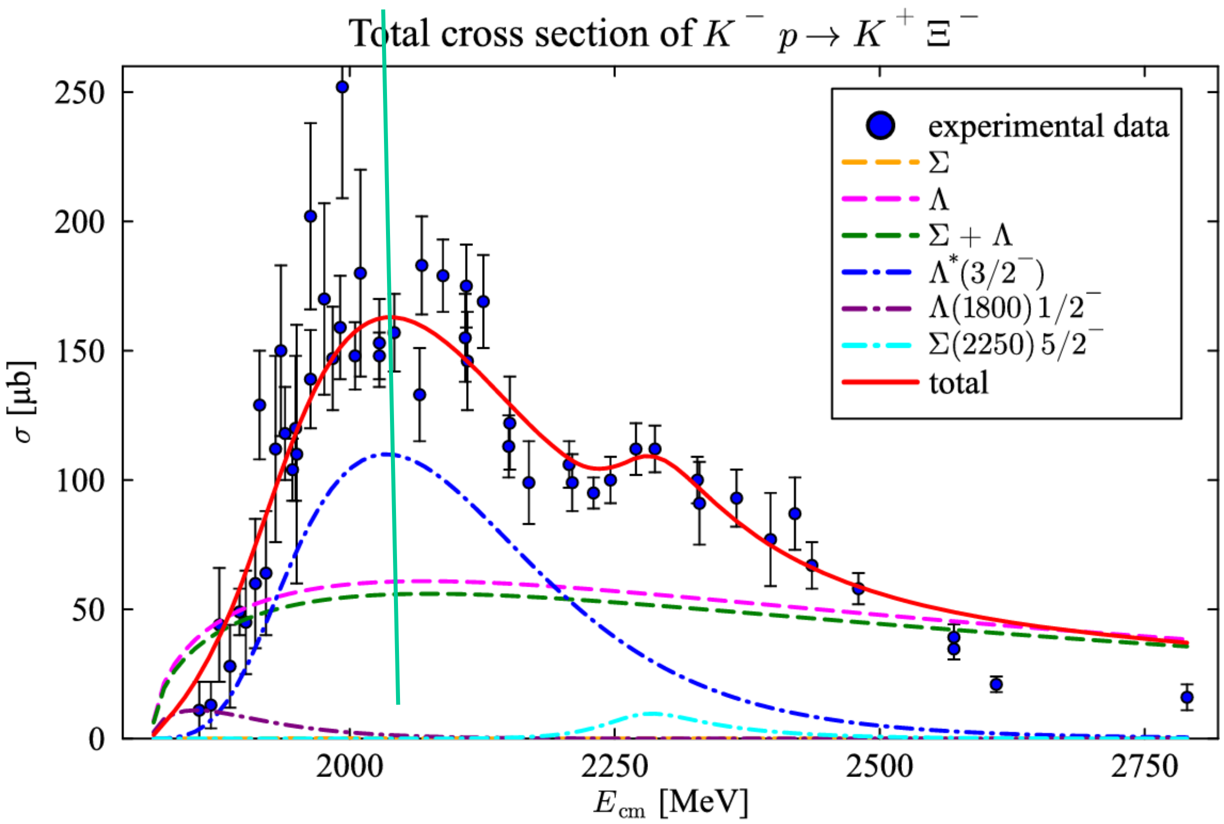
$\bar{K}\Sigma \sim \Xi(1680)$, $\bar{K}\Sigma^* \sim \Xi(1820)$, $\bar{K}^*\Sigma \sim \Xi(2080)$, $\bar{K}^*\Sigma^* \sim \Xi(2270)$

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

4. Production of KΞ, KΞ*, K*Ξ, K*Ξ* molecules

KΞ* molecule

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



KΞ ~1810 — **Λ(1/2⁻)**

KΞ* ~ 2027 — **Λ(3/2⁻)**

K*Ξ ~ 2210 — **Λ(1/2⁻,3/2⁻)**

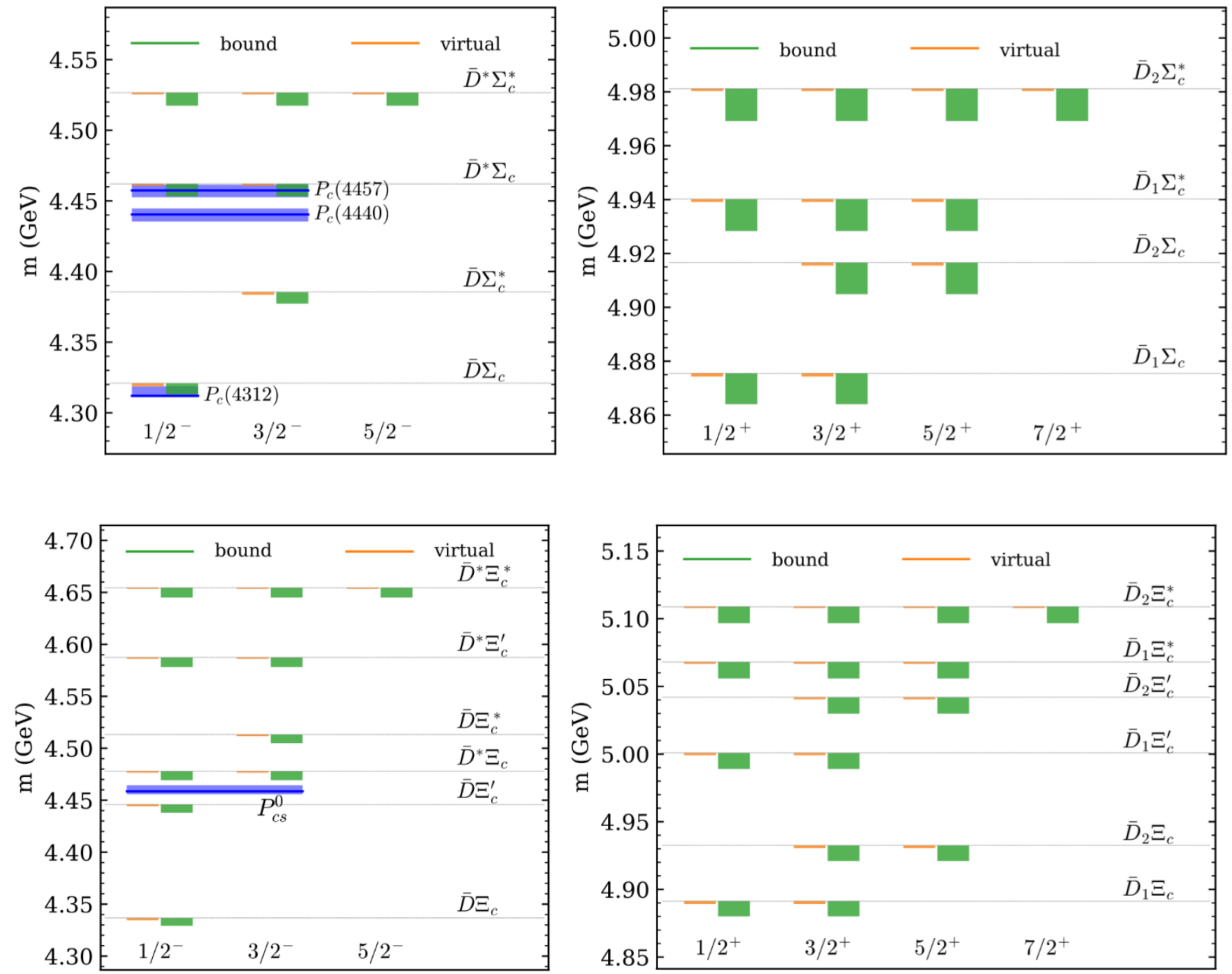
K*Ξ* ~ 2427 — **Λ(1/2⁻,3/2⁻,5/2⁻)**

5. Summary & prospects

- **Many pentaquark states with strangeness are expected to exist, with strong evidence for some of them in $c\bar{c}$ decays, γp and Kp**
- **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**

A survey of hadronic molecules with hidden charm

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



P_c

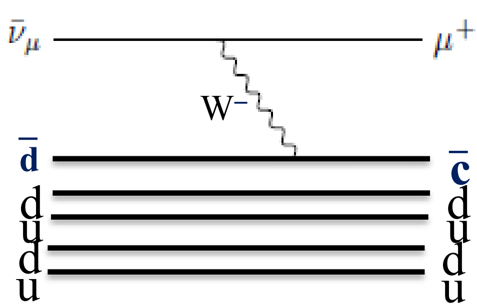
P_{cs}

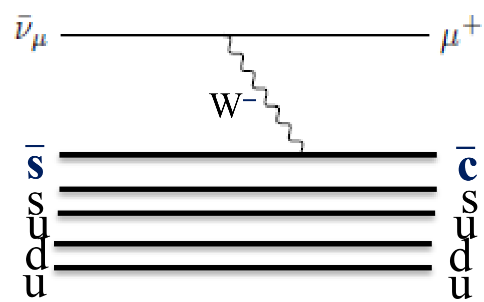
$\bar{\nu}$p - nice tool for exploring pentaquarks

K.S.Qiao, B.S.Zou, PRD113(2026)113005

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

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





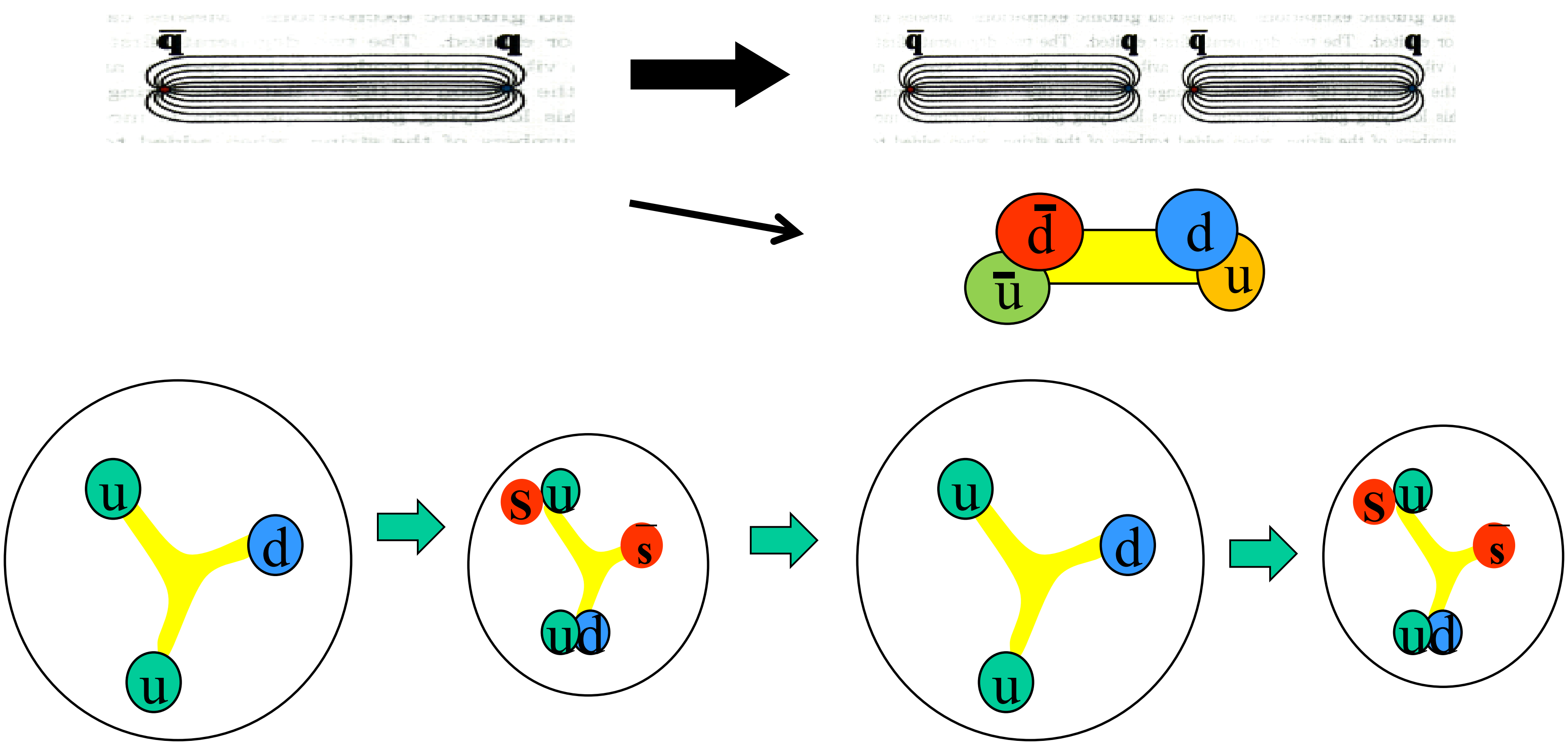
$\bar{c}$dudu & $\bar{c}$sudu pentaquark states are predicted to exist

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



Thank you for your attention !