Building up pentaquark spectrum as hadronic molecules

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Outline：

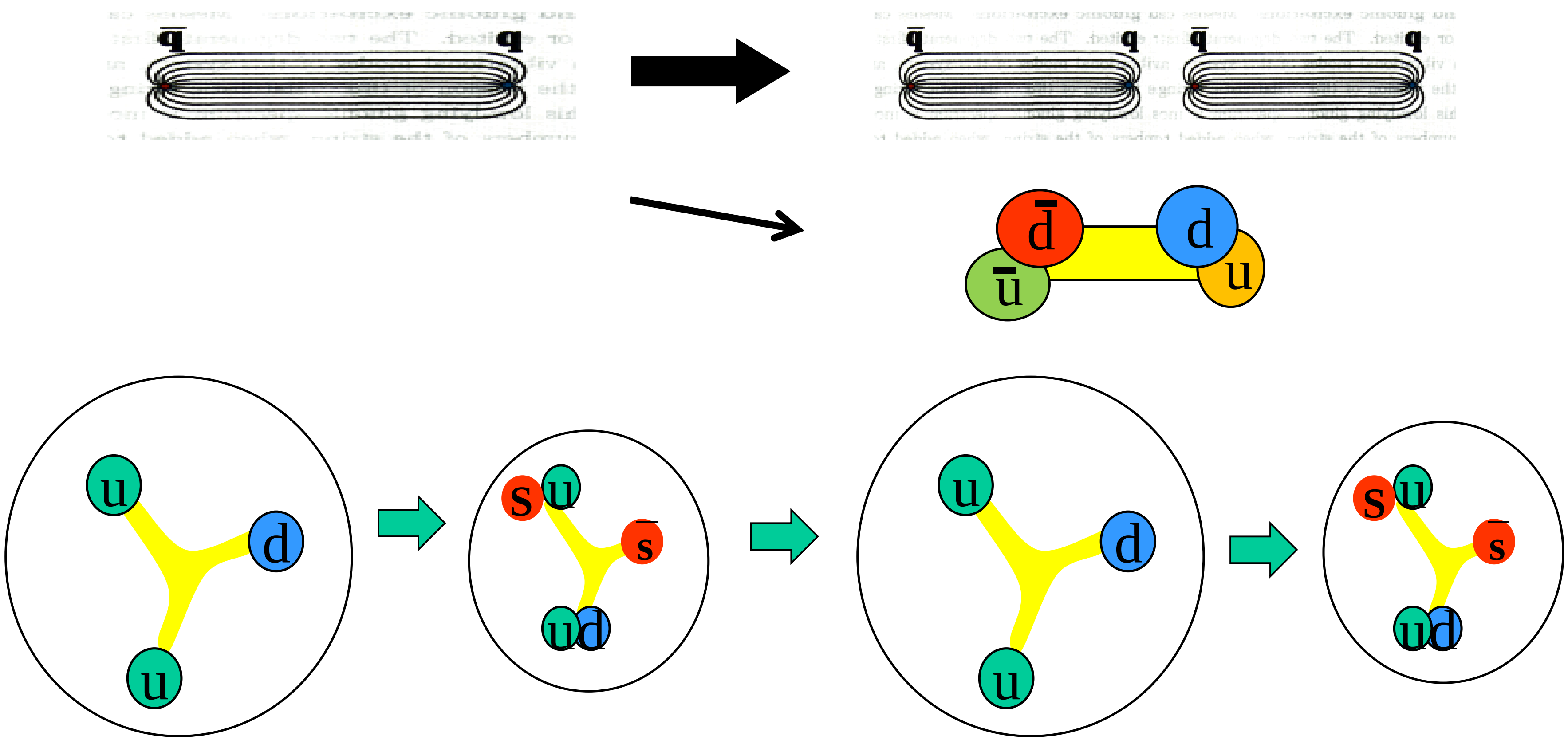
- Motivation for pentaquarks
- Pentaquark spectrum as hadronic molecules
- Pentaquarks at BEPC3 or super tau-charm

1. Motivation for pentaquarks

A key problem in QCD and hadron structure

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

crucial for quark confinement & hadron structure



For the proton, $\bar{d} - \bar{u} \sim 0.12$, spin crisis, $\bar{s}s$

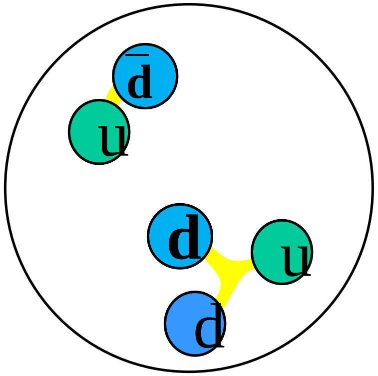
→ ~30% pentaquarks in the proton

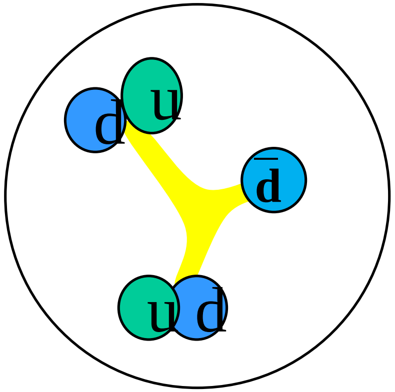
Meson cloud picture: Thomas, Speth, Henley, Meissner, Miller, Weise, Oset, Brodsky, Ma, …

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

Penta-quark picture : Riska, Zou, Zhu, …

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





Nature of 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 Λ*(1670) :** PDG → large $g_{\Lambda^*\Lambda\eta}$

narrower width (35MeV) than Λ*(1405)

Difficulties to pin down pentaquarks

Fate of the first pentaquark predicted and observed:

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 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."

New direction for hunting for pentaquarks:

“Prediction of narrow N* and Λ* resonances with hidden charm above 4 GeV”,
Wu, Molina, Oset, Zou, PRL105 (2010) 232001

	(I,S)	M	Γ	Γ_i						J^P
	$(1/2,0)$			πN	ηN	$\eta' N$	$K\Sigma$		$\eta_c N$	
N* - $\bar{D}\Sigma_c$		4261	56.9	3.8	8.1	3.9	17.0		23.4	$1/2^-$
	$(0,-1)$			$\bar{K}N$	$\pi\Sigma$	$\eta\Lambda$	$\eta'\Lambda$	$K\Xi$	$\eta_c\Lambda$	
Λ* $\bar{D}\Xi_c$		4209	32.4	15.8	2.9	3.2	1.7	2.4	5.8	
$\bar{D}\Xi'_c$		4394	43.3	0	10.6	7.1	3.3	5.8	16.3	

TABLE V: Mass (M), total width (Γ), and the partial decay width (Γ_i) for the states from $PB \to PB$, with units in MeV.

	(I,S)	M	Γ	Γ_i						J^P
	$(1/2,0)$			ρN	ωN	$K^*\Sigma$			$J/\psi N$	
N*- $\bar{D}^*\Sigma_c$		4412	47.3	3.2	10.4	13.7			19.2	$1/2^-$, $3/2^-$
	$(0,-1)$			K^*N	$\rho\Sigma$	$\omega\Lambda$	$\phi\Lambda$	$K^*\Xi$	$J/\psi\Lambda$	
Λ* $\bar{D}^*\Xi_c$		4368	28.0	13.9	3.1	0.3	4.0	1.8	5.4	
$\bar{D}^*\Xi'_c$		4544	36.6	0	8.8	9.1	0	5.0	13.8	

TABLE VI: Mass (M), total width (Γ), and the partial decay width (Γ_i) for the states from $VB \to VB$ with units in MeV.

Further studies support such hidden charm N*

W.L.Wang, F.Huang, Z.Y.Zhang, B.S.Zou, PRC84(2011)015203:

Chiral quark model → $\bar{D}\Sigma_c$ state ~ 4.31 GeV

Z.C.Yang, Z.F.Sun, J.He, X.Liu, S.L.Zhu, Chin. Phys. C36 (2012) 6

Schoedinger Equation method with π, η, ρ, ω, σ exchanges
→ $\bar{D}^*\Sigma_c$ $(1/2^-, 3/2^-)$ N* state ~ 4.36 – 4.46 GeV

J.J.Wu, T.S.H.Lee, B.S.Zou, PRC85(2012)044002:

EBAC-DCC model → $\bar{D}\Sigma_c$ $(1/2^-)$ ~ 4.3 GeV,
$\bar{D}^*\Sigma_c$ $(1/2^-, 3/2^-)$ ~ 4.4 - 4.5 GeV

C.W.Xiao, J.Nieves, E.Oset, PRD 88 (2013) 056012:

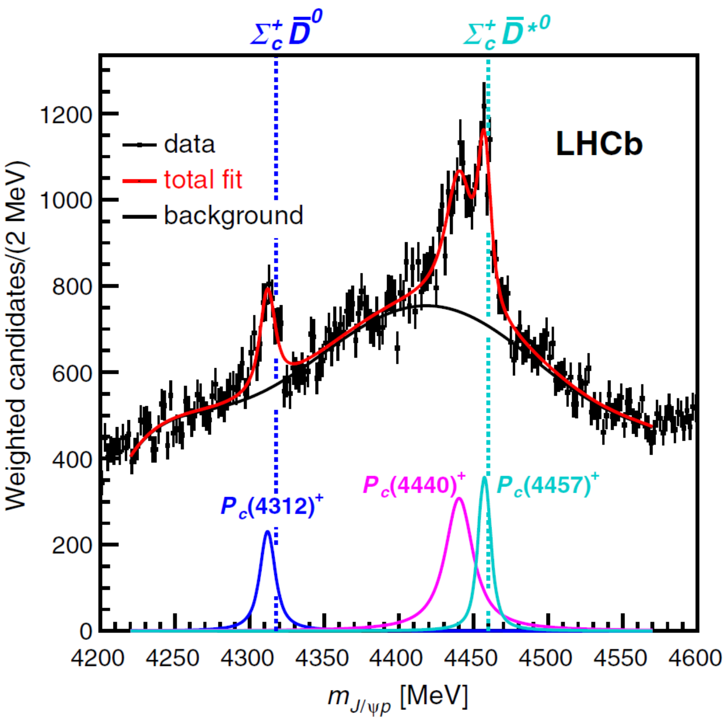
Heavy quark spin symmetry → 7 such N* molecules
$\bar{D}\Sigma_c$ $(1/2^-)$ ~ 4.26 GeV, $\bar{D}\Sigma_c^*$ $(3/2^-)$ ~ 4.33 GeV,
$\bar{D}^*\Sigma_c$ $(1/2^-, 3/2^-)$ ~ 4.41, 4.42 GeV,
$\bar{D}^*\Sigma_c^*$ $(1/2^-, 3/2^-, 5/2^-)$ ~ 4.48 - 4.49 GeV

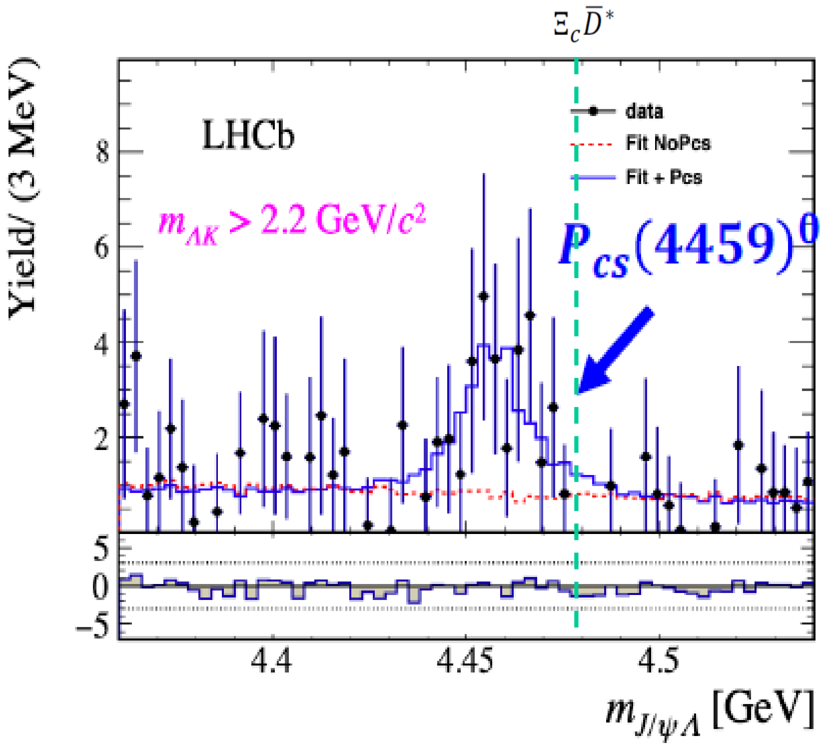
M.Karliner, J.L.Rosner, PRL115(2015)122001:

Pion exchange → $\bar{D}^*\Sigma_c$ $(1/2^-, 3/2^-)$ ~ 4.5 GeV

LHCb, PRL122 (2019) 222001

Sci. Bull. (2021) arXiv:2012.10380





Consistent with expectation for hadronic molecules within theoretical uncertainties

LHCb discoveries – historical achievement for pentaquarks !

very important for understanding whole baryon spectroscopy

Theories after LHCb observation of P_c & P_{cs} states

Thresholds $\bar{D}\Sigma_c^*$ (4383MeV), $\bar{D}^*\Sigma_c$ (4460MeV), $p\chi_{c1}$ (4449MeV)

1) $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$ molecular states

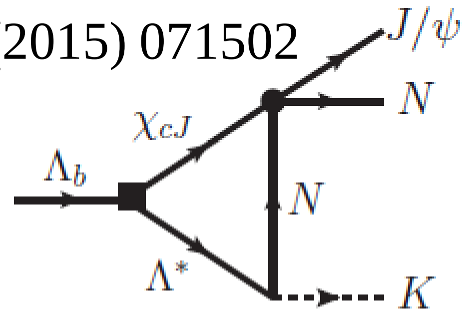
R.Chen, X.Liu, X.Q.Li, S.L.Zhu, PRL115 (2015) 132002;
L.Roca, J.Nieves, E.Oset, PRD92 (2015) 094003;
J.He, PLB 753 (2016)547 ;

2) diquark *cu* & triquark $\bar{c}(ud)$ states

L.Maiani, A.D.Polosa, V. Riquer, PLB749 (2015) 289;
R.Lebed, PLB749 (2015) 454;
G.N.Li, M.He, X.G.He, JHEP 1512 (2015) 128;
R.Zhu, C.F.Qiao, PLB756 (2016) 259;

3) Kinematic triangle-singularity

F.K.Guo, Ulf-G.Meißner, W.Wang, Z.Yang, PRD92 (2015) 071502
X.H.Liu, Q.Wang, Q.Zhao, PLB757 (2016) 231

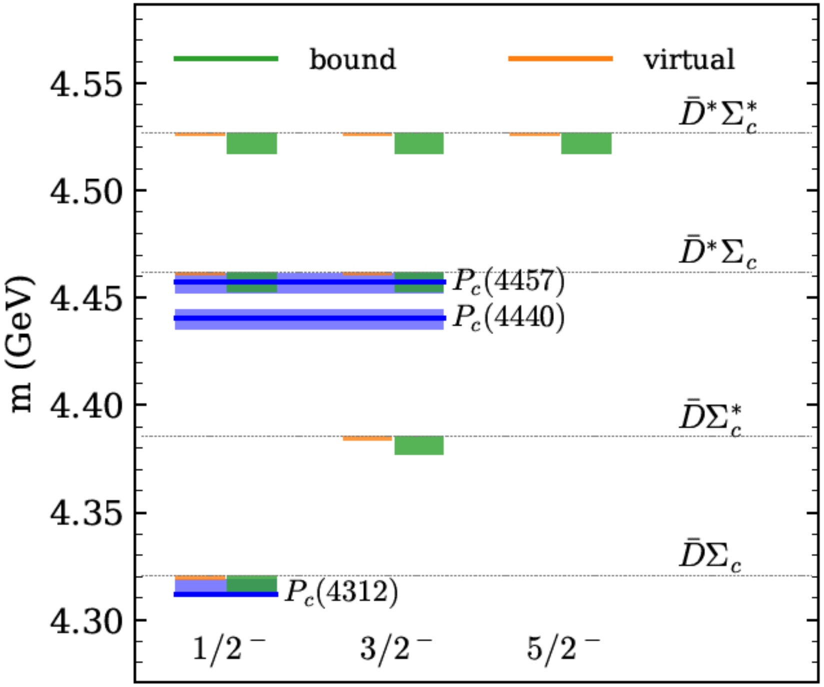


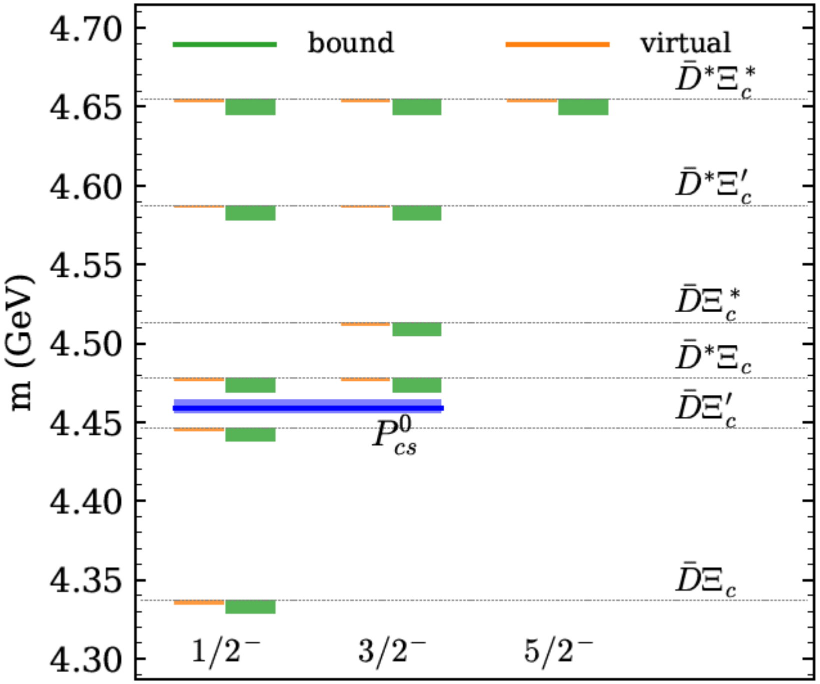
For comprehensive reviews, cf.:

H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1
F.K.Guo, C.Hanhart, U.Meissner, Q.Wang, Q.Zhao, B.S.Zou, RMP 90 (2018)015004
Y.R.Liu, H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Prog.Part.Nucl.Phys. 107 (2019) 237

2. Pentaquark spectrum as hadronic molecules

1) P_c & P_{cs} spectrum



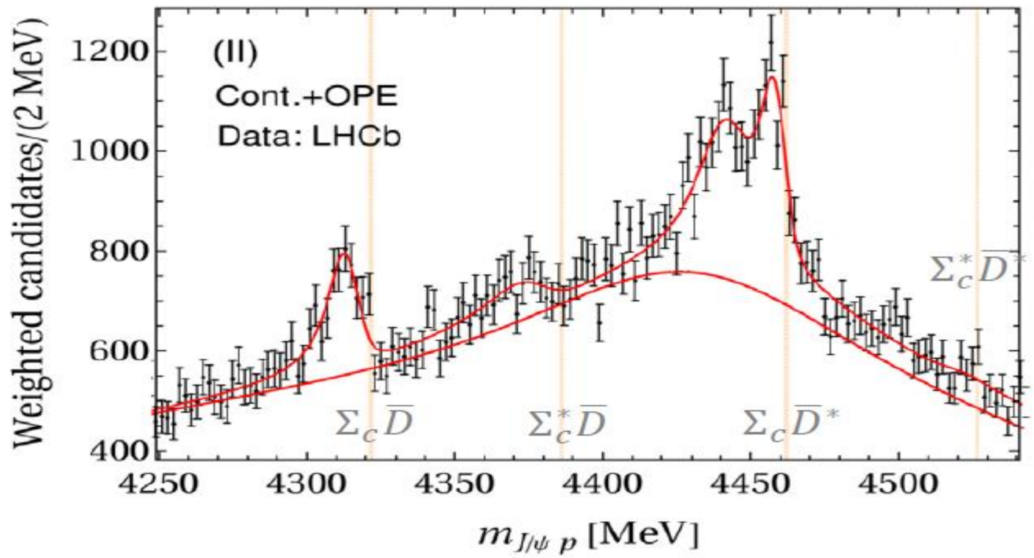


X.K.Dong, F.K.Guo, B.S.Zou, Progr. Phys. 41 (2021) 65; PRL126 (2021) 152001

Predictions from molecular picture:

$\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$ → 7 bound states

M.Z.Liu et al., PRL122 (2019) 242001; M.L.Du et al., PRL124 (2020) 072001



$\bar{D}\Xi_c$ (4337MeV), $\bar{D}^*\Xi_c$ (4478MeV), $\bar{D}\Xi'_c$ (4444MeV), $\bar{D}^*\Xi'_c$ (4585MeV),

$\bar{D}\Xi^*_c$ (4513MeV), $\bar{D}^*\Xi^*_c$ (4654MeV) → 10 bund states

→ predictions to be checked !

2) $D^{(*)}N$ molecular Λ_c pentaquark spectrum

$\pi\pi$ - $\bar{K}K(I=0)$
σ - $f_0(980)$

$M_\pi + M_{\Sigma c} = 2590$ MeV
$M_D + M_N = 2803$ MeV

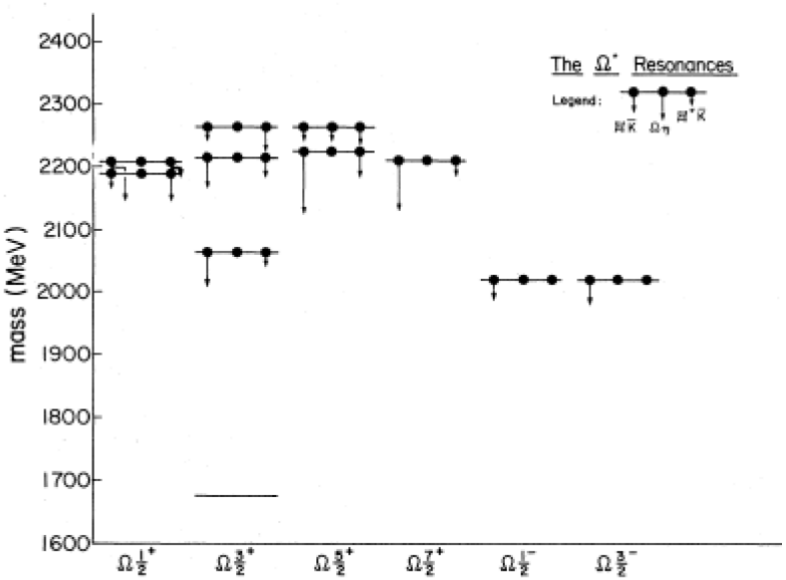
Similarity $\pi\Sigma$ - $\bar{K}N(I=0)$ vs $\pi\Sigma_c$ - $DN(I=0)$

$\Lambda(1380)$ - $\Lambda(1405)$ $\Lambda_c(2595)$ - $\Lambda_c(2765)$ $1/2^-$?

D*N molecule : $\Lambda_c(2940)$ $3/2^-$ & $1/2^-$? $M_{D*} + M_N = 2945$ MeV

$\bar{K}\Sigma_c \sim \Xi_c(2930)$ $1/2^-$, $\bar{K}\Sigma_c^* \sim \Xi_c(3015)$ $3/2^-$,
$D\Sigma \sim \Xi_c(3020)$ $1/2^-$, $D\Sigma^* \sim \Xi_c(3190)$ $3/2^-$, $D^*\Sigma \sim \Xi_c(3200)$, ...

3) $\bar{K}^{(*)}\Xi^{(*)}$ molecular Ω^* pentaquark spectrum



Ω(2470)

Ω(2380)

Ω(2250)

Ω(2012)

PDG J^P ?

Ω(2200) 1/2&3/2⁻ -- $\bar{K}^*\Xi^*$

Ω(2012) 3/2⁻ -- $\bar{K}\Xi^*$

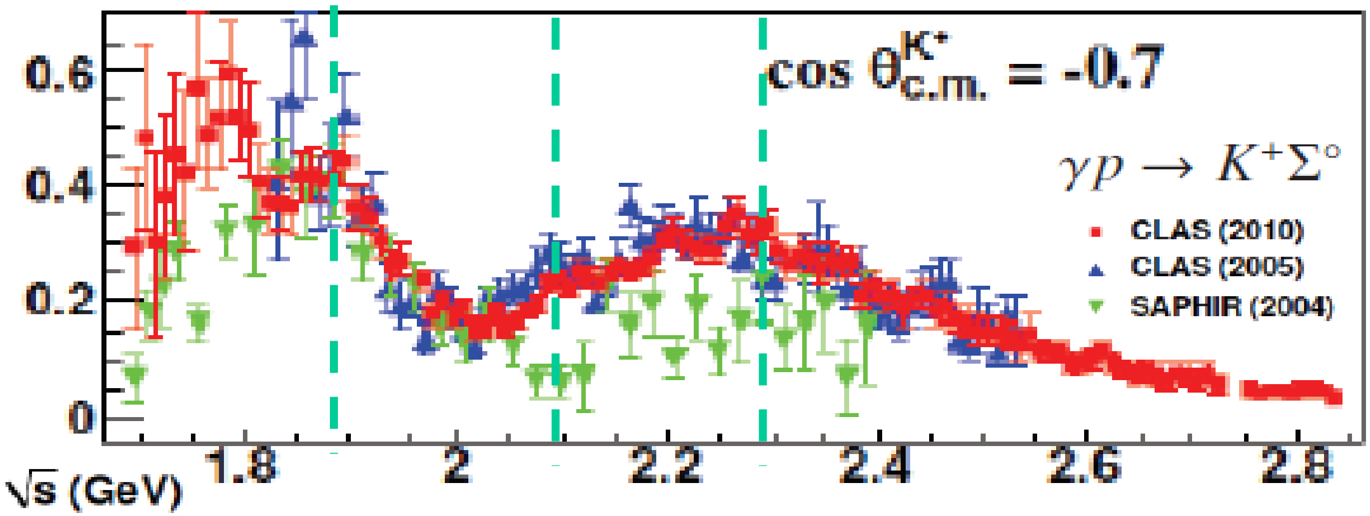
Ω(1800) 1/2⁻ -- $\bar{K}\Xi$

Ω*(sss) predicted by K.T.Chao, Isgur, Karl, PRD38 (1981) 155

Ω* predicted from $\bar{K}^{(*)}\Xi^{(*)}$ molecules

4) Strange partners of P_c and P_{cs} states

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



$K\Xi$ ~1810 $\Lambda(1/2^-)$

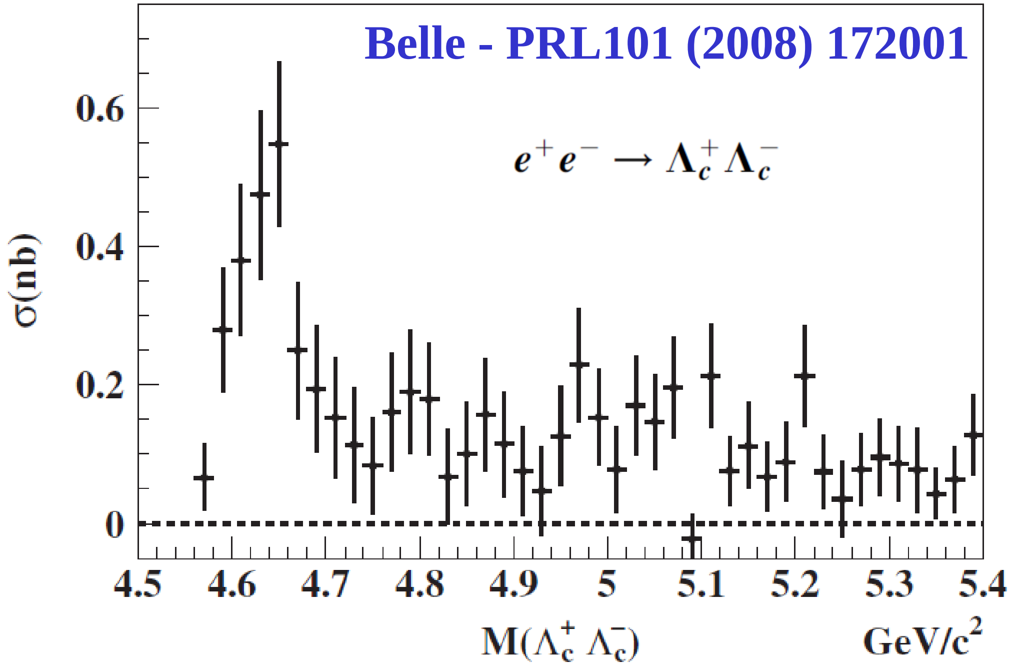
$K\Xi^*$ ~ 2027 $\Lambda(3/2^-)$

$K^*\Xi$ ~ 2210 $\Lambda(1/2^-,3/2^-)$

$K^*\Xi^*$ ~ 2427 $\Lambda(1/2^-,3/2^-,5/2^-)$

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

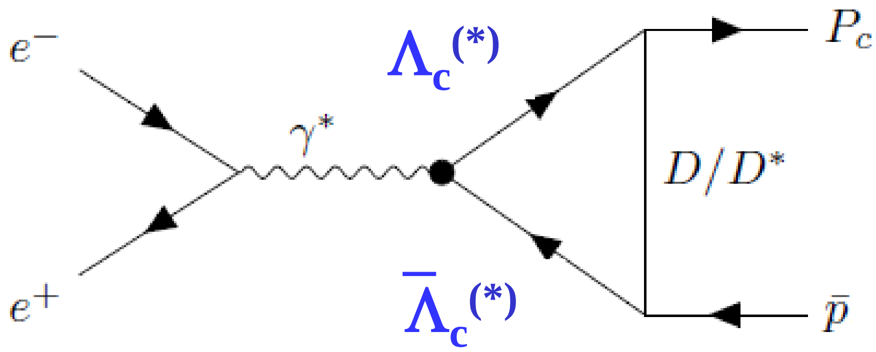
3. Pentaquarks at BEPC3 or super tau-charm



BEPC3: for E_{cm} ~ 5.0-5.6 GeV, $\mathcal{L} \sim 5*10^{32}/cm^2/s$, ~ 5/fb/year

For $e^+e^- \to \bar{\Lambda}_c \Lambda_c^* \to \bar{\Lambda}_c \Sigma_c \pi$, $\bar{\Lambda}_c$ Dp , $\bar{\Lambda}_c \Lambda_c \pi\pi$, σ ~ 100 pb ,

capable to pin down J^p of Λ_c (2765) and search for Λ_c (2940) $1/2^-$



For $e^+e^- \rightarrow \bar{\Lambda}_c\Lambda_c^{(*)}$ +cc $\rightarrow \bar{p}P_c$ + cc $\rightarrow \bar{\Lambda}_c p D^{(*)}$ +cc , $\sigma \sim 100$ fb ,

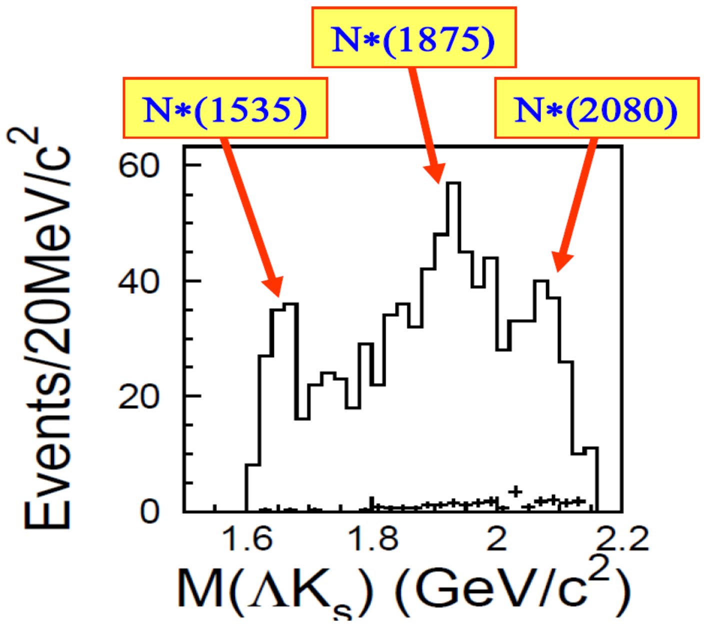
very difficult to study P_c states at BEPC3

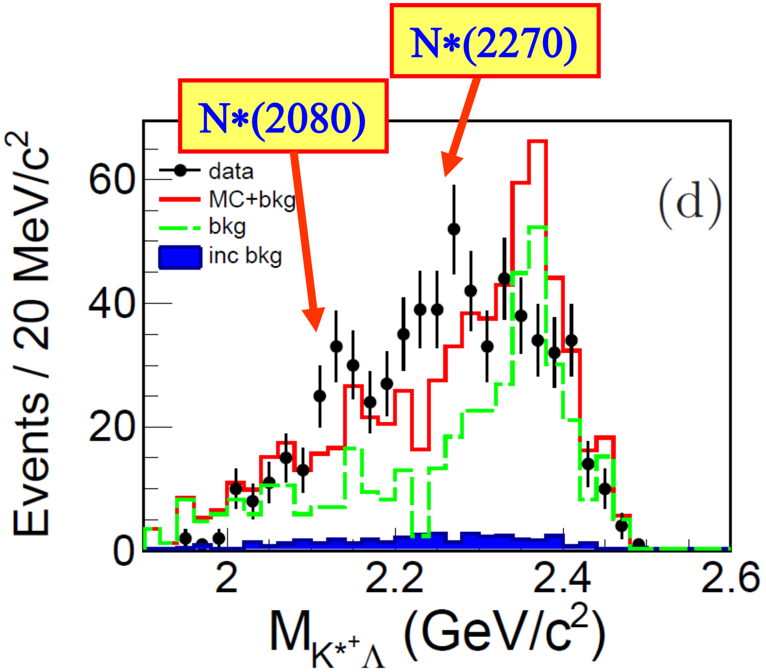
Possible to look for various pentaquarks with strangeness

Strangeness partners of P_c states at BES ?

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

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





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

BESII, PLB659 (2008) 789

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

BESIII, arXiv:1908.02979

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

Conclusion

- **Difficult to study Pc states at BEPC3**
- **Capable to study charm and strange pentaquarks**

Benchmarking channels: $e^+e^- \rightarrow \bar{\Lambda}_c\, p\, D^{(*)}$ +c.c.

$e^+e^- \rightarrow \bar{\Omega}\, \Xi^-\, K_S$ + c.c.

Thank you for your attention!