

Hadron spectroscopy from strangeness to charm and beauty with ep collisions

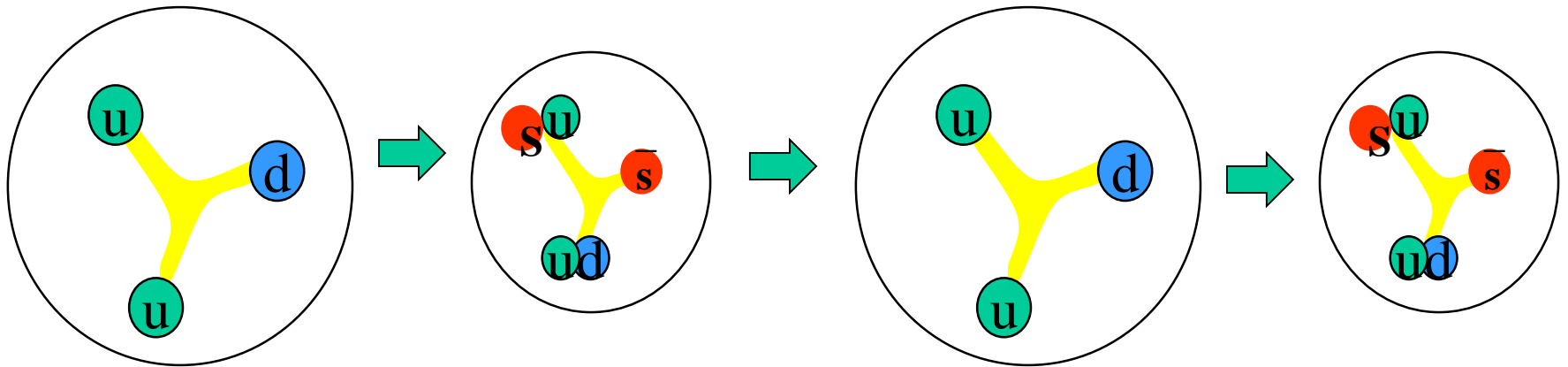
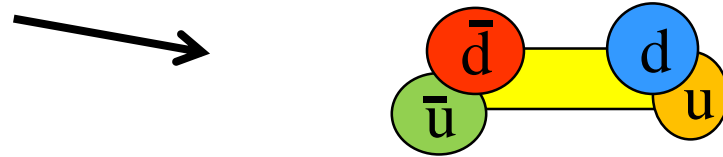
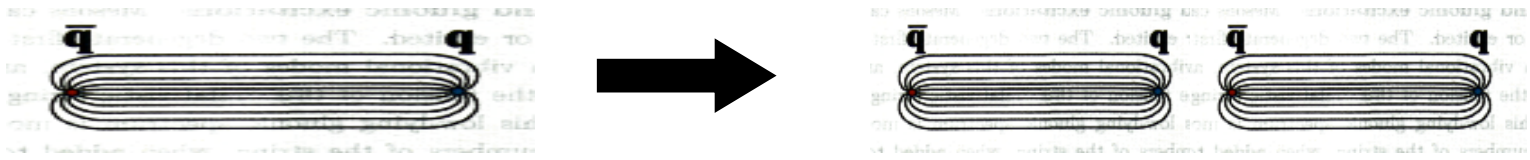
Bing-Song Zou (ITP, CAS)

- 1. Key problem and strangeness in hadron spectroscopy**
- 2. From strangeness to charm & beauty**
- 3. Prospects with ep collisions**

1. Key problem & strangeness in hadron spectroscopy

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

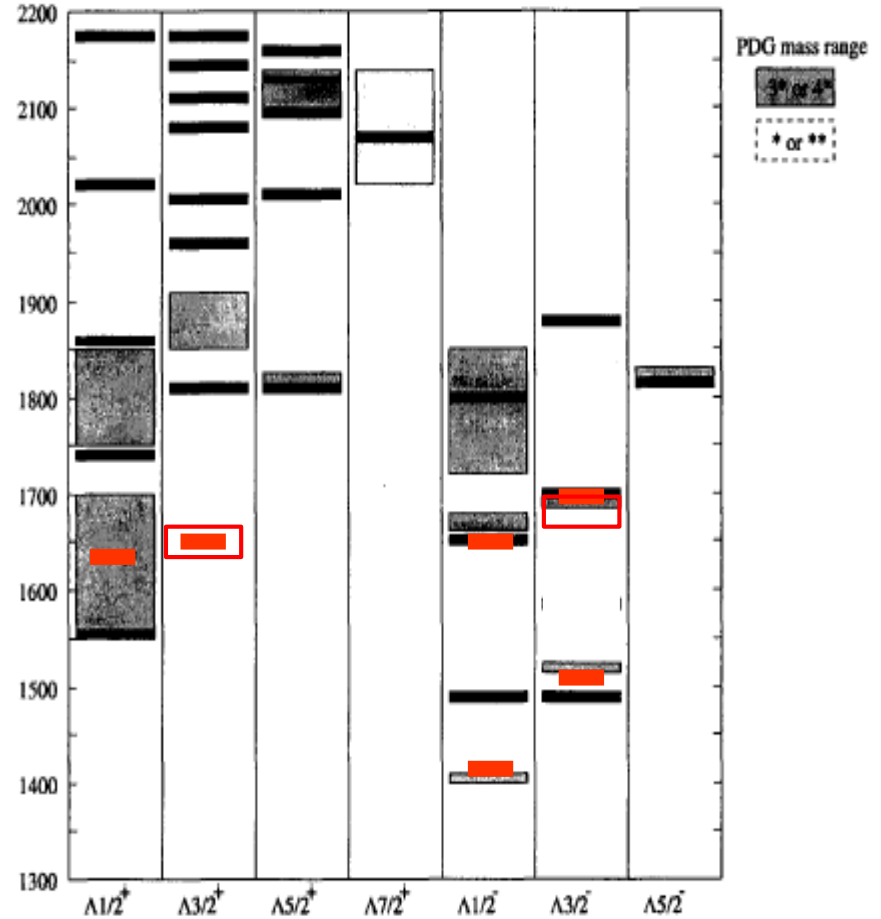
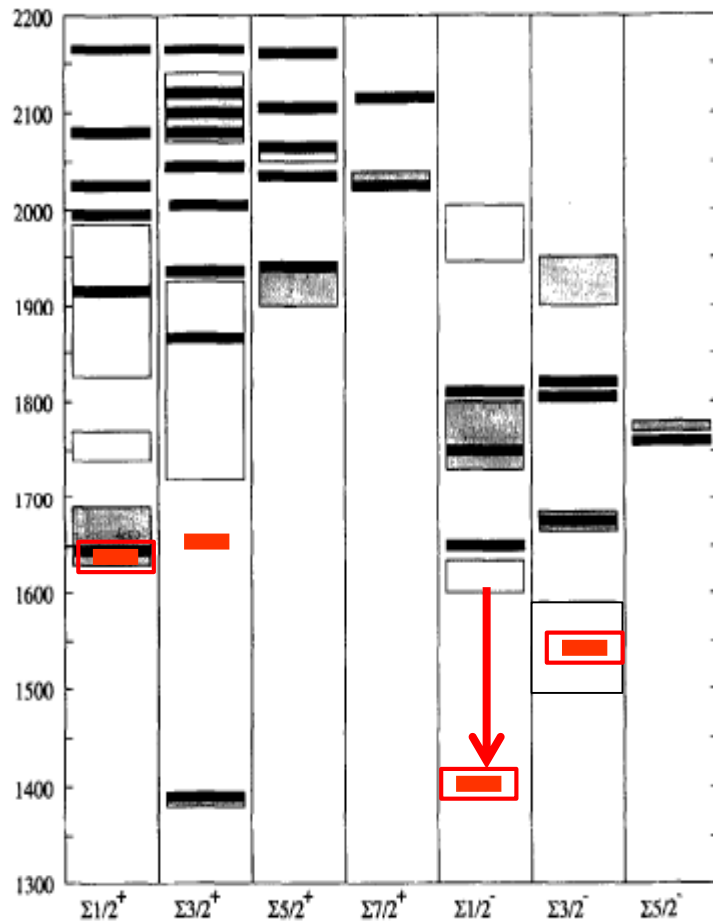
crucial for quark confinement & hadron structure



quenched or unquenched quark models give very different predictions of hyperon spectrum

Distinctive

Predictions by quenched - & unquenched - quark models



Quenched quark model: Capstick-Roberts, Prog.Part.Nucl.Phys. 45 (2000) S241-S331

Unquenched model: Helminen-Riska, Nucl. Phys. A 699 (2002) 624

A.Zhang, S.L.Zhu et al., HEPNP 29 (2005) 250

1/2⁻ baryon nonet with strangeness

- Mass pattern : quenched or unquenched ?

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

Zou et al, NPA835 (2010) 199 ; CLAS, PRC87(2013)035206

- Strange decays of N*(1535) : PDG → large $g_{\text{N}^*\text{N}\eta}$

$$\text{J}/\psi \rightarrow \bar{p}\text{N}^* \rightarrow \bar{p} (\text{K}\Lambda) / \bar{p} (\text{p}\eta) \rightarrow \text{large } g_{\text{N}^*\text{K}\Lambda}$$

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

$$\gamma\text{p} \rightarrow \text{p}\eta' \text{ \& } \text{pp} \rightarrow \text{pp}\eta' \rightarrow \text{large } g_{\text{N}^*\text{N}\eta'}$$

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

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

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 $\Lambda^*(1405)$

3/2⁻ baryon nonet with strangeness

- Mass pattern : quenched or unquenched ?

uds (L=1) 3/2⁻ ~ $\Lambda^*(1670)$ ~ [ud]{ss} \bar{s}

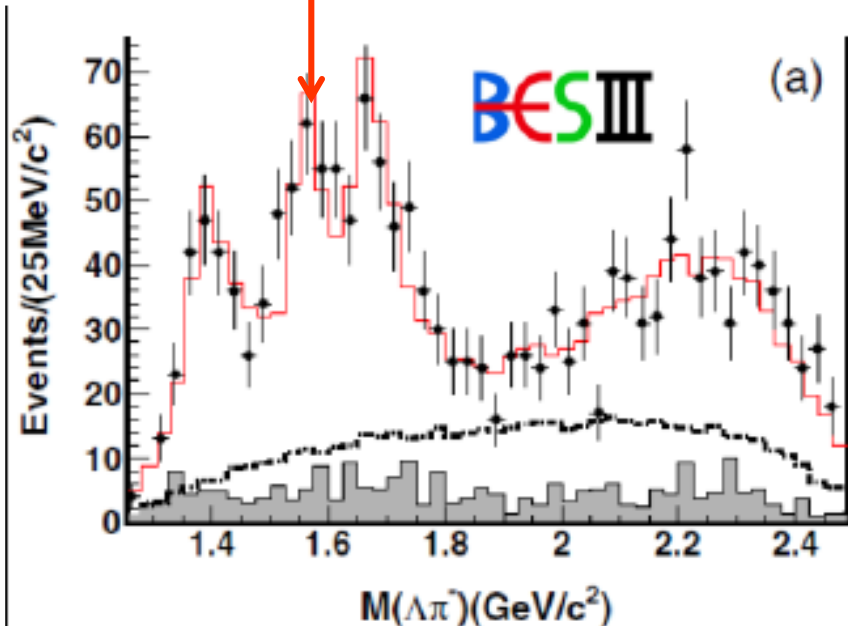
uud (L=1) 3/2⁻ ~ $N^*(1520)$ ~ [ud]{uq} \bar{q}

uds (L=1) 3/2⁻ ~ $\Lambda^*(1520)$ ~ [ud]{sq} \bar{q}

uus (L=1) 3/2⁻ ~ $\Sigma^*(1540)$ ~ [ud]{sq} \bar{q}

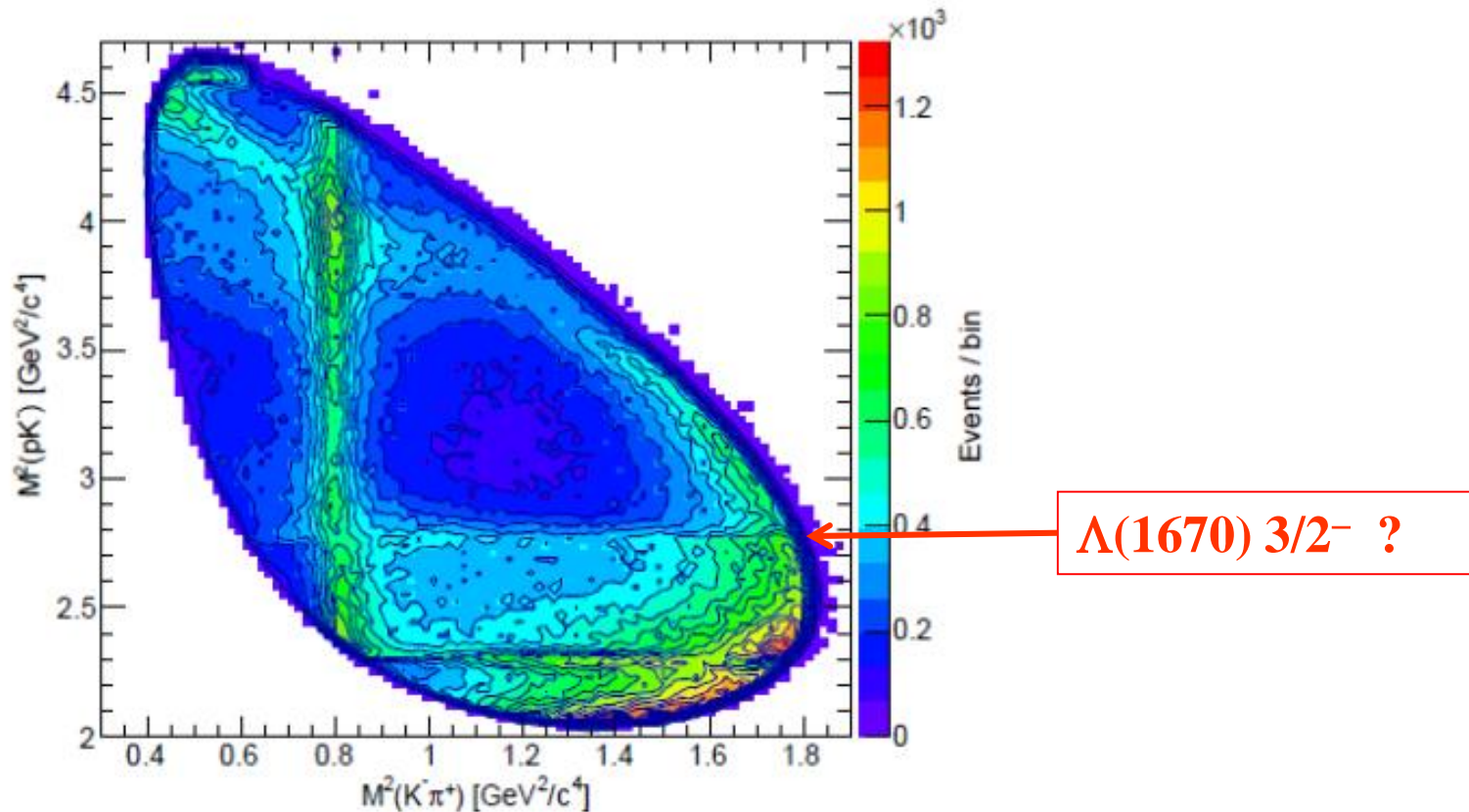
$\Sigma(1580)$ 3/2⁻

BESIII, PRD88 (2013) 112007



Shi&Zou, PRC91(2015) 035202 :
possible new $\Sigma^*(1542)$ 3/2⁻
in $K^-p \rightarrow \pi^0 \Lambda$

new $\Lambda^*(1670)3/2^-$ with width of 1.5 MeV [ud]{ss} \bar{s}
from $K^- p \rightarrow \Lambda \eta$ Liu&Xie, PRC86(2012)055202



Belle: $\Lambda_c^+ \rightarrow p K^- \pi^+$, PRL117 (2016) 011801

May be checked by BelleII & BESIII on $\Lambda_c^+ \rightarrow \Lambda \eta \pi^+$

Alternative pictures :

Hadronic molecules

$$N^*(1440) \sim N\sigma$$

$$N^*(1535) \sim K\Sigma-K\Lambda$$

$$\Lambda^*(1405) \sim KN-\Sigma\pi$$

$$\Lambda^*(1520) \sim \Sigma^*\pi$$

Penta-quark states

$$N^*(1440) \sim [ud][ud] \bar{q}$$

$$N^*(1535) \sim [ud][us] \bar{s}$$

$$\Lambda^*(1405) \sim [ud][sq] \bar{q}$$

$$\Lambda^*(1520) \sim [ud]\{sq\} q$$

**Kaiser, Weise, Oset, Ramos,
Oller, Meissner, Hyodo, Jido,
Hosaka, ...**

Successful extension to 1^+ & 2^+ meson nonets (Oset et al.)

$$\text{eg., } f_1(1420) \sim \bar{K}K^*$$

quenched vs un-quenched for mesons

$\bar{q}q \ ^3S_1$ nonet

$\phi(1020) \quad \bar{s}s$

$K(892) \quad \bar{s}d$

$\omega(782) \quad \bar{u}u + \bar{d}d$

$\rho(770) \quad \bar{u}u - \bar{d}d$

$\bar{q}q \ ^3P_0$ or \bar{q}^2q^2 nonet ?

$a_0(980) \quad \bar{u}u - \bar{d}d, \quad [\bar{u}s][us] - [\bar{d}s][ds]$

$f_0(980) \quad \bar{s}s, \quad [\bar{u}s][us] + [\bar{d}s][ds]$

$\kappa(800) \quad \bar{s}d, \quad [\bar{s}u][ud]$

$f_0(600) \quad \bar{u}u + \bar{d}d, \quad [\bar{u}d][ud]$

Important implications:

- $\bar{q}q\underline{q}q$ in S-state more favorable than $\underline{q}q$ with $L=1$!
& $\underline{q}q\underline{q}q$ in S-state more favorable than $\bar{q}q$ with $L=1$!

$1/2^-$ baryon nonet $\sim \bar{q}q^2q^2$ state + ...

0^+ meson octet $\sim \bar{q}^2q^2$ state + ...

multi-quark components are important for hadrons!

Totally different predictions for $1/2^-$ hyperons:

unquenched

$$\Sigma^* \quad [us][du] \bar{d} \quad \sim \quad 1400 \text{ MeV}$$

$$\Xi^* \quad [us][ds] \bar{d} \quad \sim \quad 1550 \text{ MeV}$$

$$\Omega^* \quad [us] ss \bar{u} \quad \sim \quad 1800 \text{ MeV}$$

quenched

$$uus \text{ (L=1)} \quad \sim \quad 1650 \text{ MeV}$$

$$uss \text{ (L=1)} \quad \sim \quad 1760 \text{ MeV}$$

$$sss \text{ (L=1)} \quad \sim \quad 2000 \text{ MeV}$$

Meson-Baryon states

Y.S.Oh

$$\Sigma^* \quad \sim \quad 1475 \text{ MeV}$$

$$\Xi^* \quad \sim \quad 1616 \text{ MeV}$$

$$\Omega^* \quad \sim \quad 1837 \text{ MeV}$$

K. P. Khemchandani et al.

$$\sim \quad 1426 \text{ MeV}$$

$$\sim \quad 1606 \text{ MeV}$$

Ramos & Oset

Experiment knowledge on hyperon states still very poor !

Ω^* in PDG:

- **** $\Omega(1672) 3/2^+$,
- *** $\Omega(2250)$
- ** $\Omega(2380), \Omega(2470)$

Ξ^* in PDG:

- **** $\Xi(1320) 1/2^+, \Xi(1530) 3/2^+$
- *** $\Xi(1690), \Xi(1820) 3/2^-, \Xi(1950), \Xi(2030)$
- ** $\Xi(2250), \Xi(2370)$
- * $\Xi(1620), \Xi(2120), \Xi(2500)$

Σ^* in PDG2012

**** $\Sigma(1189)1/2^+$ $\Sigma^*(1385)3/2^+$ $\Sigma^*(1670)3/2^-$
 $\Sigma^*(1775)5/2^-$ $\Sigma^*(1915)5/2^+$ $\Sigma^*(2030)7/2^+$

*** $\Sigma^*(1660)1/2^+$ $\Sigma^*(1750)1/2^-$ $\Sigma^*(1940)3/2^-$
 $\Sigma^*(2250)??$

** $\Sigma^*(1620)1/2^-$ $\Sigma^*(1690)??$ $\Sigma^*(1880)1/2^+$
 $\Sigma^*(2080)3/2^+$ $\Sigma^*(2455)??$ $\Sigma^*(2620)??$

* $\Sigma^*(1480)??$ $\Sigma^*(1560)??$ $\Sigma^*(1580)3/2^-$
 $\Sigma^*(1770)1/2^+$ $\Sigma^*(1840)3/2^+$ $\Sigma^*(2000)3/2^-$
 $\Sigma^*(2070)5/2^+$ $\Sigma^*(2100)7/2^-$ $\Sigma^*(3000)??$
 $\Sigma^*(3170)??$

All from old experiments of 1970-1985 !!

No established $1/2^- \Sigma^*$, Ξ^* , Ω^* !

2. From strangeness to charm & beauty

Many N^* & Λ^* are proposed to be dynamically generated states and penta-quark states

Problem:

None of them can be clearly distinguished from qqq due to tunable ingredients and possible large mixing of various configurations

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.”

although $\Lambda_c(2595) 1/2^-$ was proposed to be DN molecule by Tolos et al., CPC33(2009)1323. Haidenbauer et al., EPJA47(2011)18

Solution: Extension to hidden charm and beauty for baryons

$N^*(1535)$ $\bar{s}suud$

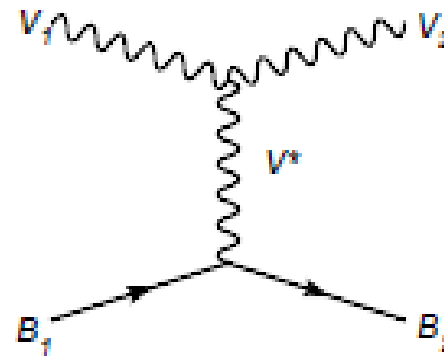
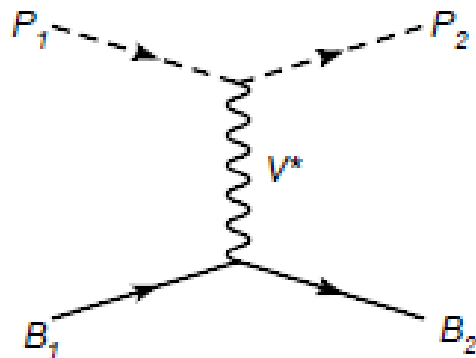
$N^*(4260)$ $\bar{c}cuud$ J.J.Wu, R.Molina, E.Oset, B.S.Zou.
Phys.Rev.Lett. 105 (2010) 232001

$N^*(11050)$ $\bar{b}buud$ J.J.Wu, L.Zhao, B.S.Zou. PLB709(2012)70

$\Lambda^*(1405)$ $\bar{q}quds$

$\Lambda^*(4210)$ $\bar{c}cuds$ J.J.Wu, R.Molina, E.Oset, B.S.Zou.
Phys.Rev.Lett. 105 (2010) 232001

$\Lambda^*(11020)$ $\bar{b}buds$ J.J.Wu, L.Zhao, B.S.Zou. PLB709(2012)70



	(I, S)	M	Γ	Γ_i					J^P
N^*	$(1/2, 0)$			πN	ηN	$\eta' N$	$K\Sigma$	$\eta_c N$	$1/2^-$
		4261	56.9	3.8	8.1	3.9	17.0	23.4	
Λ^*	$(0, -1)$			KN	$\pi\Sigma$	$\eta\Lambda$	$\eta'\Lambda$	$K\Xi$	$\eta_c\Lambda$
		4209	32.4	15.8	2.9	3.2	1.7	2.4	5.8
		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 $PB \rightarrow PB$, with units in MeV.

	(I, S)	M	Γ	Γ_i					J^P
N^*	$(1/2, 0)$			ρN	ωN	$K^*\Sigma$	$J/\psi N$	$1/2^-, 3/2^-$	
		4412	47.3	3.2	10.4	13.7	19.2		
Λ^*	$(0, -1)$			K^*N	$\rho\Sigma$	$\omega\Lambda$	$\phi\Lambda$	$K^*\Xi$	$J/\psi\Lambda$
		4368	28.0	13.9	3.1	0.3	4.0	1.8	5.4
		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 $VB \rightarrow VB$ with units in MeV.

Super-heavy narrow N^* and Λ^* with hidden charm
Definitely not qqq states !

Hidden charm N^* above 4 GeV decaying to pJ/ψ are supported by other approaches

$\bar{D}\Sigma_c + \bar{D}^*\Sigma_c$ coupled channel state ~ 4.23 GeV

T. Uchino, W.H.Liang, E.Oset, arXiv:1504.05726

$\bar{D}\Sigma_c$ state in a chiral quark model ~ 4.3 GeV

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

$\bar{D}\Sigma_c$ state in EBAC-DCC model ~ 4.3 GeV

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

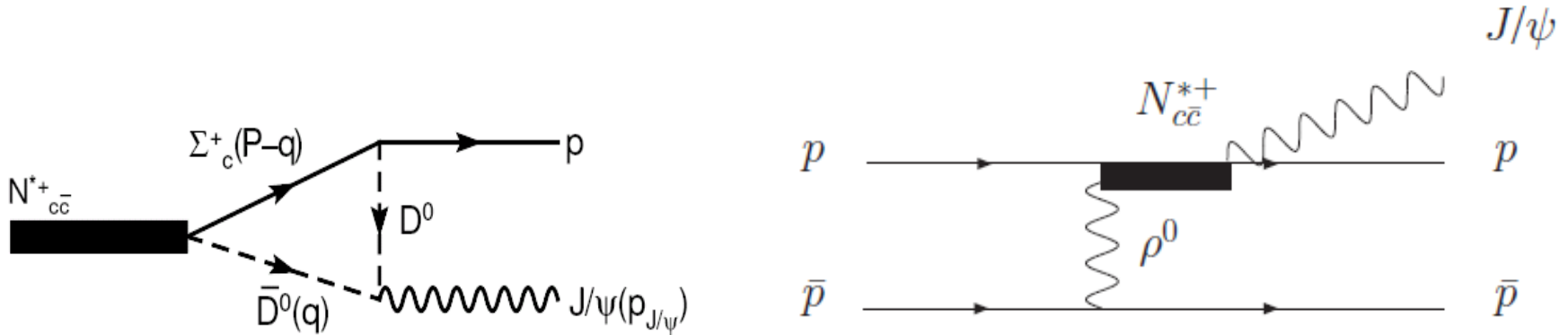
$\bar{D}\Sigma_c$ state in Schoedinger Equation method ~ 4.3 GeV

Z.C.Yang, Z.F. Sun, J. He, X.Liu, S.L.Zhu, CPC36(2012)6

$\bar{c}cqqq$ with 3 kinds of qq hyperfine interaction ~ 4.1 GeV

S.G.Yuan, K.W.We, J.He, H.S.Xu, B.S.Zou, EPJA48(2012)61

Prediction for PANDA



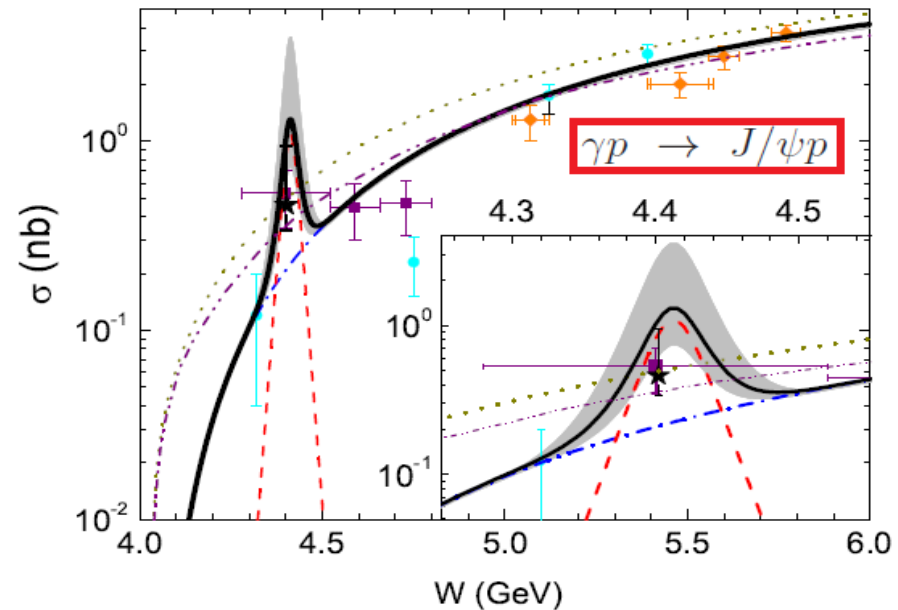
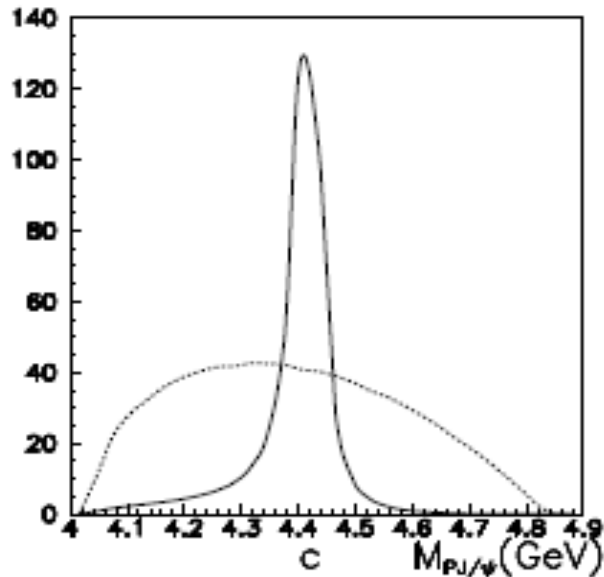
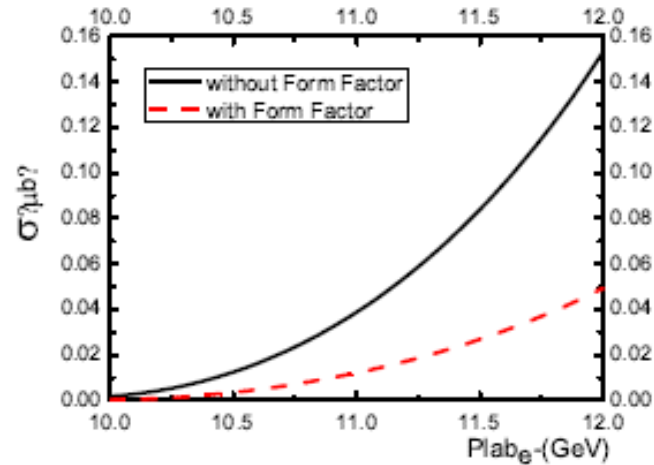
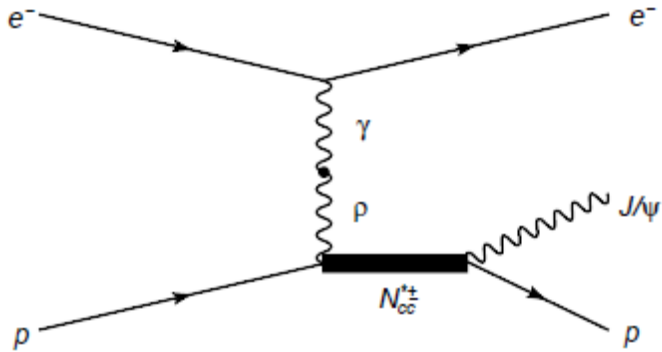
$$\Gamma_{R \rightarrow J/\psi p} = 0.01 \text{ MeV},$$

$$\bar{p}p \rightarrow \bar{p}p J/\psi \sim 0.1 \text{ nb}$$

~ 100 events per day at PANDA/FAIR by $L=10^{31} \text{ cm}^{-2}\text{s}^{-1}$

These Super-heavy narrow N^* and Λ^* can be found at PANDA !

Prediction for 12GeV@JLab



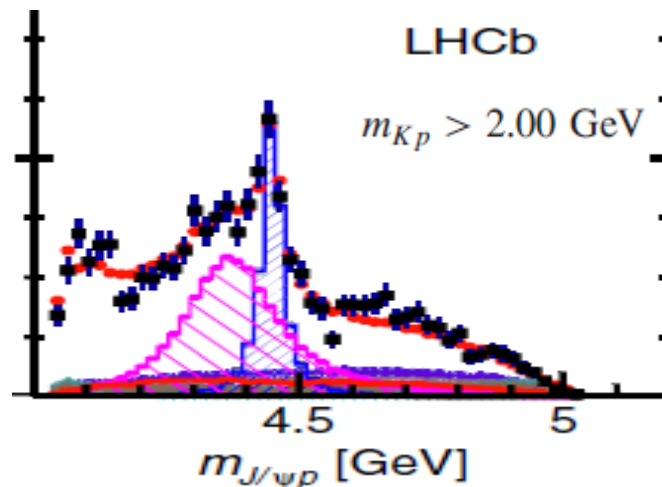
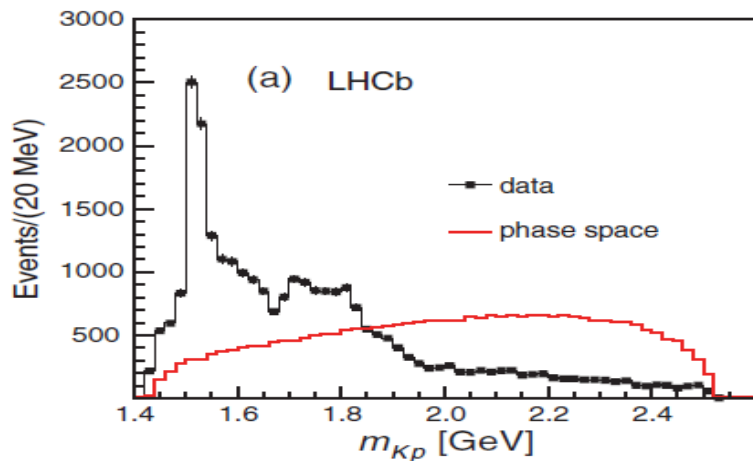
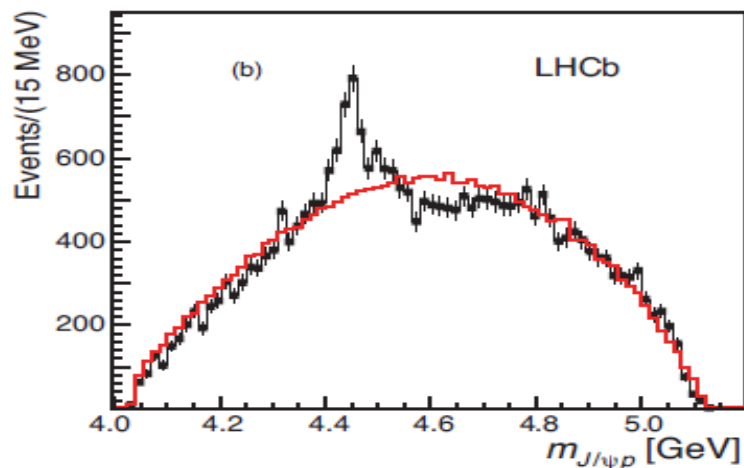
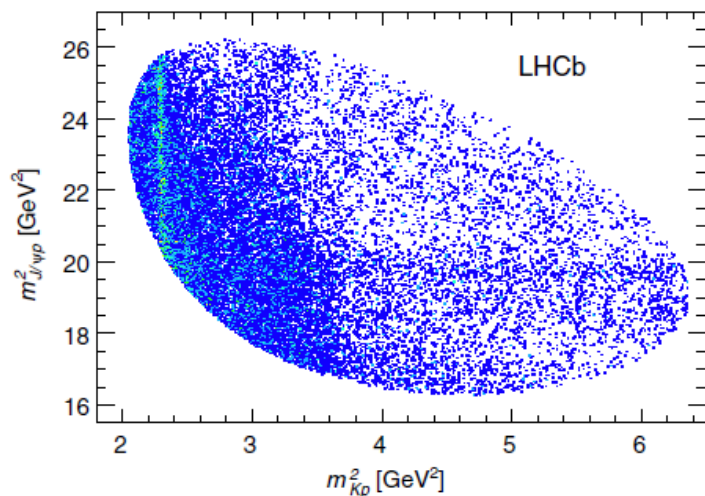
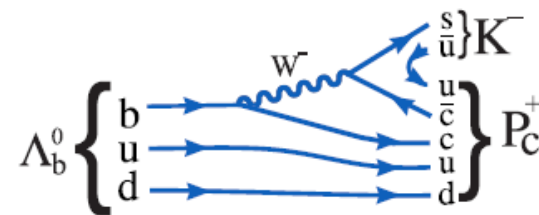
Y. Huang, J.He, H.F.Zhang and X.R.Chen, JPG41, 115004 (2014)

Proposals for looking for N_{cc}^- & Λ_{cc}^- with π^- , K beams at JPARC

- a) **X.Y.Wang, X.R.Chen, “The production of hidden charm baryon $N^*(4261)$ from $\pi^-p \rightarrow \eta_c n$ reaction”, EPL109 (2015) 41001.**
- b) **E.J.Garzon, J.J.Xie, “Effects of a N_{cc}^- resonance with hidden charm in the $\pi^-p \rightarrow D^- \Sigma_c^+$ reaction near threshold”, PRC 92 (2015) 035201**
- c) **X.Y.Wang, X.R.Chen, “Production of the superheavy baryon $\Lambda^*(4209)$ in kaon-induced reaction”, EPJA51 (2015) 85**

Observation of $P_c^+(4380)$ & $P_c^+(4450)$ by LHCb

LHCb, Phys.Rev.Lett. 115 (2015) 072001 :
Observation of two N^* from $\Lambda_b^0 \rightarrow J/\psi K^- p$



Explanations after LHCb observation

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;

H.X.Chen, W.Chen, X.Liu, T.G.Steele, S.L.Zhu, PRL115 (2015)172001

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;

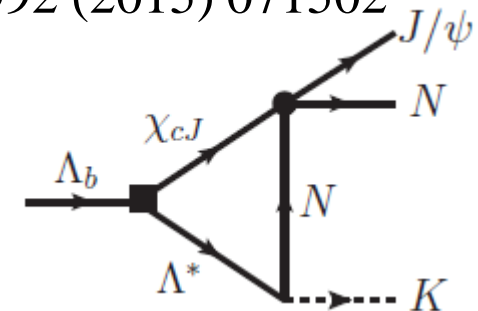
G.N.Li, M.He, X.G.He, JHEP 1512 (2015) 128;

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 a comprehensive review, cf.:

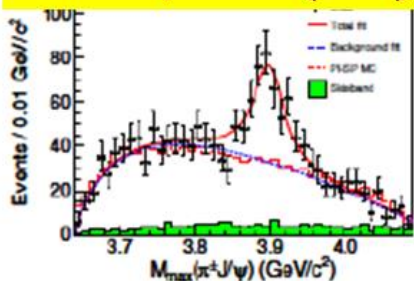
H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1

BESIII上发现的Zc家族



Zc(3900)⁺

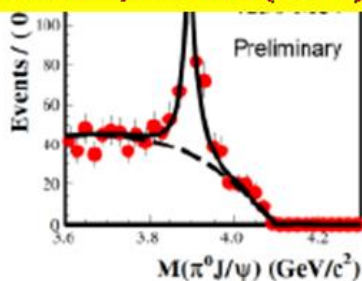
PRL 110, 252001 (2013)



$$e^+e^- \rightarrow \pi^- \pi^+ J/\psi$$

Zc(3900)⁰

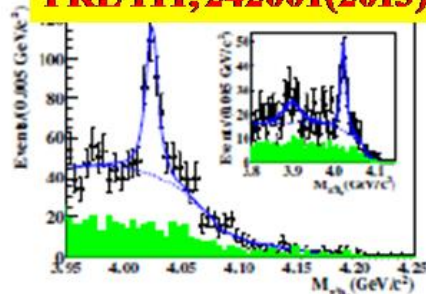
PRL 115, 112003 (2015)



$$e^+e^- \rightarrow \pi^0 \pi^0 J/\psi$$

Zc(4020)⁺

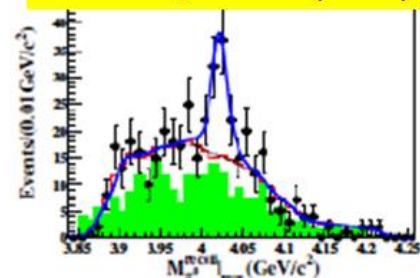
PRL 111, 242001(2013)



$$e^+e^- \rightarrow \pi^- \pi^+ h_c$$

Zc(4020)⁰

PRL 113, 212002 (2014)

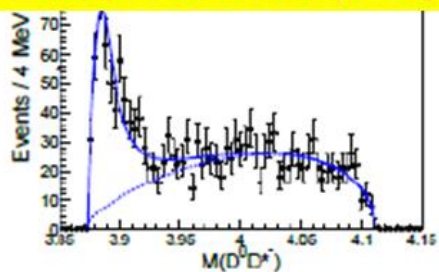


$$e^+e^- \rightarrow \pi^0 \pi^0 h_c$$

Zc(3885)⁺

ST: PRL 112, 022001(2014)

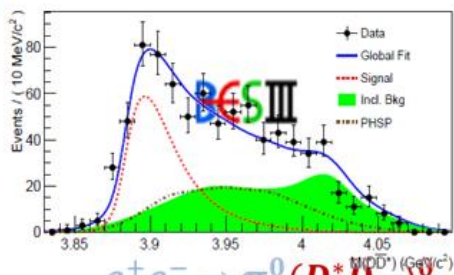
DT: PRD92, 092006 (2015)



$$e^+e^- \rightarrow \pi^- (D\bar{D}^*)^+$$

Zc(3885)⁰

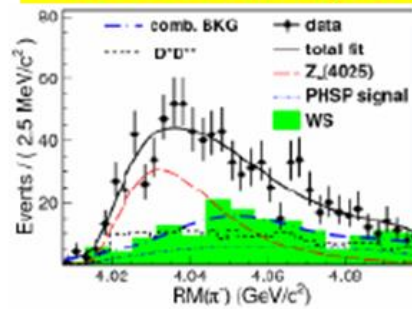
PRL 115, 222002 (2015)



$$e^+e^- \rightarrow \pi^0 (D^* \bar{D}^*)^0$$

Zc(4025)⁺

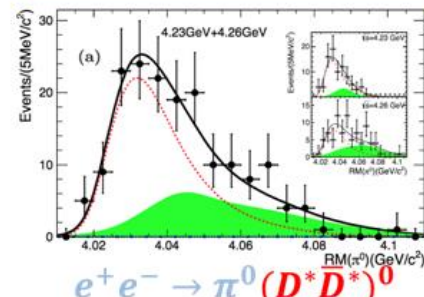
PRL 112, 132001 (2014)



$$e^+e^- \rightarrow \pi^- (D^* \bar{D}^*)^+$$

Zc(4025)⁰

PRL 115, 182002 (2015)



$$e^+e^- \rightarrow \pi^0 (D^* \bar{D}^*)^0$$

“Y(4260)的结构以及带电Zc(3900)的产生”

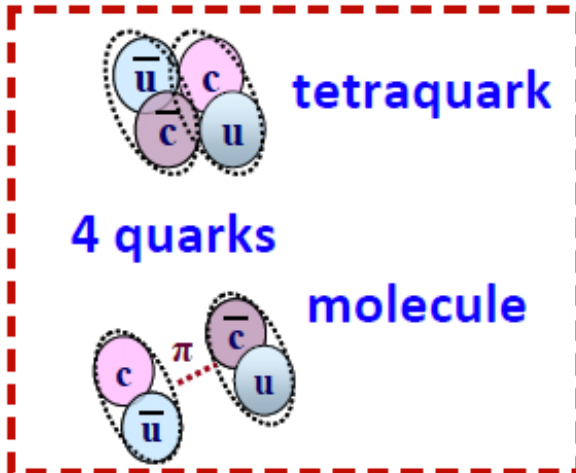
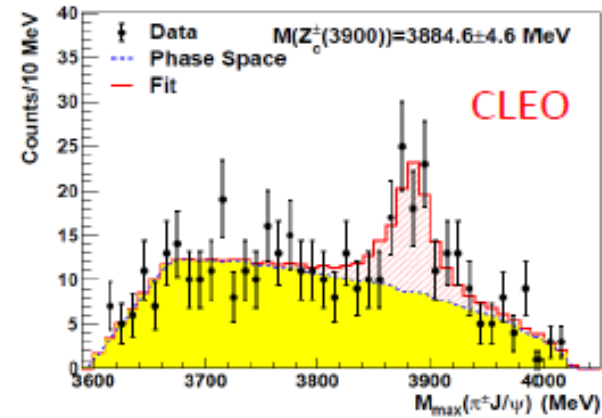
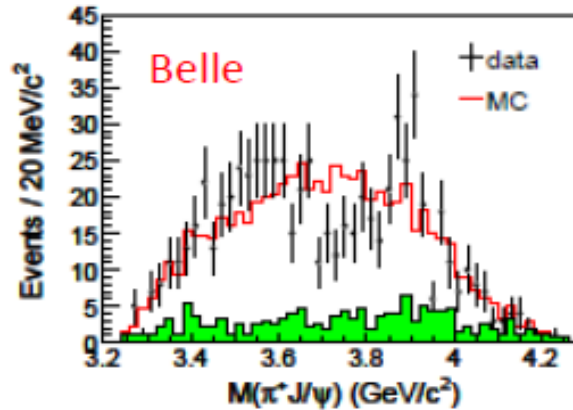
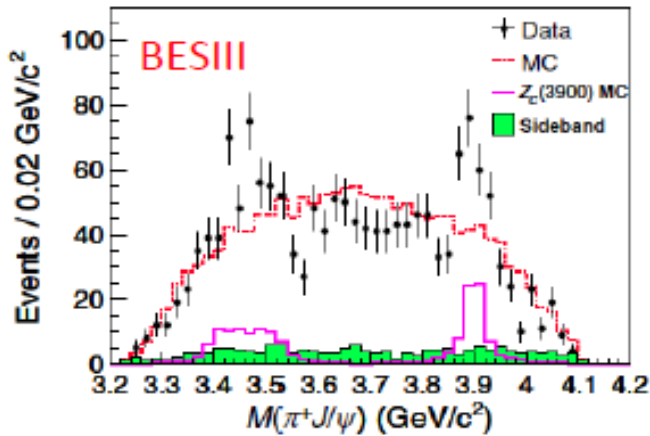
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PRL 110, 252001 (2013)

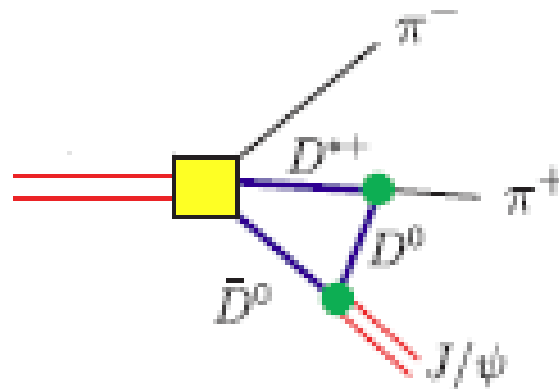
PHYSICAL REVIEW LETTERS

WEEK ENDING
21 JUNE 2013

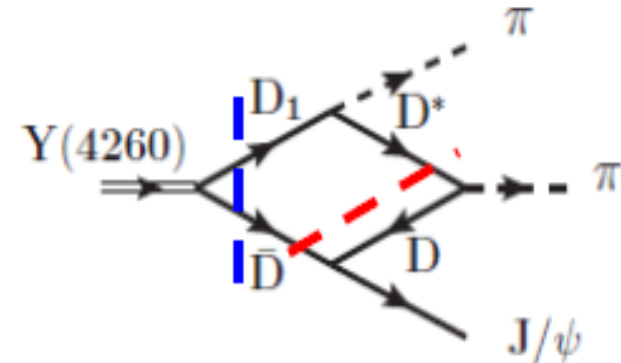
Observation of a Charged Charmoniumlike Structure in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV



Exotic!



D.Y.Chen, X.Liu,
PRD84(2011)034032



Q.Wang, C.Hanhart, Q.Zhao
PRL111(2013)132003

New Particles		relevant thresholds	
$Z_c(3900)$	$\bar{d}u \bar{c}c$	D^*D	3880 MeV
$Z_c(4020)$		D^*D^*	4020 MeV
$Z_b(10610)$	$\bar{d}u \bar{b}b$	B^*B	10605 MeV
$Z_b(10650)$		B^*B^*	10650 MeV
$P_c(4380)$	$uud \bar{c}c$	$D\Sigma_c^*$	4382 MeV
$P_c(4450)$		$D^*\Sigma_c$	4459 MeV

Hadron-hadron resonances ?

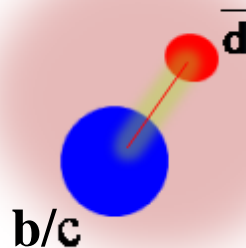
Most interesting hadron systems accessible in near future

◆ my favorite strategy:

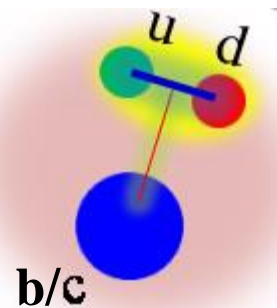
$\bar{c}c u u d$ & $\bar{c}c u d s$ \rightarrow $s s s$ - $\bar{q} q s s s$ \rightarrow $c q q$ - $\bar{q} q c q q$
 \rightarrow hyperons \rightarrow light baryons

$\bar{c}c \bar{u} d$ & $\bar{c}c s \bar{u} d$ \rightarrow $\bar{c}c$ - $\bar{q} q$ $\bar{c}c$ \rightarrow $\bar{c}q$ - $\bar{c}q \bar{q} q$
 \rightarrow K mesons \rightarrow light mesons

$s \rightarrow c \rightarrow b$



charm & beauty meson



charm & beauty baryon

3. Prospects with ep collisions

- 1) $E_{\text{cm}} \sim 15 \text{ GeV}$: pentaquarks with hidden charm and beauty,
baryons with open charm and beauty
- 2) $E_{\text{cm}} \sim 6 \text{ GeV}$: pentaquarks with hidden charm and
baryons with open charm and strangeness
- 3) $E_{\text{cm}} \sim 4 \text{ GeV}$: hyperons

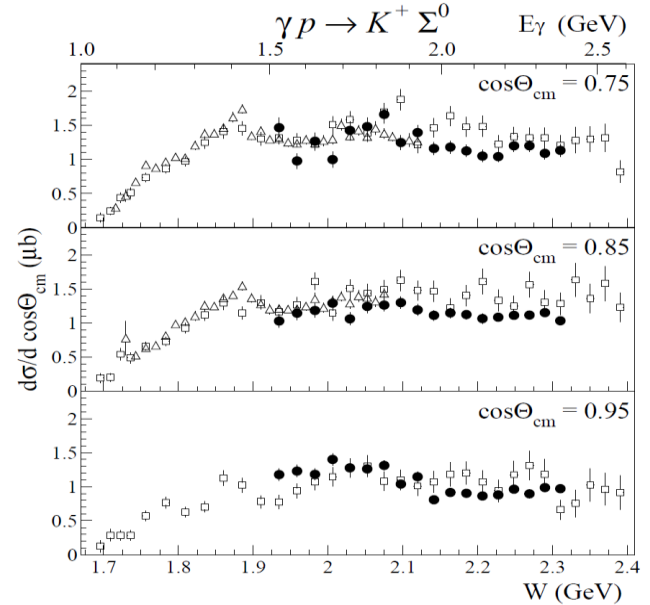
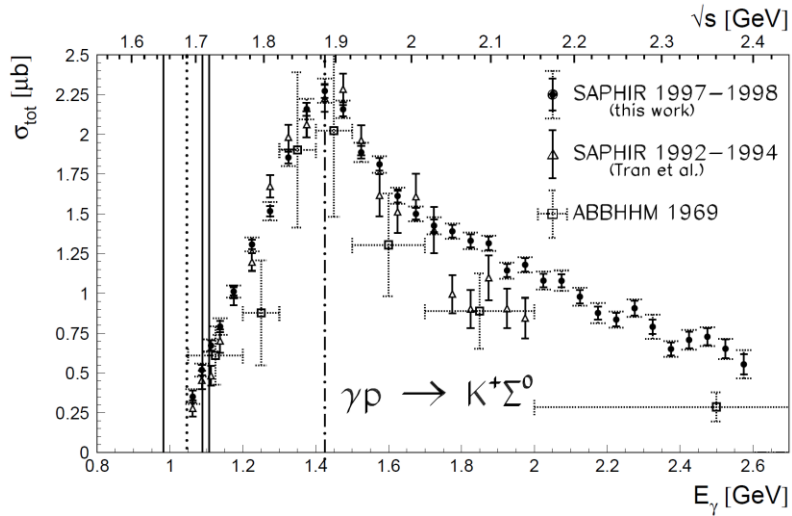
both baryon and meson spectroscopy can be studied.

EicC with $E_{\text{cm}} \sim 15 \text{ GeV}$ -- top choice in near future for China

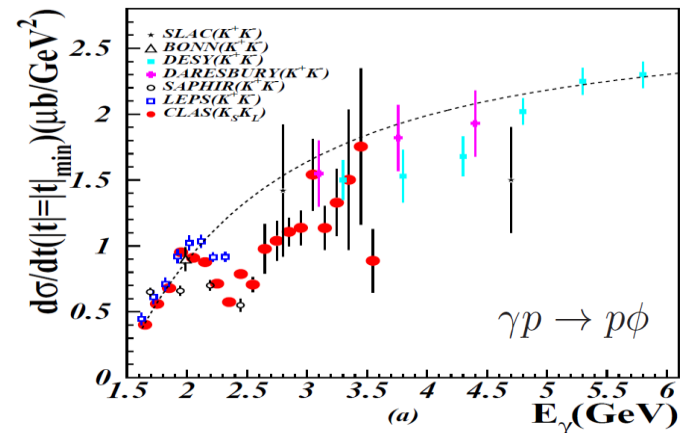
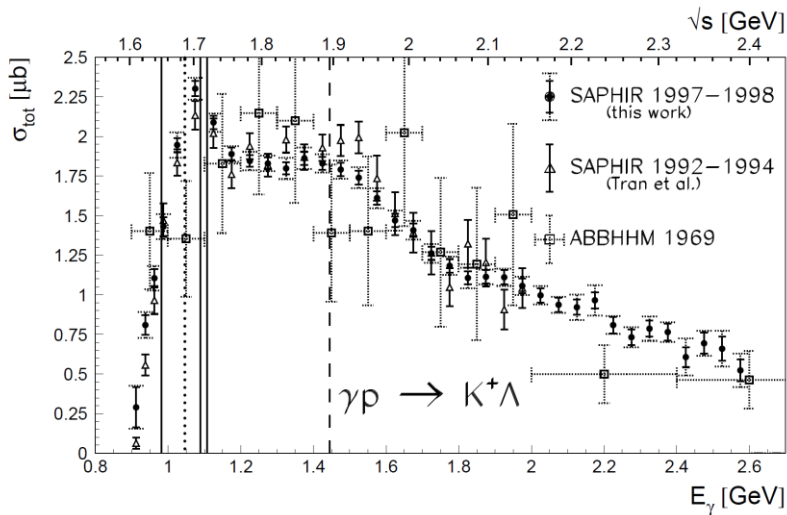
**CEBAF-12GeV & SCLF-8GeV – complementary &
preparation for EicC**

Strangeness partners of P_c states: $N^*(1875)$ & $N^*(2080)$

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



LEPS, PRC73 (2006) 035214



CLAS, PRC89 (2014) 055206

Glander, K.H. *et al.* EPJA19 (2004) 251-273



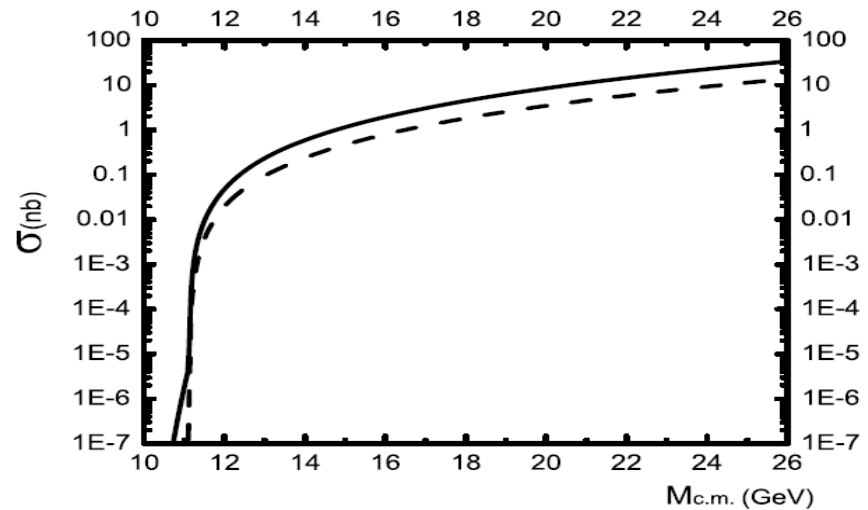
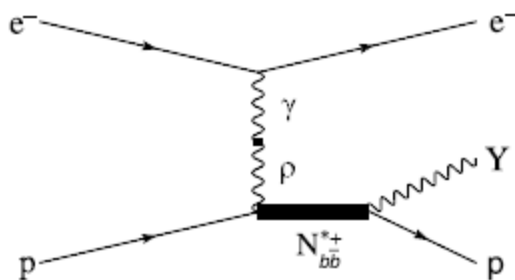
Prediction of super-heavy N^* and Λ^* resonances with hidden beauty

Jia-Jun Wu^{a,*}, Lu Zhao^a, B.S. Zou^{a,b}

M (MeV)	Γ (MeV)	Γ_i (MeV)				
11 052	1.38	πN 0.10	ηN 0.21	$\eta' N$ 0.11	$K \Sigma$ 0.42	$\eta_b N$ 0.52
11 100	1.33	ρN 0.09	ωN 0.30	$K^* \Sigma$ 0.39	ΥN 0.51	

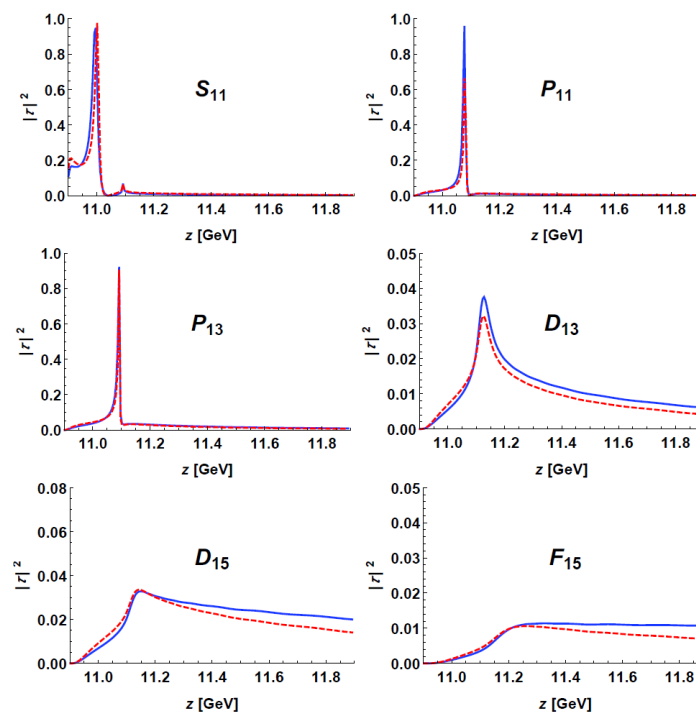
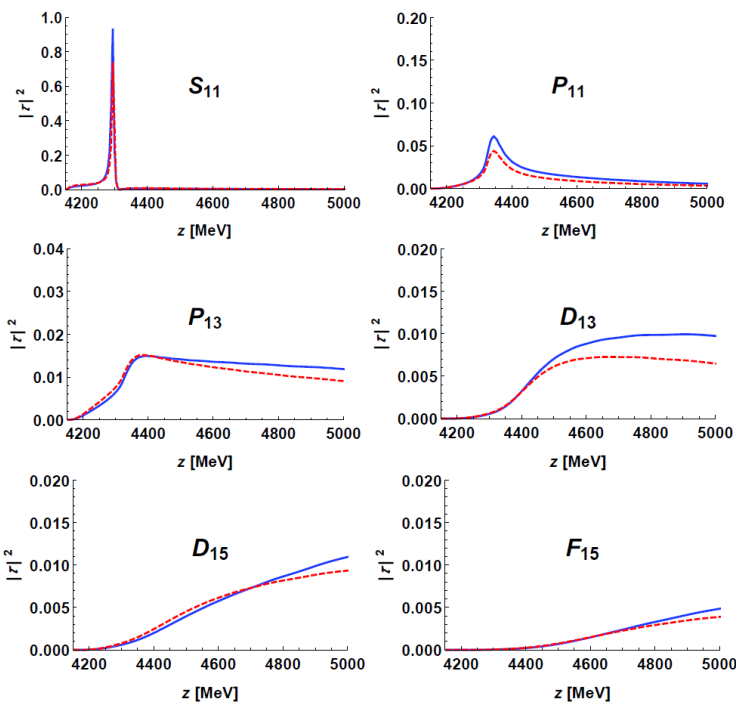
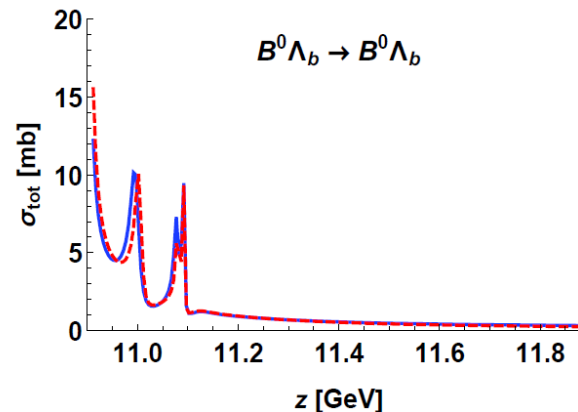
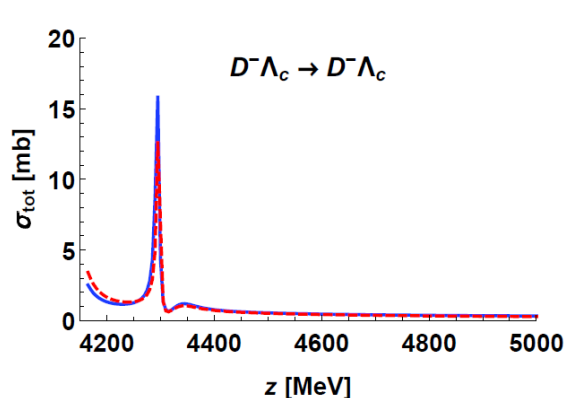
$1/2^-$

$1/2^-, 3/2^-$



$\bar{D}\Lambda_c - \bar{D}\Sigma_c$ and $B\Lambda_b - B\Sigma_b$ dynamical coupled channel study

C.W.Shen, Roehen, Meissner, Zou, CPC42(2018) 023106



More pentaquarks with hidden beauty than with hidden charm

Partial decay widths of $P_c^+(4380)$ & $P_c^+(4450)$

Y.H.Lin, C.W.Shen, F.K.Guo, B.S.Zou, PRD95(2017)114017

Mode	Widths (MeV)			
	$P_c(4380)$		$P_c(4450)$	
	$\bar{D}\Sigma_c^*(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{5}{2}^+)$
$\bar{D}^*\Lambda_c$	131.3 ✓	35.3 ✓	72.3 ✓	20.5 ✓
$J/\psi p$	3.8	16.6	16.3	4.0
$\bar{D}\Lambda_c$	1.2	17.0 ✓	41.4 ✓	18.8 ✓
πN	0.06	0.07	0.07	0.2
$\chi_{c0} P$	0.9	0.004	0.02	0.002
$\eta_c P$	0.2	0.09	0.1	0.04
ρN	1.4	0.15	0.14	0.3
ωp	5.3	0.6	0.5	0.3
$\bar{D}\Sigma_c$	0.01	0.1	1.2	0.8
$\bar{D}\Sigma_c^*$	7.7	1.4
$\bar{D}\Lambda_c \pi$	11.6
Total	144.3	69.9	139.8	46.4

It is very important to study $P_c \rightarrow \bar{D}^*\Lambda_c$ & $\bar{D}\Lambda_c$!
& $P_b \rightarrow B^*\Lambda_b$ & $B\Lambda_b$!

Conclusion:

EicC – super-beauty factory for both mesons & baryons

**unique role for studying pentaquarks with hidden beauty
& baryons with open beauty**

A super project for investment!

谢谢大家!