Hadron spectroscopy with charm and beauty at EicC/HIAF

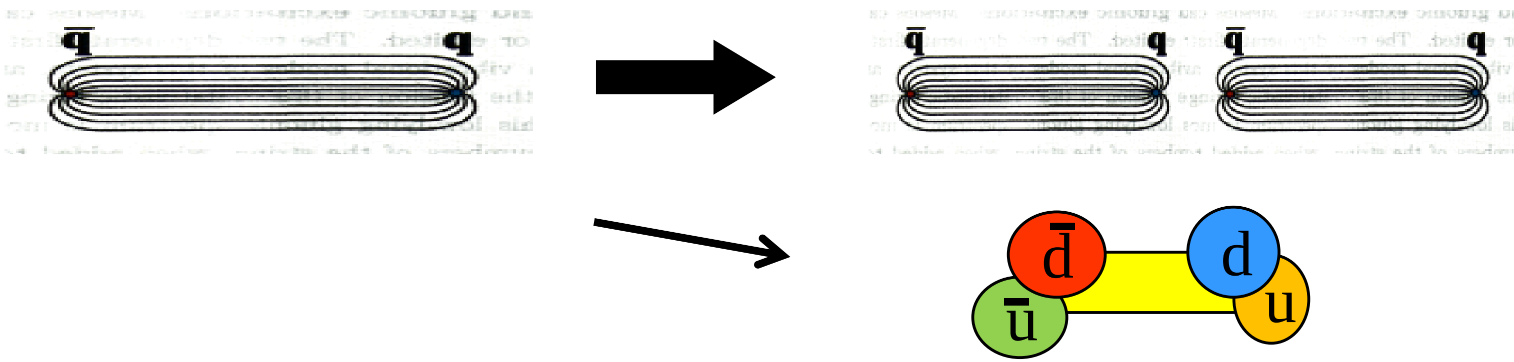
Bing-Song Zou (ITP, CAS)

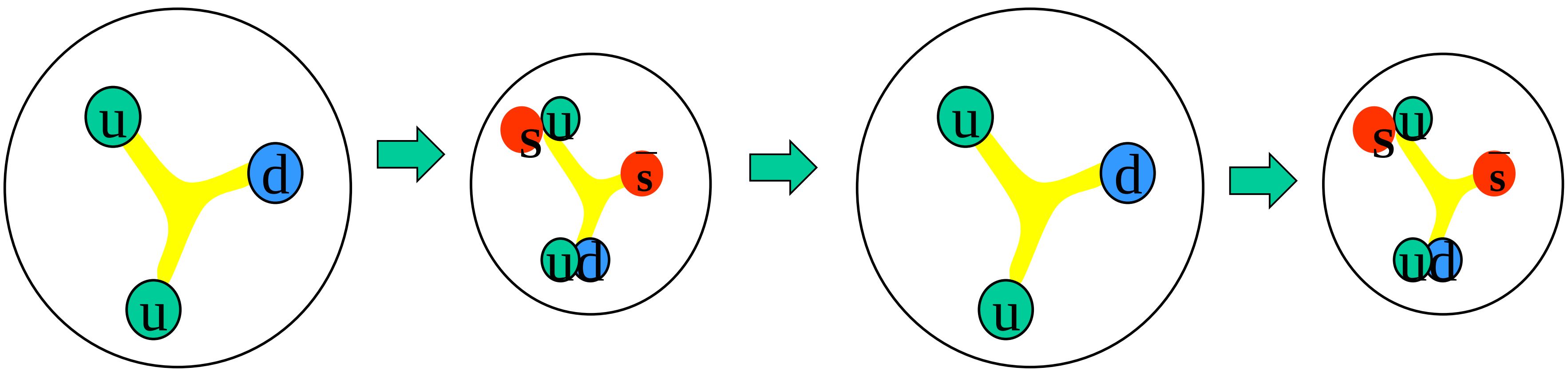
1. Key problem and strangeness in hadron spectroscopy
2. From strangeness to charm & beauty
3. Prospects at EicC/HIAF

1. Key problem & strangeness in hadron spectroscopy

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

crucial for quark confinement & hadron structure

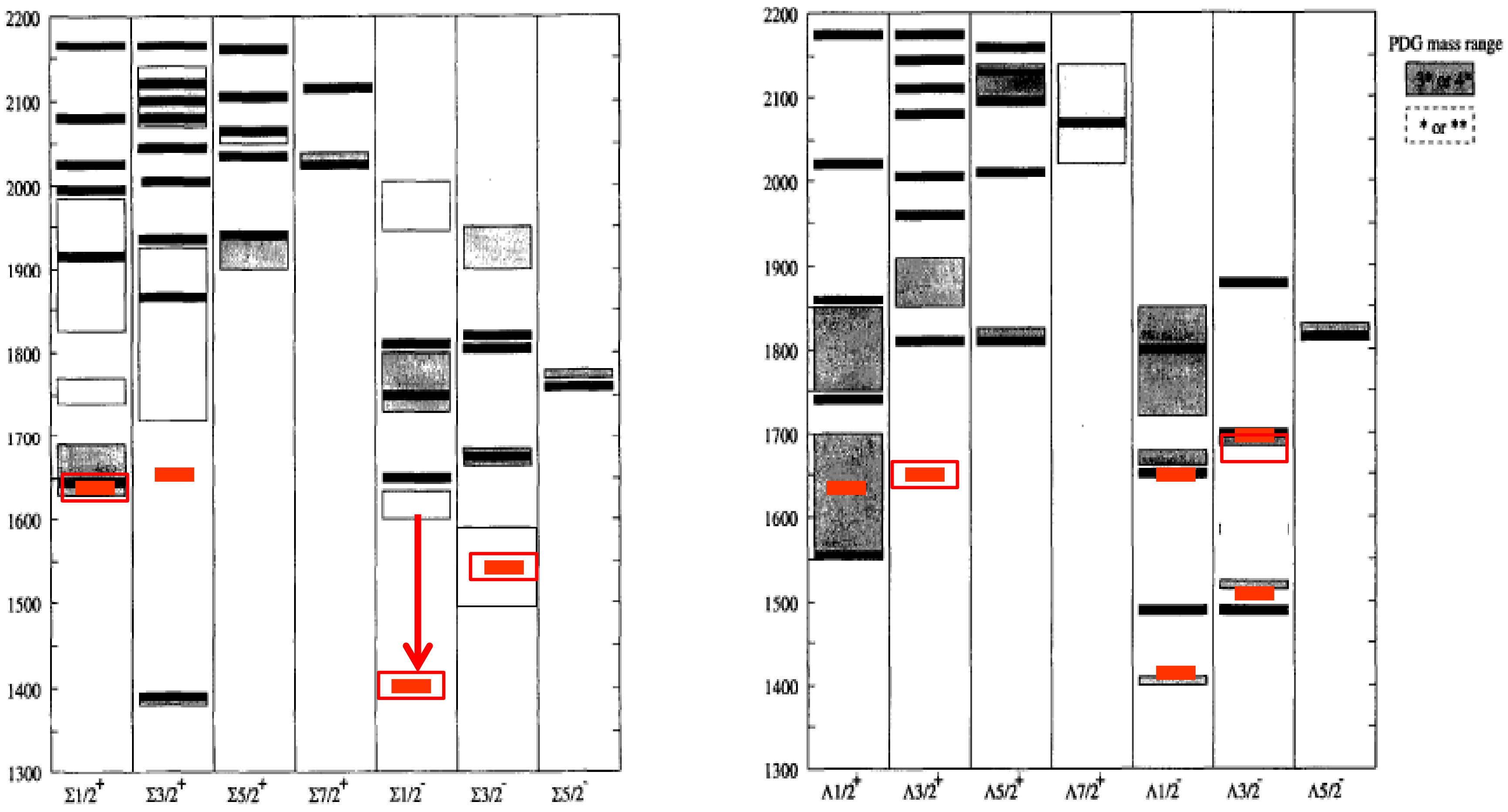




quenched or unquenched quark models give very different predictions of hyperon spectrum

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 ?**

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

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

uds (L=1) $1/2^-$ ~ $\Lambda^*(1405)$ ~ $[ud][su]\bar{u}$

uus (L=1) $1/2^-$ ~ $\Sigma^*(1390)$ ~ $[us][ud]\bar{d}$

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)

$3/2^-$ baryon nonet with strangeness

- Mass pattern : quenched or unquenched ?

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

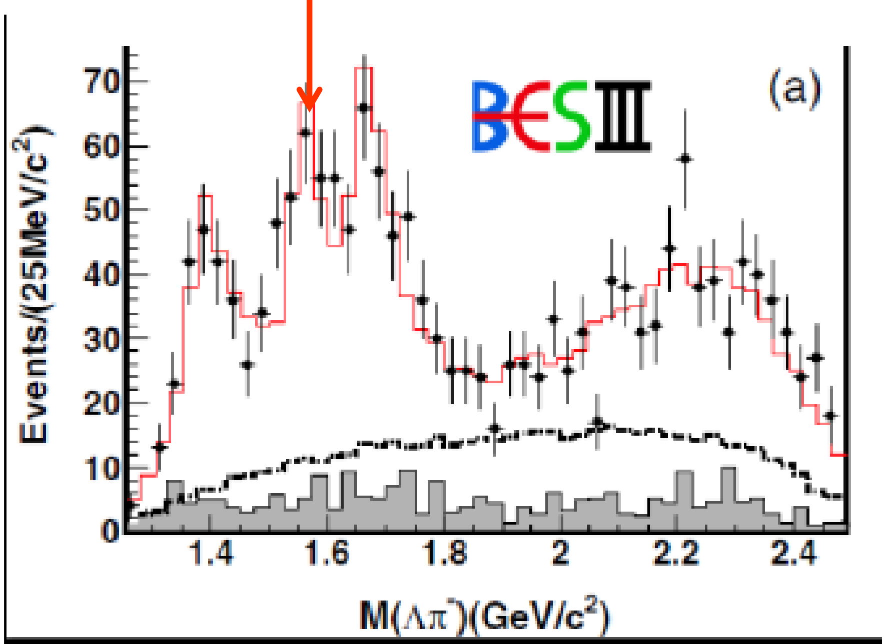
uud (L=1) $3/2^-$ ~ $N^*(1520)$ ~ $[ud]\{uq\}\,\bar{q}$

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

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

$\Sigma(1580)\ 3/2^-$

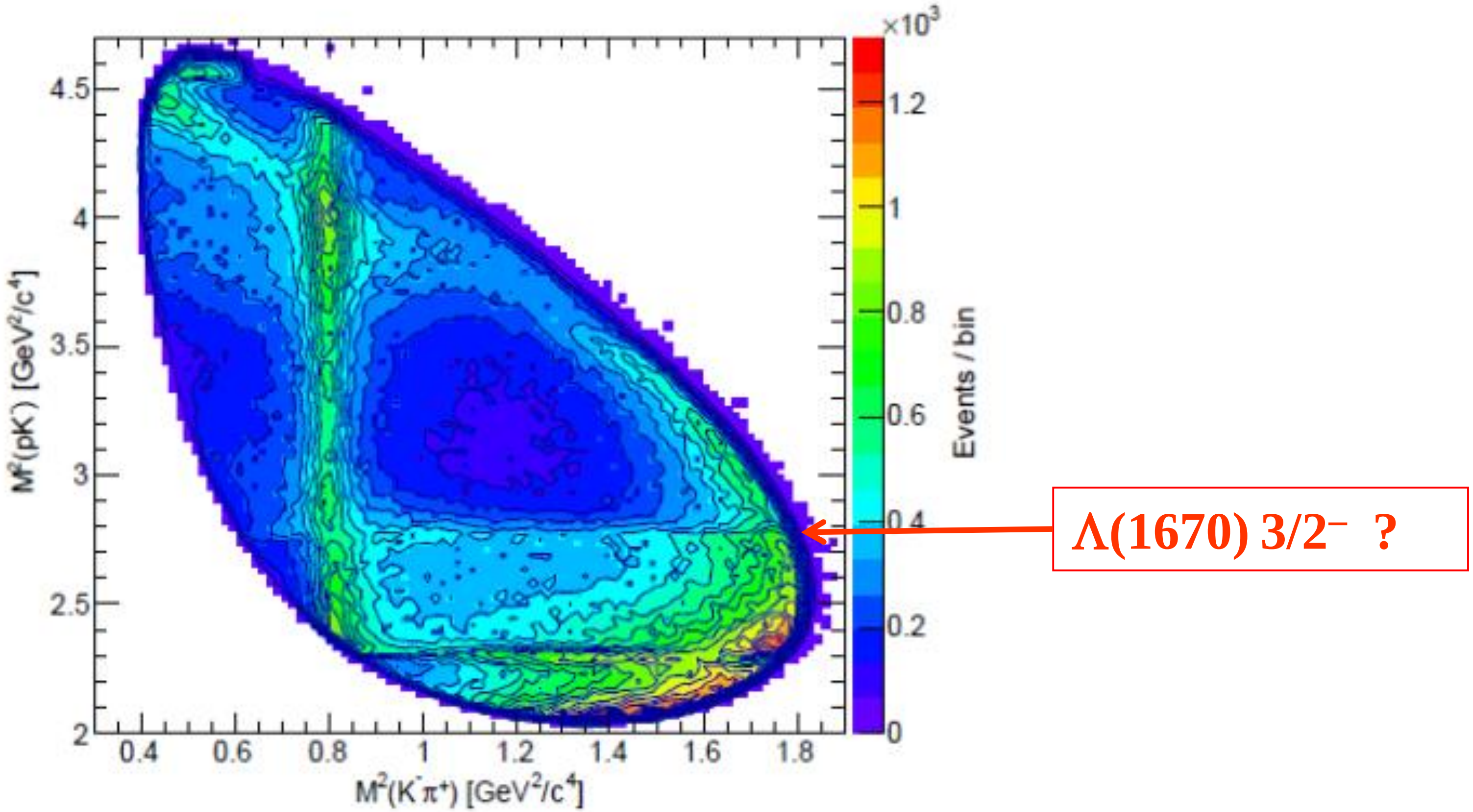
BESIII, PRD88 (2013) 112007



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	Penta-quark states
N*(1440) ~ Nσ	N*(1440) ~ [ud][ud] $\bar{q}$
N*(1535) ~ KΣ-KΛ	N*(1535) ~ [ud][us] $\bar{s}$
Λ*(1405) ~ KN-Σπ	Λ*(1405) ~ [ud][sq] $\bar{q}$
Λ*(1520) ~ Σ*π	Λ*(1520) ~ [ud]{sq} $\bar{q}$

Kaiser, Weise, Oset, Ramos, Oller, Meissner, Hyodo, Jido, Hosaka, …

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

eg., f_1(1420) ~ $\bar{K}$K*

quenched vs un-quenched for mesons

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

$\phi(1020)$	$\bar{s}s$
$K(892)$	$\bar{s}d$
$\omega(782)$	$\bar{u}u + \bar{d}d$
$\rho(770)$	$\bar{u}u - \bar{d}d$

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

$a_0(980)$	$\bar{u}u - \bar{d}d$,	$[\bar{u}\bar{s}][us] - [\bar{d}\bar{s}][ds]$
$f_0(980)$	$\bar{s}s$,	$[\bar{u}\bar{s}][us] + [\bar{d}\bar{s}][ds]$
$\kappa(800)$	$\bar{s}d$,	$[\bar{s}\bar{u}][ud]$
$f_0(600)$	$\bar{u}u + \bar{d}d$,	$[\bar{u}\bar{d}][ud]$

Important implications:

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

$1/2^-$ baryon nonet ~ $\bar{q}q^2q^2$ state + …

0^+ meson octet ~ $\bar{q}^2q^2$ state + …

multiquark components are important for hadrons!

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

unquenched		quenched
Σ^*	$[us][du]\bar{d}$ ~ 1400 MeV	uus (L=1) ~ 1650 MeV
Ξ^*	$[us][ds]\bar{d}$ ~ 1550 MeV	uss (L=1) ~ 1760 MeV
Ω^*	$[us]ss\bar{u}$ ~ 1800 MeV	sss (L=1) ~ 2000 MeV

Meson-Baryon states

Y.S.Oh	K. P. Khemchandani et al.
Σ^* ~ 1475 MeV	~ 1426 MeV
Ξ^* ~ 1616 MeV	~ 1606 MeV
Ω^* ~ 1837 MeV	Ramos & Oset

Experiment knowledge on hyperon states still very poor !

Ω* in PDG:

**** Ω(1672) $3/2^+$,

*** Ω (2250)

** Ω (2380), Ω (2470)

Ξ* in PDG:

**** Ξ(1320) $1/2^+$, Ξ(1530) $3/2^+$

*** Ξ(1690) , Ξ(1820) $3/2^-$, Ξ(1950) , Ξ(2030)

** Ξ(2250) , Ξ(2370)

* Ξ(1620) , Ξ(2120) , Ξ(2500)

Σ^* in PDG2012

****	**Σ(1189)$1/2^+$ Σ^*(1385)$3/2^+$ Σ^*(1670)$3/2^-$** **Σ^*(1775)$5/2^-$ Σ^*(1915)$5/2^+$ Σ^*(2030)$7/2^+$**
***	**Σ^*(1660)$1/2^+$ Σ^*(1750)$1/2^-$ Σ^*(1940)$3/2^-$** **Σ^*(2250)??**
**	**Σ^*(1620)$1/2^-$ Σ^*(1690)?? Σ^*(1880)$1/2^+$** **Σ^*(2080)$3/2^+$ Σ^*(2455)?? Σ^*(2620)??**
*	**Σ^*(1480)?? Σ^*(1560)?? Σ^*(1580)$3/2^-$** **Σ^*(1770)$1/2^+$ Σ^*(1840)$3/2^+$ Σ^*(2000)$3/2^-$** **Σ^*(2070)$5/2^+$ Σ^*(2100)$7/2^-$ Σ^*(3000)??** **Σ^*(3170)??**

All from old experiments of 1970-1985 !!

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

2. From strangeness to charm & beauty

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

Problem:

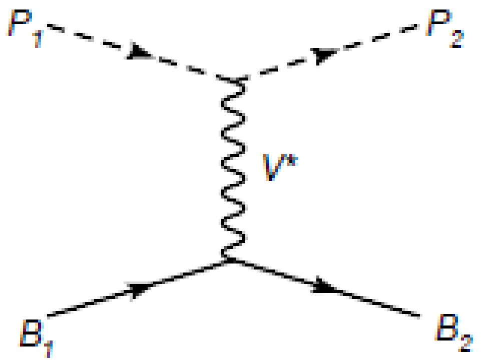
None of them can be clearly distinguished from qqq due to tunable ingredients and possible large mixing of various configurations

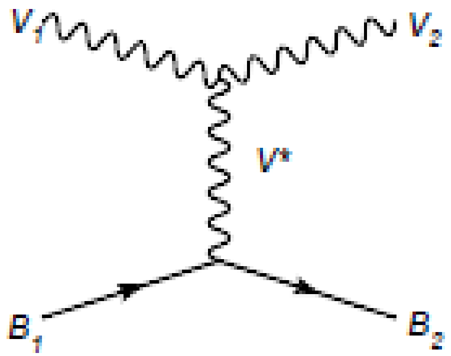
PDG2010: "The clean Λ_c spectrum has in fact been taken to settle the decades-long discussion about the nature of the Λ(1405) —true 3-quark state or mere $\bar{K}N$ threshold effect?— unambiguously in favor of the first interpretation."

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
Λ*(1405)	$\bar{q}$quds	
Λ*(4210)	$\bar{c}$cuds	J.J.Wu, R.Molina, E.Oset, B.S.Zou. Phys.Rev.Lett. 105 (2010) 232001
Λ*(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	$\eta' N$	$K\Sigma$		$\eta_c N$	
		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*		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 $PB \to PB$, with units in MeV.

	(I, S)	M	Γ			Γ_i				
N*	$(1/2, 0)$			ρN	ωN	$K^*\Sigma$			$J/\psi N$	
		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*		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 $VB \to VB$ 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

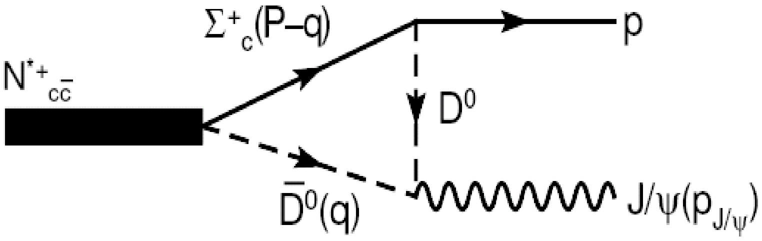
$\bar{D}\Sigma_c$ state in Schoedinger Equation method ~ 4.3 GeV

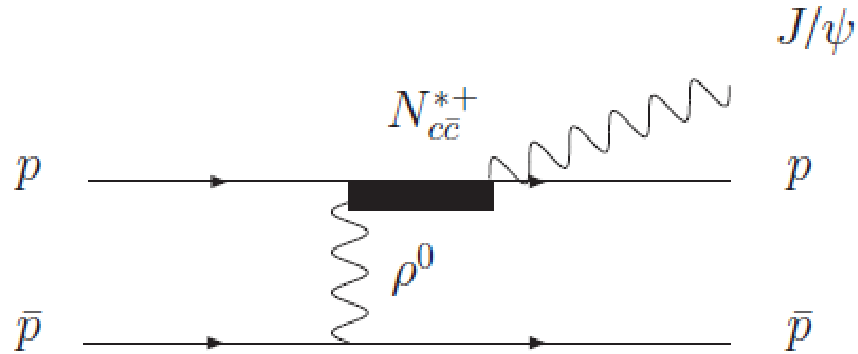
Z.C.Yang, Z.F. Sun, J. He, X.Liu, S.L.Zhu, CPC36(2012)6

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

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

Prediction for PANDA





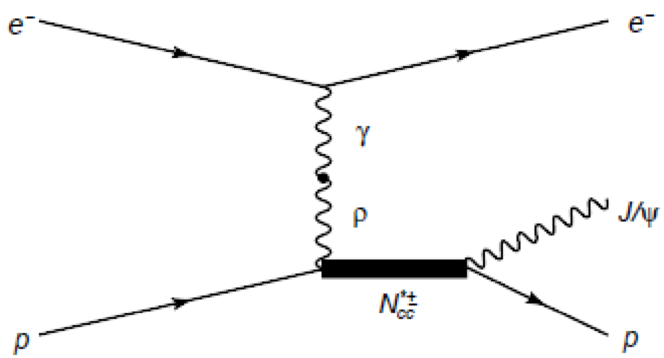
$$\Gamma_{R\to J/\psi p} = 0.01\ \text{MeV},$$

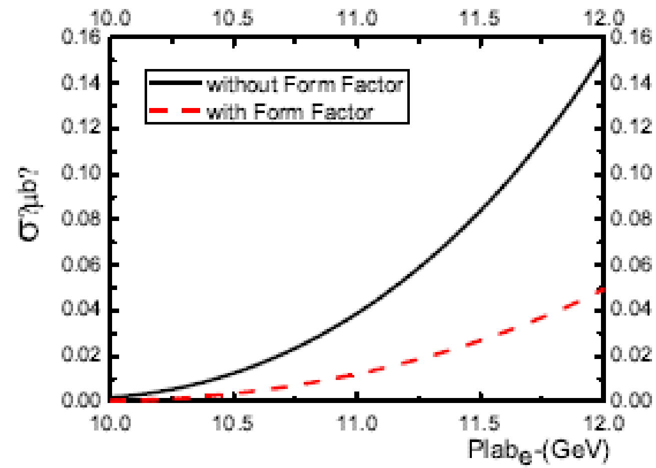
$\bar{p}p \to \bar{p}pJ/\psi \sim 0.1$ nb

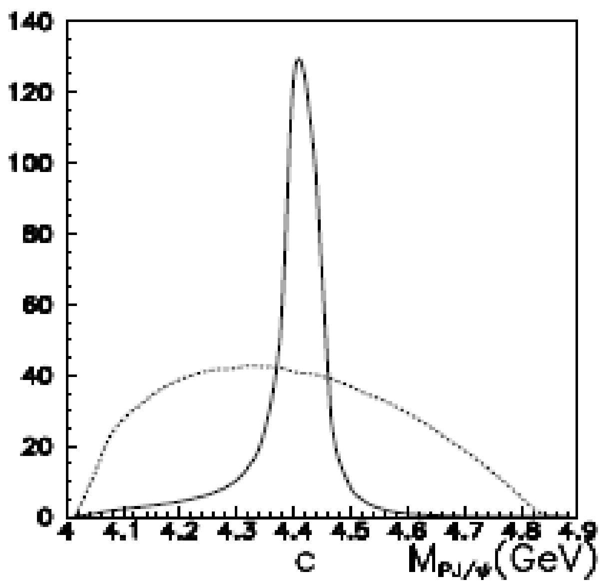
~ 100 events per day at PANDA/FAIR by L=10^{31} cm^{-2}s^{-1}

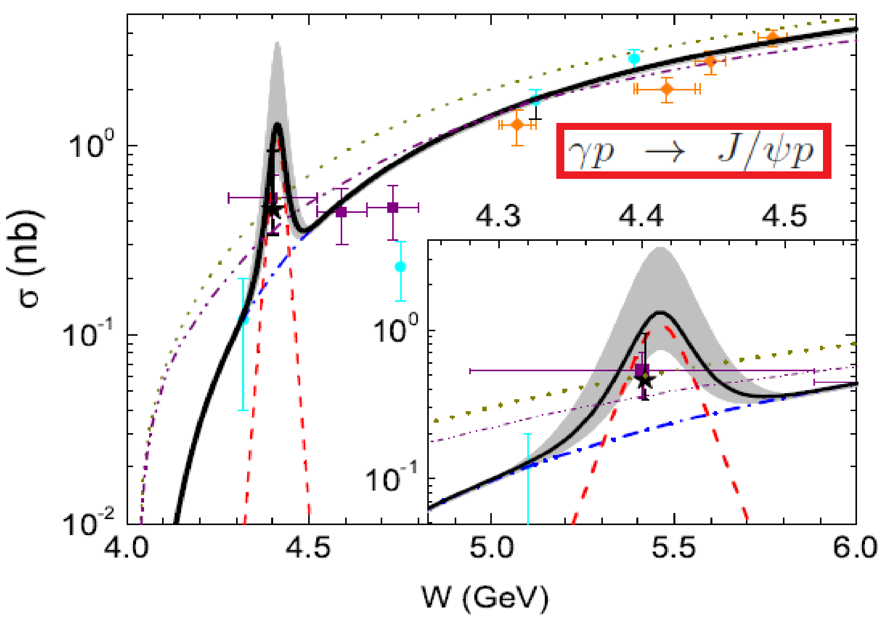
These Super-heavy narrow N* and Λ* can be found at PANDA !

Prediction for 12GeV@JLab









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

Proposals for looking for $N_{c\bar{c}}$ & $\Lambda_{c\bar{c}}$ 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.

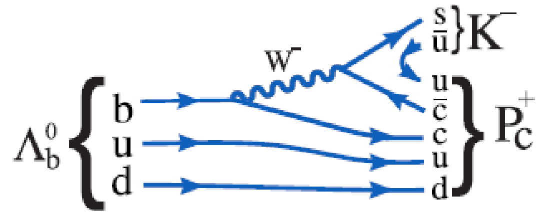
b) E.J.Garzon, J.J.Xie, "Effects of a $N_{c\bar{c}}$ resonance with hidden charm in the $\pi^- p \rightarrow D^- \Sigma_c^+$ reaction near threshold", PRC 92 (2015) 035201

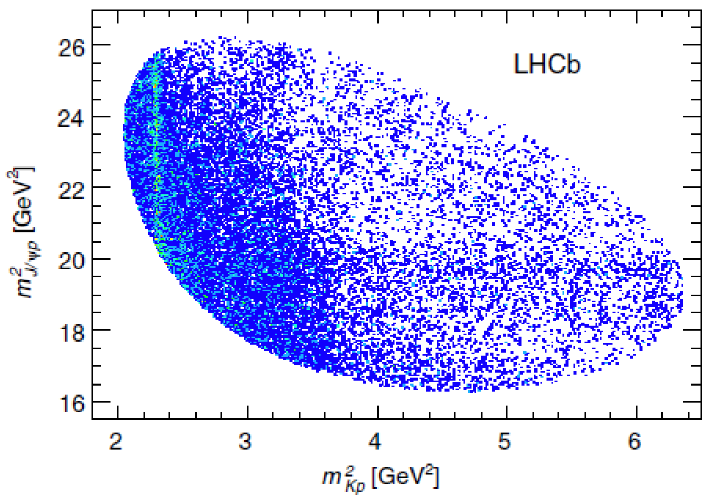
c) X.Y.Wang, X.R.Chen, "Production of the superheavy baryon Λ*(4209) in kaon-induced reaction", EPJA51 (2015) 85

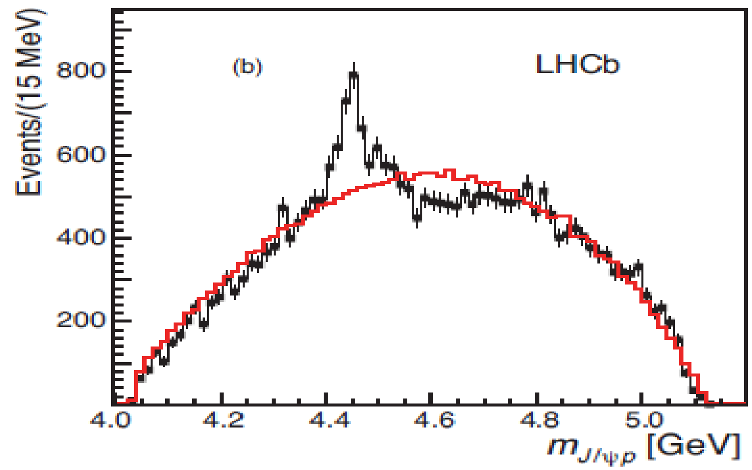
Observation of $P_c^+(4380)$ & $P_c^+(4450)$ by LHCb

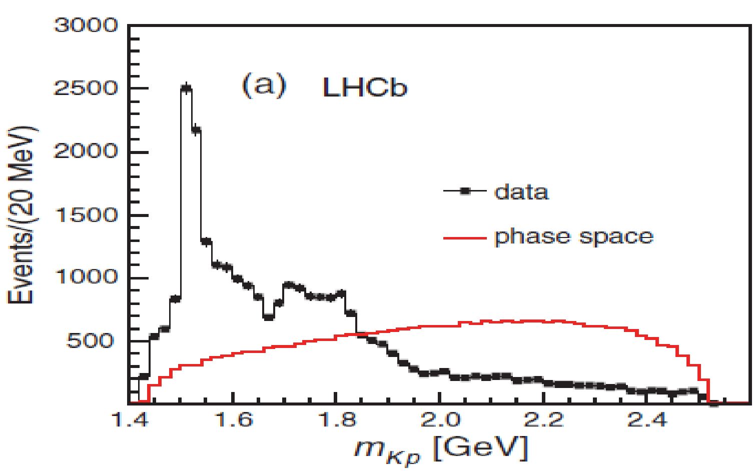
LHCb, Phys.Rev.Lett. 115 (2015) 072001 :

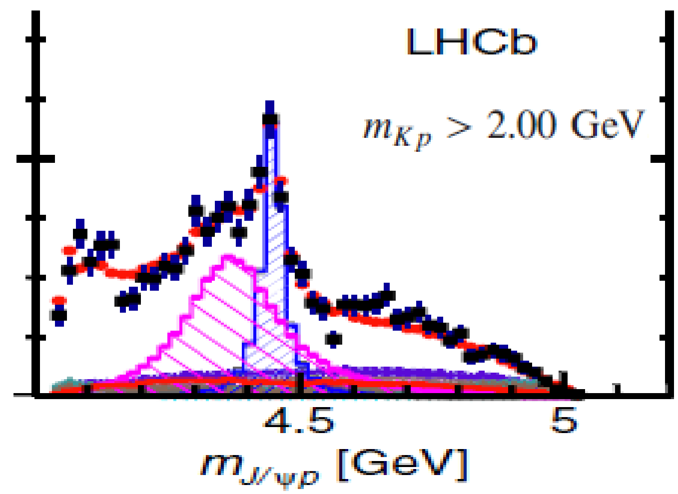
Observation of two N* from $\Lambda_b^0 \to J/\psi K^- p$











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

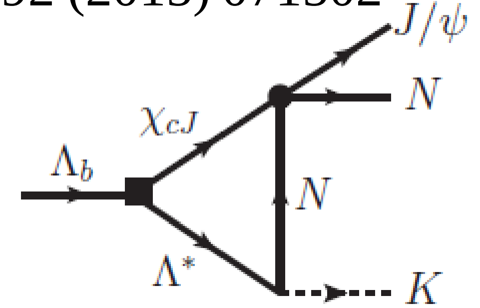
R.Chen, X.Liu, X.Q.Li, S.L.Zhu, PRL115 (2015) 132002;
H.X.Chen, W.Chen, X.Liu, T.G.Steele, S.L.Zhu, PRL115 (2015)172001
L.Roca, J.Nieves, E.Oset, PRD92 (2015) 094003;
J.He, PLB 753 (2016)547 ;

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.Mei ßner, W.Wang, Z.Yang, PRD92 (2015) 071502
X.H.Liu, Q.Wang, Q.Zhao, PLB757 (2016) 231



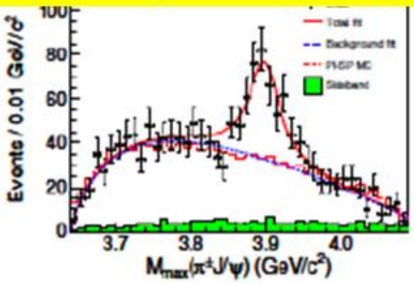
For a comprehensive review, cf.:

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)$^+$

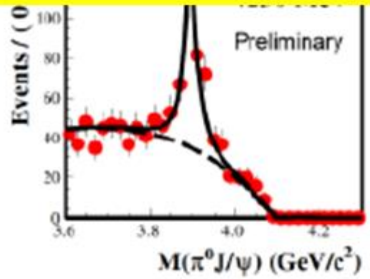
PRL 110, 252001 (2013)



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

Zc(3900)^0

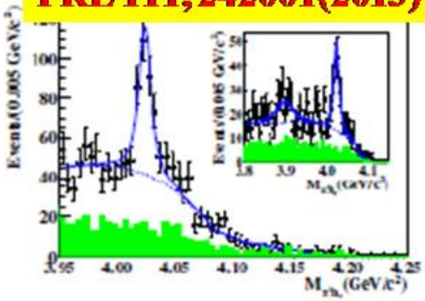
PRL 115, 112003 (2015)



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

Zc(4020)$^+$

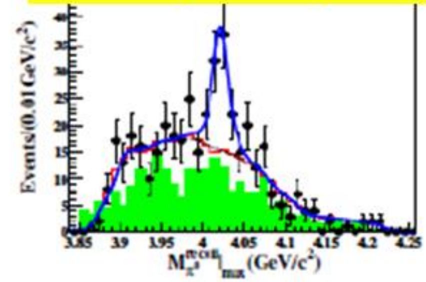
PRL 111, 242001(2013)



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

Zc(4020)^0

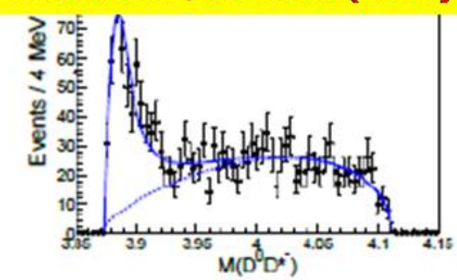
PRL113,212002 (2014)



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

Zc(3885)$^+$

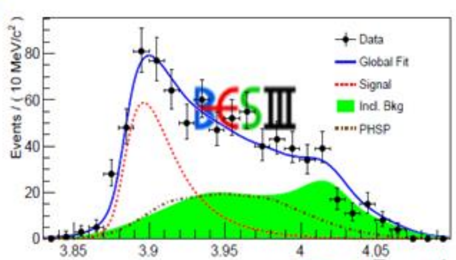
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)



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

Zc(3885)^0

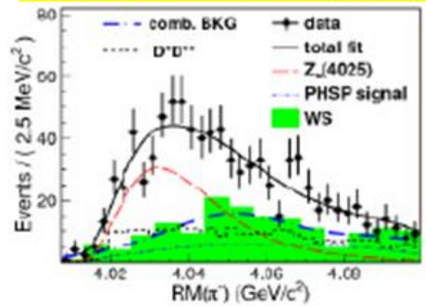
PRL 115, 222002 (2015)



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

Zc(4025)$^+$

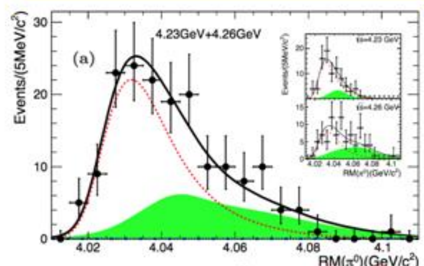
PRL 112, 132001 (2014)



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

Zc(4025)^0

PRL115, 182002 (2015)



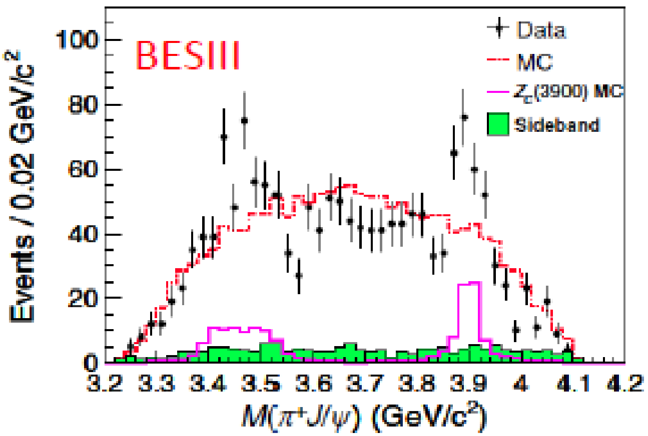
$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

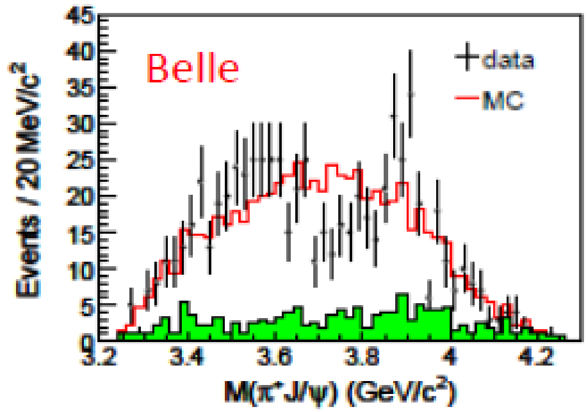
“Y(4260)的结构以及带电Zc(3900)的产生”

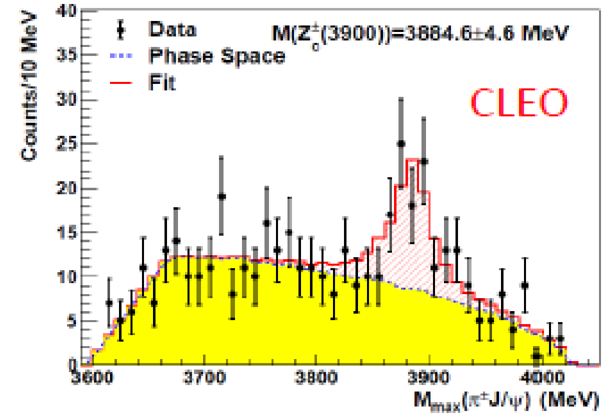
a

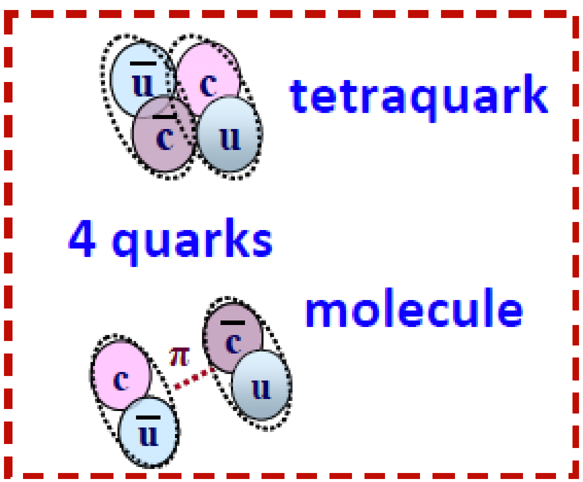
PRL **110**, 252001 (2013) PHYSICAL REVIEW LETTERS week ending 21 JUNE 2013

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

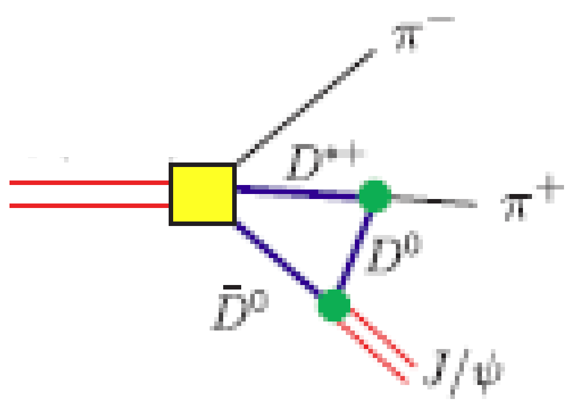




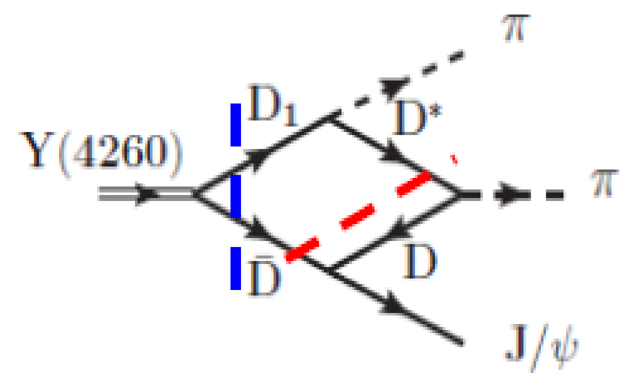




Exotic!



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 ?

F.K.Guo, Hanhart, Meissner,Q.Wang,Q.Zhao,Zou, Rev.Mod.Phys.90 (2018)015004

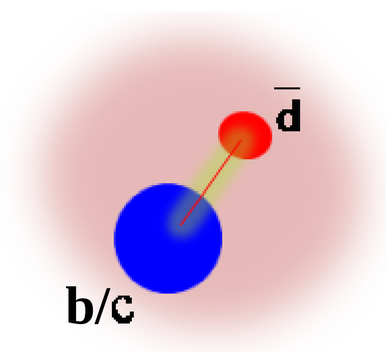
Most interesting hadron systems accessible in near future

- **my favorite strategy:**

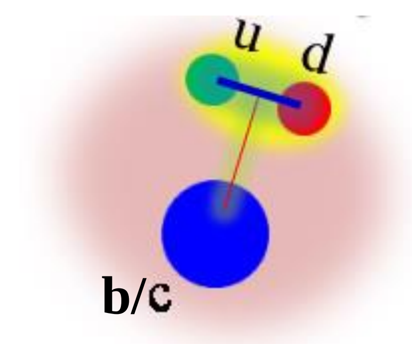
$\bar{c}cuud$ & $\bar{c}cuds$ → sss - $\bar{q}qsss$ → cqq - $\bar{q}qcqq$
→ hyperons → light baryons

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

s → c → b



charm & beauty meson



charm & beauty baryon

3. Prospects at EicC/HIAF

1) E_{cm} ~ 15 GeV : pentaquarks with hidden charm and beauty,
baryons with open charm and beauty

2) E_{cm} ~ 6 GeV : pentaquarks with hidden charm and
baryons with open charm and strangeness

3) E_{cm} ~ 4 GeV : hyperons

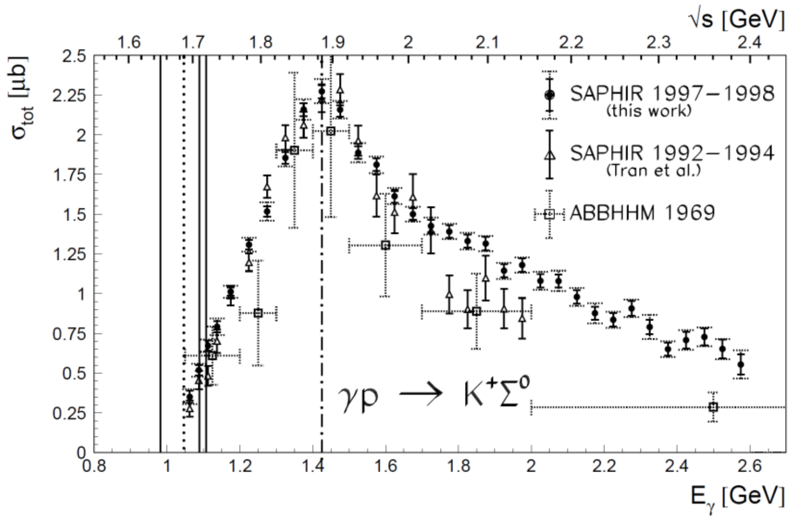
both baryon and meson spectroscopy can be studied.

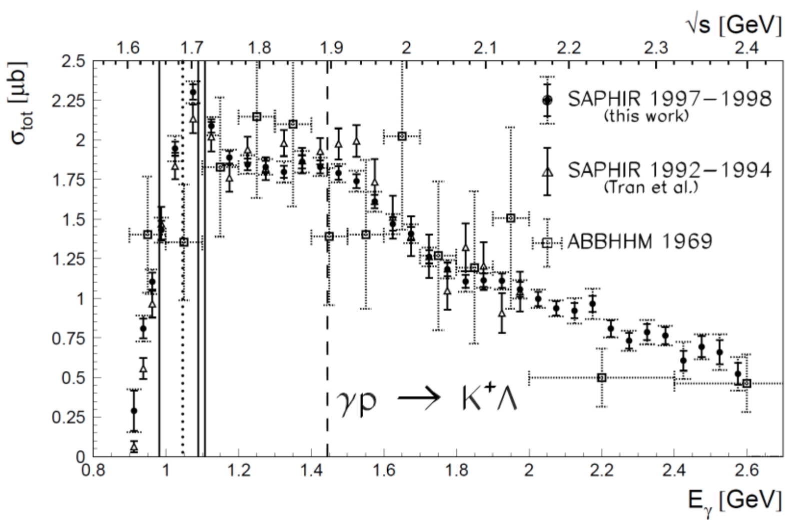
EicC with E_{cm} ~ 15 GeV -- top choice in near future for China

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

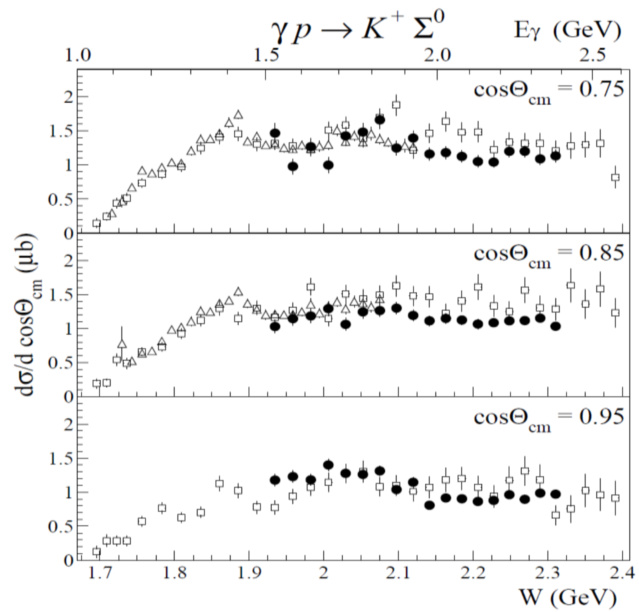
Strangeness partners of P_c states: N*(1875) & N*(2080)

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

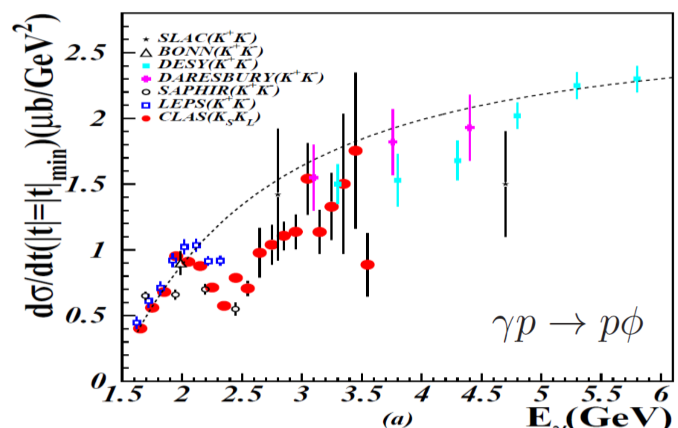




Glander, K.H. *et al.* EPJA19 (2004) 251-273



LEPS, PRC73 (2006) 035214



CLAS, PRC89 (2014) 055206

Physics Letters B 709 (2012) 70–76

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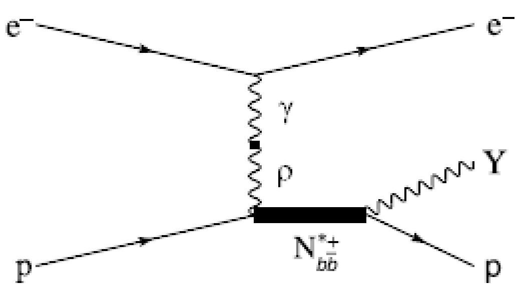
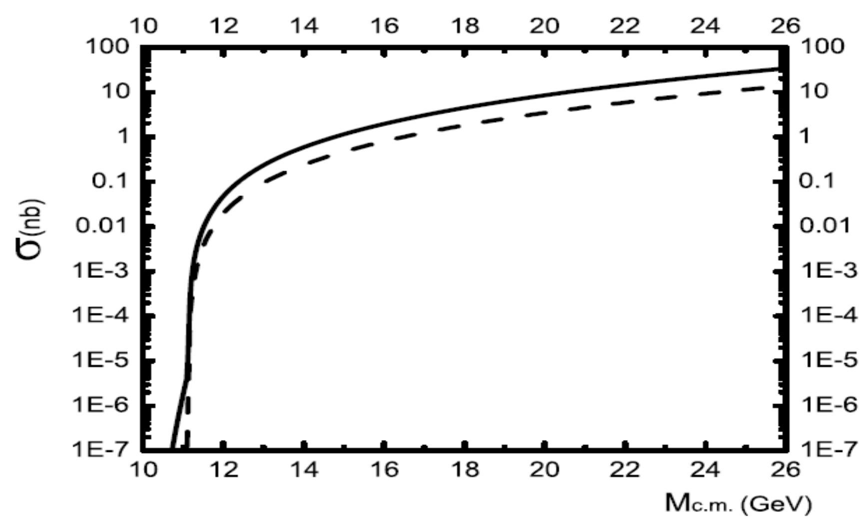
Prediction of super-heavy N^* and Λ^* resonances with hidden beauty

Jia-Jun Wu [a,*], Lu Zhao [a], B.S. Zou [a,b]

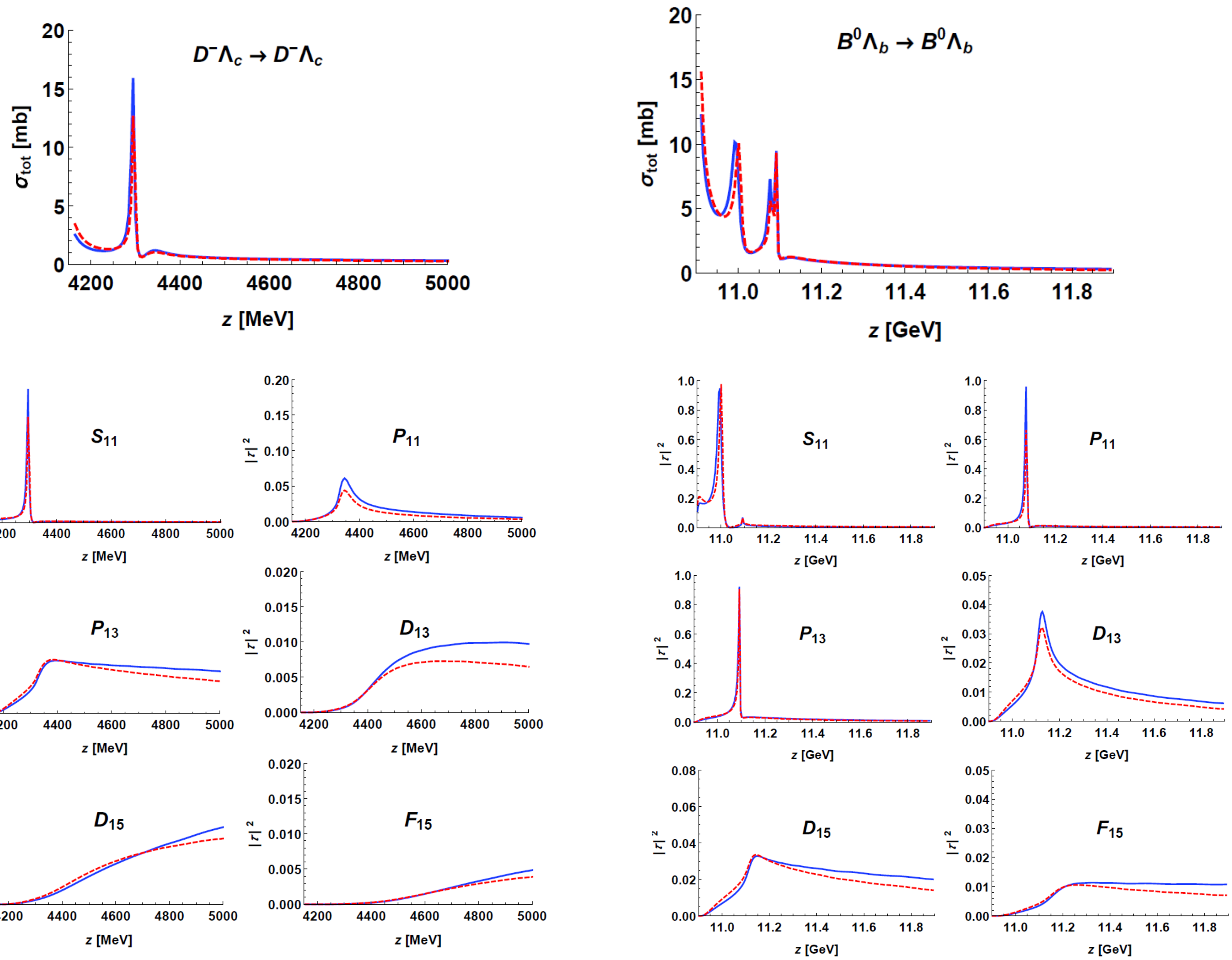
M (MeV)	Γ (MeV)	Γ_i (MeV)					
		πN	ηN	$\eta' N$	$K\Sigma$	$\eta_b N$	
11 052	1.38	0.10	0.21	0.11	0.42	0.52	$1/2^-$
		ρN	ωN	$K^*\Sigma$	ΥN		
11 100	1.33	0.09	0.30	0.39	0.51		$1/2^-$, $3/2^-$





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

C.W.Shen, Roechen, 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

	Widths (MeV)			
	$P_c(4380)$		$P_c(4450)$	
Mode	$\bar{D}\Sigma_c^*(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{5}{2}^+)$
$\bar{D}^*\Lambda_c$	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！