

Penta-quark states from Strangeness to charm and beauty

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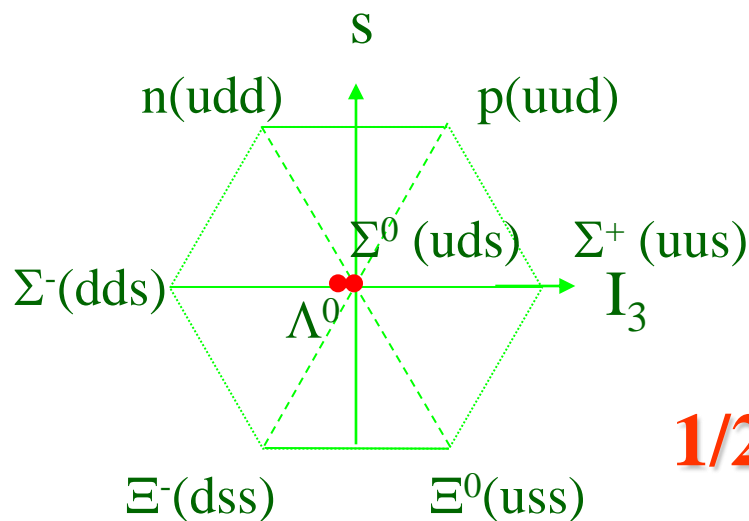
Outline :

- 1. Introduction**
- 2. Penta-quark states with strangeness**
- 3. From Strangeness to charm & beauty**
- 4. Conclusions**

1. Introduction

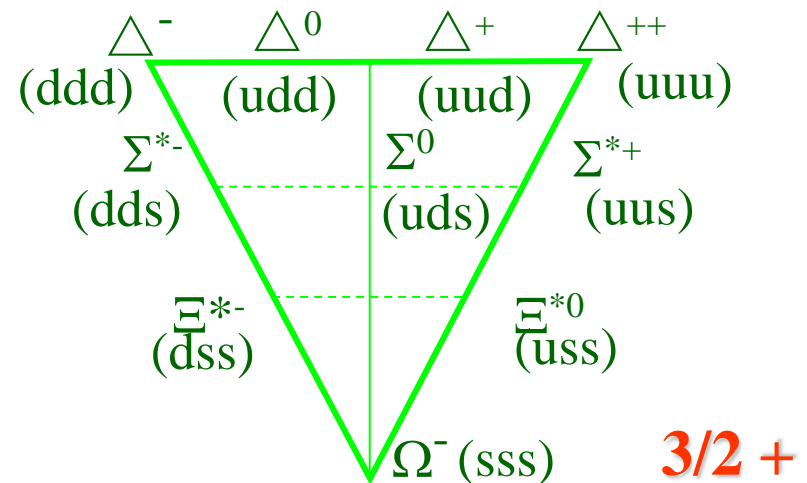
Spectroscopy \rightarrow interaction dynamics & structures

atomic spectrum	\rightarrow	atomic quantum theory
nuclear spectrum	\rightarrow	shell model, collective motion
hadron spectrum	\rightarrow	? Important discovery



**SU(3) 3q-quark
model for baryons**

$L=0$



$1/2 +$

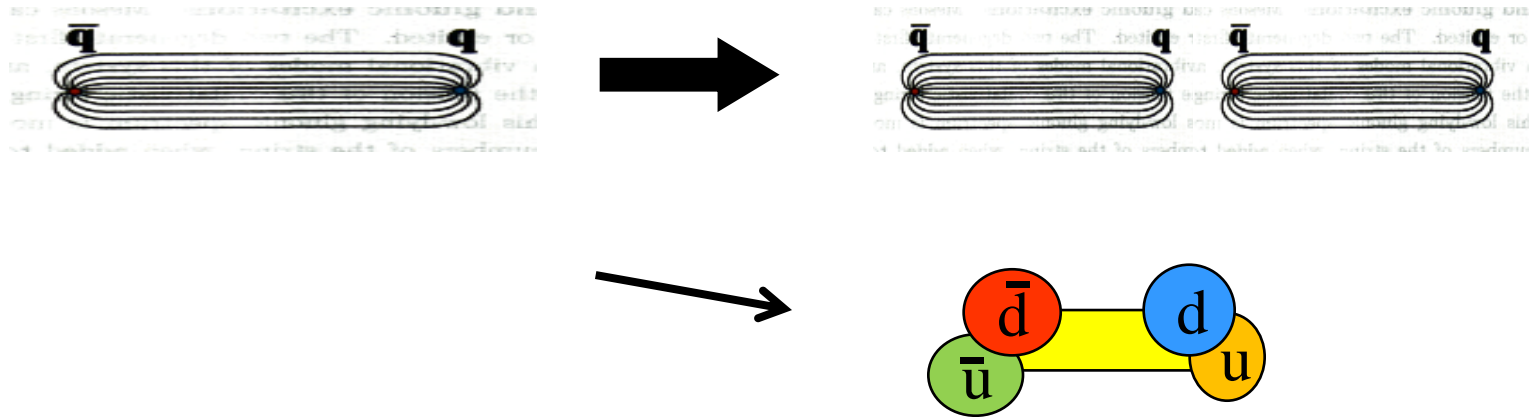
$3/2 +$

Prediction $m_{\Omega^-} \cong 1670 \text{ MeV}$

experiment $m_{\Omega^-} \cong 1672.45 \pm 0.29 \text{ MeV}$

Key problem in QCD and hadron structure

Quark confinement – self-interaction of gluons



gluons $\rightarrow \bar{q}q$: crucial for quark confinement
and hadron structure
to be more challenging than
atomic and nuclear structures

The number of constituents in a hadron is not a constant!

2. Penta-quark states with strangeness

- $1/2^-$ baryon nonet : quenched or unquenched ?

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

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

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

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

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

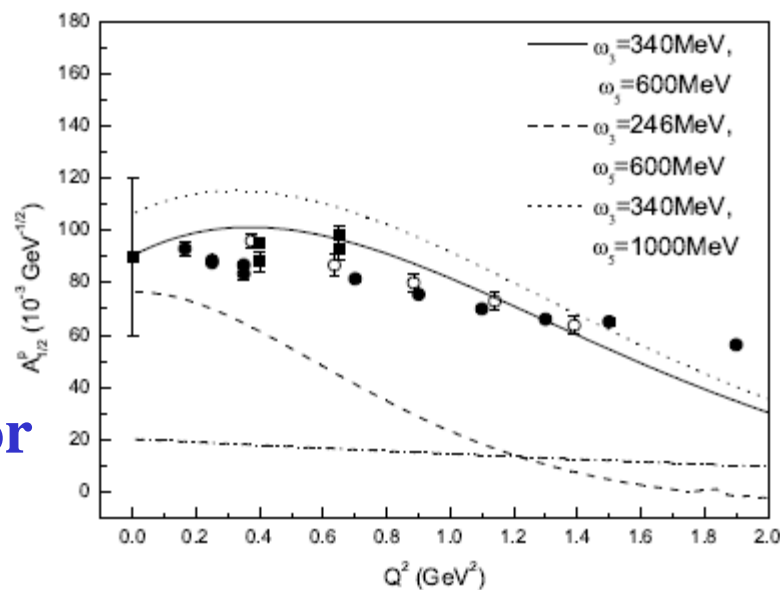
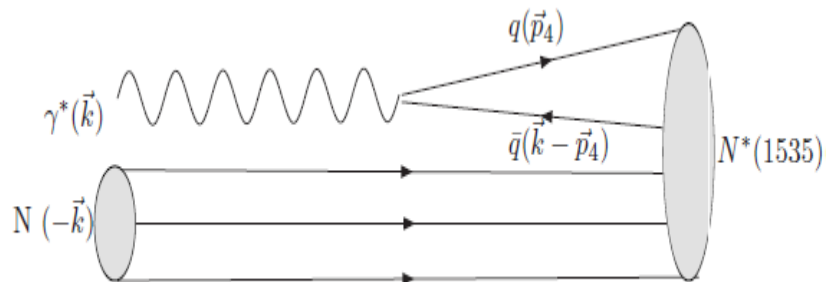
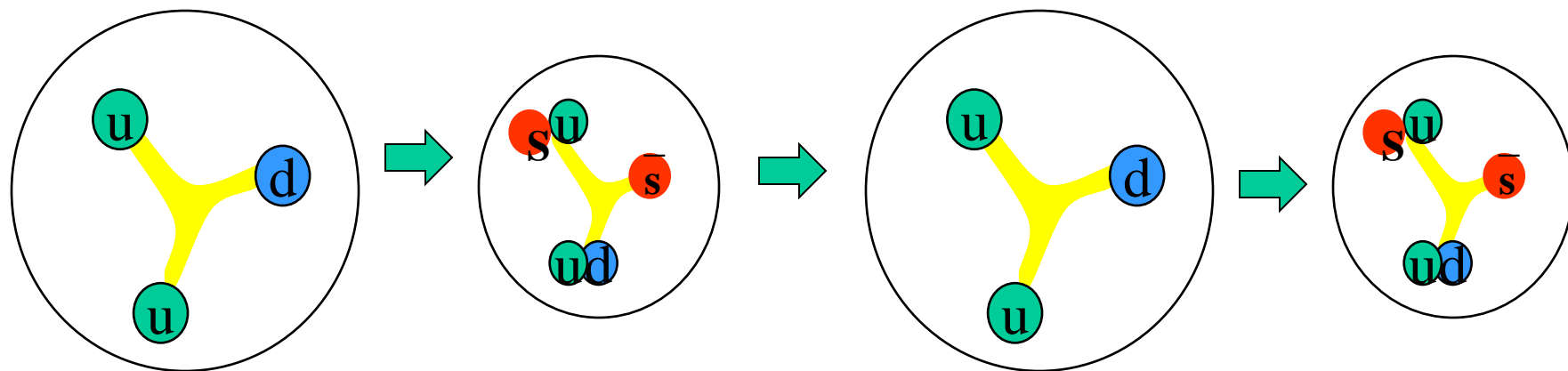
- Strange decays of $N^*(1535)$ and $\Lambda^*(1670)$:

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

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

B.C.Liu, B.S.Zou, PRL96(2006)042002 ,“Mass and $K\Lambda$ Coupling of the $N^*(1535)$ ”

The breathing mode for the $N^*(1535)$



Important role for N^* EM form factor

An & Zou, EPJA39(2009)195

Alternative pictures :

Hadronic molecules

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

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

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

Penta-quark states

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

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

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

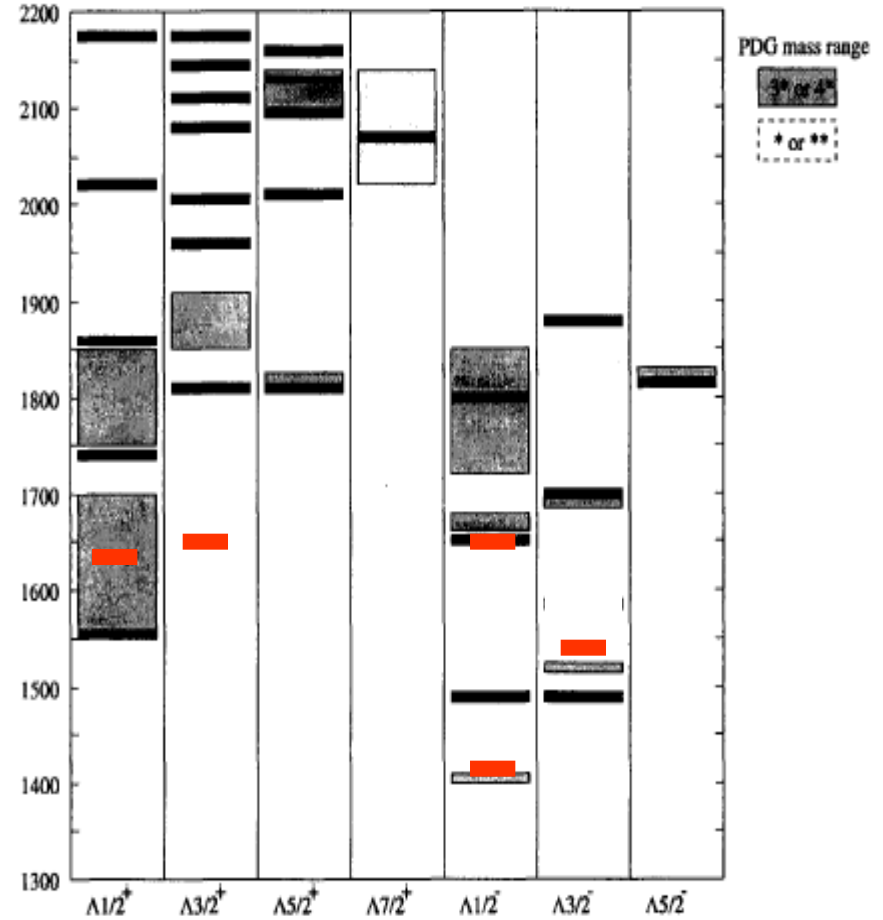
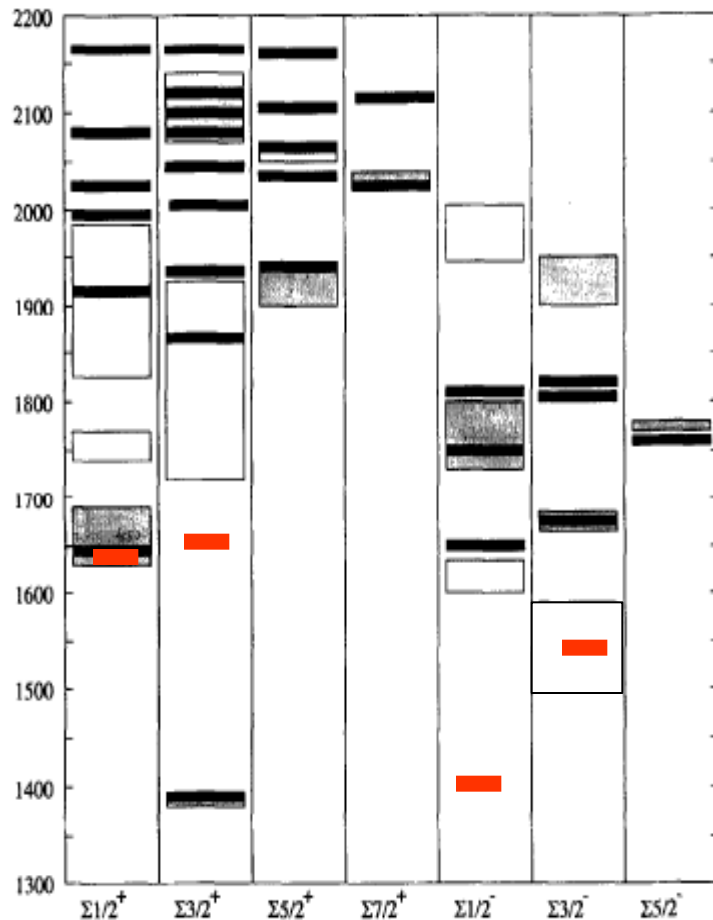
Kaiser, Weise, Oset, Ramos,
Oller, Meissner, Hyodo, Jido,
Hosaka, ...

Important implications:

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

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

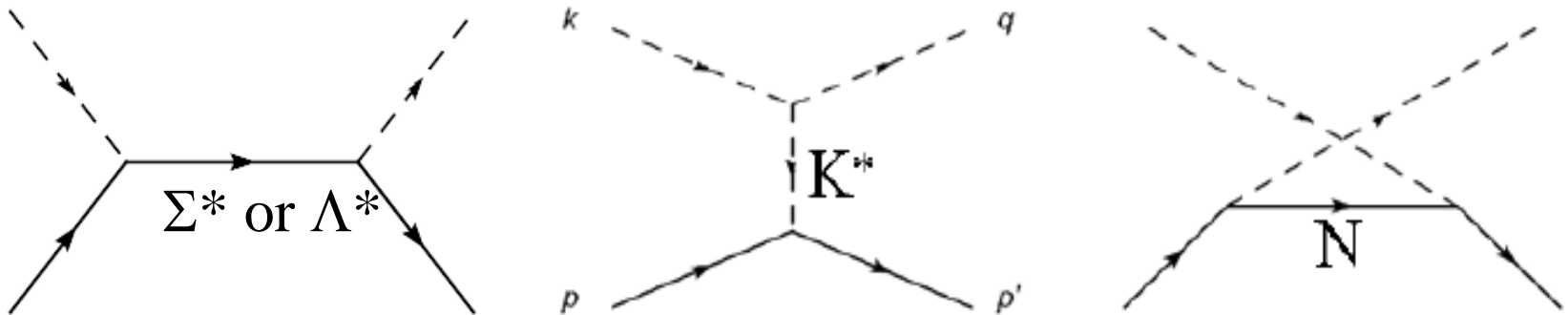
New results on Σ^* & Λ^* from CB data

Crystal Ball: Prakhov et al., **PRC 80**(2009) 025204

$$K^- + p \rightarrow \pi^0 + \Lambda \quad \& \quad K^- + p \rightarrow \pi^0 + \Sigma^0$$

$$p_K = 514\text{--}750 \text{ MeV}, \quad \sqrt{s} = 1569 - 1676 \text{ MeV}$$

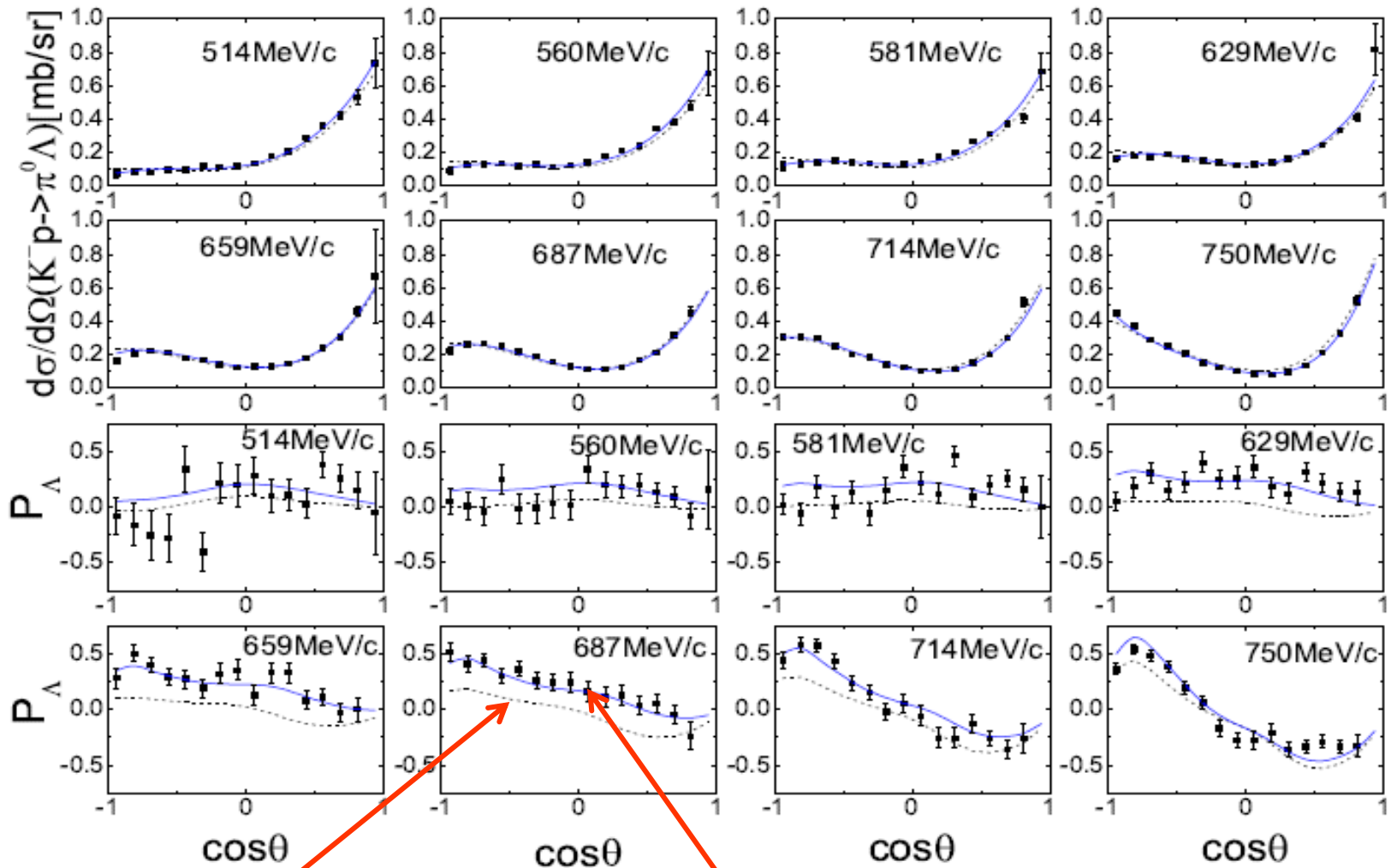
The high precision new data can give valuable information on Σ^* & Λ^*



P.Gao, B.S.Zou, A.Sibirtsev, NPA867(2011)41

NPA referee: “This is an excellent, clear, concise and convincing piece of work. I wish we saw more analyses like this.”

new CB data on $K^-p \rightarrow \pi^0 \Lambda$: No $\Sigma(1620) 1/2^-$ needed !!



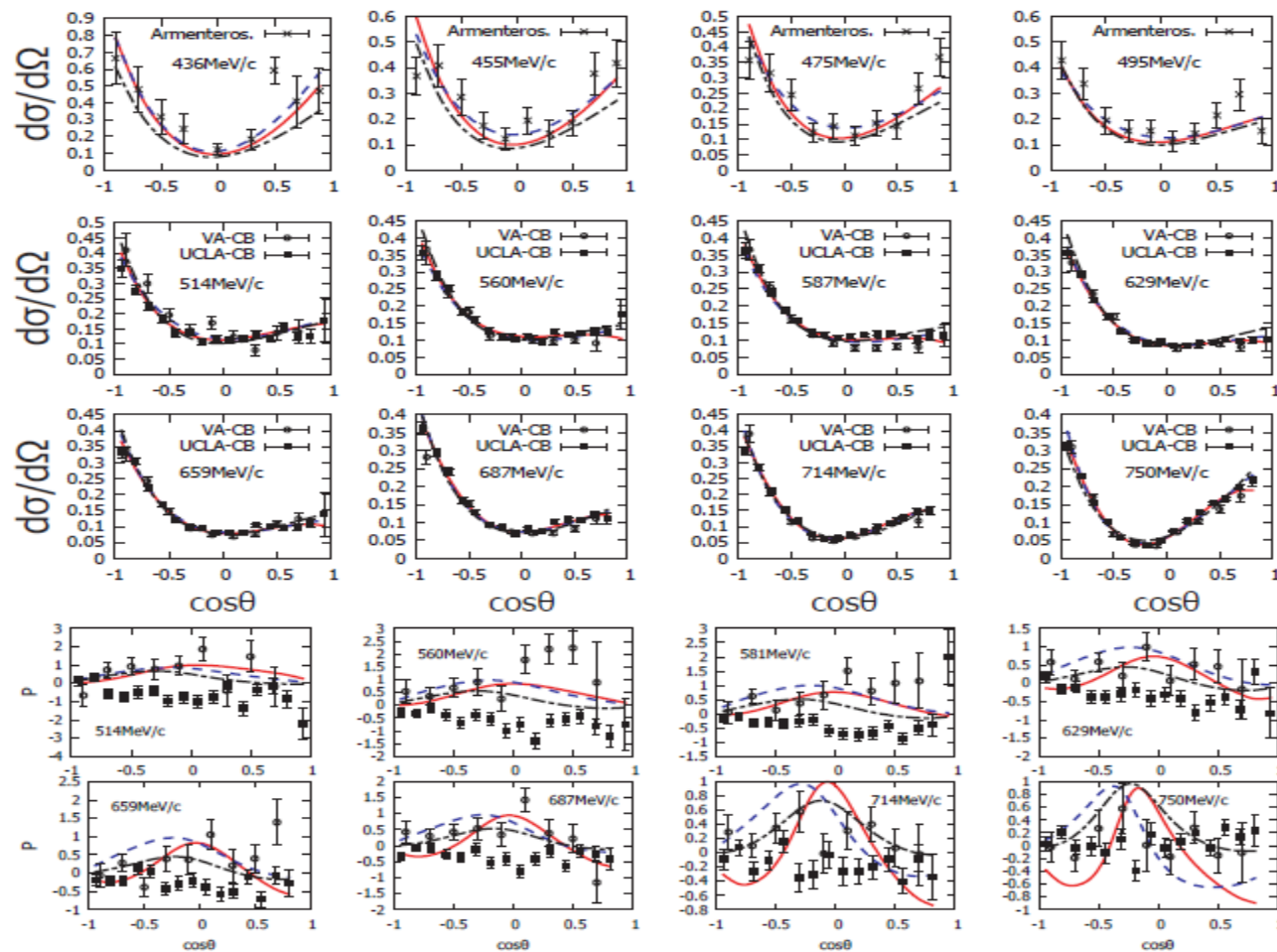
with basic ingredients

adding $\Sigma(1635) 1/2^+$

CB Λ Polarization data is crucial for discriminating $\Sigma(1620) 1/2^-$ from $\Sigma(1635) 1/2^+$
PDG2014 downgrades $\Sigma(1620) 1/2^-$ from ** to *

Fits to new CB data on $K^-p \rightarrow \pi^0 \Sigma^0$

J. Shi, B. S. Zou, PRC91(2015) 035202



$\Lambda^*(1680)3/2^+$ replaces $\Lambda^*(1690)3/2^-$ ****

Strong support for unquenched quark model!

3. 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

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

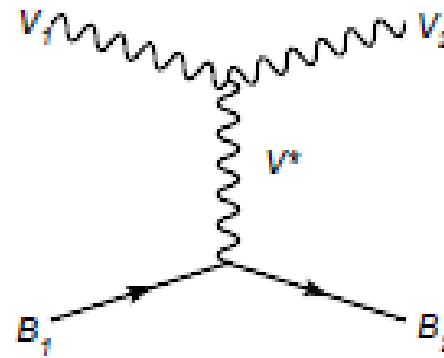
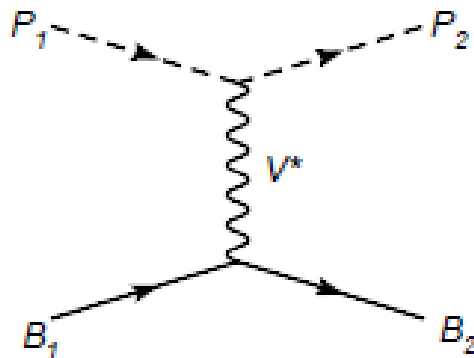
$N^*(4260)$ $\bar{c}cuud$ J.J.Wu, R.Molina, E.Oset, B.S.Zou.
Phys.Rev.Lett. 105 (2010) 232001

$N^*(11050)$ $\bar{b}buud$ 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				
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
Λ^*	$(0, -1)$			$K N$	$\pi \Sigma$	$\eta \Lambda$	$\eta' \Lambda$	$K \Xi$
		4209	32.4	15.8	2.9	3.2	1.7	2.4
		4394	43.3	0	10.6	7.1	3.3	5.8

$\bar{D}\Sigma_c$

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				
N^*	$(1/2, 0)$			ρN	ωN	$K^* \Sigma$		$J/\psi N$
		4412	47.3	3.2	10.4	13.7		19.2
Λ^*	$(0, -1)$			$K^* N$	$\rho \Sigma$	$\omega \Lambda$	$\phi \Lambda$	$K^* \Xi$
		4368	28.0	13.9	3.1	0.3	4.0	1.8
		4544	36.6	0	8.8	9.1	0	5.4

$\bar{D}^* \Sigma_c$

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

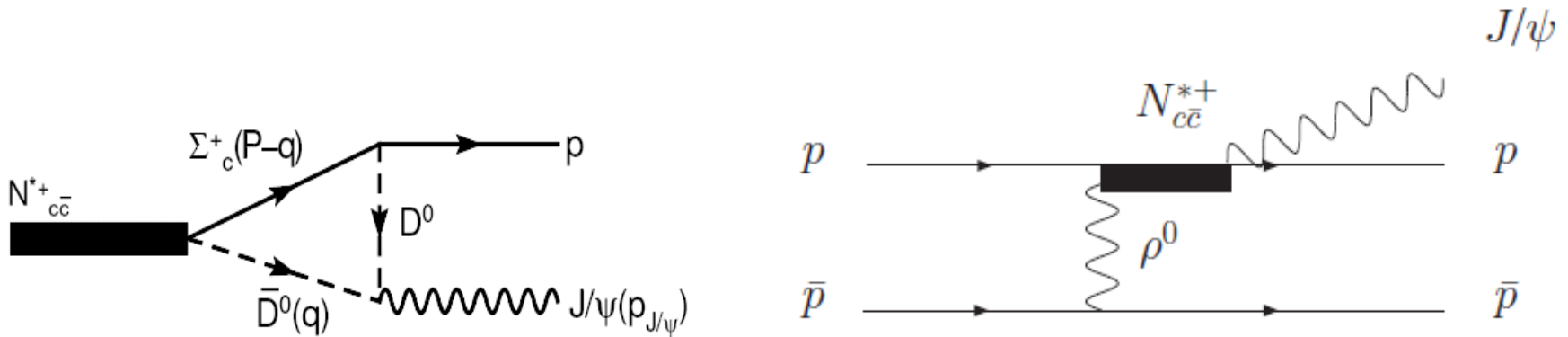
$\bar{D}\Sigma_c$ state in Schoedinger Equation method ~ 4.3 GeV

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.Wei, J.He, H.S.Xu, B.S.Zou, EPJA48(2012)61

Prediction for PANDA



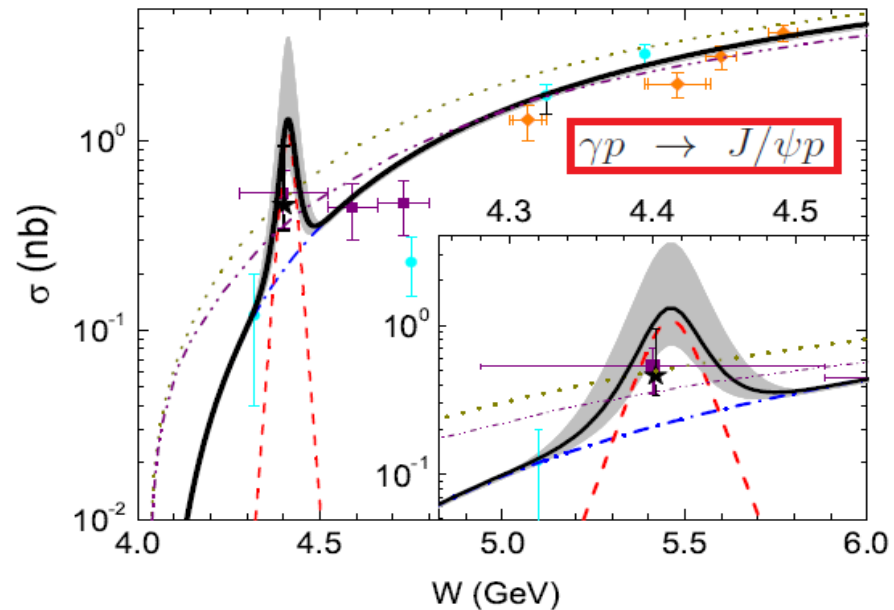
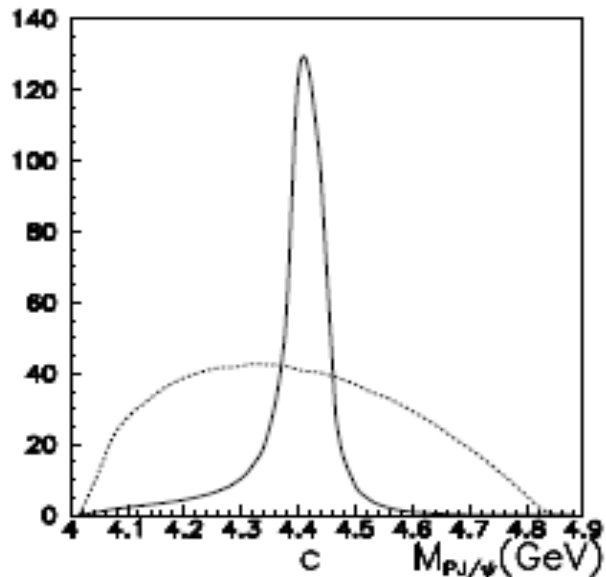
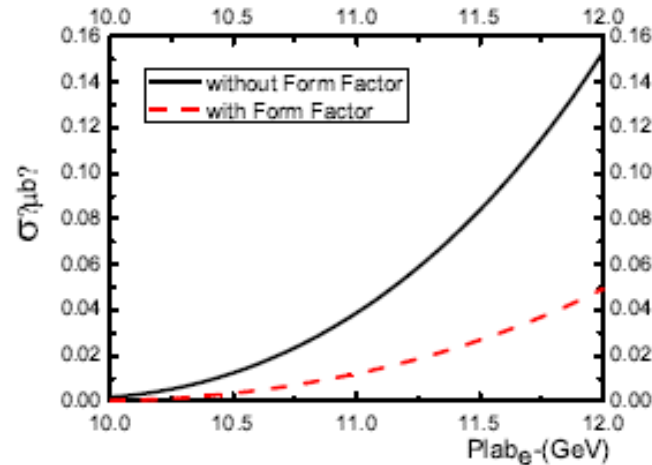
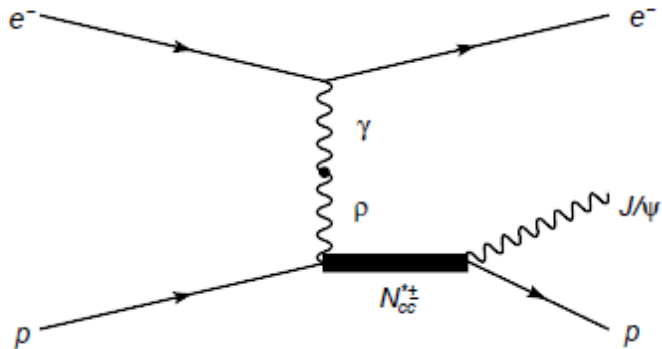
$$\Gamma_{R \rightarrow J/\psi p} = 0.01 \text{ MeV},$$

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

~ 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

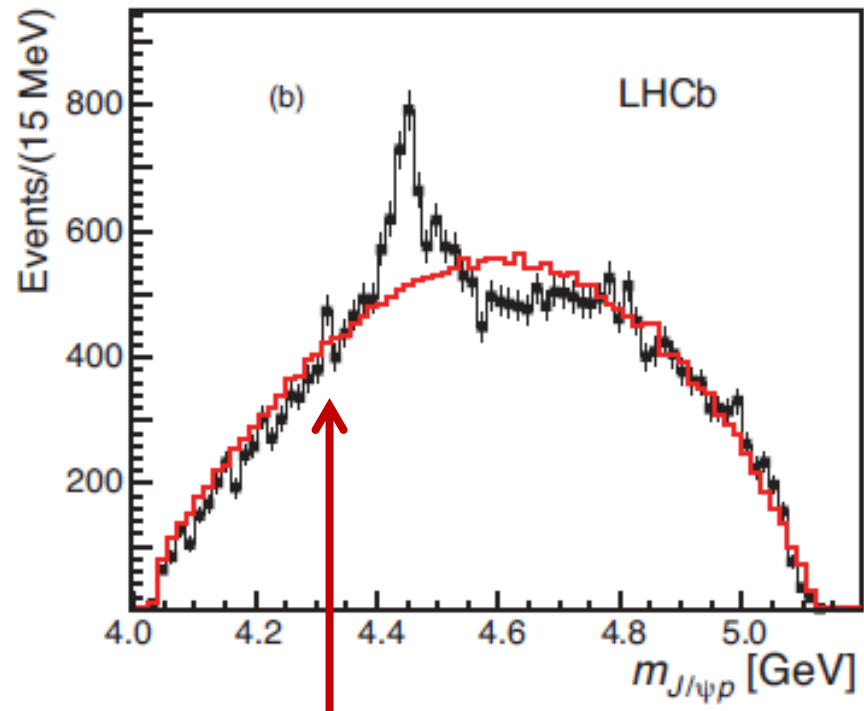
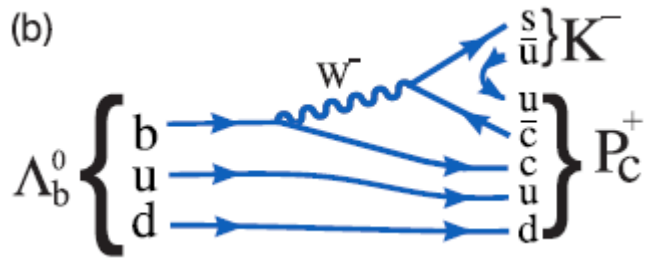


Y. Huang, J.He, H.F.Zhang and X.R.Chen, JPG41, 115004 (2014)

LHCb (arXiv:1507.03414) :

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

- 1) $4380 \pm 8 \pm 29$ MeV, $205 \pm 18 \pm 86$ MeV, $3/2^-$ $P_c^+(4380)$
compatible with our predicted $N^*(4412) 3/2^-$
- 2) $4450 \pm 2 \pm 3$ MeV, $39 \pm 5 \pm 19$ MeV, $5/2^+$ $P_c^+(4450)$



Is this our predicted lowest $N^*(4300) 1/2^-$

Other theoretical explanations on LHCb results:

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

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

R.Chen, X.Liu, X.Qi.Li, S.L.Zhu, arXiv:1507.03704 [hep-ph];

L.Roca, J.Nieves, E.Oset, arXiv:1507.04249 [hep-ph];

J.He, arXiv:1507.05200 [hep-ph];

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

L.Maiani, A.D.Polosa, V. Riquer, arXiv:1507.04980 [hep-ph];

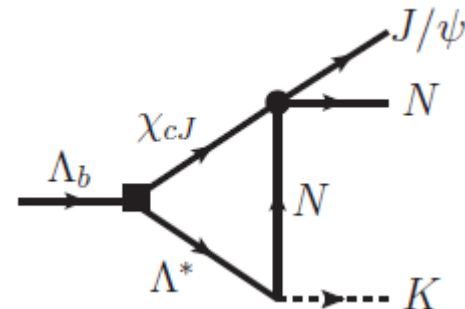
R.Lebed, arXiv:1507.05867 [hep-ph];

G.N.Li, M.He, X.G.He, arXiv:1507.08252 [hep-ph];

3) Kinematic triangle-singularity

F.K.Guo, Ulf-G.Meißner, W.Wang, Z.Yang, arXiv:1507.04950 [hep-ph]

X.H.Liu, Q.Wang, Q.Zhao, arXiv:1507.05359 [hep-ph]



4. Conclusions

- Hadron spectroscopy reveals unquenched quark picture
- Superheavy narrow N^* and Λ^* are predicted to exist
 $\bar{D}^{(*)}\Sigma_c, \bar{D}_s^{(*)}\Lambda_c \rightarrow B\Sigma_b, B_s\Lambda_b$ bound states
 $\sim 4.3 \text{ GeV} \qquad \qquad \qquad \sim 11 \text{ GeV}$
and partly confirmed by LHCb experiment
- Distinguishable predictions for penta-quark spectroscopy are yelling for further experimental confirmation
- New penta-quark spectroscopy provides a new idea platform for understanding multiquark dynamics
- They can be looked for at 12GeV@Jlab and
maybe also at JPARC, super-B, RHIC , EIC?

Thanks !

Σ^* in PDG

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

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

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

* $\Sigma^*(1480)??$ $\Sigma^*(1560)??$ $\Sigma^*(1580)3/2^-$
 $\Sigma^*(1620)1/2^-$ $\Sigma^*(1770)1/2^+$ $\Sigma^*(1840)3/2^+$
 $\Sigma^*(2000)3/2^-$ $\Sigma^*(2070)5/2^+$ $\Sigma^*(2100)7/2^-$
 $\Sigma^*(3000)??$ $\Sigma^*(3170)??$

All from old experiments of 1970-1985 !!

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

$Y(3S) \rightarrow Y(1S) \pi \pi$ decay: Is the $\pi \pi$ spectrum puzzle an indication of a $b\bar{b}q\bar{q}$ resonance?

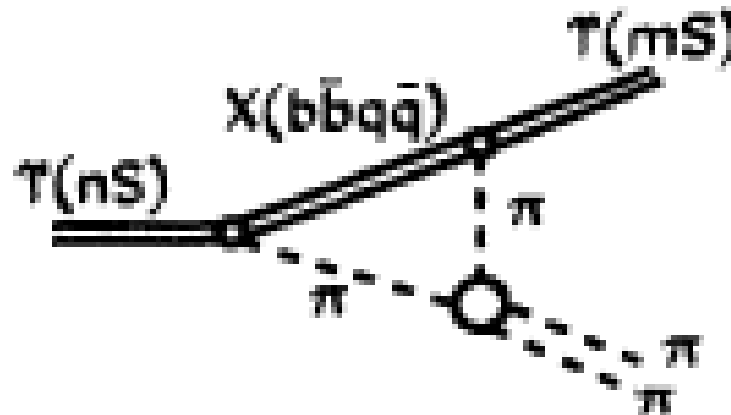
V. V. Anisovich,^{1,2} D. V. Bugg,¹ A. V. Sarantsev,^{1,2} and B. S. Zou¹

¹Queen Mary and Westfield College, London E1 4NS, United Kingdom

²Petersburg Nuclear Physics Institute, Gatchina, 188350, Russia

(Received 22 August 1994; revised manuscript received 2 February 1995)

The $\pi\pi$ mass spectrum in $Y(3S) \rightarrow Y(1S)\pi\pi$ has a peculiar double peak structure. This structure and the $Y(1S)\pi$ spectrum are reproduced by introducing a triangle singularity associated with a $b\bar{b}\pi$ resonance ($J^P = 1^+$) in the mass range 10.4–10.8 GeV.



Belle Collaboration, PRL108 (2012) 122001 \rightarrow $Z_b(10610)$, $Z_b(10650)$

“Observation of Two Charged Bottomoniumlike Resonances in $Y(5S)$ Decays”

important to confirm them and find their partners

Zc(3900) production from Y(4260) decays

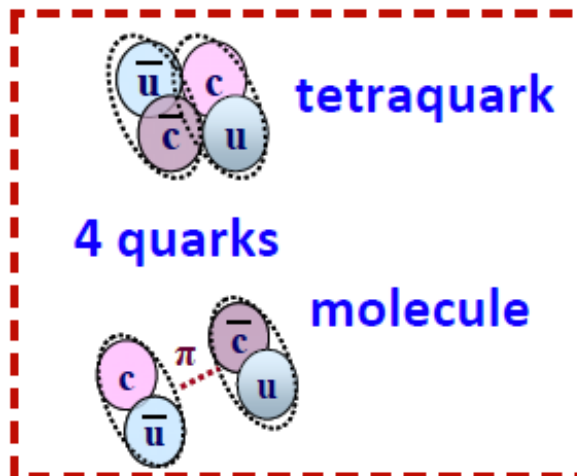
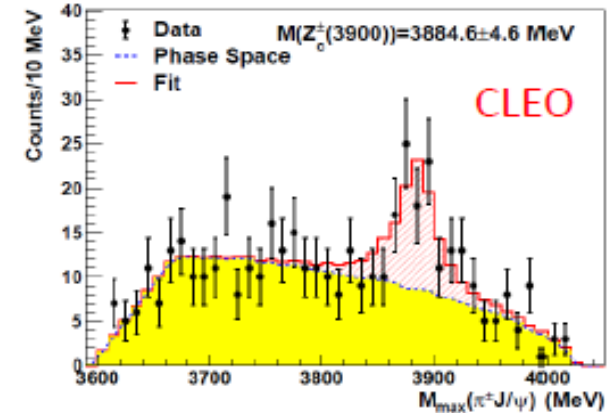
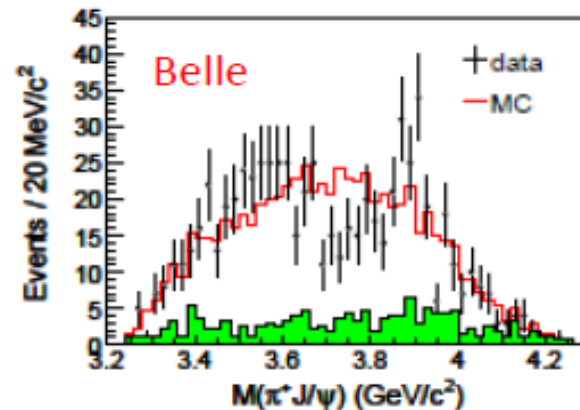
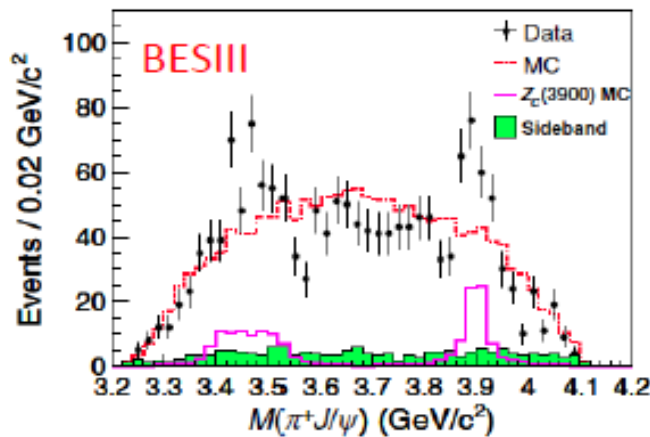
$\bar{d}u\bar{c}c$ states ?

PRL 110, 252001 (2013)

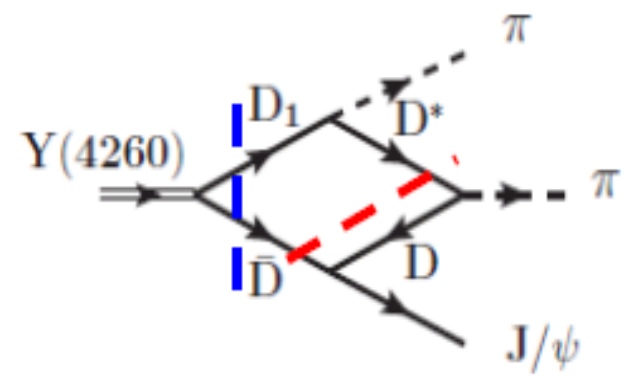
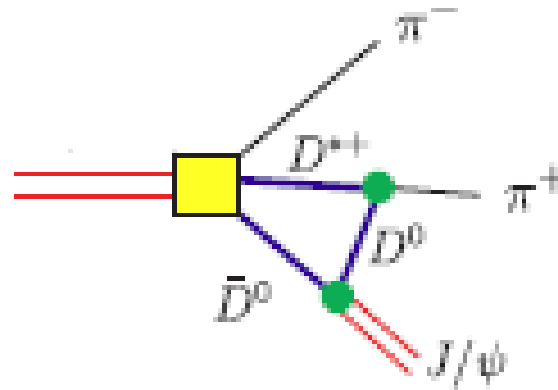
PHYSICAL REVIEW LETTERS

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,

Q.Wang, C.Hanhart, Q.Zhao

PRD84(2011)034032 PRL111(2013)132003