

# **Hadronic molecules**

## **from strangeness to charm and beauty**

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**“Hadronic Molecules”, Rev. Mod. Phys. 90 (2018)015004**

## **Outline :**

- 1. Hadronic molecules with strangeness**
- 2. Hadronic molecules with hidden charm & LHCb  $P_c$  states**
- 3. Strange & beauty partners of  $P_c$  states**
- 4. Prospects**

# 1. Hadronic molecules with strangeness

Brief history for the discovery of hadronic molecules

1932: Neutron & Deuteron - the 1-st hadronic molecule

1947:  $\pi$ , K

1959: KN & molecule predicted by Dalitz Tuan, PRL2, 425

1961:  $\Lambda(1405) \rightarrow \Sigma\pi$  observed by Alston et al., PRL6, 698

post-1962:  $f_0(980)$  &  $a_0(980)$   $\bar{K}K$  molecules? Isgur, ...  
 $f_1(1420)$   $\bar{K}K^*$  molecule? Tornqvist, ...  
 $f_0(1710)$   $\bar{K}^*K^*$  molecule? Oset, ...  
 $N^*(1535)$   $\bar{K}\Sigma$  -  $\bar{K}\Lambda$  molecule? Kaiser, ...  
 $D^*_{s0}(2317)$  &  $D^*_{s1}(2460)$   $\bar{K}D$  &  $\bar{K}D^*$  molecules? Barnes, ...

.....

Many hadrons are proposed to be hadronic molecules

**Problem:**

None of them can be clearly distinguished from  $qqq$  or  $\bar{q}q$  due to tunable ingredients and possible large mixing of various configurations

PDG2010: “The clean  $\Lambda_c$  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

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

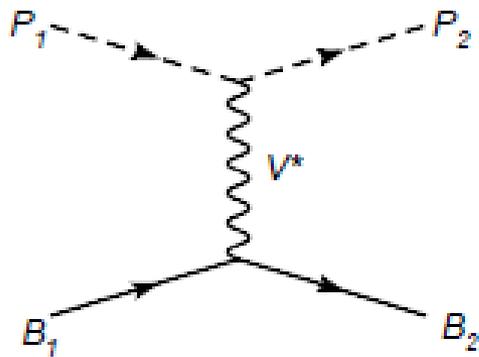
$\Lambda^*(4210)$   $\bar{c}cuds$  J.J.Wu, R.Molina, E.Oset, B.S.Zou.  
Phys.Rev.Lett. 105 (2010) 232001

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

## 2. Hadronic molecules with hidden charm & LHCb $P_c$ states

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

$K\Sigma, Kp \rightarrow \bar{D}^{(*)}\Sigma_c, \bar{D}_s^{(*)}\Lambda_c$  bound states



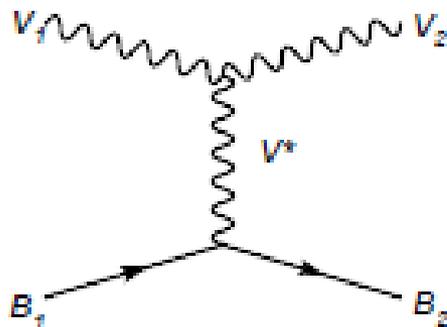
$$\mathcal{L}_{VVV} = ig \langle V^\mu [V^\nu, \partial_\mu V_\nu] \rangle$$

$$\mathcal{L}_{PPV} = -ig \langle V^\mu [P, \partial_\mu P] \rangle$$

$$\mathcal{L}_{BBV} = g (\langle \bar{B} \gamma_\mu [V^\mu, B] \rangle + \langle \bar{B} \gamma_\mu B \rangle \langle V^\mu \rangle)$$

$$V_{ab}(P_1 B_1 \rightarrow P_2 B_2) = \frac{C_{ab}}{4f^2} (E_{P_1} + E_{P_2}),$$

$$V_{ab}(V_1 B_1 \rightarrow V_2 B_2) = \frac{C_{ab}}{4f^2} (E_{V_1} + E_{V_2}) \vec{\epsilon}_1 \cdot \vec{\epsilon}_2,$$



$$T = [1 - VG]^{-1}V \quad T_{ab} = \frac{g_a g_b}{\sqrt{s} - z_R}$$

	$(I, S)$	$z_R$ (MeV)	$g_a$		$J^P$
$N^*$	$(1/2, 0)$		$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$	$1/2^-$
		4269	2.85	0	
$\Lambda^*$	$(0, -1)$		$\bar{D}_s\Lambda_c^+$	$\bar{D}\Xi_c$	$\bar{D}\Xi'_c$
		4213	1.37	3.25	0
		4403	0	0	2.64

TABLE III: Pole positions  $z_R$  and coupling constants  $g_a$  for the states from  $PB \rightarrow PB$ .

	$(I, S)$	$z_R$ (MeV)	$g_a$		
$N^*$	$(1/2, 0)$		$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c^+$	$1/2^-, 3/2^-$
		4418	2.75	0	
$\Lambda^*$	$(0, -1)$		$\bar{D}_s^*\Lambda_c^+$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi'_c$
		4370	1.23	3.14	0
		4550	0	0	2.53

TABLE IV: Pole position and coupling constants for the bound states from  $VB \rightarrow VB$ .

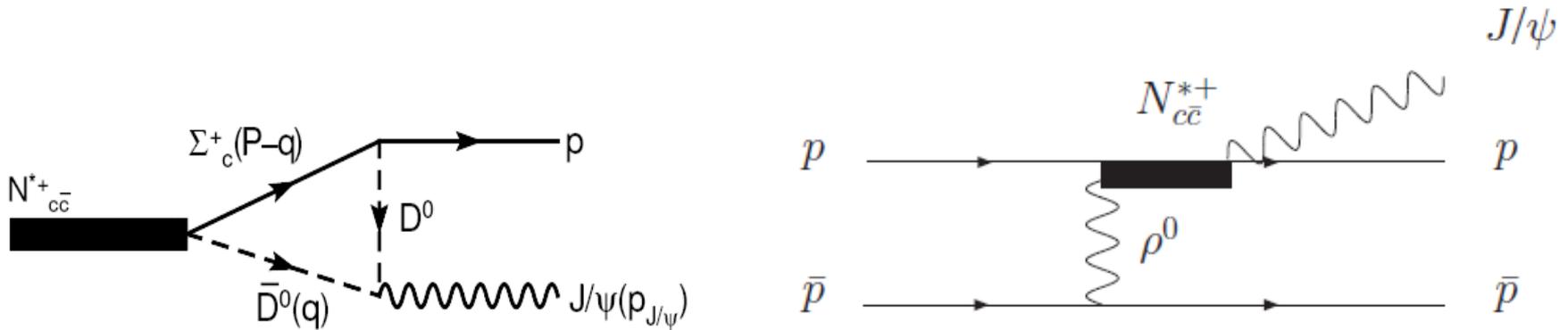
	$(I, S)$	$M$	$\Gamma$	$\Gamma_i$					$J^P$
$N^*$	$(1/2, 0)$			$\pi N$	$\eta N$	$\eta' N$	$K\Sigma$	$\eta_c N$	$1/2^-$
		4261	56.9	3.8	8.1	3.9	17.0	23.4	
$\Lambda^*$	$(0, -1)$			$KN$	$\pi\Sigma$	$\eta\Lambda$	$\eta'\Lambda$	$K\Xi$	$\eta_c\Lambda$
		4209	32.4	15.8	2.9	3.2	1.7	2.4	5.8
		4394	43.3	0	10.6	7.1	3.3	5.8	16.3

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

	$(I, S)$	$M$	$\Gamma$	$\Gamma_i$					$J^P$
$N^*$	$(1/2, 0)$			$\rho N$	$\omega N$	$K^*\Sigma$	$J/\psi N$	$1/2^-, 3/2^-$	
		4412	47.3	3.2	10.4	13.7	19.2		
$\Lambda^*$	$(0, -1)$			$K^*N$	$\rho\Sigma$	$\omega\Lambda$	$\phi\Lambda$	$K^*\Xi$	$J/\psi\Lambda$
		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 ( $\Gamma$ ), and the partial decay width ( $\Gamma_i$ ) for the states from  $VB \rightarrow VB$  with units in MeV.

# Prediction for PANDA



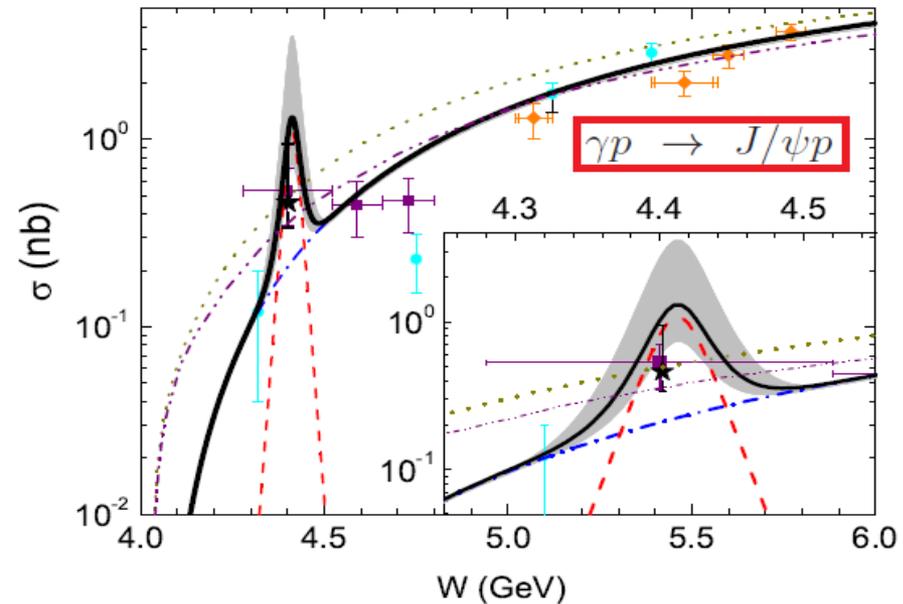
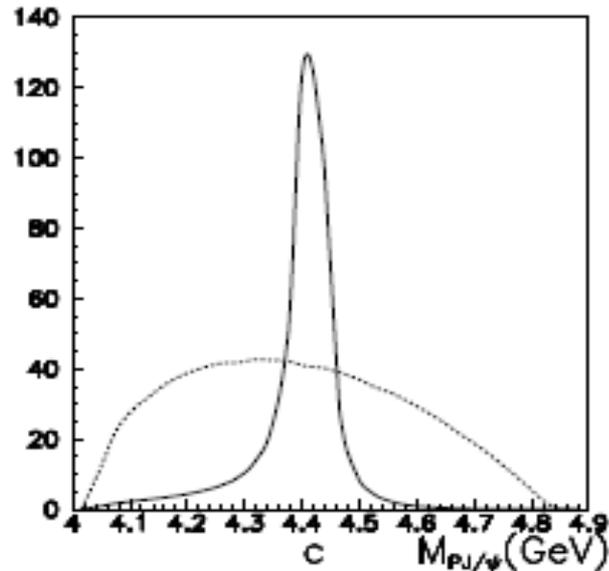
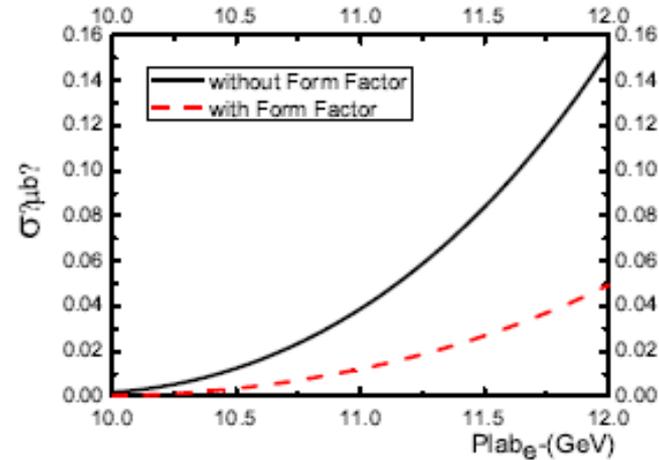
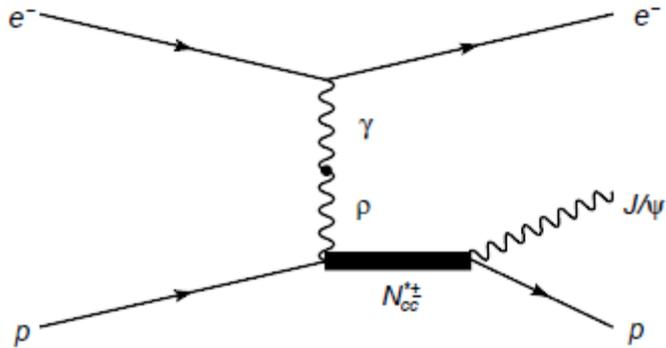
$$\bar{p}p \rightarrow \bar{p}pJ/\psi > 0.1 \text{ nb}$$

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

**These Super-heavy narrow  $N^*$  and  $\Lambda^*$  can be found at PANDA !**

Albrecht Gillitzer@Juelich had a plan to find them at PANDA

# Prediction for 12GeV@JLab



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

## Proposals for looking for $N_{cc}^-$ & $\Lambda_{cc}^-$ with $\pi^-$ , 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**

# Hidden charm $N^*$ above 4 GeV decaying to $pJ/\psi$ are supported by other approaches

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

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

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

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

$\bar{D}\Sigma_c$  &  $\bar{D}^*\Sigma_c$  state in Schoedinger Equation method  $\sim 4.3$  GeV

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

$\bar{D}\Sigma_c^*$ ,  $\bar{D}^*\Sigma_c$ ,  $\bar{D}^*\Sigma_c^*$  states with  $J^P = 3/2^-$

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

**S.G.Yuan, K.W.Wei, J.He, H.S.Xu, B.S.Zou, “Study of  $\bar{c}cqqq$  five quark system with three kinds of quark-quark hyperfine interaction,”  
Eur. Phys. J. A48 (2012) 61**

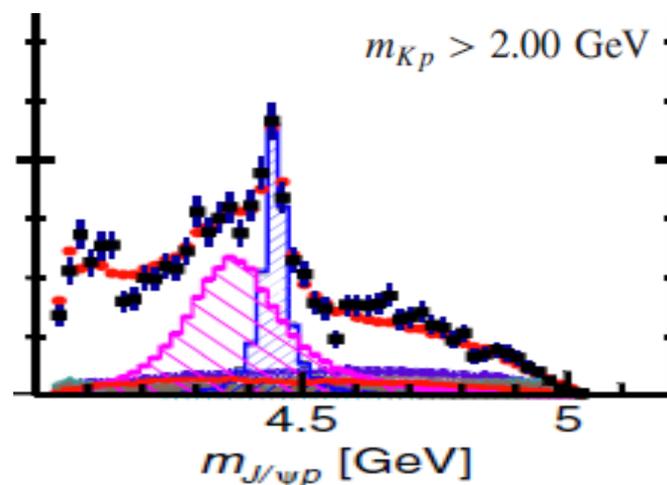
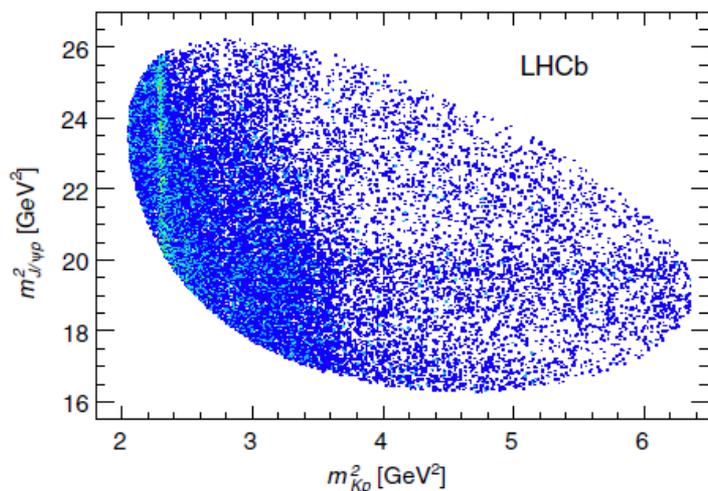
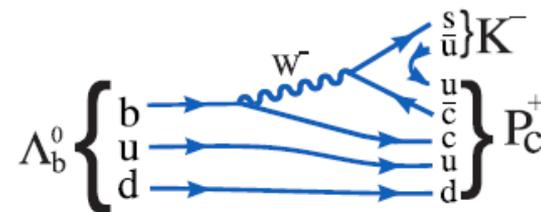
$J^P$	<i>CM</i>		<i>FS</i>		<i>Inst.</i>	
	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$
$\frac{1}{2}^-$	4273	4267	4084	3933	4209	4114
$\frac{1}{2}^-$	4377	4363	4154	4013	4216	4131
$\frac{1}{2}^-$	4453	4377	4160	4119	4277	4204
$\frac{1}{2}^-$	4469	4471	4171	4136	4295	4207
$\frac{1}{2}^-$	4494	4541	4253	4156	4360	4272
$\frac{1}{2}^-$	4576		4263		4362	
$\frac{1}{2}^-$	4649		4278		4416	
$\frac{3}{2}^-$	4431	<u>4389</u>	4154	4013	4216	4131
$\frac{3}{2}^-$	4503	<u>4445</u>	4171	4119	4295	4204
$\frac{3}{2}^-$	4549	4476	4263	4136	4362	4272
$\frac{3}{2}^-$	4577	4526	4278	4236	4416	<u>4322</u>
$\frac{3}{2}^-$	4629		4362		4461	
$\frac{5}{2}^-$	4719	4616	4362	4236	4461	4322

$J^P$	<i>CM</i>		<i>FS</i>		<i>Inst.</i>	
	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$
$\frac{1}{2}^+$	4622	4456	4291	4138	4487	4396
$\frac{1}{2}^+$	4636	4480	4297	4140	4501	4426
$\frac{1}{2}^+$	4645	4557	4363	4238	4520	4426
$\frac{1}{2}^+$	4658	4581	4439	4320	4540	4470
$\frac{1}{2}^+$	4690	4593	4439	4367	4557	4482
$\frac{1}{2}^+$	4696	4632	4467	4377	4587	4490
$\frac{1}{2}^+$	4714	4654	4469	4404	4590	4517
$\frac{1}{2}^+$	4728	4676	4486	4489	4614	4518
$\frac{1}{2}^+$	4737	4714	4492	4508	4616	4549
$\frac{1}{2}^+$	4766	4720	4510	4515	4626	4566
$\frac{3}{2}^+$	4623	<u>4457</u>	4291	4138	4487	4396
$\frac{3}{2}^+$	4638	4515	4297	4140	4501	4426
$\frac{3}{2}^+$	4680	4561	4363	4238	4520	4426
$\frac{3}{2}^+$	4692	4582	4439	4320	4540	4470
$\frac{3}{2}^+$	4695	4625	4439	4367	4557	4482
$\frac{5}{2}^+$	4705	4539	4297	4140	4501	<u>4426</u>
$\frac{5}{2}^+$	4719	4649	4439	4320	4540	4470
$\frac{5}{2}^+$	4773	4689	4467	4367	4587	4482
$\frac{5}{2}^+$	4793	4696	4486	4404	4615	4490
$\frac{5}{2}^+$	4821	4710	4492	4515	4632	4517
$\frac{7}{2}^+$	4945	4841	4638	4508	4698	4566
$\frac{7}{2}^+$	4955	4862	4671	4551	4712	4634
$\frac{7}{2}^+$	4974	4919	4705	4587	4765	4669
$\frac{7}{2}^+$	5010		4759		4797	

**$M(5/2^+) - M(3/2^-) : 130 \sim 300 \text{ MeV}$**

# LHCb observation of 2 pentaquarks

LHCb, Phys.Rev.Lett. 115 (2015) 072001 :  
**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,  $P_c^+(4380)$
- 2)  $4450 \pm 2 \pm 3$  MeV,  $39 \pm 5 \pm 19$  MeV,  $P_c^+(4450)$

The preferred  $J^P$  assignments are of opposite parity, with one state having spin 3/2 and the other 5/2.

## LHCb pentaquark states vs Predictions

Consistence : mass of  $P_c(3/2^-)$ ,  $pJ/\psi$  decay mode

Problems:

- 1)  $P_c^+(4380)$  -- larger decay width than prediction
- 2) Where are lower  $P_c(1/2^-)$  states ?

# Progress on $P_c$ states 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;

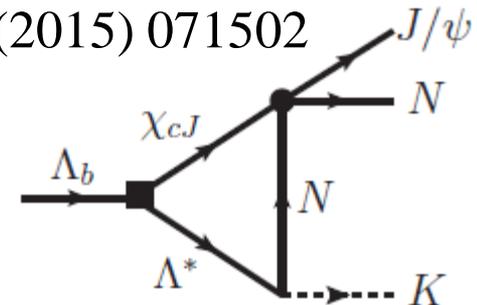
G.N.Li, M.He, X.G.He, JHEP 1512 (2015) 128;

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 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**

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

[1] R.Chen, X.Liu, X.Q.Li, S.L.Zhu, PRL115 (2015) 132002;

$$P_c^+(4380) \text{ -- } \bar{D}^*\Sigma_c \quad 3/2^- \text{ ; } \quad P_c^+(4450) \text{ -- } \bar{D}^*\Sigma_c^* \quad 5/2^-$$

[2] Y.Yamaguchi, E. Santopinto, PRD96 (2017) 014018

$$P_c^+(4380) \text{ -- } \bar{D}^{(*)}\Sigma_c^{(*)} - \bar{D}^{(*)}\Lambda_c \quad 3/2^+ \text{ ; } \quad P_c^+(4450) \text{ -- } \bar{D}^{(*)}\Sigma_c^{(*)} - \bar{D}^{(*)}\Lambda_c \quad 5/2^-$$

[3] J.He, PLB 753 (2016)547 ; PRD95 (2017)074004

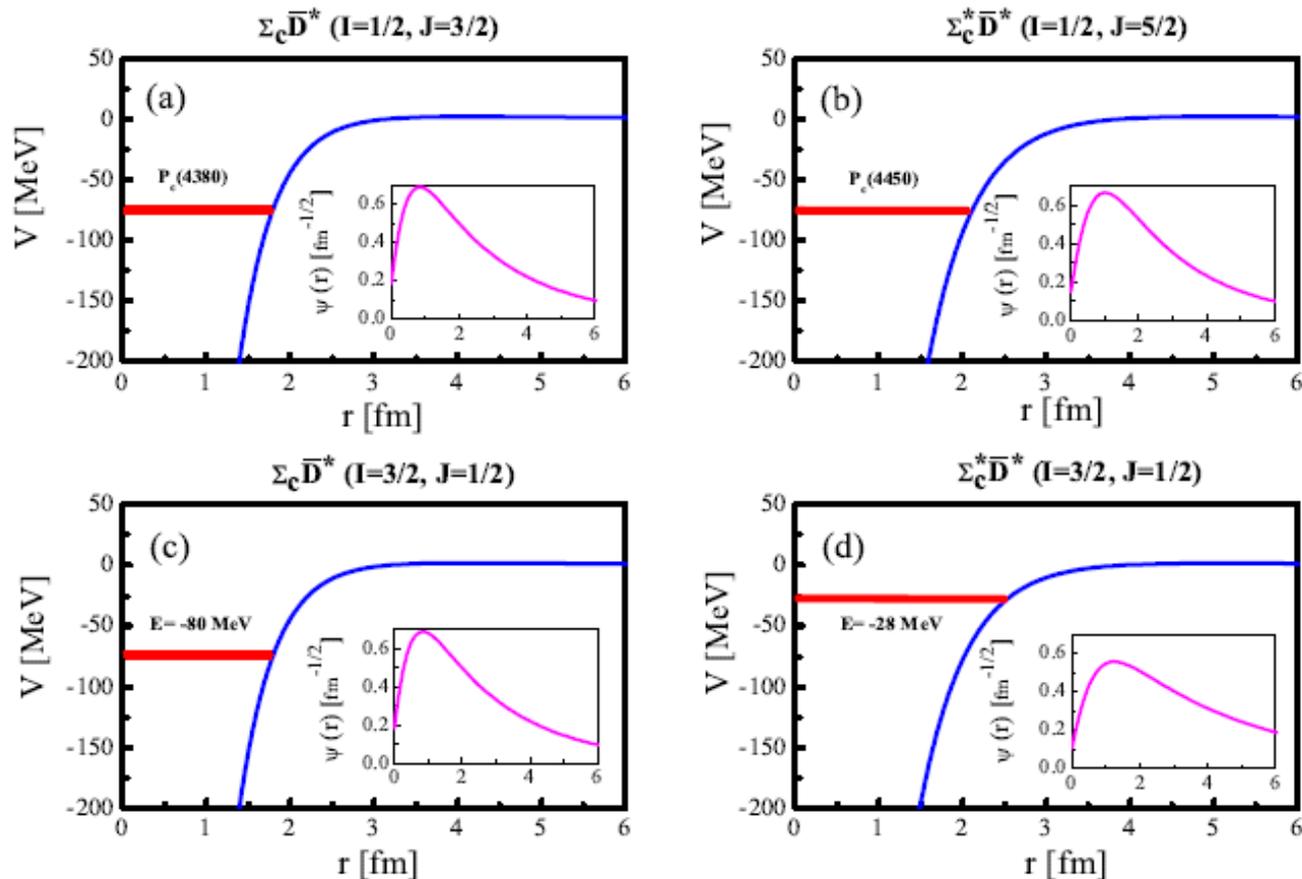
Y.H.Lin, C.W.Shen, F.K.Guo, B.S.Zou, PRD95(2017)114017

$$P_c^+(4380) \text{ -- } \bar{D}\Sigma_c^*/ \bar{D}^*\Sigma_c \quad 3/2^- \text{ ; } \quad P_c^+(4450) \text{ -- } \bar{D}^*\Sigma_c \quad 5/2^+$$

**→ Different predictions to be checked !**

[1] R.Chen, X.Liu, X.Q.Li, S.L.Zhu, PRL115 (2015) 132002

## OPE: Prediction of $I=3/2$ pentaquarks !



[2] Y.Yamaguchi, E. Santopinto, PRD96 (2017) 014018

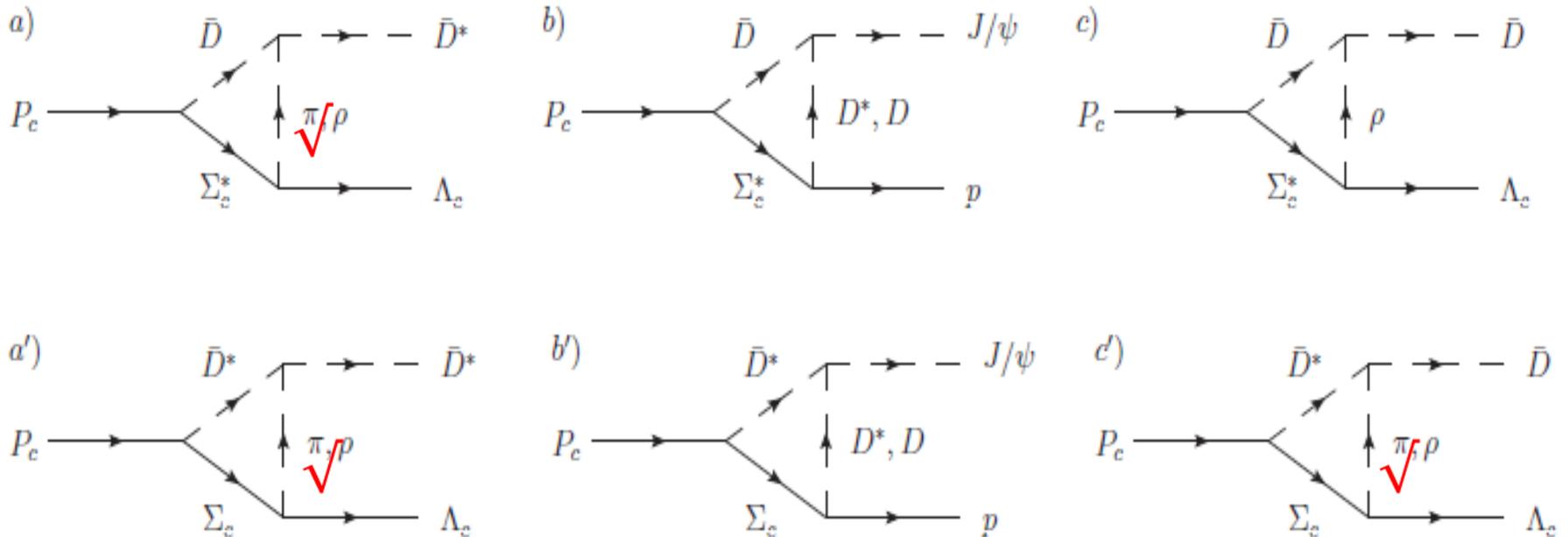
**Prediction of a few more  $J=3/2$  pentaquarks !**

$\Lambda$ [MeV]	1300	1400	1500	1600
$J^P = 3/2^-$	4236.9 - $i0.8$	4136.0	4006.3	3848.2
	4381.3 - $i11.4$	4307.9 - $i18.8$	4242.6 - $i1.4$	4150.1
	4368.5 - $i64.9$	4348.7 - $i21.1$	4312.7 - $i16.0$	4261.0 - $i7.0$
$J^P = 3/2^+$	4223.0 - $i97.9$	4206.7 - $i41.2$	4169.3 - $i5.3$	4104.2
	4363.3 - $i57.0$	<u>4339.7 - <math>i26.8</math></u>	4311.8 - $i6.6$	4268.5 - $i1.3$
$J^P = 5/2^-$	—	<u>4428.6 - <math>i89.1</math></u>	4391.7 - $i88.8$	4338.2 - $i56.2$
$J^P = 5/2^+$	—	—	4368.0 - $i9.2$	4305.8 - $i1.9$
	—	—	—	—

**Problem: much larger width than observed  $P_c^+(4450)$   
meanwhile too small width for  $P_c^+(4380)$**

### [3] Disentangling $\bar{D}\Sigma_c^* / \bar{D}^*\Sigma_c$ nature of $P_c^+$ states from their decays

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



**One pion exchange is important !**

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

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 ✓
$\pi N$	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
$\rho N$	1.4	0.15	0.14	0.3
$\omega p$	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  $P_c \rightarrow \bar{D}^*\Lambda$  &  $\bar{D}\Lambda$  !**

## LHCb pentaquark states vs Post-explanations

Consistent for  $P_c^+(4380)$  to be a  $\bar{D}\Sigma_c^*$  ( $3/2^-$ ) molecule with a large decay width to  $\bar{D}^*\Lambda_c$

Consistent for  $P_c^+(4450)$  to be a  $\bar{D}^*\Sigma_c$  ( $5/2^+$ ) molecule

### Problems:

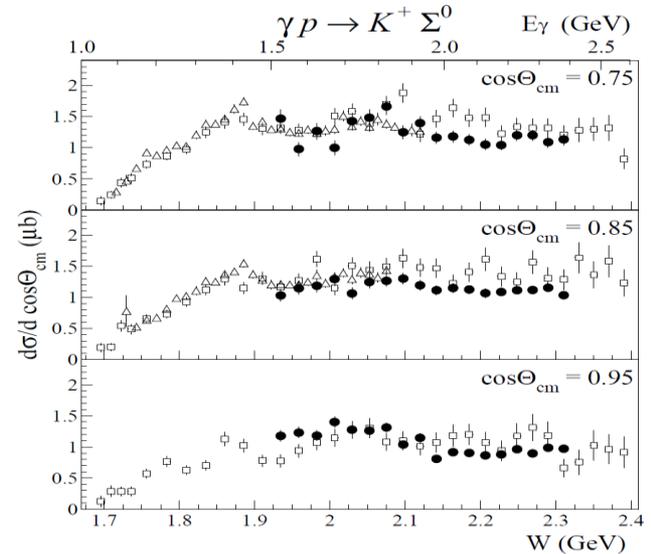
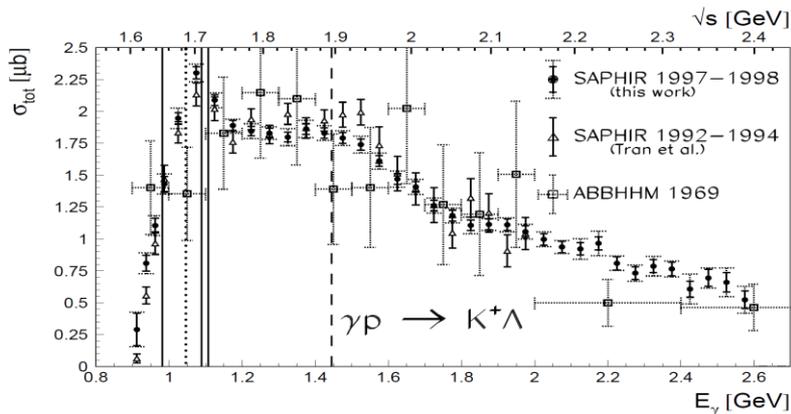
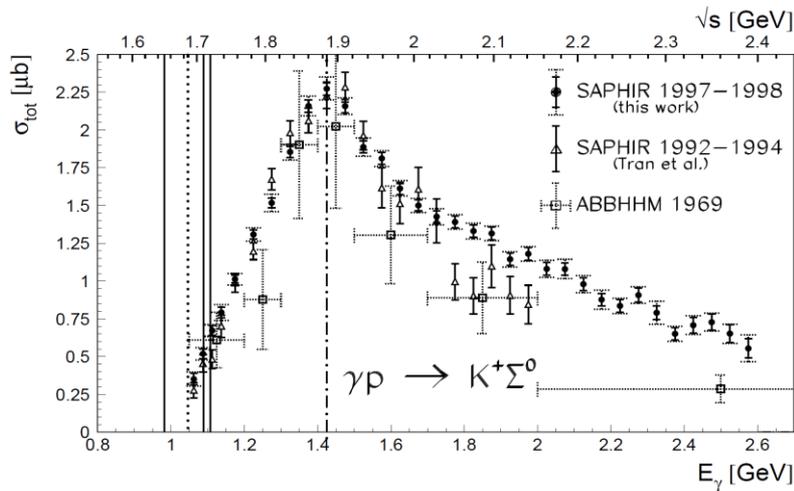
- 1) Where are lower  $P_c$  ( $1/2^-$ ) states ?
- 2) Where are predicted  $\Lambda_{cc}$  states ?

**Many more pentaquarks are expected !**

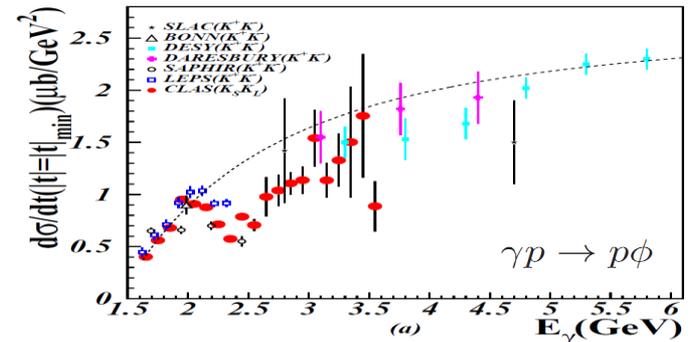
# 3. Strange & beauty partners of $P_c$ states

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

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



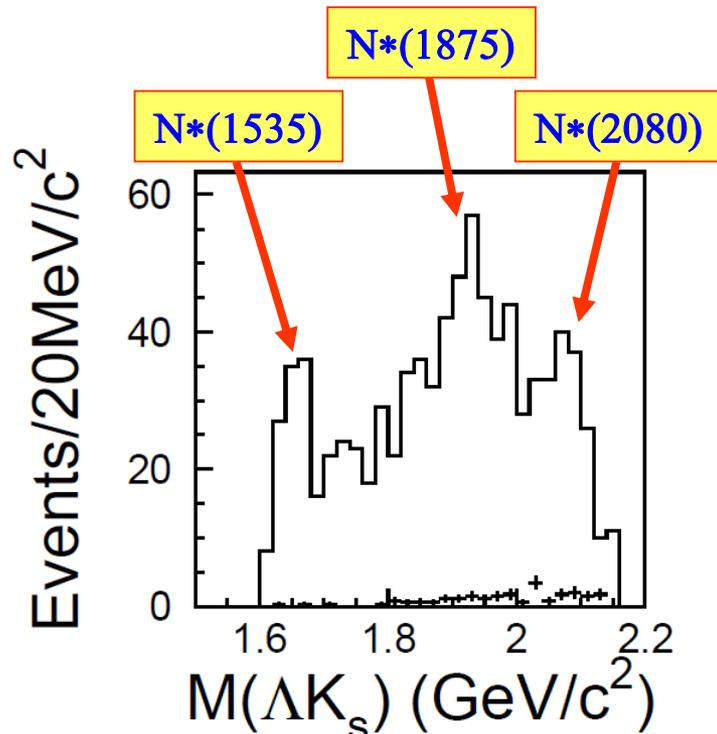
LEPS, PRC73 (2006) 035214



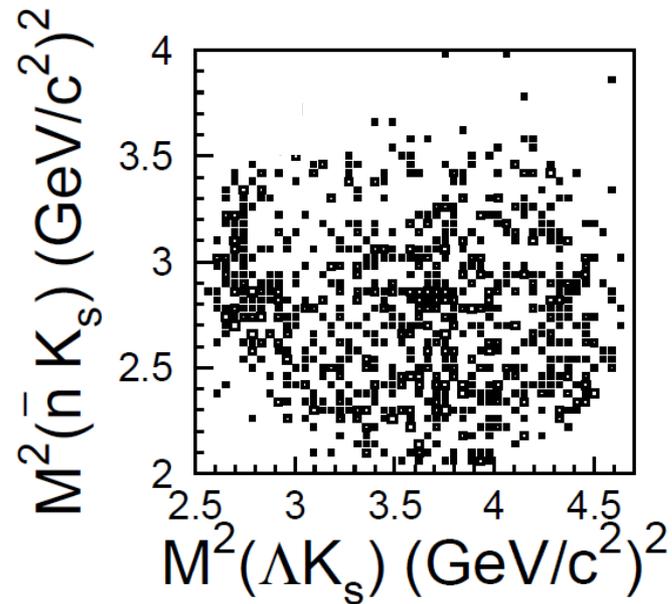
CLAS, PRC89 (2014) 055206

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

# $N_{ss}$ penta-quarks at BES ?!

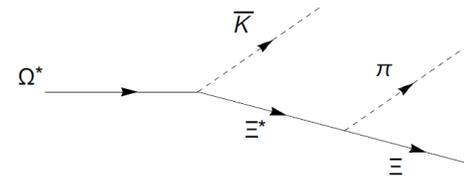
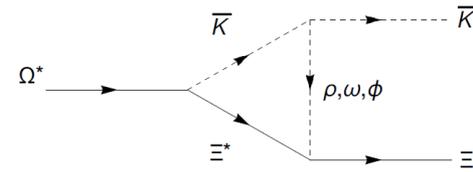
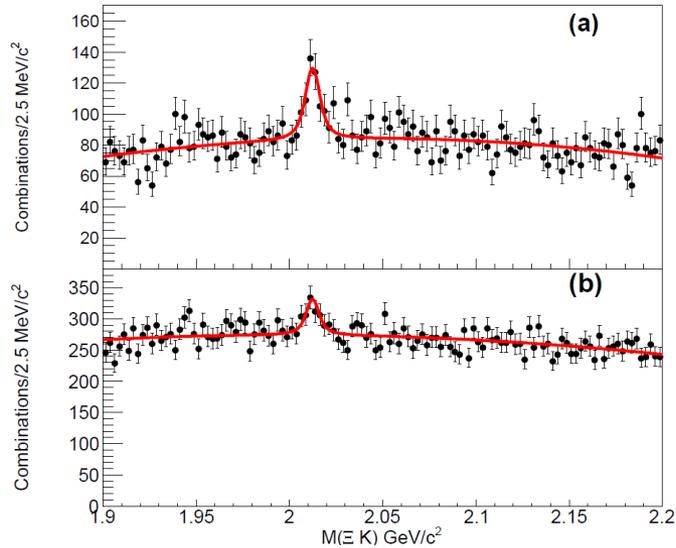


$$J/\psi \rightarrow nK_S^0 \bar{\Lambda}$$



BESII, Phys. Lett. B659 (2008) 789

# $\Omega(2012)$ -- $\bar{K}\Xi^*$ (2015) Molecule of $J^P = 3/2^-$ ?



Belle Collaboration,  
arXiv:1805.09384

M.P.Valderrama, arXiv:1807.00718;  
Y.H.Lin, B.S.Zou, arXiv:1807.00997



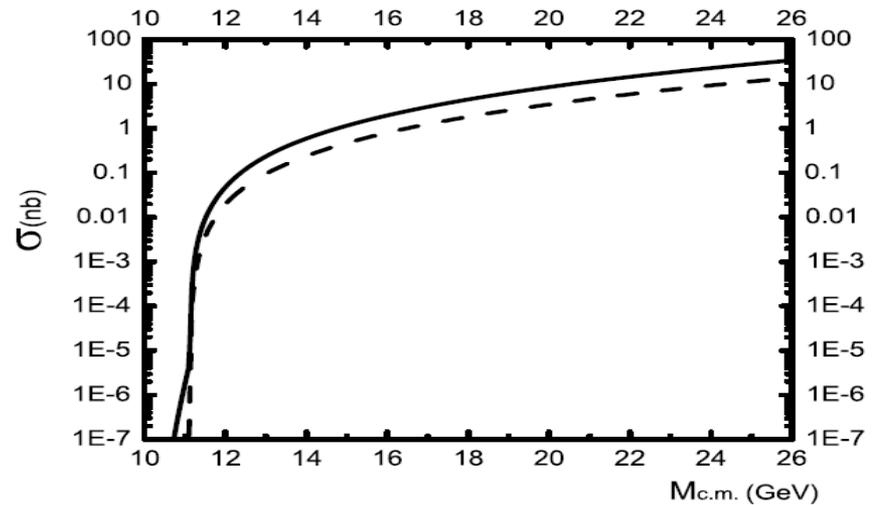
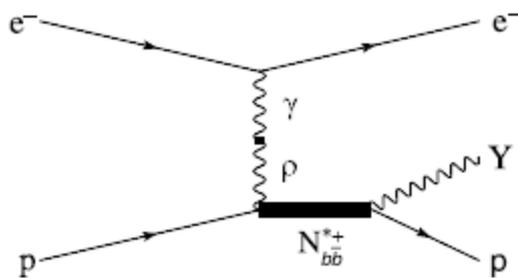
## Prediction of super-heavy $N^*$ and $\Lambda^*$ resonances with hidden beauty

Jia-Jun Wu<sup>a,\*</sup>, Lu Zhao<sup>a</sup>, B.S. Zou<sup>a,b</sup>

$M$ (MeV)	$\Gamma$ (MeV)	$\Gamma_i$ (MeV)				
11 052	1.38	$\pi N$ 0.10	$\eta N$ 0.21	$\eta' N$ 0.11	$K \Sigma$ 0.42	$\eta_b N$ 0.52
11 100	1.33	$\rho N$ 0.09	$\omega N$ 0.30	$K^* \Sigma$ 0.39	$\Upsilon N$ 0.51	

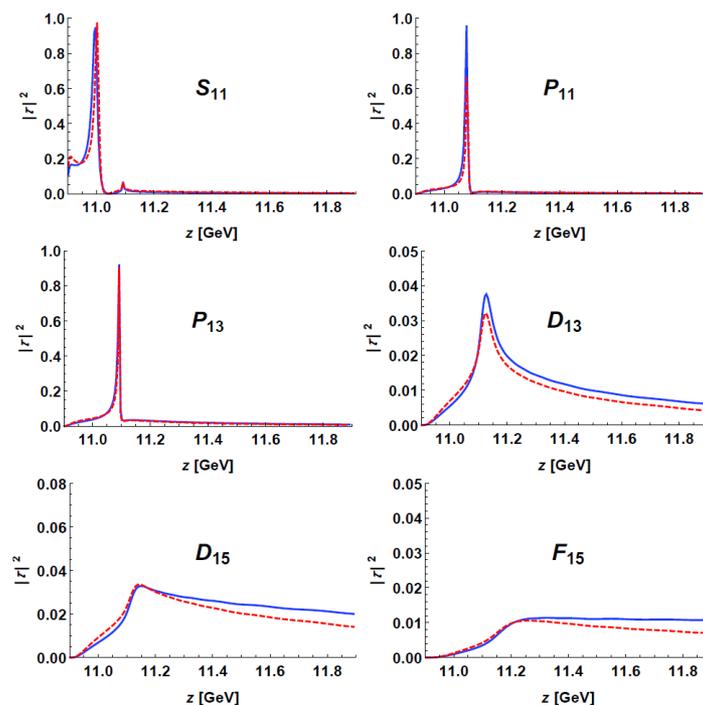
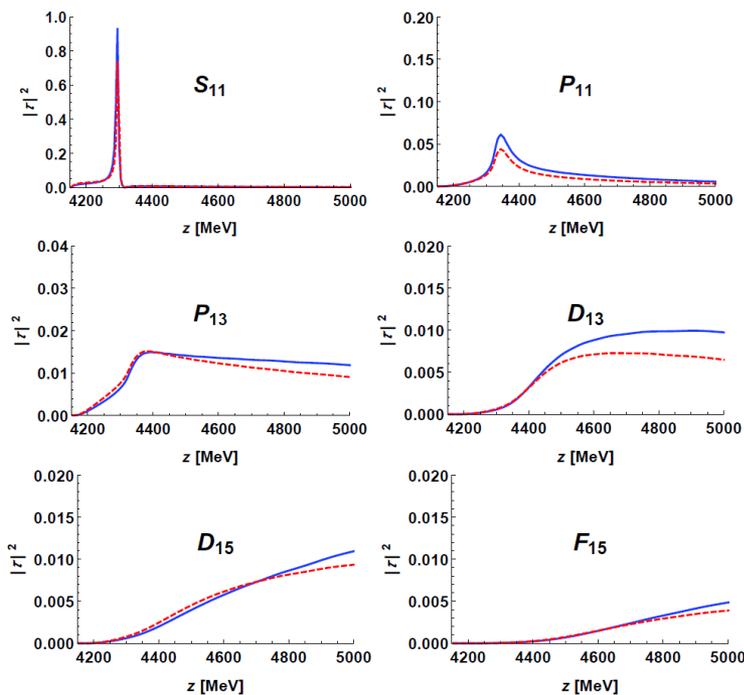
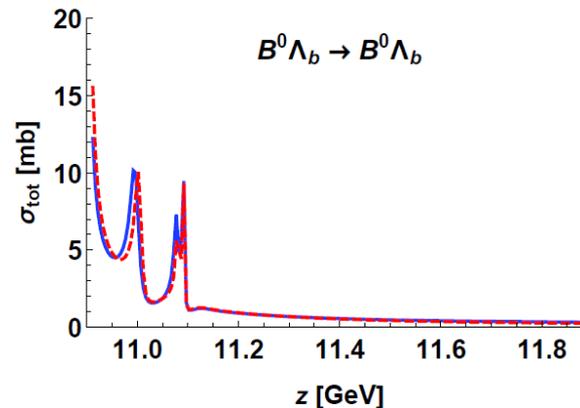
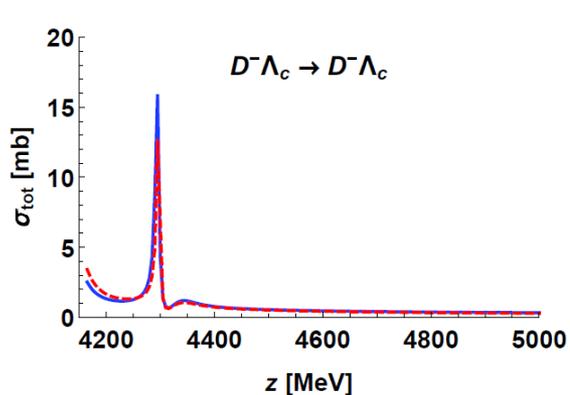
$1/2^-$

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



# $\bar{D}\Lambda_c - \bar{D}\Sigma_c$ 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

# Decay behavior of $P_s$ & $P_b$ pentaquark states

Y.H.Lin, C.W.Shen, B.S.Zou, ArXiv: 1805.06843

Mode	Widths (MeV)			
	$J^P = 3/2^-$		$J^P = 1/2^-$	
	$N(1875)$	$K\Sigma^*$	$N(2080)$	$K^*\Sigma$
$N\sigma(500)$	2.6	0.05	0.3	
$\pi N$	3.8	0.2	22.7	
$\rho N$	2.3	3.8	6.1	
$\omega p$	6.6	11.3	18.2	
$K\Sigma$	0.03	1.4	9.1	
$K\Lambda$	0.7	3.7	19.3	
$\eta p$	0.6	0.4	1.8	
$\pi\Delta$	201.4	82.6	46.9	
$K^*\Lambda$	-	2.4	7.9	
$\phi p$	-	19.2	27.0	
$K\Sigma^*$	-	7.3	1.3	
$K\Lambda(1520)$	-	0.1	1.3	
$K\Lambda(1405)$	-	8.0	8.8	
$K\pi\Lambda$	10.1	-	-	
$K\pi\Sigma$	-	41.3	46.1	
Total	228.2	181.7	216.8	

Mode	Widths (MeV)		
	$J^P = 3/2^-$		$J^P = 1/2^-$
	$B\Sigma_b^*$	$B^*\Sigma_b$	$B^*\Sigma_b$
$B^*\Lambda_b$	271.1	19.9	167.0
$\Upsilon p$	0.3	0.04	0.1
$\rho N$	5.5	0.02	0.1
$\omega p$	20.9	0.07	0.4
$B\Lambda_b$	-	7.3	135.9
$B\Sigma_b$	-	-	-
$\eta_b p$	0.02	0.0001	0.0009
$\chi_{b0} p$	1.4	0.0008	0.2
$\pi N$	0.7	0.005	0.003
$B\Sigma_b^*$	-	-	-
Total	299.9	27.4	303.8

**Guidance for  $P_s$  &  $P_b$  search**

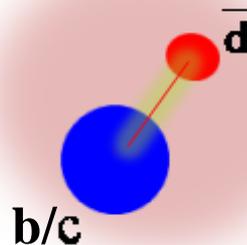
## 4. Prospects

### ◆ my favorite strategy for hadron spectroscopy:

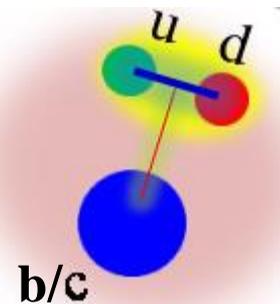
$\bar{c}c u u d$  &  $\bar{c}c u d s$   $\rightarrow$   $s s s$  -  $\bar{q} q s s s$   $\rightarrow$   $c q q$  -  $\bar{q} q c q q$   
 $\rightarrow$  hyperons  $\rightarrow$  light baryons

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

$s \rightarrow c \rightarrow b$



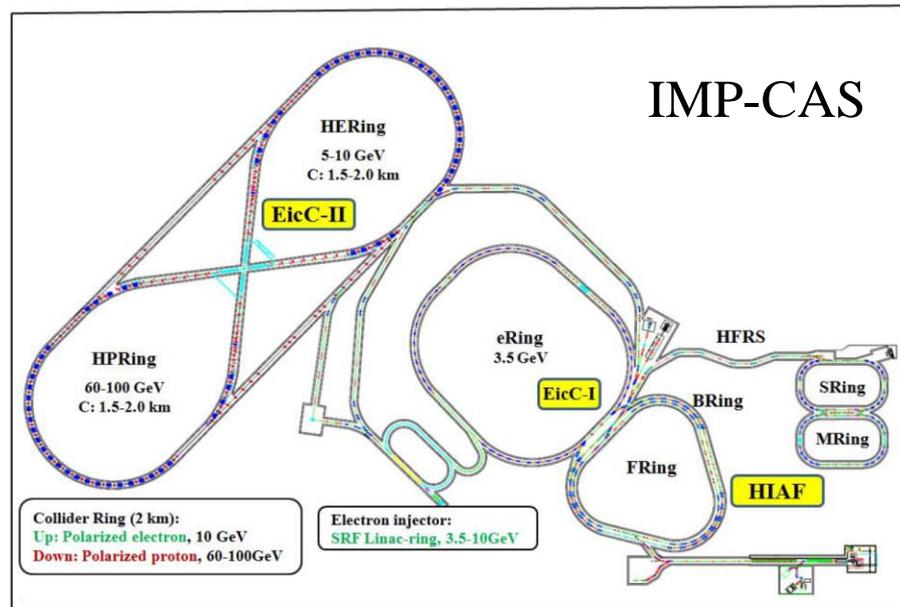
charm & beauty meson



charm & beauty baryon

- New penta-quark spectroscopy provides a new ideal platform for understanding multiquark dynamics
- Further experimental confirmation and extension for whole penta-quark spectroscopy from  $\gamma N$ ,  $\pi N$ ,  $KN$ ,  $e^+e^- \rightarrow \bar{\Lambda}_b \Lambda_b$ , etc.

**ep/ $\gamma$ p@JLab,  $\pi$ 10/K10@JPARC, BelleII, BESIII, Eic/EicC, PANDA@FAIR, STCF etc. may play important role here!**

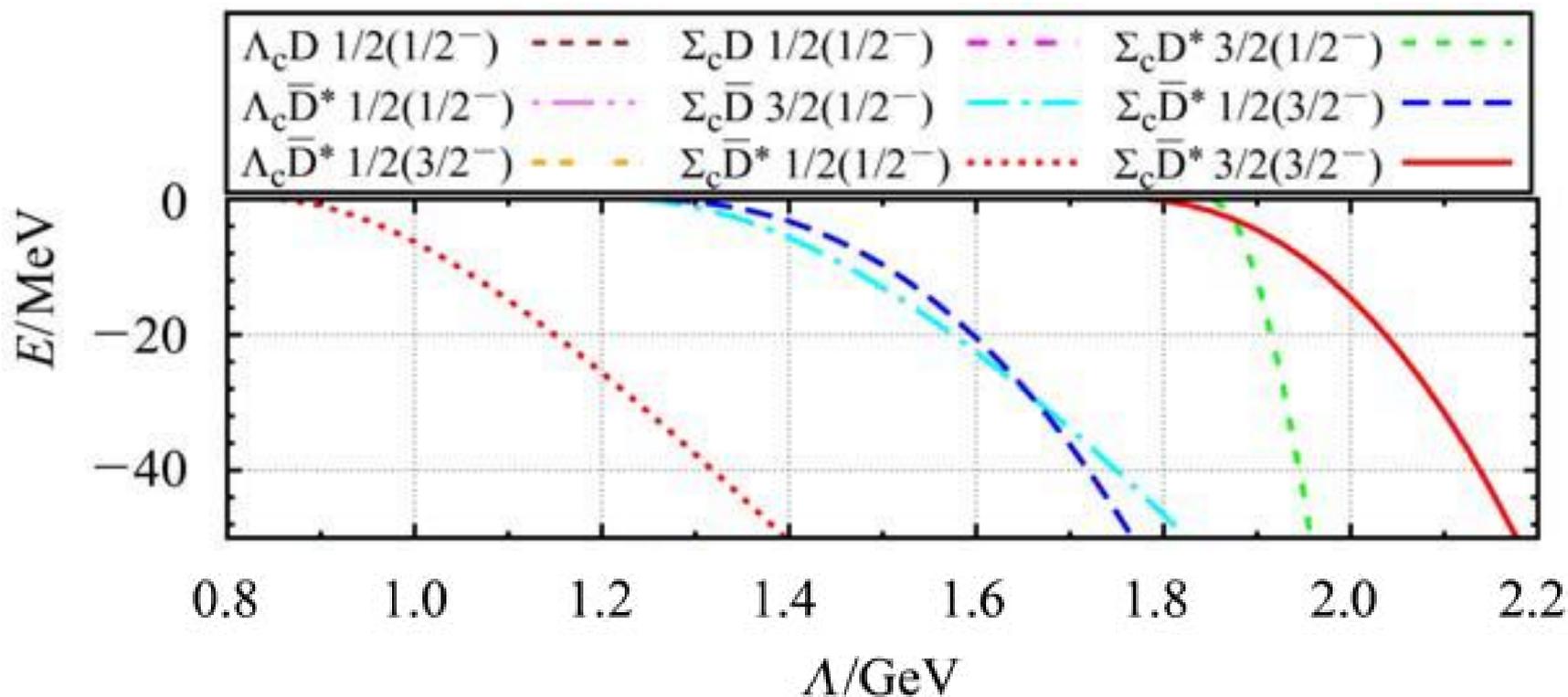


Thank you for  
your attention!

[2] Z.C.Yang, Z.F.Sun, J.He, X.Liu, S.L.Zhu, "The possible hidden-charm molecular baryons composed of anti-charmed meson and charmed baryon," Chin. Phys. C36 (2012) 6

Schoedinger Equation method with  $\pi, \eta, \rho, \omega, \sigma$  exchanges:

$\bar{D}^*\Sigma_c$  ( $3/2^-$ )  $N^*$  state -- 4360 ~ 4460 MeV



[3] C.W.Xiao, J.Nieves, E.Oset, “Combining heavy quark spin and local hidden gauge symmetries in the dynamical generation of hidden charm baryons”, PRD 88 (2013) 056012

### 3 $J^P = 3/2^-$ $P_c^+$ states : $\bar{D}\Sigma_c^*$ , $\bar{D}^*\Sigma_c$ , $\bar{D}^*\Sigma_c^*$ states

TABLE II. The coupling constants to various channels for certain poles in the  $J = 3/2$ ,  $I = 1/2$  sector.

$4334.45 + i19.41$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
$g_i$	$1.31 - i0.18$	$0.16 - i0.23$	$0.20 - i0.48$	$2.97 - i0.36$	$0.24 - i0.76$
$ g_i $	1.32	0.28	0.52	2.99	0.80
$4417.04 + i4.11$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
$g_i$	$0.53 - i0.07$	$0.08 - i0.07$	$2.81 - i0.07$	$0.12 - i0.10$	$0.11 - i0.51$
$ g_i $	0.53	0.11	2.81	0.16	0.52
$4481.04 + i17.38$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
$g_i$	$1.05 + i0.10$	$0.18 - i0.09$	$0.12 - i0.10$	$0.22 - i0.05$	$2.84 - i0.34$
$ g_i $	1.05	0.20	0.16	0.22	2.86

a  $J^P = 5/2^-$   $P_c^+$  state :  $\bar{D}^*\Sigma_c^*$  bound states at 4487 MeV

# “Y(4260)的结构以及带电Zc(3900)的产生”

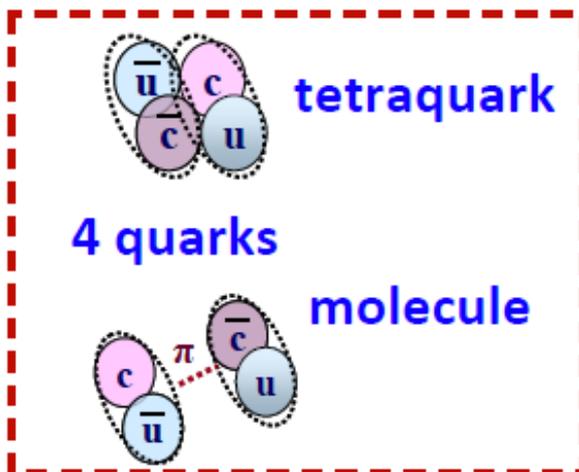
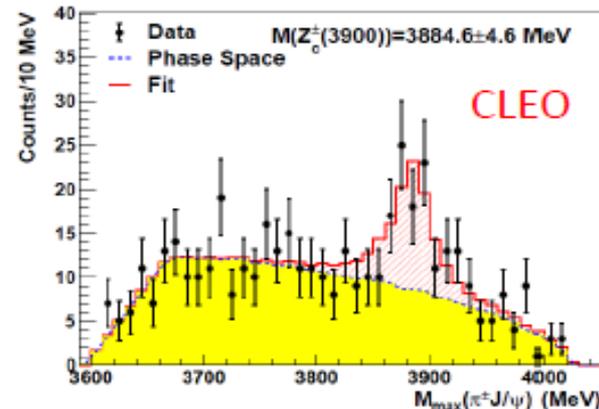
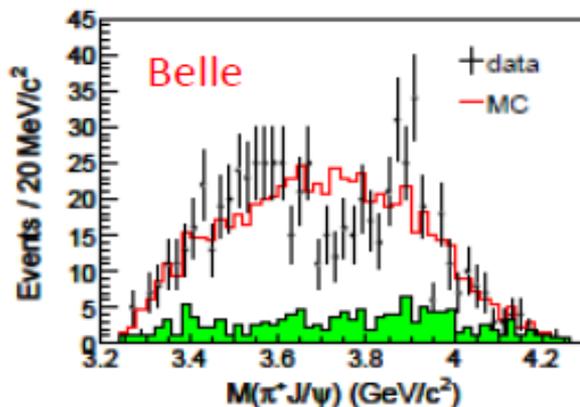
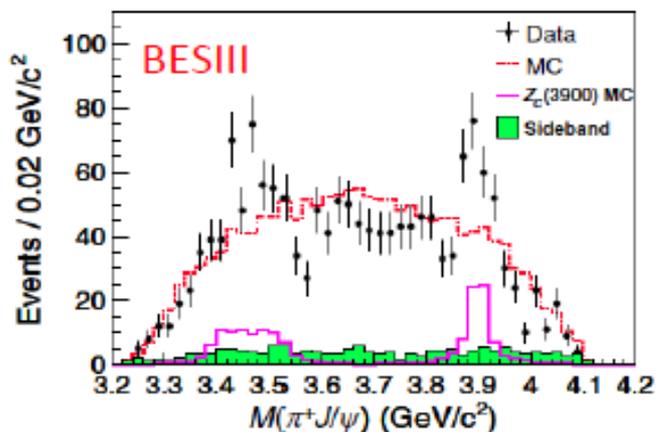
a

PRL 110, 252001 (2013)

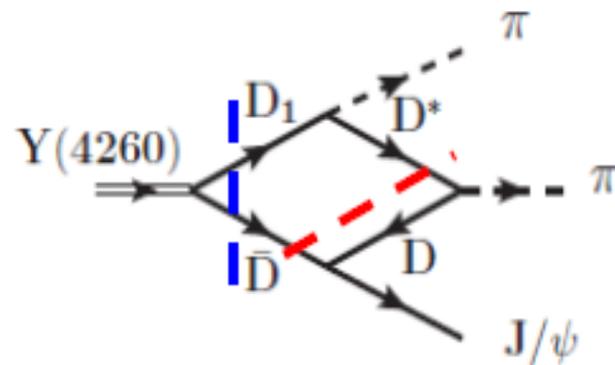
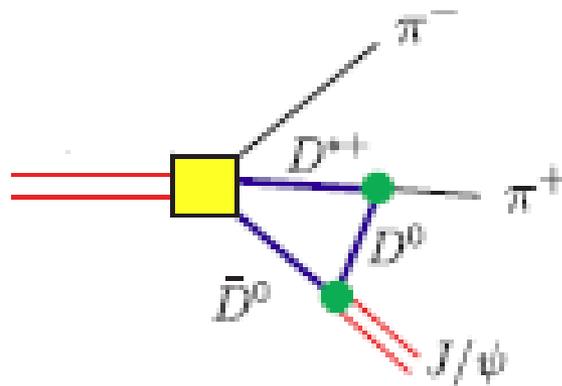
PHYSICAL REVIEW LETTERS

WEEK ENDING  
21 JUNE 2013

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



Exotic!



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

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