

Progress on the study of pentaquark states

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Outline :

- 1. Pentaquarks before LHCb P_c states**
- 2. LHCb pentaquarks vs predictions**
- 3. Progress on P_c states after LHCb observation**
- 4. Strange & beauty partners of P_c states**
- 5. Prospects**

1. Pentaquarks before LHCb P_c states

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.”

Fate of the last famous fake pentaquark $\theta^+(1540)$:

1997: $Z^+(1530)$ predicted by Diakonov et al., ZPA359, 305

2003: $\theta^+(1540) \rightarrow K^+n$ claimed by LEPS, PRL91, 012002

2003: $\bar{s}(ud)(ud)$ for $\theta(1540)$ by Jaffe&Wilczek, PRL91, 232003

2003: $\bar{s}ud)(ud)$ for $\theta(1540)$ by Karliner&Lipkin, PLB575, 249

2004: supported by 10 expts $\rightarrow \theta(1540)$ well-established by PDG

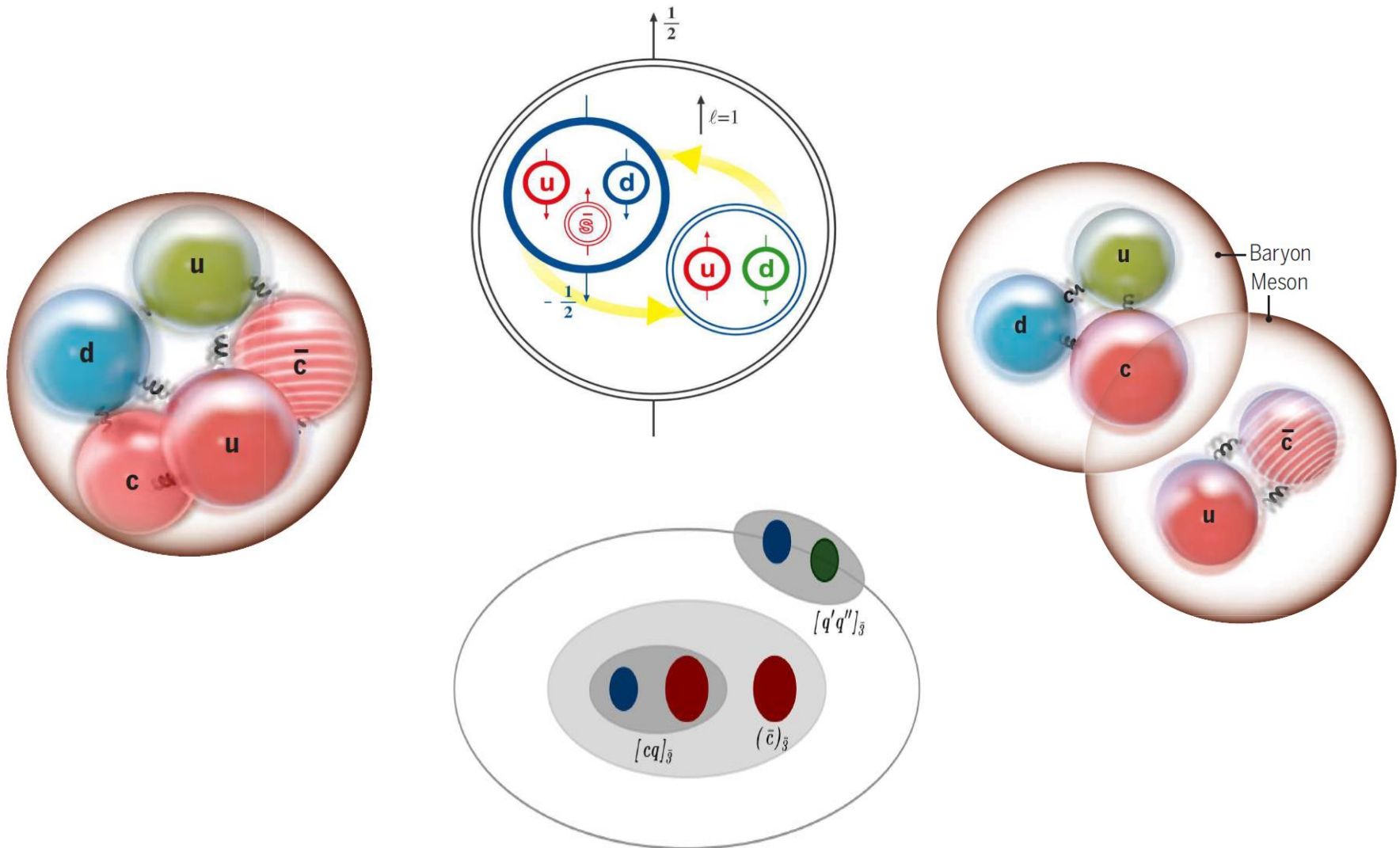
2004: not supported by BESII, PRD70, 012004

2005: not supported by many high stats experiments

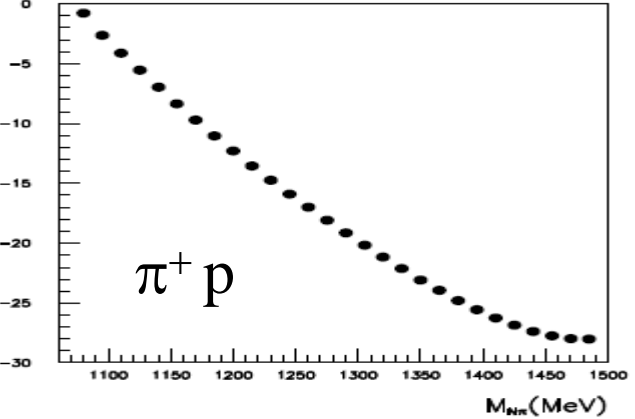
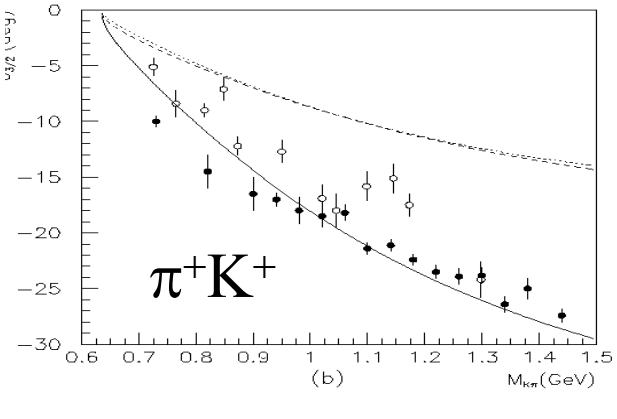
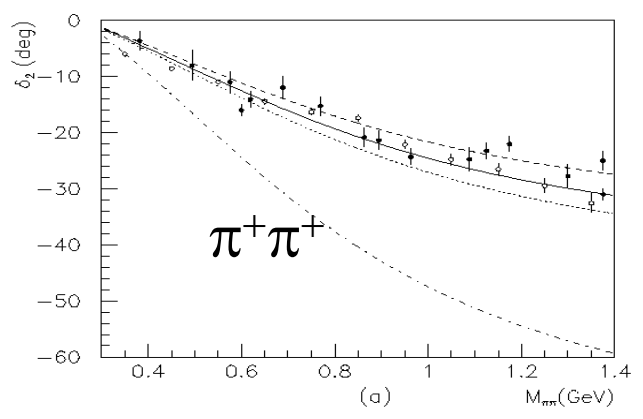
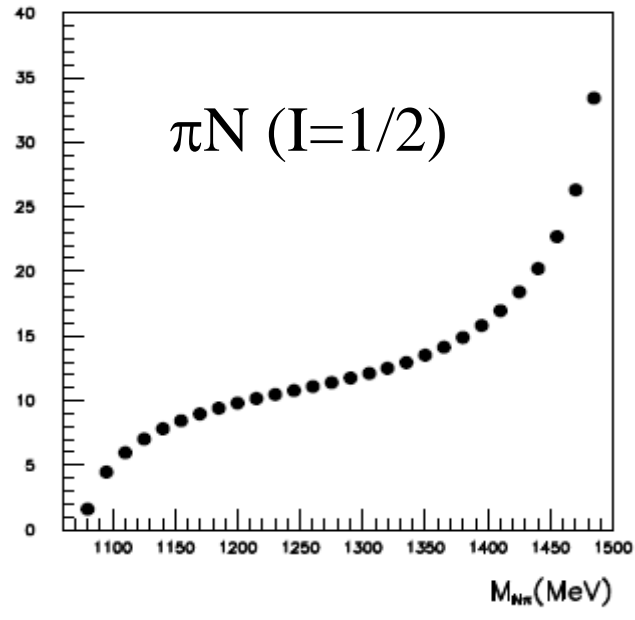
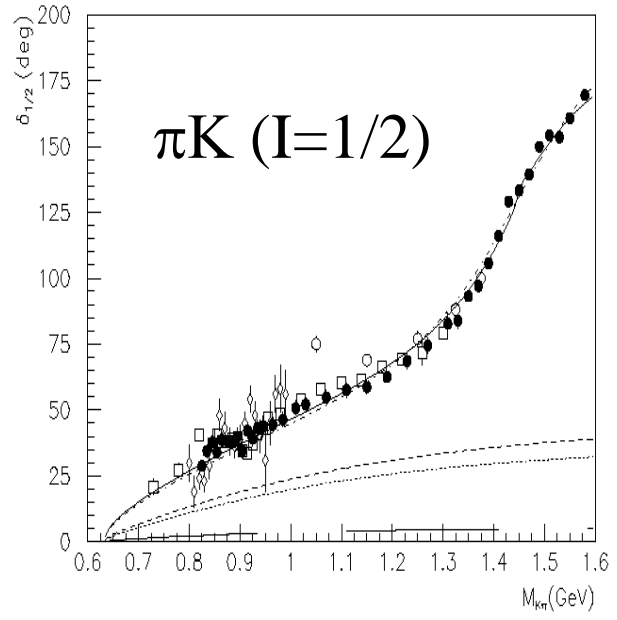
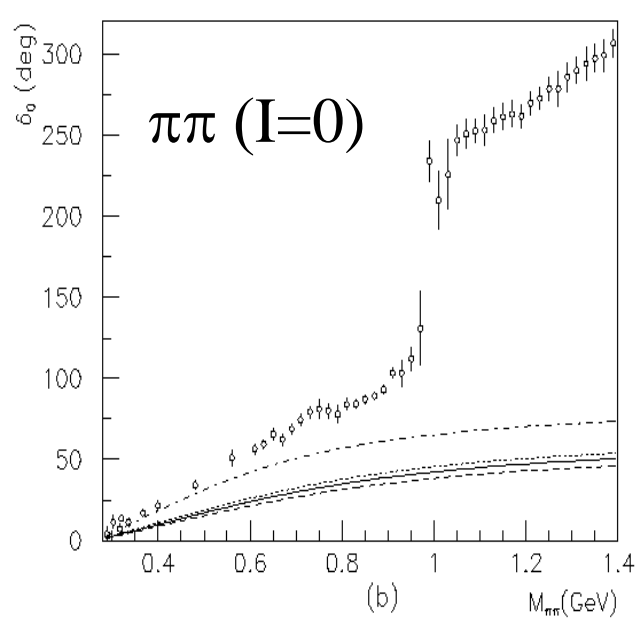
2006: removed from PDG

Note: $\theta^+(1540)$ is not supported by hadronic molecule model & chiral quark model by Huang, Zhang, Yu, Zou, PLB586(2004)69

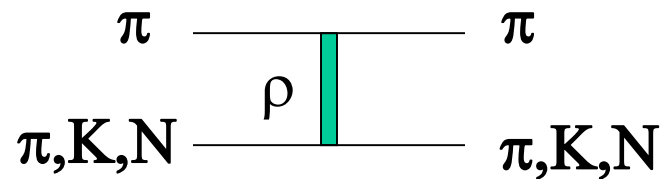
While lacking expt constrains on models of compact pentaquarks, models for hadronic molecules are much better constrained.



Similarity for $\pi\pi$, πK and πN s-wave scattering phase shifts



Important role by t-channel ρ exchange for all these processes



$\pi\pi$

πK & πN

$$K_{\rho}^{I=0} = -2 K_{\rho}^{I=2}, \quad K_{\rho}^{I=1/2} = -2 K_{\rho}^{I=3/2}$$

D. Lohse, J.W. Durso, K. Holinde, J. Speth, Nucl.Phys.A516, 513 (1990)

B.S.Zou, D.V.Bugg, Phys. Rev. D50, 591 (1994)

An interesting paper by T.Hyodo, D.Jido, A.Hosaka, PRL 97 (2006) 192002
“Exotic hadrons in s-wave chiral dynamics”

	$\bar{K}N(I=0)$	$\bar{K}N(I=1)$	$KN(I=0)$	$KN(I=1)$
Phase shifts:	strong +	weaker +	weaker -	strong -
VMD :	$-V_\omega - 3V_\rho$	$-V_\omega + V_\rho$	$V_\omega - V_\rho$	$V_\omega + 3V_\rho$

Similarity between $\pi\Sigma - \bar{K}N(I=0)$ and $\pi\pi - \bar{K}K(I=0)$

dipole structure for $\Lambda(1405) \leftarrow \sigma - f_0(980)$

VMD – ChPT unitarized $\rightarrow N^*(1535)$ as $K\Sigma$ bound state

Kaiser et al., PLB362(1995)23

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

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

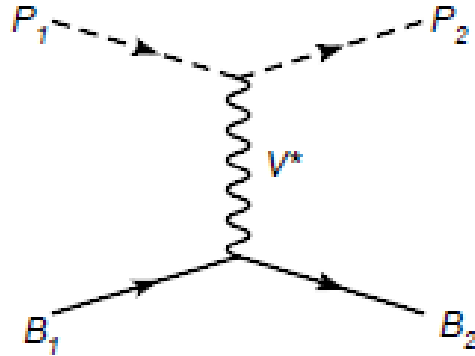
$\Lambda^*(1405)$ $\bar{q}quds$

$\Lambda^*(4210)$ $\bar{c}cuds$ 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

From $K\Sigma$, $\bar{K}N \rightarrow \bar{D}\Sigma_c$, $\bar{D}_s\Lambda_c \rightarrow B\Sigma_b$, $B_s\Lambda_b$ bound states

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



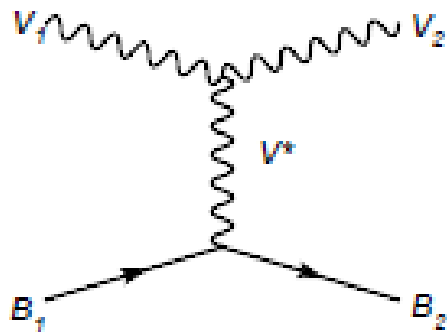
$$\mathcal{L}_{VVV} = ig\langle V^\mu [V^\nu, \partial_\mu V_\nu] \rangle$$

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

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

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

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



$$T = [1 - VG]^{-1}V$$

$$T_{ab} = \frac{g_a g_b}{\sqrt{s} - z_R}$$

$N^* - \bar{D}\Sigma_c$	(I, S)	M	Γ	Γ_i					
	Λ^*	$(1/2, 0)$			πN	ηN	$\eta' N$	$K\Sigma$	$\eta_c N$
		4261	56.9	3.8	8.1	3.9	17.0	23.4	
Λ^*	$(0, -1)$			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

J^P

$1/2^-$

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.

$N^* - \bar{D}^*\Sigma_c$	(I, S)	M	Γ	Γ_i					
	Λ^*	$(1/2, 0)$			ρN	ωN	$K^*\Sigma$		$J/\psi N$
		4412	47.3	3.2	10.4	13.7		19.2	
Λ^*	$(0, -1)$			K^*N	$\rho\Sigma$	$\omega\Lambda$	$\phi\Lambda$	$K^*\Xi$	$J/\psi\Lambda$
		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

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

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.

Further studies support such hidden charm N^*

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

Chiral quark model $\rightarrow \bar{D}\Sigma_c$ state ~ 4.3 GeV

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

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

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

Heavy quark spin symmetry $\rightarrow 7$ such N^* molecules

$\bar{D}\Sigma_c (1/2^-) \sim 4.26$ GeV, $\bar{D}\Sigma_c^* (3/2^-) \sim 4.33$ GeV,
 $\bar{D}^*\Sigma_c (1/2^-, 3/2^-) \sim 4.41, 4.42$ GeV,
 $\bar{D}^*\Sigma_c^* (1/2^-, 3/2^-, 5/2^-) \sim 4.48 - 4.49$ GeV

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

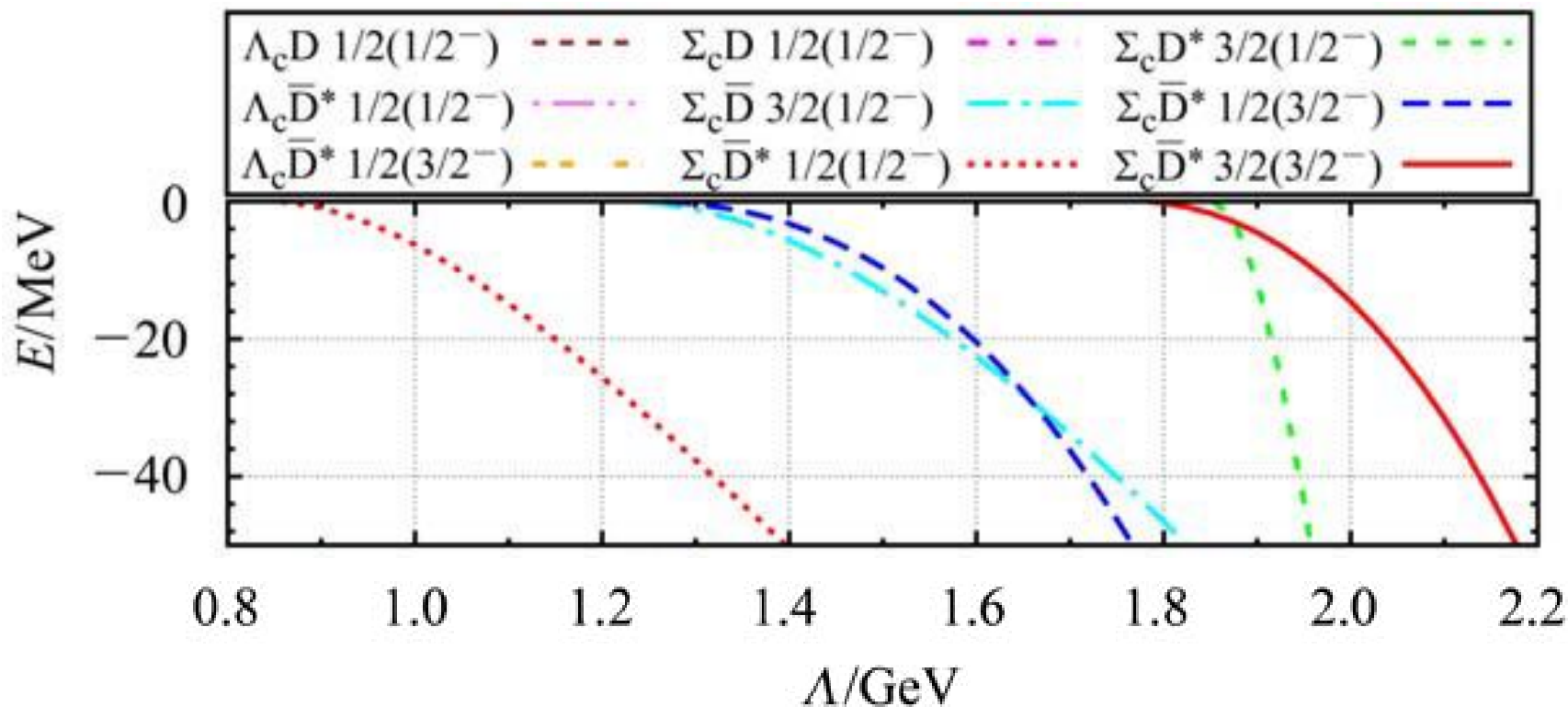
Pion exchange $\rightarrow \bar{D}^*\Sigma_c (1/2^-, 3/2^-) \sim 4.5$ GeV

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

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

$\bar{D}^*\Sigma_c$ ($1/2^-, 3/2^-$) N^* state -- 4360 ~ 4460 MeV

$\bar{D}\Sigma_c$ ($I=3/2$) N^* state -- ~ 4300 MeV



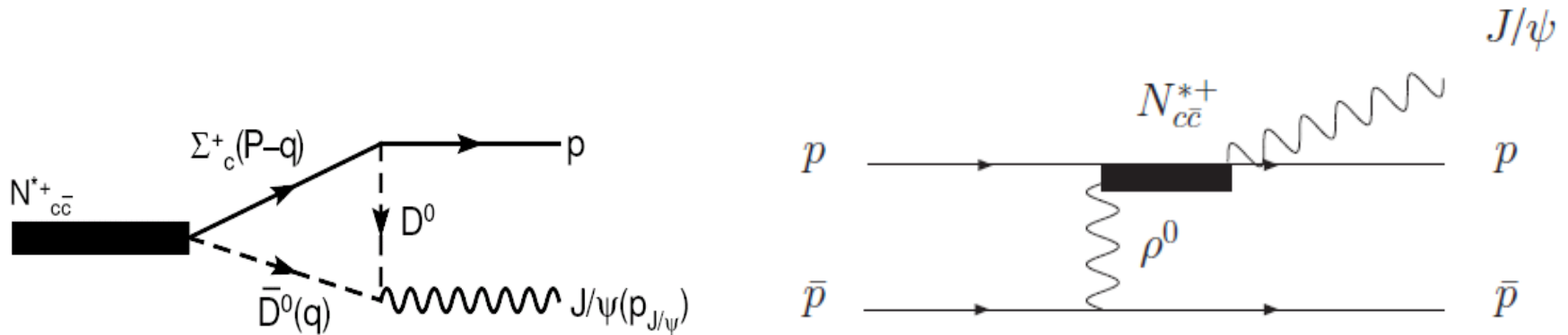
**S.G.Yuan, K.W.We, J.He, H.S.Xu, B.S.Zou, “Study of $\bar{c}cqqq$ five quark system with three kinds of quark-quark hyperfine interaction,”
Eur. Phys. J. A48 (2012) 61**

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	

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

Prediction for PANDA



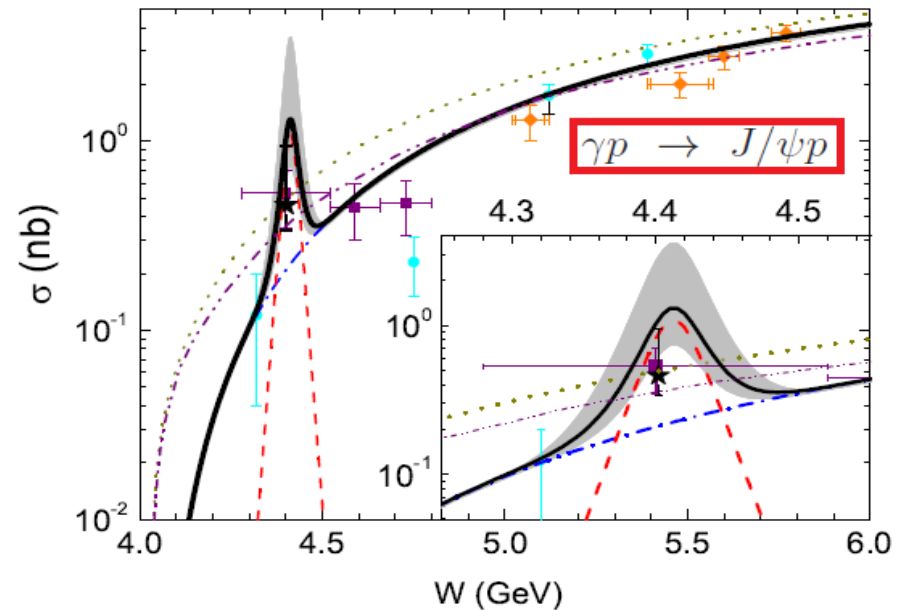
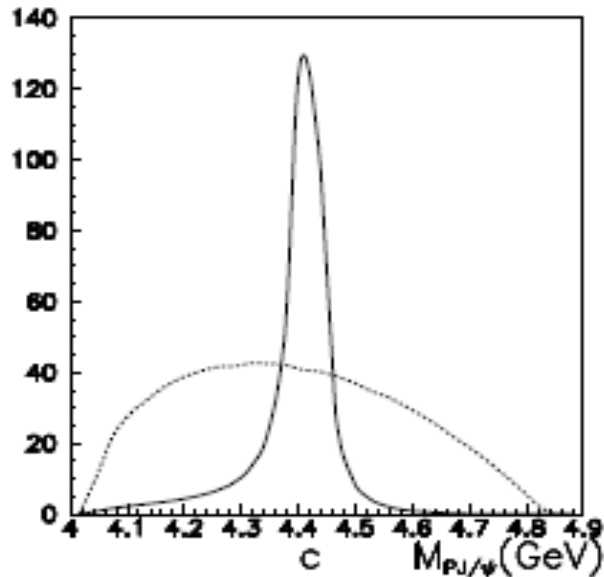
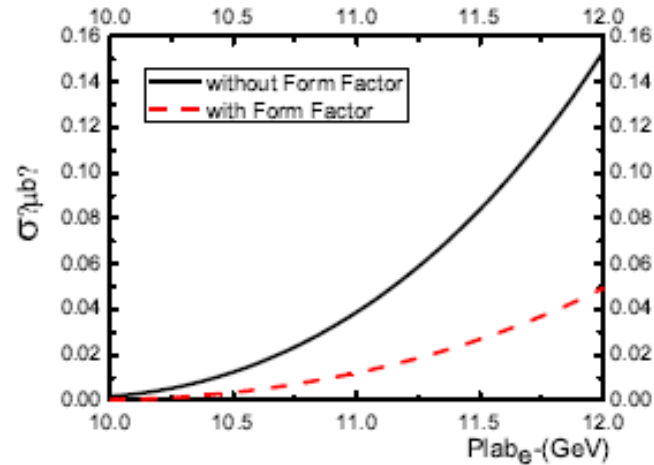
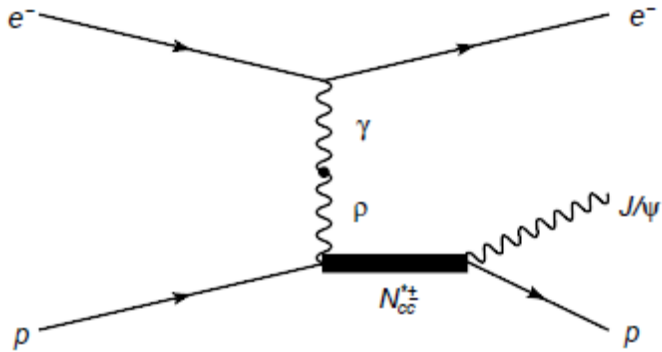
$$\bar{p}p \rightarrow \bar{p}pJ/\psi > 0.1 \text{ nb}$$

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

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

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

Prediction for 12GeV@JLab



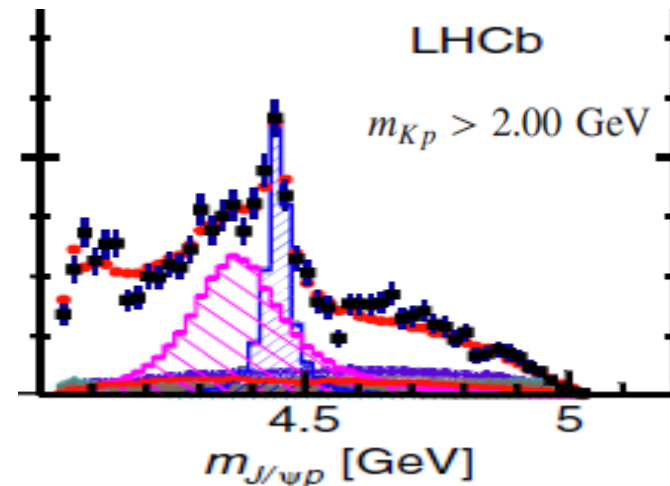
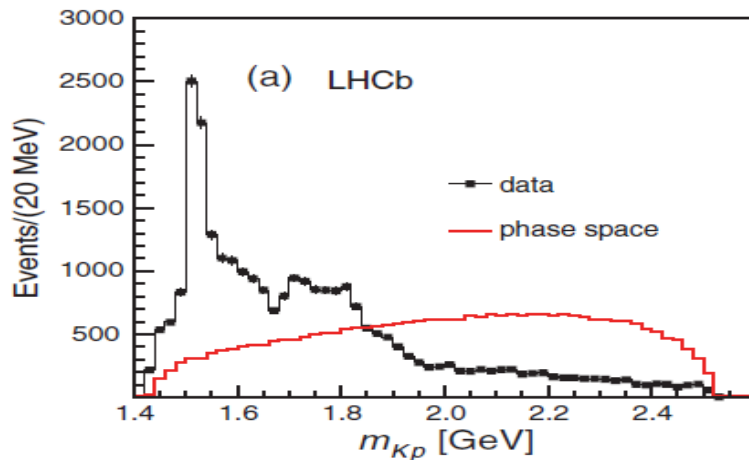
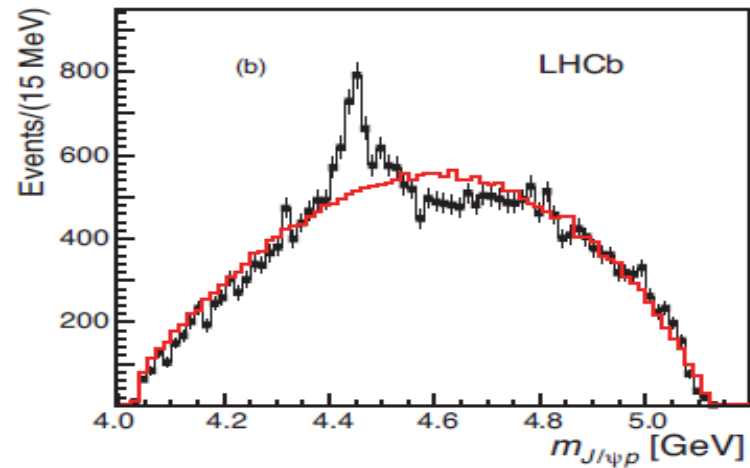
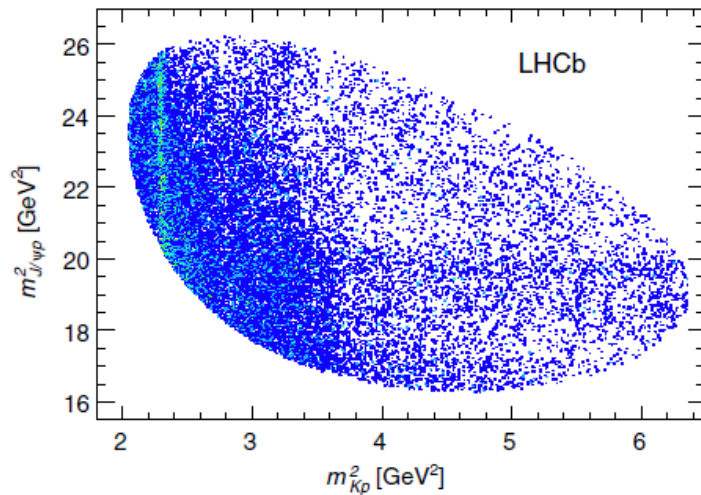
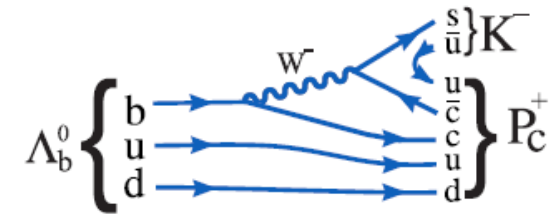
Y. Huang, J.He, H.F.Zhang and X.R.Chen, JPG41, 115004 (2014)

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

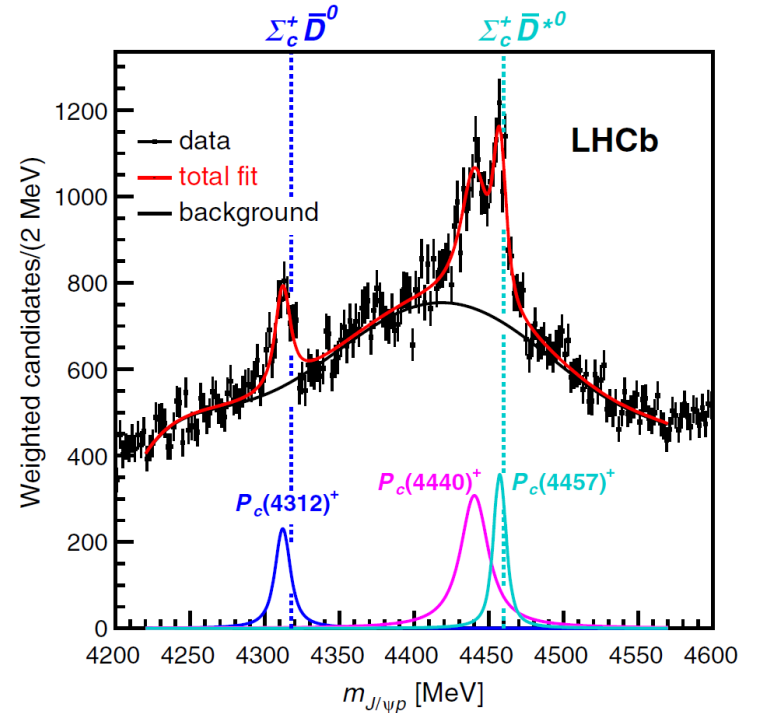
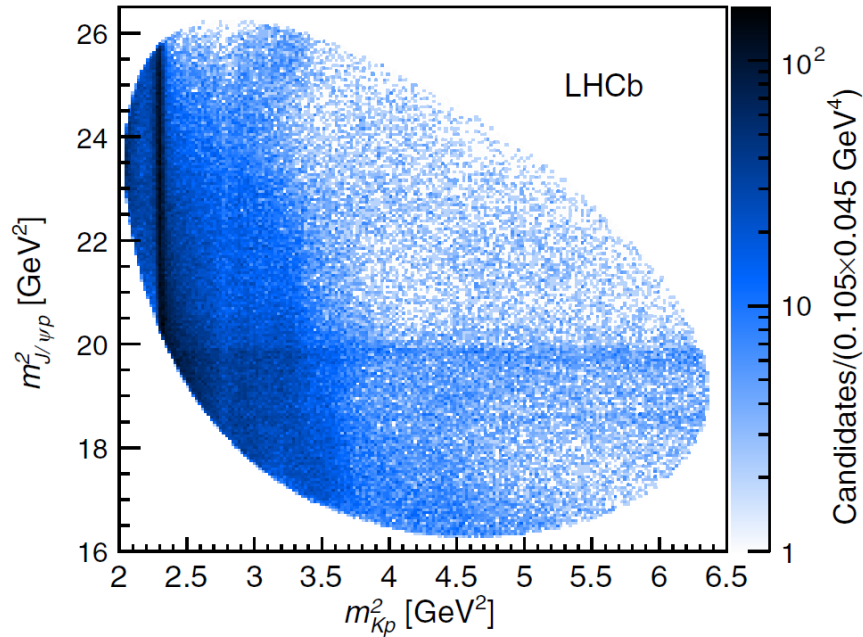
- a) **X.Y.Wang, X.R.Chen, “The production of hidden charm baryon $N^*(4261)$ from $\pi^-p \rightarrow \eta_c n$ reaction”, EPL109 (2015) 41001.**
- b) **E.J.Garzon, J.J.Xie, “Effects of a N_{cc}^- resonance with hidden charm in the $\pi^-p \rightarrow D^- \Sigma_c^+$ reaction near threshold”, PRC 92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

2. LHCb pentaquarks vs predictions

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



LHCb, Phys.Rev.Lett. 122 (2019) 222001

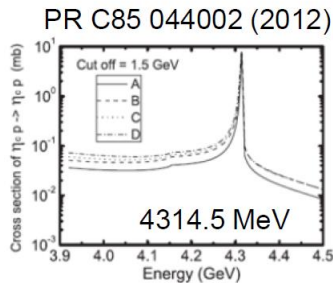


State	M [MeV]	Γ [MeV]	(95% C.L.)	\mathcal{R} [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(<27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(<49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(<20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Comparison to numerical predictions

- Many theoretical predictions for $\Sigma_c^+ \bar{D}^{(*)0}$ published before 2015, **some in quantitative agreement with the LHCb data**

- Wu, Molina, Oset, Zou, PRL 105, 232001 (2010),
- Wang, Huang, Zhang, Zou, PR C 84, 015203 (2011),
- Yang, Sun, He, Liu, Zhu, Chin. Phys. C 36, 6 (2012),
- Wu, Lee, Zou, PR C 85 044002 (2012),
- Karliner, Rosner, PRL 115, 122001 (2015)



ΔE – binding energy

Example:

Nucleon resonances with hidden charm in coupled-channels models

Jia-Jun Wu, T.-S. H. Lee, and B. S. Zou
Phys. Rev. C **85**, 044002 – Published 17 April 2012

arXiv:1202.1036

TABLE III: The pole position ($M - i\Gamma/2$) and “binding energy” ($\Delta E = E_{thr} - M$) for different cut-off parameter Λ and spin-parity J^P . The threshold E_{thr} is 4320.79 MeV of $\bar{D}\Sigma_c$ in PB system and 4462.18 MeV of $\bar{D}^*\Sigma_c$ in VB system. The unit for the listed numbers is MeV.

$J^P = \frac{1}{2}^-$	PB System			VB System	
	Λ	$M - i\Gamma/2$	ΔE	$M - i\Gamma/2$	ΔE
650	800	$5.8^{+1.0}_{-6.8}$	MeV	4462.178 - 0.002i	0.002
	1200	4318.964 - 0.362i	1.826	4459.513 - 0.417i	2.667
	1500	4314.531 - 1.448i	6.259	4454.088 - 1.662i	8.092
	2000	4301.115 - 5.835i	19.68	4438.277 - 7.115i	23.90
$J^P = \frac{3}{2}^-$	650	-	-	-	-
	800	-	-	4462.178 - 0.002i	0.002
	1200	-	-	4459.507 - 0.420i	2.673
	1500	-	-	4454.057 - 1.681i	8.123
	2000	-	-	4438.039 - 7.268i	23.14

$$\Delta E(4312) = 5.8^{+1.0}_{-6.8} \text{ MeV} \quad \Delta E(4457) = 2.5^{+4.3}_{-4.1} \text{ MeV}$$

Λ - cut off on exchanged meson mass.

$$\Delta E(4440) = 19.5^{+4.9}_{-4.3} \text{ MeV}$$

LHCb pentaquark states vs Predictions

Consistence : $P_c(4312) \rightarrow \bar{D}\Sigma_c(1/2^-)$
 $P_c(4380) \rightarrow \bar{D}\Sigma_c^*(3/2^-)$
 $P_c(4440) \& P_c(4457) \rightarrow \bar{D}^*\Sigma_c(1/2^-, 3/2^-)$

Problems:

- 1) $P_c(4380)$ -- much larger decay width than prediction
- 2) Other P_c states have narrower width than prediction
- 3) All P_c states have negative parity ?

3. 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;

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;

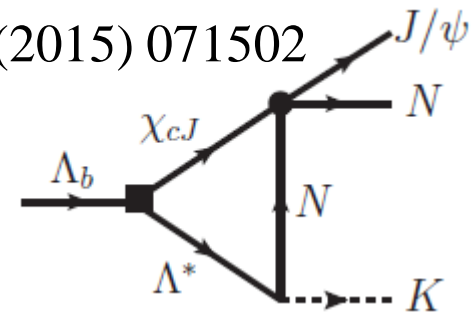
G.N.Li, M.He, X.G.He, JHEP 1512 (2015) 128;

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

Different predictions from various models :

**Diquark model by
A.Ali et al., PLB793 (2019) 365**

J^P	This work	Refs. [22, 23]
$S_{ld} = 0, L = 0$		
$1/2^-$	3830 ± 34	4086 ± 42
	4150 ± 29	4162 ± 38
$3/2^-$	4240 ± 29	4133 ± 55
$S_{ld} = 0, L = 1$		
$1/2^+$	4030 ± 39	4030 ± 62
	4351 ± 35	4141 ± 44
	4430 ± 35	4217 ± 40
$3/2^+$	4040 ± 39	
	4361 ± 35	
$5/2^+$	4440 ± 35	
	4457 ± 35	4510 ± 57

**Hadrocharmonium states by
M.Eides et al., arXiv:1904.11616**

Constituents	Binding energy [MeV]	Mass [MeV]	Spin-parity
$\eta_c(2S)N$	176.1	4401	$1/2^-$
$\chi_{c1}(1P)N$	44.2	4406	$3/2^+, 1/2^+$
$h_c(1P)N$	43.9	4421	$1/2^+, 3/2^+$
$\chi_{c2}(1P)N$	43.7	4452	$5/2^+, 3/2^+$

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

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

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

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

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

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

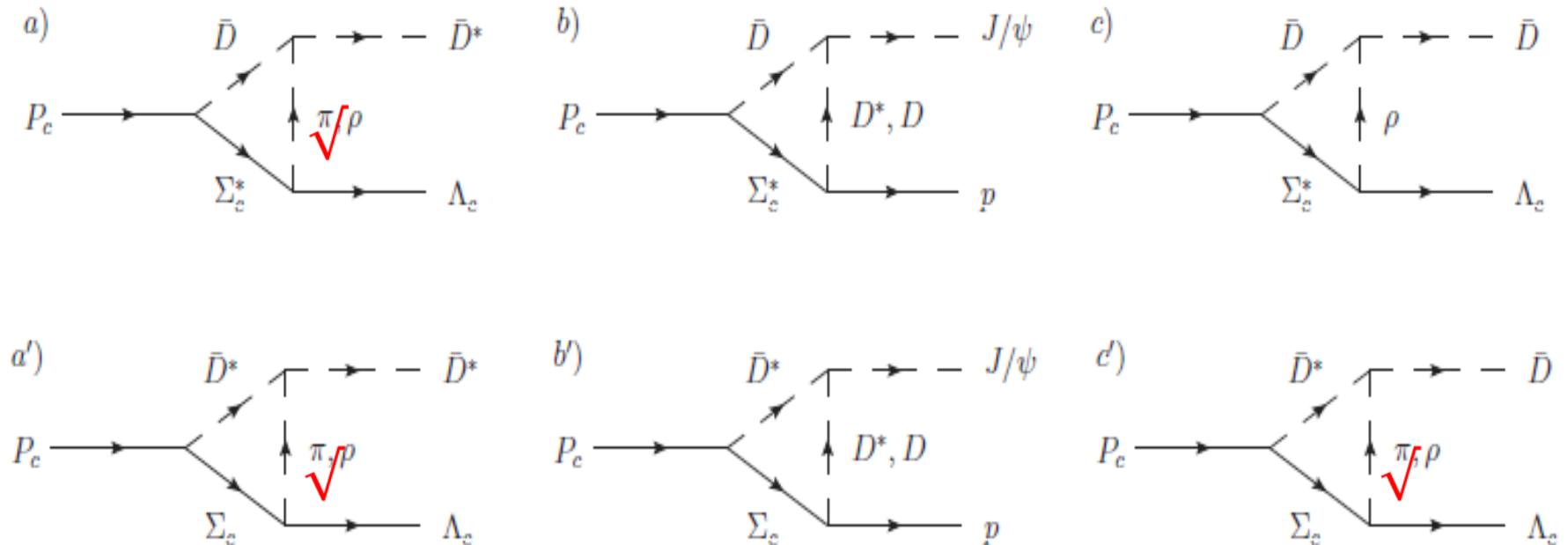
Y.H.Lin, C.W.Shen, F.K.Guo, B.S.Zou, PRD95(2017)114017

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

→ Different predictions to be checked !

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 very important !

$\bar{D}\Sigma_c^*$ & $\bar{D}^*\Sigma_c^*$ are much broader than $\bar{D}\Sigma_c$ & $\bar{D}^*\Sigma_c$ states

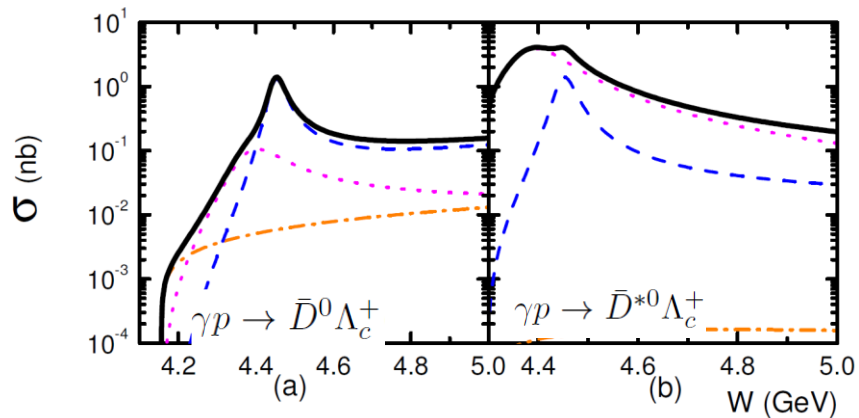
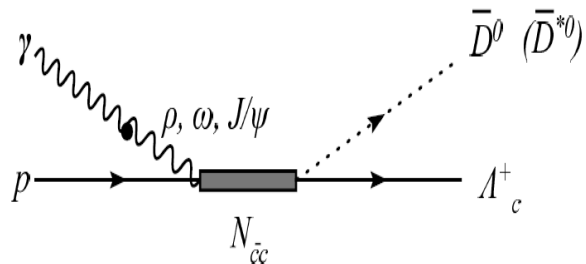
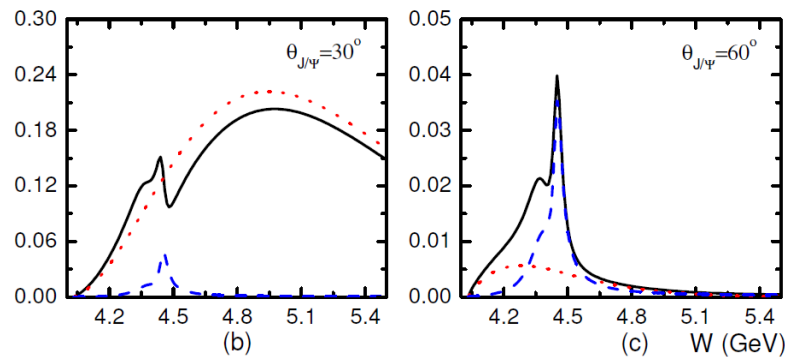
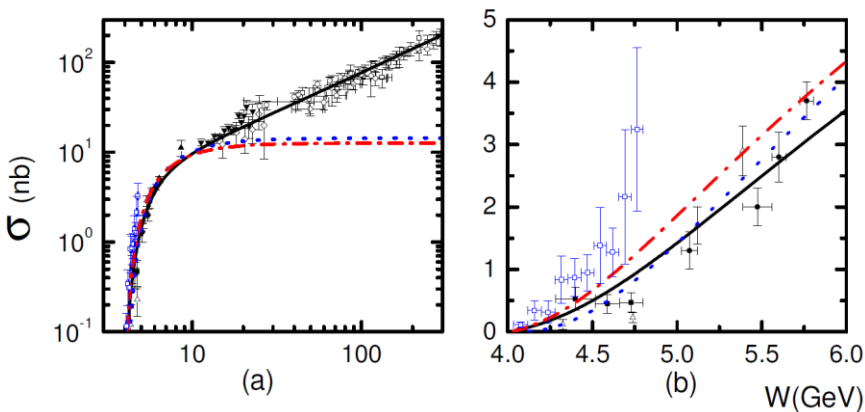
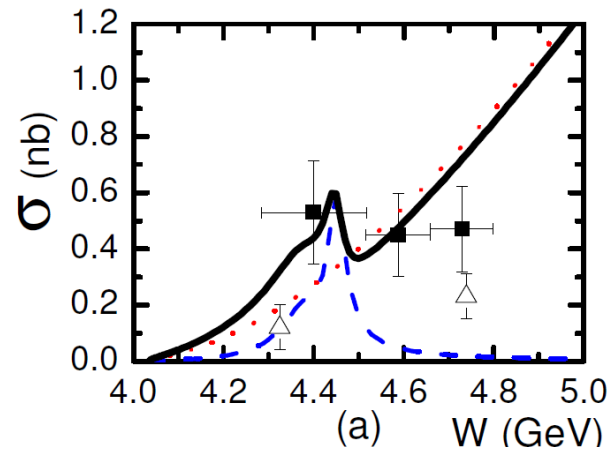
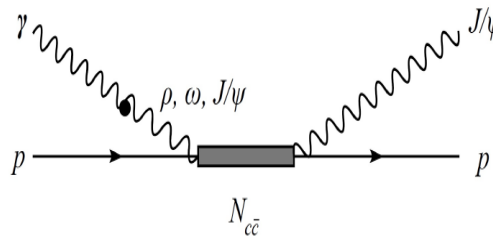
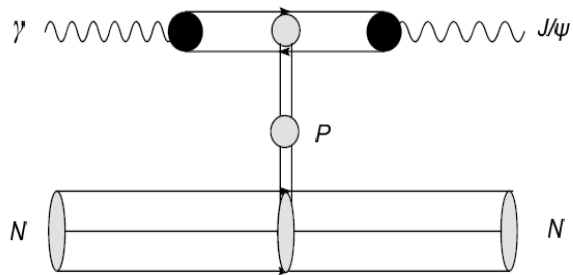
Partial decay widths of $P_c^+(4380)$ & $P_c^+(4450)$

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 ✓
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 $P_c \rightarrow \bar{D}^*\Lambda_c$ & $\bar{D}\Lambda_c$!

Pin down P_c^+ states from their photo-production

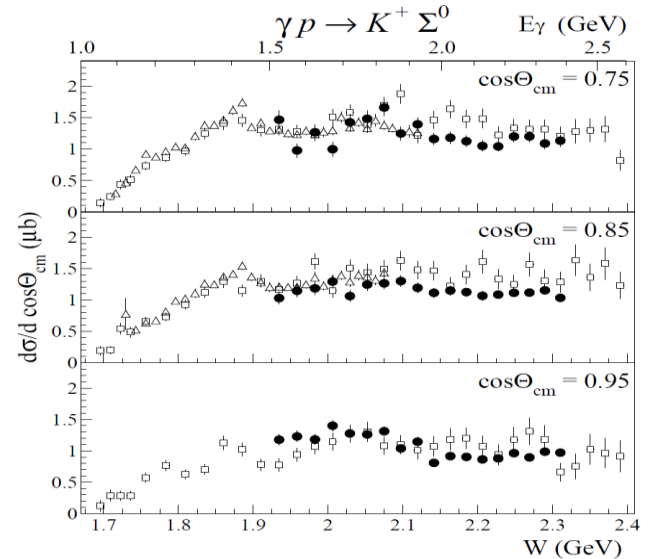
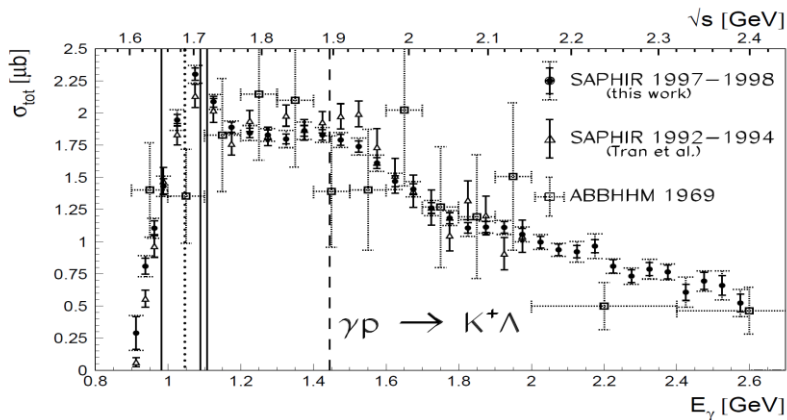
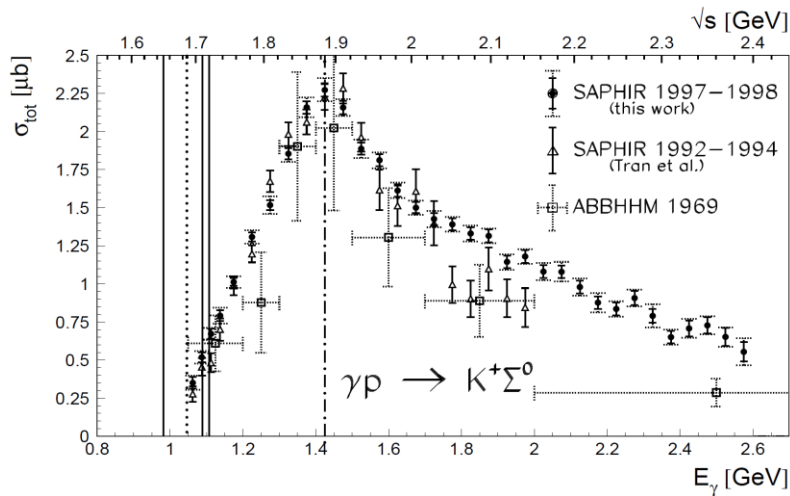
J.J.Wu, T.S.H.Lee, B.S.Zou, arXiv:1906.05375



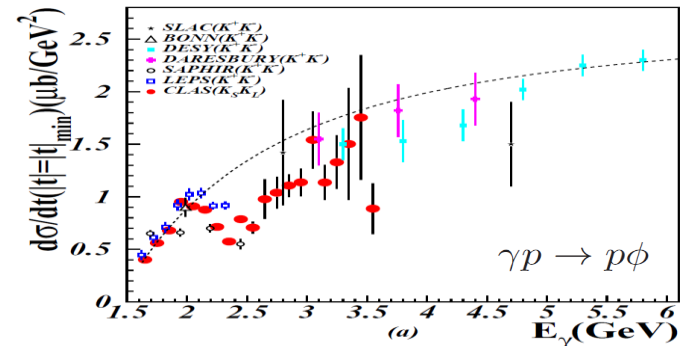
4. Strange & beauty partners of P_c states

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

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



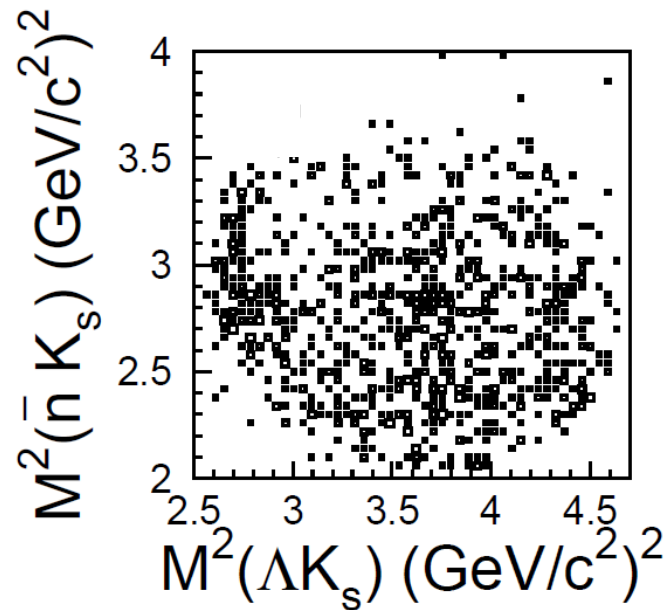
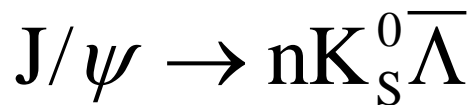
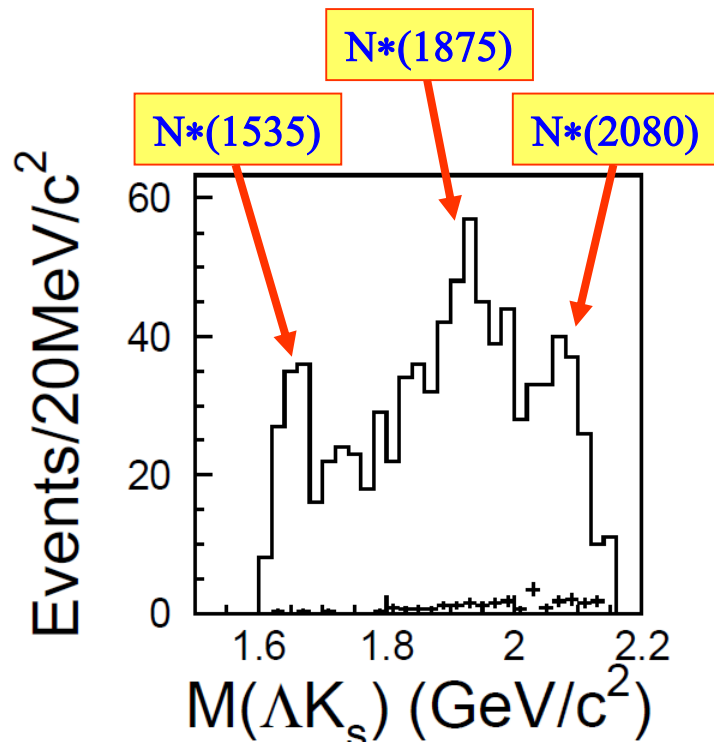
LEPS, PRC73 (2006) 035214



CLAS, PRC89 (2014) 055206

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

N_{ss} penta-quarks at BES ?!



BESII, Phys. Lett. B659 (2008) 789



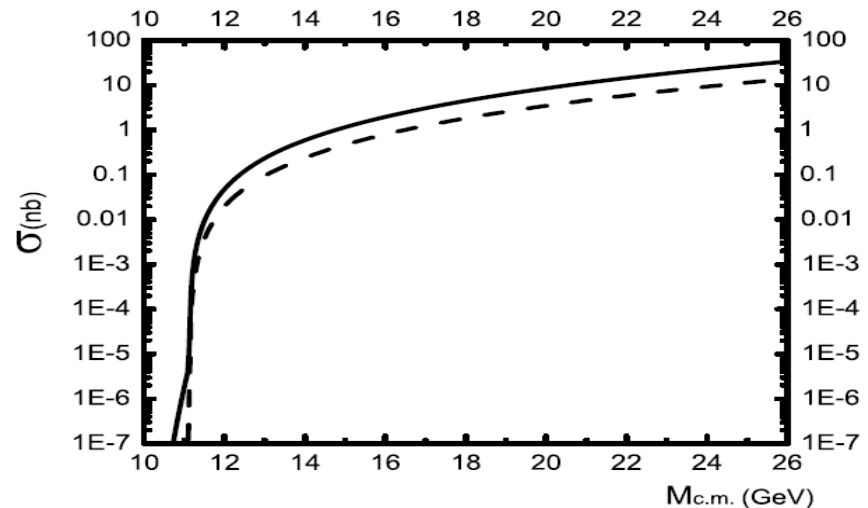
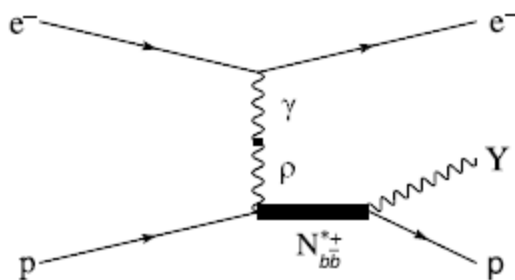
Prediction of super-heavy N^* and Λ^* resonances with hidden beauty

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	

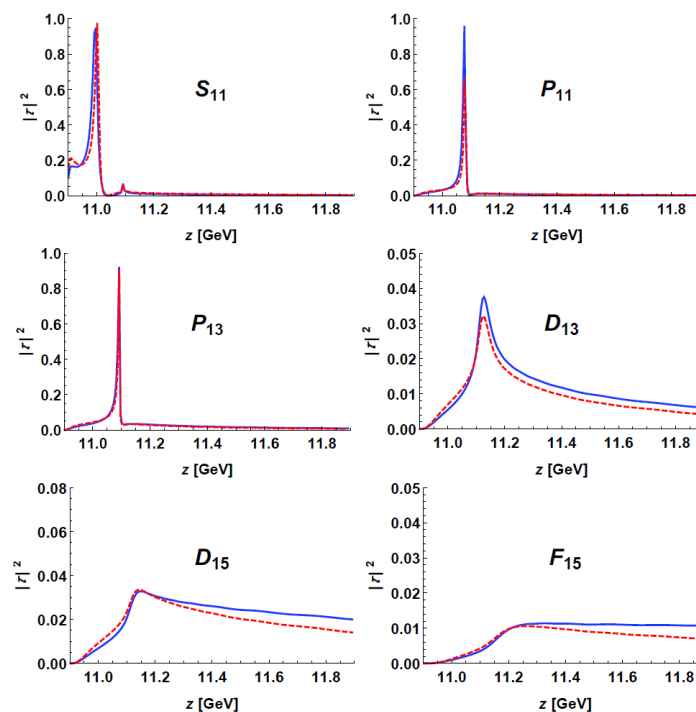
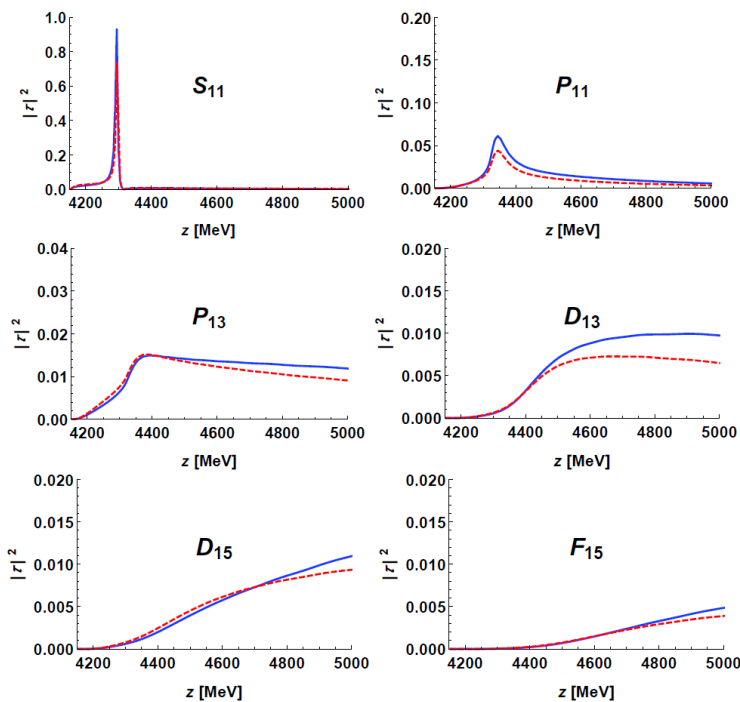
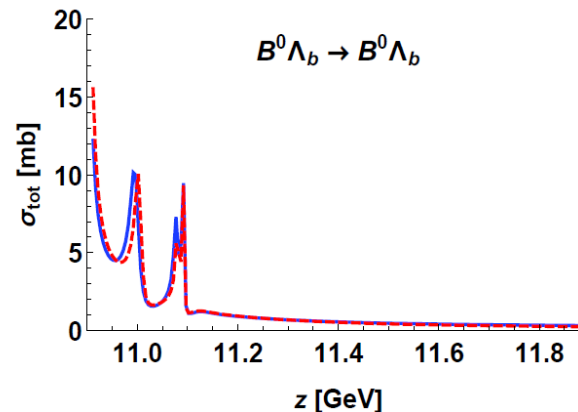
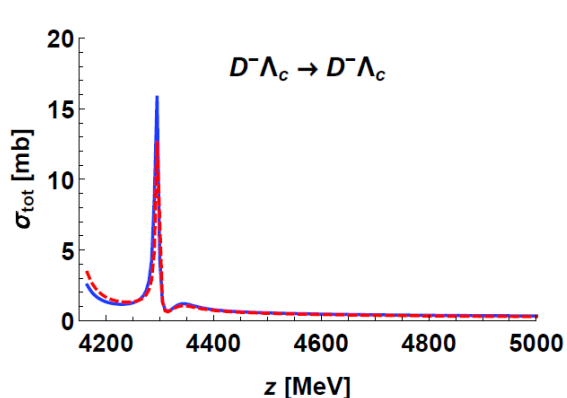
$1/2^-$

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



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

Decay behavior of P_s & P_b pentaquark states

Y.H.Lin, C.W.Shen, B.S.Zou, NPA980(2018)21

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	
πN	3.8	0.2	22.7	
ρN	2.3	3.8	6.1	
ωp	6.6	11.3	18.2	
$K\Sigma$	0.03	1.4	9.1	
$K\Lambda$	0.7	3.7	19.3	
ηp	0.6	0.4	1.8	
$\pi\Delta$	201.4	82.6	46.9	
$K^*\Lambda$	-	2.4	7.9	
ϕp	-	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
Υp	0.3	0.04	0.1
ρN	5.5	0.02	0.1
ωp	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
πN	0.7	0.005	0.003
$B\Sigma_b^*$	-	-	-
Total	299.9	27.4	303.8

Guidance for P_s & P_b search

Decay behaviors of possible $\Lambda_{c\bar{c}}$ states in hadronic molecule pictures

C.W.Shen, J.J.Wu, B.S.Zou (2019), ArXiv:1906.03896

Guidance for P_{sc} search

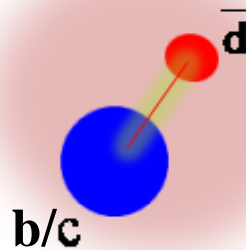
5. Prospects

◆ my favorite strategy for hadron spectroscopy:

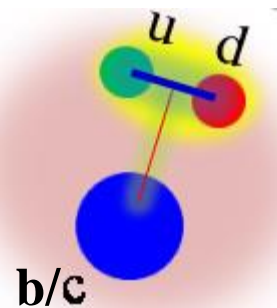
$\bar{c}c u u d$ & $\bar{c}c u d s$ \rightarrow $s s s$ - $\bar{q} q s s s$ \rightarrow $c q q$ - $\bar{q} q c q q$
 \rightarrow hyperons \rightarrow light baryons

$\bar{c}c \bar{u} d$ & $\bar{c}c s \bar{u} d$ \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 γN , πN , KN , $e^+e^- \rightarrow \bar{\Lambda}_b \Lambda_b$, etc.**
 $ep/\gamma p$ @JLab, $\pi 10/K 10$ @JPARC, BelleII, BESIII, Eic/EicC, PANDA@FAIR, STCF etc. may play important role here!

Thank you for
your attention!