Theoretical Review on Pentaquarks

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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

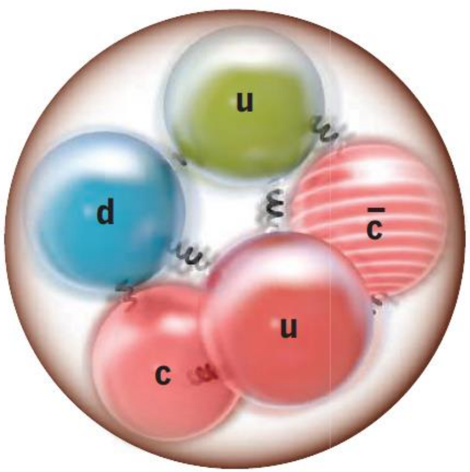
2004: not supported by BESII, PRD70, 012004

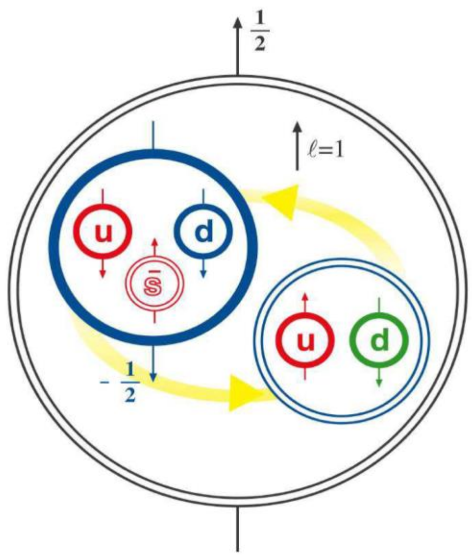
2005: not supported by many high stats experiments

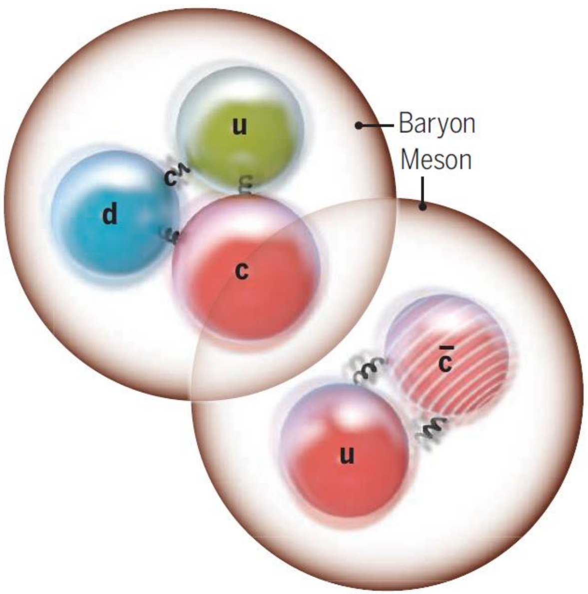
2006: removed from PDG

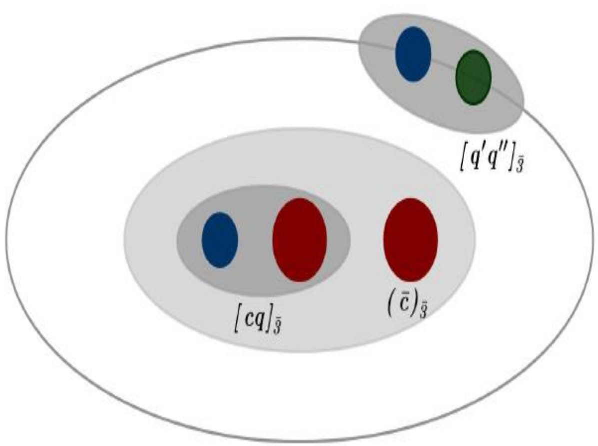
Note: $\theta^+(1540)$ is not supported by hadronic molecule model & chiral quark model by Huang, Zhang, Yu, Zou, PLB586(2004)69

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

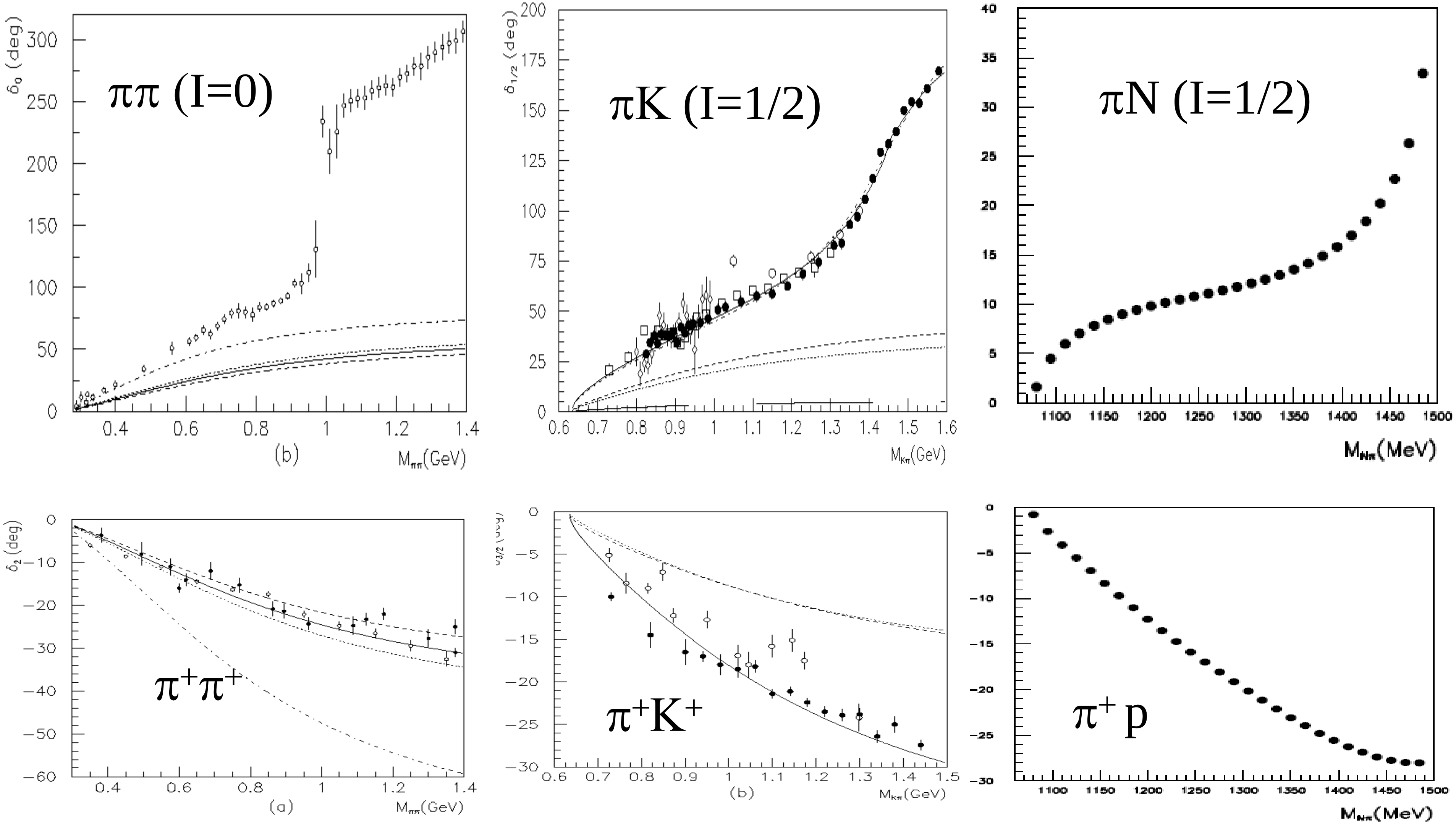




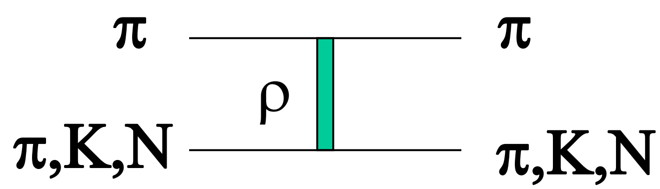




Similarity for ππ, πK and πN s-wave scattering phase shifts



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



$\pi\pi$ πK & πN

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

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 $\Lambda(1405)$ ← σ - $f_0(980)$

VMD – ChPT unitarized → 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

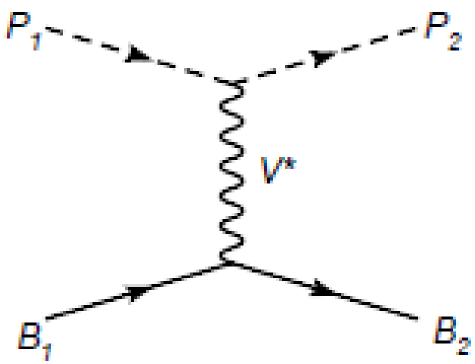
Λ*(1405) $\bar{q}quds$

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

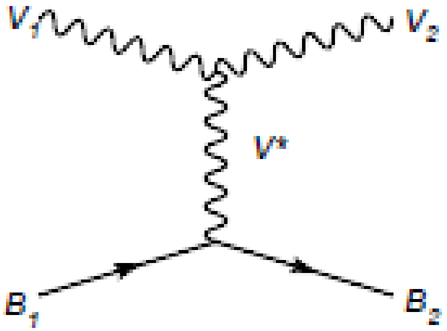
From $K\Sigma$, $\bar{K}N$ → $\bar{D}\Sigma_c$, $\bar{D}_s\Lambda_c$ → $B\Sigma_b$, $B_s\Lambda_b$ bound states

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



$$\mathcal{L}_{VVV} = ig\langle V^\mu [V^\nu, \partial_\mu V_\nu]\rangle$$
$$\mathcal{L}_{PPV} = -ig\langle V^\mu [P, \partial_\mu P]\rangle$$
$$\mathcal{L}_{BBV} = g(\langle \bar{B}\gamma_\mu [V^\mu, B]\rangle + \langle \bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle)$$

$$V_{ab(P_1B_1\to P_2B_2)} = \frac{C_{ab}}{4f^2}(E_{P_1} + E_{P_2}),$$
$$V_{ab(V_1B_1\to V_2B_2)} = \frac{C_{ab}}{4f^2}(E_{V_1} + E_{V_2})\vec{\epsilon}_1\cdot\vec{\epsilon}_2,$$



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

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

J.J.Wu, R.Molina, E.Oset, B.S.Zou, PRL 105 (2010) 232001

	(I,S)	M	Γ	Γ_i						J^P
N* - $\bar{D}\Sigma_c$	$(1/2,0)$			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						J^P
N*- $\bar{D}^*\Sigma_c$	$(1/2,0)$			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.

Further studies support such hidden charm N*

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

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

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

EBAC-DCC model → $\bar{D}\Sigma_c$ $(1/2^-)$ ~ 4.3 GeV,

$\bar{D}^*\Sigma_c$ $(1/2^-, 3/2^-)$ ~ 4.4 - 4.5 GeV -

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

Heavy quark spin symmetry → 7 such N* molecules

$\bar{D}\Sigma_c$ $(1/2^-)$ ~ 4.26 GeV, $\bar{D}\Sigma_c^*$ $(3/2^-)$ ~ 4.33 GeV,

$\bar{D}^*\Sigma_c$ $(1/2^-, 3/2^-)$ ~ 4.41, 4.42 GeV,

$\bar{D}^*\Sigma_c^*$ $(1/2^-, 3/2^-, 5/2^-)$ ~ 4.48 - 4.49 GeV

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

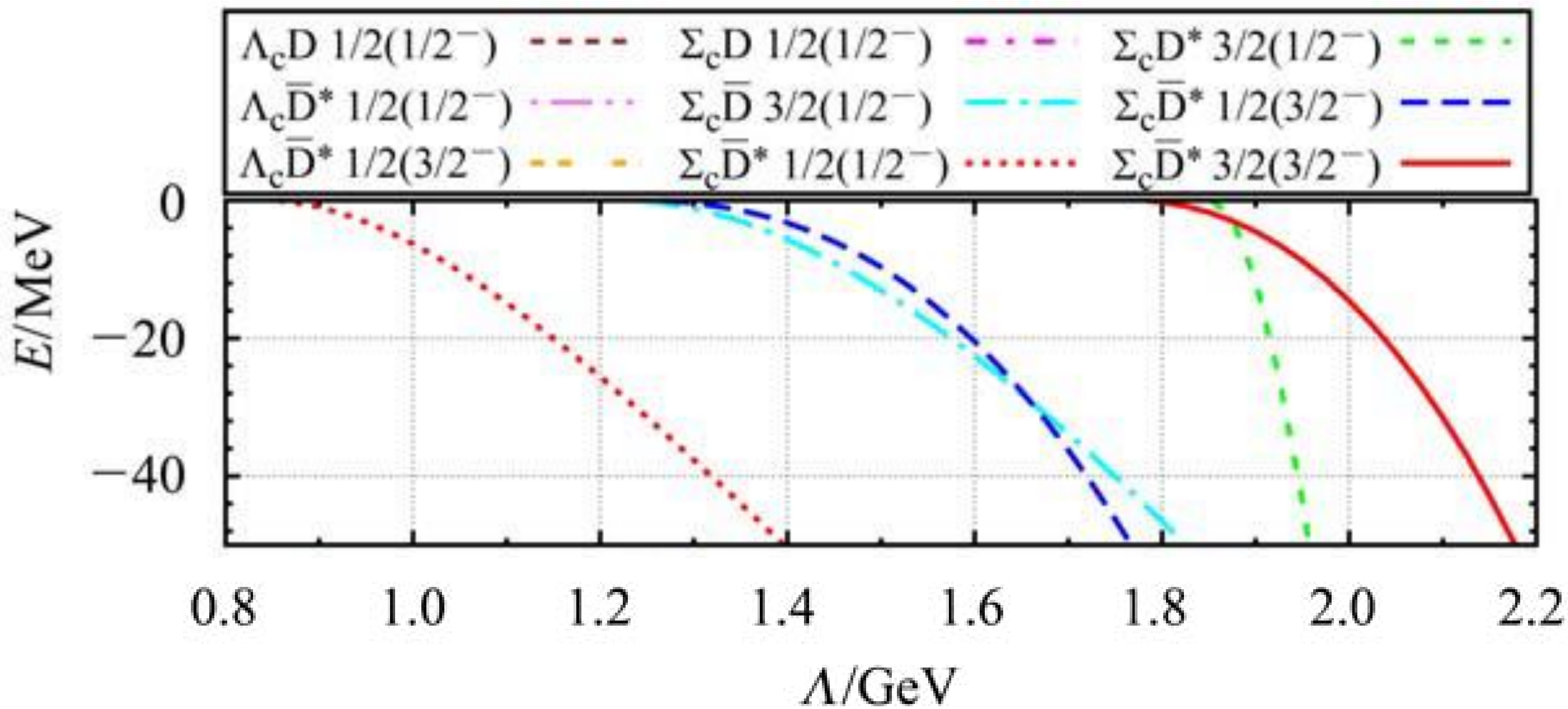
Pion exchange → $\bar{D}^*\Sigma_c$ $(1/2^-, 3/2^-)$ ~ 4.5 GeV

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

Schoedinger Equation method with π, η, ρ, ω, σ 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



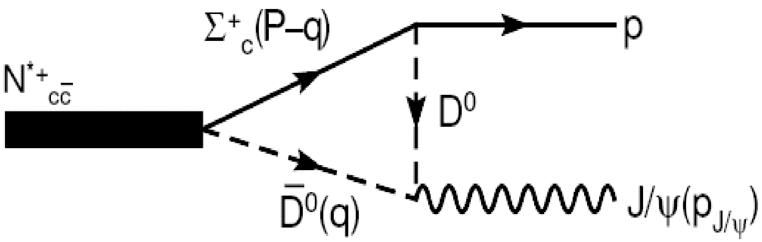
S.G.Yuan, K.W.Wei, J.He, H.S.Xu, B.S.Zou, "Study of $\bar{c}cqqq$ five quark system with three kinds of quark-quark hyperfine interaction," Eur. Phys. J. A48 (2012) 61

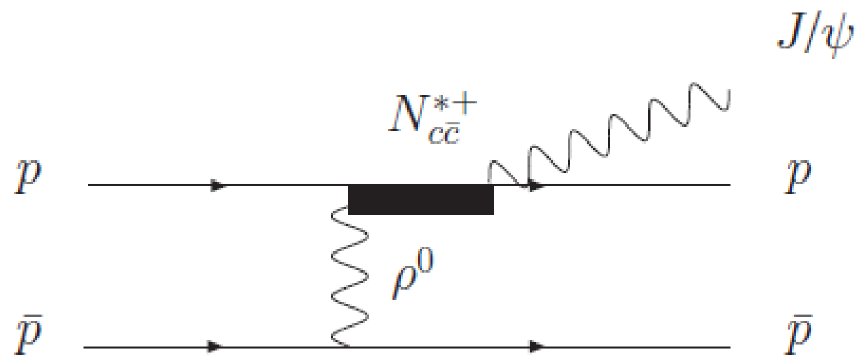
	CM		FS		Inst.	
J^P	$uds c\bar{c}$	$uud c\bar{c}$	$uds c\bar{c}$	$uud c\bar{c}$	$uds c\bar{c}$	$uud c\bar{c}$
$\frac{1}{2}^-$	4273	4267	4084	3933	4209	4114
$\frac{1}{2}^-$	4377	4363	4154	4013	4216	4131
$\frac{1}{2}^-$	4453	4377	4160	4119	4277	4204
$\frac{1}{2}^-$	4469	4471	4171	4136	4295	4207
$\frac{1}{2}^-$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

	CM		FS		Inst.	
J^P	$uds c\bar{c}$	$uud c\bar{c}$	$uds c\bar{c}$	$uud c\bar{c}$	$uds c\bar{c}$	$uud c\bar{c}$
$\frac{1}{2}^+$	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	4457	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	4426
$\frac{5}{2}^+$	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 ~300 MeV

Prediction for PANDA





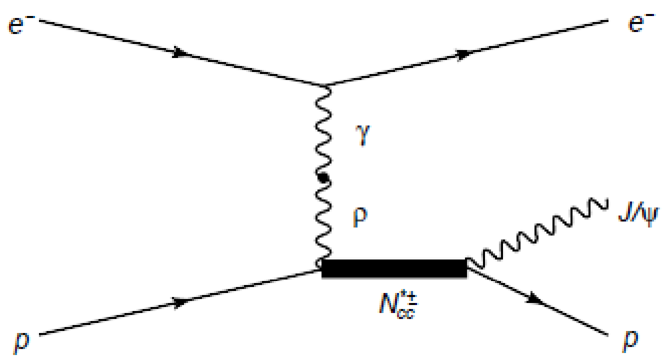
$\bar{p}p \rightarrow \bar{p}pJ/\psi$ > 0.1 nb

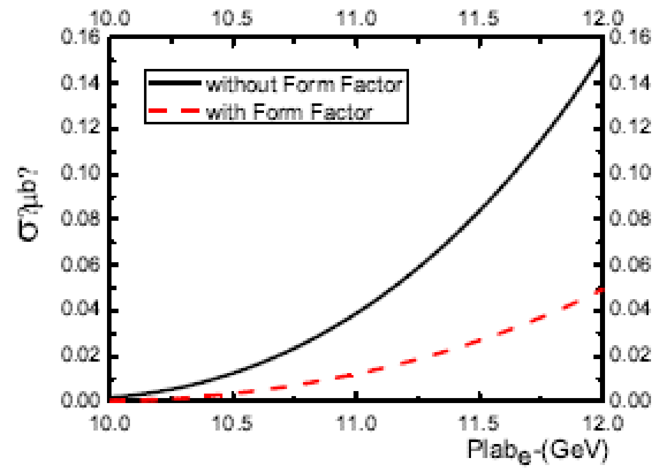
> 100 events per day at PANDA/FAIR by $L=10^{31}$ $cm^{-2}s^{-1}$

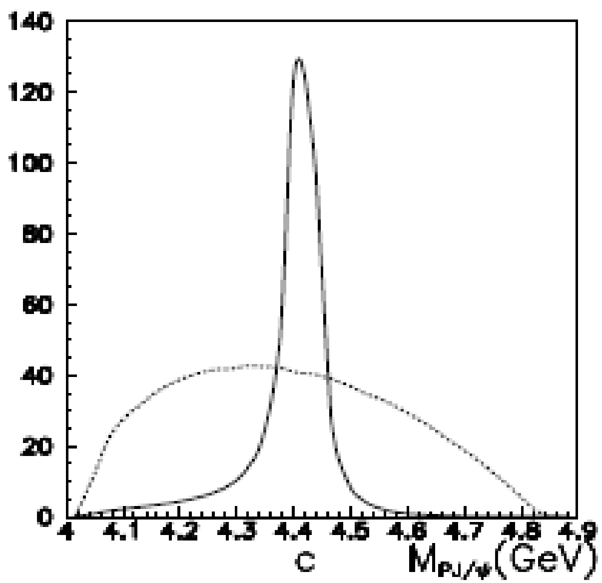
These Super-heavy narrow N* and Λ* can be found at PANDA !

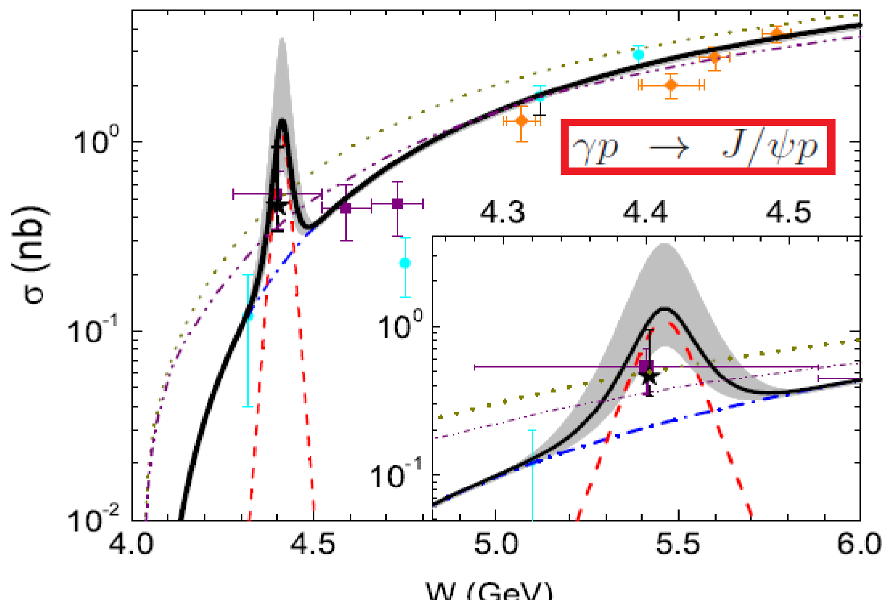
Albrecht Gillitzer@Juelich had a plan to find them at PANDA

Prediction for 12GeV@JLab









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

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

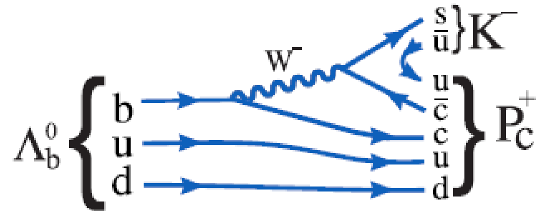
b) E.J.Garzon, J.J.Xie, “Effects of a $N_{c\bar{c}}$ resonance with hidden charm in the $\pi^- p \rightarrow D^- \Sigma_c^+$ reaction near threshold”, PRC 92 (2015) 035201

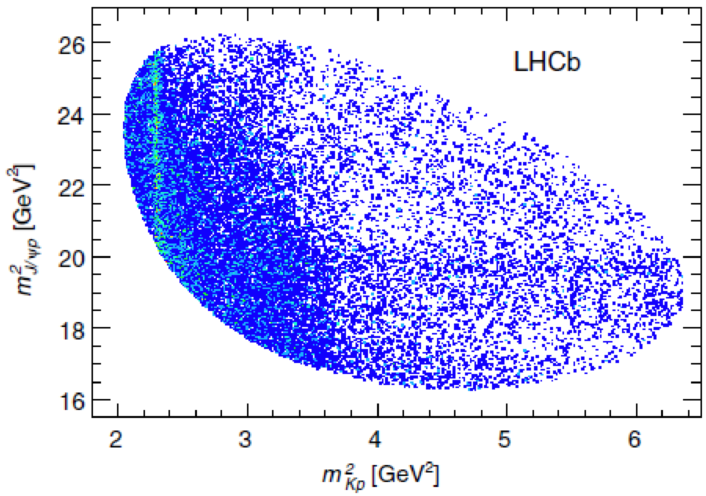
c) X.Y.Wang, X.R.Chen, “Production of the superheavy baryon Λ*(4209) in kaon-induced reaction”, EPJA51 (2015) 85

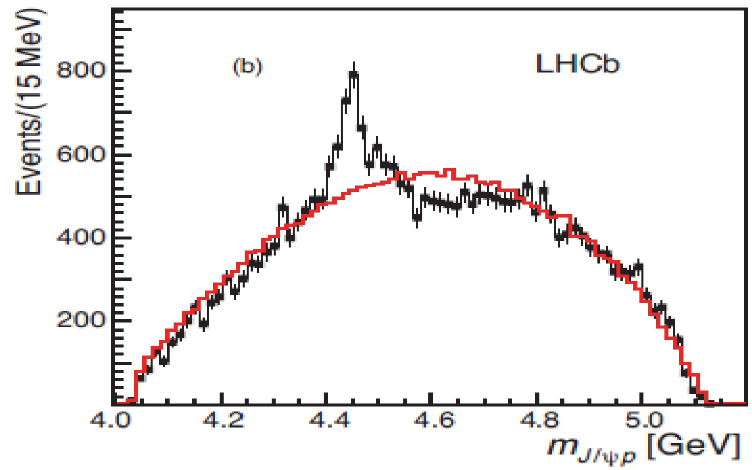
2. LHCb pentaquarks vs predictions

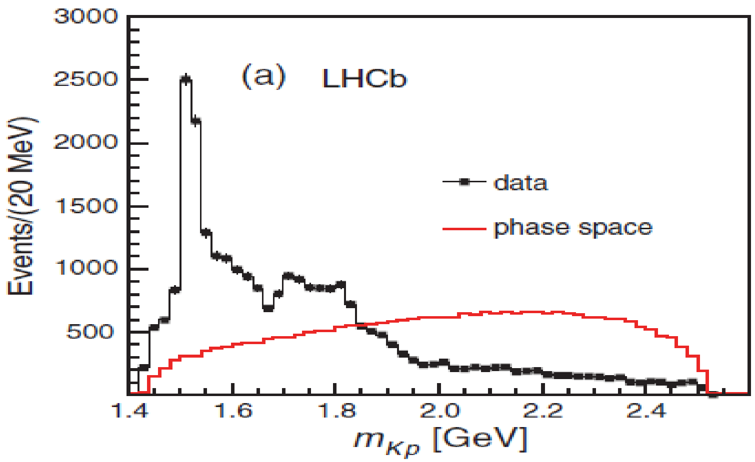
LHCb, Phys.Rev.Lett. 115 (2015) 072001 :

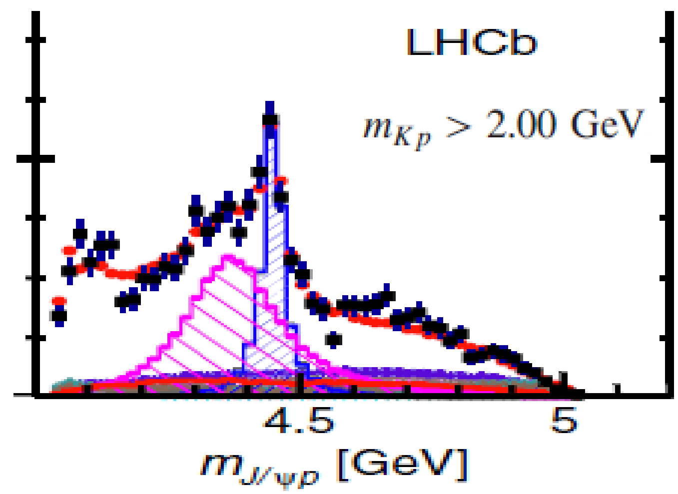
Observation of two N* from $\Lambda_b^0 \to J/\psi K^- p$



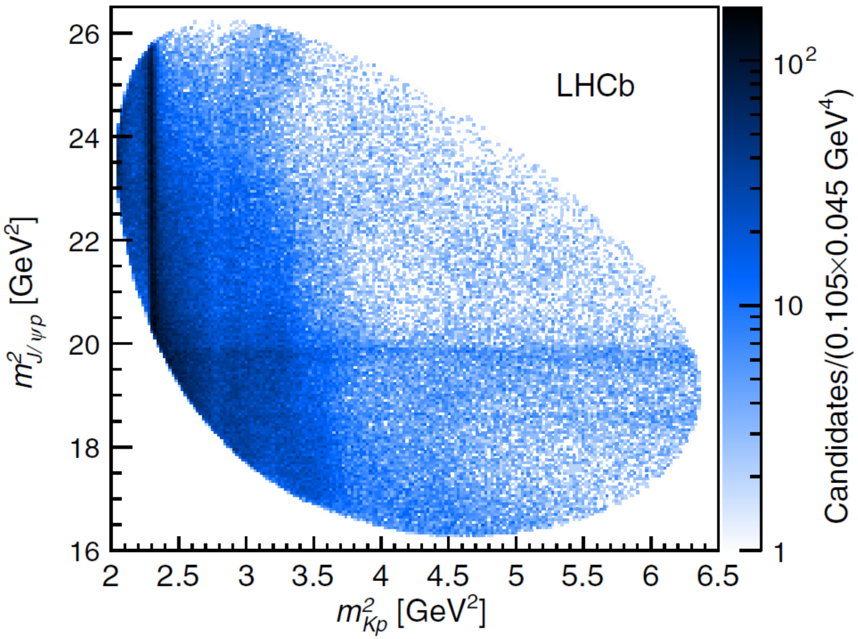


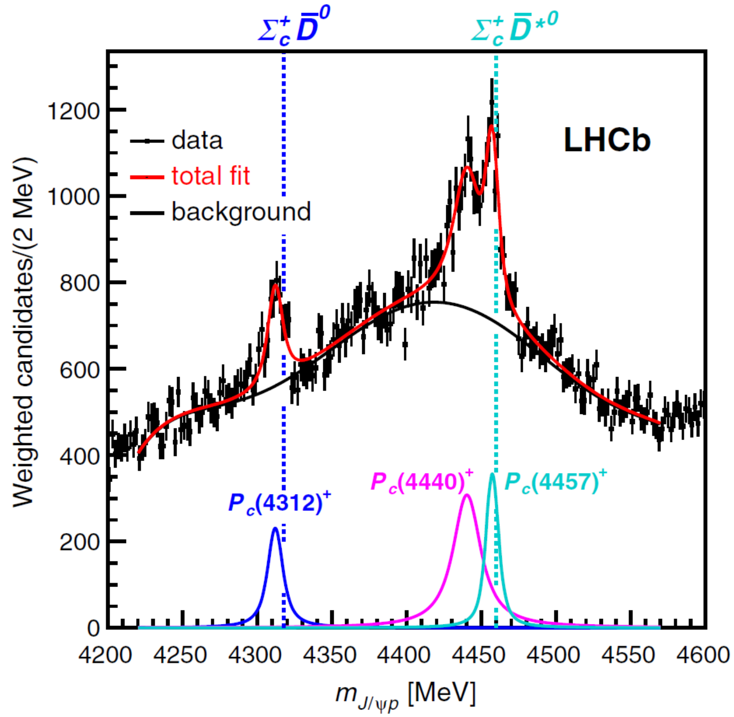






LHCb, Phys.Rev.Lett. 122 (2019) 222001



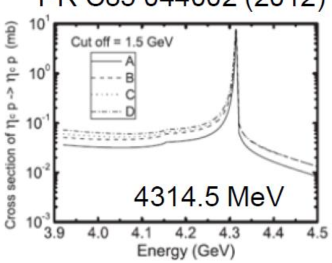


State	M [MeV]	Γ [MeV]	(95% C.L.)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(<27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(<49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm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

Comparison to numerical predictions

- Many theoretical predictions for $\Sigma_c^+ \overline{D}^{(*)0}$ published before 2015, **some in quantitative agreement with the LHCb data**
  - Wu,Molina,Oset,Zou, PRL105, 232001 (2010),
  - **Wang,Huang,Zhang,Zou, PR C84, 015203 (2011),**
  - **Yang,Sun,He,Liu,Zhu, Chin. Phys. C36, 6 (2012)**,
  - **Wu,Lee,Zou, PR C85 044002 (2012),**
  - Karliner,Rosner, PRL 115, 122001 (2015)

PR C85 044002 (2012)



ΔE – binding energy

Example:

Nucleon resonances with hidden charm in coupled-channels models

Jia-Jun Wu, T.-S. H. Lee, and B. S. Zou

arXiv:1202.1036

Phys. Rev. C **85**, 044002 – Published 17 April 2012

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.

		PB System		VB System	
$J^P = \frac{1}{2}^-$	Λ	$M - i\Gamma/2$	ΔE	$M - i\Gamma/2$	ΔE
	650	-	-		
	800		-	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

$\Delta E(4312) = 5.8^{+1.0}_{-6.8}$ MeV

$\Delta E(4457) = 2.5^{+4.3}_{-4.1}$ MeV

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

Λ - cut off on exchanged meson mass.

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

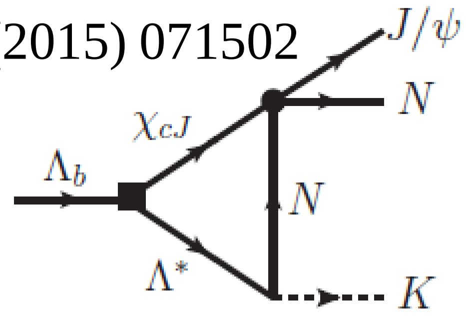
R.Chen, X.Liu, X.Q.Li, S.L.Zhu, PRL115 (2015) 132002;
L.Roca, J.Nieves, E.Oset, PRD92 (2015) 094003;
J.He, PLB 753 (2016)547 ;

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	
	4440 ± 35	
$5/2^+$	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;

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

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

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

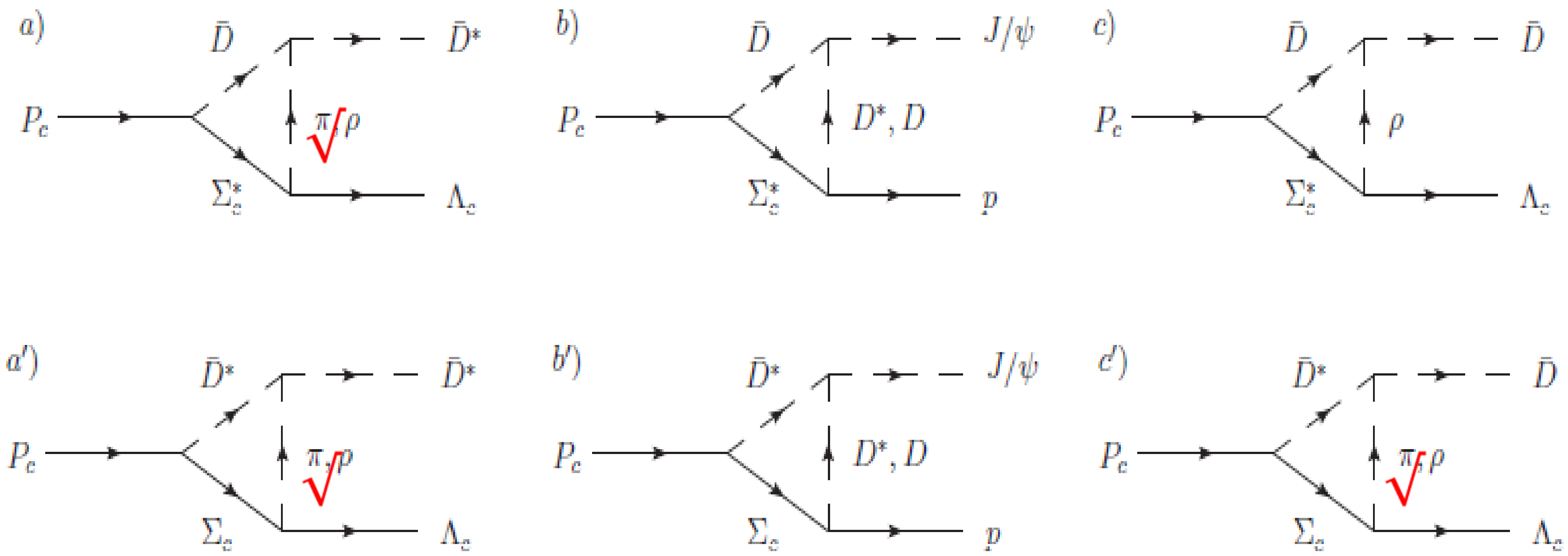
[3] J.He, PLB 753 (2016)547 ; PRD95 (2017)074004
Y.H.Lin, C.W.Shen, F.K.Guo, B.S.Zou, PRD95(2017)114017

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

→ 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

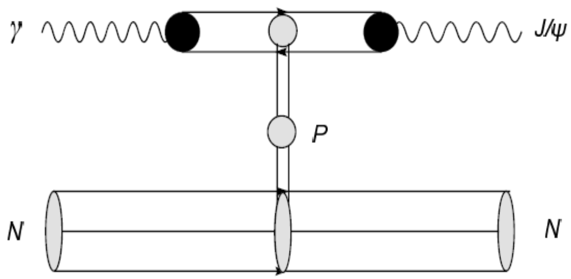
Partial decay widths of $P_c^+(4380)$ & $P_c^+(4450)$

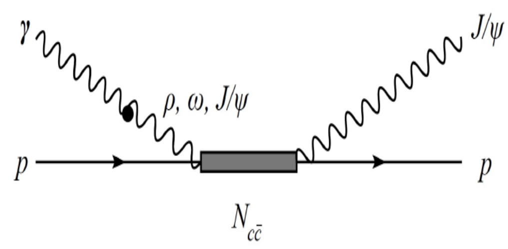
	Widths (MeV)			
	$P_c(4380)$		$P_c(4450)$	
Mode	$\bar{D}\Sigma_c^*(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{5}{2}^+)$
$\bar{D}^*\Lambda_c$	131.3 √	35.3 √	72.3 √	20.5 √
$J/\psi p$	3.8	16.6	16.3	4.0
$\bar{D}\Lambda_c$	1.2	17.0 √	41.4 √	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

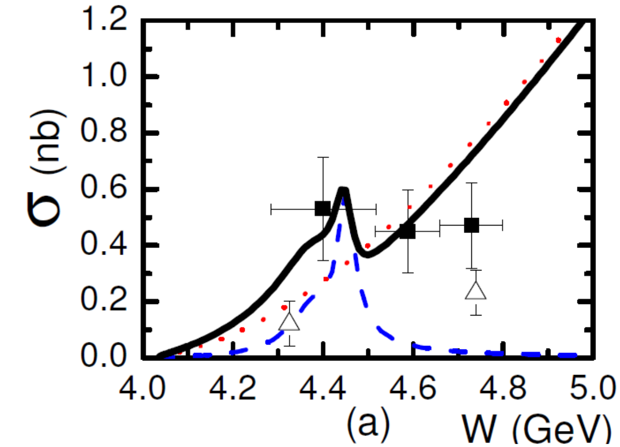
It is very important to study $P_c \rightarrow \bar{D}^*\Lambda_c$ & $\bar{D}\Lambda_c$!

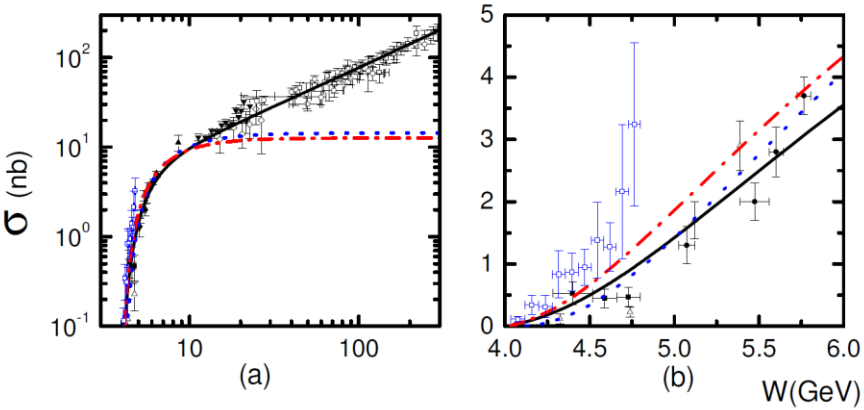
Pin down P_c^+ states from their photo-production

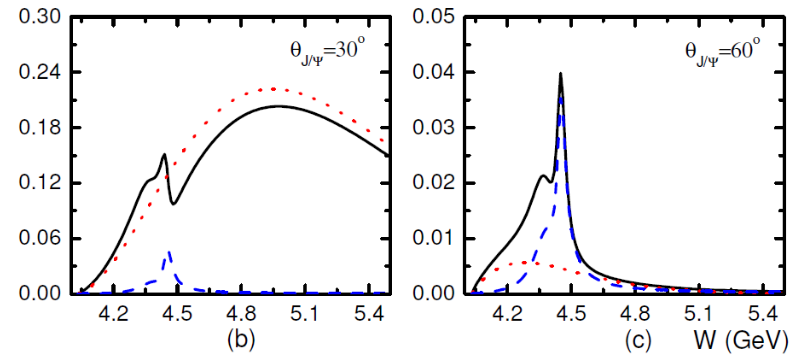
J.J.Wu, T.S.H.Lee, B.S.Zou, **arXiv:1906.05375**

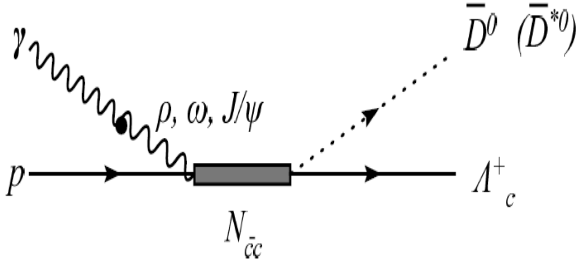


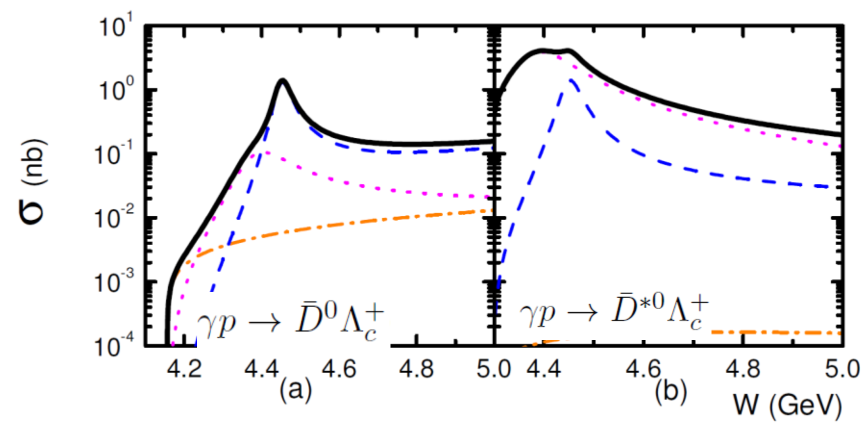








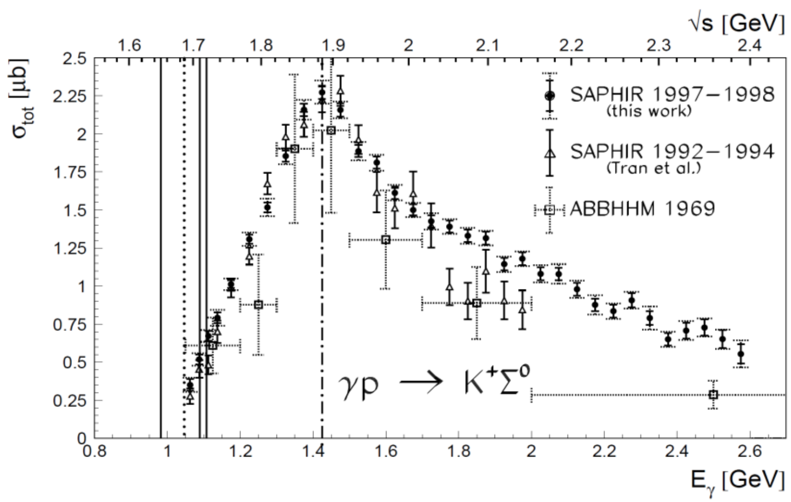


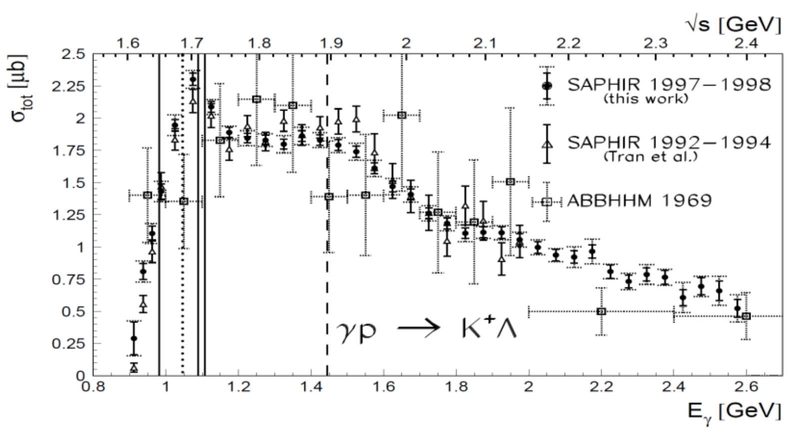


4. Strange & beauty partners of P_c states

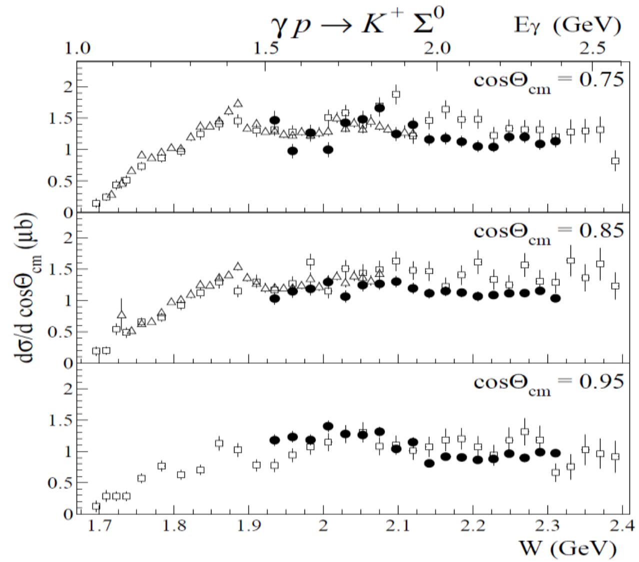
Strangeness partners of P_c states: N*(1875) & N*(2080)

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

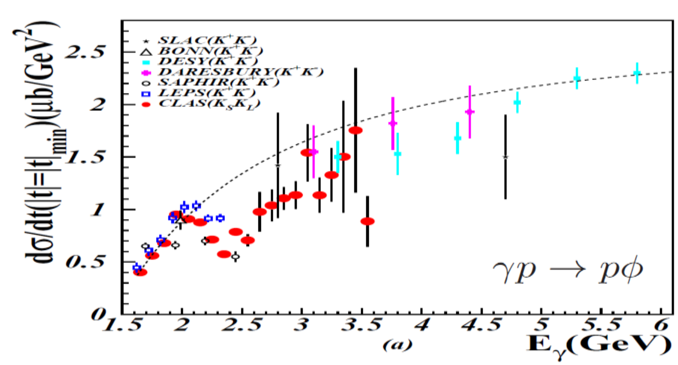




Glander, K.H. *et al.* EPJA19 (2004) 251-273

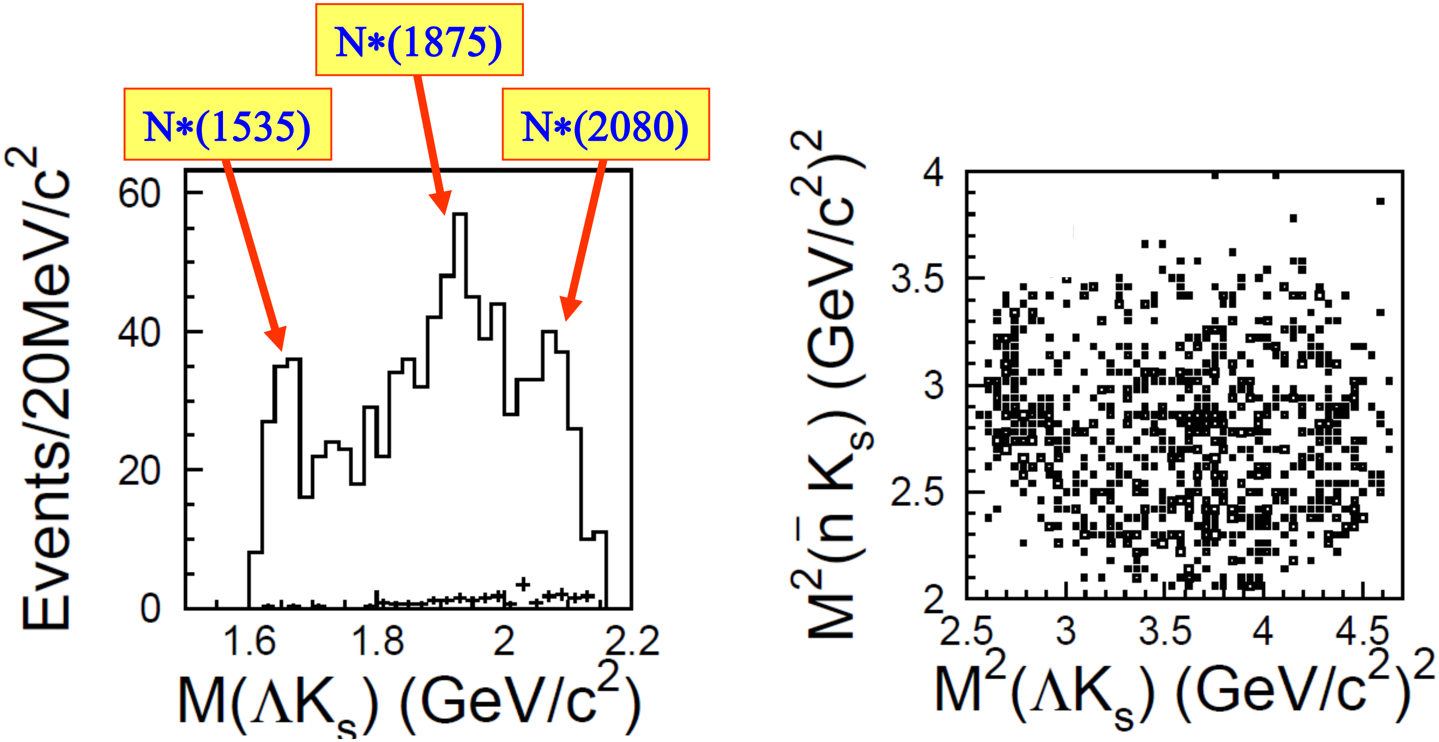


LEPS, PRC73 (2006) 035214



CLAS, PRC89 (2014) 055206

$N_{s\bar{s}}$ penta-quarks at BES ?!



$J/\psi \to nK_S^0\overline{\Lambda}$

BESII, Phys. Lett. B659 (2008) 789

Physics Letters B 709 (2012) 70–76

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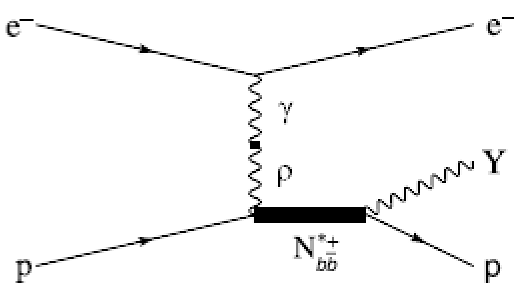
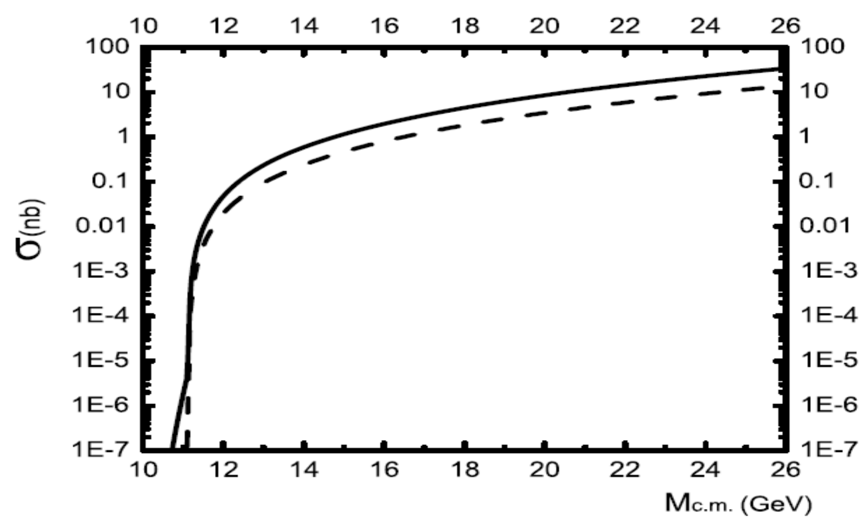
Prediction of super-heavy N^* and Λ^* resonances with hidden beauty

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

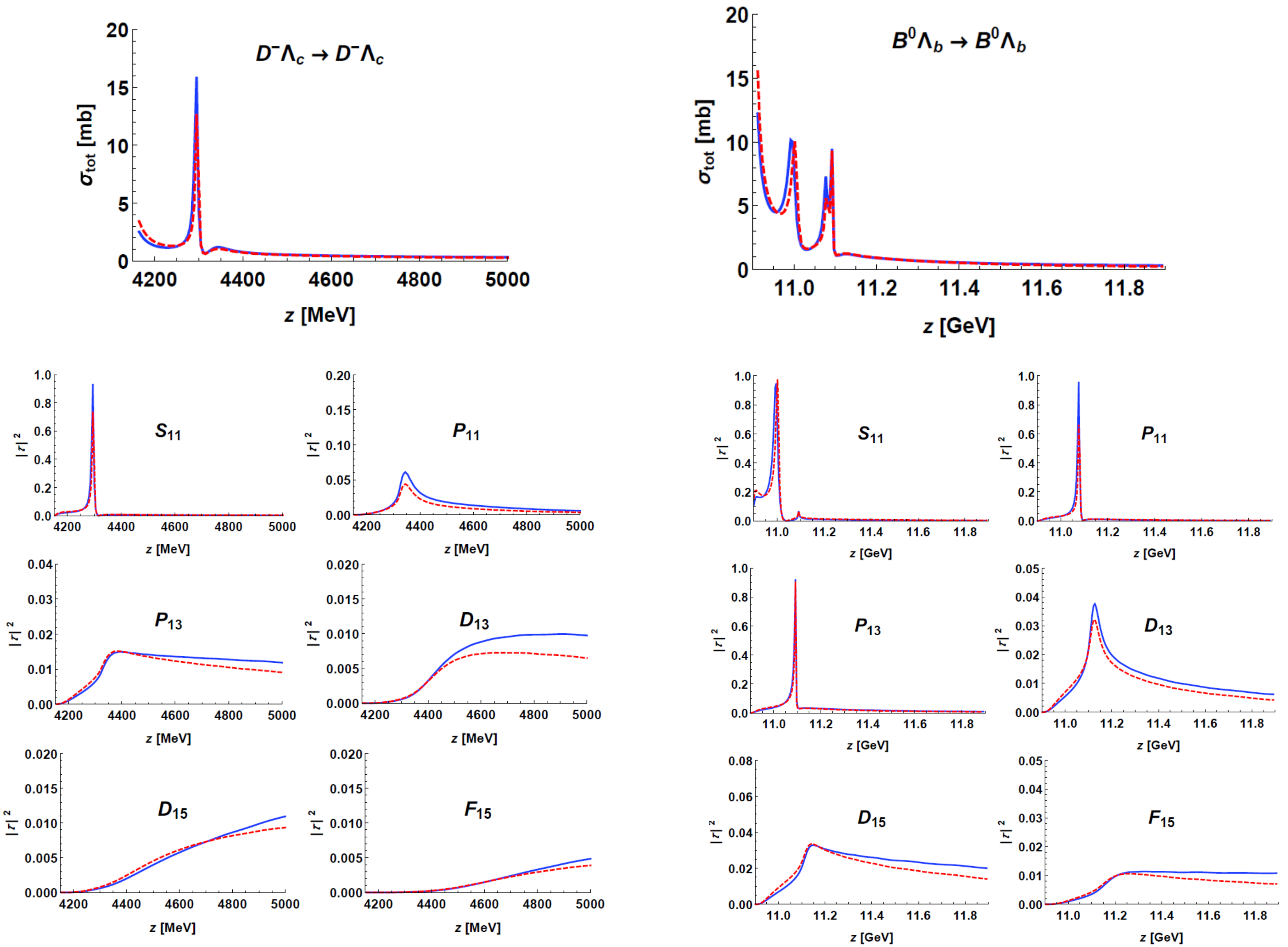
M (MeV)	Γ (MeV)	Γ_i (MeV)					
		πN	ηN	$\eta' N$	$K\Sigma$	$\eta_b N$	
11 052	1.38	0.10	0.21	0.11	0.42	0.52	**$1/2^-$**
		ρN	ωN	$K^*\Sigma$	ΥN		
11 100	1.33	0.09	0.30	0.39	0.51		**$1/2^-$, $3/2^-$**





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

Decay behavior of P_s & P_b pentaquark states

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

Mode	Widths (MeV)		
	$J^P = 3/2^-$		$J^P = 1/2^-$
	$N(1875)\ K\Sigma^*$	$N(2080)\ K^*\Sigma$	$N(2080)\ K^*\Sigma$
$N\sigma(500)$	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

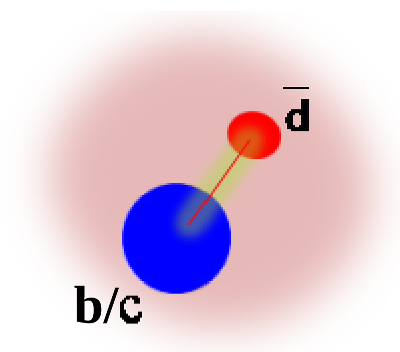
5. Prospects

- **my favorite strategy for hadron spectroscopy:**

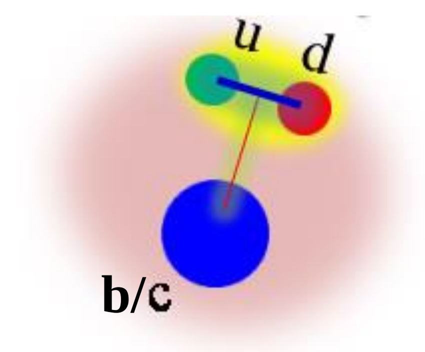
$\bar{c}$cuud & $\bar{c}$cuds → sss - $\bar{q}$qsss → cqq - $\bar{q}$qcqq
→ hyperons → light baryons

$\bar{c}$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

- **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/γp@JLab, π10/K10@JPARC, BelleII, BESIII, Eic/EicC, PANDA@FAIR, STCF etc. may play important role here!

Thank you for your attention!