Hidden charm penta-quarks

Bing-Song Zou
Institute of Theoretical Physics, CAS, Beijing

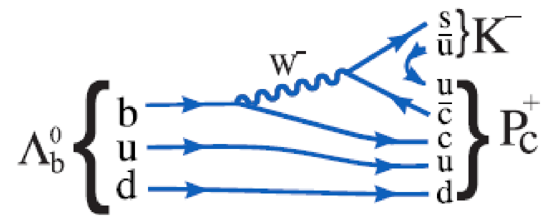
Outline :

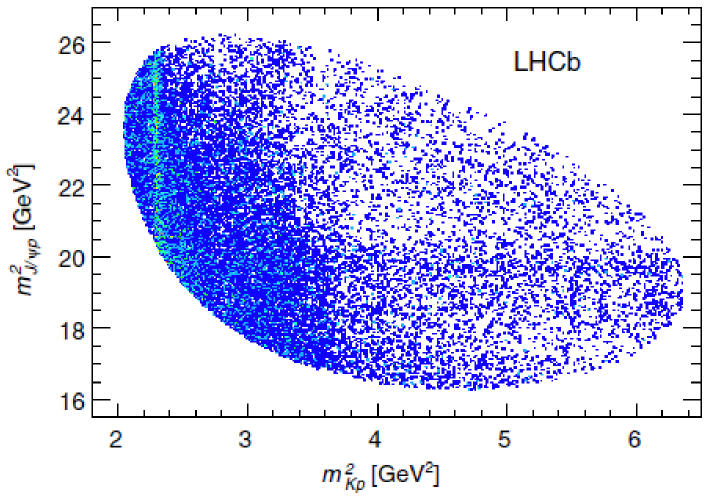
1. **Remarks on LHCb pentaquarks**
2. **Predictions prior to LHCb observation**
3. **Explanations after LHCb observation**
4. **Prospects**

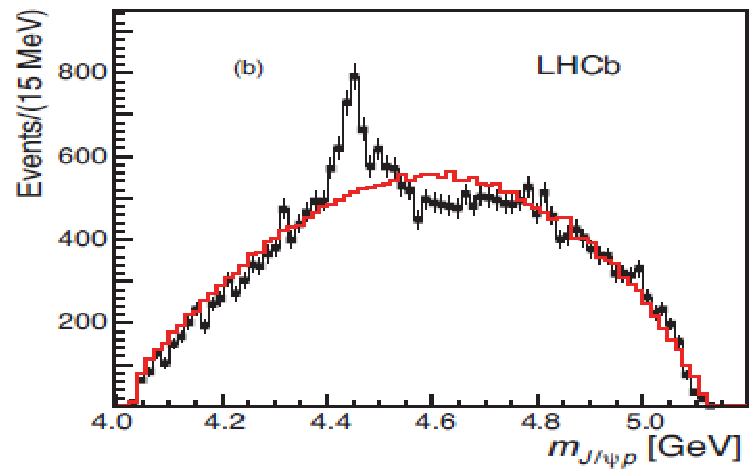
1. Remarks on LHCb penta-quarks

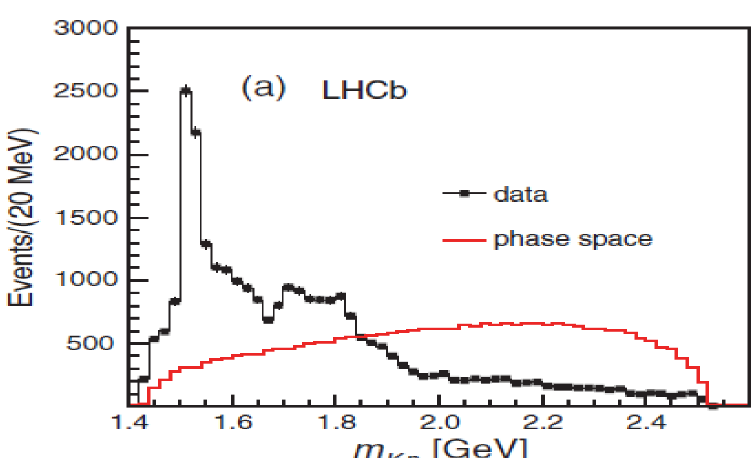
LHCb, Phys.Rev.Lett. 115 (2015) 072001 :

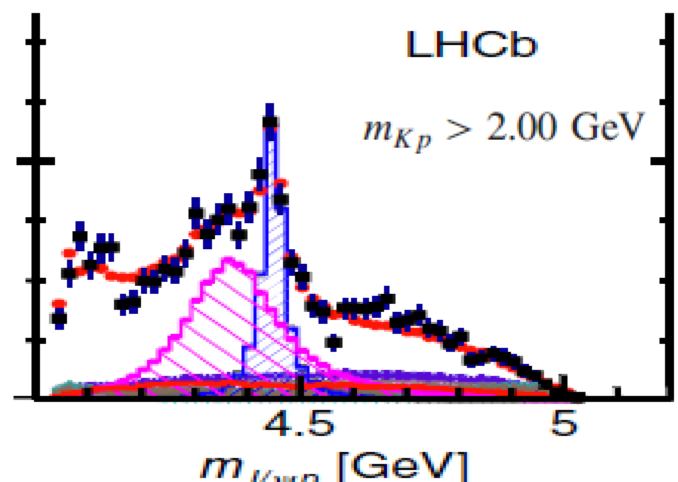
Observation of two N* from $\Lambda_b^0 \to J/\psi K^- p$











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.

Significances $> 9\sigma$ for both P_c^+ states

This opens a new window for studying hadronic dynamics for the multi-quark states

Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

R. Aaij *et al.**
(LHCb Collaboration)

224 citations

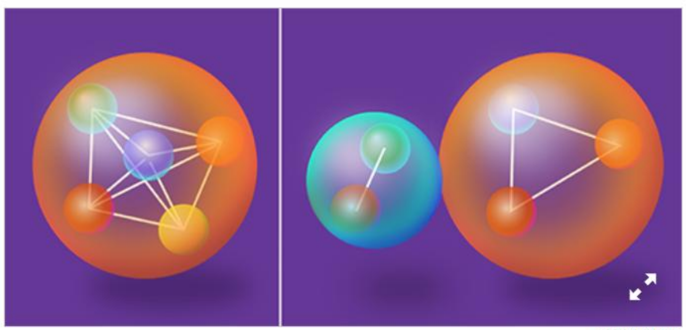
APS physics | Physics

Viewpoint: Elusive Pentaquark Comes into View

Kenneth Hicks, Department of Physics and Astronomy, Ohio University, Athens, OH 45701, USA

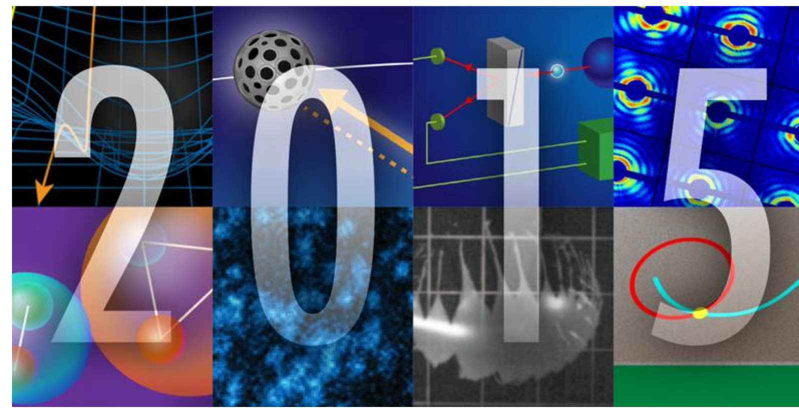
August 12, 2015 • *Physics* 8, 77

A new type of particle containing five quarks has been observed by the LHCb experiment.



APS/Carin Cain

APS: Highlights of the Year 2015

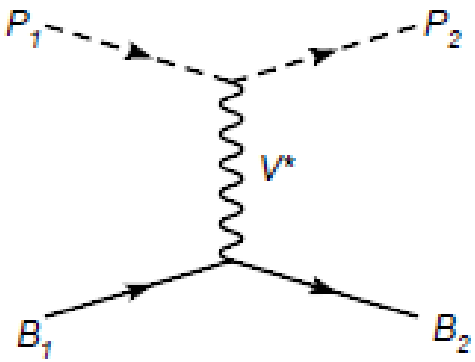


#2. Particle High Five: Observation of 2 penta-quarks by LHCb

For a comprehensive review, cf.:
H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1-121

2. Predictions prior to LHCb observation

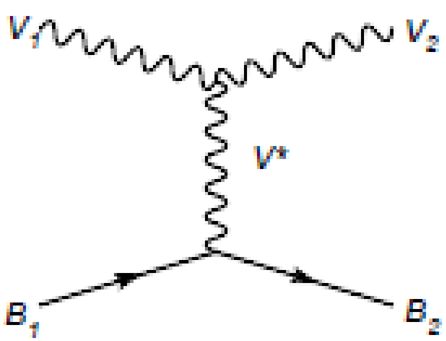
[1] J.J.Wu, R.Molina, E.Oset, B.S.Zou, “Prediction of narrow N* and Λ* resonances with hidden charm above 4 GeV”, PRL105 (2010) 232001; “Dynamically generated N* and Λ* resonances in the hidden charm sector around 4.3 GeV,” PRC84 (2011) 015202



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

$$V_{ab(P_1B_1\to P_2B_2)} = \frac{C_{ab}}{4f^2}(E_{P_1} + E_{P_2}),$$

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



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

KΣ, Kp → $\bar{D}^{(*)}\Sigma_c$, $\bar{D}_s^{(*)}\Lambda_c$ bound states

	(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		
Λ*	$(0,-1)$		$\bar{D}_s\Lambda_c^+$	$\bar{D}\Xi_c$	$\bar{D}\Xi'_c$	
		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 $PB \to PB$.

	(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		
Λ*	$(0,-1)$		$\bar{D}_s^*\Lambda_c^+$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi'_c$	
		4370	1.23	3.14	0	
		4550	0	0	2.53	

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

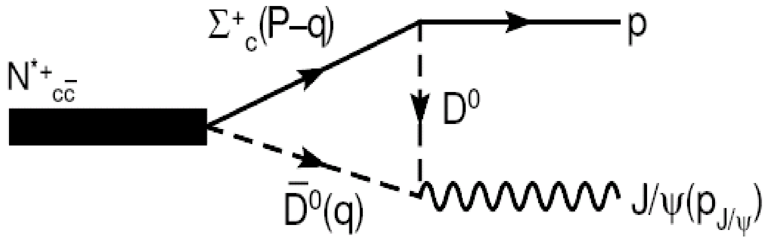
	(I,S)	M	Γ	Γ_i						J^P
N*	$(1/2,0)$			πN	ηN	$\eta' N$	$K\Sigma$		$\eta_c N$	
		4261	56.9	3.8	8.1	3.9	17.0		23.4	$1/2^-$
	$(0,-1)$			$\bar{K}N$	$\pi\Sigma$	$\eta\Lambda$	$\eta'\Lambda$	$K\Xi$	$\eta_c\Lambda$	
Λ*		4209	32.4	15.8	2.9	3.2	1.7	2.4	5.8	
		4394	43.3	0	10.6	7.1	3.3	5.8	16.3	

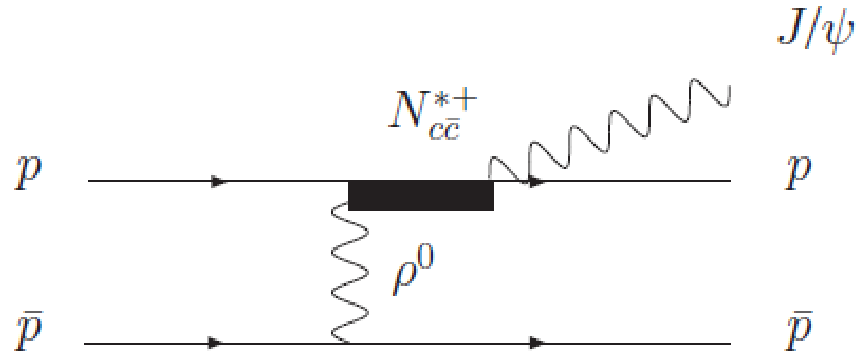
TABLE V: Mass (M), total width (Γ), and the partial decay width (Γ_i) for the states from $PB \to PB$, with units in MeV.

	(I,S)	M	Γ	Γ_i						
N*	$(1/2,0)$			ρN	ωN	$\bar{K}^*\Sigma$			$J/\psi N$	
		4412	47.3	3.2	10.4	13.7			19.2	$1/2^-$, $3/2^-$
	$(0,-1)$			$\bar{K}^*N$	$\rho\Sigma$	$\omega\Lambda$	$\phi\Lambda$	$K^*\Xi$	$J/\psi\Lambda$	
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.

Prediction for PANDA





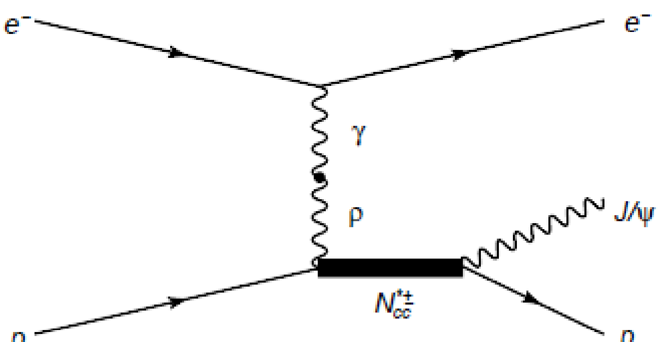
$$\Gamma_{R\to J/\psi p} = 0.01\ \mathrm{MeV},$$

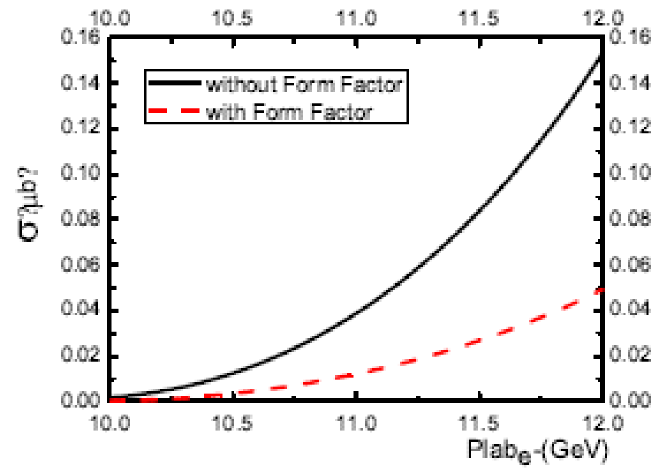
$\bar{p}p \rightarrow \bar{p}pJ/\psi \sim 0.1$ nb

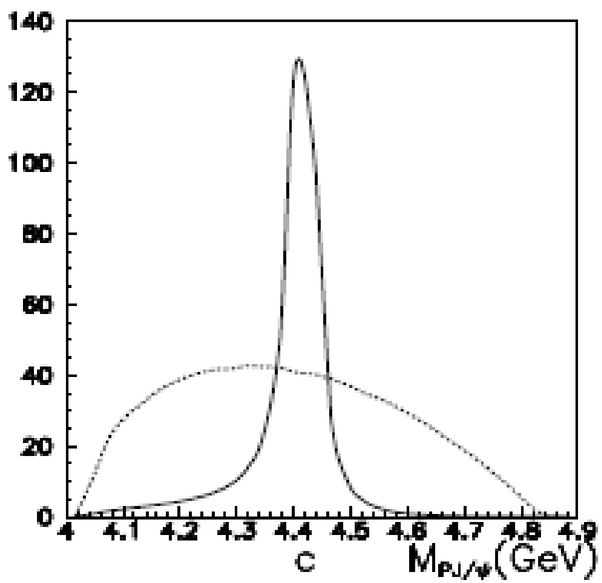
~ 100 events per day at PANDA/FAIR by $L=10^{31}$ $cm^{-2}s^{-1}$

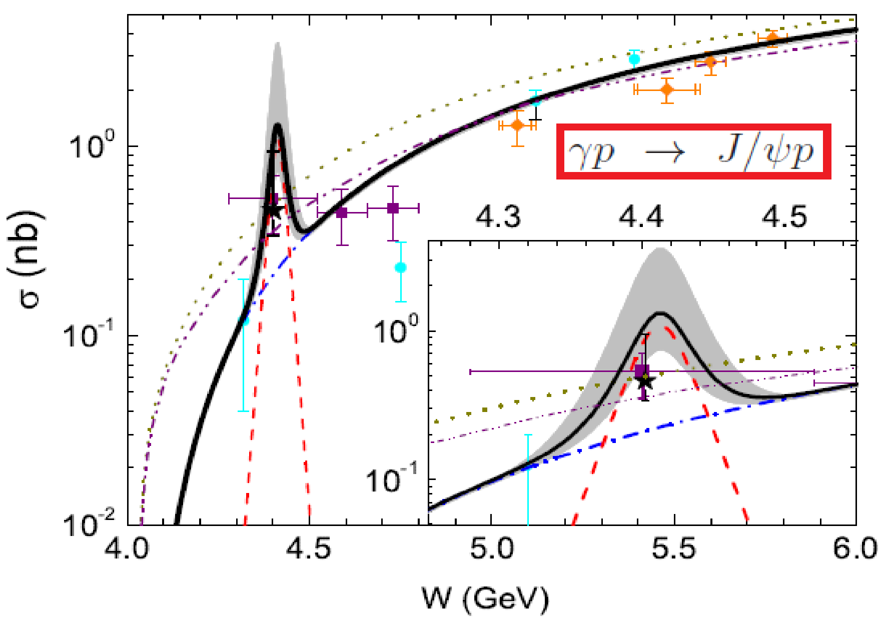
These Super-heavy narrow N* and Λ*
can be found at PANDA !

Prediction for 12GeV@JLab









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

Proposals for looking for $N_{c\bar{c}}$ & $\Lambda_{c\bar{c}}$ with π^-, K beams at JPARC

a) X.Y.Wang, X.R.Chen, "The production of hidden charm baryon N*4261) from $\pi^- p \rightarrow \eta_c n$ reaction", EPL109 (2015) 41001.

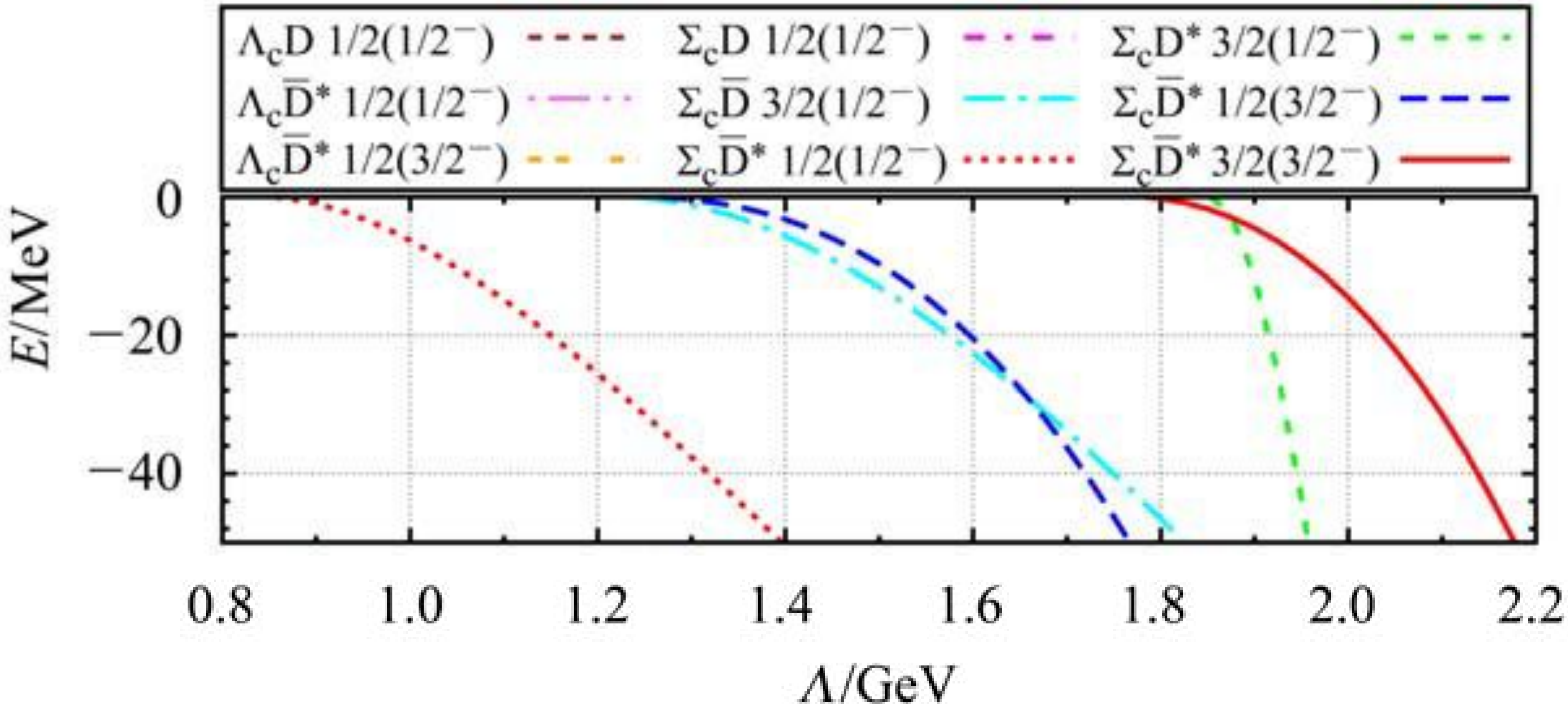
b) E.J.Garzon, J.J.Xie, "Effects of a $N_{c\bar{c}}$ resonance with hidden charm in the $\pi^- p \rightarrow D^- \Sigma_c^+$ reaction near threshold", PRC 92 (2015) 035201

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

[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 π, η, ρ, ω, σ 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

Hidden charm N* above 4 GeV decaying to pJ/ψ are supported by other approaches

$\bar{D}\Sigma_c$ 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

[4] 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	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$
$\frac{1}{2}^-$	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	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	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$
$\frac{1}{2}^+$	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	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

LHCb pentaquark states   vs   Predictions

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

Problems:

1) $P_c^+(4380)$ -- larger decay width than prediction

2) mass deference of $P_c\,(5/2^+)$ & $P_c\,(3/2^-)$ too small

3) Where are lower $P_c\,(1/2^-)$ states ?

3. Explanations after LHCb observation

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

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

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

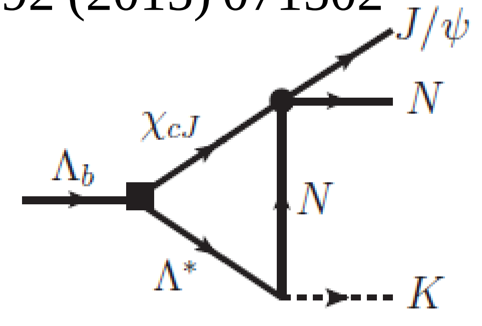
2) diquark *cu* & triquark $\bar{c}(ud)$ states

L.Maiani, A.D.Polosa, V. Riquer, PLB749 (2015) 289;
R.Lebed, PLB749 (2015) 454;
G.N.Li, M.He, X.G.He, JHEP 1512 (2015) 128;
R.Zhu, C.F.Qiao, PLB756 (2016) 259;

3) Kinematic triangle-singularity

F.K.Guo, Ulf-G.Meißner, W.Wang, Z.Yang, PRD92 (2015) 071502
X.H.Liu, Q.Wang, Q.Zhao, PLB757 (2016) 231

→ talk by Qiang Zhao



$\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$ 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] H.X.Chen, W.Chen, X.Liu, T.G.Steele, S.L.Zhu, PRL115 (2015)172001

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

[3] J.He, PLB 753 (2016)547 ; arXiv:1607.03223

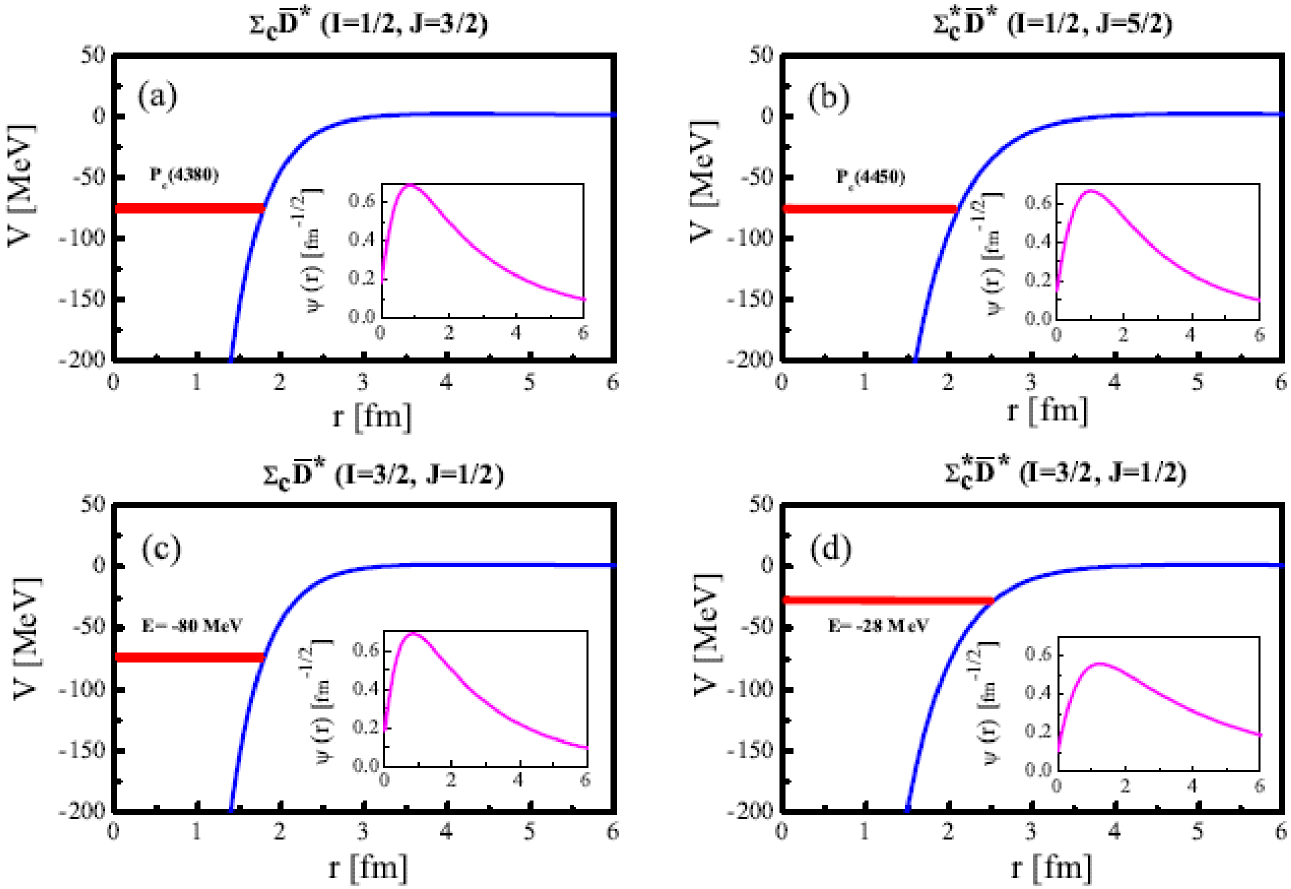
$P_c^+(4380)$ -- $\bar{D}\Sigma_c^*/\ \bar{D}^*\Sigma_c$ $3/2^-$; $P_c^+(4450)$ -- $\bar{D}^*\Sigma_c$ $5/2^+$

[4] Y.Yamaguchi, E. Santopinto, arXiv:1606.08330;

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

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

OPE: Prediction of I=3/2 pentaquarks !



[4] Y.Yamaguchi, E. Santopinto, arXiv:1606.08330

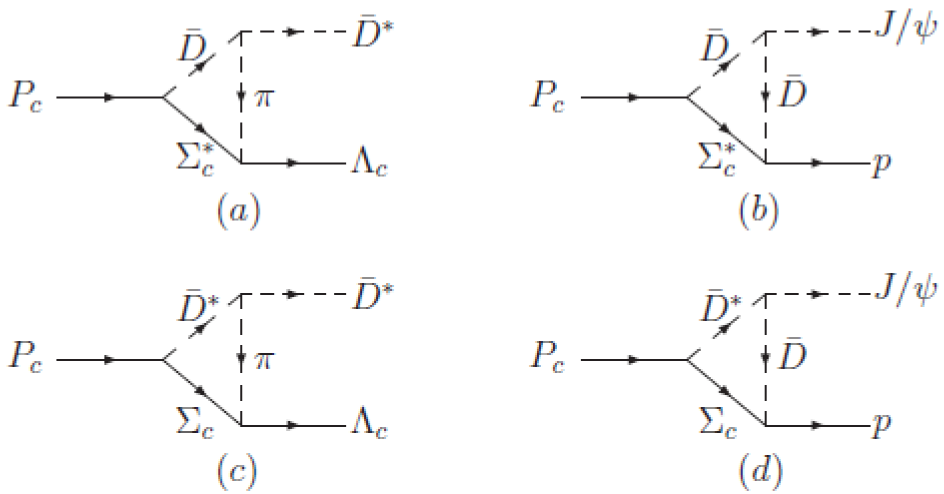
Prediction of a few more J=3/2 pentaquarks !

Λ [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
	$4363.3 - i57.0$	$4339.7 - i26.8$	$4311.8 - i6.6$	$4268.5 - i1.3$
$J^P = 5/2^-$	—	$4428.6 - i89.1$	$4391.7 - i88.8$	$4338.2 - i56.2$
$J^P = 5/2^+$	—	—	$4368.0 - i9.2$	$4305.8 - i1.9$
	—	—	—	—

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

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

C.W.Shen, F.K.Guo, J.J.Xie, B.S.Zou, NPA 954(2016)393



$$\frac{\Gamma(P_c(4380) \to \bar{D}^*\Sigma_c \to \bar{D}^*\Lambda_c)}{\Gamma(P_c(4380) \to \bar{D}^*\Sigma_c \to J/\psi p)} \sim 20$$

$$\frac{\Gamma(P_c(4380) \to \bar{D}\Sigma_c^* \to \bar{D}^*\Lambda_c)}{\Gamma(P_c(4380) \to \bar{D}\Sigma_c^* \to J/\psi p)} \sim 1$$

Natural explanation for the larger decay width of $P_c^+(4380)$

Preliminary partial decay widths of $P_c^+(4380)$

C.W.Shen, F.K.Guo, B.S.Zou, in preparation

		$P_c(\bar{D}\Sigma_c^*)$	$P_c(\bar{D}^*\Sigma_c)$
	Exchange Meson	Γ_1	Γ_2
$\bar{D}^*\Lambda_c$	π	90.0	4.2
$\bar{D}^*\Lambda_c$	ρ	25.7	13.1
$J/\psi p$	D	4.3	0.1
$J/\psi p$	D^*	0.7	18.2
$\bar{D}\Lambda_c$	ρ/π	1.5	12.2
πp	D^*/D	15.9	9.3
$\chi_{c0}p$	D/D^*	1.6	0.003
$\eta_c p$	D^*/D	1.7	0.9
$\bar{D}\pi\Lambda_c$		7.3	0
$Total$		148.7	58.0

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 $\bar{D}^*\Sigma_c$ $(3/2^-$ or $5/2^+)$ molecule

Problems:

1) **Where are lower** $P_c\,(1/2^-)$ states ?

2) **Where are predicted** $\Lambda_{c\bar{c}}$ states ?

Many more pentaquarks are expected !

4. Prospects

- **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.**

  π10/K10@JPARC , BelleII may play important role here!

- **Systematic theoretical study of the penta-quark spectroscopy**

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

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

Thanks !