Hadron Spectroscopy from strangeness to charm and beauty @HYP2012

Hadron Spectroscopy from production and decay of Λ_c & Λ_b

@HYP2018

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Outline :

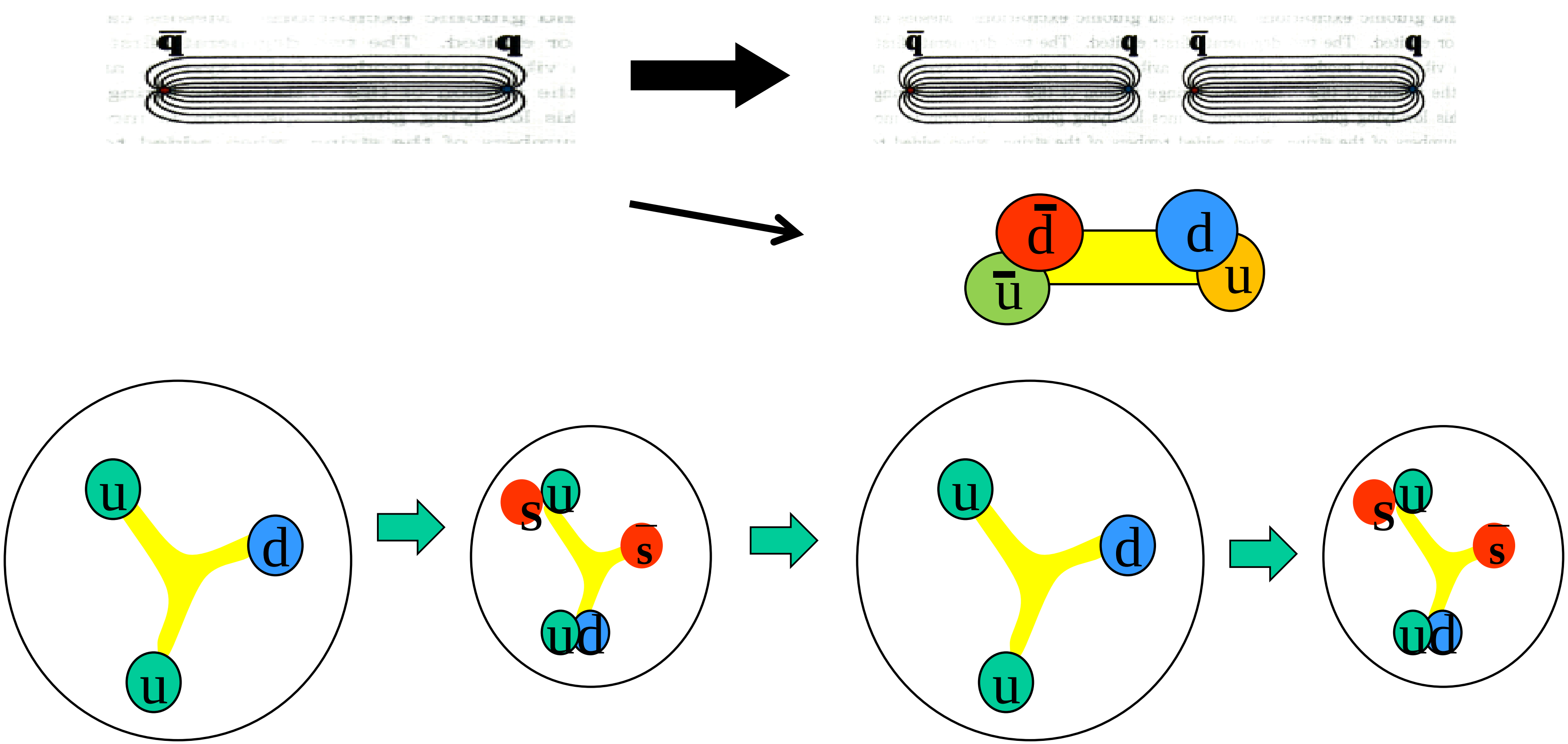
1. Hadron spectroscopy from strangeness to charm & beauty
2. Hadron spectroscopy from decay of Λ_c & Λ_b
3. from production of Λ_c & Λ_b
4. Prospects

1. Hadron spectroscopy from s to c & b

Key problem in hadron spectroscopy:

Unquenching dynamics: gluons → $\bar{q}q$

crucial for quark confinement & hadron structure



quenched or unquenched quark models give very different hadron spectrum with strangeness

$1/2^+$ baryon octet with strangeness

uss (L=0) ~ Ξ(1320)
uus (L=0) ~ Σ(1189) → quenched quark model
uds (L=0) ~ Λ(1115)
uud (L=0) ~ N(938)

$1/2^-$ baryon nonet with strangeness

- Mass & decay pattern : quenched or unquenched ?

uds (L=1) $1/2^-$ ~ Λ*(1670) ~ [us][ds] $\bar{s}$
uud (L=1) $1/2^-$ ~ N*(1535) ~ [ud][us] $\bar{s}$
uds (L=1) $1/2^-$ ~ Λ*(1405) ~ [ud][su] $\bar{u}$
uus (L=1) $1/2^-$ ~ Σ*(1390) ~ [us][ud] $\bar{d}$

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

From strangeness to charm & beauty

Many N* & Λ* are proposed dynamically generated states and multi-quark states

Problem:

None of them can be clearly distinguished from qqq due to tunable ingredients and possible large mixing of various configurations

PDG2010: "The clean Λ_c spectrum has in fact been taken to settle the decades-long discussion about the nature of the Λ(1405) —true 3-quark state or mere $\bar{K}N$ threshold effect?— unambiguously in favor of the first interpretation."

although Λ_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) $\bar{s}suud$

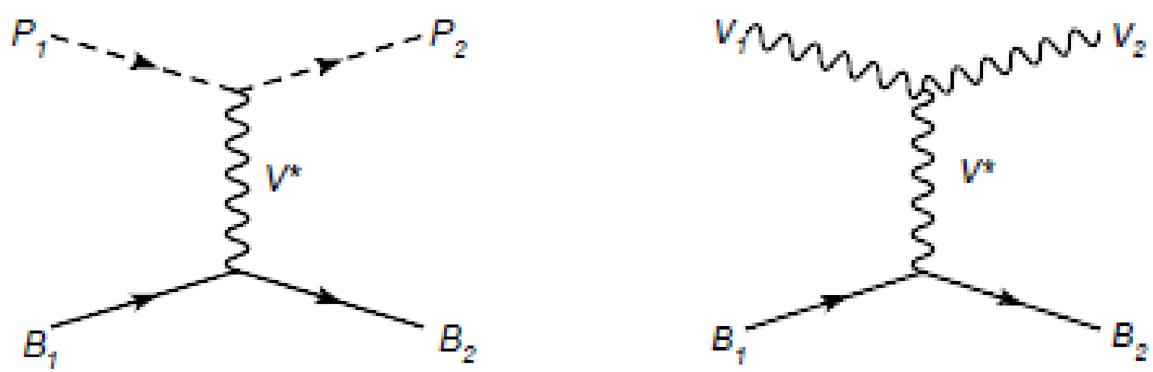
N*(4260) $\bar{c}cuud$ J.J.Wu, R.Molina, E.Oset, B.S.Zou, Phys.Rev.Lett. 105 (2010) 232001

N*(11050) $\bar{b}buud$ J.J.Wu, L.Zhao, B.S.Zou, PLB709(2012)70

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



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

	(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	$K^*\Sigma$			$J/\psi N$	
		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.

Super-heavy narrow N* and Λ* with hidden charm

Definitely not qqq states !

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

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

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

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

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

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

Z.C.Yang, Z.F. Sun, J. He, X.Liu, S.L.Zhu, CPC36(2012)6

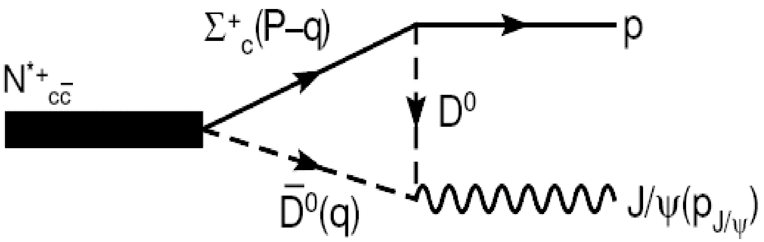
$\bar{c}cqqq$ with 3 kinds of qq hyperfine interaction ~ 4.3 GeV

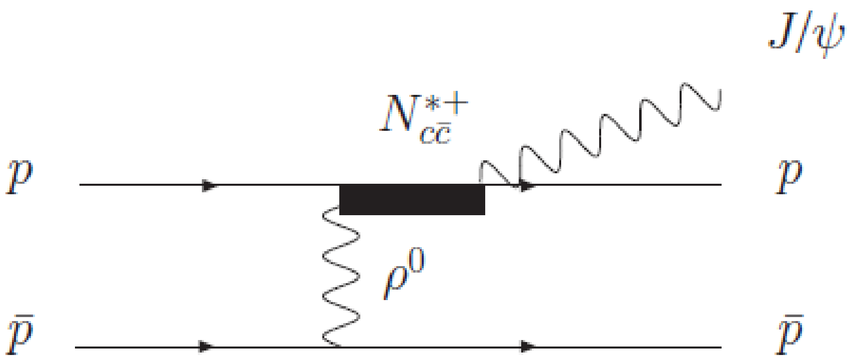
S.G.Yuan, K.W.Wei, J.He, H.S.Xu, B.S.Zou, EPJA48(2012)61

$\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$ states with $J^P = 3/2^-$ ~ 4.4 GeV

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

Prediction for PANDA





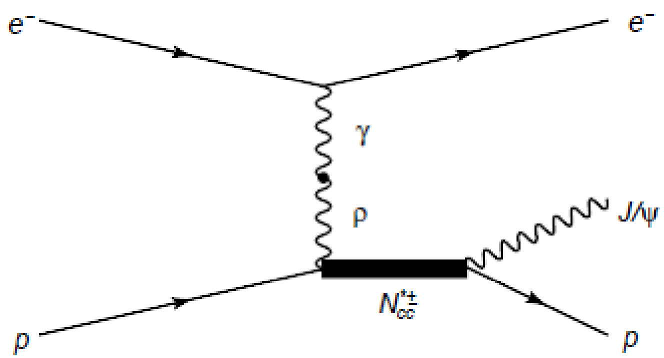
$\bar{p}p \rightarrow \bar{p}pJ/\psi$ > 0.1 nb

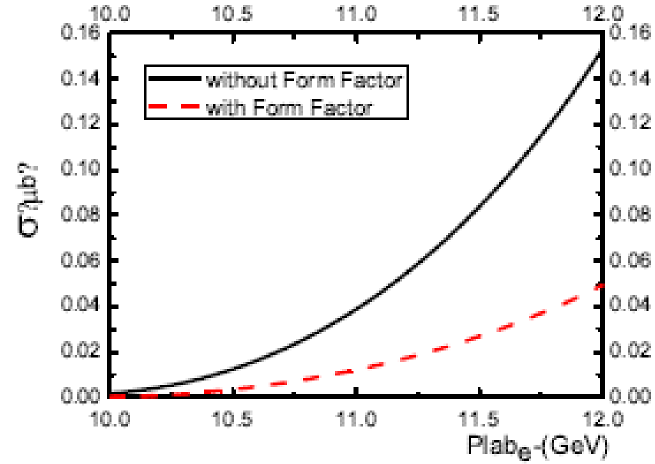
> 100 events per day at PANDA/FAIR by $L=10^{31}$ $cm^{-2}s^{-1}$

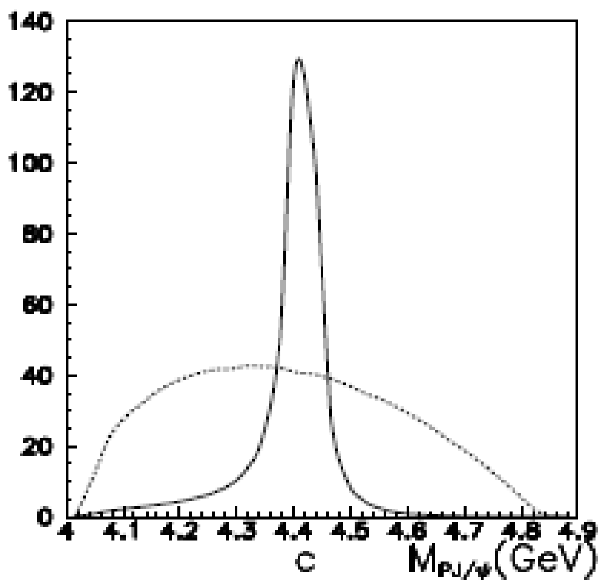
These Super-heavy narrow N* and Λ* can be found at PANDA !

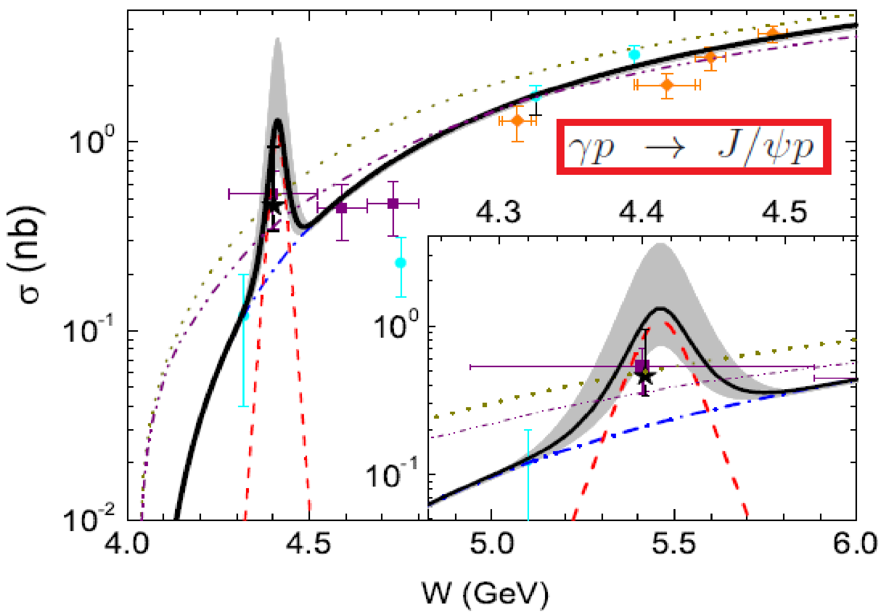
Albrecht Gillitzer@Juelich had a plan to find them at PANDA

Prediction for 12GeV@JLab









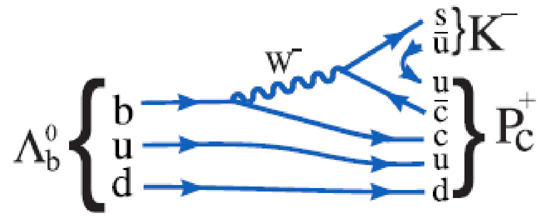
Y. Huang, J.He, H.F.Zhang and X.R.Chen, JPG41, 115004 (2014)

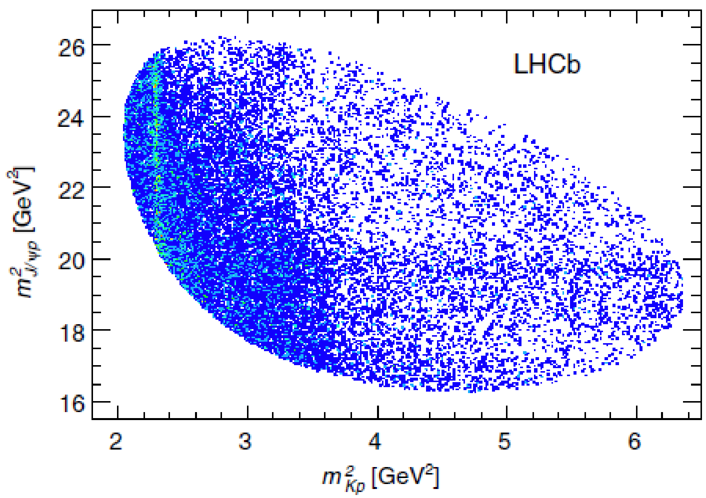
2. Hadron spectroscopy from decay of Λ_c & Λ_b

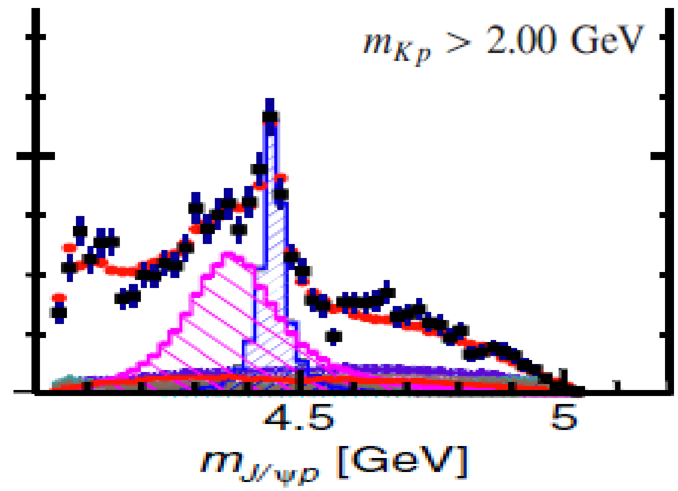
LHCb, Phys.Rev.Lett. 115 (2015) 072001 :

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

598 cites - the top cited paper on HS since 2010







1) **4380±8±29 MeV , 205±18±86 MeV, $P_c^+(4380)$**

2) **4450±2±3 MeV , 39±5±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.

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

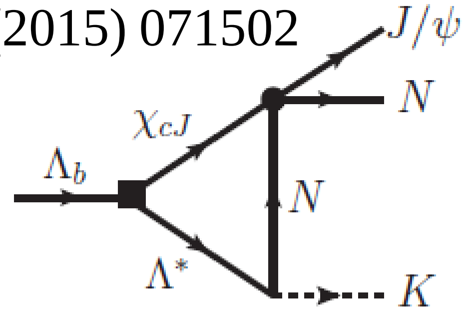
R.Chen, X.Liu, X.Q.Li, S.L.Zhu, PRL115 (2015) 132002;
H.X.Chen, W.Chen, X.Liu, T.G.Steele, S.L.Zhu, PRL115 (2015)172001
L.Roca, J.Nieves, E.Oset, PRD92 (2015) 094003;
J.He, PLB 753 (2016)547 ;

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.Mei ßner, 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;

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

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

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

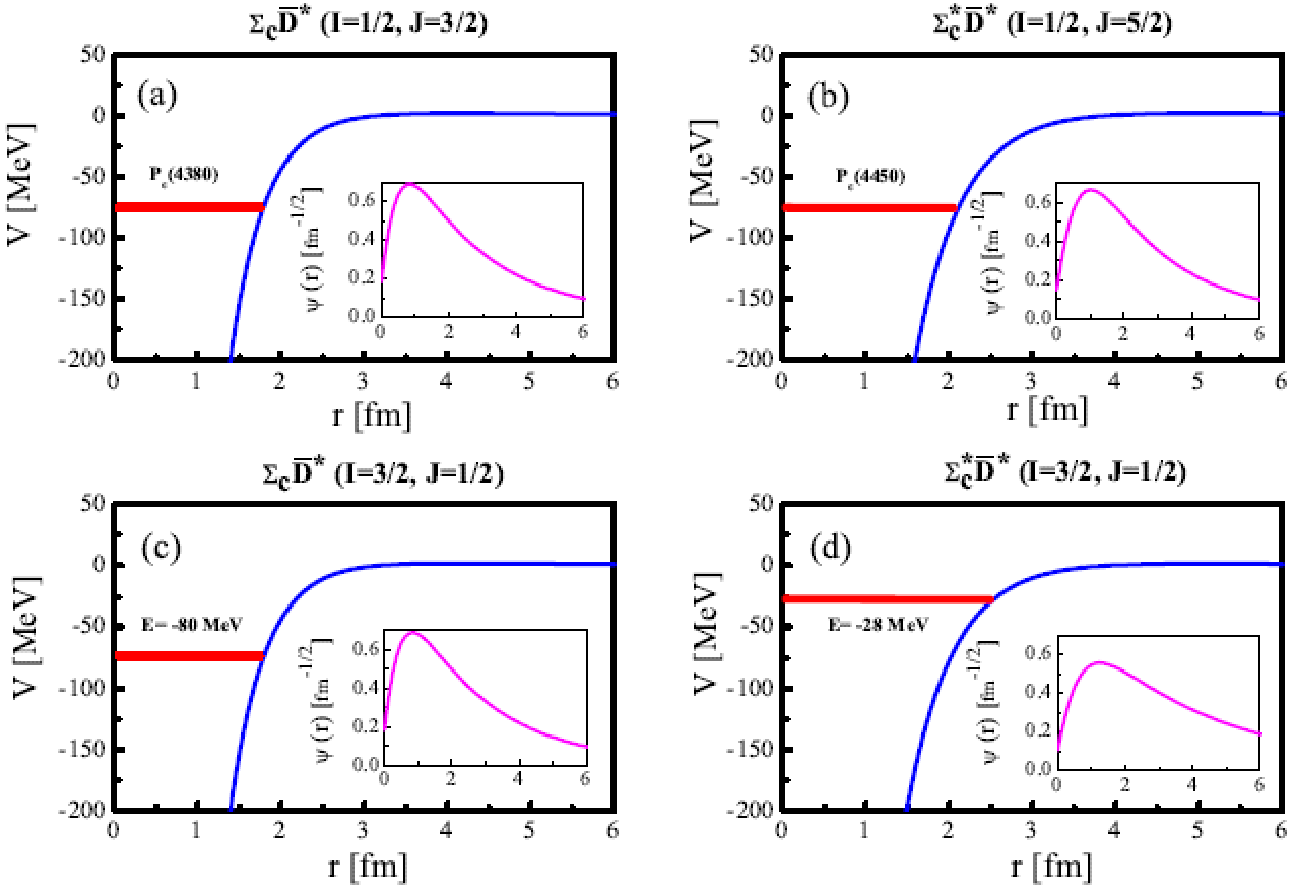
[3] J.He, PLB 753 (2016)547 ; PRD95 (2017)074004
Y.H.Lin, C.W.Shen, F.K.Guo, B.S.Zou, PRD95(2017)114017

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

→ **Different predictions to be checked !**

[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

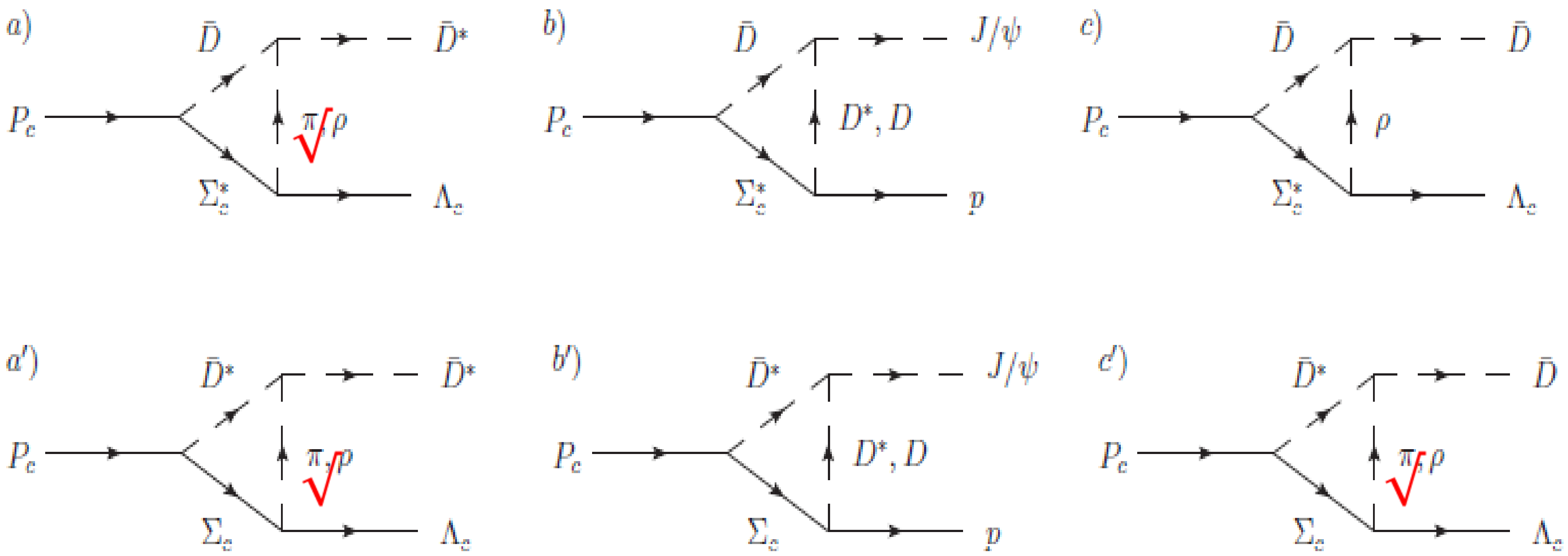
Prediction of a few more J=3/2 pentaquarks !

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 $P_c^+(4380)$

[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 $P_c^+(4380)$ & $P_c^+(4450)$

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

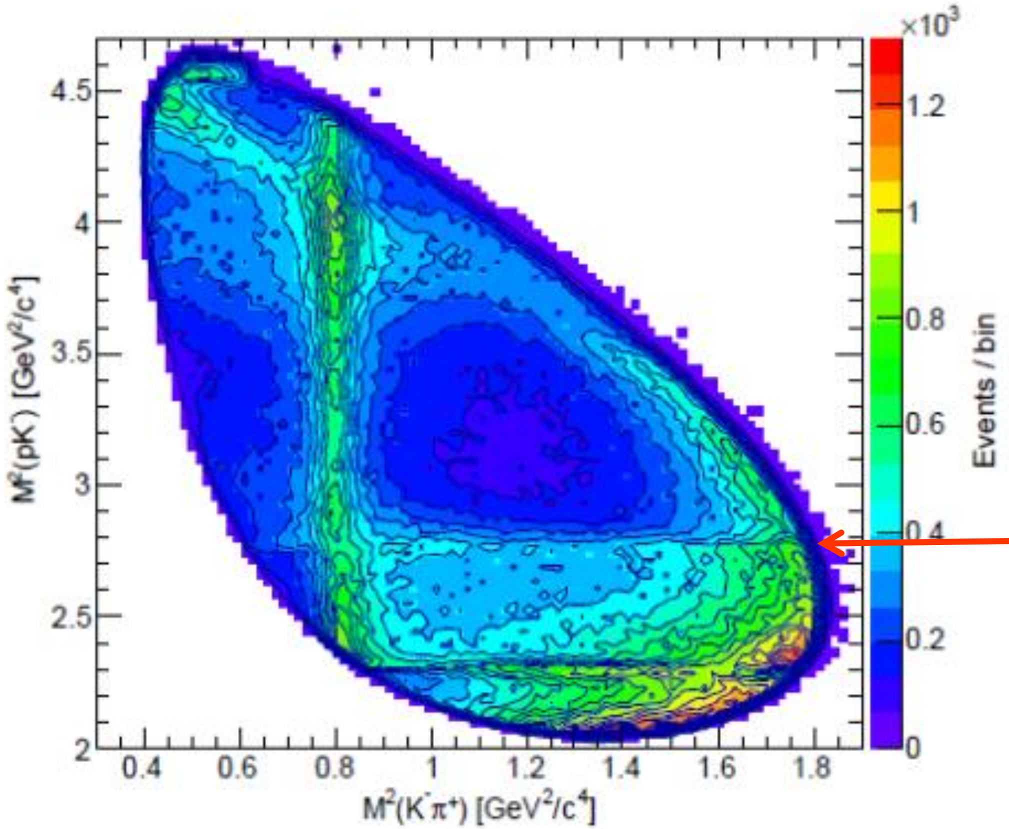
$\Lambda_b(5620)$ decays : a new source for P_c & Λ_c* & Σ_c*

Γ_4	$pD^0\pi^-$		$(6.3 \pm 0.7) \times 10^{-4}$		2370
Γ_5	$\Lambda_c(2860)^+\pi^-$, $\Lambda_c^+ \to D^0 p$				2017
Γ_6	$\Lambda_c(2880)^+\pi^-$, $\Lambda_c^+ \to D^0 p$				
Γ_7	$\Lambda_c(2940)^+\pi^-$, $\Lambda_c^+ \to D^0 p$				
Γ_8	$pD^0 K^-$		$(4.6 \pm 0.8) \times 10^{-5}$		2269
Γ_9	$pJ/\psi\pi^-$		$(2.6^{+0.5}_{-0.4}) \times 10^{-5}$		1755
Γ_{10}	$p\pi^- J/\psi$, $J/\psi \to \mu^+\mu^-$		$(1.6 \pm 0.8) \times 10^{-6}$		
Γ_{11}	$pJ/\psi K^-$		$(3.2^{+0.6}_{-0.5}) \times 10^{-4}$		1589
Γ_{12}	$P_c(4380)^+ K^-$, $P_c \to pJ/\psi$	[1]	$(2.7 \pm 1.4) \times 10^{-5}$		2015
Γ_{13}	$P_c(4450)^+ K^-$, $P_c \to pJ/\psi$	[1]	$(1.3 \pm 0.4) \times 10^{-5}$		
Γ_{14}	$\chi_{c1}(1P)pK^-$		$(7.6^{+1.5}_{-1.3}) \times 10^{-5}$		1242
Γ_{15}	$\chi_{c2}(1P)pK^-$		$(7.9^{+1.6}_{-1.4}) \times 10^{-5}$		1198
Γ_{16}	$pJ/\psi(1S)\pi^+\pi^- K^-$		$(6.6^{+1.3}_{-1.1}) \times 10^{-5}$		1410
Γ_{17}	$p\psi(2S)K^-$		$(6.6^{+1.2}_{-1.0}) \times 10^{-5}$		1063
Γ_{18}	$p\overline{K}^0\pi^-$		$(1.3 \pm 0.4) \times 10^{-5}$		2693
Γ_{19}	$pK^0 K^-$		$< 3.5 \times 10^{-6}$	CL=90%	2639

New source for Λ_b better than LHCb is expected from EIC !

new $\Lambda^*(1670)3/2^-$ with width of 1.5 MeV $[ud]\{ss\}\ \bar{s}$

from $K^- p \to \Lambda\eta$ Liu&Xie, PRC86(2012)055202



$\Lambda(1670)\ 3/2^-$?

Belle: $\Lambda_c^+ \to p\ K^-\ \pi^+$, PRL117 (2016) 011801

May be checked by BelleII & BESIII on $\Lambda_c^+ \to \Lambda\eta\ \pi^+$

$3/2^-$ baryon nonet with strangeness

- Mass pattern : quenched or unquenched ?

uds (L=1) $3/2^-$ ~ $\Lambda^*(1670)$ ~ [ud]{ss} $\bar{s}$

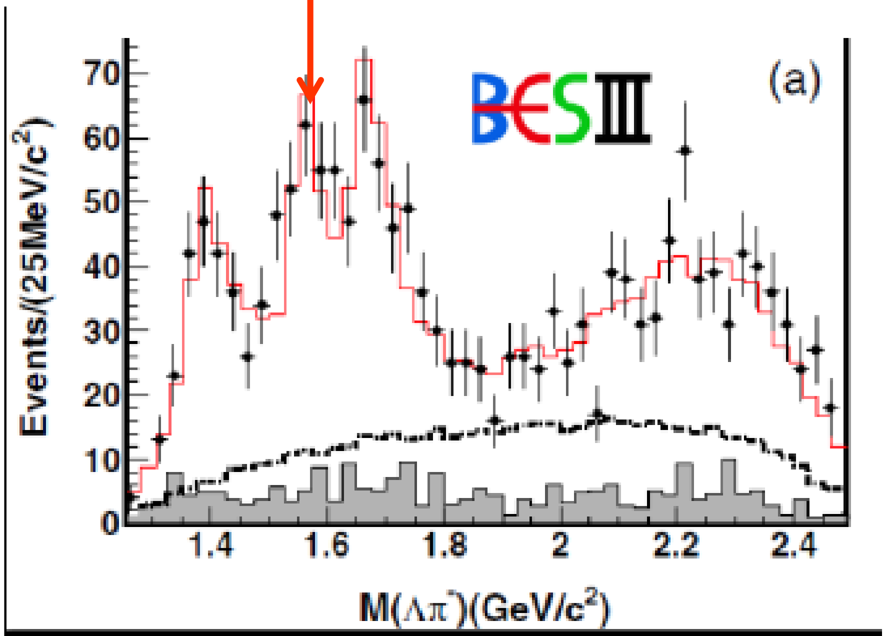
uud (L=1) $3/2^-$ ~ N*(1520) ~ [ud]{uq} $\bar{q}$

uds (L=1) $3/2^-$ ~ $\Lambda^*(1520)$ ~ [ud]{sq} $\bar{q}$

uus (L=1) $3/2^-$ ~ $\Sigma^*(1540)$ ~ [ud]{sq} $\bar{q}$

$\Sigma(1580)\ 3/2^-$

BESIII, PRD88 (2013) 112007



Shi&Zou, PRC91(2015) 035202 :
possible new $\Sigma^*(1542)3/2^-$
in $K^-p \rightarrow \pi^0\Lambda$

Λ_c(2286) decays: a new source for N* & Λ* & Σ* & Ξ*

Γ_2	$pK^-\pi^+$	$(6.23 \pm 0.33)\%$
Γ_8	$nK^0_S\,\pi^+$	$(1.82 \pm 0.25)\%$
Γ_9	$p\overline{K}^0\eta$	$(1.6 \pm 0.4)\%$
Γ_{29}	$\Lambda\pi^+\pi^0$	$(7.0 \pm 0.4)\%$
Γ_{38}	$\Lambda\pi^+\eta$	$(2.2 \pm 0.5)\%$
Γ_{42}	$\Lambda K^+\overline{K}^0$	$(5.6 \pm 1.1) \times 10^{-3}$
Γ_{43}	$\Xi(1690)^0 K^+$, $\Xi^{*0} \to \Lambda\overline{K}^0$	$(1.6 \pm 0.5) \times 10^{-3}$
Γ_{47}	$\Sigma^+\pi^+\pi^-$	$(4.42 \pm 0.28)\%$

Many interesting channels for Λ(1405), Σ(1390), N*(1535), …
from Belle, BESIII, GlueX…

J.J.Xie et al., PRD95 (2017) 074024; PRD96 (2017)054009

3. Hadron spectroscopy from production of Λ_c & Λ_b

$\bar{D}^{(*)}\Lambda_c$ & $B^{(*)}\Lambda_b$: most favored decay modes of P_c & P_b pentaquarks !

Decay Mode	Widths (MeV) $P_c(4380)$ $\bar{D}\Sigma_c^*(\frac{3}{2}^-)$	$P_c(4380)$ $\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$P_c(4450)$ $\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$P_c(4450)$ $\bar{D}^*\Sigma_c(\frac{5}{2}^+)$
$\bar{D}^*\Lambda_c$	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

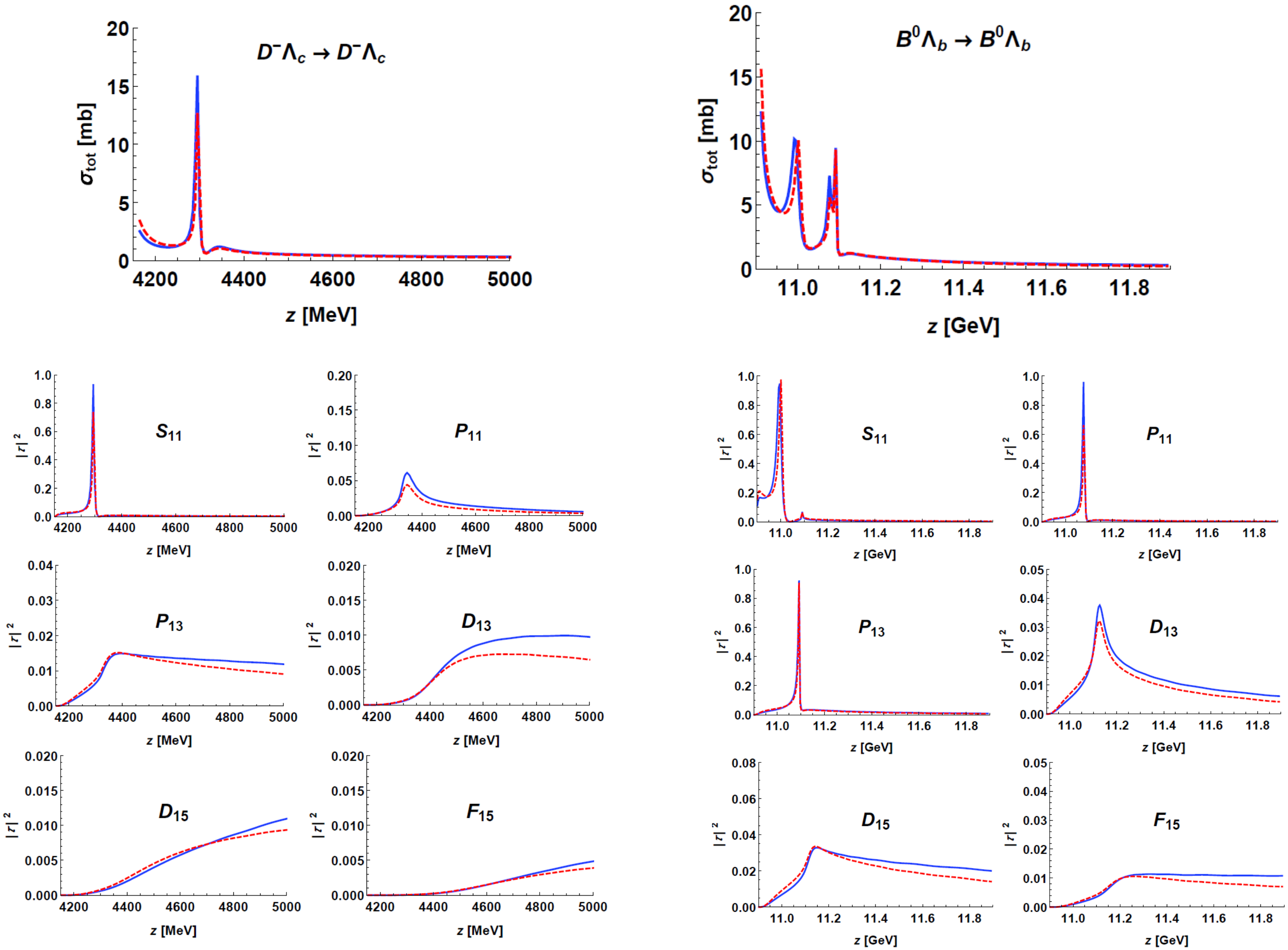
Mode	Widths (MeV) $J^P = 3/2^-$ $B\Sigma_b^*$	$J^P = 3/2^-$ $B^*\Sigma_b$	$J^P = 1/2^-$ $B^*\Sigma_b$
$B^*\Lambda_b$	271.1	19.9	167.0
Υp	0.3	0.04	0.1
ρN	5.5	0.02	0.1
ωp	20.9	0.07	0.4
$B\Lambda_b$	-	7.3	135.9
$B\Sigma_b$	-	-	-
$\eta_b p$	0.02	0.0001	0.0009
$\chi_{b0} p$	1.4	0.0008	0.2
πN	0.7	0.005	0.003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

Y.H.Lin, C.W.Shen, F.K.Guo, B.S.Zou, PRD95(2017)114017
Y.H.Lin, C.W.Shen, B.S.Zou, ArXiv: 1805.06843

γp, πp → $N_{c\bar{c}}$ / $N_{b\bar{b}}$ → $\bar{D}^{(*)}\Lambda_c$ / $B^{(*)}\Lambda_b$: best places to look for them !

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

Best places for looking for $N_{c\bar{c}}$, $N_{b\bar{b}}$ & $\Lambda_{c\bar{c}}$, $\Lambda_{b\bar{b}}$ pentaquarks:

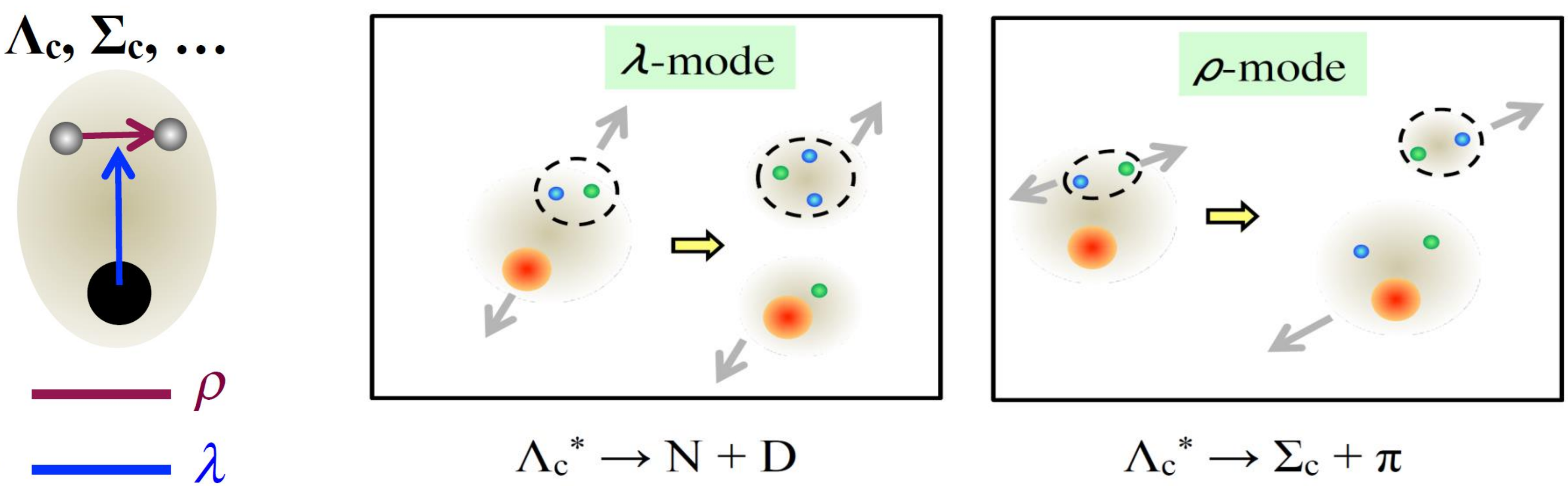
$\gamma p, \pi p \rightarrow N_{c\bar{c}} / N_{b\bar{b}} \rightarrow \bar{D}^{(*)}\Lambda_c / B^{(*)}\Lambda_b$, $J/\psi p$, $\eta_c p$, Υp, $\eta_b p$

$K^- p \rightarrow \Lambda_{c\bar{c}} / \Lambda_{b\bar{b}} \rightarrow \bar{D}_s^{(*)}\Lambda_c / B_s^{(*)}\Lambda_b$, $J/\psi\Lambda$, $\eta_c\Lambda$, $\Upsilon\Lambda$, $\eta_b\Lambda$

Best places for looking for rich Λ_c^*, Σ_c^*, Λ_b^*, Σ_b^* spectra:

$\gamma p, \pi p, K^- p, e^+e^- \rightarrow \Lambda_c X_1 X_2, \Lambda_b X_1 X_2$

A.Hosaka et al., NPA954 (2016) 341: “Production and decay of charmed baryons” → internal structure of Λ_c^*



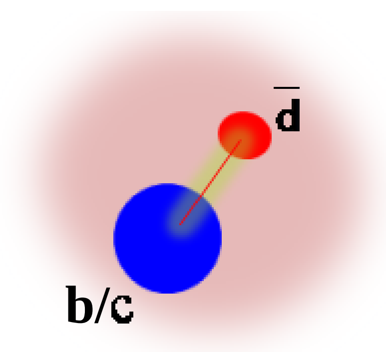
4. Prospects

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

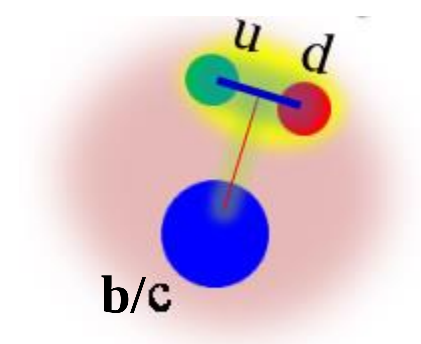
$\bar{c}cuud$ & $\bar{c}cuds$ → sss - $\bar{q}qsss$ → cqq - $\bar{q}qcqq$
→ hyperons → light baryons

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

s → c → b



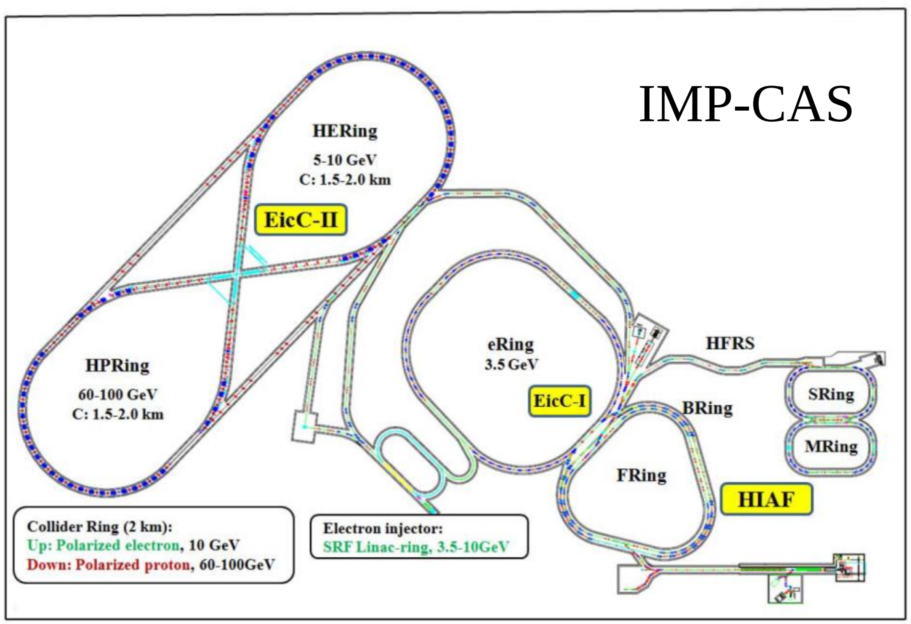
charm & beauty meson

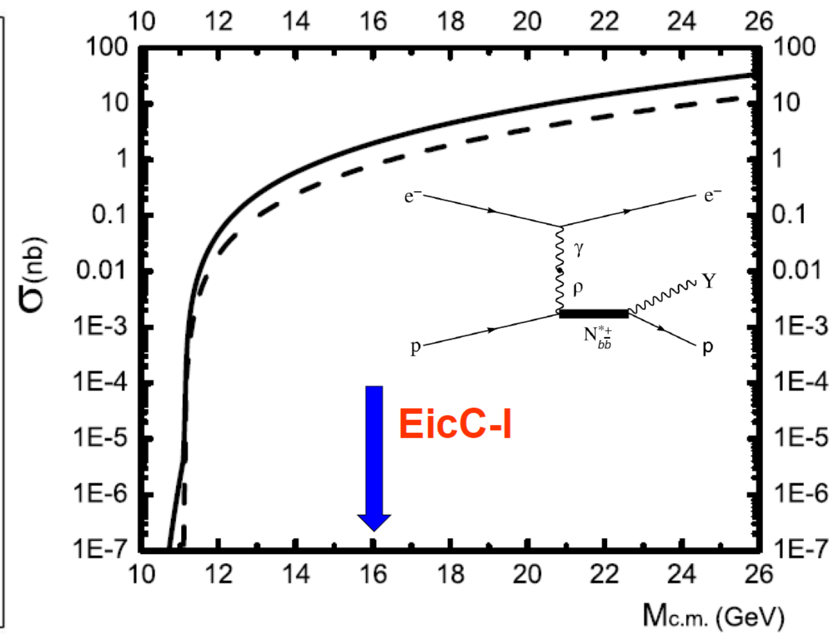


charm & beauty baryon

- **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, $e^+e^- \to \bar{\Lambda}_b \Lambda_b$, etc.**

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





Wu, Zhao, Zou, PLB709(2012)70

EicC-I : Super-B factory for both B-mesons and B-baryons !

Thank you for your attention!