Penta-quark states

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

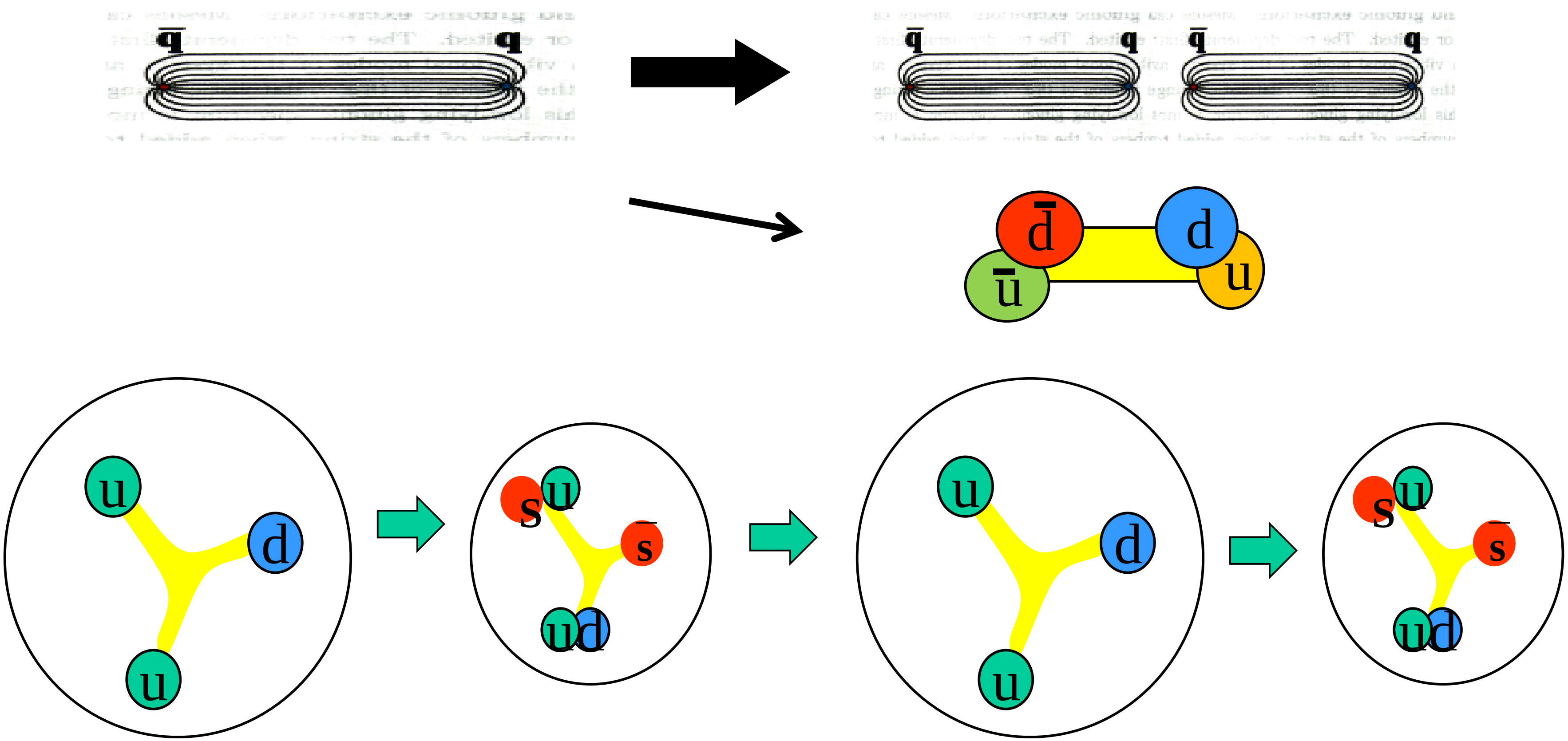
Outline :

1. Importance of unquenching dynamics
2. Penta-quark states with strangeness
3. From Strangeness to charm & beauty
4. Conclusions

1. Importance of unquenching dynamics

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

crucial for quark confinement & hadron structure

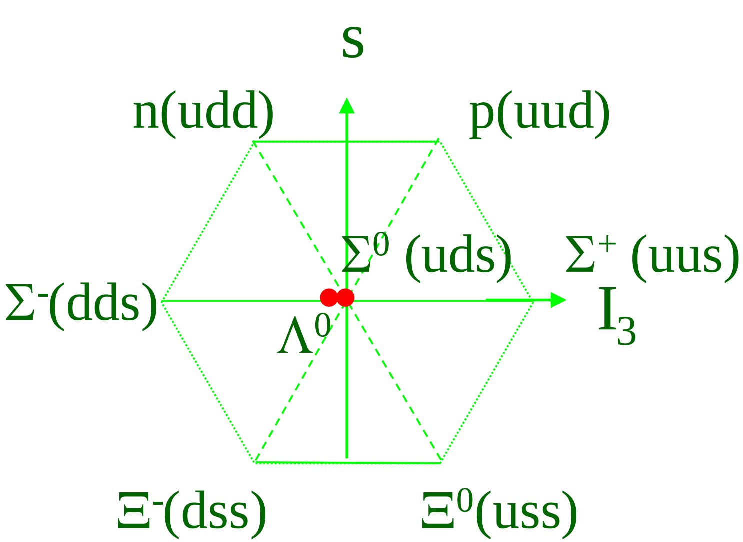


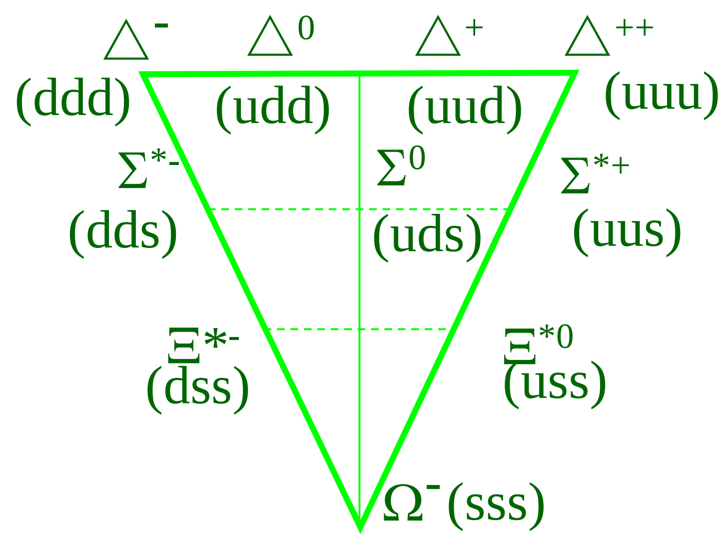
quenched or unquenched quark models give very different predictions of hadron spectrum

2. Penta-quark states with strangeness

SU(3) 3q-quark model for baryons

1/2 + **spin-parity** **3/2 +**





Successful for spatial ground states !

Prediction $m_{\Omega^-} \cong$ **1670 MeV**

experiment $m_{\Omega^-} \cong$ **1672.45 ±0.29 MeV**

quenched vs un-quenched for mesons

$\bar{q}q$ $^3S_1$ nonet

$\phi(1020)$ $\bar{s}s$

$K(892)$ $\bar{s}d$

$\omega(782)$ $\bar{u}u + \bar{d}d$
$\rho(770)$ $\bar{u}u - \bar{d}d$

$\bar{q}q$ $^3P_0$ or $\bar{q}^2q^2$ nonet ?

$a_0(980)$ $\bar{u}u - \bar{d}d$, $[\bar{u}\,\bar{s}][us]-[\bar{d}\,\bar{s}][ds]$
$f_0(980)$ $\bar{s}s$, $[\bar{u}\,\bar{s}][us]+[\bar{d}\,\bar{s}][ds]$

$\kappa(800)$ $\bar{s}d$, $[\bar{s}\,\bar{u}][ud]$

$f_0(600)$ $\bar{u}u + \bar{d}d$, $[\bar{u}\,\bar{d}][ud]$

$1/2^-$ baryon nonet with strangeness

- Mass pattern : quenched or unquenched ?

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

uud (L=1) $1/2^-$ ~ $N^*(1535)$ ~ $[ud][us]\bar{s}$

uds (L=1) $1/2^-$ ~ $\Lambda^*(1405)$ ~ $[ud][su]\bar{u}$

uus (L=1) $1/2^-$ ~ $\Sigma^*(1390)$ ~ $[us][ud]\bar{d}$

Wu-Dulat-Zou, PRD80(2009)017503; CLAS, PRC87(2013)035206

- Strange decays of N*(1535) : PDG → large $g_{N^*N\eta}$

$J/\psi \to \bar{p}N^* \to \bar{p}(K\Lambda)$ / $\bar{p}(p\eta)$ → large $g_{N^*K\Lambda}$

Liu&Zou, PRL96 (2006) 042002; Geng,Oset,Zou&Doring, PRC79 (2009) 025203

$\gamma p \to p\eta'$ & $pp \to pp\eta'$ → large $g_{N^*N\eta'}$

M.Dugger et al., PRL96 (2006) 062001; Cao&Lee, PRC78(2008) 035207

$\pi^- p \to n\phi$ & $pp \to pp\phi$ & $pn \to d\phi$ → large $g_{N^*N\phi}$

Xie, Zou & Chiang, PRC77(2008)015206; Cao, Xie, Zou & Xu, PRC80(2009)025203

- Strange decays of Λ*(1670) : PDG → large $g_{\Lambda^*\Lambda\eta}$

narrower width (35MeV) than Λ*(1405)

$3/2^-$ baryon nonet with strangeness

- **Mass pattern : quenched or unquenched ?**

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

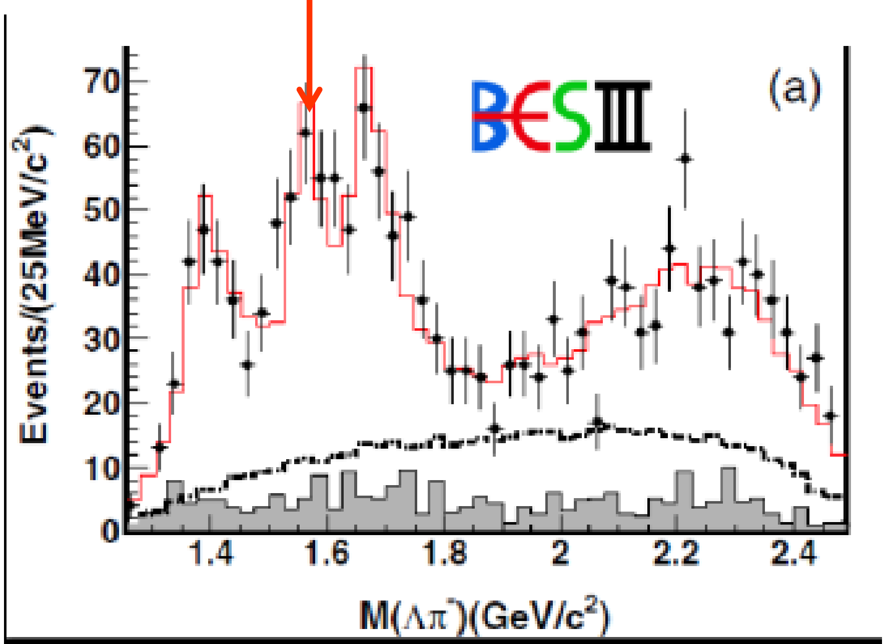
uud (L=1) $3/2^-$ ~ N*(1520) ~ [ud]{uq} $\bar{q}$

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

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

Σ(1580) $3/2^-$

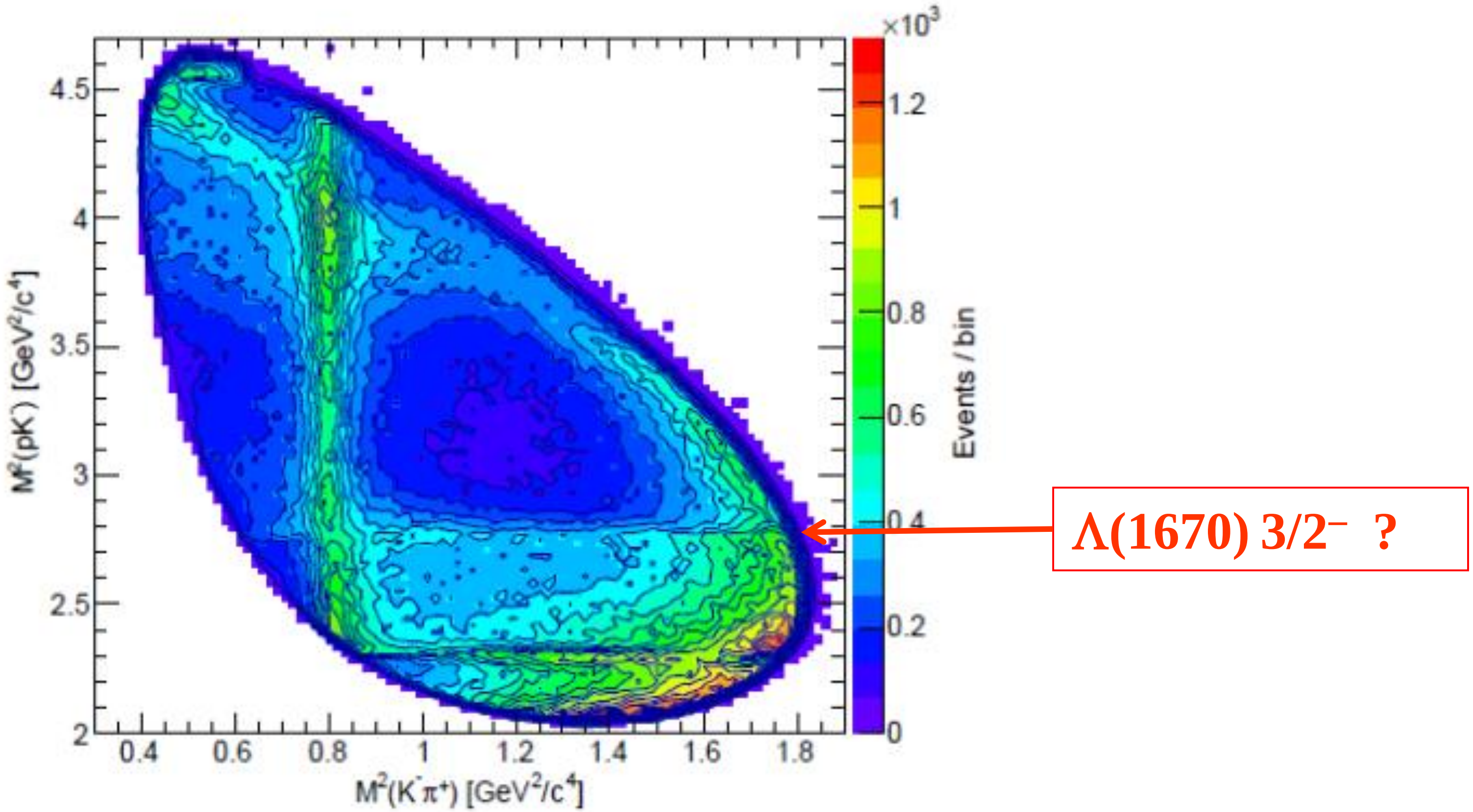
BESIII, PRD88 (2013) 112007



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

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

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



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

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

Alternative pictures :

Hadronic molecules

$N^*(1440) \sim N\sigma$

$N^*(1535) \sim K\Sigma\text{-}K\Lambda$

$\Lambda^*(1405) \sim KN\text{-}\Sigma\pi$

$\Lambda^*(1520) \sim \Sigma^*\pi$

Kaiser, Weise, Oset, Ramos,
Oller, Meissner, Hyodo, Jido,
Hosaka, …

Penta-quark states

$N^*(1440) \sim [ud][ud]\,\bar{q}$

$N^*(1535) \sim [ud][us]\,\bar{s}$

$\Lambda^*(1405) \sim [ud][sq]\,\bar{q}$

$\Lambda^*(1520) \sim [ud]\{sq\}\,\bar{q}$

Successful extension to 1^+ & 2^+ meson nonets (Oset et al.)

eg., $f_1(1420) \sim \bar{K}K^*$

Important implications:

□ $\bar{q}qqqq$ in S-state more favorable than qqq with $L=1$!
& $\bar{q}qqq$ in S-state more favorable than $\bar{q}q$ with $L=1$!

$1/2^-$ baryon nonet ~ $\bar{q}q^2q^2$ state + …

0^+ meson octet ~ $\bar{q}^2q^2$ state + …

multiquark components are important for hadrons!

Totally different predictions for $1/2^-$ hyperons:

unquenched		quenched
Σ* [us][du] $\bar{d}$	~ 1400 MeV	uus (L=1) ~ 1650 MeV
Ξ* [us][ds] $\bar{d}$	~ 1550 MeV	uss (L=1) ~ 1760 MeV
Ω* [us] ss $\bar{u}$	~ 1800 MeV	sss (L=1) ~ 2000 MeV

Meson-Baryon states

Y.S.Oh	K. P. Khemchandani et al.
Σ* ~ 1475 MeV	~ 1426 MeV
Ξ* ~ 1616 MeV	~ 1606 MeV
Ω* ~ 1837 MeV	Ramos & Oset

Experiment knowledge on hyperon states still very poor !

Ω^* in PDG:

**** $\Omega(1672)\ 3/2^+$,

*** $\Omega\ (2250)$

** $\Omega\ (2380)$, $\Omega\ (2470)$

Ξ^* in PDG:

**** $\Xi(1320)\ 1/2^+$, $\Xi(1530)\ 3/2^+$

*** $\Xi(1690)$, $\Xi(1820)\ 3/2^-$, $\Xi(1950)$, $\Xi(2030)$

** $\Xi(2250)$, $\Xi(2370)$

* $\Xi(1620)$, $\Xi(2120)$, $\Xi(2500)$

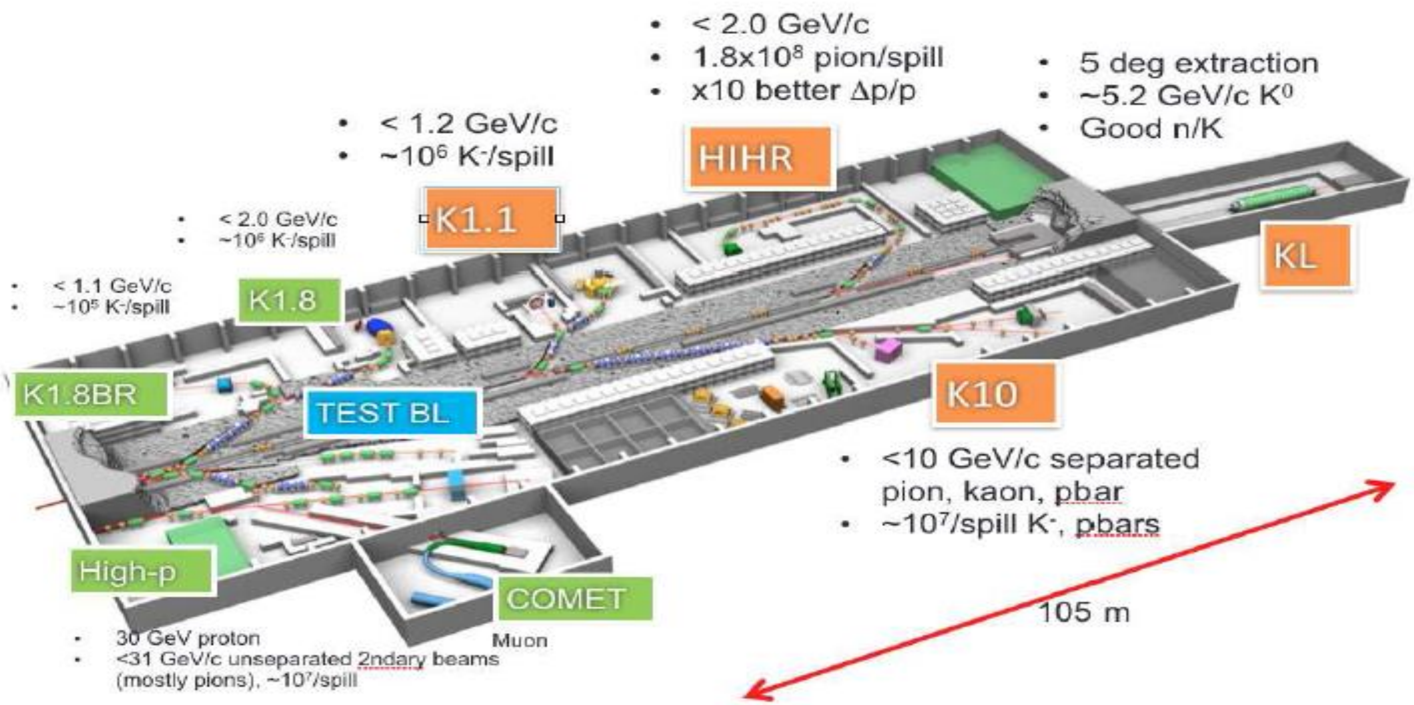
Σ* in PDG

****	Σ (1189)$1/2^+$ Σ*(1385)$3/2^+$ Σ*(1670)$3/2^-$ Σ*(1775)$5/2^-$ Σ*(1915)$5/2^+$ Σ*(2030)$7/2^+$
***	Σ*(1660)$1/2^+$ Σ^*(1750)$1/2^-$ Σ^*(1940)$3/2^-$ Σ*(2250)??
**	Σ*(1620)$1/2^-$ Σ*(1690)?? Σ*(1880)$1/2^+$ Σ*(2080)$3/2^+$ Σ*(2455)?? Σ*(2620)??
*	Σ*(1480)?? Σ*(1560)?? Σ*(1580)$3/2^-$ Σ*(1770)$1/2^+$ Σ*(1840)$3/2^+$ Σ*(2000)$3/2^-$ Σ*(2070)$5/2^+$ Σ*(2100)$7/2^-$ Σ*(3000)?? Σ*(3170)??

All from old experiments of 1970-1985 !!

No established $1/2^-$ Σ^* , Ξ*, Ω* !

K^-, K_L beam experiments at JPARC&Jlab



Elegant new source for Λ*, Σ*, Ξ* & Ω* hyperon spectroscopy

$K^-p \rightarrow \Sigma^0\pi^0, \Sigma^{*0}\pi^0, \Lambda\eta, \Lambda\pi^0\pi^0$: $\Lambda^*(1680)3/2^+$, $\Lambda^*(1670)3/2^-$

$K^-p \rightarrow \Sigma^0\pi^0\pi^0$: $\Sigma^*(1380)1/2^-$, $\Sigma^*(1540)\ 3/2^-$

$K_Lp \rightarrow \Lambda\pi^+, \Sigma^0\pi^+, \Sigma^+\pi^0, \Sigma^{*0}\pi^+, \Sigma^{*+}\pi^0$: $\Sigma^*(1540)\ 3/2^-$

$K_Lp \rightarrow \Sigma^0\eta\pi^+, \Lambda\eta\pi^+$: $\Sigma^*(1380)1/2^-$, $\Sigma^*(1540)\ 3/2^-$, $\Lambda^*(1670)3/2^-$

$K^-p \rightarrow K^+K^0\Omega^*$ $\Omega^*(1800)$?!

BEPCII & BelleII → important role for hyperon spectroscopy

J/Ψ decay branching ratios (BR×10^3) for some interested channels

$p\bar{p}$	$\Lambda\bar{\Lambda}$	$\Sigma^0\bar{\Sigma}^0$	$\Xi\bar{\Xi}$	$\Lambda\bar{\Sigma}^-\pi^+$	$pK^-\bar{\Lambda}$	$pK^-\bar{\Sigma}^0$
2.1 ± 0.1	1.4 ± 0.1	1.3 ± 0.2	1.8 ± 0.4	1.1 ± 0.1	0.9 ± 0.2	0.3 ± 0.1
$p\bar{n}\pi^-$	$p\bar{p}\pi^0$	$p\bar{p}\pi^+\pi^-$	$p\bar{p}\eta$	$p\bar{p}\eta'$	$p\bar{p}\omega$	$K^-\Lambda\bar{\Xi}^+$?
2.0 ± 0.1	1.1 ± 0.1	6.0 ± 0.5	2.1 ± 0.2	0.9 ± 0.4	1.3 ± 0.3	$K^+\bar{\Lambda}\Xi^-$?

BEPCII 10^{10} J/Ψ & 10^9 Ψ'

Completing N*, Λ*, Σ*, Ξ* spectra

Establish the lowest $1/2^-$ Λ*, Σ*, Ξ* and Ω* !

BelleII Y(ns) → all Λ*, Σ*, Ξ* and Ω* ?

PANDA $\bar{p}p$ → all Λ*, Σ*, Ξ* and Ω* !

3. From strangeness to charm & beauty

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

Problem:

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

Λ(1405) – predicted by Dalitz as $\bar{K}N$ state in 1959, seen in 1961

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) $\bar{q}quds$

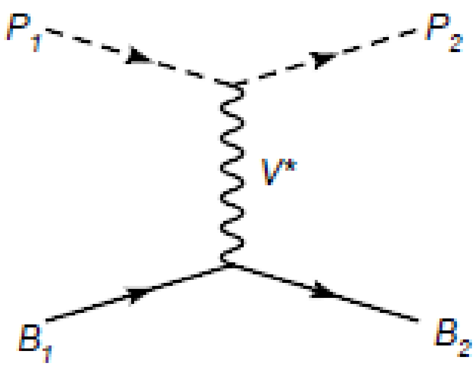
Λ*(4210) $\bar{c}cuds$ J.J.Wu, R.Molina, E.Oset, B.S.Zou. Phys.Rev.Lett. 105 (2010) 232001

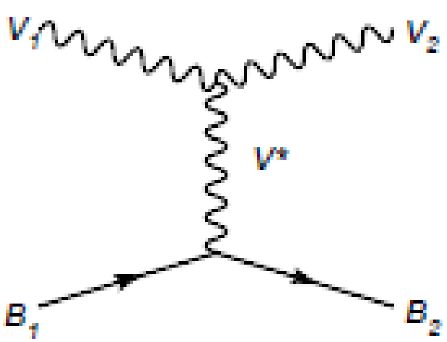
Λ*(11020) $\bar{b}buds$ J.J.Wu, L.Zhao, B.S.Zou. PLB709(2012)70

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

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

J.J.Wu, L.Zhao, B.S.Zou. PLB709(2012)70





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

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

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

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

	(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		
	$(0,-1)$		$\bar{D}_s\Lambda_c^+$	$\bar{D}\Xi_c$	$\bar{D}\Xi'_c$	
Λ*		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		
	$(0,-1)$		$\bar{D}^*_s\Lambda_c^+$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi'_c$	
Λ*		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	$1/2^-$
Λ*	$(0,-1)$			$\bar{K}N$	$\pi\Sigma$	$\eta\Lambda$	$\eta'\Lambda$	$K\Xi$	$\eta_c\Lambda$	
		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	

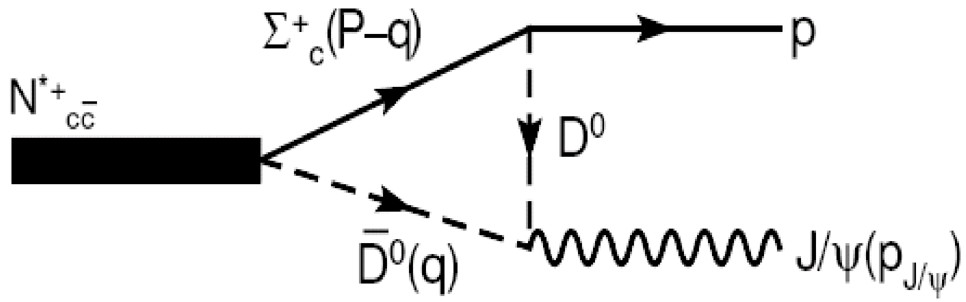
TABLE V: Mass (M), total width (Γ), and the partial decay width (Γ_i) for the states from $PB \to PB$, with units in MeV.

	(I,S)	M	Γ	Γ_i						J^P
N*	$(1/2,0)$			ρN	ωN	$K^*\Sigma$			$J/\psi N$	
		4412	47.3	3.2	10.4	13.7			19.2	$1/2^-$, $3/2^-$
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	

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 !



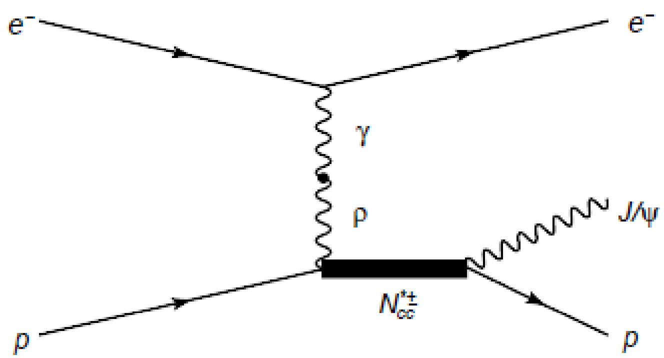
3 orders of magnitude smaller than N* → pη_c

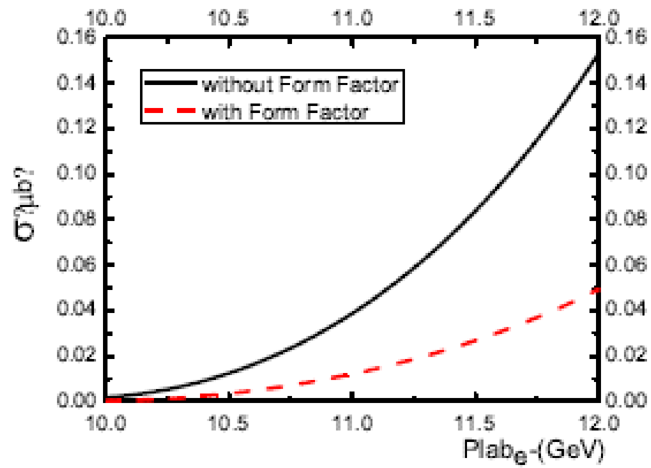
$\bar{p}p \to \bar{p}pJ/\psi$ ~ 0.03 nb

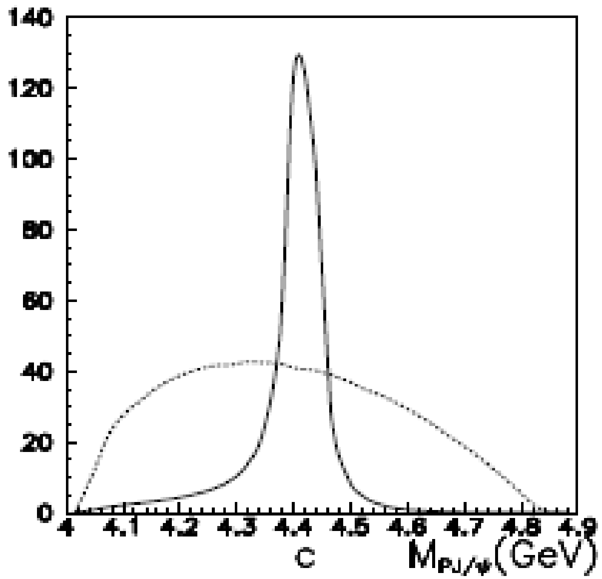
~ 250 events per day at PANDA/FAIR by L=10^{31} cm^{-2}s^{-1}

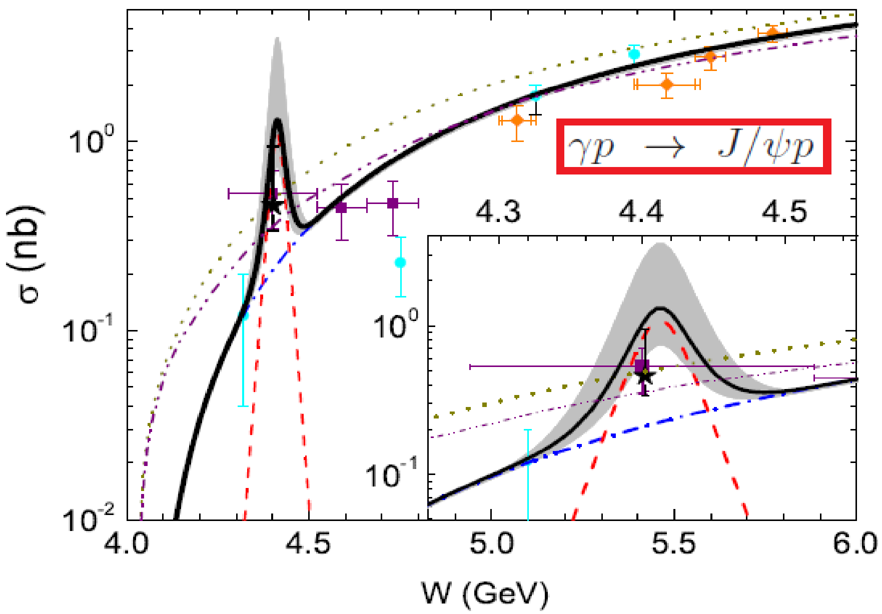
These Super-heavy narrow N* and Λ* can be found at PANDA !

Prediction for 12GeV@JLab









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

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

$\bar{D}^*\Sigma_c$ + $\bar{D}\Sigma_c^*$ + $\bar{D}^*\Sigma_c^*$ coupled channel state ~ 4.4 GeV

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

$\bar{D}\Sigma_c$ 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

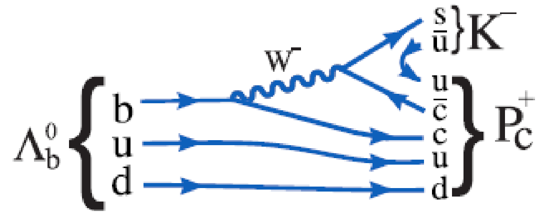
$\bar{c}$cqqq with 3 kinds of qq hyperfine interaction ~ 4.1 GeV

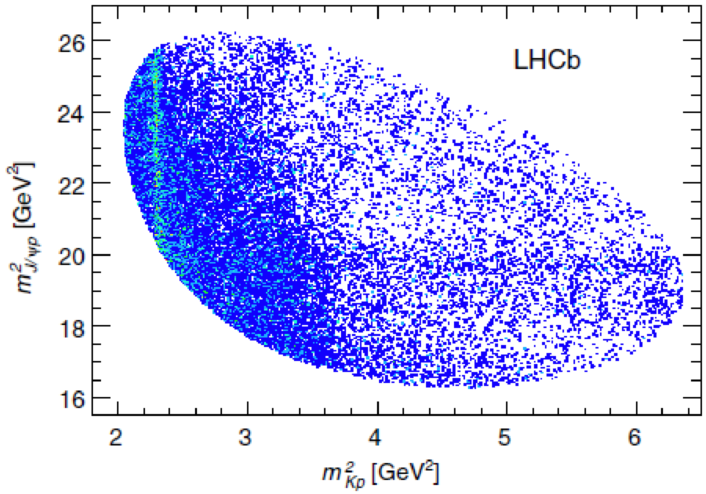
S.G.Yuan, K.W.Wei, J.He, H.S.Xu, B.S.Zou, EPJA48(2012)61

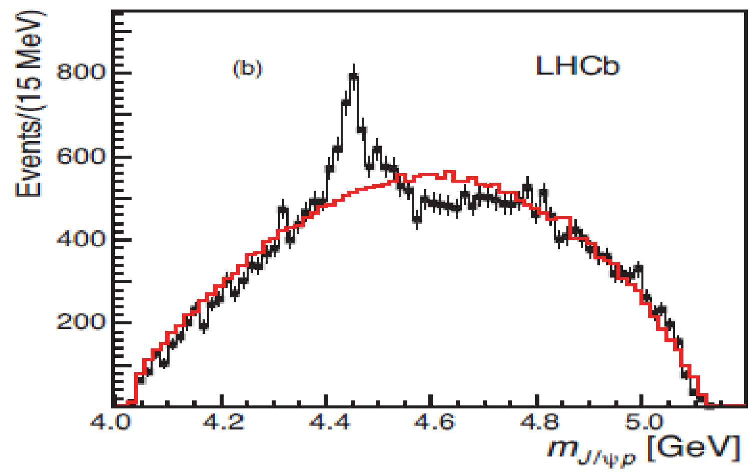
Observation of $P_c^+(4380)$ & $P_c^+(4450)$ by LHCb

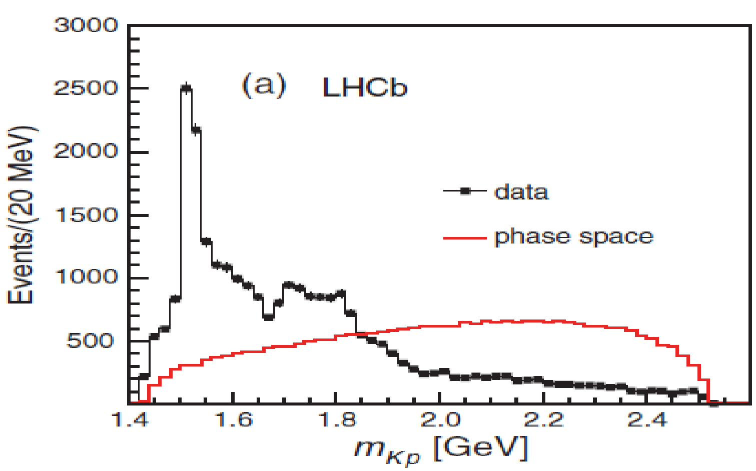
LHCb, Phys.Rev.Lett. 115 (2015) 072001 :

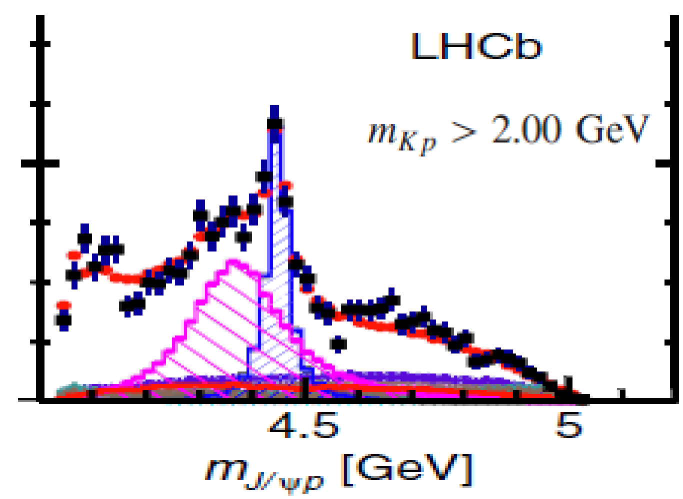
Observation of two N* from $\Lambda_b^0 \to J/\psi K^- p$











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.

Significances > 9σ for both P_c^+ states

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

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

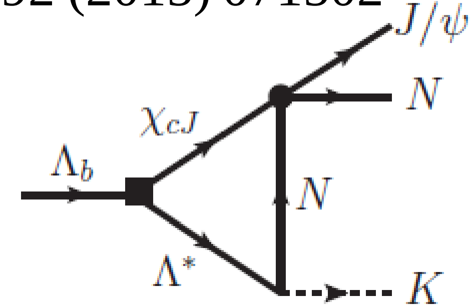
R.Chen, X.Liu, X.Q.Li, S.L.Zhu, PRL115 (2015) 132002;
H.X.Chen, W.Chen, X.Liu, T.G.Steele, S.L.Zhu, PRL115 (2015)172001
L.Roca, J.Nieves, E.Oset, PRD92 (2015) 094003;
J.He, PLB 753 (2016)547 ;

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

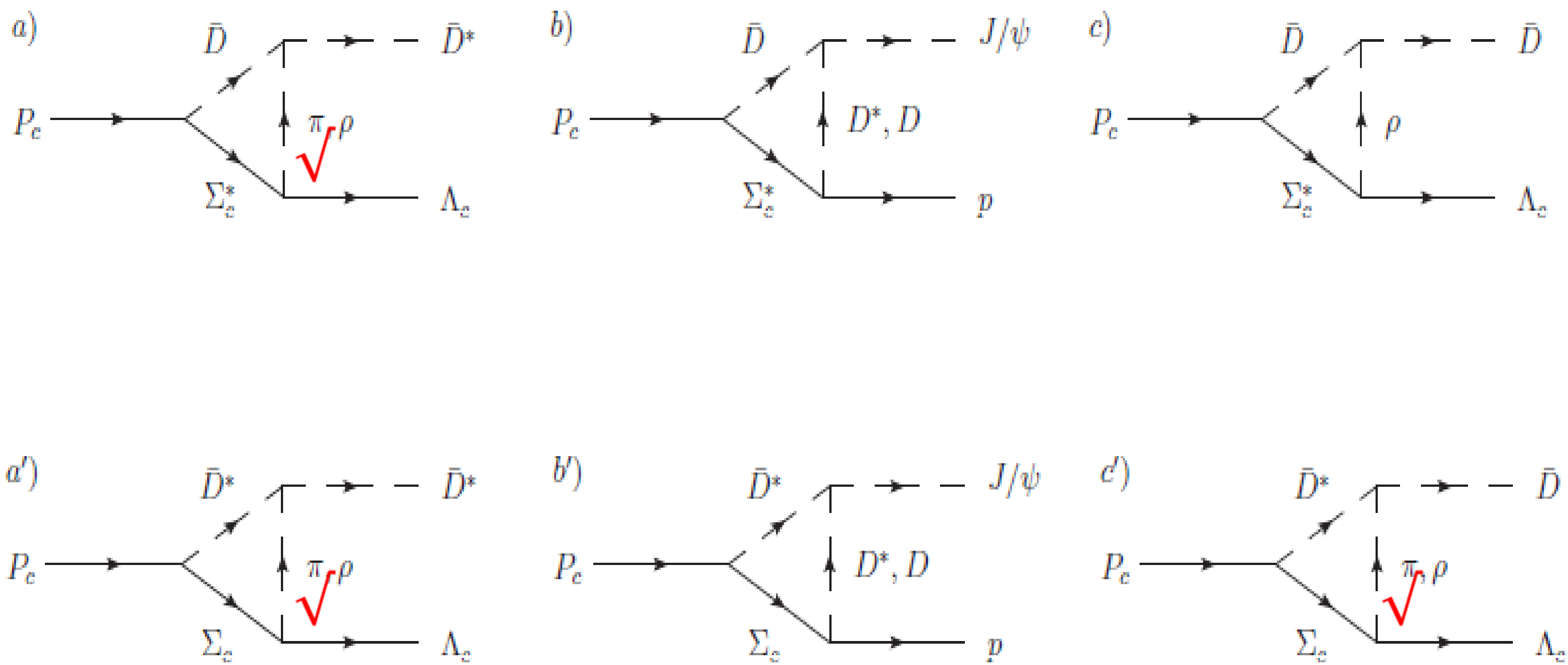


For a comprehensive review, cf.:

H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1

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, ArXiv: 1703.01045



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 √	41.6 √	80.5 √	22.6 √
$J/\psi p$	3.8	8.4	8.3	2.0
$\bar{D}\Lambda_c$	1.2	17.0 √	41.4 √	18.8 √
πN	0.06	0.05	0.05	0.1
$\chi_{c0}p$	0.9	0.002	0.01	0.001
$\eta_c p$	0.2	0.08	0.1	0.04
ρN	1.4	0.08	0.07	0.1
ωp	5.3	0.3	0.3	0.2
$\bar{D}\Sigma_c$	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	67.7	139.7	46.2

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

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

- **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.**

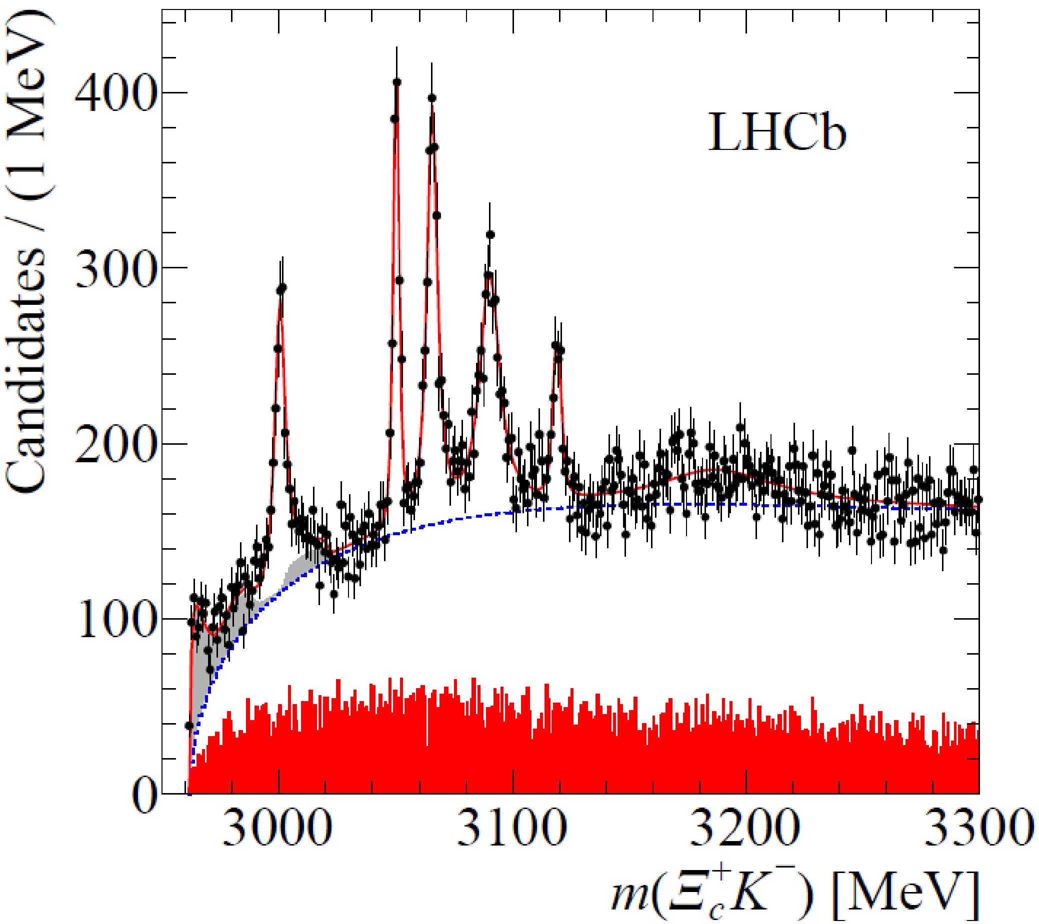
  π10/K10@JPARC , BelleII may play important role here!

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

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

  ssc - $\bar{q}$qssc

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

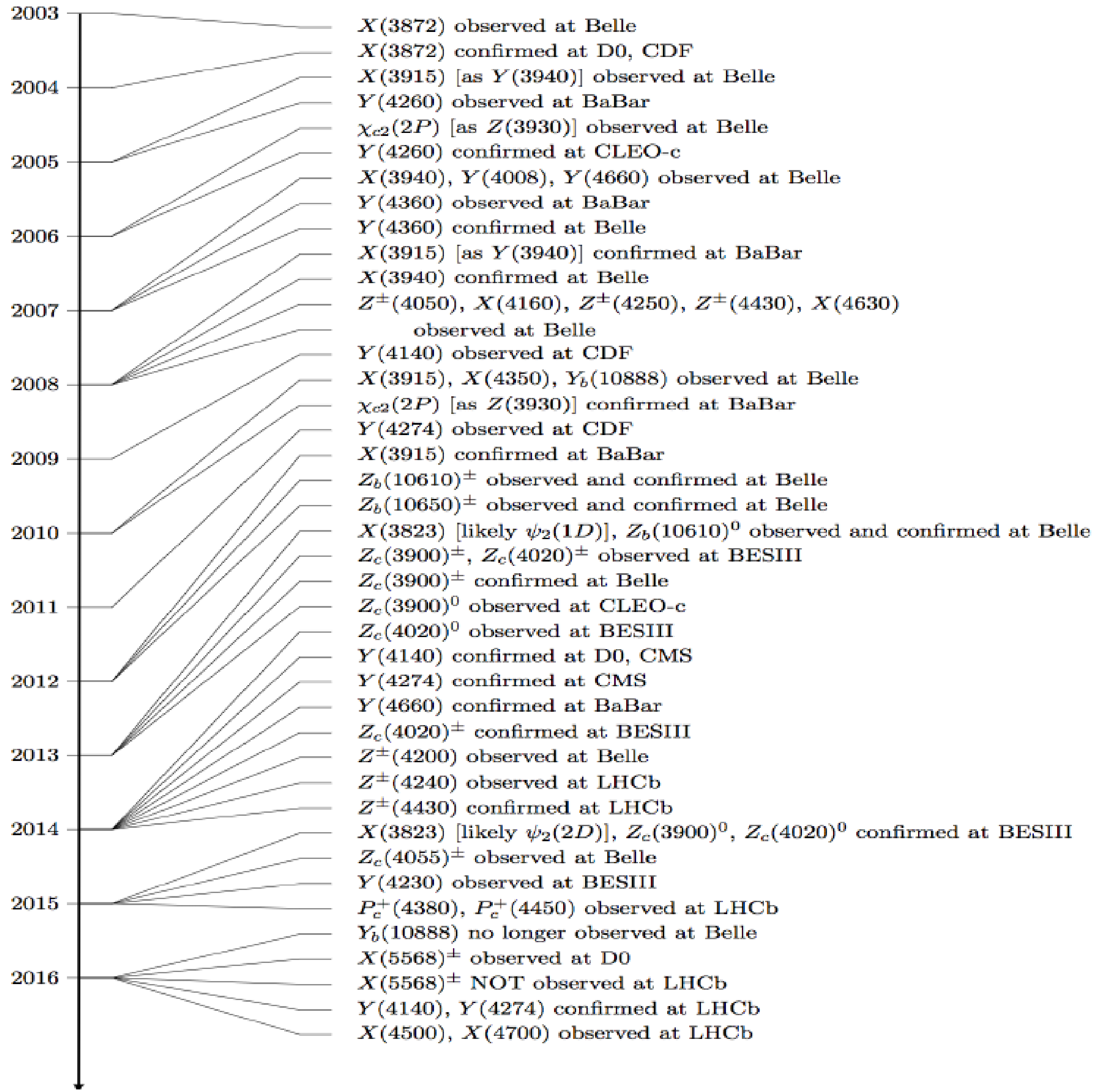


arXiv:1703.04639

Ω_c states

$\bar{p}p$@PANDA – a better place for more Ω_c states ?

Discovery Timeline: [Lebed, Mitchell, Swanson; arXiv : 1610.04528]



Meson sector:

If f_0(980) as $\bar{K}$K molecule, then → DK, $\bar{D}$D, $\bar{B}$B molecules

D_{s0}(2317)

Y.J.Zhang, H.C.Chiang, P.N.Shen, B.S.Zou, PRD74 (2006) 014013

If f_1(1420) as $\bar{K}$*K state, then → $\bar{D}$*D, $\bar{B}$*B molecules

X(3872), Z_c , Z_b

X. Liu, Luo, Y. Liu, S.L.Zhu, EPJC61, 411 (2009); PRD84 (2011) 054002

$\bar{K}$*K* → $\bar{D}$*D*, $\bar{B}$*B*

T.Fernandez-Carames, A.Valcarce, J.Vijande, PRL103 (2009) 222001

Z_b(10610) ~ B*(5325)B(5280); Z_c(10650) ~ B*(5325)B*(5325);
Z_c(3900) ~ D*(2010)D(1870); Z_c(4025) ~ D*(2010)D*(2010);
Z_c(4250) ~ D(1870)D_1(2420); Z_c(4430) ~ D*(2010)D_1(2420)

For a comprehensive review, cf.:

H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1-121

4. Conclusions

- Hadron spectroscopy reveals unquenched quark picture
- Superheavy narrow N* and Λ* are predicted to exist

  $\bar{D}^{(*)}\Sigma_c$, $\bar{D}_s^{(*)}\Lambda_c$ → $B\Sigma_b$, $B_s\Lambda_b$ bound states

  ~ 4.3 GeV ~11 GeV

  and partly confirmed by LHCb experiment

- Distinguishable predictions for penta-quark spectroscopy are yelling for further experimental confirmation

- New penta-quark spectroscopy provides a new idea platform for understanding multiquark dynamics

- They can be looked for at LHCb, 12GeV@Jlab, JPARC and maybe also at PANDA, RHIC , EIC?

Thanks !