Five-quark Components in Baryons and Pentaquark States

Bing-Song Zou

Institute of Theoretical Physics, CAS, Beijing
& University of Chinese Academy of Sciences

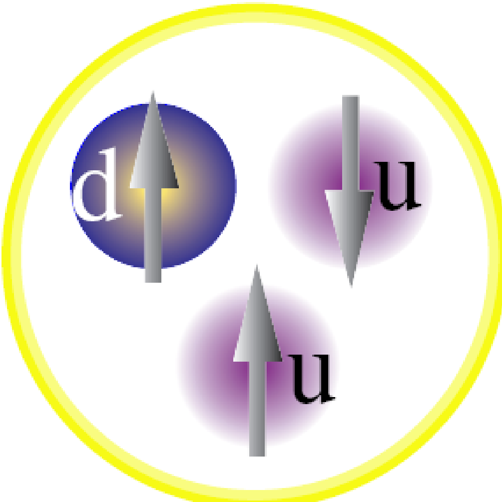
Outline:

- 5-quark components in the proton
- Nature of $1/2^-$ baryon nonet with strangeness
- Pentaquarks with hidden charm – P_c states
- Strange and beauty partners of P_c states
- Prospects

1. Five-quark components in the proton

Classical picture of the proton

Constituent Quarks



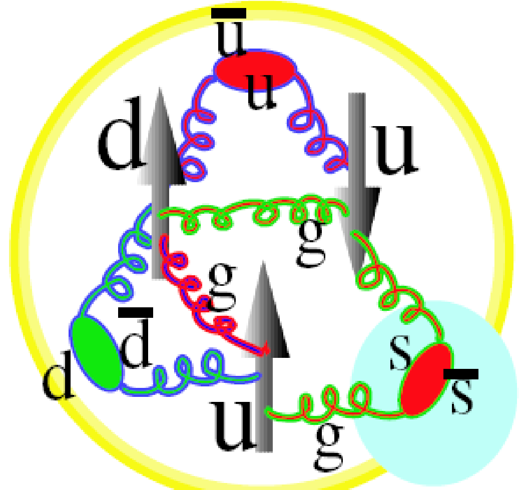
($Q^2 = 0\ GeV^2$)

baryon octet

masses,magn. momenta

1964-1974

Parton Distributions



($Q^2 > 1\ GeV^2$)

structure functions

momentum, spin

$\bar{u}(x) = \bar{d}(x)$, $\bar{s}(x) = s(x)$

1974–1992

Flavor asymmetry of light quarks in the nucleon sea

Deep Inelastic Scattering (DIS) + Drell-Yan (DY) process

→ $\bar{d} - \bar{u} \sim 0.12$ for a proton

Garvey&Peng, Prog. Part. Nucl. Phys.47, 203 (2001)

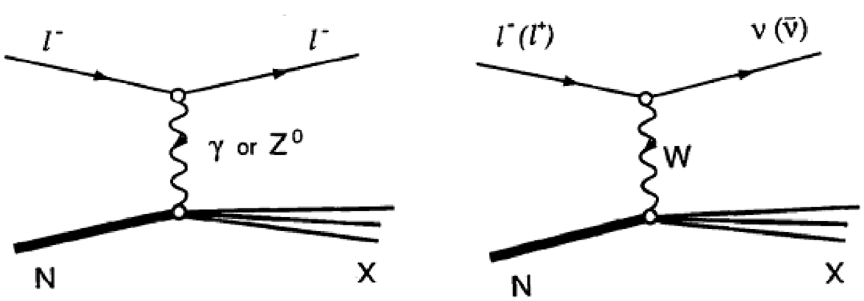
Table 1. Values of the integral $\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx$ determined from the DIS, semi-inclusive DIS, and Drell-Yan experiments.

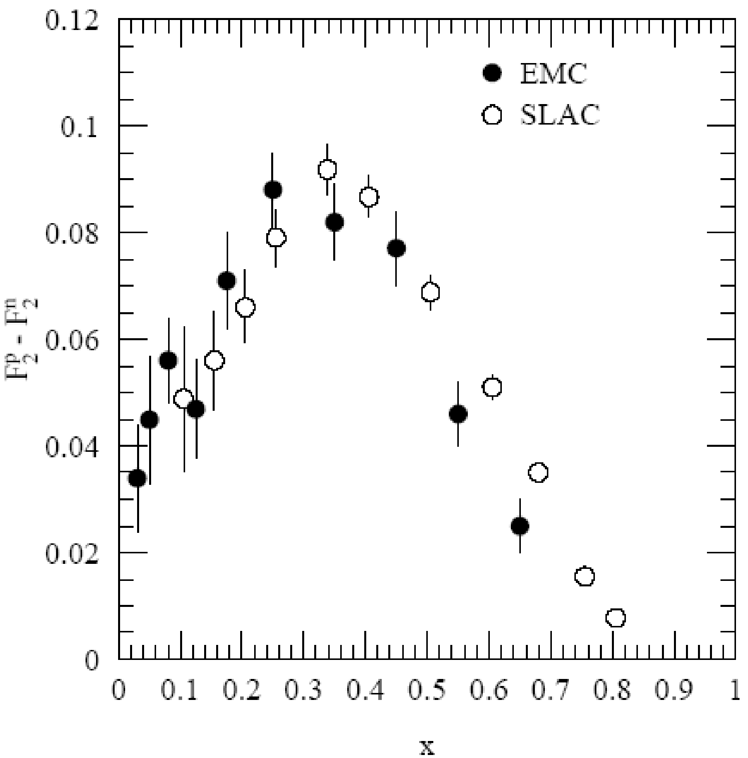
Experiment	$\langle Q^2 \rangle$ (GeV^2/c^2)	$\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx$
NMC/DIS	4.0	0.147 ± 0.039
HERMES/SIDIS	2.3	0.16 ± 0.03
FNAL E866/DY	54.0	0.118 ± 0.012

DIS Gottfried Sum Rule : assuming $\bar{d} = \bar{u}$

$$I_2^p - I_2^n = \int_0^1 [F_2^p(x,Q^2) - F_2^n(x,Q^2)]/x\ dx = \sum_i [(Q_i^p)^2 - (Q_i^n)^2] = 1/3.$$

$$\int_0^1 [F_2^p(x,Q^2) - F_2^n(x,Q^2)]/x\ dx = \frac{1}{3} + \frac{2}{3}\int_0^1 [\bar{u}(x,Q^2) - \bar{d}(x,Q^2)]dx.$$





Deep Inelastic Scattering (DIS)

$$\sigma_{DY}(p+d)/2\sigma_{DY}(p+p) \simeq (1+\bar{d}(x_2)/\bar{u}(x_2))/2.$$

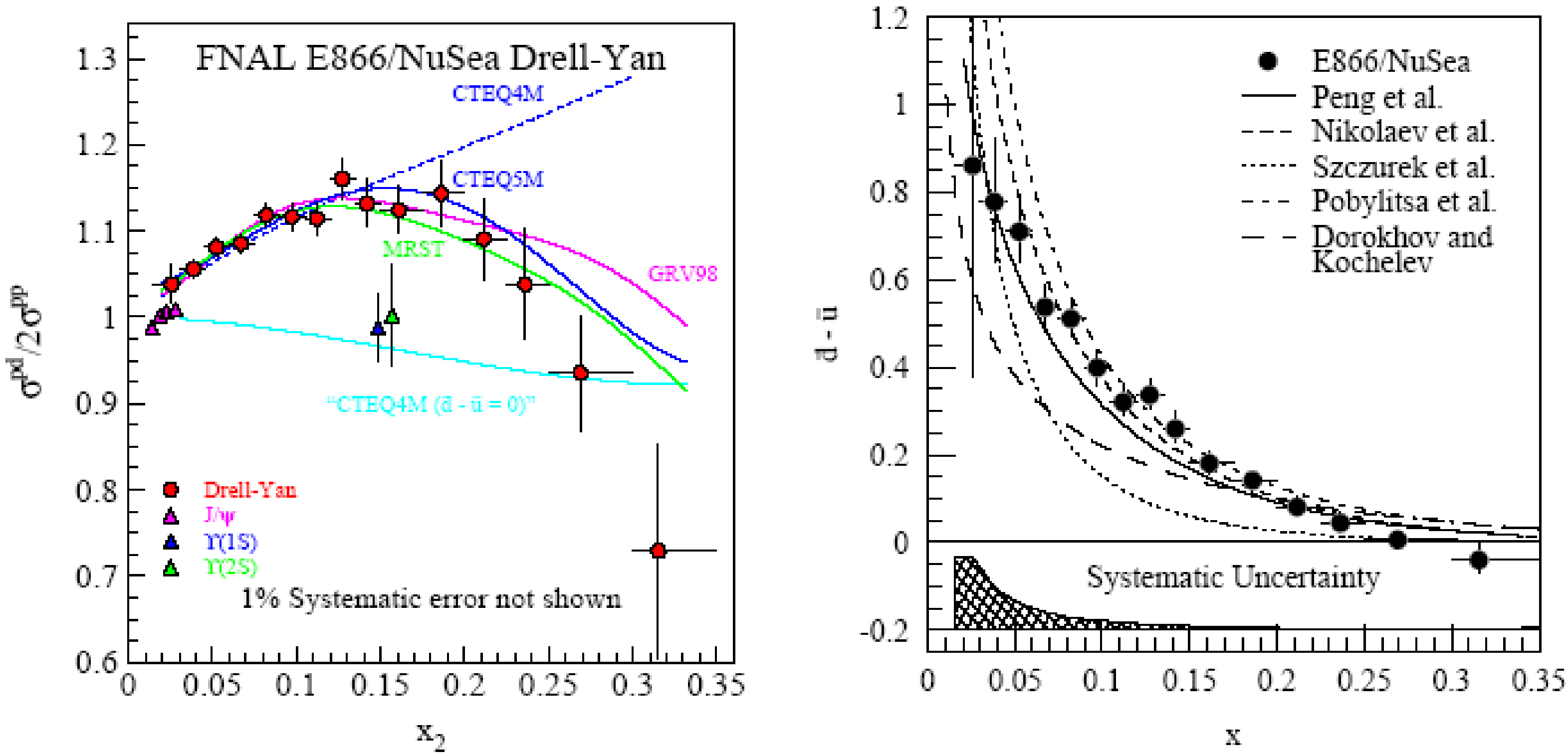
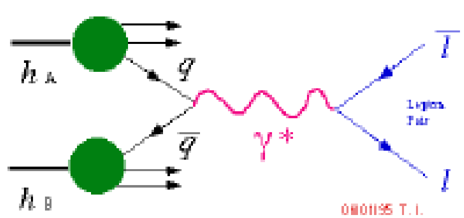


FIGURE 1. Left panel: Cross section ratios of $p+d$ over $2(p+p)$ for Drell-Yan, J/Ψ, and Υ production from FNAL E866. Right panel: Comparison of E866 $\bar{d}-\bar{u}$ data with calculations from various models [2].

The Drell-Yan Process



$$\bar{d}/\bar{u} > 1$$

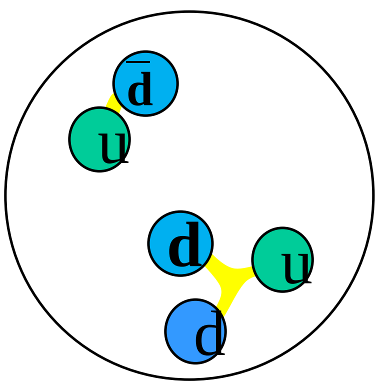
Two major theoretical schemes for $\bar{d} - \bar{u} \sim 0.12$

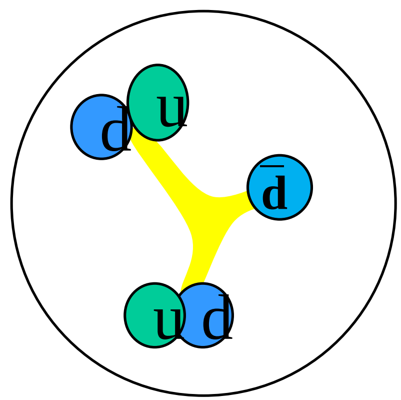
Meson cloud picture: Thomas, Speth, Henley, Meissner, Miller, Weise, Oset, Brodsky, Ma, …

$| p > \sim | uud > + \varepsilon_1 | n (udd) \pi^+ (\bar{d}u) >$
$\quad + \varepsilon_2 | \Delta^{++} (uuu) \pi^- (\bar{u}d) > + \varepsilon' | \Lambda (uds) K^+ (\bar{s}u) > \ldots$

Penta-quark picture : Riska, Zou, Zhu, …

$| p > \sim | uud > + \varepsilon_1 | [ud][ud] \bar{d} > + \varepsilon' | [ud][us] \bar{s} > + \ldots$





Detailed balance model : Zhang, Ma, Zou, Yang, Alberg, Henley

$$uud \leftrightarrow uudg \rightarrow \begin{cases} uudd\bar{d} & 1/2 \\ uudu\bar{u} & 1/3 \end{cases} \quad \ldots\ldots\ldots\ldots$$

$$1 : 1$$

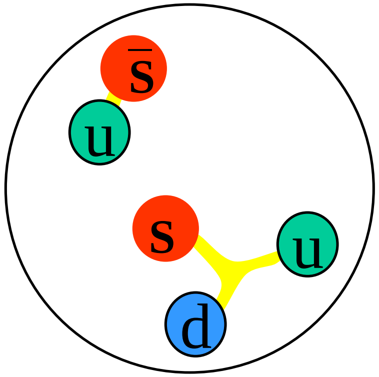
$$p = 0.168\,(uud) + 0.168\,(uudg) + 0.084\,(uudd\bar{d}) + 0.056\,(uudu\bar{u}) + 0.084\,(uudgg) + \ldots$$

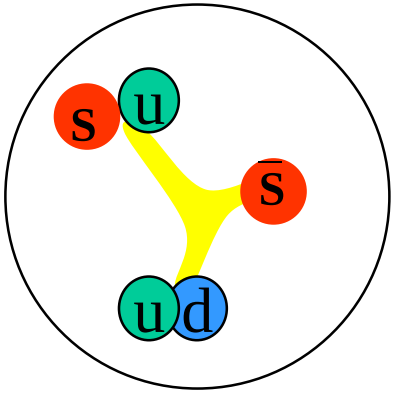
$$\bar{d} - \bar{u} \sim 0.124$$

$(uud+ng)$ 50% $(uudd\bar{d}+ng)$ 22.4% $(uudu\bar{u}+ng)$ 15.0%

Predictions for $\bar{s}$ / s asymmetry from two schemes :

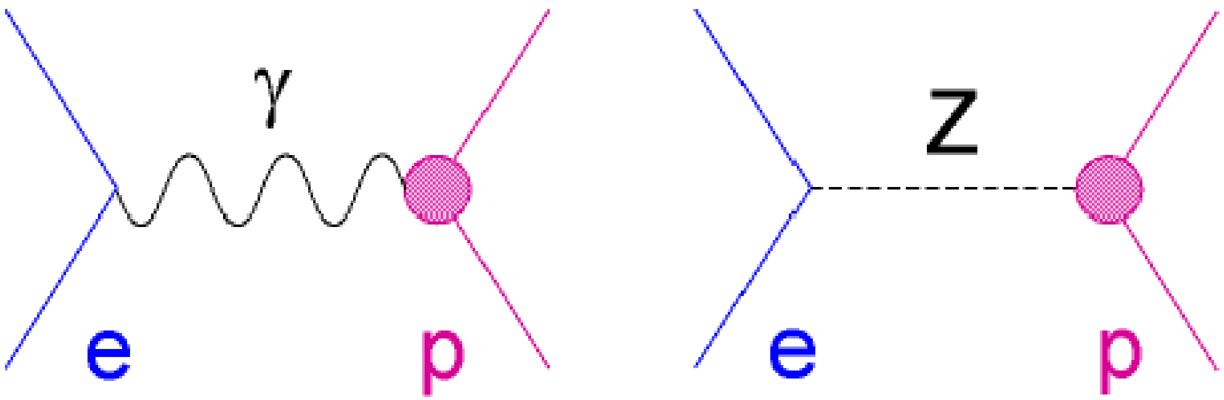
	meson cloud	penta-quark
strange spin Δs :	< 0	< 0
magnetic moment μ_s :	< 0	> 0
strange radium r_s :	< 0	> 0





Expt: $\Delta s = -0.05 \sim -0.1$ D. de Florian et al., PRD71 (2005) 094018

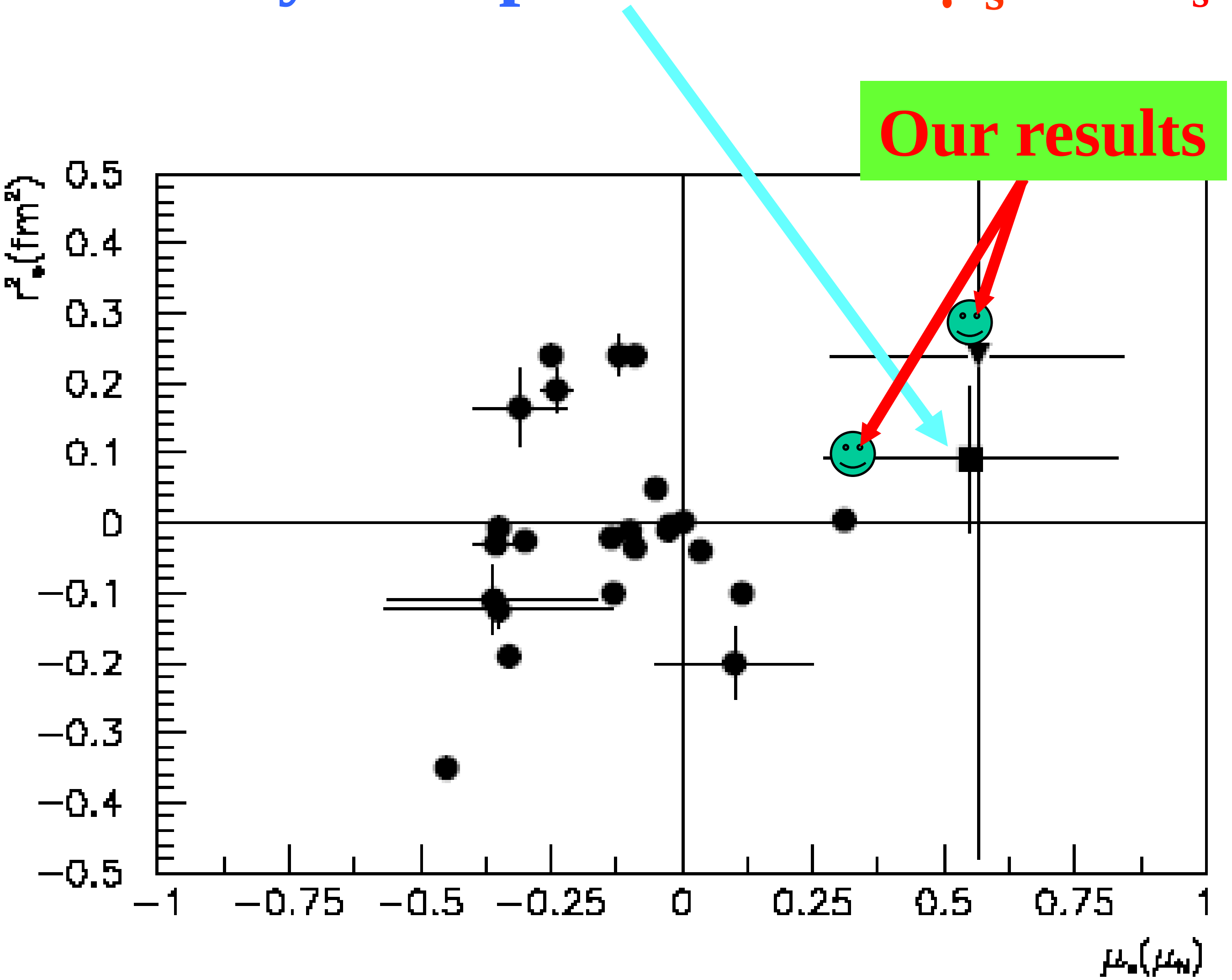
The strange magnetic moment μ_s and radii r_s from parity violating electron scattering



G0,HAPPEX/CEBAF, SAMPLE/MIT-Bates, A4/MAMI

HAPPEX/CEBAF, Phys.Rev.Lett. 96 (2006) 022003
G0/CEBAF, Phys.Rev.Lett. 95 (2005) 092001
A4/MAMI, Phys.Rev.Lett. 94 (2005) 152001
SAMPLE/MIT-Bates: Phys.Lett.B583 (2004) 79

Theory vs experiment for μ_s and r_s



Zou&Riska, PRL95(2005)072001; Riska&Zou, PLB636 (2006) 265
An-Riska-Zou, PRC73 (2006) 035207

Experiment extraction of μ_s and r_s wrong?

R.Young et al., PRL97 (2006) 102002 → $\mu_s \sim 0$
S.Baunack et al.(A4), PRL102(2009)151803

With ~25% $\bar{q}qqqq$ components in the proton, the "spin crisis" and single spin asymmetry may also be naturally explained.

An-Riska-Zou, PRC73 (2006) 035207; F.X.Wei, B.S.Zou, hep-ph/0807.2324

$$\Delta_u = 0.85 \pm 0.17$$
$$\Delta_d = -(0.33 \sim 0.56)$$

$$\Delta_u = \frac{4}{3}|A_{3q}|^2$$
$$\Delta_d = -\frac{1}{3}(1 - P_{s\bar{s}})$$
$$\Delta L_q = \frac{4}{3}(P_{d\bar{d}} + P_{s\bar{s}})$$

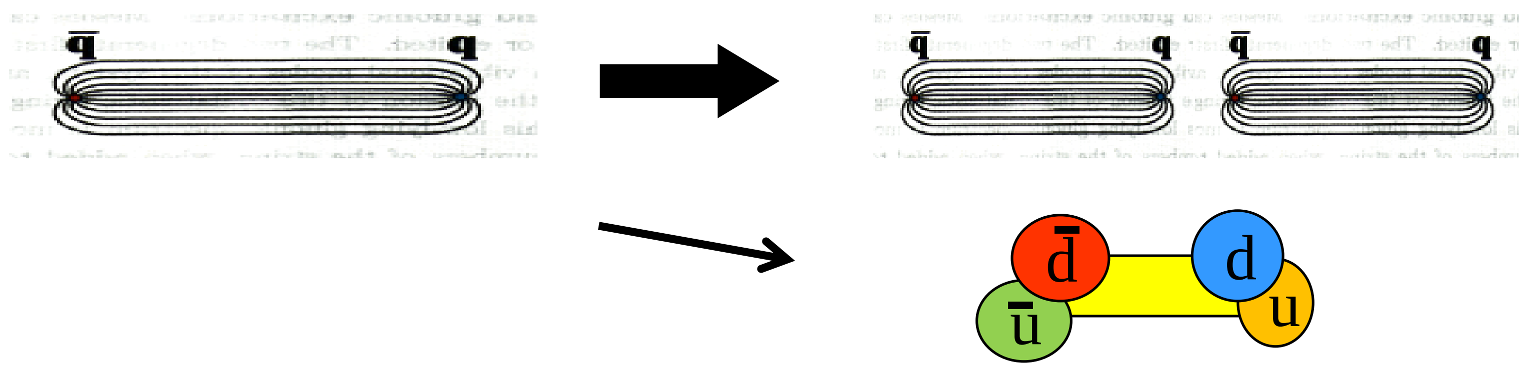
We must go beyond the simple 3q models,

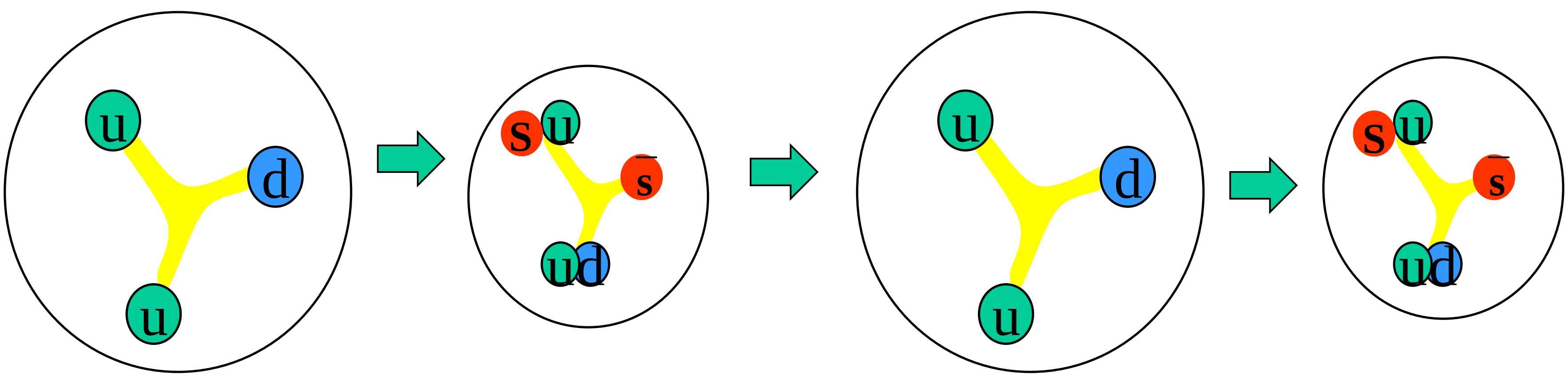
meson cloud vs penta-quark not settled yet.

Quenched & unquenched quark models

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

crucial for quark confinement & hadron structure





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

2. Nature of $1/2^-$ 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) $1/2^-$ ~ $\Sigma^*(1390)$ ~ $[us][ud]\bar{d}$

  Zou et al, NPA835 (2010) 199 ; 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

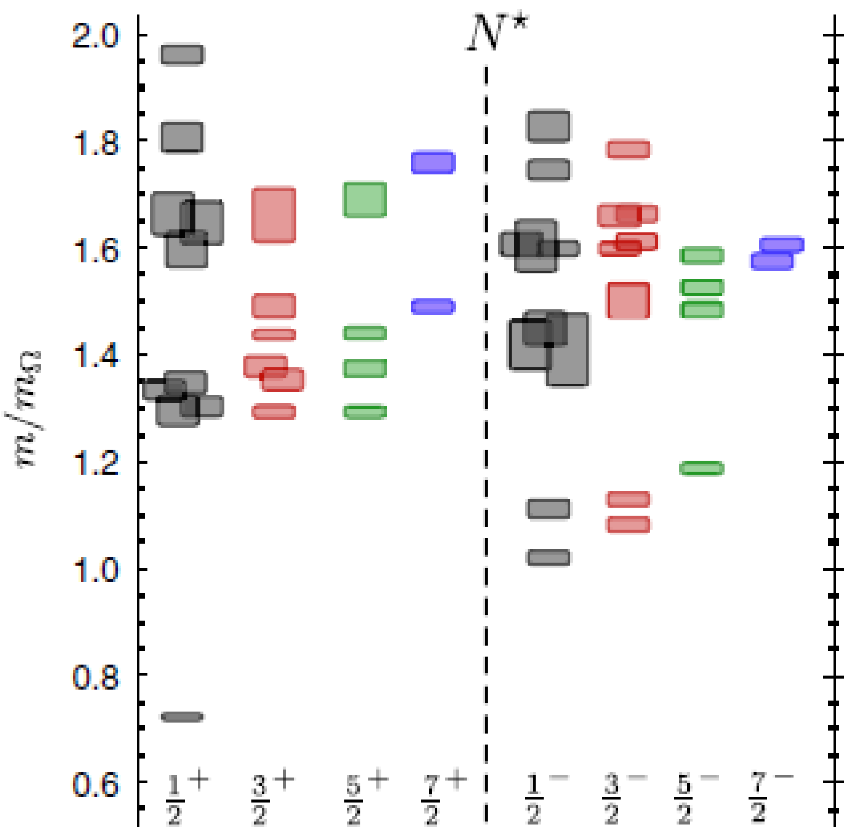
  $\pi^- p \to n\phi$ & $pp \to pp\phi$ & $pn \to d\phi$ → large $g_{N^*N\phi}$

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

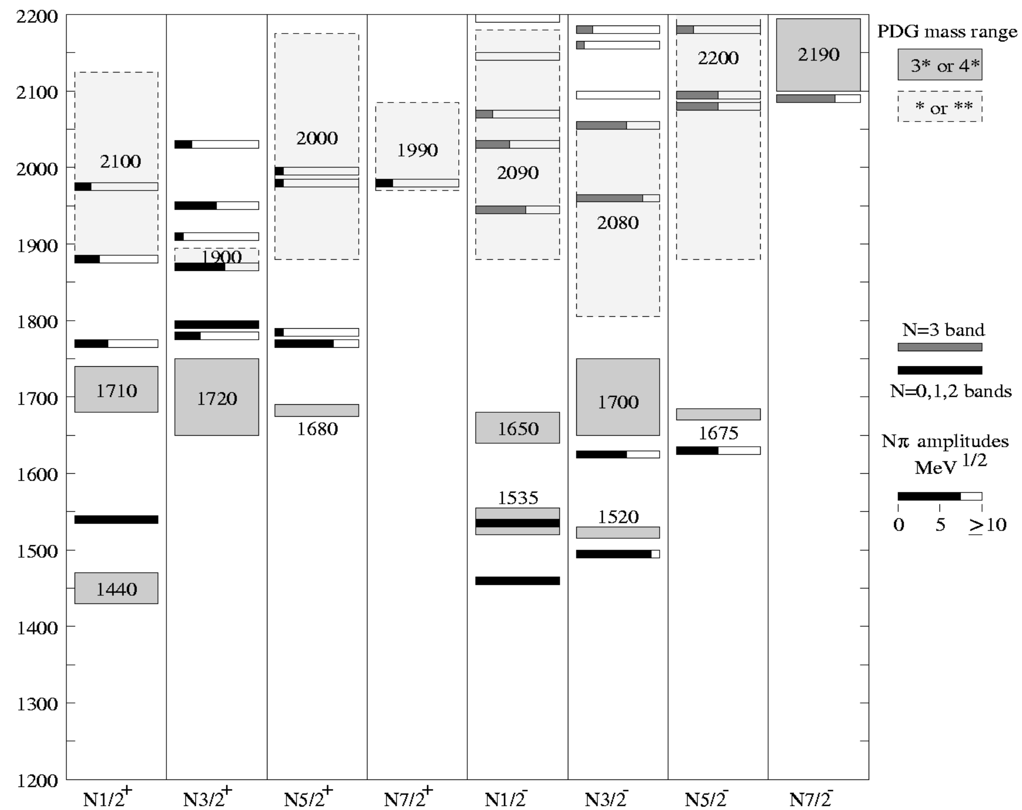
- **Strange decays of Λ*(1670) : PDG → large $g_{\Lambda^*\Lambda\eta}$**

  narrower width (35MeV) than Λ*(1405)

Problems for quenched q^3 picture for baryon resonances:
1) "Missing resonances" ; 2) mass ordering for the lowest ones

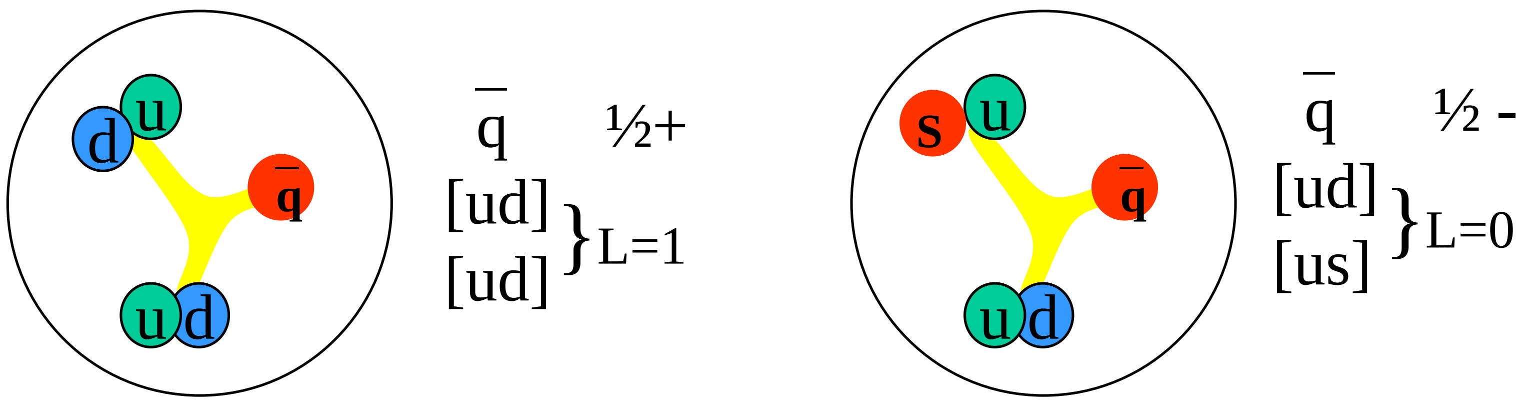


Lattice, R.Edwards et al, PRD84(2011)074508



q^3 model, Capstck&Roberts, PPNP45(2000)S241

Why N*(1535) 1/2$^-$ is heavier than N*(1440) 1/2$^+$?



N*(1535) ~ uud (L=1) + ε [ud][us] $\bar{s}$ + …

N*(1440) ~ uud (n=1) + ξ [ud][ud] $\bar{d}$ + …

Λ*(1405) ~ uds (L=1) + ε [ud][su] $\bar{u}$ + …

N*(1535): [ud][us] $\bar{s}$ → larger coupling to Nη, Nη', Nϕ & KΛ, weaker to Nπ & KΣ, and heavier !

B.C. Liu & B.S.Zou, PRL96 (2006) 042002

quench vs un-quench 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 ?		
$a_0(980)$	$\bar{u}u - \bar{d}d$,	$[\bar{u}\,\bar{s}][us] - [\bar{d}\,\bar{s}][ds]$
$f_0(980)$	$\bar{s}s$,	$[\bar{u}\,\bar{s}][us] + [\bar{d}\,\bar{s}][ds]$
$\kappa(800)$	$\bar{s}d$,	$[\bar{s}\,\bar{u}][ud]$
$f_0(600)$	$\bar{u}u + \bar{d}d$,	$[\bar{u}\,\bar{d}][ud]$

$D^*_{s0}(2317) \sim \bar{s}c\ (L=1) + [\bar{q}\,\bar{s}][qc] + DK + \ldots$

$D^*_{s1}(2460) \sim \bar{s}c\ (L=1) + D^*K + \ldots$

$X(3872) \sim \bar{c}c\ (L=1) + [\bar{q}\,\bar{c}][qc] + D^*D + \ldots$

Alternative pictures :

Hadronic molecules

N*(1440) ~ Nσ

N*(1535) ~ KΣ-KΛ

Λ*(1405) ~ KN-Σπ

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

Penta-quark states

N*(1440) ~ [ud][ud] $\bar{q}$

N*(1535) ~ [ud][us] $\bar{s}$

Λ*(1405) ~ [ud][sq] $\bar{q}$

Σ* ~ 1430 MeV **Oller, Meissner, Oh, Khemchandani, ...**

Ξ* ~ 1610 MeV **Oh, Ramos, Oset, …**

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 + …

Draging out $\bar{q}q$ from gluon field –
an important excitation mechanism for hadrons !
multiquark components are important for hadrons !

Totally different predictions for the lowest Ξ* & Ω* :

	$\bar{q}q^4$ (L=0)	q^3 (L=1)
Ξ* (1/2⁻)	[us][ds] $\bar{d}$ ~ 1540 MeV	uss ~ 1800 MeV
Ω*(1/2⁻)	[us] ss $\bar{u}$ ~ 1840 MeV	sss ~ 2000 MeV
	Yuan-An-Wei-Zou-Xu, PRC87(2013)025205	Capstick-Isgur, PRD34(1986)2809

Ω*(3/2⁻) as sss - $\bar{u}$usss mixture : ~ 1780 MeV

by instanton/NJL interaction

An-Metsch-Zou, PRC87(2013) 065207; An-Zou, PRC89 (2014) 055209

Σ^* in PDG: **** Σ (1189)$1/2^+$ $\Sigma^*(1385)3/2^+$ $\Sigma^*(1670)3/2^-$
$\Sigma^*(1775)5/2^-$ $\Sigma^*(1915)5/2^+$ $\Sigma^*(2030)7/2^+$

*** $\Sigma^*(1660)1/2^+$ $\Sigma^*(1750)1/2^-$ $\Sigma^*(1940)3/2^-$ $\Sigma^*(2250)$??

** $\Sigma^*(1620)1/2^-$ $\Sigma^*(1690)$?? $\Sigma^*(1880)1/2^+$
$\Sigma^*(2080)3/2^+$ $\Sigma^*(2455)$?? $\Sigma^*(2620)$??

* $\Sigma^*(1480)$?? $\Sigma^*(1560)$?? $\Sigma^*(1580)3/2^-$ $\Sigma^*(1770)1/2^+$
$\Sigma^*(1840)3/2^+$ $\Sigma^*(2000)3/2^-$ $\Sigma^*(2070)5/2^+$ $\Sigma^*(2100)7/2^-$
$\Sigma^*(3000)$?? $\Sigma^*(3170)$??

Ξ^* in PDG: **** $\Xi(1320)$ $1/2^+$, $\Xi(1530)$ $3/2^+$
*** $\Xi(1690)$, $\Xi(1820)$ $3/2^-$, $\Xi(1950)$, $\Xi(2030)$
** $\Xi(2250)$, $\Xi(2370)$
* $\Xi(1620)$, $\Xi(2120)$, $\Xi(2500)$

Ω^* in PDG: $\Omega(1672)$ $3/2^+$ **** , Ω (2250)***, Ω (2380) **, Ω (2470) **

Experiment knowledge on hyperon states still very poor !

Difficulties to pin down pentaquarks

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 fading 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 θ(1540) by Jaffe&Wilczek, PRL91, 232003

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

2004: supported by 10 expts → θ(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

3. Pentaquarks with hidden charm – P_c states

New direction for hunting for pentaquarks:

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

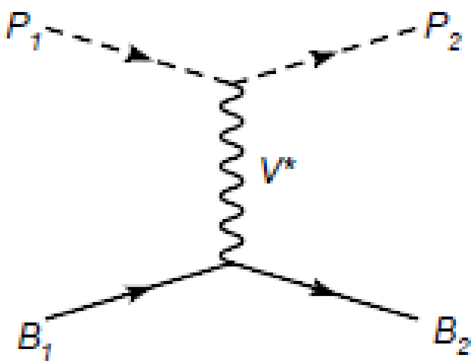
Λ*(1405) $\bar{q}quds$

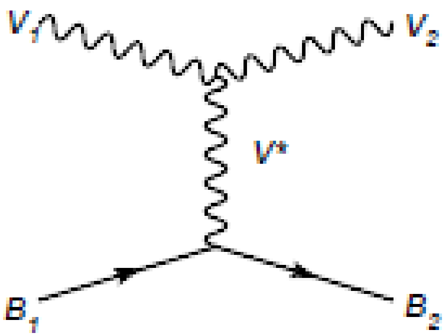
Λ*(4210) $\bar{c}cuds$ J.J.Wu, R.Molina, E.Oset, B.S.Zou. Phys.Rev.Lett. 105 (2010) 232001

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

From KΣ, $\bar{K}N$ → $\bar{D}\Sigma_c$, $\bar{D}_s\Lambda_c$ → $B\Sigma_b$, $B_s\Lambda_b$ 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
	$(1/2,0)$			πN	ηN	$\eta' N$	$K\Sigma$		$\eta_c N$	
N* - $\bar{D}\Sigma_c$		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
	$(1/2,0)$			ρN	ωN	$K^*\Sigma$			$J/\psi N$	
N*- $\bar{D}^*\Sigma_c$		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.

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:

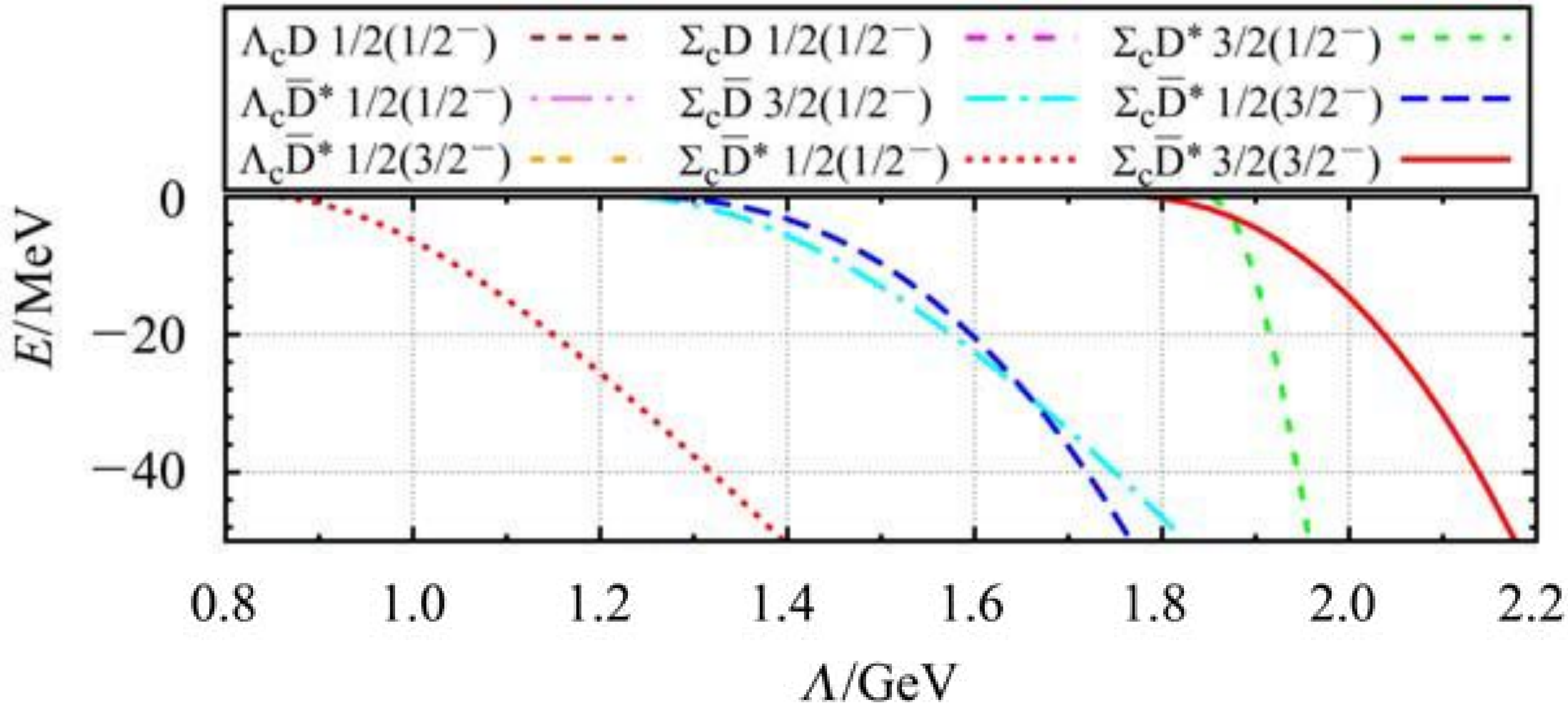
Pion exchange → $\bar{D}^*\Sigma_c$ $(1/2^-, 3/2^-)$ ~ 4.5 GeV

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) Δ* state -- ~ 4300 MeV



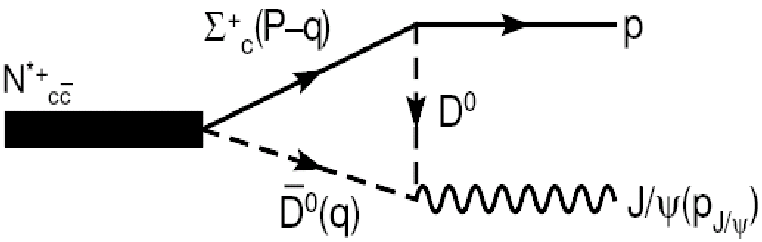
S.G.Yuan, K.W.Wei, J.He, H.S.Xu, B.S.Zou, “Study of $\bar{c}cqqq$ five quark system with three kinds of quark-quark hyperfine interaction,” Eur. Phys. J. A48 (2012) 61

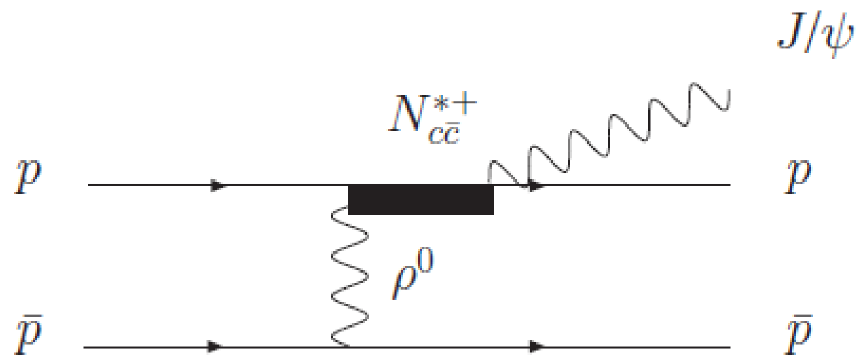
	CM		*FS*		*Inst.*	
J^P	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$
$\frac{1}{2}^-$	4273	4267	4084	3933	4209	4114
$\frac{1}{2}^-$	4377	4363	4154	4013	4216	4131
$\frac{1}{2}^-$	4453	4377	4160	4119	4277	4204
$\frac{1}{2}^-$	4469	4471	4171	4136	4295	4207
$\frac{1}{2}^-$	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

Prediction for PANDA





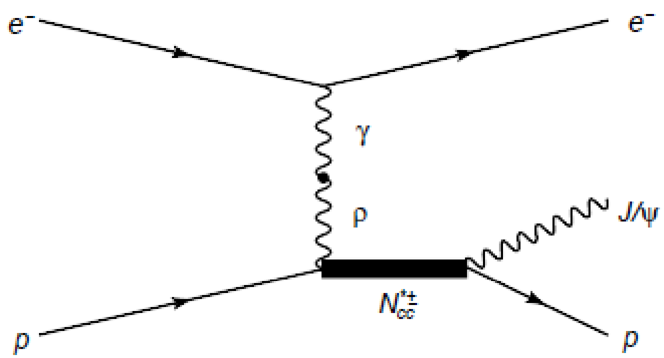
$\bar{p}p \rightarrow \bar{p}pJ/\psi$ > 0.1 nb

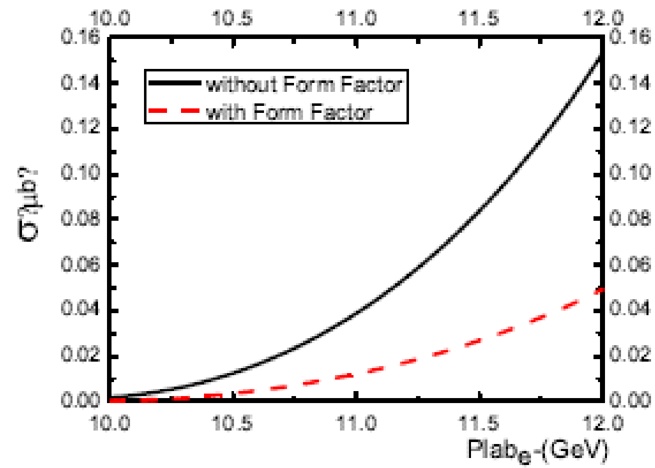
> 100 events per day at PANDA/FAIR by L=10^{31} $cm^{-2}s^{-1}$

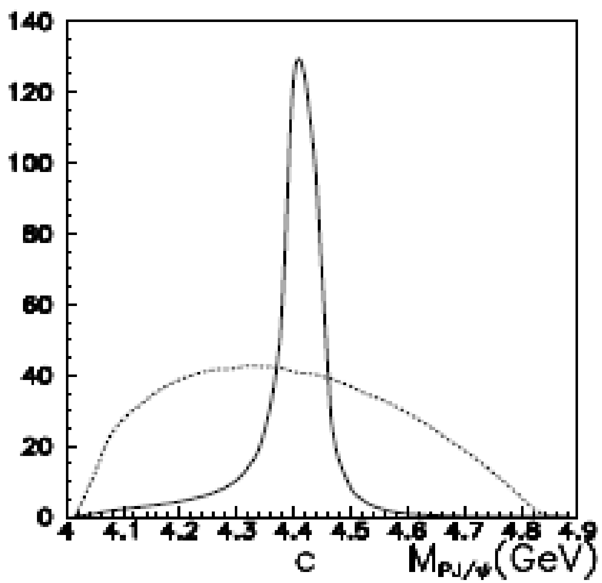
These Super-heavy narrow N* and Λ*
can be found at PANDA !

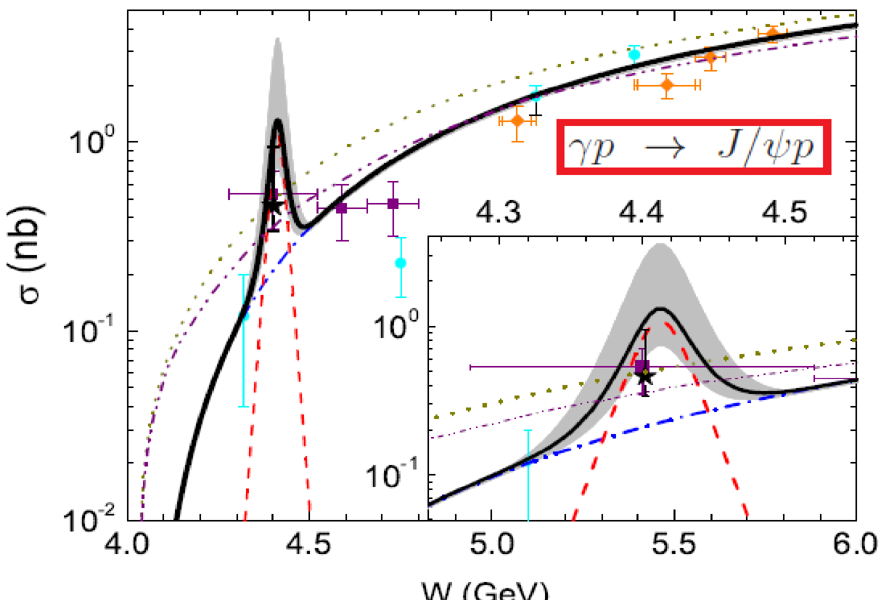
Albrecht Gillitzer@Juelich had a plan to find them at PANDA

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.

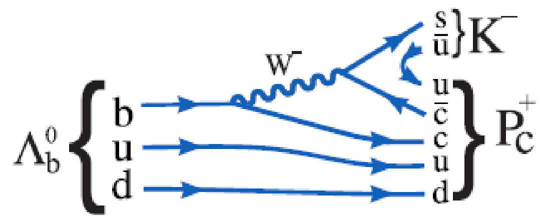
b) E.J.Garzon, J.J.Xie, "Effects of a $N_{c\bar{c}}$ resonance with hidden charm in the $\pi^- p \rightarrow D^- \Sigma_c^+$ reaction near threshold", PRC 92 (2015) 035201

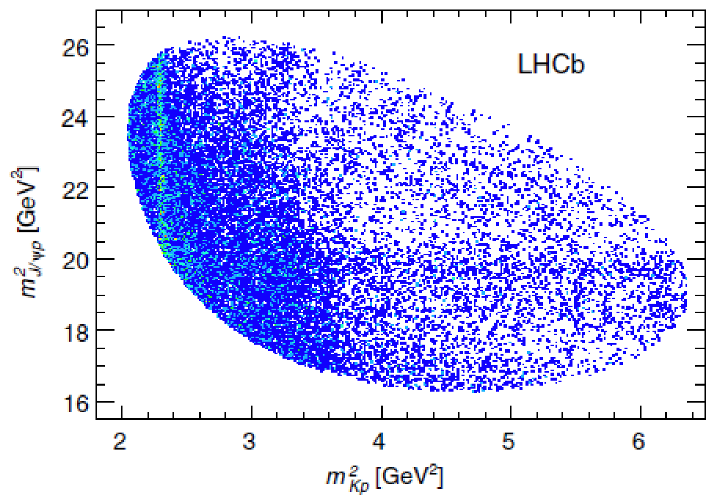
c) X.Y.Wang, X.R.Chen, "Production of the superheavy baryon Λ*(4209) in kaon-induced reaction", EPJA51 (2015) 85

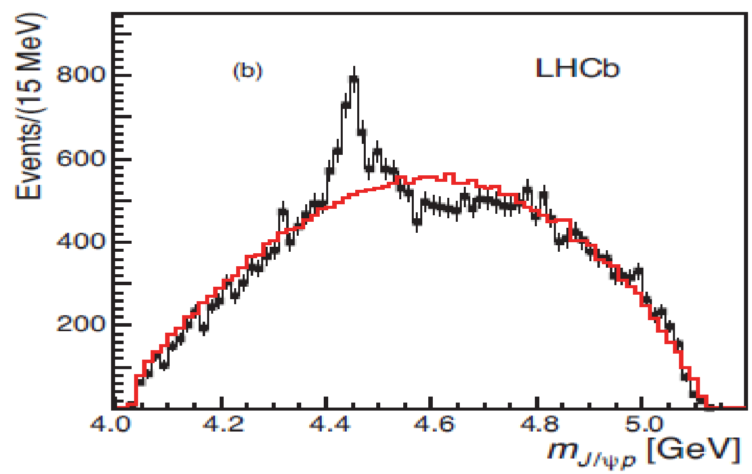
LHCb observation of P_c pentaquarks

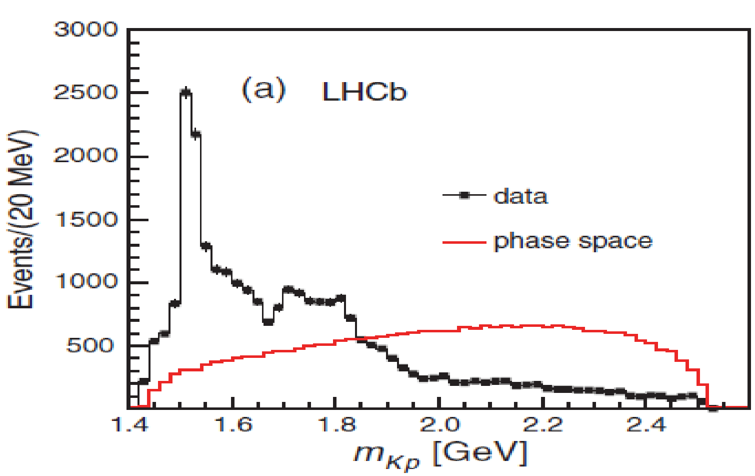
LHCb, Phys.Rev.Lett. 115 (2015) 072001 :

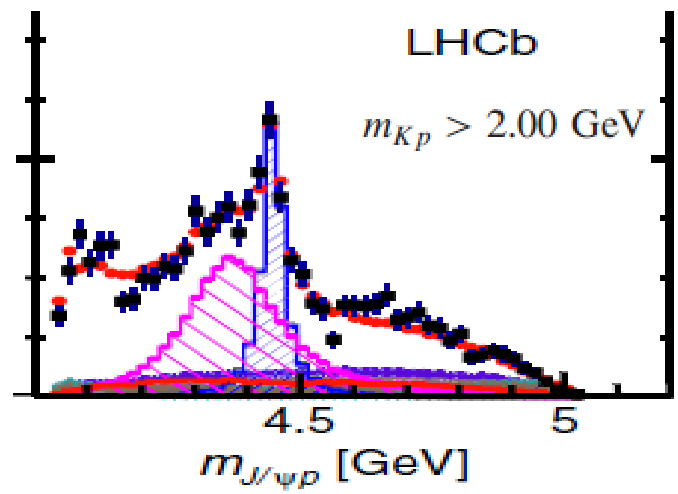
Observation of two N* from $\Lambda_b^0 \to J/\psi K^- p$



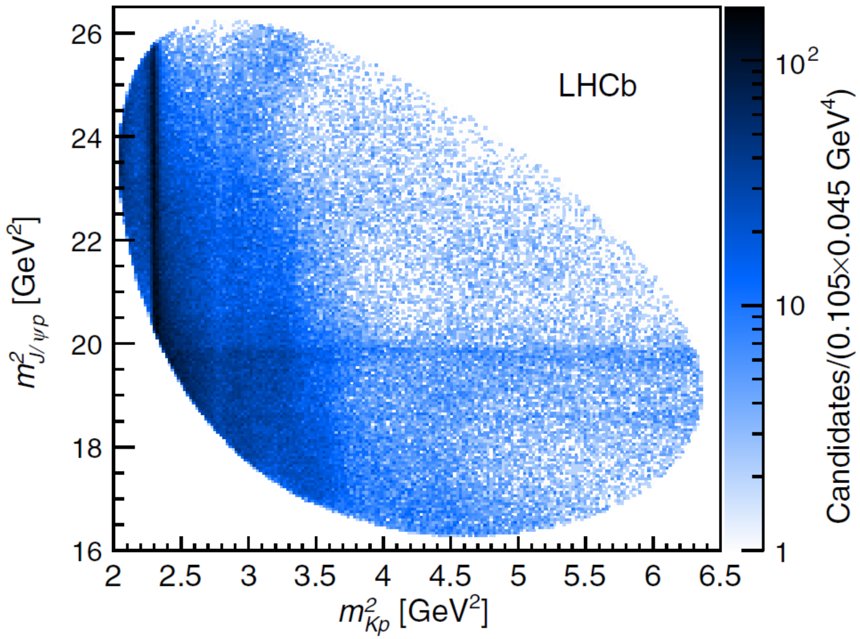


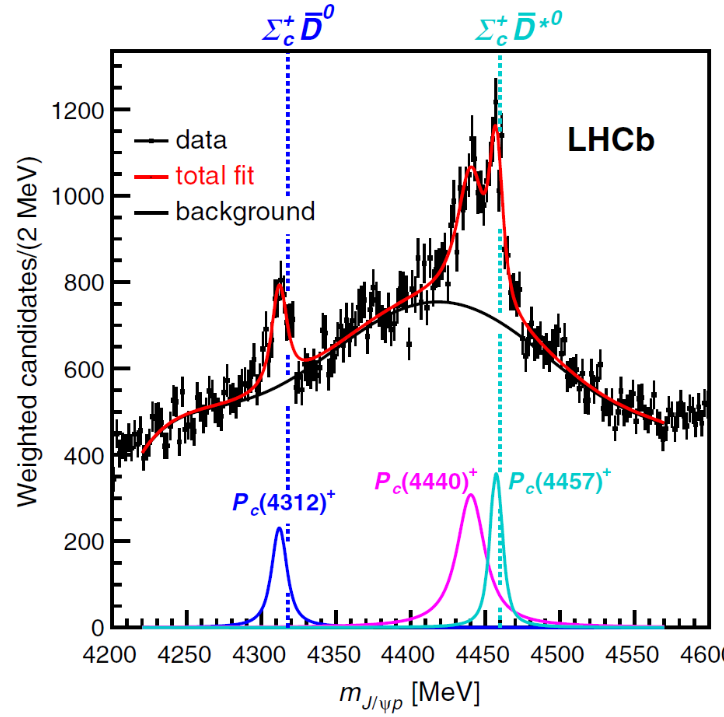






LHCb, Phys.Rev.Lett. 122 (2019) 222001



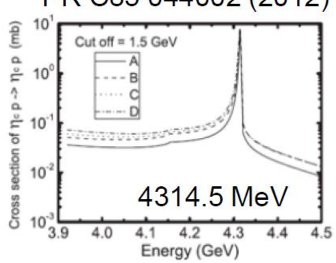


State	M [MeV]	Γ [MeV]	(95% C.L.)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(<27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(<49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm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

Comparison to numerical predictions

- Many theoretical predictions for $\Sigma_c^+\bar{D}^{(*)0}$ 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

Λ - cut off on exchanged meson mass.

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

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

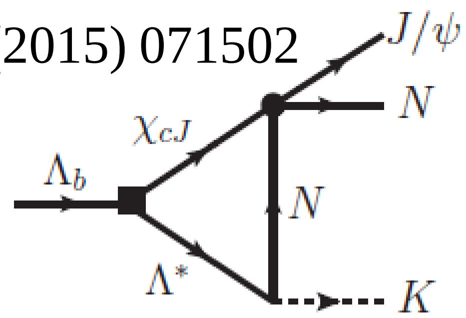
R.Chen, X.Liu, X.Q.Li, S.L.Zhu, PRL115 (2015) 132002;
L.Roca, J.Nieves, E.Oset, PRD92 (2015) 094003;
J.He, PLB 753 (2016)547 ;

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

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

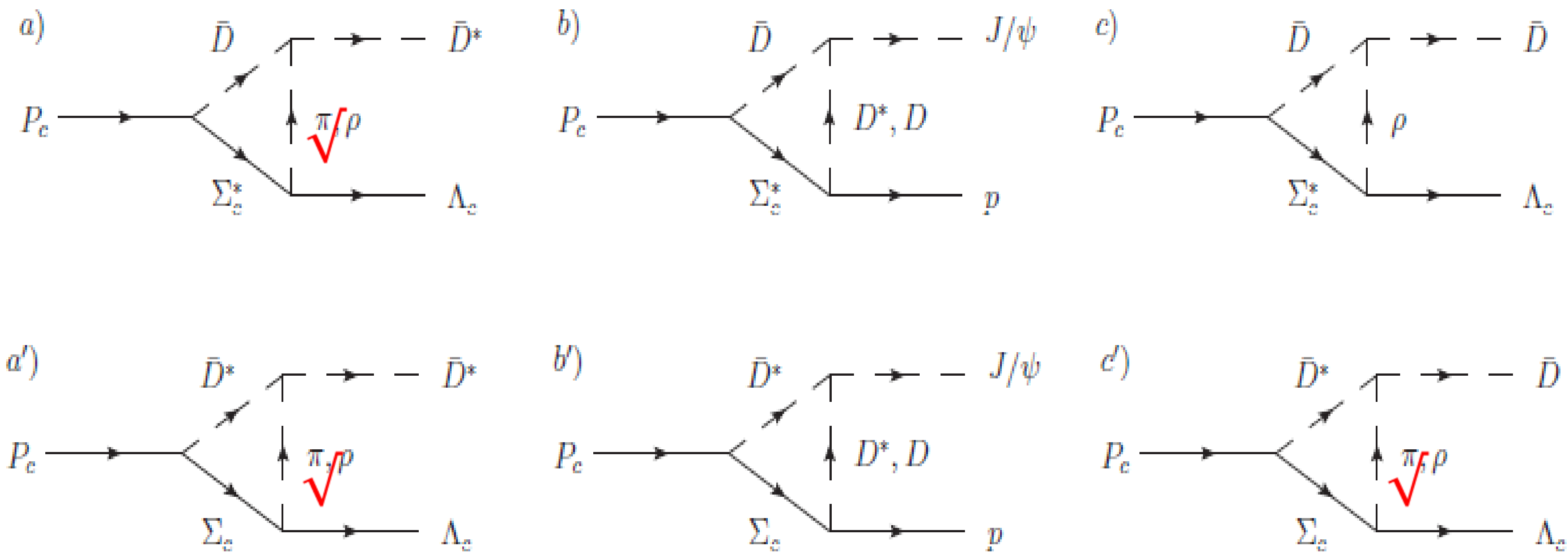
[3] J.He, PLB 753 (2016)547 ; PRD95 (2017)074004
Y.H.Lin, C.W.Shen, F.K.Guo, B.S.Zou, PRD95(2017)114017

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

→ **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

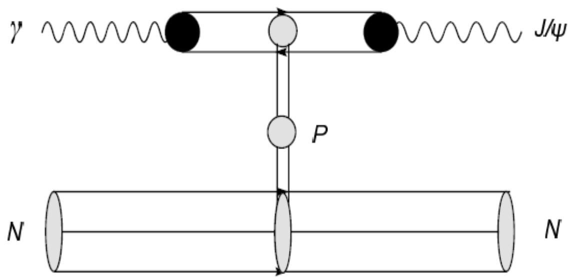
Partial decay widths of $P_c^+(4380)$ & $P_c^+(4450)$

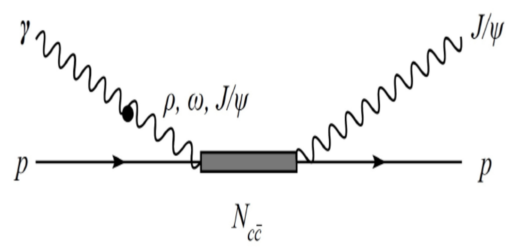
	Widths (MeV)			
	$P_c(4380)$		$P_c(4450)$	
Mode	$\bar{D}\Sigma_c^*(\frac{3}{2}-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}-)$	$\bar{D}^*\Sigma_c(\frac{5}{2}+)$
$\bar{D}^*\Lambda_c$	131.3 √	35.3 √	72.3 √	20.5 √
$J/\psi p$	3.8	16.6	16.3	4.0
$\bar{D}\Lambda_c$	1.2	17.0 √	41.4 √	18.8 √
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

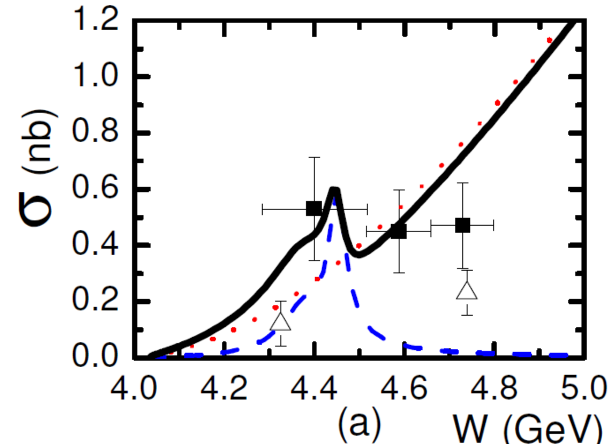
It is very important to study $P_c \rightarrow \bar{D}^*\Lambda_c$ & $\bar{D}\Lambda_c$!

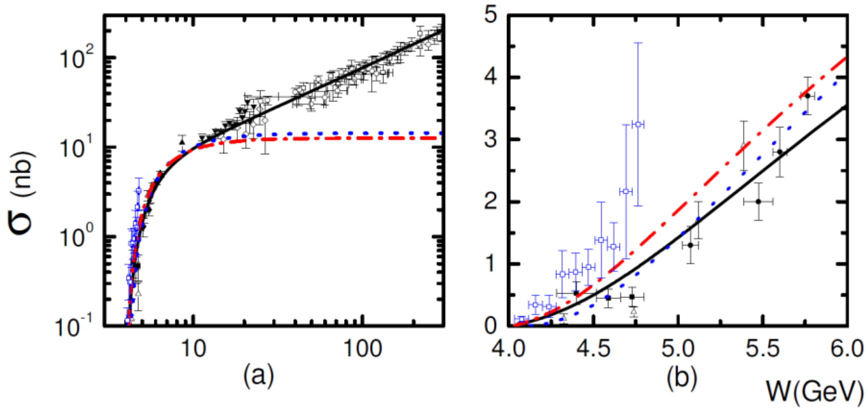
Pin down P_c^+ states from their photo-production

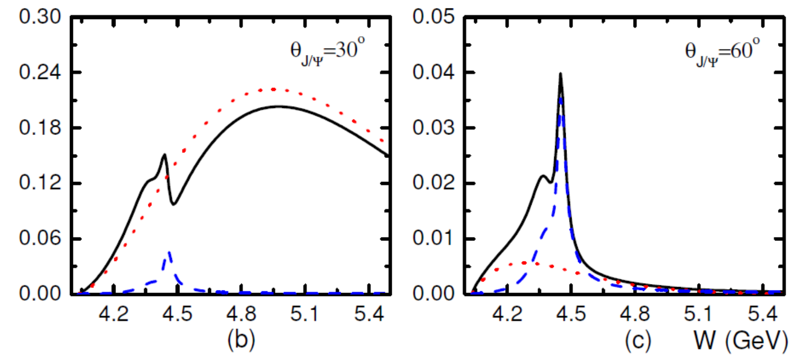
J.J.Wu, T.S.H.Lee, B.S.Zou, **arXiv:1906.05375**

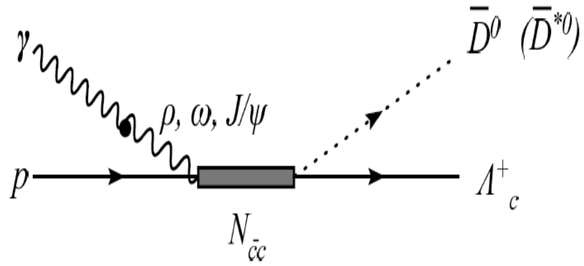


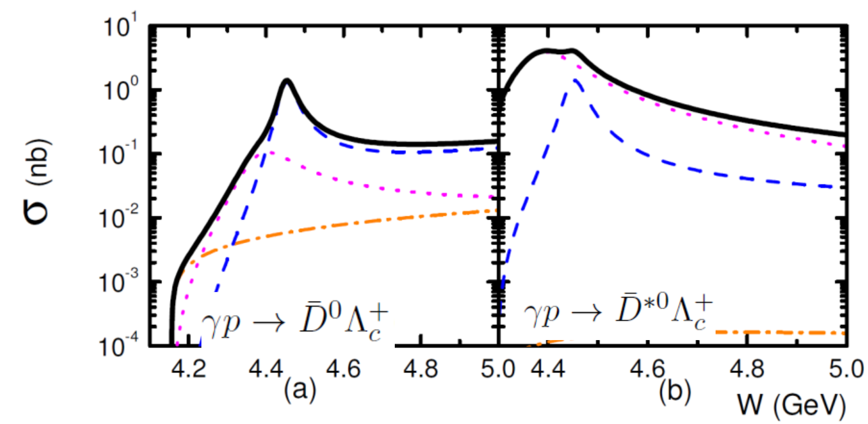








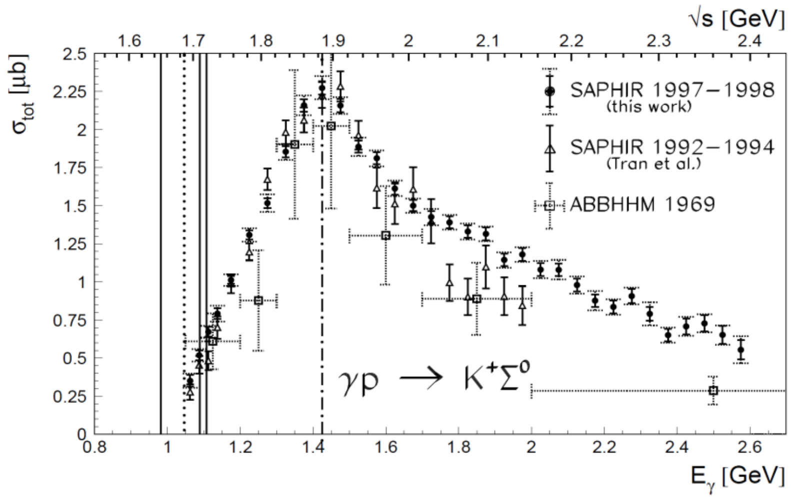


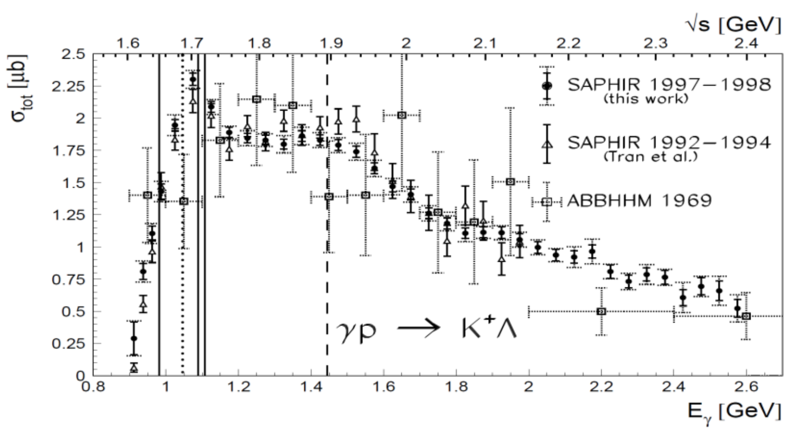


4. Strange & beauty partners of P_c states

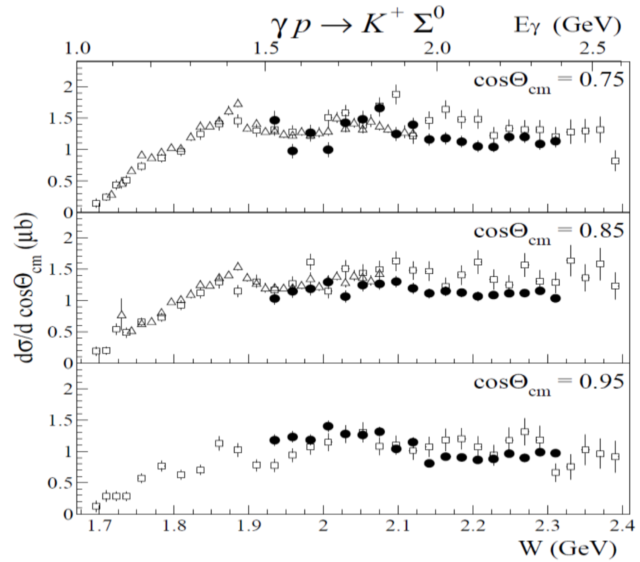
Strangeness partners of P_c states: N*(1875) & N*(2080)

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

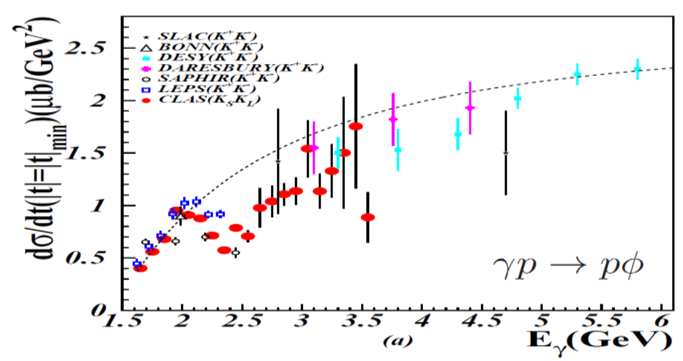




Glander, K.H. *et al.* EPJA19 (2004) 251-273



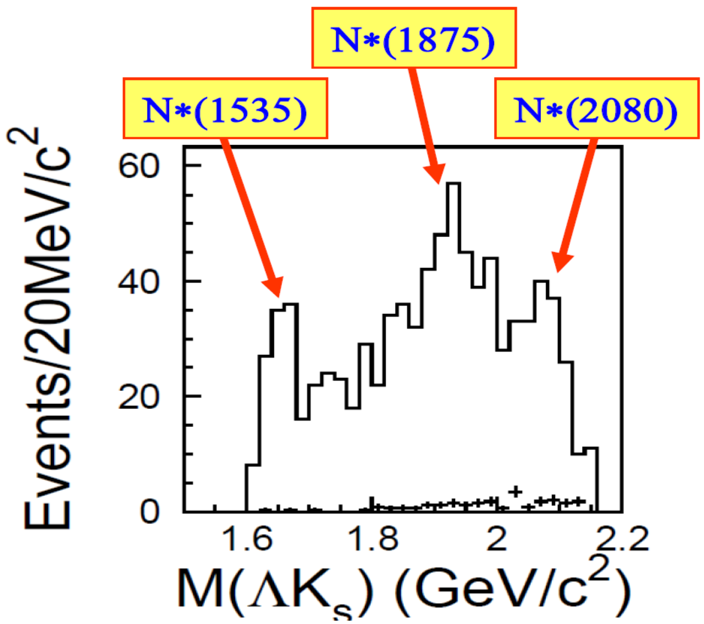
LEPS, PRC73 (2006) 035214

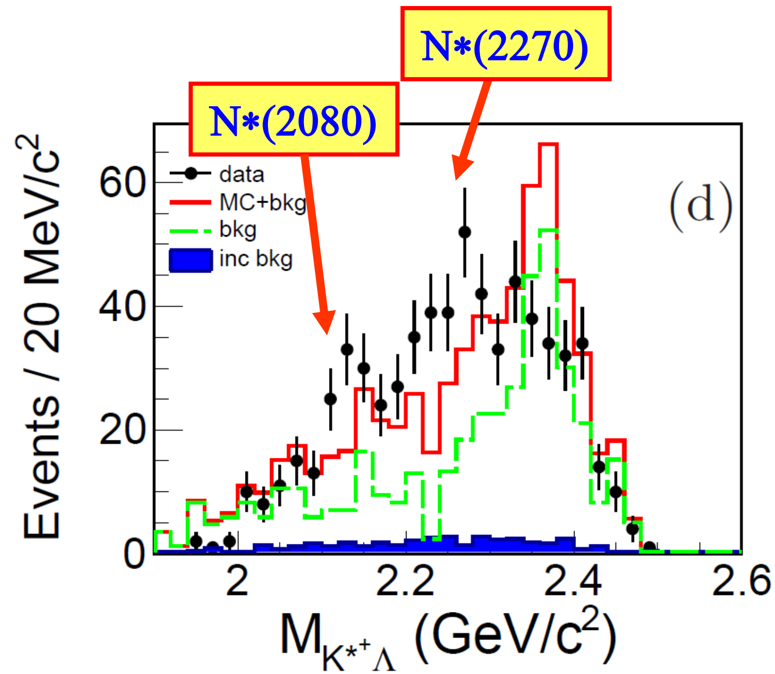


CLAS, PRC89 (2014) 055206

Strangeness partners of P_c states at BES ?

N*(1875)	N*(2080)	N*(2270)
KΣ* ~1880	K*Σ ~ 2086	K*Σ* ~ 2280





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

BESII, PLB659 (2008) 789

$\chi_{c0} \rightarrow \bar{p}K^{*+}\Lambda$ **+c.c.**

BESIII, arXiv:1908.02979

Physics Letters B 709 (2012) 70–76

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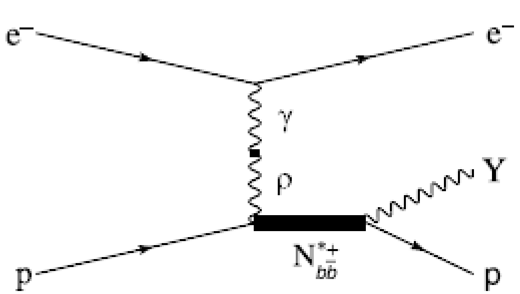
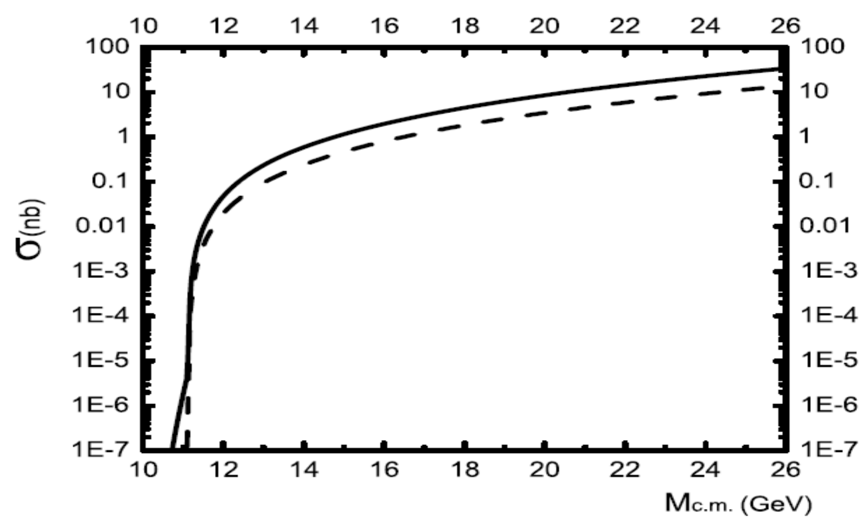
Prediction of super-heavy N^* and Λ^* resonances with hidden beauty

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

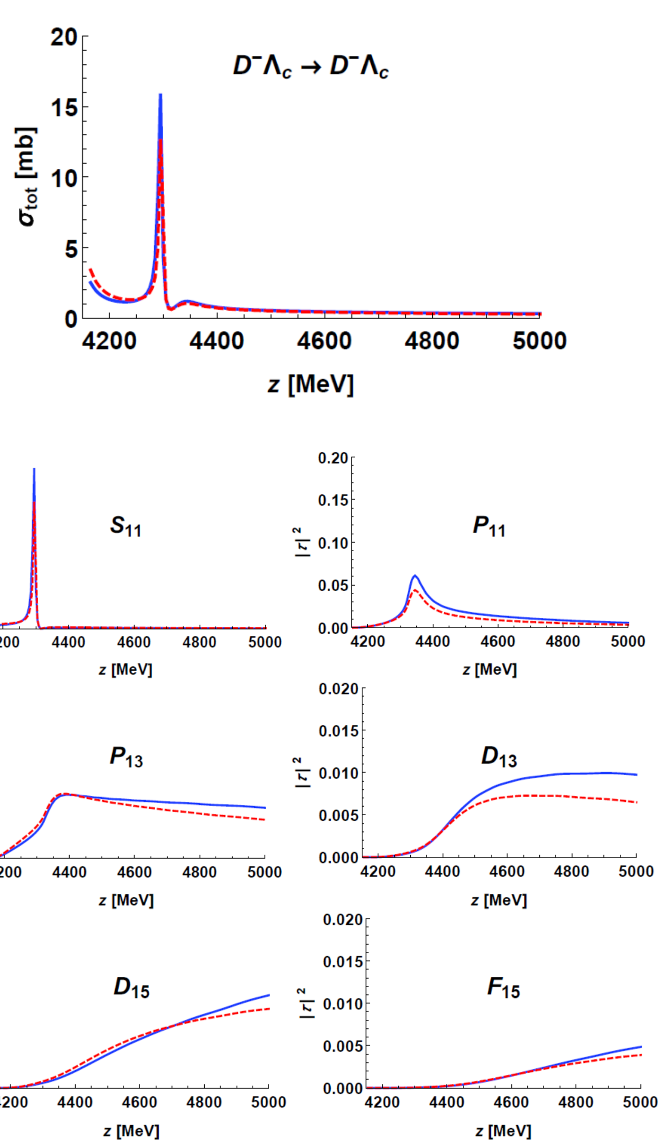
M (MeV)	Γ (MeV)	Γ_i (MeV)					
		πN	ηN	$\eta' N$	$K\Sigma$	$\eta_b N$	
11 052	1.38	0.10	0.21	0.11	0.42	0.52	$1/2^-$
		ρN	ωN	$K^*\Sigma$	ΥN		
11 100	1.33	0.09	0.30	0.39	0.51		$1/2^-$, $3/2^-$

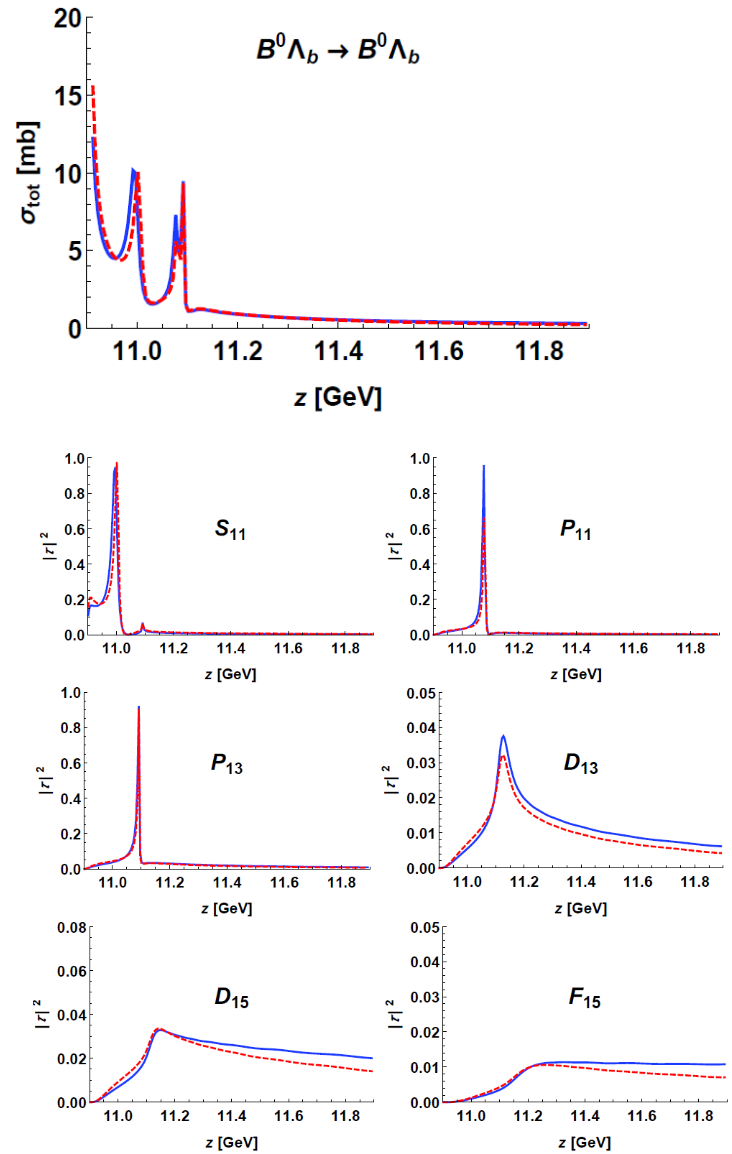




$\bar{D}\Lambda_c - \bar{D}\Sigma_c$ and $B\Lambda_b - B\Sigma_b$ dynamical coupled channel study

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

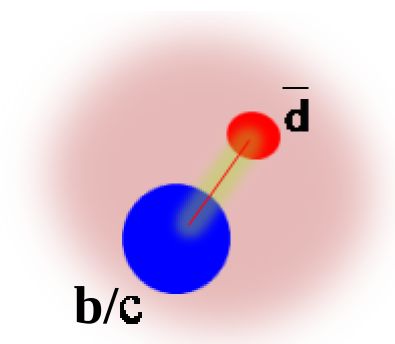
5. Prospects

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

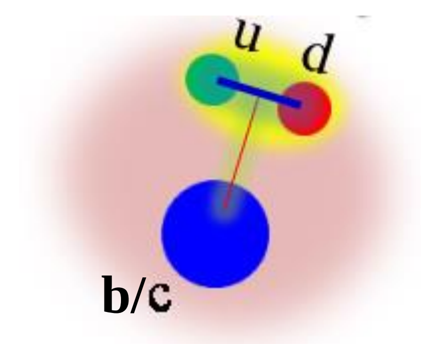
$\bar{c}cuud$ & $\bar{c}cuds$ → sss - $\bar{q}qsss$ → cqq - $\bar{q}qcqq$
→ hyperons → light baryons

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