Five-quark Components in Baryons and Pentaquark States

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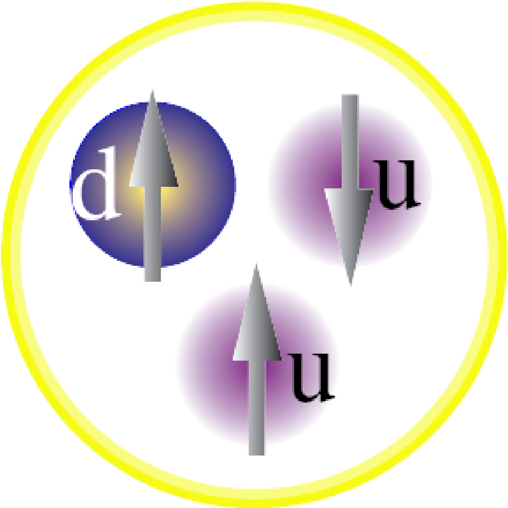
Outline:

- 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



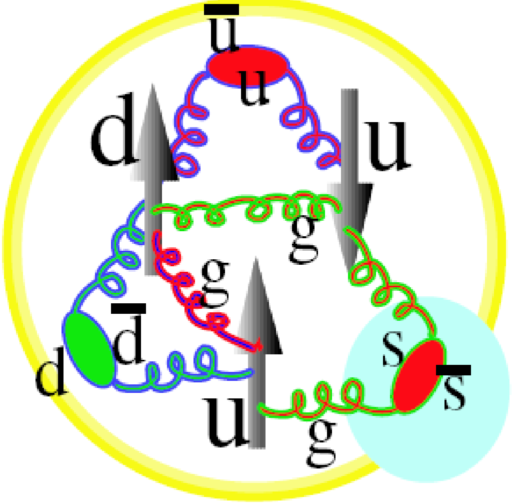
($Q^2 = 0$ GeV^2)

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)

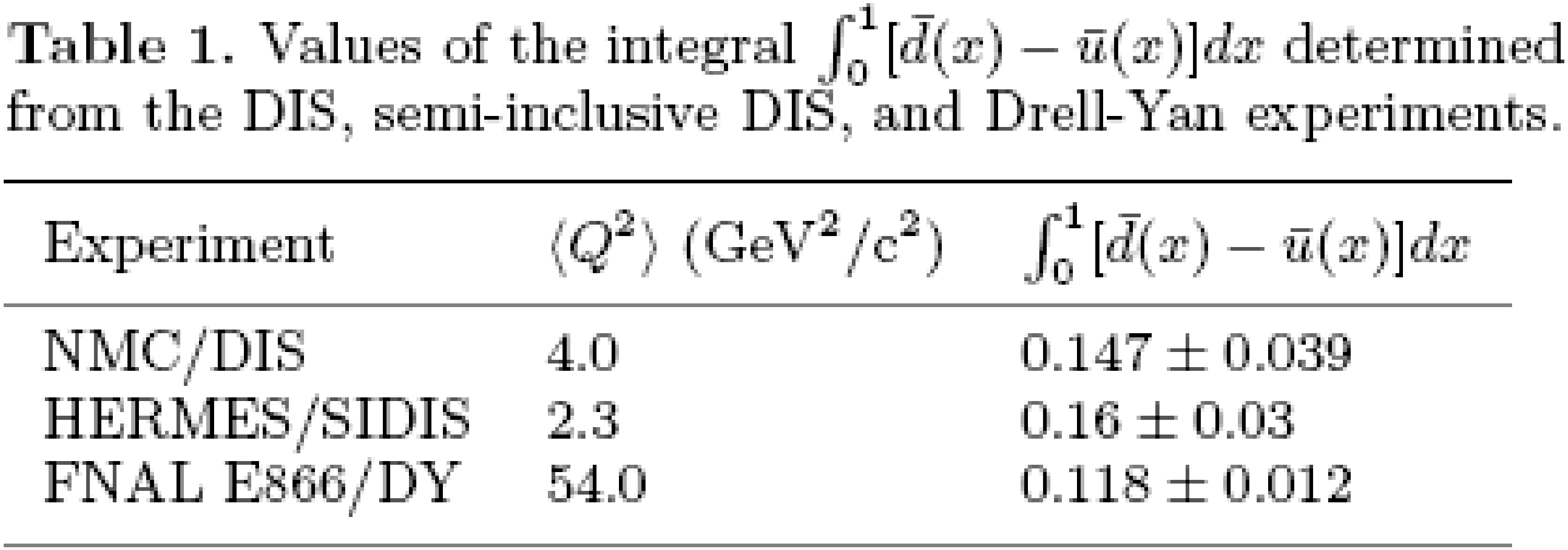


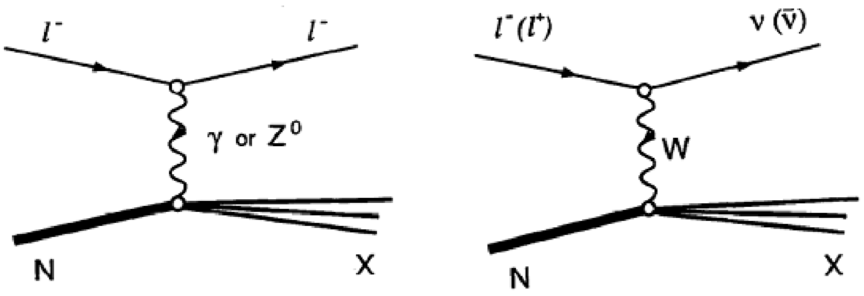
Table 1. Values of the integral $\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx$ determined from the DIS, semi-inclusive DIS, and Drell-Yan experiments.

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

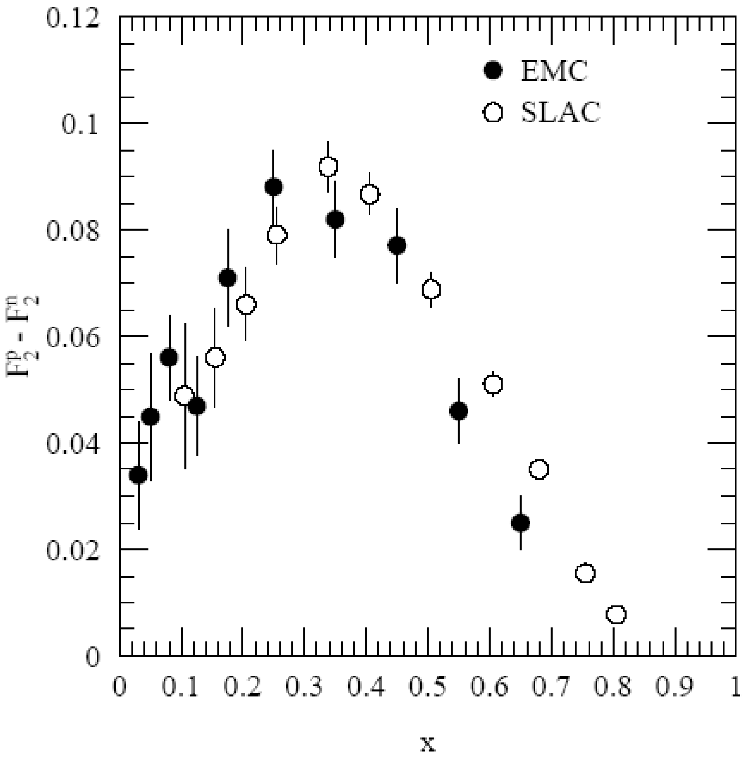
DIS Gottfried Sum Rule : assuming $\bar{d} = \bar{u}$

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

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



Deep Inelastic Scattering (DIS)



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

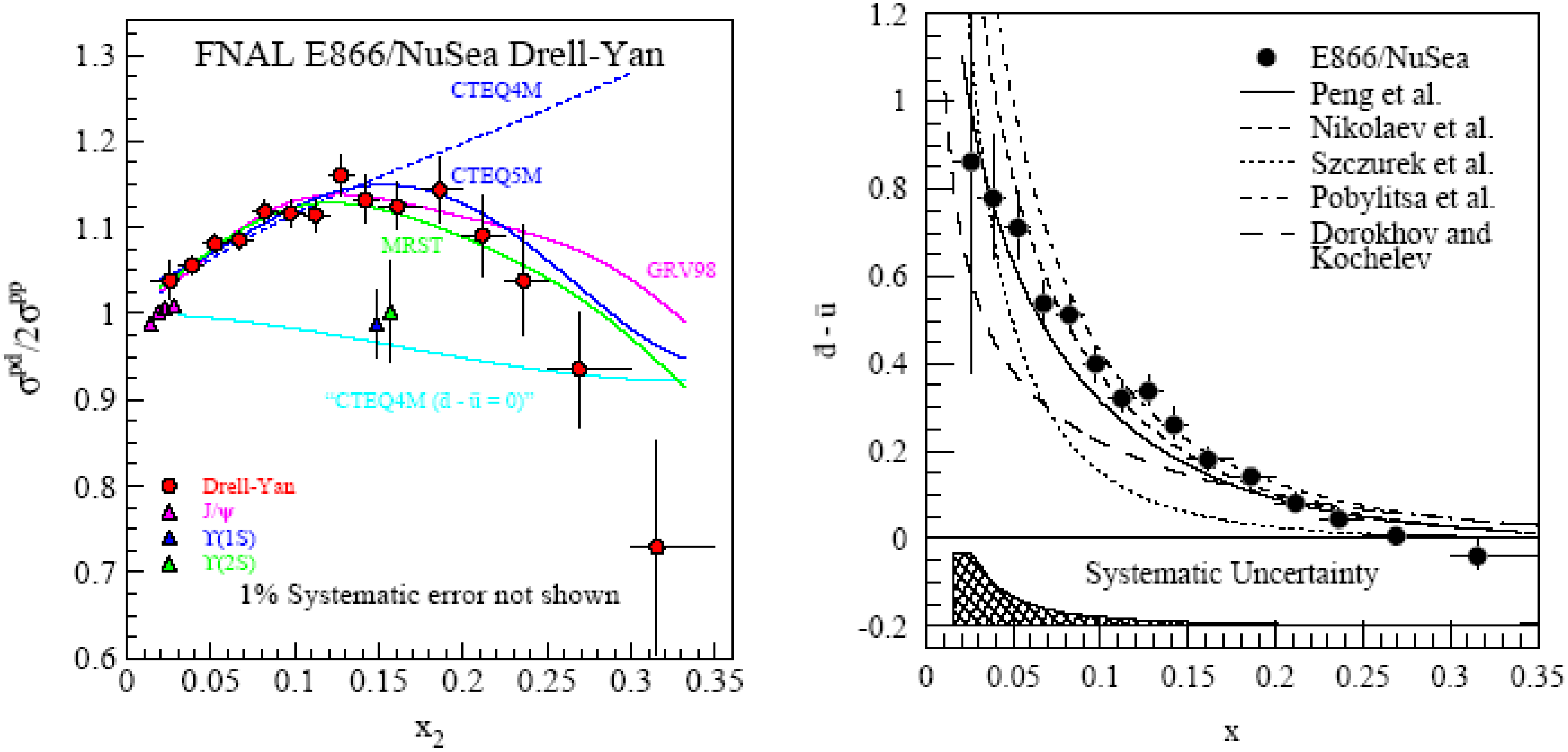
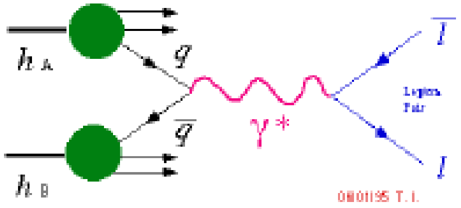


FIGURE 1. Left panel: Cross section ratios of $p+d$ over $2(p+p)$ for Drell-Yan, J/Ψ, and Υ production from FNAL E866. Right panel: Comparison of E866 $\bar{d}-\bar{u}$ data with calculations from various models [2].

The Drell-Yan Process



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

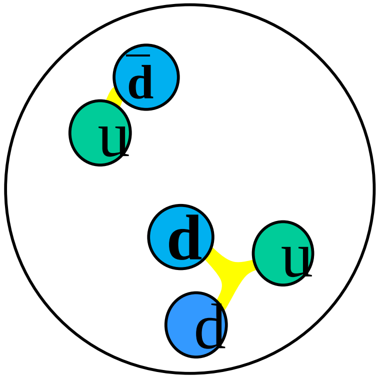
Two major theoretical schemes for $\bar{d} - \bar{u} \sim 0.12$

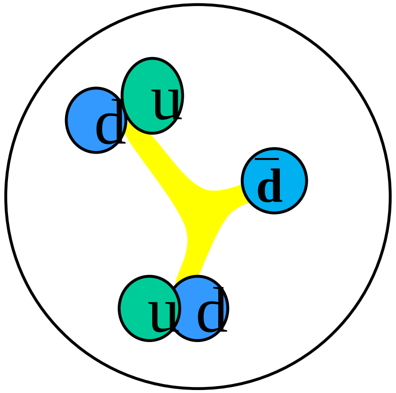
Meson cloud picture: Thomas, Speth, Henley, Meissner, Miller, Weise, Oset, Brodsky, Ma, …

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

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

$$\begin{tikzcd} & & \mathrm{uudd}\,\bar{d} \quad 1/2 & \\ \mathrm{uud} \arrow[r, leftrightarrow] & \mathrm{uudg} \arrow[ur, leftrightarrow] \arrow[dr, leftrightarrow] & & \dots\dots\dots \\ 1 \quad : & 1 & \mathrm{uudu}\,\bar{u} \quad 1/3 & \end{tikzcd}$$

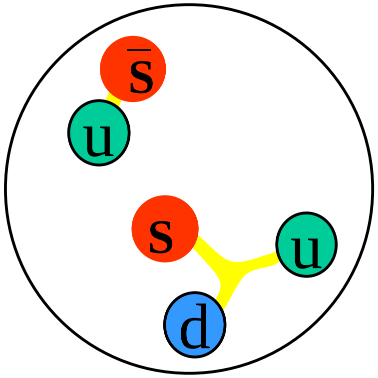
$$p = 0.168\,(\mathrm{uud}) + 0.168\,(\mathrm{uudg}) + 0.084\,(\mathrm{uudd}\,\bar{d}) + 0.056\,(\mathrm{uudu}\,\bar{u})$$

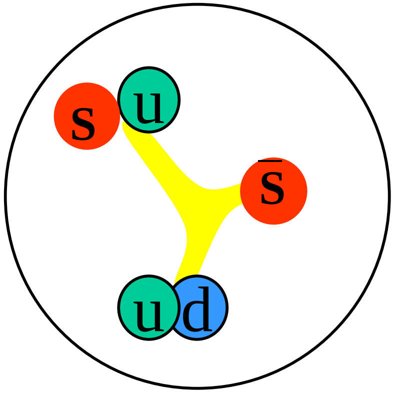
$$+\ 0.084\,(\mathrm{uudgg}) + \dots \qquad \bar{d} - \bar{u} \sim 0.124$$

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

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

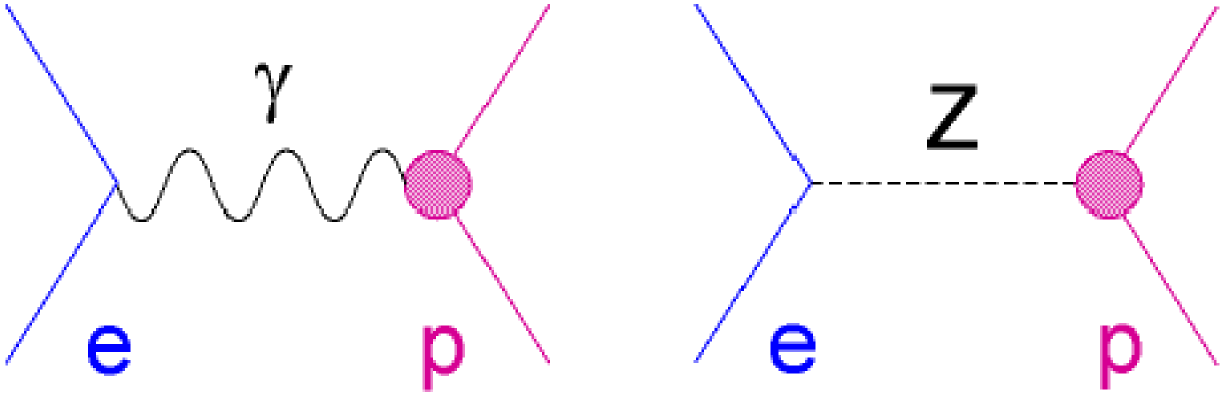
	meson cloud	penta-quark
strange spin Δs :	< 0	< 0
magnetic moment μ_s :	< 0	> 0
strange radium r_s :	< 0	> 0





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

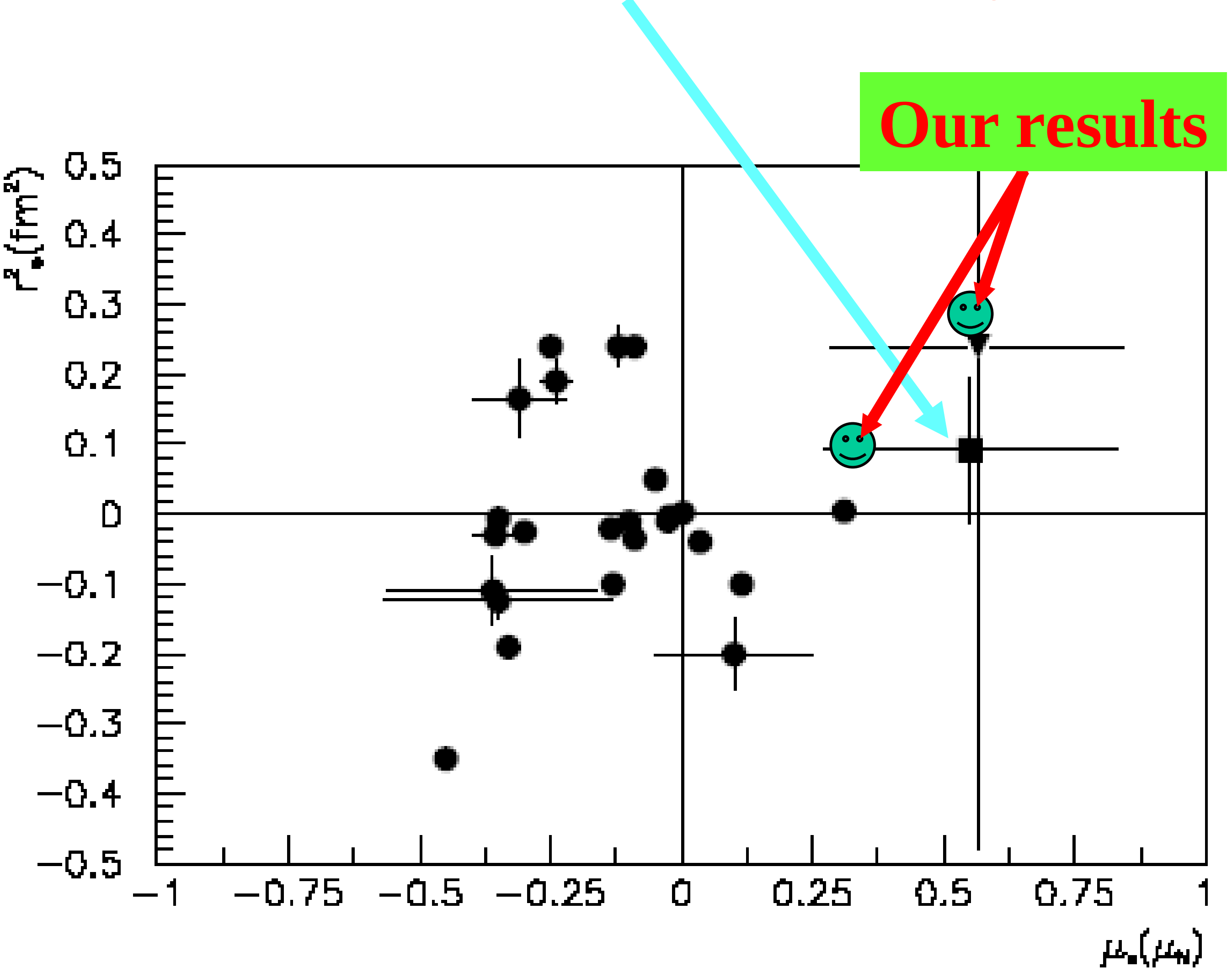
The strange magnetic moment μ_s and radii r_s from parity violating electron scattering



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

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

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

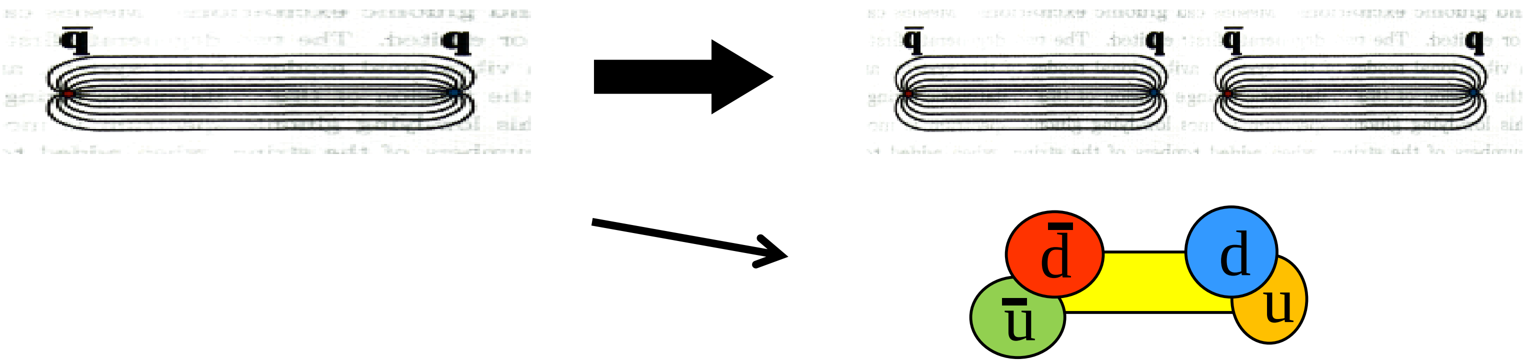
We must go beyond the simple 3q models,

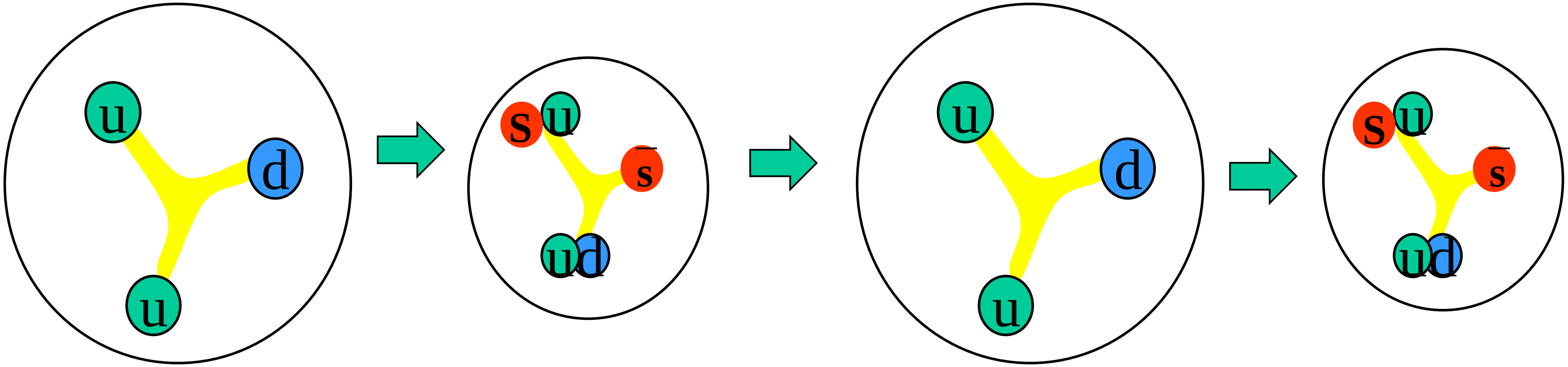
meson cloud vs penta-quark not settled yet.

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) $1/2^-$ ~ $\Lambda^*(1670)$ ~ $[us][ds]\,\bar{s}$ $\bar{K}\Xi - \eta\Lambda$
uud (L=1) $1/2^-$ ~ $N^*(1535)$ ~ $[ud][us]\,\bar{s}$ $\bar{K}\Sigma - \bar{K}\Lambda - \eta N$
uds (L=1) $1/2^-$ ~ $\Lambda^*(1405)$ ~ $[ud][su]\,\bar{u}$ $\bar{K}N - \pi\Sigma$
uus (L=1) $1/2^-$ ~ $\Sigma^*(1390)$ ~ $[us][ud]\,\bar{d}$ $\bar{K}N - \pi\Sigma - \pi\Lambda$

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

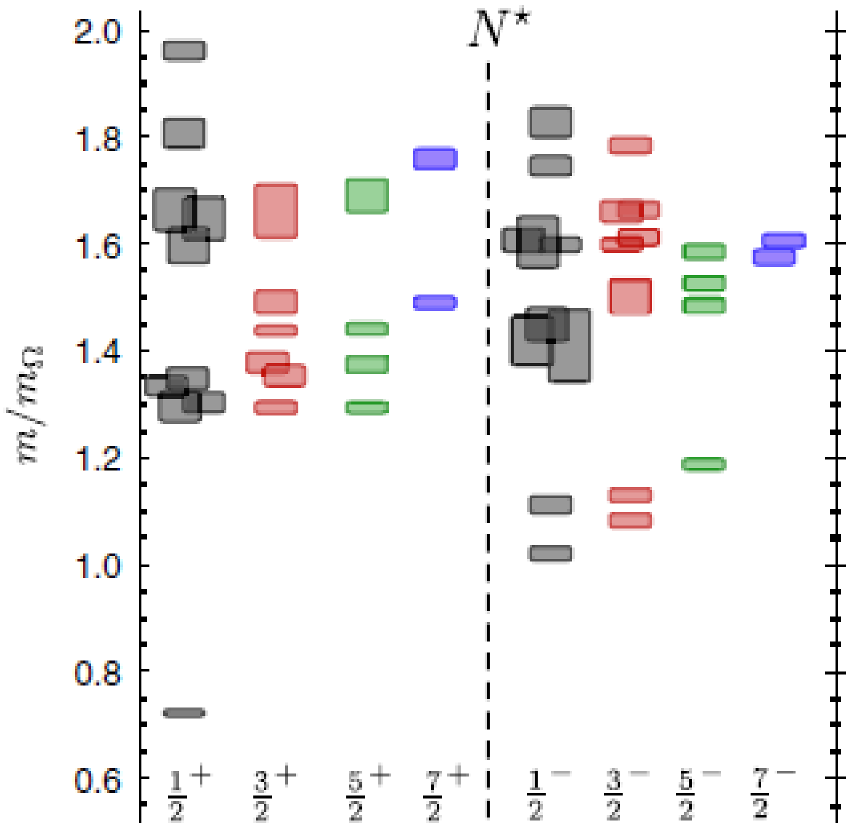
$\pi^- p \to n\phi$ & $pp \to pp\phi$ & $pn \to d\phi$ → large $g_{N^*N\phi}$

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

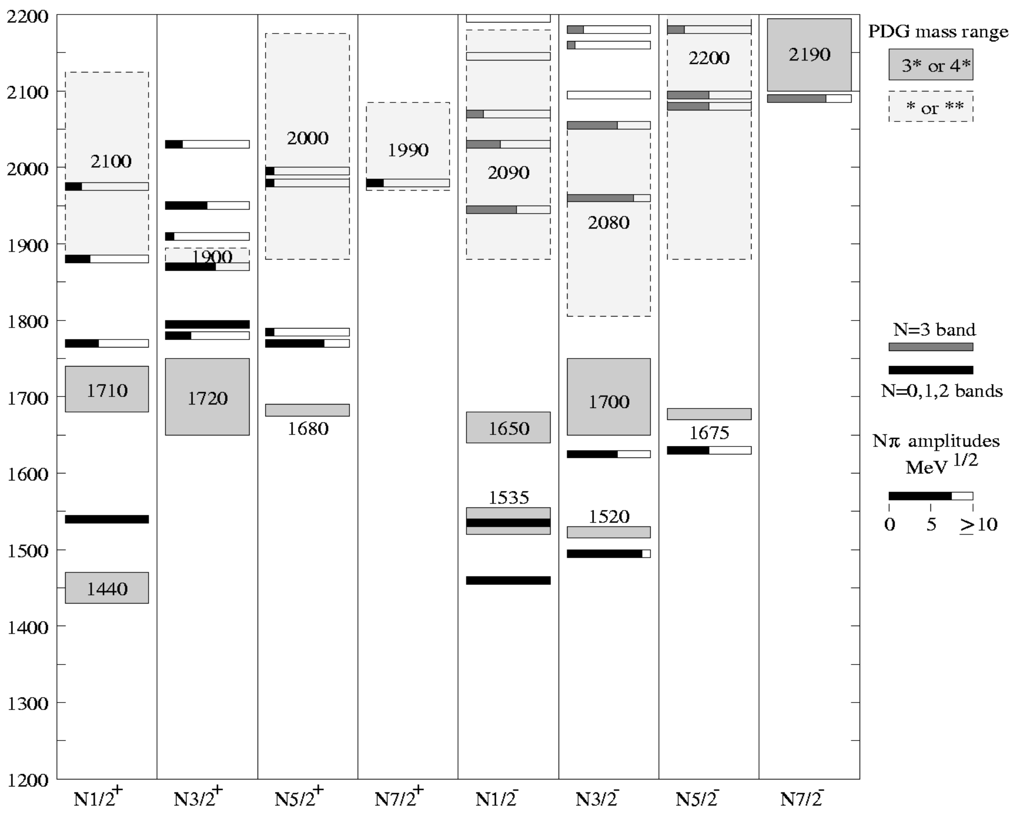
- **Strange decays of $\Lambda^*(1670)$: PDG → large $g_{\Lambda^*\Lambda\eta}$**

narrower width (35MeV) than $\Lambda^*(1405)$

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

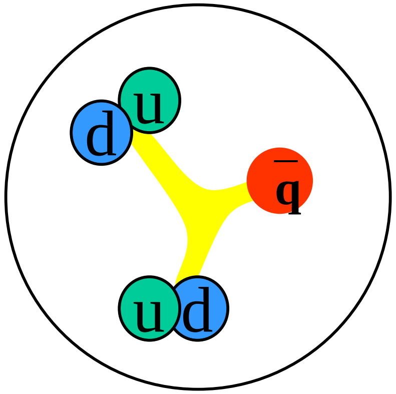


Lattice, R.Edwards et al, PRD84(2011)074508



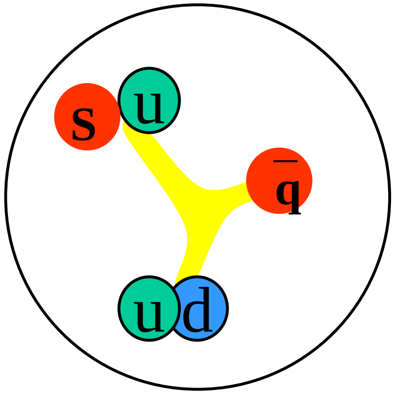
q^3 model, Capstck&Roberts, PPNP45(2000)S241

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



$\bar{q}$ ½+

$\left.\begin{array}{l}[ud]\\ [ud]\end{array}\right\}L=1$



$\bar{q}$ ½ -

$\left.\begin{array}{l}[ud]\\ [us]\end{array}\right\}L=0$

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

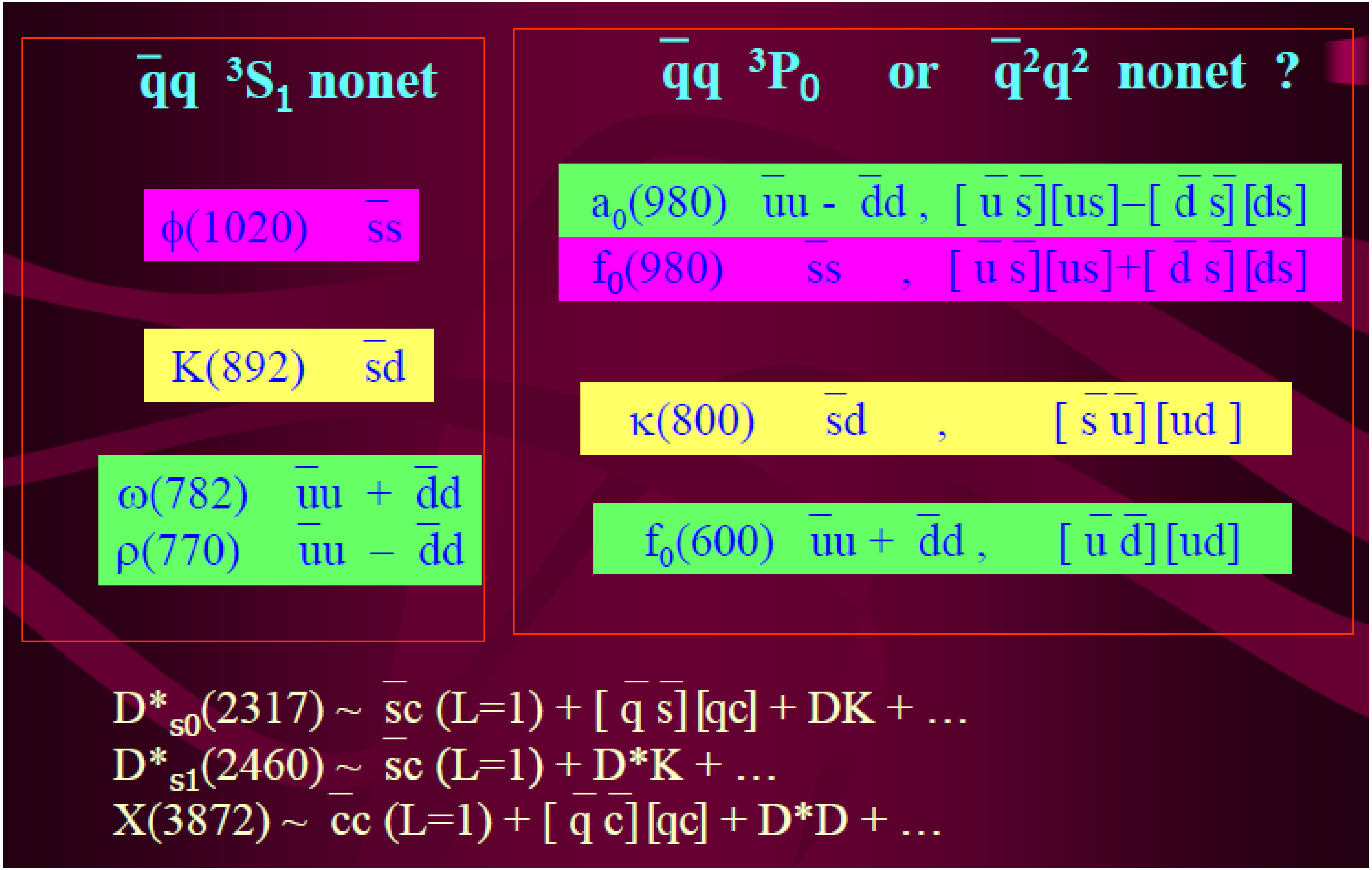
N*(1440) ~ uud (n=1) + ξ [ud][ud] $\bar{d}$ + …

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

φ(1020) $\bar{s}s$

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

ω(782) $\bar{u}u + \bar{d}d$
ρ(770) $\bar{u}u - \bar{d}d$

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

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

κ(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	**Penta-quark states**
N*(1440) ~ Nσ	**N*(1440) ~ [ud][ud] $\bar{q}$**
N*(1535) ~ KΣ-KΛ	**N*(1535) ~ [ud][us] $\bar{s}$**
Λ*(1405) ~ KN-Σπ	**Λ*(1405) ~ [ud][sq] $\bar{q}$**

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

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$^+$ 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)??

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

Ω* in PDG: Ω(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: $\theta^+(1540)$ → 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 → $\theta(1540)$ 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

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

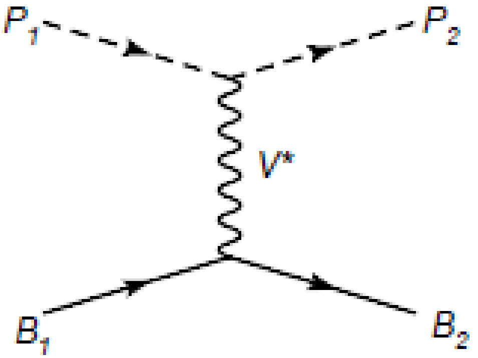
Λ*(1405) $\bar{q}$quds

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

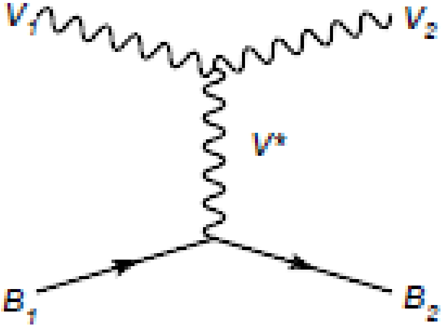
From $K\Sigma$, $\bar{K}N$ → $\bar{D}\Sigma_c$, $\bar{D}_s\Lambda_c$ → $B\Sigma_b$, $B_s\Lambda_b$ bound states

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



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

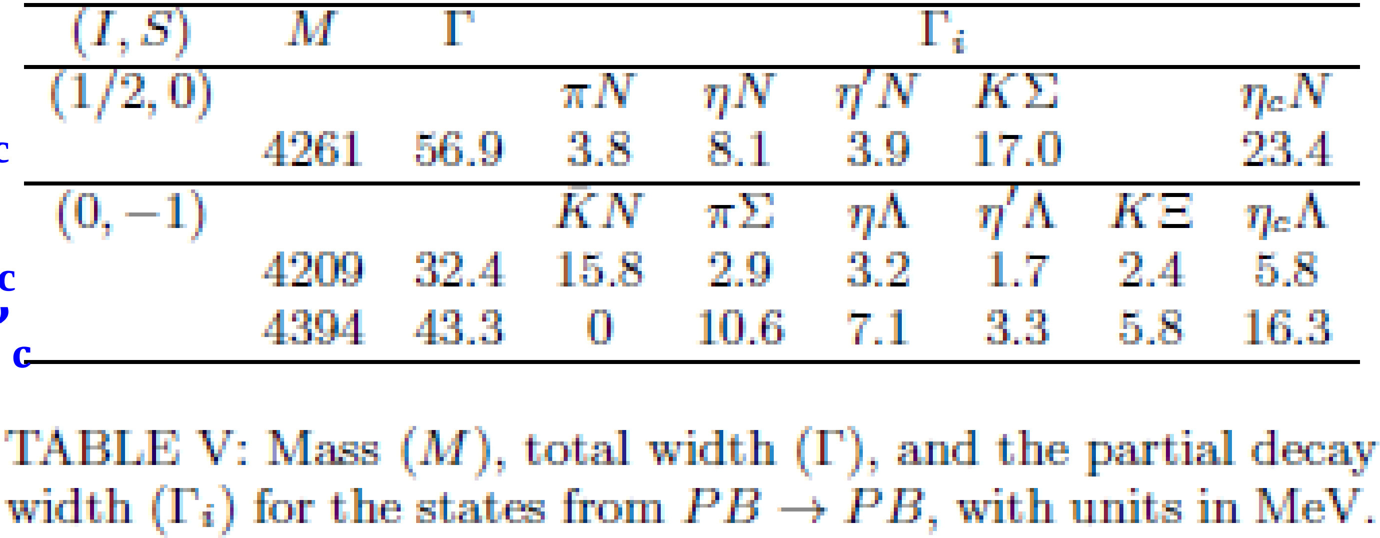
$$\begin{aligned}
V_{ab(P_1B_1\to P_2B_2)} &= \frac{C_{ab}}{4f^2}(E_{P_1} + E_{P_2}), \\
V_{ab(V_1B_1\to V_2B_2)} &= \frac{C_{ab}}{4f^2}(E_{V_1} + E_{V_2})\vec{\epsilon}_1\cdot\vec{\epsilon}_2,
\end{aligned}$$



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

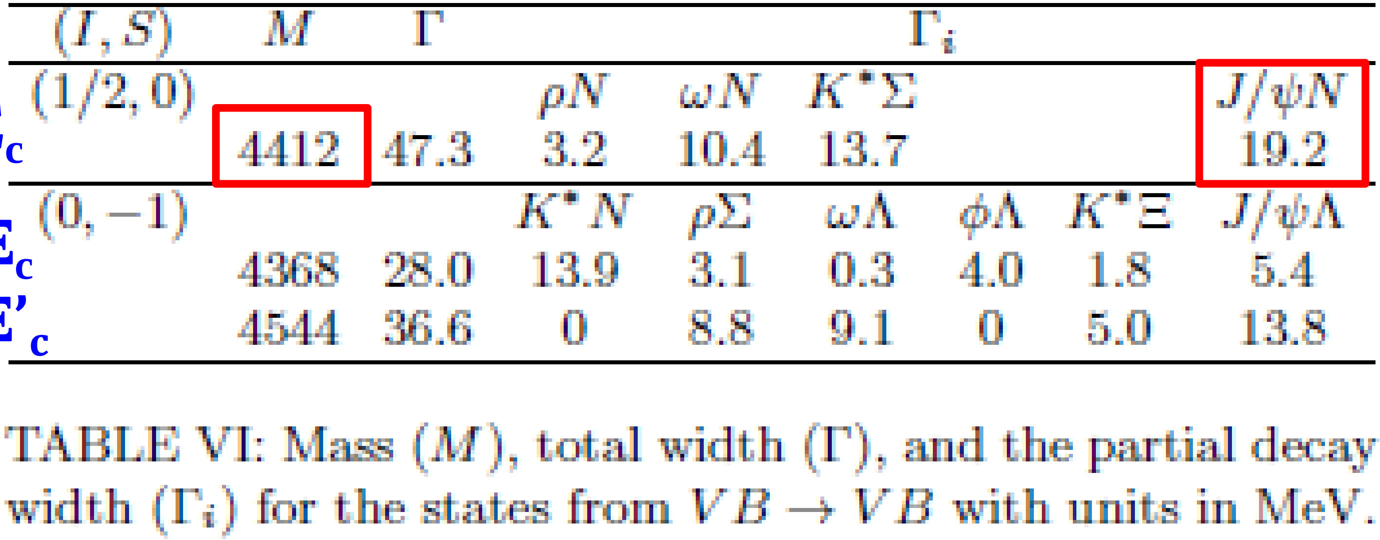
$$T_{ab} = \frac{g_a g_b}{\sqrt{s} - z_R}$$

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	$\eta' N$	$K\Sigma$		$\eta_c N$	$1/2^-$
		4261	56.9	3.8	8.1	3.9	17.0		23.4	
Λ^* $\bar{D}\Xi_c$	$(0,-1)$			$\bar{K}N$	$\pi\Sigma$	$\eta\Lambda$	$\eta'\Lambda$	$K\Xi$	$\eta_c\Lambda$	
		4209	32.4	15.8	2.9	3.2	1.7	2.4	5.8	
$\bar{D}\Xi'_c$		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	$1/2^-$, $3/2^-$
Λ^* $\bar{D}^*\Xi_c$	$(0,-1)$			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	
$\bar{D}^*\Xi'_c$		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 ~ 4.31 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 ~ 4.36 – 4.46 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

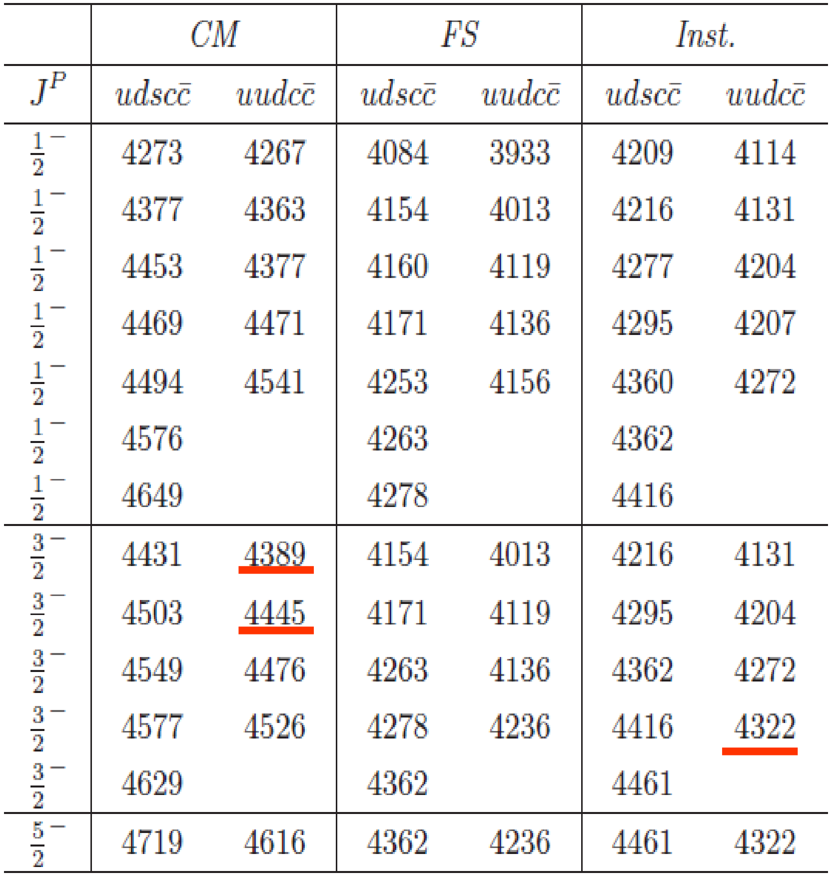
C.W.Xiao, J.Nieves, E.Oset, PRD 88 (2013) 056012:

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

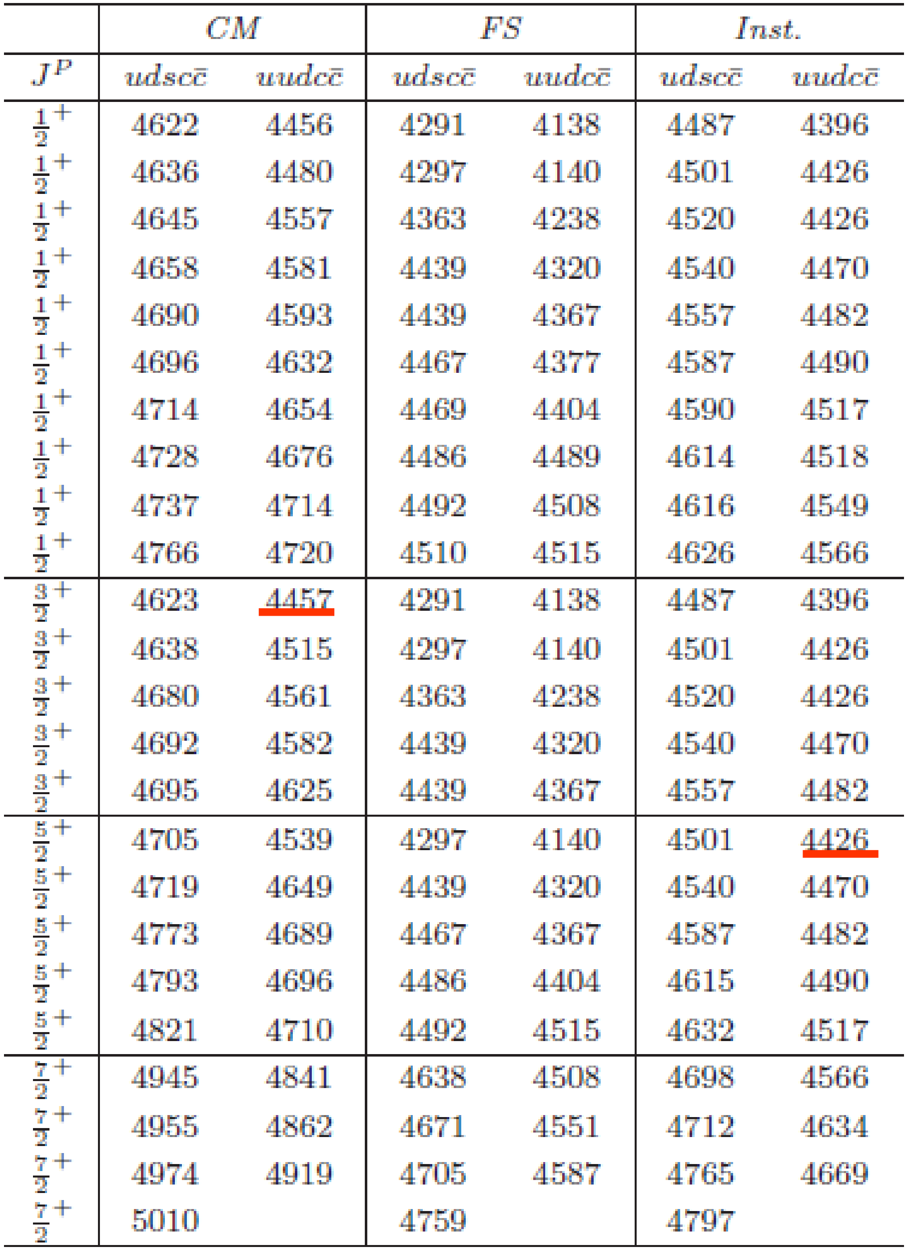
M.Karliner, J.L.Rosner, PRL115(2015)122001:

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

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



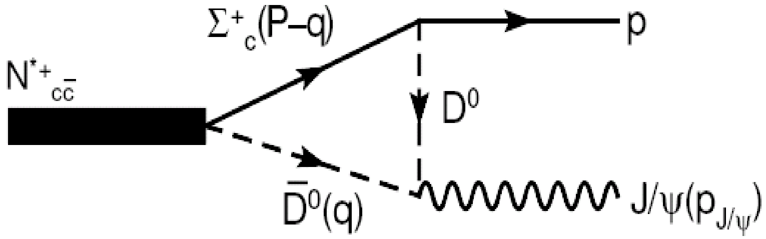
	CM		FS		Inst.	
J^P	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$
$\frac{1}{2}^-$	4273	4267	4084	3933	4209	4114
$\frac{1}{2}^-$	4377	4363	4154	4013	4216	4131
$\frac{1}{2}^-$	4453	4377	4160	4119	4277	4204
$\frac{1}{2}^-$	4469	4471	4171	4136	4295	4207
$\frac{1}{2}^-$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

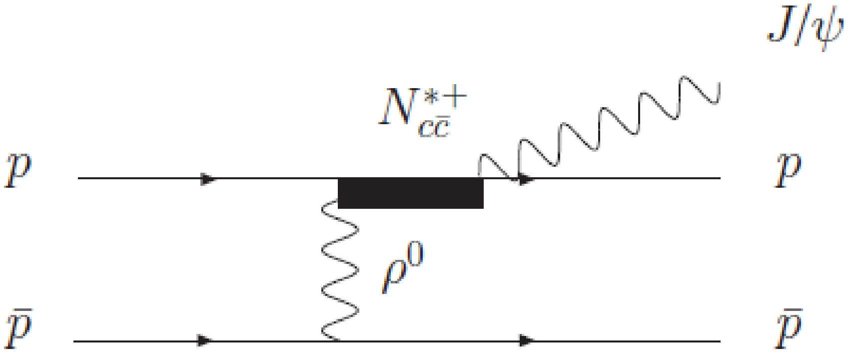


	CM		FS		Inst.	
J^P	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$
$\frac{1}{2}^+$	4622	4456	4291	4138	4487	4396
$\frac{1}{2}^+$	4636	4480	4297	4140	4501	4426
$\frac{1}{2}^+$	4645	4557	4363	4238	4520	4426
$\frac{1}{2}^+$	4658	4581	4439	4320	4540	4470
$\frac{1}{2}^+$	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





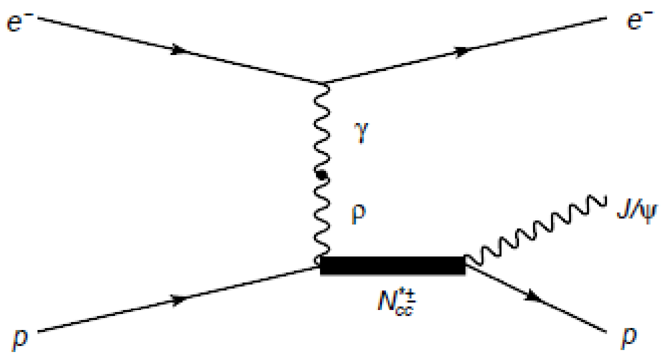
$\bar{p}p \to \bar{p}pJ/\psi > 0.1$ nb

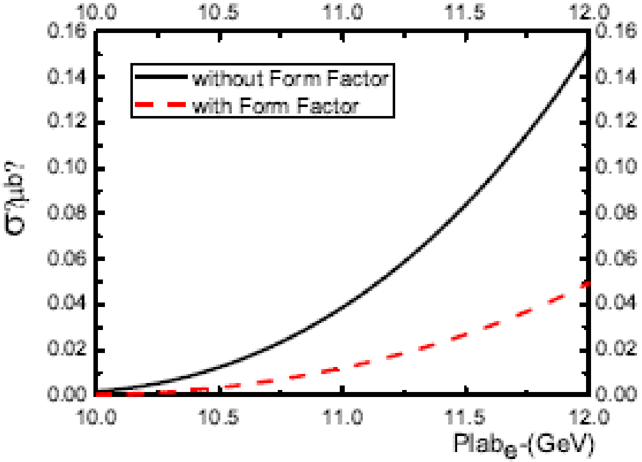
> 100 events per day at PANDA/FAIR by $L=10^{31}$ $cm^{-2}s^{-1}$

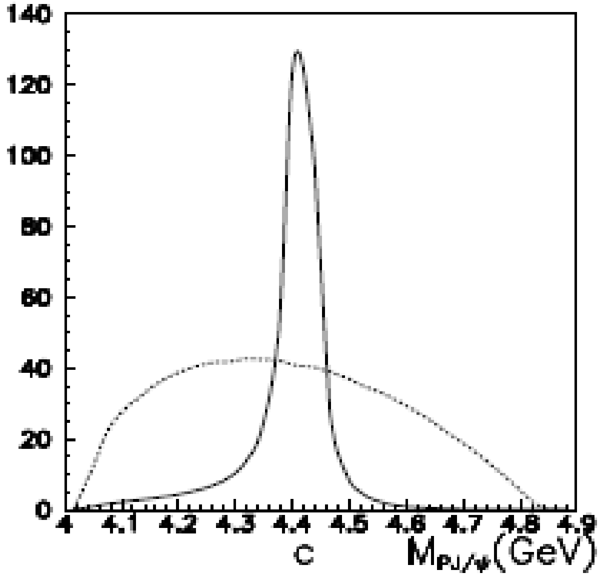
These Super-heavy narrow N* and Λ*
can be found at PANDA !

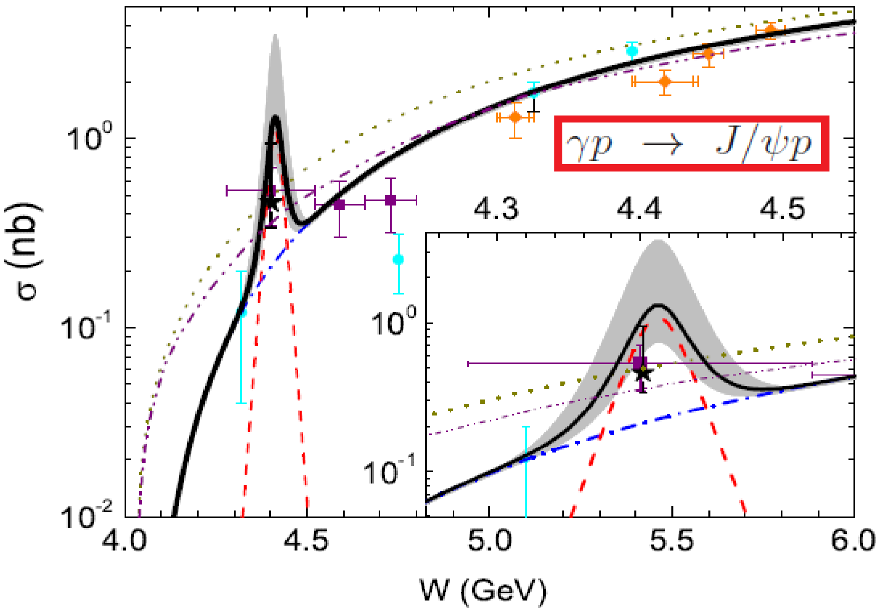
Albrecht Gillitzer@Juelich had a plan to find them at PANDA

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.

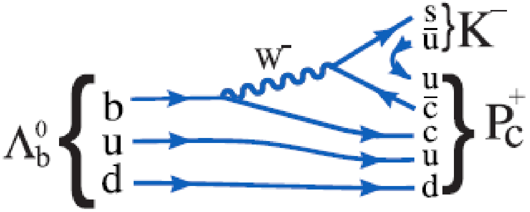
b) E.J.Garzon, J.J.Xie, "Effects of a $N_{c\bar{c}}$ resonance with hidden charm in the $\pi^- p \rightarrow D^- \Sigma_c^+$ reaction near threshold", PRC 92 (2015) 035201

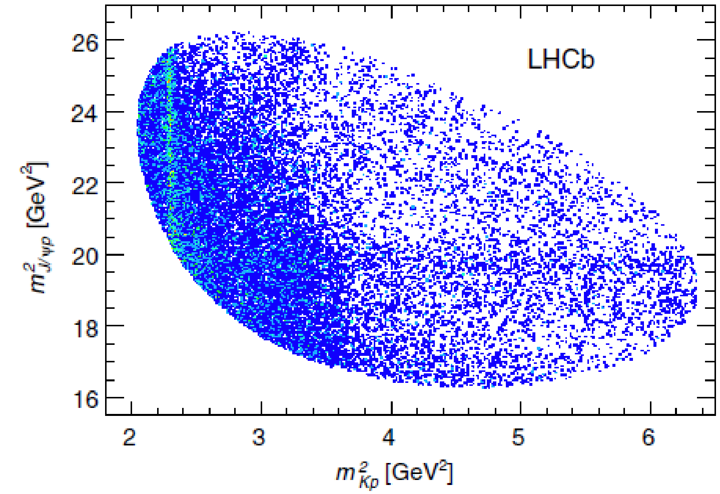
c) X.Y.Wang, X.R.Chen, "Production of the superheavy baryon Λ*(4209) in kaon-induced reaction", EPJA51 (2015) 85

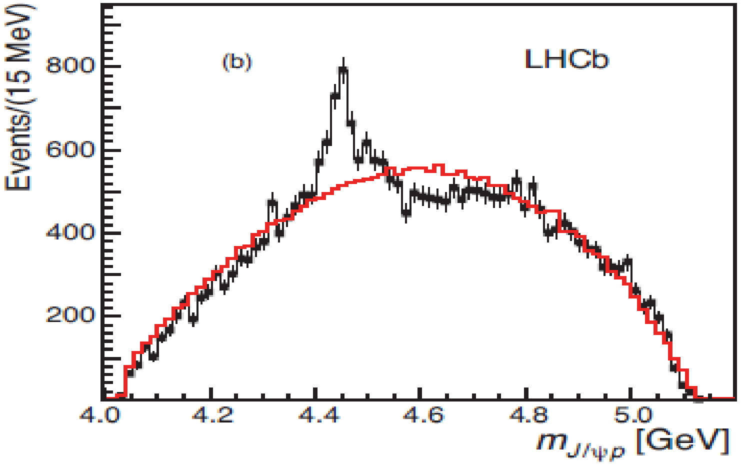
LHCb observation of $\mathrm{P_c}$ pentaquarks

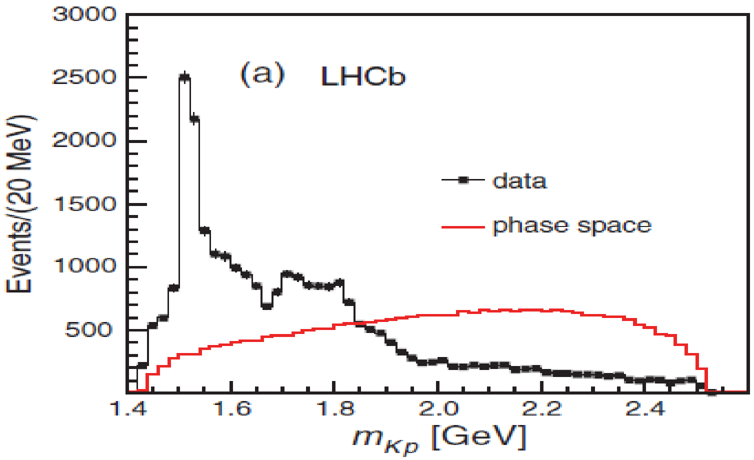
LHCb, Phys.Rev.Lett. 115 (2015) 072001 :

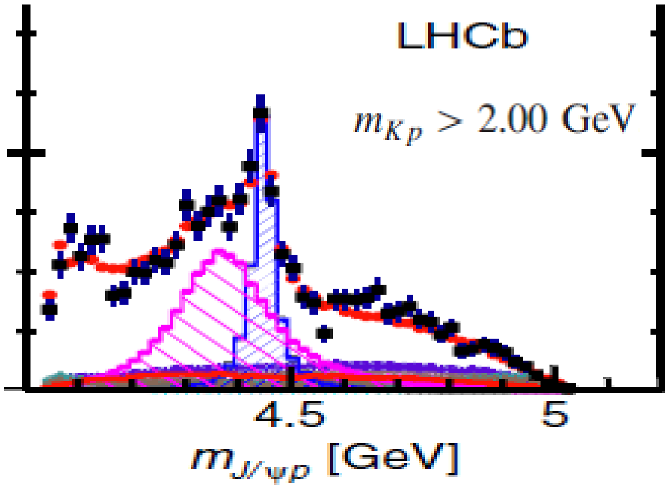
Observation of two N* from $\Lambda_b^0 \to J/\psi K^- p$



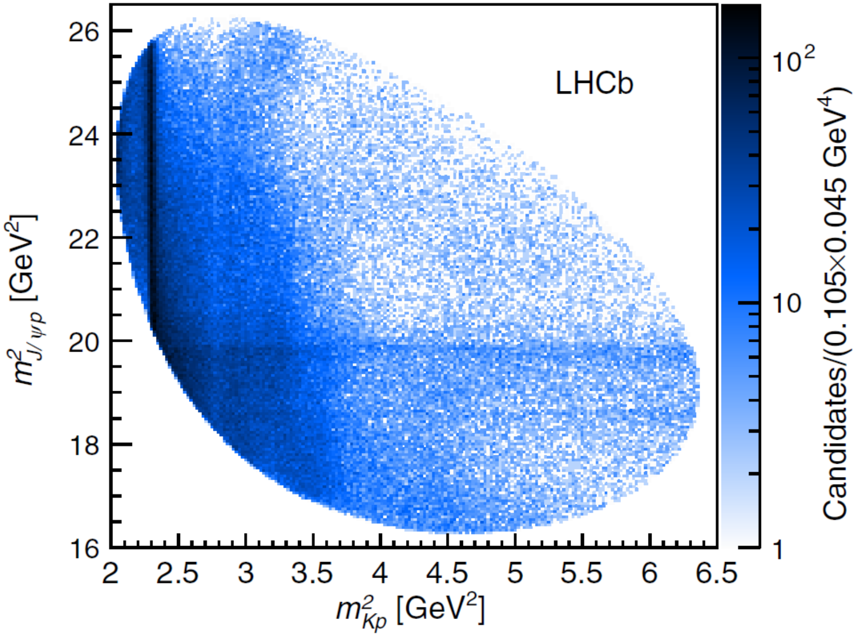


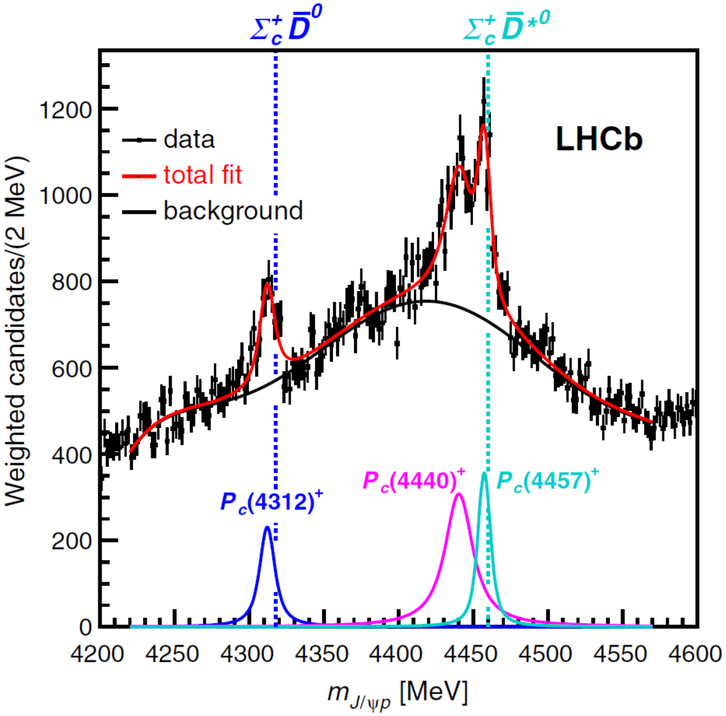


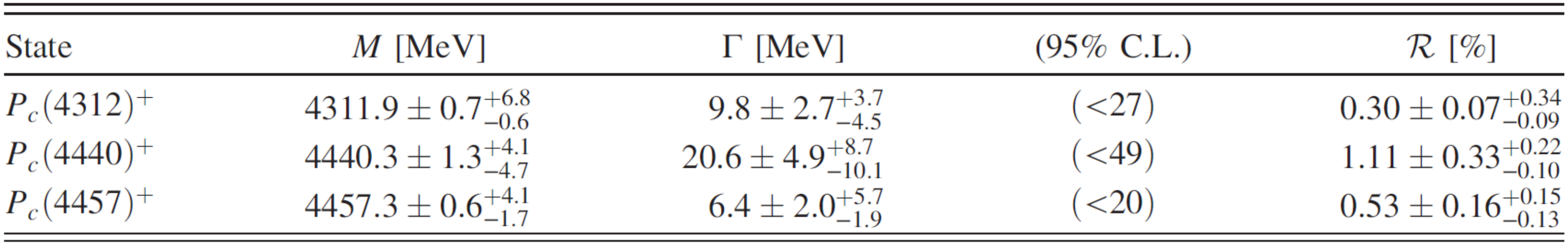




LHCb, Phys.Rev.Lett. 122 (2019) 222001





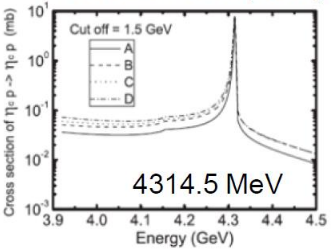


State	M [MeV]	Γ [MeV]	(95% C.L.)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(<27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(<49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm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

Comparison to numerical predictions

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

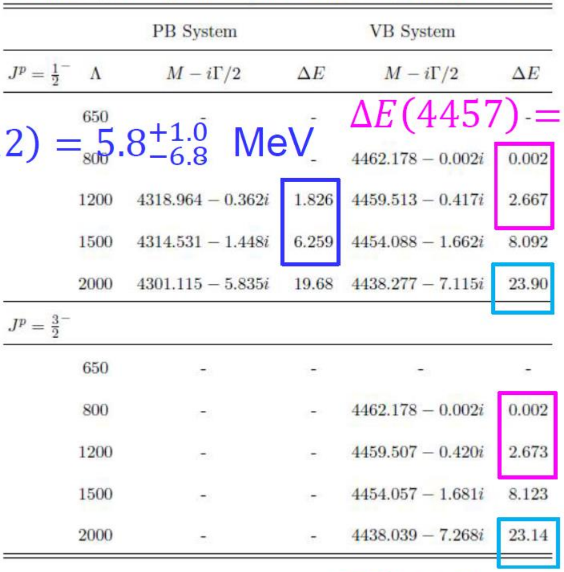
Example:

Nucleon resonances with hidden charm in coupled-channels models

Jia-Jun Wu, T.-S. H. Lee, and B. S. Zou
Phys. Rev. C **85**, 044002 – Published 17 April 2012

arXiv:1202.1036

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	-	-	[illegible]	[illegible]
	800	[illegible]	-	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.

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

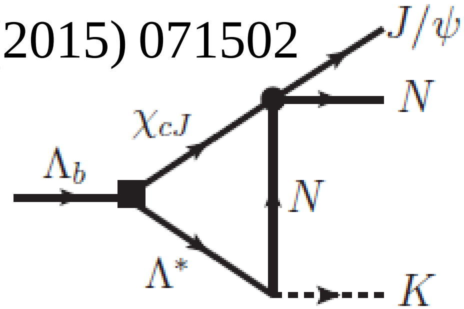
R.Chen, X.Liu, X.Q.Li, S.L.Zhu, PRL115 (2015) 132002;
L.Roca, J.Nieves, E.Oset, PRD92 (2015) 094003;
J.He, PLB 753 (2016)547 ;

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

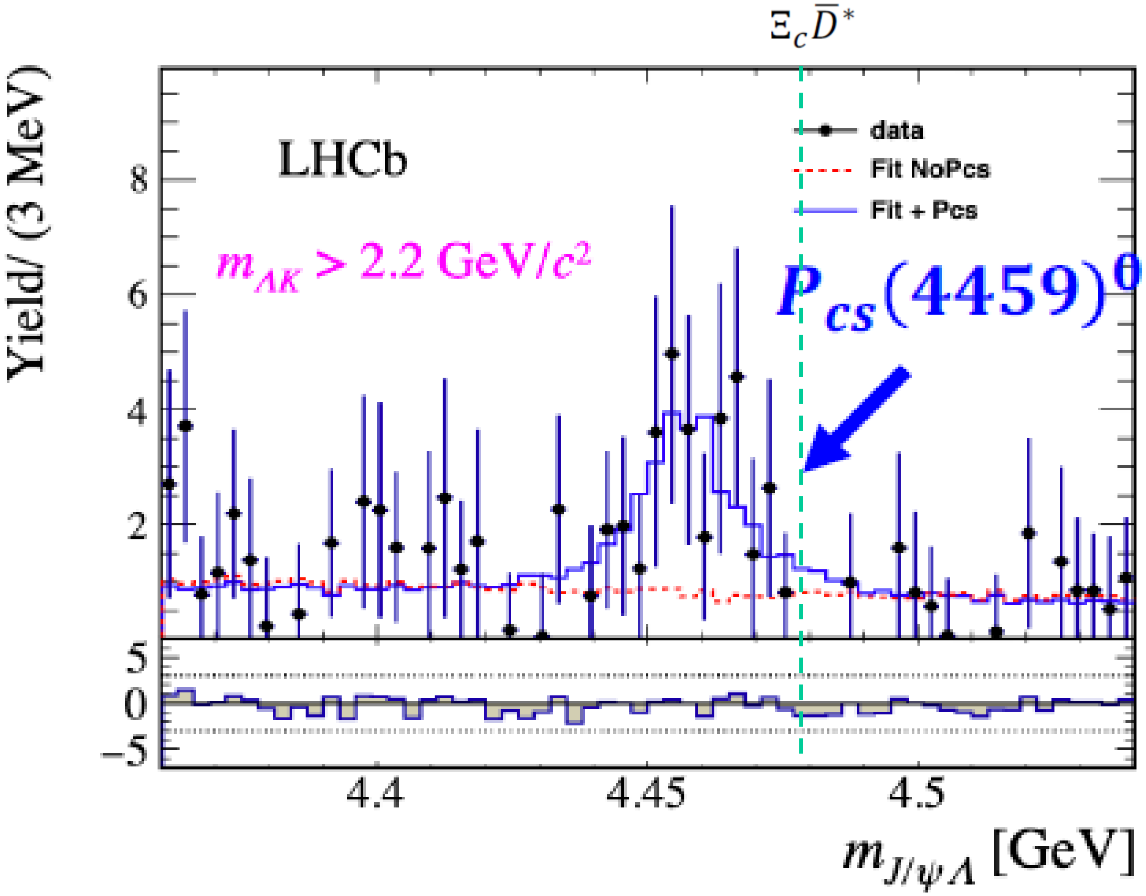
F.K.Guo, Ulf-G.Meißner, W.Wang, Z.Yang, PRD92 (2015) 071502
X.H.Liu, Q.Wang, Q.Zhao, PLB757 (2016) 231



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

$\Xi_b^- \rightarrow J/\psi \Lambda K^-$ by LHCb   LHCb-PAPER-2020-039



$\bar{D}\Xi_c$ (4337MeV), $\bar{D}^*\Xi_c$ (4478MeV), $\bar{D}\Xi'_c$ (4444MeV), $\bar{D}^*\Xi'_c$ (4585MeV),

$\bar{D}\Xi^*_c$ (4513MeV), $\bar{D}^*\Xi^*_c$ (4654MeV)

Multiquark states – crucial for hadron structure !

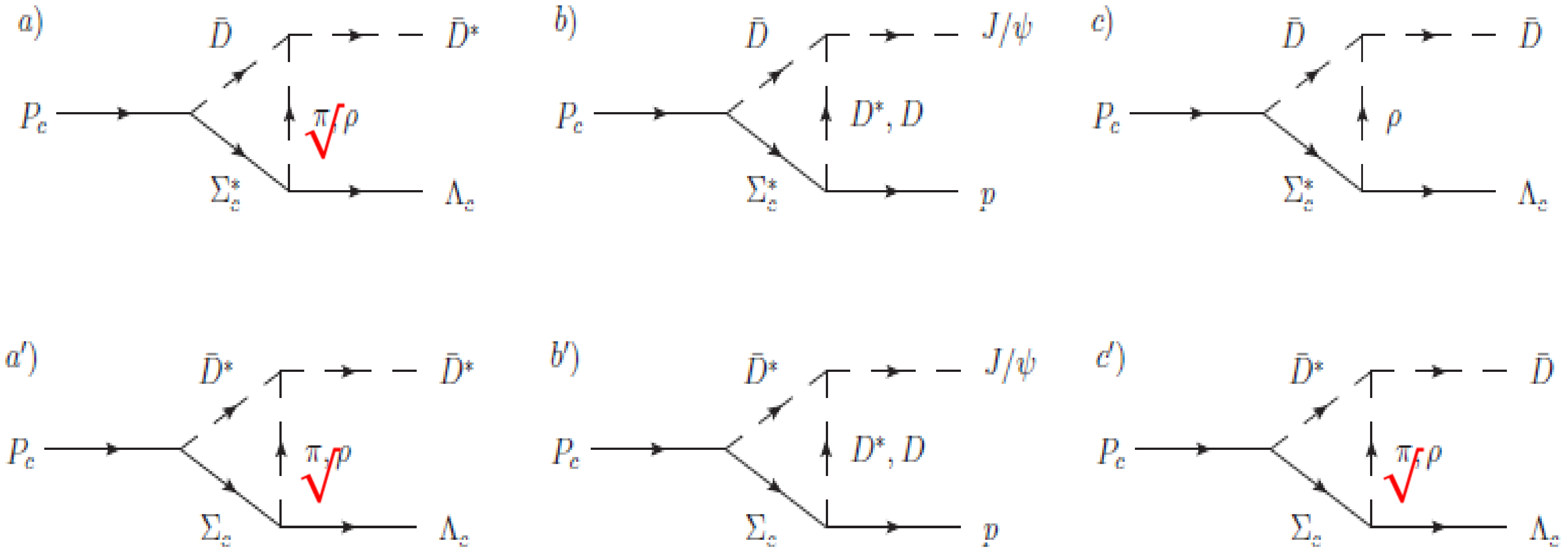
X(3872)	→	top cited paper for Belle (2003)	1863 cites
Zc(3900)	→	top cited paper for BES (2012)	805 cites
Pc states	→	top cited paper for LHCb (2015)	1109 cites

H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1:
"The hidden-charm pentaquark and tetraquark states" 610 cites

F.K.Guo, C.Hanhart, U.Meissner, Q.Wang, Q.Zhao, B.S.Zou,
Rev.Mod.Phys. 90 (2018)015004: "Hadronic molecules" 474 cites

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

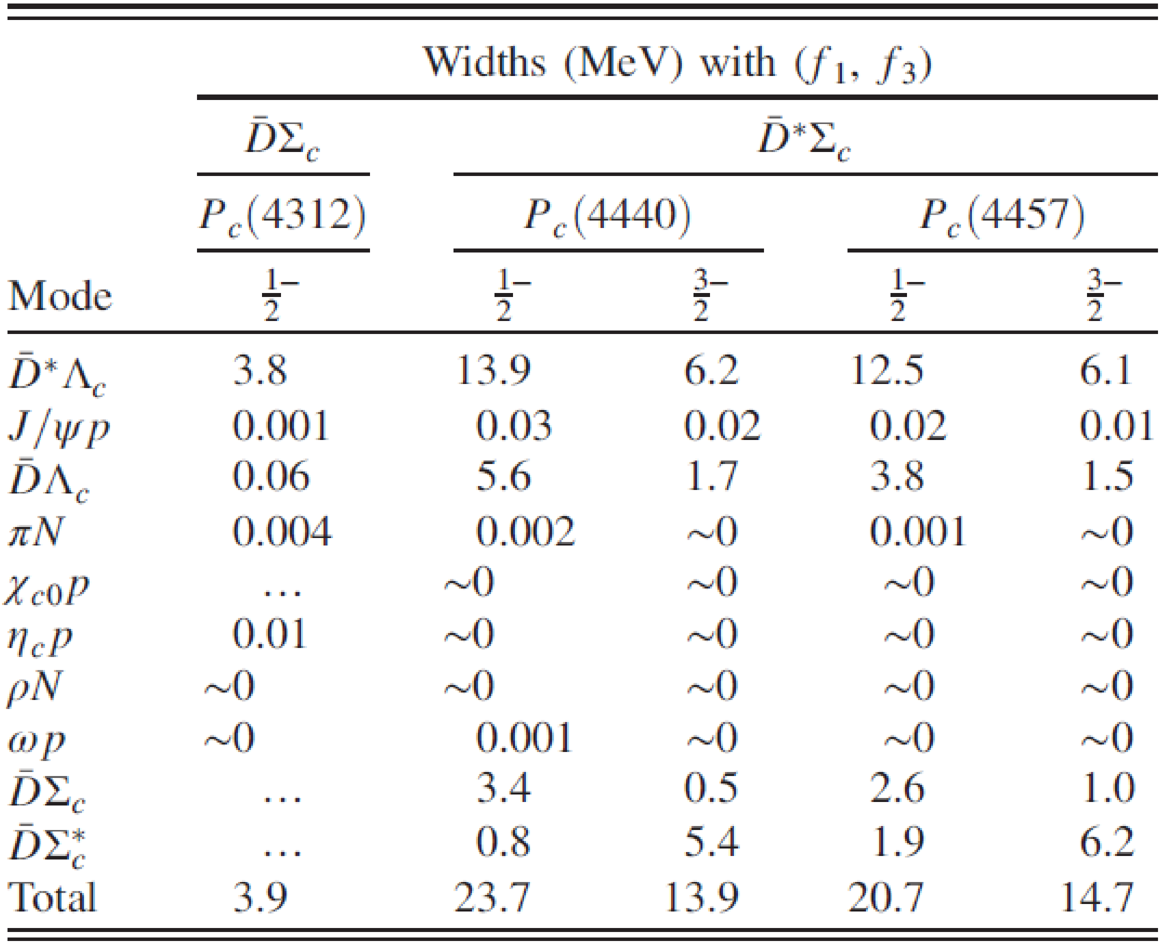


One pion exchange is very important !

$\bar{D}\Sigma_c^*$ & $\bar{D}^*\Sigma_c^*$ are much broader than $\bar{D}\Sigma_c$ & $\bar{D}^*\Sigma_c$ states

Partial decay widths of $P_c(4312)$, $P_c(4440)$ & $P_c(4457)$

Y.H.Lin, B.S.Zou, PRD100 (2019) 056005

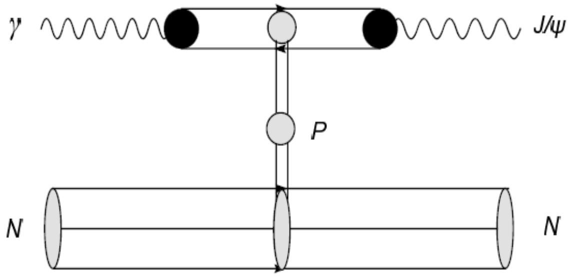


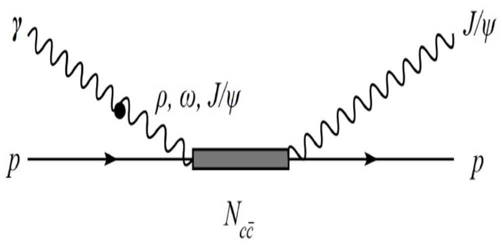
	Widths (MeV) with (f_1, f_3)				
	$\bar{D}\Sigma_c$	$\bar{D}^*\Sigma_c$			
	$P_c(4312)$	$P_c(4440)$		$P_c(4457)$	
Mode	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$
$\bar{D}^*\Lambda_c$	3.8	13.9	6.2	12.5	6.1
$J/\psi p$	0.001	0.03	0.02	0.02	0.01
$\bar{D}\Lambda_c$	0.06	5.6	1.7	3.8	1.5
πN	0.004	0.002	~0	0.001	~0
$\chi_{c0}p$	…	~0	~0	~0	~0
$\eta_c p$	0.01	~0	~0	~0	~0
ρN	~0	~0	~0	~0	~0
ωp	~0	0.001	~0	~0	~0
$\bar{D}\Sigma_c$	…	3.4	0.5	2.6	1.0
$\bar{D}\Sigma_c^*$	…	0.8	5.4	1.9	6.2
Total	3.9	23.7	13.9	20.7	14.7

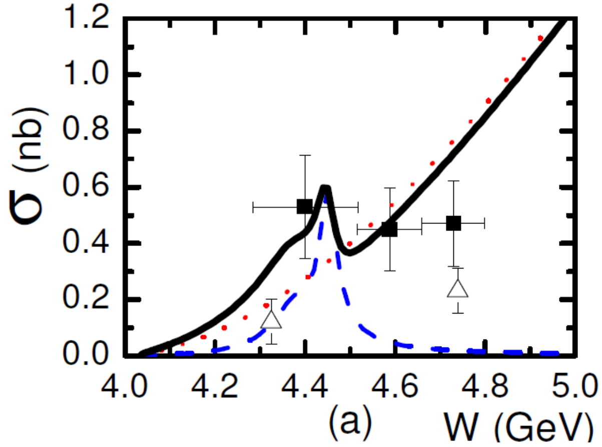
It is very important to study $P_c \rightarrow \bar{D}^*\Lambda_c$ & $\bar{D}\Lambda_c$!

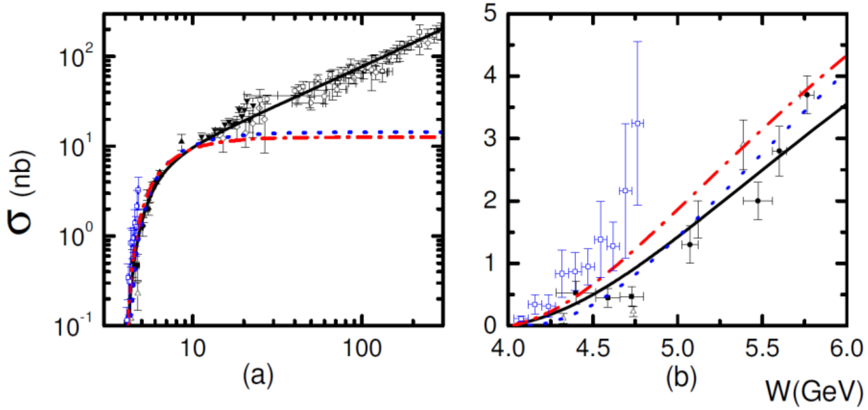
Pin down P_c^+ states from their photo-production

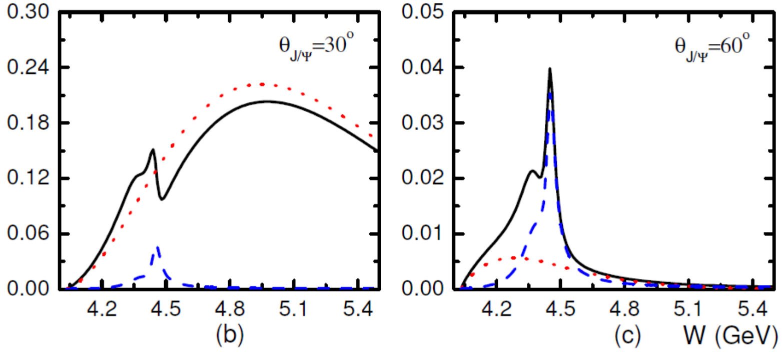
J.J.Wu, T.S.H.Lee, B.S.Zou, PRC100 (2019)035206

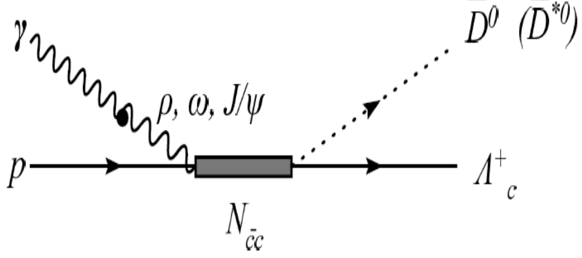


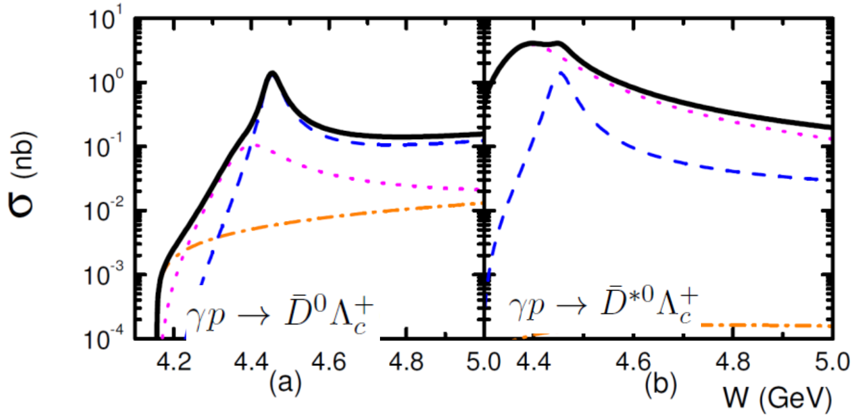










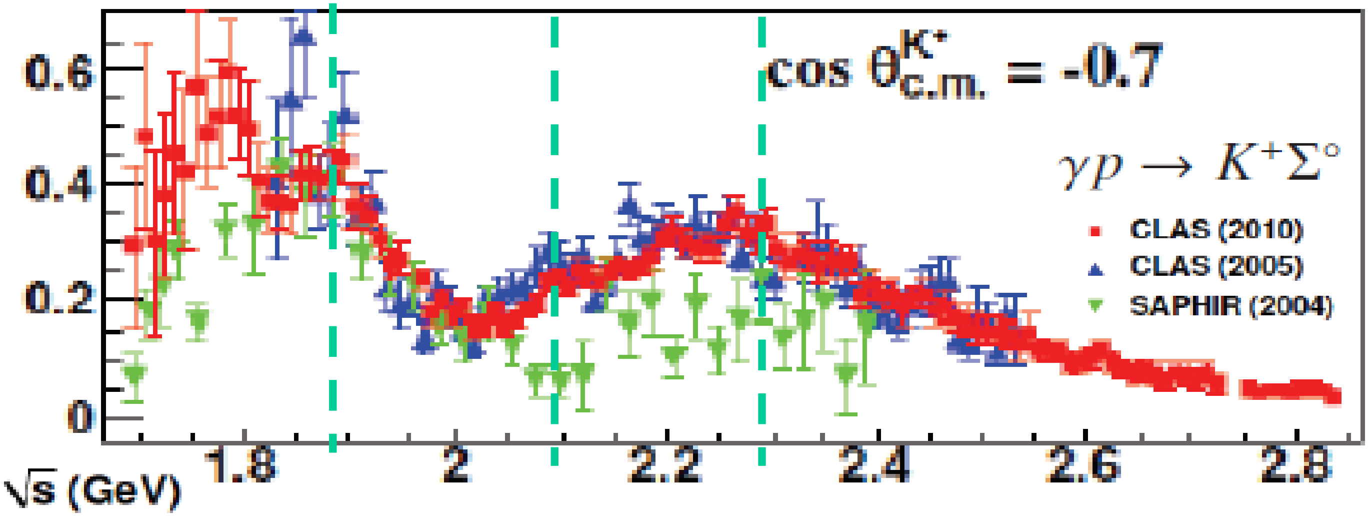


4. Strange & beauty partners of P_c states

Strange partners of P_c and P_{cs} states

KΣ* ~1880 K*Σ ~ 2086 K*Σ* ~ 2280

N*(1875) N*(2080) N*(2270)



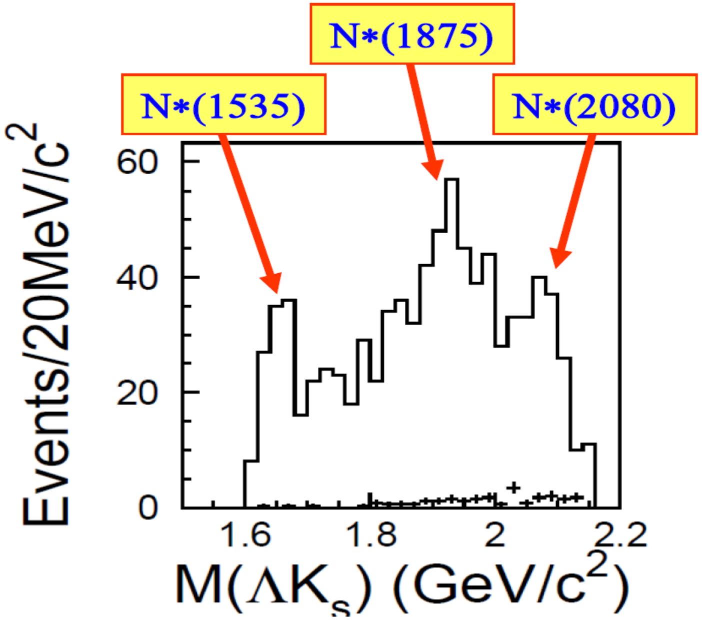
KΞ ~1810 KΞ* ~ 2027 K*Ξ ~ 2210 K*Ξ* ~ 2427

$\Lambda(1/2^-)$ $\Lambda(3/2^-)$ $\Lambda(1/2^-,3/2^-)$ $\Lambda(1/2^-,3/2^-,5/2^-)$

K*N ~1833 : $\Lambda(1800)1/2^-$, $\Lambda(3/2^-)$

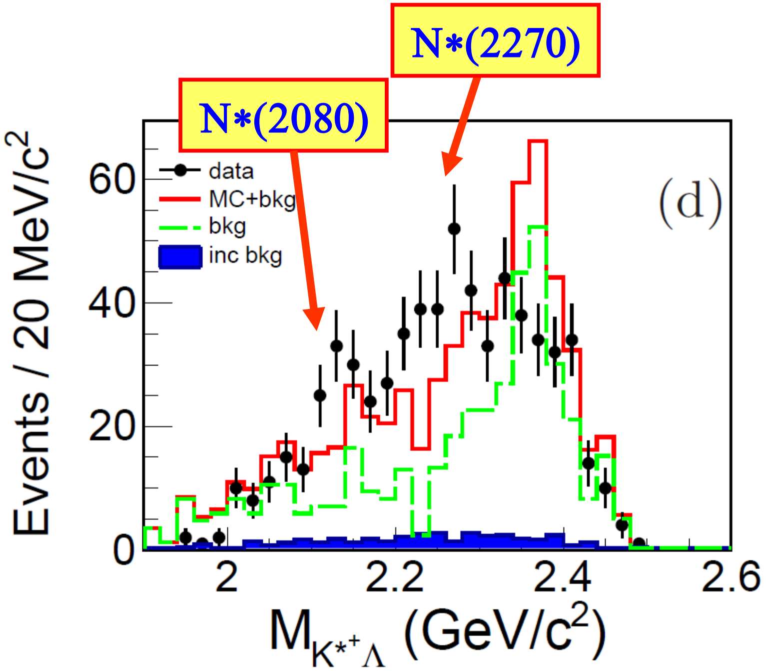
Strangeness partners of P_c states at BES ?

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



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

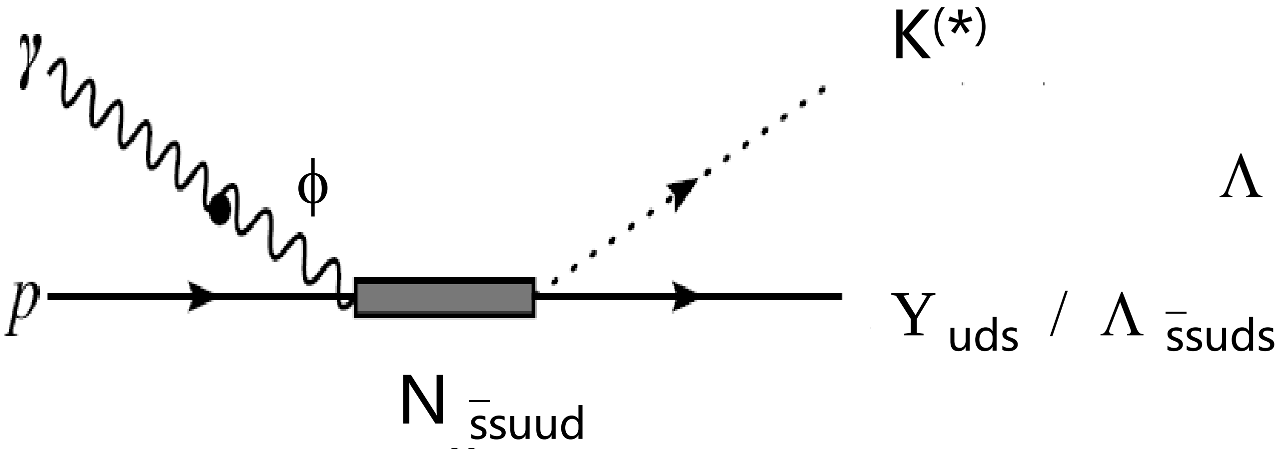
BESII, PLB659 (2008) 789



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

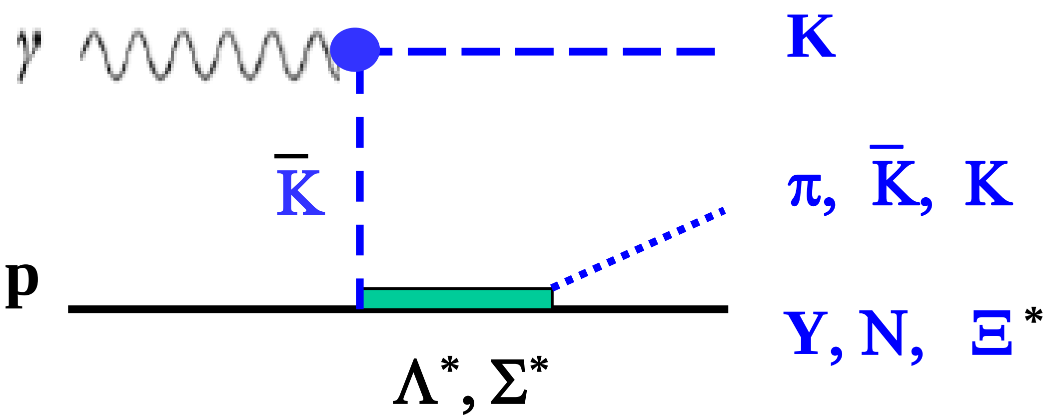
BESIII, arXiv:1908.02979

Photo-production of pentaquark states with hidden strangeness



$\Lambda_{\bar{s}suds} \rightarrow \Lambda\phi, \Lambda\eta$

Photo-production of hyperons



Physics Letters B 709 (2012) 70–76

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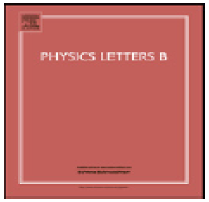
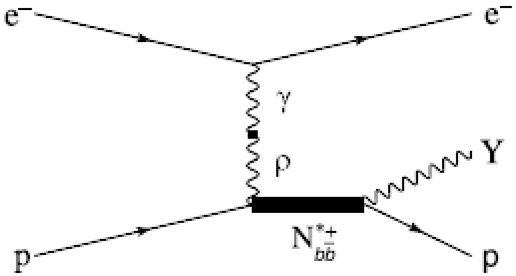
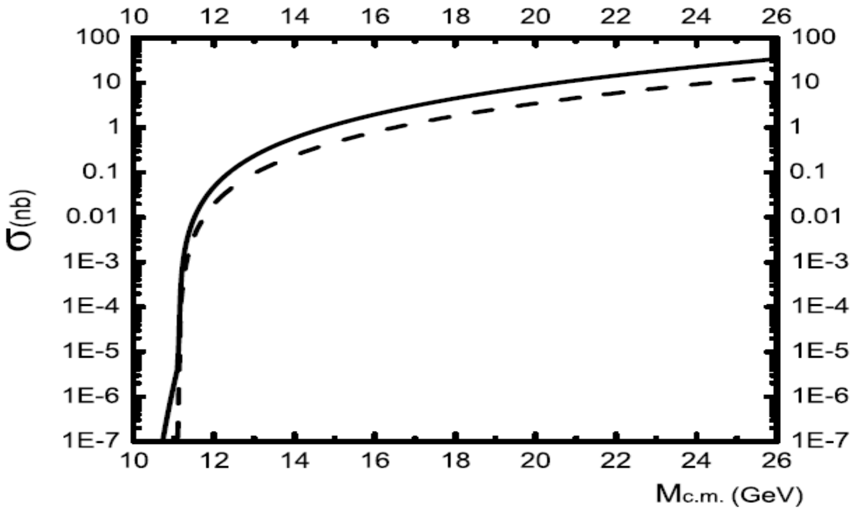


Prediction of super-heavy N^* and Λ^* resonances with hidden beauty

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

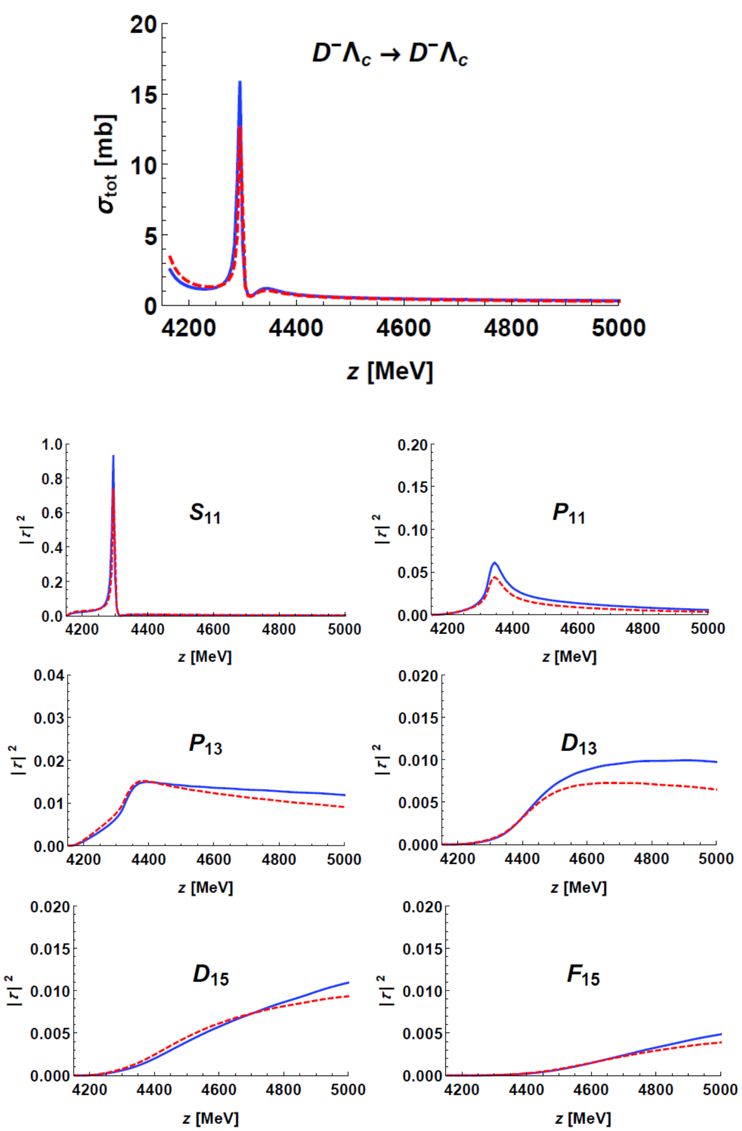
M (MeV)	Γ (MeV)	Γ_i (MeV)					
		πN	ηN	$\eta' N$	$K\Sigma$	$\eta_b N$	
11 052	1.38	0.10	0.21	0.11	0.42	0.52	**$1/2^-$**
		ρN	ωN	$K^*\Sigma$	ΥN		
11 100	1.33	0.09	0.30	0.39	0.51		**$1/2^-$, $3/2^-$**

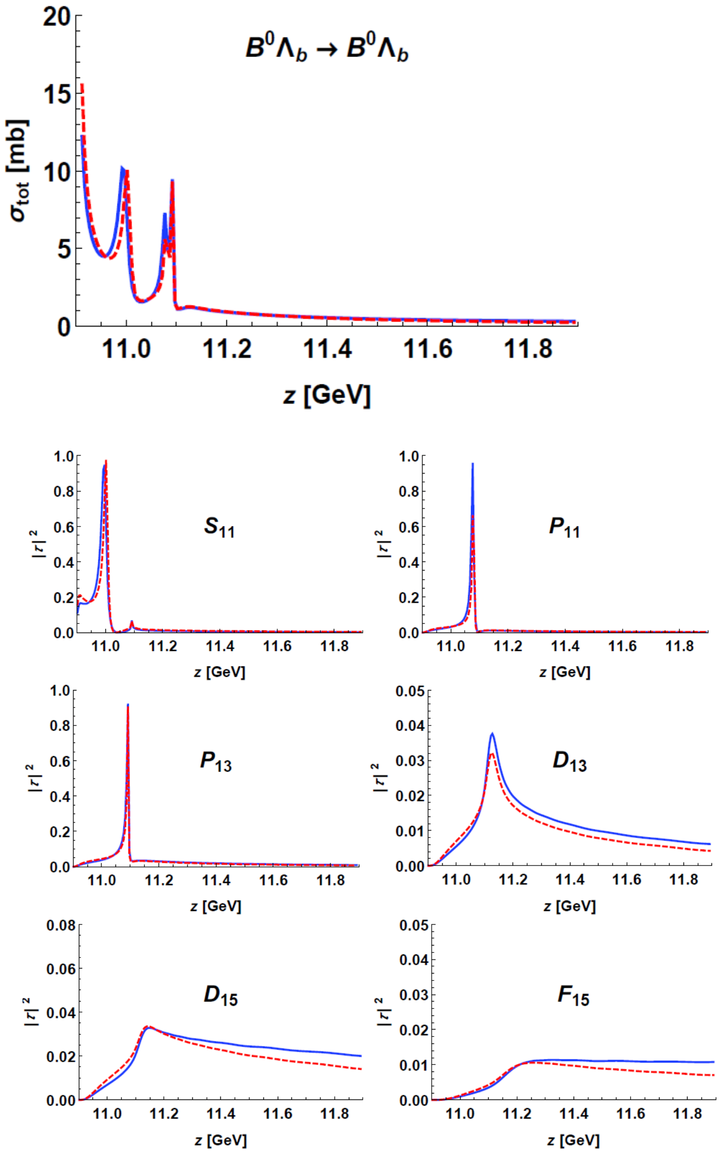




$\bar{\mathrm{D}}\Lambda_{\mathrm{c}}-\bar{\mathrm{D}}\Sigma_{\mathrm{c}}$ and $\mathrm{B}\Lambda_{\mathrm{b}}-\mathrm{B}\Sigma_{\mathrm{b}}$ dynamical coupled channel study

C.W.Shen, Roechen, Meissner, Zou, CPC42(2018) 023106

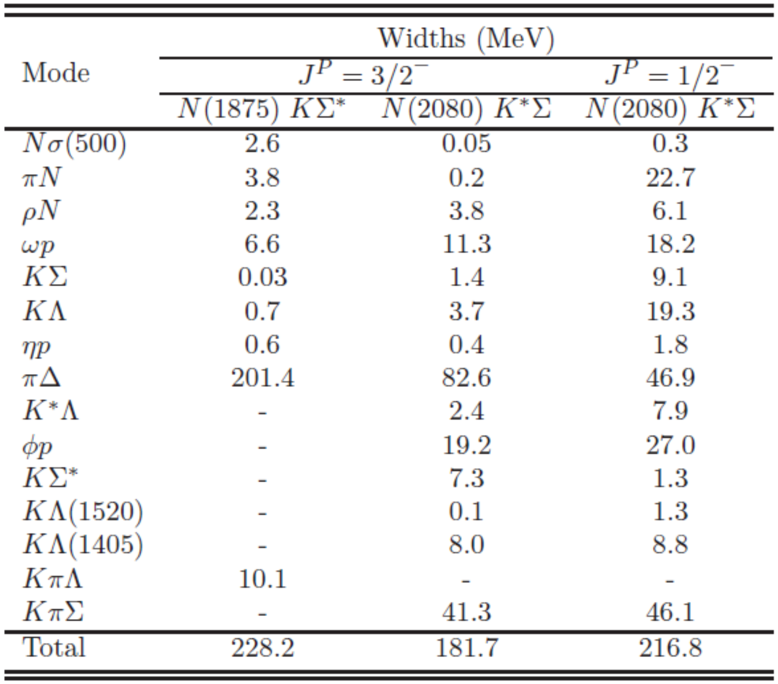




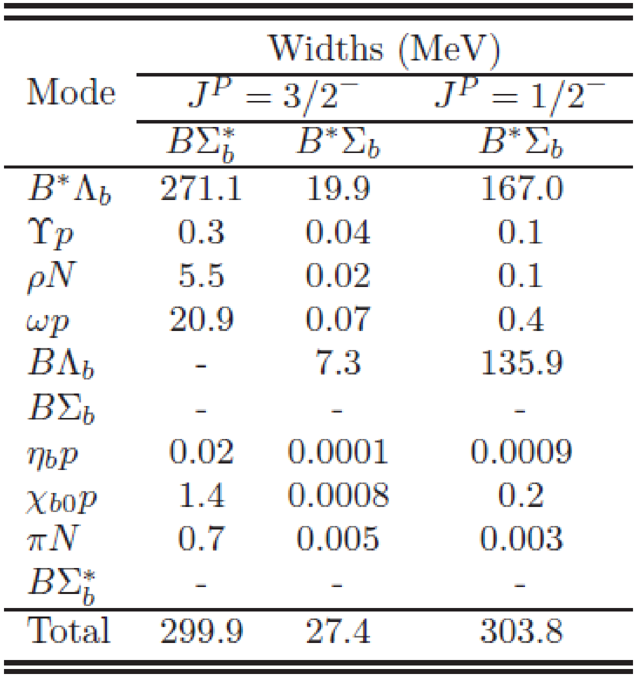
More pentaquarks with hidden beauty than with hidden charm

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

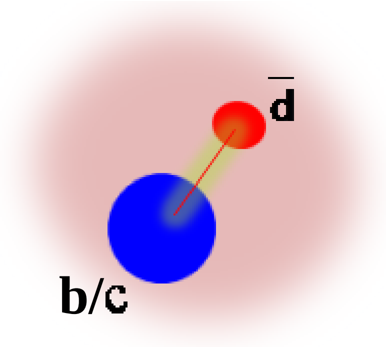
5. Prospects

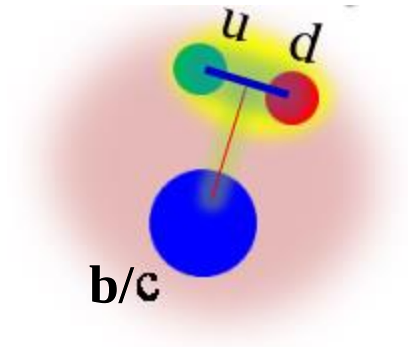
◆ **my favorite strategy for hadron spectroscopy:**

$\bar{c}cuud$ & $\bar{c}cuds$ → 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!