Strangeness -1 Dibaryons

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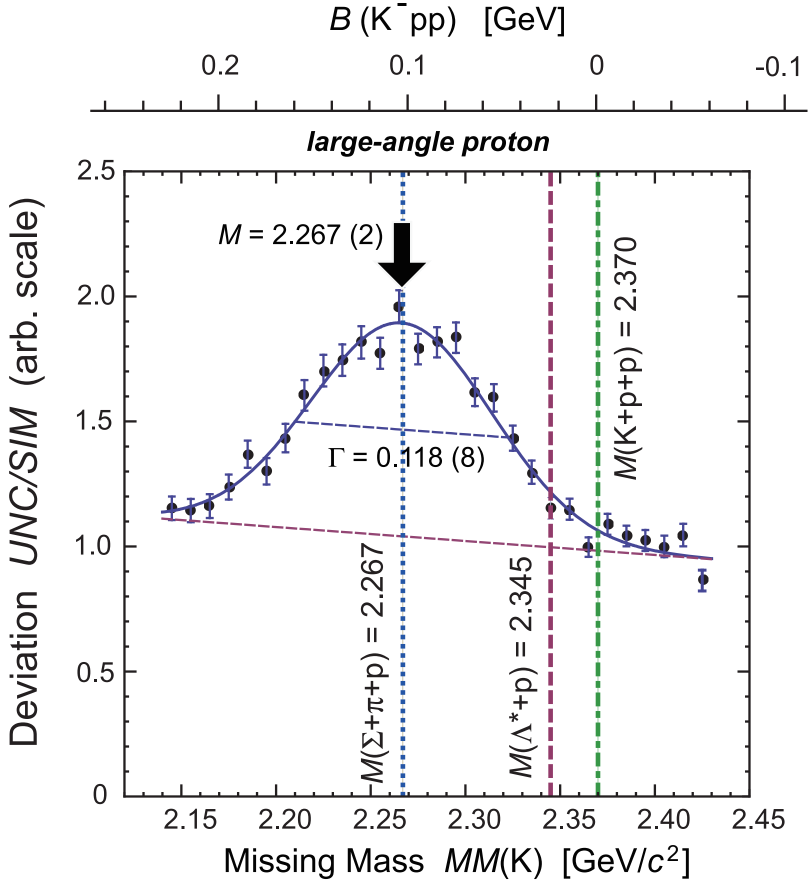
- Relevance to K^-pp quasibound state
- Deuteron-like baryon-baryon quasibound states
- Dibaryons as 6-quark configurations
- Strangeness $\mathcal{S} = -1$ dibaryon candidates & searches
- Pion-assisted dibaryons: $\pi\Lambda N$ $(J^\pi = 2^+, I = \frac{3}{2})$
  Extensions to $\mathcal{S} = -2, -3$ and Charm $\mathcal{C} = +1, +2$
- Work in progress on $\pi K N$ and $\pi \bar{K} N$ systems

Gal-Garcilazo, PRD 78, 014013 (2008); PRC 81, 055205 (2010)

Relevance to K^-pp quasibound state



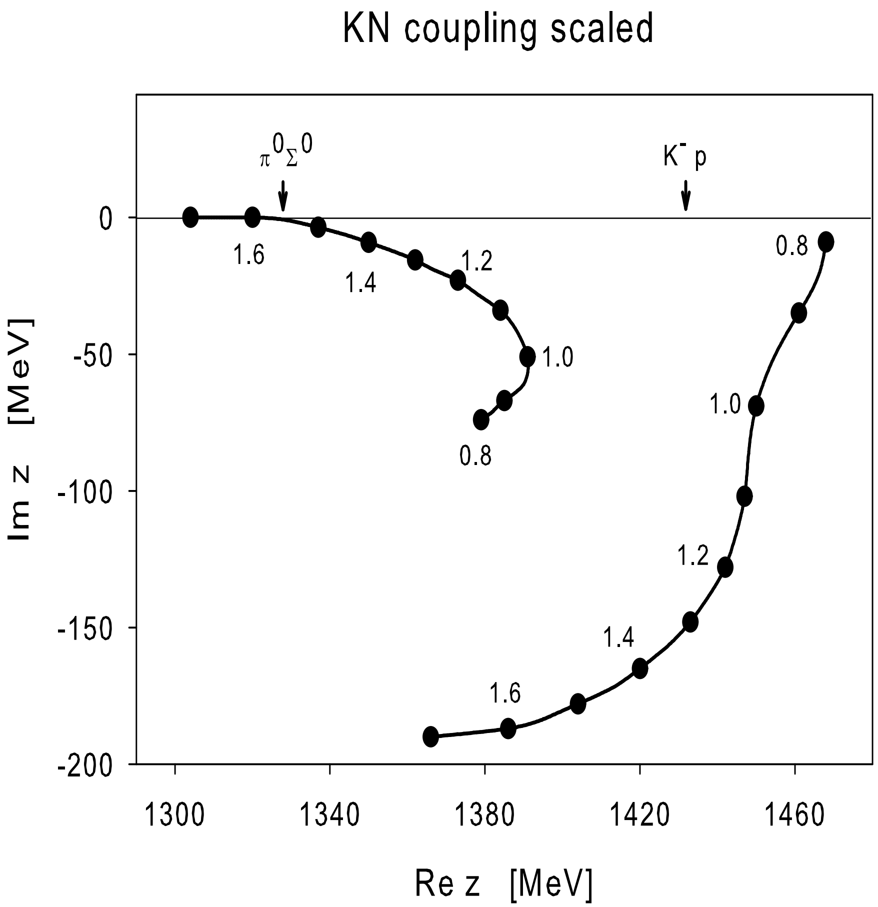
Yamazaki et al., PRL **104** (2010) 132502

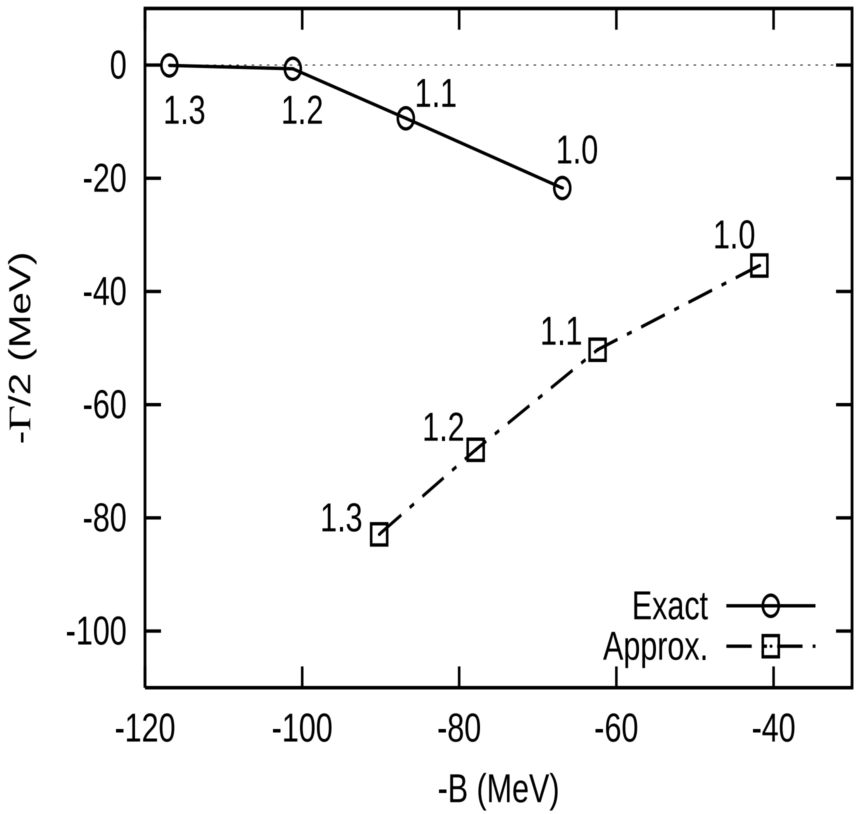
Broad $K^{-}pp$ structure in $pp \rightarrow \Lambda p K^{+}$ at $\pi N \Sigma$ threshold

Forthcoming experiments: $pp \rightarrow (K^{-}pp) + K^{+}$ at GSI,

$K^{-3}\mathrm{He} \rightarrow (K^{-}pp) + n$ and $\pi^{+}d \rightarrow (K^{-}pp) + K^{+}$ at J-PARC

Very broad K^- quasibound states (QBS) at the lower threshold?





Cieply+Gal, arXiv:0809.0422
$\bar{K}N - \pi\Sigma$ poles upon $\bar{K}N$ scaling
$\Gamma_{\rm QBS} \to 0$, also upon $\pi\Sigma$ scaling

Ikeda+Sato, PRC **79** (2009) 035201
Faddeev K^-pp QBS pole motion
$\Gamma_{\rm QBS} \to 0$ in coupled channels,
but not in single-channel Faddeev

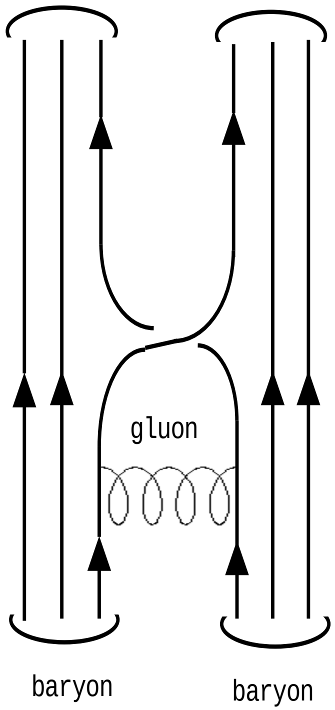
Deutron-like baryon-baryon bound states

- Nijmegen extended-soft-core (ESC) meson-exchange models with broken $\mathrm{SU}(3)_{\mathrm{f}}$ for $\mathcal{S} = 0, -1, -2$ report no QBS
  Rijken et al. NPA 835 (2010) 160 [HYP09]
  Model NSC97, PRC 59 (1999) 3009, found QBS in particular for ${}^1S_0$: $\Sigma\Sigma$ $I = 2$; $\Sigma\Xi$ $I = 3/2$; $\Xi\Xi$ $I = 1$ (all in broken $\mathrm{SU}(3)_{\mathrm{f}}$ $\mathbf{27}$) and for ${}^3S_1$: $\Sigma\Xi$ $I = 3/2$ (in broken $\mathrm{SU}(3)_{\mathrm{f}}$ $\overline{\mathbf{10}}$).

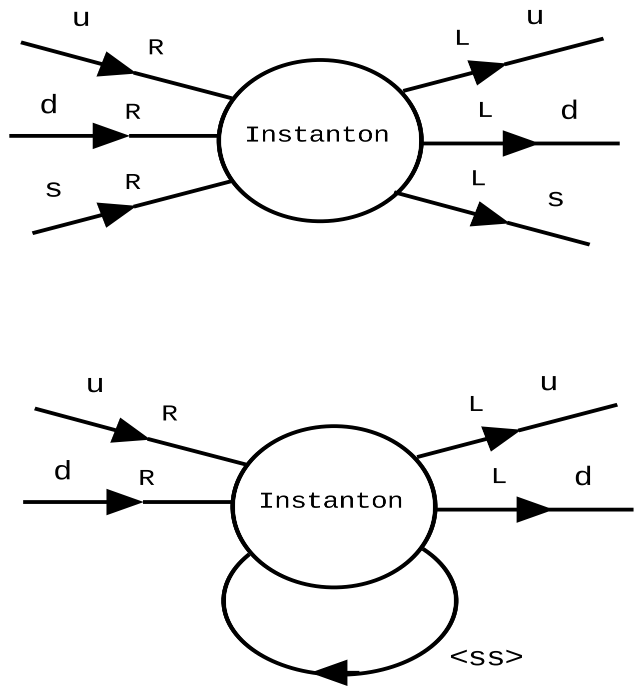
- Bonn-Juelich chiral effective field theory (EFT) applied in lowest order (LO) to $\mathcal{S} = -1, -2, -3, -4$, with low energy constants (LEC) constrained by $\mathrm{SU}(3)_{\mathrm{f}}$ and fitted to low-energy YN data, as reviewed by Haidenbauer in NPA 835 (2010) 168 [HYP09], finds no QBS for $\mathcal{S} = -1, -2$. The $\mathcal{S} = -3, -4$ sectors require only the 5 LECs determined in the YN sector fit, independently of the 6th LEC required in the $\mathcal{S} = -2$ sector (this LEC is consistent with zero). Hence get PREDICTIONS for QBS: $\Lambda\Xi$ in ${}^1S_0$ and ${}^3S_1$, $\Sigma\Xi$ $I = 3/2$ in ${}^1S_0$ but not in ${}^3S_1$, and $\Xi\Xi$ in $I = 1, {}^1S_0$ and $I = 0, {}^3S_1$. Model dependence is assessed by varying a cutoff momentum in the range $550 - 700$ MeV/c.

Dibaryons as six-quark configurations

Quark Cluster Model, Oka+Yazaki, PLB 90 (1980) 41 & more Refs.



Gluon-exchange mediated BB quark-exchange interaction



Instanton induced interaction: 3-body (upper) 2-body (lower)

Color Magnetic (CM) gluon exchange interaction

For orbitally symmetric color-singlet n-quark cluster:

$$V_{CM} \approx \sum_{i<j} -(\lambda_i \cdot \lambda_j)(s_i \cdot s_j)\mathcal{M}_0 \to [-\frac{n(10-n)}{4} + \Delta\mathcal{P}_{\rm f} + \frac{S(S+1)}{3}]\mathcal{M}_0$$

where $\mathcal{M}_0 \sim 75$ MeV, $\mathcal{P}_{\rm f} = \pm 1$ for any symmetric/antisymmetric flavor pair, $\Delta\mathcal{P}_{\rm f}$ means with respect to the SU(3)$_{\rm f}$ **1** antisymmetric representation of n quarks, $n = 3$ for a baryon (B) and $n = 6$ for BB.

For $n = 6$, SU(3)$_{\rm f}$ **1** [2,2,2] is Jaffe's **H** [PRL 38 (1977) 195]:

$$\mathbf{H} \sim \mathcal{A}[\sqrt{1/8}\,\Lambda\Lambda + \sqrt{1/2}\,N\Xi - \sqrt{3/8}\,\Sigma\Sigma,] \qquad \mathcal{S} = -2,\;\; I = S = L = 0$$

$$< V_{CM} >_{\mathbf{H}} - 2 < V_{CM} >_{\Lambda} = -2\mathcal{M}_0$$

$$< V_{CM} >_{\mathbf{H}} = -6\mathcal{M}_0 = -\frac{3}{2}(< V_{CM} >_{\Delta} - < V_{CM} >_{N}) \sim -450 \text{ MeV}$$

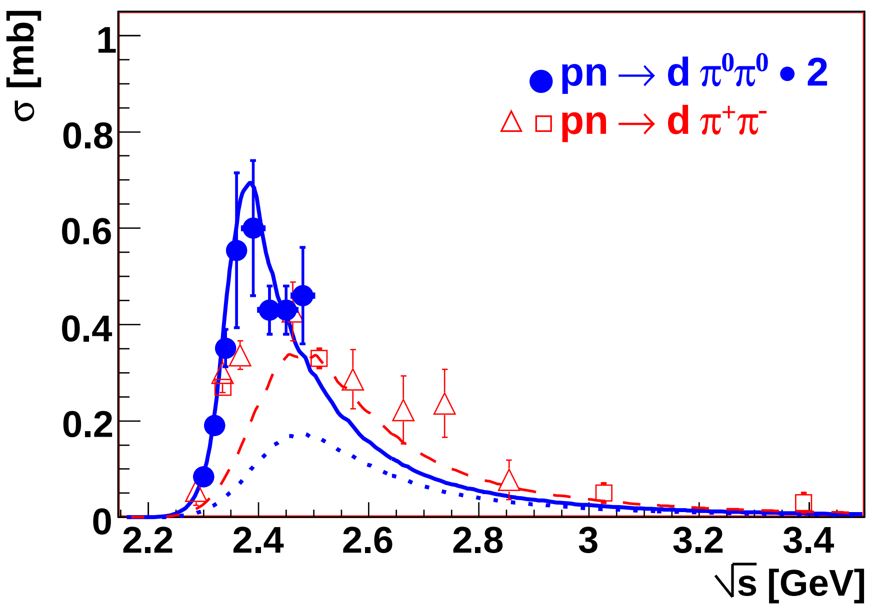
H summary:

- QCM calculations: owing to a repulsive Instanton induced interaction, **H** is barely bound or unbound, perhaps a $\Lambda\Lambda$ resonance below the $N\Xi$ threshold [Takeuchi+Oka, PRL 91 (1991) 1271; Oka+Takeuchi, NPA 524 (1991) 649].
- QCD sum rule calculations: $B_{\mathbf{H}} = 40 \pm 70$ MeV; $m_{\mathbf{H}}$ correlated with m_{nn} [Kodama+Oka+Hatsuda, NPA 580 (1994) 445].
- ${}_{\Lambda\Lambda}^{6}$He particle stability rules out $B_{\mathbf{H}} > 7$ MeV, otherwise ${}_{\Lambda\Lambda}^{6}$He would have disintegrated into $\mathbf{H} + {}^{4}$He, at odds with its observed weak decay.

Leading dibaryon candidates [Oka, PRD 38 (1988) 298]:

$\mathcal{S}$	SU(3)$_\mathrm{f}$	I	J^π	BB structure	$\Delta < V_{CM} > /\mathcal{M}_0$
0	[3,3,0] $\overline{\mathbf{10}}$	0	3^+	$\Delta\Delta$	0
-1	[3,2,1] $\mathbf{8}$	1/2	2^+	$\sqrt{1/5}\,(N\Sigma^* + 2\,\Delta\Sigma)$	-1
-2	[2,2,2] $\mathbf{1}$	0	0^+	$\sqrt{1/8}\,(\Lambda\Lambda + 2\,N\Xi - \sqrt{3}\,\Sigma\Sigma)$	-2
-3	[3,2,1] $\mathbf{8}$	1/2	2^+	$\sqrt{1/5}\,[\sqrt{2}\,N\Omega - (\Lambda\Xi^* - \Sigma^*\Xi + \Sigma\Xi^*)]$	-1

Evidence for a $\Delta\Delta$ bound state, $B \sim 130$ MeV & $\Gamma \sim 80$ MeV ?



$\sigma(pn \to d\pi^0\pi^0)$, Bashkanov et al. (CELSIUS/WASA), PRL 102 (2009) 052301

Dotted line: $\sigma(NN \to d\pi\pi)_{I=0}$ from $pn \to d\pi^+\pi^-$ & $pp \to d\pi^+\pi^0$ data

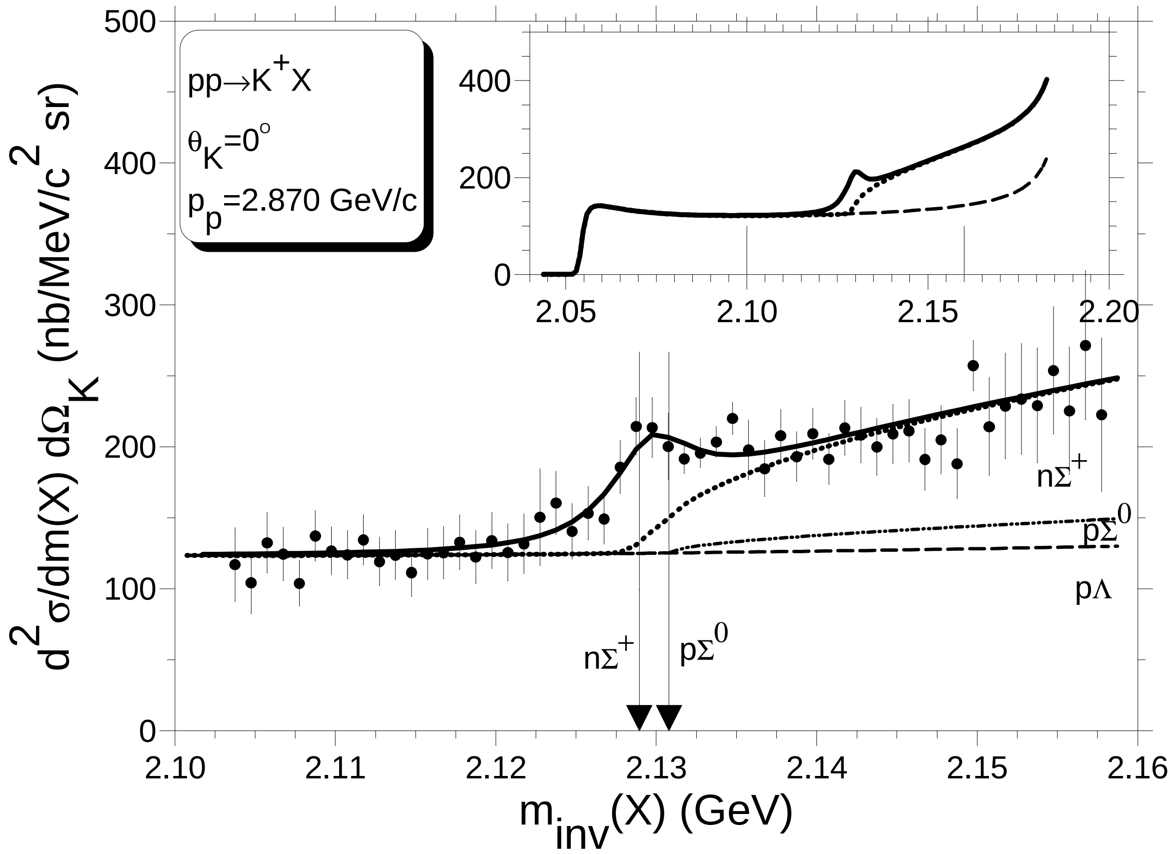
$I = 0\ {}^7S_3\ \Delta\Delta$ quasibound state requires a ${}^3D_3\ pn$ resonance

$\mathcal{S} = -1$ dibaryon candidates & searches

- $I = 1/2$ $J^\pi = 1^+$ Λp resonance or cusp at the $\Sigma^+ n$ threshold?

  Evidence from $K^- d \to \pi^- \Lambda p$ at-rest [Tan, PRL 23 (1969) 395]
  supported by recent $pp \to K^+ X$ $\theta_K = 0^\circ$ @$p_{\rm lab} = 2.87$ GeV/c
  [HIRES Collab. COSY, PLB 692 (2010) 10]
  Whether a cusp or a ΣN ${}^3S_1 - {}^3D_1$ QBS was studied in
  Faddeev calcs. [Toker+Gal+Eisenberg, NPA 362 (1982) 405;
  Torres+Dalitz+Deloff, PLB 174 (1986) 213]
  Tan reported also a structure 10 MeV higher, at 2139 MeV.

- $L \neq 0$ $6q$ dibaryons were suggested by Mulders+Aerts+de Swart, PRD 21 (1980) 2653, and Aerts+Dover, PLB 146 (1984) 95, who placed the lowest $\mathcal{S} = -1$ $L = 1$ dibaryons D_t and D_s near the ΣN threshold ($\pm \approx 20$ MeV, respectively)
  D_s was refuted in a ^{3}He$(K^-, \pi^+)nX$ BNL search
  [Chrien+Dover+Gal, Czech J. Phys. 42 (992) 1089;
  K. Johnston et al., PRC 46 (1992) R1573]

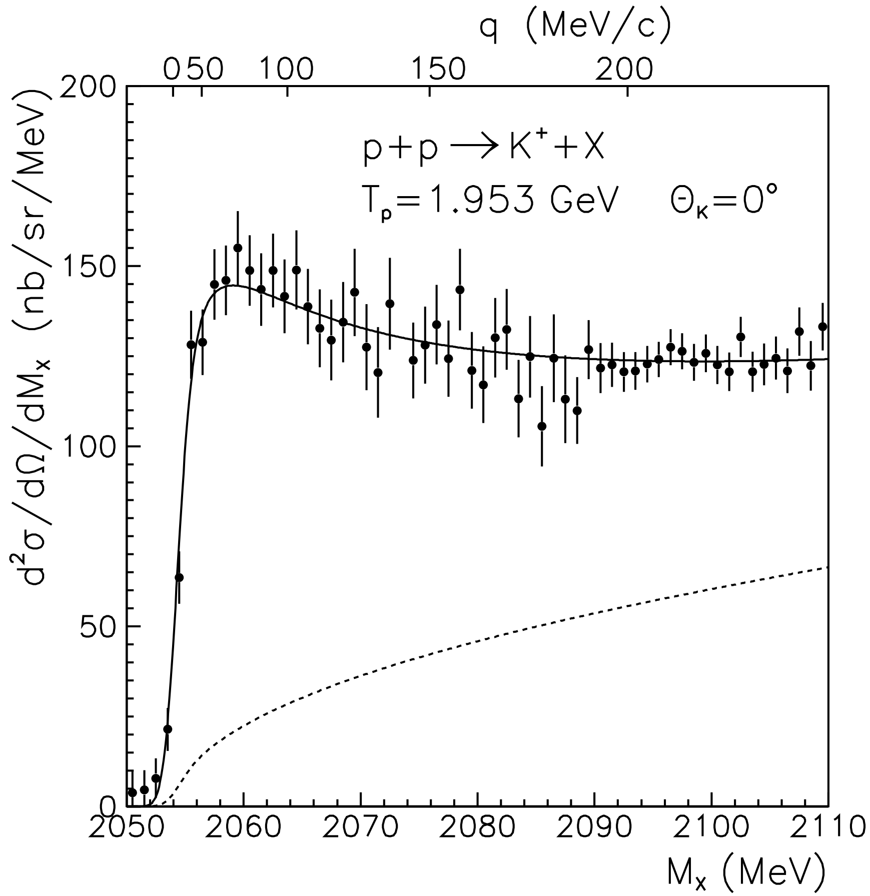


HIRES Collab. COSY, A. Budzanowski et al. PLB 692 (2010) 10

Invariant mass spectrum of YN

The solid curve is a combined fit for $pp \to K^+(\Lambda p,\ \Sigma^0 p,\ \Sigma^+ n)$

A Breit-Wigner is fitted to the threshold cusp



HIRES Collab., PLB 687 (2010) 31

Missing mass spectrum BELOW the ΣN threshold ($\sim$ 2130 MeV)

No evidence for signals suggested earlier at Saturne near 2097 MeV

[Siebert et al. NPA 567 (1994) 819]

Pion assisted dibaryons: $\pi \Lambda N$ etc.

- Extraneous NN dibaryons, e.g. $I = 0, J^\pi = 0^+, 0^-, 2^-, \cdots$ and $I = 1, J^\pi = 1^+, 3^+, \cdots$ are Pauli forbidden for NN [Mulders+Aerts+de Swart, PRL 40 (1978) 1543].
  Lowest predicted: $I = 0;\ 0^-, 2^-$ at 2110 MeV, 0^- discussed by Bilger+Clement+Schepkin, PRL 71 (1993) 42, as candidate for a πNN resonance suggested by DCX on nuclei at 2065 MeV. Here NN is $I = 1, {}^1S_0$, and s-wave pion interactions do not resonate.

- Why not make use of the strong πN $\Delta(1232)$ resonance, ideally for a $I = 2,\ J^\pi = 2^+$ extraneous dibaryon?

- Because the lowest NN configuration is $I = 1,\ J^\pi = 1^+$ $({}^3S_1)$ which is Pauli forbidden. However, it is ΔN allowed.

- Try p-wave pion for nonidentical baryons, e.g. a QBS $\pi\Lambda N$ with $I = 3/2,\ J^\pi = 2^+$, driven by $\Delta(1232)$ and by $\Sigma^*(1385)$, which is a $N\Sigma^*(1385) - \Delta(1232)\Lambda$ dibaryon, much lower than the $I = 1/2, J^\pi = 2^+$ dibaryon $\sqrt{1/5}\ (N\Sigma^* + 2\ \Delta\Sigma)$ found by Oka near the $\Delta\Sigma$ threshold.

Garcilazo-Gal, PRC 81, 055205 (2010): Coupled channels πYN Faddeev-calculated binding energy (MeV) of $\pi\Lambda N$ for five πY interaction models (A-E) using the $^3S_1 - {}^3D_1$ Chiral Quark Model YN interaction, with scattering length a and effective range r_0 (fm). The momentum $p_{\rm lab}(\delta = 0)$ (MeV/c) is the Λ laboratory momentum where the $^3S_1$ ΛN phase shift changes sign. The last line corresponds to switching off the YN interaction. The πY form-factor r.m.s. momentum ranges between 3.72 to 3.16 fm^{-1} for A to E, respectively.

a	r_0	$p_{lab}(\delta = 0)$	A	B	C	D	E
-1.35	3.39	987	147	99	65	30	6
-1.40	3.32	1011	147	99	66	30	6
-1.64	3.09	1146	150	102	68	32	8
-1.71	3.03	1198	150	102	68	33	9
-1.78	2.98	1272	151	103	69	33	9
-1.86	2.93	1446	152	104	69	34	10
–	–	–	170	120	84	47	21

Binding energy of $\pi\Lambda N$ (MeV) for πY model A and the Chiral Quark Model $^3S_1 - {}^3D$ YN interaction, plus a short-range ΛN potential

$$V(r) = \gamma_R \frac{e^{-\beta_R r}}{r} - \gamma_A \frac{e^{-\beta_A r}}{r}$$

with scattering length $a = -1.40$ fm and effective range $r_0 = 3.32$ fm.
Units: γ in MeV-fm, β_A in fm^{-1}, $\beta_R = 10$ fm^{-1}, $p_{\rm lab}(\delta = 0)$ (MeV/c) is the Λ laboratory momentum where the $^3S_1$ ΛN phase shift changes sign.

γ_R	γ_A	β_A	$p_{\rm lab}(\delta = 0)$	$B_{\pi\Lambda N}$
1000	240	5.371	873	107
2000	530	5.811	846	88
3000	720	5.749	822	70
4000	990	5.928	810	59
5000	1260	6.056	802	51
6000	1360	5.921	788	39
7000	1670	6.086	775	34

Summary:

- $\pi\Lambda N$ is bound under a wide choice of parameterizations of the πY form factor. The form factors of the πB subsystems are sufficiently short ranged such that the pion undergoes almost coherently attraction to both baryons. The short ranged repulsion between the two baryons in the CQM is insufficient to overcome the attraction gained by the pion unless the CQM is modified arbitrarily at very short distances to do this job. Altogether, the sensitivity to the parameterization of the πY interaction form factor and the uncertainty of the short range behavior of the YN interaction leave plenty of room, theoretically, for a quasibound $\mathcal{S} = -1$, $(J^P, I) = (2^+, \frac{3}{2})$, $\pi\Lambda N$ dibaryon.
- Search reactions: $K^- + d \to \mathcal{D}^- + \pi^+, \quad \pi^- + d \to \mathcal{D}^- + K^+$ and $\quad p + p \to \mathcal{D}^+ + K^+, \quad \mathcal{D}$ decaying to ΣN with $M_{\mathcal{D}}$ up to $\pi\Sigma N$ threshold.
- Extensions to $\pi\Xi N$ and $\pi\Lambda\Xi$, to $\pi N\Lambda_c(2286)$ and other charmed candidates.
- Extensions to $\pi\bar{K}N$ & πKN, $(J^P, I) = (\frac{3}{2}^-, 1)$ QBS driven by two-body p-wave resonances $\Delta(1232)$ and $K^*(892)$. For $\mathcal{S} = +1$, QBS occurs for $V_{KN} = 0$ but repulsive V_{KN} kills it. Robust QBS in $\mathcal{S} = -1$ sector. Identify with $\Sigma(1480)$ *?