Pion assisted dibaryons

JU symposium, Krakow, June 2015

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- Non-strange dibaryons: from Dyson-Xuong (1964) to $N\Delta$ & $\Delta\Delta$ dibaryon status (2015).
- Experimental discoveries: JLab & COSY.
- Long-range dynamics of pions, nucleons & Δ's: 3-body calculations of $N\Delta$ & $\Delta\Delta$ dibaryons.
  A. Gal, H. Garcilazo, PRL 111, 172301 (2013) and Nucl. Phys. A 928 (2014) 73-88.
- Strange dibaryons: expectations & status. Pion-assisted $\mathcal{S}=-1$ studies; $\mathcal{C}=1$ & beyond.

Nonstrange s-wave dibaryon SU(6) predictions
F.J. Dyson, N.-H. Xuong, PRL 13 (1964) 815

dibaryon	I	S	SU(3)	legend	mass
$\mathcal{D}_{01}$	0	1	$\overline{\mathbf{10}}$	deuteron	A
$\mathcal{D}_{10}$	1	0	**27**	nn	A
$\mathcal{D}_{12}$	1	2	**27**	$N\Delta$	$A+6B$
$\mathcal{D}_{21}$	2	1	**35**	$N\Delta$	$A+6B$
$\mathcal{D}_{03}$	0	3	$\overline{\mathbf{10}}$	$\Delta\Delta$	$A+10B$
$\mathcal{D}_{30}$	3	0	**28**	$\Delta\Delta$	$A+10B$

Assuming 'lowest' SU(6) multiplet, 490, within 56 × 56.

M=A+$B[I(I+1)$+$S(S+1)$**-2]**, **A=1878 MeV from** $M(d)$≈$M(v)$.

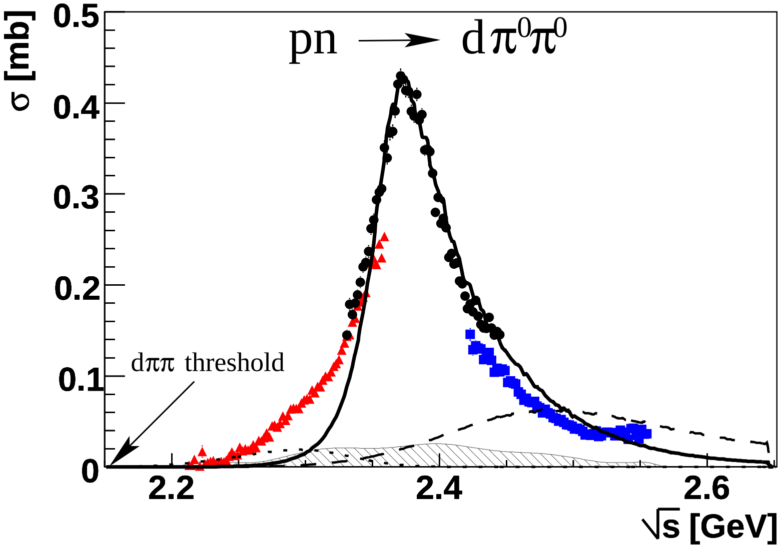
$B = 47$ **MeV from** $M(\mathcal{D}_{12})$≈**2160 MeV observed in** $\pi^+ d \rightarrow pp$.

Hence, $M(\mathcal{D}_{03}) = M(\mathcal{D}_{30}) \approx 2350$ **MeV** [**2**$M(\Delta)$ ≈**2465 MeV**].

Kamae-Fujita, PRL 38 (1977) 468, 471: proton polarization in $\gamma d \rightarrow pn$ **supports a dibaryon at** M ≈**2380 MeV.**

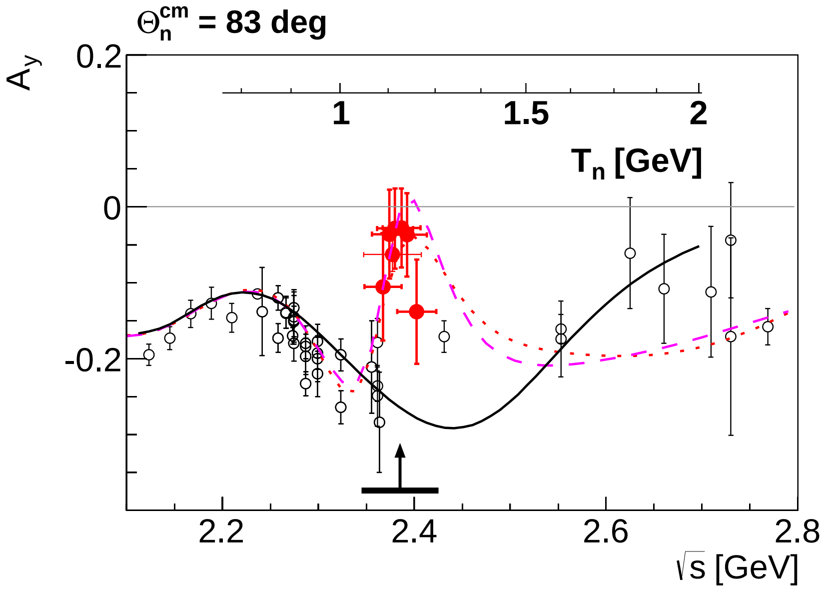
Evidence for $\mathcal{D}_{03}(2380)$, $B \sim 80$ & $\Gamma \sim 70$ MeV

Adlarson et al. PRL 106 (2011) 242302 & 112 (2014) 202301



from $pd \to d\pi^0\pi^0 + p_s$

also in $pd \to d\pi^+\pi^- + p_s$



$^3D_3 - {}^3G_3$ pn resonance

np analyzing power

SAID NN fit requires a resonance pole

WASA@COSY & SAID, PRC 90 (2014) 035204

Given $\Gamma(\Delta) \approx$120 MeV, what makes $\mathcal{D}_{03}$ that narrow?

Quark-based model calculations of $\mathcal{D}_{03}$ & $\mathcal{D}_{12}$

M(GeV)	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	exp/phen
$\mathcal{D}_{03}$ $(\Delta\Delta)$	2.35	2.36	2.44	2.38	$\leq$2.26	2.40	2.46	2.36**	2.38
$\mathcal{D}_{12}$ $(N\Delta)$	2.16*	2.36	–	2.36	–	–	2.17	–	$\approx$2.15

1. **Dyson-Xuong, PRL 13 (1964) 815; *input **postdiction.**
2. **Mulders-Aerts-de Swart, PRD 21 (1980) 2653.**
3. **1980: Oka-Yazaki, PLB 90, 41 (2.46) Cvetic et al. 93, 489 (2.42)**
4. **Mulders-Thomas, JPG 9 (1983) 1159.**
5. **Goldman-Maltman-Stephenson-Schmidt-Wang, PRC 39 (1989) 1889.**
6. **...Zhang-Shen..., PRC 60 (1999) 045203; arXiv:1505.05395 & therein.**
7. **Mota-Valcarce-Fernandez-Entem-Garcilazo, PRC 65 (2002) 034006.**
8. **Ping-Huang-Pang-Wang, PRC 79 (2009) 024001, 89 (2014) 034001.**

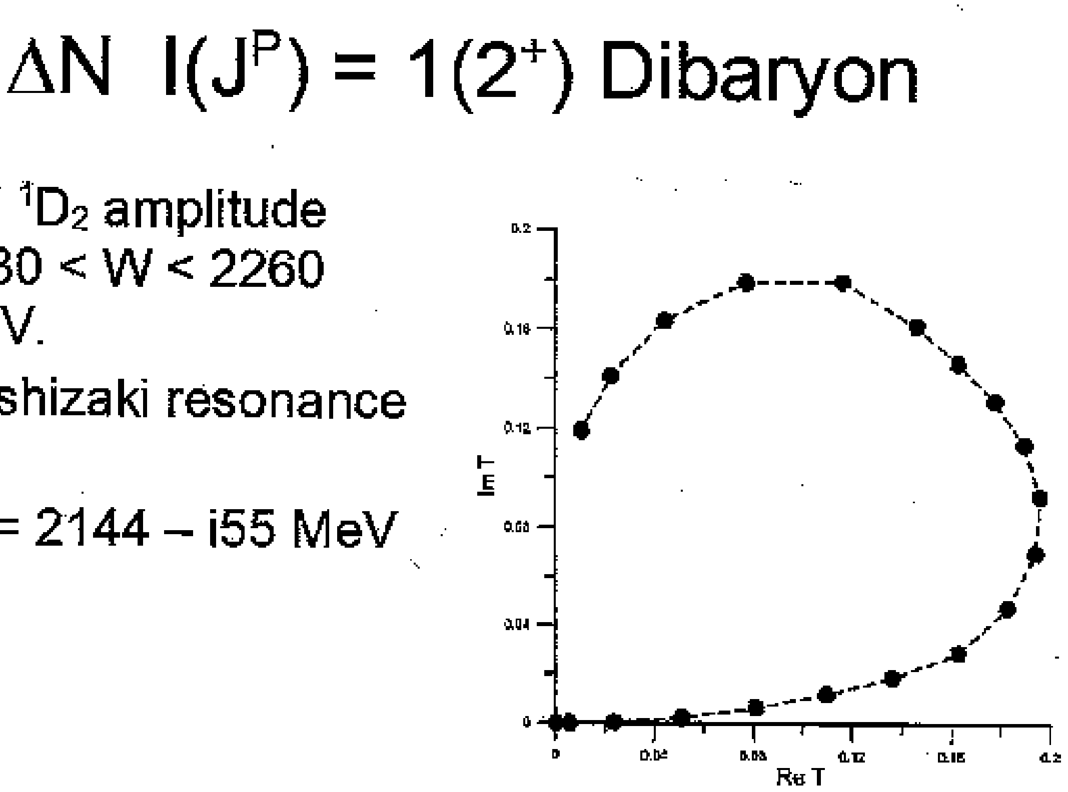
BOTH $\mathcal{D}_{12}$ & $\mathcal{D}_{03}$ predicted correctly only by [1].

Long-range dynamics of dibaryons

A.Gal, H.Garcilazo, PRL 111, 172301 (2013)

Nucl. Phys. A 928 (2014) 73-88

$\mathcal{D}_{12}$ $N\Delta$ dibaryon candidate



ΔN $I(J^P) = 1(2^+)$ Dibaryon

NN $^1D_2$ amplitude
$1880 < W < 2260$
MeV.

Hoshizaki resonance
at

$W = 2144 - i55$ MeV

$NN \leftrightarrow \pi d$ reactions resonate near $N\Delta$ threshold

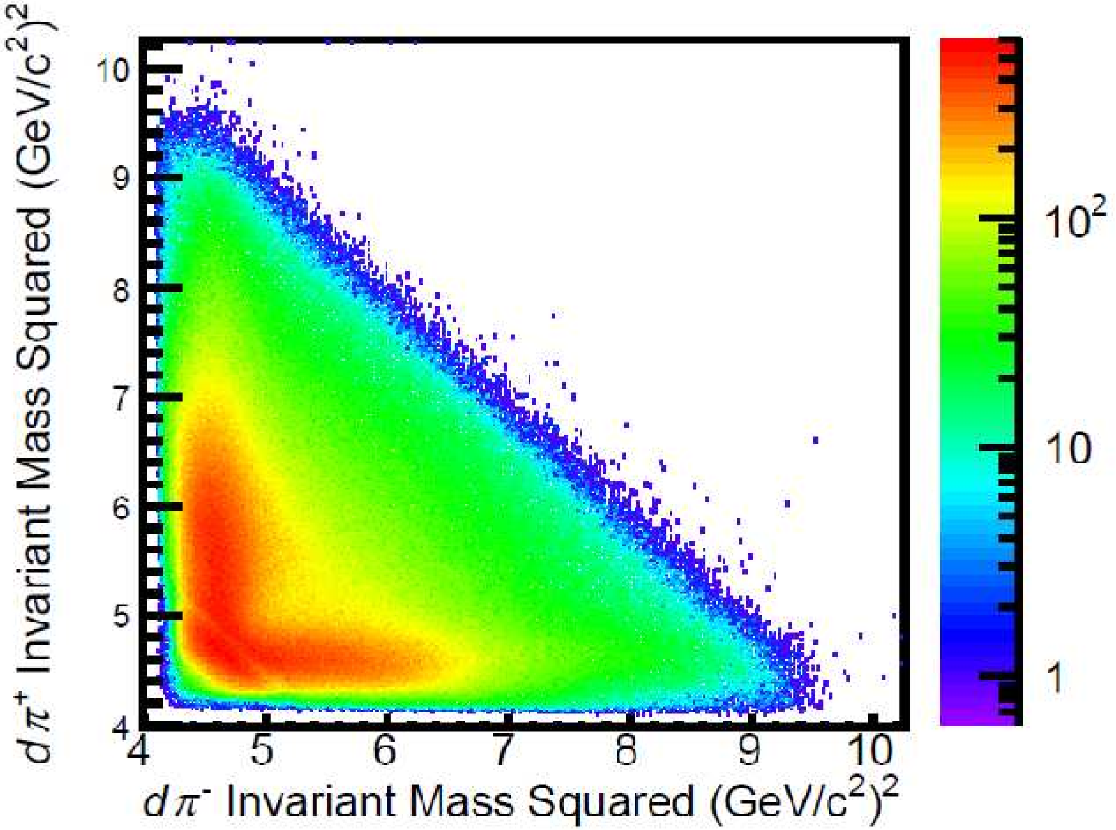
Hoshizaki, PTP 89 (1993) 563: W=2144-i55 MeV

Arndt et al. PRD 35 (1987) 128: W=2148-i63 MeV

$\mathcal{D}_{12}(2150)$ $N\Delta$ dibaryon near threshold (2.17 GeV)

- **Long ago established in coupled-channel $pp(^1D_2) \leftrightarrow \pi^+ d(^3P_2)$ scattering & reactions. Hoshizaki's & Arndt et al's analyses: $M \approx 2.15$ GeV, $\Gamma \approx 110 - 130$.**
- **Nonrelativistic πNN Faddeev calculation, Ueda (1982): $M = 2.12$ GeV, $\Gamma = 120$ MeV.**
- **Our relativistic-kinematics Faddeev calculation gives $M \approx 2.15$ GeV, $\Gamma \approx 120$ MeV. M & Γ robust to variations of NN & πN input.**
- **CLAS $\gamma d \to d\pi^+\pi^-$ data [APS 04/2015] suggest $M_{BW} \approx 2.12$ GeV, $\Gamma_{BW} \approx 125$ MeV.**

$\mathcal{D}_{12}$ $N\Delta$ dibaryon search at JLab

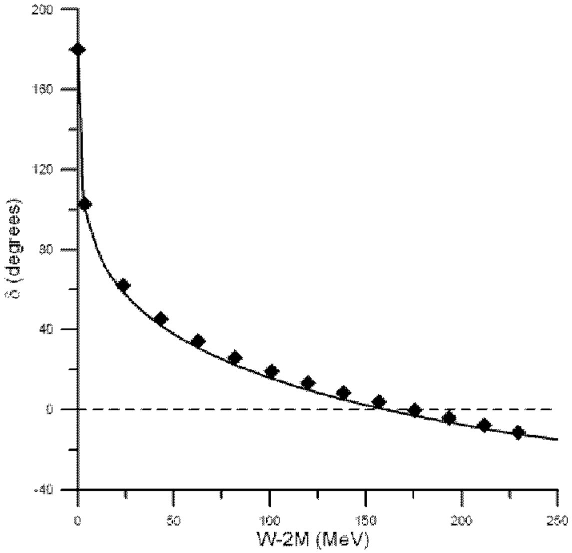


$M_{d\pi^+}$ **vs.** $M_{d\pi^-}$ **in** $\gamma d \to d\pi^+\pi^-$ **(APS 04/2015).**

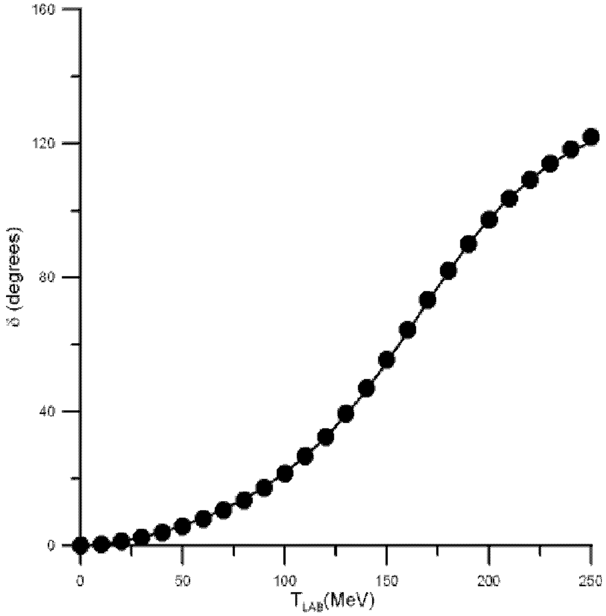
Acceptance-corrected CLAS (g13) data.

Suggests $d\pi^\pm$ **correlation below** $N\Delta$ **threshold.**

Separable potential fits to NN & πN data



fit to NN $\delta(^3S_1)$

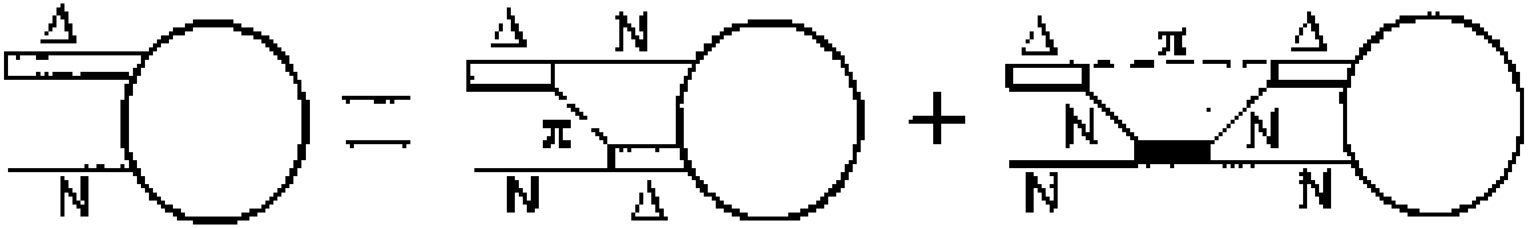


fit to πN $\delta(P33)$

Separable s-wave potentials $v_j \Rightarrow$ **sparable** t **matrices** t_j **entering** πNN **Faddeev equations:** $T_i = t_i + t_i G_0 \sum_{j \neq i} T_j$

Solve for $I(J^P) = 1(1^+),\ 1(2^+),\ 2(1^+),\ 2(2^+)$ **corresponding to** $N\Delta$**-acceptable** $I(J^P)$ **values.**

πNN Faddeev Equations

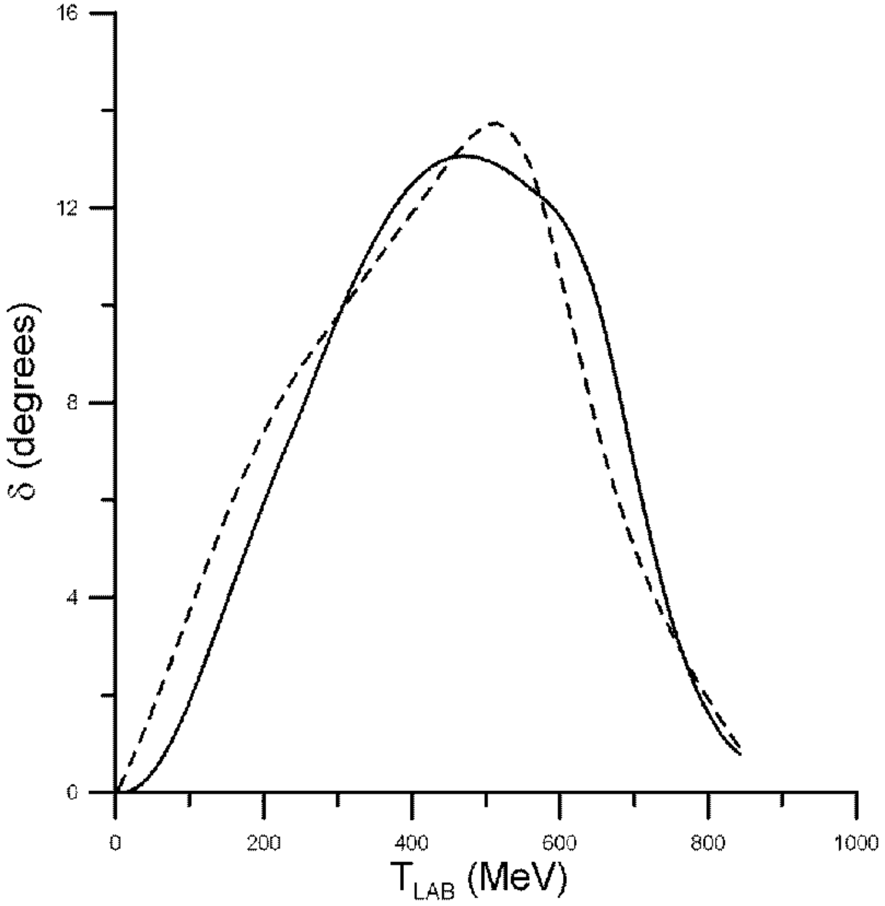


- **For separable interactions, Faddeev equations reduce to one effective 2-body equation.**
  Resonance poles: $IJ = 12, 21$ **(yes),** $11, 22$ **(no).**
  $W(\mathcal{D}_{12}) \approx 2153 - \mathrm{i}65, \;\; W(\mathcal{D}_{21}) \approx 2167 - \mathrm{i}67$ **(MeV)**
- **Given this** $\mathcal{D}_{12}(2150)$ $N\Delta$ **dibaryon, how does one find a related** $N\Delta$**-isobar form factor?**

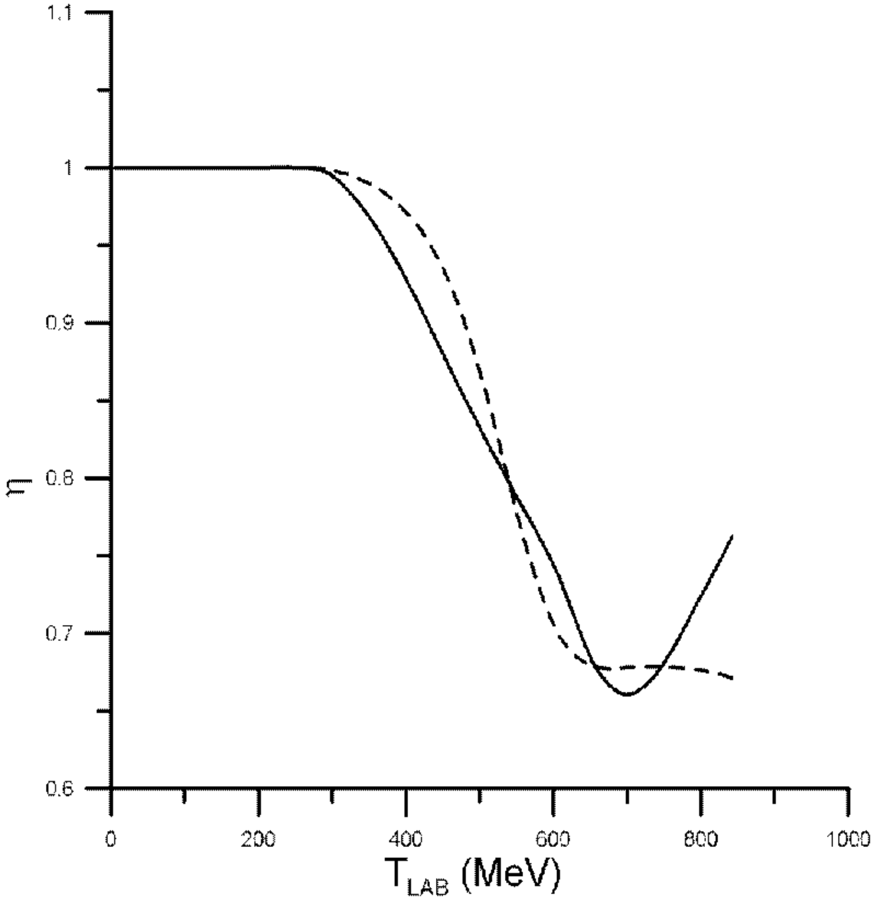
Construction of $N\Delta$ form factor

- **Construct** $(NN)_{\ell=2}$–$(NN')_{\ell=0}$–$(N\Delta')_{\ell=0}$ **separable potential.** N'–**fictitious** P_{13} **baryon with** $m_{N'} = m_\pi + m_N$ **to generate** πNN **inelastic cut.** Δ'– **stable** Δ **with** $m_{\Delta'} = 1232$ **MeV.**
- **No ad-hoc pole is introduced into** $(N\Delta')_{\ell=0}$**.**
- **Require form-factor cutoff mommenta** $\leq$**3 fm**$^{-1}$ **to be consistent with long-range physics e.g. no** $\pi N \to \rho N$**.**
- **Fitting** NN $\delta(^1D_2)$ **&** $\eta(^1D_2)$ **determines the** $\mathcal{D}_{12}(2150)$**-isobar** $(N\Delta')_{\ell=0}$ **form factor.**

Fitting $NN\ \delta(^1D_2)$ & $\eta(^1D_2)$



$NN\ ^1D_2$ phase shift fit

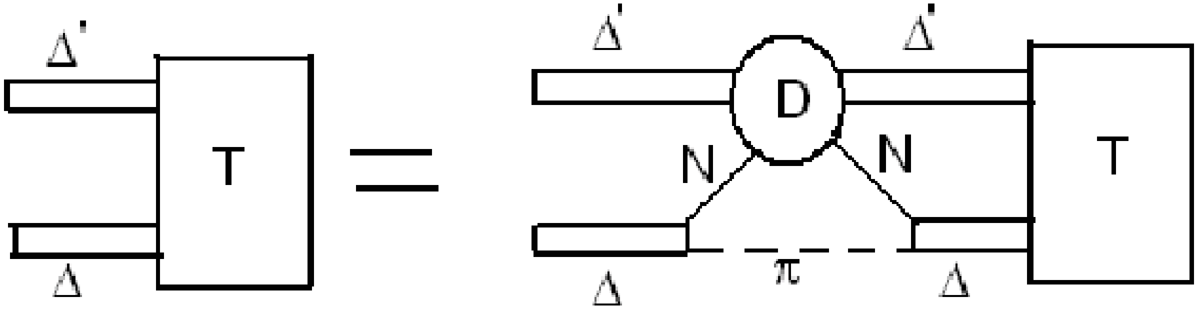


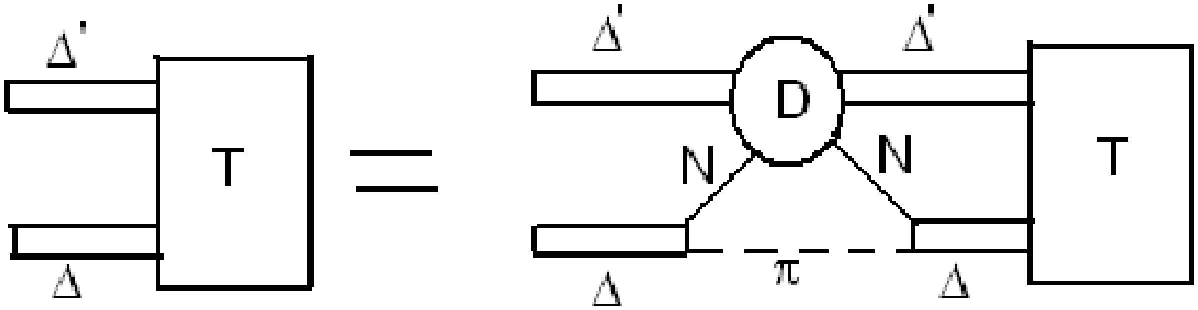
$NN\ ^1D_2$ inelasticity fit

Dashed: gwdac.phys.gwu.edu [SAID], Solid: best fit

Calculation of $\mathcal{D}_{03}(2380)$ $\Delta\Delta$ dibaryon in terms of π's, N's & Δ's

- **Approximate $\pi\pi NN$ problem by $\pi N\Delta'$ problem.**
- **Separable pair interactions: πN Δ-isobar form factor by fitting $\delta(P_{33})$; $N\Delta'$ $\mathcal{D}_{12}(2150)$-isobar form factor by fitting $NN(^1D_2)$ scattering.**
- **3-body S-matrix pole equation reduces to effective $\Delta\Delta'$ diagram:**





- **Searching numerically for S-matrix resonance poles by going complex, $q_j \rightarrow q_j \exp(-i\phi)$, thus opening sections of the unphysical Riemann sheet to accommodate poles of the form $W = M - \mathrm{i}\Gamma/2$.**
- **In the πN propagator, where Δ' is a spectator, replace real mass $m_{\Delta'}$=1232 MeV by Δ-pole complex mass m_Δ=1211-i49.5×(2/3) MeV, x=2/3 accounting for quantum-statistics correlations for decay products of two I(JP)=0(3+) Δ's, assuming s-wave decay nucleons.**

Results & Discussion

- **Using 0.9 & 1.3 fm sized P_{33} form factors: M=2363±20, Γ=65±17, (x=1: 78±17 MeV) in good agreement with WASA@COSY.**
- **Although bound w.r.t. $\Delta\Delta$, $\mathcal{D}_{03}(2380)$ is resonating w.r.t. the $\pi - \mathcal{D}_{12}(2150)$ threshold. The subsequent decay $\mathcal{D}_{12}(2150) \to \pi d$ is seen in the πd Dalitz plot projection.**
- **NN-decoupled dibaryon resonances $\mathcal{D}_{21}$ & $\mathcal{D}_{30}$ predicted 10–30 MeV higher, respectively; see also Bashkanov-Brodsky-Clement, Novel 6q Hidden-Color Dibaryons in QCD, PLB 727 (2013) 438. Width calculation?**

Recent Quark Model Calculations

- **Orbitally symmetric [6] I(JP)=0(3+) w.f. is $\sqrt{1/5}\Delta\Delta + \sqrt{4/5}$CC. How do CC hidden-color components affect the mass & width?**
- **H. Huang et al., PRC 89 (2014) 034001, use the Salamanca chiral quark model (CQM) to go from 1→4 ΔΔ channels, then to full 10: M = 2425 → 2413 → 2393 MeV Γ=177→175→150 MeV, so Γ is too big.**
- **F. Huang et al., arXiv 1505.05395, find in their CQM: M≈2400±20 MeV & 67% CC, arguing for a strongly suppressed ΔΔ width since strong decay cannot occur from CC components...**

Extension to Strangeness

$\mathcal{S}$ = -2, -3, -4 deuteron-like $\mathbf{8}_F \times \mathbf{8}_F$ dibaryons?

	$\Sigma\Sigma$ $(I=2,{}^1S_0)$	$\Lambda\Xi$ $(I=\frac{1}{2},{}^1S_0)$	$\Sigma\Xi$ $(I=\frac{3}{2},{}^1S_0)$	$\Sigma\Xi$ $(I=\frac{3}{2},{}^3S_1)$	$\Xi\Xi$ $(I=1,{}^1S_0)$
NSC97	+	−	+	+	+
EFT (LO)	−	+	+	−	+
EFT (NLO)	−	−	−	−	−

NSC97: V.G.J. Stoks, T.A. Rijken, Phys. Rev. C **59** (1999) 3009

EFT (LO): J. Haidenbauer, U.-G. Meißner, Phys. Lett. B **684** (2010) 275

EFT (NLO): JH, UGM, S. Petschauer, Eur. Phys. J. A **51** (2015) 17

- Based on ≈40 Λp, Σp, $\Xi^- p$ low-energy data points.
- Systematics of EFT (LO): 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.
- ${}^1S_0$ in SU(3)$_{\rm f}$ **27** (as nn), ${}^3S_1$ in SU(3)$_{\rm f}$ $\overline{\mathbf{10}}$ (as deuteron).
- Model dependence is assessed by varying a cutoff momentum in the range 550 – 700 MeV/c. **SU(3) breaking aborts binding at NLO.**

Color Magnetic (CM) gluon exchange interaction

For orbitally symmetric $L = 0$ 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 $\mathrm{SU}(3)_{\rm f}$ **1** antisymmetric representation of n quarks, $n = 3$ for a baryon (B) and $n = 6$ for BB.

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

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

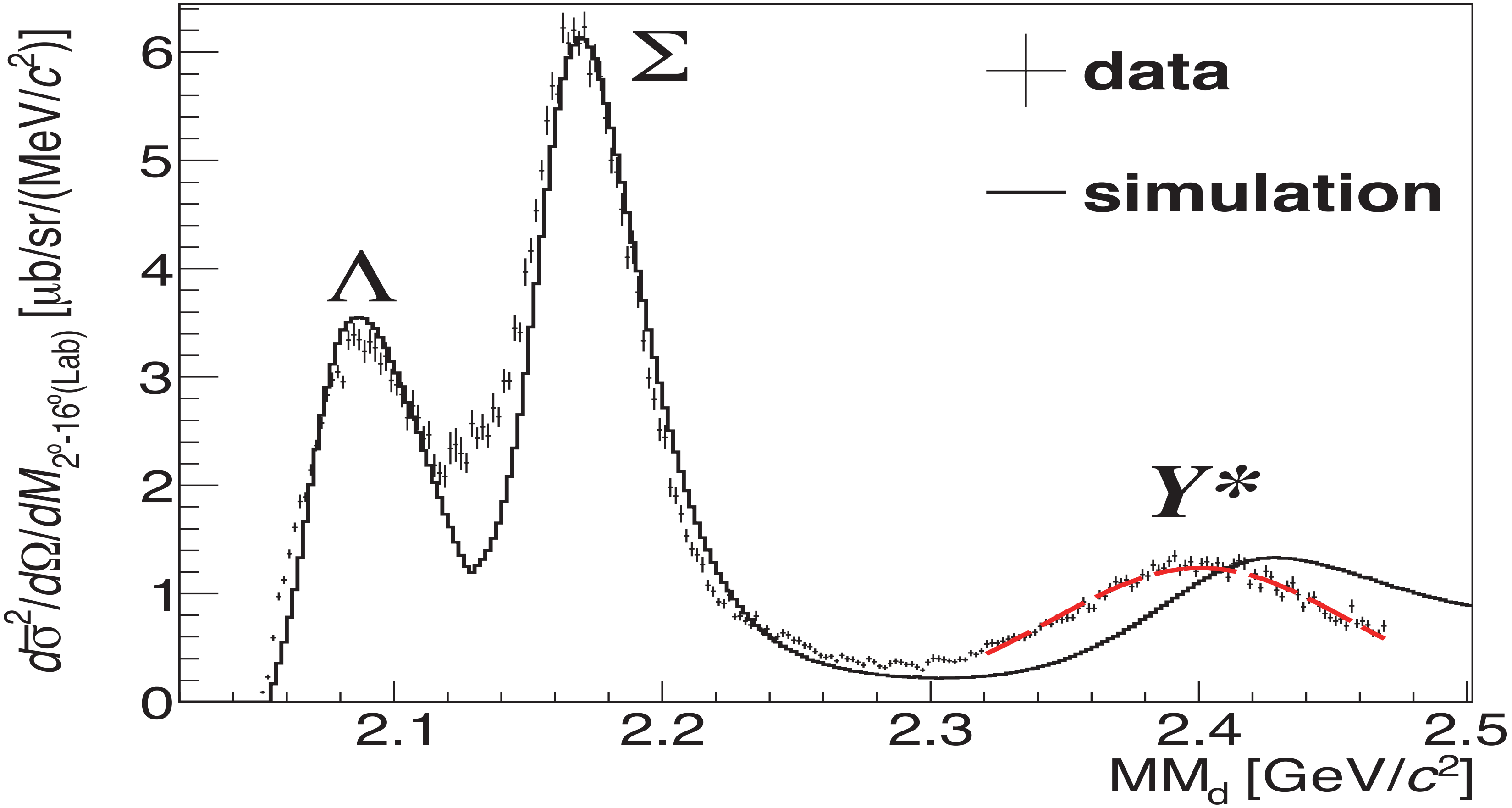
$$< V_{CM} >_{\mathcal{H}} -2 < V_{CM} >_{\Lambda} = -2\mathcal{M}_0$$

$$\text{where} \quad 4\mathcal{M}_0 =< V_{CM} >_{\Delta} - < V_{CM} >_{N} \sim M_{\Delta} - M_N \approx 300 \text{ MeV}$$

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

$\mathcal{S}$	SU(3)$_\mathrm{f}$	I	J^π	BB structure	$\Delta < V_{CM} >$
0	[3,3,0] $\overline{\mathbf{10}}$	0	3^+	$\mathcal{D}_{03}\ (\Delta\Delta)$	0
-1	[3,2,1] **8**	1/2	2^+	$\sqrt{1/5}\ (N\Sigma^* + 2\ \Delta\Sigma)$	$-\mathcal{M}_0$
-2	[2,2,2] **1**	0	0^+	$\mathcal{H} = \sqrt{1/8}\ (\Lambda\Lambda + 2\ N\Xi - \sqrt{3}\ \Sigma\Sigma)$	$-2\mathcal{M}_0$
-3	[3,2,1] **8**	1/2	2^+	$\sqrt{1/5}\ [\sqrt{2}\ N\Omega - (\Lambda\Xi^* - \Sigma^*\Xi + \Sigma\Xi^*)]$	$-\mathcal{M}_0$

- **A bound $\mathcal{H}$ overbinds $^{\ 6}_{\Lambda\Lambda}$He [Gal, PRL 110 (2013) 179201]. SU(3)$_\mathrm{f}$ breaking pushes it to $\approx N\Xi$ threshold, 26 MeV above $\Lambda\Lambda$ threshold [HAL QCD, NPA 881 (2012) 28; Haidenbauer & Meißner, ibid. 44].**
- **$N\Omega$ dibaryon: HAL QCD, Nucl. Phys. A 928 (2014) 89.**
- **Let's focus on $\mathcal{S}=-1$.**



Missing-mass spectrum in $d(\pi^+, K^+)$ at 1.69 GeV/c

J-PARC E27, PTEP 2014, 101D03

(i) ΣN threshold cusp at ≈2130 MeV.

(ii) Y^* quasi-free peak shifted by ≈−22 MeV, indicating $Y^* N$ attraction [$Y^* = \Sigma(1385)$ & $\Lambda(1405)$].

$\Lambda(1405)N$: K^-pp bound-state calculations

(MeV)	chiral, energy dep. calculations				non-chiral, static calculations			
	var. [1]	var. [2]	Fad. [3]	Fad. [4]	var. [5]	Fad. [6]	Fad. [7]	var. [8]
B	16	17–23	9–16	32	48	50–70	60–95	40–80
Γ	41	40–70	34–46	49	61	90–110	45–80	40–85

Robust binding & large widths; chiral models give weak binding.

Searches at Frascati, GSI, J-PARC are inconclusive.

1. N. Barnea, A. Gal, E.Z. Liverts, PLB **712** (2012)
2. A. Doté, T. Hyodo, W. Weise, NPA **804** (2008) 197, PRC **79** (2009) 014003
3. Y. Ikeda, H. Kamano, T. Sato, PTP **124** (2010) 533
4. J Revai, N.V. Shevchenko, PRC **90** (2014) 034004
5. T. Yamazaki, Y. Akaishi, PLB **535** (2002) 70
6. N.V. Shevchenko, A. Gal, J. Mareš, PRL **98** (2007) 082301
7. Y. Ikeda, T. Sato, PRC **76** (2007) 035203, PRC **79** (2009) 035201
8. S. Wycech, A.M. Green, PRC **79** (2009) 014001 (including p waves)

from $\Lambda(1405)N$ **to** $\Sigma(1385)N$

- $\Lambda(1405)N$ is in a way a doorway to the quasibound $I = 1/2$, $J^P = 0^-$ $\bar{K}NN$ dibaryon. Lower $\mathcal{S} = -1$ components are $\pi\Lambda N$ and $\pi\Sigma N$, the lowest of which is $\pi\Lambda N$, but it cannot support any strongly attractive meson-baryon s-wave interaction.

- The $\pi\Lambda N$ system can benefit from strong meson-baryon p-wave interactions fitted to the $\Delta(1232) \to \pi N$ and $\Sigma(1385) \to \pi\Lambda$ form factors. Maximize isospin and angular momentum couplings by full alignment: $I = 3/2$, $J^P = 2^+$. In particular, ΛN is in ${}^3S_1$. This is a **Pion Assisted Dibaryon**, see **Gal & Garcilazo, PRD 78 (2008) 014013.**

- Add the $\pi\Sigma N$ channel [PRC 81 (2010) 055205, and finalized in NPA 897 (2013) 167].
  A $\pi\Lambda N$ resonance about 10–20 MeV below the $\pi\Sigma N$ threshold is found by solving coupled-channel Faddeev equations. Results are sensitive to the pion-baryon p-wave form factors.

- This resonance is a pion assisted quasibound dibaryon, suggesting doorway states of the type $\Sigma(1385)N$ and $\Delta(1232)Y$, the lower of which is $\Sigma(1385)N$ with $I = 3/2$ and ${}^5S_2$, $J^P = 2^+$. These are different labels from the $I = 1/2$ and ${}^1S_0$, $J^P = 0^-$ for $\Lambda(1405)N$ viewed as a doorway to K^-pp.

- Adding a $\bar{K}NN$ channel does not help, because the leading ${}^3S_1$ NN configuration is Pauli forbidden.

- Search for this $\mathcal{Y}$ dibaryon at GSI & J-PARC in:
  $p + p \rightarrow \mathcal{Y}^{++} + K^0, \quad \mathcal{Y}^{++} \rightarrow \Sigma^+ + p,$
  or $\pi^+ + d \rightarrow \mathcal{Y}^{++} + K^0, \quad \mathcal{Y}^{++} \rightarrow \Sigma^+ + p.$

- A (π^+, K^+) reaction as in E27 would lead to YN decay states similar to those anticipated in searches of K^-pp. Another possibility at J-PARC or GSI is:
  $\pi^- + d \rightarrow \mathcal{Y}^- + K^+, \quad \mathcal{Y}^- \rightarrow \Sigma^- + n.$

Summary

- **The two experimentally established nonstrange dibaryons $\mathcal{D}_{12}(2150)$ & $\mathcal{D}_{03}(2380)$ are derived quantitatively with long-range hadronic physics guidelines using pions, nucleons & Δs input.**
- **Search for NN-decoupled $\mathcal{D}_{21}$ & $\mathcal{D}_{30}$ dibaryons.**
- **Develop EFT description for these dibaryons.**
- **Does $\Sigma(1385)$ play the role of $\Delta(1232)$ for strange dibaryon candidates?**
  $\Sigma(1385)N$ ($I=\frac{3}{2}, 2^+$) vs. $\Lambda(1405)N$ ($I=\frac{1}{2}, 0^-$).
- **Charmed dibaryons?**
  $\pi\Lambda_c N$ ($I=\frac{3}{2}, 2^+$) Gal..., PRD 90 (2014) vs.
  DNN ($I=\frac{1}{2}, 0^-$) ...Oset, PRC 86 (2012)].