$N\Delta$ & $\Delta\Delta$ dibaryons revisited

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- Quark-based expectations for dibaryons.
- Non-strange dibaryons, from Dyson & Xuong (1964) to Oka & Yazaki (1980) & to Goldman et al. (1989): the INEVITABLE $\Delta\Delta$ dibaryon.
- Experimental searches: COSY recent news.
- 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)

Dibaryons as six-quark configurations

Color Magnetic (CM) gluon exchange interaction

For orbitally symmetric color-singlet n-quark cluster:

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

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]:

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

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

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

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

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

- Table suggests that the $\mathcal{S} = -2$ **H** is the most bound. However, thresholds & other SU(3) breaking effects abort binding.
- Coupled-channel **H** near ΞN threshold, $\approx$ 26 MeV above $\Lambda\Lambda$. **HAL QCD, NPA 881 (2012) 28; Haidenbauer & Meißner, ibid. 44; Shanahan, Thomas & Young, arXiv:1308.1748.**
- **Let's focus on the nonstrange $\Delta\Delta$ dibaryon candidate**

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	$\mathbf{27}$	nn	A
$\mathcal{D}_{12}$	1	2	$\mathbf{27}$	$N\Delta$	$A+6B$
$\mathcal{D}_{21}$	2	1	$\mathbf{35}$	$N\Delta$	$A+6B$
$\mathcal{D}_{03}$	0	3	$\overline{\mathbf{10}}$	$\Delta\Delta$	$A+10B$
$\mathcal{D}_{30}$	3	0	$\mathbf{28}$	$\Delta\Delta$	$A+10B$

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

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

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

Hence, $M(\mathcal{D}_{03}) = M(\mathcal{D}_{30}) \approx 2350$ MeV.

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

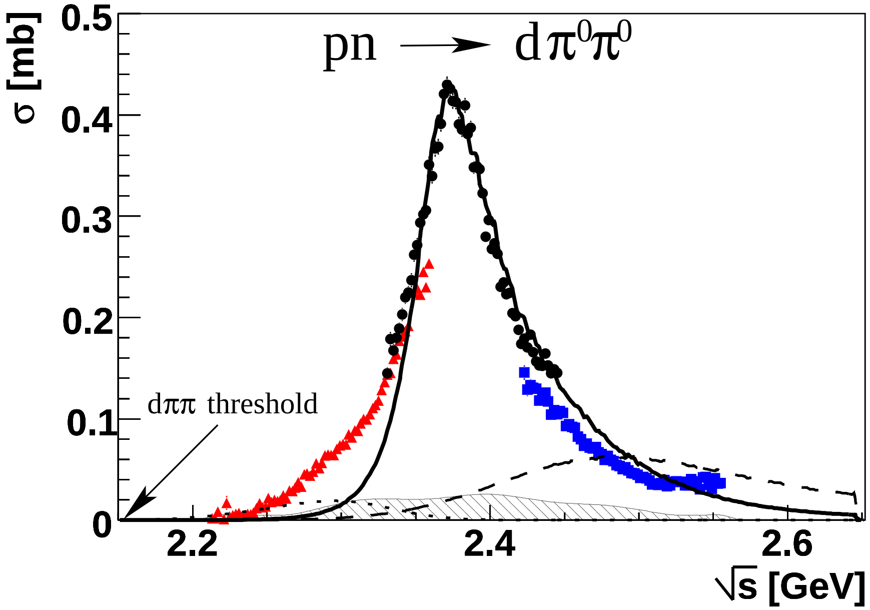
M(GeV)	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	exp.
$\mathcal{D}_{03}$ ($\Delta\Delta$)	2.35	2.36	2.46	2.38	2.20	$\leq$2.26	2.43	2.46	2.37
$\mathcal{D}_{12}$ ($N\Delta$)	2.16*	2.36	–	2.36	–	–	2.34*	2.17	$\approx$2.17

1. Dyson-Xuong, PRL 13 (1964) 815; *input.
2. Mulders-Aerts-de Swart, PRD 21 (1980) 2653.
3. Oka-Yazaki, PLB 90 (1980) 41.
4. Mulders-Thomas, JPG 9 (1983) 1159.
5. Maltman, NPA 438 (1985) 669.
6. Goldman-Maltman-Stephenson-Schmidt-Wang, PRC 39 (1989) 1889.
7. Garcilazo et al., PRC 56 (1997) 84; *Garcilazo-Pena, PRC 44 (1991) 2311.
8. Mota-Valcarce-Fernandez-Entem-Garcilazo, PRC 65 (2002) 034006.

Recent news from WASA@COSY

Evidence for $\mathcal{D}_{03}(2370)$ $\Delta\Delta$ dibaryon, $B \sim 90$ & $\Gamma \sim 70$ MeV

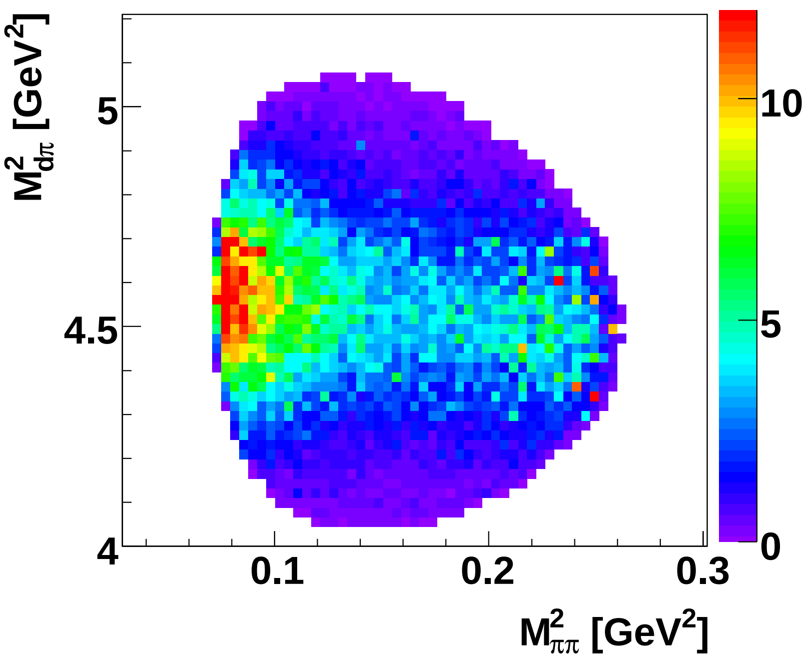
${}^3D_3 - {}^3G_3$ pn resonance?

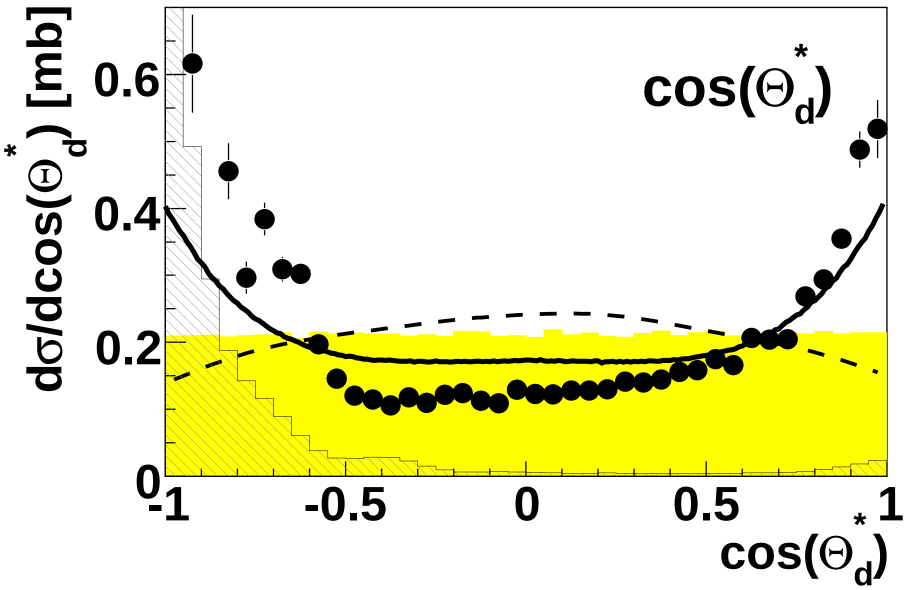


Adlarson et al. (WASA@COSY), PRL 106, 242302 (2011)

Total cross section from $pd \to d\pi^0\pi^0 + p_s$ **at several energies, seen also in** $pd \to d\pi^+\pi^- + p_s$**. What makes it that narrow?**

Pair correlations and particle distributions





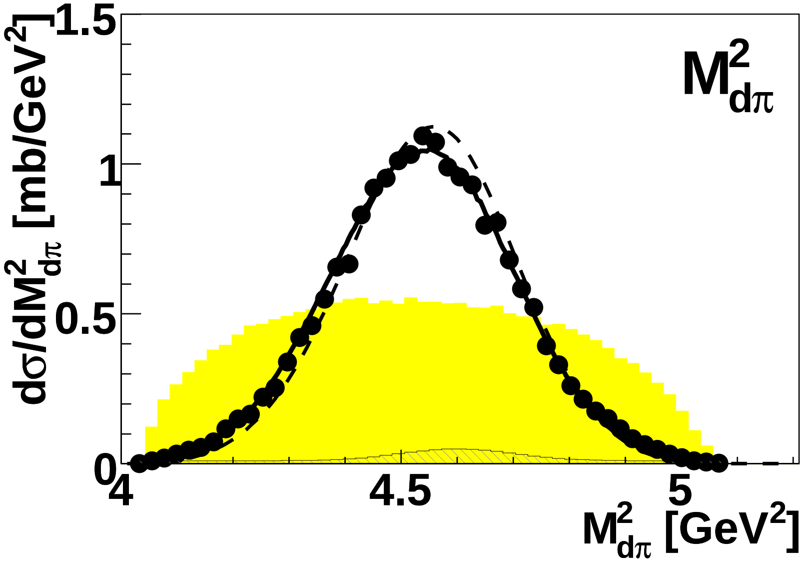
Dalitz plot $M^2_{d\pi^0}$ vs. $M^2_{\pi^0\pi^0}$

d cm angular distribution: J^P=3$^+$ (solid), J^P=1$^+$ (dash)

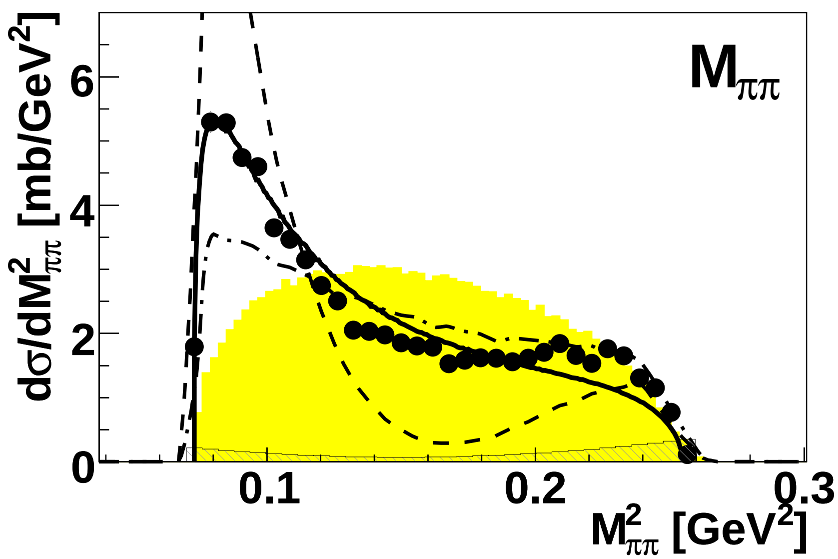
Plots at $\sqrt{s}$=2.38 GeV

from Adlarson et al. (WASA@COSY), PRL 106, 242302 (2011)

Dalitz plot projections at $\sqrt{s}$=2.38 GeV



$M^2_{d\pi^0}$ at $\sqrt{s}$=2.38 GeV



$M^2_{\pi^0\pi^0}$ at $\sqrt{s}$=2.38 GeV

from Adlarson et al. (WASA@COSY), PRL 106, 242302 (2011)

Curves denote calculations for a s-channel resonance decaying to $\Delta\Delta$ with J^P=3^+ (solid) & J^P=1^+ (dash). Shaded areas denote phase-space distributions.

Long-range dynamics of dibaryons

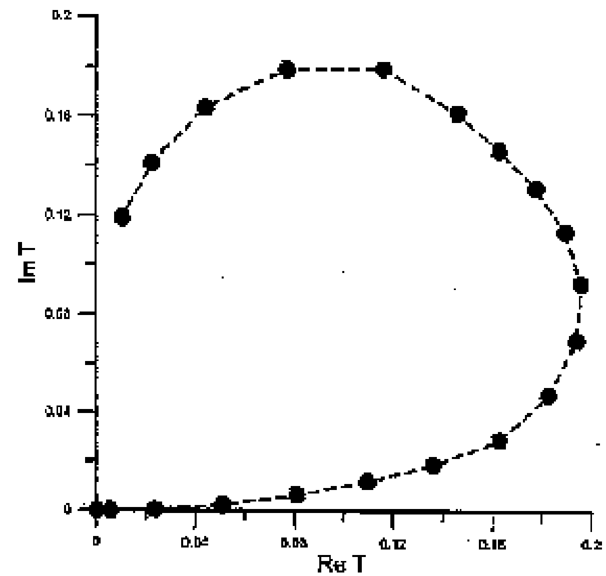
A.Gal, H.Garcilazo, PRL 111, 172301 (2013)

$\mathcal{D}_{12}$ $N\Delta$ 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 at 2.17 GeV.

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

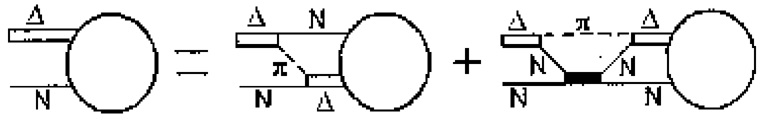
- **Long ago established in coupled-channel $pp(^1D_2) \leftrightarrow \pi^+ d(^3P_2)$ scattering & reactions. Hoshizaki's & Arndt et al's analyses: $M \approx 2.14 - 2.17$ GeV, $\Gamma \approx 115$.**

- **Nonrelativistic πNN Faddeev calculation, Ueda (1982): $M = 2.12$ GeV, $\Gamma = 120$ MeV.**

- **Our relativistic-kinematics calculation gives $M \approx 2.15$ GeV, $\Gamma \approx 120$ MeV.**

- **M & Γ robust to variations of NN & πN input.**

$J^P=2^+$ πNN Faddeev Equations



- **For separable interactions, Faddeev equations reduce to one effective 2-body scattering equation. Solve homogeneous part for resonance poles.**
- **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

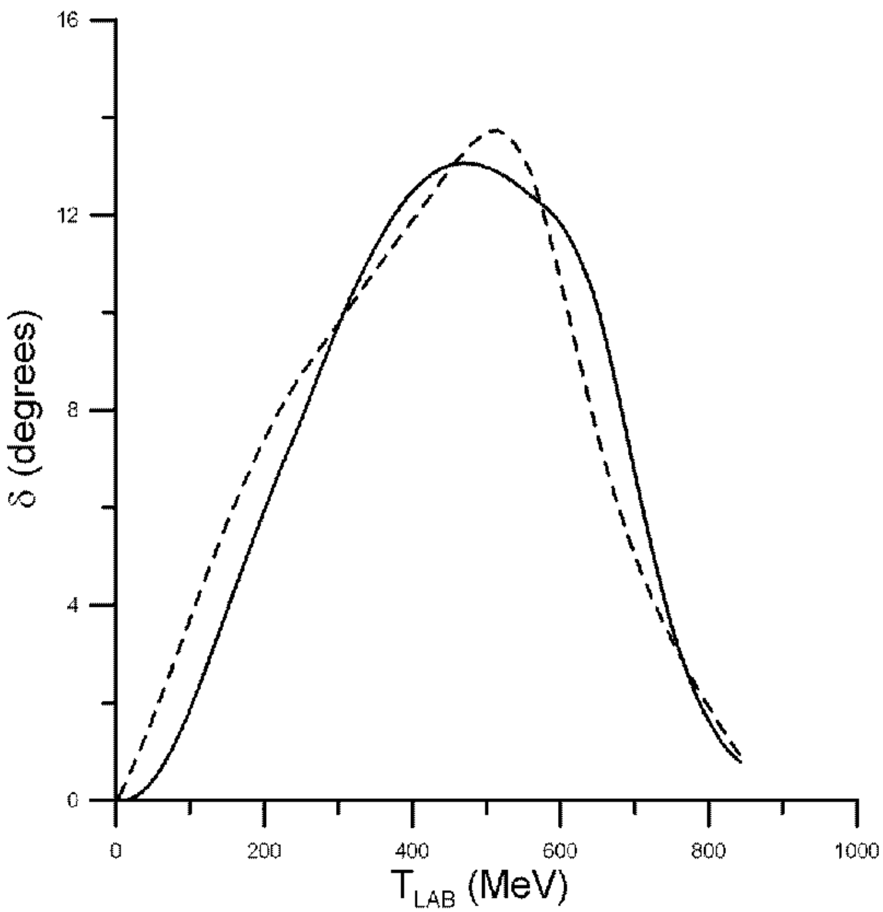
- **Construct** $(NN)_{\ell=2}$–$(NN')_{\ell=0}$–$(N\Delta')_{\ell=0}$ **separable potential.** N'**–fictitious** P_{13} **baryon with** $m_{N'} = m_\pi + m_N$ **to generate** πNN **inelastic cut.** Δ'**– stable** Δ **with** $m_{\Delta'} = 1232$ **MeV.**

- **No ad-hoc pole is introduced into** $(N\Delta')_{\ell=0}$**.**

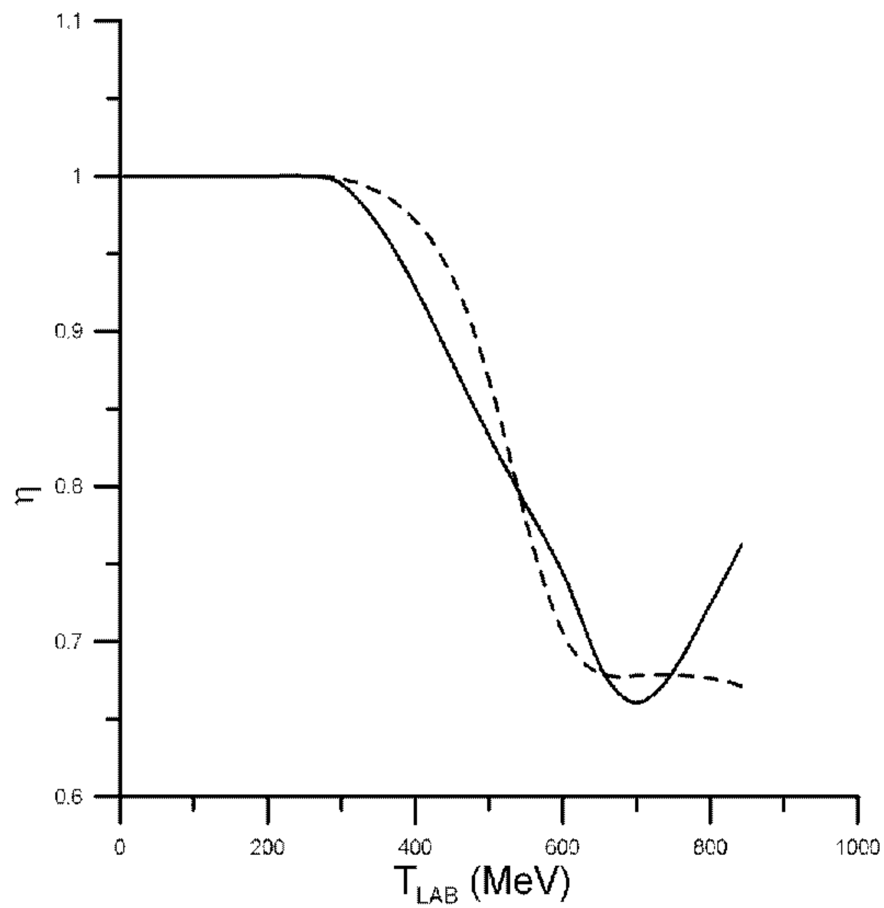
- **Require form-factor cutoff mommenta** $\leq$**3 fm**$^{-1}$ **to be consistent with long-range physics e.g. no** $\pi N \to \rho N$**.**

- **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**

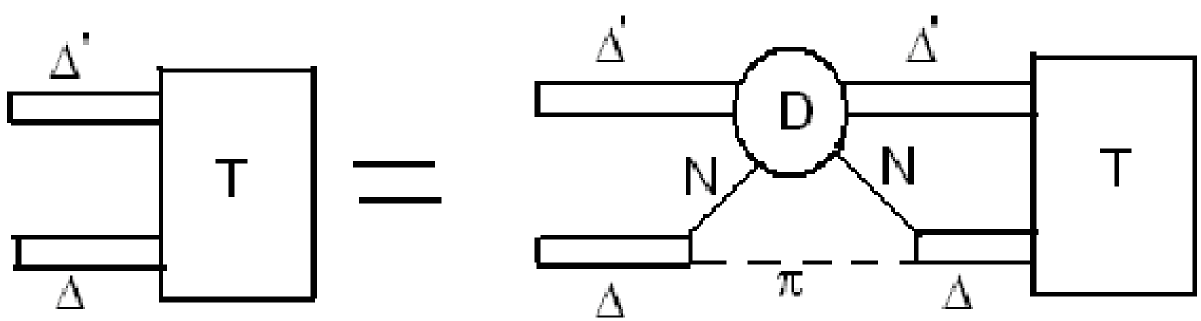


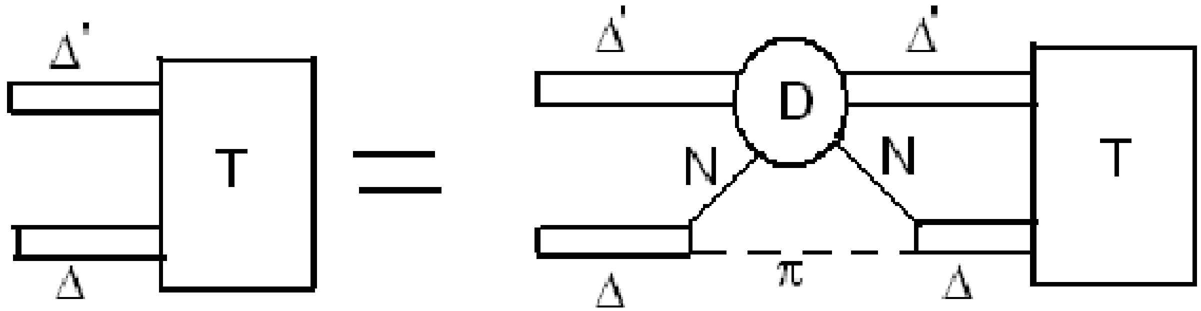
NN $^1D_2$ **inelasticity fit**

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

Calculation of $\mathcal{D}_{03}(2370)$ $\Delta\Delta$ 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, $q_j \to q_j \exp(-i\phi)$, thus opening sections of the unphysical Riemann sheet to accommodate poles of the form $W = M - i\Gamma/2$.**
- **In the πN propagator, where Δ' is a spectator, replace real mass $m_{\Delta'} = 1232$ MeV by Δ-pole complex mass $m_\Delta = 1211 - i49.5 \times (2/3)$ MeV, factor 2/3 accounting for quantum-statistics correlations between decay products of the two $I(J^P) = 0(3^+)$ Δ's, assuming s-wave decay nucleons.**

Results & Discussion

- **Using two different P_{33} form factors, with spatial size 0.9 & 1.3 fm, we get** $M = 2363 \pm 20$, $\Gamma = 65 \pm 17$ **MeV, in good agreement with WASA@COSY.**
- **Although bound w.r.t. $\Delta\Delta$, $\mathcal{D}_{03}(2370)$ 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.**
- **Search for other, NN-decoupled dibaryon resonances: $\mathcal{D}_{21}$ and $\mathcal{D}_{30}$, arXiv:1308.6404 Bashkanov-Brodsky-Clement: Novel Six-Quark Hidden-Color Dibaryon States in QCD.**

Summary

- The two experimentally established nonstrange (s-wave ?) dibaryons $\mathcal{D}_{12}(2150)$ and $\mathcal{D}_{03}(2370)$ are quantitatively derived from long range physics description requiring only pions, nucleons and Δ's for input.
- Search for other, in particular $\mathcal{D}_{21}$ & $\mathcal{D}_{30}$ dibaryon candidates.
- Develop EFT description for these dibaryons.
- Does $\Sigma(1385)$ play the role of $\Delta(1232)$ for strange dibaryon candidates?

Special thanks to my collaborator Humberto Garcilazo