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

EXA 2014, Vienna, Sept. 2014

Avraham Gal, Hebrew University, Jerusalem

- **Quark-based expectations for dibaryons.**
- **Non-strange: from Dyson-Xuong (1964) to Oka-Yazaki (1980) & to Goldman et al. (1989): the INEVITABLE $\Delta\Delta$ dibaryon. 2014 update.**
- **Experimental discoveries: 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) and Nucl. Phys. A 928 (2014) 73-88

Dibaryons as six-quark configurations

Color Magnetic (CM) gluon exchange interaction

For orbitally symmetric $L = 0$ color-singlet n-quark cluster:

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

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 $\mathbf{H}(uuddss)$ [PRL 38 (1977) 195]:

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

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

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

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

$\mathcal{S}$	$\mathrm{SU(3)_f}$	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^+	$\sqrt{1/5}\,[\sqrt{2}\,N\Omega - (\Lambda\Xi^* - \Sigma^*\Xi + \Sigma\Xi^*)]$	$-\mathcal{M}_0$

- **Is $\mathcal{S}$=−2 H dibaryon the most bound? $\mathrm{SU(3)_f}$ breaking pushes it to $\approx N\Xi$ threshold, 26 MeV above $\Lambda\Lambda$ threshold. HAL QCD, NPA 881 (2012) 28; Haidenbauer & Meißner, ibid. 44; Shanahan, Thomas & Young, arXiv:1308.1748.**
- **$N\Omega$ dibaryon: HAL QCD, Nucl. Phys. A 928 (2014) 89.**
- **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	**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** $M(d)\approx M(v)$.

$B = 47$ **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** [**2**$M(\Delta)\approx$**2465 MeV**].

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	2.46	2.38	$\leq$2.26	2.40	2.46	2.36**	2.37
$\mathcal{D}_{12}$ $(N\Delta)$	2.16*	2.36	–	2.36	–	–	2.17	–	$\approx$2.15

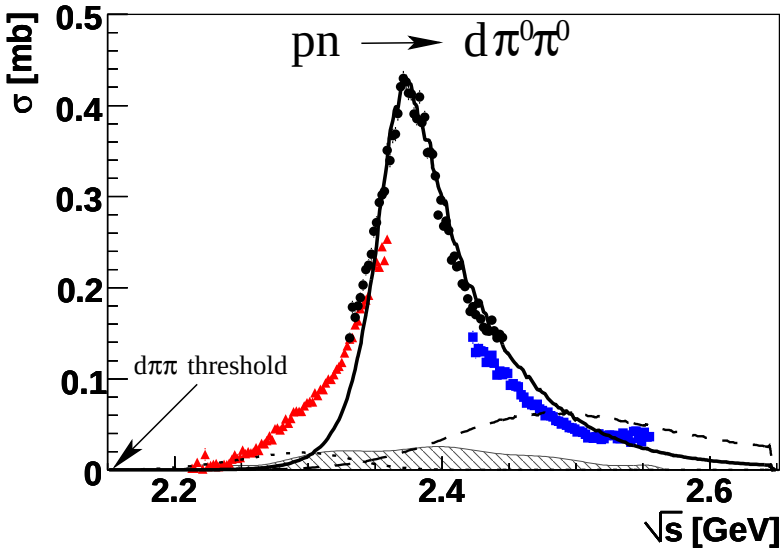
1. **Dyson-Xuong, PRL 13 (1964) 815; *input.**
2. **Mulders-Aerts-de Swart, PRD 21 (1980) 2653.**
3. **Oka-Yazaki, PLB 90 (1980) 41.**
4. **Mulders-Thomas, JPG 9 (1983) 1159.**
5. **Goldman-Maltman-Stephenson-Schmidt-Wang, PRC 39 (1989) 1889.**
6. **Yuan-Zhang-Yu-Shen-Huang-Wang-Wong, 60 (1999) 045203; 1408.0458.**
7. **Mota-Valcarce-Fernandez-Entem-Garcilazo, PRC 65 (2002) 034006.**
8. **Ping-Huang-Pang-Wang, PRC 79 (2009) 024001, 89 (2014) 034001.**

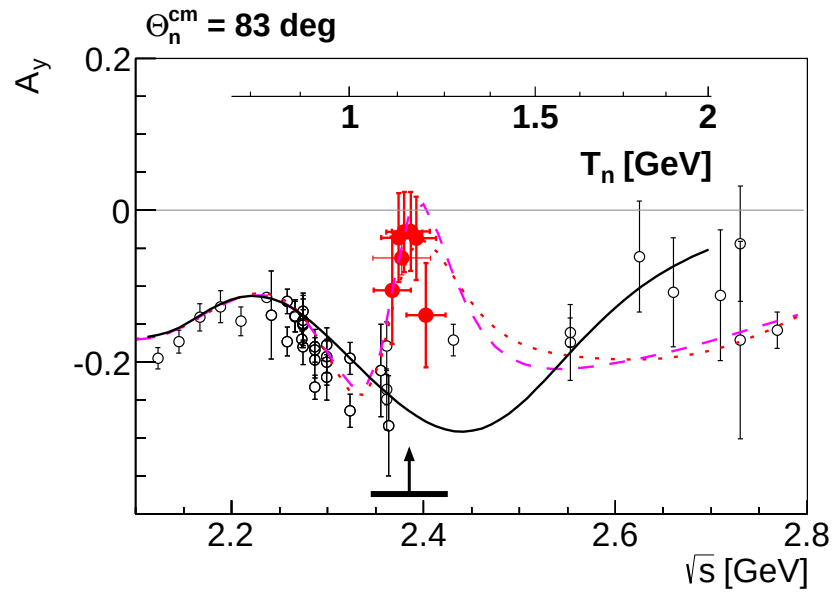
BOTH $\mathcal{D}_{12}$ & $\mathcal{D}_{03}$ predicted correctly only by [1].

Recent news from WASA@COSY

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

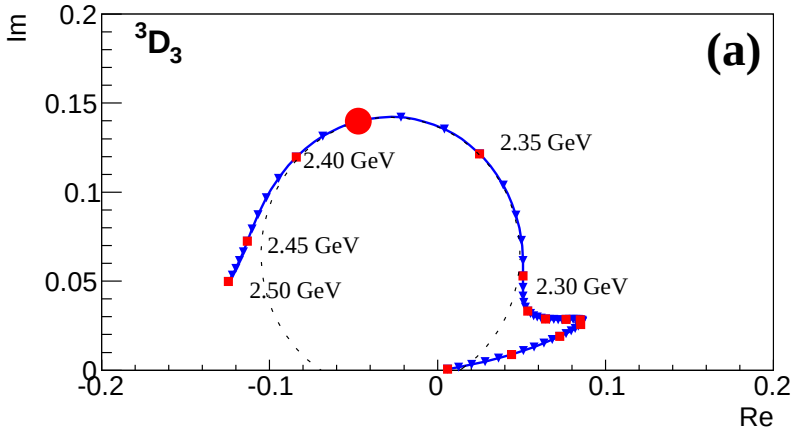
np **analyzing power**

SAID NN **fit requires a resonance pole**

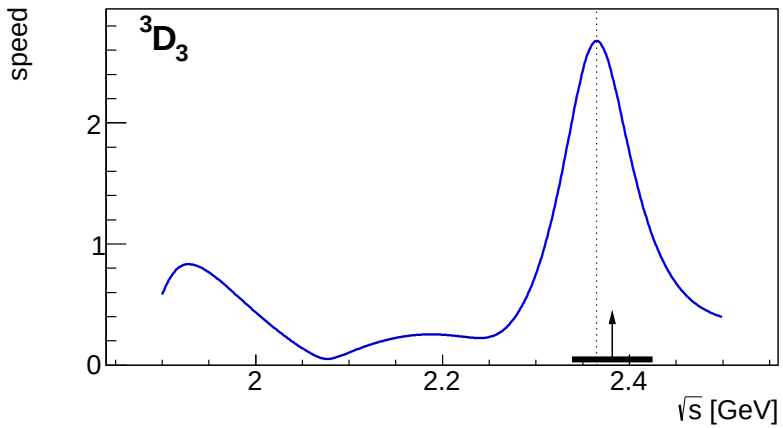
Given $\Gamma(\Delta) \approx$**120 MeV, what makes** $\mathcal{D}_{03}$ **that narrow?**

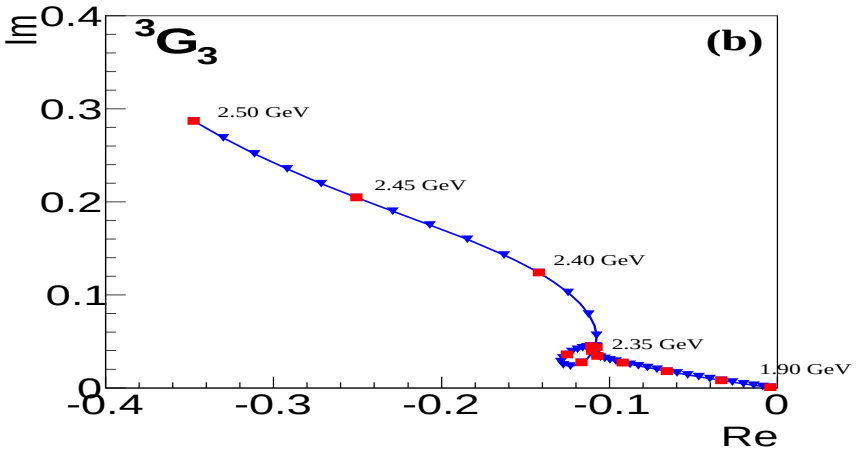
Adlarson et al. (WASA@COSY+SAID), arXiv:1408.4928

$^3D_3$ Argand diagram

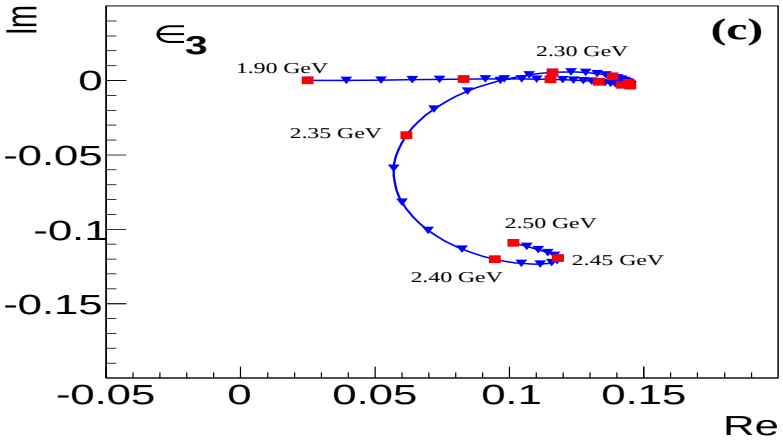


$^3D_3$ Speed plot



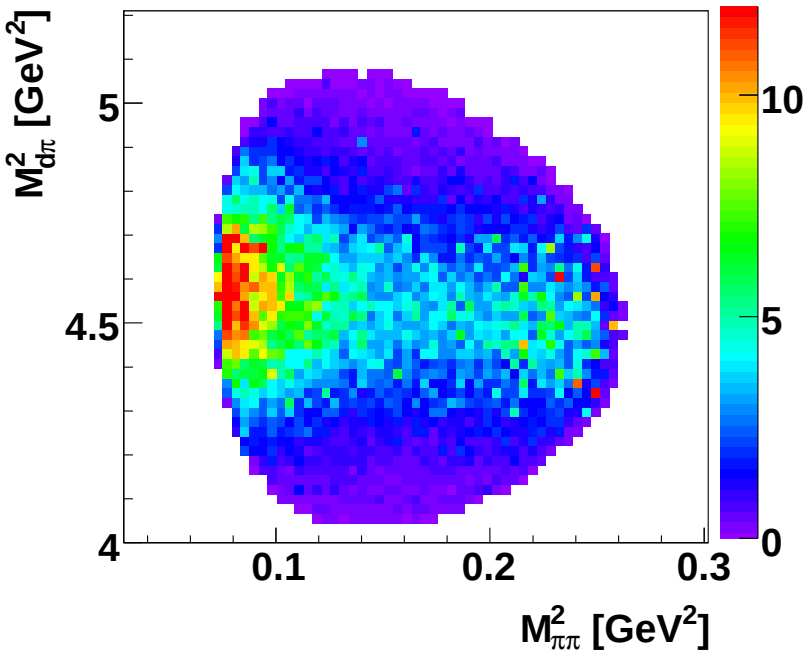


$^3G_3$ Argand diagram

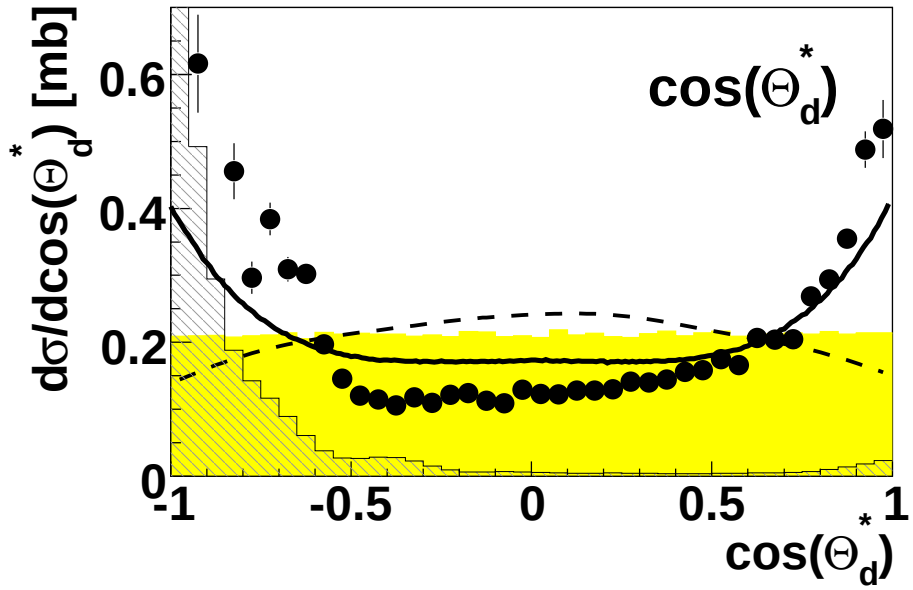


ϵ_3 mixing parameter

Pair correlations and particle distributions



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

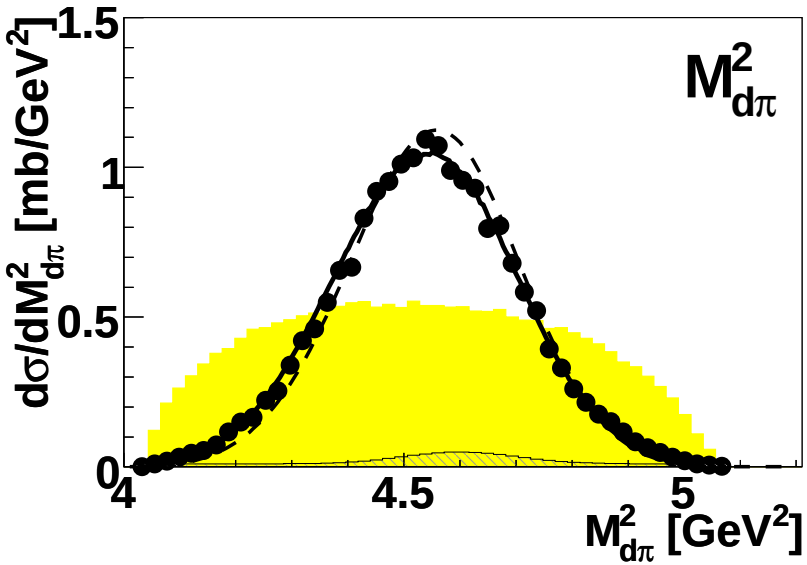


d cm angular distribution:
J^P=3$^+$ (solid), J^P=1$^+$ (dash)

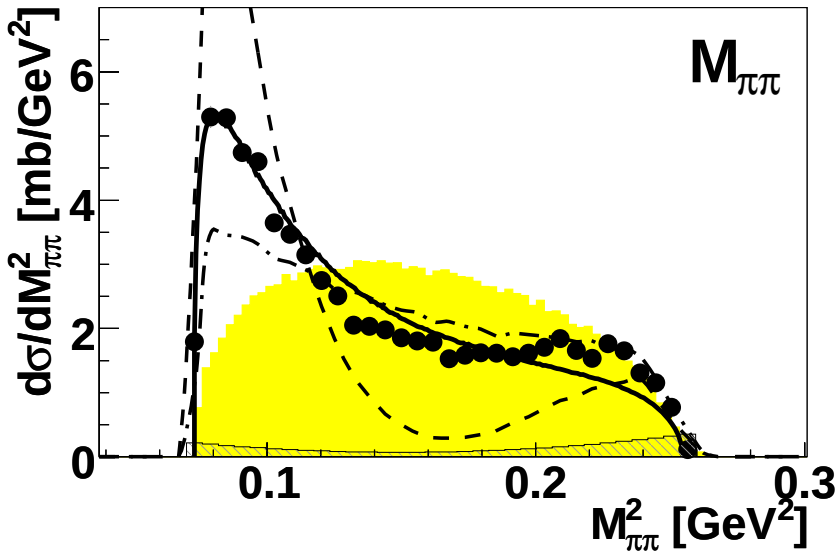
Plots at $\sqrt{s}$=2.38 GeV

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)

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

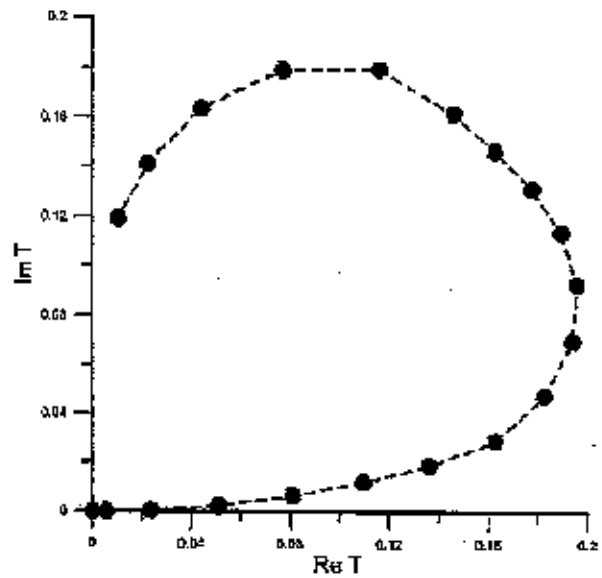
$\mathcal{D}_{12}$ $N\Delta$ dibaryon candidate

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)

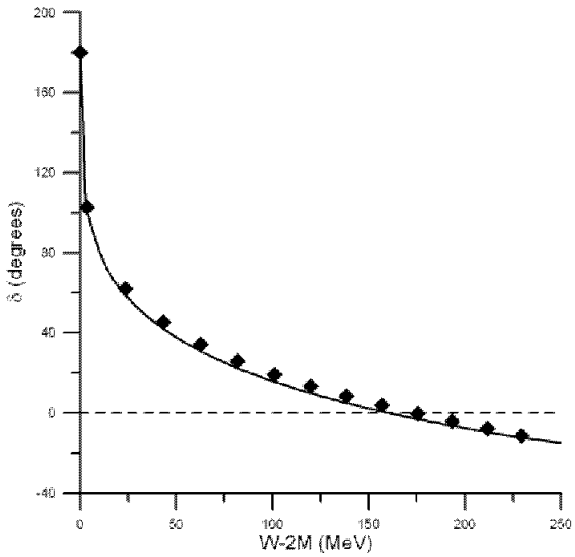
- **Long ago established in coupled-channel** $pp(^1D_2) \leftrightarrow \pi^+ d(^3P_2)$ **scattering & reactions. Hoshizaki's & Arndt et al's analyses:** $M \approx 2.15$ **GeV,** $\Gamma \approx 110 - 130$**.**

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

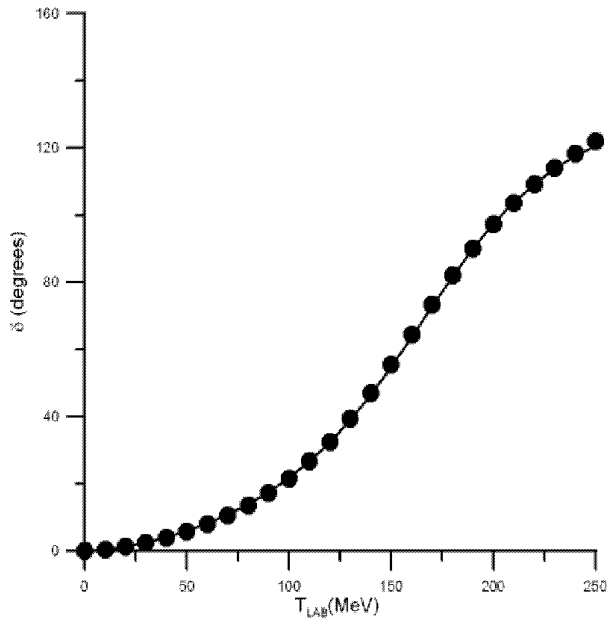
- **Our relativistic-kinematics Faddeev calculation gives** $M \approx 2.15$ **GeV,** $\Gamma \approx 120$ **MeV.**

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

Separable potential fits to NN & πN data



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

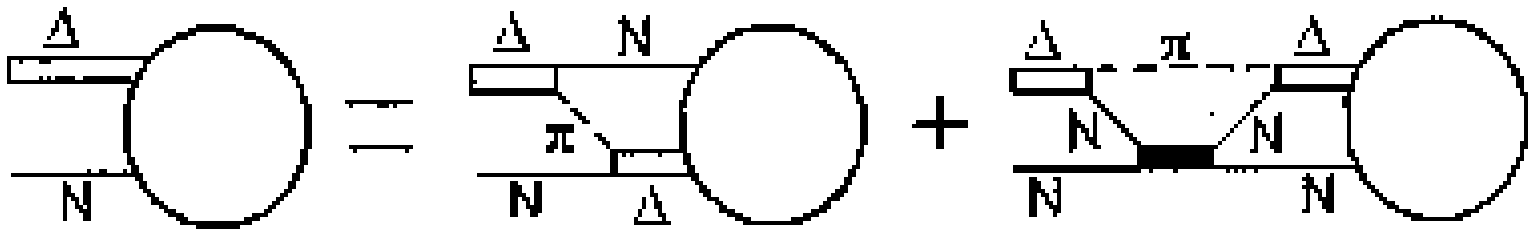


fit to πN $\delta(P33)$

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

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

$I(J^P) = 1(2^+)$ 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

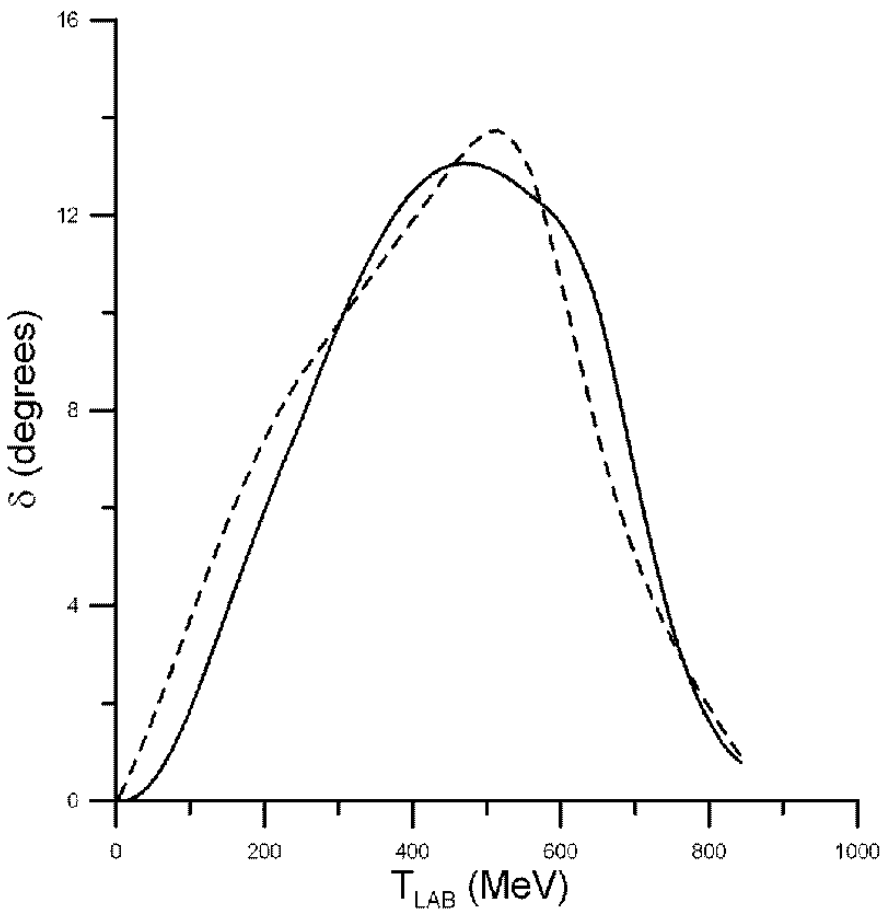
- **Construct** $(NN)_{\ell=2}$–$(NN')_{\ell=0}$–$(N\Delta')_{\ell=0}$ **separable potential.** N'–**fictitious** P_{13} **baryon with** $m_{N'} = m_\pi + m_N$ **to generate** πNN **inelastic cut.** Δ'– **stable** Δ **with** $m_{\Delta'} = 1232$ **MeV.**

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

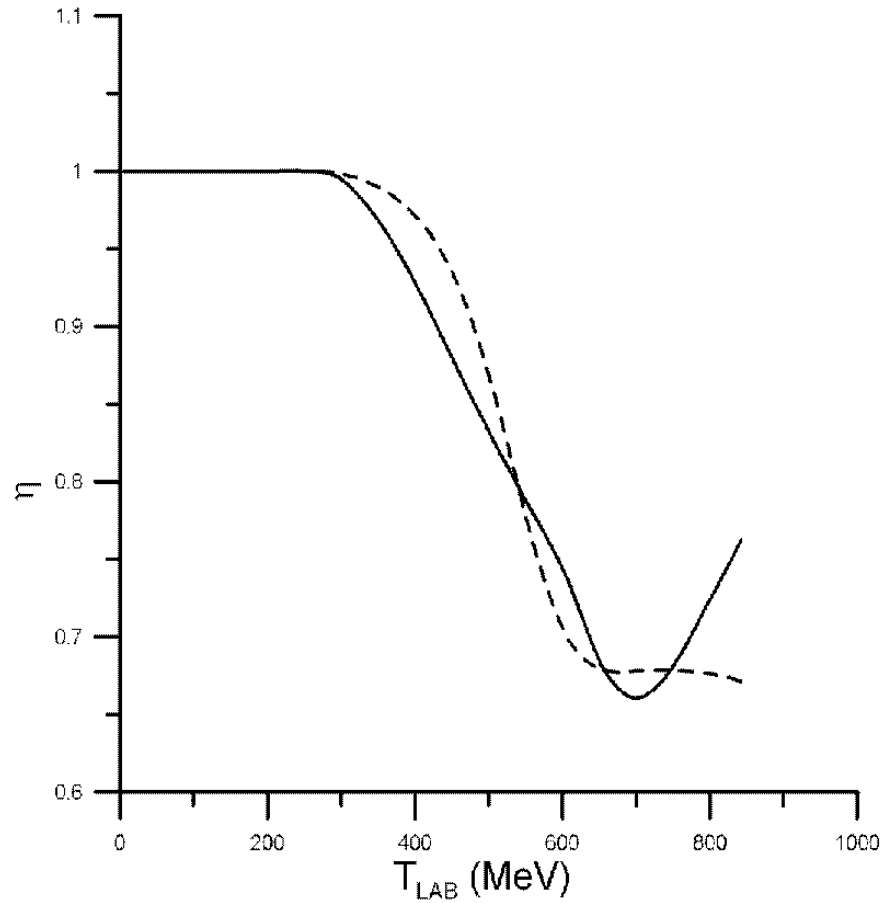
- **Require form-factor cutoff mommenta** $\leq$**3 fm**$^{-1}$ **to be consistent with long-range physics e.g. no** $\pi N \to \rho N$**.**

- **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**

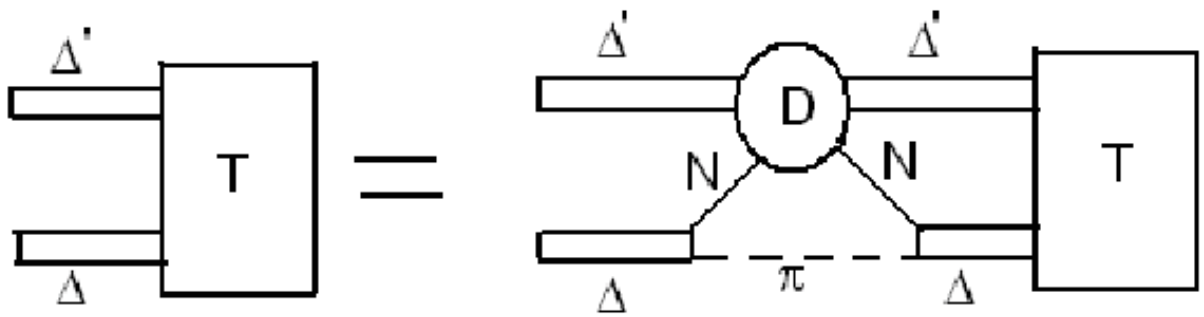


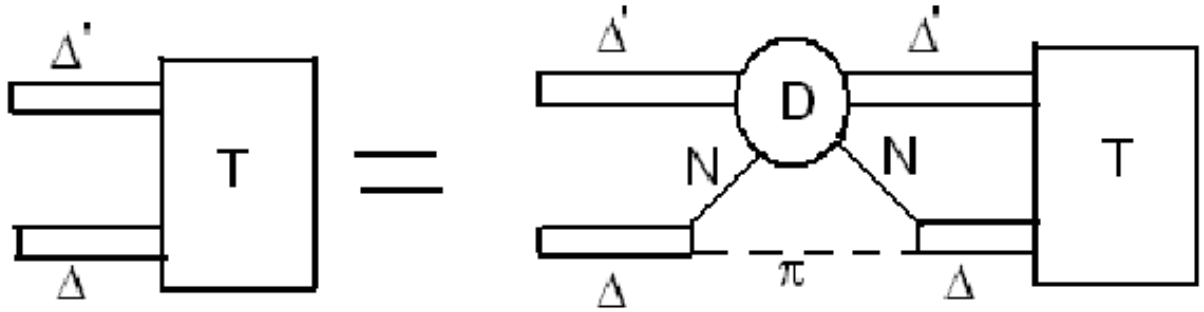
NN $^1D_2$ **inelasticity fit**

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

Calculation of $\mathcal{D}_{03}(2370)$ $\Delta\Delta$ 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 $W = M - \mathrm{i}\Gamma/2$.**
- **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$\times$(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. $\Delta\Delta$, $\mathcal{D}_{03}(2370)$ 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.**
- **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 1408.0458, find in their own CQM: M≈2390 MeV & 67% CC, arguing for a BIG ΔΔ width-suppression since CC components are not subject to strong decay...**

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?**
  see Garcilazo-Gal, NPA 897 (2013) 167.
  Many thanks to my coauthor Humberto Garcilazo