Structure & width of the d*(2380) dibaryon

QNP 2018, Tsukuba, Japan, Nov. 2018

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- Introduction to non-strange dibaryons, from 1964 to present status report by H. Clement in Prog. Part. Nucl. Phys. 93 (2017) 195-242.
- Long-range dynamics of pions, nucleons & Δ's: 3-body calculations of $N\Delta$ & $\Delta\Delta$ dibaryons by A. Gal, H. Garcilazo, PRL 111, 172301 (2013) and Nucl. Phys. A 928 (2014) 73-88.
- Is Γ_{d^*}=80±10 MeV ($\ll 2\Gamma_{\Delta\Delta} \approx$ 230 MeV) compatible with a compact $\Delta\Delta$ dibaryon (B$_{d^*}$≈80 MeV)? A. Gal, PLB 769 (2017) 436.

Introduction

Nonstrange s-wave dibaryon SU(6) predictions

F.J. Dyson, N.-H. Xuong, PRL 13 (1964) 815

dibaryon	I	S	SU(3)	legend	mass	QNP 2018
$\mathcal{D}_{01}$	0	1	$\overline{10}$	deuteron	A	√
$\mathcal{D}_{10}$	1	0	27	virtual	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	$\overline{10}$	$\Delta\Delta$	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).

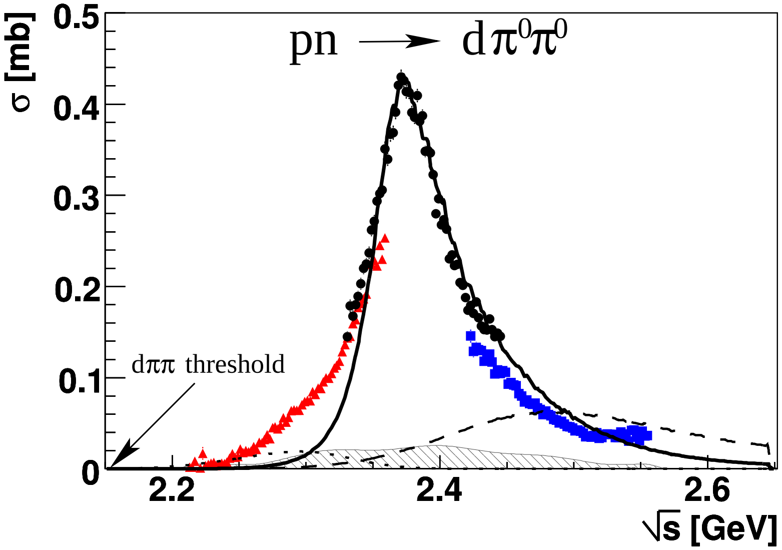
B=47 MeV from M($\mathcal{D}_{12}$)≈2160 MeV observed in π^+d→pp.

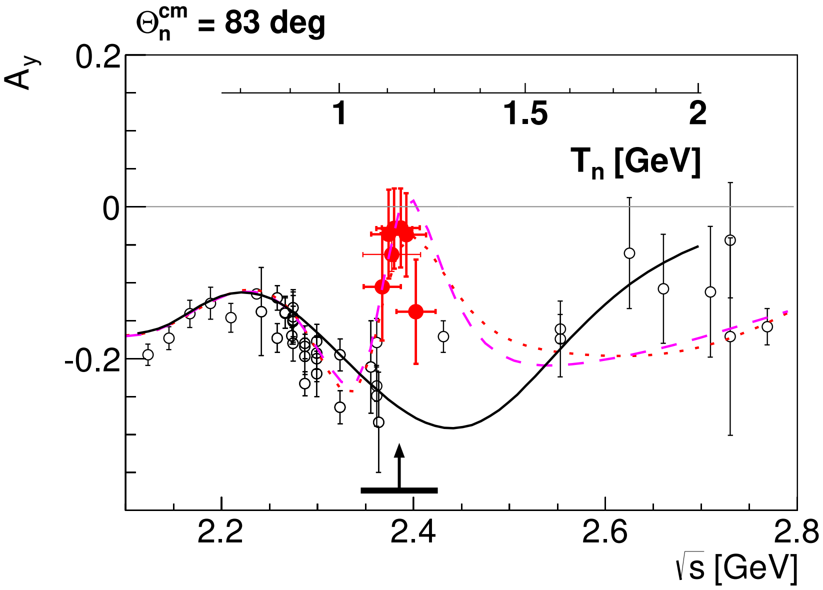
Hence, M($\mathcal{D}_{03}$)=M($\mathcal{D}_{30}$)≈2350 MeV [2M(Δ)≈2465 MeV].

Kamae-Fujita, PRL 38 (1977) 468, 471: proton polarization in γd→pn supports a dibaryon at M≈2380 MeV.

Evidence for $\mathcal{D}_{03}(2380\pm10)$, $\Gamma=80\pm10$ MeV

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





from pd→d$\pi^0\pi^0$+p$_s$

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

also in pd→d$\pi^+\pi^-$+p$_s$

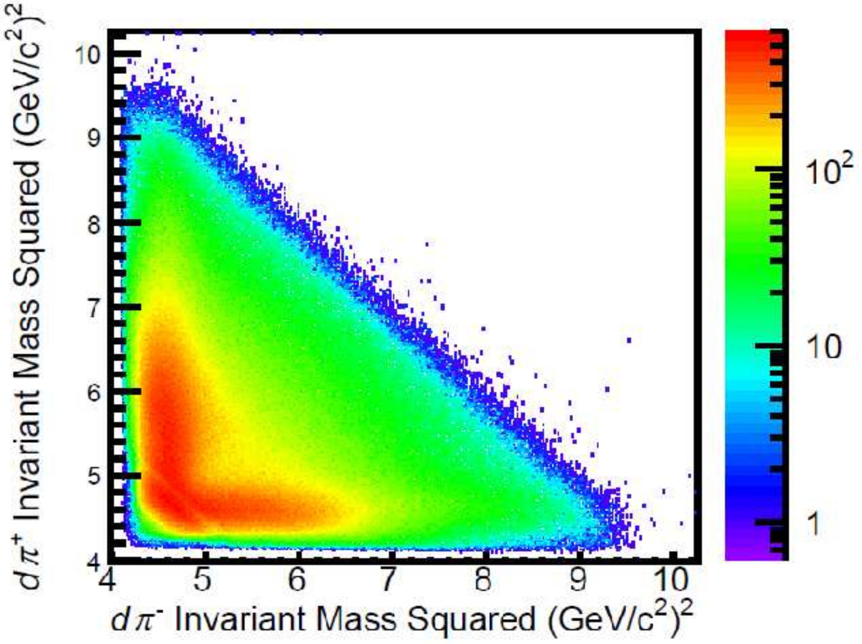
np analyzing power

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?

Dibaryon searches in $\gamma d \rightarrow d\pi\pi$

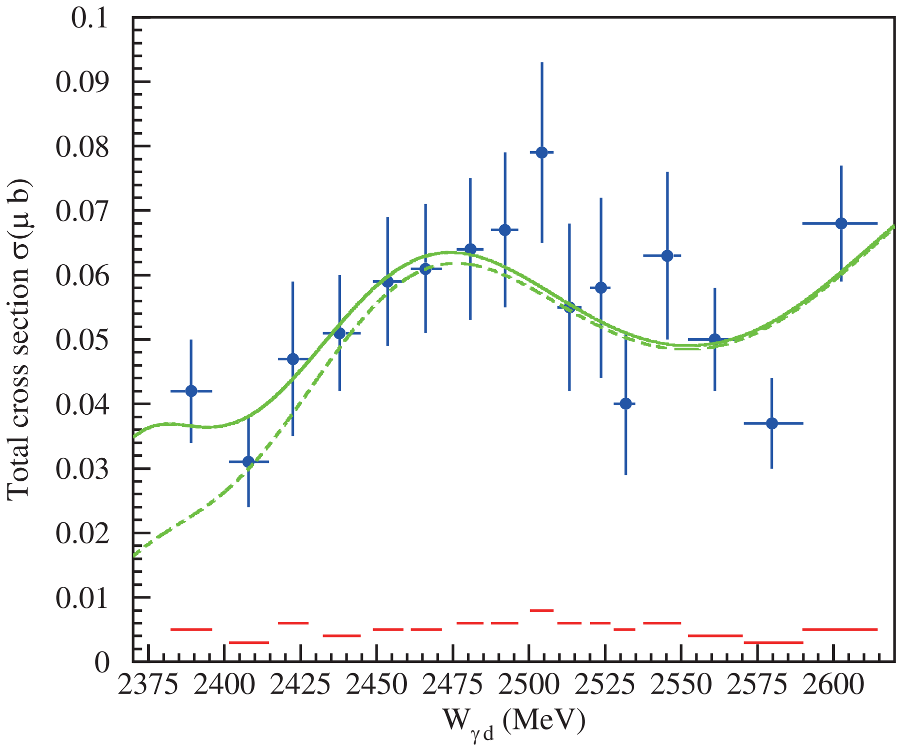


$d\pi^+$ vs. $d\pi^-$ in $\gamma d \rightarrow d\pi^+\pi^-$

CLAS prelim. (APS 04/2015)

$\mathcal{D}_{12}$ signal? with BW fit

$(M,\Gamma)=(2.12,\ 0.125)$ GeV



$\sigma_{\mathrm{tot}}(W_{\gamma d})$ in $\gamma d \rightarrow d\pi^0\pi^0$

ELPH, PLB 772 (2017) 398

& arXiv:1805.08928

$\mathcal{D}_{03}$ signal? (2.37, 0.068)

$\mathcal{D}_{12}$ signal? (2.15, 0.110)

$\mathcal{D}_{12}$ enters in $\mathcal{D}_{03}$ hadronic model reported below

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 → PRD 96 (2017) 014036.
7. Mota-Valcarce-Fernandez-Entem-Garcilazo, PRC 65 (2002) 034006.
8. Ping-Huang-Pang-Wang, PRC 79 (2009) 024001, 89 (2014) 034001.

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

Long-range dynamics of dibaryons

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

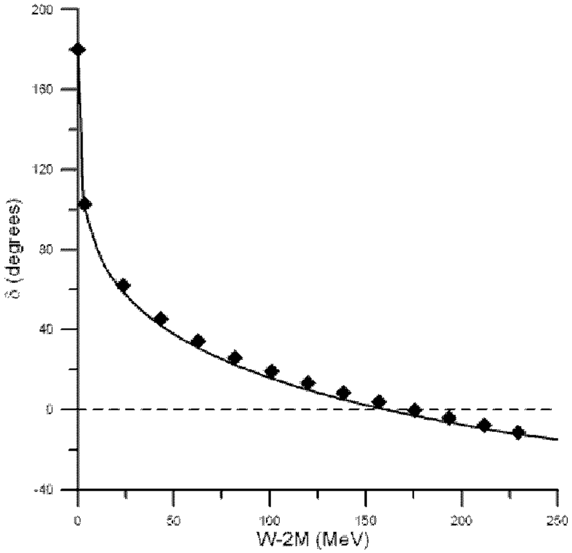
Nucl. Phys. A 928 (2014) 73-88

A. Gal, Phys. Lett. B 769 (2017) 436

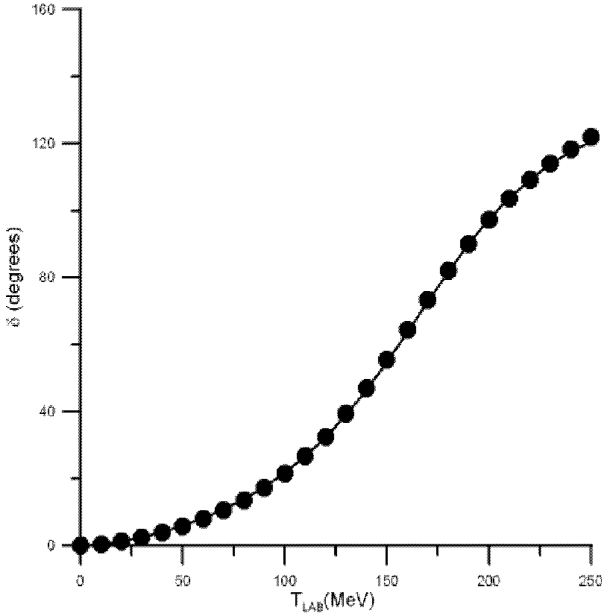
$\mathcal{D}_{12}(2150)$ $N\Delta$ dibaryon near threshold (2.17 GeV)

- **Long ago established in coupled-channel $pp(^1D_2) \leftrightarrow \pi^+d(^3P_2)$ scattering & reactions. Arndt et al (1987) & Hoshizaki's (1993): $M \approx 2.15$ GeV, $\Gamma \approx 110 - 130$ MeV.**
- **Nonrelativistic πNN Faddeev calculation, Ueda (1982): $M = 2.12$ GeV, $\Gamma = 120$ MeV.**
- **CLAS $\gamma d \to d\pi^+\pi^-$ data [APS 04/2015] suggest $M_{BW} \approx 2.12$ GeV, $\Gamma_{BW} \approx 125$ MeV.**
- **Our relativistic-kinematics Faddeev calculation gives robust values M≈2.15 GeV, Γ≈120 MeV against variations of NN & πN input.**

Separable potential fits to NN & πN data



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



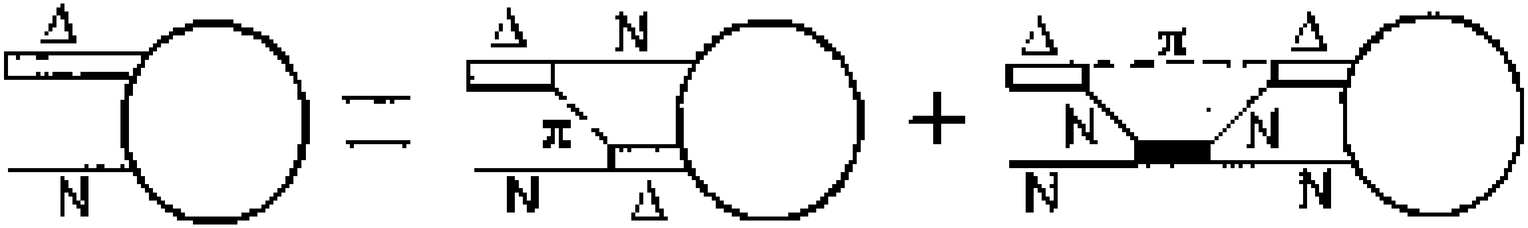
fit to $\pi N\ \delta(P33)$

Separable s-wave potentials $v_j \Rightarrow$ separable 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)**
  [$\mathcal{D}_{21}$ **observed: WASA@COSY, PRL 121 (2018) 052001**]
- **Construct a** $\mathcal{D}_{12}(2150)$**-isobar** $(N\Delta)_{\ell=0}$ **interaction that, coupled with** $(NN)_{\ell=2}$**, fits** $NN\ \delta(^1D_2)$ **&** $\eta(^1D_2)$**.**
  Limit cutoff momenta $\leq$**3 fm**$^{-1}$ **to stay within**
  long-range physics **e.g. no** $\pi N \to \rho N$**.**

Construction of $N\Delta$ form factor

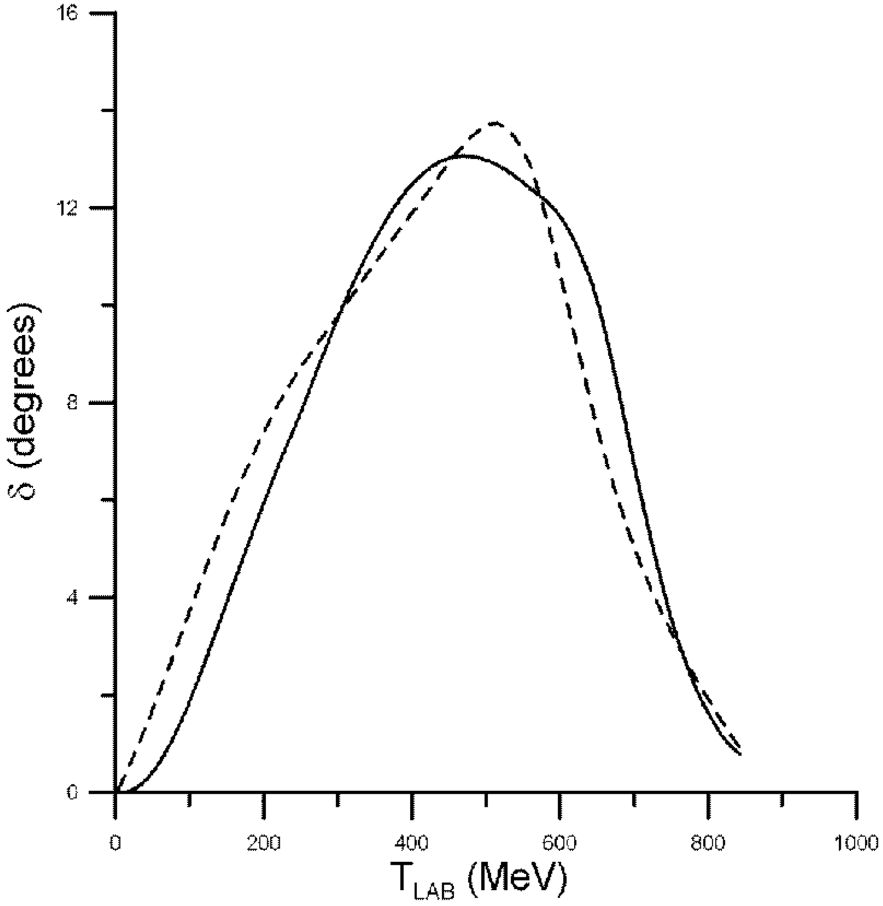
- **Construct** $(NN)_{\ell=2}$–$(NN')_{\ell=0}$–$(N\Delta')_{\ell=0}$ **separable potential.** N'**–fictitious** P_{13} **baryon with** $m_{N'} = m_\pi + m_N$ **to generate** πNN **inelastic cut.** Δ'**– stable** Δ **with** $m_{\Delta'} = 1232$ **MeV.**

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

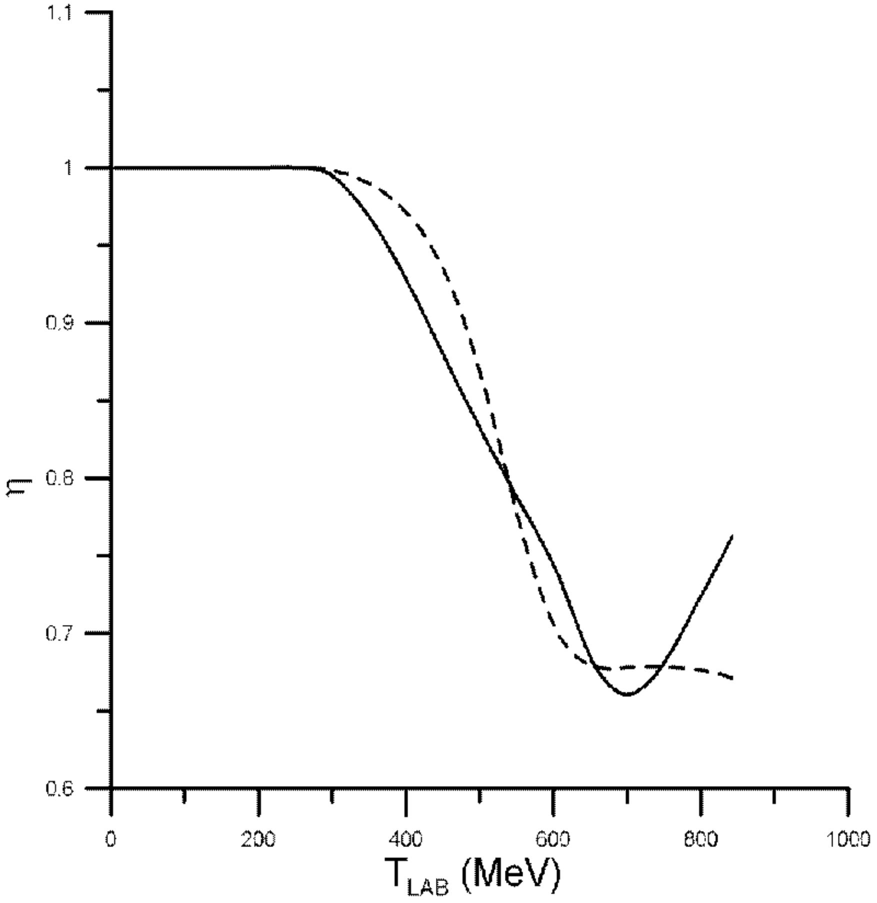
- **Require form-factor cutoff momenta** $\leq$**3 fm**$^{-1}$ **to be consistent with long-range physics e.g. no** $\pi N \to \rho N$**.**

- **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**

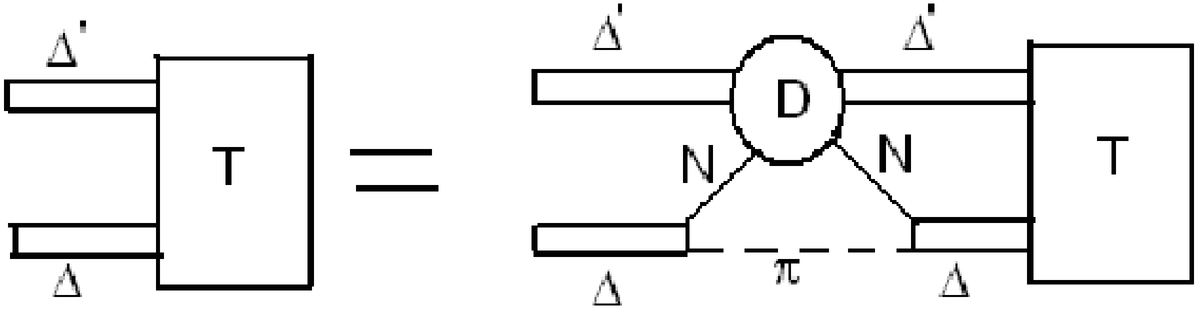


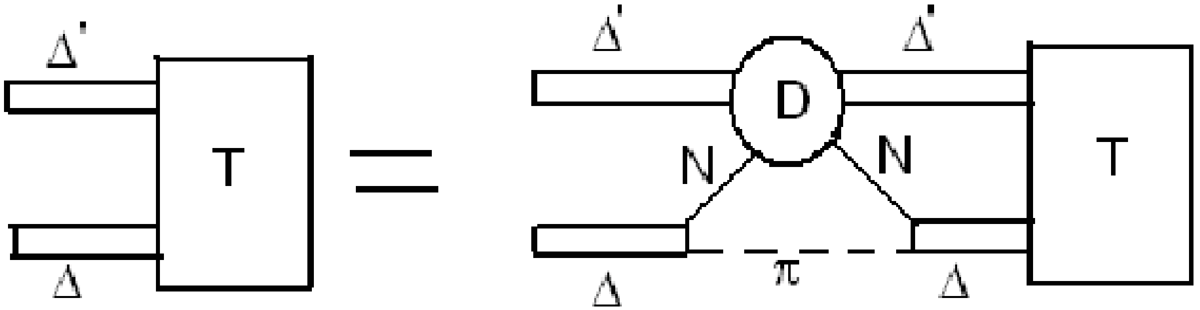
$NN\ ^1D_2$ **inelasticity fit**

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, $q_j \to q_j \exp(-i\phi)$, 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×(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

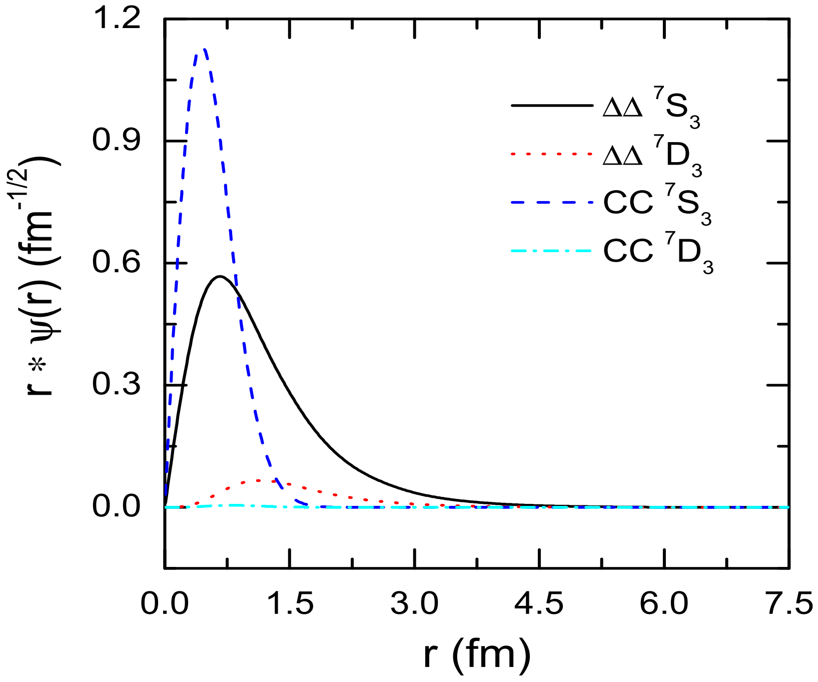
- **Using a 1.36 fm sized P_{33} form factor:** M**=2383,** Γ**=82 MeV (x=1: 94 MeV)** **in good agreement with WASA@COSY.**
- **Although bound w.r.t.** $\Delta\Delta$**,** $\mathcal{D}_{03}(2380)$ **is resonating w.r.t. the** $\pi - \mathcal{D}_{12}(2150)$ **threshold. The subsequent decay** $\mathcal{D}_{12}(2150) \rightarrow \pi d$ **is seen in the** πd **Dalitz plot projection.**
- NN**-decoupled dibaryon resonances** $\mathcal{D}_{21}$ **&** $\mathcal{D}_{30}$ **predicted 10–30 MeV higher, respectively; Bashkanov-Brodsky-Clement, PLB 727 (2013) 438, discuss effects of Hidden-Color (CC) BB components:** $\sqrt{1/5}\Delta\Delta + \sqrt{4/5}$**CC.** **Effect of CC on width calculation?**

Recent Quark Model d*(2380) Calculations

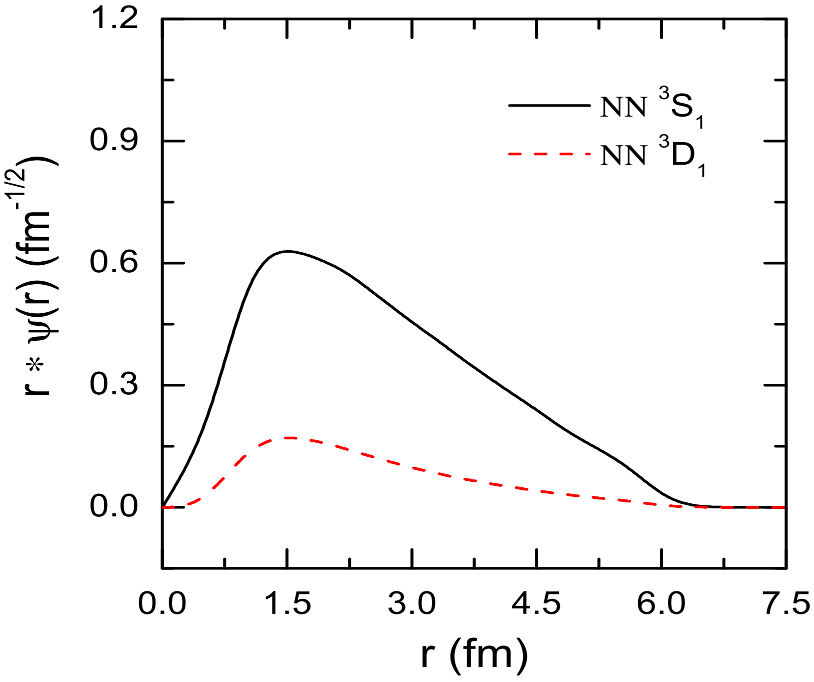
- Park-Park-Lee, PRD 92 (2015) 014037, find the orbitally symmetric [6] I(JP)=0(3+) hexaquark unbound by hundreds of MeV.
- H. Huang et al., PRC 89 (2014) 034001, use the Salamanca chiral quark model (CQM) to go from 1→4 ΔΔ channels, then to full 10:
  $M = 2425 \rightarrow 2413 \rightarrow 2393$ MeV
  Γ=177→175→150 MeV, so Γ is too big.
- Beijing CQM [Y. Dong et al. PRC 94 (2016) 014003] finds M≈2400±20 MeV & 67% non-decaying CC components, leading to Γ≈70 MeV.
  A dubious calculation, as discussed below.

Quark-based ΔΔ w.f. & deuteron w.f.

arXiv 1408.0458, Chin. Phys. C 39 (2015) 071001



ΔΔ wavefunction



deuteron wavefunction

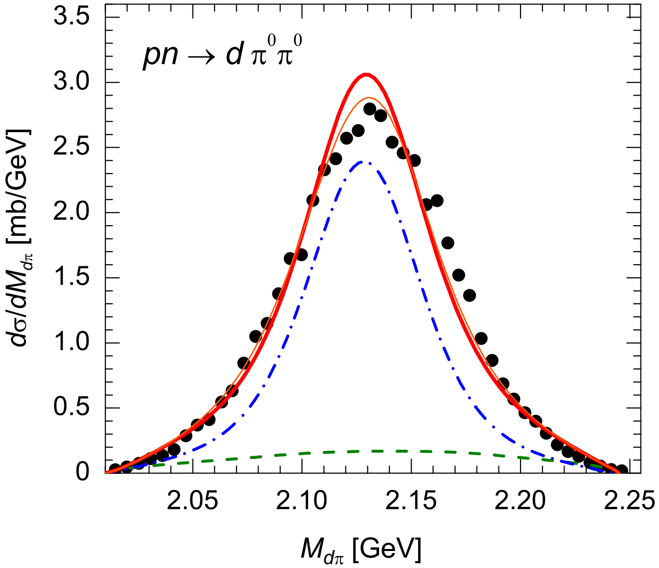
- r.m.s. radius R(ΔΔ)=0.76 fm $\ll$ R(deuteron)$\approx$2 fm.
- Small R(ΔΔ) implies high Δ-momentum components.

Width Considerations

- d*(2380) is bound w.r.t. ΔΔ by 84 MeV, by 42 MeV on average for each Δ, thereby reducing $\Gamma_{\Delta}^{\text{free}}$=115 MeV to $\Gamma_{\Delta}^{\text{bound}}$=81 MeV.
- However, since none of the Δs is at rest, $s_{\Delta}^{\text{bound}}$ decreases further to $(1232\text{-}42)^2 - P_{\Delta\Delta}^2$, where $P_{\Delta\Delta} \times R_{\Delta\Delta} \geq 3/2$.
- For $R_{\Delta\Delta} \leq 0.8$ fm, $\Gamma_{\Delta}^{\text{bound}} \leq 34$ MeV, so for the $\pi\pi$ decay modes $\Gamma_{\Delta\Delta}^{\text{bound}} = 5/3\, \Gamma_{\Delta}^{\text{bound}} \leq 56$ MeV.
- With $R_{\Delta\Delta}=0.76$ fm, as in the Beijing CQM, $\Gamma_{\Delta\Delta}^{\text{bound}} \leq 47$ MeV, hence quark-based ΔΔ models can't reproduce the LARGE d*(2380) width.
- See also J.A. Niskanen, PRC 95 (2017) 054002.

Introducing a $\pi\mathcal{D}_{12}$ component (I)

A. Gal, PLB 769 (2017) 436

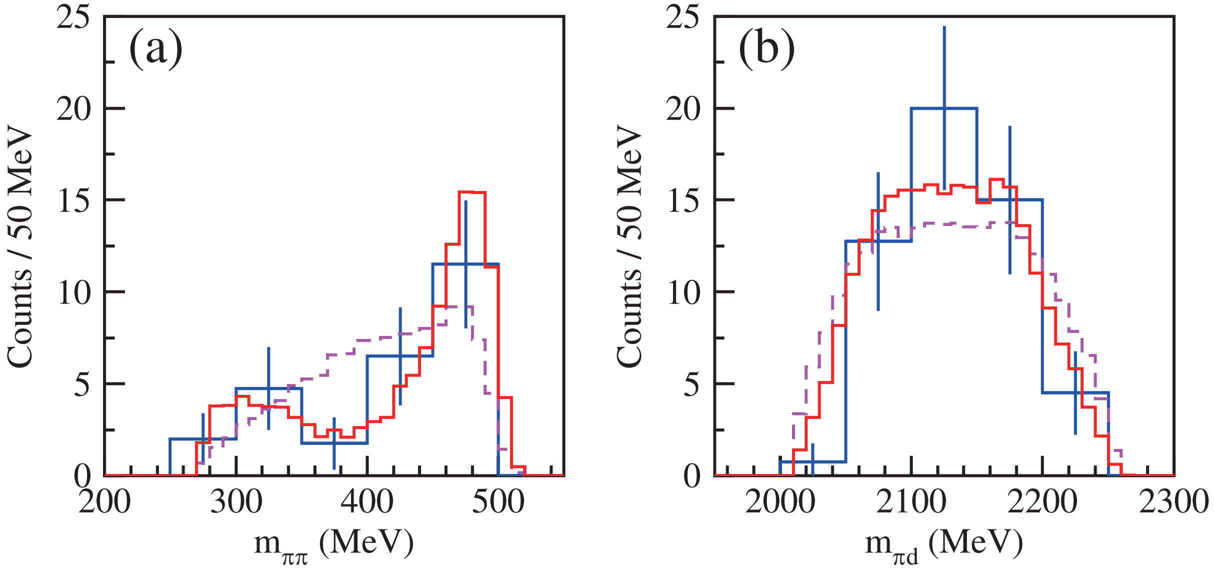


$\mathrm{M}_{d\pi}$ decay distribution of d*(2380) for 2 input choices of $\mathcal{D}_{12}$

M.N. Platonova & V.I. Kukulin, NPA 946 (2016) 117

- **The $\mathcal{D}_{12}(2150)$ $N\Delta$ dibaryon is seen in d*(2380) decay. With size ~2 fm, its ~100 MeV pionic decay width is not quenched within the d*(2380).**

Introducing a $\pi\mathcal{D}_{12}$ component (II)



Invariant mass distributions at W=2.39 GeV
ELPH, PLB 772 (2017) 398

Lower bump in (a), known as ABC effect,
is due to $\Delta\Delta$ decay, with reduced $\Delta \to N\pi$ phase space.
Upper bump in (a) is due to d*(2380)→ $\mathcal{D}_{12}(2150)\pi$ decay,
where the $N\Delta$ dibaryon pionic decay width ∼100 MeV
in (b) is not quenched owing to its large size ∼2 fm.

This compensates for the $\Delta\Delta$ quenched width.

d*(2380) decay widths (MeV) & branching ratios (BR,%)

final	$\Delta\Delta$ $(\alpha=1)$		$\pi\mathcal{D}_{12}$ $(\alpha=0)$		mixed $(\alpha=\frac{5}{7})$		exp.
state	$\Gamma_f^{d^*}$	BR	$\Gamma_f^{d^*}$	BR	$\Gamma_f^{d^*}$	BR	BR
$d\pi^0\pi^0$	9.3	12.4	7.6	10.1	8.4	11.2	14(1)
$d\pi^+\pi^-$	17.0	22.7	14.0	18.6	15.3	20.4	23(2)
$pn\pi^0\pi^0$	9.7	12.9	7.9	10.5	8.7	11.6	12(2)
$pn\pi^+\pi^-$	21.7	28.9	17.2	22.9	19.3	25.8	30(5)
$pp\pi^-\pi^0$	4.15	5.55	2.9	3.9	3.55	4.7	6(1)
$nn\pi^+\pi^0$	4.15	5.55	2.9	3.9	3.55	4.7	6(1)
$NN\pi$	–	–	11.5	15.4	6.2	8.3	(≤ 9)
NN	9	12	11	14.7	10	13.3	12(3)
total	75	100	75	100	75	100	103

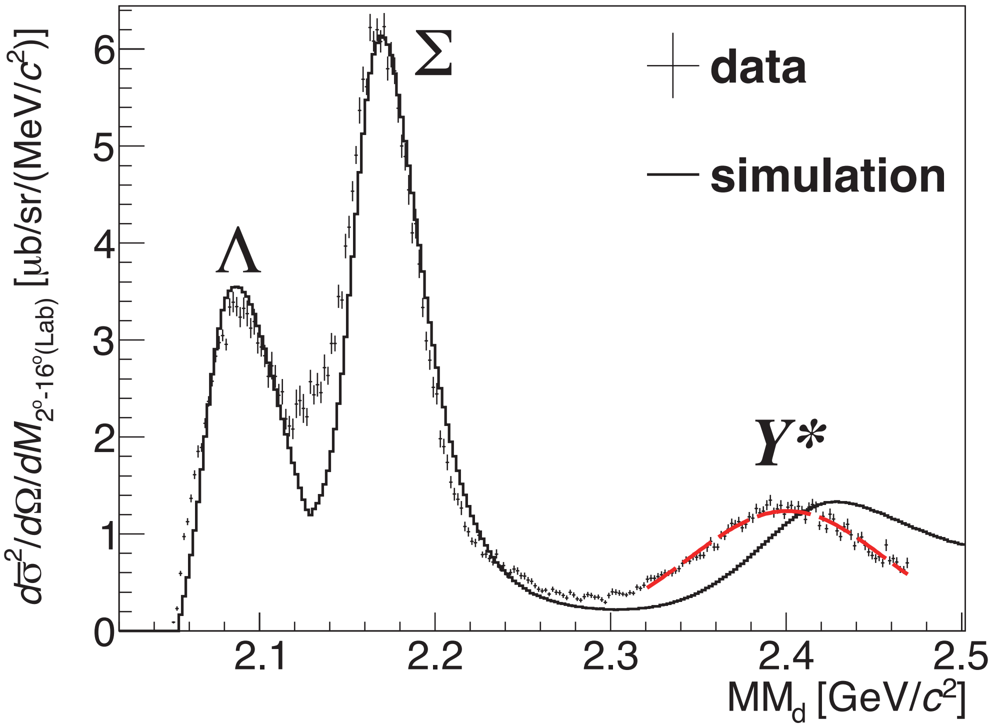
$$\alpha\Gamma_{NN\pi\pi}^{\Delta\Delta}+(1-\alpha)\Gamma_{NN\pi\pi}^{\pi\mathcal{D}_{12}}=\Gamma_{NN\pi\pi}^{d^*}$$

$\Gamma_{NN\pi\pi}^{\Delta\Delta}$=44 & $\Gamma_{NN\pi\pi}^{\pi\mathcal{D}_{12}}$=100 for $\Gamma_{NN\pi\pi}^{d^*}$=60 MeV $\Rightarrow \alpha=\frac{5}{7}$

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.
- The d*(2380) is a $\Delta\Delta$ bound state embedded in the $\pi\mathcal{D}_{12}$(2150) continuum. This is crucial for understanding its **LARGE** width.
- Δ(1232)$\rightarrow\Sigma$(1385) for strange dibaryons?
  Σ(1385)N ($I = \frac{3}{2}$, 2$^+$) vs. Λ(1405)N ($I = \frac{1}{2}$, 0$^-$).
- $\pi\Lambda_c N$ ($I = \frac{3}{2}$, 2$^+$) Gal..., PRD 90 (2014) vs. DNN ($I = \frac{1}{2}$, 0$^-$) ...Oset, PRC 86 (2012)].

Addendum: J-PARC E27 $d(\pi^+, K^+)$ missing-mass spectrum



Y* quasi-free peak shifted by ≈−22 MeV,

indicating Y*N attraction [Y* = Σ(1385) & Λ(1405)].

Two dibaryons below K$^-$pp threshold?

(i) deep Σ*N, E27 (ii) shallow Λ*N, E15.

$\Lambda(1405)N$ & $\Sigma(1385)N$ dibaryons?

- **$\Lambda(1405)N$ is a doorway to an I=1/2, J^P=0$^-$ $\bar{K}NN$, found quasibound in all calculations. Its lower components are $\pi\Lambda N$ and $\pi\Sigma N$, but $\pi\Lambda N$ 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 $\Delta(1232) \rightarrow \pi N$ and $\Sigma(1385) \rightarrow \pi\Lambda$ form factors. Maximize isospin and angular momentum couplings by full alignment: I=3/2, J^P=2$^+$, Good example of a Pion Assisted Dibaryon, not Oka's I=1/2, J^P=2$^+$ CM-based candidate.**
  Gal-Garcilazo, NPA 897 (2013) 167 & Refs. therein.

- **A $\pi\Lambda N - \pi\Sigma N$ resonance about 10–20 MeV below the $\pi\Sigma N$ threshold is found by solving coupled-channel Faddeev equations. The resonance energy is sensitive to the pion-baryon p-wave form factors.**
- **Expect doorway states $\Sigma(1385)N$ and $\Delta(1232)Y$, the lower of which is $\Sigma(1385)N$ with I=3/2, J^P=2$^+$. These are different from I=1/2, J^P=0$^-$ assigned to $\Lambda(1405)N$, viewed as a doorway to $\bar{K}NN$.**
- **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 expected in searches of K^-pp. Another possibility at J-PARC or GSI is:**
  $\pi^- \ + \ d \ \rightarrow \ \mathcal{Y}^- \ + \ K^+$, $\quad \mathcal{Y}^- \rightarrow \Sigma^- \ + \ n$.