Photoproduction of Structure in the $d\pi$ System Near the NΔ Mass: Sign of a Quasi-Bound State?

Reinhard Schumacher
Carnegie Mellon University

work with: Paul Mattione
Jefferson Lab CLAS Collaboration

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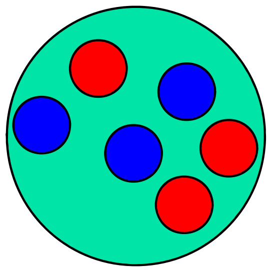
NΔ

Outline / Overview

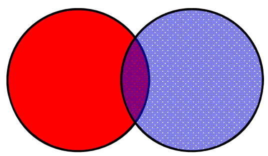
- Theoretical expectations about two-baryon resonant states
- Experimental observations
  - ΔΔ quasi-bound state: WASA/COSY
  - πd & pp elastic scattering: SAID analysis
- Photoproduction at CLAS/JLab
  - $\gamma\, d \rightarrow d\, \pi^+ \pi^-$ exclusive channel
  - $N\Delta$ quasi-bound state or ISI/FSI?

NΔ

Two-baryon resonances



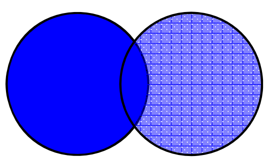
$^3S_1$



$I(J^P) = 0(1^+)$

"$\mathcal{D}_{IJ} = \mathcal{D}_{01}$"

$^1S_0$

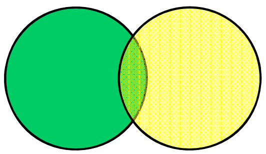


$I(J^P) = 1(0^+)$

"$\mathcal{D}_{10}$"

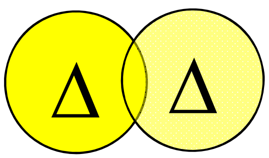
- 6 quarks in a bag
- The deuteron
  - 2.2 MeV bound
  - The only clear-cut "dibaryonic molecule"
- Recall the *nn*, *pp*, and *np* strong spin singlet states are unbound…
  - … by only ~100 keV
  - One of the great "fine-tuning" mysteries of nature!!

NΔ Two-baryon resonances



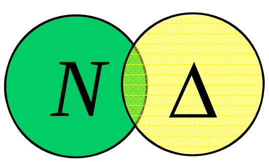
I (J^P)

- Bound $N\Delta$, $\Delta\Delta$, $\Lambda\Lambda$ (H-particle)
  - Binding?
  - Width: 'narrow' or 'wide'?
  - Spin, Isospin ?



I (J^P)=0 (3^+)
"$\mathcal{D}_{03}$"

- Recent WASA@COSY claim of discovery



I (J^P)=1 (2^+) (?)
"$\mathcal{D}_{12}$"

- CLAS study: new observations

NΔ

Some Thresholds

$$m_\Delta + m_N = 1232 + 939 = 2171 \text{ MeV}$$

$$m_d + m_\pi = 1875 + 140 = 2015 \text{ MeV}$$

$$156 \text{ MeV}$$

The decay of $N\Delta$ to $d\pi$ liberates about 156 MeV at the centroid of the (quasi-) bound state.

For comparison:

$$m_\Delta + m_\Delta = 2 \times 1232 = 2464 \text{ MeV}$$

NΔ

Theoretical Expectations

- “Y=2 states in SU(6) theory”
  - F. Dyson & N. Xuong, PRL (1964)
  - I=1 J=2 state and I=2 J=1 state in $\overline{27}$ multiplet
- “Multi-quark states Q^6 dibaryon resonances”
  - Mulders, Aerts, De Swart, PRD (1980)
  - Bag model: *N*Δ state in a $^5S_2$ configuration decaying to the $^1D_2$ *NN* partial wave channel
- “Flavor octet dibaryons in the quark model”
  - M. Oka PRD (1988)
  - One-gluon exchange color magnetic interaction leads to certain strange dibaryons

NΔ Theoretical Expectations

- "*NN* core interactions…from1 gluon exchange"
  - T. Barnes, S. Capstick, M.D. Kovarik, E.S. Swanson, PRC (1983)
  - OGE and quark-exchange model
  - Deuteron and *N*Δ states *not* found, but "molecular" (weakly bound) ΔΔ was found
- "Deeply-bound dibaryon resonances"
  - K. Maltman, Nucl Phys (1984)
  - QCD-like potential model with hyperfine effects
  - I=0 S=3, well below the ΔΔ & *N*Δπ thresholds

NΔ Theoretical Expectations

- "3-body model calculations of *N*Δ and ΔΔ dibaryon resonances"
  - A. Gal, H. Garcilazo, Nucl. Phys. **A928** 73 (2014)
  - πNN model with separable pairwise interactions
  - Solve πNN and $\pi N\Delta$ Faddeev equations
  - $\mathcal{D}_{12}$ $N\Delta$ found for $I(J^P) = 1(2^+)$ & $2(1^+)$
  - $\mathcal{D}_{03}$ $\Delta\Delta$ found for $I(J^P) = 0(3^+)$ & $3(0^+)$

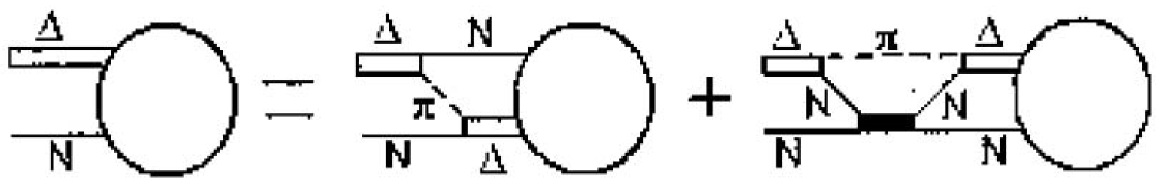


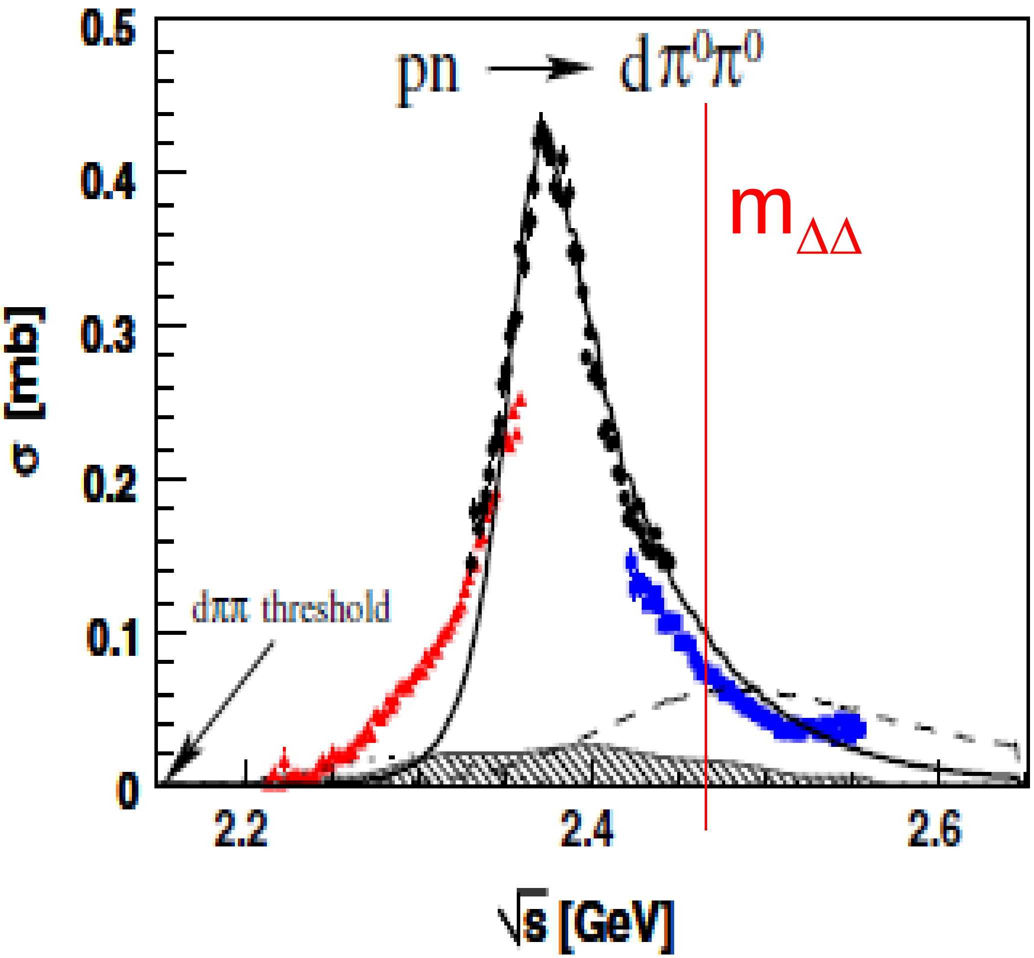
Figure 2: Diagrammatic representation of the πNN Faddeev equations solved in the present work to calculate $N\Delta$ dibaryon resonance poles.

NΔ Quasi-bound states

- Evidence for ΔΔ (“$\mathcal{D}_{03}$”)
  - WASA-at-COSY experiments (Jülich)

P. Adlarson et al, Phys Rev Lett 106, 242302 (2011)
…and numerous others since.

NΔ | $d^*(2380)$ Resonance in $I\,(J^P) = 0\,(3^+)$



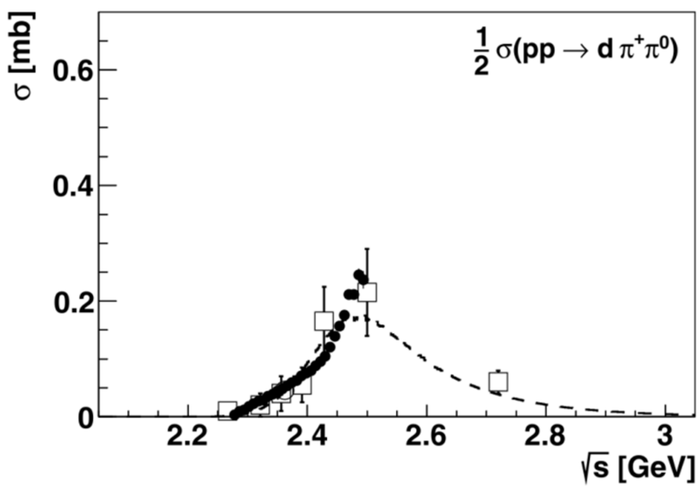
- The WASA@COSY result for ΔΔ state
- $M \sim 2370$ MeV $= 2m_\Delta - 90$ MeV
- $\Gamma \sim 70$ MeV $< 1/3\ \Gamma_{\Delta\Delta}$
- ΔΔ state interpretation has been disputed*

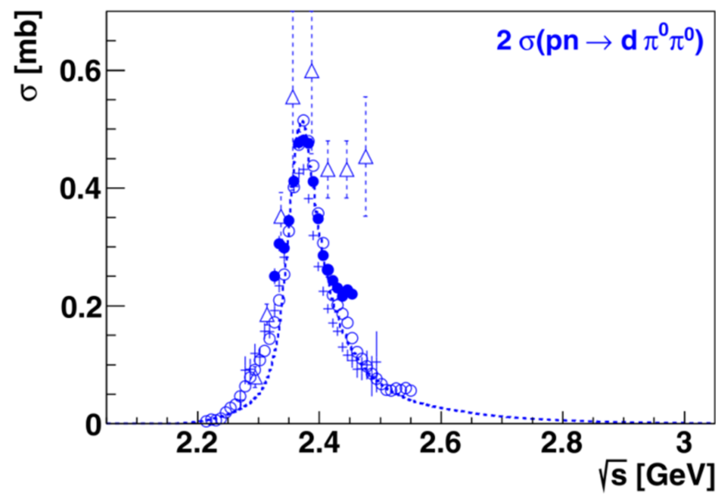
P. Adlarson et al, Phys Rev Lett 106, 242302 (2011)
…and numerous others since.

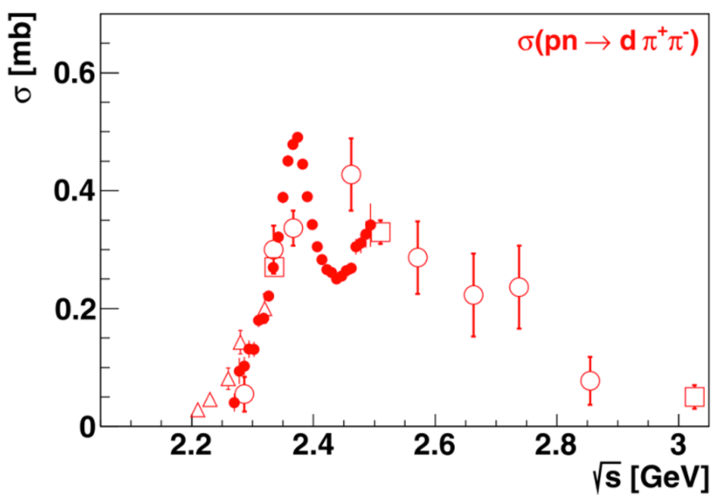
* D. V. Bugg, Eur.Phys.J. **A50** 104 (2014)

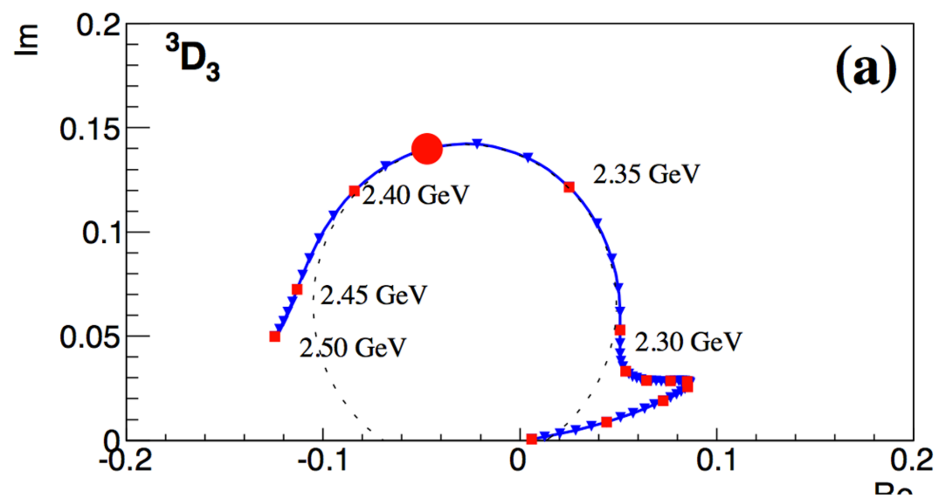
WASA@COSY $d^*(2380)$ Resonance

- Evidence for $d^*(2380)$ $\mathcal{D}_{03}$ state in $NN \to d\pi\pi$ in several isospin channels
- SAID Analysis pole position: 2380(10) – i40(5) MeV









P. Adlarson *et al.* (WASA-at-COSY Collaboration), Phys. Rev. C **88**, 055208 (2013).
P. Adlarson *et al.* (WASA-at-COSY & SAID Data Analysis Center), Phys Rev C **90**, 035204 (2014).

NΔ | A Scenario for $d^*(2380)$ Decay

- Interpretation of WASA/COSY results for reaction $p\,n \rightarrow d\,\pi^0\,\pi^0$
- Interference mechanism in d^* decay:
  - Sequential decay thru D_{12} ($I\,J^P = 1\,2^+$) state
    - $D_{03} \rightarrow D_{03} + \pi \rightarrow d + (\pi\pi)_0$
  - σ channel (ππ – S wave)
    - $D_{03} \rightarrow d + \sigma \rightarrow d + (\pi\pi)_0$

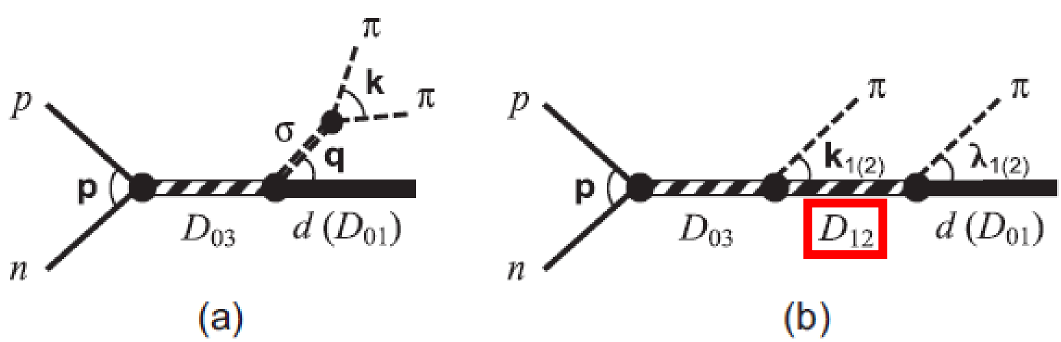
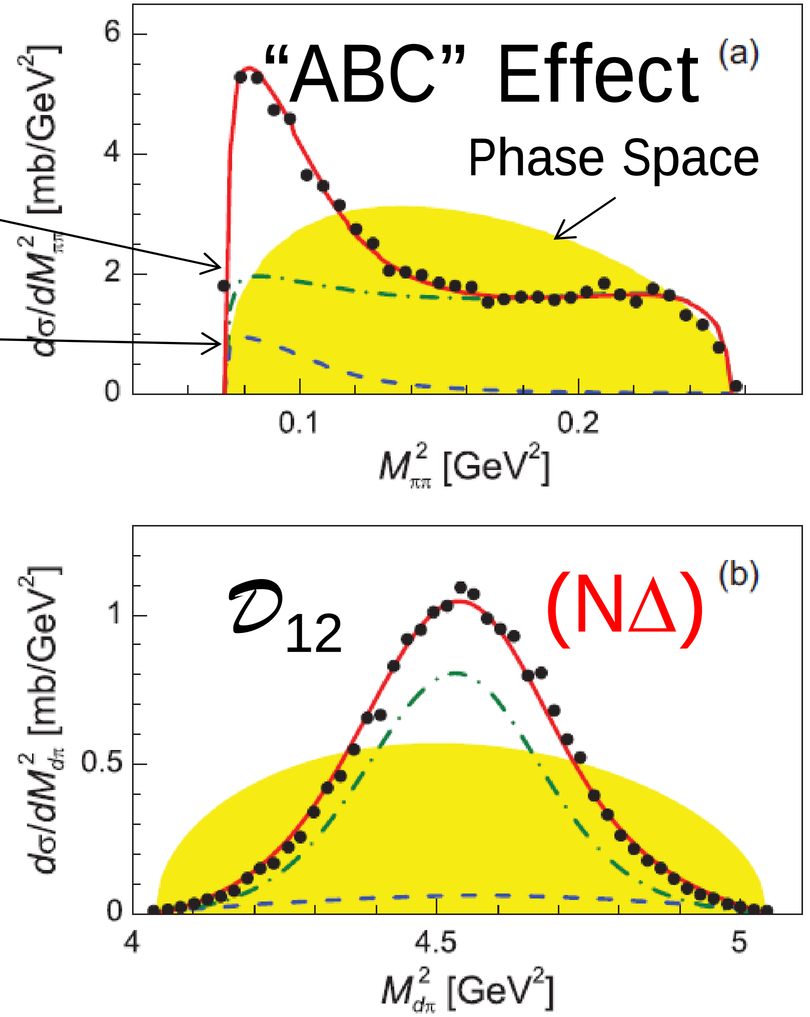


FIG. 1. The leading mechanisms for the reaction $pn \rightarrow d + (\pi\pi)_0$ in the ABC region. The three-momenta in the c.m. frame of two particles are indicated between the respective lines.

M.N. Platonova, V.I. Kukulin, Phys Rev C **87**, 025202 (2013)

NΔ | A Scenario for $d^*(2380)$ Decay

- Interference in decay of d^* $(I\ J^P = 0\ 3^+)$:
  - Sequential decay thru $\mathcal{D}_{12}$ $(I\ J^P = 1\ 2^+)$ state
    - $\mathcal{D}_{03} \rightarrow \mathcal{D}_{12} + \pi \rightarrow d + (\pi\pi)_0$
  - σ channel (ππ - s wave)
    - $\mathcal{D}_{03} \rightarrow d + \sigma \rightarrow d + (\pi\pi)_0$
- σ mass and width small compared to PDG
  - sign of partial chiral symmetry restoration in dense matter?



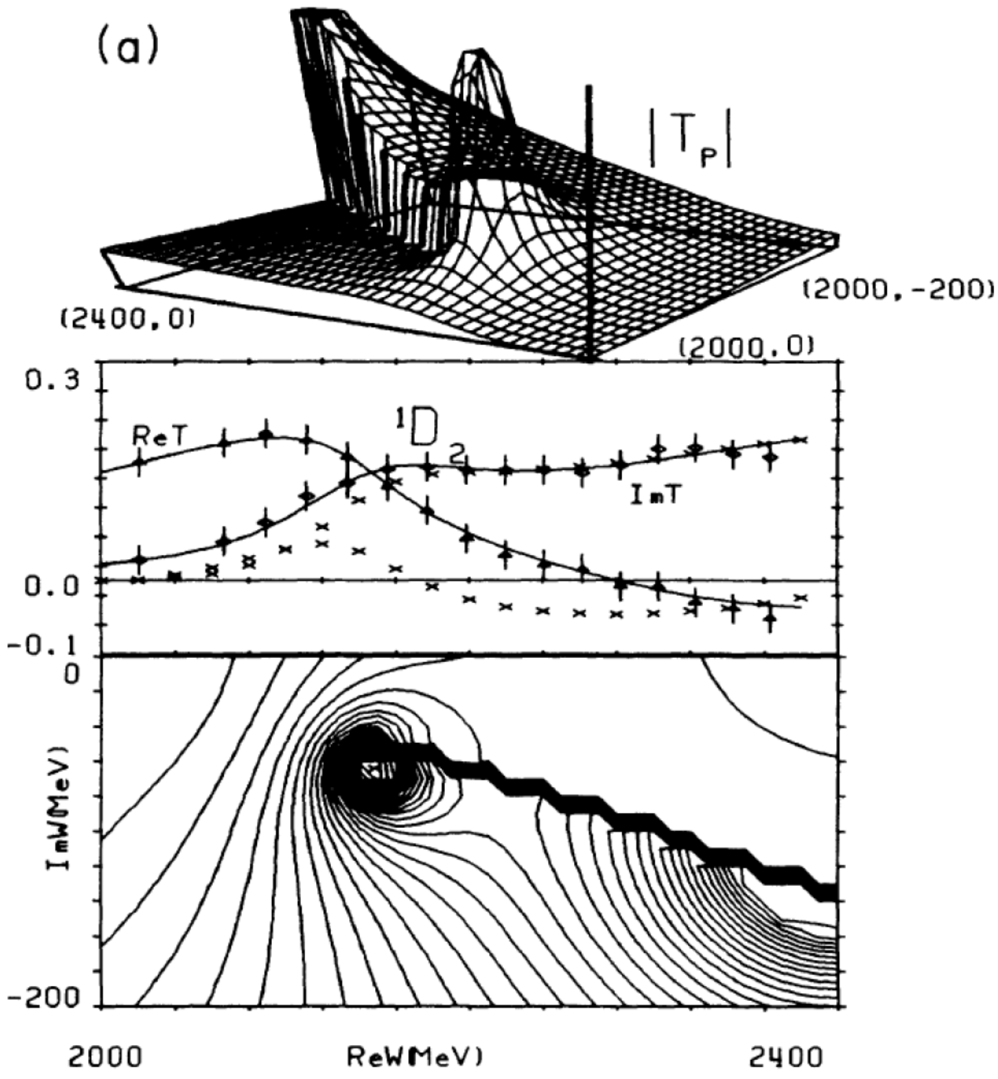
M.N. Platonova, V.I. Kukulin, Phys Rev C **87**, 025202 (2013)

P. Adlarson (Wasa@COSY) *et al.*, Phys. Rev. Lett. 106, 242202 (2011)

NΔ Quasi-bound states

- What about NΔ?
  - If a ΔΔ ("$\mathcal{D}_{03}$") state exists, so should NΔ
  - Expect NΔ to have $I\ J^P = 1\ 2^+$ ("$\mathcal{D}_{12}$")

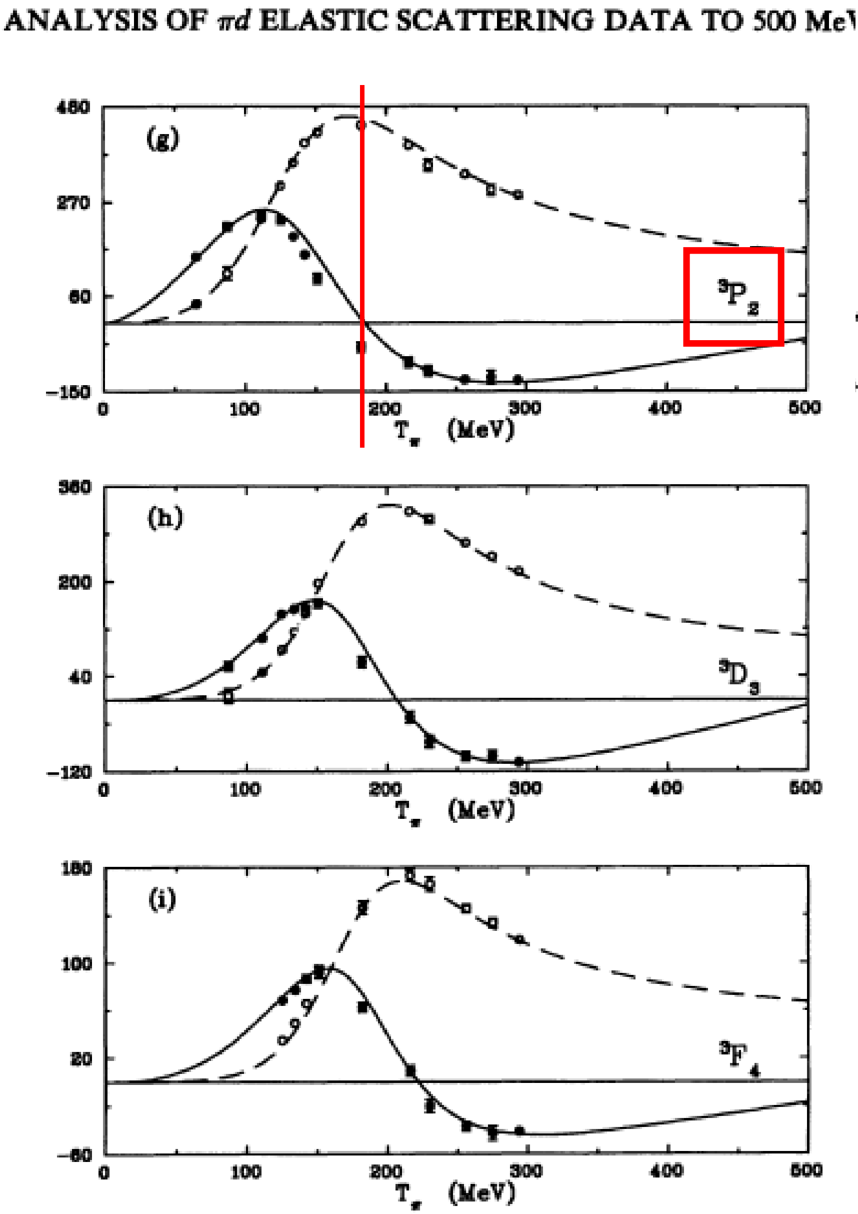
NΔ | *pp* Elastic Scattering

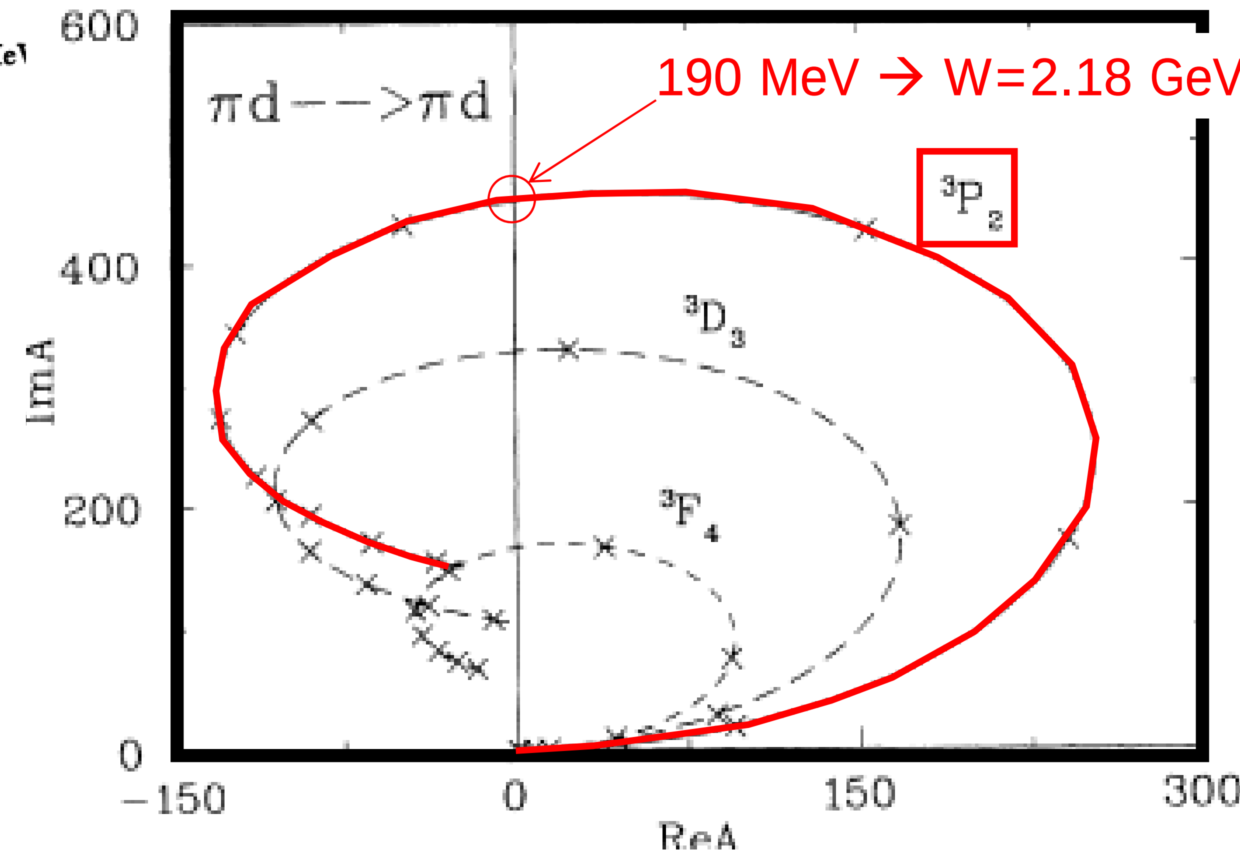


- Partial Wave Analysis
- $^1D_2$ wave in *pp* elastic scattering: structure at 2148 – i63 MeV
- Most prominent "resonance pole" seen in SAID analysis
- Textbook exercise: If an $N\Delta$ quasi-bound state exists, it can decay to *pp* ONLY if $J^P_{N\Delta} = 2^+$

R. Arndt, J. Hyslop, L. D. Roper, Phys Rev D 35, 128 (1987)

NΔ | $\pi d \rightarrow \pi d$ Elastic PWA





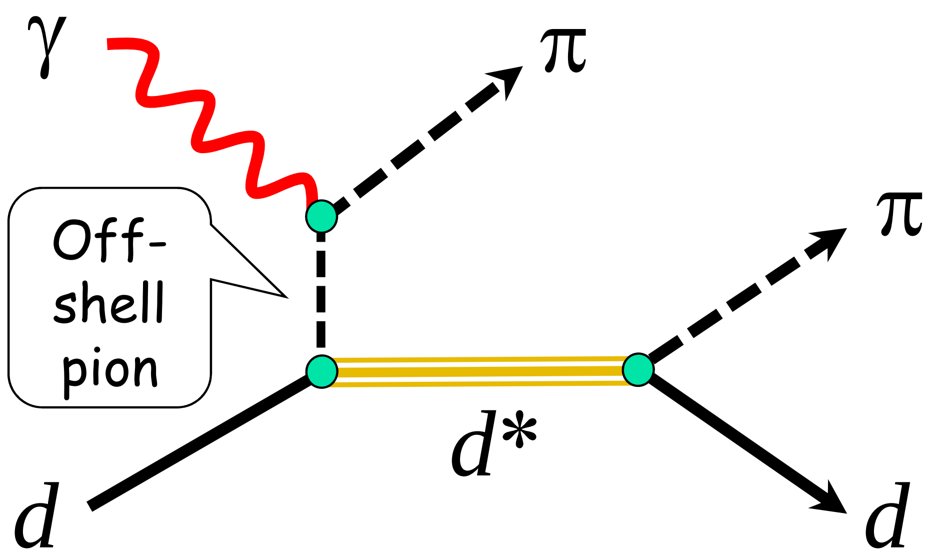
- $^3P_2$ wave in πd elastic scattering is most prominent
- SAID analysis: "resonance-like" behavior in several partial waves

R. Arndt, I. Strakovsky, R. Workman, Phys Rev C 50, 1796(1994)

NΔ | S-matrix poles for $N\Delta$ ($\mathcal{D}_{12}$)

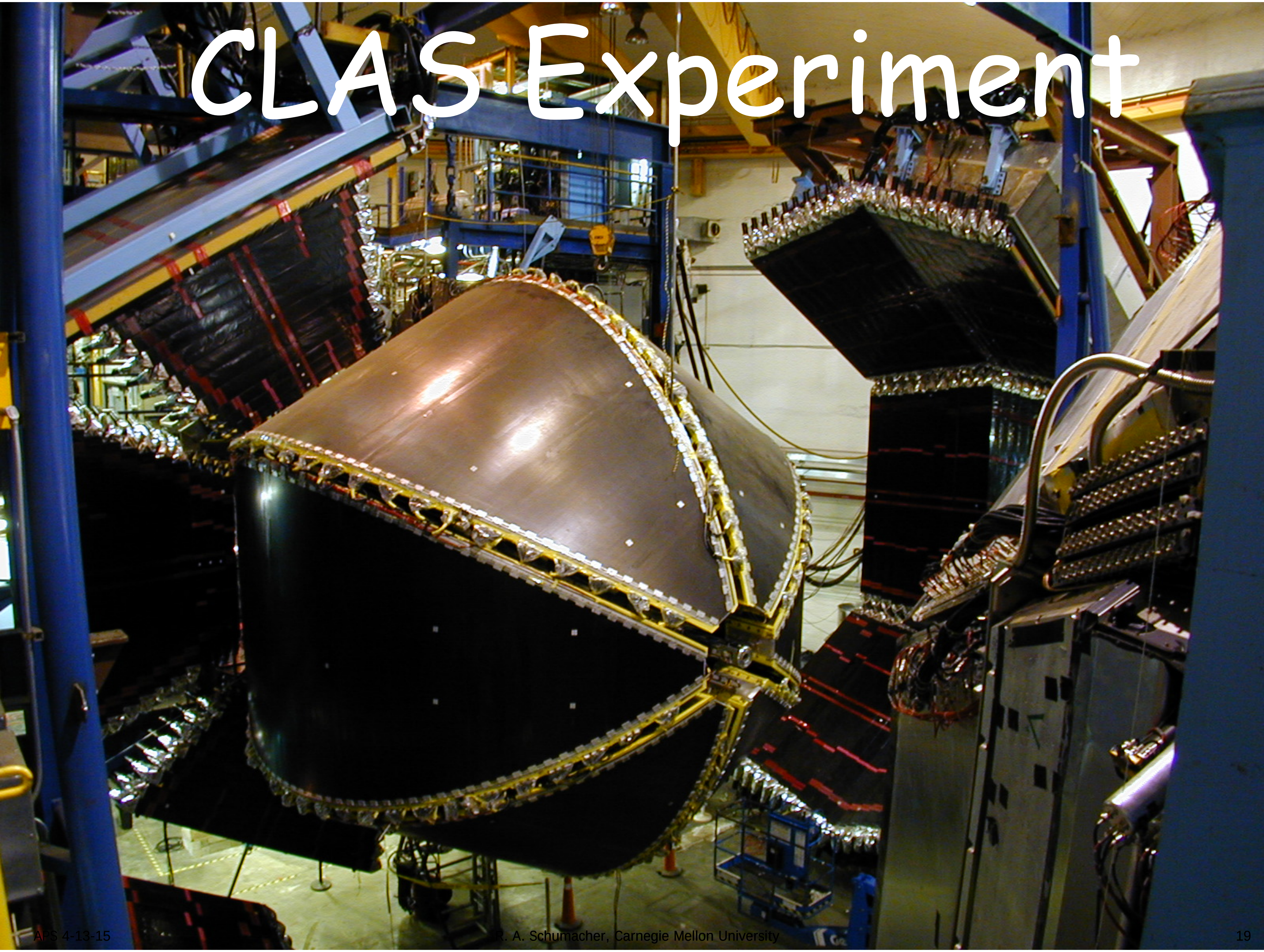
Pole Position $\mathcal{D}_{12}$ (MeV)	Model Approach	Ref.
$2147 - i60$	Faddeev model	A. Gal, H. Garcilazo, Nucl. Phys. **A928** 73 (2014)
$2148 - i63$	$pp(^1D_2) \leftrightarrow \pi d(^3P_2)$ coupled channels	R.A. Arndt, J.S. Hyslop, L.D. Roper, Phys. Rev. D 35 (1987) 128.
$2144 - i55$	$pp(^1D_2) \leftrightarrow \pi d(^3P_2)$ coupled channels	N. Hoshizaki, Phys. Rev. C 45 (1992), R1424, Prog. Theor. Phys. 89 (1993) 563.

NΔ Photoproduction Scenario



- Resembles πd elastic scattering but with an off-shell pion.
  - Suppose it to be dominant at small $-t$

CLAS Experiment



NΔ

What can CLAS see?

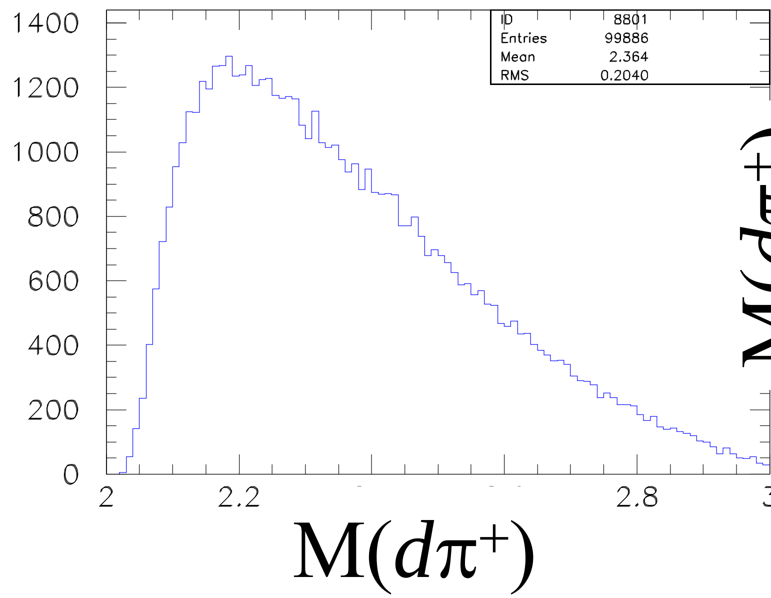
- Photons on a deuteron target
  - g10, g13, g14 data sets
- Spin-1 photon & spin-1 deuteron:
  - $\vec{1} + \vec{1} \rightarrow \vec{J} = \vec{0}, \vec{1}, \vec{2}$ in S wave, is favorable
- Isospin $\mathrm{I} = \{0,1\} + 0$ → $0,\ 1$ allowed
- We looked for both $\mathrm{N}\Delta$ and $\Delta\Delta$ structures
- $\gamma\, d \rightarrow p\, p\, \pi^-$ - messy mix of partial waves
- $\gamma\, d \rightarrow d\, \pi^+ \pi^-$ - coherent exclusive production: clean!

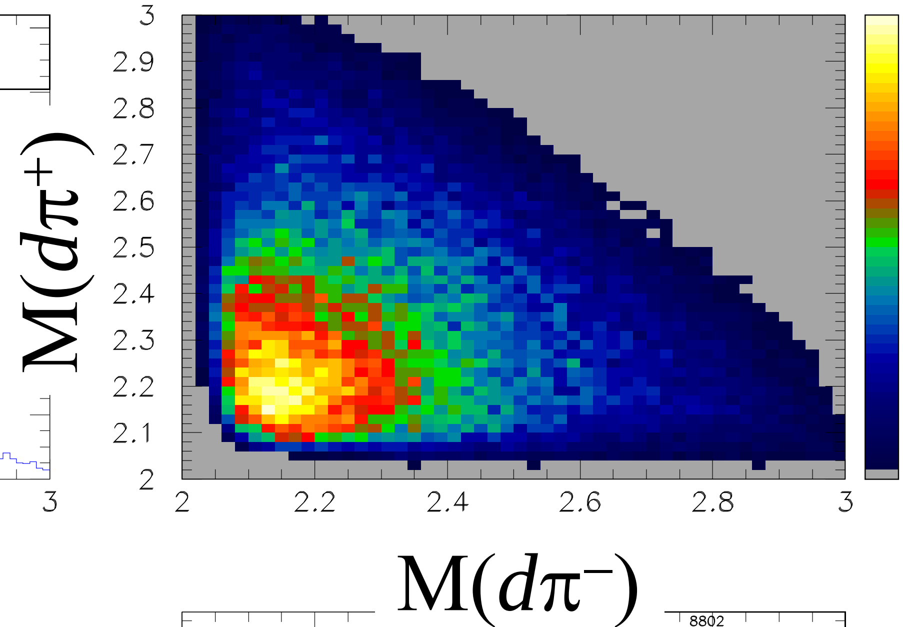
NΔ Parametric Monte Carlo

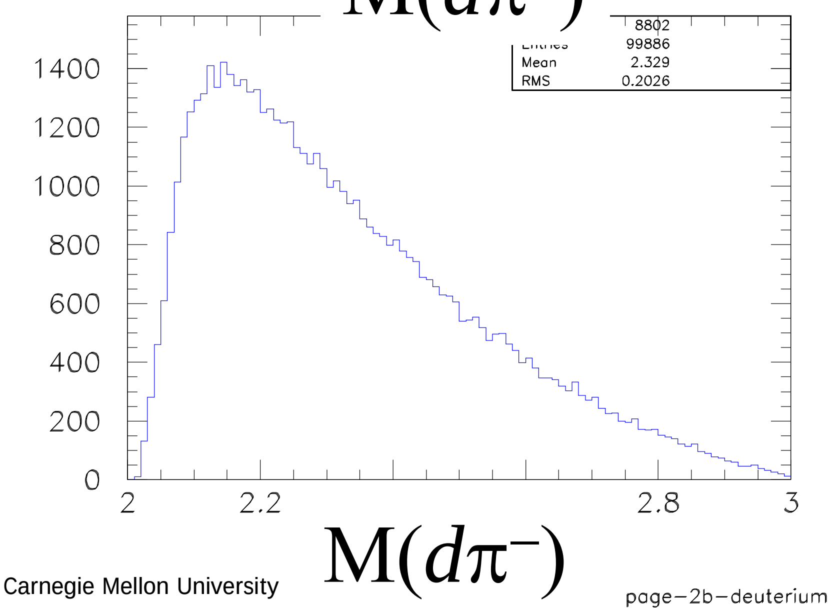
- $\gamma\, d \to \{d\, \pi\}\, \pi$ - signal channel
- $\gamma\, d \to d\, \rho$ - main background
- $\gamma\, d \to d\, \pi\, \pi$ - phase space background

- Model the run conditions:
  - Bremsstrahlung photon beam
  - Reverse CLAS torus field
  - Assume t-channel dominance (slope 2 GeV^2)

NΔ | Parametric Monte Carlo

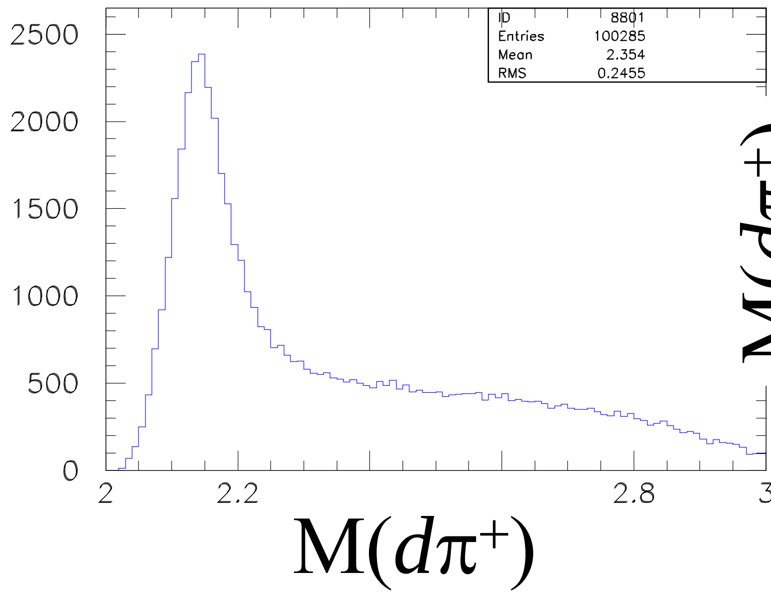


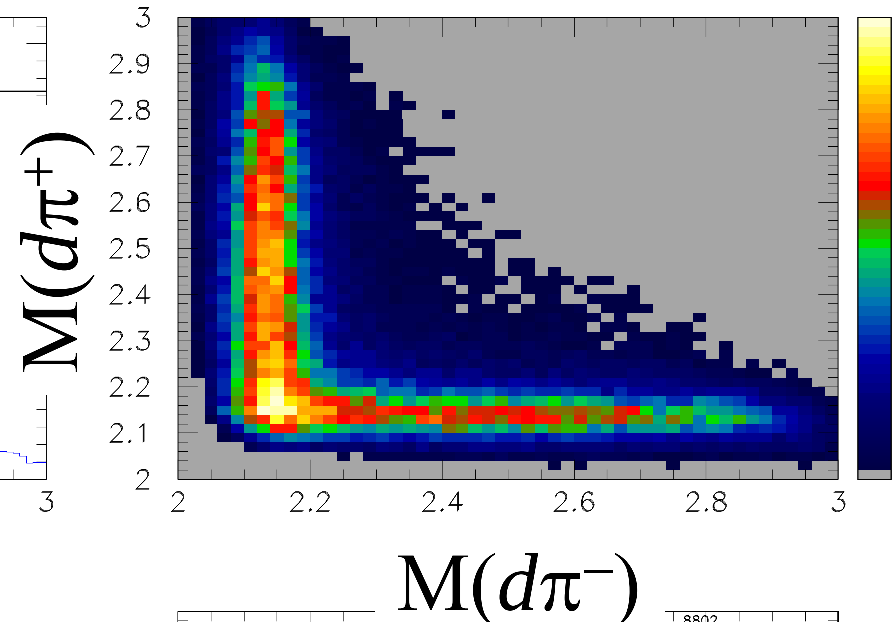




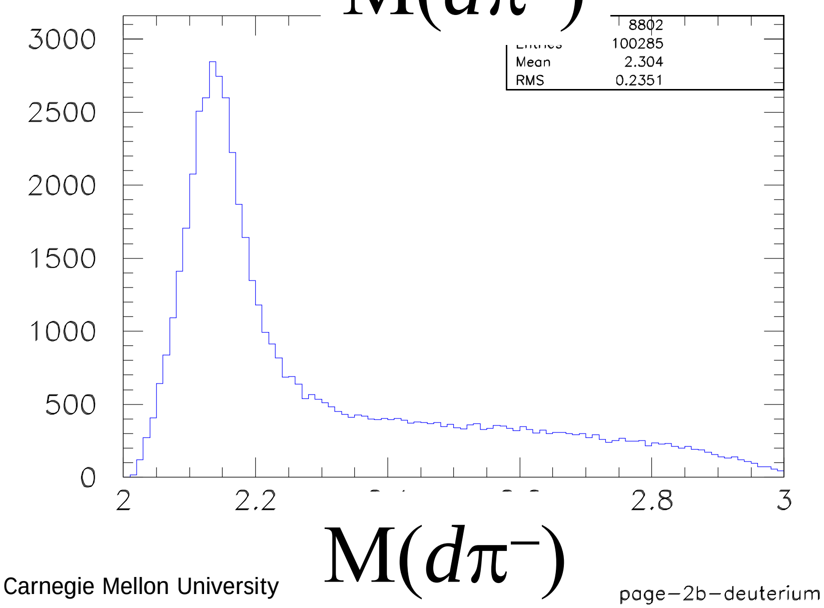
- $\gamma\, d \rightarrow d\, \pi^+\, \pi^-$ phase space background

NΔ Parametric Monte Carlo

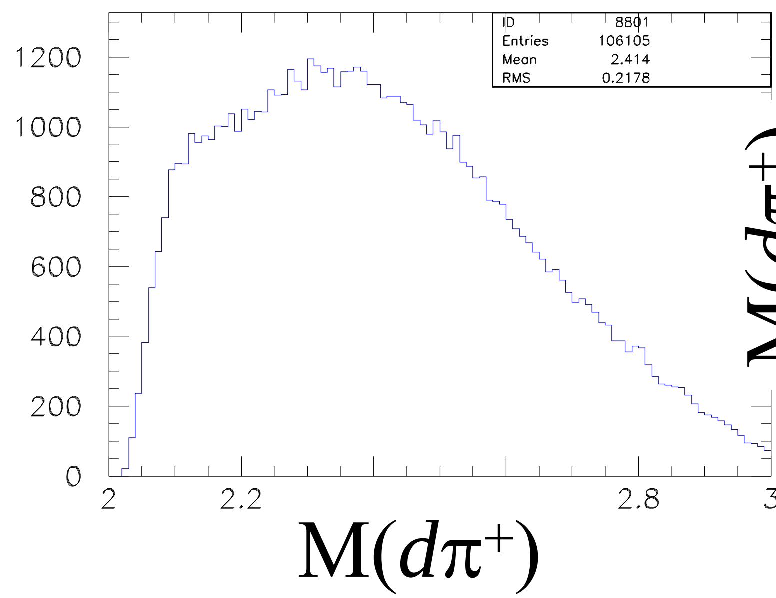


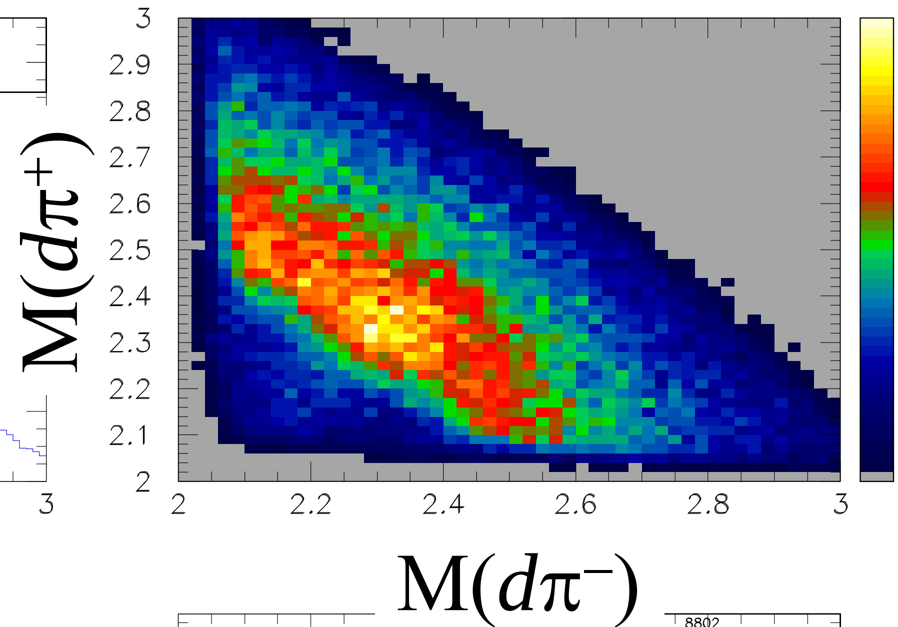


- $\gamma\, d \rightarrow \{d\, \pi^{\pm}\}\, \pi^{\mp}$ signal events

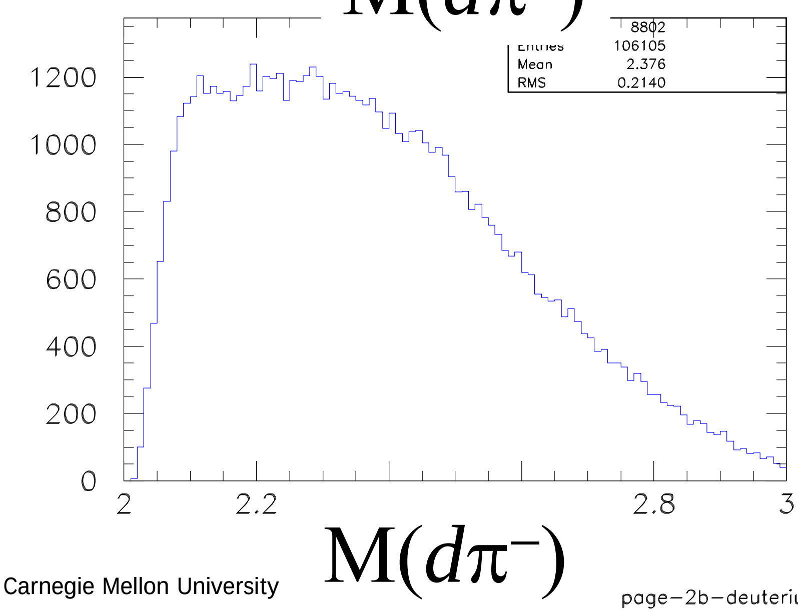


NΔ Parametric Monte Carlo





- $\gamma\, d \rightarrow d\, \pi^+\, \pi^-$
  ρ background



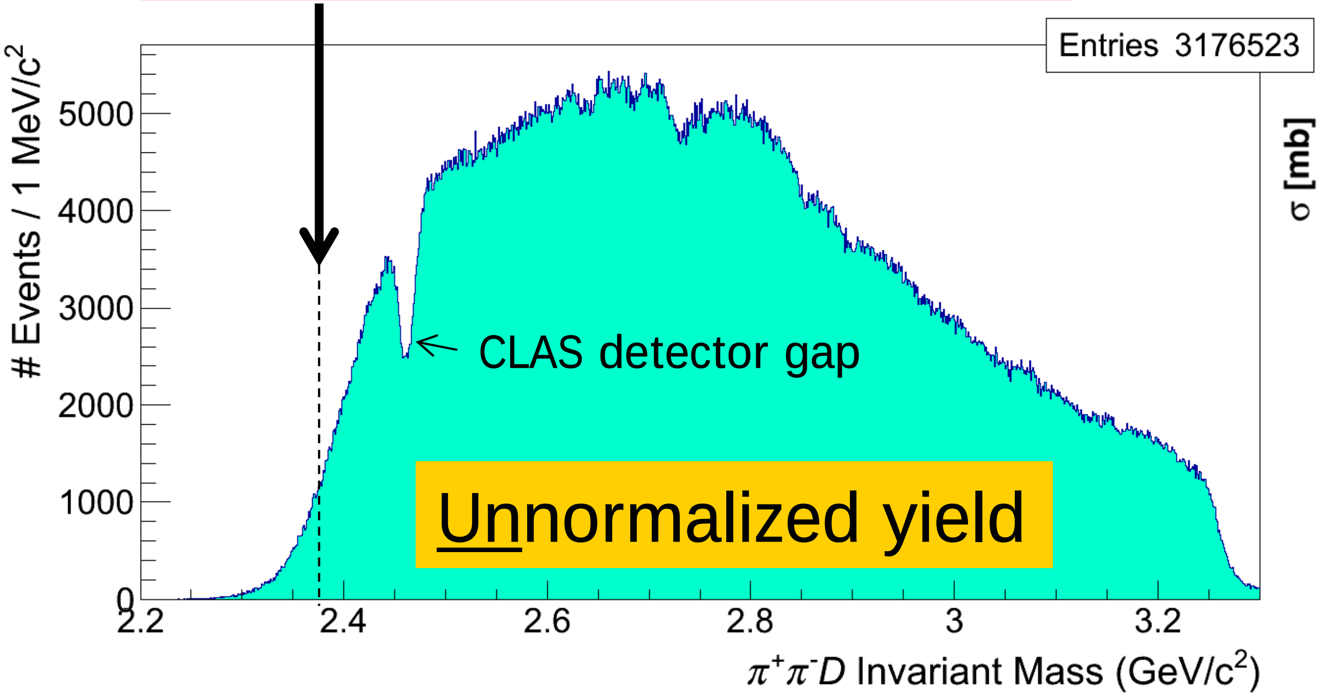
page−2b−deuterium

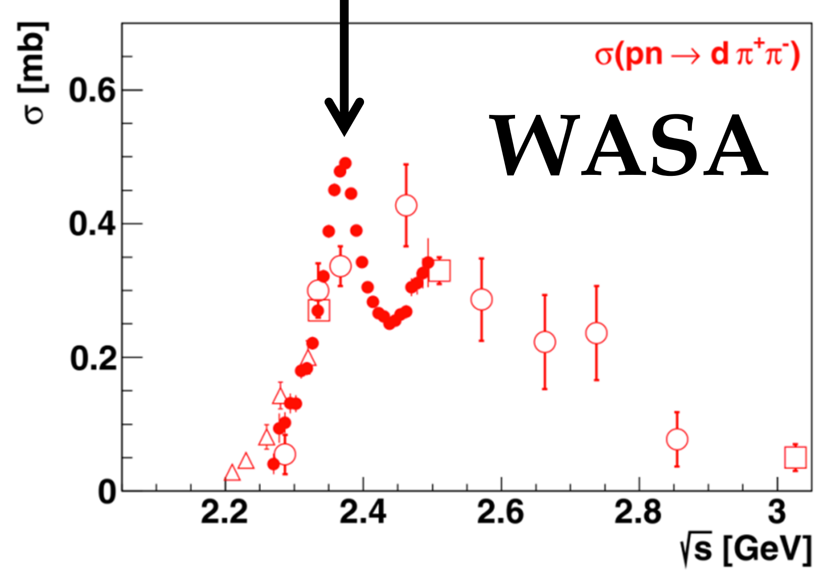
- Preliminary CLAS data showing
  - No sign of a "ΔΔ" signal
  - Evidence for ρ background
  - Evidence for a "NΔ" signal

NΔ | $d\pi^+\pi^-$ Invariant Mass

- Gash at W = 2.46 GeV/c^2: known gap in CLAS coverage
- No ΔΔ visible in CLAS/g13 (maybe not formed in γd)
- Recall WASA@COSY claims ΔΔ at W = 2.37 GeV/c^2 in $pn \rightarrow d\pi^+\pi^-$

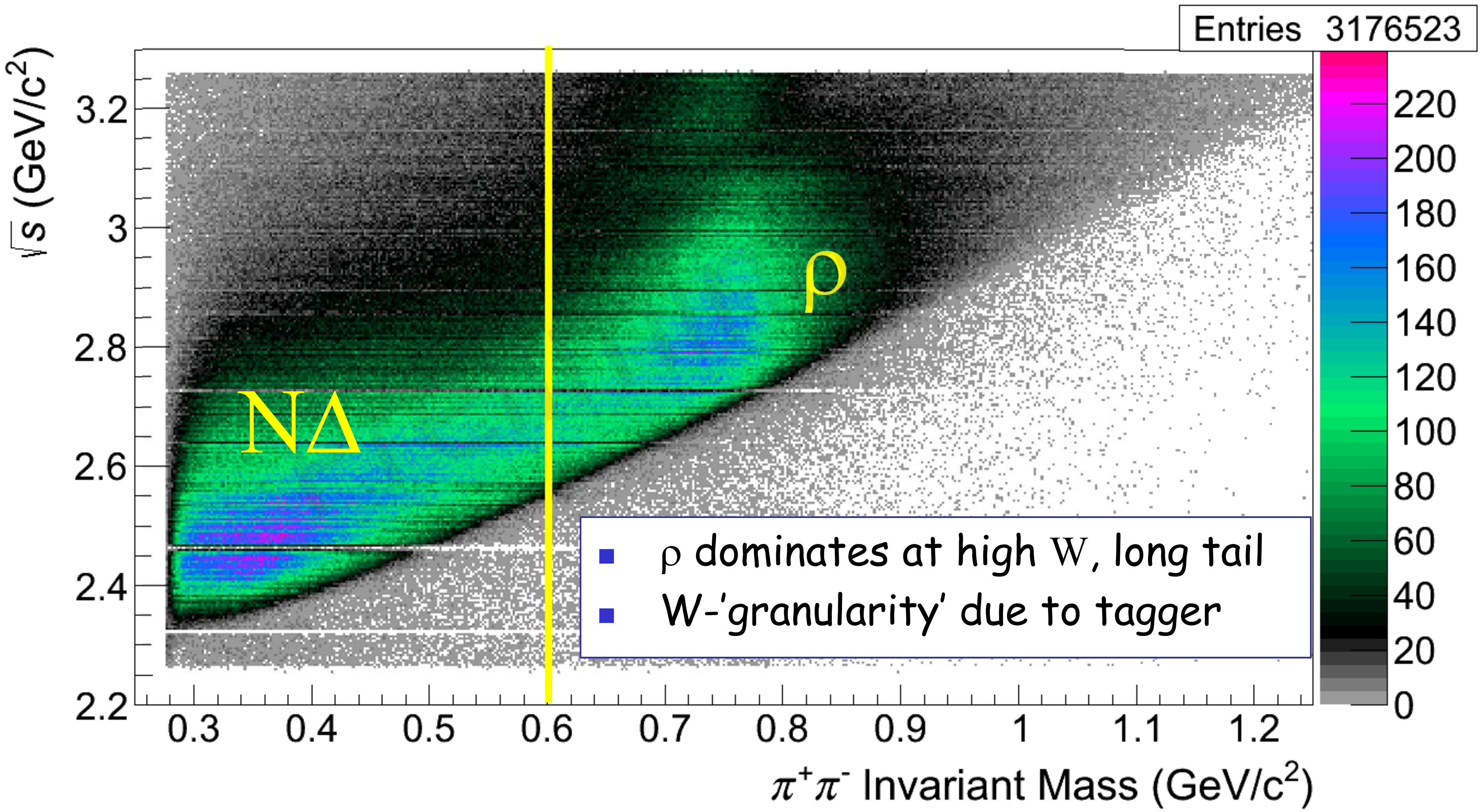
No hint of a "ΔΔ" bump!





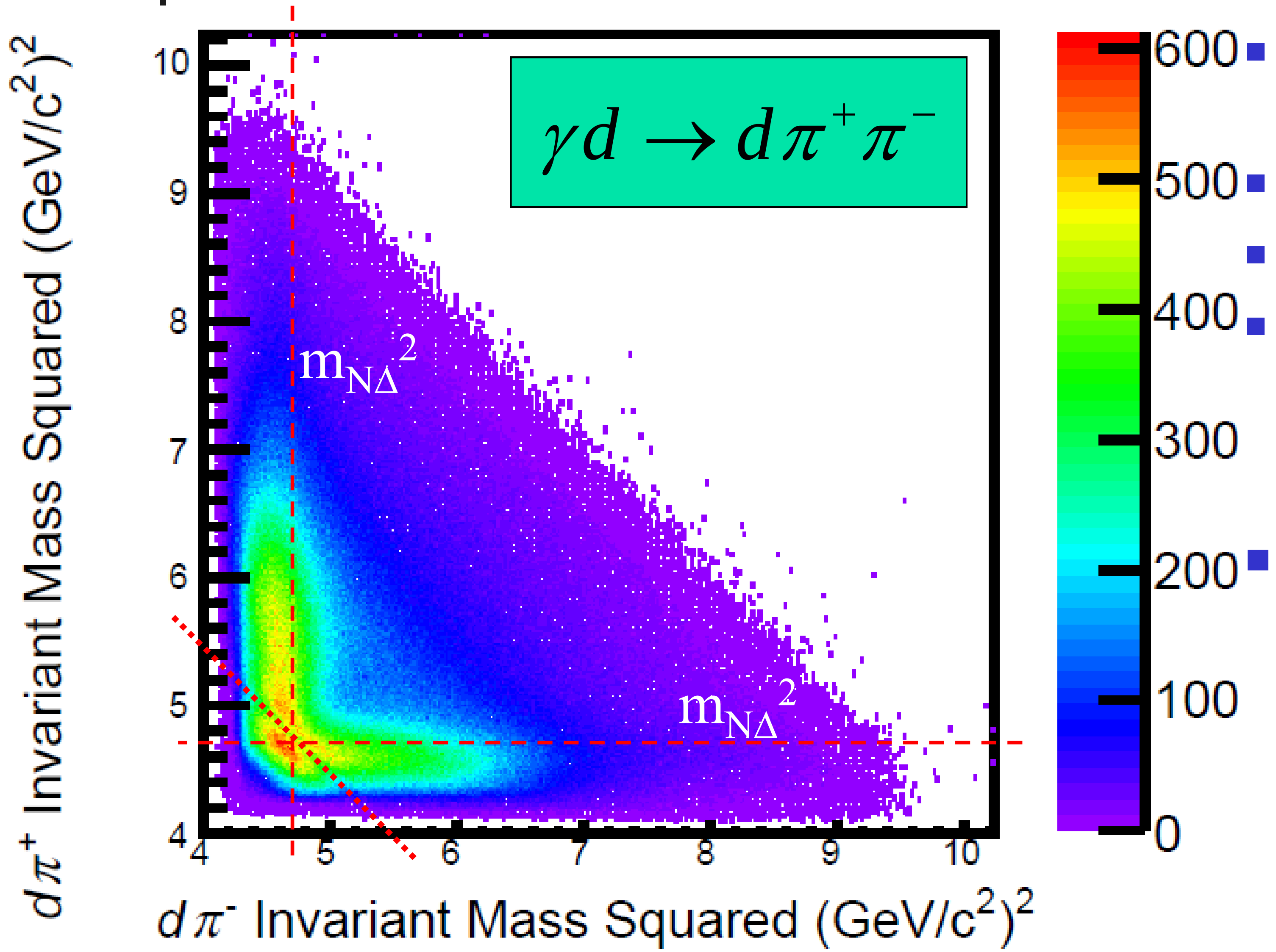
P. Adlarson *et al.*, Phys. Rev. C **88**, 055208 (2013).

NΔ | $\gamma d \to d\,\rho,\ \ \rho \to \pi^+\pi^-$ background



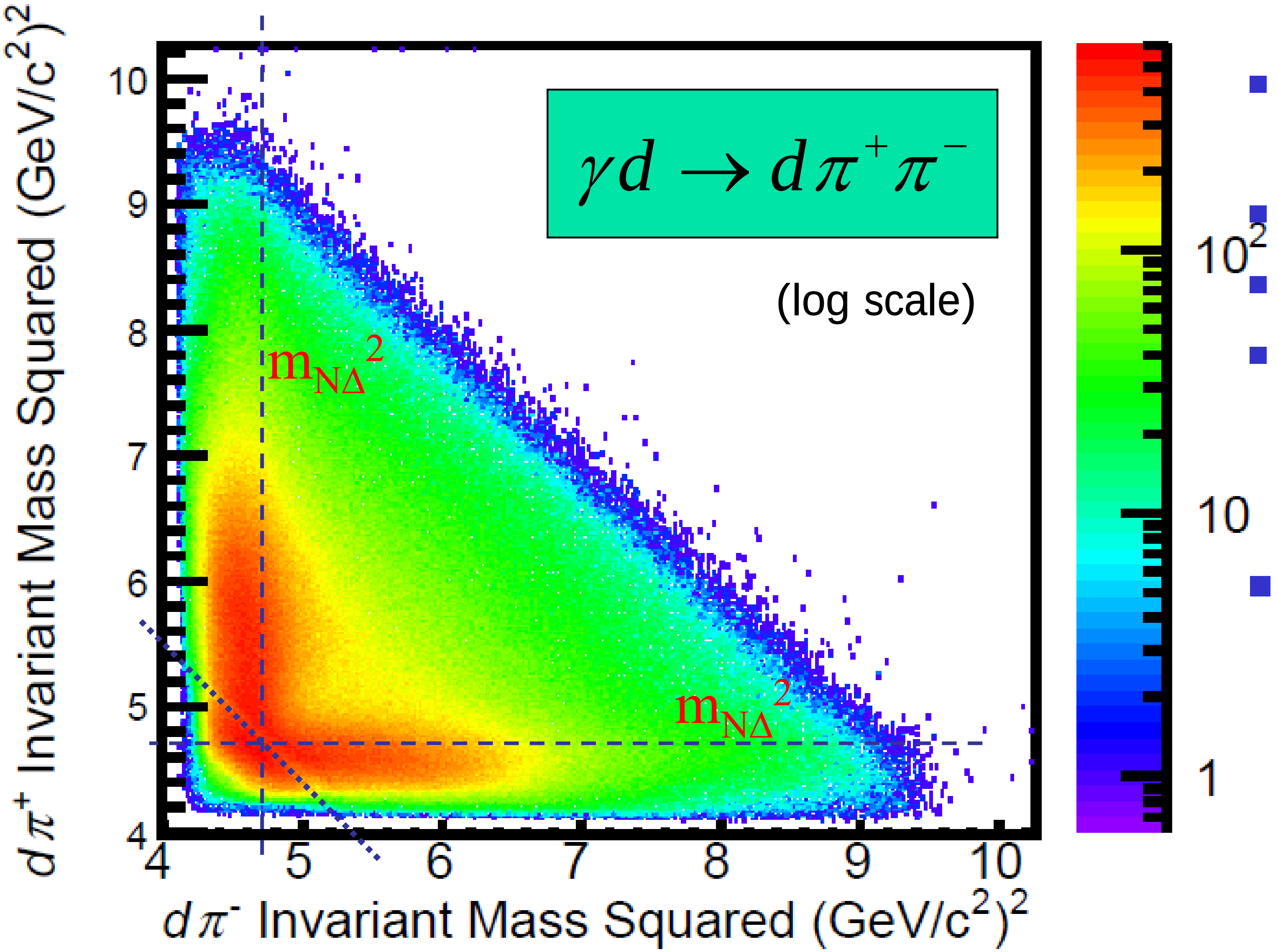
- ρ dominates at high W, long tail
- W-'granularity' due to tagger

NΔ | Dalitz Plot: $d\pi^+$ vs. $d\pi^-$



- Acceptance-corrected CLAS (g13) data
- $-0.75 < \cos\theta_{\pi\pm} < 0.94$
- $2.45 < W < 3.15$ GeV
- W~constant on diag.
  - Gap at W=2.45 GeV due to missing tagger channel
- Clear preference for $d\pi^\pm$ correlation near the NΔ mass!

NΔ | Dalitz Plot: $d\pi^+$ vs. $d\pi^-$



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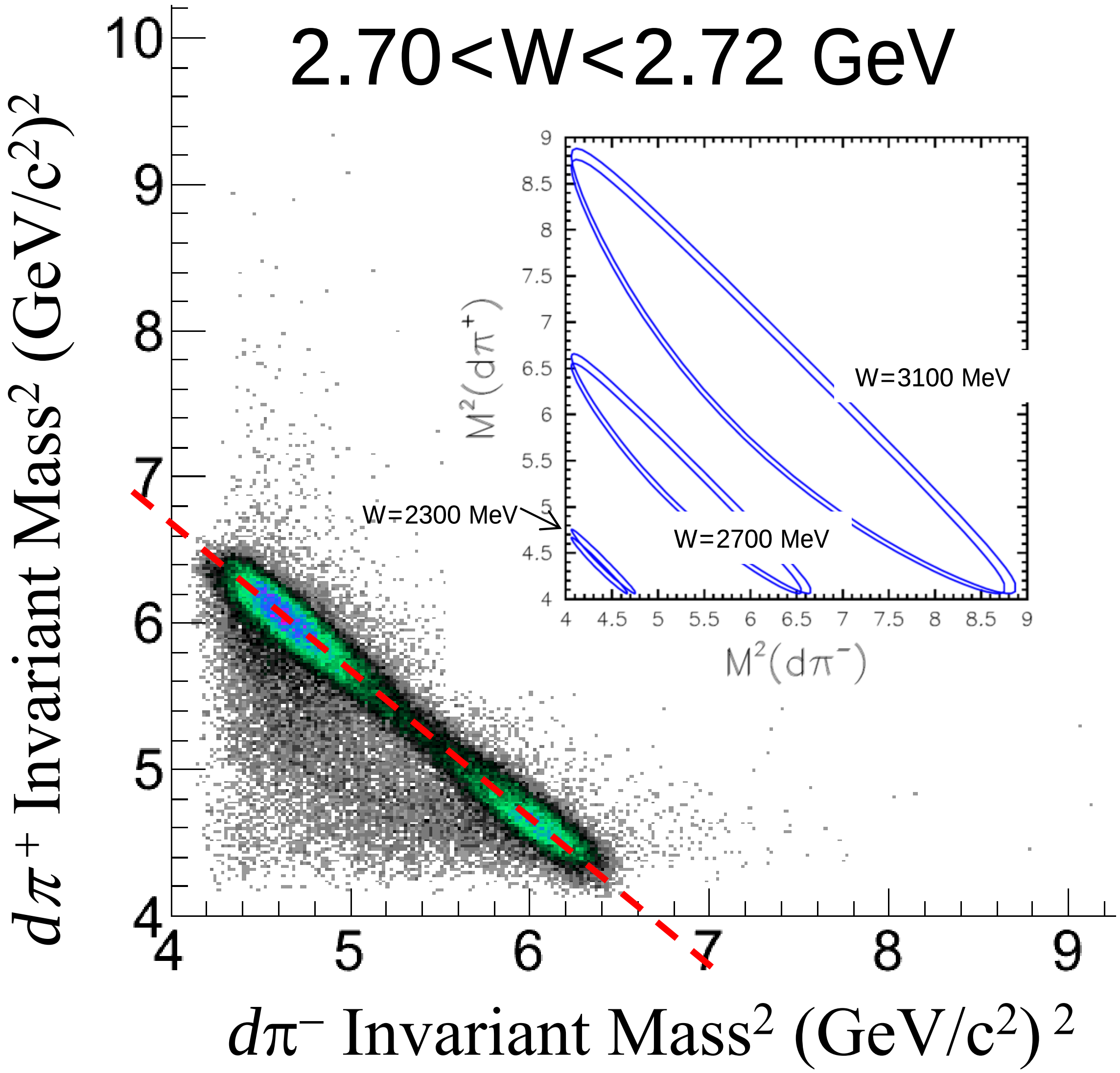
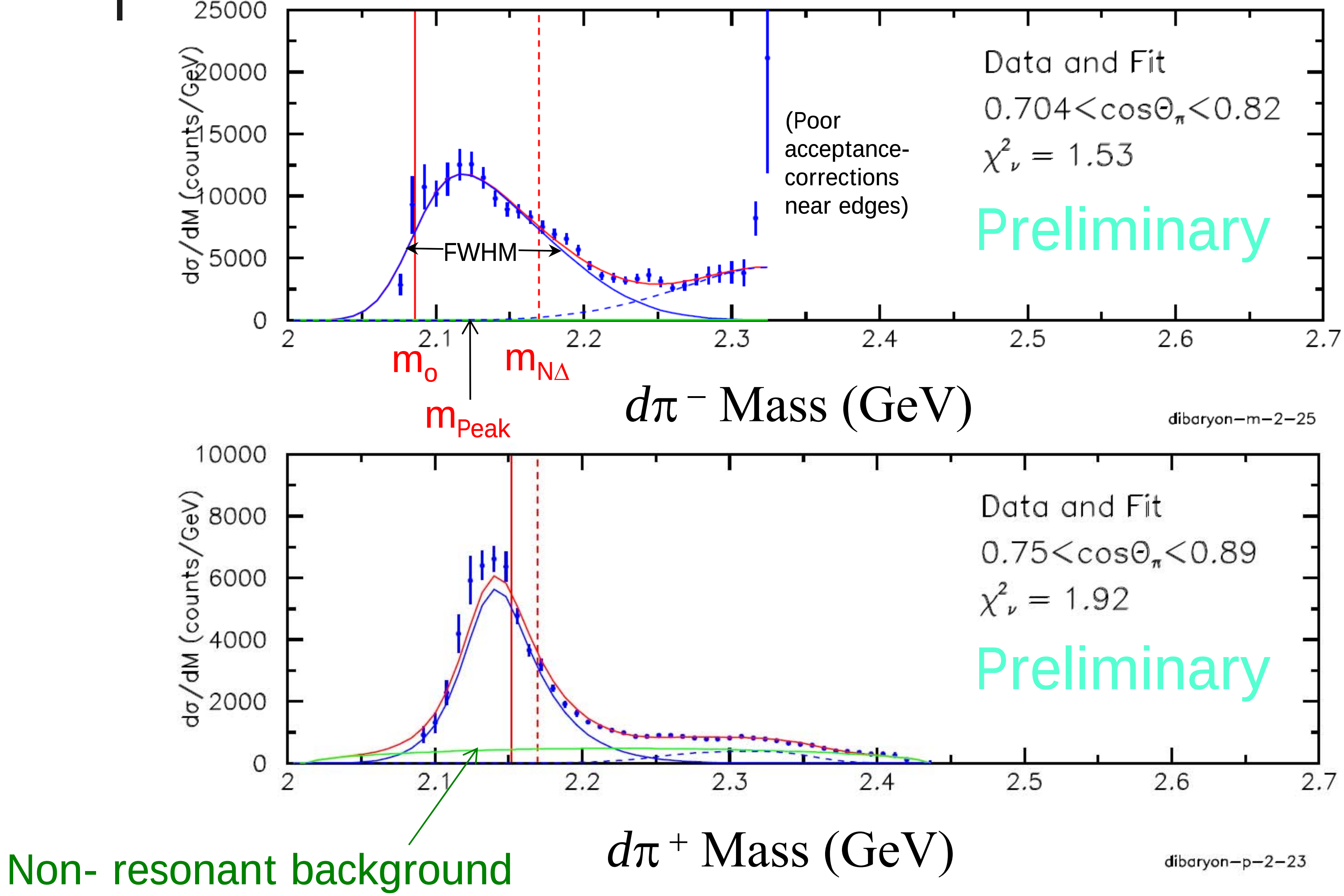
NΔ| Fit to Resonance-like Shapes



- Use narrow data slices in $W = \sqrt{s}$
- Assume a Breit-Wigner line shape
- Let $d\pi$ system decay to NΔ (L=0), $d\pi$ (L=1), and NN (L=2)
- ρ not cut away; model as P.S. background
- Incoherent amplitudes
- Following fits are prelude to PWA analysis

NΔ $\gamma d \rightarrow (d\pi)\,\pi$ $2.55 < W < 2.60$ GeV



NΔ Fit to Resonance-like Shapes

$$\frac{d\sigma}{dm} \sim \left\{\frac{1}{p_{\gamma d}^{cm}}\right\} \frac{m_0^2 \Gamma_i \Gamma_f}{(m_0^2 - m^2)^2 + m_0^2 (\Gamma_{N\Delta}^{L=0} + \Gamma_{\pi d}^{L=1} + \Gamma_{pp}^{L=2})^2}$$

Let the fit "choose" the preferred shape from L=0,1,2

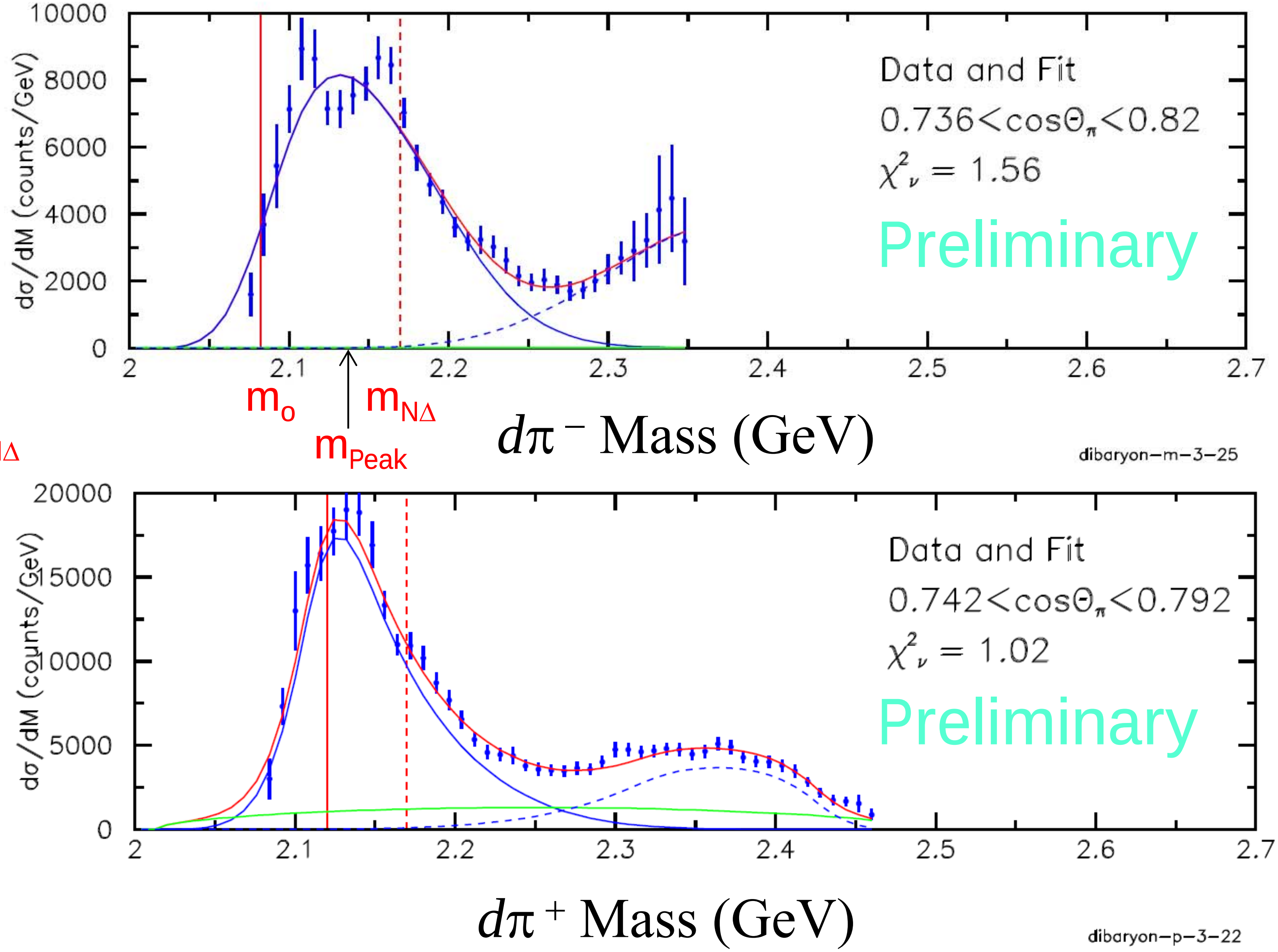
$$\Gamma_{pp}^{L=2} = \alpha_{pp} \Gamma_0 \left(\frac{q^{pp}}{q_0^{pp}}\right)^{2L+1=5} \left(\frac{m}{m_0}\right) (B_{L=2}^{'}(q,q_0))^2$$

$$\Gamma_{\pi d}^{L=1} = \alpha_{\pi d} \Gamma_0 \left(\frac{q^{\pi d}}{q_0^{\pi d}}\right)^{2L+1=3} \left(\frac{m}{m_0}\right) (B_{L=1}^{'}(q,q_0))^2 = \Gamma_f \triangleq \Gamma_i$$

$$\Gamma_{N\Delta}^{L=0} = \alpha_{N\Delta} \Gamma_0 \left(\frac{q^{N\Delta}}{q_0^{N\Delta}}\right)^{2L+1=1} \left(\frac{m}{m_0}\right) (B_{L=0}^{'}(q,q_0))^2 \xrightarrow[\text{Non-relativistic}]{} \alpha_{N\Delta} \Gamma_0 \left(\frac{m}{m_0}\right) (1)$$

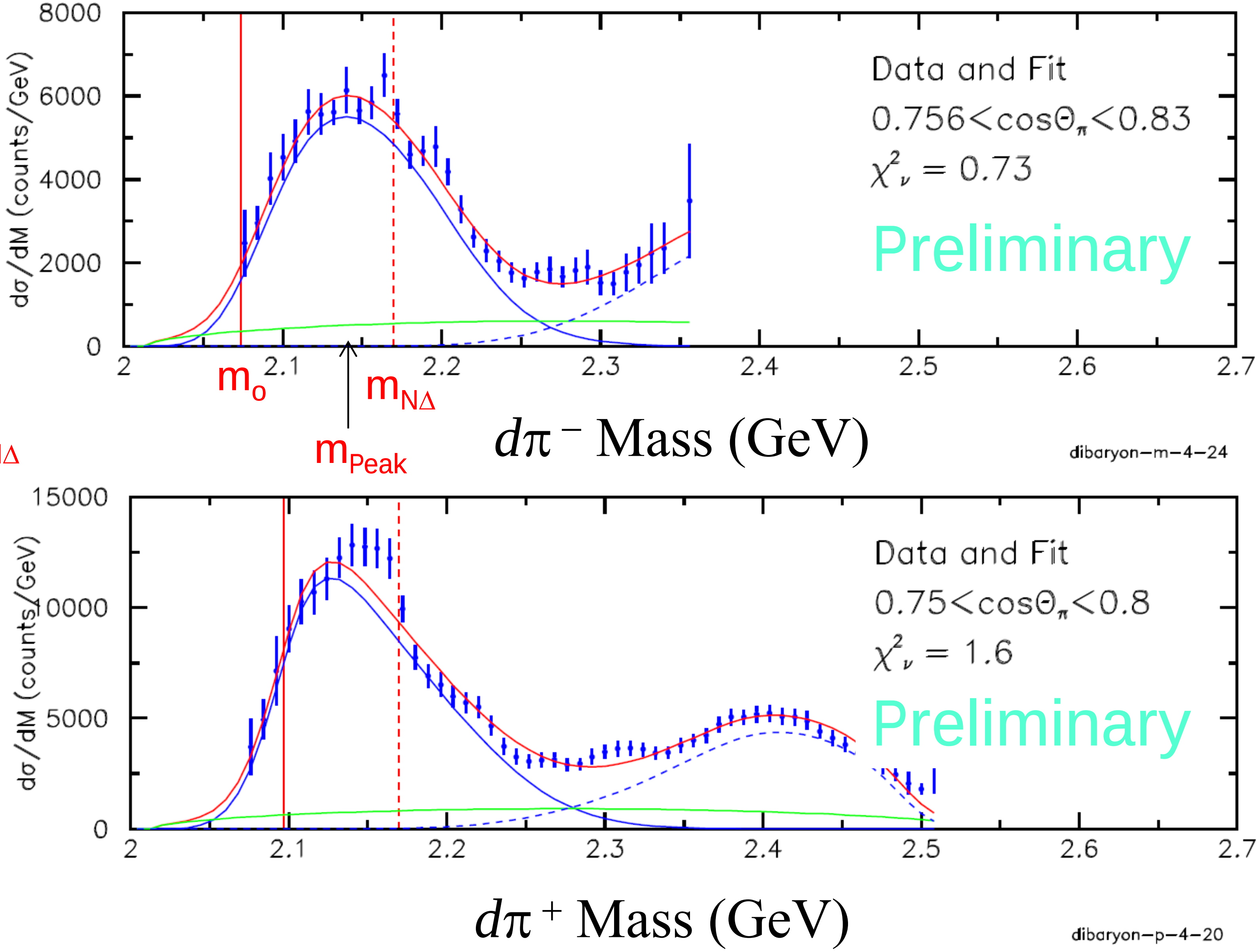
NΔ | $\gamma d \rightarrow (d\pi)\,\pi$ 2.60 <W<2.65 GeV

Evidently, $m_{Peak} < m_{N\Delta}$



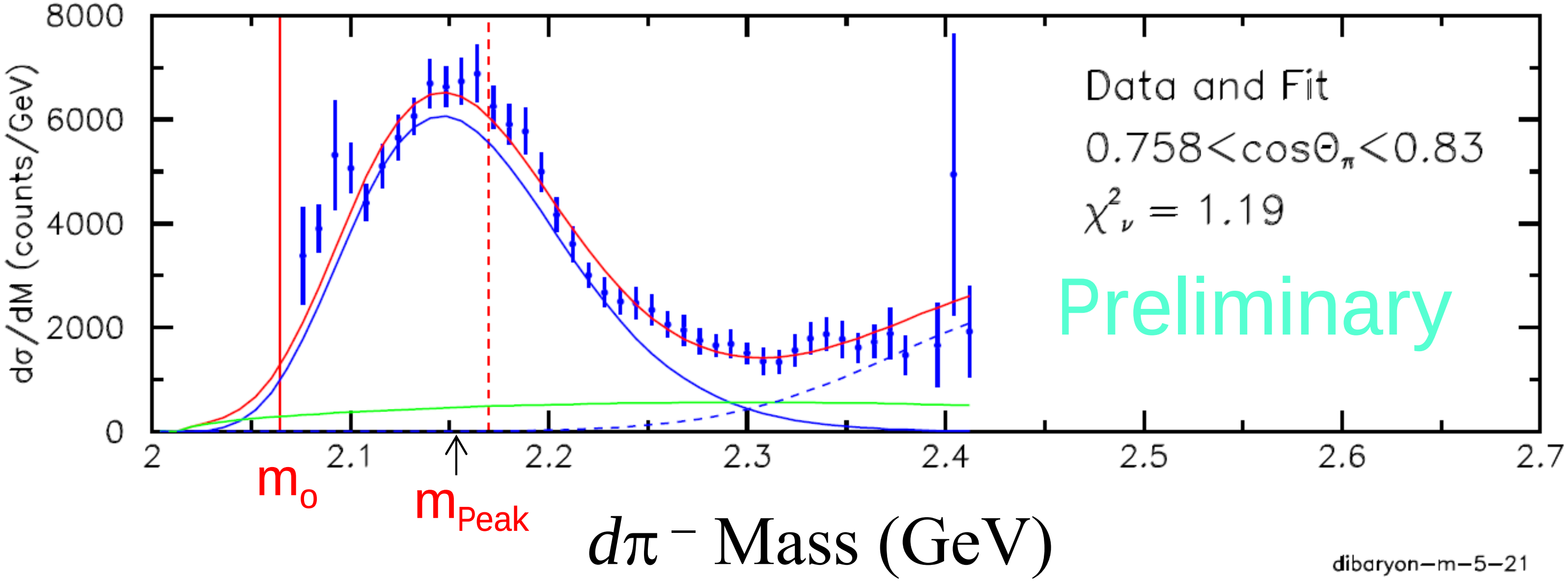
NΔ

$\gamma d \rightarrow (d\pi)\,\pi$ 2.65 <W<2.70 GeV

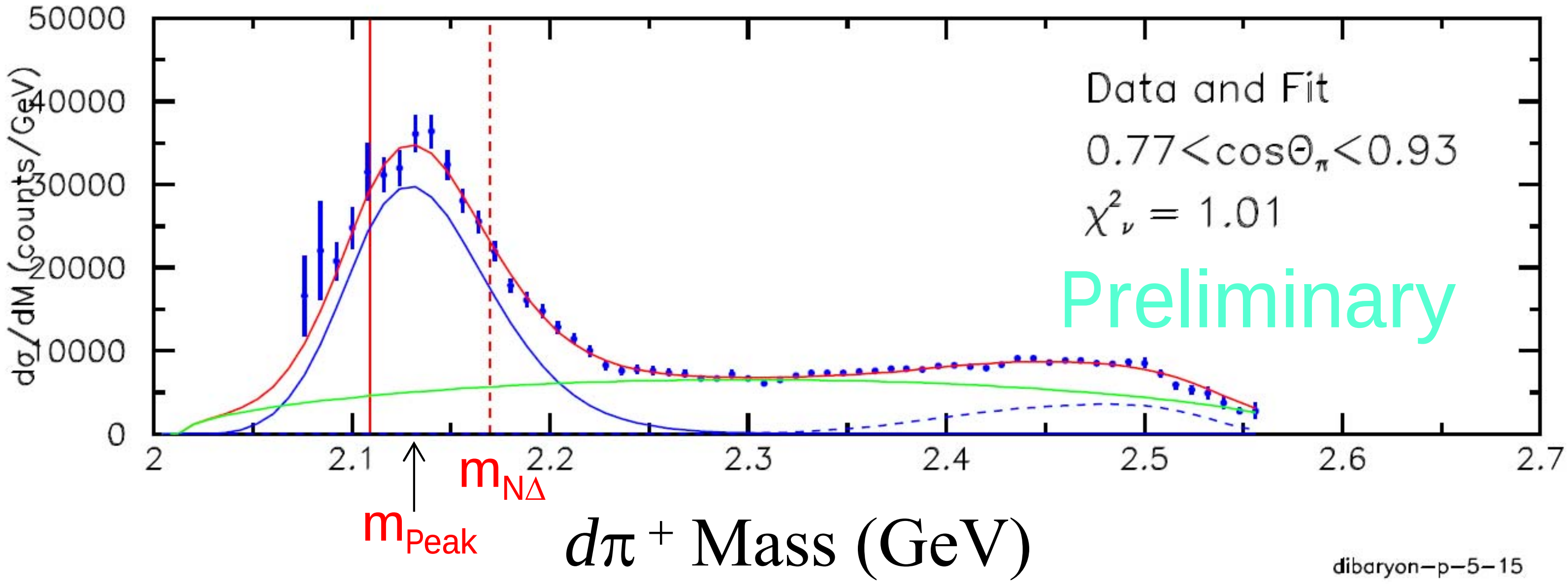


Evidently,
$m_{Peak} < m_{N\Delta}$

NΔ $\gamma d \rightarrow (d\pi)\,\pi \quad 2.70 < W < 2.75$ GeV



Evidently, $m_{Peak} < m_{N\Delta}$

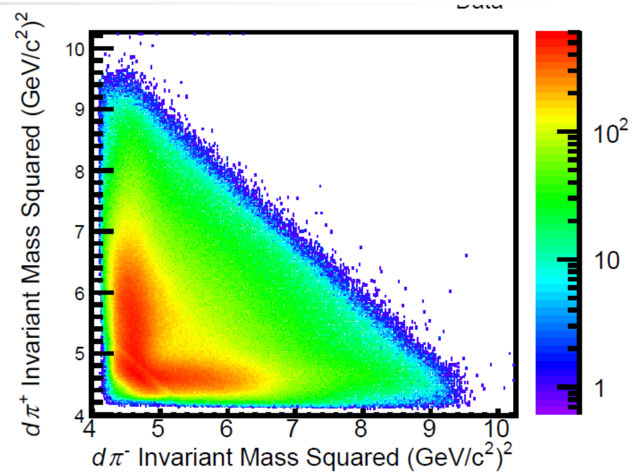


$N\Delta$ Observations

- Peaks are all below the $N\Delta$ centroid, but widths are not identical: $\cos\theta_\pi$ dependent
- Very preliminary result:
  - $m_{peak} \quad = 2115 \pm 10$ MeV/c^2
  - FWHM $= 125 \pm 25$ MeV
- We have remaining acceptance issues near high and low edges
- Fits "choose" non-relativistic BW line shapes with $\Gamma_{\pi d}^{L=1} \triangleq \Gamma_i$ numerator only few % $L = 1, 2$ decay branches denominator

NΔ Summary/Conclusion

- Big $\pi^{\pm}d$ signal seen in CLAS photo-production data, peaking below the NΔ mass.
  - Strongest at forward pion angle.

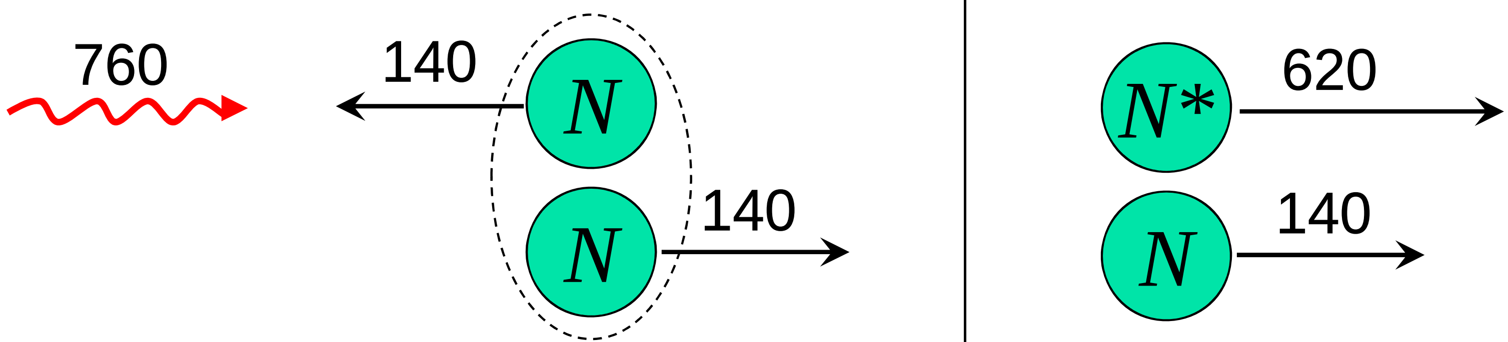


- Resonance mass and width depends on line-shape model, ρ treatment, amplitude interferences…
- We are NOT now claiming that this $d\pi$-system bump is necessarily the expected resonant $\mathcal{D}_{12}$ state… but it could be. Caveats:
  - Final/initial state interactions, other dynamics…
  - Scattering matrix poles vs. peaks in spectra…

Supplemental slides

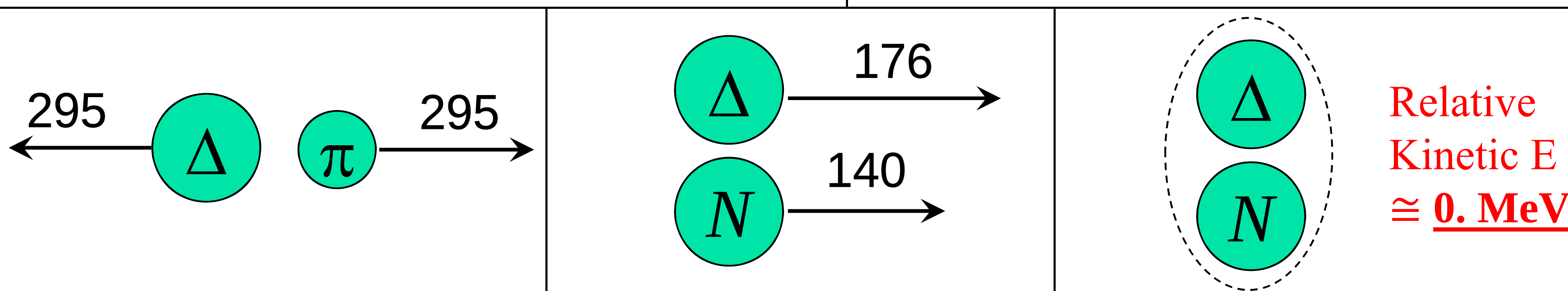
NΔ | Why not Deuteron Breakup?

- Would the system survive on the way to forming an NΔ State?
  - Fermi motion helps!
- Let $\gamma d \rightarrow NN^*(1520) \rightarrow N\Delta\pi$, <170 MeV/c Fermi motion, and let N^* decay along z-axis



1) $\gamma N \rightarrow N^*$ Lab Frame

2) N^*N Lab Frame



3) $N^*(1520)$ Rest Frame

4) ΔN Lab Frame

5) ΔN c.m. Frame

Theory Approaches for ΔΔ

- Group theory predicts both states $I\,J^P = 0\,3^+$ (D_{03} a.k.a. d*) and $I\,J^P = 3\,0^+$ (D_{30})
- Hidden-color configurations make both bound, but D_{03} more so:
  - Chiral-quark model
    - 2393 vs. 2440 MeV
  - Quark Delocalization Color Screening Model 2357 vs. 2423 MeV

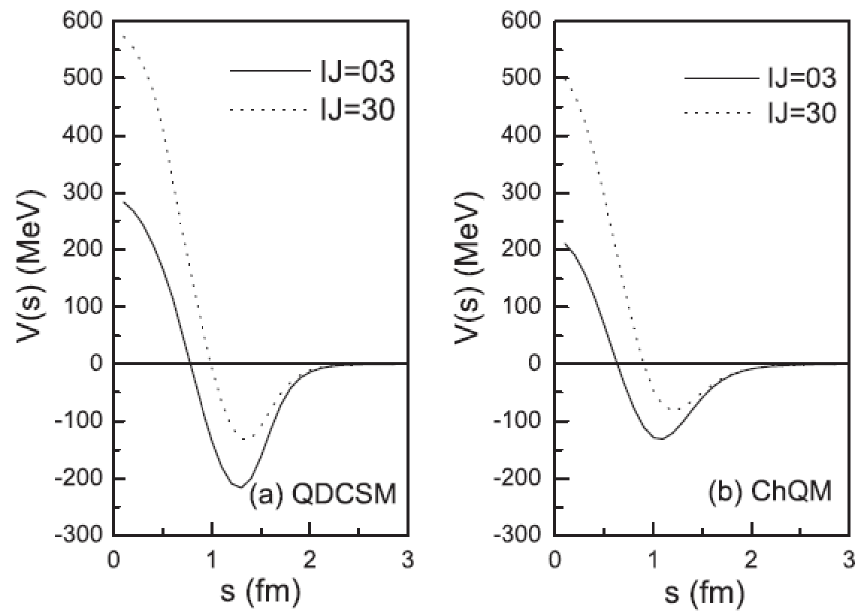
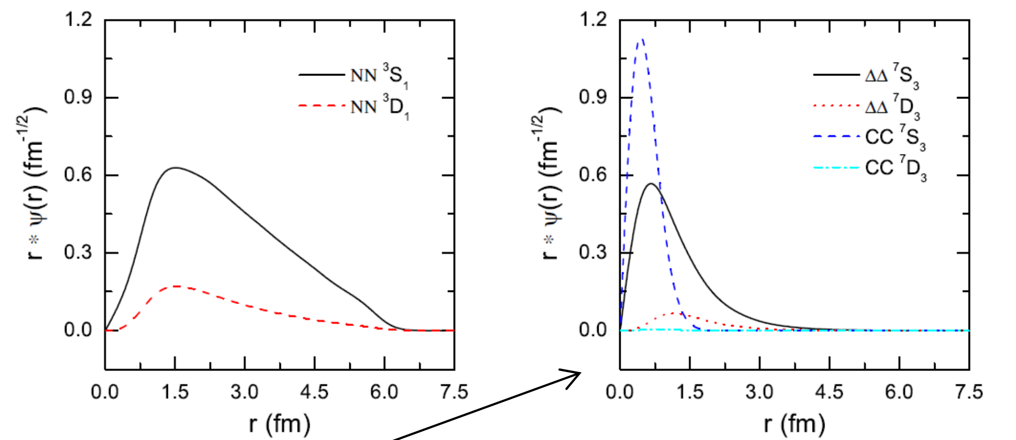


FIG. 1. The potentials of S-wave ΔΔ for $IJ^P = 03^+$ and $IJ^P = 30^+$ cases within two quark models.

H. Huang, J. Ping, F. Wang, Phys Rev C 89, 034001 (2014)

NΔ | Theory Approaches for ΔΔ

- Most exotic interpretation for d* $(I\ J^P = 0\ 3^+)$: a "hexa-quark" dominated structure
- Chiral Quark Model with Resonating Group Method
  - Mass 2.38 to 2.42 GeV
  - 2/3 hidden color configuration (CC)



(a) Deuteron (b) d^*

1. Relative wave functions in the extended chiral SU(3) quark model with f/g=0 for deuteron (left) and d^* (right).

  - RMS size 0.76 – 0.88 fm (!)
  - "Narrow" (~70 MeV), since CC component does not break up directly

F. Huang, ZY Zhang, PN Shen, WL Wang, arXiv:1408.0458 (2014)

CLAS Experiment

- Photoproduction:
  - Targets: unpolarized LH_2, polarized p, & HD-ice
  - Beams: unpolarized, circular, linear, to ~5 GeV
  - Reconstructed $K^+p\pi^-(\pi^0)$ or $K^+\pi^+\pi^-(n)$
  - 20×10^9 triggers → 1.41×10^6 $KY\pi$ events in g11a
- Electroproduction:
  - Q^2 from ~0.5 to ~3 $(GeV/c)^2$
  - Structure functions from Rosenbluth and beam-helicity separations