

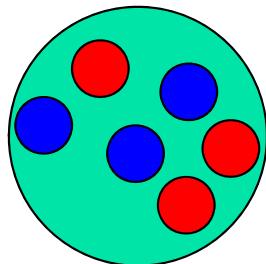
# Photoproduction of Structure in the $d\pi$ System Near the $\text{NA}$ Mass: Sign of a Quasi- Bound State?

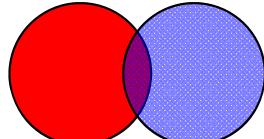
Reinhard Schumacher  
**Carnegie Mellon University**

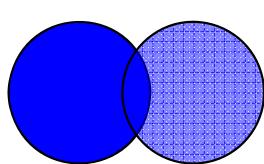
work with: Paul Mattione  
Jefferson Lab CLAS Collaboration

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

# Two-baryon resonances

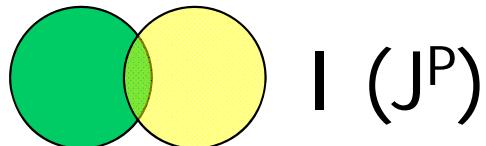


$^3S_1$         $I(J^P) = 0(1^+)$

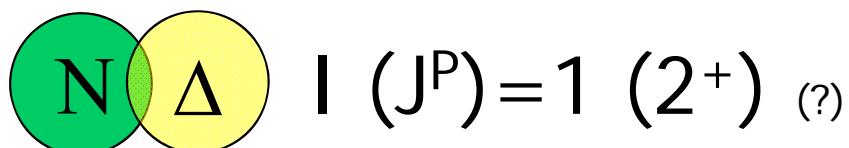
$^1S_0$         $I(J^P) = 1(0^+)$

- 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  $\sim 100$  keV
  - One of the great "fine-tuning" mysteries of nature!!

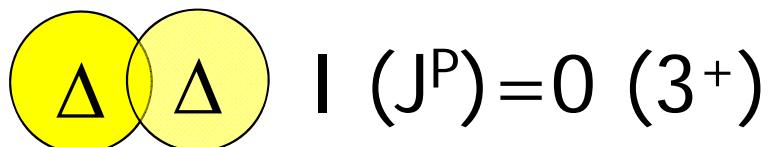
# Two-baryon resonances



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



- CLAS study: new observations
- Recent WASA@COSY claim of discovery



# Some Thresholds

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

$$m_d + m_\pi = 1875 + 140 = \underline{2015 \text{ MeV}} \\ 156 \text{ MeV}$$

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

For comparison:

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

# 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 $\Delta$  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

# Theoretical Expectations

- “NN core interactions...from 1 gluon exchange”
  - T. Barnes, S. Capstick, M.D. Kovarik, E.S. Swanson, PRC (1983)
  - OGE and quark-exchange model
  - Deuteron and N $\Delta$  states *not* found, but “molecular” (weakly bound)  $\Delta\Delta$  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  $\Delta\Delta$  & N $\Delta\pi$  thresholds

# Theoretical Expectations

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



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

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

Pole Position $\mathcal{D}_{12}$ (MeV)	Model Approach	Ref.
2147 – i60	Faddeev model	A. Gal, H. Garcilazo, Nucl. Phys. <b>A928</b> 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.

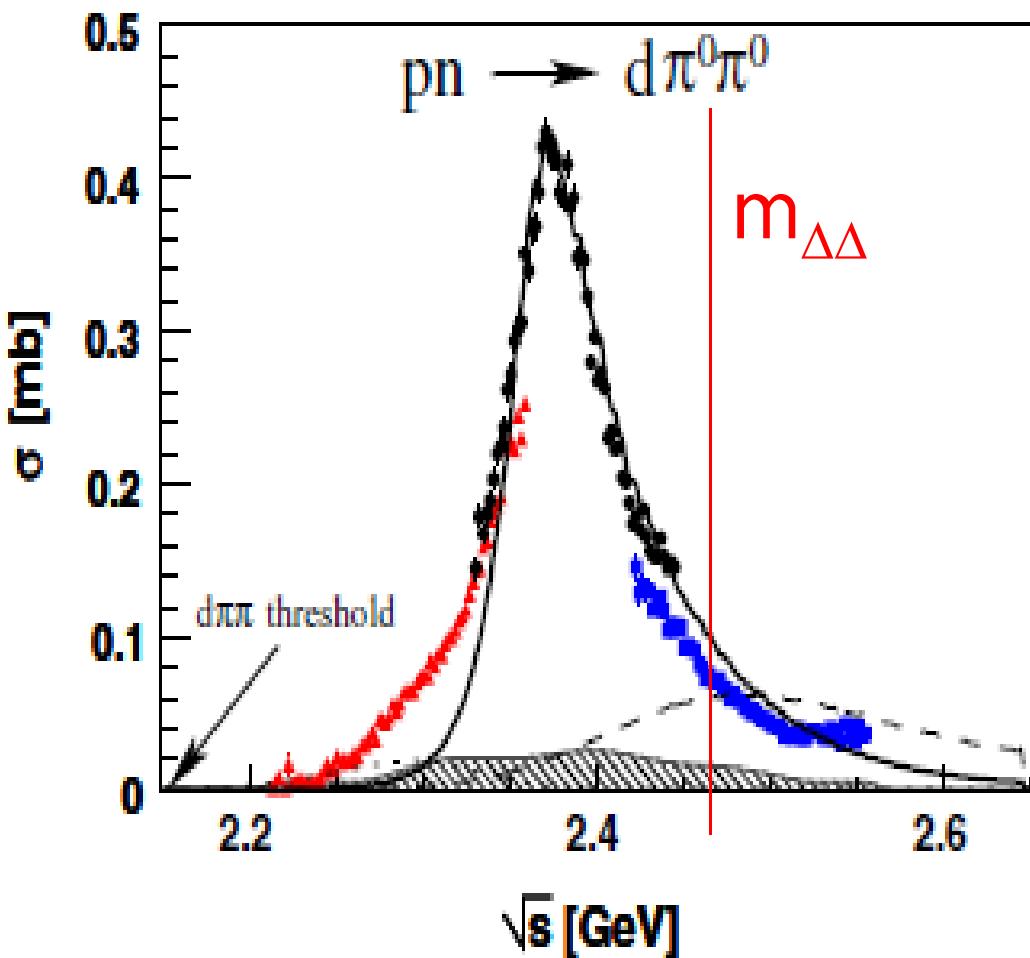
# Quasi-bound states

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

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

# $N\Delta$ | $d^*(2380)$ Resonance in $I(J^P) = 0(3^+)$



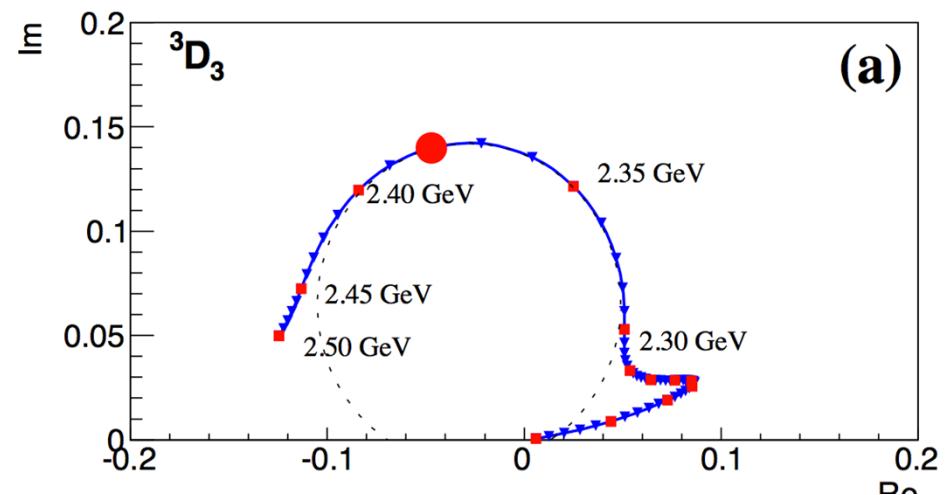
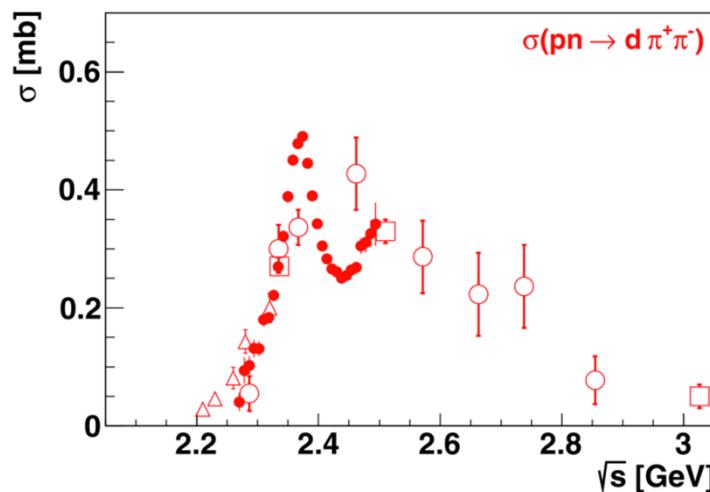
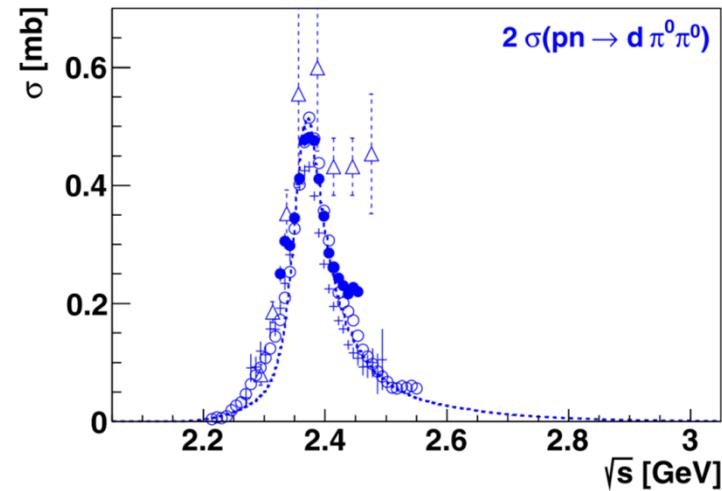
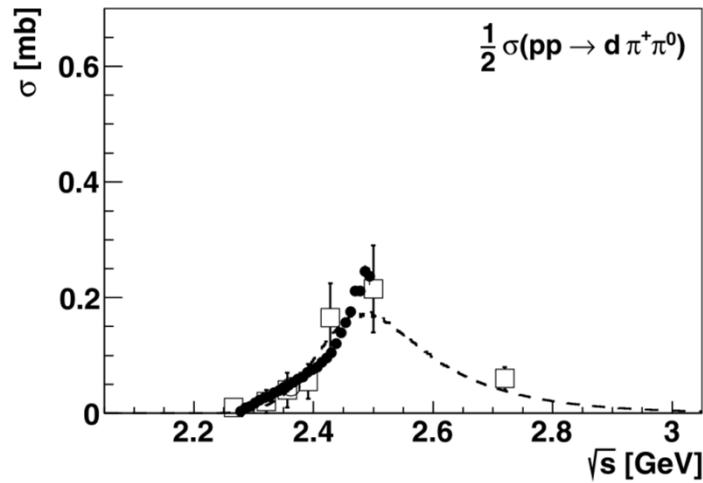
P. Adlarson et al, Phys Rev Lett 106, 242302 (2011)  
...and numerous others since.

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

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

# NΔ WASA@COSY $d^*(2380)$ Resonance

- Evidence for  $d^*(2380) \Delta\Delta$  state in  $NN \rightarrow d\pi\pi$  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 Theory Approaches for ΔΔ

- Interpretation of WASA/COSY results for reaction  $p\ n \rightarrow d\ \pi^0\ \pi^0$
- Interference of mechanisms for  $d^*$  ( $I\ J^P = 0\ 3^+$ ):

- Sequential decay thru

$D_{12}$  ( $I\ J^P = 1\ 2^+$ ) state

- $D_{03} \rightarrow D_{03} + \pi \rightarrow d + (\pi\pi)_0$

- $\sigma$  channel ( $\pi\pi$  - s wave)

- $D_{03} \rightarrow d + \sigma \rightarrow d + (\pi\pi)_0$

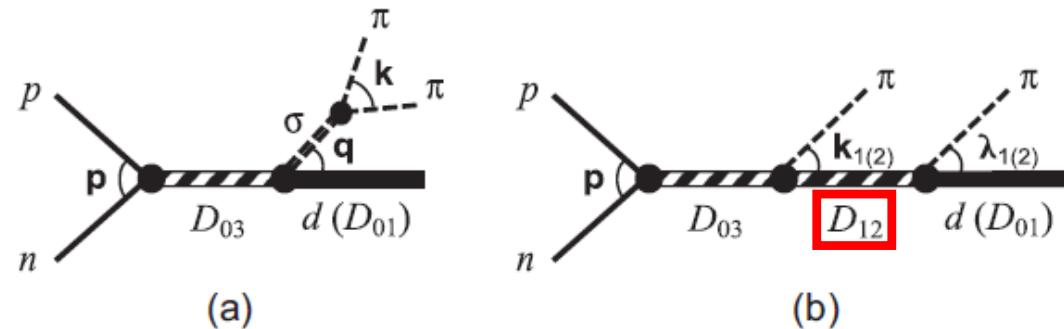


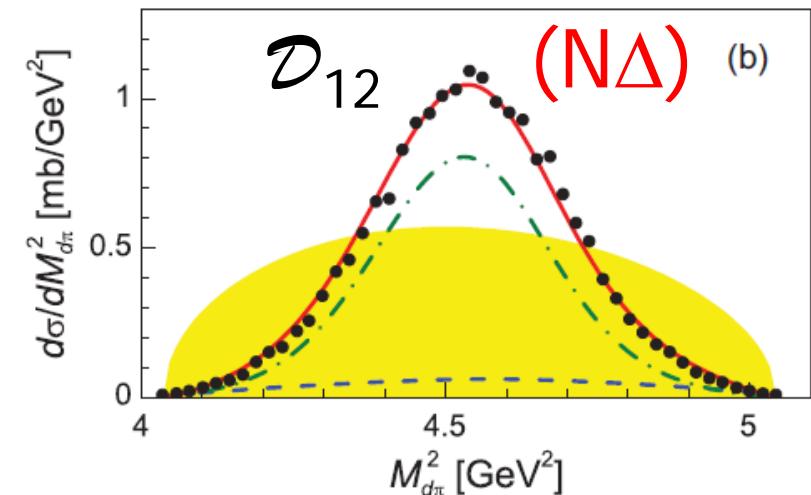
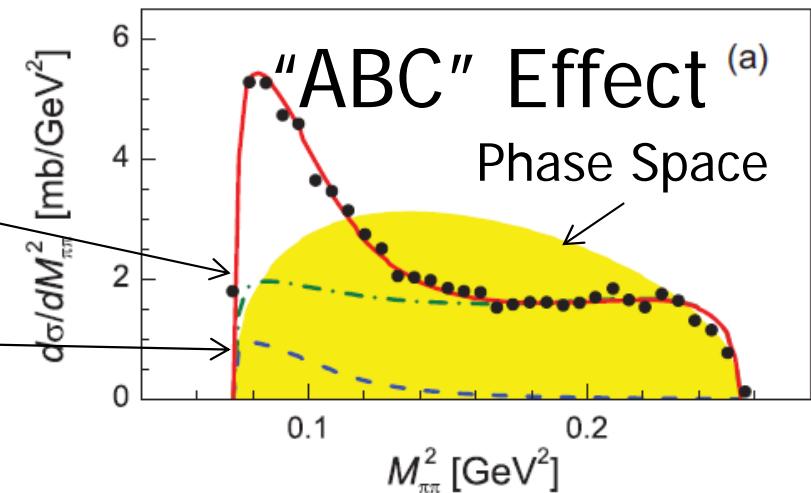
FIG. 1. The leading mechanisms for the reaction  $pn \rightarrow d + (\pi\pi)_0$  in the ABC region. The three-momenta in the c.m. frame of two particles are indicated between the respective lines.

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

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

# NΔ Theory Approaches for ΔΔ

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

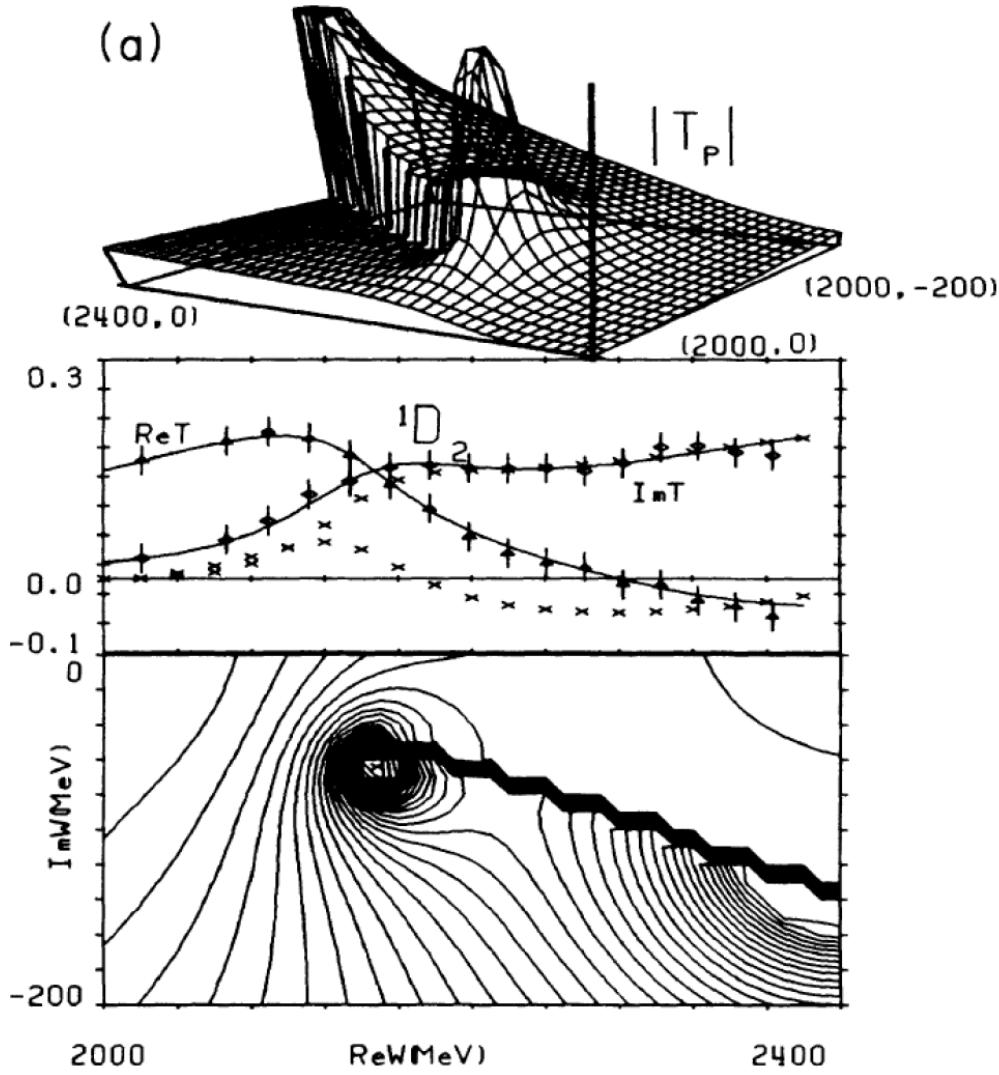


M.N. Platonova, V.I. Kukulin, Phys Rev C **87**, 025202 (2013)  
 P. Adlarson et al., Phys. Rev. Lett. **106**, 242202 (2011)

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

NΔ

# pp Elastic Scattering

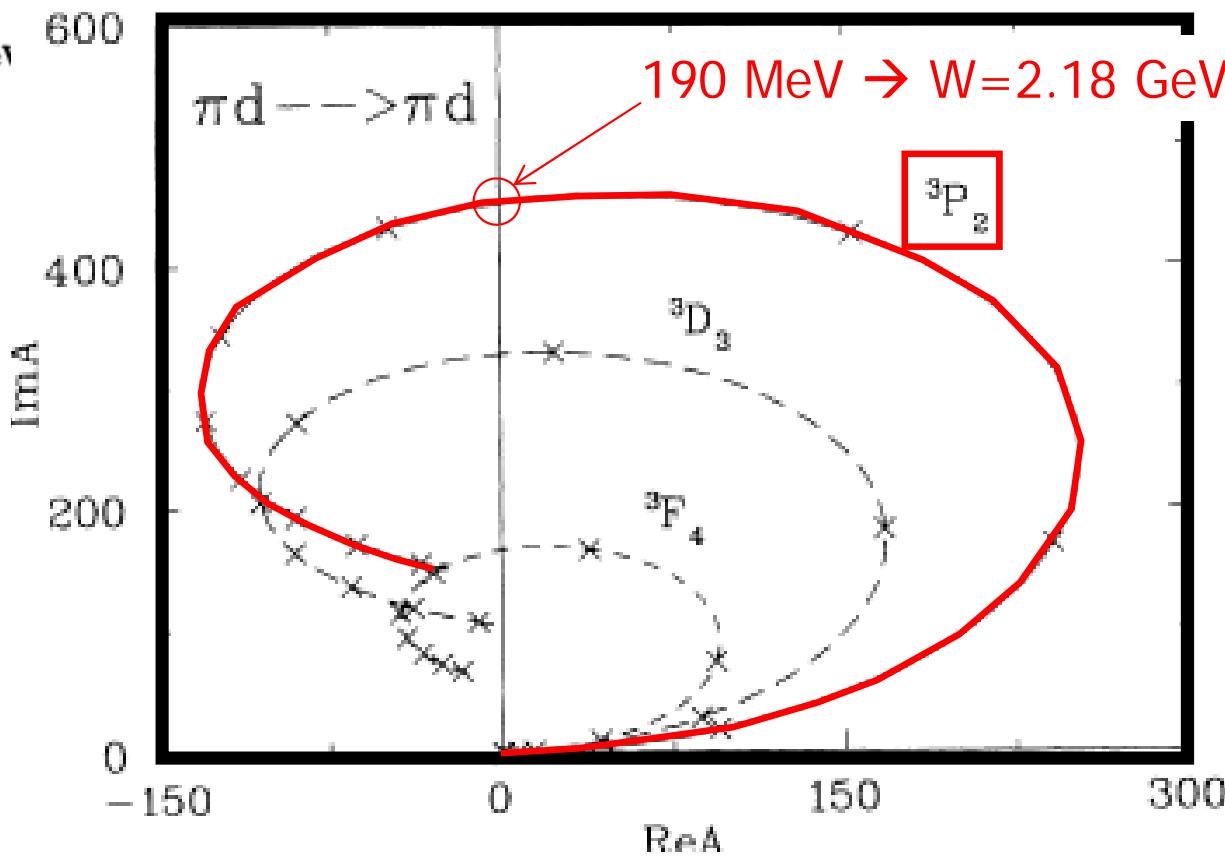
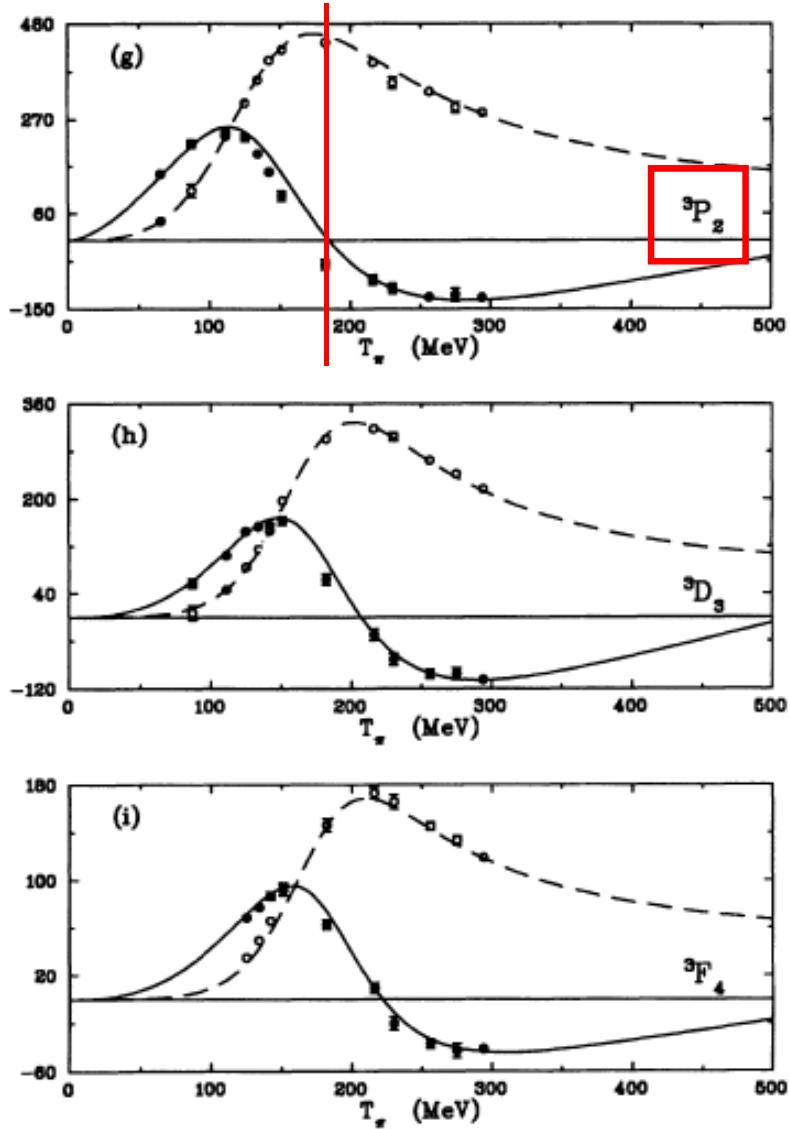


- Partial Wave Analysis
- ${}^1D_2$  wave in pp elastic scattering: structure at 2148 - i63 MeV
- Most prominent “resonance pole” seen in SAID analysis
- Textbook exercise: If an NΔ quasi-bound state exists, it can decay to  $pp$  ONLY if  $J_{N\Delta}^P = 2^+$

NΔ

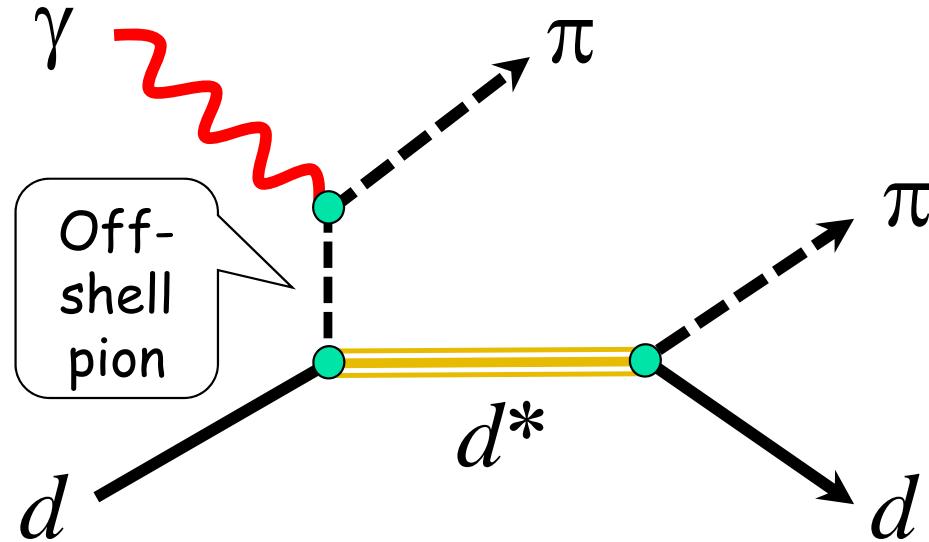
# $\pi d \rightarrow \pi d$ Elastic PWA

ANALYSIS OF  $\pi d$  ELASTIC SCATTERING DATA TO 500 MeV



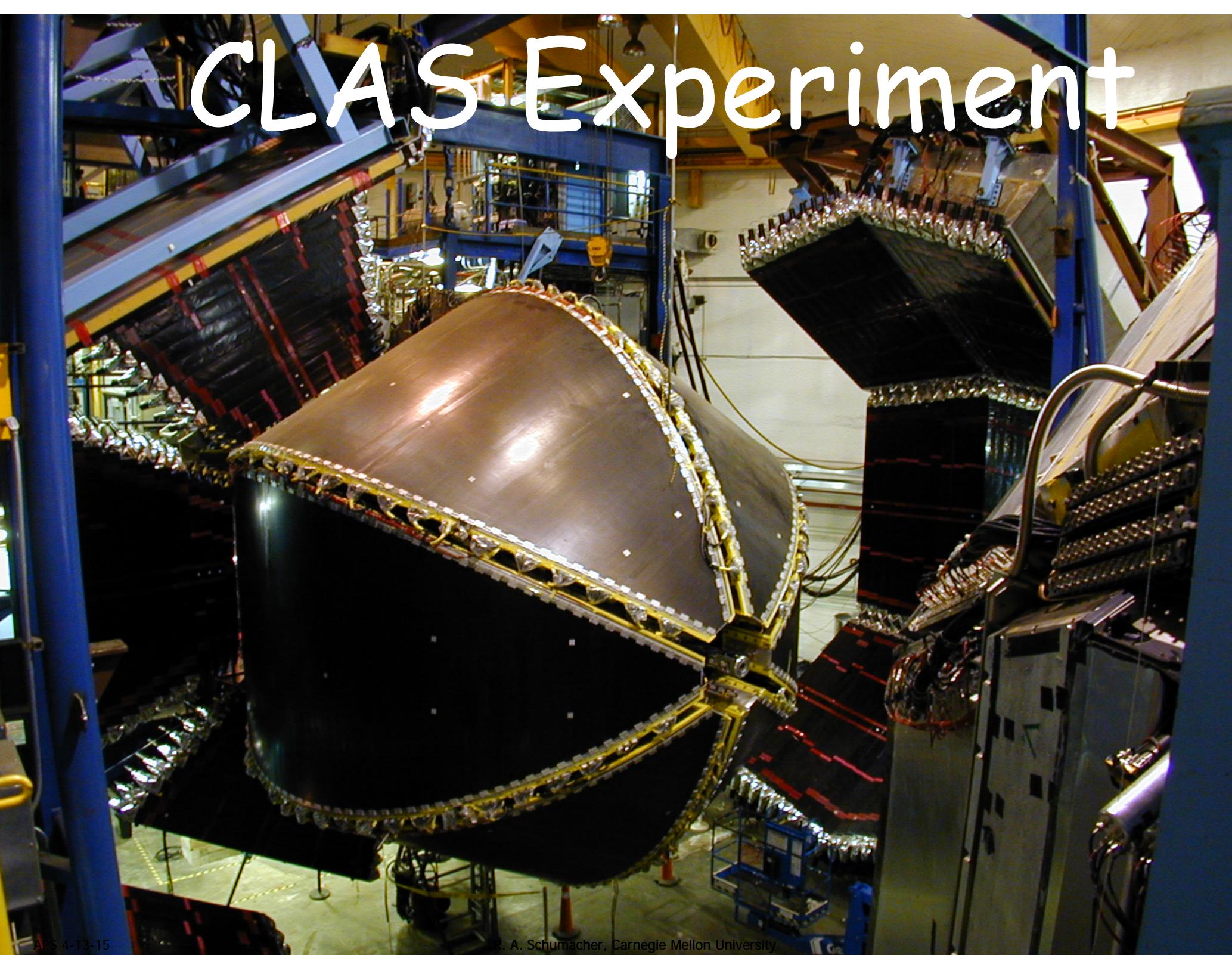
- $^3P_2$  wave in  $\pi d$  elastic scattering is most prominent
- SAID analysis: "resonance-like" behavior in several partial waves

# Photoproduction Scenario



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

# CLAS Experiment



# CLAS Experiment

## ■ Photoproduction:

- Targets: unpolarized  $LH_2$ , polarized p, & HD-ice
- Beams: unpolarized, circular, linear, to  $\sim 5$  GeV
- Reconstructed  $K^+p\pi^-(\pi^0)$  or  $K^+\pi^+\pi^-(n)$
- $20 \times 10^9$  triggers  $\rightarrow 1.41 \times 10^6$  KY $\pi$  events in g11a

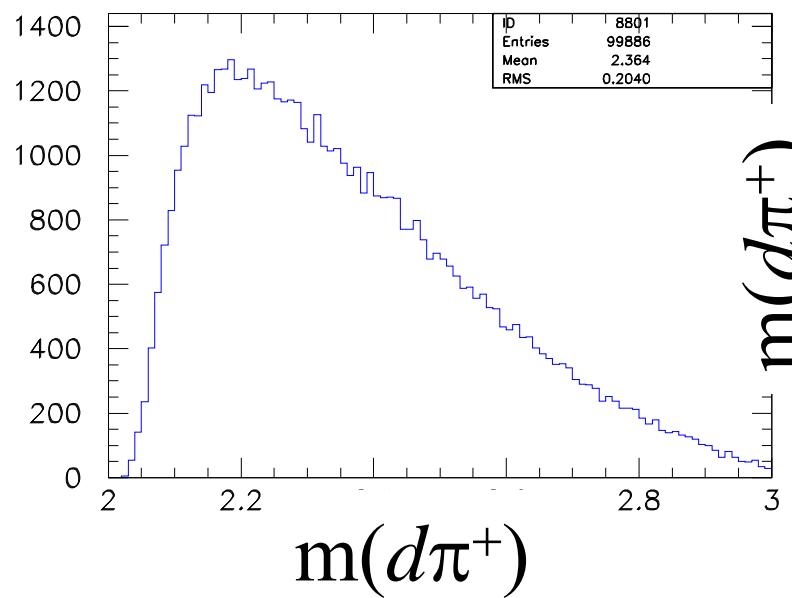
## ■ Electroproduction:

- $Q^2$  from  $\sim 0.5$  to  $\sim 3$   $(GeV/c)^2$
- Structure functions from Rosenbluth and beam-helicity separations

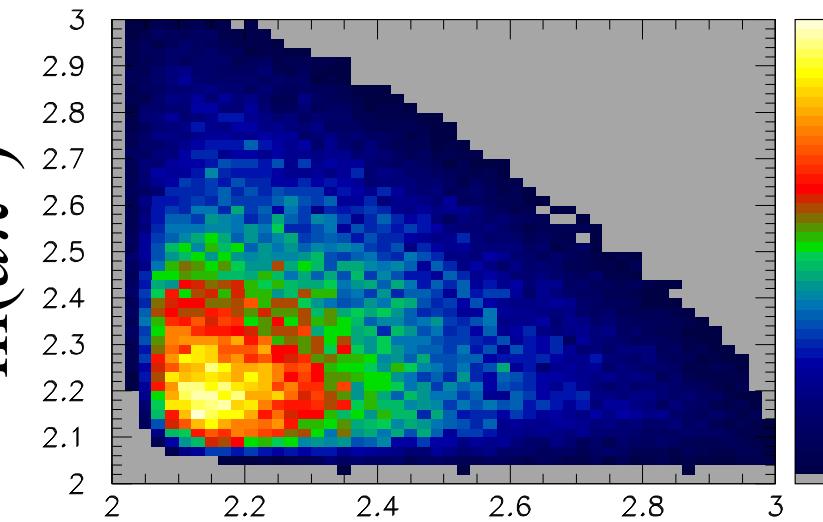
- Photons on a deuteron target
  - $g_{10}, g_{13}, g_{14}$  data sets
- Spin-1 photon & spin-1 deuteron:
  - $\vec{1} + \vec{1} \rightarrow \vec{J} = \vec{0}, \vec{1}, \vec{2}$  in S wave, is favorable
- Isospin  $I = \{0,1\} + 0 \rightarrow 0, 1$  allowed
- We looked for both N $\Delta$  and  $\Delta\Delta$  structures
- $\gamma d \rightarrow p p \pi^-$  - messy mix of partial waves
- $\gamma d \rightarrow d \pi^+ \pi^-$  - coherent exclusive production: clean!

- $\gamma d \rightarrow \{d \pi\} \pi$  - signal channel
- $\gamma d \rightarrow d \rho$  - main background
- $\gamma d \rightarrow d \pi \pi$  - phase space background
  
- Model the run conditions:
  - Bremsstrahlung photon beam
  - Reverse CLAS torus field
  - Assume  $t$ -channel dominance (slope 2 GeV<sup>2</sup>)

# Parametric Monte Carlo

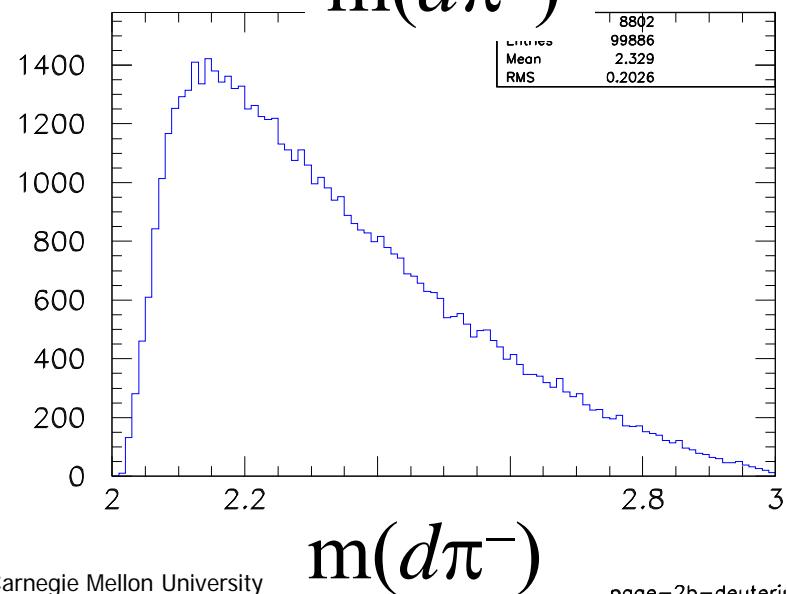


$m(d\pi^+)$



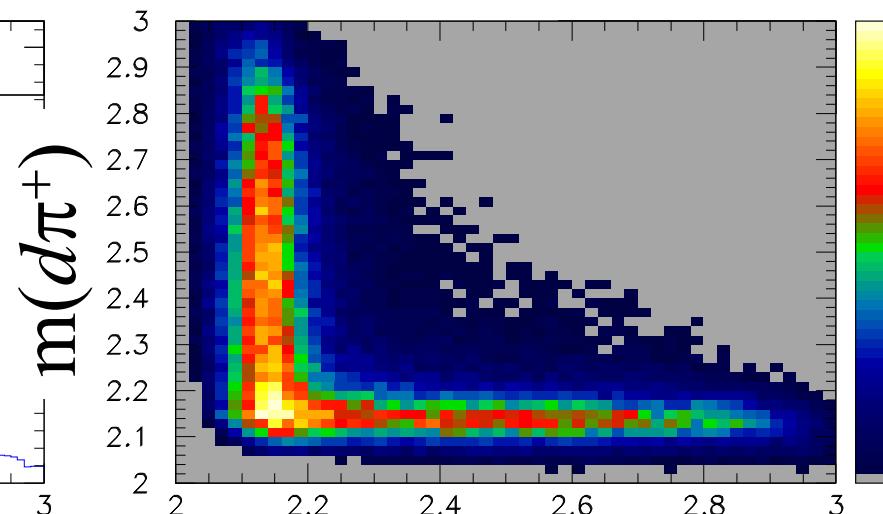
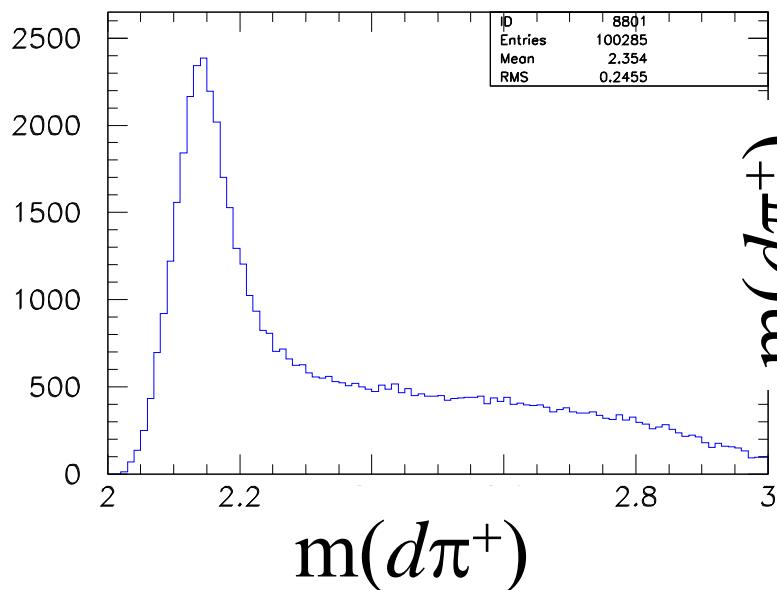
$m(d\pi^-)$

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

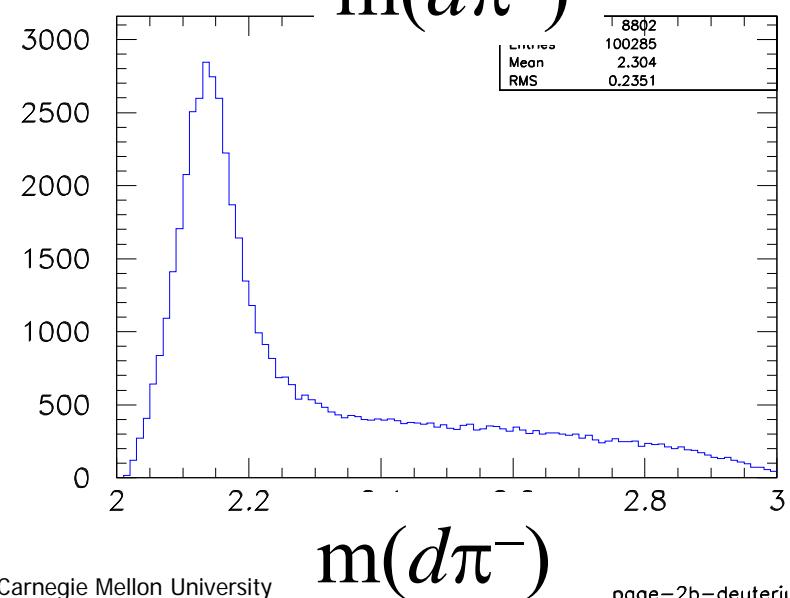


$m(d\pi^-)$

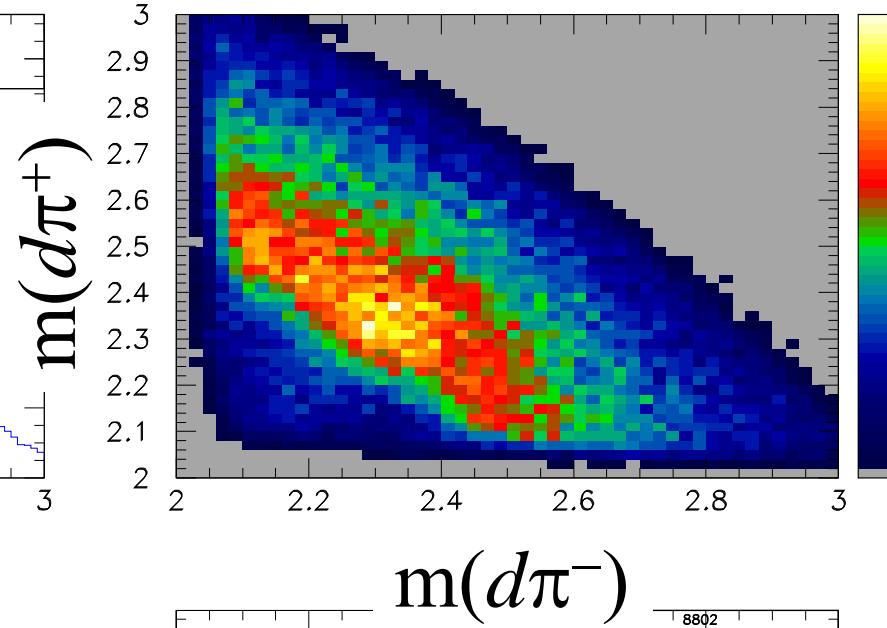
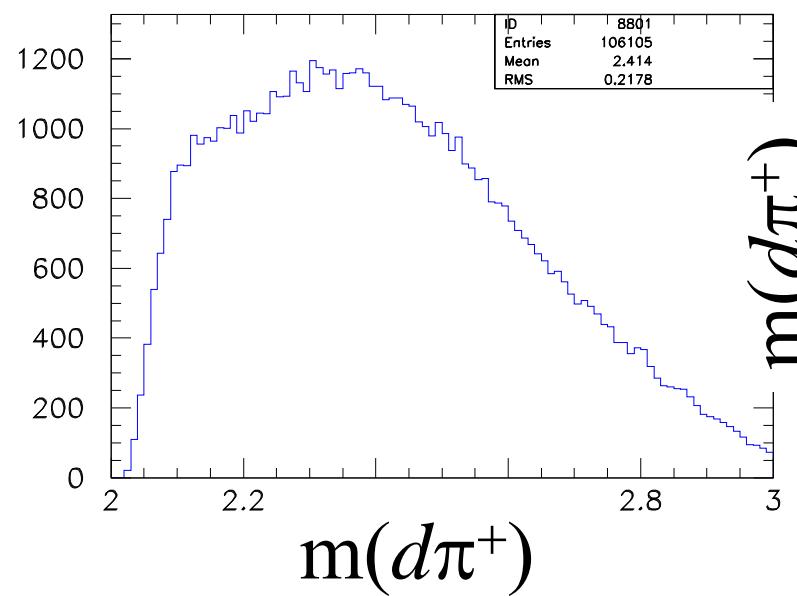
# Parametric Monte Carlo



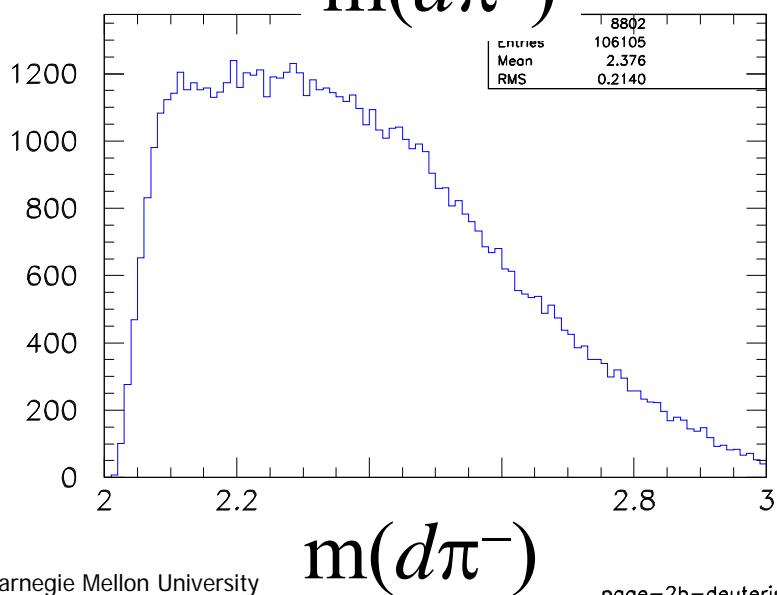
- $\gamma d \rightarrow \{d \pi^\pm\} \pi^\mp$   
signal events

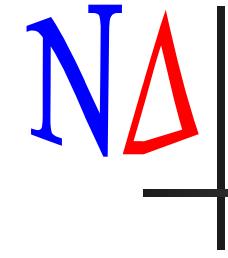


# Parametric Monte Carlo



- $\gamma d \rightarrow d \pi^+ \pi^-$   
 $\rho$  background



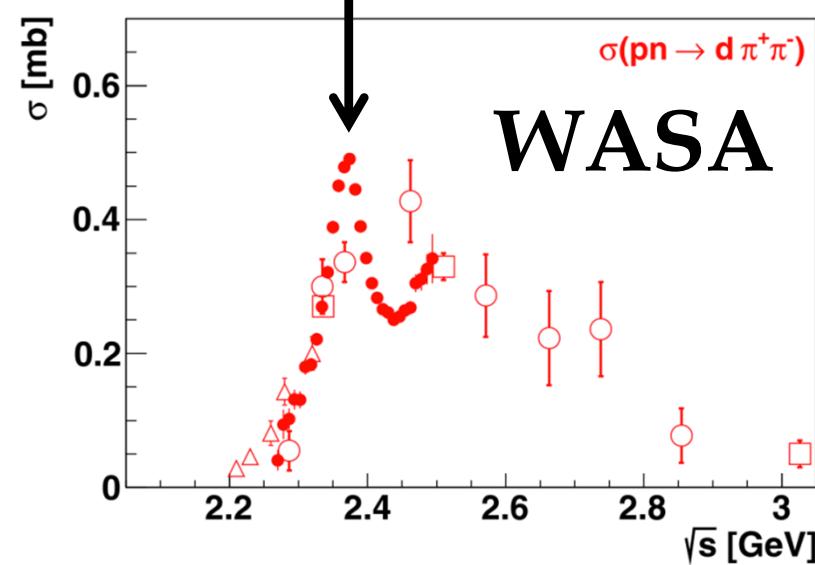
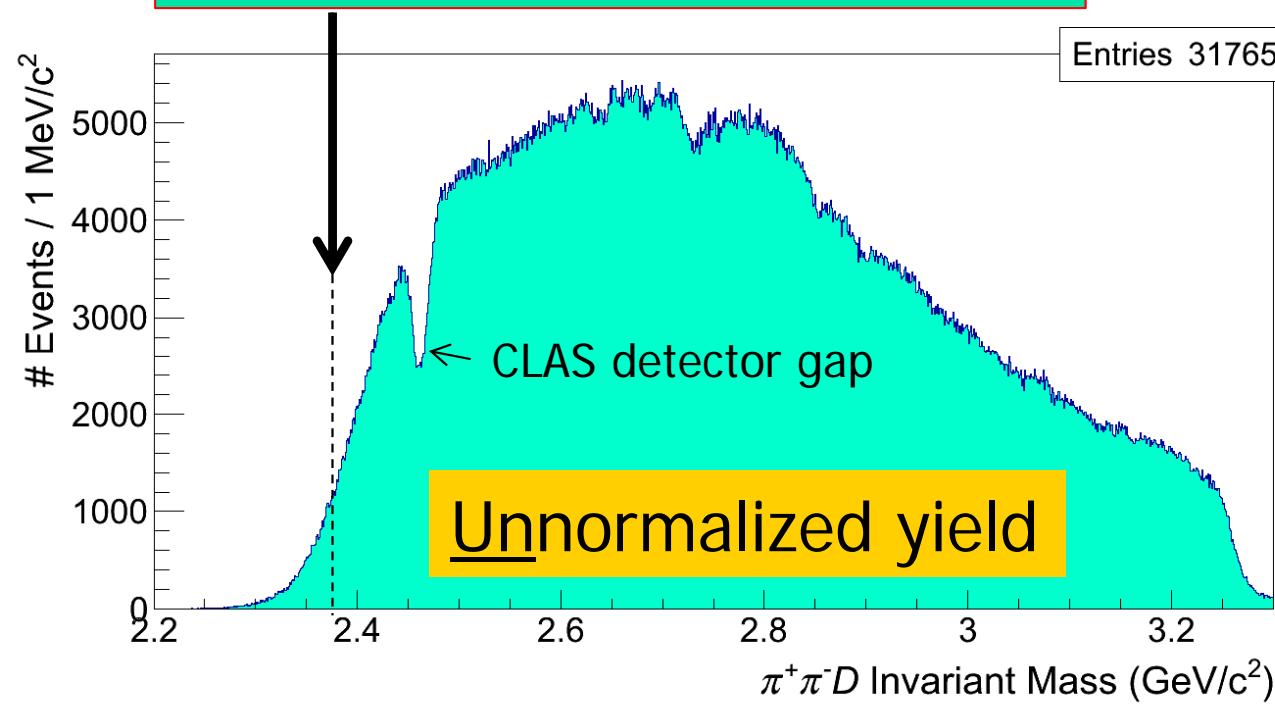


- Preliminary CLAS data  
showing
  - No sign of a “ $\Delta\Delta$ ” signal
  - Evidence for  $\rho$  background
  - Evidence for a “ $N\Delta$ ” signal

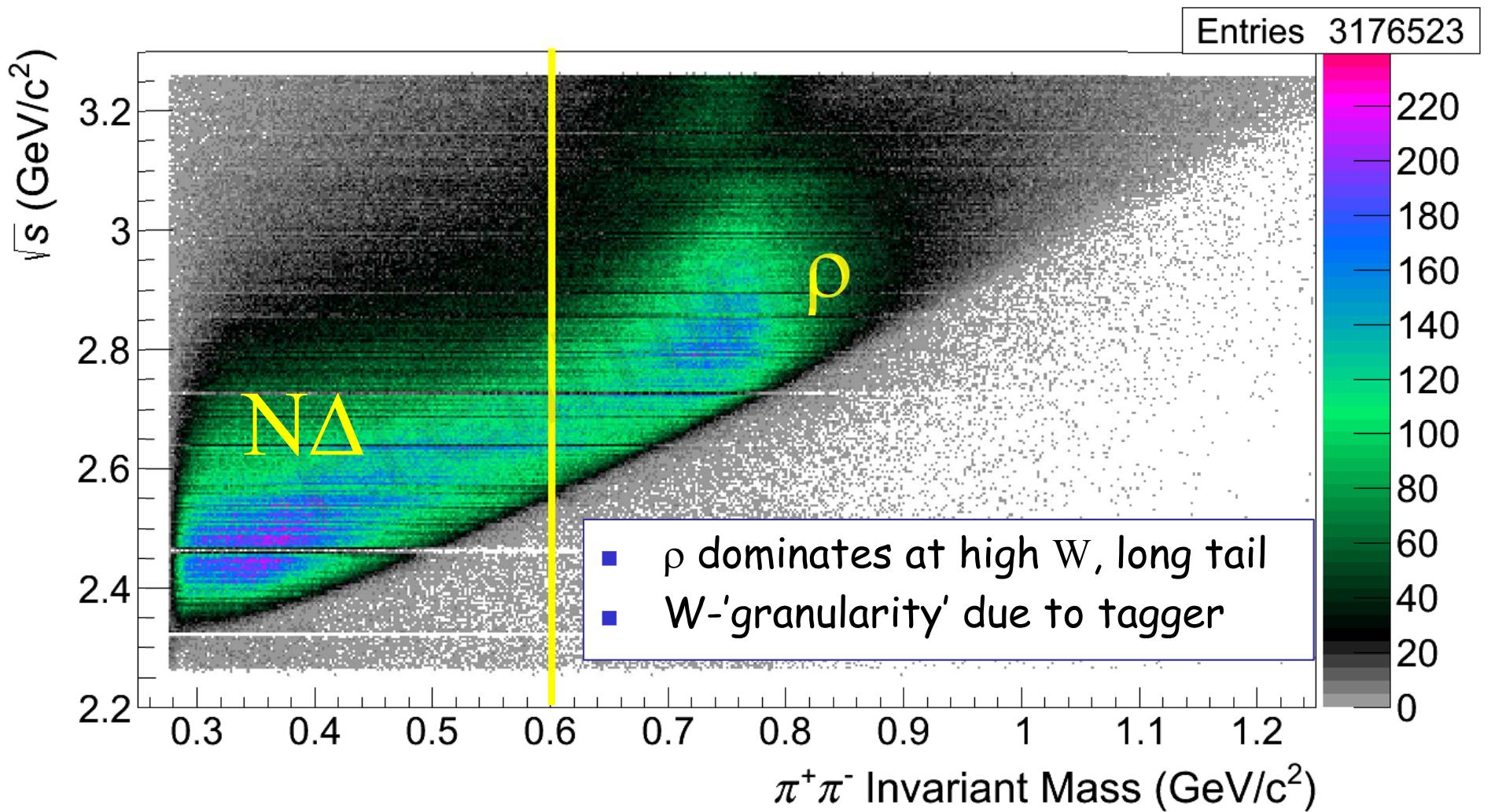
# $d\pi^+\pi^-$ Invariant Mass

- Gash at  $W = 2.46 \text{ GeV}/c^2$ : known gap in CLAS coverage
- No obvious  $\Delta\Delta$  visible in CALS/g13 (maybe PWA, or not formed in  $\gamma d$ )
- Recall WASA@COSY claims  $\Delta\Delta$  at  $W = 2.37 \text{ GeV}/c^2$  in  $pn \rightarrow d\pi^+\pi^-$

No hint of a “ $\Delta\Delta$ ” bump!

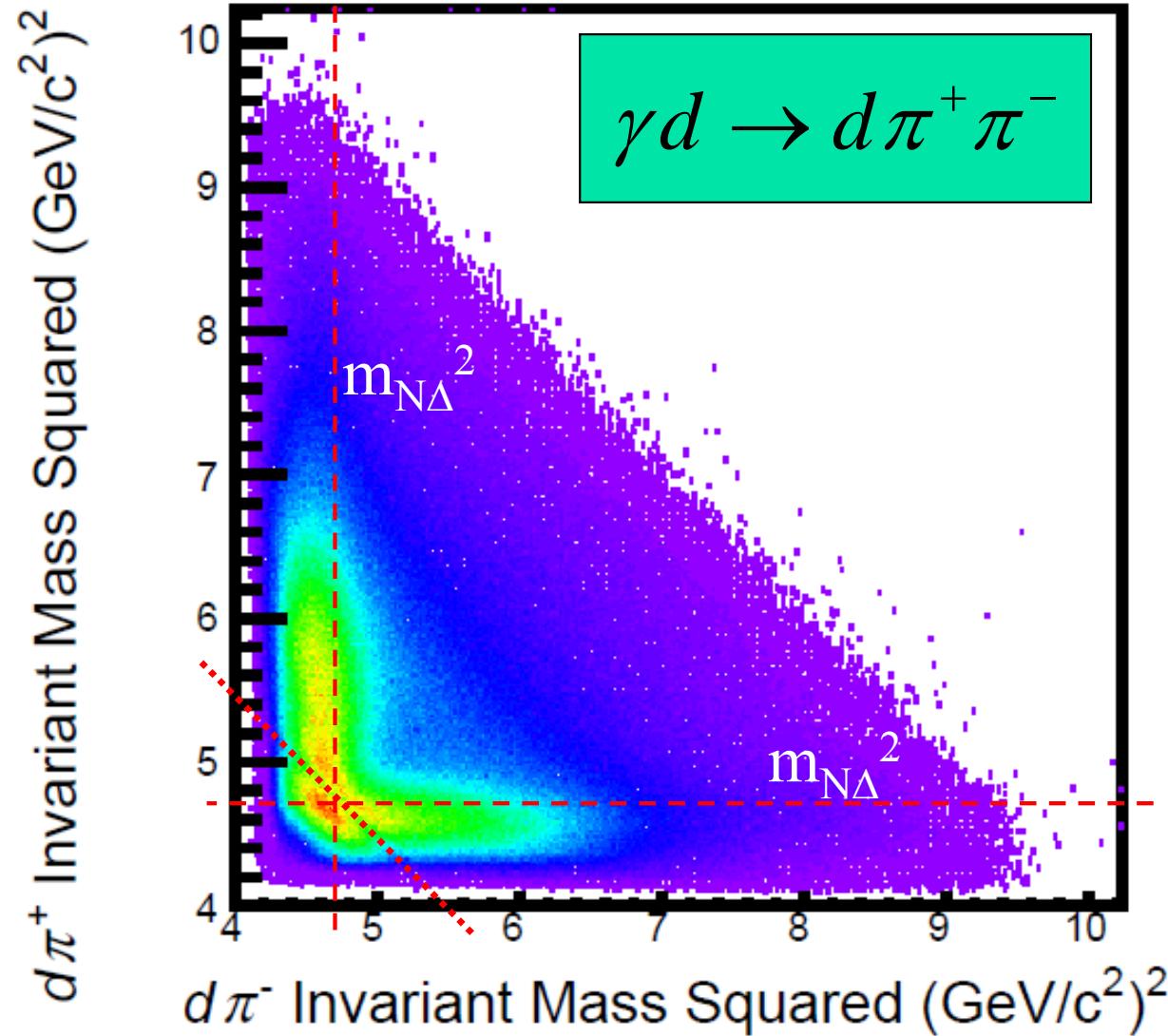


# $N\Delta$ | $\gamma d \rightarrow d \rho, \rho \rightarrow \pi^+ \pi^-$ background



N $\Delta$

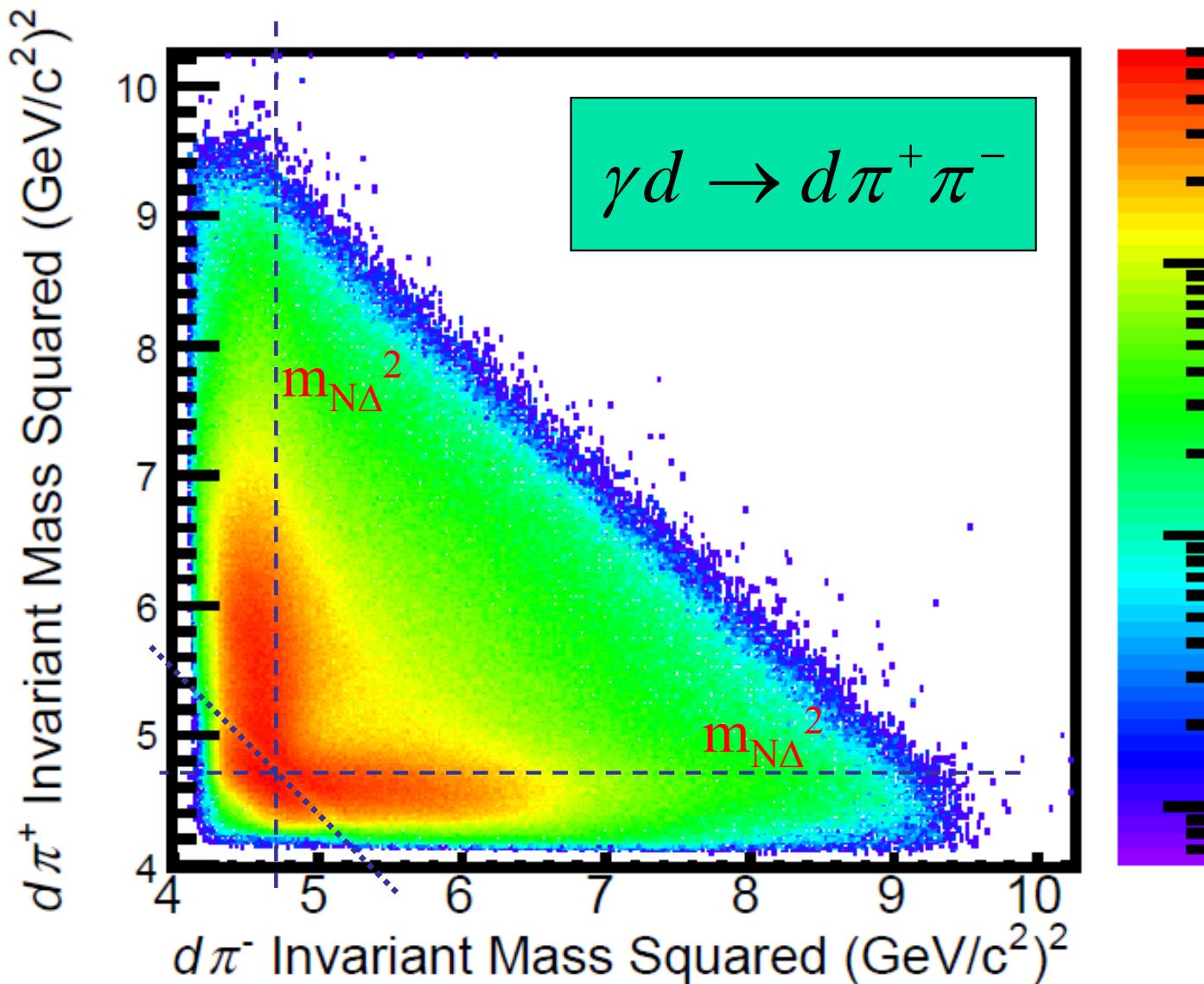
# Dalitz Plot: $d\pi^+$ vs. $d\pi^-$



- Acceptance-corrected CLAS (g13)
  - $-0.75 < \cos\theta_{\pi^\pm} < 0.94$
  - $2.45 < W < 3.15$  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 N $\Delta$  mass!**

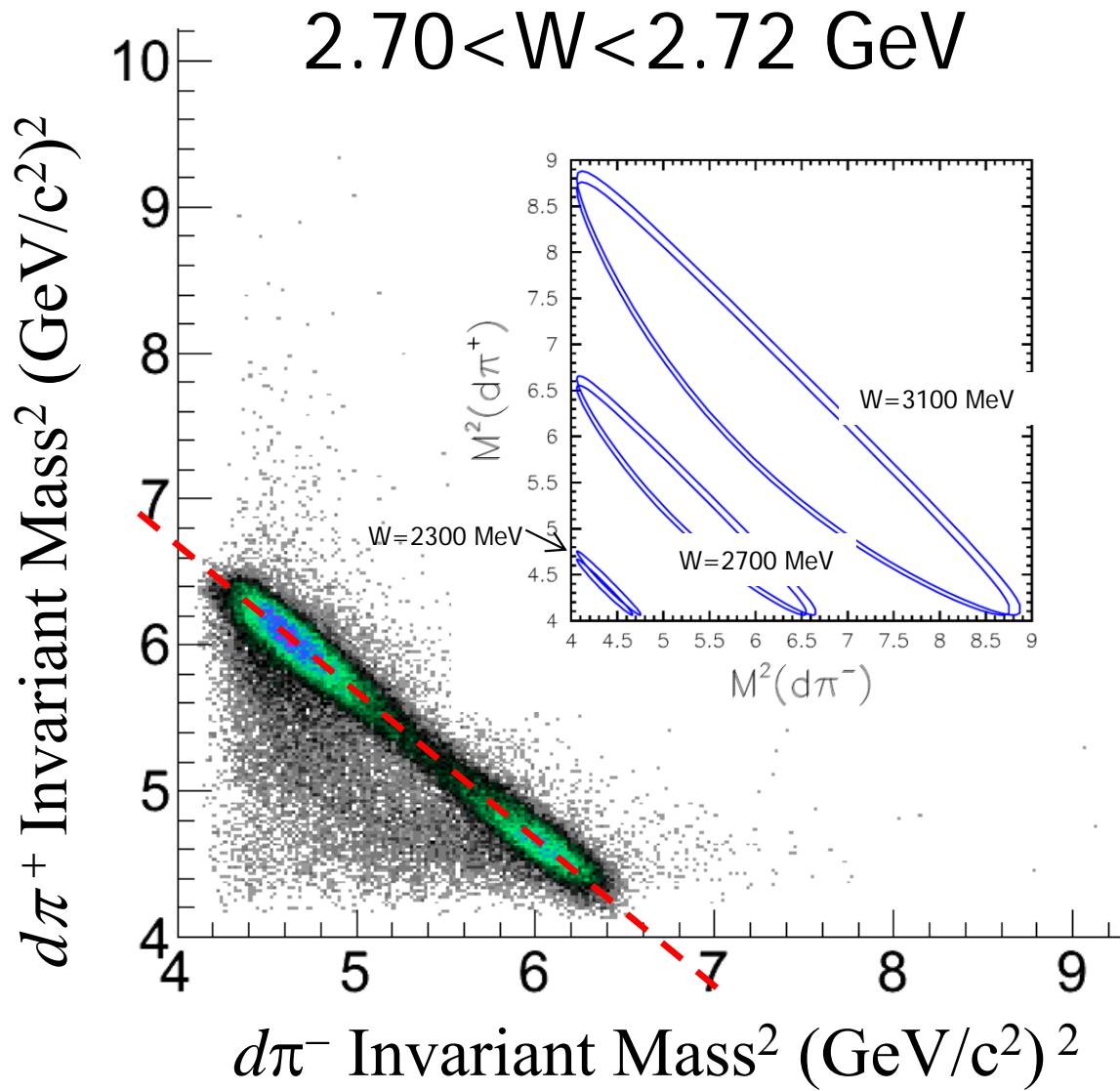
N $\Delta$

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



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- W~constant on diag.
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# N $\Delta$ Fit to Resonance-like Shapes



- Use 50 MeV slices in  $W = \sqrt{s}$
- Assume a Breit-Wigner line shape
- Let  $d\pi$  system decay to  $N\Delta$  ( $L=0$ ),  $d\pi$  ( $L=1$ ), and  $NN$  ( $L=2$ )
- $\rho$  not cut away; model as P.S. background
- Incoherent amplitudes
- Following fits are preliminary! Prelude to PWA analysis

# N $\Delta$ Fit to Resonance-like Shapes

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

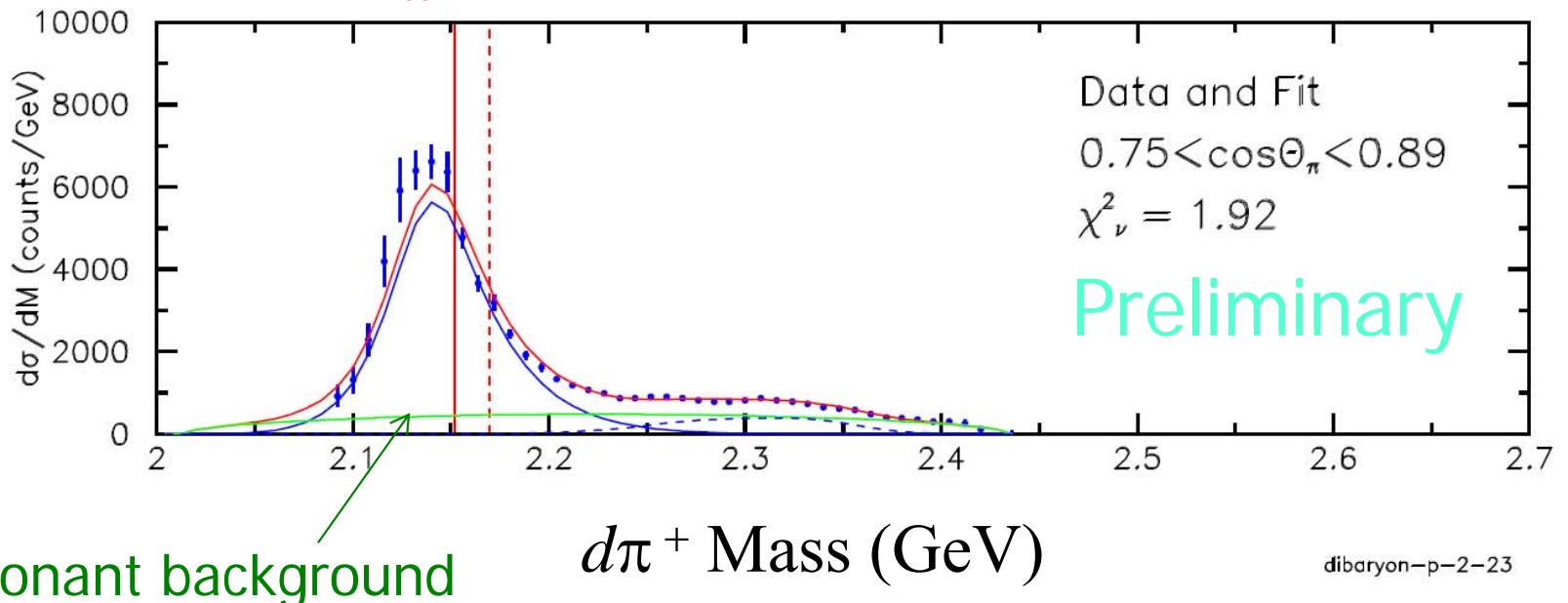
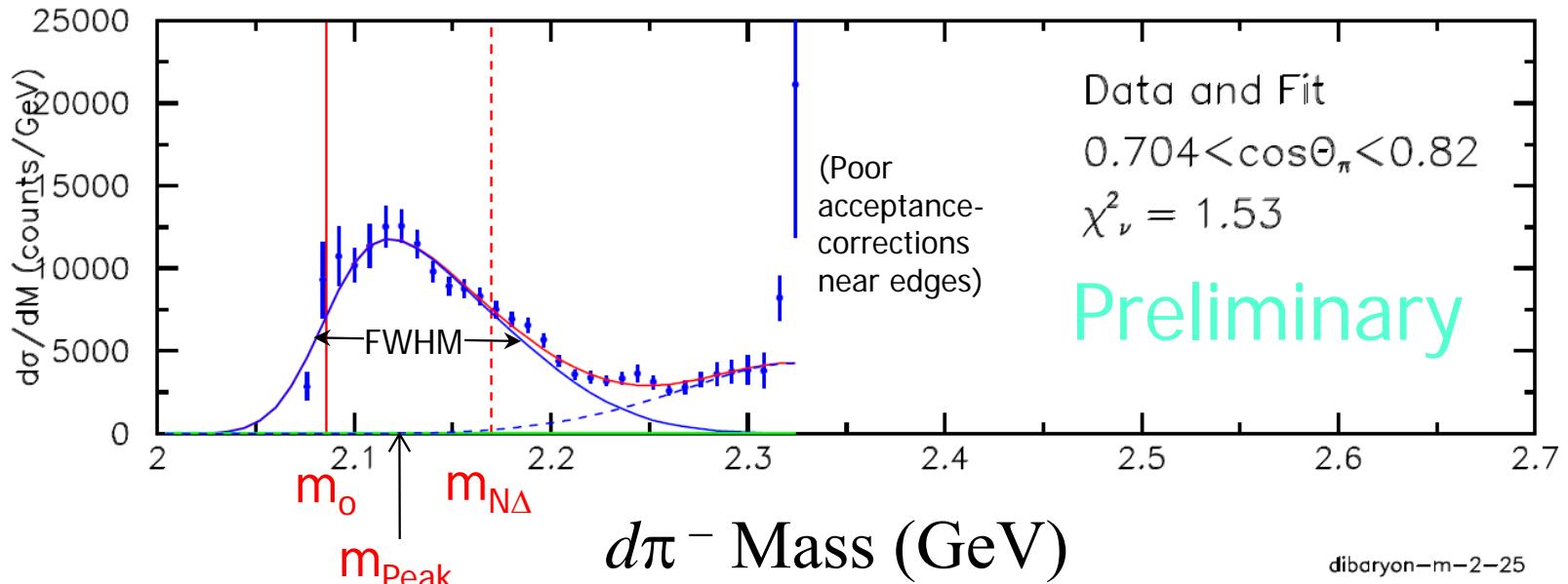
$$\Gamma_{pp}^{L=2} = \alpha_{pp} \Gamma_0 \left( \frac{q^{pp}}{q_0^{pp}} \right)^{2L+1=5} \left( \frac{m}{m_0} \right) (B'_{L=2}(q, q_0))^2$$

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

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

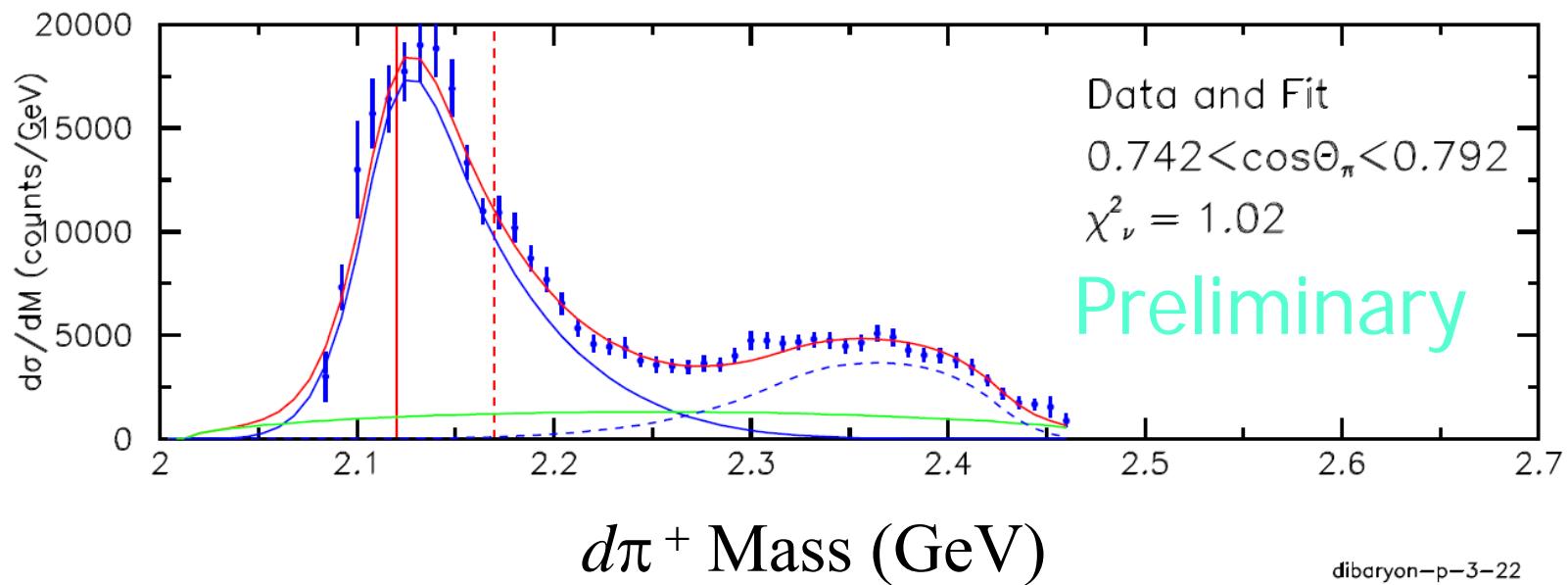
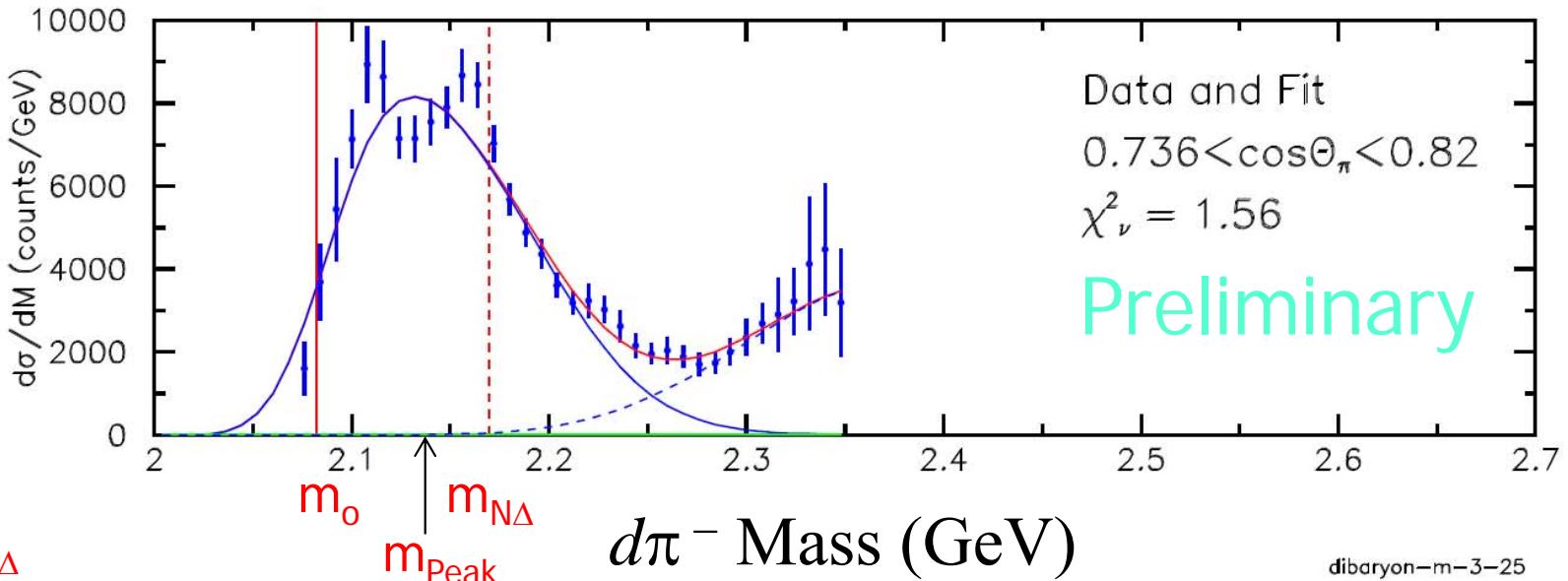
Let the fit “choose”  
the preferred shape  
from L=0,1,2

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

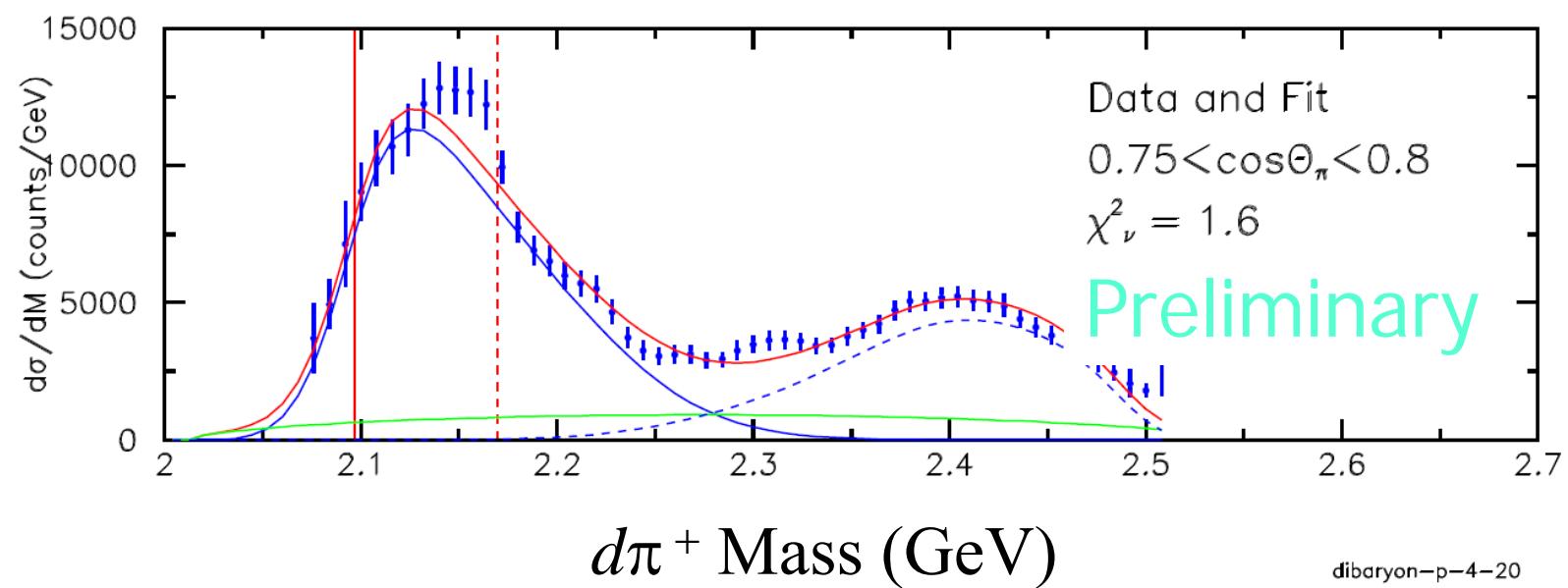
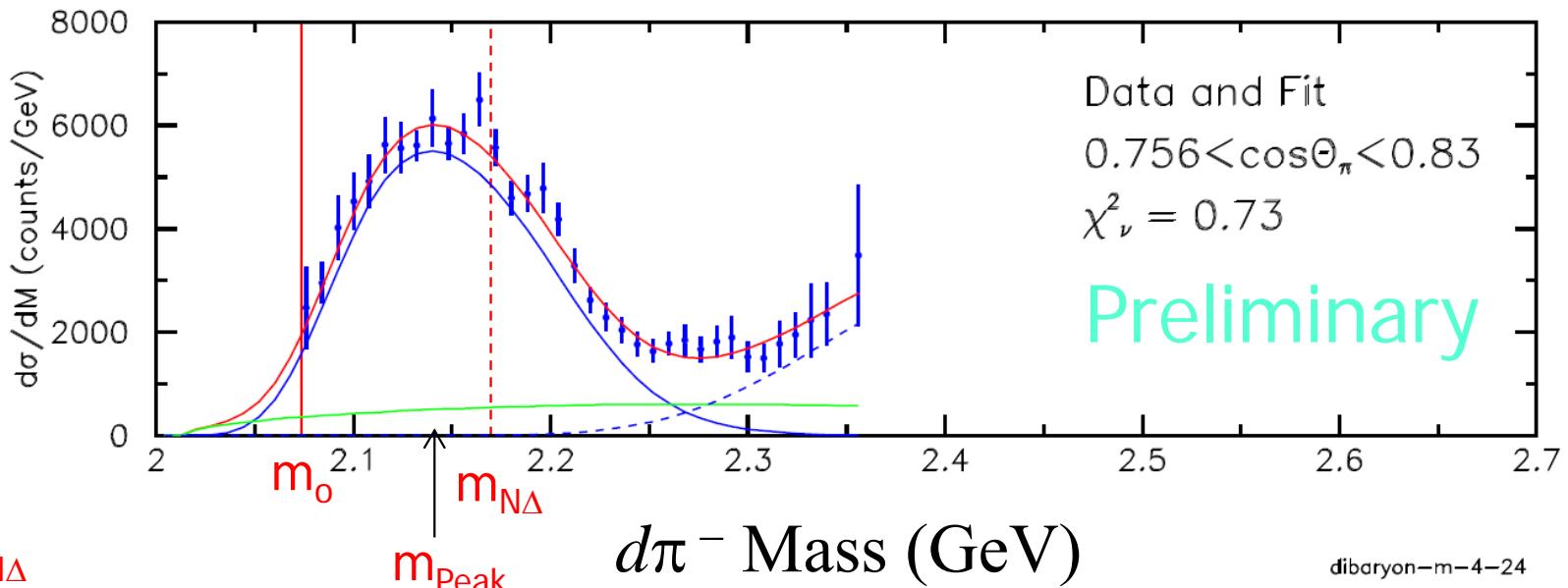


Non-resonant background

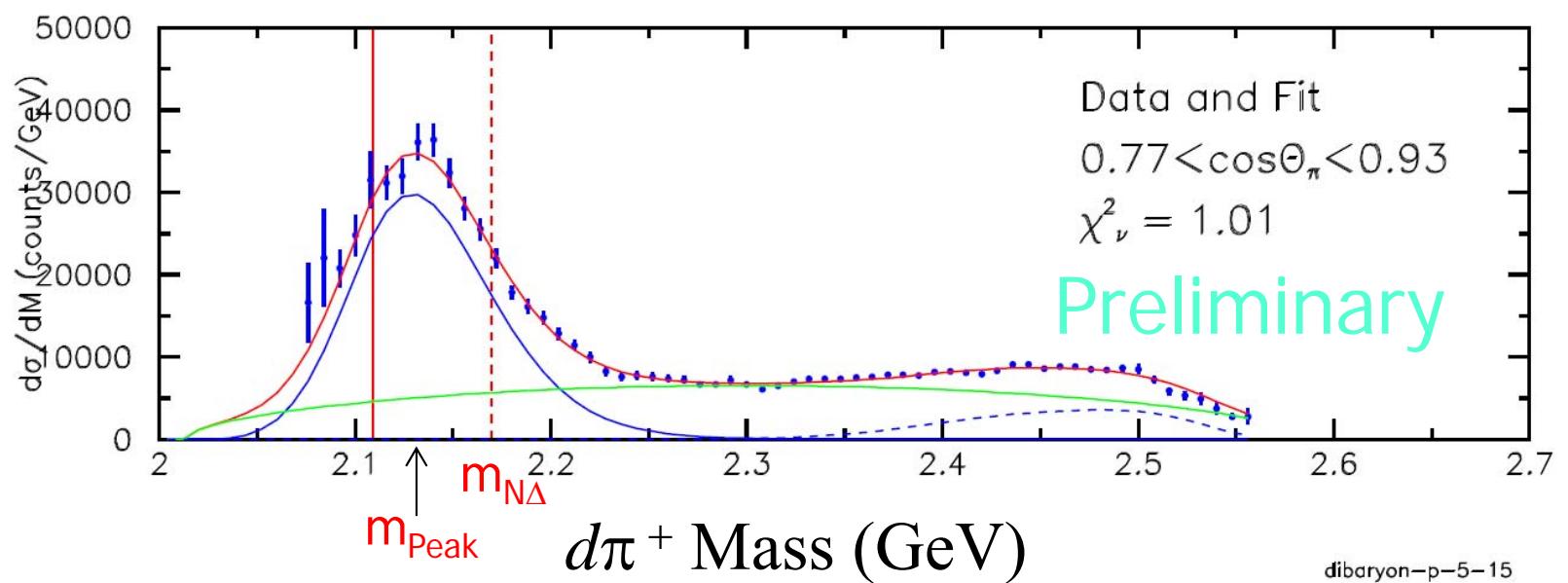
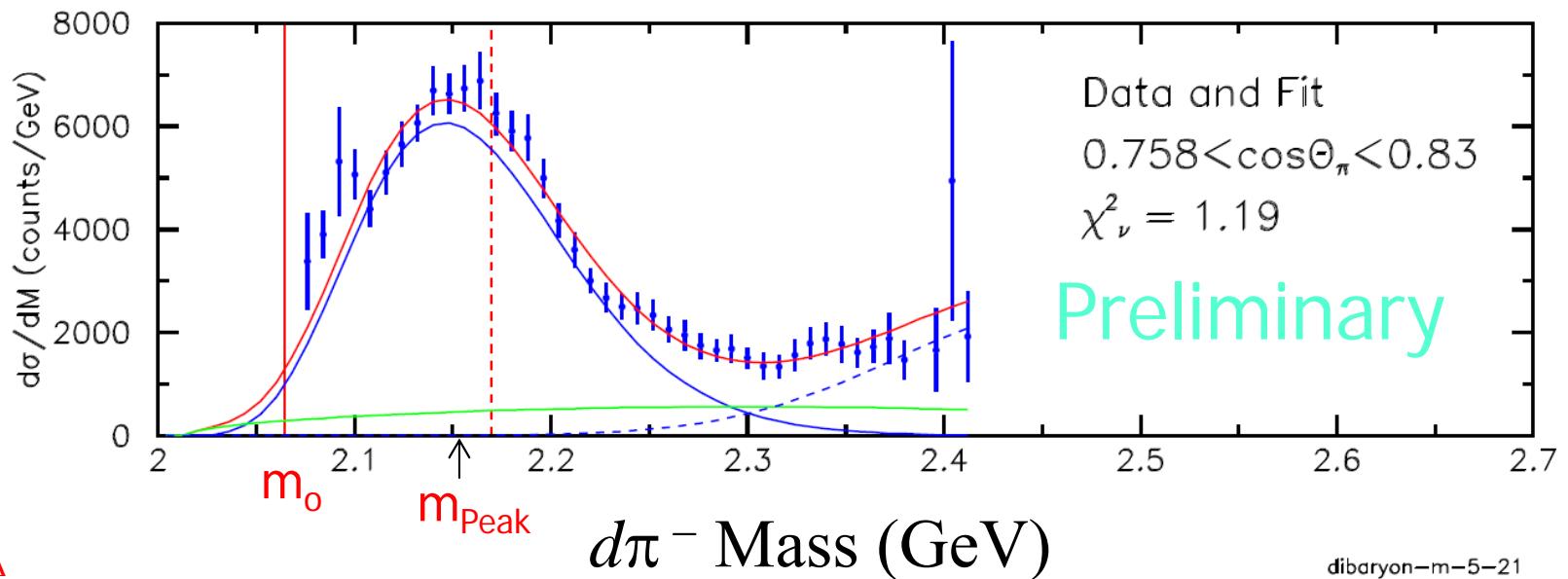
# N $\Delta$ | $\gamma d \rightarrow (d\pi) \pi$ $2.60 < W < 2.65$ GeV



# N $\Delta$ | $\gamma d \rightarrow (d\pi) \pi$ $2.65 < W < 2.70$ GeV



# N $\Delta$ | $\gamma d \rightarrow (d\pi) \pi$ $2.70 < W < 2.75$ GeV

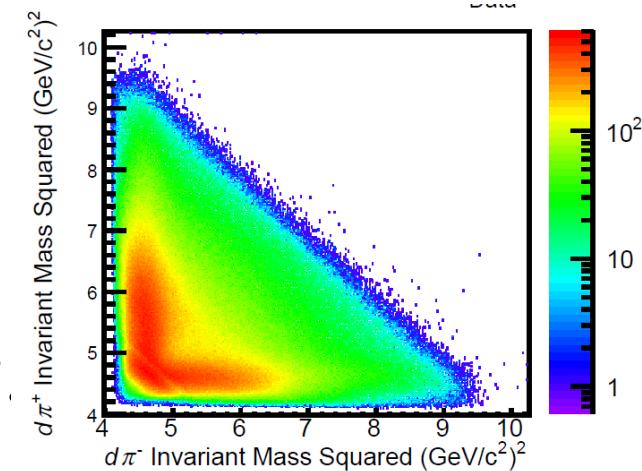


# N $\Delta$ Observations

- Peaks are all below the N $\Delta$  centroid
- Peaks widths are not identical:  $\cos \theta_\pi$  dependent; very preliminary result:
  - $m_{\text{peak}} = 2115 \pm 10 \text{ MeV}/c^2$
  - FWHM =  $125 \pm 25 \text{ MeV}$
- 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

# Summary/Conclusion

- Big  $\pi^\pm d$  signal seen in CLAS photo-production data, peaking below the N $\Delta$  mass.
  - Dominant at forward pion angles
- Extracting mass and width depends on line-shape model,  $\rho$  treatment, amplitude interferences...
- We are NOT claiming that this  $d\pi$ -system bump is necessarily the expected resonant  $D_{12}$  state... but it could be
  - Final/initial state interactions, other dynamics...
  - Scattering matrix poles vs. peaks in spectra...

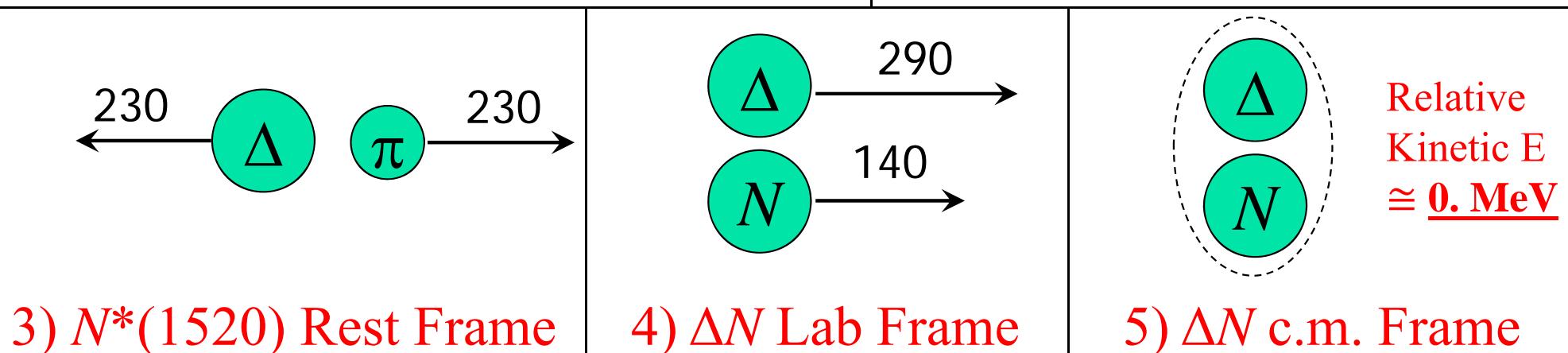
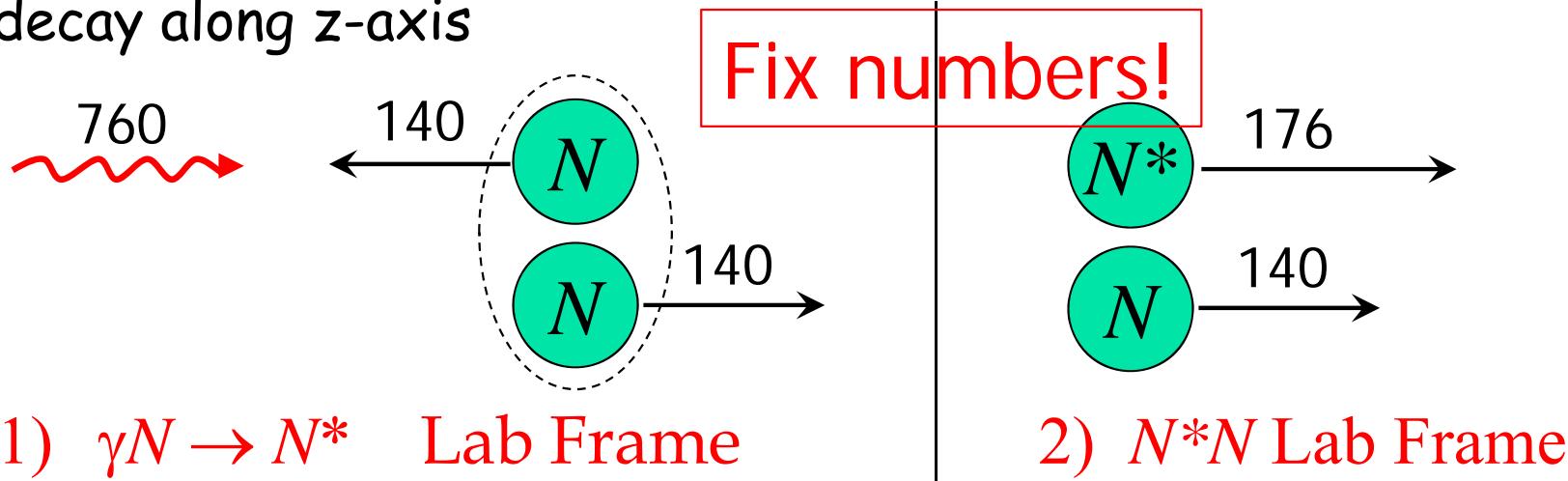


# NΔ Supplemental slides

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# 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



# NΔ 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

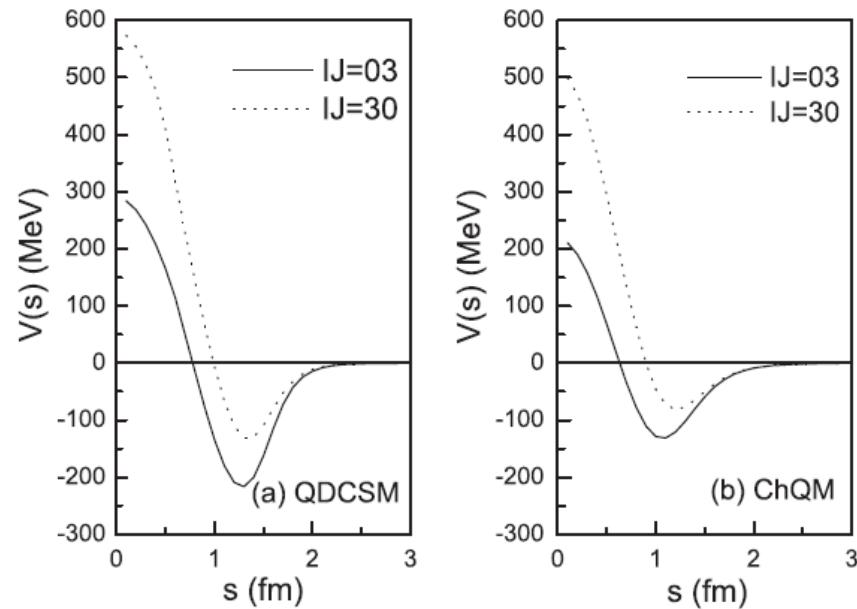


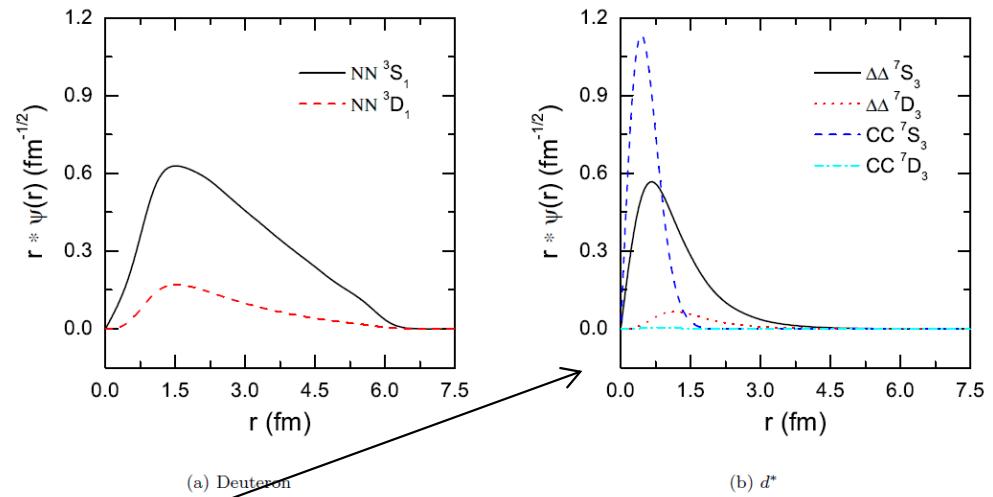
FIG. 1. The potentials of  $S$ -wave  $\Delta\Delta$  for  $I J^P = 03^+$  and  $I J^P = 30^+$  cases within two quark models.

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

# N $\Delta$ Theory Approaches for $\Delta\Delta$

- 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)



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

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

# NΔ Backup slides

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