

# Searching for $d^*$ Dibaryons with CLAS

Paul Mattione, Jefferson Lab

Working with:  
Reinhard Schumacher, Carnegie Mellon University

# Dibaryon Resonance Theory

- \* Spin-flavor SU(6)<sup>†</sup>:
  - \* <sup>†</sup>F. Dyson and N. Xuong, Phys. Rev. Lett. **13** 815 (1964).
  - \* Predict multiplets for  $N\Delta$ ,  $\Delta\Delta$  states
- \* Bag model<sup>†</sup>:
  - \* <sup>†</sup>P. J. Mulders, *et al.*, Phys. Rev. D **21**, 2653 (1980).
- \* QCD-like potential model<sup>†</sup>:
  - \* <sup>†</sup>K. Maltman, Nucl. Phys. A **438**, 669 (1985).
- \* Quark model<sup>†</sup>:
  - \* <sup>†</sup>M. Oka, Phys. Rev. D **38**, 298 (1988).
- \* 1-gluon exchange<sup>†</sup>:
  - \* <sup>†</sup>T. Barnes, *et al.*, Phys. Rev. C **48**, 539 (1993).

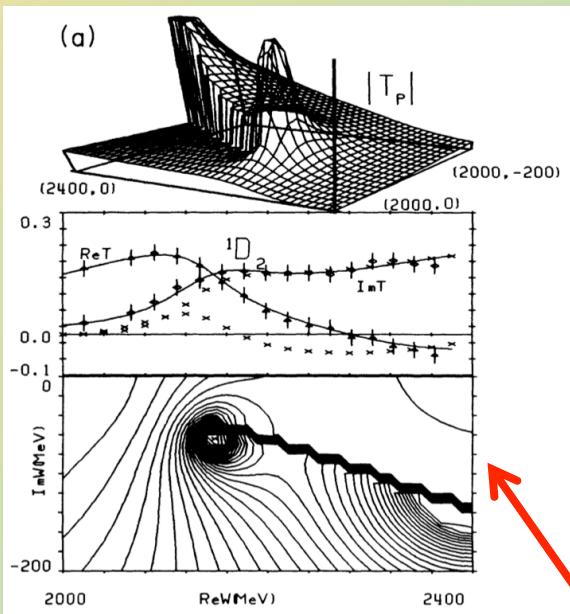
# Dibaryon Resonance Theory

- \* 3-body hadronic models & Faddeev equations<sup>†</sup>:
  - \* <sup>†</sup>A. Gal, H. Garcilazo, Nucl. Phys. A **928**, 73 (2014).
  - \*  $\pi NN, \pi N\Delta$  channels:  $N\Delta, \Delta\Delta$  bound below threshold
- \* QCD sum rule study of  $d^*(2380)$ <sup>†</sup>:
  - \* H.-X. Chen *et al.*, Phys. Rev. C **91**, 025204 (2015).
  - \* 6-quark interpolating currents,  $\Delta\Delta$ -like operators
- \* Intermediate dibaryons in  $\pi$  production in  $NN$ <sup>†</sup>:
  - \* <sup>†</sup>M.N. Platonova, V.I. Kukulin, Nucl. Phys. A **946**, 117 (2016).
  - \* Relativistic helicity amplitudes: ONE & intermediate  $N\Delta$
- \* Meson assisted dibaryons<sup>†</sup>:
  - \* <sup>†</sup>A. Gal, Acta Physica Polonica B **47**, 471 (2016).
  - \* Enhance binding of  $L = 0 BB'$  through strong  $\pi B, \pi B'$  attractions

# SAID Dibaryon Evidence

- \* pp & pn (R. A. Arndt, *et al.*, Phys. Rev. D **35**, 128 (1987)):
  - \* Resonance like-structures:  $^1D_2$ ,  $^3F_3$ ,  $^3P_2 - ^3F_2$ ,  $^3F_4 - ^3H_4$
- \*  $\pi^+d \rightarrow pp$  (R. A. Arndt, *et al.*, Phys. Rev. C **48**, 1926 (1993)):
  - \* Argand plot: Strong  $^1D_2P$ ,  $^3F_3D$ ,  $^1G_4F$  resonance-like structures
- \*  $\pi^+d \rightarrow \pi^+d$  (R. A. Arndt, *et al.*, Phys. Rev. C **50**, 1796 (1994)):
  - \* Argand plot: Strong  $^3P_2$ ,  $^3D_3$ ,  $^3F_4$  resonance-like structures

$\pi^+d \rightarrow \pi^+d$



Jefferson Lab

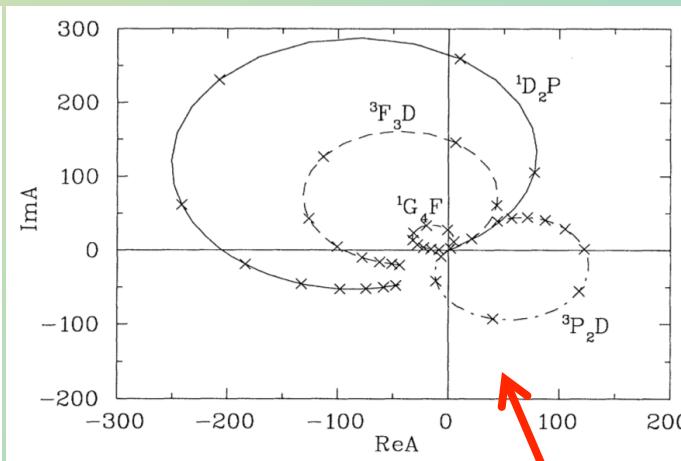


FIG. 7. Argand plot of dominant partial-wave amplitudes. The X points denote 50 MeV steps. All amplitudes have been multiplied by a factor of  $10^3$ .

pp & pn

Paul Mattione - Baryons 2016 - May 19, 2016

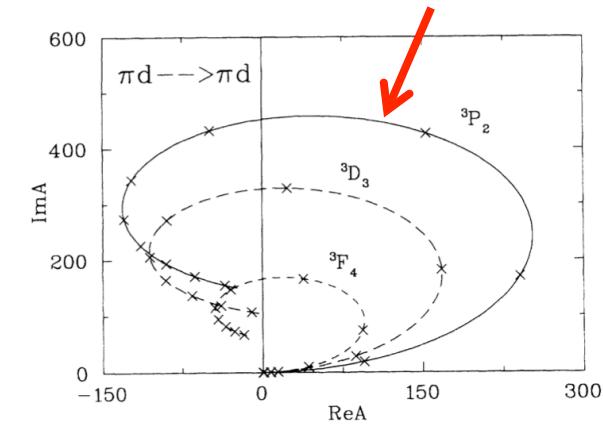


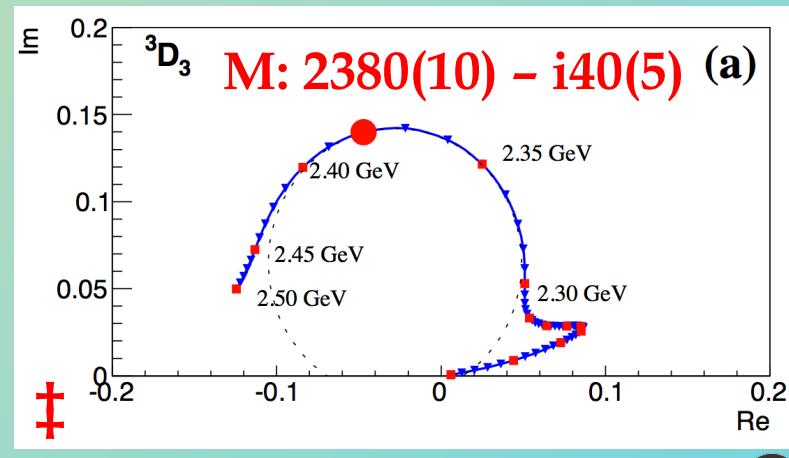
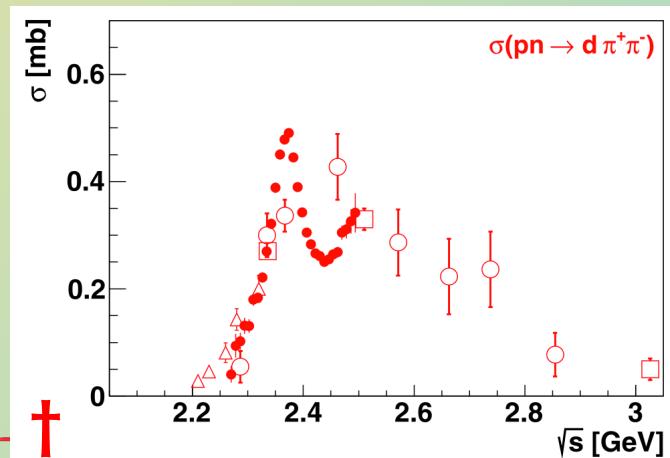
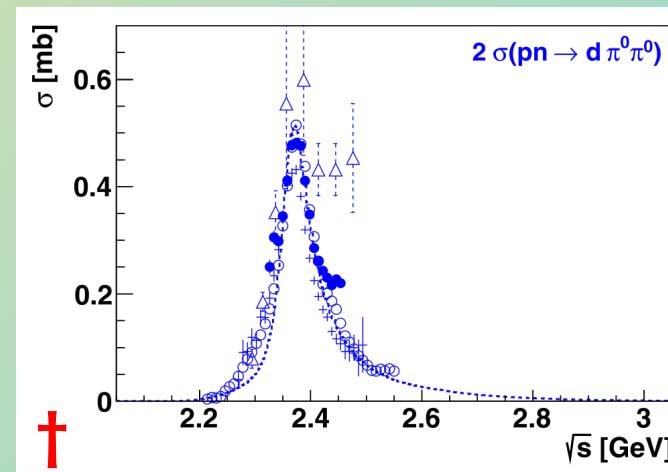
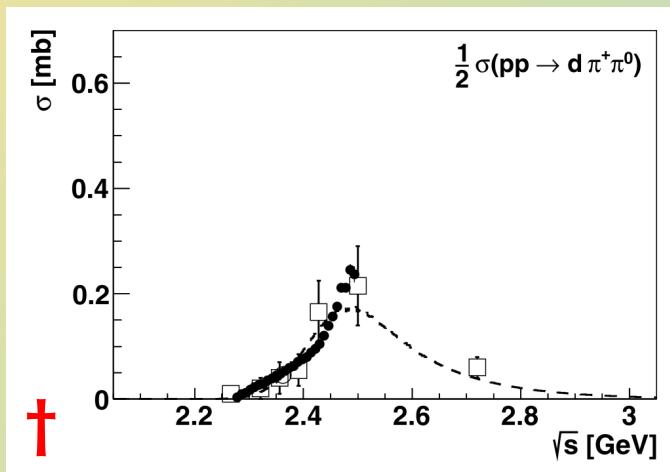
FIG. 7. Argand plot of the dominant  $\pi d \rightarrow \pi d$  partial-wave amplitudes  $^3P_2$ ,  $^3D_3$ , and  $^3F_4$  which correspond to the  $^1D_2$ ,  $^3F_3$ , and  $^1G_4$  pp states, respectively. (Compare Fig. 7 of Ref. [3]). The X points denote 50 MeV steps. All amplitudes have been multiplied by a factor of  $10^3$ .

$\pi^+d \rightarrow pp$

**clasp**  
CEBAF Large Acceptance Spectrometer

# WASA-at-COSY $d^*(2380)$

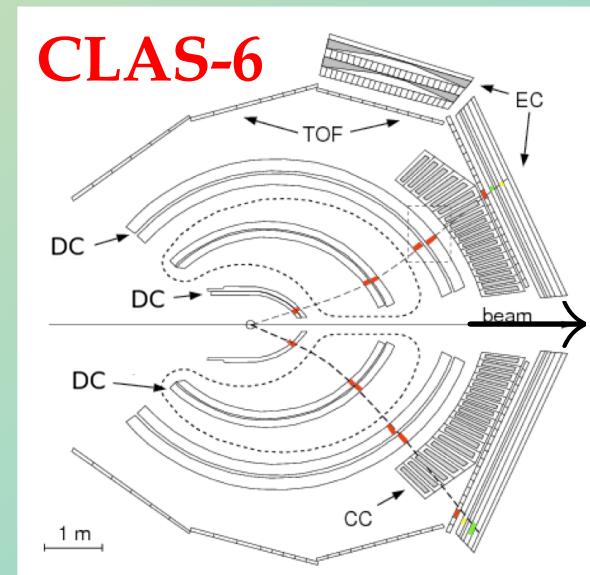
- \* Evidence for  $d^*(2380) \Delta \Delta$  state in  $pN \rightarrow d \pi \pi$ 
  - \* <sup>t</sup>P. Adlarson *et al.* (WASA-at-COSY), Phys. Rev. C 88, 055208 (2013)
  - \* <sup>‡</sup>P. Adlarson *et al.* (WASA-at-COSY & SAID), Phys. Rev. C 90, 035204 (2014).



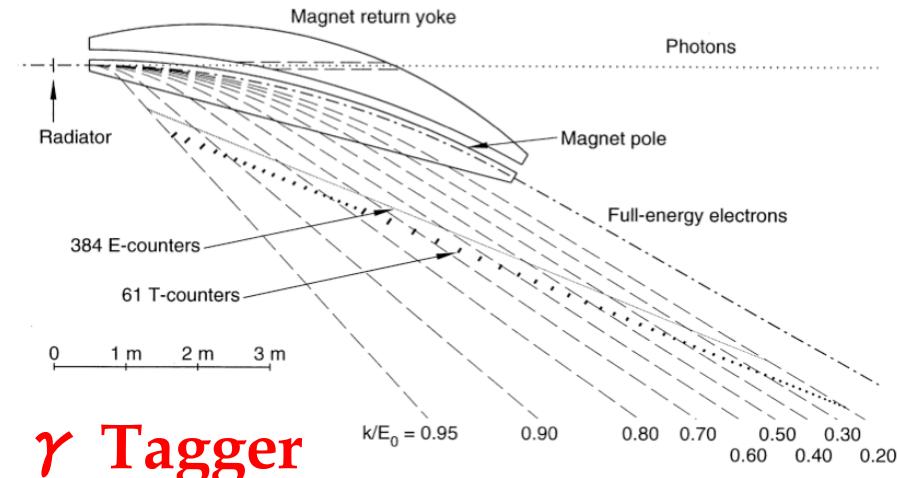
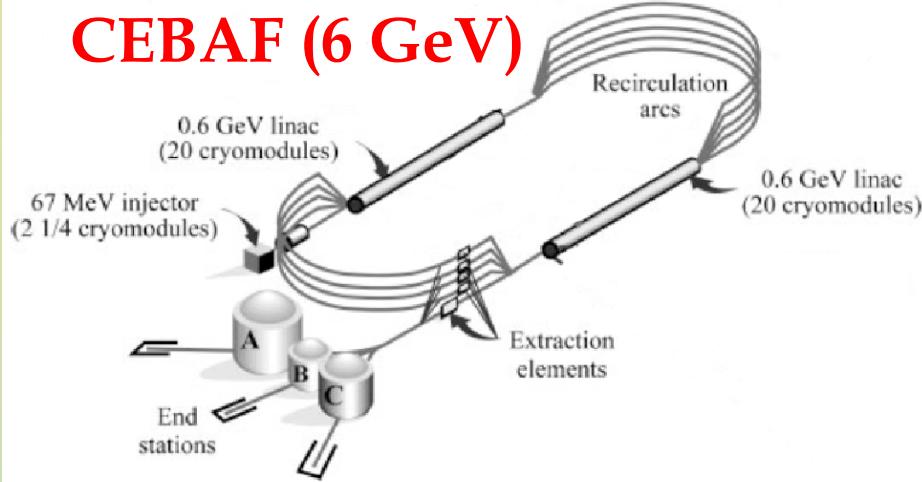
# CLAS g13 d\* Searches

# CLAS g13 Experiment

- \* JLab CEBAF accelerator:  $e^-$  beam, 6 GeV era
- \* g13 experiment: 2006 – 2007,  $LD_2$  target
  - \* Analysis:  $E_{e^-} = 2.655, 1.990$  GeV
  - \*  $\gamma$  beam: Radiator,  $\gamma$  tagger detects  $e^-$
- \* Hall-B CLAS-6 detector<sup>†</sup>: 6 sectors
  - \* DC: Tracking, ST & TOF: Timing



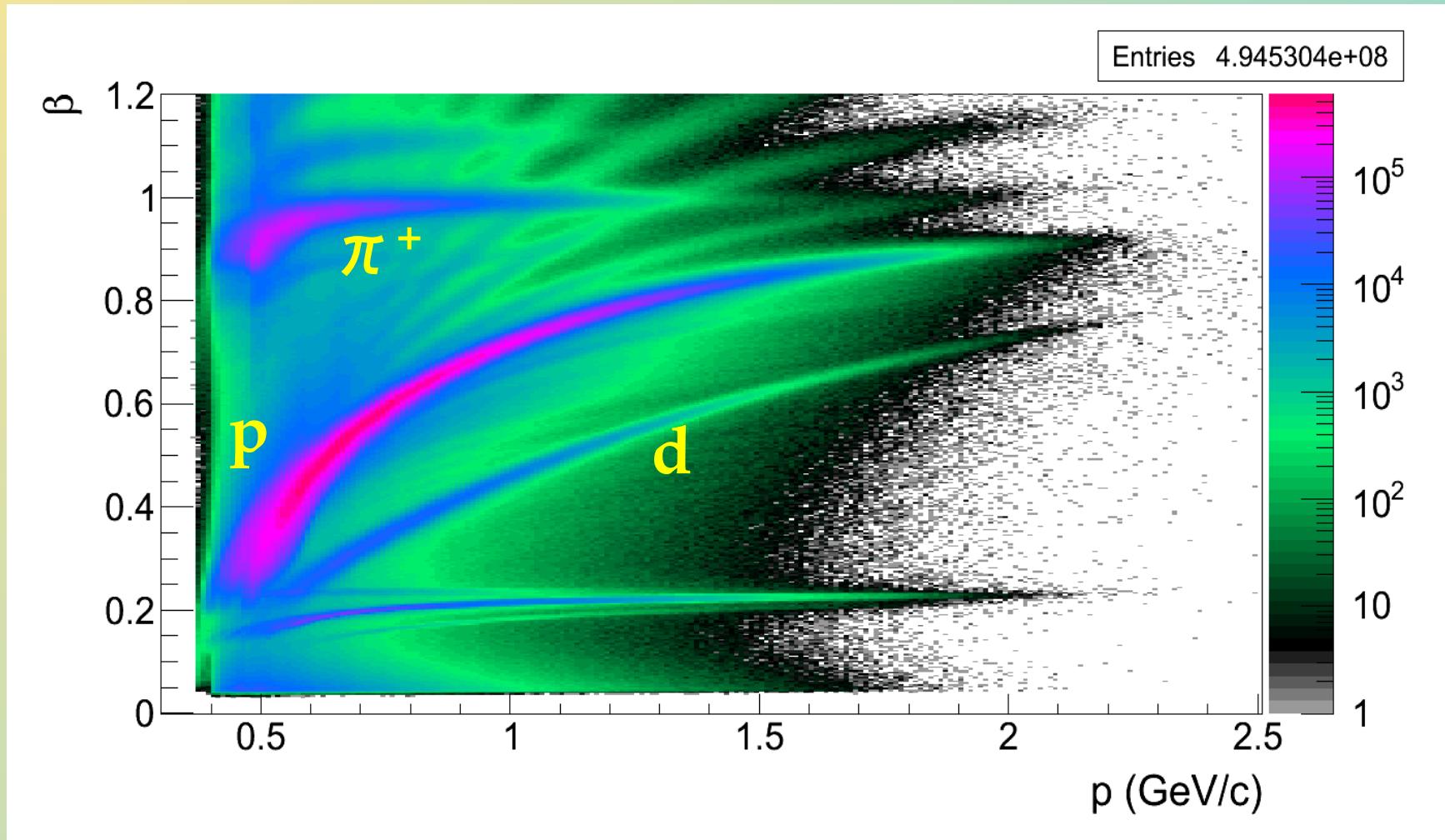
## CEBAF (6 GeV)



<sup>†</sup>B. A. Mecking *et al.* (CLAS), Nucl. Instr. and Meth. A **503**, 513 (2003)

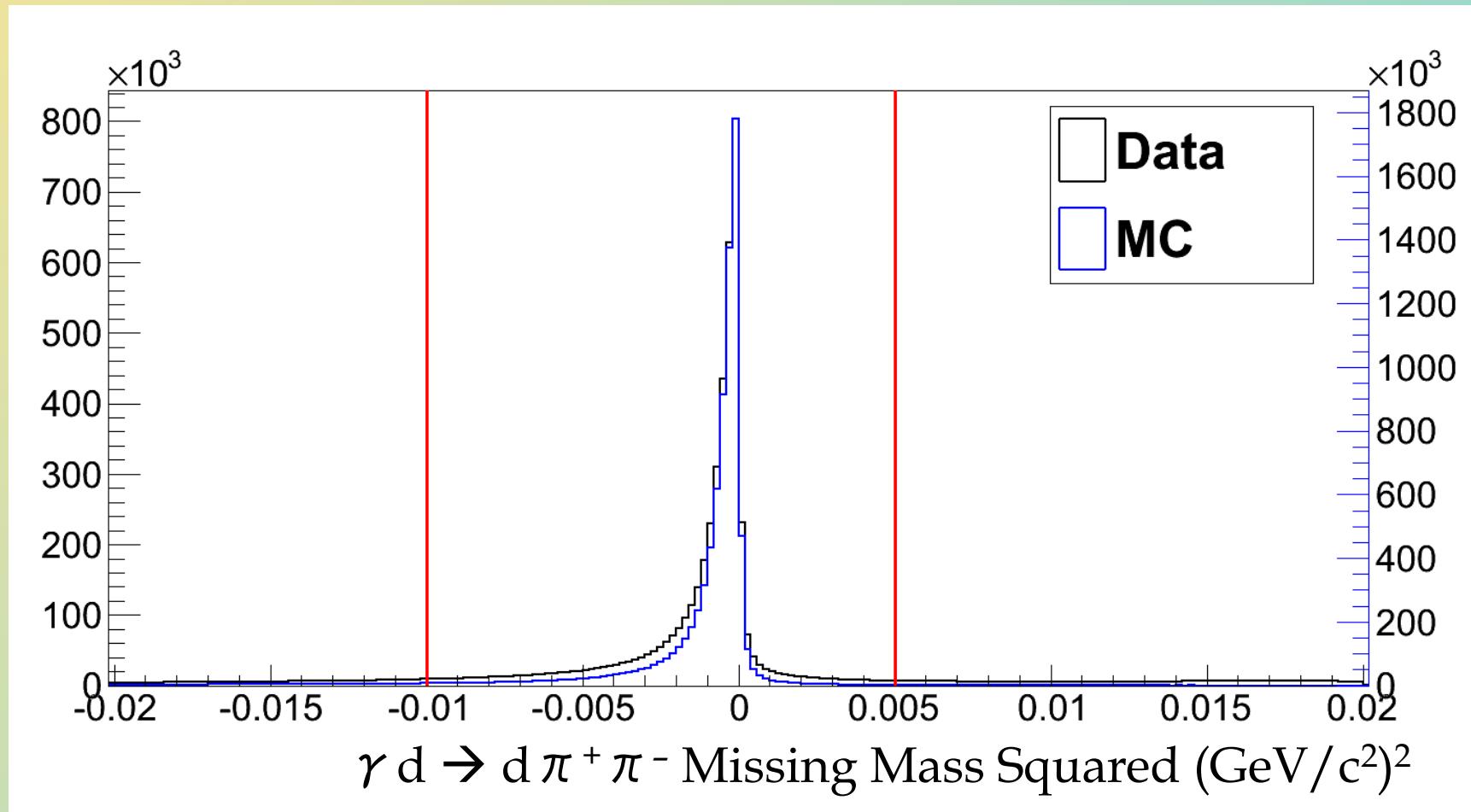
# Deuteron ID

- \* Can reconstruct deuterons with CLAS



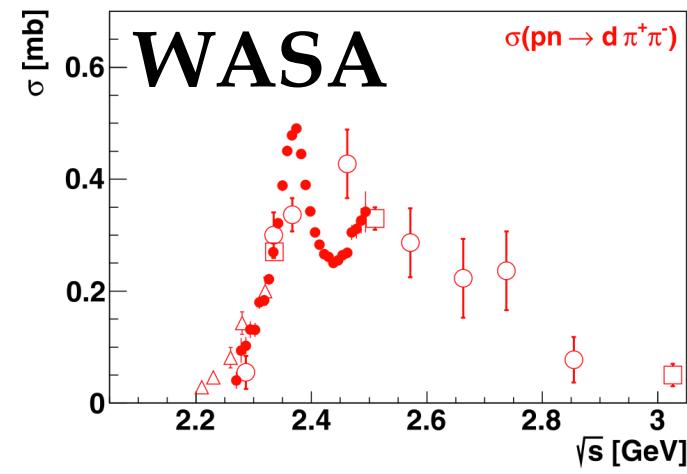
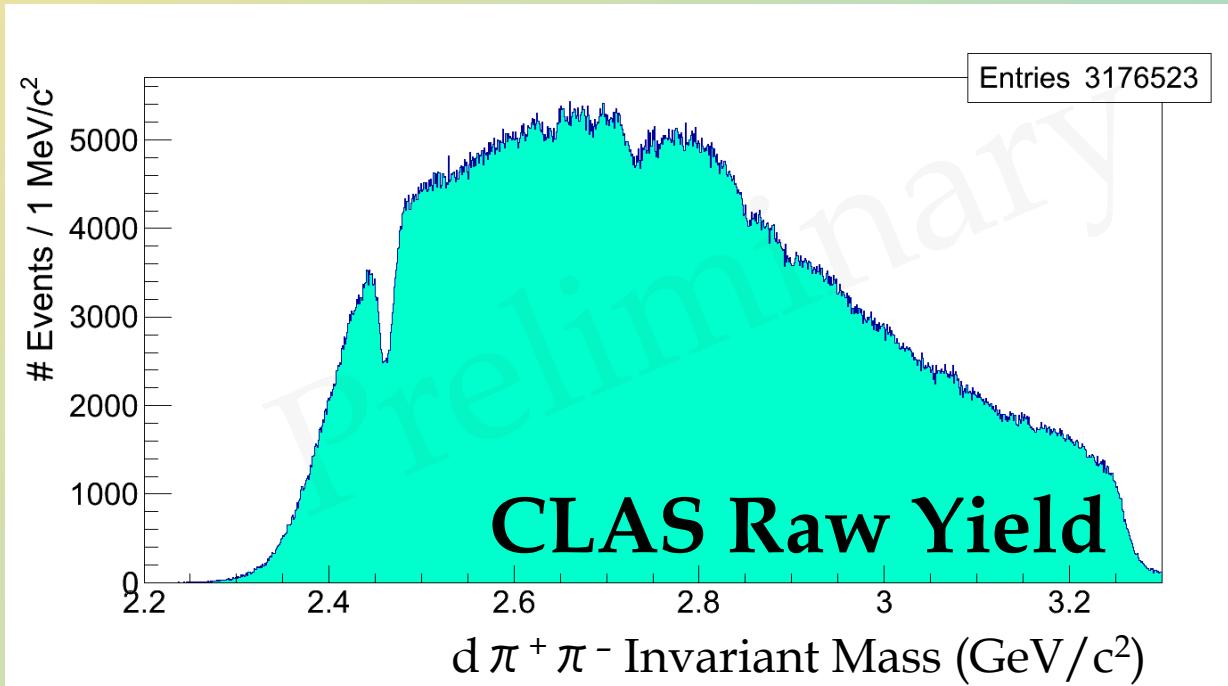
# Missing Mass Squared

- \* Virtually no background
  - \* Scale normalized by peak height



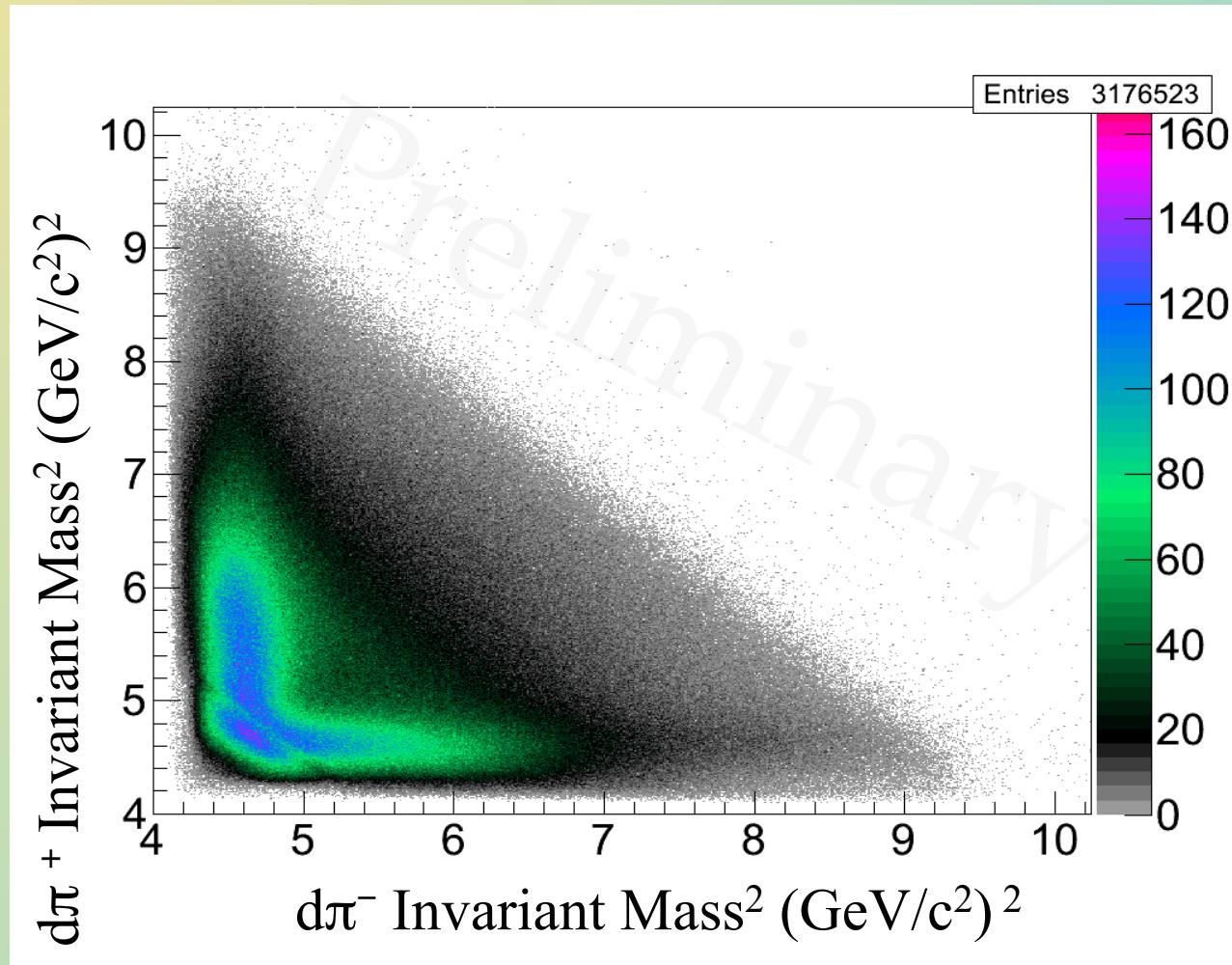
# $d \pi^+ \pi^-$ Invariant Mass

- \* Raw  $d \pi^+ \pi^-$  yields: Not acceptance-corrected
  - \* Gash at  $W = 2.46 \text{ GeV}/c^2$ : Bad tagger counter
- \* WASA-at-COSY:  $\Delta \Delta$  at  $W = 2.37 \text{ GeV}/c^2$  in  $pn \rightarrow d \pi^+ \pi^-$
- \* No obvious  $\Delta \Delta$  visible in g13: Maybe PWA, or not in  $\gamma d$



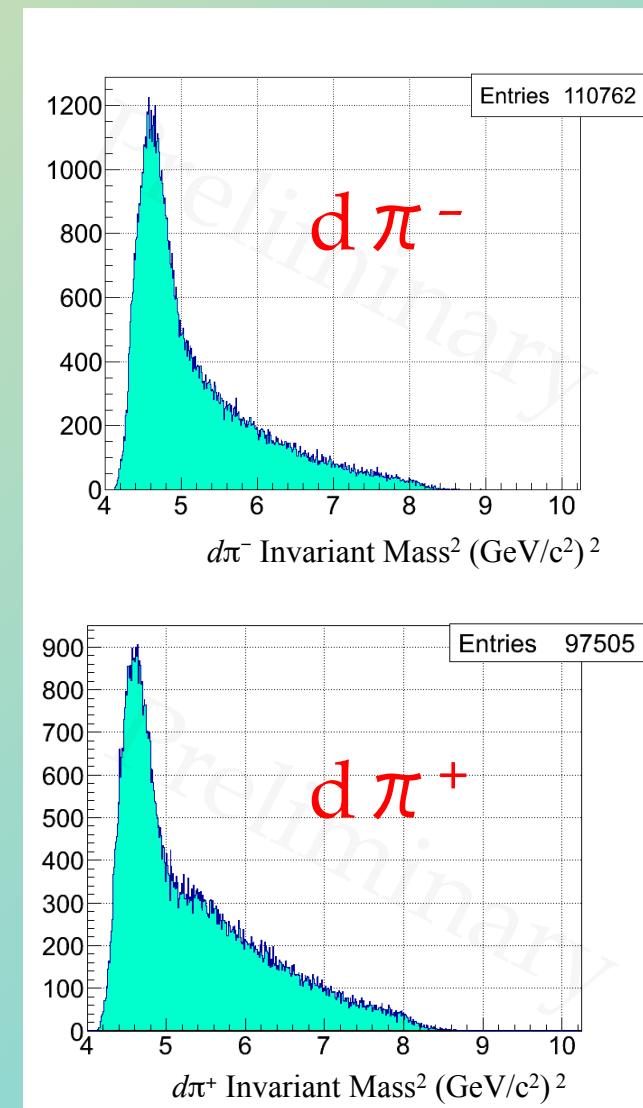
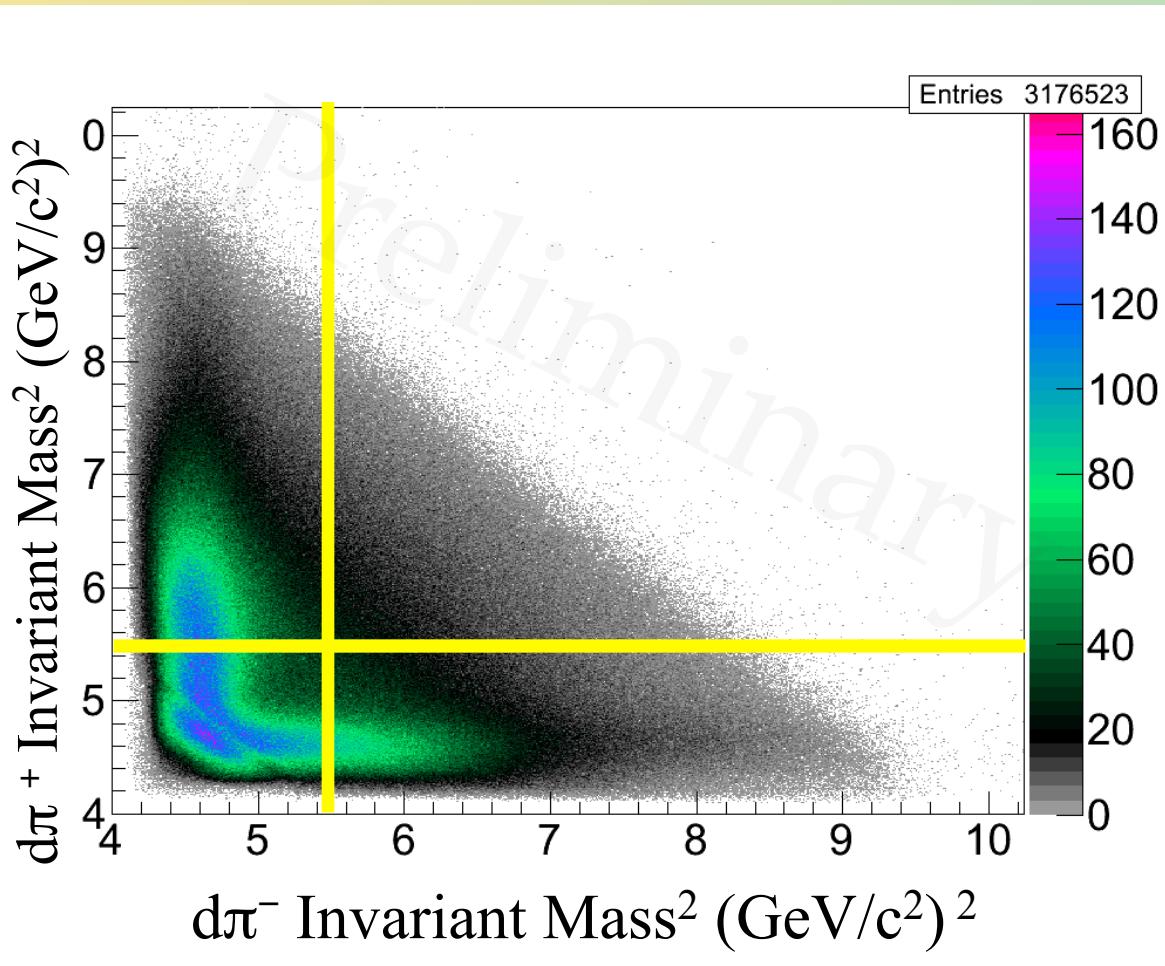
# Dalitz Plot: $d\pi^+$ vs. $d\pi^-$

- \* Raw yields, All W
  - \* Gash: Bad tagger counter ( $W = 2.46 \text{ GeV}/c^2$ )



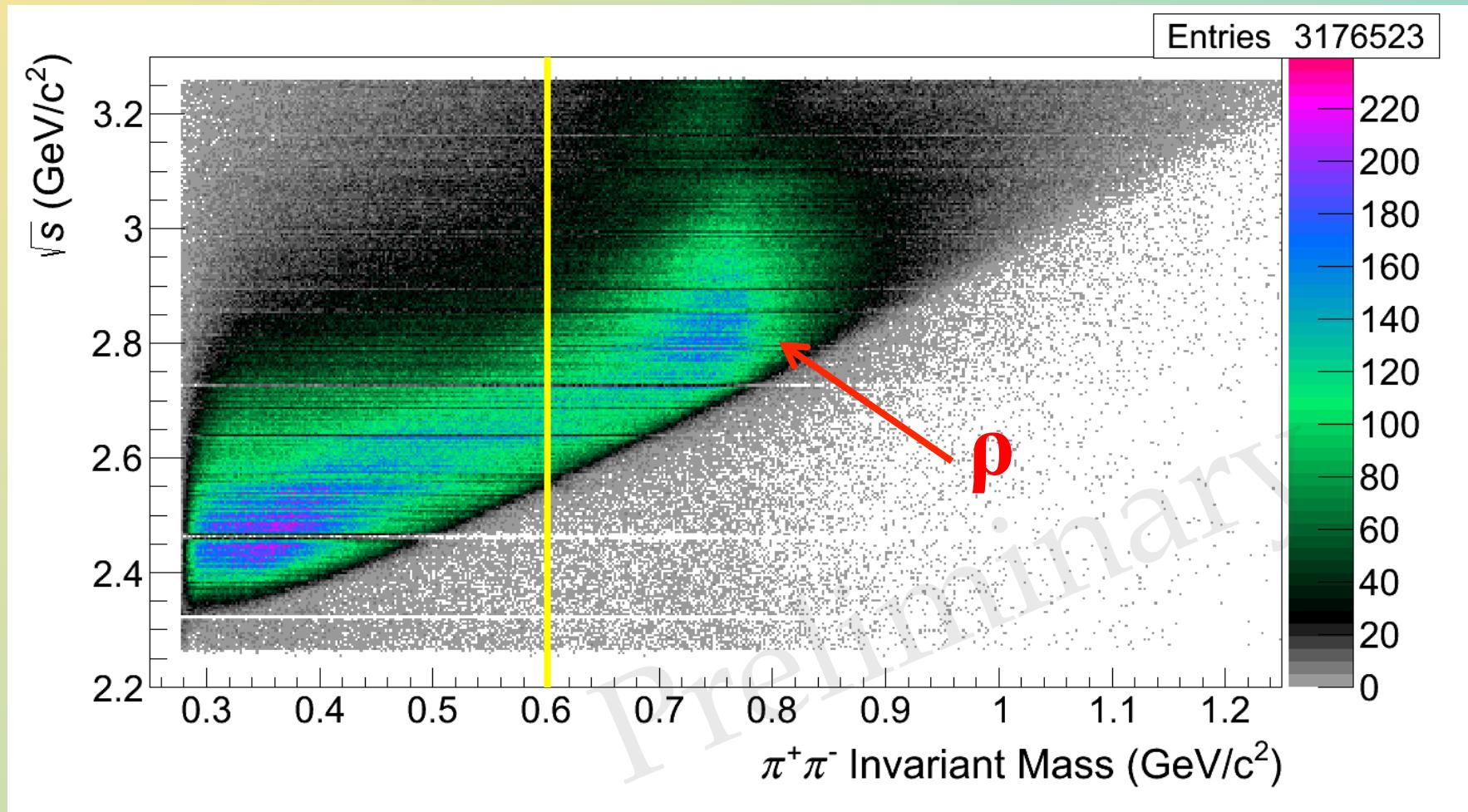
# Dalitz Plot: $d\pi^+$ vs. $d\pi^-$

- \* Raw yield 1D slices:  $d\pi$  peaks dominate



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

- \* Raw yield:  $\rho$  dominates at high  $W$ , long tail



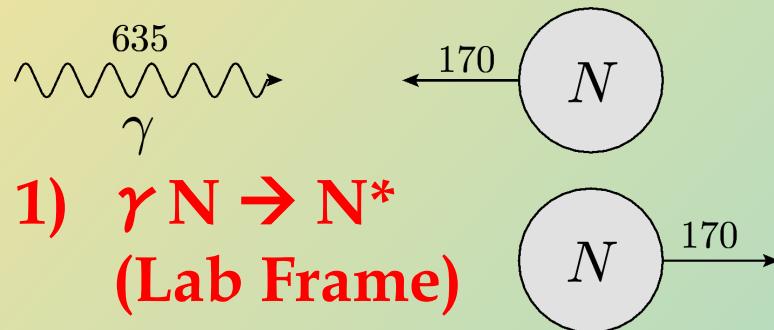
W-granularity:  $\gamma$ -beam tagger detector

# Deuteron Breakup?

- \* Would deuteron break-up trying to form  $N\Delta$ ?
  - \* Deuteron binding energy is 2.225 MeV
  - \* Not necessarily: Fermi motion

# Deuteron Breakup?

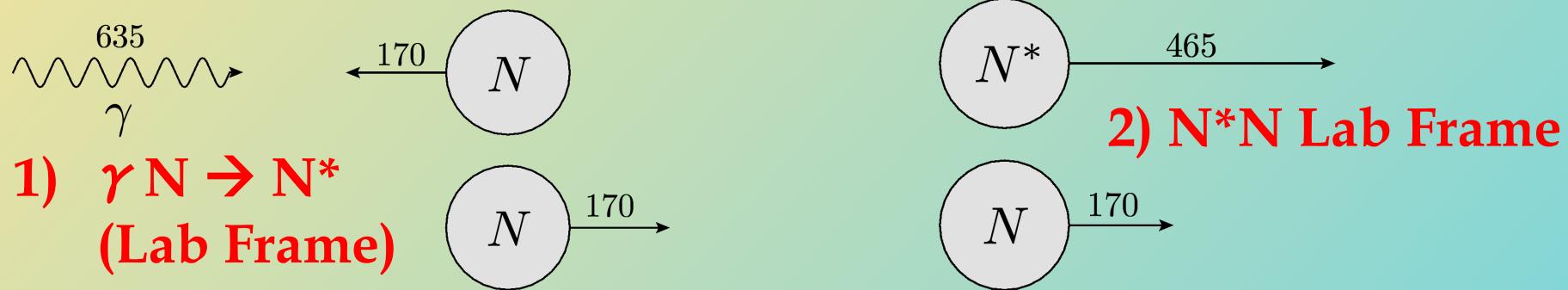
- \* Would deuteron break-up trying to form  $N\Delta$ ?
  - \* Deuteron binding energy is 2.225 MeV
  - \* Not necessarily: Fermi motion
- \* Suppose  $\gamma d \rightarrow N^*(1520)N \rightarrow \Delta N \pi$ , 170 Fermi p,  $N^*$  decay on z-axis



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

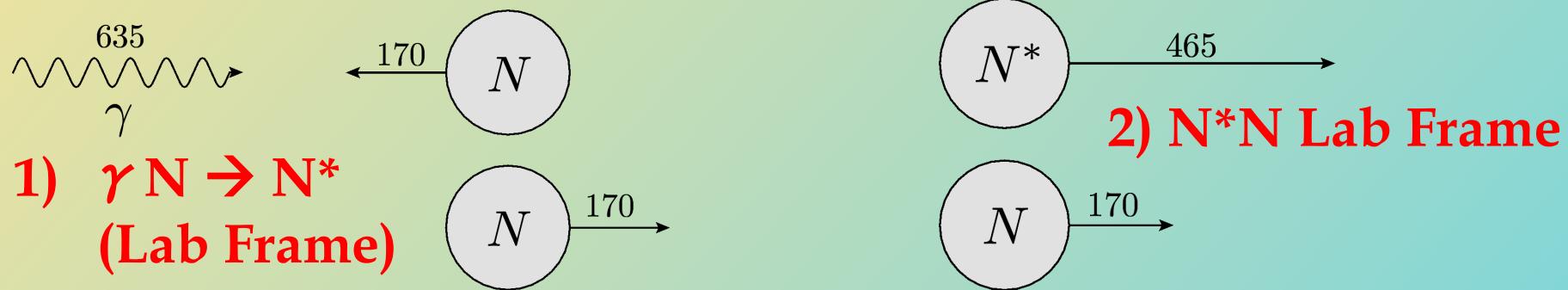
# Deuteron Breakup?

- \* Would deuteron break-up trying to form  $N\Delta$ ?
- \* Deuteron binding energy is 2.225 MeV
- \* Not necessarily: Fermi motion
- \* Suppose  $\gamma d \rightarrow N^*(1520)N \rightarrow \Delta N \pi$ , 170 Fermi p,  $N^*$  decay on z-axis

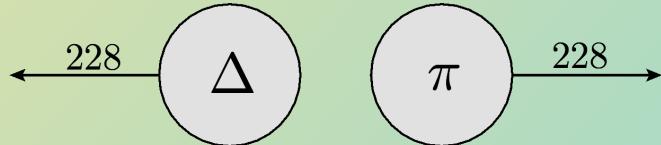


# Deuteron Breakup?

- \* Would deuteron break-up trying to form  $N\Delta$ ?
- \* Deuteron binding energy is 2.225 MeV
- \* Not necessarily: Fermi motion
- \* Suppose  $\gamma d \rightarrow N^*(1520)N \rightarrow \Delta N \pi$ , 170 Fermi p,  $N^*$  decay on z-axis

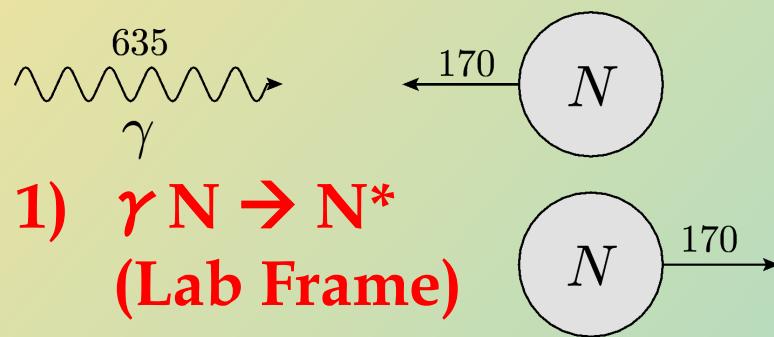


**3)  $N^*(1520)$  Rest Frame**



# Deuteron Breakup?

- \* Would deuteron break-up trying to form  $N\Delta$ ?
- \* Deuteron binding energy is 2.225 MeV
- \* Not necessarily: Fermi motion
- \* Suppose  $\gamma d \rightarrow N^*(1520)N \rightarrow \Delta N \pi$ , 170 Fermi p,  $N^*$  decay on z-axis

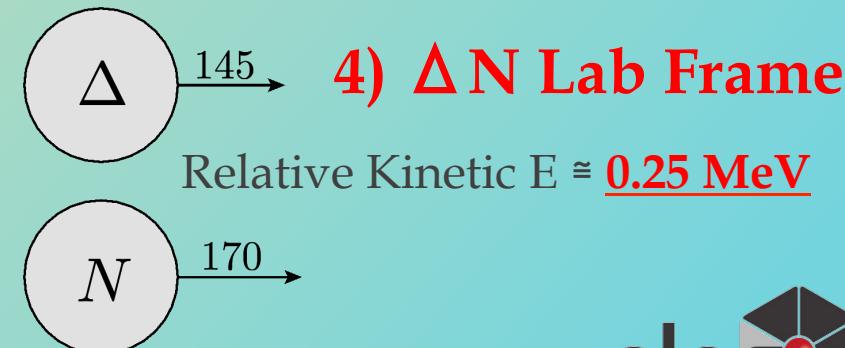
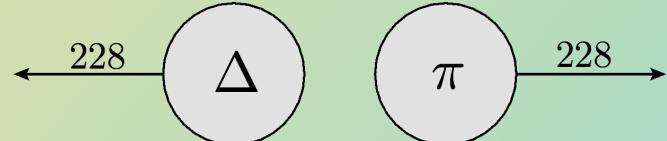


**1)  $\gamma N \rightarrow N^*$   
(Lab Frame)**



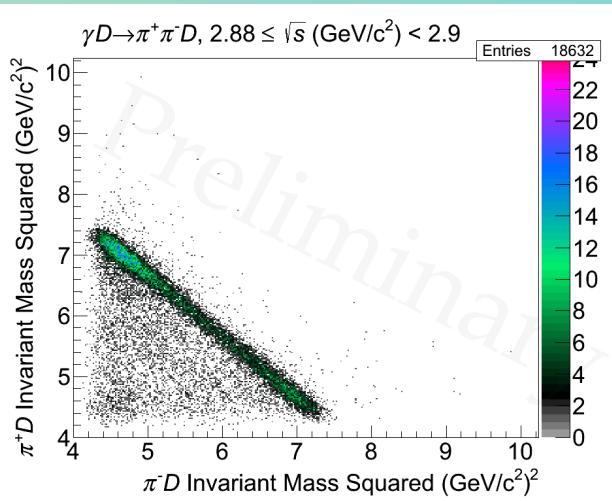
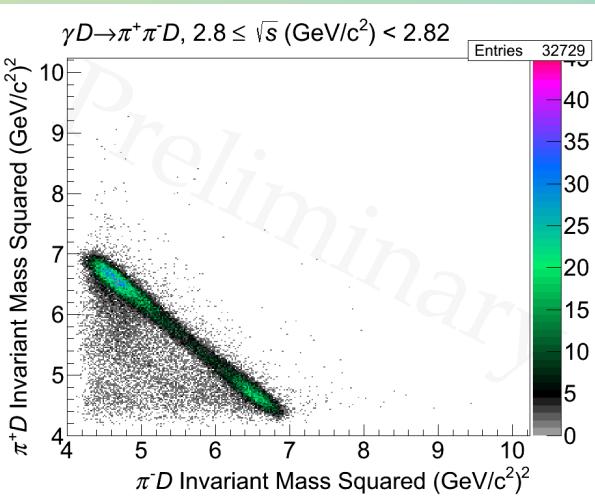
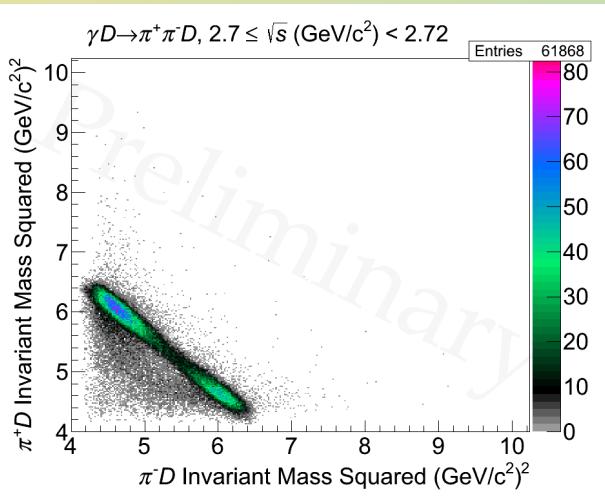
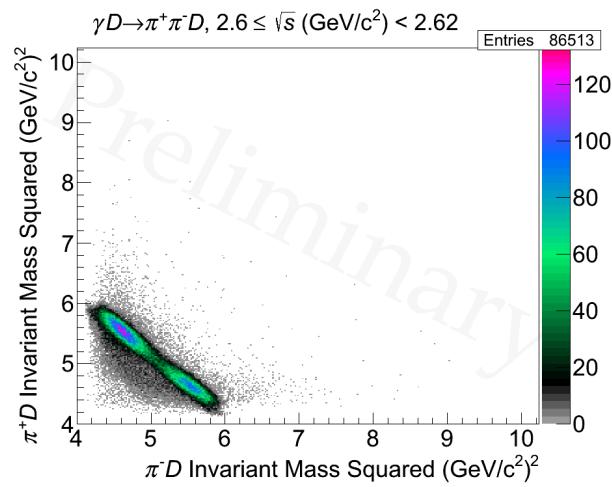
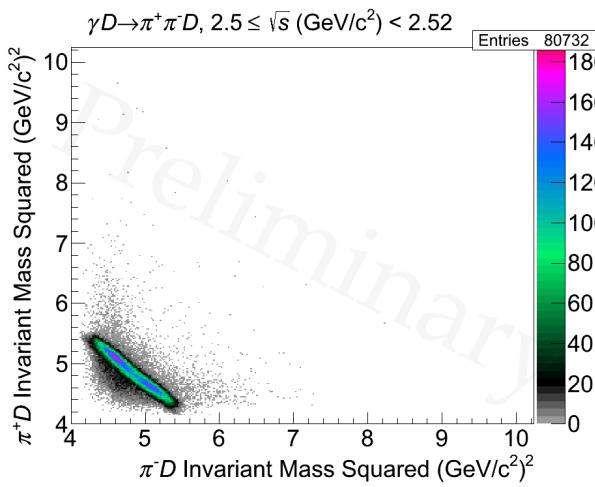
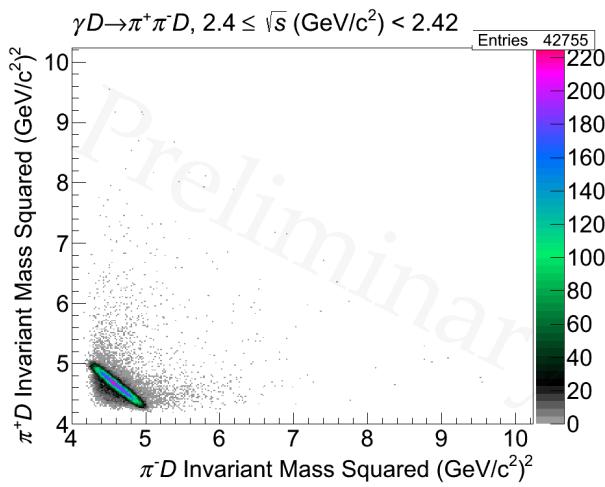
**2)  $N^*N$  Lab Frame**

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



# Dalitz Plot W-Bins

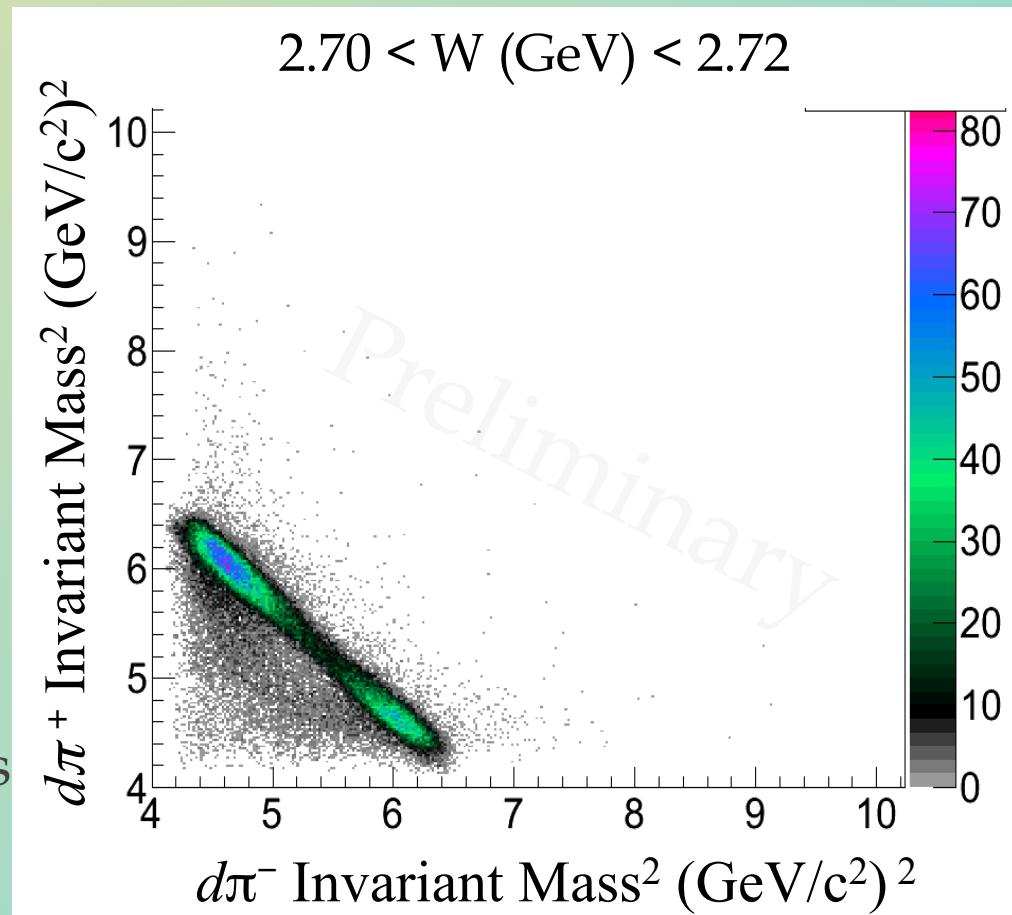
- \* W-bins are thin: kinematics (d is heavy), 500 MeV/c d min-p cut



Non-physical events: Likely wrong beam  $\gamma$

# Simple Fits to the Data

- \* Fit acceptance-corrected data in narrow bins of  $W$
- \* Fit  $d\pi^-$  mass to Breit-Wigner
- \* Fit  $d\pi^-$  BW decay to:
  - \*  $L = 0 (N\Delta)$
  - \*  $L = 1 (d\pi)$
  - \*  $L = 2 (NN)$
  - \* Let fit choose best match
- \*  $\rho$  modeled as phase-space
- \* Incoherent sum of amplitudes
  - \* No interference terms
- \* Prelude: Need full PWA



# Breit-Wigner Fit Functions

- \* Relativistic d  $\pi$  Breit-Wigners in  $\gamma d \rightarrow d \pi^+ \pi^-$
- \*  $\alpha$ : Fit parameters: Let fit “choose” preferred shape: L = 0, 1, 2

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

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

$$\Gamma_{\pi d}^{L=1} = \alpha_{\pi d} \Gamma_0 \left( \frac{q^{\pi d}}{q_0^{\pi d}} \right)^{2L+1=3} \left( \frac{m}{m_0} \right) (B'_{L=1}(q, q_0))^2 = \Gamma_f \stackrel{\triangle}{=} \Gamma_i \quad \text{Final-state: } d \pi$$

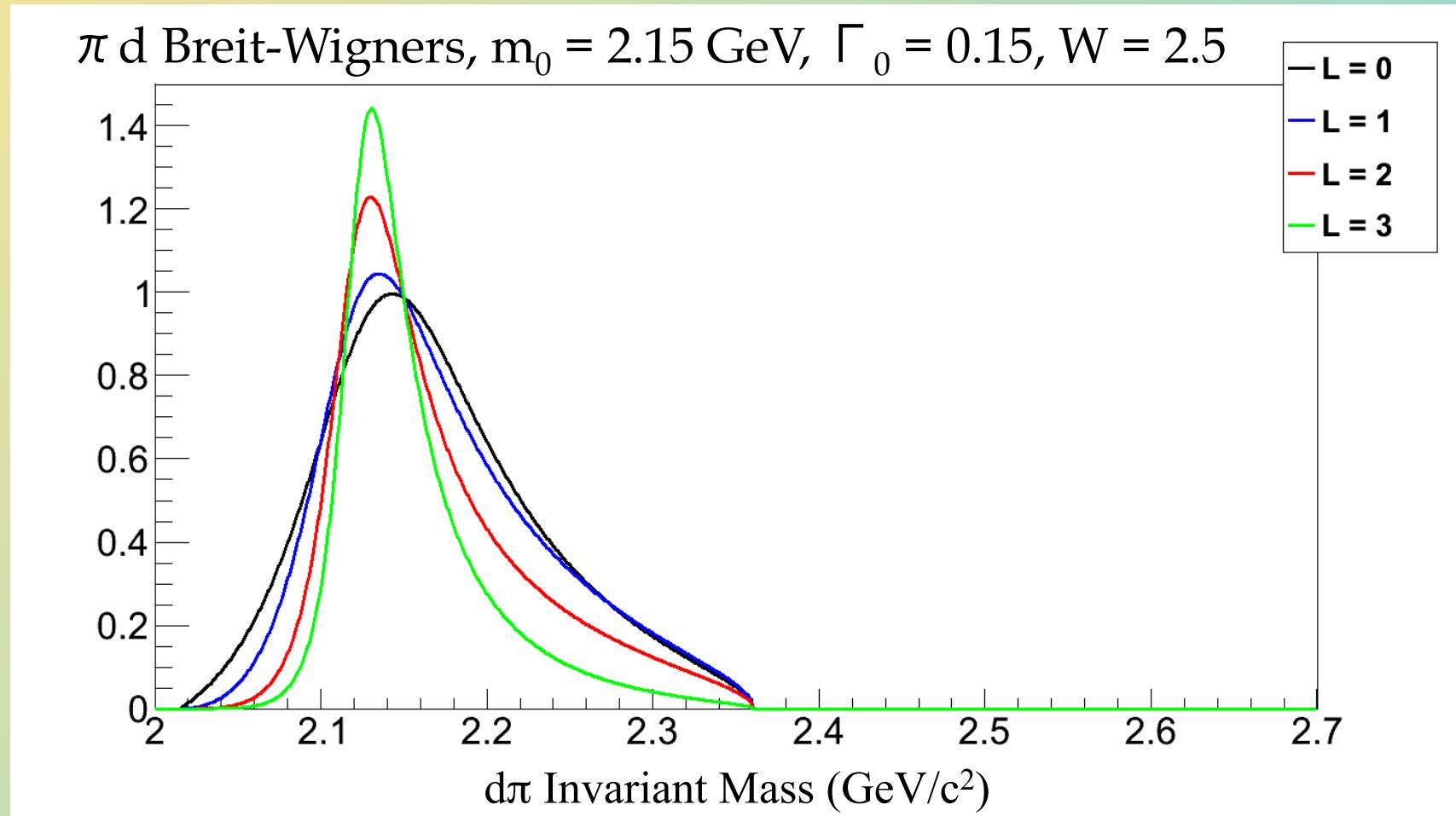
$$\Gamma_{N\Delta}^{L=0} = \alpha_{N\Delta} \Gamma_0 \left( \frac{q^{N\Delta}}{q_0^{N\Delta}} \right)^{2L+1=1} \left( \frac{m}{m_0} \right) (B'_{L=0}(q, q_0))^2 \xrightarrow{\text{Non-relativistic}} \alpha_{N\Delta} \Gamma_0 \left( \frac{m}{m_0} \right) (1)$$

Fits by Reinhard Schumacher, CMU

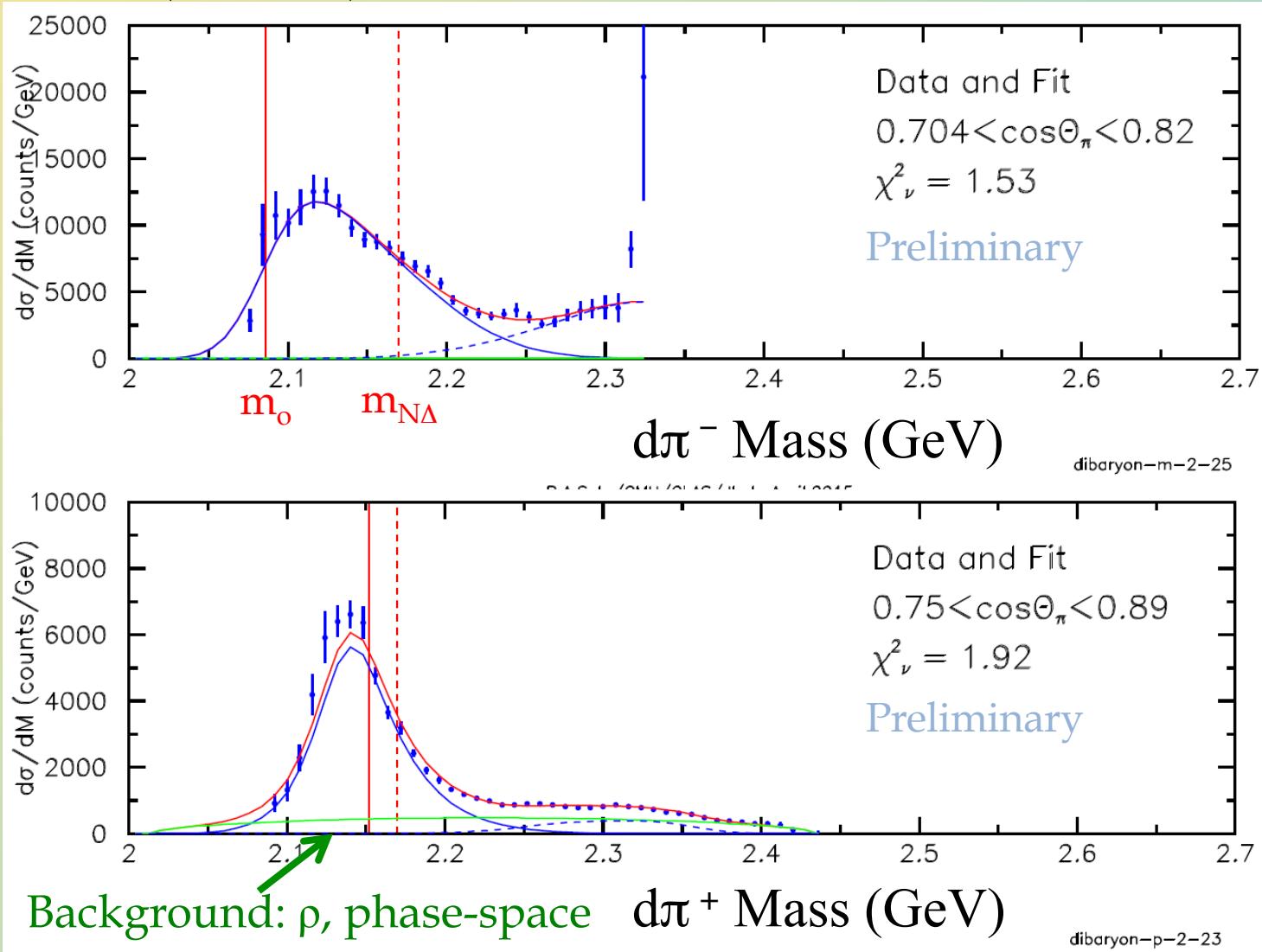
Paul Mattione – Baryons 2016 – May 19, 2016

# Breit-Wigner Distributions

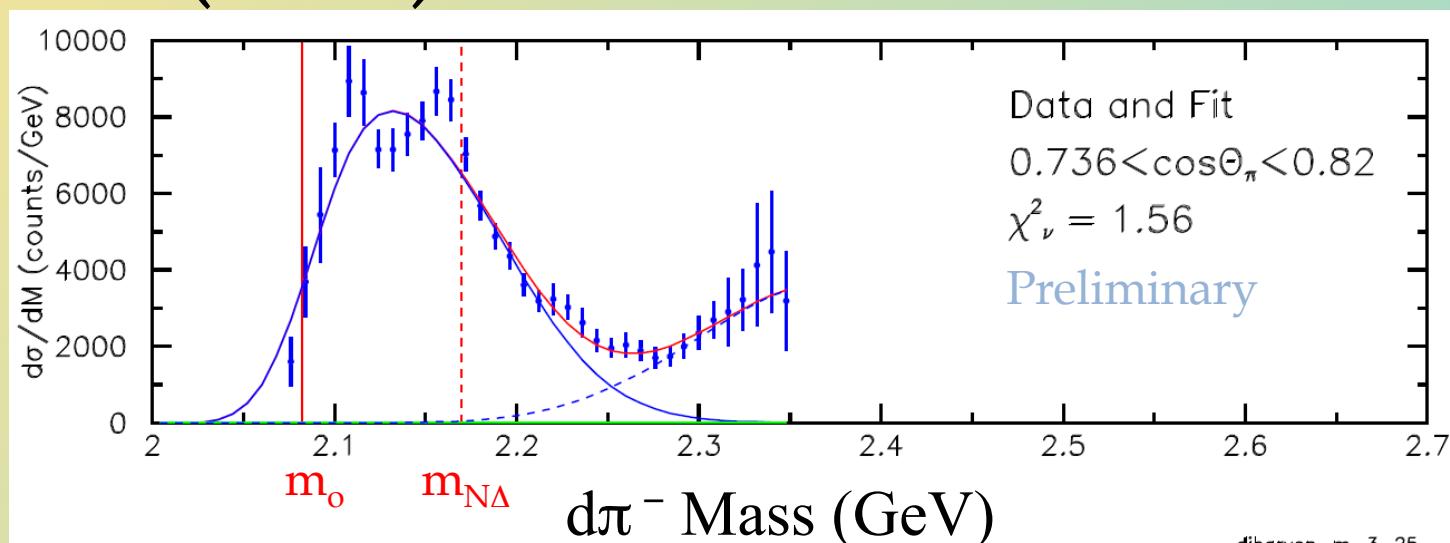
- \* Various L: Relativistic d $\pi$  Breit-Wigners (& phase-space factor)



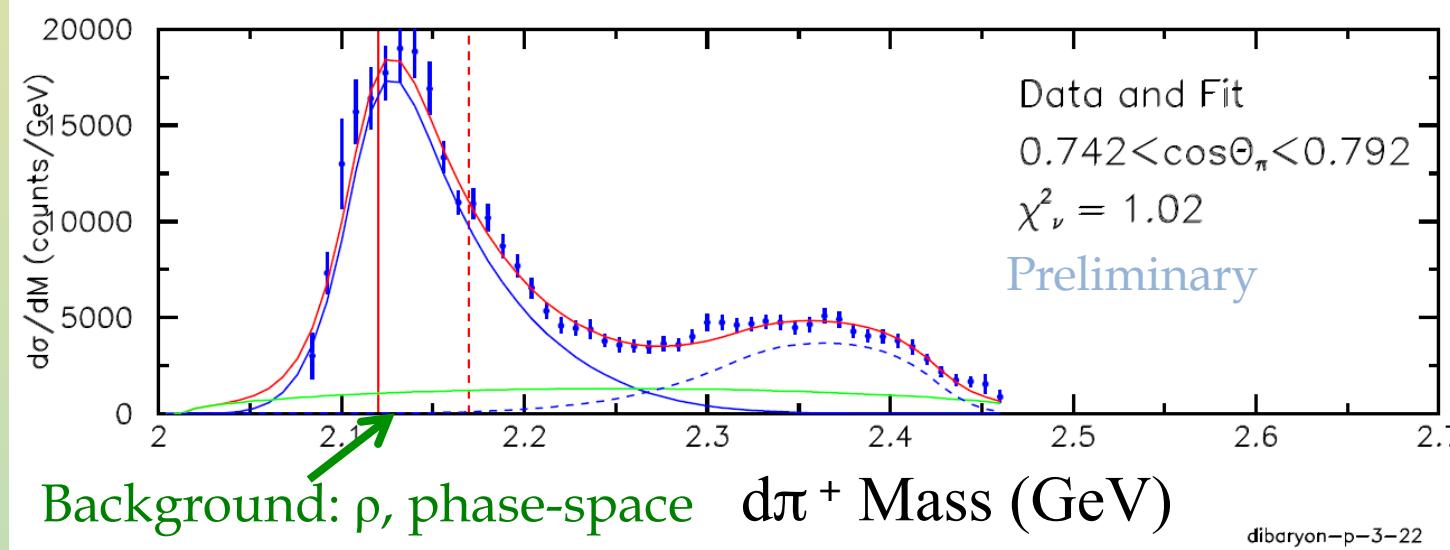
# $\gamma d \rightarrow (d\pi) \pi, 2.55 < W < 2.6 \text{ GeV}$



# $\gamma d \rightarrow (d\pi) \pi, 2.6 < W < 2.65 \text{ GeV}^{24}$



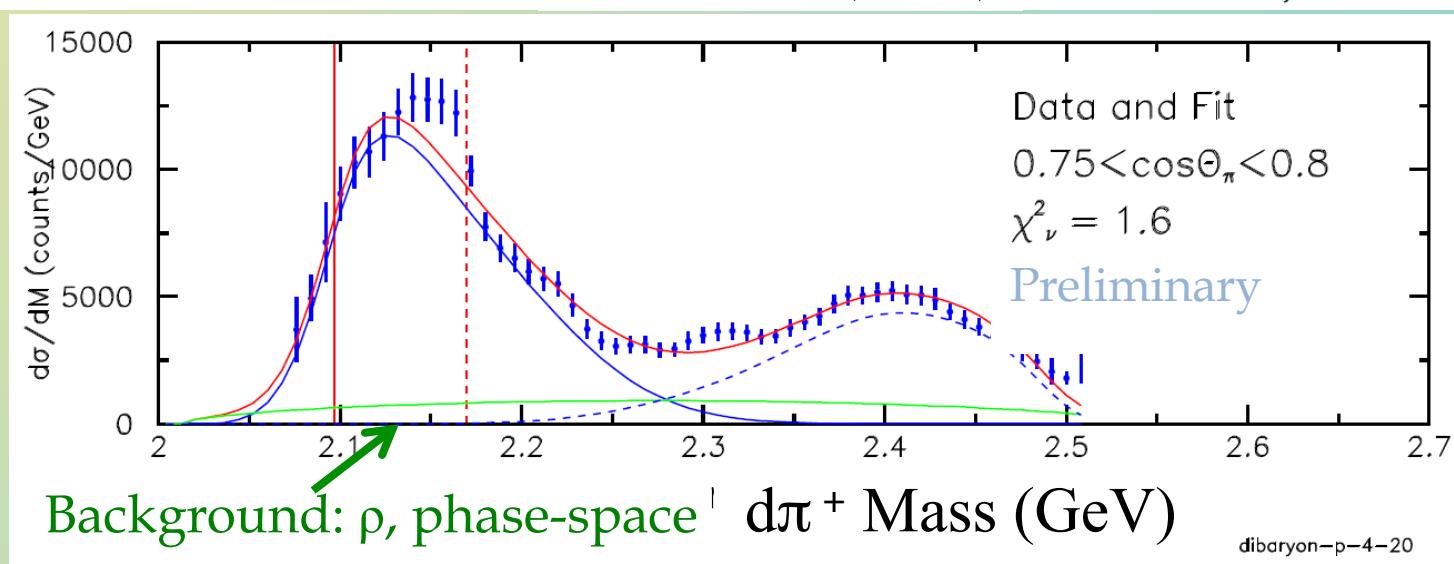
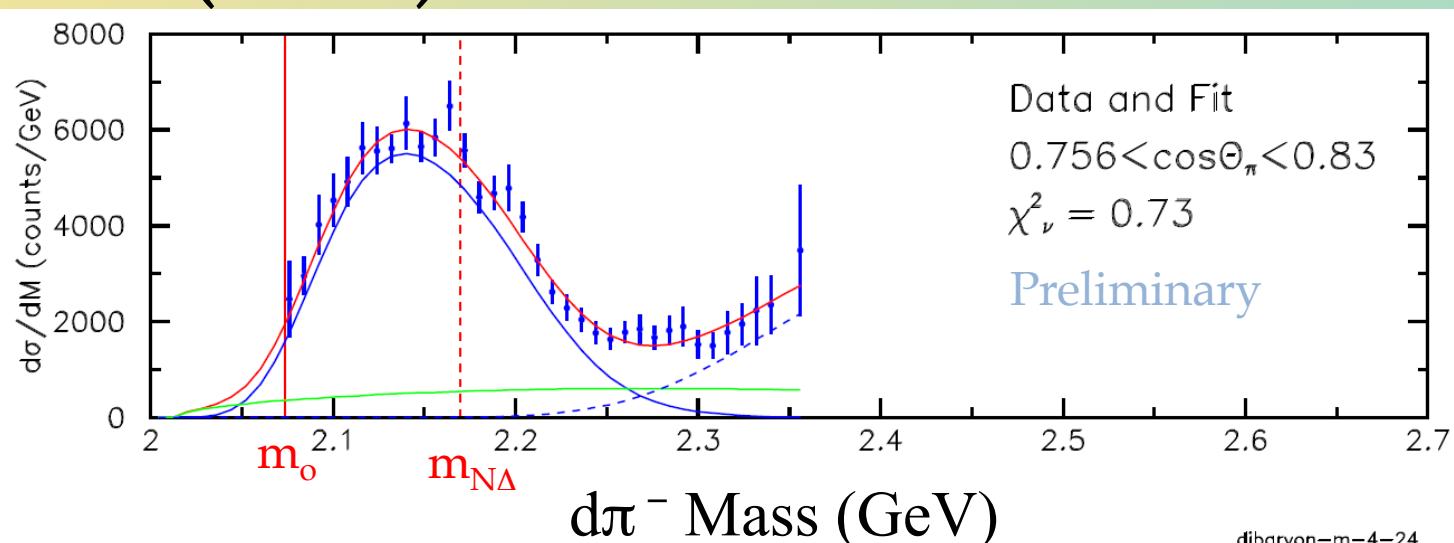
dibaryon-m-3-25



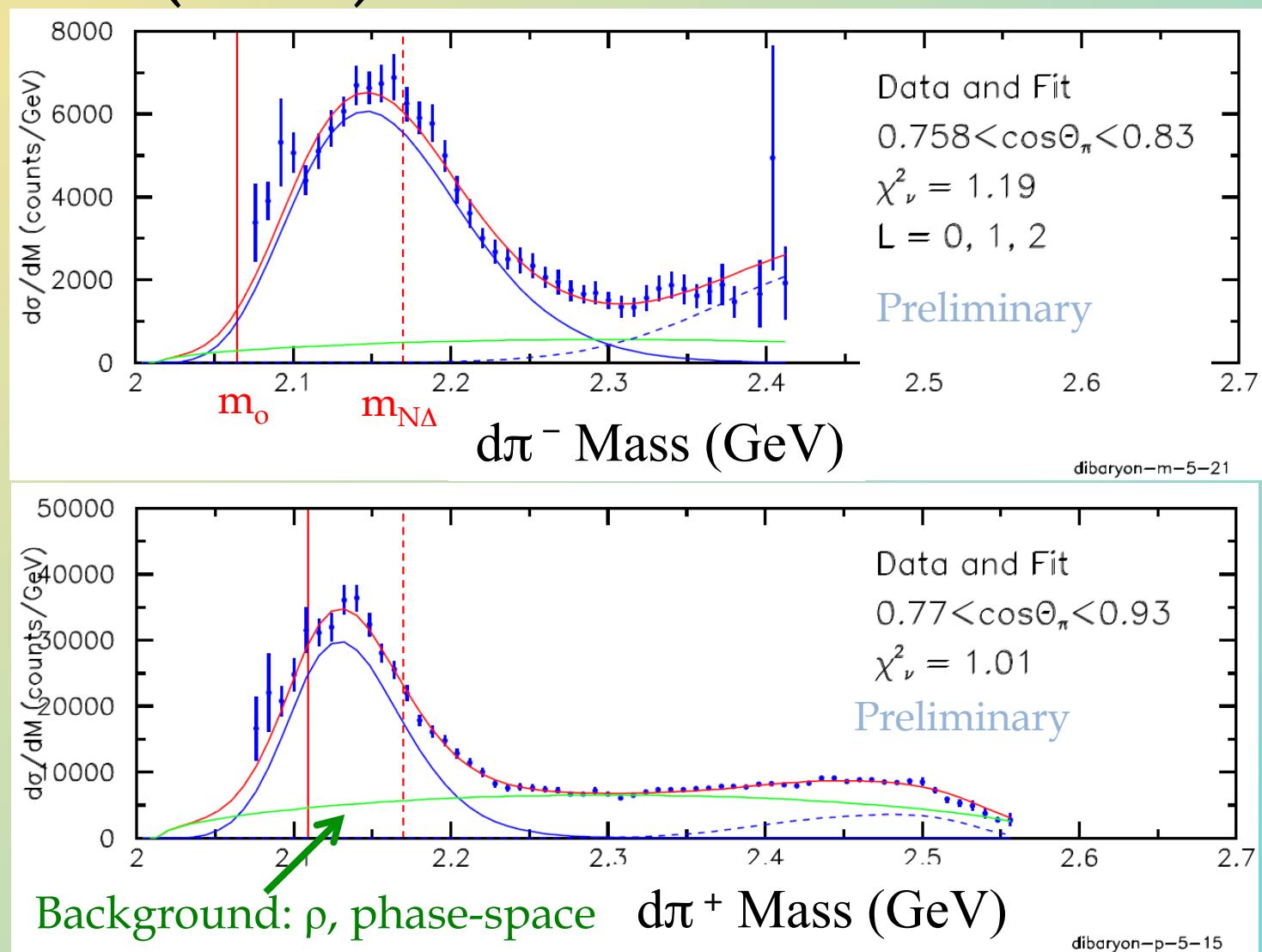
dibaryon-p-3-22

Background:  $\rho$ , phase-space     $d\pi^+$  Mass (GeV)

# $\gamma d \rightarrow (d \pi^-) \pi^+, 2.65 < W < 2.7 \text{ GeV}$



# $\gamma d \rightarrow (d\pi) \pi, 2.7 < W < 2.75 \text{ GeV}^{26}$



# Fit Observations

- \* Peaks all below the  $N\Delta$  threshold (possibly a bound-state?)
- \* But widths are  $\cos(\theta_\pi)$  dependent
- \* Fits dominantly “choose”  $L = 1$
- \* Very preliminary, naïve-fit result (both peaks):
  - \*  $m_{\text{peak}} = 2115 \pm 10 \text{ MeV}/c^2$
  - \*  $\text{FWHM} = 125 \pm 25 \text{ MeV}/c^2$

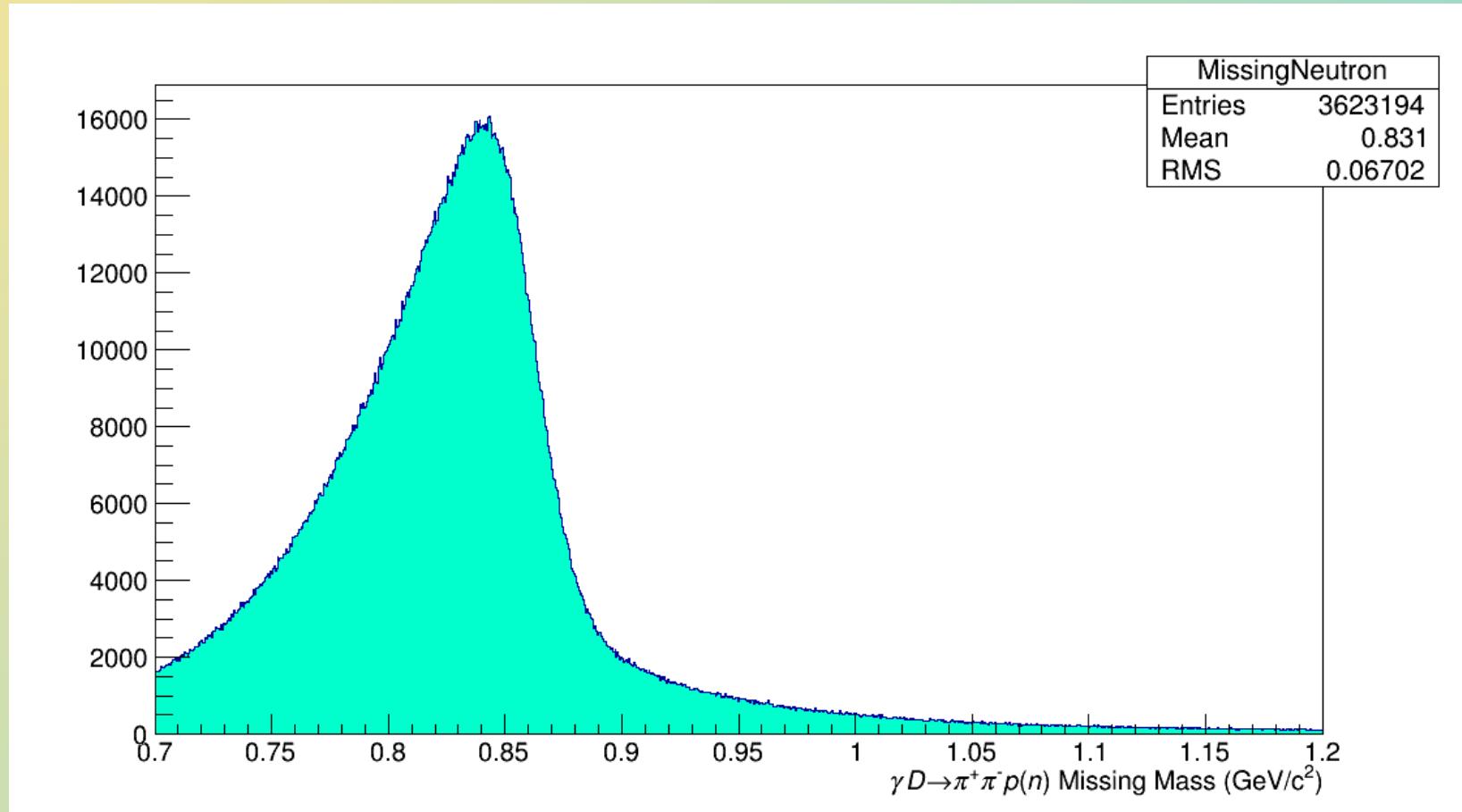
# Summary & Conclusions

# Summary

- \* 3.1 million  $\sim$ clean  $\gamma d \rightarrow d\pi^+\pi^-$  events
- \* No  $\Delta\Delta$  observed in  $\gamma d \rightarrow d\pi^+\pi^-$
- \* Strong  $d\pi$  structures seen in  $d\pi^+\pi^-$  Dalitz plot
  - \* Mass peaks below  $N\Delta$  threshold
  - \* Fits are very simple naïve
- \* Need full amplitude analysis to determine nature of peaks
  - \* Dynamically generated?
- \* Setting up amplitude analysis
  - \* Covariant helicity-coupling amplitudes
  - \* Tricky: Three-body final state

# Mis-PID Missing Mass

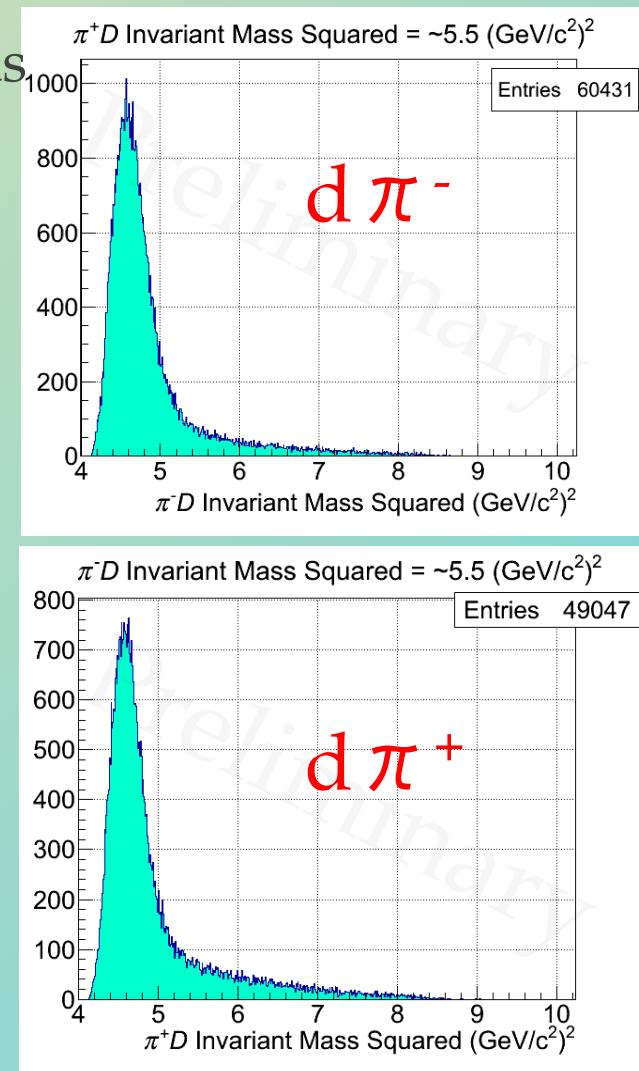
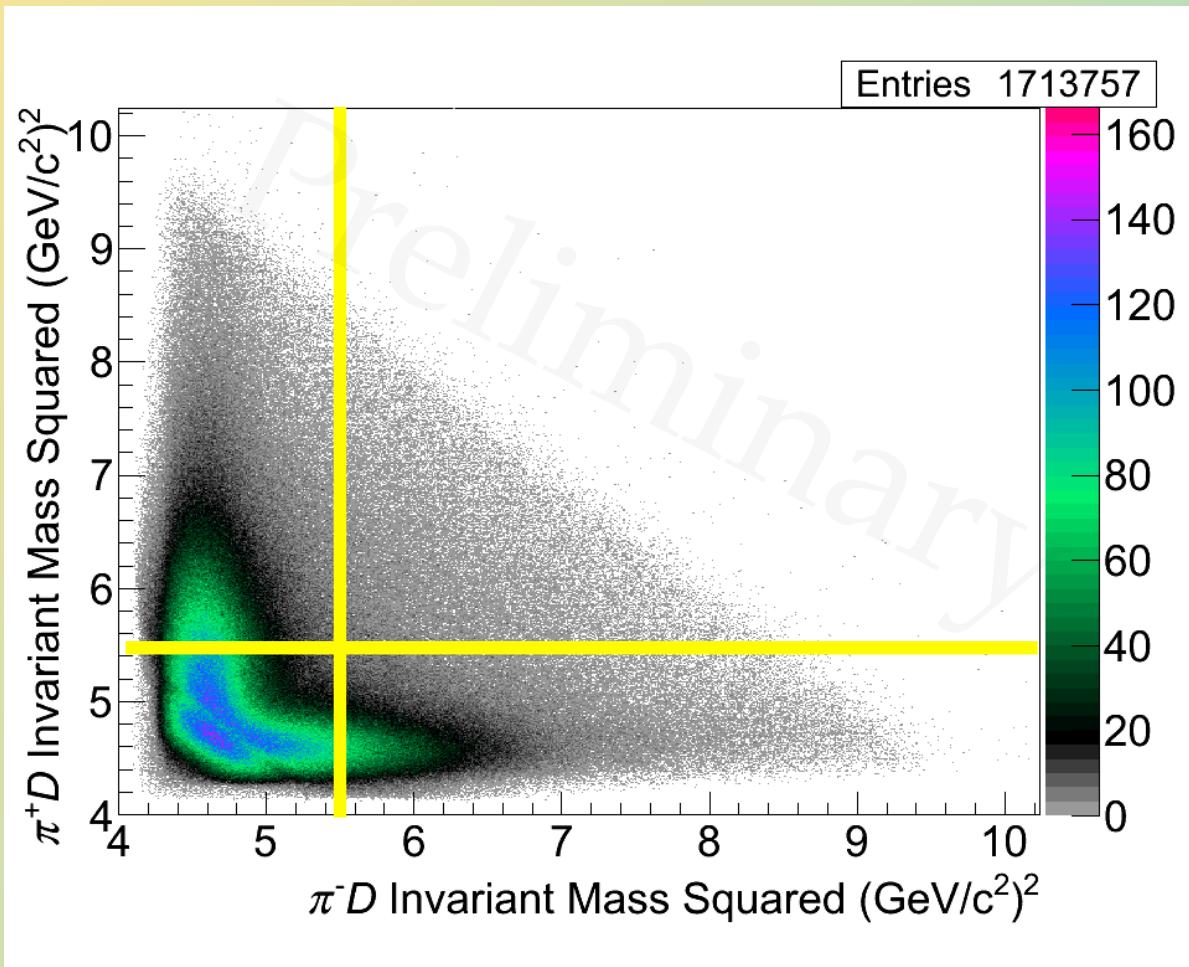
- \* If deuteron was proton, calculated neutron missing mass



- \* No background from misidentifying the d

# Dalitz w/ $\rho$ -Cut: d $\pi^+$ vs. d $\pi^-$

- \*  $\rho$  cut removed most background under peaks



# Angular Momentum

- \* Assume  $d\pi$  structures are bound states of  $N\Delta$ 
  - \* Adding angular momentum: For:  $J \rightarrow j_1, j_2$ :  $|j_1 - j_2| \leq J \leq j_1 + j_2$
- \* From  $N\Delta$ :
  - \*  $L_{N\Delta}$  most likely = 0 (bound state near threshold)
  - \*  $P_{N\Delta} = P_N P_\Delta (-1)^L \Rightarrow P_{N\Delta} = +1$
  - \*  $J_{N\Delta} = J_N + J_\Delta + L_{N\Delta} = 1, 2 \Rightarrow J_{N\Delta} = 1 \text{ or } 2$
- \* From  $\pi d$ :
  - \*  $P_{\pi d} = P_\pi P_d (-1)^L = P_{N\Delta} = +1 \Rightarrow L_{\pi d} = 1, 3, 5 \dots$
  - \*  $J_{\pi d} = J_\pi + J_d + L_{\pi d} = J_{N\Delta} = 1 \text{ or } 2 \Rightarrow L_{\pi d} = 1 \text{ or } 3$
- \* Thus if the  $\pi d$  bands are  $N\Delta$  resonances, we expect:
  - \*  $J^P_{N\Delta} = 1^+ \text{ or } 2^+, \quad L_{\pi d} = 1 \text{ or } 3$
- \* Previous evidence in pp scattering:  $J^P_{N\Delta} = 2^+$

Particle	$J^P$
$\gamma$	$1^-$
$\pi$	$0^-$
$N$	$\frac{1}{2}^+$
$\Delta$	$\frac{3}{2}^+$
$D$	$1^+$

# Breit-Wigner Distributions

- \* Relativistic Breit-Wigner (of particle ( $d^*$ )) mass  $m_{d^*}$  and width  $\Gamma(M)$ :

$$BW(M) = \frac{m_{(d^*)}\Gamma_{(d^*)}}{(M^2 - m_{(d^*)}^2)^2 + m_{(d^*)}^2 [\Gamma(M)]^2}$$

Blue: Fit parameters

- \*  $\Gamma(M)$  is effectively the coupling strength to a given channel
- \*  $\Gamma(M)$  is not constant: Depends on kinematic constraints:
  - \* Momentum ( $q$ ) of final state particle in decay CM frame
  - \* Orbital angular momentum  $L$  of decay products

$$\Gamma(M) = \Gamma_{(d^*)} \left( \frac{q}{q_0} \right)^{2L+1} \left( \frac{m_{(d^*)}}{M} \right) [B'_L(q, q_0)]^2 \quad B'_0 = 1$$

$$B'_1(q, q_0) = \sqrt{\frac{1 + q_0^2 d^2}{1 + q^2 d^2}}$$

$q_0 = q(m_D)$ ,  $d$  typically = 1 fm (Radius / Impact Parameter)

# Breit-Wigner Distributions

- \* We want to fit acceptance-corrected yields:  $\propto d\sigma/d\Omega$
- \* If reaction:  $A, B \rightarrow X \rightarrow C, D$  then in the CM frame:
 
$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2} \frac{1}{W^2} \frac{p_C}{p_A} |\mathcal{M}|^2, \quad |\mathcal{M}|^2 \propto BW(M)$$
See (e.g.) Halzen & Martin
- \* Similarly, for:  $A, B \rightarrow C, D \quad D \rightarrow F, G$  ([This study](#)) fit to:

$$\frac{d\sigma}{d\Omega} (M) \propto \frac{1}{W^2} \frac{p_C(W) p_F(M)}{p_A(W)} \frac{\text{Relativistic Breit-Wigner}}{(M^2 - m_D^2)^2 + m_D^2 [\Gamma(M)]^2}$$

(p<sub>A</sub> & p<sub>C</sub> in CM, p<sub>F</sub> in CM of D)

- \* Where, in general, for  $A \rightarrow B, C$ :

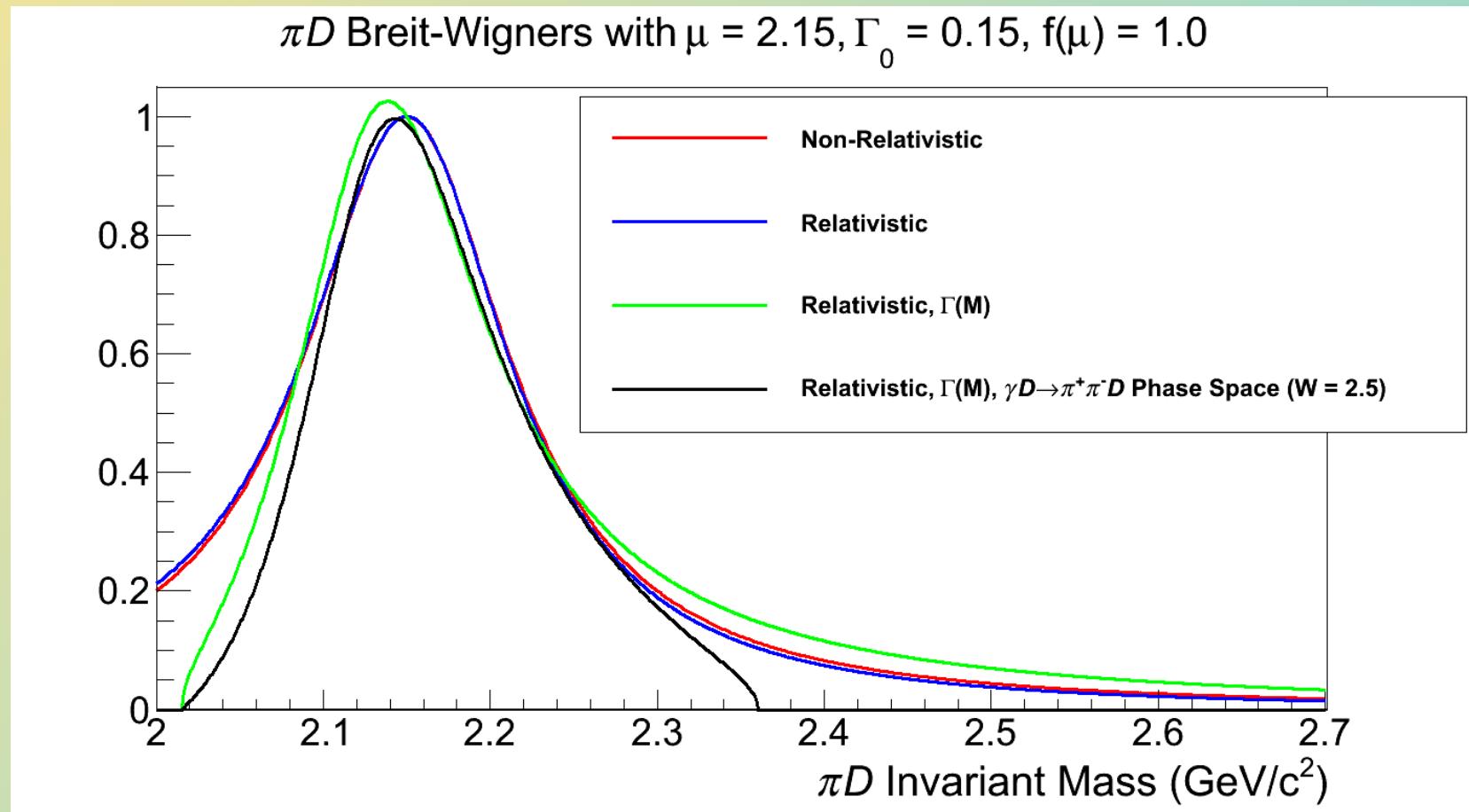
$$p_B(m_A) = \frac{1}{2m_A} \sqrt{\left(m_A^2 - (m_B + m_C)^2\right) \left(m_A^2 - (m_B - m_C)^2\right)}$$

For more details, see (e.g.) PDG + Kei Moriya's thesis.

Paul Mattione – Baryons 2016 – May 19, 2016

# Breit-Wigner Distributions

- \*  $d\pi^-$  Breit-Wigners in  $\gamma d \rightarrow d \pi^+ \pi^-$  (all with  $L = 0$ )



- \*  $\Gamma(M)$ , phase space critical for fitting line shape

# Some Thresholds

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

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

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

For comparison:

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