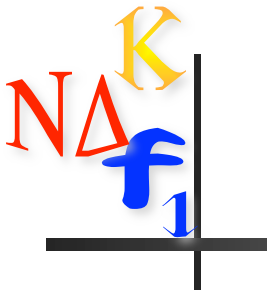


Some Recent Results in Electromagnetic Meson and Baryon Physics from CLAS

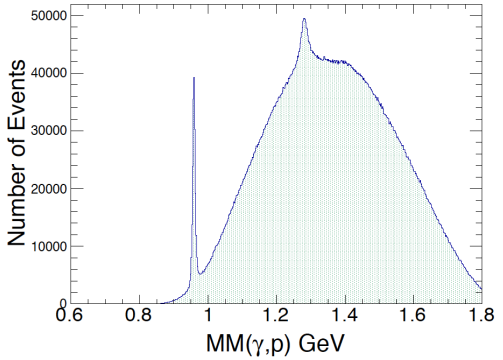
Reinhard Schumacher

Carnegie Mellon University

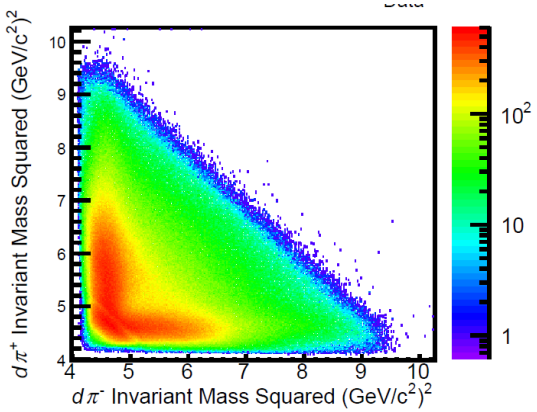
MIN2016, Kyoto Japan, Aug. 1, 2016

Outline: two topics

- The $f_1(1285)$ meson in photo-production
  - Unusual reaction mechanism

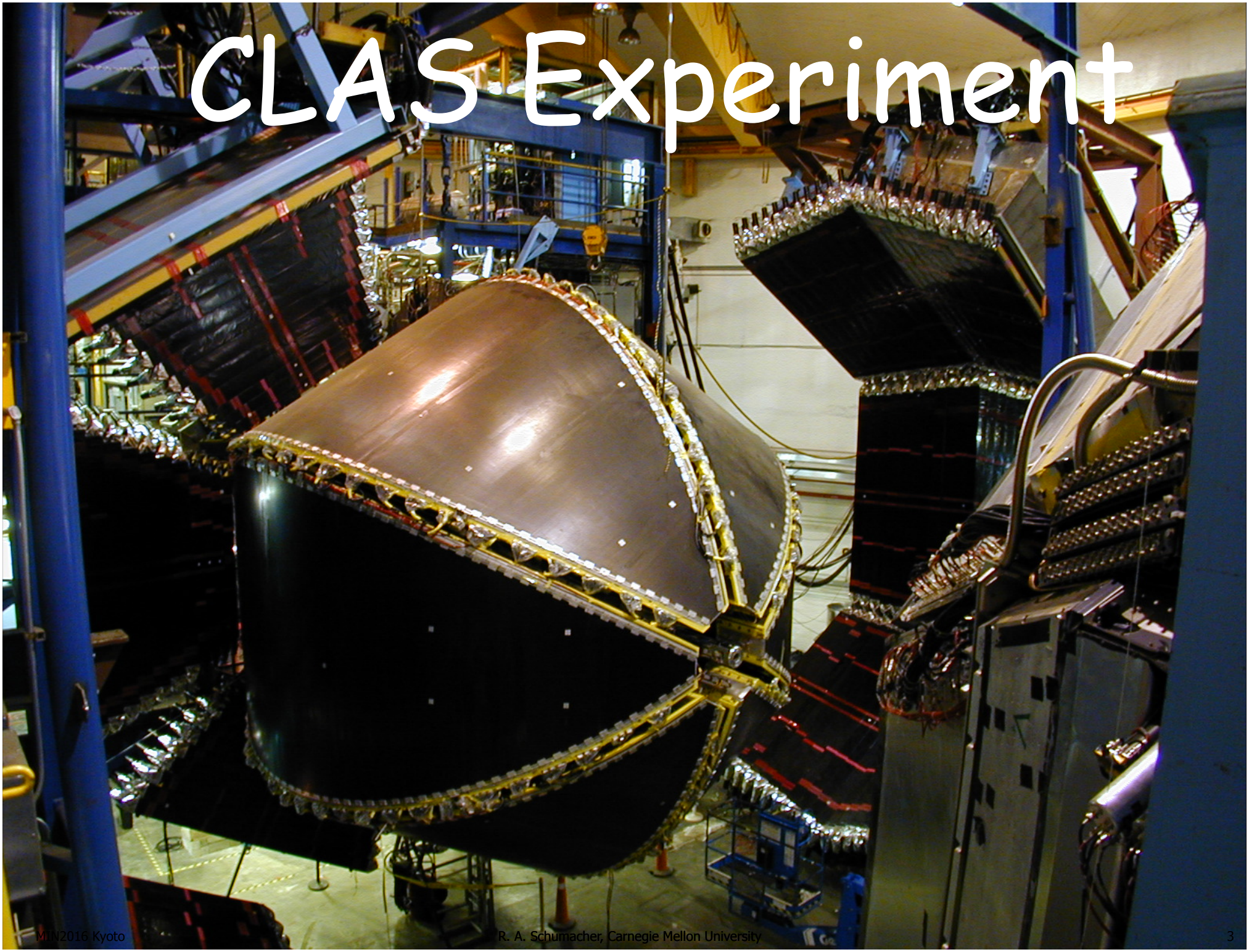


- Evidence for an $N\Delta$ quasi-bound structure decaying to $d\,\pi$
  - Seen in coherent two-pion photoproduction off the deuteron



- (Skip $\Lambda(1405)$ topic mentioned in online abstract)

CLAS Experiment



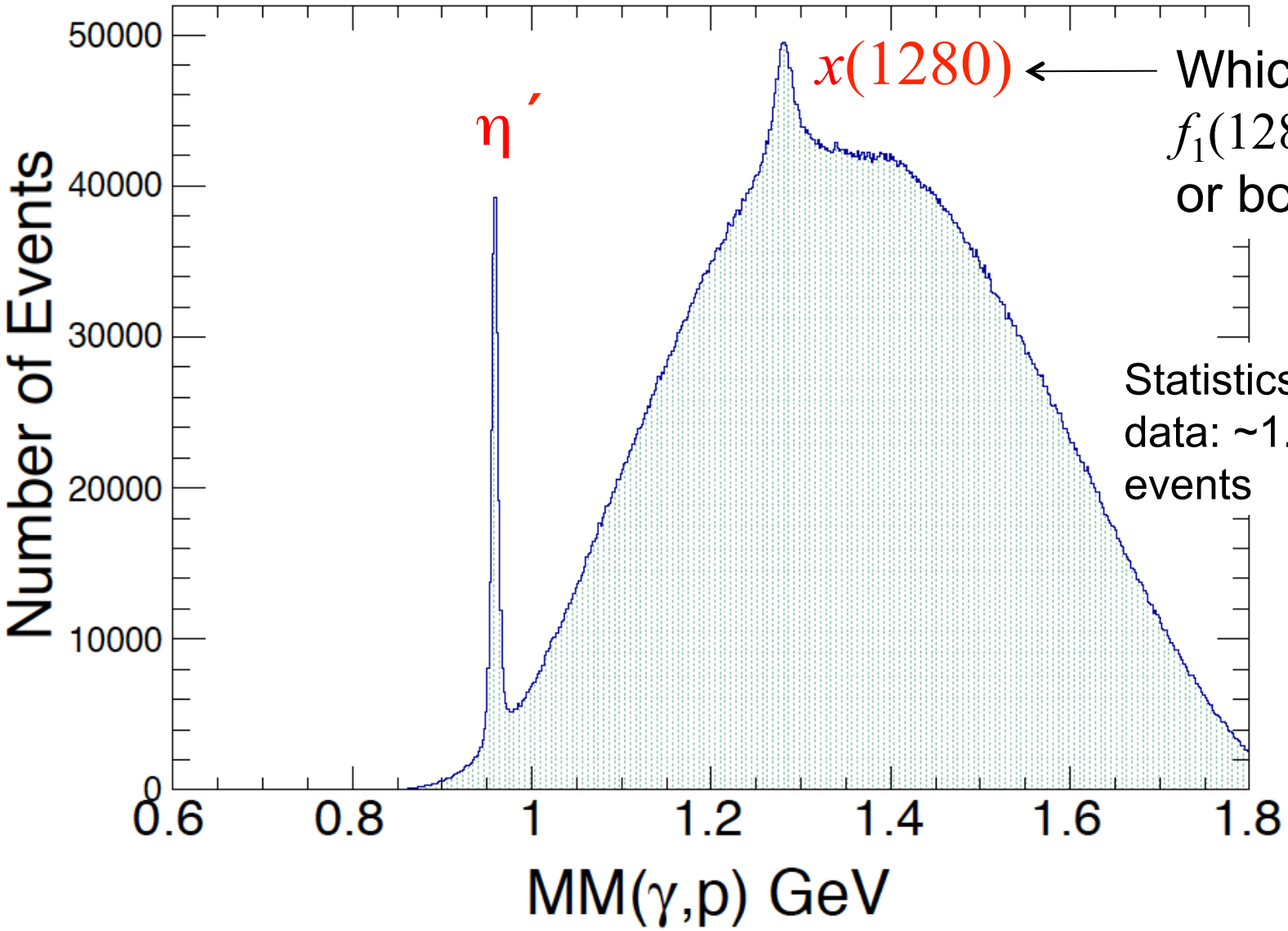
CLAS Experiment

- Operations from 1998 to mid-2012
- Photoproduction:
  - Targets: unpolarized LH_2, LD_2, polarized p, & HD-ice
  - Beams: unpolarized, circular, linear, to ~5 GeV
  - Reconstructed: charged tracks: $K^{\pm}, p, \pi^{\pm}$
  - 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

Photoproduction of the $f_1(1285)$ Meson

Publication: Photoproduction of the $f_1(1285)$ Meson, R. Dickson *et al.* (CLAS Collaboration), Phys. Rev. C **93**, 065202 (2016).

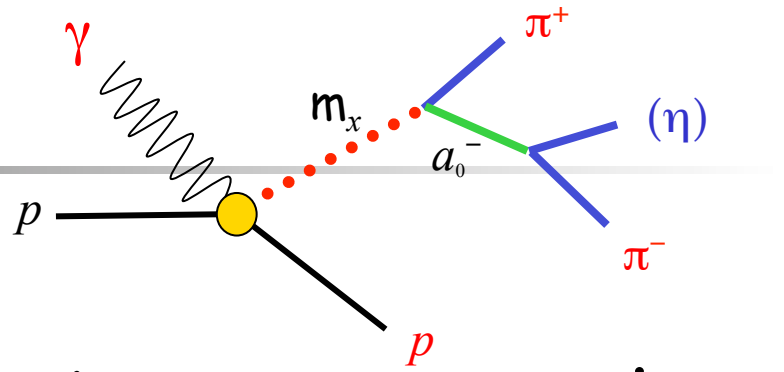
First Observation of $f_1(1285)$ or $\eta(1295)$ in $\gamma p \rightarrow p\, x \rightarrow p\, \pi^+ \pi^- (\eta)$



Which state is it?
$f_1(1285)$, $\eta(1295)$,
or both?

Statistics in CLAS g11 data: ~1.5 x 10^5 $x(1280)$ events

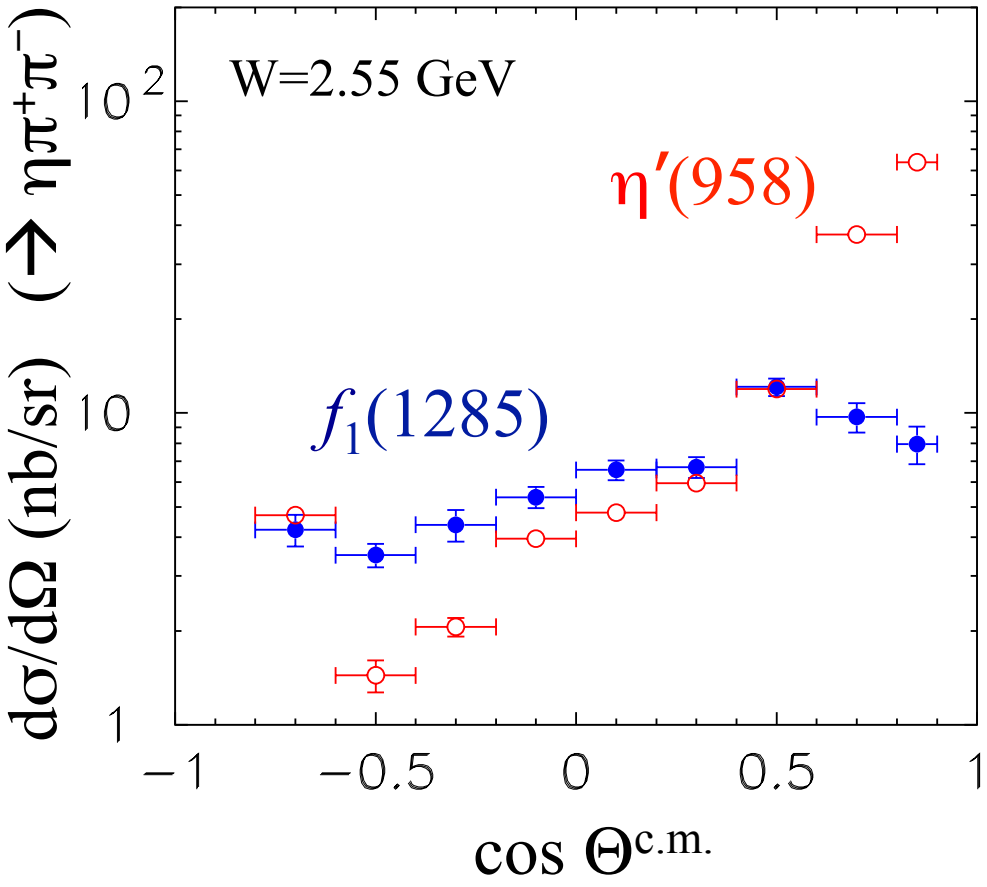
Two Players:



- $f_1(1285)$ $I^G(J^{PC}) = 0^+(1^{++})$
  - Well-established axial-vector meson seen in hadronic reactions;
    - Seen in experimental PWA analyses
    - Seen in Lattice QCD
  - Possible "dynamically generated" $K\overline{K^*} - c.c.$ state

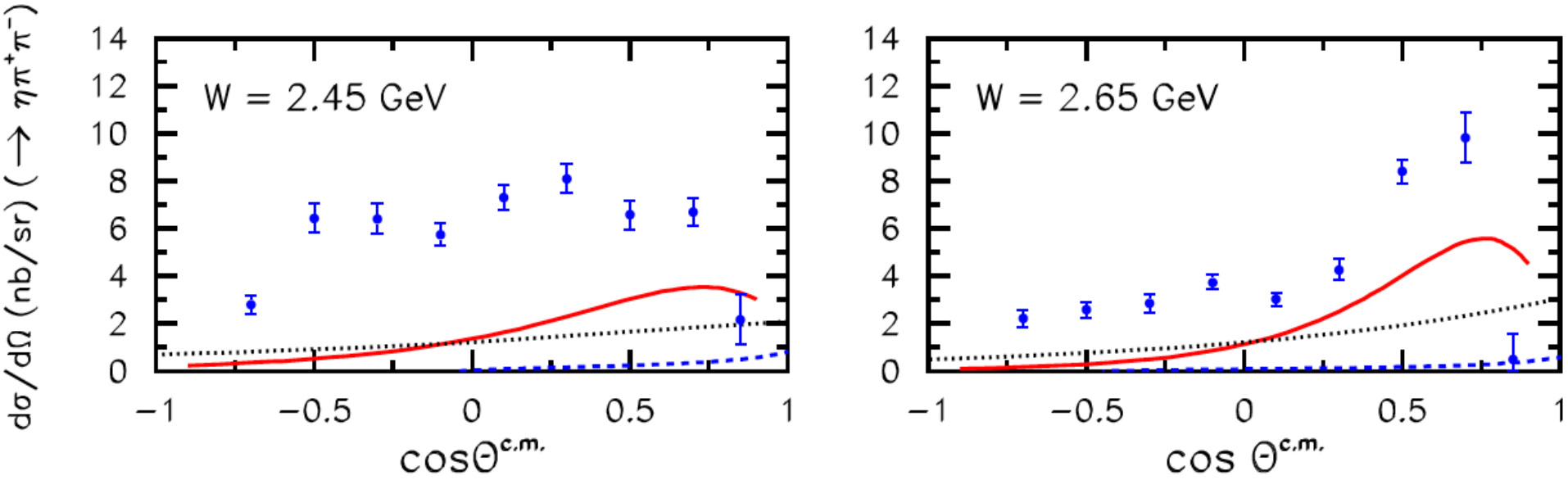
- $\eta(1295)$ $I^G(J^{PC}) = 0^+(0^{-+})$
  - A "controversial" state seen in $\pi^- p \rightarrow \eta\, \pi^+\, \pi^-\, n$
    - Seen only in PWA, e.g. J. Manak et al., E852/BNL
  - Important in the enumeration of mesonic states

Compare Mesons: f_1 and $\eta'(958)$



- $f_1(1285)$ is produced "flatter" than the η'
- (Note logarithmic scale)
- Clue about production: not meson-exchange dominated like the η'

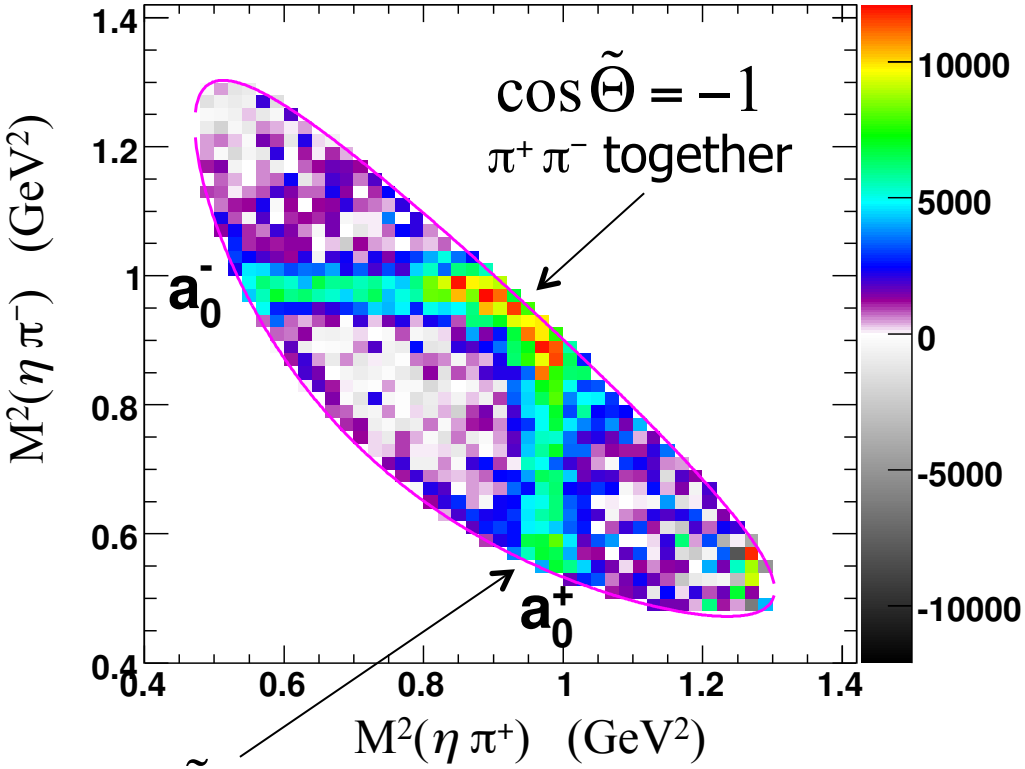
Comparison with Models



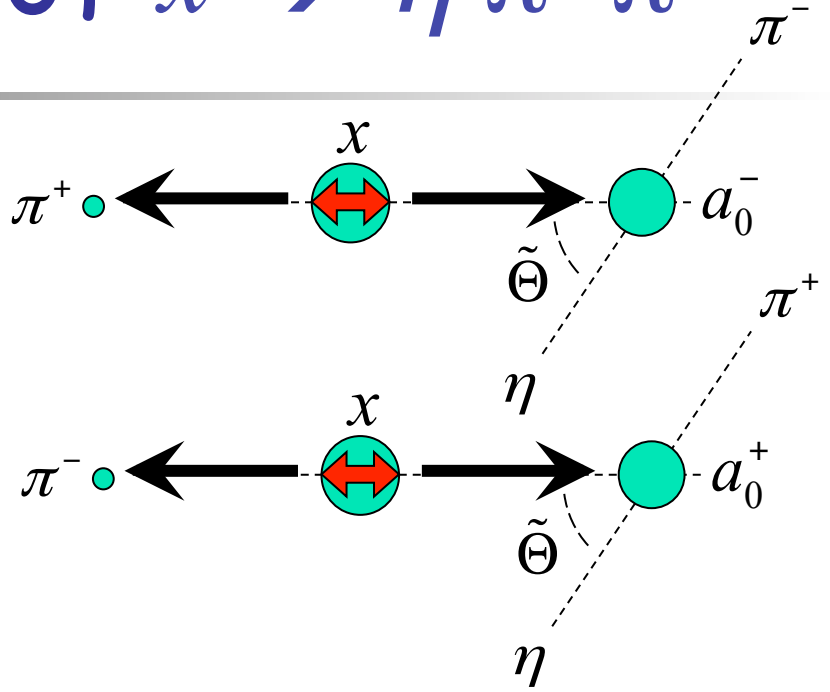
- Solid red: Effective Lagrangian with meson exchange
  - Kochelev *et al.*
- Dashed: Effective Lagrangian with meson exchange
  - Uncontrolled hadronic form factor cut-offs
  - J-J. Xie (unpublished, private comm.)
- Dotted: "Holographic QCD" model
  - S. Domokos: meson exchange with specific recipe to compute couplings

S. Domokos *et al.*, Phys. Rev. **D 80**, 115018 (2009) N. Kochelev *et al.*, Phys. Rev. **C 80**, 025201 (2009)

Dalitz analysis of $x \rightarrow \eta \pi^+ \pi^-$



$\cos\tilde{\Theta} = +1$
$\pi^+\pi^-$ back-to-back



-two amplitudes $A_{m=\pm1}(m_{a_0^+\pi^-}, m_{a_0^-\pi^+})$ to sum for each event

- Background-subtracted acceptance-corrected Dalitz plot reveals dominance of decay via $a_0^{\pm}\,\pi^{\mp}$ intermediate states.
- Strong interference of bands seen. Amplitude analysis!

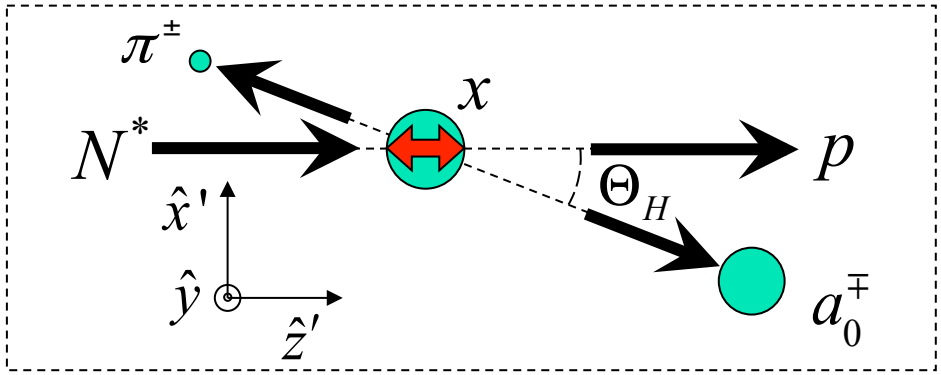
From decay: find spin & parity

$$x \rightarrow a_0^{\pm} + \pi^{\mp}$$

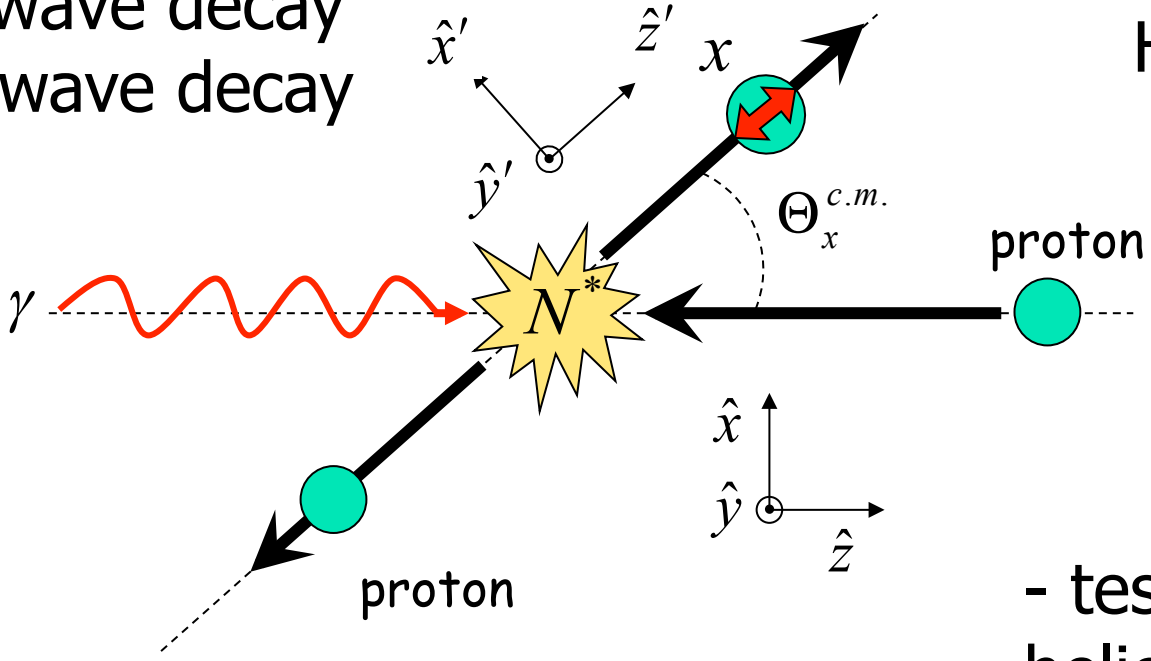
$$J^P \rightarrow 0^+ + 0^- + L^{-1^L}$$

f_1: p-wave decay

η : s-wave decay



Helicity system

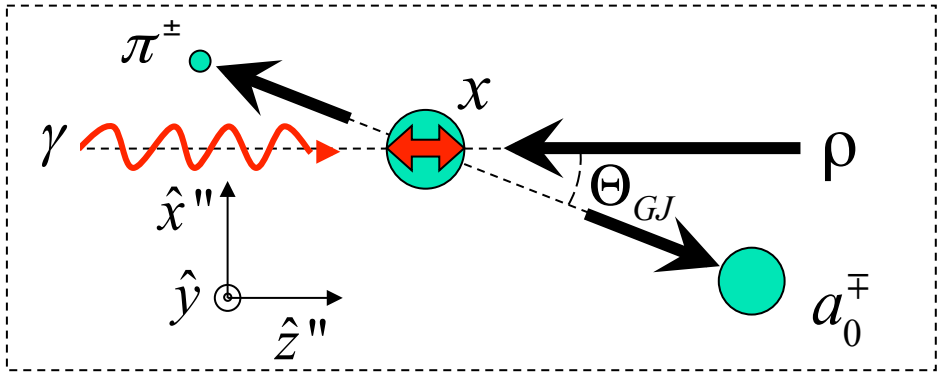


- tests "s-channel helicity conservation"

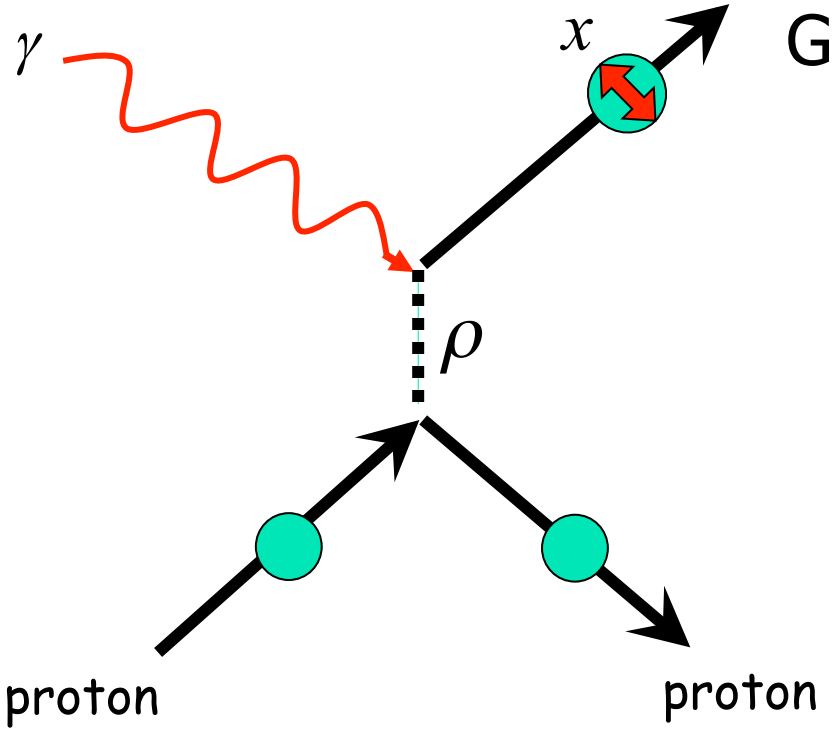
From decay: find spin & parity

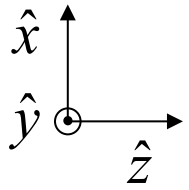
$$x \rightarrow a_0^{\pm} + \pi^{\mp}$$

$$J^P \rightarrow 0^+ + 0^- + L^{-1^L}$$



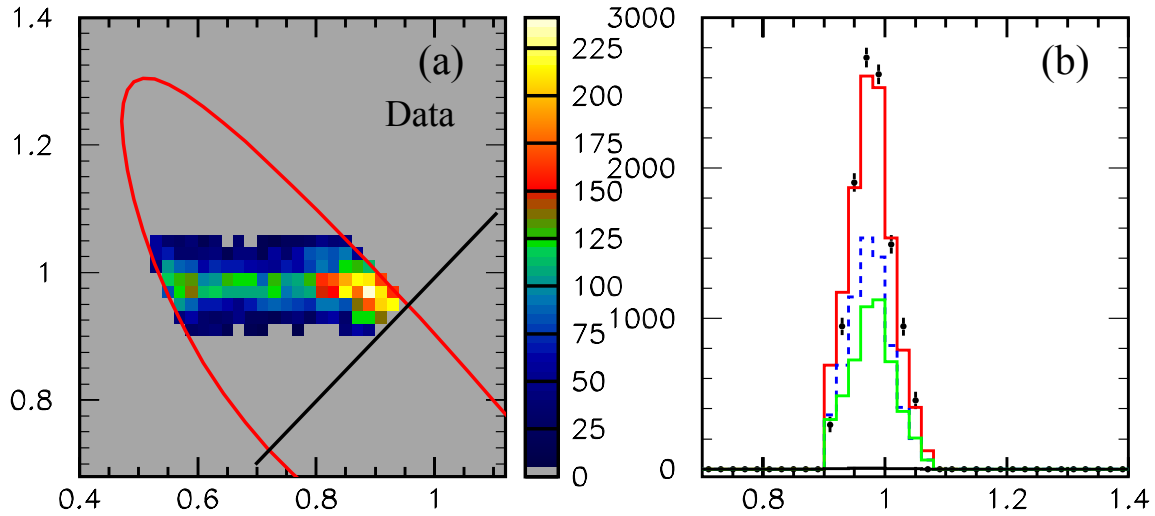
Gottfried-Jackson system





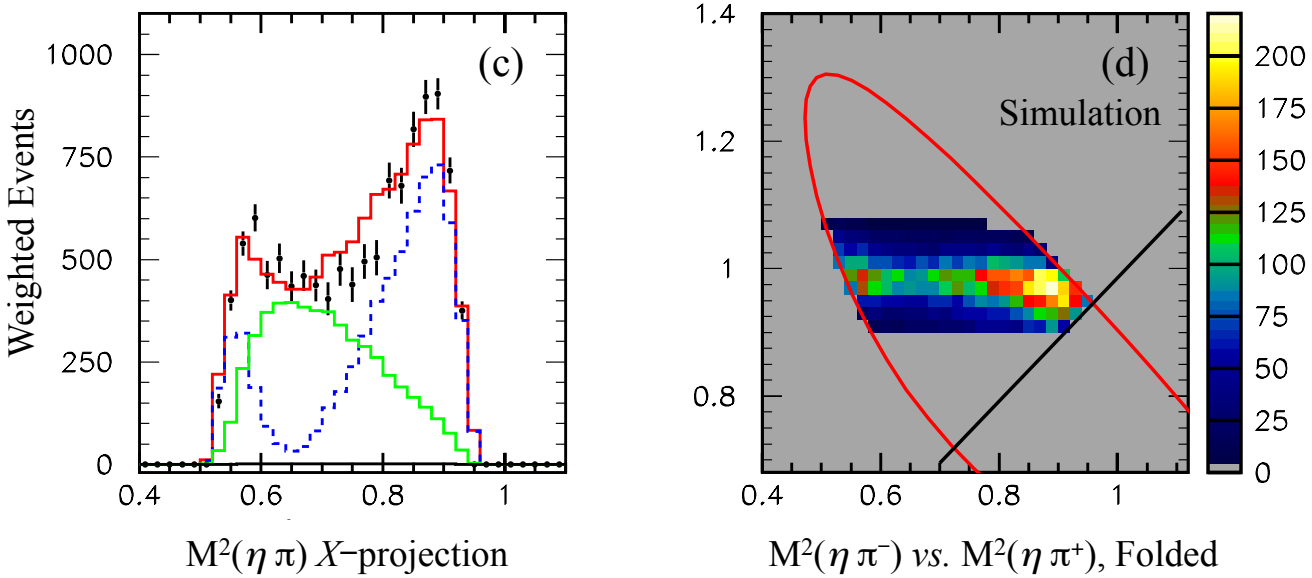
- tests "t-channel helicity conservation"

Helicity system fit succeeds!



$M^2(\eta\pi^-)$ *vs.* $M^2(\eta\pi^+)$, Folded

$M^2(\eta\pi)$ *Y*–projection

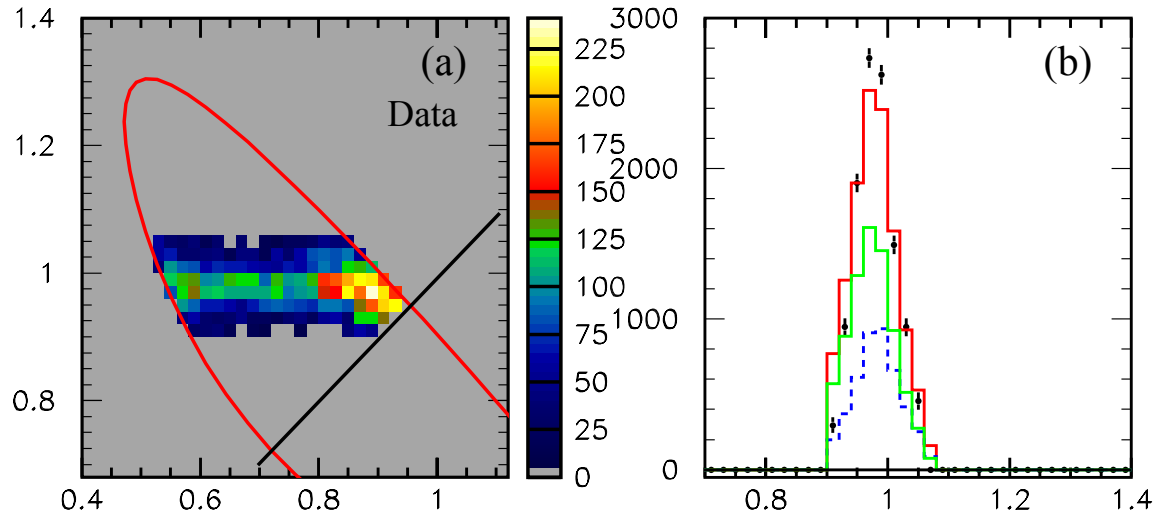


$M^2(\eta\pi)$ *X*–projection

$M^2(\eta\pi^-)$ *vs.* $M^2(\eta\pi^+)$, Folded

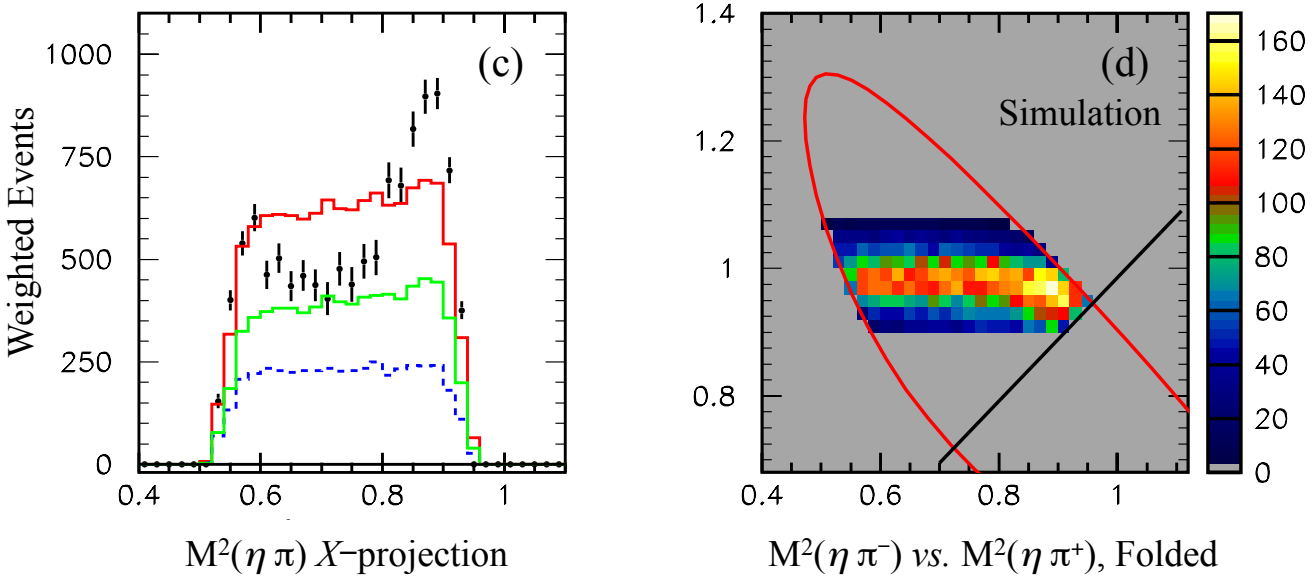
- *s*-channel helicity system
- Components:
  - Blue: L=1, m=0
  - Green: L=1, m=±1
  - Red: Total
- $a_0^{\pm}$ interference reproduced
- *p*-wave decay and positive parity demonstrated
- Decaying meson is definitely the $f_1(1285)$

Gottfried-Jackson system fit



$M^2(\eta\pi^-)$ *vs.* $M^2(\eta\pi^+)$, Folded

$M^2(\eta\pi)$ *Y*−projection



$M^2(\eta\pi)$ *X*−projection

$M^2(\eta\pi^-)$ *vs.* $M^2(\eta\pi^+)$, Folded

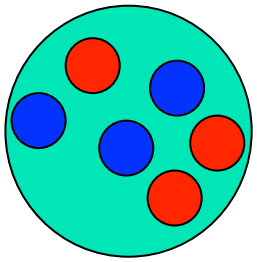
- *t*-channel helicity system
- Components:
  - Blue: L=1, m=0
  - Green: L=1, m=±1
  - Red: Total
  - Cyan: L=0 fit
- a_0 interference NOT reproduced
- Decaying meson is not aligned in this system

Conclusions re $f_1(1285)$:

- The photoproduced meson CLAS sees at 1281 MeV is the $f_1(1285)$, not the $\eta(1295)$.
- It comes from the decay of N^* or other non-t-channel processes.
- Can it be done in the nuclear medium?
- MIN theme of medium modifications: <u>how is this axial-vector meson altered in the medium</u>?
  - Discuss…

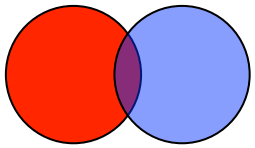
Photoproduction of Structure in the $d\pi$ System Near the $N\Delta$ Mass: Sign of a Quasi- Bound State?

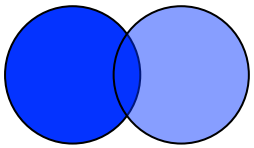
Two-baryon resonances



- 6 quarks in a bag

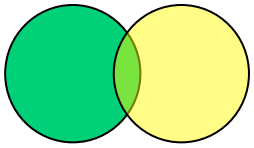
- The deuteron
  - 2.2 MeV bound
  - The only clear-cut "dibaryonic molecule"

$^3S_1$  $I(J^P)=0(1^+)$ "$\mathcal{D}_{01}$"

$^1S_0$  $I(J^P)=1(0^+)$ "$\mathcal{D}_{10}$"

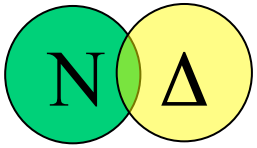
- Recall the *nn*, *pp*, and *np* strong spin singlet states are unbound…
  - … by only ~100 keV
  - One of the great "fine-tuning" mysteries of nature!!

Two-baryon resonances



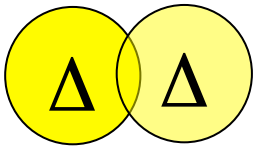
I (J^P)

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



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

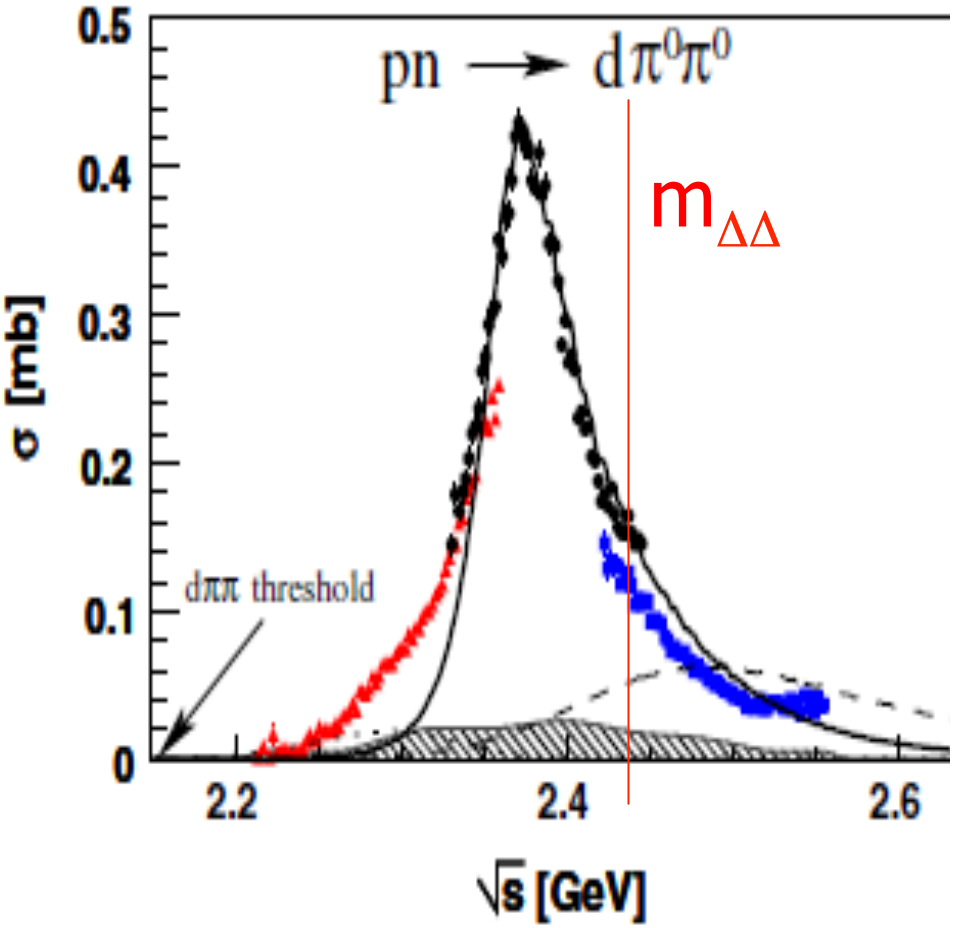
- CLAS study: new observations



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

- Recent WASA@COSY discovery

$d^*(2380)$ 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 "$\mathcal{D}_{03}$"
- interpretation has been controversial

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

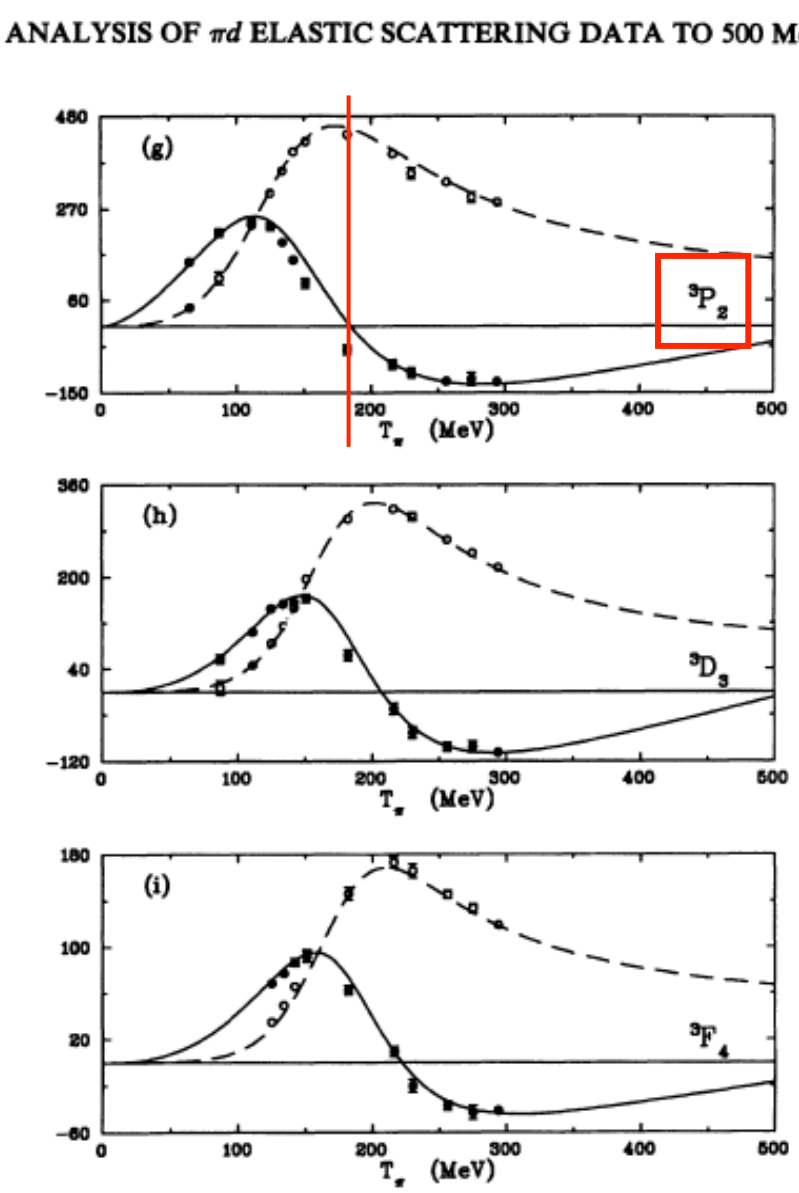
Quasi-bound states

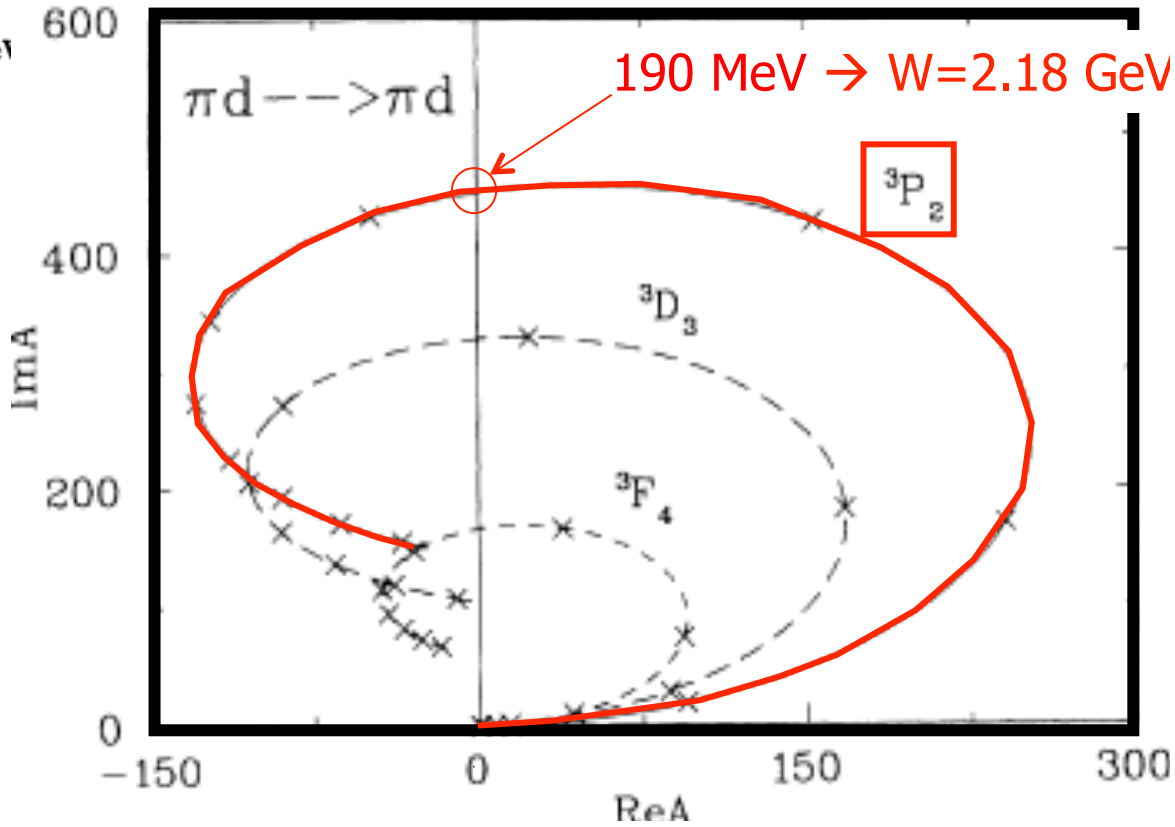
- What about $N\Delta$?
  - If a $\Delta\Delta$ ("$\mathcal{D}_{03}$") state exists, so should $N\Delta$
  - Expect $N\Delta$ to have $I\ J^P = 1\ 2^+$ ("$\mathcal{D}_{12}$")

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

Pole Position $\mathcal{D}_{12}$ (MeV)	Model Approach	Ref.
$2147 - i60$	Faddeev model $\pi NN,\ \pi\Delta N$	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.

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

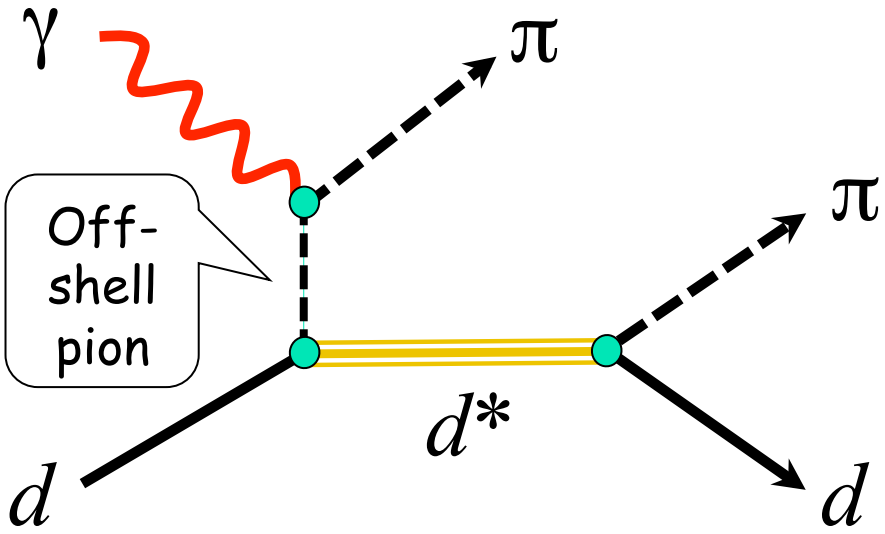




- $^3P_2$ wave in πd elastic scattering is most prominent
- SAID analysis: "resonance-like" behavior in several partial waves

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

Photoproduction Scenario



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

What can CLAS see?

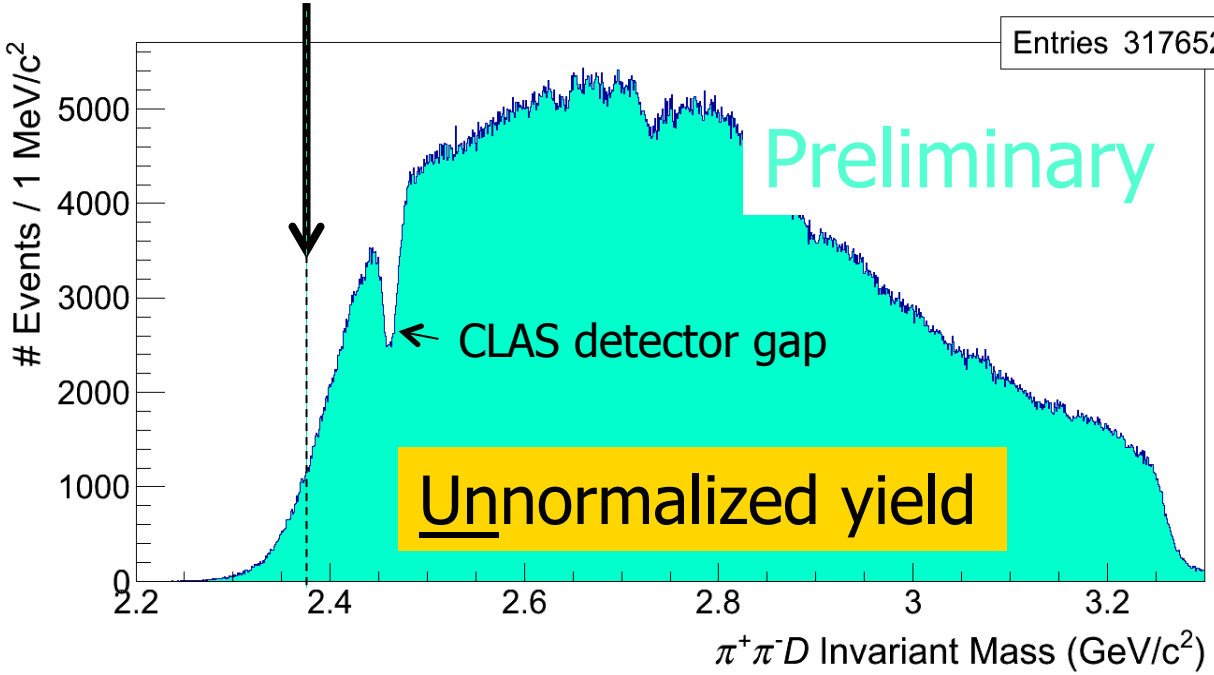
- Photons on a deuteron target
  - g10, g13, g14 data sets
- Spin-1 photon & spin-1 deuteron:
  - $\vec{1} + \vec{1} \rightarrow \vec{J} = \vec{0}, \vec{1}, \vec{2}$ in S wave, is favorable
- Isospin $\mathrm{I} = \{0,1\} + 0$ → $0, 1$ allowed
- We looked for both $\mathrm{N}\Delta$ and $\Delta\Delta$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

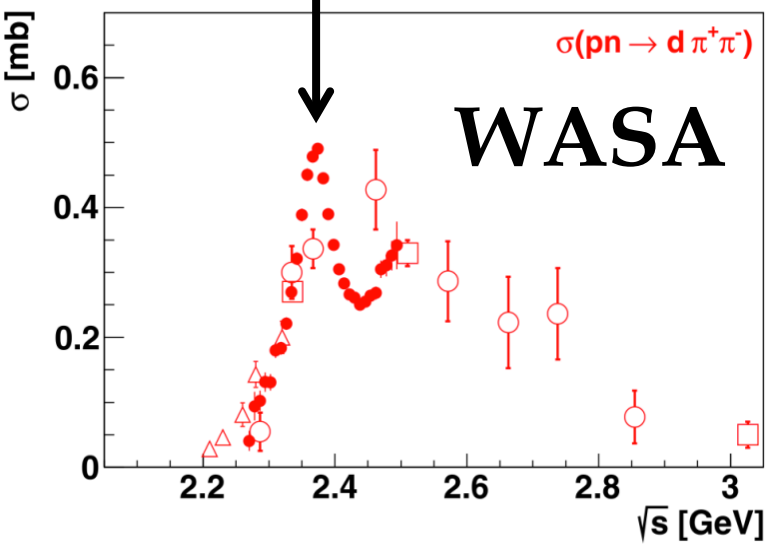
- Preliminary CLAS data showing
  - No sign of a "ΔΔ" signal
  - Evidence for ρ background
  - Evidence for a "NΔ" signal

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

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

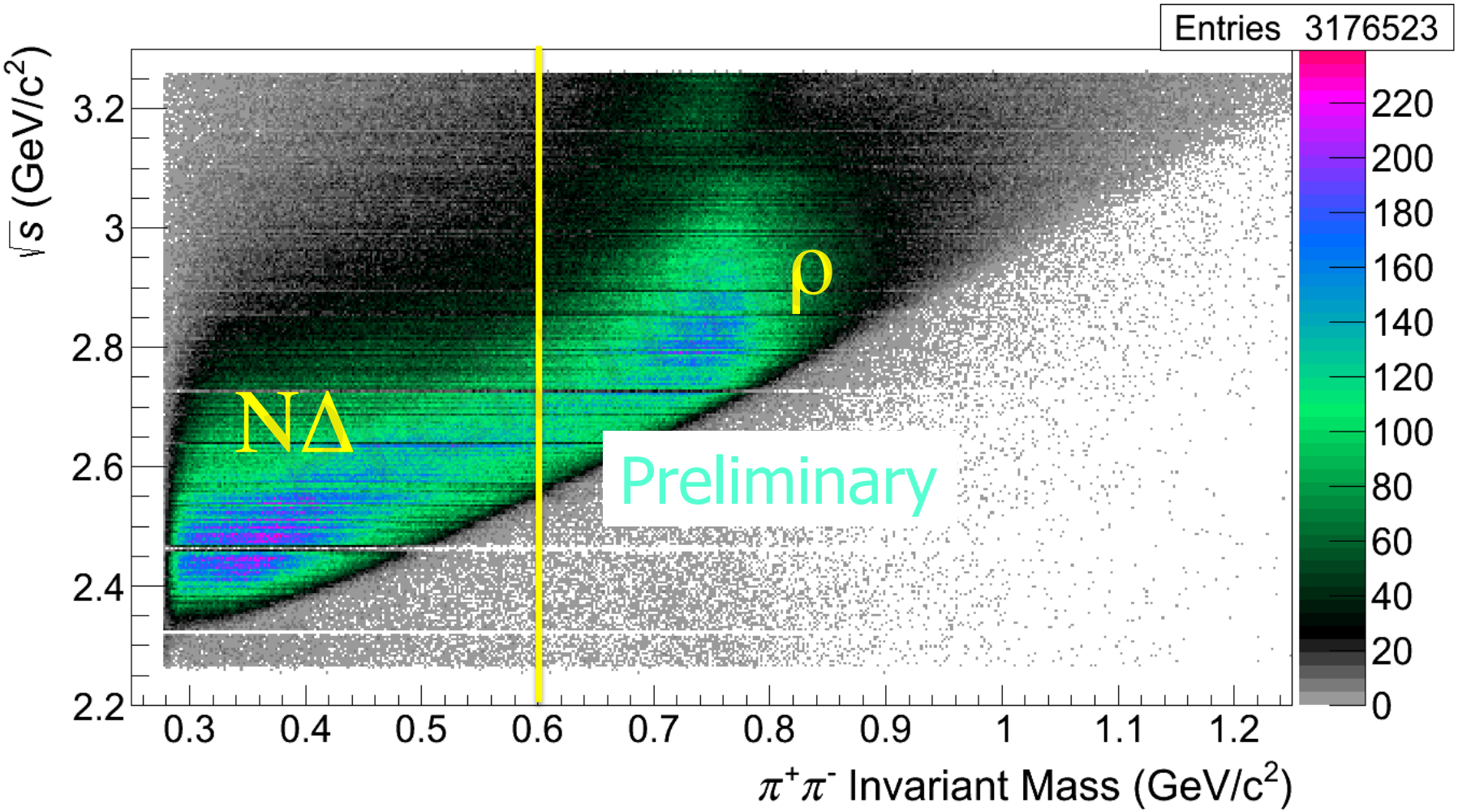
No hint of a "ΔΔ" bump!



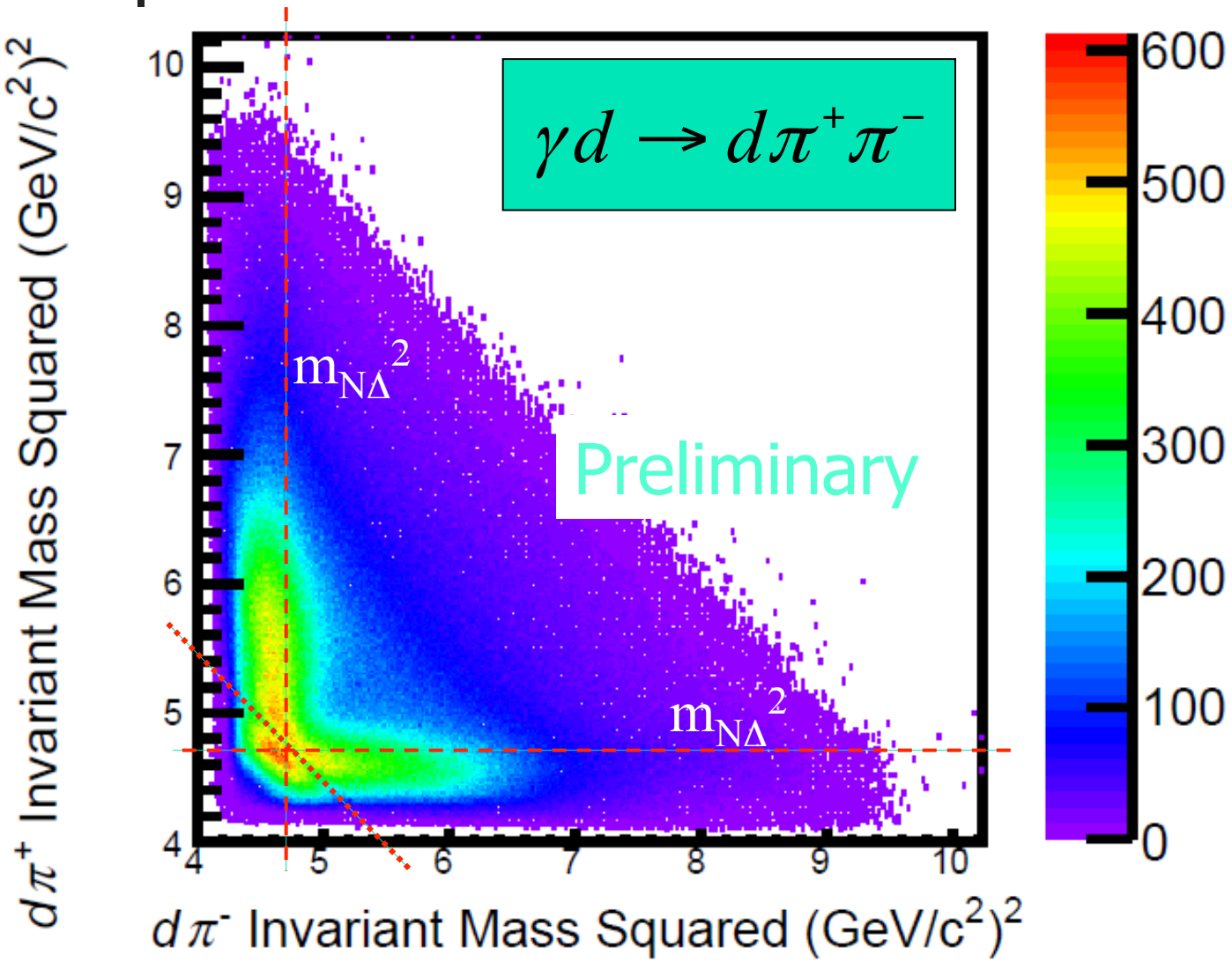


P. Adlarson *et al.*, Phys. Rev. C **88**, 055208

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

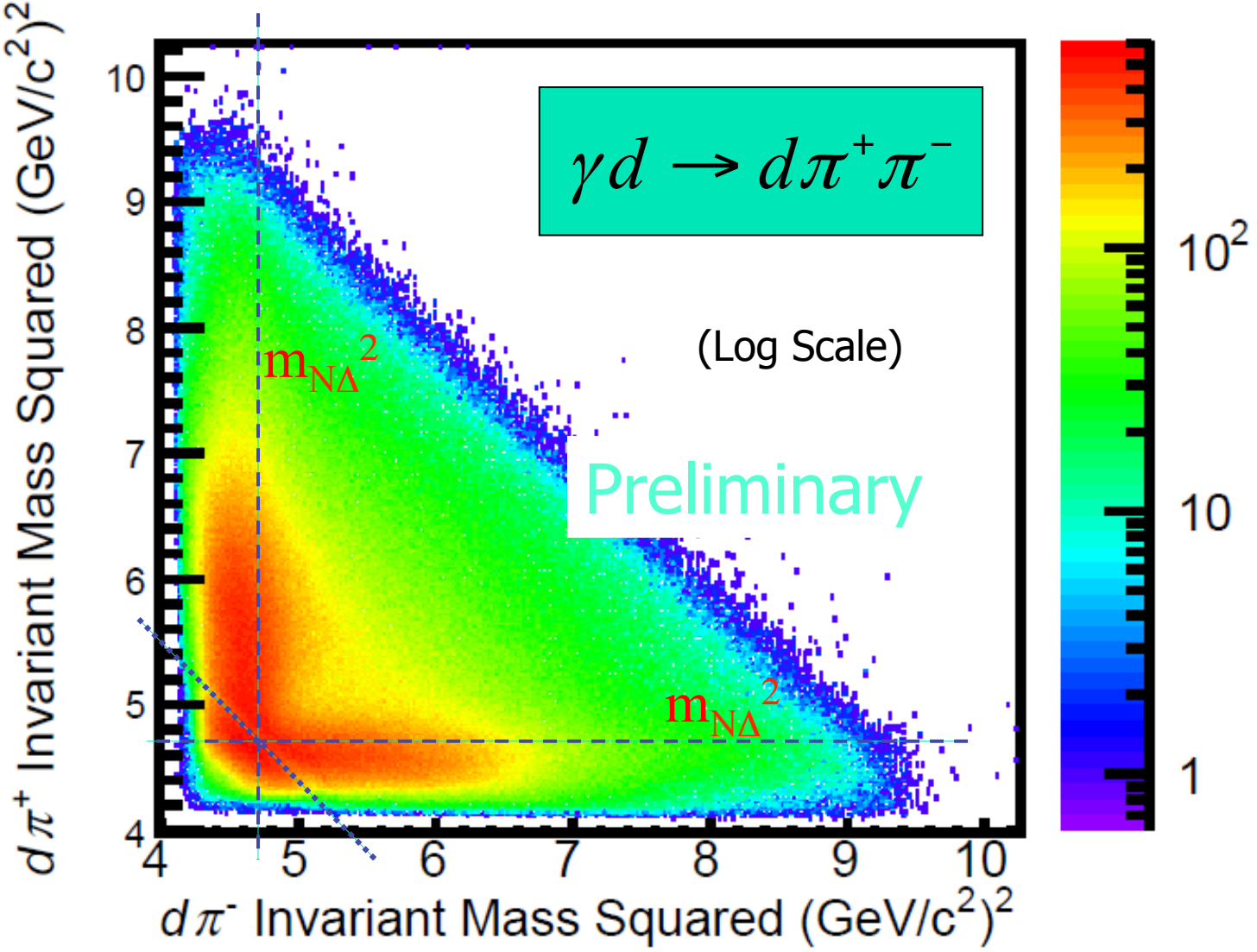


Dalitz Plot: $d\pi^+$ vs. $d\pi^-$



- 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 photon channel
- Clear preference for $d\pi^\pm$ correlation near the NΔ mass!

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



Acceptance-corrected CLAS (g13)

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$2.45 < W < 3.15$ GeV

W~constant on diag.

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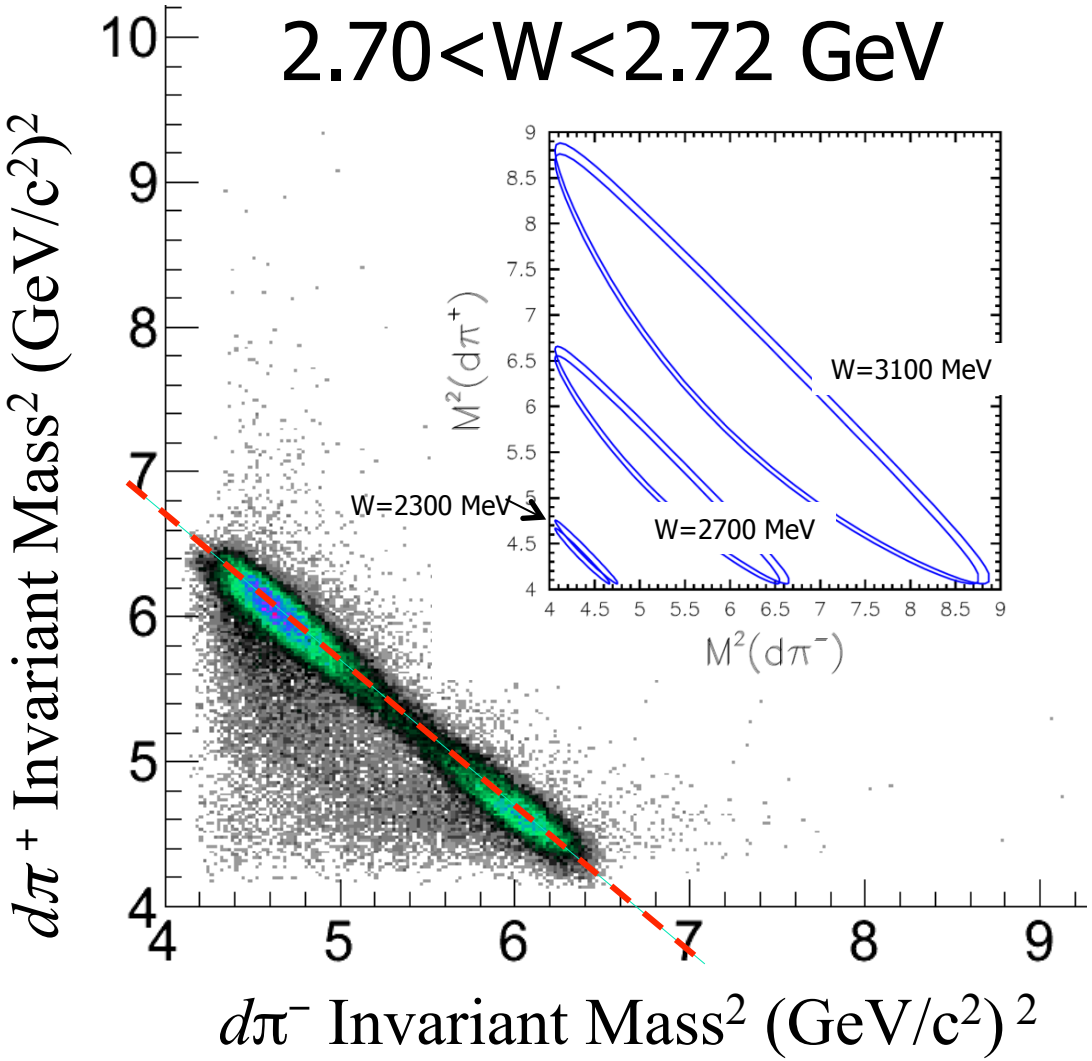
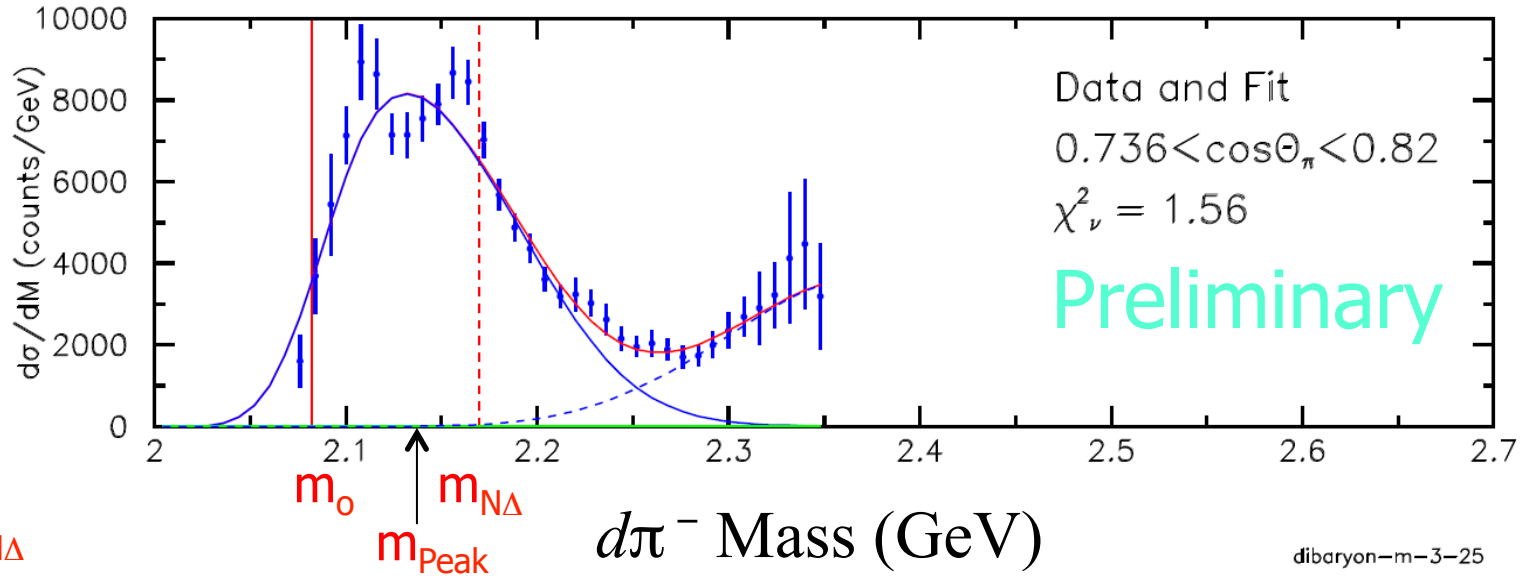
Clear preference for $d\pi^\pm$ correlation near the NΔ mass!

Fit to Resonance-like Shapes



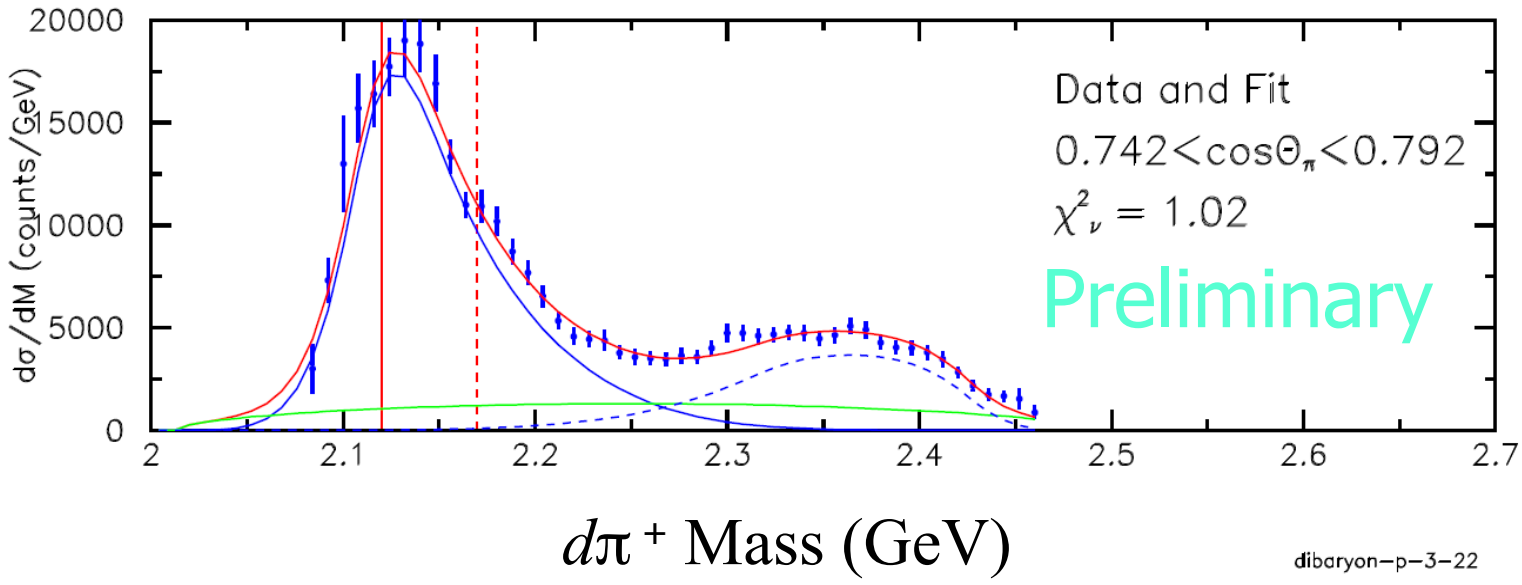
- Use 50 MeV slices in
- Assume a Breit-Wigner line shape
- Let $d\pi$ system decay to $N\Delta$ (L=0), $d\pi$ (L=1), and NN (L=2)
- ρ not cut away; model as P.S. background
- Incoherent amplitudes
- Following fits are preliminary! Prelude to PWA analysis

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



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

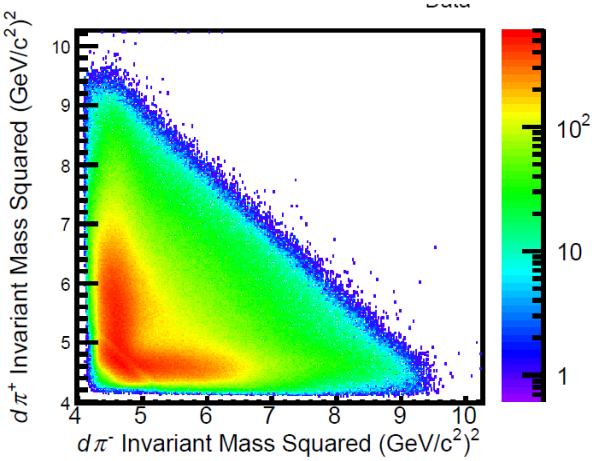
m_o $m_{N\Delta}$ m_{Peak}



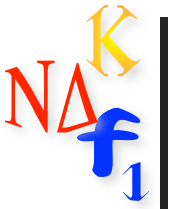
Observations

- Peaks are all below the $N\Delta$ centroid
- Peaks widths are not identical: $\cos\theta_\pi$ dependent; very preliminary result:
  - $m_{peak} = 2115 \pm 10\ MeV/c^2$
  - $FWHM = 125 \pm 25\ MeV$
- We have remaining acceptance issues near high and low edges
- Best fits are found using non-relativistic BW line shapes with $L_{\pi d} = 1$

Summary re NΔ → $d\,\pi$ Structure



- Big $\pi^{\pm}d$ signal seen in CLAS photo-production data, peaking below the NΔ mass.
  - Dominant at forward pion angles.
- Extracting mass and width depends on line-shape model, ρ treatment, amplitude interferences…
- We are NOT claiming that this $d\pi$-system bump is necessarily the expected resonant $\mathcal{D}_{12}$ state… but it could be
  - Final/initial state interactions, other dynamics…
  - Scattering matrix poles vs. peaks in spectra…
- Spin determination in progress via $\vec{\gamma}\vec{d} \rightarrow d\pi^+\pi^-$



Overall Summary

- First study of $f_1(1285)$ in photoproduction
  - Unusual photo-production mechanism
  - Study in nuclear medium shifts?

- Signs of an $N\Delta$ quasi-bound structure decaying to $d\pi$
  - Coherent two-pion photoproduction off deuteron
  - $\mathcal{D}_{12}$ candidate (preliminary)