MESON 2016

Photoproduction of the $f_1(1285)$ Meson

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Ph.D. work of Ryan Dickson, completed 2011

arXiv:1604.07425 [nucl-ex], Accepted by Phys. Rev. C

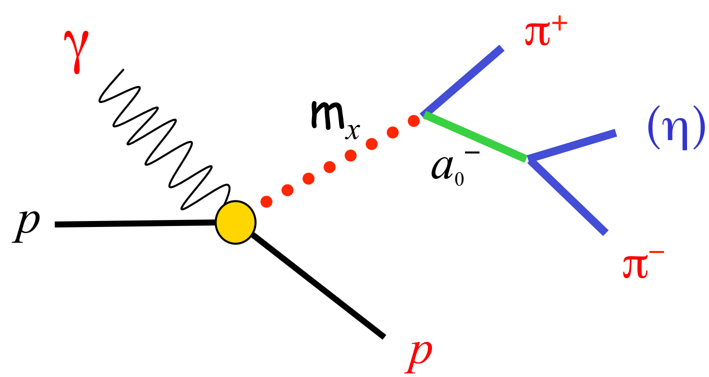
Jefferson Lab

MESON2016, Krakow PL, June 3, 2016

clas CEBAF Large Acceptance Spectrometer

Outline

- What are the $f_1(1285)$ and $\eta(1295)$ mesons?
- Identification of the state in CLAS/g11
- Results for:
  - Mass and Width
  - Differential cross sections – model comparisons
  - Branching ratios $\eta\pi\pi$, $\gamma\rho^0$, $K\,K\,\pi^-$
  - Dalitz plot analysis
    - spin and parity determination

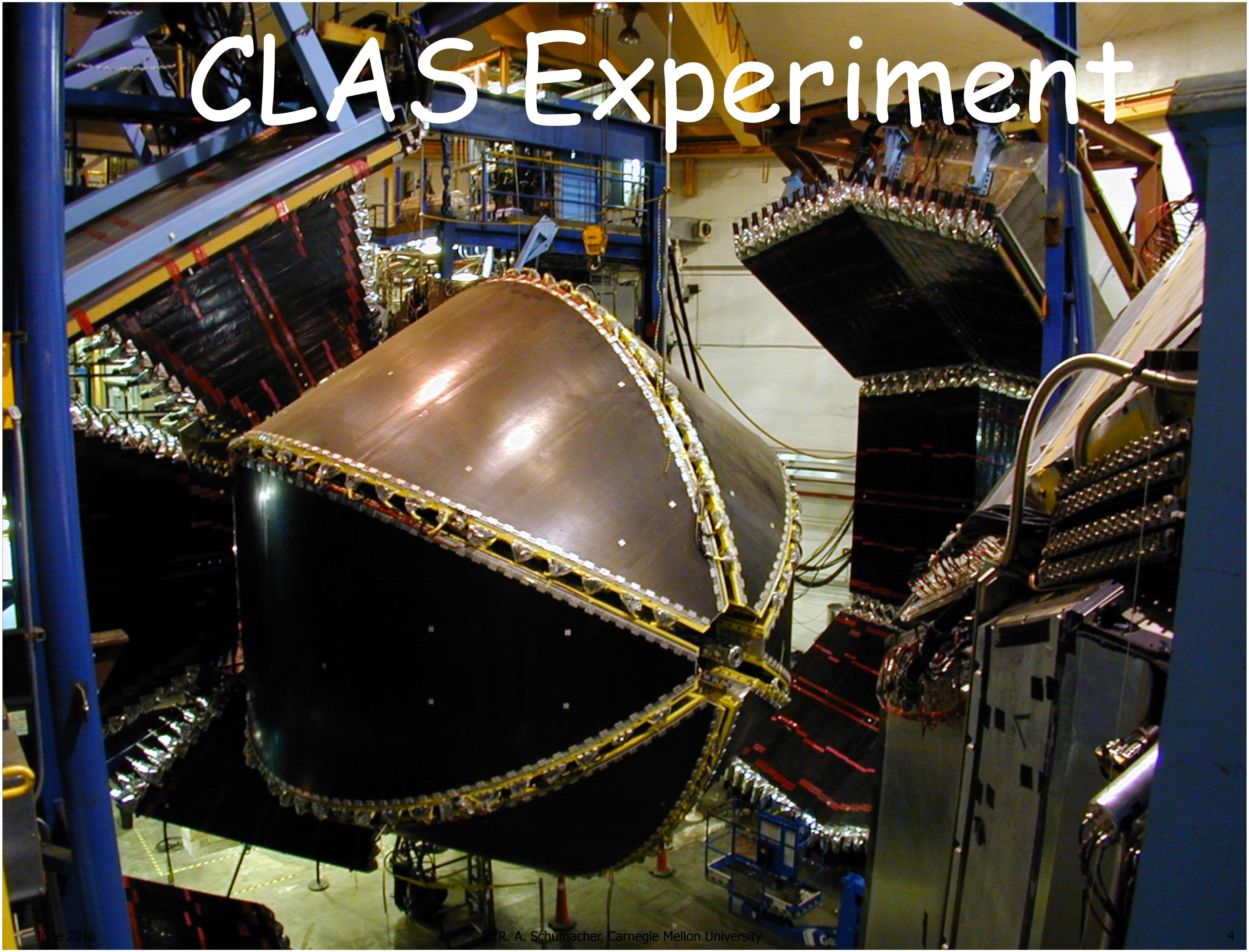


Two Players:

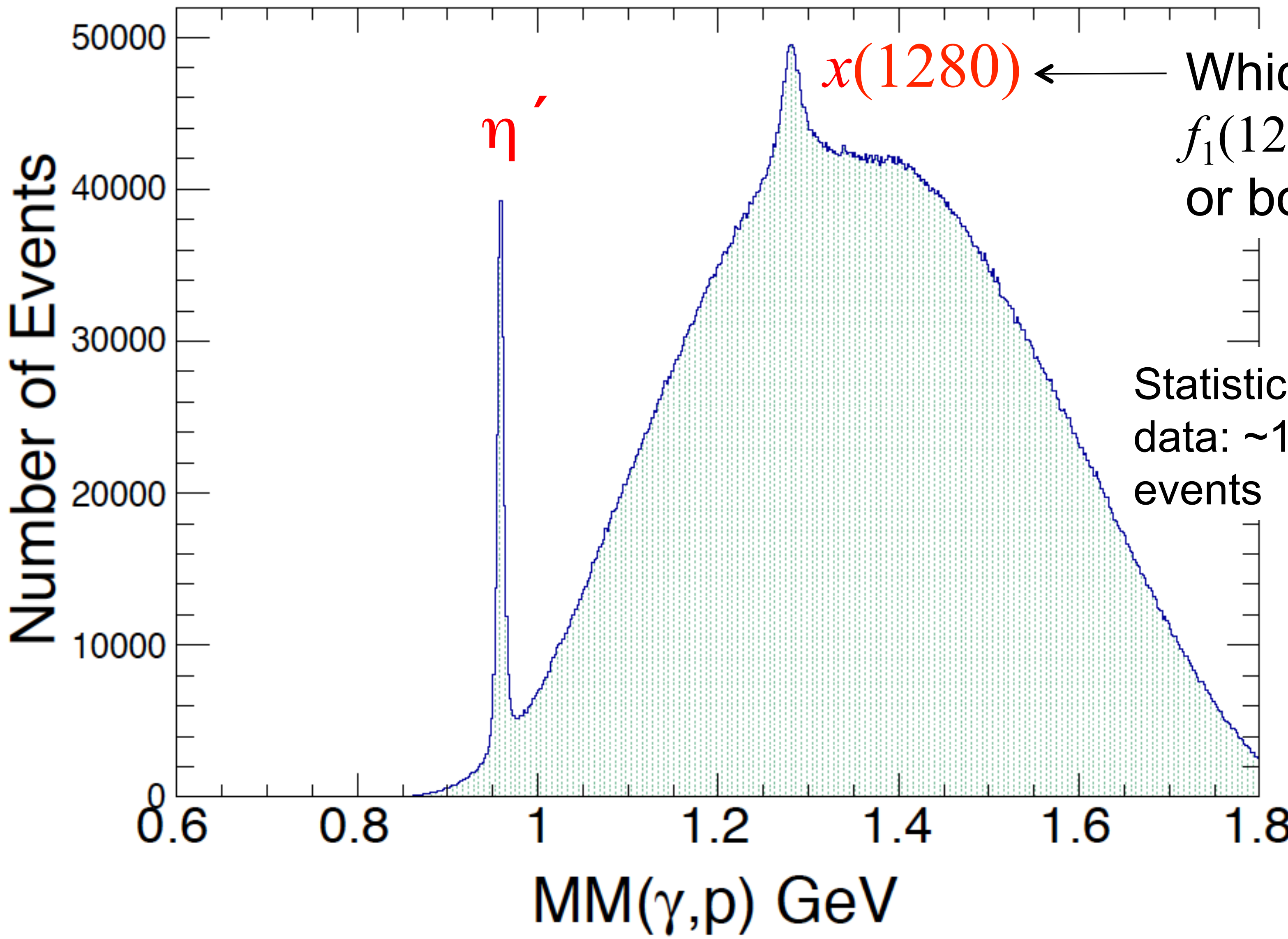
- $f_1(1285)$ $I^G(J^{PC}) = 0^+(1^{++})$
  - Well-established axial-vector meson seen in hadronic reactions;
    - Seen in experimental PWA analyses
    - Seen in Lattice QCD
  - Possible "dynamically generated" $K\overline{K^*} - \text{c.c.}$ state

- $\eta(1295)$ $I^G(J^{PC}) = 0^+(0^{-+})$
  - 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

CLAS Experiment



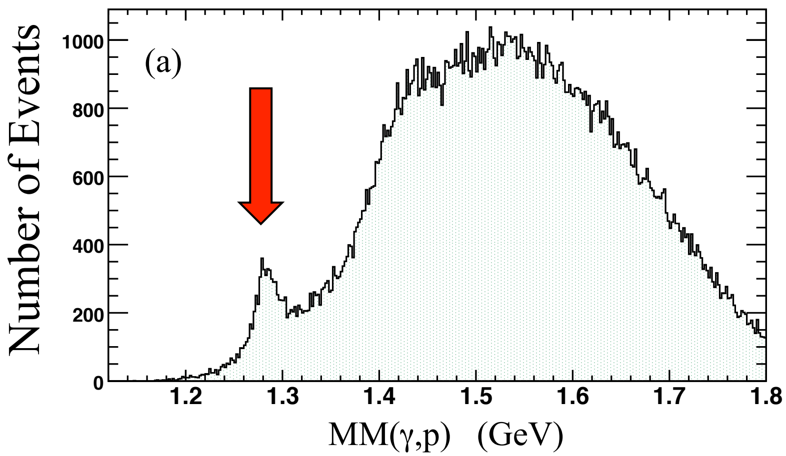
First Observation of $f_1(1285)$ or $\eta(1295)$ in $\gamma p \rightarrow p\, x \rightarrow p\, \pi^+ \pi^- (\eta)$

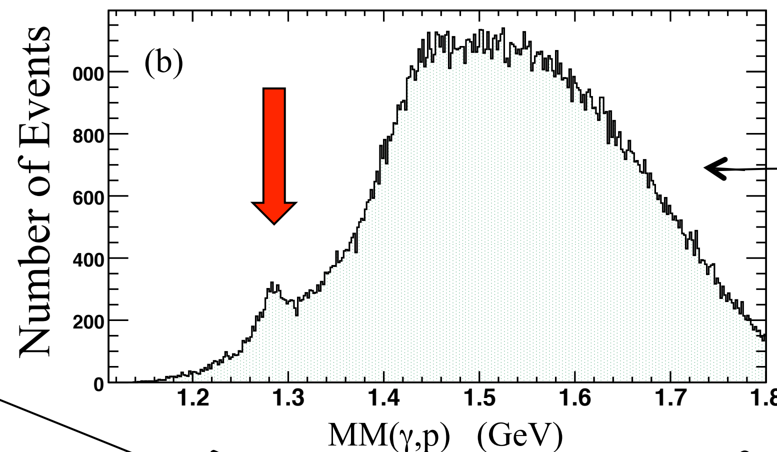


Which state is it? $f_1(1285)$, $\eta(1295)$, or both?

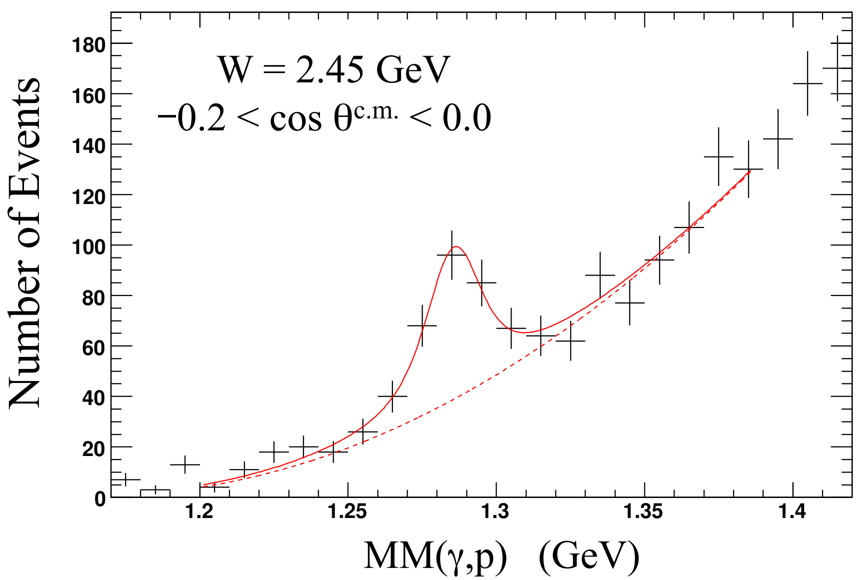
Statistics in CLAS g11 data: ~1.5 x 10^5 $x(1280)$ events

Two $x \rightarrow K\,K\,\pi$ decay modes

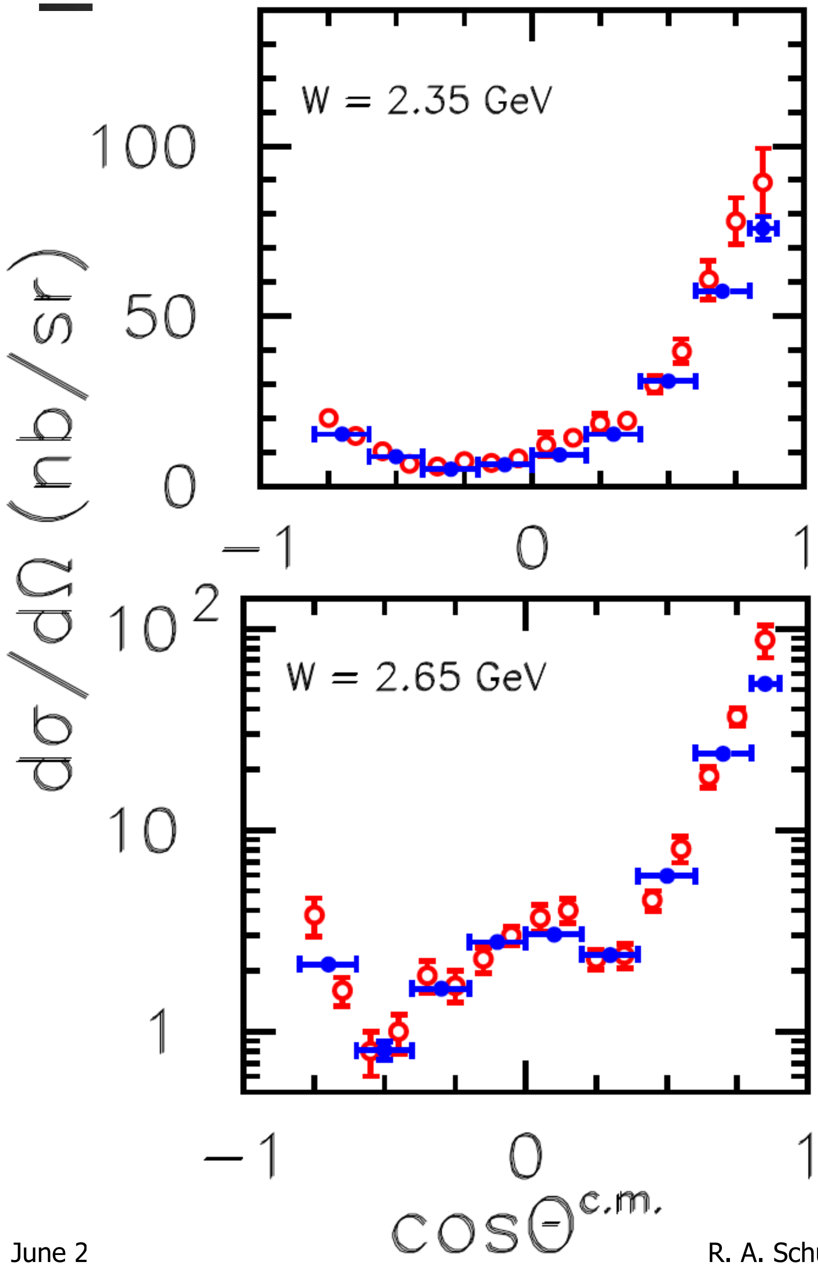




- Detect $p\,K^+\pi^-\,(K^0)$
  - (left)
- Detect $p\,K^-\pi^+\,(\overline{K^0})$
  - (right)
- Combine channels prior to yield extraction using Voigtian + polynomial



Cross-check η′ cross section



- Compare two CLAS analyses of η′ photoproduction
  - Same data set, using different methods
    - Red: Williams & Krahn *et al.**
    - Blue: Dickson *et al.* (this work)
  - Good agreement between independent analyses
- Use (small) differences to quantify systematic uncertainty

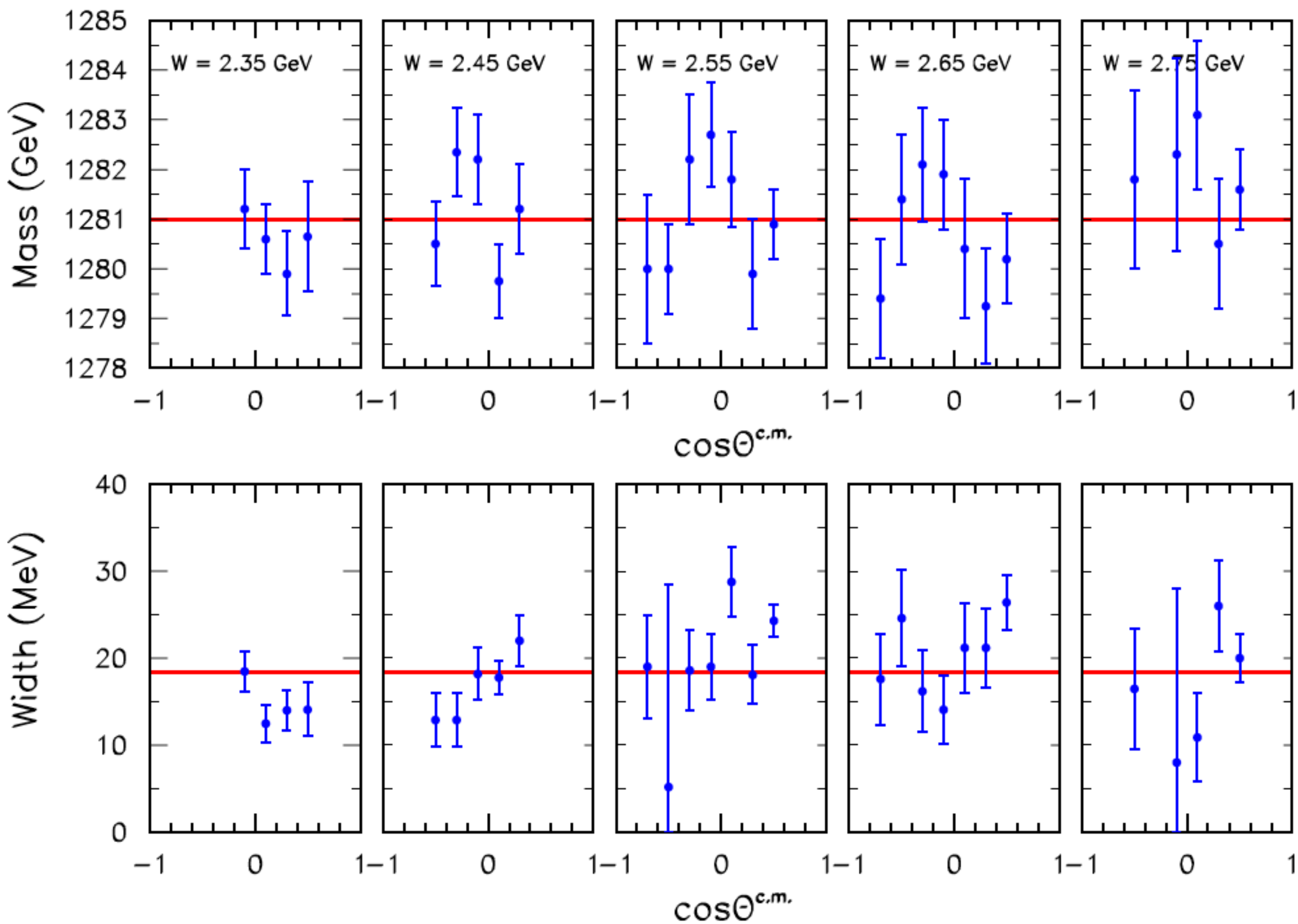
(Note log scale)

*M. Williams *et al.*, Phys. Rev. **C 80**, 045213 (2009)

Results

arXiv:1604.07425 [nucl-ex], Accepted by Phys. Rev. C
R. Dickson et al., CLAS Collaboration

Mass & Width Measurement



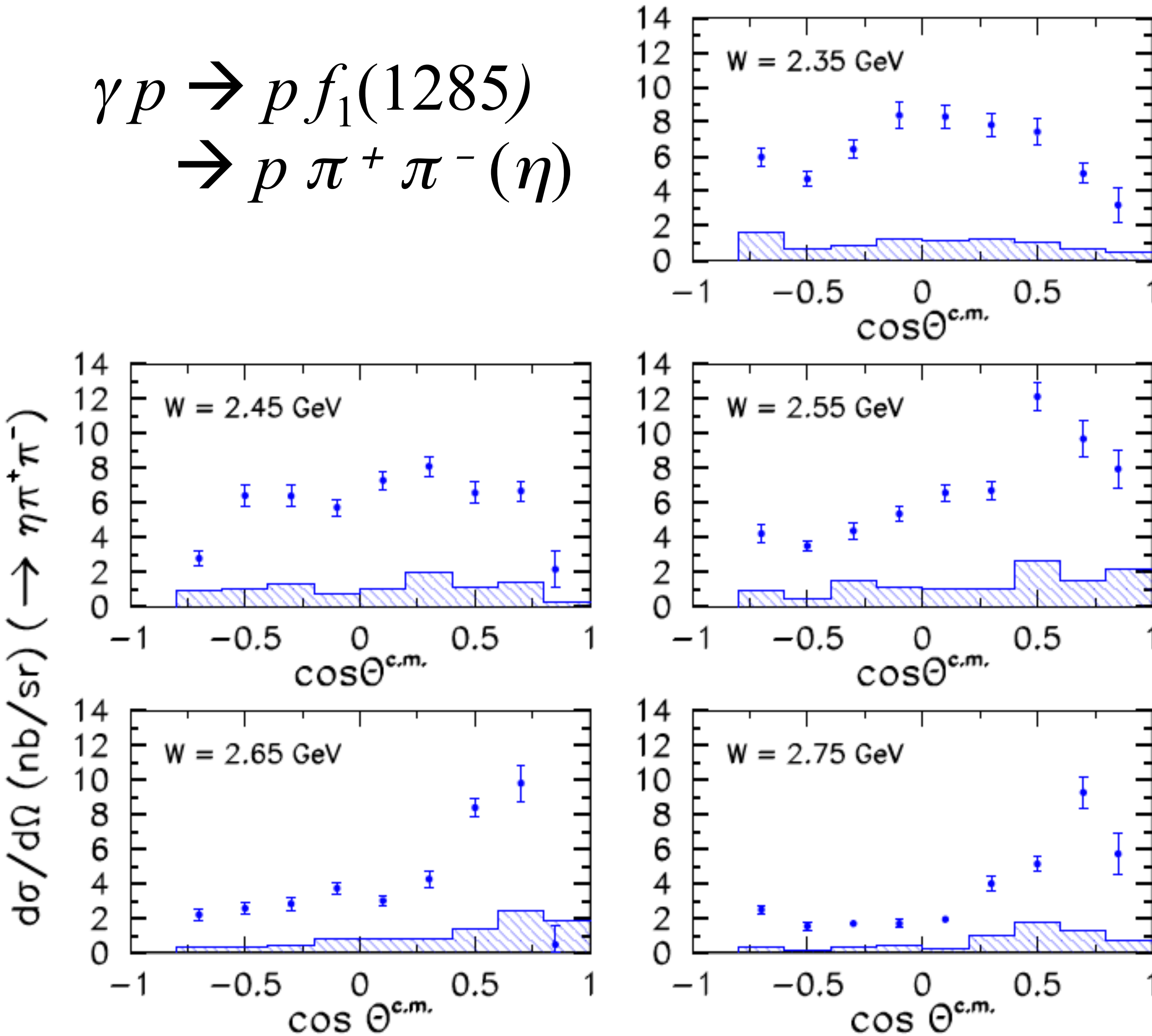
Mass & Width Measurement

Channel		Mass (MeV/c^2)	Width (MeV/c^2)
$\eta' \to \eta\pi^+\pi^-$	CLAS	958.48 ± 0.04	$\Gamma \ll \sigma_{exp}$
$x \to \eta\pi^+\pi^-$	CLAS	1281.0 ± 0.8	18.4 ± 1.4
η'	PDG	957.78 ± 0.06	0.198 ± 0.009
$f_1(1285)$	PDG	1281.9 ± 0.5	24.2 ± 1.1
$\eta(1295)$	PDG	1294 ± 4	55 ± 5

- Mass consistent with PDG value for $f_1(1285)$ not $\eta(1295)$
- Width is smaller than PDG by several σ

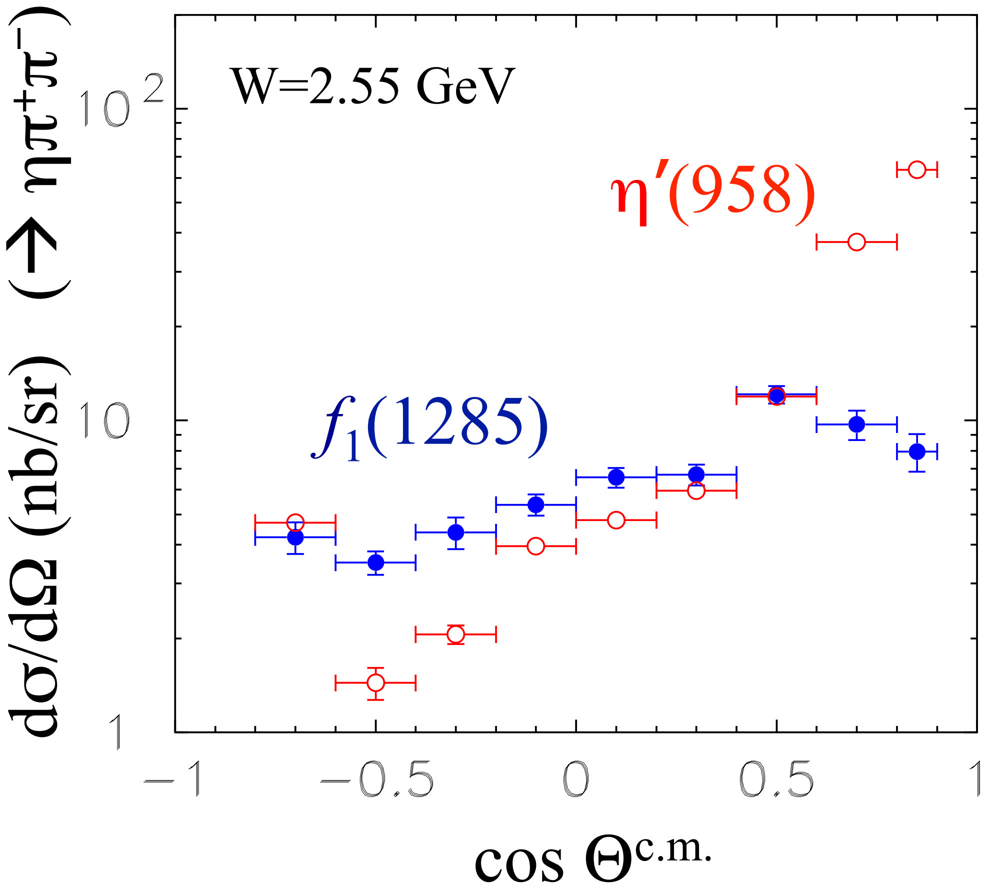
Cross Section vs. Angle and W

$\gamma p \rightarrow p f_1(1285)$
$\rightarrow p \pi^+ \pi^- (\eta)$



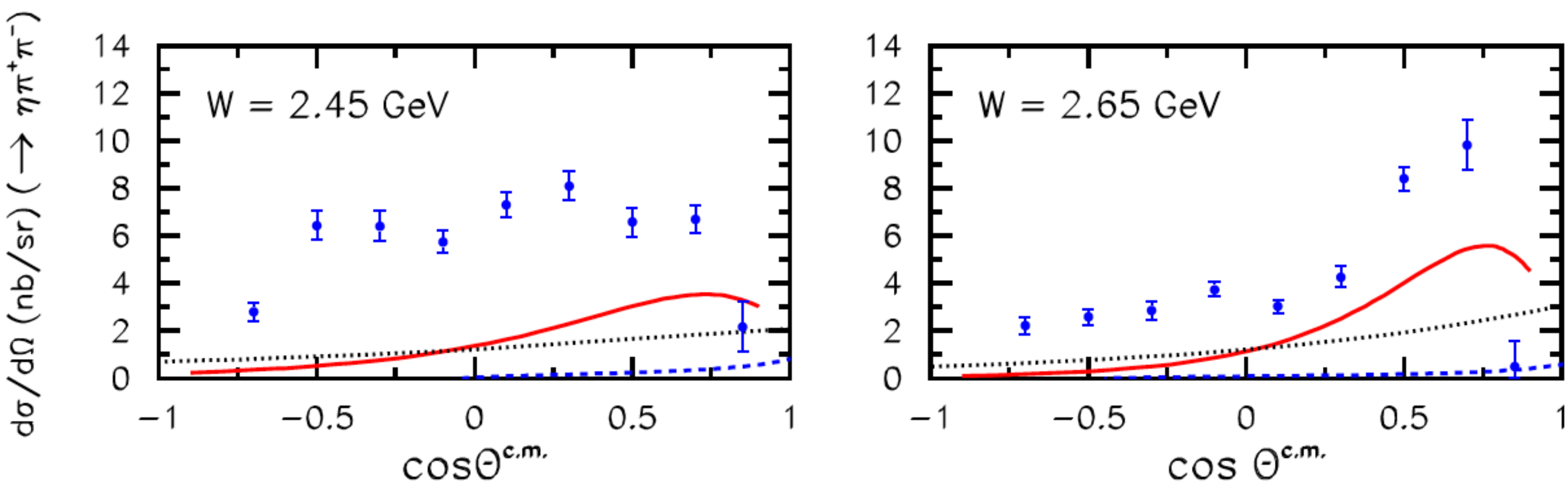
- Differential cross-sections
  - $\eta\pi^+\pi^-$ final state
  - total rate not measured
- Systematic uncertainty
- Very weak forward peaking seen
  - Cross section falls at very forward angles

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



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

Comparison with Models

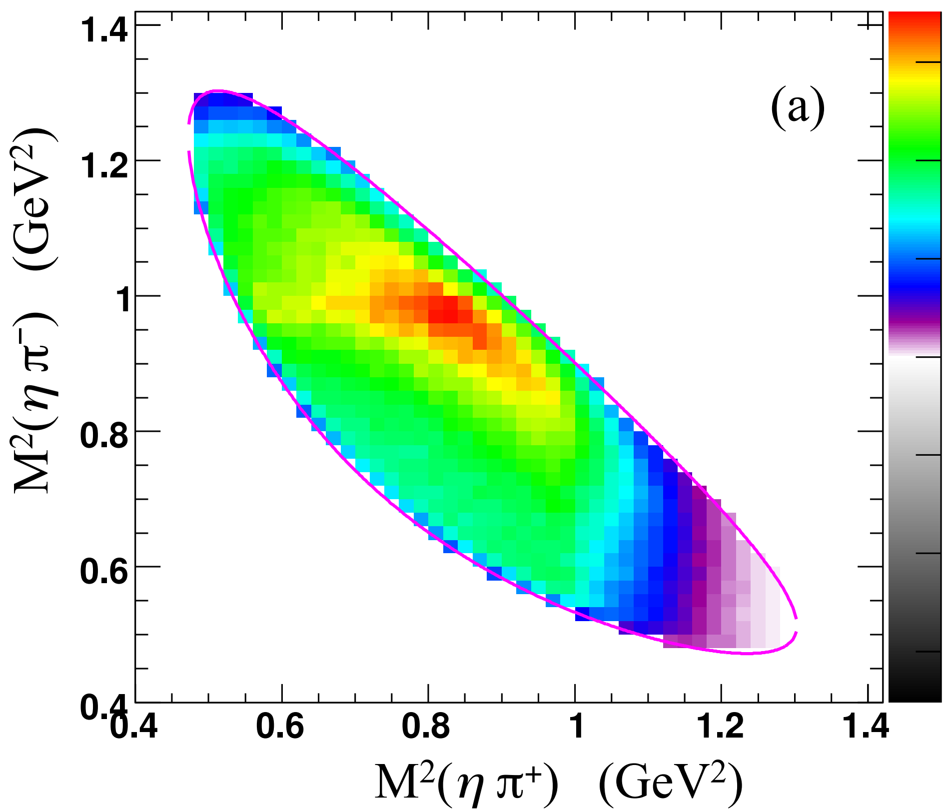


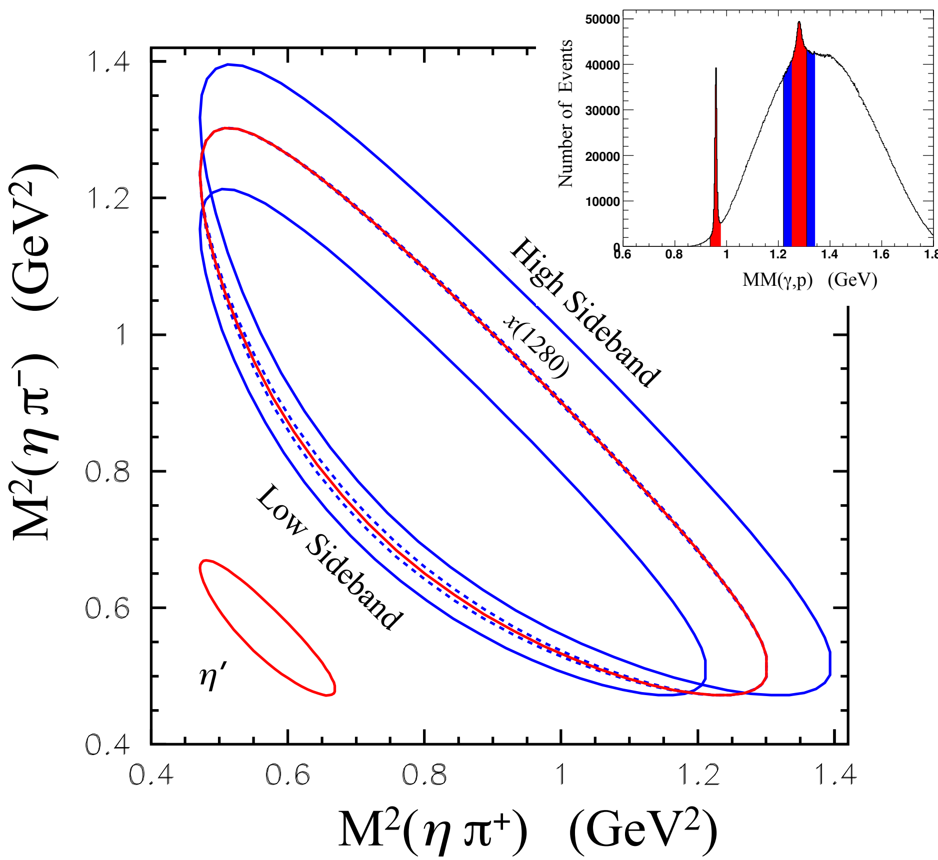
- Solid red: Effective Lagrangian with meson exchange
  - Kochelev *et al.*
- Dashed: Effective Lagrangian with meson exchange
  - Uncontrolled hadronic form factor cut-offs
  - J-J. Xie (unpublished, private comm.)
- Dotted: "Holographic QCD" model
  - S. Domokos: meson exchange with specific recipe 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 $x \rightarrow \eta\,\pi^+\pi^-$

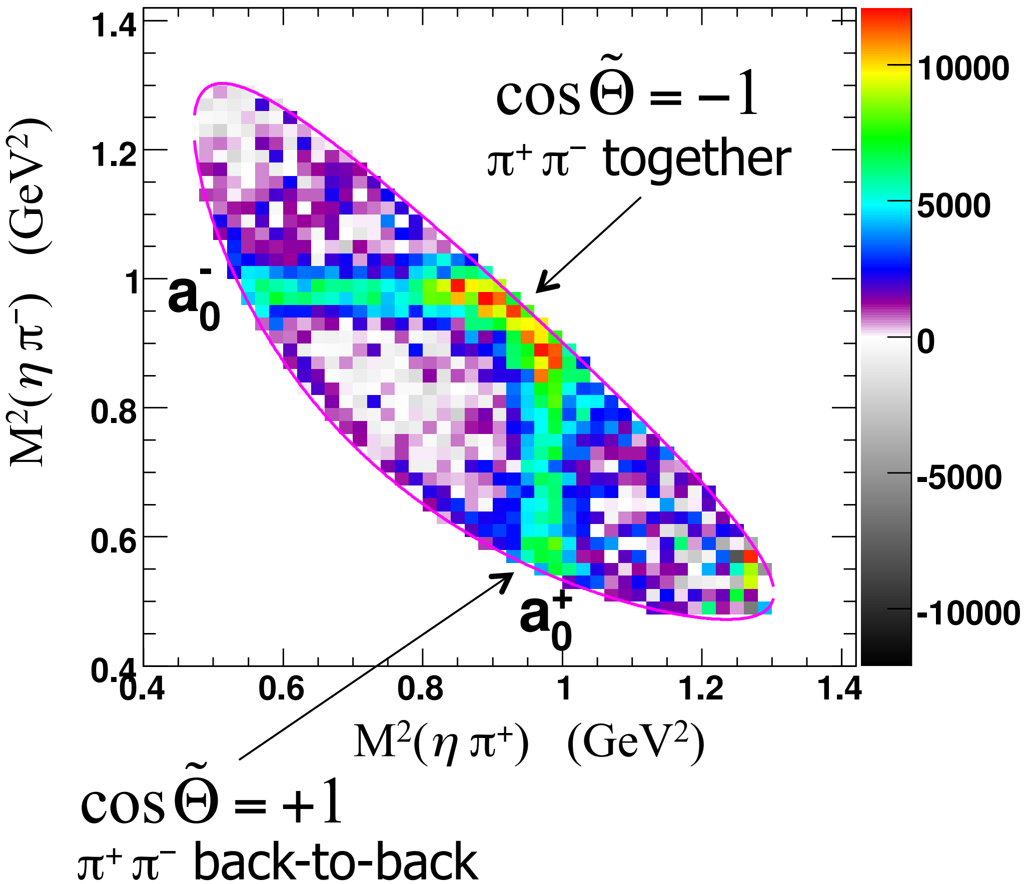
Raw Event Distribution

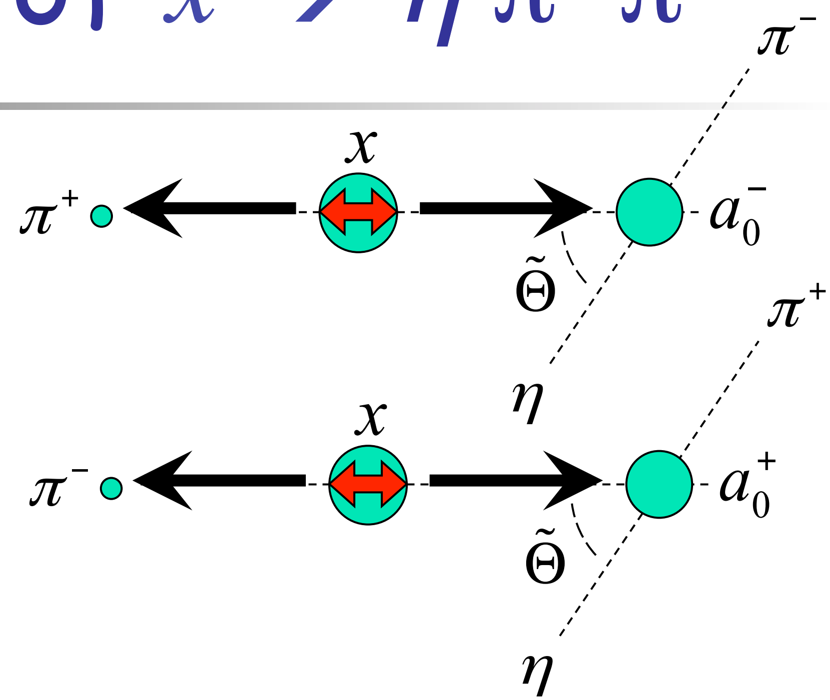




- Event-by-event, rescale meson sidebands to lie within the Dalitz plot contour
- Algebraic method developed to do this projection…

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





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

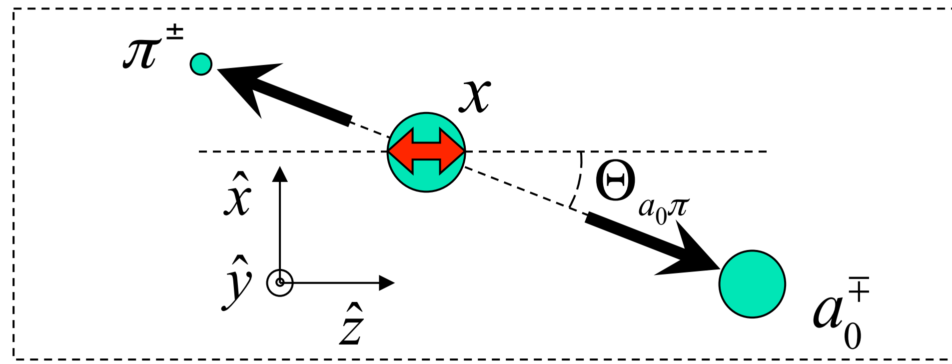
- Background-subtracted acceptance-corrected Dalitz plot reveals <u>dominance of decay via $a_0^{\pm}\,\pi^{\mp}$ intermediate states.</u>
- Strong interference of bands seen. Amplitude analysis!

From decay: find spin & parity

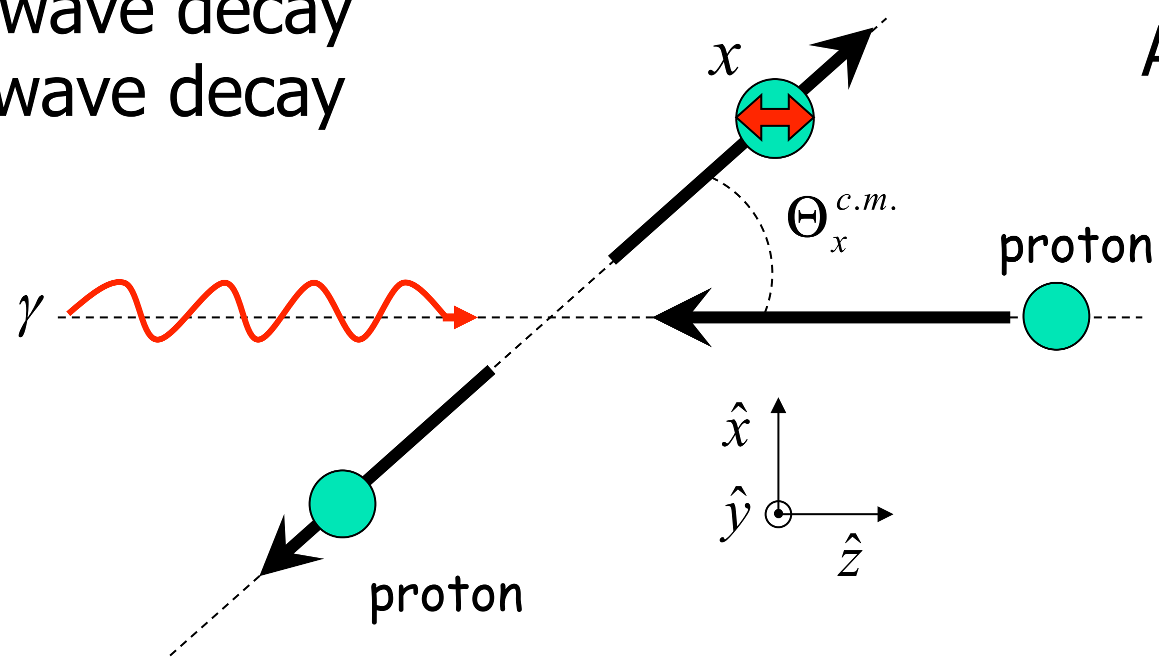
$$x \rightarrow a_0^{\pm} + \pi^{\mp}$$

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

f_1: p-wave decay
η: s-wave decay



Adair system

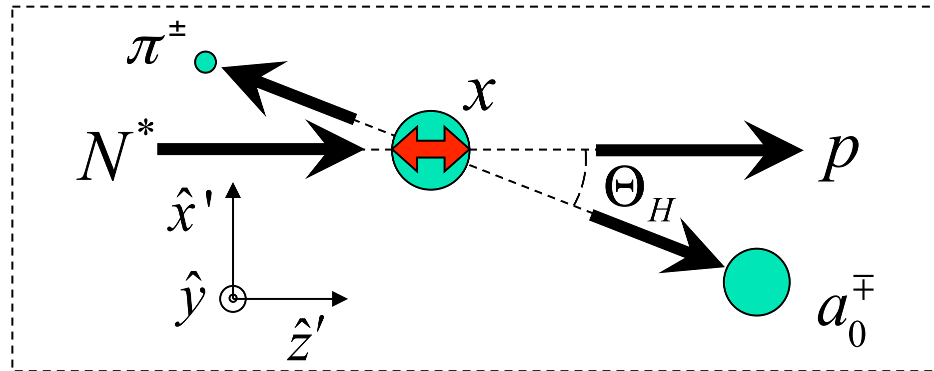


From decay: find spin & parity

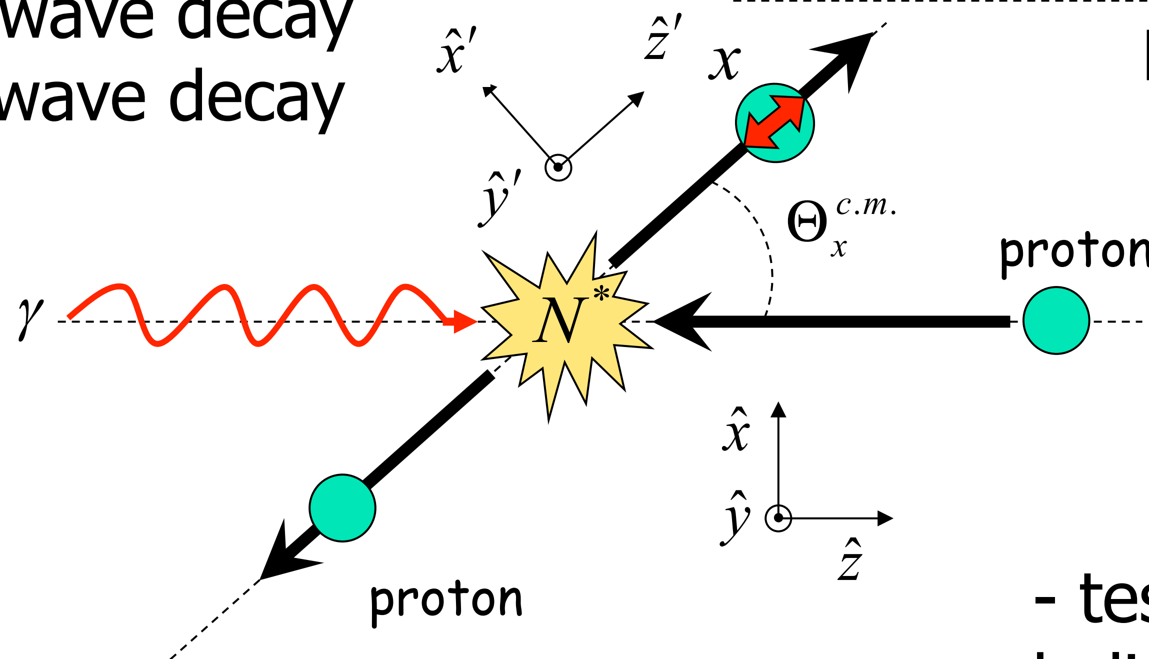
$$x \rightarrow a_0^{\pm} + \pi^{\mp}$$

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

f_1: p-wave decay
η: s-wave decay



Helicity system

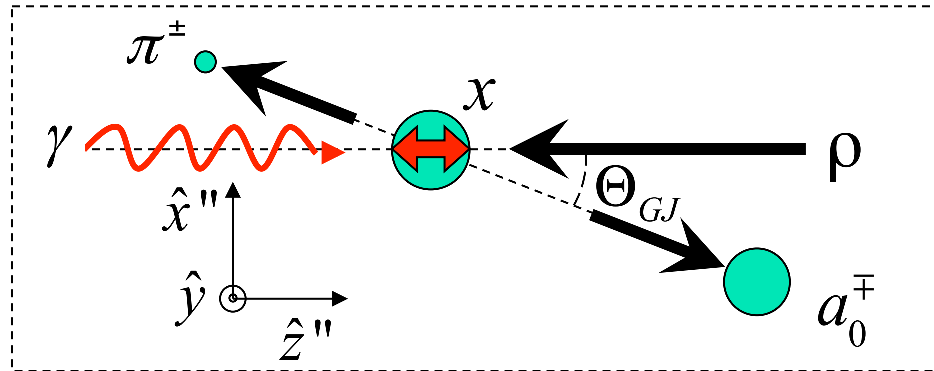


- tests "s-channel helicity conservation"

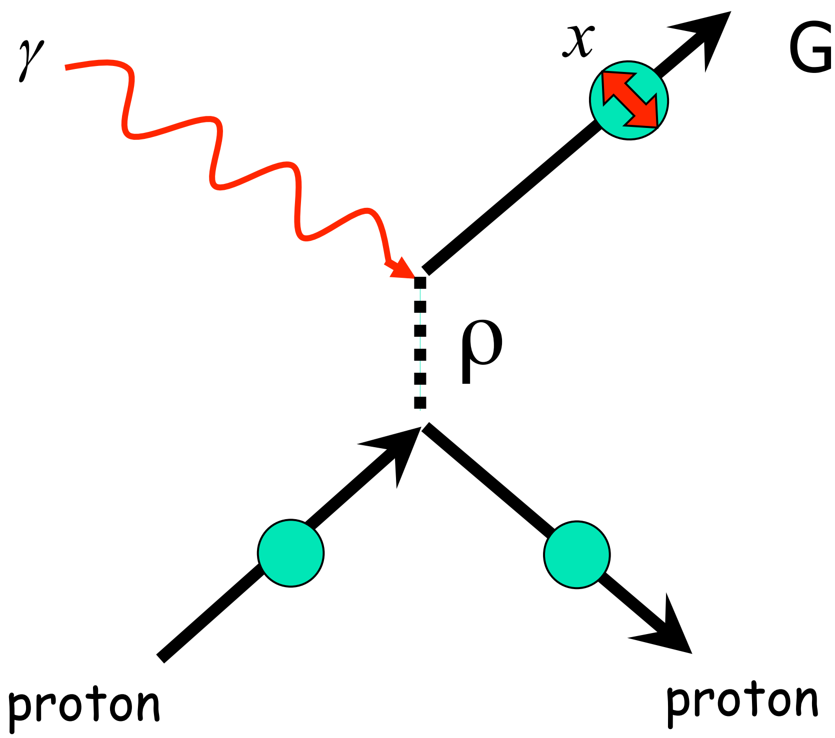
From decay: find spin & parity

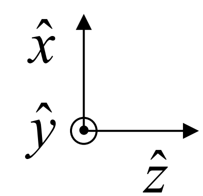
$$x \rightarrow a_0^{\pm} + \pi^{\mp}$$

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



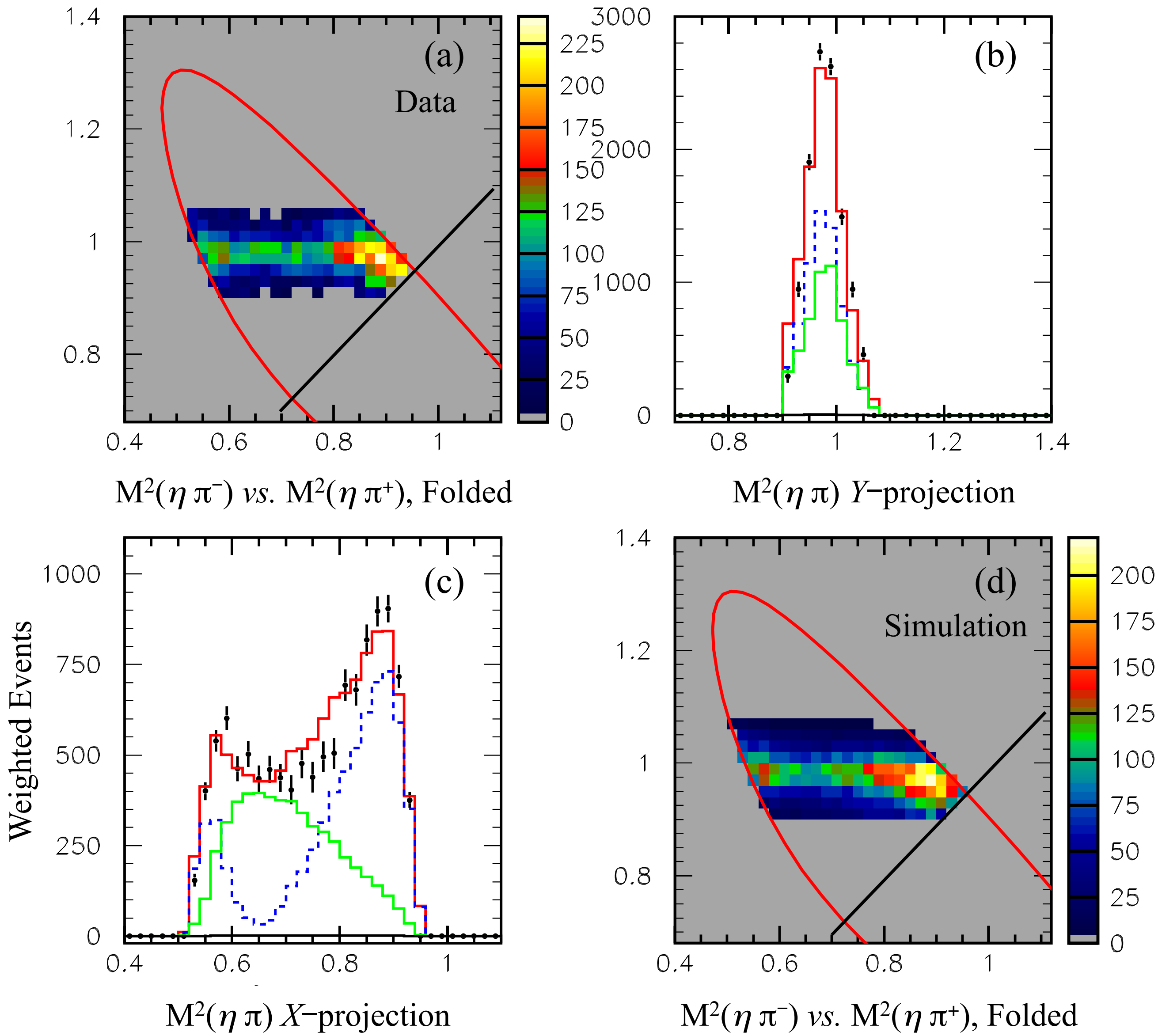
Gottfried-Jackson system





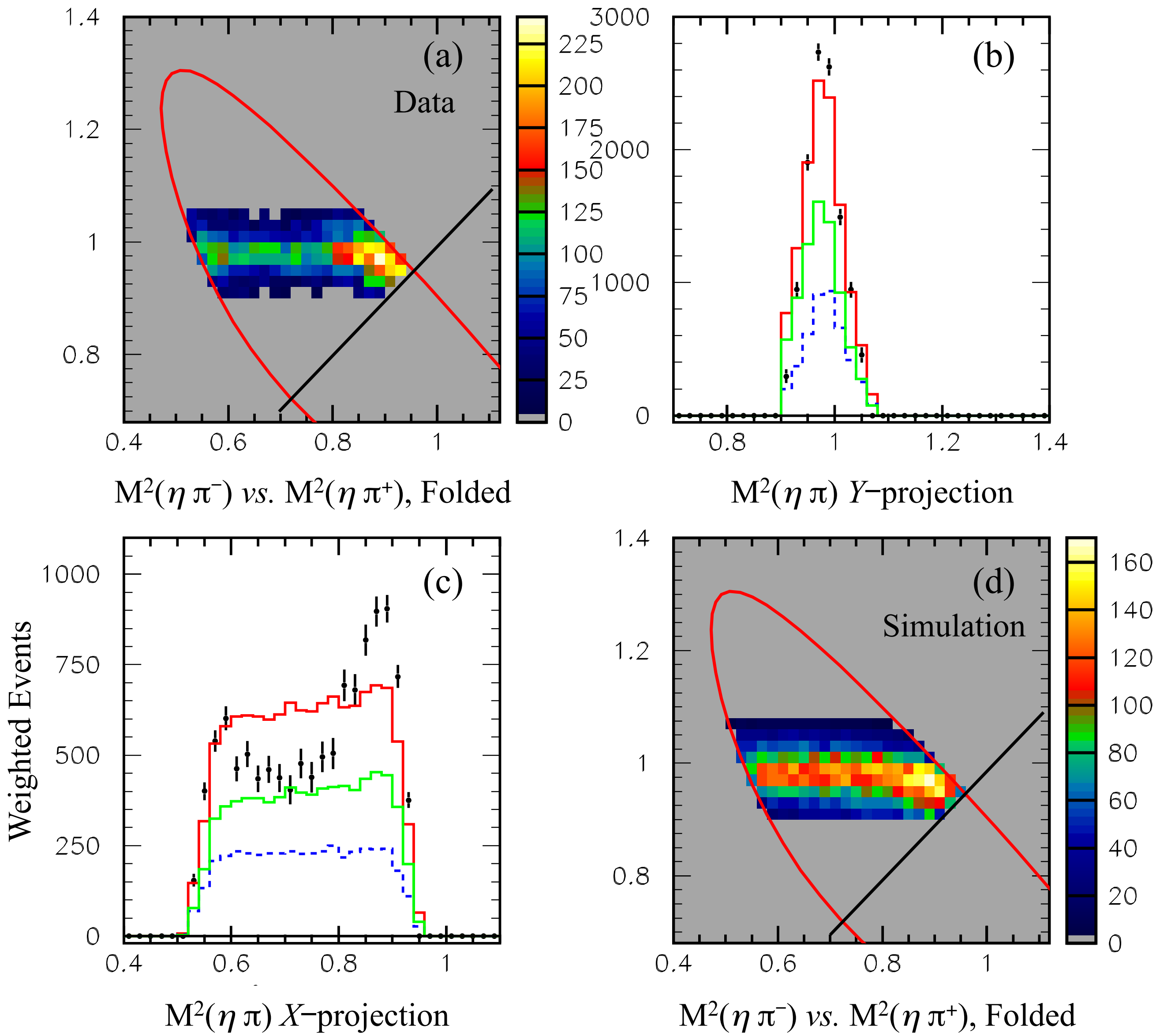
- tests "t-channel helicity conservation"

Helicity system fit



- 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 negative parity demonstrated
- Decaying meson is definitely the $f_1(1285)$

Gottfried-Jackson system fit



- *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

Properties of $f_1(1285)$ vs. $\eta(1295)$

	$f_1(1285)$	$\eta(1295)$	CLAS
$I^G(J^{PC})$	$0^+(1^{++})$	$0^+(0^{-+})$	$J^P = 1^+$
Mass (MeV)	1281.9 ± .5	1294 ± 4	1281.0 ± 0.8
Width, Γ (MeV)	24.2 ± 1.1	55 ± 5	18.4 ± 1.4
Decays:			
4π	33 ± 2%	-	-
$\eta\ \pi\ \pi$	52 ± 2%	Seen	-
$\frac{\Gamma(a_0\pi\ (noKK))}{\Gamma(\eta\pi\pi\ (total))}$	69 ± 13%	-	74 ± 9%
$\frac{\Gamma(K\bar{K}\pi)}{\Gamma(\eta\pi\pi)}$	17.1 ± 1.3%	-	21.6 ± 3.1%
$\frac{\Gamma(\gamma\rho^0)}{\Gamma(\eta\pi\pi)}$	10.5 ± 2.2%	Not seen	4.7 ± 1.8%

Conclusions:

arXiv:1604.07425 [nucl-ex], Accepted by Phys. Rev. C
R. Dickson et al., CLAS Collaboration

- The photoproduced meson CLAS sees at 1281 MeV is the $f_1(1285)$.
- Production mechanism is more consistent with s-channel process (N^*-decay…) than t-channel process (meson-exchange)
  - Cross section is much "flatter" than η' production
  - The $f_1(1285)$ is aligned in the s-channel helicity system, seen via $\eta\,\pi^+\pi^-$ Dalitz-plot amplitude analysis
- $\Gamma \sim 18.2$ MeV; narrower than PDG average
- Branching ratios measured:
  - $K\,K\,\pi\,/\,\eta\,\pi\,\pi$, $a_0\,\pi\,/\,\eta\,\pi\,\pi$ and $\gamma\,\rho^0/\,\eta\,\pi\,\pi$

Backup Slides

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

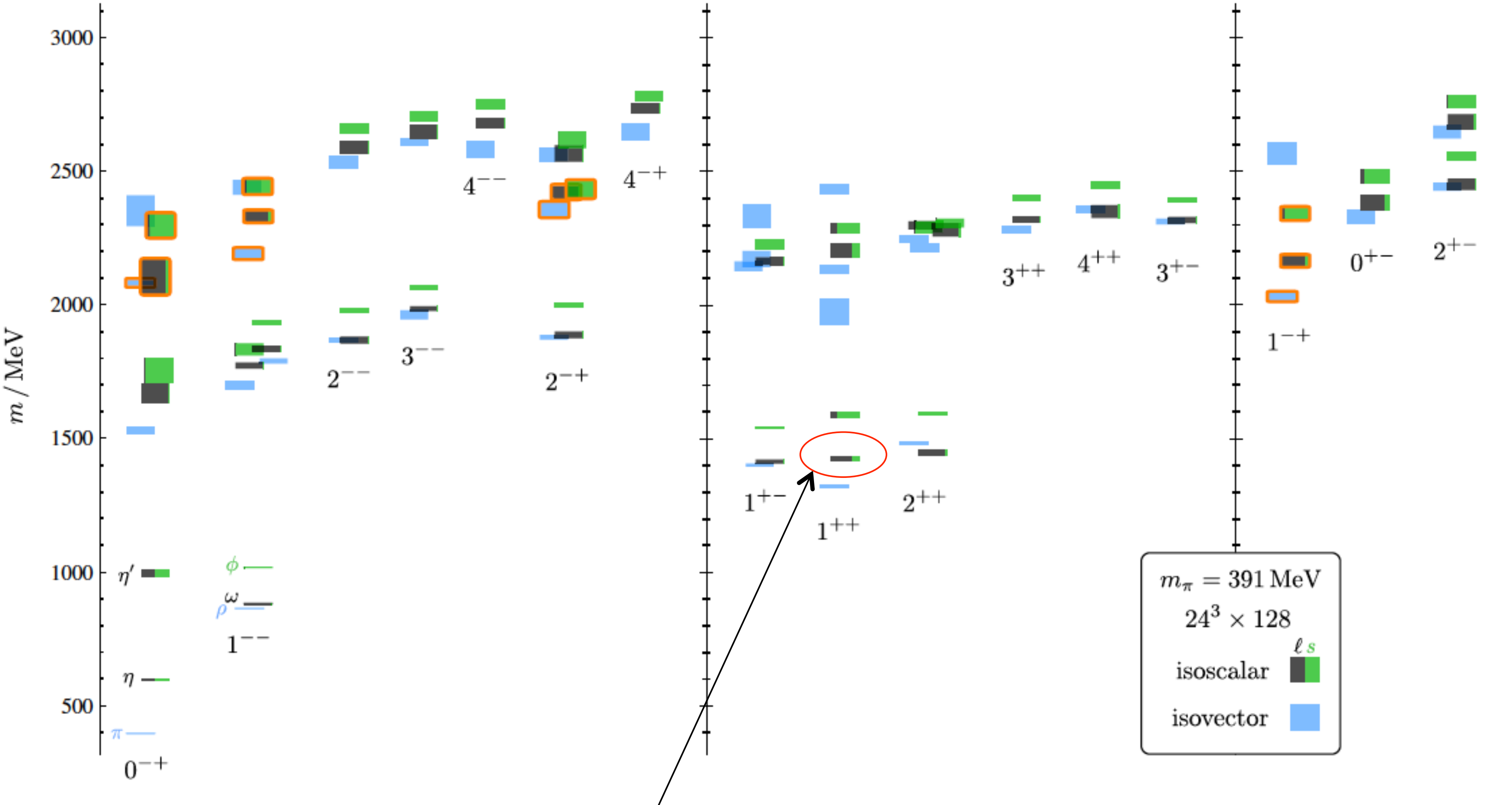
Quark Model for Mesons PDG 2014

Table 15.2: Suggested $q\overline{q}$ quark-model assignments for some of the observed light mesons. Mesons in bold face are included in the Meson Summary Table. The wave functions f and f' are given in the text. The singlet-octet mixing angles from the quadratic and linear mass formulae are also given for the well established nonets. The classification of the 0^{++} mesons is tentative: The light scalars $a_0(980)$, $f_0(980)$, and $f_0(500)$ are often considered as meson-meson resonances or four-quark states, and are omitted from the table. Not shown either is the $f_0(1500)$ which is hard to accommodate in the nonet. The isoscalar 0^{++} mesons are expected to mix. See the "Note on Scalar Mesons" in the Meson Listings for details and alternative schemes.

$n\,^{2s+1}\ell_J$	J^{PC}	I = 1 $u\overline{d}$, $\overline{u}d$, $\frac{1}{\sqrt{2}}(d\overline{d}-u\overline{u})$	I = $\frac{1}{2}$ $u\overline{s}$, $d\overline{s}$; $\overline{d}s$, $-\overline{u}s$	I = 0 f'	I = 0 f	$\theta_{\rm quad}$ [°]	$\theta_{\rm lin}$ [°]
$1\,^1S_0$	0^{-+}	**π**	**K**	**η**	**$\eta'(958)$**	−11.4	−24.5
$1\,^3S_1$	1^{--}	**$\rho(770)$**	**$K^*(892)$**	**$\phi(1020)$**	**$\omega(782)$**	39.1	36.4
$1\,^1P_1$	1^{+-}	**$b_1(1235)$**	**K_{1B}**†	$h_1(1380)$	**$h_1(1170)$**		
$1\,^3P_0$	0^{++}	**$a_0(1450)$**	**$K_0^*(1430)$**	**$f_0(1710)$**	**$f_0(1370)$**		
$1\,^3P_1$	1^{++}	**$a_1(1260)$**	**K_{1A}**†	**$f_1(1420)$**	**$f_1(1285)$**		
$1\,^3P_2$	2^{++}	**$a_2(1320)$**	**$K_2^*(1430)$**	**$f_2'(1525)$**	**$f_2(1270)$**	32.1	30.5
$1\,^1D_2$	2^{-+}	**$\pi_2(1670)$**	**$K_2(1770)$**†	$\eta_2(1870)$	**$\eta_2(1645)$**		
$1\,^3D_1$	1^{--}	**$\rho(1700)$**	**$K^*(1680)$**		**$\omega(1650)$**		
$1\,^3D_2$	2^{--}		**$K_2(1820)$**				
$1\,^3D_3$	3^{--}	**$\rho_3(1690)$**	**$K_3^*(1780)$**	**$\phi_3(1850)$**	**$\omega_3(1670)$**	31.8	30.8
$1\,^3F_4$	4^{++}	**$a_4(2040)$**	**$K_4^*(2045)$**		**$f_4(2050)$**		
$1\,^3G_5$	5^{--}	$\rho_5(2350)$	$K_5^*(2380)$				
$1\,^3H_6$	6^{++}	$a_6(2450)$			$f_6(2510)$		
$2\,^1S_0$	0^{-+}	**$\pi(1300)$**	$K(1460)$	**$\eta(1475)$**	**$\eta(1295)$**		
$2\,^3S_1$	1^{--}	**$\rho(1450)$**	**$K^*(1410)$**	**$\phi(1680)$**	**$\omega(1420)$**		

† The $1^{+\pm}$ and $2^{-\pm}$ isospin $\frac{1}{2}$ states mix. In particular, the K_{1A} and K_{1B} are nearly equal (45°) mixtures of the $K_1(1270)$ and $K_1(1400)$. The physical vector mesons listed under 1^3D_1 and 2^3S_1 may be mixtures of 1^3D_1 and 2^3S_1, or even have hybrid components.

LQCD: Excited Isoscalar Mesons



The $J^{PC} = 1^{++}$ mesons, including the $f_1(1285)$, are 'seen' in recent lattice calculations…

J. Dudek *et al.* Phys. Rev. D **88**, 094505 (2013)

Dynamically Generated Mesons

- The $f_1(1285)$ as a $\{\mathrm{K\overline{K}^*} + \mathrm{c.c.}\}$ composite state
  - Chiral Lagrangian + unitarization of the pseudoscalar – vector meson nonet interaction
  - Lattice calculations
  - Expect "non-standard" production mechanisms, if true

M. F. M. Lutz and E. E. Kolomeitsev Nucl Phys **A730** 392, (2004)
L. Roca, E. Oset, J. Singh Phys Rev **D72**, 014002 (2005)
F. Aceti, Ju-Jun Xie, E. Oset, arXiv:1505.06134 (2015)

Branching Ratios

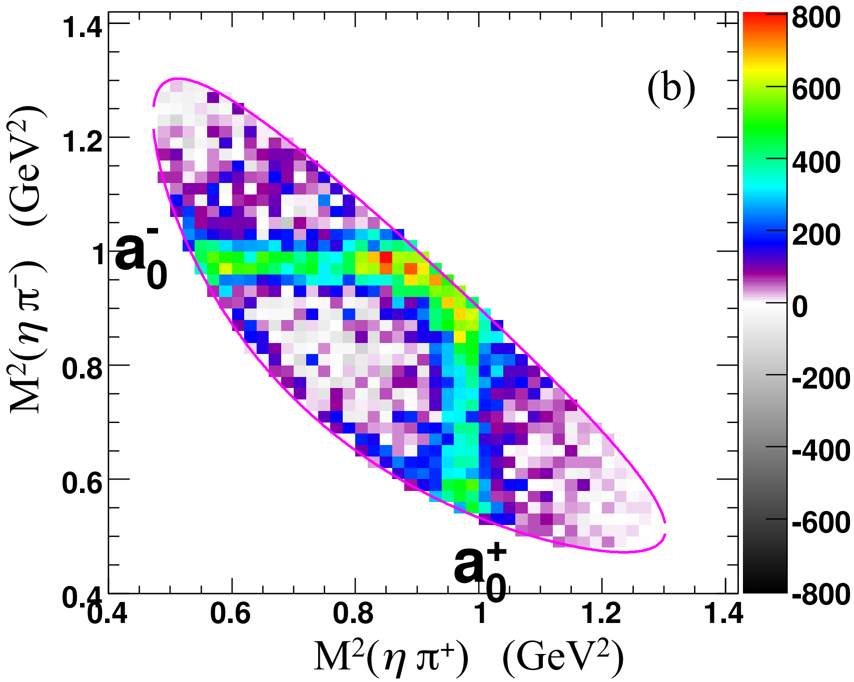
Item	Value	Stat. Uncert.	Syst. Uncert.	PDG $f_1(1285)$
$\eta\pi^+\pi^-$ Event Yield	1.33×10^5	4.9×10^3	2.9×10^3	
$\eta\pi^+\pi^-$ Acceptance	0.0652	9.7×10^{-5}	0.0072	
$K^\pm K^0\pi^\mp$ Event Yield	6570	180	340	
$K^\pm K^0\pi^\mp$ Acceptance	0.0149	3.18×10^{-5}	0.0016	
$\gamma\rho^0$ Event Yield	3790	790	850	
$\gamma\rho^0$ Acceptance	0.0248	6.4×10^{-5}	0.0050	
Isospin C.G. $\Gamma(K^\pm K^0\pi^\mp)/\Gamma(KK\pi)$	2/3			
Isospin C.G. $\Gamma(\eta\pi^+\pi^-)/\Gamma(\eta\pi\pi)$	2/3			
$\gamma\rho^0$ correction from η' $d\sigma/d\Omega$	0.95			
Branching Fraction $\Gamma(K\bar{K}\pi)/\Gamma(\eta\pi\pi)$	0.216	0.010	0.031	0.171 ± 0.013
Branching Fraction $\Gamma(\gamma\rho^0)/\Gamma(\eta\pi\pi)$	0.047	0.010	0.015	0.105 ± 0.022

TABLE III. Relative branching fractions of the $f_1(1285)$ meson, with estimated uncertainties from all sources.

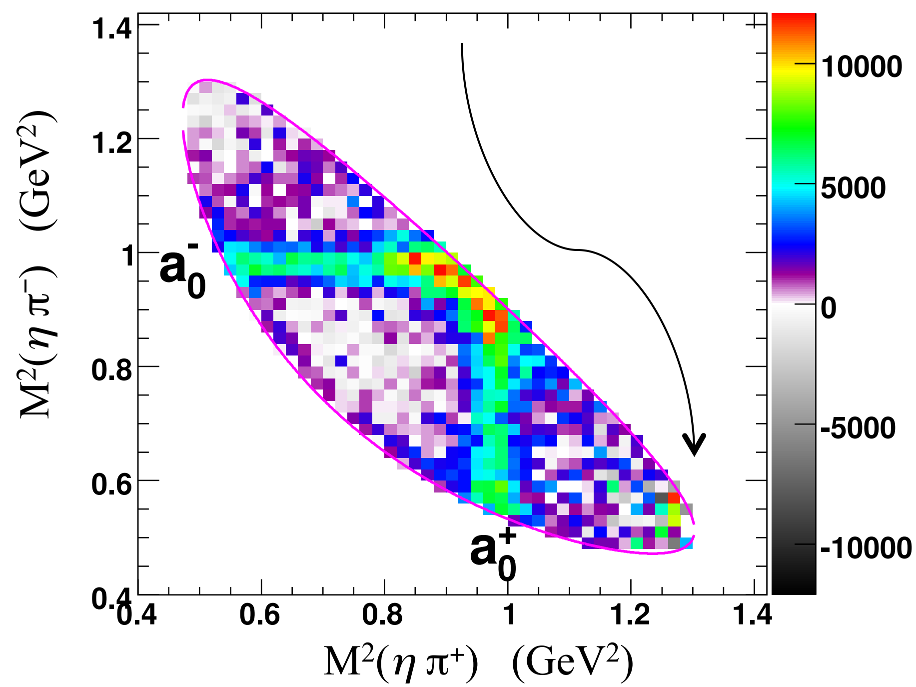
- $K\bar{K}\pi / \eta\pi\pi$ ratio agrees with PDG average
  - (isospin factors applied)
- $\gamma\rho^0/\eta\pi\pi$ ratio smaller than PDG average by 55%

Dalitz analysis of $x \to \eta\, \pi^+ \pi^-$

Background Subtracted



Acceptance Corrected



- Subtract huge multi-pion background to reveal…
- … dominance of decay via $a_0^{\pm}\, \pi^{\mp}$ intermediate state.
- Strong interference of bands seen. Amplitude analysis!

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

$$A_{m=\pm1}(m_{a_0^+\pi^-}, m_{a_0^-\pi^+}) = BW(m_{a_0^+\pi^-})W_{1,\pm1}(\Theta_{a_0^+\pi^-}, \phi_{a_0^+\pi^-}) + BW(m_{a_0^-\pi^+})W_{1,\pm1}(\Theta_{a_0^-\pi^+}, \phi_{a_0^-\pi^+})$$

$$A_{m=0}(m_{a_0^+\pi^-}, m_{a_0^-\pi^+}) = BW(m_{a_0^+\pi^-})\left(W_{1,0}(\Theta_{a_0^+\pi^-}, \phi_{a_0^+\pi^-}) + W_{0,0}\right) + BW(m_{a_0^-\pi^+})\left(W_{1,0}(\Theta_{a_0^-\pi^+}, \phi_{a_0^-\pi^+}) + W_{0,0}\right)$$

$$BW(m\,|\,m_0,\Gamma_0) = \frac{\sqrt{m_0\Gamma_0}}{m_0^2 - m^2 - i m_0 \Gamma_0 \dfrac{q(m)}{q(m_0)}}$$

- a Breit–Wigner for each a_0

- angular distribution in the selected system

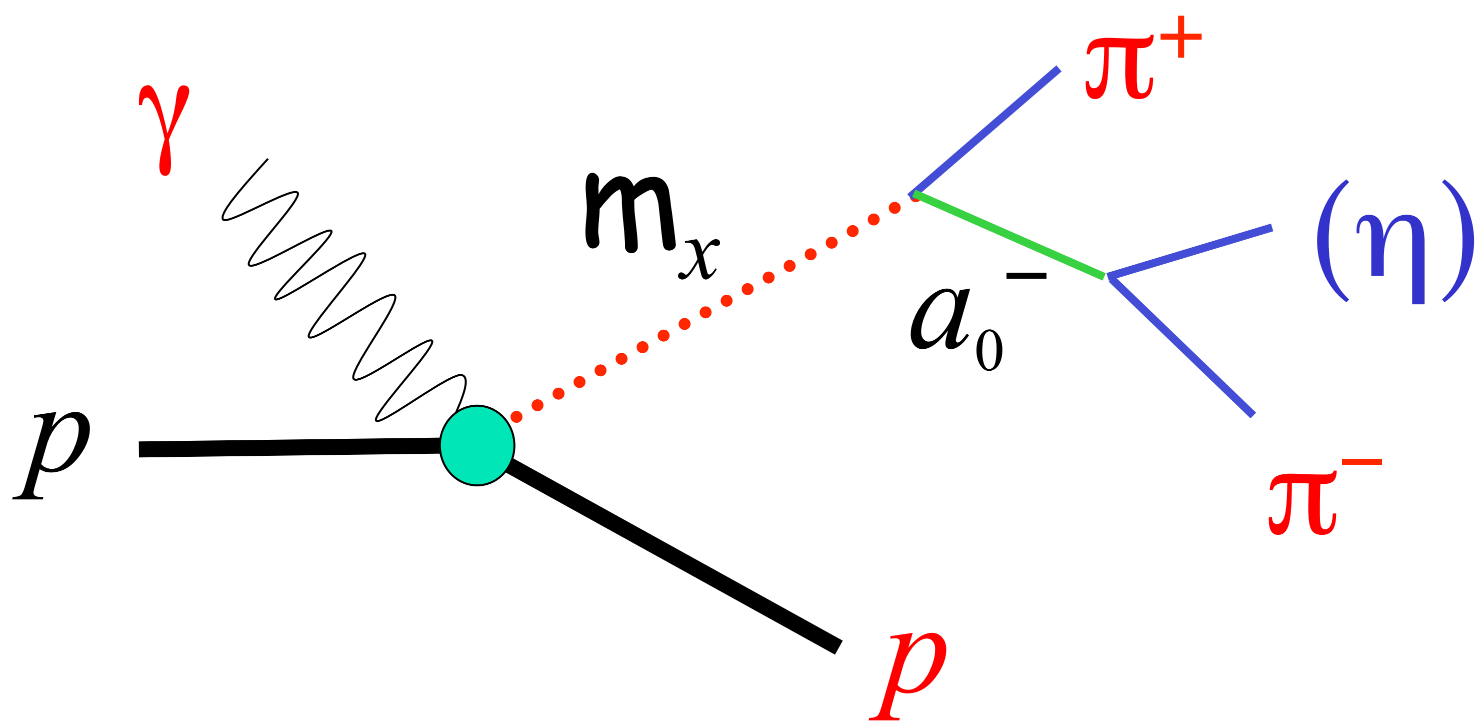
$$f_1: \quad W_{L=1,\, m=0,\pm1}(\Theta_H, \phi) = a\, Y_{1,+1}(\Theta_H, \phi) + b\, Y_{1,0}(\Theta_H, \phi) + a\, Y_{1,-1}(\Theta_H, \phi)$$

$$\eta: \quad W_{L=0,\, m=0}(\Theta_H, \phi) = c\, Y_{0,0}$$

-total decay-weighted magnitude squared

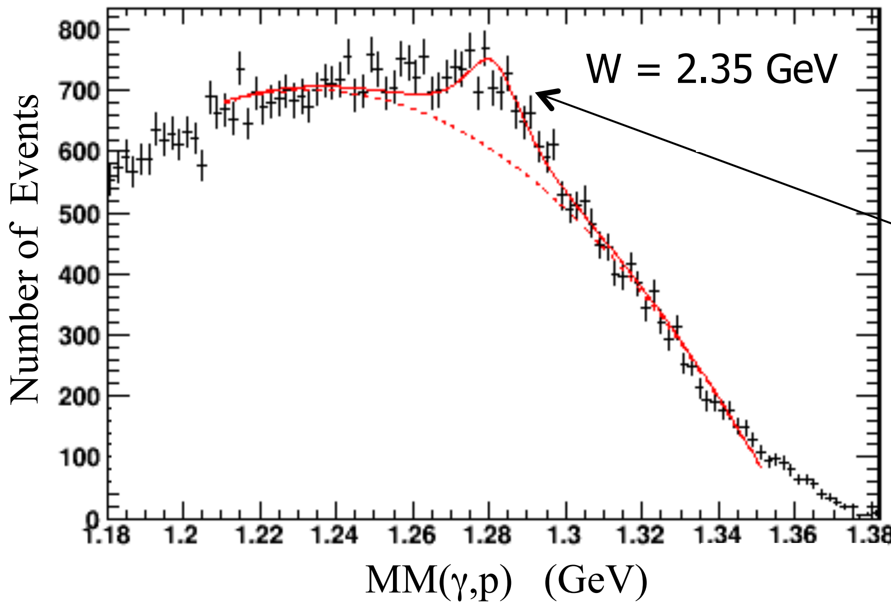
$$T\left(m_{a_0^+\pi^-}, m_{a_0^-\pi^+}\right) = \frac{q(m_{a_0^+\pi^-})}{q(m_0)}\frac{q(m_{a_0^-\pi^+})}{q(m_0)}\left(\left|A_{m=\pm1}\left(m_{a_0^+\pi^-}, m_{a_0^-\pi^+}\right)\right|^2 + \left|A_{m=0}\left(m_{a_0^+\pi^-}, m_{a_0^-\pi^+}\right)\right|^2\right)$$

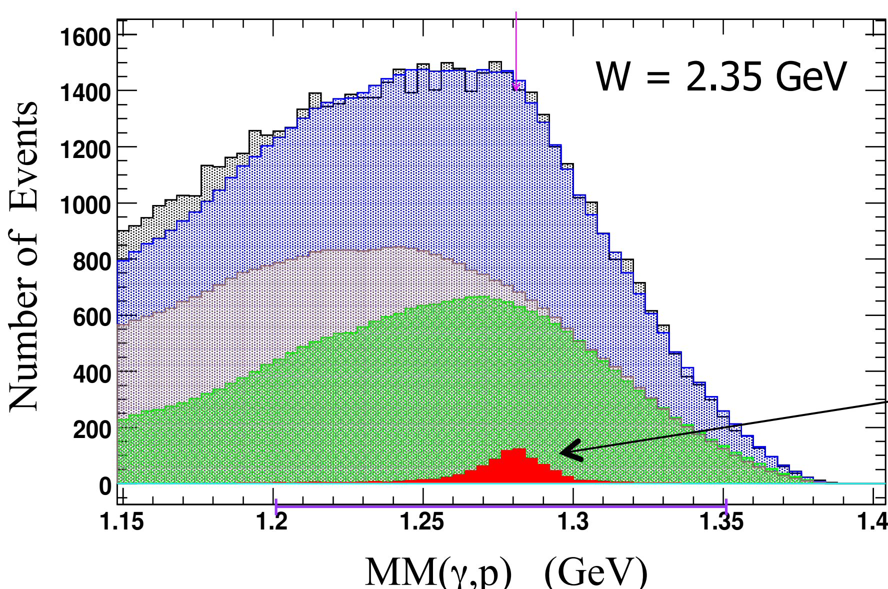
One Reaction Topology
(example)



red = measured particles

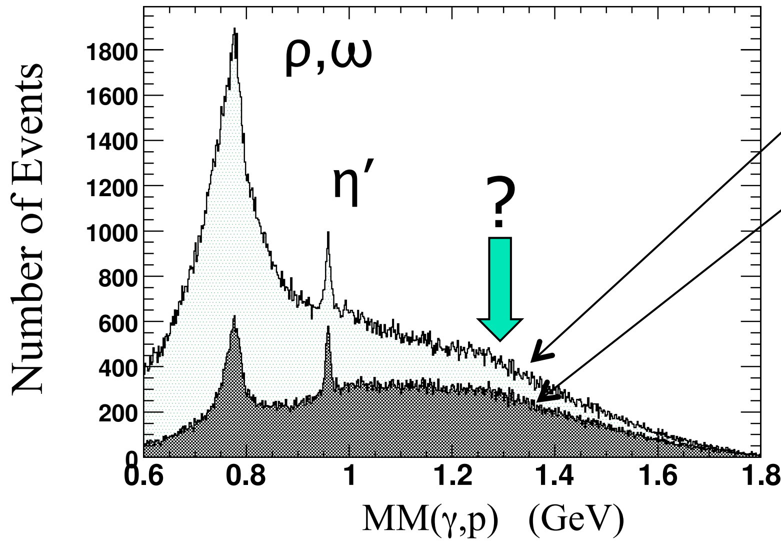
Two yield extraction methods



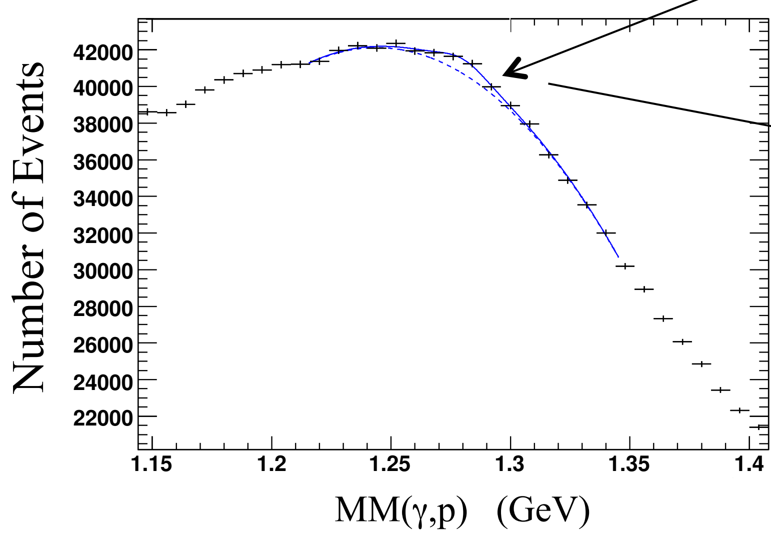


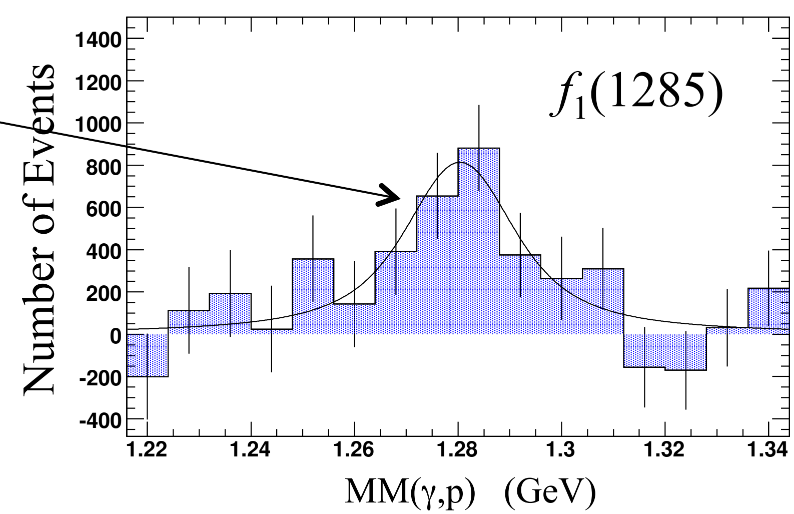
- Voigtian lines shape using known CLAS resolution
  - Convolution of BW and Gaussian
- Monte Carlo fitting using signal and estimated multi-pion backgrounds
  - $p\ \rho\ \pi\ \pi$ (green)
  - $p\ \phi_1(1370)$ (purple)
  - $p\ x(1280)$ (red) - signal
  - Total (blue)

Looking for $\gamma\rho^0$ decays

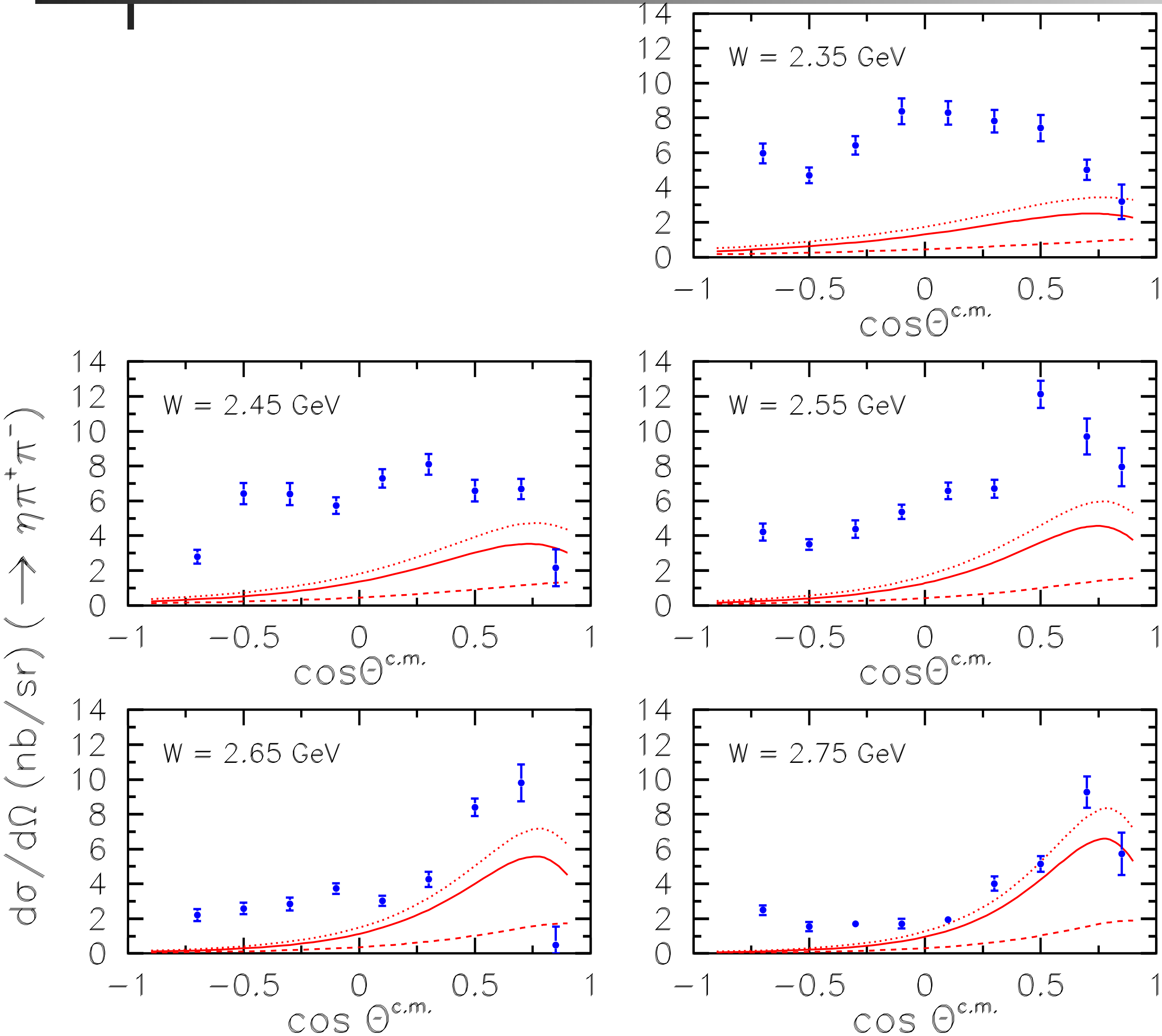


- Kinematic fit to $\gamma p \rightarrow p\pi^+\pi^-(\gamma)$
- Select $p_{perp} > 40$ MeV/c
- 2nd kin. fit to $\gamma p \rightarrow p\pi^+\pi^-(\pi^0)$ to reject π^0 background
- Very small signal: only extract branching ratio to $\eta\ \pi^+\ \pi^-$
  - Sum over all kinematics





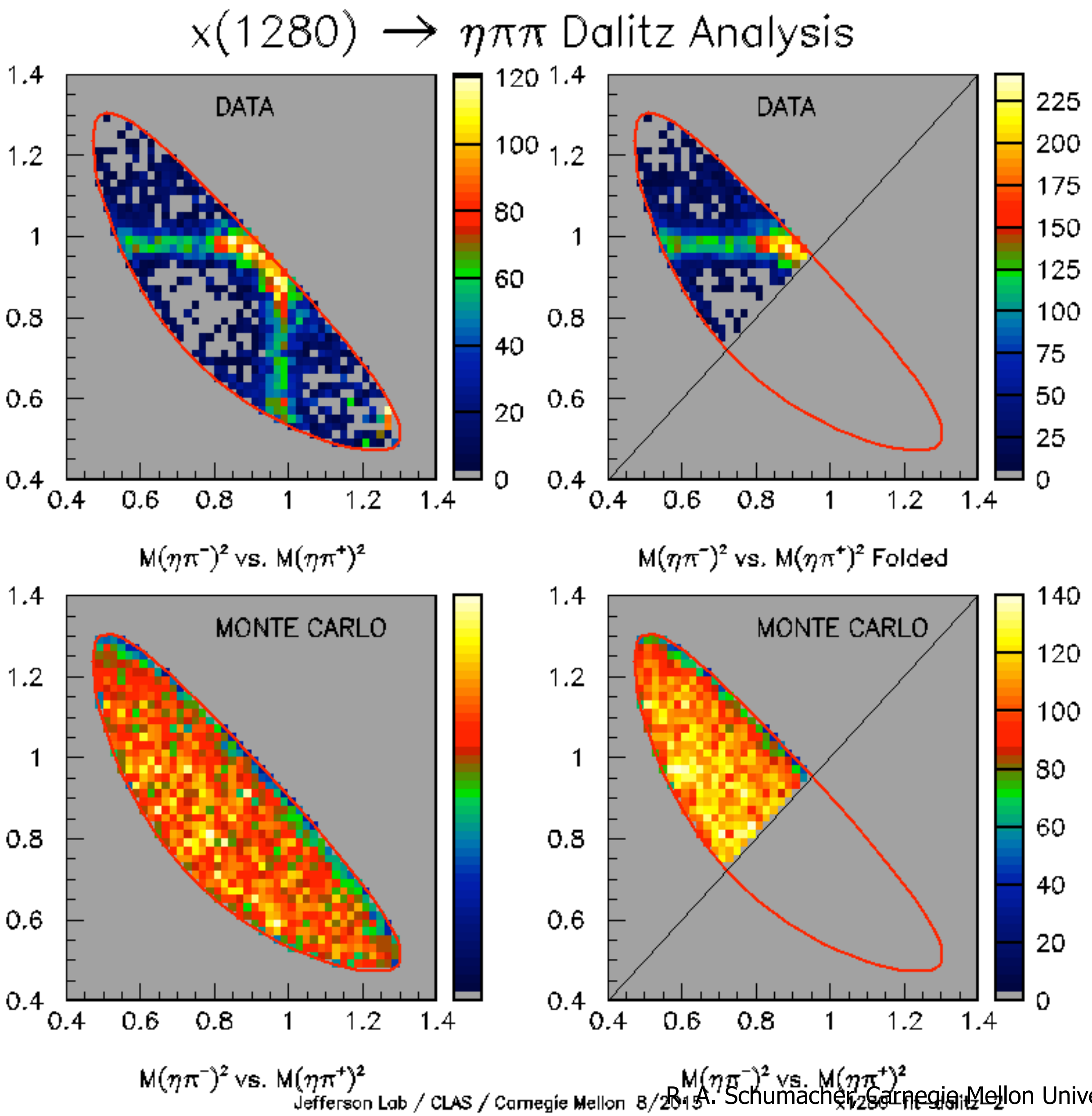
Comparison with Models



- N. Kochelev model
  - Effective Lagrangian
  - t-channel ρ and ω exchange
  - Solid: $f_1(1285)$
  - Dashed: $\eta(1295)$
  - Dotted: sum
- Poor match to data

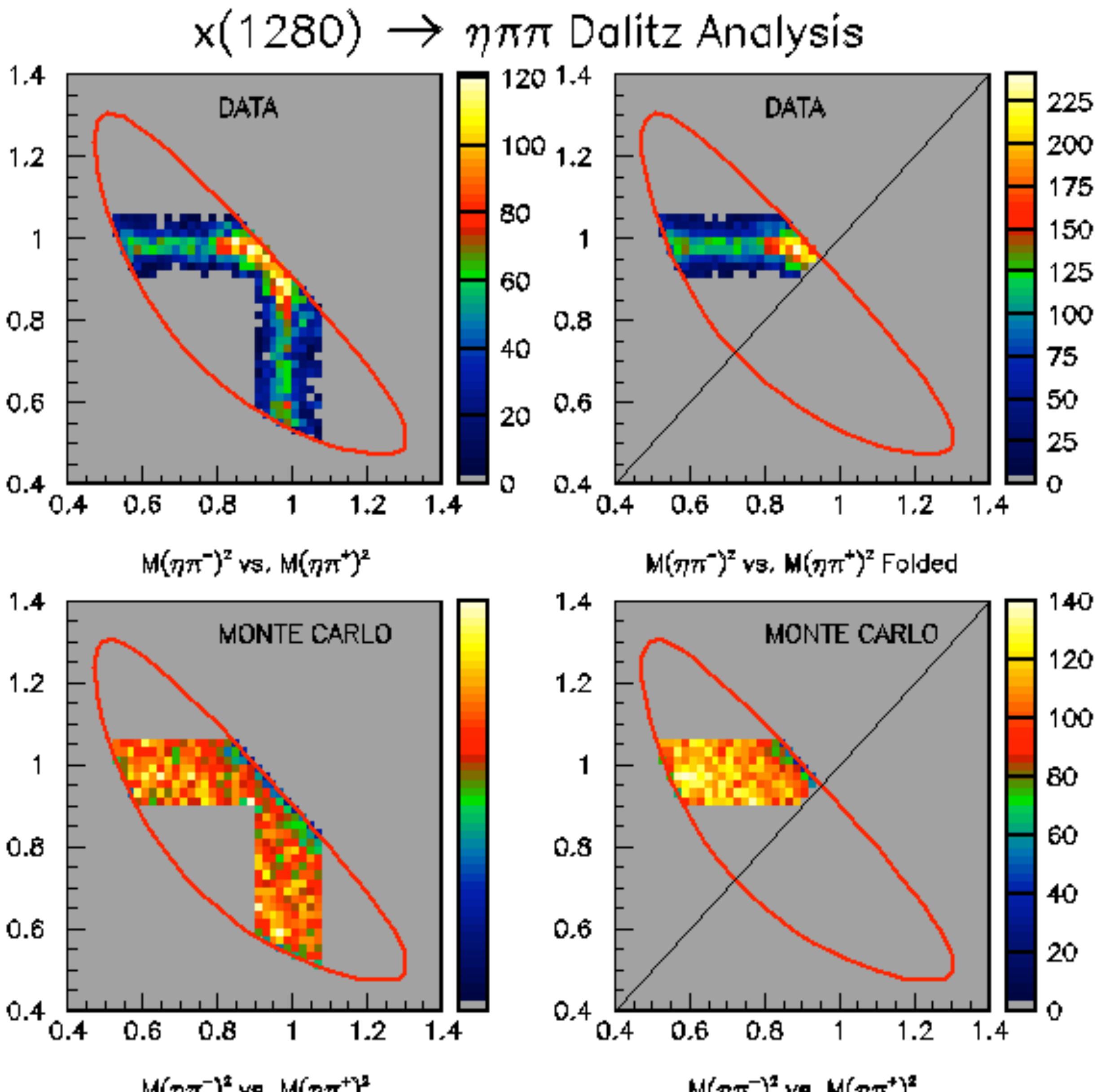
N. Kochelev, M. Battaglieri, R. DeVita, Phys. Rev. C **80**, 025201 (2009)

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



- Fold data on symmetry axis
- Generate "phase space" Monte Carlo events with finite width of meson and CLAS resolution included
- "Weight" the events with amplitude-based intensity

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



- Fit to full plot did not converge, so trim data to focus on 'bands'.
- Structure in unweighted Monte Carlo due to finite width and resolution effects

Helicity system fit

- The $f_1(1285)$ is "aligned" in the helicity system.
- The mix of $\mathrm{m} = 0$ and $\mathrm{m} = \pm 1$ is a property of the production mechanism in the range $2.30 < \mathrm{W} < 2.80$ GeV.

$$P_{\pm} : P_0 = 31.8 : 69.2, \pm 1.4\%.$$

  - Discuss later…
- We also measure the ratio

$$\frac{\Gamma(a_0\pi(noKK))}{\Gamma(\eta\pi\pi(total))} = 74 \pm 2(stat) \pm 9(syst)\%$$

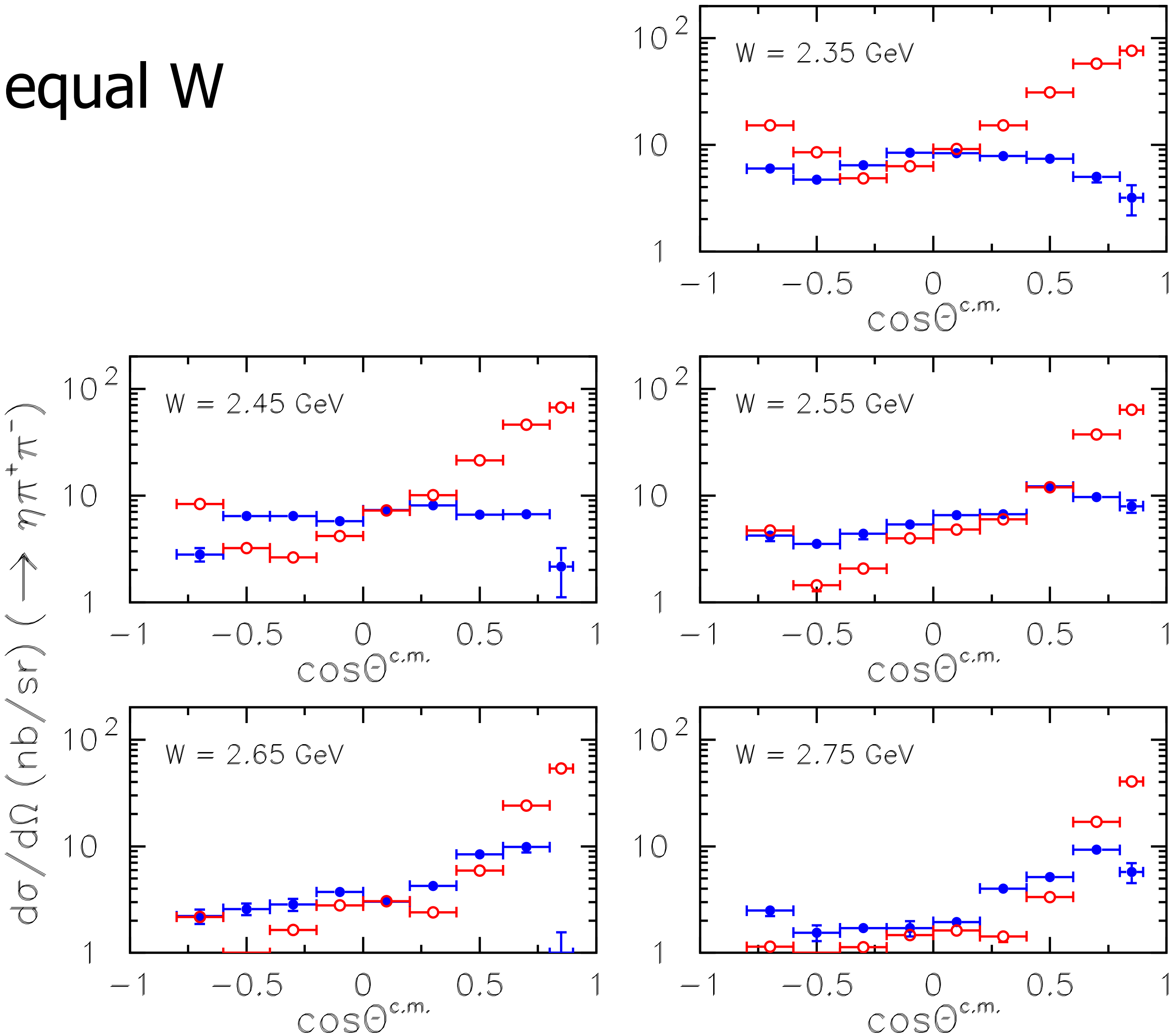
  - Consistent with PDG value

Speculation re $f_1(1285)$ production

- Alignment in helicity system suggests s-channel N* production decays to $f_1(1285)\, p$
  - Can we infer J^P of the N* baryon resonance?
  - $3/2^+ \rightarrow 1^+ + ½^+$ in s-wave leads to $P_\pm : P_0 = 1 : 2$ as seen in the data
  - $½^+ \rightarrow 1^+ + ½^+$ in s-wave leads to $P_\pm : P_0 = 2 : 1$, opposite to what data show
- But there are no known N* states with low J at $W \sim 2.5$ GeV, so the question remains open

Compare meson types

At equal W



Compare meson types

At equal excess energy above threshold