New Results from Jefferson Lab on N* resonances

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JAEA Seminar

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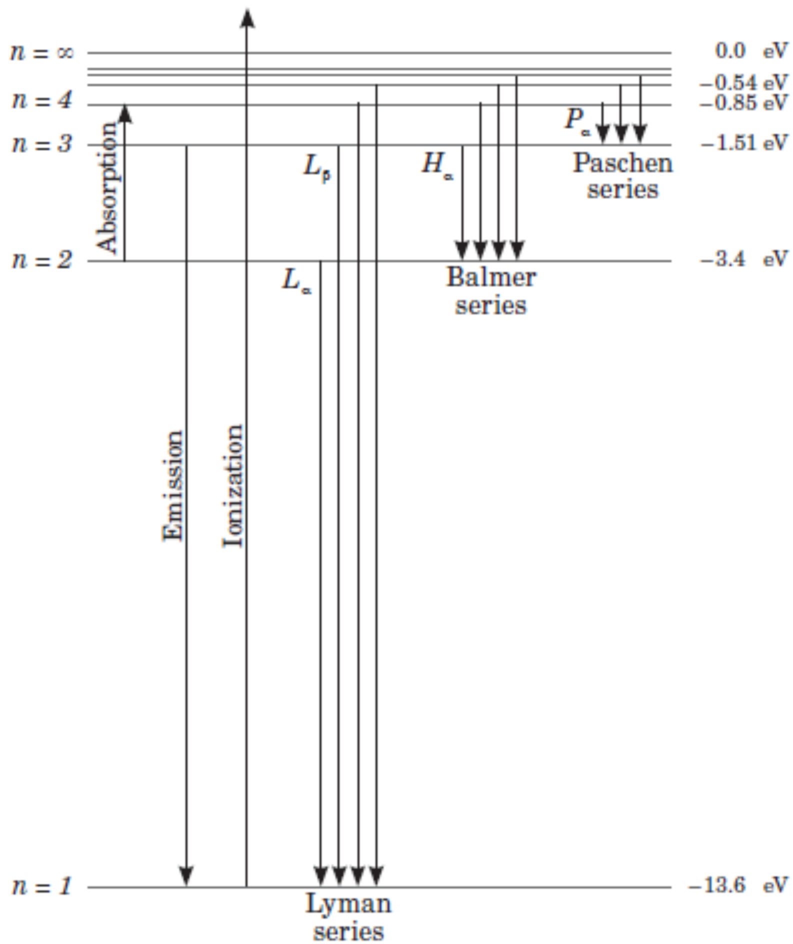
Some Background

- N* resonances are a prediction of the constituent quark model.
  – The most well-known is the Isgur-Karl model.
- Most N*'s identified in pion elastic scattering
  – Recently, photoproduction data has contributed.
  – ANL-Osaka and Bonn-Gatchina PWA see new N*'s.
- Lattice QCD now has predictions for N*'s.
  – Still waiting for calc's with realistic quark masses.

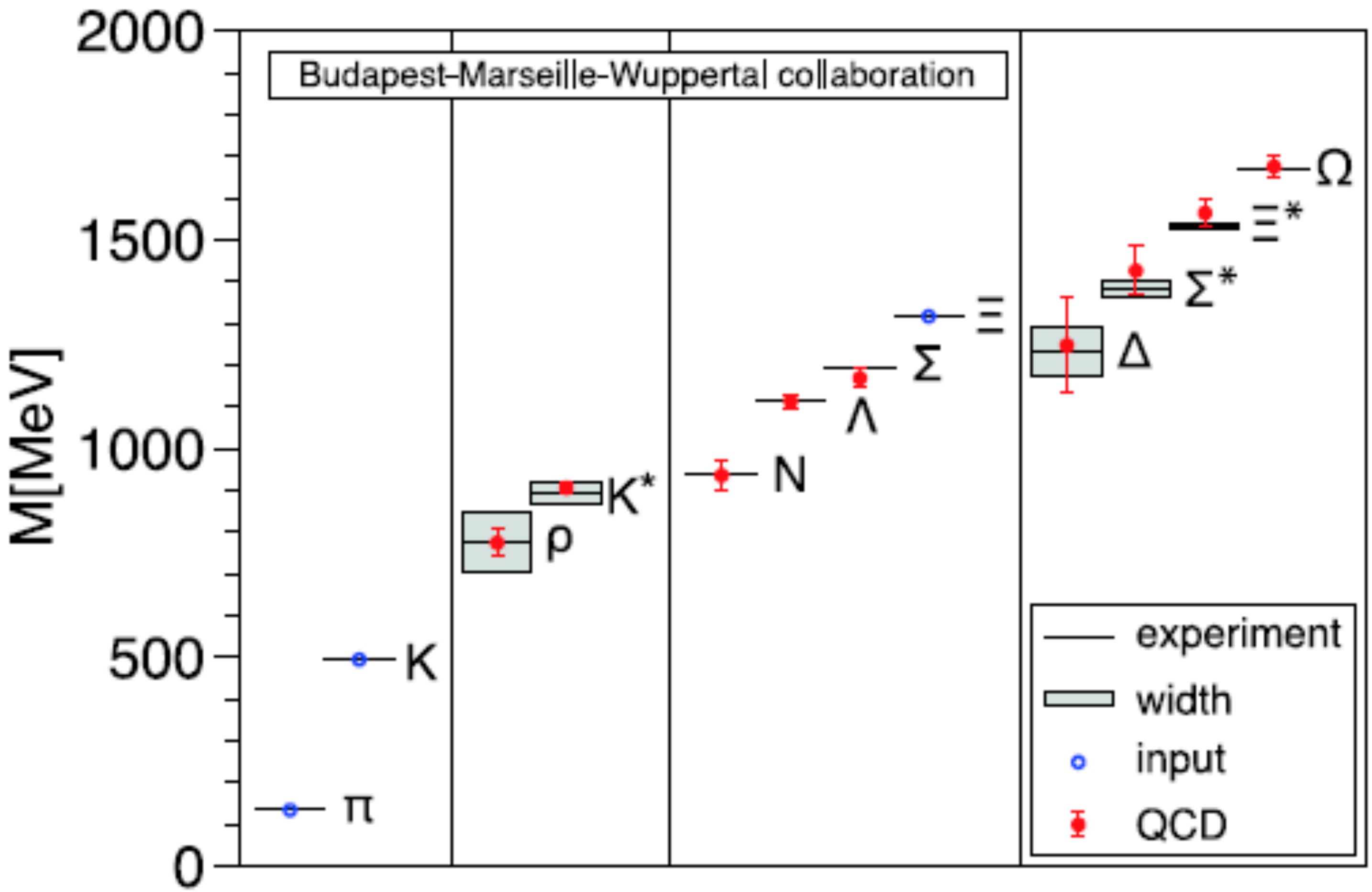
An Analogy



The spectrum of energy levels of the hydrogen atom provided insights into the structure of the atom from Bohr and later, with more precise data, to the theory of quantum mechanics.

Even today, the spectrum of hydrogen continues to give surprises (*e.g.* proton radius).

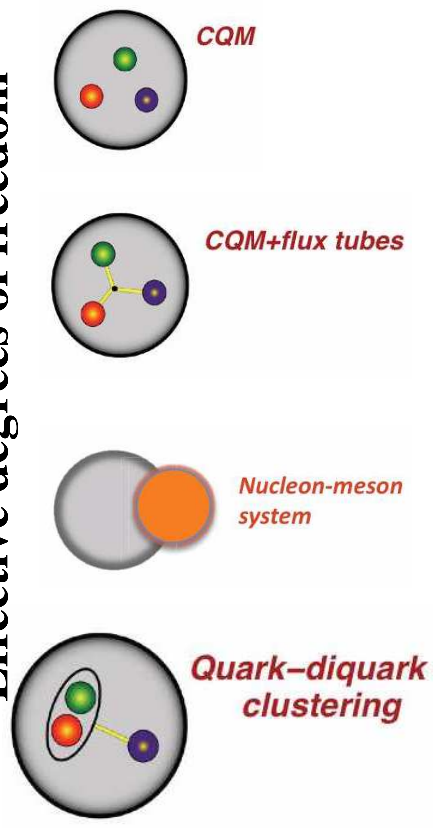
Lattice Gauge: Ground States

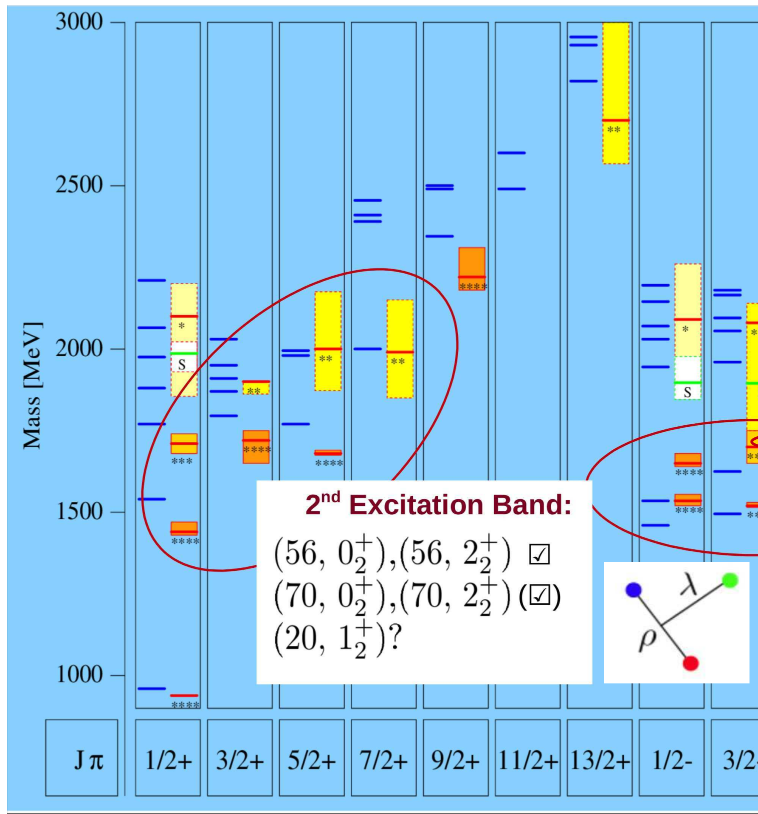


New N* resonances from $K^+ \Lambda$

[1] R. Bradford *et al.* (CLAS), PRC **75**, 035205 (2007), Observables C_x, C_z from $\vec{\gamma} p \to K^+ \vec{\Lambda}$
[2] Fits: BnGa Model, V.A. Nikonov *et al.*, Phy. Lett. B **662**, 245 (2008)

Effective degrees of freedom





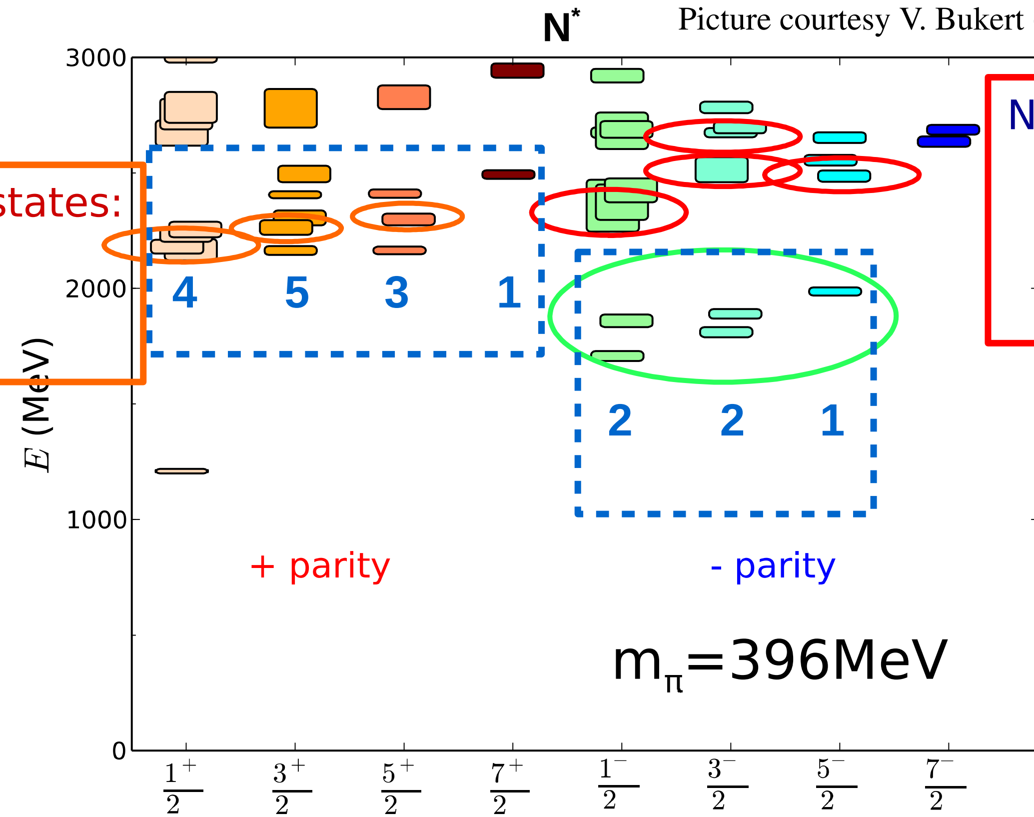
N^*	J^P ($L_{2I,2J}$)	2010	2012
N(1440)	$1/2^+$ (P_{11})	****	****
N(1520)	$3/2^-$ (D_{13})	****	****
N(1535)	$1/2^-$ (S_{11})	****	****
N(1650)	$1/2^-$ (S_{11})	****	****
N(1675)	$5/2^-$ (D_{15})	****	****
N(1680)	$5/2^+$ (F_{15})	****	****
N(1685)			*
N(1700)	$3/2^-$ (D_{13})	***	***
N(1710)	$1/2^+$ (P_{11})	***	***
N(1720)	$3/2^+$ (P_{13})	****	****
N(1860)	$5/2^+$		**
N(1875)	$3/2^-$		***
N(1880)	$1/2^+$		**
N(1895)	$1/2^-$		**
N(1900)	$3/2^+$ (P_{13})	**	***
N(1990)	$7/2^+$ (F_{17})	**	**
N(2000)	$5/2^+$ (F_{15})	**	**
~~N(2080)~~	D_{13}	**	
~~N(2090)~~	S_{11}	*	
N(2040)	$3/2^+$		*
N(2060)	$5/2^-$		**
N(2100)	$1/2^+$ (P_{11})	*	*
N(2120)	$3/2^-$		**
N(2190)	$7/2^-$ (G_{17})	****	****
~~N(2200)~~	D_{15}	**	
N(2220)	$9/2^+$ (H_{19})	****	****

The N(1900) $3/2^-$ cannot be formed in a quark-diquark model.

Lattice QCD predicts N* states

R. Edwards *et al.* Phys. Rev. D **84** 074508 (2011)
Picture courtesy V. Bukert (CLAS collaboration meeting 2015)

New '+' parity states:
N(1860)5/2$^+$
N(1900)3/2$^+$
N(1880)1/2$^+$



New '–' parity states:
N(2060)5/2$^-$
N(2120)3/2$^-$
N(1875)3/2$^-$
N(1895)1/2$^-$

Known states:
N(1675)5/2$^-$
N(1700)3/2$^-$
N(1520)3/2$^-$
N(1650)1/2$^-$
N(1535)1/2$^-$

- - - LQCD manifests broad features of $SU(6) \otimes O(3)$ symmetry.

New states accommodated in LQCD calculations (ignoring mass scale) with J^P values consistent with CQM.

Analyses underway at CLAS

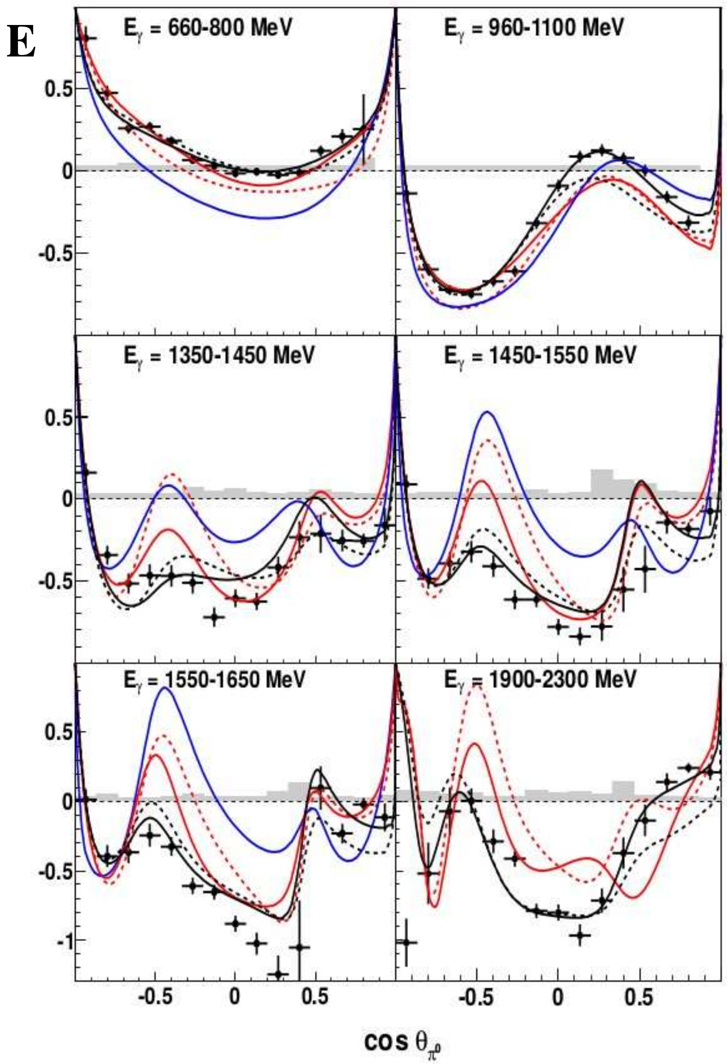
Vector meson (ω, ρ, ϕ) decay modes have mostly remained unexplored. Vast pool of information yet to be unearthed:

- For a better understanding of known resonances, it is essential to study their vector meson decay modes.
- They carry the same J^{PC} as the photon so it is highly expected that they play an important role in the baryon spectrum.
- This talk will focus on $\gamma p \to p\pi^+\pi^-$ and $\gamma p \to p\omega \to p\pi^+\pi^-(\pi^0)$ reactions. The former gives information on $N^* \to p\rho$ which is difficult to study directly due to the broad nature of ρ.
- Ongoing analysis on $\gamma p \to p\phi$ cross section from CLAS-g12 (A. Hurley, FSU).

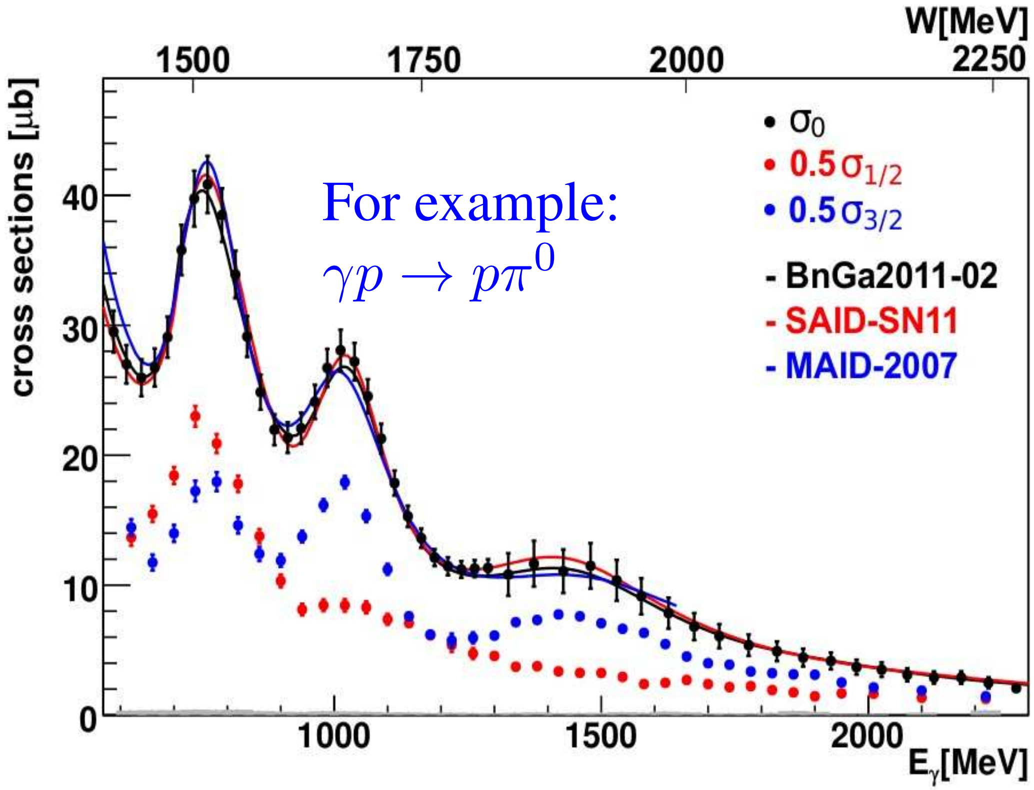
	Status			Status as seen in —						
Particle J^P	overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$N(1700)\,3/2^-$	***	***	**	*			*	*	*	***
$N(1710)\,1/2^+$	***	***	***	***		**	***	**	*	**
$N(1720)\,3/2^+$	****	****	***	***			**	**	**	*
$N(1860)\,5/2^+$	**	**							*	*
$N(1875)\,3/2^-$	***	*	***			**	***	**		***
$N(1880)\,1/2^+$	**	*	*		**		*			
$N(1895)\,1/2^-$	**	*	**	**			**	*		
$N(1900)\,3/2^+$	***	**	***	**		**	***	**	*	**
$N(1990)\,7/2^+$	**	**	**					*		
$N(2000)\,5/2^+$	**	*	**	**			**	*	**	
$N(2040)\,3/2^+$	*									
$N(2060)\,5/2^-$	**	**	**	*				**		
$N(2100)\,1/2^+$	*									
$N(2150)\,3/2^-$	**	**	**				**			**
$N(2190)\,7/2^-$	****	****	***			*	**		*	
$N(2220)\,9/2^+$	****	****								
$N(2250)\,9/2^-$	****	****								
$N(2600)\,11/2^-$	***	***								
$N(2700)\,13/2^+$	**	**								

Particle Data Group 2014

Spin-observables are important



M. Gottschall *et al.* PRL 112 (2014)



Spin observables sensitive to the interference between resonances. Reveal discrepancies between model predictions and experimental data.

JLAB/CLAS experiment: FROST

FROST experiment using CLAS, JLab

- World-wide effort to extract polarization observables in photoproduction reactions: CLAS @ JLab (U.S.), ELSA, MAMI (Germany), SPring-8 (Japan), GRAAL (France)
- Getting close to completing the set of accessible polarization observables. 'Complete experiment in pseudoscalar meson production': next talk

$p\omega$:

Beam \ Target	Transversely Pol.	Longitudinally Pol.
Linearly Pol.	**Σ, T, H, P**	**Σ, G**
Circularly Pol.	**F, T**	**E**

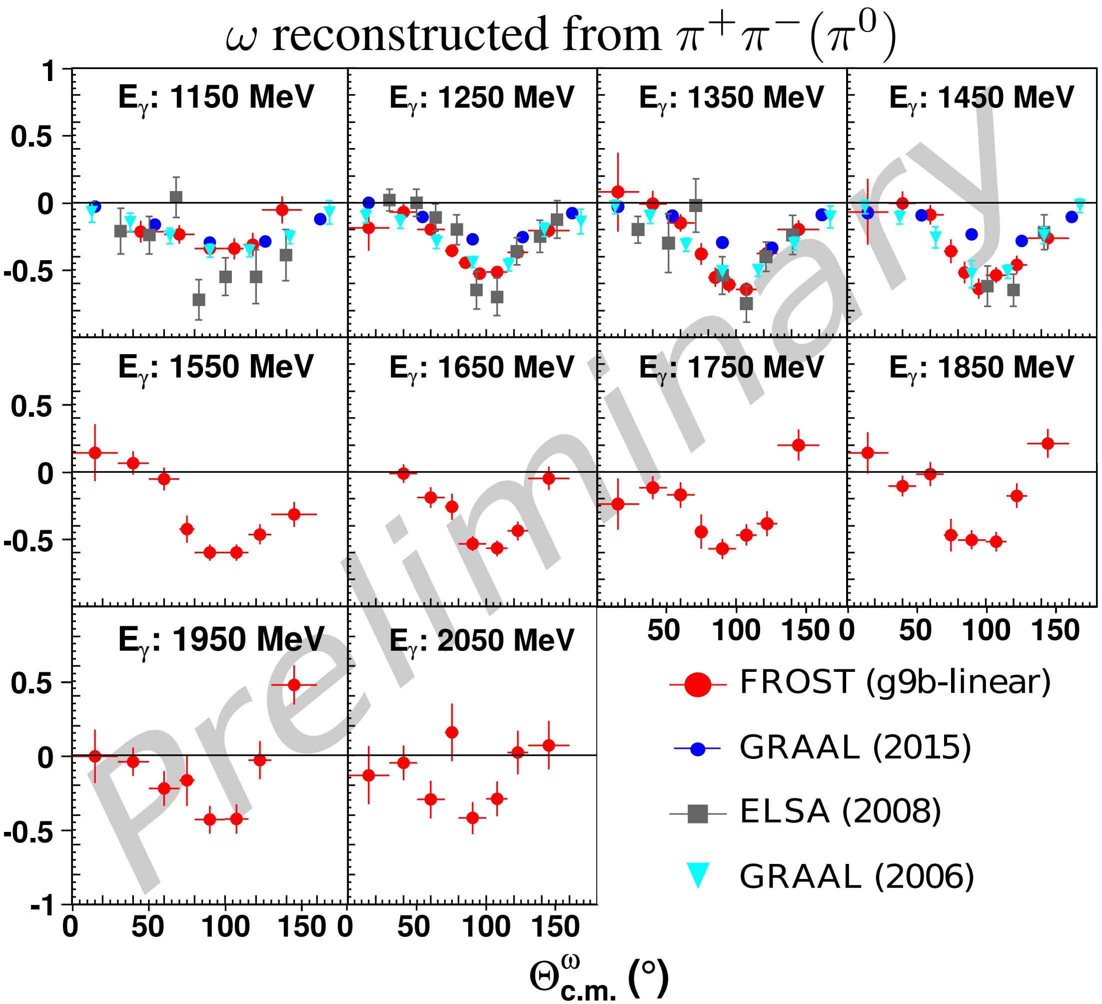
$p\pi^+\pi^-$:

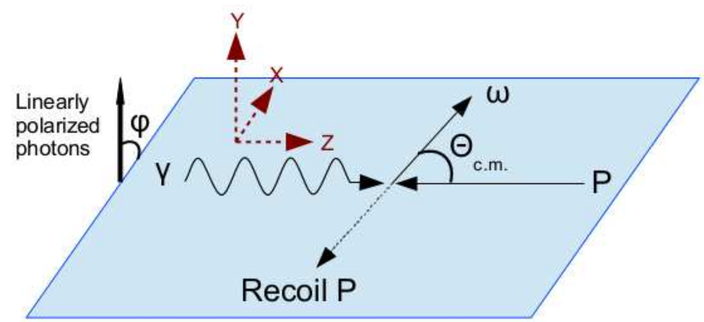
Beam \ Target	Transversely Pol.	Longitudinally Pol.
Linearly Pol.	$P^{s,c}_{x,y}$, $P_{x,y}$, $I^{s,c}$	$P^{s,c}_{z}$, P_{z}, $I^{s,c}$
Circularly Pol.	$P^{\odot}_{x,y}$, $P_{x,y}$, $I^{\odot}$	$P^{\odot}_{z}$, P_{z}, $I^{\odot}$

Prelim. results (Priyashree, FSU) (Analysis Note under review)

Prelim. results available

FROST data: Σ for γp -> ωp



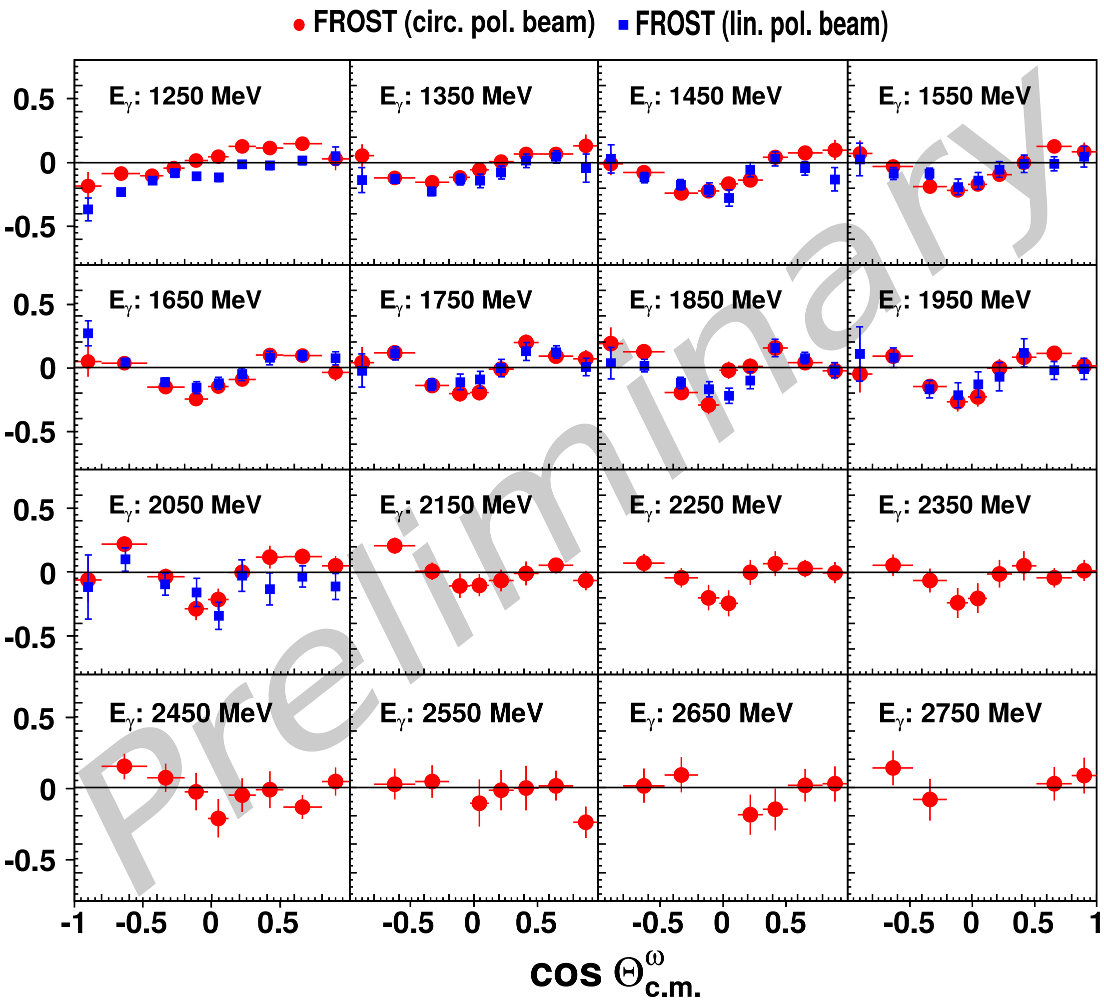


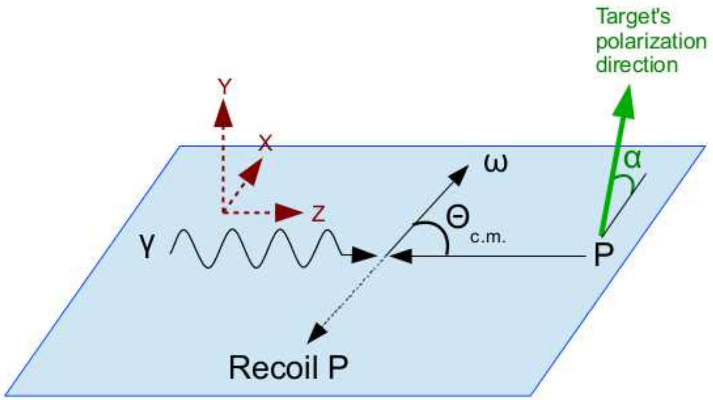
$$\sigma = \sigma_0[1 - \boldsymbol{\Sigma}\,\delta_l \cos(2\phi)$$
$$+\Lambda\cos(\alpha)(-\delta_l \mathbf{H}\sin(2\phi) + \delta_\odot \mathbf{F})$$
$$-\Lambda\sin(\alpha)(-\mathbf{T} + \delta_l \mathbf{P}\cos(2\phi))]$$
$$-\Lambda_z(-\delta_l \mathbf{G}\sin(2\phi) \quad + \quad \delta_\odot \mathbf{E})]$$

$\delta_\odot(\delta_l)$: degree of beam pol.

Λ : degree of target pol.

FROST data: T for $\gamma p \to \omega p$





$$\sigma = \sigma_0[1 - \mathbf{\Sigma}\,\delta_l \cos(2\phi)$$
$$+\Lambda\cos(\alpha)(-\delta_l \mathbf{H}\sin(2\phi) + \delta_\odot \mathbf{F})$$
$$-\Lambda\sin(\alpha)(-\mathbf{T} + \delta_l \mathbf{P}\cos(2\phi))]$$
$$-\Lambda_z(-\delta_l \mathbf{G}\sin(2\phi) + \delta_\odot \mathbf{E})]$$

$\delta_\odot(\delta_l)$: degree of beam pol.

Λ : degree of target pol.

The two experimental results on target asym. **T** from FROST agree well.

Partial Wave Analysis of γp->ωp

Pol. SDMEs and Σ were crucial to understand the t-channel background: Major contribution from pomeron exchange mechanism.

BnGa PWA 2016
(coupled-channel) using ELSA data

Notable contribution | Suggestive evidence

CLAS PWA 2009

Notable contribution | Suggestive evidence

* rating in PDG 2014

Particle J^P	overall	$N\omega$
$N(1680)\ 5/2^+$	****	
$N(1685)\ ??$	*	
$N(1700)\ 3/2^-$	***	
$N(1710)\ 1/2^+$	***	**
$N(1720)\ 3/2^+$	****	
$N(1860)\ 5/2^+$	**	
$N(1875)\ 3/2^-$	***	**
$N(1880)\ 1/2^+$	**	
$N(1895)\ 1/2^-$	**	
$N(1900)\ 3/2^+$	***	**
$N(1990)\ 7/2^+$	**	
$N(2000)\ 5/2^+$	**	
$N(2040)\ 3/2^+$	*	
$N(2060)\ 5/2^-$	**	
$N(2100)\ 1/2^+$	*	
$N(2150)\ 3/2^-$	**	
$N(2190)\ 7/2^-$	****	*
$N(2220)\ 9/2^+$	****	
$N(2250)\ 9/2^-$	****	

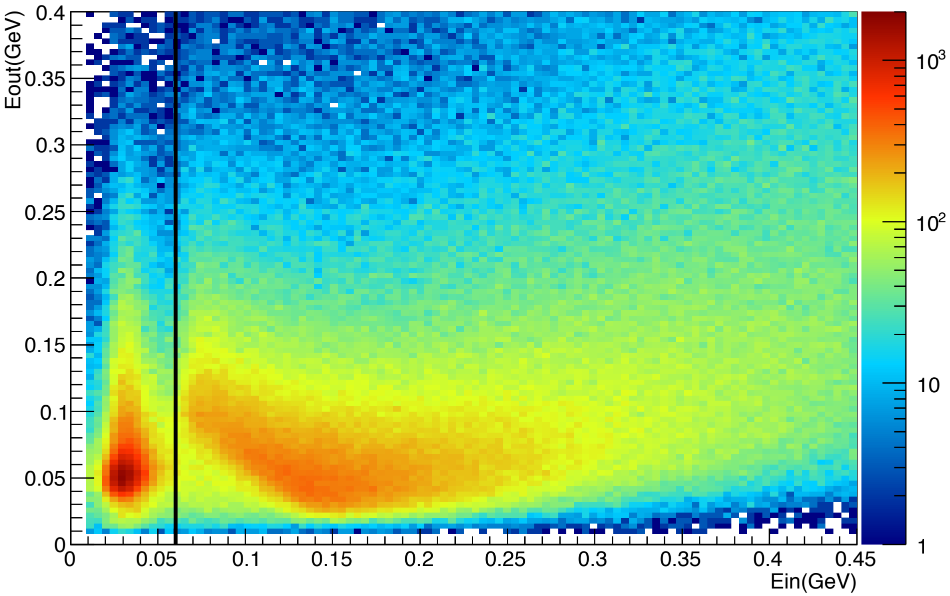
I. Denisenko *et al.*, Phys. Lett. B (2016)
M. Williams *et al.*, PRC **80**, 065208 (2009)

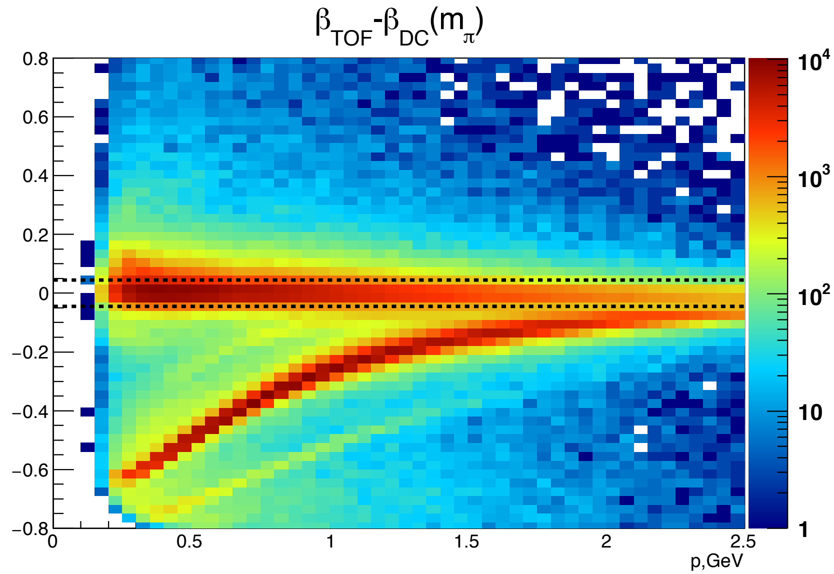
New CLAS data for $(e,e'\pi^+\pi^-)$

CLAS experiment: e1-6

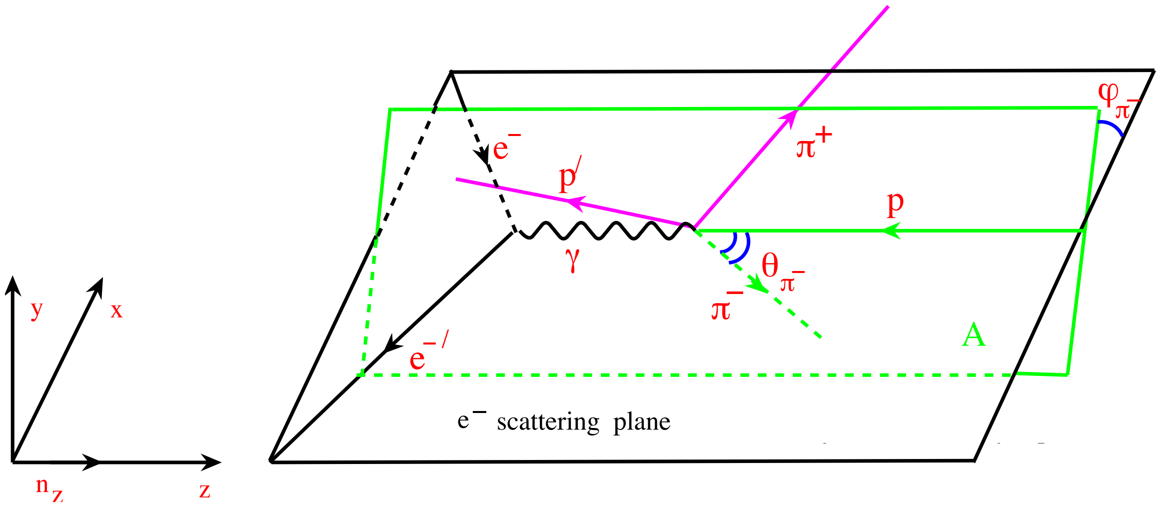
- Data collected: October-December 2001
- Beam energy: 5.754 GeV
- LH2 target (5.0 cm long)
- Electron beam trigger: (e,e')
- Center-of-mass energy W: 1.4 – 2.0 GeV
- 4-momentum transfer Q^2: 2.0 – 5.0 GeV^2
- Analysis of (e,e'2π) done by E. Isupov (MSU)

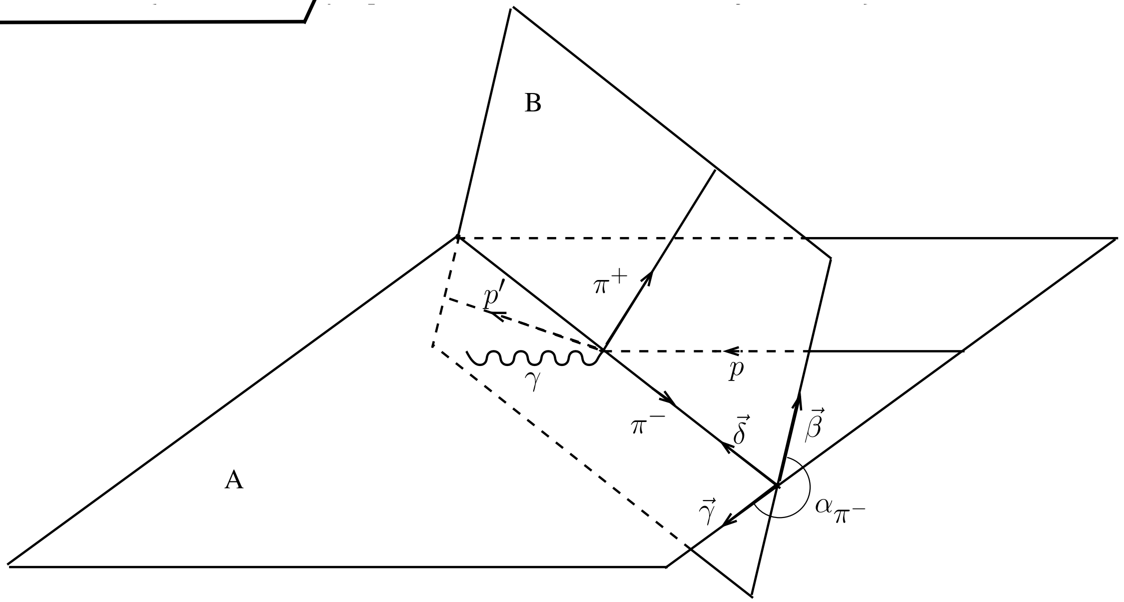
Electron and pion Identification



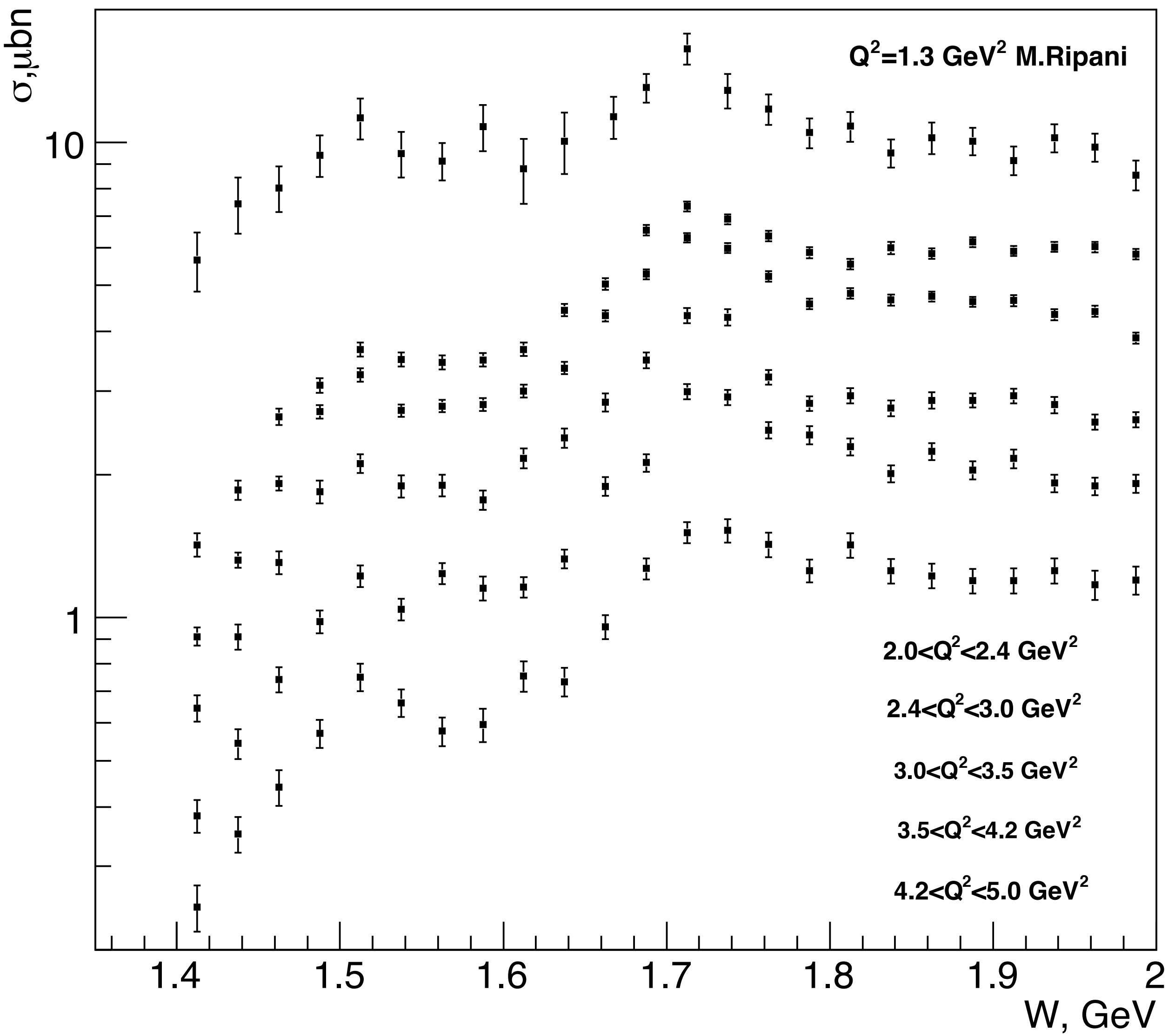


Kinematics of (e,e'2π)





CLAS e1-6: cross section results

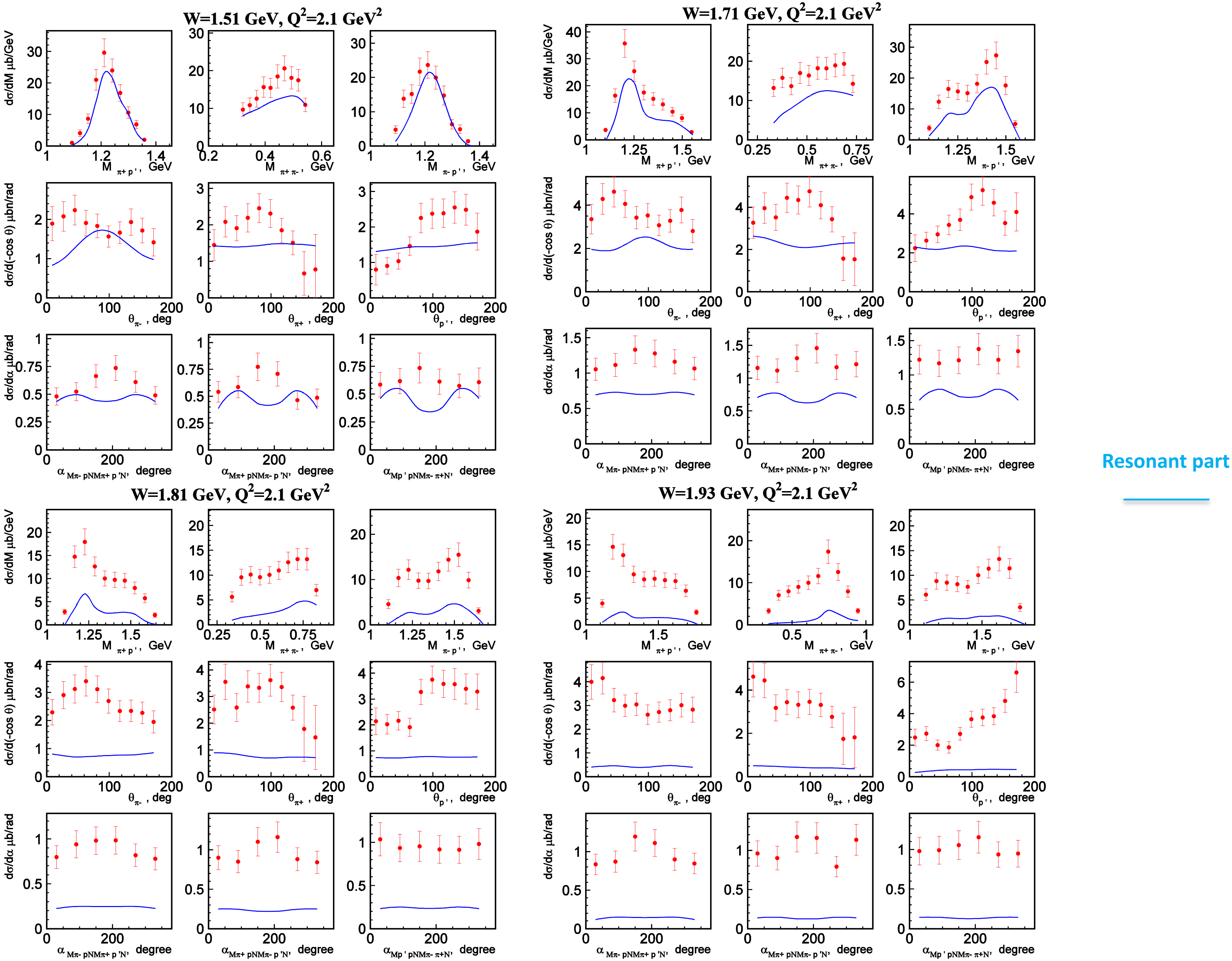


The JM model: N* parameters

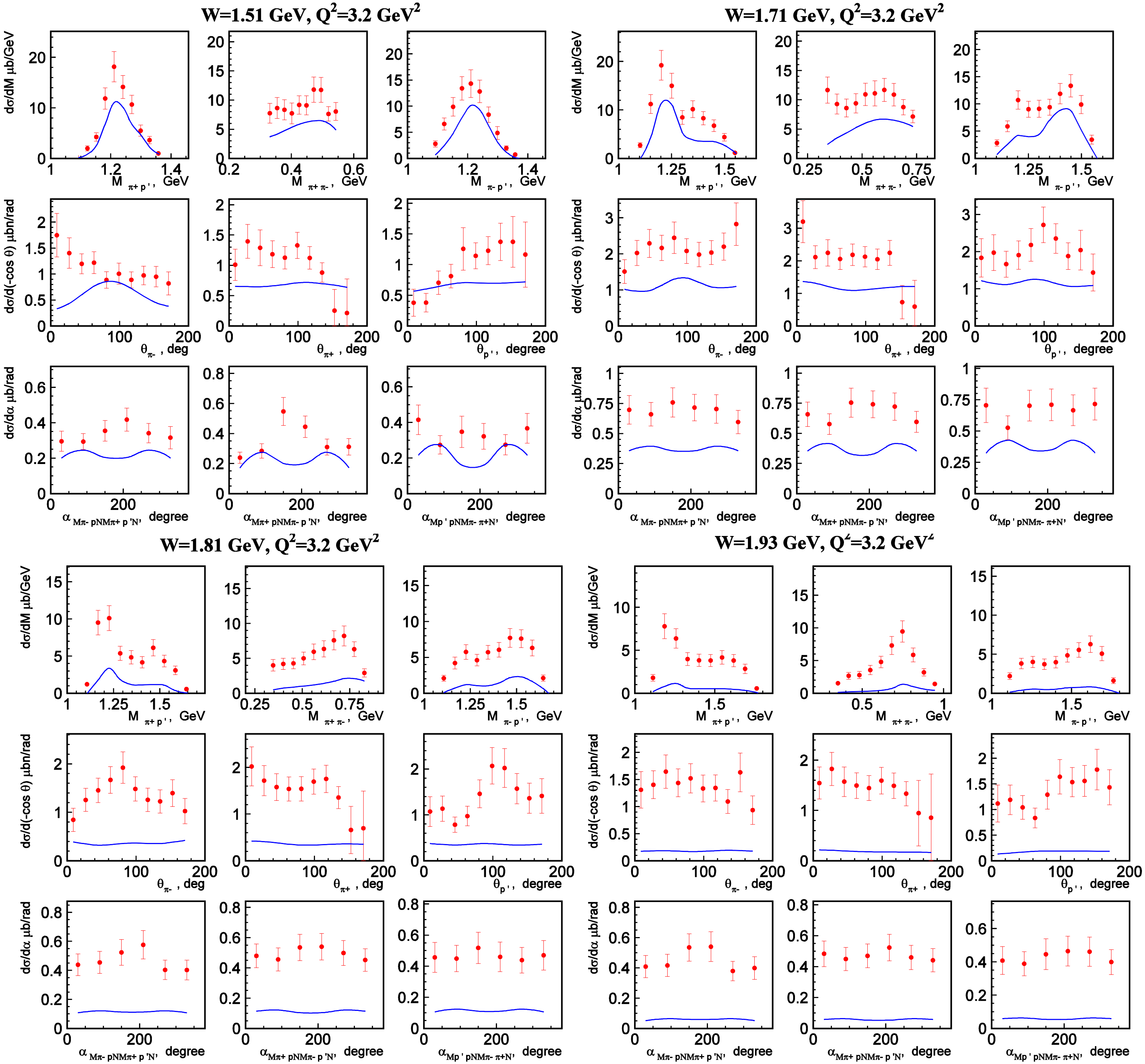
Resonance hadronic decay parameters

(taken from the CLAS data on Nπ/Nππ photo-/electroproduction)

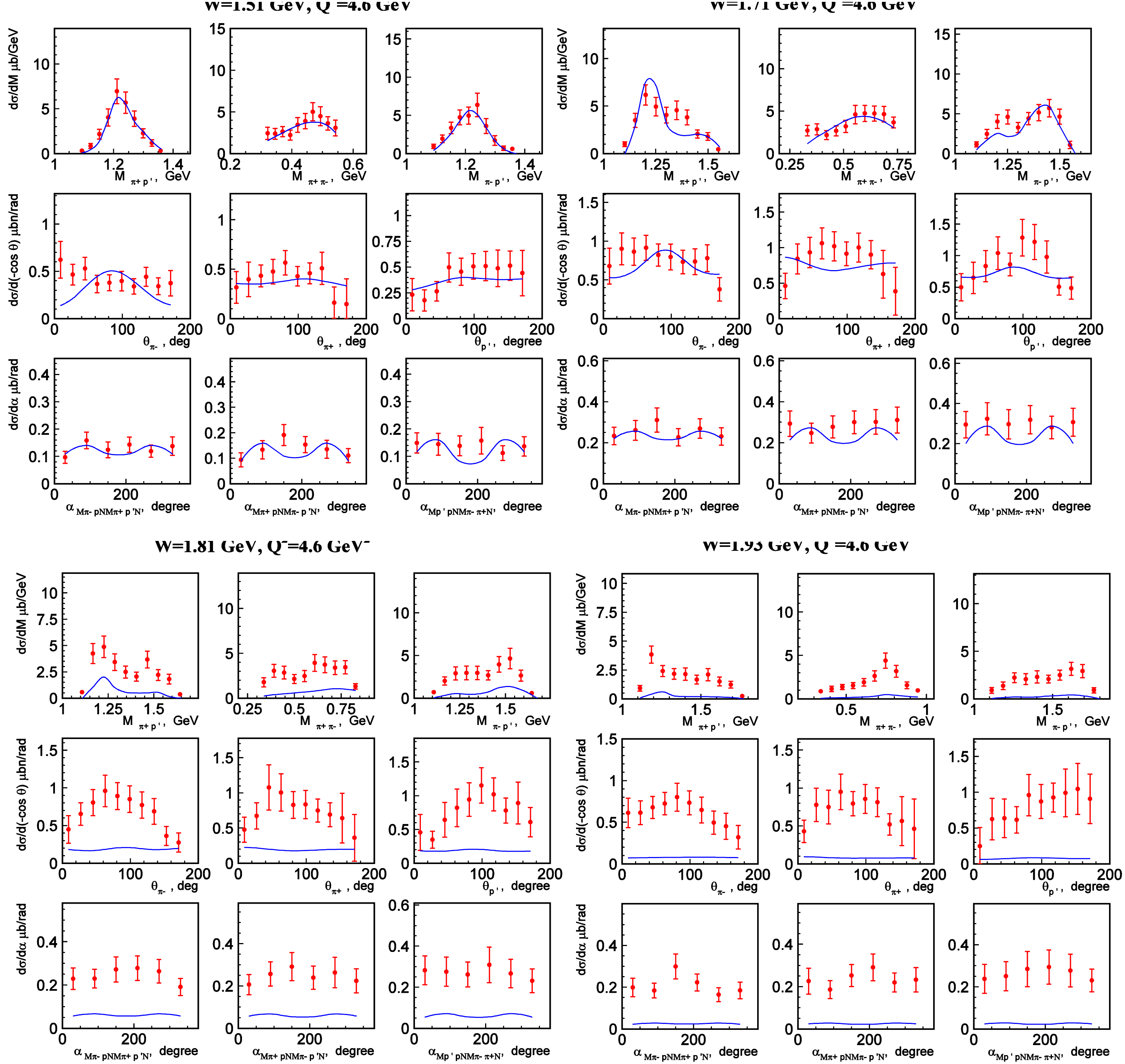
N*	BF(πΔ),%	BF(ρp),%	Γ, MeV	BF(πΔ),%	BF(ρp),%	Γ, MeV
	CLAS	CLAS	CLAS	PDG	PDG	PDG
$N(1440)1/2^+$	19	1.7	387	20-30	<8	200-450
$N(1520)3/2^-$	25	9.4	130	15-25	15-25	100-125
$N(1535)1/2^-$	2	10	131	<4	1-5	125-175
$\Delta(1620)1/2^-$	43	49	158	30-60	7-25	130-150
$N(1650)1/2^-$	5	6	155	<24	4-12	120-180
$N(1680)5/2^+$	12	6	118	5-15	3-15	120-140
$\Delta(1700)3/2^-$	84	5	276	30-60	30-50	200-400
$N(1720)3/2^+$	39	44	117	70-90	70-85	150-400
$N'(1720)3/2^+$	51	9	115			



W=1.51 GeV, Q2=2.1 GeV2
W=1.71 GeV, Q2=2.1 GeV2
W=1.81 GeV, Q2=2.1 GeV2
W=1.93 GeV, Q2=2.1 GeV2
dσ/dM μb/GeV
dσ/d(-cos θ) μbn/rad
dσ/dα μb/rad
M π+ p', GeV
M π+ π-, GeV
M π- p', GeV
θπ-, deg
θπ+, deg
θp', degree
α Mπ- pNMπ+ p 'N', degree
αMπ+ pNMπ- p 'N', degree
αMp ' pNMπ- π+N', degree
Resonant part



Resonant part



Resonant part

Missing N* at W~1.9 GeV

Evolution of the ratio: (computed resonant contributions)/(measured fully integrated cross section) averaged within four intervals of W in all Q^2-bins available from the measurements

Q^2, GeV^2	1.41<W<1.61, GeV	1.61<W<1.74, GeV	1.74<W<1.86, GeV	1.86<W<1.99, GeV
2.1	0.75	0.66	0.28	0.15
2.6	0.64	0.56	0.24	0.13
3.2	0.63	0.58	0.27	0.13
3.8	0.76	0.71	0.26	0.12
4.6	0.85	0.91	0.31	0.13

Adding more N* at higher mass is needed in the JM model.
NOTE: calculations done by Victor Mokeev (JLAB/MSU).

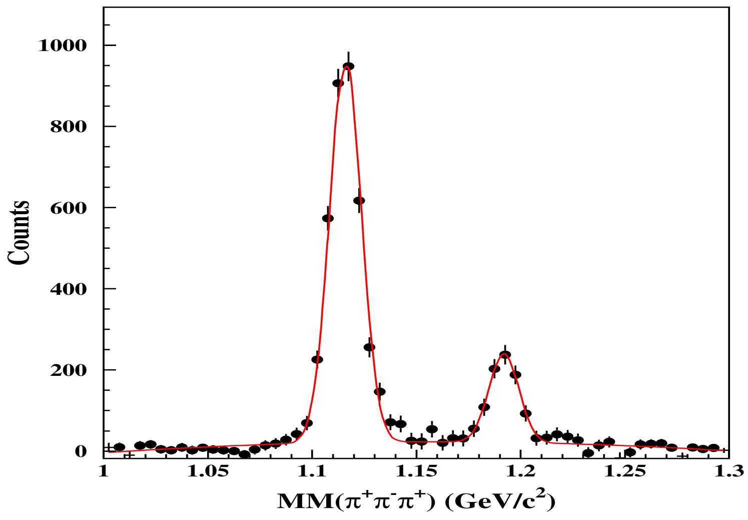
PWA of $K^{*+}\Lambda$ photoproduction

- Original analysis of W. Tang (PhD, Ohio U)
- Analysis of spin-density matrix (A.V. Anisovich, Bonn)
- Partial Wave Analysis: Bonn-Gatchina model

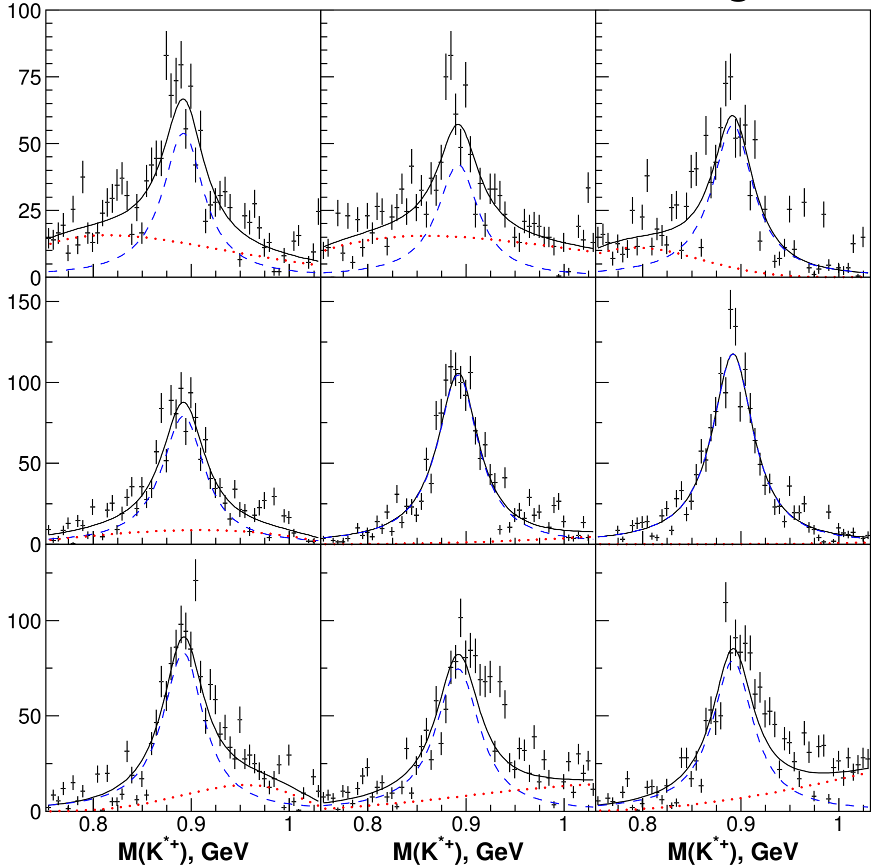
$$W(\cos\Theta,\Phi) = \frac{3}{4\pi}\left(\frac{1}{2}(1-\rho_{00}) + \frac{1}{2}(3\rho_{00}-1)\cos^2\Theta \right.$$
$$\left. -\sqrt{2}Re\rho_{10}\sin 2\Theta\cos\Phi - \rho_{1-1}\sin^2\Theta\cos 2\Phi\right).$$

Missing mass and Invariant mass

Integrated over all angles:

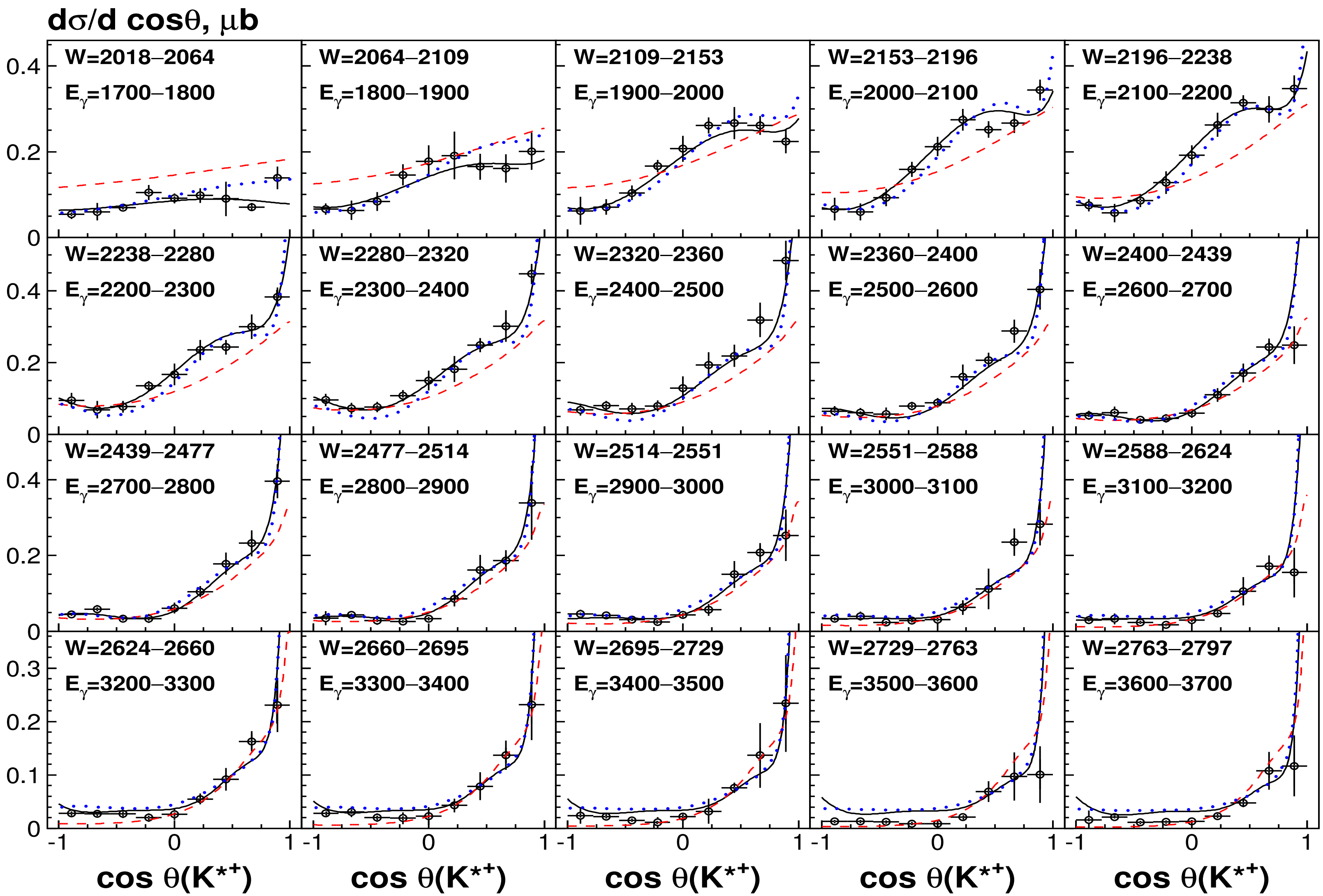


From backward to forward K* angles:

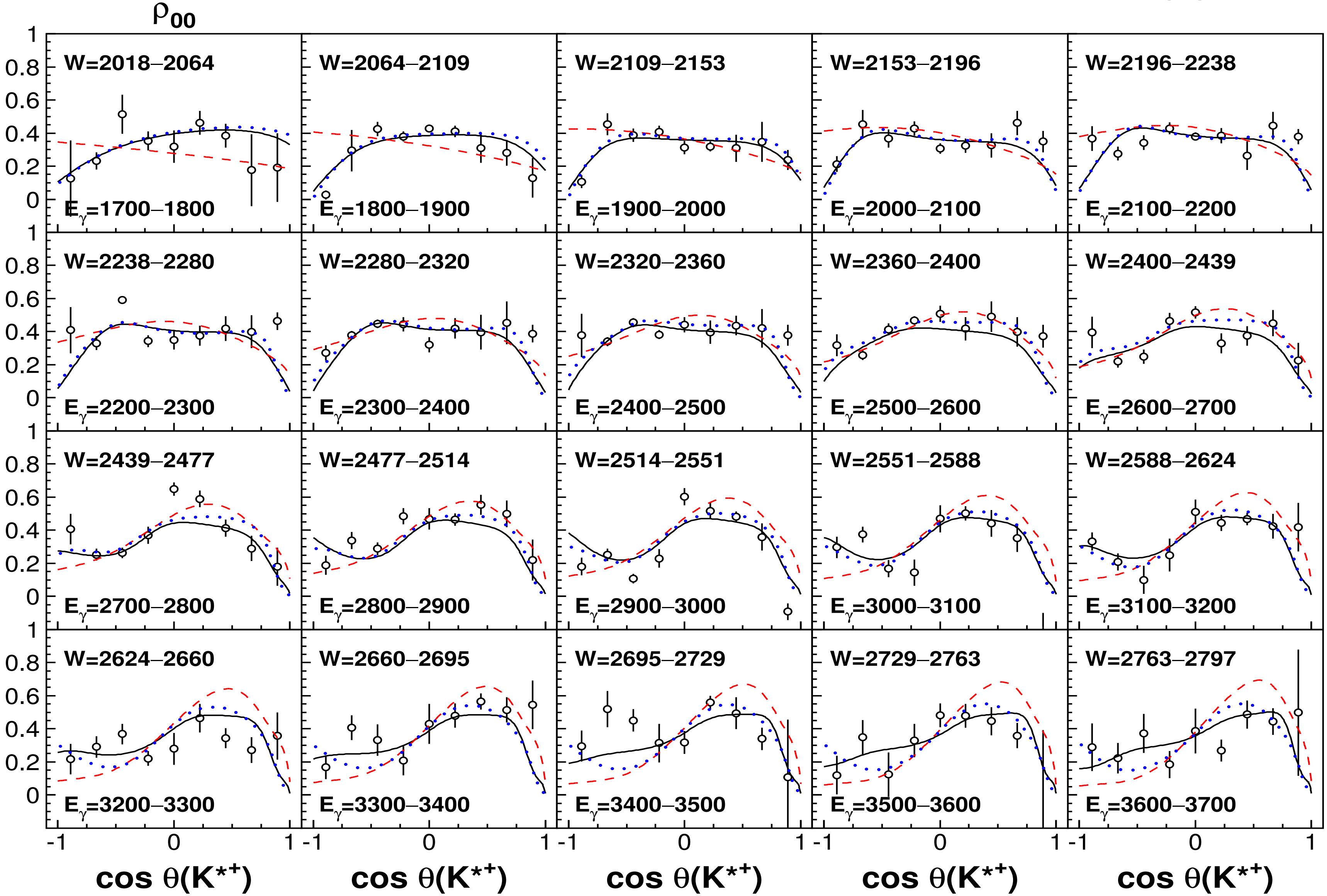


$K^{*+}\Lambda$: Differential cross sections

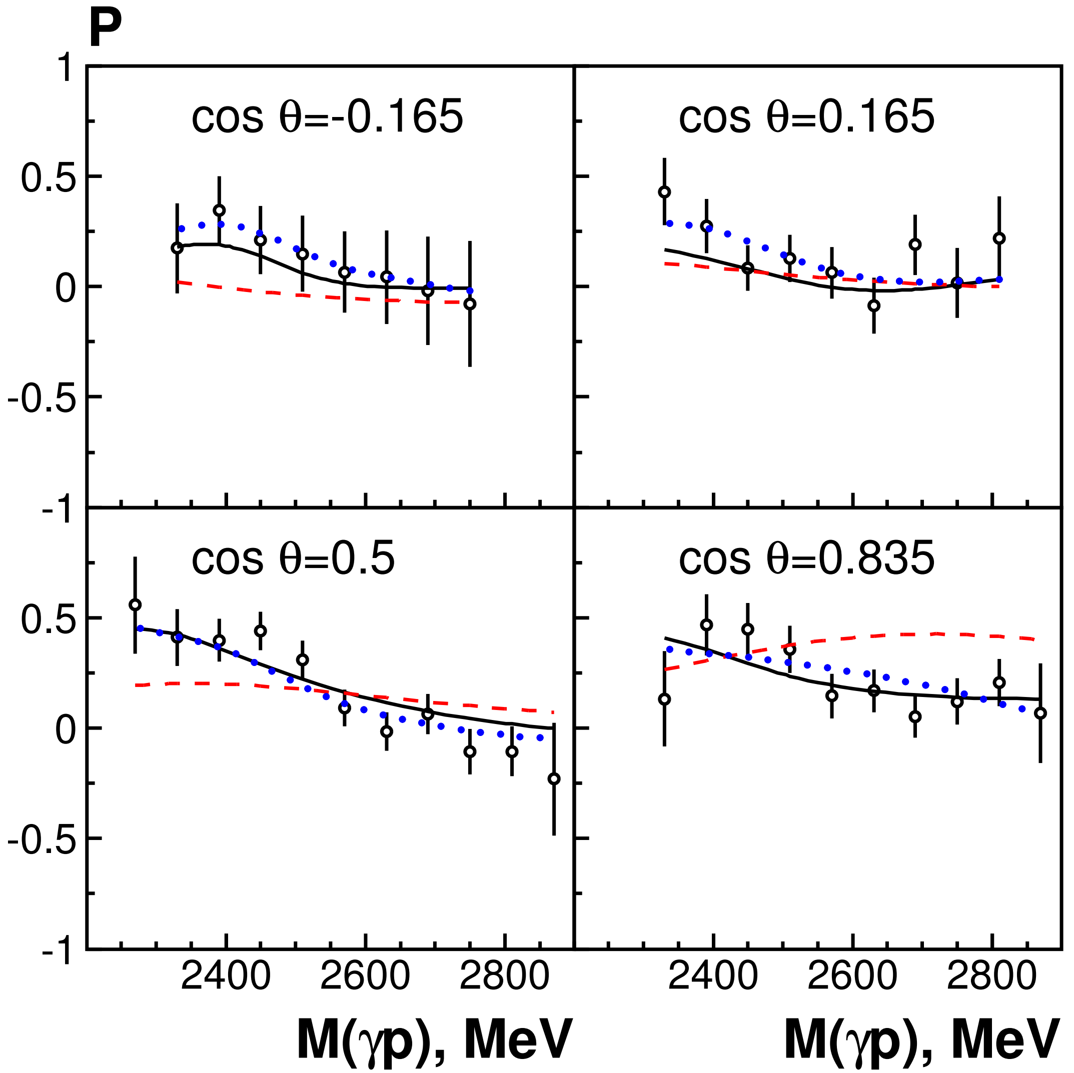
Solid: new BoGa fit, Dotted: fit w/o higher mass N*, Dashed: t-channel only



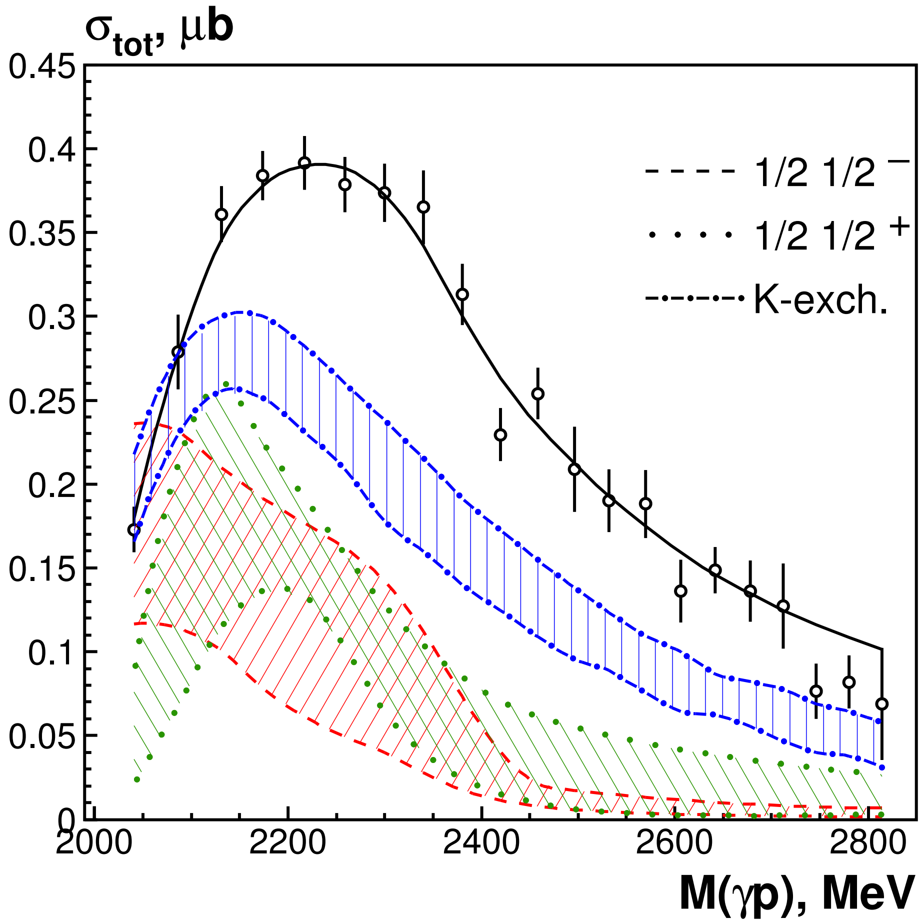
$K^{*+}\Lambda$: spin-density matrix ρ_{00}



Λ recoil polarization



$K^{*+}\Lambda$: total cross section



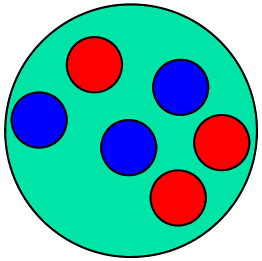
Preliminary!! New N*'s:

Table 1: Masses and widths of tentative additional resonances contributing to the reaction $\gamma p \to K^{*+}\Lambda$.

Resonance	Mass	width
$N(2355)1/2^-$	2355 ± 20 MeV	235 ± 30 MeV
$N(2250)3/2^-$	2250 ± 35 MeV	240 ± 40 MeV
$N(2300)5/2^-$	2300^{+30}_{-60} MeV	205 ± 65 MeV

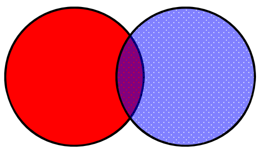
Dibaryons

(some slides borrowed from Reinhard Schumacher)



- 6 quarks in a bag

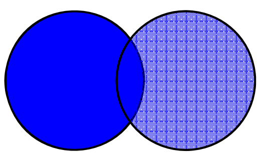
$^3S_1$



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

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

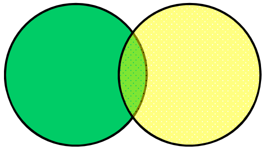
$^1S_0$



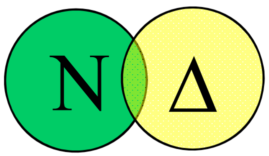
$I(J^P)=1(0^+)$

- 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!!

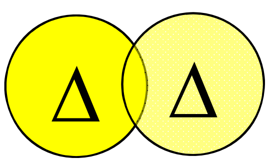
(Slide borrowed from R. Schumacher)



I (J^P)



I (J^P)=1 (2^+) (?)



I (J^P)=0 (3^+)

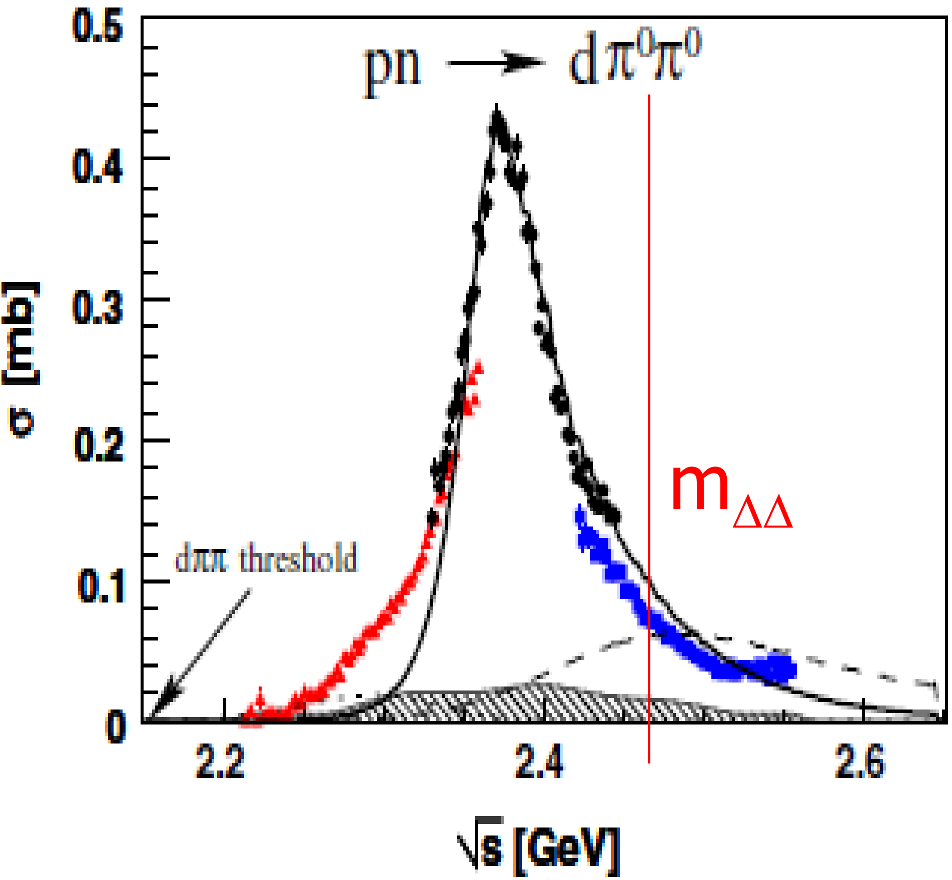
- Bound NΔ, bound ΔΔ, ΛΛ (Jaffe's "H-particle")
  - Binding?
  - Width: 'narrow' or 'wide'?
  - Spin, Isospin ?
- CLAS study: new observations
- Recent WASA@COSY claim of discovery

(Slide borrowed from R. Schumacher)

“3-body model of NΔ and ΔΔ dibaryons”

- A. Gal, H. Garcilazo, arXiv:1402.3171 (2014)
- Three-body model with separable pairwise interactions
- Solve πNN and πNΔ Faddeev equations
- NΔ found below threshold for $I(J^P) = 1(2^+)$ & $2(1^+)$
- ΔΔ found below threshold for $I(J^P) = 0(3^+)$ & $3(0^+)$

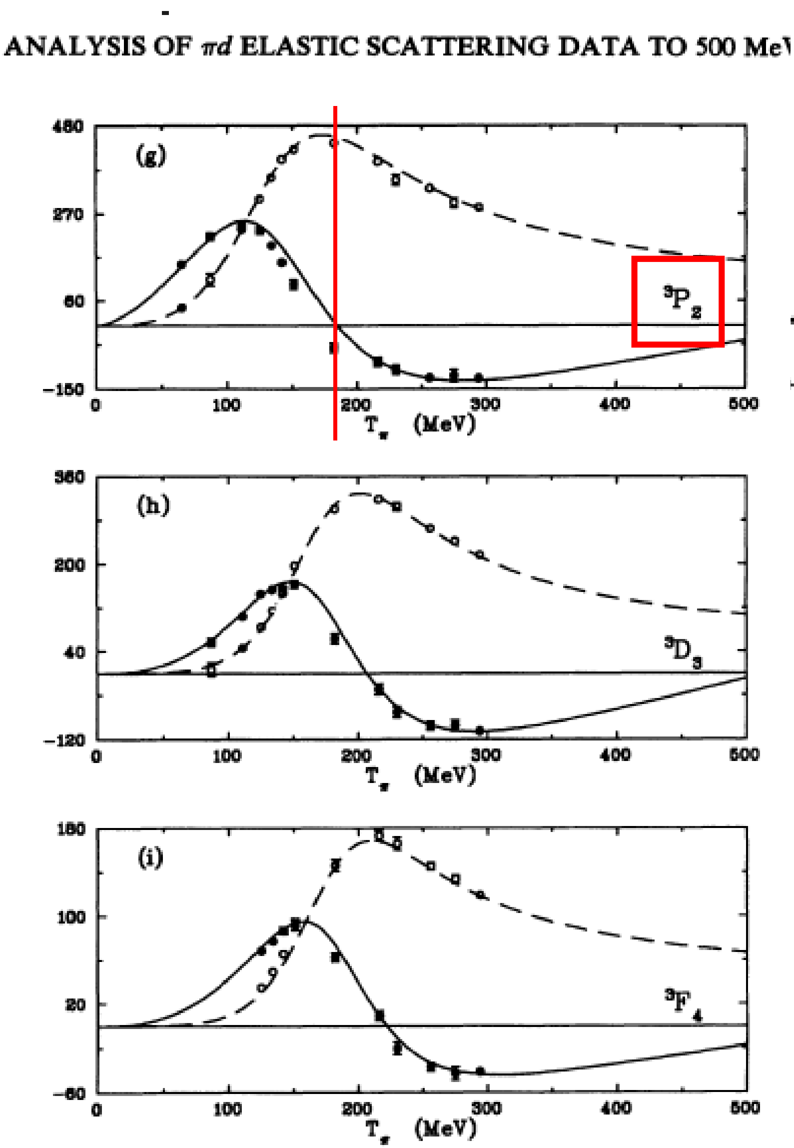
ΔΔ resonance with I (J^P) = 0 (3^+)

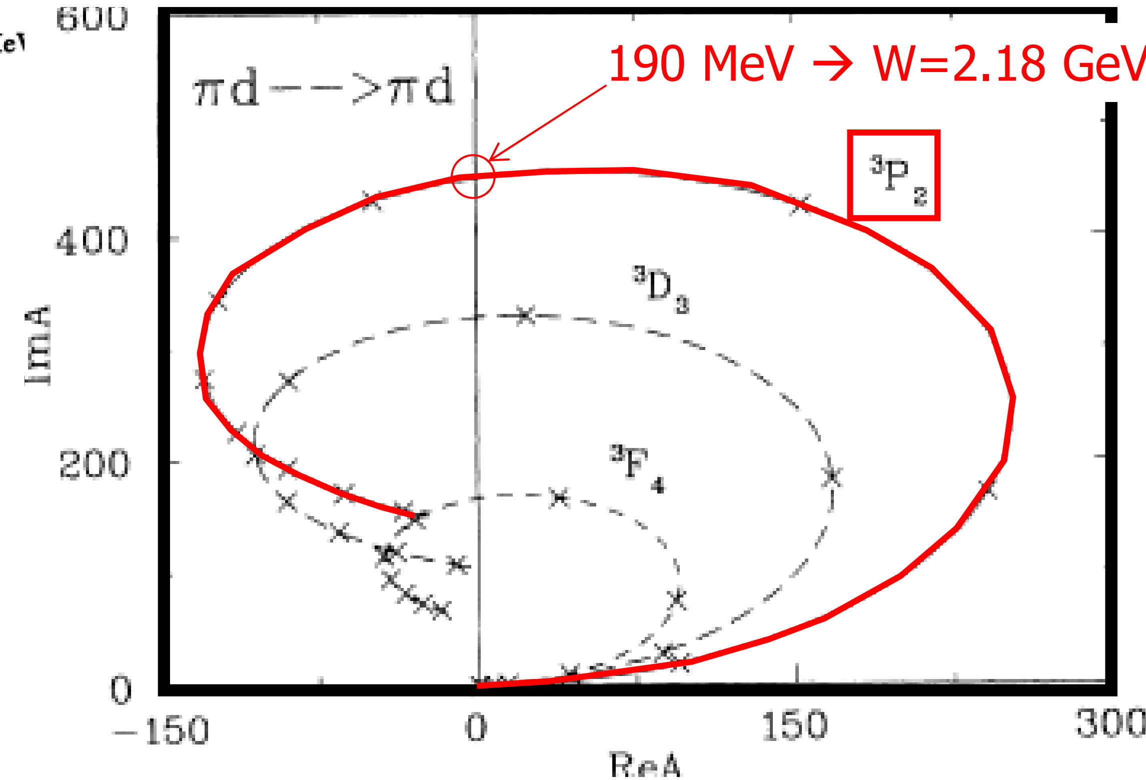


P. Adlarson et al, Phys Rev Lett 106, 242302 (2011)

- The WASA@COSY result for ΔΔ
- $M \sim 2370$ MeV $= 2m_\Delta - 90$ MeV
- $\Gamma \sim 70$ MeV $< 1/3\ \Gamma_{\Delta\Delta}$
- "*ABC effect*": enhancement of low-mass pion pairs
- Dibaryon interpretation is controversial (D. Bugg)

(Slide borrowed from R. Schumacher)



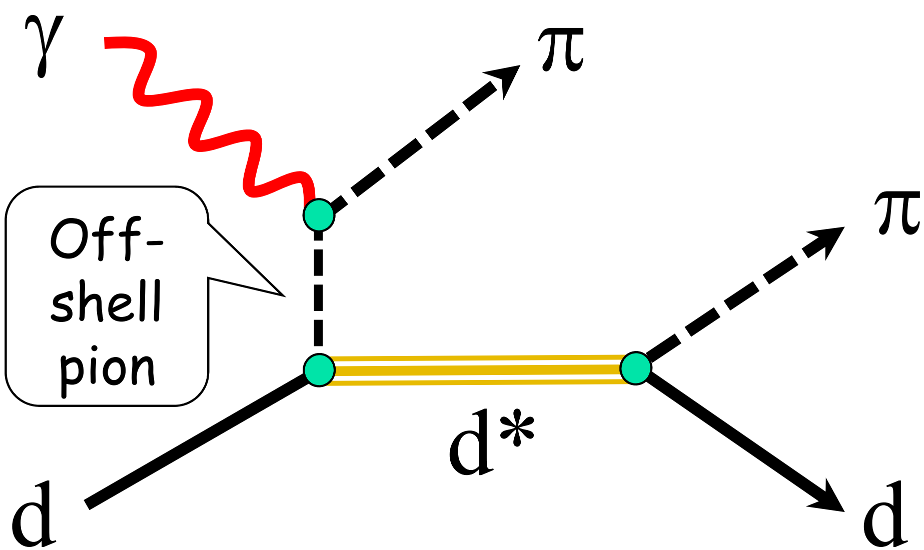


- $^3P_2$ wave in πd elastic scattering is most prominent
- SAID analysis: "resonance-like" behavior in several partial waves

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

(Slide borrowed from R. Schumacher)

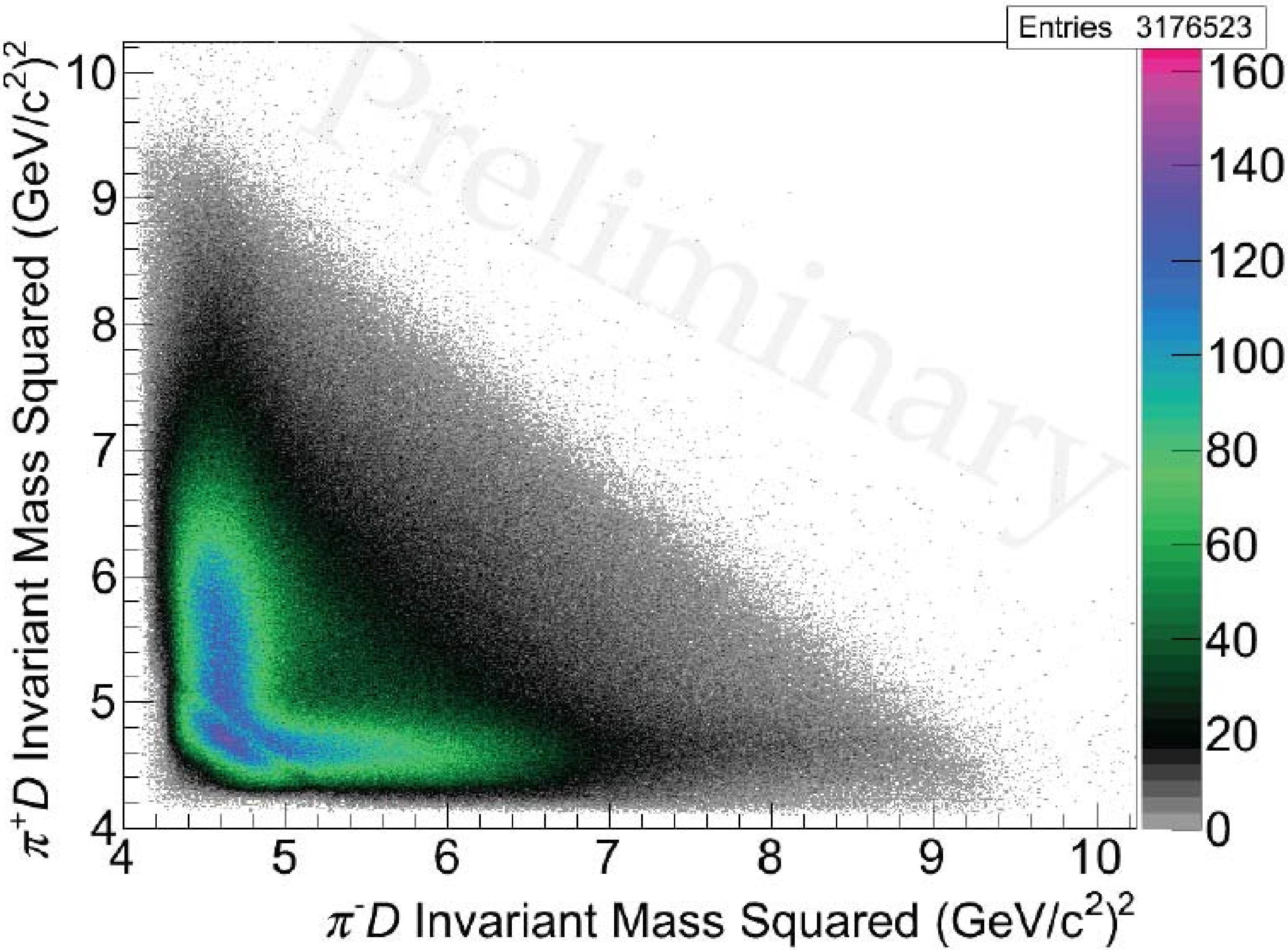
Photoproduction at CLAS



- Resembles πd elastic scattering but with an off-shell pion.

(Slide borrowed from R. Schumacher)

R. Schumacher, P. Mattione (CMU): CLAS Preliminary!!



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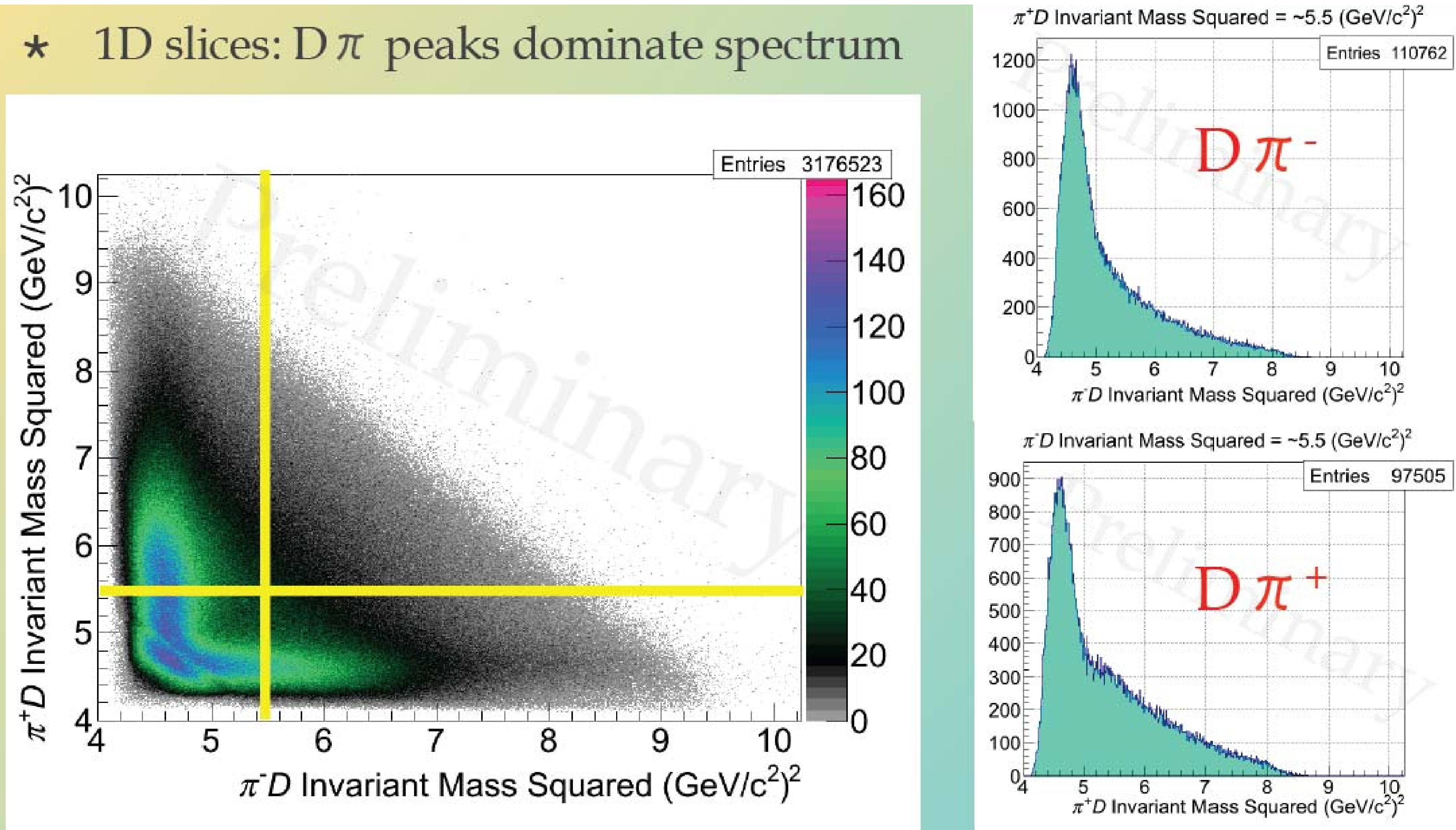
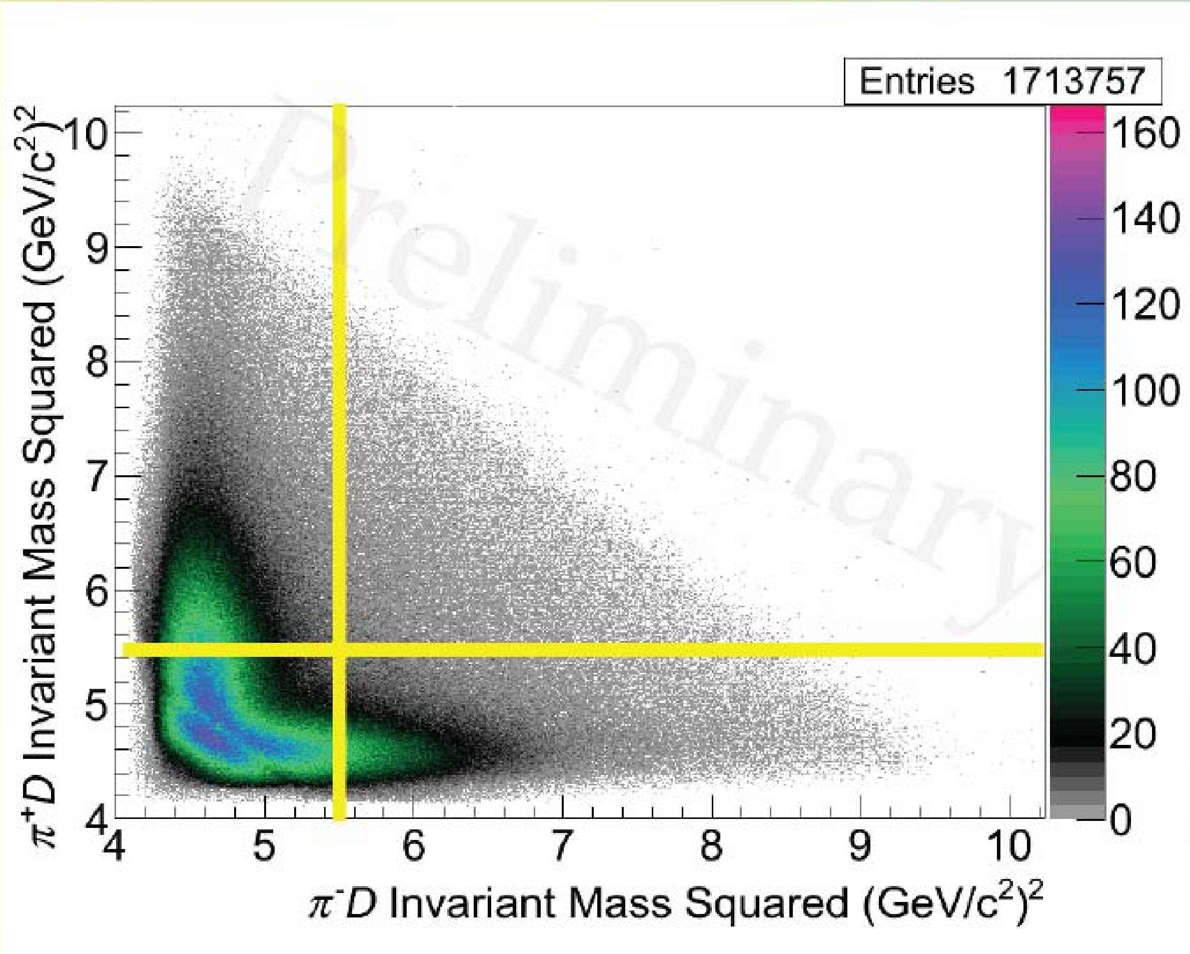
Projections: CLAS preliminary!!

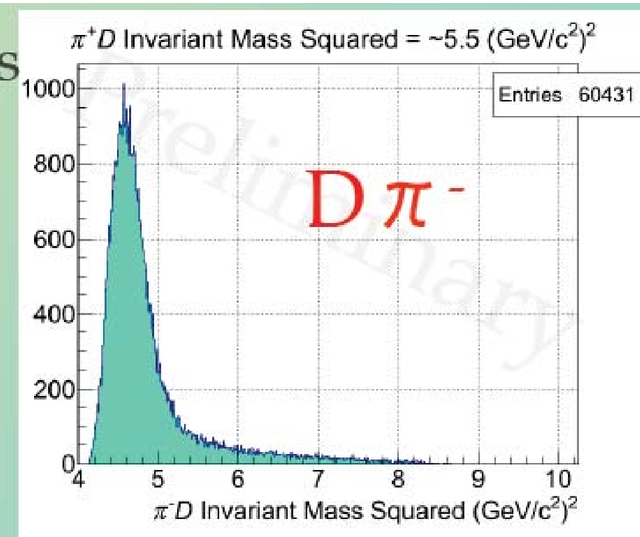


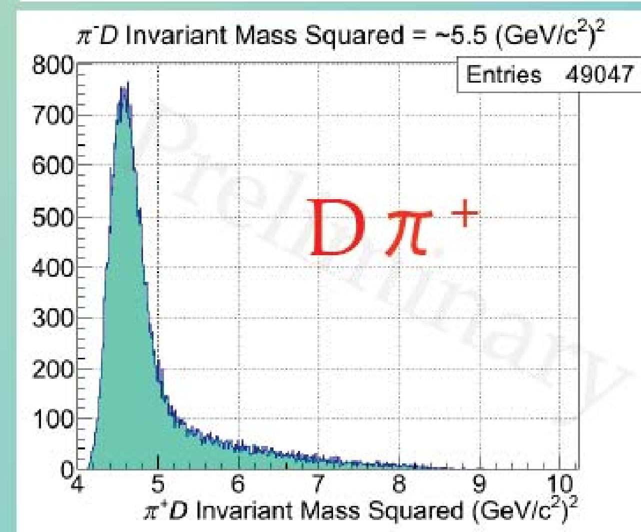
(Slide borrowed from R. Schumacher)

Background from ρ-meson removed: Preliminary!!

* ρ cut removed most background under peaks

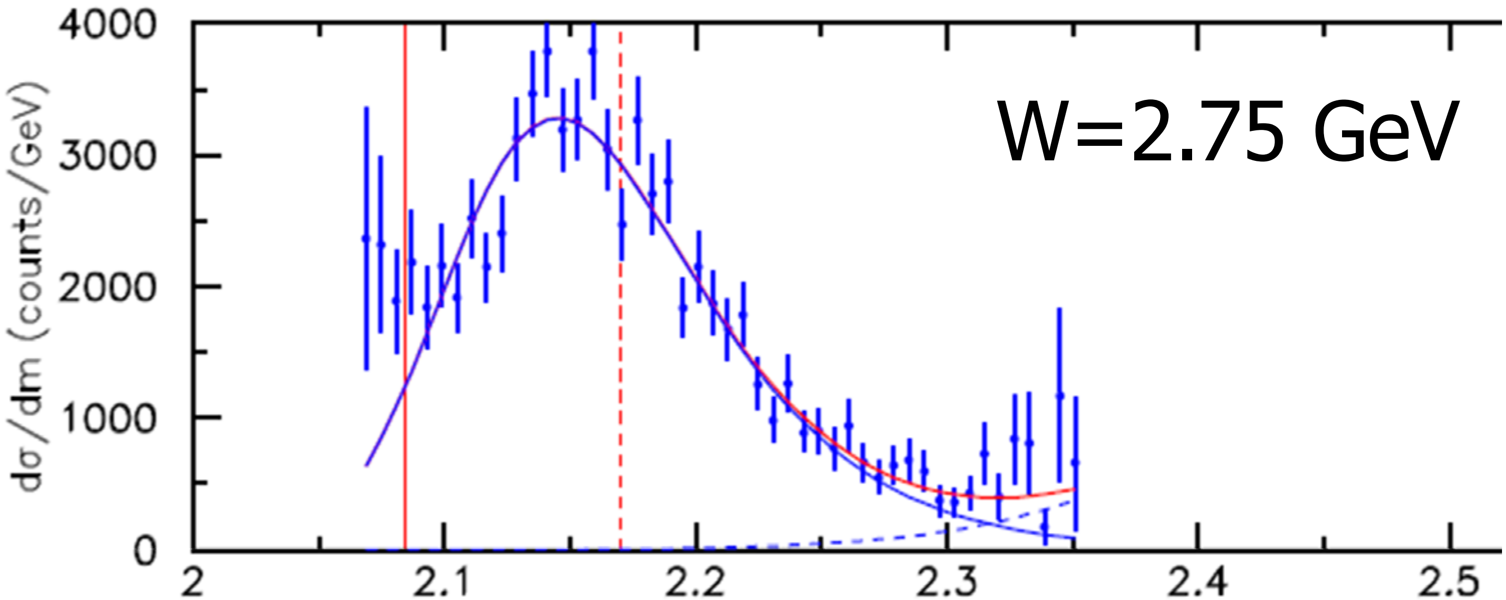






(Slide borrowed from R. Schumacher)

Fit to resonance shape: Preliminary!



(Slide borrowed from R. Schumacher)

Next Steps

- Study of coherent ρ-meson photoproduction
  - PhD of T. Chetry, Ohio U. grad student.
- PWA that includes all possible final states:
  - First steps being done by CMU (P. Mattione)
- In addition to d^{*++} and d^{*0}, look for d^{*+}.
  - Also part of T. Chetry's PhD.
  - Interferes with ω-meson photoproduction.
  - Clearly shows isospin 1 triplet of dibaryon states.

Summary

- Lots of new data from CLAS
  - FROST experiment: γ p -> ω p
  - e1-6 experiment: (e,e'2π)
  - Reanalysis of g11: $K^{*+}\Lambda$
  - Deuteron target: possible d* resonance?
- Using PWA, we can pull apart the N* contributions to each data set
- By comparing with LQCD, we learn about QCD

Backup Slides