CLAS γn → pπ- Cross Section, N* Amplitudes

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Jefferson Lab

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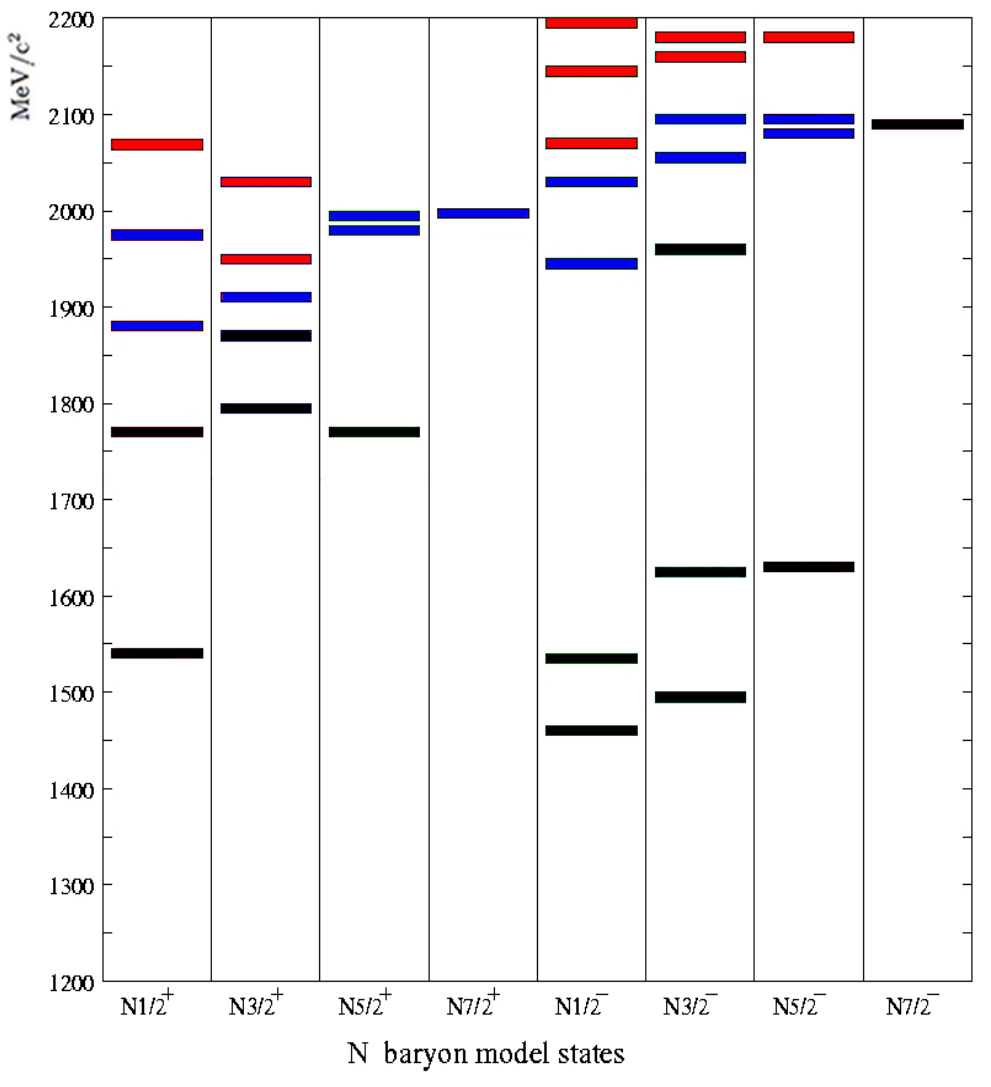
clas
CEBAF Large Acceptance Spectrometer

N* Predictions: Quark Model

- Predictions: Capstick, Isgur†
  - Relativized quark model
  - States organized by J^P
  - Agrees well with lattice predictions below 2 GeV
- Many states missing, many others poorly understood



Legend: PDG status
Black: Certain or likely: ****, ***
Blue: Fair or poor: **, *
Red: No evidence

†S. Capstick, N. Isgur, Phys. Rev. D **34**, 2809 (1986)

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  - Relativized quark model
  - States organized by J^P
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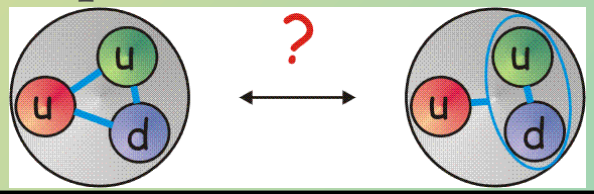
- Many states missing, many others poorly understood
- Diquarks?



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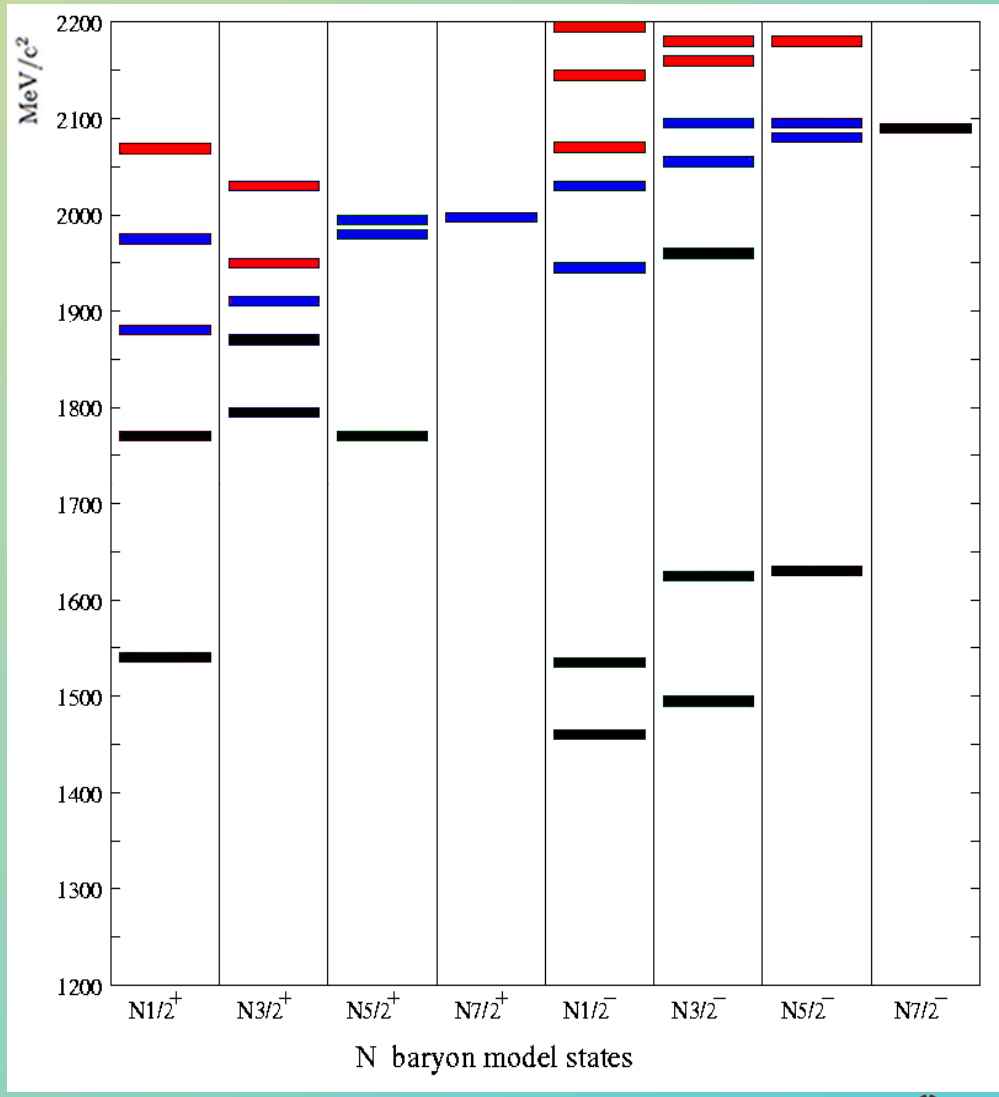

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γp vs. γn, Isospin

- For N* couplings to γN, important to study both γp & γn
  - Disentangle Isoscalar (A^S), isovector (A^V) EM amplitudes†
- γN → πN: Primary γN channel in resonance region
  - 4 possible reactions (below)
  - SAID: Sparse γn → πN data (~3.5k points) vs. γp → πN (~35k)

$$A_{\gamma p\to\pi^+ n} = \sqrt{\frac{1}{3}}A^V_{I=3/2} - \sqrt{\frac{2}{3}}\left(A^V - A^S\right)_{I=1/2}$$

$$A_{\gamma n\to\pi^- p} = \sqrt{\frac{1}{3}}A^V_{I=3/2} - \sqrt{\frac{2}{3}}\left(A^V + A^S\right)_{I=1/2}$$

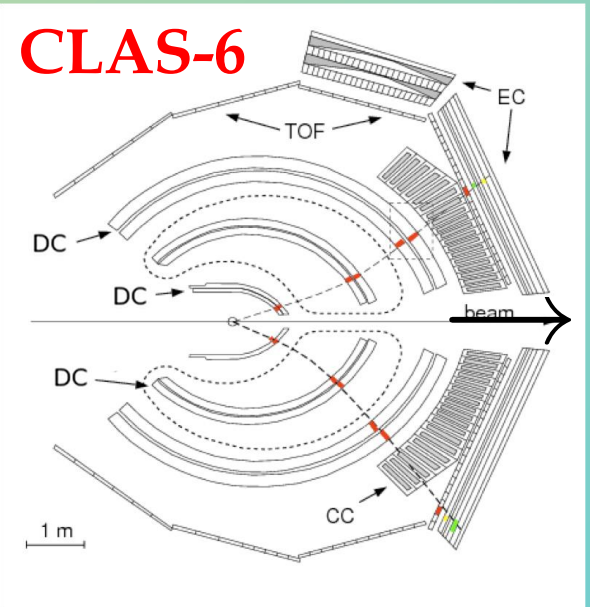
$$A_{\gamma p\to\pi^0 p} = \sqrt{\frac{2}{3}}A^V_{I=3/2} + \sqrt{\frac{1}{3}}\left(A^V - A^S\right)_{I=1/2}$$

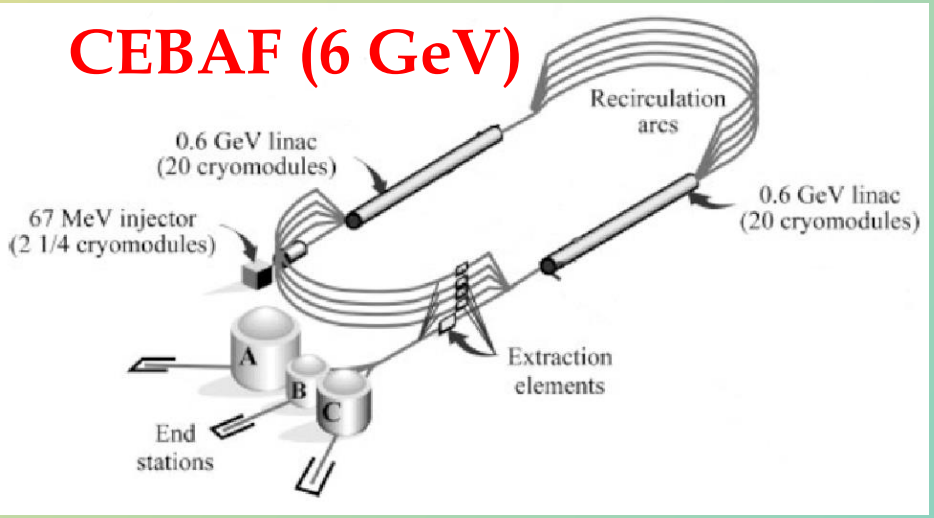
$$A_{\gamma n\to\pi^0 n} = \sqrt{\frac{2}{3}}A^V_{I=3/2} + \sqrt{\frac{1}{3}}\left(A^V + A^S\right)_{I=1/2}$$

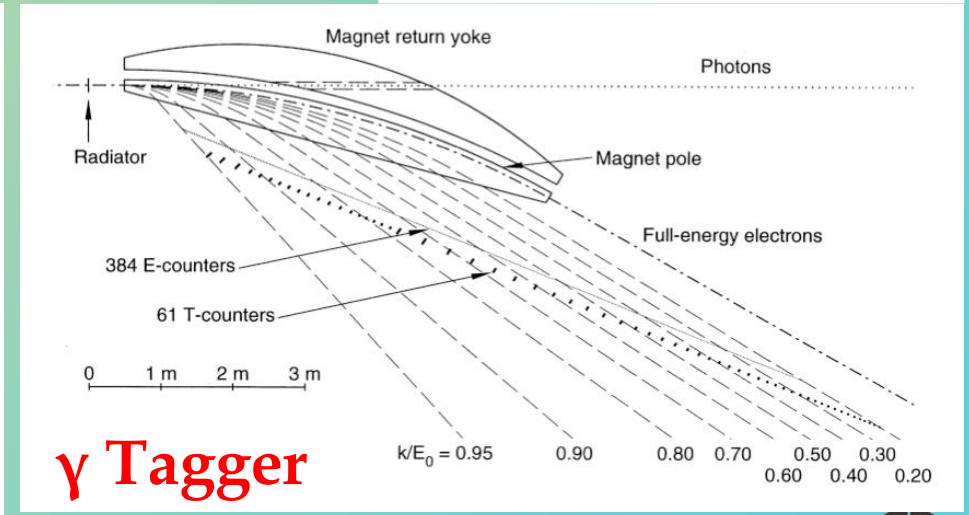
†R. L. Walker, Phys. Rev. **182**, 1729 (1969)

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
  - γ beam: Radiator, γ tagger detects e^-
- Hall-B CLAS-6 detector†: 6 sectors
  - DC: Tracking, ST & TOF: Timing



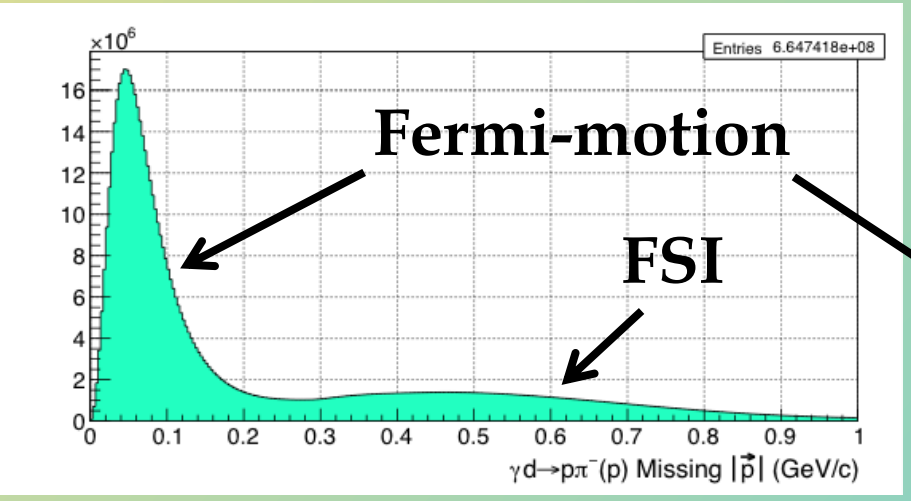


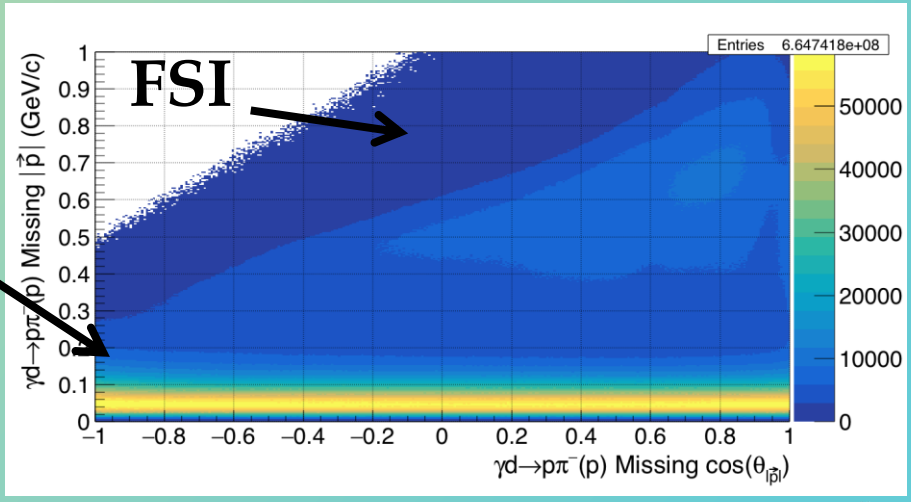


†B. A. Mecking *et al.* (CLAS), Nucl. Instr. and Meth. A **503**, 513 (2003)

Final-State Interactions in γd

- γn: No free neutron targets
  - Deuteron target: Isotropic Fermi-motion, final-state interactions (FSI)
  - Correct for FSI to extract γn cross sections from γd measurements
- On γd, measure "quasi-free" (QF) differential cross sections
  - QF: Cut (FSI) events with missing-p > 200 MeV/c
  - FSI corrections: Model-dependent fit to data†





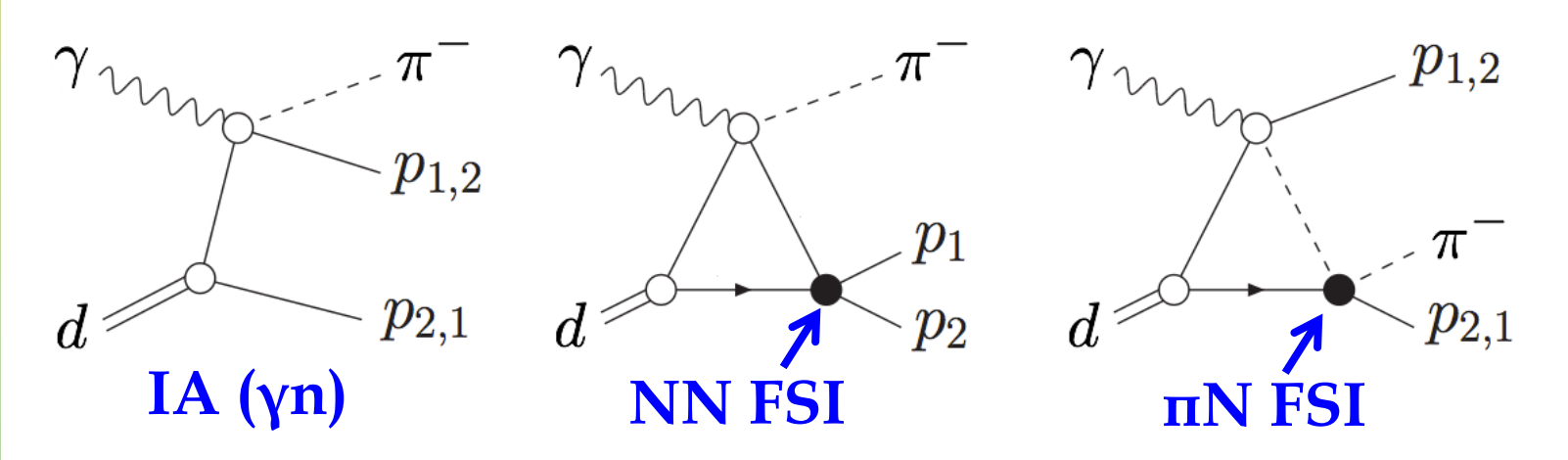
†V. E. Tarasov *et. al*, Phys. Rev. C **84**, 035203 (2011)

†Modeling FSI in γd → ppπ⁻

- Must correct for FSI to extract γn → pπ⁻ from QF γd → ppπ⁻
  - GWU & ITEP Moscow
- γd → ppπ⁻ amplitude: $\mathcal{M}_{\gamma d} = \mathcal{M}_{\mathrm{IA}} + \mathcal{M}_{NN} + \mathcal{M}_{\pi N}$
  - Leading terms: Impulse approximation (IA), NN FSI, πN FSI
  - Fit constrained by SAID γN → πN , NN → NN, Nπ → Nπ

$$\frac{d\sigma}{d\Omega}(\gamma n) = R(E_\gamma, \theta)^{-1} \frac{d\sigma}{d\Omega}(\gamma d)$$

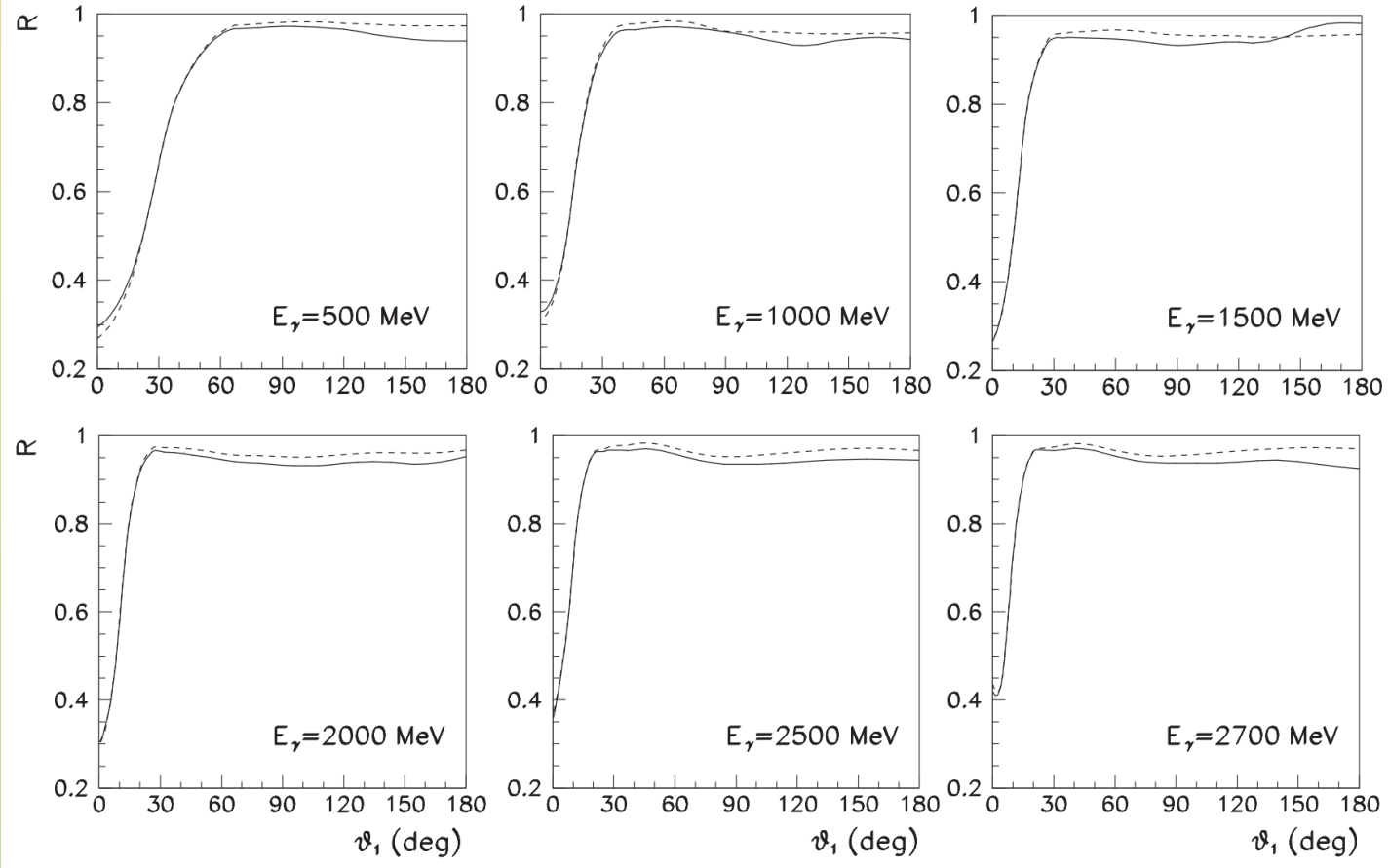
$$R(E_\gamma, \theta) = \mathcal{M}_{\gamma d} / \mathcal{M}_{IA}$$



†V. E. Tarasov *et. al*, Phys. Rev. C **84**, 035203 (2011)

FSI Correction Factor

- Correction† < 10% except at forward angles: pp-FSI dominates
  - When pp both slow, backwards: Maximal wave function overlap
  - π^- faster than p: Leaves d sooner: Less FSI



$$\frac{d\sigma}{d\Omega}(\gamma n) = R(E_\gamma, \theta)^{-1} \frac{d\sigma}{d\Omega}(\gamma d)$$

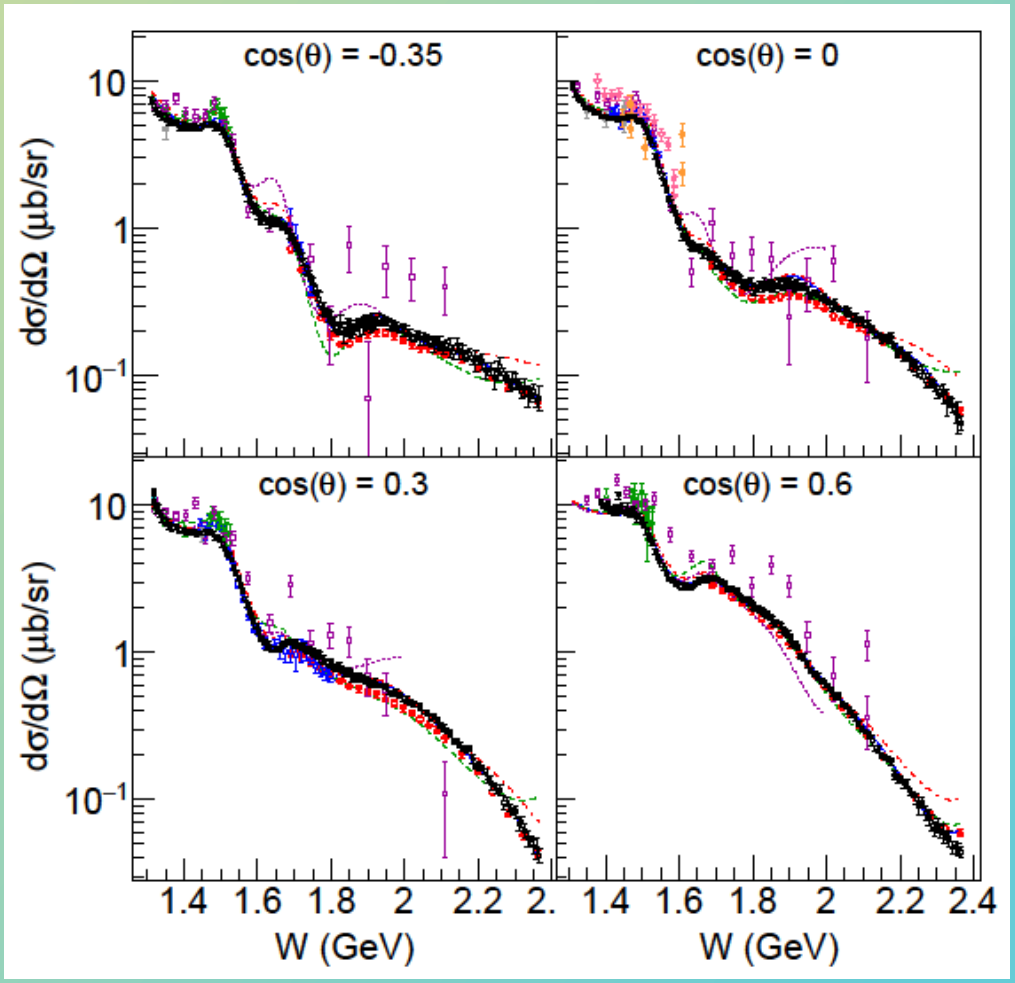
Uncertainties:
E_γ < 1.8 GeV: 2%
1.8 < E_γ < 2.7: 3%
E_γ > 2.7 GeV: 5%

Legend
Solid: NN + πN FSI
Dash: NN FSI

†V. E. Tarasov *et. al*, Phys. Rev. C **84**, 035203 (2011)

$\gamma n \rightarrow p\pi^-$ Cross Section

- CLAS g13
  - ≈ 400M events, 8424 bins
  - 157 E_γ bins (10, 20 MeV)
  - W ≈ 1.31 – 2.37 GeV: N*'s
  - σ_{Total} typically 3.5% - 15%
  - σ_{Scale} ≈ 3.4% (not shown)



Legend

$\gamma n \rightarrow p\pi^-$: **CLAS g13**, **CLAS g10**, **SLAC**, **DESY**, **MAMI-B**, **Frascati**

$\pi^- p \rightarrow \gamma n$: **BNL**, **LBL**, **LAMPF**

Fits (lines): **SAID MA27**, **SAID PR15**, **BnGa 2014-02**, **MAID 2007**

Peaks at low-E_γ : Δ(1232), N*'s
At higher E_γ, more channels

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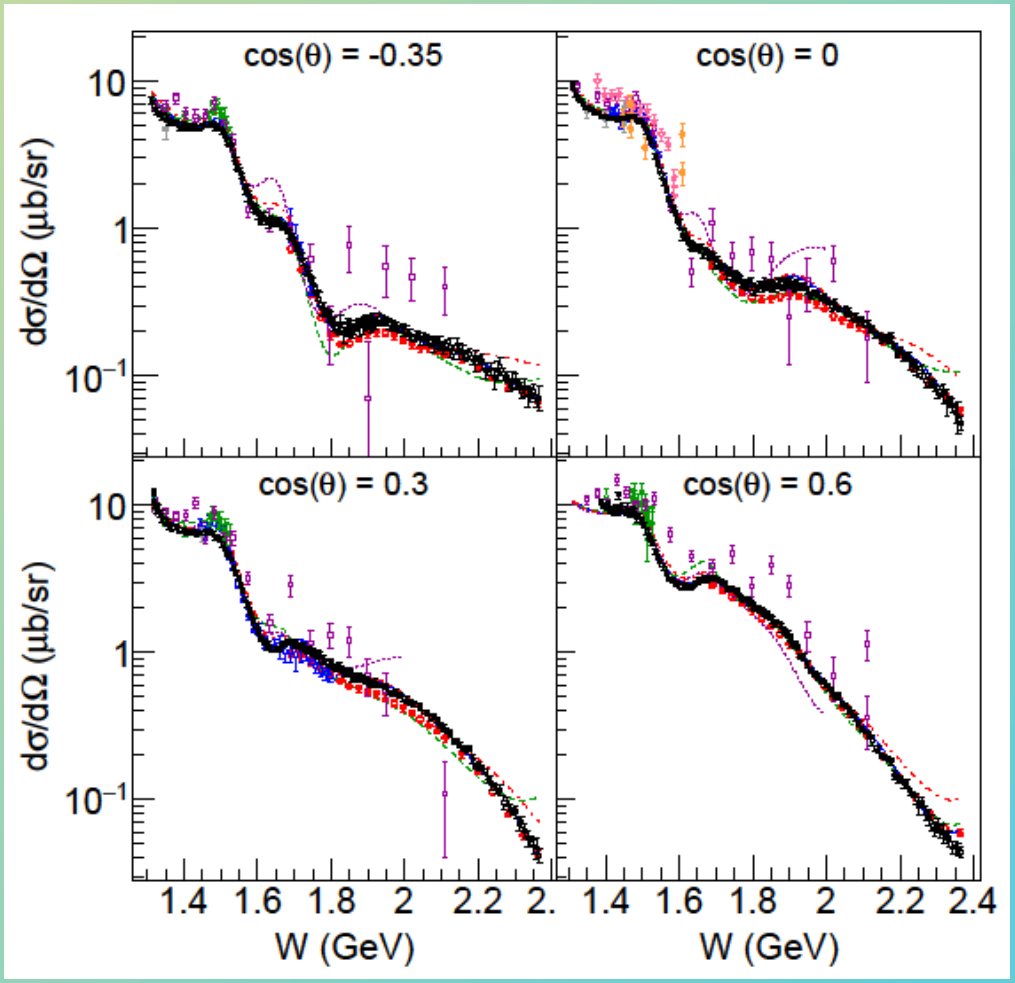
  - W ≈ 1.31 – 2.37 GeV: N*'s
  - σ_{Total} typically 3.5% - 15%
  - σ_{Scale} ≈ 3.4% (not shown)
- New SAID fit of data: MA27
  - Previous fit: PR15
  - BnGa, MAID: Not fit to g13



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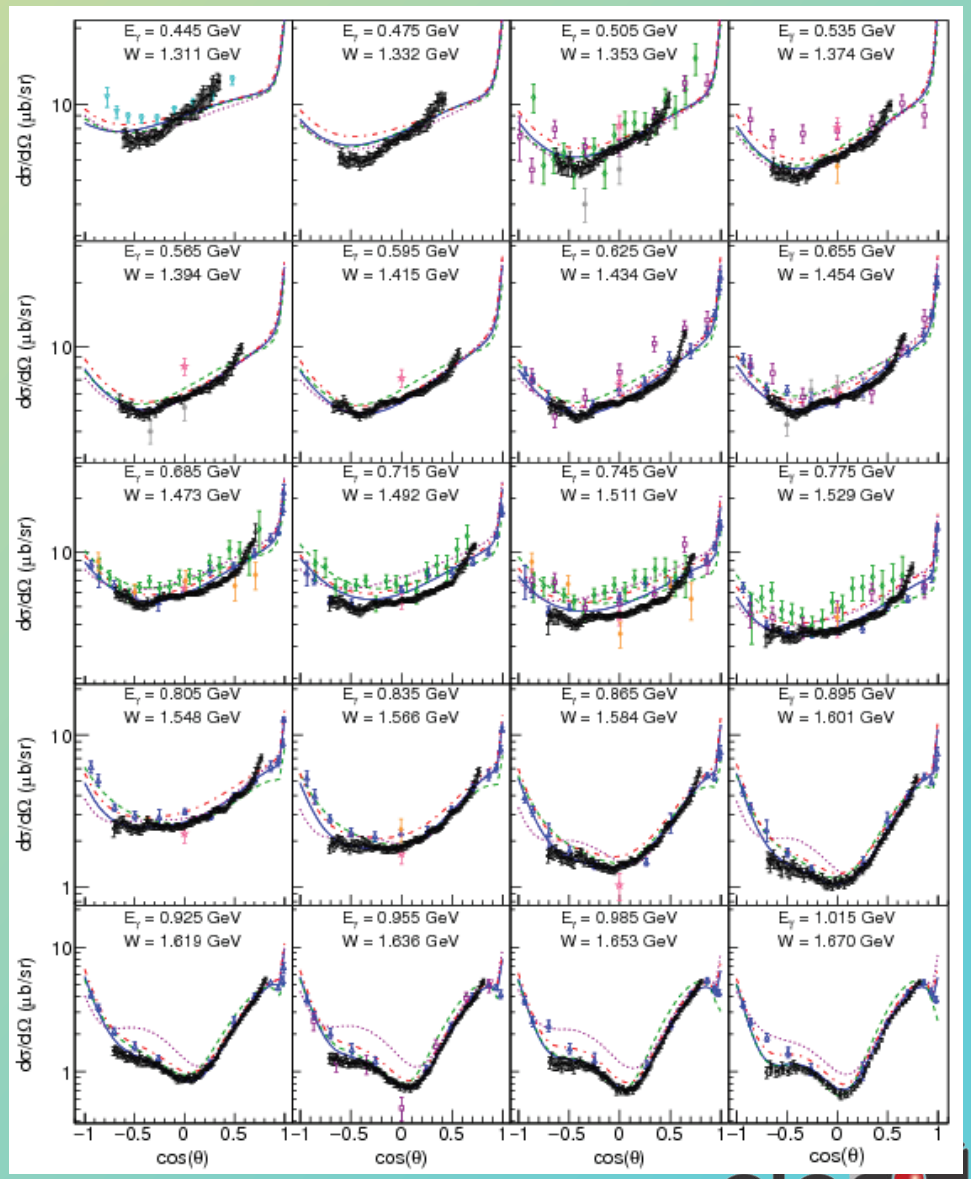
Peaks at low-E_γ : Δ(1232), N*'s
At higher E_γ, more channels

$\gamma n \rightarrow p\pi^-$ Cross Section

- Peak low-θ: t-channel π^-
- Low energies ($E_\gamma \leq 1$ GeV)
  - Much old, low-stats data
  - Some E_γ :
    g13 < BNL, DESY, Frascati
  - Low-θ, Low-E_γ :
    Different trend than SLAC
  - Otherwise good agreement



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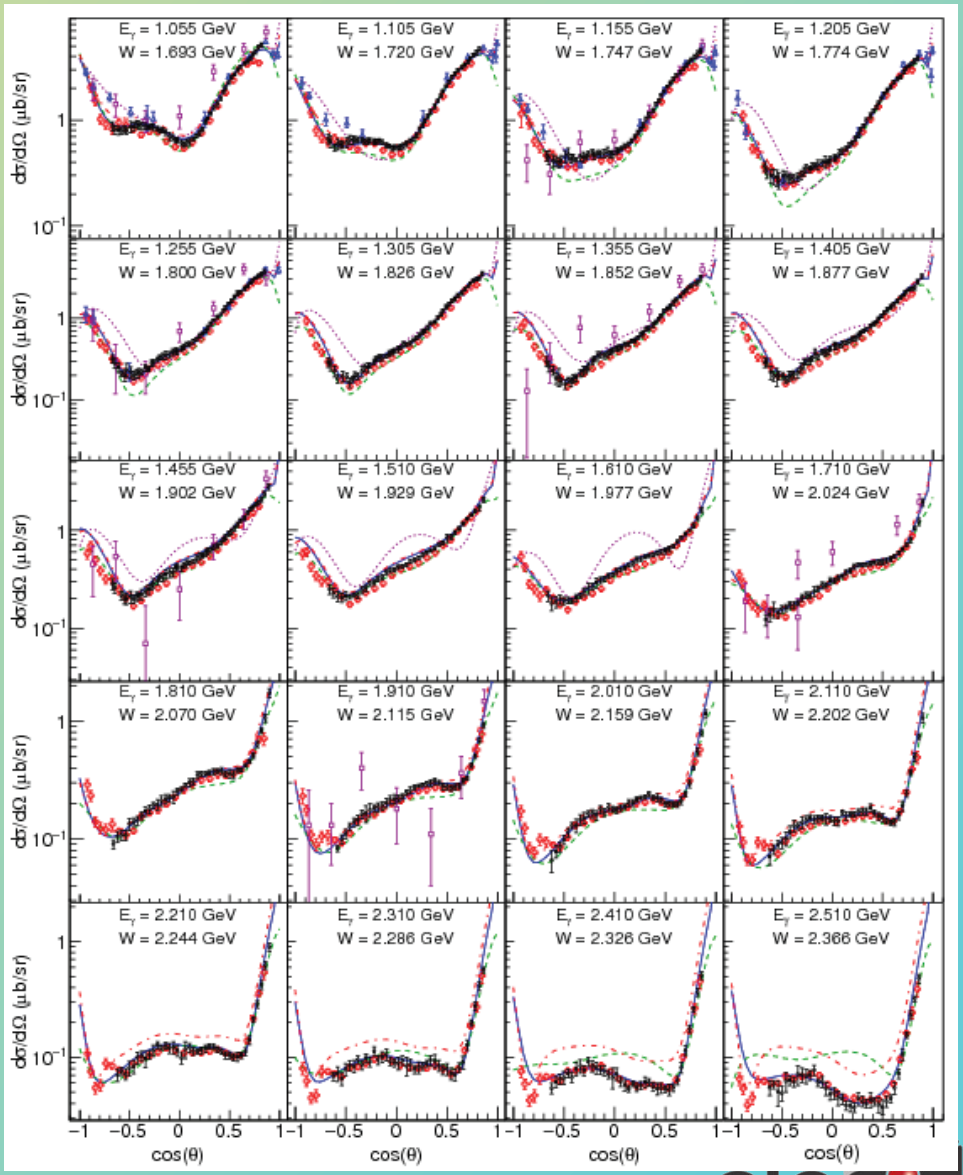
$\gamma n \rightarrow p\pi^-$ Cross Section

- CLAS g10
  - ≈ 850 bins, 1/10 g13
  - 34 E_γ bins (50, 100 MeV)
  - $\sigma_{Scale} \approx 12\%$ (not shown)
- High energies ($E_\gamma > 1$ GeV)
  - CLAS g10 systematically low
    - But has high σ_{Scale}
  - Overall excellent agreement



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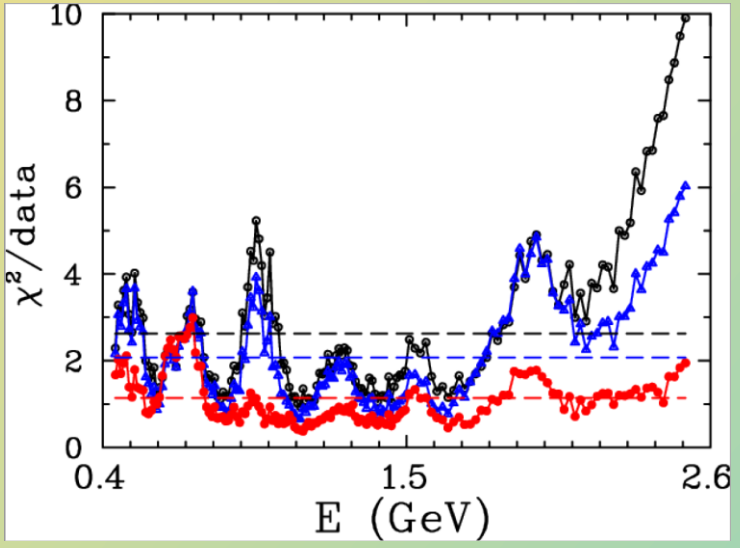
SAID MA27 Fit

- Simultaneous fit to all 4 γN channels to extract EM multipoles
  - SAID πN → πN amplitudes used to constrain γN → πN fits
  - Also, resonance BW parameters fixed from πN fits



Legend
Black: PR15 vs. g13 w/o FSI correction
Blue: PR15 vs. g13 (χ^2/Data = **2.1**)
Red: MA27 vs. g13 (χ^2/Data = **1.1**)

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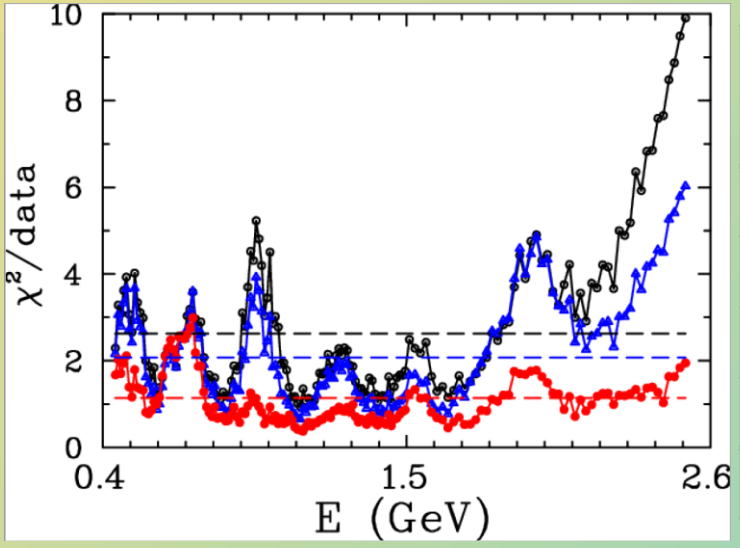

Channel	SAID PR15 (no g13)		SAID MA27 (w/ g13)	
	# Data	χ^2/Data	# Data	χ^2/Data
$\gamma p \rightarrow p\pi^0$	25540	2.15	25540	2.17
$\gamma p \rightarrow n\pi^+$	9859	**2.39**	9859	**2.10**
$\gamma n \rightarrow p\pi^-$	3162	**2.07**	11614	**1.42**
$\gamma n \rightarrow n\pi^0$	364	3.17	364	**4.23**
Sum	38927	2.22	47377	2.17

Legend
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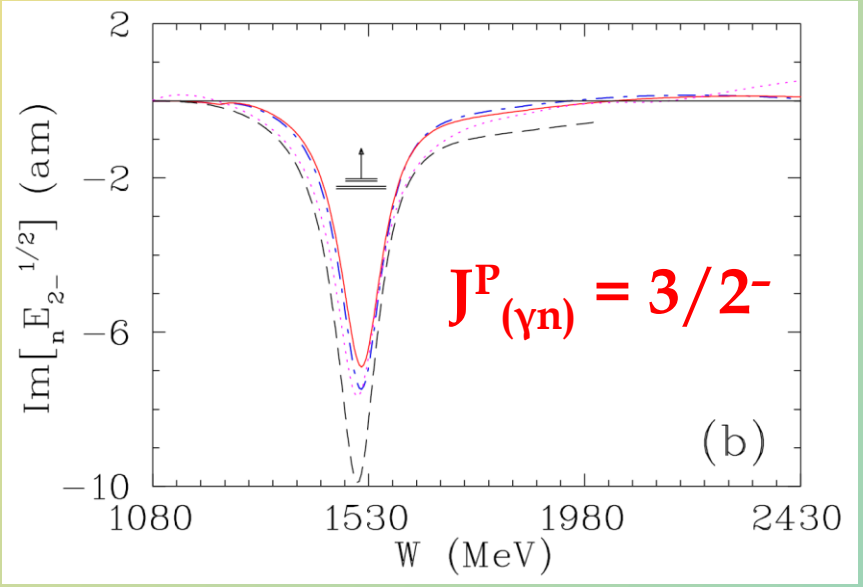
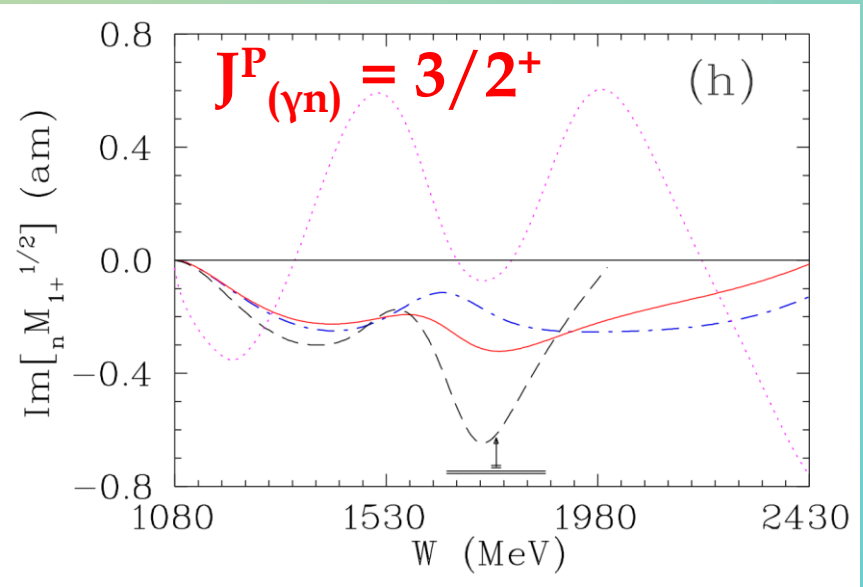
Blue: PR15 vs. g13 (χ^2/Data = **2.1**)
Red: MA27 vs. g13 (χ^2/Data = **1.1**)

MA27 γn Multipole Amplitudes

* Where dominant resonance (N(1520)3/2⁻), all curves are similar
* Where not (N(1720)3/2⁺ weak γn coupling), differences are starker





Legend
Black: MAID 2007
Blue: PR15
Red: MA27
Magenta: BnGa 2014-02

Amplitude Notation: $_n(E/M)_{L\pm}^I$
n: Neutron
E: Electric multipole ($J^P_\gamma = 1^-, 2^+, 3^-, \ldots$)
M: Magnetic multipole ($J^P_\gamma = 1^+, 2^-, 3^+, \ldots$)
L±: $J_{\gamma n} = L \pm ½$
I: Isospin

γn → N* Helicity Amplitudes

* Amplitudes at pole position ($GeV^{-1/2}$): First-ever full determination†
  * Previous attempts only extracted modulus

Resonance	Coupling	MA27 modulus, phase	GB12	BG2013	MAID2007	Capstick	PDG 2016
$N(1440)1/2^+$	$A_{1/2}(n)$	0.065±0.005, 5°±3°	0.048± 0.004	0.043±0.012	0.054	-0.006	0.040±0.010
$N(1535)1/2^-$	$A_{1/2}(n)$	-0.055±0.005, 5°±2°	-0.058± 0.006	-0.093±0.011	-0.051	-0.063	-0.075±0.020
$N(1650)1/2^-$	$A_{1/2}(n)$	0.014±0.002, -30°±10°	-0.040± 0.010	0.025±0.020	0.009	-0.035	-0.050±0.020
$N(1720)3/2^+$	$A_{1/2}(n)$	-0.016±0.006, 10°±5°		-0.080±0.050	-0.003	0.004	-0.080±0.050
$N(1720)3/2^+$	$A_{3/2}(n)$	0.017±0.005, 90°±10°		-0.140±0.065	-0.031	0.011	-0.140±0.065

†New Method: A. Svarc *et. al*, Phys. Rev. C **89**, 065208 (2014)

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* MA27 vs. SAID GB12: Large change for N(1650)
* MA27 vs. PDG & BG2013: Large differences, ~agree within σ's

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* Modulus uncertainties dramatically reduced:

% Uncertainty (Modulus)

Resonance	Coupling	GB12	BG2013	PDG 2016	MA27
$N(1440)1/2^+$	$A_{1/2}(n)$	8.3%	28%	25%	7.7%
$N(1535)1/2^-$	$A_{1/2}(n)$	10%	12%	27%	9.1%
$N(1650)1/2^-$	$A_{1/2}(n)$	25%	80%	40%	14%
$N(1720)3/2^+$	$A_{1/2}(n)$		62%	62%	38%
$N(1720)3/2^+$	$A_{3/2}(n)$		46%	46%	29%

γn → N* Helicity Amplitudes

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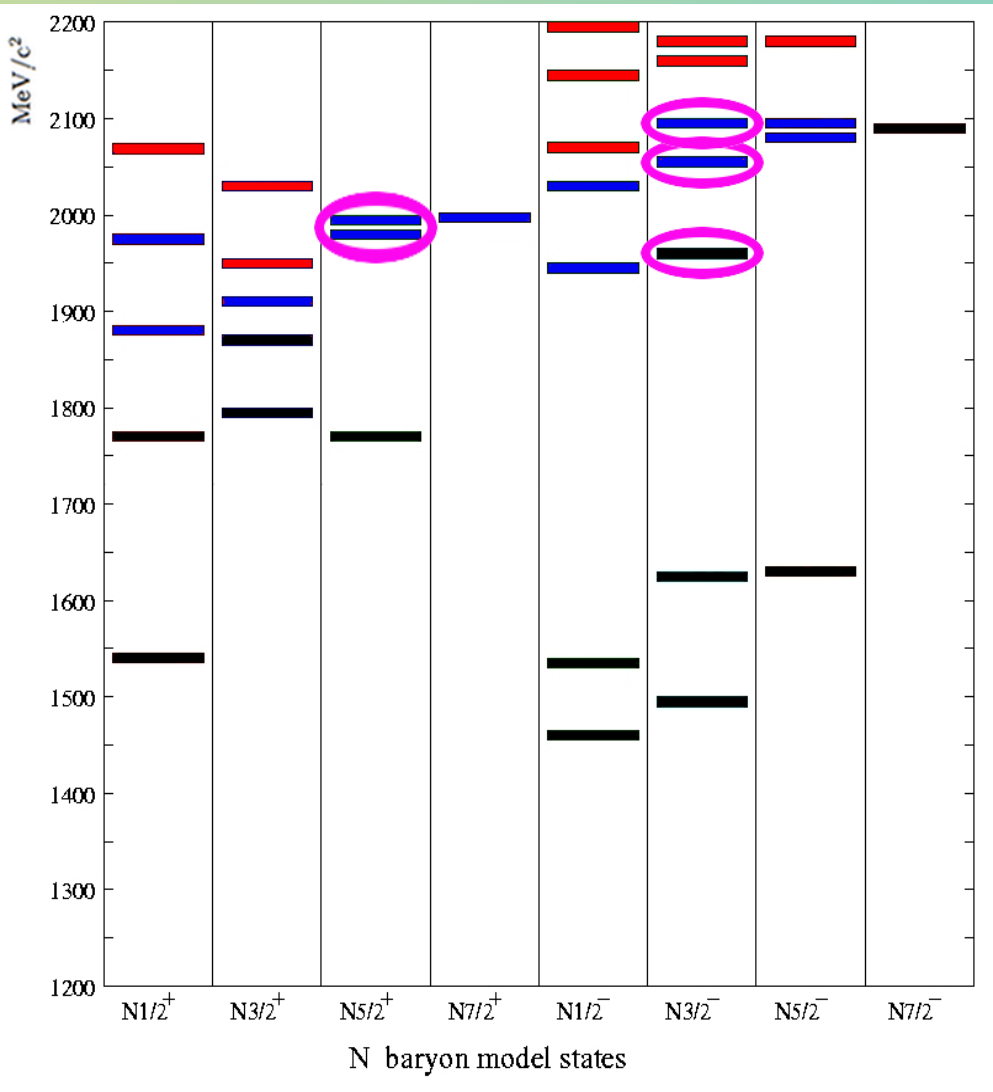
- Coming to PRC (approved), (arXiv:1706.01963)

Bonus Content: CLAS γd $K^*(892)^0\Lambda$, $K^+\Sigma^*(1385)^-$

N* Coupling to KY*

- High-mass N*'s "missing"
- N* decays to KY, **KY***, K*Y
  - Y: Strange baryon: Λ, Σ, …
  - Couplings sizable to πN†
- γd → K⁺Σ*(1385)⁻(p)
  - LEPS‡: Limited to θ ≤ 53°
- Preliminary CLAS dσ/dΩ
  - W ≈ 1.92 – 2.36 GeV



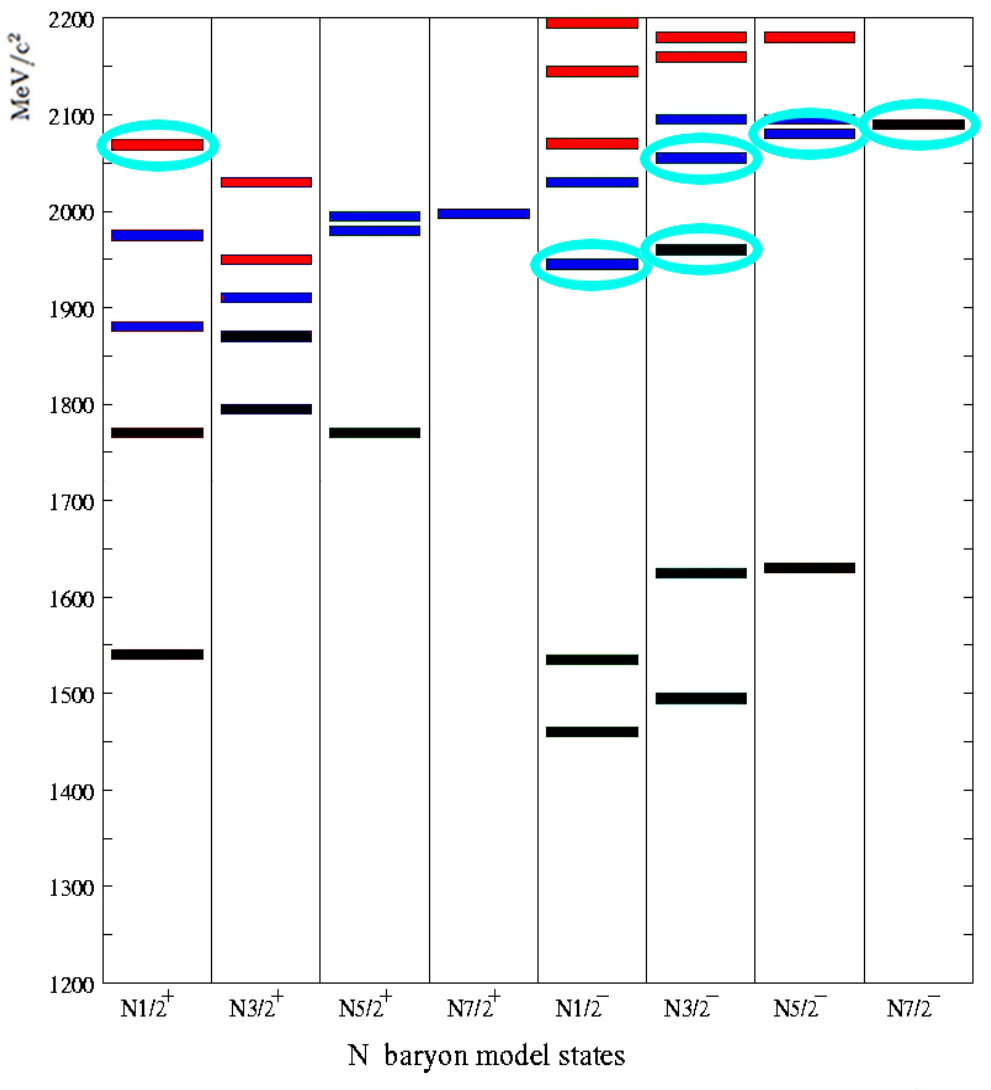
Legend
Black: Certain or likely: ****, ***
Blue: Fair or poor: **, *
Red: No evidence
Magenta: γN → KΣ*(1385)

†PRD **58**, 074011 (1998)

‡PRL **102**, 012501 (2009)

N* Coupling to K*Y

- High-mass N*'s "missing"
- N* decays to KY, KY*, **K*Y**
  - Couplings sizable to $\pi N^{\dagger}$
- $\gamma d \rightarrow K^*(892)^0\Lambda(p)$
  - No $d\sigma/d\Omega$ measurements
  - $K^+\pi^-\Lambda(p)$ final state:
    - Same as $K^+\Sigma^*(1385)^-$
- Preliminary CLAS $d\sigma/d\Omega$
  - $W \approx 2.11 - 2.36$ GeV



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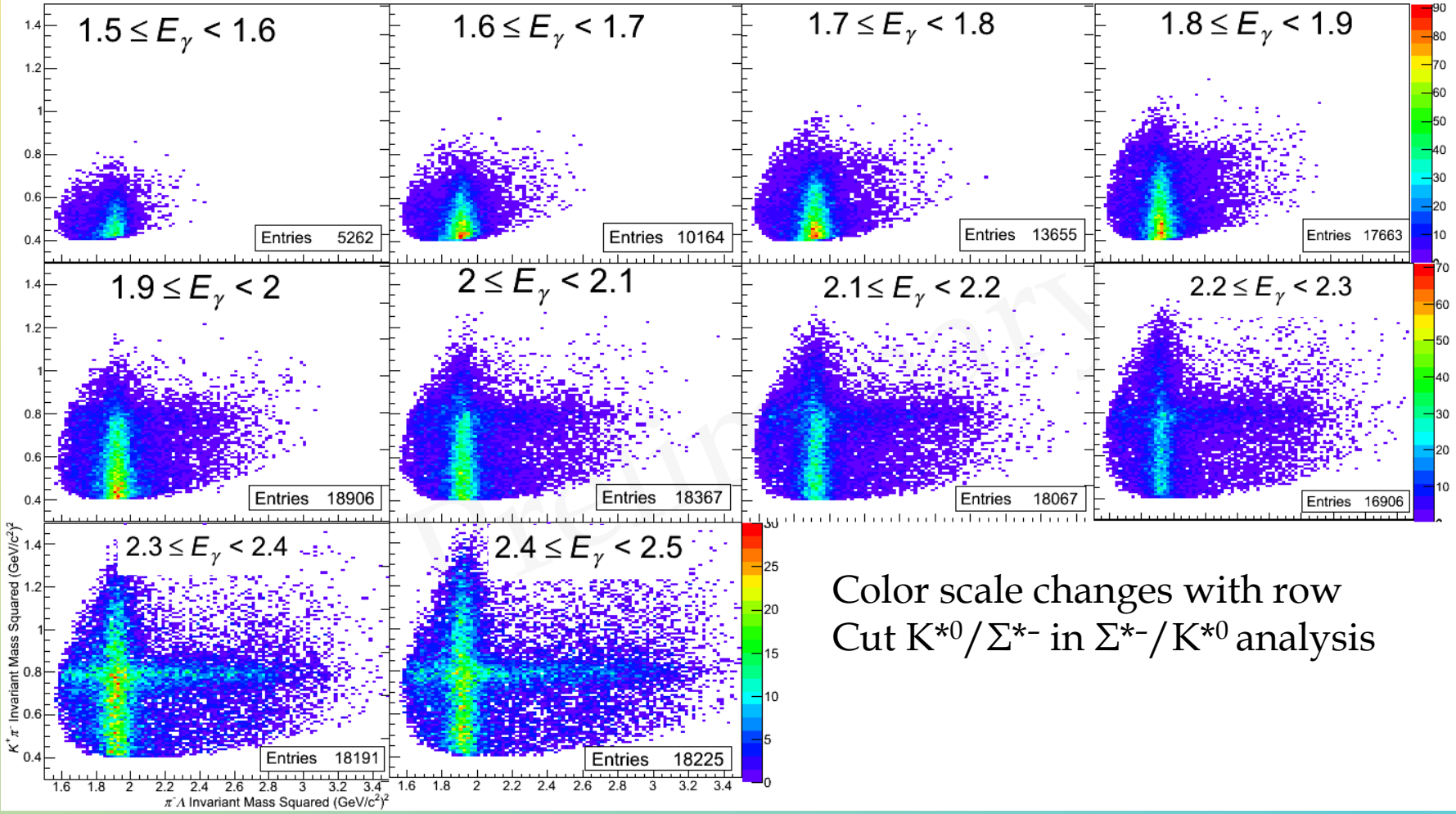
Red: No evidence
Cyan: $\gamma N \rightarrow K^*(892)\Lambda$

†S. Capstick, W. Roberts, Phys. Rev. D **58**, 074011 (1998)

$K^+\pi^-\Lambda$ Dalitz Plots

* Yield: ≈ 17k $K^*(892)^0\Lambda$, ≈ 100k $K^+\Sigma^*(1385)^-$

$K^*(892)^0 \rightarrow K^+\pi^-$

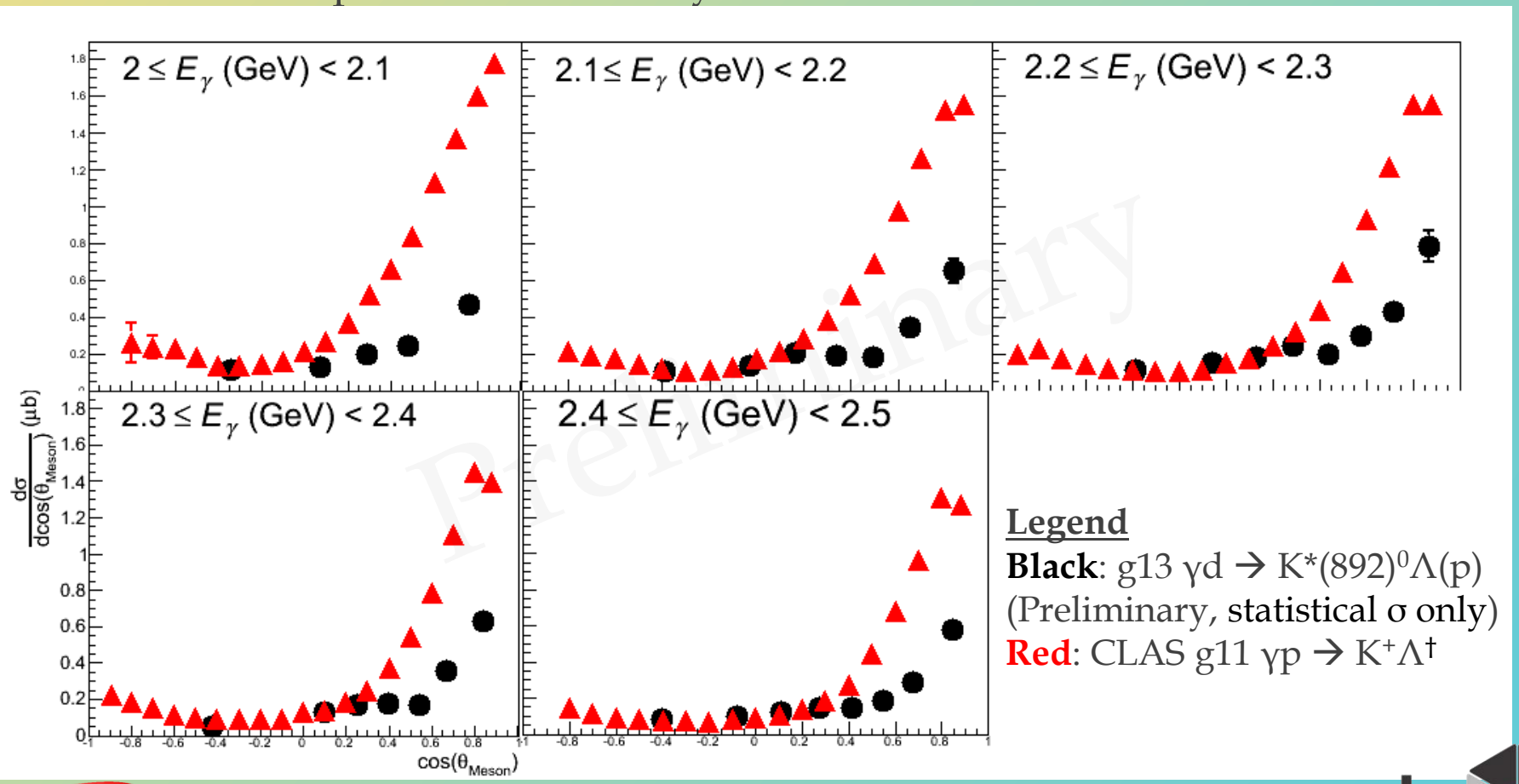


Color scale changes with row
Cut K^{*0}/Σ^{*-} in Σ^{*-}/K^{*0} analysis

$\Sigma^*(1385)^- \rightarrow \Lambda\pi^-$

$\gamma d \rightarrow K^*(892)^0\Lambda(p)$ vs. $\gamma p \rightarrow K^+\Lambda$

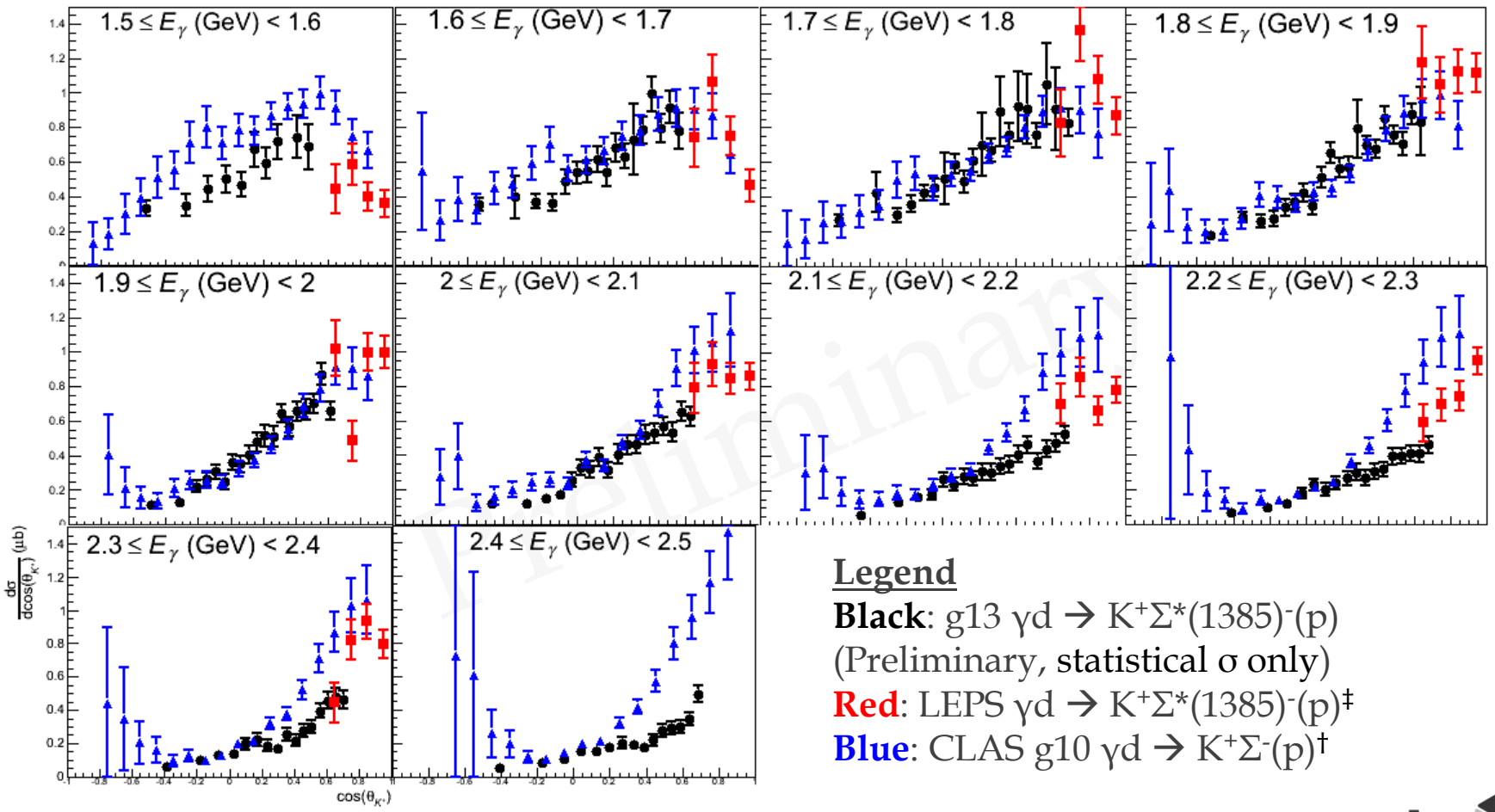
* ~Comparison vs. ground state: Similar at mid-θ
  * $K^0\Lambda$ submitted to PRC (is similar): N. Compton *et al.* (CLAS) arXiv:1706.04748
* $K^*\Lambda$: N* coupled-channels analyses



†M. E. McCracken *et al.* (CLAS), Phys. Rev. C **81**, 025201 (2010)

$K^+\Sigma^*(1385)^-(p)$ vs. $K^+\Sigma^-(p)$

* Scale comparison vs. ground state†: Similar in most regions
* $K\Sigma^*(1385)$: N* coupled-channels analyses



Legend

Black: g13 γd → $K^+\Sigma^*(1385)^-(p)$ (Preliminary, statistical σ only)

Red: LEPS γd → $K^+\Sigma^*(1385)^-(p)$‡

Blue: CLAS g10 γd → $K^+\Sigma^-(p)$†

†Phys. Lett. B **688**, 289 (2010) ‡PRL **102**, 012501 (2009)

Summary & Outlook

- N* spectrum: Strong force and hadronic structure
  - Role of quark correlations in the nucleon
  - Need both γp and γn: Isospin decomposition of amplitudes
  - Search for "missing" N*'s in KY, K*Y, and KY* channels

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- $\gamma n \rightarrow p\pi^-$ differential cross sections: PRC approved (arXiv:1706.01963)
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  - Precision measurement: 3.4% scale σ, 12% for g12

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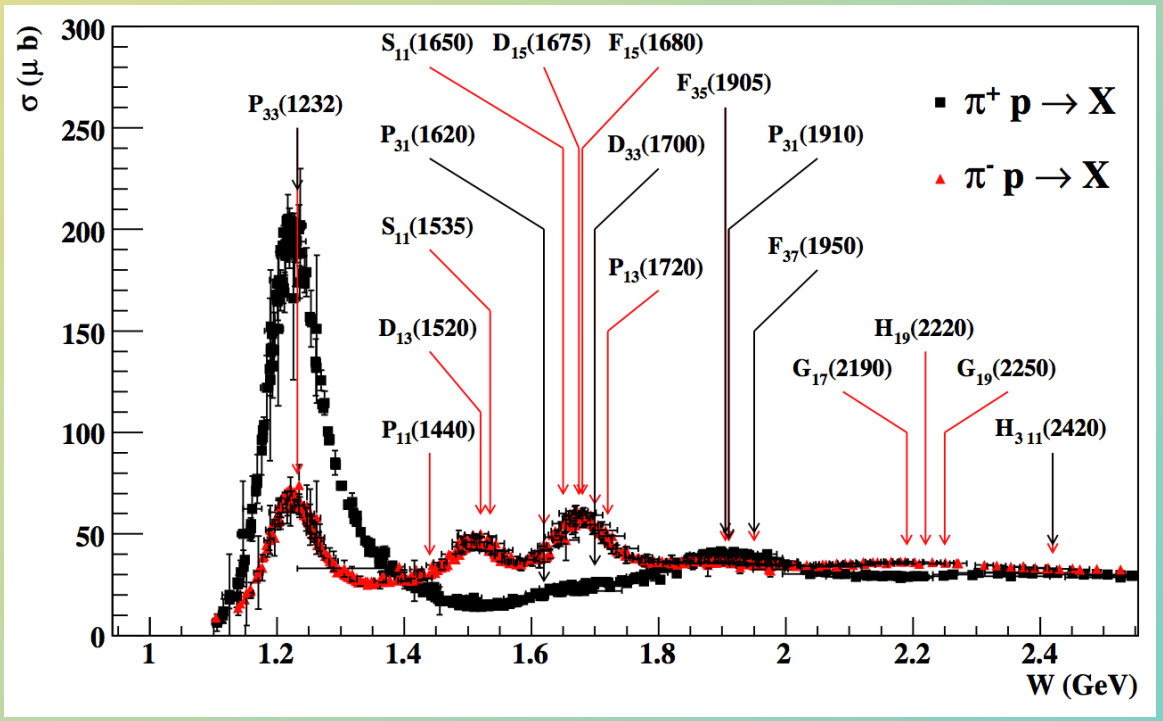
- Outlook:
  - Missing N*'s: Need more precision data (especially polarized!)
  - K*Y & KY* sizable vs. KY: Include in coupled-channels analyses

Reference

N* and Δ Resonances

- PDG: 18 well-established (****) nucleon resonances: 11 N*'s, 7 Δ's
  - Most discovered through coupling to πN
  - Many wide, overlapping: Difficult to distinguish
- Measure spectra of N*'s, Δ's: Understanding of QCD in the baryon



Notation: $L_{(2I)(2J)}(M)$
L: Orbital angular momentum
I: Isospin
J: Spin
M: Mass

N*'s, Δ's: 2I = 1, 3

†M. Williams, Ph.D. Thesis, Carnegie Mellon University (2007)

Evidence for N* Resonances

- N* status: Particle Data Group†
  - 27 N* states (11 ****)
  - Most evidence in πN
- Much new evidence from γN
  - JLab (CLAS), SPring-8, ELSA, GRAAL, MAMI

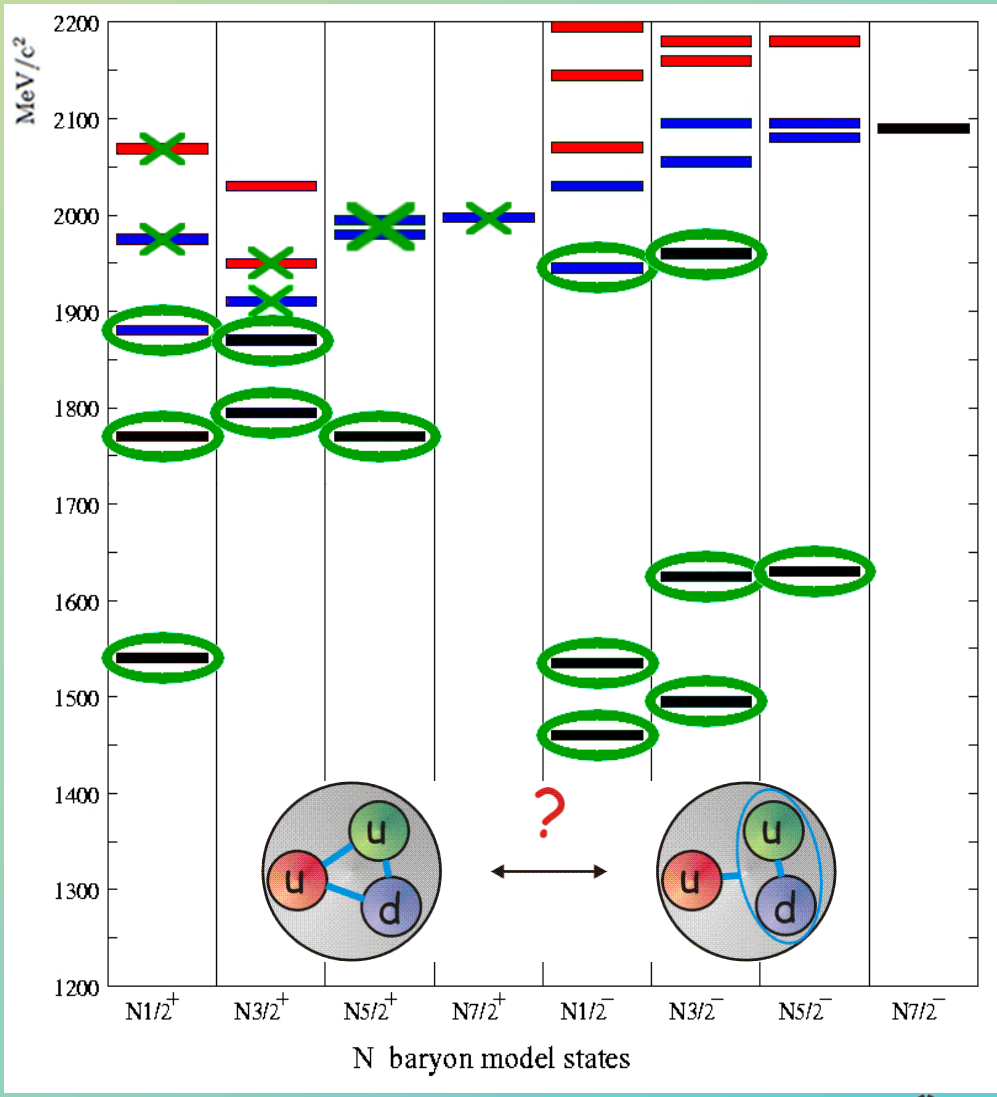
			Status as seen in								
Particle	J^P	overall	$N\gamma$	$N\pi$	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N	$1/2^+$	****									
$N(1440)$	$1/2^+$	****	****	****		***				*	***
$N(1520)$	$3/2^-$	****	****	****	***					***	***
$N(1535)$	$1/2^-$	****	****	****	****					**	*
$N(1650)$	$1/2^-$	****	****	****	***			***	**	**	***
$N(1675)$	$5/2^-$	****	****	****	*			*		*	***
$N(1680)$	$5/2^+$	****	****	****	*	**				***	***
$N(1700)$	$3/2^-$	***	**	***	*			*	*	*	***
$N(1710)$	$1/2^+$	****	****	****	***		**	****	**	*	**
$N(1720)$	$3/2^+$	****	****	****	***			**	**	**	*
$N(1860)$	$5/2^+$	**		**						*	*
$N(1875)$	$3/2^-$	***	***	*			**	***	**		***
$N(1880)$	$1/2^+$	**	*	*		**		*			
$N(1895)$	$1/2^-$	**	**	*	**			**	*		
$N(1900)$	$3/2^+$	***	***	**	**		**	***	**	*	**
$N(1990)$	$7/2^+$	**	**	**					*		
$N(2000)$	$5/2^+$	**	**	*	**			**	*	**	
$N(2040)$	$3/2^+$	*		*							
$N(2060)$	$5/2^-$	**	**	**	*				**		
$N(2100)$	$1/2^+$	*		*							
$N(2120)$	$3/2^-$	**	**	**				*	*		
$N(2190)$	$7/2^-$	****	***	****			*	**		*	
$N(2220)$	$9/2^+$	****		****							
$N(2250)$	$9/2^-$	****		****							
$N(2300)$	$1/2^+$	**		**							
$N(2570)$	$5/2^-$	**		**							
$N(2600)$	$11/2^-$	***		***							
$N(2700)$	$13/2^+$	**		**							

Legend
****: Existence is certain
***: Existence is likely
**: Evidence is fair
*: Evidence is poor

†C. Patrignani *et al.* (PDG), Chin. Phys. C, 40, 100001 (2016)

N* Predictions: Diquark Model

- Alternative: Diquark model†
  - Correlated quark-pair
  - Less DF: Less N* states
- "Missing" N*'s
  - Quark correlations?
  - Or N*'s couple weakly to measured channels? (Nπ)
- Measure spectrum of N*'s
  - Study QCD in baryons



Legend
Black: Certain or likely: ****, ***
Blue: Fair or poor: **, *
Red: No evidence
Green: Di-quark model

†J. Ferreti *et al.*, Phys. Rev. C **83**, 065204 (2011)

γn → pπ⁻, Helicity

* γN → N* Amplitudes: Helicity-dependent, very large errors†
* g13: Measure γn → pπ⁻ dσ/dΩ: Improve helicity amplitudes

$$\lambda = \boldsymbol{J} \cdot \hat{\boldsymbol{p}} = \boldsymbol{S} \cdot \hat{\boldsymbol{p}}$$

$$J_\gamma = 1, J_N = \frac{1}{2}$$

$$|\mathcal{M}_{\gamma N \to N\pi}|^2 \propto \sum_{\lambda_i \lambda_f} \left| \sum_{J^P, L, S, \text{etc.}} A_{\gamma N \to N\pi} \right|^2$$

$N^* \to \gamma N$	$A^p_{\lambda=1/2}$	$A^n_{\lambda=1/2}$	$A^p_{\lambda=3/2}$	$A^n_{\lambda=3/2}$
$N\,(1440)\,\frac{1}{2}^+$	-0.060 ± 0.004	$\mathbf{0.040 \pm 0.010}$		
$N\,(1520)\,\frac{3}{2}^-$	$\mathbf{-0.020 \pm 0.005}$	-0.050 ± 0.010	0.140 ± 0.010	-0.115 ± 0.010
$N\,(1535)\,\frac{1}{2}^-$	0.115 ± 0.015	$\mathbf{-0.075 \pm 0.020}$		
$N\,(1650)\,\frac{1}{2}^-$	0.045 ± 0.010	$\mathbf{-0.050 \pm 0.020}$		
$N\,(1675)\,\frac{5}{2}^-$	$\mathbf{0.019 \pm 0.008}$	-0.060 ± 0.005	$\mathbf{0.020 \pm 0.005}$	-0.085 ± 0.010
$N\,(1680)\,\frac{5}{2}^+$	$\mathbf{-0.015 \pm 0.006}$	$\mathbf{0.029 \pm 0.010}$	0.133 ± 0.012	$\mathbf{-0.033 \pm 0.009}$

†C. Patrignani *et al.* (PDG), Chin. Phys. C, 40, 100001 (2016)

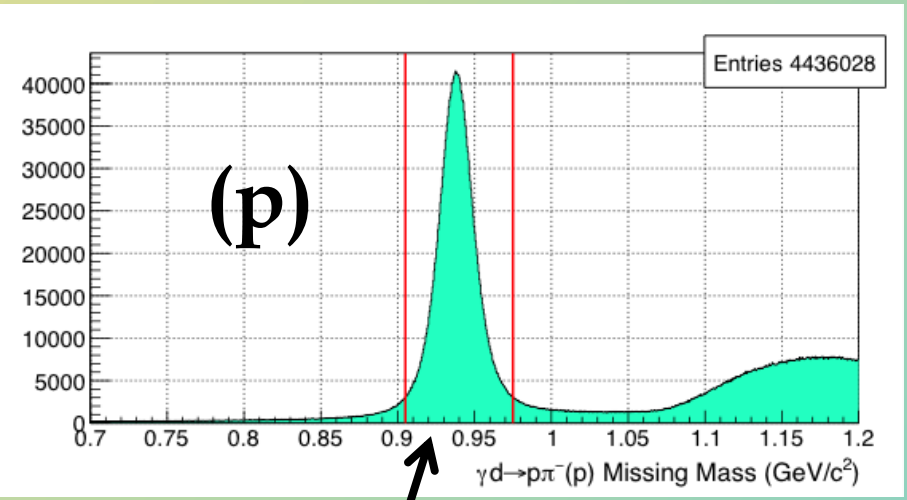
Polarization Observables

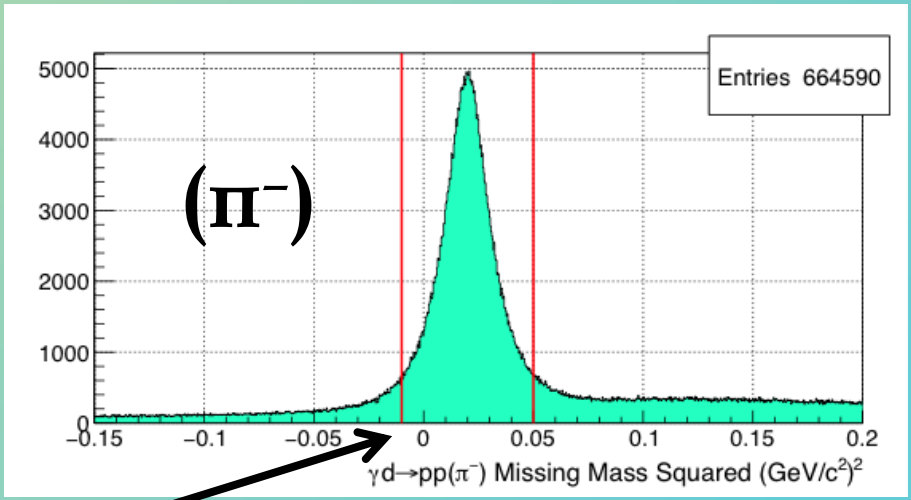
* Combination of polarized beams, targets, and recoil polarization:
  * 16 observables
* Provide spin-dependent constraints for N* extraction

Photon Beam	Target and/or Recoil Polarization																	
	Neither		Recoil			Target			Recoil & Target									
			x	y	z				x			y			z			
						x'	y'	z'	x'	y'	z'	x'	y'	z'	x'	y'	z'
Unpolarized				P			T		T_x		L_x		Σ		T_z		L_z
Linearly Polarized	σ	Σ	O_x	T	O_z	H	P	G	L_z	C_z	T_z	E		F	L_x	C_x	T_x
Circularly Polarized			C_x		C_z	F		E		O_z		G		H		O_x	

Reconstruction Efficiencies

- Needed new, sophisticated reconstruction efficiency studies
- Select $\gamma d \rightarrow p\pi^-(p)$ events to study p, $\gamma d \rightarrow pp(\pi^-)$ to study π^-
  - Efficiency: See how often missing particles are reconstructed
  - Study how well simulation models CLAS efficiency
  - Function of particle type, p, θ, φ, vertex-z

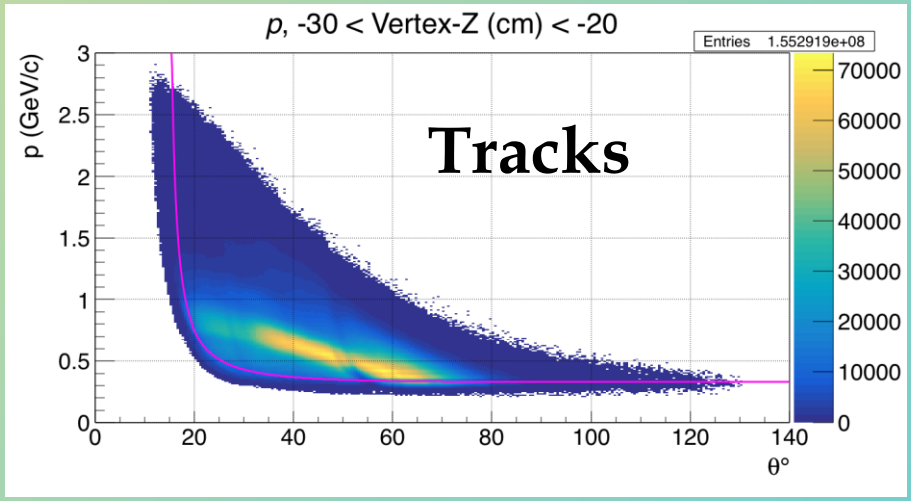


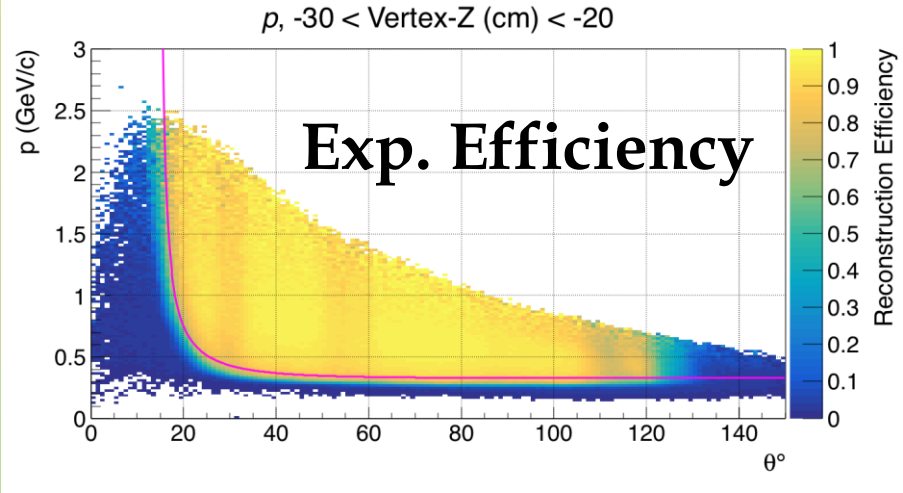


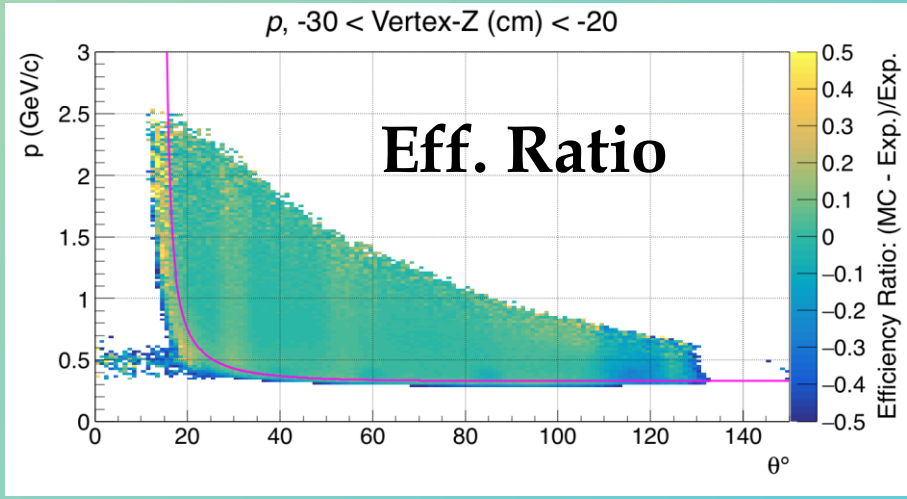
Background present, small, ignored: Studying features

p Reconstruction Efficiency

- Efficiency: Low at edges, holes
- Cut: Where MC efficiency doesn't match experiment
- Minimum p = 330 MeV/c

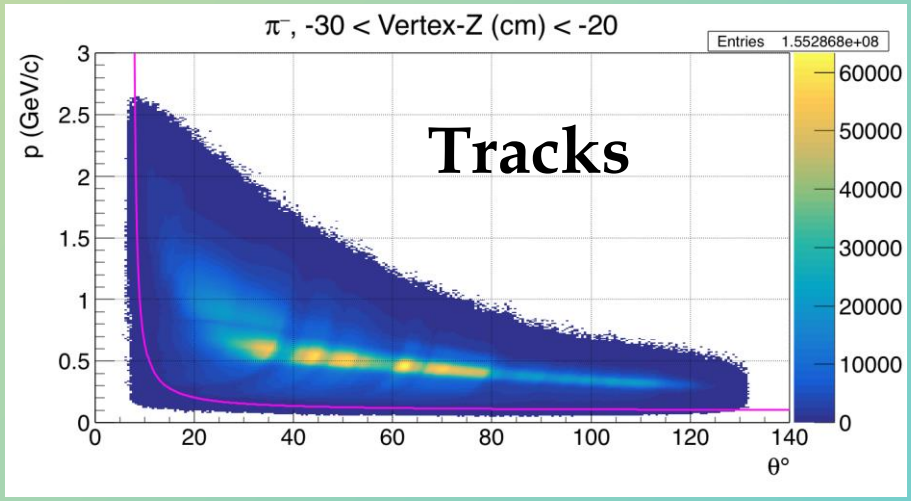


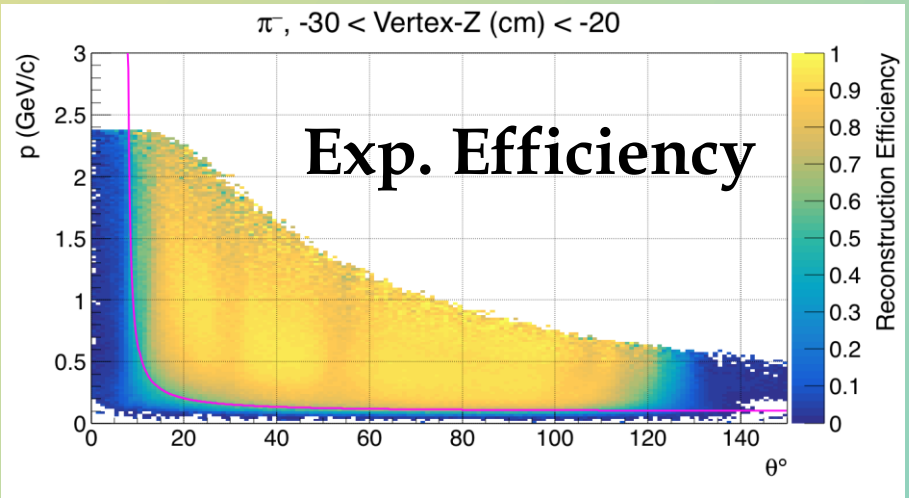


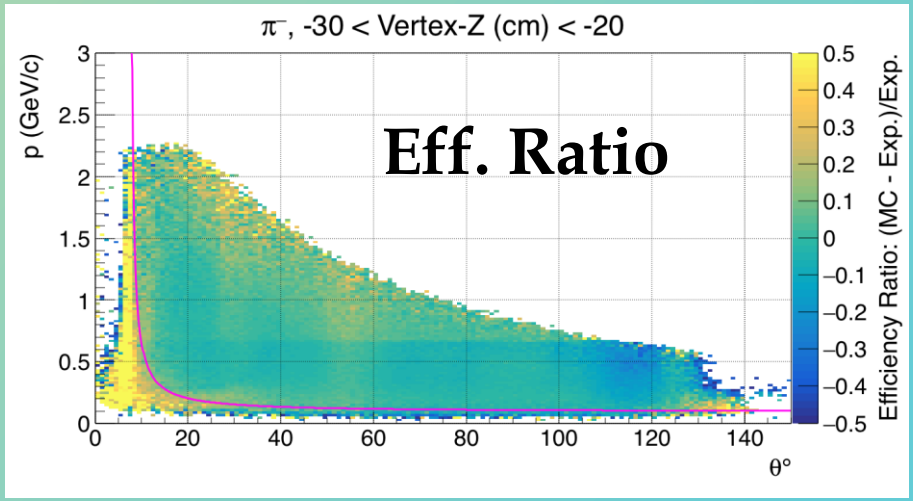


π^- Reconstruction Efficiency

- Efficiency: Low at edges, holes
- Cut: Where MC efficiency doesn't match experiment
- Minimum p = 100 MeV/c

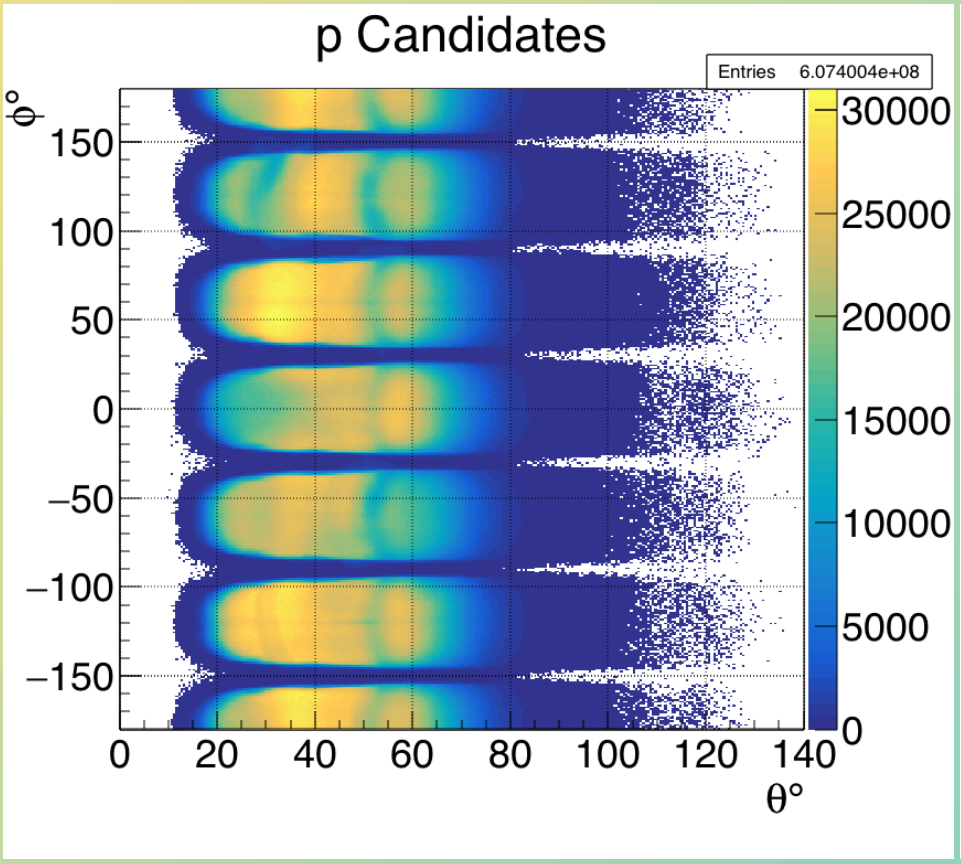


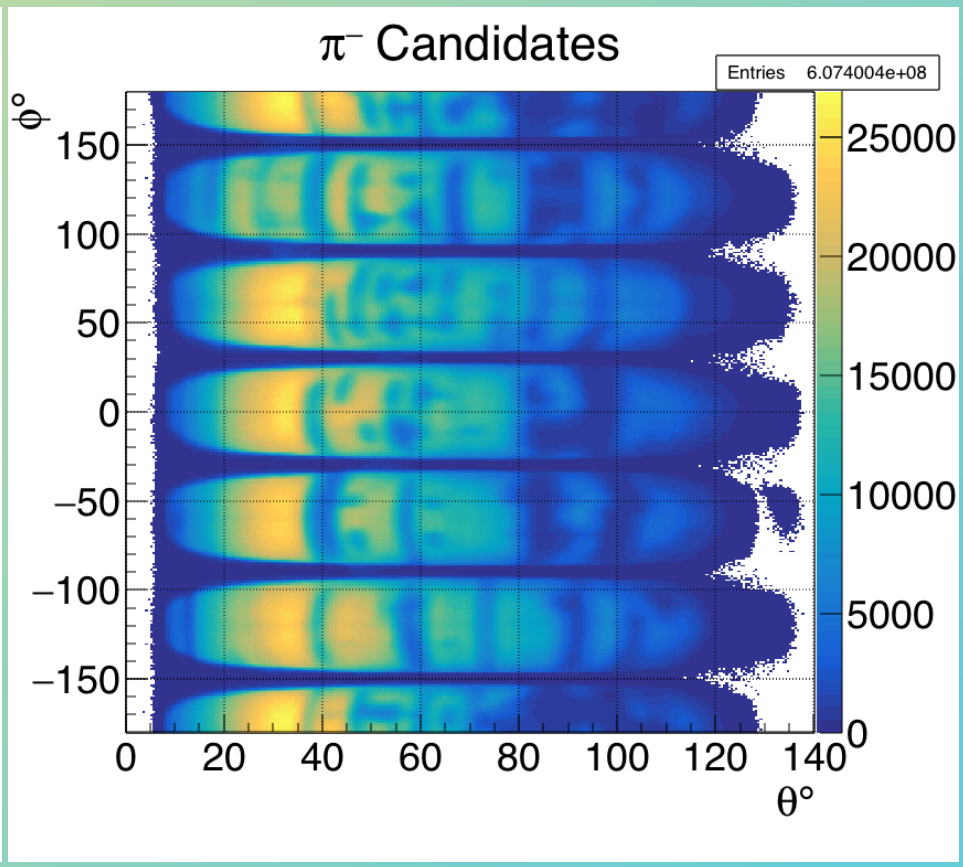




Reconstructed Kinematics

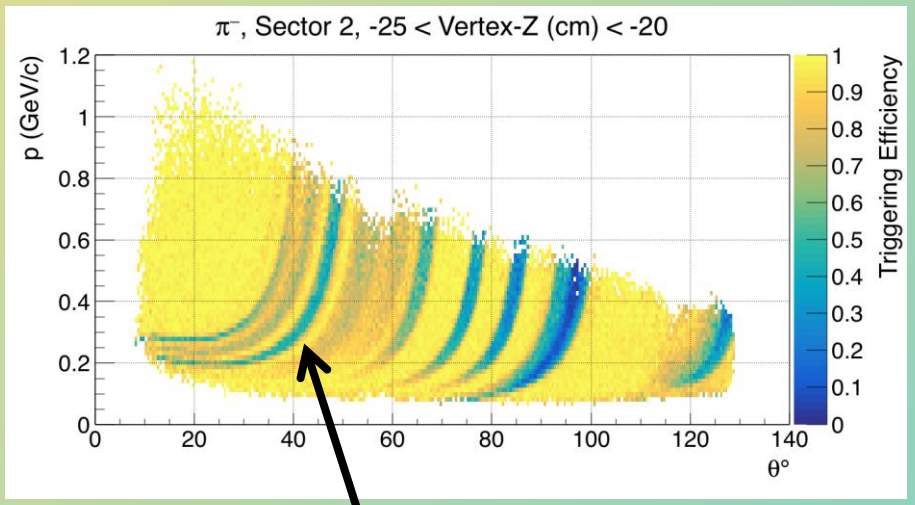
- Track distributions: Detector was aging
  - Needed more sophisticated CLAS efficiency studies

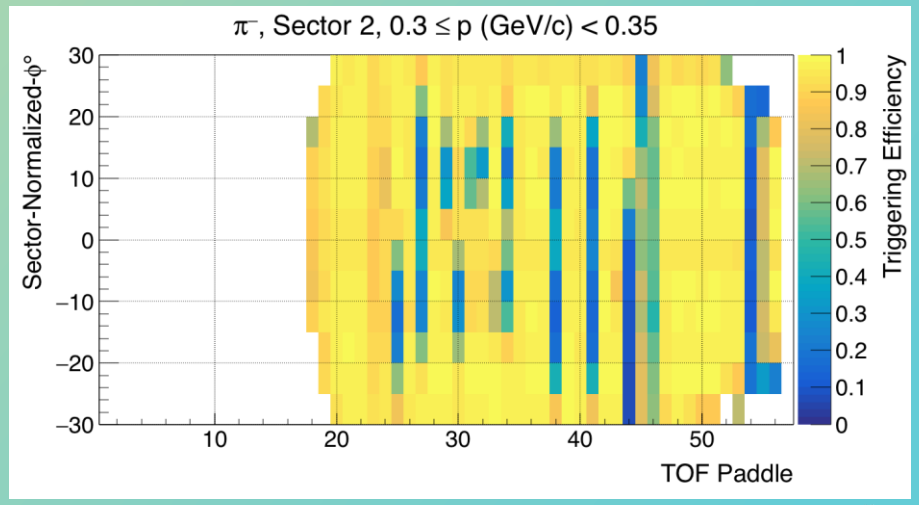




π^- Triggering Efficiency

- g13: 2-sector trigger (Start-Counter x TOF)
- Study $\gamma d \rightarrow pp\pi^-$ events, when each track in different sector
  - Each track pair: If both fired trigger signal, study 3rd-track signal rate
  - Function of particle type, p, TOF scintillator, φ
- TOF thresholds: Readout = 20 mV, pre-trigger = 100 mV
  - g13 weak PMTs: Set to max voltage, gain often still too low

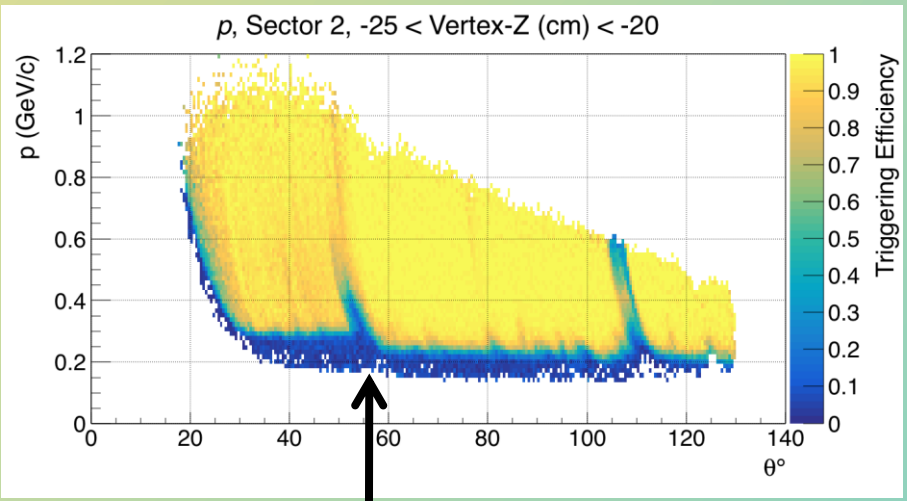


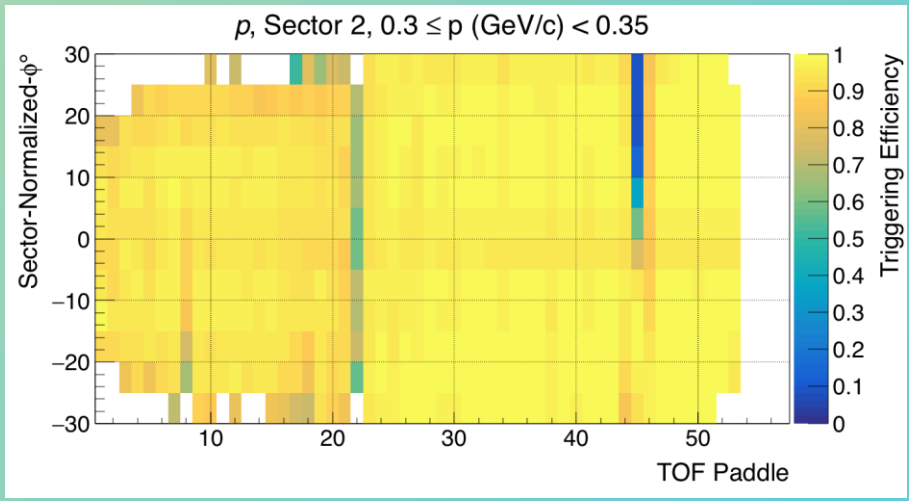


Overlap between TOF panels: Forward carriage, N/S clamshells

Proton Triggering Efficiency

- g13: 2-sector trigger (Start-Counter x TOF)
- Study γd → ppπ⁻ events, when each track in different sector
  - Each track pair: If both fired trigger signal, study 3rd-track signal rate
  - Function of particle type, p, TOF scintillator, φ
- Low efficiency for weak/dead TOF PMTs, TOF panel overlap
  - One PMT on each end of TOF scintillators

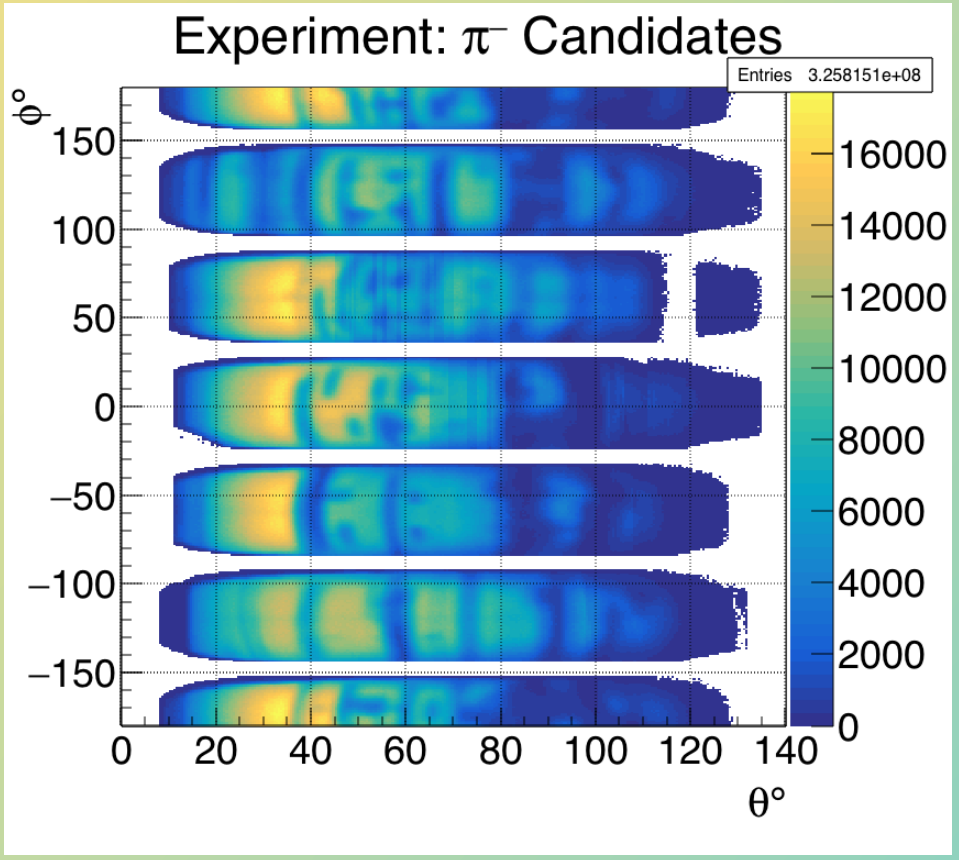


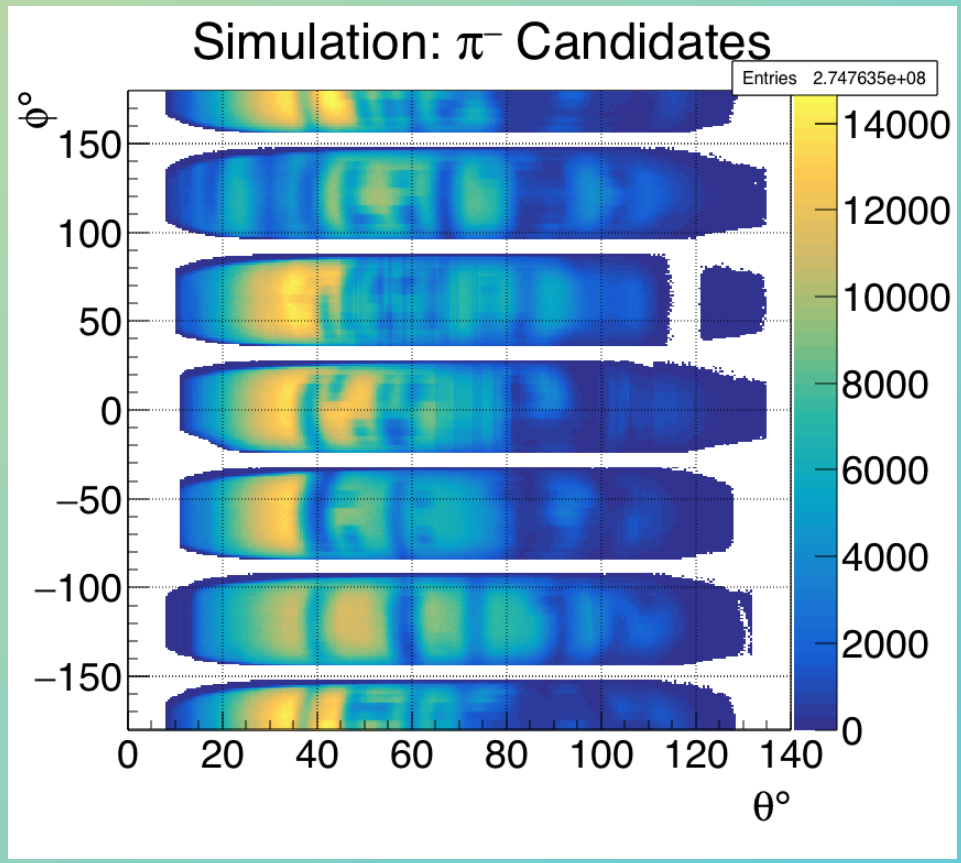


Overlap between TOF panels: Forward carriage, N/S clamshells

Compare Experiment, MC: π^-

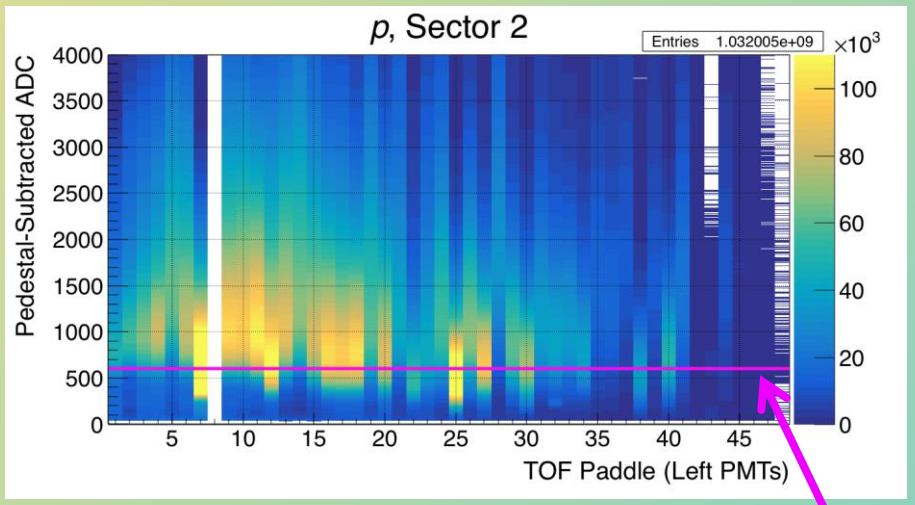
* $\gamma d \rightarrow p\pi^-(p)$ distributions match pretty closely

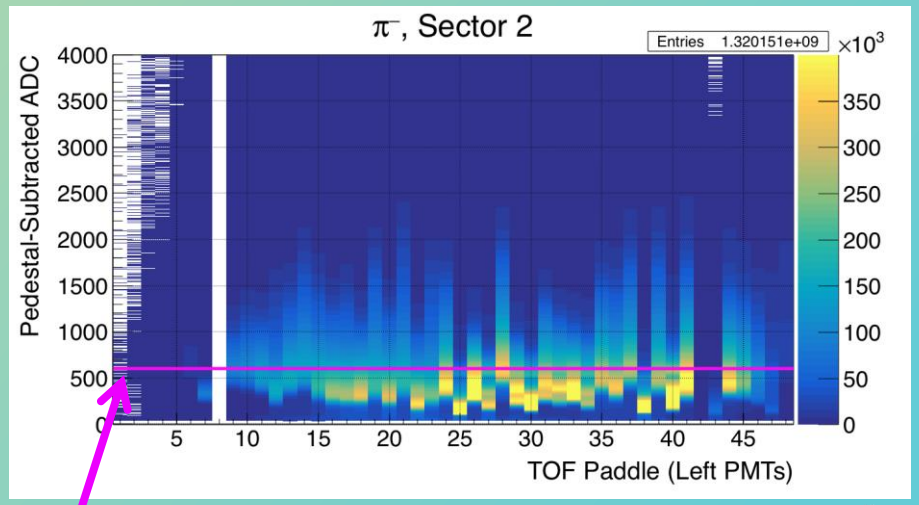




Triggering Efficiency: PMTs

- TOF thresholds: Readout = 20 mV, pre-trigger = 100 mV
  - Left & right PMTs are summed for pre-trigger
- Weak PMTs: Set to max voltage, gain often still too low
- π's worse than protons: Much less dE/dx in scintillators
- After study: Pre-trigger threshold reduced for g9b (FROST)

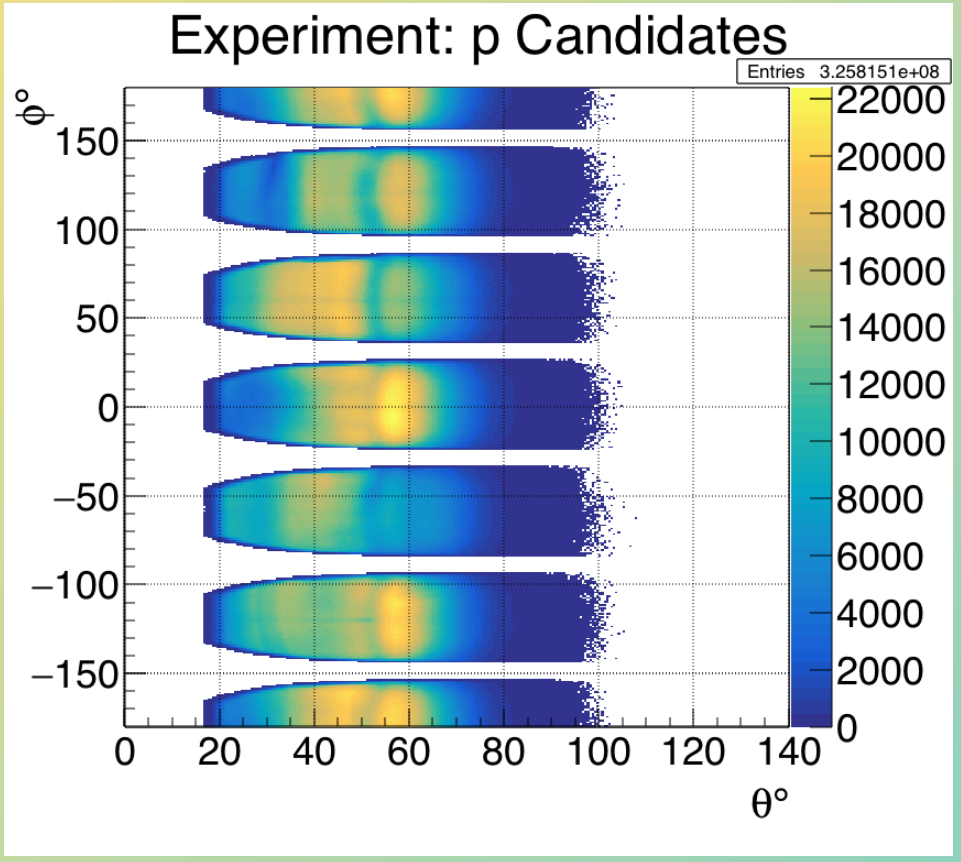


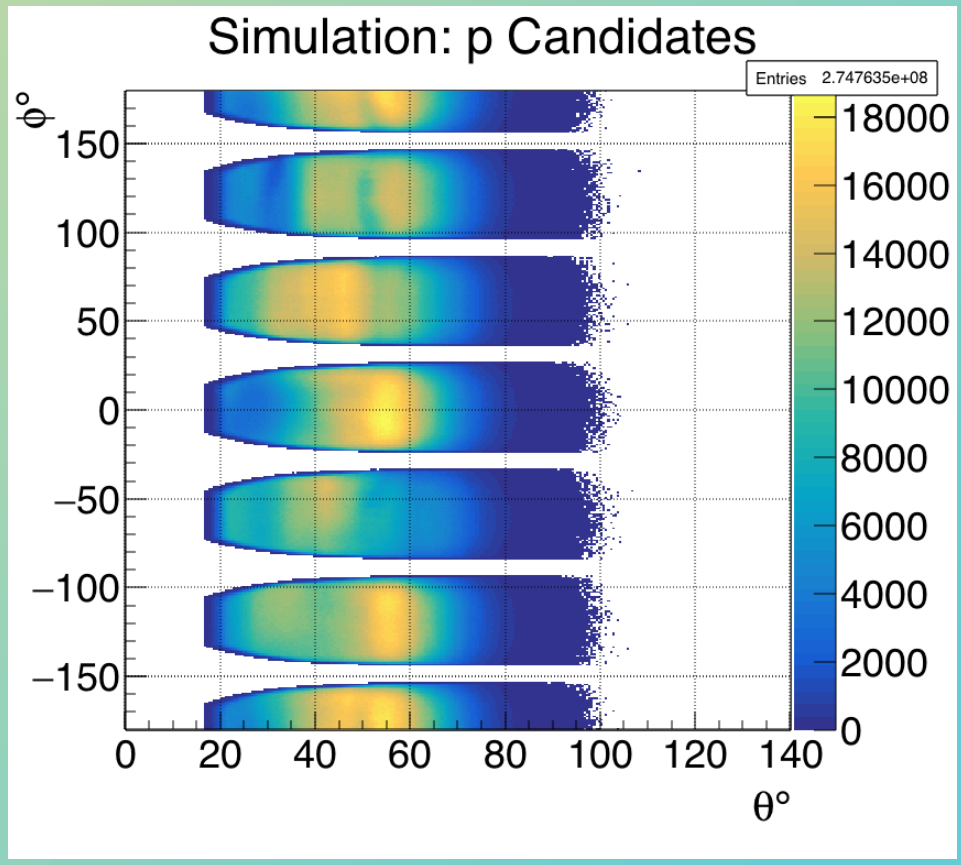


Thresholds set assuming MIP peak here (ADC – pedestal = 600)

Compare Experiment, MC: p

- After cuts: γd → pπ⁻(p) distributions match VERY closely
  - Need to regenerate MC with measured cross section (Used SAID)

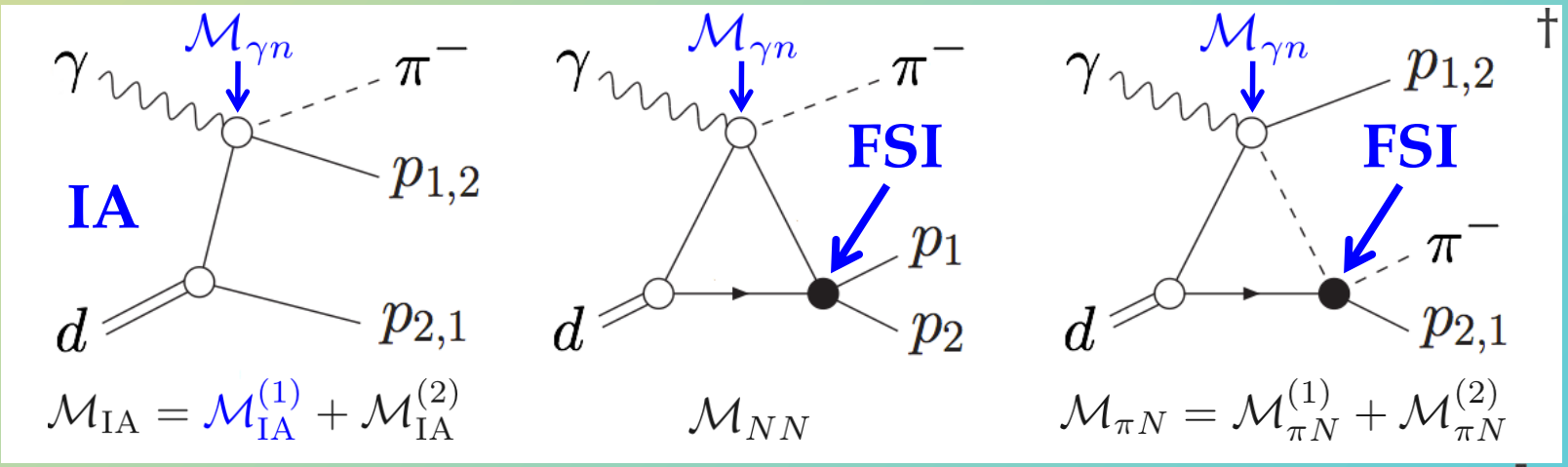




Primary sources of holes: Triggering & drift chamber inefficiencies

†Modeling FSI in γd → ppπ⁻

- Must correct for FSI to extract γn → pπ⁻ from QF γd → ppπ⁻
  - Working with GWU & ITEP (Moscow)
- γd → ppπ⁻ amplitude: $\mathcal{M}_{\gamma d} = \mathcal{M}_{\mathrm{IA}} + \mathcal{M}_{NN} + \mathcal{M}_{\pi N}$
  - Leading terms: Impulse approximation (IA), NN FSI, πN FSI
  - Fit constrained by SAID γN → πN , NN → NN, Nπ → Nπ
- QF γd → ppπ⁻: Slow proton is spectator: $\mathcal{M}^{QF}_{\gamma d} = \mathcal{M}^{(1)}_{\mathrm{IA}}$



†V. E. Tarasov *et. al*, Phys. Rev. C **84**, 035203 (2011)

†Modeling FSI in γd → ppπ⁻

* 1st approximation: FSI ≈ small & IA dominates: γn similar to QF
  * Relate γn → pπ⁻ to QF γd → ppπ⁻ via correction factors:

$$\frac{d\sigma_{\gamma d}^{\mathrm{QF}}}{d\Omega}\left(E_\gamma,\theta\right) = f_n\left(p_{\max}\right) R\left(E_\gamma,\theta\right) \frac{d\overline{\sigma}_{\gamma n}}{d\Omega}\left(\overline{E}_\gamma,\theta\right)$$

* Where $R = R_P R_{\mathrm{FSI}}$ and:
  * R_{FSI}: Corrects for FSI
  * R_P: Corrects for difference between IA, QF
  * $f_n(p_{max})$: ≈ Fraction of n with $p < p_{max}$
    * p_{max} = 200 MeV/c

$$R_{\mathrm{FSI}} = \frac{d\sigma_{\gamma d}}{d\Omega_1} \Big/ \frac{d\sigma_{\gamma d}^{\mathrm{IA}}}{d\Omega_1}$$

$$R_P = \frac{d\sigma_{\gamma d}^{\mathrm{IA}}}{d\Omega_1} \Big/ \frac{d\sigma_{\gamma d}^{\mathrm{QF}}}{d\Omega_1}$$

$$f_n\left(p_{\max}\right) = 4\pi \int_0^{p_{\max}} \rho\left(p\right) p^2 dp$$

* Note $\overline{E}_\gamma \approx E_\gamma$ and $\overline{\sigma}_{\gamma n} \approx \sigma_{\gamma n}$ at low p_{max}
  * Difference: Target d → target virtual-n, deuteron wave function

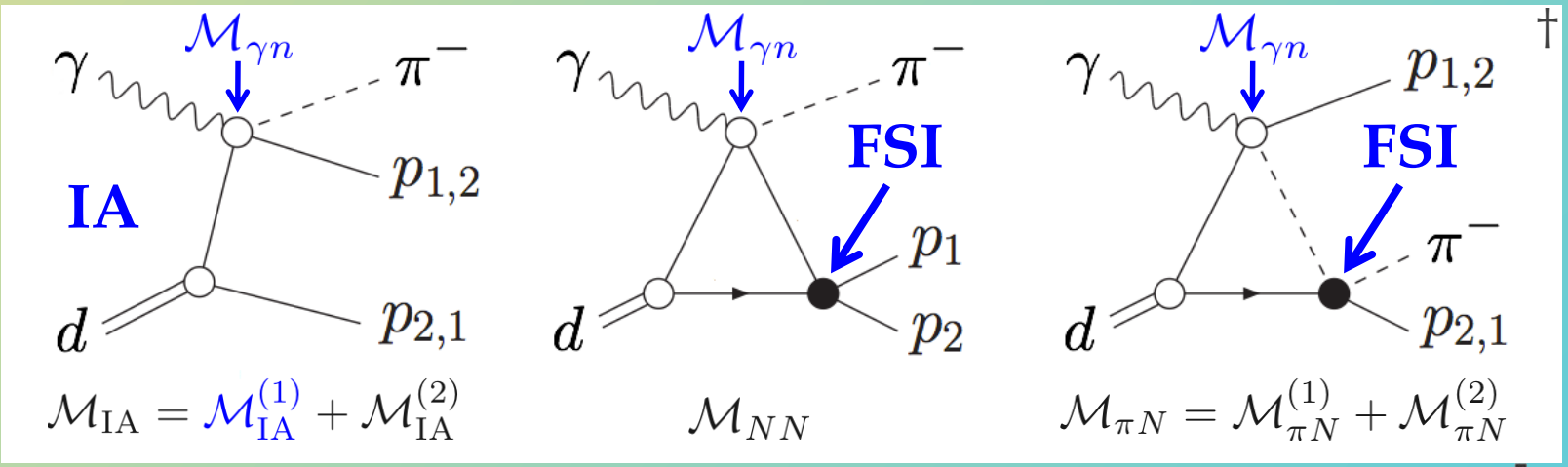
†V. E. Tarasov *et. al*, Phys. Rev. C **84**, 035203 (2011)

†Calculating R, γn → pπ⁻

- Set R = 1, compute $\sigma_{\gamma n}$ (& $\mathcal{M}_{\gamma n}$) from quasi-free $\sigma_{\gamma d}$ data
- Calculate R from CGLN amplitudes, using $\mathcal{M}_{\gamma n}$
- Re-compute $\sigma_{\gamma n}$, iterate until R converges

$$\frac{d\sigma^{\mathrm{QF}}_{\gamma d}}{d\Omega}(E_\gamma,\theta) = f_n(p_{\max})\, R(E_\gamma,\theta)\, \frac{d\overline{\sigma}_{\gamma n}}{d\Omega}(\overline{E}_\gamma,\theta) \qquad R = \frac{d\sigma_{\gamma d}}{d\Omega_1}\bigg/\frac{d\sigma^{\mathrm{QF}}_{\gamma d}}{d\Omega_1}$$

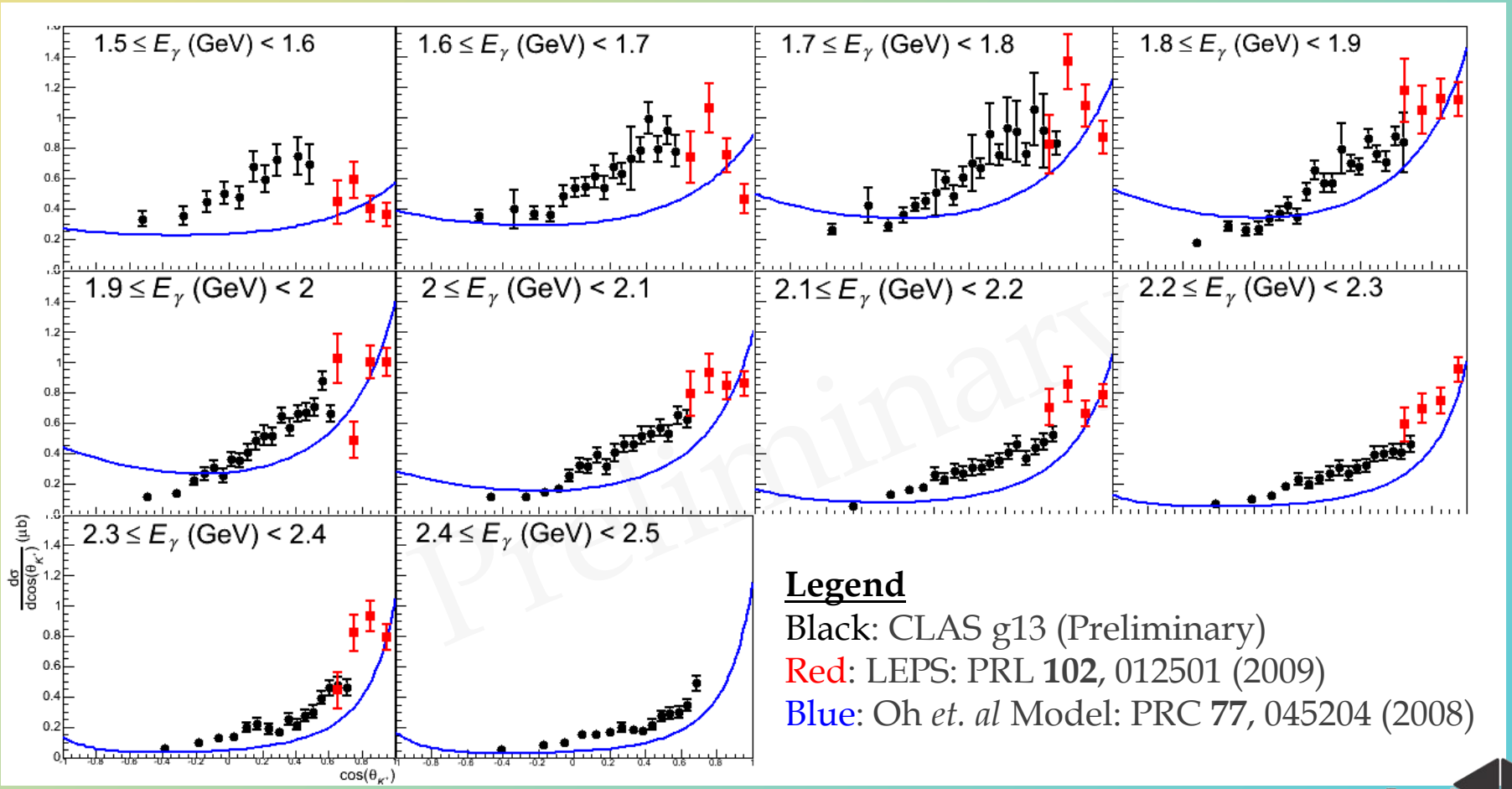
$$\mathcal{M}_{\gamma d} = \mathcal{M}_{\mathrm{IA}} + \mathcal{M}_{NN\,\mathrm{FSI}} + \mathcal{M}_{\pi N\,\mathrm{FSI}} \qquad \mathcal{M}^{QF}_{\gamma d} = \mathcal{M}^{(1)}_{\mathrm{IA}}$$



†V. E. Tarasov *et. al*, Phys. Rev. C **84**, 035203 (2011)

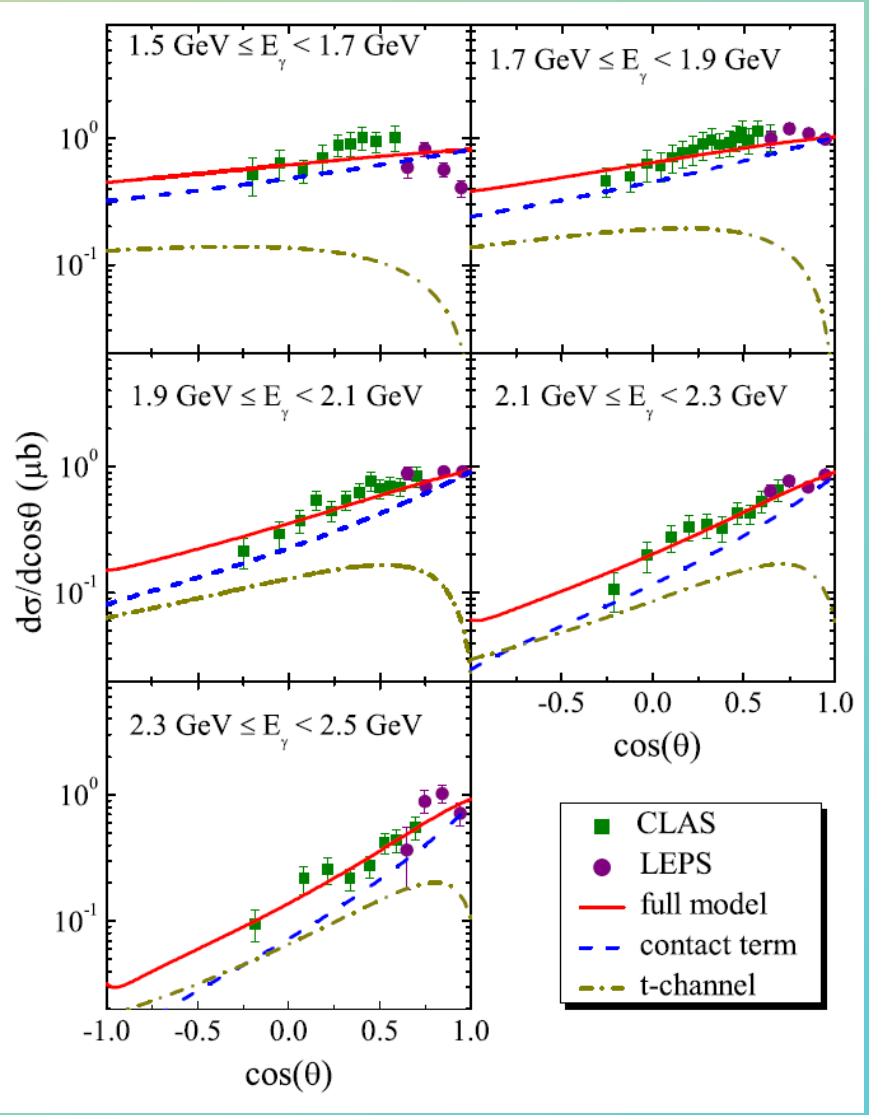
γd → $K^+\Sigma^*(1385)^-(p)$ Cross Section

- Preliminary, QF g13: ≈ 100k events, W ≈ 1.92 – 2.36 GeV, statistical σ only
- Y. Oh, *et. al* model: Effective Lagrangians, t-channel K^+, K^{*+} dominates



γd → $K^+\Sigma^*(1385)^-(p)$ Cross Section

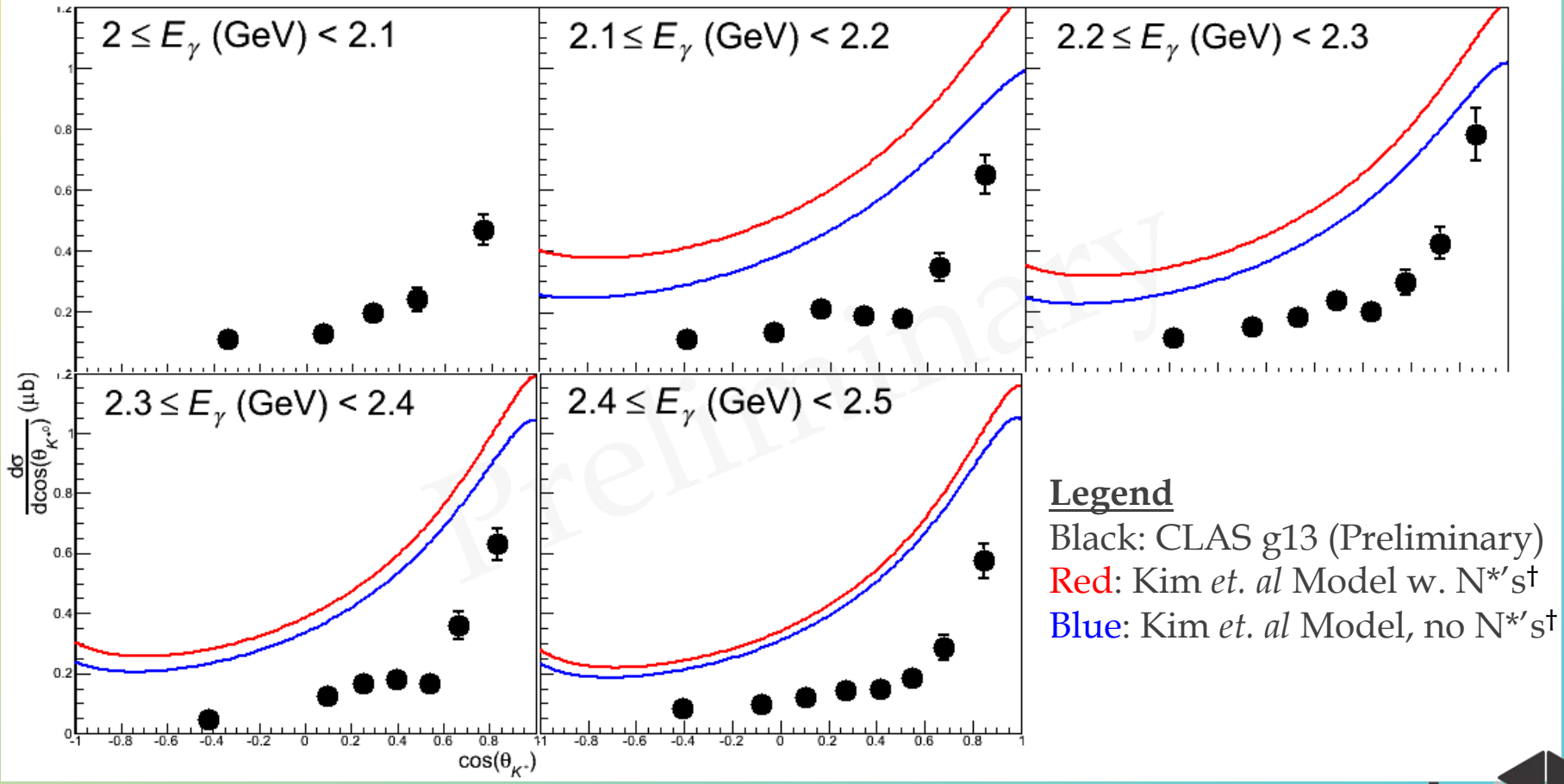
- Preliminary CLAS g13: Conference proceedings
- X.-Y. Wang, J. He, Haberzettl†
- Effective Lagrangians, w/ Reggeized t-channel exchange
- t-channel & contact dominant
  - Contact term: May indicate significant FSI



†X.-Y. Wang *et. al*, Phys. Rev. C **93**, 045204 (2016)

γd → K*(892)^{0}Λ(p) Cross Section

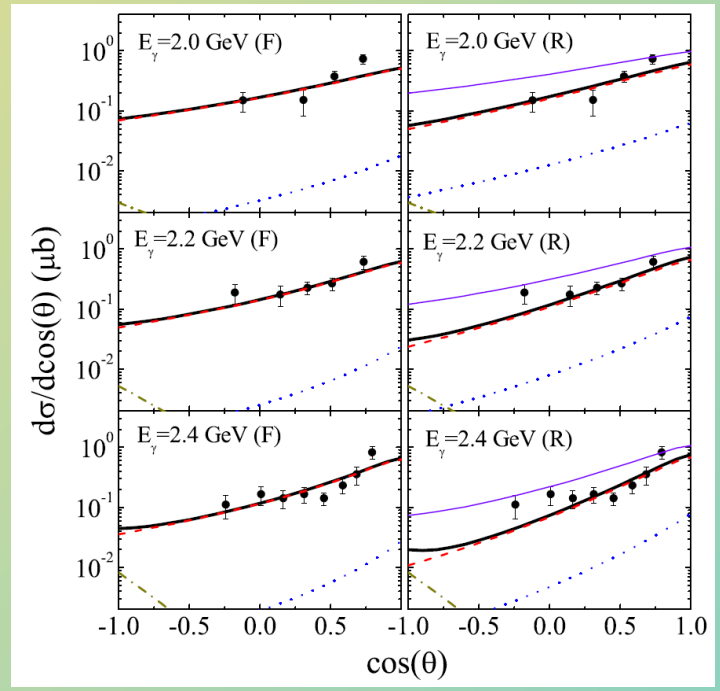
- Preliminary, QF g13: ≈ 17k events, W ≈ 2.11 – 2.36 GeV, statistical σ only
- Kim, *et. al* model: Effective Lagrangians: t-channel K^0 dominates†

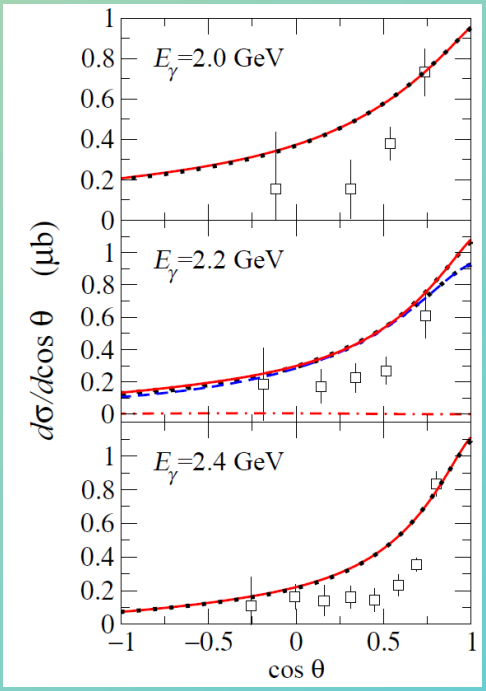


†S.-H. Kim *et. al*, Phys. Rev. D **84**, 114023 (2011)

γd → K*(892)^{0}Λ(p) Cross Section

* X.-Y. Wang, J. He†: Effective Lagrangian, Regge & Feynman models
* B.-G. Yu, Y. Oh, K.-J. Kong‡: Regge: EM moments of J = 1 K*
* Both based off preliminary data (conference proceedings)
  * Both: t-channel K exchange dominant





† PRC **93**, 035202 (2016)

‡ arXiv:hep-ph/1608.00455