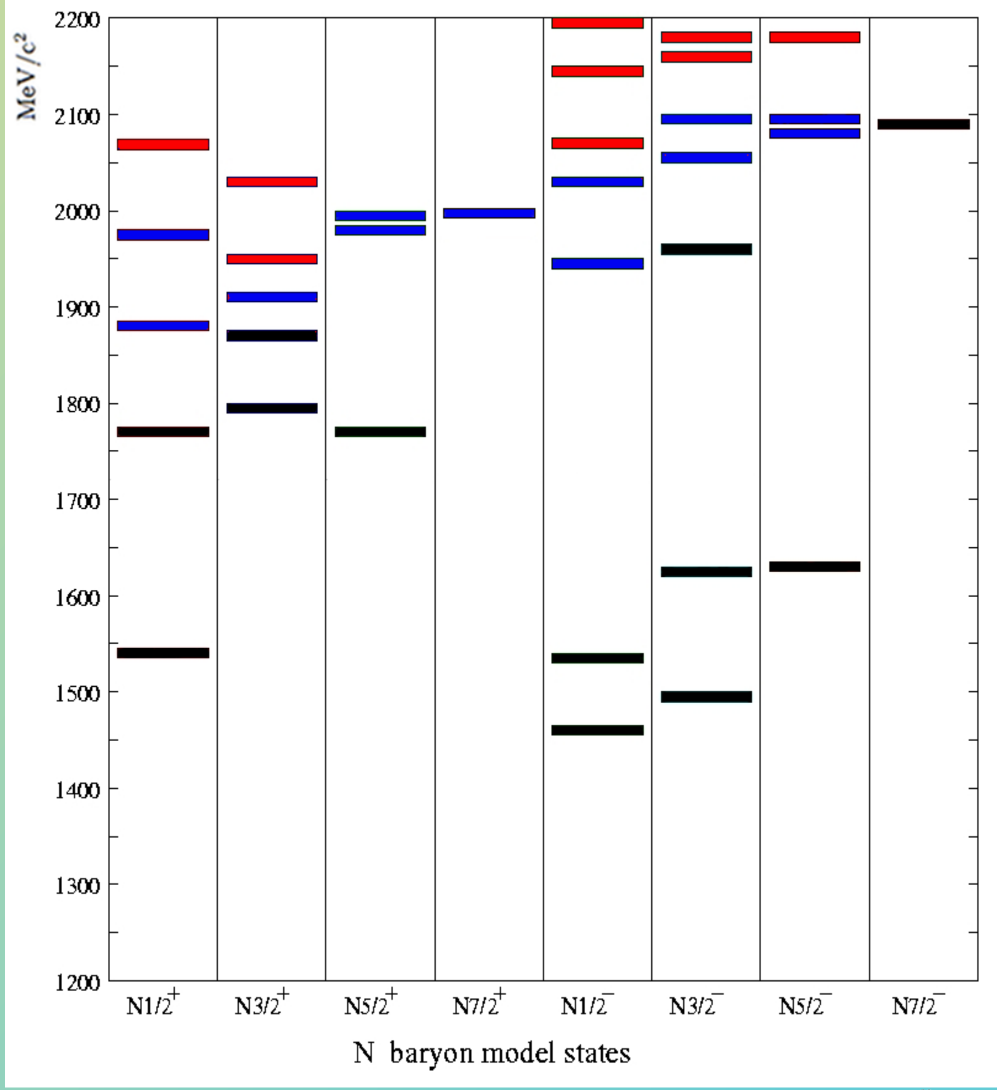
g13 $\gamma n \rightarrow p\pi^-$ Differential Cross Section, N* Amplitudes

Paul Mattione, Jefferson Science Associates

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
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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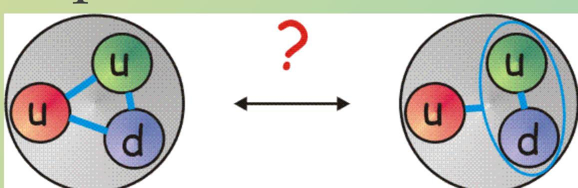
- ⋆ Diquarks?



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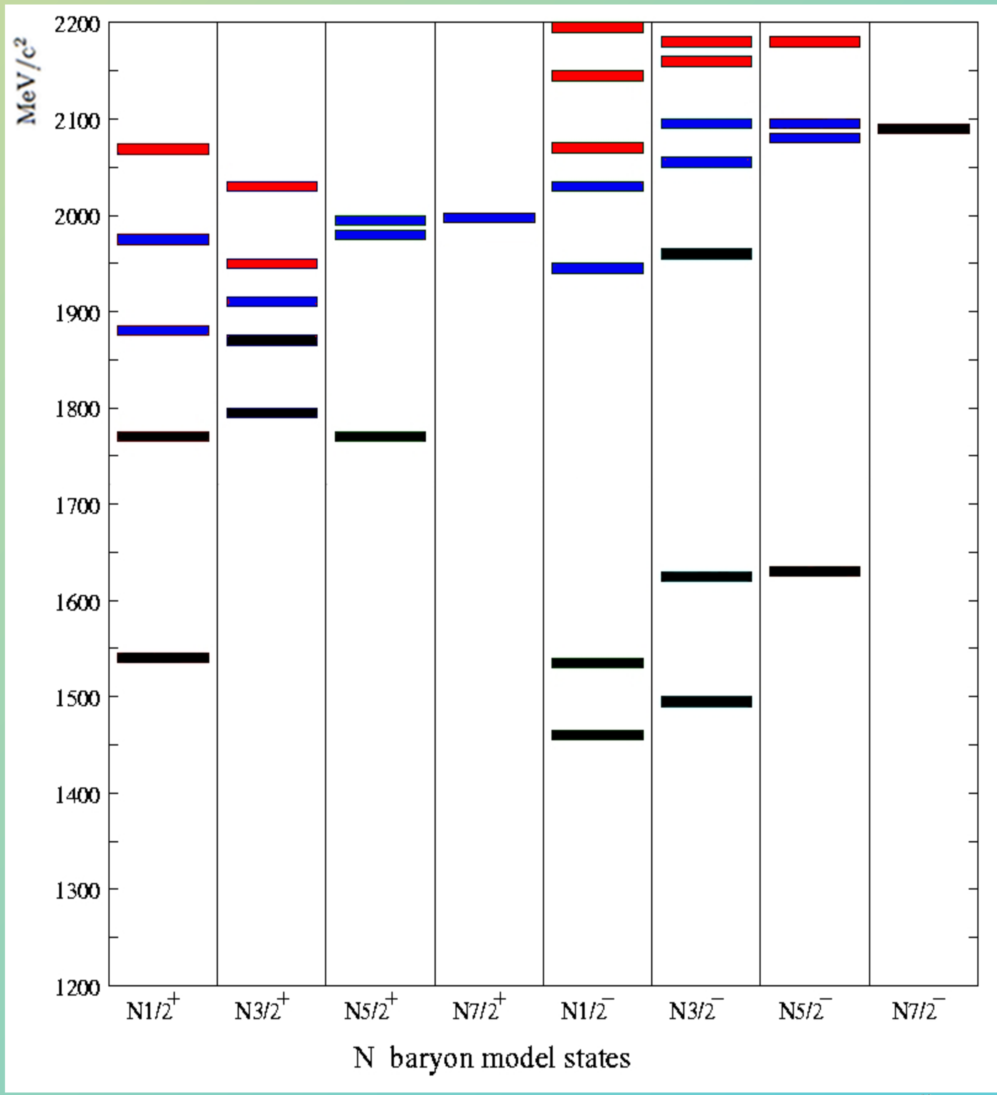

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γp vs. γn, Isospin

- 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 (3500 points) vs. γp → πN (35400)

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

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

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

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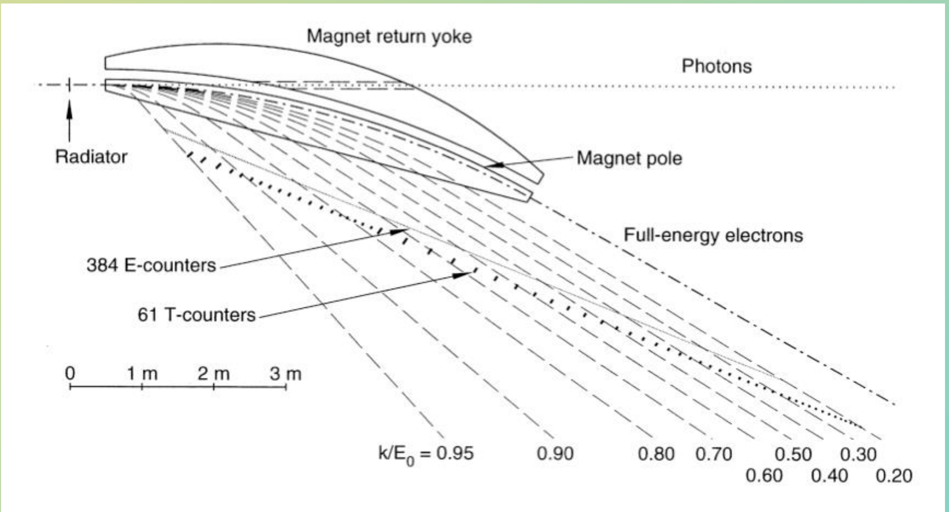
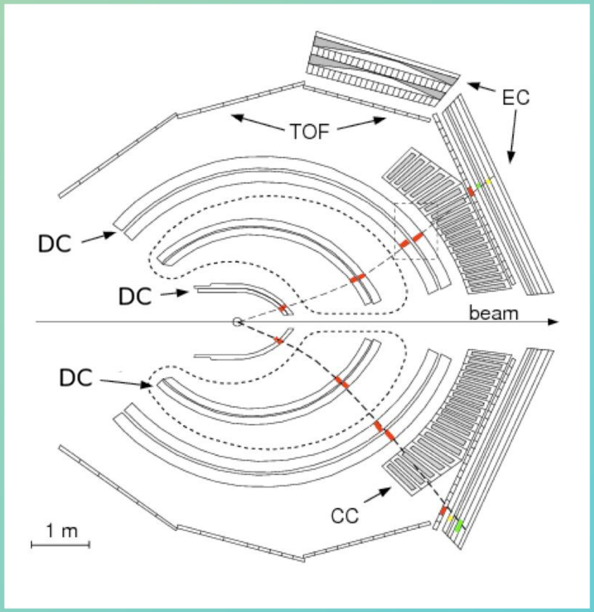
†R. L. Walker, Phys. Rev. **182**, 1729 (1969)

CLAS g13 Experiment

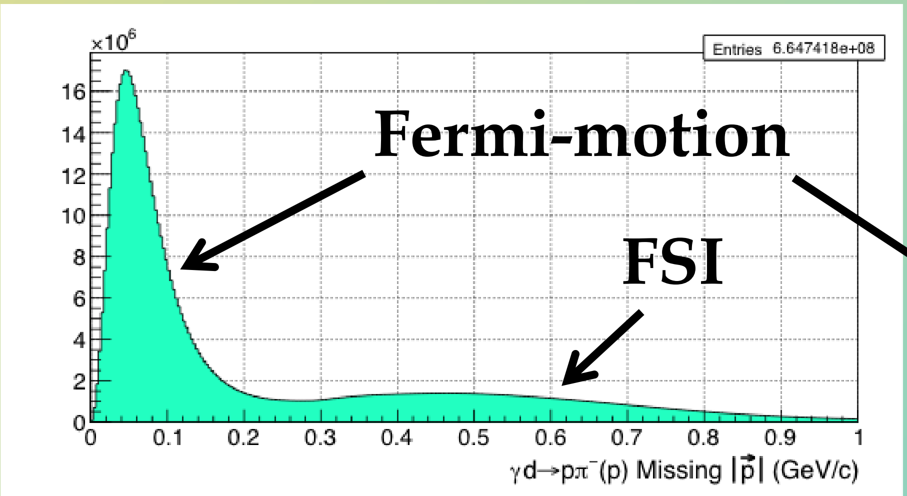
- g13 experiment: 2006 – 2007, LD_2 target
  - Analysis (g13a): E_{e-} = 2.655, 1.990 GeV

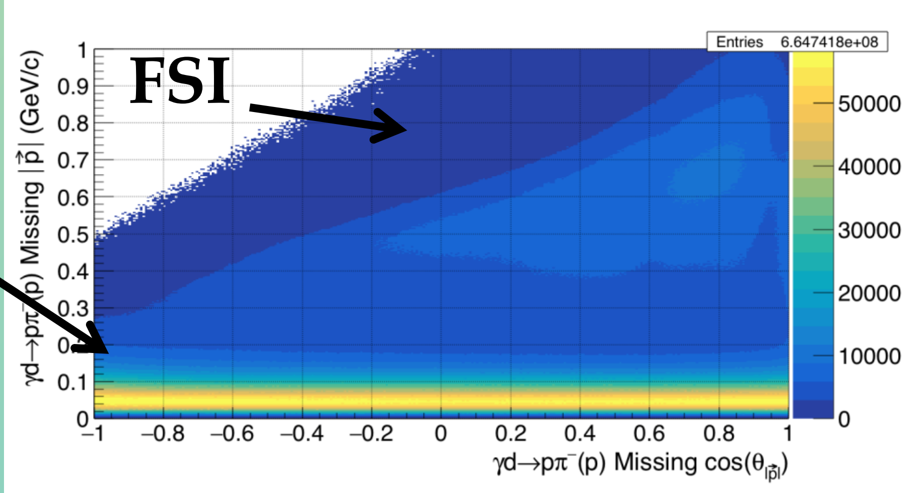




Final-State Interactions in γd

* 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†

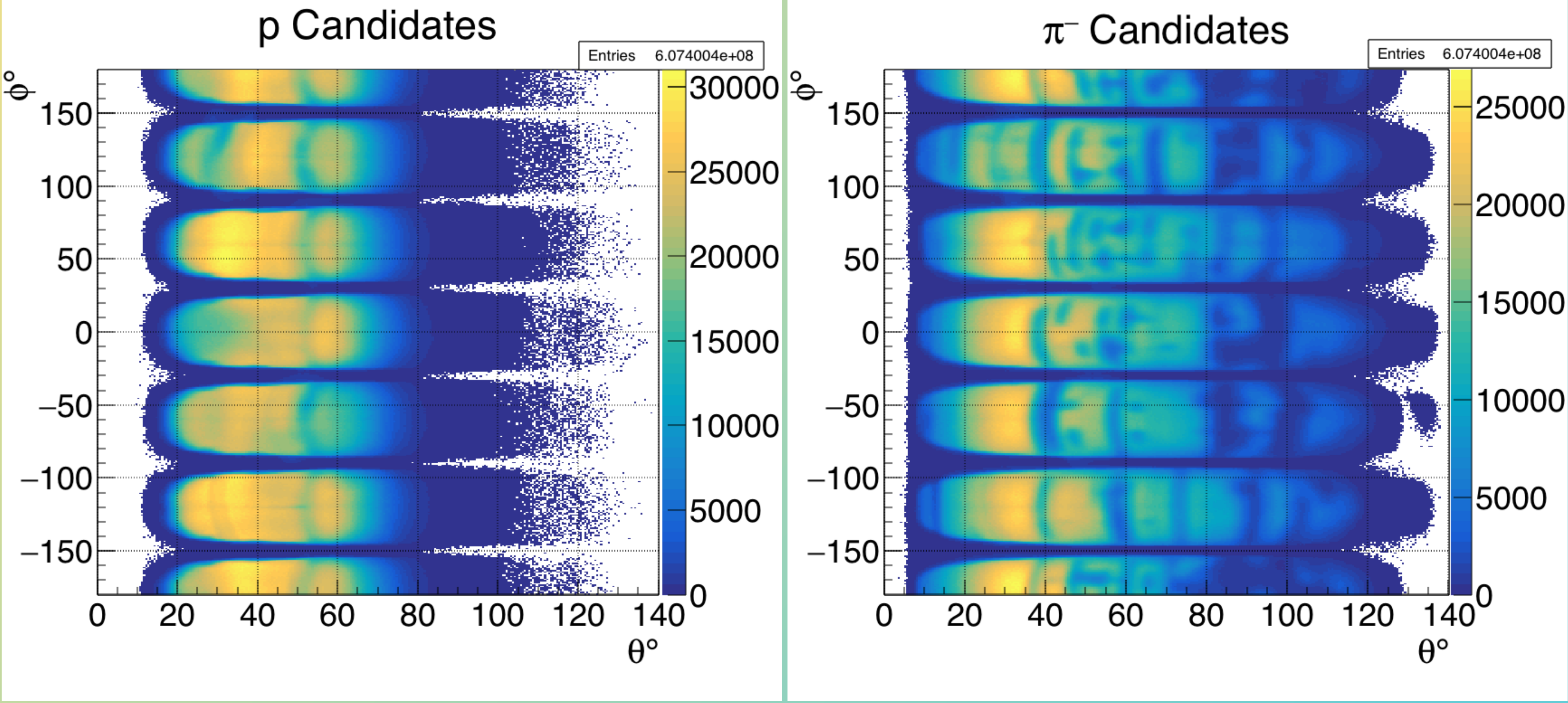




†V. E. Tarasov *et. al*, Phys. Rev. C **84**, 035203 (2011)

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

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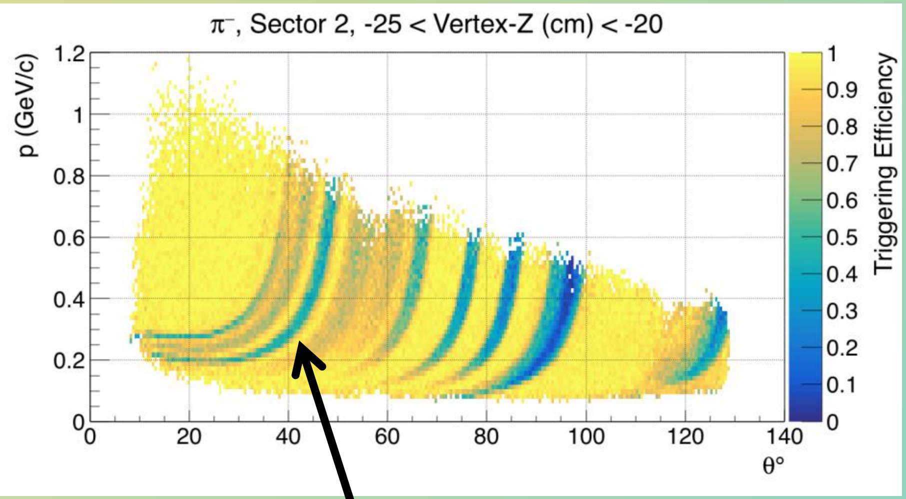

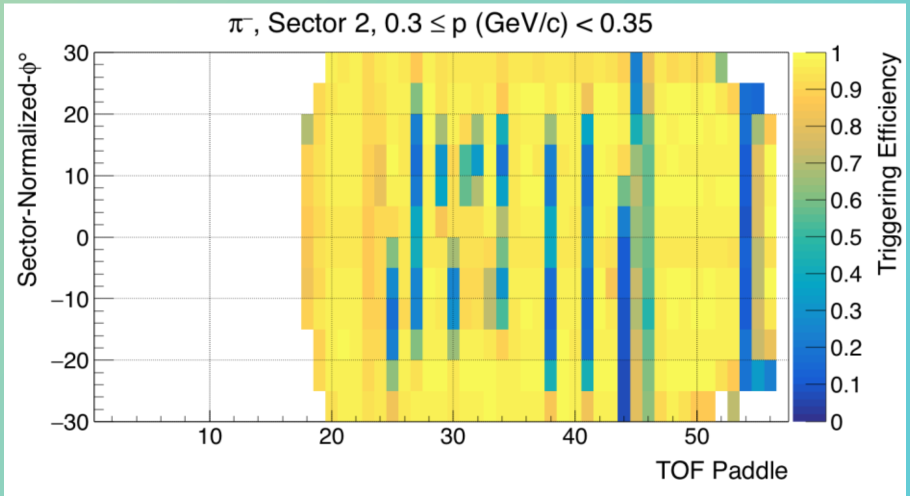

Overlap between TOF panels: Forward carriage, N/S clamshells

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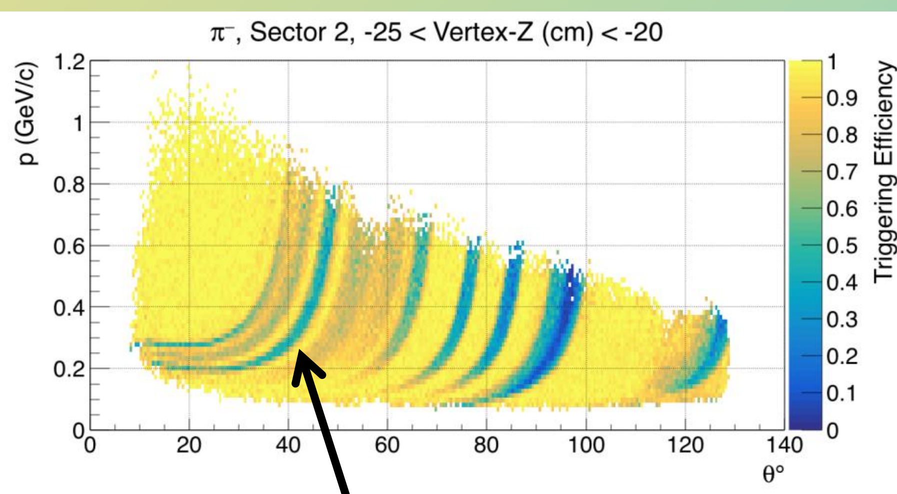
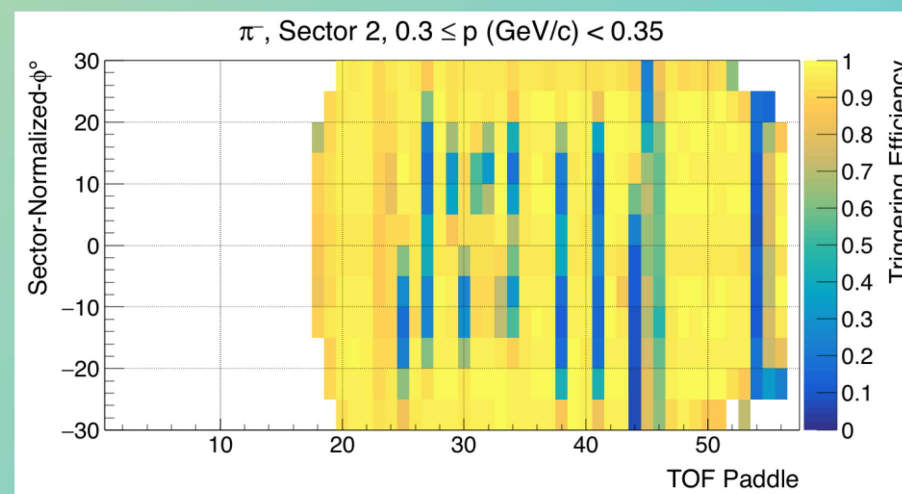
- Study $\gamma d \to pp\pi^-$ events, when each track in different sector
  - Each track pair: If both fired trigger signal, study 3rd-track signal rate
  - Function of particle type, p, TOF scintillator, φ
- TOF thresholds: Readout = 20 mV, pre-trigger = 100 mV
  - g13 weak PMTs: Set to max voltage,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

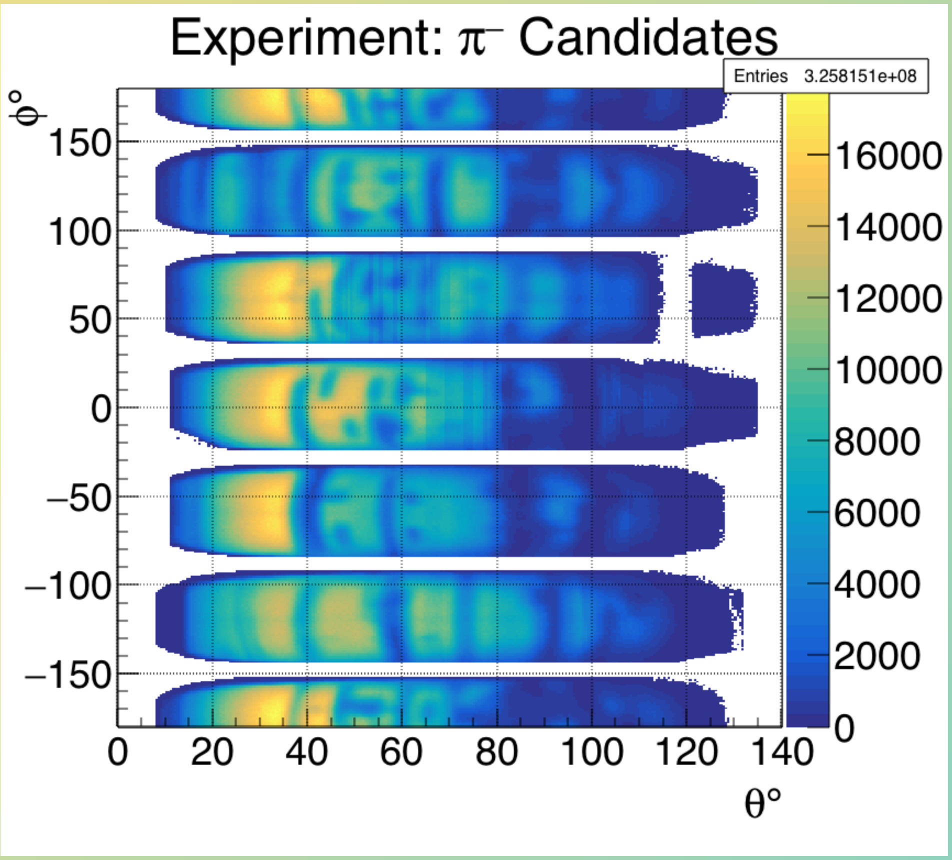


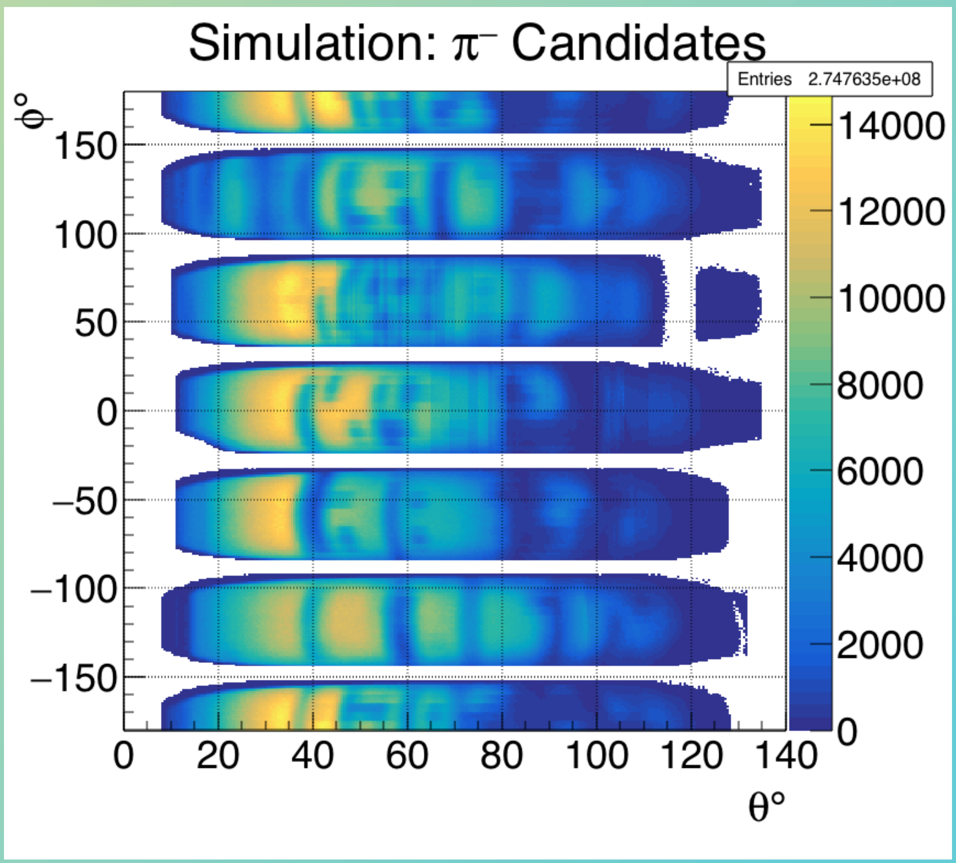


Overlap between TOF panels: Forward carriage, N/S clamshells

Compare Experiment, MC: π^-

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



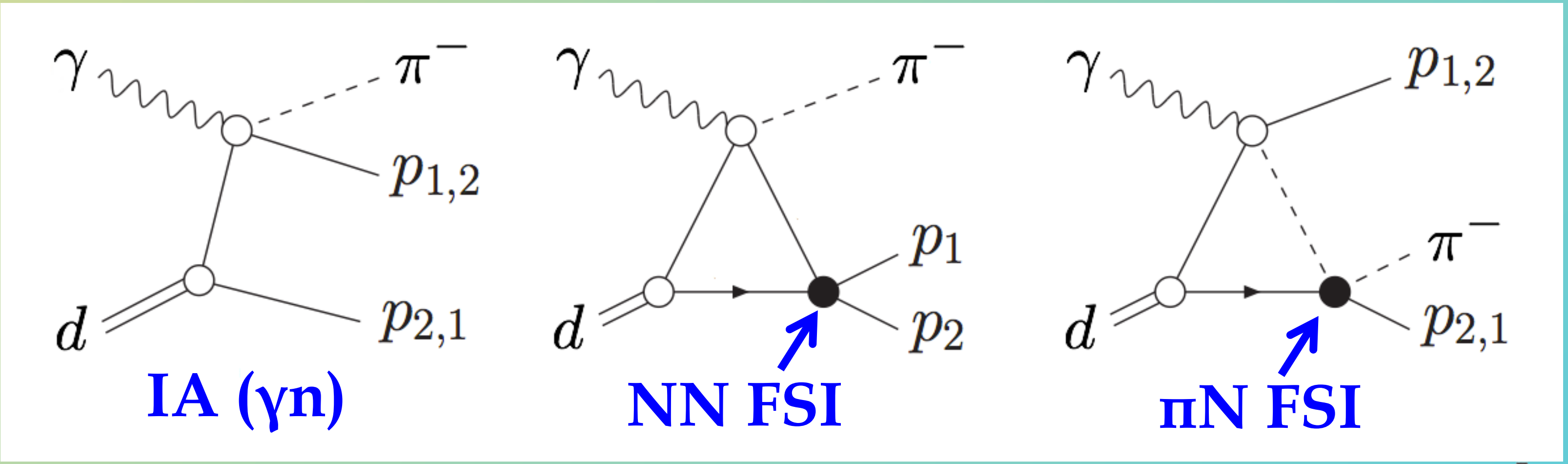


†Modeling FSI in $\gamma d \rightarrow pp\pi^-$

- Must correct for FSI to extract $\gamma n \rightarrow p\pi^-$ from QF $\gamma d \rightarrow pp\pi^-$
  - GWU & ITEP Moscow
- $\gamma d \rightarrow pp\pi^-$ amplitude: $\mathcal{M}_{\gamma d} = \mathcal{M}_{\rm IA} + \mathcal{M}_{NN} + \mathcal{M}_{\pi N}$
  - Leading terms: Impulse approximation (IA), NN FSI, πN FSI
  - Fit constrained by SAID $\gamma N \rightarrow \pi N$, $NN \rightarrow NN$, $N\pi \rightarrow N\pi$

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

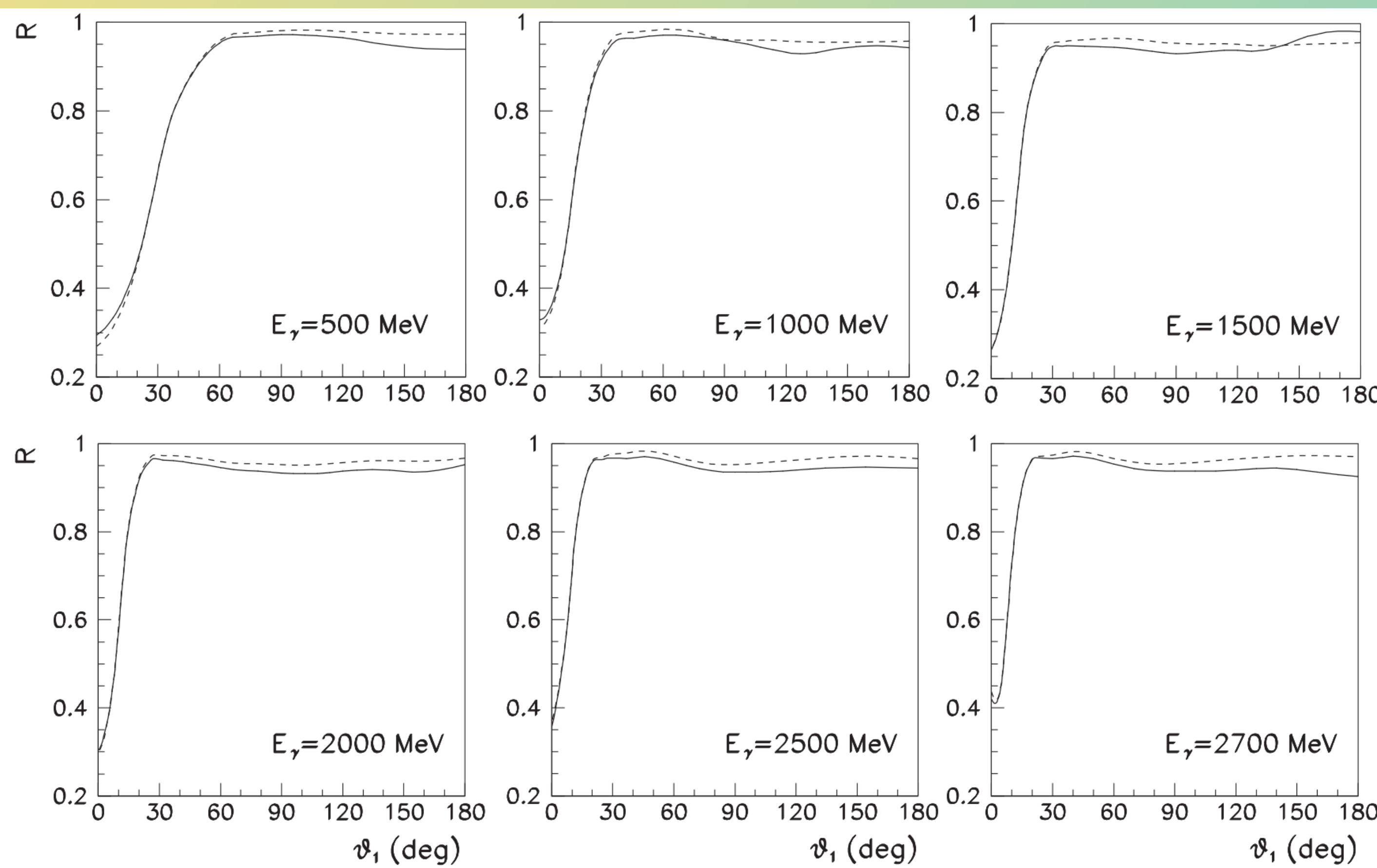
$$R(E_\gamma, \theta) = \mathcal{M}_{\gamma d} / \mathcal{M}_{IA}$$



†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:

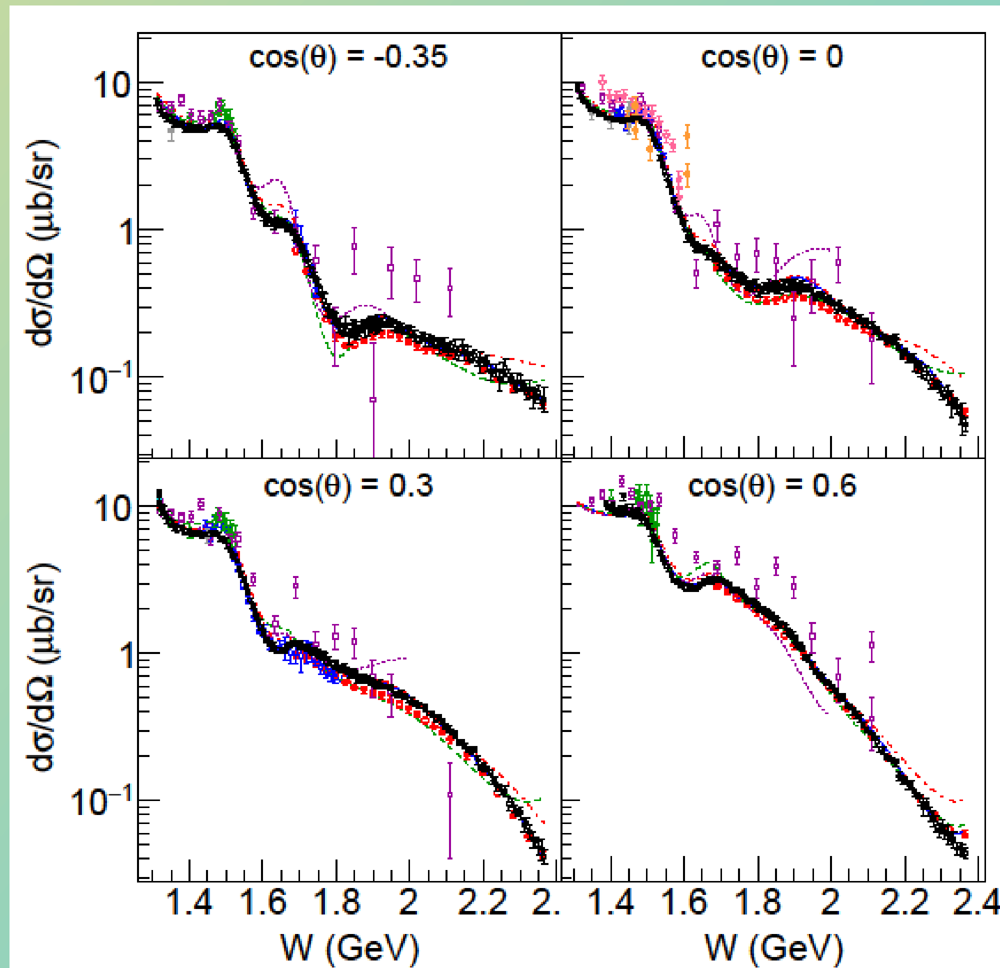
$E_\gamma < 1.8$ GeV: 2%
$1.8 < E_\gamma < 2.7$: 3%
$E_\gamma > 2.7$ GeV: 5%

Legend
Solid: NN + πN FSI
Dash: NN FSI

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

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

- CLAS g13
  - 8424 bins, ≈ 400M events
  - 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

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

$\pi^- p \to \gamma n$: **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

Legend
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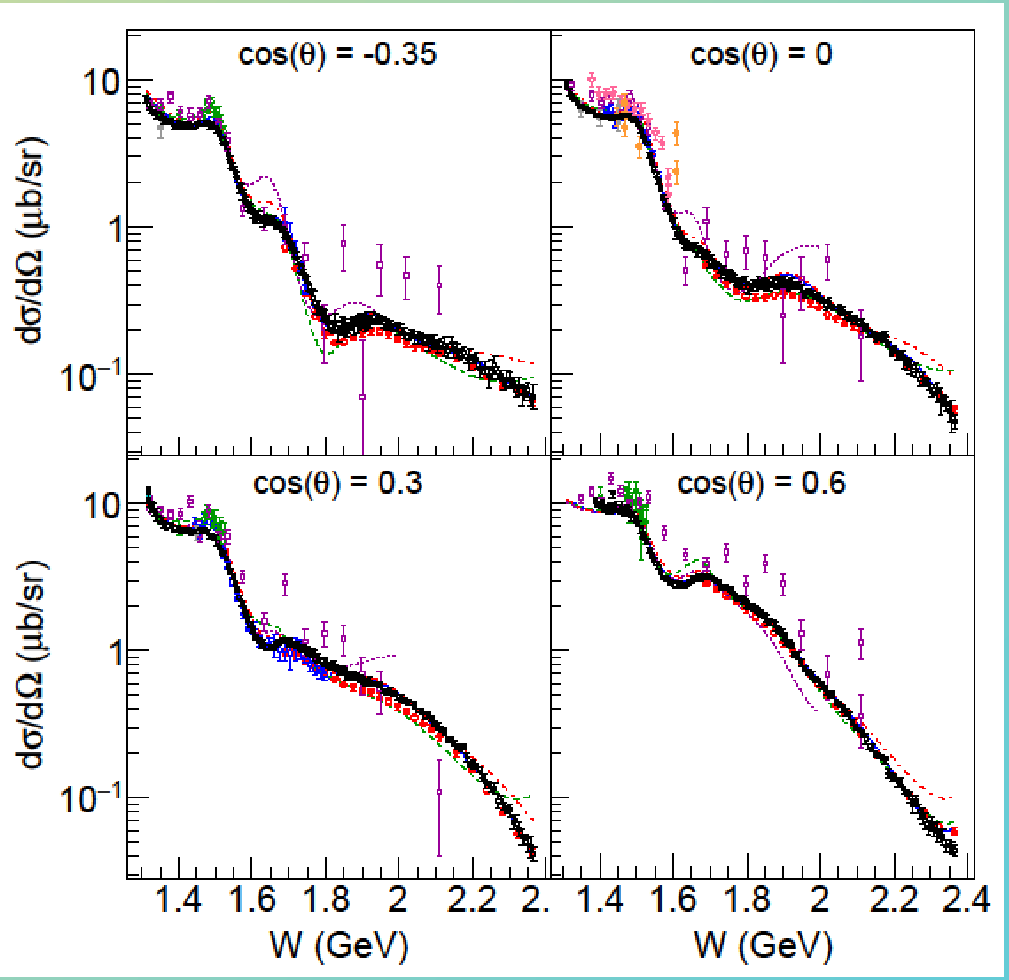
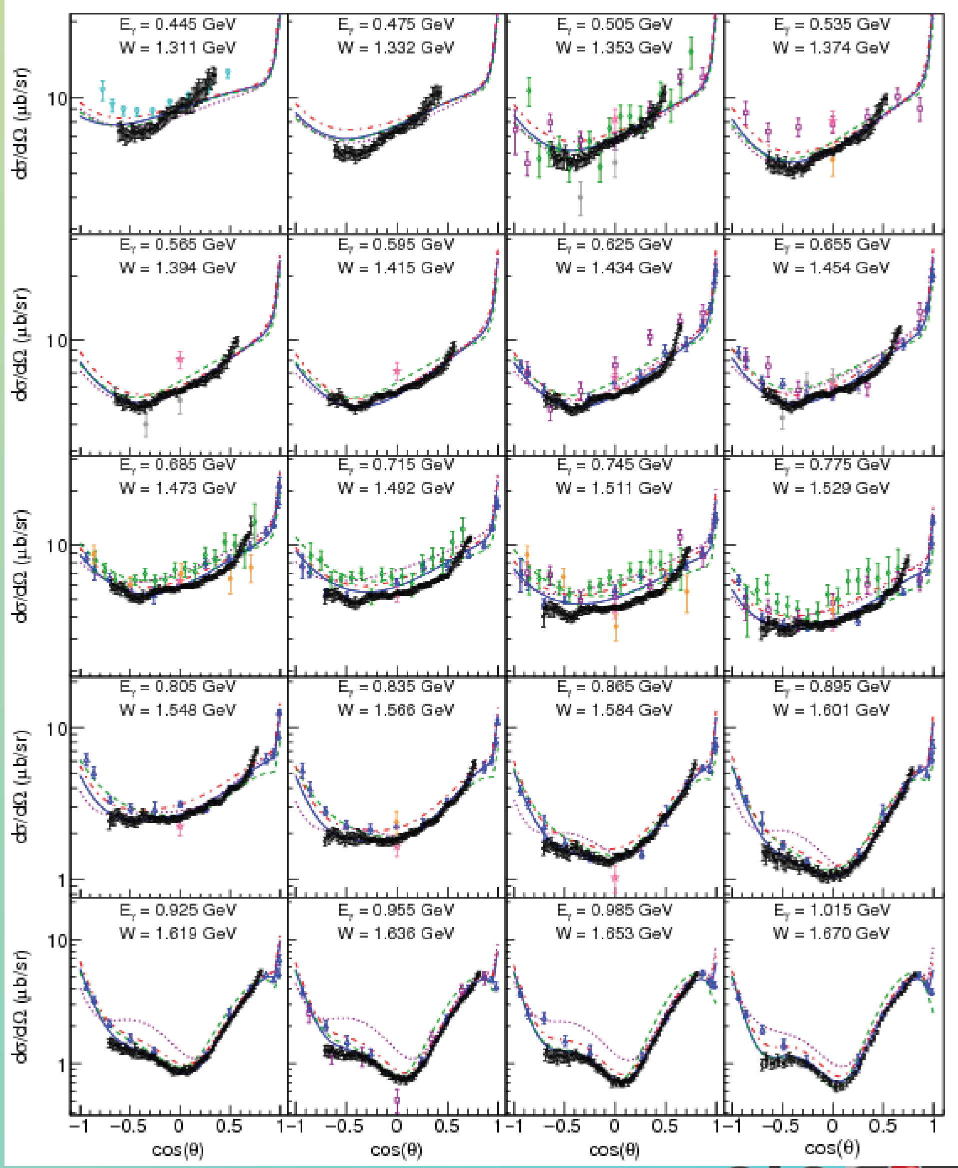


Peaks at low-E_γ : Δ(1232), N*'s
At higher E_γ, more channels

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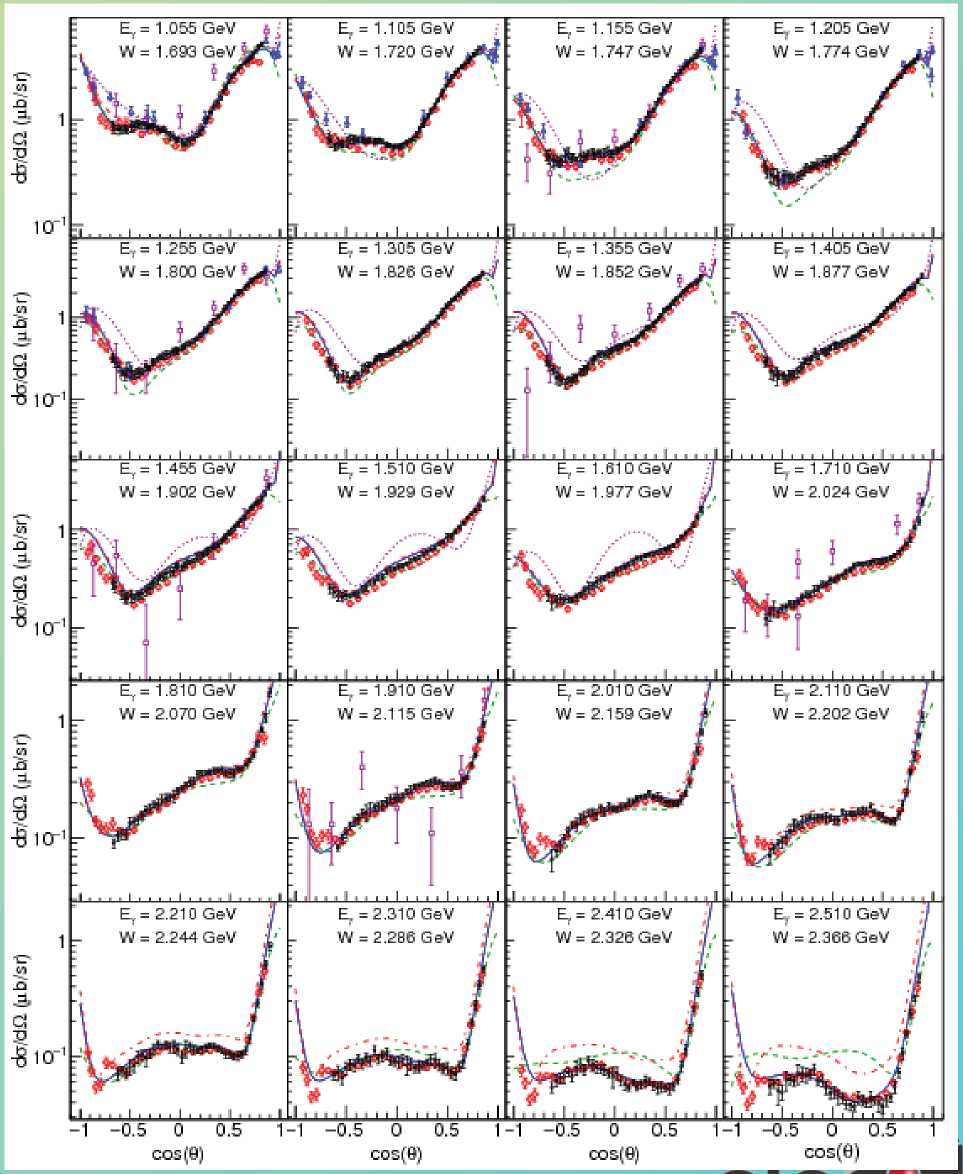
$\gamma n \rightarrow p\pi^-$ Cross Section

- 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



Legend

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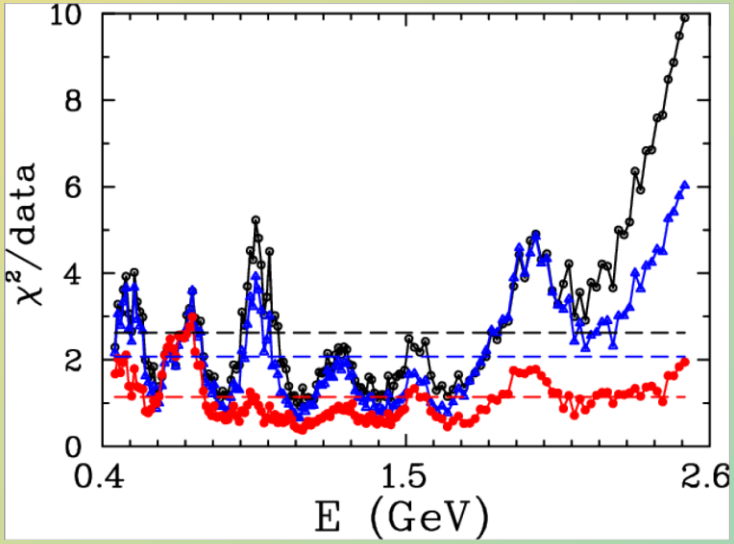
SAID MA27 Fit

- 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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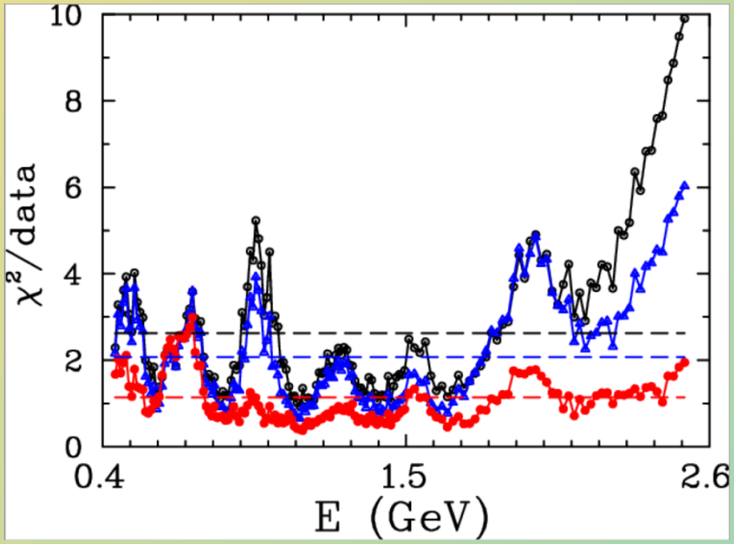

Channel	SAID PR15 (no g13)		SAID MA27 (w/ g13)	
	# Data	χ^2/Data	# Data	χ^2/Data
$\gamma p \to p\pi^0$	25540	2.15	25540	2.17
$\gamma p \to n\pi^+$	9859	**2.39**	9859	**2.10**
$\gamma n \to p\pi^-$	3162	**2.07**	11614	**1.42**
$\gamma n \to n\pi^0$	364	3.17	364	**4.23**
Sum	38927	2.22	47377	2.17

Legend
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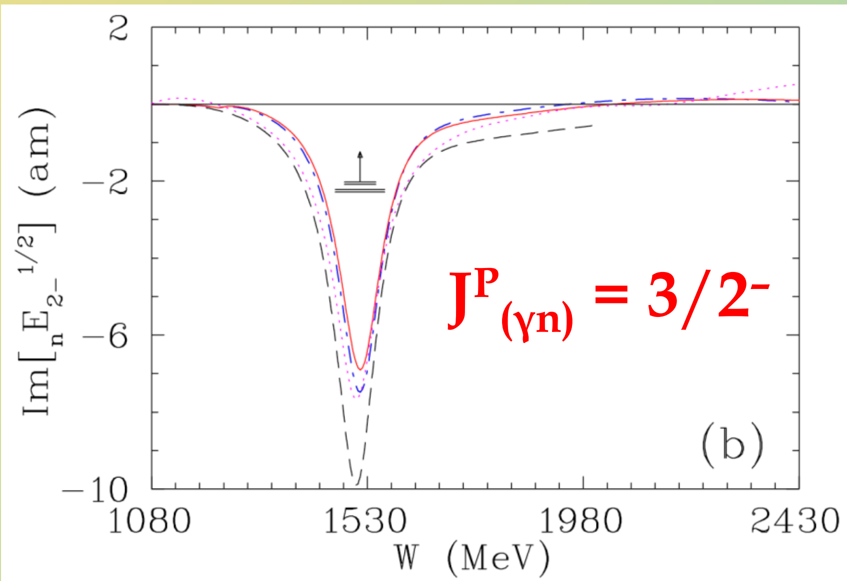
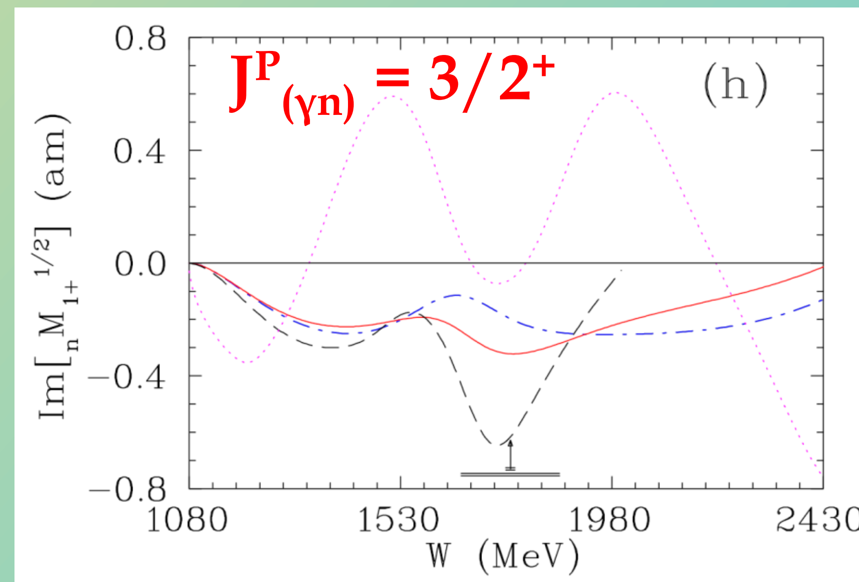
γn Multipole Amplitudes

- 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 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%

Summary & Outlook

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  * Role of quark correlations in the nucleon
  * Need both γp and γn: Isospin decomposition of amplitudes

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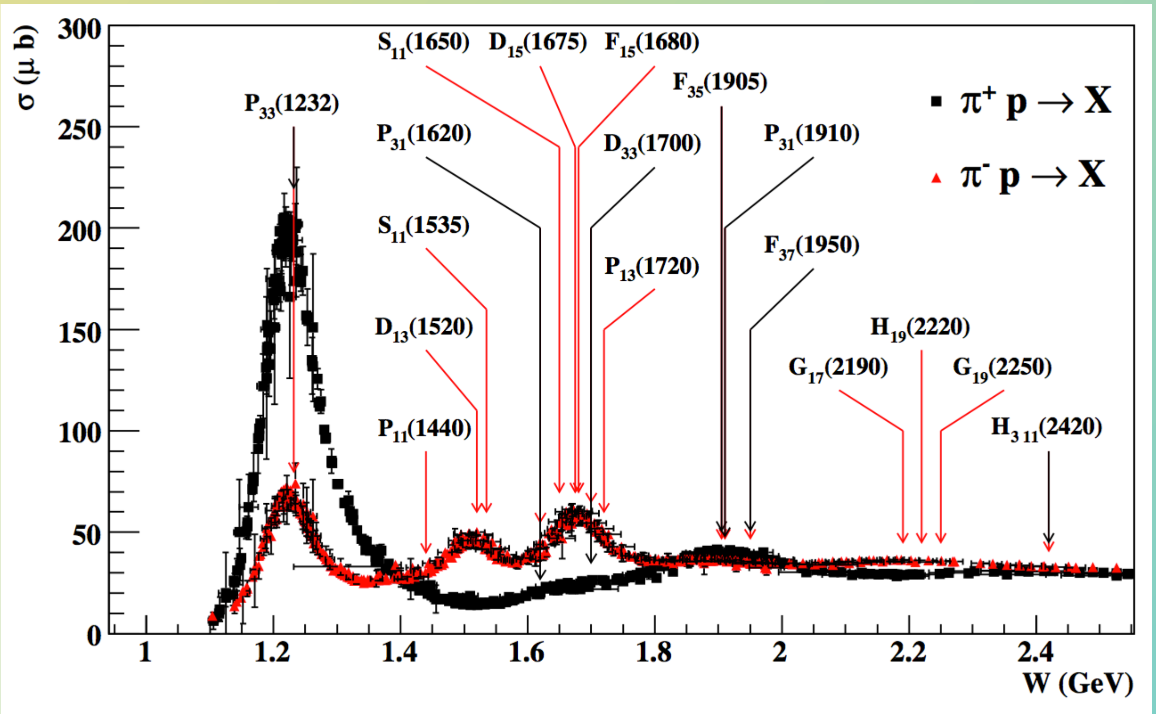
  - First-ever determination of $\gamma n \rightarrow N^*$ amplitudes
- Missing N*'s: Need more precision data (especially polarized!)

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

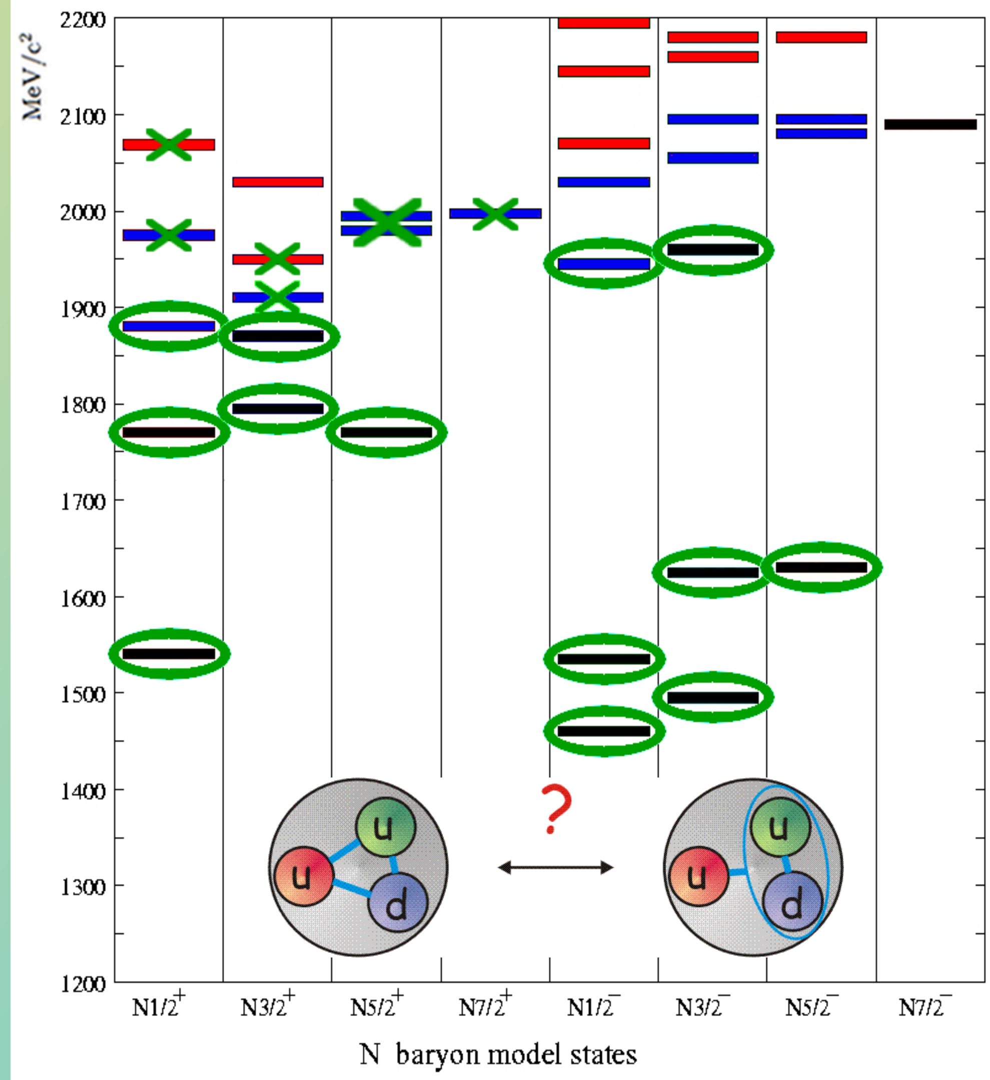
Particle J^P	overall	Status as seen in $N\gamma$	$N\pi$	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N $1/2^+$	****									
$N(1440)\,1/2^+$	****	****	****		***				*	***
$N(1520)\,3/2^-$	****	****	****	***					***	***
$N(1535)\,1/2^-$	****	****	****	****					**	*
$N(1650)\,1/2^-$	****	****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

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)

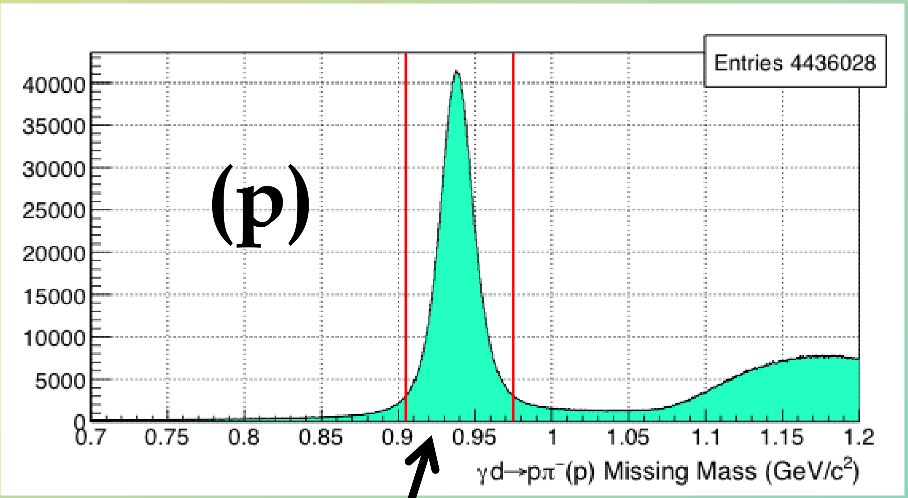
Polarization Observables

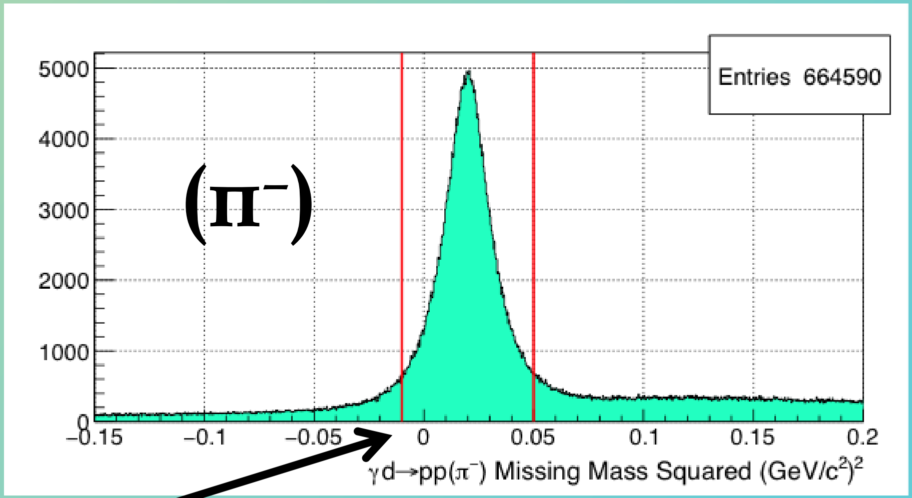
- Combination of polarized beams, targets, and recoil polarization:
  - 16 observables
- Provide spin-dependent constraints for N* extraction

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

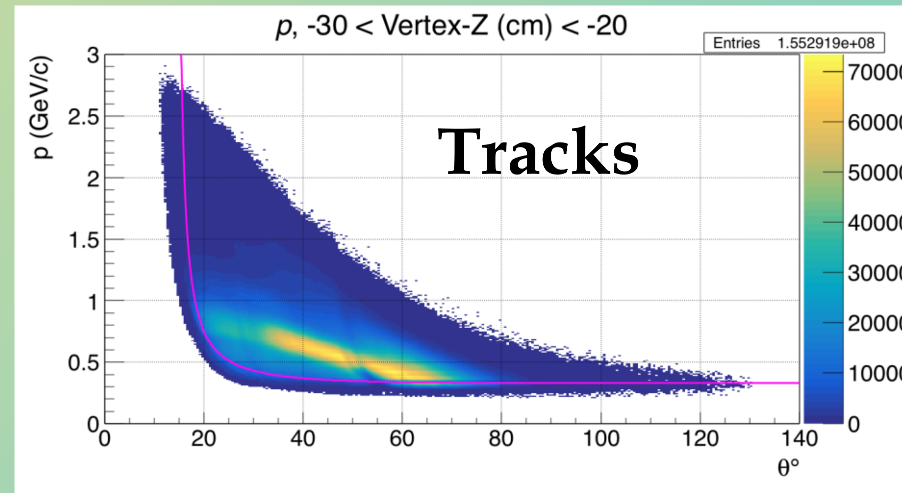


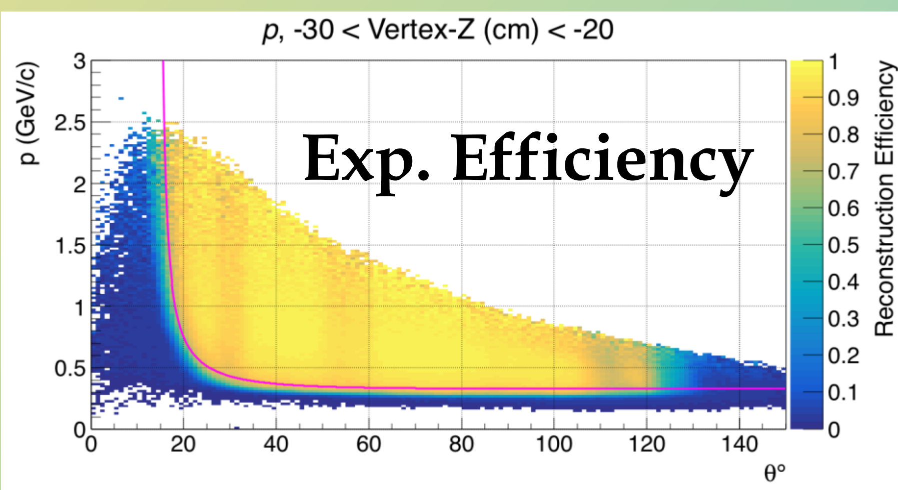


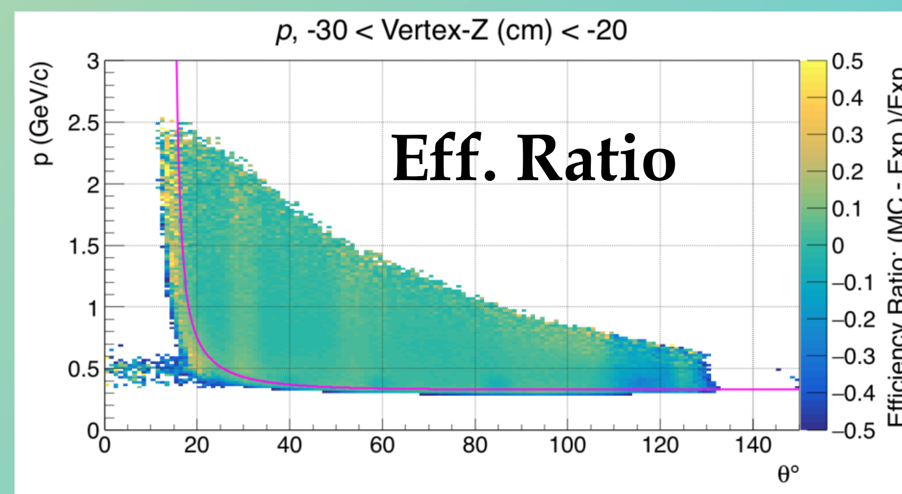
Background present, small, ignored: Studying features

p Reconstruction Efficiency

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

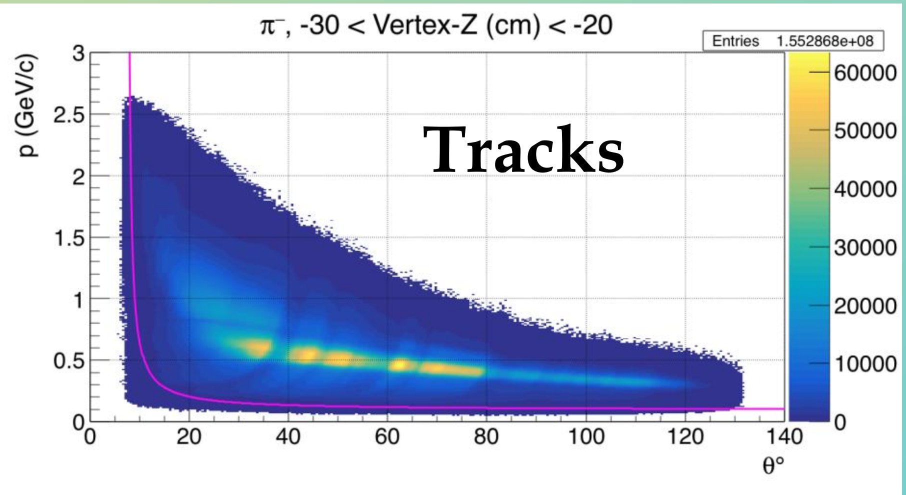


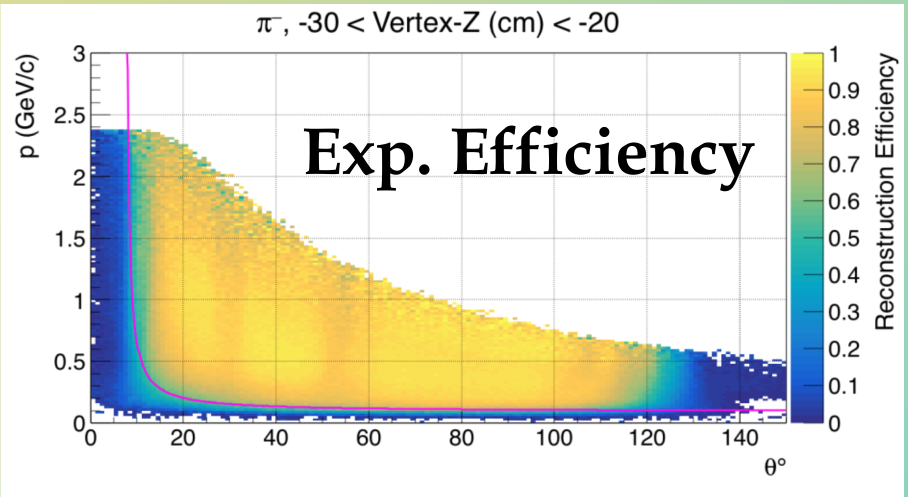


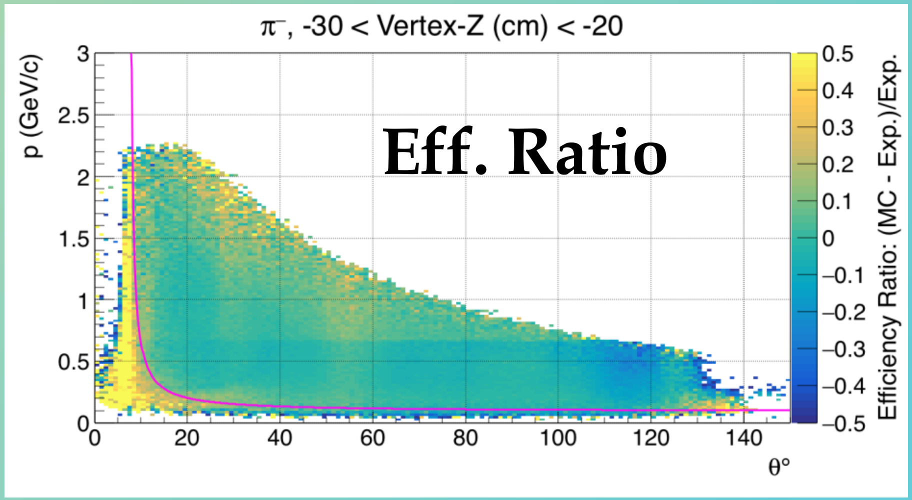


π⁻ Reconstruction Efficiency

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

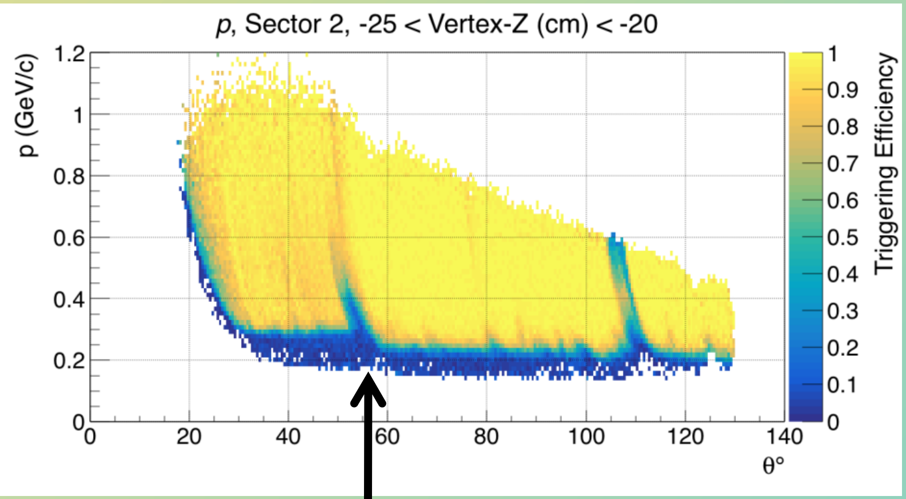


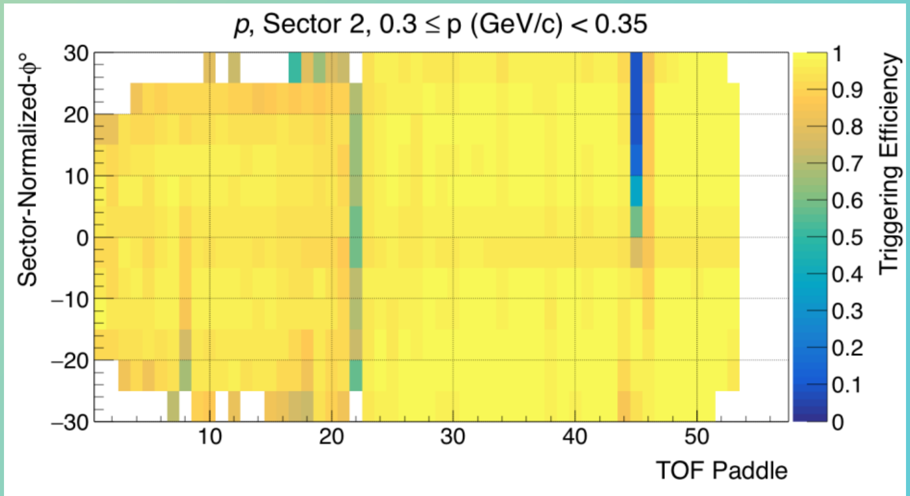




Proton Triggering Efficiency

- 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
- Low efficiency for weak/dead TOF PMTs, TOF panel overlap
  - One PMT on each end of TOF scintillators

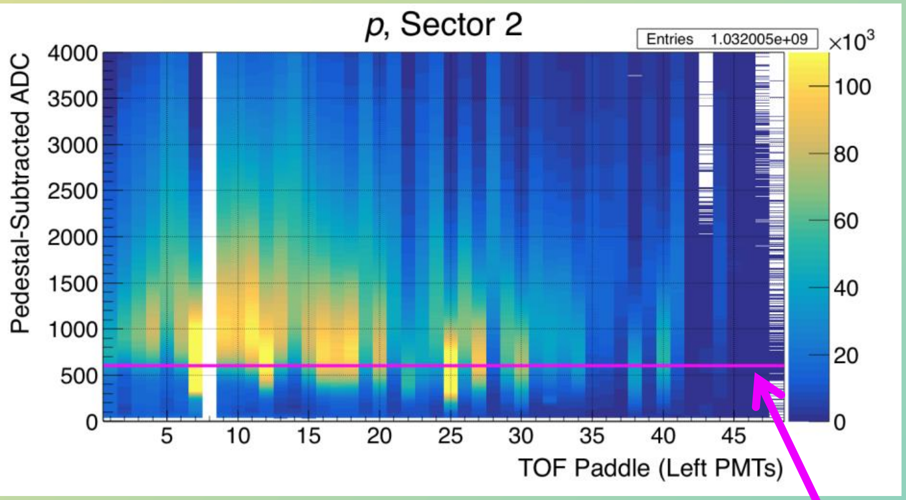


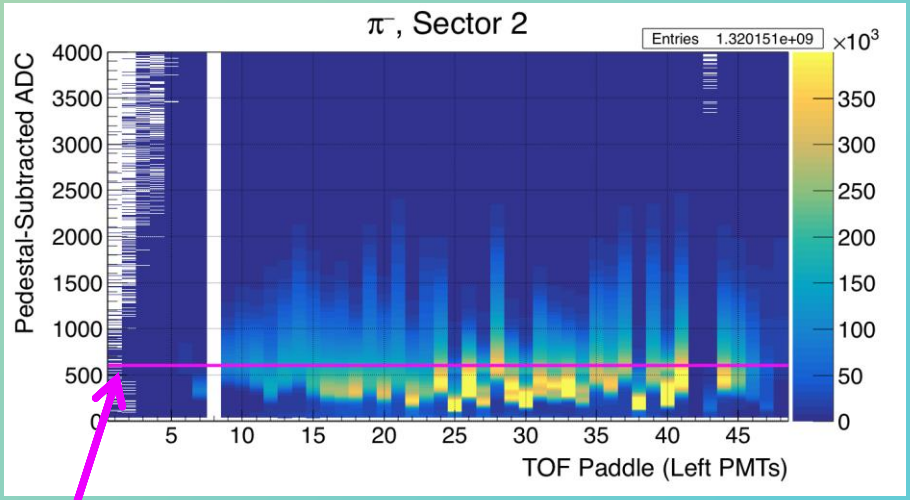


Overlap between TOF panels: Forward carriage, N/S clamshells

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)

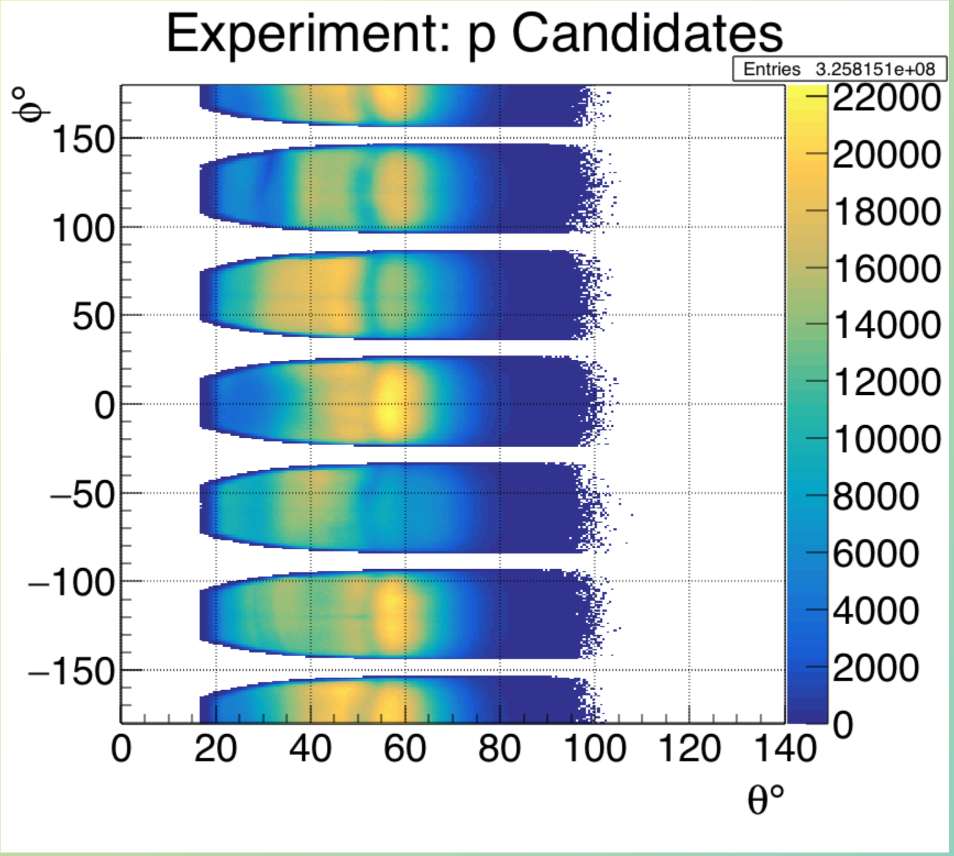


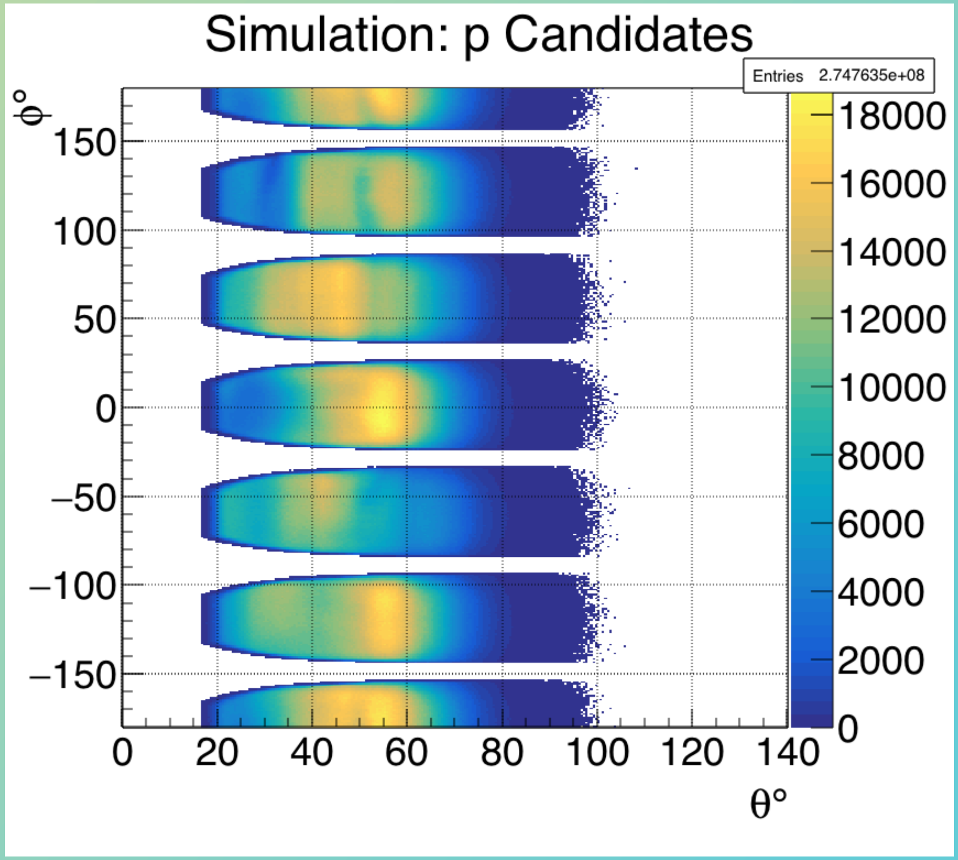


Thresholds set assuming MIP peak here (ADC – pedestal = 600)

Compare Experiment, MC: p

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

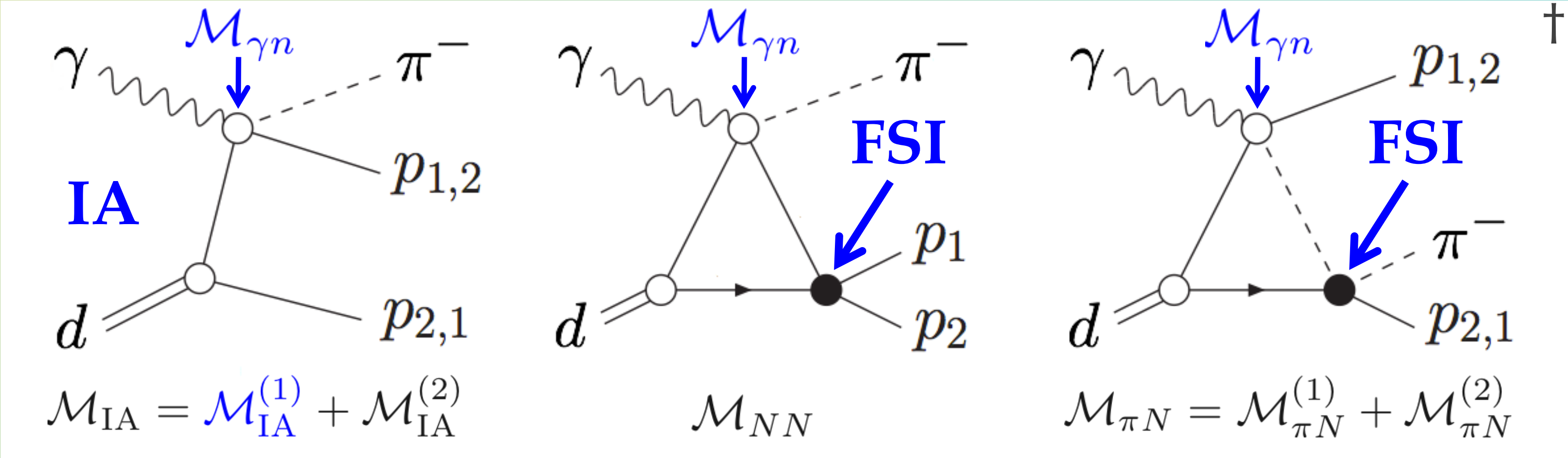




Primary sources of holes: Triggering & drift chamber inefficiencies

†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: $\mathcal{M}_{\gamma d} = \mathcal{M}_{\text{IA}} + \mathcal{M}_{NN} + \mathcal{M}_{\pi N}$
  - 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: $\mathcal{M}_{\gamma d}^{QF} = \mathcal{M}_{\text{IA}}^{(1)}$



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

†Modeling FSI in $\gamma d \rightarrow pp\pi^-$

- 1st approximation: FSI ≈ small & IA dominates: γn similar to QF
  - Relate $\gamma n \rightarrow p\pi^-$ to QF $\gamma d \rightarrow pp\pi^-$ 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

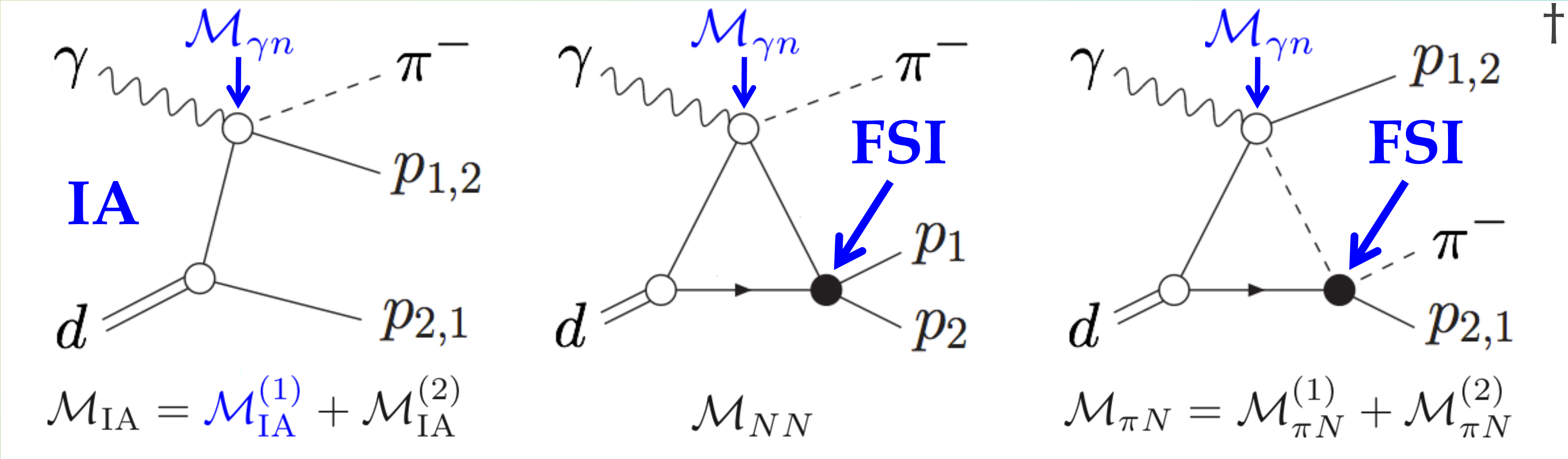
†V. E. Tarasov *et. al*, Phys. Rev. C **84**, 035203 (2011)

†Calculating R, $\gamma n \rightarrow p\pi^-$

- 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

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

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



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