Extracting (un)polarized cross sections for pion photoproduction off the neutron from deuteron data

arXiv:1804.04757

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Introduction

Meson productions induced by photon and electron beams

Interests

- Information on N^* properties (mass, width, missing resonances, etc.)

  complementary to πN scattering data ← "complete" measurements
- Electromagnetic $N \rightarrow N^*$ transition form factors (Q^2 −dependence)

  → important information for hadron structures

Measurements of neutron target data (incl. polarization obs.) are recently active

$\gamma n \rightarrow \pi^0 n$	$d\sigma/d\Omega$	A2@MAMI	PRL 112, 142001 (2014)
	E	A2@MAMI	PLB 770, 523 (2017)
$\gamma n \rightarrow \pi^- p$	$d\sigma/d\Omega$	CLAS@JLab	PRC 96, 035204 (2017)
	E	CLAS@JLab	PRL 118, 242002 (2017)
$\gamma n \rightarrow \eta n$	$d\sigma/d\Omega$	A2@MAMI	PRC 90, 015205 (2014)
	E	A2@MAMI	PRC 95, 055201 (2017)

More data are available, and more are coming soon

Why neutron target data ?

First motivation

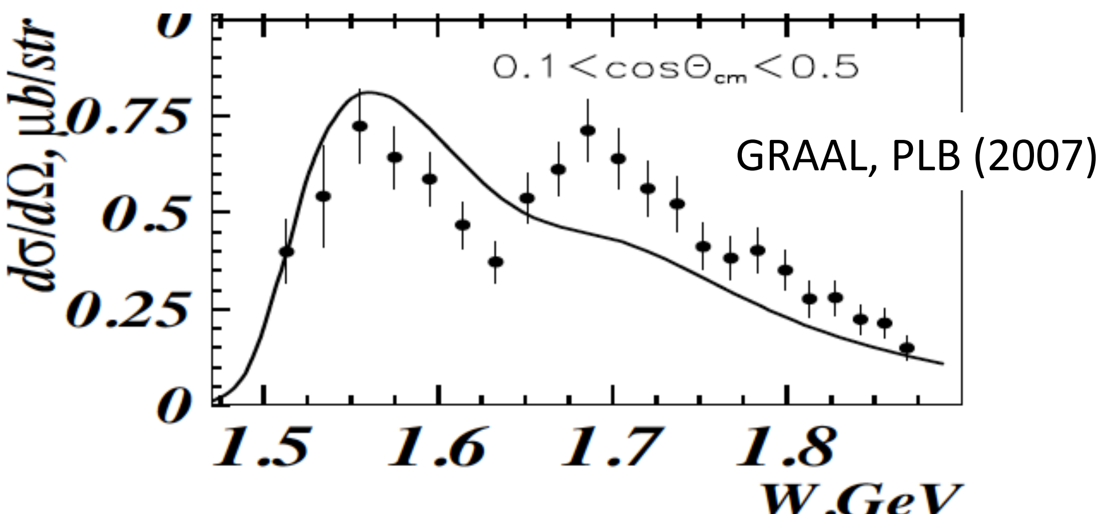
$\gamma^{(*)}\, p \rightarrow N^*$ AND $\gamma^{(*)}\, n \rightarrow N^*$ form factors $\Rightarrow$ Isospin structure of $\gamma^{(*)}\, N \rightarrow N^*$ form factors

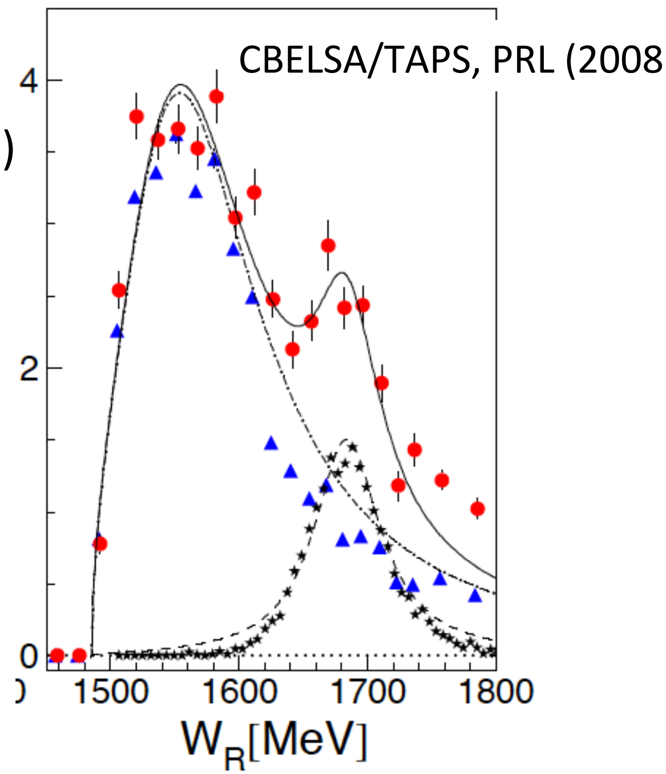
- Interesting quantities for understanding hadron structures
- Necessary for application to neutrino-induced reactions

  $\rightarrow$ needed for analyzing data from neutrino-oscillation experiments SXN et al. PRD (2015)

Unexpected surprises

Narrow bump at $W \sim 1.68$ GeV in $\gamma\, n \rightarrow \eta n$ (not in πN data)



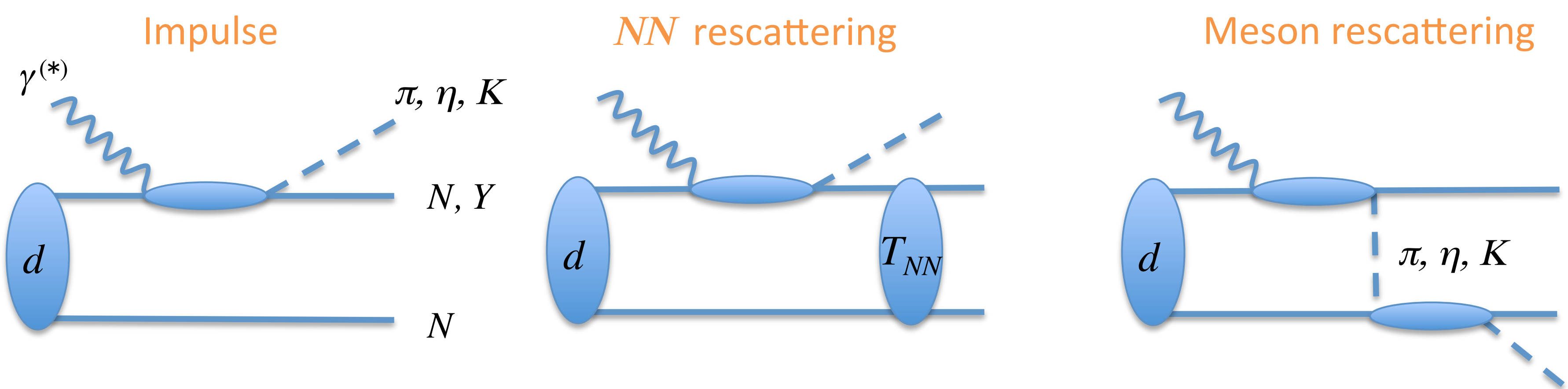


Photon and electron-induced meson productions off deuteron

To obtain $\gamma^{(*)}$ 'n' → πN, ηN, $K Y$ data, Deuteron is the primary target; we need to understand:

How to extract $\gamma^{(*)}$ 'n' → MB cross sections from $\gamma^{(*)} d$ → MBN data

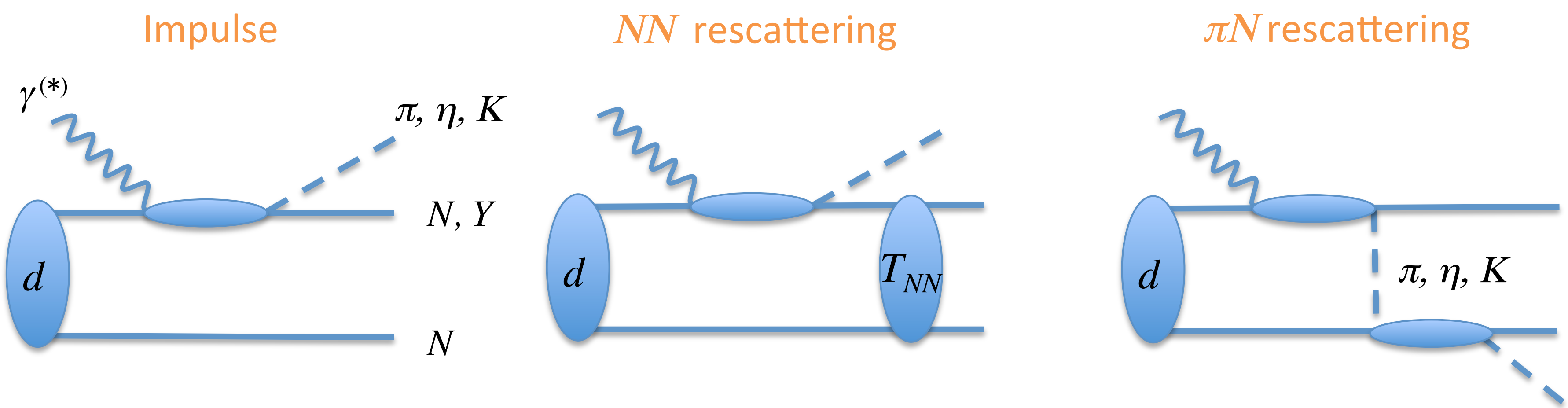
To address this question theoretically, we first need understand meson productions on deuteron



Features

- Photo- and electro-excitations of bound nucleons
- initial nucleons are in Fermi motion
- Final state interactions (FSI)

Photon and electron-induced meson productions off deuteron



Q : How to extract $\sigma(\gamma^{(*)}\,{}'n' \rightarrow MB)$ from $\sigma(\gamma^{(*)} d \rightarrow MBN)$?

- Common (and practical) procedure

Kinematical cuts ➔ quasi-free $\gamma^{(*)}\,{}'n' \rightarrow MB$ events selected

Concerns : FSI and/or cuts could distort $\sigma(\gamma^{(*)}\,{}'n' \rightarrow MB)$ from true one ?

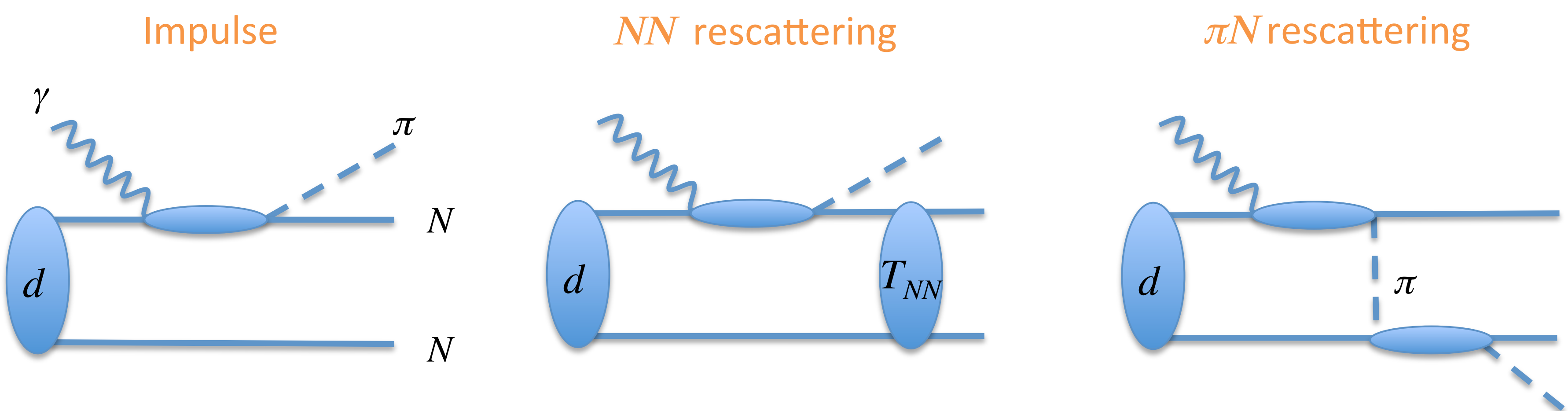
This work

- A dynamical model for $\gamma d \rightarrow \pi NN$ with FSI is developed
- $d\sigma/d\Omega_\pi$ and Σ, E, G for $\gamma d \rightarrow \pi NN$ are calculated; FSI effects examined
- $d\sigma/d\Omega_\pi$ and Σ, E, G for γ 'n' $\rightarrow \pi^0 n, \pi^- p$ are extracted from $\gamma d \rightarrow \pi NN$
- We address how FSI and cuts could distort γ 'n' observables

$\gamma d \rightarrow \pi NN$ reaction model based on dynamical coupled-channels model

Model for $\gamma d \rightarrow \pi N N$

Multiple scattering theory truncated at the first-order rescattering



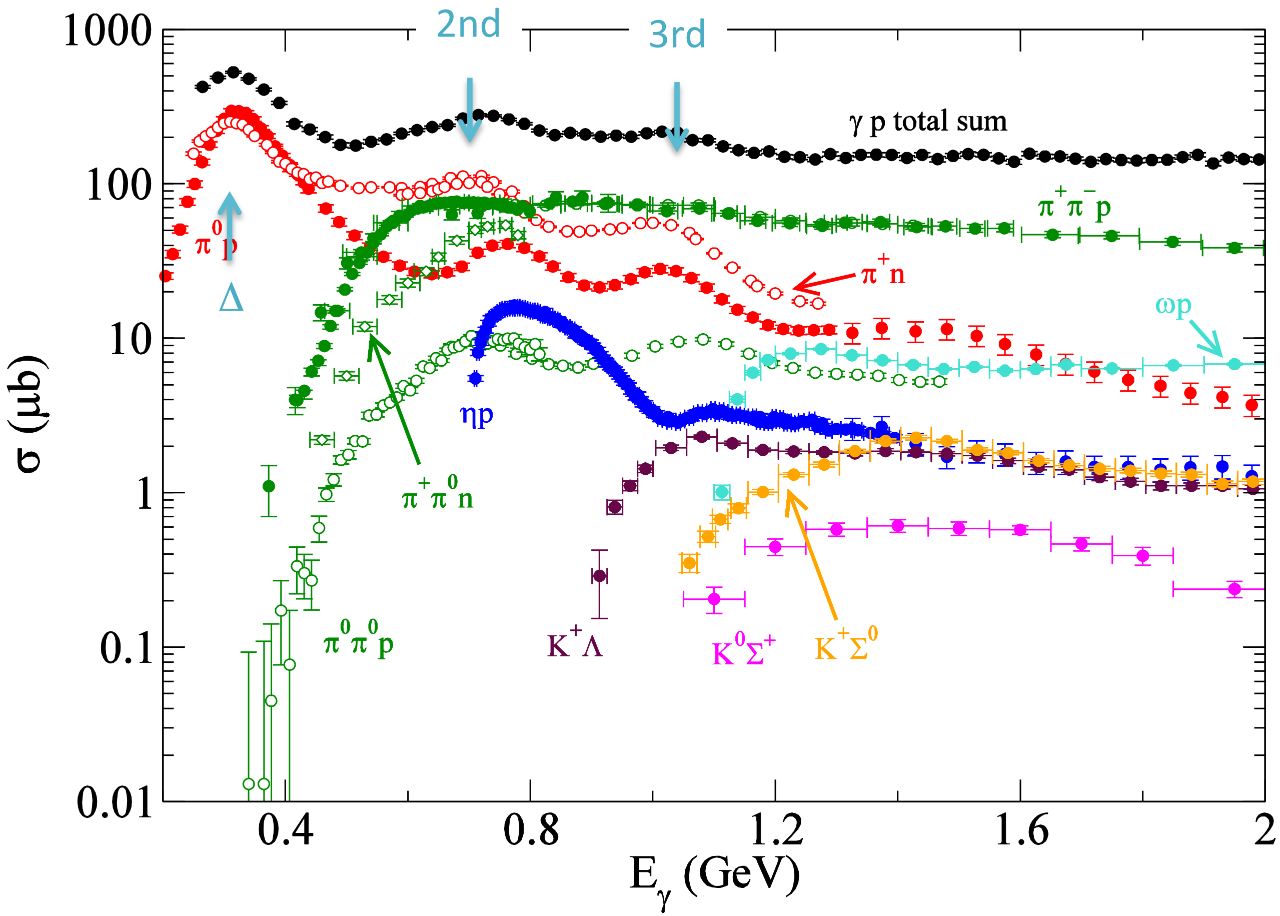
Elementary amplitudes

$\gamma N \rightarrow \pi N$, $\pi N \rightarrow \pi N$ amplitude ← DCC model (Kamano et al., PRC94 (2016))

T_{NN}, deuteron w.f. ← CD-Bonn potential (Machleidt et al., PRC 63 (2001))

3-dim. loop integral with off-shell amplitudes are numerically evaluated

Dynamical coupled-channels model for meson productions in resonance region



Data for $\gamma\, p$ ➔ X

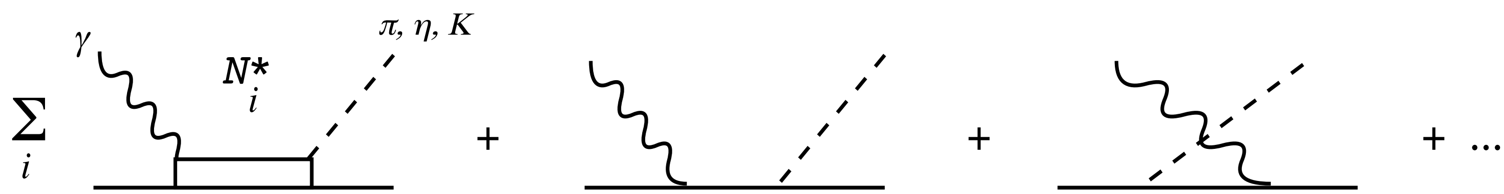
Need develop a model

to describe these reactions

- Several nucleon resonances form characteristic peaks
- 2π production is comparable to 1π
- η, K productions (multi-channel couplings are important physics)

Dynamical coupled-channels model for resonance region

Resonance excitation + non-resonant meson-exchange mechanisms



Theoretically sound model should also account for:

- Channel-couplings required by unitarity (πN, ηN, $K\Lambda$, $K\Sigma$ stable channels)
- 2 π production mechanisms (ρN, σN , $\pi\Delta$ ←→ $\pi\pi N$ channels)

Dynamical Coupled-Channels (DCC) model accounts for these features

developed through analyzing data for γN, πN ➔ πN, ηN, $K\Lambda$, $K\Sigma$

~ 26,000 data points

DCC (Dynamical Coupled-Channel) model

Matsuyama et al., Phys. Rep. **439**, 193 (2007)

Kamano et al., PRC 88, 035209 (2013)

Coupled-channel Lippmann-Schwinger equation for meson-baryon scattering

$$T_{ab} = V_{ab} + \sum_c V_{ac} G_c T_{cb}$$

$$\{a, b, c\} = \pi N,\ \eta N,\ \pi\pi N\ , \pi\Delta, \sigma N, \rho N\ ,\ K\Lambda,\ K\Sigma$$

Coupled-channels and hadron rescattering required by unitarity is fully taken into account

In addition, γN channel is included perturbatively

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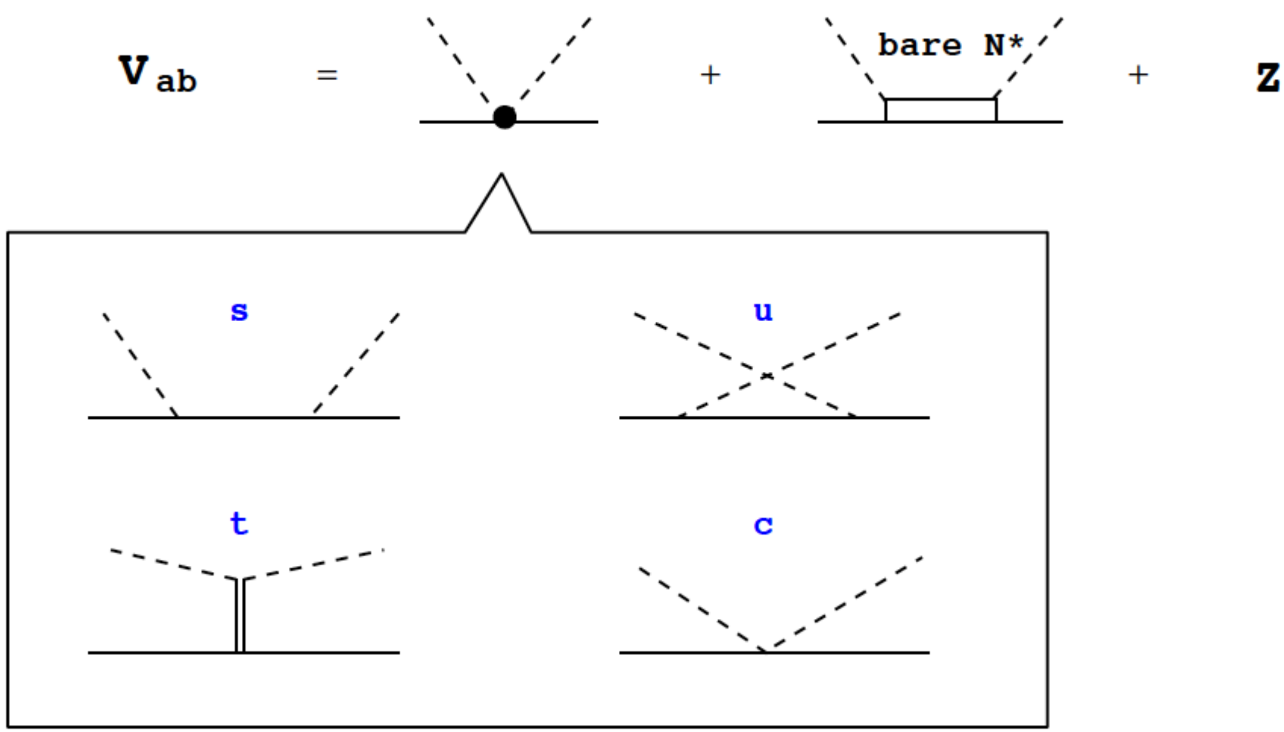

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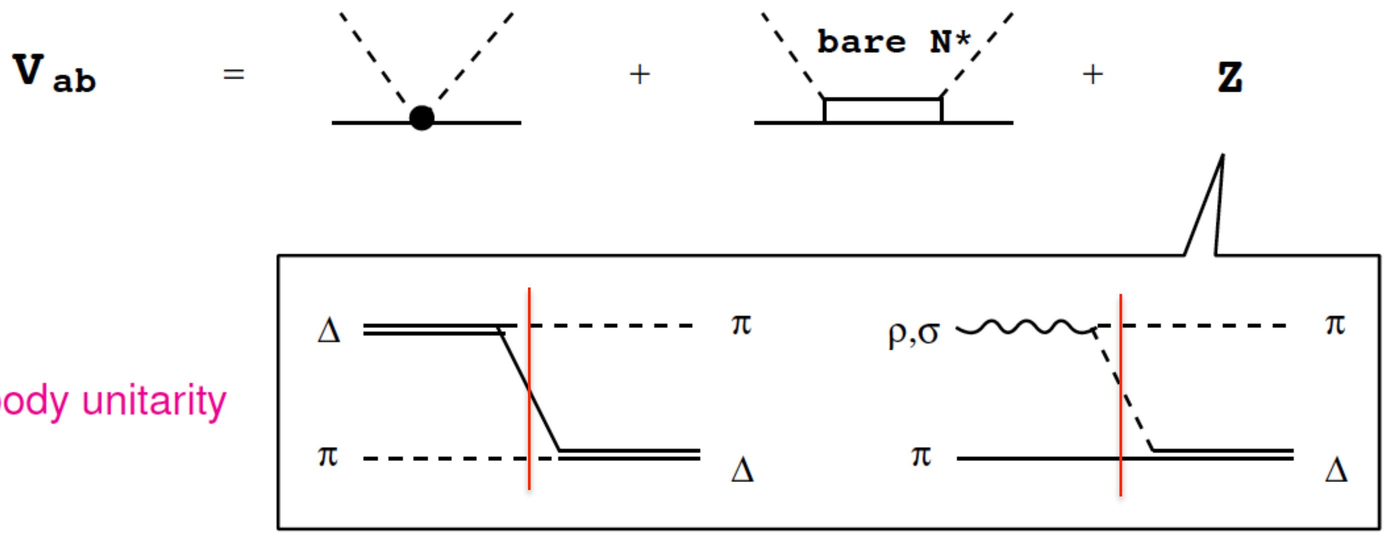

essential for three-body unitarity

DCC (Dynamical Coupled-Channel) model

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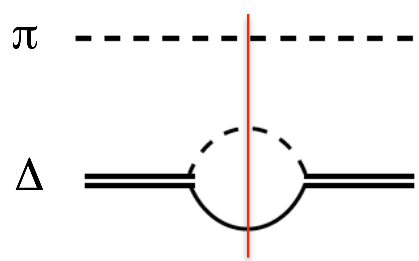
Coupled-channel Lippmann-Schwinger equation for meson-baryon scattering

$$T_{ab} \quad = \quad V_{ab} + \sum_{c} V_{ac}\, G_c\, T_{cb}$$

$G\,c \;=$

for stable channels



for unstable channels

DCC (Dynamical Coupled-Channel) model

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Coupled-channel Lippmann-Schwinger equation for meson-baryon scattering

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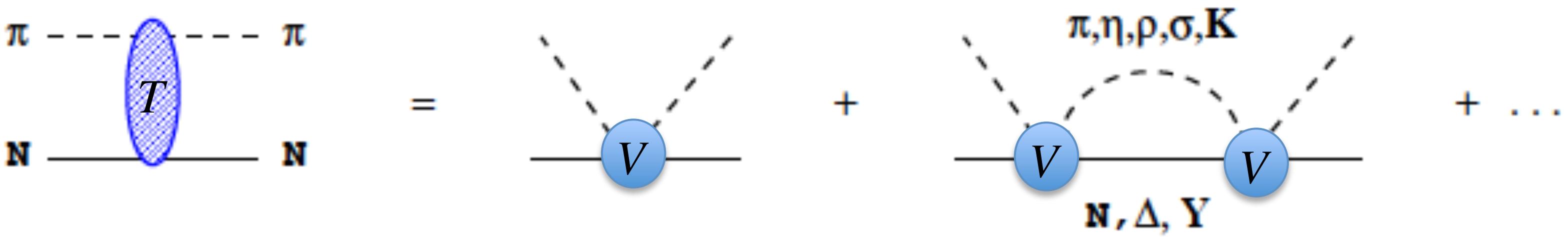
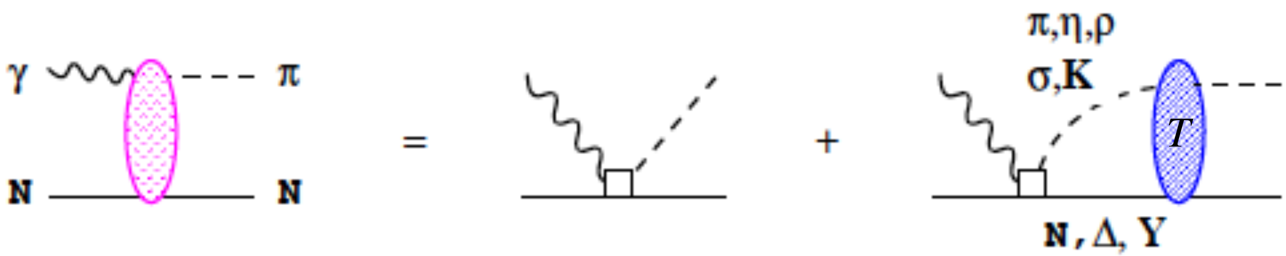


In addition, γN channel is included perturbatively

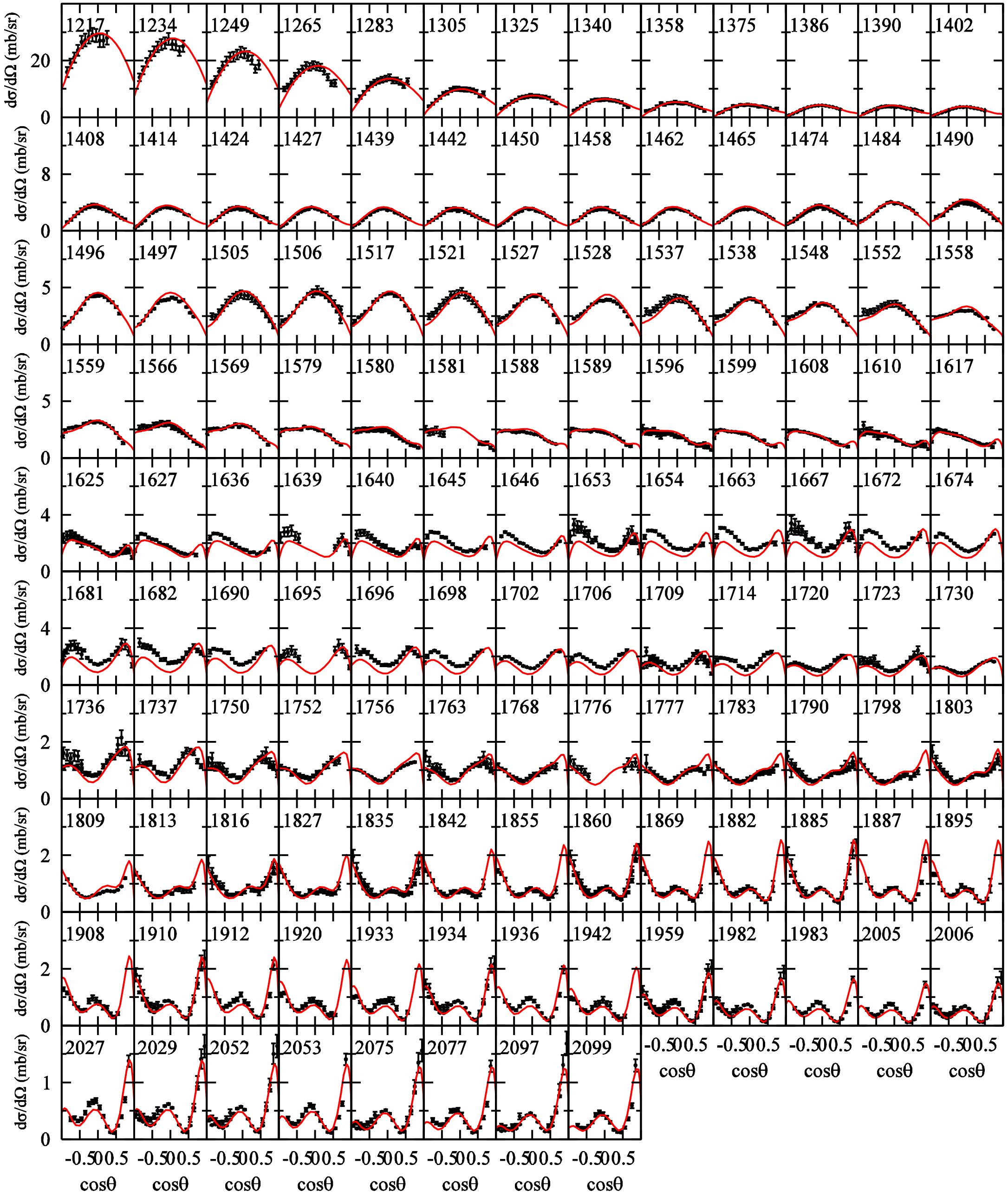


γp → π^0p

dσ/dΩ for W < 2.1 GeV

Comparison of DCC model with data

Kamano, Nakamura, Lee, Sato, PRC 88 (2013)



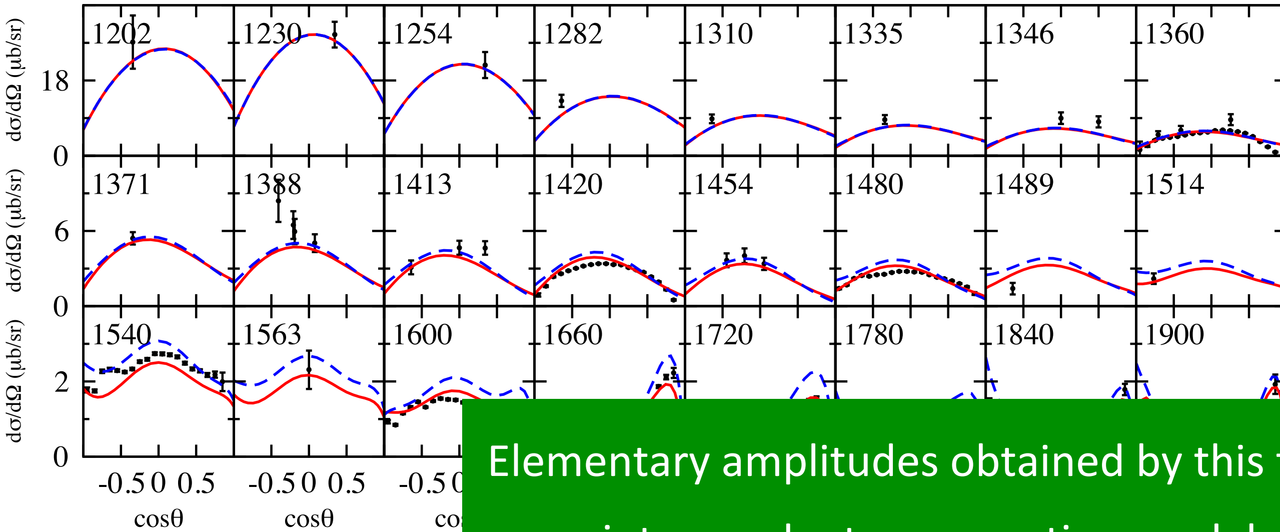
Reasonable fit to data

in the whole resonance region

γn → π^0n

dσ/dΩ for W < 2 GeV

SXN, Kamano, Lee, Sato, arXiv:1804.04757



: new fit

: previous fit

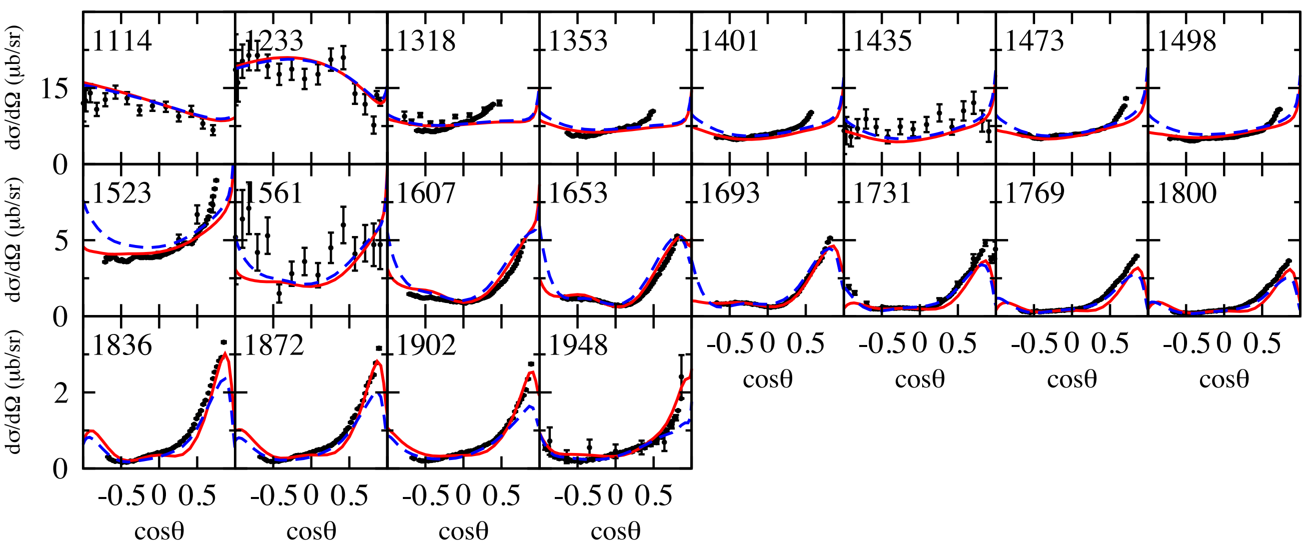
PRC 88 (2013)

Recent MAMI data included

PRL 112, 142001 (2014)

Elementary amplitudes obtained by this fit go into our deuteron reaction model

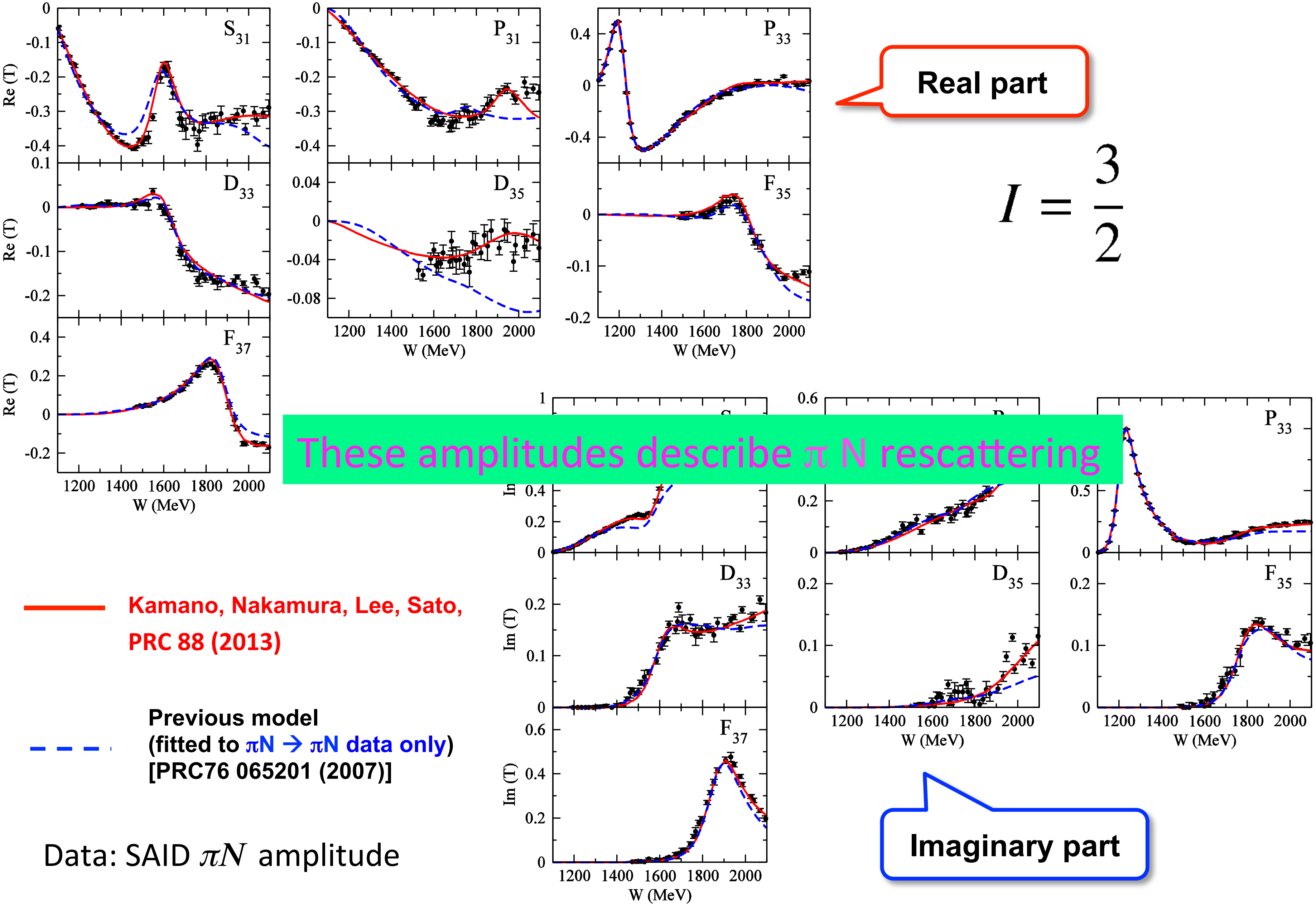
γn → π^-p



Recent JLab data included

PRC 96, 035204 (2017)

Partial wave amplitudes of π N scattering



$$I = \frac{3}{2}$$

Kamano, Nakamura, Lee, Sato, PRC 88 (2013)

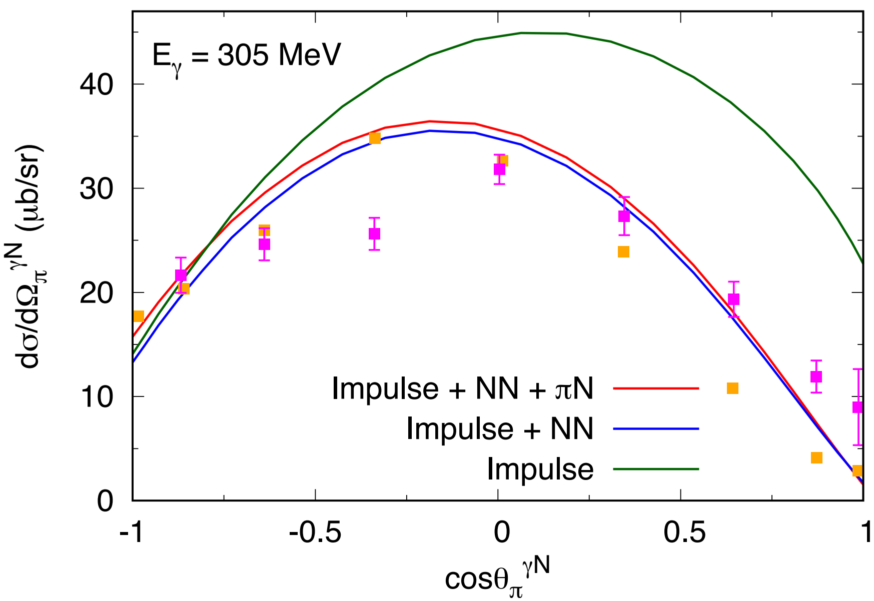
Previous model (fitted to $\pi N \rightarrow \pi N$ data only) [PRC76 065201 (2007)]

Data: SAID πN amplitude

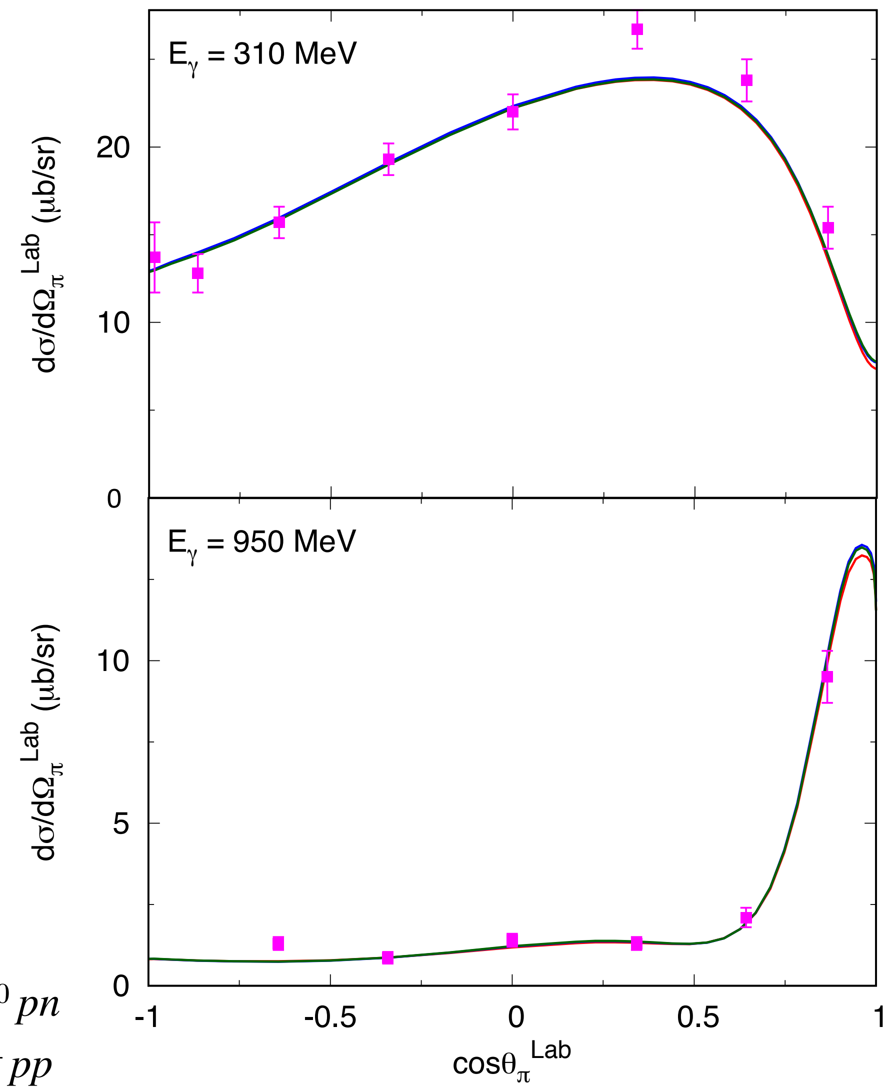
Results

$\gamma\, d \rightarrow \pi N N$: model predictions and data

$\gamma\, d \rightarrow \pi^0 pn$



$\gamma\, d \rightarrow \pi^- pp$



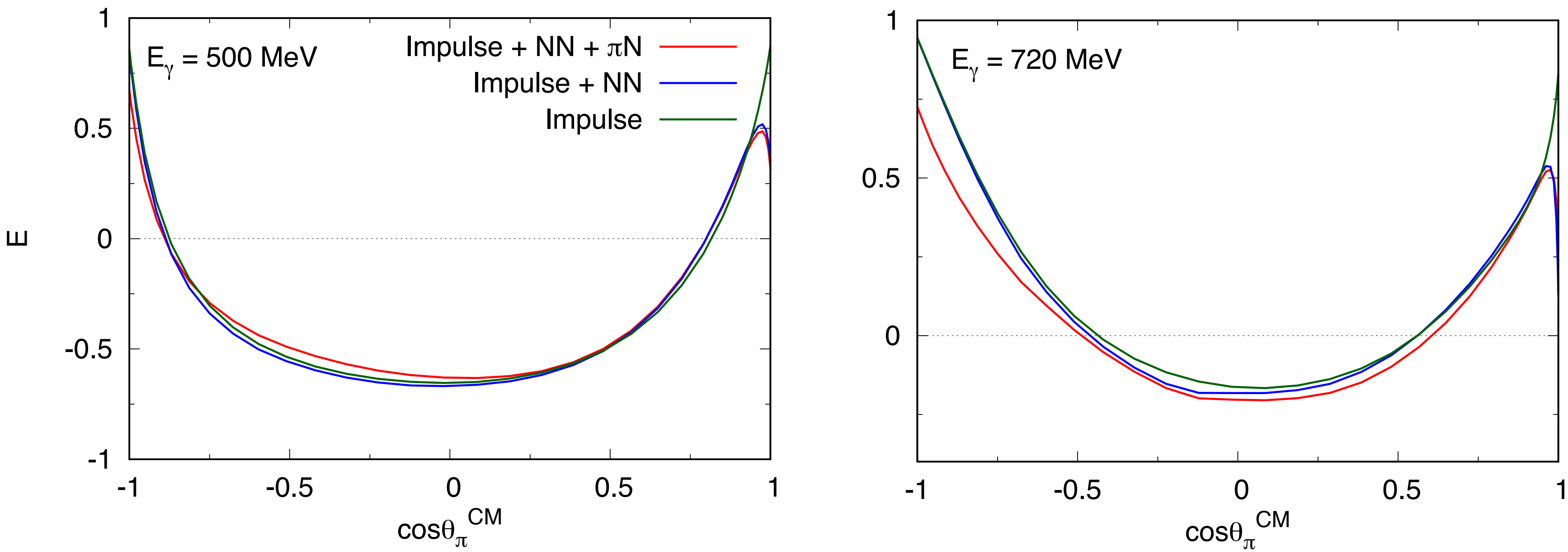
- Large NN FSI effect for π^0 productions
  ← NN and deuteron wave fn. are orthogonal
- FSI effects are small for π^- productions
- Reasonable agreement with data

Data: EPJA 6, 309 (1999); 10, 365 (2001) for $\gamma\, d \rightarrow \pi^0 pn$
NPB 65, 158 (1973) for $\gamma\, d \rightarrow \pi^- pp$

Model predictions for E of $\gamma\, d \rightarrow \pi N N$

Polarization observable E : $$E \equiv \frac{\sigma_{+-} - \sigma_{++}}{\sigma_{+-} + \sigma_{++}} \qquad \sigma_{+\pm} \equiv \sigma(s_\gamma^z = +1, s_d^z = \pm 1)$$

$\gamma\, d \rightarrow \pi^0 pn$



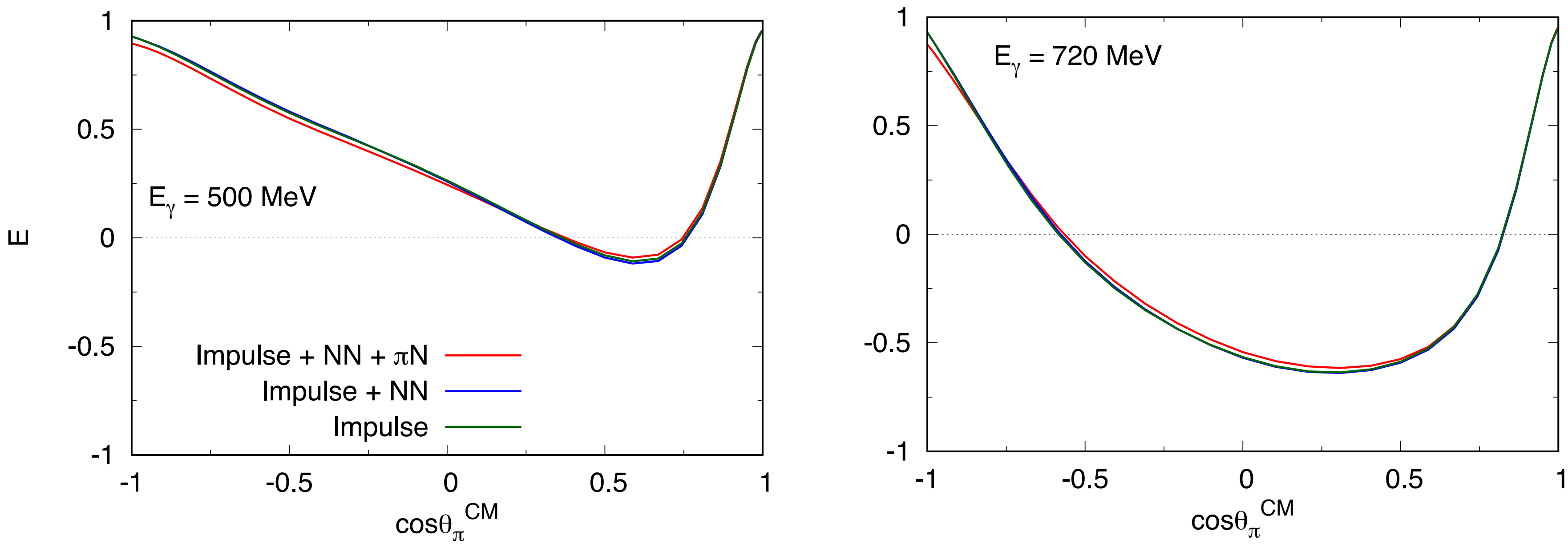
- FSI effects are smaller than $d\sigma/d\Omega_\pi$, but still visible

  → not completely cancelled out in the ratio

Model predictions for E of $\gamma\, d \rightarrow \pi\, N\, N$

Polarization observable E : $$E \equiv \frac{\sigma_{+-} - \sigma_{++}}{\sigma_{+-} + \sigma_{++}} \qquad \sigma_{+\pm} \equiv \sigma(s_\gamma^z = +1, s_d^z = \pm 1)$$

$\gamma\, d \rightarrow \pi^-\, pp$



- FSI effects are small as the same for $d\sigma/d\Omega_\pi$

Quasi-free γ 'n' cross sections

extracted from γd cross sections

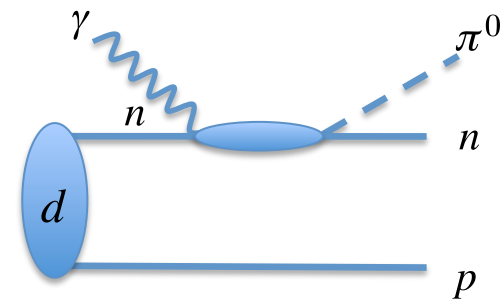
How to extract $\sigma(\gamma\,\text{'}n\text{'} \to \pi^0 n)$ from $\sigma(\gamma d \to \pi^0 np)$

First we need to establish a formula to relate $\sigma(\gamma\,\text{'}n\text{'} \to \pi^0 n)$ and $\sigma(\gamma d \to \pi^0 np)$

Ideal situation : only this mechanism contributes →

No FSI, No exchange terms, No deuteron D-wave

"quasi-free mechanism"



↓

$$\frac{d^2\sigma(\gamma d \to \pi^0 np; E_\gamma)}{dW\, d\cos\theta_\pi^*} = \phi(W)\,\frac{\tilde{E}_\gamma}{E_\gamma}\,\frac{d\sigma(\gamma n \to \pi^0 n; W)}{d\cos\theta_\pi^*}$$

E_γ ($\tilde{E}_\gamma$) : γ–d (γ–'n') Lab frame

W : $\pi^0 n$ invariant mass $\qquad \cos\theta_\pi^* \equiv \hat{q}_\gamma \cdot \hat{k}_\pi$ in π^0-n CM frame

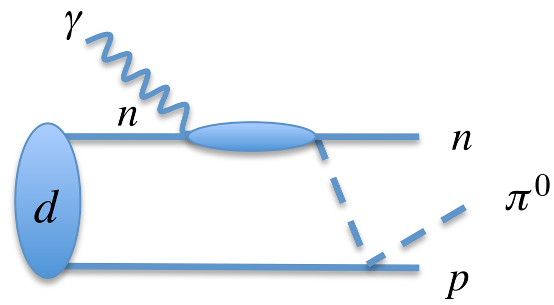
$$\phi(W) \equiv \int dp_p^3\; \delta(W - W(\vec{p}_p, E_\gamma))\, \left|\psi_d(\vec{p}_p)\right|^2, \qquad W(\vec{p}_p, E_\gamma) \equiv \sqrt{(E_\gamma + m_d - E_p(\vec{p}_p))^2 - (\vec{q}_\gamma - \vec{p}_p)^2}$$

$\phi(W)$: Probability of a photon of E_γ interacting with the nucleon with W

How to extract $\sigma(\gamma\,{'n'} \rightarrow \pi^0 n)$ from $\sigma(\gamma d \rightarrow \pi^0 np)$

In reality, photon hits the other nucleon and FSI contribute

→ kinematical cuts are applied to remove them



Counterpart from our model : $\left.\dfrac{d^2\sigma(\gamma d \to \pi^0 np)}{dW\, d\cos\theta^*_\pi}\right|_{\text{cuts}}$

Assuming that this is solely from quasi-free contribution integrated over the same phase-space

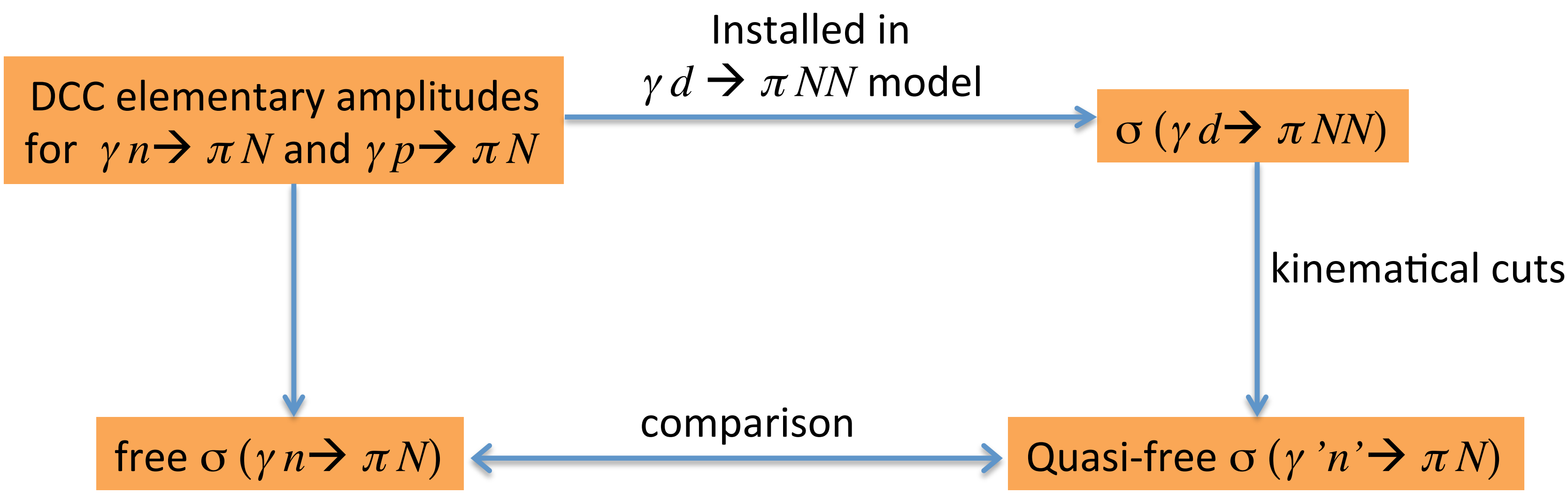
$$\left.\frac{d^2\sigma(\gamma d \to \pi^0 np)}{dW\, d\cos\theta^*_\pi}\right|_{\text{cuts}} = \phi_{\text{mod}}(W)\,\frac{\tilde{E}_\gamma}{E_\gamma}\,\frac{d\sigma(\gamma n \to \pi^0 n)}{d\cos\theta^*_\pi}\,, \qquad \phi_{\text{mod}}(W) \equiv \int^{\text{cuts}} dp^3_p\ \delta(W - W(\vec{p}_p, E_\gamma))\,\left|\psi_d(\vec{p}_p)\right|^2$$

↑

Formula to extract $\sigma(\gamma\,{'n'} \rightarrow \pi^0 n)$ from $\sigma(\gamma d \rightarrow \pi^0 np)$ from either experiment or model

Examine within our model how much $\sigma(\gamma\,{'n'} \rightarrow \pi^0 n)$ deviates from 'free' $\sigma(\gamma n \rightarrow \pi^0 n)$ due to FSI

Q: How FSI and kinematical cuts could distort γ *'n'* observables ($d\sigma/d\Omega, \Sigma, E, G$) ?



Kinematical cuts

For extracting γ 'n' → $\pi^- p$ from γd → $\pi^- pp$, we use :

[1] CLAS@JLab, PRC 86 (2012)
[2] CLAS@JLab, PRC 96 (2017)
[3] CLAS@JLab, PRL 118 (2017)

Ref.	[1] ($d\sigma/d\Omega$)	[2] ($d\sigma/d\Omega$)	[3] (E)
E_γ (MeV)	301 – 455	445 – 2510	700 - 2400
π^- momentum (MeV)	> 80	> 100	> 400
Faster proton momentum (MeV)	> 270	> 360	> 400
Slower proton momentum (MeV)	< 270	< 200	< 100
$\Delta\phi_\pi = \lvert \phi_\pi - \phi_{\text{faster proton}} \rvert$	–	–	$160^o < \Delta\phi < 200^o$

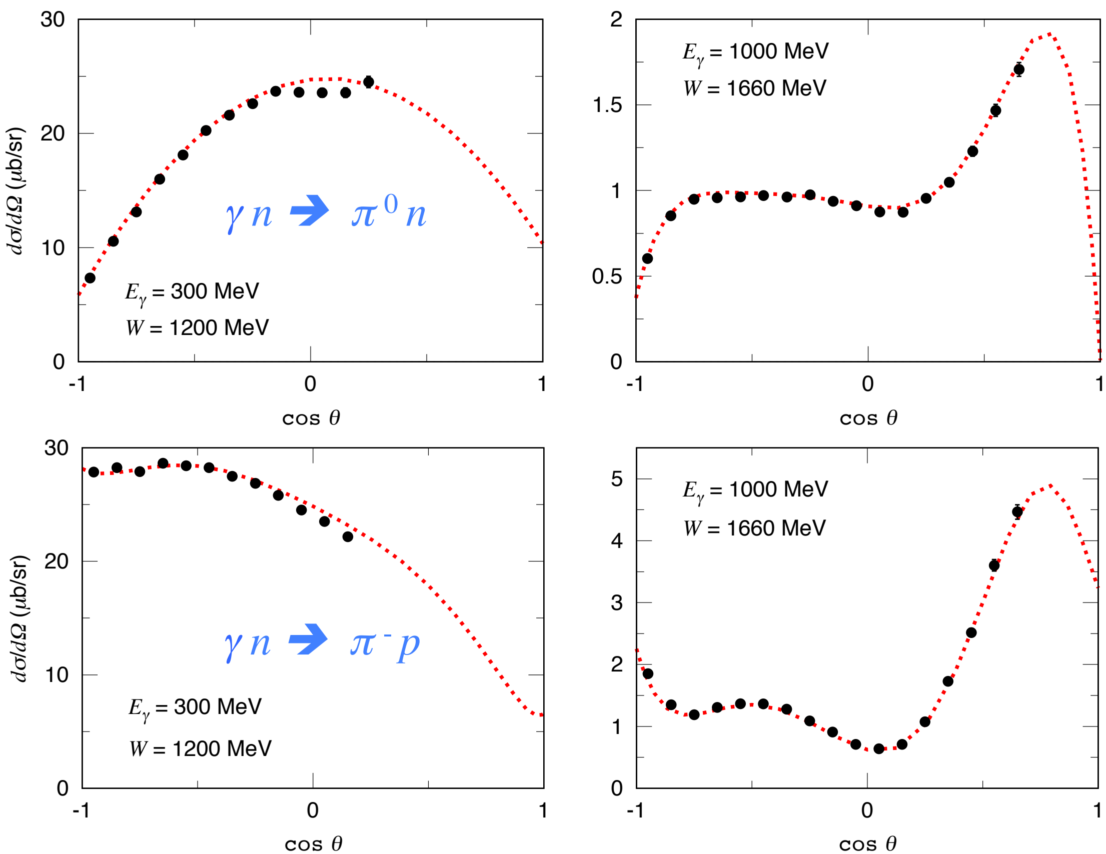
For extracting γ 'n' → $\pi^0 n$ from γd → $\pi^0 pn$, the same cuts are used after modification

"π^-" → "π^0", "Faster proton" → "neutron", "Slower proton" → "proton"

NOTE: Different kinematical cuts were used in A2@MAMI analysis on $\gamma\, n \rightarrow \pi^0 n$

Check the extraction method in ideal case

Q: With quasi-free mechanism only, examine if the formula $\left.\frac{d^2\sigma(\gamma d \to \pi^0 np)}{dW\, d\cos\theta^*_\pi}\right|_{\rm cuts} = \phi_{\rm mod}(W)\, \frac{\tilde{E}_\gamma}{E_\gamma}\, \frac{d\sigma(\gamma n \to \pi^0 n)}{d\cos\theta^*_\pi}$ returns σ(γ 'n' → πN) that agree with 'free' σ($\gamma\, n$ → πN)



● : extracted σ(γ 'n' → πN)

······· : free σ($\gamma\, n$ → πN)

Note:

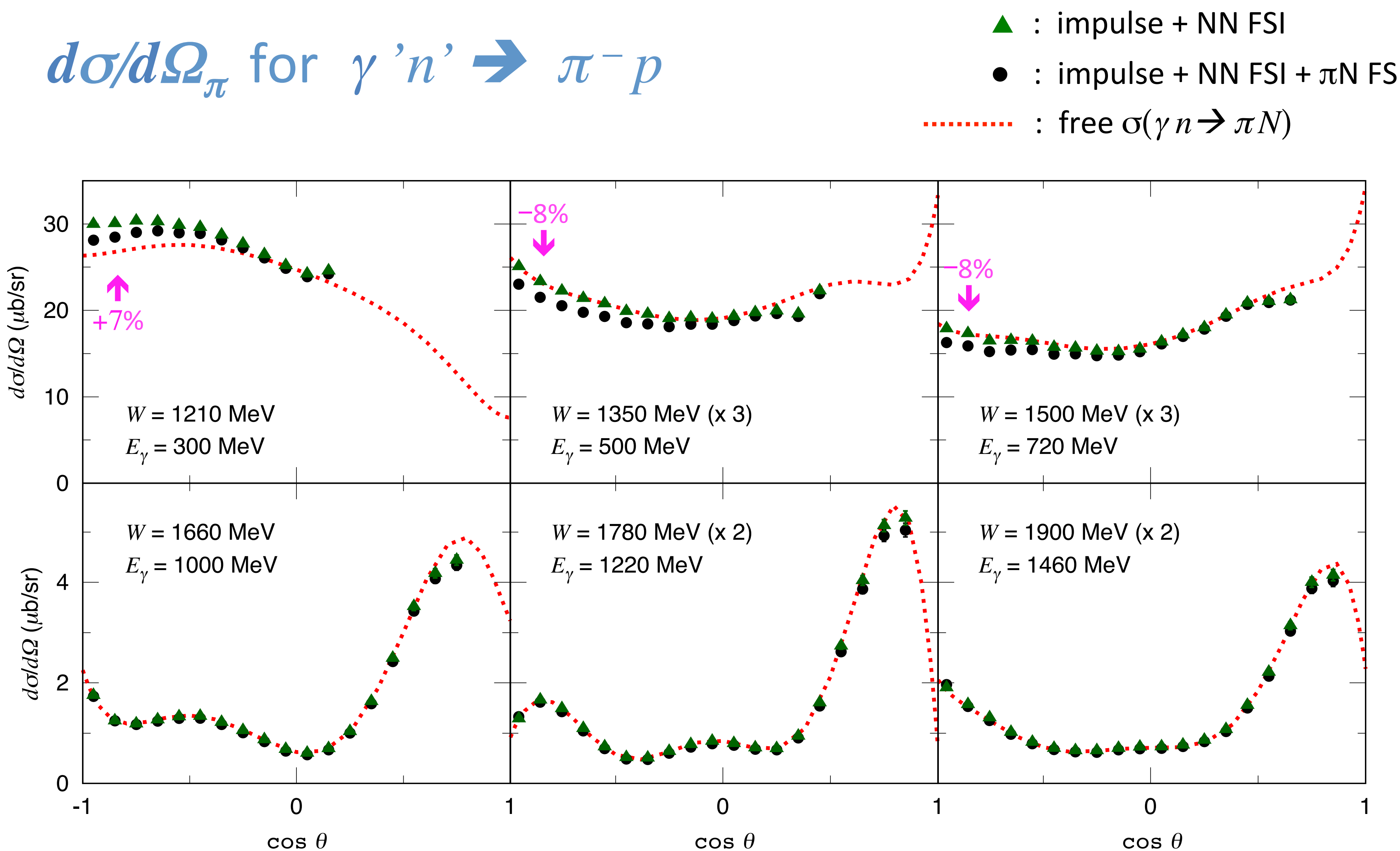
* Phase-space integrals for σ($\gamma\, d$) are done with Monte-Carlo method to easily implement any cuts; statistical error bars are very small

* Forward pion productions are invisible due to the kinematical cuts

Free σ($\gamma\, n$ → πN) are well reproduced as expected for the ideal case

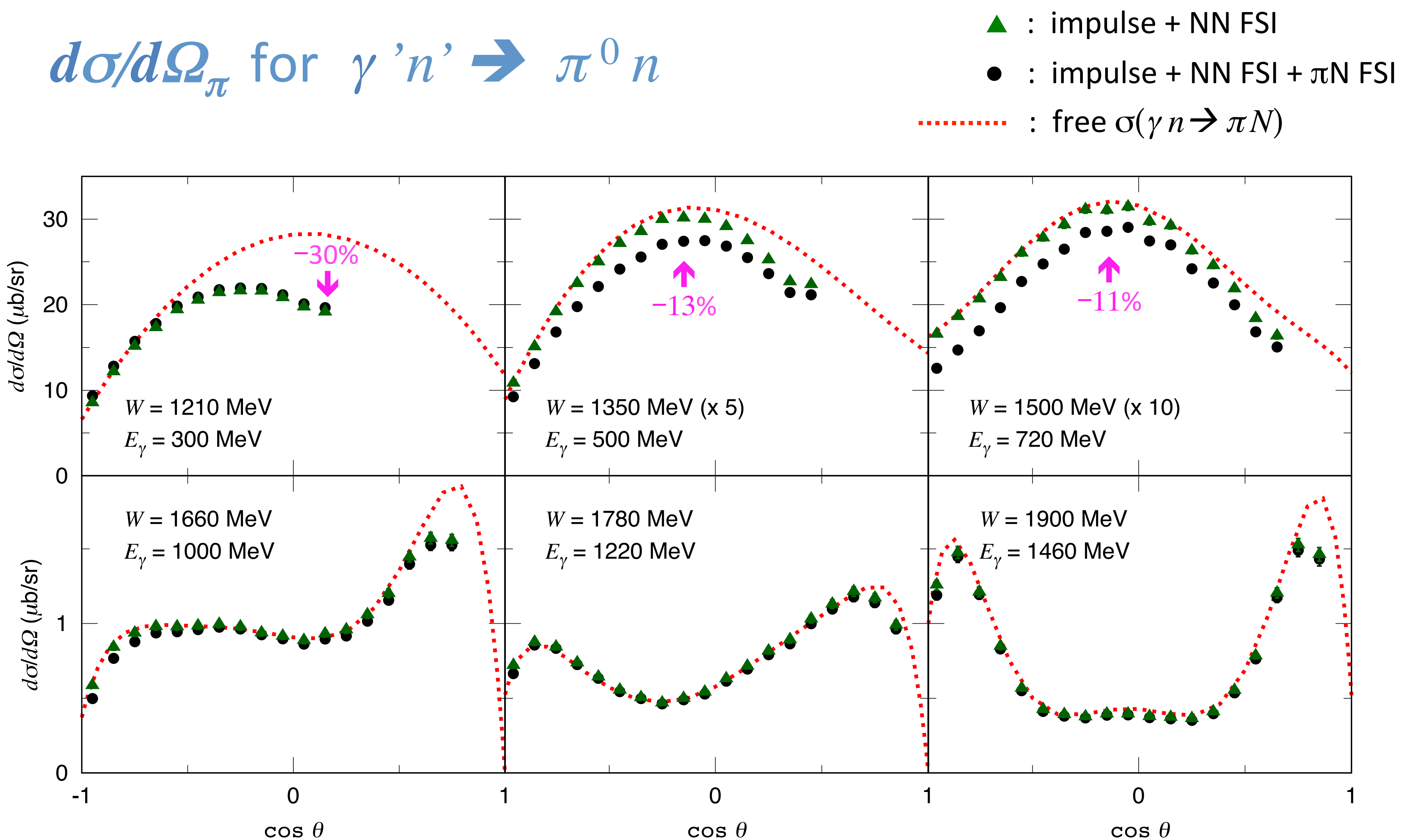
Now go on to realistic case !

$d\sigma/d\Omega_\pi$ for γ 'n' ➔ $\pi^- p$



- πN FSI reduce $d\sigma/d\Omega_\pi$ of backward pion
- kinematical cuts cannot remove the FSI effect
- Larger FSI effects for smaller E_γ

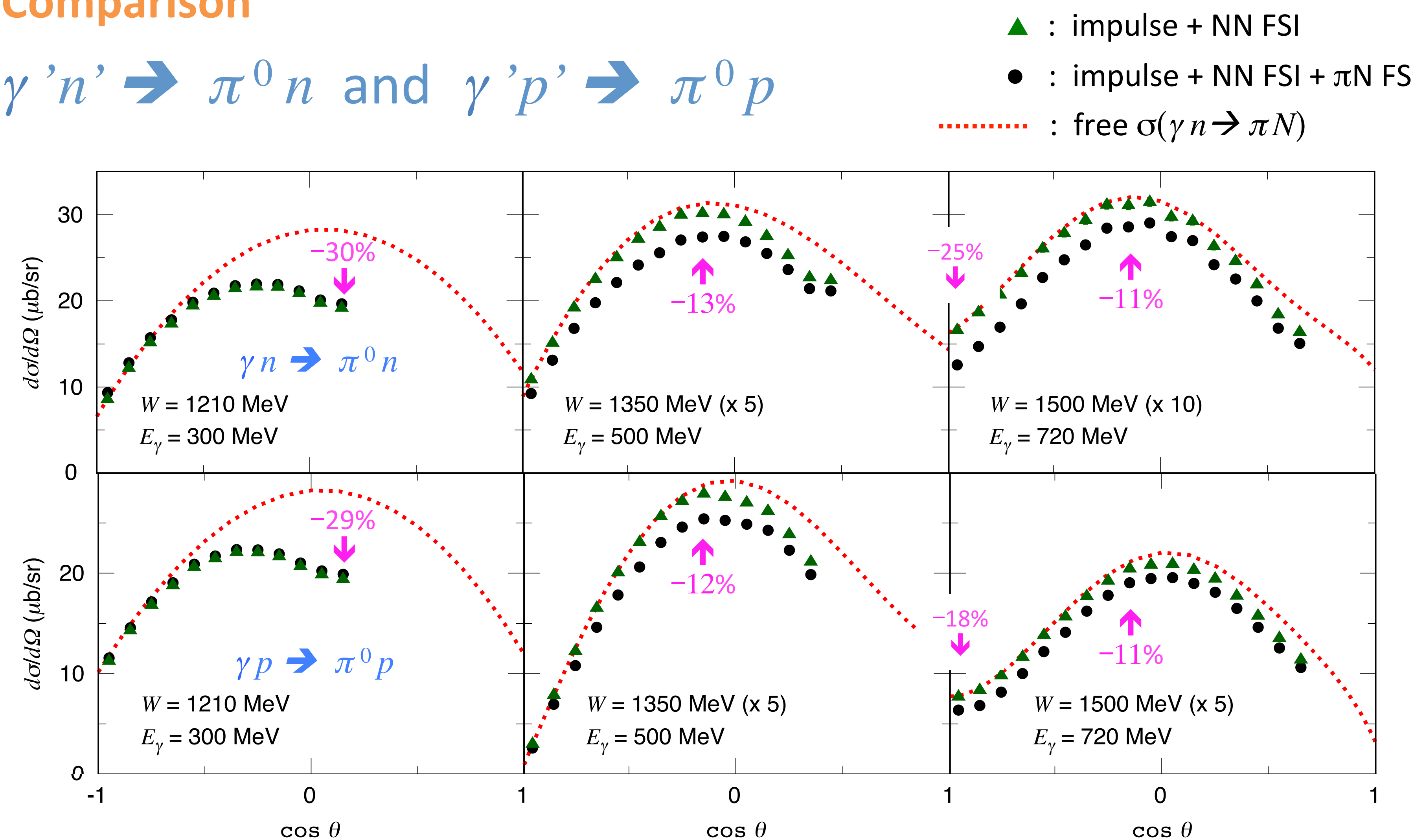
$d\sigma/d\Omega_\pi$ for γ 'n' → $\pi^0 n$



- Significant FSI effects reduce $d\sigma/d\Omega_\pi$; πN and NN FSI are comparably important
- kinematical cuts cannot remove FSI effect
- Larger FSI effects for smaller E_γ

Comparison

γ 'n' ➔ $\pi^0 n$ and γ 'p' ➔ $\pi^0 p$



- FSI effects on γ 'n' ➔ $\pi^0 n$ and γ 'p' ➔ $\pi^0 p$ are generally similar (a few % difference)

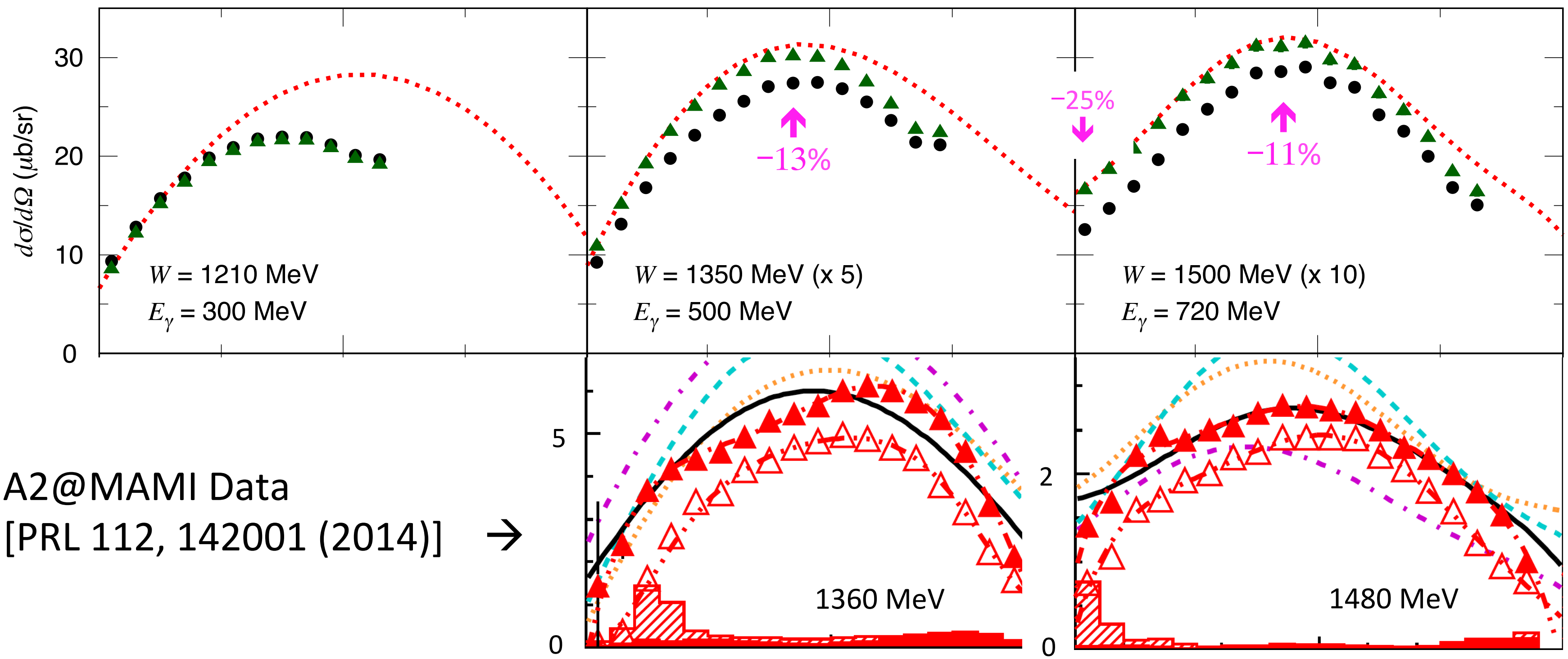
  ⇔ Same FSI effects are assumed in A2@MAMI analysis [PRL 112 (2014)]

- But sometimes more different

Comparison with Data : FSI effect

γ 'n' → $\pi^0 n$

▲ : impulse + NN FSI
● : impulse + NN FSI + πN FSI
······ : free σ(γ n → π N)



A2@MAMI Data
[PRL 112, 142001 (2014)] →

- Fairly good agreement on the FSI effects estimated in A2@MAMI analysis
- A2@MAMI analysis assumed $\frac{\sigma(\gamma' n' \to \pi^0 n)}{\text{free } \sigma(\gamma n \to \pi^0 n)} = \frac{\sigma(\gamma' p' \to \pi^0 p)}{\text{free } \sigma(\gamma p \to \pi^0 p)}$ no theoretical estimate
- FSI effects can depend on the cuts; MAMI analysis uses different cuts

Extraction of polarization observables for γ 'n' → $\pi^0 n$ from γd → $\pi^0 np$

A possible complication : relativistic nucleon spin rotation

← Lorentz boost from γn CM frame to γd Lab frame

We confirmed this effect is very small for Σ, E, G to be discussed here → ignored

Polarized cross sections can be extracted using formula similar to the unpolarized one

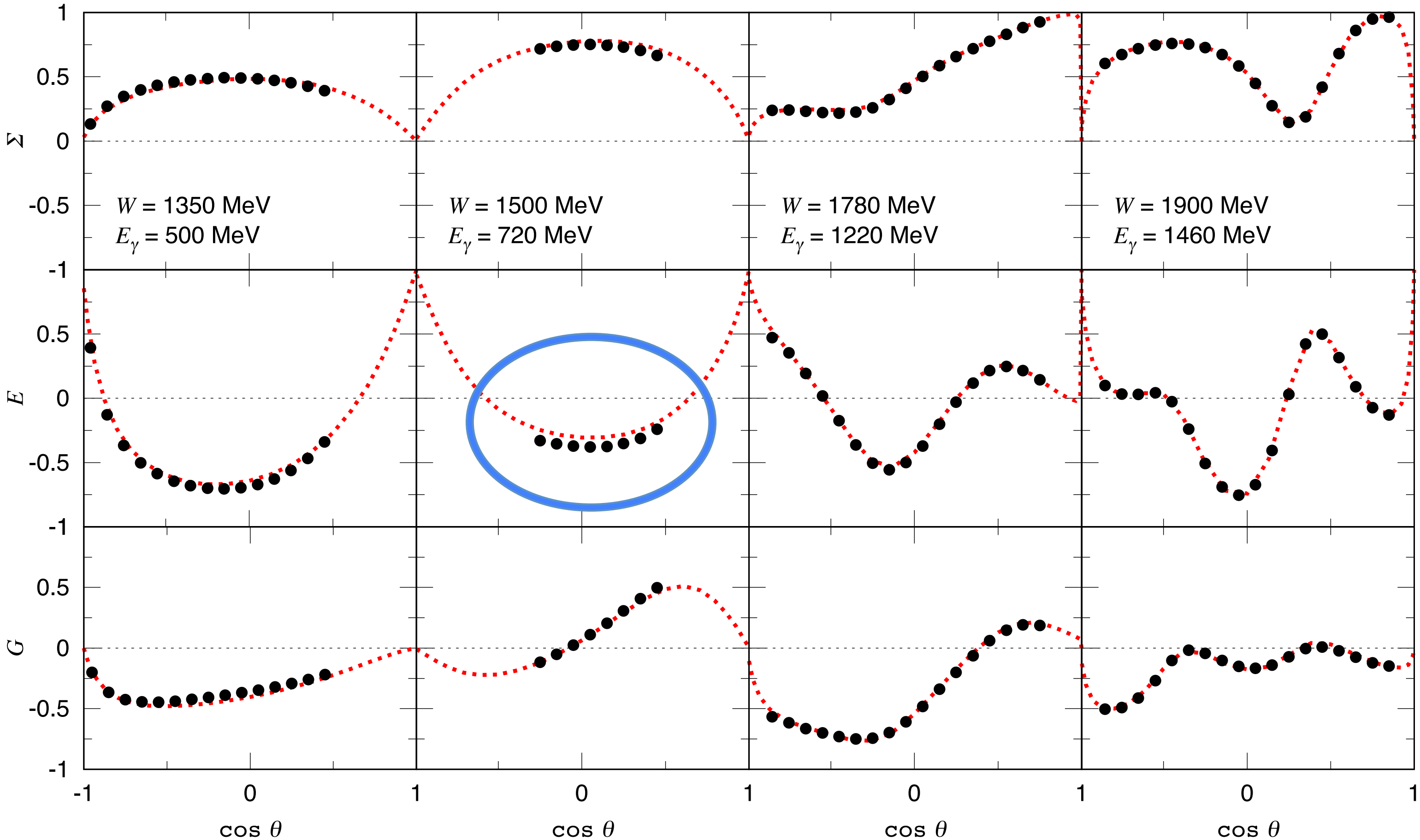
$$\left.\frac{d^2\sigma(\gamma d \to \pi^0 np;\ \lambda, s_d = +1)}{dW\, d\cos\theta^*_\pi}\right|_{\text{cuts}} = \phi_{\text{mod}}(W)\, \frac{\tilde{E}_\gamma}{E_\gamma}\, \frac{d\sigma(\gamma n \to \pi^0 n; \lambda, s_N = +1/2)}{d\cos\theta^*_\pi}$$

$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{d\sigma(\lambda = -1, s_N = +1/2) - d\sigma(\lambda = +1, s_N = +1/2)}{d\sigma(\lambda = -1, s_N = +1/2) + d\sigma(\lambda = +1, s_N = +1/2)}$$

Σ, E, G for γ 'n' ➔ $\pi^0 n$

● : impulse + NN FSI + πN FSI

⋯⋯ : free $\sigma(\gamma n \to \pi N)$



- Free $\gamma n \to \pi N$ polarization asymmetries are well reproduced
- FSI effects are very small ; canceled by taking the ratios; One exception
- No FSI effects are assumed in A2@MAMI analysis for E [PLB 770 (2017)]

(More) common extraction method

Extraction formula used so far in this presentation

$$\left.\frac{d^2\sigma(\gamma d \to \pi^0 np; E_\gamma)}{dW\, d\cos\theta^*_\pi}\right|_{\text{cuts}} = \phi_{\text{mod}}(W)\, \frac{\tilde{E}_\gamma}{E_\gamma}\, \frac{d\sigma(\gamma n \to \pi^0 n; W)}{d\cos\theta^*_\pi}\,, \quad \phi_{\text{mod}}(W) \equiv \int^{\text{cuts}} dp^3_p\; \delta(W - W(\vec{p}_p, E_\gamma))\, \left|\psi_d(\vec{p}_p)\right|^2$$

Integrate both sides with respect to W, assuming dominant contribution from nucleon-at-rest in deuteron

(and/or fairly weak W-dependence)

(More) commonly used extraction formula

$$\left.\frac{d^2\sigma(\gamma d \to \pi^0 np; E_\gamma)}{d\cos\theta^*_\pi}\right|_{\text{cuts}} = \frac{d\sigma(\gamma n \to \pi^0 n; \bar{W})}{d\cos\theta^*_\pi} \int^{\text{cuts}} dp^3_p\, \frac{\tilde{E}_\gamma}{E_\gamma}\, \left|\psi_d(\vec{p}_p)\right|^2\,, \qquad \bar{W}^2 = (E_\gamma + m_N)^2 - E_\gamma^2$$

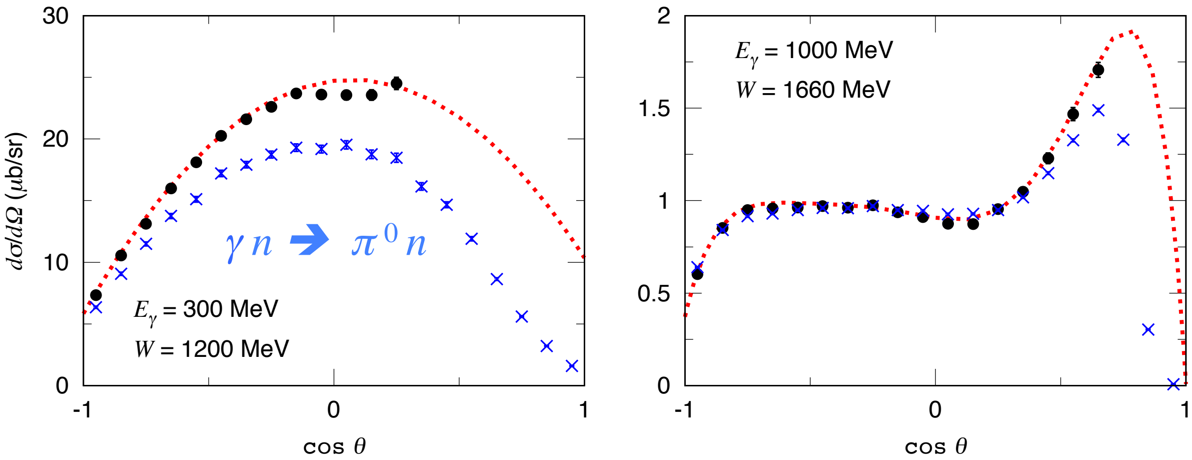
Used in recent CLAS@JLab analyses: PRC 96 (2017) for $d\sigma/d\Omega_\pi$

PRL 118 (2017) for E

also in theoretical analysis Tarasov et al., PRC 84, 035203 (2011)

Examine the validity of this formula without W-cut

(More) common extraction method



Quasi-free mechanism only;

no FSI, no exchange terms

● : extracted with W-cut

x : without W-cut

······ : free $\sigma(\gamma n \rightarrow \pi N)$

- E_γ=300 MeV : Significant difference in $\Delta(1232)$-region

  1. Sharp peak of $\sigma_{\gamma n}$ at W~1.2 GeV
  2. $\sigma_{\gamma d}$ is an average of $\sigma_{\gamma n}$ over W~1.18−1.21 GeV (W<1.2 GeV in $\cos\theta > 0.3$) because of Fermi motion

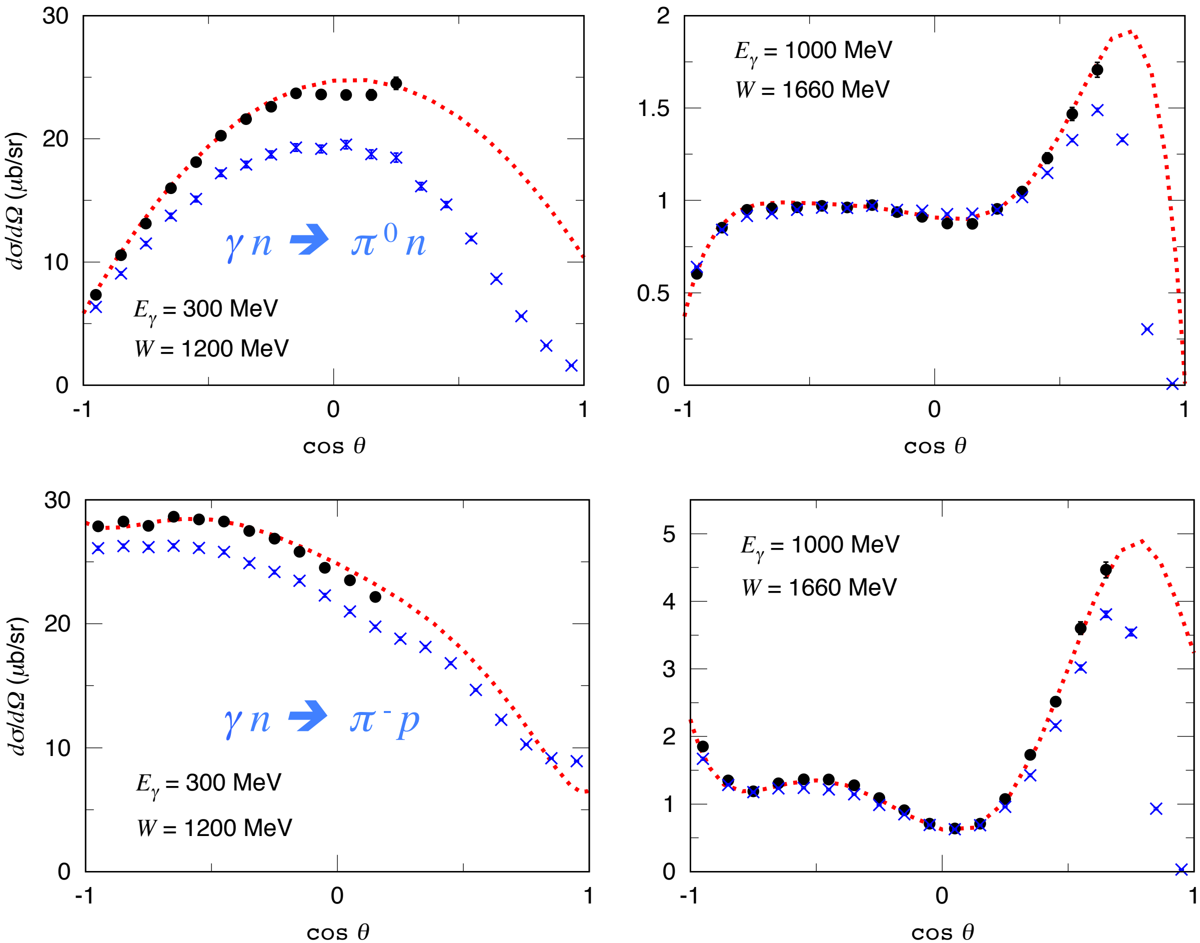
  → extracted $\sigma_{\gamma n}$ without W-cut is necessarily smaller than $\sigma_{\gamma n}$ at W=1.2 GeV

- E_γ=1GeV : Good agreement between with and without W-cut in $\cos\theta < 0.3$

  1. Mild and monotonic W-dependence of $\sigma_{\gamma n}$ for W~1.6−1.7 GeV

  → W-dependence is canceled in $\sigma_{\gamma d}$ by W-average; cancel is incomplete in $\cos\theta > 0.3$

(More) common extraction method



Quasi-free mechanism only;

no FSI, no exchange terms

● : extracted with W-cut

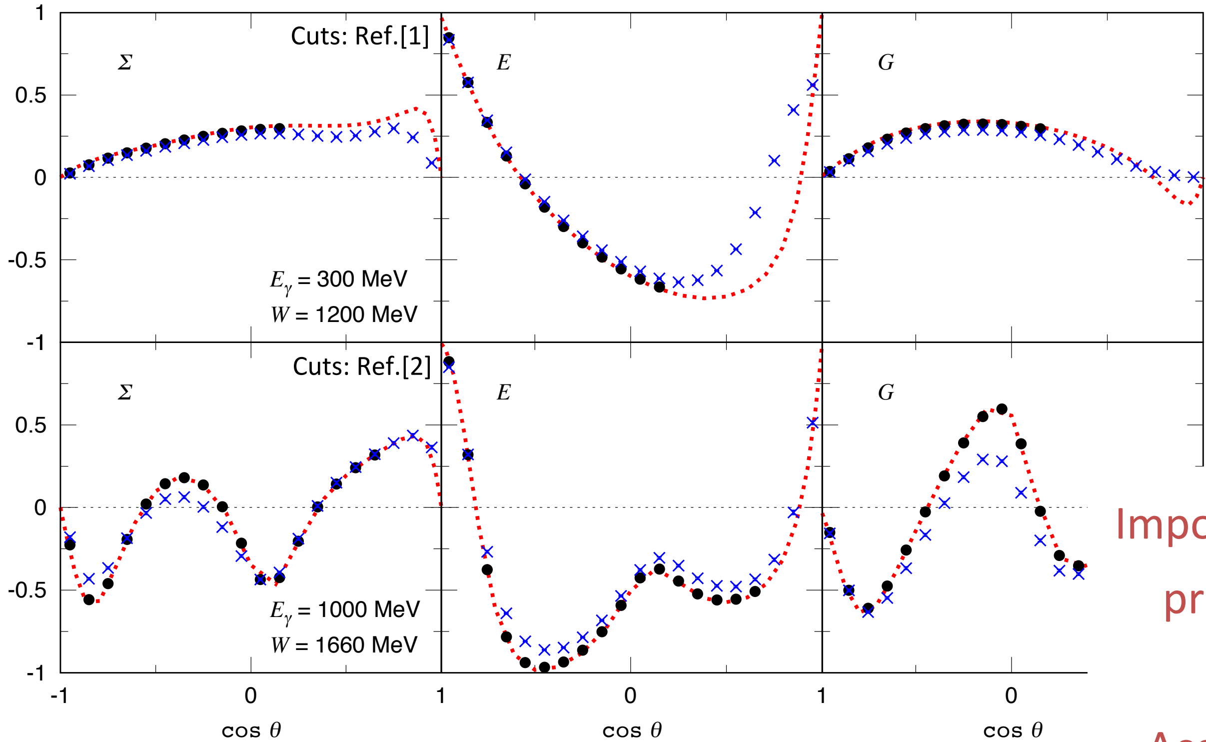
x : without W-cut

: free $\sigma(\gamma\, n \rightarrow \pi N)$

Similar result for $\gamma\, n \rightarrow \pi^- p$

(More) common extraction method

Polarization observables for $\gamma n \rightarrow \pi^- p$



Quasi-free mechanism only;

no FSI, no exchange terms

● : extracted with W-cut

x : without W-cut

: free $\sigma(\gamma n \rightarrow \pi N)$

Important to apply W-cut to suppress problematic Fermi motion effect

↓

Accuracy of extracted observables

Reasons for deviations from free ones

- E at E_γ=300MeV, $\cos\theta > 0.3$: nucleon-at-rest kinematics is not allowed by cuts; contributions are from different W
- G at E_γ=1GeV : Average non-monotonic W-dependence → W-dependence not cancelled

Conclusion

Conclusions

- $d\sigma/d\Omega_\pi$ and Σ, E, G for γ *'n'* ➔ $\pi^0 n$, $\pi^- p$ are extracted from γd ➔ πNN using kinematical cuts of CLAS@JLab analyses
- $d\sigma/d\Omega_\pi$ for γ *'n'* ➔ $\pi^0 n$ are significantly distorted by FSI effects;
  FSI effects on γ *'n'* ➔ $\pi^0 n$ and γ *'p'* ➔ $\pi^0 p$ are sometimes visibly different
  FSI effects remain even after the kinematical cuts being applied
- Σ, E, G for γ *'n'* ➔ πN are mostly unaffected by FSI effects
  FSI effects are mostly cancelled in the ratios
- Without applying the W-cut, extracted observables can be rather largely distorted by Fermi motion

Future plan

- Similar study for electroproductions
- Similar study for γ 'n' → ηn, $K\Lambda$, $K\Sigma$
- More polarization observables including recoil polarization

Thank you very much for your attention

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