Double Polarization Observable E in η, π^0 and $2\pi^0$ Photoproduction off Protons and Neutrons

Manuel Dieterle

Osaka, May 26th 2015

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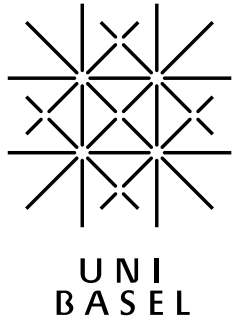
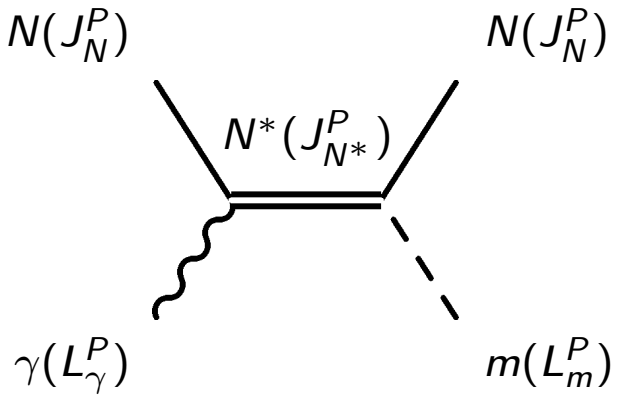


Outline

Study Nucleon Resonances $\Leftrightarrow$ Test Hadron Models

Photoexcitation of Nucleons



$m(L^P_m)$: pseudoscalar meson
$N^*(J^P_{N^*})$: definite P, J

- Decompose IS, FS into Multipole Components

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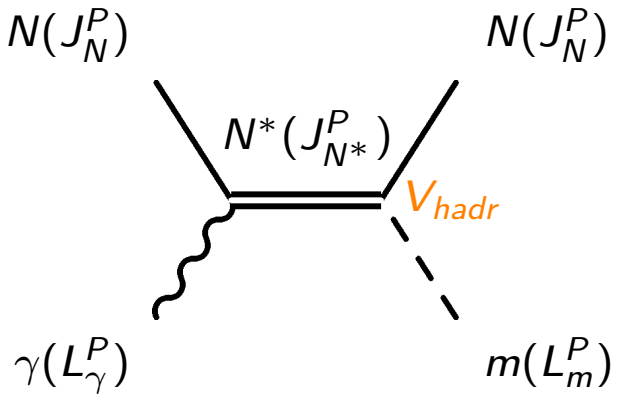

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V_{hadr} :	Isospin Conservation

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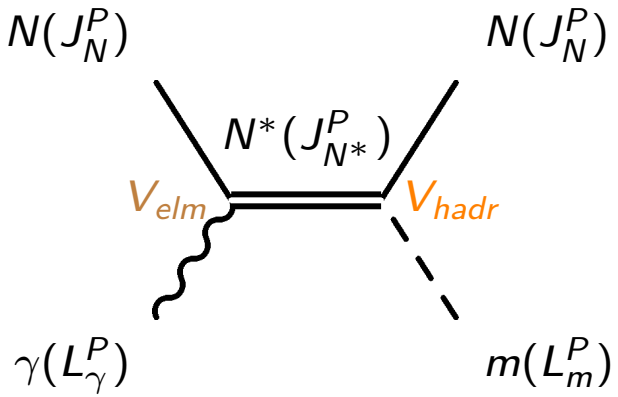

$m(L^P_m)$:	pseudoscalar meson
$N^*(J^P_{N^*})$:	definite P, J
V_{hadr} :	Isospin Conservation
V_{elm} :	Isospin Violation

- Decompose IS, FS into Multipole Components
- Isospin Filter: η $(I = I_3 = 0) \Rightarrow$ only $I = 1/2$ N^* possible
- Isoscalar $(\Delta I = 0)$ and Isovector $(\Delta I = 0, \pm 1)$ components of the elm. current
- Three independent matrix elements $\left\langle I_f, I_{f3} \middle| \hat{A} \middle| I_i, I_{i3} \right\rangle$

$$A^{IS} = \left\langle \tfrac{1}{2}, \pm\tfrac{1}{2} \middle| \hat{S} \middle| \tfrac{1}{2}, \pm\tfrac{1}{2} \right\rangle \quad \mp A^{IV} = \left\langle \tfrac{1}{2}, \pm\tfrac{1}{2} \middle| \hat{V} \middle| \tfrac{1}{2}, \pm\tfrac{1}{2} \right\rangle \quad A^{V3} = \left\langle \tfrac{3}{2}, \pm\tfrac{1}{2} \middle| \hat{V} \middle| \tfrac{1}{2}, \pm\tfrac{1}{2} \right\rangle$$

Isospin Amplitudes

η (Isoscalar):

$$A(\gamma p \to \eta p) = A^{IS} + A^{IV}$$
$$A(\gamma n \to \eta n) = A^{IS} - A^{IV}$$

- Neutron measurement required for complete multipole decomposition

Isospin Amplitudes

η (Isoscalar):

$$\begin{aligned} A(\gamma p \to \eta p) &= A^{IS} + A^{IV} \\ A(\gamma n \to \eta n) &= A^{IS} - A^{IV} \end{aligned}$$

π (Isovector):

$$\begin{aligned} A(\gamma p \to \pi^+ n) &= -\sqrt{\frac{1}{3}} A^{V3} + \sqrt{\frac{2}{3}} \left(A^{IV} - A^{IS} \right) \\ A(\gamma p \to \pi^0 p) &= +\sqrt{\frac{2}{3}} A^{V3} + \sqrt{\frac{1}{3}} \left(A^{IV} - A^{IS} \right) \\ A(\gamma n \to \pi^- p) &= +\sqrt{\frac{1}{3}} A^{V3} - \sqrt{\frac{2}{3}} \left(A^{IV} + A^{IS} \right) \\ A(\gamma n \to \pi^0 n) &= +\sqrt{\frac{2}{3}} A^{V3} + \sqrt{\frac{1}{3}} \left(A^{IV} + A^{IS} \right) \end{aligned}$$

- Neutron measurement required for complete multipole decomposition

Measurements on the Neutron - Deuterium

- no free neutron targets ➢light nuclei, i.e. deuterium

Measurements on the Neutron - Deuterium

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- nuclear Fermi motion ➢kinematical reconstruction

$$W_B^2 = (P_\gamma + P_{N,i})^2 = 2E_\gamma m_N + m_N^2 \quad \Rightarrow \quad W_R^2 = (P_\eta + P_{N,f})^2$$

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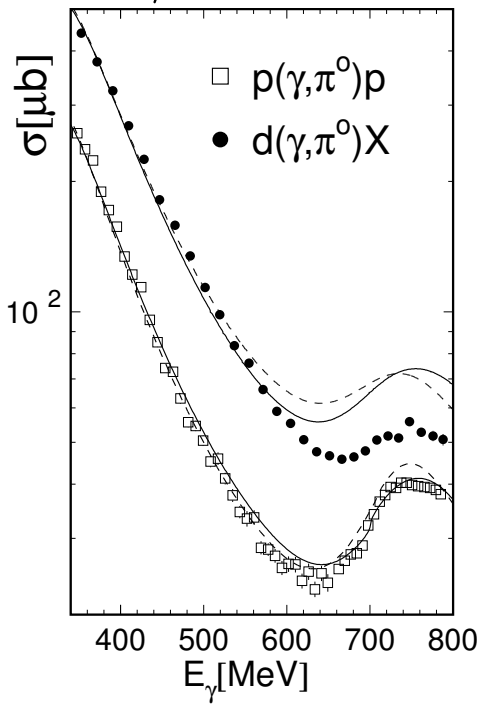
- N-N/m-N Final State Interactions ➢free $\Leftrightarrow$ quasi-free protons



inclusive measurement $\gamma d \to X\pi^0$

- agreement in Δ region
- suppression at higher energies
- $\gamma d \to d\pi^0$ negligible at these energies
- problem with neutron models?
- large FSI?
- both?

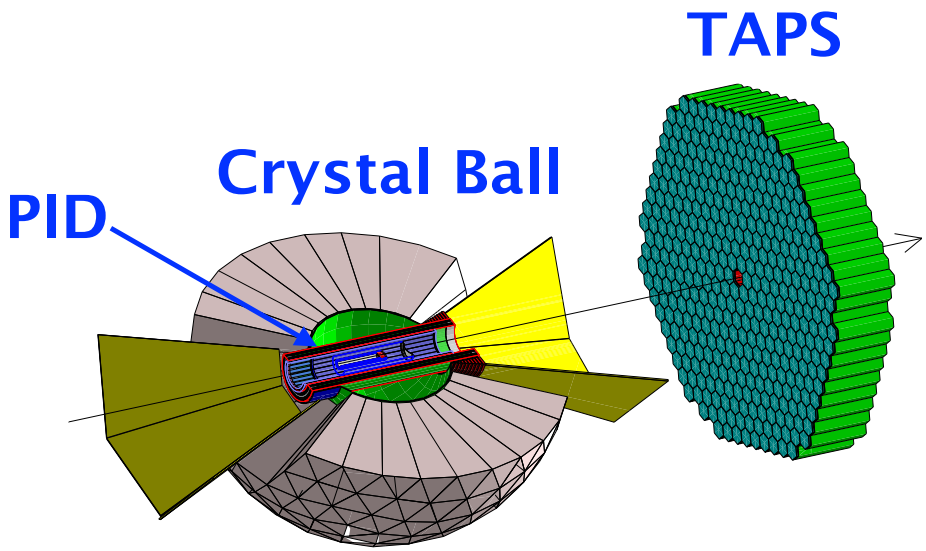
B. Krusche et al., Eur.Phys.J. A6 (1999) 309-324

--- *MAID* — *SAID*

Experimental Setup

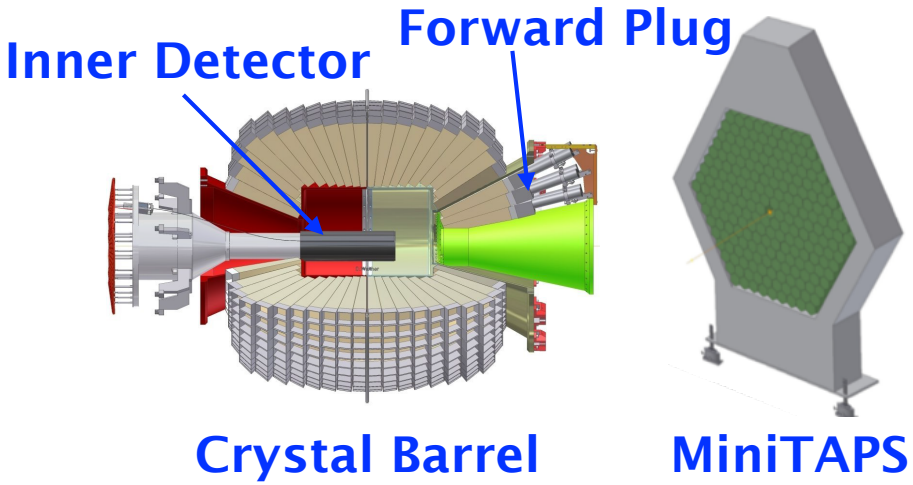
A2 @ MAMI

- Continuous beam
- $E_\gamma \leq 1.6$ GeV
- CB: 672 NaI
- TAPS: BaF_2 & $PbWO_4$
- PID



CBELSA/TAPS @ ELSA

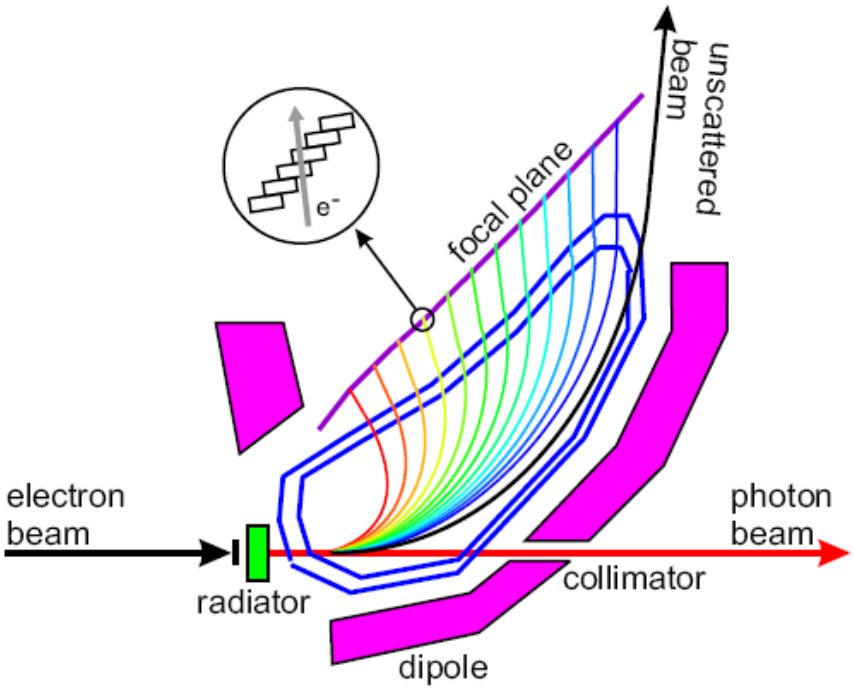
- Quasi-continuous beam
- $E_\gamma \leq 3.2$ GeV
- CBB: 1230 CsI
- MiniTAPS: 216 BaF_2
- Inner Detector



Tagger and Targets

Bremsstrahlungs Tagging

$$E_\gamma = E_0 - E'$$

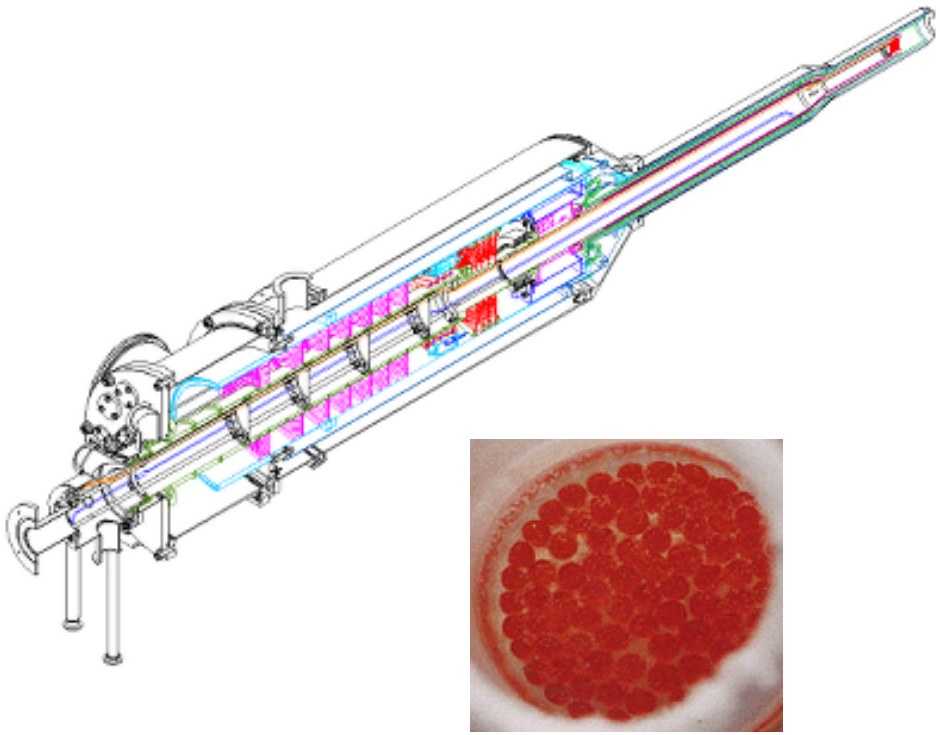


Unpolarised Target

- liquid deuterium

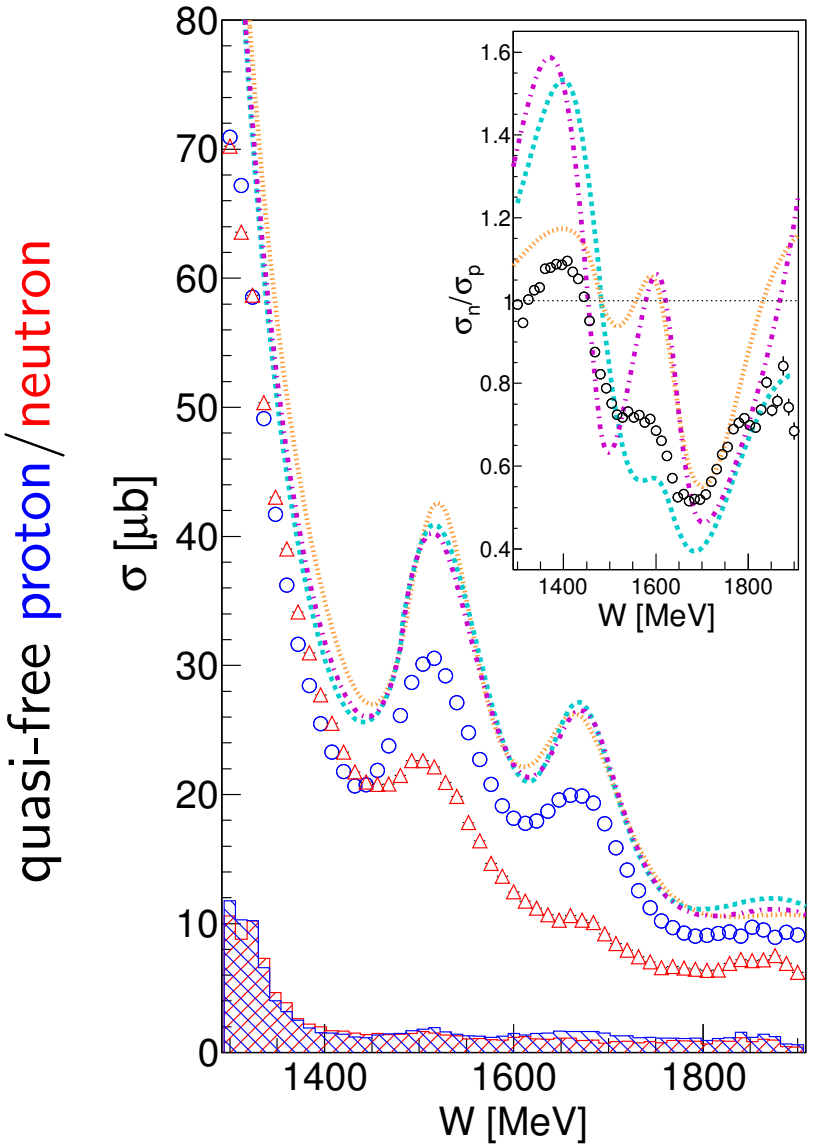
Polarised Target

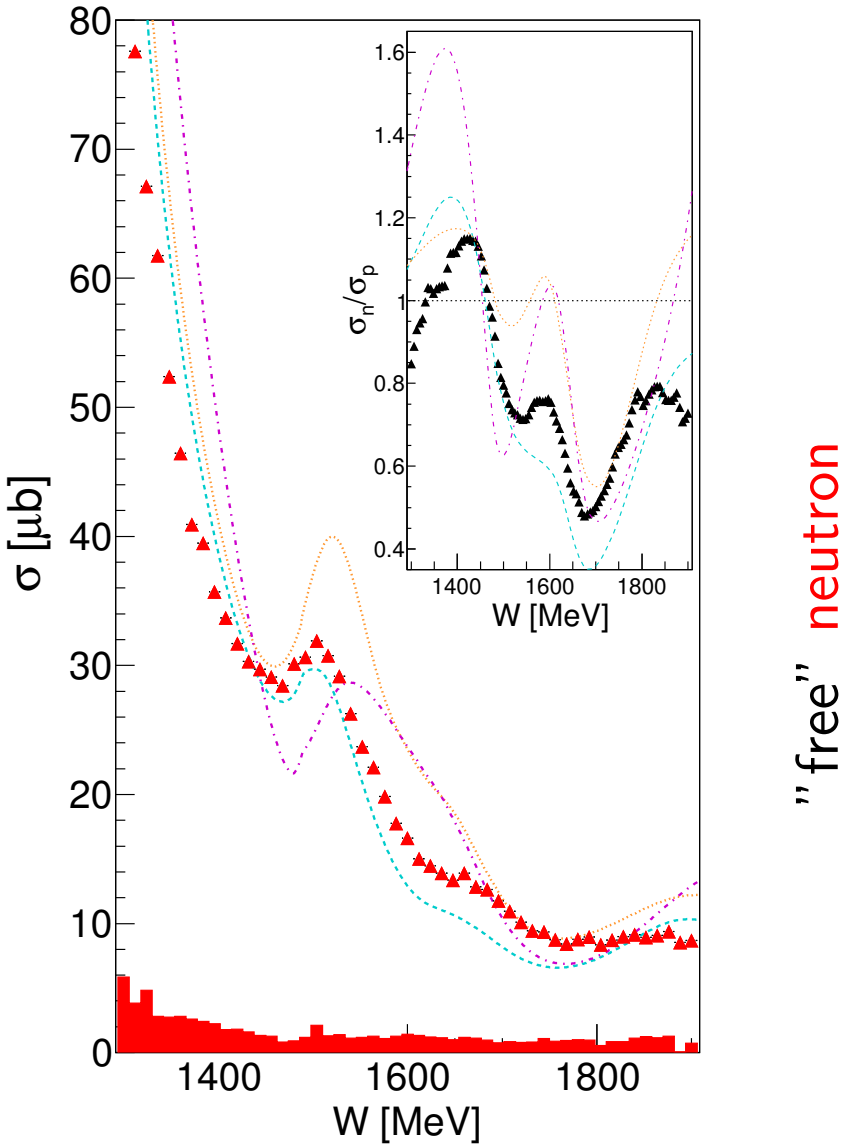
- deuterated Butanol



Single π^0

$\bigcirc \gamma d \to p(n)\pi^0$ $\triangle \gamma d \to n(p)\pi^0$ $\blacktriangle \gamma n \to n\pi^0$ SAID MAID BnGa





MAMI, *M. Dieterle et al., Phys. Rev. Lett. 112, 142001*

Single π^0

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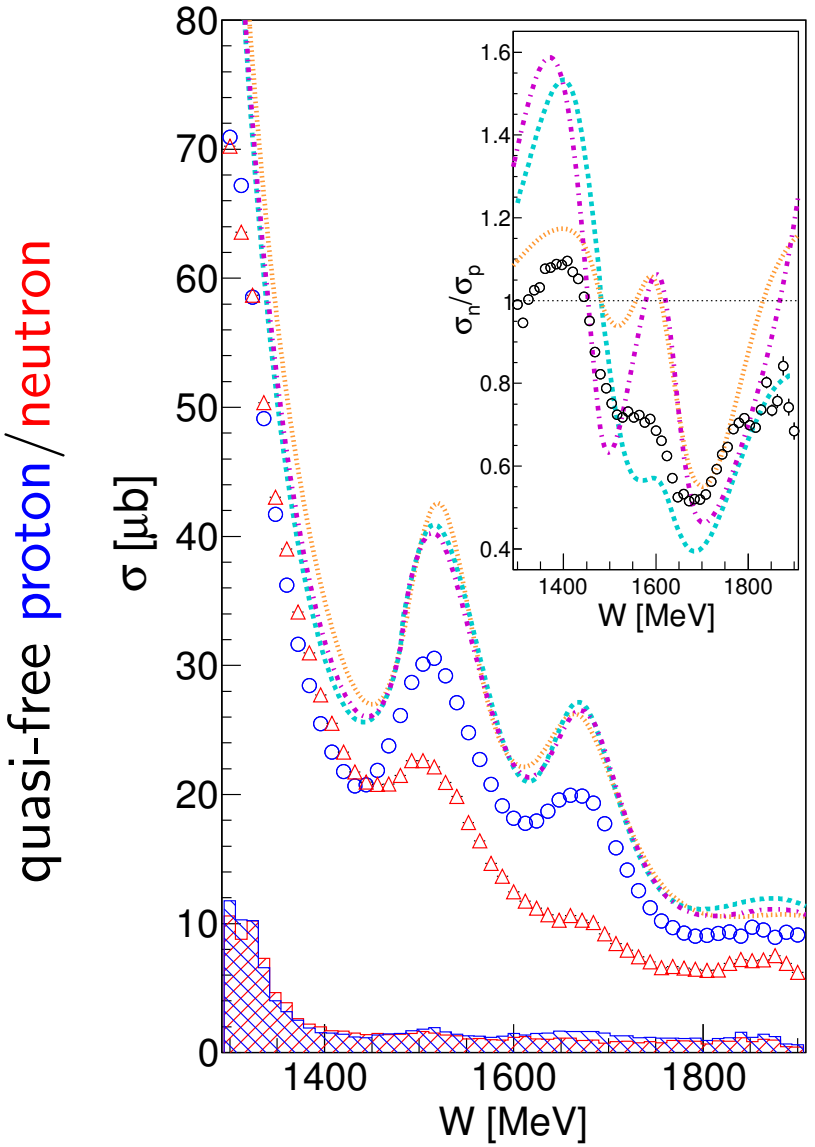
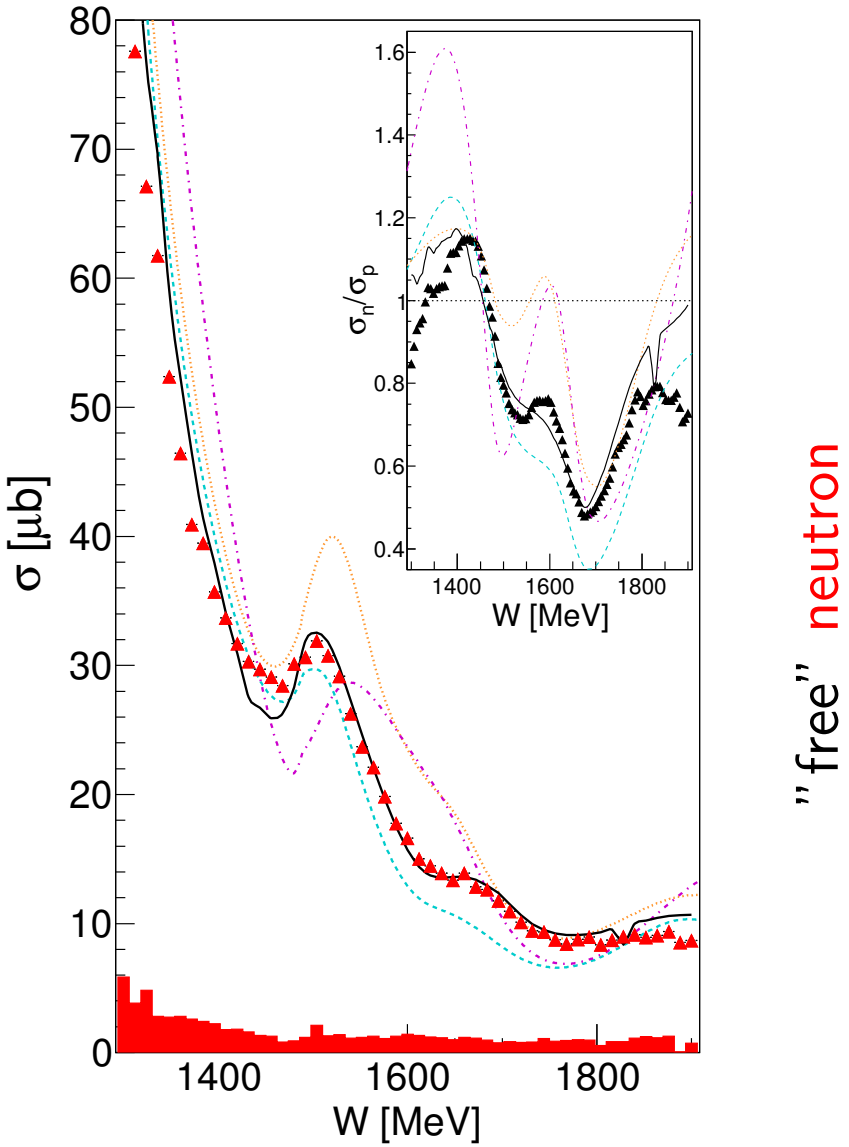


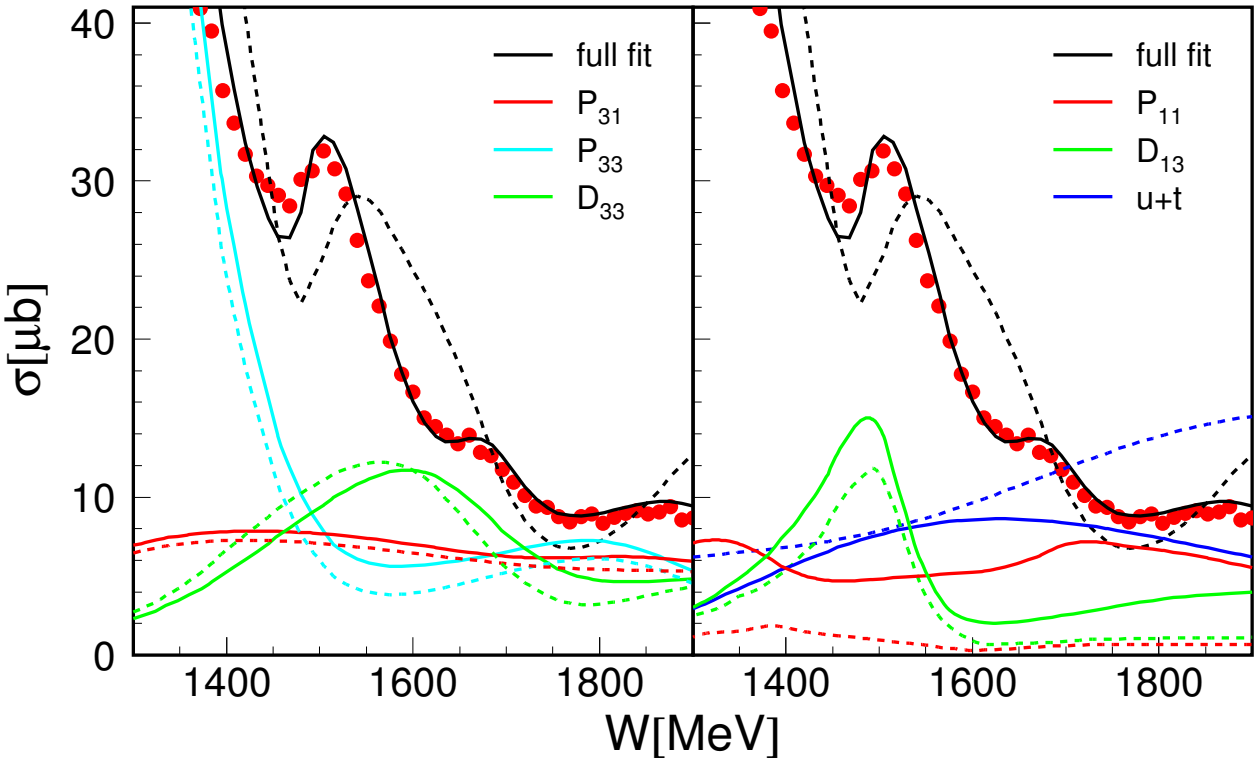


MAMI, *M. Dieterle et al., Phys. Rev. Lett. 112, 142001*

Single π^0 - Impact of the Data

M. Dieterle et al., Phys. Rev. Lett. 112, 142001

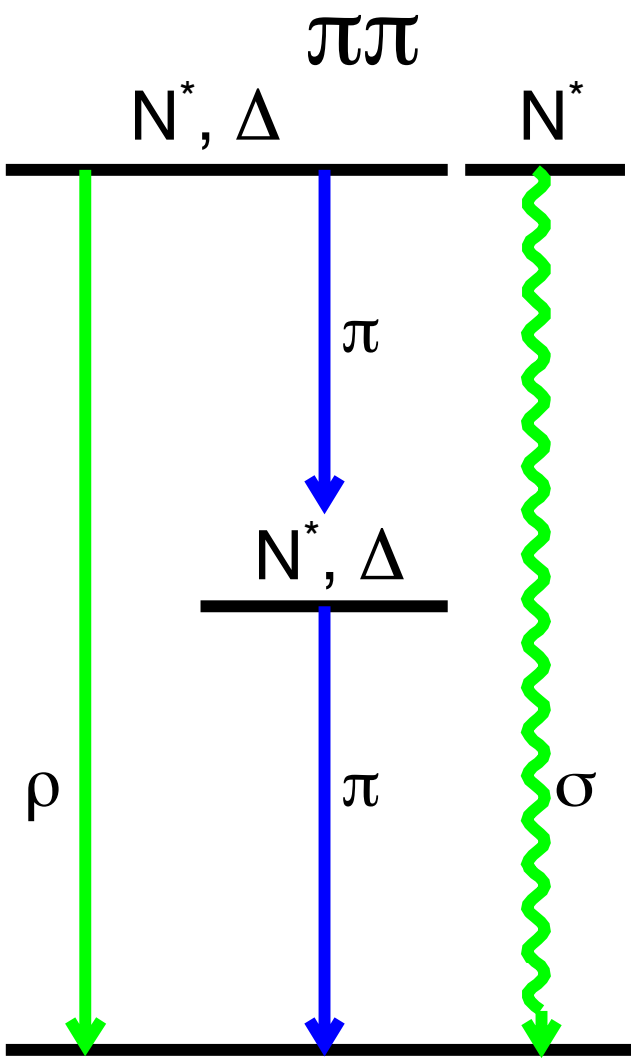
$I = 3/2$
Δ



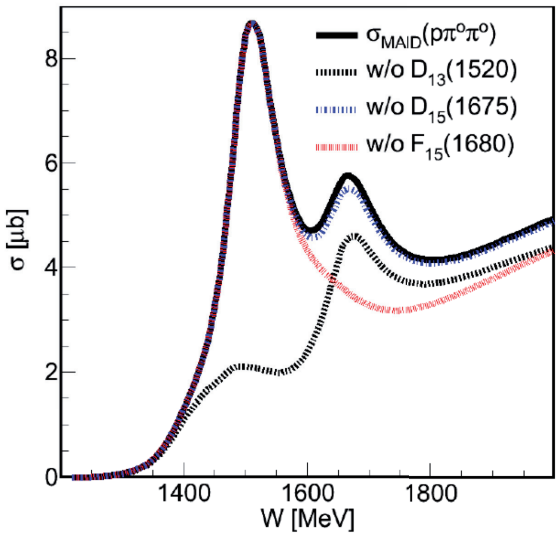
$I = 1/2$
N^*

- small changes for $I = 3/2$ low order resonant partial waves (fixed from $\gamma p \to p\pi^0$)
- drastic changes in $I = 1/2$ $P_{11}(1440)$, $D_{13}(1700)$ (photon coupling changes sign) and non-resonant background contributions from $u-$ and $t-$channel (mostly t-channel, i.e. vector-meson exchange)

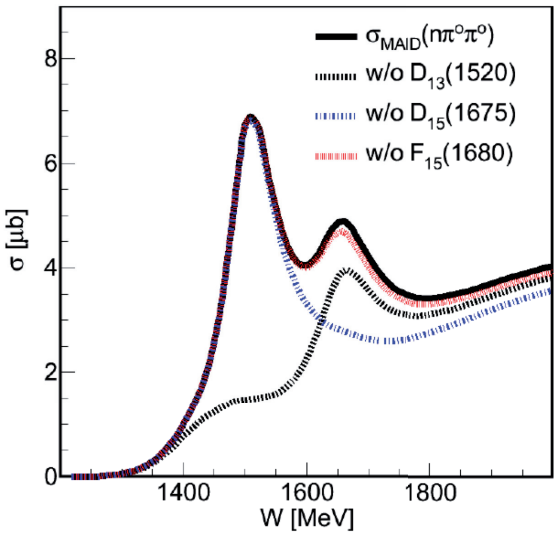
$2\pi^0$ - Access to higher lying Resonances



Proton MAID



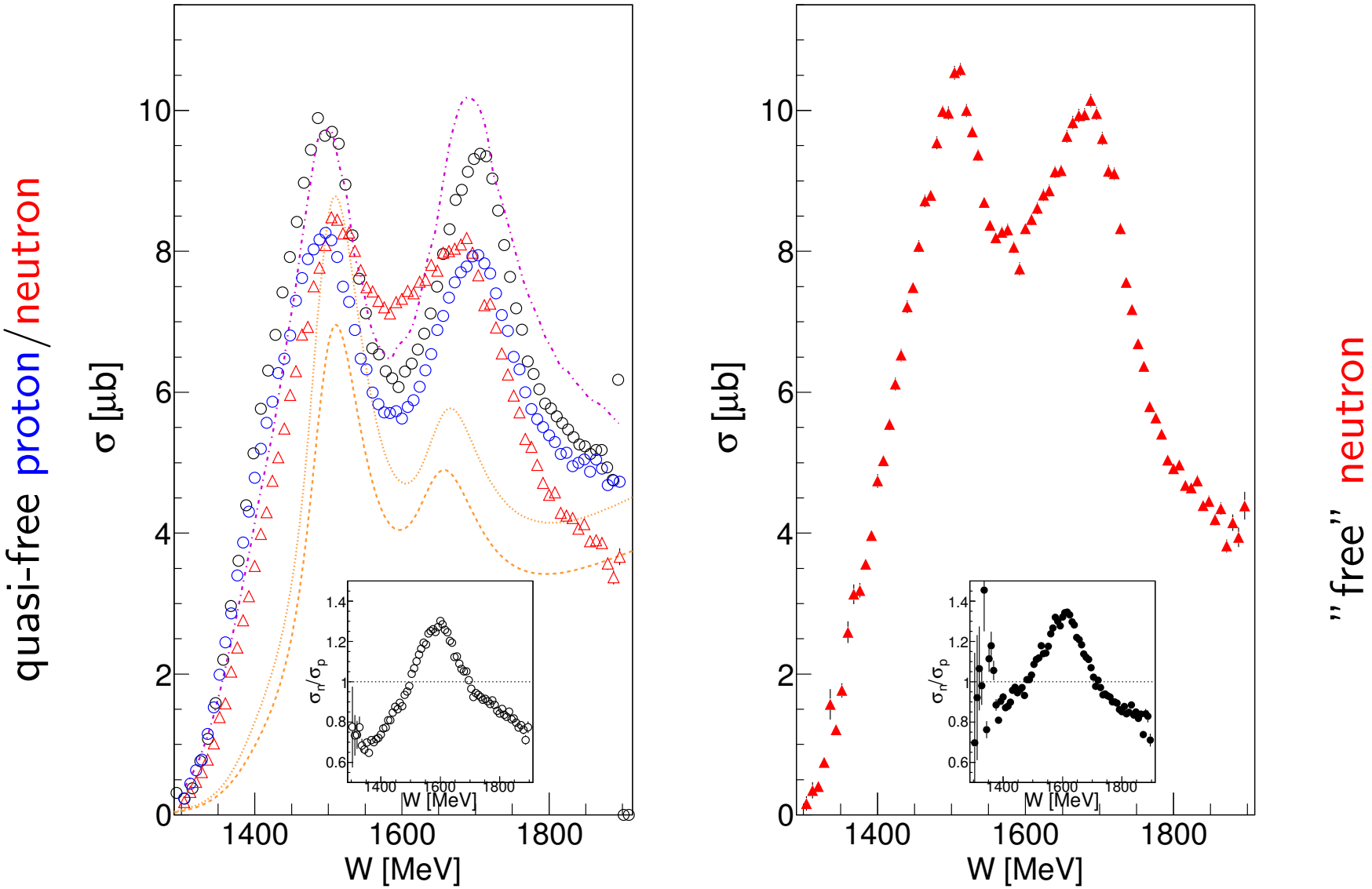
Neutron MAID



- Proton: D_{13}, F_{15} dominate
- Neutron: D_{13}, D_{15} dominate

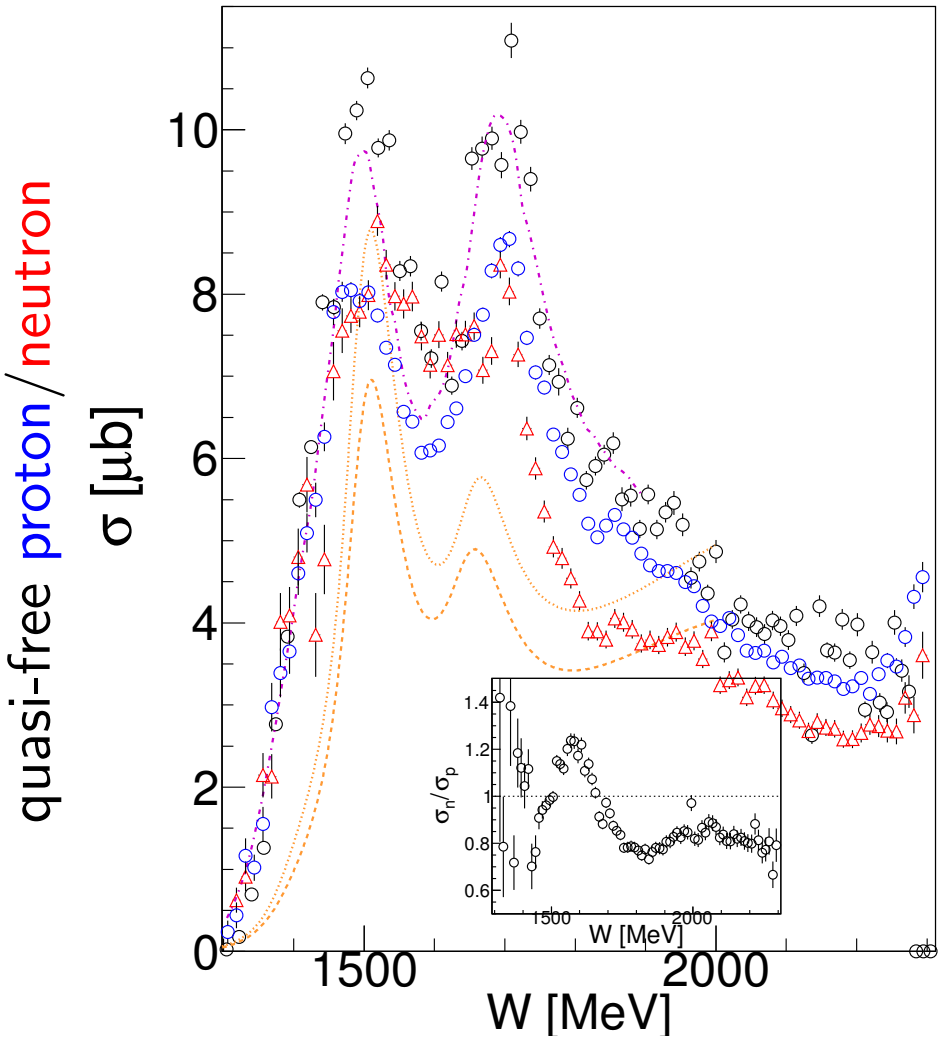
$2\pi^0$

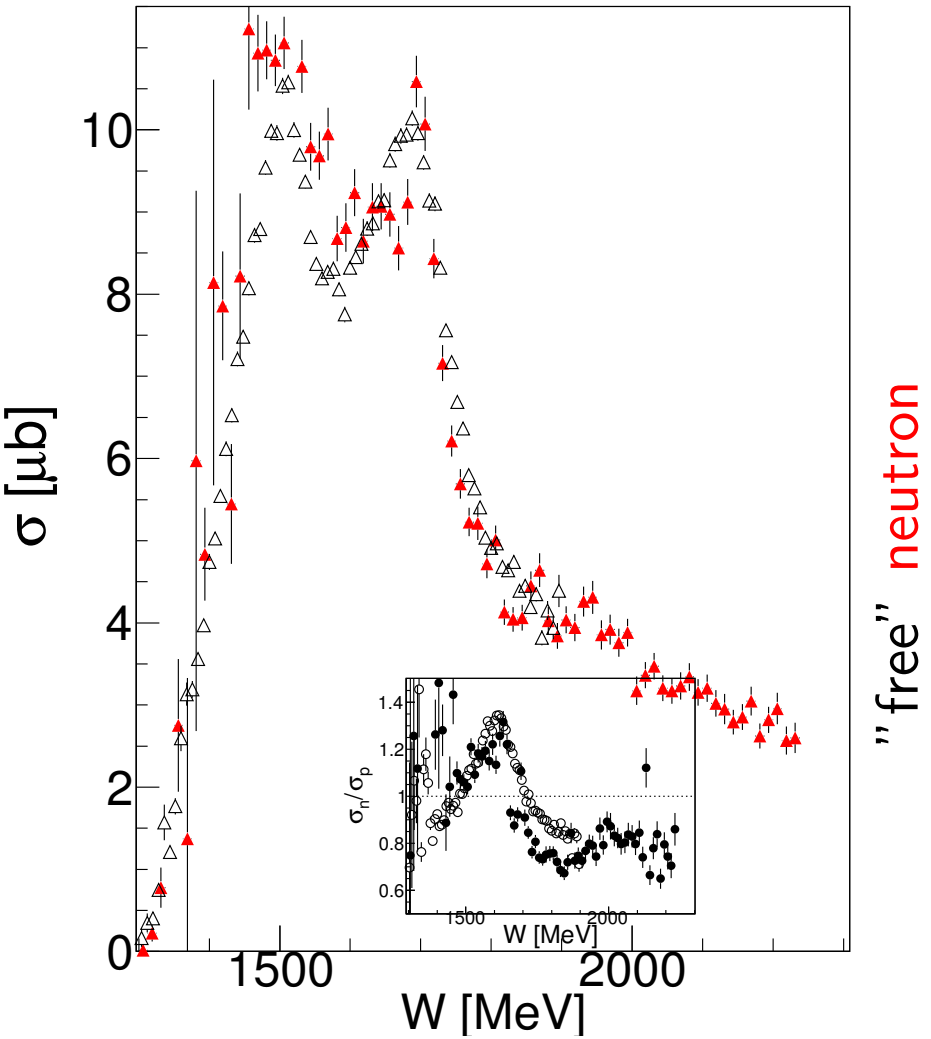
$\bigcirc \gamma p \to p\pi^0$ $\bigcirc \gamma d \to p(n)\pi^0$ $\triangle \gamma d \to n(p)\pi^0$ $\blacktriangle \gamma n \to n\pi^0$ MAIDn MAIDp BnGa



MAMI, *M. Dieterle, M. Oberle et al., in preparation*

$2\pi^0$ $\bigcirc\gamma p \to p\pi^0$ $\bigcirc\gamma d \to p(n)\pi^0$ $\triangle\gamma d \to n(p)\pi^0$ $\blacktriangle/\triangle\gamma n \to n\pi^0$ (ELSA/MAMI) — / ··· MAIDn/p -·- BnGa

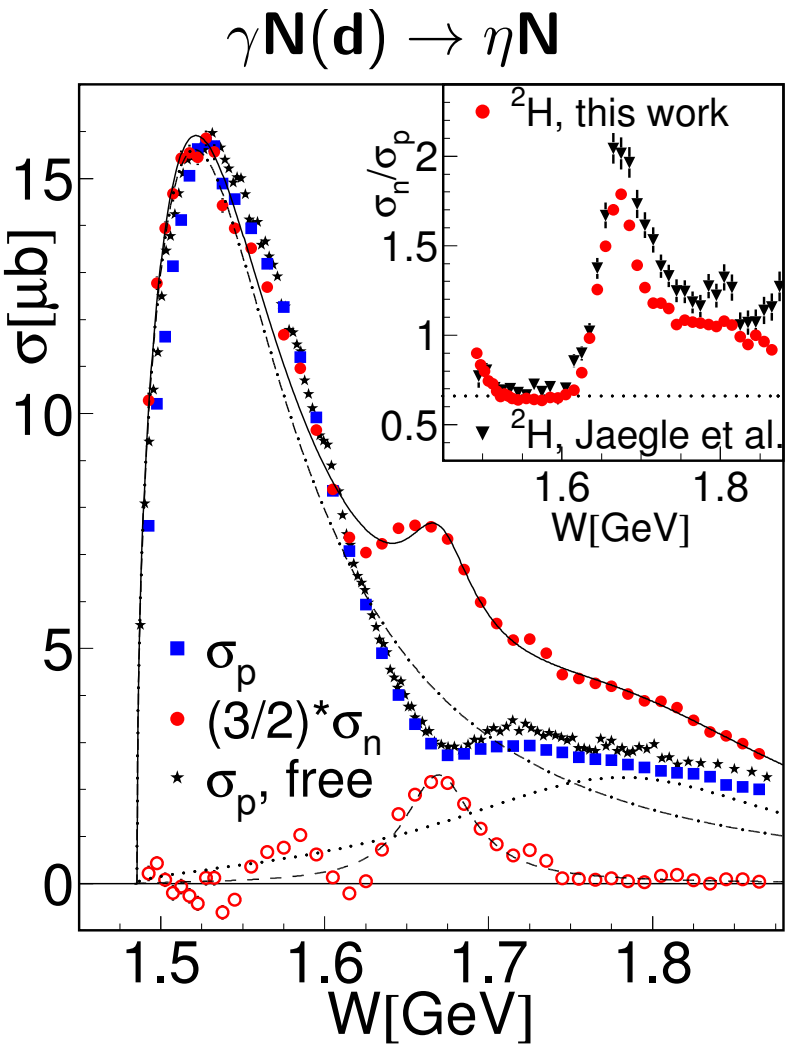


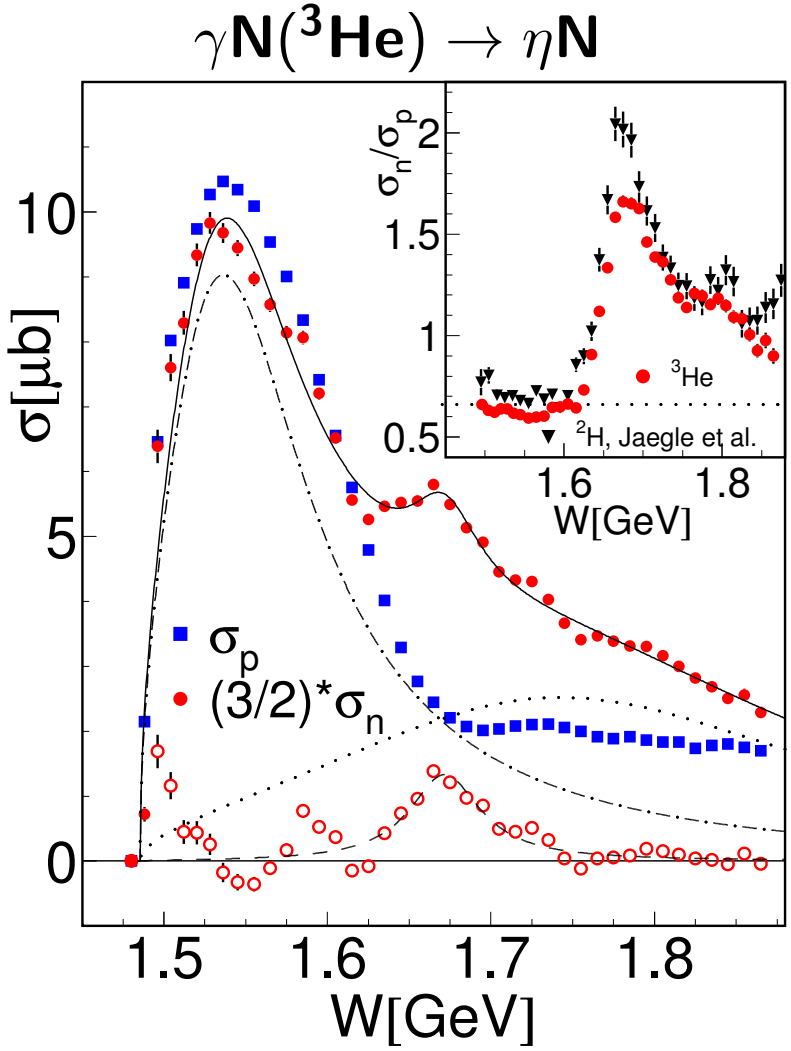


ELSA, *M. Dieterle et al., in preparation*

η Photoproduction

D. Werthmüller, L. Witthauer et al., Phys. Rev. Lett. 111, 232001
L. Witthauer et al., Eur. Phys. J. A 49 (2013) 154





$\Rightarrow$ Nuclear Effect (FSI, meson rescattering) unlikely

Unpolarized Results: Summary

- Neutron Data increasingly available
- Effects from Fermi motion can be handled (experimental resolution remains)
- Effects from FSI can be investigated with free to quasi-free proton results

$\Rightarrow$ use polarization observables to identify amplitudes and quantum numbers

Polarization Observables

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}(\theta)\cdot\Big[1 - p_\gamma^{lin}\Sigma(\theta)\cos(2\phi) + p_x\cdot\Big(-p_\gamma^{lin}H(\theta)\sin(2\phi) + p_\gamma^{circ}F(\theta)\Big) - p_y\cdot\Big(+p_\gamma^{lin}P(\theta)\cos(2\phi) - T(\theta)\Big) - p_z\cdot\Big(-p_\gamma^{lin}G(\theta)\sin(2\phi) + p_\gamma^{circ}E(\theta)\Big)\Big]$$

P_γ		$P_T\cdot\vec{e}_i$		
		x	y	z
unpol	σ	-	T	-
linearly	$-\Sigma$	H	$-P$	$-G$
circularly	-	F	-	$-E$

Polarization Observables

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P_γ		$P_T\cdot\vec{e}_i$		
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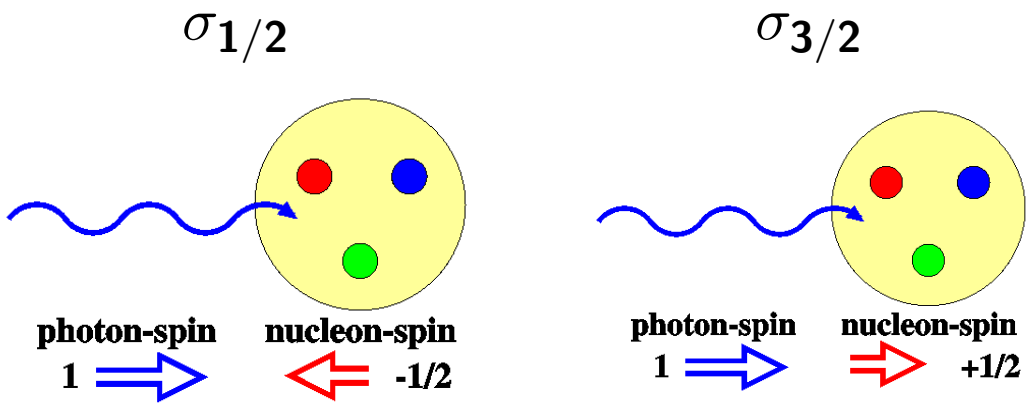
unpol	σ	-	T	-
linearly	$-\Sigma$	H	$-P$	$-G$
circularly	-	F	-	$-E$

Double Polarization Observable E



$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

Double Polarization Observable E

- $\nexists$ polarized deuterium $\Rightarrow$ dButanol: $\mathbf{C_4D_9OD}$
- 2 ways to measure E:

w/o carbon subtraction:

$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{2\sigma_{tot}}$$

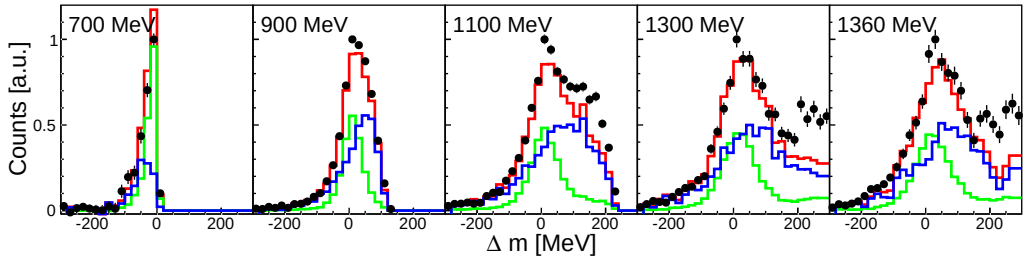
with carbon subtraction:

$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

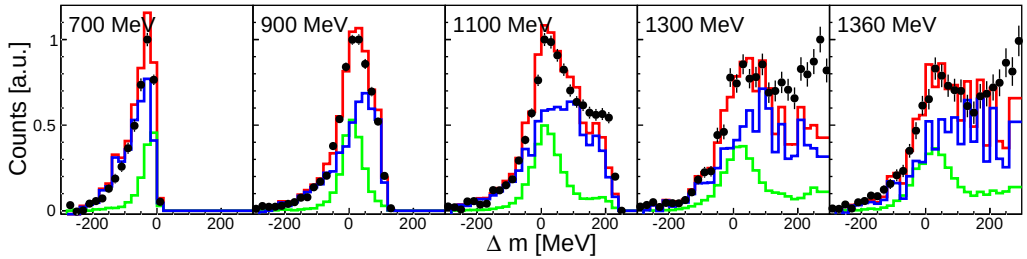
Carbon Subtraction (η)

+ dButanol — Carbon — LD2 — LD2 + Carbon

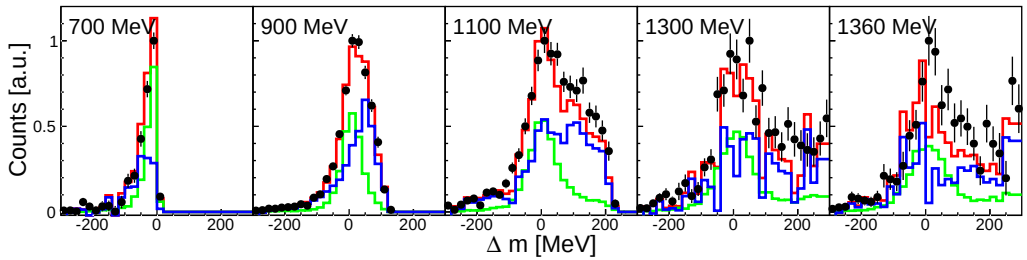
$\eta \to 2\gamma$ p



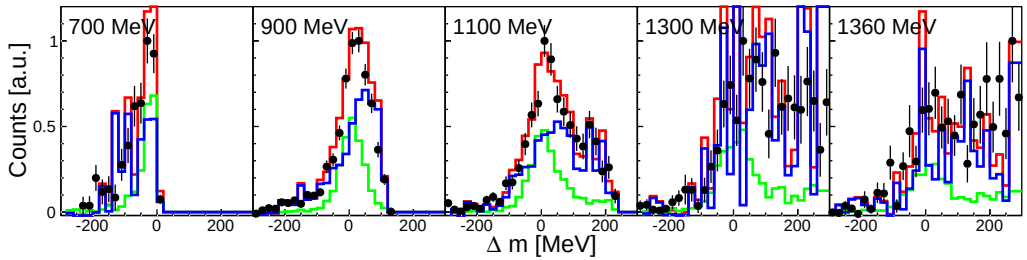
$\eta \to 2\gamma$ n



$\eta \to 6\gamma$ p



$\eta \to 6\gamma$ n



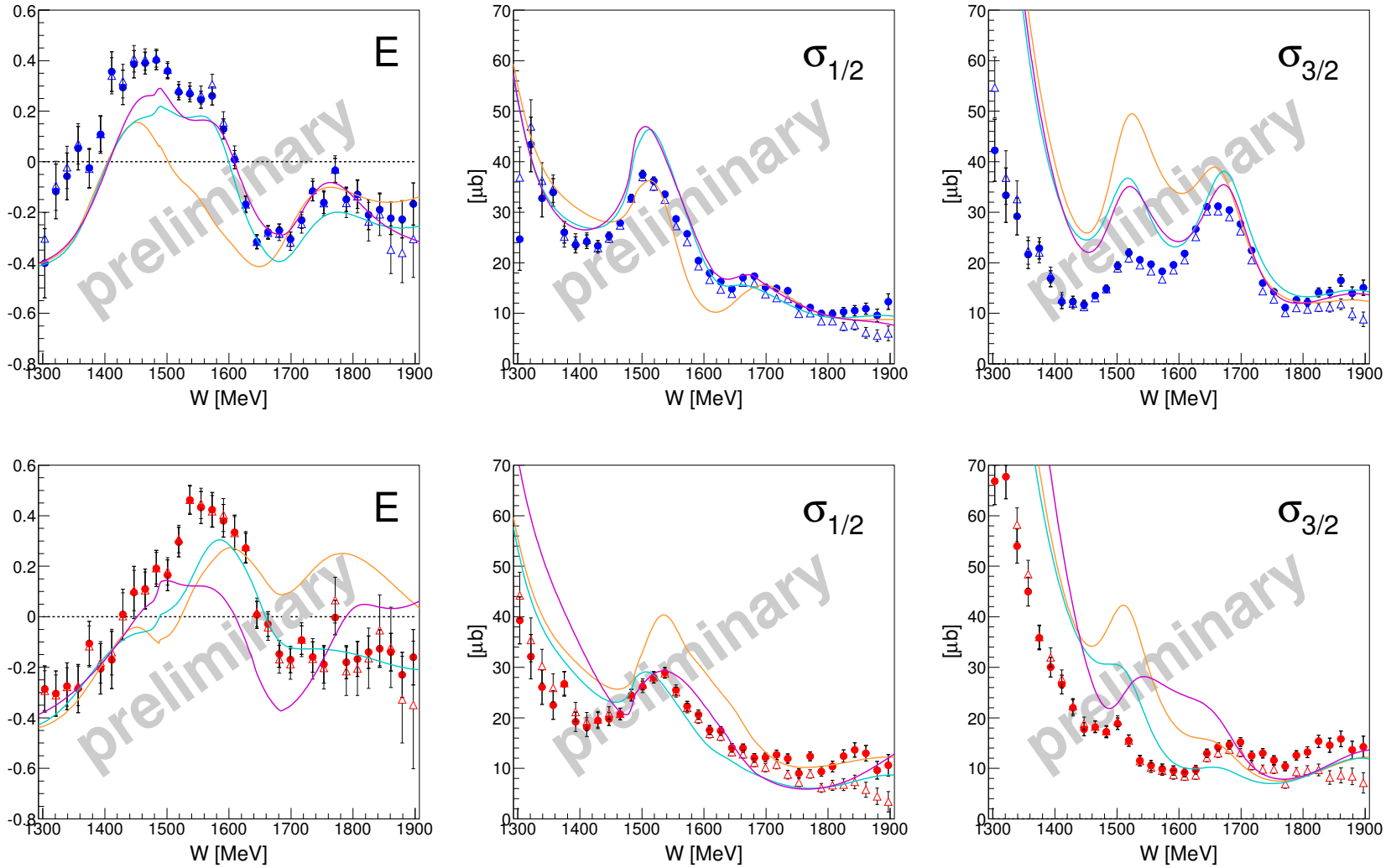
π^0 Helicity Asymmetries

• direct △ sum — SAID — MAID — BnGa

@MAMI

On Proton

On Neutron



M. Dieterle et al., in preparation

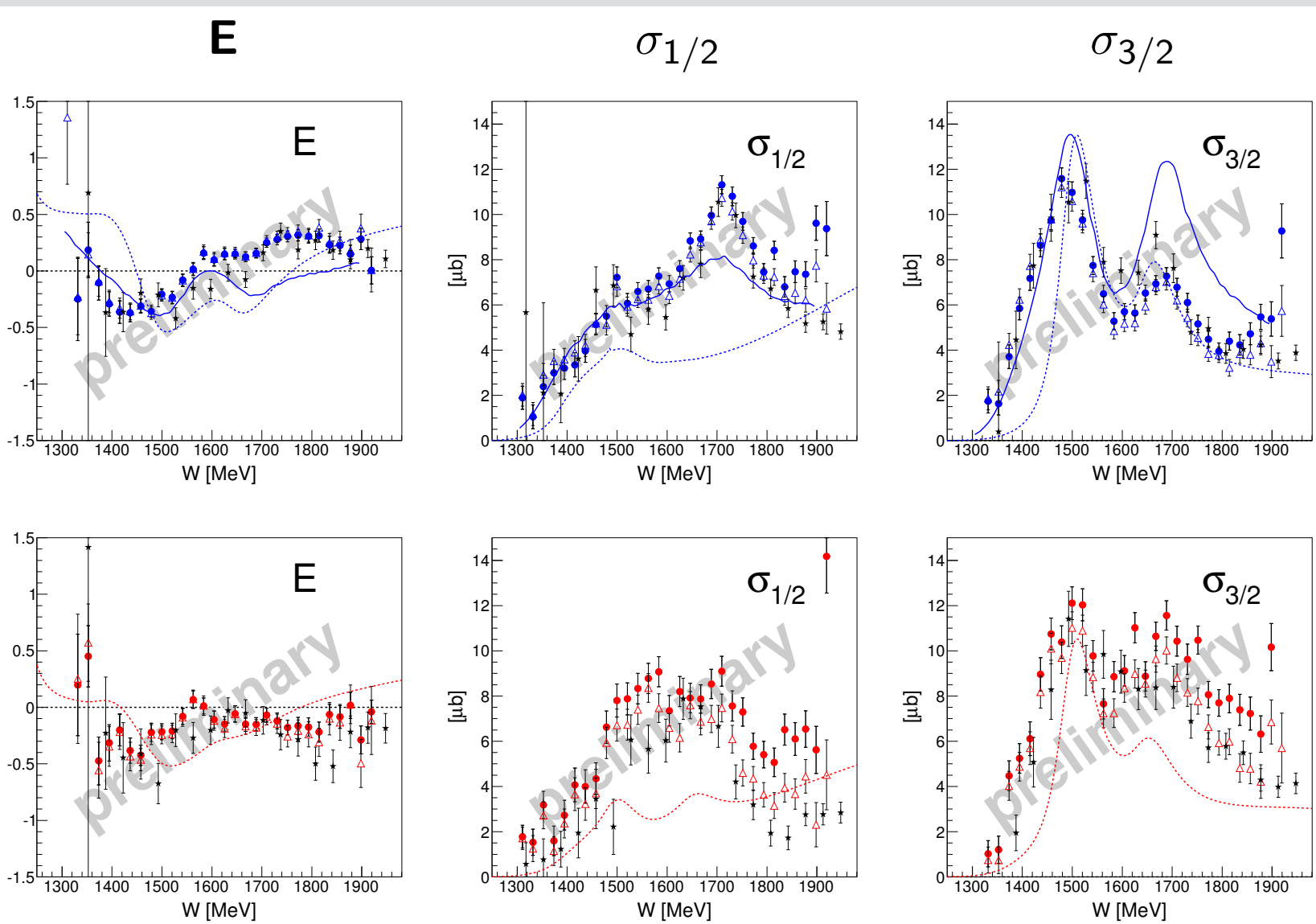
$2\pi^0$ Helicity Asymmetries

• direct △ sum ★ ELSA —— BnGa - - - MAID

@MAMI/ELSA

On Proton

On Neutron



M. Dieterle et al., in preparation

η Helicity Asymmetries

○ direct ●sum —— MAID - - - BnGa

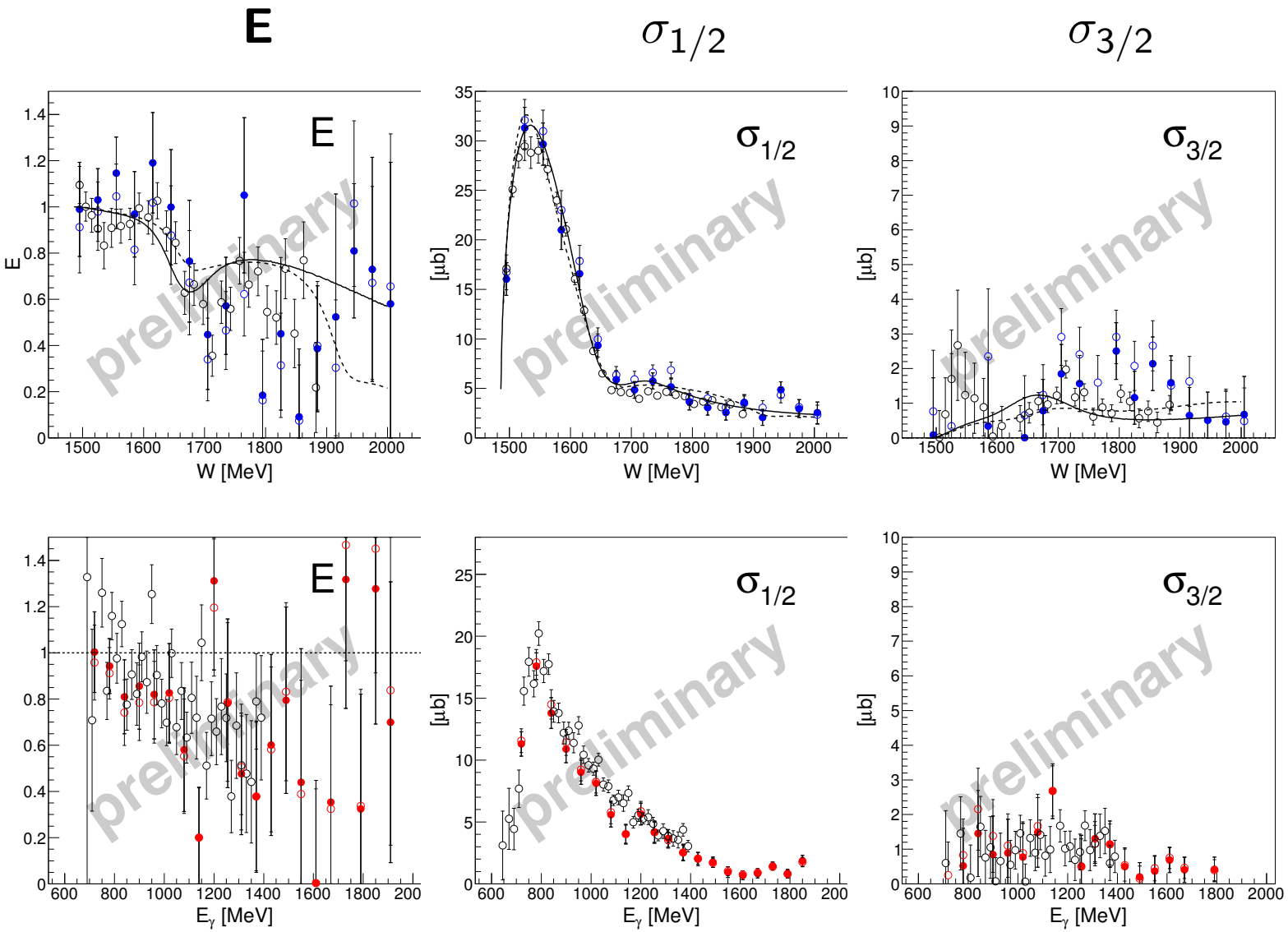
@ELSA

On Proton

On Neutron

exclusive

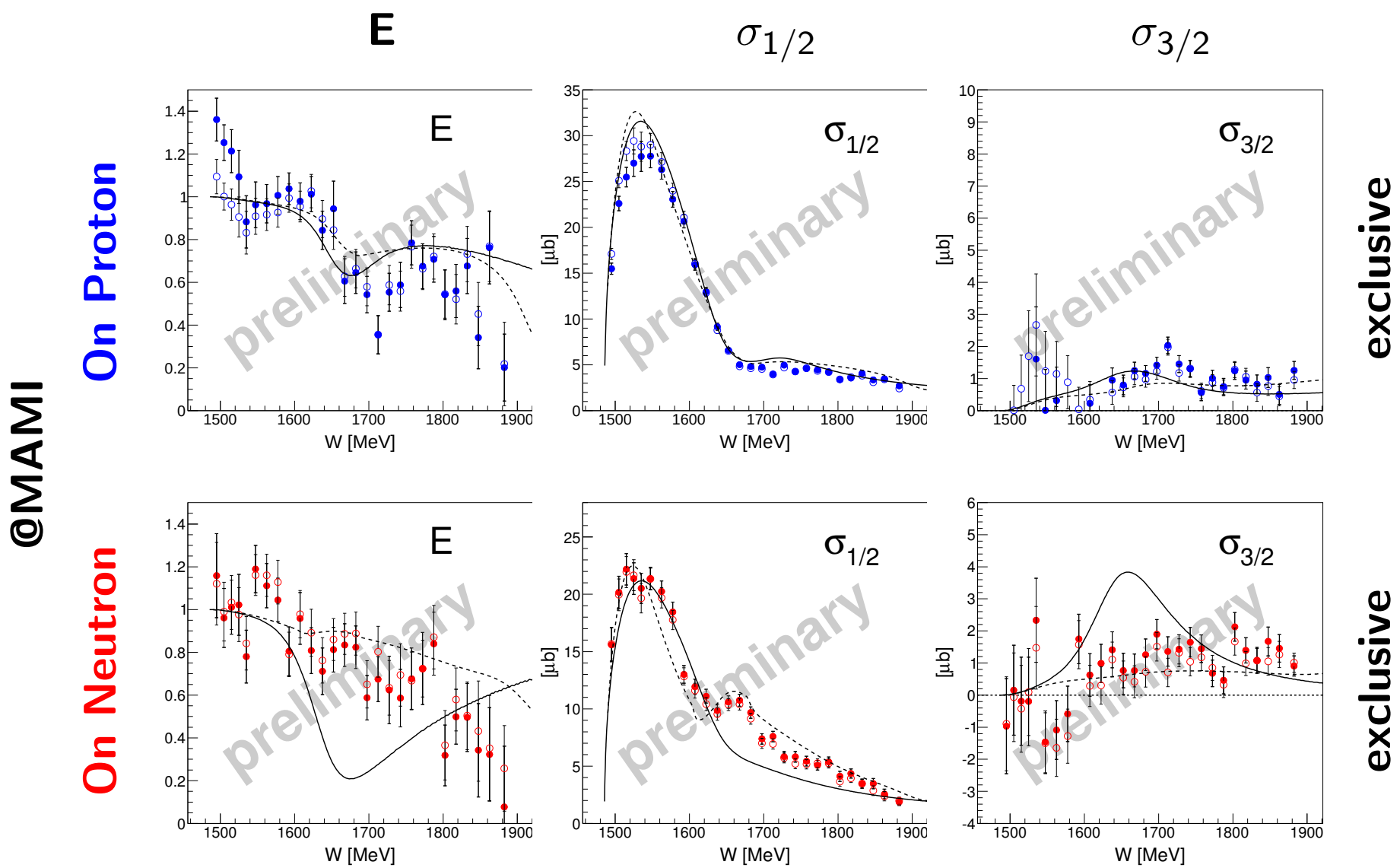
inclusive



L. Witthauer et al., in preparation

η Helicity Asymmetries

○ direct ●sum —— MAID - - - BnGa



L. Witthauer et al., in preparation

Summary

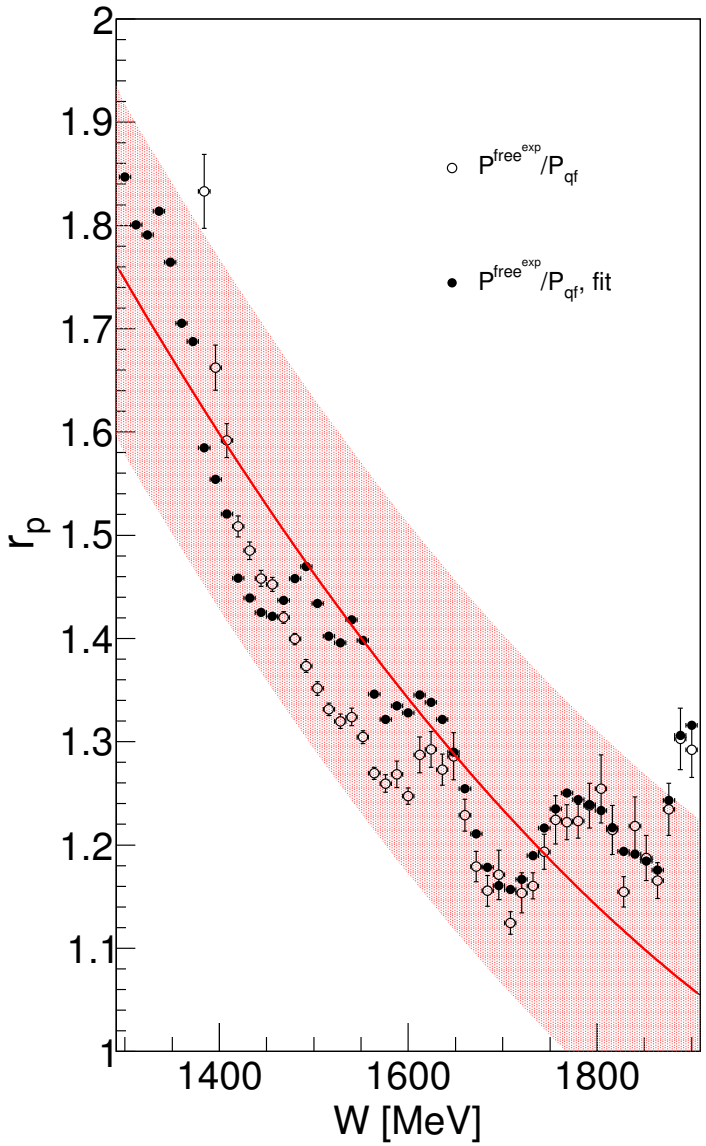
- Neutron Data increasingly available
- Effects from Fermi motion can be handled (experimental resolution remains)
- Effects from FSI can be investigated with free to quasi-free proton results
- measured **E** for:
  - $\gamma p(n) \to \eta p(n)$ and $\gamma n(p) \to \eta n(p)$
  - $\gamma p(n) \to \pi^0 p(n)$ and $\gamma n(p) \to \pi^0 p(n)$
  - $\gamma p(n) \to 2\pi^0 p(n)$ and $\gamma n(p) \to 2\pi^0 n(p)$
- η bump only in $\sigma_{1/2}$: S_{11}, P_{11} resonance?
- new input for theoretical models!

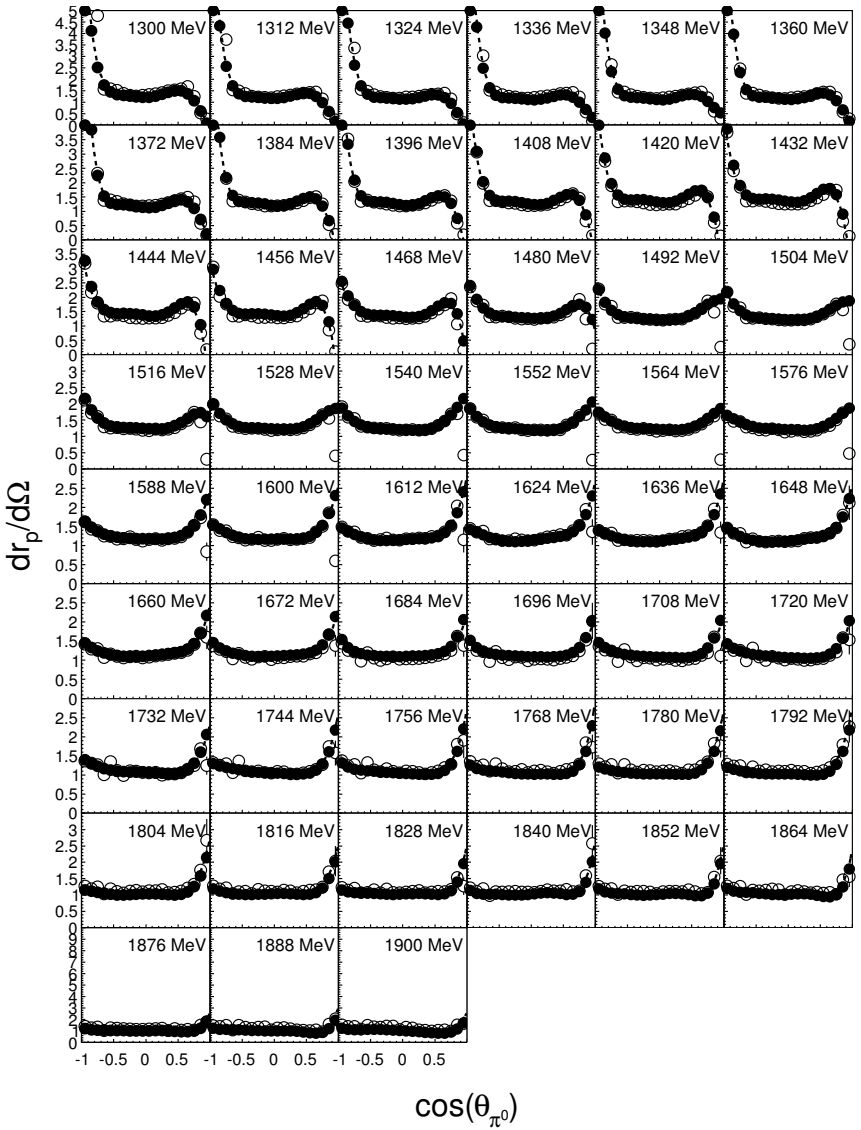
Thanks for your attention

This work is supported by:

Correct Final State Effects

○ free/quasi-free ● correction factor

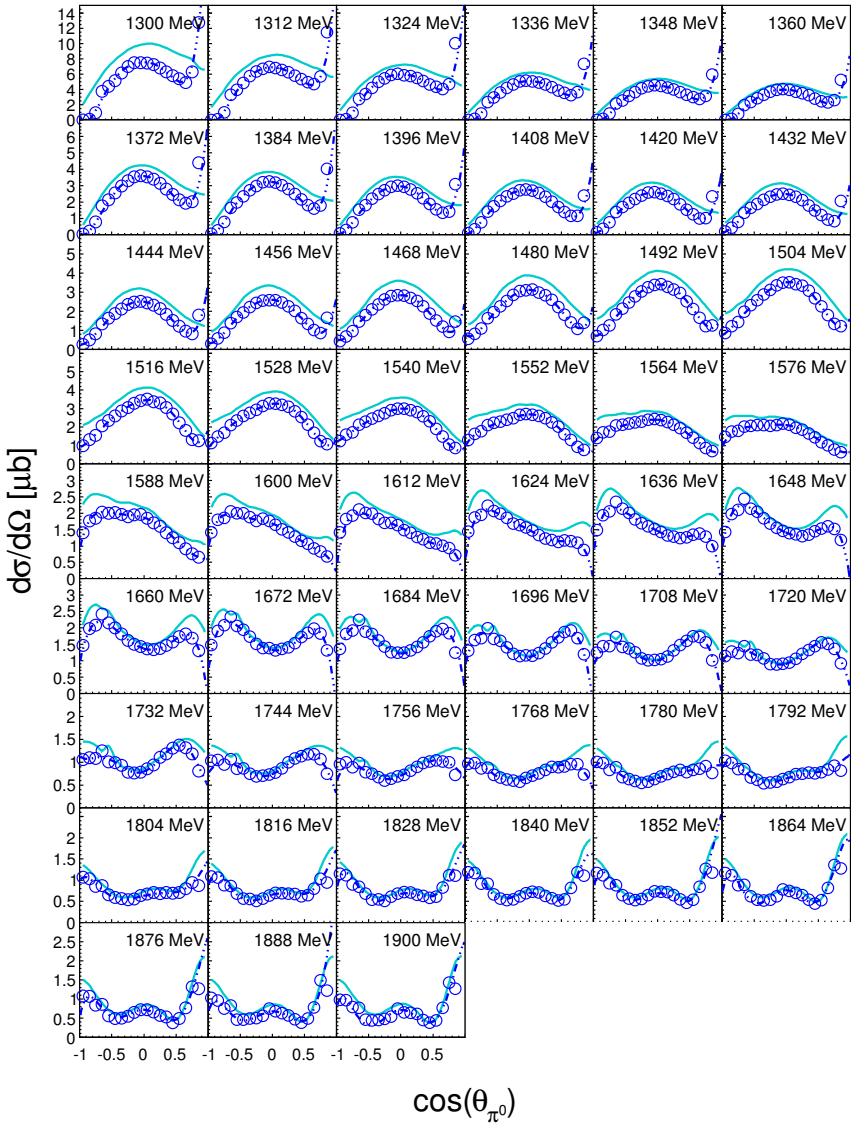




Correct Final State Effects

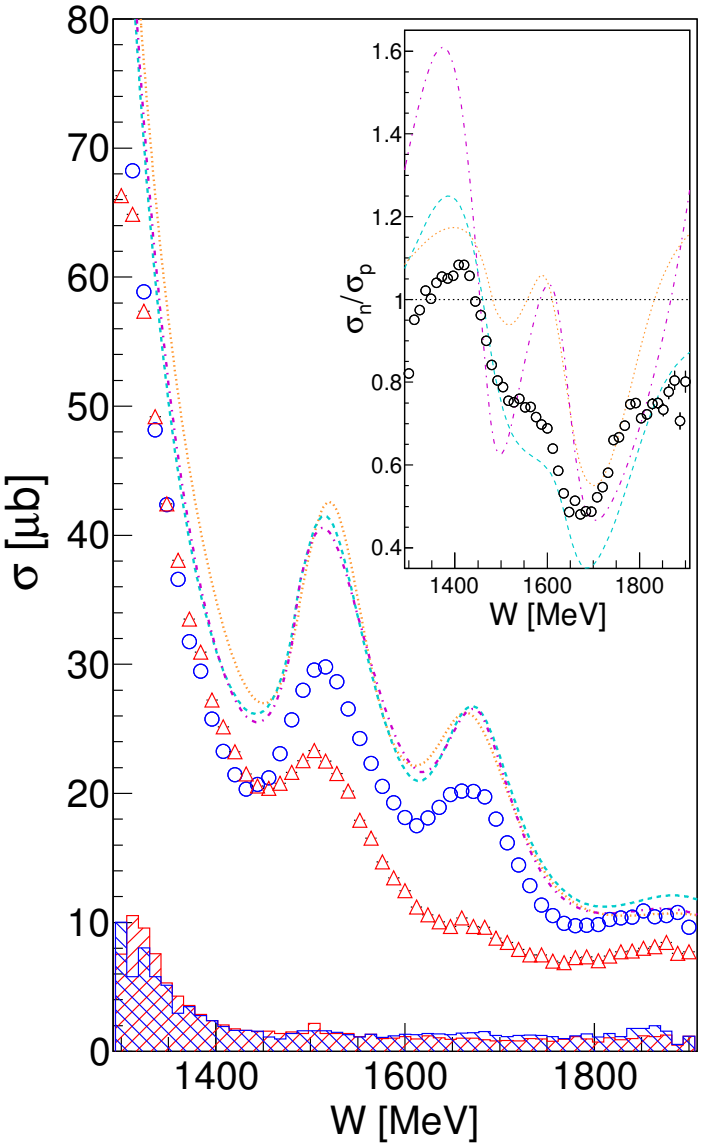
$\bigcirc \gamma p \to p\pi^0$ —— SAID

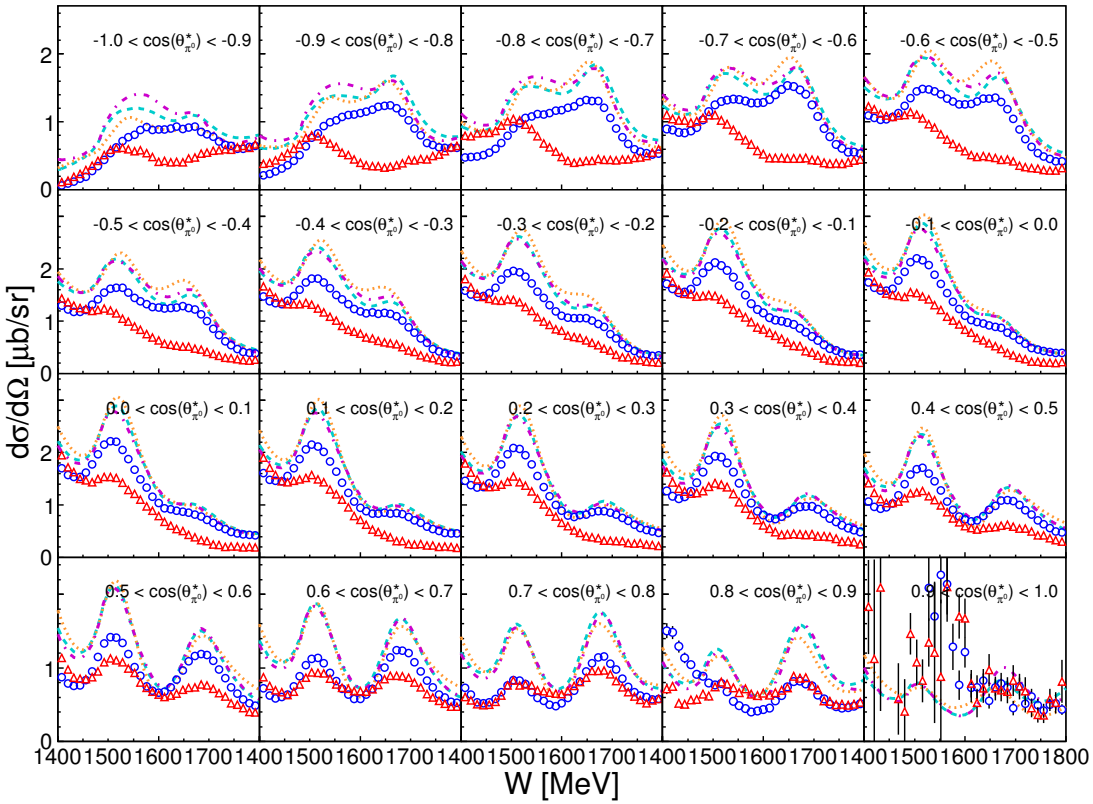
- assume similar effects for $\gamma p(n) \to p(n)\pi^0$ as for $\gamma n(p) \to n(p)\pi^0$
- correction factor from $(\gamma p \to p\pi^0)/(\gamma p(n) \to p(n)\pi^0)$
- apply to quasi-free neutron data



π^0 Cross Sections

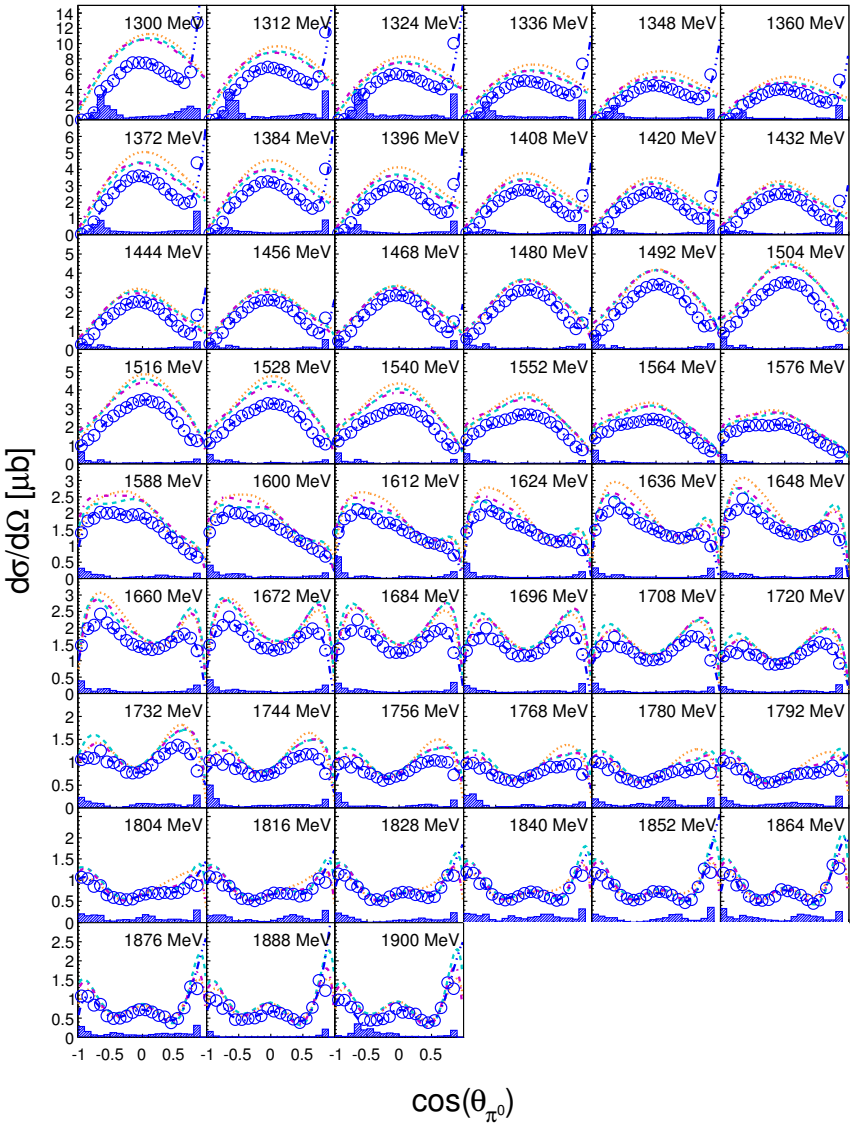
$\bigcirc$ $\gamma p \to p\pi^0$ $\triangle$ $\gamma n \to n\pi^0$ SAID-p MAID-p BnGa-p

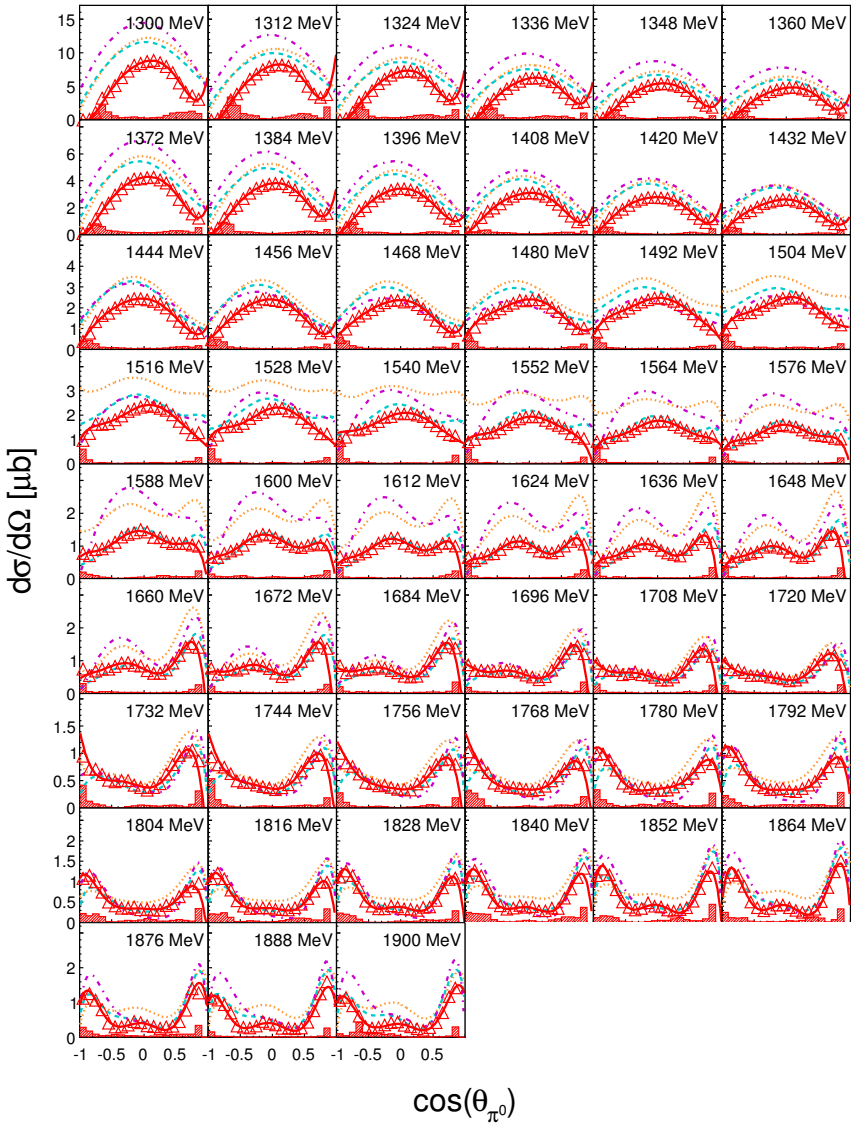




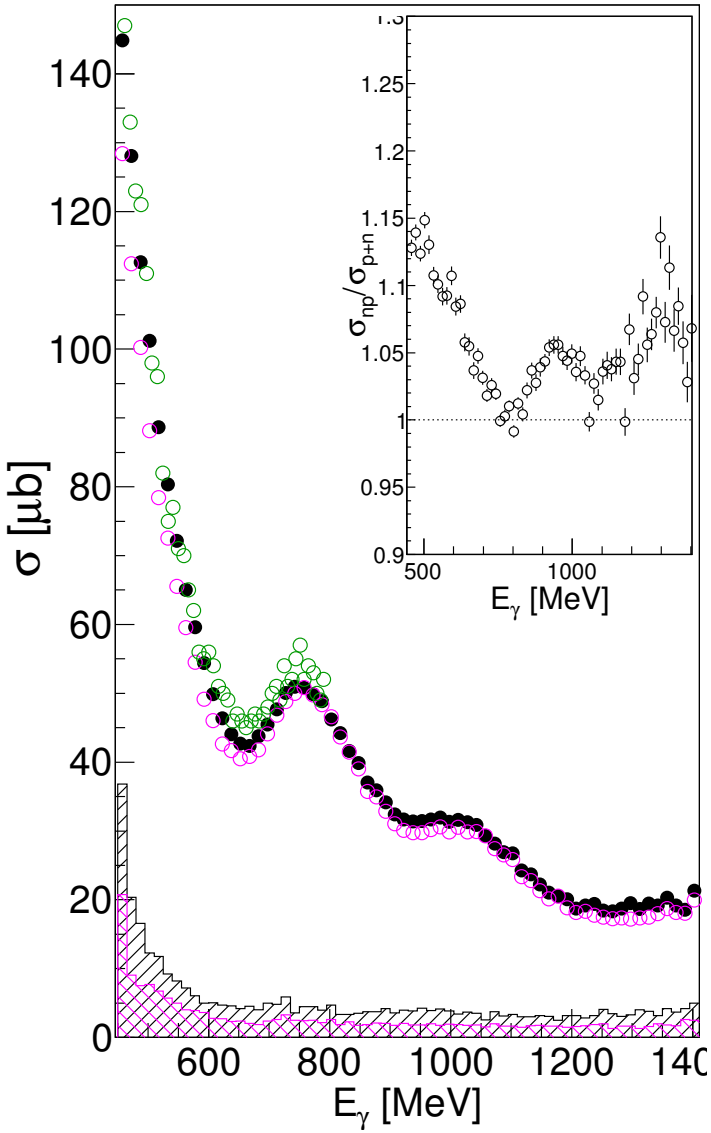
π^0 Cross Sections

$\bigcirc$ $\gamma p \to p\pi^0$ $\triangle$ $\gamma n \to n\pi^0$ SAID-p MAID-p BnGa-p





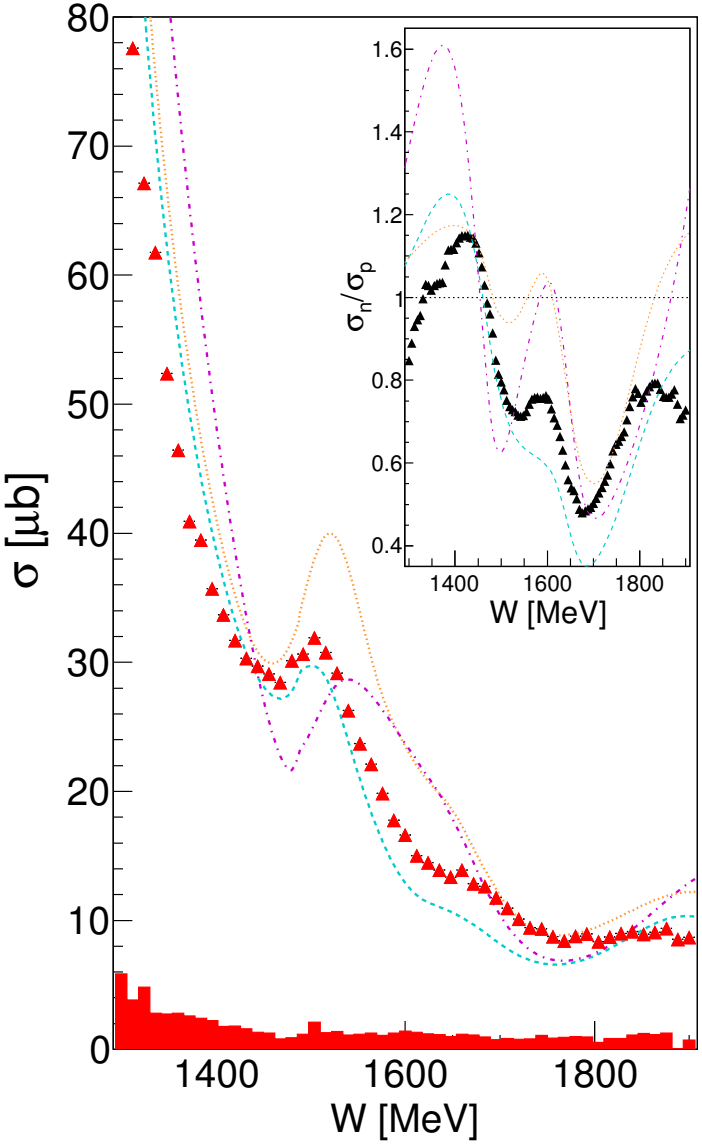
Analysis Cross Check - QF-Inclusive

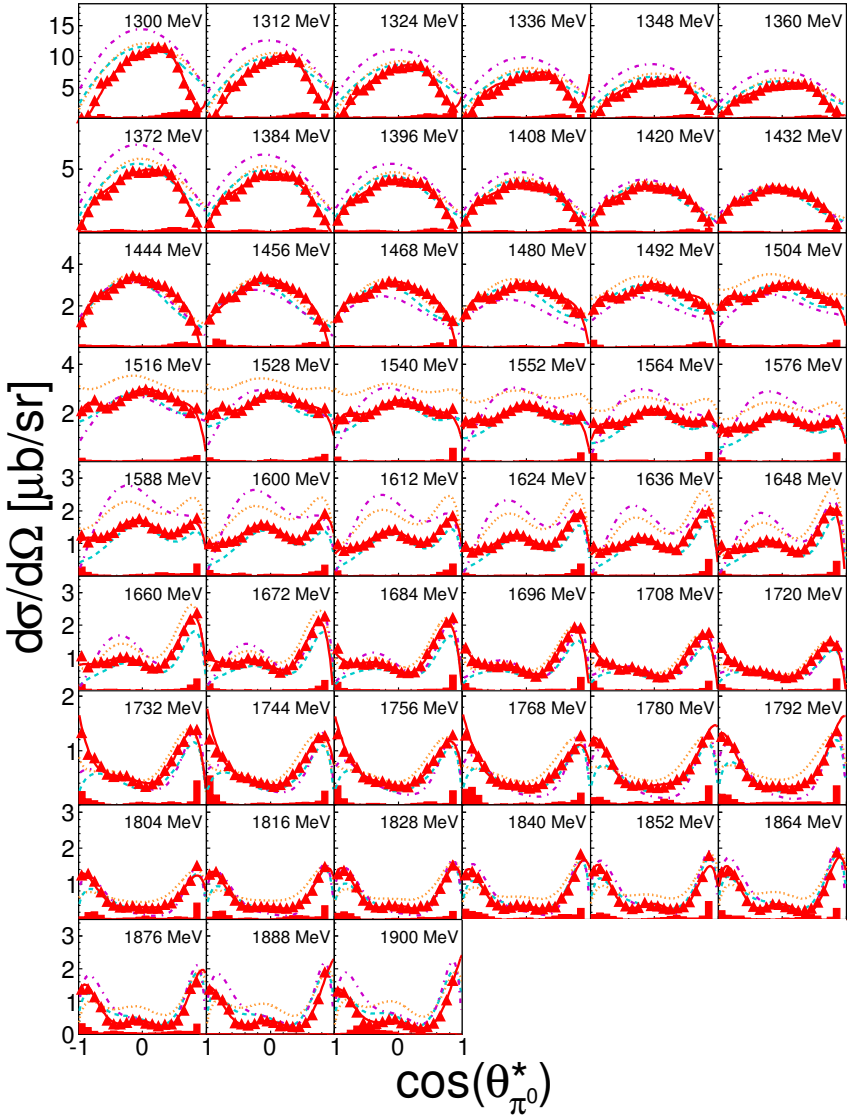


- compare qf-inclusive cross section with sum of proton and neutron cross sections $(\gamma n \to n\pi^0) + (\gamma p \to p\pi^0) \approx \gamma N \to (N)\pi^0$
- good agreement between two reconstructions
- good agreement with former data
- nucleon identification/detection under control

Free Cross Sections

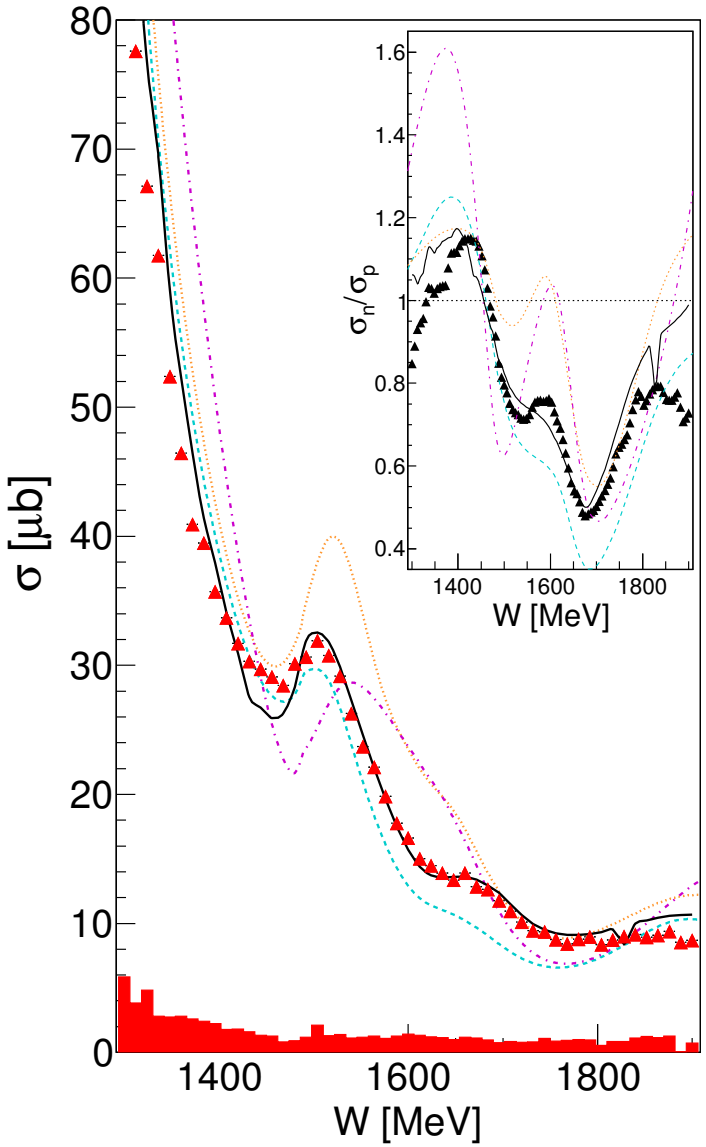
▲$\gamma n \rightarrow n\pi^0$ SAID MAID BnGa

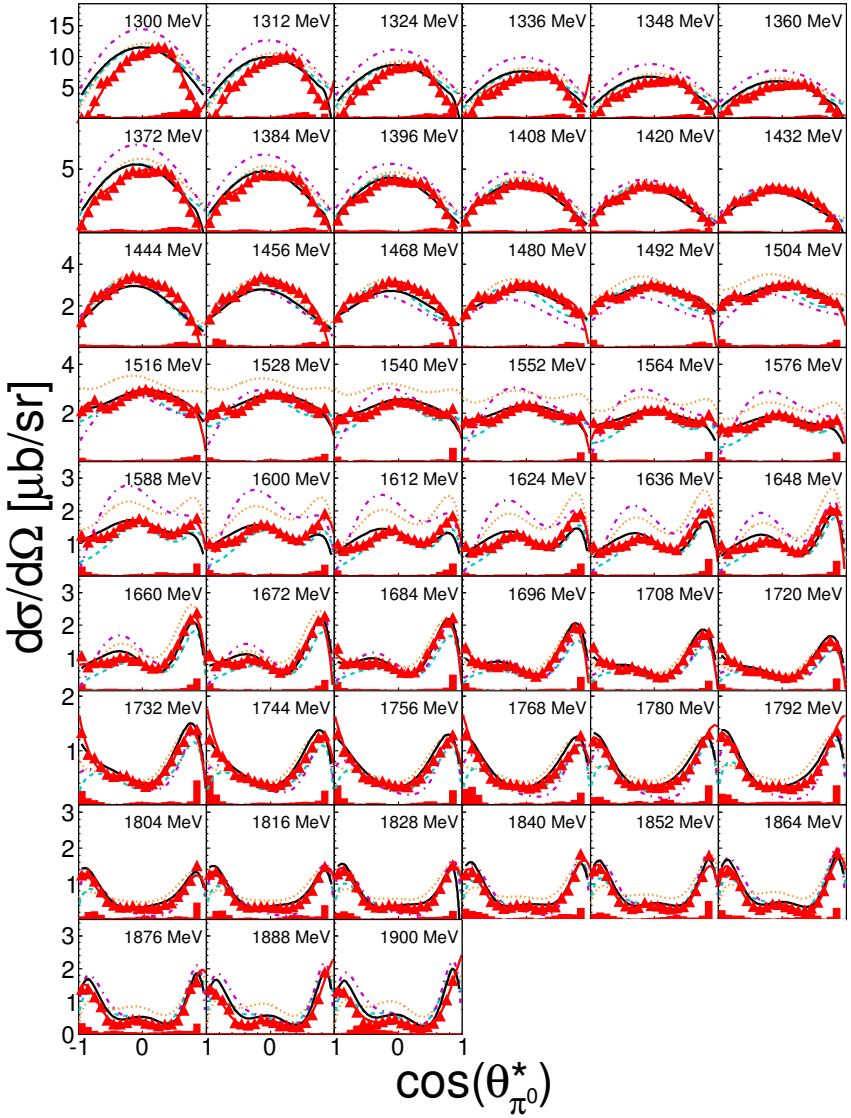




Free Cross Sections

$\blacktriangle \gamma n \rightarrow n\pi^0$ SAID MAID BnGa BnGa_refit

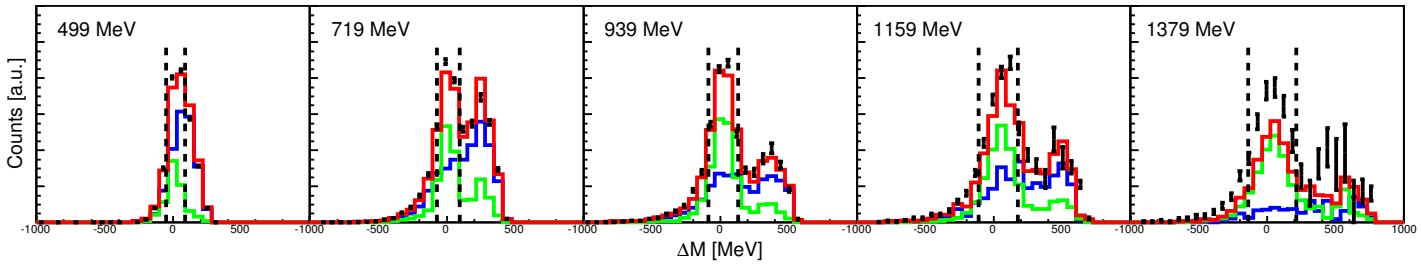




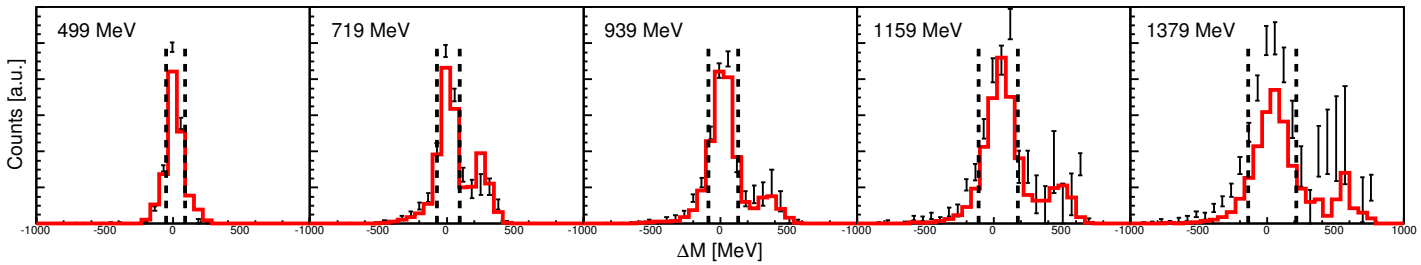
π^0 Carbon Subtraction

+ dButanol — Carbon — LD2 — LD2 + Carbon

p

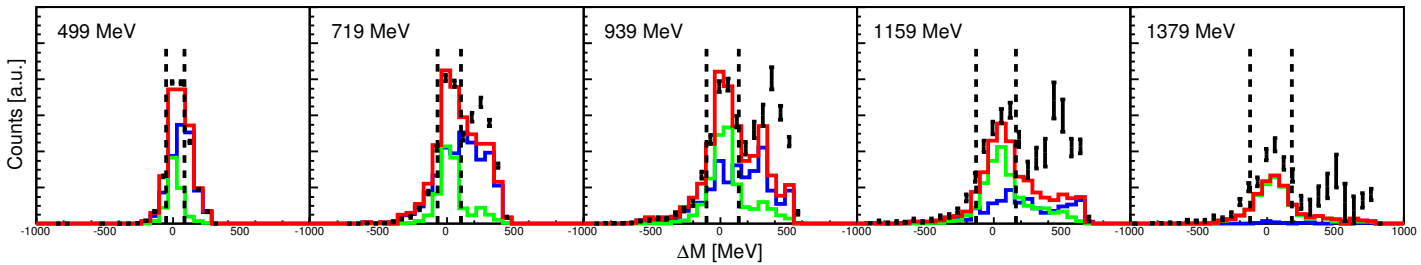


$-0.8 < \cos(\theta^*_{2\pi^0}) < -0.6$

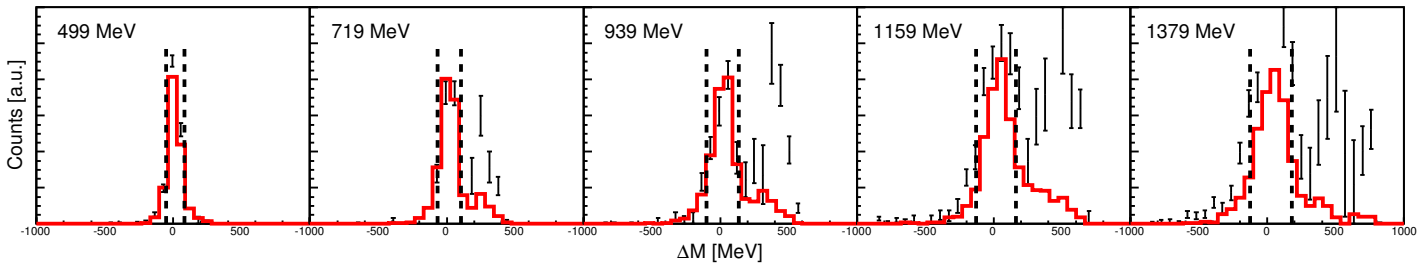


$-0.8 < \cos(\theta^*_{2\pi^0}) < 0.6$

n



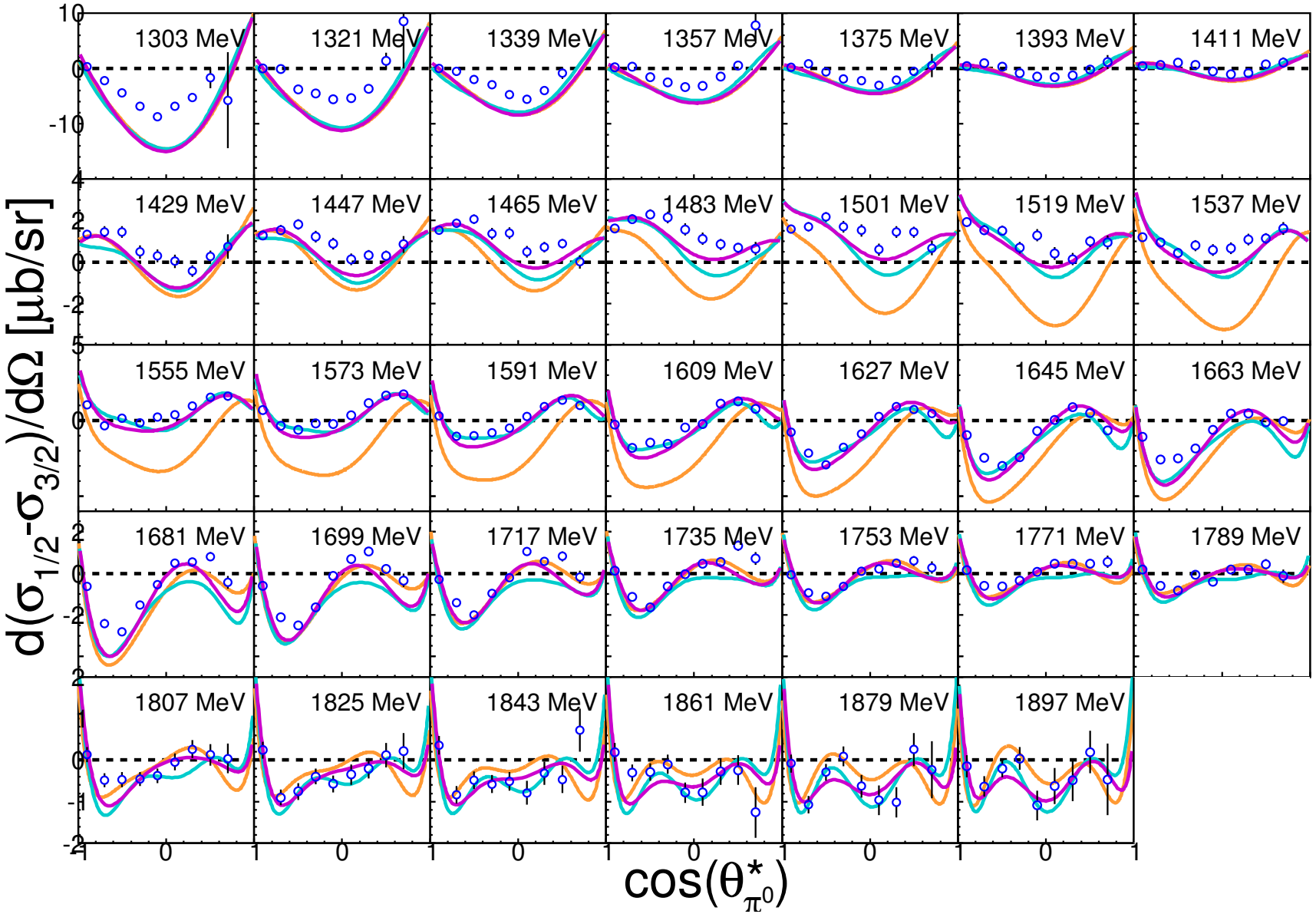
$-0.8 < \cos(\theta^*_{2\pi^0}) < -0.6$



$-0.8 < \cos(\theta^*_{2\pi^0}) < 0.6$

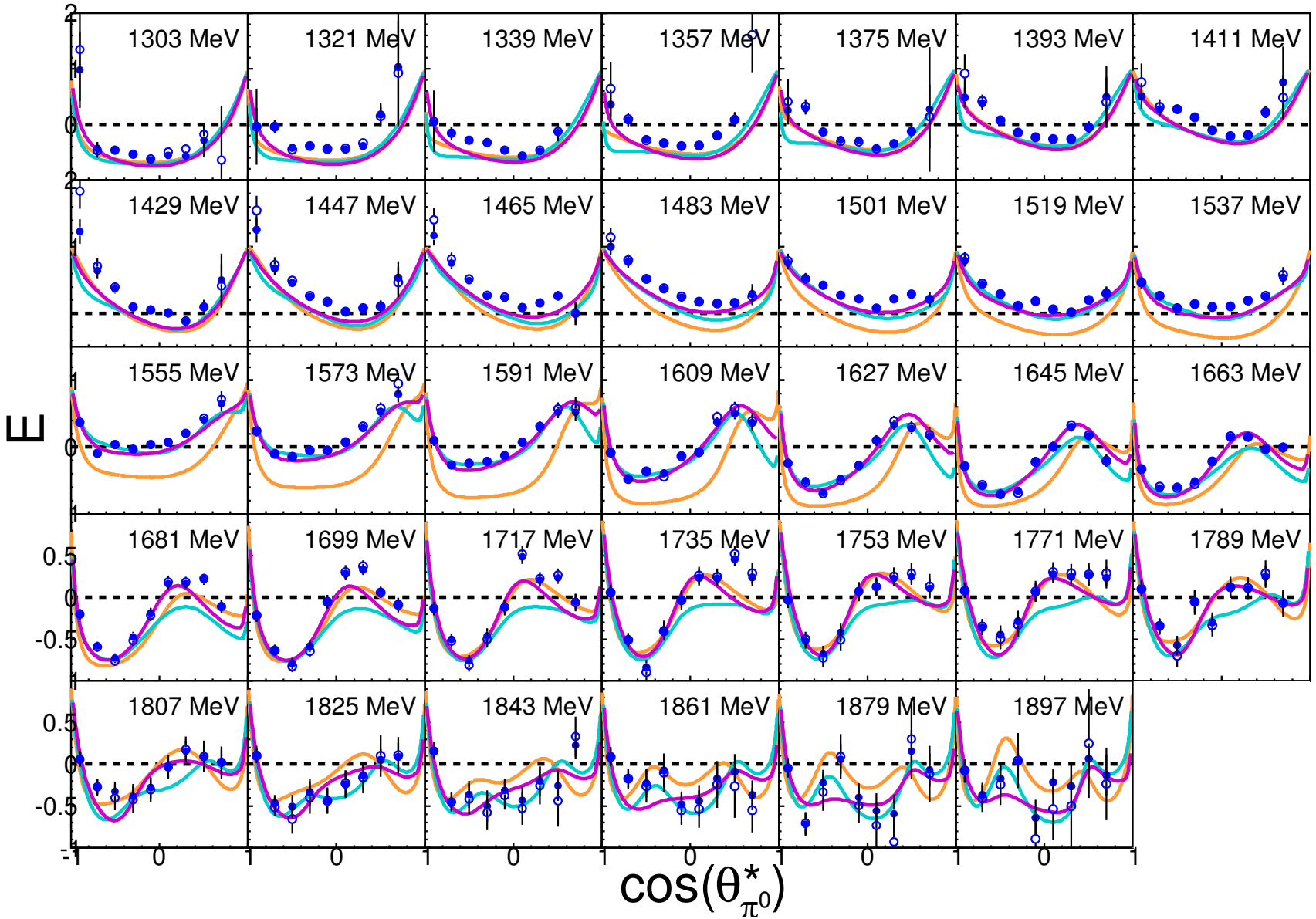
$\pi^0 p$ - $d(\sigma_{1/2} - \sigma_{3/2})/d\Omega$

• direct △ sum — SAID — MAID — BnGa



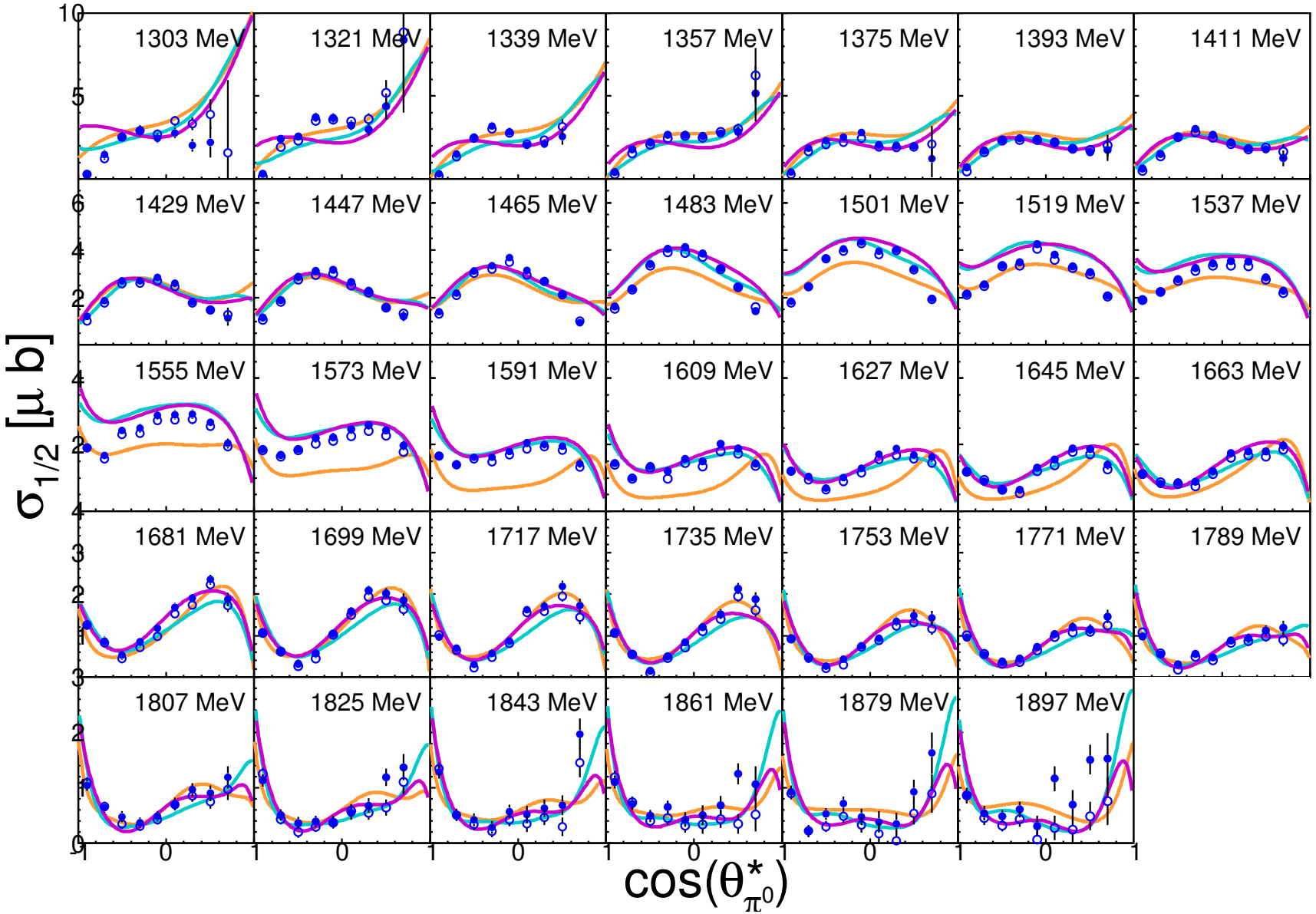
$\pi^0 p$ - $dE/d\Omega$

• direct △ sum — SAID — MAID — BnGa



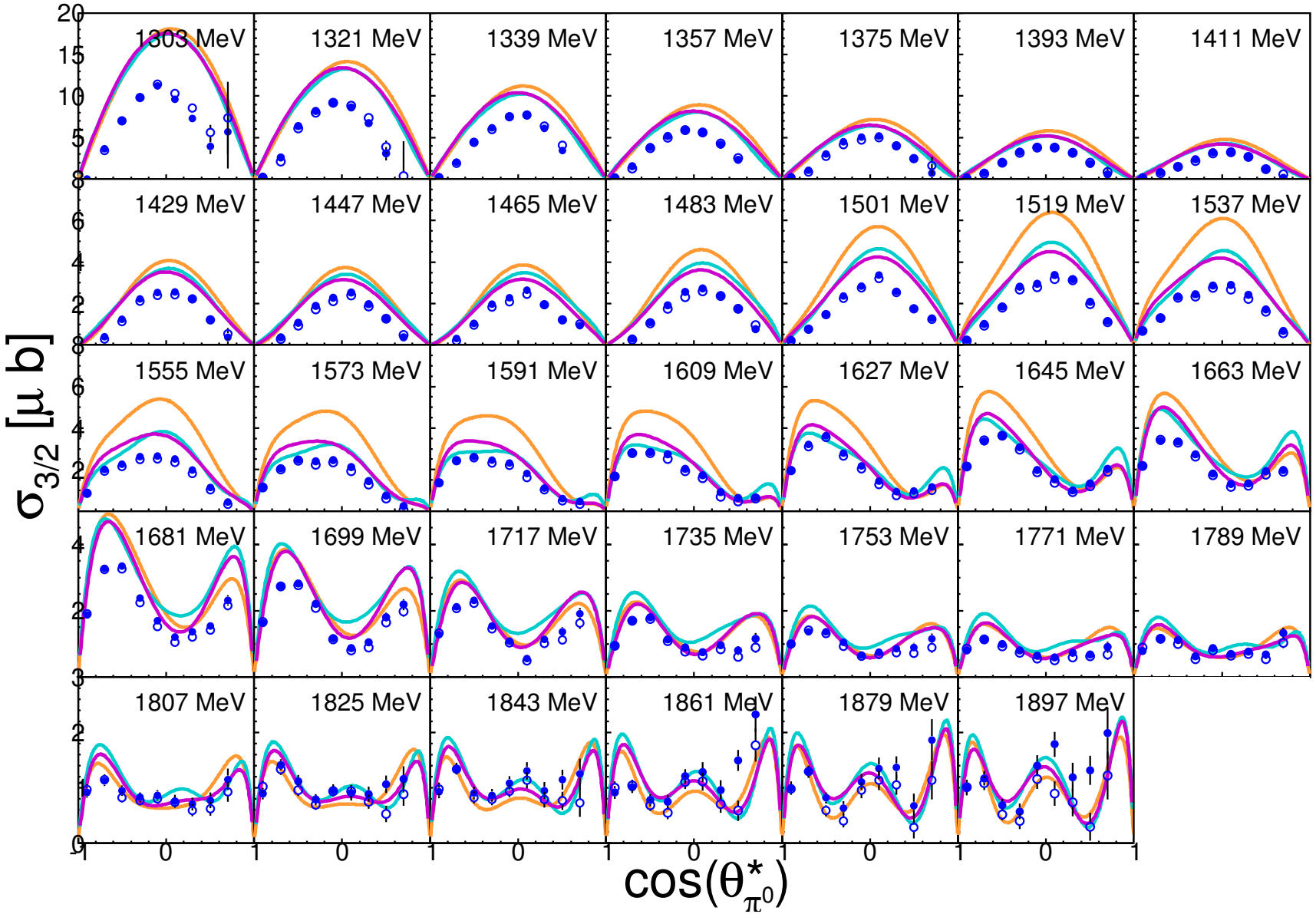
$\pi^0 p$ - $d\sigma_{1/2}/d\Omega$

● direct △ sum — SAID — MAID — BnGa



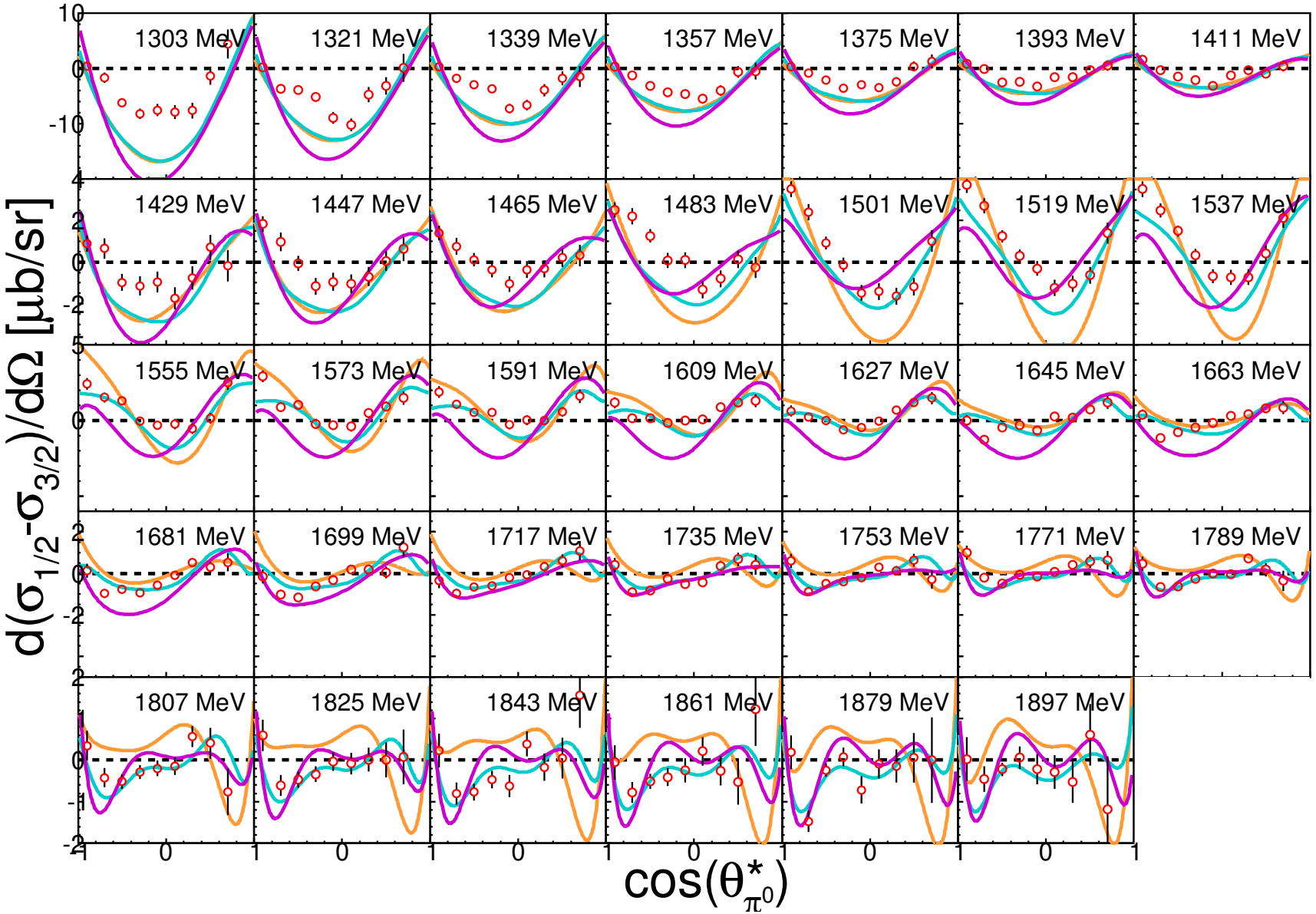
$\pi^0 p$ - $d\sigma_{3/2}/d\Omega$

● direct △ sum — SAID — MAID — BnGa



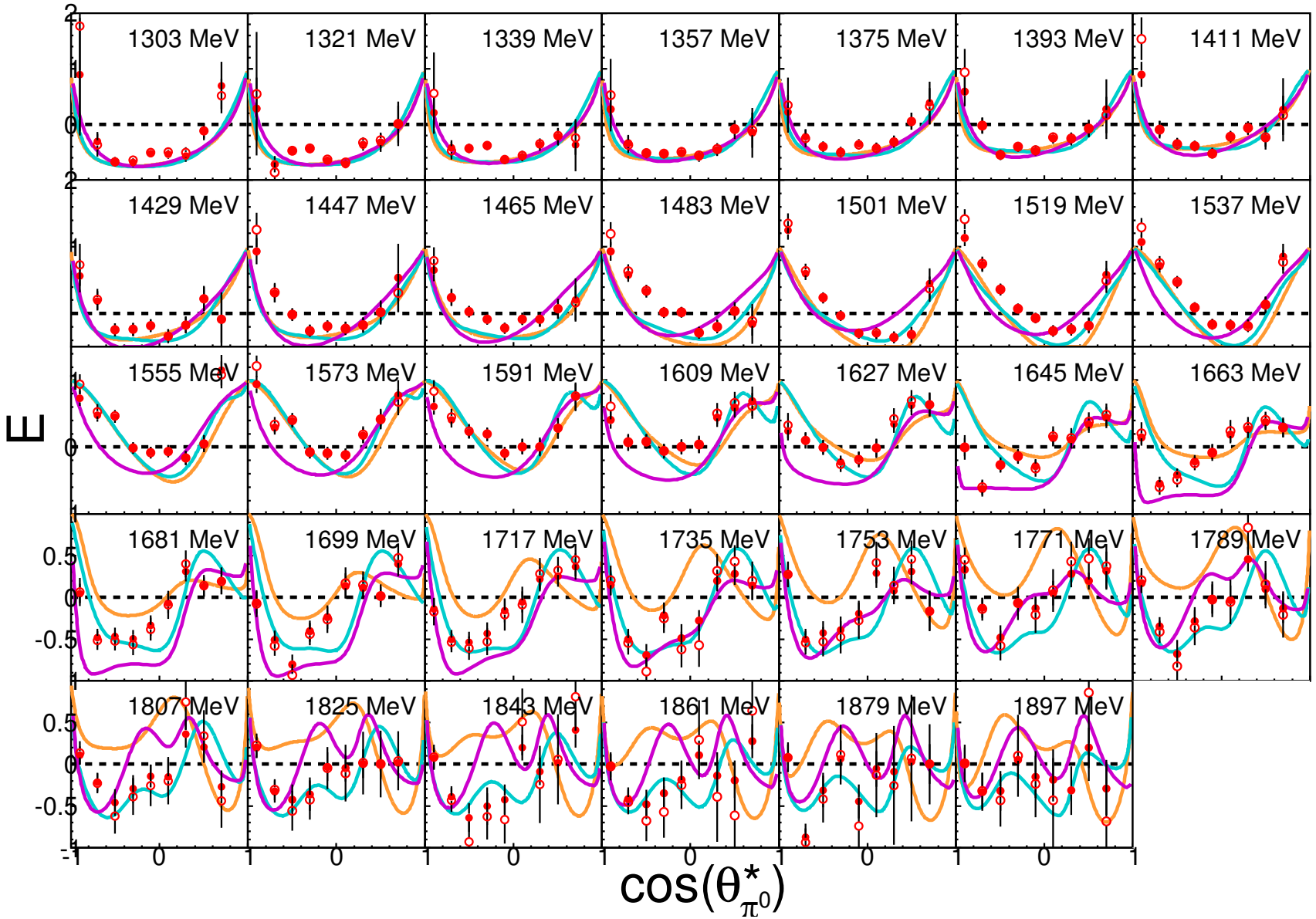
$\pi^0 n$ - $d(\sigma_{1/2} - \sigma_{3/2})/d\Omega$

• direct △ sum — SAID — MAID — BnGa



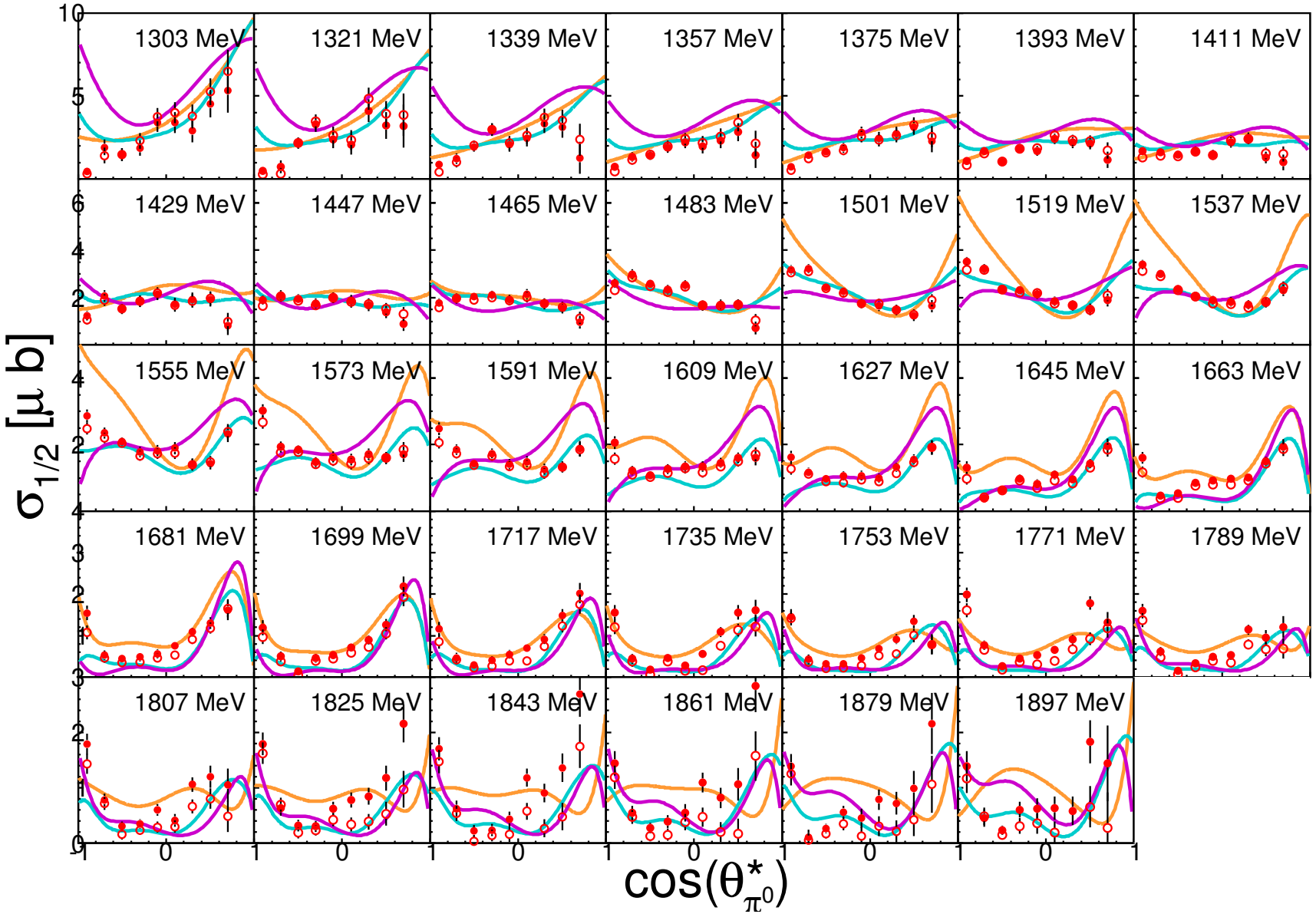
$\pi^0 n$ - $dE/d\Omega$

• direct △ sum — SAID — MAID — BnGa



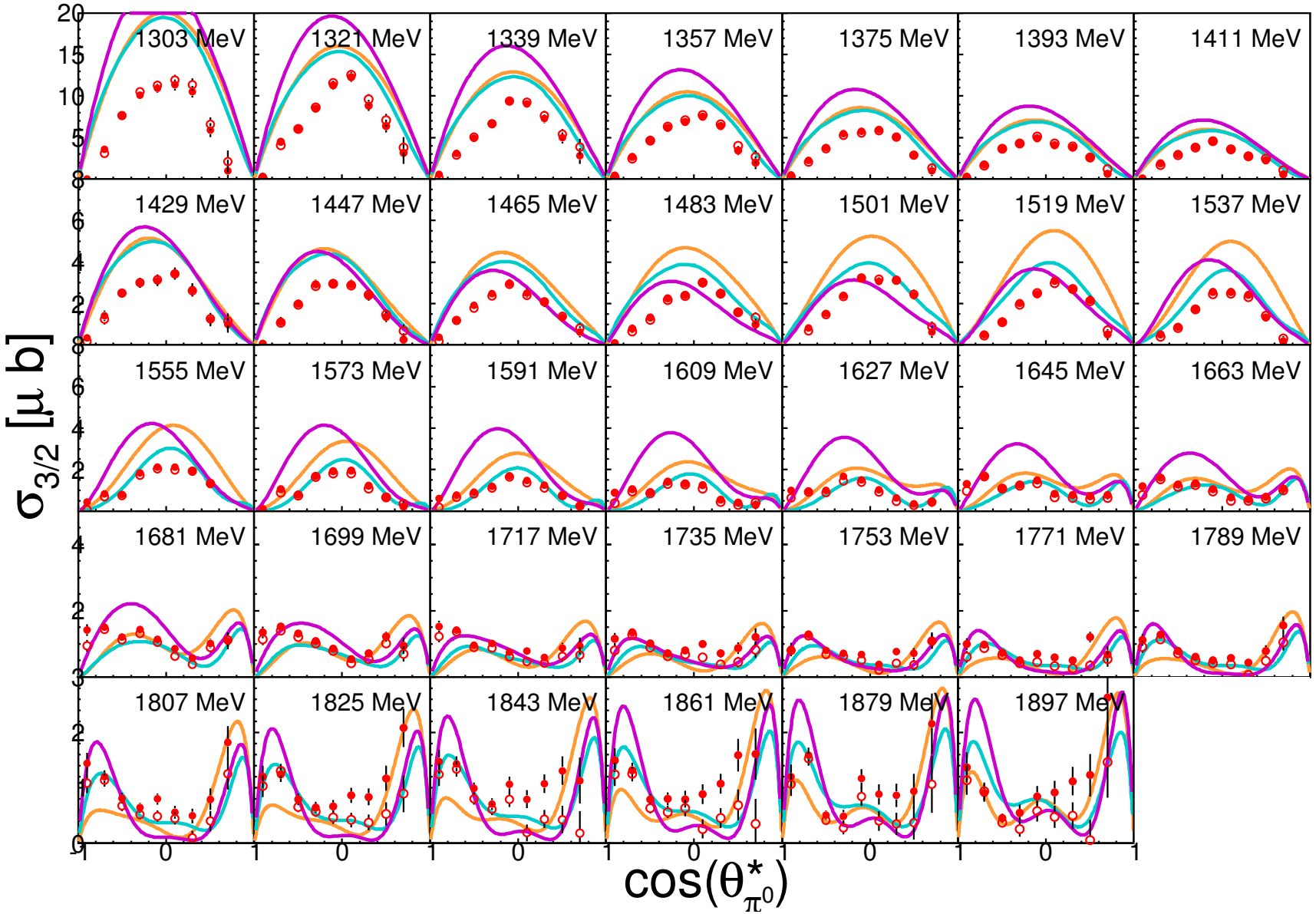
$\pi^0 n$ - $d\sigma_{1/2}/d\Omega$

• direct △ sum — SAID — MAID — BnGa



$\pi^0 n$ - $d\sigma_{3/2}/d\Omega$

• direct △ sum — SAID — MAID — BnGa



Reaction Identification

$$\gamma + \mathbf{p(n)} \rightarrow \mathbf{2\pi^0}(\rightarrow 4\gamma) + \mathbf{p(n)}$$

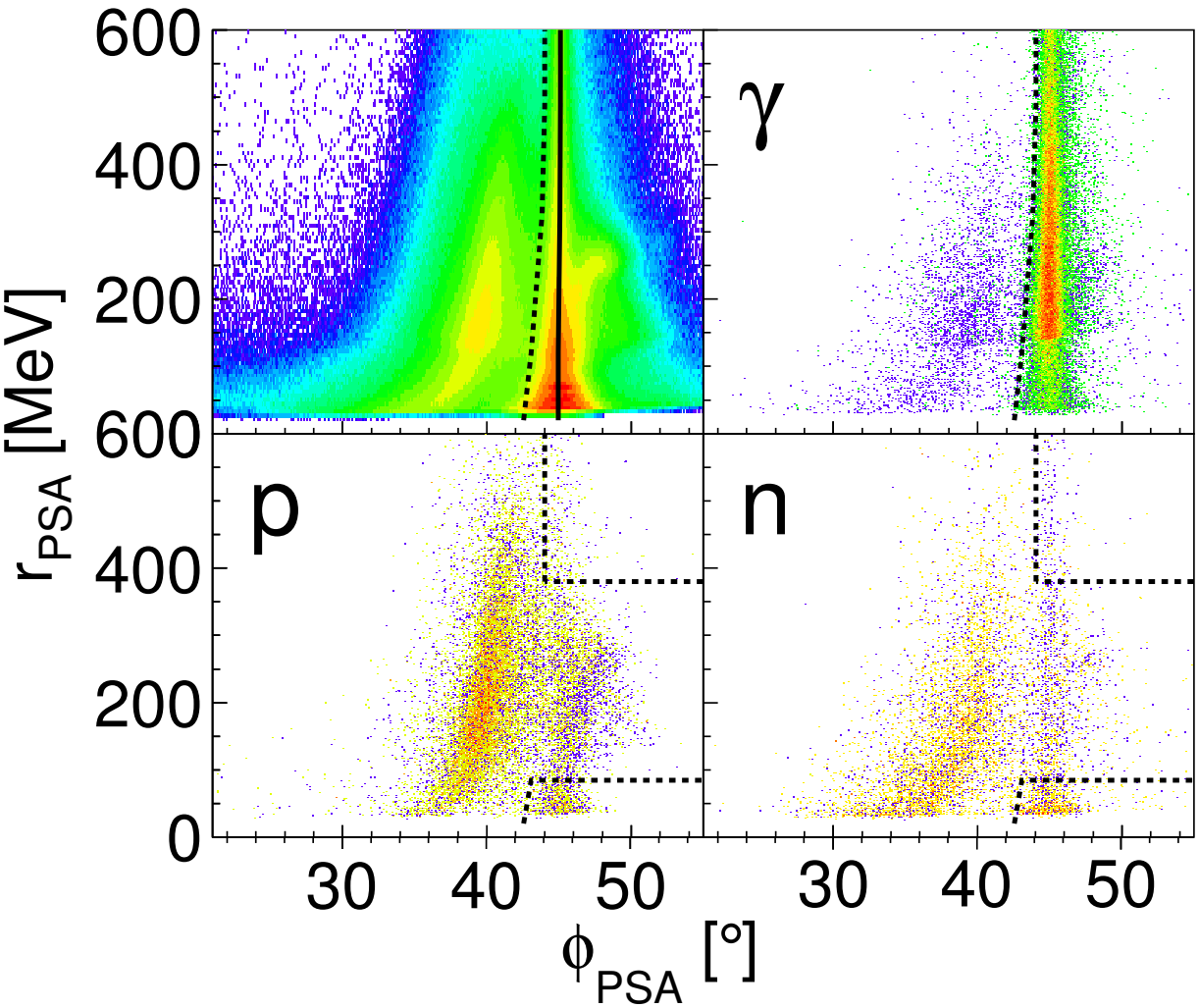
Reaction	**Requirement: exclusive**	**inclusive**
on Proton	4 neutral ($2\pi^0$) 1 charged (p)	4 neutral 1(0) charged
on Neutron	5 neutral ($2\pi^0 + n$) 0 charged	5(4) neutral 0 charged

χ^2**−test:** Reconstruct the $2\pi^0$ out of the neutral particles
(on Neutron: Remaining neutral hit is the Neutron candidate)

Pulse Shape Analysis (PSA) (Remove wrong candidates)

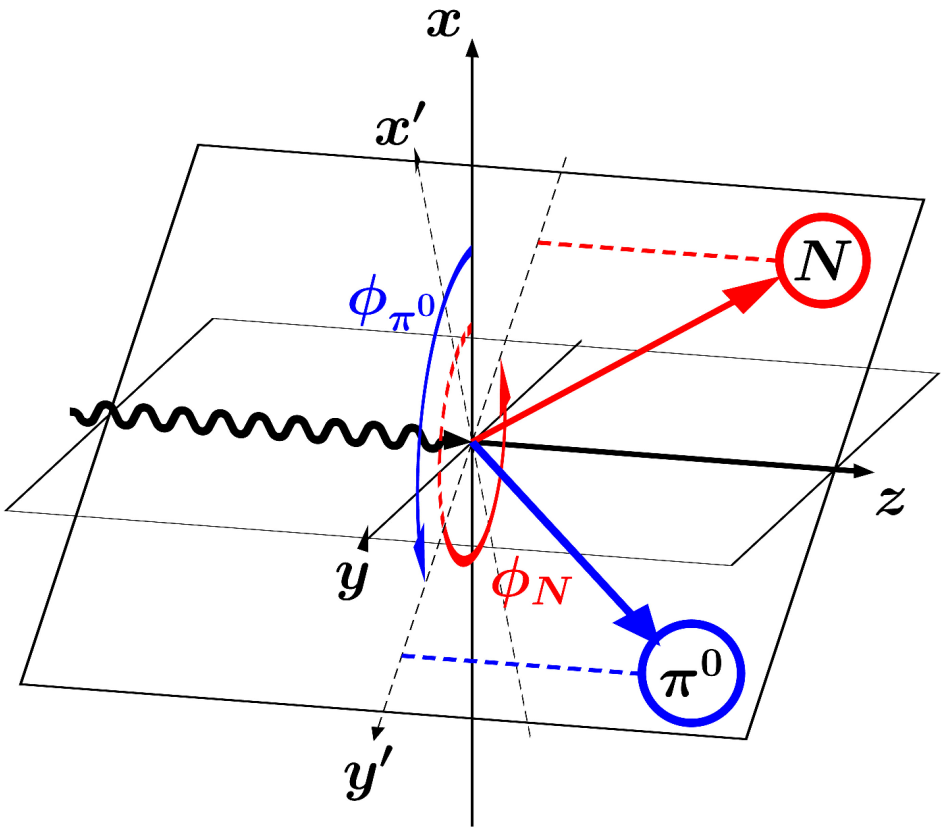
Photons: 3σ cut

Nucleons: exclusion zones 85 – 380 MeV

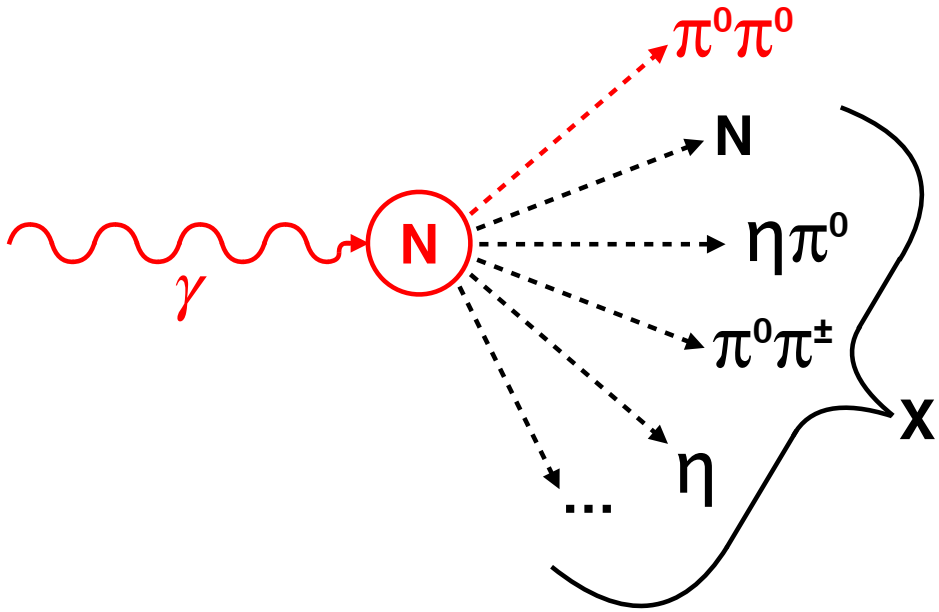


Reaction Identification

Coplanarity



Missing Mass



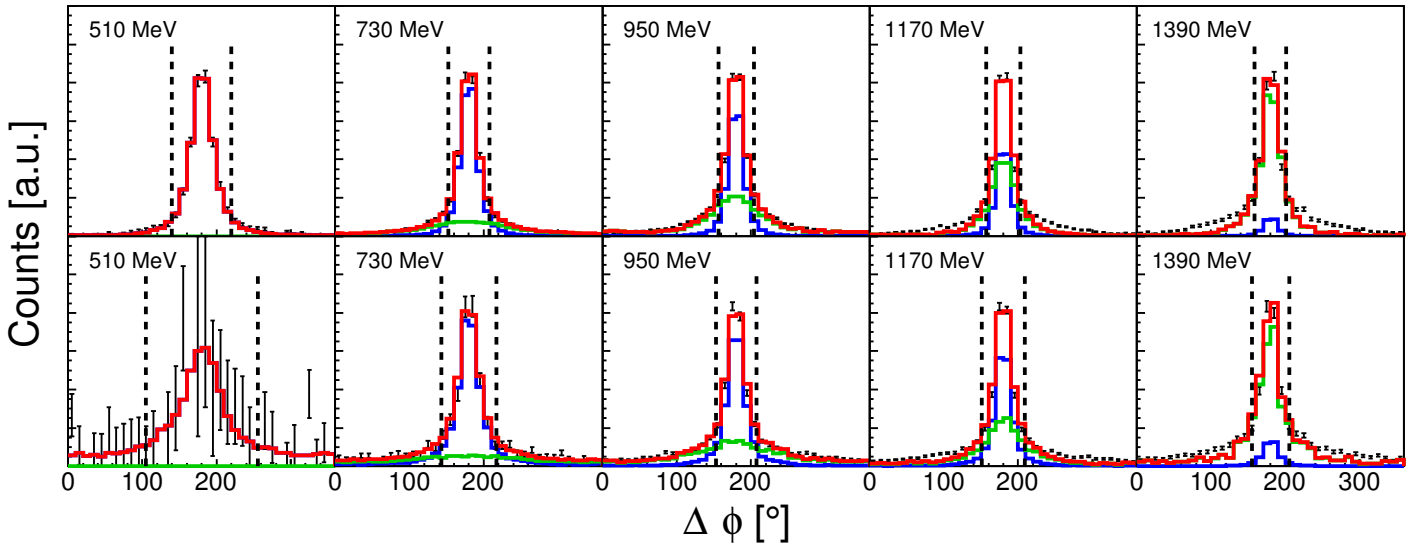
$$\Delta\phi = 360^\circ - |\phi_{2\pi^0} - \phi_N|$$

$$\Delta M = |\mathrm{P}_{\mathrm{Beam}} + \mathrm{P}_N - \mathrm{P}_{2\pi^0}| - m_N$$

Coplanarity Cut

+ LD2 — MC signal — MC bg — MC total — 2σ cut

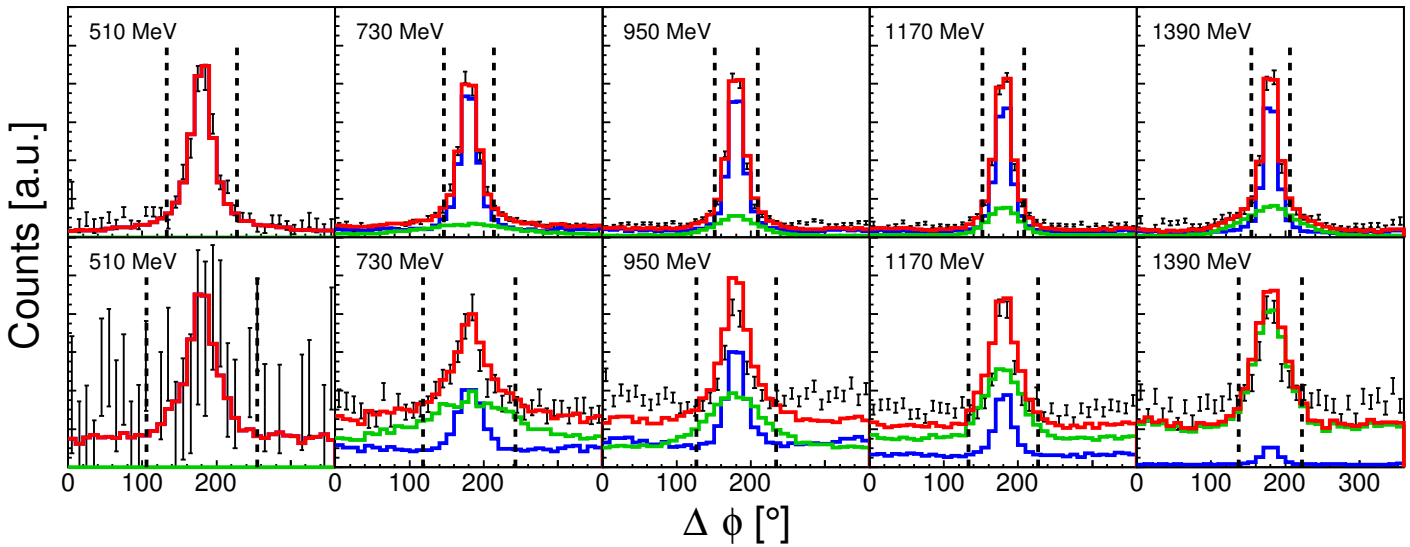
p



$-0.6 < \cos(\theta^*_{2\pi^0}) < -0.2$

$0.6 < \cos(\theta^*_{2\pi^0}) < 1.0$

n



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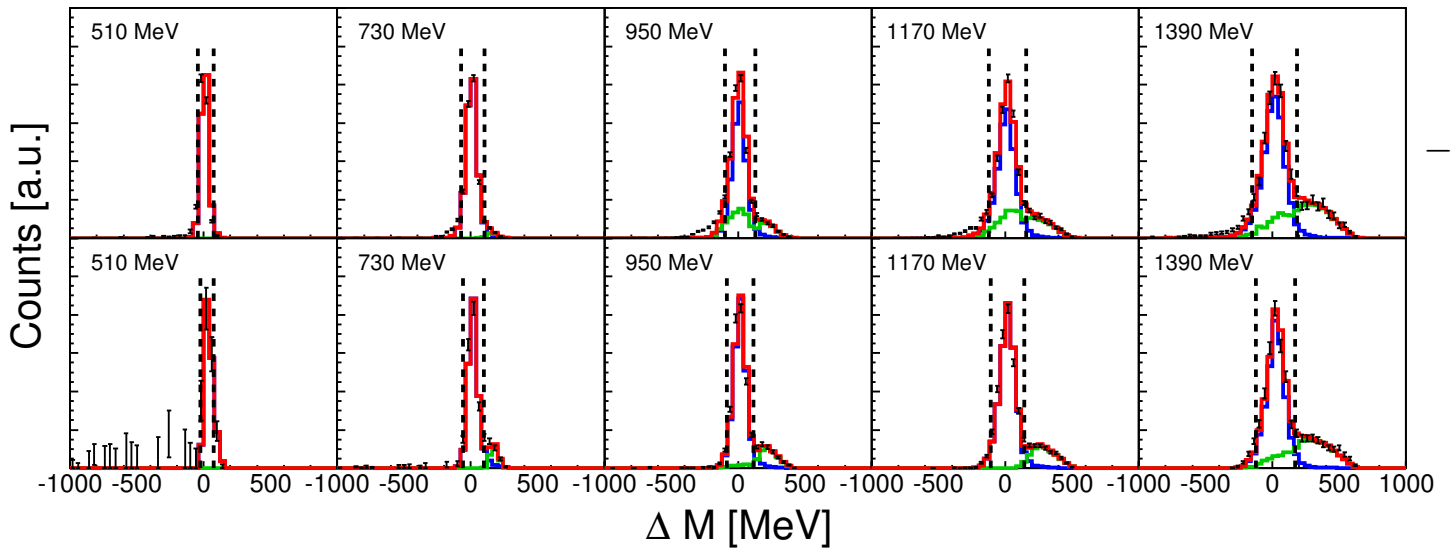
Missing Mass

+ LD2 — MC signal — MC bg — MC total — 2σ cut

p



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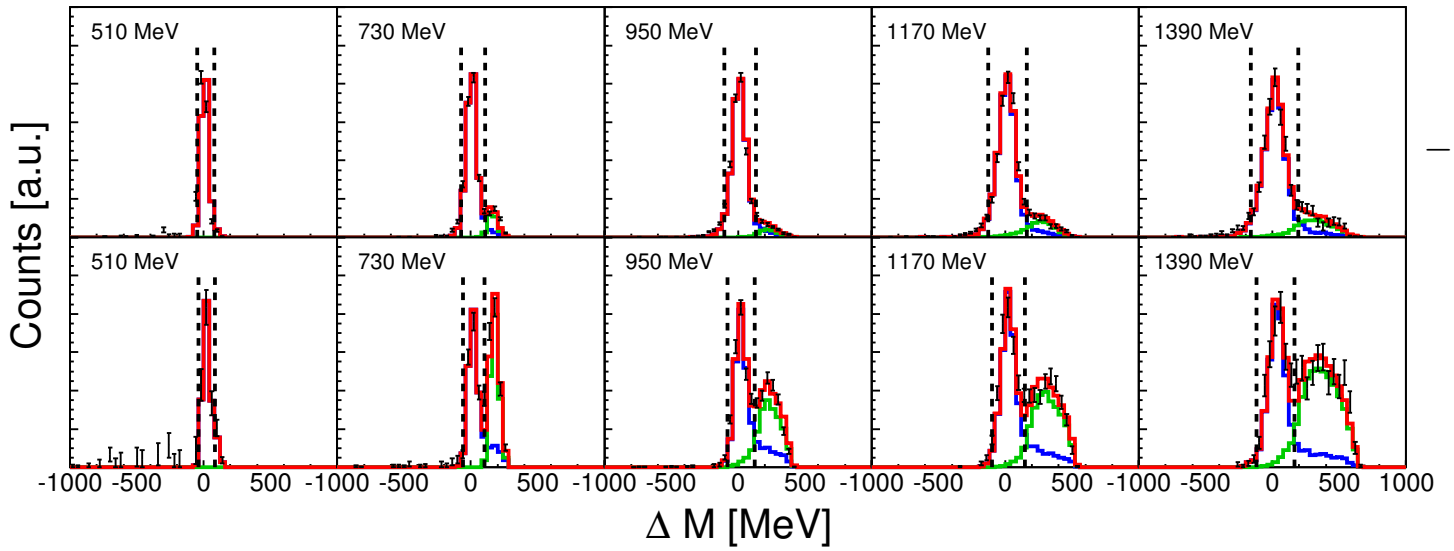


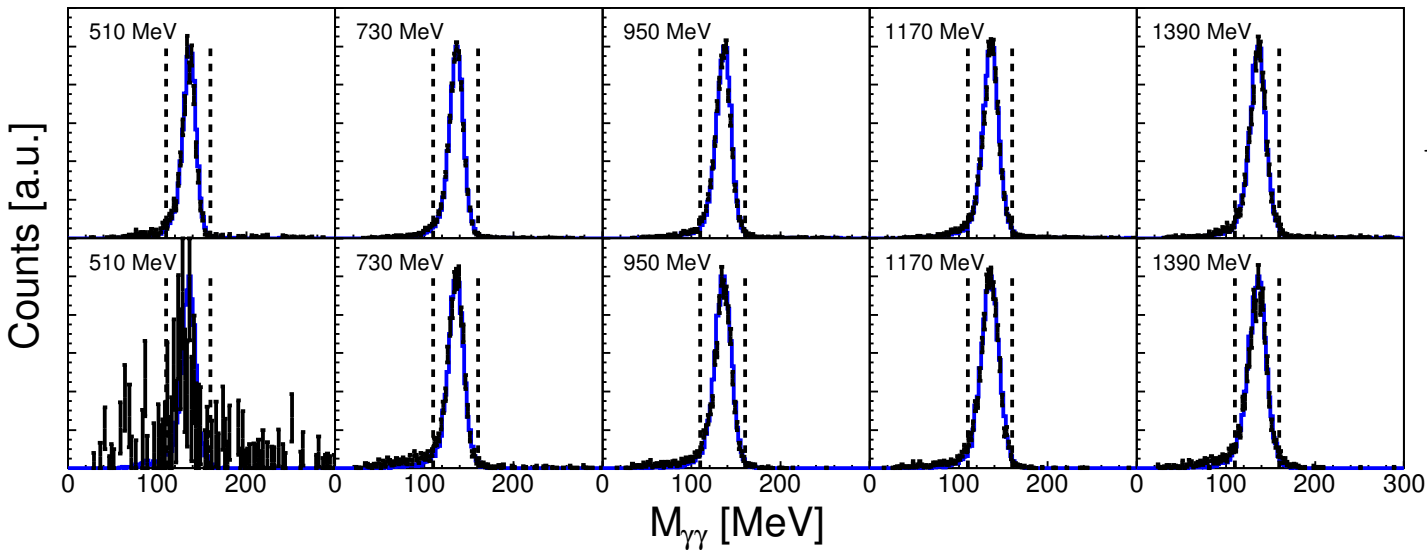
$-0.6 < \cos(\theta^*_{2\pi^0}) < -0.2$

$0.6 < \cos(\theta^*_{2\pi^0}) < 1.0$

Final Invariant Mass

+LD2 — MC proton — MC neutron — [110, 160] MeV cut

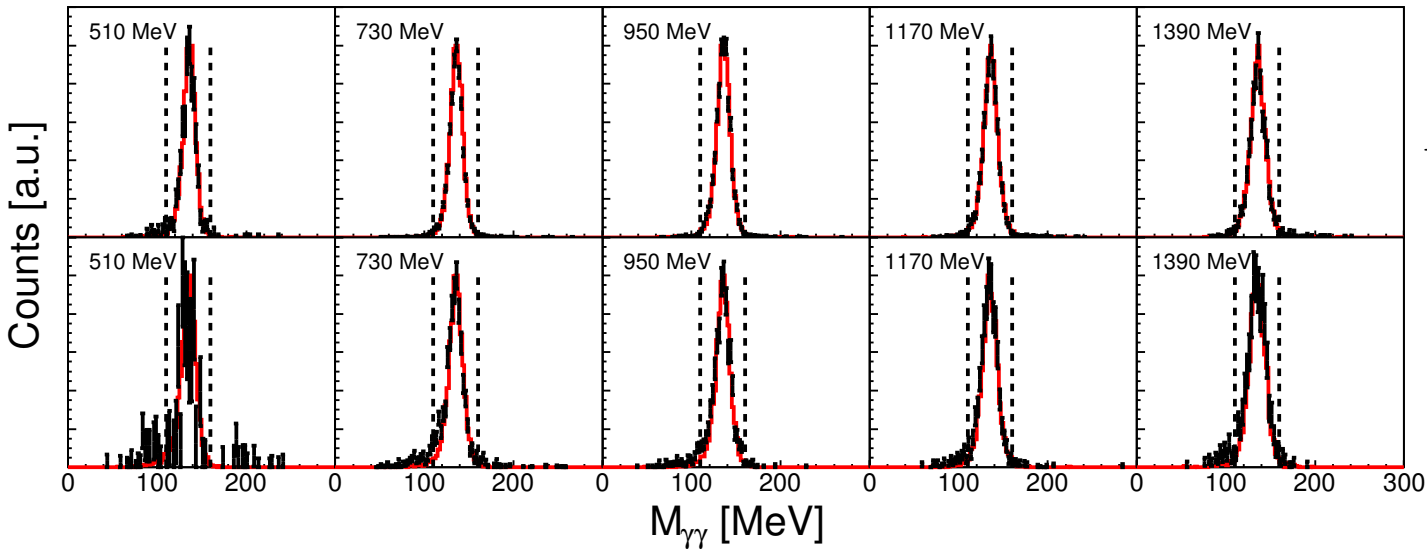
p



$-0.6 < \cos(\theta^*_{2\pi^0}) < -0.2$

$0.6 < \cos(\theta^*_{2\pi^0}) < 1.0$

n



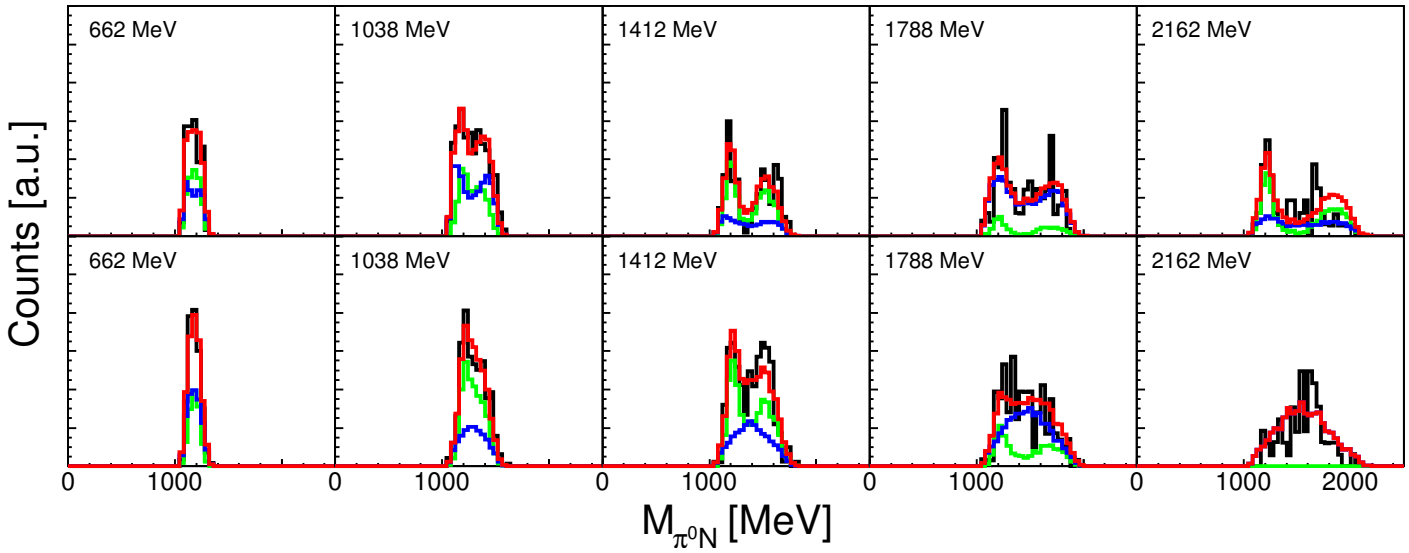
$-0.6 < \cos(\theta^*_{2\pi^0}) < -0.2$

$0.6 < \cos(\theta^*_{2\pi^0}) < 1.0$

Sequential Decays

+ Data — Phase Space — $\Delta^0(1232)$ — Sum

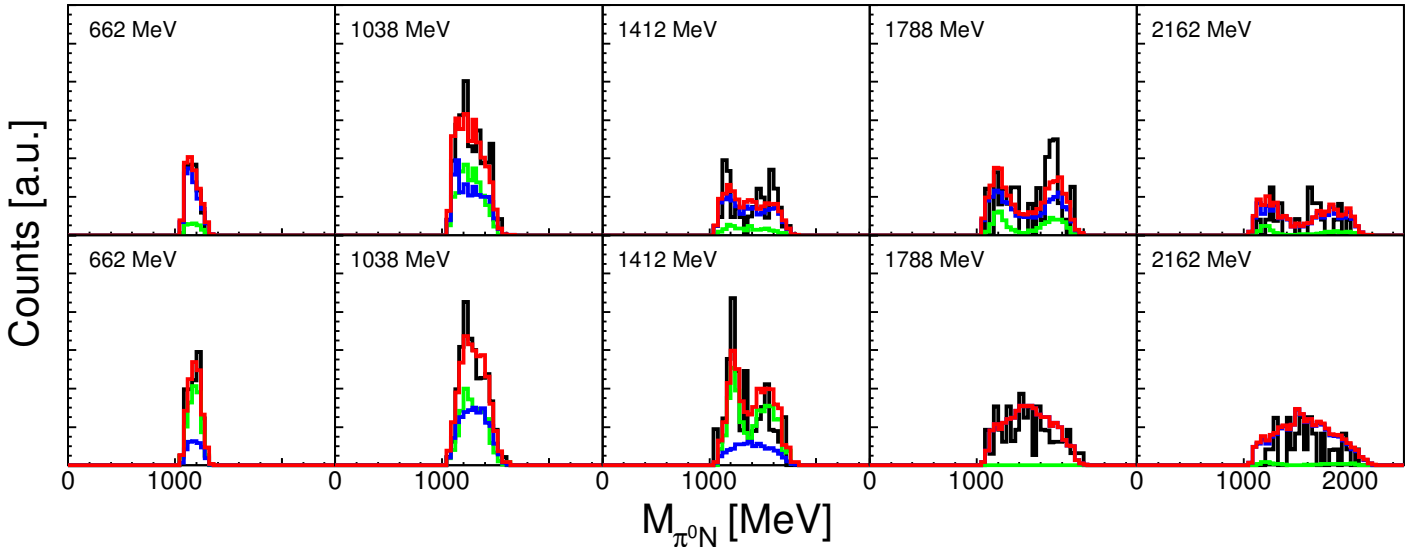
p



$-0.6 < \cos(\theta^*_{2\pi^0}) < -0.2$

$0.6 < \cos(\theta^*_{2\pi^0}) < 1.0$

n

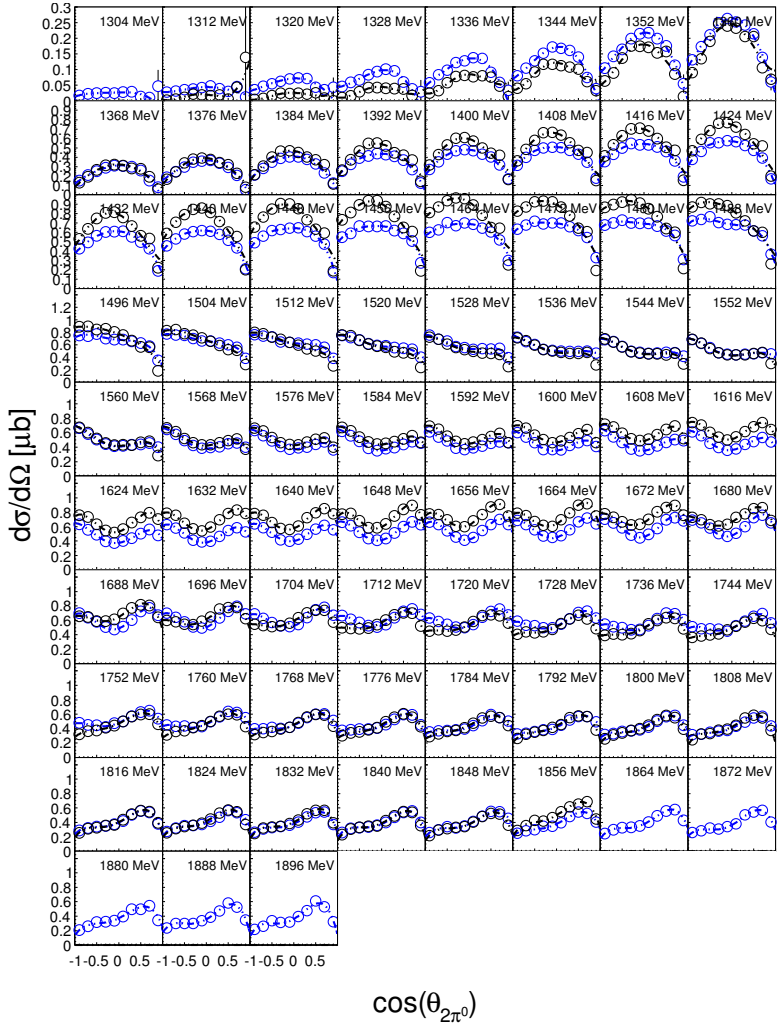


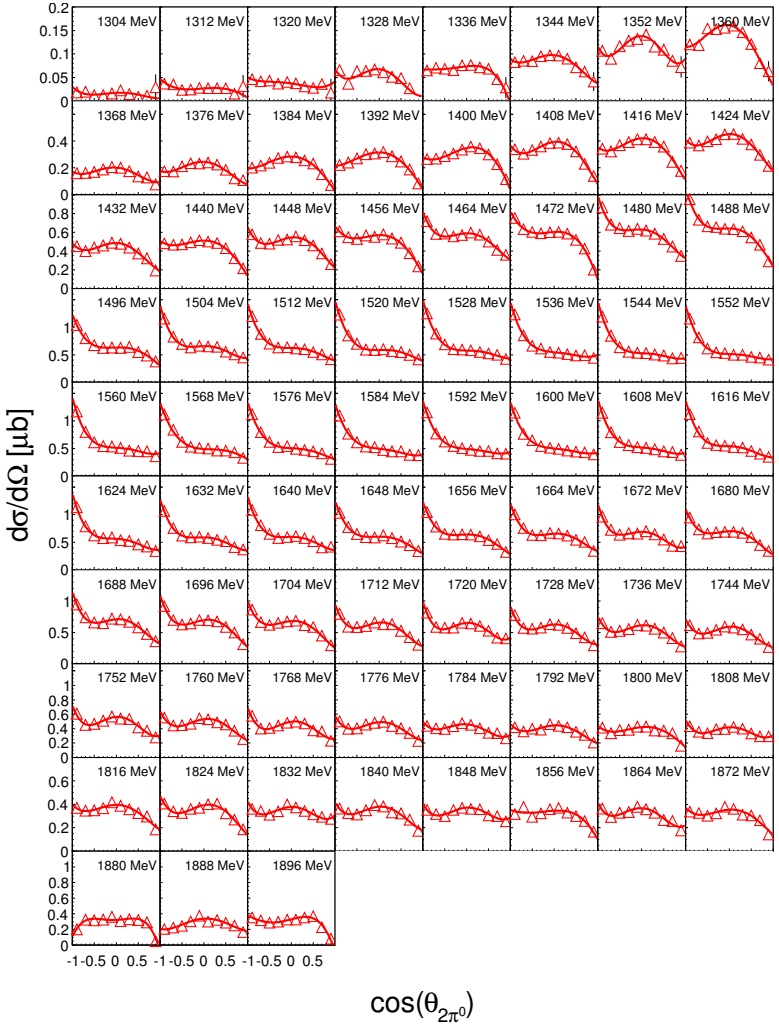
$-0.6 < \cos(\theta^*_{2\pi^0}) < -0.2$

$0.6 < \cos(\theta^*_{2\pi^0}) < 1.0$

$2\pi^0$ Photoproduction

○Proton ○Neutron

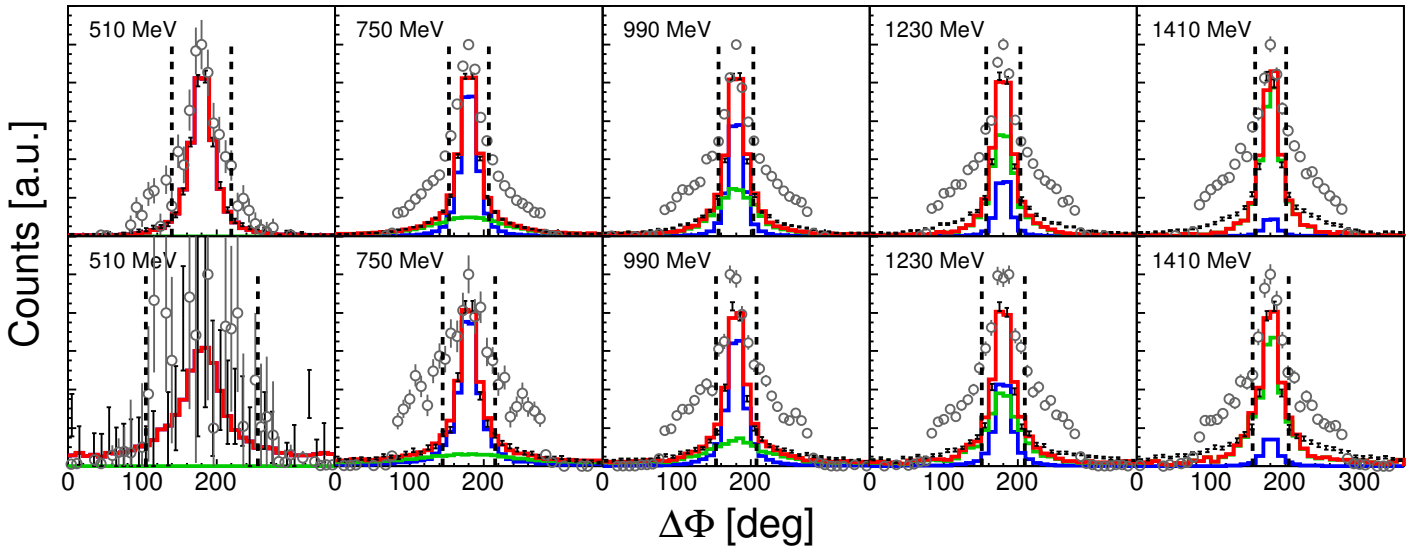




Coplanarity Cut

○ dButanol + LD2 — MC signal — MC bg — MC total — 2σ cut

p



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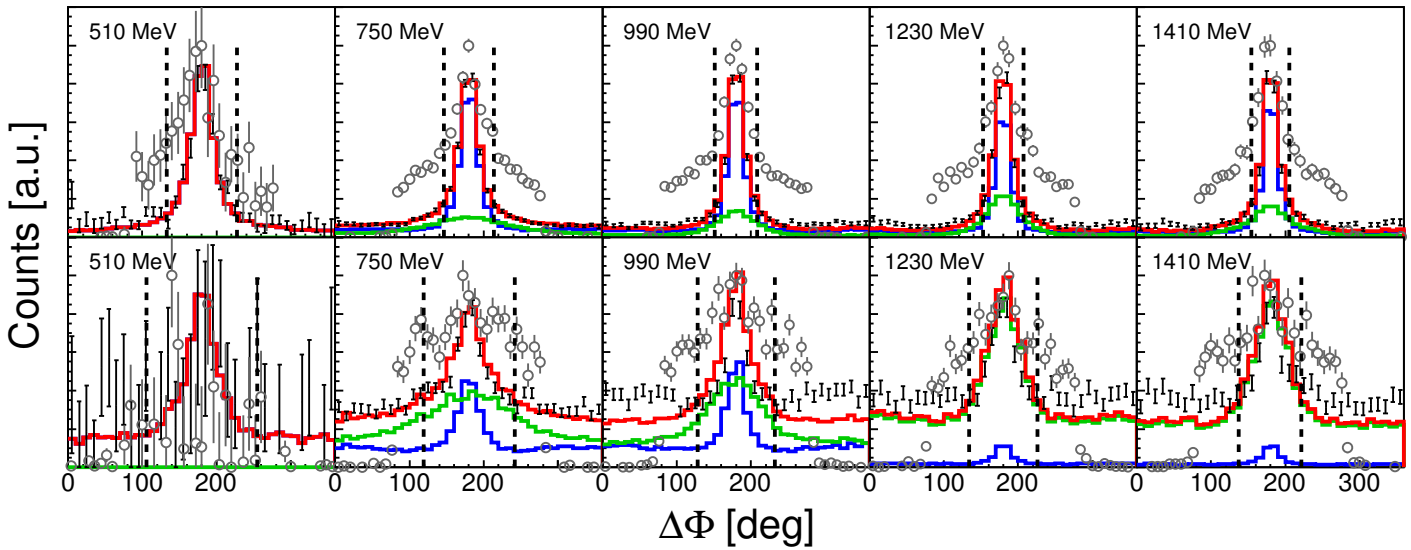
$0.6 < \cos(\theta^*_{2\pi^0}) < 1.0$

n



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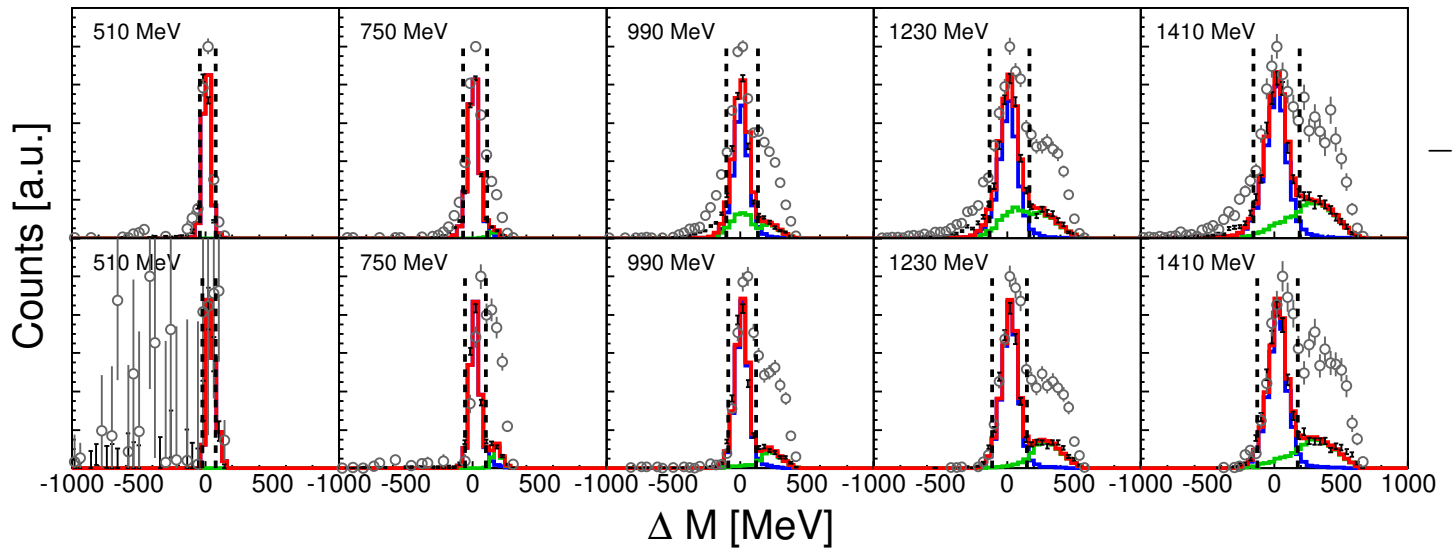
$0.6 < \cos(\theta^*_{2\pi^0}) < 1.0$

Missing Mass

○ dButanol + LD2 — MC signal — MC bg — MC total — 2σ cut

p



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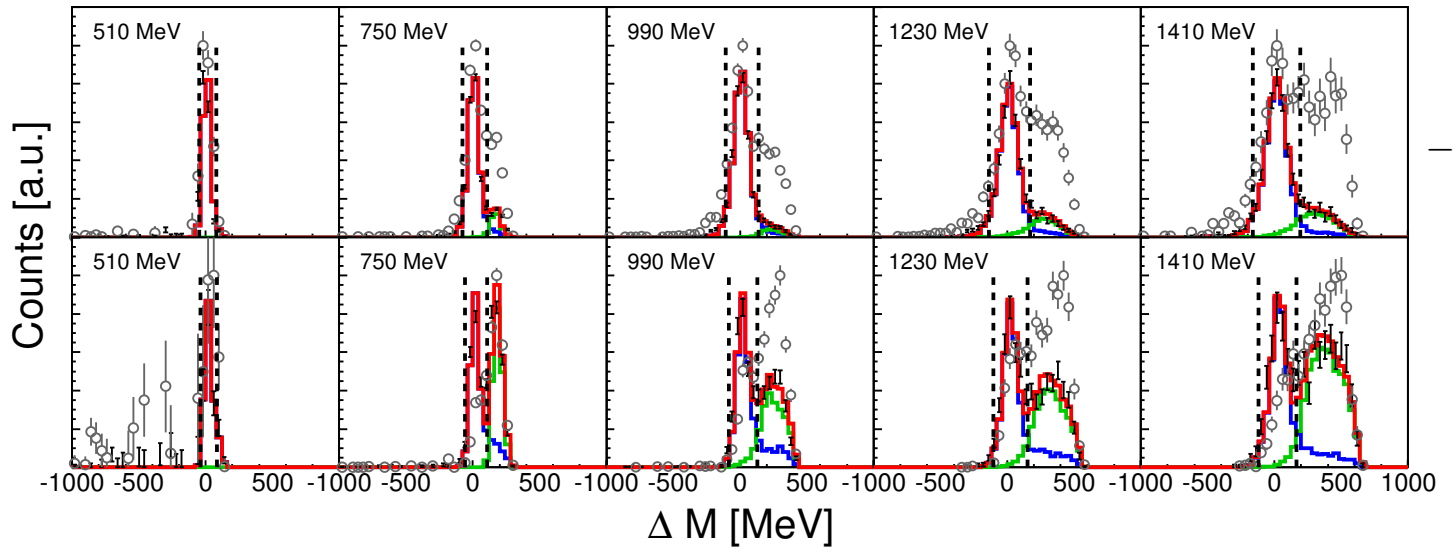
$0.6 < \cos(\theta^*_{2\pi^0}) < 1.0$

n



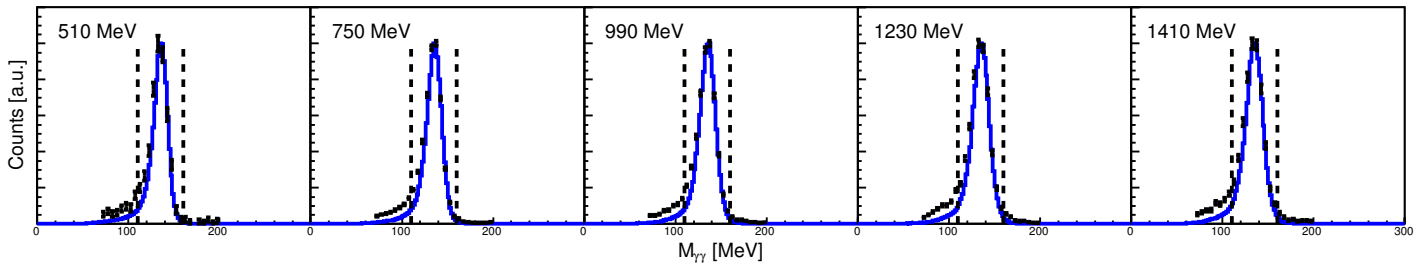
$-0.6 < \cos(\theta^*_{2\pi^0}) < -0.2$

$0.6 < \cos(\theta^*_{2\pi^0}) < 1.0$

Final Invariant Mass

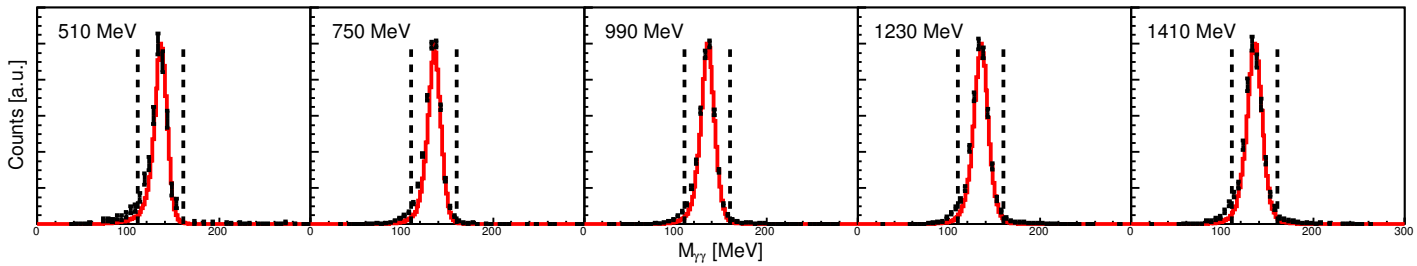
+ C_4D_9OD — MC proton — MC neutron — [110, 160] MeV cut

p



$-1.0 < \cos(\theta^*_{2\pi^0}) < 1.0$

n

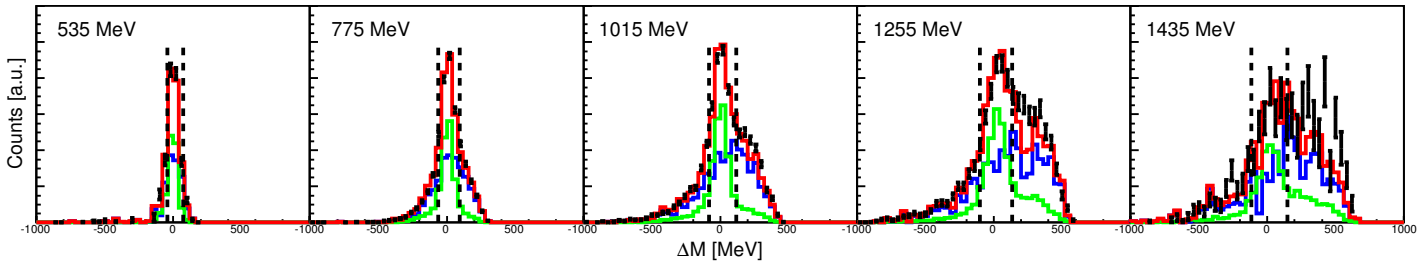


$-1.0 < \cos(\theta^*_{2\pi^0}) < 1.0$

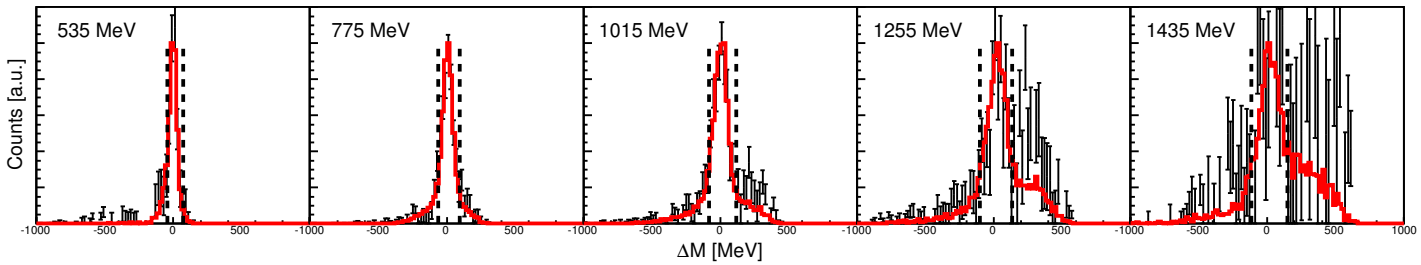
Carbon Subtraction

●dButanol — Carbon — LD2 — LD2 + Carbon

p

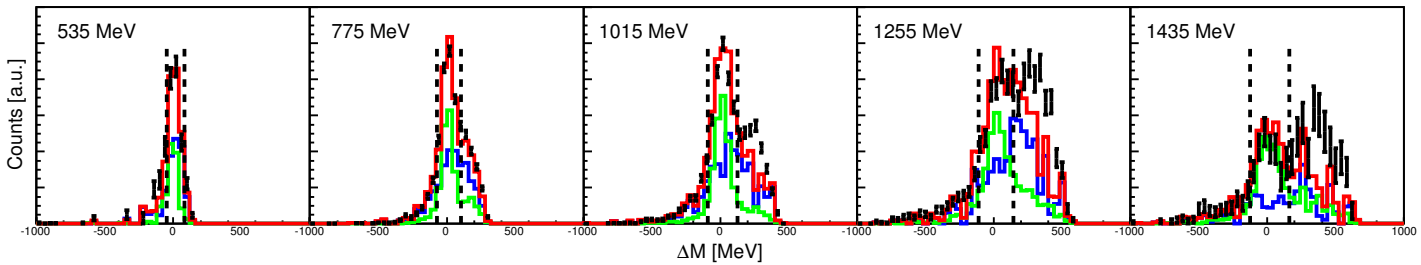


$-0.6 < \cos(\theta^*_{2\pi^0}) < -0.2$

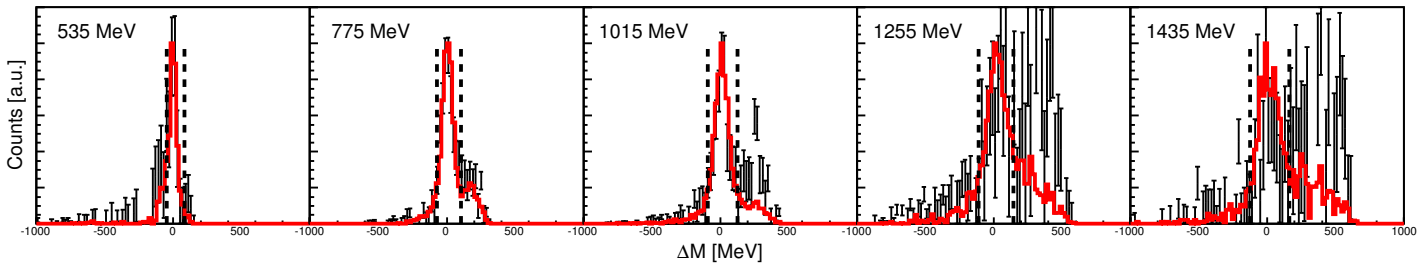


$0.6 < \cos(\theta^*_{2\pi^0}) < 1.0$

n



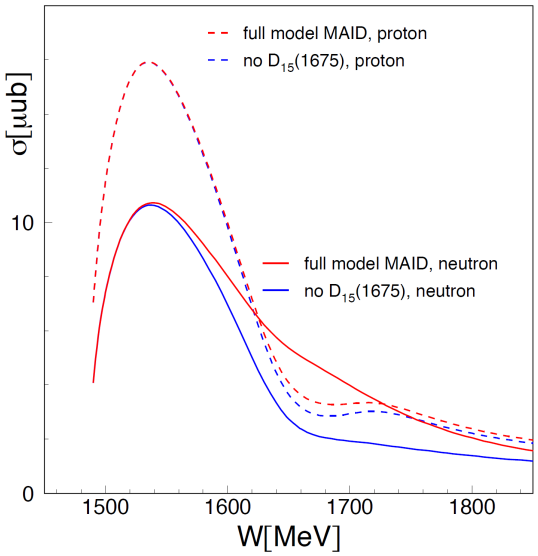
$-0.6 < \cos(\theta^*_{2\pi^0}) < -0.2$



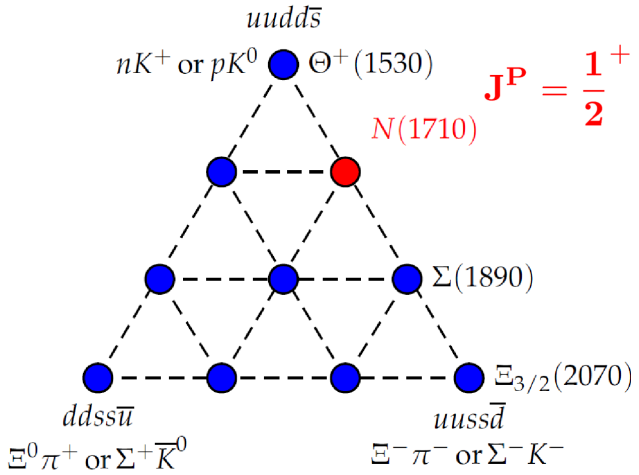
$0.6 < \cos(\theta^*_{2\pi^0}) < 1.0$

η Photoproduction

1. **etaMAID:**
   Large contribution of the $D_{15}(1675)$
   ➢ high value for the branching ratio of $\Gamma_{\eta N}/\Gamma_{tot} = 17\%$
   (PDG: $\Gamma_{\eta N}/\Gamma \simeq 0 - 1\%$)
   (L.Tiator, NSTAR2005)

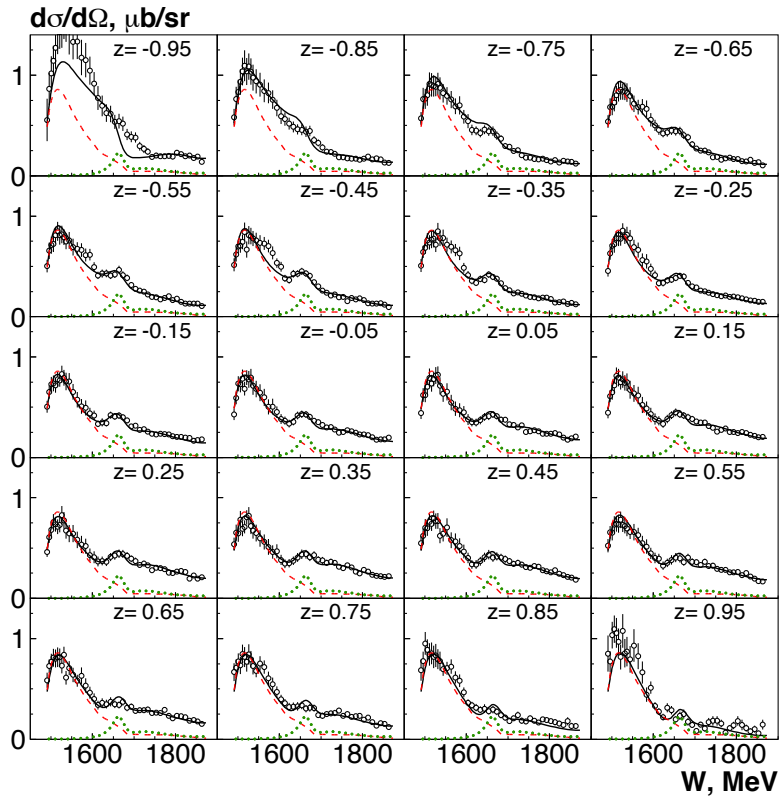


2. **Chiral Soliton model:**
   non-strange member of the baryon antidecuplet: $P_{11}(1680)$.
   bigger coupling to the neutron than to the proton
   (D.Diakonov et al., arXiv:hep-ph/9703373v2)

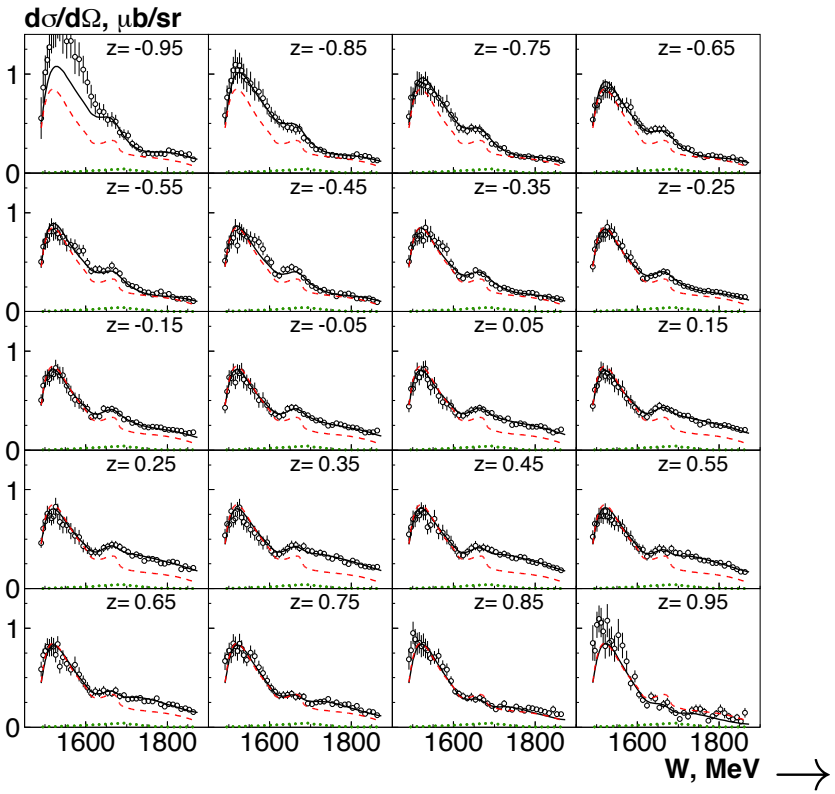


Narrow Structure: Fit with BnGa

Narrow $P_{11}(1685)$:



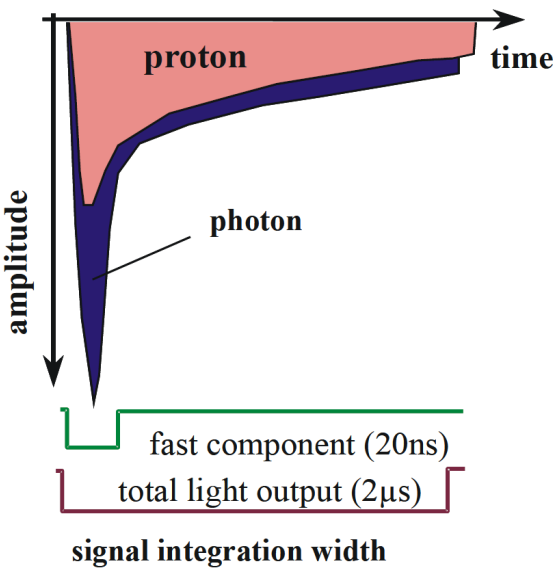
$S_{11}(1650)$ Interference :

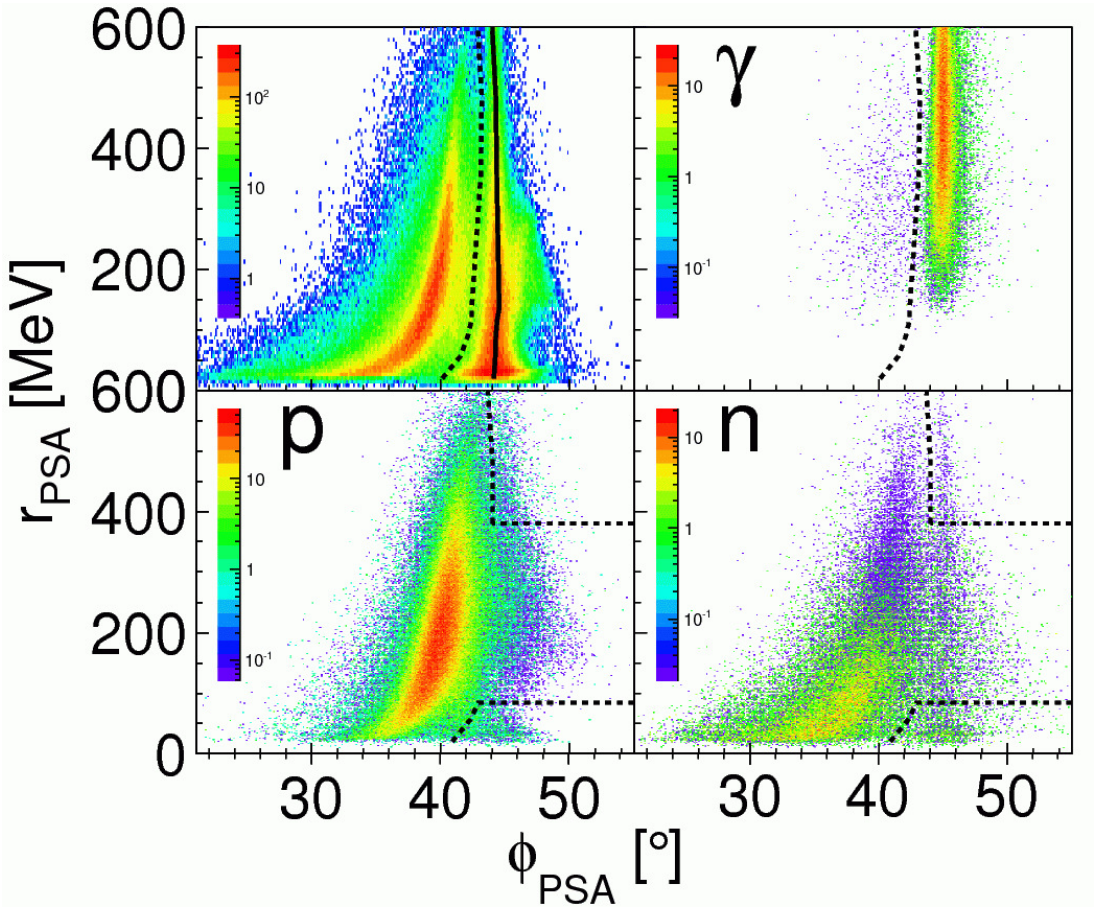


sign change of elm.

$A_{1/2}$coupling of $S_{11}(1650)$

Pulse Shape Analysis (TAPS)



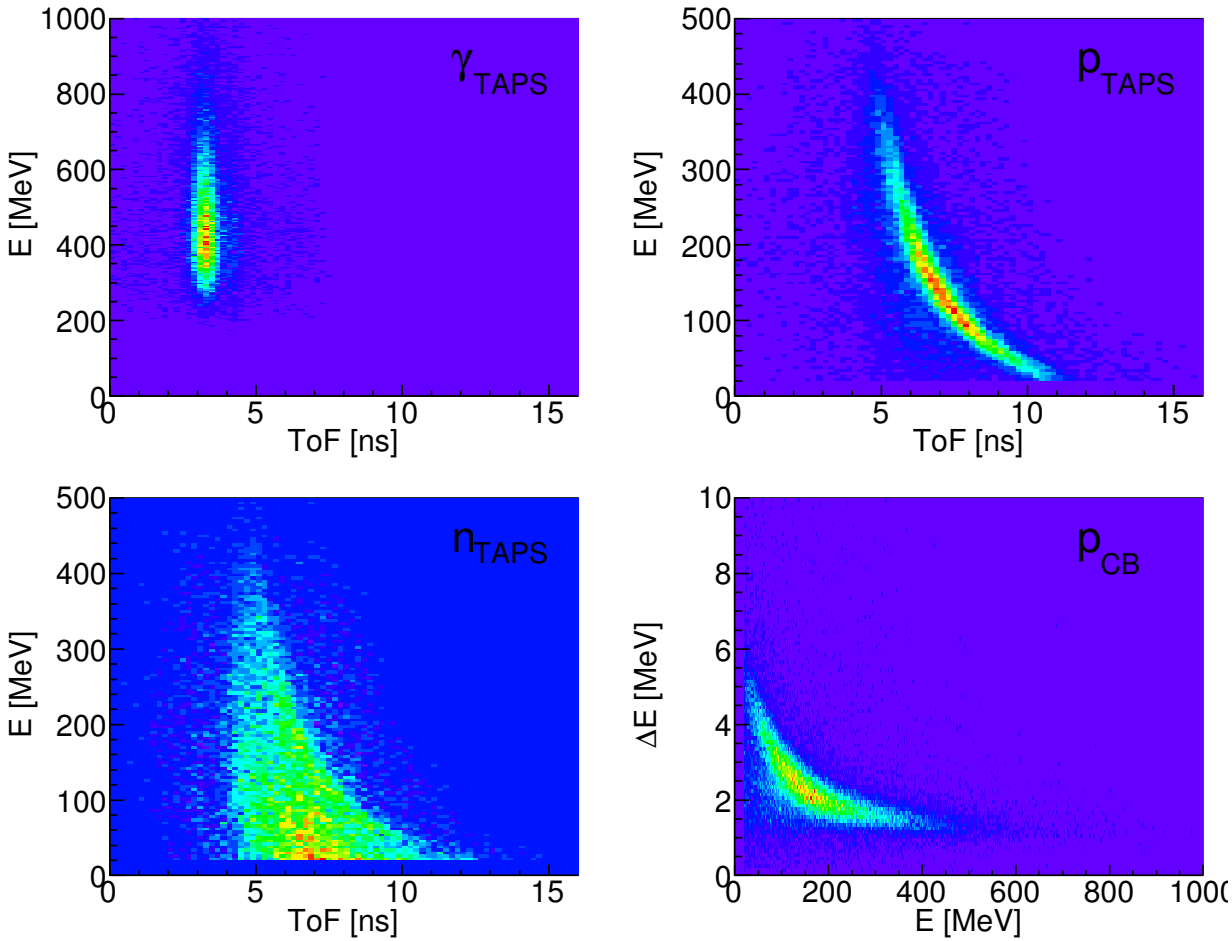


Photon : 3σ

nucleon: exclusion zone]85,380[MeV

Other identification possibilities

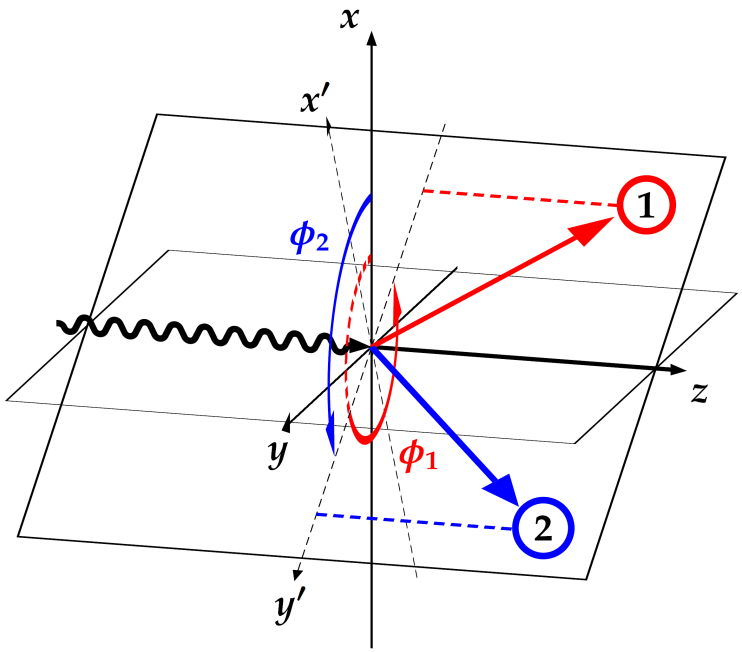
energy versus time of flight and ΔE versus E

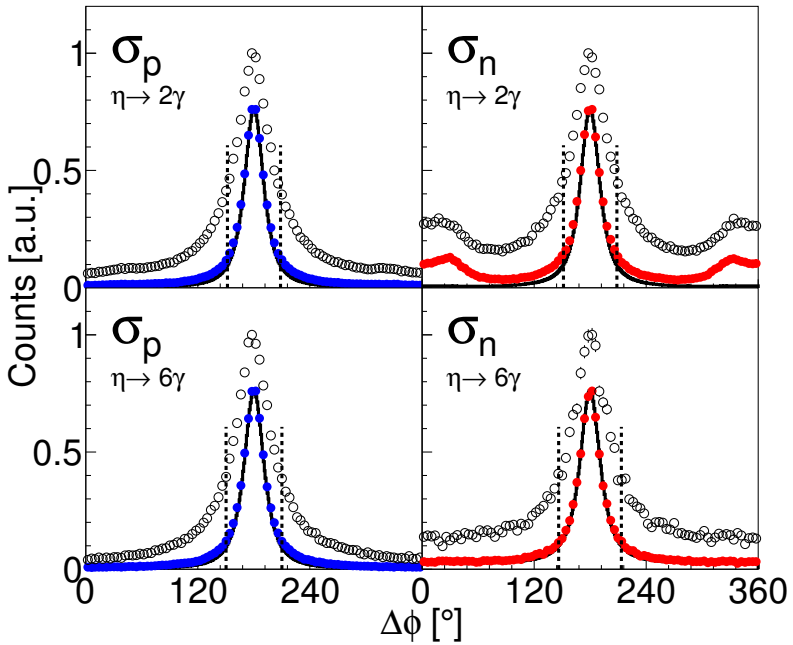


Background Suppression

Coplanarity:

$$\Delta\phi = \phi_N - \phi_\eta$$



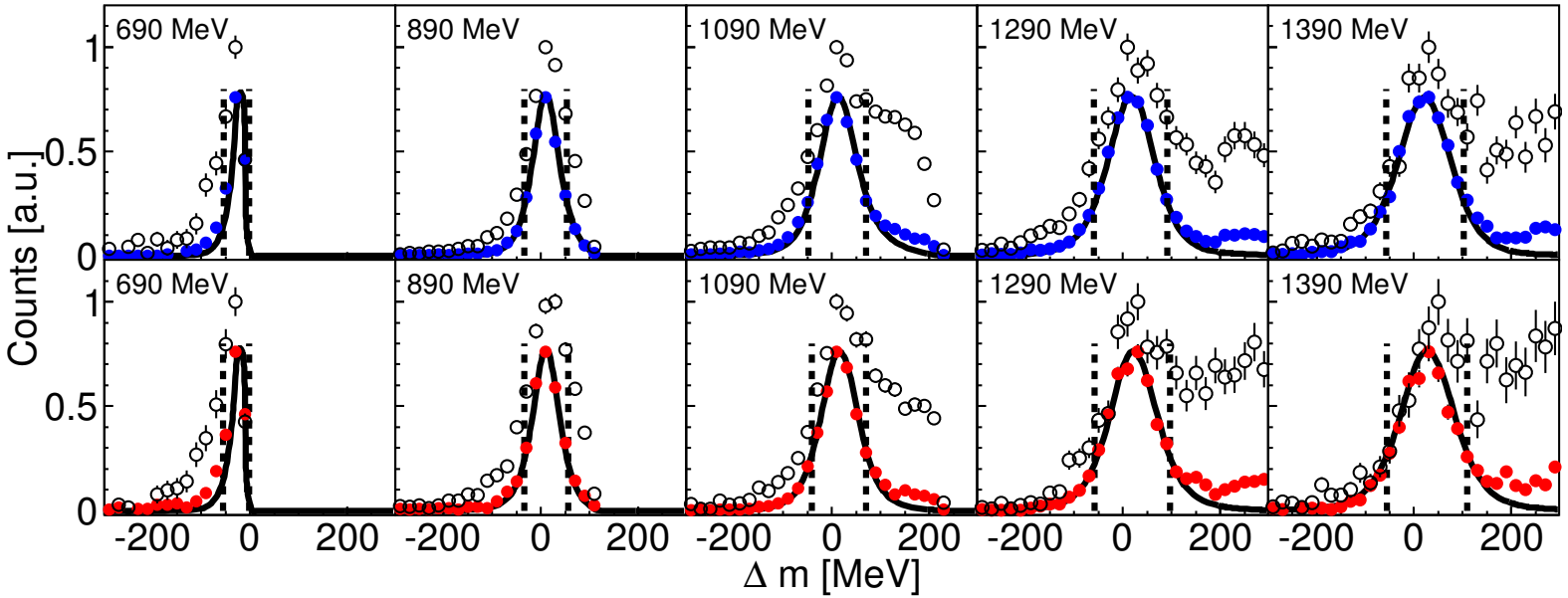


cut on $\pm 2\ \sigma$

Background Suppression

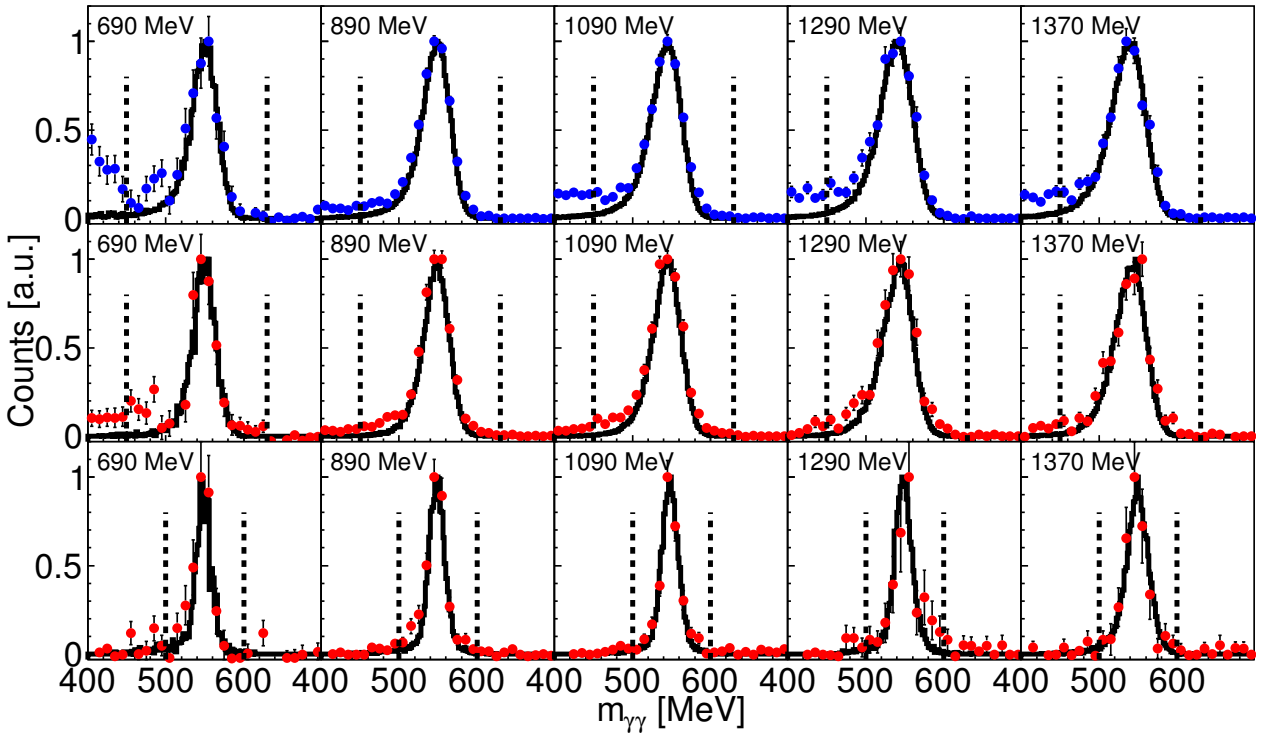
Missing Mass:

$$\Delta M = |P_{Beam} + P_N - P_\eta)| - m_N$$



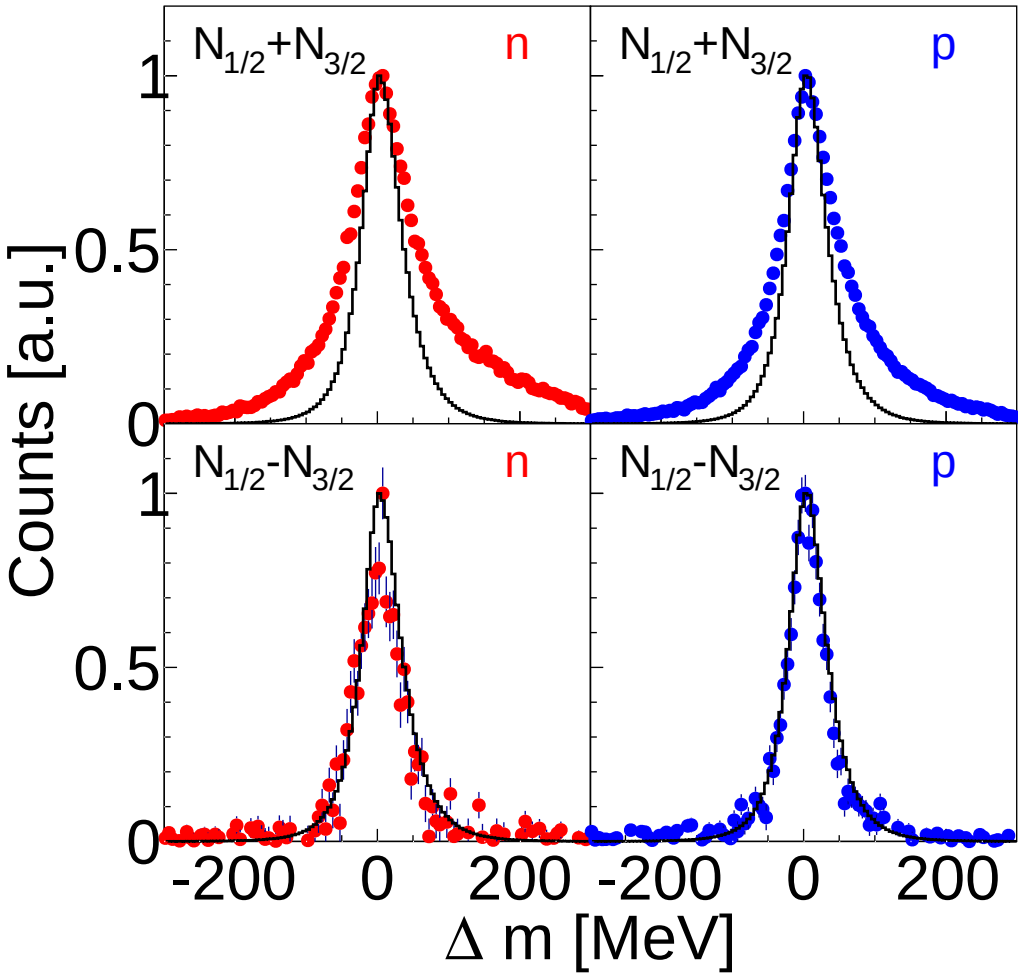
cut on $\pm 1.5\ \sigma$

Invariant Mass Distributions



- integrate $m_{\gamma\gamma}\,(E, \cos(\theta))$ 2γ: 450-630 MeV 6γ: 500-600 MeV

Carbon Subtraction



- $N_{1/2} + N_{3/2}$:
  carbon contribution
  $\rightarrow$ carbon subtraction needed!
- $N_{1/2} - N_{3/2}$:
  no carbon left!