



New results on ω photoproduction

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Outlook

Motivation

The GRAAL experiment

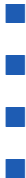
Data Analysis

Results

Conclusions



The ω meson



$$\omega(782) \quad I^G(J^{PC}) = 0^-(1^{--})$$

Mass $M = 782.65 \pm 0.12$ MeV

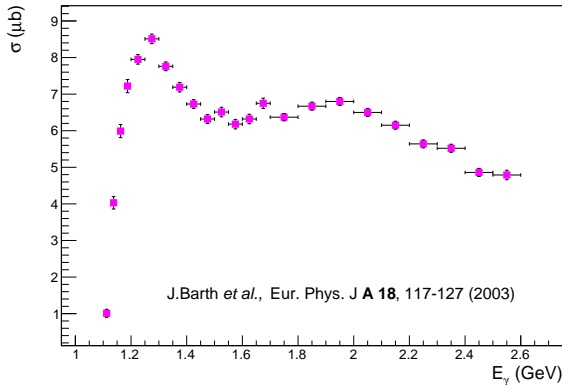
Full width $\Gamma = 8.49 \pm 0.08$ MeV

DECAY MODES:

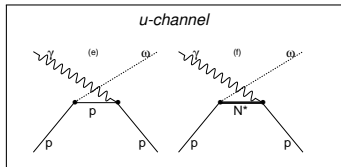
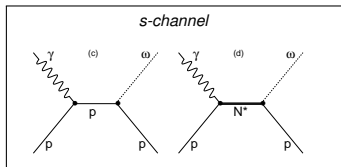
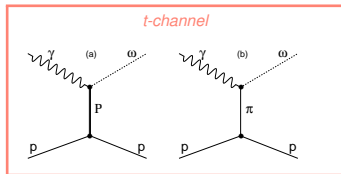
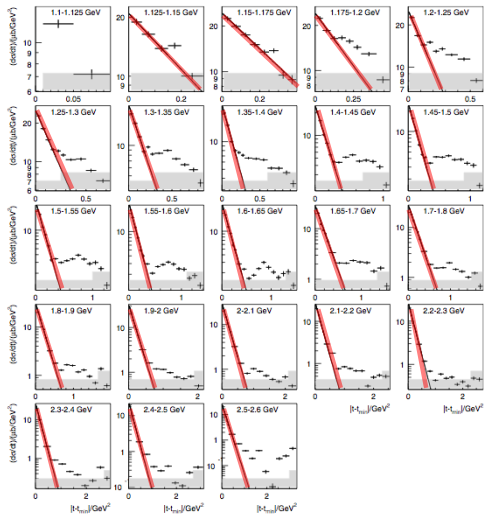
$\pi^+ \pi^- \pi^0$ B.R.: 89.2 ± 0.7 %
 $\pi^0 \gamma$ B.R.: 8.28 ± 0.28 %

J.Beringer *et al.* (Particle Data Group),
 PR D **86**, 010001 (2012)

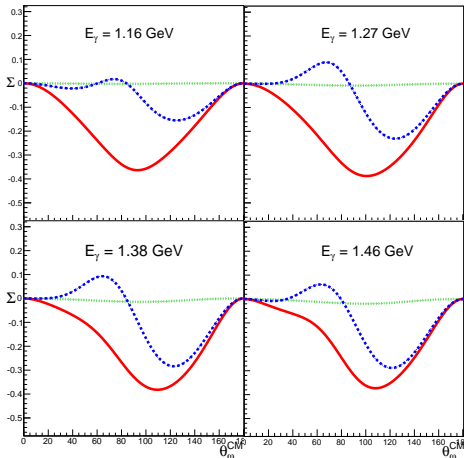
$\gamma + p \rightarrow \omega + p$



Differential Cross Section



Polarisation Observables: the Beam Asymmetry Σ



— only t-channel

— t- and s-channel
all terms

— t- and s-channel
excluding $P_{13}(1720)$

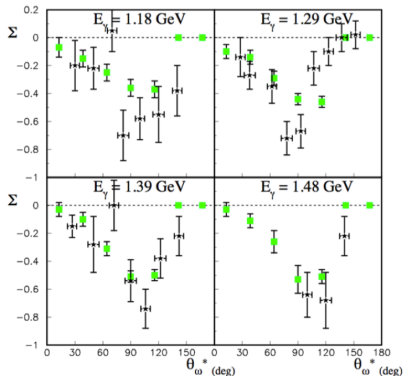
Model by Q. Zhao:

Nucl.Phys. **A 675**, 217c (2000)

Phys.Rev. **C 71**, 054004 (2005)

Σ : Actual Status

Experimental Results:



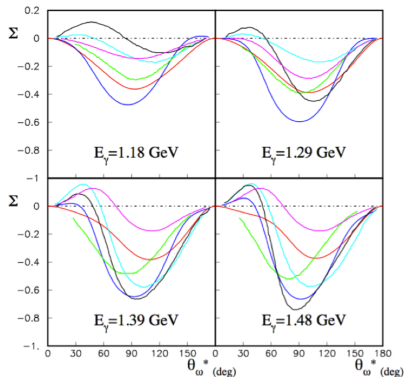
■ A.Ajaka *et al.*, Phys. Rev. Lett. **96**, 132003 (2006)

$$\omega \rightarrow \pi^+ \pi^0 \pi^-$$

★ F.Klein *et al.*, Phys. Rev. D **78**, 117101 (2008)

$$\omega \rightarrow \pi^0 \gamma$$

Theoretical Results:



— GIESSEN, Phys. Rev. **C 66**, 055212 (2002)

— GIESSEN, Phys. Rev. **C 66**, 055212 (2002)

— GIESSEN, Phys. Rev. **C 71**, 055206 (2005)

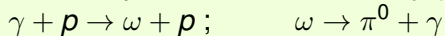
— Q.Zhao, Phys. Rev. **C 71**, 054004 (2005)

— BoGa, Phys. Rev. **D 78**, 117101 (2008)

— M.Paris, Phys. Rev. **C 79**, 025208 (2009)

ω photoproduction at GRAAL

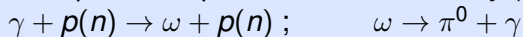
1. free proton - radiative decay (B.R. 8.5%)



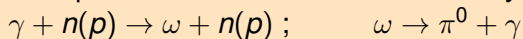
2. free proton - 3 pion decay (B.R. 89.2%)



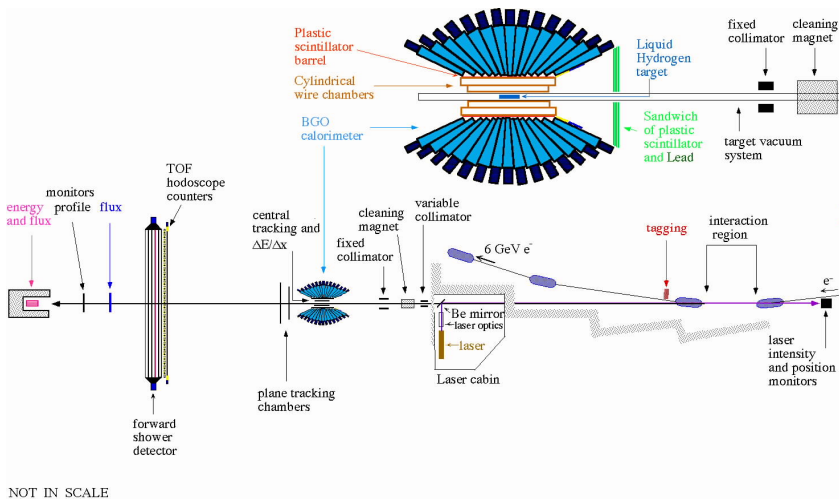
3. quasi free proton - radiative decay (B.R. 8.5%)



4. quasi free neutron - radiative decay (B.R. 8.5%)



The GRAAL experiment

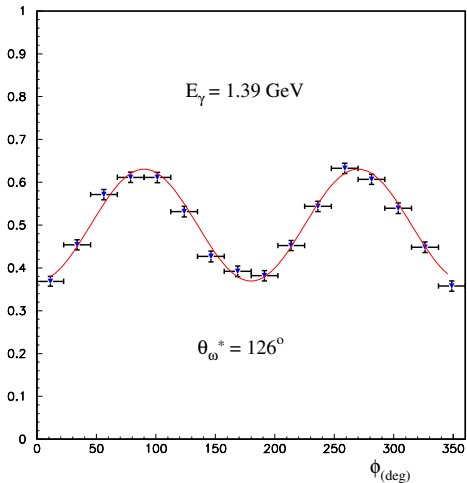
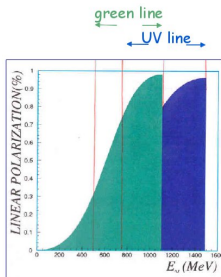


Extraction of Σ values

$$\left(\frac{d\sigma}{d\Omega}\right)_{V,H} = \left(\frac{d\sigma}{d\Omega}\right)_{unp}(1 \pm P\Sigma \cos(2\varphi))$$

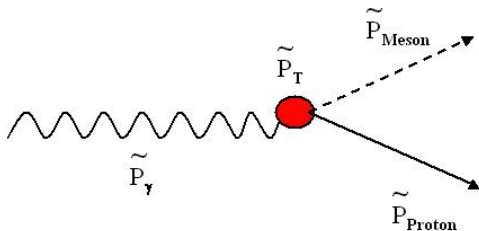
$$N_{V,H} \propto k_{V,H}\epsilon(\varphi)(1 \pm P\Sigma \cos(2\varphi))$$

$$\frac{N_V/k_V}{N_V/k_V + N_H/k_H} = \frac{1}{2}(1 + P\Sigma \cos(2\varphi))$$



The final state nucleon identification

In the laboratory frame:



$$\tilde{P}_\gamma = (E_\gamma; p_\gamma^x, p_\gamma^y, p_\gamma^z)$$

$$\tilde{P}_T = (M_T; 0, 0, 0)$$

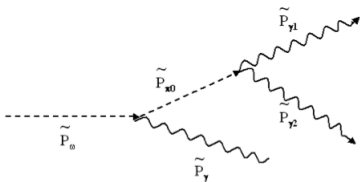
$$\tilde{P}_\omega = (E_\omega; p_\omega^x, p_\omega^y, p_\omega^z)$$

$$\tilde{P}_N = (E_N; p_N^x, p_N^y, p_N^z)$$

$$M_{miss,N} = \sqrt{(E_\gamma + M_T - p_N^z)^2 - (p_N^x)^2 - (p_N^y)^2 - (E_\gamma + p_N^z)^2}$$

Energy	Central Detector	Forward Detector
Proton	YES	YES
Neutron	NO	YES

The radiative decay: events reconstruction



- 3 γ in the BGO
- 2 γ in the BGO + 1 γ forward
energy assigned by energy conservation

(γ, γ, γ) system: E_ω ; $p_\omega^x, p_\omega^y, p_\omega^z$

Kinematic reconstruction:

In the center-of-mass frame:

$$E_\gamma, M_T \rightarrow \begin{aligned} \beta &= \frac{E_\gamma}{E_\gamma + M_T} \\ s &= 2E_\gamma M_T \\ \gamma &= \frac{1}{\sqrt{1 - \beta^2}} \end{aligned}$$

$$\begin{aligned} E_N^* &= \frac{s + M_N^2 - M_\omega^2}{2\sqrt{s}} \\ E_\omega^* &= \frac{s - M_N^2 + M_\omega^2}{2\sqrt{s}} \\ p^* &= \frac{\sqrt{[s - (M_N + M_\omega)^2][s - (M_P - M_\omega)^2]}}{4s} \end{aligned}$$

Back to the laboratory frame:

$$\theta_N, \phi_N \rightarrow \begin{aligned} E_N &= \gamma(E_N^* + \beta p_N^* \cos \theta_N^*) \\ p_N \cos \theta_N &= \gamma(\beta E_N^* + p_N^* \cos \theta_N^*) \end{aligned}$$

$$\begin{aligned} & \rightarrow 2^{nd} \text{ order equation in } E_N \\ & + \text{energy balance:} \\ & E_N^{calc}, E_\omega^{calc}, \theta_\omega^{calc}, \phi_\omega^{calc} \end{aligned}$$

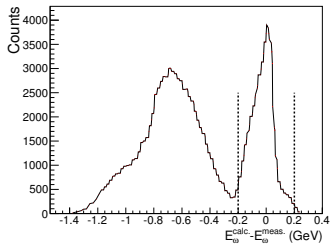
The radiative decay: events selection (free proton)

Competitive reactions:

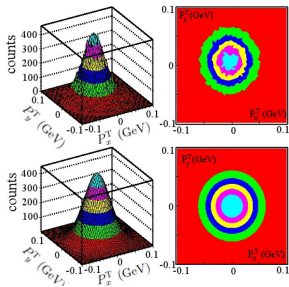
- $\gamma + p \rightarrow (\Delta^+ + \pi^0 \rightarrow) \pi^0 + \pi^0 + p$

- $\gamma + p \rightarrow \pi^0 + p$

1. $|E_{\omega}^{meas} - E_{\omega}^{calc}| < 200 \text{ MeV}$



2. $\frac{(P_{TOT}^x)^2}{\sigma_x^2} + \frac{(P_{TOT}^y)^2}{\sigma_y^2} \leq n^2$

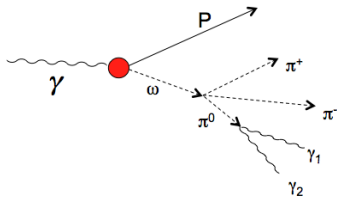


3. $M_{miss,p} > 200 \text{ MeV}$

4. $M_{\omega} > 680 \text{ MeV}$

The 3-pion decay: events reconstruction

(free proton)



P:	$E_P,$	$\theta_P,$	ϕ_P
$\pi^+:$	$E_{\pi^+},$	$\theta_{\pi^+},$	ϕ_{π^+}
$\pi^-:$	$E_{\pi^-},$	$\theta_{\pi^-},$	ϕ_{π^-}
$\gamma_1:$	$E_{\gamma_1},$	$\theta_{\gamma_1},$	ϕ_{γ_1}
$\gamma_2:$	$E_{\gamma_2},$	$\theta_{\gamma_2},$	ϕ_{γ_2}

$$\begin{aligned}
 E : & \quad \sqrt{(P_{\pi^+})^2 + M_{\pi^+}^2} + \sqrt{(P_{\pi^-})^2 + M_{\pi^-}^2} + E_{\gamma_1} + E_{\gamma_2} & = E_{\gamma} + M_P - E_P \\
 P^x : & \quad P_{\pi^+} \sin \theta_{\pi^+} \cos \phi_{\pi^+} + P_{\pi^-} \sin \theta_{\pi^-} \cos \phi_{\pi^-} + E_{\gamma_1} \sin \theta_{\gamma_1} \cos \phi_{\gamma_1} + E_{\gamma_2} \sin \theta_{\gamma_2} \cos \phi_{\gamma_2} & = -P_P^x \\
 P^y : & \quad P_{\pi^+} \sin \theta_{\pi^+} \sin \phi_{\pi^+} + P_{\pi^-} \sin \theta_{\pi^-} \sin \phi_{\pi^-} + E_{\gamma_1} \sin \theta_{\gamma_1} \sin \phi_{\gamma_1} + E_{\gamma_2} \sin \theta_{\gamma_2} \sin \phi_{\gamma_2} & = -P_P^y \\
 P^z : & \quad P_{\pi^+} \cos \theta_{\pi^+} + P_{\pi^-} \cos \theta_{\pi^-} + E_{\gamma_1} \cos \theta_{\gamma_1} + E_{\gamma_2} \cos \theta_{\gamma_2} & = E_{\gamma} - P_P^z
 \end{aligned}$$

$$\mathbf{p}^{x,y} \rightarrow \mathbf{P}_{\pi^+}, \mathbf{P}_{\pi^-}$$

$$\mathbf{p}^{x,y,z} \rightarrow \mathbf{P}_{\pi^+}, \mathbf{P}_{\pi^-}, \mathbf{E}_{\gamma_2}$$

The 3-pion decay: fitting procedure

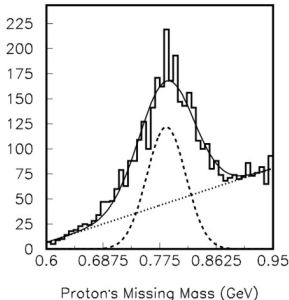
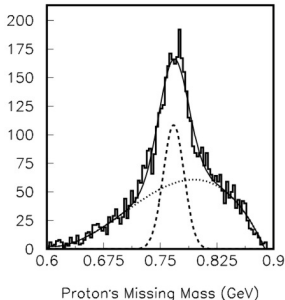
Competitive reactions:

- $\gamma + p \rightarrow \pi^+ + \pi^0 + \pi^- + p$
- $\gamma + p \rightarrow \eta + p \rightarrow \pi^+ + \pi^0 + \pi^- + p$

Pre-cleaning of the data-set:

$$1. M_{(\pi^+, \pi^0, \pi^-)} < 2 \text{ GeV}$$

$$2. 100 \text{ MeV} < M_{\pi^0} < 170 \text{ MeV}$$



fit performed bin-by-bin:

- 2 polarization states
- 4 energy bins
- 5 polar angle (θ_{ω}^*) bins
- 16 azimuthal angle (ϕ_{ω}) bins

Gaussian: ω events
 3rd order polynomial: background

(1st order polynomial in the last energy bin)

The radiative decay: events selection (quasi-free nucleon)

Free proton:

$$1. |E_{\omega}^{meas} - E_{\omega}^{calc}| < 200 \text{ MeV}$$

$$2. \frac{(P_{TOT}^x)^2}{\sigma_x^2} + \frac{(P_{TOT}^y)^2}{\sigma_y^2} \leq n^2$$

$$\sigma_x = \sigma_y = 30 \text{ MeV}/c; n = 3$$

$$3. M_{miss,p} > 200 \text{ MeV}$$

$$4. M_{\omega} > 680 \text{ MeV}$$

Quasi-free nucleon:

$$1. |E_{\omega}^{meas} - E_{\omega}^{calc}| < 200 \text{ MeV}$$

$$2. \frac{(P_{TOT}^x)^2}{(\sigma_x^{qf})^2} + \frac{(P_{TOT}^y)^2}{(\sigma_y^{qf})^2} \leq n^2$$

$$\sigma_x^{qf} = \sigma_y^{qf} = 70 \text{ MeV}/c; n = 4$$

$$3. \frac{(M_{\gamma,\gamma,\gamma}^{inv} - M_{\omega})^2}{(\sigma_{\gamma,\gamma,\gamma}^{inv})^2} + \frac{(M_{miss,N} - M_{\omega})^2}{(\sigma_{miss,N}^{inv})^2} < n^2$$

$$\sigma_{\gamma,\gamma,\gamma}^{inv} = 60 \text{ MeV}/c^2$$

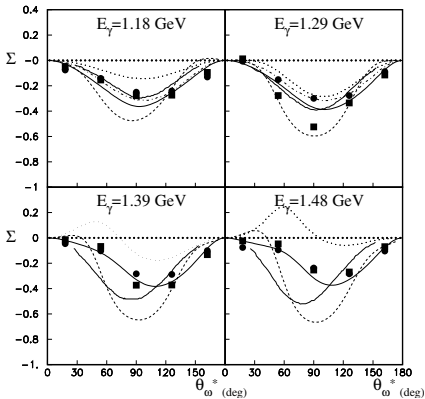
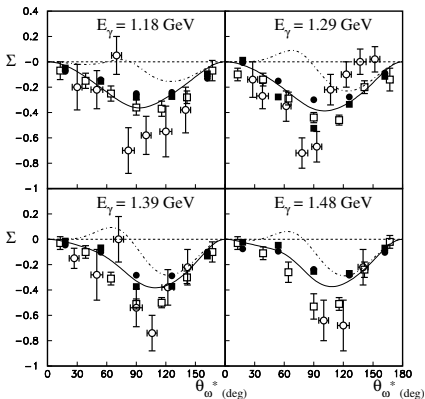
$$\sigma_{miss,N}^{inv} = 80 \text{ MeV}/c^2$$

$$n = 3$$

Only for the neutron:

$$|\phi_{\pi^0} - \phi_n| \notin (150^\circ; 210^\circ)$$

$\gamma + p \rightarrow \omega + p$: the beam asymmetry



● this work: $\omega \rightarrow \pi^0 \gamma$

■ this work: $\omega \rightarrow \pi^+ \pi^0 \pi^-$

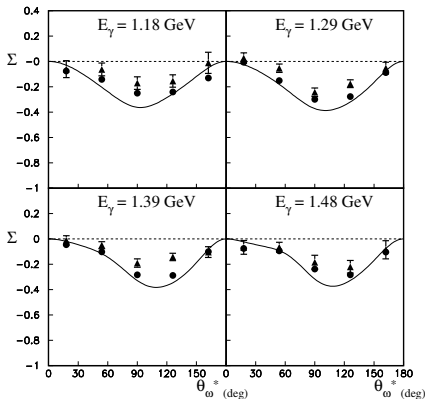
○ CBELSA/TAPS: $\omega \rightarrow \pi^0 \gamma$

□ previous GRAAL: $\omega \rightarrow \pi^+ \pi^0 \pi^-$

_____ BoGa
 - - - - - Titov et al.
 - - - - - Matsuyana et al.
 ········· GIESSEN
 _____ Zhao

$\gamma + qfN \rightarrow \omega + qfN$: the beam asymmetry

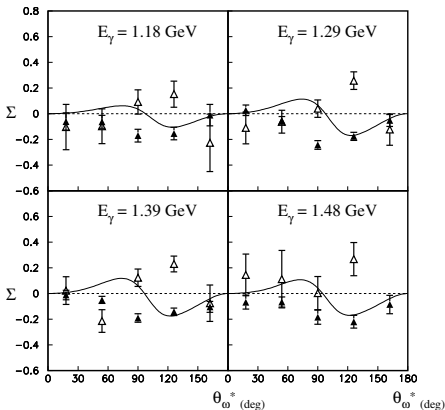
quasi-free proton:



- free proton, $\omega \rightarrow \pi^0 + \gamma$
- ▲ quasi free proton, $\omega \rightarrow \pi^0 + \gamma$

— Zhao (free proton)

quasi-free neutron:



- ▲ quasi free proton, $\omega \rightarrow \pi^0 + \gamma$
- △ quasi free neutron, $\omega \rightarrow \pi^0 + \gamma$

— Zhao (free neutron)

Conclusions

- high statistics measurement of Σ for the reaction $\vec{\gamma} + p \rightarrow \omega + p$ from the complete GRAAL data-set:
 - $\omega \rightarrow \pi^0 + \gamma$: event selection
 - $\omega \rightarrow \pi^+ + \pi^0 + \pi^-$: fitting procedure
 - agreement between the two decay modes
 - data well described by Zhao model $\rightarrow P_{13}(1720)$
- measurement of Σ for the reaction off the quasi-free proton target
 - $\omega \rightarrow \pi^0 + \gamma$: event selection
 - agreement with the free proton results
 - quasi-free neutron data \rightarrow results of free neutron target
- first measurement of Σ for ω photoproduction off neutron
 - $\omega \rightarrow \pi^0 + \gamma$: event selection
 - results affected by higher statistical error (w.r.t. proton)
 - completely different angular distributions (w.r.t. proton):
small (or compatible with 0) for $\theta_\omega^* \in (0^\circ, 90^\circ)$;
positive for $\theta_\omega^* \simeq 120^\circ$
 - change of sign in Σ foreseen by Zhao (but opposite w.r.t. data)
 - theoretical interpretation still missing