Recent results about ω photoproduction

Beam Asymmetry at GRAAL
(and at BGO-OD)

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20th September 2015

Outlook

Motivation

ω photoproduction at GRAAL

- The GRAAL experiment
- Results

ω photoproduction at BGO-OD

- The BGO-OD Experiment
- Preliminary Analysis of the *Pilot Run*

Conclusions

The ω meson

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

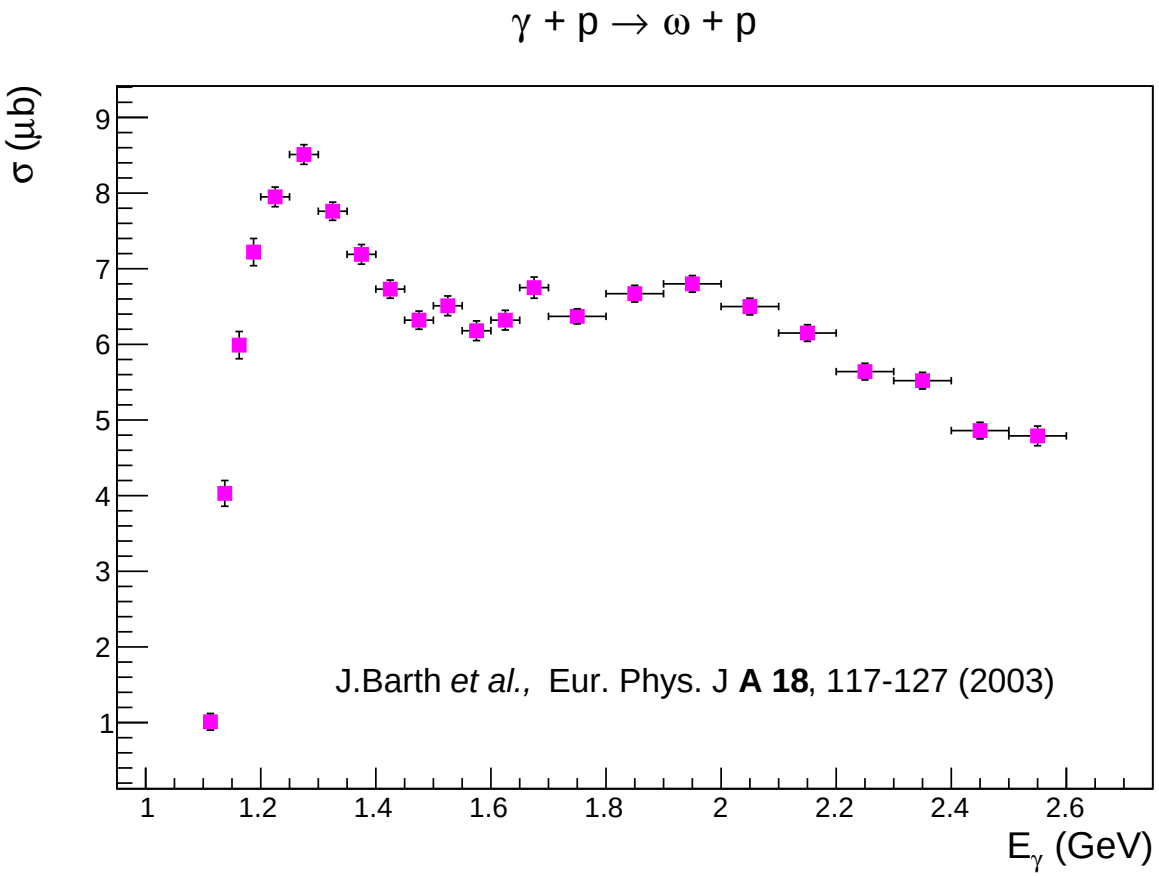
Mass M = 782.65 $\pm$ 0.12 MeV

Full width Γ = 8.49 $\pm$ 0.08 MeV

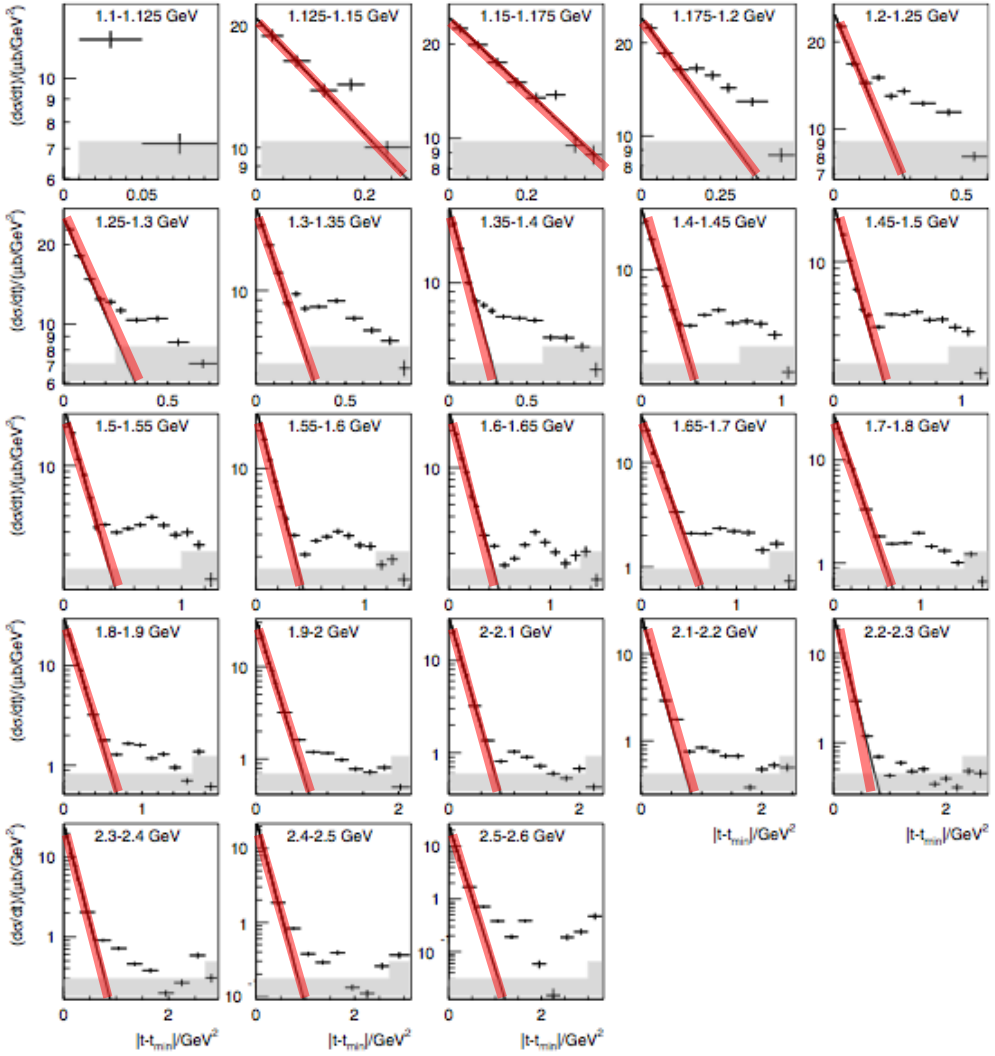
DECAY MODES:

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

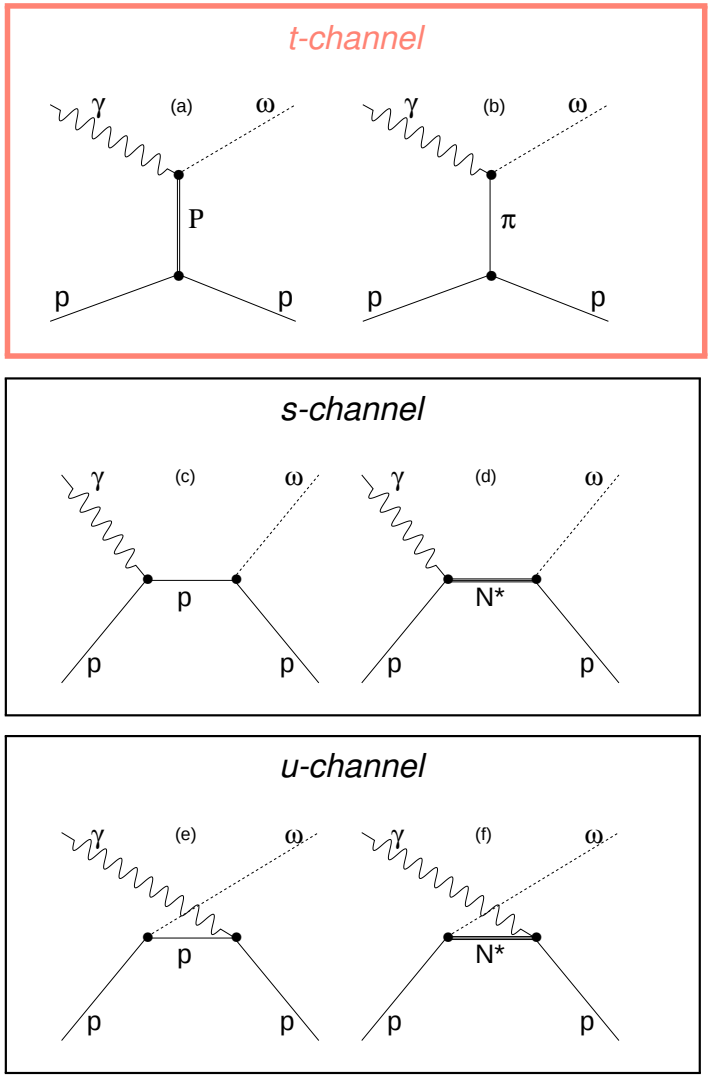
K.A.Olive *et al.* (Particle Data Group), Chin. Phys. C**38**, 090001 (2014)



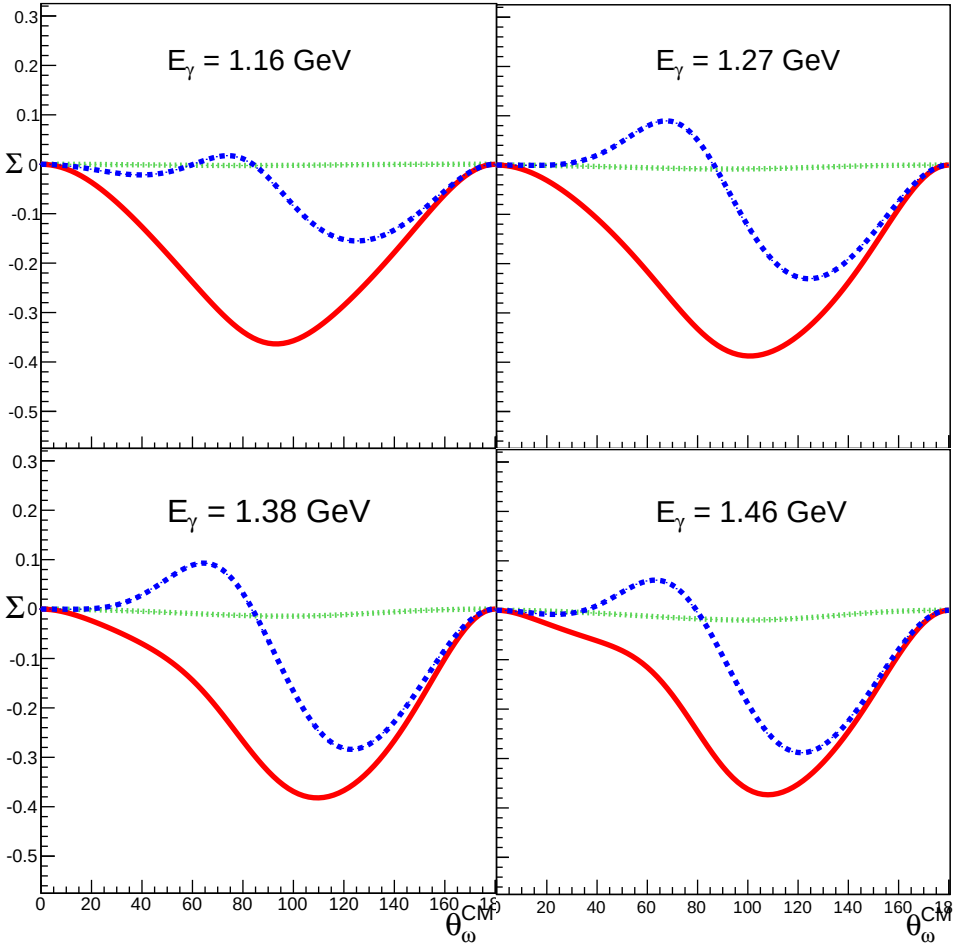
Differential Cross Section



J.Barth *et al.*, Eur. Phys. J **A 18**, 117-127 (2003)



Polarisation Observables: the Beam Asymmetry Σ



only t-channel

t- and s-channel
all terms

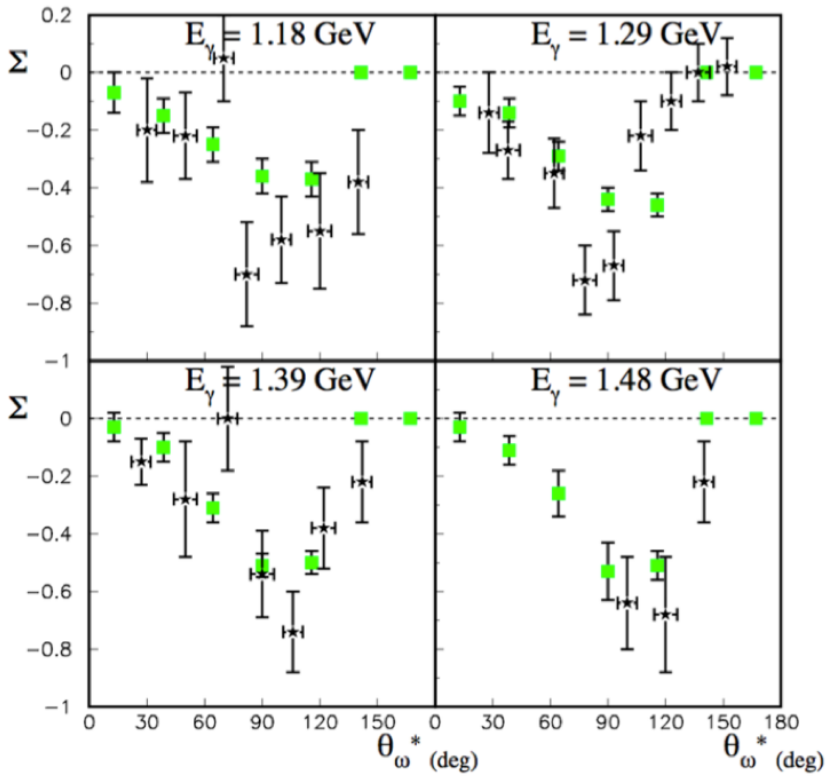
t- and s-channel
excluding $P_{13}(1720)$

Model by Q. Zhao:

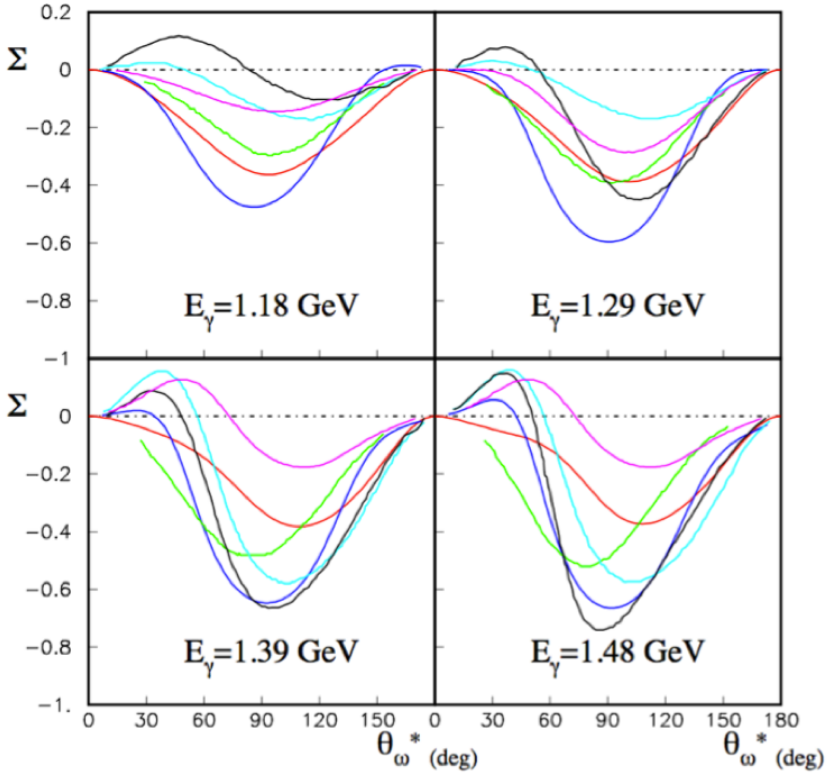
Nucl.Phys.**A 675**, 217c (2000)
Phys.Rev. **C 71**, 054004 (2005)

Σ: Status of the Art (up to 2014)

Experimental Results:



Theoretical Results:

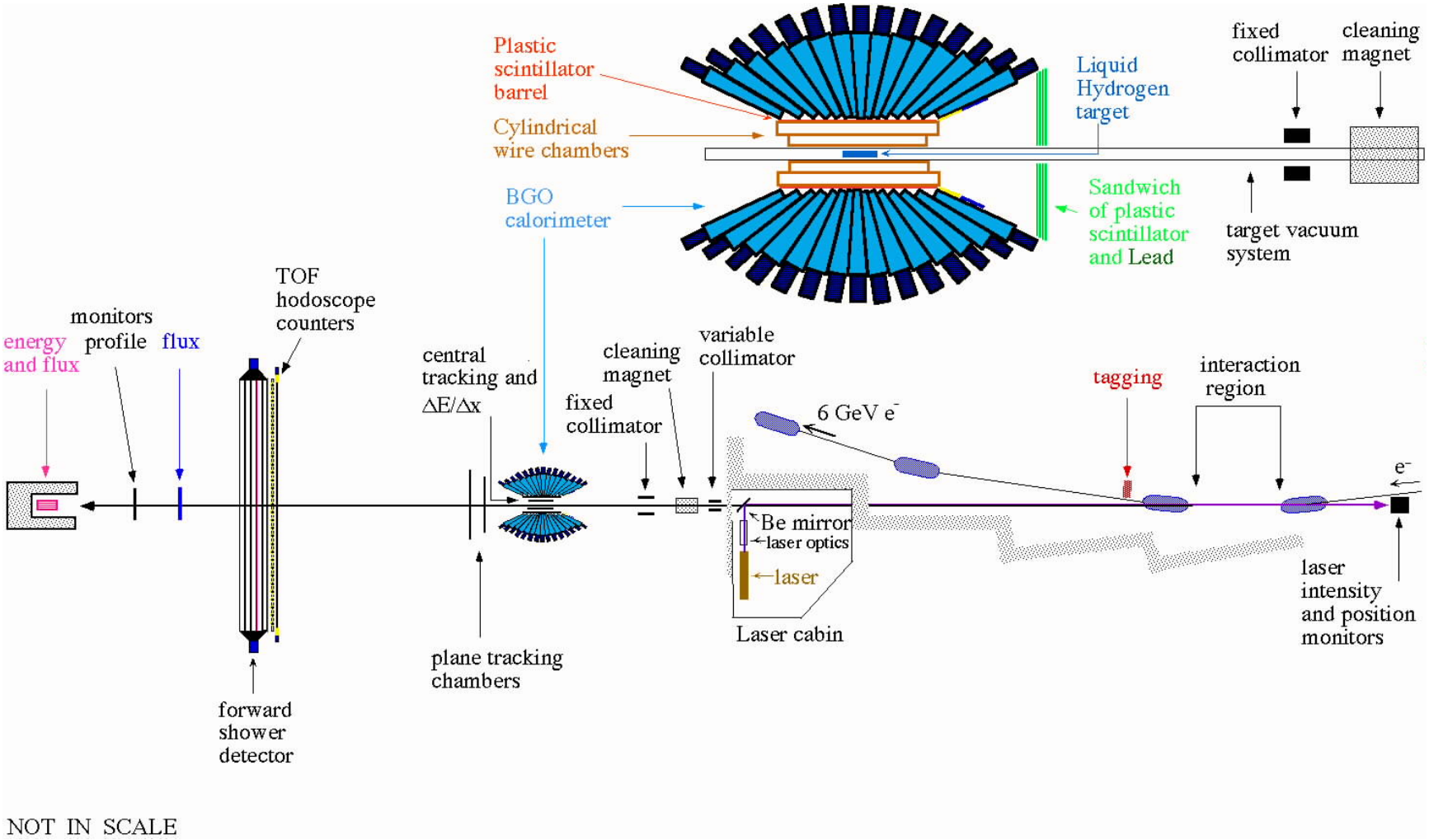


A.Ajaka *et al.*, Phys. Rev. Lett. **96**, 132003 (2006)
$\omega \to \pi^+\pi^0\pi^-$

F.Klein *et al.*, Phys. Rev. **D 78**, 117101 (2008)
$\omega \to \pi^0\gamma$

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)

The GRAAL experiment

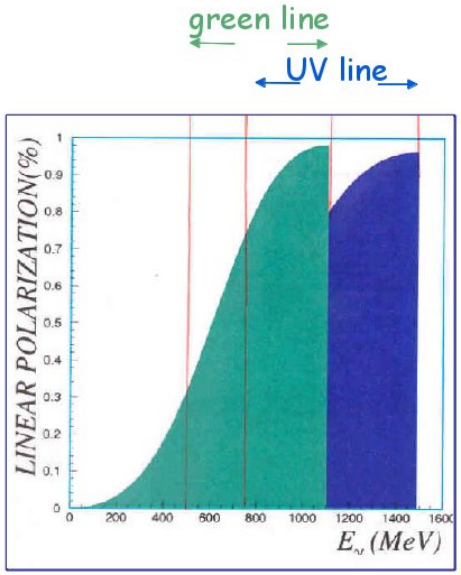


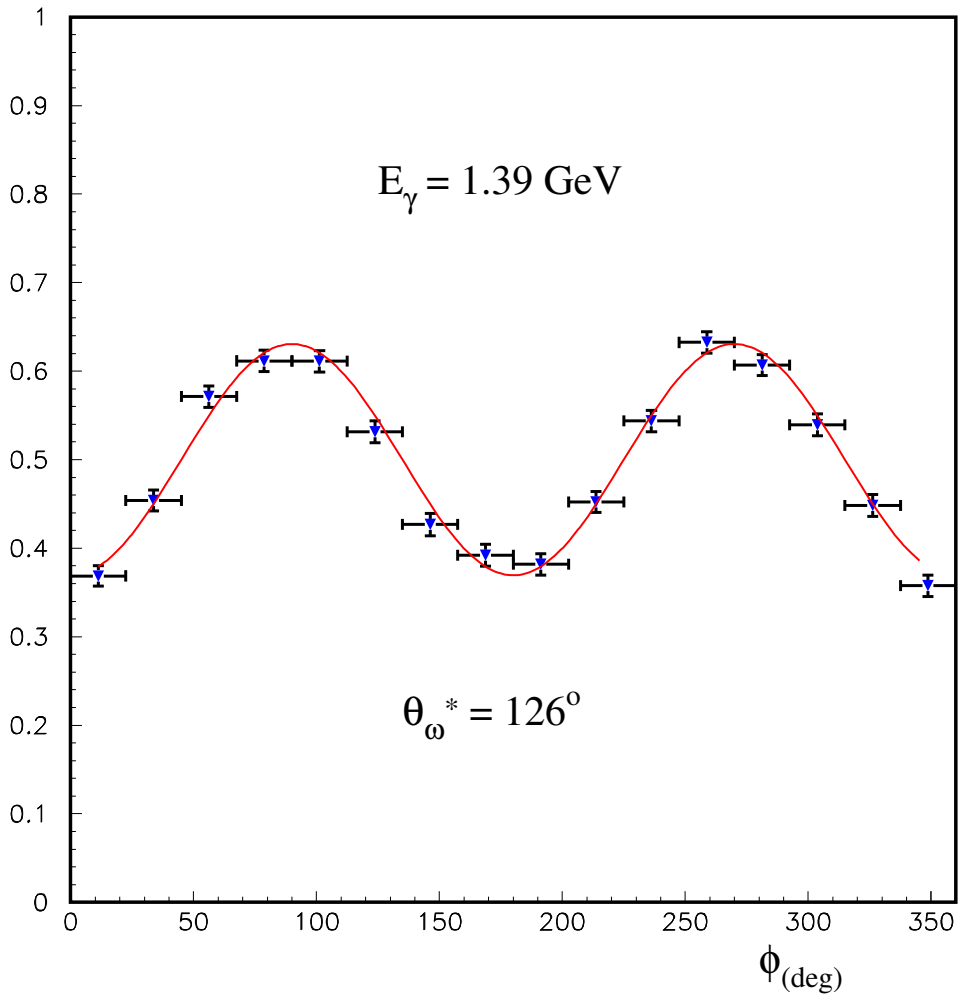
Extraction of Σ values

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

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

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





ω photoproduction at GRAAL

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

$\gamma + p \rightarrow \omega + p$; $\omega \rightarrow \pi^0 + \gamma$

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

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

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

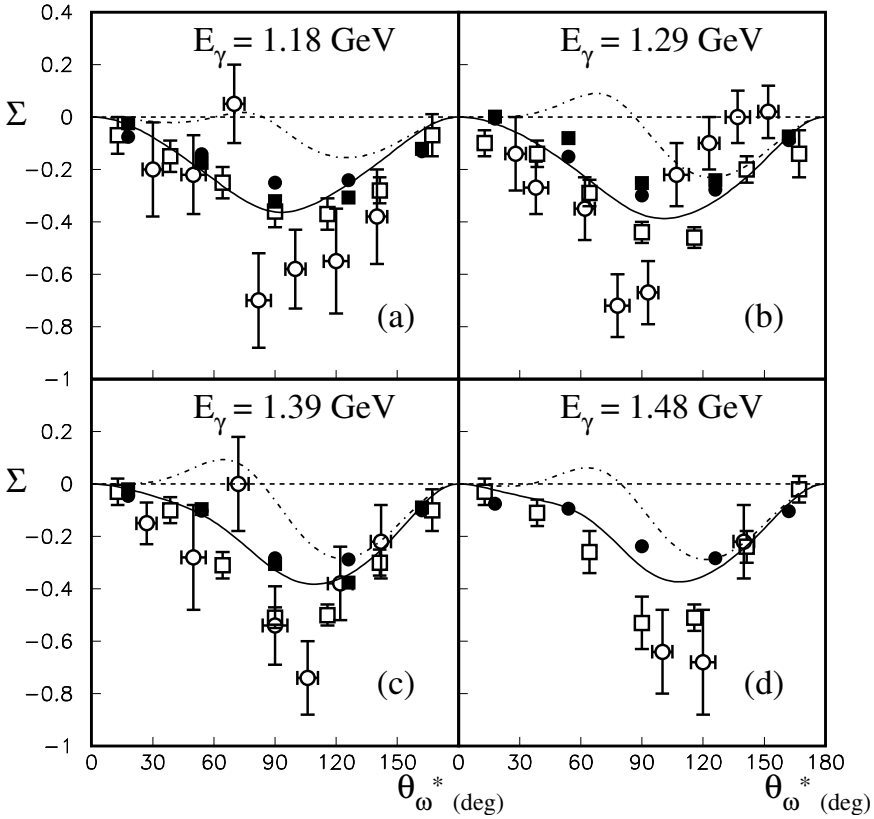
$\gamma + p(n) \rightarrow \omega + p(n)$; $\omega \rightarrow \pi^0 + \gamma$

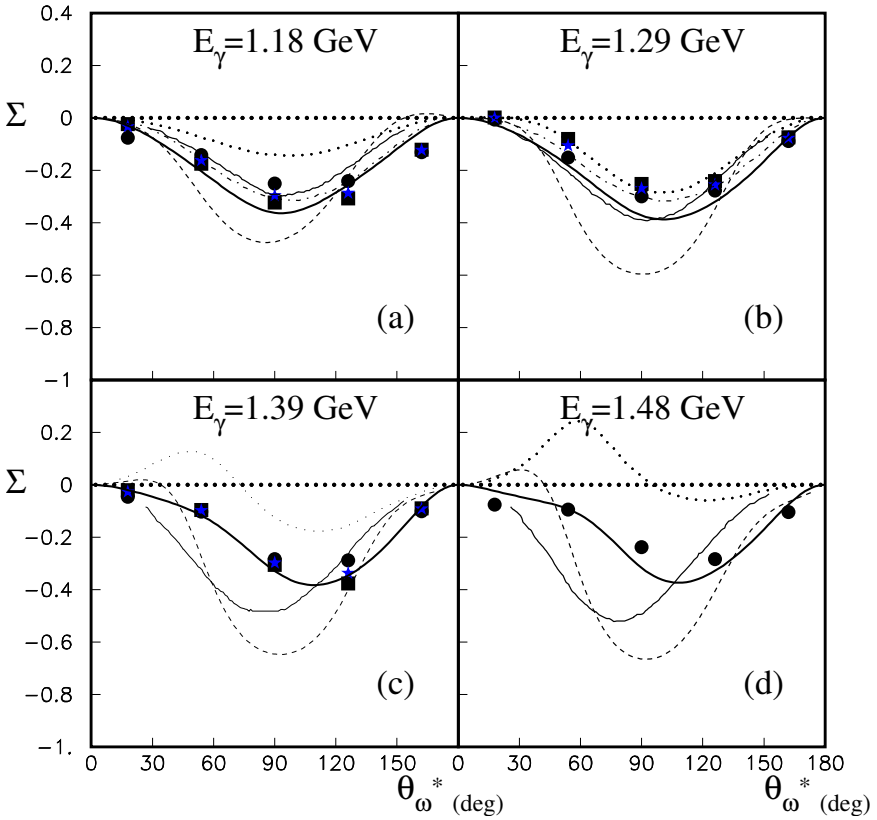
4. quasi free neutron - radiative decay (B.R. 8.5%)

$\gamma + n(p) \rightarrow \omega + n(p)$; $\omega \rightarrow \pi^0 + \gamma$

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

V. Vegna *et al.*, Phys. Rev. C **91**, 065207 (2015)





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

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

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

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

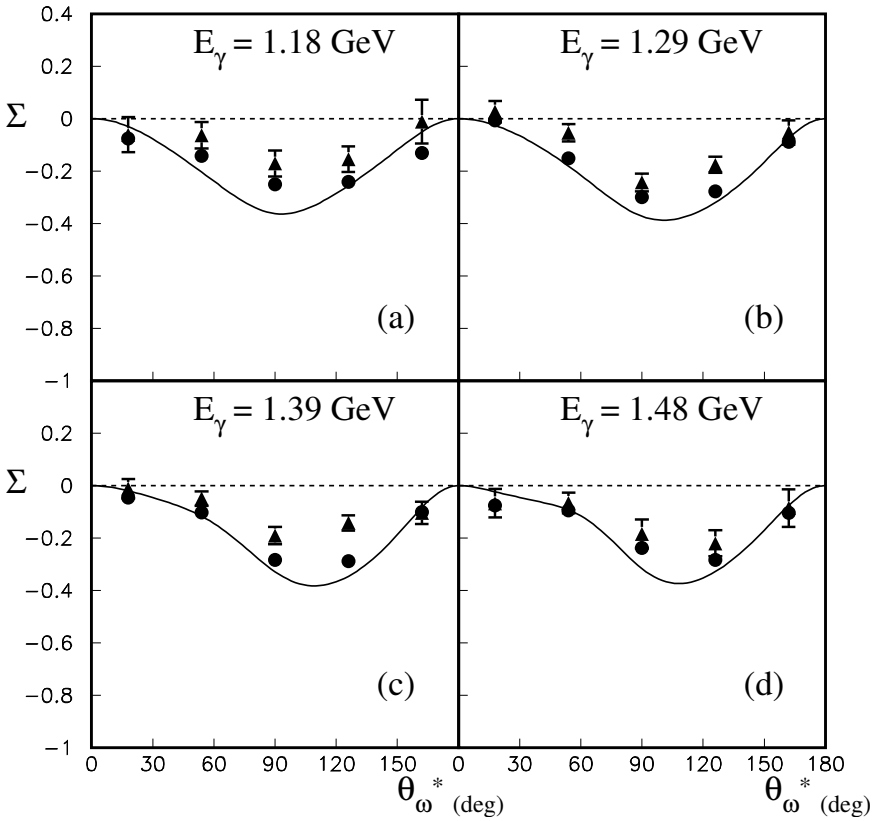
BoGa
Titov et al.
Matsuyana et al.
GIESSEN
Zhao

◆ this work: weighted mean for the two decays

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

V. Vegna *et al.*, Phys. Rev. C **91**, 065207 (2015)

quasi-free proton:

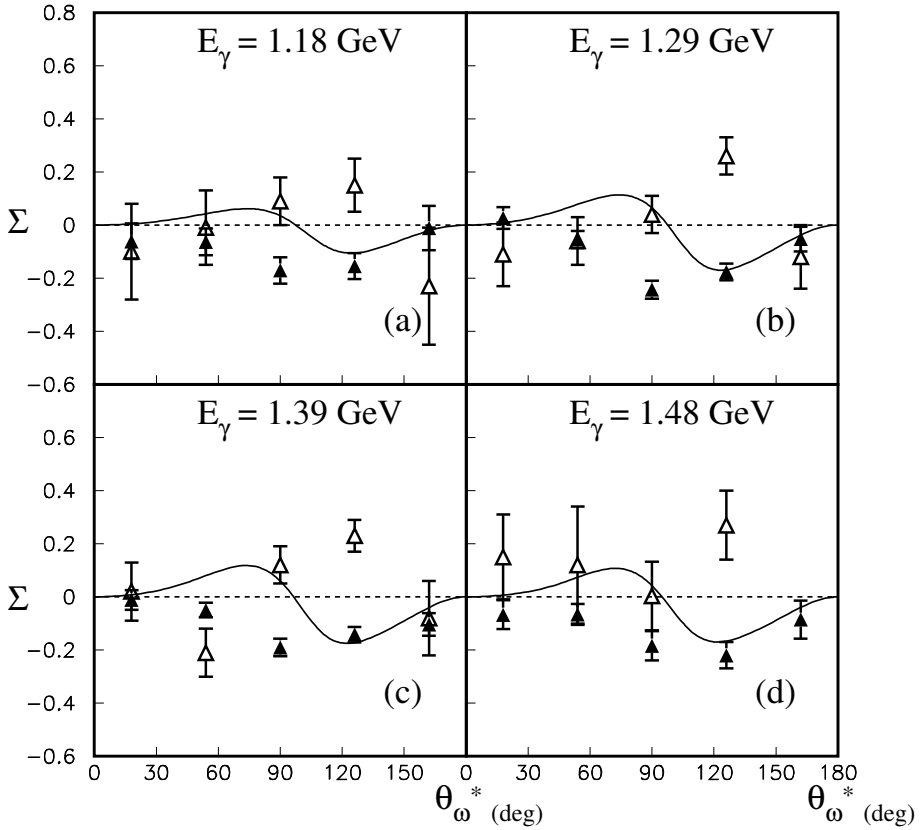


● free proton, $\omega \to \pi^0 + \gamma$

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

Zhao (free proton)

quasi-free neutron:



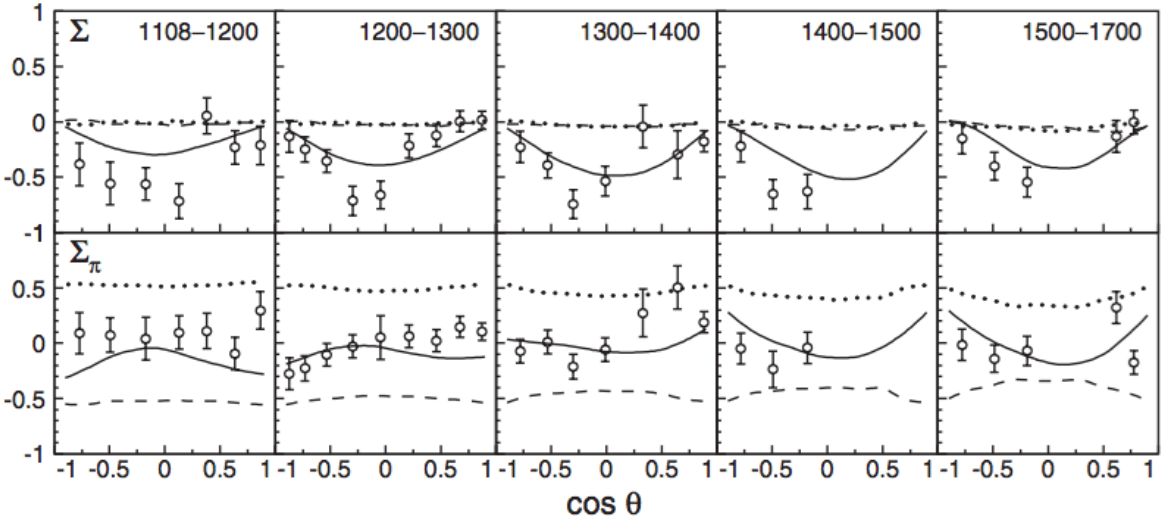
▲ quasi free proton, $\omega \to \pi^0 + \gamma$

△ quasi free neutron, $\omega \to \pi^0 + \gamma$

Zhao (free neutron)

The beam asymmetry Σ at higher energies

Original picture from F.Klein *et al.*, Phys. Rev. **D 78**, 117101 (2008)



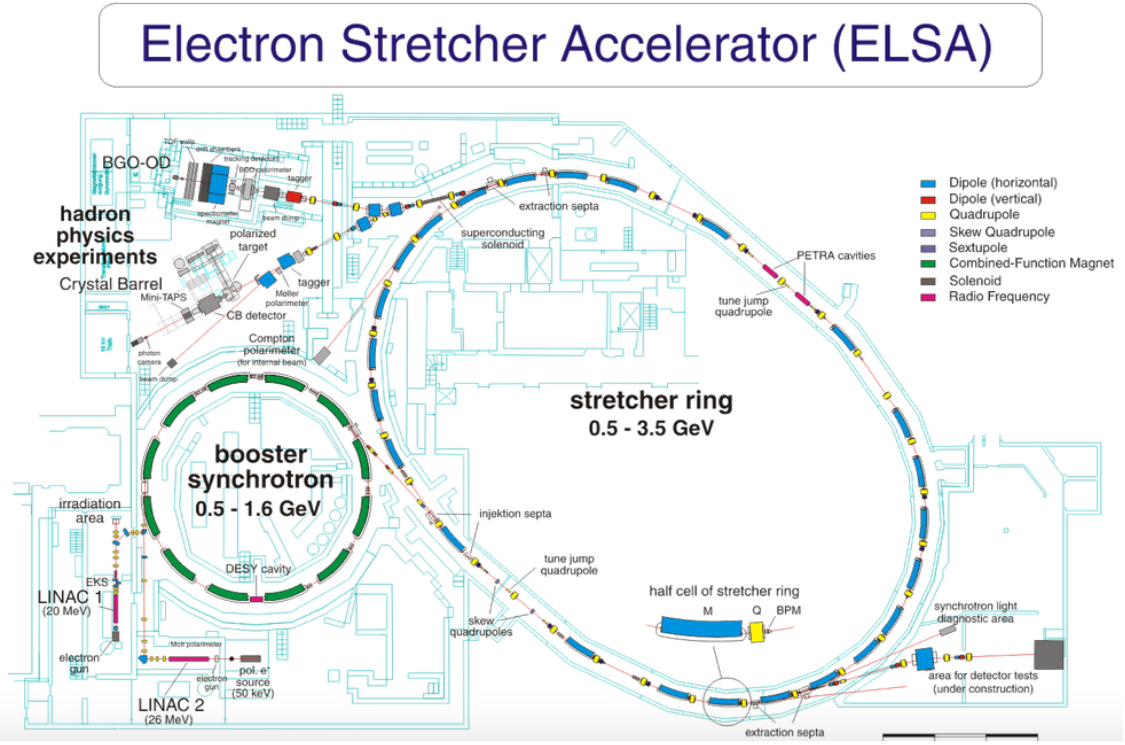
New measurement for $E_{\vec{\gamma}} > 1.5$ GeV:

- more statistics
- more energy bins

We need:

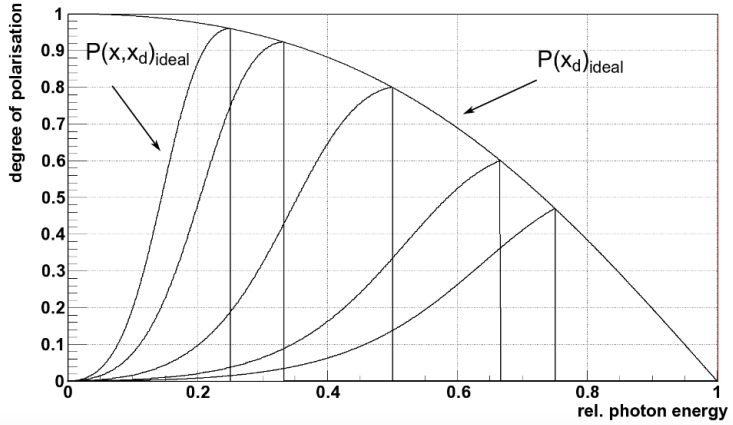
1. linearly polarised photons up to (at least) 1.8 GeV
2. detector optimized for charged particles

Linearly polarised photons at ELSA

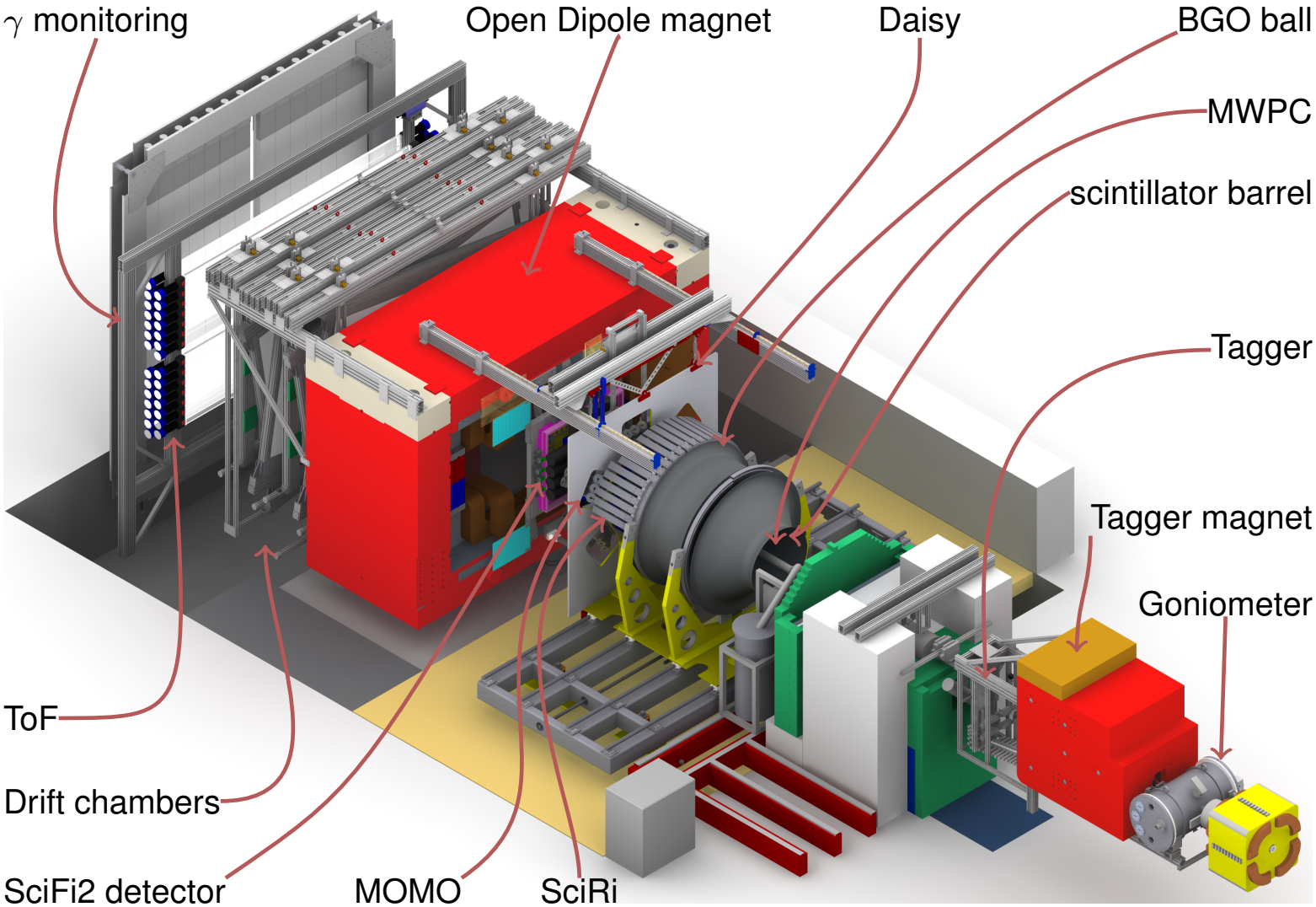


- 3-steps accelerator
- e^--beam up to 3.2 GeV
- polarised/unpolarised

Linearly photon beam produced through Bremsstrahlung over diamond



The BGO-OD experiment



Preliminary Analysis

Pilot Run: 22nd June -12th July

- E_{ELSA} = 2.9 GeV
- Pol. Peak @ E_γ = 1.5 GeV
- Open trigger condition

Pre-selection events:

- 1 electron in the tagger (E_γ)
- 2 photons in the BGO ($E_{1,2}$, $\theta_{1,2}$, $\phi_{1,2}$)
- 3 charged particles (only $\theta_{a,b,c}$ and $\phi_{a,b,c}$)

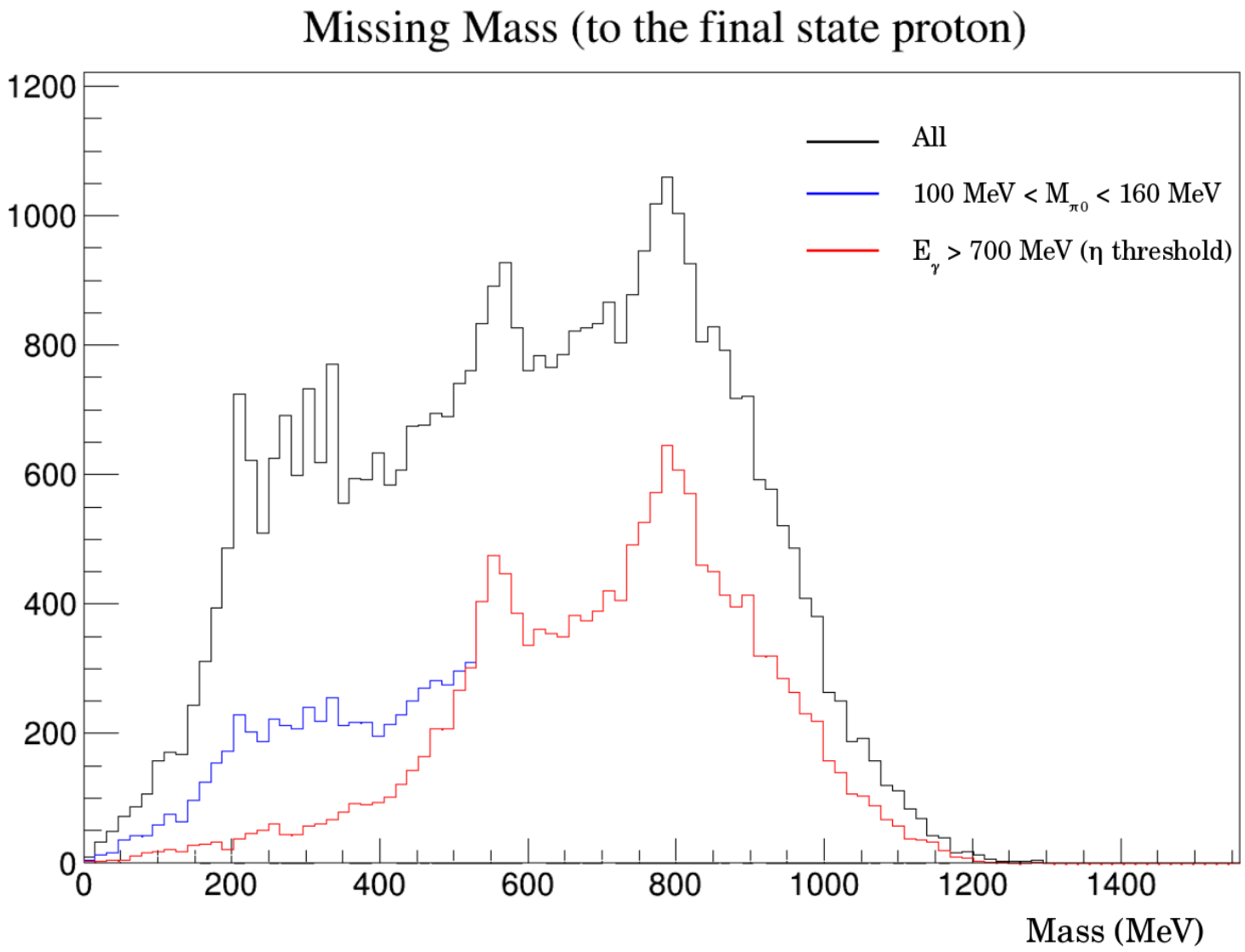
Event reconstruction: does NOT exploit the performances of the detector

$$\begin{cases} P_x^{TOT} : & 0 = & E_1 \sin\theta_1 \cos\phi_1 + E_2 \sin\theta_2 \cos\phi_2 + |\vec{p}_a| \sin\theta_a \cos\phi_a + |\vec{p}_b| \sin\theta_b \cos\phi_b + |\vec{p}_c| \sin\theta_c \cos\phi_c \\ P_y^{TOT} : & 0 = & E_1 \sin\theta_1 \sin\phi_1 + E_2 \sin\theta_2 \sin\phi_2 + |\vec{p}_a| \sin\theta_a \sin\phi_a + |\vec{p}_b| \sin\theta_b \sin\phi_b + |\vec{p}_c| \sin\theta_c \sin\phi_c \\ P_z^{TOT} : & E_\gamma = & E_1 \cos\theta_1 + E_2 \cos\theta_2 + |\vec{p}_a| \cos\theta_a + |\vec{p}_b| \cos\theta_b + |\vec{p}_c| \cos\theta_c \end{cases}$$

$\Rightarrow$ Calculation of the momenta of the charged particles ($|\vec{p}_a|$, $|\vec{p}_b|$ and $|\vec{p}_c|$)

Particle *identification* according with energy conservation.

First observed ω events (15% of the statistics)



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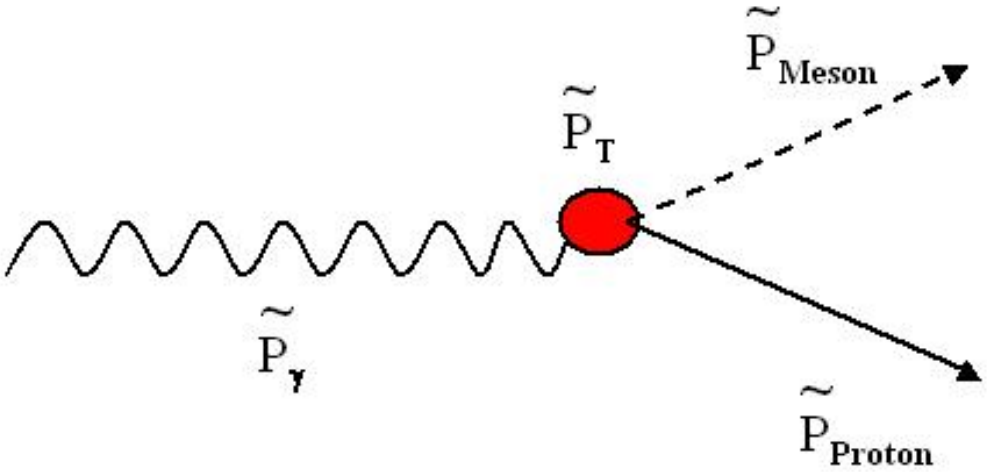
Conclusions

- high statistics measurement of Σ for the reaction $\vec{\gamma} + p \to \omega + p$ from the complete GRAAL data-set:
  - $\omega \to \pi^0 + \gamma$: event selection
  - $\omega \to \pi^+ + \pi^0 + \pi^-$: fitting procedure
  - agreement between the two decay modes
  - data well described by Zhao model $\to$ $P_{13}(1720)$
- measurement of Σ for the reaction off the quasi-free proton target
  - $\omega \to \pi^0 + \gamma$: event selection
  - small-disagreement with the free proton results $\Rightarrow$?
- first measurement of Σ for ω photoproduction off neutron
  - $\omega \to \pi^0 + \gamma$: event selection
  - completely different angular distributions (w.r.t. proton):
    small (or compatible with 0) for $\theta^*_\omega \in (0°, 90°)$;
    positive for $\theta^*_\omega \simeq 120°$
- measurements at higher energies ($\omega \to \pi^+\pi^0\pi^-$) forseen at BGO-OD

The final state nucleon identification

In the laboratory frame:



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

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

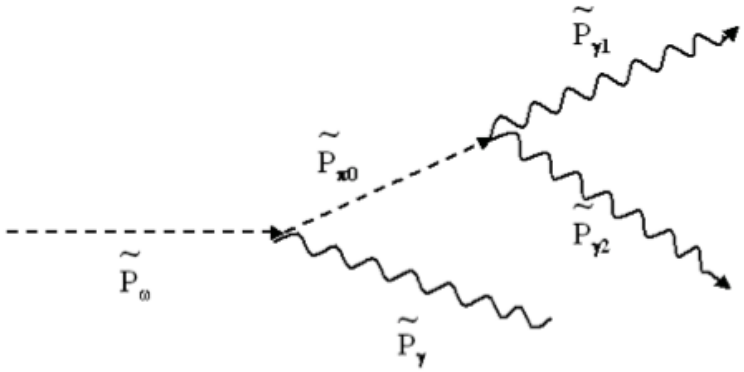
$$\tilde{P}_\omega = (E_\omega; p_\omega^x, p_\omega^y, p_\omega^z)$$

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

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

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^x_ω, p^y_ω, p^z_ω

Kinematic reconstruction:

In the center-of-mass frame:

$$E_\gamma, M_T \rightarrow \begin{array}{l} \beta = \frac{E_\gamma}{E_\gamma + M_T} \\ s = 2E_\gamma M_T \\ \gamma = \frac{1}{\sqrt{1-\beta^2}} \end{array} \rightarrow \begin{array}{l} E^*_N = \frac{s+M_N^2-M_\omega^2}{2\sqrt{s}} \\ E^*_\omega = \frac{s-M_N^2+M_\omega^2}{2\sqrt{s}} \\ p^* = \frac{\sqrt{[s-(M_N+M_\omega)^2][s-(M_P-M_\omega)^2]}}{4s} \end{array}$$

Back to the laboratory frame:

$$\theta_N, \phi_N \rightarrow \begin{array}{l} E_N = \gamma(E^*_N + \beta p^*_N \cos\theta^*_N) \\ p_N \cos\theta_N = \gamma(\beta E^*_N + p^*_N \cos\theta^*_N) \end{array} \rightarrow$$

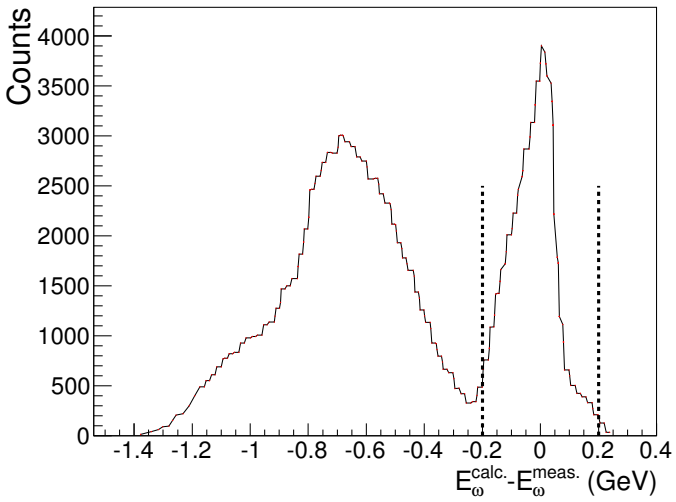
2nd order equation in E_N
+ energy balance:
E_N^{calc}, E_ω^{calc}, θ_ω^{calc}, ϕ_ω^{calc}

The radiative decay: events selection (free proton)

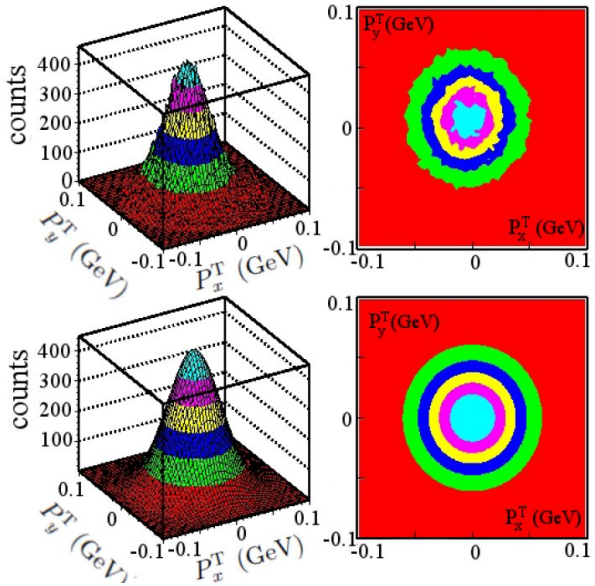
Competitive reactions:

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

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



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

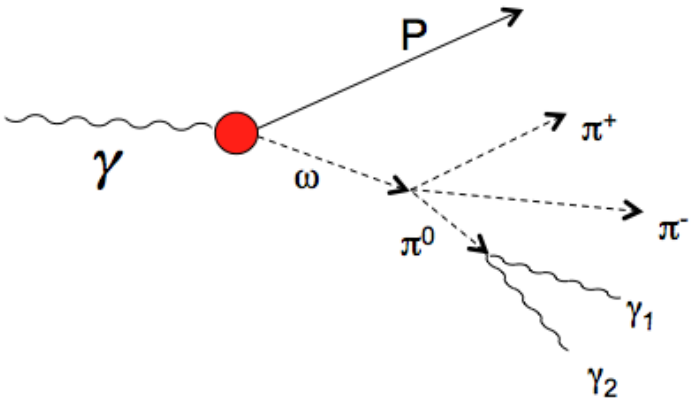


3. $M_{miss,p} > 200 MeV$

4. $M_\omega > 680 MeV$

The 3-pion decay: events reconstruction

(free proton)



P:	E_P,	θ_P,	ϕ_P
π^+:	E_{π^+},	θ_{π^+},	ϕ_{π^+}
π^-:	E_{π^-},	θ_{π^-},	ϕ_{π^-}
γ_1:	E_{γ_1},	θ_{γ_1},	ϕ_{γ_1}
γ_2:	E_{γ_2},	θ_{γ_2},	ϕ_{γ_2}

$$
\begin{aligned}
E: &\quad \sqrt{(P_{\pi^+})^2 + M_{\pi^+}^2} + \sqrt{(P_{\pi^-})^2 + M_{\pi^-}^2} + E_{\gamma_1} + E_{\gamma_2} &&= E_\gamma + M_P - E_P \\
P^x: &\quad P_{\pi^+} \sin\theta_{\pi^+} \cos\phi_{\pi^+} + P_{\pi^-} \sin\theta_{\pi^-} \cos\phi_{\pi^-} + E_{\gamma_1} \sin\theta_{\gamma_1} \cos\phi_{\gamma 1} + E_{\gamma_2} \sin\theta_{\gamma_2} \cos\phi_{\gamma 2} &&= -P_P^x \\
P^y: &\quad P_{\pi^+} \sin\theta_{\pi^+} \sin\phi_{\pi^+} + P_{\pi^-} \sin\theta_{\pi^-} \sin\phi_{\pi^-} + E_{\gamma_1} \sin\theta_{\gamma_1} \sin\phi_{\gamma 1} + E_{\gamma_2} \sin\theta_{\gamma_2} \sin\phi_{\gamma 2} &&= -P_P^y \\
P^z: &\quad P_{\pi^+} \cos\theta_{\pi^+} + P_{\pi^-} \cos\theta_{\pi^-} + E_{\gamma_1} \cos\theta_{\gamma_1} + E_{\gamma_2} \cos\theta_{\gamma_2} &&= E_\gamma - P_P^z
\end{aligned}
$$

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

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

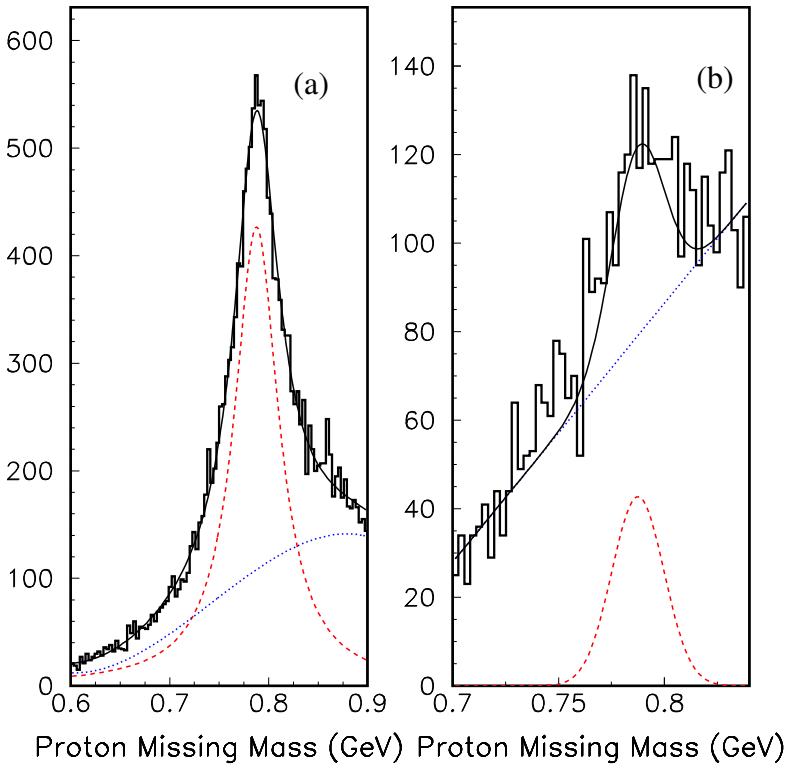
The 3-pion decay: fitting procedure

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. $100 MeV < M_{\pi^0} < 170 MeV$
2. $M_{(\pi^+,\pi^0,\pi^-)} < 2 GeV$



fit performed bin-by-bin:

- 2 polarization states
- 4 energy bins
- 5 polar angle (θ^*_ω) bins
- 16 azimuthal angle (ϕ_ω) bins

Breit-Wigner + 3rd order polynomial

last energy bin: limited statistics (pannel b)

The quasi-free nucleon target

Free proton:

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

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

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

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

4. $M_\omega > 680$ MeV

Quasi-free nucleon:

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

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

$\sigma_x^{qf} = \sigma_y^{qf} = 70$ 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 MeV/c^2
$\sigma_{miss,N}^{inv}$ = 80 MeV/c^2
$n = 3$

Only for the neutron:
$|\phi_{\pi^0} - \phi_n| \notin (150°; 210°)$