$K^0\Lambda$ photoproduction on the neutron at $E_\gamma < 1.2$ GeV

Yusuke TSUCHIKAWA
for the FOREST collaboration

Department of Physics, Nagoya University

$K^0 \Lambda$ *photoproduction on the neutron at* $E_\gamma < 1.2\ GeV$

Outline

Introduction - Baryon spectroscopy and KY channels
- Narrow peak structures of special interest at W ~ 1.67 and 1.71 GeV

Experiment - ELPH & 4π electromagnetic calorimeter FOREST

Analysis - Particle identification, Kinematic fit
- Yield counting, Background subtraction

Results - Differential and Total cross sections
- Y^* contributions for the $K^0\Lambda$ photoproduction

Summary

Baryon spectroscopy via KY *photoproduction*

-> accessible highly excited baryons which hardly couple to $\boldsymbol{\pi N}$ $(\boldsymbol{\eta N})$

- $K^+\Lambda(\Sigma)$: recently well studied (CLAS, LEPS, SAPHIR, MAINZ,…)
- $K^0\Lambda(\Sigma^0)$: few reports

$\boxed{\boldsymbol{\gamma n \rightarrow K^0\Lambda} \textbf{ reaction}}$

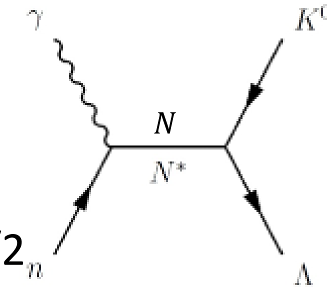
Isospin selective -> $\boldsymbol{K\Lambda}$**: 1/2**, $K\Sigma$: 3/2

Expected **few t-channel contributions**

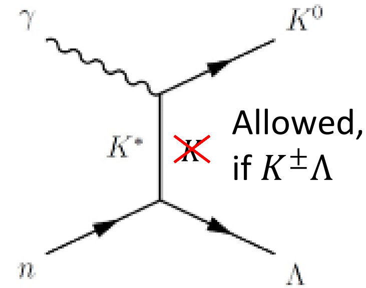
All of the participants are *NEUTRAL*

→ no K (not K^*) can be exchanged

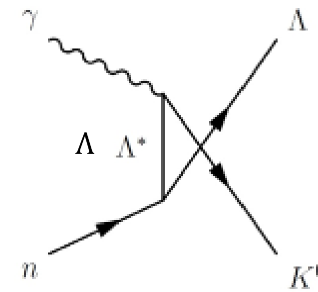
→ Born term contributions are expected to be smaller than that of the $K^+\Lambda$ case



s-channel



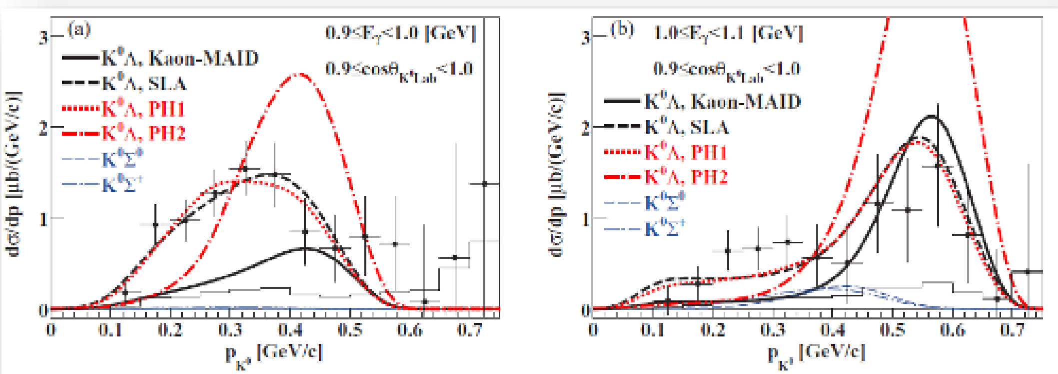
t-channel



u-channel

Good probe for $\boldsymbol{N^*}$ and $\boldsymbol{Y^*}$

K. Tsukada et al. (**NKS** collaboration), Phys. Rev. C **83** 039904



The previous measurement near the reaction threshold was done for

$\underline{E_\gamma = [0.9, 1.1)\mathrm{GeV}}$ and $\underline{\cos\theta_K^{Lab} = [0.9, 1.0)}$

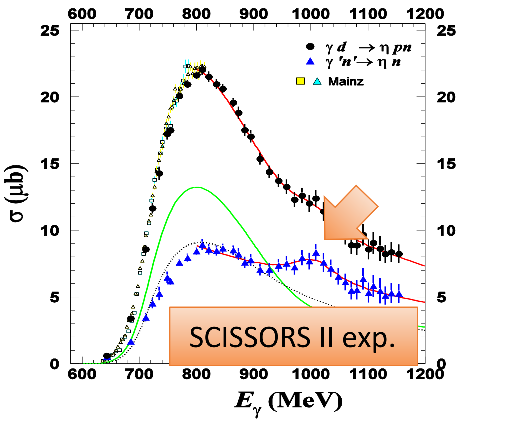
<u>**Need the study with entire angle region**</u>

$N(1670)$

$\boxed{\gamma N \rightarrow \eta N}$

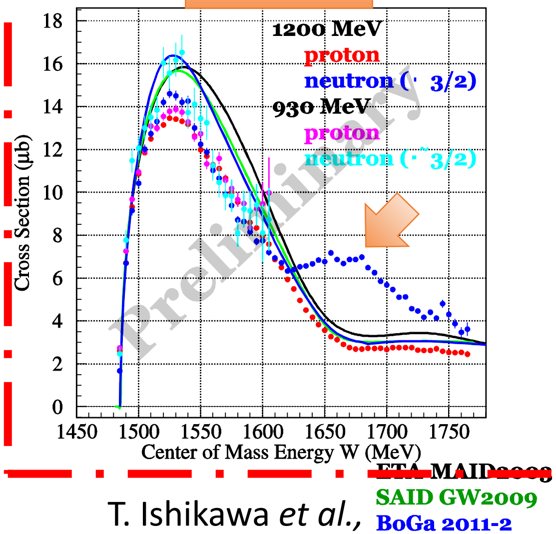
$\gamma n \rightarrow \eta n$ -> A narrow resonance-like structure @1670 MeV
$\gamma p \rightarrow \eta p$ -> *No* such structure (but a dip?)

LNS (ELPH)



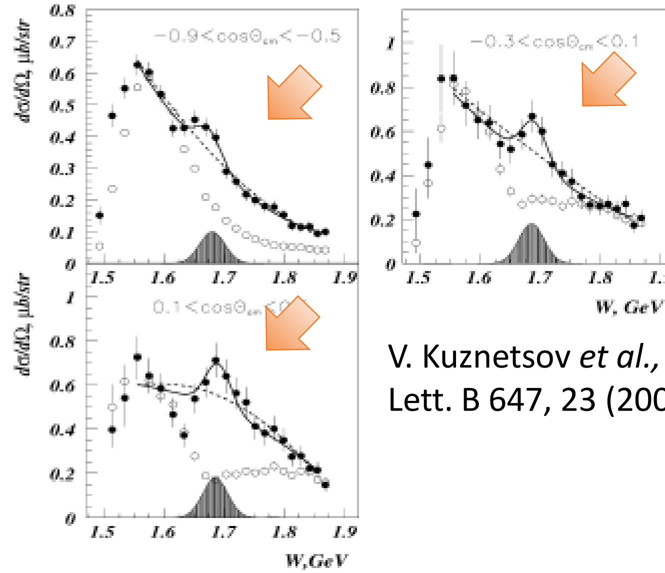
F. Miyahara *et al.*, Prog. Theor. Phys. Suppl. **168,** 90, (2007)

FOREST



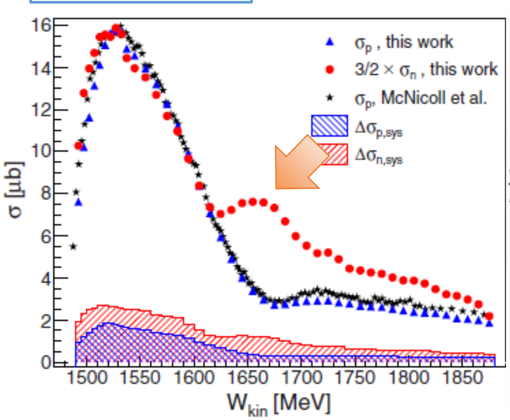
T. Ishikawa *et al.*, PoS (Hadron2013)025

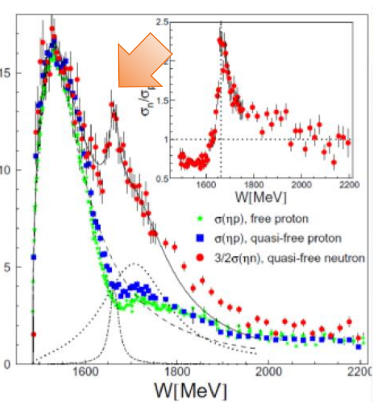
GRAAL



V. Kuznetsov *et al.*, Phys. Lett. B 647, 23 (2007)

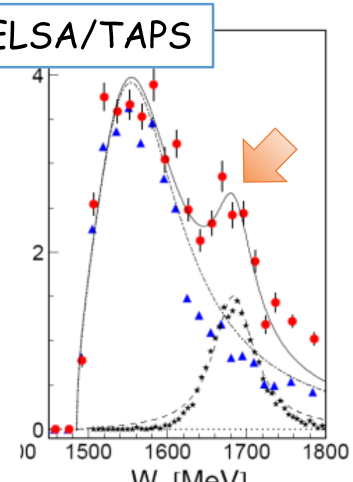
A2@Mainz

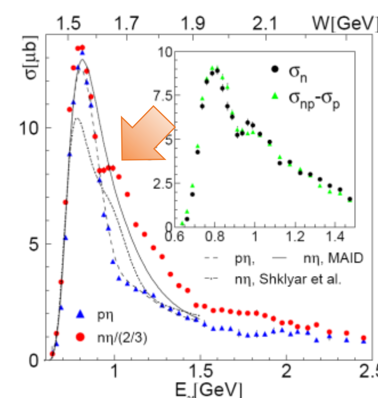




R.Wertmuller *et al.*, PRC 90, 015205 (2014)

CBELSA/TAPS





J.Jeagle *et al*, PRL **100**, 252002 (2008)

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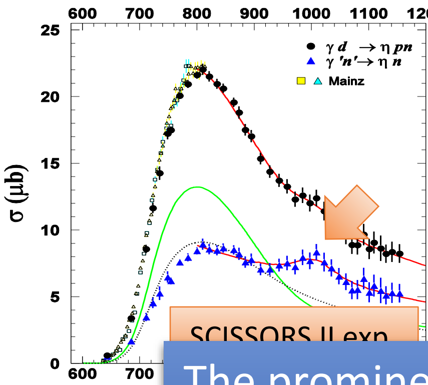

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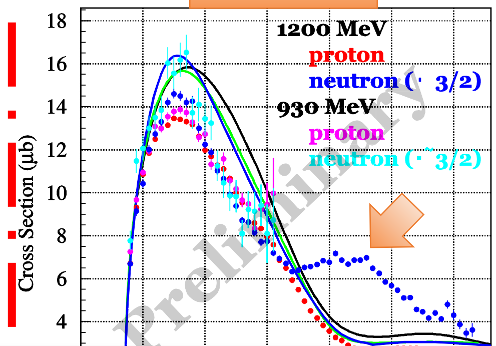
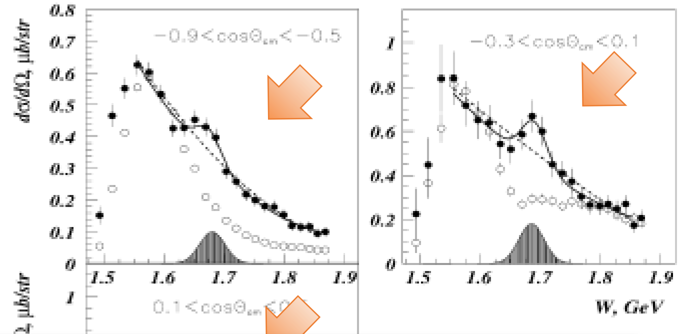


GRAAL



F. Miyal
Phys. Su

l., Phys.
007)

The prominent structure observed in the $\gamma n \to \eta n$

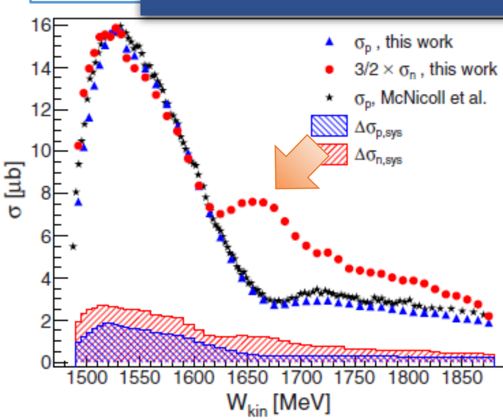
Reported by many exp. groups **LNS (ELPH), GRAAL, MAINZ, CB-ELSA/TAPS**

→ Consistent results:

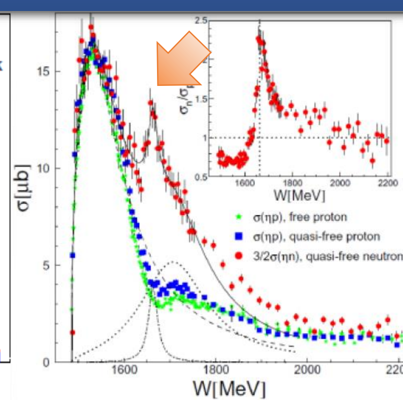
Narrow width ($\sim$ **30 MeV**) and peak position $\sim$ **1670** MeV

Observed in the $\boldsymbol{n(\gamma,\eta)n}$ reaction but ***not* in the** $\boldsymbol{p(\gamma,\eta)p}$ case

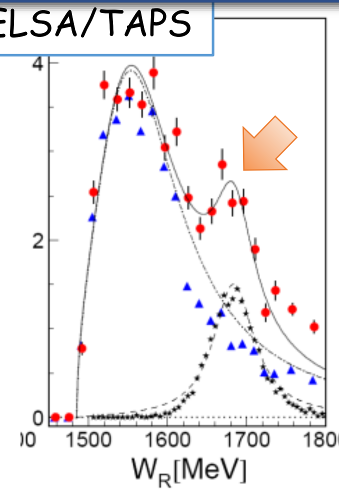
A2@M

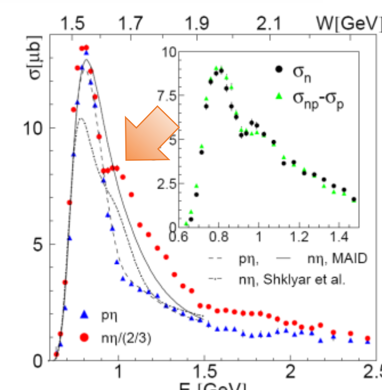


R.Wertmuller *et al.*, PRC 90, 015205 (2014)



CBELSA/TAPS



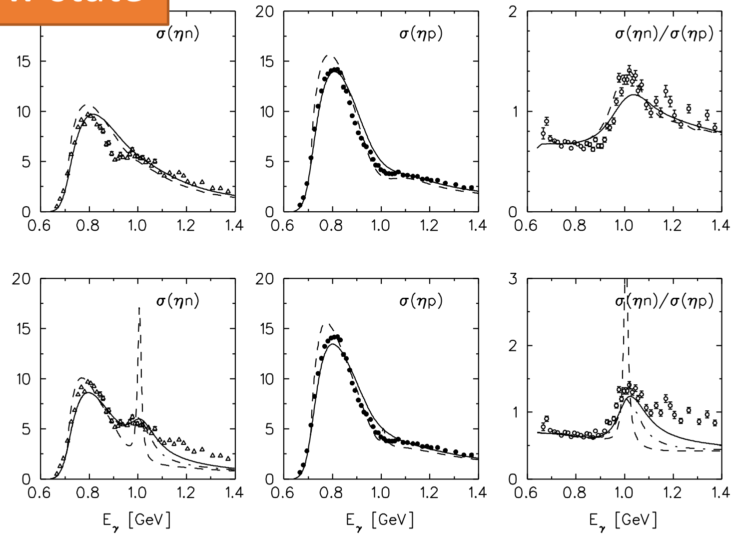


J.Jeagle *et al*, PRL **100**, 252002 (2008)

$N(1670)$

Intrinsic narrow state

A. Fix et al., Eur. Phys. J. A 32, 311–319 (2007).

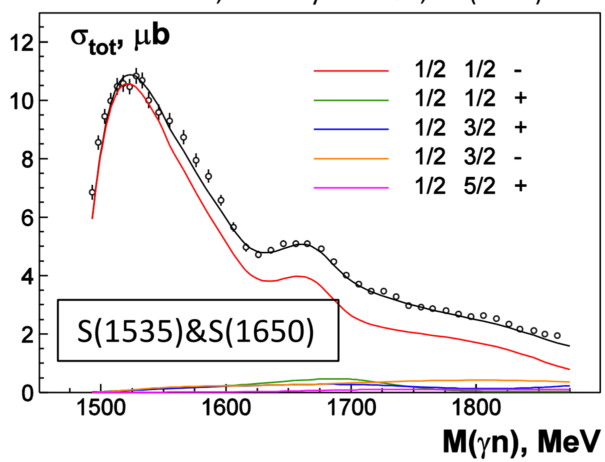


Recent theoretical interpretations

- Intrinsic narrow state
- Coupled-channel effects
- Interference effects
- KY threshold effects
- …

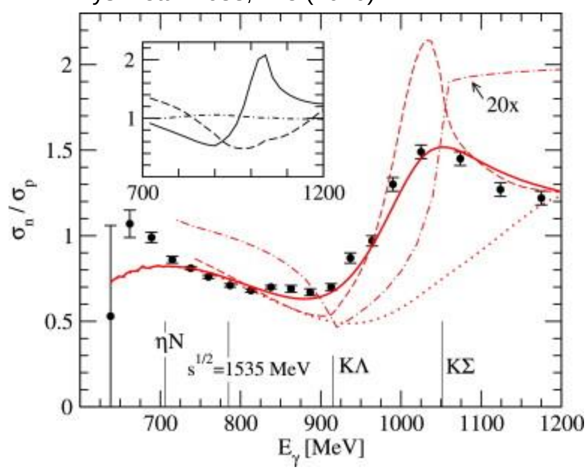
Interference effect

Anisovich et al., Eur. Phys. J. A **51**, 72 (2015)



Threshold effect (KY ch.)

M. Döring and K. Nakayama,
Phys. Lett. B 683, 145 (2010).



More experimental information is needed
-> How about the $K^0\Lambda$ case?

Similarities between
ηn & $K^0\Lambda$

- **Isospin 1/2**
- **γn initial state**
- **$s\bar{s}$ component**

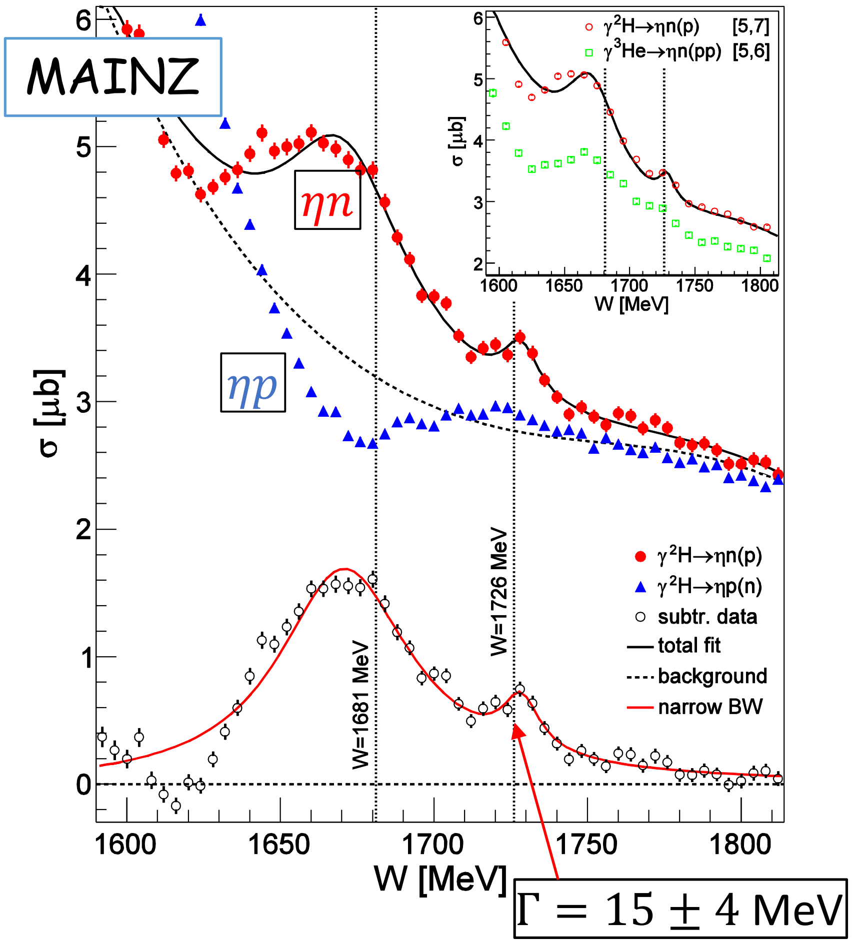
Confirmation of the N(1670) must be a valuable info.

$N(1710)$?

Another narrow, but small, peak structure has been also observed in $\eta(\pi^0)$ photoproduction

Re-analysis of the $\gamma(n,n)\eta$ reaction (re-binned ver.)

Werthmuller et al., arXiv 1511.0829 (very recent!)



Σ asymmetry of the $\gamma(p,p)\pi^0$ reaction

Kuznetsov et al., Phys. Rev. C 91, 042201 (2015)

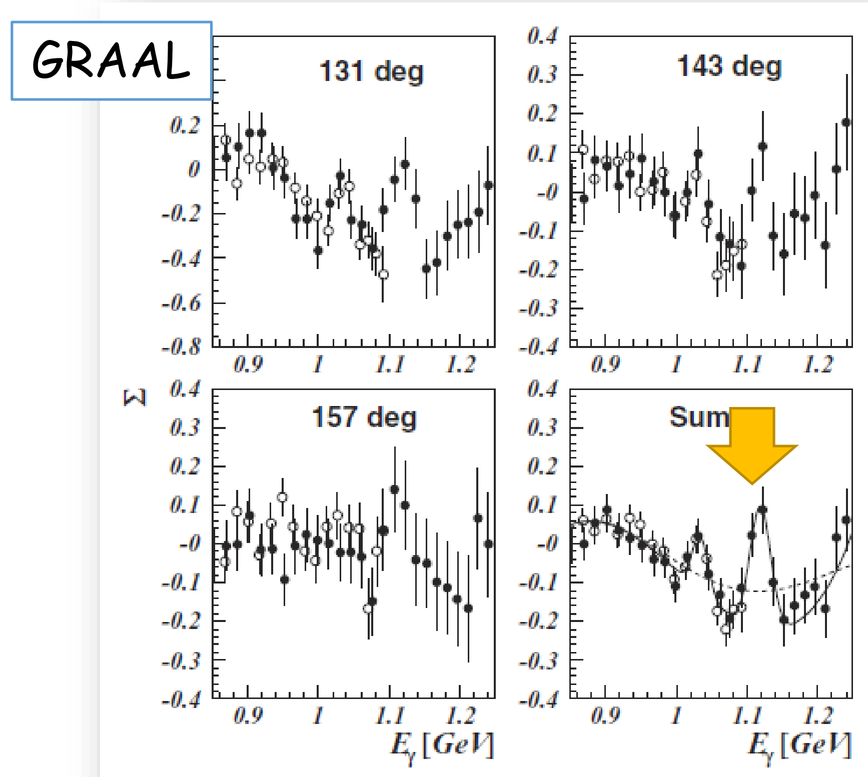
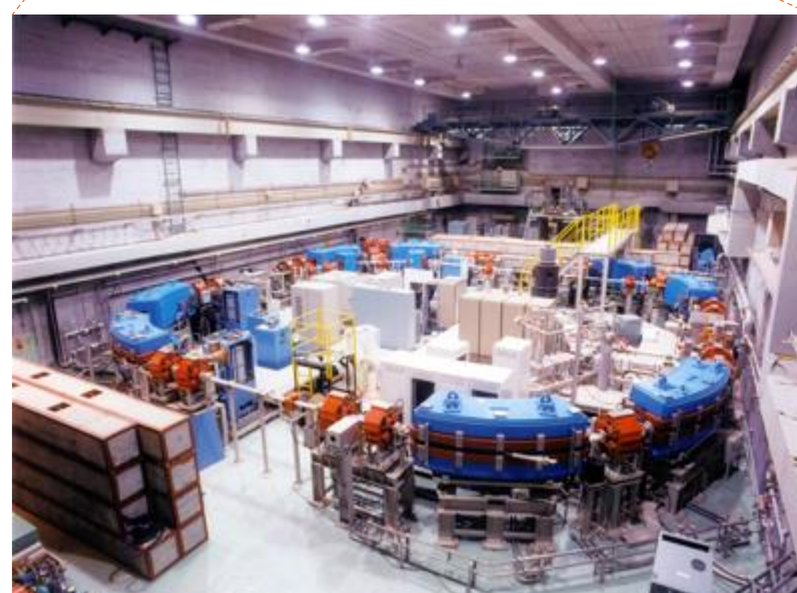


FIG. 3. Beam asymmetry Σ for Compton scattering on the proton. Dark (open) circles are the results obtained with UV (green) laser.

Experiment

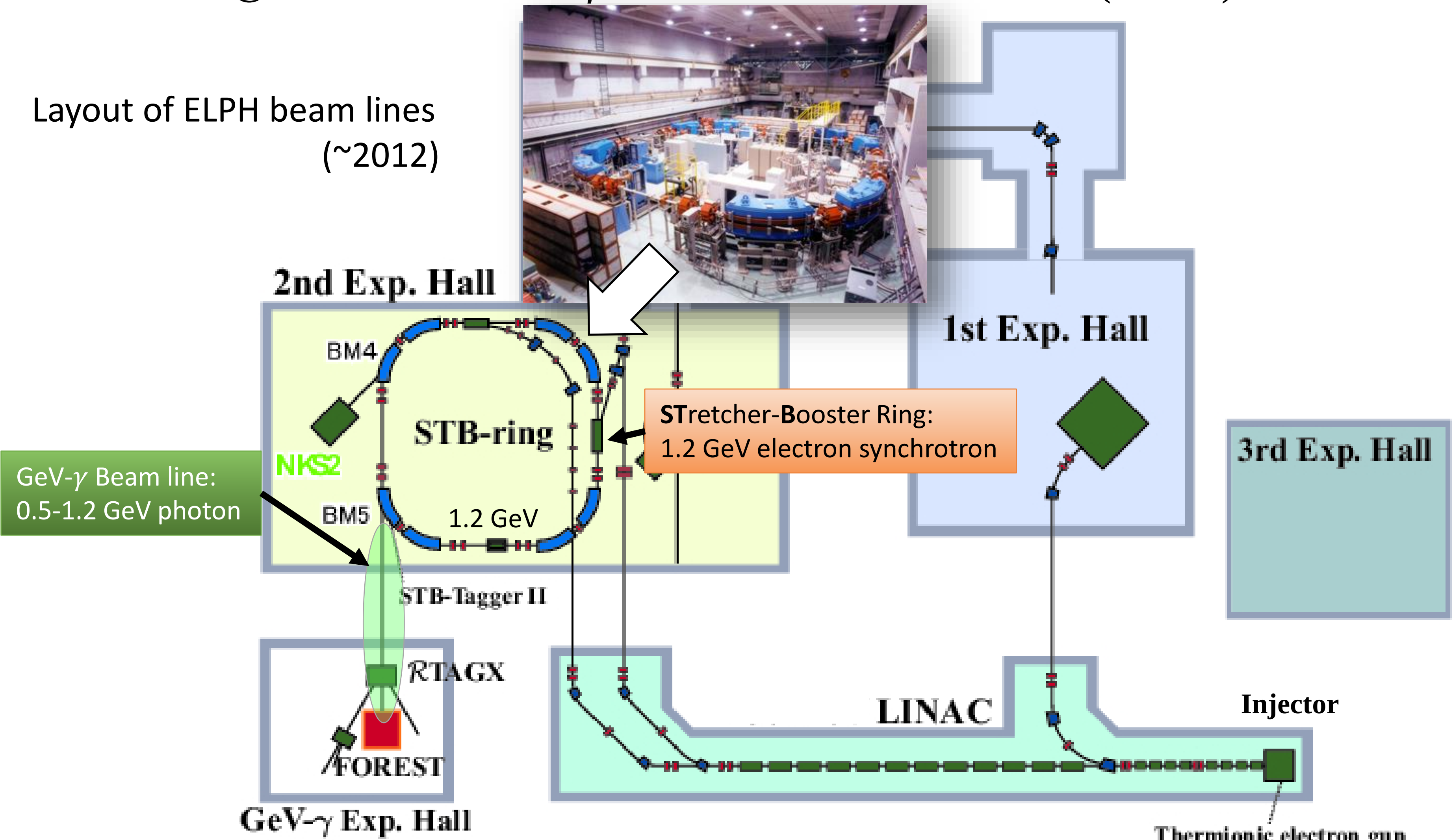
Research Center for **El**ectron **Ph**oton Science (ELPH)



Experiment @ ELPH, Tohoku University, Sendai

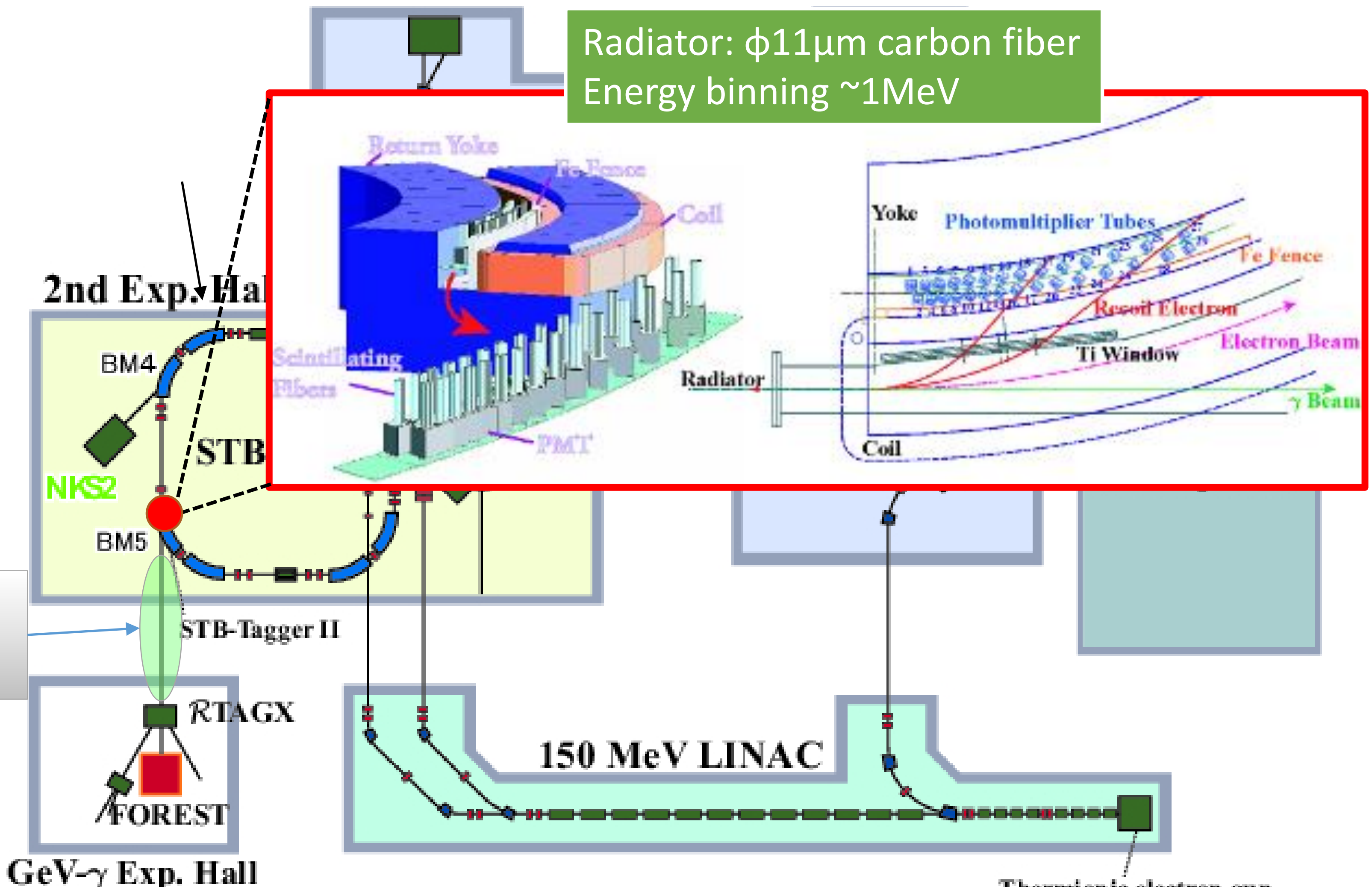
1.2 GeV Electron Synchrotron and photon beam line
@ Research Center for Electron Photon Science (ELPH)

Layout of ELPH beam lines
(~2012)



Experiment @ ELPH, Tohoku University, Sendai

Photon Tagging System



GeV-γ Beam line: 0.5-1.2 GeV photon

4 π electromagnetic calorimeter complex **FOREST**

252 Lead/SciFi mod.s
LEPS Backward Gamma

192 Pure CsI
SCISSORS III

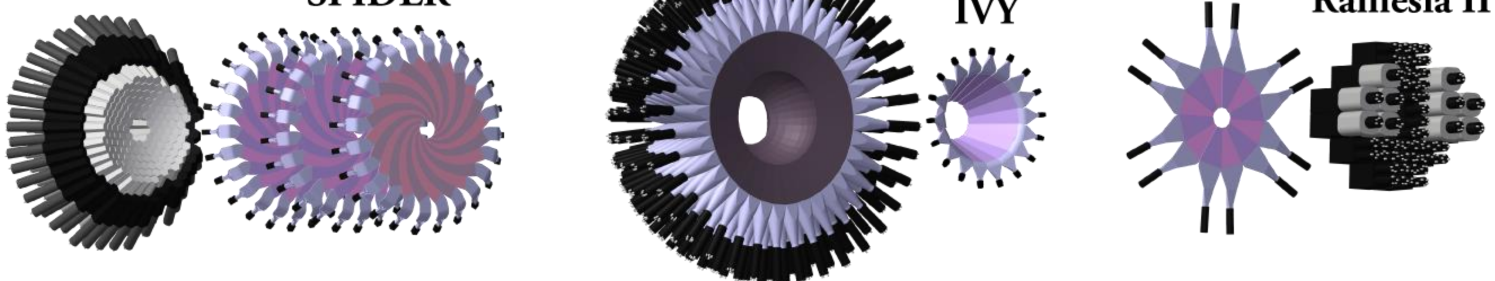
24 PS × 3 layers
SPIDER

PS × 18
IVY

PS × 12
LOTUS

62 Lead/Glass
Rafflesia II

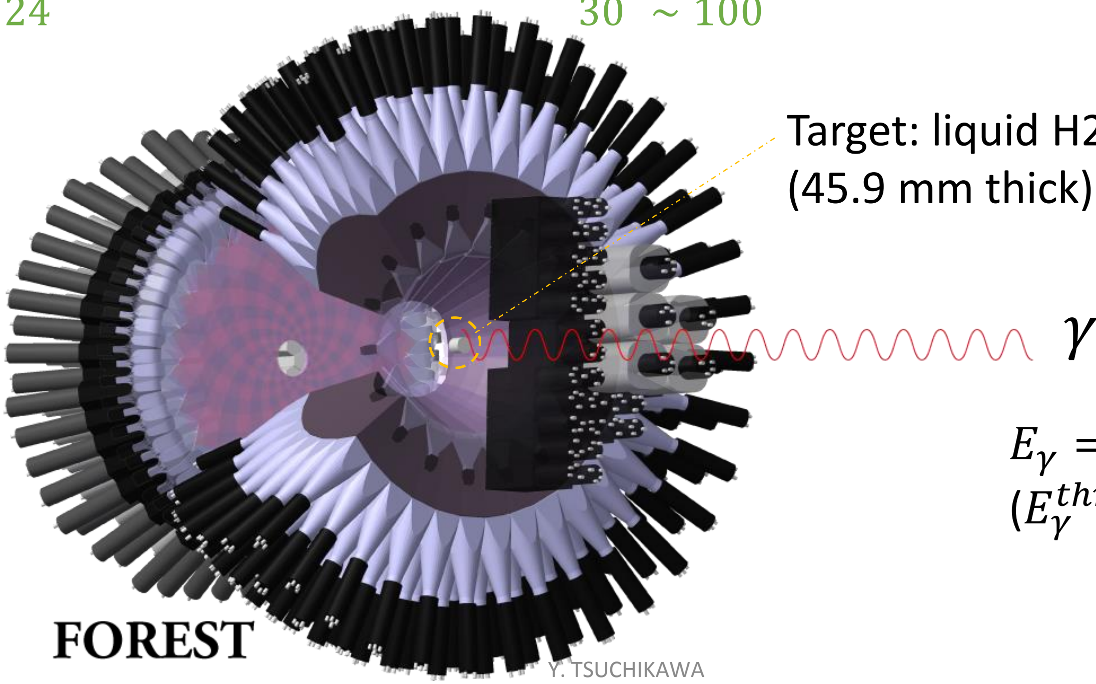
(Forward)



(Backward)

σ_E/E (1 GeV γ) ~3 % ~ 7 % ~ 5 %

Coverage θ $5^\circ \sim 24^\circ$ $30^\circ \sim 100^\circ$ $110^\circ \sim 170^\circ$

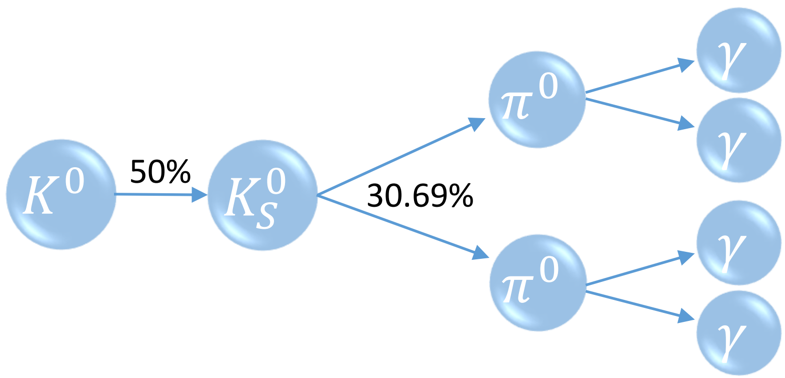


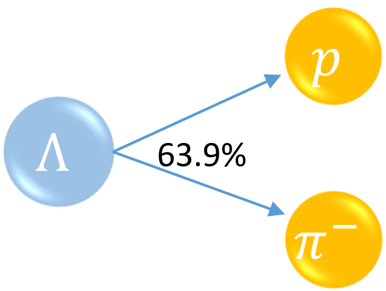
Target: liquid H2/**D2** target
(45.9 mm thick)

$E_\gamma = 750 - 1150$ MeV
$(E_\gamma^{thr}(K^0\Lambda) = 915$ MeV$)$

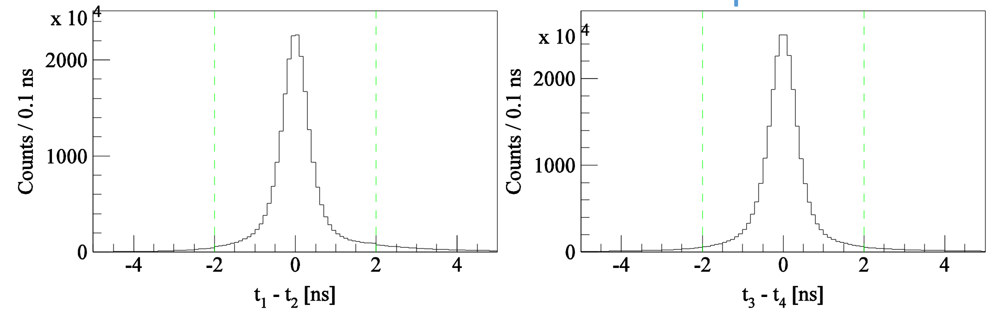
Particle identification

Focusing decay chains:



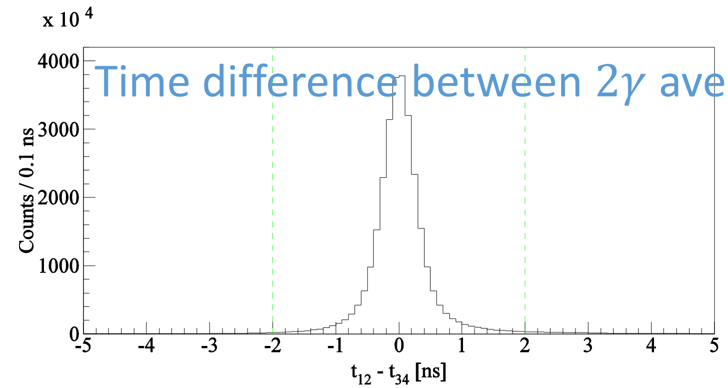


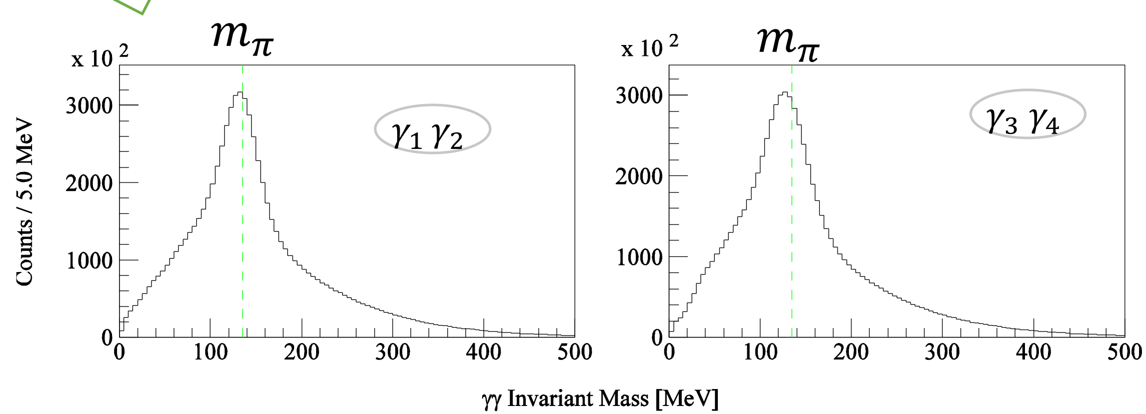
Time differences between 2 photons



> No selection for the best $\gamma\gamma$ partner was performed at this point

Time difference between 2γ averages



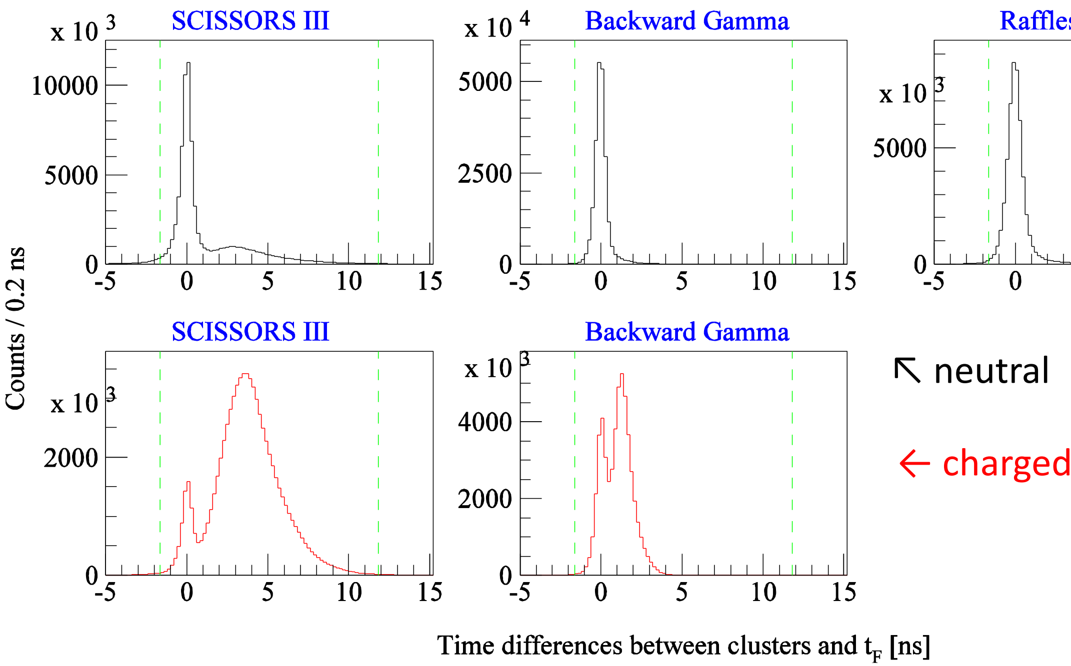


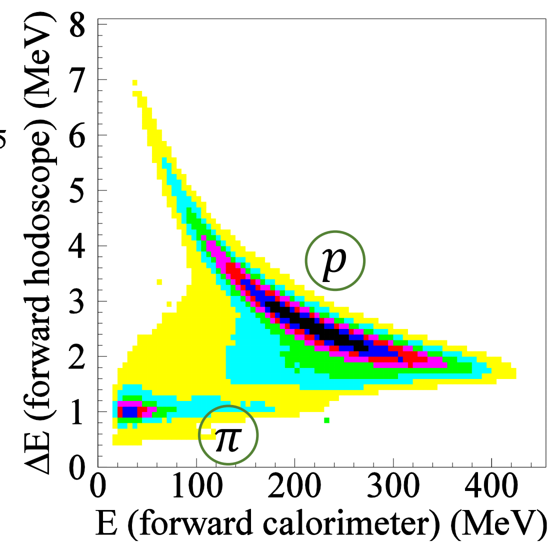
$\gamma\gamma$ invariant masses

Particle identification

The event timing criterion: average timing of 4 photons

Other clusters



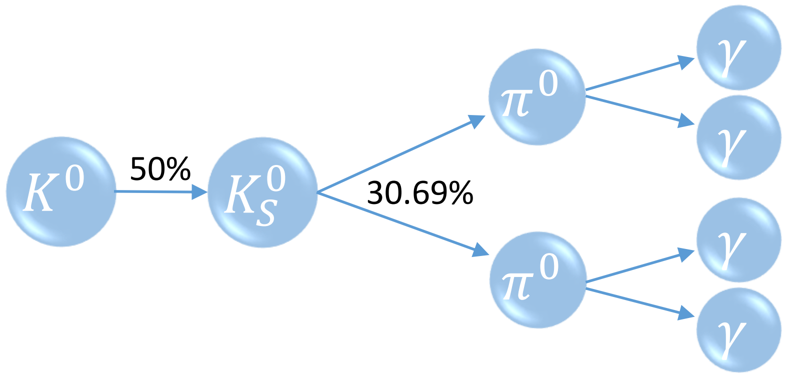


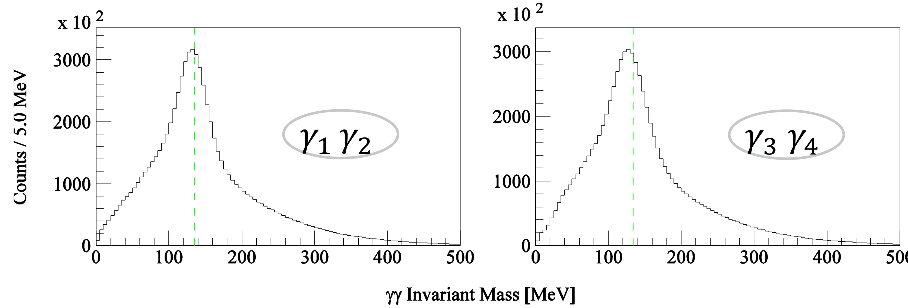
Two charged particles were distinguished
by TOF based kinematic cut conditions

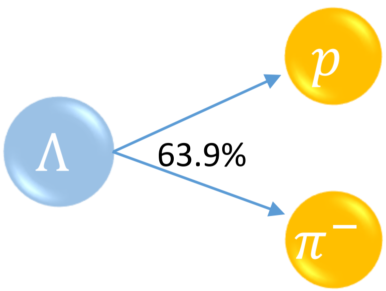
Requirement: *No other neutral particles but two more charged particles*

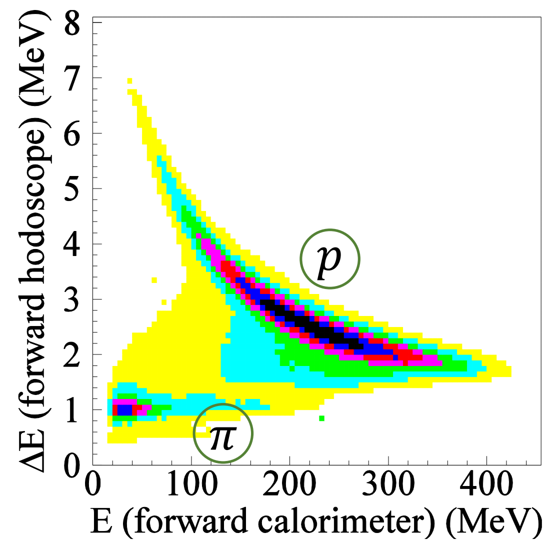
Particle identification

Focusing decay chains:









All of the particles in the final state (**4 photons** and **2 charged** particles) are identified

$$\gamma d \rightarrow K^0 \Lambda p \rightarrow K_S^0 \Lambda p \rightarrow (\pi^0 \pi^0)(p\pi^-)p \rightarrow (4\gamma)(p\pi^-)p$$

Proton in the deuteron is assumed as a *spectator*

Kinematic fit with 4 constraints

16 variables:
γ_i momentum, polar, and azimuthal angles: E_i, θ_i, ϕ_i $(i = 1, \ldots, 4)$, same for proton: P_p, θ_p, ϕ_p,
and Photon beam energy: E_γ

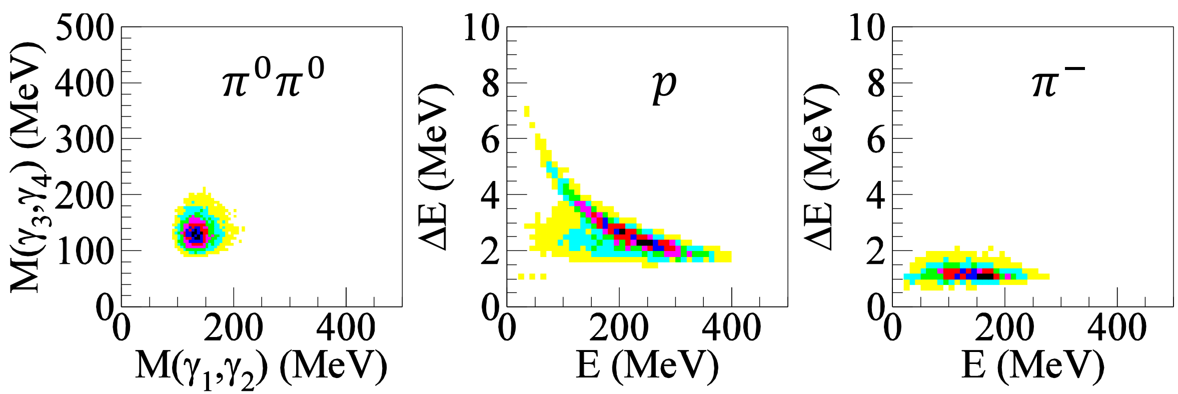
"$\gamma\gamma$ invariant mass $= m_{\pi^0}$" x2

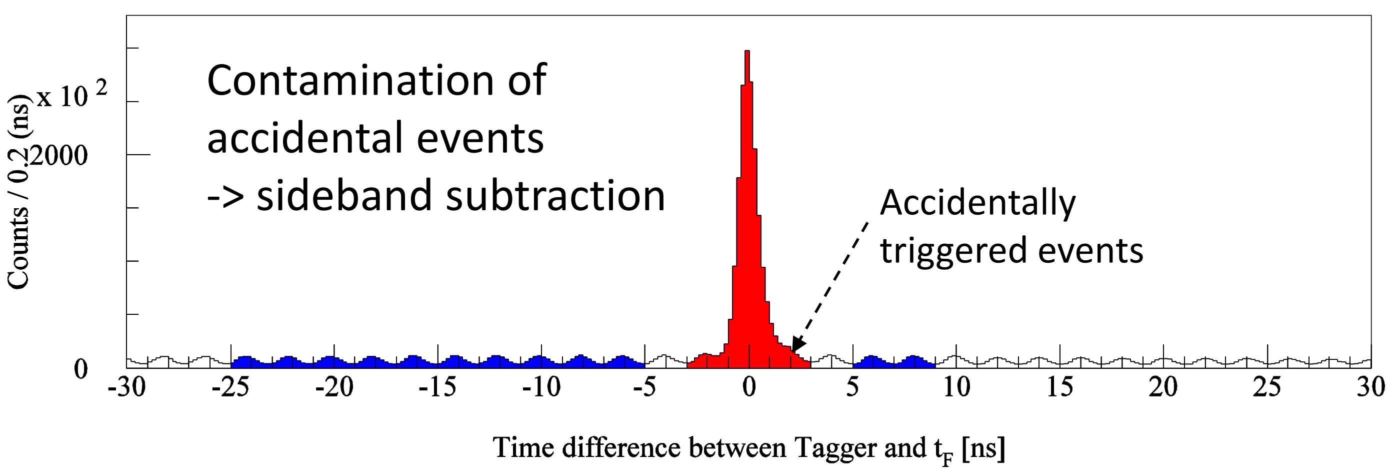
1. $M^2(\gamma_1, \gamma_2) \equiv 2E_1E_2(1 - \sin\theta_1 \sin\theta_2 \cos(\phi_1 - \phi_2) - \cos\theta_1 \cos\theta_2) = m_{\pi^0}^2$
2. $M^2(\gamma_3, \gamma_4) \equiv 2E_3E_4(1 - \sin\theta_3 \sin\theta_4 \cos(\phi_3 - \phi_4) - \cos\theta_3 \cos\theta_4) = m_{\pi^0}^2$

"4γ missing mass $= m_\Lambda$" : 3. $M_X^2(\gamma_1, \gamma_2, \gamma_3, \gamma_4) \equiv E_X^2 - P_X^2 = \left(E_\gamma + m_n - \sum_{i=1}^{4} E_i\right)^2 - P_X^2(E_i, \theta_i, \phi_i, E_\gamma) = m_\Lambda^2$

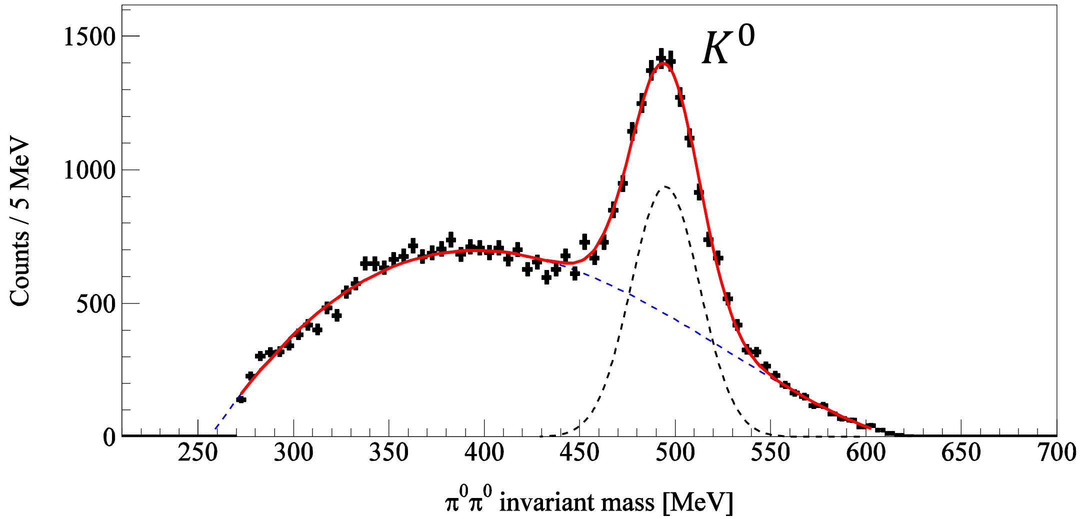
"$4\gamma p$ missing mass = m_{π^-}": 4. $M_X^2(\gamma_1, \gamma_2, \gamma_3, \gamma_4, p) = m_{\pi^-}^2$

Selected events with detected values





K^0 signal and background



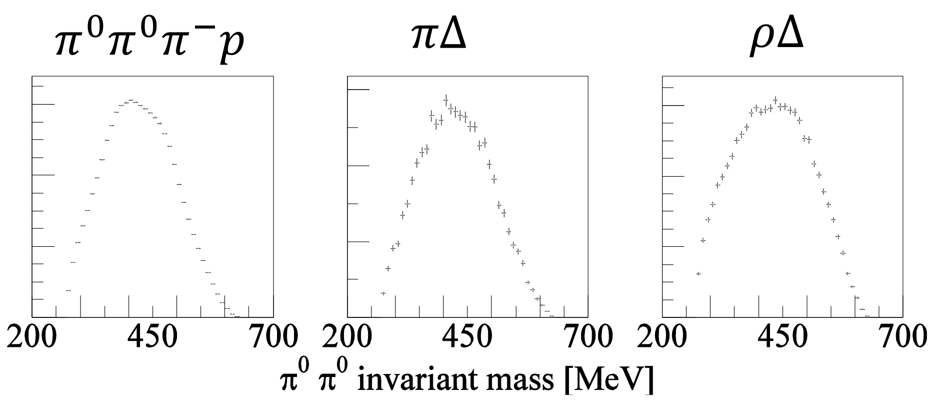
4th pol. + gaussian
$\mu = 494.9(3)$ MeV
$\sigma = 17.9(3)$ MeV
About 8,400 K^0 signals

Clear peak but **S/N ~50%**

Reactions as background sources have been investigated via GEANT4-based simulations.
Candidates of the reactions:

$$\gamma n \to \pi X(\Delta, N^*, \rho N) \to \pi^- \pi^0 \pi^0 p,$$
$$\gamma n \to \pi^0 \pi^0 \pi^- p.$$

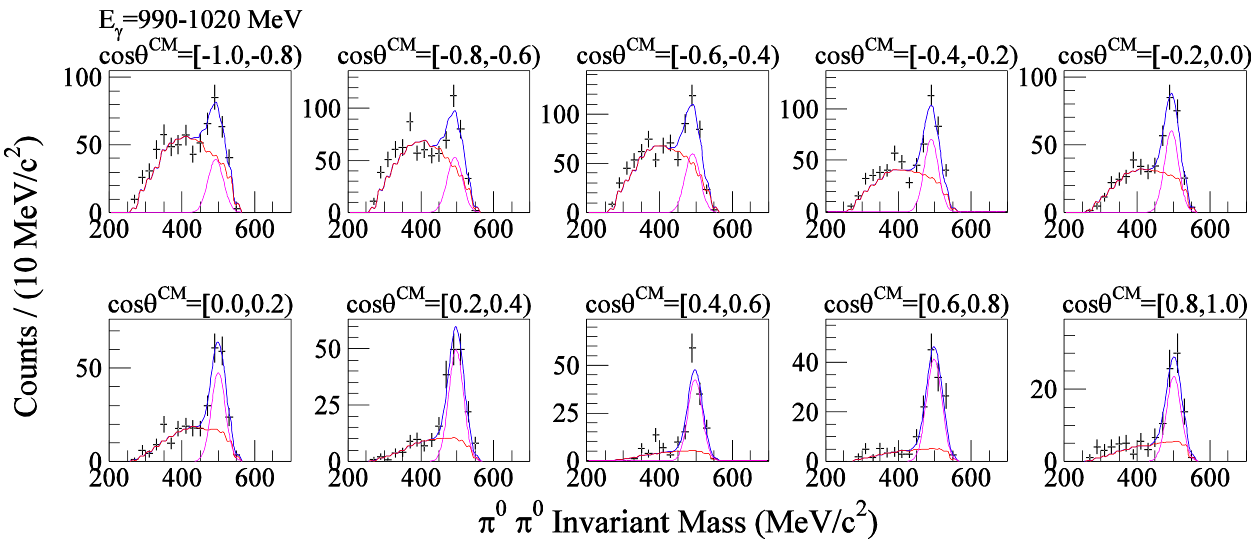
Those candidates do not show significant differences on 2 pi invariant mass distributions with one another.



Yield counting

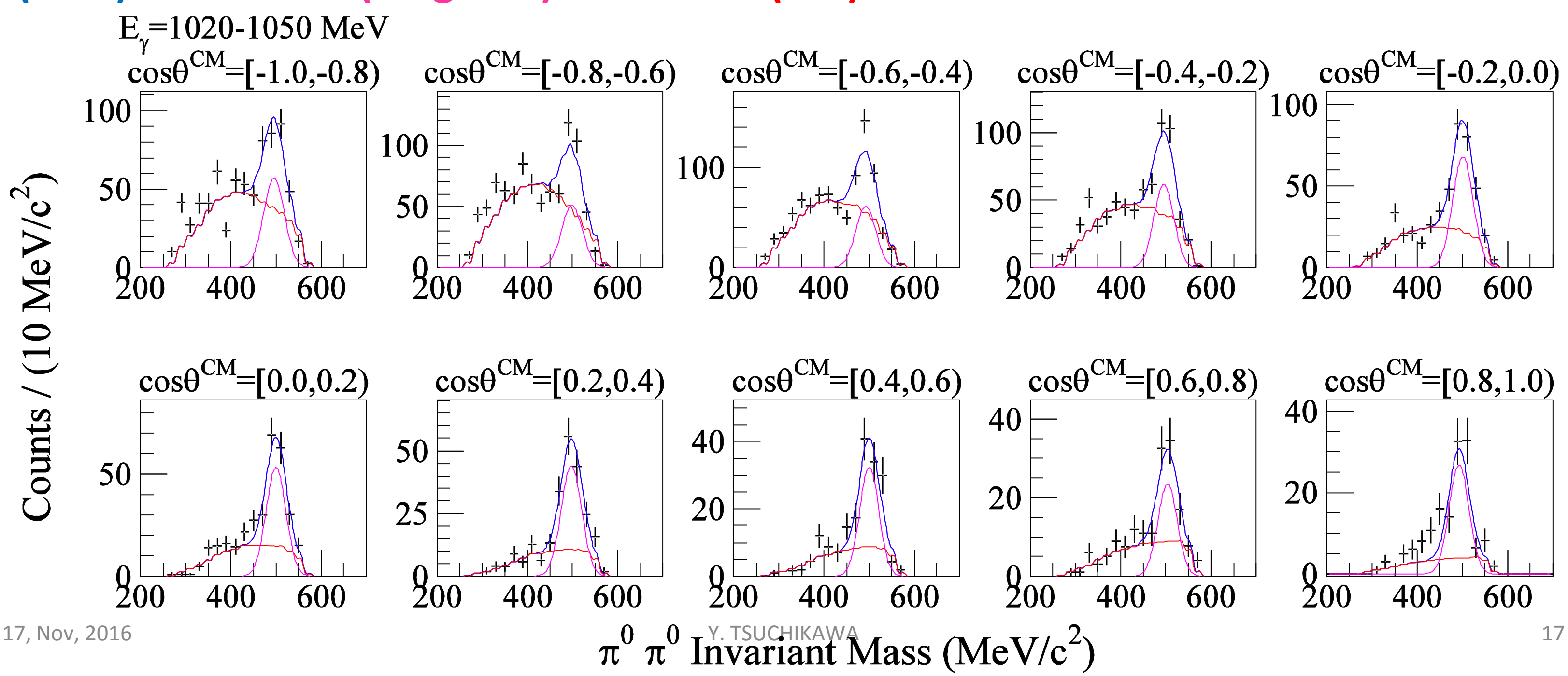
The simulated distributions ($\gamma n \to \pi^0\pi^0\pi^- p$) well reproduce the BG distributions

Examples of the fit results



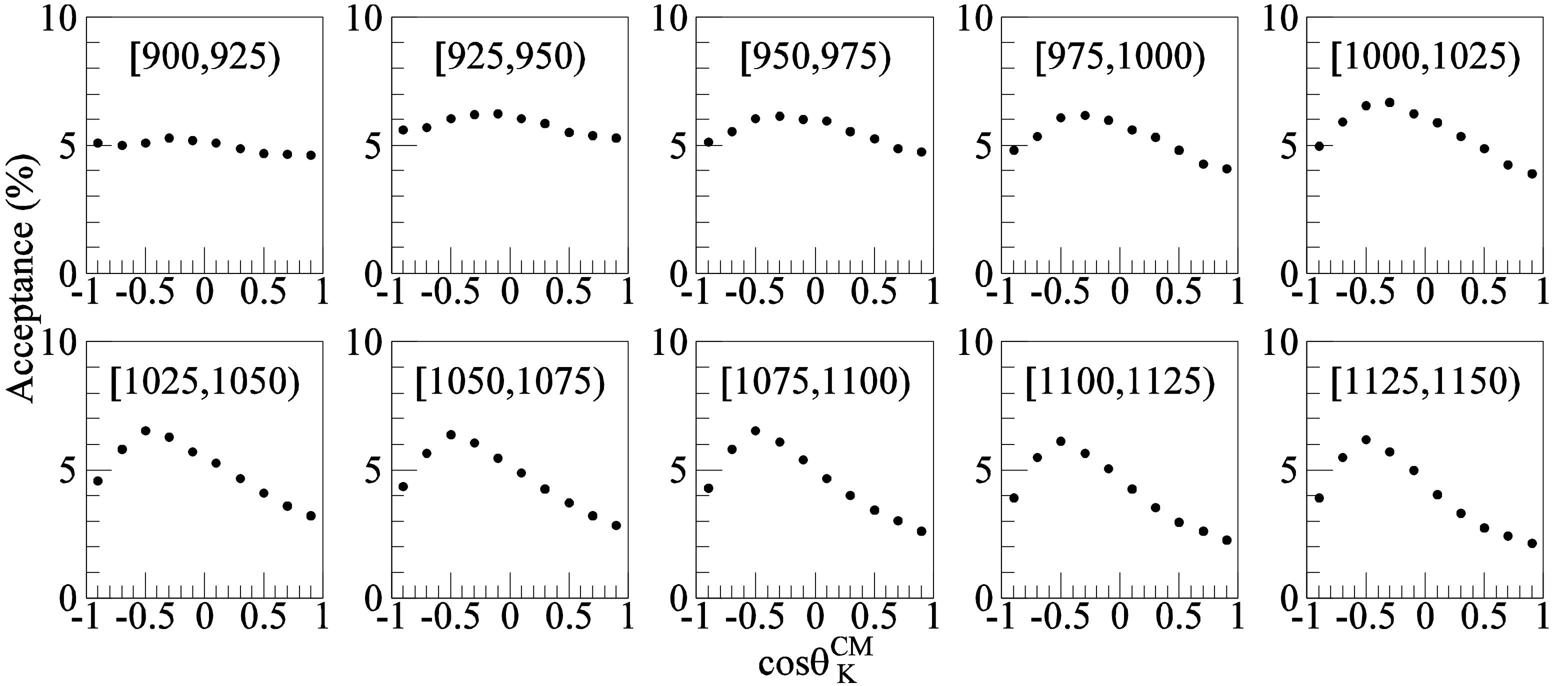
Fit for yield counting:

Total (blue) = Gaussian (magenta) + BG dist. (red)



Acceptance

Full coverage for $\cos\theta_K^{CM}$ to the whole range of E_γ

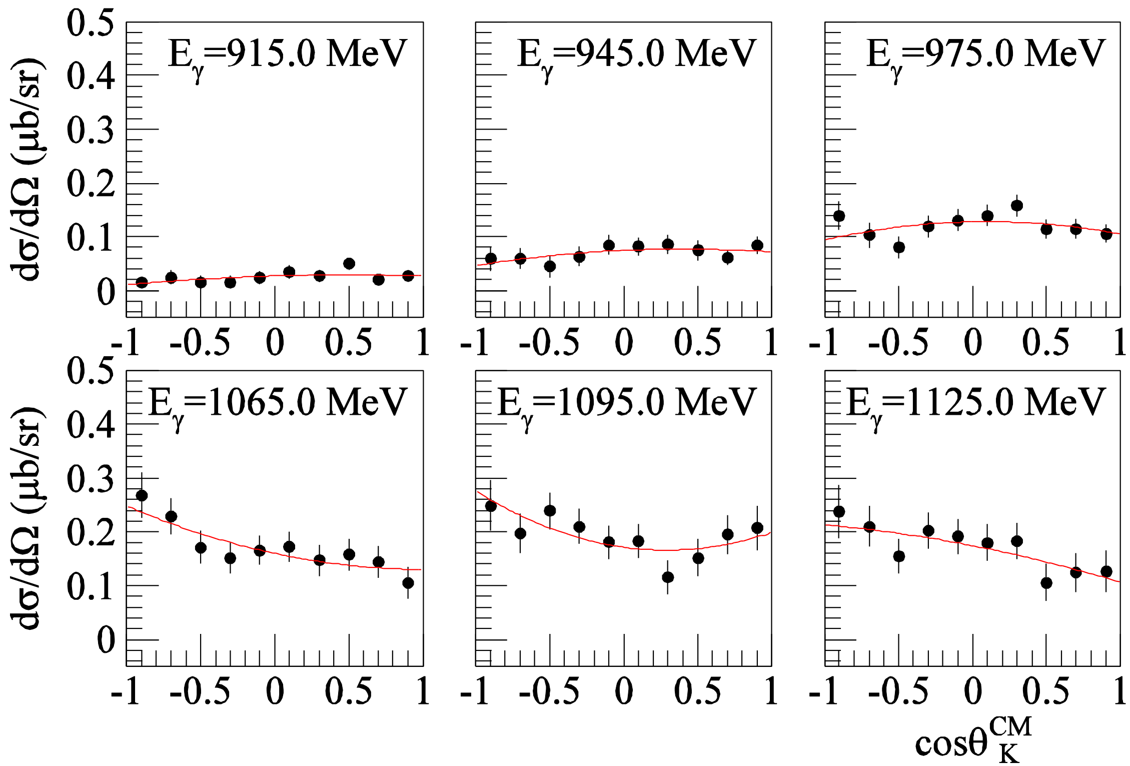


Decrease of the acceptance in the forward angle at higher energy parts

-> lost of high energy proton from the detector hole around the beam axis

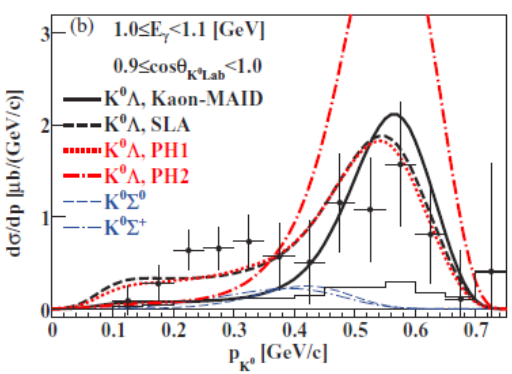
Differential Cross Sections

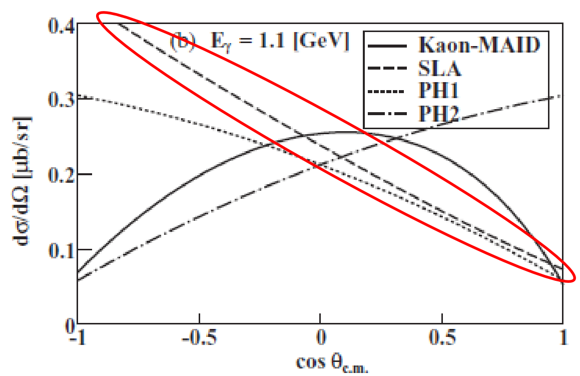
First measurement (CM frame, whole θ range)



θ_K^{CM}: Kaon emission angle in the γn center-of-mass frame

Legendre fit





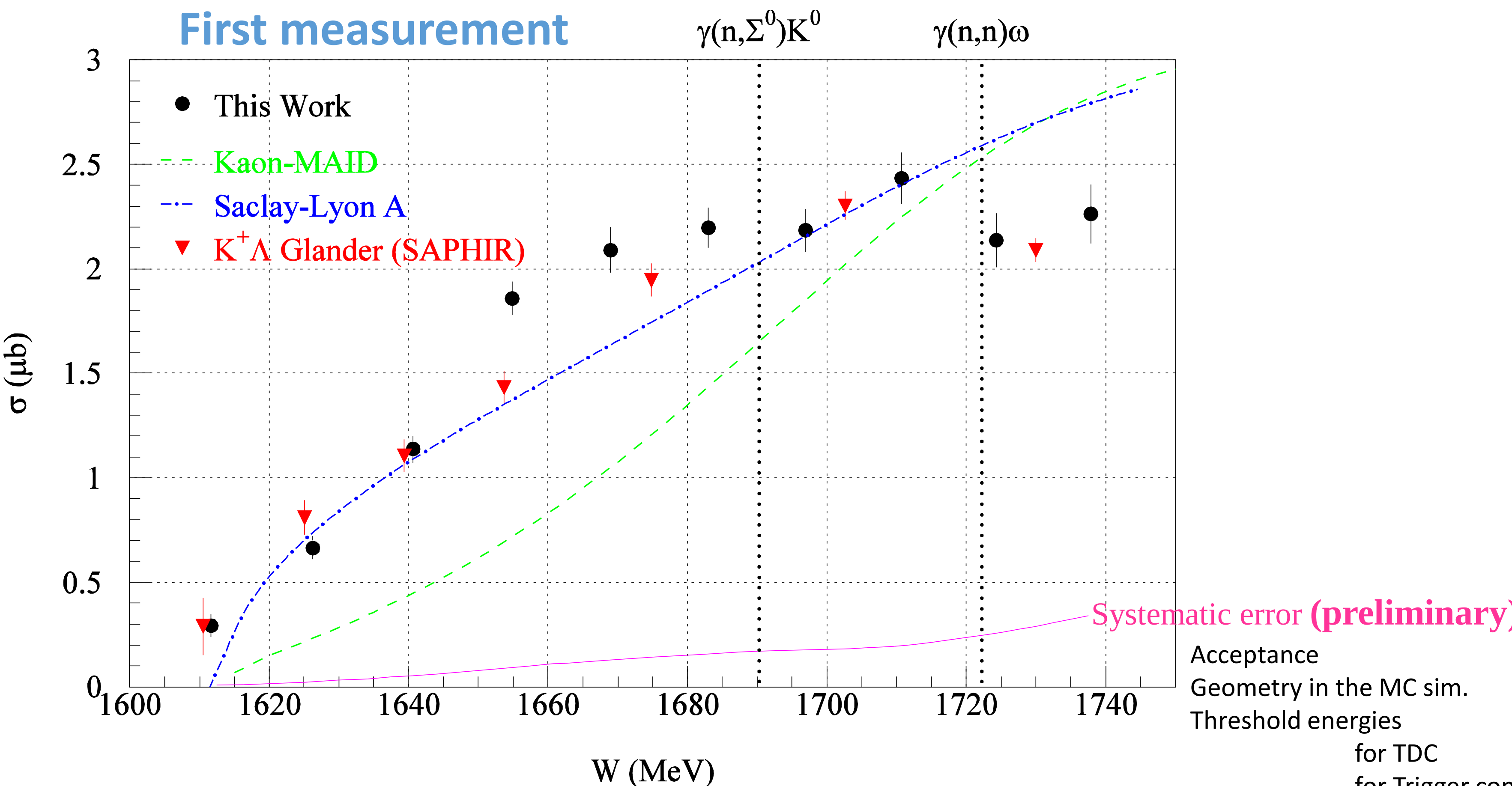
K. Tsukada et al., Phys. Rev. C **83** 039904

Angular distribution:

Flat -> **<u>Backward enhancement</u>**

This result supports the experimental remark in the previous measurement for the $\gamma n \rightarrow K^0\Lambda$ reaction reported by K. Tsukada et al.

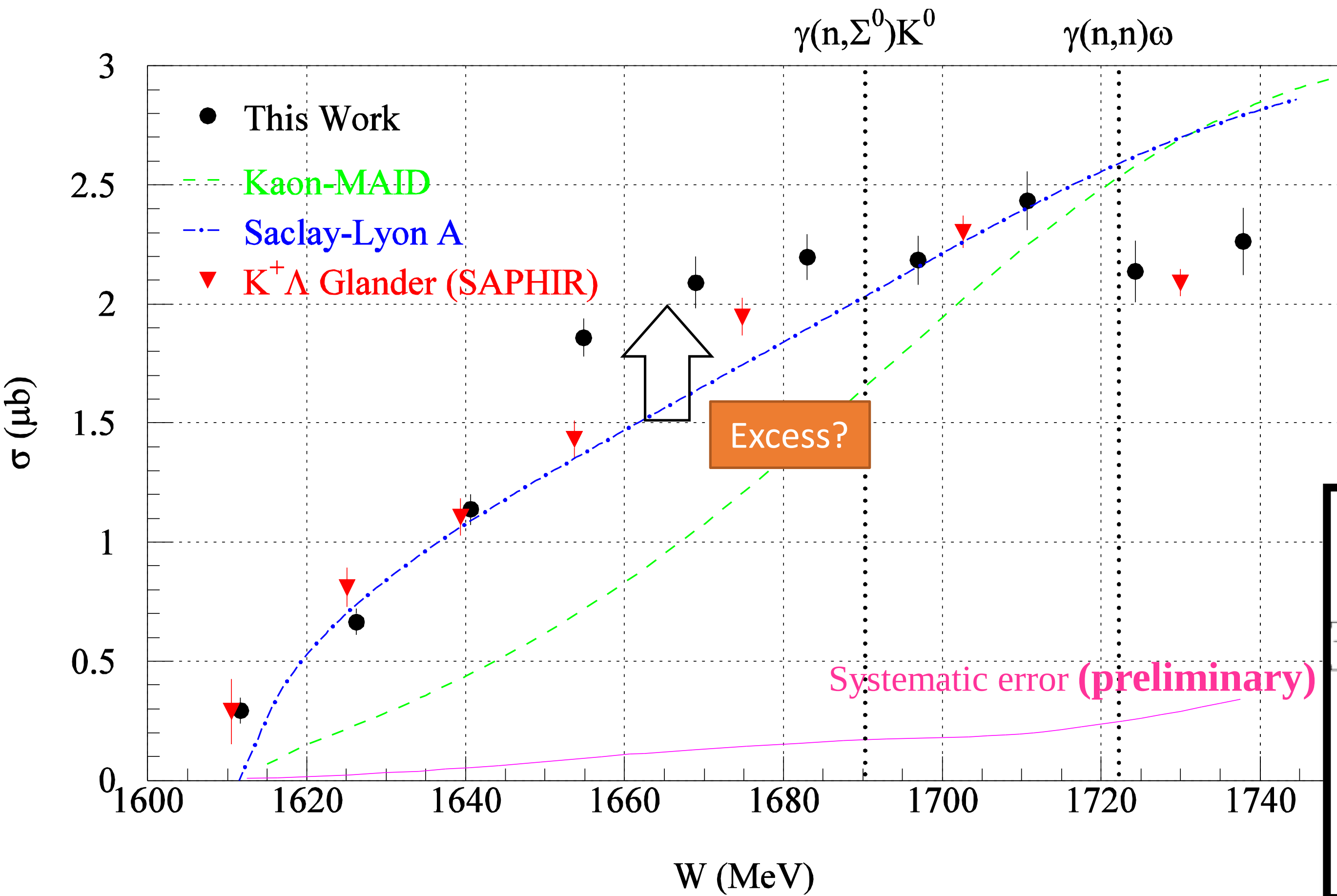
Total Cross Section

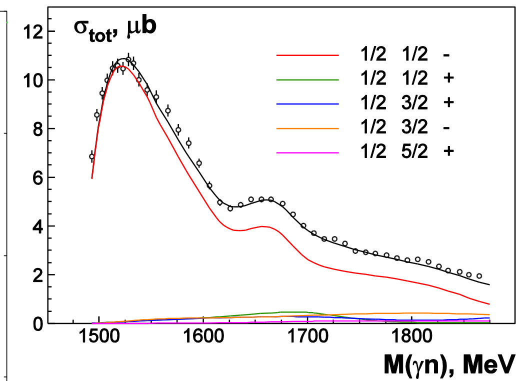


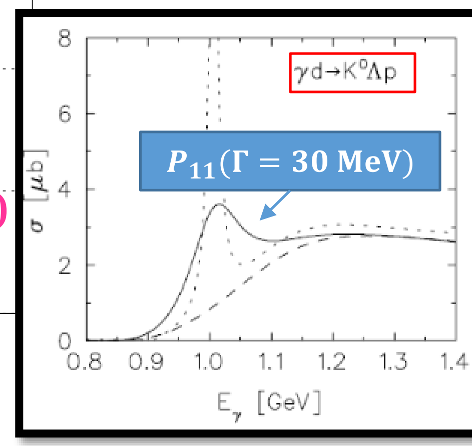
(The target neutron is assumed at rest.)

Acceptance
Geometry in the MC sim.
Threshold energies
for TDC
for Trigger cond.
Number of incident photon
Number of target

Total Cross Sections





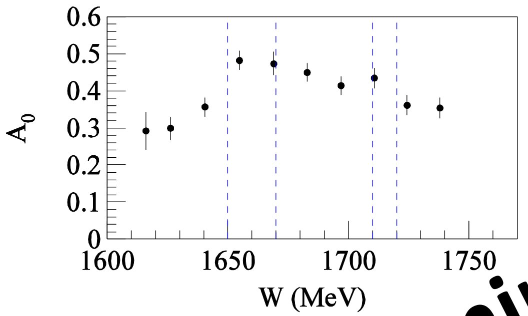


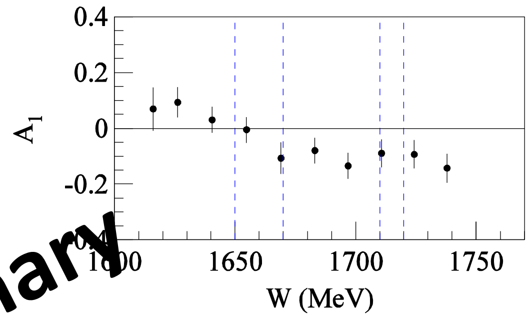
A. Fix et al., Eur. Phys. J. A 32, 311–319 (2007).

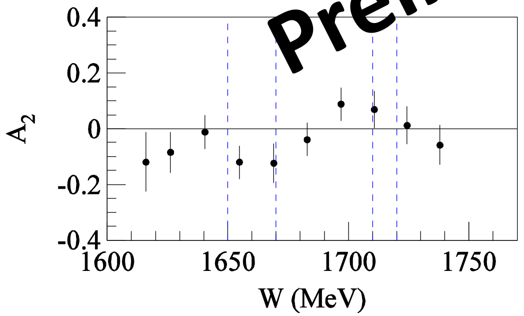
Legendre coefficients

$$\frac{d\sigma}{d\Omega} = \frac{q^*}{k^*} \sum_{i=0}^{2} A_i P_i(\cos\theta_K^*)$$

$$\begin{aligned}\frac{k^*}{q^*}\frac{d\sigma}{d\Omega} = |\mathcal{F}_1|^2 + |\mathcal{F}_2|^2 + \frac{1}{2}|\mathcal{F}_3|^2 + \frac{1}{2}|\mathcal{F}_4|^2 + \mathrm{Re}(\mathcal{F}_1\mathcal{F}_4^*) + \mathrm{Re}(\mathcal{F}_2\mathcal{F}_3^*) \\ + \{\mathrm{Re}(\mathcal{F}_3\mathcal{F}_4^*) - 2\mathrm{Re}(\mathcal{F}_1\mathcal{F}_2^*)\}\cos\theta^* \\ - \left\{\frac{1}{2}|\mathcal{F}_3|^2 + \frac{1}{2}|\mathcal{F}_4|^2 + \mathrm{Re}(\mathcal{F}_1\mathcal{F}_4^*) + \mathrm{Re}(\mathcal{F}_2\mathcal{F}_3^*)\right\}\cos^2\theta^* \\ - \{\mathrm{Re}(\mathcal{F}_3\mathcal{F}_4^*)\}\cos^3\theta^*\end{aligned}$$







Preliminary

L_{2I2J}	J^P	BW mass	BW full width	$\mathcal{BR}$		PDG status
$S_{11}(1535)$	$1/2^-$	1525–1545	125–175	πN ηN	0.35–0.55 0.42 ± 0.10	****
$S_{11}(1650)$	$1/2^-$	1645–1670	110–170	πN ηN $K\Lambda$	0.50–0.90 0.05–0.15 0.03–0.11	****
$D_{15}(1675)$	$5/2^-$	1670–1680	130–165	πN $K\Lambda$	0.35–0.45 < 0.01	****
$?_{?1}(1685)$	$?^?$	∼1670	∼30	ηn ηp	seen not seen	*
$D_{13}(1700)$	$3/2^-$	1650–1750	100–250	πN $\pi\pi N$ $K\Lambda$	0.12±0.05 0.85–0.95 < 0.03	***
$P_{11}(1710)$	$1/2^+$	1680–1740	50–250	πN ηN $K\Lambda$	0.05–0.20 0.10–0.30 0.05–0.25	***
$P_{13}(1720)$	$3/2^+$	1700–1750	150–400	πN ηN $K\Lambda$	0.11 ± 0.03 0.04 ± 0.01 0.01–0.15	****

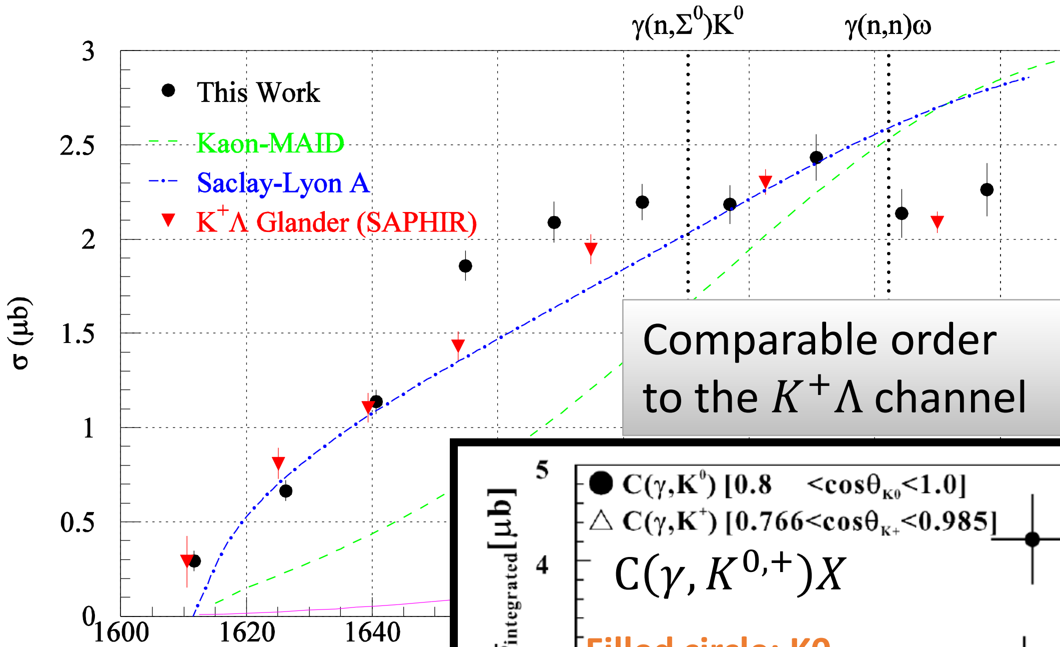
S-wave interference?
Narrow P11?

Total Cross Section

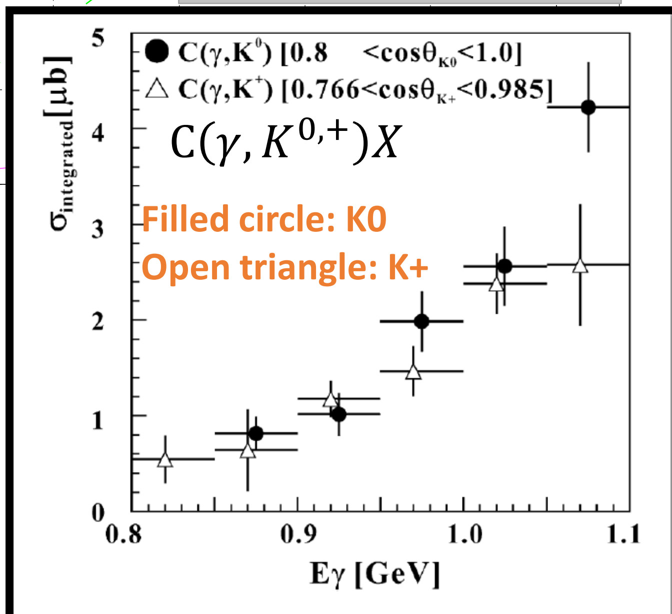
A. Salam, T. Mart & K. Miyagawa, Mod. Phys. Lett. A 24, 11 (2009)

Final state interaction?

-> **expected to be small** in the $\gamma d \rightarrow K^0 Y N$ reactions



Comparable order to the $K^+\Lambda$ channel



T. Watanabe et al., Phys. Lett. B 651, 269 (2007).

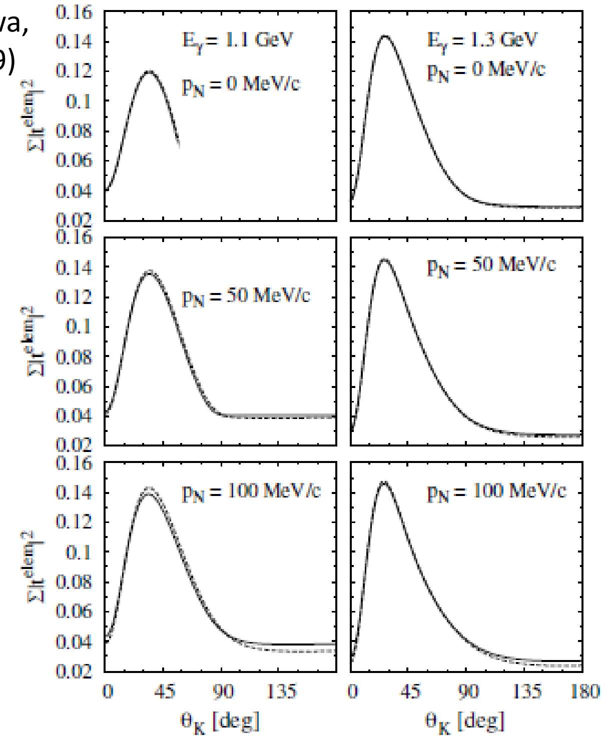
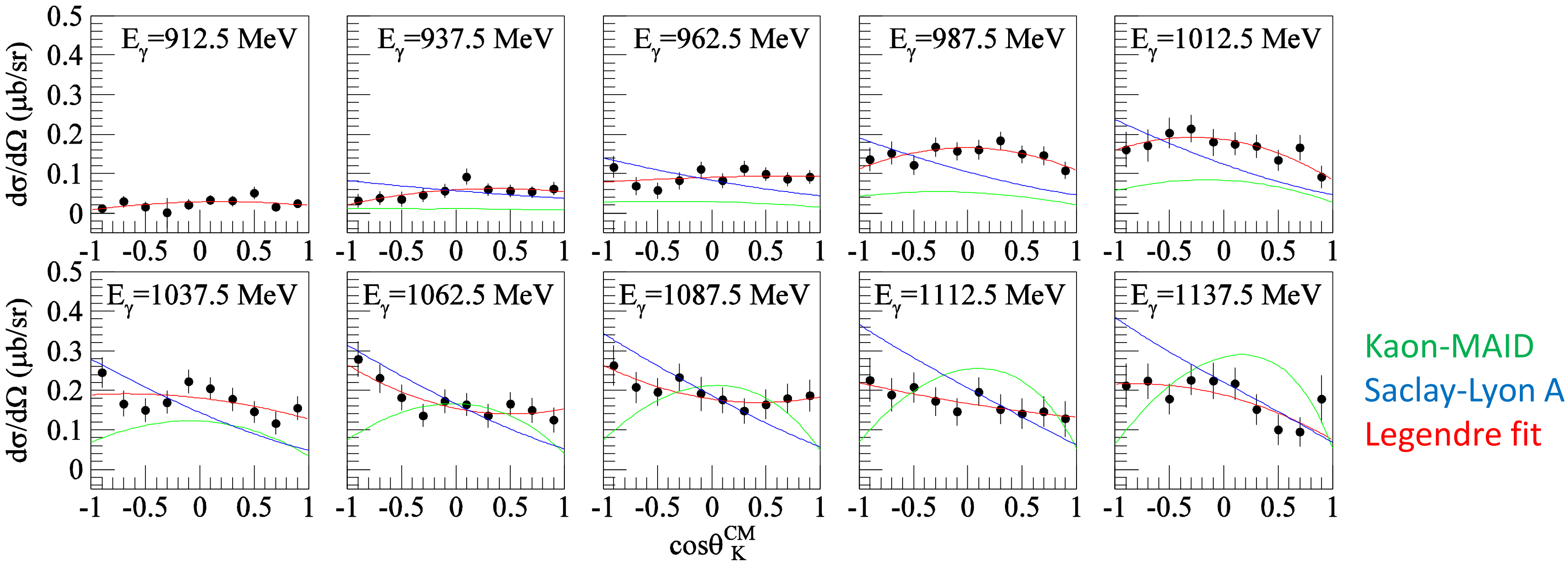


Fig. 5. Elementary amplitude as a function of kaon angle θ_K for photon energies $E_\gamma = 1.1$ GeV (left panels) and 1.3 GeV (right panels) with $\vec{p}_N$ fixed at $\theta_N = 30^\circ$ and $\phi_N = 180^\circ$, but the magnitude varied with 0, 50, 100 MeV/c. The solid line for the extracted ones and the dash ones are obtained from the free-process.

Differential Cross Sections and theoretical curves



Resonance term	Kaon-MAID	Saclay-Lyon A
s-channel	$S_{11}(1650)$	$P_{13}(1720)$
	$P_{11}(1710)$	
	$P_{13}(1720)$	
	$D_{13}(1895)$	
t-channel	$K^*(892)$	$K^*(892)$
	$K_1(1270)$	$K_1(1270)$
u-channel		$S_{01}(1407)$
		$S_{01}(1670)$
		$P_{01}(1810)$
		$P_{11}(1660)$

Compared to two theoretical curves:
Kaon-MAID and Saclay-Lyon A

Present results favor the SLA model
→ **u-channel Y* contribution**
may play an important role
in the $\gamma n \to K^0\Lambda$ reaction

Summary

- The $\gamma d \rightarrow K^0 \Lambda p$ photoproduction reaction is studied with electromagnetic calorimeter complex FOREST at ELPH, Sendai
- K^0 signals are well confirmed by $\gamma d \rightarrow K_S^0 \Lambda p \rightarrow (\pi^0 \pi^0)(p \pi^-) p \rightarrow (4\gamma)(p \pi^-) p$ reaction chains

- Shape of the background shown in the $\pi^0 \pi^0$ invariant mass distribution can be well reproduced by the simulated distribution of $\gamma n \rightarrow \pi^0 \pi^0 \pi^- p$ non-resonant reaction
- Differential cross sections show flat to backward enhancement as E_γ increases
- The total cross section shows comparable order of magnitude to the $K^+ \Lambda$ photoproduction cross section

- Comparison with the theoretical calculations may indicate that the hyperon resonance Y^* plays an important role in this reaction at higher energies
- An excess-like structure was observed in the vicinity of 1670 MeV it may be related to the prominent structure observed in the $\gamma n \rightarrow \eta n$ reaction