Measurement of the polarization observables T,P,H and F for $p\pi^0$, $n\pi^+$ (and $p\eta$) final states

Physics Advisory Committee Meeting 2020

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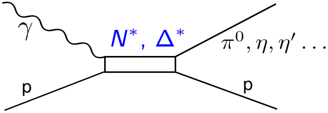
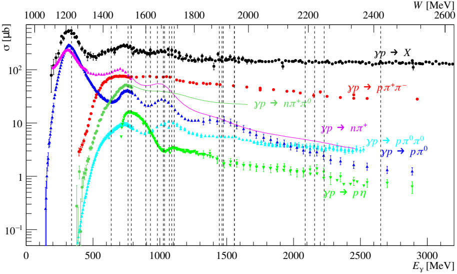
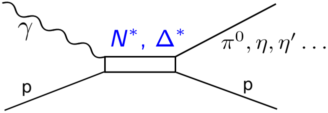
Motivation

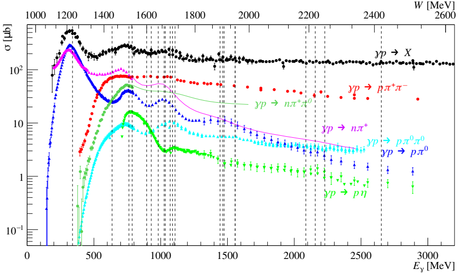
Baryon spectroscopy





Baryon spectroscopy

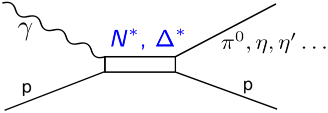


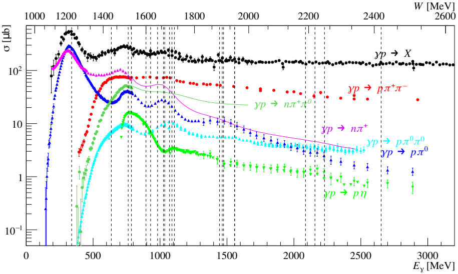


- $\frac{d\sigma}{d\Omega}_0(W,\theta) \propto \sum_{\text{spins}} |<f|\mathcal{F}|i>|^2$

  Photoproduction amplitude $\mathcal{F} \leftrightarrow$ 4 complex amplitudes (CGLN: F_1, F_2, F_3, F_4)

Baryon spectroscopy



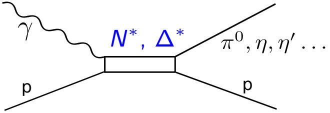


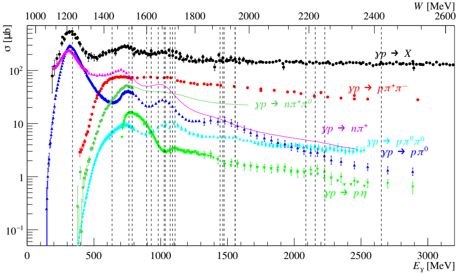
- $\frac{d\sigma}{d\Omega}_0(W,\theta) \propto \sum_{\text{spins}} | < f|\mathcal{F}|i > |^2$

  Photoproduction amplitude $\mathcal{F} \leftrightarrow$ 4 complex amplitudes (CGLN: F_1, F_2, F_3, F_4)

- PWA: e.g. $F_1 = \sum_{\ell=0}^{\infty}(\ell M_{\ell+} + E_{\ell+})P'_{\ell+1} + [(\ell+1)M_{\ell-} + E_{\ell-}]P'_{\ell-1}$
  - $E_{\ell\pm}(W), M_{\ell\pm}(W)$: Multipoles
  - $P_{\ell\pm1}(\cos\theta_{cm})$: Legendre polynomials

Baryon spectroscopy





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- $\sigma \sim |E_{0+}|^2 + |E_{1+}|^2 + |M_{1+}|^2 + |M_{1-}|^2 + \ldots$

  $\rightarrow$ unpolarized total cross section is sensitive to dominant contributing resonances

Polarization Observables

- Advantage: Sensitive to interferences between dominant partial waves and smaller partial waves

Photon polarization		Target polarization			Recoil nucleon polarization			Target and recoil polarizations			
		X	Y	Z(beam)	X'	Y'	Z'	X' X	X' Z	Z' X	Z' Z
unpolarized	σ	-	T	-	-	P	-	$T_{x'}$	$L_{x'}$	$T_{z'}$	$L_{z'}$
linear	$-\Sigma$	H	(-P)	-G	$O_{x'}$	(-T)	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(L_{x'})$	$(-T_{x'})$
circular	-	F	-	-E	$C_{x'}$	-	$C_{z'}$	-	-	-	-

- At least 8 observables required by Chiang (*W.T.Chiang et al., Nucl. Phys. A 700 (2002) 429-453*) for the extraction of the full spin amplitudes of photoproduction (complete experiment):

$$\sigma \quad + \quad \Sigma, T, P \quad + \quad \text{4 double pol. observables of } BT,\ BR \text{ and/or } TR$$

Complete sets of 4 observables

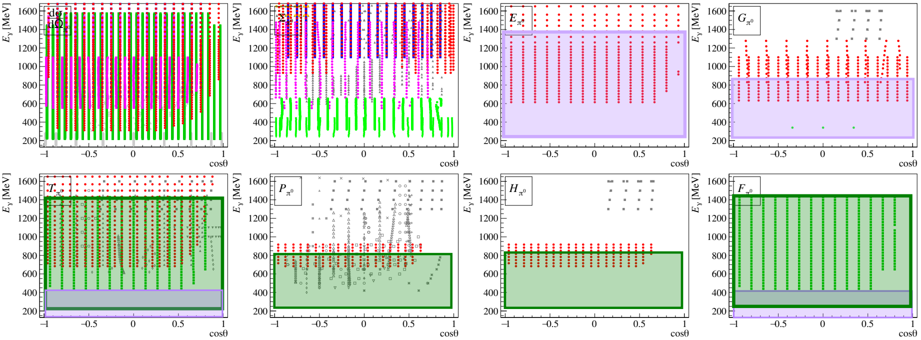
- L. Tiator (2016): mathematically complete sets of just 4 observables are possible in a truncated partial-wave analysis (TPWA)
- Using just the group S and BT, 6 combinations are possible (L. Tiator (2016), Y. Wunderlich, PhD thesis)

Set-Nr.	Observables			
1	σ_0	$\check{\Sigma}$	$\check{\boldsymbol{P}}$	$\check{F}$
2	σ_0	$\check{\Sigma}$	$\check{F}$	$\check{\boldsymbol{H}}$
3	σ_0	$\check{T}$	$\check{\boldsymbol{P}}$	$\check{F}$
4	σ_0	$\check{T}$	$\check{\boldsymbol{P}}$	$\check{G}$
5	σ_0	$\check{T}$	$\check{F}$	$\check{\boldsymbol{H}}$
6	σ_0	$\check{T}$	$\check{G}$	$\check{\boldsymbol{H}}$

- What has been measured so far?

Existing database for $\gamma p \to p\pi^0$

- σ_0, Σ exist with good energy ($\leq$ 30 MeV) and angular (10°) coverage
- G, E and T, F extracted from previous measurements at A2
- Goal: extend database for $T, \boldsymbol{P}, \boldsymbol{H}, F$ for a model-independent TPWA



● A2 data
● CBELSA/TAPS data
● CLAS data
● GRAAL data
● old data (<2005)
partially publ./to be published A2 data
proposed measurement

TPWA with existing data for $p\pi^0$

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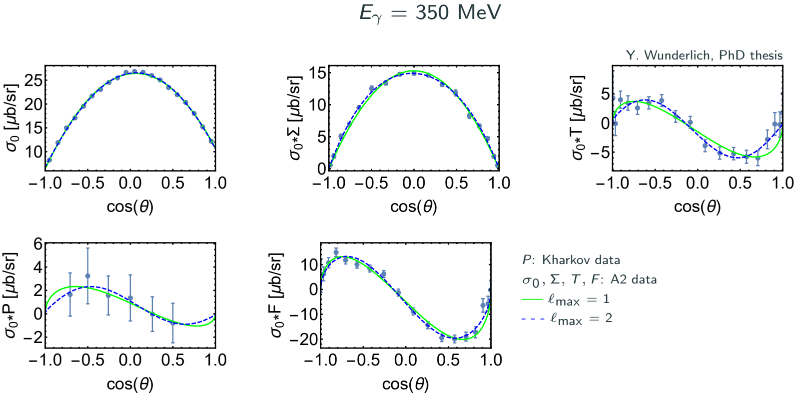
Truncated PWA performed for $E_\gamma = (280 - 420)$ MeV for $p\pi^0$ using $\sigma_0, \Sigma, T, P, F$



- Observable with lowest statistics dictates energy binning
- The polarization observable P is limiting factor for analysis
- Error bars of P in the range of 40-100%

TPWA with data for $p\pi^0$

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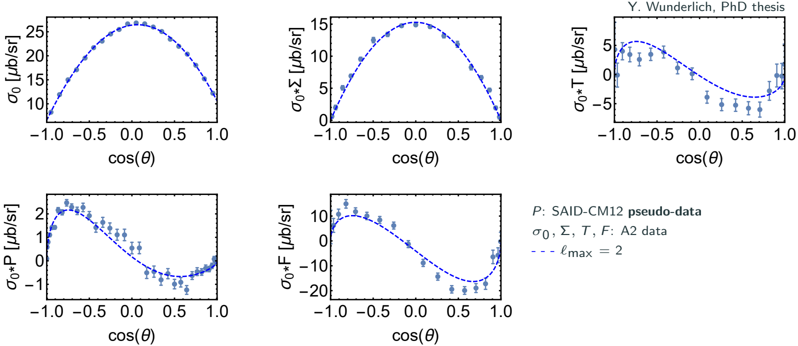
Truncated PWA performed for $E_\gamma = (280 - 420)$ MeV for $p\pi^0$ using $\sigma_0, \Sigma, T, P, F$

$E_\gamma = 350$ MeV

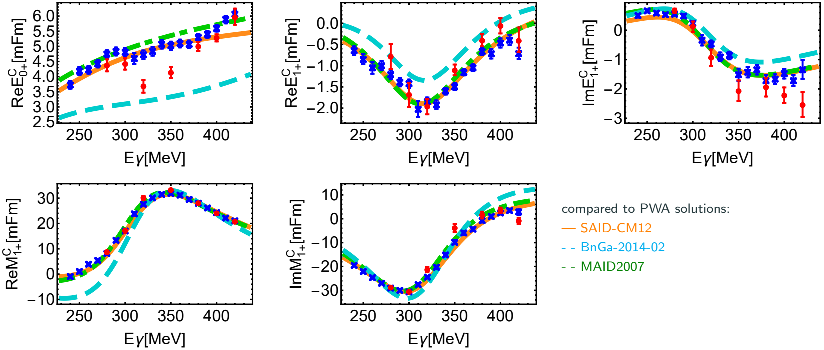


- Replacing P data with SAID-CM12 pseudo-data for P with $\sim 5\%$ errors

Truncated PWA performed for $E_\gamma = (280 - 420)$ MeV for $p\pi^0$ using $\sigma_0, \Sigma, T, P, F$

- Fit results for $\ell_{\text{max}} = 2$ with D-waves fixed to SAID-CM12
- Fit results: ● using existing P data
  - ● using SAID-CM12 pseudo-data for P with $\sim$ 5% errors

Y. Wunderlich, PhD thesis



- using 7 or 8 observables (in the 2^{nd} resonance region) leads to less ambiguities for D-wave multipoles

Why measure $n\pi^+$ in addition?

- determine multipole amplitudes for $n\pi^+$ and $p\pi^0$ photoproduction
- combine these to get isospin multipoles

$$\mathcal{M}_{\ell\pm}^{(1/2)} = \frac{1}{3}\left(\mathcal{M}_{\ell\pm}^{\pi^0 p} + \sqrt{2}\mathcal{M}_{\ell\pm}^{\pi^+ n}\right)$$

$$\mathcal{M}_{\ell\pm}^{(3/2)} = \mathcal{M}_{\ell\pm}^{\pi^0 p} - \frac{1}{\sqrt{2}}\mathcal{M}_{\ell\pm}^{\pi^+ n}$$

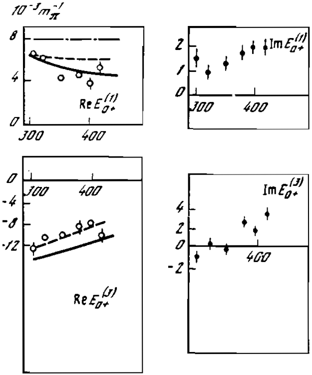
- first direct fit for small energy range (280 MeV - 420 MeV) by

  V. F. Grushin et al., Yad. Fiz. 38, 1448 (1983)

- revisited by

  R. Workman et al., Phs. Rev. C 83, 035201 (2011)

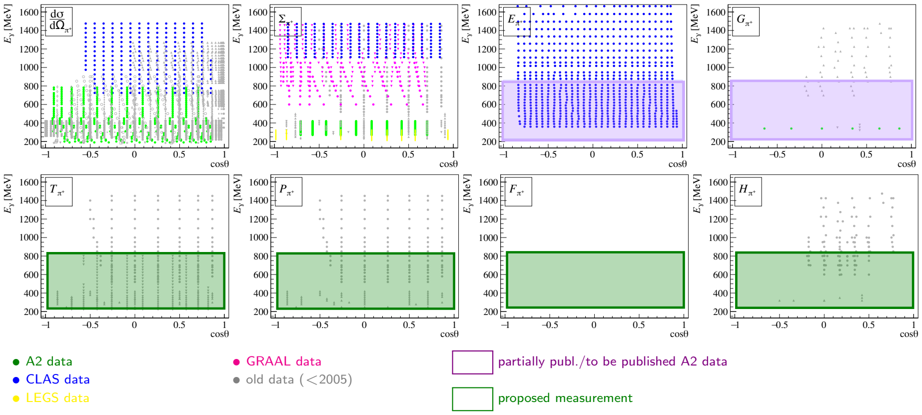
V. F. Grushin et al., Yad. Fiz. 38, 1448 (1983)



$\Rightarrow$ For simultaneous extraction of all isospin multipoles (I = 1/2 and 3/2) we need complete data sets for both(!) channels with comparable kinematic coverage

Existing database for $n\pi^+$

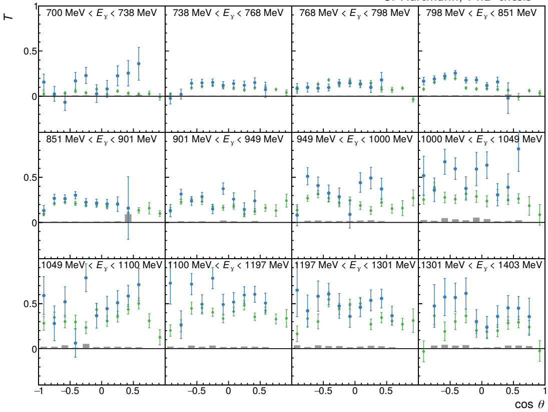
- σ_0, Σ exist with good energy and angular coverage
- G, E extracted from previous measurements at A2



- Goal: perform a model-independent TPWA with 8 observables $\{\sigma_0, \Sigma, G, E, \boldsymbol{T}, \boldsymbol{P}, \boldsymbol{H}, \boldsymbol{F}\}$ to extract isospin multipoles for $E_\gamma = 230$ MeV - 830 MeV

Why measure $p\eta$?

- Goal: resolve discrepancy of factor 1.40 ± 0.05 between CBELSA/TAPS and A2 data using the same data



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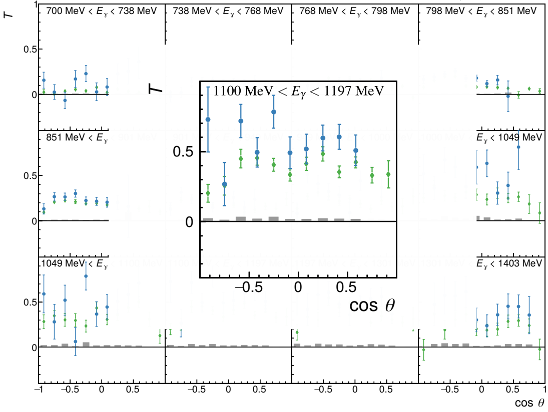
J. Hartmann, PhD thesis

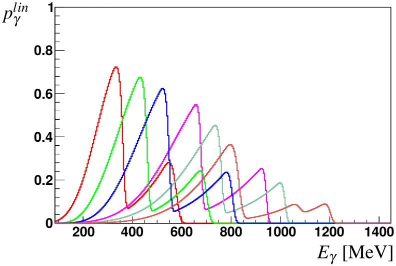


Proposed experiment

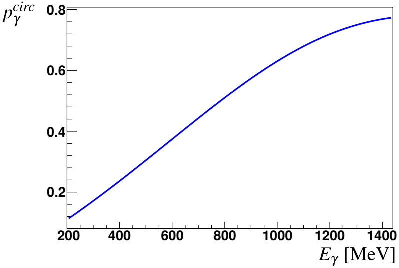
Photon beam polarization

- MAMI beam energy: 1557 MeV (MAMI-C), long. polarized electrons
- photon beam: elliptically pol. (long. polarized electrons + diamond radiator)
- coherent edge positions: 350 MeV, 450 MeV, 550 MeV, 650 MeV, 750 MeV, 850 MeV with 2 mm collimator
- relevant energy range: 230 MeV - 830 MeV (P, H), 230 MeV - 1448 MeV (T, F)
- need to perform Mott measurements for p_e (needed for p_γ^{circ})

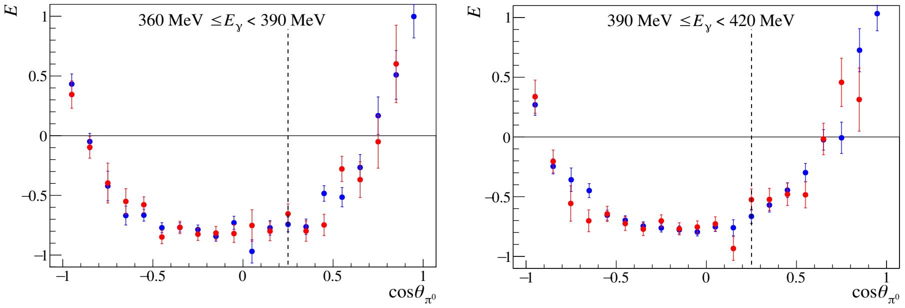
needed for P, H



needed for F



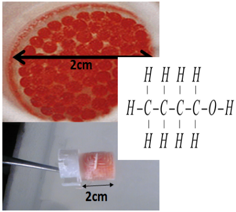
- photon beam: elliptically polarized
- A2 data (for G and E) already taken successfully with elliptically pol. photons
- data taken with 450 MeV coherent edge (diamond) give same results for E as taken with amorphous data (F. Afzal, PhD thesis)



Target

- transversely pol. frozen spin butanol target
- ^{3}He/ ^{4}He dilution cryostat with 27 mK
- maximum pol.: $\sim$90%, average pol.: $\sim$70%
- relaxation times: $\sim$1000 h
- need to measure with carbon foam target (+^{3}He/ ^{4}He) immediately after the butanol data to minimize the systematic error of the carbon background subtraction

Butanol Target

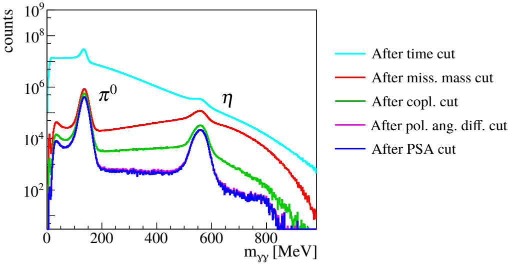


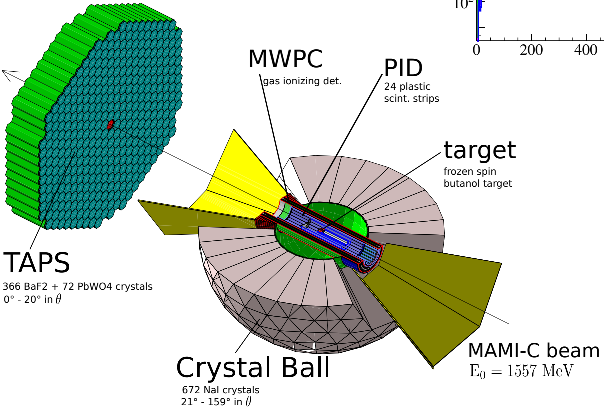
Carbon Target

Crystal Ball (CB) and TAPS needed

$\epsilon_{acc} = 75\%\ (p\pi^0),\ 50\%\ (p\eta)$

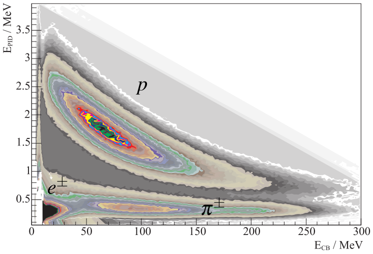
low background contribution ($\lesssim$ 2-6%)

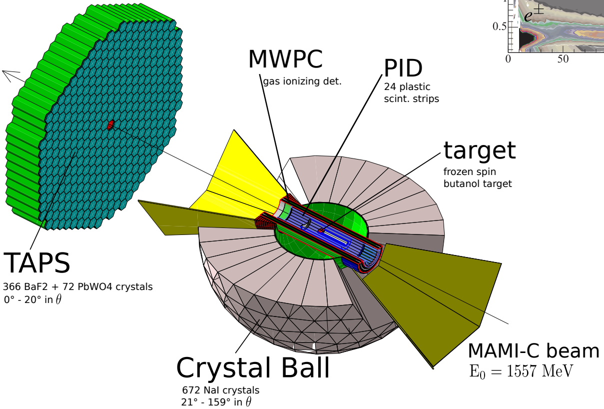




PID, MWPCs and TAPS vetoes needed as well

$$\epsilon_{\text{acc}} = \begin{cases} 30\%, & E_\gamma \leq 450\text{MeV} \\ 8\%, & E_\gamma > 450\text{MeV} \end{cases} \quad (n\pi^+)$$





Detector equipment

PID, MWPCs and TAPS vetoes needed as well

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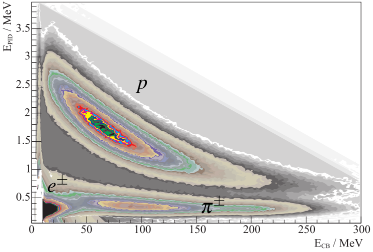
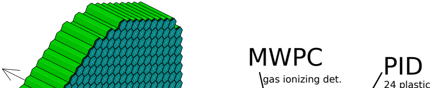
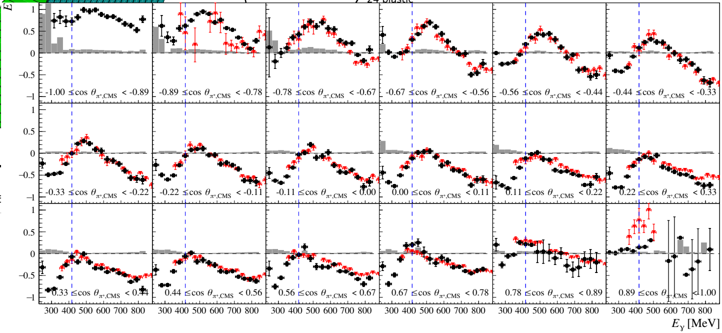






K. Spieker, PhD thesis, 2019

• this work • CLAS [1] S. Strauch et al., Phys. Lett. B 750 (2015) 53-58

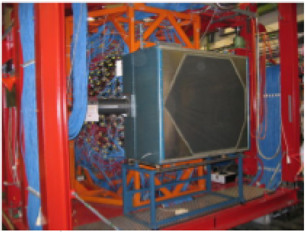
Detector equipment

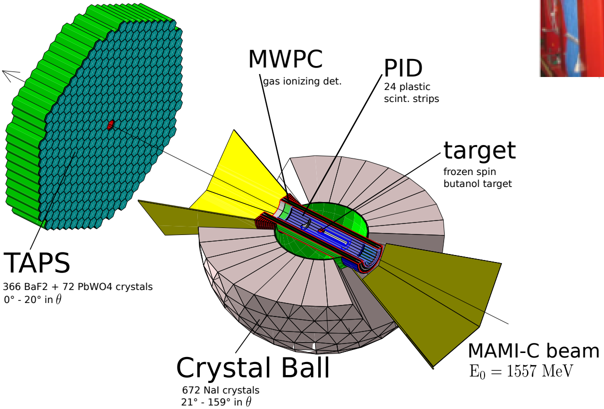
Trigger configuration:

CB Esum $\sim$ 40 MeV OR

TAPS BaF_2 M1+ ($\sim$ 40 MeV) vetoed by Cherenkov

Place Cherenkov detector between CB and TAPS





Requested beamtime

- time has to be estimated for $n\pi^+$ and for P, H
- 18 energy bins ($\Delta E = 34$ MeV wide) and $N_\theta = 18$

$$t_{\text{beamtime}} = N_\theta \left[p_\gamma^2 \cdot p_T^2 \cdot (\Delta O)^2 \cdot \dot{N}_\gamma \cdot n_T \cdot \sigma_{\text{tot}} \cdot \epsilon_{\text{acc}} \cdot \Gamma \cdot f_{\text{livetime}} \right]^{-1}$$

- p_γ: degree of linear pol. component
- $p_T \sim 70\%$: average target polarization degree
- $\Delta O = 0.05$: statistical precision of observable
- $\dot{N}_\gamma \sim 5 \times 10^7\ \text{s}^{-1}$: photon flux ($\dot{N}_\gamma(\Delta E) = \dot{N}_{e^-}(\Delta E) \cdot \epsilon_{\text{tagg}}$)
- $n_T = 0.0918\ \text{barn}^{-1}$: number of free protons in butanol target
- σ_{tot}: total unpolarized cross section
- $\epsilon_{\text{acc}} = \begin{cases} 0.3 & E_\gamma \leq 450\text{MeV} \\ 0.08 & E_\gamma > 450\text{MeV} \end{cases}$: average det. and recon. efficiency
- $\Gamma = 1$: branching ratio
- $f_{\text{livetime}} \sim 60\%$

coherent edge [MeV]	$\text{time}_{\text{butanol}}$ [h]	$\text{time}_{\text{carbon}}$ [h]	time_{G} [h]
350	8	1	11
450	18	2	55
550	74	10	20
650	119	16	90
750	147	20	67
850	363	49	92
total	**729 h (30 d)**	**98 h (4 d)**	335 h (14 d)

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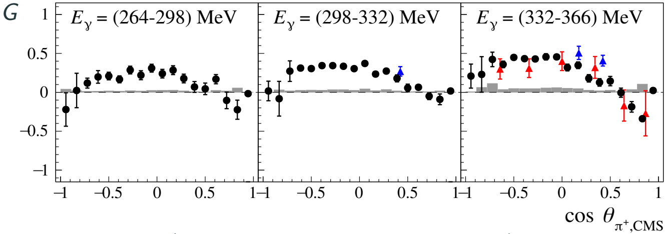

● New final A2 data (K. Spieker et al., in preparation for publication)

▲ J. Ahrens et al., Eur. Phys. J. A 26 (2005) 135

▲ A. Belayev et al., Sov. J. Nucl. Phys. 40 (1984) 83

beamtime estimation

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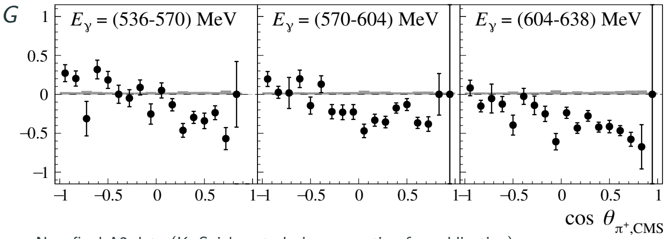

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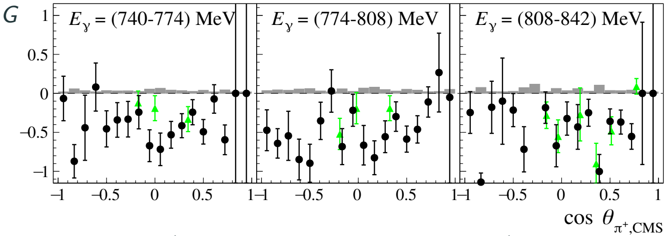

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▲ P.J. Bussey et al., Nucl. Phys. B 403-414 (1980) 83

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In addition time needed for

- time for daily tagging efficiency + Mott measurement ($3\ \text{h} \cdot 34 = 102\ \text{h}$)
- time to change/pol. target: 200 h

$\Rightarrow$ **930 h of pure data-taking + 200 h for target maintenance**

Summary

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- Goal: Simultaneous measurement of T, P, H, F (230 MeV $\leq E_\gamma \leq$ 830 MeV) using elliptically polarized photons and transversely polarized butanol target
  $\Rightarrow$ Complete BT data set up to 830 MeV
  $\Rightarrow$ Determine $p\pi^0$ and $n\pi^+$ multipole amplitudes at the same time
  $\Rightarrow$ Extract isospin multipoles for $\Delta(1232)\frac{3}{2}^+(P_{33})$ and second resonance region ($N(1440)\frac{1}{2}^+(P_{11})$, $N(1520)\frac{3}{2}^-(D_{13})$, $N(1535)\frac{1}{2}^-(S_{11})$)

- MAMI beam: 1557 MeV, long. pol. electrons
- Target: transversely polarized frozen-spin butanol target
- Detectors: Crystal Ball, TAPS, PID, MWPCs, Cherenkov
- Trigger: CB Esum ($\sim$ 40 MeV) OR BaF_2 M1+ ($\sim$ 40 MeV) vetoed by Cherenkov
- Requested time: **24 h + 200 h + 930 h $\approx$ 1150 h**

Backup Slides

Event rate estimation

$$\dot{N}_\pi = \dot{N}_\gamma \cdot n_T \cdot \sigma_{\text{tot}} \cdot \epsilon_{\text{acc}} \cdot \Gamma$$

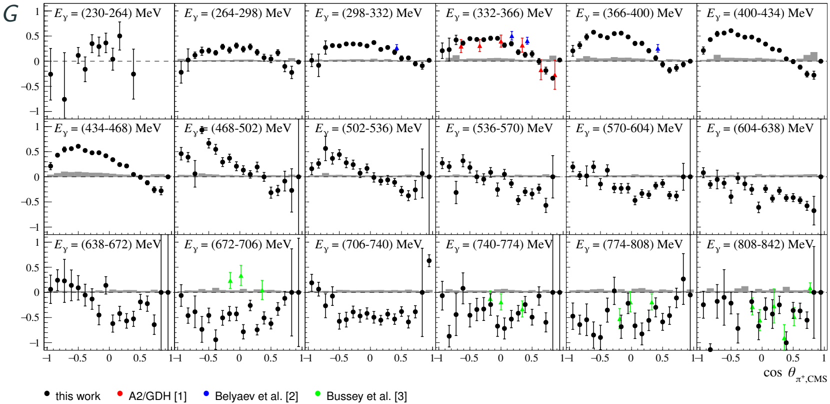
For 230 MeV $\leq E_\gamma \leq$ 830 MeV:

- $p\pi^0$: 1367 Hz (185 Hz)
- $n\pi^+$: 303 Hz (41 Hz)

Typical trigger rate for $f_{\text{livetime}} = 60\%$ is $\sim$ 3 kHz (based on previous measurements)

Quality of already taken G-data (comparable to P, H) for $n\pi^+$

- New final A2 data (in preparation for publication)



[1] J. Ahrens et al., Eur. Phys. J. A 26 (2005) 135
[2] A. Belayev et al., Sov. J. Nucl. Phys. 40 (1984) 83
[3] P.J. Bussey et al., Nucl. Phys. B 403-414 (1980) 83

K. Spieker, PhD thesis, 2019

Polarization observables

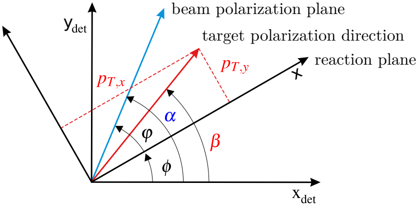
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \left[1 - p_\gamma^{\text{lin}}\Sigma\cos(2\varphi) + p_{T,y}T - p_{T,y}p_\gamma^{\text{lin}}P\cos(2\varphi) - p_{T,x}p_\gamma^{\text{lin}}H\sin(2\varphi) + p_{T,x}p_\gamma^{\text{circ}}F\right]$$

$$A_\Sigma(\phi) := \frac{1}{p_\gamma^{\text{lin}}}\frac{\sigma_\uparrow^\perp+\sigma_\downarrow^\perp-\sigma_\uparrow^\parallel-\sigma_\downarrow^\parallel}{\sigma_\uparrow^\perp+\sigma_\downarrow^\perp+\sigma_\uparrow^\parallel+\sigma_\downarrow^\parallel} = \frac{1}{p_\gamma^{\text{lin}}}\frac{\sigma^\perp-\sigma^\parallel}{\sigma^\perp+\sigma^\parallel} = \Sigma_B\cos(2(\alpha-\phi))$$

$$A_T(\phi) := \frac{1}{p_T}\frac{\sigma_\uparrow^\parallel+\sigma_\uparrow^\perp-\sigma_\downarrow^\parallel-\sigma_\downarrow^\perp}{\sigma_\uparrow^\parallel+\sigma_\uparrow^\perp-\sigma_\downarrow^\parallel-\sigma_\downarrow^\perp} = \frac{1}{p_T}\frac{\sigma_\uparrow-\sigma_\downarrow}{\sigma_\uparrow+\sigma_\downarrow} = d\cdot T\sin(\beta-\phi)$$

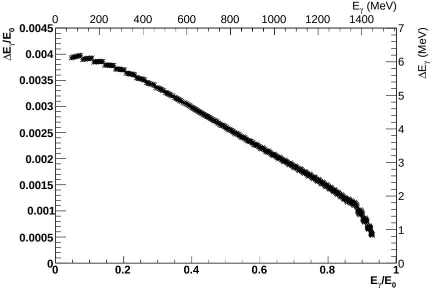
$$A_{P,H}(\phi) := \frac{1}{p_T p_\gamma^{\text{lin}}}\frac{\sigma_\uparrow^\perp-\sigma_\downarrow^\perp-\sigma_\uparrow^\parallel+\sigma_\downarrow^\parallel}{\sigma_\uparrow^\perp+\sigma_\downarrow^\perp+\sigma_\uparrow^\parallel+\sigma_\downarrow^\parallel} = d\cdot P\cos(2(\alpha-\phi))\sin(\beta-\phi) + d\cdot H\sin(2(\alpha-\phi))\cos(\beta-\phi)$$

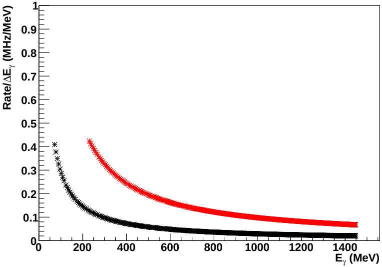
$$A_F(\phi) := \frac{1}{p_T p_\gamma^{\text{circ}}}\frac{\sigma_\uparrow^{\uparrow h}+\sigma_\downarrow^{\downarrow h}-\sigma_\downarrow^{\uparrow h}-\sigma_\uparrow^{\downarrow h}}{\sigma_\uparrow^{\uparrow h}+\sigma_\downarrow^{\downarrow h}+\sigma_\downarrow^{\uparrow h}+\sigma_\uparrow^{\downarrow h}} = d\cdot F\cos(\beta-\phi)$$



Photon beam flux

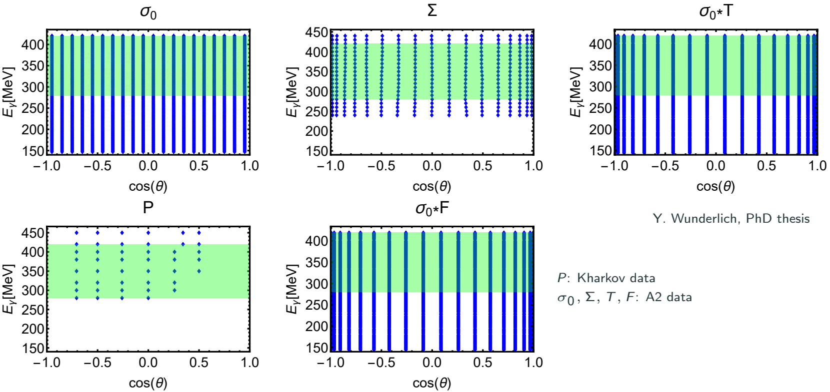
- tagged energy range: 230 MeV - 1448 MeV
- 25 tagger channels of new tagger can be switched off
- first channel is run at 2.5 MHz
- $\epsilon_{\text{tagg}} = 0.27$ for 2 mm collimator
- total photon flux in tagged range: $\sim 5 \cdot 10^7$ s^{-1}





TPWA with existing data for $p\pi^0$

Truncated PWA performed for $E_\gamma = (280 - 420)$ MeV for $p\pi^0$ using $\sigma_0, \Sigma, T, P, F$



Y. Wunderlich, PhD thesis

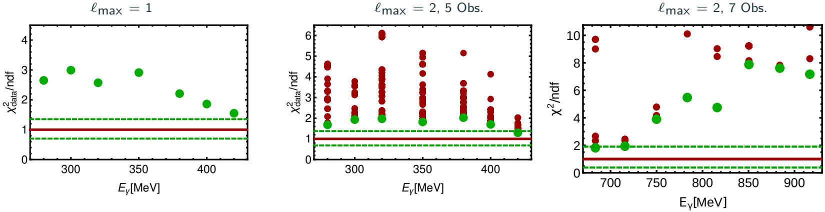
P: Kharkov data
σ_0, Σ, T, F: A2 data

- Observable with lowest statistics dictates energy binning
- The polarization observable P is limiting factor for analysis
- Error bars of P in the range of 40-100%

TPWA with data for $p\pi^0$

Truncated PWA was performed also between 683 MeV - 916 MeV using 7 observables ($\sigma_0, \Sigma, T, P, H, G, E$) using mostly CBELSA/TAPS data for $p\pi^0$ (Y. Wunderlich, PhD thesis)

- Less ambiguities are present for $D-$ wave multipoles



- We expect to have 8 observables for TPWA ($\sigma_0, \Sigma, \boldsymbol{T}, \boldsymbol{P}, \boldsymbol{H}, \boldsymbol{F}, G, E$) for a large energy range of 230 MeV - 830 MeV with comparable energy binning and angular coverage

Experimental specifications:

MAMI

- MAMI beam energy: 1557 MeV (MAMI-C)
- MAMI beam polarization: long. polarized

Photon beam

- tagged energy range: 230 MeV - 1448 MeV
- radiator: diamond
- photon beam pol.: elliptically pol. (circular and linear)

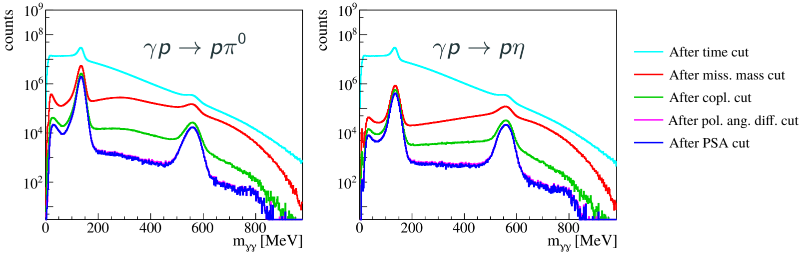
Equipment

- detectors: Crystal Ball, TAPS, PID, MWPCs, Cherenkov
- target: frozen spin butanol and carbon(+He)
- trigger: CB Esum OR (BaF_2 M1+ vetoed by C)

Reconstruction of $p\pi^0$ and $p\eta$ final states

- $p\pi^0$ and $p\eta$ can be easily selected (previous G/E beamtime)
- Crystal Ball and TAPS are needed to detect the two decay photons (+p)

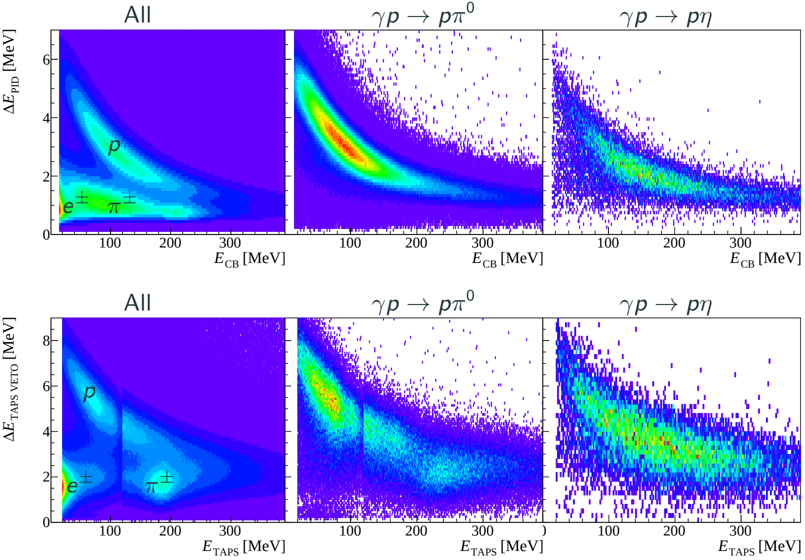
3 PED



- low background: $\leq 2\%$ ($p\pi^0$) and $\leq 6\%$ ($p\eta$)

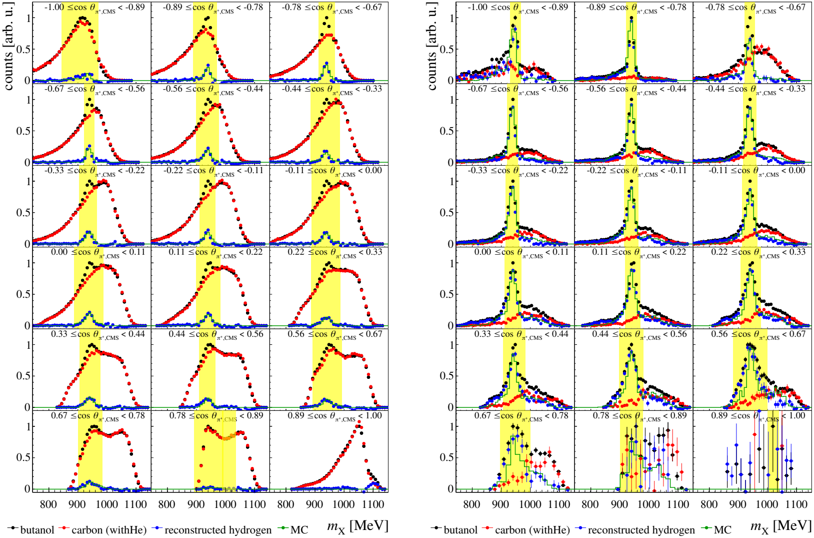
$\Delta E - E$ spectra (PID, TAPS vetoes)

PID and TAPS vetoes information not necessarily needed for $p\pi^0$ and $p\eta$



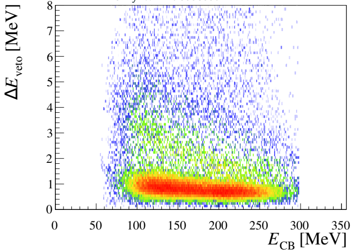
Reconstruction of $n\pi^+$ (Missing mass spectra)

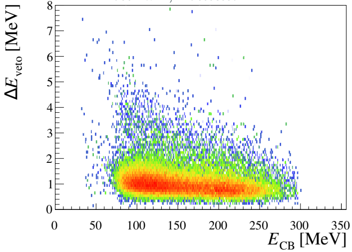
- $E_\gamma < 450$ MeV only π^+ det. sufficient
- $E_\gamma > 450$ MeV both π^+ and n needed



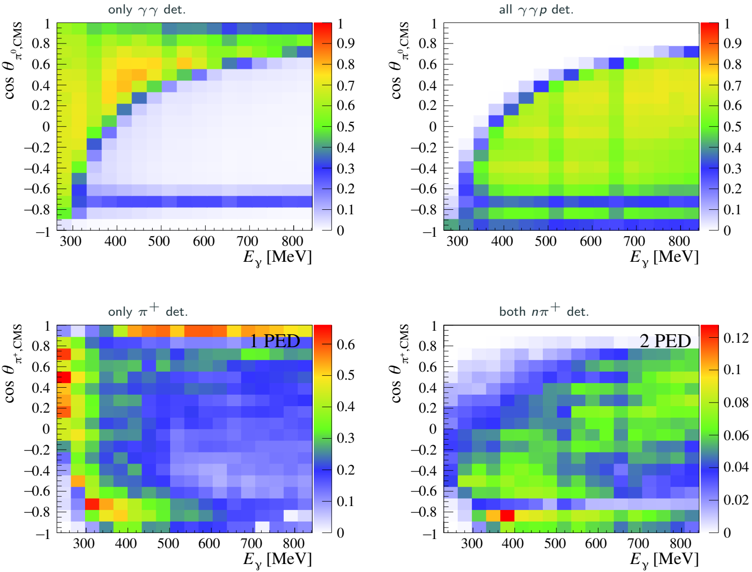
Reconstruction of $n\pi^+$

- PID, MWPCs and TAPS vetoes needed
- $\Delta E_{\text{PID}} - E_{\text{CB}}$ spectra after carbon subtraction





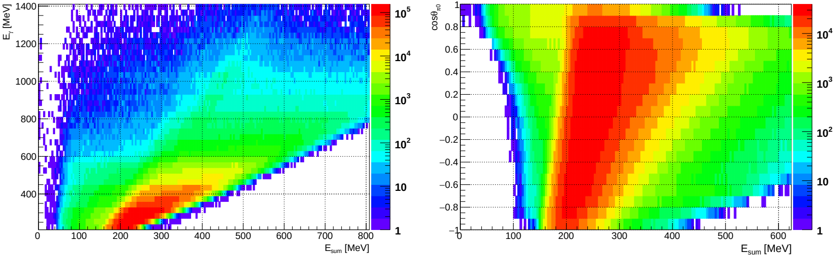
Reconstruction and detection efficiency



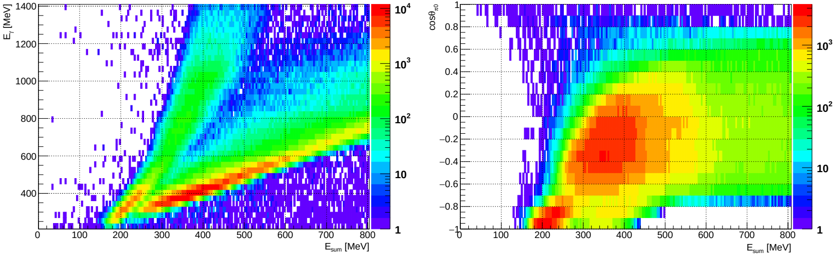
Trigger configuration for $p\pi^0$

- Optimal trigger configuration: CBEsum: 80-120 MeV (TAPS LED1: 80-120 MeV)

only $\gamma\gamma$



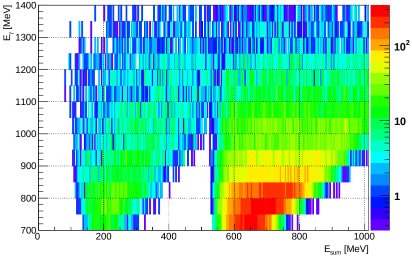
all $\gamma\gamma p$

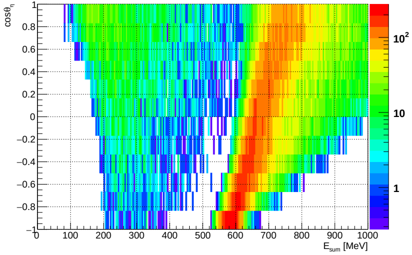


Trigger configuration for $p\eta$

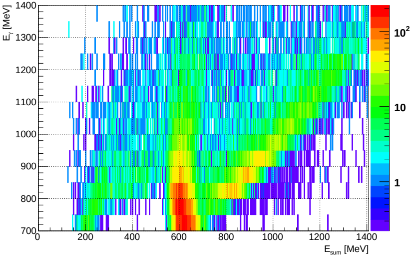
- Optimal trigger configuration: CBEsum: 150-200 MeV (TAPS LED1: 150-200 MeV)

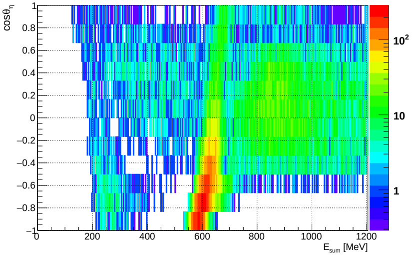
only $\gamma\gamma$





all $\gamma\gamma p$

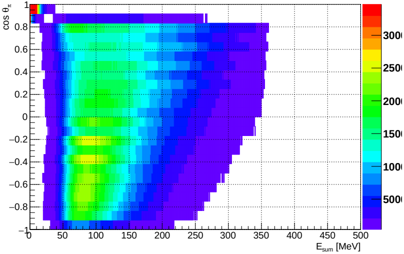




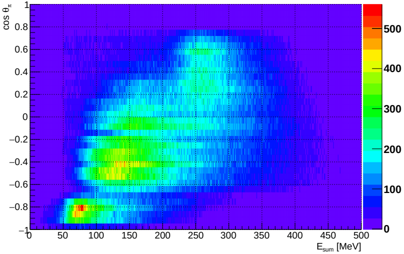
Trigger configuration for $n\pi^+$

- Optimal trigger configuration: CBEsum: 40-50 MeV, TAPS LED1: 40-50 MeV

only π^+ det., $E_\gamma < 450$ MeV



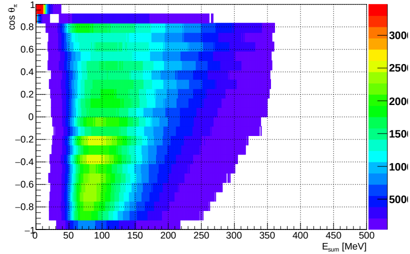
both π^+, n det., 230 MeV $\leq E_\gamma \leq$ 830 MeV



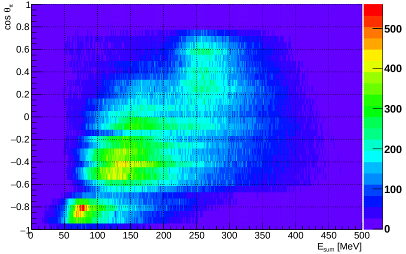
Trigger configuration for $n\pi^+$

- Optimal trigger configuration: CBEsum: 40-50 MeV, TAPS LED1: 40-50 MeV

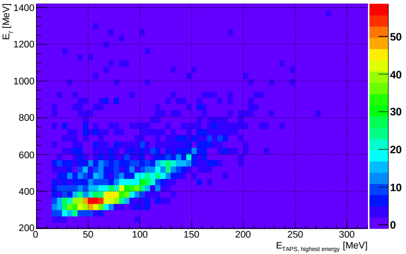
only π^+ det., $E_\gamma < 450$ MeV



both π^+, n det., 230 MeV $\leq E_\gamma \leq$ 830 MeV



both π^+, n det., 230 MeV $\leq E_\gamma \leq$ 830 MeV



both π^+, n det., 230 MeV $\leq E_\gamma \leq$ 830 MeV