

Determination of the beam asymmetry Σ in η - and η' -photoproduction using Bayesian statistics

JAKOB MICHAEL KRAUSE

Masterarbeit in Physik
angefertigt im Helmholtz-Institut für Strahlen- und
Kernphysik

vorgelegt der
Mathematisch-Naturwissenschaftlichen Fakultät
der
Rheinischen Friedrich-Wilhelms-Universität
Bonn

Sep 2022

DRAFT

I hereby declare that this thesis was formulated by myself and that no sources or tools other than those cited were used.

Bonn,
Date

.....
Signature

- 1. Gutachterin: JUN. PROF. DR. ANNIKA THIEL
- 2. Gutachter: PROF. DR. JOCHEN DINGFELDER

DRAFT

Contents

1	Introduction	1
1.1	Photoproduction of Pseudoscalar Mesons	4
1.2	Measurement of Polarization Observables	5
1.3	Introduction to BAYESIAN statistics	5
1.4	Motivation and Structure of this Thesis	5
2	Experimental Setup	7
2.1	Production of (polarized) high energy photon beam	7
2.1.1	Tagger	8
2.2	Beam Target	8
2.3	Calorimeters	8
2.4	Trigger	8
3	Event selection	11
3.1	Preselection and charge cut	11
3.2	Time of particles	12
3.3	Kinematic constraints	14
3.3.1	Derivation of cut conditions	14
3.3.2	Determination of cut ranges	15
3.3.3	Quality of event selection	21
3.4	Investigation of background and additional cuts	22
3.4.1	Inspecting plausibility of background reactions	22
3.4.2	Misidentification of background reactions	25
3.4.3	Examination of additional cuts	28
3.5	Summary of event selection	31
4	Extraction of the beam asymmetries Σ_η and $\Sigma_{\eta'}$	33
4.1	Methods	34
4.1.1	Event yield asymmetries	34
4.1.2	Event based fit	36
4.2	Determination of Σ_η using Bayesian statistics	36
4.2.1	Event yield asymmetries	36
4.2.2	Event based fit	36
4.2.3	Discussion	36
4.3	Determination of $\Sigma_{\eta'}$	36
4.3.1	Application of event based fit to toy Monte Carlo data	36

4.3.2	Application of event based fit to data	36
4.3.3	Systematic Error	36
6	Summary and outlook	27
A.1	Statistical error for the asymmetry $A(\phi)$	29
	Bibliography	31
	List of Figures	33
	List of Tables	35

DRAFT

APPENDIX A

A.1 Statistical error for the asymmetry $A(\phi)$

Let $\tilde{N}_i^{\parallel/\perp}$ be the normalized event yields at bin ϕ_i . As mentioned in section 4.1, the asymmetry A_i at bin i is then given by

$$A_i = \frac{\tilde{N}_i^\perp - \tilde{N}_i^\parallel}{p_\gamma^\parallel \tilde{N}_i^\perp + p_\gamma^\perp \tilde{N}_i^\parallel} = \Sigma \cos \left(2 \left(\alpha^\parallel - \phi_i \right) \right), \quad (\text{A.1})$$

where the event yields are normalized over all M ϕ -bins

$$\tilde{N}_i^{\parallel/\perp} = \frac{N_i^{\parallel/\perp}}{\sum_{j=1}^M N_j^{\parallel/\perp}}.$$

To estimate statistical errors according to GAUSSIAN error propagation, the partial derivatives with respect to $N_i^{\parallel/\perp}$ have to be built:

$$(\Delta A_i)^2 = \left(\frac{\partial A_i}{\partial \tilde{N}_i^\parallel} \Delta \tilde{N}_i^\parallel \right)^2 + \left(\frac{\partial A_i}{\partial \tilde{N}_i^\perp} \Delta \tilde{N}_i^\perp \right)^2, \quad (\text{A.2})$$

where

$$\left(\frac{\partial A_i}{\partial \tilde{N}_i^\parallel} \right)^2 = \left[\frac{\tilde{N}_i^\perp (p_\gamma^\perp + p_\gamma^\parallel)}{(p_\gamma^\parallel \tilde{N}_i^\perp + p_\gamma^\perp \tilde{N}_i^\parallel)^2} \right]^2 \quad \left(\Delta \tilde{N}_i^\parallel \right)^2 = \frac{\tilde{N}_i^\parallel}{\left(\sum_{j=1}^M \tilde{N}_j^\parallel \right)^2} + \frac{\tilde{N}_i^\parallel}{\left(\sum_{j=1}^M \tilde{N}_j^\parallel \right)^2} \quad (\text{A.3})$$

Bibliography

- [San+11] A. M. Sandorfi, S. Hoblit, H. Kamano and T.-S. H. Lee,
Determining pseudoscalar meson photoproduction amplitudes from complete experiments,
Journal of Physics G: Nuclear and Particle Physics **38** (2011) 053001, ISSN: 1361-6471,
URL: <http://dx.doi.org/10.1088/0954-3899/38/5/053001>.
- [Afz19] F. N. Afzal, *Measurement of the beam and helicity asymmetries in the reactions*
 $\gamma p \rightarrow p\pi^0$ and $\gamma p \rightarrow p\eta$,
PhD thesis: Rheinische Friedrich-Wilhelms-Universität Bonn, 2019,
URL: <https://hdl.handle.net/20.500.11811/8064>.
- [Afz+20] F. Afzal et al.,
Observation of the $p\eta'$ Cusp in the New Precise Beam Asymmetry Σ Data for $\gamma p \rightarrow p\eta$,
Phys. Rev. Lett. **125** (15 2020) 152002,
URL: <https://link.aps.org/doi/10.1103/PhysRevLett.125.152002>.

List of Figures

1.1	Running coupling of QCD. The colored data points represent different methods to obtain a value for α_s . For more details it may be referred to [pdg].	2
1.2	Calculated nucleon (isospin $I = 1/2$) resonances compared to measurements. Left in each column are the calculations [bonnmodel], the middle shows the measurements and PDG rating [pdg]	3
1.3	FEYNMAN diagram for the s-channel photoproduction of pseudoscalar mesons, adapted from [Afz19]	4
2.1	[cb]	7
2.2	[cb]	8
2.3	[cb]	8
2.4	D. WALTHER in [urban]	9
2.5	[cb]	9
2.6	[cb]	10
3.1	Distribution of event classes in $\eta' \rightarrow \gamma\gamma$ production	12
3.2	Time information of all final state particles and the beam photon for 3PED η' production	13
3.3	Reaction time t_r for 3PED η' production	14
3.4	Coplanarity of the $p\eta'$ final state with all other cuts applied for the energy bin $1\,500\,\text{MeV} \leq E_\gamma < 1\,600\,\text{MeV}$. The vertical dashed lines show the cut ranges obtained from a gaussian fit to the data (open circles). The solid black histograms represent fitted MC data of $\eta' \rightarrow \gamma\gamma$	18
3.5	Polar angle difference of the $p\eta'$ final state with all other cuts applied for the energy bin $1\,500\,\text{MeV} \leq E_\gamma < 1\,600\,\text{MeV}$. The vertical dashed lines show the cut ranges obtained from a gaussian fit to the data (open circles). The solid black histograms represent fitted MC data of $\eta' \rightarrow \gamma\gamma$	18
3.6	Missing mass of the $p\eta'$ final state with all other cuts applied for the energy bin $1\,500\,\text{MeV} \leq E_\gamma < 1\,600\,\text{MeV}$. The vertical dashed lines show the cut ranges obtained from a fit to data (open circles) employing a NovosIBIRSK function. The solid colored histograms represent fitted MC data from relevant photoproduction reactions: in black η' , in green π^0 , in red η , in blue ω , in yellow $2\pi^0$, magenta $\pi^0\eta$. The turquoise histogram is the sum of all MC histograms.	19

3.7	Invariant mass of the $p\eta'$ final state with all other cuts applied for all energy and angular bins. The open circles represent the measured data, the solid colored histograms fitted MC data from relevant photoproduction reactions: in black η' , in green π^0 , in red η , in blue ω , in yellow $2\pi^0$ and in magenta $\pi^0\eta$. The turquoise histogram is the sum of all MC histograms.	20
3.8	Invariant mass of the $p\eta'$ final state with all other cuts applied for the energy bin $1\,500\text{ MeV} \leq E_\gamma < 1\,600\text{ MeV}$. The vertical dashed lines show the cut ranges obtained from a gaussian fit to the η' MC data (solid black histogram). The open circles represent the measured data, the solid colored histograms fitted MC data from relevant photoproduction reactions: in black η' , in green π^0 , in red η , in blue ω , in yellow $2\pi^0$ and in magenta $\pi^0\eta$. The turquoise histogram is the sum of all MC histograms.	21
3.9	Acceptance for the reaction $\gamma p \rightarrow p\eta'$ after all cuts that have been discussed so far for 2.5PED and 3PED events	22
3.10	Fraction of background events in the analyzed beam energy and angular bins.	23
3.11	Acceptance for possible background contributions	24
3.12	Generated energies of the two lowest energy photons in $2\pi^0$ photoproduction MC data. The threshold of 20 MeV is marked by a vertical red line. Lowest energy photon is shown on the top, second lowest energy photon is shown on the bottom.	25
3.13	Generated energies of the two lowest energy photons in $2\pi^0$ and $\pi^0\eta$ photoproduction MC data. The threshold of 20 MeV is marked by a vertical red line. Lowest energy photon is shown on the top, second lowest energy photon is shown on the bottom.	26
3.14	Polar angle difference $\Delta\theta$ between the photon with second highest energy and second lowest energy of the $\pi^0\eta$ final state.	26
3.15	Illustration of the misidentification process during reconstruction	27
3.16	Generated CMS angle $\cos\theta_{\text{gen.}}$ vs. reconstructed CMS angle $\cos\theta_{\text{rec.}}$ for both background reactions. The slope $\cos\theta_{\text{gen.}} = \cos\theta_{\text{rec.}}$ is indicated by the solid line.	28
3.17	Detector hits of the recoil proton, as obtained from MC data for the production of η' , $2\pi^0$ and $\pi^0\eta$. CB: Crystal Barrel, FW: forward dector, MT: MiniTAPS	30
3.18	Difference in measured and calculated beam energy. Data points are shown as open circles, MC data as solid histograms: in black η' , in green π^0 , in red η , in blue ω , in yellow $2\pi^0$ and in magenta $\pi^0\eta$. The turquoise histogram is the sum of all MC histograms.	31
3.19	Invariant mass spectrum passing different stages in the event selection process. In the end clear peaks for all possibly produced mesons are visible. The vertical lines indicate the mean cut ranges over all energy and angle bins.	32
4.1	Left: Definition of angles α, ϕ, φ . Right: Photon momentum \vec{k} and polarization $\vec{\epsilon}$ define the beam polarization plane while the reaction plane is defined by the recoil proton p and produced meson M	33

List of Tables

1.1	Summary of the particles of the SM	1
1.2	Allowed quantum numbers for the intermediate resonance state N^*/Δ^*	4
3.1	The five most probable decay modes of the η' meson. The most probable further decay with according branching ratio is shown in brackets.[pdg]	11
3.2	Examined MC reactions that were used in sum for the fit	16
3.3	Fit functions and cut ranges for each variable	17
3.4	Total cross sections σ in the energy range 1 500 to 1 800 MeV, branching ratios (BR) to $n\gamma$ final states and maximum acceptance \tilde{A} for signal and possible background contributions	23
3.5	Relative loss in signal and background events if a cut on ΔE is applied.	29