# Determination of the beam asymmetry $\Sigma$ in $\eta$- and $\eta'$-photoproduction off the proton using Bayesian statistics

Master thesis for the CBELSA/TAPS collaboration

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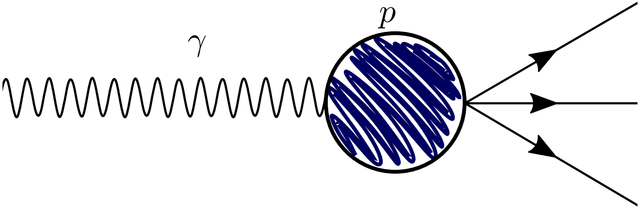
# Setting the scene

**The Standard Model of Particle Physics**

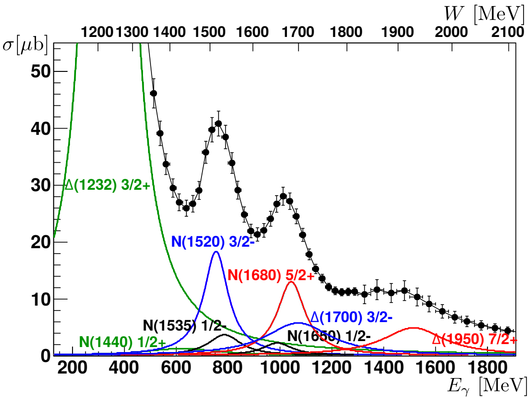
- matter consists of 12 (anti-)*fermions*
- quarks interact via *strong interaction*
- form bound states: mesons ($q\bar{q}$) and baryons ($qqq$)

baryon spectroscopy (photoproduction) gives insight in strong interaction



# Setting the scene

Observe resonances $N^*/\Delta^*$ in the cross sections $\sigma(\gamma p \to pM)$




Total cross section $\sigma(\gamma p \to p\pi^0)$ [Wunderlich et al. 2017]

$\rightarrow$goal: (help to) identify contributing resonances as strong bound states!

# Theoretical basics

- resonances are broad, overlapping, require complicated partial-wave-analysis (PWA)
- constraints for the analysis can be derived from polarization observables
- ultimate goal: "complete experiment"; unambiguous, model-independent PWA solution → several single and double polarization observables needed

## Beam-target polarization observables

| | | target polarization | | |
|---|---|---|---|---|
| **photon** | | $x$ | $y$ | $z$ |
| unpolarized | $\sigma_0$ | - | $T$ | - |
| linearly polarized | $-\Sigma$ | $H$ | $-P$ | $-G$ |
| circularly polarized | - | $F$ | - | $-E$ |

[**san**]

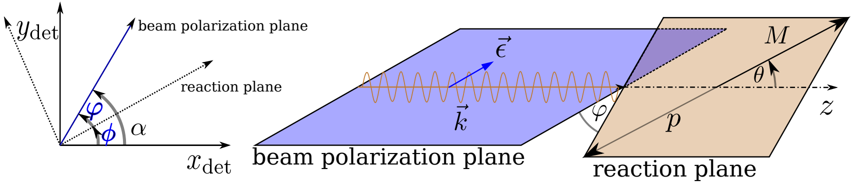
# Theoretical basics

## Beam asymmetry $\boldsymbol{\Sigma}$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(E_\gamma, \cos\theta, \varphi) = \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}_0(E_\gamma, \cos\theta) \cdot \left[1 - p_\gamma^{\mathrm{lin}} \boldsymbol{\Sigma} \cos(2\varphi)\right]$$

polarization angle $\varphi$, polarization degree $p_\gamma^{\mathrm{lin}}$

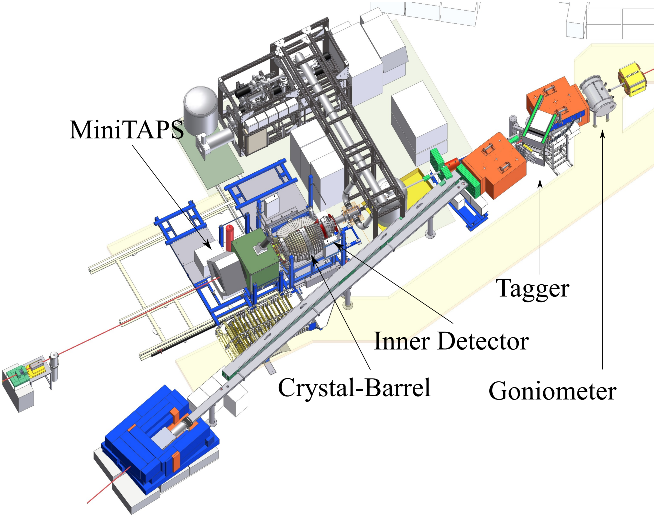
[**san**]




Definition of the polarization angle

# CBELSA/TAPS experiment

- generate photon beam from accelerated electrons via bremsstrahlung, with $E_\gamma \leq 3.2\,\mathrm{GeV}$
- photon beam impinges on liquid hydrogen target: $\gamma p \to pM \to pX$
- measure decay products $X$ of different final states: $M = \pi^0/\eta/\eta'/\ldots$
- data set: July-October 2013, 1065 h beam time



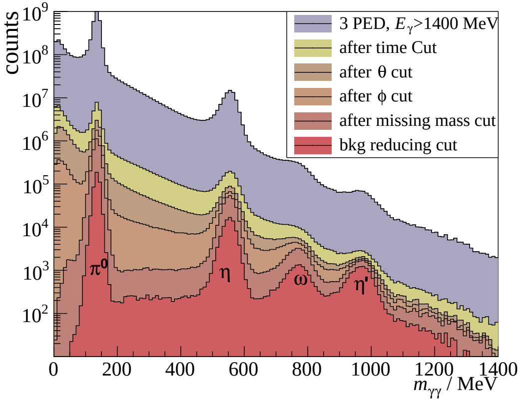

Overview of the experimental area, adapted from [cb]

# Event selection of the $\eta' \to \gamma\gamma$ final state

Analysis performed in 2x6 bins of $(E_\gamma, \cos\theta_{\eta'}^{\mathrm{CMS}})$, $E_\gamma \in [1400, 1800]$ MeV

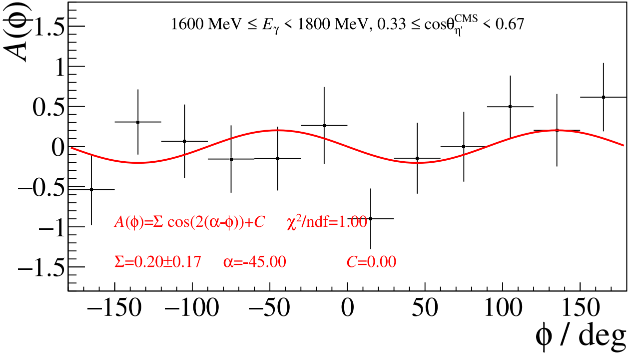
- 3 detector hits, 2 uncharged, 1 charged
- coincident detector hits
- kinematic cuts derived from energy-momentum conservation $p_\gamma + p_p = p'_p + p_{\eta'}$
- additional cuts to reduce background contributions

total: $\sim 11000$ $\eta' \to \gamma\gamma$ events

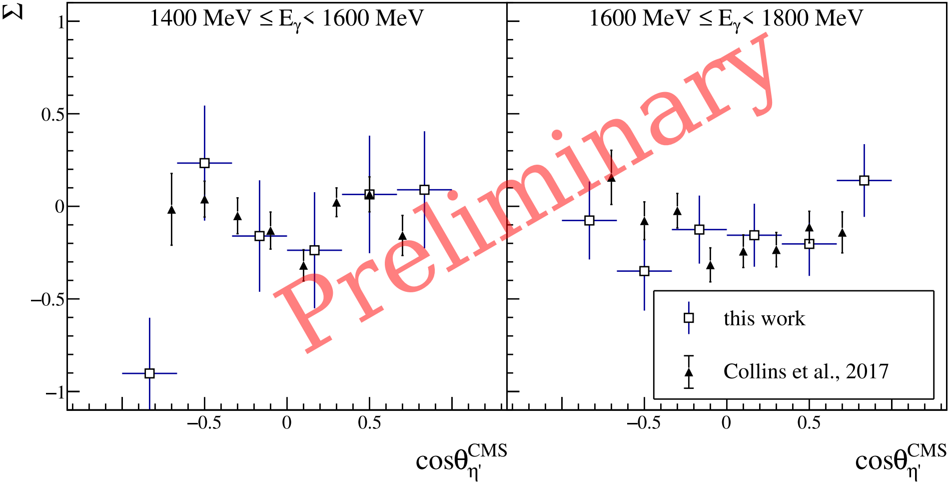


# Extraction method for $\Sigma_{\eta'}$

- measure in 2 distinct orthogonal polarization settings $\perp, \parallel$
- $\chi^2$-fit to event yield asymmetries
  $A(E_\gamma, \theta, \phi) = \frac{N^\perp(E_\gamma,\theta,\phi) - N^\parallel(E_\gamma,\theta,\phi)}{p_\gamma^\parallel N^\perp(E_\gamma,\theta,\phi) + p_\gamma^\perp N^\parallel(E_\gamma,\theta,\phi)} = \Sigma(E_\gamma, \theta) \cos\left(2\left(\alpha^\parallel - \phi\right)\right)$
- fit from $\sim 800$ $\eta' \to \gamma\gamma$ events



# Preliminary results for $\Sigma_{\eta'}$




Beam asymmetry $\Sigma_{\eta'}$ for all energy and angle bins, compared with results of [**clas**]

# Confirming pre-published results of $\Sigma_\eta$

- Polarization observables are needed for different final states $(\pi^0, \eta, \eta', \dots)$
- results for $\eta$ have already been published [**eta**]
- goal: confirm results using different fitting method

# Confirming pre-published results for $\Sigma_\eta$

## Event selection ($\eta$)

analysis performed in 11x12 bins of $(E_\gamma, \cos\theta)$ by [**eta**]

## Method

- fit to event yield asymmetries using BAYESIAN inference
- BAYES' theorem: $p(\theta|y) \propto \mathcal{L}(y|\theta) \cdot \pi(\theta)$
  - *marginal posteriors:* $p(\theta_j|y) = \prod_{i \neq j} \int \mathrm{d}\theta_i p(\theta|y)$
  - obtained using MARKOV-chain-Monte-Carlo (MCMC)

sampling algorithms: STAN

[**stan**]

# Confirming pre-published results for $\Sigma_\eta$

## Event selection ($\eta$)

analy

## Meth

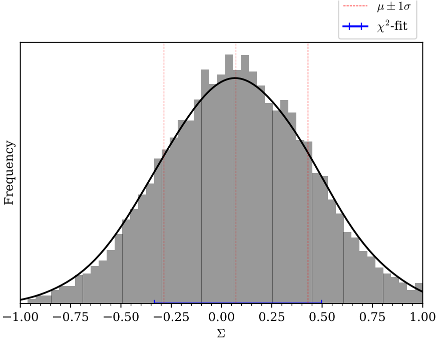
- f
- I

**Before**

Point estimate: $\Sigma_{\chi^2} \pm \Delta(\Sigma_{\chi^2})$

**Now**

marginal posteriors: $p(\Sigma|y)$

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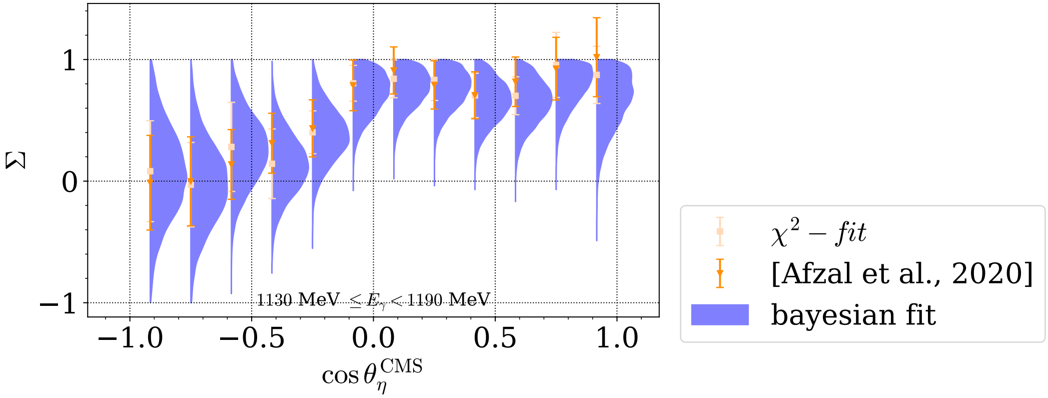
# Confirming pre-published results for $\Sigma_\eta$

../bayes/realdeal/sigma_eta_alt.pdf

# Confirming pre-published results for $\Sigma_\eta$




Beam asymmetry Σ for one energy and all angle bins

Additional advantage: sample only in physically allowed parameter space

# Conclusion

## Summary

- $\Sigma$ extracted for $\eta$ and $\eta'$ final state
- $\eta$ results obtained with BAYESIAN fit agree with previous results
- $\eta'$ results agree with previous results

## Outlook

- extract $\Sigma$ using unbinned maximum likelihood fit for $\eta/\eta'$
- apply BAYESIAN approach to above method
- consider bkg contaminations in results of $\Sigma_{\eta'}$

# Backup & References

# Additional theoretical basics

## Unpolarized differential cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{4}\rho \sum_{\text{spins}} |\langle f|\mathcal{F}|i\rangle|^2,$$

where

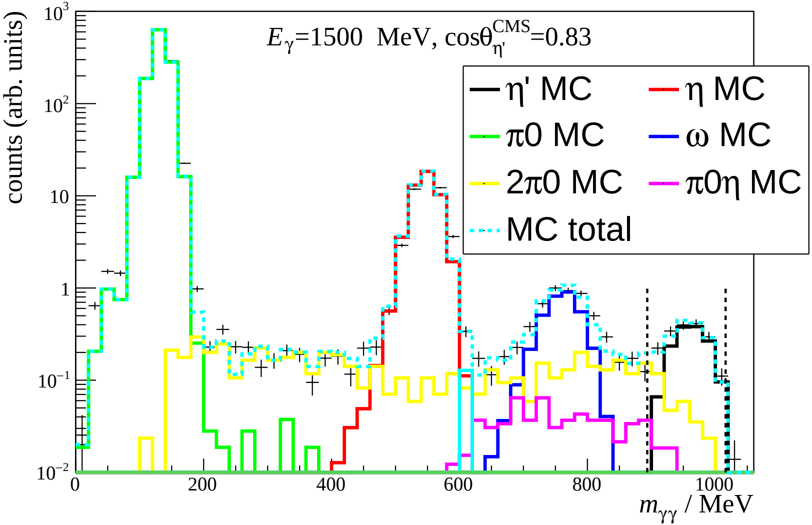
$$\mathcal{F} = i(\vec{\sigma}\cdot\vec{\epsilon})F_1 + (\vec{\sigma}\cdot\hat{q})(\vec{\sigma}\cdot(\hat{k}\times\vec{\epsilon}))F_2 + i(\vec{\sigma}\cdot\hat{k})(\hat{q}\cdot\vec{\epsilon})F_3 + i(\vec{\sigma}\cdot\hat{q})(\hat{q}\cdot\vec{\epsilon})F_4$$

$F_i$ : complex CGLN Amplitudes

[**cgln**]

$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \in \mathbb{R}$, not sufficient do determine $\mathcal{F}$ unambiguously
$\rightarrow$ Polarization Observables can be related to $F_i$

# Background estimation using Monte-Carlo simulations



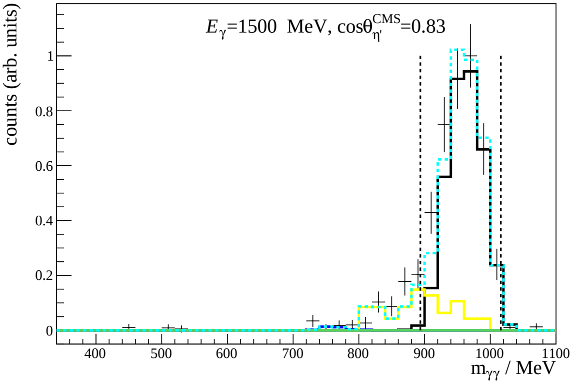

bkg contamination ∼ 27%

# Background estimation using Monte-Carlo simulations

$2\pi^0/\pi^0\eta$ events pass event selection, because $E_{\gamma_i} \lesssim 20$ MeV, or $\theta_{\gamma_i} \approx \theta_{\gamma_j}$

**Background reducing cuts**

- $p$ in MT for $E_\gamma < 1500$ MeV
- $E_{\gamma_i} < 1500$ MeV
- 1 PED/Cluster for $\gamma_i$
- Clustersize($p$) $< 6$
- Clustersize($\gamma_i$) in FW




bkg contamination $\sim 13\%$

# Diagnostics of a BAYESIAN fit

- $\hat{R}$: measure of convergence for chains
- Monte-Carlo-Standard-Error: measure for adequate sample size
- *posterior predictive checks*: "goodness of fit"

../bayes/realdeal/ppd_checks_alt/ebin6costbin1.pdf

# References I

Wunderlich, Y. et al. (May 2017). 'Determining the dominant partial wave contributions from angular distributions of single- and double-polarization observables in pseudoscalar meson photoproduction'. In: *The European Physical Journal A* 53.5. ISSN: 1434-601X. DOI: 10.1140/epja/i2017-12255-0. URL: http://dx.doi.org/10.1140/epja/i2017-12255-0.