Partial Wave Analyses of $\bar{p}p$ Annihilations in Flight

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Motivation

With regard to the upcoming $\bar{\mathrm{P}}$ANDA experiment, analyses of existing $\bar{p}p$ data are valuable

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- Development and test of the PAWIAN partial wave analysis package

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With regard to the upcoming P̄ANDA experiment, analyses of existing p̄p data are valuable

➡ **Crystal Barrel at LEAR**

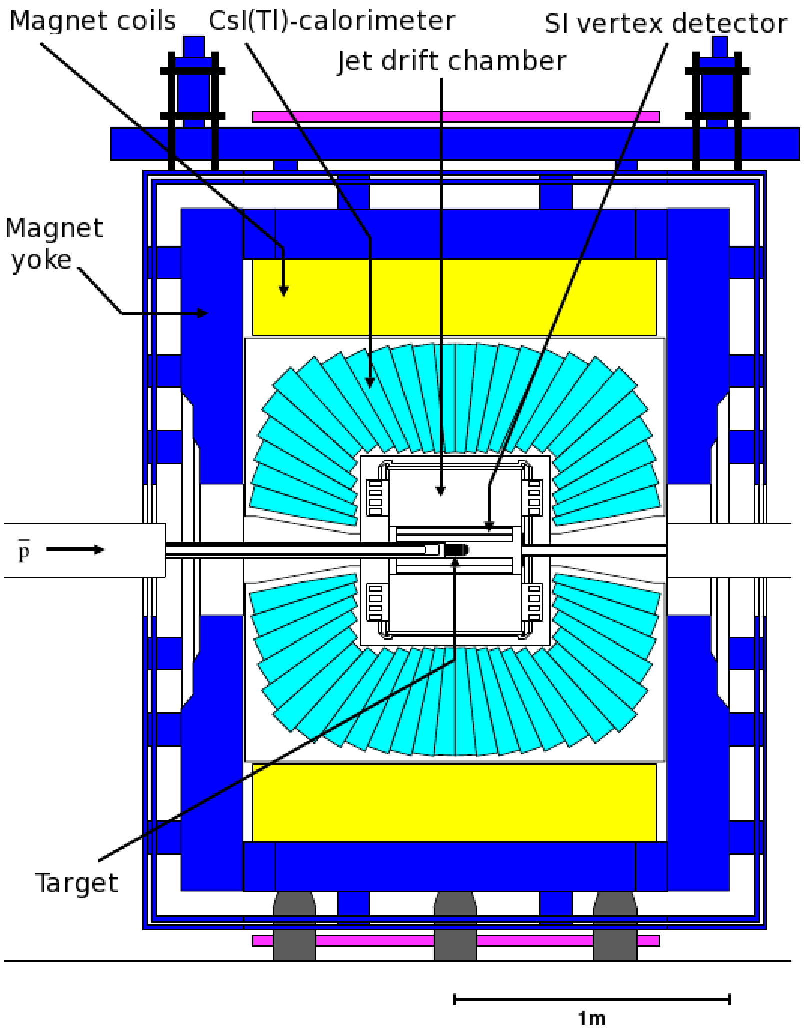
- Development and test of the PAWIAN partial wave analysis package
- Study of the production of vector mesons and the initial p̄p states
- Evaluation of the p̄p orbital angular momenta
- Determination of resonance contributions
- Evaluation of the spin density matrix (SDM) for different mesons

➡ Coupled channel partial wave analysis of

$$\bar{p}p \rightarrow K^+K^-\pi^0 \ / \ \pi^0\pi^0\eta \ / \ \pi^0\eta\eta$$

Crystal Barrel LEAR

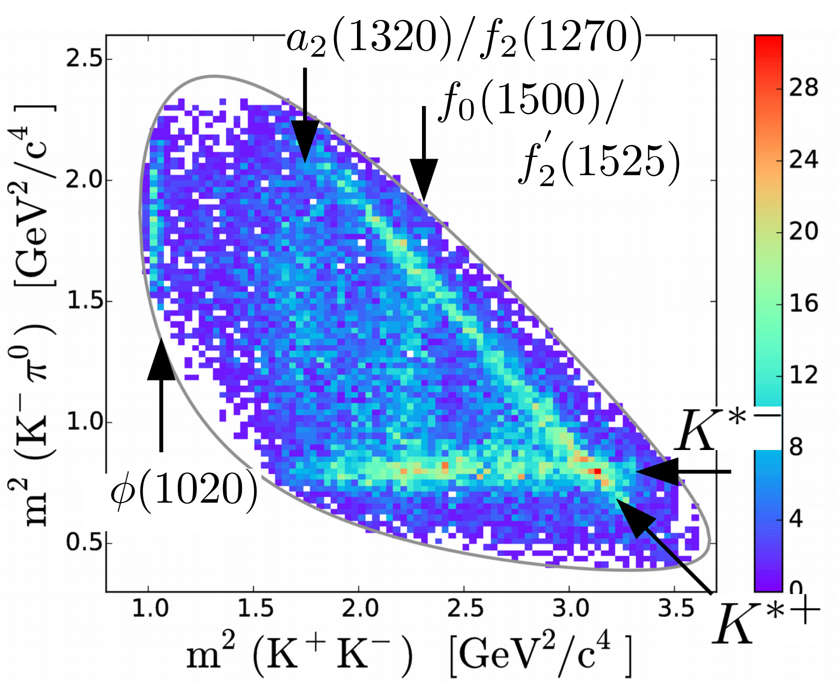
- Fixed target experiment at LEAR (CERN) data taking 1989 - 1996
- p̄p-annihilation in flight and at rest
- $p_{\bar{\mathrm{p}}}$ = 105 MeV/c ... 2 GeV/c
- $94\% \cdot 4\pi$ detector
- Targets: LH_2, LD_2, GH_2
- Trigger on 0 or 2 charged particles



Excellent opportunity for the investigation of specific physics aspects for P̄ANDA

Event selection: $\bar{p}p \rightarrow K^+K^-\pi^0$

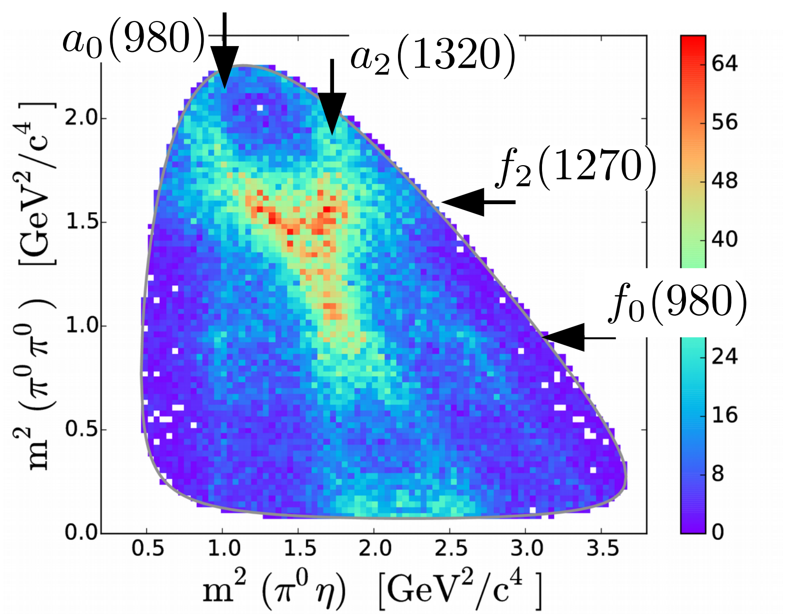
- Selected Crystal Barrel data: ~17500 exclusive events @ 900 MeV/c
- Kinematic fit for signal event selection and background suppression
- Main contributions:
  - $\phi\pi^0$
  - $a_2(1320)\pi^0/f_2(1270)\pi^0$
  - $f_0(1500)\pi^0/f_2'(1525)\pi^0$
  - $K^*(892)^\pm K^\mp$



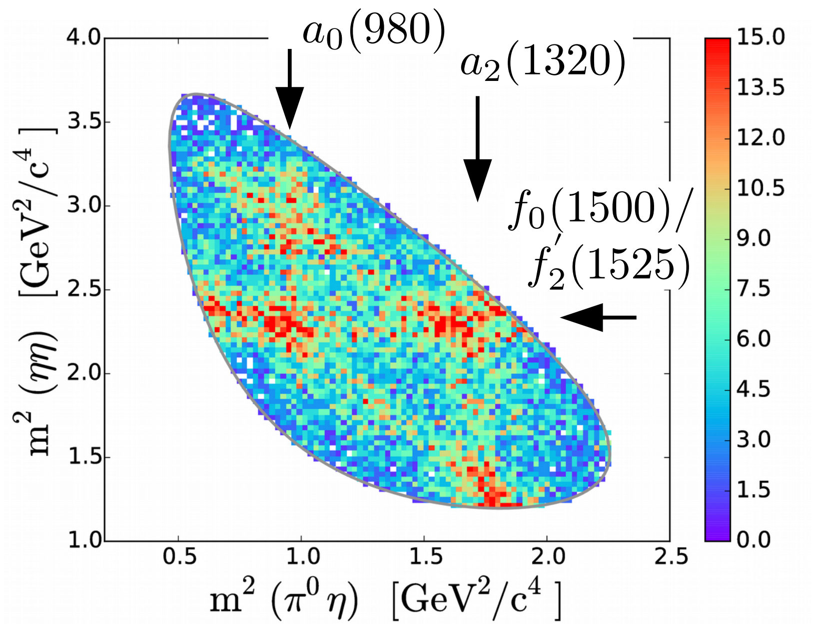
- Possible contributions:
  - $K_0^{*\pm}(1430)K^\mp$
  - $K_2^{*\pm}(1430)K^\mp$
  - $f_2(1270)\pi^0$
  - $\phi(1680)\pi^0$
  - $f_2'(1525)\pi^0$
  - $a_2(1700)\pi^0$
  - $a_0(980/1450)\pi^0$
  - Other $f_0\pi^0$ / $(KK)_S$ -wave
  - ...

$\bar{p}p \rightarrow \pi^0\pi^0\eta$ $\bar{p}p \rightarrow \pi^0\eta\eta$

- ~97000 events @ 900 MeV/c
- Main contributions:
  - $a_2(1320)\pi^0$
  - $a_0(980)\pi^0$
  - $f_2(1270)\eta$
  - $f_0(980)\eta$ / $(\pi\pi)_S$ -wave

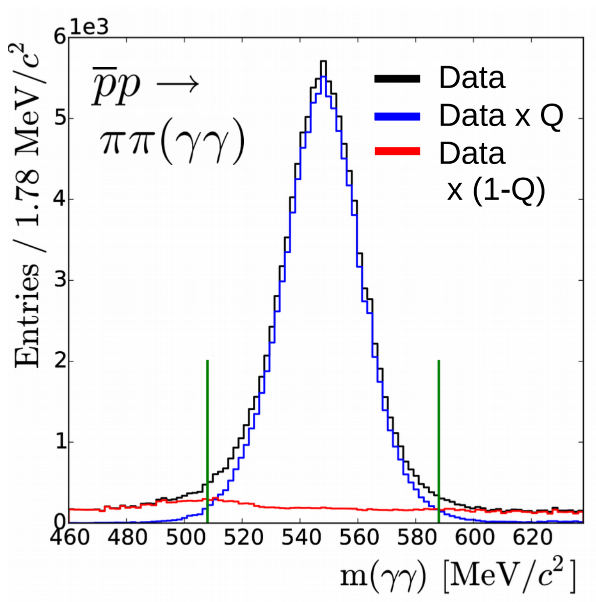


- ~12000 events @ 900 MeV/c
- Main contributions:
  - $a_2(1320)\eta$
  - $a_0(980)\eta$
  - $f_0(1500)\pi^0$ / $(\eta\eta)_S$ -wave

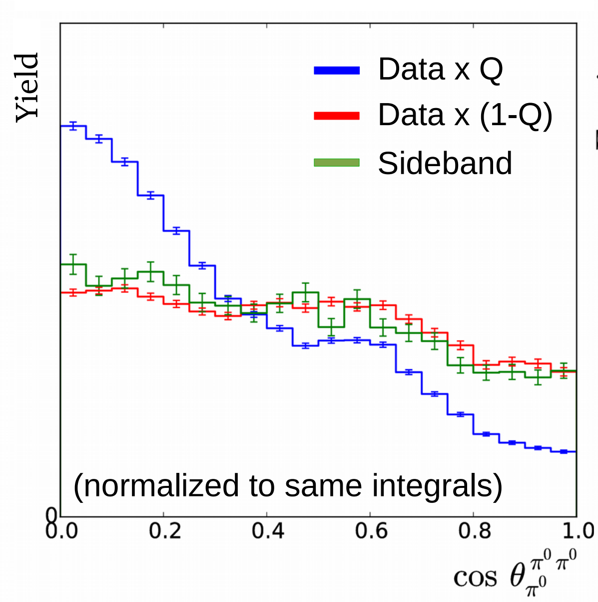


Event-based Background Suppression

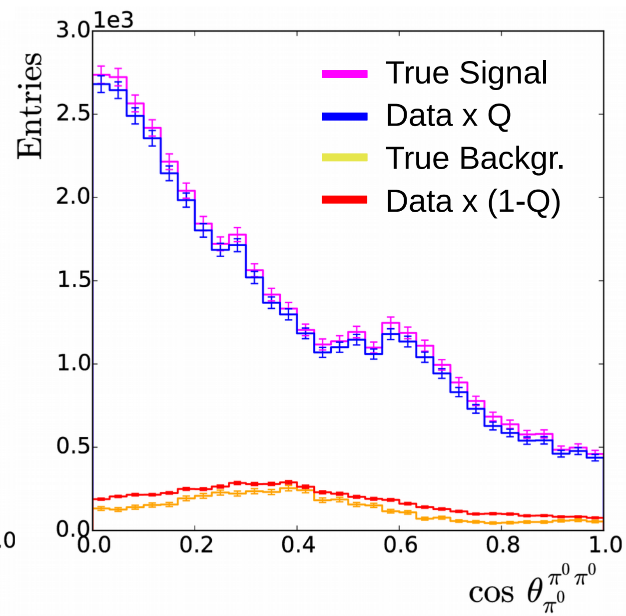
- Multivariate side-band subtraction using probabilistic event weights
  M. Williams et al, JINST 4, P10003, (2009)
- See talk of C. Sowa: ”Study of excited η Mesons in Photoproduction at CLAS”
- Example: background in $\pi^0\pi^0\eta$ due to $\bar{p}p \rightarrow \omega(\rightarrow \pi^0\gamma)\pi^0\pi^0$



Background in η signal region: can not be removed using the kinematic fit



Signal region vs. sidebands



MC mixture of $\pi^0\pi^0\eta$ and $\omega\pi^0\pi^0$ events with physics model from PWA

Partial Wave Analyses (PWA) of p̄p Reactions

FS particle spin

p̄p Singlet / Triplet states

$\mathrm{J^{PC}}$ prod. amplitudes

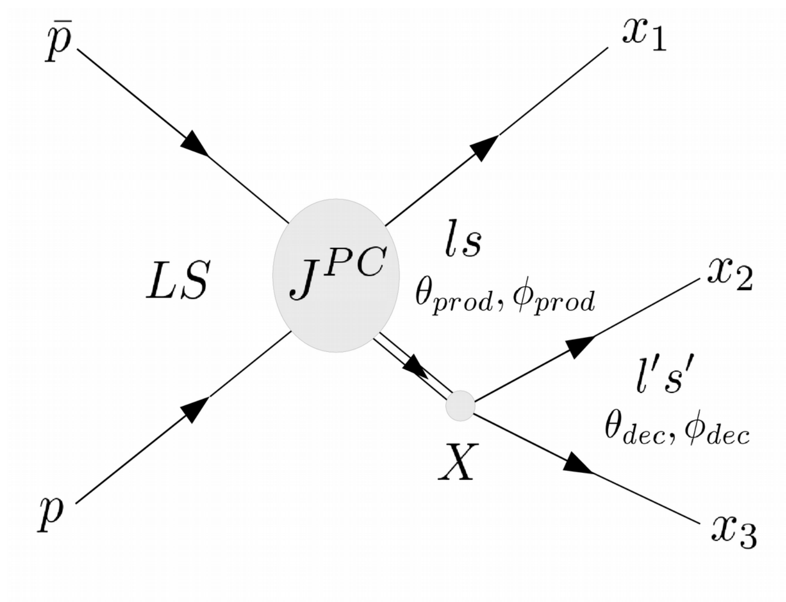
$$\frac{d\sigma}{d\Omega} \propto \sum_{\lambda_{FS}} \sum_{(2S+1)_S} \Big| \sum_{J^{PC}} T_{LS}^{\bar{p}p\to J^{PC}} \times$$

$$\times \sum_{X} \sum_{ls} T_{ls}^{J^{PC}\to X x_1} A_{l's'}^{X\to x_2 x_3} \Big|$$

Resonances

Res. prod. amp.

Res. decay amp.



- Amplitudes include angular distributions (D-functions), spin/isospin couplings (Clebsch-Gordan) and dynamics (Breit Wigner, k-matrix, ...)
- Full PWA from the initial to the final state
- Maximum contributing p̄p orbital momentum L_{max} = 4 is taken from previous results: Eur. Phys. J. C 75 3 (2015) 124

Coupled Channel Analysis - Overview

Simultaneous fits of different reaction channels which share a part of their parameter sets

- More reliable determination of resonance contributions and SDM elem.
- Additional constraints, less fit parameters, ...
- k-matrix formalism describes dynamics across channels by design, ensures unitarity

Resonance	Dynamics	$K^+K^-\pi^0$	$\pi^0\pi^0\eta$	$\pi^0\eta\eta$
ϕ	rel. BW.	X		
$\phi(1680)$	rel. BW.	X		
$K^{*\pm}$	rel. BW.	X		
$K_0^*(1430)$	$K\pi$-S-wave	X		
f_0	$\pi\pi$-S-wave	X (1)	X (2)	X (1)
$a_0(980)$	k-matrix	X (1)	X (1)	X (2)
$a_0(1450)$	k-matrix	X (1)	X (1)	X (2)
$a_2(1320)$	k-matrix	X (1)	X (1)	X (2)
$a_2(1700)$	k-matrix	X (1)	X (1)	
$f_2(1270)$	k-matrix	X (1)	X (2)	
$f_2'(1525)$	k-matrix	X (1)		X (1)
$\rho_3(1700)$	k-matrix	X		
$\pi_1^0(1400)$	rel. BW.		X (1)	X (2)

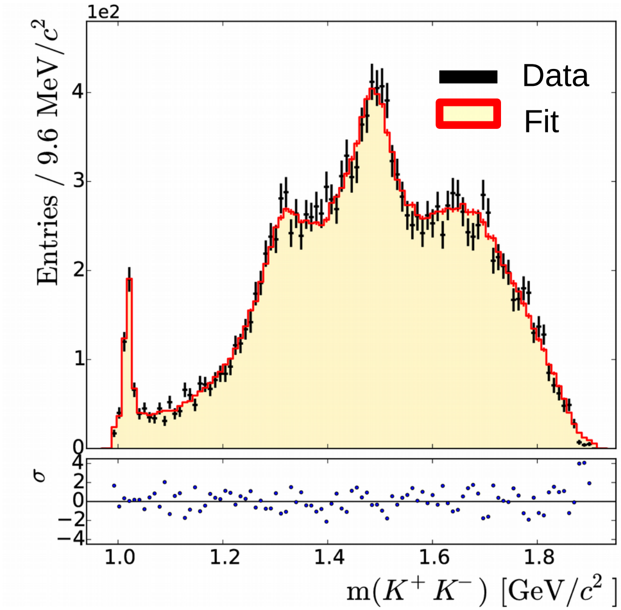
X basis fit X current best fit X alternative fits

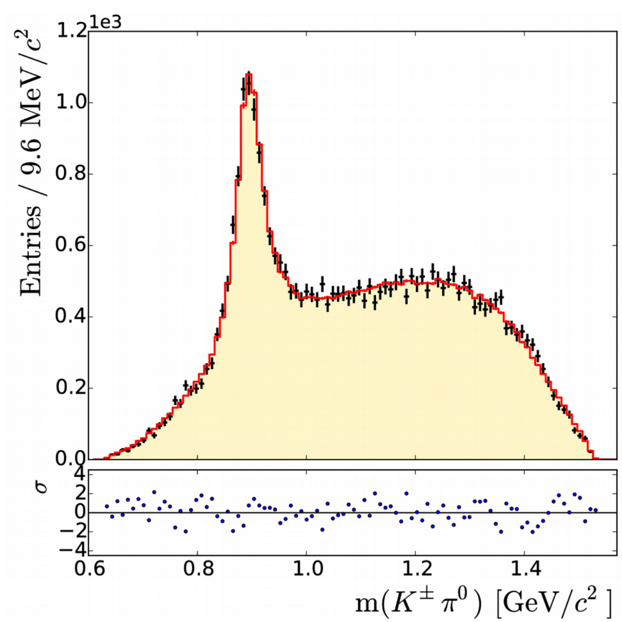
$(K\pi)_S(I=1/2)$ - wave used by FOCUS Phys. Lett. B653 (2007) 1-11 1-pole, 2-channel matrix

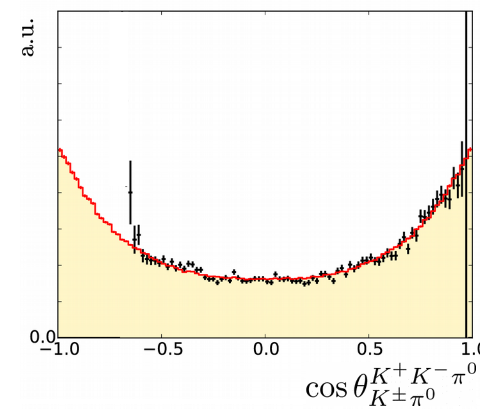
k-matrix parametrization by Anisovich and Sarantsev Eur. Phys. J. A16, 229(2003) 5-pole, 5-channel matrix

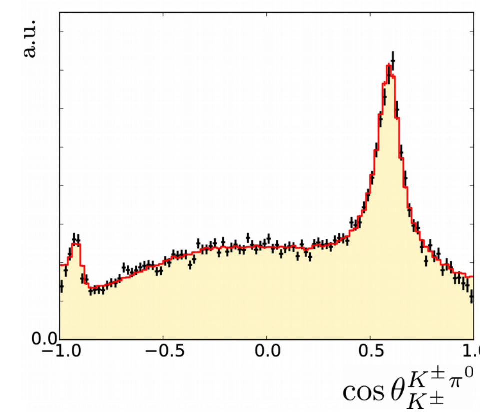
Model selection using different approaches (AIC, BIC, LRT)

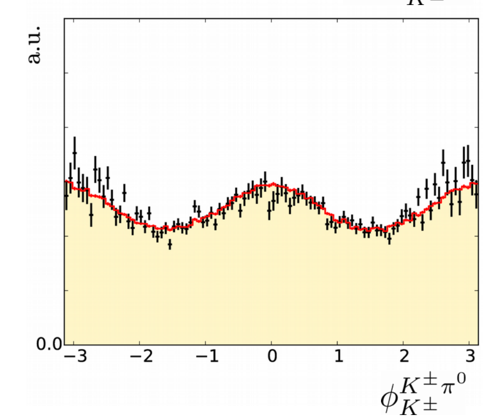
Coupled-Fit Results for $K^+K^-\pi^0$











← corrected for efficiency →

Resonance	Cont. [%]
K^*	38.0 ±0.9
f_2 matrix	18.5 ±1.2
$(K\pi)_S$	17.8 ±1.1
$(KK)_S$	16.4 ±1.1
a_2 matrix	14.4 ±0.6
$\phi(1680)$	11.3 ±0.6
ϕ	1.91 ±0.23
a_0 matrix	0.58 ±0.03
Σ	118.9 %

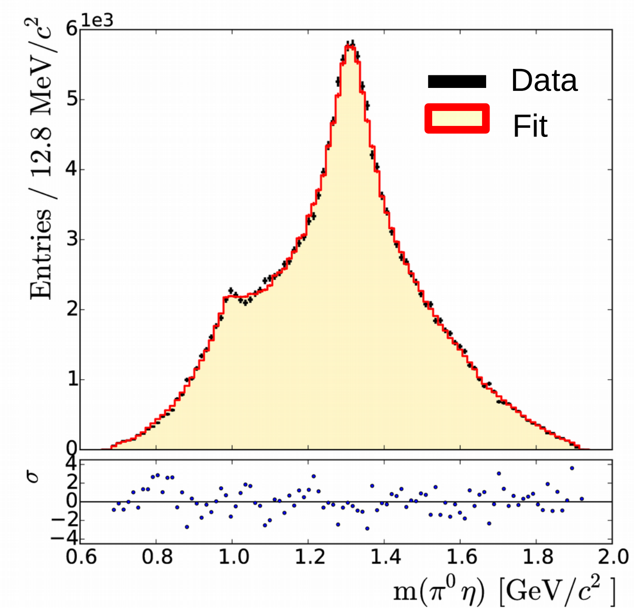
Goodness of fit evaluation using the “Energy Test”

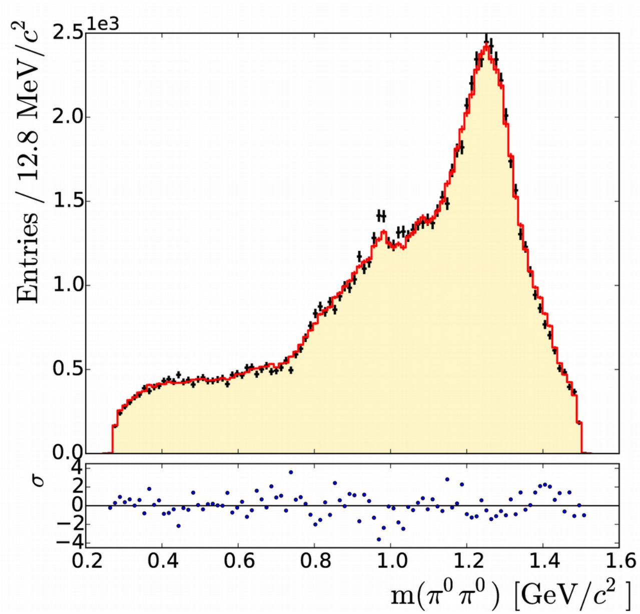
B. Aslan and G. Zech, Nucl. Instrum. Methods A537 (2005) 626-636.

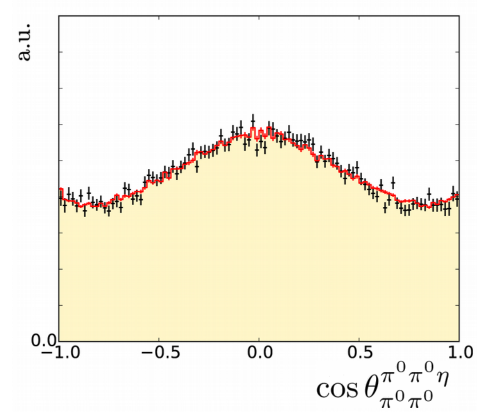
p = 0.06

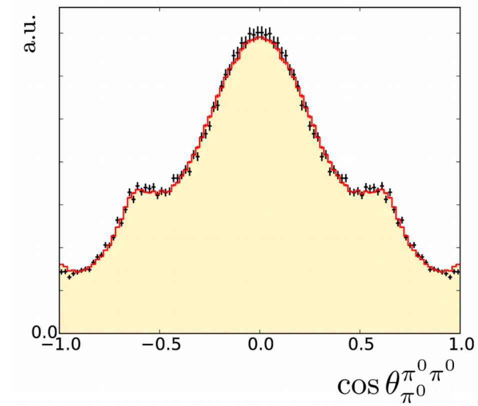
“Fit probability”

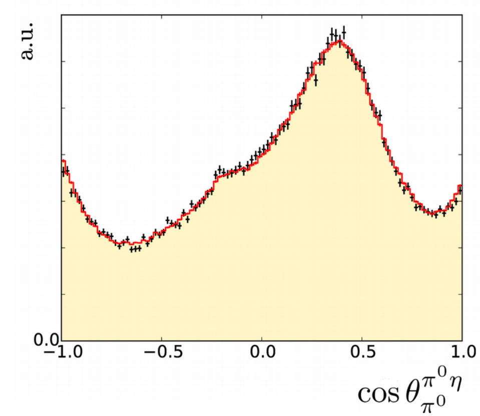
Coupled-Fit Results for $\pi^0\pi^0\eta$



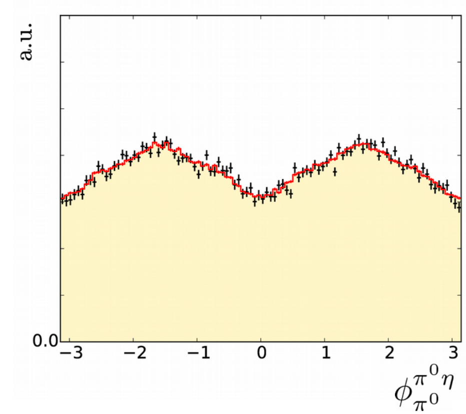








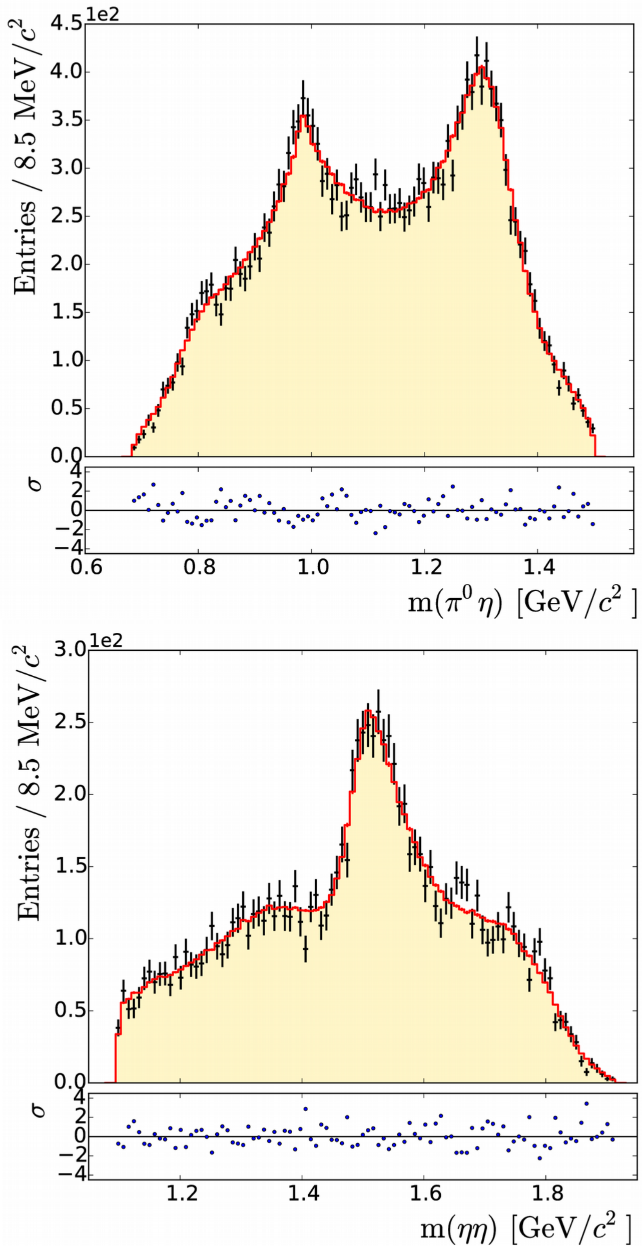
$\leftarrow$ corrected for efficiency $\rightarrow$

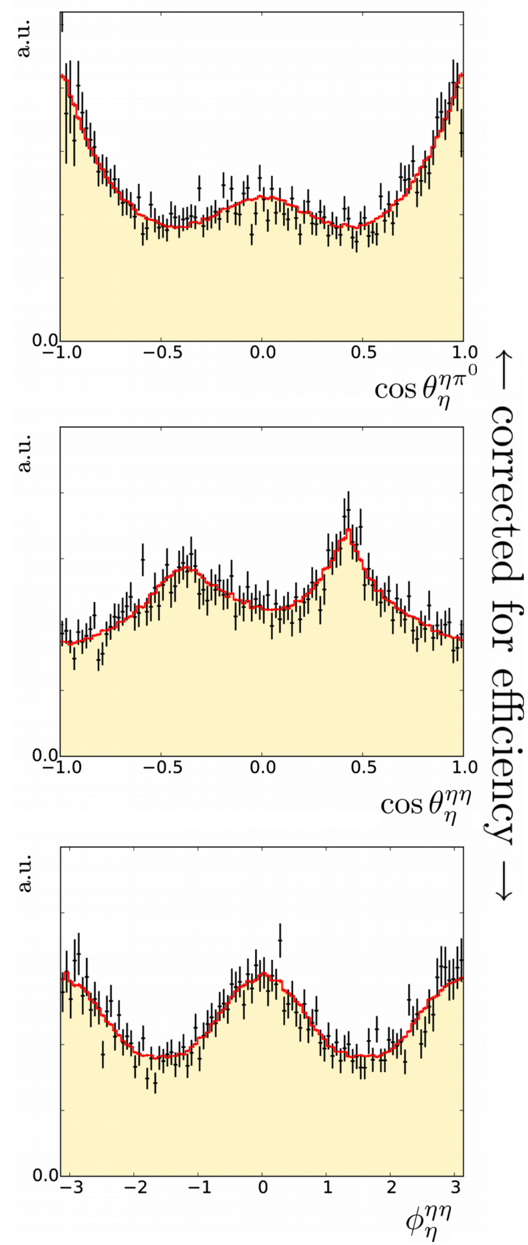


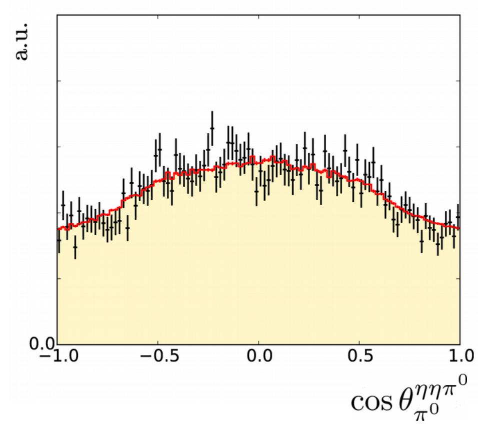
Resonance	Cont. [%]
a_2 matrix	52.5 $\pm$0.6
f_2 matrix	31.5 $\pm$0.6
$(\pi\pi)_S$	20.9 $\pm$0.6
a_0 matrix	19.1 $\pm$0.5
Σ	124.0

$p = 0.017$

Coupled-Fit Results for $\pi^0\eta\eta$





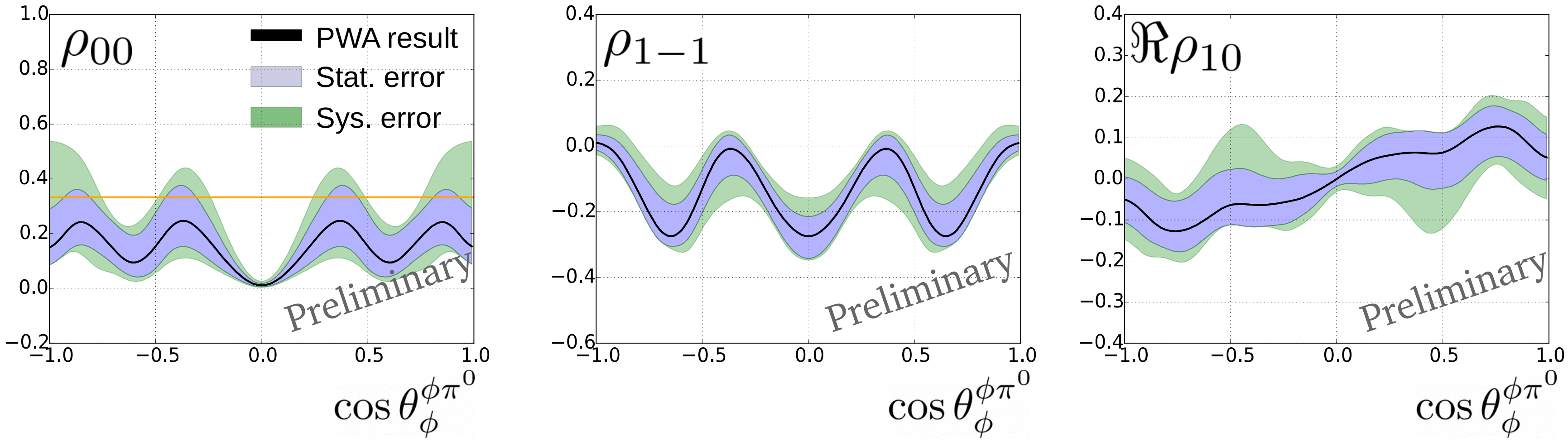


Resonance	Cont. [%]
$(\eta\eta)_S$	52.2 ±2.0
a_2 matrix	30.9 ±1.3
f_2 matrix	11.8 ±0.4
a_0 matrix	11.1 ±0.9
Σ	106.0

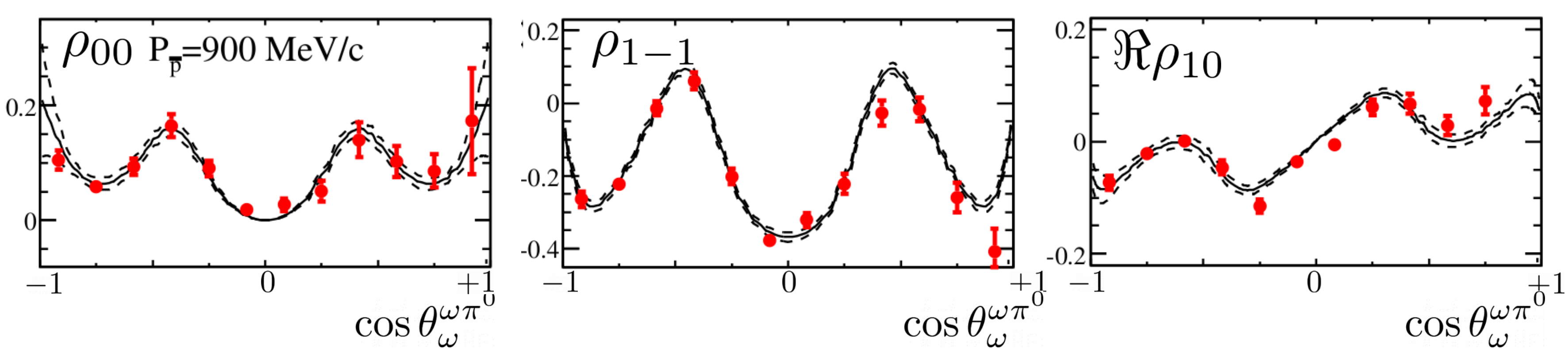
$p = 0.30$

Spin Density Matrix (SDM) Elements of the $\phi(1020)$

- Spin S particle: n x n -matrix with n = 2S + 1
- Diagonal elements give the total probability to find a certain spin state
- Obtained from PWA (this work, helicity frame):

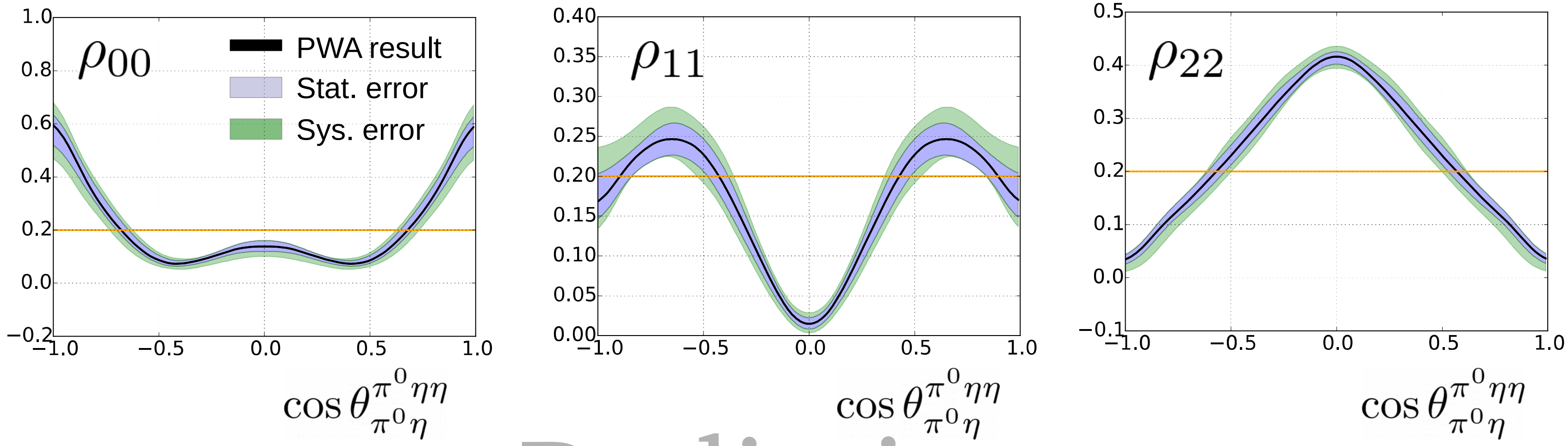


- Previous results for the ω in $\overline{p}p \rightarrow \omega\pi^0$ Eur. Phys. J. C 75 3 (2015) 124



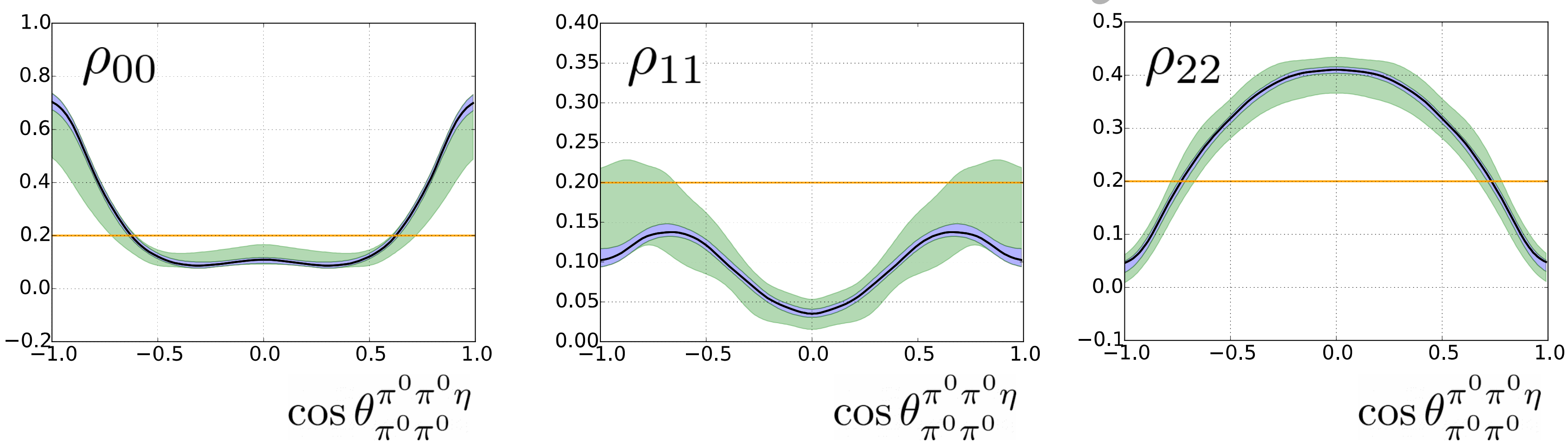
SDM Elements of $a_2(1320)$ and $f_2(1270)$

- $a_2(1320)$ (η recoil)



Preliminary

- $f_2(1270)$ (η recoil)



Summary

- Analyses of Crystal Barrel LEAR data with relevance for P̄ANDA
- p̄p initial states and production of vector mesons
- Development and test of the PAWIAN PWA package
- Coupled channel analysis of $\bar{p}p \rightarrow K^+K^-\pi^0$ / $\pi^0\pi^0\eta$ / $\pi^0\eta\eta$ is in progress
  - Sophisticated treatment of background using event weights
  - Resonance contributions have been determined
  - SDM of ϕ, a_2, f_2 are extracted from the fitted amplitudes
    ➡ SDM of the ϕ shows an alignment and significant similarities to the ω SDM
  - Spin-exotic $\pi_1(1400)$ contribution has to be investigated