

Partial Wave Analysis for $\bar{p}p$ and e^+e^- Annihilation Processes

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and
the Interpretation of Baryon Resonances
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Outline

- PWA software for PANDA and other hadron spectroscopy experiments
- PWA @ PANDA
 - detector and physics program
 - challenges for PWA @ PANDA
- Analyses of Crystal Barrel @ LEAR data in-flight with relevance for PANDA
 - investigation of the $\bar{p}p$ annihilation process and the production mechanisms of vector mesons
 - ➔ $\bar{p}p \rightarrow \omega \pi^0$
 - ➔ $\bar{p}p \rightarrow K^+K^-\pi^0$ with the focus on $\phi\pi^0$ and $K^{*\pm} K^\mp$
 - search for resonances in $\bar{p}p \rightarrow \pi^+\pi^-\eta$
- PWA of BESIII data

PWA Software Package

PWA activities for PANDA started in Bochum in 2010 with the aims:

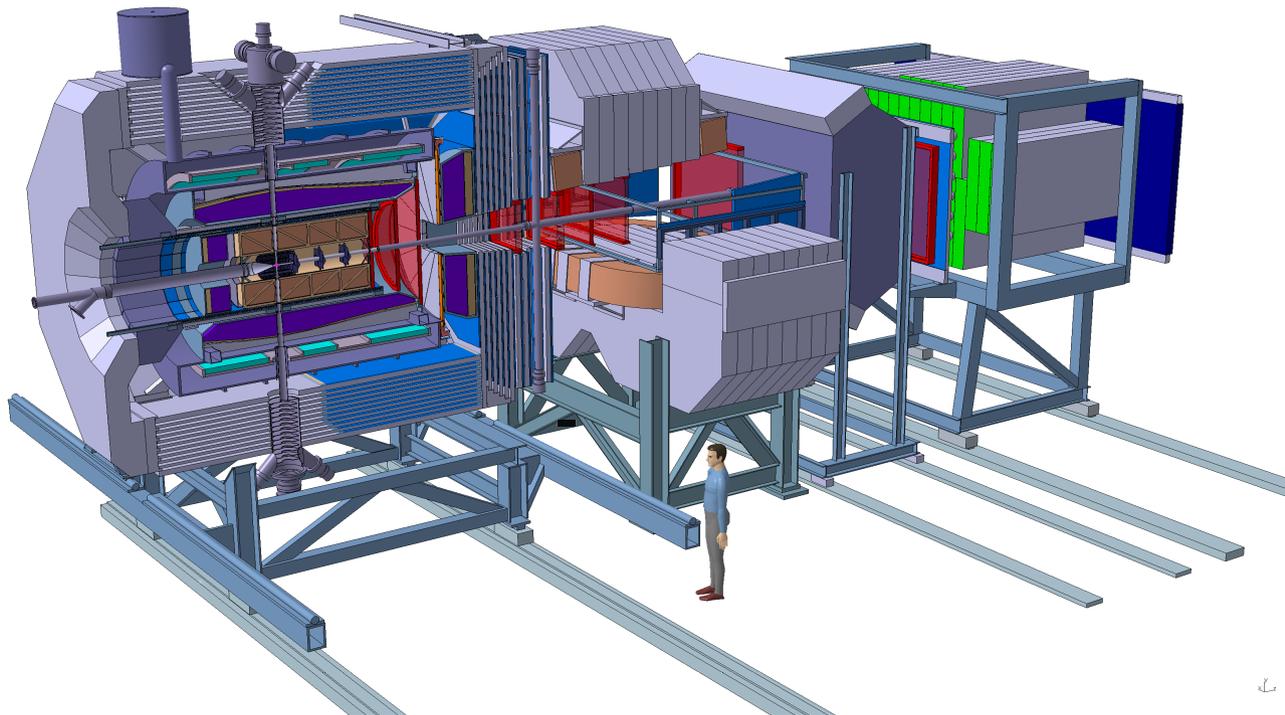
- to develop a generic PWA software package
- to support all physics cases to be studied @ PANDA and partly @ other hadron spectroscopy experiments

Software package PAWIAN (**PA**rtial **W**ave **I**nteractive **A**nalysis) already in a good shape and first analyses have been started

- Full hypothesis and other input settings defined via configuration files
- Event based maximum likelihood fit
- Minimization with MINUIT2 and prefit with genetic algorithms
- Running on multi-core CPUs and computing clusters
- qft++: decay amplitudes in various formalisms ([M. Williams \(CLAS, GlueX\) Computer Physics Communications, Vol. 180, Issue 10, 2009](#))
- First tools for coupled channel analyses available

PANDA @ FAIR

- Fixed target experiment @ FAIR, Darmstadt
- $\bar{p}p$ - and $\bar{p}A$ -annihilation with \bar{p} -momentum between 1.5-15 GeV/c
- Rich physics program with the focus on charmonium and open charm spectroscopy and the search for exotic states
- Detector with $\sim 4\pi$ acceptance for neutral and charged particles



PWA Challenges @ PANDA

$\bar{p}p$ production mechanism

- Number of initial $\bar{p}p$ states rises with increasing beam momentum
 - number of fit parameters rises dramatically
- $p_{\bar{p}} = 1.94 \text{ GeV}/c$ @ CB-LEAR → largest contributing momentum $L_{\text{max}} \approx 5$
- $p_{\bar{p}} = 15 \text{ GeV}/c$ @ PANDA → $L_{\text{max}} = ?$
 - threshold effects relevant for the production of heavy resonances (e.g. charmonia) → number of fit parameters reduced

J	Singulett $\lambda = 0$	J^{PC}	Triplett $\lambda = \pm 1$	J^{PC}	Triplett $\lambda = \pm 1, 0$	J^{PC}
0	1S_0	0^{-+}			3P_0	0^{++}
1	1P_1	1^{+-}	3P_1	1^{++}	$^3S_1, ^3D_1$	1^{--}
2	1D_2	2^{-+}	3D_2	2^{--}	$^3P_2, ^3F_2$	2^{++}
3	1F_3	3^{+-}	3F_3	3^{++}	$^3D_3, ^3G_3$	3^{--}
4	1G_4	4^{-+}	3G_4	4^{--}	$^3F_4, ^3H_4$	4^{++}
5	1H_5	5^{+-}	3H_5	5^{++}	$^3G_5, ^3I_5$	5^{--}
6	1I_6	6^{-+}	3I_6	6^{--}	$^3H_6, ^3J_6$	6^{++}

Statistics

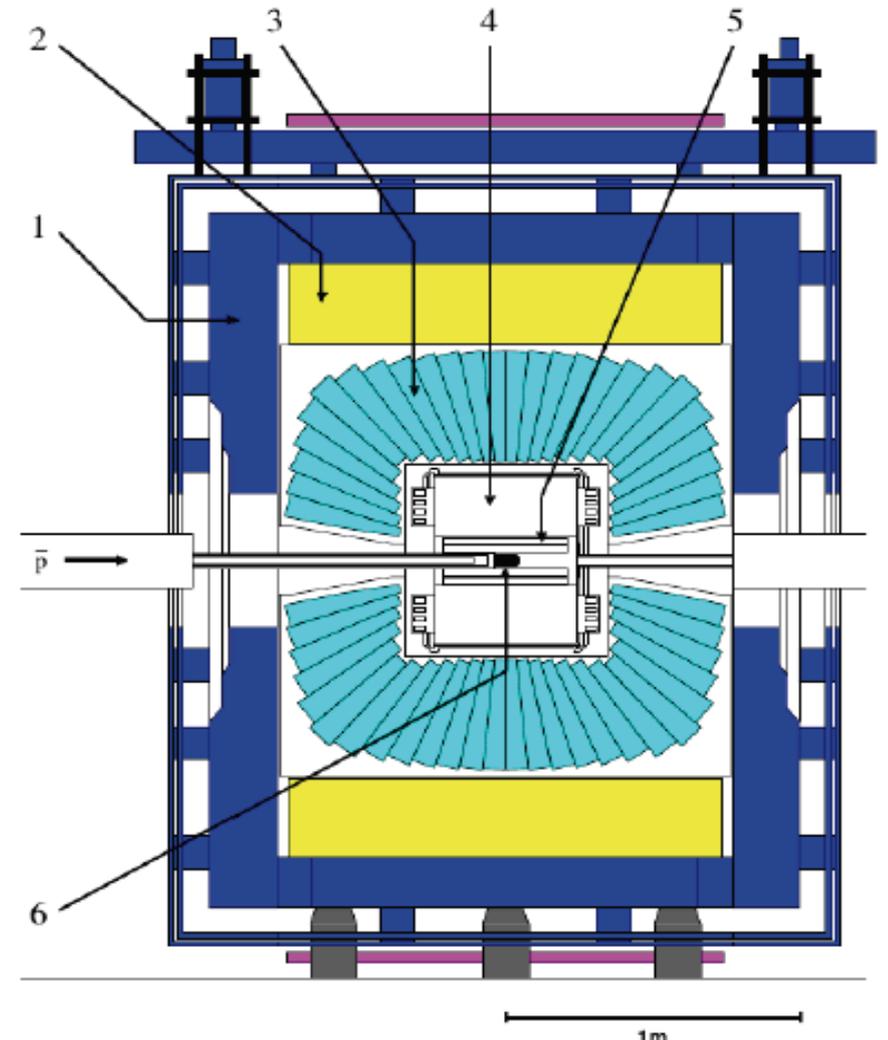
- Low cross sections for some channels of interest (pb-nb)
- Minimum number of events are needed for reliable fits

PWA with Crystal Barrel Data

Crystal Barrel experiment @ LEAR (CERN)

- Fixed target experiment
- $\bar{p}p$ annihilation at rest and in flight
 - highest beam momentum 1.94 GeV/c
 - overlap with PANDA
- Physics program
 - study of the annihilation process
 - spectroscopy of light mesons
 - search for exotics: glueballs, hybrids and multiquark states
- In operation between 1989 and 1996

Excellent opportunity for the investigation of physics aspects relevant for PANDA



(1) Iron Joke, (2) Magnet Coil
(3) CsI(Tl)-Calorimeter, (4) Jet-Drift-Chamber
(5) Vertex-Detector, (6) LH₂-Target

PWA: $\bar{p}p \rightarrow \omega\pi^0$

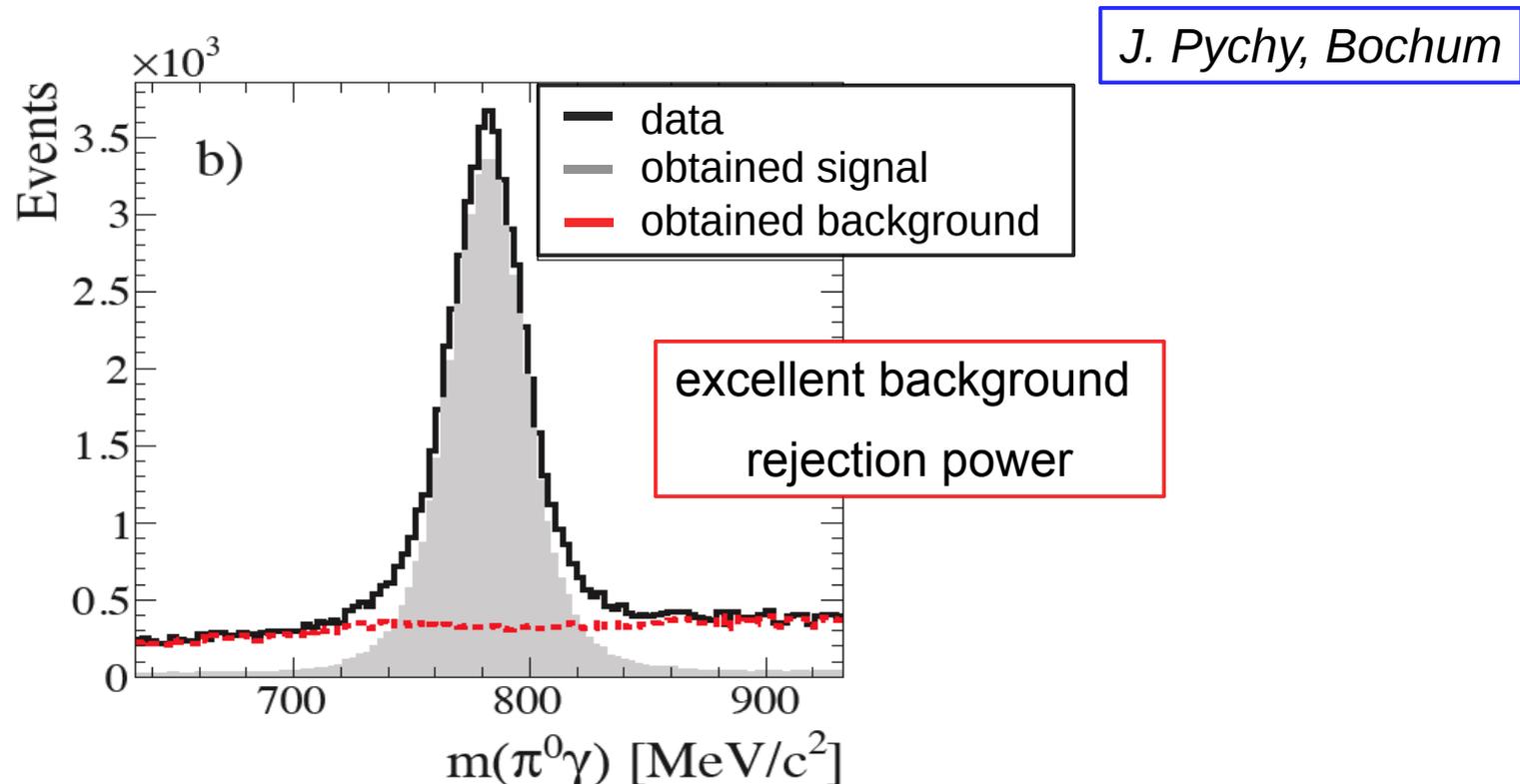
- Simple reaction with easy access to the initial $\bar{p}p$ -system
- Determination of the ω spin-density matrix (SDM), which contains the full information of the production mechanism
- Two decay modes $\omega \rightarrow \pi^0\gamma$ and $\omega \rightarrow \pi^+\pi^-\pi^0$ separately analyzed at various beam momenta between 0.6-1.94 GeV/c

PWA Strategy

- Preparation of accurate and clean data samples by applying kinematic fits and an event based background rejection
 - old event tapes recovered and old offline software re-installed
- Fits to determine the largest contributing momentum L_{\max} of the $\bar{p}p$ system
 - description of the full decay chain including the ω decay by making use of the helicity and the canonical formalism
- Extraction of the ω -SDM by two independent methods
 - from the PWA fit result
 - from the angular distribution of the decay products (Schilling method)

$\bar{p}p \rightarrow \omega\pi^0$: Background Rejection

- New background rejection method by assigning a probability to each event being a signal event (*M. Williams, M. Bellis, C.A. Meyer: arXiv:0809.2548 [nucl-ex]*)
 - determination of the signal to background ratio for the n nearest neighbors in the phase space
- Origin of the background not necessarily needed to be known

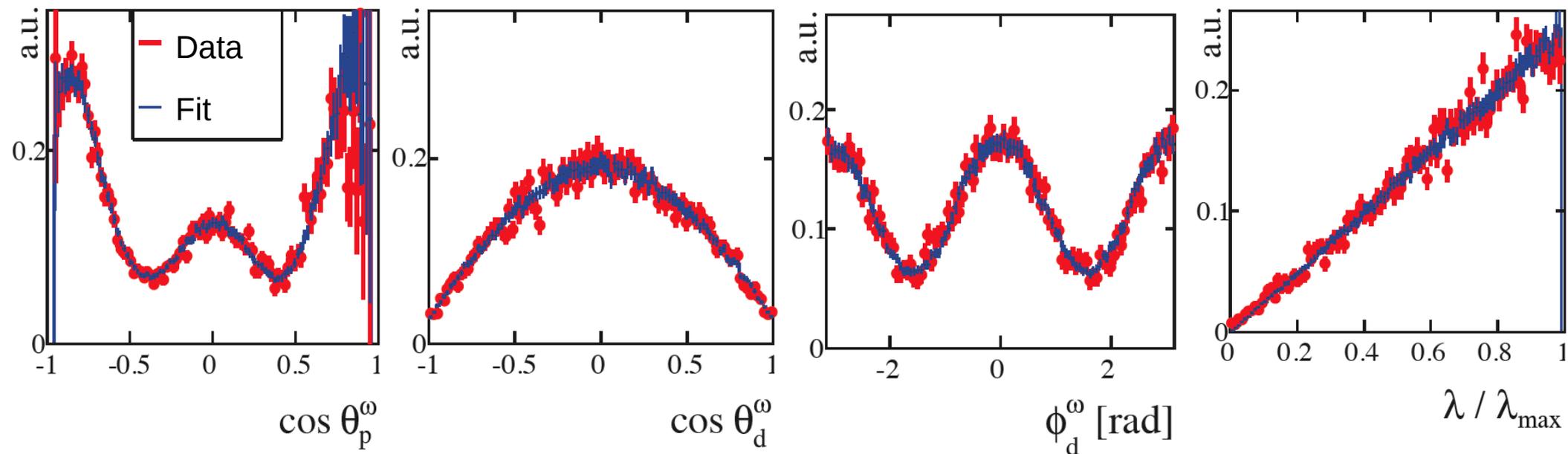


PWA results for $\bar{p}p \rightarrow \omega\pi^0$

- L_{\max} determined unambiguously
- L_{\max} increases from 3 @ 600 MeV/c to 5 @ 1940 MeV/c

$$\bar{p}p \rightarrow \omega \pi^0 \rightarrow (\pi^+ \pi^- \pi^0) \pi^0 \quad p_{\bar{p}} = 900 \text{ MeV/c}$$

J. Pychy, Bochum



$\bar{p}p \rightarrow \omega\pi^0$: ω Spin-Density Matrix

- SDM provides all information on the production mechanism
- Vector mesons: 3x3 complex elements
- Normalization, parity and hermicity conservation: 4 independent real parameters

$$\rho = \begin{pmatrix} 1/2(1 - \rho_{00}) & \Re\rho_{10} + i\Im\rho_{10} & \rho_{1-1} \\ \Re\rho_{10} - i\Im\rho_{10} & \rho_{00} & -\Re\rho_{10} + i\Im\rho_{10} \\ \rho_{1-1} & -\Re\rho_{10} - i\Im\rho_{10} & 1/2(1 - \rho_{00}) \end{pmatrix}$$

- Alignment if $\rho_{11} \neq \rho_{00}$

- Extraction of all elements via PWA:

$$\rho_{\lambda_\omega \lambda'_\omega}^0 = \frac{1}{N} \sum_{M_{\bar{p}p}} A_{M_{\bar{p}p}, \lambda_\omega} A_{M_{\bar{p}p}, \lambda'_\omega}^* \quad \text{with} \quad N = \sum_{M_{\bar{p}p}, \lambda_\omega} |A_{M_{\bar{p}p}, \lambda_\omega}|^2$$

*H. Koch,
Helicity amplitude for $\bar{p}p \rightarrow \omega\pi^0$,
Internal PANDA Note*

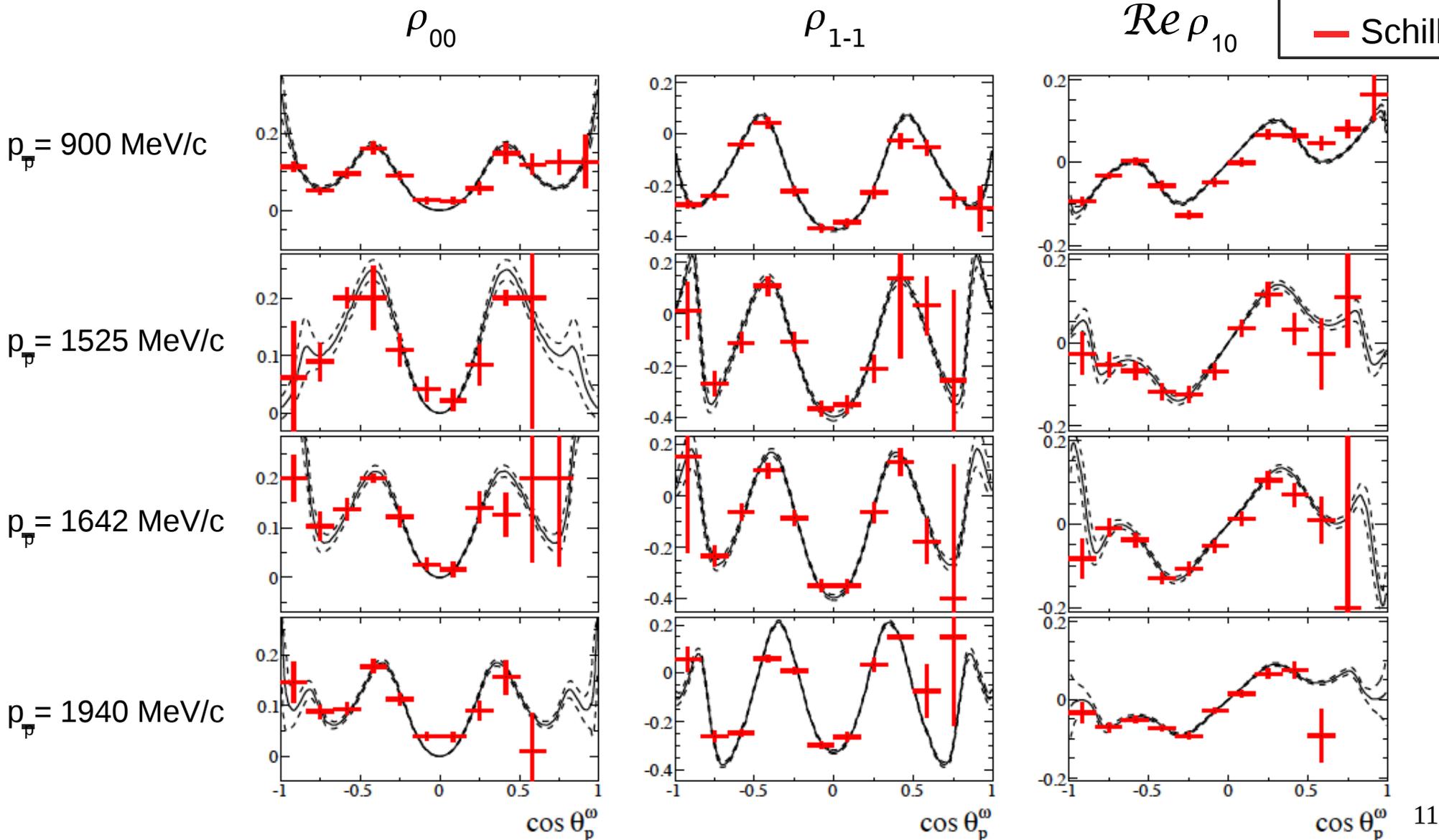
- Extraction of 3 parameters via fit to decay angular distribution ($\omega \rightarrow \pi^+ \pi^- \pi^0$)

$$W(\cos(\theta), \phi) \propto \frac{1}{2}(1 - \rho_{00}) + \frac{1}{2}(3\rho_{00} - 1) \cos\theta \\ - \sqrt{2} \Re\rho_{10} \sin 2\theta \cos\phi - \rho_{1-1} \sin^2\theta \cos 2\phi$$

*Schilling, Seyboth and Wolf,
Nucl.Phys. B15 (1970) 397-412,
Erratum-ibid. B18 (1970) 332*

$\bar{p}p \rightarrow \omega\pi^0$: ω Spin-Density Matrix

SDM parameters in the ω helicity frame for $\omega \rightarrow \pi^+\pi^-\pi^0$

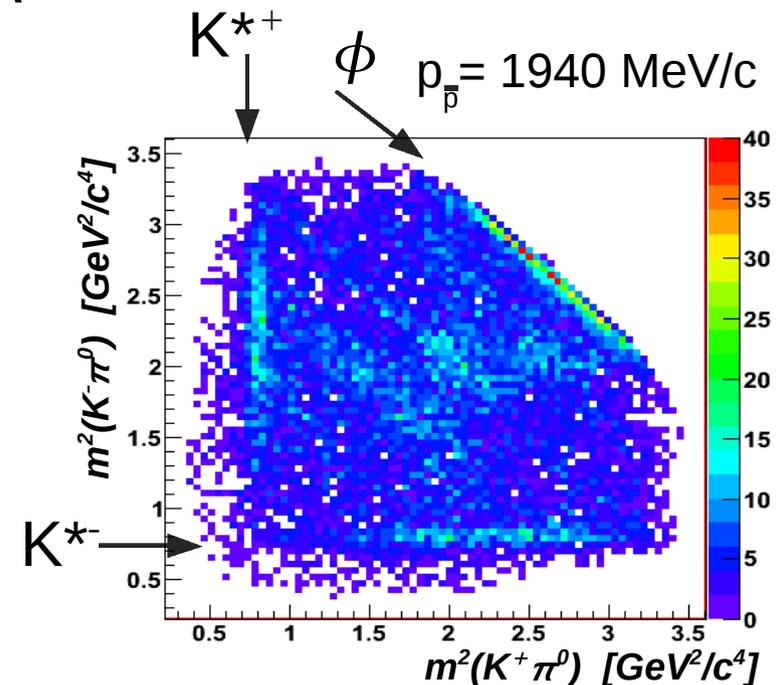
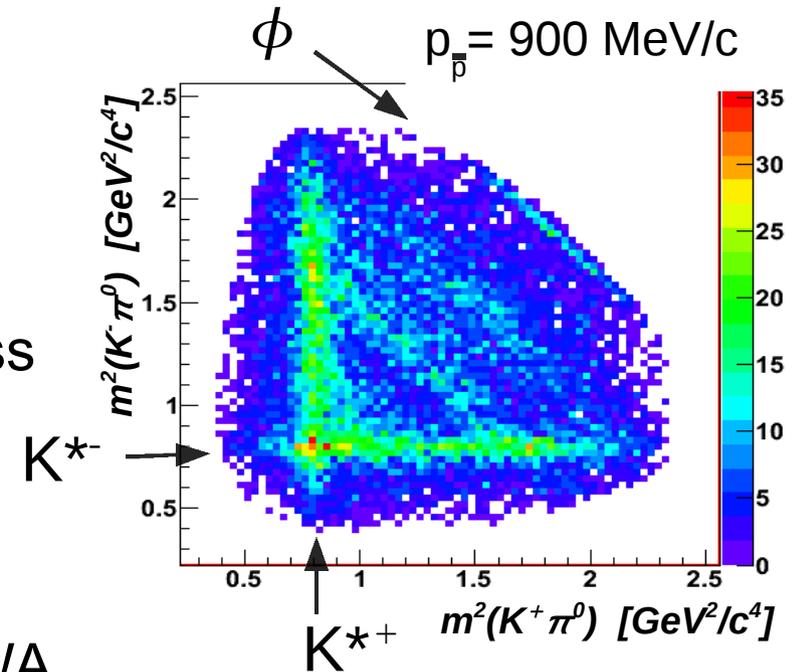


$\bar{p}p \rightarrow \omega\pi^0$: ω Spin-Density Matrix

- Good agreement between the two independent methods
- $\rho_{00} < 0.33$ for all production angles and for all beam momenta
 - strong alignment visible
- Strong oscillation along the production angle for all beam momenta
 - origin not yet clear
 - formation of intermediate resonances?

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

- Contains $\phi\pi^0$ and $K^{*\pm}K^\mp$ events
- Production of vector mesons with strangeness
 - different process in comparison to ω production
 - re-arrangement vs. annihilation
- Interference of resonances requires a full PWA of the complete channel
- SDM derived from ϕ and $K^{*\pm}$ amplitudes



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

- Full PWA from the initial to the final state
- $L_{\max} = 3$ @ 900 MeV/c and $L_{\max} = 4$ @ 1940 MeV/c
- Hypotheses based on previous results (*Crystal Barrel: Phys. Lett. B639 (2006) 165*)
 - $\phi\pi^0$, $\phi(1680)\pi^0$,
 - $f_2(1270)\pi^0$, $f'_2(1525)\pi^0$
 - $a_2(1320)\pi^0$
 - K^*K , $K^*(1680)K$
 - all $f_0\pi^0$ channels via $(KK)_S$ -wave ←
 - all K_0^*K channels via $(K\pi)_S$ ($l=1/2$) wave
 - $K(K\pi)_S$ ($l=3/2$) wave
- Challenge for K^*K and $K(K\pi)_S$
 - expansion to eigenstates of C- and G-parity
 - distinction between $l=0$ and $l=1$ not possible

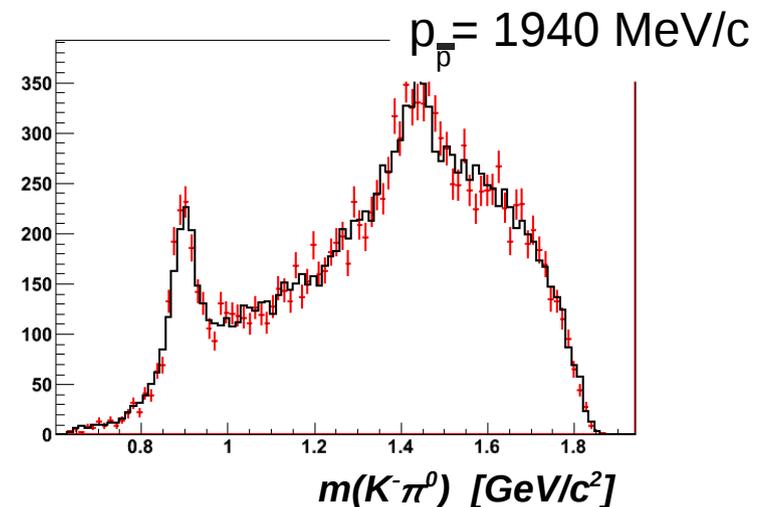
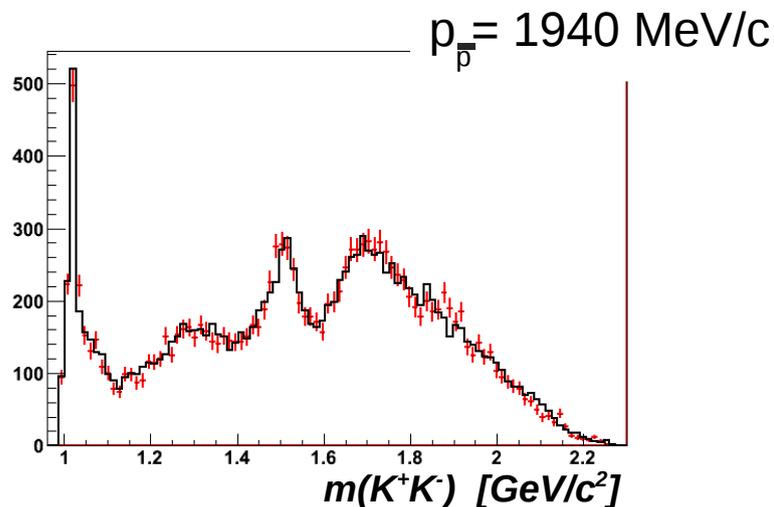
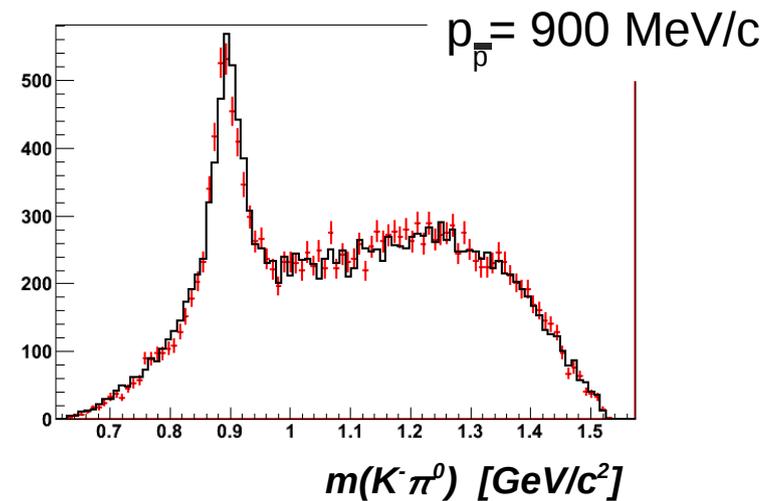
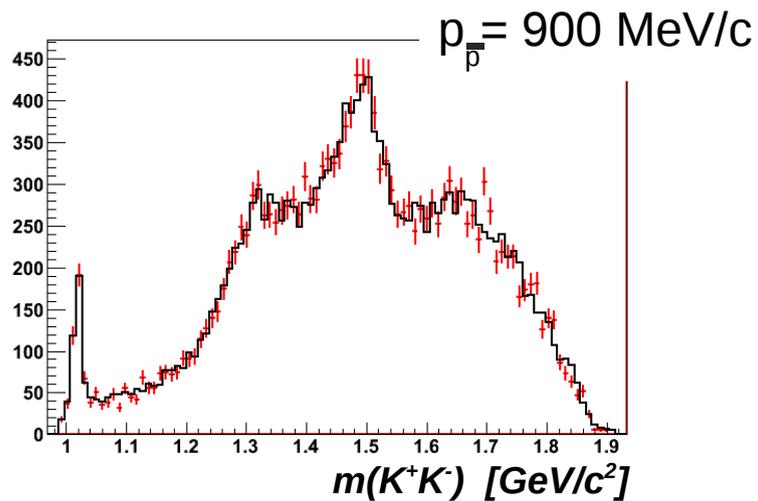
K-matrix parametrization by
Anisovich and Sarantsev,
Eur. Phys. J. A16, 229(2003)

K-matrix parametrization used
by FOCUS:
Phys. Lett. B653 (2007) 1-11

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

- Excellent description of the data
- Extraction of the SDMs for ϕ and K^* possible

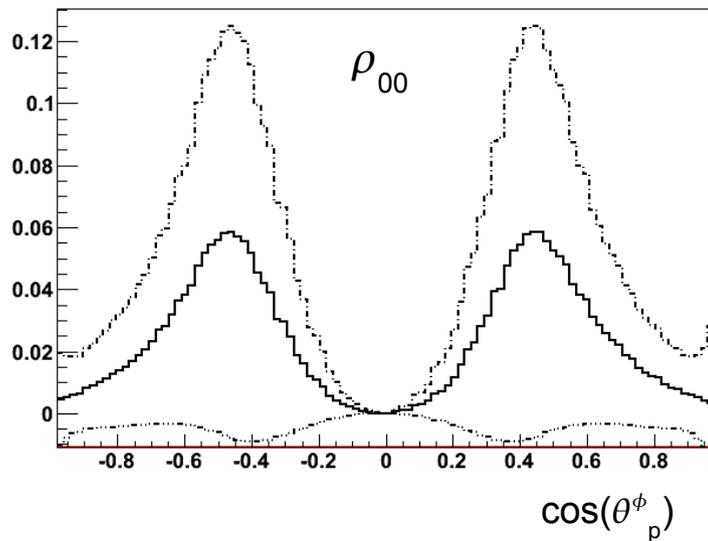
J. Pychy, Bochum



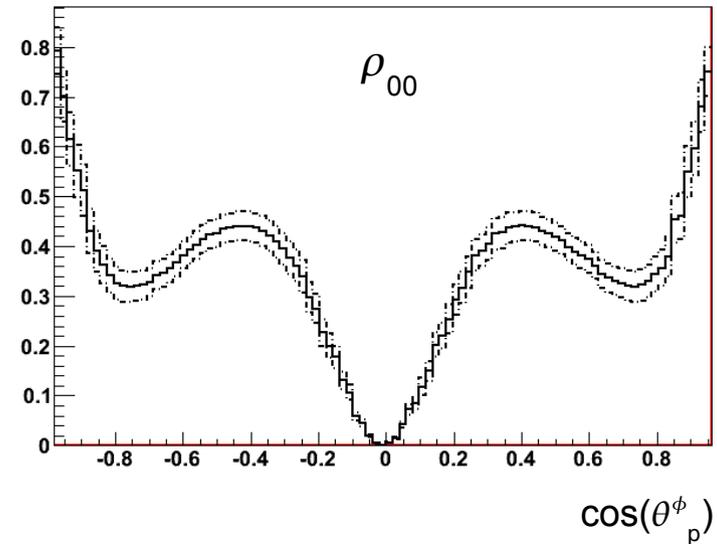
ϕ Spin Density Matrix in $\bar{p}p \rightarrow K^+K^-\pi^0$

J. Pychy, Bochum

$p_{\bar{p}} = 900$ MeV/c



$p_{\bar{p}} = 1940$ MeV/c



- Small ρ_{00} for all production angles @ 900 MeV/c
- $0\% < \rho_{00} < 80\%$ @ 1940 MeV/c
- Strong alignment and oscillation along the production angle
 - formation of intermediate resonances?

PWA: $\bar{p}p \rightarrow \pi^+ \pi^- \eta$

- Resonances decaying to $\pi^\pm \eta$ with exotic quantum numbers $J^{PC}=1^{-+}$ possible

$\pi_1(1400)$

- Evidence in πp scattering experiments (B852, GAMS, . . .) and $\bar{p}p$ annihilation (OBELIX, Crystal Barrel @ LEAR)

- Crystal Barrel

- $\bar{p}d \rightarrow \pi^- \pi^0 \eta$ $p_{\text{spectator}}$ @ rest

- $\bar{p}p \rightarrow \pi^0 \pi^0 \eta$ @ rest with LH_2 and gaseous hydrogen target

- significant $\pi_1(1400)$ production from spin triplet states

- First analyses of in-flight data @ 900 MeV/c started

- › many $\bar{p}p$ -states contribute → 1^{-+} production?

PWA: $\bar{p}p \rightarrow \pi^+\pi^-\eta$ @ 900 MeV/c

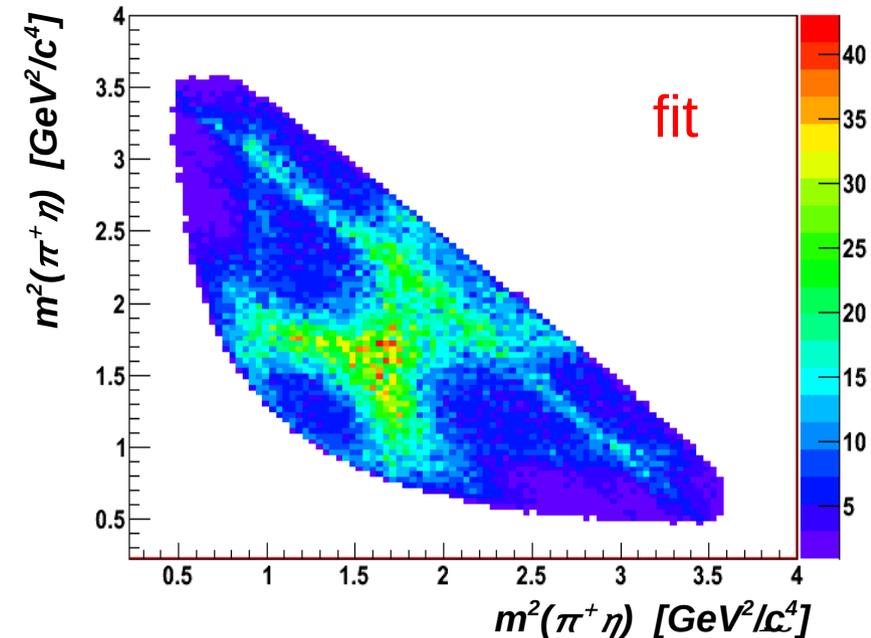
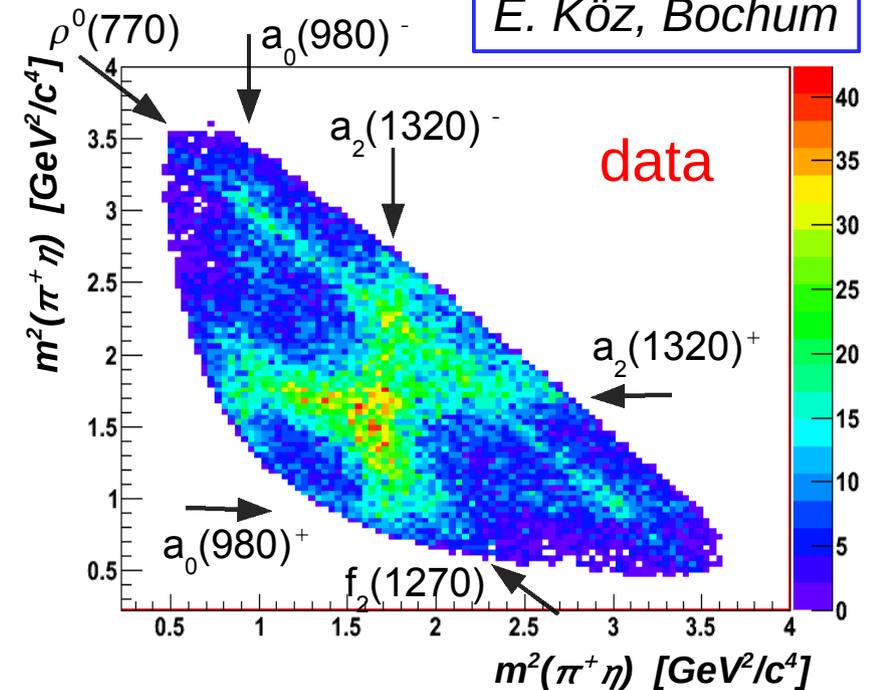
E. Köz, Bochum

• Base Hypothesis

- $a_0(980)^\pm \pi^\mp$, Flatté parametrization
- $a_2(1320)^\pm \pi^\mp$
- $f_2(1270) \eta$
- all $f_0 \eta$ channels via $(\pi\pi)_S$ -wave
- $\rho^0(770) \eta$

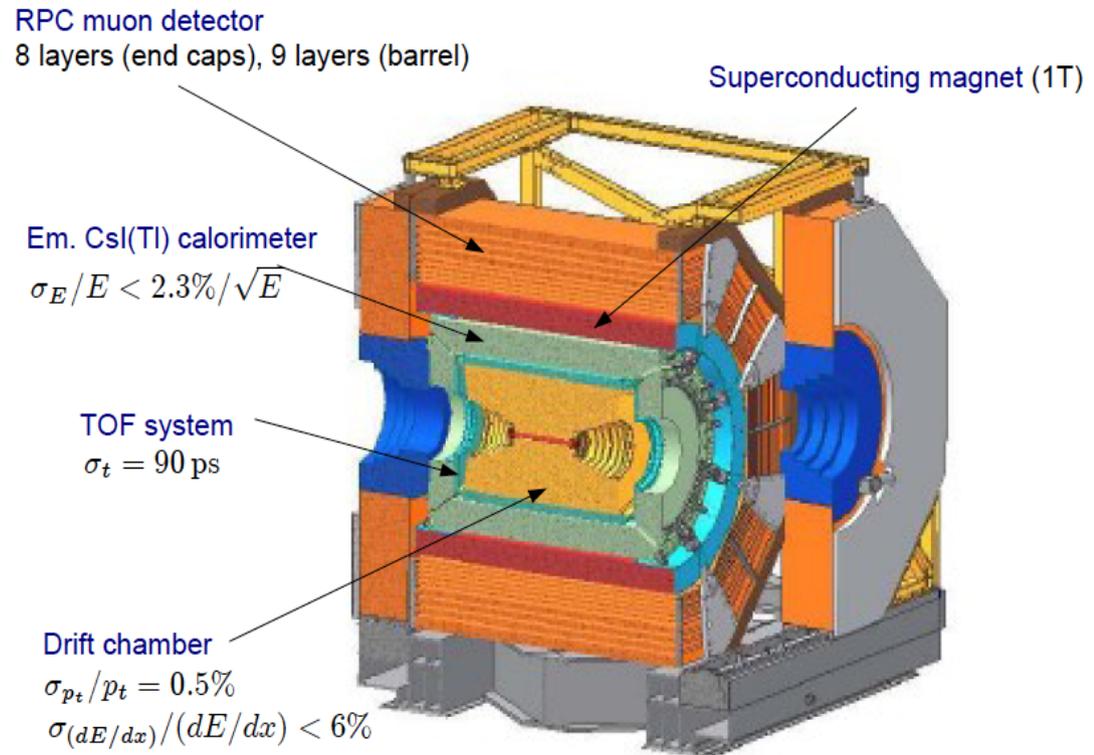
• Current status

- $L_{\max} = 4$ for the initial $\bar{p}p$ states
- small contribution of $\omega \eta$
- hints for 1^- spin exotic wave in the $\pi^\pm \eta$ system
- work in progress



PWA of BESIII Data

- Symmetric e^+e^- collider
 - beam energy 1.0-2.3 GeV
 - max. luminosity $10^{33} \text{ cm}^{-2}\text{s}^{-1}$
- Physics program
 - light meson spectroscopy
 - charmonium spectroscopy
 - open charm physics
 - . . .



- PWA activities focused on search for exotic particles
 - initial states limited to $J^{PC}=1^{--}$ with helicities $\lambda = \pm 1$
- Radiative decays of charmonia, especially of J/ψ
 - gluon rich process

$J/\psi \rightarrow \phi\phi\gamma$

- Glueballs decay flavor blind
 - strong coupling to $\phi\phi$
 - one of the most promising channels: $J/\psi \rightarrow \phi\phi\gamma \rightarrow (K^+K^-)(K^+K^-)\gamma$
- Lightest tensor glueball predicted between 2.0-2.4 GeV/c²
- Unexpected large cross sections of three f_2 resonances in $\pi^-p \rightarrow n\phi\phi$
(*Atkin et. al.: Phys.Lett. B201 (1988) 568-572*)

PWA Strategy

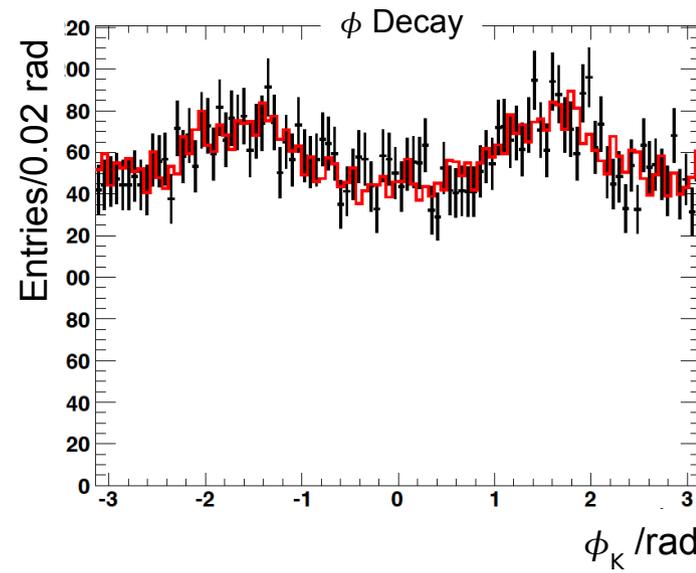
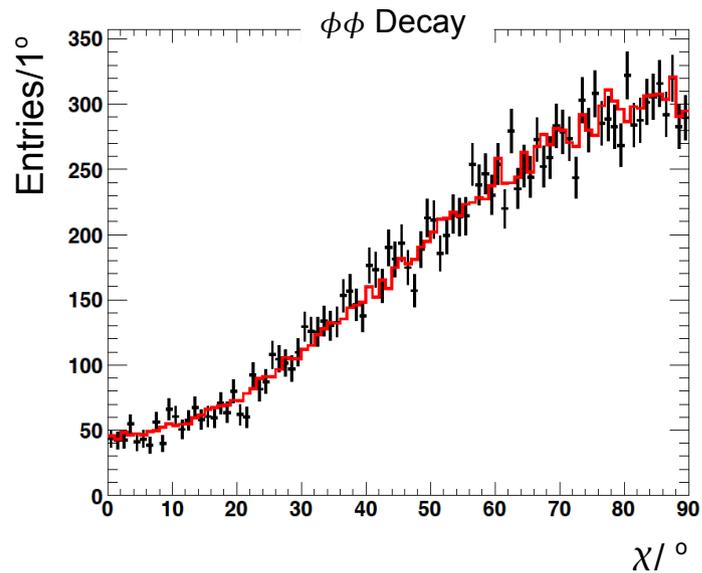
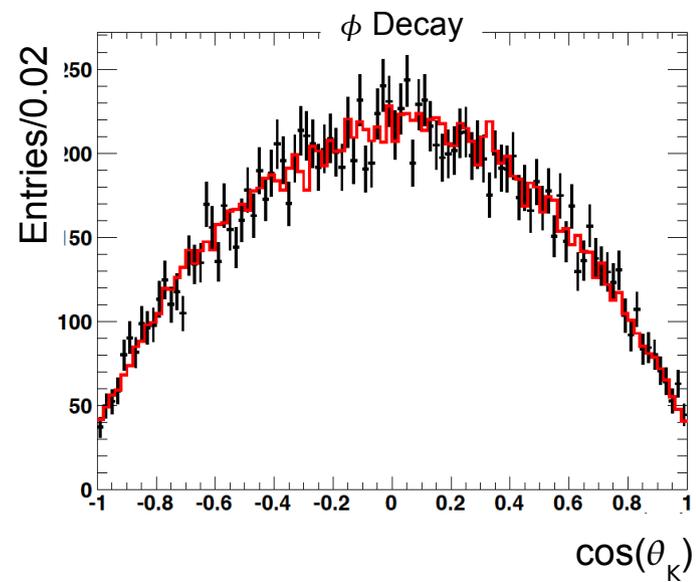
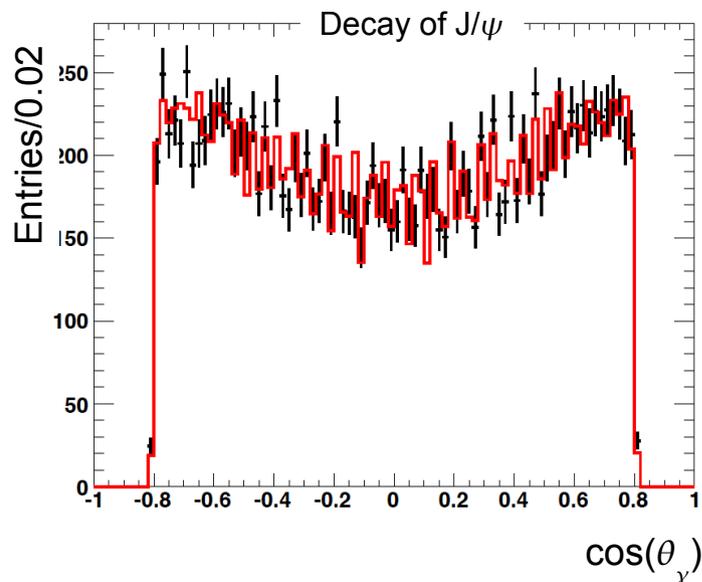
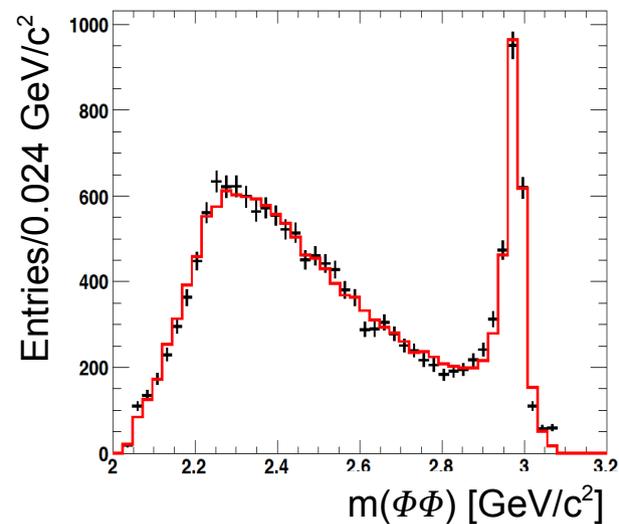
- Mass independent fits by scanning the invariant $\phi\phi$ mass
 - identification of the strongest waves
- Mass dependent fits in the complete phase space using Breit-Wigner and Flatté parametrizations
- Helicity and canonical formalism

$J/\psi \rightarrow \phi\phi\gamma$

P. Friedel, PhD thesis, Bochum

Mass dependent fit

Data
weighted MC



Summary

- New developed PWA software package PAWIAN is in a good shape and first analyses results have been shown
- Analyses of Crystal Barrel @ LEAR data in-flight
 - $\bar{p}p \rightarrow \omega\pi^0$
 - L_{\max} rises from 3 @ 600 MeV/c to 5 @ 1940 MeV/c
 - ω -SDM: strong alignment and oscillating ρ_{00} along the production angle consistent with Schilling method
 - $\bar{p}p \rightarrow K^+K^-\pi^0$
 - ϕ -SDM: similar alignment effects and oscillation along the production angle visible
 - $\bar{p}p \rightarrow \pi^+\pi^-\eta$ @ 900 MeV/c
 - hints for a spin exotic 1^- wave in $\pi^\pm\eta$
- PWA of BESIII data with the same PWA package
 - focus on radiative decays of charmonia
 - first promising results achieved