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

Bertram Kopf

Leap 2013
11th International Conference on Low Energy Antiproton Physics
Uppsala, 10-15 June, 2013

RUHR UNIVERSITÄT BOCHUM RUB

bmb+f Großgeräte der physikalischen Grundlagenforschung

Outline

- PWA software for PANDA and other hadron spectroscopy experiments

- PWA @ PANDA
  - detector and physics program
  - PWA challenges for PANDA

- Analyses of Crystal Barrel @ LEAR data 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 $K^{*\pm}\,K^{\mp}$

- PWA of BESIII data

PWA Software Package

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

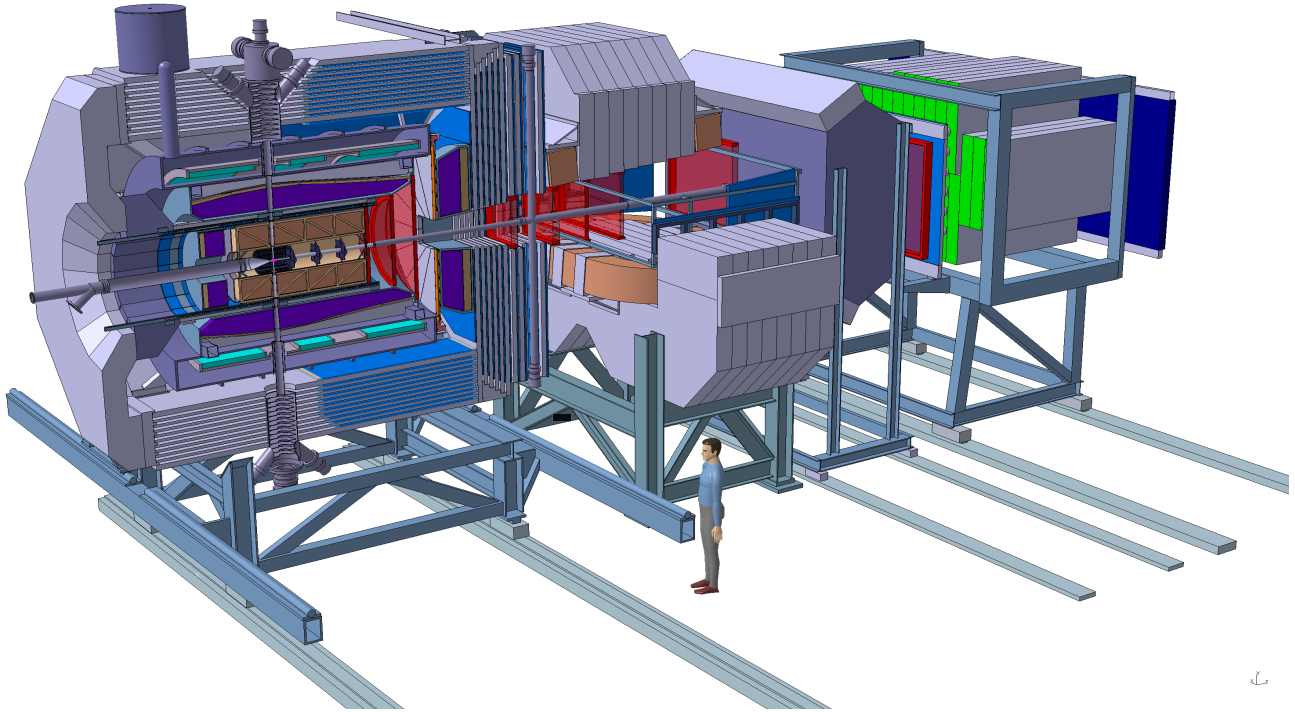
- to develop a generic PWA software package
- to support all physics cases to be studied with PANDA and partly other hadron spectroscopy experiments

Software package PAWIAN (**PA**rtial **W**ave **I**nteractive **AN**alysis) 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 in multithreaded and networked mode
- qft++: decay amplitudes in various formalisms (*M. Williams (CLAS, GlueX)* Computer Physics Communications, Vol. 180, Issue 10, 2009)

PANDA @ FAIR

- Fixed target experiment integrated into the HESR @ 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 of exotic states



PWA Challenges @ PANDA

$\bar{p}p$ production mechanism

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

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

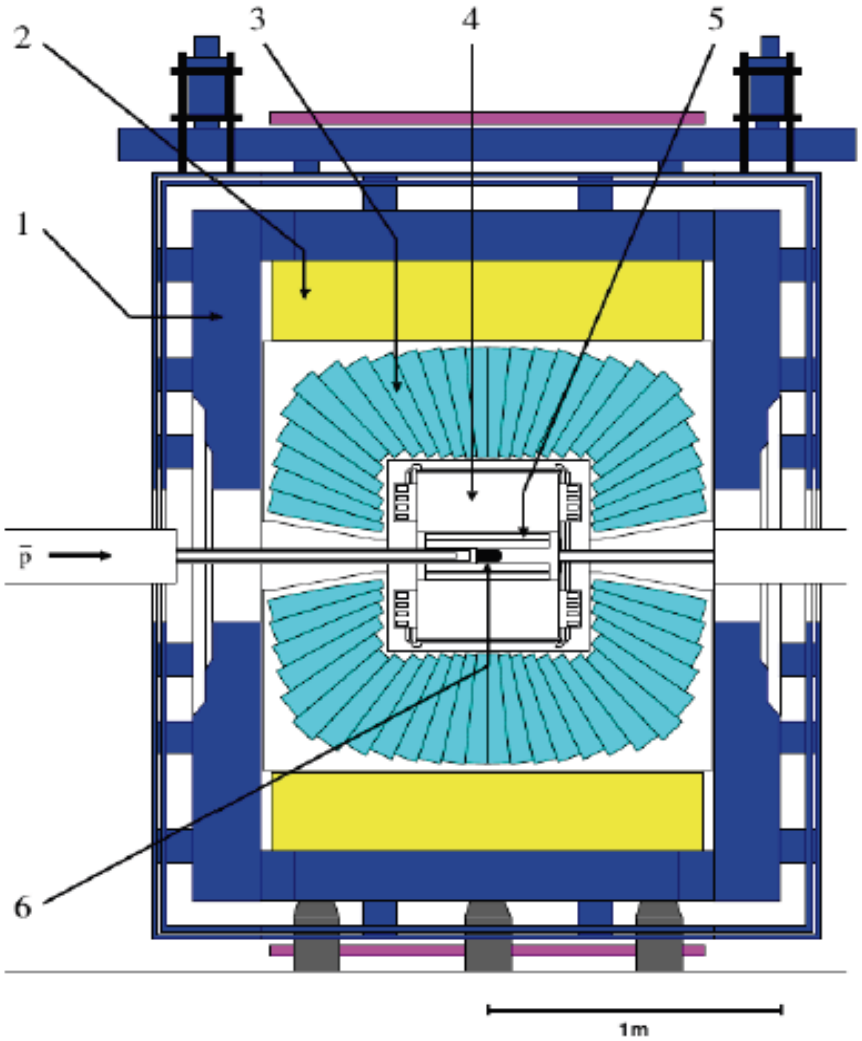
- Low cross sections for some channels of interest (pb-nb)
- How many events are needed for reliable fits?

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
- 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 specific physics aspects for PANDA



(1) Iron Joke, (2) Magnet Coil
(3) CsI(Tl)-Calorimeter, (4) Jet-Drift-Chamber
(5) Vertex-Detector, (6) LH_2-Target

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

- Relatively 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 $\omega \to \pi^0\gamma$ and $\omega \to \pi^+\pi^-\pi^0$ separately analyzed at various beam momenta between 0.6-1.94 GeV/c

PWA Strategy

- Preparation of accurate and clean data samples by applying a kinematic fit and an event based background rejection
  - old offline software re-installed
- Fits to determine the largest contributing 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 canonical formalism
- Extraction of the ω-SDM with two independent methods from
  - the obtained PWA fit result
  - angular distribution of the decay products (Schilling method)

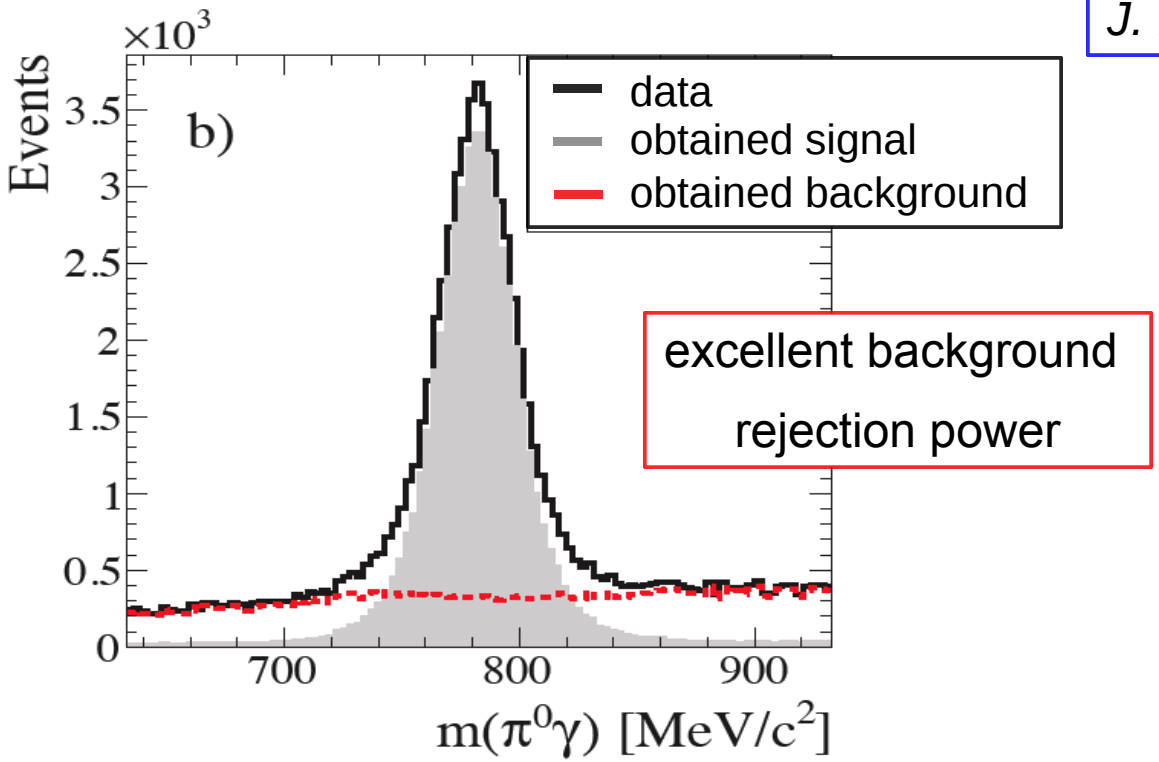
$\bar{p}p \to \omega\pi^0$: Background Rejection

- New background rejection method by assigning a probability for each event to be a signal event (*M. Williams, M. Bellis, C.A. Meyer: arXiv:0809.2548 [nucl-ex]*)

- Event weight for each event
  - determination of the signal to background ratio for the n nearest neighbors in the phase space

- Origin of the background sources not necessarily needed to be known

J. Pychy, Bochum



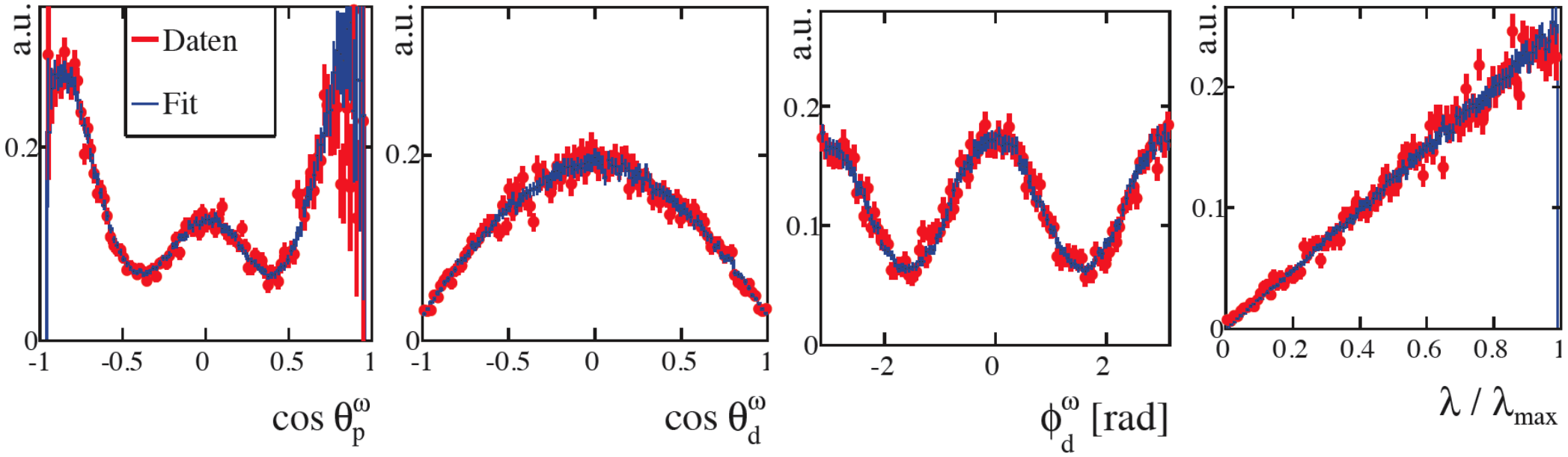
excellent background rejection power

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

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

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

J. Pychy, Bochum



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

- SDM provides all information of the production mechanism
- Spin 1 particle: 3x3 complex elements
- Normalization, parity and hermicity conservation yields to only 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 the elements via PWA:

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

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

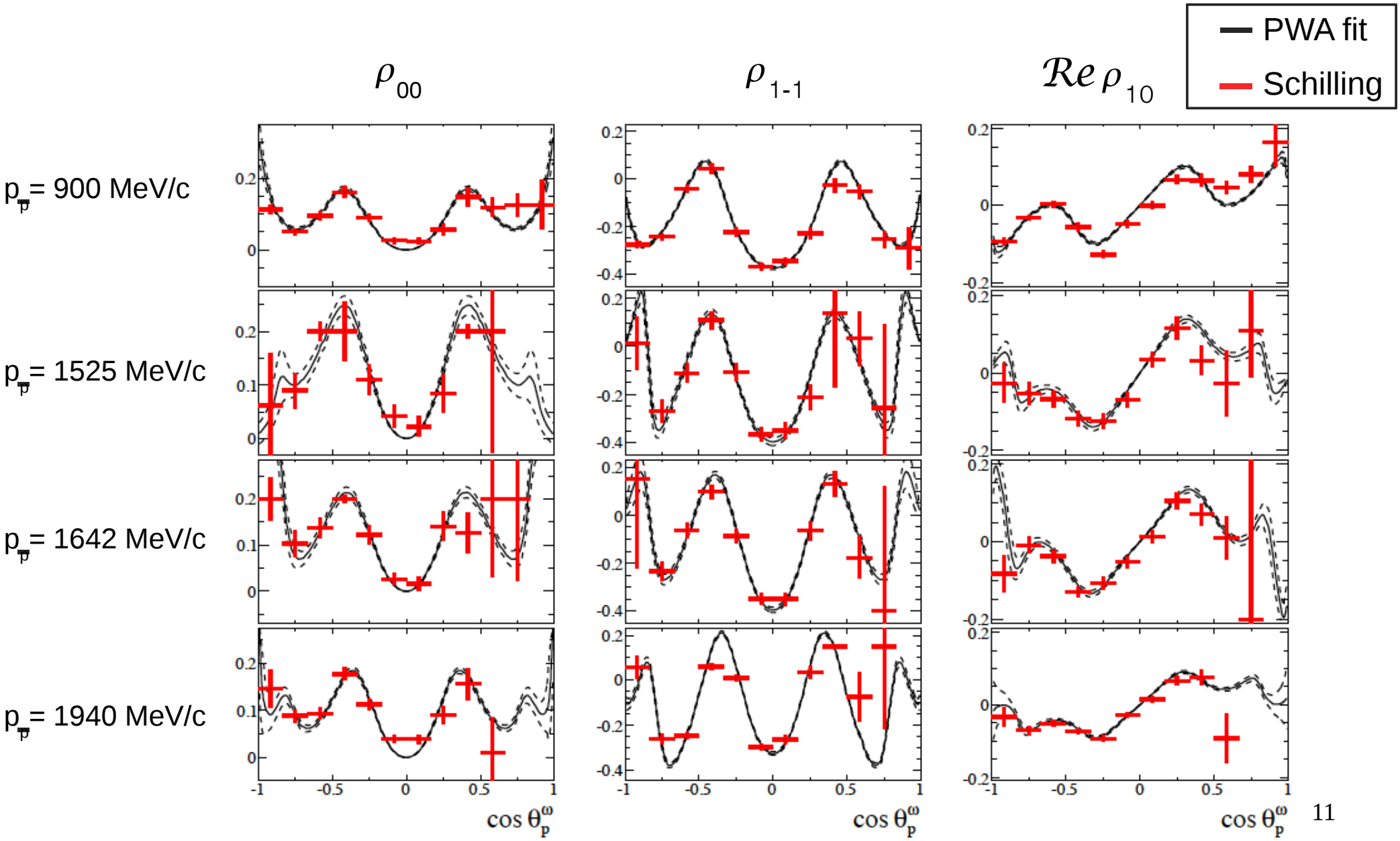
- Extraction of the parameters via fit to decay angular distribution ($\omega \to \pi^+\pi^-\pi^0$)

$$W(cos(\theta,\phi)) \propto \frac{1}{2}(1-\rho_{00}) + \frac{1}{2}(3\rho_{00}-1)\,cos\theta$$
$$-\sqrt{2}\,\Re\rho_{10}\,sin2\theta\,cos\phi - \rho_{1-1}\,sin^2\theta\,cos2\phi$$

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

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

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

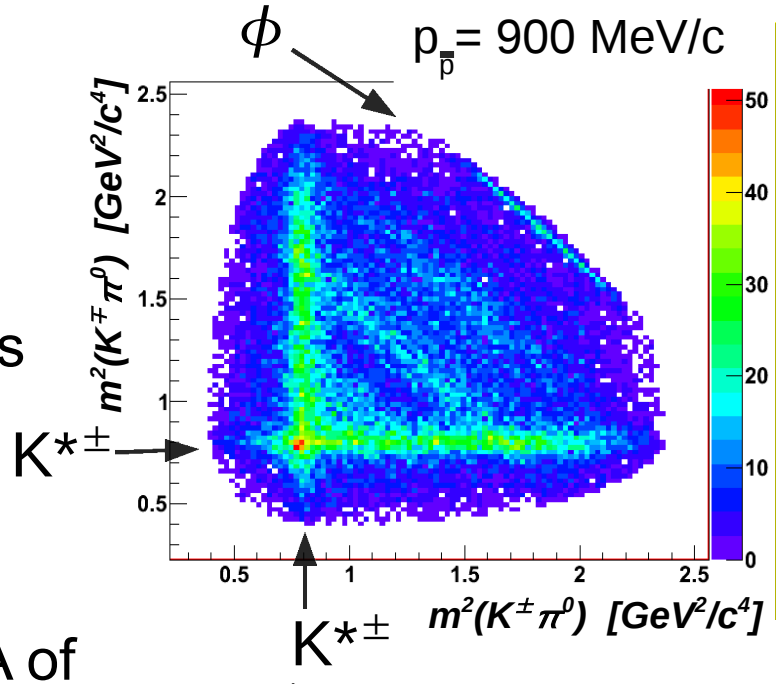


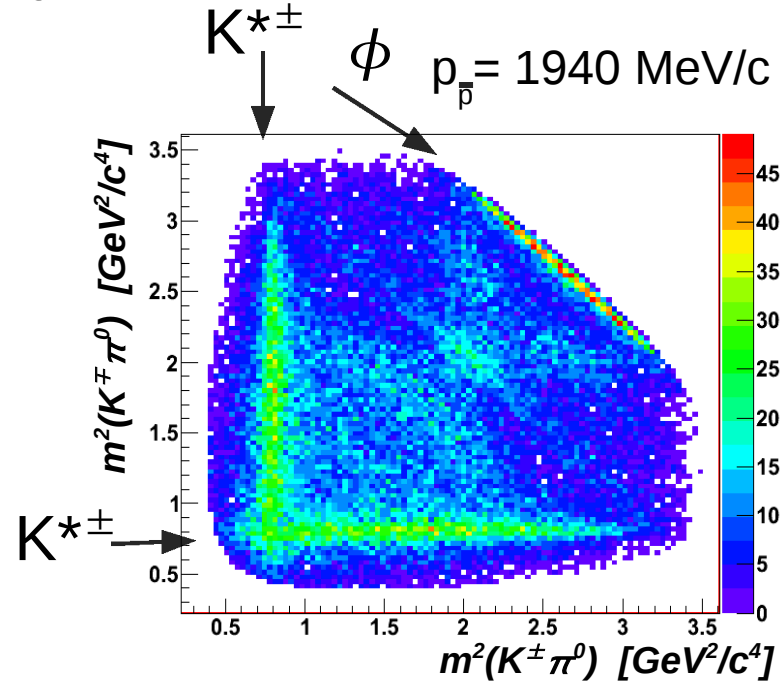
$\bar{p}p \to \omega\pi^0$: ω Spin Density Matrix

- Good agreement between the two independent methods
- $\rho_{00} < 0.33$ over the whole production angle for all beam momenta
  - strong alignment visible
- Strong oscillatory dependence along the production angle for all beam momenta
  - origin not yet clear
  - formation of intermediate resonances?
- Comparison of SDMs obtained for different decay modes is a good check for the understanding of the detector
  - accurate access to the systematics
  - suitable for first measurements @ PANDA

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

- Contains $\phi\pi^0$ and $K^{*\pm}K^{\mp}$ events
- Production of vector mesons with strangeness
  - different process in comparison to ω production
  - rearrangement vs. annihilation
- Interference of resonances require a full PWA of the complete channel
- SDM via extraction of the fitted 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}=4 @ 900 MeV/c and 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 $K^{*\pm}_0$ K channels via $(K\pi)_S$ (I=1/2) wave
  - K $(K\pi)_S$(I=3/2) wave

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

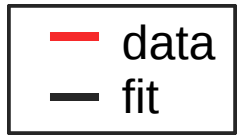
K-matrix parametrization used by FOCUS: *Phys. Lett. B653 (2007) 1-11*

- Many resonances yield in a large number fit parameters
  - 420 @ 900 MeV/c
  - 464 @ 1940 MeV/c

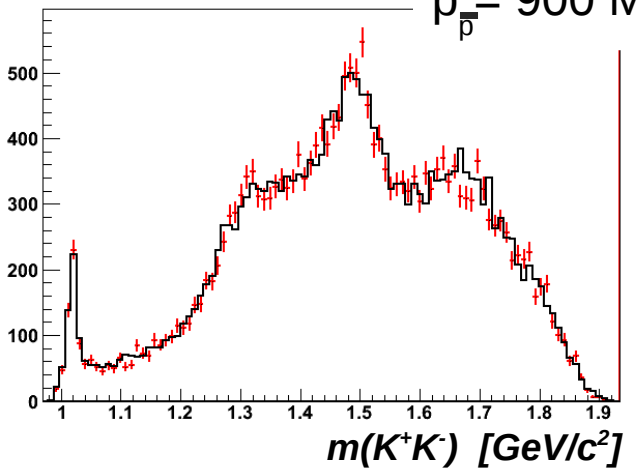
PWA: $\bar{p}p \rightarrow K^+K^-\pi^0$

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

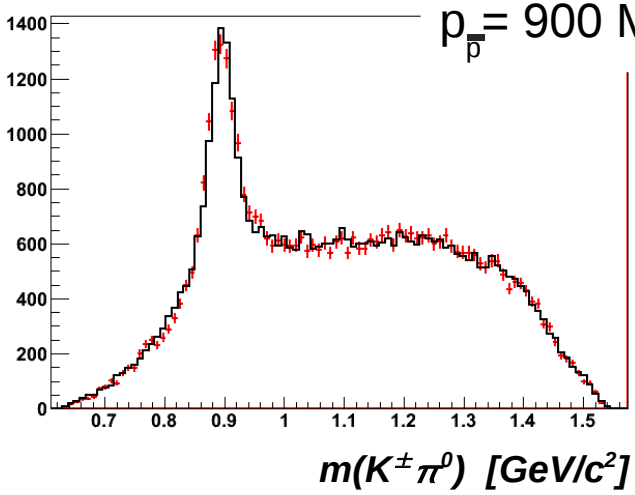
J. Pychy, Bochum



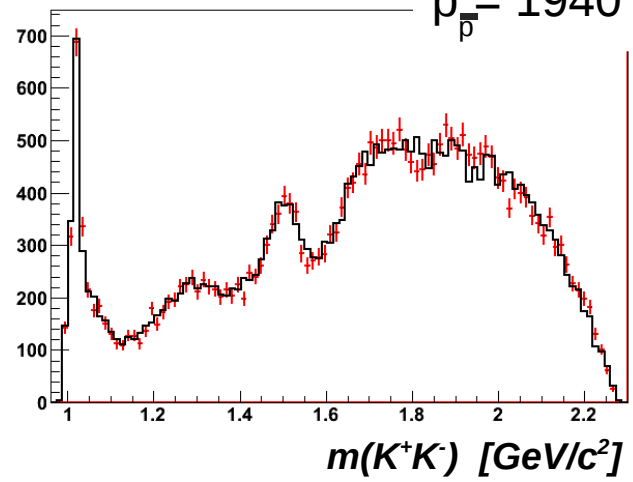
$p_{\bar{p}}$ = 900 MeV/c



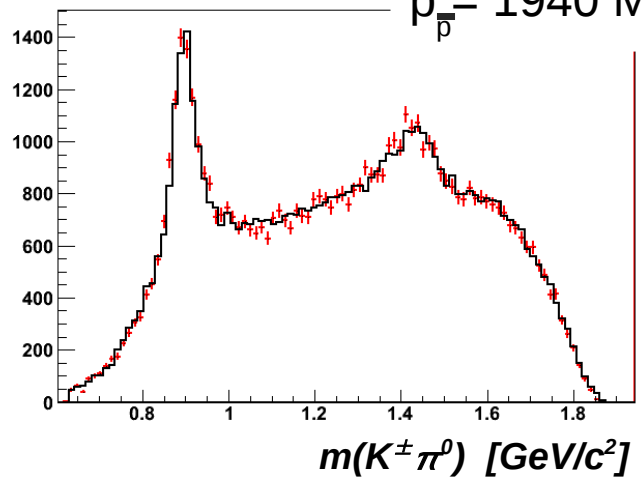
$p_{\bar{p}}$ = 900 MeV/c



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

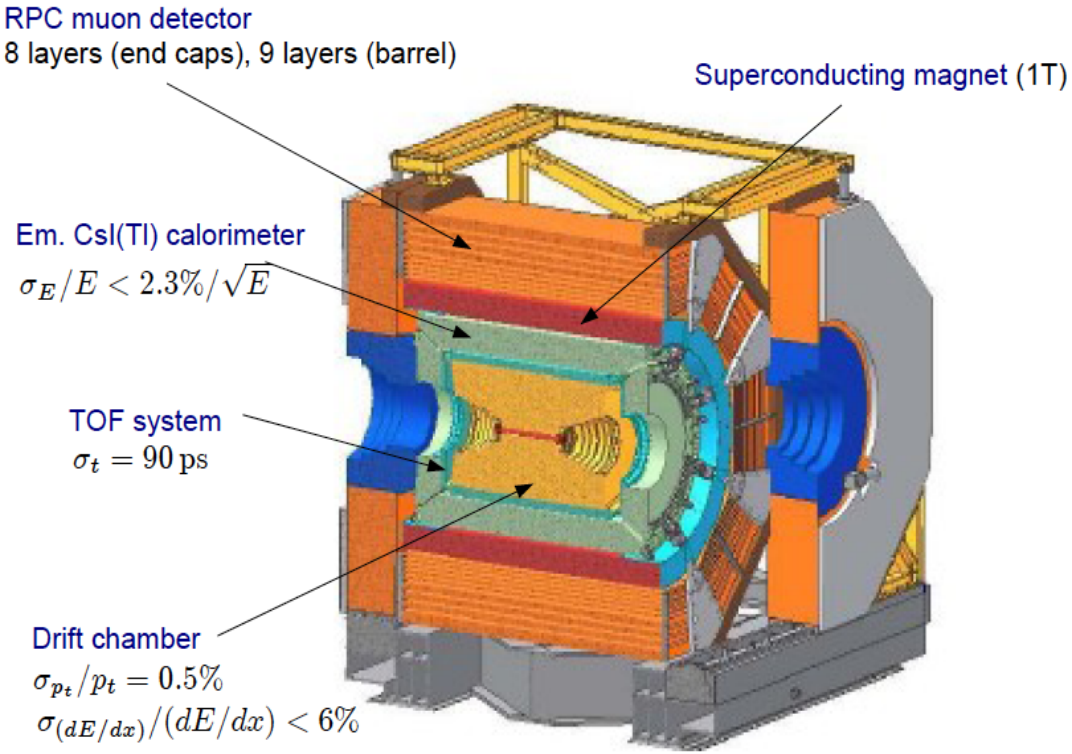


$p_{\bar{p}}$ = 1940 MeV/c



PWA of BESIII Data

- Symmetric e^+e^- collider
  - beam energy 1.0-2.3 GeV
  - max. luminosity $10^{33}\,cm^{-2}s^{-1}$
- 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 from charmonia, especially from J/ψ
  - gluon rich process

J/ψ->$\phi\phi\gamma$

- Glueballs decay flavor blind
  - strong coupling to $\phi\phi$
  - one of the most promising channel: J/$\psi \rightarrow \phi\phi\gamma \rightarrow$ (K^+K^-) (K^+K^-) γ
- Lightest tensor glueball predicted between 2.0-2.4 GeV/c^2
- 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 formalism
- First results very promising and good description of the data

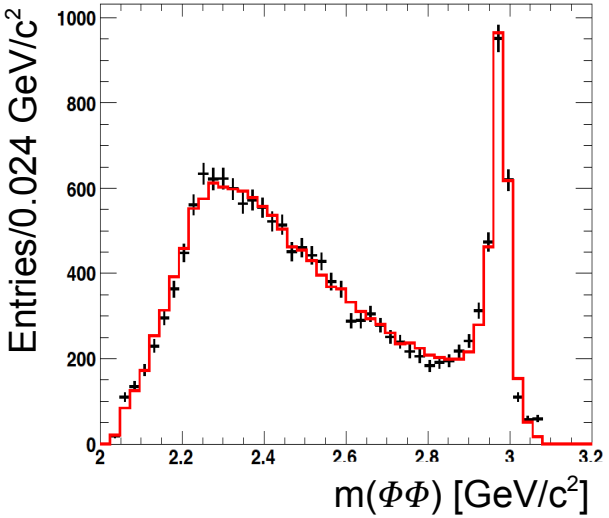
J/ψ->$\phi\phi\gamma$

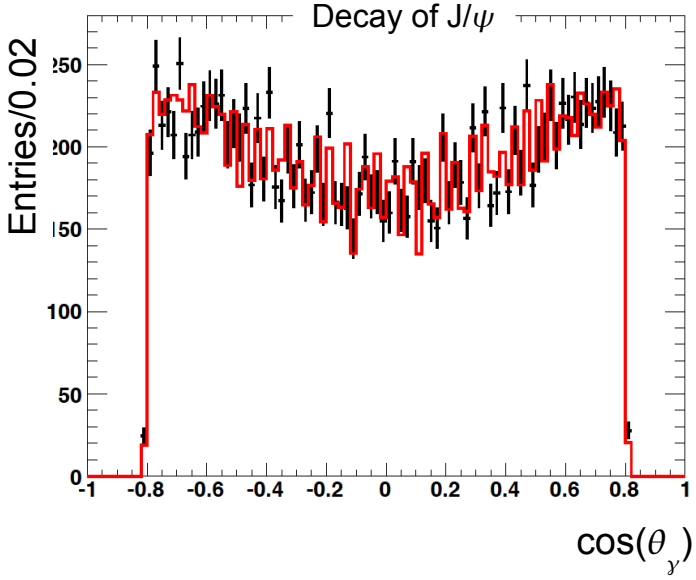
P. Friedel, PhD thesis, Bochum

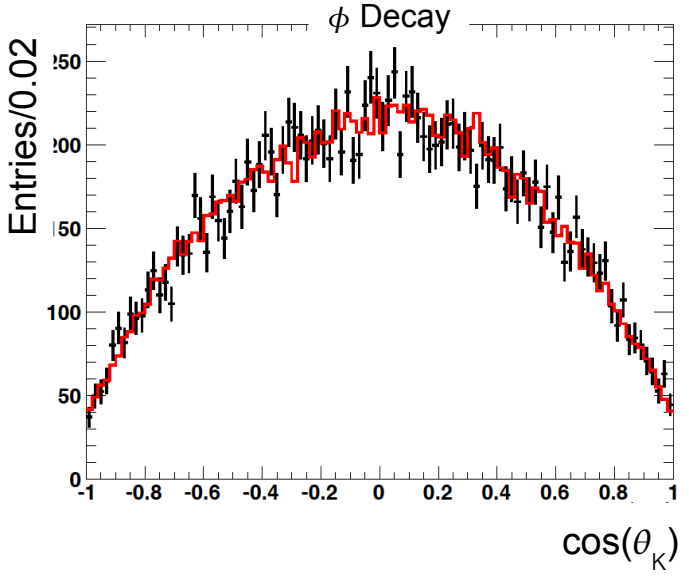
Mass dependent fit

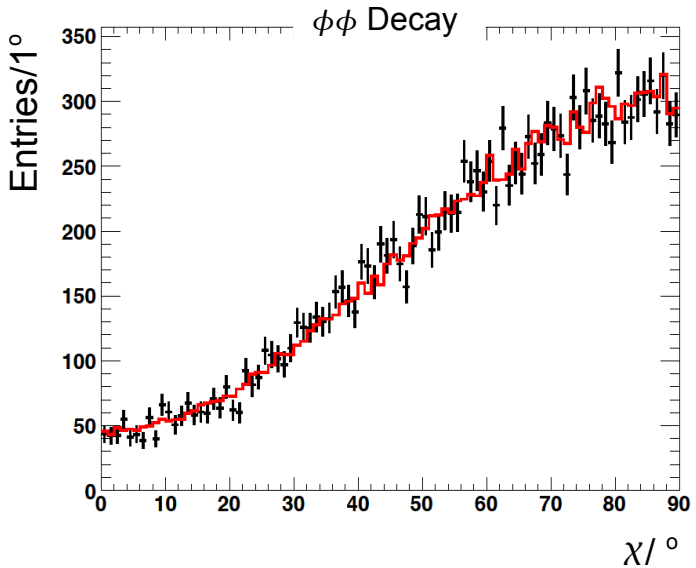
Data

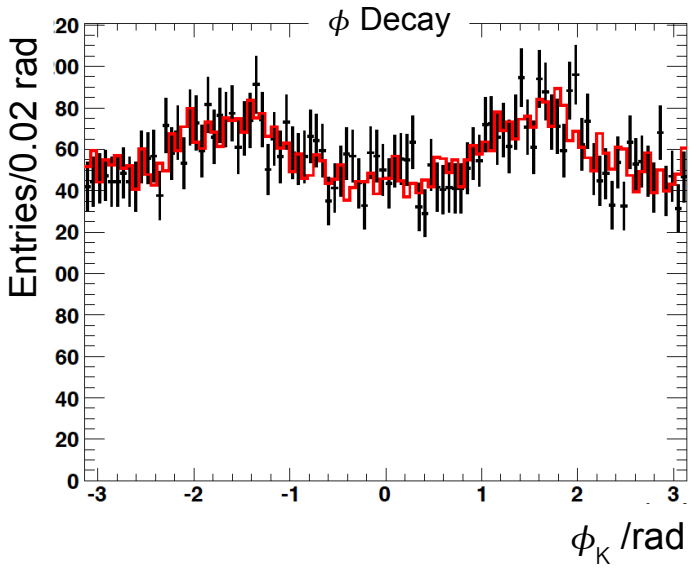
weighted MC











Summary

- New developed PWA software package is in a good shape and first analyses have been shown

- Analyses of Crystal Barrel @ LEAR data with relevance for PANDA
  - $\bar{p}p$ initial states and production of vector mesons
  - $\bar{p}p \rightarrow \omega\pi^0$
    - new background rejection method
    - L_{max} rises from 3 @ 600 MeV/c to 5 @ 1940 MeV/c
    - extraction of the ω-SDM via full PWA
    - strong alignment and oscillation of ρ_{00} along the production angle
  - $\bar{p}p \rightarrow K^+K^-\pi^0$
    - excellent description of the data
    - extraction of the SDM for ϕ and K* possible

- PWA of BESIII data with the same PWA package
  - focus on radiative decays of charmonia
  - first promising results achieved