Light Exotics at PANDA

Trento
Spectroscopy of Resonances and QCD
February 8 – 12, 2016

Bertram Kopf
Outline

• Introduction

• Present experimental status and its interpretation

• PANDA
  ➢ physics program
  ➢ detector

• Partial Wave Analyses with CB-LEAR in-flight data
  ➢ investigation of the \( \bar{p}p \) annihilation mechanism via \( \bar{p}p \rightarrow \omega \pi^0 \)
  ➢ coupled channel analysis of \( \bar{p}p \rightarrow K^+K^-\pi^0, \pi^0\pi^0\eta, \pi^0\eta\eta \) @ 0.9 GeV/c
Introduction

3 categories of exotics

- **Hybrids**
  - $q\bar{q}$ states with excited gluonic degrees of freedom

- **Glueballs**
  - hadrons without any valence quark content

- **Multiquark states**
  - molecule: loosely bound pair of mesons
  - tetraquarks: tightly bound $(q\bar{q} q\bar{q})$ states

**Exotic quantum numbers** allowed which are forbidden for conventional $q\bar{q}$ mesons:

$J^{PC} = 0^- 0^{+-} 1^{++} 2^{+-}$ etc.
Glueballs

**Characteristics of the production**
- should be mainly produced in gluon rich environments like radiative $J/\psi$ decays, central production, or $\bar{p}p$ annihilation
- should be weakly coupled to $\gamma$ induced processes like $\gamma\gamma$ fusion

![Diagram of Glueball Production](image)

**Characteristics of the decay**
- rather narrow decay width
- flavor blind

![Diagram of Glueball Decay](image)

Glueballs

- LQCD: lightest glueballs with exotic quantum numbers
  - $M(J^{PC}=0^{++}) \sim 4140$ MeV/c$^2$
  - $M(J^{PC}=2^{++}) \sim 4740$ MeV/c$^2$

- Glueballs in the light meson mass range ($< 3$ GeV/c$^2$) only with non exotic quantum numbers $J^{PC}=0^{++}, 0^{+-}, 2^{++}$

LQCD calculations

0^{++} Glueball

- Lots of scalar resonances observed in the light meson mass region
  - too many to fit in the ground state nonet: $\sigma$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$, . . .

- Possible explanation
  - $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ are mixtures between conventional $q\bar{q}$ states and glueball
  - $f_0(1500)$ and $f_0(1710)$ are candidates with large gluonic content
    - strongly produced in gluon rich processes and suppressed in $\gamma\gamma$ fusion
    - characteristic decay pattern

Crystal Barrel @ LEAR

$J/\psi \rightarrow \gamma \eta \eta$ @ BESIII

Many pseudo-scalar resonances observed in the light meson region

- $\eta, \eta', \eta(1295), \eta(1405), \eta(1475), \eta(1760), \ldots$

$\eta(1405)$ is favored to be the $0^{-+}$ glueball

- strongly produced in radiative $J/\psi$ decays and also seen in $\bar{p}p$ annihilation
- weak coupling to $\gamma\gamma$
- $\eta(1295)$ and $\eta(1475)$ radial excitations of ground state nonet members $\eta$ and $\eta'$

But

- $\eta(1405)$ not seen in central production
- LQCD predictions: $M_g(0^{-+}) > 2$ GeV/$c^2$
- does the $\eta(1295)$ exist at all?
- are $\eta(1405)$ and $\eta(1475)$ two different states?
2^{++} Glueball

- Poor evidence for a 2^{++} glueball so far
  - lightest tensor glueball predicted between 2 - 2.4 GeV/c^2
  - 2 isoscalar tensor nonets due to the quark model: ^3P_3 and ^3F_2
  - more than 10 conventional q\bar{q} states expected in the light meson mass region
  - only 6 are listed in the PDG summary table

- Hints in πp → φφn at BNL
  - unexpected large cross section for 3 possible tensor mesons between 2-2.4 GeV/c^2
Hybrids

- Hybrids with exotic quantum numbers can be identified easily
  - no overlap with conventional mesons
  - prediction for the lightest hybrid: $I^G J^{PC} = 1^- 1^{-+}$ with $M \sim 1.8 - 2.1$ GeV/c$^2$
  - favored decay modes: $\pi b_1$ and $\pi f_1$
  - evidence for 3 different $\pi_1$ states so far

- $\pi_1(1400)$
  - observed in $\pi p$ scattering and $\bar{p} p$, $\bar{p} n$ annihilation
  - mass too low for a hybrid state
  - seen only in the $\pi \eta$ decay mode
  - non-resonant background, threshold effect, molecule?

- $\pi_1(1600)$ most promising hybrid candidate
  - observed by several experiments in $b_1 \pi$, $f_1 \pi$, $\eta' \pi$

- $\pi_1(2015)$
  - evidence in $\pi p$ scattering
  - listed as further state in PDG
Exotics in the Light Mass Region

- Last 30 years: many data analyzed, but still unresolved questions

- Lots of broad and overlapping resonances

- Mixing of conventional $q\bar{q}$ states with exotic states possible

- Complete and unambiguous knowledge of all $q\bar{q}$ multiplets is needed

- Many resonance properties obtained by analyzing single channels using Breit-Wigner parametrization

- Accurate determinations of pole positions are essential

- Multi channel analyses with sophisticated approaches (e.g. K-matrix) by combining data of different decay and production modes needed
- High statistics and gluon rich $\bar{p}p$ annihilation data extremely helpful

- Lack of $\bar{p}p$ data in the resonance region above 2 GeV/$c^2$

- $\bar{P}$ANDA has a high discovery potential in the field of light mesons and light exotics

- $\bar{p}p$ production cross sections for glueballs and light hybrids similar to the ones for light hadrons: $\sim 1–100 \mu b$
PANDA at FAIR

High Energy Storage Ring

- Storage Ring for $\bar{p}$
  - High intensity mode
    - $L = 2 \cdot 10^{32}$ cm$^{-2}$ s$^{-1}$
    - $\Delta p/p \sim 10^{-4}$
- High resolution mode
  - $L = 2 \cdot 10^{31}$ cm$^{-2}$ s$^{-1}$
  - $\Delta p/p \sim 5 \cdot 10^{-5}$
• $\bar{p}p$- and $\bar{p}A$- annihilation
  - $\bar{p}$ momentum 1.5-15 GeV/c

• Charmonium and open charm spectroscopy

• Search for exotics in the light meson and charmonium sector

• Baryon spectroscopy

• Baryon-antibaryon production

• Meson production in nuclear medium

• Hypernuclear physics

• Nucleon structure from EM processes

Multipurpose detector required!
- Standard HEP design for fixed target experiment: target+forward spectrometer
- Target spectrometer: Solenoid with $B_z = 2$ T
- Forward spectrometer: Dipole with $B \cdot L = 2$ Tm
PWA Challenges at \( \bar{p} \)A\( \bar{p} \)ND\( \bar{p} \)A

- Complexity of the \( \bar{p}p \) annihilation mechanism
  - \( J \) rises with beam momentum
  - various initial states \( \rightarrow \) many fit parameters

- Development of a new PWA software package

- Analysis of Crystal Barrel LEAR Data

\begin{itemize}
  \item Complexity of the \( \bar{p}p \) annihilation mechanism
    \begin{itemize}
      \item \( J \) rises with beam momentum
      \item various initial states \( \rightarrow \) many fit parameters
    \end{itemize}
  \item Development of a new PWA software package
  \item Analysis of Crystal Barrel LEAR Data
\end{itemize}

\[ \begin{array}{c|c|c|c}
  J & \text{Singulett} & \text{Triplet} & \text{Triplet} \\
  & \lambda = 0 & \lambda = \pm 1 & \lambda = \pm 1, 0 \\
  \hline
  0 & ^1S_0 & 0^- & ^3P_0 & 0^+ \\
  1 & ^1P_1 & 1^- & ^3P_1 & 1^+ \\
  2 & ^1D_2 & 2^- & ^3D_2 & 2^- \\
  3 & ^1F_3 & 3^- & ^3F_3 & 3^- \\
  4 & ^1G_4 & 4^- & ^3G_4 & 4^- \\
  5 & ^1H_5 & 5^- & ^3H_5 & 5^- \\
  6 & ^1I_6 & 6^- & ^3I_6 & 6^- \\
\end{array} \]
PWA at PANDA

- Development of a PWA software with the aim
  - to provide a generic software package
  - to support all physics cases to be studied at PANDA
  - to partly support other hadron spectroscopy experiments

Software package PAWIAN (PArtial Wave Interactive Analysis) already in a good shape, and several analyses have been performed

- Full hypothesis and other input settings defined via configuration files
  - Formalisms (Canonical, Helicity, Rarita-Schwinger)
  - Dynamics (Breit-Wigner, Flatté, K-matrix, ...)

- Event based maximum likelihood fit, minimization by Minuit2
- Multithreading and networking support
- Support for coupled channel analyses
- Event generator, histogramming, analysis tools, ...
• Fixed target experiment

• In operation between 1989 and 1996
  ➢ leading $\bar{p}p$-experiment in the field of light meson spectroscopy

• $\bar{p}p$ annihilation at rest and in flight
  ➢ highest beam momentum 1.94 GeV/c
  ➢ overlap with PANDA

Excellent opportunity for the investigation of physics aspects relevant for PANDA
### PANDA vs. Crystal Barrel at LEAR

<table>
<thead>
<tr>
<th></th>
<th>PANDA</th>
<th>Crystal Barrel LEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>p momentum</td>
<td>1.5 - 15 GeV/c</td>
<td>0 - 1.94 GeV/c</td>
</tr>
<tr>
<td>s^{1/2}</td>
<td>2.25 - 5.47 GeV/c^2</td>
<td>1.86 - 2.4 GeV/c^2</td>
</tr>
<tr>
<td>(\Delta p / p)</td>
<td>(10^{-4} - 5 \times 10^{-5})</td>
<td>(10^{-4})</td>
</tr>
<tr>
<td>detector coverage</td>
<td>(\sim 4\pi)</td>
<td>&lt; (4\pi) (depending on (\bar{p}) momentum)</td>
</tr>
<tr>
<td>elaborated PID</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>(\bar{p}p) annihilation rate</td>
<td>(\sim 10^7) events/s</td>
<td>(\sim 10^5) events/s (in flight)</td>
</tr>
</tbody>
</table>

*optimized for \(\bar{p}p\) annihilation at rest*
PWA: $\bar{p}p \rightarrow \omega \pi^0$

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

**PWA Strategy**

- Fits to determine the largest contributing momentum $L_{\text{max}}$ of the $\bar{p}p$ system
  - description of the full decay chain including the $\omega$ decay by making use of the helicity formalism and transformation to the LS scheme
- Extraction of the $\omega$-SDM from the PWA fit result
### Fit Results: $\bar{p}p \rightarrow \omega\pi^0$}

#### Julian Pychy, RUB

\[
\omega \rightarrow \pi^+\pi^-\pi^0
\]

<table>
<thead>
<tr>
<th>momentum [MeV/c]</th>
<th>$L_{max}$</th>
<th>$\frac{\ln L(L_{max})}{\ln L(L_{max}+1)}$</th>
<th>$\frac{\ln L(L_{max}+1)}{\ln L(L_{max})}$</th>
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<tbody>
<tr>
<td>900</td>
<td>4</td>
<td>2.2 $\sigma$</td>
<td>0.13 $\sigma$</td>
</tr>
<tr>
<td>1525</td>
<td>4</td>
<td>9.0 $\sigma$</td>
<td>0.90 $\sigma$</td>
</tr>
<tr>
<td>1642</td>
<td>5</td>
<td>3.2 $\sigma$</td>
<td>0.06 $\sigma$</td>
</tr>
<tr>
<td>1940</td>
<td>5</td>
<td>&gt;10 $\sigma$</td>
<td>1.04 $\sigma$</td>
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</table>

\[
\omega \rightarrow \pi^0\gamma
\]

<table>
<thead>
<tr>
<th>momentum [MeV/c]</th>
<th>$L_{max}$</th>
<th>$\frac{\ln L(L_{max})}{\ln L(L_{max}+1)}$</th>
<th>$\frac{\ln L(L_{max}+1)}{\ln L(L_{max})}$</th>
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<tbody>
<tr>
<td>600</td>
<td>2</td>
<td>&gt;10 $\sigma$</td>
<td>1.05 $\sigma$</td>
</tr>
<tr>
<td>900</td>
<td>4</td>
<td>6.5 $\sigma$</td>
<td>0.22 $\sigma$</td>
</tr>
<tr>
<td>1050</td>
<td>4</td>
<td>&gt;10 $\sigma$</td>
<td>0.01 $\sigma$</td>
</tr>
<tr>
<td>1350</td>
<td>5</td>
<td>5.6 $\sigma$</td>
<td>0.03 $\sigma$</td>
</tr>
<tr>
<td>1525</td>
<td>5</td>
<td>&gt;10 $\sigma$</td>
<td>0.25 $\sigma$</td>
</tr>
<tr>
<td>1642</td>
<td>5</td>
<td>5.0 $\sigma$</td>
<td>8.10^{-3} $\sigma$</td>
</tr>
<tr>
<td>1800</td>
<td>5</td>
<td>&gt;10 $\sigma$</td>
<td>0.55 $\sigma$</td>
</tr>
<tr>
<td>1940</td>
<td>5</td>
<td>&gt;10 $\sigma$</td>
<td>0.69 $\sigma$</td>
</tr>
</tbody>
</table>

### Results in agreement with


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

**Graphs:**
- $P_{\bar{p}} = 900 \text{ MeV/c}$
- $\cos \theta_{\bar{p}p}$
- $\cos \theta_{\omega}$
- $\phi_{\omega}$

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Spectroscopy of Resonances and QCD, Trento, Feb. 8-12, 2016

Bertram Kopf, Ruhr-Universität Bochum
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

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

- Alignment if \( \rho_{11} \neq \rho_{00} \neq \frac{1}{3} \)

- Extraction of all elements via PWA:

\[
\rho_{\lambda \omega}^{0} = \frac{1}{N} \sum_{M_{\bar{p}p}} A_{M_{\bar{p}p}, \lambda \omega} A^{*}_{M_{\bar{p}p}, \lambda \omega} \quad \text{with} \quad N = \sum_{M_{\bar{p}p}, \lambda \omega} \left| A_{M_{\bar{p}p}, \lambda \omega} \right|^{2}
\]
SDM: $\bar{p}p \rightarrow \omega \pi^0 \rightarrow (\pi^+ \pi^- \pi^0) \pi^0$

- Significant alignment, heavily dependent on the production angle

- March 2015: published in European Physical Journal C

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- Significant alignment, heavily dependent on the production angle

- March 2015: published in European Physical Journal C
• Simultaneous fit of different decay channels and initial state reactions

• Advantages compared to single channel fits
  ➢ constraints due to common amplitudes
  ➢ unique description of the dynamics (e.g. K-matrix, dispersion relation, …)
  ➢ conservation of the unitarity
  ➢ better description of threshold effects
  ➢ less fit parameters
  ➢ less ambiguities
Coupled Channel Analysis: $\bar{p}p \rightarrow K^+K^-\pi^0, \pi^0\pi^0\eta, \pi^0\eta\eta$

Why $K^+K^-\pi^0$?

- $\phi\pi^0$
  - comparison of production process with $\bar{p}p \rightarrow \omega\pi^0$

- $K^* K$
  - production process of $K^*$
  - closely related to $D^* D$ channels with relevance for PANDA
  - complex due to large number of initial $J^{PC}$ states with $l_{\bar{p}p} = 0$ and $l_{\bar{p}p} = 1$

- $a\pi^0$ and $f\pi^0$
  - possible glueball contribution in $f_0$ resonances
  - $a$ and $f$ resonances are not distinguishable due to $l_{\bar{p}p} = 0,1$
Coupled Channel Analysis: $\bar{p}p \rightarrow K^+K^-\pi^0, \pi^0\pi^0\eta, \pi^0\eta\eta$

**Why $K^+K^-\pi^0$ in combination with $\pi^0\pi^0\eta$ and $\pi^0\eta\eta$?**

- a and f resonances distinguishable
  - also helpful for the extraction of the $\phi$ contribution

- Possible contribution of spin exotic $\pi_1$ resonances
  - e.g. access to the individual resonance contributions in the 1.3-1.4 GeV region: $f_2(1270) \rightarrow KK; \ a_2(1320) \rightarrow KK, \pi\eta; \ \pi_1(1400) \rightarrow \pi\eta$

![Diagram of coupled channel analysis]

Spectroscopy of Resonances and QCD, Trento, Feb. 8-12, 2016

Bertram Kopf, Ruhr-Universität Bochum
**Coupled Channel Analysis: $\bar{p}p \rightarrow K^+K^-\pi^0, \pi^0\pi^0\eta, \pi^0\eta\eta$**

- Preparation of clean data samples at $p_\bar{p} = 0.9$ GeV/c
  - kinematic fit
  - event-based background suppression
- Individual single channel fits as starting point
- Coupled channel fits with
  - K-matrix formalism for the description of the dynamics across the channels
  - relativistic Breit-Wigner function for dynamics of isolated resonances

```
<table>
<thead>
<tr>
<th>Resonance</th>
<th>Dynamics</th>
<th>$K^+K^-\pi^0$</th>
<th>$\pi^0\pi^0\eta$</th>
<th>$\pi^0\eta\eta$</th>
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</thead>
<tbody>
<tr>
<td>$\phi$</td>
<td>rel. BW.</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\phi(1680)$</td>
<td>rel. BW.</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>$K^{*+/-}$</td>
<td>rel. BW.</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>$K^{*0}(1430)$</td>
<td>K-$\pi$-S-wave</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_0$</td>
<td>$\pi\pi$-S-wave</td>
<td>X (1)</td>
<td>X (2)</td>
<td>X (1)</td>
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<tr>
<td>$a_0(980)$</td>
<td>k-matrix</td>
<td>X (1)</td>
<td>X (1)</td>
<td>X (2)</td>
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<td>$a_0(1450)$</td>
<td>k-matrix</td>
<td>X (1)</td>
<td>X (1)</td>
<td>X (2)</td>
</tr>
<tr>
<td>$a_2(1320)$</td>
<td>k-matrix</td>
<td>X (1)</td>
<td>X (1)</td>
<td>X (2)</td>
</tr>
<tr>
<td>$a_2(1700)$</td>
<td>k-matrix</td>
<td>X (1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>k-matrix</td>
<td>X (1)</td>
<td></td>
<td>X (2)</td>
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<tr>
<td>$f_2'(1525)$</td>
<td>k-matrix</td>
<td>X (1)</td>
<td></td>
<td>X (1)</td>
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<tr>
<td>$\rho_3(1700)$</td>
<td>k-matrix</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$\pi^0_1(1400)$</td>
<td>rel. BW.</td>
<td></td>
<td>X (1)</td>
<td>X (2)</td>
</tr>
</tbody>
</table>

X basis fit X current best fit X alternative fits
```

*(K\pi)_S(I=1/2)- wave used by FOCUS

*(K\pi)_S(I=1/2)- wave used by FOCUS

k-matrix parametrization by Anisovich and Sarantsev

Model selection using different approaches (AIC, BIC, LRT)
Coupled Fit Results for $\bar{p}p \rightarrow K^+K^-\pi^0$ @ 0.9 GeV/c

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Cont. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*$</td>
<td>38.0 ±0.9</td>
</tr>
<tr>
<td>$f_2$ matrix</td>
<td>18.5 ±1.2</td>
</tr>
<tr>
<td>$(K\pi)_S$</td>
<td>17.8 ±1.1</td>
</tr>
<tr>
<td>$(KK)_S$</td>
<td>16.4 ±1.1</td>
</tr>
<tr>
<td>$a_2$ matrix</td>
<td>14.4 ±0.6</td>
</tr>
<tr>
<td>$\phi(1680)$</td>
<td>11.3 ±0.6</td>
</tr>
<tr>
<td>$\phi$</td>
<td>1.91 ±0.23</td>
</tr>
<tr>
<td>$a_0$ matrix</td>
<td>0.58 ±0.03</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>118.9 %</td>
</tr>
</tbody>
</table>
Coupled Fit Results for $\bar{p}p \rightarrow \pi^0\pi^0\eta$ @ 0.9 GeV/c

- significant improvement if $\pi_1(1400) \rightarrow \pi^0\eta$ is included
- less significance for $\pi_1(1600)$
- further investigations needed
Coupled Fit Results for $\bar{p}p \rightarrow \pi^0\eta\eta$ @ 0.9 GeV/c

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Cont. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\eta\eta)_S$</td>
<td>52.2 ± 2.0</td>
</tr>
<tr>
<td>$a_2$ matrix</td>
<td>30.9 ± 1.3</td>
</tr>
<tr>
<td>$f_2$ matrix</td>
<td>11.8 ± 0.4</td>
</tr>
<tr>
<td>$a_0$ matrix</td>
<td>11.1 ± 0.9</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>106.0</td>
</tr>
</tbody>
</table>
Coupled Fit Results: SDM of the $\phi(1020)$

- SMD in the helicity system of $\phi$ extracted from the obtained production amplitudes of $\bar{p}p \rightarrow \phi \pi^0 \rightarrow (K^+K^-)\pi^0$
- Alignment visible and strongly depending on the production angle
- Similar behavior as for the $\omega$ for all 3 elements

![Graphs showing $\rho_{00}$, $\rho_{1-1}$, and $\Re \rho_{10}$ as functions of $\cos \theta_{\phi \pi^0}$]
Coupled Fit Results: $\bar{p}p \rightarrow K^* K$

- Asymmetric angular distributions for $K^{*-}$
  - similar shape compared to $\bar{p}p \rightarrow K^+ K^-$ (spark chamber experiment)
- $\rho_{00}$ for $K^{*+}$ and $K^{*-}$
  - asymmetric distribution in $\theta$ production angle
  - $\rho_{00} \sim 1/3$

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For $\bar{p}p \rightarrow K^* K^+$

- PWA result
- Stat. error
- Sys. error

---

For $\bar{p}p \rightarrow K^+ K^-$

- Preliminary

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For $\bar{p}p \rightarrow K^* K^-$

- (cos $\Theta_{K^-}$)

---


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32
• Lots of new light mesons discovered over the last 30 years

• Many still unresolved questions in the field of light (exotic) mesons
  ➢ broad and overlapping resonances
  ➢ mixing of conventional mesons with exotics

• Multi channel analyses are needed

• PANDA will provide high statistics and gluon rich environment
  ➢ essential for the search for light exotics

• PWA at PANDA
  ➢ development of a new PWA package
  ➢ analysis of Crystal Barrel LEAR data in-flight with relevance for PANDA

• $\bar{p}p \rightarrow \omega \pi^0$
  ➢ $L_{\text{max}}$ rises from 2 @ 0.6 GeV/c to 5 @ 1.94 GeV/c
  ➢ $\omega$-SDM: strong spin alignment depending on the production angle

• Coupled channel analysis of $\bar{p}p \rightarrow K^+K^-\pi^0, \pi^0\pi^0\eta$ and $\pi^0\eta\eta$ @ 0.9 GeV/c
  ➢ $\phi$-SDM: similar alignment effects
  ➢ $K^\ast$: asymmetric distributions of the production angle