RUB

Coupled Channel Analysis with p̄p-Data

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RUHR UNIVERSITÄT BOCHUM RUB

Großgeräte der physikalischen Grundlagenforschung

Outline

- Introduction
  - Crystal Barrel at LEAR
  - Reminder: $\overline{p}p \to \omega\pi^0$
  - Goodness of fit: the energy test
- PWA of CB-LEAR data with relevance for PANDA
  - $\overline{p}p \to K^+K^-\pi^0$
  - $\overline{p}p \to \pi^+\pi^-\pi^0$
  - First coupled channel analysis
  - Spin density matrices
- Summary and outlook

Motivations

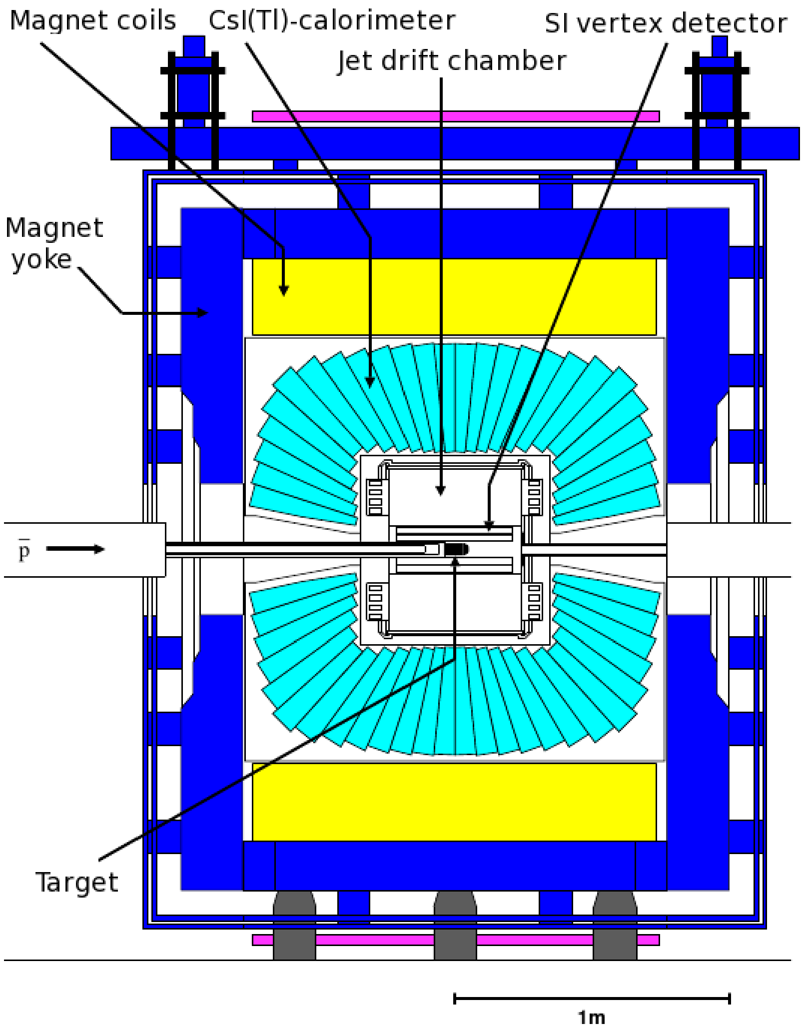
With regard to the upcoming PANDA experiment, analyses of existing $\bar{\mathrm{p}}\mathrm{p}$-data are valuable

➡ **Crystal Barrel at LEAR**

- Development and test of analysis tools for PANDA, such as the partial wave analysis (PWA) software
- Gain experience with fitting strategies and identification of resonances
- Study of the production of vector mesons and the initial $\bar{\mathrm{p}}\mathrm{p}$-states
- Evaluation of the contributing orbital angular $\bar{\mathrm{p}}\mathrm{p}$-momenta
  - $p_{\bar{\mathrm{p}},max}$ = 1.94 GeV/c @ CB-LEAR ➡ $L_{max} \approx 5$
  - $p_{\bar{\mathrm{p}}}$ = (1.5 - 15) GeV/c @ PANDA ➡ L_{max} = ?
- Evaluation of the spin density matrix for different mesons
- Modern hardware allows more sophisticated analyses of old data

Crystal Barrel

- Fixed target experiment at LEAR (CERN) data taking 1989 - 1996
- p̄p-annihilation in flight and at rest
- $p_{\overline{\mathrm{p}}}$ = 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 PANDA

Partial wave analyses of $\bar{p}p$ reactions

FS particle spin

J^{PC} prod. amplitudes

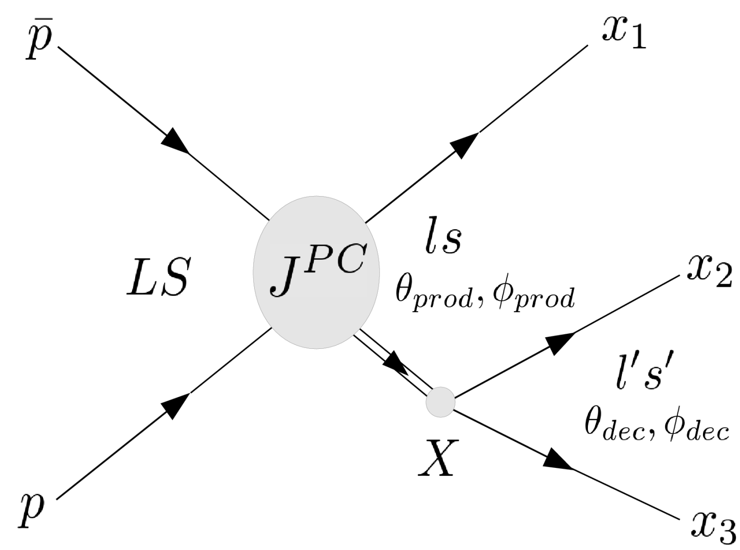
$\bar{p}p$ Singlet / Triplet states

$$\frac{d\sigma}{d\Omega} \propto \sum_{\lambda_{FS}} \sum_{(2S+1)_S} \left| \sum_{J^{PC}} T_{LS}^{\bar{p}p\to J^{PC}} \times \sum_{X} \sum_{ls} T_{ls}^{J^{PC}\to X x_1} A_{l's'}^{X\to x_2 x_3} \right|$$

Resonances

Res. prod. amp.

Res. decay amp.

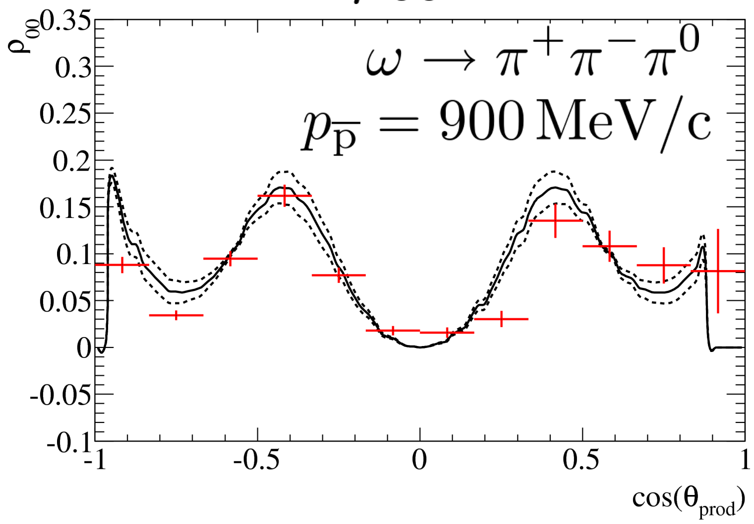


- Amplitudes include angular distributions (D-functions), spin/isospin couplings (Clebsch-Gordan) and dynamics (Breit Wigner, K-Matrix, ...)
- Pawian automatically builds the full amplitude and takes account of spin-, isospin-, C/G-parity conservations
- Maximum contributing orbital $\bar{p}p$ momentum L_{max} is unknown and has to be determined e.g. by significances of likelihood improvements

Reminder: $\bar{p}p \to \omega\pi^0$ (Meeting June 2013)

- Partial wave analysis of the channels $\omega \to \pi^0\gamma$ and $\omega \to \pi^+\pi^-\pi^0$ using CB at LEAR data
- L_{max} values found using $\mathcal{L}$ ratios:
  - L_{max}=3 @ $p_{\bar{p}}$ = 600 MeV/c
  - L_{max}=4 @ $p_{\bar{p}}$ = 900-1525 MeV/c
  - L_{max}=5 @ $p_{\bar{p}}$ = 1940 MeV/c

SDM ρ_{00} element



- Spin density matrix (SDM) revealed strong alignment of the ω in both channels, strongly dependent on production angle
- Hints for intermediate resonances?

Motivation

- Further studies of the $\mathrm{K}^{+}\mathrm{K}^{-}\pi^{0}$ and $\pi^{+}\pi^{-}\pi^{0}$ final states with all intermediate resonances
- Evaluation of L_{max} and the mass / resonance – dependency
- SDM evaluation of other particles like ϕ, ρ, $f_2(1270)$
- Complicated channels that require a full PWA
- Coupled channel analyses

Goodness of fit – the energy test

- QA of PWA result requires an unbinned, multivariate gof test. One of the most powerful is the energy test.

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

- Data and a sample of the fitted pdf are regarded like electric charges of opposite sign in multivariate space

  ➡ "electrostatic" energy is minimal if the samples originate from the same parent distribution

- Generalized energy:

$$\phi_{NM} = \frac{1}{M(M-1)} \sum_{j>i} R(|\mathbf{y}_i - \mathbf{y}_j|) - \frac{1}{NM} \sum_{i,j} R(|\mathbf{x}_i - \mathbf{y}_j|)$$

Data sample (annotating $M(M-1)$ and $\mathbf{y}_i - \mathbf{y}_j$); Fit sample (annotating NM and $\mathbf{x}_i$); Metric has to be defined (annotating $|\mathbf{x}_i - \mathbf{y}_j|$)

$$N >> M$$

- Different potential functions for different applications:

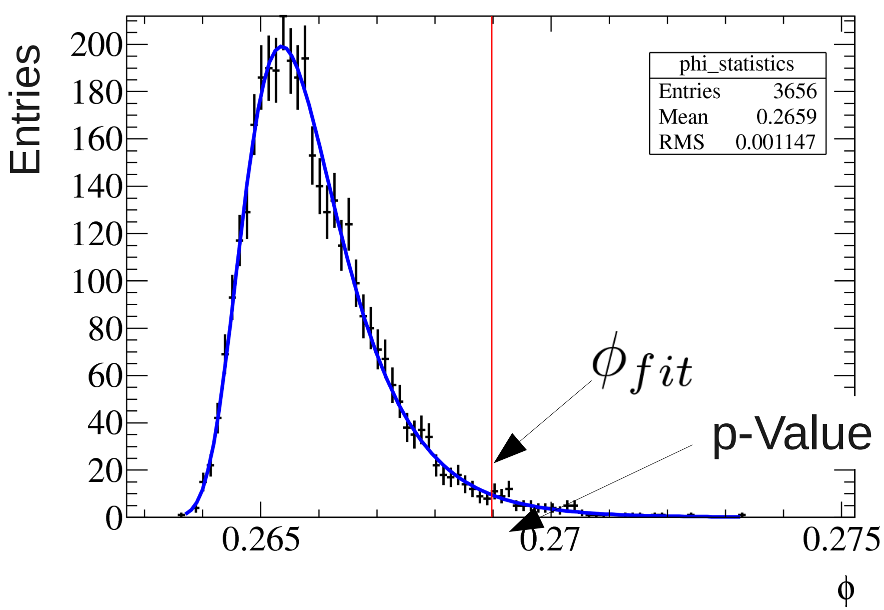
$$R_{\log}(r) = -\ln(r+\epsilon)$$ long range, e.g. linear omnipresent background

$$R_{\mathrm{G}}(r) = e^{-r^2/2s^2}$$ short range, e.g. localized peaking background

Energy Test - p-Value

Unlike for the χ^2 test, the test statistics (the ϕ distribution) has to be generated for each pdf

- Monte Carlo simulation: generate new “data” from pdf and calculate energy. May become time consuming due to detector simulation.
- Resampling: relabel the N+M events randomly to get different N data and M fit points, calculate energy.

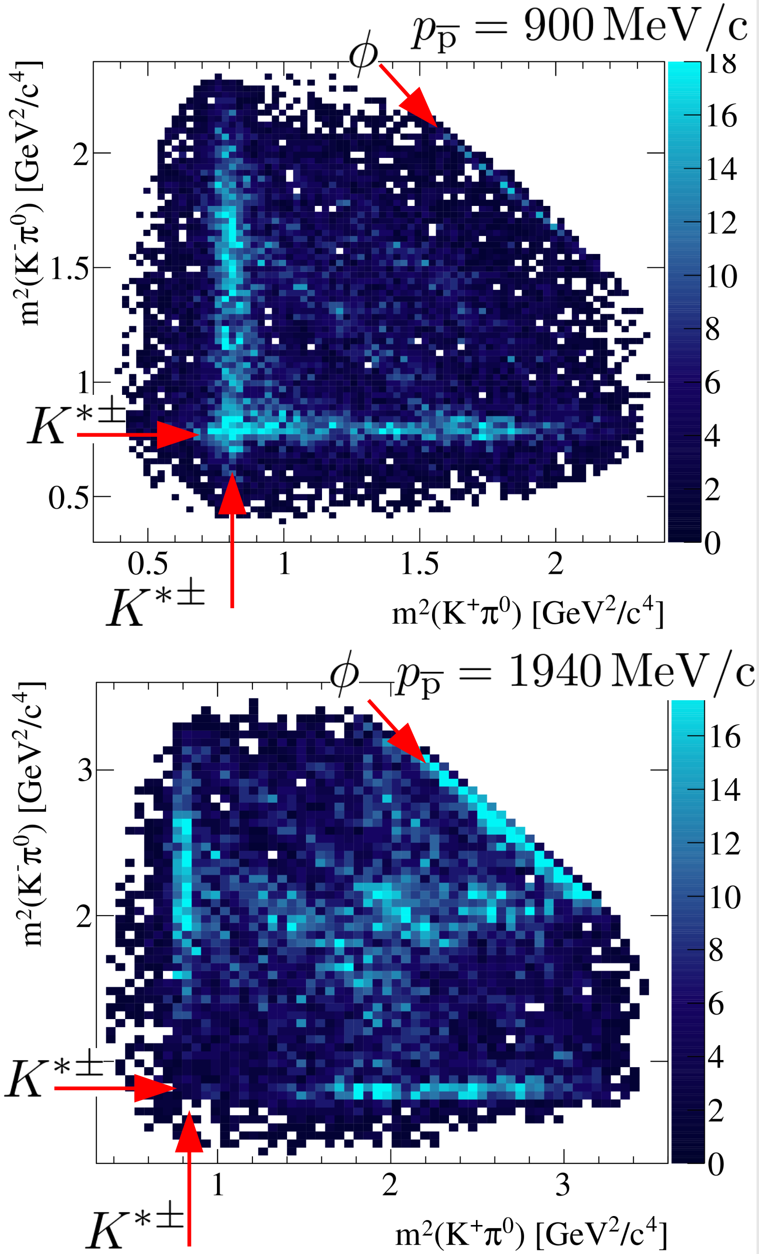


High statistics simulation can be avoided by fitting the distibution:

$$f(x) = \frac{1}{\sigma}\left(1+\xi\frac{x-\mu}{\sigma}\right)^{-1/\xi-1} \cdot \exp\left\{-\left(1+\xi\frac{x-\mu}{\sigma}\right)^{-1/\xi}\right\}$$

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

- Contains $\phi\pi^0$ and $K^{*\pm}K^{\mp}$ events
- Production of vector mesons with strangeness
  - different process in comparison to $\overline{\mathrm{p}}\mathrm{p} \rightarrow \pi^{+}\pi^{-}\pi^{0}$
  - rearrangement vs. annihilation
- Interference of resonances requires a PWA of the complete channel
- Spin density matrix via extraction of the fitted ϕ and $K^{*\pm}$ amplitudes
- Selected CB data:
  ~18100 events @ 900 MeV / c
  ~14400 events @ 1940 MeV / c



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

- Full PWA from the initial to the final state
- Hypotheses based on previous results (Crystal Barrel: Phys. Lett. B639 (2006) 165)
  - $\phi\pi^0,\ \phi(1680)\pi^0$
  - $f_2(1270)\pi^0,\ f_2'(1525)\pi^0$
  - $a_2(1320)\pi^0$
  - $K^{*\pm}K^{\mp},\ K^*(1680)^{\pm}K^{\mp}$
  - Five $f_0\pi^0$
    New: via $(KK)_S$-wave
  - $K_0^{*\pm}K^{\mp}$
    New: via $(K\pi)_S(I=1/2)$- wave
    [$(K\pi)_S(I=3/2)$- wave]

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

K-matrix parametrization used by FOCUS Phys. Lett. B653 (2007) 1-11 1 / 0 -pole, 2-channel matrix

- Generalized K-Matrix support in preparation

Amplitude prefactors

- K^*K systems are no G- and C-parity eigenstates and can have isospin I=0 or I=1
- Thus, those states have to be symmetrized, e.g. (J=1)

$$|I,I_z\rangle^C = |1,0\rangle^+ = 1/2 \cdot \left[+|K_{1^-}^{*0}\overline{K}^0\rangle + |K_{1^-}^{*+}K^-\rangle - |\overline{K}_{1^-}^{*0}K^0\rangle - |K_{1^-}^{*-}K^+\rangle\right]$$

- This yields to amplitude prefactors:

J^{PC}	0^{-+}				
Transition	l	L	I	x	y
$K_0^*(1/2)\overline{K}$	0	0	0	+	+
$K_0^*(1/2)\overline{K}$	0	0	1	-	-
$K_0^*(3/2)\overline{K}$	0	0	1	+	+
$K_1^*\overline{K}$	1	1	0	+	+
$K_1^*\overline{K}$	1	1	1	-	-

J^{PC}	1^{+-}				
Transition	l	L	I	x	y
$K_0^*(1/2)\overline{K}$	0	1	0	-	+
$K_0^*(1/2)\overline{K}$	0	1	1	+	-
$K_0^*(3/2)\overline{K}$	0	1	1	-	+
$K_1^*\overline{K}$	1	0,2	0	-	+
$K_1^*\overline{K}$	1	0,2	1	+	-

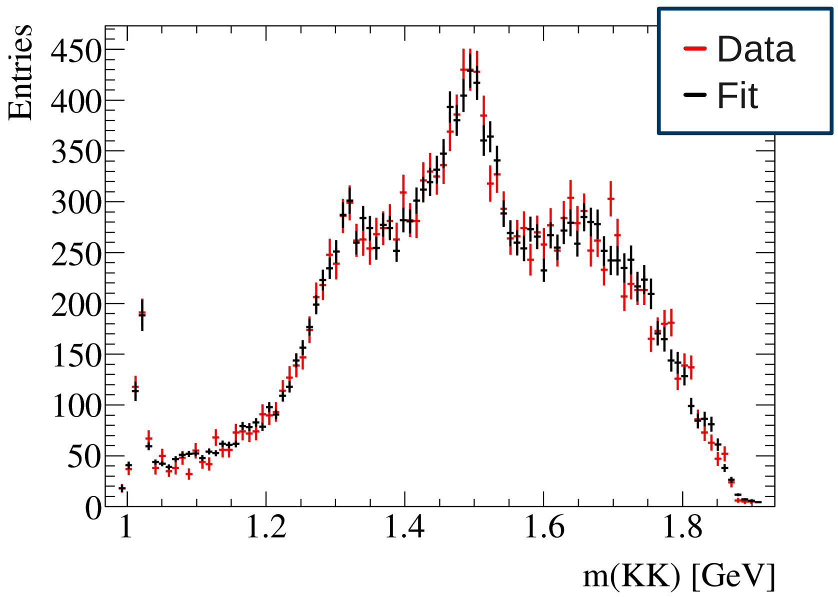
Destructive interference

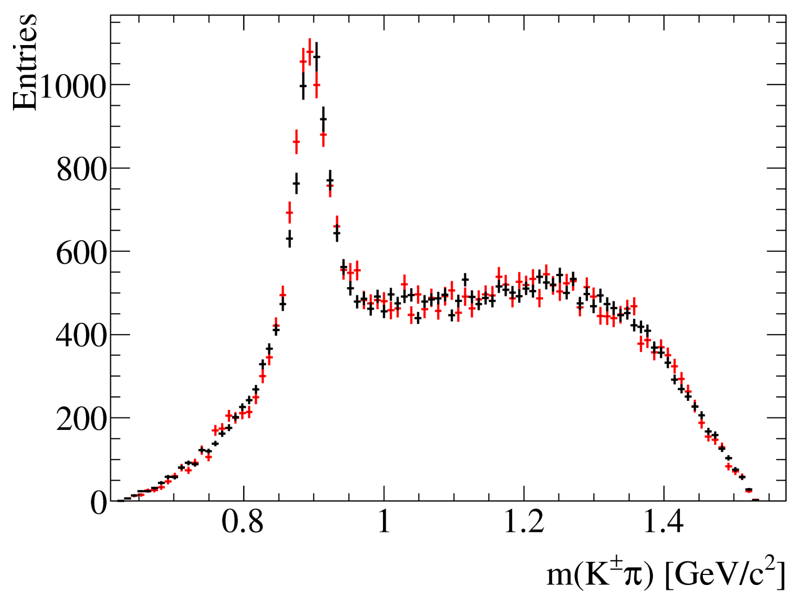
[...]

- $K^{*+}K^-$ and $K^{*-}K^+$ production can be described using the same amplitudes, but the correct prefactors are essential

Fit results $p_{\overline{p}} = 900\,\mathrm{MeV}/c$

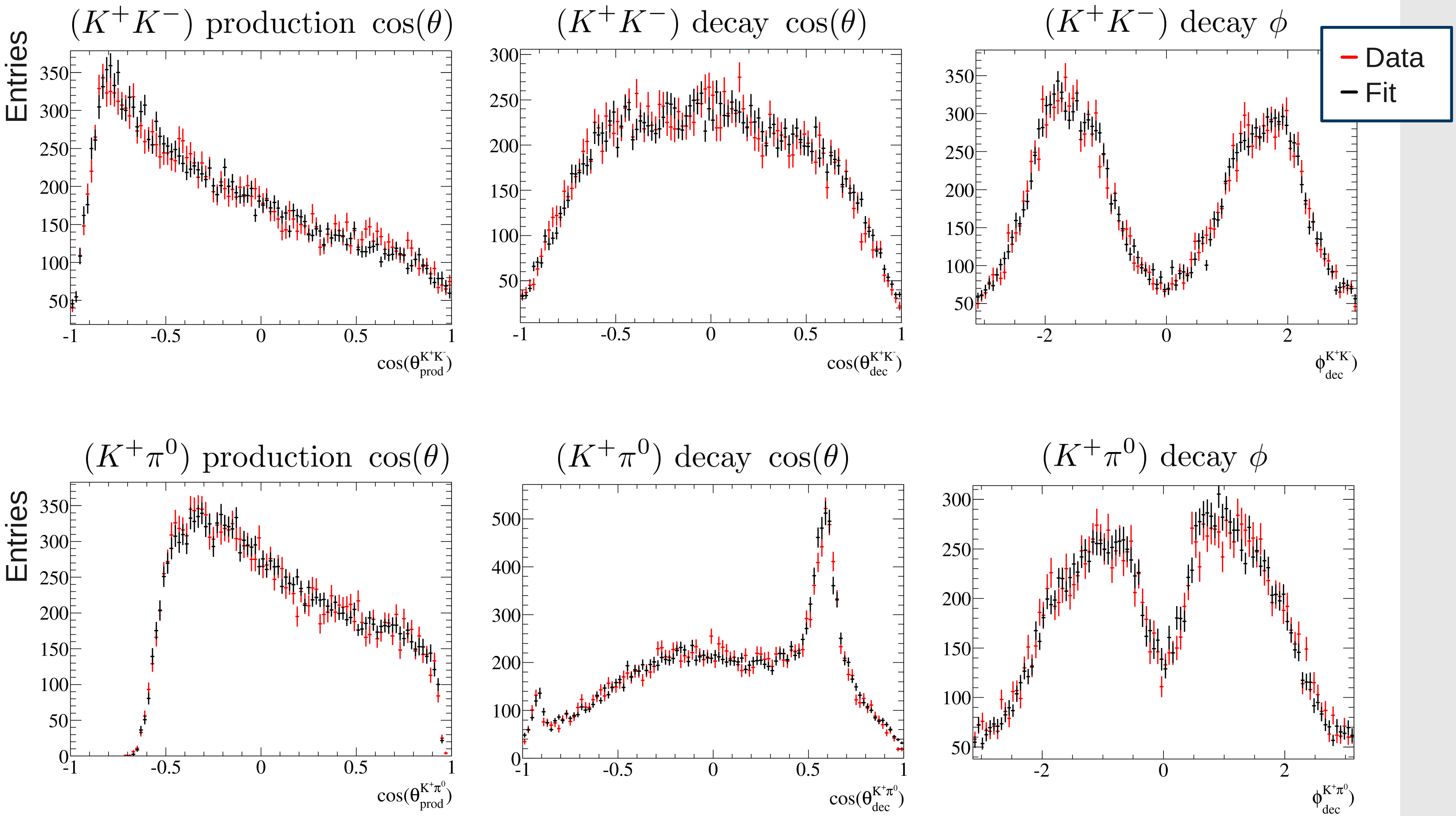
L_{max}	# free param.	$-\ln\mathcal{L}$	$\mathcal{L}$-ratio signific.
1	127	-4720.8	-
2	216	-5205.6	> 10 σ
3	301	-5581.6	> 10 σ
4	384	running	





- L_{max}= 3: $p_g = 0.22$ $p_{log} = 0.38$ easily accepted on 5% significance level
- LH improvements up to $L_{max} = 3$ significant
- Higher global L_{max} values and resonance dependent L_{max} values need to be tested

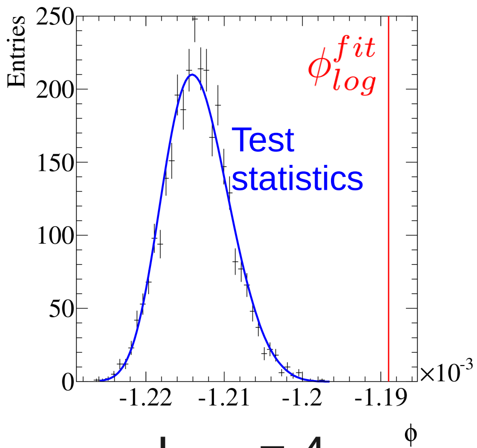
Angular distributions



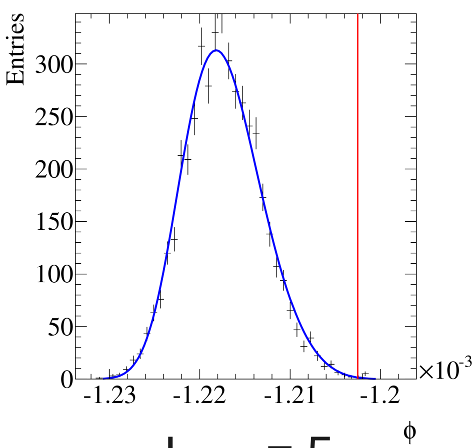
Fit results $p_{\bar{p}} = 1940\,\mathrm{MeV/c}$

L_{max}	# free param.	$-\ln\mathcal{L}$	$\mathcal{L}$-ratio signific.
4	428	-3357.4	-
5	529	-3510.9	9.8 σ
6	not tested yet		

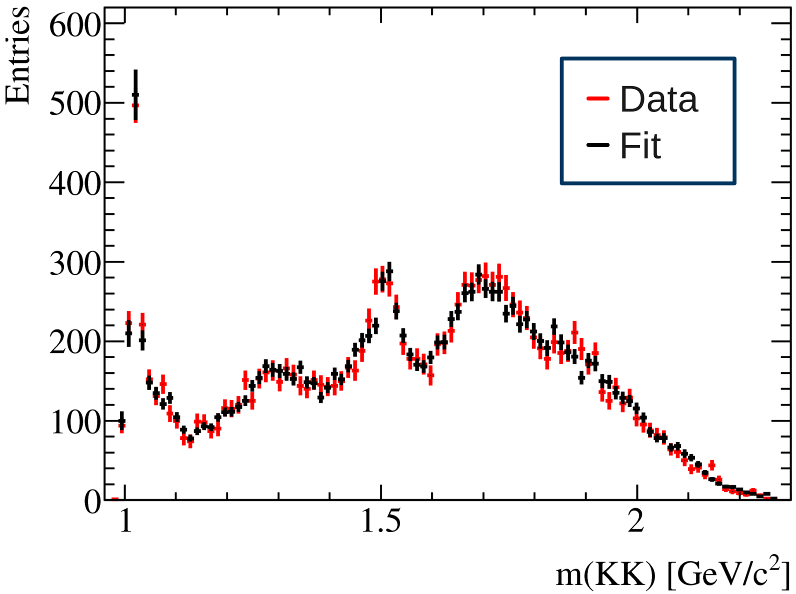
- $L_{max} = 5$:
  $p_g \approx 0.0014$ $p_{log} \approx 0.0090$

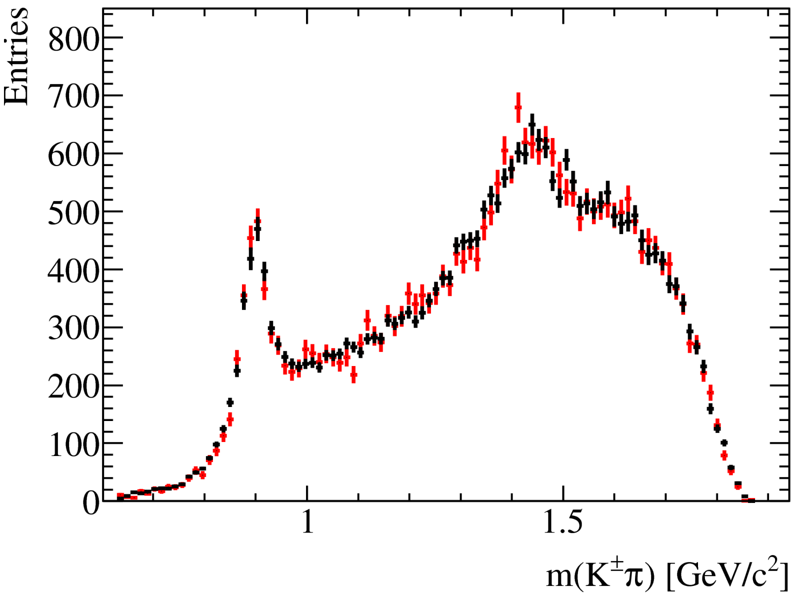


$L_{max} = 4$



$L_{max} = 5$





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

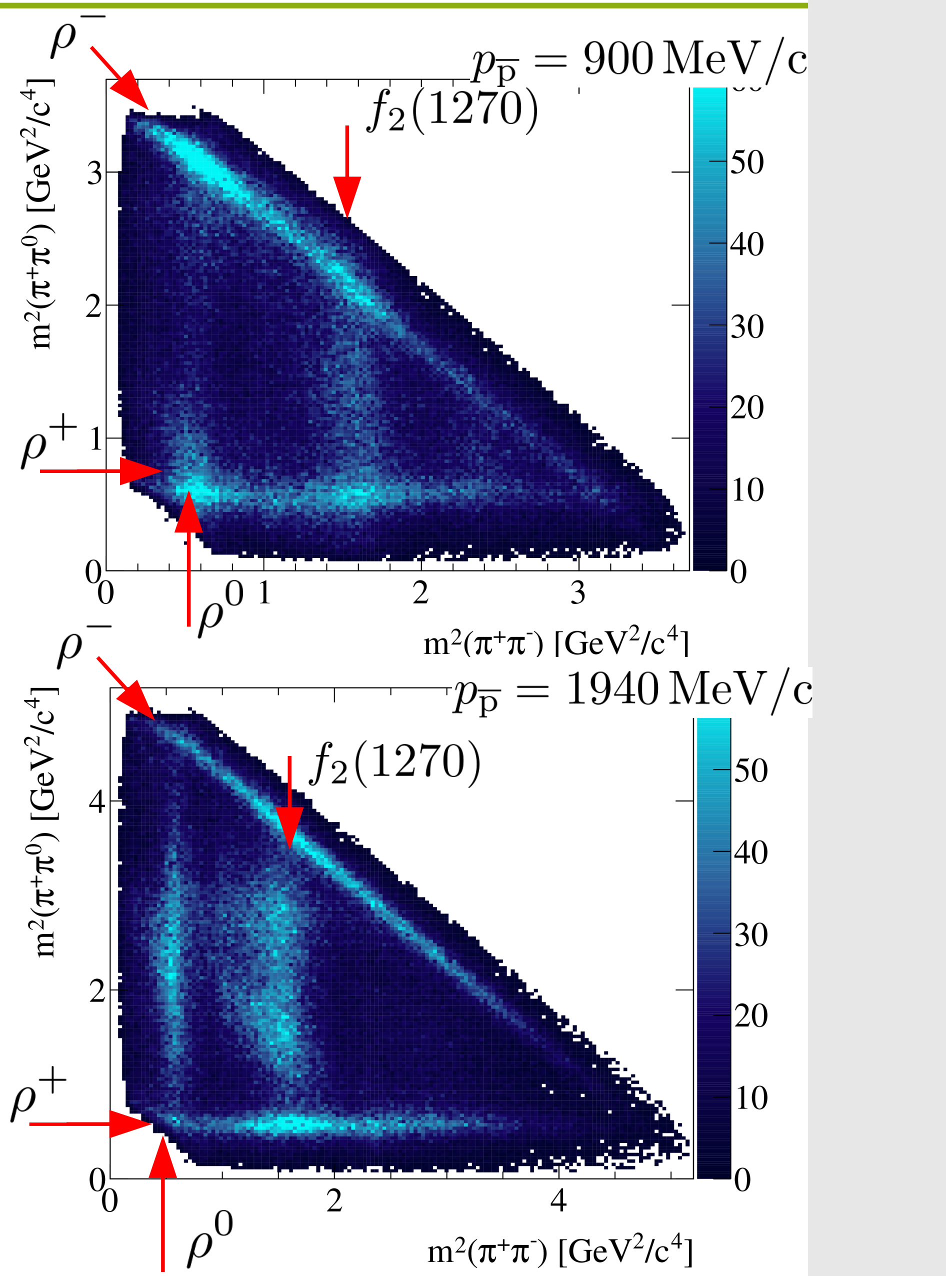
- Current hypothesis:
  - $\rho(770)\pi, \rho(1450)\pi, \rho(1700)\pi$
  - $f_2(1270)\pi^0$
  - $(\pi\pi)_S$-wave
- Possibly also contributing:

  $\rho_3(1690)\pi^0$ $\omega(\to \pi^+\pi^-)\pi^0$
  $f_2^{'}(1525)\pi^0$

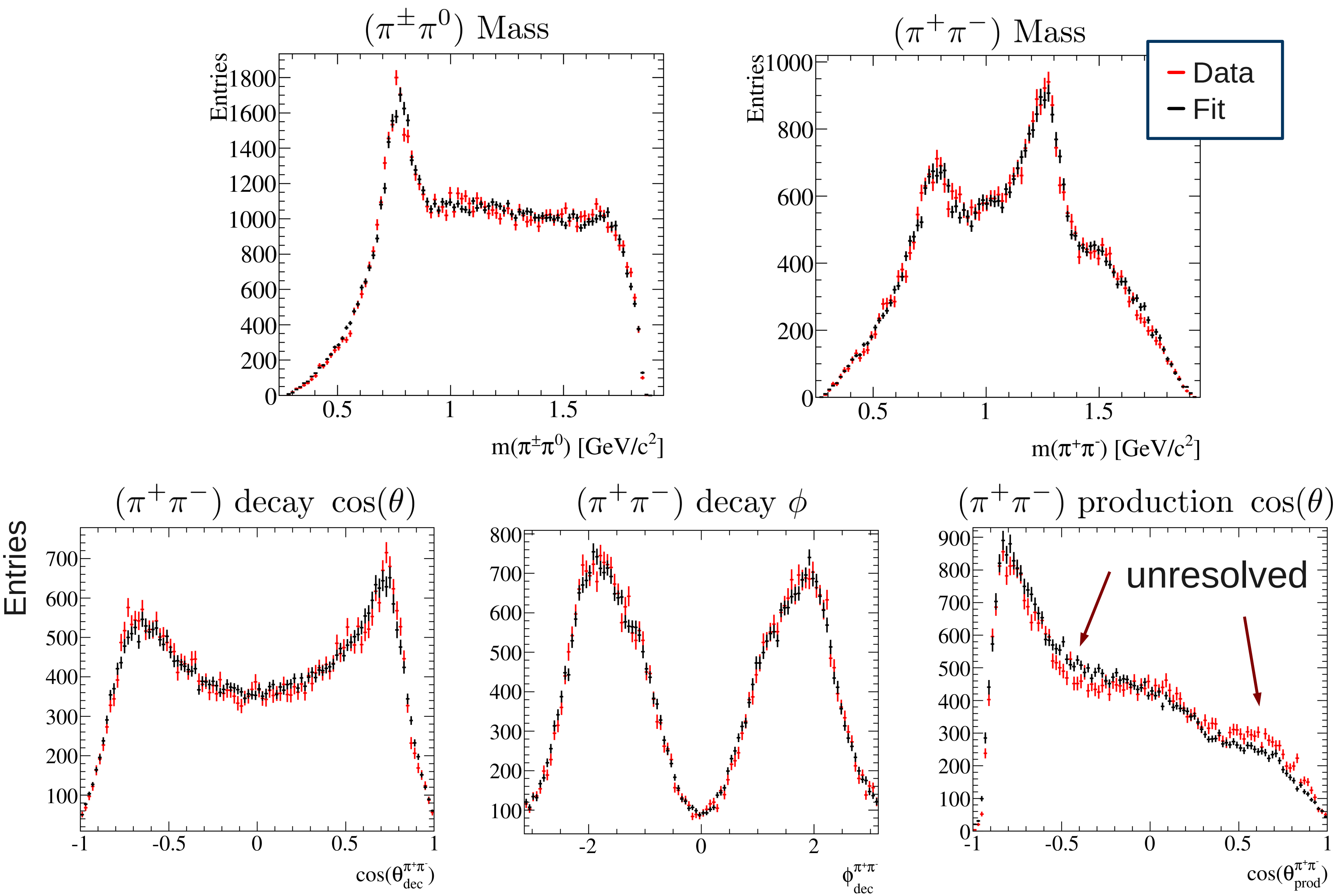
- Selected CB Data:

  ~247000 @ 900 MeV / c
  ~231000 @ 1940 MeV / c

  Temporarily limited to 40000 each



PWA: first fit results $\bar{\mathrm{p}}\mathrm{p} \rightarrow \pi^+\pi^-\pi^0$



$$(p_{\bar{\mathrm{p}}} = 900\,\mathrm{MeV}, \mathrm{L}_{max} = 3)$$

Coupled channel analysis

➡ Simultaneously fitting different reaction channels that share a part of their parameter sets

- Some parameters might be better accessible in one channel than in another
- K-Matrix describes dynamics across channels by design, ensures unitarity
- Hard constraints, less total parameters, better convergence
- Higher statistics
- Reduction of systematic effects: different datasets might have different background, detection characteristics, MC quality, ...
- Check for the physical validity of the parameters

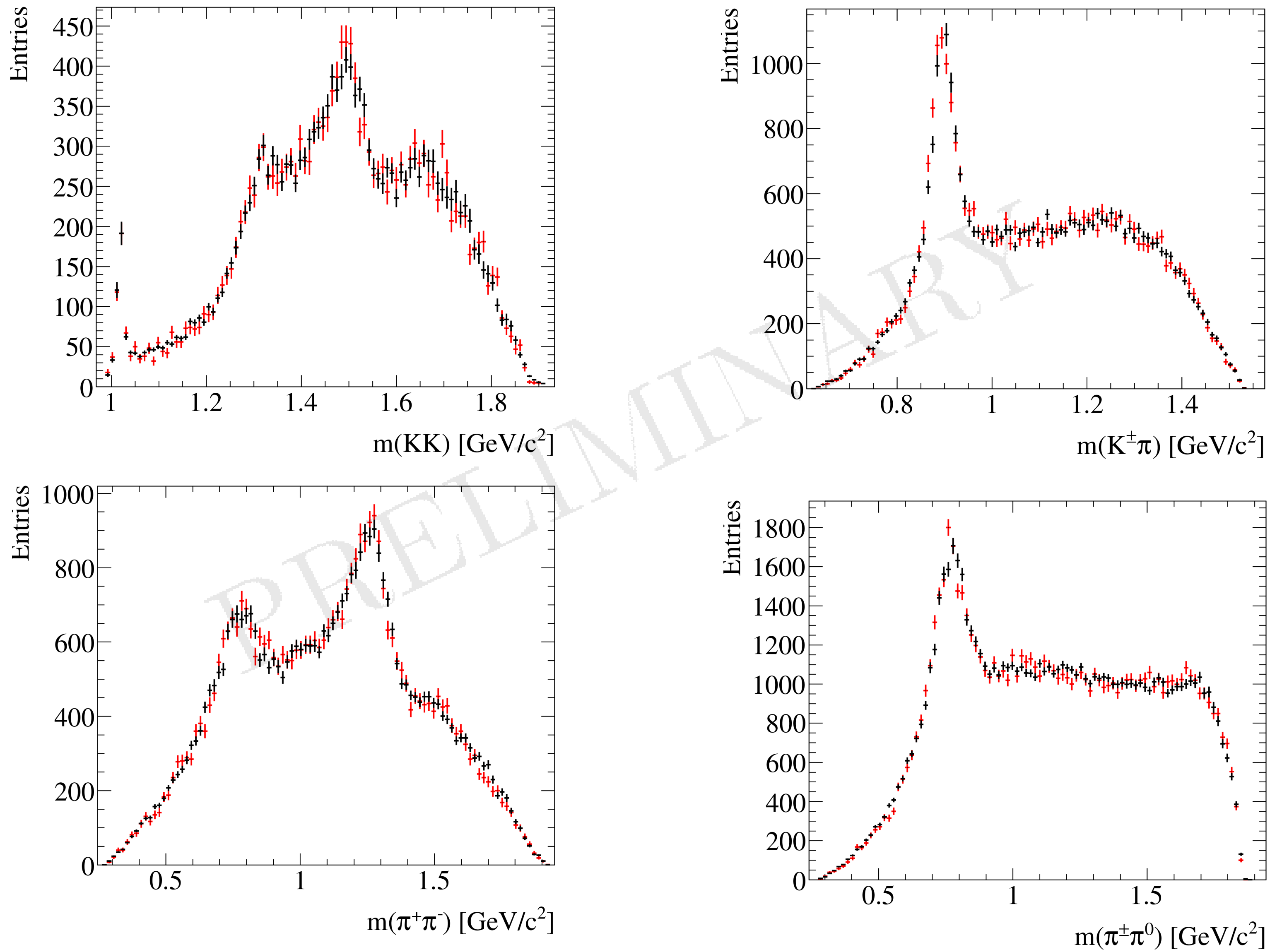
Coupled channel analysis

- Coupled fit of $\overline{\mathrm{p}}\mathrm{p} \rightarrow \mathrm{K}^+\mathrm{K}^-\pi^0$ and $\overline{\mathrm{p}}\mathrm{p} \rightarrow \pi^+\pi^-\pi^0$ (and later: $\overline{\mathrm{p}}\mathrm{p} \rightarrow \pi^+\pi^-\eta$) in progress
- $f_0(980)$, $f_0(1300)$, $f_0(1500)$, $f_0(1750)$ and $f_0(1200-1600)$ present in both channels and described by $(KK/\pi\pi)_S$-Wave
- $a_2(1320)$ only present in the kaon channel
  ➡ can now be seperated from $f_2(1270)$
- Current fit status:

Fit	# free param.	$-\ln\mathcal{L}$
separated	301 + 214 = 515	-5581.5 + -9624.2 = -15205.7
coupled	405	-5414.1 + -9599.0 = -15013.1

(running)

Coupled channel analysis – current results



$$(p_{\overline{\mathrm{p}}} = 900\,\mathrm{MeV}, \mathrm{L}_{max} = 3)$$

Spin density matrix ρ

- Spin S particle : n x n -matrix with n = 2S+1
- Provides full information on production mechanism, diagonal elements give propability of certain spin state ($\mathrm{Tr}(\rho) = 1$)
- $\rho_{00} \neq \rho_{11} = \rho_{-1-1}$ Alignment
  $\rho_{11} \neq \rho_{-1-1}$ Polarization
  (Spin 1)
- Extraction via particle production amplitudes

H. Koch,
Helicity amplitude for p̄p->ωπ[0],
Internal PANDA Note

$$\rho_{\lambda_X \lambda'_X} = \frac{1}{\sum_{\lambda_{\overline{p}},\lambda_p,\lambda_x,\lambda_X} |T_{\lambda_{\overline{p}}\lambda_p\lambda_x\lambda_X}|^2} \cdot \sum_{\lambda_{\overline{p}},\lambda_p,\lambda_x} T^*_{\lambda_{\overline{p}}\lambda_p\lambda_x\lambda_X} T_{\lambda_{\overline{p}}\lambda_p\lambda_x\lambda'_X}$$

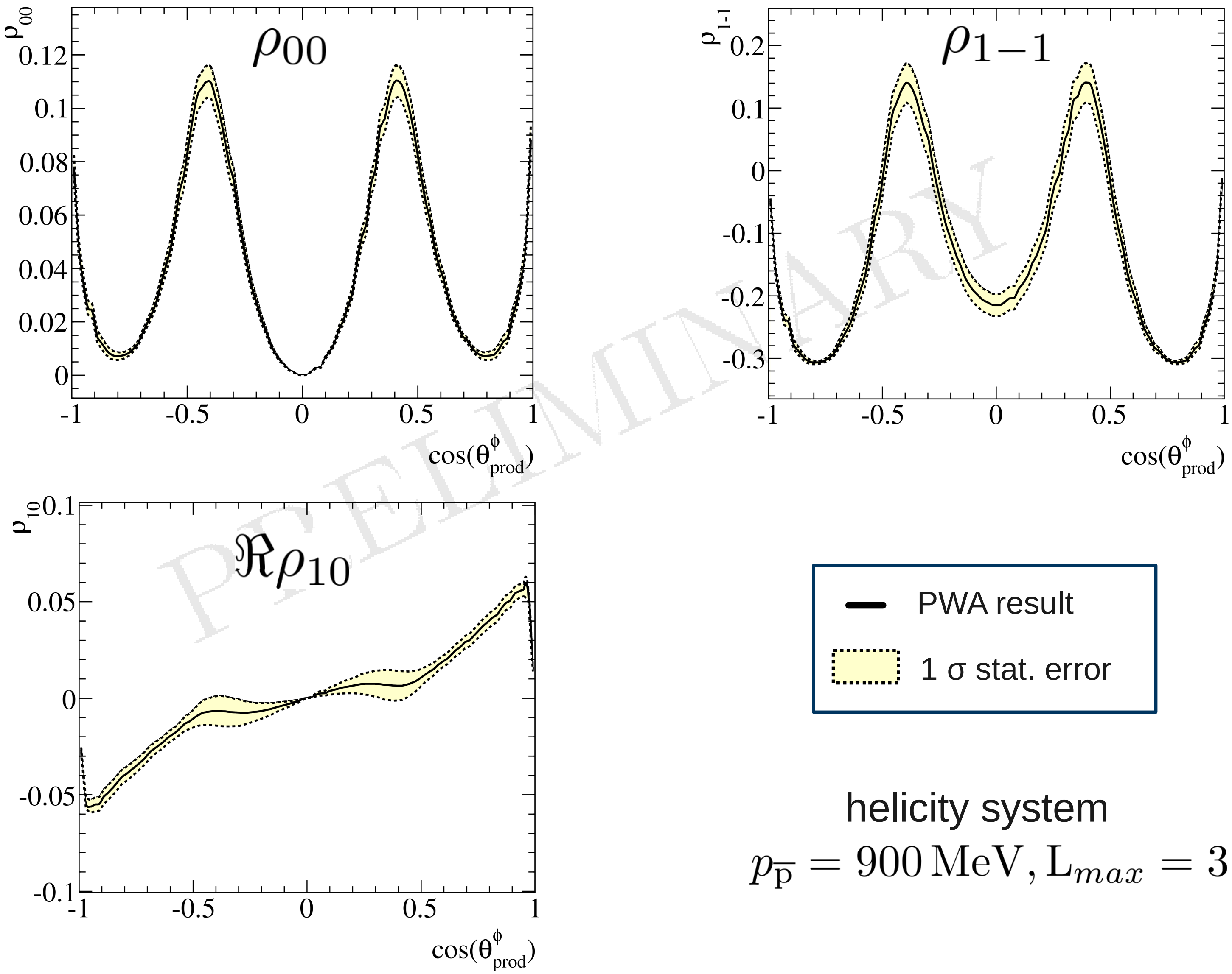
- Or via fit to decay angular distribution

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

“Schilling's method”

$$W_{\text{pseudoscalars}}(\cos\theta, \phi) = \frac{3}{4\pi}\Big(\frac{1}{2}(1-\rho_{00}) + \frac{1}{2}(3\rho_{00}-1)\cos^2\theta - \sqrt{2}\Re\rho_{10}\sin 2\theta\cos\phi - \rho_{1-1}\sin^2\theta\cos 2\phi\Big)$$

Spin density matrix ($\phi \to K^+K^-$)

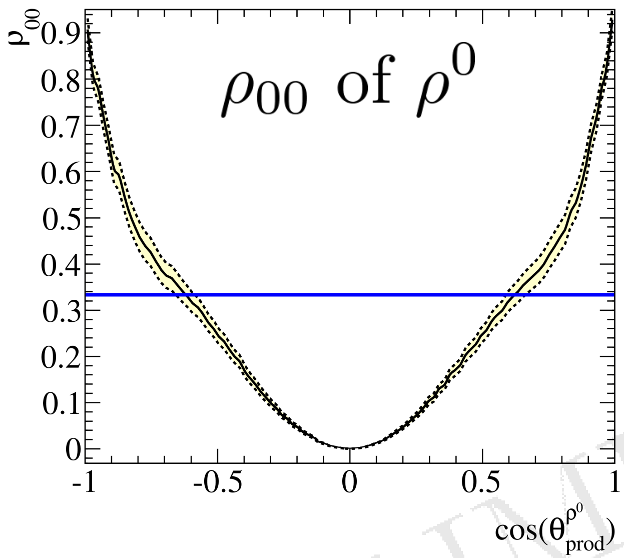


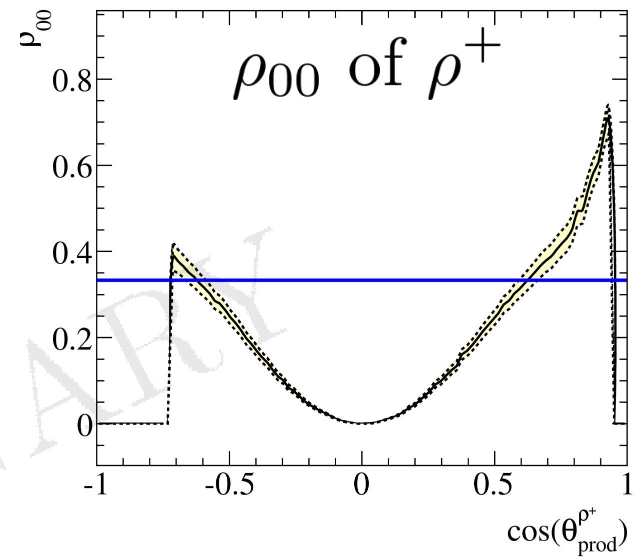
helicity system

$$p_{\overline{\mathrm{p}}} = 900\,\mathrm{MeV}, \mathrm{L}_{max} = 3$$

Spin density matrix ($\rho \rightarrow \pi\pi$)

$$I(\overline{p}p) = 0$$



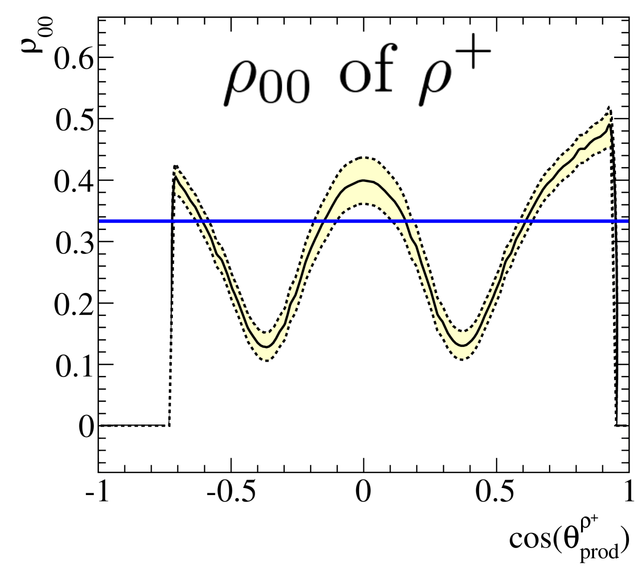


PRELIMINARY

$$I(\overline{p}p) = 1$$

PWA result

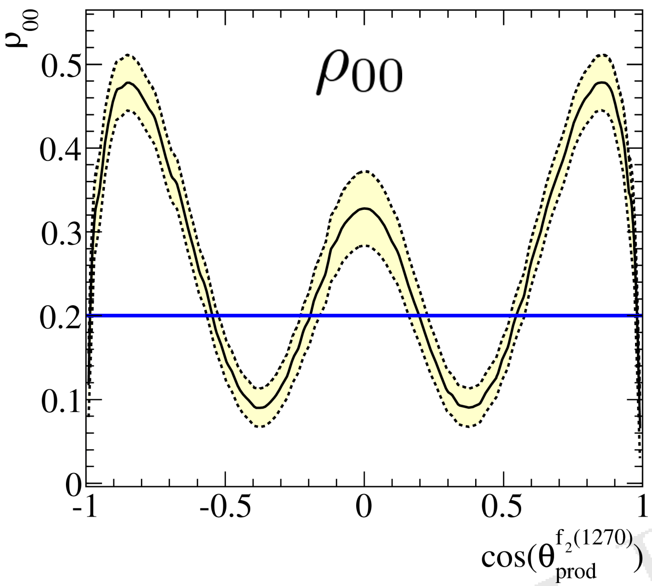
1 σ stat. error

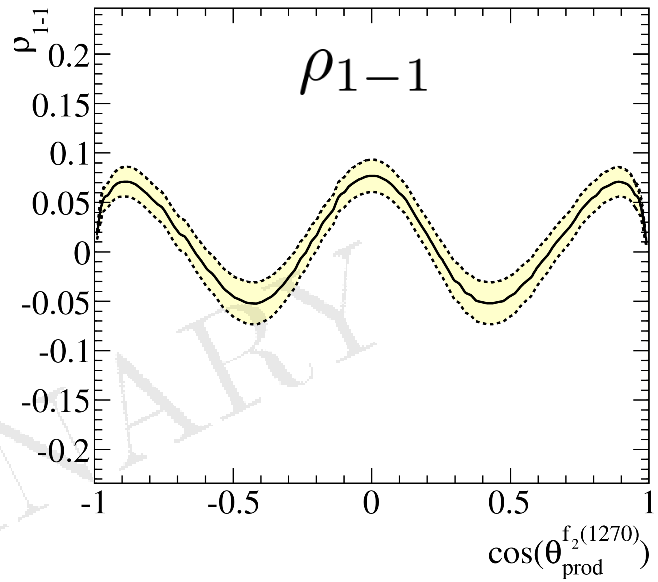


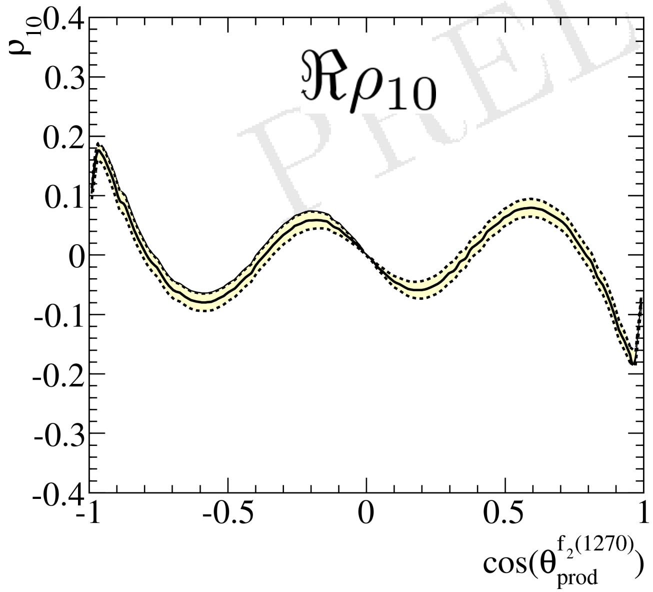
helicity system

$$p_{\overline{\mathrm{p}}} = 900\,\mathrm{MeV}, \mathrm{L}_{max} = 3$$

Spin density matrix $f_2(1270)$







PWA result

1 σ stat. error

helicity system

$p_{\overline{\text{p}}} = 900\,\text{MeV}, \text{L}_{max} = 3$

Summary and outlook

- Analyses of Crystal Barrel LEAR data with relevance for PANDA
- p̄p initial states and production of vector mesons
- Full PWA of the channels $\mathrm{K}^+\mathrm{K}^-\pi^0$ and $\pi^+\pi^-\pi^0$ in progress
  - Excellent description of the data $\mathrm{K}^+\mathrm{K}^-\pi^0$ at 900 MeV / c
  - L_{max} ≥ 3 for 900 MeV / c and ≥ 5 for 1940 MeV / c
  - First coupled channel analysis shows reasonable results
- Spin density matrix can be extracted from production amplitudes for $\phi, \rho, f_2(1270)$, $a_2(1320)$, K^* ...
- L_{max} evaluation for each resonance
- $\pi\pi$ production angles need to be understood
- Coupling of more channels like $\pi^0\pi^0\pi^0$, $\pi^0\pi^0\eta$, $\pi^0\eta\eta$...

Thank you