Partial Wave Analysis of $\bar{p}p \to \phi\phi$

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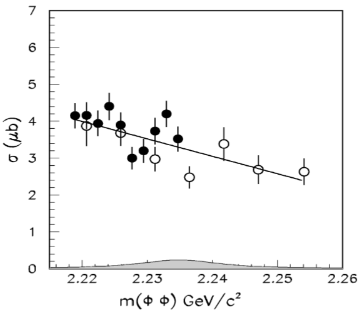
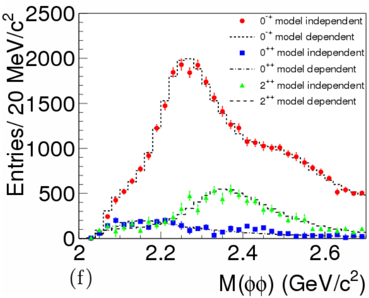
Motivation

- $\bar{p}p \to \phi\phi$ cross section exceeds expectations from a simple application of the OZI rule by two orders of magnitude
- Observation of $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ in $\pi^- p \to \phi\phi n$ *(BNL, Phys.Lett.B201,568-572)* and $J/\psi \to \gamma\phi\phi$
- Hint for intermediate glueball state?
- Lattice QCD predicts tensor glueball state at about 2.4 GeV$/c^2$

JETSET, Phys.Rev.D57,5370

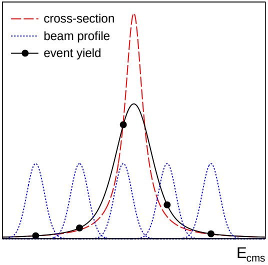


BESIII, Phys.Rev.D93,112011



Motivation

- Scan the cross section of $\bar{p}p \to \phi\phi$ in the mass region of the tensor glueball candidate ($\sqrt{s} = (2.25 - 2.6)$ GeV)
- Resonant and non-resonant reactions have same signature
  $\to$ Partial Wave Analysis needed to extract 2^{++} contribution
- Software package PAWIAN[1](**PA**rtial **W**ave **I**nteractive **AN**alysis), developed at Ruhr-Universität Bochum
- How to extract the contribution of resonances created in formation processes?

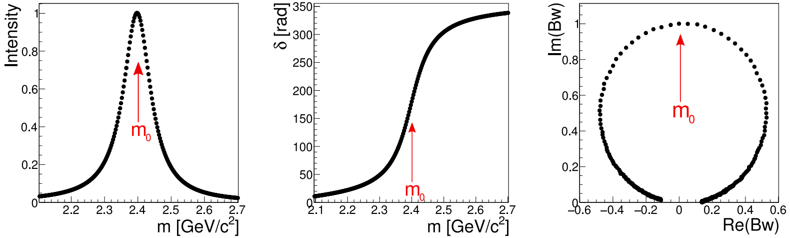


PANDA, Eur. Phys. J. A (2019) 55:42

[1] B. Kopf *et al.*, Hyperfine Interact. **229** no. 1-3, 69-74 (2014)

Identifying Resonances with Mass Independent PWA

Indications for the presence of a resonance with Breit-Wigner shape



- Phase-motion as an indication for the presence of a resonance
- Only relative phases extractable
  $\rightarrow$ A stable, slowly changing reference phase needed!

$\bar{p}p$ initial States

- Amplitudes described by helicity formalism $\rightarrow \lambda = \vec{s} \cdot \vec{p}$
- $\bar{p}p$ system couples to spin singlet $\lambda = 0$ and spin triplet $\lambda = \pm 1, 0$ states

J	Singlet λ=0	J^{PC}	Triplet $\lambda = \pm 1$	J^{PC}	Triplet $\lambda = 0, \pm 1$	J^{PC}
0	$^1S_0$	0^{-+}			$^3P_0$	0^{++}
1	$^1P_0$	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^{++}

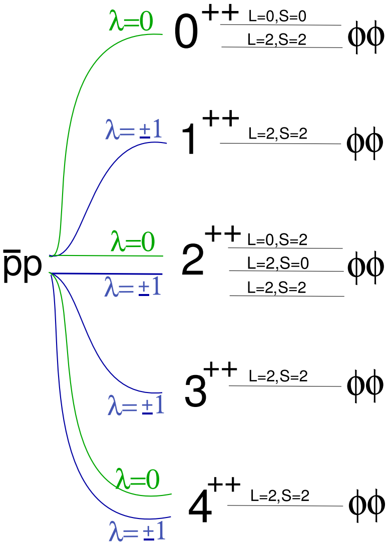
$\bar{p}p$ initial States

- Possible resonances for X in $\bar{p}p \to X \to \phi\phi$ ($J^{PC}(\phi) = 1^{--}$)

J	Singlet λ=0	J^{PC}	Triplet $\lambda = \pm 1$	J^{PC}	Triplet $\lambda = 0, \pm 1$	J^{PC}
0	$^1S_0$	0^{-+}			$^3P_0$	0^{++}
1			$^3P_1$	1^{++}		
2	$^1D_2$	2^{-+}			$^3P_2, ^3F_2$	2^{++}
3			$^3F_3$	3^{++}		
4	$^1G_4$	4^{-+}			$^3F_4, ^3H_4$	4^{++}
5			$^3H_5$	5^{++}		
6						

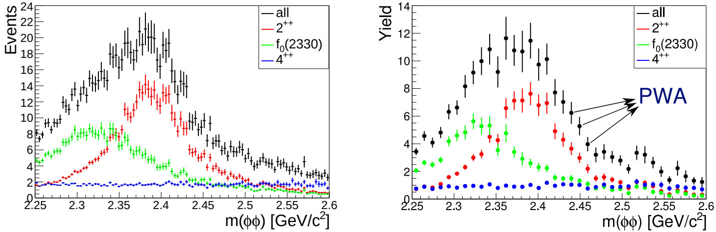
- States with high J should be supressed due to small phase space
- L + S must be even due to identical daughter particles in the decay
- Possible production and decay amplitudes (L,S< 4):

J^{PC}	No. of possible partial waves
0^{++}	2
1^{++}	1
2^{++}	6
3^{++}	1
4^{++}	2



Generated Data Sample Breit-Wigner Scenario

- Generating data sets with fixed center of mass energy, leaving a gap between each energy point



- Breit-Wigner scenario:
  $\rightarrow 2^{++}$ $m = 2.4\,\mathrm{GeV},\ \Gamma = 100\,\mathrm{MeV}$
  $\rightarrow 0^{++}$ $m = 2.33\,\mathrm{GeV},\ \Gamma = 150\,\mathrm{MeV}$
  $\rightarrow 4^{++}$ component with fixed phase
- 10000 generated Monte Carlo events per $\sqrt{s}$
  $\bar{p}p \rightarrow X \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-,\ X = 2^{++}/4^{++}/0^{++}$
- Bin-Width = 200 keV, "gap" = 10 MeV

Hypotheses Test

- Event based maximum likelihood fits
- Complete decay chain is taken into account
  $\bar{p}p \rightarrow X \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$
- Extraction of contribution and phases with model independent PWA
  $\rightarrow$ Dynamics for each scan point fixed
  $\rightarrow$ No need for choosing a model for description of dynamics
  $\rightarrow$ Individual partial wave fits for each scan point

$$\frac{d\sigma}{d\Omega} \propto w = \left|\sum A_{\lambda=0}^{S=0}\right|^2 + \left|\sum A_{\lambda=0}^{S=1}\right|^2 + \left|\sum A_{\lambda=-1}^{S=1}\right|^2 + \left|\sum A_{\lambda=1}^{S=1}\right|^2$$

- 5 different intermediate states $\rightarrow$ 31 different hypotheses
  Which hypothesis achieves the best fit result?

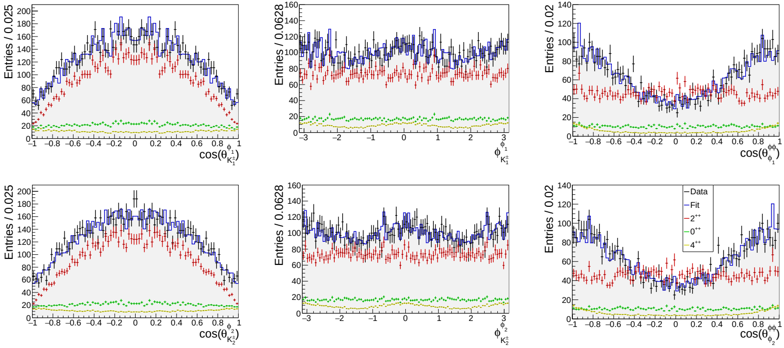
$$\mathrm{AIC} = -2 \cdot ln(\mathcal{L}) + 2 \cdot k$$
$$\mathrm{BIC} = -2 \cdot ln(\mathcal{L}) + k \cdot ln(n)$$

K. P. Burnham and D. R. Anderson. Model Selection and Multimodel Inference. Springer, 2002

PWA of BW Toy MC Scenario

- Hypothesis containing only generated contributions achieves best fit result for each bin!

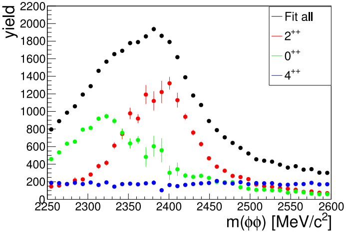
Angular distributions for energy bin at 2.4 GeV$/c^2$



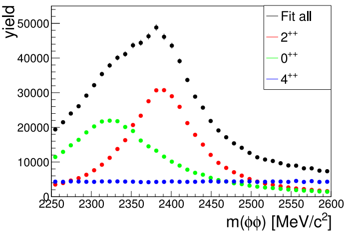
PWA of BW Toy MC Scenario

- Hypothesis containing only generated contributions achieves best fit result for each bin!

Extracted contributions

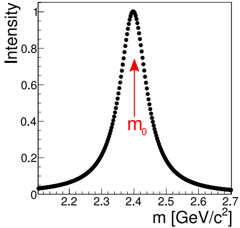


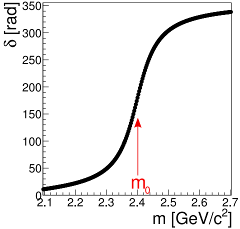
Generated contributions

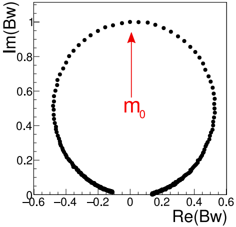


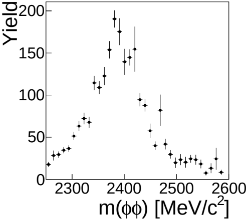
PWA of BW Toy MC Scenario

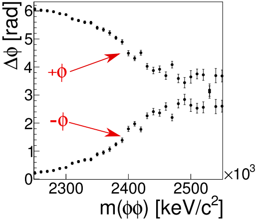
- $w = |\sum A^{S=1}_{\lambda=0}|^2 + |\sum A^{S=1}_{\lambda=-1}|^2 + |\sum A^{S=1}_{\lambda=1}|^2$
- $|Ae^{i\phi_A} + Be^{i\phi_B} + Ce^{i\phi_C} + \ldots|^2 = |Ae^{i-\phi_A} + Be^{i-\phi_B} + Ce^{i-\phi_C} + \ldots|^2$



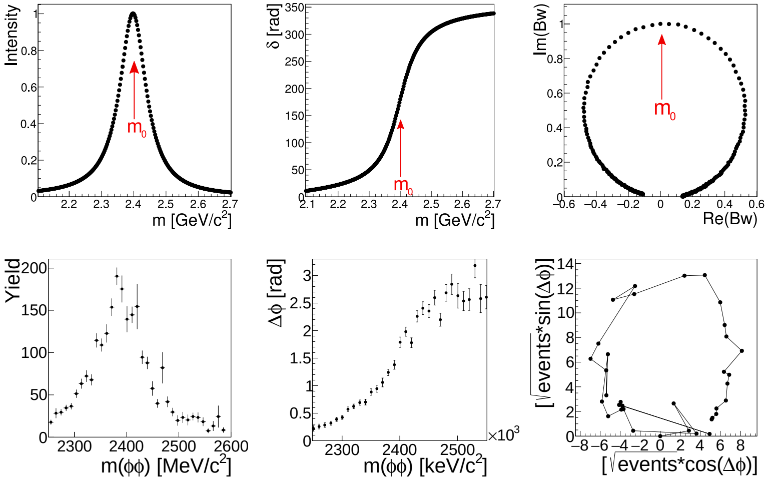








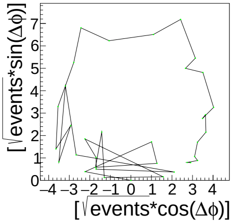
- $|Ae^{i\phi_A} + Be^{i\phi_B} + Ce^{i\phi_C} + ...|^2 = |Ae^{i-\phi_A} + Be^{i-\phi_B} + Ce^{i-\phi_C} + ...|^2$
- Ambiguity arises due to possible complex conjugation



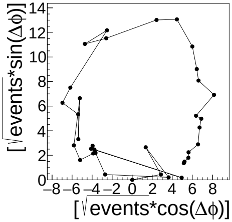
PWA of BW Toy MC Scenario

Dependence on 4^{++} to 2^{++} ratio

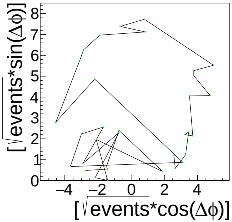
74%



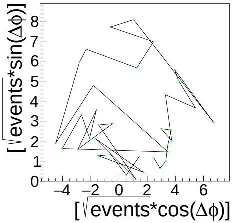
35%



15%

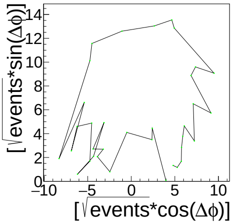


5%



Increase statistics

5%

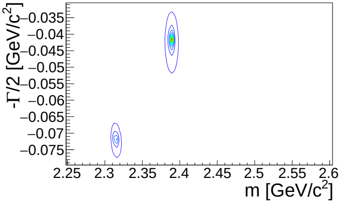


Toy MC Scenario with two 2^{++} poles (K-Matrix)

- Breit-Wigner parameterization only valid for isolated resonances far away from thresholds
- K-Matrix formalism for more realistic scenario
- P-vector approach used to describe production

$\rightarrow$Glueball Scenario with two 2^{++} poles coupling to two channels

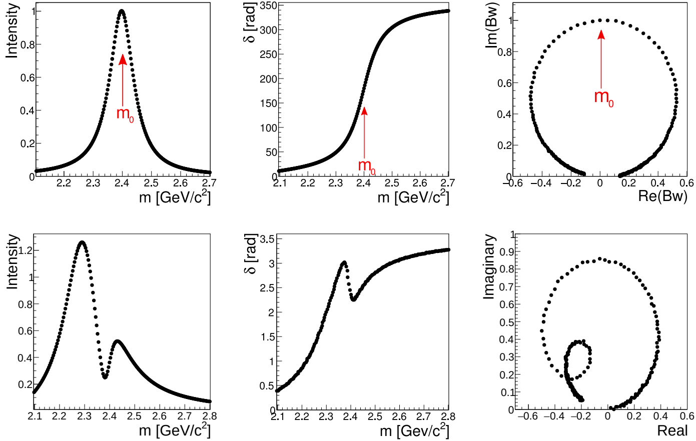
$$\bar{p}p \rightarrow X \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$$
$$\bar{p}p \rightarrow X \rightarrow K^+K^-$$



Pole	mass [GeV/c^2]	width [MeV/c^2]	$g_{K^+K^-}$	$g_{\phi\phi}$
1	2.32	144	0.1	0.64
2	2.39	83	0.47	0.57

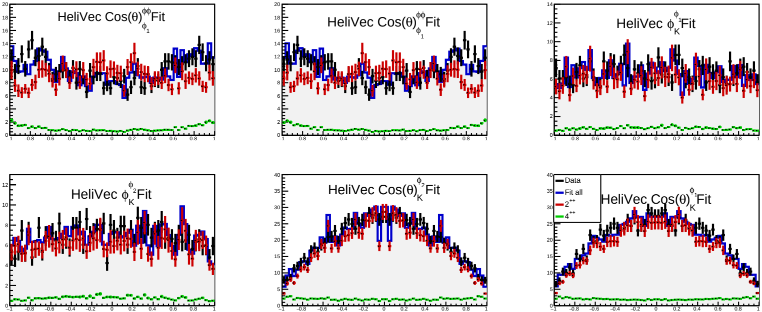
Toy MC Scenario with two 2^{++} poles (K-Matrix)

- More complex phase motions and Argand plots
- Model independent and model dependent analysis possible
  $\rightarrow$ Extraction of parameters like coupling strength and elasticity possible



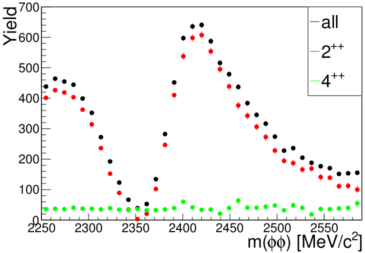
- Hypothesis containing only generated contributions achieves best fit result for each bin!

Angular distributions for energy bin at 2.4 GeV/c^2

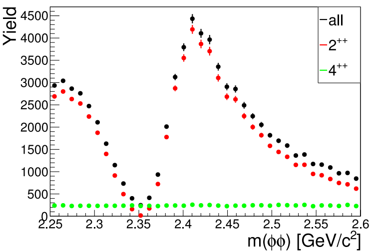


- Hypothesis containing only generated contributions achieves best fit result for each bin!

Extracted contributions

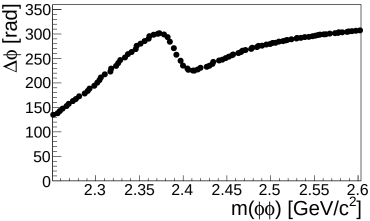


Generated contributions

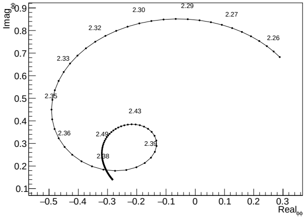


Model Independent Approach K-Matrix Scenario (Toy MC)

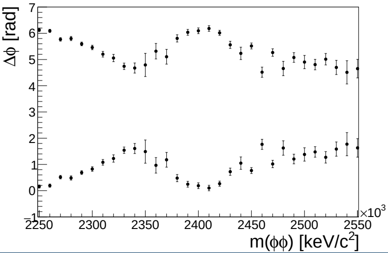
Generated $\phi\phi$ phase



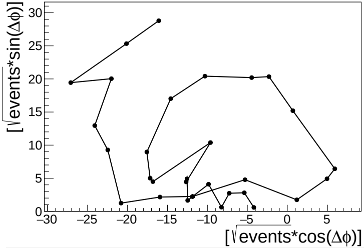
Generated $\phi\phi$ Argand plot



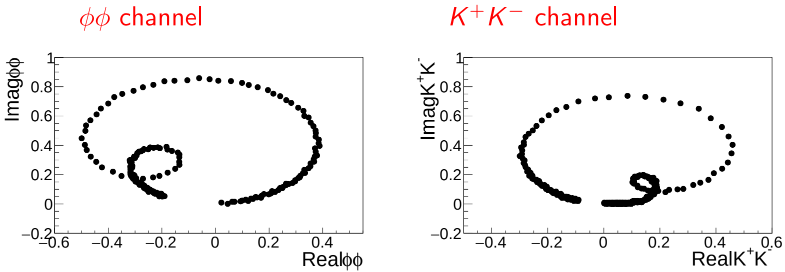
Extracted $\phi\phi$ phase



Extracted $\phi\phi$ Argand plot



Model Dependent Approach K-Matrix Scenario (Toy MC)



- All extracted parameters equal to generated ones
- Model indep. approach to identify contributing resonance + Model dep. for extracting further resonance parameters

What do we learn from Toy MC Studies?

- Separation of different contributions with model independent approach and extraction of phase motions feasible for BW and K-Matrix scenario
- Hypothesis containing only generated contributions achieves best fit result
- Procedure can be used to analyse any resonance created in a formation process
- How to deal with ambiguities
- Sensitive to the size of the "circle"?
- Studies including detector simulation and reconstruction

Reconstruction with PandaRoot

- PandaRoot release dec18p1
- Day 1 detector setup
- Ideal tracking
- Track reconstruction with kaon hypothesis
- Simulation and reconstruction of with PAWIAN generated "data" and phase space distributed events

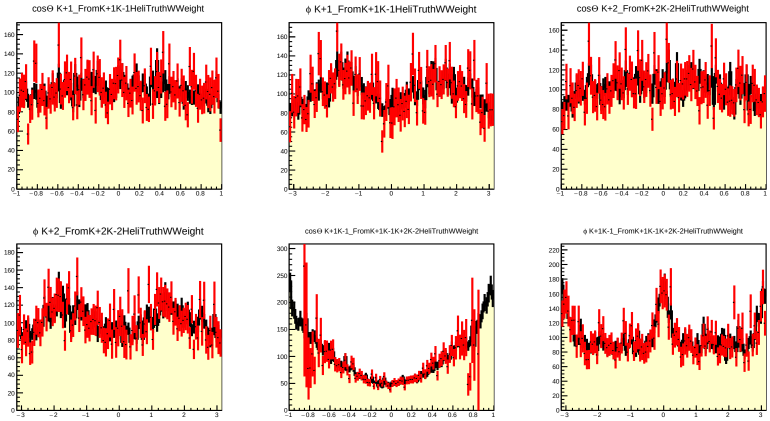
Selection Criteria

- List of $\bar{p}p$ candidates by forming all combinations of 2 K^+ and 2 K^-
- Vertex Fit (RhoKinVtxFitter) $P > 0.001$
- 4C Fit (RhoKinFitter) $P > 0.001$
  $\rightarrow$ additional cut on $\bar{p}p$ mass to eject events which violate energy conservation
- $r = \sqrt{(m(K_1K_2) - m_\phi)^2 + (m(K_3K_4) - m_\phi)^2} < 10\,\mathrm{MeV}/c^2$
- No PID requirements so far
  $\rightarrow$ More then 99% of events have 4 particles with kaon pdg code in final state
- After applying all selection criteria only one remaining combination for $> 99\%$ of events
- Eject events with more then one combination
- $11\% <$ Efficiency$(\sqrt{s}) < 24\%$

PWA with Reconstructed Events (BW Scenario)

- Proper efficiency correction and extrapolation of efficiency holes → high statistics needed
- Hypotheses test → States contributing with less then 1% with incoherent behaviour not taken into account

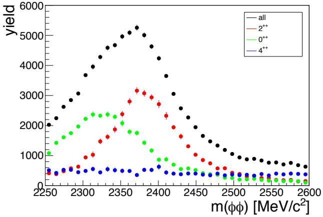
Angular distributions for energy bin at 2.25 GeV/c^2



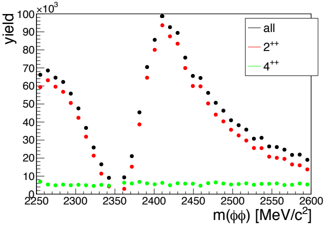
- Extraction of contributions feasible for reconstructed MC!

Extracted contributions — Generated contributions

Breit-Wigner

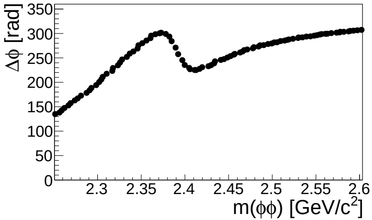


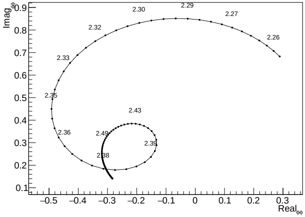
K-Matrix



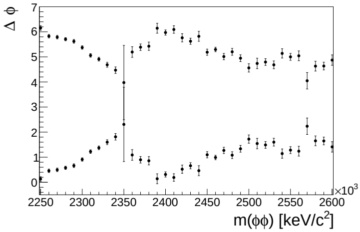
PWA with Reconstructed Events (KM Scenario)

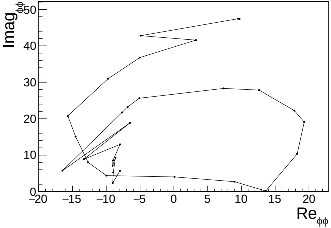
Generated Toy MC K-Matrix Scenario





Reconstructed MC K-Matrix Scenario





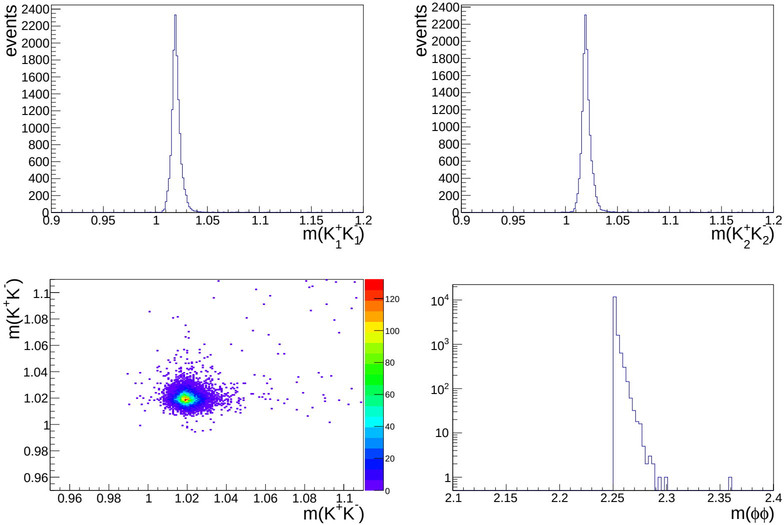
Summary and Outlook

- The reaction $\bar{p}p \to X \to \phi\phi \to 4K$ was generated with correct angular distributions using PAWIAN
  $\to$ PWA tested on simple Breit-Wigner and sophisticated K-Matrix scenario for toy MC
  $\to$ Reconstruction of generated events taken the PANDA detector into account
  $\to$ PWA feasible for reconstructed MC with efficiency correction and extrapolation $\to$ high statistics needed
- Extraction of contributions and phases feasible
- Homogeneous efficiency distribution of ϕ meson production angle important
- Ongoing background studies with generic DPM events

Release note in preparation!

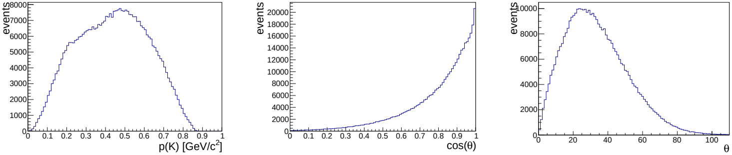
Appendix

Invariant K^+K^- mass after Vertex and 4C Fit $p_{\bar{p}} = 1.5\,\text{GeV}$

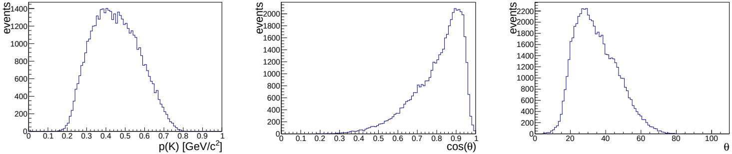


Kinematics Truth and Reco $p_{\bar{p}} = 1.5\,\mathrm{GeV}$

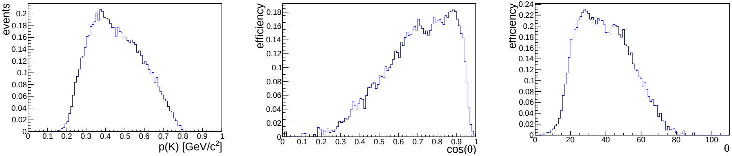
MC Truth



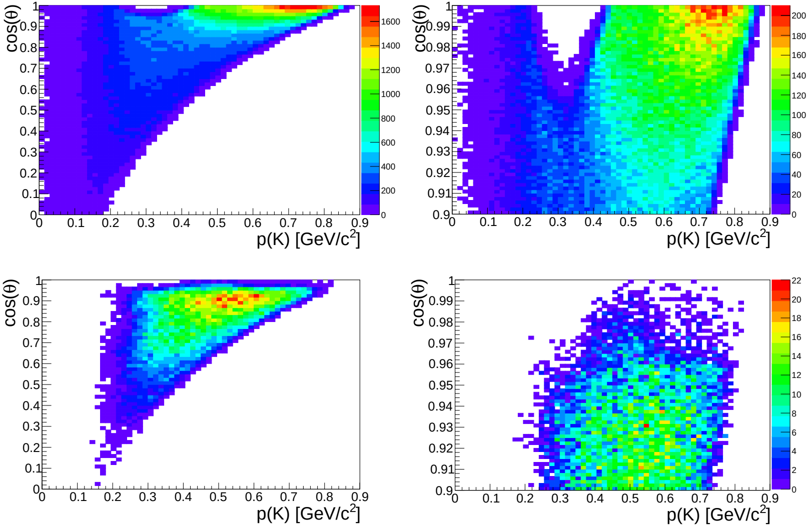
MC Reco



Efficiency

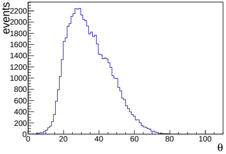


Momentum Vs. $Cos(\theta)$ $p_{\bar{p}} = 1.5\,\mathrm{GeV}$

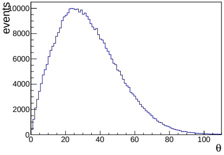


Efficiencies for Kaons

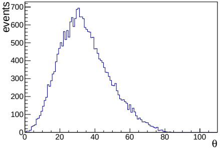
θ reco.



θ gen.



θ gen.p(K)>200MeV/c



Tracking	P [GeV/c]	θ	ϵ_K
ideal	0.2 - 1	0 - 25	63%
realistic	0.2 - 1	0 - 25	45%
ideal	0.2 - 1	25 - 100	87%
realistic	0.2 - 1	25 - 100	78%
ideal	0.1 - 0.2	25 - 100	13%
realistic	0.1 - 0.2	25 - 100	3%
ideal	1	25 - 100	92%
realistic	1	25 - 100	85%
ideal	1	0 - 25	76%
realistic	1	0 - 25	63%

- Analysis with missing kaon (slides 6/2019)
- Kaons decaying and not reaching FTS

  $\rightarrow$ Track decaying Kaons