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

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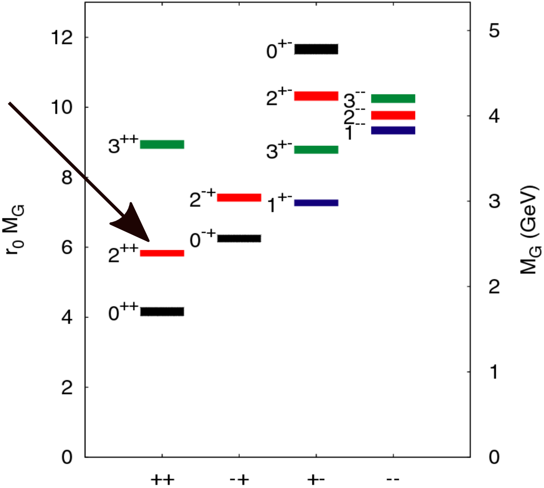
$\overline{\text{P}}$ANDA Meeting, June 2019

Motivation

- Lattice QCD predicts tensor glueball state at about $2.4\,\mathrm{GeV}/c^2$

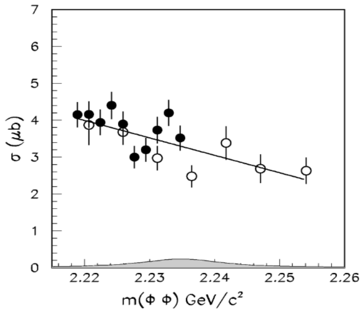


Phys.Rev. D73 (2006) 014516

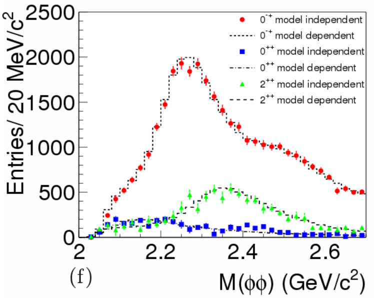
Motivation

- $\bar{p}p \to \phi\phi$ 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?

JETSET, Phys.Rev.D57,5370



BESIII, Phys.Rev.D93,112011

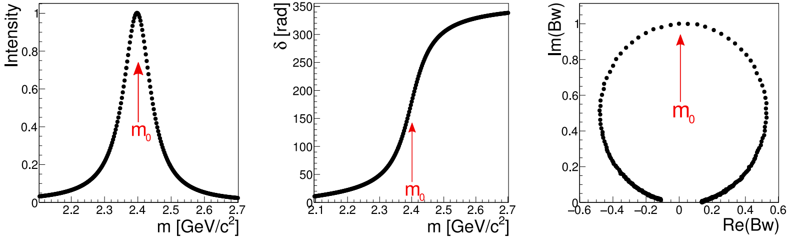


Motivation

- Scan the cross section of $\bar{p}p \to \phi\phi$ in the mass region of the tensor glueball candidate ($\sqrt{s} = (2.25 - 2.6)\,\text{GeV}$)
- 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?

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

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!

- 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

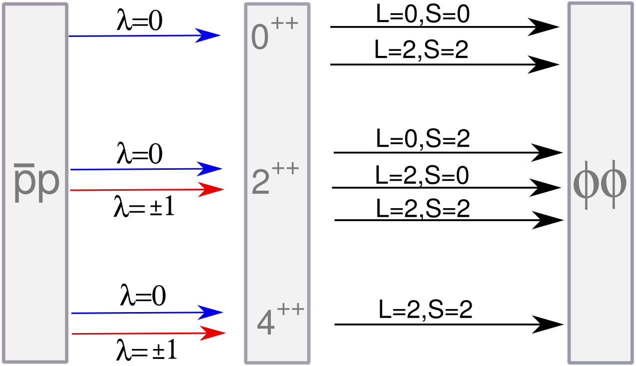
J	Singlet λ=0	J^{PC}	Triplet $\lambda = \pm 1$	J^{PC}	Triplet $\lambda = 0, \pm 1$	J^{PC}
0	$^1S_0$	0^{-+}			$^3P_0$	0^{++}
1	$^1P_0$	1^{+-}	$^3P_1$	1^{++}	$^3S_1, ^3D_1$	1^{--}
2	$^1D_2$	2^{-+}	$^3D_2$	2^{--}	$^3P_2, ^3F_2$	2^{++}
3	$^1F_3$	3^{+-}	$^3F_3$	3^{++}	$^3D_3, ^3G_3$	3^{--}
4	$^1G_4$	4^{-+}	$^3G_4$	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^{++}

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

J	Singlet λ=0	J^{PC}	Triplet $\lambda = \pm1$	J^{PC}	Triplet $\lambda = 0, \pm1$	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						

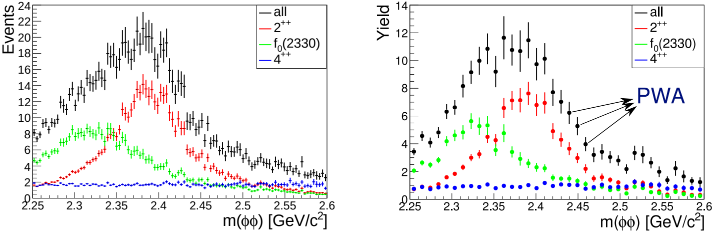
Identifying Resonances with Mass Independent PWA

- 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):



Identifying Resonances with Mass Independent PWA

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



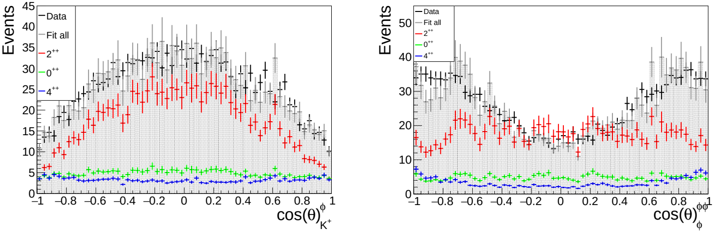
- Extracting complex amplitudes by perfoming partial wave fits for each energy bin individually using randomized start parameters
- Event based maximum likelihood fit
- Complete decay chain is taken into account
  $\bar{p}p \to X \to \phi\phi \to K^+K^-K^+K^-$

2^{++} Glueball Scenario with overlapping Resonances (BW)

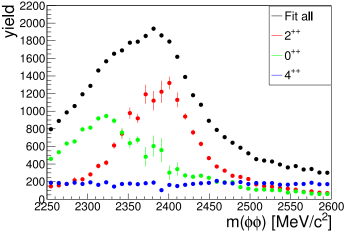
- Focus on "realistic" example:
  $\rightarrow 2^{++}$ Glueball m $= 2.4$ GeV, $\Gamma = 100$ MeV
  $\rightarrow 0^{++}$ ($f_0(2330)$) m $= 2.33$ GeV, $\Gamma = 150$ MeV
  $\rightarrow 4^{++}$ component with fixed phase
- 10000 generated Monte Carlo events per $\sqrt{s}$
  $\bar{p}p \rightarrow X \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$, $X = 2^{++}/4^{++}/f_0(2330)$
- Bin-Width = 200 keV, "gap" = 10 MeV
- Clear seperation of overlapping J^{++} resonances possible?
- How many events per bin needed for a clear identification?
- How does the identification depend on signal to J^{++} component ratio?

2^{++} Glueball Scenario with overlapping Resonances (BW)

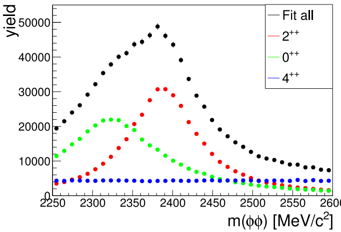
Angluar distributions for energy bin at $2.4\,\mathrm{GeV}/c^2$



Extracted contributions

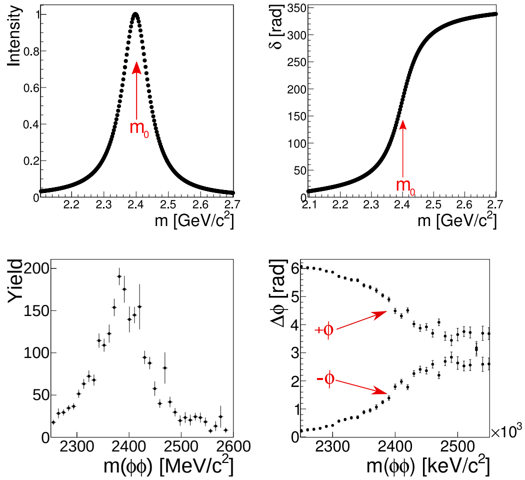


Generated contributions



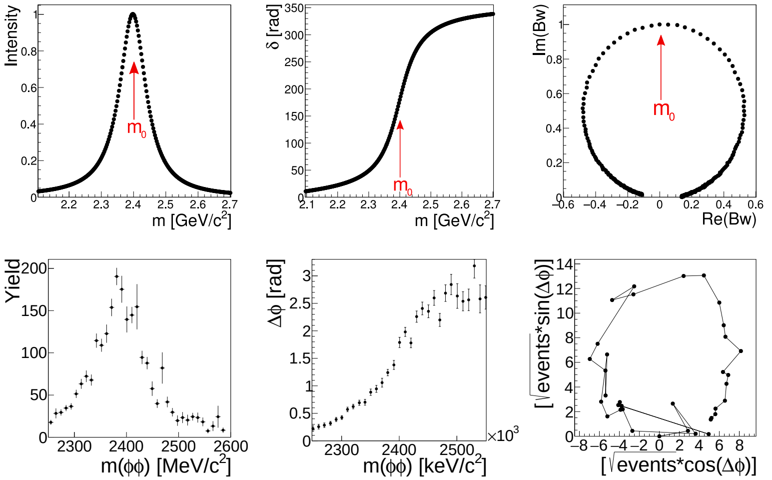
2^{++} Glueball Scenario with overlapping Resonances (BW)

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



2^{++} Glueball Scenario with overlapping Resonances (BW)

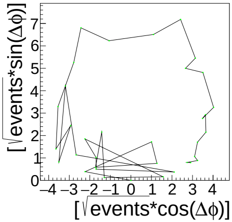
- $w = |\sum A^{S=1}_{\lambda=0}|^2 + |\sum A^{S=1}_{\lambda=-1}|^2 + |\sum A^{S=1}_{\lambda=1}|^2$
- $|Ae^{i\phi_A} + Be^{i\phi_B} + Ce^{i\phi_C} + ...|^2 = |Ae^{i-\phi_A} + Be^{i-\phi_B} + Ce^{i-\phi_C} + ...|^2$



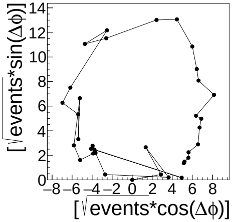
2^{++} Glueball Scenario with overlapping Resonances (BW)

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

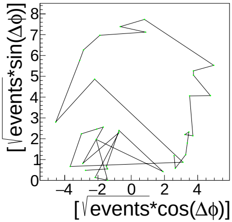
74%



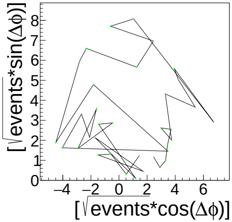
35%



15%

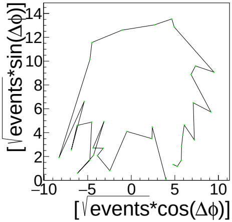


5%



Increase statistics →

5%

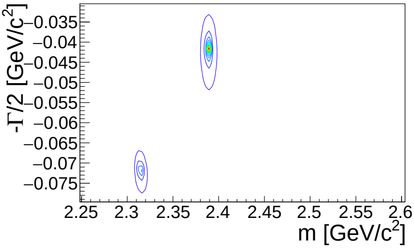


Glueball Scenario with two 2^{++} poles (K-Matrix)

- Breit-Wigner parameterization only valid for isolated resonances far away from thresholds
- K-Matrix formalism for more realistic scenario

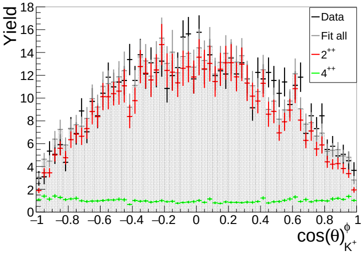
$\rightarrow$Glueball Scenario with two 2^{++} poles decaying to two channels (K-Matrix formalism)

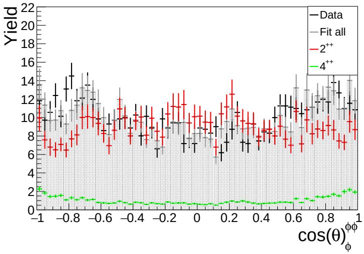
$$\bar{p}p \rightarrow X \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$$
$$\bar{p}p \rightarrow X \rightarrow K^+K^-$$



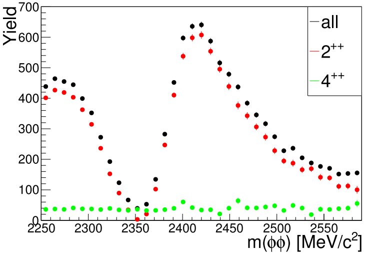
Glueball Scenario with two 2^{++} poles (K-Matrix)

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

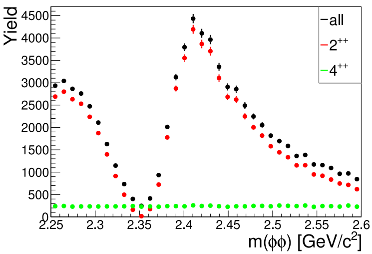




Extracted contributions

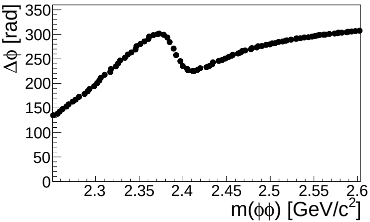


Generated contributions

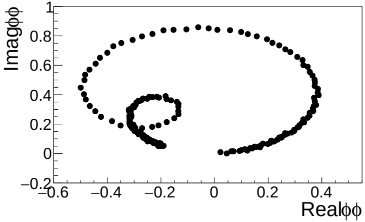


Glueball Scenario with two 2^{++} poles (K-Matrix)

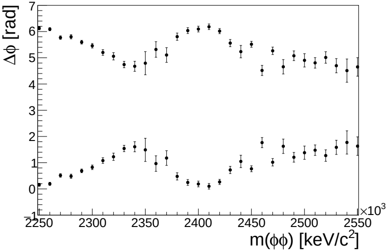
Generated $\phi\phi$ phase



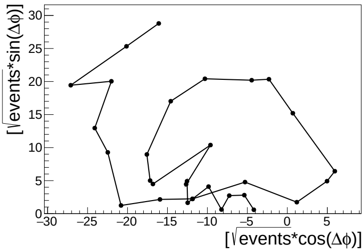
Generated $\phi\phi$ Argand plot



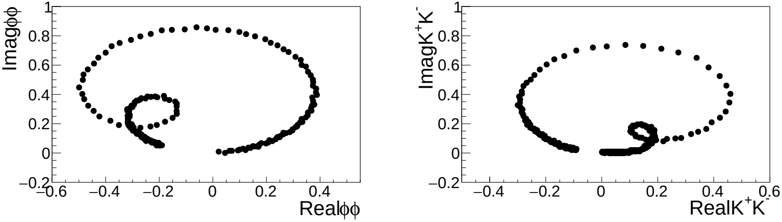
Extracted $\phi\phi$ phase



Extracted $\phi\phi$ Argand plot



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



- Results of model dependent coupled channel PWA equal to generated contributions and phases
- Sensitive to the size of the circles with mass independent PWA?
  $\rightarrow$ Further studies needed

Reconstruction with PandaRoot

Breit-Wigner Scenario

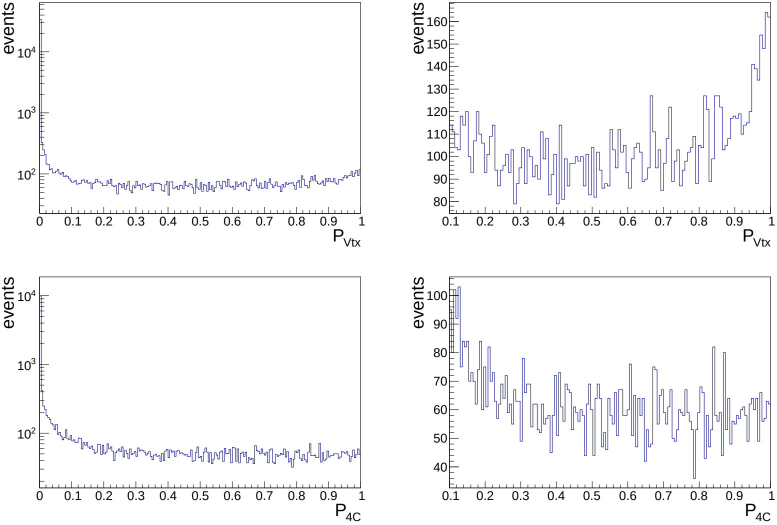
Technical aspects

- PandaRoot release dec17p2
- Phase 1 detector setup (default, gem3+fts1256)
- Ideal tracking
- Track reconstruction with kaon hypothesis
- Simulation and reconstruction of 100k with PAWIAN generated "data" events for each $\sqrt{s}$
- Simulation and reconstruction of 1M with PAWIAN generated phase space distributed events for each $\sqrt{s}$

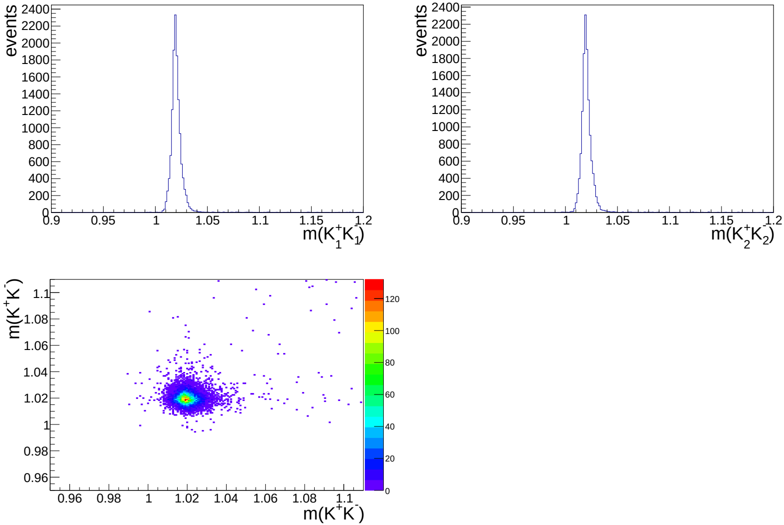
Selection Criteria $p_{\bar{p}} = 1.5\,\mathrm{GeV}$

- 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
- $10\% <$Efficiency($\sqrt{s}$)$< 20\%$

Probabilites Vertex and 4C Fit $p_{\bar{p}} = 1.5\,\mathrm{GeV}$

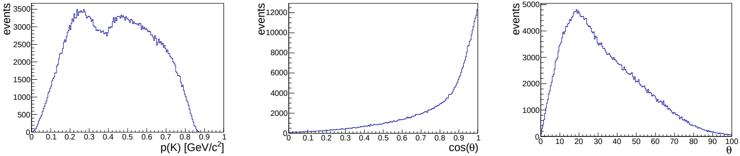


Invariant K^+K^- mass after Vertex and 4C Fit $p_{\bar{p}} = 1.5\,\mathrm{GeV}$

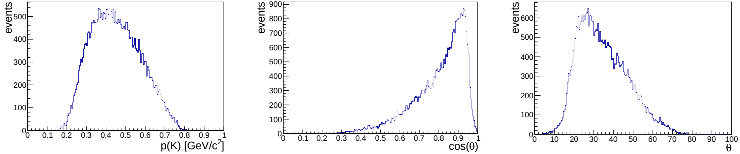


Kinematics Truth and Reco $p_{\bar{p}} = 1.5\,\text{GeV}$

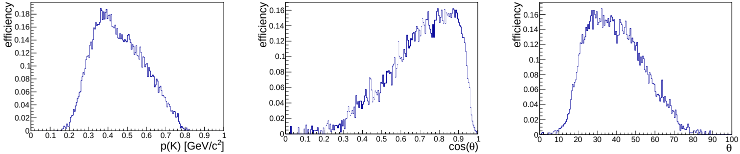
MC Truth



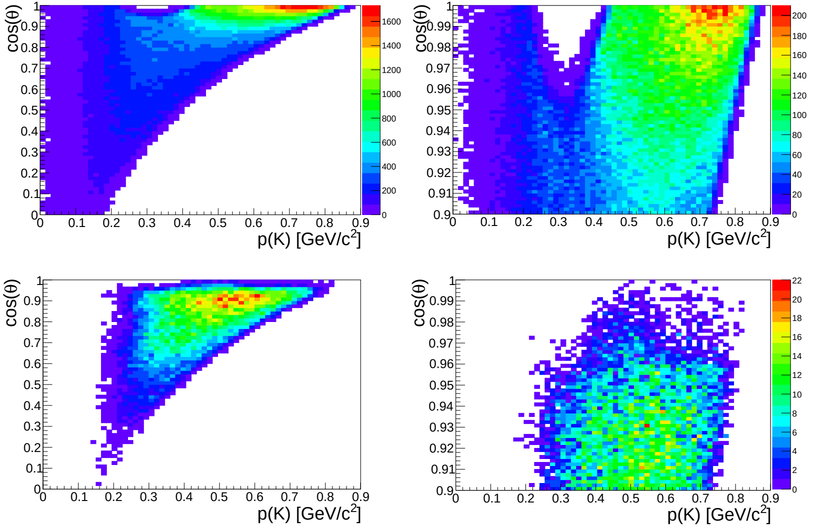
MC Reco



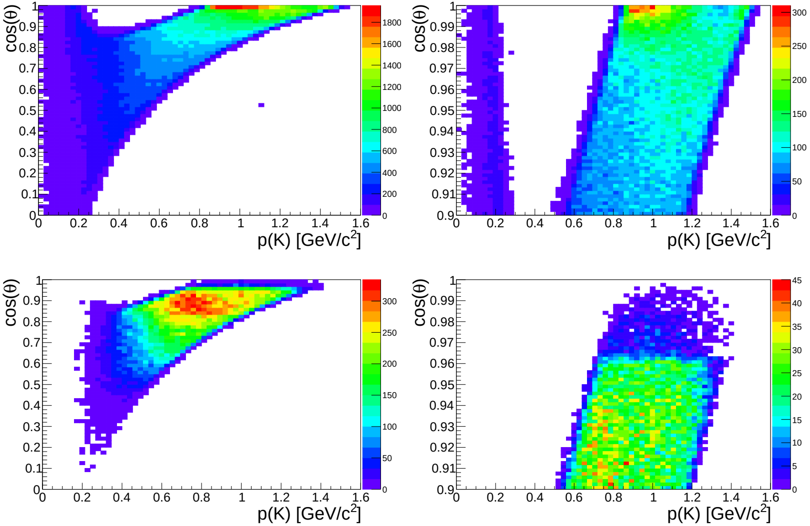
Efficiency



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

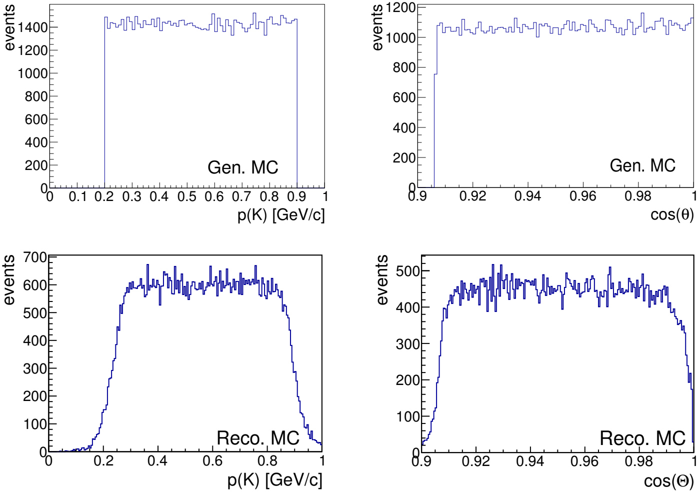


Momentum Vs. $Cos(\theta)$ $p_{\bar{p}} = 2.5\,\text{GeV}$

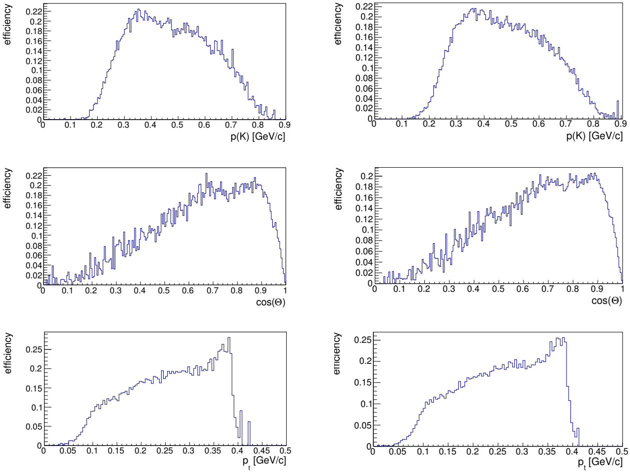


→ Loss of tracks not due to low kaon momenta

Box Generator for single Kaon studies: Flat Distribution in 0.2 GeV/c < p(K)< 0.9 GeV/c and 0.9<cos(Θ)< 1 (March 2018)



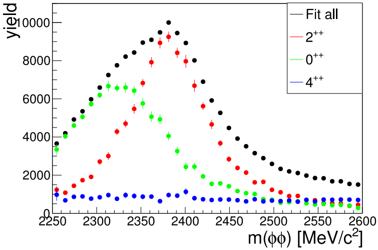
Phase 1 detector setup | Full detector setup



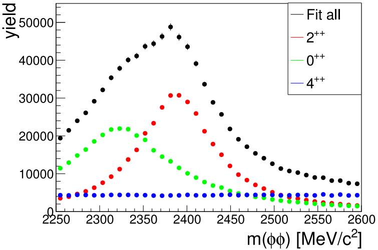
→ Loss of tracks not due to phase 1 detector setup

Partial Wave Analysis with Reconstructed Events

Extracted contributions



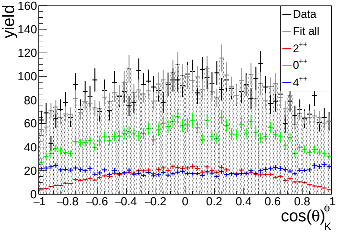
Generated contributions

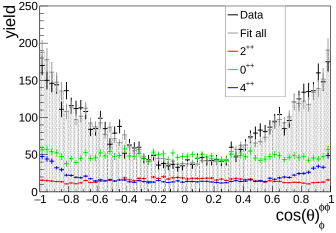


Contribution at $\sqrt{s} = 2.25$	Ideal	PandaRoot
all	50010.3	50010.1
2^{++}	9202.5	15025.4
4^{++}	11632.2	11290.2
0^{++}	28776.6	42464.1

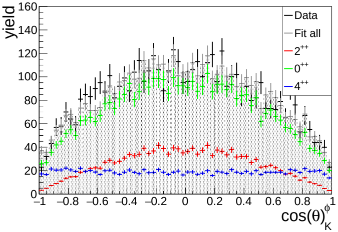
$\rightarrow$ Extracted 2^{++} and 0^{++} contributions not in agreement with generated ones !

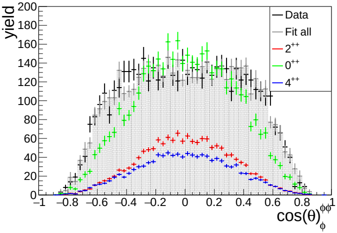
Generated angular distribution





Reco angular distribution



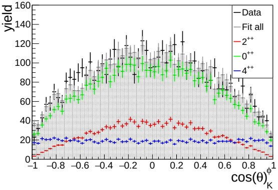


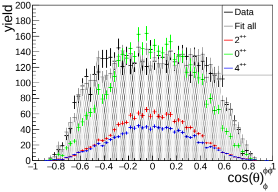
$\rightarrow$Differences due to loss of kaons with small decay angles?

Partial Wave Analysis of ideal data with $\theta_K > 20^\circ$

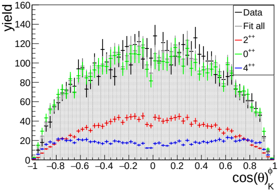
- Eject all events of generated data sample with $\theta_K < 20^\circ$

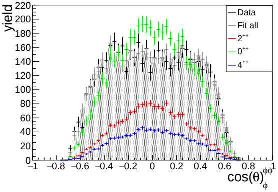
Reco angular distribution





Generated angular distribution with $\theta_K > 20^\circ$





- Results of PWA with cutted angluar distribution of ideal data sample similar to results of PWA with PandaRoot reconstruction

Partial Wave Analysis of ideal data with $\theta_K > 20^\circ$

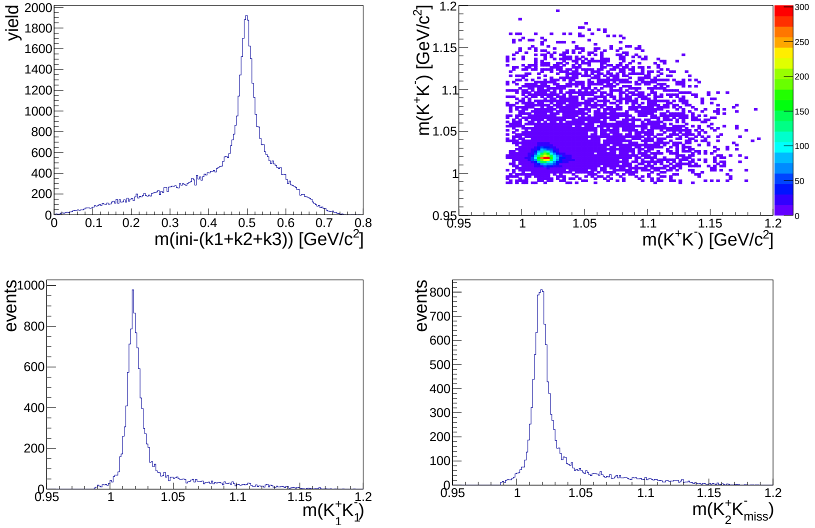
Contribution $\sqrt{s} = 2.25$	Ideal	PandaRoot	Ideal with $\theta_K > 20^\circ$
all	50010.3	50010.1	49950.1
2^{++}	9202.5	15025.4	17873.6
4^{++}	11632.2	11290.2	10258
0^{++}	28776.6	42464.1	48592.5

- Even for generated data samples, without detector efficiency included, no proper extraction of contributions possible if kaons with small decay angles get lost
- Further cutting on angluar distribution reveals:
  $\rightarrow$ Proper PWA possible for loss of kaons with $\theta_K < 6^\circ$
- Reconstruction of tracks down to $\theta_K \sim 6^\circ$ absolutley needed for PWA!
- Try different analysis approach

Analysis with one missing Kaon

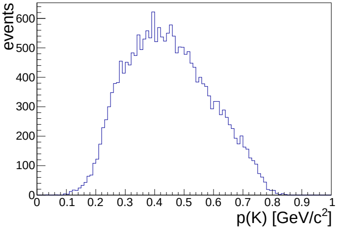
- Require at least 3 Kaons in final state
- Determination of missing four vector via initial state and 3 reconstructed tracks
- Cut on missing mass $(m_{miss} - m_K) < 0.03$ and set kaon mass
- $r = \sqrt{(m(K_1K_2) - m_\phi)^2 + (m(K_3m_{miss}) - m_\phi)^2} < 15\,\text{MeV}/c^2$
- Efficieny two times higher then with previous analysis
- Cut on invariant $p_{\bar{p}}$ mass for better comparison with previous analysis

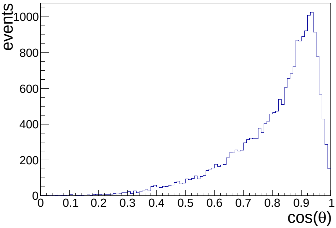
Analysis with one missing Kaon



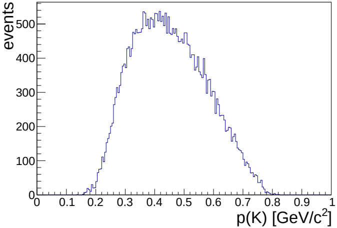
Analysis with one missing Kaon

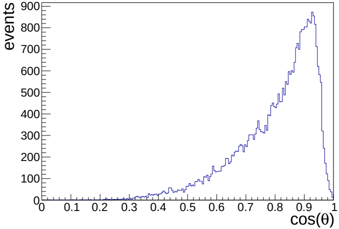
New selection





Old selection





- Slightly better efficiency for small angles then previous analysis

Analysis with one missing Kaon

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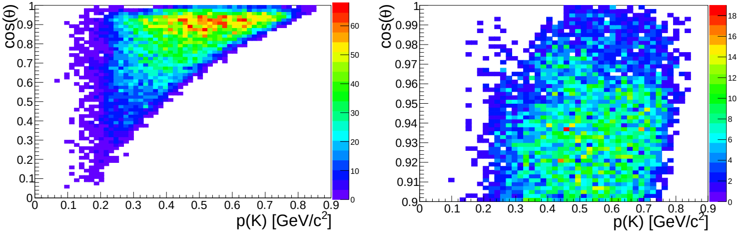
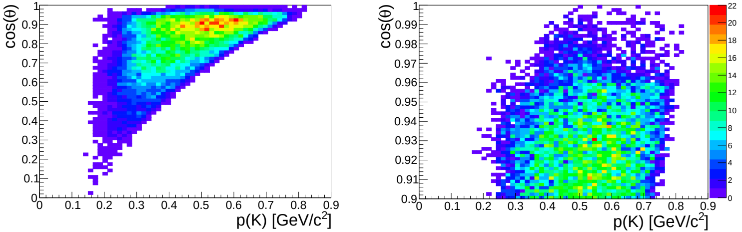


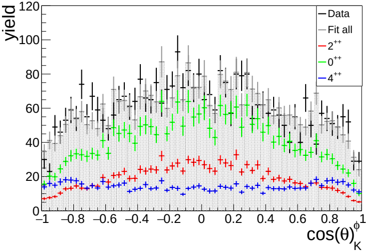
Old selection

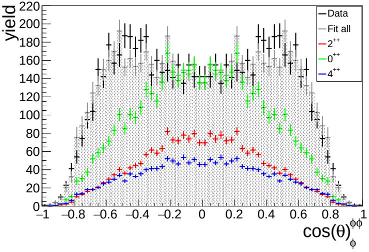


- Good enough for proper PWA?

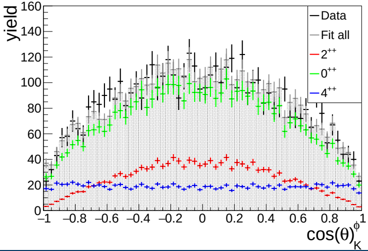
PWA with Reconstructed Events (Missing Kaon Analysis)

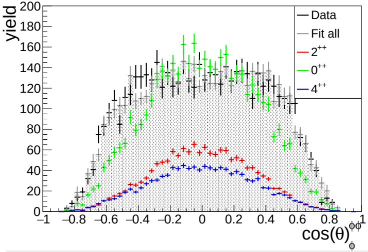
Reco angular distribution missing kaon





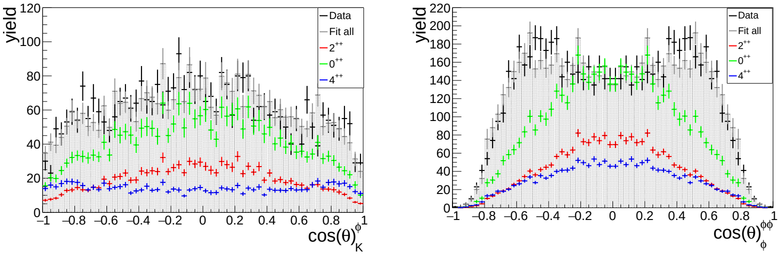
Reco angular distribution 4 reconstructed tracks



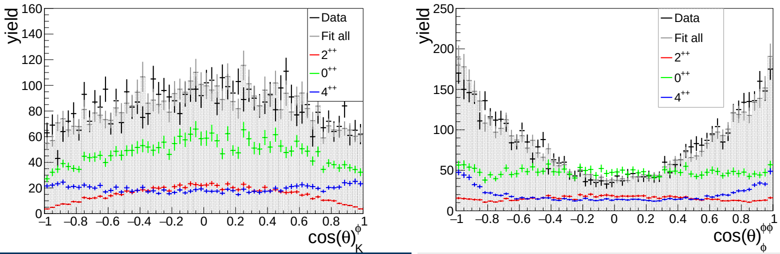


PWA with Reconstructed Events (Missing Kaon Analysis)

Reco angular distribution missing kaon



Generated angular distribution



PWA with Reconstructed Events

Contrib.	Ideal	PandaRoot	Ideal with $\theta_K > 20°$	PandaRoot$_{missK}$
all	50010.3	50010.1	49950.1	35830
2^{++}	9202.5	15025.4	17873.6	11533.9
4^{++}	11632.2	11290.2	10258	8538.3
0^{++}	28776.6	42464.1	48592.5	24824

- No proper extraction of contributions possible for both analysis approaches
- The $\overline{\text{P}}$ANDA detector should have the ability to reconstruct kaons with small decay angles to analyse the reaction $\bar{p}p \rightarrow \phi\phi$

Summary

1. Generated data samples:
   - Separation of different J^{++} contributions with a model independent approach and extraction of phase motions feasible for discussed scenarios
   - Quality of separation depends on number of signal and number of background events and not on ratio
   - Precedure can be used to analyse any resonance created in formation processes
2. Generated data samples:
   - Kaons with decay angle down to $\sim 6^\circ$ need to be reconstructed to perform proper PWA
3. Simulation and reconstruction with PandaRoot:
   - Low efficiency for kaons with decay angles below 20°
   - No reconstruction of kaons with decay angles below 10° for two different analysis approaches
   - No proper PWA possible with reconstructed events so far
4. Fastsim as cross check?

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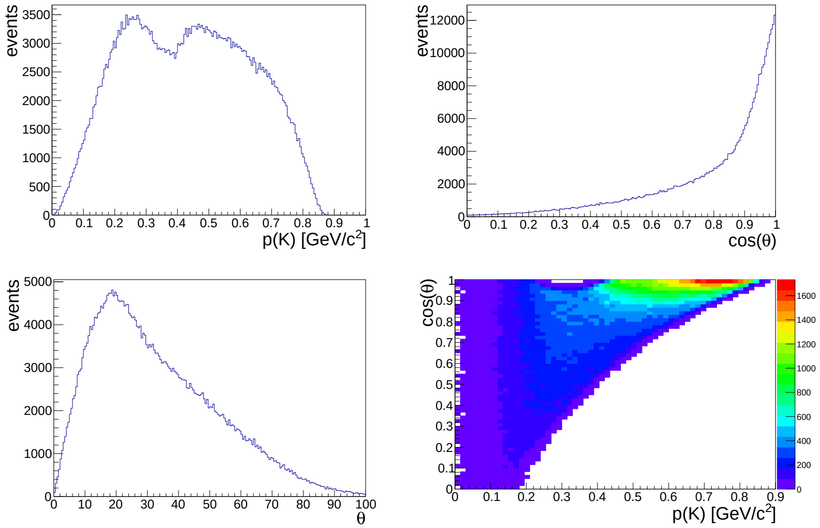
Backup

Monte Carlo Truth Kinematics $p_{\bar{p}} = 1.5\,\text{GeV}$



Monte Carlo Truth Kinematics $p_{\bar{p}} = 1.5\,\mathrm{GeV}$