# Feasibility Studies of $\bar{p}p \to \phi\phi$

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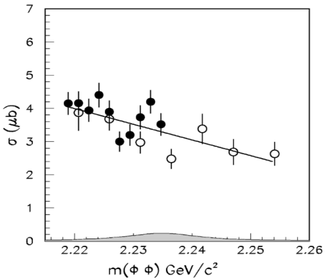
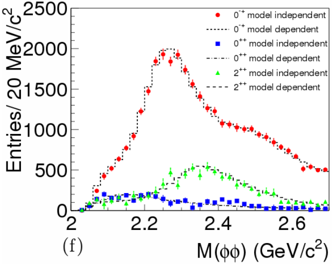
# Motivation

- Lattice QCD calculations for tensor glueball $\rightarrow m_{2^{++}} \approx 2.4\,\text{GeV}/c^2$

  *Phys.Rev. D73 (2006) 014516*
- $\bar{p}p \rightarrow \phi\phi$ offers gluonrich environment
- JETSET experiment: $\bar{p}p \rightarrow \phi\phi$ cross section exceeds expectations by two order of magnitude *JETSET, Phys.Rev.D57,5370*
- Hint for intermediate glue?
- BNL and BESIII: Observation of $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ in $\pi^- p \rightarrow \phi\phi n$ and $J/\psi \rightarrow \gamma\phi\phi$ *BNL, Phys.Lett.B201,568-572, BESIII, Phys.Rev.D93,112011*



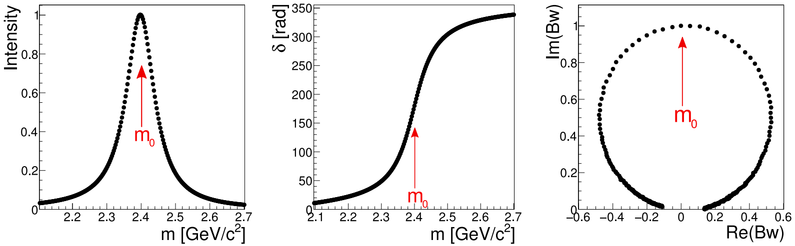



# Motivation

- Scan the $\bar{p}p \to \phi\phi$ cross section in the mass region of the observed tensor resonances ($2.25 - 2.6\,\mathrm{GeV}$)
  $\to$ $2^{++}$ resonances are produced in formation
- Identify resonances in the $\phi\phi$ system by means of a partial wave analysis
- Identifying contributing states?
  $\to$ Toy MC studies
- Identifying contributing states including acceptance/resolution of the $\overline{\mathrm{P}}$ANDA detector
  $\to$ Study of simulated and reconstructed MC
- PWA software PAWIAN is used

# Phase Motions of BW Resonances

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!

1. Model independent PWA gives hints about contributing resonances
2. Model dependent PWA gives further information (pole positions, coupling strengths etc.)

# $\bar{p}p$ Annihilation

- 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

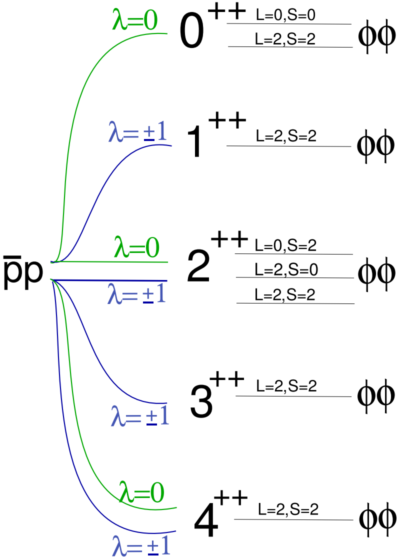
| J | Singlet $\lambda$=0 | $J^{PC}$ | Triplet $\lambda = \pm 1$ | $J^{PC}$ | Triplet $\lambda = 0, \pm 1$ | $J^{PC}$ |
|---|---|---|---|---|---|---|
| 0 | $^1S_0$ | $0^{-+}$ | | | $^3P_0$ | $0^{++}$ |
| 1 | $^1P_0$ | $1^{+-}$ | $^3P_1$ | $1^{++}$ | $^3S_1, ^3D_1$ | $1^{--}$ |
| 2 | $^1D_2$ | $2^{-+}$ | $^3D_2$ | $2^{--}$ | $^3P_2, ^3F_2$ | $2^{++}$ |
| 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 | $^1I_6$ | $6^{-+}$ | $^3I_6$ | $6^{--}$ | $^3H_6, ^3J_6$ | $6^{++}$ |

# $\bar{p}p$ Annihiliation

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

| J | Singlet $\lambda$=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 | | | | | | |

# $\bar{p}p$ Annihiliation




- $L$ = Angular momentum
- $S$ = Spin
- $\lambda$ = Helicity
- $\phi \to K^+K^-$ only possible via $L = 1, S = 0$
- Different production and decay modes for intermediate resonances
  $\to$ 6 partial waves for $X = 2^{++}$
- Results shown for partial wave $2^{++}{}_{\lambda=0/L=0,S=0}$

# Weight Function and Selection of Hypotheses

- $w = \left|\sum A^{S=0}_{\lambda=0}\right|^2 + \left|\sum A^{S=1}_{\lambda=0}\right|^2 + \left|\sum A^{S=1}_{\lambda=-1}\right|^2 + \left|\sum A^{S=1}_{\lambda=1}\right|^2$
- Since the full decay tree is taking into account, the weight function contains the transition amplitudes $X \to \phi_1\phi_2$, $\phi_1 \to K_1^+K_1^-$ and $\phi_2 \to K_2^+K_2^-$
- Which resonances are contributing?
  $\to$ Hypotheses with assumptions about contributing states, production and decay amplitudes
  $\to$ Which Hypothesis fits the best?
- AIC and BIC information criteria from model selection theory

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

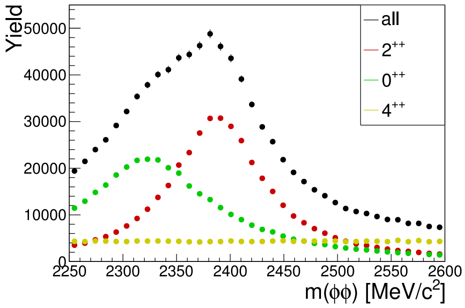
1. $\text{AIC} = -2 \cdot ln(\mathcal{L}) + 2 \cdot k$     $k$ = number of free parameters
2. $\text{BIC} = -2 \cdot ln(\mathcal{L}) + k \cdot ln(n)$     $n$ = number of data points

# Toy MC Studies

1. Breit-Wigner Scenario
2. K-Matrix Scenario

# Generated Data Sets

- 36 data points between 2.25 GeV and 2.6 GeV
- Distance between each point = 10 MeV
- Bin width each point = 200 keV → Due to high HESR beam resolution
- $10^4$ toy MC events per scan point with $\bar{p}p \to X \to \phi\phi \to K^+K^-K^+K^-$, $X = 0^{++}, 2^{++}, 4^{++}$
- All dynamics described by relativistic BW functions



# Mass Independent PWA

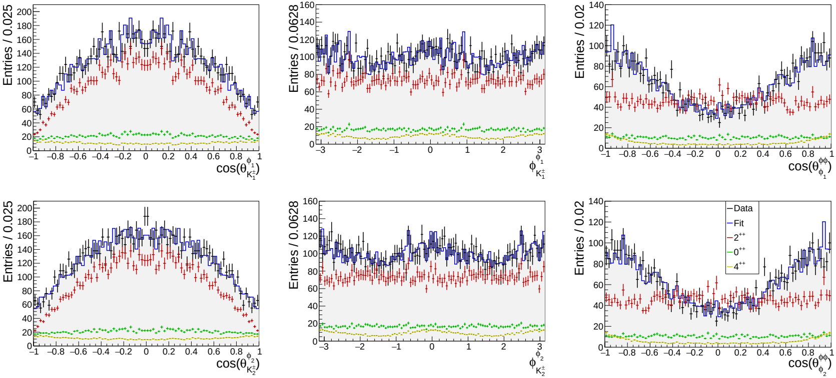
- Decay dynamics fixed for each scan point
  $\rightarrow$ No need to chose a model
  $\rightarrow$ Extracting complex amplitudes by performing individual partial wave fits for each scan point
  $\rightarrow$ Event based maximum likelihood fits
- 31 possible hypotheses need to be fitted to the data
  $\rightarrow$ Selection of best Hypothesis via AIC and BIC (AIC+BIC) criteria
- Best Hypothesis :
  30 scan points $\rightarrow$ $0^{++}2^{++}4^{++}$
  6 scan points $\rightarrow$ $0^{++}2^{++}4^{++} + X$
- Contribution of $X < 1\%$ and scan points appear arbitrary in mass range $\rightarrow$ can be neglected

| AIC+BIC | Hypothesis at($\sqrt{s} = 2.4$ GeV) |
|---|---|
| $-47589.5$ | $0^{++}2^{++}4^{++}$ |
| $-47575.5$ | $0^{++}2^{++}4^{++}1^{++}$ |
| $-46886.3$ | $0^{++}2^{++}4^{++}3^{++}$ |
| $-46483.5$ | $0^{++}2^{++}1^{++}$ |

| AIC+BIC | Hypothesis at($\sqrt{s} = 2.42$ GeV) |
|---|---|
| $-47150.7$ | $0^{++}2^{++}4^{++}3^{++}$ |
| $-47132.7$ | $0^{++}2^{++}4^{++}$ |
| $-46682.7$ | $0^{++}2^{++}4^{++}1^{++}3^{++}$ |
| $-46661.1$ | $0^{++}2^{++}4^{++}1^{++}$ |

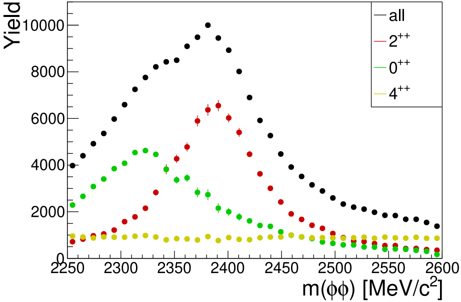
# Mass Independent PWA - Angular Distributions

Fit in good agreement with generated data
Angular distributions for bin at 2.4 GeV



# Mass Independent PWA - Contributions

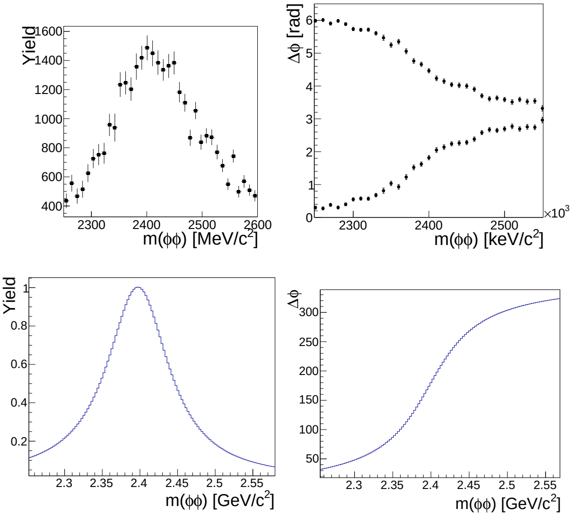
- Contributions in good agreement with generated ones




- $w = |\sum A^{S=1}_{\lambda=0}|^2 + |\sum A^{S=1}_{\lambda=-1}|^2 + |\sum A^{S=1}_{\lambda=1}|^2$
- $|Ae^{i\phi_A} + Be^{i\phi_B} + Ce^{i\phi_C} + ...|^2 = |Ae^{i-\phi_A} + Be^{i-\phi_B} + Ce^{i-\phi_C} + ...|^2$
- Following results shown for $2^{++}{}_{\lambda=0/L=0/S=2}$ (fixed decay amplitude and phase)

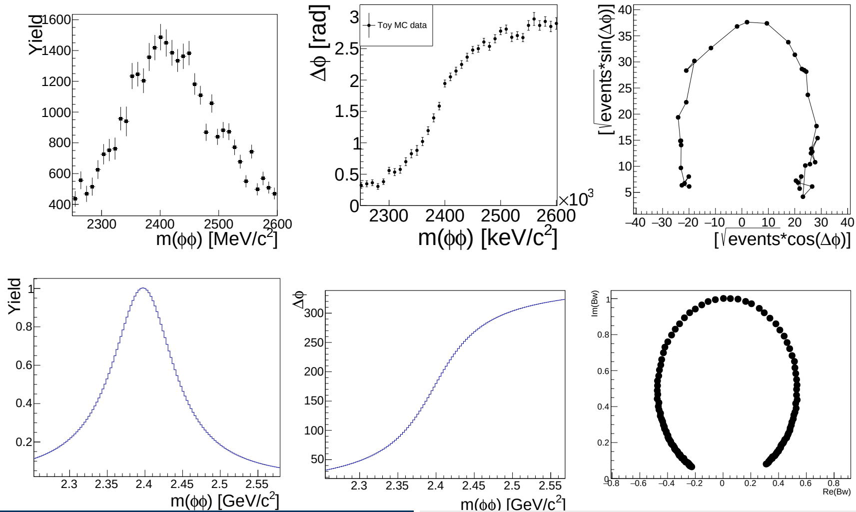
# Mass Independent PWA - Contributions and Phases

→ "Trivial ambiguites" NOT to be confused with "Non-trivial ambiguities" seen in $J/\psi \to \gamma\pi^0\pi^0$... *BESIII, Phys.Rev.D92,5*



# Mass Independent PWA - Phases and Ambiguities

$\rightarrow$ "Trivial ambiguites" NOT to be confused with "Non-trivial ambiguities" seen in $J/\psi \rightarrow \gamma\pi^0\pi^0$...*BESIII, Phys.Rev.D92,5*



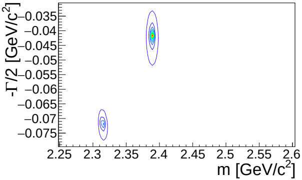
# Toy MC Studies

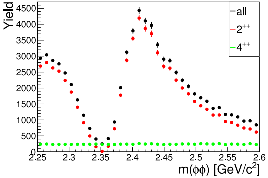
1. Breit-Wigner Scenario

2. K-Matrix Scenario

- Mass range, bin width and distance between scan points equal to BW scenario
- $10^4$ toy MC events per scan point with $\bar{p}p \to X \to \phi\phi \to K^+K^-K^+K^-$, $X = 2^{++}, 4^{++}$
- $2^{++}$ dynamics described by K-Matrix formalism with two poles decaying to two channels $\bar{p}p \to X \to \phi\phi$, $\bar{p}p \to X \to K^+K^-$

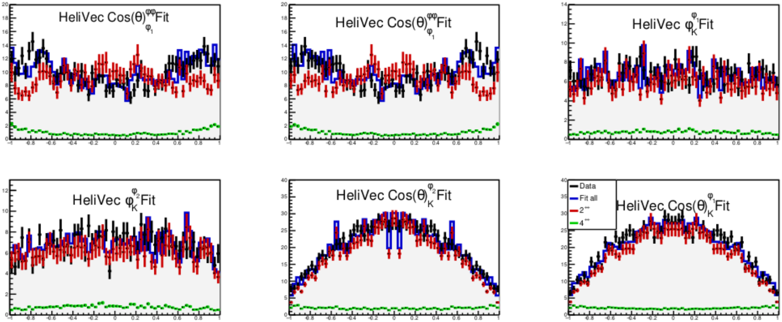
| Pole | mass [GeV/$c^2$] | width [MeV/$c^2$] | $g_{K^+K^-}$ | $g_{\phi\phi}$ |
|---|---|---|---|---|
| 1 | 2.32 | 144 | 0.1 | 0.64 |
| 2 | 2.39 | 83 | 0.47 | 0.57 |



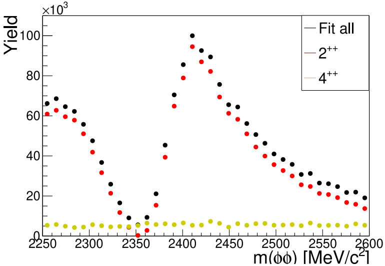



## Mass Independent PWA - Angular Distributions

- Hypotheses tests and selection of hypothesis equal to BW scenario
- Hypothesis containing only $2^{++}4^{++}$ chosen as best hypothesis
- Angular distributions for bin at 2.4 GeV



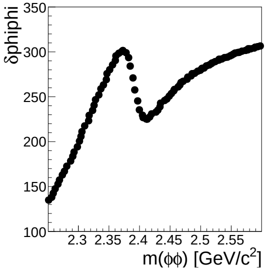
# Mass Independent PWA - Contributions and Phases

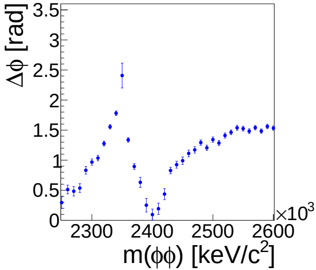



- Contributions in good agreement with generated ones
- "Non-trivial" ambiguities and visible extracted phase motion
- Extracted phase is not! T-Matrix phase (Work in progess)

T-Matrix phase

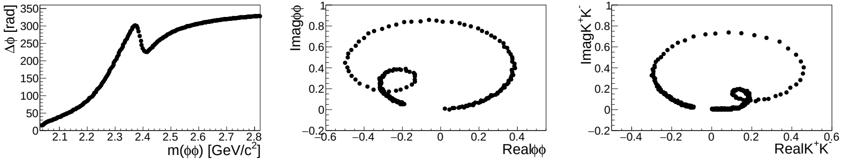
Extracted $\phi_{\lambda=0,L=0,S=2}$



# Model Dependent Coupled Channel PWA

- Identifying contributing states via mass independent PWA
  $\rightarrow$ Choose reasonable model for model dependent PWA
- Gives access to coupling strength, pole positions etc.
- Coupling of multiple channels possible




- Performance of coupled channel PWA with
  $\bar{p}p \rightarrow X \rightarrow \phi\phi$
  $\bar{p}p \rightarrow X \rightarrow K^+K^-$

# Studies Including Detector Simulation

1. Reconstruction with PandaRoot
2. PWA

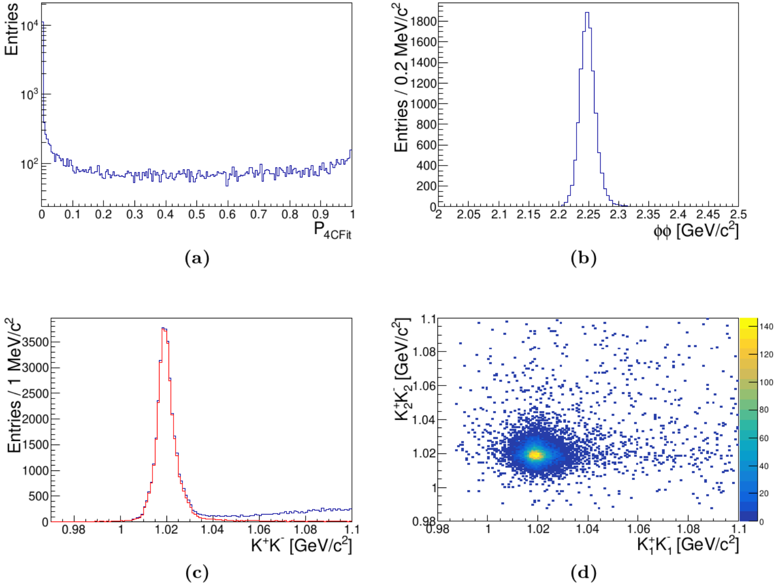
# Technical Aspects

- PandaRoot release oct19
- Phase 1 detector setup
- Ideal track reconstruction
- Track reconstruction with kaon hypothesis
- Each scan point is simulated and reconstructed individually
- Simulation of generated Events containing proper angular distributions
- Simulation of PHP distributed events

# Event Selection

- List of $\bar{p}p$ candidates by forming all combinations of 2 $K^+$ and 2 $K^-$
- Loose PID
- 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
- $r = \sqrt{(m(K_1K_2) - m_\phi)^2 + (m(K_3K_4) - m_\phi)^2} < 12\,\mathrm{MeV}/c^2$
- 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

# Event Selection for $p_{\bar{p}} = 1.5\,\mathrm{GeV}$

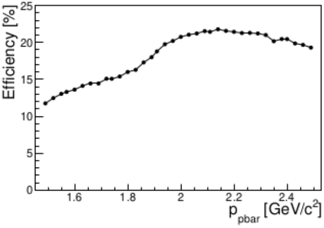


# DPM Background Studies at $p_{\bar{p}} = 1.5\,\mathrm{GeV}$

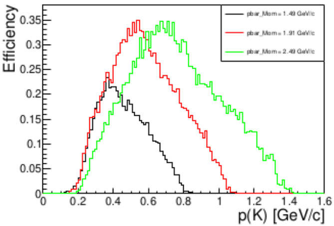
- Selected data sample needs to be as clean as possible for PWA
- $C = \frac{N_{bg}}{N_{data}} = \frac{\sigma_{bg} \cdot \epsilon_{bg}}{\sigma_{bg} \cdot \epsilon_{bg} + \sigma_{signal} \cdot BR(\phi \to K^+K^-)^2 \cdot \epsilon_{signal}} < 0.01$
  $\frac{\sigma_{bg}}{\sigma_{signal}} \sim 3.33 \cdot 10^4$
  $\epsilon_{signal} \sim 11\%$
  $BR(\phi \to K^+K^-) = 49\%$
  $\to \epsilon_{bg} < 8 \cdot 10^{-9}$
  $\to N_{bg,gen} = \frac{1}{\epsilon_{bg}} > 1.25 \cdot 10^8$
- $1.27 \cdot 10^8$ DPM events generated of which $8 \cdot 10^6$ were fully simulated and reconstructed due to pre-filter
- Analysis techniques for 4K events (future): Consider in PWA or Q-factor method *(Journal of Instrumentation 4 no.10, 2009, P10003)*

| Final State | No. evts. (Without PID) | No. evts. (Final event selection) |
|---|---|---|
| $\pi^+\pi^-\pi^+\pi^-$ | 10 | 0 |
| $\bar{p}p\pi^+\pi^-$ | 12 | 0 |
| $K^+K^-K^+K^-$ | 4 | 4 |

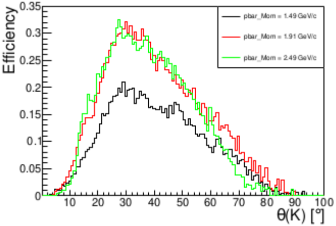
# Selection efficiencies




(a)




(b)




(c)

# Approx. Run Time

- Run time taking into account: signal cross sections (JETSET), efficiency, luminosity (HESR) *K. Götzen, Average Luminosities and Event Rates at PANDA, 2015*
- Run time for 36 scan points with $10^4$ reconstructed events per point $< 1$ week

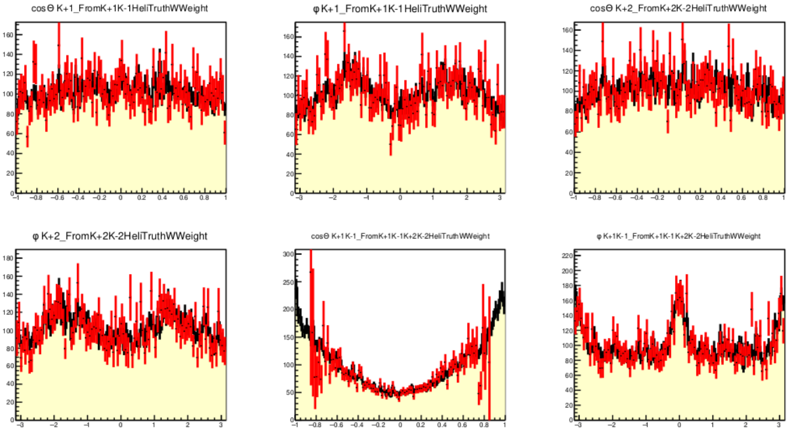
| $p_{\bar{p}}$ [GeV/c] | 1.49 | 1.52 | 1.55 | 1.57 | 1.60 | 1.63 |
|---|---|---|---|---|---|---|
| $\epsilon$ [%] | 11.75 | 12.47 | 13.04 | 13.30 | 13.61 | 14.12 |
| $\overline{L}_{\mathrm{HESRr}}$ [$(\mathrm{nb\cdot d})^{-1}$] | 788 | 792 | 796 | 800 | 804 | 809 |
| Run time [h] | 3.6 | 3.4 | 4.8 | 4.7 | 4.6 | 4.4 |
| $p_{\bar{p}}$[GeV/c] | 2.11 | 2.14 | 2.17 | 2.20 | 2.23 | 2.26 |
| $\epsilon$ [%] | 21.43 | 21.78 | 21.56 | 21.43 | 21.27 | 21.29 |
| $\overline{L}_{\mathrm{HESRr}}$ [$(\mathrm{nb\cdot d})^{-1}$] | 875 | 878 | 881 | 885 | 888 | 891 |
| Run time [h] | 2.7 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 |

# Studies Including Detector Simulation

1. Reconstruction with PandaRoot
2. PWA

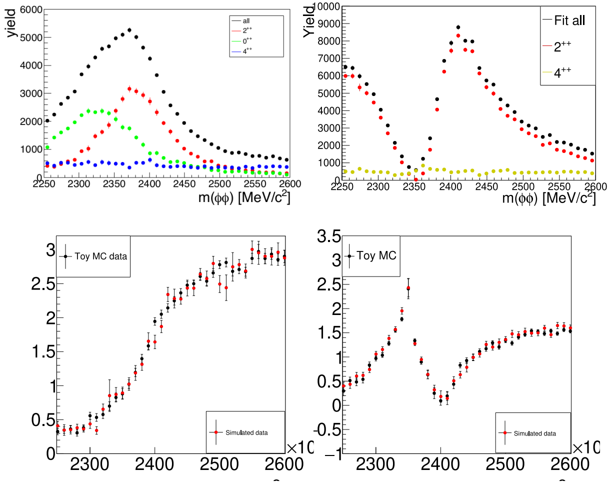
# PWA with Simulated Events - Fits

- Same fit and analysis procedure like Toy MC analysis
- Fit in good agreement with data
- Efficiency correction needed
- Angluar distributions for bin at 2.25 GeV (BW-Scenario)



- Good agreement between extracted phases and contributions of Toy MC and simulated data

BW scenario KM scenario



# Summary and Conclusion

- The reaction $\bar{p}p \to \phi\phi \to 4K$ was generated with angular distributions according to assumed resonance model using PAWIAN
- PWA and model selection tested for simple Breit-Wigner and sophisticated K-Matrix scenario
  $\to$ Identification of contributing resonances feasible
- Reconstruction of generated events including efficiency and resolution of the $\overline{\text{P}}$ANDA detector
- DPM background study
  $\to$ Non $4K$ background events can be suppressed sufficiently
- Good agreement between extracted phases and contributions of toy MC and reconstructed MC
- Estimated run time for scan: $< 1$ week