

# PWA of $\bar{p}p \rightarrow \phi\phi$

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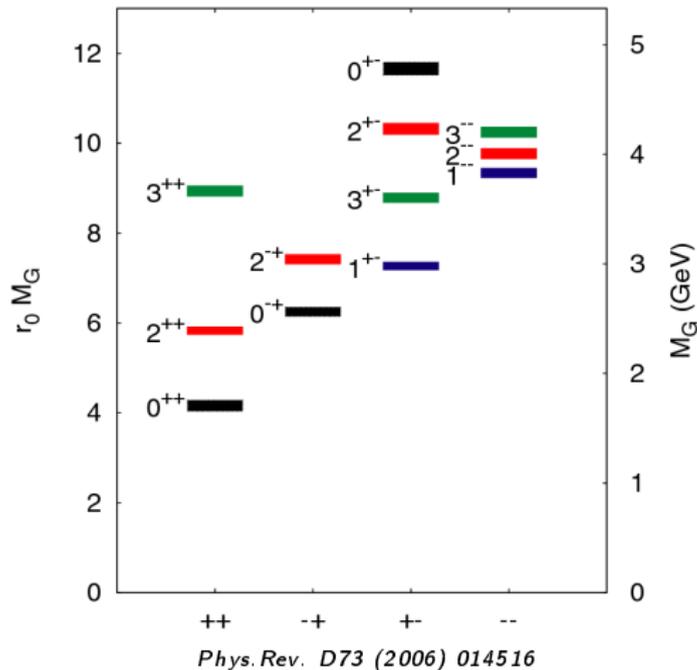
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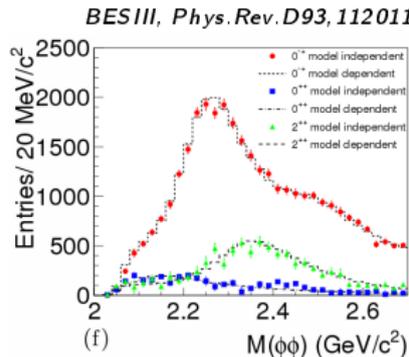
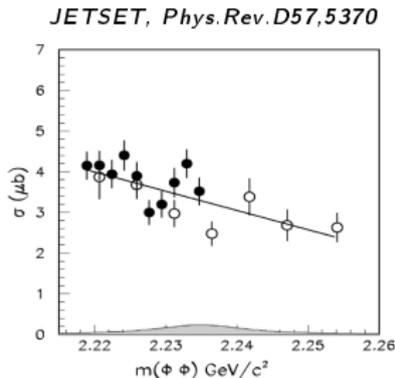


- 1 Motivation
- 2  $\bar{p}p$  initial States
- 3 Model Independent PWA
  - $2^{++}$  signal +  $0^{++}$  component
  - $2^{++}$  signal +  $0^{++}$  +  $4^{++}$  component
  - Overlapping Resonances
- 4 Conclusion and Outlook

- QCD predicts tensor glueball state at  $2.4 \text{ GeV}/c^2$

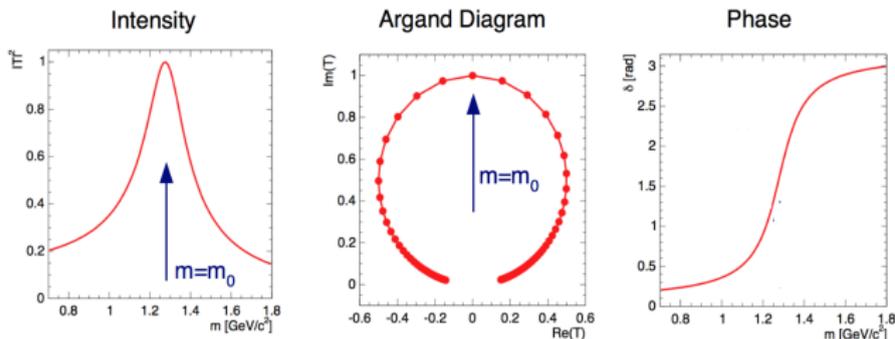


- JETSET experiment  $\rightarrow$  Magnitude of  $\bar{p}p \rightarrow \phi\phi$  cross section exceeds expectations from a simple application of the OZI rule by two orders of magnitude
- Observation of resonances in  $\pi^- p \rightarrow \phi\phi n \rightarrow$  PWA revealed presence of three interfering tensor resonances  $f_2(2010)$ ,  $f_2(2300)$  and  $f_2(2340)$
- BESIII experiment  $\rightarrow$  Tensor resonances also in  $J/\psi \rightarrow \gamma\phi\phi$
- Large cross section coming from intermediate glue



- Scan the cross section of  $\bar{p}p \rightarrow \phi\phi$  in the mass region of the tensor glueball candidate ( $\sqrt{s} = (2.25 - 2.7)\text{GeV}/c^2$ )
- Resonant and non-resonant reactions have same signature  
→ Partial Wave Analysis needed to extract  $2^{++}$  contribution
- How to extract the contribution of resonances created in formation processes?  
→ Model Independent Approach
- Software package PAWIAN (**PA**rtial **W**ave Interactive **AN**alysis)

## Indications for the presence of a resonance



*K. Peters, arXiv:hep-ph/0412069v1*

- Phase-motion as an indication for the presence of a resonance
- Only extraction of relative phases possible  
→ 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:

$$\text{singlet: } \sqrt{\frac{1}{2}}|(\uparrow\downarrow - \downarrow\uparrow)\rangle = |S = 0, \lambda = 0\rangle$$

$$\text{triplet: } |\uparrow\uparrow\rangle = |S = 1, \lambda = 1\rangle, \sqrt{\frac{1}{2}}|(\uparrow\downarrow + \downarrow\uparrow)\rangle = |S = 1, \lambda = 0\rangle,$$

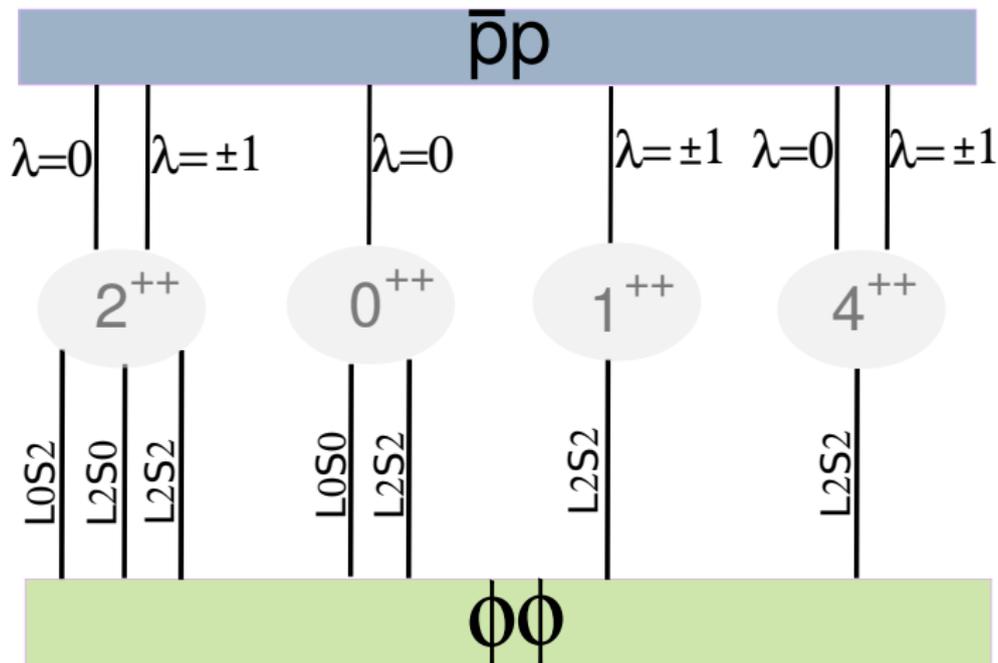
$$|\downarrow\downarrow\rangle = |S = 1, \lambda = -1\rangle$$

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	$^1I_6$	$6^{-+}$	$^3I_6$	$6^{--}$	$^3H_6, ^3J_6$	$6^{++}$

- Possible resonances for  $X$  in  $\bar{p}p \rightarrow X \rightarrow \phi\phi$  ( $J^{PC}(\phi) = 1^{--}$ )
- Initial states with high  $J$  should be suppressed

$J$	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						

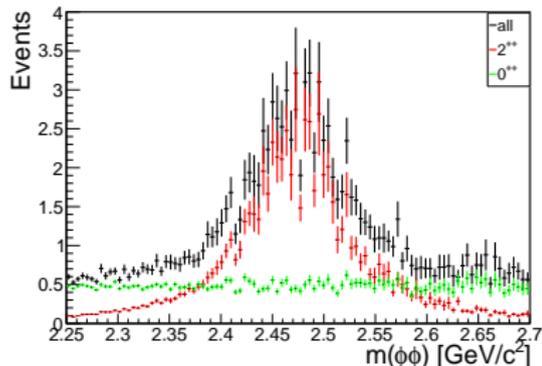
- Possible production and decay amplitudes ( $L, S < 4$ )
- $L + S$  must be even due to identical daughter particles in the decay



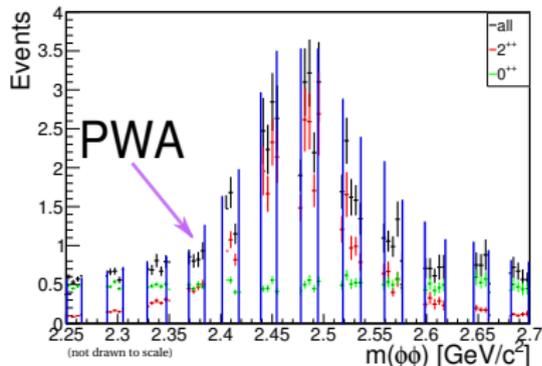
## $2^{++}$ signal $0^{++}$ component

- $2^{++}$  ( $\lambda = 0$ , L2S0) signal with  $m = 2.47$  GeV, width = 100 MeV and  $0^{++}$  (L0S0) component with fixed phase
- Generation of 1Mil  $\bar{p}p \rightarrow X \rightarrow \phi\phi$  ( $X = 2^{++}/0^{++}$ ) toy data events
- Data divided into 100 keV sized mass bins, “gap” of 10 MeV between each bin is left  $\rightarrow$  reproduction of energy scan character
- Partial wave fits performed for each mass bin individually
- Event based maximum likelihood fit

Generated contributions



Model independent PWA with scan character



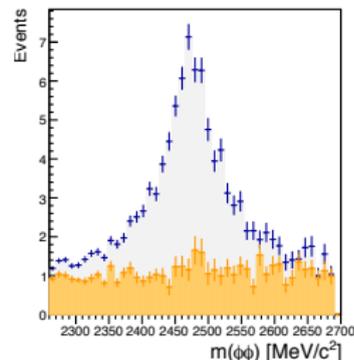
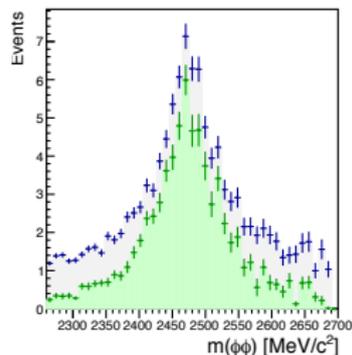
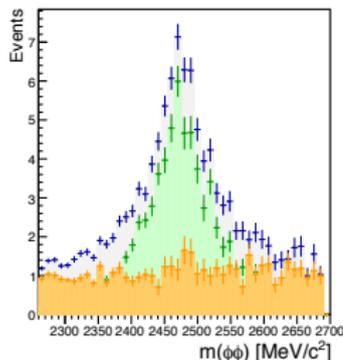
- Use final fit result parameters as start parameters for the next bin

state	fixed parameter	free parameter
$2^{++}$	decay amplitude ( $\text{mag}, \phi$ )	production amplitude ( $\text{mag}, \phi$ )
$0^{++}$	decay amplitude ( $\text{mag}, \phi$ )	production amplitude ( $\text{mag}$ )
	$\phi \rightarrow \text{KK}$ amplitudes fixed	

Extracted contributions after fit

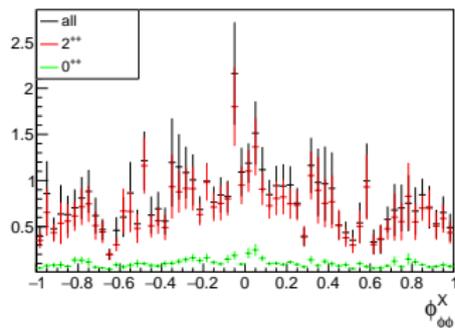
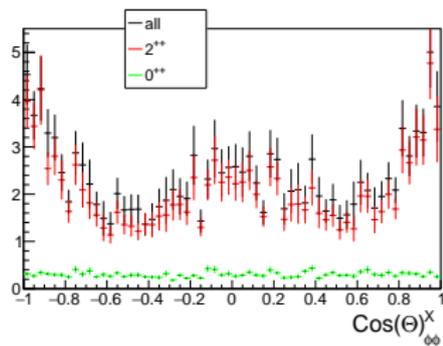
$2^{++}$

$0^{++}$

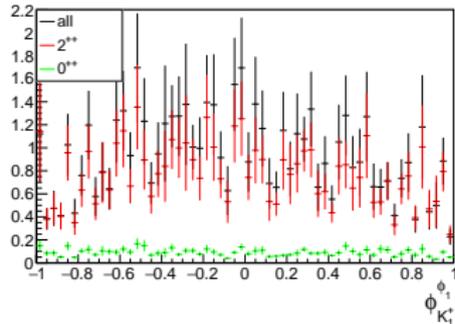
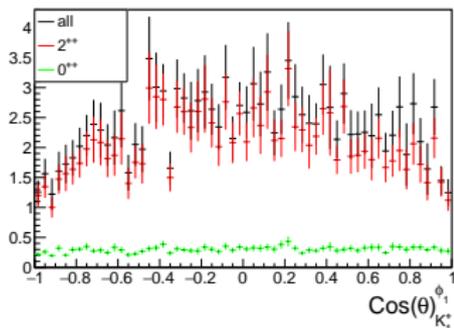


## Angular distributions for bin at $2.47 \text{ GeV}/c^2$

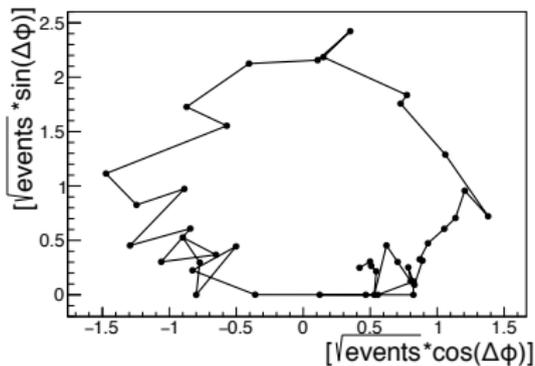
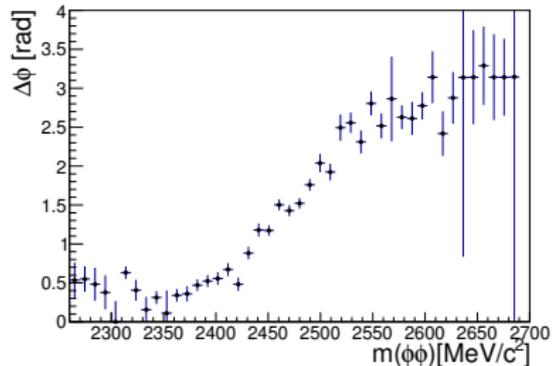
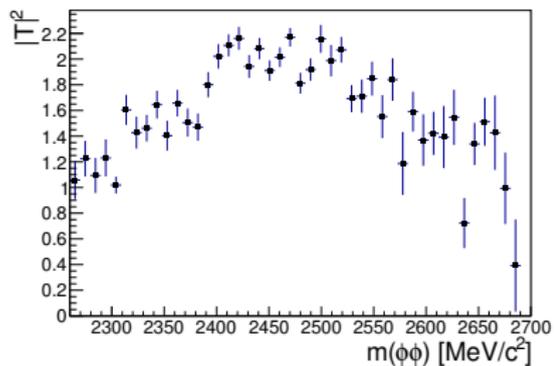
$$X \rightarrow \phi\phi$$



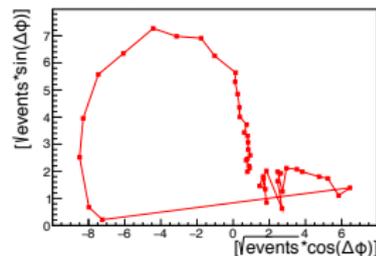
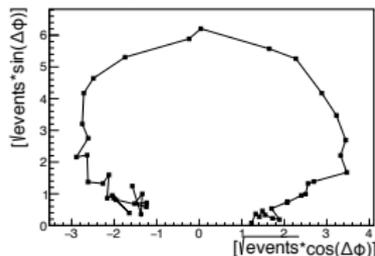
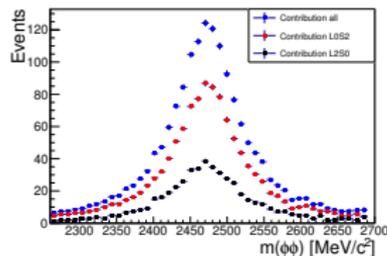
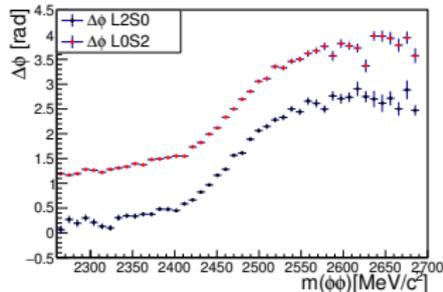
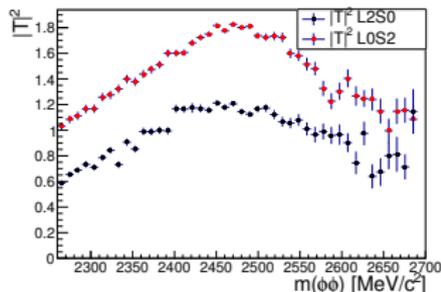
$$\phi_1 \rightarrow K_1^+$$



# $2^{++}$ signal $0^{++}$ component



- 2 “Decay chains” for  $2^{++}$  signal ( $\lambda = 0 \rightarrow L0S2, L2S0$ )
- 1 MeV sized mass bins
- $2^{++}$ :  $\text{mag}$  and  $\phi$  of decay amplitudes free, production amplitude parameters fixed



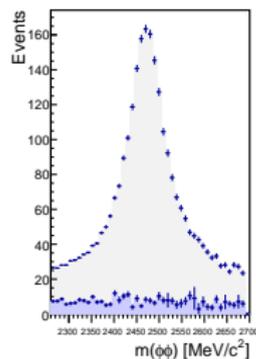
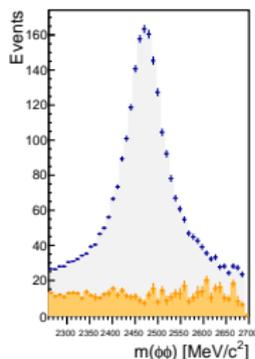
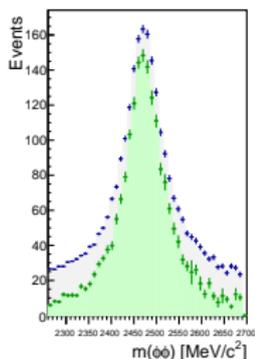
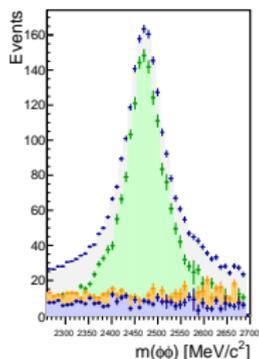
# $2^{++}$ signal $0^{++} + 4^{++}$ component

- How to access the  $2^{++}\lambda = \pm 1$  phases?  
 → Add additional component with  $\lambda = \pm 1$  production mode
- Clear separation of 3 different  $J^{++}$  contributions?
- How to handle 2 “Decay chains” for the  $0^{++}$  component?

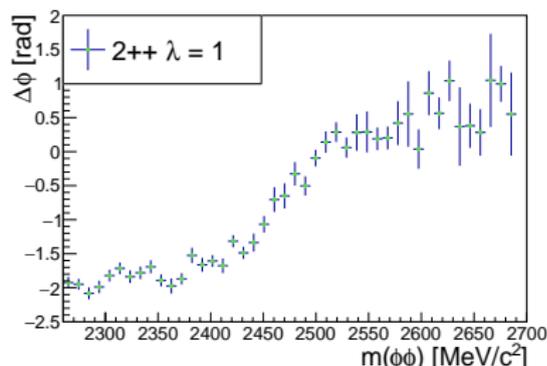
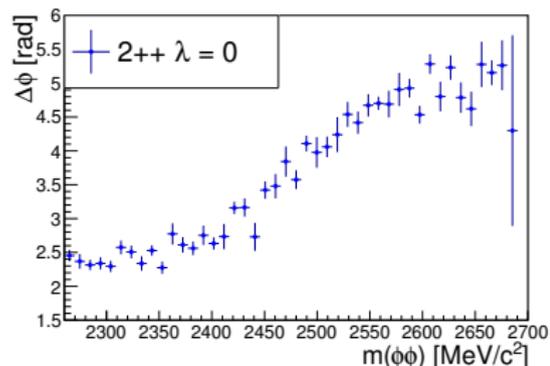
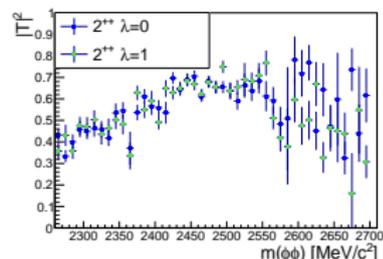
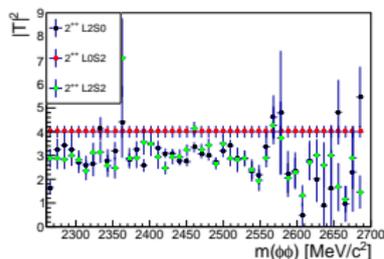
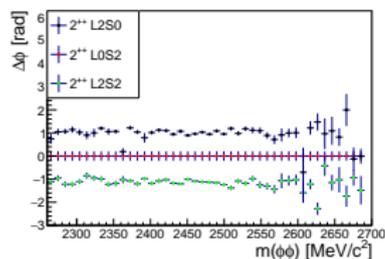
state	fixed parameter	free parameter
$2^{++}$ (L0S2),(L2S0),(L2S2)	L0S2 amplitude ( $\text{mag}, \phi$ )	rest( $\text{mag}, \phi$ )
$0^{++}$ (L0S0),(L2S2)	production amplitude ( $\text{mag}, \phi$ )	L0S0( $\text{mag}$ ), L2S2( $\text{mag}, \phi$ )
$4^{++}$ (L2S2)	decay amplitude ( $\text{mag}, \phi$ ), prod( $\lambda = 1$ ) $\phi$	prod( $\lambda = 1, 0$ ) $\text{mag}$ , prod( $\lambda = 0$ ) $\phi$

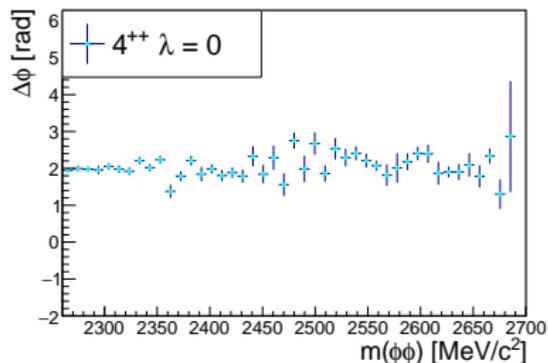
Extracted contributions after fit	$2^{++}$	$0^{++}$	$4^{++}$
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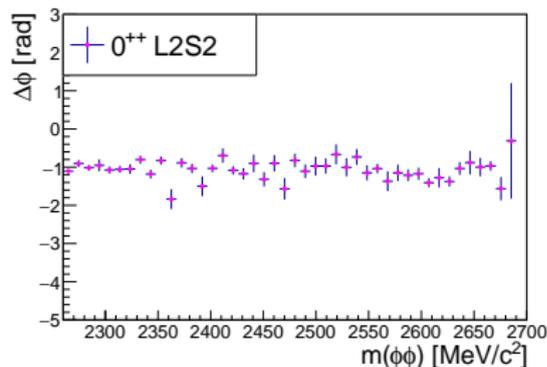
## $2^{++}$ signal



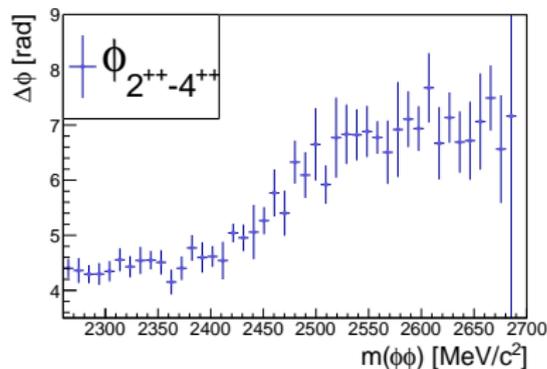
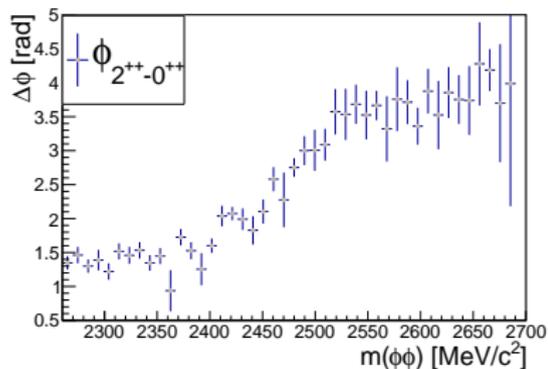
# $2^{++}$ signal $0^{++} + 4^{++}$ components



$$\Delta\phi_1(\phi_{2^{++}\lambda=0} - \phi_{0^{++}})$$



$$\Delta\phi_2(\phi_{2^{++}\lambda=0} - \phi_{4^{++}\lambda=0})$$



- Procedure to extract the phase in each bin for the identification of a resonance tested on different combinations of  $J^{++}$  states including all possible “Decay chains”  
→  $2^{++}0^{++}1^{++}$ ,  $2^{++}4^{++}1^{++}$ ,  $2^{++}0^{++}1^{++}4^{++}$ ...
- Clear separation of overlapping  $J^{++}$  resonances possible?
- Move on to a more “realistic” example: Glueball resonance at 2.4 GeV and width of 100 MeV,  $f_0(2330)$  resonance,  $4^{++}$  component with fixed phase
- Tensor glueball → 6 “Decay chains”,  $f_0(2330)$  → 2 “Decay chains”
- How many events per bin needed for a clear identification?
- How does the identification depend on signal to  $J^{++}$  component ratio?

- 1 Mil Monte-Carlo events generated

state	fixed parameter	free parameter
Glueball (L0S2),(L2S0),(L2S2)	L0S2 amplitude (mag, $\phi$ )	rest(mag, $\phi$ )
f <sub>0</sub> (2330) (L0S0),(L2S2)	L0S0 (mag, $\phi$ )	rest(mag, $\phi$ )
4 <sup>++</sup> (L2S2)	decay amplitude (mag, $\phi$ ), prod( $\lambda = 1, 0$ ) $\phi$	prod( $\lambda = 1, 0$ )mag

- Identify phase, magnitude and contribution with complex number for each “Decay chain”:

$$\rightarrow A_{\lambda=0,1 \rightarrow LXSX} e^{i\phi_{\lambda=0,1 \rightarrow LXSX}} = A_{\lambda=0,1} e^{i\phi_{\lambda=0,1}} \cdot A_{LXSX} e^{i\phi_{LXSX}}$$

- Propagation of uncertainties of combined magnitude and phase:

$$u_y = \sqrt{\sum_{i=1}^m \left(\frac{\partial y}{\partial x_i} \cdot u_i\right)^2 + 2 \sum_{i=1}^{m-1} \sum_{k=i+1}^m \left(\frac{\partial y}{\partial x_i}\right) \left(\frac{\partial y}{\partial x_k}\right) \cdot u(x_i, x_k)}$$

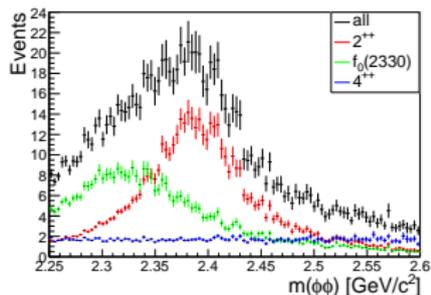
- Correlation coefficients of covariance matrix:

→ 28 covariance matrix elements for 2<sup>++</sup> “Decay chains”

→ 17 covariance matrix elements for f<sub>0</sub> “Decay chains”

# $2^{++}$ Glueball Scenario With Overlapping Resonances

Generated contributions

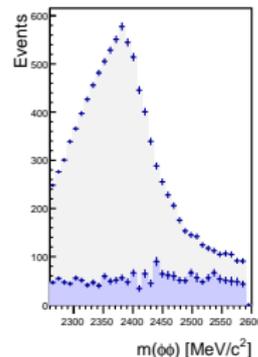
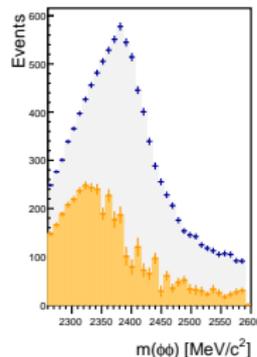
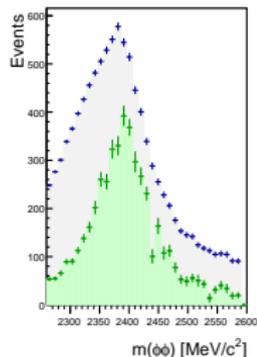
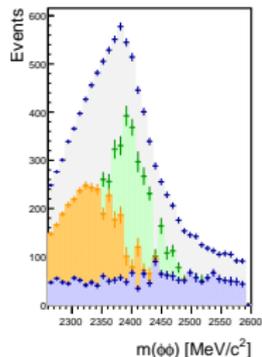


Extracted contributions

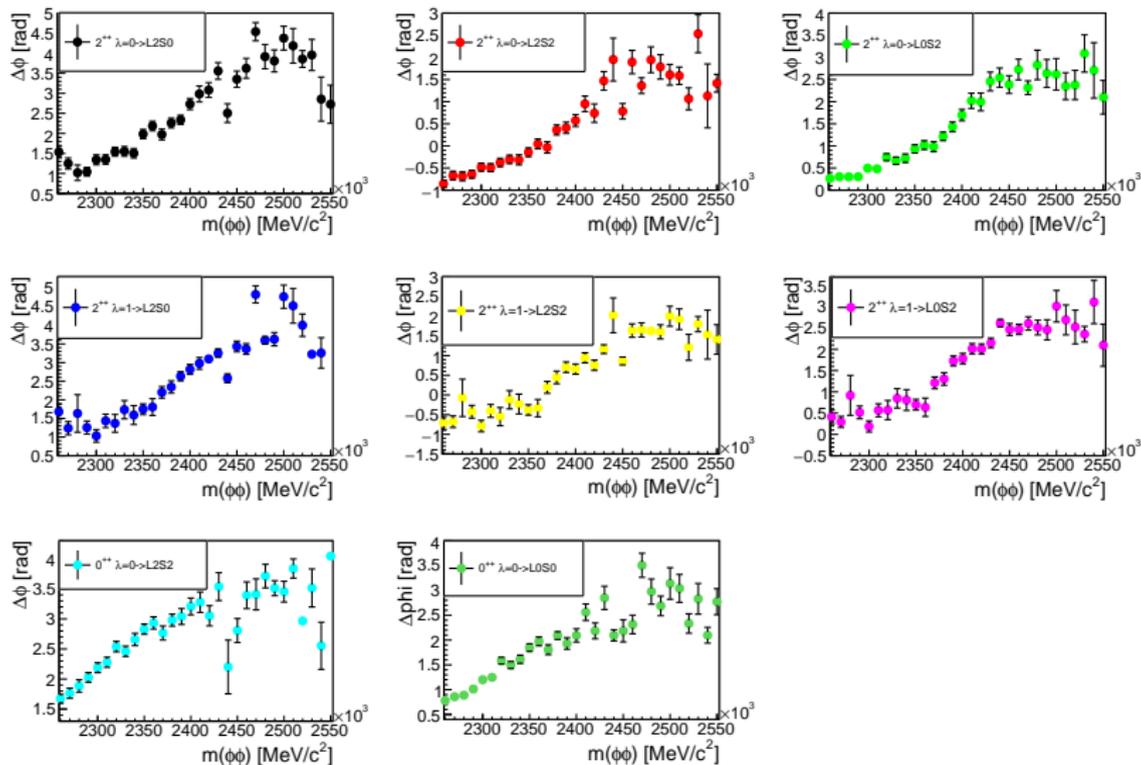
$2^{++}$

$0^{++}$

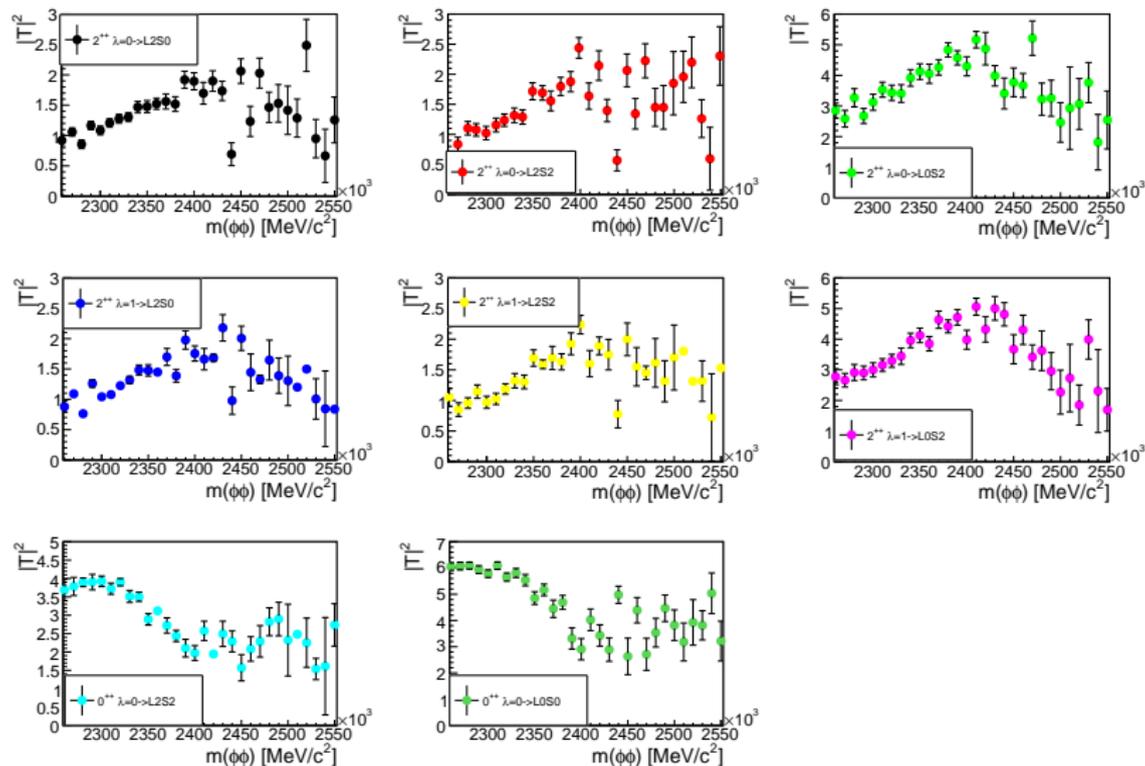
$4^{++}$



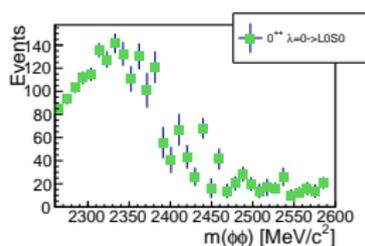
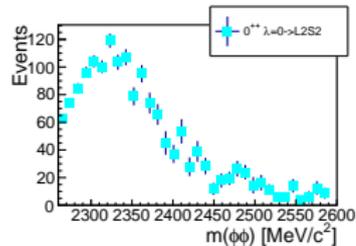
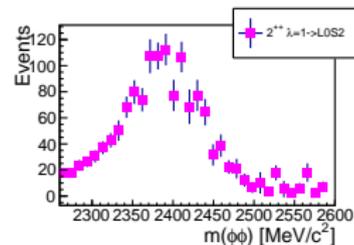
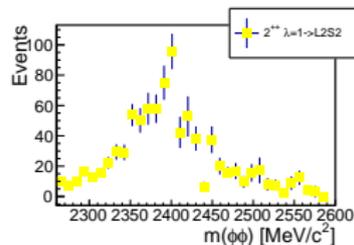
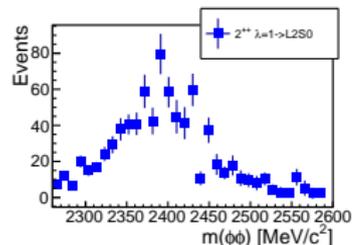
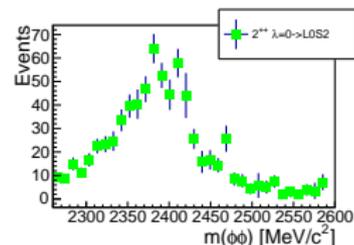
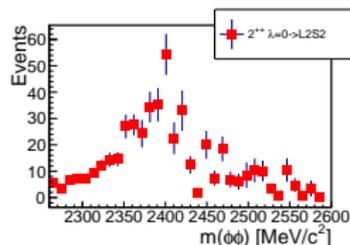
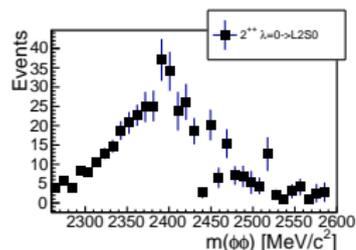
## Combined extracted phases



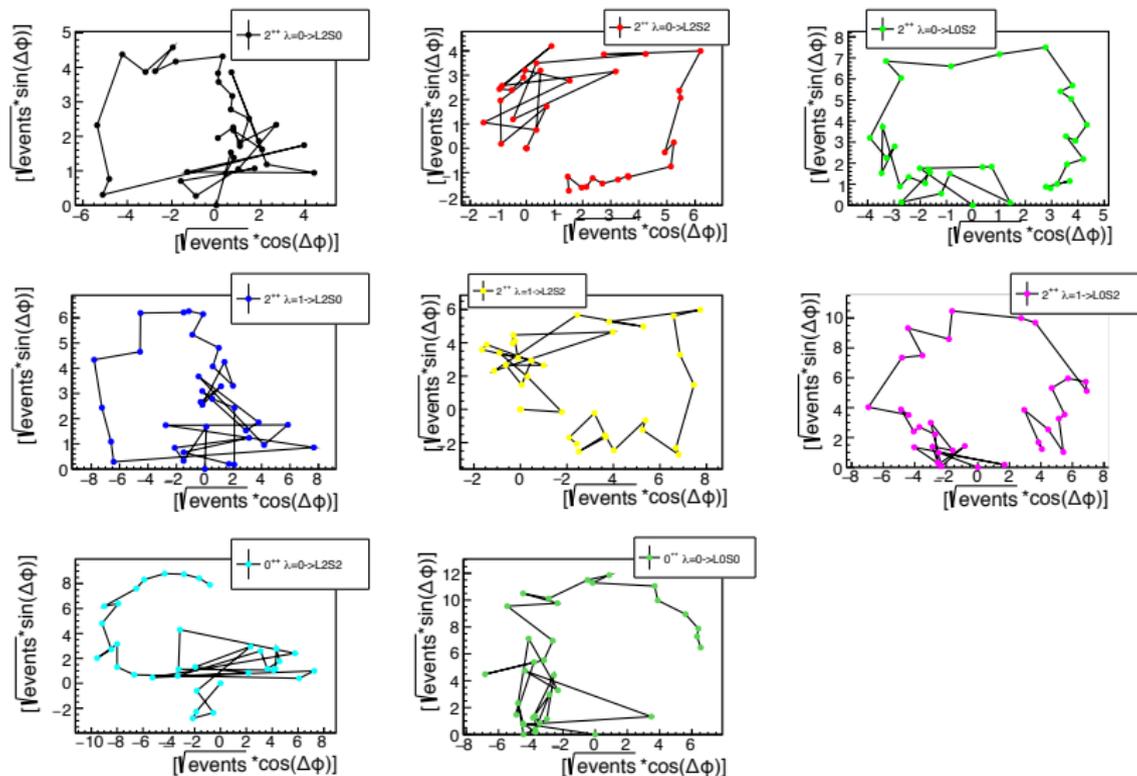
## Combined extracted magnitudes



## Extracted contributions

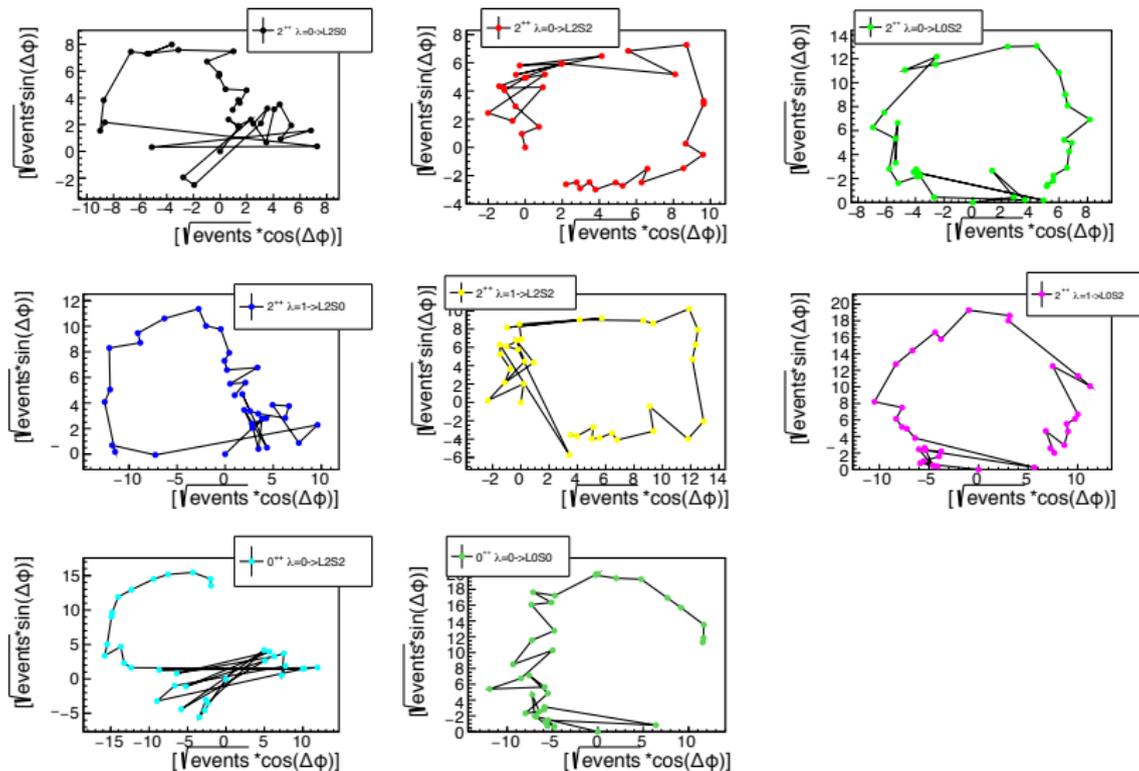


Argand plots ( $2^{++}$  contribution to  $4^{++}$  contribution ratio: 35%)

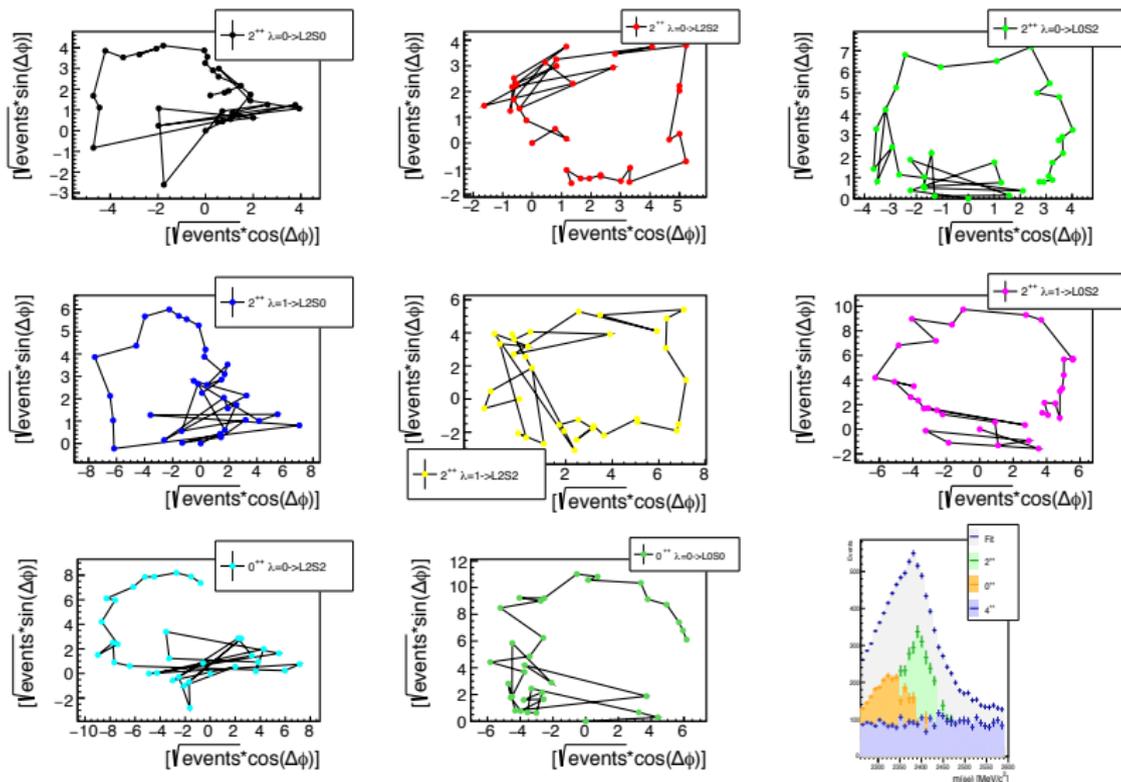


## Argand Plots ( $2^{++}$ contribution to $4^{++}$ contribution ratio: 35%)

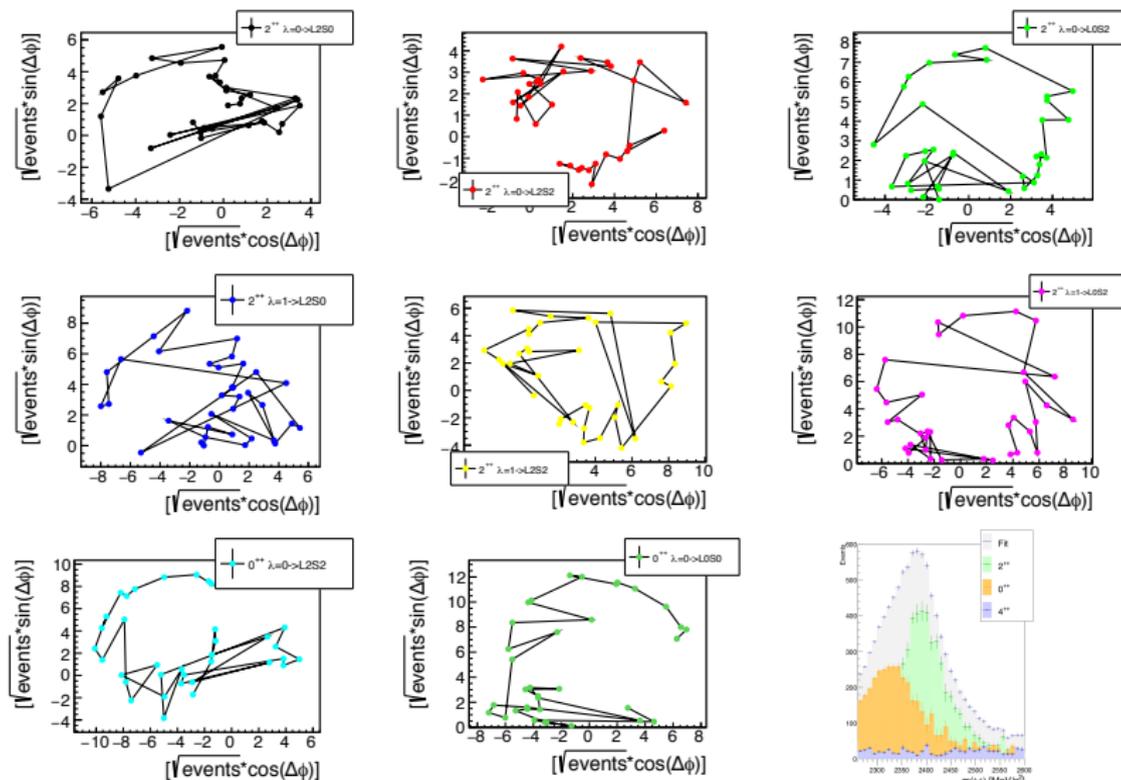
3 times higher number of generated events



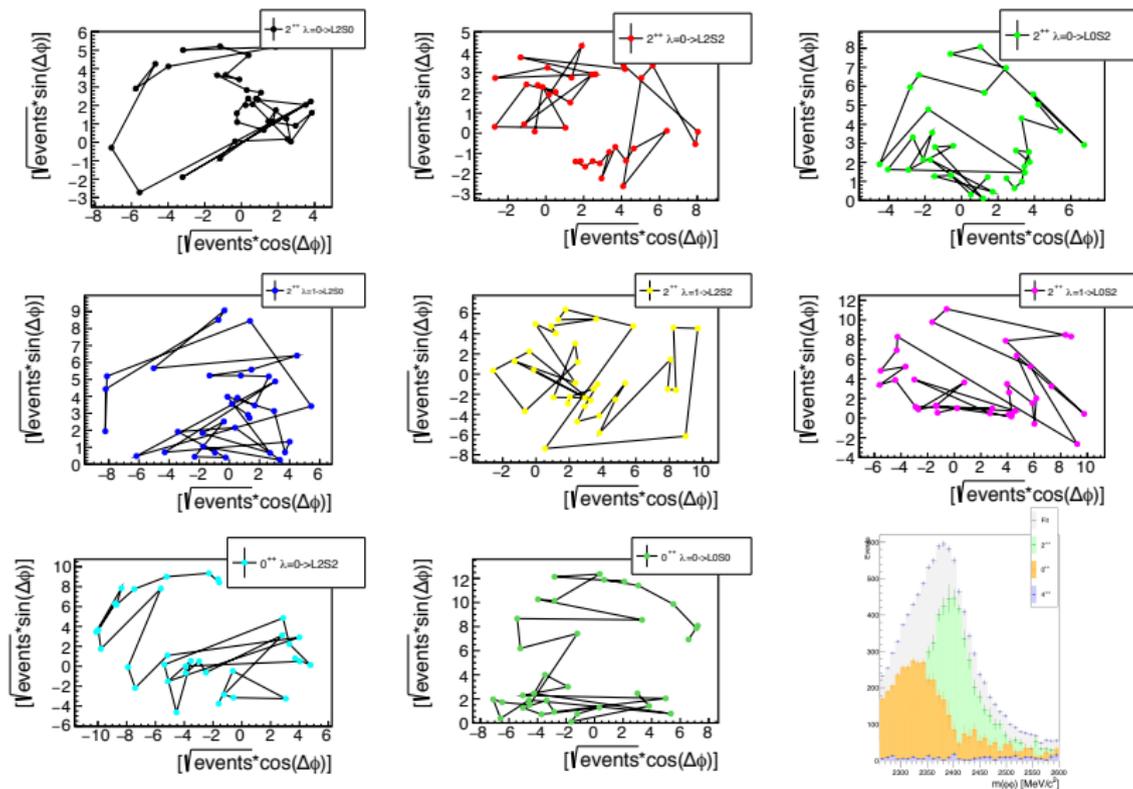
2<sup>++</sup> contribution to 4<sup>++</sup> contribution ratio: 74%



2<sup>++</sup> contribution to 4<sup>++</sup> contribution ratio: 15%

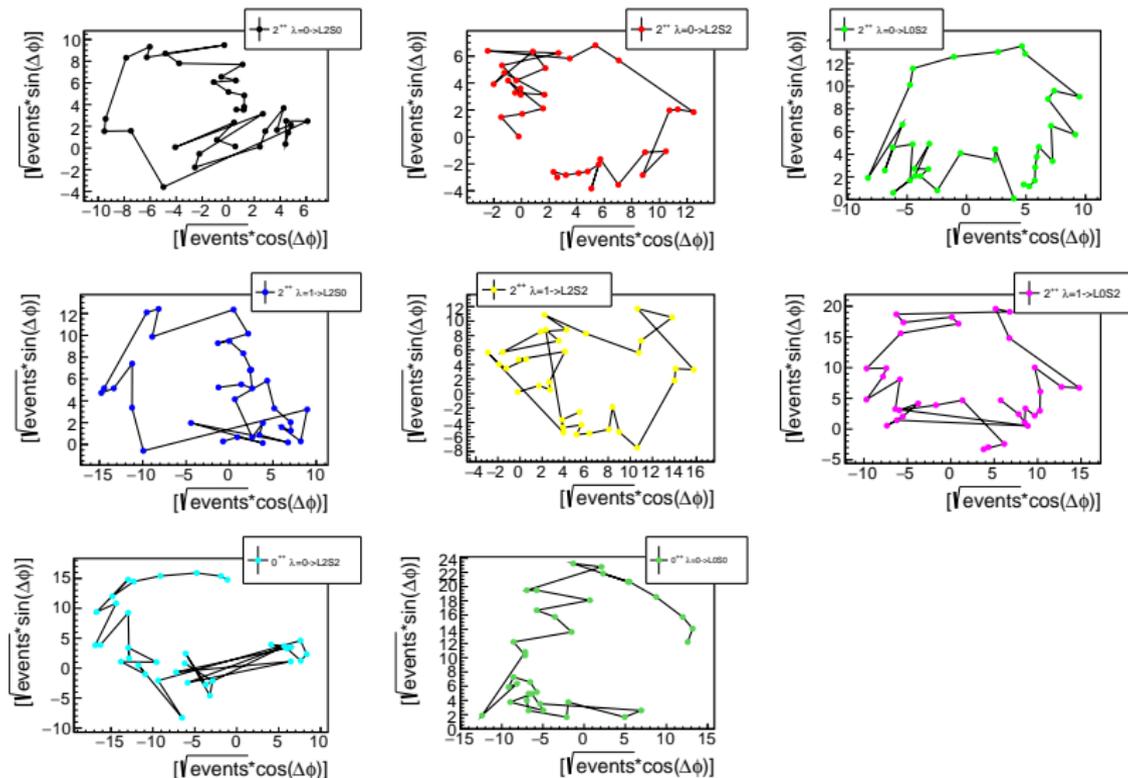


2<sup>++</sup> contribution to 4<sup>++</sup> contribution ratio: 5%



$2^{++}$  contribution to  $4^{++}$  contribution ratio: 5%

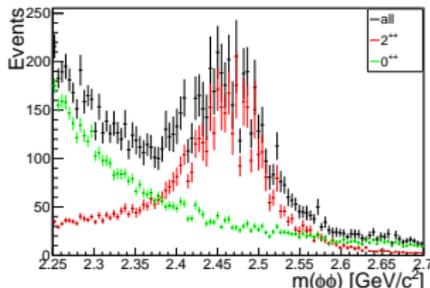
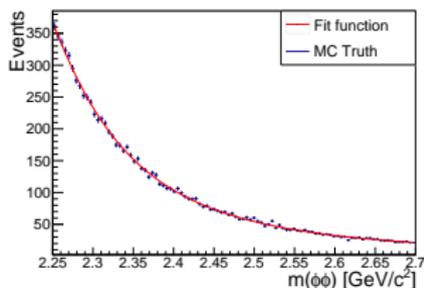
3 times higher number of generated events



- Separation of different  $J^{++}$  contributions with a model independent approach
- Procedure to observe phase-motions as an indication for the presence of a resonance created in formation tested on different toy data sets
- Quality of separation depends on number of signal and number of  $J^{++}$  component events
- Quality of separation does not depend on signal to  $J^{++}$  component ratio
- Procedure can be used to analyse any resonance created in formation processes
- Problem of choosing the right start parameters for the fits to reach the global minimum  
→Redo fits with random parameters
- Take singlet states into account

- $2^{++}$  ( $\lambda = 0$ , L2S0) signal with  $m = 2.47$  GeV, width = 100 MeV and  $0^{++}$  (L0S0) component
- Generation of 1Mil  $\bar{p}p \rightarrow X \rightarrow \phi\phi$  ( $X = 2^{++}/0^{++}$ ) toy data events

Generated contributions



Reweight events with inverse fit function

